Measurement of the Pion Polarisability at COMPASS

Jan Friedrich

Technische Universität München

Graduiertenkolleg Mainz
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Outline

- Compton scattering and polarisabilities
  - Motivation
  - Related processes for unstable particles
  - Primakoff kinematics
- The COMPASS 2004 pilot hadron run
- Data analysis and preliminary results

- How are hadrons built up in terms of their constituents?

Static properties $\Leftrightarrow$ form factors

Hadron structure

- How are hadrons built up in terms of their constituents?

  Static properties $\Leftrightarrow$ form factors

- How do hadrons react to (small) external forces?

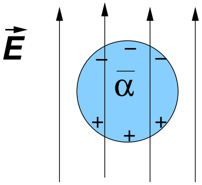
  Non-pointlike response $\Leftrightarrow$ polarisabilities

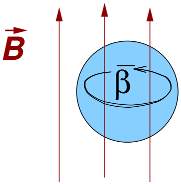
classical

$$\vec{d} = (eZ)2\ell = \bar{\alpha}\vec{E}$$

$$K\ell = (eZ)E$$

$$\bar{\alpha} = \frac{2(eZ)^2}{K}$$





- for point-like target completely determined by QED
- polarisability contribution starting at $\mathcal{O}(E_\gamma)$ (for spin-$\frac{1}{2}$)

Compton scattering

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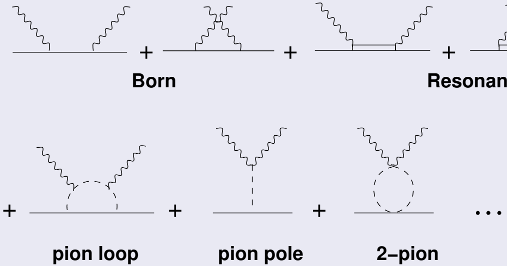
Nucleon case



Compton scattering

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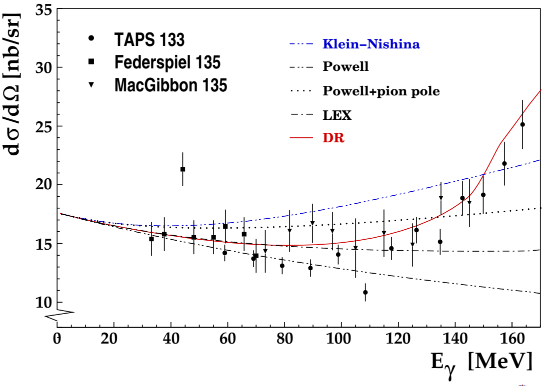
- polarisability contribution starting at $\mathcal{O}(E_\gamma)$ (for spin-$\frac{1}{2}$)

Proton data

$$\bar{\alpha}_p = 12.1 \pm 0.3_{\text{stat}} \mp 0.4_{\text{syst}} \pm 0.3_{\text{mod}} \cdot 10^{-4}\text{fm}^3$$

$$\bar{\beta}_p = 1.6 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.4_{\text{mod}} \cdot 10^{-4}\text{fm}^3$$

(cancellation of para- and diamagnetic contributions)



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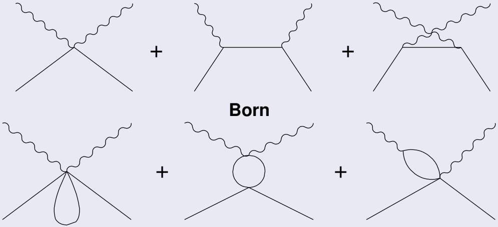
Pion case



$$\mathcal{M} = 8\pi i \cdot m_\pi \left[\left(-\frac{\alpha}{m_\pi} + \bar{\alpha} \cdot \omega_1 \omega_2 \right) \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 + \bar{\beta} \cdot (\vec{q}_1 \times \vec{\epsilon}_1) \cdot (\vec{q}_2 \times \vec{\epsilon}_2) \right]$$

Pion

- Low-energy expansion of QCD: Chiral perturbation theory

Pion has a special role as the Goldstone boson
(massless in the chiral limit)

- are the basic features correctly described?

Meson Polarisabilities

Pion

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ChPT 1-loop for $\pi^{\pm}$

$$\begin{aligned}\bar{\alpha}+\bar{\beta} &= 0\\ \bar{\alpha}-\bar{\beta} &= \frac{2e^2}{\pi m_\pi f_\pi^2}\left(L_9^r+L_{10}^r\right)\\ &= +5.4\pm 0.8\cdot 10^{-4}\mathrm{fm}^3\end{aligned}$$

Meson Polarisabilities

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ChPT 2-loop for $\pi^\pm$

$$\begin{aligned}\bar{\alpha} + \bar{\beta} &= 0.3 \pm 0.1 \cdot 10^{-4}\mathrm{fm}^3 \\ \bar{\alpha} - \bar{\beta} &= 5.7 \pm 1.0 \cdot 10^{-4}\mathrm{fm}^3\end{aligned}$$

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Dispersion sum rules $\pi^\pm$

$$\begin{aligned}\bar\alpha + \bar\beta &= 0.39 \pm 0.4 \cdot 10^{-4}\mathrm{fm}^3 \\ \bar\alpha - \bar\beta &\approx 10 \cdot 10^{-4}\mathrm{fm}^3\end{aligned}$$

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Kaon

- Higher mass $\Leftrightarrow$ smaller polarisability by a factor ~ 5
- theoretically very exciting – need for experimental data!

