Mini-Workshop
„Electromagnetic Radiation off Colliding Hadron Systems: Dileptons and Bremsstrahlung“

Editors:
Eckart Grosse, Burkhard Kämpfer
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Since several years various groups of the Institute of Nuclear and Hadron Physics at Forschungszentrum Rossendorf (FZR) are involved in medium energy physics projects where electromagnetic signals play a role:

(i) pp bremsstrahlung experiments at COSY-ToF have been proposed by a group from Dresden with FZR participation, and a large part of the ToF detector system has been built in Rossendorf.

(ii) The FZR is presently building one of the large wire chamber planes for the HADES detector at GSI and is also actively taking part in the HADES commissioning.

(iii) The theory group here at Rossendorf is working in the field of dilepton production and other electromagnetic processes.

To discuss the research in these fields with colleagues from other places and to coordinate the efforts this mini-workshop was organized. The idea was to discuss the results of the experiments at different accelerators, the status of the calculations and the plans for future investigations. Besides bremsstrahlung special emphasis will be on dielectron production; other processes with electromagnetic signals (like vector-meson production) have also been discussed.

E. Grosse  B. Kämpfer
Electromagnetic Radiation off Colliding Hadron Systems:
Dileptons & Bremsstrahlung

Miniworkshop at the
Forschungszentrum Rossendorf near Dresden,
Institute of Nuclear and Hadron Physics
April 16 - 17, 1999
Lecture Hall (Kleiner Hörsaal im Haus 120)

Programme

Thursday, April 15: Arrival
Friday, April 16:

9.00 a. m.  E. Grosse (Rossendorf):
            U. Mosel (Giessen):
            J. Bacelar (Groningen):

            chairman: E. Grosse
            Opening
            Hadrons in medium - overlook and perspective
            Virtual bremsstrahlung experiments in few-body
            systems at KVI

Break

11.15 a.m.  J. Ritman (Giessen):
            V. Hejny (Jülich):

            chairman: H. Freiesleben
            Rho, omega, phi production in pp reactions near
            threshold
            Photoproduction of light mesons - results from
            TAPS at MAMI

Lunch
(Canteen)

1.45 p.m.   O. Scholten (Groningen):
            C. Fuchs (Tübingen):
            N. Kalantar (Groningen):

            chairman: B. Kämpfer
            pp bremsstrahlung: theory & polarization effects
            Background contributions to dilepton spectra in
            pp collisions
            Bremsstrahlung experiments at KVI

Break
4.15 p.m.  S. Scherer (Mainz):  
NN bremsstrahlung and Compton scattering - examples of the impossibility of measuring off-shell effects

J. Zlomanzcuuk (Uppsala/Warszawa):
Bremsstrahlung experiments at CELSIUS

E. Kuhlmann (Dresden/Jülich):
Bremsstrahlung experiments at COSY/ToF

Buffet - Dinner

Saturday, April 17:

9.00 a.m.  J. Wambach (Darmstadt):
Dileptons and chiral symmetry restoration
G. Wolf (Budapest)
Describing the in-medium rho & omega

Break

10.45 a.m.  M. Krivoruchenko (Tübingen):
Decay rates for dilepton production in HICs
F. Dohrmann (Rossendorf):
The HADES project
P. Tlusty (Rez):
Status of the HADES - TOF

Lunch (Haus 120)

1.00 p.m.  R. Holzmann (GSI):
First experiments with HADES: $e^+e^-$ production in pp and AA collisions
R. Schicker (GSI):
Dalitz decay measurements with HADES
W. Koenig (GSI):
Omega meson spectroscopy at HADES in pi-A reactions

Departure
## Participants

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<th>Who</th>
<th>From</th>
<th>Where</th>
<th>When</th>
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<td>Bakelar, J.</td>
<td>Groningen</td>
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Schulte-Wissermann M.
Senger, P.
Stroht, J.
Thusty, P.
Wambach, J.
Wolf, G.
Wüstenfeld, J.
Zlomanzcuk, J.
Zumbruch, P.

Dresden
Darmstadt
Darmstadt
Rez
Darmstadt
Budapest
Darmstadt
Uppsala/Warzaw
Darmstadt

privat
Unterkunft bei Dr. Naumann
Pension Becker
Pension Rüger
Pension Zu den Linden
Unterkunft bei Dr. Wagner
Pension ARCADE
Pension ARCADE
Pension Zu den Linden

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from Rossendorf:

H.W. Barz
M. Debowski
S. Dshemuchadse
K. Gallmeister
E. Grosse
B. Kämpfer
R. Kotte
K. Möller
H. Müller
L. Naumann
O. Pavlenko
C. Schneider
D. Wohlfarth
TRANSPARENCIES OF THE MINIWORKSHOP

Electromagnetic Radiation off Colliding Hadron Systems: Dileptons and Photons

U. Moed:
Hadrons in medium: overview and perspective

J. Baechler:
Virtual bremsstrahlung experiments in few-body systems at KVI

J. Ritman:
Meson production experiments in pp reactions with the DISTO spectrometer

V. Hejny:
Photoproduction of light mesons - results from TAPS at MAMI

O. Schröder:
Proton-proton bremsstrahlung

C. Pacheco:
Background contributions to dilepton spectra in pp collisions

N. Kalantar:
Bremsstrahlung experiments at KVI

S. Schott:
NN bremsstrahlung and Compton scattering - examples of the impossibility of measuring off-shell effects

J. Zimanyi:
Bremsstrahlung in pp collisions at 310 MeV

E. Kahlmaier:
Bremsstrahlung experiments at COSY-TOF

J. Wambach:
Dileptons and chiral symmetry restoration

Gy. Wolf:
Vector mesons in nuclear matter

M. Kümmerlen:
Decay rates for dilepton production in HI collisions

P. Dohrmann:
The HADES project

P. Thury:
Status of the HADES-TOF

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First experiments with HADES: e⁺e⁻ production in pp and AA collisions

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Ω meson spectroscopy at HADES in πA reactions
U. Mosel:
Hadrons in medium – overlook and perspective
Hadrons in Medium
Introduction and Overview*

Based on work with:
E. Bratkovskaya, W. Cassing,
M. Effenberger, H. Lenske,
S. Leupold

• Motivation/Introduction
• QCD Sum Rules vs Hadronic Models
  • Observables: Dileptonproduction
    • Heavy-Ion Reactions
    • Pion-Induced Reactions
    • Photoabsorption and Photodileptons
    • Effects at High Energies and Momenta
• Summary/Conclusions

*Supported by BMBF, DFG and GSI Darmstadt
Electromagnetic Form Factors

Transition rate for em process

\[ \sim \int d^3x dt e^{-i(\vec{p}_x \vec{x} + E_y t)} \left| \mathcal{M}(\vec{x}, t) \right|^2 \]

- Space-like

\[ E_y^2 - \vec{p}_x^2 < 0 \]

Effective mass

\[ E_y^* \sim M_y^* \]

Spherical distribution

\[ \sim \delta(\vec{r}, \vec{p}) \]

\[ M_y^* \geq 2 \text{ GeV} \quad \text{for } pp \]

\[ M_y^* \geq 0.28 \text{ GeV} \quad \text{for } \pi^+ \pi^- \]

Spatial distributions

\[ \sim \delta(\vec{r}, \vec{p}) \]
\[ \Gamma_{\pi^0}(q^2) = 1 + \left( \frac{\alpha}{\pi} \right) \frac{q^2}{m_{\pi}^2 - i m_{\pi} \Gamma_{\pi^0}(q^2) - q^2} + \left( \frac{\alpha}{\pi} \right) \frac{q^2 \epsilon_i q_{\mu} \epsilon^*_{\nu}}{m_{\pi}^2 - i m_{\pi} \Gamma_{\pi^0}(q^2) - q^2} \]

![Graph of Monopole Fit](image)

"Monopole Fit"

(with \( q^2 \)-dependent strengths)
How well does VDM work?

- Pions good up to ~ 2 GeV
  Form factor measured, peak at m other mesons (e.g.) don't work.

- Nucleon couplings within factors of 2
  Form factor cannot be measured in pole region → "unphysical region"

Ways out:
- Dispersive theoretical analysis of forward form factors with isospin
- Folded shape of other channels for form factors.
Clean Experiment

\[ e^+ e^- \rightarrow e^+ e^- + \sum_{N^*} N^* \]

+ crossed diagrams + t-channel

+ Bethe Heitler contribution

"Compton Scattering in Time-like Vector"  

\[ QCD \, Sum \, Rule \, Result \]

Hatsuda & Lee 1992
\[ \sigma(e^+e^- \to \text{hadrons}) = -\frac{e^2}{s} \text{Im} \Pi(q^2) \]

Simple VMD: \[ j^\mu = \frac{e^2}{g} \gamma^\mu \]

\[ \Pi(q^2) = \frac{m^2}{q^2} D_V(q^2) \]

Vector Meson Propagator:

\[ D_V(q^2) = \frac{1}{q^2 - m^2 - i\epsilon} \]

Current-Current Correlator:

\[ \Pi^{\mu\nu}(q) = \int d^4x e^{i qx} \langle 0| T[j^\mu(x) j^\nu(0)] | 0 \rangle \]

\[ = (q^2 g^{\mu\nu} - q^\mu q^\nu) \Pi(q^2) \]

\[ \text{Im} \Pi(q^2) = \frac{m^2}{g^2} \frac{1}{D_V} \text{Im} \Pi_V(q^2) \]

\[ \equiv \frac{\text{Im} \Pi_V(q^2)}{g^2} F_V(q^2) \]

Im selfenergy \( \sim \text{Im} \Pi \)
Spectral Function of Vector Mesons

\[ A(q^2) = -\frac{1}{\pi} \Im D_V(q^2) = -\frac{1}{\pi m_{V}^2} \Im \Pi(q^2) \quad (1) \]

\[ \int_0^\infty dq_0^2 A(q_0, \bar{q}) = 1 \quad \text{Prob. Distr.} \quad (2) \]

2 Strategies to determine A:

- QCDSR \( \rightarrow \) \( \text{\Gamma}_{\text{MC}, \text{P}} \) \( \rightarrow \) \( \Pi_{\nu, A} \)
- Hadron Model
QCD Sum Rule

Compare OPE of current-current correlator for space-like distances with spectral function in time-like region.

Use Dispersion Relation to connect both regions \((Q^2 = -q^2 = -s)\)

\[
\frac{Q^2}{\pi} \int_0^\infty ds \frac{\Im \Pi(s)}{s(s + Q^2)} = -\frac{1}{8\pi^2} \left( 1 + \frac{\alpha_s}{\pi} \right) \ln \frac{Q^2}{\Lambda^2} + \frac{m_q\langle \bar{q}q \rangle}{Q^4} + \frac{\langle \alpha_s G^2 \rangle}{24Q^4} + \frac{\langle (\bar{q}q)^2 \rangle}{Q^6} + \ldots
\]

Lhs dominated by soft scale \((\sim m_\rho)\), rhs (OPE) separates hard, perturbative from soft, non-perturbative scale (condensates). Parametrize \(\Im \Pi\) in terms of few parameters, to be extracted from Sum Rule.

In-medium OPE

\[
\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle_0 + \frac{\sigma_N}{2m_q} \rho
\]

\[
\frac{\langle \alpha_s G^2 \rangle}{\pi} = \frac{\langle \alpha_s G^2 \rangle_0}{\pi} - \frac{8}{9} m_\rho^0 \rho N
\]

\[
\langle (\bar{q}q)^2 \rangle \sim \kappa \langle \bar{q}q \rangle^2
\]

Mean Field Approximation
systematic errors due to uncertainties in condensates included

Leupold, Peters, Mosel, NPA (98)

A628 (1998) 54
**Hadron properties in Medium:**

- masses
- widths
- coupling strengths

all linked by "tq" approximation:

\[ \Pi_V = -4\pi \int_{k=0} f_{VN}(0) \rho \] (for meson)

Good for 

- mass: \[ m_m = m_V \delta_{VN} \rho N \]

with \[ \delta_{VN} = \frac{B_{VNN}}{B_{VNN}} \]

- width:

\[ \Gamma_N = \frac{\rho V_{NN}}{m_N} \]

Is there more than 2?
Models of In-Medium $\rho$

- **Hermann, Friman, Noerenberg (1993)**
  
  ![Diagram](image)
  
  broadens $\rho$, shifts strength down

- **Asakawa, Ko (1993)**
  
  combine HFN model with QCDSR, $\rho$ pole moves down, broadens

- **Klingl, Weise (1997)**
  
  method similar to AK, but much more refined hadronic model

- **Rapp, Wambach (1997)**
  
  $N^*N^{-1}$ + 'state of the art' pion dynamics, significant broadening of $\rho$

- **Friman, Pirner (1997)**
  
  2 $p$-wave resonances with $\rho$-decay widths: $N(1720)$, $\Delta(1905)$, broadens and weakens free $\rho$ pole, moves strength down to new $N^*N^{-1}$ peak.


  **ALL** $p$-wave resonances up to 1.9 GeV

  ![Diagram](image)

  $s$-wave resonances, in particular $N(1520)$ with $\Gamma_\rho = 20\% \Gamma_{tot} \approx 25$ MeV

  ![Diagram](image)

  **Selfconsistent feedback of $\rho$ spectral function on $N^*$ width.**
Spectral function

\[ A = -\frac{i}{\pi} \text{Im} \, \langle T \rangle \]

**Plot 1:**
- **Axes:** M (GeV), \( \varphi_t \) (GeV\(^{-1}\))
- **Data Points:**
  - Peak at \( M \approx 0 \) and \( \varphi_t \approx 0 \)

**Plot 2:**
- **Graphs:**
  - Top: N(1520)
  - Bottom: N(1520)
- **Axes:** M (GeV), \( \varphi_t \) (GeV\(^{-1}\))
- **Legend:**
  - Transverse
  - Longitudinal

\[ \Pi \sim \Phi : \text{non-\( \Phi \) consistent} \]

\[ \Pi^{\mu \nu} \sim (\omega^2 \mathbf{P}_T^\mu - \varphi \mathbf{P}_L^\mu) F(q^2) \]

\[ x \sum \frac{E^k - mn}{\omega^2 - (E^k - mn)^2} \]

(for small \( \varphi \))
Figure 7: Same as Fig. 6, but for the longitudinal spectral function.

Figure 6: Self-consistent transverse spectral function of the rho meson for \( p_x = 0 \). Lower part: Cuts through the upper part for different three-momenta together with the vacuum spectral function.
S+W 200 GeV

Koch-Sing
LKr-Dalitz
Cassing-Chehab-Ko
Brincker-Sone-Gate
EGG-63, 221
UGGD-Frankfurt

\[ \text{H} \]

\[ \text{Koch, Sm} \]

\[ \text{G(0A)} \]

\[ \text{J} \]

\[ \text{Prediction} \]

\[ \text{PRC54(96) 1903} \]

\[ \text{V. Koch} \]

\[ \text{Pb+Pb} \]

\[ \text{Koch et al.} \]

\[ \text{Prediction} \]

\[ \text{PRC54(96) 1903} \]

\[ \text{control Pb+Pb} \]
Coupled Channel BUU

\[
\left( \frac{\partial}{\partial t} + \frac{\partial H_i}{\partial \rho} \frac{\partial}{\partial \vec{r}} - \frac{\partial H_i}{\partial \vec{r}} \frac{\partial}{\partial \rho} \right) F_i = G_i A_i - L_i F_i
\]

Gain

Loss

Take into account all resonances rated at least 2 stars in Manley et al.:

CC-Space

\( P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535), P_{33}(1600), S_{31}(1620), S_{11}(1650), D_{15}(1675), F_{15}(1680), P_{13}(1879), S_{31}(1900), F_{35}(1905), P_{31}(1910), D_{35}(1930), F_{37}(1950), F_{17}(1990), G_{17}(2190), D_{35}(2350) \).
Resonance coupling to:

$N\pi, N\eta, N\omega, \Lambda K, \Delta(1232)\pi, N\rho, N\sigma, N(1440)\pi, \Delta(1232)\rho.$

\[
\begin{align*}
\pi N &\leftrightarrow \rho N \\
\pi N &\leftrightarrow \omega N \\
\pi N &\rightarrow \omega\pi N \\
\omega N &\rightarrow \pi\pi N \\
\omega N &\rightarrow \omega N \\
\pi N &\leftrightarrow \phi N \\
\pi N &\rightarrow \phi\pi N \\
\phi N &\rightarrow \pi\pi N \\
\phi N &\rightarrow \phi N
\end{align*}
\]

*String fragmentation for $m > 2.1 \text{ GeV}$

\[
\frac{\partial}{\partial t} + \frac{\partial H_i}{\partial p_x} \frac{\partial}{\partial \vec{r}} - \frac{\partial H_i}{\partial p_y} \frac{\partial}{\partial \vec{p}} F_i = G_i A_i - L_i F_i
\]

\[
H_i = \sqrt{(\mu + S_i)^2 + \vec{p}^2}
\]

"Spectral p\_density"

\[
f_i(\vec{r}, \vec{p}, \mu, t) = \frac{F_i(\vec{r}, \vec{p}, \mu, t)}{A_i(\vec{r}, \vec{p}, \mu, t)} \quad \text{ps-density}
\]

Spectral function

\[
A_i(\mu) = \frac{\mu^2 \Gamma_{tot}(\mu, \vec{r}, \vec{p})}{\pi (\mu^2 - M_i^2)^2 + \mu^2 \Gamma_{tot}^2(\mu, \vec{r}, \vec{p})}
\]

\[
\Gamma(\vec{r}, t, \vec{p}, \mu) \rightarrow \Gamma(\rho(\vec{r}, t), |\vec{p}|, \mu)
\]

Consistency condition

\[
\Gamma_{tot, \rho} = \gamma L \rho
\]

\[
\text{earlier only for } A, \text{ now also for } F_i
\]

PROPAGATION OF FREE AND RESONANCE:

First in Eubank et al. for $\Delta (1973)$
Gain and Loss Terms illustrated for $p + N \rightarrow R$

Gain term:

$$G_\rho = \frac{1}{A_\rho} \int \frac{d^3 p_R}{(2\pi)^3} d\mu_R$$

$$\times F_R(\vec{r}, \vec{p}_R, \mu_R, t) \frac{d\Gamma_{R\rightarrow N\rho}}{d^3 p d\mu_R} (1 - f_n(\vec{r}, \vec{p}_n, t))$$

Loss term:

$$L_\rho = \Gamma_{\rho\rightarrow n\pi} + \int \frac{d^3 p_n}{(2\pi)^3} f_n(\vec{r}, \vec{p}_n, t) v_{n\rho} \sigma_{n\rho\rightarrow R}$$

Dileptons through strict VMD

$$\Gamma_{\nu \rightarrow e^+ e^-} (M) = C_\nu \frac{m_e}{M^3}$$

Testparticle Approach

for "Spectral Phase-Space Density"

$$F(\vec{r}, t, \vec{p}, \mu) = \sum_i \delta(\vec{r} - \vec{r}_i(t))(\vec{p} - \vec{p}_i(t))$$

$$\times \delta(\mu - \mu_i)$$

$\mu_i$: mass of testparticle $i$.

Propagate testparticles in scalar pot:

$$S_i(p_i(t)) = \left( -\mu_i \frac{m_e}{\mu_i} \right) \frac{p_i(t)}{m_e}$$

$$w_i^x(p_i(t)) = \mu_i \frac{m_e}{\mu_i} + S_i(p_i(t))$$

Correct any plc.1!
Cross section for production of resonance $R$ in collision of meson $m$ with baryon $B$:

$$
\sigma_{mB \rightarrow R} = \frac{2J_R}{(2J_m + 1)(2J_B + 1)} \times 4\pi \frac{s\Gamma_{mB}^{in}\Gamma_{mB}^{out}}{k^2 (s - M_R^2)^2 + s\Gamma_{tot}^{out}}
$$

$$
\Gamma_{mB}^{out} = \Gamma_{mB}^{in} \frac{\rho_{mB}(s)}{\rho_{mB}(M_R)}
$$

$$
\rho_{mB}(s) = \int d\mu_m d\mu_B
$$

$$
\times A_m(\mu_m) A_B(\mu_B) \frac{q(s, \mu_m, \mu_B)}{s} B_{mB}^2(qR)
$$

$$
A_i(\mu) = \frac{2}{\pi} \frac{\mu^2 \Gamma_{tot}(\mu)}{\mu^2 - M_i^2 + \mu^2 \Gamma_{tot}(\mu)}
$$

$$
\Gamma_{mB}^{in} = C_{mB}^{R} \Gamma_{mB}^{0} \frac{k B_{mB}^2(kR)}{s \rho_{mB}(M_R)}
$$
\[ \Gamma_{\omega} = \Gamma_{\pi} + \Gamma_{\rho} \]

\[ \Gamma_{\rho} = \int \frac{\rho^2}{F_0} \, \sigma \, d\sigma \]

\[ \Gamma_{\pi} = \int \frac{\pi^2}{F_0} \, \sigma \, d\sigma \]

\[ \frac{\Gamma_{\pi}}{F_0} = \frac{\Gamma_{\rho}}{F_0} \cdot S \]
Photonuclear In-medium Effect

N. Bianchi et al., PL B325 (93) 333
FIG. 15. The dilepton yield from ω mesons for γPb at 1.5 GeV. The solid line indicates the bare mass case, the dot-dashed line is the result with in-medium masses, the dashed line shows the effect of collisional broadening together with the dropping mass.
Conclusions

- QCD Sum Rules give only wide constraints for in-medium properties of hadrons → Original expectation of QCD mandated lowering of mass too naive.

