Chiral Dynamics and the Pion Polarisability Measurements at COMPASS

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Technische Universität München

for the COMPASS collaboration

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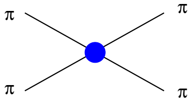
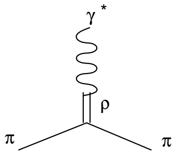
Chiral Perturbation Theory vs. Experiment

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



- Electromagnetic structure: charge distribution
  - Form factor described by coupling to $\rho(770)$ (resonance effect) $\sqrt{< r^2 >} \approx 0.66$ fm



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  - contribution to Compton scattering
  - ChPT prediction obtained by the relation to $\pi^+ \to e^+\nu_e\gamma$ [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]

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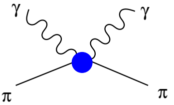

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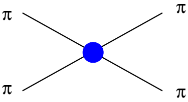

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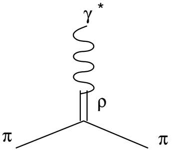

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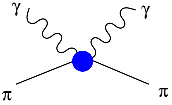

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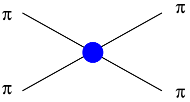

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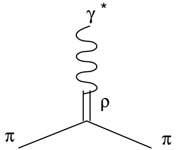

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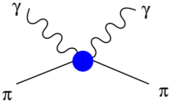

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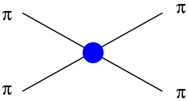

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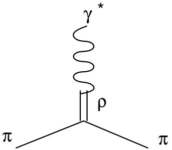

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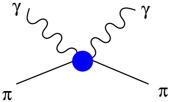
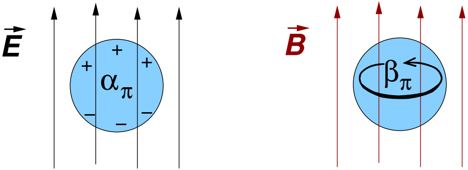
how to measure α_π and β_π?



One of the ChPT predictions: 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

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

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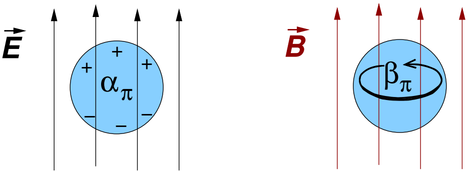

polarisabilities α_π, β_π [10^{-4} fm^3]

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

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Exemplifying the size of the pion polarisability

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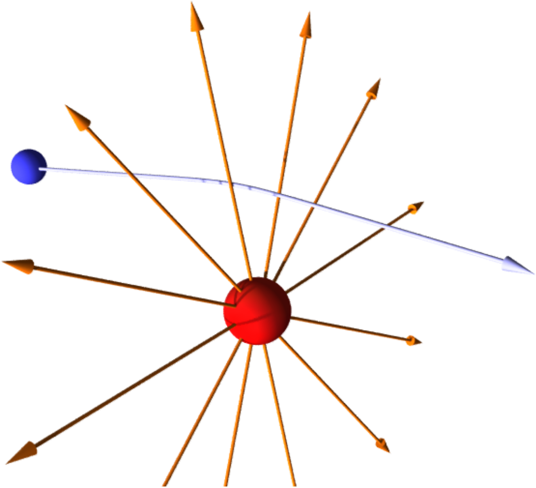
Primakoff measurement technique

- Charged pion traversing the nuclear electric field
    - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$



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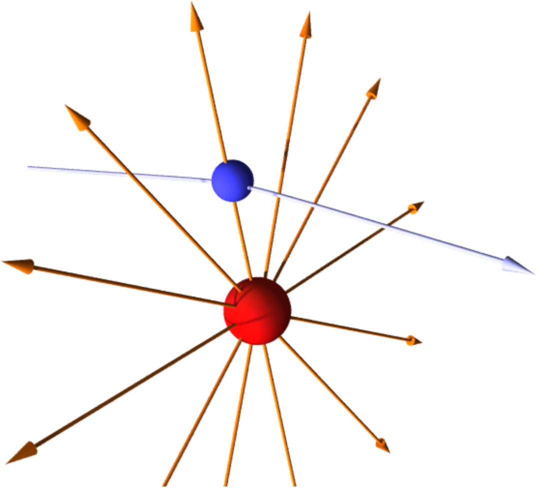