Compton scattering on unstable particles

1st option

test the particle during its production process

A) $e^+e^- \longrightarrow e^+e^- \; \pi^+\pi^- \qquad (\gamma\gamma \longrightarrow \pi^+\pi^-)$

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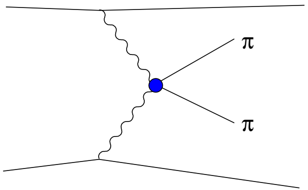


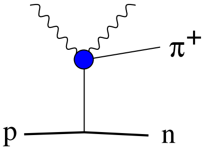
Compton scattering on unstable particles

1st option

test the particle during its production process

A) $e^+e^- \rightarrow e^+e^- \; \pi^+\pi^-$ $\quad (\gamma\gamma \rightarrow \pi^+\pi^-)$

B) radiative pion photoproduction on the nucleon
$\gamma \, \mathrm{p} \longrightarrow \gamma \, \mathrm{n} \, \pi^+$

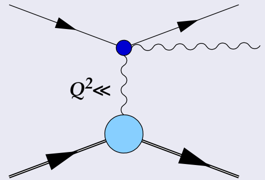


Compton scattering on unstable particles

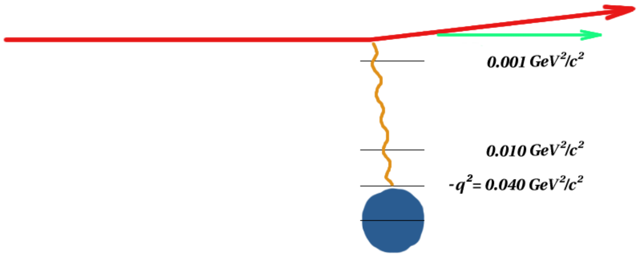
2nd option

use ultra-relativistic particle beam (quasi-stable)

on "photon target":
Coulomb photon of a heavy nucleus participates in (semi-)hadronic interaction – Primakoff effect



Pion-nucleus scattering at small Q^2



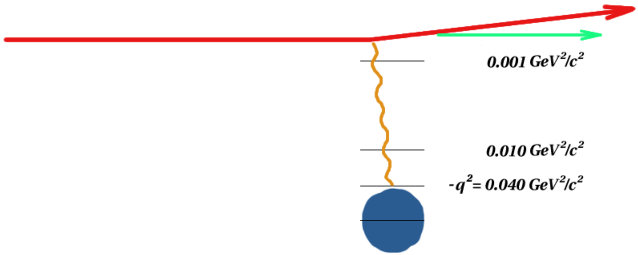
$\pi + Pb \rightarrow X^- + Pb$

diffractive scattering:
$\rightarrow$ meson spectroscopy
$\rightarrow$ exotics

$Q^2 < 0.001$ GeV^2/c^2

- $\pi + \gamma^{(*)} \rightarrow \pi' + \pi^0$
- $\pi + \gamma^{(*)} \rightarrow \pi' + \gamma$
  Primakoff reaction
  $\rightarrow$ pion polarisability

Pion-nucleus scattering at small Q^2



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diffractive scattering:
$\rightarrow$ meson spectroscopy
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e.m./strong Interference

Recently approached in eikonal approx. (G. Faeldt)

$Q^2 < 0.001$ GeV^2/c^2

- $\pi + \gamma^{(*)} \rightarrow \pi' + \pi^0$
- $\pi + \gamma^{(*)} \rightarrow \pi' + \gamma$
  Primakoff reaction
  $\rightarrow$ pion polarisability

Polarisability Extraction

E_γ dependence assuming $\overline{\beta}_\pi + \overline{\alpha}_\pi = 0$

$$\frac{d\sigma_{Prim}}{dE_\gamma} = \frac{d\sigma_{pl}}{dE_\gamma} + \frac{d\sigma(\overline{\alpha}_\pi, \overline{\beta}_\pi)}{dE_\gamma} = \frac{d\sigma_{pl}}{dE_\gamma} + \frac{d\sigma(\overline{\beta}_\pi)}{dE_\gamma} =$$

$$= \frac{4Z^2\alpha^3}{m_\pi^2} \cdot \frac{E_{\pi'}}{E_{Beam}E_\gamma} \cdot \left(\frac{2}{3} \ln \frac{Q^2_{max}}{Q^2_{min}} - \frac{19}{9} + 4\sqrt{\frac{Q^2_{min}}{Q^2_{max}}} \right) +$$

$$+ \frac{4Z^2\alpha^3}{m_\pi^2} \cdot \frac{E_\gamma}{E^2_{Beam}} \cdot \frac{\overline{\beta}_\pi m_\pi^3}{\alpha} \cdot \left(\ln \frac{Q^2_{max}}{Q^2_{min}} - 3 + 4\sqrt{\frac{Q^2_{min}}{Q^2_{max}}} \right)$$

$$Q_{min} = \frac{E_\gamma m_\pi^2}{2E_{Beam}E_{\pi'}}$$

$$\omega = \frac{E_\gamma}{E_{Beam}}$$

Ratio $R_\pi = d\sigma_{Prim}/d\sigma_{pl}$

$$R_\pi(\omega) \approx 1 + \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{\omega^2}{1-\omega}\overline{\beta}_\pi$$

