Measurement of the Pion Polarizability at COMPASS

Jan M. Friedrich

Physik-Department, TU München

COMPASS collaboration

Particle Physics Seminar
April 3, 2015

Short story of the pion

- Yukawa 1935: hypothesis of $\sim$100 MeV massive exchange particle "μ" for the strong interaction between protons and neutrons
- Discovery of muons 1936

Short story of the pion

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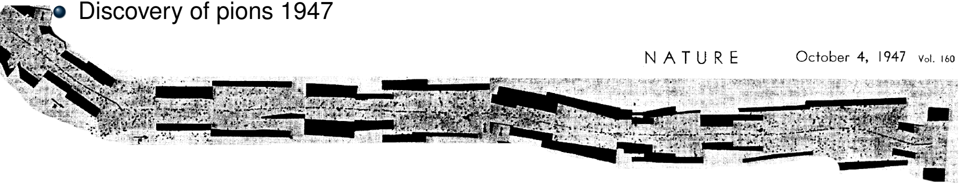
- Discovery of muons 1936
- Discovery of pions 1947



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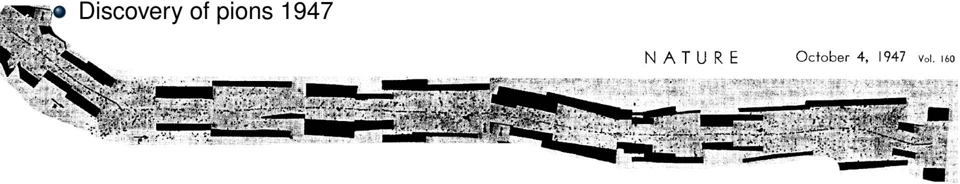

- 1958: decay $\pi^+ \to \mu^+\nu_\mu$ dominant, small branching $\pi^+ \to e^+\nu_e$
  $\Rightarrow$ $V - A$ theory of weak interaction
- 1961: Spin-1 mesonic excitation of the pion (ρ-resonance at BNL)
- 1964: quark hypothesis
- 1966: pion scattering lengths

$\vdots$

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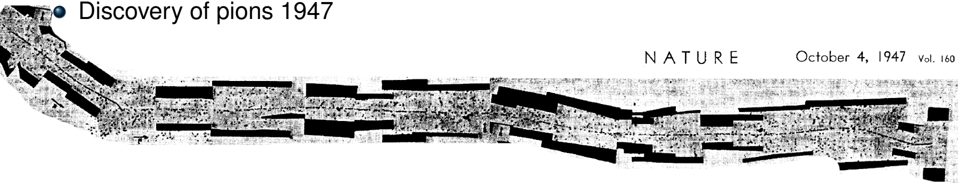

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  $\Rightarrow$ $V - A$ theory of weak interaction
- 1961: Spin-1 mesonic excitation of the pion (ρ-resonance at BNL)
- 1964: quark hypothesis
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  ⋮
- 1982: first data on the pion polarisability

latest pubished data on the pion polarisability

PRL **114,** 062002 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

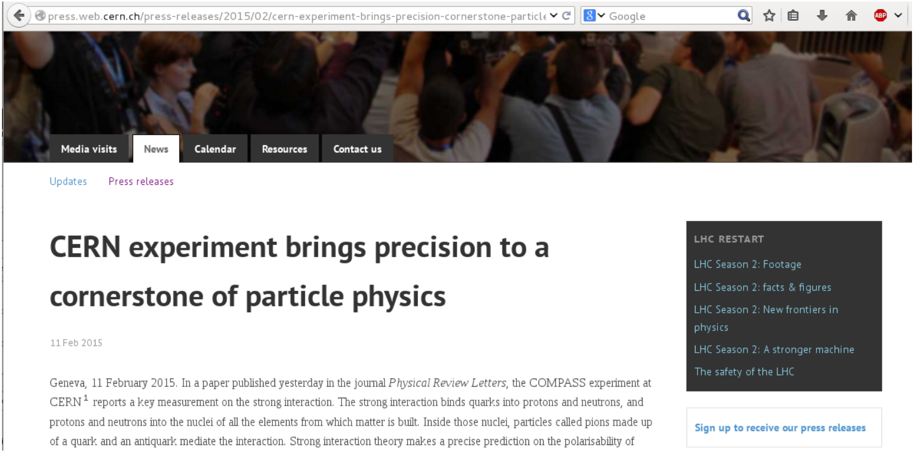
Measurement of the Charged-Pion Polarizability

C. Adolph,[8] R. Akhunzyanov,[7] M. G. Alexeev,[27] G. D. Alexeev,[7] A. Amoroso,[27,29] V. Andrieux,[22] V. Anosov,[7]
... [213 authors]
(COMPASS Collaboration)

(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \rightarrow \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \rightarrow \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong

Press echo in spring 2015



press.web.cern.ch/press-releases/2015/02/cern-experiment-brings-precision-cornerstone-particle

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CERN experiment brings precision to a cornerstone of particle physics

11 Feb 2015

Geneva, 11 February 2015. In a paper published yesterday in the journal *Physical Review Letters*, the COMPASS experiment at CERN[1] reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the elements from which matter is built. Inside those nuclei, particles called pions made up of a quark and an antiquark mediate the interaction. Strong interaction theory makes a precise prediction on the polarisability of

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PRÄZISIONSMESSUNG ZUR STARKEN WECHSELWIRKUNG

Pionen genannte Kernteilchen tragen wesentlich zur so genannten starken Wechselwirkung bei. Sie ist die Kraft, die Atomkerne zusammenhält und für die Masse der uns umgebenden Materie verantwortlich ist. Erstmals ist es Physikern nun gelungen, die Verformbarkeit von Pionen exakt zu bestimmen. Das Ergebnis, zu dem Physiker der Technischen Universität München (TUM) maßgeblich beigetragen haben, stimmt gut mit den theoretischen Vorhersagen überein und revidiert frühere Messungen, deren Ergebnisse nicht mit dem Standardmodell der Physik vereinbar

CERN experiment brings precisi

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Exakte Messung der Polarisierbarkeit von Pionen stützt Standardmodell

Präzisionsmessung zur starken Wechselwirkung

10.02.2015, *Forschung*

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Das in der TUM entwickelte Detektormodul – Foto: TUM

Press echo in spring 2015

ScienceDaily
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Featured Research

CERN experiment brings precision to a cornerstone of particle physics

Date: February 11, 2015
Source: CERN
Summary: The COMPASS experiment at CERN reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the elements from which matter is built. Inside those nuclei, particles called pions made up of a quark and an antiquark mediate the interaction. Strong interaction theory makes a precise prediction on the polarisability of pions – the degree to which their shape can be stretched. This polarisability has baffled scientists since the 1980s, when the first measurements appeared to be at odds with the theory. New result is in close agreement with theory.

Neue Zürcher Zeitung

PHYSIK UND CHEMIE

Pionen-Experiment am Cern

Da schwabbelt nichts

11.2.2015, 17:08 Uhr

rtz. Wieder hat ein Experiment die theoretischen Vorhersagen des Standardmodells der Teilchenphysik bestätigt. Diesmal massen die Forschenden die Verformbarkeit sogenannter Pionen. Diese gibt Aufschluss darüber, wie stark die Bindungskraft zwischen den Elementarteilchen im Inneren von Atomkernen ist.

AVENIR
Fondamental

À LA UNE

Le pion se déforme moins que prévu

C'est la confirmation d'une donnée de physique fondamentale que fournit l'expérience COMPASS menée au CERN sur une mesure rel à l'interaction forte, la force qui lie quarks, neutrons et protons.

Focus.it

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L'interazione forte dei quark ha meno segreti

L'esperimento COMPASS al CERN fornisce una misura chiave dell'interazione forte.

Lo spettrometro dell'esperimento COMPASS. È lungo 60 metri e la suo interno vengono sparati raggi di particelle subatomiche ad alta intensità. | CERN

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DA COMPASS UNA MISURA CHIAVE DELL'INTERAZIONE FORTE

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CERN Physicists Measure Polarizability of Pion

Scientists from CERN's COMPASS collaboration have made the most precise measurement ever of the polarizability of pion – the fundamental parameter of strong interaction. Everything we see in the Universe is made up of fundamental particles and leptons. Quarks are bound together in groups of three to make up the building blocks [...]

cea | Irfu
Institut de recherche sur les lois fondamentales de l'Univers

Une expérience du CERN affine une mesure essentielle pour décrire l'interaction forte

L'expérience COMPASS du CERN, impliquant le CEA et des partenaires internationaux, rapporte une concernant l'interaction forte. Celle-ci lie ensemble les composants des noyaux atomiques (quarks dans les nucléons dans le noyau). Les résultats, concernant une propriété du plus léger des mésons - le pion, dans la revue Physics Review Letters, sont en parfait accord avec la théorie des perturbations chirales des années 80.

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Feb 16, 2015 by Sci-News.com « PREVIOUS | NEXT »

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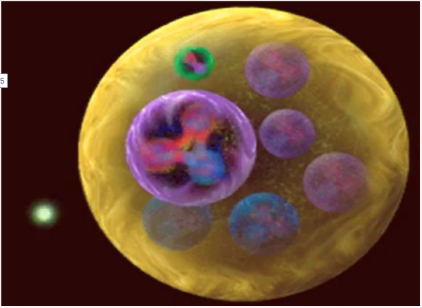

An electron (green) hits a proton in a nucleus, creating a pion (green-skinned particle) and transforming the proton into a neutron. Image credit: Joanna Griffin / Jefferson Lab.

Everything we see in the Universe is made up of fundamental particles called

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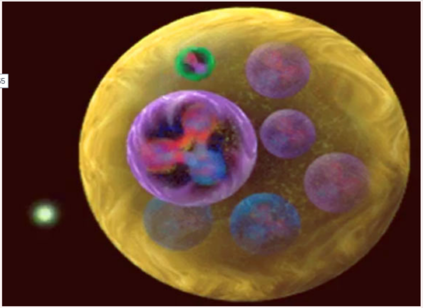

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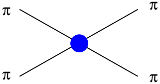
How to understand quark-gluon dynamics?

