Results and prospects for low-energy QCD processes from COMPASS

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COMPASS collaboration

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

International Conference on Exotic Atoms and Related Topics - EXA2017
13 September, 2017

Bundesministerium für Bildung und Forschung

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Technische Universität München

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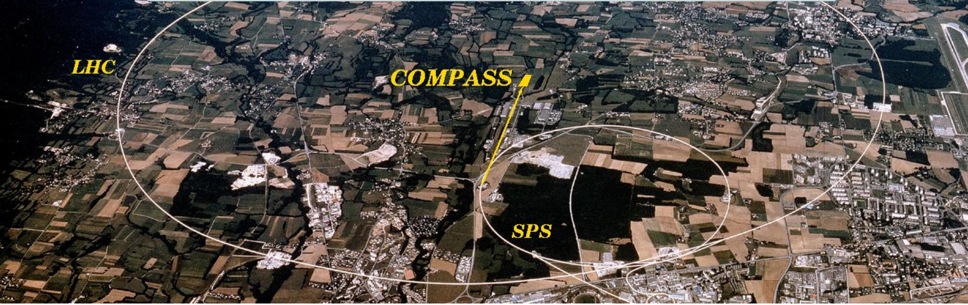
CERN SPS: protons $\sim$ 400 GeV (5 – 10 sec spills)

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



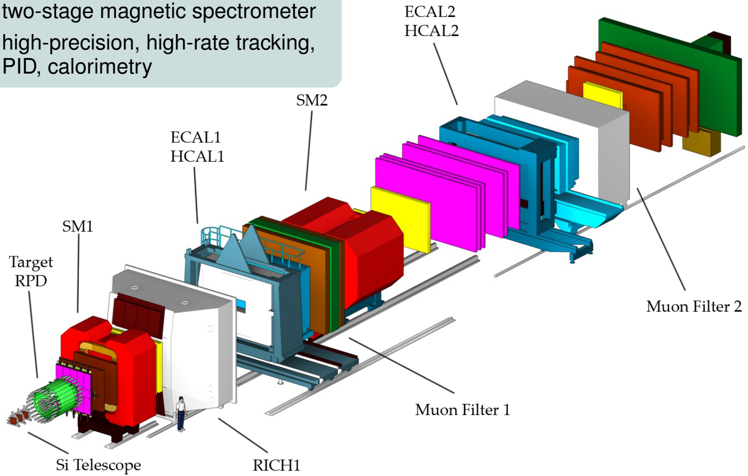
COMPASS

Experimental Setup

Technische Universität München

Fixed-target experiment

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



COMPASS

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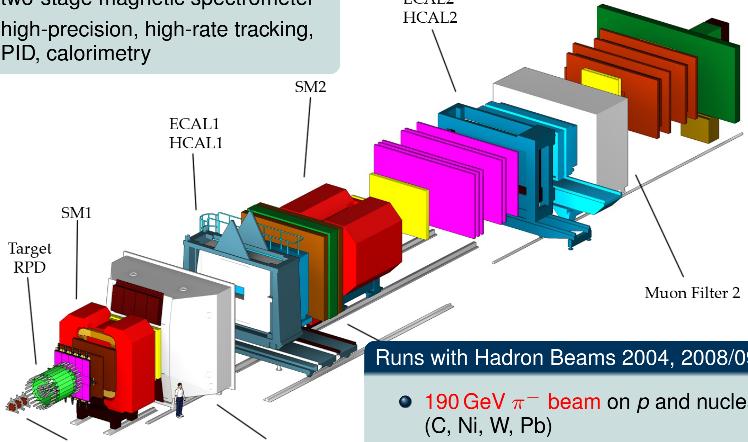
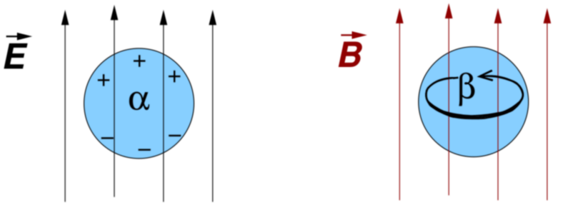