Data on the Pion Polarisability

	$\alpha+\beta$ $[10^{-4}\,\mathrm{fm}^3]$	$\alpha-\beta$ $[10^{-4}\,\mathrm{fm}^3]$
Bürgi/Gasser (ChPT)	0.3 ± 0.1	5.7 ± 1.0
Mark II	$0.22 \pm 0.07 \pm 0.04$	4.8 ± 1.0
CELLO	$0.33 \pm 0.06 \pm 0.01$	
Serpukhov	$1.8 \pm 3.1 \pm 2.5$	12.3 ± 2.6
MAMI		$11.6 \pm 1.5 \pm 3.0 \pm 0.5$
COMPASS	?	?

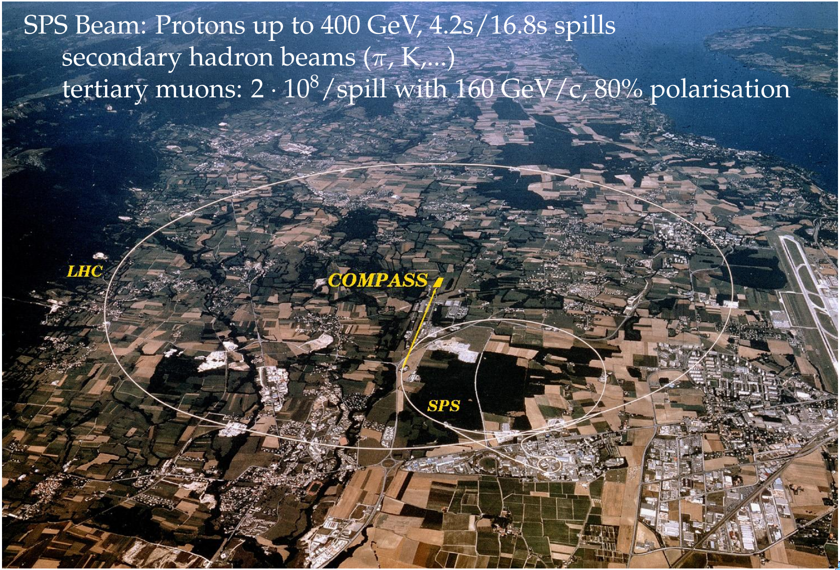
- different reactions with different systematics
- challenging measurements (Mainz $\sim$ 1000 h beam time!)
- no coherent picture of pion polarisability yet

CERN aerial view

SPS Beam: Protons up to 400 GeV, 4.2s/16.8s spills

secondary hadron beams (π, K,...)

tertiary muons: $2 \cdot 10^8$/spill with 160 GeV/c, 80% polarisation



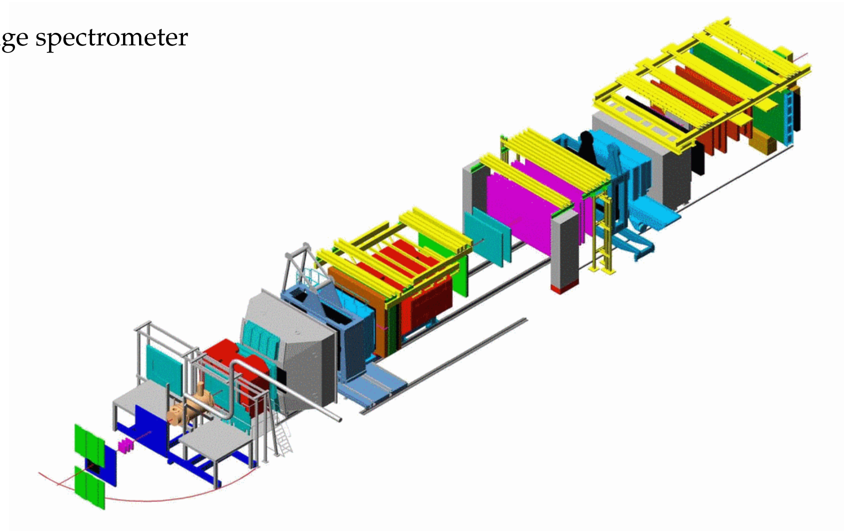
Czech Republic, France, Germany, India, Israel,
Italy, Japan, Poland, Portugal, Russia, CERN

240 physicists from 28 institutes

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna,
Erlangen, Freiburg, Lisboa, Mainz, Moscow, Munich, Nagoya,
Parg, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw

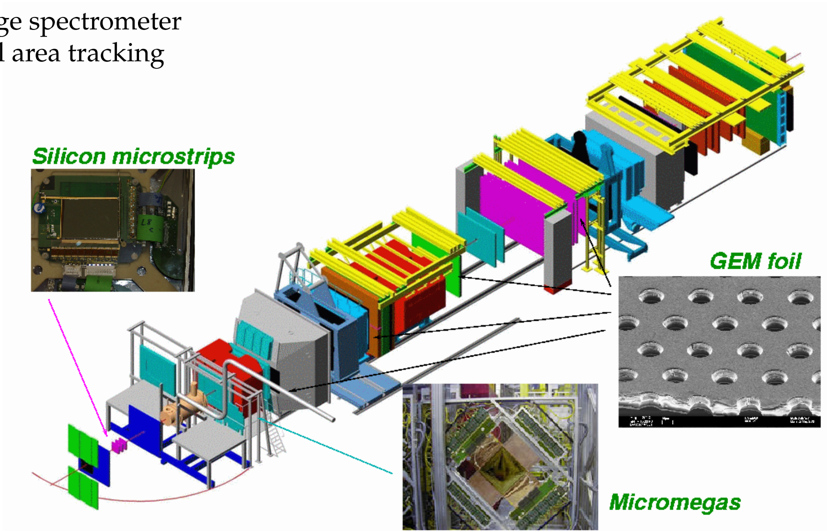
Data acquisition 2002, 03, 04, 06 with muon beam
on polarised LiD target
Oct. 2004: pilot hadron run (π^-)

2 stage spectrometer



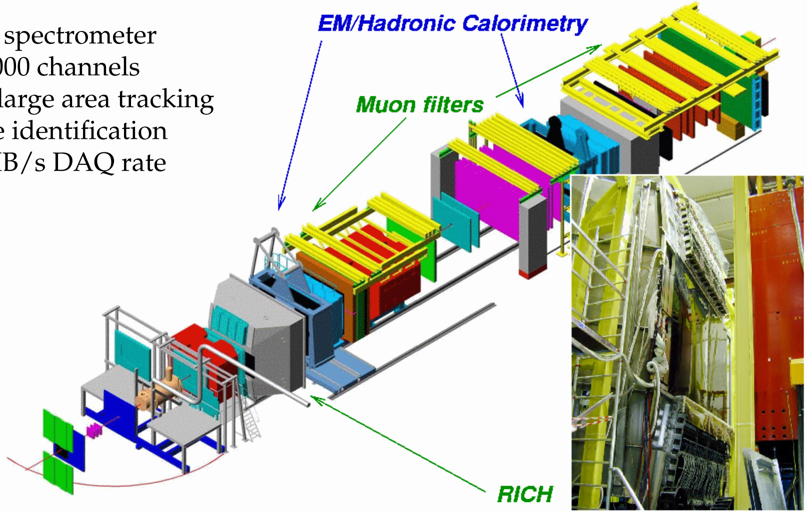
The COmmon Muon and Proton Apparatus for Structure and Spectroscopy

2 stage spectrometer
small area tracking

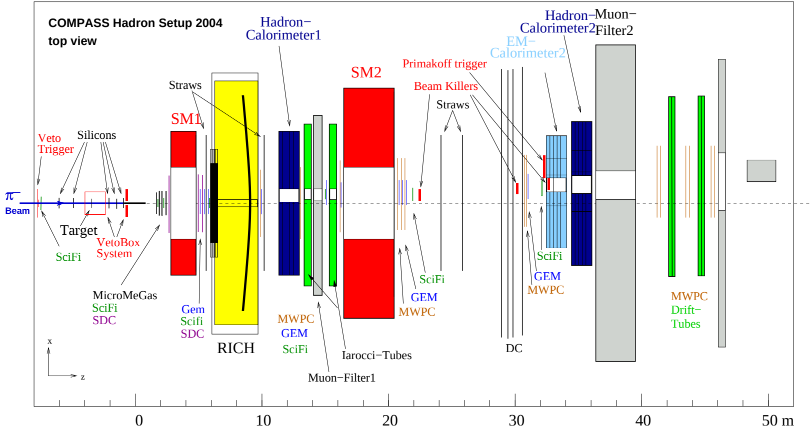


The COmmon Muon and Proton Apparatus for Structure and Spectroscopy

2 stage spectrometer
$\sim$ 200.000 channels
small/large area tracking
particle identification
$\sim$ 50 MB/s DAQ rate