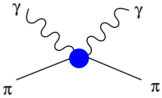
complicated system of
interacting quarks and gluons

$\xrightarrow{\text{ChPT}}$

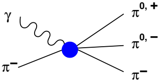
effective degrees of freedom
at low energy: mass, charge,
spin, effective (self-)coupling



π only



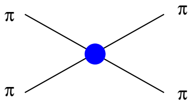
π—photon



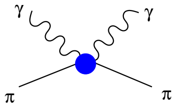
$\pi - \pi$—photon

Chiral Perturbation Theory vs. Experiment

- pion scattering lengths: 2-loop predictions
  - $a_0^0 m_\pi = 0.220 \pm 0.005$ confirmed by E865 in $K^+ \to \pi^+\pi^- e^+\nu_e$
  - $(a_0^0 - a_0^2) m_\pi = 0.264 \pm 0.006$ confirmed by NA48 in 0.268 ± 0.010 $K^+ \to \pi^+\pi^0\pi^0$



- pion polarisability: electric α_π, magnetic β_π
  - contribution to Compton scattering
  - ChPT prediction obtained by the relation to $\pi^+ \to e^+\nu_e\gamma$ [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006] [PIBETA, M. Bychkov et al., PRL 103, 051802, 2009]

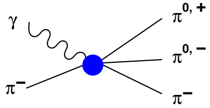


$$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \cdot 10^{-4}\mathrm{fm}^3$$
$$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4}\mathrm{fm}^3$$
$$\alpha_\pi = (2.9 \pm 0.5) \cdot 10^{-4}\mathrm{fm}^3$$

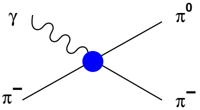
- ChPT prediction contradicting the experimental findings (prior to our analysis)

More pion-photon reactions

- Pion scattering including a real photon
  - Leading-order prediction from ChPT
    $\leftrightarrow$ pion scattering lengths
    combined with photon coupling
  - chiral loop contribution
    theory prediction available, no measurement



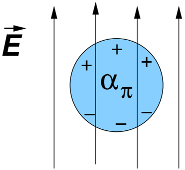
- Chiral anomaly $F_{3\pi}$
  - established on 10% level
  - further development: inclusion of the ρ resonance
    theoretical work by Kubis, Hoferichter, Sakkas
    PRD86(2012)116009

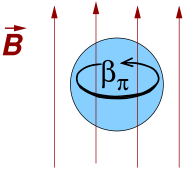


ChPT prediction for the pion polarisability

$$\pi + \gamma \rightarrow \pi + \gamma$$

Compton cross-section contains information about e.m. polarisability
(as deviation from the expectation for a pointlike particle)





polarisabilities α_π, β_π [10^{-4} fm^3]

ChPT (2-loop) prediction: $\alpha_\pi - \beta_\pi =$ 5.7±1.0 $\alpha_\pi + \beta_\pi =$ 0.16±0.1

experiments: 4 — 14 ($\beta_\pi \approx -\alpha_\pi$ assumed)

ChPT prediction for the pion polarisability

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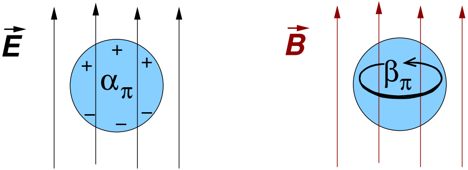


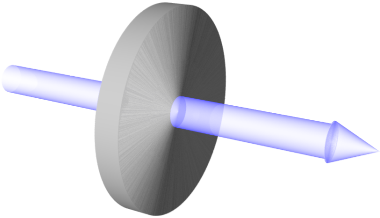
polarisabilities α_π, β_π [10^{-4} fm^3]

ChPT (2-loop) prediction: $\alpha_\pi = 2.93$, $\beta_\pi = -2.77$

experiments: 2 – 7 ($\beta_\pi \approx -\alpha_\pi$ assumed)

Principle of the COMPASS measurement

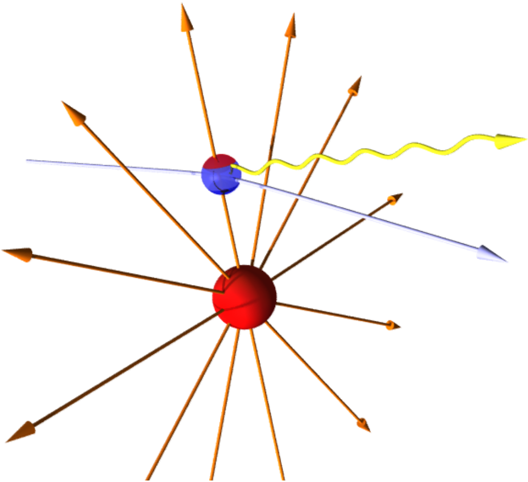
- steer high-energetic pion beam on a ∼4mm nickel disk
- observe scattered pions in coincidence with produced hard photons
- measured cross-section shape is linked to pion Compton scattering



Polarisability effect in Primakoff technique

Primakoff measurement technique

- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\text{kV/fm}$
- Bremsstrahlung emission
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\text{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton scattering
- Polarisability contribution
  - Compton cross-section typically diminished
  - expected charge separation $\sim 10^{-5}\,\text{fm} \cdot e$



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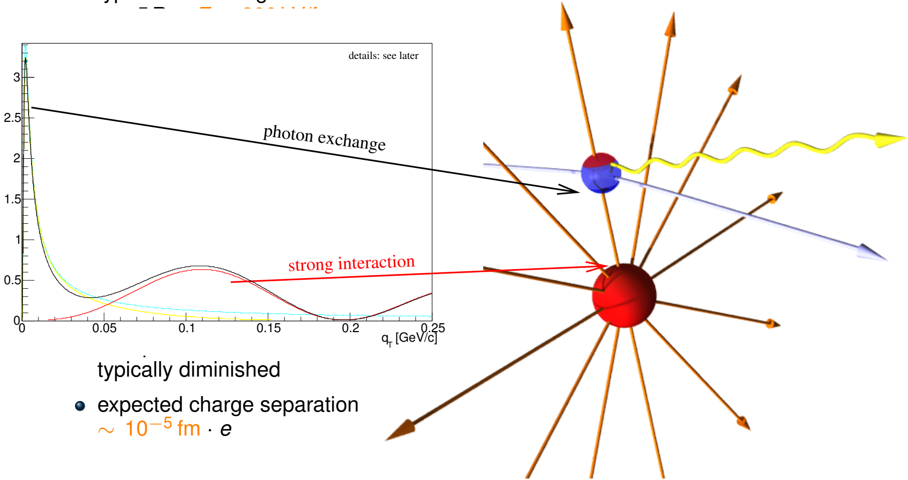

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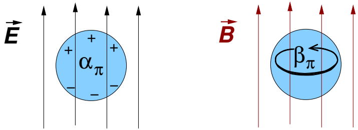
Pion Compton Scattering

$$\pi \; \gamma \;\; \rightarrow \;\; \pi \; \gamma$$



- Two kinematic variables, in CM: total energy $\sqrt{s}$, scattering angle θ_{cm}

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

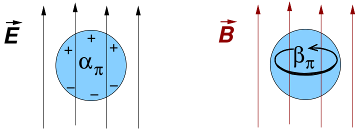
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

$$z_\pm = 1 \pm \cos\theta_{cm}$$

- $\sigma_{tot}(s)$ rather insensitive to pion's low-energy structure
- Up to 20% effect on *backward* angular distributions of $d\sigma/d\Omega_{cm}$

Pion Compton Scattering

$$\pi \ \gamma \ \rightarrow \ \pi \ \gamma$$



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Pion Compton scattering: embedding the process

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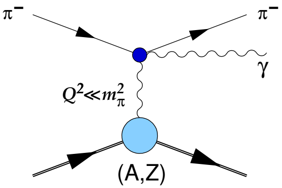
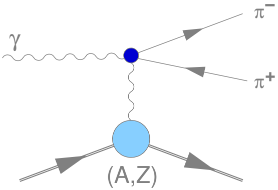
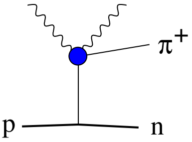
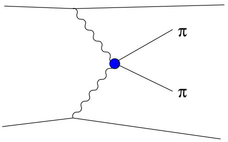




Primakoff processes

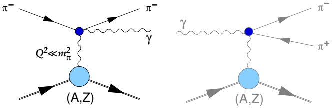


Radiative pion photoproduction

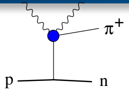


Photon-Photon fusion

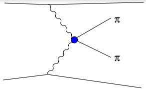
Pion polarisability: world data before COMPASS



