High-Energy Hadron Scattering at Low Momentum Transfer: Chiral Dynamics, Pion Polarisability, Radiative Couplings

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on leave of absence from

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for the COMPASS collaboration

ATHOS 2013 workshop

Kloster Seeon, 21.5.2013

supported by: Maier-Leibnitz-Labor der TU und LMU München,

Excellence Cluster: Origin and Structure of the Universe, BMBF

High-E Reactions: Momentum Transfer Regimes

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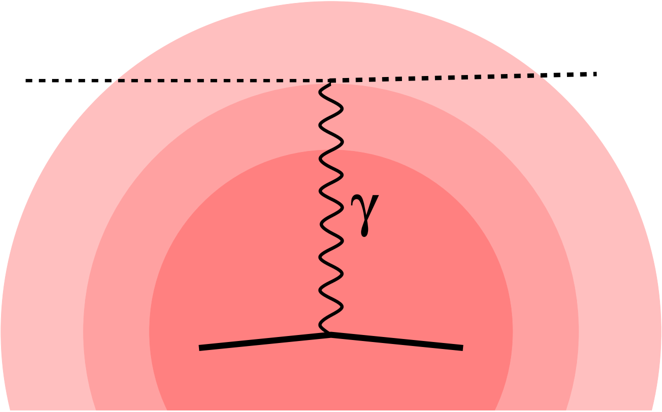
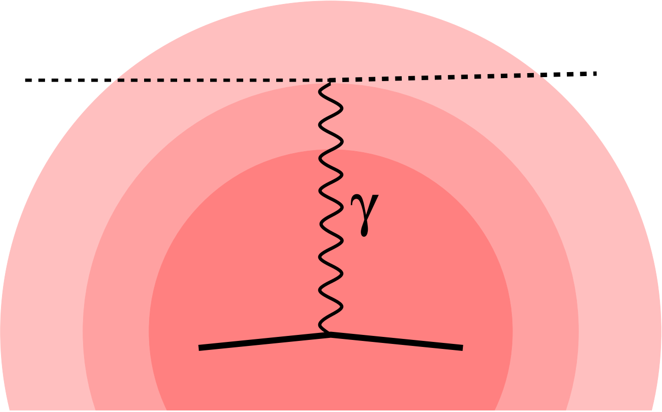


- Small momentum transfer ⇔ large distance in coordinate space
- At large distance the long-range el.mag. potential dominates

High-E Reactions: Momentum Transfer Regimes



- Photon propagator ⇔ Fourier transform of (real) el.mag. potential

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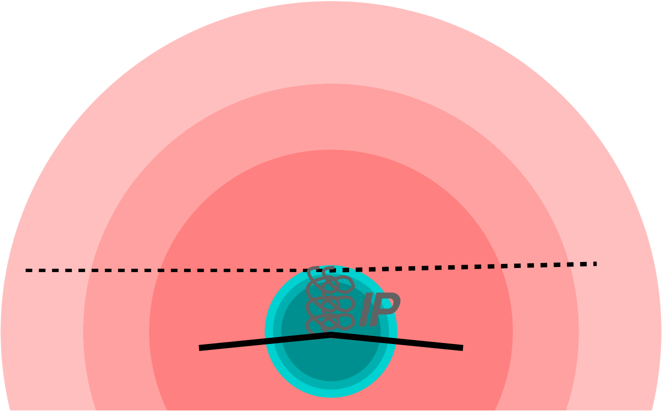

- Diffractive regime: Pomeron $\Leftrightarrow$ Effect of (imaginary) strong potential
- Obtained in the *Glauber model* as integral along the flight path

High-E Reactions: Momentum Transfer Regimes

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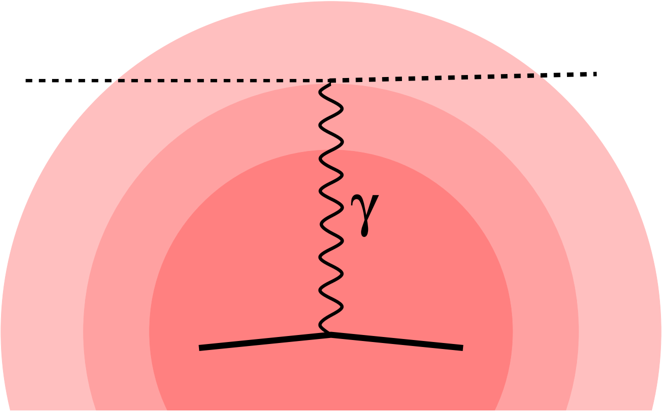
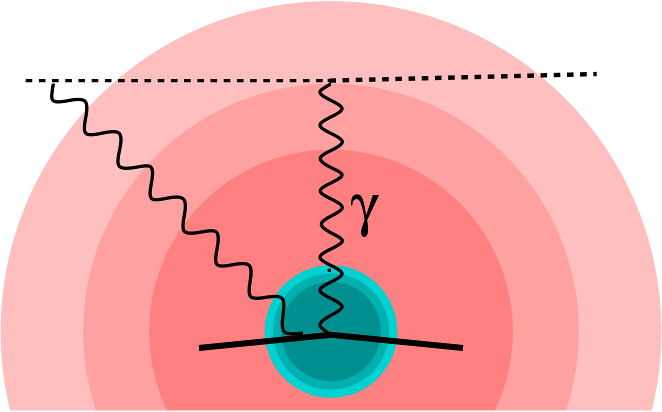