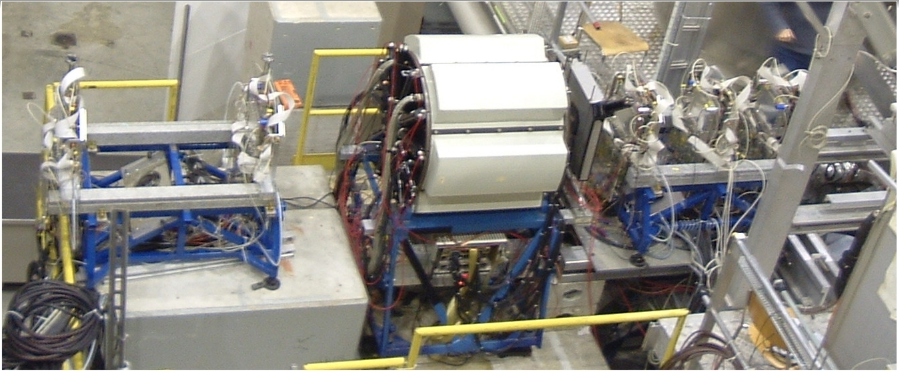


Layout of the COMPASS 2004 pilot hadron run

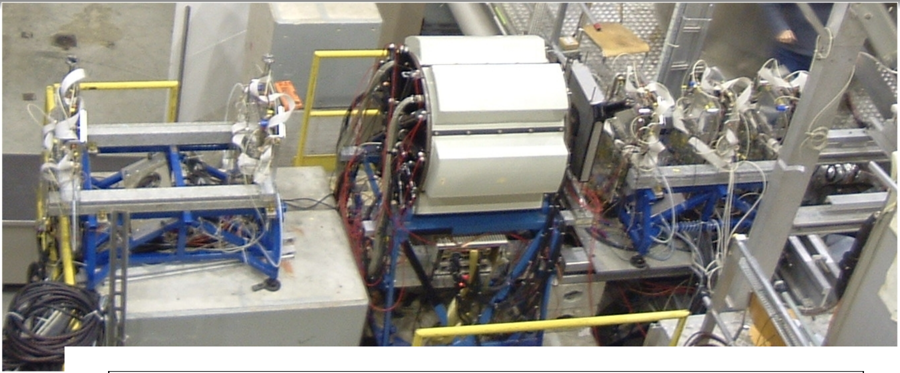


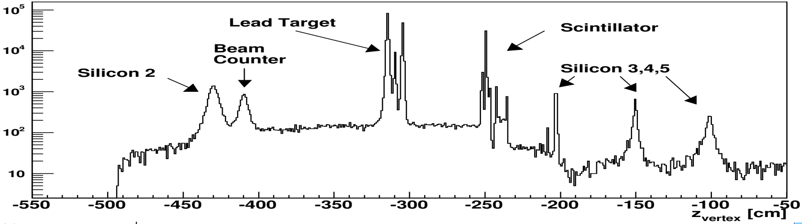
- 4 weeks data taking in autumn 2004
- 190 GeV π^-/μ^--beam, 10^6 particles/s
- Targets: Pb ($X_0 = 0.29, 0.5$), Cu (0.25), C (0.12)

Target region



Target region





(diffractive $\pi^+\pi^-\pi^-$ vertices)

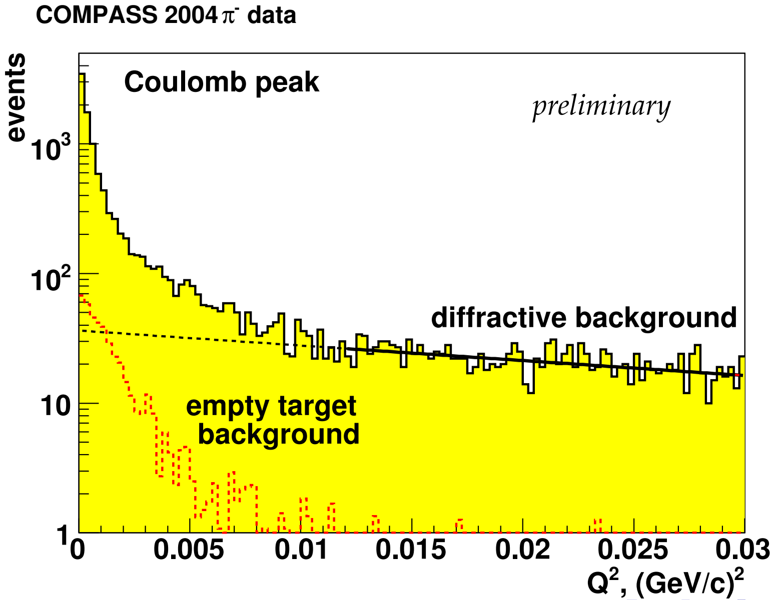
Primakoff Reaction

Selection of $\pi^- + \gamma^{(*)} \to \pi^- + \gamma$

- exactly one primary vertex in the target ($p_{T,\pi^-} > 15$ MeV)
- exactly one π^- track of high quality, $E_{\pi^-} < 170$ GeV
- exactly one Ecal2 cluster as photon candidate
- $|\, E_{\pi^-} + E_\gamma - E_{beam} \,| < 25$ GeV
- $Q^2 < 0.0075\ \mathrm{GeV}^2/c^2$, $M_{\pi\gamma} < 3.75 m_\pi$

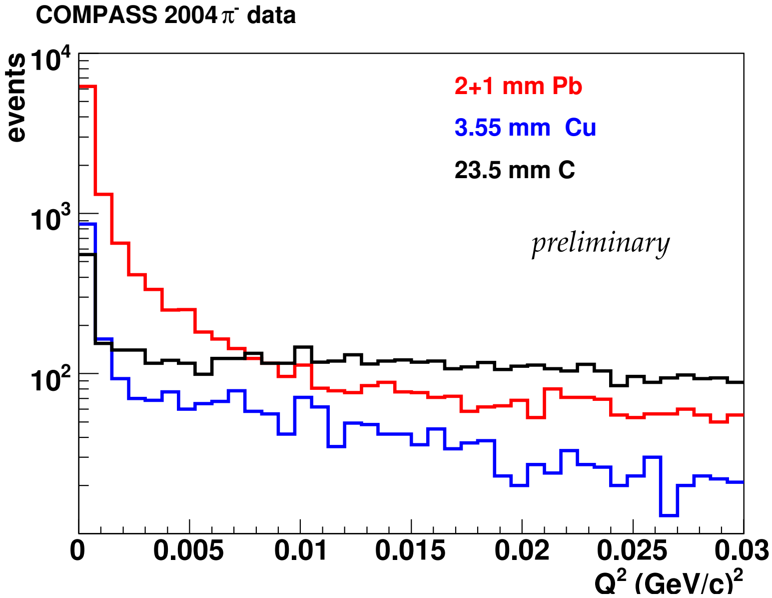
Background

- $K^- \longrightarrow \pi^-\pi^0$ (empty target subtraction)
- diffractive channels with one high-energetic photon (different Q^2 dependence)