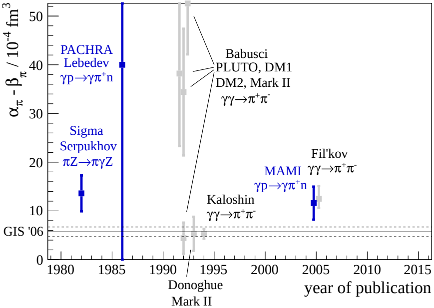
Primakoff processes

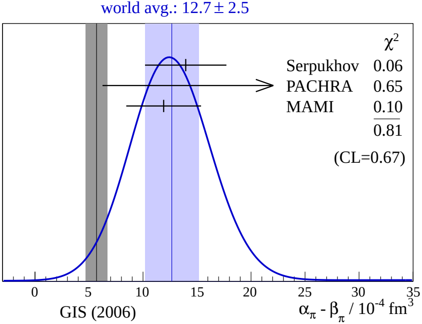


Radiative pion photoproduction



Photon-Photon fusion





GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD

Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

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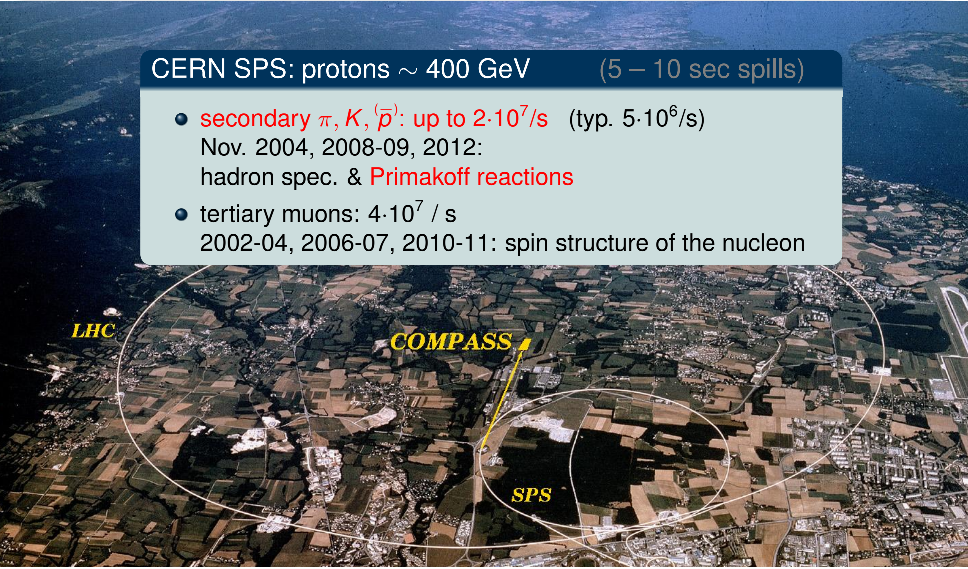
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Technische Universität München

CERN SPS: protons ~ 400 GeV (5 – 10 sec spills)

- secondary π, K, $\overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11: spin structure of the nucleon

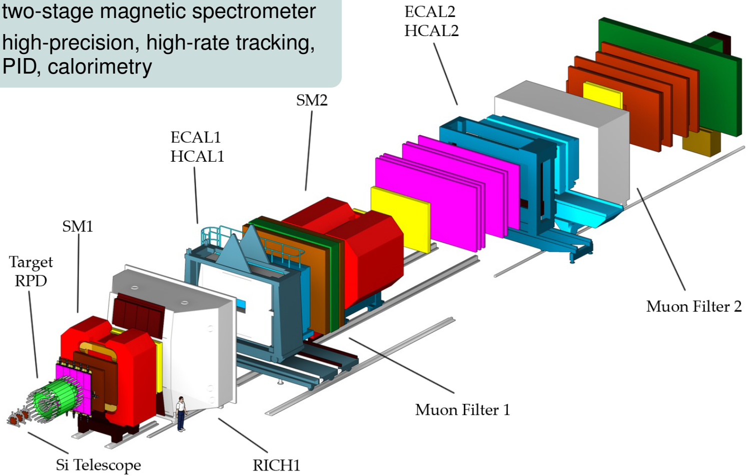


COMPASS

Experimental Setup

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



COMPASS

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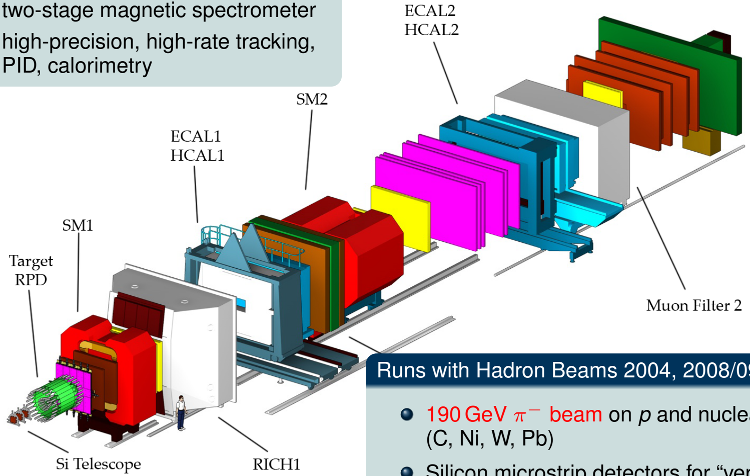
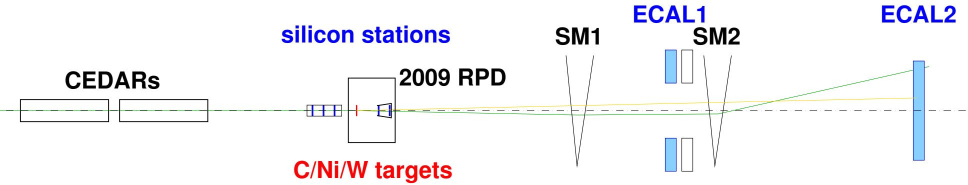


Runs with Hadron Beams 2004, 2008/09, 2012

- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for “vertexing”
- recoil and (digital) ECAL triggers

Principle of the measurement



Silicon detector module, two-sided $\sigma_{x,y} \sim 5\mu m$

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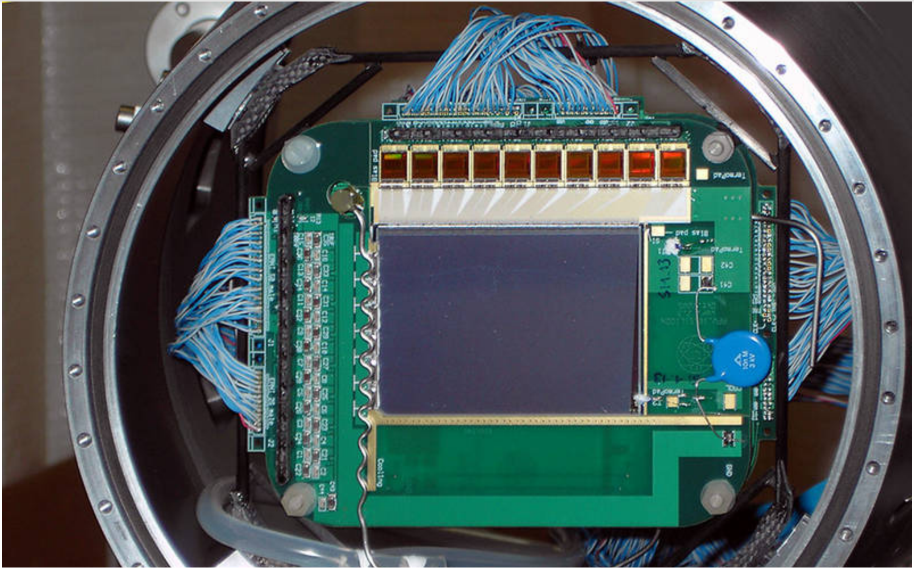

Silicon cryostat in the recoil detector

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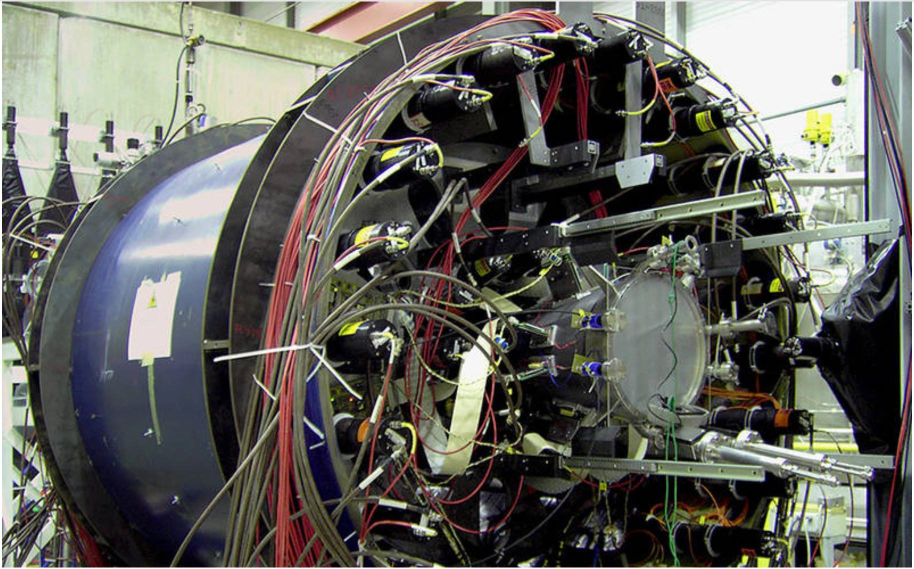

Extraction of the pion polarisability

- Identify exclusive reactions

$$\pi\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \pi\gamma$$

  at smallest momentum transfer $< 0.001\ \mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{meas}(x_\gamma)}{N_{sim}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1-x_\gamma}\,\alpha_\pi$$

  is derived, depending on $x_\gamma = E_{\gamma(lab)}/E_{Beam}$.
  Measuring R the polarisability α_π can be concluded.