Runs with Hadron Beams 2004, 2008/09, 2012

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

Electromagnetic Polarisabilities

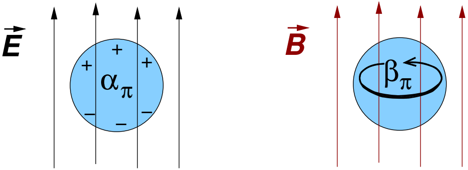


- structure-dependent response to outer e.m. fields:

$$\Delta H = -\frac{1}{2}\left(\alpha \cdot \vec{E}^2 + \beta \cdot \vec{B}^2\right)$$

- well-known for atoms and molecules
- measured on 10%-level for nucleons (also spin dependent)

Pion polarisability and ChPT



pion polarisabilities α_π, β_π in units of 10^{-4} fm^3

size of the pion $\sim$ 1 fm^3 [cf. atoms: polarisability $\approx$ size $\approx$ 1 Å^3]

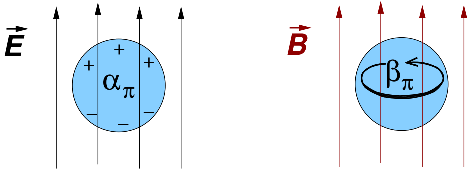
Theory: ChPT (2-loop) prediction:
$$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0$$
$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1$$

experiments for $\alpha_\pi - \beta_\pi$ lie in the range $4 \cdots 14$

($\alpha_\pi + \beta_\pi = 0$ assumed)

ChPT: chiral perturbation theory: low-energy expansion of QCD

Pion polarisability and ChPT



pion polarisabilities α_π, β_π in units of 10^{-4} fm^3

Theory: ChPT (2-loop) prediction:

$$\alpha_\pi = 2.93 \pm 0.5$$
$$\beta_\pi = -2.77 \pm 0.5$$

input to theory: measurement of the radiative $\pi^- \to e^- \nu_e \gamma$ decay
PIBETA experiment at PSI, PRL 103 (2009) 051802

experiments for α_π lie in the range $2 \cdots 7$

Pion Compton Scattering

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

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

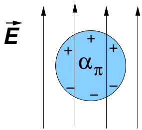
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

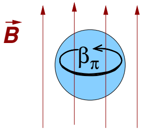
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

Pion Compton Scattering

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





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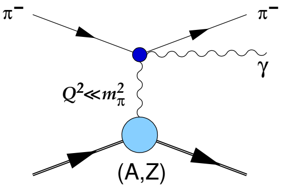
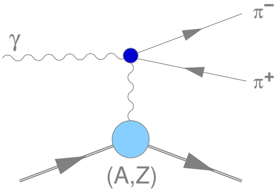
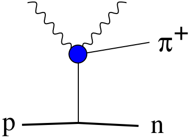
Pion Compton scattering: embedding the process

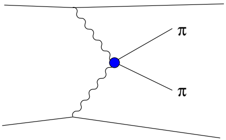




Primakoff processes

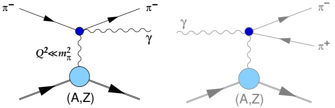


Radiative pion photoproduction



Photon-Photon fusion

Pion polarisability: world data before COMPASS



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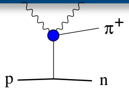

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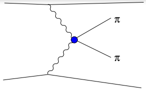

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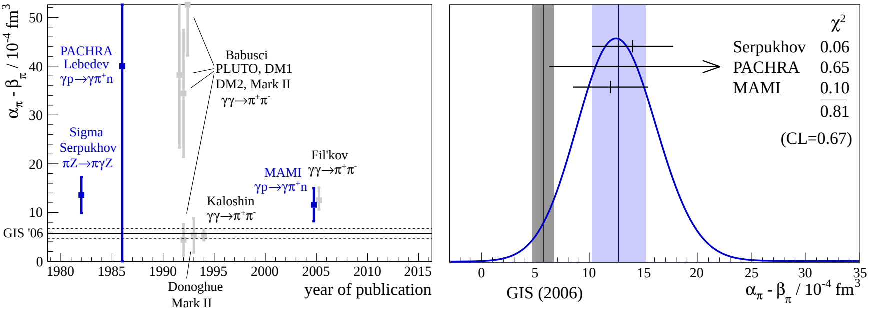
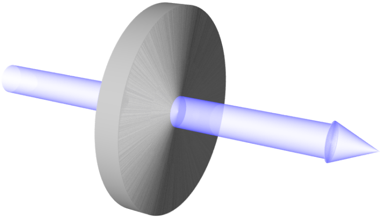


GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD

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

Principle of the Primakoff technique

- high-energetic pion beam on 4mm nickel disk
- observe scattered pions in coincidence with produced hard photons with energy fraction $x_\gamma = E_\gamma / E_{beam}$
- study the cross-section shape



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.