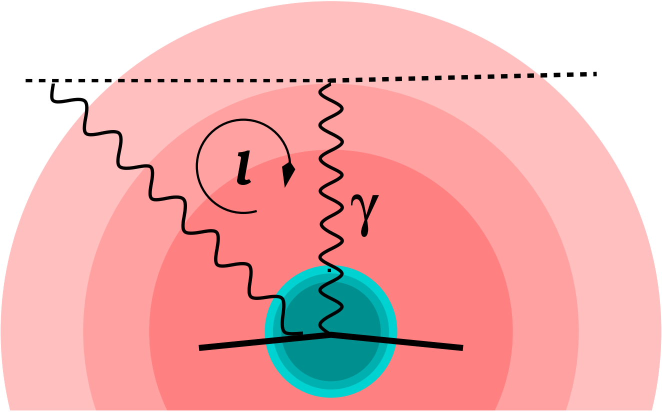
- Analogously for the el.mag. potential, the *Coulomb phase* is obtained
- no observable effect for elastic scattering on static, large-mass potential

High-*E* Reactions: Momentum Transfer Regimes



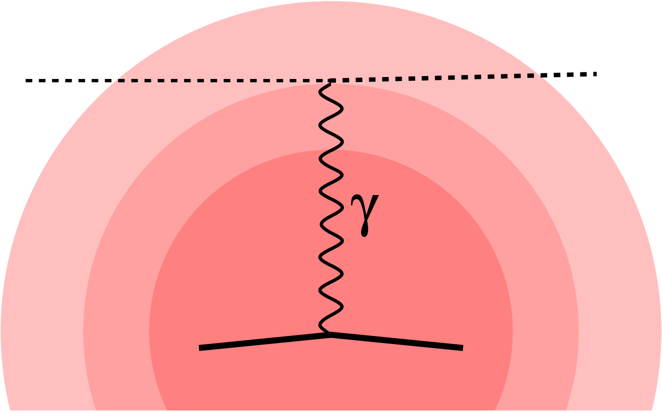
- sizeable effect of the Coulomb phase for inelastic processes
- QFT treatment: multi-photon exchange

High-E Reactions: Momentum Transfer Regimes



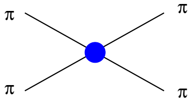
- loop integral involves full excitation spectra → imaginary part
- recoil not treated in potential (phase-shift) analysis

High-E Reactions: Momentum Transfer Regimes

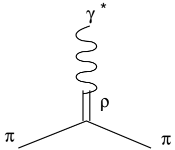


Chiral Perturbation Theory vs. Experiment

- 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



- 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]

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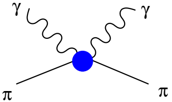

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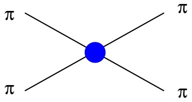

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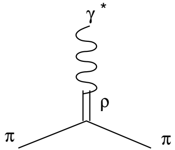

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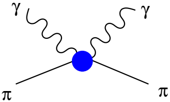

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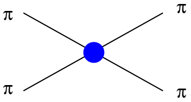

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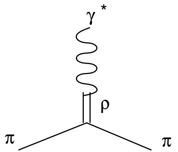

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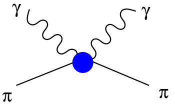

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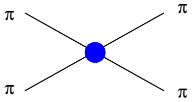

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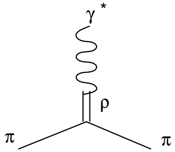

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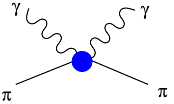
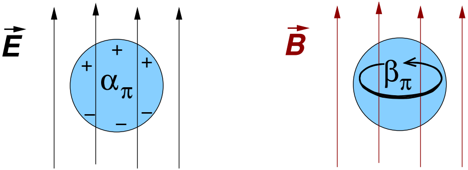


how to measure α_π and β_π?

