Tests of ChPT with COMPASS

Jan M. Friedrich

CERN

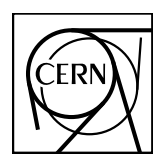
on leave of absence from Physik-Department, TU München

for the COMPASS collaboration

13th International Conference on Meson-Nucleon Physics
and the Structure of the Nucleon

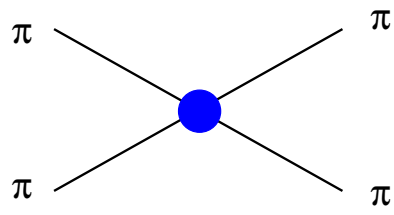
MeNu2013

Rome 30.9.-4.10.2013

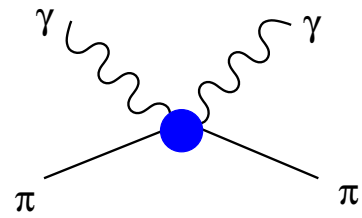


Chiral Perturbation Theory vs. Experiment

- 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]

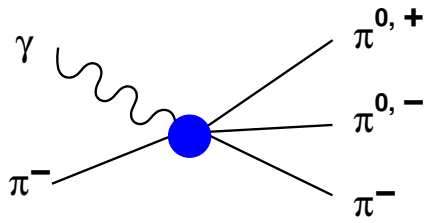


$$\begin{aligned} \alpha_\pi + \beta_\pi &= (0.2 \pm 0.1) \cdot 10^{-4}\text{fm}^3 \\ \alpha_\pi - \beta_\pi &= (5.7 \pm 1.0) \cdot 10^{-4}\text{fm}^3 \\ \alpha_\pi &= (2.9 \pm 0.5) \cdot 10^{-4}\text{fm}^3 \end{aligned}$$

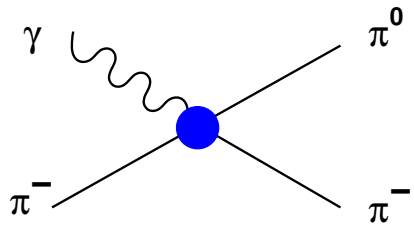
- ChPT prediction contradicting the experimental findings (prior to this analysis)

More pion-photon reactions

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



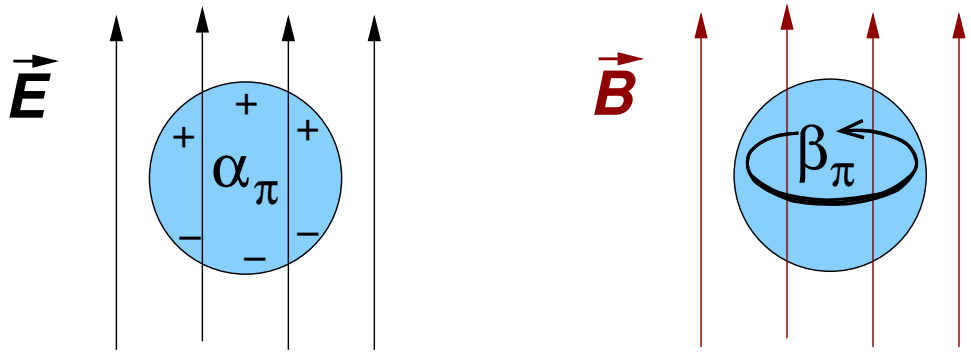
- Chiral anomaly $F_{3\pi}$
  - established on 10% level
  - further development: inclusion of the ρ resonance
    theoretical work by Kubis, Hoferichter, Sakkas
    PRD86(2012)116009



ChPT prediction for the pion polarisability

$$\pi + \gamma \to \pi + \gamma$$

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]

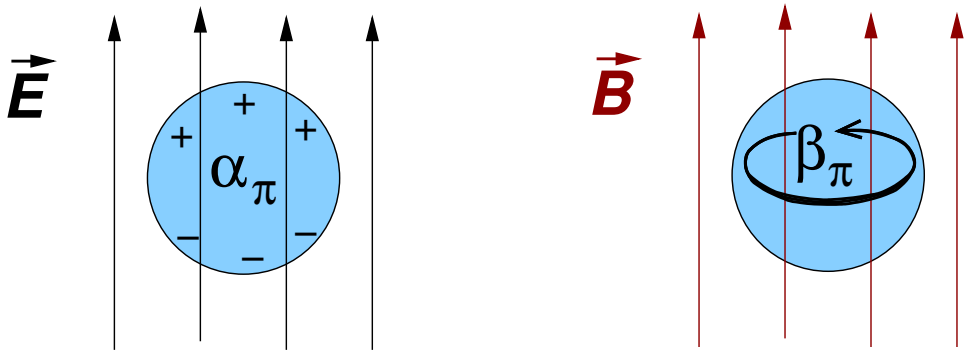
ChPT (2-loop) prediction: $\alpha_\pi - \beta_\pi = 5.7 \pm 1.0$ $\qquad \alpha_\pi + \beta_\pi = 0.16$

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

ChPT prediction for the pion polarisability

$$\pi + \gamma \to \pi + \gamma$$

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]

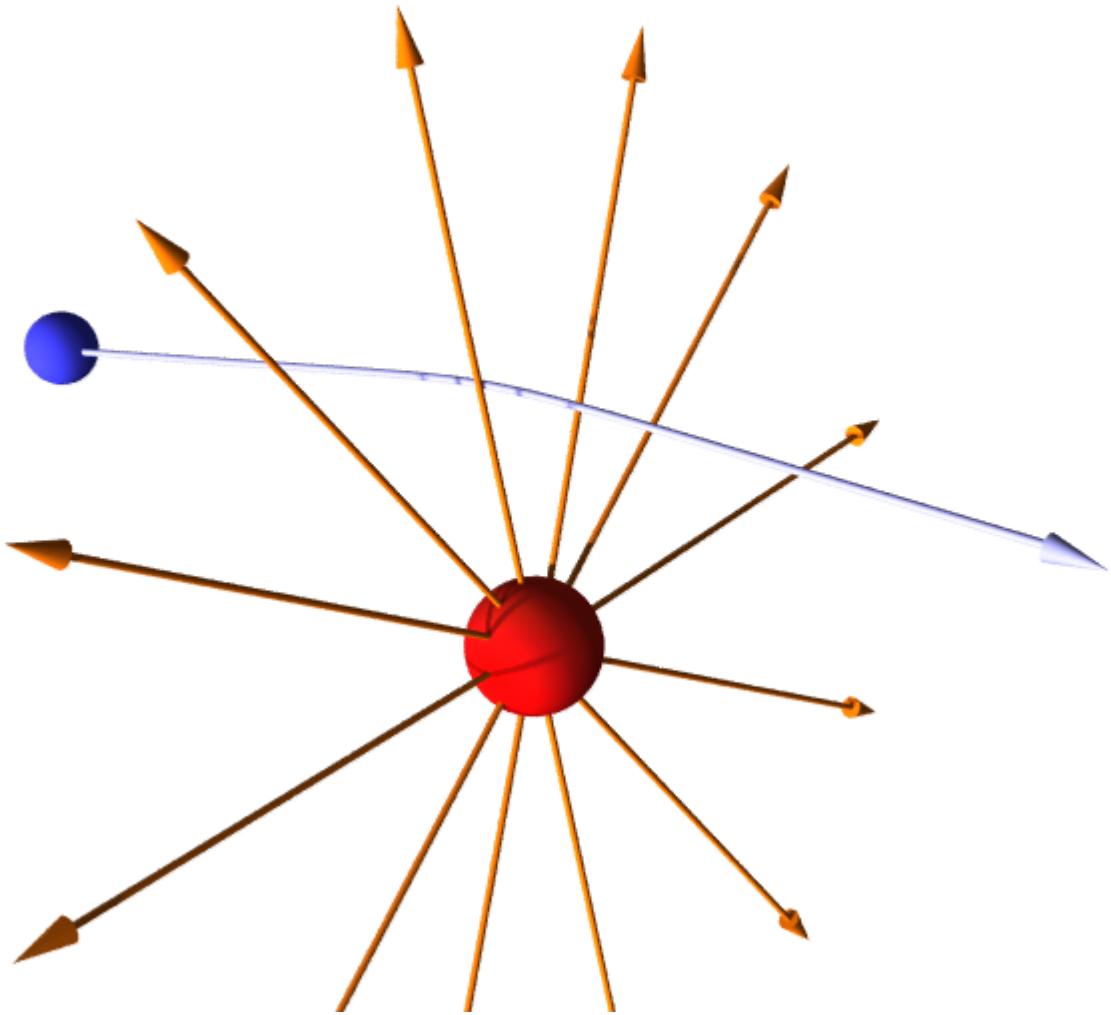
ChPT (2-loop) prediction: $\alpha_\pi = 2.93, \quad \beta_\pi = -2.77$

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

Polarisability effect in Primakoff technique

Primakoff measurement technique

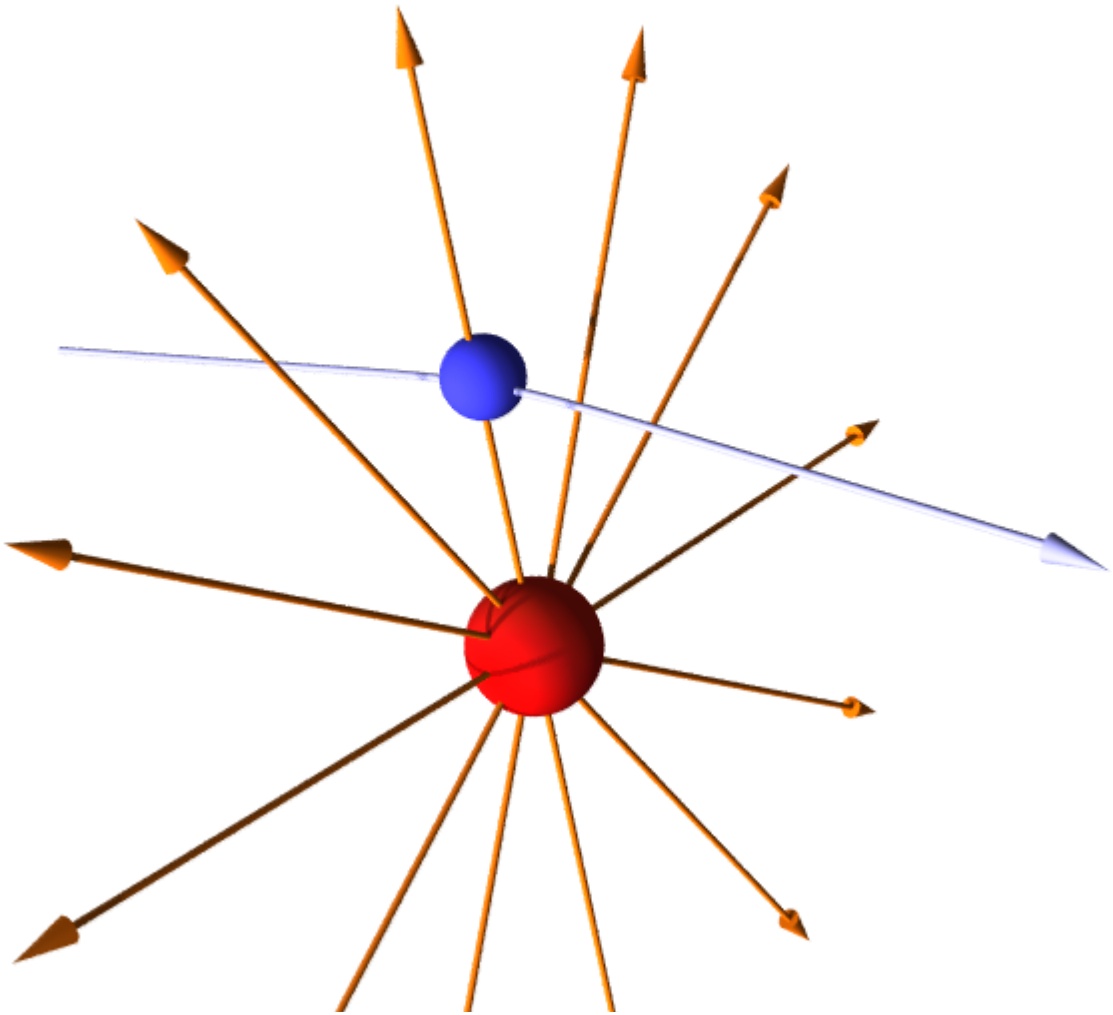
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$



Polarisability effect in Primakoff technique

Primakoff measurement technique

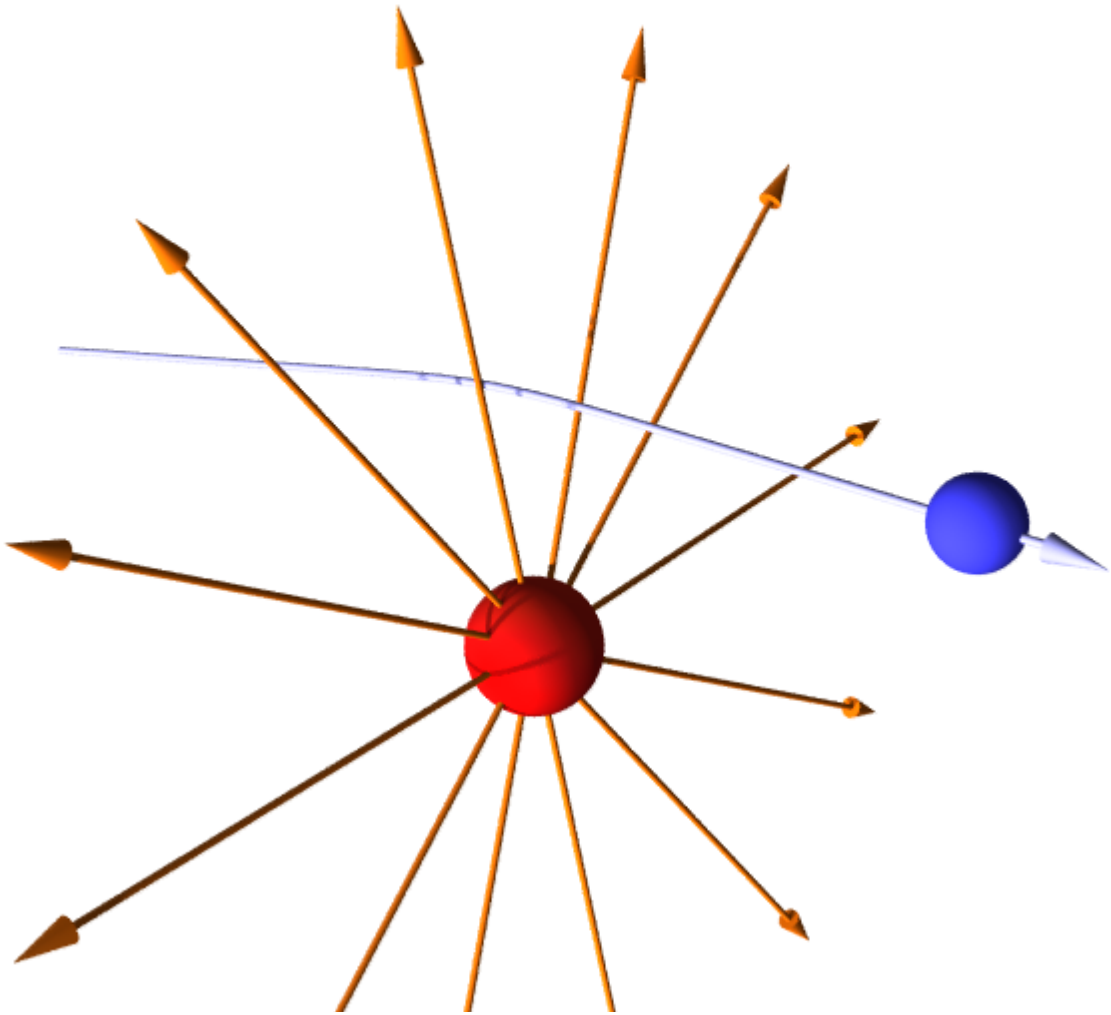
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$