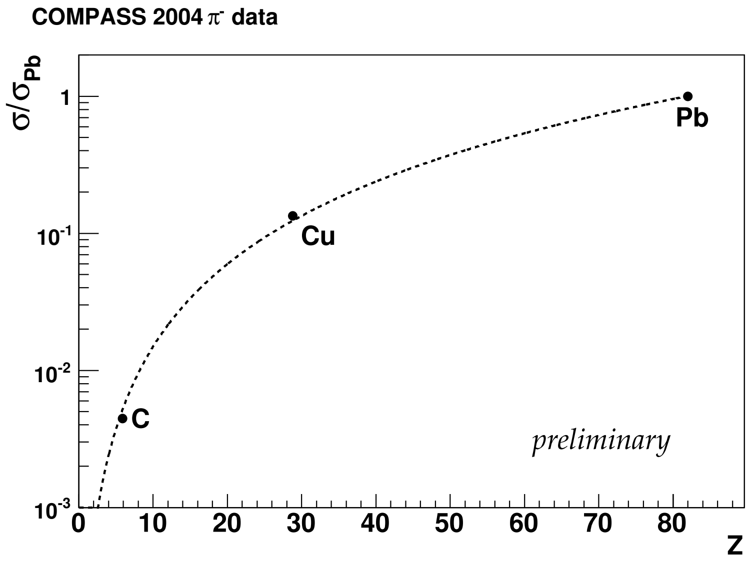


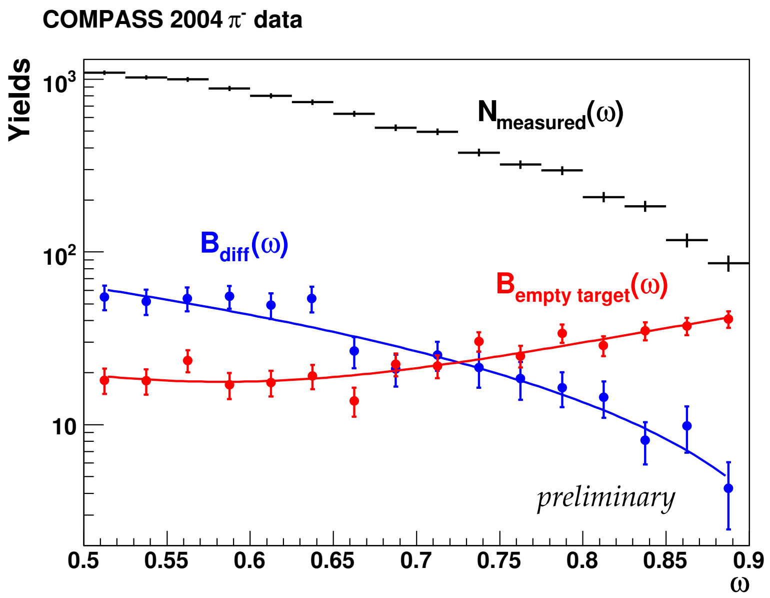
COMPASS 2004 π- data
events
Coulomb peak
preliminary
diffractive background
empty target
background
10^3
10^2
10
1
0
0.005
0.01
0.015
0.02
0.025
0.03
Q^2, (GeV/c)^2