- Control systematics by

$$\mu\gamma_{\{\mathrm{Ni}\to\mathrm{Ni}'\}} \to \mu\gamma$$

  and

$$K^- \to \pi^-\pi^0 \to \pi\gamma\gamma$$

Extraction of the pion polarisability

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- Control systematics by

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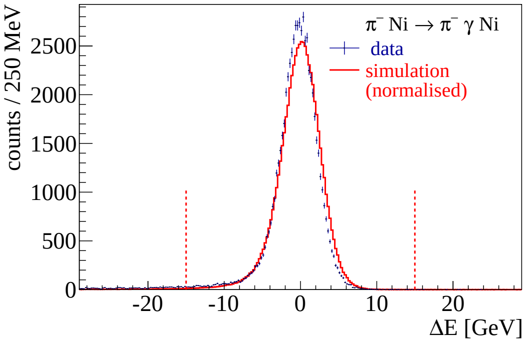
Identifying the $\pi\gamma \to \pi\gamma$ reaction

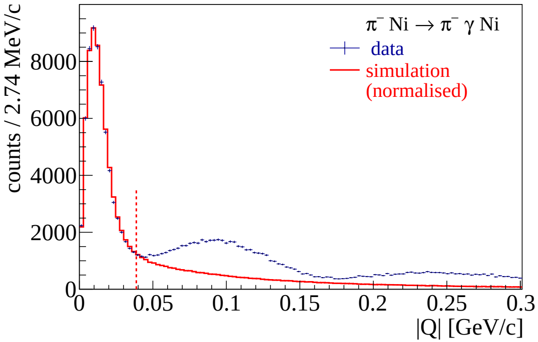
Phys. Rev. Lett. 114, 062002 (2015)



- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx$ 2.6 GeV (1.4%)
- $\sim$ 63.000 exclusive events ($x_\gamma > 0.4$) (Serpukhov $\sim$ 7000 for $x_\gamma > 0.5$)

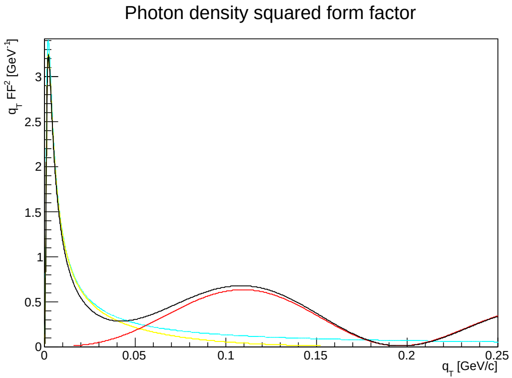
Primakoff peak

Phys. Rev. Lett. 114, 062002 (2015)



- $\Delta Q_T \approx$ 12 MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx$ 190 MeV$/c$
- data a little more narrow than simulation $\rightarrow$ negative interference?

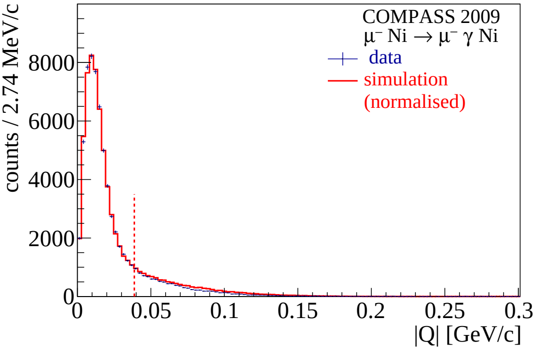
Coulomb-nuclear interference



- calculation following G. Fäldt (Phys. Rev. C79, 014607)
- eikonal approximation: pions traverse Coulomb and strong-interaction potentials

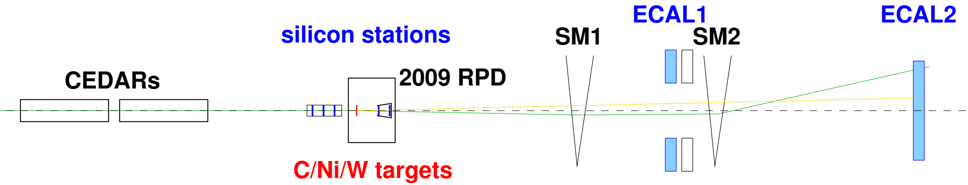
Primakoff peak: muon data

Phys. Rev. Lett. 114, 062002 (2015)



- muon control measurement: pure electromagnetic interaction

Principle of the measurement



ECAL2: 3000 cells of different types

ECAL2: quest for precision

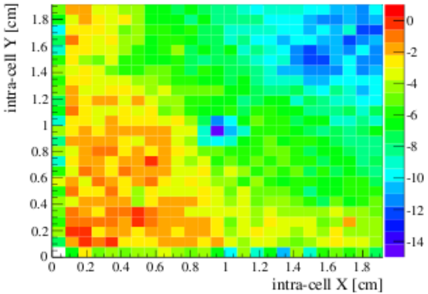


Figure 3.5: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range 133 GeV $< E_\gamma <$ 152 GeV .

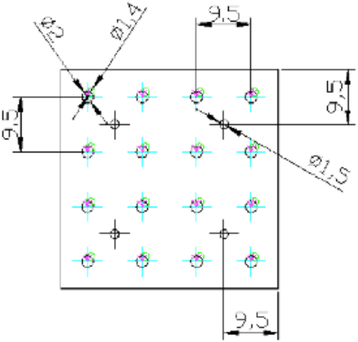
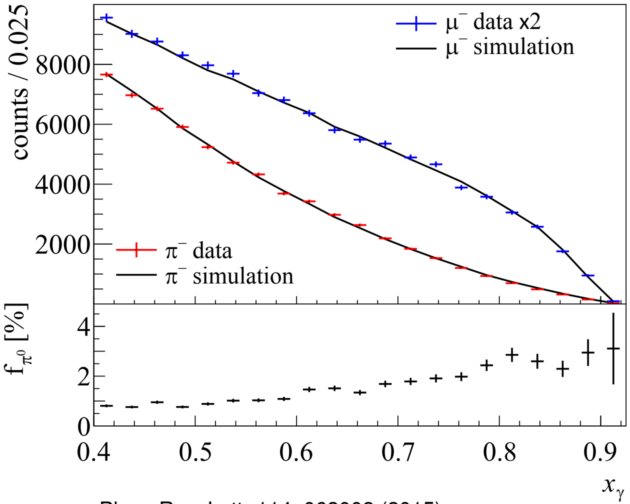


Figure 3.6: Technical drawing of a full shashlik cell to be compared with the figure to the left.

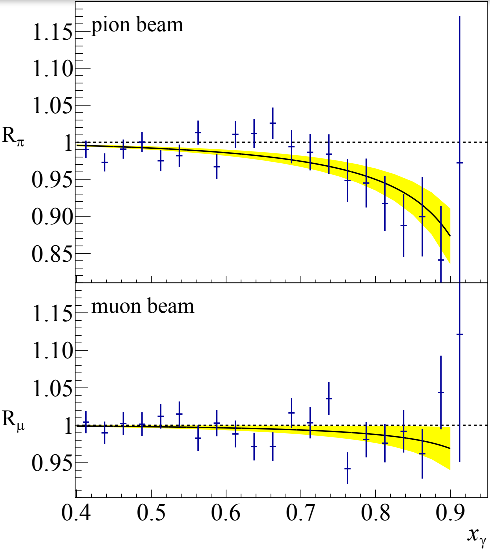
from: Th. Nagel, PhD thesis TUM 2012

Photon energy spectra for muon and pion beam



Phys. Rev. Lett. 114, 062002 (2015)

Pion polarisability: COMPASS result



$\alpha_\pi = (\ 2.0 \pm 0.6_{\text{stat}}\ ) \times 10^{-4}\,\text{fm}^3$

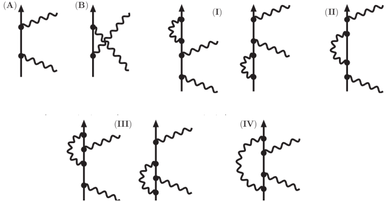
(assuming $\alpha_\pi = -\beta_\pi$)

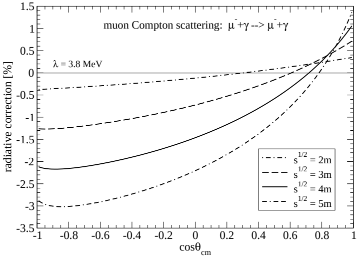
"false polarisability" from muon data:

$(\ 0.5 \pm 0.5_{\text{stat}}\ ) \times 10^{-4}\,\text{fm}^3$

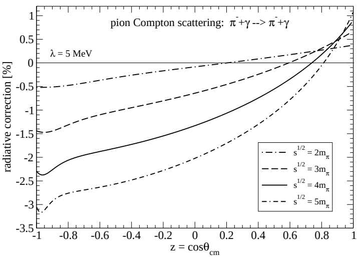
Phys. Rev. Lett. 114, 062002 (2015)

Radiative corrections (Compton scattering part)





Nucl.Phys. A837 (2010)



Eur.Phys.J. A39 (2009) 71

source of systematic uncertainty	estimated magnitude $\mathrm{CL} = 68\,\%$ $[10^{-4}\,\mathrm{fm}^3]$
tracking	0.5
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.7

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tracking	0.5
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.7

COMPASS result for the pion polarisability:

$$\alpha_\pi = (\,2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}\,) \times 10^{-4}\,\text{fm}^3$$

with $\alpha_\pi = -\beta_\pi$ assumed

Pion polarisability: world data including COMPASS

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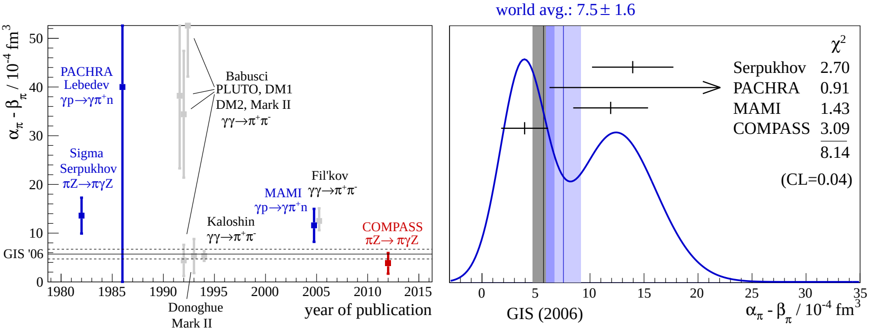
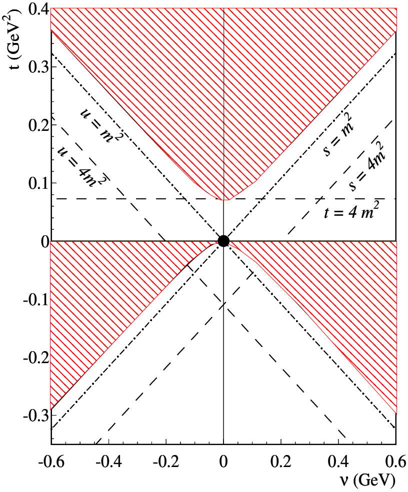