One of the ChPT predictions: pion polarisability

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

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±1.0 $\alpha_\pi + \beta_\pi =$ 0.16

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

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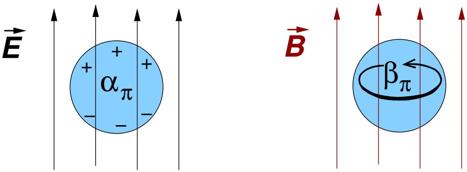

polarisabilities α_π, β_π [10^{-4} fm^3]

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

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Exemplifying the size of the pion polarisability

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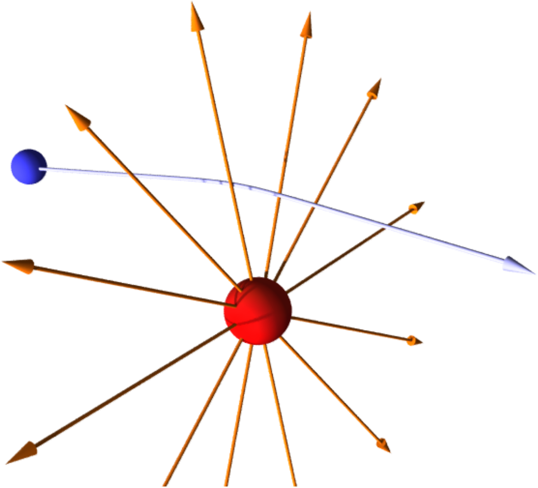
Primakoff measurement technique

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



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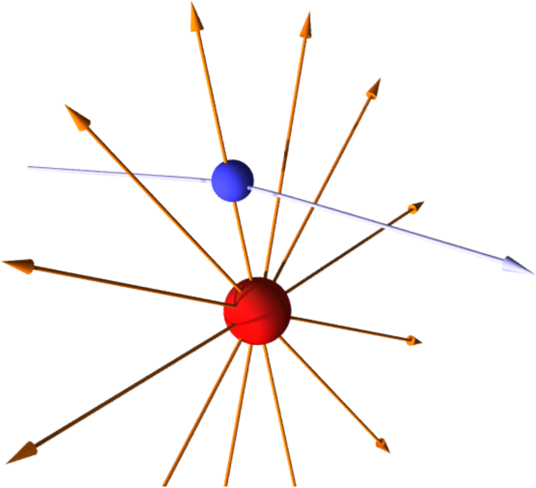

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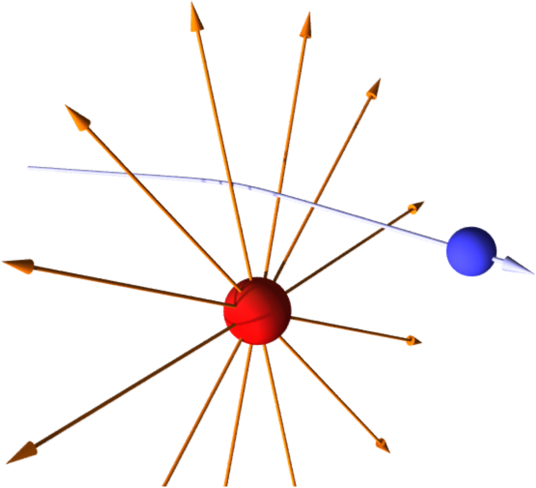

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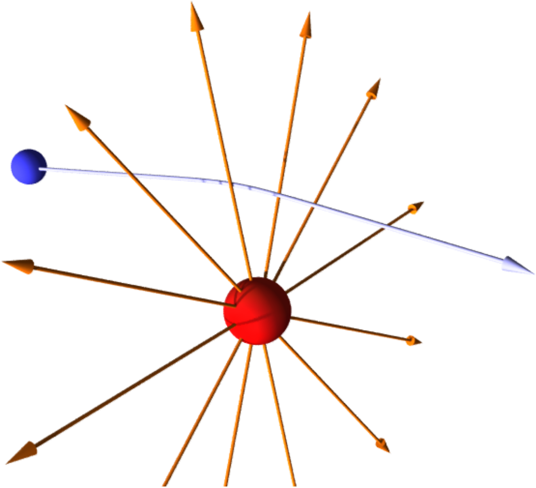

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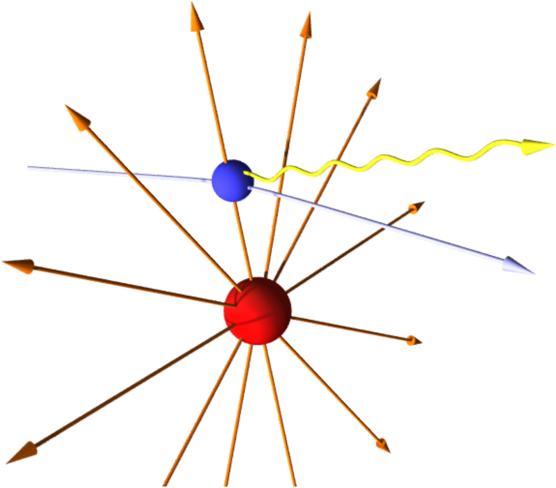

