g-2 workshop Mainz:

Overview and Status of Measurements of $F_{3\pi}$ at COMPASS

D. Steffen on behalf of the COMPASS collaboration

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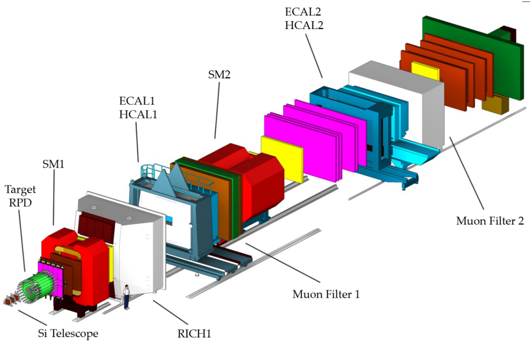
COMPASS - Overview

COmmon
Muon
Proton
Apparatus for
Structure and
Spectroscopy

- Fixed target experiment at SPS accelerator at CERN (M2 beamline)
- High intensity beams: max. $4 \cdot 10^7 \frac{\text{muons}}{\text{s}}$; $2 \cdot 10^7 \frac{\text{hadrons}}{\text{s}}$
- Various physics programs
- 2 Primakoff runs (2009 and 2012)



Setup in 2009

COMPASS - Overview

spectrometer setup:

- Length: 60m
- Two-stage magnetic spectrometer
- Each stage: Tracking, dipole magnet, calorimeters

- Fixed target experiment at SPS accelerator at CERN (M2 beamline)
- High intensity beams: max. $4 \cdot 10^7 \, \frac{\text{muons}}{\text{s}}$; $2 \cdot 10^7 \, \frac{\text{hadrons}}{\text{s}}$
- Various physics programs
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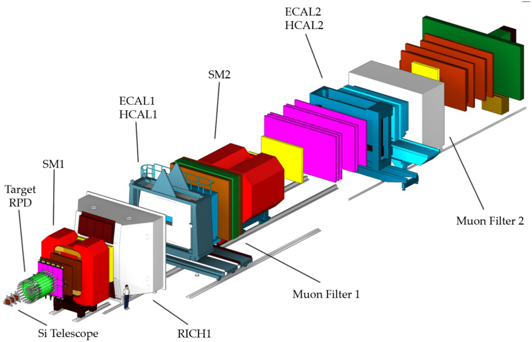
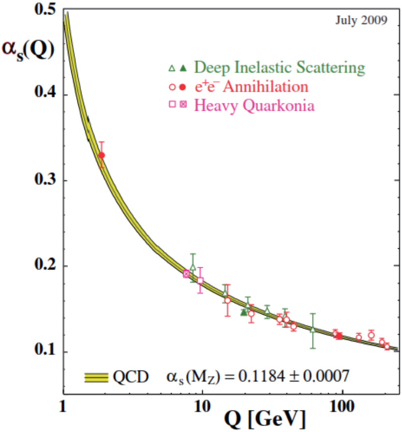


Setup in 2009

Strong Interaction in the Standard Model



At high energies (small distances)

$\alpha_s \ll 1 \Rightarrow$ QCD processes calculable via perturbation expansion in α_s

At low energies (long distances)

- $\alpha_s = \mathcal{O}(1) \Rightarrow$ perturbation expansion in α_s not applicable
- Alternatives for theoretical predictions:
  - Numerical simulation of QCD (lattice QCD)
  - Effective Field Theories

Chiral Perturbation Theory (ChPT)

ChPT is the low-energy approximation of QCD

- Fundamental degrees of freedom = hadrons
- Model-independent approach to describe meson-meson, meson-baryon, and **meson-photon** interactions
- ChPT provides predictions ⇒ can be tested by experiments