- The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability
- The expectation from ChPT is confirmed within the uncertainties

About crossing



- red hatched:
  physical regions
  $\gamma + \gamma \to \pi + \pi$
  $\gamma + \pi \to \gamma + \pi$
- two-pion thresholds
  at $s = 4m_\pi^2$, $u = 4m_\pi^2$,
  $t = 4m_\pi^2$
- DR integration paths
  $t = 0$ (forward),
  $\theta = 180^\circ$ (backward)
  $u = m_\pi^2$, $s = m_\pi^2$, ...

from: D. Drechsel, talk at IWHSS 2011 Paris

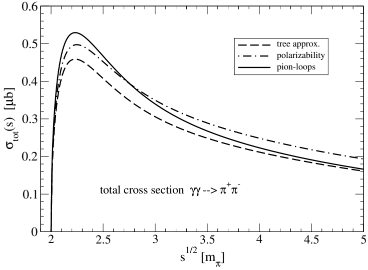
Photon-photon fusion process $\gamma\gamma \to \pi^+\pi^-$

- Planned measurements at ALICE and JLab

$$\sigma_{tot}(s) = \frac{2\pi\alpha^2}{\hat{s}^3 m_\pi^2}\Big\{\left[4 + \hat{s} + \hat{s}|C(\hat{s})|^2\right]\sqrt{\hat{s}(\hat{s}-4)}$$

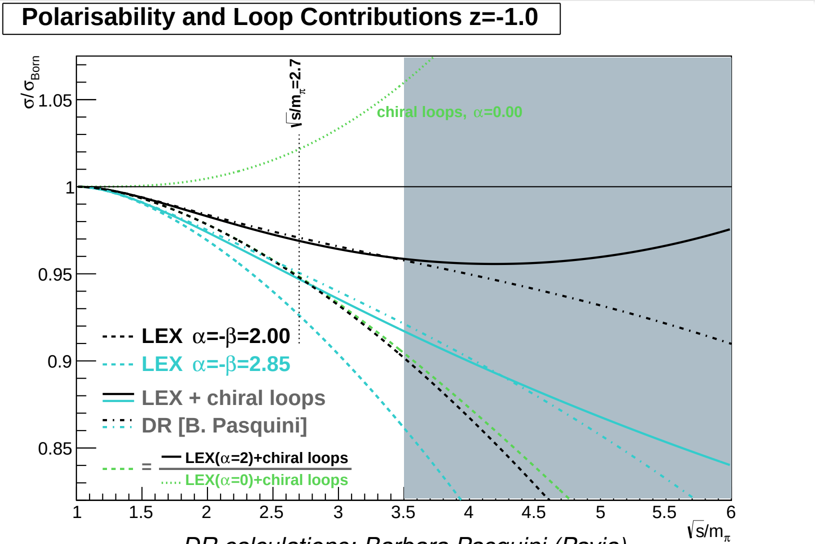
$$+8\left[2 - \hat{s} + \hat{s}\,\mathrm{Re}C(\hat{s})\right]\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}\Big\},$$

$$C(\hat{s}) = -\beta_\pi \frac{m_\pi^3}{2\alpha}\hat{s} - \frac{m_\pi^2}{(4\pi f_\pi)^2}\left\{\frac{\hat{s}}{2} + 2\left[\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2} - \frac{i\pi}{2}\right]^2\right\}$$



courtesy Norbert Kaiser (TUM)

Dispersion relations and ChPT



DR calculations: Barbara Pasquini (Pavia)

Pion polarisability on the lattice

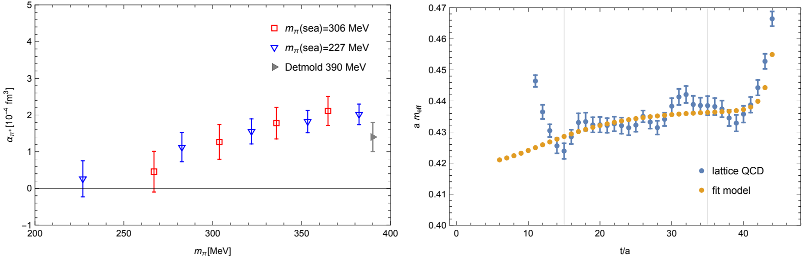


FIGURE 3. Left: electric polarizability for the charged pions as a function of the valence quark mass. The data for $m_\pi = 390\,\mathrm{MeV}$ is taken from [5]. Right: effective mass for a charged pion correlator together with the scalar particle correlator determined from the fit. The fitting range is indicated by the vertical bars.

Alexandru *et al.*, Pion electric polarizability from lattice QCD, arXiv:1501.06516

Pion polarisability measurements at COMPASS

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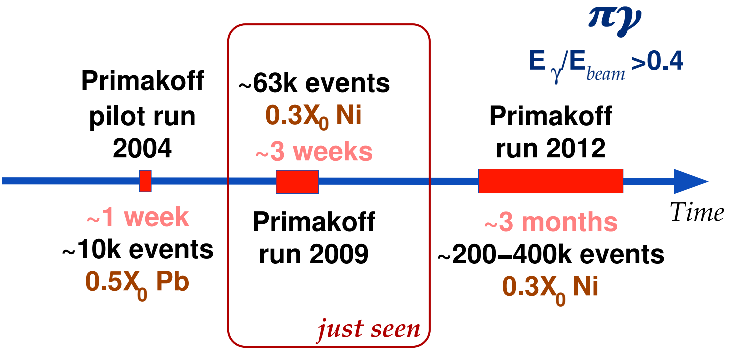

Summary and Outlook

- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined

$$\boxed{\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\,\text{fm}^3} \quad \text{assuming } \alpha_\pi + \beta_\pi = 0$$

  - Most precise experimental determination
  - Systematic control: $\mu\gamma \rightarrow \mu\gamma$, $K^- \rightarrow \pi^-\pi^0$
- Chiral dynamics in $\pi^-\gamma \rightarrow \pi^-\pi^0$ and $\pi\gamma \rightarrow \pi\pi\pi$ reactions
  - Charged-channel $\pi\gamma \rightarrow \pi^-\pi^-\pi^+$ tree-level ChPT prediction confirmed
  - Neutral-channel $\pi\gamma \rightarrow \pi^-\pi^0\pi^0$ analysis ongoing
  - Resonance properties, radiative couplings
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

Thanks for your attention!

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Backup

Primakoff reactions accessible at COMPASS

Access to $\pi + \gamma$ reactions via the Primakoff effect:

At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

$$\pi^- + \gamma \rightarrow \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \;/\; \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \qquad \Longleftarrow \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$

analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$

2004 Primakoff results

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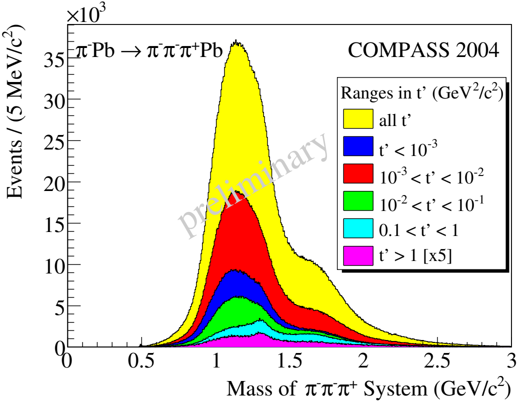
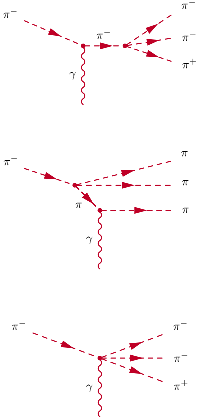
$$\pi^- \text{ Pb} \to \text{Pb } \pi^- \pi^- \pi^+$$

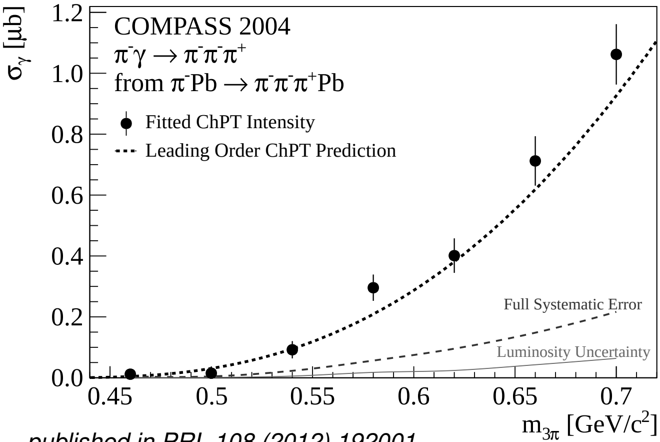


- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

First Measurement of $\pi\gamma \to 3\pi$ Absolute Cross-Section

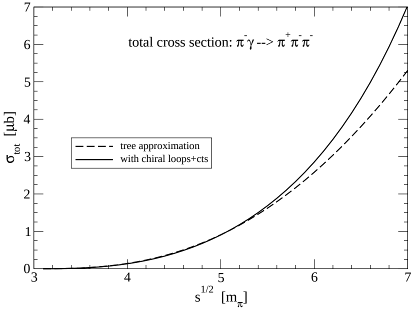
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$

