Studies on Pion Dynamics at COMPASS:

Pion Polarisability
Chiral Dynamics in $\pi\gamma \to 3\pi$

Jan M. Friedrich

Physik Department
Technische Universität München

for the COMPASS collaboration

Confinement X
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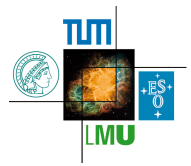
supported by: Maier-Leibnitz-Labor der TU und LMU München,
Excellenzcluster: Origin and Structure of the Universe, BMBF



Polarisability of the pion as a composite object

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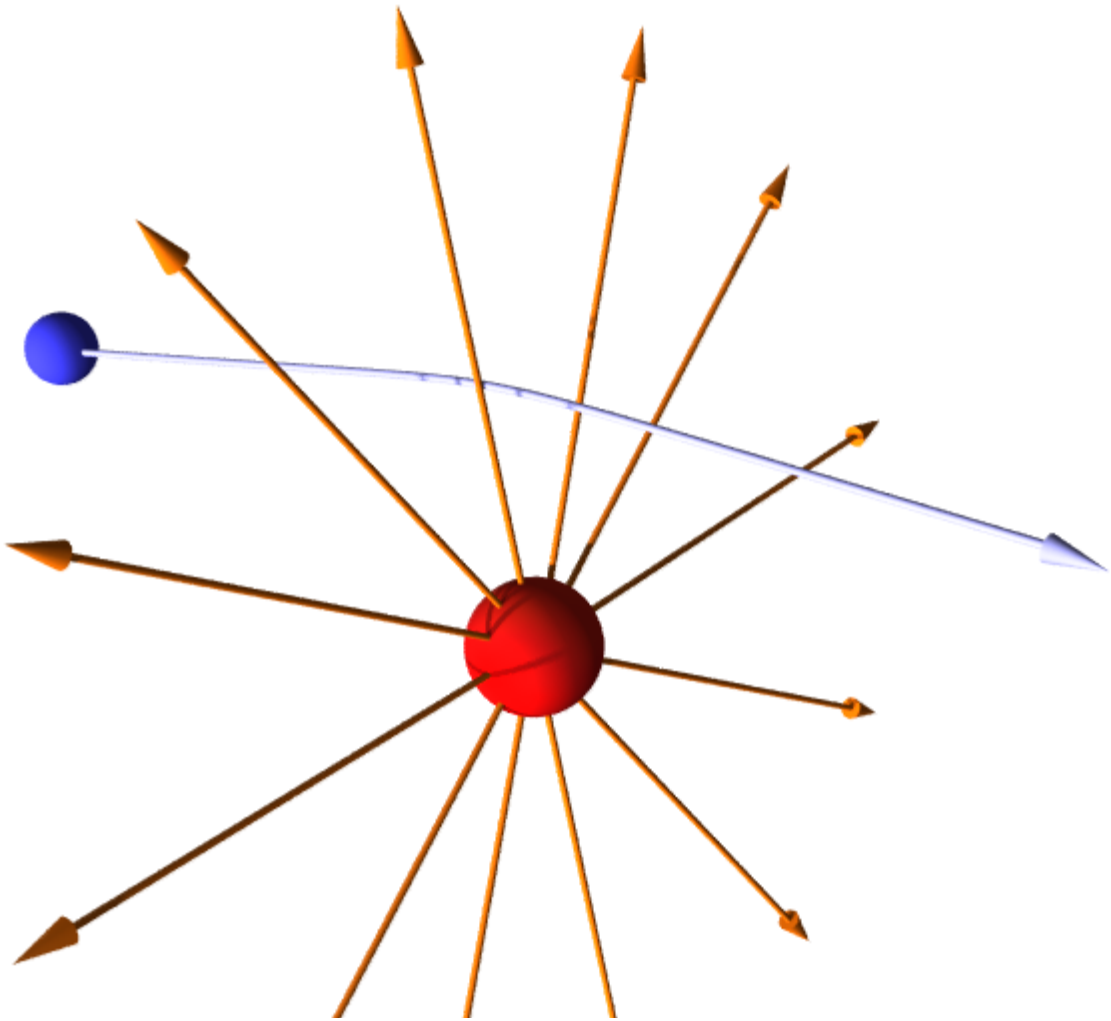
- Pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{nucl}$: $E \sim 300\,\mathrm{kV/fm}$



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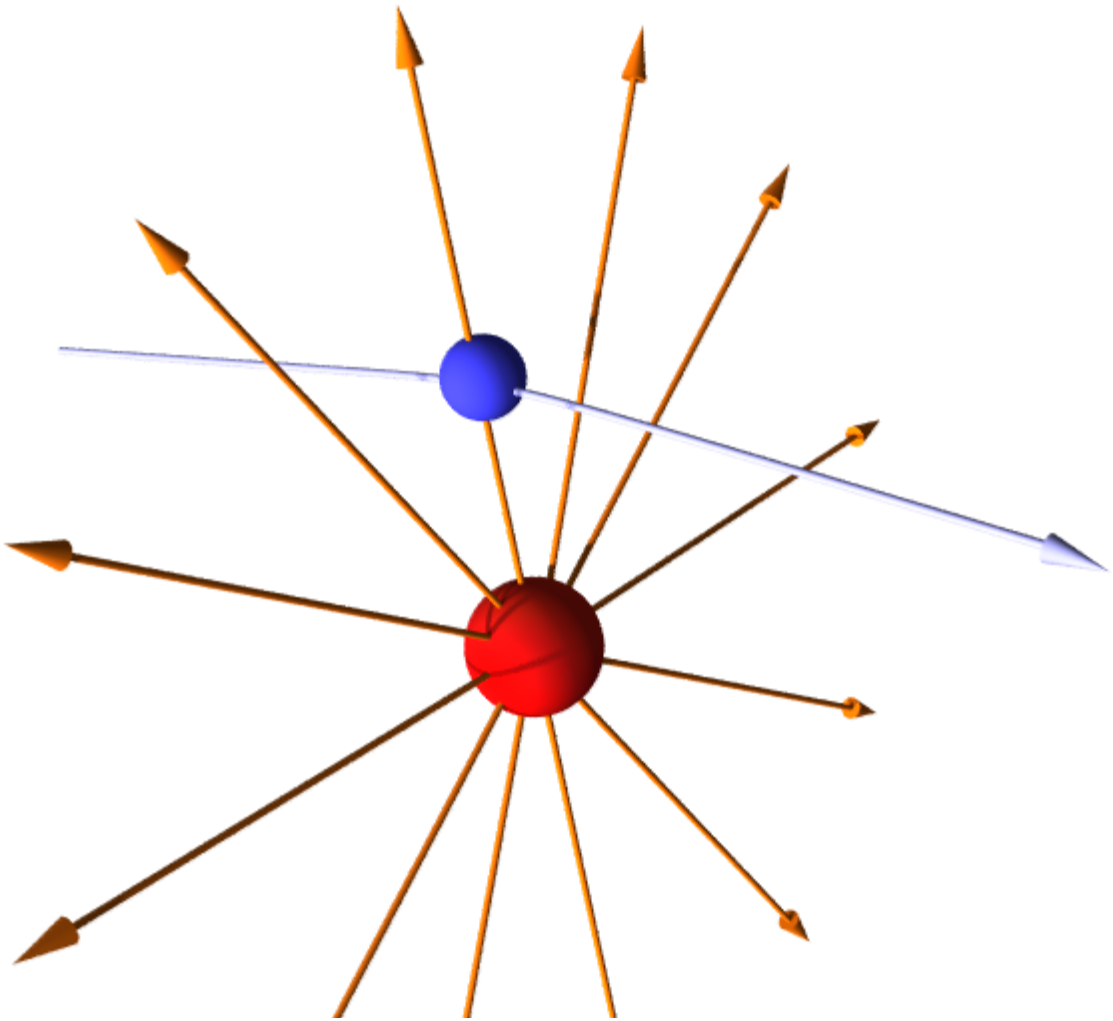

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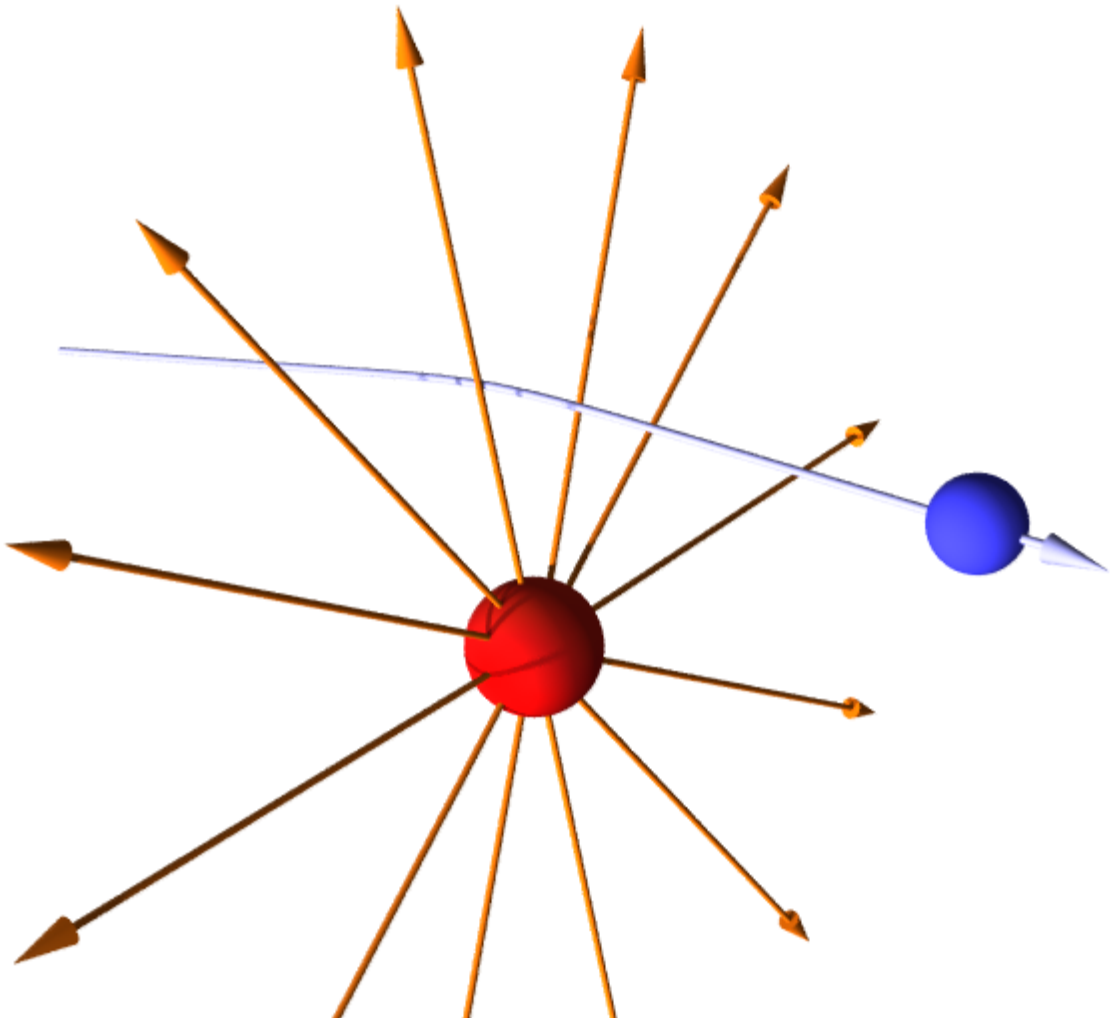