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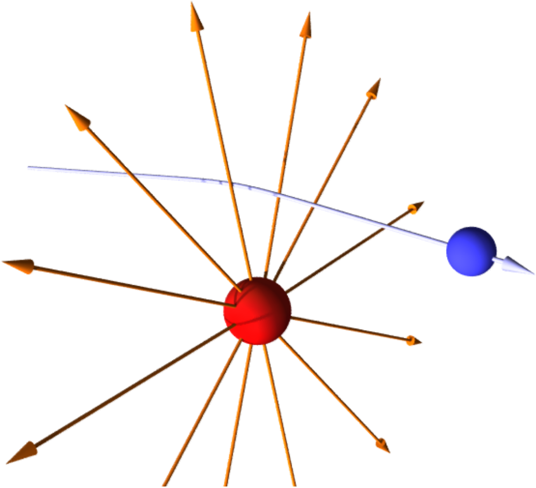

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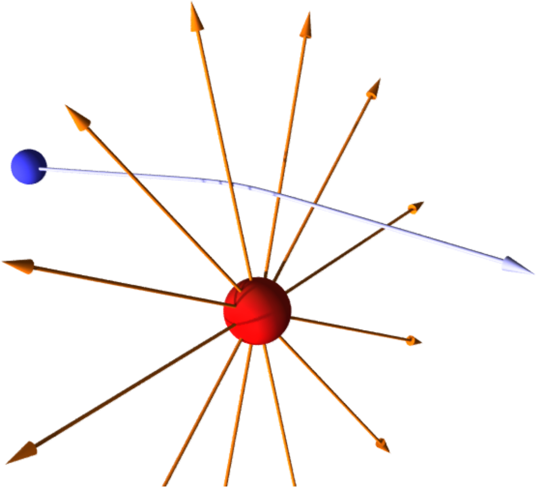

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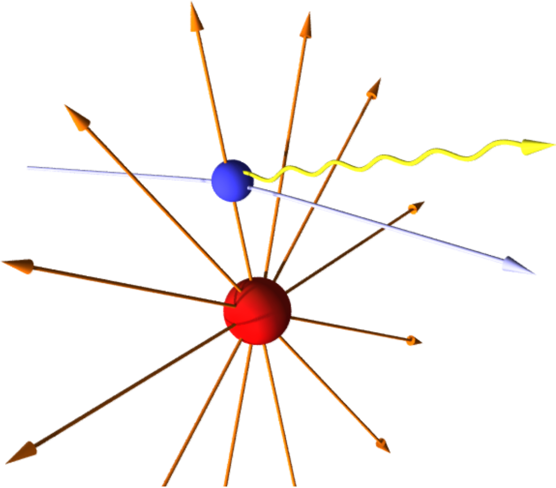

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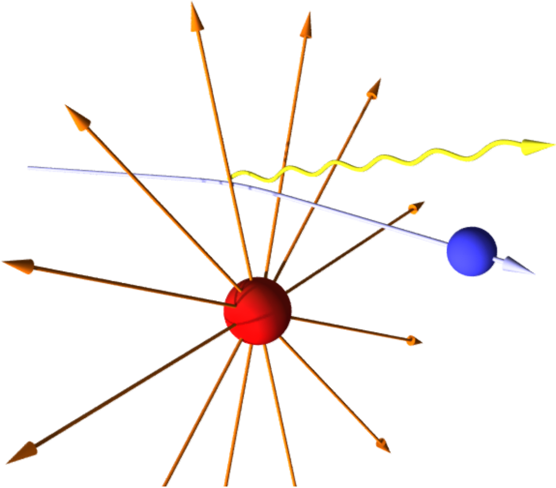

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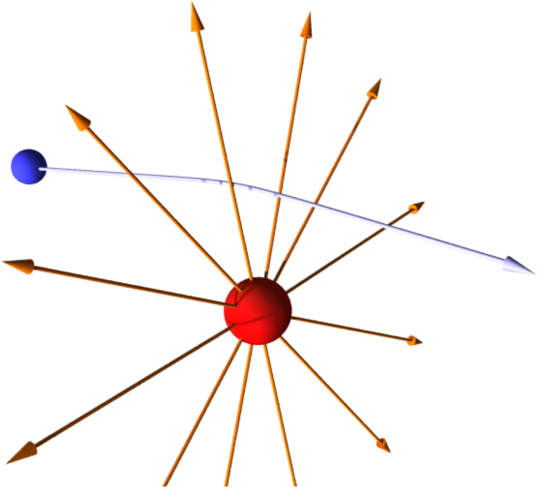

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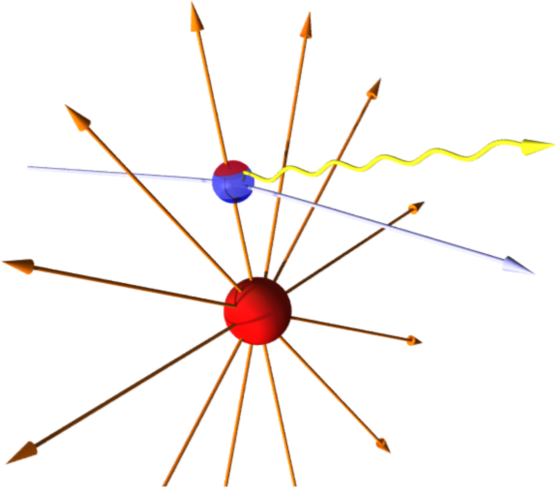