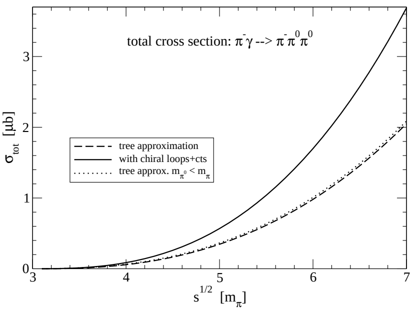




published in PRL 108 (2012) 192001

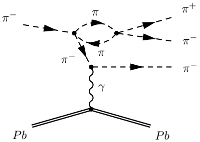
Higher-order effects

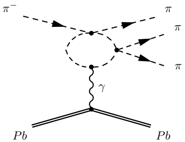




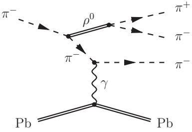
Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)



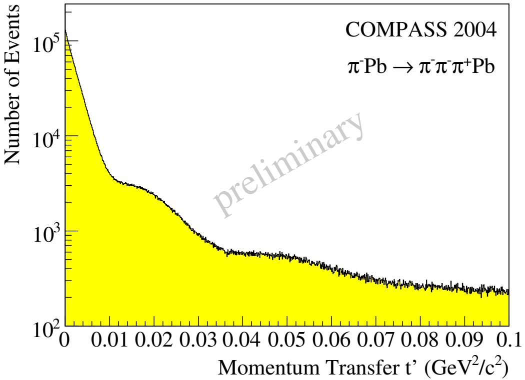


not (yet) included:



2004 Primakoff results

π^- Pb $\to$ Pb π^- π^- π^+



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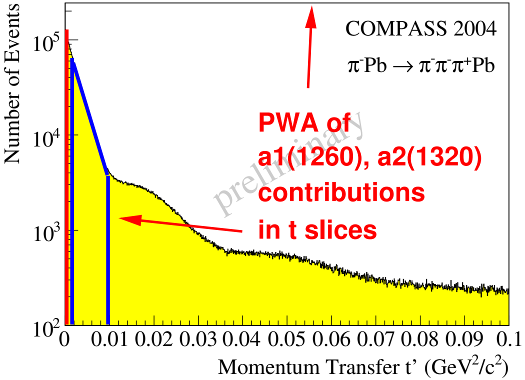
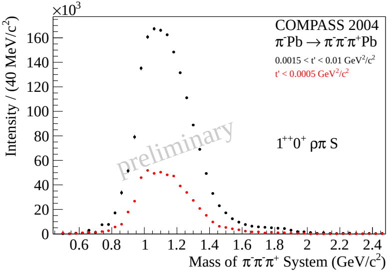
2004 Primakoff results

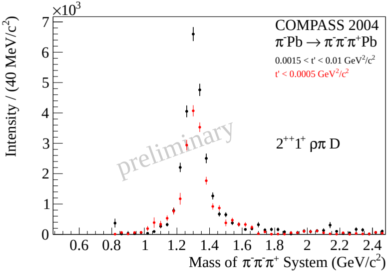
π^- Pb $\rightarrow$ Pb $\pi^-\ \pi^-\ \pi^+$

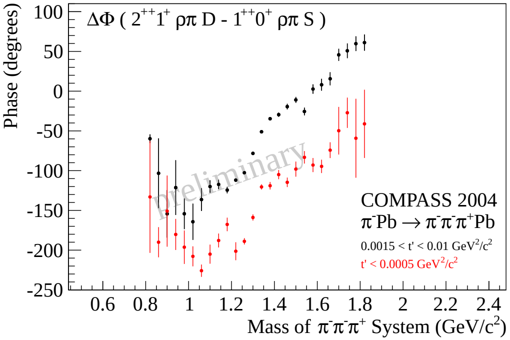


- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim$ 1 000 000 events

PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions







Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

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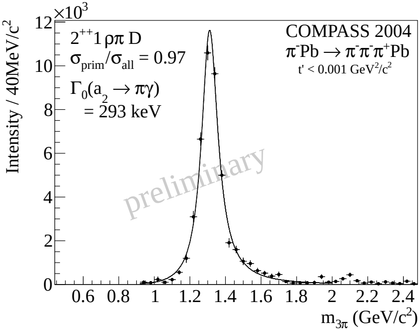

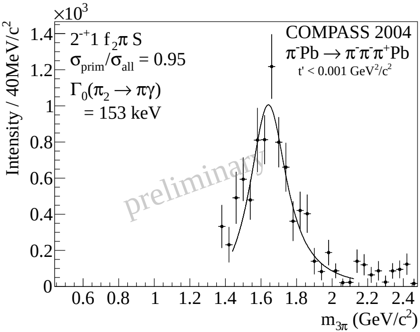

$\Gamma_0(a_2(1320) \to \pi\gamma)$ *M2* $\Gamma_0(\pi_2(1670) \to \pi\gamma)$ *E2*

$\Leftrightarrow$ meson w.f.'s: $\Gamma_{i\to f} \propto |\langle\Psi_f|\, e^{-i\vec{q}\cdot\vec{r}}\, \hat{\epsilon}\cdot\vec{p}\,|\Psi_i\rangle|^2$, VMD

- normalization via beam kaon decays
- large Coulomb correction

published in EPJ A50 (2014) 79

Phase $a_2 - a_1$ in detail: t' dependence

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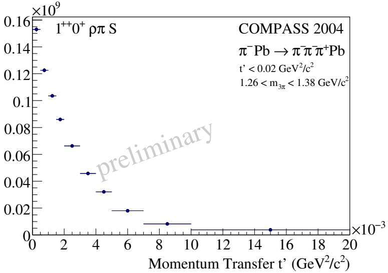
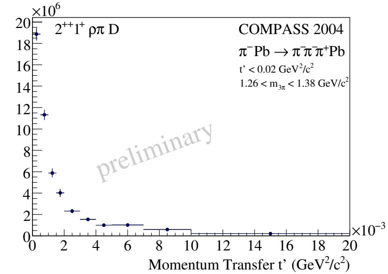
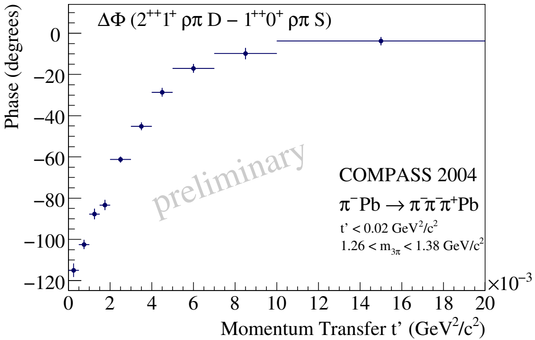


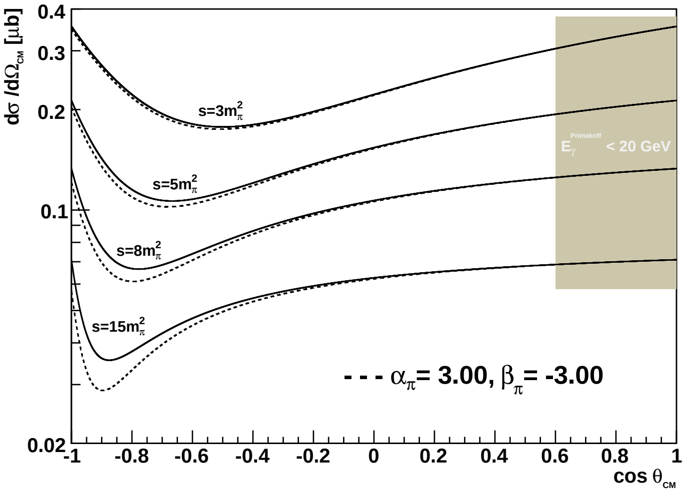




- transition of $\pi\gamma$ to $\pi I\!P \rightarrow a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

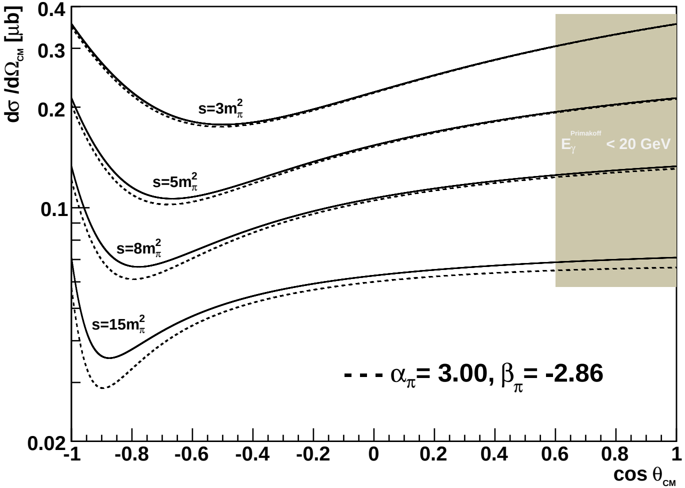
Polarisability effect (LO ChPT values)

loop effects not shown



Polarisability effect (NLO ChPT values)

loop effects not shown



Polarisability effect (wrong sign $\alpha_\pi + \beta_\pi$)

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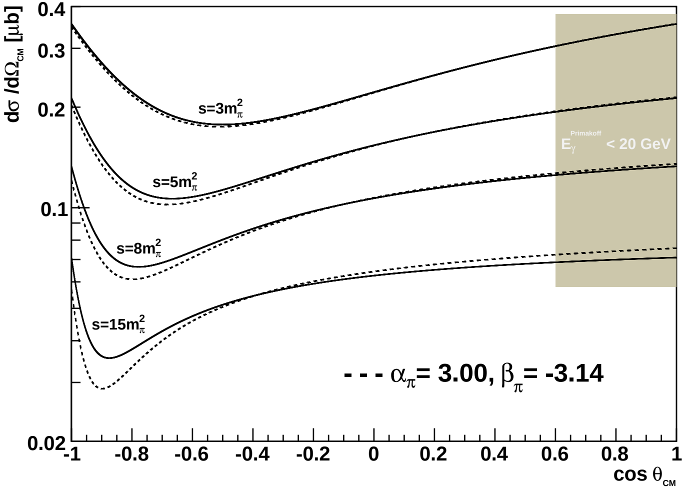
loop effects not shown