Polarisability effect in Primakoff technique

Primakoff measurement technique

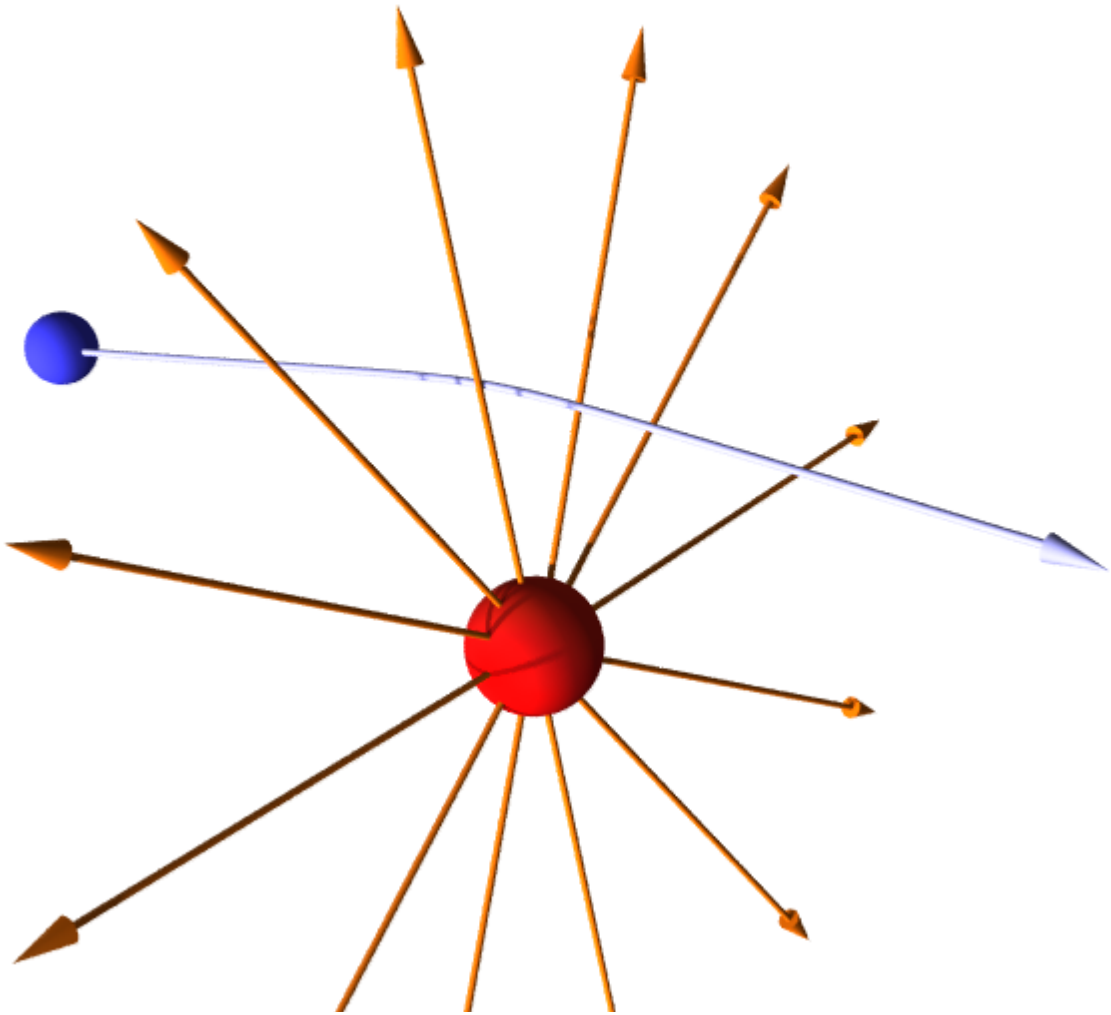
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$



Polarisability effect in Primakoff technique

Primakoff measurement technique

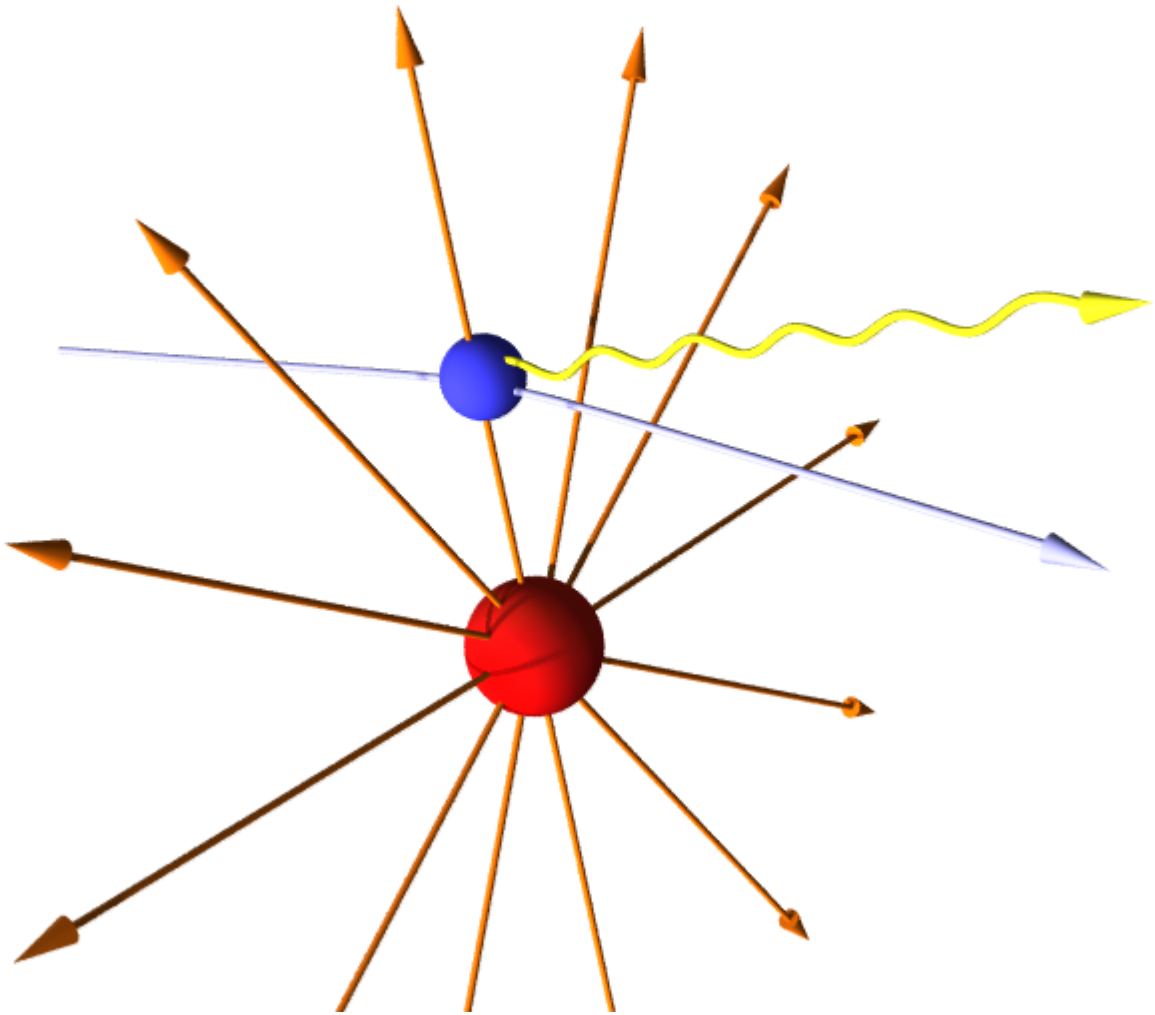
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$
- **Bremsstrahlung emission**
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton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



Polarisability effect in Primakoff technique

Primakoff measurement technique

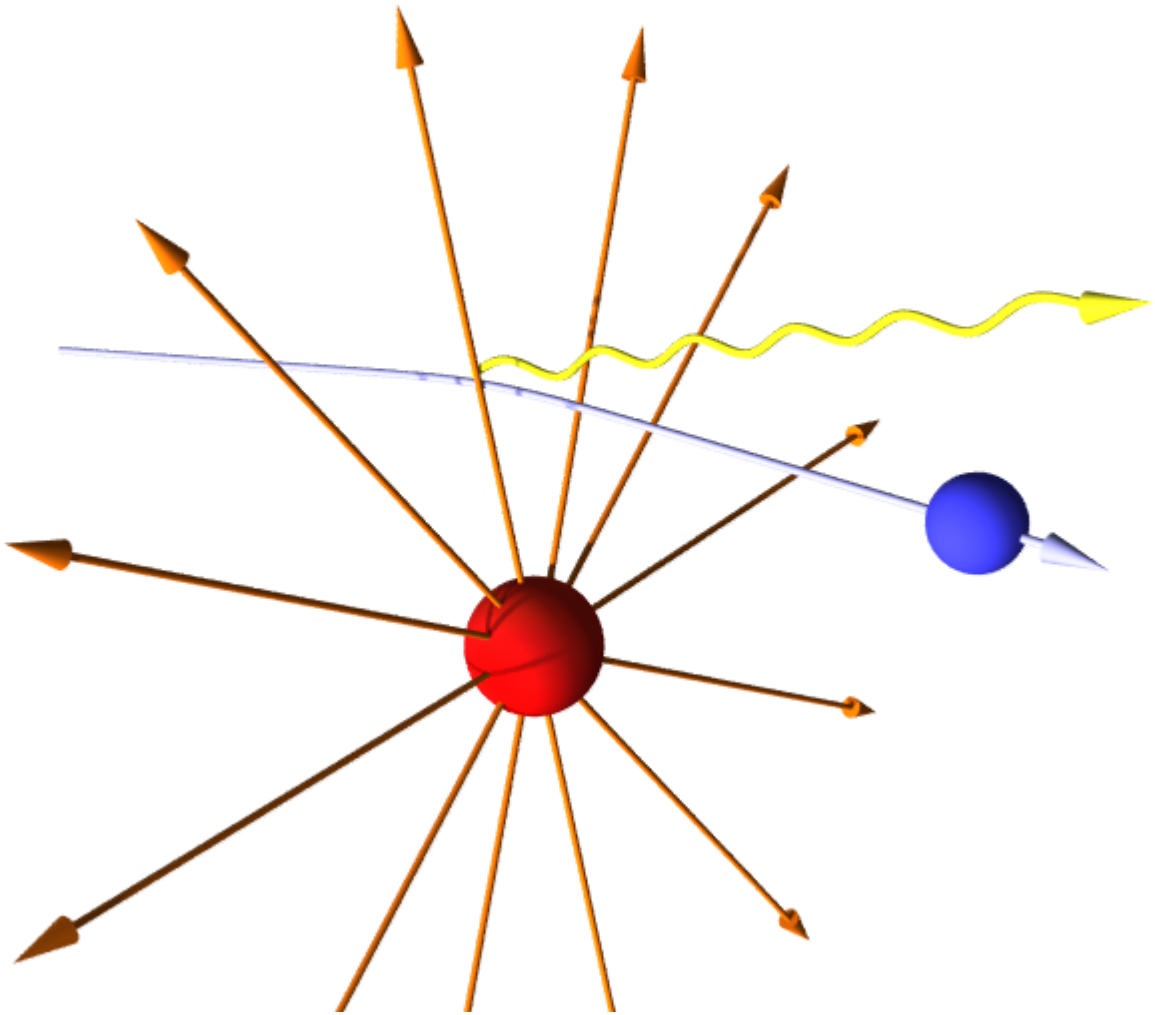
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$
- **Bremsstrahlung emission**
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton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



Polarisability effect in Primakoff technique

Primakoff measurement technique

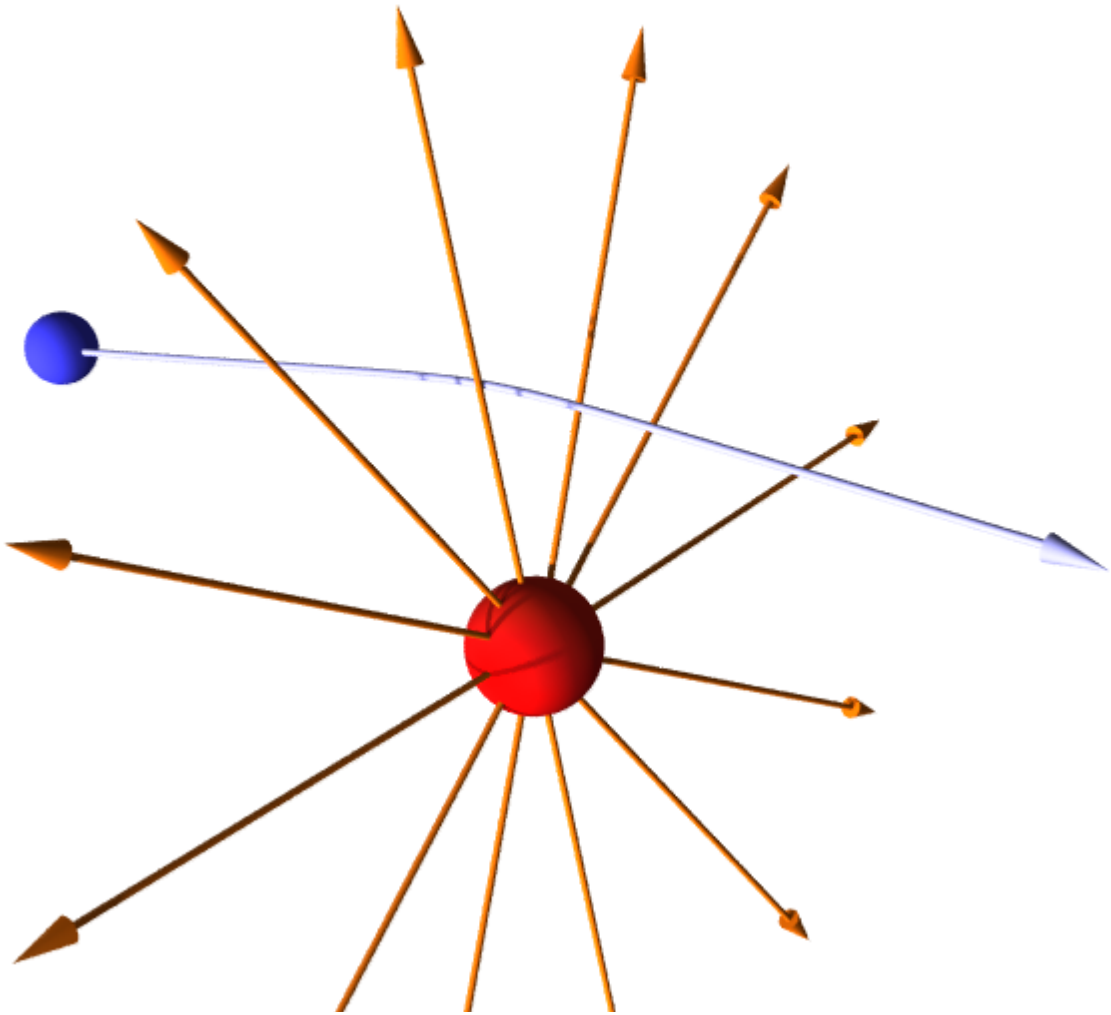
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$
- **Bremsstrahlung emission**
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton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