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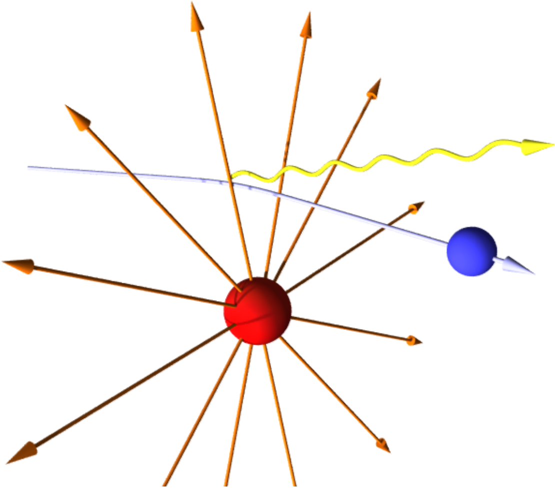
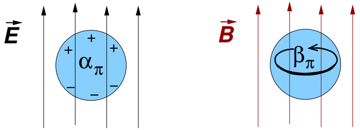


Pion Compton Scattering

$$\underbrace{\pi \quad \gamma}_{\text{Ni} \to \text{Ni}',\ q^2 \approx 0} \quad \to \quad \pi \quad \gamma$$



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

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$z_\pm = 1 \pm \cos\theta_{cm}$ $\qquad \alpha = 1/137$ fine structure constant (!)

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

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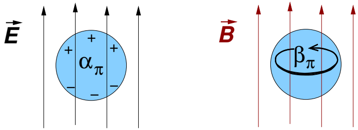

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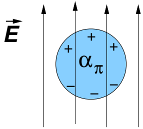

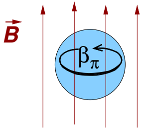

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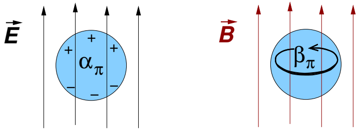

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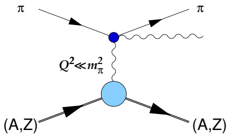
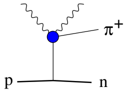
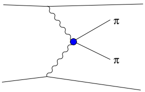
Pion polarisability: world data before COMPASS



Primakoff process



Radiative pion photoproduction



Photon-Photon fusion

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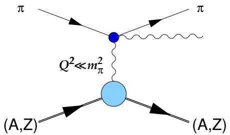

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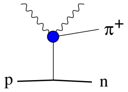

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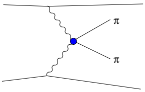

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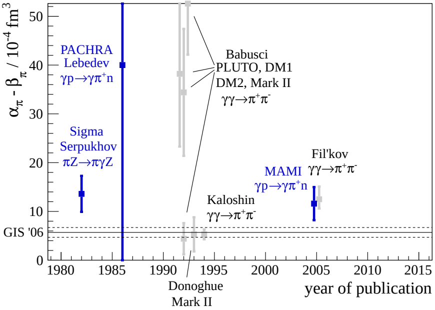

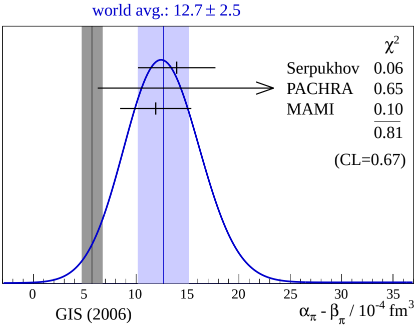

GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)

plots from Thiemo Nagel, PhD thesis, TUM 2012

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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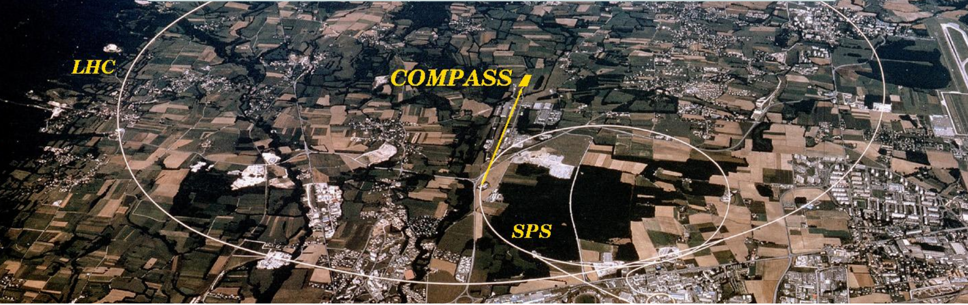
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$ / 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