- All realistic hadronic models give significant broadening up to dissolution of $\rho$ meson. Mass shift meaningless.

- Transverse and longitudinal $\rho$ spectral functions differ significantly. → Check in polarization measurements.

- In-medium changes of $\rho$ also affect nucleon resonance widths → photoabsorption cross section.
• Heavy-Ion Collisions achieve large peak densities and thus large sensitivity to in-medium $\rho$ spectral function. But: smear over time (density, temperature), average over polarization.

• Pion- and Photon-induced reactions give equally strong signal, cleaner, should enable to differentiate between longitudinal and transverse $\rho$'s.

• At high energies collision broadening of $\rho$ mesons remarkably constant: $\delta \Gamma_\rho \approx 100$ MeV. Initial State Shadowing only effective if $\lambda_\rho \approx 2\, fm \leq l_{\text{coh}}$. 
J. Bacelar:
Virtual bremsstrahlung experiments in few-body systems at KVI
Workshop on E.M. Radiation off colliding hadron systems: Dileptons and Bremsstrahlung

Virtual Bremsstrahlung experiments in few-body systems at KVI

J. Bacelar - April 1999

- Introd. to virtual bremsstrahlung in NN
- Experimental techniques
- The proton-proton system: ppe\(^+\)e\(^-\)
- The p-d capture: \(^3\)He\(\gamma\), \(^3\)He\(^+\)e\(^-\)
- Future plans

\[
\text{Below pion threshold}
\]

\[
\sigma_{\text{el}} \rightarrow T_{\text{on-shell}} = \langle \text{on} | V + VGV + ... | \text{on} \rangle
\]

\[
\sigma\gamma \rightarrow T_{\frac{1}{2}} \text{off-shell} = \langle \text{off} | V + VGV + ... | \text{on} \rangle
\]
Below pion threshold

\[ \begin{align*}
\sigma_{el} \rightarrow T_{on-shell} &= \langle \text{on}|V + VGV + \ldots|\text{on} \rangle \\
\sigma_\gamma \rightarrow T_{1/2 off-shell} &= \langle \text{off}|V + VGV + \ldots|\text{on} \rangle 
\end{align*} \]

Virtual photon has a mass
Transverse as well as longitudinal polarizations.
Decays into electron-positron pair

**Nucleon-nucleon interaction**

\[ \begin{align*}
\gamma^* \rightarrow \pi_0, & \quad M < 90 \text{ MeV} \\
\pi_0 \rightarrow \gamma + \pi_0, & \quad M = 135 \text{ MeV}
\end{align*} \]

\[ \begin{align*}
E = 190 \text{ MeV} & \quad \rightarrow \quad E = 280 \text{ MeV}
\end{align*} \]
Nucleon-Nucleon Bremsstrahlung

Relevant Feynman Diagrams

a) External Bremsstrahlung (Single Scattering)
b) Internal Bremsstrahlung (Double Scattering)
c) MEC + Δ + N\bar{N} + ...

LT-decomposition

\[ A \sim \frac{e^2}{M_\gamma^2} l' \cdot \mu \]

\[ |A|^2 \sim \frac{W_T}{M_\gamma^2} (1 - \frac{2l^2}{M_\gamma^2} \sin^2 \theta) + \frac{W_L}{M_\gamma^2} (1 - \frac{4l^2}{k_0^2} \cos^2 \theta) + \frac{2l^2}{M_\gamma^4} \sin^2 \theta (W_{TT} \cos 2\phi + W_{TT'} \sin 2\phi) + \frac{2l^2}{M_\gamma^3 k_o} \sin 2\theta (W_{LT} \cos \phi + W_{LT'} \sin \phi) \]
Dif. X-section $pp e^+ e^-$
Absolute scale: systematical error $\pm 15\%$

Results $pp$

*published in: K.V.I. v. der. 1972*
Results \( pp \to pp e^+e^- \)

\[
\begin{align*}
W_T & \sim |J_x|^2 + |J_y|^2 \\
W_{TT} & \sim |J_y|^2 - |J_x|^2 \\
W_{LT} & \sim J_x J_y^* \\
W_{LT}' & \sim J_x J_y \\
W_L & \sim |J_z|^2
\end{align*}
\]

\[ p + p \to p + p + \gamma + \gamma \]
Measured cross-sections
\( ppe^+e^- \) data BLOCK exp.
\( e^+e^- \) contribution subtracted
Preliminary data: 1. Messchendorp

Calculations by G. Martinus, O. Scholten, J.A. Tjon.

Resultaten
Calculations

- Calculation by A. Korchin, O. Scholten and D. van Neck
  - Wave function $^3$He with Argonne V18
  - Contact term $\Rightarrow$ Current conservation

Experimental setup

- 190 MeV polarized proton beam, LH$_2$/LD$_2$
Channel selection

Results pd

Calculations by A. Yu. Korchin et al.

J.G. Messchendorp

KVI
Results $pd$

Calculations by A. Yu. Korchin et al.

Results $p+d \rightarrow ^3\text{He}+e^+e^-$

Calculations by A. Yu. Korchin et al.

- $\alpha=1.2$
- $\alpha=0$

Results $pd$ capture
Conclusions

- $p + p \rightarrow p + p + e^+e^-$
  - First experiment success: $W_T, W_L, W_{TT}, W_{TL}, W'_T, W'_L$ obtained
- $p + p \rightarrow p + p + \gamma + \gamma$
  - First experimental results
  - Interferometer methods, virtual $\pi^0$
    with Plastic Ball
- $p + d \rightarrow ^3He + e^+e^-$
  - Real and virtual capture measured
  - Model calc. explain data
  - High accuracy with Plastic Ball
J. Ritman:
Meson production experiments in pp reactions with the DISTO spectrometer
Meson Production Experiments in pp Reactions with the DISTO Spectrometer

- DISTO Spectrometer
- $\phi/\omega$ Production: Results at 2.85 GeV
- Total $K^-$ Cross section
- $\rho$ Meson Production
- $\eta-\eta'$ and the $U_A(1)$ Anomaly in QCD
- Summary and Outlook

**DISTO Spectrometer**

\[
\bar{p}p \rightarrow pK_{\Lambda}(\Sigma^0) \quad \text{and} \quad \bar{p}p \rightarrow pp(\phi, \omega, \rho, \eta, \eta')
\]
Experimental Method

- 4 Charged Particles in Final State
  Momentum determination via tracking in dipole B-field
  Particle Identification with:
  Water Cherenkov detectors
  Plastic Hodoscopes

- Kinematically complete/overdetermined measurement

  \( pp \rightarrow pp \phi \rightarrow pp K^+ K^- \) \hspace{1cm} (BR = 50%)

  Missing Mass (pp) = Invariant Mass (KK)

  \( pp \rightarrow pp \omega \rightarrow pp \pi^+ \pi^- \pi^0 \) \hspace{1cm} (\pi^0 \rightarrow \gamma\gamma) \hspace{1cm} (BR = 89\%*99\%)

  Missing Mass (pp) = Mass_\omega

  Missing Mass (pp\pi^+\pi^-) = Mass_\pi^0

ϕ/ω Data

Strong deviation from OZI by up to Factor 100 for ϕγ

S-Wave component dominant
Strangeness in the Nucleon and the OZI rule

**OZI rule:** Diagrams with disconnected quark lines are strongly suppressed

\[ |\phi> = \cos\delta \ lss> + \sin\delta \ lqq> \sim lss> \]
\[ |\omega> = \sin\delta \ lss> - \cos\delta \ lqq> \sim lqq> \]

**If** \( |p> = |uud> \):

\[ \phi/\omega \sim 0.0043 \]

Near Threshold (large S-wave contribution)

**DISTO Collaboration**

(Dubna, Indiana, Saclay, Torino, Cracow, Giessen, GSI, FFM)

pp reactions at 83 MeV above threshold

(lowest previously 1730 MeV)
Identification of $\omega$-meson

$pp \rightarrow pp \omega \rightarrow pp \pi^+ \pi^- \pi^0$

**OZI Violation?**

Dramatic in $pp$ annihilation:
- $ss$ in the nucleon?
- or 2-step processes?

figure by V.E. Markushin

non-Dramatic:
- $pp$ high energies (factor 3-6)
- $pp$ low energies (factor ~12)

2-step processes?

figure by A.I. Titov et al.
$\phi / \omega$ - Ratio (Phys Rev Lett 81, 4572 (1998))


Factor 12 enhancement to OZI similar to higher energy pp-data but LEAR up to 100

Sibirtsev et al.: reasonable description with OME-Model

Data:
- Arenton et al.: PRD 25 (82) 2241
- Bardt et al.: PLB68 (77)
- Blobel et al.: PLB59 (75)
- S.V. Golovkin et al., ZPA359 (97)

Theory:

$\phi, \omega$ Absolute Cross Section Ratio

Preliminary

$\phi / \omega \sim 0.19/6 \sim 0.03$

OZI = 0.0043

A. Titov, B. Kämpfer & V. Shklyar, PRC 59, 999 (99).
Angular Distributions

\[ \phi / \omega \]

- **\( \phi \)** - mostly S-wave relative to pp system
- **\( \omega \)** - strongly peaked

**Inclusive K^- Production**

(No other channel Available)
$K^+ K^-$ Production in pp and HI Reactions

- **A** Not Published
- **B** Data from $ppK^0 \bar{K}^0$
- **C** Sum of Some Exclusive Channels


$Y_{\pi} \rightarrow NK^-$ not sufficient

Caseing et al., NPA 614, 415 (1997)
Structure of the $\eta'$ Meson

- By far heaviest member of PS nonet
  958 MeV $>>$ 135 MeV

- QCD fluctuations ($U_A(1)$ anomaly) allows
  $\eta'$ to gain mass from PS gluon states

- What is $g_{NN\eta'}$?

- Coupling to baryon resonances?
"$\eta'$ Production Cross Section"


Diagram showing data and simulation (Sim.) for production cross section, with axes labeled:
- $(M_{miss}^p)^2$ vs. $(M_{miss}^p)^2$ [GeV$^2$/c$^4$]
- $(M_{miss}^p)^2$ vs. $(M_{miss}^p)^2$ [GeV$^2$/c$^4$]

Graph on the right plots cross section [nb] vs. \(\sqrt{S} - 2834 [\text{MeV}]\), with data points and curves indicating different experiments and collaborations:
- P. Moskal et al. (COSY 11)
- F. Hibou et al. (SPES 3)
- Idrach et al.
- Caso et al.

Legend includes symbols and references for each data point.
Production of $\phi$ and $\omega$ Mesons in Near-Threshold $pp$ Reactions

F. Balestra,$^{4}$ Y. Bedfer,$^{3}$ R. Bertini,$^{3,4}$ L. C. Bland,$^{2}$ A. Brenschede,$^{8,9}$ F. Brochard,$^{3}$ M. P. Busa,$^{4}$ V. Chalyshnev,$^{1}$ Seonho Choi,$^{2}$ M. Debowski,$^{6}$ M. Dzenidzic,$^{2}$ I. V. Falomkin,$^{1}$ J.-Cl. Faivre,$^{3}$ L. Fava,$^{4}$ L. Ferrero,$^{4}$ J. Forgyciarz,$^{6,7}$ V. Frolov,$^{1}$ R. Garfagnini,$^{4}$ D. Gill,$^{10}$ A. Grasso,$^{4}$ E. Grosse,$^{3,9}$ S. Heinz,$^{3}$ V. V. Ivanov,$^{1}$ W. W. Jacobs,$^{2}$ W. Kühl,$^{8}$ A. Maggiora,$^{4}$ M. Maggiora,$^{4}$ A. Manara,$^{3,4}$ D. Pauzner,$^{4}$ H.-W. Pfitz,$^{8}$ G. Piragino,$^{4}$ G. B. Pontecorvo,$^{1}$ A. Popov,$^{1}$ J. Ritman,$^{8}$ P. Salabura,$^{6}$ P. Senger,$^{5}$ J. Stroth,$^{9}$ F. Tosello,$^{4}$ S. E. Vigdor,$^{2}$ and G. Zosti$^{4}$

(DISTO Collaboration)

$^{1}$JINR, Dubna, Russia
$^{2}$Indiana University Cyclotron Facility, Bloomington, Indiana
$^{3}$Laboratoire National Saurine, CEA Saclay, France
$^{4}$Dipartimento di Fisica "A. Avogadro" and INFN, Torino, Italy
$^{5}$Gesellschaft für Schwerionenforschung, Darmstadt, Germany
$^{6}$M. Smoluchowski Institute of Physics, Jagellonian University, Kraków, Poland
$^{7}$H. Niewodniczanski Institute of Nuclear Physics, Kraków, Poland
$^{8}$II. Physikalisches Institut, University of Gießen, Gießen, Germany
$^{9}$Institut für Kernphysik, University of Frankfurt, Frankfurt, Germany
$^{10}$TRIUMF, Vancouver, Canada

(Received 26 August 1998)

The ratio of the exclusive production cross sections for $\phi$ and $\omega$ mesons has been measured in $pp$ reactions at $T_{NN} = 2.85$ GeV. The observed $\phi/\omega$ ratio is $(3.7 \pm 0.7^{+0.3}_{-0.2}) \times 10^{-3}$. After phase space corrections, this ratio is about a factor of 10 enhanced relative to naive predictions based upon the Okubo-Zweig-Iizuka rule, in comparison to an enhancement by a factor of $\sim 3$ previously observed at higher energies. The modest increase of this enhancement near the production threshold is compared to the much larger increase of the $\phi/\omega$ ratio observed in specific channels of $pp$ annihilation experiments.
Summary & Outlook

- First measurement of $\phi$ meson near threshold in $pp$
- $\phi/\omega$ Ratio rises slightly at threshold
- What is Strangeness content of protons?
- Higher statistics -> polarization observables?
- First measurement of inclusive $K^-$ yield
- $\rho$ Meson identification
- $\eta'$ NN Measured with small FSI
- 2.1 & 2.5 GeV Data: $\omega, \eta'$ Excitation function
V. Hejny:
Photoproduction of light mesons – results from TAPS at MAMI
Photoproduction of light mesons with TAPS at MAMI

V. Hejny
II. Physikalisches Institut, Universität Gießen
* for the
TAPS - Collaboration
and the
A2 - Collaboration

Introduction

**Goal:**
investigations on the nucleon by photoexcitation and observation of the decay into mesons

**Diagram:**
- N*(I=1/2)
- Δ(I=3/2)
- Mass [MeV]
- Cross sections and resonance properties on proton and neutron
- Medium modifications of resonances

*Present address: Institut für Kernphysik, Forschungszentrum Jülich*
Experimental Setup

**MAMI:** High Quality cw-Beam

$E_{\text{electron}} = 180 - 880 \text{ MeV}$

Duty Factor $= 100\%$

**TAGGER:** Tagged Photons

$\Delta E = 2 \text{ MeV (at } E = 880 \text{ MeV)}$

$E_{\gamma} = E_{\text{beam}} - E_{\gamma}$

Bremsspectrum

Coincidence

- 6 $\text{BaF}_2$ blocks
- 64 crystals
- 64 individual veto detectors

forward wall:
- 120 plastic-$\text{BaF}_2$ phoswich modules

scattering chamber with liquid helium or deuterium target

**TAPS:** BaF$_2$-Photon-Spectrometer

**TAPS setup**

detector setup:

- 6 $\text{BaF}_2$ blocks
- 64 crystals
- 64 individual veto detectors

standard TAPS modul:

- plastic scintillator (charged particle veto)
- $\text{BaF}_2$ crystal
- photomultiplier
Identification of mesons

decay channel $\eta, \pi^0 \rightarrow 2 \gamma$

→ photon identification
  ▶ charged particle identification using veto counters
  ▶ particle discrimination exploiting $\text{BaF}_2$ pulse shape
  ▶ photon-photon coincidence within $\text{BaF}_2$ time resolution ($\sigma \sim 150\text{ps}$)

→ invariant mass analysis

\[
m_{\gamma\gamma} = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2}
= \sqrt{2E_1E_2(1 - \cos \theta_{12})}
\]

pulse shape analysis

→ intrinsic feature of $\text{BaF}_2$

→ pulse shape spectra
  (forward wall and standard $\text{BaF}_2$)
Photoabsorption on Nuclei

Different Channels on Proton:

\[ \sigma_n / \sigma_p = 2/3 \]
A(γ,η)X: data <-> models

**Input:**
- processes p(γ,η)p, n(γ,η)n
- fermi motion
- η, N* propagation in nuclei
- Pauli blocking of final states
- collision broadening

R.C. Carrasco (Valencia)  
A. Hombach et al. (Gießen)  

η mean free path  
Monte Carlo

η, N* propagation as in heavy ion collisions

π⁰ production from p and d

total cross section:

- sp ⊗ fermi momentum
- η: fermi motion dominant effect on d (and ⁴He)
- π⁰: additional 'deuteron effects'
- no theoretical description yet available

[Graphs and diagrams showing data for various elements and photon energy]
**A(γ,π^0)X: total cross sections**

- 12C(γ,π^0)X
- 40Ca(γ,π^0)X
- 93Nb(γ,π^0)X
- nαPb(γ,π^0)X

**mass number dependence**

\[ \sigma(A) \sim A^\alpha \]

- 1
- 50
- 150
- 250
- 750

\[ (\sigma/A^{2/3})/(\sigma(12C)/12^{2/3}) \]

**mass number dependence**

- 1
- 50
- 150
- 250
- 750

\[ (\sigma/A^{2/3})/(\sigma(12C)/12^{2/3}) \]

**A(γ,π^0)X: models**

- Standard BUU
- Δ absorption from Δ-hole models
- Additional medium modification for ρ meson:

\[ \Delta(m_\rho) \downarrow \Rightarrow \Gamma_{N\rho}(D_{13}) \uparrow \]

**A(γ,π^0)X: models**

- 12C(γ,π^0)X
- 40Ca(γ,π^0)X
- 93Nb(γ,π^0)X
- nαPb(γ,π^0)X

**A(γ,π^0)X: models**

- Standard BUU
- Δ absorption from Δ-hole models
- Additional medium modification for ρ meson:

\[ \Delta(m_\rho) \downarrow \Rightarrow \Gamma_{N\rho}(D_{13}) \uparrow \]
**Pb(γ,π^0)Pb: Identification**

- \( E_γ = 200 - 210 \) MeV
- \( E_γ = 270 - 280 \) MeV

**A(γ,π^0)A: Δ resonance modification?**

- Model: (Peters et al.)
- Relativistic, non-local DWIA

- Free production operator
- Full nucleon prop. + \( δm_Δ = -30 \) MeV
- Full nucleon prop. + \( δm_Δ = -30 \) MeV
  + \( δΓ_Δ = 20 \) MeV

**Angular distributions**

- \( Q \) [deg]

**\(^{12}\text{C}; q = 0.18 \text{ GeV}\)**

**\(^{12}\text{C}; q = 0.1 \text{ GeV}\)**

**\(^{40}\text{Ca}; q = 0.1 \text{ GeV}; δΓ_Δ = 30 \text{ MeV}\)**

**\( E_γ \) [Gev]**
Total Cross Section:

- Dalitz-Plots & Total Cross Section:
  - Decay of $D_{13}$ via $\Delta$
  - Low Statistics at Threshold: $4\gamma$ Cross Section
    \[ \Rightarrow \text{Exp. 1995} \]
  - Dalitz Plots
    \[ \Rightarrow \text{New Proposal} \]

[1] Härter et al.,

Extracted cross section on $n$ for:
same model used as in $\eta$ photoproduction

d$(\gamma, \pi^0 \pi^0) p$: $n(\gamma, \pi^0 \pi^0) n$
total cross sections on proton and deuteron

\[ \Rightarrow \text{Exp. 1995} \]

\[ \Rightarrow \text{New Proposal} \]
Summary

- photoproduction of $\pi^0$, $2\pi$ and $\eta$ mesons measured on proton, deuteron and complex nuclei.
  
  $\leftrightarrow$ medium modifications.

- no effects seen for $\Sigma_{11}(1535)$ resonance using $\eta$ photoproduction.

- coherent $\pi^0$ data can be described assuming modifications: $\delta m_\Delta = -30$ MeV, $\delta \Gamma_\Delta = 20$ MeV (Peters et al.)