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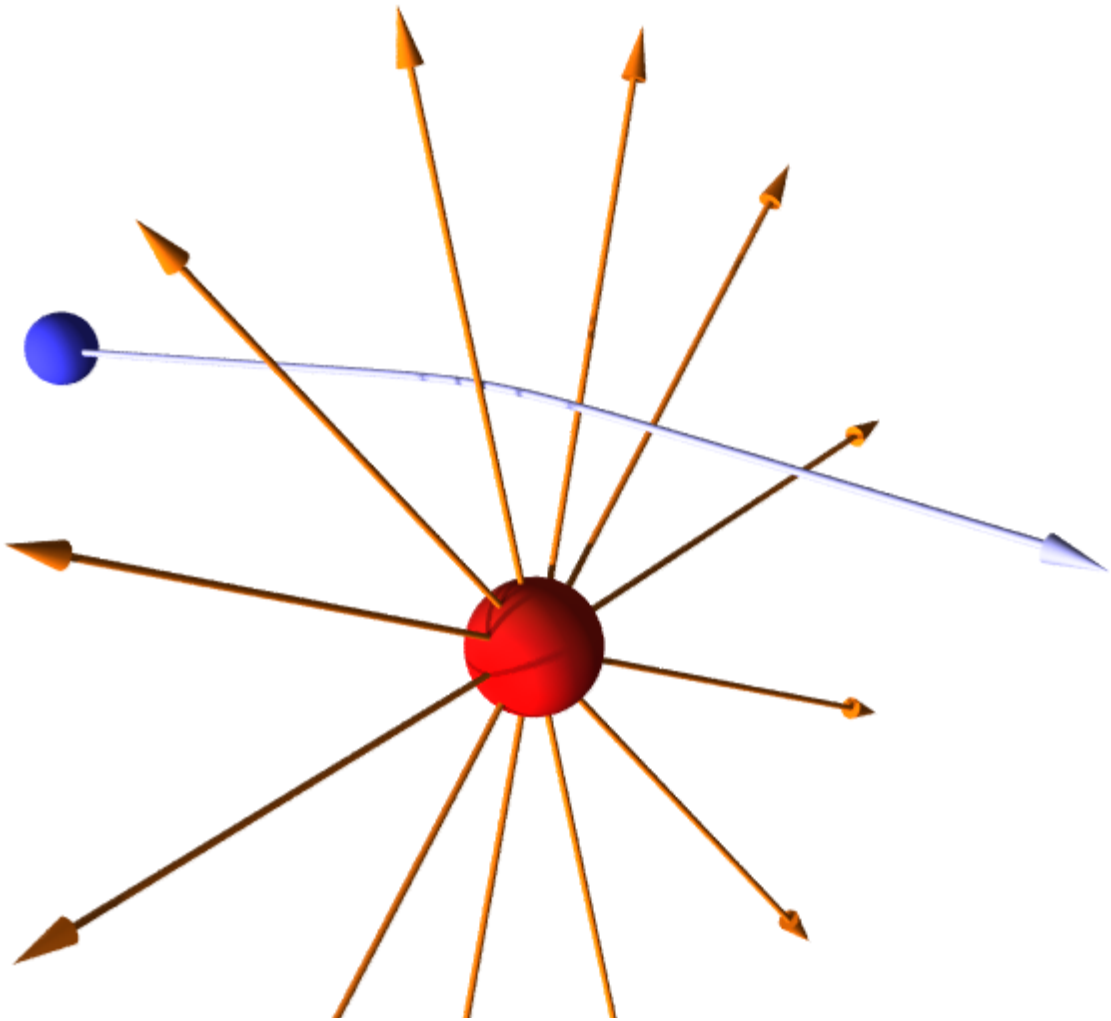
  - scattering off *equivalent photons* (Weizsäcker-Williams)
  - pion (or muon) Compton scattering



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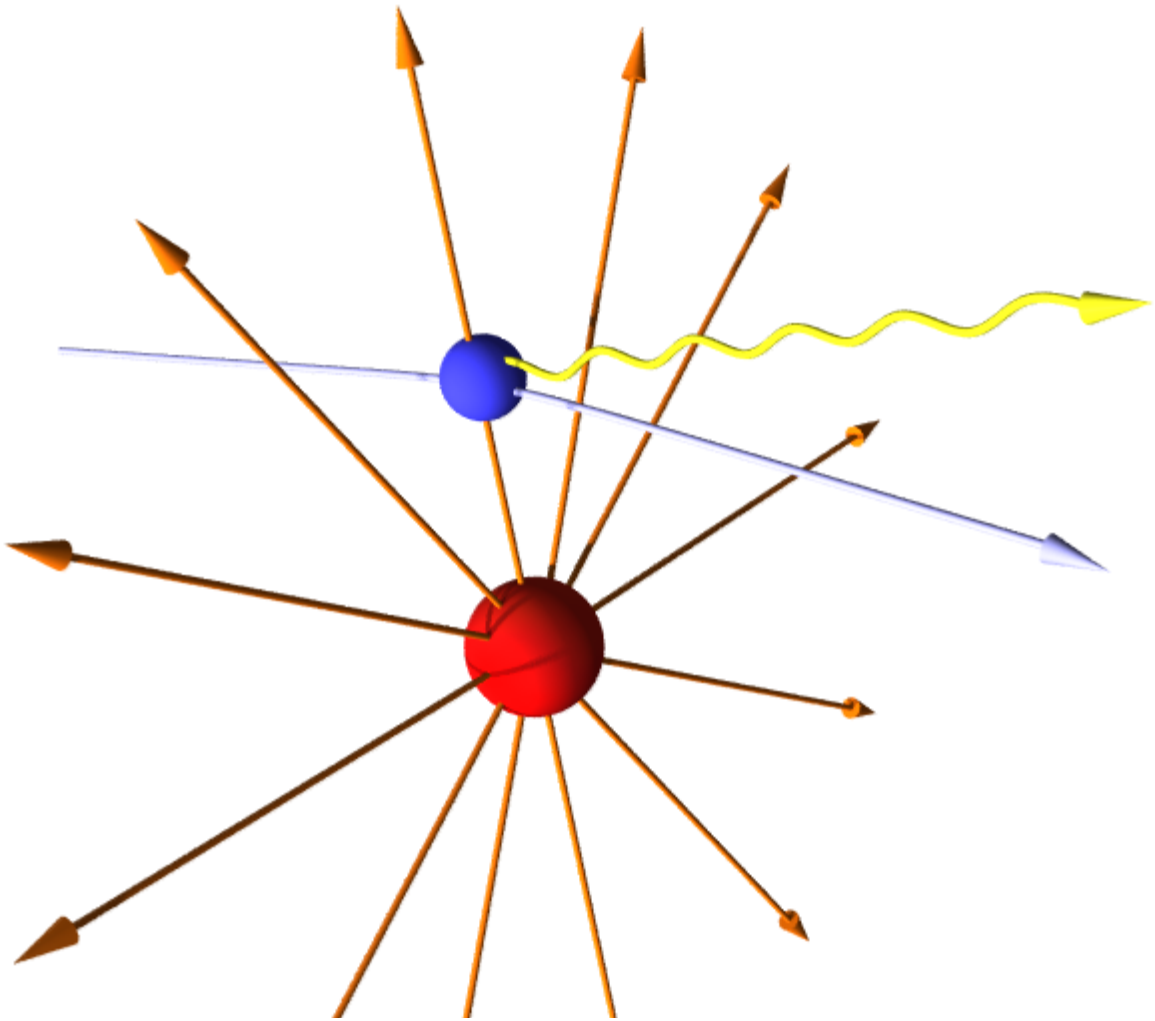

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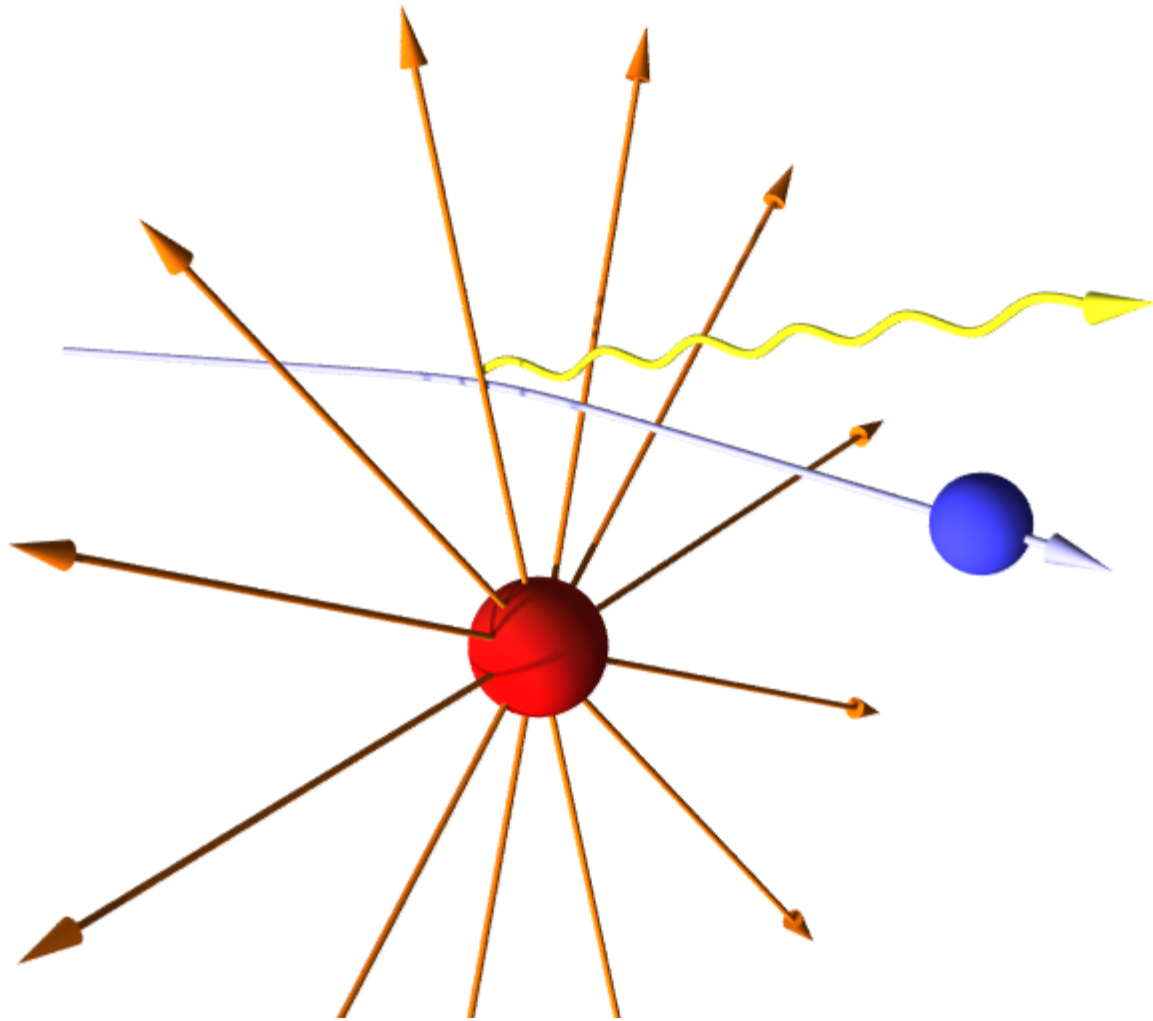

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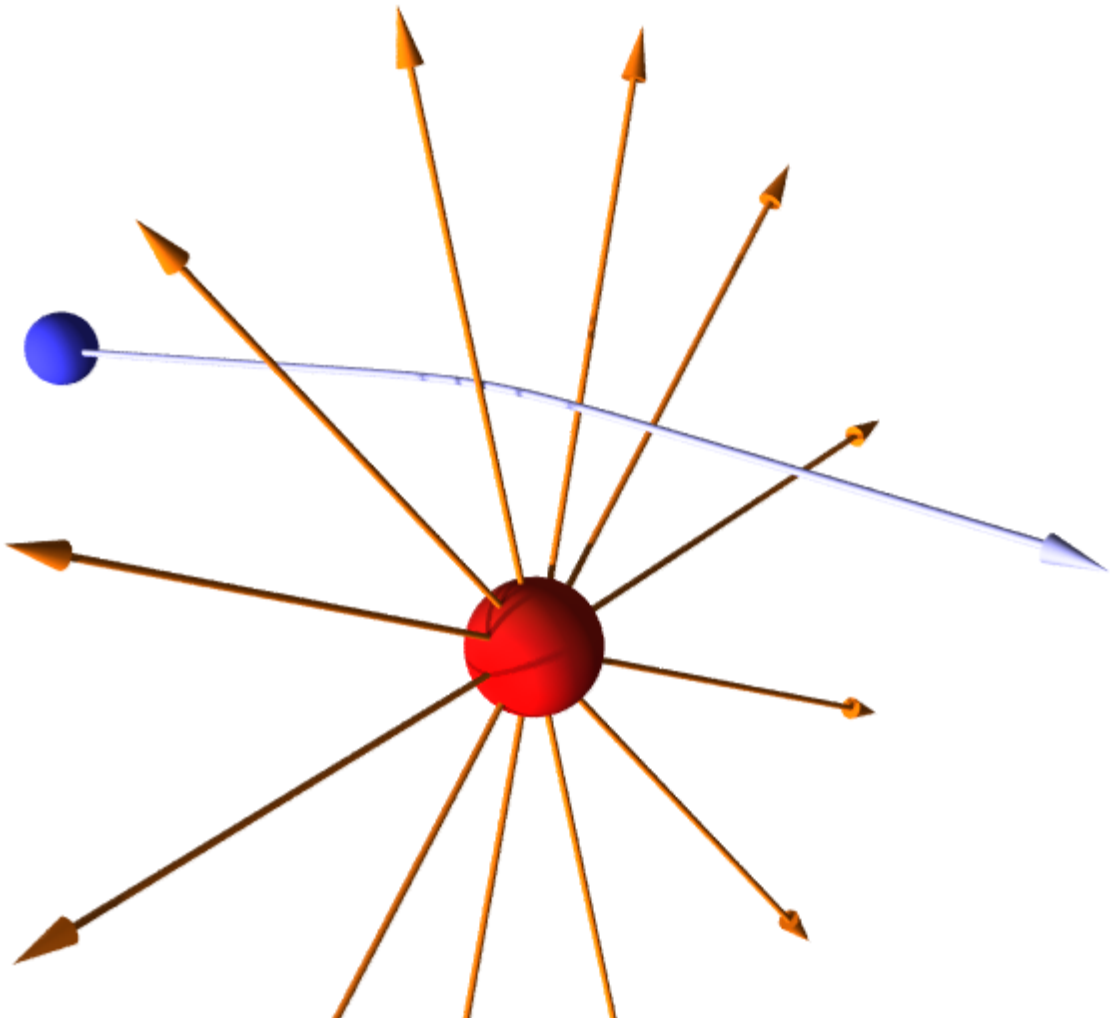
  - Compton cross-section typically diminished
  - Theory prediction: $\alpha_\pi^{\text{ChPT}} = 2.9 \pm 0.5 \cdot 10^{-4}\ \text{fm}^3$
  - expected charge separation $\sim 10^{-5}\,\text{fm} \cdot e$



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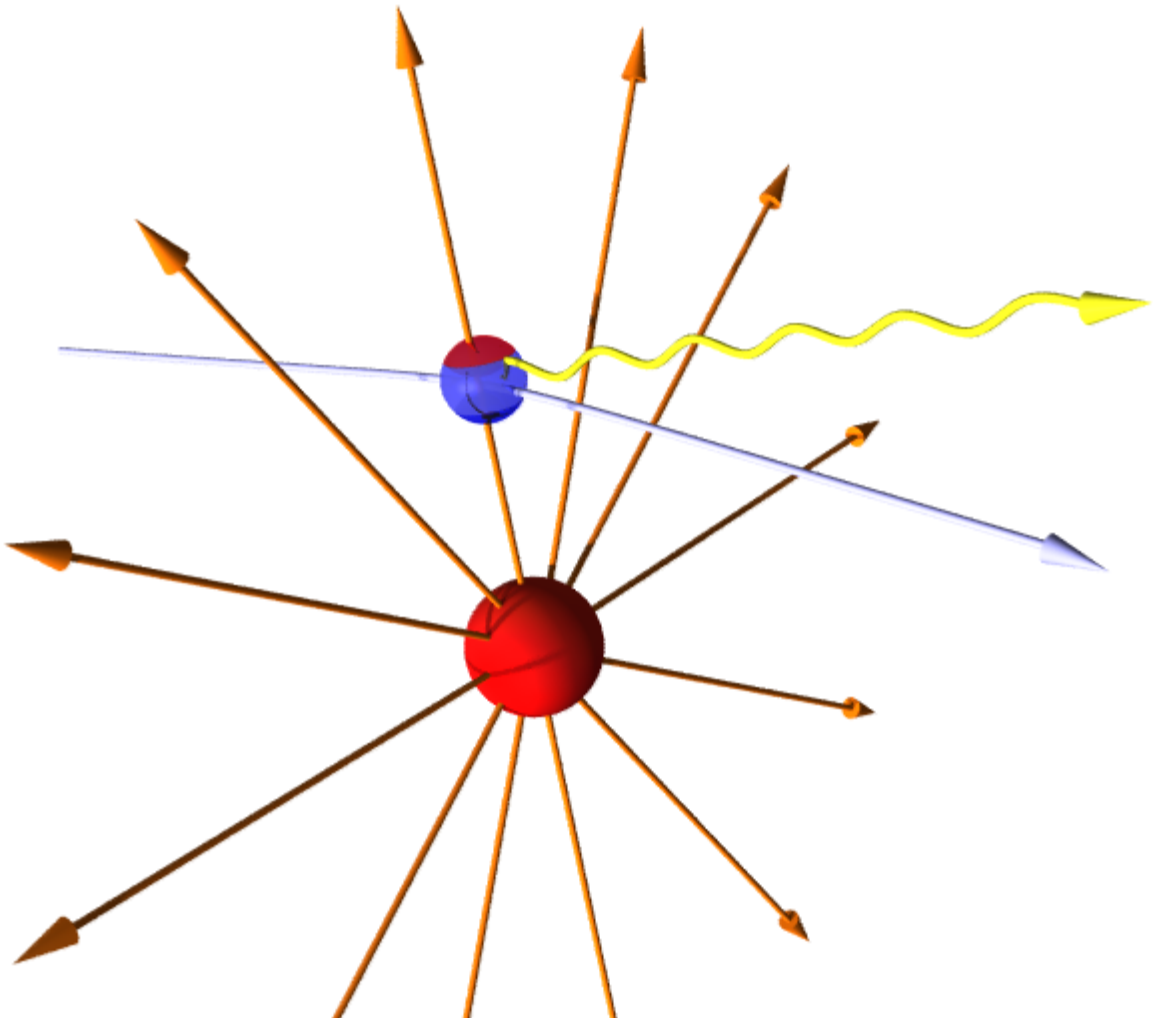

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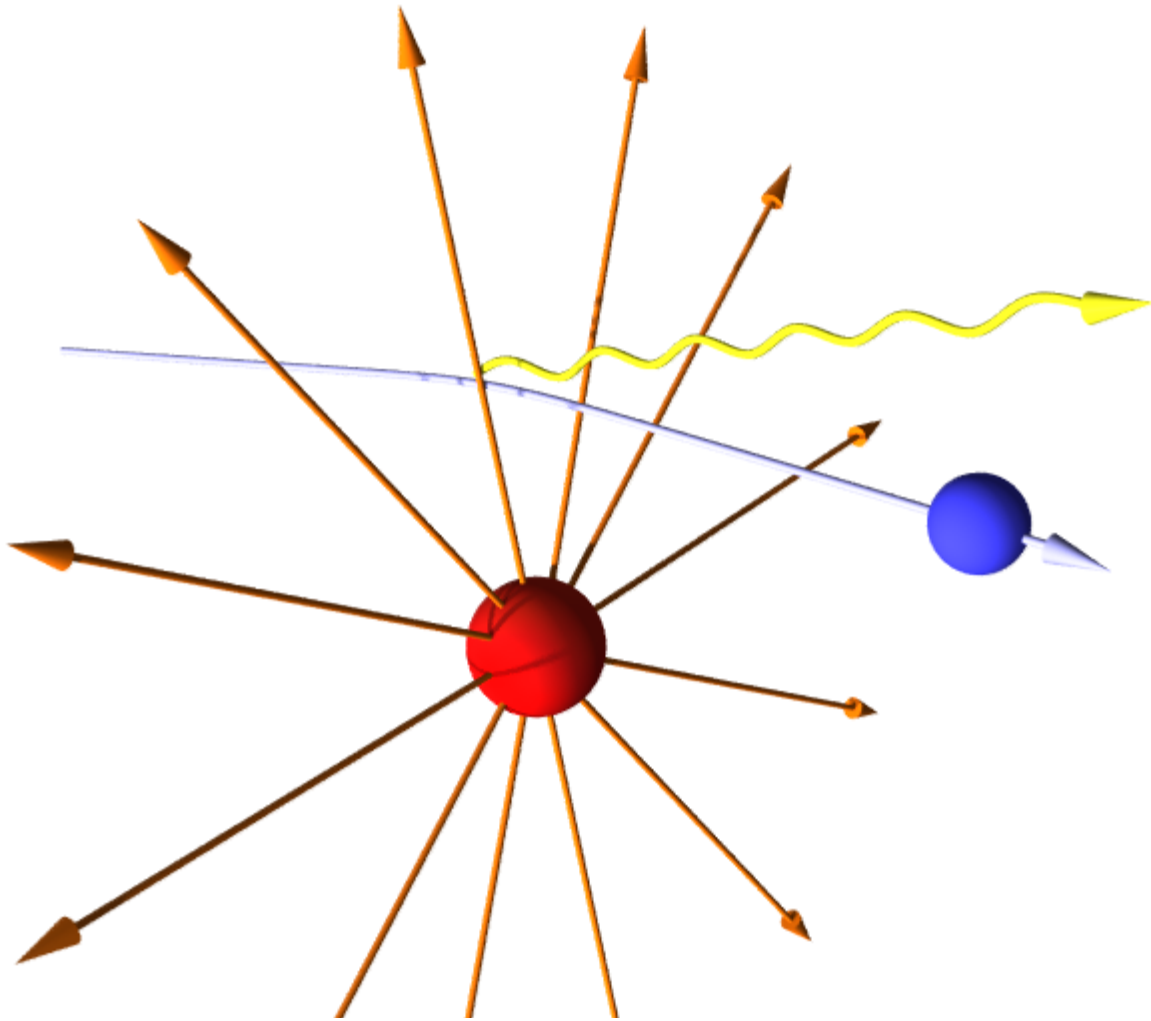
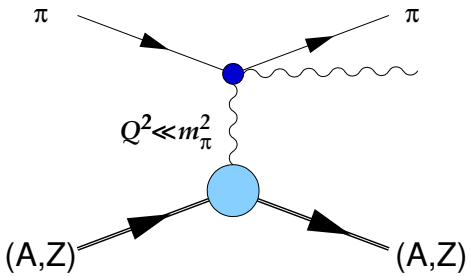
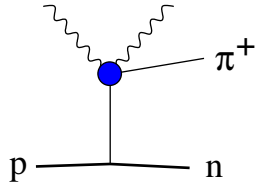


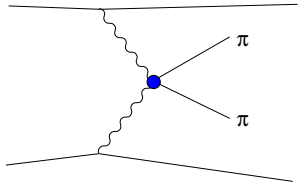
Pion polarisability: world data before COMPASS



Primakoff process



Radiative pion photoproduction



Photon-Photon fusion

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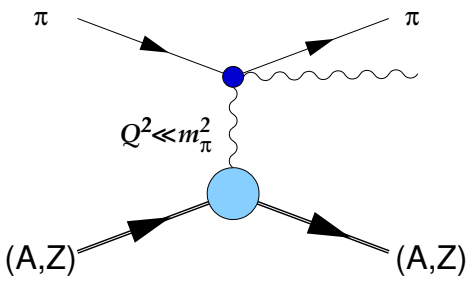

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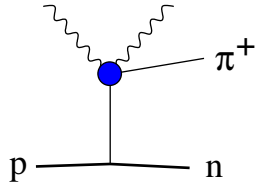

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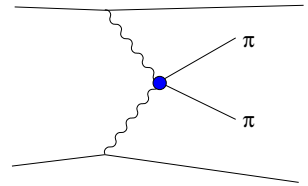

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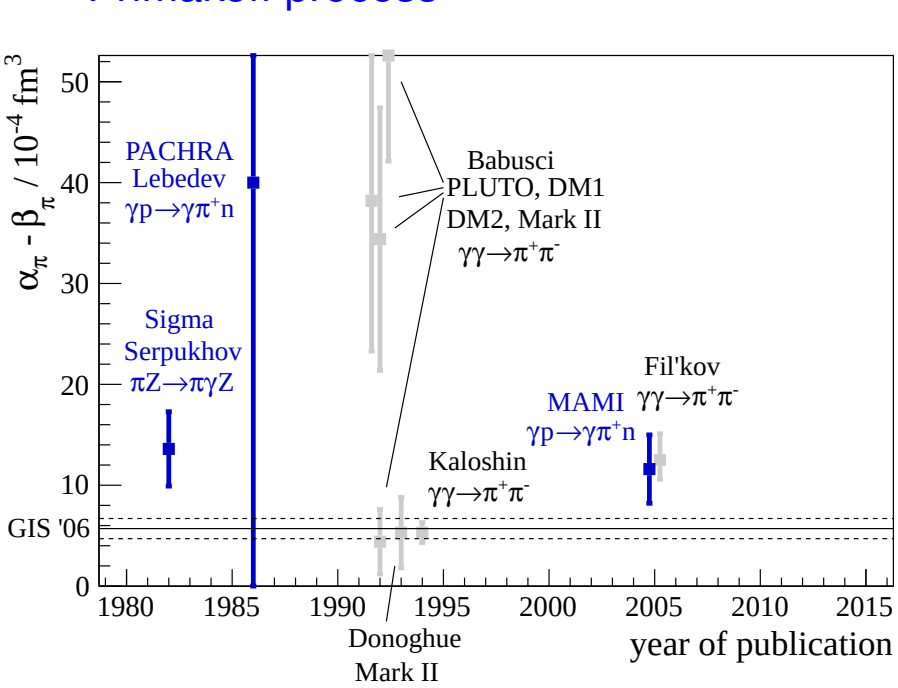

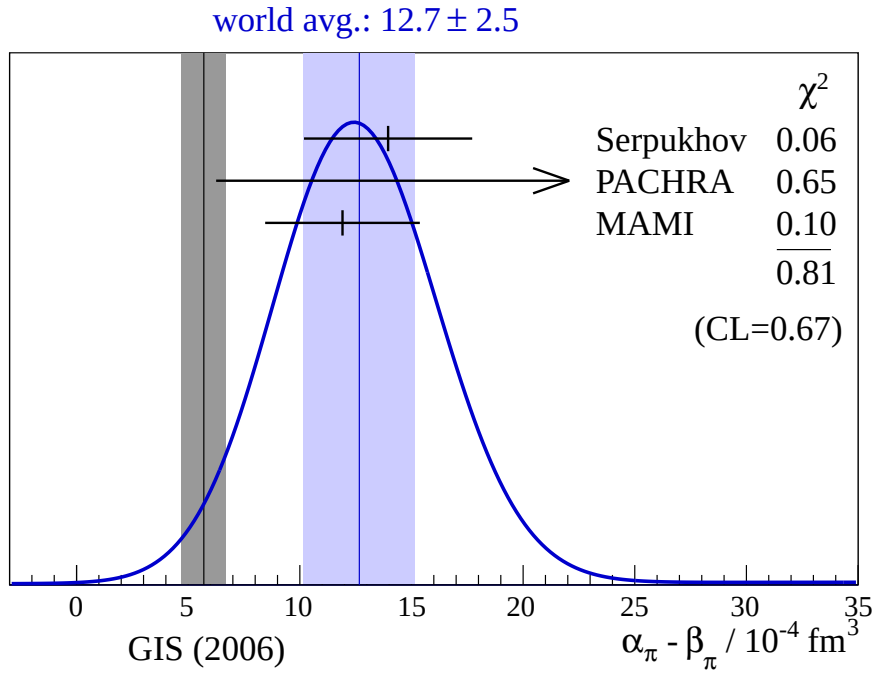

GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)
plots from Thiemo Nagel, PhD thesis, TUM 2012

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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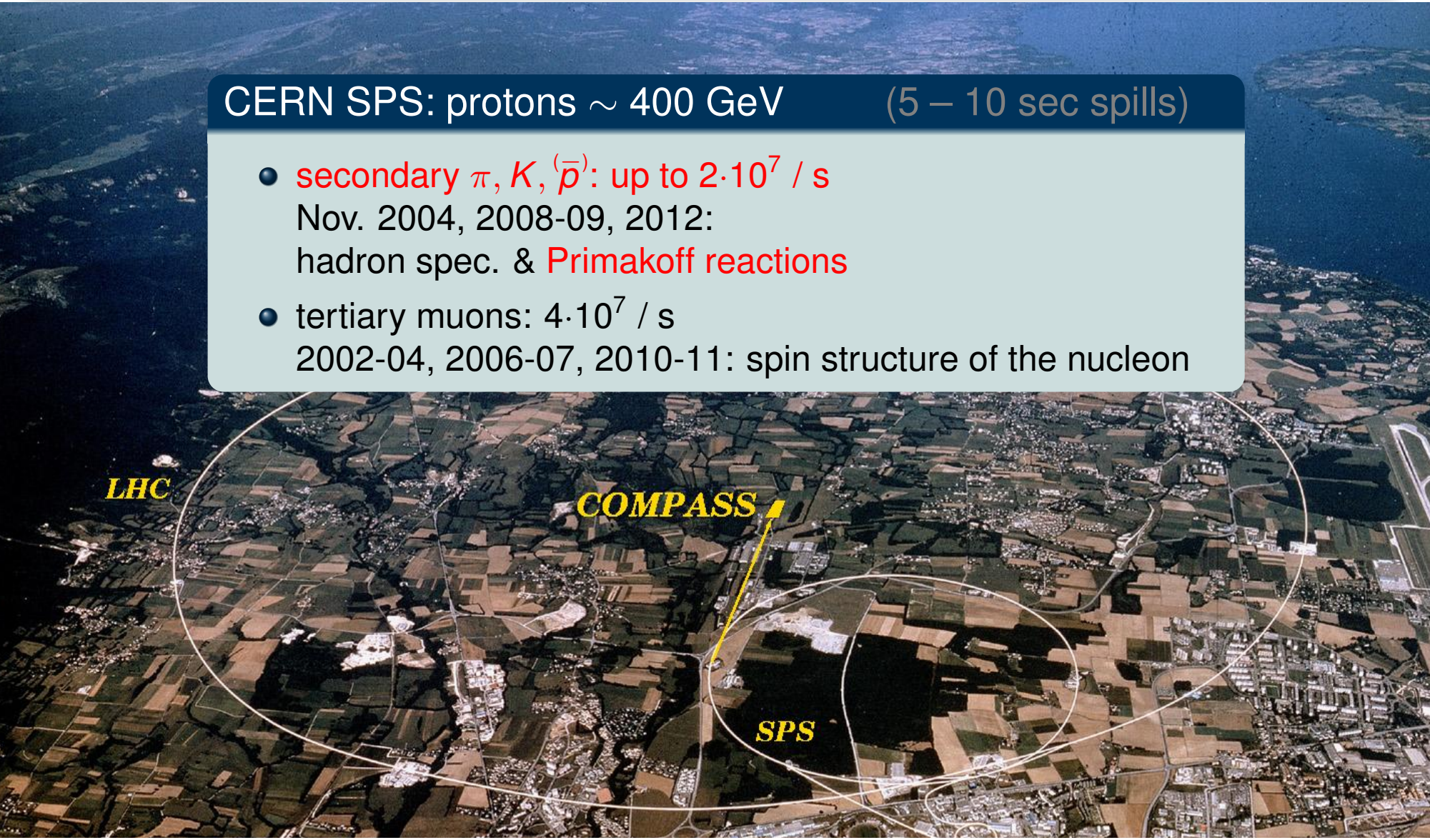
CERN SPS: protons $\sim$ 400 GeV (5 – 10 sec spills)

- 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

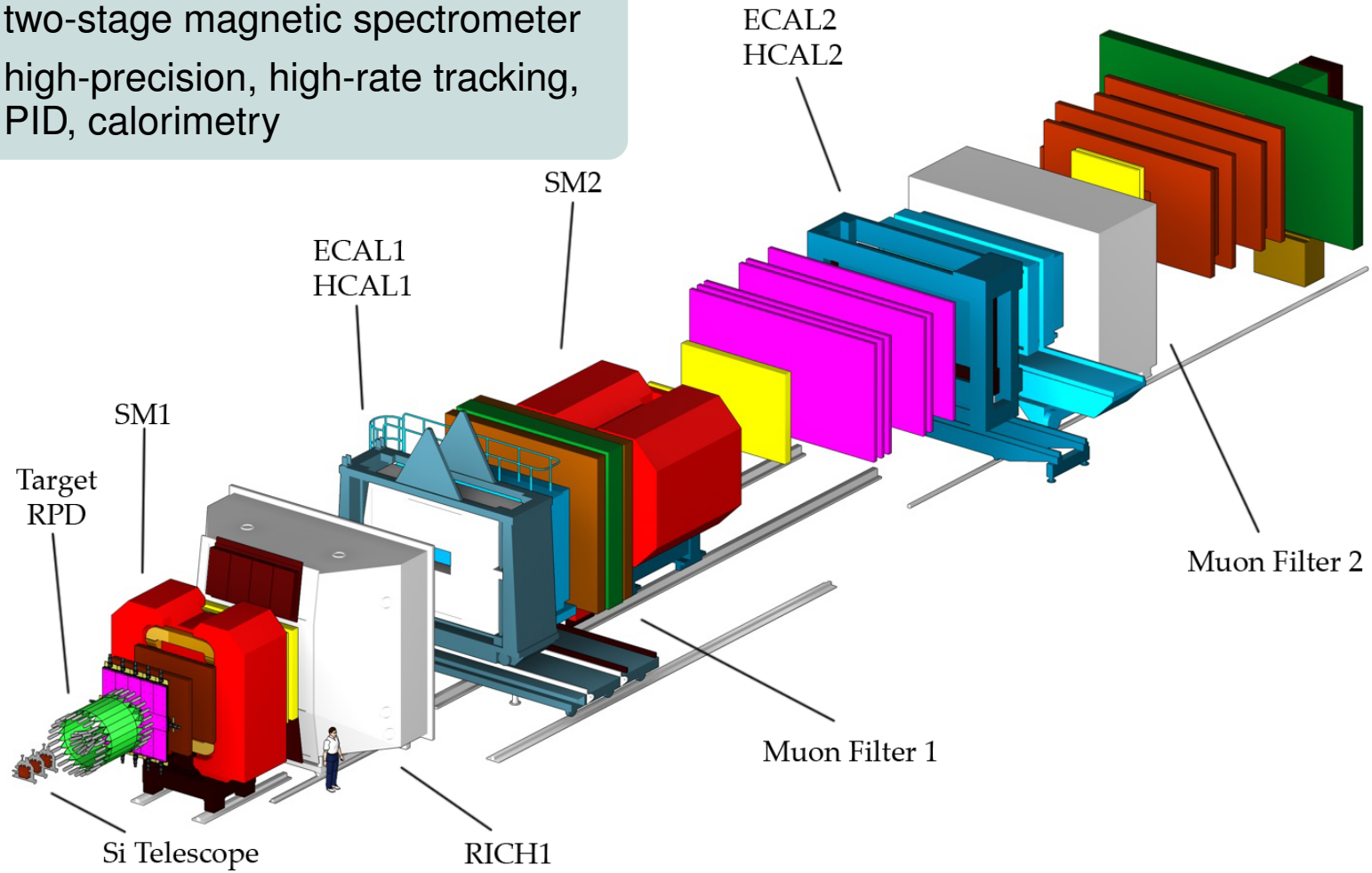


COMPASS

Experimental Setup

Fixed-target experiment

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



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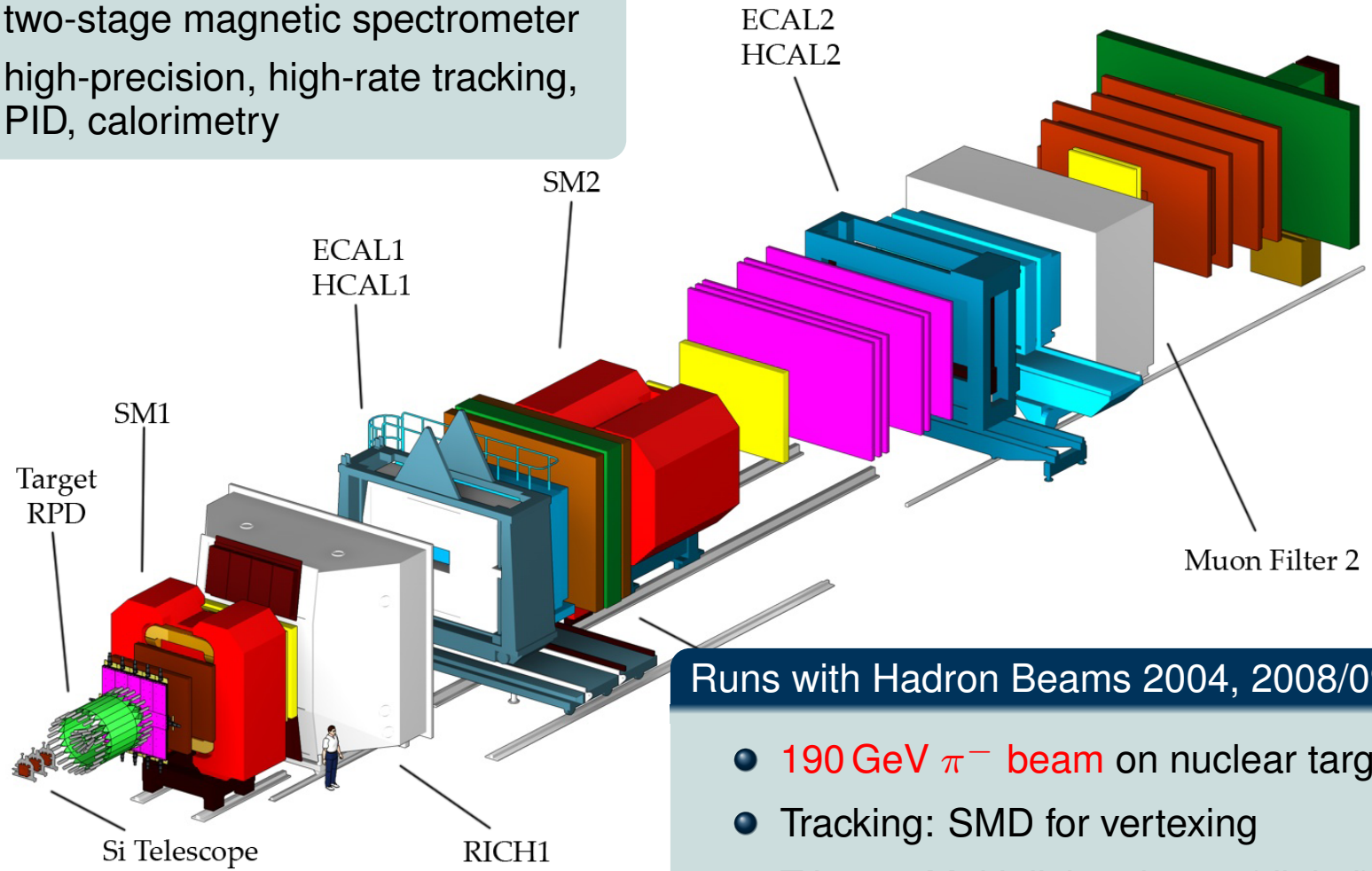


Runs with Hadron Beams 2004, 2008/09, 2012

- 190 GeV π^- beam on nuclear targets
- Tracking: SMD for vertexing
- Trigger: Multiplicity trigger, (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 ($\sim Z^2$)

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

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

Principle of the polarisability measurement

- Identify $\pi\mathrm{Ni} \to \mathrm{Ni}\pi\gamma$ exclusive reactions
  at smallest momentum transfer $< 0.001\ \mathrm{GeV}^2/c^2$

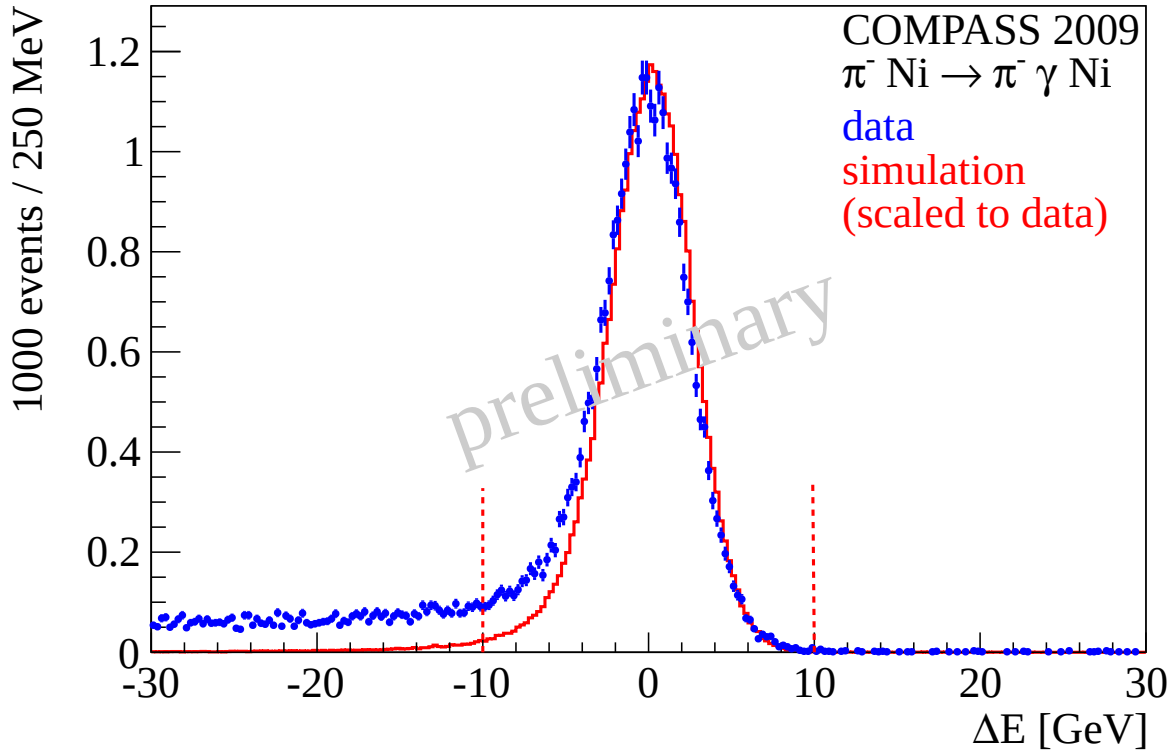
- Assuming $\alpha_\pi + \beta_\pi = 0$, the dependence on $x_\gamma = E_\gamma / E_{Beam}$

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

  is used to determine the polarisability α_π

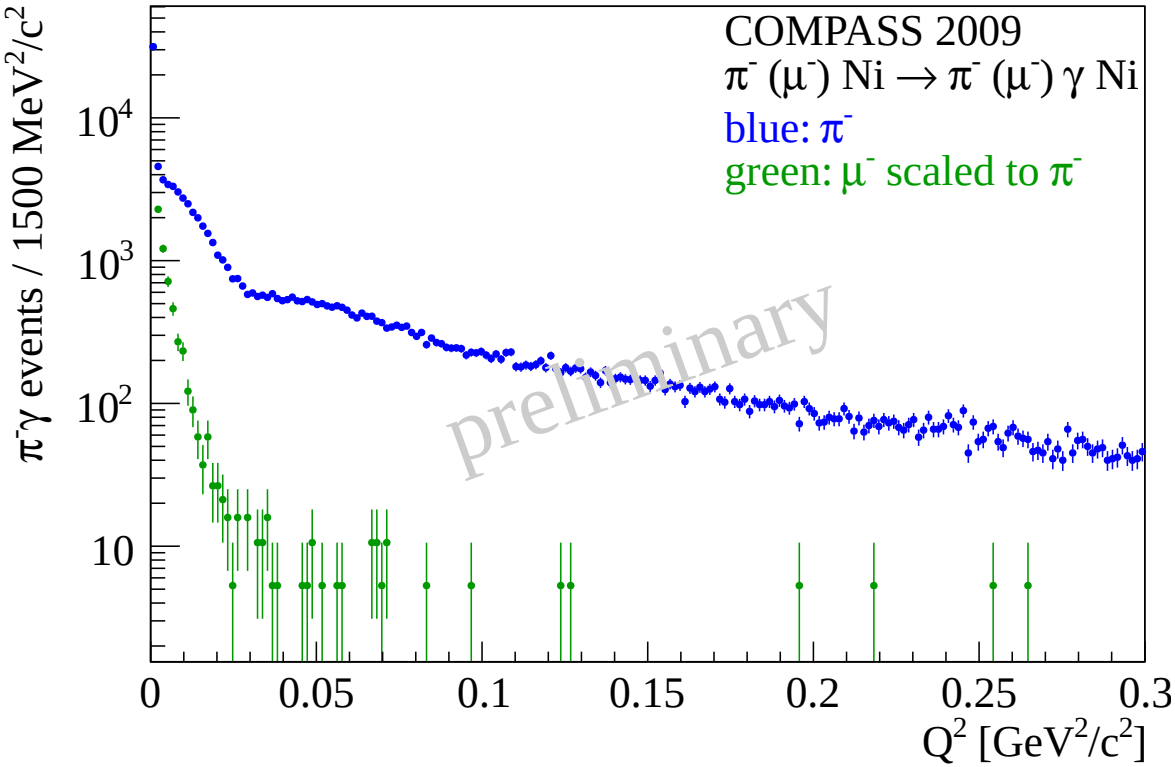
- Control systematics by investigating $\mu\mathrm{Ni} \to \mathrm{Ni}\mu\gamma$, $K^- \to \pi^-\pi^0$

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



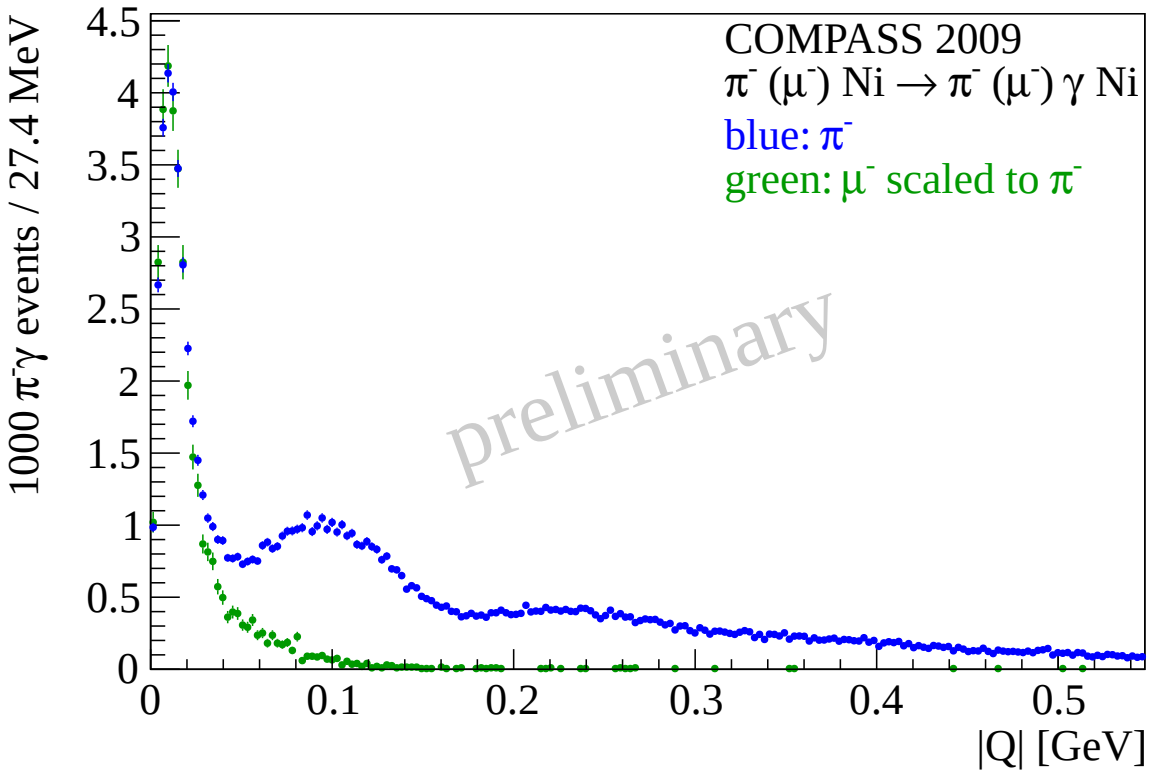
- Exclusivity peak $\sigma \approx 2.6$ GeV (COMPASS 2004 best effort ≈ 5.6)
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Primakoff peak



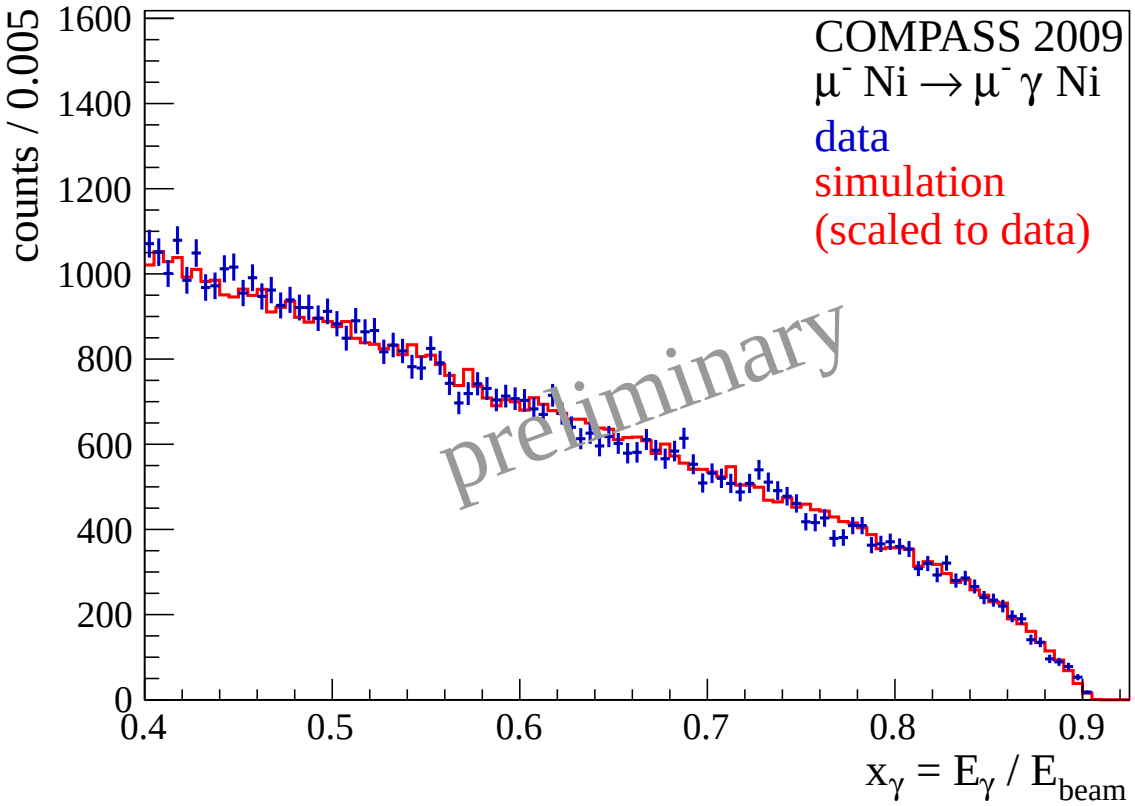
- Q^2-spectrum: photon-exchange peak in first bin
- muon control measurement:
  pure electromagnetic interaction, no polarisability effect

Primakoff peak

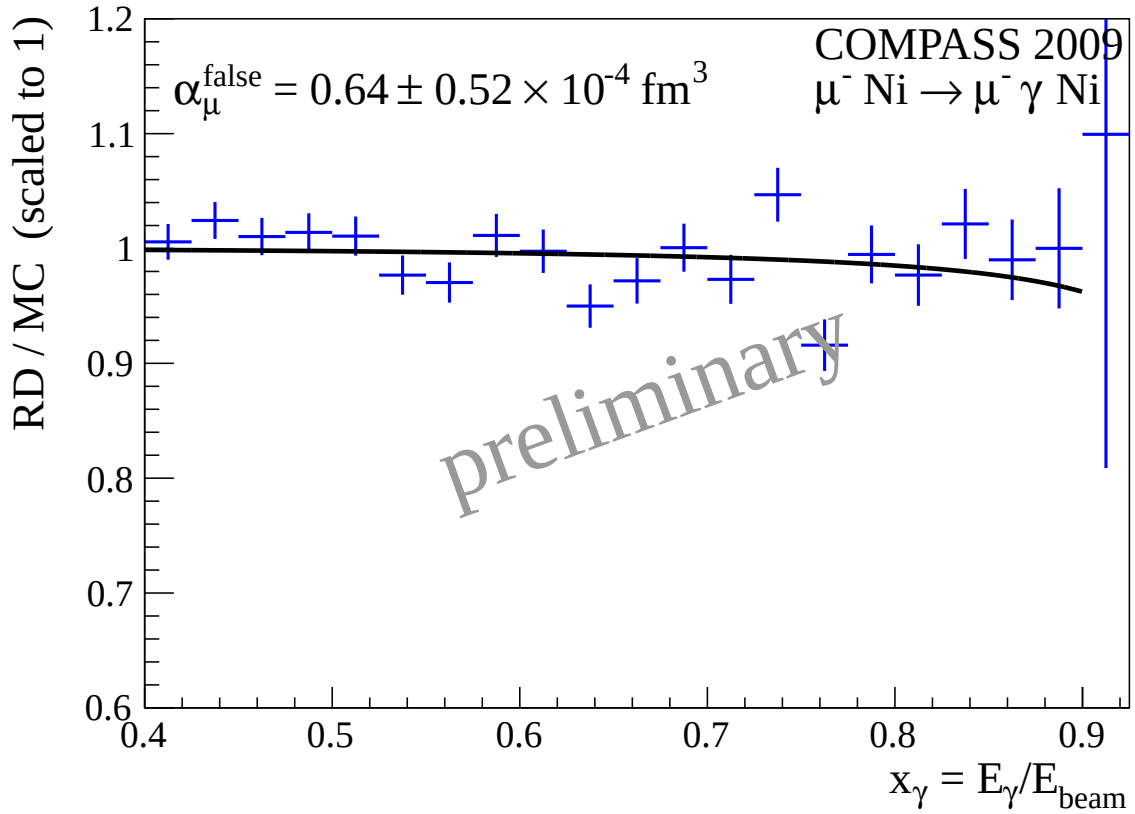


- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 170$ MeV$/c$

On the way to polarisability: Photon energy spectrum

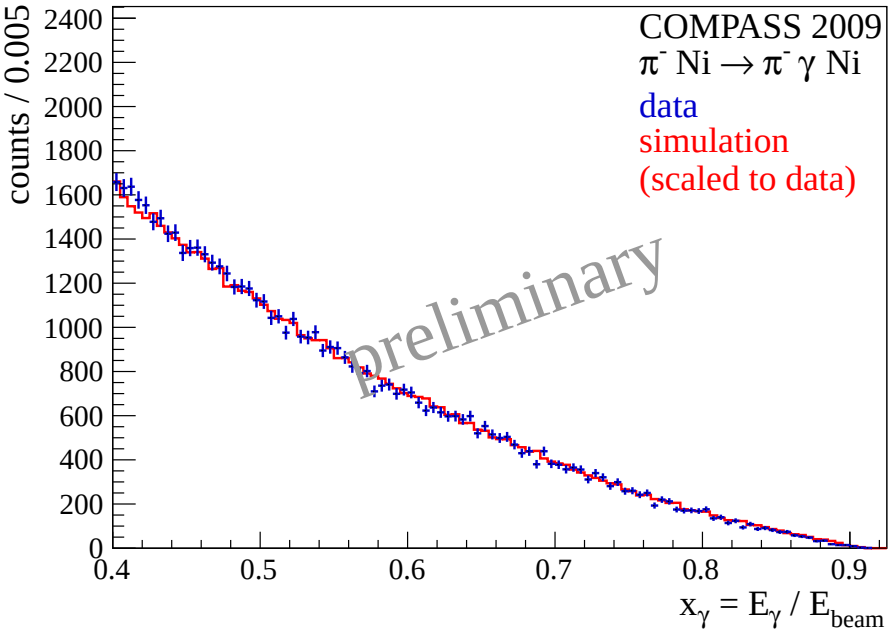


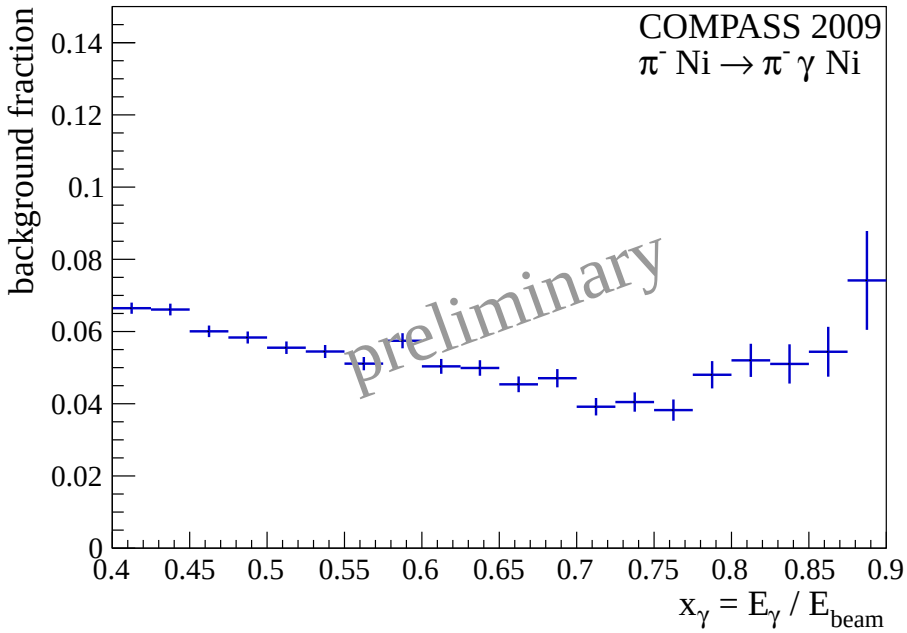
Photon energy spectrum for the muon case: RD/MC ratio



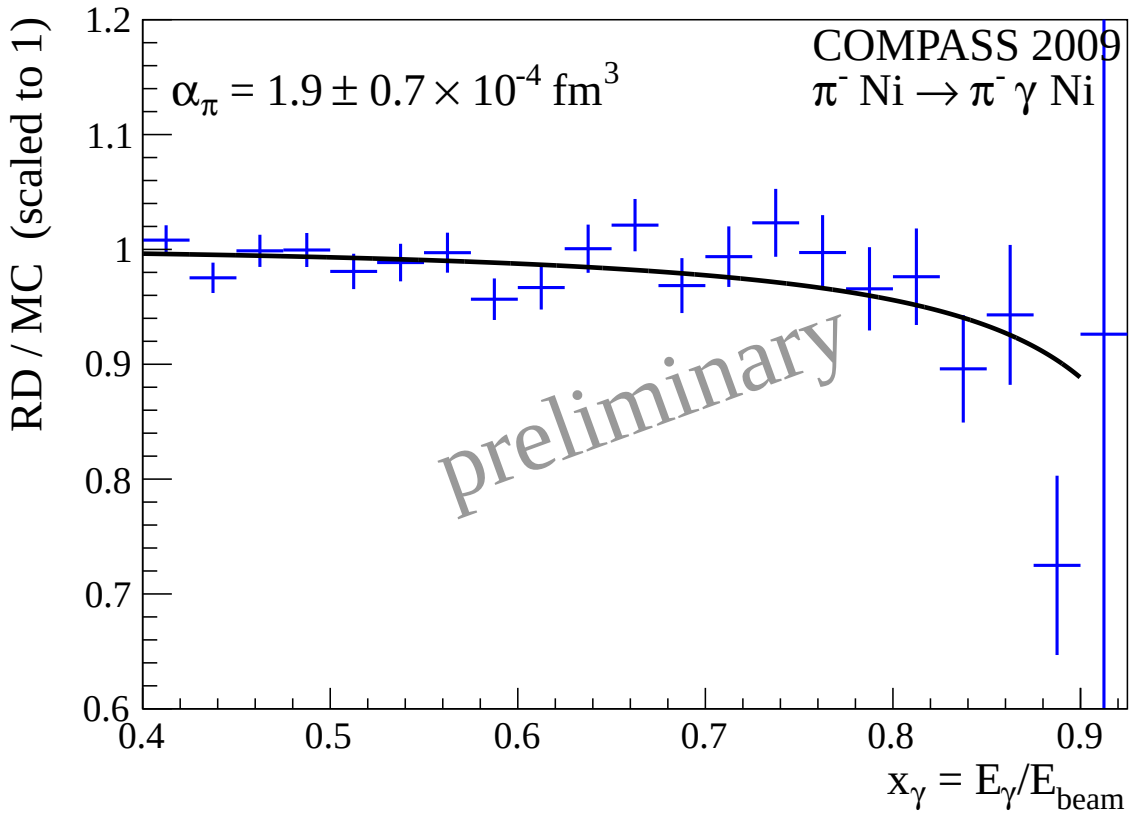
- muon data well compatible with expectation from simulation
- systematic uncertainty from sources common to pions and muons $\approx 0.6 \times 10^{-4}$ fm^3

Photon energy spectrum for pions





Pion polarisability – preliminary COMPASS result



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

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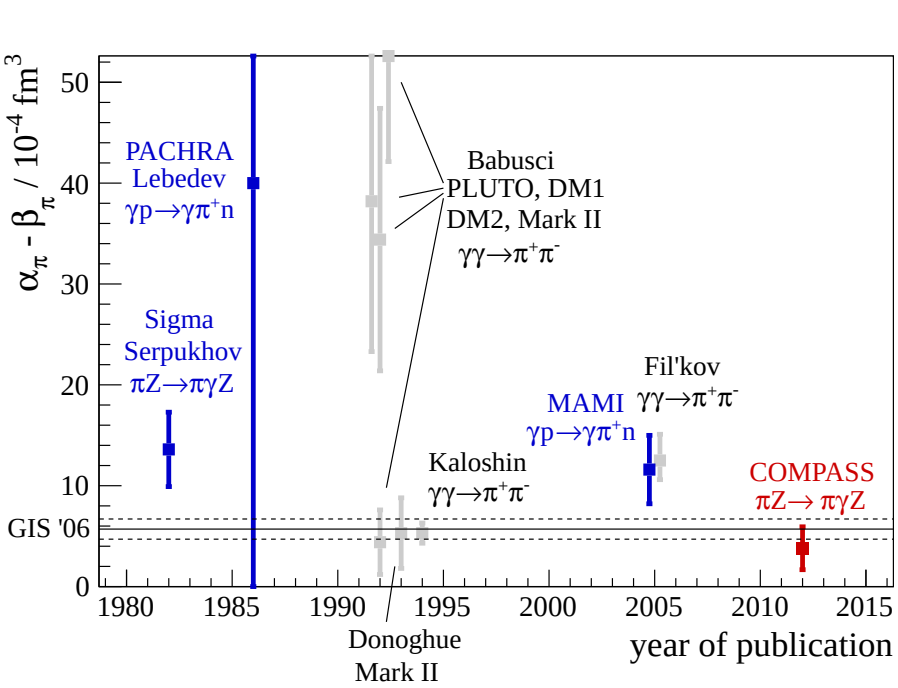
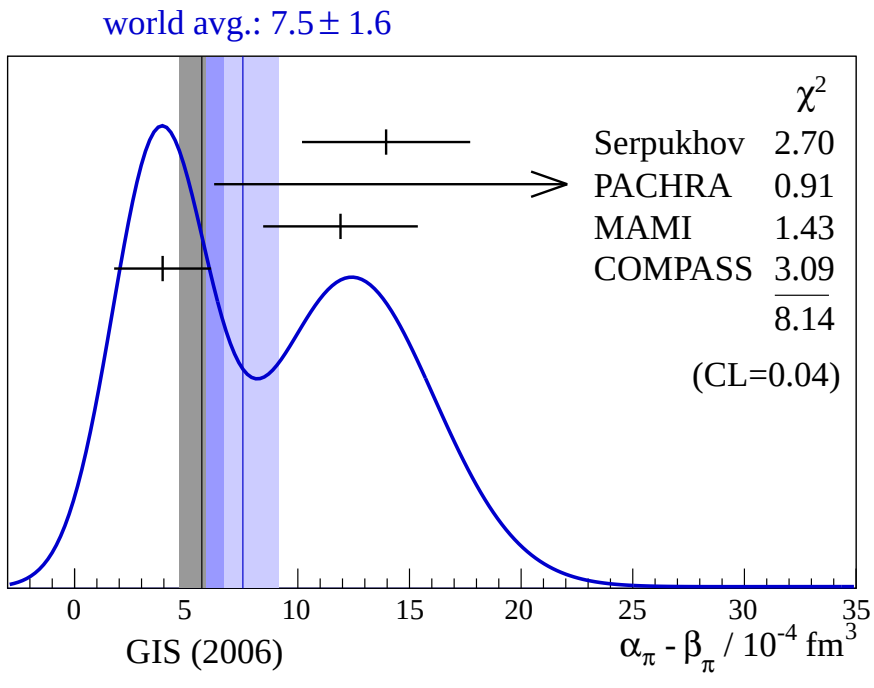
COMPASS preliminary:

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

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

Primakoff reactions accessible at COMPASS

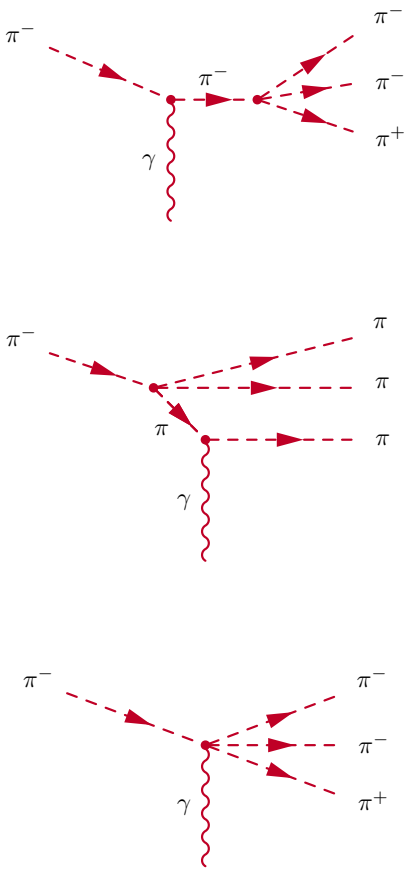
Access to $\pi + \gamma$ reactions via the Primakoff effect:

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

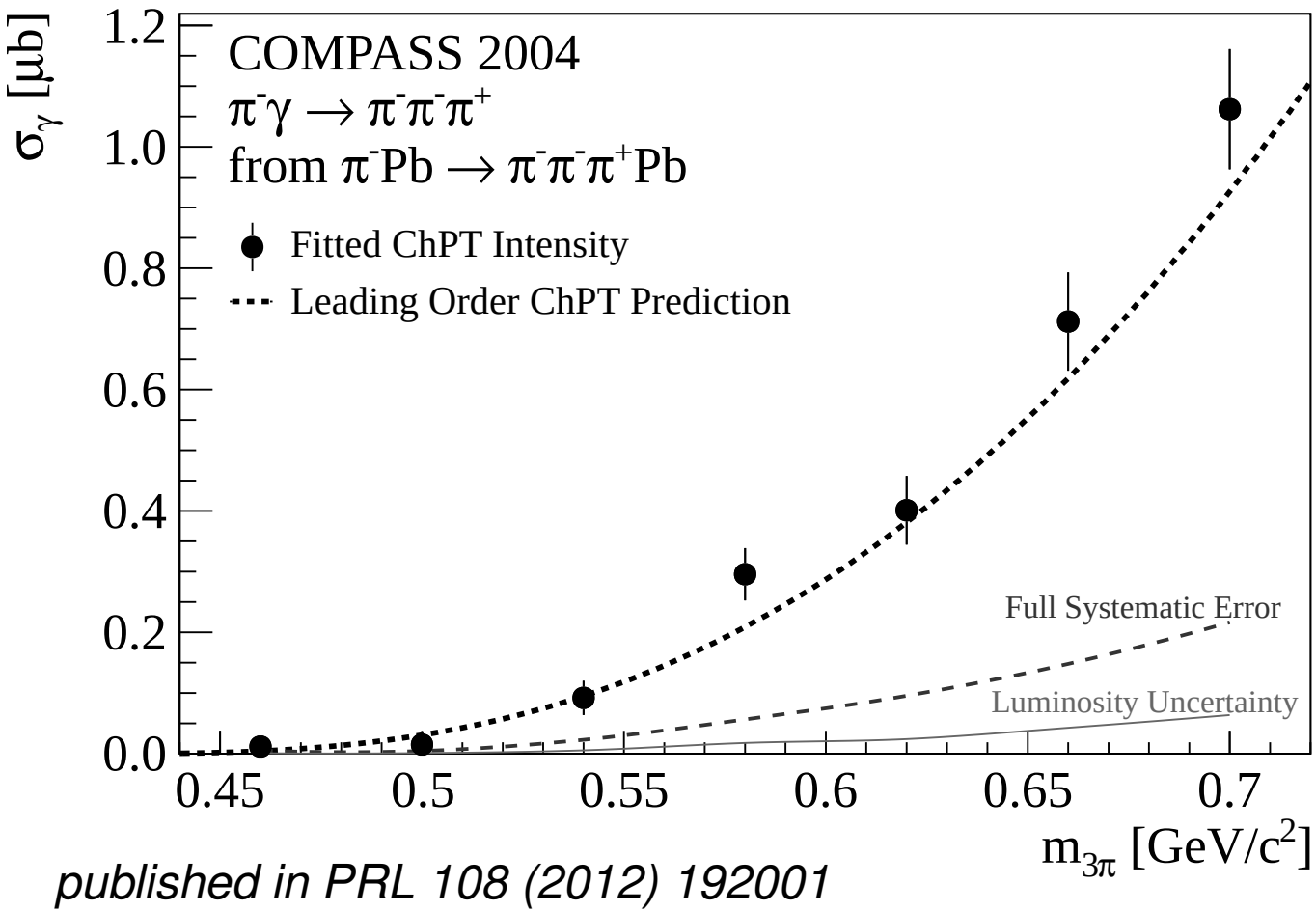
$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \ / \ \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \quad \Longleftarrow \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + \ldots \end{cases}$$

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

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

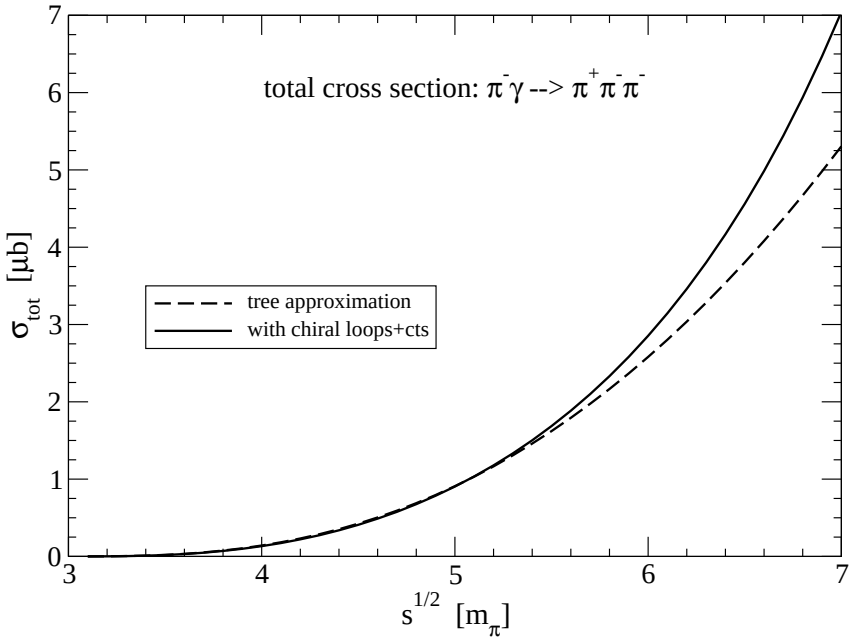


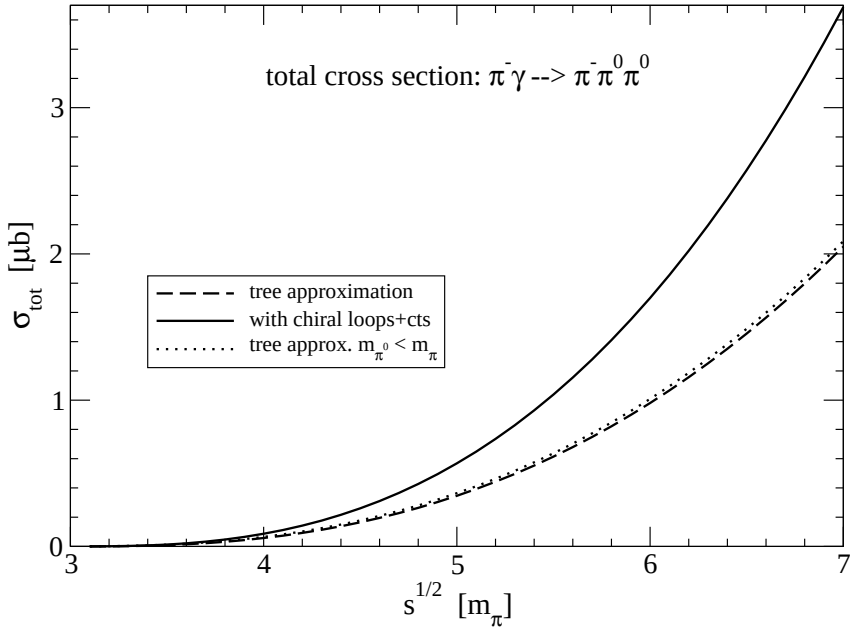
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



published in PRL 108 (2012) 192001

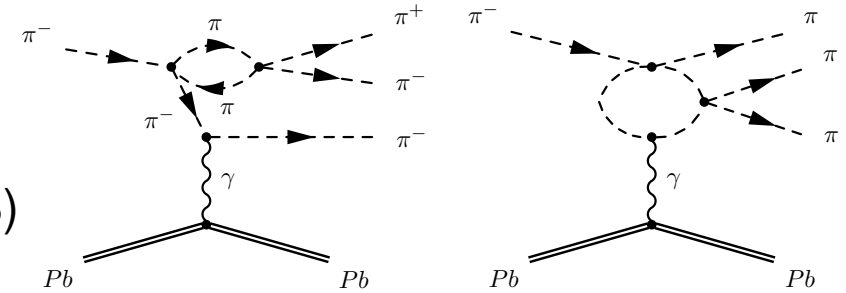
Higher-order effects



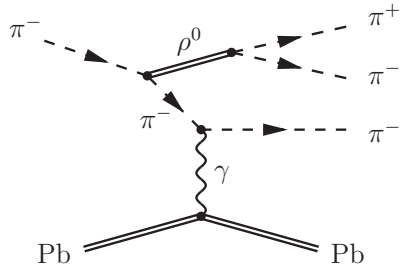


Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)



not (yet) included:



Summary and Outlook

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

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

  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
- Chiral dynamics in $\pi\gamma \to \pi\pi\pi$ 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
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

COMPASS: *unique apparatus for Primakoff measurements tackling a broad physics program*