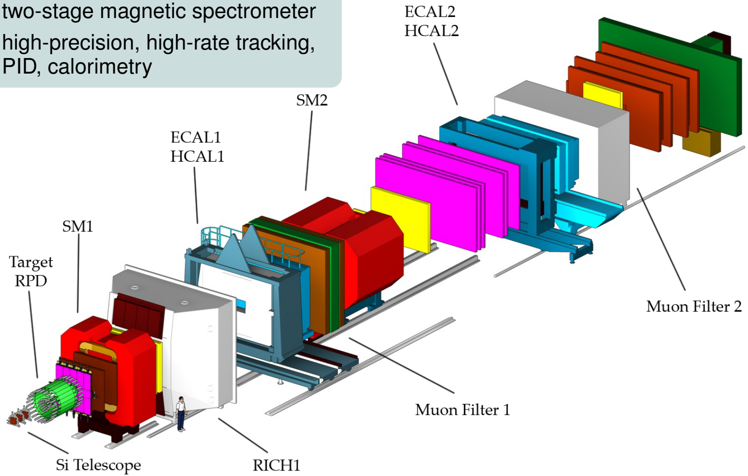
COMPASS

Technische Universität München

Experimental Setup

Fixed-target experiment

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



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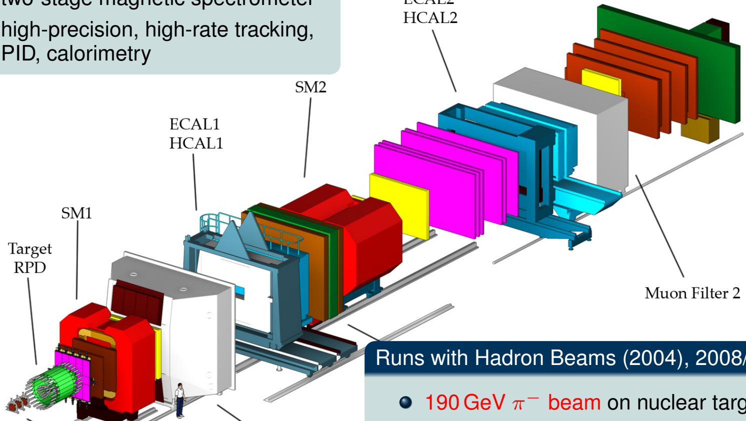

Runs with Hadron Beams (2004), 2008/09, 2012

- 190 GeV π^- beam on nuclear targets (Ni, W)
- Silicon microstrip detectors for “vertexing”
- (digital) ECAL trigger

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 ($\sim Z^2$)

$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma & \Longleftarrow \\ \pi^- + \pi^0 \,/\, \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$

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

Principle of the polarisability measurement

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- Identify exclusive reactions

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

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

- 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

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

and

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

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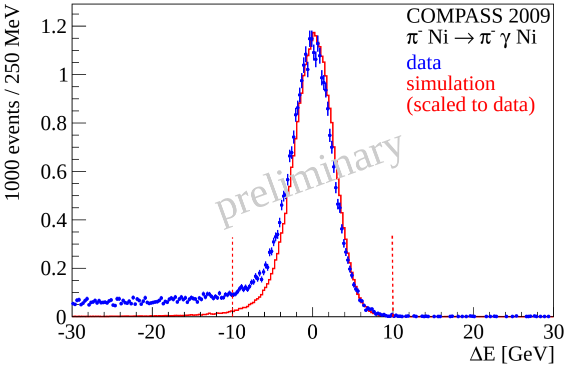
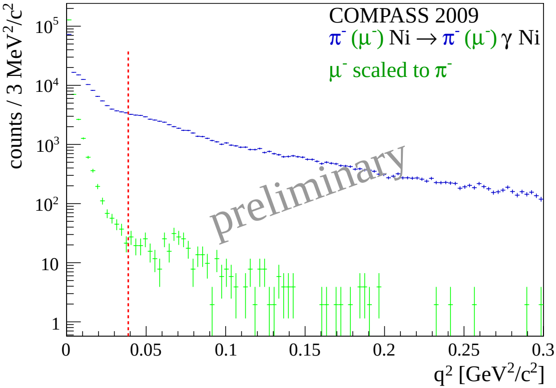
Identifying the $\pi\gamma \to \pi\gamma$ reaction



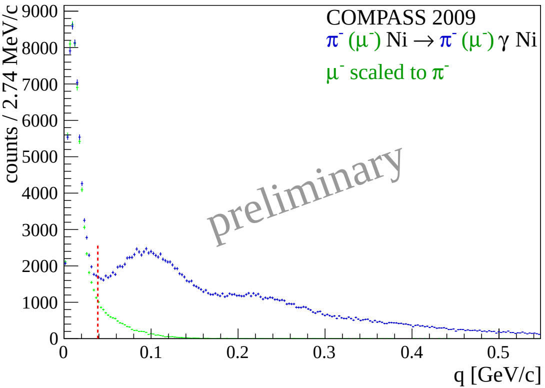
- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Primakoff peak