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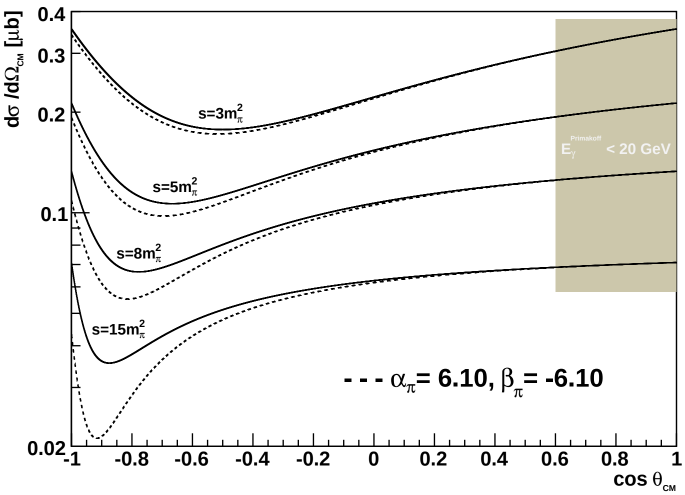
Polarisability effect (Serpukhov values)

loop effects not shown



Pion Polarisability: Experimental Techniques

- Radiative π^+ production on the proton:

$$\boldsymbol{\gamma\,\pi^{*}\longrightarrow\pi\,\gamma} \qquad [\text{via } \gamma\, p \to n\,\pi^+\,\gamma]$$

Mainz (2005) measurement: $\alpha_\pi - \beta_\pi = 11.6 \pm 1.5 \pm 3.0 \pm 0.5$

"± 0.5": model error *only within the used ansatz*,

full systematics not under control

- Primakoff Compton reaction:

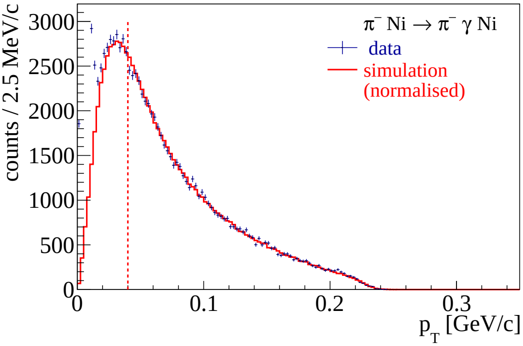
$$\boldsymbol{\gamma^{*}\,\pi\longrightarrow\pi\,\gamma} \qquad [\text{via } \pi\, Z \to Z\,\pi\,\gamma]$$

tiny extrapolation $\gamma^* \to \gamma$ $\mathcal{O}(10^{-3} m_\pi^2)$

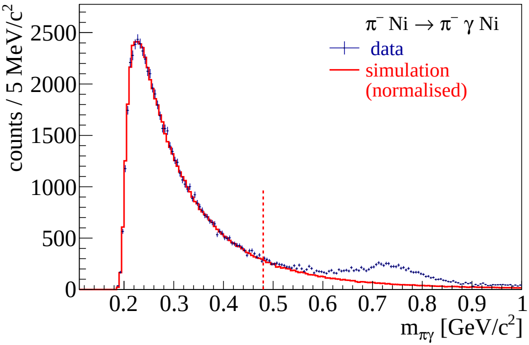
fully under theoretical control

[N. Kaiser, J.F., Nucl. Phys. A 812 (2008) 186]

Minimum transverse momentum of the charged particle

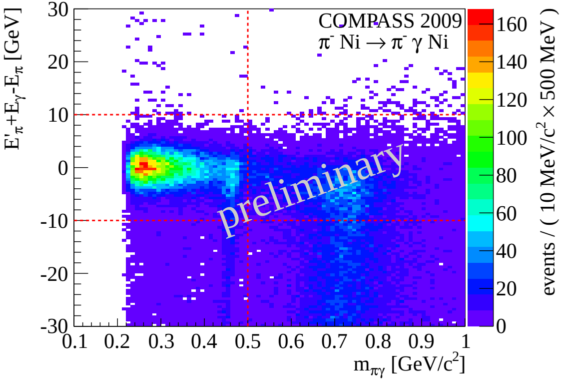


CM energy in $\pi\gamma \to \pi\gamma$



- ρ contribution from $\pi\gamma \to \pi\pi^0$

Exclusivity vs. $\sqrt{s}$



- ρ contribution from $\pi\gamma \to \pi\pi^0$

Mandelstam $\{s,t\} \leftrightarrow$ Laboratory $\{E_\gamma, \theta_\gamma\}$

for $\pi\gamma \rightarrow \pi\gamma$

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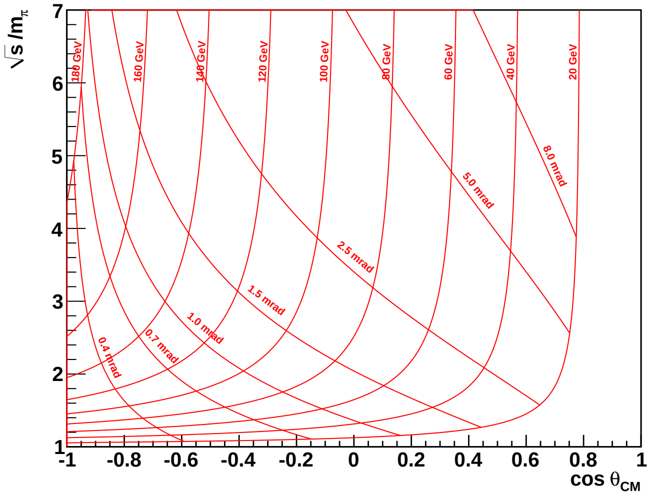
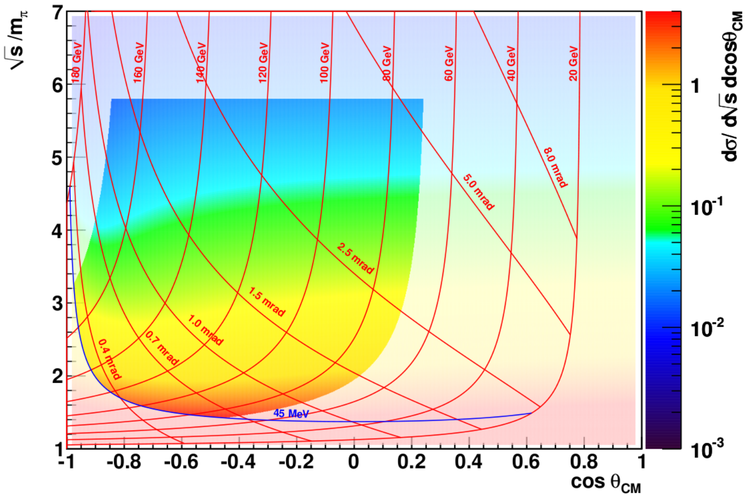


Cross section

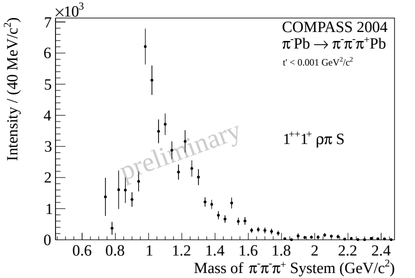


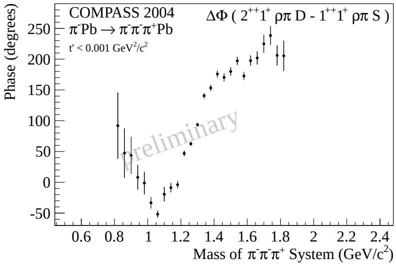
$\gamma\gamma \to \pi\pi$ and the pion polarisability

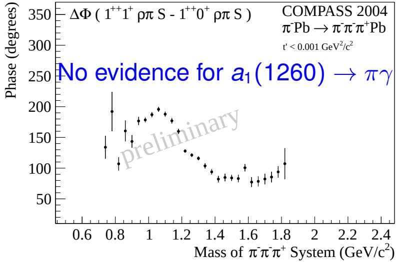
M.R. Pennington in the 2nd DAΦNE Physics Handbook,
"What we learn by measuring $\gamma\gamma \to \pi\pi$ at DAΦNE":

> All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \to \pi\pi$. Though the low energy $\gamma\gamma \to \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the *extrapolation* not very far, the dominance of the pion pole (...) means that the energy scale for this continuation is m_π. Thus the polarisabilities cannot be determined accurately from $\gamma\gamma$ experiments in a model-independent way and must be measured in the Compton scattering region.