Polarisability effect in Primakoff technique

Primakoff measurement technique

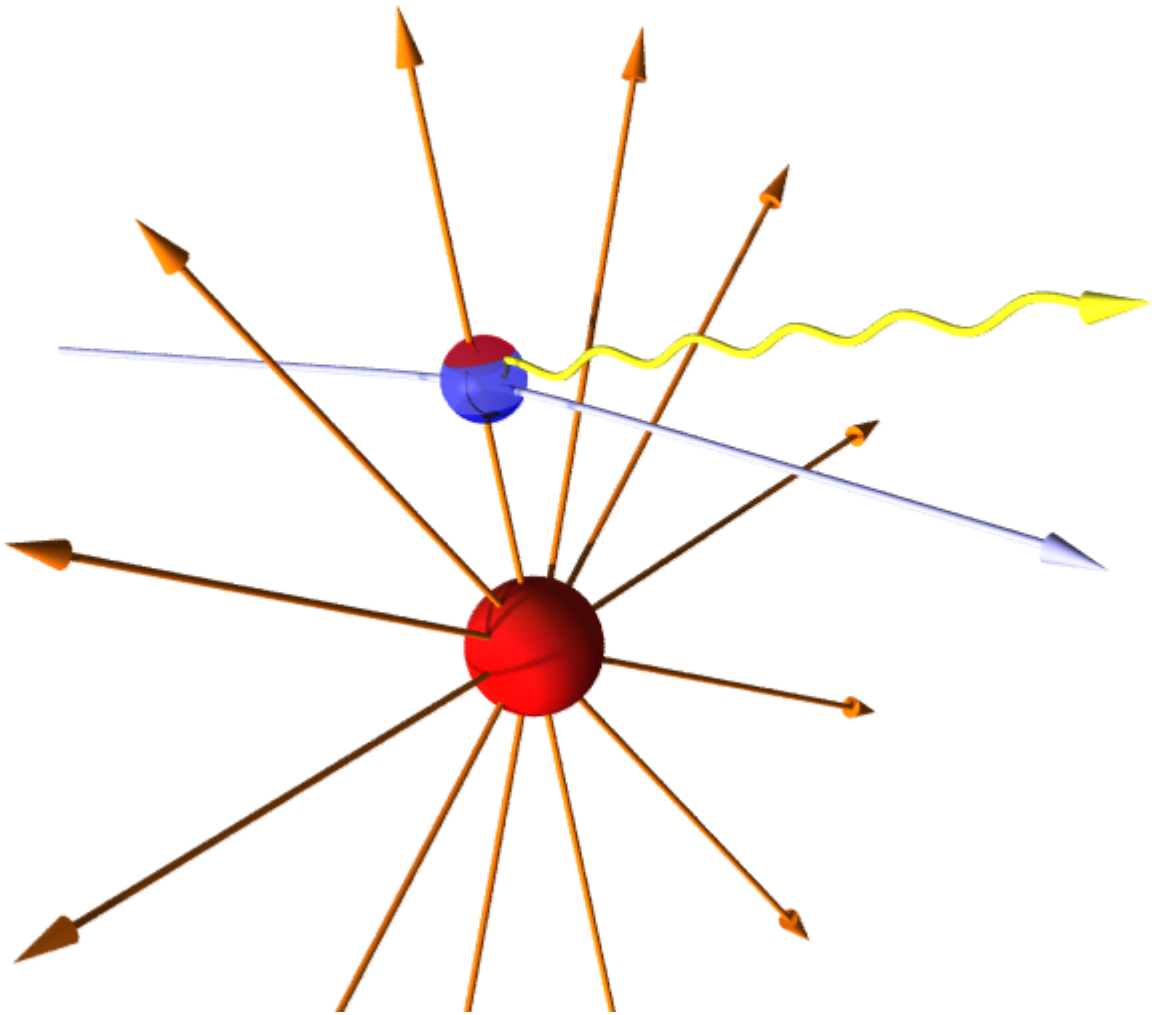
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$
- Bremsstrahlung emission
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton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



Polarisability effect in Primakoff technique

Primakoff measurement technique

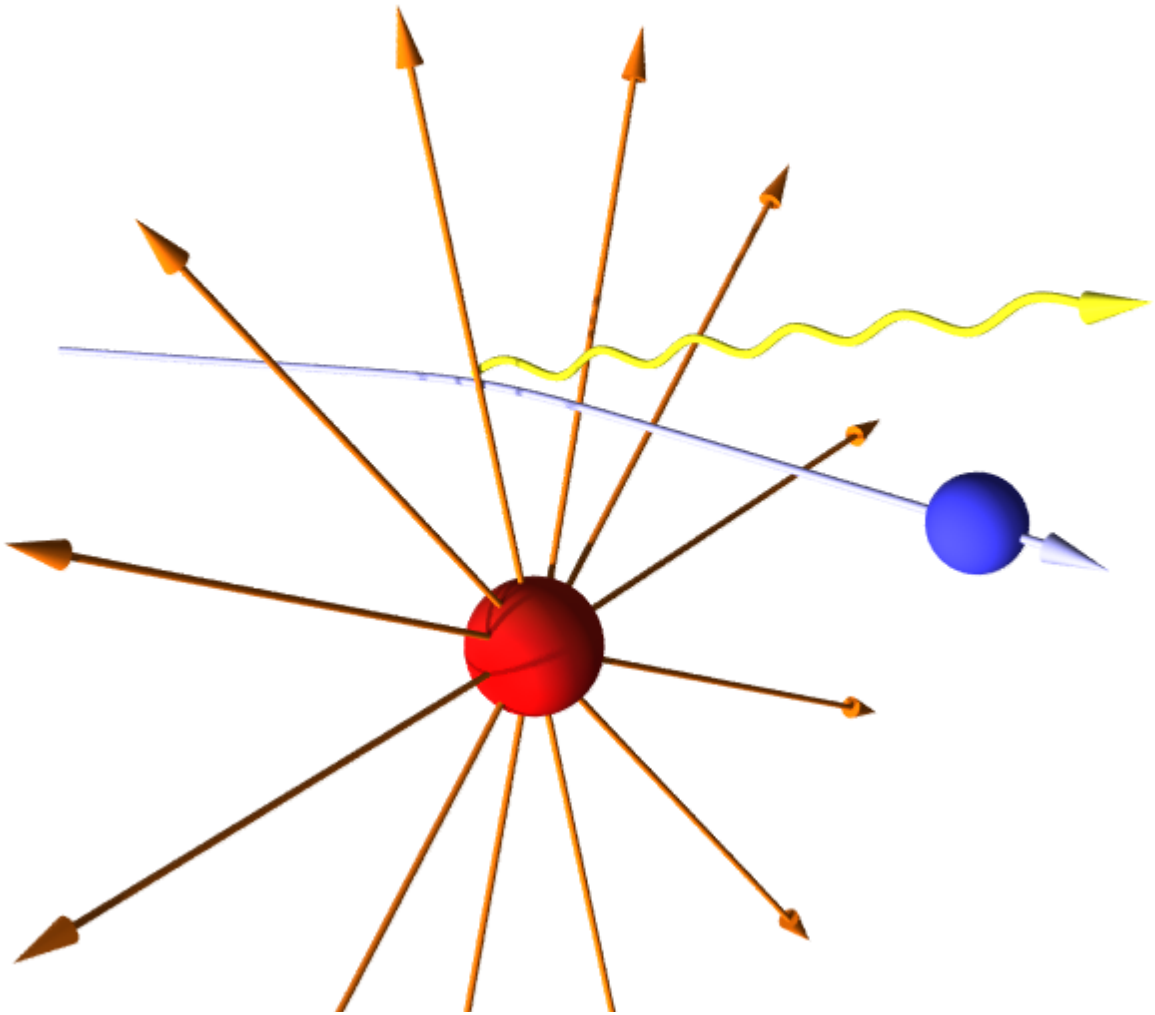
- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300\,\mathrm{kV/fm}$
- **Bremsstrahlung emission**
  - particle scatters off *equivalent photons*
  - tiny momentum transfer $Q^2 \approx 10^{-5}\,\mathrm{GeV}^2/c^2$
  - pion/muon (quasi-)real Compton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



Polarisability effect in Primakoff technique

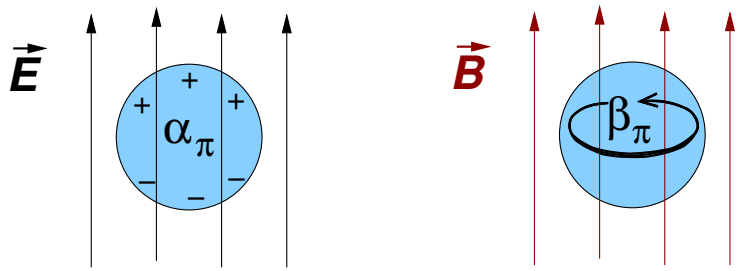
Primakoff measurement technique

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



Pion Compton Scattering

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



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

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

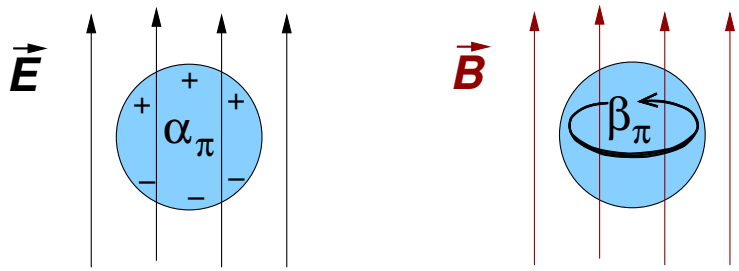
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

- $\sigma_{tot}(s)$ 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

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



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

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

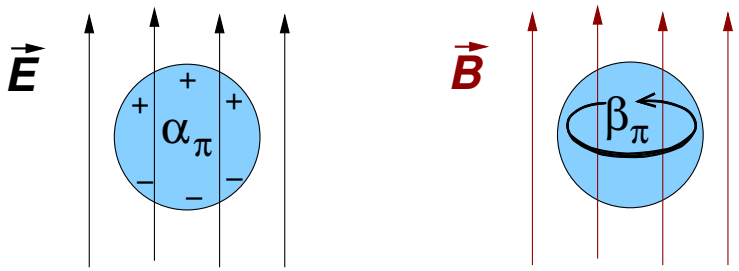
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

- $\sigma_{tot}(s)$ 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

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



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

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

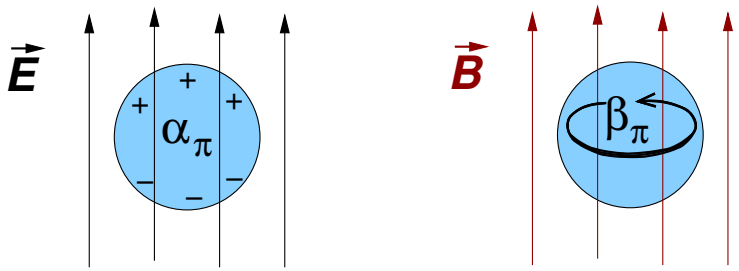
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

- $\sigma_{tot}(s)$ 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

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



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

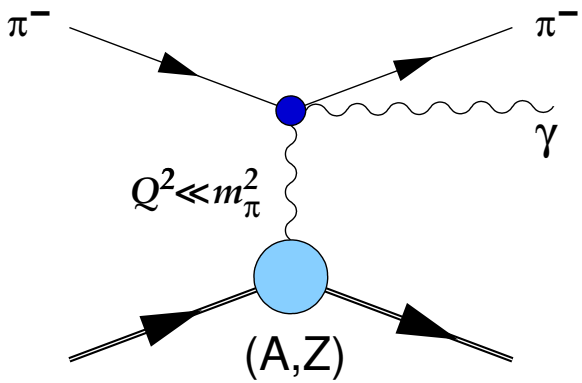
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

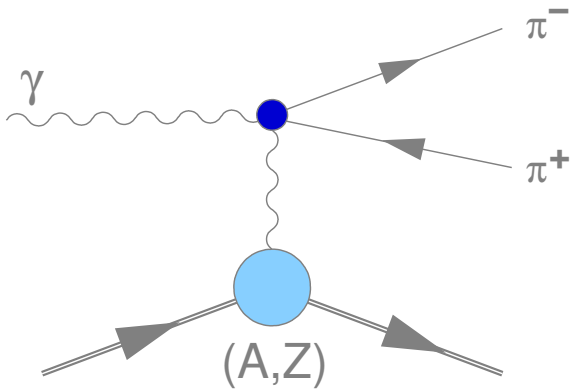
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

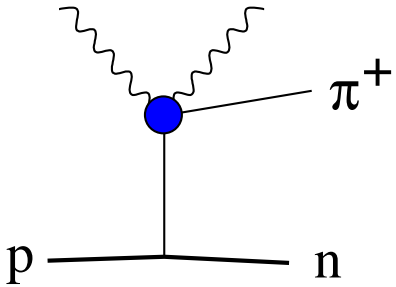
- $\sigma_{tot}(s)$ rather insensitive to pion's low-energy structure
- Up to 20% effect on *backward* angular distributions of $d\sigma/d\Omega_{cm}$

Pion Compton scattering: embedding the process

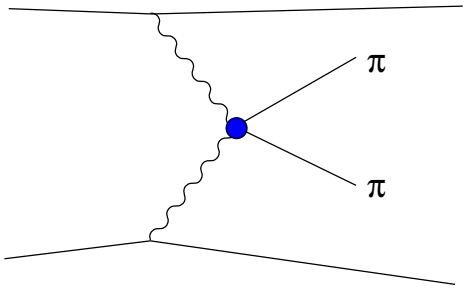




Primakoff processes

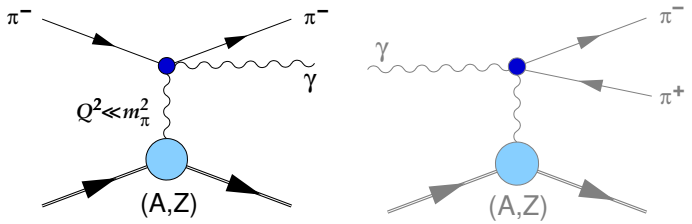


Radiative pion photoproduction

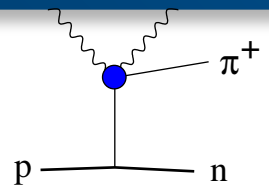


Photon-Photon fusion

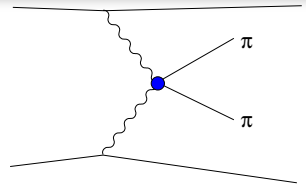
Pion polarisability: world data before COMPASS



Primakoff processes

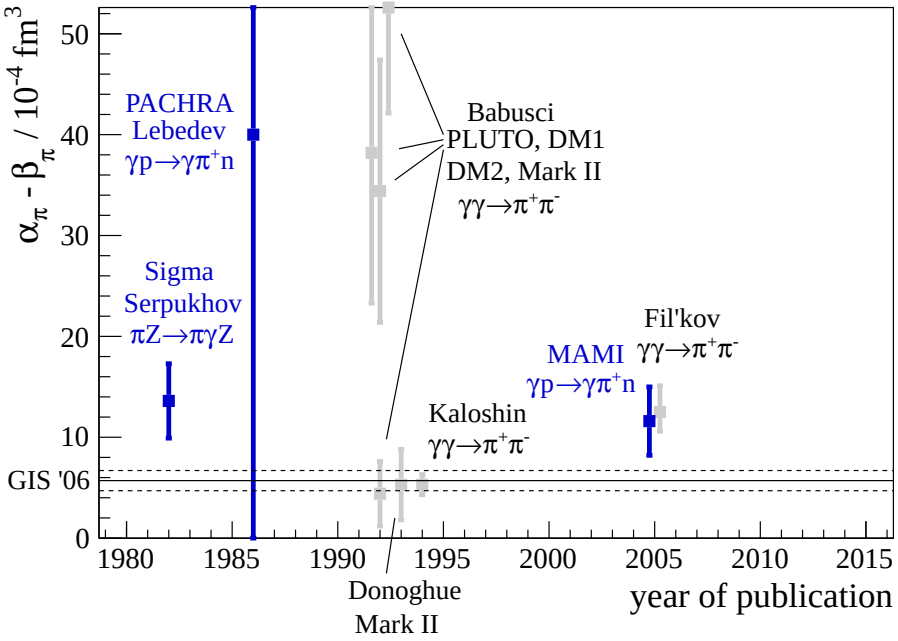


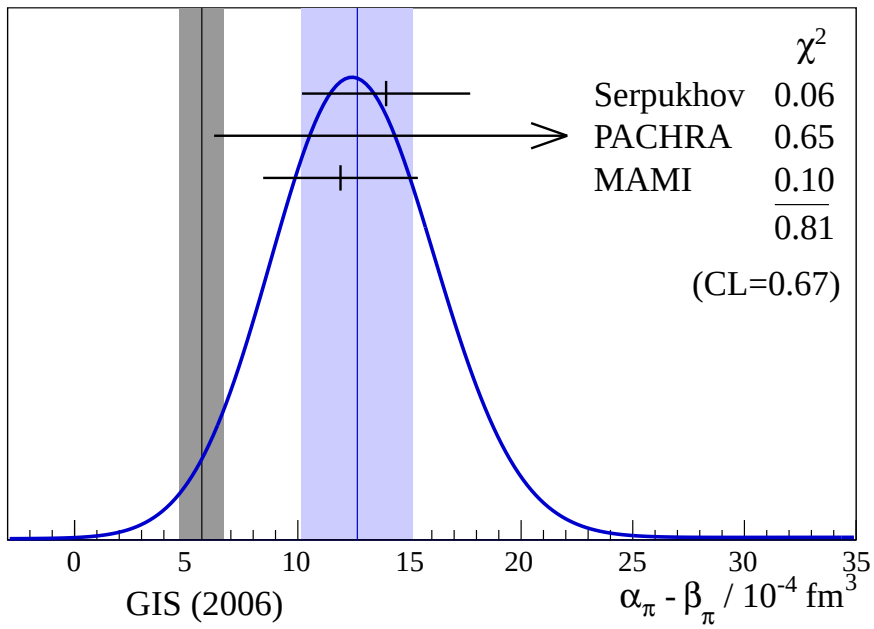
Radiative pion photoproduction



Photon-Photon fusion

world avg.: 12.7 ± 2.5





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

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

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

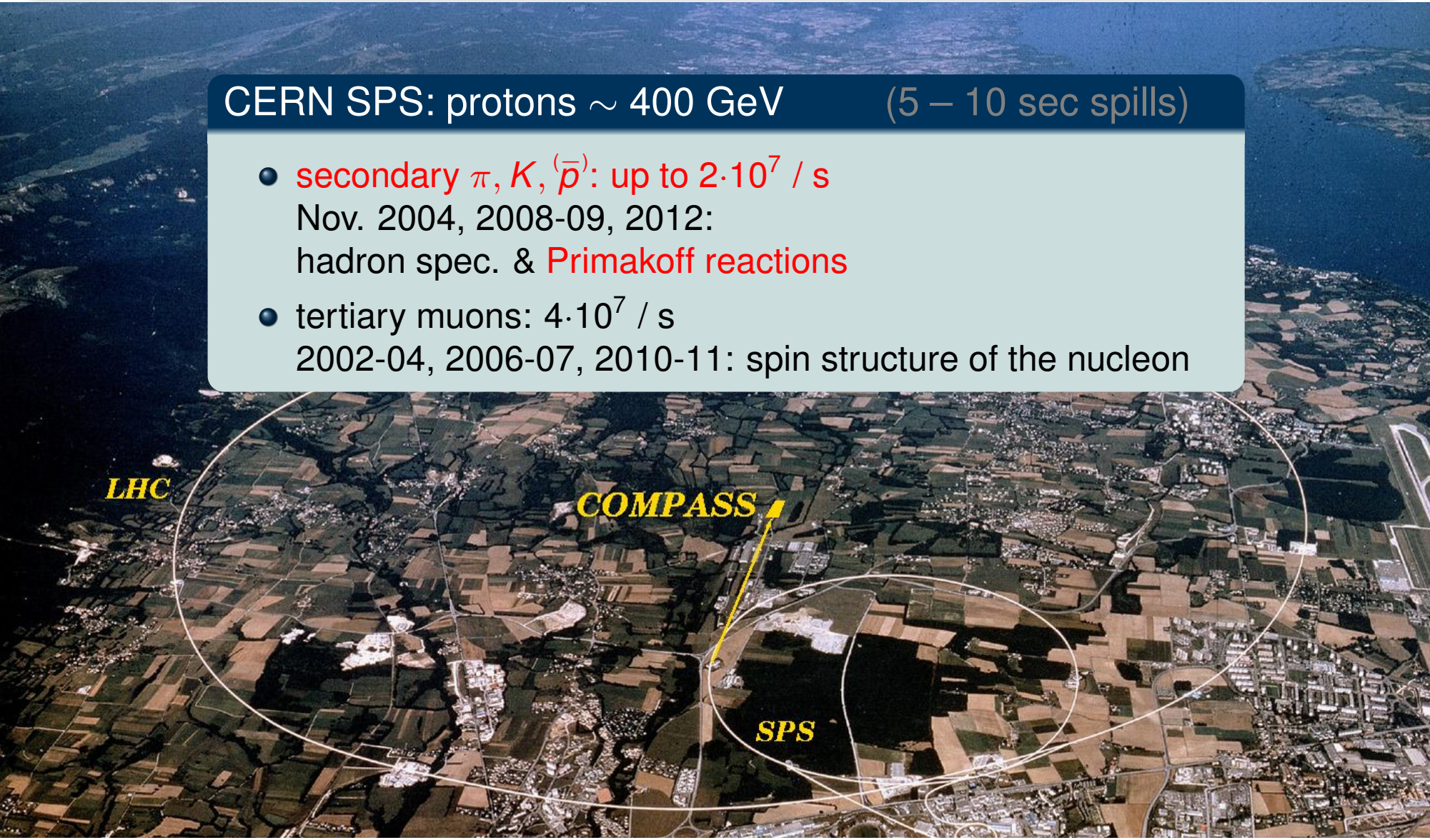
Technische Universität München

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Technische Universität München

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

- secondary $\pi, K, (\bar{p})$: 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

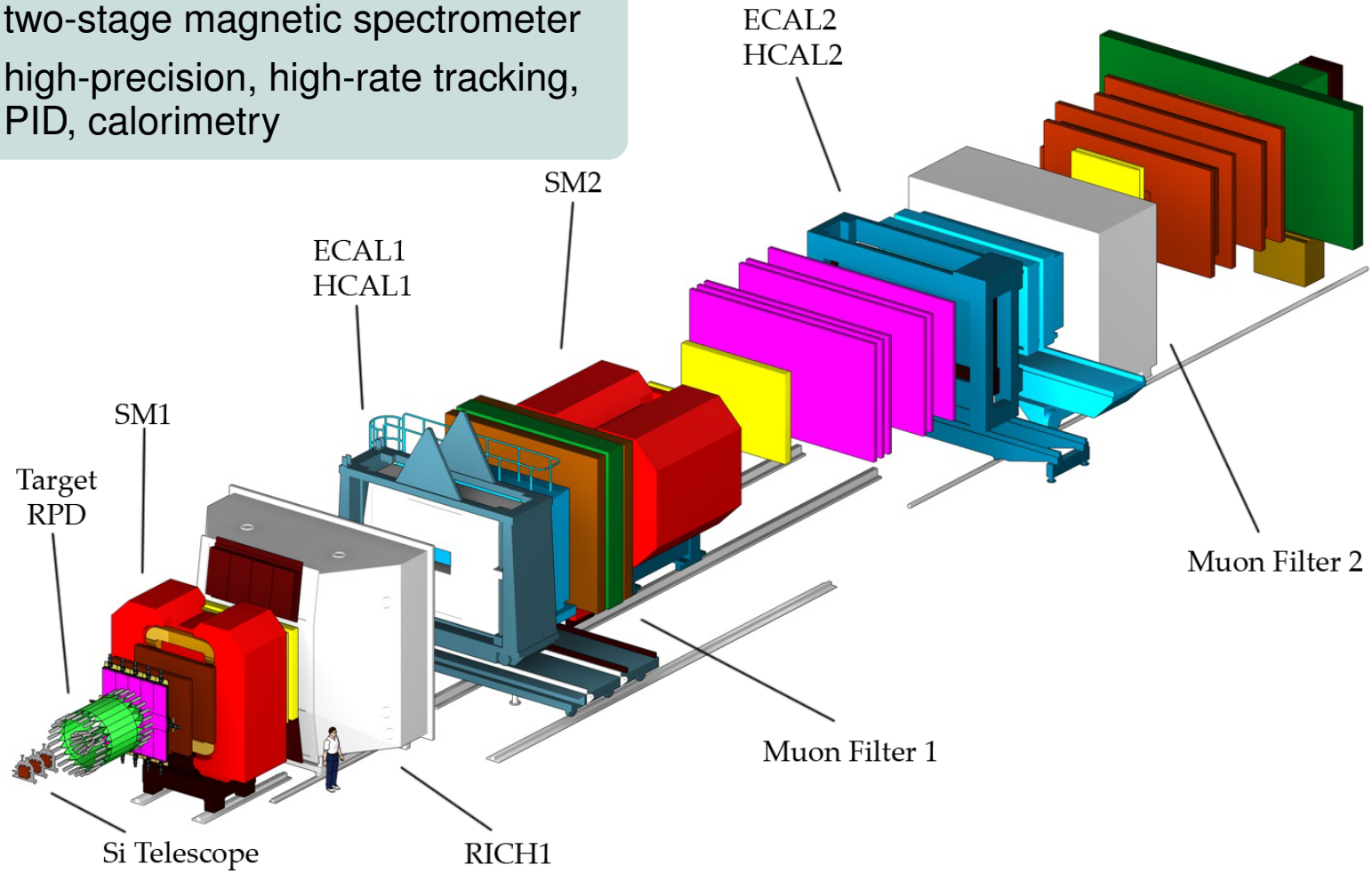


COMPASS

Experimental Setup

Fixed-target experiment

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



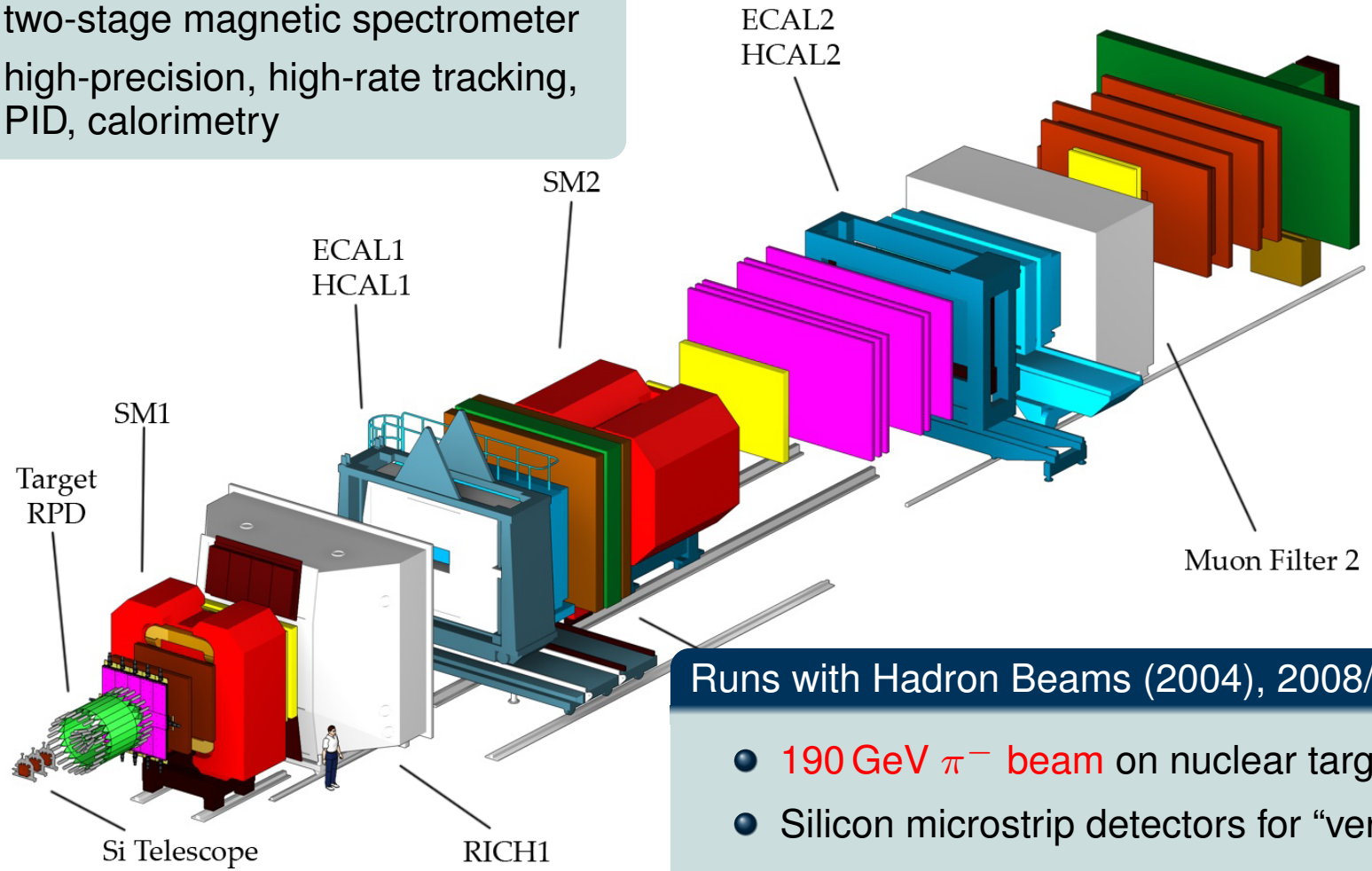
COMPASS

Experimental Setup

Technische Universität München

Fixed-target experiment

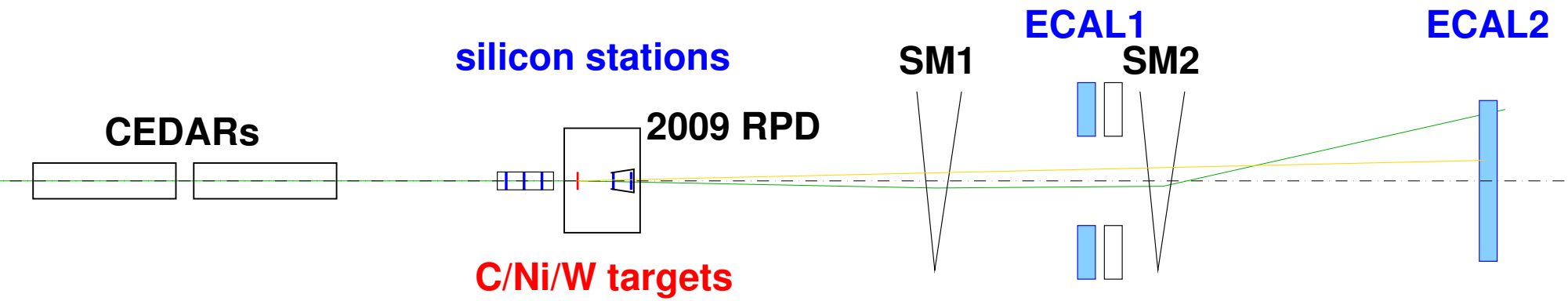
- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



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

Principle of the measurement



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

- 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

- 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

- 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

- 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.