Q^2 distribution for different targets

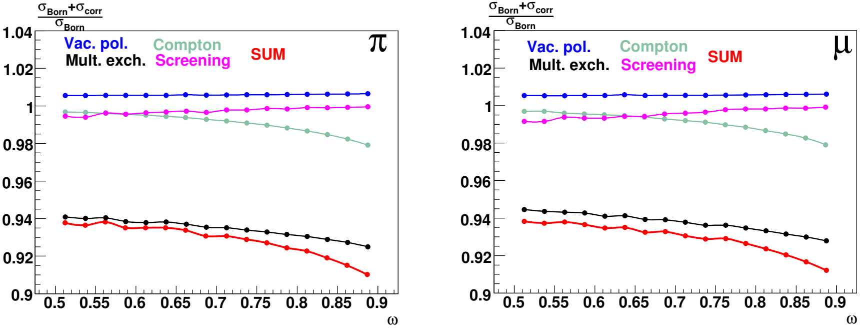


Z^2 dependence of Primakoff cross section

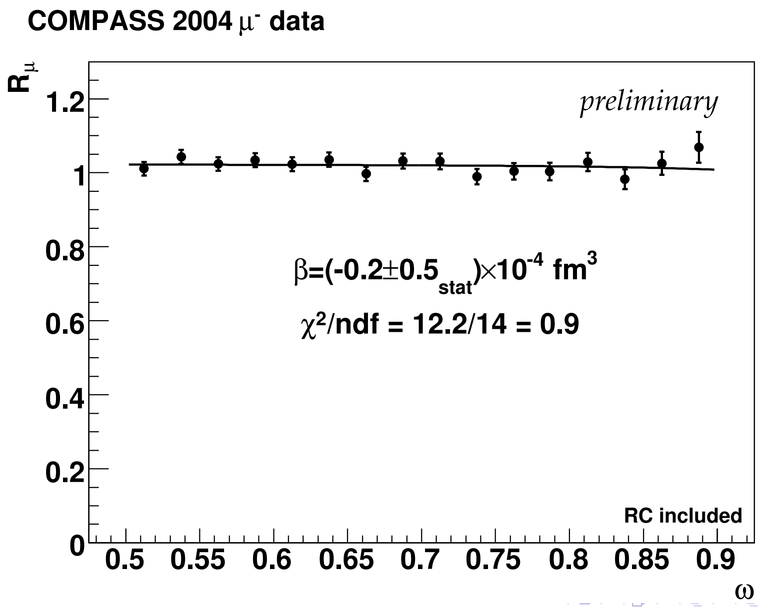



COMPASS 2004 π⁻ data
Yields
10³
10²
10
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
ω
N measured(ω)
B diff(ω)
B empty target(ω)
preliminary

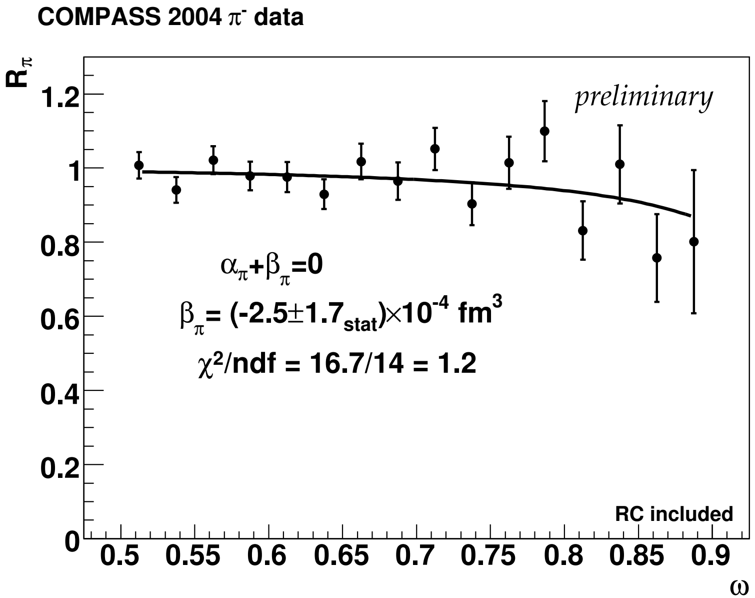
Radiative corrections for π and μ data



Muon control measurement



Pion measurement



Systematic error estimate

	Error, 10^{-4}fm^3
Setup description in MC (μ data)	± 0.5
Diffractive and empty target background subtraction	± 0.3
Muons background	$+0.2$
Electrons background	$<+0.1$
SYSTEMATIC TOTAL	± 0.6

Result and Outlook

From COMPASS data taken in ~ 3 days of beam time (7300 events), the pion polarisability value

$$\overline{\beta}_\pi = -2.5 \pm 1.7_{stat} \pm 0.6_{syst} \cdot 10^{-4}\mathrm{fm}^3$$

is extracted (preliminary).

Outlook

- Additional data on tape (adjusted MC needed)
- Independent extraction of $\overline{\alpha}_\pi$ and $\overline{\beta}_\pi$
- New improved measurement at COMPASS

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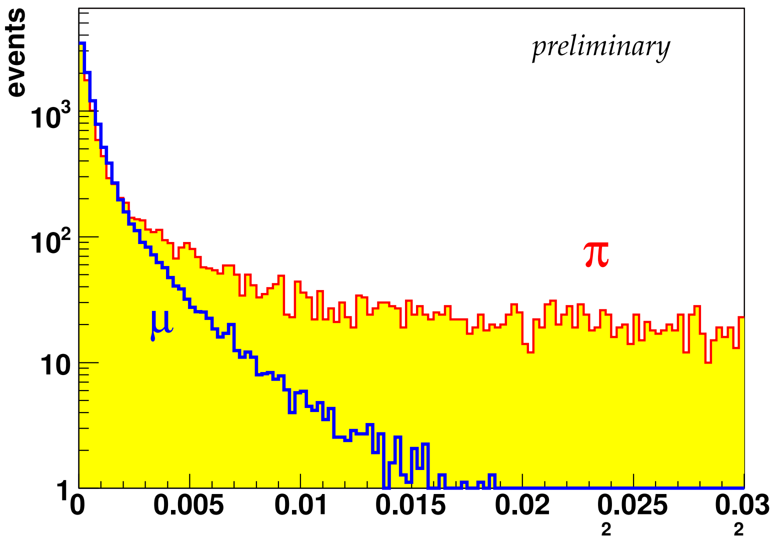
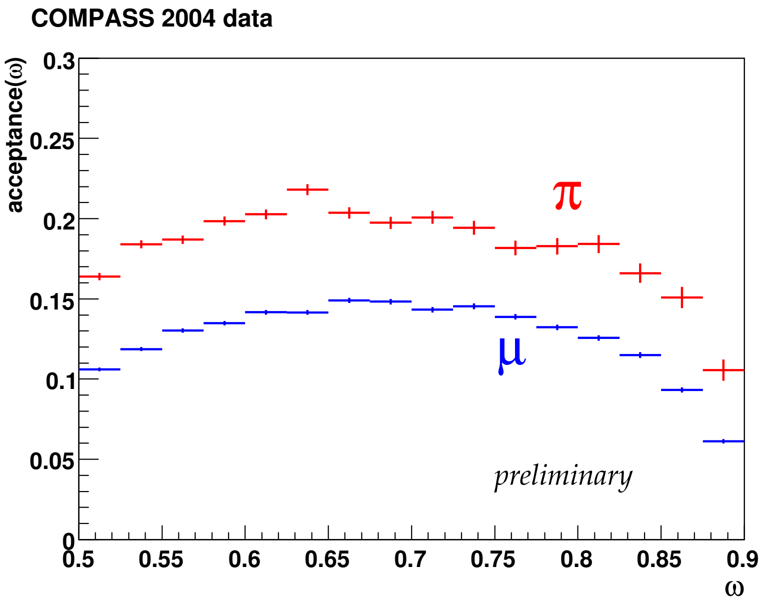
COMPASS	-	$5.0 \pm 3.4 \pm 1.2$