- calculations of $\pi^0$ and $2\pi^0$ channel on nuclei give better descriptions assuming modification of the $\rho$ meson (smaller mass, larger width) (Effenberger et al.)

- no models available for missing strength in $\pi^0$ production from $d$ in the second resonance region (FSI seems very important).
O. Scholten:
Proton–proton bremsstrahlung
Proton - proton Bremsstrahlung

Olaf Scholten
Full calculation of off-shell effects

$$I_A = \frac{f}{0} + \frac{f}{0} + 1 + 2$$

full = $I_A + \frac{f}{0}$

+ : Project on positive energy states in intermediate propagators

+/- : Keep Dirac propagators

$I_A$: Impulse Approx = Born terms

Full: include rescattering

<table>
<thead>
<tr>
<th>$E &gt; 0$</th>
<th>$E &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{\sqrt{E}}$</td>
<td>$\sqrt{-E}$</td>
</tr>
<tr>
<td>$\frac{1}{M}$</td>
<td>$\frac{1}{M}$</td>
</tr>
</tbody>
</table>

Important??

$$< \frac{\gamma}{2} > : \frac{1}{\sqrt{M}}$$

$$\frac{1}{\sqrt{M}} \times \frac{1}{\sqrt{M}}$$

$$\frac{1}{M} \times \frac{1}{M}$$

Graph showing $d^2\sigma / d\Omega_\gamma$ vs. $\theta_\gamma$ for $E = 280$ MeV, $\theta_\gamma = 12^\circ$, $\theta_\gamma = 12.4^\circ$.
Meson Exchange Currents

N-N Potential

Blankenbecler - Sugar

3D reduction of Bethe - Salpeter
Evaluate helmel at \( E = 0 \)

\[ V : 0 \beta \varepsilon \]

\[ \text{cut off } \frac{\Lambda^2}{\Lambda^2 - p^2} ; \Lambda^2 = 1.5 M^2 \]

in bremsstrahlung!

equal-time approx.

effect approx.: few percent decrease of \( 0 \)

Mechanism:

\[ \pi \]

large for p n

\( \approx 0 \) for p p

add to p p \( T \)
Microscopic model calculations

G. Martinus

- Relativistic T-matrix
  Fleischer-Tjon OBE potential
  Blankenbecler-Sugar

- Full relativity
  negative energy states
  "Z. graph"

- Rescattering

- Meson exchange currents

- Δ-isobar currents

Proton-Proton Bremsstrahlung

$p + p \rightarrow p + p + \gamma$

Data by Harry Huisman

SPA by Timmermans, Gibson and Liou

$\theta_2 = 16^\circ$
$\theta_\gamma = 145^\circ$

Full calculation by K. Nakayama

$\theta_1 = 16^\circ$
$\theta_\gamma = 145^\circ$

Full calculation by Martinus et al.

Full calculation by J. Eden et al.

Data point: Rogers et al. PRC 22 2512 (1980)

Data by Harry Huisman
Present day calculations

Additional

Off-shell effects
or equivalently
Dynamics of interacting $N$
or equivalently
Meson loop corrections to
$N$-self energy
$NN$-vertices

Very advanced;
disagreement with (some) data

$KVI$ 130 MeV
$COSY$ 280
Uppsala 320
Osaka 392

in progress
What can we learn?

missing ingredients

• T. matrix - coupling to reg E states
  - structure intermediate 2 nucleon prop.

• Propagator: $\frac{1}{P - m + \Sigma(P)}$

• $\gamma$ vertex: $\gamma^\mu + \frac{i}{2m} F(P') \sigma^\mu \gamma^\nu$

• contact terms: due to

Different effects indistinguishable
  from each other

Off-shell form factors

$\tilde{\Gamma}(w^2) = e \left[ \tilde{F}_1(w^2) \gamma^\mu + i \tilde{F}_2(w^2) \sigma^\mu \gamma^5 \right]$

Current conservation: $\tilde{F}_1(w^2) \equiv 1$

$\tilde{F}_2(w^2) = F_2^+(w^2) \Lambda^+ + F_2^-(w^2) \Lambda^-$

$F_2^+(w^2) = \chi + \chi \lambda \frac{w^2 - m^2}{m^2} + \ldots$

Buton magn. free parameter

$\chi \propto L^2$

$F_2^-(w^2) = \chi^2 + \ldots$

2 free parameters

1-loop calculations:

$-5 \lambda < \chi < 20 \lambda$

Model:

\[ \mathcal{L} = \mathcal{L}_{\text{photon}} + \mathcal{L}_{\text{vector}} + \ldots \]
Virtual Bremsstrahlung
\((e^+e^-)\) pair production

Similar to electron scattering

Both: structure functions
Matrix element \( M = J_u J_e^* \)
Observables
\[ |M|^2 = (J_u J_e^*) (J_e J_u^*)^* \]

Differences:
\((e,e')\): charge densities
\((e^+e^-)\): current density
**Classical Response**

- Electron Scattering (on bound state)

\[
\text{Hadronic currents: } \frac{e}{\pi m_{e}^{2} v} = \int \rho(x,t) e^{i\omega t} dt \cdot \delta^{3} x = \\
\omega = \int \rho(x) e^{i\omega x} d^{3} x = \text{fourier transform}
\]

\[
\text{Currents: } \mathbf{J} = \int \left( \int \mathbf{\vec{p}}(x,t) e^{i\omega t} dt \right) e^{i\mathbf{q} \cdot \mathbf{x}} d^{3} x \\
= 0 \text{ for } \omega = 0 \\
= \text{time-averaged current} = 0 \text{ of init. state} \quad \text{fin. state} \quad \text{for } (\omega=0)
\]

\[
\mathbf{q} \cdot \mathbf{J} = 0 = \omega \mathbf{J} - \mathbf{\vec{\nabla}} \cdot \mathbf{J}
\]
\[
\Rightarrow \quad \mathbf{J} = \frac{\omega}{\mathbf{1} \cdot \mathbf{q}} \mathbf{J} = 0 \text{ for } \omega \to 0
\]

**Virtual Bremsstrahlung**

\[
M^{2} = \frac{e^{2}}{2 m_{e}^{2} v} \left[ V_{l} (1-z) \left( V_{l} \cos \theta + V_{r} \sin \theta \right) + \left( V_{l} \cos \theta - V_{r} \sin \theta \right) \right]
\]

Electron scattering measures charge density
Clasical Response

- Bremsstrahlung (from continuum)
  - virtual

$J \gamma \rightarrow J^0 \rightarrow J$ for $\gamma \rightarrow 0$

time independent: $\int 2 e^{i \omega t} dt = 0$

$\overline{J} = \int \left( \int q(x,t) d^3x \right) e^{i \omega t} dt$

$= \text{total charge } Z \text{ for } \gamma \rightarrow 0$

Hadronic Currents:

$\text{currents: } J = \left( \int q(x,t) d^3x \right) e^{i \omega t} dt$

for $\gamma \rightarrow 0 \Rightarrow J = \int \overline{q}(t) e^{i \omega t} dt$

Fourier components of space averaged radial current density

Alternative: $\int J^x = 0 \Rightarrow \omega J^y = \vec{E} \cdot \vec{J}$

$\therefore J^0 = \frac{\vec{E} \cdot \vec{J}}{\omega} = 1 / \omega \left| J_L \right| = 0$

Numerics:

$J^0 \rightarrow 0$ for $\gamma \rightarrow 0$

due to several orders of magnitude cancellations.

$\Rightarrow$ numerical inaccuracies

$\Rightarrow$ safe procedure:

$J^0 = \frac{\vec{E} \cdot \vec{J}}{\omega}$

$\overline{J}$ calculated
Conclusions:

- Although "simple".
- PPF is non-trivial.
- Discrepancy between Exp & Th.
  - Non-nucleonic degrees.
  - Off-shell form factors.

Should be consistent with:

\[ \pi N \rightarrow \pi N \]
\[ \eta N \rightarrow \pi N \]
\[ \eta N \rightarrow \eta N \]
C. Fuchs:

Background contributions to dilepton spectra in pp collisions
Background contributions to the
dilepton production
in pp and $\bar{p}p$ collisions

C. Fuchs, M. Kivorniachenko, A. Täpler

Tübingen
Importance of $e^-$ decays which contribute to the background?

M. Krivoruchenko

nucl-th/9904024
Production Cross Sections, \( p+p \) Reactions

Measured (COSY):
- \( pp \to pp\sigma \)
- \( pp \to pp\omega \)
- \( pp \to pp\phi \)
- \( pp \to pp\eta \)

Parameterizations:
- Silbirtscv (Cassling)

Isospin relations for \( \eta \)-production:

\[
|\eta N\rangle = \cos \frac{\sqrt{8} \eta (NN)}{\sqrt{8} N\eta (NN)} + \ldots + \eta (NN)
\]

\[
\sigma (pp \to pp\sigma) = \sigma (pp \to pp\omega)
\]

Assumption:
\[
\sigma (\pi^+ p \to \omega \Delta^+) = \sigma (\pi^- p \to \omega \Delta^+)
\]

Reason: 20% accuracy

\[
\Rightarrow \quad N\pi \to \Delta\eta \quad 16 \text{ channels}
\]

- \( N\pi \to \Lambda\eta \), 10 channels
- \( N\pi \to \Lambda\omega \), 9
- \( N\pi \to \Delta\omega \), 16

...
Direct Decays of Vector Mesons

\[ \Gamma(V \to e^+e^-) = \frac{3\pi\alpha^2}{8g_\psi^2} \frac{m_V^4}{M^4} \left(1 + \frac{2m_e^2}{M^2}\right) \rho^2(M_1m_e,m_e) \]

\[ \rho^2(M_1m_e,m_e) = \frac{\sqrt{(s-(m_1+m_e)^2)(s-(m_1-m_e)^2)}}{2\sqrt{s}} \]

Mass distribution (Breit Wigner):

\[ f(M) = \frac{1}{\pi} \frac{2Mm_V\Gamma(M)}{(M^2-m_0^2)^2 + m_0^2\Gamma^2(M)} \]

\[ \frac{d\Gamma}{dM} = f(M) \frac{\Gamma(V \to e^+e^-)}{\Gamma_0(M)} \]

\( \approx \) No cut threshold for \( \rho \to e^+e^- \) decay

\[ \text{direct rho0 decay} \]

\[ \text{M [GeV]} \]

\[ \text{dM/dX [mb/GeV]} \]
Summary

- Four-body decays (e.g., $\pi^+\pi^-\pi^0\pi^0$) give in some cases important contributions to the usual dilepton decay.

- However, mainly in the low energy region, these contributions are difficult to observe.

- In some cases, the $K^+\pi^-$ threshold disappears in the direct $K^-\pi^-$ decay.

- A large contribution at small $M_{ee}$ results matches with the Bremsstrahlung contribution.

- Some reactions may be appropriate to study $K^-\pi^-$ decays at $M_{ee} < 0.5$ GeV.
N. Kalantar:
Bremsstrahlung experiments at KVI
Probing Few-Body Systems with Bremsstrahlung

Nasser Kalantar

Mini-workshop on Electromagnetic Radiation off Colliding Hadron Systems: Dileptons & Bremsstrahlung

Dresden, Germany

April 16, 1999

Outline

- Nucleon-Nucleon Bremsstrahlung
  - General remarks
  - Review of some experimental work on $p p \gamma$ and $p d \gamma$ at other laboratories

- KVI experiments on $p p$ and $p d$ systems
  - Detection system
  - Preliminary bremsstrahlung results

- Summary and outlook

*****************************************************************************


* KVI, Groningen; GSI, Darmstadt;
* NPI, Rež u Prahy;
Nucleon-Nucleon Bremsstrahlung

Relevant Feynman Diagrams

a) External Bremsstrahlung (Single Scattering)

b) Internal Bremsstrahlung (Double Scattering)

c) MEC + Δ + N N + …

Soft-Photon

\[
\lim_{\hbar \omega \to 0} \frac{d^3 N}{(d^3 k / k_0)} = \frac{\alpha^2 z^2}{4 \pi^2} \left| \frac{\mathbf{e}^* \cdot \mathbf{p}' - \mathbf{e}^* \cdot \mathbf{p}}{\mathbf{k} \cdot \mathbf{p} - \mathbf{k} \cdot \mathbf{p}'} \right|^2
\]

For \(pn\):
\[
\lim_{\hbar \omega \to 0} \frac{d^3 N}{(d^3 k / k_0)} \propto \Rightarrow \text{Dipole}
\]

For \(pp\):
\[
\lim_{\hbar \omega \to 0} \frac{d^3 N}{(d^3 k / k_0)} \propto = 0 \Rightarrow \text{Quadrupole}
\]
OESA

Exact calc.

\[ \theta_1 = 12.4^\circ, \theta_2 = 12.0^\circ \]

\[ T_{\text{lab}} = 280 \text{ MeV} \]

\[ \theta_1 = 12.4^\circ, \theta_2 = 12.0^\circ \]

\[ T_{\text{lab}} = 280 \text{ MeV} \]

\[ \theta_1 = 12.4^\circ, \theta_2 = 14.0^\circ \]

\[ T_{\text{lab}} = 280 \text{ MeV} \]

\[ \theta_1 = 12.4^\circ, \theta_2 = 14.0^\circ \]

\[ T_{\text{lab}} = 280 \text{ MeV} \]

- OBEQ
  - Herrmann, Nakayama

- OBEPT
  - Data not normalized.

- Paris

- It is obvious from both cross section data and analyzing power that 'off-shell' effects must be taken into account.

- Small differences between potentials.

---

IUCF Data

\[ \frac{d\sigma}{d\Omega}/\text{d}Q \] - (MeV)

\[ \theta_{\text{deg}} \]

\[ \theta_{\text{deg}} \]

- OBEQ
  - Paris (no Coulomb correction)

- OBEQ
  - Paris (with Coulomb correction)

Available $pp\gamma$ data (Modern):

- TRIUMF: coplanar, small $\theta_p$
  but NORMALIZATION problems
- IUCF: integrated, small $\theta_p$
  but DIFFICULT to calculate

Recent and Proposed $NN\gamma$ Experiments:

- KVI: coplanar, non-coplanar, small $\theta_p$, large $\Omega_p$ and $\Omega_\gamma$
- CELSIUS: $4\pi$ detector, ring experiment
- COSY: $4\pi$ detector, high energies, low luminosity
- LANSCE: np$\gamma$ measurement ($n$ beam)
- IUCF: small $\theta_p$, C$\gamma\gamma$, ring experiment
- RCNP: coplanar, large $\theta_p$, high energies

KVI Experiments

- High precision absolute cross-section measurements on $pp\gamma$ to compare to "complete" calculations.
- Absolute cross-section measurements and channel selection of the $pd\gamma$ reactions.
- Use of polarized beam for high-precision measurements of the analyzing power of $\bar{p}p\gamma$ and $\bar{p}d\gamma$.
- $p$-Nucleus bremsstrahlung measurements to look at $A$-dependence.
- $\alpha p$-bremsstrahlung measurement.

Note: All measurements involve real and virtual photons.

All measurements are exclusive.

All measurements are ingredients for reaction-mechanism studies in heavy-ion collisions.
Following exit channels exist for \( p + d \) bremsstrahlung:

1. \( p + d \rightarrow ^3\text{He} + \gamma \)
2. \( p + d \rightarrow p + d + \gamma \)
3. \( p + d \rightarrow p + n + p_{\text{spec}} + \gamma \)

(1) and (2) are energetically distinguished from (3) and .
Detection System for $NN\gamma$ Experiments

SALAD (Small Angle Large Acceptance Detector):

- Detection of hadrons
- Two wire chambers for tracking:
  - Wire spacing 2 mm
  - Cathode-Anode spacing 4 mm
- Two stacks of Scintillators:
  - 24 thick elements for energy
  - 26 thin elements for veto

TAPS (Arm Test Particle Spectrometer):

- Detection of photons
- $\approx 400$ crystals
- $\approx 25\%$ of $4\pi$ for BLOCK geometry
- $\approx 20\%$ of $4\pi$ for SUPERCLUSTER geometry

Schematic Top View of SALAD and TAPS
(supercluster geometry)
Elastic $pp$ Cross Sections

Data: H. Huisman
The calculations are from Virginia and Nijmegen
Proton-Proton Bremsstrahlung
\[ \vec{p} + p \rightarrow p + p + \gamma \]

Schematic Top View of SALAD and TAPS
(block geometry)

Data: H. Huisman
- SPA by Timmermans, Gibson and Liou
- Full calculation by K. Nakayama
- Full calculation by Martinus, Scholten and Tjon
- Data point: Rogers et al. PRC 22 2512 (1980)
Proton-Proton Bremsstrahlung

\( \vec{p} + p \rightarrow p + p + \gamma \)

\[ \frac{d\sigma}{d\Omega_1} \frac{d\Omega_2}{d\Omega_3} [\text{nb/sr}] \]

\( \theta_1 = 8^\circ \)
\( \theta_2 = 16^\circ \)
\( \phi = 0^\circ \)

- Martius nucl
- Martius full
- SPA Liou

\[ \begin{align*}
\text{supercluster} \\
\text{block geometry} \\
\text{triumf 200 MeV}
\end{align*} \]

\( \theta_1 = 8^\circ \)
\( \theta_2 = 16^\circ \)
\( \phi = 0^\circ \)

Data: H. Hulsman
- SPA by Timmermans, Gibson and Liou
- Full calculation by Martins, Scholten and Tjon
- calculation by Martins, Scholten and Tjon
- Data points: Rogers et al. PRC 22 2512 (1980)

Various parameters as a function of TIME

- Supercluster
- Block Geometry
- Elastic
- MWPC
- Trigger
- ppγ

Run number 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Run number 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Channel Selection

Following exit channels exist for $p + d$ bremsstrahlung:

1. $p + d \rightarrow p + d + \gamma$
2. $p + d \rightarrow ^3\text{He} + \gamma$
3. $p + d \rightarrow p + n + p_{spac} + \gamma$
4. $n + d \rightarrow \ldots$

(1) and (2) are energetically distinguished from (3) and ...
"Coherent" \( pd\gamma \): Diagnostics

Reconstructed versus Measured Energies

Preliminary Data: M. Volkerts

- SPA Calculation for \( pn \) downscaled by a factor of 3
- Classical calculation for \( pd \) on arbitrary scale

\( p + d \rightarrow p + d + \gamma \)
Summary

- New results emerging for cross sections and analyzing powers for \( pp \) and \( pd \) bremsstrahlung, improved in phase-space coverage as well as statistics;
- Spin observables are immune to large normalization uncertainties;
- Still disagreements between the most modern calculations and the data!

Outlook

- Other regions of phase space are being analyzed for possible hints to theorists;
- For the first time, large non-coplanar geometries with high accuracies have been measured yielding new observables;
- Study underway to measure large proton angles moving towards SPA;
- \( 4\pi \) detection for \( \gamma^* \) studies.
S. Scherer:
NN bremsstrahlung and Compton scattering
– examples of the impossibility of measuring off-shell effects
Nucleon Nucleon Bremsstrahlung and Compton Scattering:
Examples of the Impossibility of Measuring Off-shell Effects

S. Scherer
Institut für Kernphysik, Mainz

Dresden, 16 April 1999

1) Motivation

- What is the electromagnetic interaction of a bound, off-mass-shell nucleon in e.g. \((e,e'p)\)

- Medium modifications, swollen nucleon

- Simple example

\[
\Gamma^\mu(p',p) = (p' + p)^\mu F(q^2, p'^2, p^2) + (p' - p)^\mu G(q^2, p'^2, p^2)
\]

in collaboration with H. W. Fearing

http://www.kph.uni-mainz.de/lecture.html
• Two form functions $F$ and $G$ of three scalar variables:

$$q^2, p'^2, p^2$$

• Is it possible to experimentally test and uniquely identify contributions from off-shell electromagnetic form functions?