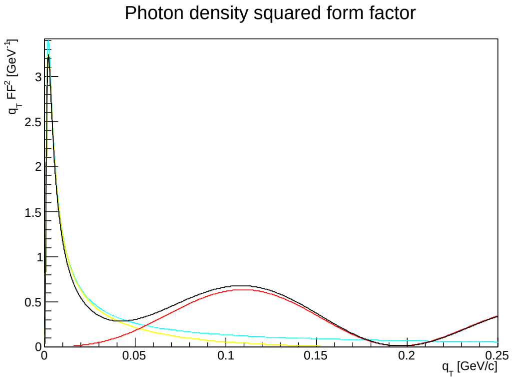
- Q^2-spectrum: photon-exchange peak in first bin
- muon control measurement:
  pure electromagnetic interaction, no polarisability effect

Primakoff peak



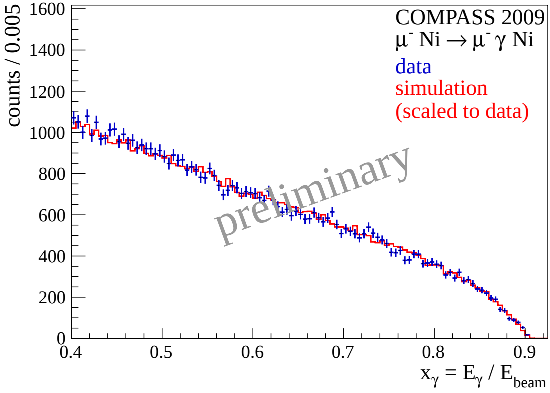
- $\Delta Q_T \approx$ 12 MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$

Coulomb-nuclear interference

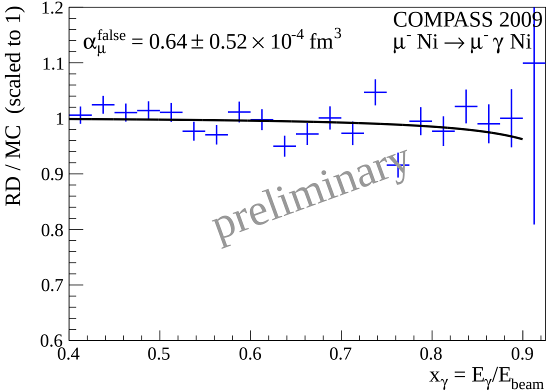


- Calculation following a 2009 paper of Göran Fäldt (Uppsala)
- Eikonal approximation: pions cross Coulomb and strong-interaction potentials

On the way to polarisability: Photon energy spectrum



Photon energy spectrum for the muon case: RD/MC ratio



- muon data well compatible with expectation from simulation
- systematic uncertainty from sources common to pions and muons $\approx 0.6 \times 10^{-4}\,\text{fm}^3$

Photon energy spectrum for pions

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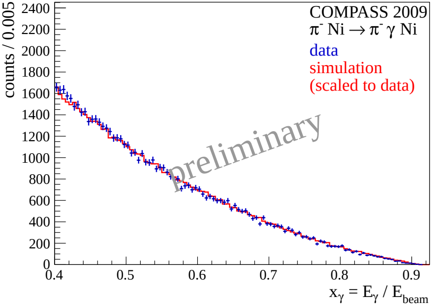
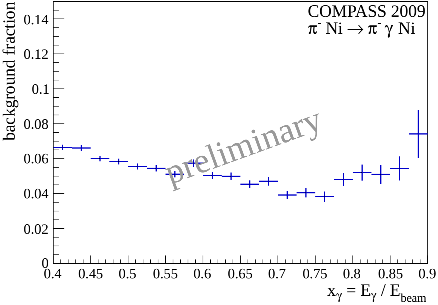
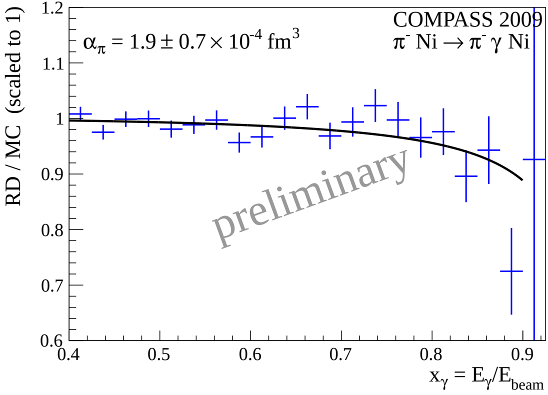