Q^2 for muon data

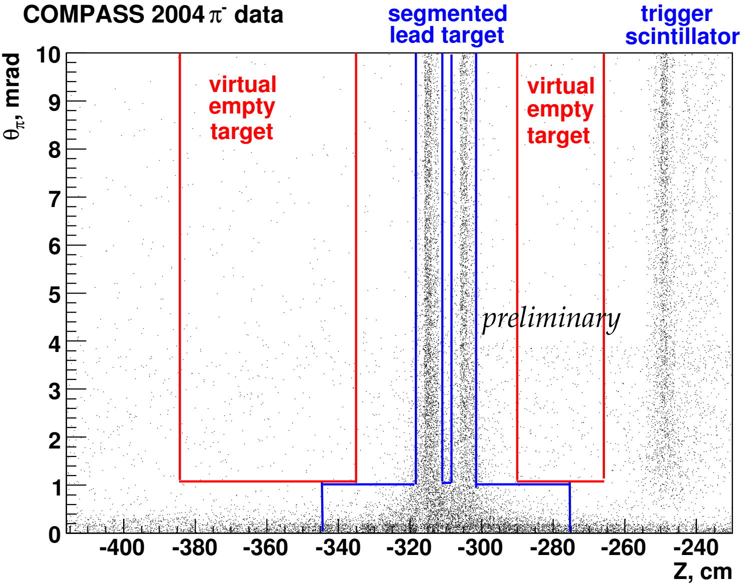
COMPASS 2004 data



Acceptance from MC simulation

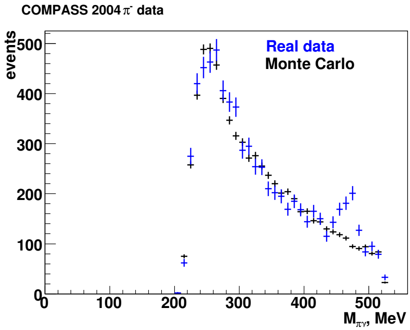


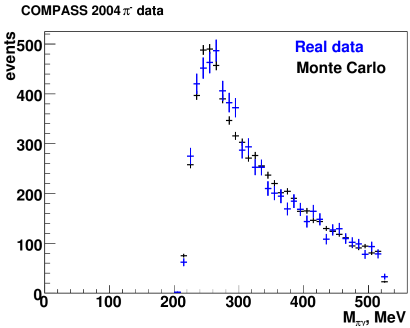
Virtual Empty Target Method



Empty target background subtraction

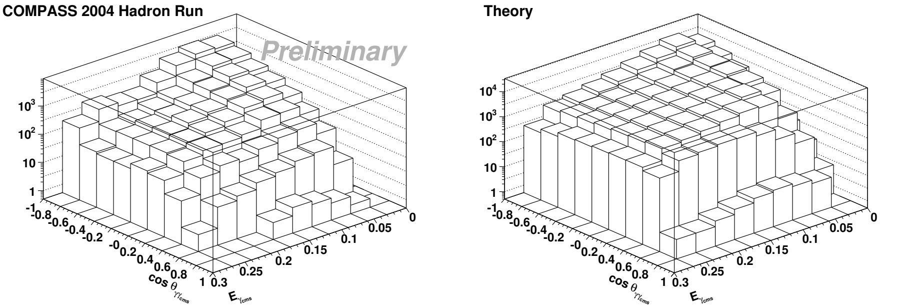
without, with empty target subtraction





preliminary spectra

2-dimensional $E_\gamma - \theta_\gamma$ raw spectrum



with MC-correction

(mainly γ conversion, π^- decay, Ecal2 beam hole)
$\rightarrow$ determination of α and β without $\alpha + \beta = 0$ constraint

Possible improvements

Analysis

- new production of data
  - alignment
  - vertexing (for z<-100cm)
  - time-dependent Ecal2 calibration
  - retrieve scaler information
- refined Monte Carlo for different settings

New measurement

- CEDAR for incoming particle ID
- stable setup
- optimized material budget