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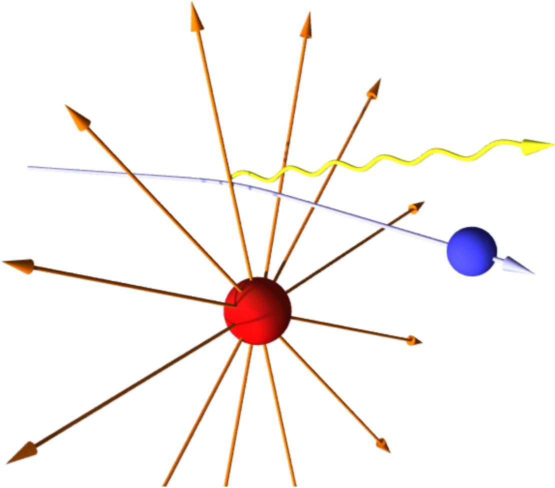

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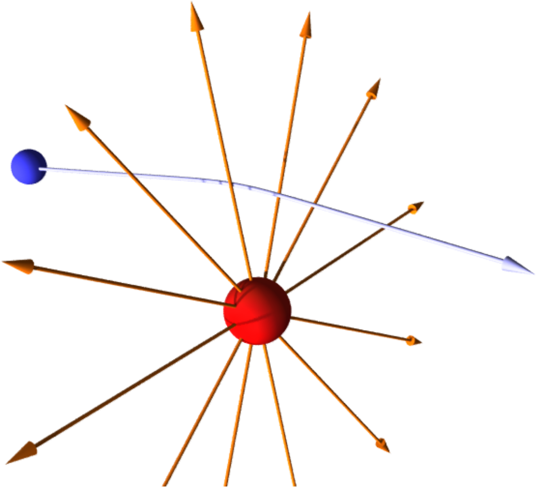
  - Theory prediction: $\alpha_\pi^{\text{ChPT}} = 2.9 \pm 0.5 \cdot 10^{-4}\ \text{fm}^3$
  - expected charge separation $\sim 10^{-5}\ \text{fm} \cdot e$



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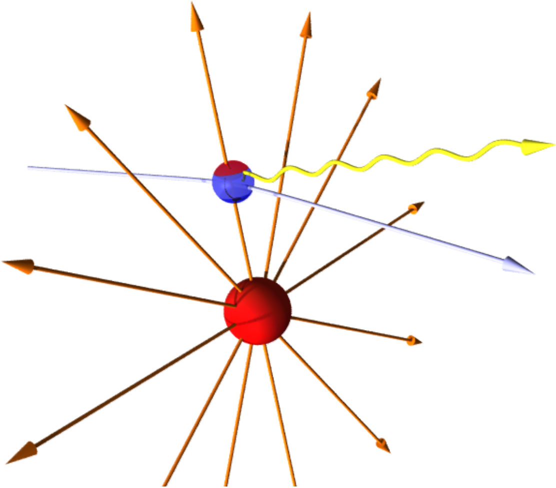

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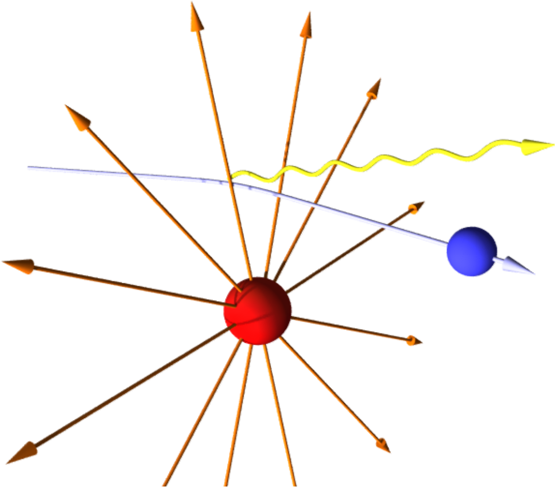
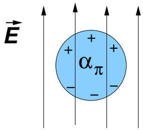
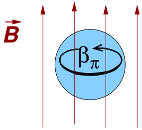


Pion Compton Scattering

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





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

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

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$z_\pm = 1 \pm \cos\theta_{cm}$ $\quad\alpha = 1/137$ 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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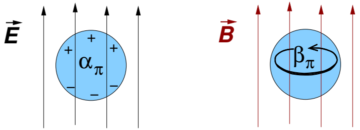

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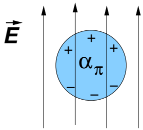

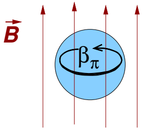

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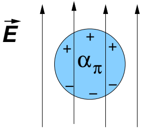
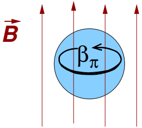




- Two kinematic variables, in CM: total energy $\sqrt{s}$, scattering angle θ_{cm}

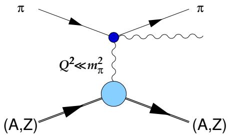
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2 (s^2 z_+^2 + m_\pi^4 z_-^2)}{s(s z_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\, (s - m_\pi^2)^2}{4s^2 (s z_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

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

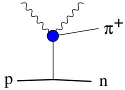
$z_\pm = 1 \pm \cos\theta_{cm}$ $\alpha = 1/137$ fine structure constant (!)