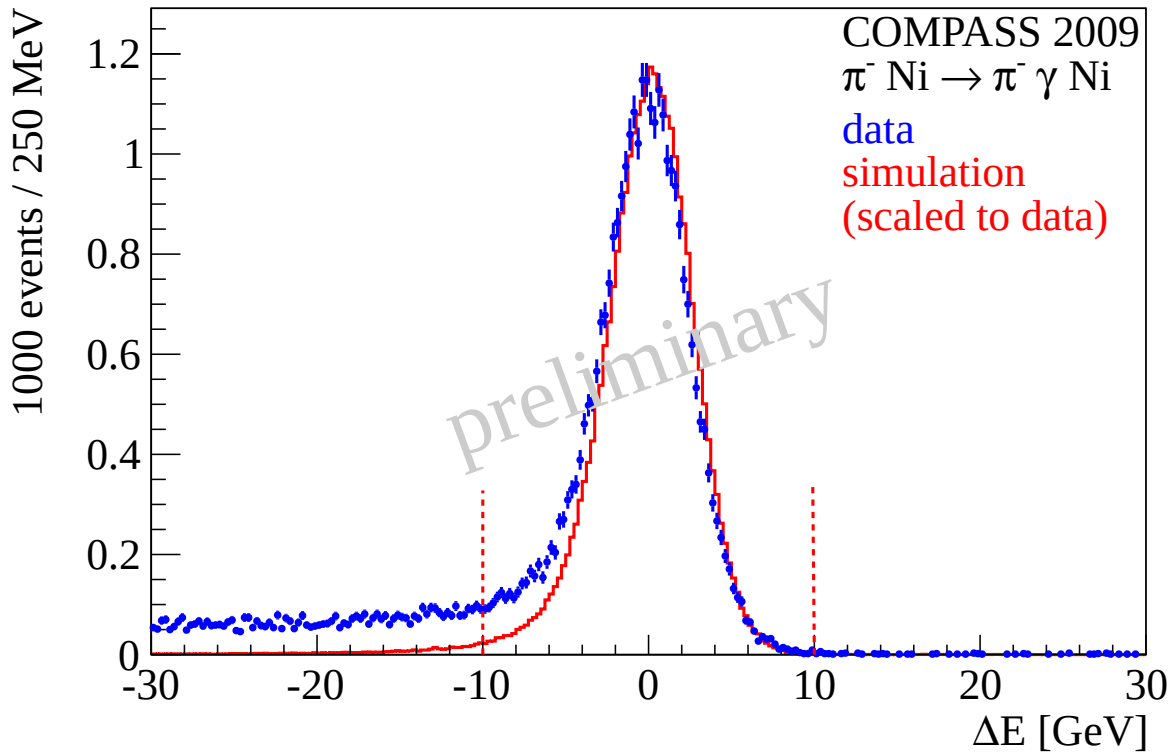
- Control systematics by

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

and

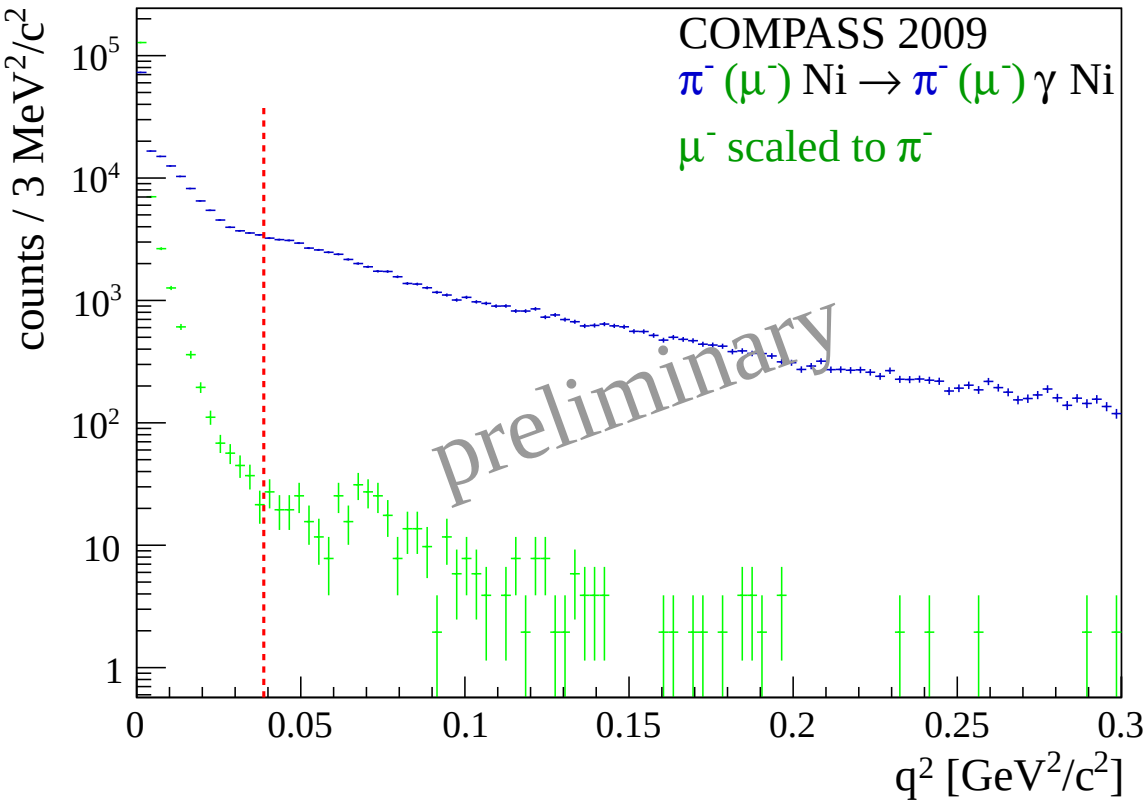
$$K^- \to \pi^-\pi^0 \to \pi\gamma\gamma$$

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



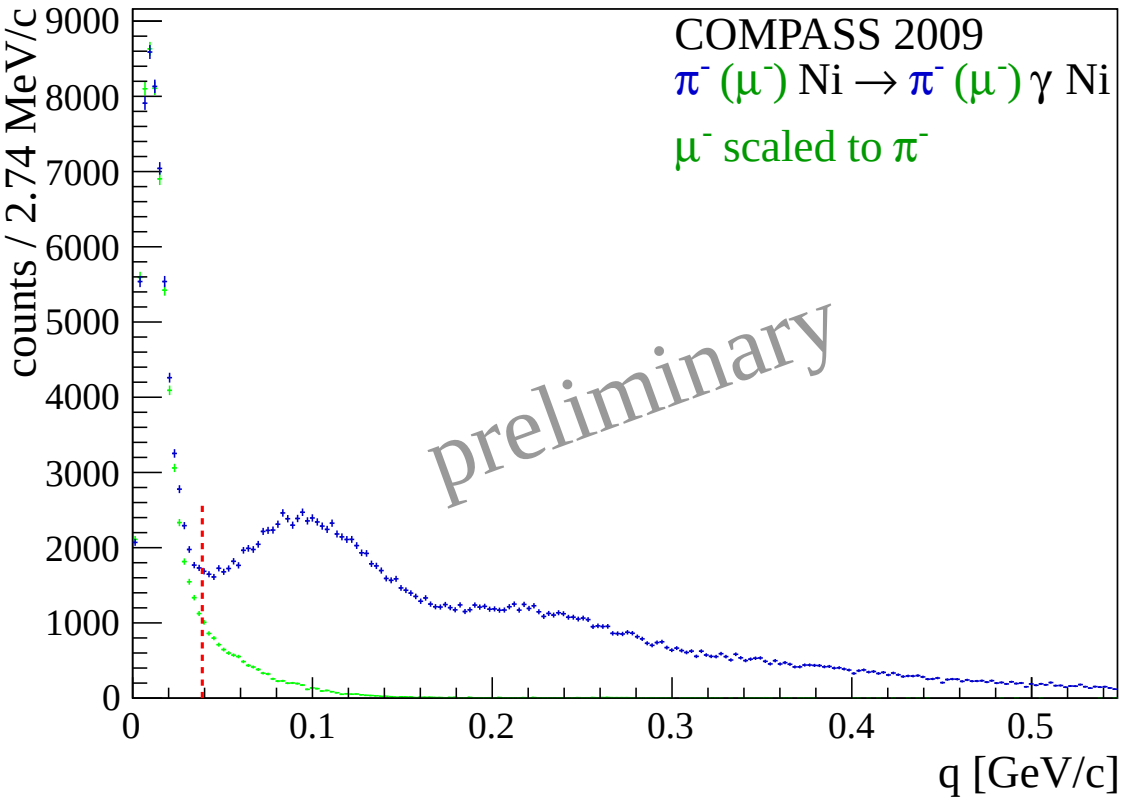
- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Primakoff peak



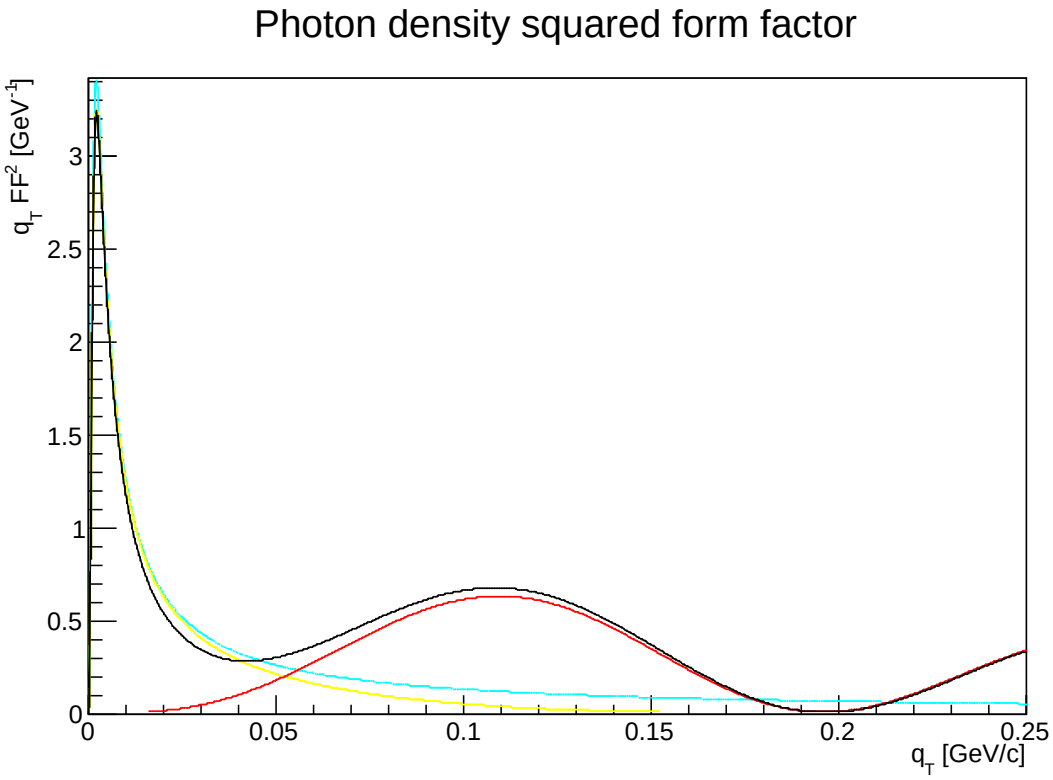
- Q^2-spectrum: photon-exchange peak in first bin
- muon control measurement:
  pure electromagnetic interaction, no polarisability effect

Primakoff peak



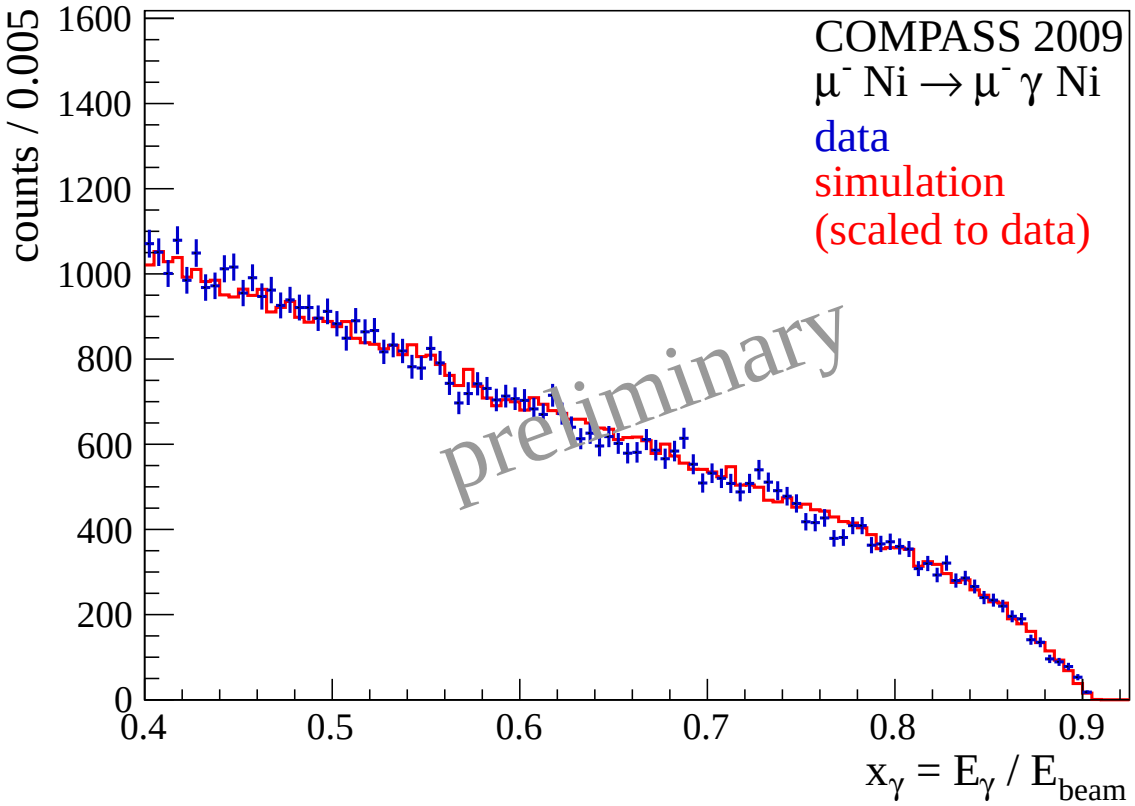
- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$

Coulomb-nuclear interference

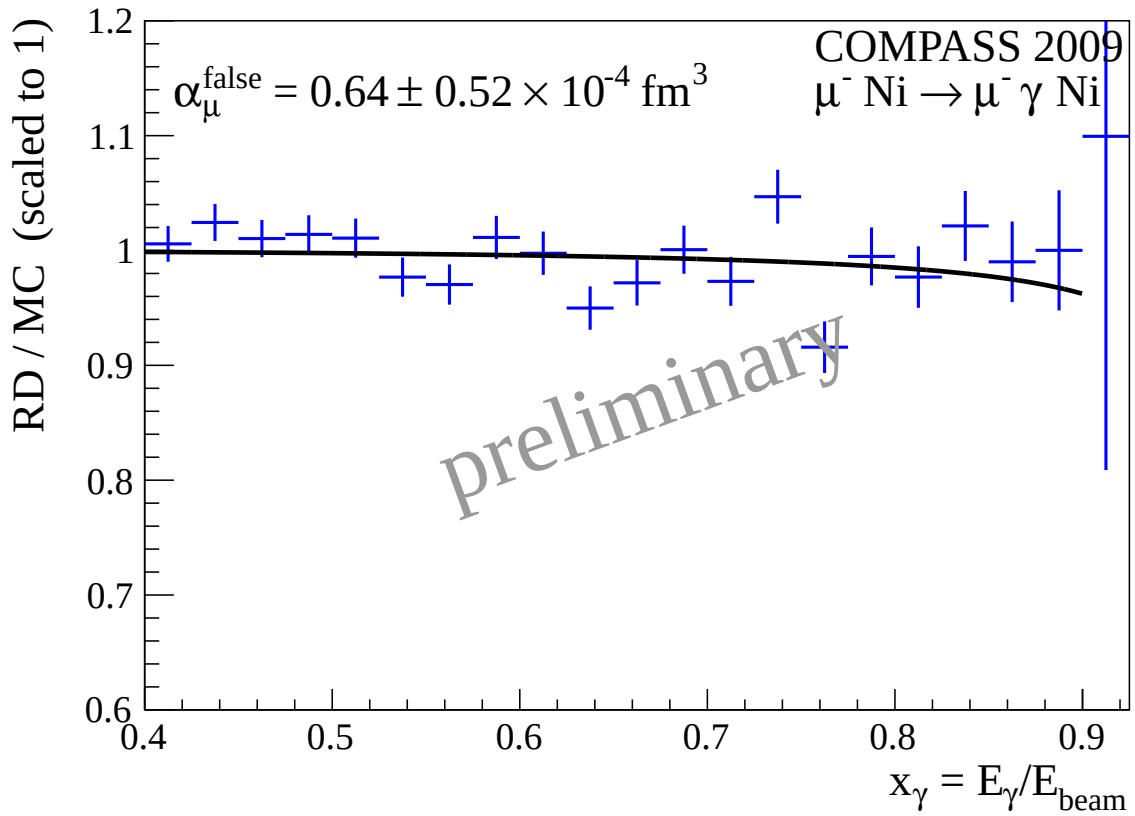


- Calculation following a 2009 paper of Göran Fäldt (Uppsala)
- Eikonal approximation: pions cross Coulomb and strong-interaction potentials

On the way to polarisability: Photon energy spectrum

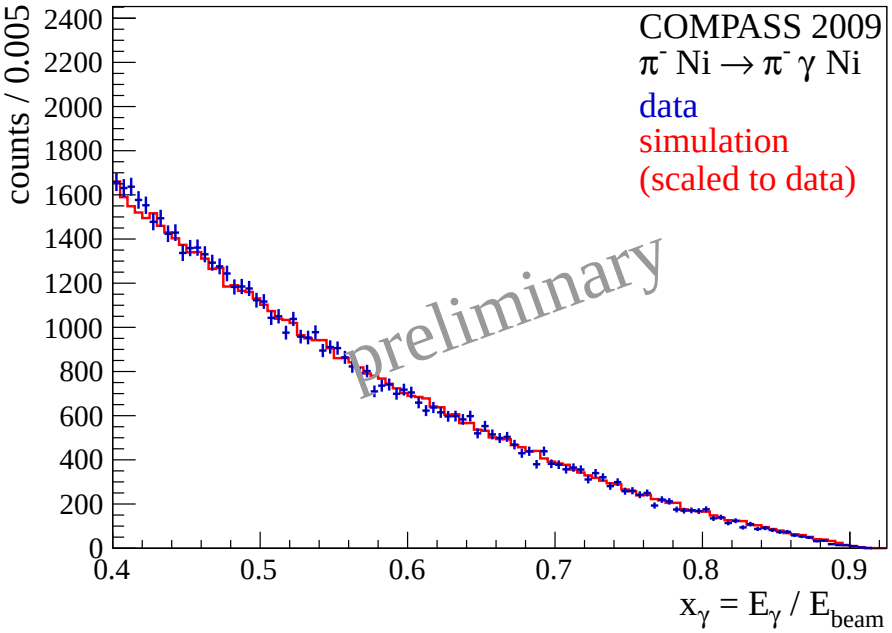


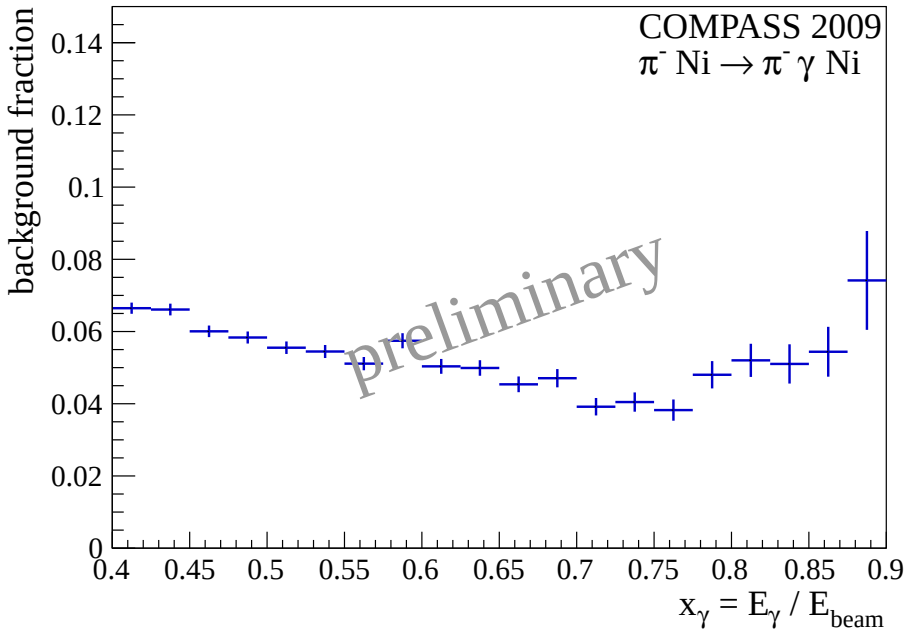
Photon energy spectrum for the muon case: RD/MC ratio



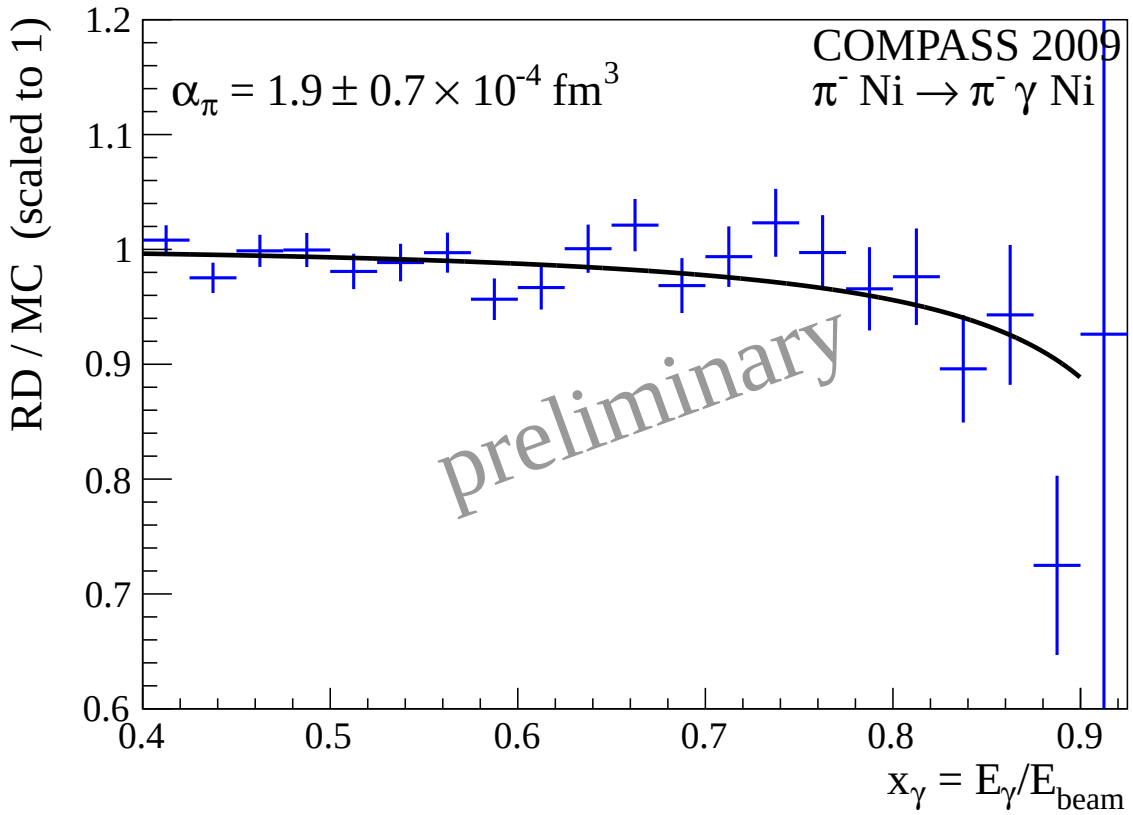
- muon data well compatible with expectation from simulation
- systematic uncertainty from sources common to pions and muons $\approx 0.6 \times 10^{-4}$ fm^3

Photon energy spectrum for pions



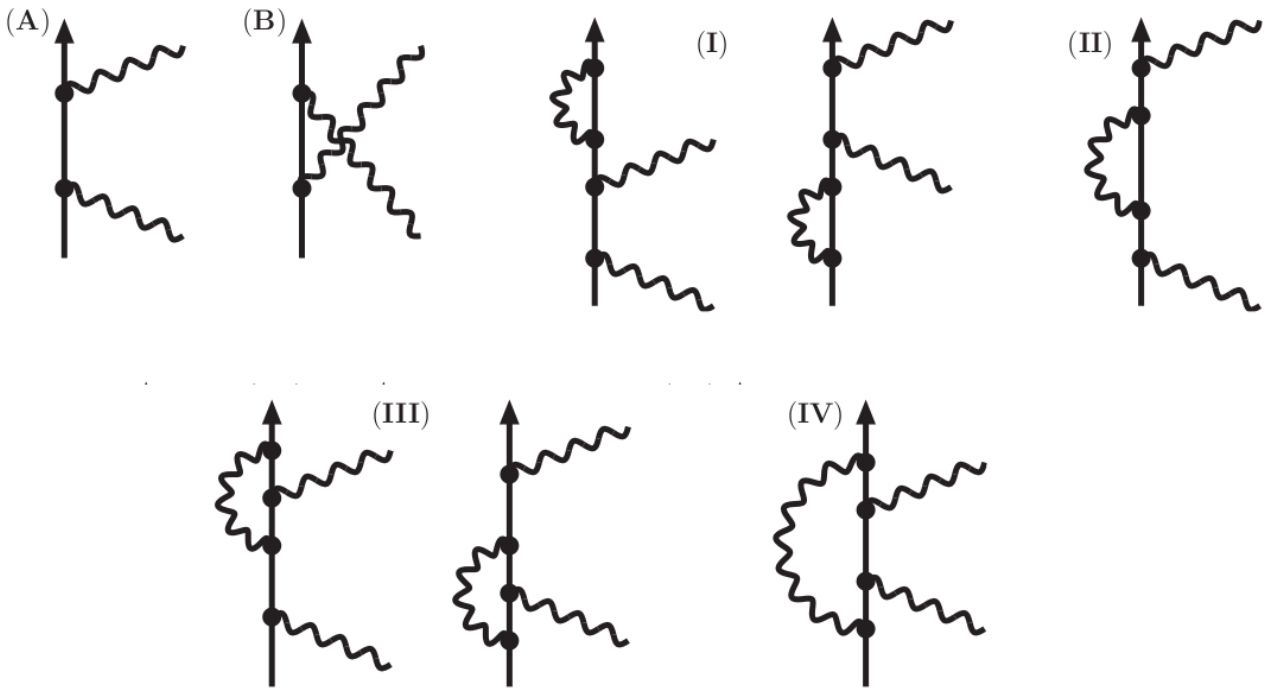


Pion polarisability – preliminary COMPASS result

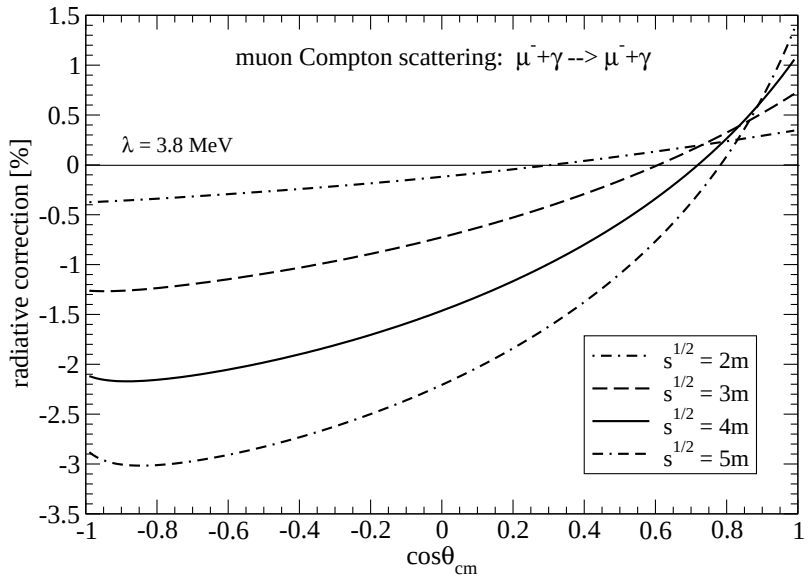


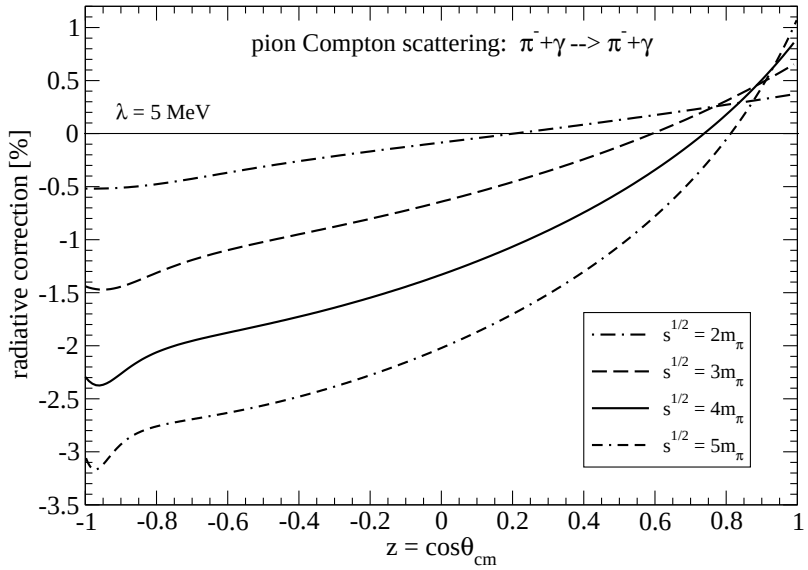
Radiative corrections

- 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, JMF (TUM) *Radiative corrections to pion Compton scattering, Nucl.Phys. A812(2008)186, Radiative corrections to pion-nucleus bremsstrahlung, Eur.Phys.J. A39(2009)71*

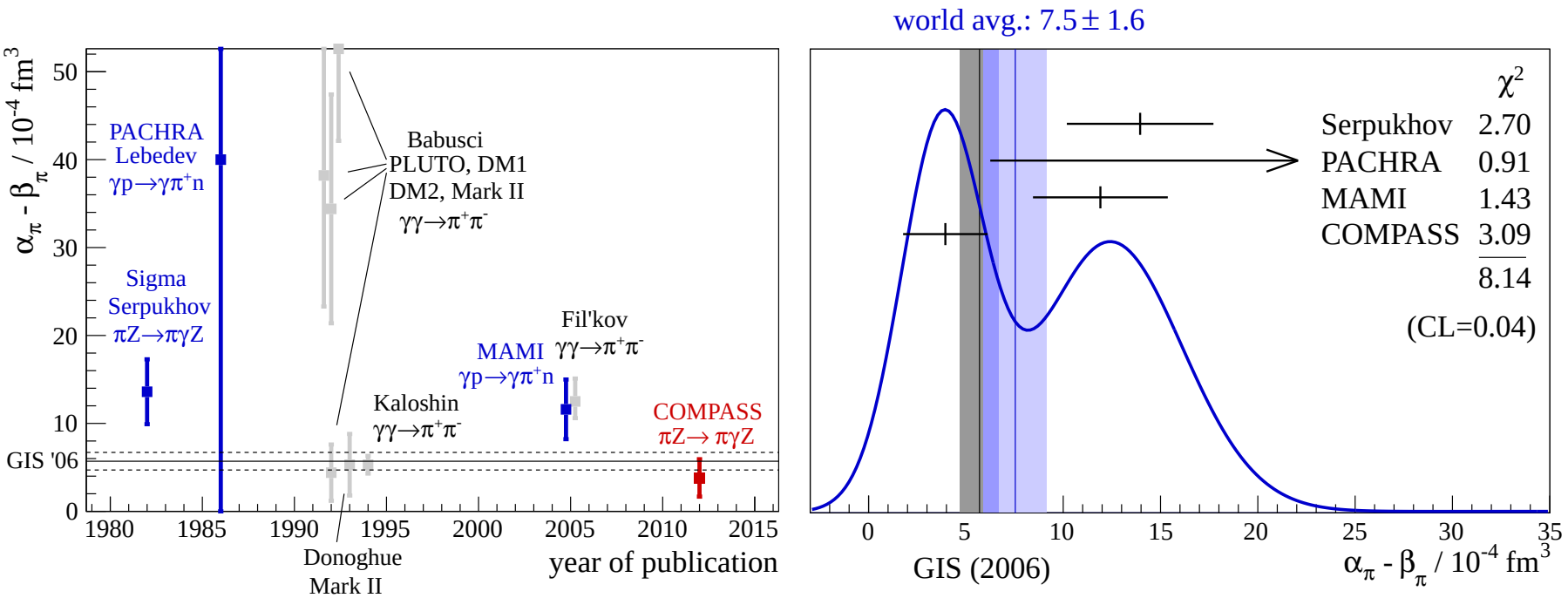
source of systematic uncertainty	estimated magnitude CL = 68 % [10^{-4} fm^3]
tracking	0.6
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.8

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

COMPASS preliminary:

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

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

Nov. 2004

- recorded statistics (eff. 3 days) competitive to the Serpukhov measurement
- explorative measurement, proving feasibility

Nov. 2009

- as shown, publication in preparation

2012

- 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)

Primakoff reactions accessible at COMPASS

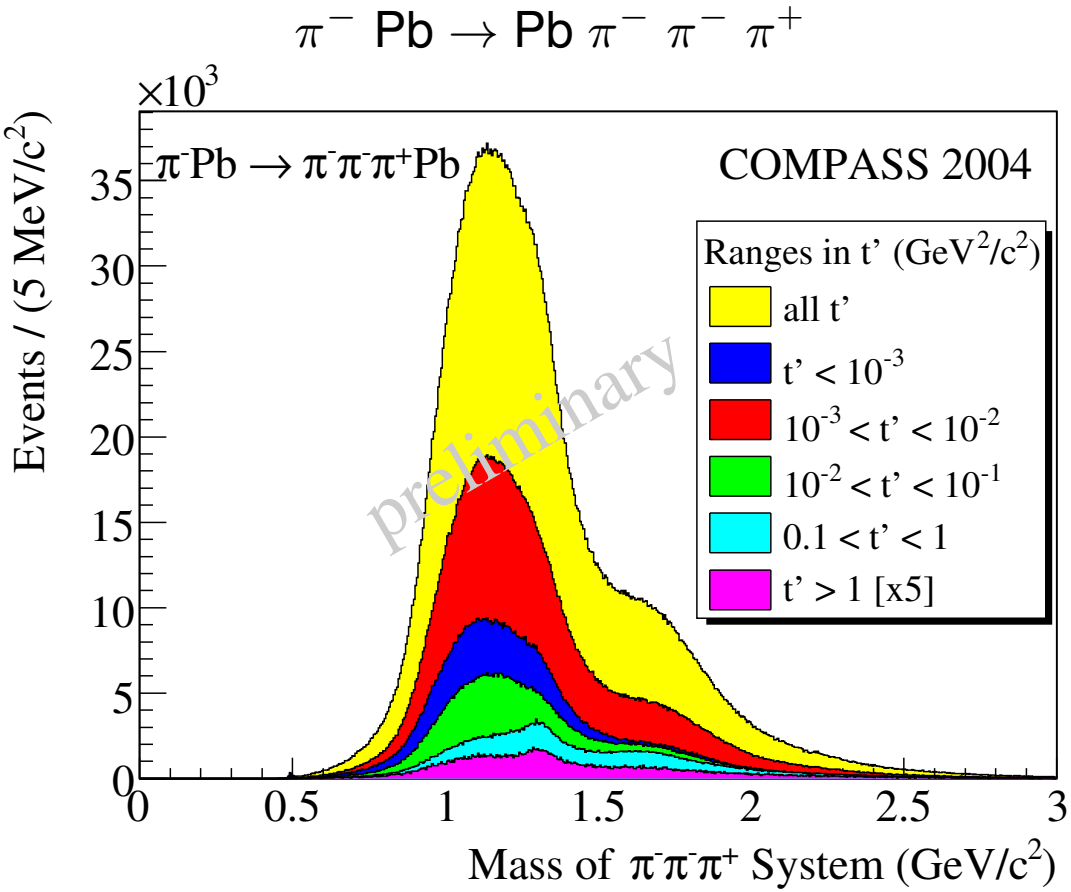
Access to $\pi + \gamma$ reactions via the Primakoff effect:

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

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

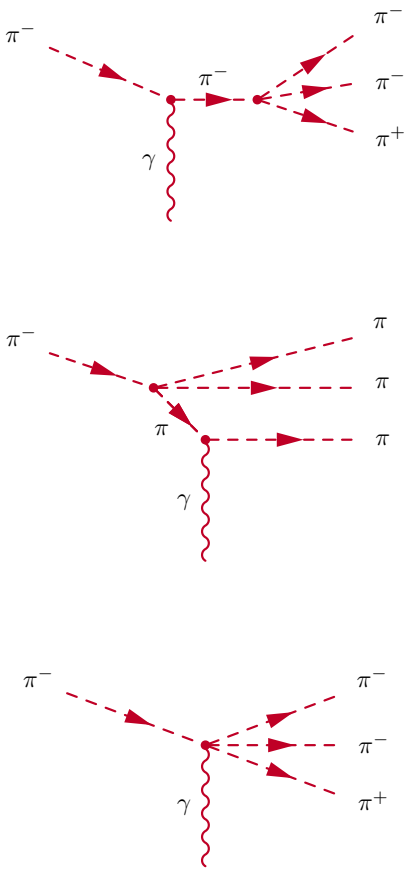
analogously: Kaon-induced reactions $K^- + \gamma \to \cdots$

2004 Primakoff results

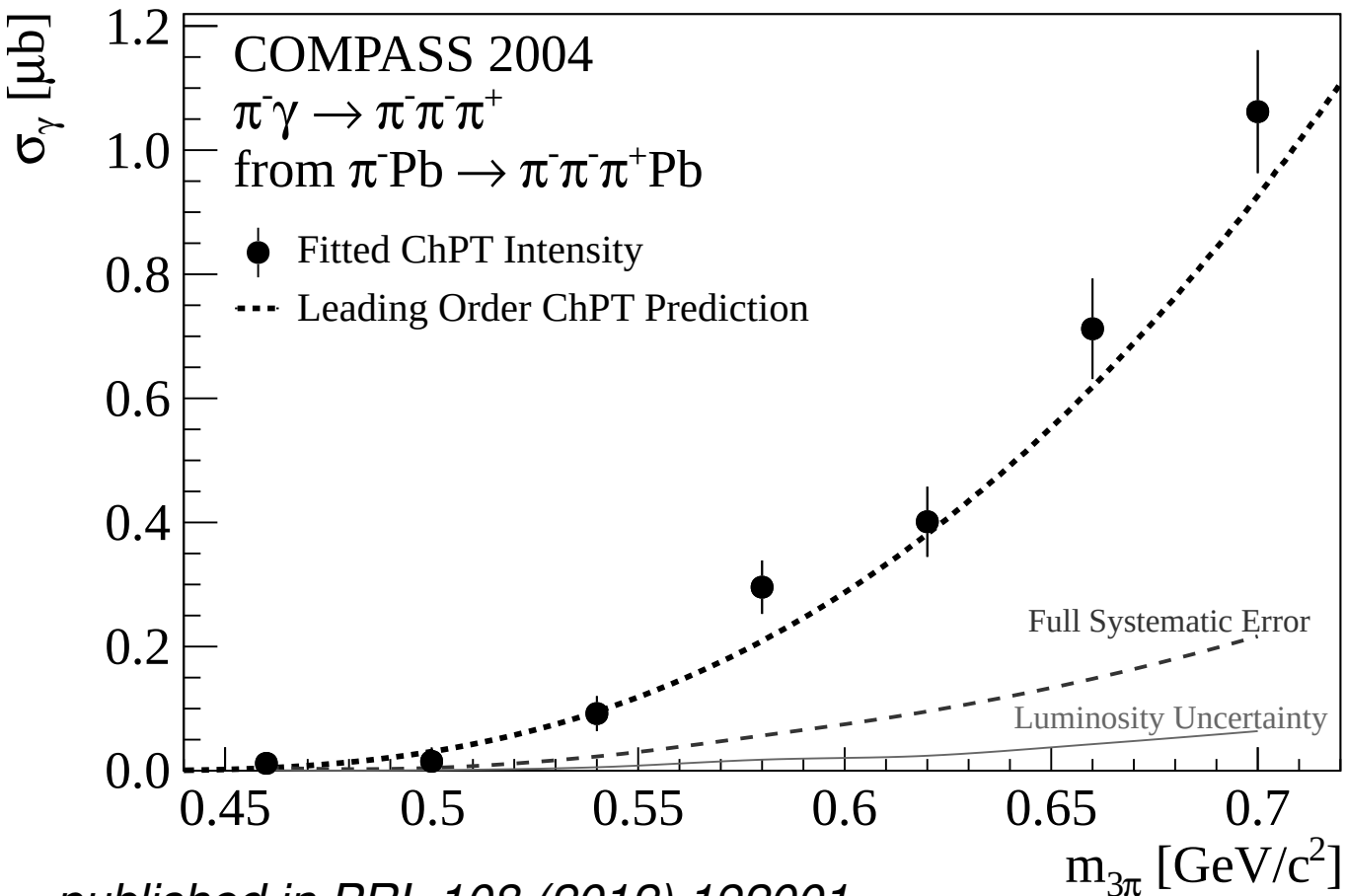


- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim 1\,000\,000$ events

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

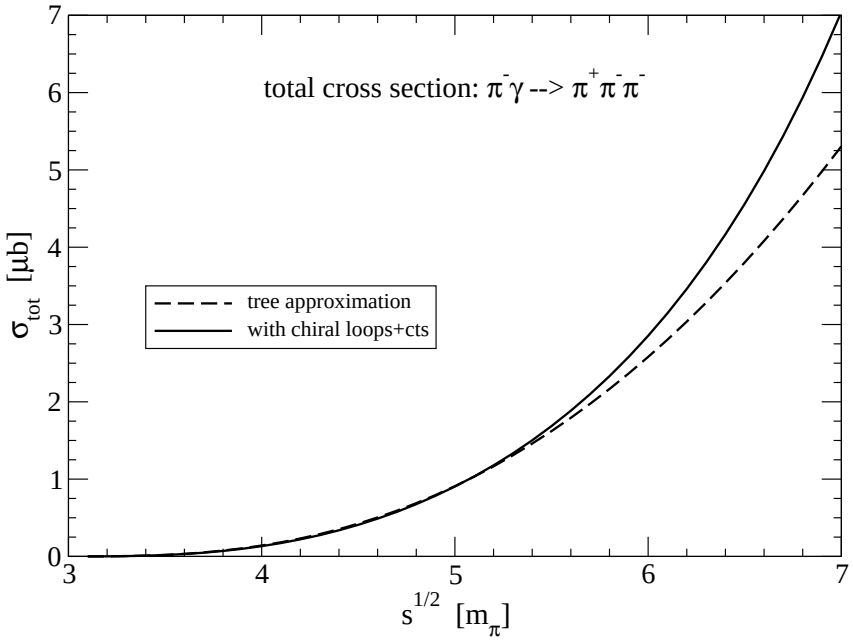


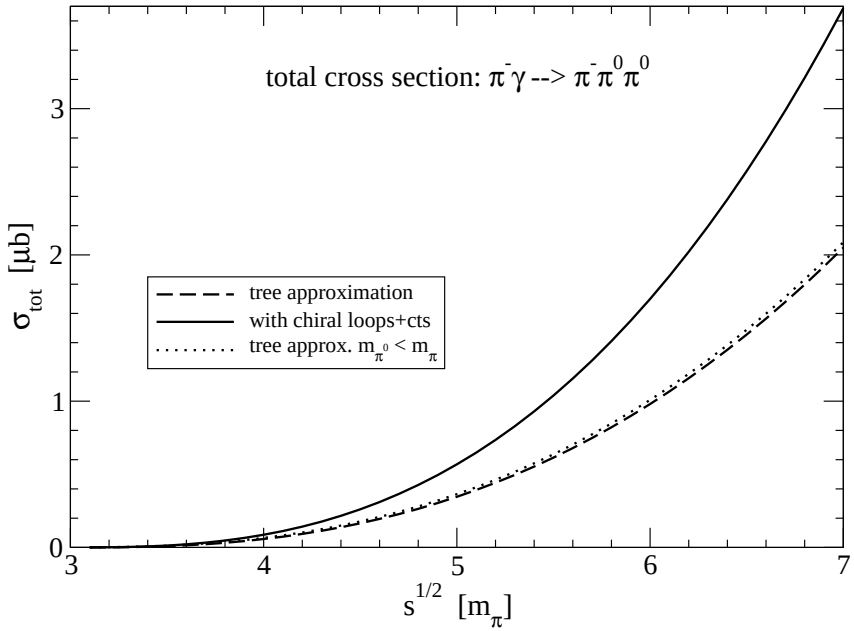
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



published in PRL 108 (2012) 192001

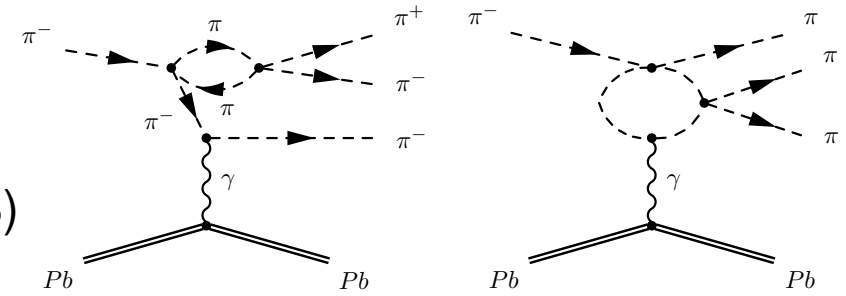
Higher-order effects



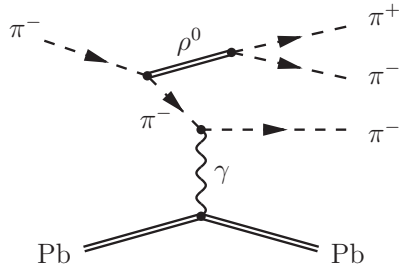


Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)

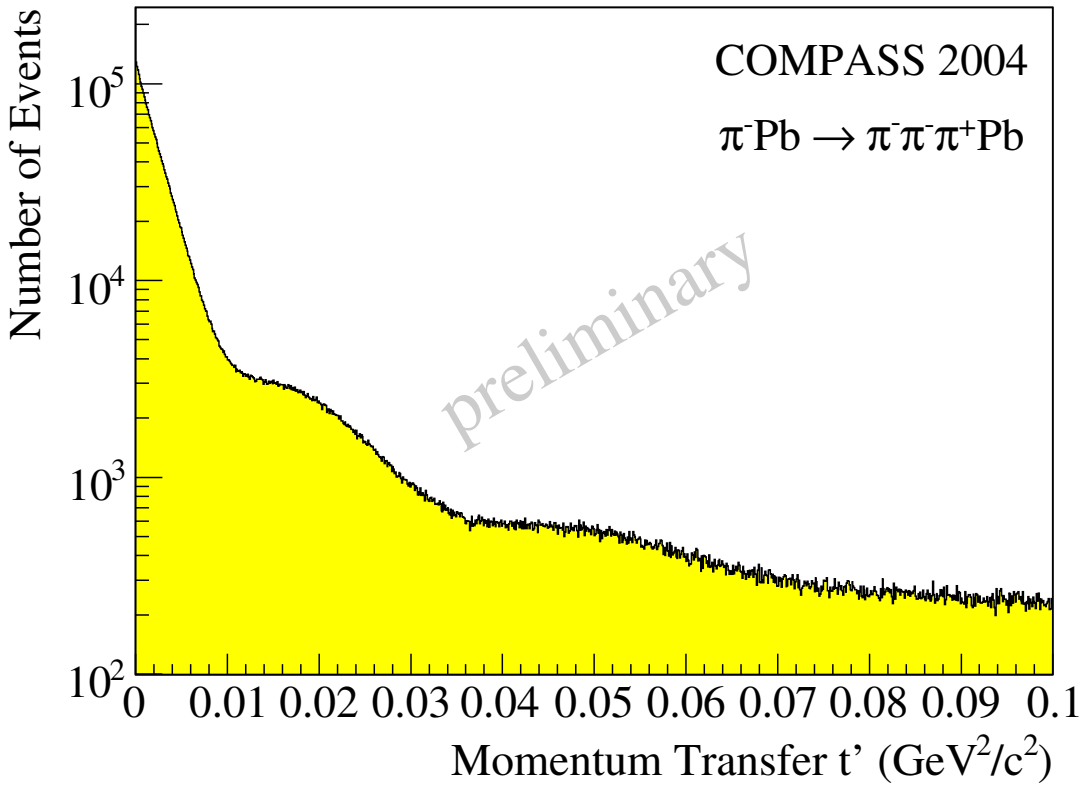


not (yet) included:



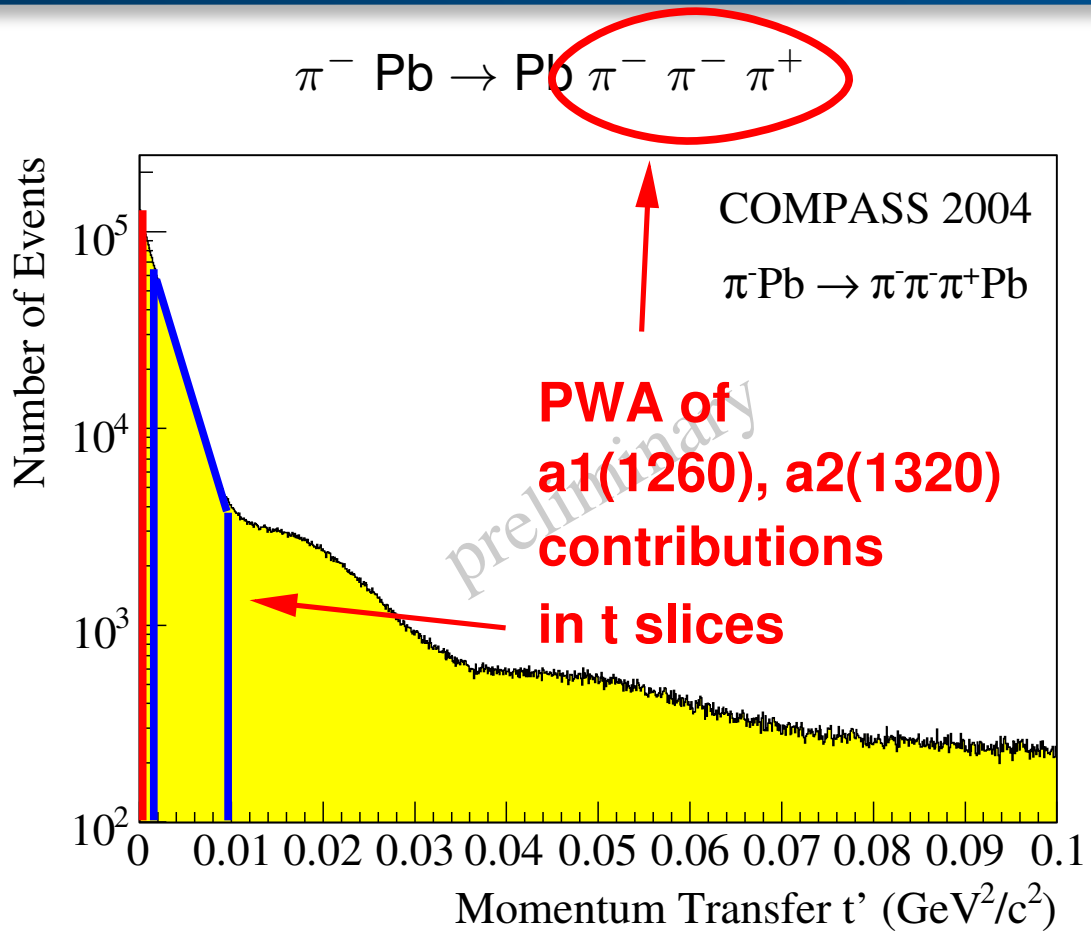
2004 Primakoff results

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



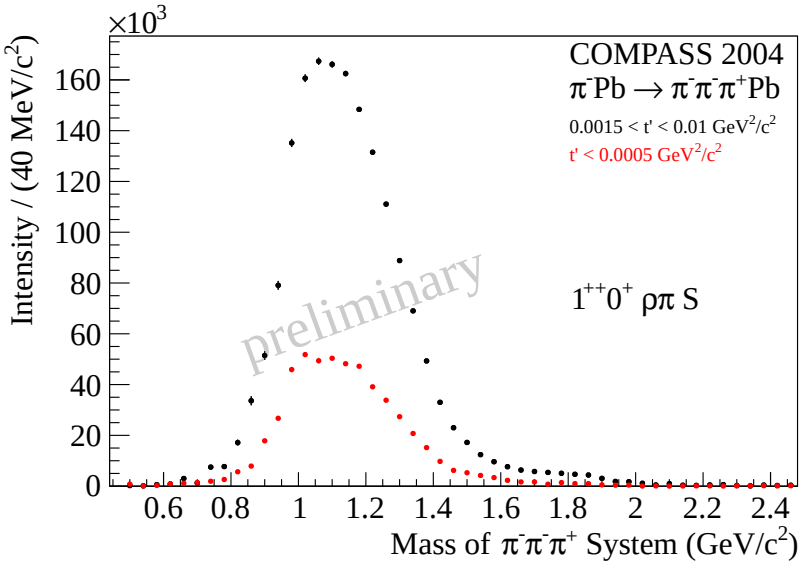
- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim 1\,000\,000$ events

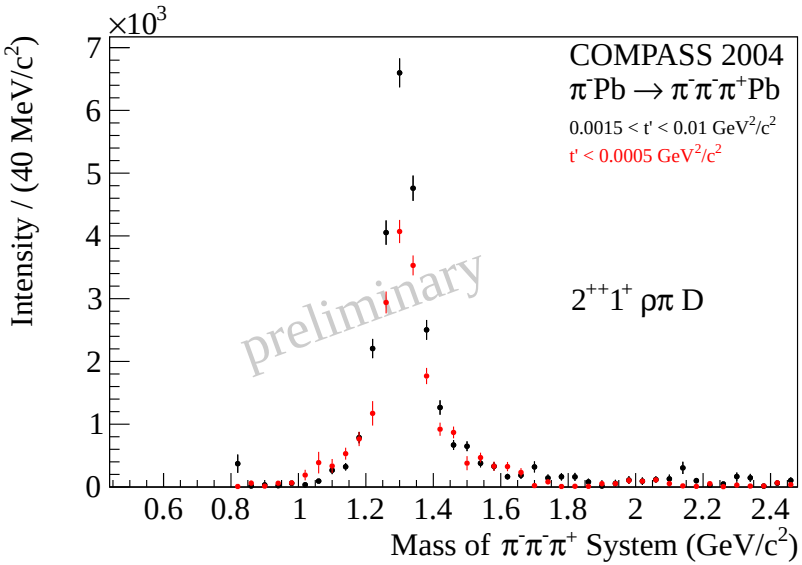
2004 Primakoff results

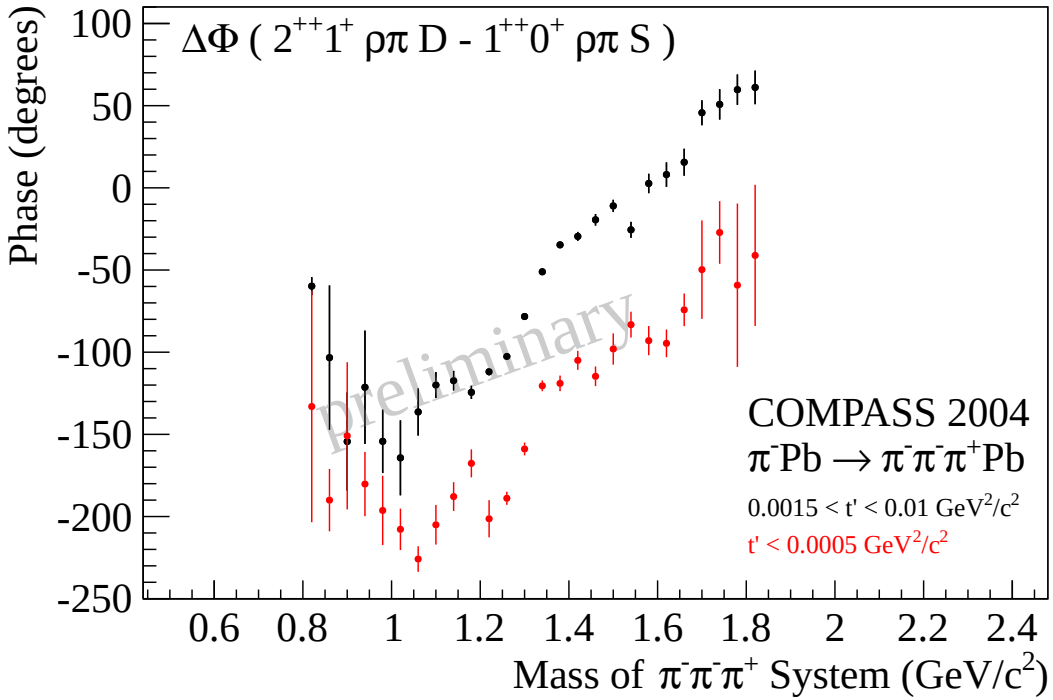


- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim 1\,000\,000$ events

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

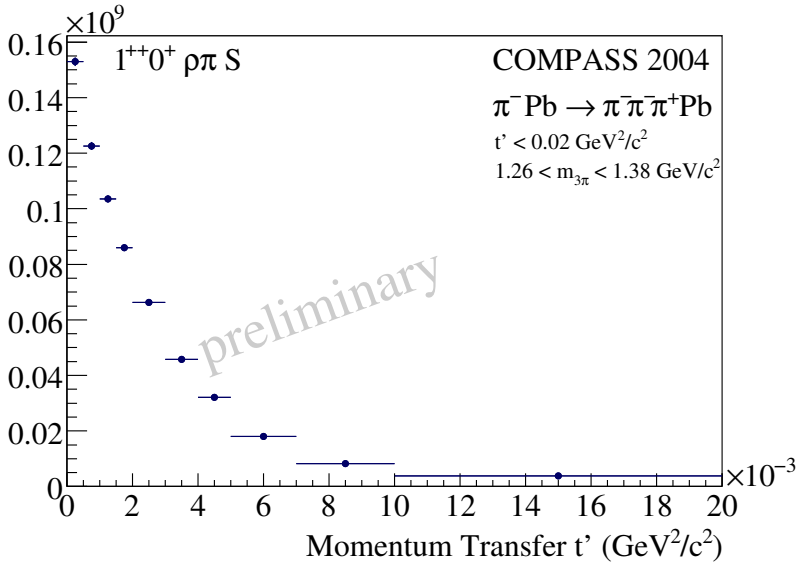


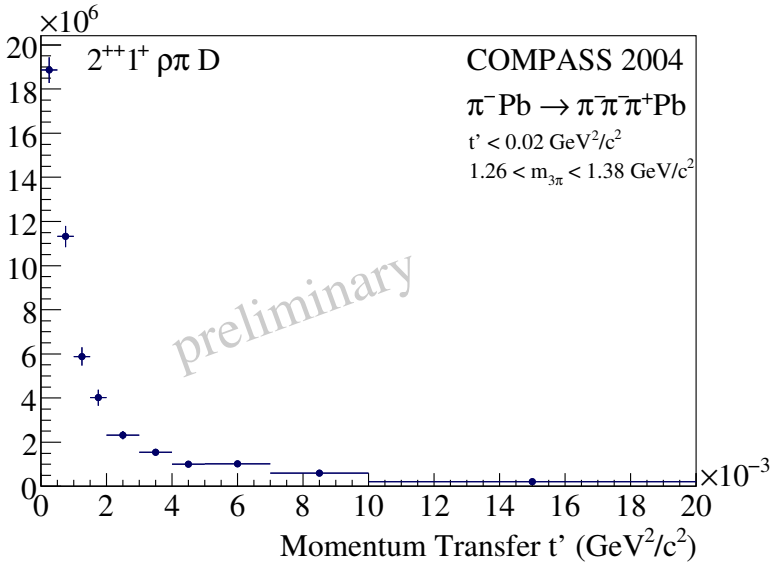


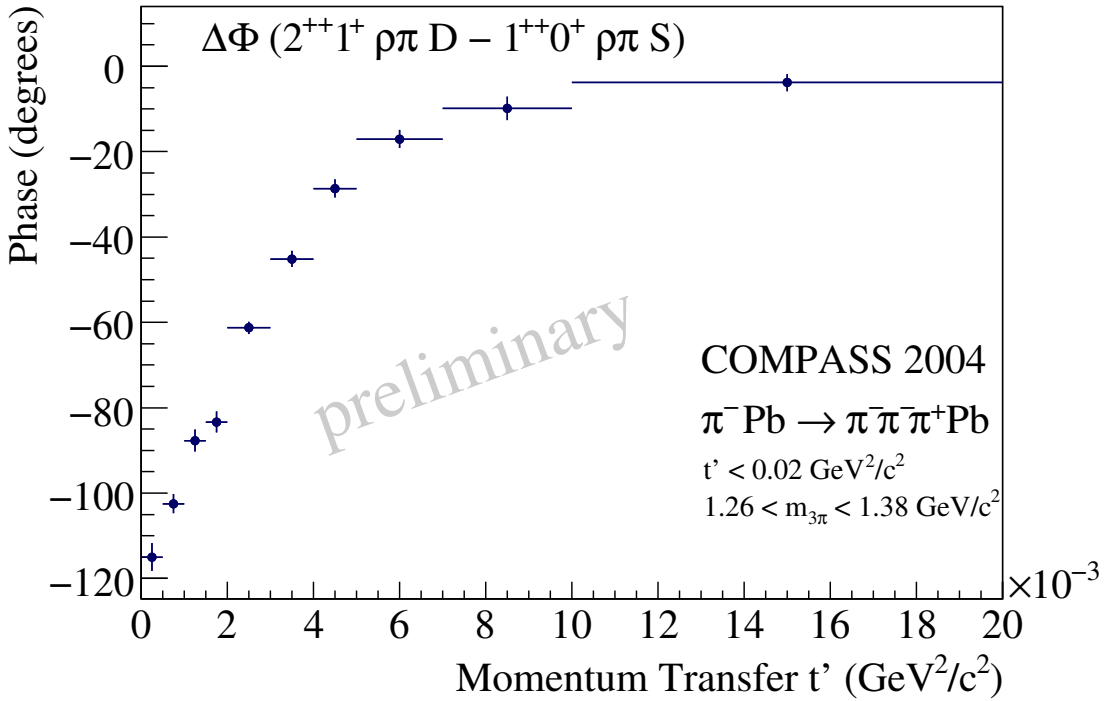


Phase $a_2 - a_1$ in detail: t' dependence

Technische Universität München







- 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

Summary and Outlook

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

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

  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
- Chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ 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