- Depends on MC simulation of the acceptance, control systematics by

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

and

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

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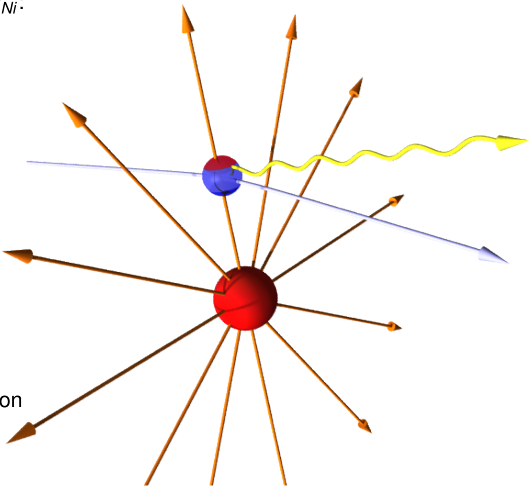
  and

$$K^- \to \pi^-\pi^0 \to \boldsymbol{\pi\gamma}\gamma$$

Polarisability effect in Primakoff technique

- Charged pions traverse the nuclear electric field
  - typical field strength at $d = 5R_{Ni}$: $E \approx 300\,\text{kV/fm}$
- Bremsstrahlung process:
  - particles scatter 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
  - corresponding charge separation $\approx 10^{-5}\,\text{fm} \cdot e$



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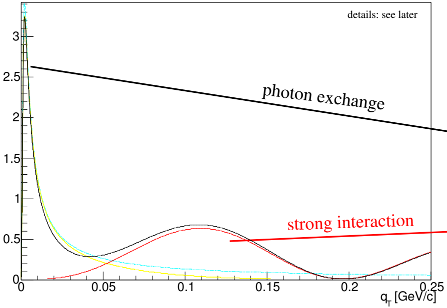
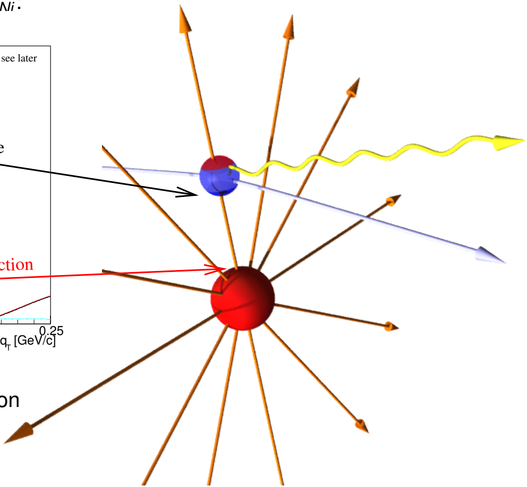
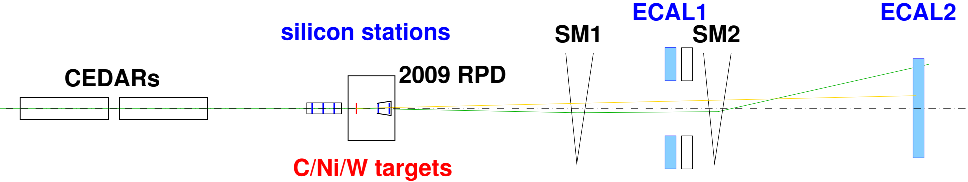




typically diminished

  - corresponding charge separation $\approx 10^{-5}$ fm $\cdot\, e$

Principle of the measurement



spatial resolution of tracks $\sim 10\mu$m
angular resolution of photons $\sim 30\mu$rad

ECAL2: 3000 cells of different types

ECAL2: the quest for precision

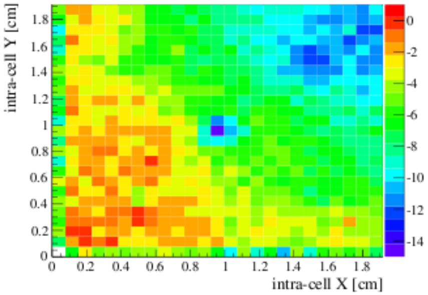


Figure 3.5: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range 133 GeV $< E_\gamma <$ 152 GeV .