Goal of COMPASS experiment

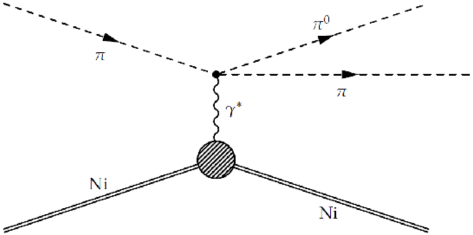
- Test ChPT predictions for pion-photon reactions $\pi^- \gamma \to X^-$ with various final states X^-

$$\pi^- + \gamma^{(*)} \to \begin{cases} \pi^- + \gamma & \text{Compton reaction, pion polarisabilities} \\ \pi^- + \pi^0 & \text{single-pion production, chiral anomaly} \\ \pi^- + \pi^0 + \pi^0 & \text{double-pion prod., chiral tree \& loop} \\ \dots & \end{cases}$$

Primakoff Reaction - Overview

- First proposed by H. Primakoff to study π^0 lifetime via $\gamma\gamma \to \pi^0 \to \gamma\gamma$
- particle-photon collisions with the photon provided by the strong Coulomb field of a nucleus.
- Weizsäcker and Williams: Coulomb field of relativistic charge $\approx$ flux of quasi-real photons

$$\frac{\mathrm{d}\sigma}{\mathrm{d}s\,\mathrm{d}Q^2\,\mathrm{d}\Phi_n} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)} F^2(Q^2) \frac{Q^2 - Q^2_{\mathrm{min}}}{Q^4} \cdot \frac{\mathrm{d}\sigma_{\pi\gamma\to X}}{\mathrm{d}\Phi_n}$$



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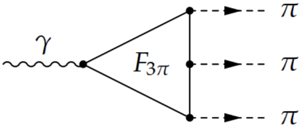
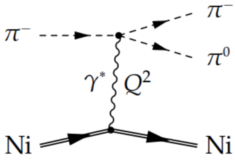
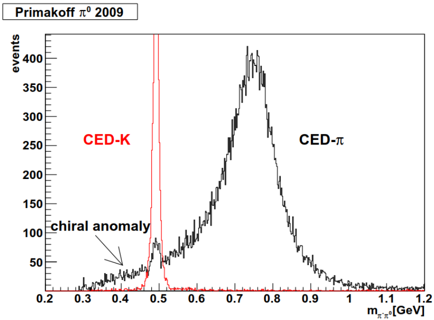
Chiral Anomaly from $\pi^- + \gamma^{(*)} \rightarrow \pi^-\pi^0$







J.Friedrich, CERN-THESIS-2012-333

- $F_{3\pi}$ = coupling constant for $\gamma \rightarrow 3\pi$
- Leading Order ChPT: $F_{3\pi} = 9.78(05)\text{GeV}^{-3}$ (verified up to 10% level)
- Determines cross section in Primakoff $\pi^-\text{Ni} \rightarrow \pi^-\pi^0\text{Ni}$ reaction
  - low-mass tail in 2π invariant mass spectrum not driven by any resonance but by chiral anomaly
  - Problem: Dominant contribution of $\rho(770) \rightarrow \pi^-\pi^0$ affects also low masses

$F_{3\pi}$ in $\pi^-\pi^0$-Invariant-Mass Spectrum

Problem:

Dominant contribution of $\rho(770) \to \pi^-\pi^0$ affects also low masses

Solution:

Extension of ChPT amplitude using dispersion relations

$\Rightarrow$ Inclusion of $\rho(770)$-resonance into amplitude

$\Rightarrow$ Amplitude valid up to $1.2\,\mathrm{GeV/c^2}$:

$$\sigma(s) = \frac{(s-4M_\pi^2)^{3/2}(s-M_\pi^2)}{1024\pi\sqrt{s}} \int_{-1}^{1} \mathrm{d}z(1-z^2)|\mathcal{F}(s,t,u)|^2$$