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

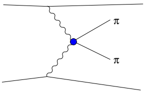
Pion polarisability: world data before COMPASS



Primakoff process

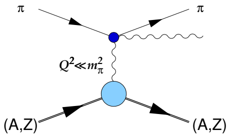


Radiative pion photoproduction



Photon-Photon fusion

Pion polarisability: world data before COMPASS



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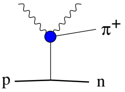

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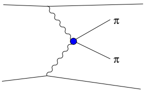

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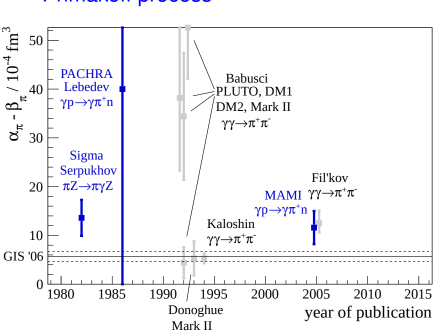

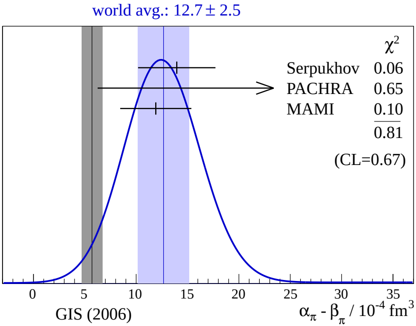

GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006)
plots from Thiemo Nagel, PhD thesis, TUM 2012

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 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.

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

  and

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

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and

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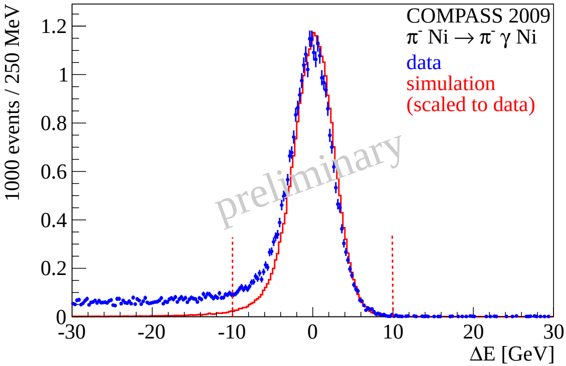
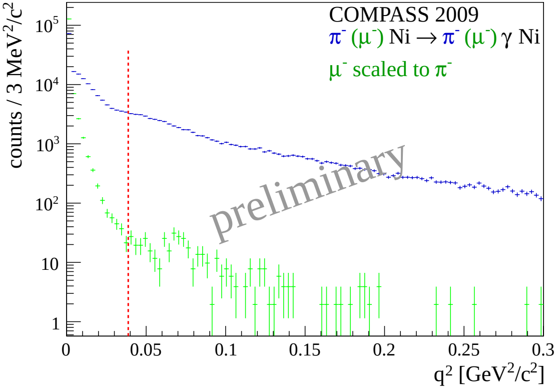
Identifying the $\pi\gamma \to \pi\gamma$ reaction



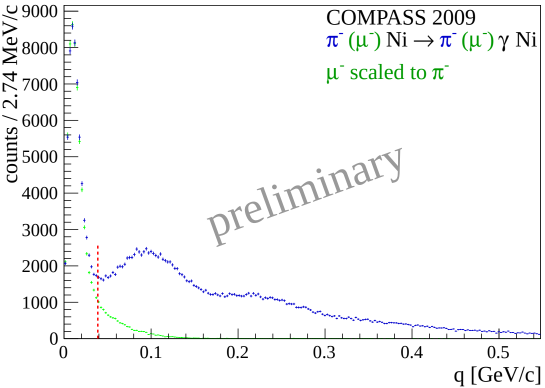
- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Primakoff peak



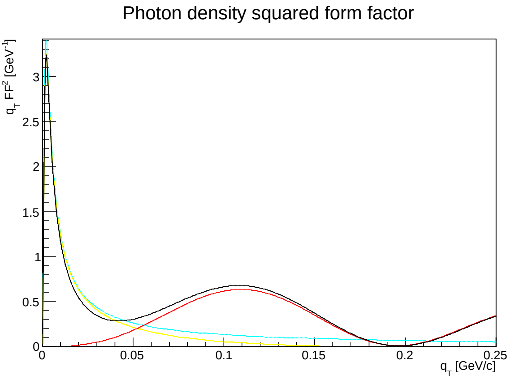
- Q^2-spectrum: photon-exchange peak in first bin
- muon control measurement:
  pure electromagnetic interaction, no polarisability effect