• Example: pole terms of $\gamma^* \pi \to \gamma \pi$

$$\begin{align*}
\gamma & \quad q \\
\pi & \quad (p_i + q)^2 \neq m^2 \\
\gamma' & \quad q' \\
\pi & \quad p_i + q = p_f + q' \\
\end{align*}$$

• Observable: form factor

$$F(q^2) = F(q^2, m_{\pi}^2, m_{\pi}^2)$$

• Analogy in $NN$ bremsstrahlung: $NN$ off shell, e.m. vertex off shell

Example

[Simplified version of H. W. Fearing, Phys. Rev. Lett. 81, 758 (1998)]

• Simple example: $\pi^+ + \pi^0 \to \pi^+ + \pi^0 + \gamma$

• Nonlinear $\sigma$ model describes pion interactions at low energies

$$\mathcal{L} = \frac{F^2}{4} \text{Tr} \left[D_\mu U (D^\mu U)^\dagger\right] + \frac{F^2 m_{\pi}^2}{4} \text{Tr}(U + U^\dagger)$$

$$F = 93 \text{ MeV}$$

• $U$ is an SU(2) matrix containing the pion fields

• Covariant derivative generates interaction with e.m. field

$$D_\mu U = \partial_\mu U + i e A_\mu [Q, U], \quad Q = \begin{pmatrix} \frac{2}{3} & 0 \\ 0 & -\frac{1}{3} \end{pmatrix}$$
Alternative parametrizations of $U$: 

$$U(x) = \frac{1}{F} \left[ \sqrt{F^2 - \bar{\pi}^2} + i \bar{\pi} \cdot \bar{\pi}(x) \right]$$

$$= \exp \left[ i \frac{\bar{\pi} \cdot \bar{\pi}'(x)}{F} \right]$$

correspond to a field transformation 

$$\frac{\bar{\pi}}{F} = \bar{\pi}' \sin \left( \frac{\pi'}{F} \right) = \frac{\bar{\pi}'}{F} \left( 1 - \frac{1}{6} \frac{\bar{\pi}''}{F^2} + \ldots \right)$$

Analogy 

$$\vec{x} = (x, y, z)$$

$$= (r \sin(\theta) \cos(\phi), r \sin(\theta) \sin(\phi), r \cos(\theta))$$

change of variables from cartesian to spherical coordinates

Feynman rule for the $\pi^+\pi^0$ scattering amplitude

The same on-shell scattering amplitude but different off-mass-shell behavior!
Apply to $\pi^+(p_1) + \pi^0(p_2) \rightarrow \pi^+(p_3) + \pi^0(p_4) + \gamma(k)$

\[ M_1 = \frac{i}{F^2} T_0(p_1 - k, p_3) \left( \frac{i}{(p_1 - k)^2 - m_\pi^2} (-2iep_1 \cdot \epsilon) - 2iep_3 \cdot \epsilon \frac{i}{(p_3 + k)^2 - m_\pi^2} F^2 T_0(p_1, p_3 + k) \right) \]

\[ = \left( \frac{p_3 \cdot \epsilon}{p_3 \cdot k} - \frac{p_1 \cdot \epsilon}{p_1 \cdot k} \right) \frac{ie}{F^2} [T_0(p_1, p_3) - 2(p_1 - p_3) \cdot k] \]
Here: Complete cancellation of "off-shell" effects and contact interactions

In general: Two mechanisms are indistinguishable

Manifestation of the "equivalence theorem" of field theory:
Lagrangians which are related by field transformations generate the same on-shell S-matrix elements and thus the same observables.

Off-shell form functions not only model dependent but also representation dependent
2) Toy model Lagrangian for pn bremsstrahlung and Compton scattering off $p$

- **Question:** Is it possible to uniquely associate observable effects with off-mass-shell behavior of the $np$ amplitude or of the electromagnetic vertex?

Toy model Lagrangian:

$$\mathcal{L} = \bar{p}(i\not{\Phi} - M)p - \frac{e\kappa}{4M} F_{\mu\nu} \bar{\sigma}^{\mu\nu} p + \bar{n}(i\not{\Phi} - M)n + g\bar{p}\bar{n}n$$

- $p$: proton field
- $n$: neutron field (for simplicity no anomalous magnetic moment)
- Covariant derivative: $i\not{\Phi}p = (i\not{\Phi} - eA)p$
- Field strength tensor: $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

Result for $p(p_1) + n(p_2) \rightarrow p(p_3) + n(p_4) + \gamma(q)$ with toy model:

$$\mathcal{M} = ieg\bar{u}_n u_p \left\{ \frac{1}{\not{\Phi}_1 - \not{q} - M} \left( \not{p} - \frac{\kappa}{4M} [\not{q}, \not{\ell}] \right) + \left( \not{p} - \frac{\kappa}{4M} [\not{q}, \not{\ell}] \right) \frac{1}{\not{\Phi}_3 + \not{q} - M} \right\} u_p$$
• Consider field transformation

\[ p = p' + \delta p' = (1 + \alpha \bar{\eta}n + \beta \sigma_{\mu\nu}F^{\mu\nu})p' \]

• \( \alpha \) and \( \beta \) arbitrary real parameters

• \( \alpha \) generates different off-mass-shell np amplitude

• \( \beta \) generates different off-mass-shell e.m. vertex

\[ \mathcal{L}(p, n) = \mathcal{L}(p' + \delta p', n) = \mathcal{L}'(p', n) \]

• Different functional forms of \( \mathcal{L} \) and \( \mathcal{L}' \)

• Off-mass-shell modifications of “old” vertices

\[
\Delta \mathcal{M}_{pm} = i\alpha \bar{\eta}n[(\phi_3 - M) + (\phi_1 - M)]_p
\]

\[
\Delta \mathcal{M}_{pp\gamma} = -i\beta \{(\phi_f - M)[\not\!q, \not\!\gamma] + [\not\!q, \not\!\gamma](\phi_i - M)\}
\]

• Illustration for e.m. vertex:

\[
\Gamma^\mu(p_f, p_i) = \sum_{\alpha, \beta=\pm, -} \Lambda_\alpha(p_f) \left( \gamma^\mu F_1^{\alpha\beta} + \frac{\sigma_{\mu\nu} q_\nu F_2^{\alpha\beta}}{2M} + \frac{q^\mu}{M F_3^{\alpha\beta}} \right) \Lambda_\beta(p_i)
\]

\[
F_i^{\alpha\beta} = F_i^{\alpha\beta}(q^2, p_f^2, p_i^2), \quad q = p_f - p_i
\]

\[
\Lambda_{\pm}(p) = \frac{M \pm q}{2M}
\]

• Before field transformation:

\[
F_1^{\alpha\beta} = 1
\]

\[
F_2^{\alpha\beta} = \kappa
\]

\[
F_3^{\alpha\beta} = 0
\]

- no \( q^2 \) dependence

- no \( p_i^2 \) and \( p_f^2 \) dependence
After field transformation

\[
F_{2}^{++} = \kappa \\
F_{2}^{+-} = F_{2}^{-+} = \kappa + \vec{\beta} \quad \text{(sometimes } \kappa^{-} \text{)} \\
F_{2}^{--} = \kappa + 2\vec{\beta}
\]

where

\[
\beta = \frac{e}{8M^2\beta}
\]

- Of course, more realistic starting point possible:

\[
\mathcal{L}_{pp\gamma} = \bar{p}(i\not{\!D} - M)p - \frac{e\kappa}{4M} F_{\mu\nu} \bar{p} \sigma^{\mu\nu} p \\
- e \sum_{n=1}^{\infty} \left((-\partial^2)^{n-1} \partial^{\mu} F_{\mu\nu}\right) F_{1n} \bar{p} \gamma^{\mu} p \\
- \frac{e}{4M} \sum_{n=1}^{\infty} \left((-\partial^2)^{n} F_{\mu\nu}\right) F_{2n} \bar{p} \sigma^{\mu\nu} p
\]

\[
F_1(q^2) = 1 + \sum_{n=1}^{\infty} (q^2)^n F_{1n}
\]

\[
F_2(q^2) = \kappa + \sum_{n=1}^{\infty} (q^2)^n F_{2n}
\]

- Additional vertices relevant to bremsstrahlung and Compton scattering \(p(p_i) + \gamma(q) \rightarrow p(p_j) + \gamma(q'):\)

\[
\Delta M_{pp\gamma} = -i\alpha \beta \left\{ (p_1 - q - M)[g, \not{f}] \\
+ [g, \not{f}](p_3 + q - M) \right\},
\]

\[
\Delta M_{pp\gamma} = -i\beta^2 \left\{ [g, \not{f}](p_i - q' - M)[g', \not{f}'] \\
+ [g', \not{f'}](p_i + q - M)\right\}
\]

- Amplitude for pn bremsstrahlung the same as with original Lagrangian

- Cancellation of off-mass-shell effects and contact interactions

- Different off-mass-shell behavior of Green's functions

- Observable results identical
Phenomenological Lagrangian to generate $\kappa^-$ off-shell effects (popular in $NN$ bremsstrahlung)

$$\mathcal{L} = \bar{p}(i\not{\partial} - M)p - \frac{e\kappa}{4M} F_{\mu\nu} \bar{p} \sigma^{\mu\nu} p + \beta\bar{p}(-i \not{\partial} - e \not{A} - M)\sigma^{\mu\nu} p F_{\mu\nu} + \beta F_{\mu\nu} \bar{p} \sigma^{\mu\nu}(i\not{\partial} - e \not{A} - M)p$$

- Off-shell effects in the pole terms

- Contact interaction to preserve gauge invariance

- Field transformation

$$p = (1 - \beta \sigma_{\mu\nu} F^{\mu\nu})p'$$

eliminates $\kappa^-$ off-shell effects by generating new contact interaction

- Consider Compton scattering

$$\mathcal{M} = \mathcal{M}_{\text{Born}} + \mathcal{M}_{\text{struc}}$$

$$\mathcal{M}_{\text{struc}} = i[4\pi \omega \omega' \varepsilon \cdot \varepsilon' + 4\pi \bar{q} \times \varepsilon \cdot \bar{q}' \times \varepsilon''] + \cdots$$

Results from the above Lagrangian:

$$\tilde{\alpha} = \frac{e^2 \beta^2 + 2\beta \kappa}{4\pi 4M^3}, \quad \beta = \frac{e^2 \kappa\beta}{4\pi 2M^3}$$

where

$$\frac{e^2}{4\pi} \approx \frac{1}{137}$$

- Problem:

Given empirical numbers

$$\tilde{\alpha} = (12.1 \pm 0.8 \pm 0.5) \times 10^{-4} \text{fm}^3$$

$$\kappa = 1.79$$

$$M = 938 \text{MeV}$$

no solution to

$$\tilde{\beta}_{1/2} = -\kappa \pm \sqrt{\kappa^2 - \frac{4\pi}{e^2 4M^3 \tilde{\alpha}}}$$

$$3.20 > 71.6$$

- Conclusion

Check consistency of "phenomenological off-shell effects" with other reactions!
3) Conclusions

- Off-shell effects in e.m. and strong vertices using pn bremsstrahlung and Compton scattering off p
- Concept of field transformations
- Equivalence theorem
- Same results for observables
- Differences in off-shell behavior of Green’s functions
- Cannot uniquely distinguish between off-mass-shell contributions and contact terms
- Electromagnetic polarizabilities as consistency check of phenomenological “off-shell” Lagrangian
J. Zlomanczuk:
Bremsstrahlung in pp collisions at 310 MeV
Bremsstrahlung in pp Collisions at 310 MeV


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Some parameters of the CELSIUS ring

- Circumference: 82 m
- Max. magnetic field: 1.0 T (1.2 planned)
- Max. Momentum: 2.4 GeV/c (at present)
- Electron beam current: 470 A MeV (at present)
- Electron beam diameter: 0.3 A
- Electron cooler section 2 cm

Achieved intensities

- Proton intensity: 4.4 x 10^{14}
- Deuteron intensity: 1.1 x 10^{13}
- π- intensity: 4.1 x 10^{13}
WASA-PROMICE experimental set-up
Range Hodoscope

Material: plastic scintillator
Thickness: 44 cm (proton maximum energy ~ 280 MeV)
Angular range: 4 - 21 deg
ΔE-E plot obtained for the third layer of the FHD and the first layer of the FRH

Cooled proton beam

310 MeV

$4^\circ < \theta_p < 21^\circ$

$3.8 \text{ MeV} < T_p < 2.8 \text{ MeV}$

$3.6^\circ < \theta_x < 91^\circ$

$\Delta \phi_x \approx 50^\circ$

$T_x \geq 10 \text{ MeV}$
$p \rightarrow p\pi^0\text{ at } 310\text{ MeV}$

$N = 8 \times 10^5$ events

$MM^2_{pp}$ (MeV$^2$)

CMS $\cos \theta$
Monte Carlo simulation of the $pp \rightarrow ppy$ reaction at 310 MeV


The general feature of the angular distributions can be understood by examining the contribution arising from the external current (one-body current excluding the rescattering term)... 

$$
\frac{d^2\sigma_{\text{con}}}{d\Omega d\omega} = \alpha/(2\pi)^2/\omega \cdot \langle p'/p \rangle \cdot [\epsilon(p') \cdot \epsilon(p) \cdot T^2_{pp}]
$$

$$(8/15 \cdot \nu^4 + \nu^4 \cdot \sin^2 2\theta),$$

$$
\frac{d^2\sigma_{\text{magn}}}{d\Omega d\omega} = \alpha/(2\pi)^2/\omega/m^2 \cdot \langle p'/p \rangle \cdot [\epsilon(p') \cdot \epsilon(p) \cdot T^2_{pp}] \cdot \mu^2_p
$$

$$[(g-d)^2 + 1/3 \cdot g^2 \cdot \nu^2 + d^2 \cdot \nu^2 \cdot \cos^2 \theta],$$

where $\omega$ and $\theta$ are the photon energy and angle in CMS, $\nu$ and $\nu'$ stand for the proton velocities in the $pp$ CM systems (before and after the scattering), $d$ and $g$ are constants and $\mu_p$ is the proton magnetic moment.

Since for the phase space $d^2\sigma/d\Omega d\omega \propto \omega \cdot p'/p$ the event weight $W$ given by the phase space Monte Carlo program has been replaced with:

$$W' = W \cdot W_{pp},$$

where

$$W_{pp} = 1/(2\pi) \cdot (8/15 \cdot \nu^4 + \nu^4 \cdot \sin^2 2\theta) \cdot (1/\omega) + \omega/m^2 \cdot [(g-d)^2 + 1/3 \cdot g^2 \cdot \nu^2 + d^2 \cdot \nu^2 \cdot \cos^2 \theta] \cdot \mu^2_p \cdot (1/\omega).$$

Correlation between proton angle and energy for $pp \rightarrow ppy + X$ at 310 MeV. Illustration of the selection of the $pp \rightarrow ppy$ reaction.
$^{3}\text{He} + p \rightarrow p \alpha + \gamma$ at $310$ MeV

$E_{\gamma} = E_{p_{1}} - E_{p_{2}}$

$\delta H/M \sim \delta F$

$10^0 < \theta_1, \theta_2 < 15^0$

$15^0 < \theta_1, \theta_2 < 20^0$

$\Delta \phi < 60^0$

$E_{p_1} \rightarrow E_{p_2}$

$\frac{d^3\sigma}{d\Omega d\phi} (\text{mb} \cdot \text{s}^{-2} \cdot \text{rad}^{-1})$

Lab photon angle (deg)
Layout of the WASA 4π-Detector
E. Kuhlmann:
Bremsstrahlung experiments at COSY-TOF
Rossendorf, April 16, 1999

Bremsstrahlung Experiments at COSY-TOF

E. Kuhlmann, TU Dresden
for the

Bremsstrahlung - a tool to investigate off-shell effects (?)

(a) (b) (c)

recent development: consideration of contact term

(f)

better: supply high-quality data
**pp\# at 797 MeV/c (October '96)**

- p\#\# threshold

**COSY-TOF spectrometer**
- start-stop-detector system
- +3 veto's (≥ 2 mm φ)

- detected:
  - 2 charged particles

- reconstructed:
  - photon via missing mass analysis

P. Herrmann (thesis); Phys. Lett. B429(89)
Data analysis accompanied by extensive Monte Carlo simulation

- phase space
- detector response
- $\frac{1}{3} + \cos^2 \Theta_{12}$

cm data throughout very good agreement

the weighting factor $\frac{1}{3} + \cos^2 \Theta_{12}$ with

E_{\gamma} \text{ [GeV]}
Meson exchange and $\Delta$ isobar currents in proton-proton bremsstrahlung

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(Received 13 February 1998)

The contributions from meson exchange and direct excitation currents to proton-proton bremsstrahlung are discussed within the framework of a relativistic N/N interaction. Below the pion-production threshold the $\Delta$ isobar is shown to give the dominant contributions to the two-body currents. The intermediate- and static lines in the current operators are discussed, and are shown to give a good approximation to the full relativistic meson-exchange current in the considered kinematic region. For the $\Delta$-isobar the static line is a poor approximation of the isobar excitation current. 

PACS numbers: 13.40.-f, 14.30.e.c, 24.10.+r, 25.10.+s

![Graphs showing angular distributions](image)

**Theory:** J. Eden et al.,

*Phys. Rev. C53 (96) 1102*

*priv. communication*
Compilation of 4-fold differential cross sections
("Harvard" geometry)

old problems revisited:
How to present data of a 3-partic reaction...

... if taken with a $4\pi$-detector
possible (?) solution: $\gamma M$-system
(always coplanar)
Dalitz plots, FSI and all that

3-Teilchen Kinematik, C'M-System

\[ P = \{ M, \theta \} = \{ \sqrt{S}, \phi \} \]

\[ P = \begin{pmatrix} P_1, m_1 \\ P_2, m_2 \\ P_3, m_3 \end{pmatrix} \]

\[ S' = \sum P_i^2 = M^2 = \sum m_i^2 \]

Def.

\[ S_{ik} = (P_i + P_k)^2 = (P - P_j)^2 \]

\[ = S' + m_j^2 - 2 E_j \sqrt{S'} \]

\[ = m_i^2 + m_k^2 + 2 E_i E_k - 2 |P_i||P_k| \cos \theta_{ik} \]

Relation

\[ \sum_{\text{perm.}} S_{ik} = S' + \sum_i m_i^2 = \text{const} \]

nur Phase Raum

\[ \Rightarrow \text{Relativ Konsant} \]

\[ p p \pi^0 \]

PLB 356 (95) 8

Celsius

300 MeV

Dalitz plot of events in a plane defined by the squared invariant masses of the pion with each of the two final-state protons. The largest value of invariant masses are plotted along the x-axis. The experimental data are divided by Monte Carlo events generated according to phase space. The uncertainty in each histogram bin is typically 15%.

pm \pi^+ + \pi^-

PPC 356 (96) 20

J aime F

343 MeV

FIG. 19. The Dalitz plot for 319.2 MeV data with phase space acceptance non including FSI. These plots show the invariant mass of the proton-pion pair vs the invariant mass of the proton-neutron pair. All values in the kinematically allowed region are populated in this experiment to some degree. There is a strong enhancement at low $M_{\pi\pi}$ and high $M_{p\pi}$, which would be expected from strong pm final state interactions.
Dalitz plot for $pp\gamma$: no indications for sizeable FSI-effects

Plain phase space effect

or due to em-transition operator (suppression of $1\rightarrow 3$ transitions)

Spin structure in $pp\rightarrow pp\gamma$

Entrance channel: $^{1}S_{0}, \ ^{3}D_{2}, \ldots$

Exit channel: $^{3}P_{0,1,2}, \ ^{3}F_{1,2,3}, \ldots$

$H_5 \otimes H_{em}$

$H_5: S \rightarrow S, \ T \rightarrow T$

$H_{em}: E \rightarrow S, \ T \rightarrow T$

At high energy end of photon spectrum $M \gg E$

Matrix element for $M$

$<S'(M(k,p)p')S>$

$\propto \left[ (-)^{S_{p}} f(p',p-k) + (-)^{S_{p}} f(p',p+k) \right]$

$S'_{tot}$ total spin in entrance-exit channel

$\Rightarrow T \rightarrow T$ transitions favored

Impact on spin observables?
Near Future

- begin polarisation studies \( \vec{p} \rightarrow \vec{pp} \) performed yesterday
- measure np by use of \( LD_2 \) target
  \( pd \rightarrow n+p+p+\pi^- \)

Impact of Fermi-motion on missing mass distribution broadening

enlarged COSY-TOF spectrometer ~ 1\( \pi \) solid angle coverage

\[ 1^\circ \leq \theta_p \leq 70^\circ, \ 0^\circ \leq \phi_p \leq 360^\circ \]

time resolution for barrel elements measured via \( pp \) elastic

deduced position resolution \( \Delta z (\text{FWHM}) \leq 5 \text{ cm} \)
polarization of extracted COSY beam

$ t_{\text{spin}} \approx 10 \text{s} $

Summary

* COSY delivers (polarized) $ p $'s,
* COSY-TOF performs well at $ Q_{LAB} = 1 \text{ GeV} $,
* first data on pp $ p $ published PLB 429 (98) 195
* polarized pp $ p $ data on tape

open questions:

in general

presentation of 3-particle differential $ x $-section

for COSY

improvement of luminosity

$ \mathcal{P} = \frac{A_{f} + A_{t}}{A_{t} - A_{f}} $ \quad $ N_{i}^{\uparrow} + N_{i}^{\downarrow} $ \quad $ N_{i}^{\uparrow} = \sqrt{L_{i}^{\uparrow} \cdot R_{i}^{\uparrow}} \quad N_{i}^{\downarrow} = \sqrt{L_{i}^{\downarrow} \cdot R_{i}^{\downarrow}} $

(elimination of detector-specific asymmetry)
The COSY-TOF collaboration


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thanks to financial support by

BMBF + FZ - Jülich
J. Wambach:
Dileptons and chiral symmetry restoration
LOW-MASS DILEPTONS AND
CHIRAL SYMMETRY RESTORATION

J. Wambach

1. Introduction
2. Chiral Symmetry Breaking and its Restoration
3. Dileptons as a Probe
   3.a Hadron Gas - vs. Plasma Rates
   3.b Models for in-medium Effects
4. Chiral Symmetry Restoration and Vector Mesons
   4.a Weinberg Sum Rules
   4.b V-A Mixing
5. Comparison with Data
   5.a 'Fireball' Model
   5.b Hydrodynamics

Collaborators:
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R. Rapp, M. Urban

Relativistic Heavy Ions

RHIC's study hadronic matter under extreme conditions in temperature and density

Facilities:

- GSI/SIS \( \sim 1 \text{ AGeV} \)
- CERN/SPS \( \sim 20 \text{ AGeV} \)
- BNL/RHIC \( \sim 100 \text{ AGeV} \)
- CERN/LHC \( \sim 10 \text{ ATeV} \)
Heavy-Ion Collisions and Dileptons

Vector mesons observed in dilepton production of RHIC's
ideal probes of the early stages of the collision

Chiral Symmetry Breaking

Chiral symmetry is spontaneously broken in the physical vacuum

\[ \langle 0 | A_k^\mu (x) | \pi_j (p) \rangle = -i \delta_{jk} F_\pi p^\mu e^{-ipx} \]

→ Goldstone bosons

→ no parity doublets

\[ \bar{q}q\text{-excitations of the QCD vacuum} \]

Energy (MeV):

- \( a_1 (1260) \)
- \( f_1 (1285) \)
- \( f_1 (1420) \)
- \( \bar{p} (1200) \)
- \( \omega (782) \)

\( \pi (140) \)

\( P-S, V-A \text{ splitting in the physical vacuum} \)
Chiral Symmetry Restoration

consider a hadronic medium in thermal equilibrium

QCD partition function:

\[ Z_{QCD}(T, \mu, V) = \text{Tr} e^{-(H_{QCD} - \mu N)/T} \]

free energy density:

\[ F(T, \mu) = -\lim_{V \to \infty} \frac{T}{V} \ln Z_{QCD}(T, \mu, V) \]

from the Feynman-Hellmann theorem:

\[ \langle \bar{q}q \rangle^* = \frac{\partial F(T, \mu)}{\partial m_q} \]

quark mass \( m \) acts like an external magnet!

with the GOR: \( m^2 F^2 = -2m \langle \bar{q}q \rangle \)

\[ \delta F(T, \mu) = F(T, \mu) - F(0) \]

dilute gas of hadrons: \( \delta F(T, \mu) = \sum_h M_h \rho_h^*(T, \mu) \)

\[ \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \sim 1 - \frac{T^2}{8F^2} - 0.3 \frac{\rho}{\rho_0} + \cdots \]

no obvious connection between \( M_h \) and \( \langle \bar{q}q \rangle^* \)!
Initial conditions (currently reached):

\[ \epsilon > 1 \text{ GeV/fm}^3 \]

\[ T > 150 \text{ MeV} \]

What are the signatures?