- ▷ Comparison with theoretical value at leading order of chiral expansion:

$$F_{3\pi} = \frac{e \cdot N_C}{12\pi^2 F_\pi^3} = 9.78(05)\mathrm{GeV}^{-3}$$

Sakkas, Hoferichter, Kubis, PRD 86 (2012) 116009

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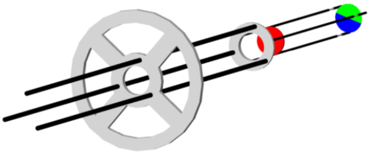
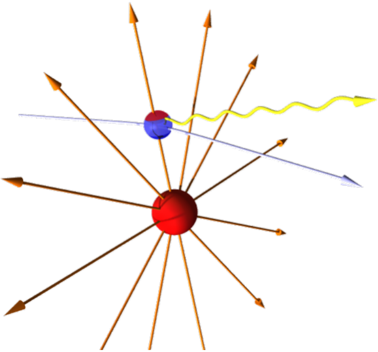
Target Choice

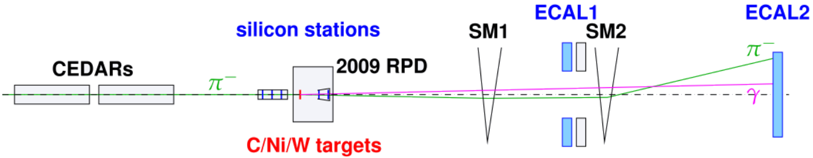
- Primakoff cross-section: $\propto Z^2$ $\Rightarrow$ large Z
- Very high Z (e.g. Pb): large corrections from 2γ processes and from screening
- Optimum choice: medium heavy Ni target





Artistic depiction of $\pi^- + \mathrm{Ni} \rightarrow \pi^- + \gamma + \mathrm{Ni}$ via the Primakoff process

Measurement Principle

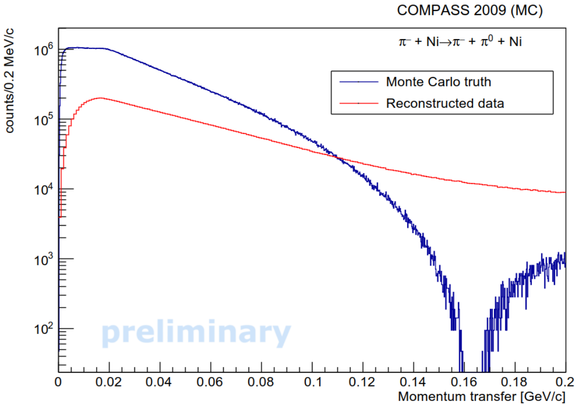


- 190 GeV negative hadron beam: 96.8% π^-, 2.4% K^-, 0.8% $\bar{p}$
- beam particle identification by Cherenkov detectors
- $4\,\mathrm{mm}$ Ni target disk ($\approx 25\%\mathrm{R.L.}$)
- Measure scattered π^- and produced photons (number depends on final state)
- Select exclusive events at lowest momentum transfers
- Small scattering angles require high resolution
  - Spatial resolution of tracking $\approx 10\,\mu\mathrm{m}$
  - Angular resolution of ECAL $\approx 30\,\mu\mathrm{rad}$

Measurement of $F_{3\pi}$ at COMPASS

Weizsäcker-Williams factorization (equivalent-photon approximation)

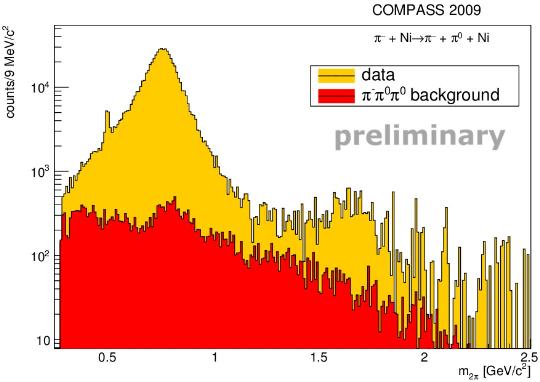
$$\frac{\mathrm{d}\sigma}{\mathrm{d}s\,\mathrm{d}Q^2\,\mathrm{d}\Phi_n} = \frac{Z^2\alpha}{\pi(s-m_\pi^2)} F^2(Q^2) \frac{Q^2 - Q^2_{\mathrm{min}}}{Q^4} \cdot \frac{\mathrm{d}\sigma_{\pi\gamma\to X}}{\mathrm{d}\Phi_n}$$