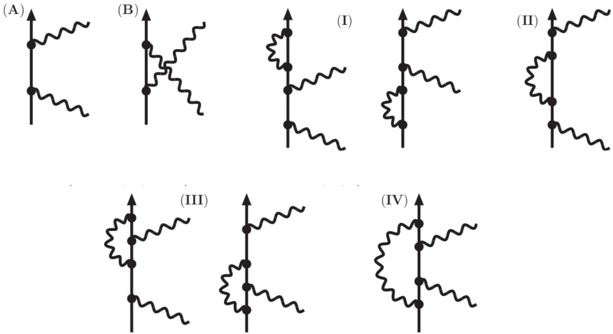


Pion polarisability – preliminary COMPASS result

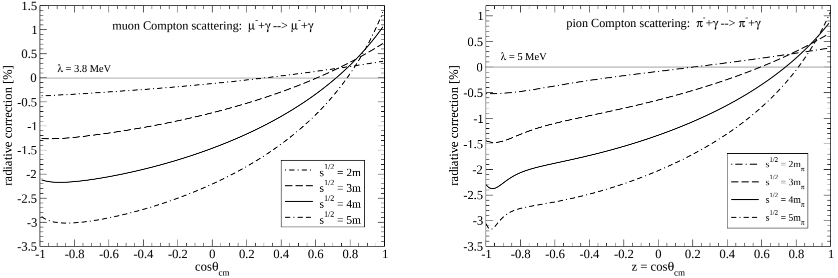


Radiative corrections

- Vacuum polarization correction
- electron screening & nucleus form factor correction
- Coulomb (multi-photon exchange) correction
- Compton corrections, Feynman diagrams for the muon case:



Radiative corrections



muon case (review): Norbert Kaiser (TUM) *Radiative corrections to real and virtual muon Compton scattering revisited, Nucl.Phys. A837 (2010) 87*

pion case: Norbert Kaiser, J.M.F. (TUM) *Radiative corrections to pion Compton scattering, Nucl.Phys. A812(2008)186, Radiative corrections to pion-nucleus bremsstrahlung, Eur.Phys.J. A39(2009)71*

source of systematic uncertainty	estimated magnitude CL $= 68\,\%$ $[10^{-4}\,\mathrm{fm}^3]$
tracking	0.6
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.8

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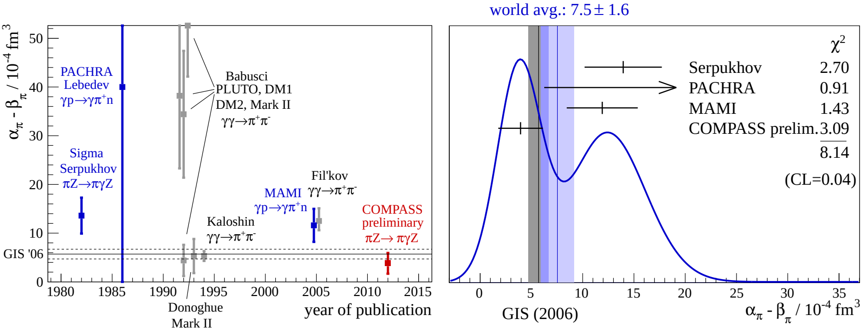
COMPASS preliminary:

$$\alpha_\pi = \mathbf{1.9} \pm \mathbf{0.7}_{\text{stat}} \pm \mathbf{0.8}_{\text{syst}} \times \mathbf{10}^{-4}\,\text{fm}^3$$

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 the uncertainties

Pion polarisability measurements at COMPASS

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Nov. 2004

- recorded statistics (eff. 3 days) competitive to the Serpukhov measurement
- problems with the calorimeter (stability, trigger logic)
  $\rightarrow$ large estimated systematic error

Nov. 2009

- analysis for the determination of the pion polarisability completed
- publication in preparation

2012 *run just completed*

- COMPASS-II proposal for a high-statistics Primakoff run
- increase statistics by a factor > 10, uncertainty on $\alpha_\pi - \beta_\pi$: ± 0.8 (ChPT: 5.7)
- First measurement of polarisability sum $\alpha_\pi + \beta_\pi$
  expected uncertainty ± 0.025 (ChPT: 0.16)

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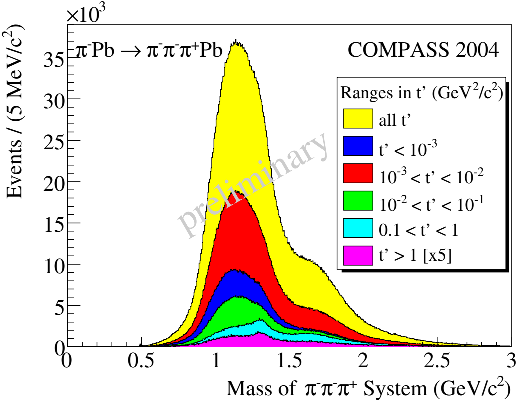
$$\pi^- + \gamma \rightarrow \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \,/\, \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \qquad \Longleftarrow \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$

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

2004 Primakoff results

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



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

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

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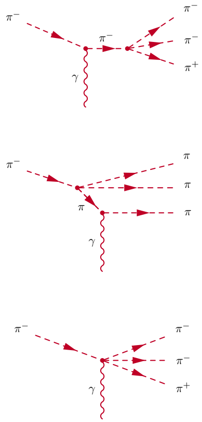
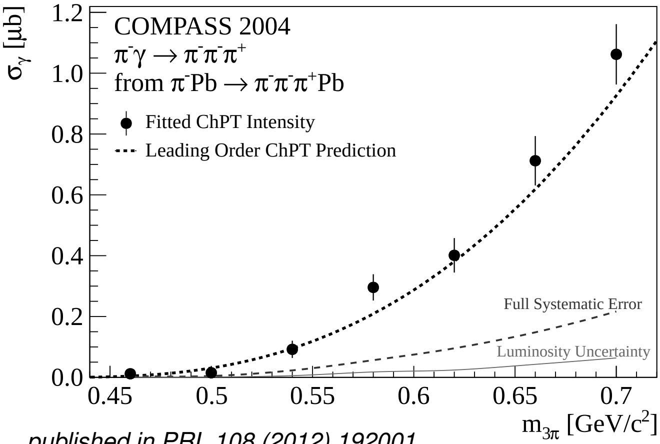
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$





published in PRL 108 (2012) 192001

Higher-order effects

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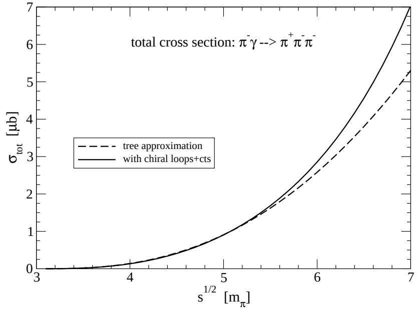
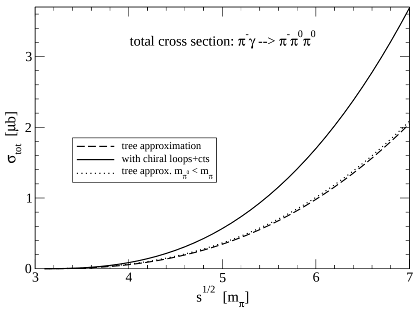
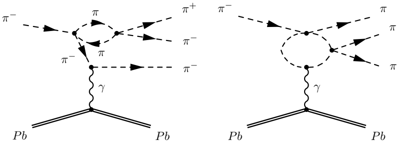


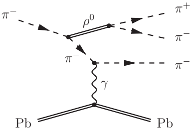


Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)

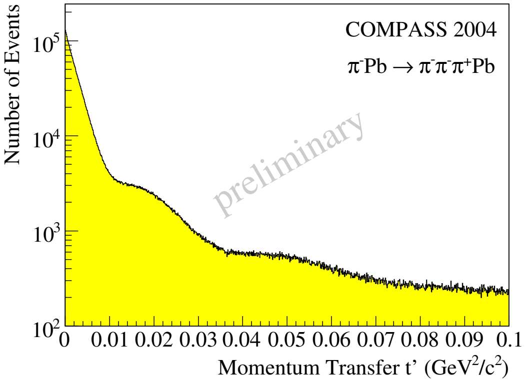


not (yet) included:



2004 Primakoff results

$$\pi^- \text{ Pb} \rightarrow \text{Pb } \pi^- \; \pi^- \; \pi^+$$



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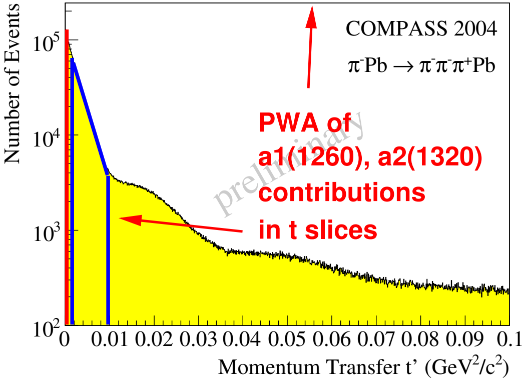