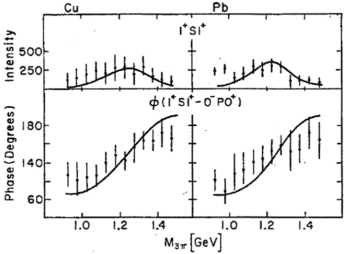
Primakoff production of a1(1260) vs. E272 result







No evidence for $a_1(1260) \to \pi\gamma$



M. Zielinski et al, Phys. Rev. Lett 52 (1984) 1195

BACKUP: Partial Wave Analysis Formalism

- Mass-independent PWA (narrow mass bins):

$$\sigma_{\mathrm{indep}}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |f_i^{\epsilon}(t')|^2 \mathrm{d}t'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2$$

  - Production strenght assumed constant in single bins
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$, with t' dependence $f_i^{\epsilon}(t')$
  - Production amplitudes T_{ir}^{ϵ} $\rightarrow$ Extended log-likelihood fit
  - Acceptance corrections included
- Spin-density matrix: $\rho_{ij}^{\epsilon} = \sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon *}$

$\rightarrow$ Physical parameters:

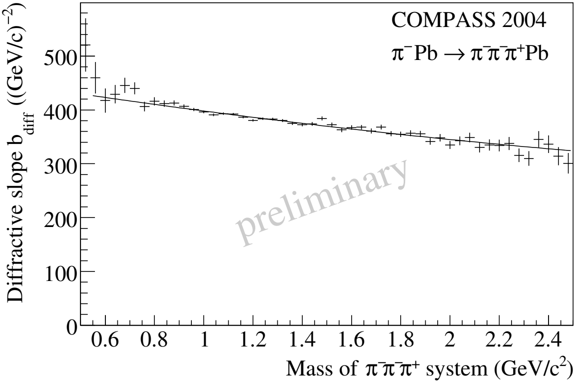
$$\mathrm{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

relative phase Φ_{ij}^{e}

$$\mathrm{Coh}\ _{i,j}^{\epsilon} = \sqrt{(\ \mathrm{Re}\ \rho_{ij}^{\epsilon})^2 + (\ \mathrm{Im}\ \rho_{ij}^{\epsilon})^2} \Big/ \sqrt{\rho_{ii}^{\epsilon} \rho_{jj}^{\epsilon}}$$

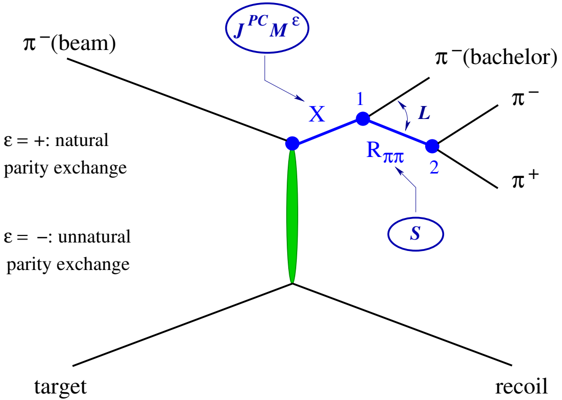
- Mass-dependent χ^2-fit (not presented here):
  - X parameterized by Breit-Wigner (BW) functions
  - Background can be added

Mass dependence of the diffractive slope



Partial Wave Analysis Formalism

Isobar Model



- Isobar model: Intermediate 2-particle decays
- Partial wave in reflectivity basis: $J^{PC} M^{\epsilon} [isobar] L$

- Mass-independent PWA (40 MeV/c^2 mass bins): 38 waves
  Fit of angular dependence of partial waves, interferences
- Mass-dependent χ^2-fit (Not presented here)

Major intensities in m(3π)-bins (acceptance corrected)

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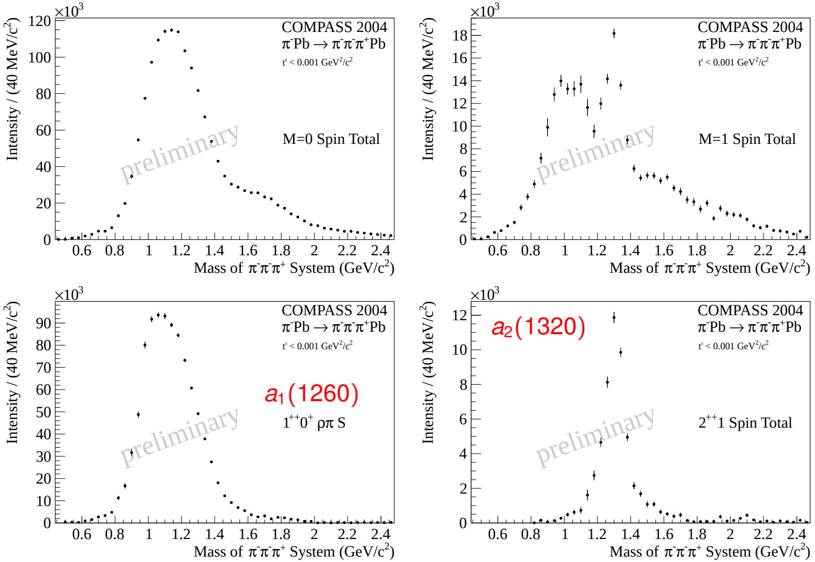
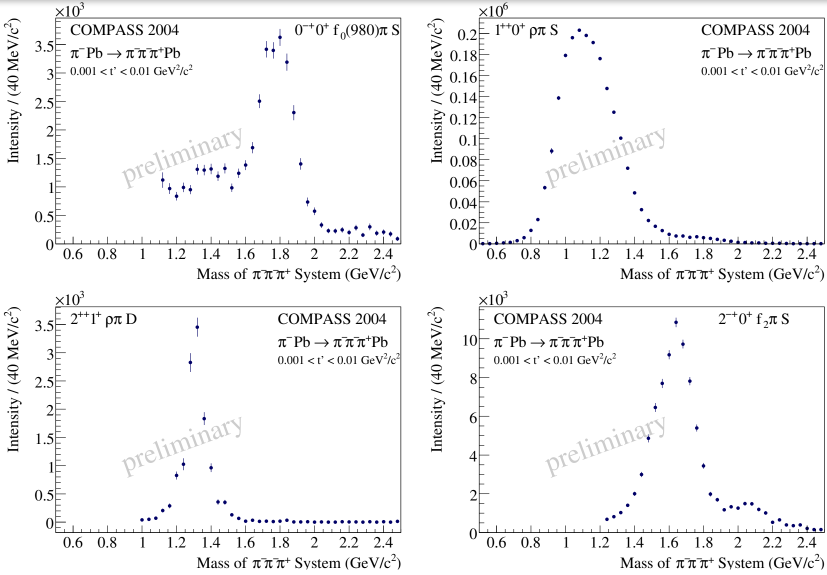


PWA of data with low t'

Intensity of selected waves: $0^{-+}0^+ f_0(980)\pi S$, $1^{++}0^+ \rho\pi S$, $2^{++}1^+ \rho\pi D$, $2^{-+}0^+ f_2(1270)\pi S$



Spin Totals for $t' < 10^{-3}$ (GeV/c)^2

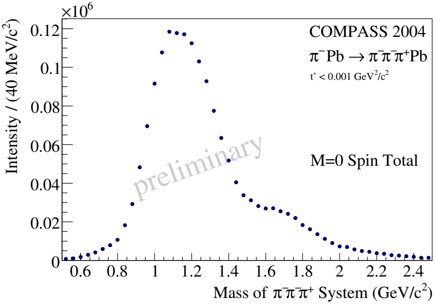
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

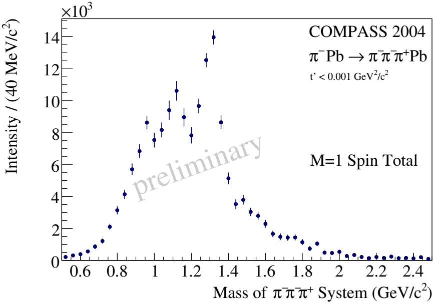
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$ $\rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

Diffractive production: M=0: $\sigma(t') \propto e^{-b_{\mathrm{diff}}(m) t'}$

M=1: $\sigma(t') \propto t' e^{-b_{\mathrm{diff}}(m) t'}$ $\rightarrow$ vanishes for $t' \approx 0$

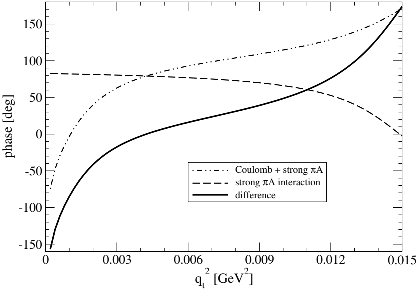


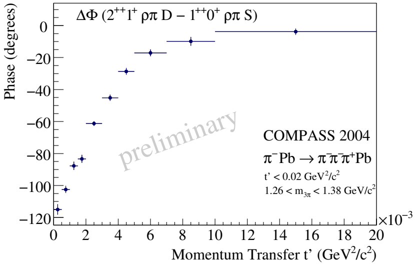
M=0



M=1

Theory: Phase a_2(strong+Coulomb)-a_1(strong)





Glauber modell

G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

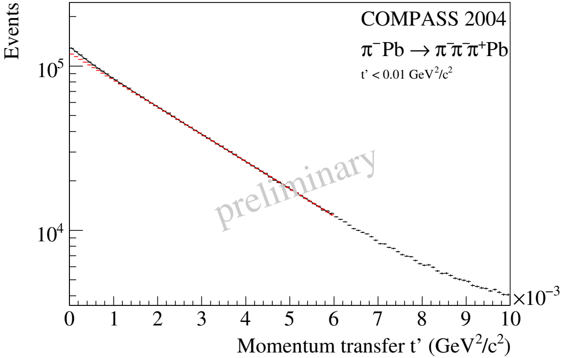
Plot: N. Kaiser (TU München)

$\Rightarrow$ indicates confirmation of interference Coulomb-interaction - strong interaction
$\Rightarrow$ detailed studies of the nature of resonances

Primakoff contribution at $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

Primakoff: $\sigma(t') \propto e^{-b_{\mathrm{Prim}}\,t'}$, $b_{\mathrm{Prim}} \approx 2000\,(\mathrm{GeV}/c)^{-2}$ (mainly resolution)

Diffractive: $\sigma(t') \propto e^{-b_{\mathrm{diff}}\,t'}$, $b_{\mathrm{diff}} \approx 400\,(\mathrm{GeV}/c)^{-2}$ for lead target



(Mass) spectrum of this Primakoff contribution?

$\Rightarrow$ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)