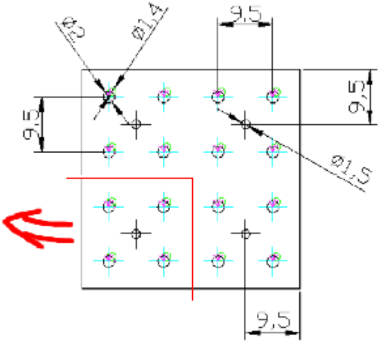


Figure 3.6: Technical drawing of a full shashlik cell to be compared with the figure to the left.

from: Th. Nagel, PhD thesis TUM 2012

latest publication 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]

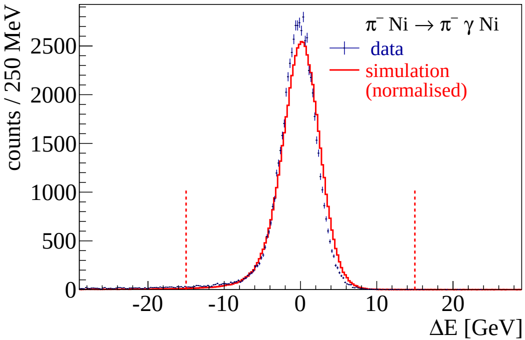
(COMPASS Collaboration)

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

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, 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

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

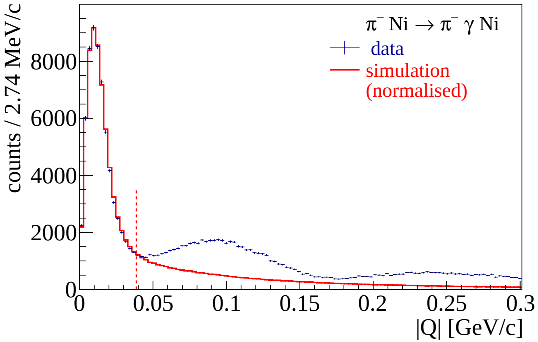
Phys. Rev. Lett. 114, 062002 (2015)



- 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

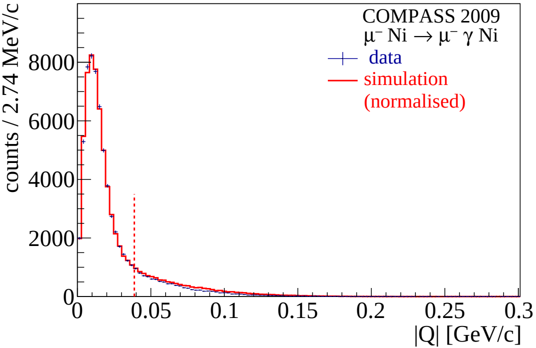
Phys. Rev. Lett. 114, 062002 (2015)



- $\Delta Q_T \approx$ 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?

Primakoff peak: muon data

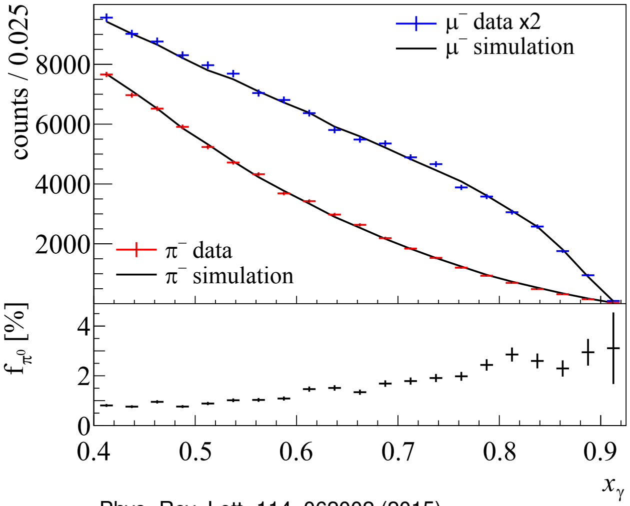
Phys. Rev. Lett. 114, 062002 (2015)



- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood

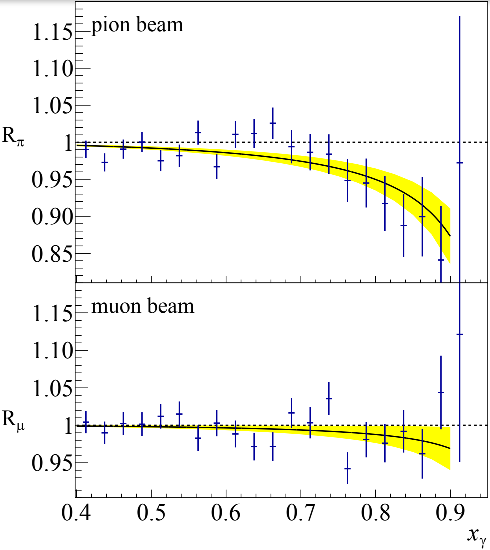
Photon energy spectra for muon and pion beam

Technische Universität München



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

Pion polarisability: COMPASS result



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

(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)

source of systematic uncertainty	estimated magnitude CL $= 68\,\%$ $[10^{-4}\,\mathrm{fm}^3]$
determination of tracking-detector efficiencies	0.5
treatment of radiative corrections	0.3
subtraction of π^0 background	0.2
strong interaction background	0.2
pion-electron elastic scattering	0.2
contribution of muons in the beam	0.05
quadratic sum	0.7

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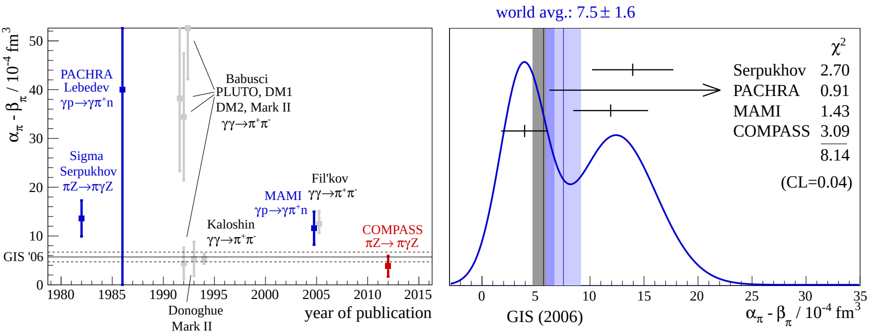
quadratic sum	0.7

COMPASS result for the pion polarisability:

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

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

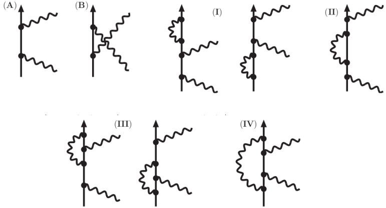
Pion polarisability: world data including COMPASS



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

Theory aspects of the π^- polarisability measurement

- Radiative corrections (Compton scattering part)



Nucl.Phys. A837 (2010), Eur.Phys.J. A39 (2009) 71

- Higher order pion dynamics: Dispersion relations vs. ChPT (B. Pasquini, OK)
- pion polarisability from lattice QCD: first studies indicate small value (large uncertainty)

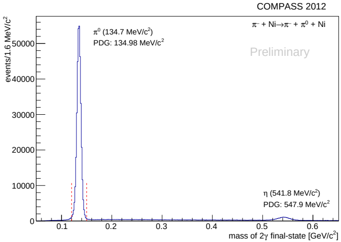
Primakoff reactions accessible at COMPASS

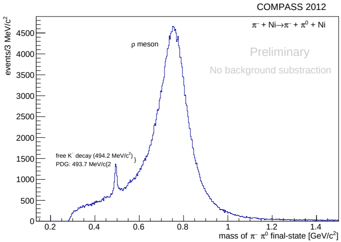
Access to $\pi\gamma-$initiated reactions via the Primakoff effect

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

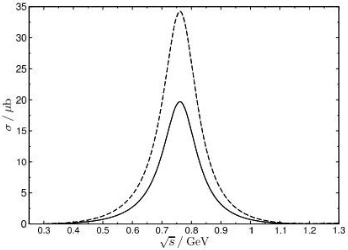
analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$

Chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$





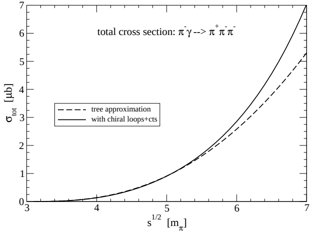
- contributions from chiral anomaly $F_{3\pi}$ and the $\rho(770)$ resonance
- can be described by a dispersive method → increased sensitivity to the chiral anomaly
- uncertainty estimate $< 1\%$

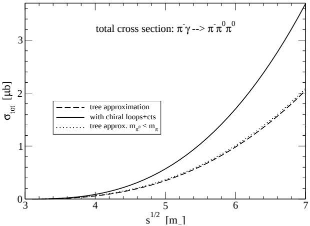


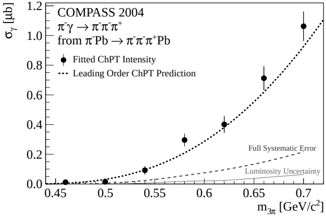
Hoferichter et al., PRD86 (2012) 116009

Chiral dynamics in $\pi\gamma \to 3\pi$

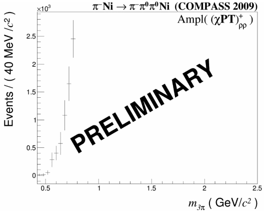
relevant physics: pion scattering lengths, pion loop contributions





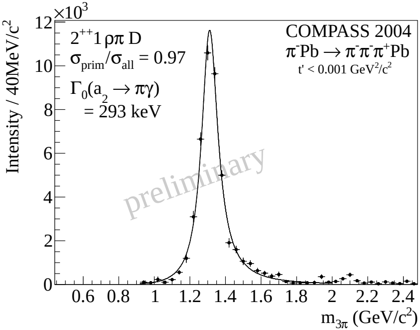


published in PRL 108 (2012) 192001

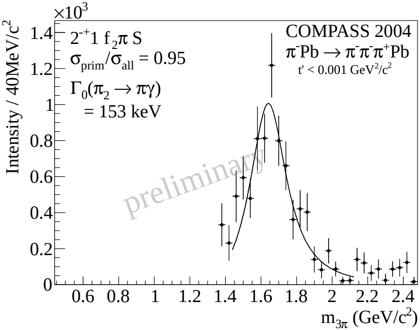


normalization: analysis ongoing

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



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



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

⇔ meson wave functions: $\Gamma_{i\to f} \propto |\langle\Psi_f| e^{-i\vec{q}\cdot\vec{r}}\, \hat{\epsilon}\cdot\vec{p}\,|\Psi_i\rangle|^2$

- normalization via beam kaon decays
- large Coulomb correction

published in EPJ A50 (2014) 79

Summary

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

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

  - most direct access to the $\pi\gamma \to \pi\gamma$ process
  - most precise experimental determination
  - control of systematics: $\mu\gamma \to \mu\gamma,\ K^- \to \pi^-\pi^0$
- Related topics at COMPASS: radiative widths and chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ reactions
  - chiral anomaly coming soon
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First studies for a kaon polarisability measurement

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

$\pi^\pm$ $\qquad I^G(J^P) = 1^-(0^-)$

π ELECTRIC POLARIZABILITY α_π

See HOLSTEIN 14 for a general review on hadron polarizability.

VALUE (10^{-4} fm^3)	EVTS	DOCUMENT ID		TECN	COMMENT
2.0±0.6±0.7	63k	[1] ADOLPH	15A	SPEC	$\pi^-\gamma \to \pi^-\gamma$ Compton scatt.

[1] Value is derived assuming $\alpha_\pi = -\beta_\pi$.

$a_1(1420)$ $\qquad I^G(J^{PC}) = 1^-(1^{++})$

OMITTED FROM SUMMARY TABLE

$a_1(1420)$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$\mathbf{1414^{+15}_{-13}}$	[1] ADOLPH	15C	COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$

[1] Using the isobar model and partial-wave analysis with 88 waves.

some of the new COMPASS entries in the RPP2016 edition

Outlook: COMPASS++ and Beyond

More channels of interest for low-energy QCD

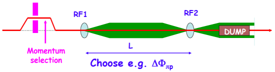
- Primakoff reaction with $\pi^-\eta$ final state
- π^0 lifetime

Mid-term future perspectives with conventional beams

- SIDIS on a transversely polarized deuteron target
- elastic muon-proton scattering at low momentum transfers
- Antiproton-induced hadron spectroscopy
- polarized-target DVCS and DY processes

Longer-term future ideas with RF-separated beams

- Kaon-induced hadron spectroscopy
- Kaon-induced Drell-Yan processes



$\Delta\Phi = 2\pi\,(L\,f\,/\,c)\,(\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

principle of RF separation

Thank you for your attention!