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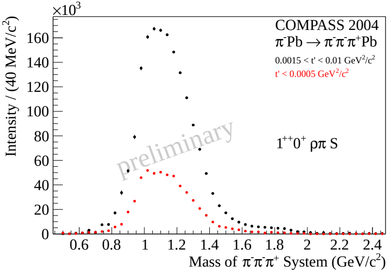
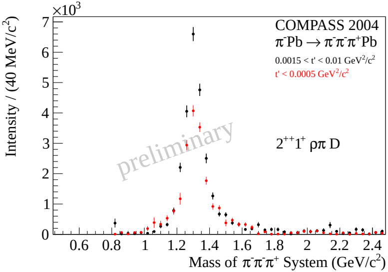
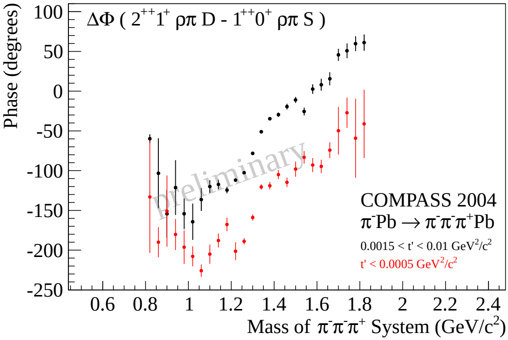
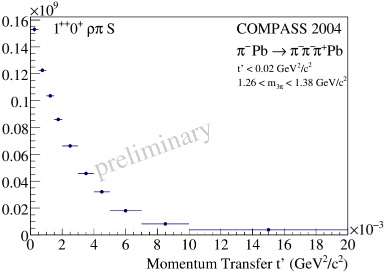
PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

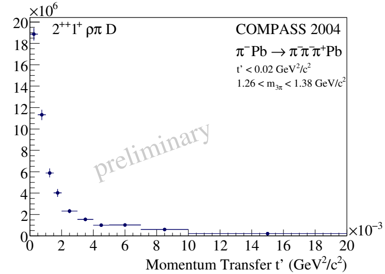


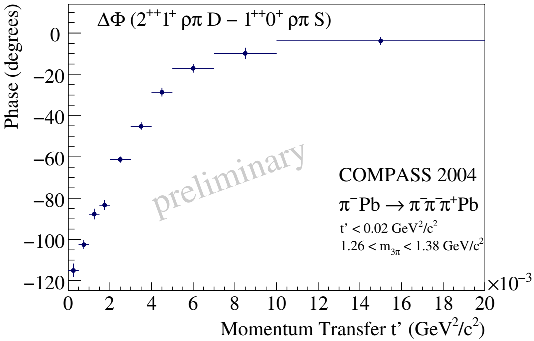




Phase $a_2 - a_1$ in detail: t' dependence







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

Primakoff production of a1(1260) vs. E272 result

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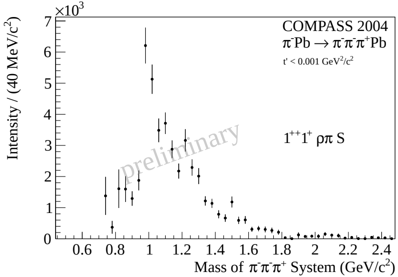
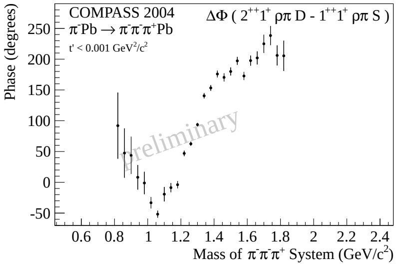
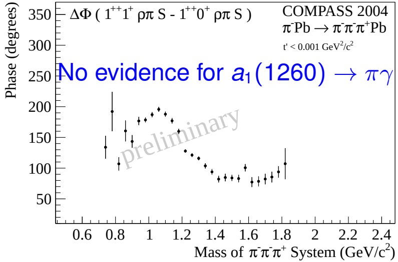
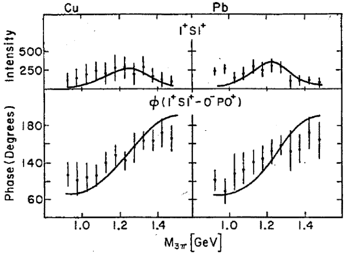






No evidence for $a_1(1260) \to \pi\gamma$



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

Summary and Outlook

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

$$\boxed{\alpha_\pi = 1.9 \pm 0.7_{\text{stat}} \pm 0.8_{\text{syst}} \times 10^{-4}\,\text{fm}^3} \text{ assuming } \alpha_\pi + \beta_\pi = 0$$

  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
- Chiral dynamics in $\pi\gamma \to \pi\pi\pi$ reactions
  - Charged-channel $\pi\gamma \to \pi^-\pi^-\pi^+$ tree-level ChPT prediction confirmed,
  - Neutral-channel $\pi\gamma \to \pi^-\pi^0\pi^0$ 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