Schematic View

[Graph showing various decay channels such as \( \rho \), \( \phi \), \( D \bar{D} \), \( J/\psi \), and \( \psi' \) along a mass axis with regions labeled Low, Intermediate, and High-Mass Region.]
Vector Mesons

- vector mesons $\rho, \omega, \phi, J/\psi$ as resonances in $e^+e^-$ annihilation

$$ R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} $$

$$ \sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{1}{\pi} \alpha^2 / 3s $$

Dilepton Rates

dilepton production from the medium:

lepton tensor:

$$ L^{\mu\nu}(q) = -\frac{\alpha^2}{6\pi^3 q^2} (g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}) $$

hadron tensor:

$$ H_{\mu\nu}(q) = \int d^4x e^{-iqx} \langle J_{\mu}^{\text{em}}(x) J_{\nu}^{\text{em}}(0) \rangle $$
electromagnetic current: $\sqrt{s} < 2m_c \sim 3$ GeV

$$J_{\mu}^{em} = \frac{2}{3} \bar{u}\gamma_{\mu}u - \frac{1}{3} \bar{d}\gamma_{\mu}d - \frac{1}{3} \bar{s}\gamma_{\mu}s = J_{\mu}^p + J_{\mu}^\omega + J_{\mu}^\phi.$$ 

$$J_{\mu}^p = \frac{1}{2}(\bar{u}\gamma_{\mu}u - \bar{d}\gamma_{\mu}d)$$
$$J_{\mu}^\omega = \frac{1}{6}(\bar{u}\gamma_{\mu}u + \bar{d}\gamma_{\mu}d)$$
$$J_{\mu}^\phi = -\frac{1}{3}(\bar{s}\gamma_{\mu}s)$$

quark gas at finite temperature:

$$R^q = N_c \sum_f e_f^2 = 3(\frac{4}{9} + \frac{1}{3} + \frac{1}{3})$$

resonance gas at finite temperature:

$$R^{\text{exp}} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$
Medium Effects

time-ordered correlation function:

$$\Pi_{\mu\nu}(q) = -i \int d^4x \, e^{iqx} \langle T(J_{\mu}^{\text{em}}(x), J_{\nu}^{\text{em}}(0)) \rangle$$

$$\text{Im} \Pi_{\mu\nu}(q) = -\frac{1}{2} (e^{iq_{\mu}} + 1) \Pi_{\mu\nu}(q)$$

virial expansion: (low $T$, small $\mu$)

$$\Pi_{\mu\nu}(q) = -(g_{\mu\nu} - \frac{q_{\mu}q_{\nu}}{q^2}) \Pi(q^2)$$

$$R(s) = -\frac{12\pi}{s} \text{Im} \Pi(q^2)$$

dominant contribution from pions and nucleons

$$\eta_{\nu} \Pi_{\mu\nu}(q) = \frac{1}{(2\pi)^2 E_{\nu}} \, C_{\mu\nu}(q, k)$$

'virtual Compton tensor' of the pion:

$$\langle \tilde{\pi}(q, k) \rangle = -i \int d^4x \, e^{iqx} \langle \pi(k) | T(J_{\mu}^{\text{em}}(x), J_{\nu}^{\text{em}}(0)) | \pi(k) \rangle$$

similar expression for the nucleon

- 'chiral reduction formalism':


$$g_{\mu\nu} C_{\mu\nu}(q, k) = -\frac{\text{Im}}{F_{\pi}^2} (2\Pi^0(q^2) + \Pi_A((q + k)^2), \ldots)$$

$$a_1 \rightarrow \pi^0 e^+ e^-$$

vector and axialvector correlators!
Low-Mass Region

Modification of the rho meson in an isospin gas

$\omega, h_1, a_1, K_0, f_1, f_1'$

$T=150 \text{ MeV}$

R. Rapp et al. (1999)
• 'chiral dynamics': \( T = 0 \)


'chiral' Lagrangian:

\[
\mathcal{L}_{\text{eff}}(U, \partial_\mu U; \mathcal{V}_\mu; B..)
\]

nucleon Compton tensor:

\[
C_{\mu\nu}^N = -i \int d^4x e^{iqx} \langle N(p') | T(J_{\mu}^{\text{em}}(x), J_{\nu}^{\text{em}}(0)) | N(p) \rangle
\]

diagrammatic expansion:

\( \pi, K \)

\( B \)

\( \rho \)

\( \rho \)

\( \phi \)

\( K \)

\( \rho \)

\( \cdot \)

\( \cdot \)

\( \cdot \)

\( \cdot \)
Re regulates via Paul- Villars Ψ = I Ψ*V

The covariance and gauge invariance →

\[ \{(x, y)^{d} \frac{\partial}{\partial x} - \frac{\partial}{\partial y} \} = (x, y)^{d} \frac{\partial}{\partial x} \]

\[ \frac{\partial}{\partial x} \frac{\partial}{\partial y} + \frac{\partial}{\partial y} \frac{\partial}{\partial x} = (\frac{\partial}{\partial x})^{2} \]

Effective Lagrangian:

\[ 1 - \left( \frac{\partial}{\partial x} \right)^{d} \frac{\partial}{\partial y} - \frac{\partial}{\partial z} = (x, y)^{d} \frac{\partial}{\partial x} \]

Vacuum correlation function:

\[ (0 \vert (0)^{d} \,(x)^{d} \,(y)^{d} \,(z)^{d} \,(0)^{d} )_{x \neq y \neq z} \int \frac{\partial}{\partial x} \frac{\partial}{\partial y} = (x, y)^{d} \frac{\partial}{\partial x} \]

\[ R \cdot \text{Rapp et al. PRL (1996), NPa (1997)} \]

Vector Dominance Model (ρ meson)
\( D^{\rho}_{\mu\nu}(q) = -i \int d^4x e^{iqx} \theta(x^0) \ll [\tilde{\rho}_\mu(x), \tilde{\rho}_\nu(0)] \gg \)

tensor structure: (Lorentz invariance broken)

\[ D^{\rho}_{\mu\nu}(q) = D^{L}_{\rho}(\omega, q) P^{L}_{\mu\nu}(q) + D^{T}_{\rho}(\omega, q) P^{T}_{\mu\nu}(q) \]

\( P_{\mu\nu}^{L,T}: \) long (trans) projectors

in-medium selfenergy:

- change of the pion dispersion relation
- direct coupling to \( N^*\)-Resonances

**rho meson:**

\[ \pi \rightarrow \pi + \rho + N^* \]

**pion:**

\[ \pi \rightarrow \pi + N \Delta \]

vertex corrections from gauge invariance:

\[ \ldots \]

physical processes included:

\[ \ldots \]

corresponding amplitudes:

\[ \ldots \]

single-nucleon processes

two-nucleon processes
Spectral Functions

\[ -\text{Im} \, D_{\gamma}(M, q, p, T) \, (\text{GeV}^{-2}) \]
\[ T=150 \, \text{MeV} \]

Photoabsorption

- important constraint of the model

total $\gamma-$ absorption cross section:

\[ \sigma_\gamma/A = -\frac{1}{\rho} \frac{e^2}{\omega} \epsilon^\mu \epsilon^\nu \frac{m_\rho^4}{g_\rho^2} D_{\mu\nu}^\rho(\omega, |q| = \omega) \]

low-density limit:

\[ \sigma_\gamma/A \rightarrow \sigma_\gamma P \]

diagrams:
proton:

\[ \gamma^p_k = \bar{\psi} \gamma^\mu \frac{T^k}{2} \psi \]

nuclei:

\[ \gamma^\text{N}_k = \bar{\psi} \gamma^\mu \gamma^5 \frac{T^k}{2} \psi \]

vector and axialvector currents:

\[ \Pi^\mu_V(q) = -i \int d^4 x e^{iqx} \langle \mathcal{T}(\gamma^\mu_k(x), \gamma^\mu_k(0)) \rangle \]
\[ \Pi^\mu_A(q) = -i \int d^4 x e^{iqx} \langle \mathcal{T}(A^\mu_k(x), A^\mu_k(0)) \rangle \]

vacuum:

\[ -\frac{1}{\pi} \text{Im} \Pi^\mu_V(q) = -(q^2 g^\mu\nu - q^\mu q^\nu) \rho_V(q^2) \]
\[ -\frac{1}{\pi} \text{Im} \Pi^\mu_A(q) = -(q^2 g^\mu\nu - q^\mu q^\nu) \rho_A(q^2) + q^\mu q^\nu F^2 \delta(q^2 - m^2_\pi) \]
Weinberg Sum Rules

In the vector sector chiral symmetry is encoded in Weinberg sum rules

\[ \int_0^\infty ds \left( \rho_V(s) - \rho_A(s) \right) = F_\pi^2 \quad \text{polarizability} \]

\[ \int_0^\infty ds \left( \rho_V(s) - \rho_A(s) \right) = 0 \quad \text{EWSR} \]

Pole approximation: (chiral limit)

\[ \rho_V(s) = \frac{s}{g_\rho^2} \chi(s - m_\rho^2) \]

\[ \rho_A(s) = \frac{s}{g_a^2} \chi(s - m_a^2) \]

then

\[ m_\rho^2 = \frac{9}{2} g_\rho^2 F_\pi^2; \quad a = \left(1 - \frac{m_\rho^2}{m_{a,1}^2}\right)^{-1} \]

for \( m_{a,1} = \sqrt{2m_\rho} \) (a = 2 KFSR relation)

Z. Huang PLB (1997)

Spectral Functions

vector: \( e^+e^- \rightarrow 2n\pi \)

axial: \( \tau \rightarrow (2n+1)\pi + \nu_\tau \)
medium: \((\vec{q} = 0)\) (J. Kapusta et al. PRD (1994))

\[
\int_{0}^{\infty} \frac{d\omega}{\omega} (\text{Im}\Pi_{V}(\omega) - \text{Im}\Pi_{A}(\omega)) = 0
\]

\[
\int_{0}^{\infty} d\omega \omega (\text{Im}\Pi_{V}(\omega) - \text{Im}\Pi_{A}(\omega)) = 0
\]

Mixing theorem: (M. Dey et al. PLB (1990))

\[
\Pi_{V}^{\mu\nu}(\omega) = (1 - \epsilon)\Pi_{V}^{\rho\sigma}(\omega) + \epsilon\Pi_{A}^{\rho\sigma}(\omega)
\]

\[
\Pi_{A}^{\mu\nu}(\omega) = (1 - \epsilon)\Pi_{A}^{\rho\sigma}(\omega) + \epsilon\Pi_{V}^{\rho\sigma}(\omega)
\]

\[
\epsilon = \frac{2}{F_{\pi}^{2}} \int \frac{d^{3}k}{(2\pi)^{3}} \frac{n(\omega_{k})}{\omega_{k}} = \frac{T^{2}}{6F_{\pi}^{2}}
\]

pole approximation:

\[
-\frac{1}{\pi} \text{Im}\Pi_{V}(\omega) = \frac{m_{\rho}^{4}}{g_{\rho}^{2}} Z_{\rho} \delta(s - m_{\rho}^{*^{2}})
\]

\[
\frac{1}{\pi} \text{Im}\Pi_{A}(\omega) = \frac{m_{a_{1}}^{4}}{g_{a_{1}}^{2}} Z_{a_{1}} \delta(s - m_{a_{1}}^{*^{2}}) + F_{\pi}^{*^{2}} \omega^{2} \delta(\omega^{2})
\]

then

chiral symmetry restored when \(m_{\rho}^{*} = m_{a_{1}}^{*}\)!
Chiral Restoration and Dileptons

symmetry restoration:

$$\epsilon = 1/2 \rightarrow T_c = \sqrt{3} F_\pi \simeq 160 \text{ MeV}$$

Dilepton rates:

\[
\frac{d^2R}{dM^2} = \frac{10}{3\pi^2} \left( \frac{M}{\Lambda} \right)^2 \left( \frac{M}{\Lambda} - \frac{\xi(\alpha)}{\xi(0)} \right)\]

\[\xi(\alpha) = \left( \frac{\alpha}{\pi} \right)^{1/2} \gamma \left( \frac{\alpha}{\pi} \right)^{-1} \]

G. Li et al. PRC (1998)
Comparison with Data

local rate: \( (\text{at given } T(x) \text{ and } \mu(x)) \)

\[
\frac{dN_{l+}}{d^4 x d^4 q} = L_{\mu\nu}(q)[H_{\rho}^{\mu\nu}(q) + H_{\omega}^{\mu\nu}(q) + H_{\phi}^{\mu\nu}(q) + \cdots]
\]

need space-time history of the collision

- homogeneous fire-ball model:
  - isotropic homogeneous expansion
  - initial conditions from transport models
  - cooling curve \( T(t) \) from transport models
  - particle abundances from \( T(t) \) in equilibrium
    except for pions: \( \mu_\pi \approx 50 \text{ (MeV)} \)

rate:

\[
A(M, \lbar) \text{: detector acceptance (Monte-Carlo)}
\]
30% Central Pb(158GeV/u)+Au

\[ \langle N_{ch} \rangle = 250 \]
\[ p_t > 0.2 \text{GeV} \]
\[ 2.1 < \eta < 2.65 \]
\[ \Theta_{ee} > 35 \text{mrad} \]

\[ \text{96 data} \]

\[ (d^2N_{ee}/dM_{ee}/dN_{ch})/[100\text{MeV/c}^2] \]

\[ 0.0 \quad 0.5 \quad 1.0 \quad 1.5 \]

\[ M_{ee} [\text{GeV}] \]

\[ 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \]

30% Central Pb(158GeV/u)+Au

\[ p_t > 0.2 \text{GeV} \]
\[ \Theta_{ee} > 35 \text{mrad} \]
\[ 2.1 < \eta < 2.65 \]
\[ q_{ee} > 0.5 \text{GeV} \]

\[ (d^2N_{ee}/dM_{ee}/dN_{ch})/[100\text{MeV/c}^2] \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \]

\[ M_{ee} [\text{GeV}/c^2] \]

\[ 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \]

\[ \text{96 data} \]

\[ \bullet \text{cocktail} \]
\[ \text{cktl + free } \pi \pi \]
\[ \text{cktl + RW} \]
\[ \text{cktl + BR} \]
CERES/NA45: 30% Central Pb(158GeV/u)+Au

\[ \frac{1}{N} \frac{d^2N}{dq^2 dq_{\perp} dq_{\parallel}} \] vs. 

\begin{align*}
1 \text{MeV/c}^2 & \text{GeV} \\
0.0 & 1.0 \\
0.0 & 1.0 \\
0.0 & 1.5
\end{align*}

30% Central Pb(158GeV/u)+Au

\[ <N_{\text{ch}}>=250 \]
\[ p_{\perp}>0.2\text{GeV} \]
\[ 2.1<\eta<2.65 \]
\[ \theta_{ee}>35\text{mrad} \]
- hydrodynamics:

  hydrodynamical equations:

  \[ \partial_{\mu} T^{\mu \nu}(x) = 0; \quad \partial_{\mu} j^\mu_B(x) = 0 \]

  energy-momentum tensor:

  \[ T^{\mu \nu}(x) = [\epsilon(x) + p(x)]u^\mu(x)u^\nu(x) - p(x)g^{\mu \nu} \]

  baryon current:

  \[ j^\mu_B(x) = \rho_B(x)u^\mu(x) \]

  - EoS from hadron gas and partonic gas
  - initial conditions from parametrizations of \( \rho^i_B, \epsilon^i, u^{\mu i} \)
  - freeze out condition

rate:
Gy. Wolf:
Vector mesons in nuclear matter
Vector mesons in nuclear matter

Gy. Wolf

QCD Sum Rules

Text:

\[ \Pi^{\mu\nu}(q) = i \int dx \, e^{iqx} \, \langle 0 \mid T (\gamma^\mu(x) \gamma^\nu(0)) \rangle \]

\[ = 2 (q^\mu q^\nu - q^0 q^\nu) \, \Pi(q^2) \]

Basic Idea

Parametrize \( \ln \Pi \) in the hadronic world

Try to calculate \( Re \Pi(q^2) \) for QCD
Apply the operator product expansion to the correlator

\[ \lim_{x \to y} C_n(x-y) \sim (x-y)^{d_0 - d_0 - d_0} \]

For small (large \( P \)) the sum can be written as an expansion in \( (x-y) \) (in \( \frac{1}{q^2} \))

in case of \( QCD \)

1. \( m_0 \phi \)
2. \( \phi \psi \phi \)
3. \( \overline{\psi} i \gamma^\nu \psi \overline{\psi} i \gamma^\nu \psi \)
4. \( m \overline{\psi} \gamma^\nu \psi \overline{\psi} \gamma^\nu \psi \)
5. \( f_{\alpha \beta} \overline{\psi} \gamma^\nu \psi \overline{\psi} \gamma^\nu \psi \)

How to calculate?

Go to high momentum \( q^2 \Rightarrow \) perturbative \( QCD \)

\( C_1 \):

\( C_q \):

\( G \):

\( C_{q_2} \):
The density is given in units of nuclear matter density $\rho = 0.17$ fm$^{-3}$.