Primakoff peak



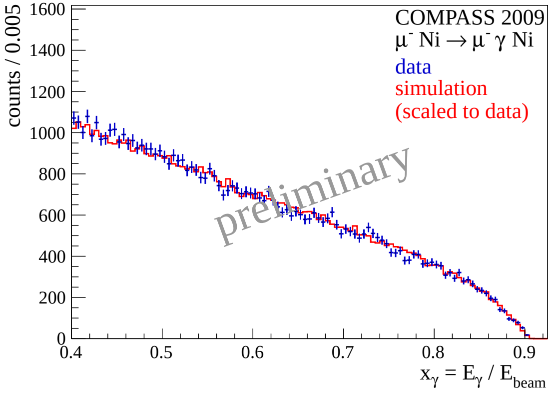
- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam → requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$

Coulomb-nuclear interference

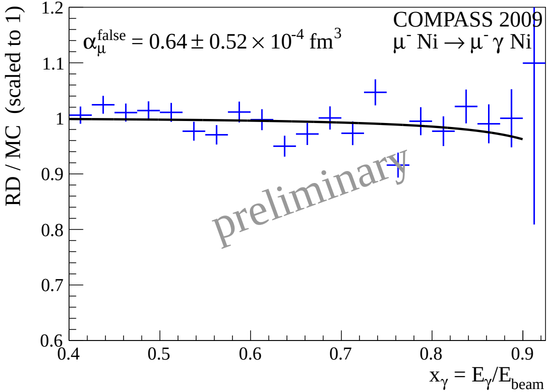


- Calculation following a 2009 paper of Göran Fäldt (Uppsala)
- Eikonal approximation: pions cross Coulomb and strong-interaction potentials

On the way to polarisability: Photon energy spectrum

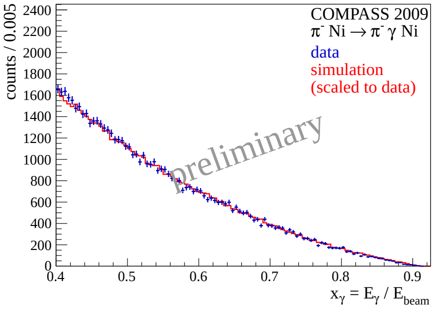


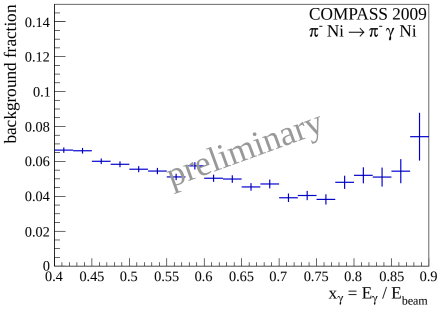
Photon energy spectrum for the muon case: RD/MC ratio



- 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

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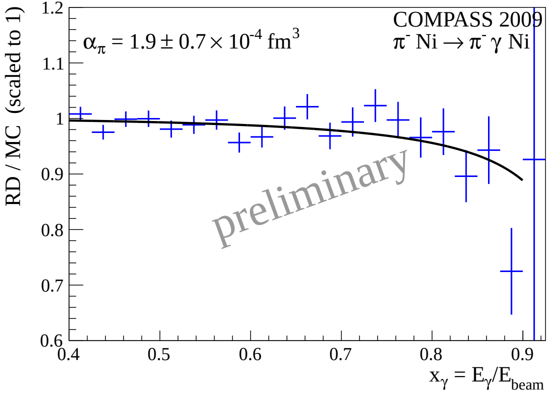

source of systematic uncertainty	estimated magnitude CL $= 68\,\%$ $[10^{-4}\,\text{fm}^3]$
tracking	0.6
radiative corrections	0.3
background subtraction in Q	0.4
pion electron scattering	0.2
quadratic sum	0.8

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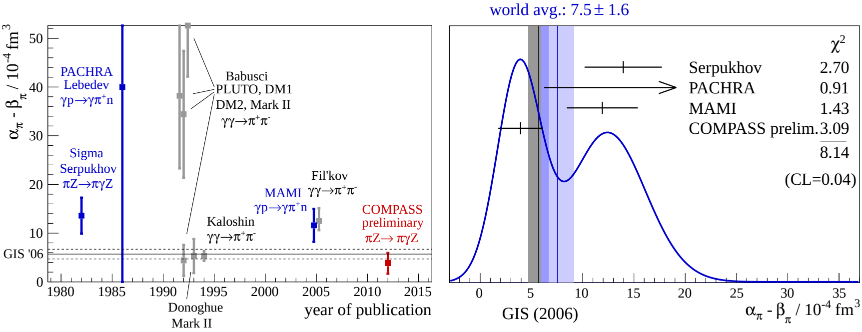
COMPASS preliminary:

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

Pion polarisability: world data including COMPASS

Technische Universität München



- 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:

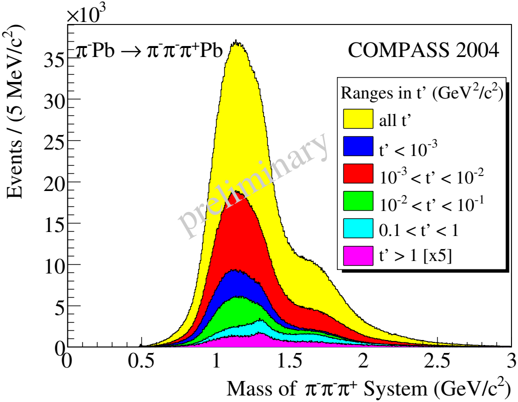
At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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

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

2004 Primakoff results

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



- "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

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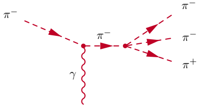
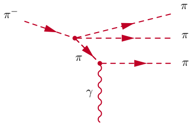
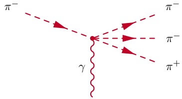
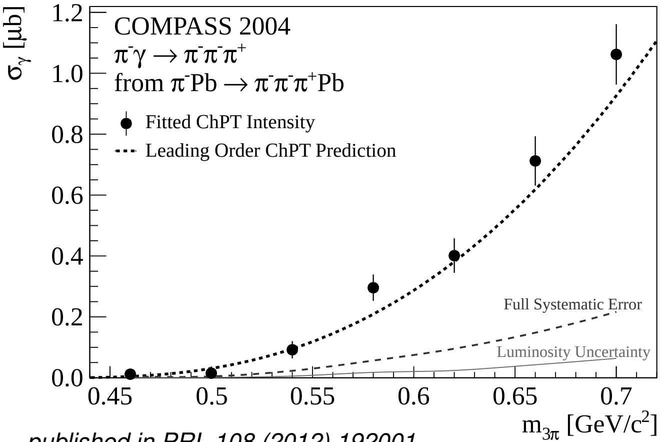




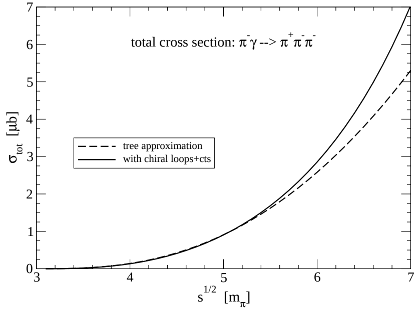


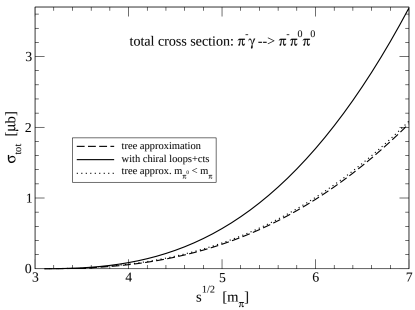
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



published in PRL 108 (2012) 192001

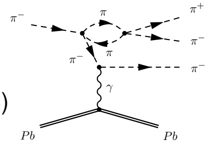
Higher-order effects

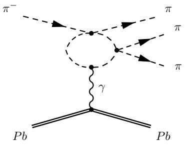




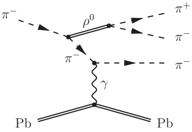
Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)





not (yet) included:



2004 Primakoff results on the resonances

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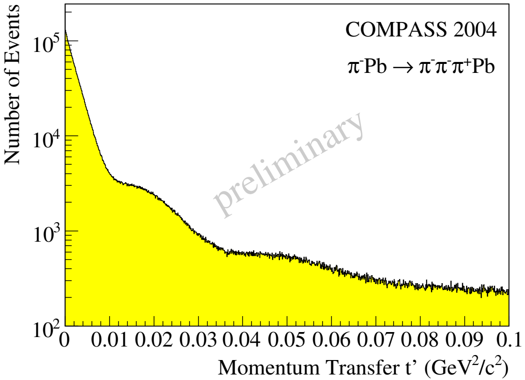
$$\pi^-\ \mathrm{Pb} \to \mathrm{Pb}\ \pi^-\ \pi^-\ \pi^+$$