- 4-momentum transfer distribution smeared due to interaction with matter and limited detector resolution
- Prominent peak at low q (despite resolution effect)
- Primakoff dominant production mechanism of $\pi^-\pi^0$ at low q

Background Estimate

- K^- decay into $\pi^-\pi^0$, $e^-\bar{\nu}_e\pi^0$, $\mu^-\bar{\nu}_\mu\pi^0$
- K^- decay into $\pi^-\pi^0\pi^0$
- $\pi^- + \mathrm{Ni} \rightarrow \pi^- + \pi^0 + \pi^0 + \mathrm{Ni}$



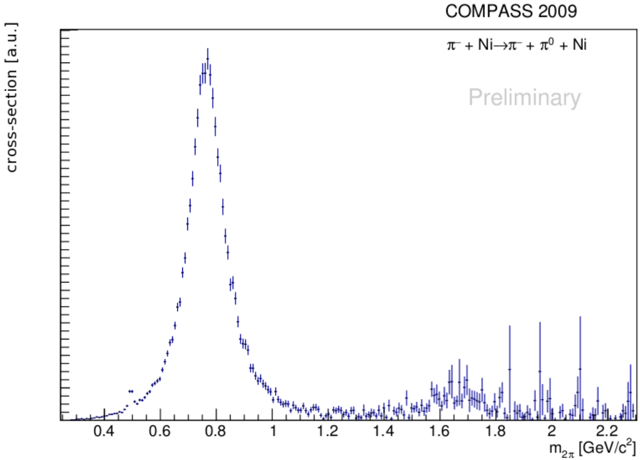
Distribution for the invariant mass of the 2π final state and the estimated background

Luminosity Determination

- Cross-section calculation needs integrated luminosity $\mathcal{L}_\pi$
  $N_\pi = \mathcal{L}_\pi \cdot \sigma \cdot \epsilon$
- Luminosity determination via free kaon decays:
  - Kaon lifetime known with high accuracy
  - Kaon fraction in M2 beam known with 5% accuracy
  - From number of kaon decays + acceptance corrections (determined from MC simulation) $\Rightarrow$ integrated number of pions

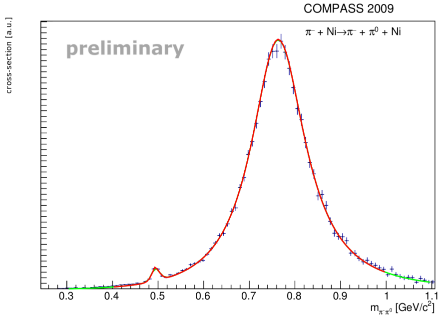
- Using $K^- \to \pi^-\pi^0$ for 2009 data: $6.0 \pm 0.7\,\mathrm{nb}^{-1}$
- Using $K^- \to \pi^-\pi^0\pi^0$ for 2009 data: $4.09 \pm 0.27\,\mathrm{nb}^{-1}$
- Using $K^- \to \pi^-\pi^-\pi^+$ for 2004 data $\Rightarrow$ no issue found, employed for several analysis

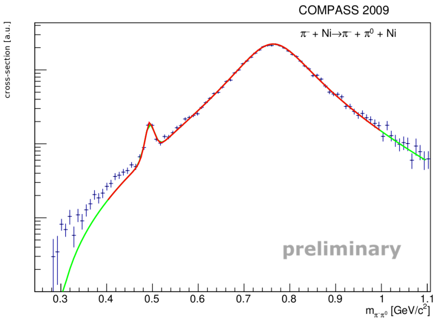
Invariant Mass Distribution



Final normalized and acceptance-corrected invariant mass distribution with subtracted background

Fit results





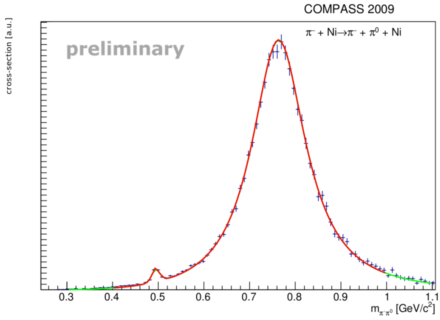
- ▷ Fit of theoretical model in good agreement with data
- ▷ Statistical uncertainty is $\mathcal{O}(1\%)$
- ▷ Absolute scale (normalization to pion flux) not yet determined

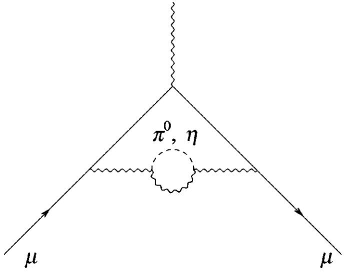
$$\mathcal{F}(s,t,u) = C_2^{(1)}\mathcal{F}_2^{(1)}(s) + C_2^{(2)}\mathcal{F}_2^{(2)}(s)$$

$\Rightarrow$ 2 fit parameters

Sakkas, Hoferichter, Kubis, PRD 86 (2012) 116009

Fit results





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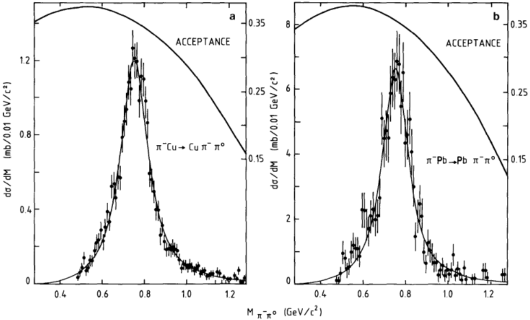
Sakkas, Hoferichter, Kubis, PRD 86 (2012) 116009

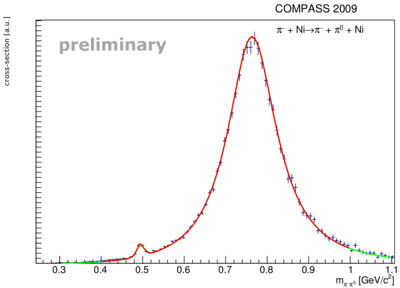
$\rho(770)$ included in theoretical model

- Can calculate radiative coupling $\rho(770) \to \pi^-\gamma$ from $\rho(770)$ yield
- Contributes to hadronic vacuum polarization terms in calculations of $g-2$ of e and μ

ρ radiative width from Capraro et al.

$\pi^-\pi^0$ invariant mass distributions





Data obtained from measurement in 1987 at CERN with same measurement principles fitted with Breit-Wigner distribution:

$$\Gamma(\rho(770) \to \pi^-\gamma) = 87 \pm 5.6\,\text{keV}$$

Capraro et al. In: (1987) NP B288 659

Data from COMPASS experiment in 2009 fitted with cross-section equation using dispersion relations.

Contents

Conclusion

COMPASS has acquired large Primakoff data set

- Measurements from channel $\pi^- + \gamma^{(*)} \to \pi^-\pi^0$:
  - Chiral anomaly $\gamma \to 3\pi$
  - Radiative width of light-quark isovector mesons $(\rho(770)^- \to \pi^-\gamma)$
- Data from run 2009 give consistent picture:
  - Fit in good agreement with data
  - Normalizing to radiative width of $\rho(770)$ yields value for $F_{3\pi}$ in agreement with theoretical result
- 4x larger data set to come from 2012 data
- Possibility to extend analysis to measure radiative couplings of excited ρ states