Figure 3: The condensate $\langle \bar{q} q \rangle$ as a function of density $\rho$ and temperature $T$. (adapted from ref. [1].)
FIG. 2. The width $\gamma$ over the mass $m$, for nuclear saturation density $\rho_0$ and for different values of $\kappa$. The full lines border the region of QCD sum rule allowed parameter pairs with $d \leq 0.2\%$ and $\Delta M^2 \geq 0.6\text{GeV}^2$, the dashed lines border the allowed region for $d \leq 1\%$ (same $\Delta M^2$). The diamond marks mass and width of the free $\rho$ meson.
Vector meson self energies

\[ \langle n.m \mid \sigma \mid n.m \rangle = \langle 01 \mid \sigma \mid 01 \rangle + 8 \langle N \mid \sigma \mid N \rangle \]

Correlation function ("propagator") of a vector meson:

\[ (q^\mu q^\nu - q^2 g^{\mu \nu}) \bar{\Pi}(q) = \int d^4x e^{iqx} \langle \bar{T}(V^\nu(x) V^\nu(0)) \rangle \]

\[ \Delta \bar{\Pi} = \int d^4x e^{iqx} \langle \bar{T}(V^\nu(x) V^\nu(0)) \rangle |N\rangle \]

LSZ reduction

\[ \bar{\Pi}(s) = -4\pi (1 + \frac{m^2}{s}) \langle NN | NN \rangle \]
\[ T^p \rightarrow \omega n \]

\[ p, n \]

Energy dependence and angular distribut

\[ \tilde{P} = p^2 L + 1 \]

does not allow a simple picture

\[ \text{Resonance } P^+ \]

no reasonable parameters

Fig. 3. Detailed differential cross sections in 20 MeV/c steps for 8 intervals of \( P^+ \), starting at

(a) \( 40 < P^+ < 60 \) rising to (b) \( 180 < P^+ < 200 \) MeV/c. Any departures from isotropy are clearly

Table 1

<table>
<thead>
<tr>
<th>( P^+ ) range (MeV/c)</th>
<th>Coefficients (( \text{mb} / \text{sr} ))</th>
<th>( \sigma ) (( \text{mb} ))</th>
<th>( \sigma / P^+ ) (( \text{mb} / \text{MeV/c} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 – 60</td>
<td>( C_0 = 1.57 \pm 1.4 )</td>
<td>( 2.2 \pm 3.4 )</td>
<td>( 2.6 \pm 3.3 )</td>
</tr>
<tr>
<td>60 – 80</td>
<td>( C_1 = 27.0 \pm 3.0 )</td>
<td>( 1.8 \pm 4.3 )</td>
<td>( 339 \pm 26 )</td>
</tr>
<tr>
<td>80 – 100</td>
<td>( C_2 = 45.0 \pm 3.1 )</td>
<td>( 1.4 \pm 4.7 )</td>
<td>( 577 \pm 40 )</td>
</tr>
<tr>
<td>100 – 120</td>
<td>( C_3 = 65.7 \pm 3.9 )</td>
<td>( -5.9 \pm 8.0 )</td>
<td>( 830 \pm 50 )</td>
</tr>
<tr>
<td>120 – 140</td>
<td>( C_4 = 85.0 \pm 5.2 )</td>
<td>( -5.9 \pm 12.3 )</td>
<td>( 1110 \pm 71 )</td>
</tr>
<tr>
<td>140 – 160</td>
<td>( C_5 = 104.3 \pm 5.8 )</td>
<td>( -13.3 \pm 9.1 )</td>
<td>( 1150 \pm 80 )</td>
</tr>
<tr>
<td>160 – 180</td>
<td>( C_6 = 119.4 \pm 5.8 )</td>
<td>( -14.9 \pm 9.1 )</td>
<td>( 1310 \pm 74 )</td>
</tr>
<tr>
<td>180 – 200</td>
<td>( C_7 = 123.6 \pm 5.0 )</td>
<td>( -15.8 \pm 12.6 )</td>
<td>( 1460 \pm 83 )</td>
</tr>
</tbody>
</table>
Coupled channel approach

measured \( \pi N \rightarrow \pi N \), \( \pi N \rightarrow \pi N \)

Inelasticities

Channels:
\( \pi N, \pi N, \pi N, \pi N, \pi \Lambda \) (\( \pi \pi \ldots \))

Vector mesons around threshold

\( ^{1}S_{0} \) s-wave (relativistic formalism)

\( ^{1}P_{1} \) s-wave

\( ^{3}P_{0} \) s- and d-wave

\( ^{3}S_{1} \) computed amplitude in the \( S \) 1 channel

\( J^{P} \) loop function, \( g^{S} \) coupling constants

\( M_{S1} = g_{S1} (1 - J_{S1} g_{S1})^{-1} \)

Solving: \( 87 \) coupling constants

\~400 data points

Energy interval: \( \pm 1.5 \) GeV
Figure 1: The real and imaginary parts of the $\rho$ and $\omega$ propagators in nuclear matter at $\rho_0$, compared to the imaginary parts in vacuum.
M. Krivoruchenko:
Decay rates for dilepton production in HICs
Dilepton Spectra from Decays of Light Unflavored Mesons

Amand Faessler, C. Fuchs (ITP - Tübingen U.)
M. I. K. (ITEP - Moscow)

M.I. Kivoruchenko

nucl-th/9904029

The invariant mass spectrum of the $e^+e^-$ and $\mu^+\mu^-$ pairs from decays of the light unflavored mesons with masses below the $\phi(1020)$-meson mass to final states containing along with a dilepton pair one photon. one meson, and two mesons are calculated within the framework of the effective meson theory.

CONTENTS:
I. Relation between the decays \( M \rightarrow M_T \) and \( M \rightarrow M^\prime T \)
II. Decays of the $\rho$, $\omega$, and $\sigma$-mesons to $e^+e^-$ pairs
III. Meson decays to photons and $e^+e^-$ pairs

\[ \text{Decay modes } \eta \rightarrow \pi^+\pi^-e^+e^- , \eta' \rightarrow \pi^+\pi^-e^+e^- \]
\[ \text{Decay modes } f_0(980) \rightarrow \pi^+\pi^-e^+e^- \text{ and } a_0(980) \rightarrow \pi^+\pi^-e^+e^- \]

IV. Meson decays to one meson and a $e^+e^-$ pair

\[ \text{Decay modes } \omega \rightarrow \pi^+\pi^-e^+e^- , \rho \rightarrow \pi^+\pi^-e^+e^- \text{, and } \sigma \rightarrow \pi^+\pi^-e^+e^- \]

\[ \text{Decay modes } \eta \rightarrow \pi^+\pi^-e^+e^- \text{ and } \eta' \rightarrow \pi^+\pi^-e^+e^- \]

V. Meson decays to two mesons and $e^+e^-$ pair

\[ \text{Decay modes } \eta \rightarrow \pi^+\pi^-e^+e^- \text{ and } \eta' \rightarrow \pi^+\pi^-e^+e^- \]
\[ \text{Decay mode } \rho \rightarrow \pi^+\pi^-e^+e^- \]
\[ \text{Decay modes } \rho \rightarrow \pi^+\pi^-e^+e^- \text{, and } \omega \rightarrow \pi^+\pi^-e^+e^- \]
\[ \text{Decay modes } \rho \rightarrow \pi^+\pi^-e^+e^- \text{ and } \eta \rightarrow \pi^+\pi^-e^+e^- \]
\[ \text{Decay mode } a_0(980) \rightarrow \eta^+\eta^-e^+e^- \]
\[ \text{Decay mode } a_0(980) \rightarrow \eta^+\eta^-e^+e^- \]

VI. Numerical results:
(a) simulations of the dilepton spectra in heavy-ion collisions
(b) experimental searches of dilepton meson decays

Electromagnetic Radiation of Colliding Hadron Systems
Dileptons & Bremsstrahlung
Forschungszentrum Rossendorf near Dresden
17/IV-1999

- Reduction of nucleon masses in nuclei: Walecka model
  J.D. Walecka, 1974; Chin, 1977.

\[ \mathcal{L} = \ldots - g \sigma \bar{\psi} \psi, \quad \langle \sigma \rangle \sim \langle \bar{\psi} \psi \rangle \]
\[ m_N^* = m_N - g \langle \sigma \rangle \]

- Firmer grounds for reduction of nucleon masses on the basis of a partial restoration of chiral symmetry and finite-density QCD sum rules:

\[ \langle \bar{q}q \rangle = 1 - \frac{\rho}{f_\pi^2} \left( \Sigma_{\pi N} + m d \left( \frac{E(\rho)}{A} \right) \right) \]

- The change of the meson properties:
  C. Amadi and G.E. Brown, 1993;
  Haisuda, Suzuki and Kuwabara, 1996.

\[ m_N^* = m_N (1 - \alpha \frac{\rho}{\rho_0}), \quad \alpha \approx 0.18 \]

- The considerations in the Nambu-Jona-Lasinio model provide an evidence for reduction of nucleon and meson masses at finite density and temperature:
Reduction of the corresponding life times of resonances:

\[ \Gamma_{\text{tot}} = \Gamma_{\text{vac}} + \Gamma_{\text{coll}}, \quad \Gamma_{\text{coll}} = \rho \sigma v \]

Brown-Rho scaling:


\[ \frac{m^*_N}{m_N} = \frac{m^*_p}{m_p} = \frac{m^*_\omega}{m_\omega} = \ldots \]

**Dispersion Theory (Eletsky, Zobe)**

\[ m^*_v = m_v \]

Hydrogen atom in gas:

Length free path:

\[ \ell_f = \frac{1}{n \sigma} \]

\[ N(t) = N(0) \exp(-\ell/\ell_f) \]

\[ \ell = vt \Rightarrow N(t) = N(0) \exp(-n \sigma vt) \]

\[ |\Psi(t)|^2 = |\Psi(0)|^2 \exp(-\Gamma t) \]

Total width:

\[ \Gamma = \Gamma_{\text{vac}} + \Gamma_{\text{coll}} \]

where \( \Gamma_{\text{voc}} \) = natural line width (= vacuum width of the atomic energy level) and

\[ \Gamma_{\text{coll}} = n \sigma v, \]

in agreement with the uncertainty relation:

\[ \Delta E \gtrsim \frac{1}{\Delta t} \Rightarrow \frac{v}{\ell_f} = n \sigma v = \Gamma_{\text{coll}} \]

The shift of atomic energy levels and broadening of the atomic lines are observed experimentally in gases.
Dilepton spectra measured by
- CERES and HELIOS-3 Collaborations
  at CERN SPS (high energies)

Experiments found a significant enhancement of the
low-energy dilepton yield below the $\rho$ and $\omega$ peaks.

Current theoretical models interpret this by the scenario of a significant reduction of the $\rho$-meson mass in dense medium.

Dilepton spectra obtained by the
- DLS Collaboration at the BEVALAC
  (energies around 1 A GeV)

cannot be reproduced by present transport calculations: There remains a discrepancy by a factor 2 to 3


- HADES experiment at GSI, Germany

MOTIVATION FOR OUR INVESTIGATIONS:

To draw serious physical conclusions, one needs to eliminate first possible trivial explanations, like those connected to the existence of the nondirect decay modes of light unflavored mesons.
THE ENHANCED PRODUCTION OF DILEPTONS
IN THE LOW- AND INTERMEDIATE MASS CONTINUUM

\[
\begin{align*}
\text{integral of measured data} &= 1.40 \pm 0.1 \quad \text{NA38} \\
&= 2.43 \pm 0.42 \quad \text{HELIOS - 3} \\
&= 5.0 \pm 2.7 \quad \text{CERES} \\
&= 2 \div 3 \quad \text{DLS}\text{ }^b \\
\end{align*}
\]

\(\phi\) for \(0.15 < M_{ee} < 0.4\) GeV

CERES data can be explained by broadening and dropping vector meson masses
DLS data cannot

CLASSIFICATION OF DILEPTON MODES

\[V = \varphi, \omega, \phi, \text{ }\]

\[P = \pi, \eta, \eta', \text{ }\]

\[S = f_0(980), a_0(980)\]

(i) \(V \rightarrow e^+ e^-\)
(ii) \(P \rightarrow \gamma e^+ e^-\) \(S \rightarrow \gamma e^+ e^-\)
(iii) \(V \rightarrow Pe^+ e^-\) \(P \rightarrow Ve^+ e^-\)
(iv) \(V \rightarrow PPe^+ e^-\) \(P \rightarrow PPe^+ e^-\) \(S \rightarrow PPe^+ e^-\)

OUTLINE OF THE TALK:

I. \(M \rightarrow M\phi\text{ AND } M \rightarrow Me^+ e^-\)

II. \(f_0(980) \rightarrow \phi e^+ e^-\)

III. \(g^0 \rightarrow \pi^+ \pi^- e^+ e^-\)

IV. NUMERICAL RESULTS FOR ALL DECAY MODES
The phase space
\[ d\Phi(k, m_1, ..., m_k) = \frac{k}{2\pi^2} \delta^4(P - \sum_{i=1}^{k} \vec{p}_i). \tag{**} \]

\( P \) is a four-momentum of the meson \( M \), \( P^2 = s_1 \), \( p_i \) are momenta of particles in the final state, including the virtual photon \( \gamma^* \).

The decay rate for the process \( M \rightarrow M'\gamma^* \) is given by
\[ d\Gamma(M \rightarrow M'\gamma^*) = \frac{1}{2\sqrt{s}} \sum_i |M_{ji}|^2 \frac{1}{M^2} \frac{(2\pi)^4}{(2\pi)^4} d\Phi_{n+2} \]

\( j_i \) is the lepton current, the term \( 1/M^4 \) comes from the photon propagator.

The value \( \Gamma(M \rightarrow M'\gamma^*) \) can related to the decay rates \( \Gamma(M \rightarrow M'\gamma) \) and \( \Gamma(\gamma^* \rightarrow e^-e^+) \). The width of a virtual photon \( \gamma^* \):
\[ \Gamma(\gamma^* \rightarrow e^-e^+) = \frac{\alpha}{3} (\Lambda^2 + 2m^2)^{-1} \left( 1 - \frac{4m^2}{\Lambda^2} \right) \]

The expression for product of the two dilepton currents, summed up over the final states of the \( e^-e^+ \) pair, has the form
\[ \sum_i j_i j_{i*} = \frac{16\pi\alpha}{3} (\Lambda^2 + 2m^2)(-g_{\mu\nu} + \frac{k_{\mu}k_{\nu}}{\Lambda^2}) \]

\( \Lambda \) is the total momentum of the pair.

Factorization of the n-body invariant phase space:
\[ d\Phi_k(v, m_1, ..., m_k) = d\Phi_{k-1}(v, m_1, ..., m_{k-2}, M_n M_{i+1} M_{i+2}, M, m_{i+1}, m_{i+2}) \]

It can be proved using the unity decomposition
\[ 1 = \int d^4q M^2 \Phi(q^2 - \Lambda^2) \delta(q - p_{i+1} - p_{i+2}) \]

into Eq (**).
The two-body phase space

\[ \Phi_a(\sqrt{s}, m_1, m_2) = \frac{\pi^a(\sqrt{s}, m_1, m_2)}{\sqrt{s}} \]

The particle momentum in the c.m. frame:

\[ p^a(\sqrt{s}, m_1, m_2) = \frac{\sqrt{(s - (m_1 + m_2)^2)(s - (m_1 - m_2)^2)}}{2\sqrt{s}} \]

The decay width becomes

\[ \Gamma(M \rightarrow M'\gamma^*) = \Gamma(M \rightarrow M'\gamma^*) \Gamma(\gamma^* \rightarrow e^+e^-) \frac{dM^2}{\pi M^2} \]

In what follows, we work with the matrix elements of the processes \( M \rightarrow M'\gamma^* \).

Decay mode \( f_0(980) \rightarrow \gamma e^+e^- \)

- The isoscalar \( f_0(980) \)-meson: \( f_0(980) \rightarrow \gamma \gamma^* \) decay has the form

\[ \delta L_{S\gamma\gamma} = f_{S\gamma\gamma} F_{\gamma\mu} F_{\gamma\mu} S \]

where \( F_{\gamma\mu} = \partial_\mu A_\nu - \partial_\nu A_\mu \).

The matrix element for the process \( S \rightarrow \gamma \gamma^* \) is given by

\[ M = -if_{S\gamma\gamma} F_{S\gamma\gamma}(M^2)(g_{\sigma\lambda} k_1 - g_{\lambda\sigma} k_1)(g_{\mu\sigma} k_2 - g_{\mu\sigma} k_2)\varepsilon^*_{\nu}(k_1)\varepsilon^*_{\mu}(k) \]

Here, \( k_1, k_2 \) are real \((k_1^2 = M^2)\).

- \( F_{S\gamma\gamma}(t) \) is transition form factor of the decay \( S \rightarrow \gamma \gamma^* \).

The square of the matrix element summed up over the photon polarizations can easily be found to be

\[ \sum_\nu |M|^2 = 8sp^2(\sqrt{s}, 0, M) \]

with \( \sqrt{s} = m_S \) the scalar meson mass.

\[ p^*(\sqrt{s}, m_1, m_2) = \frac{a}{2\sqrt{s}} \sqrt{(s - (m_1 + m_2)^2)(s - (m_1 - m_2)^2)} \]
The width of the $S \rightarrow \phi^+ e^- e^-$ decay can be written as follows

$$\frac{d\Gamma(S \rightarrow \phi^+ e^- e^-)}{\Gamma(S \rightarrow \gamma \gamma)} = \frac{2}{p^3(\sqrt{s},0,0)} \left| F_{\gamma\gamma\gamma}(M^2) \right|^2 M \Gamma(\gamma^* \rightarrow e^+ e^-) \frac{dM^2}{\pi M^4}.$$ 

- The transition form factor $F_{SS}(t)$ depends on the nature of the scalar meson $S$. The asymptotics of the form factor according to the quark counting rules:
  - $\sim 1/t$ for a 2-quark model
  - $\sim 1/t^2$ for a 4-quark MIT bag model
  - $\sim 1/t^3$ for a $KK$ molecular model

In the SND experiment at the VEPP-2M $e^+ e^-$ collider (Novosibirsk) the branching ratio $\phi \rightarrow \pi^+ \pi^- \phi$ was measured.


It goes mainly through the $\phi \rightarrow f_{2} \phi$ decay mode.

4-quark MIT bag nature of the $f_{2}$ meson

![Diagram of particles]

- VMD model: Contributions from ground-state and excited vector mesons with masses $m_i$,

$$F_{\gamma\gamma}(t) = \sum_i \frac{c_i m_i^2}{m_i^2 - t}.$$ 

The normalization condition

$$F_{SS}(t) = 1$$

and the asymptotic condition

$$F_{SS}(t) \sim 1/t^3 \text{ at } t \rightarrow \infty$$

give constraints to the residues $c_i$:

$$1 = \sum_i c_i,$$

$$0 = \sum_i c_i m_i^2.$$
At least three vector mesons should be considered to fit the asymptotic behavior:

\[ F_{0\gamma\gamma}(t) \sim \frac{m_\omega^2}{m_\omega^2 - t} + \frac{m_\rho^2}{m_\rho^2 - t} + \frac{m_X^2}{m_X^2 - t}. \]

The resulting form factor is given by

\[ F_{0\gamma\gamma}(t) = \frac{m_\omega^2 m_\rho^2 m_X^2 (1 + Ct)}{(m_\omega^2 - t)(m_\rho^2 - t)(m_X^2 - t)}. \]

where

\[ C = \frac{m_\omega^2 (m_X^2 - m_\omega^2) + m_\rho^2 (m_X^2 - m_\rho^2)}{m_\omega^2 m_\rho^2 (2m_X^2 - m_\omega^2 - m_\rho^2)}. \]

Finally:

\[ m_\nu \rightarrow m_\nu - im_\nu \Gamma_\nu \]

**FIG. 24.** The differential branching ratios for the \( f_0(980) \) - and \( a_0(980) \) -mesons into the \( \mu^+\mu^- \) channels versus the invariant mass, \( M \), of the dilepton pairs. The solid curve No. 5 gives the total \( \mu^+\mu^- \) ratio of the \( f_0 \) -meson decays. The structures in the \( f_0, a_0 \rightarrow \gamma\mu^+\mu^- \) decay modes are connected to the \( \omega \) - and \( \rho \) -mesons contributions to transition form factors of the \( f_0 \) - and \( a_0 \) -mesons.
**SPECIFIC EXAMPLE: DECAY MODE** \( \rho^0 \rightarrow \pi^+\pi^-e^+e^- \)

**MOTIVATION:**

\[ \Gamma_{\rho \rightarrow \pi\gamma} = (7.0 \pm 2.0) \times 10^{-4} \]

\[ \Gamma_{\rho \rightarrow \pi^+\pi^-\gamma} = (9.9 \pm 1.6) \times 10^{-3} \]

This decay mode \( \rho^0 \rightarrow \pi^+\pi^-e^+e^- \) gives an important (if not a dominant) contribution to the dilepton spectrum of the \( \rho^0 \)-meson decays.

The diagrams contributing to the decay \( \rho^0 \rightarrow \pi^+\pi^-\gamma^* \):

The matrix element of the process \( \rho^0 \rightarrow \pi^+\pi^-\gamma^* \):

\[ M = i e f_{\rho\pi} F_\pi(k^2) \epsilon_\pi(\rho) \bar{\psi}(p_2) \gamma^\mu \psi(p_1) \]

\[ M_{\rho\pi} = (p_1 - p_2) \epsilon_\pi \left[ \frac{(2p_1 + k)_\mu}{(p_1 + k)^2 - m^2} - \frac{(2p_2 + k)_\mu}{(p_2 + k)^2 - m^2} \right] \]

\[ \times \left[ \frac{(2p_1 + k)_\mu}{(p_1 + k)^2 - m^2} + \frac{(2p_2 + k)_\mu}{(p_2 + k)^2 - m^2} \right] \]

\[ \times \frac{1}{2m_\rho} \]

\[ \left. \begin{array}{l}
M_{\rho\pi} p_\rho = 0, \\
M_{\rho\pi} P_\rho = 0.
\end{array} \right\} \]

The square of the matrix element summed up over the photon polarizations, averaged over the initial \( \rho \)-meson polarizations and over directions of the pion momenta in the c.m. frame of the two pions:

\[ M_\rho = \frac{d\Omega_{\rho\pi\pi\gamma}}{d^4k} \bar{\psi}(p_2) \epsilon_\pi(\rho) \psi(p_1) \]

\[ = \frac{d}{d^4k} \left( \frac{1}{3} \right) \]

\[ = \frac{2}{3B_\rho} \left( 4B_\rho^2 + (M_\rho^2 - 4m^2)(s - (s - m^2))F(\xi) \right) \]

\[ + (s - 4m^2)(M_\rho^2 - 4m^2 + 2s) + 2s_{12} M_\rho^2 L(\xi) \]

\[ \Rightarrow \quad s = p_\rho^2 = m_\rho^2 \quad s_{12} = (p_1 + p_2)^2 \]

\[ F(\xi) = \frac{1}{2} \left[ \frac{1}{\sqrt{1 - \xi}} \right] \]

\[ L(\xi) = \frac{1}{2} \left[ \frac{1}{\sqrt{1 - \xi}} \right] \]

\[ \xi = \frac{2}{B_\rho} \sqrt{s_{12} p_\rho^2 (\sqrt{s_{12}}, \mu)^2 (\sqrt{s_{12}}, M_\rho)} \]

\[ B_\rho = \frac{1}{2} (s + M_\rho^2 - s_{12}) \]

The decay rate \( \Gamma(\rho^0 \rightarrow \pi^+\pi^-\gamma^*) \) takes the form

\[ \Gamma(\rho^0 \rightarrow \pi^+\pi^-\gamma^*) = \frac{\alpha^2}{16\pi^2 g_{\rho\pi}^2 F_\pi(M_\rho)^2} \int_{s_{12}}^{(s_{12} - M_\rho)^2} \frac{dM_\rho^2}{\sqrt{s_{12}}} \]

The dilepton spectrum is given by

\[ d\Gamma(\rho^0 \rightarrow \pi^+\pi^-e^+e^-) = \Gamma(\rho^0 \rightarrow \pi^+\pi^-\gamma^*) \Gamma(E) \rightarrow (e^-) \frac{dM_\rho^2}{2M_\rho^2} \]
BRANCHING RATIOS
FOR RADIATIVE MESON DECAYS

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B^{th}$</th>
<th>$B^{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^\pm \to \pi^\pm \pi^0\gamma^*$</td>
<td>$4.0 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$\rho^0 \to \pi^+\pi^-\gamma^*$</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$(0.99 \pm 0.16) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\rho^0 \to \pi^0\pi^0\gamma$</td>
<td>$1.2 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$\rho^0 \to \pi^0\eta\gamma$</td>
<td>$3.8 \times 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>$\omega \to \pi^+\pi^-\gamma^*$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$&lt; 3.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\omega \to \pi^0\pi^0\gamma$</td>
<td>$3.1 \times 10^{-5}$</td>
<td>$(7.2 \pm 2.5) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\omega' \to \pi^+\pi^-\gamma$</td>
<td>$2.1 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$\eta \to \pi^+\pi^-\gamma$</td>
<td>$6.9 \times 10^{-2}$</td>
<td>$(4.78 \pm 0.12) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\eta' \to \pi^+\pi^-\gamma$</td>
<td>$2.5 \times 10^{-1}$</td>
<td>$(2.8 \pm 0.4) \times 10^{-1}$</td>
</tr>
<tr>
<td>$f_0 \to \pi^+\pi^-\gamma^*$</td>
<td>$1.1 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$a_0^- \to \pi^+\pi^-\gamma^*$</td>
<td>$2.4 \times 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

*) for photon energies above 50 MeV

in agreement with calculations
A. Barenboim, M. Gevorkian, G. Pancheri

FIG. 15. The differential branching ratios for the $\rho$-meson decays into the $e^+e^-$ channels as functions of the invariant mass, $M$, of the dilepton pairs. The solid curves (8 and 9) are the total ratios for the $\rho^0$- and $\rho^\pm$-mesons.

\[
\frac{B(\rho^0 \to \pi^+\pi^- e^+ e^-) + B(\rho^0 \to \pi^0 \pi^- e^+ e^-)}{B(\rho^0 \to e^+ e^-)} \approx \frac{1}{3}
\]

for $M \geq 100$ MeV
### Branching Ratios for Radiative Meson Decays

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B^h$</th>
<th>$B^{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^+ \to \pi^+\pi^-\gamma^*$</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\rho^0 \to \pi^+\pi^-\gamma^*$</td>
<td>$2.1 \times 10^{-7}$</td>
<td>$2.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\rho^+ \to \pi^+\pi^-\gamma$</td>
<td>$6.9 \times 10^{-2}$</td>
<td>$4.78 \pm 0.12 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\rho^0 \to \pi^0\eta\gamma$</td>
<td>$2.1 \times 10^{-7}$</td>
<td>$2.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\omega \to \pi^0\pi^0\gamma$</td>
<td>$3.1 \times 10^{-5}$</td>
<td>$(7.2 \pm 2.5) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

* for photon energies above 50 MeV

* in agreement with calculations

A. Breunow, L. Gruw, G. Bambah


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### Integral Branching Ratios for Unflavored Meson Decays to $e^+e^-$ and $\mu^+\mu^-$ Channels

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B^h_{e^+e^-}$</th>
<th>$B^{exp}_{e^+e^-}$</th>
<th>$B^h_{\mu^+\mu^-}$</th>
<th>$B^{exp}_{\mu^+\mu^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^+ \to \pi^+e^-\gamma$</td>
<td>$4.1 \times 10^{-6}$</td>
<td>$3.4 \times 10^{-6}$</td>
<td>$1.8 \times 10^{-6}$</td>
<td>$1.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho^0 \to \pi^0e^-\gamma$</td>
<td>$2.7 \times 10^{-6}$</td>
<td>$2.4 \times 10^{-6}$</td>
<td>$6.7 \times 10^{-7}$</td>
<td>$4.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\eta \to \pi^+\pi^-e^-\gamma$</td>
<td>$7.5 \times 10^{-5}$</td>
<td>$7.2 \times 10^{-5}$</td>
<td>$2.4 \times 10^{-5}$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Input $(7.15 \pm 0.19) \times 10^{-3}$

Input $(7.15 \pm 0.19) \times 10^{-3}$
FIG. 22. The differential branching ratios for the $\eta$- and $\eta'$-mesons decays into the $\mu^+\mu^-$ channels versus the invariant mass, $M$, of the dilepton pairs. The solid curves give the total ratios. The narrow structure in the $\eta' \to \gamma\mu^+\mu^-$ decay is connected to the $\omega$-meson contribution to the $\eta' \to \gamma\gamma^*$ transition form factor.

FIG. 21. The differential branching ratios for the $\eta$- and $\eta'$-mesons decaying into the $e^+e^-$ channels versus the invariant mass, $M$, of the dilepton pairs. The solid curves (6 and 7) give the total ratios. The narrow structure in the $\eta' \to \gamma e^+e^-$ decay is connected to the $\omega$-meson contribution to the $\eta' \to \gamma\gamma^*$ transition form factor (see Eq.(IV.5)).
Fig. 20. The differential branching ratios for the $\phi$-mesons decaying into the $\mu^+\mu^-$ channels versus the invariant mass, $M$, of the dilepton pairs. The solid curve gives the total ratio of the $\mu^+\mu^-$ modes.

Fig. 19. The differential branching ratios for the $\phi$-meson decays into the $e^+e^-$ channels versus the invariant mass, $M$, of the dilepton pairs.
fig. 17. The differential branching ratios for the $\omega$-meson decays into the $e^+e^-$ channels as functions of the invariant mass, $M$, of the dilepton pairs. The solid curve is the total ratio. The background is dominated through the $\pi e^+e^-$ Dalitz decay.

$$d\mathcal{B} \sim \Gamma(M \rightarrow M'\gamma*) \frac{dM}{M}$$

1: $\Gamma(M \rightarrow M'\gamma^*) \sim \text{constant at } 2m_\pi \leq M$

$$\Rightarrow \frac{d}{d \log M} \frac{db}{d\omega} \sim -1$$

2: $\Gamma(M \rightarrow M'\gamma^*) \sim \log^3 \left( \frac{1}{M} \right) \text{ at } 2m_\pi \leq M$

$$\Rightarrow \left| \frac{d}{d \log M} \int \frac{db}{d\omega} \right| \geq 1$$

/ bremsstrahlung /

fig. 18. The differential branching ratios for the $\omega$-meson decays into the $\mu^+\mu^-$ channels as functions of the invariant mass, $M$, of the dilepton pairs. The solid curve is the total ratio.
CONCLUSION

1. BRANCHING RATIOS TO DILEPTON CHANNELS ARE CALCULATED:

   \[ M \rightarrow e^+e^-, \gamma e^+e^-, M e^+, M M e^+e^- \]

2. \( \frac{B(g \rightarrow \pi^+ e^+ e^-)}{B(g \rightarrow e^+ e^-)} \approx \frac{1}{3} \) at \( M > 100 \) MeV

3. EXCESS OF DILEPTONS AT \( M < 500 \) MeV IN HIC SEEMS TO BE NOT CONNECTED TO NEGATION OF MESON DECAY CHANNELS

4. RESULTS REPRESENT INTEREST FOR:

   (i) HIC (HIGH ENERGY)
   (ii) \( UN \rightarrow N N e^+e^- + \ldots \n
   (iii) \( TN \rightarrow N e^+e^- + \ldots \n
   (iv) SEARCHES OF DILEPTON DECA- 

   ON OF MESONS
F. Dohrmann:
The HADES project
The HADES Project

- Motivation
- Concept and Status
- HADES in 1999/2000
- Summary

Frank Dohrmann, FZ Rossendorf, Institut f. Kern- u. Hadronenphysik

Electromagnetic Radiation off Colliding Hadron Systems: Dileptons & Bremsstrahlung
Miniworkshop, Forschungszentrum Rossendorf, Dresden, April 16-17, 1999

Collisions of Hadrons and Nuclei

- Production of Mesons at SIS Darmstadt
  - Kaons $K^+, K^-$ (with strangeness) KaoS, FOPI
  - Light vector mesons $\rho, \omega, \phi$ (Decay $\rightarrow e^+e^-$ Dileptons) HADES
- Modification of effective mass $m^*$ of mesons in nuclear matter?
- **Hypothesis:** chiral symmetry is partially restored in **hot and dense** nuclear matter

- Important for description of nuclear matter under extreme conditions, i.e. early universe, neutron stars
**Light Vector Mesons**

\[
p, \omega, \Phi \rightarrow e^+e^-
\]

<table>
<thead>
<tr>
<th>Meson</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>cτ(fm)</th>
<th>dom. Decay</th>
<th>(e^+e^-) BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho)</td>
<td>768</td>
<td>152</td>
<td>1.3</td>
<td>(\pi^+\pi^-)</td>
<td>(4.4 \times 10^{-5})</td>
</tr>
<tr>
<td>(\omega)</td>
<td>782</td>
<td>8.43</td>
<td>23.4</td>
<td>(\pi^+\pi^0)</td>
<td>(7.2 \times 10^{-5})</td>
</tr>
<tr>
<td>(\Phi)</td>
<td>1019</td>
<td>4.43</td>
<td>44.4</td>
<td>(K^+K^-)</td>
<td>(3.1 \times 10^{-4})</td>
</tr>
</tbody>
</table>

---

**Vector mesons in nuclear matter**

Dilepton Spectra: Calculation by C. Ernst et al., Univ. Frankfurt a.M.

- Experiments with HADES at SIS/GSI
Results of DLS Experiment

- Data by DLS collaboration
  Porter et al. PRL 79 (1997) 1229,
  Wilson et al. PRC 57(4) (1998) 1865
- Transport calculation (HSD model)
  Bratkovskaya, Ko, PL B445 (1999) 265
  Most recent attempt to describe DLS data
  Underpredicts data by a factor of 3 in the invariant mass region
  $0.2 \text{ GeV/c}^2 < M_{ee} < 0.5 \text{ GeV/c}^2$
  Regardless of using bare meson masses or in-medium masses of mesons.
  All earlier attempts failed as well.
  Situation should be clarified by new data from HADES very soon.

Institut für Kern- und Hadronenphysik

F. Dohrmann, FZ Rossendorf
Key Parameters of HADES

Parameter (2. Generation)

- Large acceptance for Lepton pairs $\varepsilon_{\text{pair}} \sim 40\%$
- Capable of high rates ($R \sim 10^6$ s$^{-1}$ and high multiplicities)
- High resolution spectrometer
  - Resolution for reconstructed invariant masses comparable to width of free $\omega$ meson ($\Delta M / M \sim 1\% (c)$)
- Signal to background $S/B > 1$ for invariant masses up to $M_{ee} \sim 1$ GeV/c$^2$
- High granularity to study heaviest systems (U+U, 1 AGeV)

High Acceptance DiElectron Spectrometer

Geometry

- 6 sectors form hexagonal pyramid
  - $2\pi$ in $\phi$
  - $18^\circ < \theta < 85^\circ$

Dilepton Identification

- RICH
  - Radiator: C$_2$F$_{10}$
  - Spherical VUV mirror
  - Photon detector: CsI photocathode
- META
  - TOF Plastic scintillator wall
  - Lead shower detector

Track Reconstruction

- Superconducting Toroid (6 coils)
  - $B_{\text{max}} = 0.7$ T,
  - $B_p = 0.34$ T
- MDC (Multiwire Drift Chamber)
  - Low Z of wire material (Al)
  - 4 layers with high granularity, i.e. small drift cells ($= 1$ cm diameter).

In total $\sim 100,000$ channels
**e⁺e⁻ Identification with RICH**

- **Ring Imaging Cherenkov**
  \[ \cos \theta_c = \frac{1}{\beta \cdot n(\lambda)} \]
  \[ N = N_0 \cdot l_{\text{rad}}^{1/\gamma_t^2} \quad (l_{\text{rad}} = 40 \, \text{cm}) \]
  \[ N_0 = 80 - 150 \, \text{cm}^{-1} \]

- **Radiator** (hadr. blind)
  \[ 3 - \gamma_{\text{had}} < \gamma_t < \gamma_{\text{lep}} \]
  \[ C_4F_{10} : \quad \gamma_t = 18.3 \]
  \[ \Delta E = 350 \, \text{MeV/event} \quad (200 \, \text{ch.p.}) \]

- **VUV mirror**
  Poly-C substr. (2 mm) \( x/X < 2\% \) \ Al + MgF₂ coating \[ R > 80\% \]

- **Photon detector** (MWPC)
  CsI - cath.
  CaF₂ window

---

**Mirror Segments for RICH**
**MDC Design Parameters**

<table>
<thead>
<tr>
<th></th>
<th>A [mm]</th>
<th>B [mm]</th>
<th>C [mm]</th>
<th>a [mm]</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>139.21</td>
<td>767.38</td>
<td>839.19</td>
<td>5</td>
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<tr>
<td>II</td>
<td>205.00</td>
<td>905.00</td>
<td>1049.27</td>
<td>6</td>
</tr>
<tr>
<td>III</td>
<td>310.43</td>
<td>1804.80</td>
<td>2139.05</td>
<td>12</td>
</tr>
<tr>
<td>IV</td>
<td>345.46</td>
<td>2224.05</td>
<td>2689.04</td>
<td>14</td>
</tr>
</tbody>
</table>

- 24 conceptually identical modules in 4 different geometries
- 6 drift cell layers
  - stereo angles +40, −20, +0, −0, +20, −40 deg
- Maximum drift path: 5 up to 14 mm
- Cathode wires: 80 µm bare Aluminum
- Potential wires: 80 and 100 µm bare Aluminum
- Sense wires: 20 µm Tungsten/Au
- Counting Gas: He/i-C₄H₁₀
- Position resolution from prototype tests σ ~ 80 µm

---

**Full System Test MDC Typ II**
e^+e^- Identification Shower-Detector

- E.m. shower-Detektor
  - 20 m^2
- Wire chambers
  - self quenching streamer mode
  - Signal not \( \propto \Delta E \)
- Pad readout
  - Pad multiplicity before and after lead converter
  - e^+,e^- identification

Pre-Shower Detector

evt # 1349

Pre

Post
Electron Identification in RICH & TOF for U + Pb 1AGeV

TOF particle velocity distribution

- Straight line trajectory and target emission assumed
- Polar and azimuthal angular matching window $\Delta \theta, \Delta \phi \approx 8^\circ$

TOF & RICH track polar and azimuthal correlation

Institut für Kern- und Hadronphysik
Magnet

Scheme Hades Simulation

HADES simulation software (Nov. 98)

Event Generator

HGeant

Update

H2ROOT

ROOT

Digitize

Analysis
Experiments with HADES

Sim.: Au + Au, E = 1 AGeV

- 2-3 \( \rho_0 \)
- High Multiplicity
  - 200 charged hadrons & 20 photons (\( \pi^0 \)-decays)
  - high granularity
  - very good track reconstruction
- Suppression of hadr. & EM backgr.
  - "hadron-blind" trigger
  - "fast" RICH
  - Z < 10 material

\[ \pi^- + p \rightarrow \omega + n \]

\( \pi^- + p \rightarrow \omega + n \)

- \( \sim 1 \rho_0 \rightarrow \) normal nucl. density
- large WQ
- moderate multiplicity

\[ \pi + p \rightarrow \omega + n \]

\[ \pi + Be, p_{\pi^-} = 1.3 \text{ GeV/c} \]

\[ \pi + Pb, p_{\pi^-} = 1.3 \text{ GeV/c} \]

Data: \( \pi^- \)-beam September 1998

![Graph showing pion yield vs. \( m_{inv} \) and pion momentum vs. \( \Delta p/p \)]
Summary and Outlook

- High resolution dilepton spectroscopy in 0.1-2 AGeV range is of fundamental interest
- New data with high resolution is expected to test DLS data
- \( \pi, p, \) and A-beams available at GSI
- Experiments at 1\( \rho_0 \) as well as 2-3\( \rho_0 \) possible
- HADES starts in 1999 with pp collisions
  - elastic scattering
  - dielectrons
    - 160 MeV/c^2 < \( M_{ee} < 500 \) MeV/c^2
    - \( \eta \)-Dalitz and \( \Delta \)-Dalitz
- Full acceptance and high resolution will be reached 1999/2000
- in 2000: invariant masses up to 1AGeV, C+C, Ca+Ca, Au+Au
P. Thusty:
Status of the HADES-ToF
TOF DETECTOR FOR HADES

P. Thustý

Nuclear Physics Institute of the Academy of Sciences of Czech Republic,
Rež, Czech Republic

Specification of the TOF detector:

Purpose:

- trigger:
  - multiplicity of charged particles to select central collisions
  - velocity of particles to select di-lepton candidates

- analysis:
  - velocity for electron identification
  - position for tracking
  - multiplicity for impact parameter determination
  - other?
HADES: the Time Of Flight wall
Time-of-Flight 2

Reaction plane:

$$\tilde{Q} = \sum_{i=1}^{N} \omega_i \vec{p}_i$$

error of reaction plane determination in semi-central region:

$$\sigma = 33^\circ \text{ Au+Au } 0.8 \text{ A GeV}$$
$$\sigma = 46^\circ \text{ Ni+Ni } 2 \text{ A GeV}$$
$$\sigma = 52^\circ \text{ Ca+Ca } 2 \text{ A GeV}$$

dilepton angular distribution according to the reaction plane $N(\varphi)$,

$$\varphi = \phi_{e^+e^-} - \phi_R$$

$$N(\varphi) = \frac{N_0}{2\pi} (1 + 2v_1cos(\varphi) + 2v_2cos(2\varphi))$$
GEANT simulation:

Au + Au 1 AGeV

$10^8$ ions/s.

5 s extraction time,

segmented target (1%)

$5000 \rho$'s, 1000 $\omega$'s

and 100 $\phi$'s per day
Azimuthal anisotropy of dileptons from $\eta$ Dalitz decay:

Azimuthal anisotropy of combinatorial background from $\pi$ Dalitz decay:
Simulation of azimuthal dependence of $\omega$ production:

- Semi-central $^{197}$Au + $^{197}$Au collisions at 9 AGeV

- Thermal source of $\omega$ meson with $T = 84$ MeV in centre of compressed cone with radius 2.3 fm and baryon density of $2\rho_0$

- Mass shifts given by Brown-Rho scaling

- Expected resolution of HADES included
R. Holzmann:
Fist experiments with HADES: $e^+e^-$ production in pp and AA collisions
First Physics with HADES:
e\text{e}^+\text{e}^- \text{ Production in } p+p, p+A \text{ and } A+A

Romain Holzmann, GSI Darmstadt

- Status of HADES in 1999/2000
  1. 2 sectors only: reduced acceptance!
  2. 3 MDC planes only: reduced resolution!
  3. TOF not fully equipped: reduced multi-hit capability!
  4. 2\textsuperscript{nd} and 3\textsuperscript{rd} level triggers not yet optimized: reduced online selectivity!

- Experimental program in 1999/2000:
  1. commissioning of the setup: p+p elastics, various A+A
  2. disentangle e\textsuperscript{+}e\textsuperscript{-} cocktail: p+p and p+A
  3. check on DLS results: do light A+A systems
  4. see first signals of \omega and \phi in p+A and A+A

R. Holzmann, GSI Darmstadt April 14, 1999
Acceptance for 2 sectors

- Results:
  - Acc. > 10%
  - no holes for:
    - $M_{\text{inv}} > 0.2 \text{ GeV/c}^2$
    - $p_t > 0.2 \text{ GeV/c}$

>10 fold improvement over DLS !!!

R. Holzmann, GSI Darmstadt
**Generic acceptance**

- **Results:**
  - cutoff: $p_+ > 0.1$ GeV/c
  - flat: $M_{\text{inv}} > 0.6$ GeV/c²

- **Requirements**
  - identification & momentum measurement
  - $0.1$ GeV/c < $p_+ < 1.5$ GeV/c

---

**Simulated Momentum Resolution for 2,3,4 MDC planes**

- Data for MDC 1,2,3,4

---

R. Holzmann, GSI Darmstadt
**π/p - separation**

With TOF

\[ \Delta t = 100 \text{ ps (σ)} \]

For:

- \( \Delta p/p \sim 1 \% \)
  - (4 MDC planes)
- \( \Delta p/p \sim 3 \% \)
  - (3 MDC planes)

**Diagram:**

- Mass vs. Momentum [GeV/c²]
  - Protons and Pions
  - 3 MDC and 4 MDC

**Text:**

- Pion - J.
- Δ separation with TOF
- At \( t = 100 \text{ ps} \)
- \( A_{plp} \)
- \( A_{plp} \) for (4 MDC planes)
- \( A_{plp} \) for (3 MDC planes)

**Graph:**

- Mass vs. Momentum [GeV/c]
- Protons and Pions
- 3 MDC and 4 MDC
$e^+e^-$ Yield from pp reactions

DLS p+p data

Data:
W.K. Wilson et al.,
PRC 57 (1998) 1865

Calculation:
R. Holzmann

R. Holzmann, GSI Darmstadt
Exclusive $\eta$ -Production in pp Reactions

6 sectors, full resolution:

missing-mass distribution from pp momentum analysis

Expected di-electron spectra for 4 days of beam ($10^8$ protons/s)
$\eta$ from $pp$ with reduced setup

2 sectors, 3 MDC planes only:

$2 \text{ GeV} p+p \rightarrow p+p+\eta$

$\varepsilon(p+p+\eta) \approx 0.5-1.5\%$

**Dalitz:**

$\eta \rightarrow e^+e^-\gamma$

Missing mass distribution from $pp$ momentum analysis

Expected di-electron spectra for 4 days of beam ($10^8$ protons/s$^{-1}$)
Comparison with DLS Data

$\pi^-$ and $\eta$ strongly constrained by TAPS $\eta$ data!


The $\eta$ Dalitz-decay contribution does not exhaust the observed di-electron yields in the mass range $M_{\gamma\gamma} = 0.15-0.55$ GeV!

Need:
- $\Delta \rightarrow \eta e^+ e^-$
- $p\bar{h} \rightarrow p\bar{e} e^+$
- $\ldots$
Di-Electrons @ 1 AGeV: Theory (1)

Data:
R.J. Porter et al.,
PRL 79 (1997) 1229

Calculation:
E.L. Bratkovskaya et al.,
NP A609 (1998) 168

Theor. distribution folded with exper. resolution ($\Delta M/M \sim 10\%$)
Di-Electrons @ 1 AGeV: Theory (2)

Data:
R.J. Porter et al.,
PRL 79 (1997) 1229

Calculation:
E.L. Bratkovskaya
and C. M. Ko,
PL B445 (1999) 265

theor. distr. folded
with experimental
resolution
($\Delta M/M \sim 10\%$)

R. Holzmann, GSI Darmstadt
thermal source at mid rapidity
for 1 AGeV A+A:

Rapidity coverage

Evidence of non-isotropic angular distributions from

- $\pi^+, \pi^-$ data (Nagamyia et al, Sandoval et al., Peite et al.)
- BUU calculations (e.g. E. Bratkowskaya et al.)

Assuming $A_2 \simeq 0.9$ in extrapolation of cross section to $4\pi$

- $\sigma(\pi^0)$ increases by 25 %
- $\sigma(\eta)$ increases by 18 %
Di-electrons @ 2 AGeV

UrQMD calculation
(C. Ernst 1998)

not folded with exp. resolution
(ΔM/M ~ 1%)

Rates:
acceptance of a 2 sector setup

Pion Anisotropies:

800 A GeV
At + kCl

1.0 A GeV, At + At

1.8 A GeV, At + kCl

HADIS
Di-electrons @ 2 AGeV

UrQMD calculation
(C. Ernst 1998)

not folded with experimental resolution
(ΔM/M ~ 1%)

R. Holzmann, GSI Darmstadt

1. Experimental results:

$m_t$ scaling is observed in all systems at all beam energies.
2. BUU predictions (E. Bratkovskaya et al.):

Scaling expected for heavier mesons too!

3. What do we expect for the $\omega$?

Unfortunately, no clear $\omega$ signal in TAPS data.
but HADES should see it, unless...
Properties of vector mesons in the medium

\[ \rho, \omega, \phi \rightarrow \gamma^* \rightarrow e^+ + e^- \]

A list of topics for 1999/2000:

- Cocktail of free mesons
  - \( \eta \) and \( \Delta \) production in \( p + p \) and \( p + A \)

- Di-electron enhancement (DLS !) in HI collisions
  - for \( 200 \text{ MeV} / c^2 < M_{\text{inv}} < 600 \text{ MeV} / c^2 \)
  - \( C + C, Ca + Ca, (Au + Au) \)

- Hunting for vector mesons in nuclei
  - \( \omega \) and \( \phi \) production in \( p + A \) and \( A + A \)

R. Holzmann, GSI Darmstadt
R. Schicker:
Dalitz decay measurements with HADES
1) Form factors
2) Dalitz decay $\omega \rightarrow \pi^0 e^+ e^-$
3) Dalitz decay $\phi \rightarrow \pi^0 e^+ e^-$
4) Conclusions

April 17, 99

R. Schicker
Fig. 1.3. Pion form factor in the space-like region with $q^2 < 0$ from Amendolia et al. (1984a,b). Its extrapolation to the time-like region is shown to the right. The curve is obtained with an improved $\rho$ meson dominance fit (Brown et al. 1986).

Fig. 1.5. Pion form factor in the time-like region. The experimental data are taken from Quevauviller et al. (1979) and Amendolia et al. (1984a). The curve is obtained with a modified $\rho$ meson dominance model (Brown et al. 1986).
- $\omega$ Dalitz decay contributes substantially to $e^+e^-$ spectra at SIS, SPS, RHIC and LHC energies.

1) $\bar{\tau}p \rightarrow n\omega \rightarrow n\pi^0e^+e^- \rightarrow nK^+K^-e^+e^-$
2) $pp \rightarrow pp\omega \rightarrow$

1) Energy-momentum conservation:
   a) measure $K^+K^-e^-$: HADES + elmag. cal.
   b) measure $n\pi^0e^-$: HADES + LAND

$\rightarrow$ b) has larger acceptance (HADES report R)

How to measure neutron?

$\mp \rightarrow n\omega$ is threshold process; $\rightarrow$ neutron cone

$\rightarrow$ increasing pion momentum

number produced omegas (and measured)
Pionenintensität HADES Target

Daten werden noch analysiert

\[ \pi^- p \rightarrow n \chi \rightarrow n e^+ e^- \gamma \]

\[ P^o = P_{beam} + P_{tag} \]
\[ P^x = P^o - P_n \]
\[ P^y = P^o - P_n - P_{e^+} - P_{e^-} \]

![Diagram with data points and equations](image-url)
Background

\[ \pi^- p \rightarrow n e^+ e^- \gamma \]

a) $\nu N \rightarrow V \rightarrow e^- e^- (\text{not known})$

\[
BR(\nu N \rightarrow e^- e^-) = \frac{\Gamma(\nu N \rightarrow e^- e^-)}{\Gamma(\nu N \rightarrow \pi e^+)} \\
\Gamma(\nu N \rightarrow \pi e^+ = 7.5 \times 10^{-14} \text{MeV}
\]

\[
BR(\nu N \rightarrow e^- e^-) = 5 \times 10^{-6} \sim 0.04 \times BR(\nu N \rightarrow \pi e^+ e^-)
\]

b) $\pi^- p \rightarrow s \rightarrow e^- e^-$

$\pi^- p \rightarrow s \rightarrow e^- e^-$

\[
BR(\nu N \rightarrow e^- e^-) = \frac{1}{4} \times BR(\nu N \rightarrow \pi e^+ e^-)
\]

\[
\begin{align*}
\text{Rates of signal and background} \\
\text{Table:}
\end{align*}
\]

<table>
<thead>
<tr>
<th></th>
<th>react/spill</th>
<th>react/wh</th>
<th>BR(e^+ e^-)</th>
<th>react(e^+ e^-)/wh</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- p \rightarrow \nu N$</td>
<td>$3.5 \times 10^3$</td>
<td>$4.2 \times 10^6$</td>
<td>$6 \times 10^{-4}$</td>
<td>$2 \times 10^8$</td>
</tr>
<tr>
<td>background</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- p \rightarrow 2\nu N$</td>
<td>$4.4 \times 10^3$</td>
<td>$5.3 \times 10^6$</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$7 \times 10^8$</td>
</tr>
<tr>
<td>$\pi^- p \rightarrow \nu N$</td>
<td>$3.5 \times 10^3$</td>
<td>$4.2 \times 10^6$</td>
<td>$4 \times 10^{-3}$</td>
<td>$1 \times 10^8$</td>
</tr>
</tbody>
</table>

Figure 5: $|P_\nu|$ and $|P_{\bar{\nu}}|$ single distributions (top) and correlation (bottom) for the $\omega$-Dalitz decay if neutron is measured.
Figure 6: $|P_1| - |P_2|$ correlation for the $2\pi_0$ background (top) and direct $\rho$-decay (bottom). The dashed line represents the signal area.

Figure 7: Dielectron invariant mass spectra without cuts for signal (top) and $2\pi_0$ background (center). The bottom part shows the mass spectra for signal and background after the signal area condition has been applied.
VDM form factor Landsberg data - HADES data

- $\text{Dalitz decay: } \phi \to K^0\pi^0$
- $\text{BR}(\phi \to K^0\pi^0) = \text{not known } (< 1.2 \times 10^{-6})$

- $\phi$ Dalitz decay has more phase space than $\omega$ Dalitz

- $m_{\pi\pi}^{\text{max}} = m_\pi - m_{\pi^0} = 647 \text{ MeV}/c^2 \quad \omega$ Dalitz
- $m_{\pi\pi}^{\text{max}} = m_\pi - m_{\pi^0} = 885 \text{ MeV}/c^2 \quad \phi$ Dalitz

\[ n(\phi - \text{Dalitz}) = n(\omega - \text{Dalitz}) \times \frac{\text{BR}(\phi \to K^0\pi^0)}{\text{BR}(\omega \to K^0\pi^0)} \times \frac{80}{90} = 0.5 \]

\[ n(\phi - \text{Dalitz}) = 2.5 \times 10^5 / 80 \times 50 \times 0.6 = 40 \]

very hard measurement !!!

within HADES design parameters
contraction in $\sigma$-model

- space charge limit proton beam = $5 \times 10^{11}$/spill

- How much proton beam can this $\sigma$ take?

- Landolt-Börnstein
  
  $pp \rightarrow 2$ prong 14 mb at $p_{lab} = 2.8$ GeV/c
  
  $\rightarrow 4$ prong 7 mb at $p_{lab} = 4.0$ GeV/c
  
  $\rightarrow 6$ prong 0.1 mb at $p_{lab} = 4.0$ GeV/c

- $<m> \approx 2.5$ for $50 K$

- $<m>_{AuAu} \approx 100$

- double hit probability in HADES:
  
  $10^8/s \; Au + Au \approx 5 \times 10^9/s \; protons$

- open question:

  1) How to make 1st level trigger?
     (start detector doesn't work at $2 \times 10^{10}$ protons/sp).

  2) Does 1st level trigger reduce to $10^5/s$?

  3) $pp$ elastic ??

- at $p_{lab} = 3.6$ GeV/c: $(E = 2.93)$
  
  $p_{pp} \rightarrow p p \bar{p} = p_{pp} \rightarrow p p u \times \frac{1}{\sqrt{2}} = 0.8 \; mb \times 4 \times 10^{-3} = 0.3 \; mb$

  $p_{pp} \rightarrow p p \pi^+ \pi^-$

  $p_{pp} \rightarrow p p \pi^0$

  $p_{pp} \rightarrow$ is threshold reaction

  "little" above threshold $\rightarrow$ protons are forward

  $E_{1350} \approx 35$ MeV

  $p_{pp} \rightarrow p p \pi^0$

  $p_{pp} \rightarrow p p \pi^+ \pi^-$

  protons go to larger polar angles $\rightarrow$ no trigger (low eff.)

  $p p \pi^0: E^2 - \sqrt{s} \approx 920$ MeV

  $p p \pi^+ \pi^- : E^2 - \sqrt{s} \approx 775$ MeV
\[ \rho p = 3.5 \text{ GeV/c} \]

\[ \frac{R_P^\phi}{R_\pi^\phi} = \frac{I_P}{I_\pi} \times \frac{T_{pp \to pp\phi}}{T_{pp \to n\phi}} = \frac{2 \times 10^{-10}}{6 \times 10^{-11}} \times \frac{0.0003}{0.025} \]

\[ X = 4.0 \]

VDM form factor $\phi \to \pi^0 e^+ e^-$ (stat. of 1600 entries)

\[ m_{e^+e^-} \text{[MeV/c}^2\text{]} \]

additional: Mult = 2 in HADES TOF wall
Conclusions

- Pion beam at GSI can be used to produce $4 \times 10^8$
tagged omegas/week by measuring neutron with LAND.

- HADES + LAND can measure $2.5 \times 10^5$ ω-Dalitz

- $S/B > 10$

---

- The measurement of the $\phi$-Dalitz may be feasible with the proton beam at GSI
W. Koenig:

$\omega$ meson spectroscopy at HADES in $\pi A$ reactions
W spectroscopy at HADES in \( \pi + p \rightarrow \omega + n \) reactions

work started by: Arnold Schröter
work done by: Walter Schröter
work presented by: W. K.

Menu:
- Introduction & Motivation
- Why \( \pi^- \)
- \( \omega \) in medium
- \( \omega \) in HADES (\( e^+ e^- \))
- "Background"
- Summary

‘Microscopic’ and ‘macroscopic’ view of \( \pi \) induced, recoilless \( \omega \) production
Motivation

Restoration of chiral symmetry

Brown, Rho:
shift of the
vector meson mass

Candidates

\[ \rho \quad \tau = 1.3 \text{ fm/c} \]
\[ \Gamma = 152 \text{ MeV/c}^2 \]
\[ \omega \quad \tau = 23.4 \text{ fm/c} \]
\[ \Gamma = 8.4 \text{ MeV/c}^2 \]
\[ \phi \quad \tau = 44.4 \text{ fm/c} \]
\[ \Gamma = 4.4 \text{ MeV/c}^2 \]

Comparison of Pion and Proton Induced Meson Production

<table>
<thead>
<tr>
<th>Meson</th>
<th>( \rho^0_{\text{optimum}} ) [GeV/c]</th>
<th>( \sigma_{\rho-\pi} ) [mb]</th>
<th>( \sigma_{\rho-\pi}^{\text{optimum}} ) [mb]</th>
<th>( \rho^0 )</th>
<th>( \sigma_{\rho-\pi}^{\text{optimum}} ) [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>0.76</td>
<td>2.70</td>
<td>6.80</td>
<td>2.5</td>
<td>3.20</td>
</tr>
<tr>
<td>( \omega )</td>
<td>1.40</td>
<td>2.50</td>
<td>2.50</td>
<td>1.0</td>
<td>5.46</td>
</tr>
<tr>
<td>( \rho )</td>
<td>1.41</td>
<td>3.60</td>
<td>2.50</td>
<td>0.7</td>
<td>5.46</td>
</tr>
<tr>
<td>( \eta' )</td>
<td>1.60</td>
<td>0.10</td>
<td>2.10</td>
<td>21.0</td>
<td>1.60</td>
</tr>
<tr>
<td>( \phi )</td>
<td>2.00</td>
<td>0.03</td>
<td>1.00</td>
<td>33.3</td>
<td>2.00</td>
</tr>
</tbody>
</table>
Momentum distribution of $\omega$'s

Highest yield of low momentum $\omega$'s for incident $\pi$'s with $p_\pi = 1.3$ GeV/c

Meson production thresholds and $\pi$ beam intensities
expected $\omega$ rates

$\pi^- \rightarrow ^{208}_{\text{Pb}}$

$10^7 \pi^-$/spill @ 1.5 GeV/c
duty factor 20%

target:
20% interaction length
= 3.4 cm
$\pi^-$ energy loss: 0.07 GeV
$\pi^-$ multiple scattering:
$<b>=1.4^o$

<table>
<thead>
<tr>
<th>$\pi^- + p \rightarrow n + \omega$</th>
<th>$\omega$ rate [1/s]</th>
<th>$\omega^0$ rate [1/shIFT]</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>all $\omega^0$</td>
<td>39290</td>
<td>31865</td>
<td>100%</td>
</tr>
<tr>
<td>$p_e &lt; 300$ MeV/c</td>
<td>4125</td>
<td>3326</td>
<td>10.5%</td>
</tr>
<tr>
<td>detected $\omega^0$</td>
<td>200</td>
<td>100</td>
<td>0.5%</td>
</tr>
<tr>
<td>optimized target position (+20 cm)</td>
<td>825</td>
<td>655</td>
<td>2.1%</td>
</tr>
<tr>
<td>decay inside Pb</td>
<td>445</td>
<td>360</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

1 shift = 8 hours
Spatial distribution of $\rho, \omega$ production in a Pb nucleus

$e^+e^- \text{ Pairs -}

\text{Opening Angle Distribution}$
In medium particle width:

- total decay width:
  - $\Rightarrow$ free decay
  - $\Rightarrow$ absorption 
    - detailed balance: $\pi^+ \rightarrow \omega \rho$
    - $\pi^- \rightarrow \omega \bar{\eta}$
  - $\Rightarrow$ elastic and inelastic scattering
  - $\Rightarrow$ decay of the system: particle in medium
    (finite size effect) $\Gamma \sim 50\,\text{MeV}$

Decay probability depends on density.

- $\Rightarrow$ No exponential decay nor lorentzian mass distribution

Elastic scattering requires quantum mechanical calculation:
Add amplitudes.

It is not allowed to deduces lifetimes or width's from elastic scattering cross sections. (see Hydrogen atom)
Medium Modifications:

- Finite Nuclear Matter
- Collision Broadening
- Mass Shift

Rho Meson Contribution

Walter Schoen, TU Muenchen
Background contributions
(combinatorial background)

e^+ e^- combinations from different \(\pi^0\)

\[
\begin{align*}
\gamma \rightarrow \pi^0 + \gamma & \quad \Rightarrow \quad \pi^0 + p \rightarrow \pi^0 + \pi^0 + n \\
& = 1.4 \text{ mb} \\
\gamma \rightarrow \pi^0 + \gamma & \quad \Rightarrow \quad \pi^0 + p \rightarrow \pi^0 + \pi^0 + \pi^0 + n \\
& = 0.5 \text{ mb}
\end{align*}
\]

\[\Rightarrow \text{combinatorial background negligible at } m_{\omega}\]

Including detection & reconstruction efficiency with HADES:

- 2500 \(\omega\)’s
- \(p < 0.8 \text{ GeV/c}\)
in 1 week
The elementary \( p \) and \( n \)-reactions

(From Effenberger et al., Giegen)

The full cocktail including baryon resonance, caused by low statistics.
$\pi^- + A$

$p_{\pi^-} = 1.3 \text{ GeV/c}$

$\pi^- + A$

$p_{\omega^+} < 0.3 \text{ GeV/c}$
Summary

- if one does not understand
  $\pi - \pi$ reactions why measure or
calculate $Au + Au \rightarrow Z - 200$ MeV ?

- $\pi - \pi \rightarrow \pi^+ \pi^- \rightarrow \pi^+ \pi^- \rightarrow \pi^+ \pi^- (\pi^-)\pi^+$
might provide insight in
medium effect.

- life is not easy, any way.