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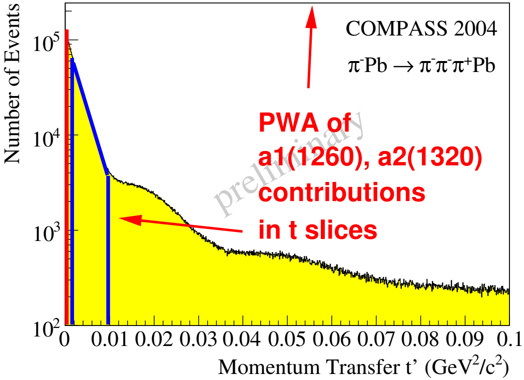

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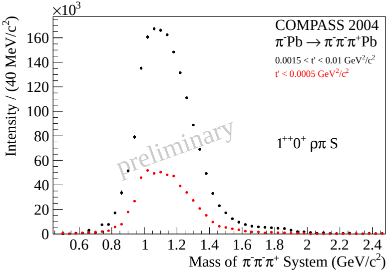
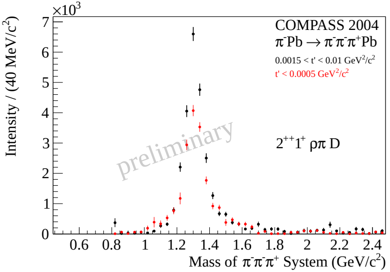
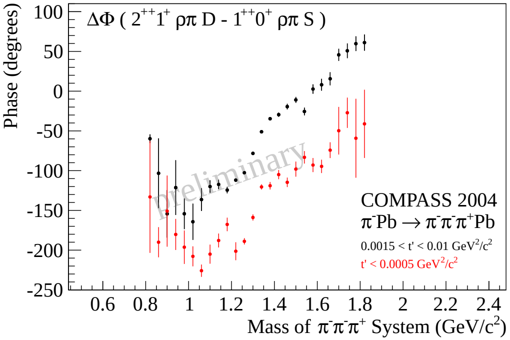
PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions







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

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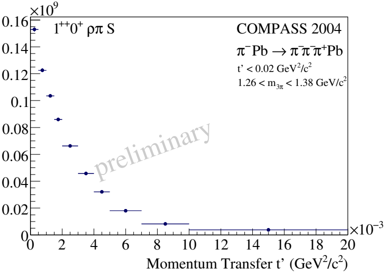
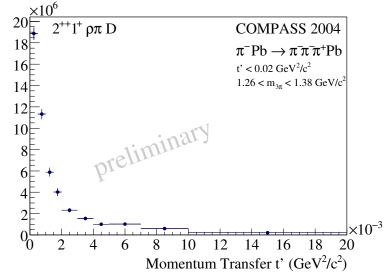
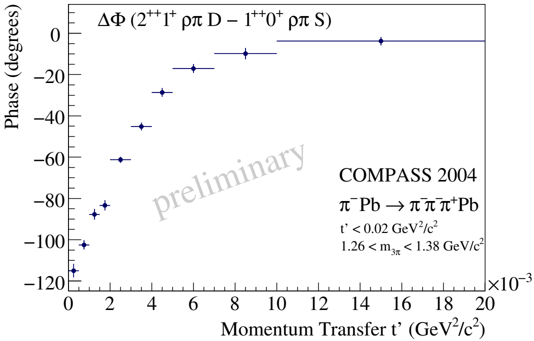
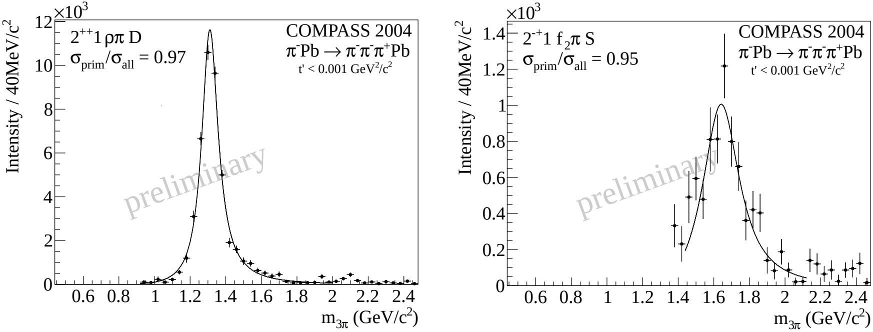






- transition of $\pi\gamma$ to $\pi I\!P \rightarrow a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

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



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

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

$\Leftrightarrow$ meson w.f.'s: $\Gamma_{i\to f} \propto |\langle\Psi_f|\, e^{-i\vec{q}\cdot\vec{r}}\, \hat{\epsilon}\cdot\vec{p}\,|\Psi_i\rangle|^2$, VMD

- normalization via beam kaon decays
- large Coulomb correction ($\sim$ 35%) *still to be applied*

Summary and Outlook

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

    $\alpha_\pi = 1.9 \pm 0.7_{\text{stat}} \pm 0.8_{\text{syst}} \times 10^{-4}\,\text{fm}^3$ 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 of $a_2, \pi_2, \ldots$
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability