Pion Polarizability Status Report

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M. Moinester, Pion Polarizability Status Report (2017), Conference C17-07-31,
https://arxiv.org/ftp/arxiv/papers/1709/1709.05159.pdf

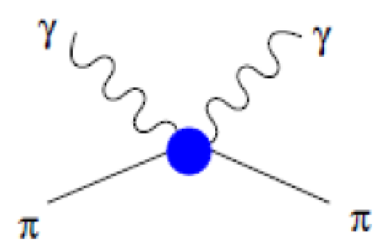
S. Scherer, M. Moinester, International Journal of Modern Physics A,
Pion Polarizability Review, ~ May 2019

Gamma-pion Compton scattering, $\gamma\pi \rightarrow \gamma\pi$, depends mainly on the pion's charge. The next order scattering depends on the pion's electric & magnetic dipole moments.These are induced by the electric and magnetic fields of the gamma during $\gamma\pi$ scattering: $d=\alpha E$, $\mu=\beta H$. Pion polarizabilities probe the rigidity of the quark-antiquark structure of the pion.

Chiral Perturbation Theory

Chiral perturbation theory (ChPT), based on an effective chiral Lagrangian, successfully describes interactions between pions (including photons) in the **non-perturbative low energy regime** of the strong interaction. Lagrangian expressed in terms of low-energy constants (LECs), determined by fitting to experimental data or derived from underlying theory.

- pion polarisability: electric α_π, magnetic β_π
  - leading structure-dependent contribution to Compton scattering
  - ChPT prediction obtained by the relation to $\pi^+ \to e^+ \nu_e \gamma$ [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]
    [PIBETA, M. Bychkov et al., PRL 103, 051802, 2009]



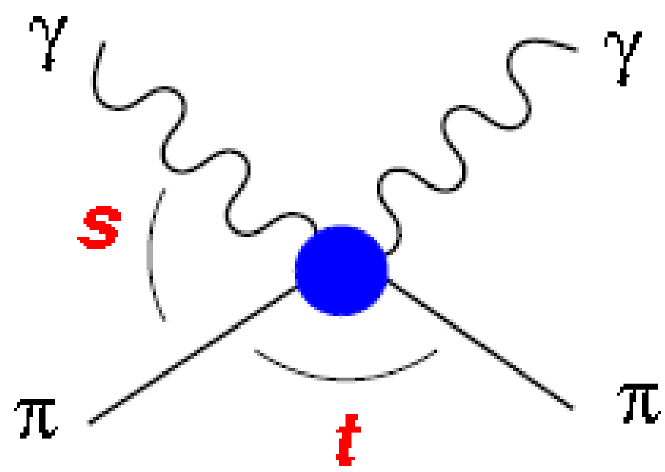
pion polarisabilities α_π, β_π in units of 10^{-4} fm^3

ChPT (2-loop) prediction:

$$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \qquad \alpha_\pi = 2.93 \pm 0.5$$

$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \qquad \beta_\pi = -2.77 \pm 0.5$$

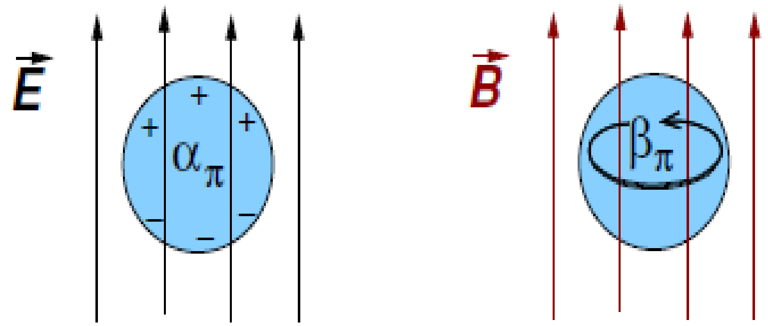
Compton cross section



- $s = (p + p_\gamma)^2$ (squared) CM energy of the $\pi\gamma$-system
- $t = (p - p_\pi)^2 \sim \cos\theta_{CM}$
- The polarisabilities α_π and β_π enter
  - with increasing s
  - as $\alpha_\pi - \beta_\pi$ in backward angles
  - as $\alpha_\pi + \beta_\pi$ in forward angles (small, but s-enhanced)
  - as $\alpha_2 - \beta_2$ with $(s - m_\pi^2)^2/s$ dependence

Pion Compton Scattering

$$\pi \; \gamma \; \rightarrow \; \pi \; \gamma$$



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

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

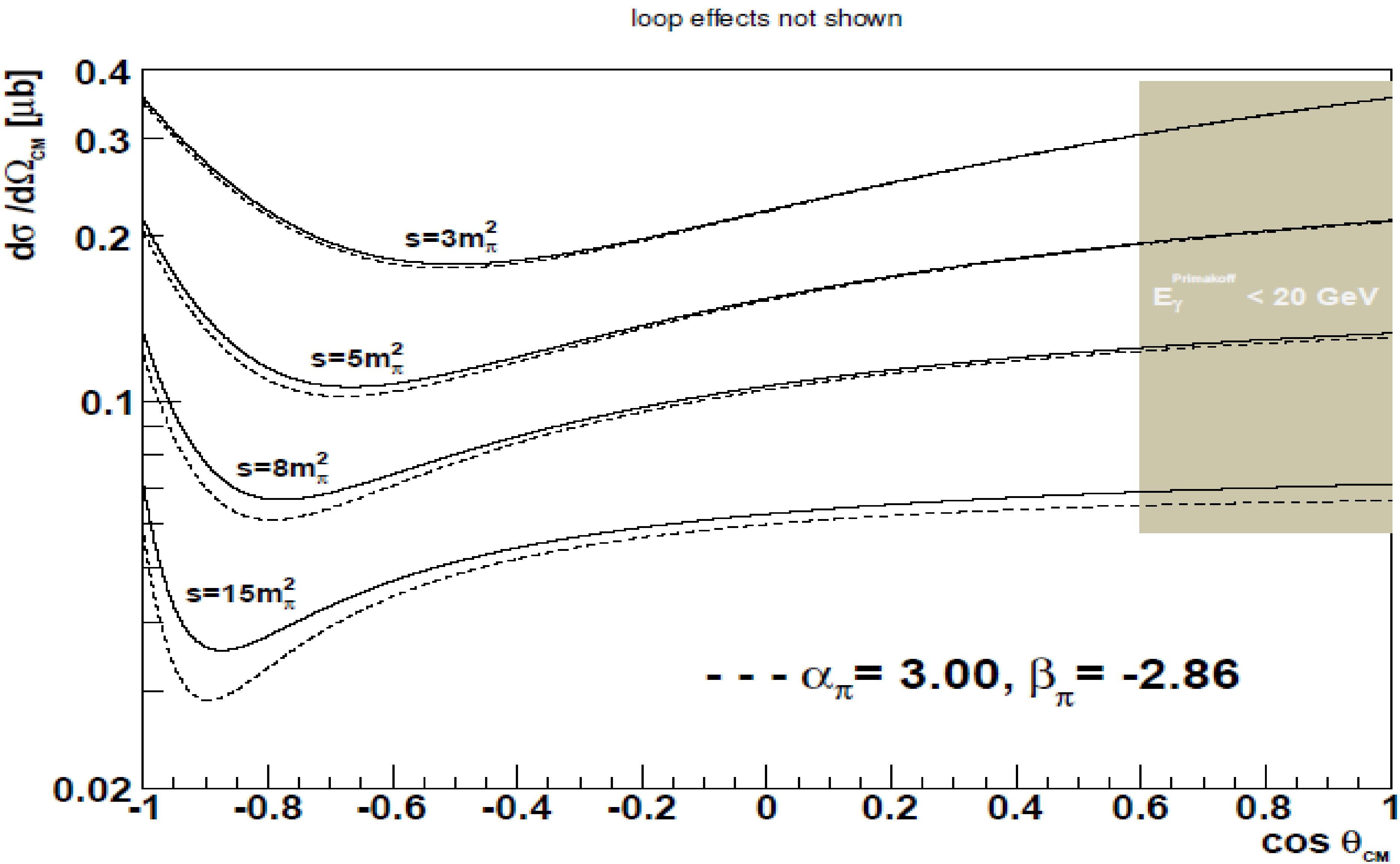
$$\mathcal{P} = z_-^2\,(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2 (\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3 (\alpha_2 - \beta_2)$$

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

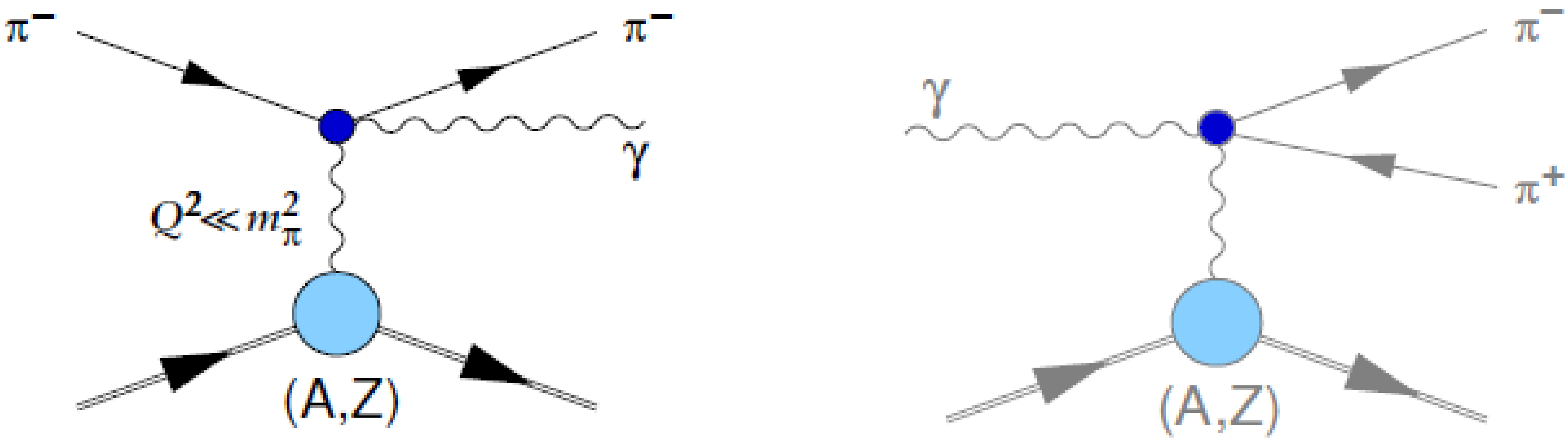
- $\sigma_{tot}(s)$ rather insensitive to pion's low-energy structure
- Up to 20% effect on *backward* angular distributions of $d\sigma/d\Omega_{cm}$

Polarisability effect (NLO ChPT values)

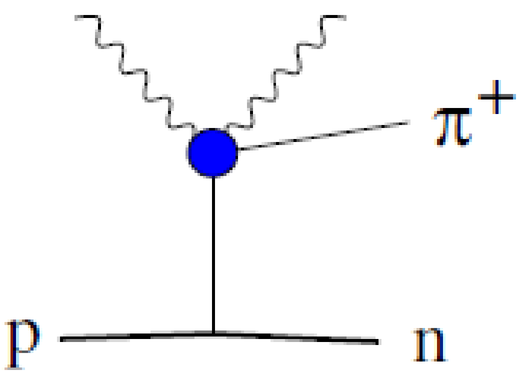
Pion polarizabilities affect the shape of the γπ Compton scattering angular distribution.



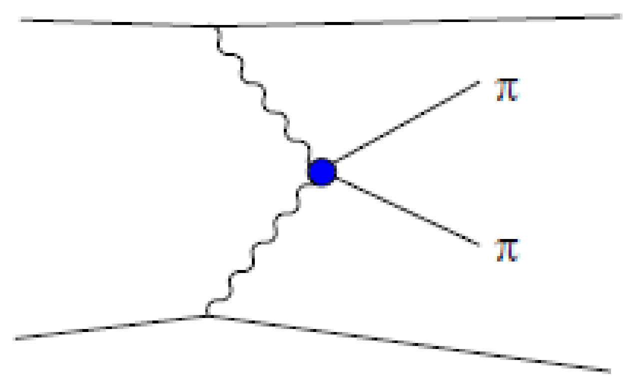
Pion Compton scattering: embedding the process



Primakoff processes



Radiative pion photoproduction



Photon-Photon fusion

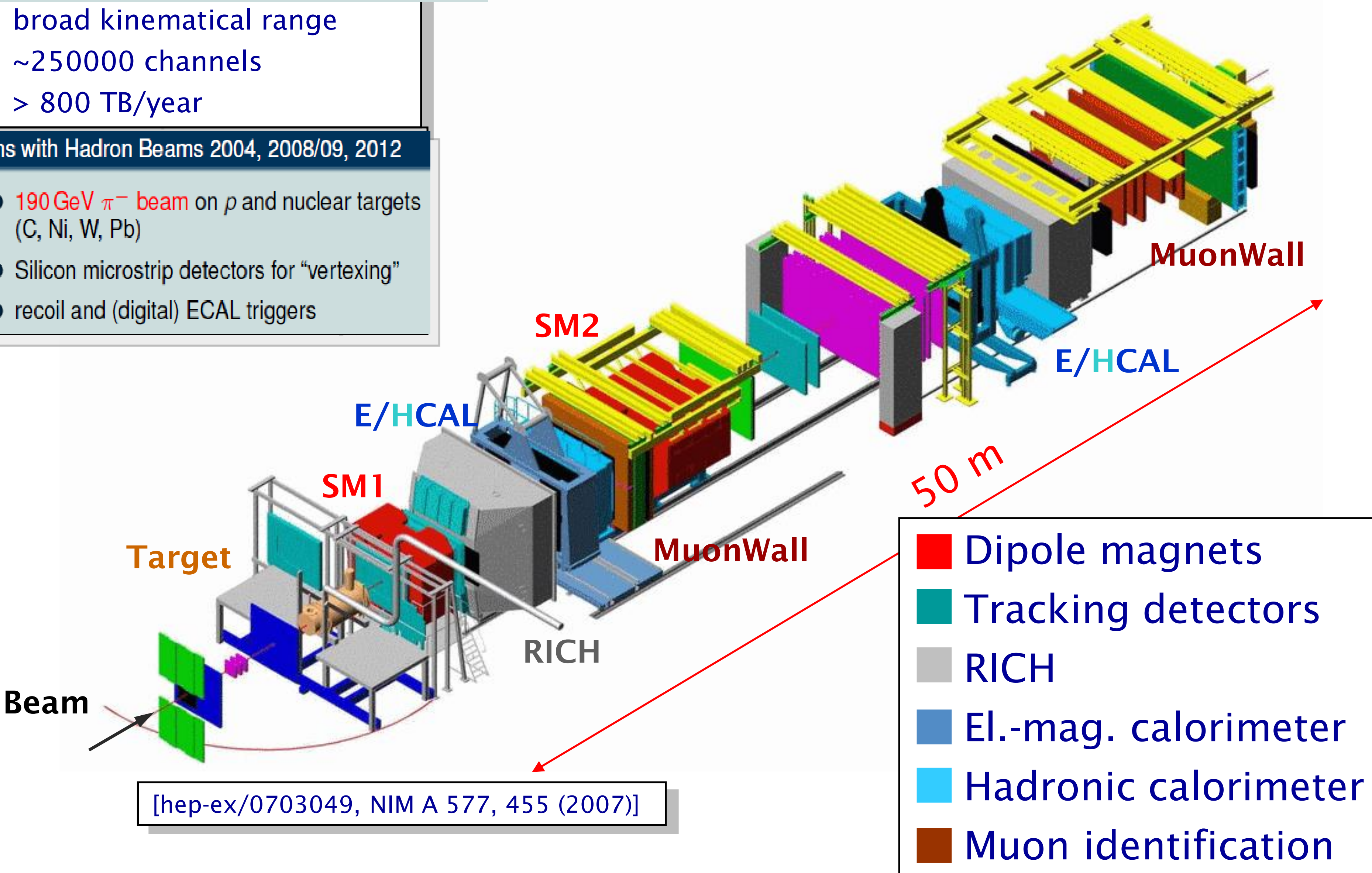
The COMPASS Experiment

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry
- broad kinematical range
- ~250000 channels
- > 800 TB/year

Runs with Hadron Beams 2004, 2008/09, 2012

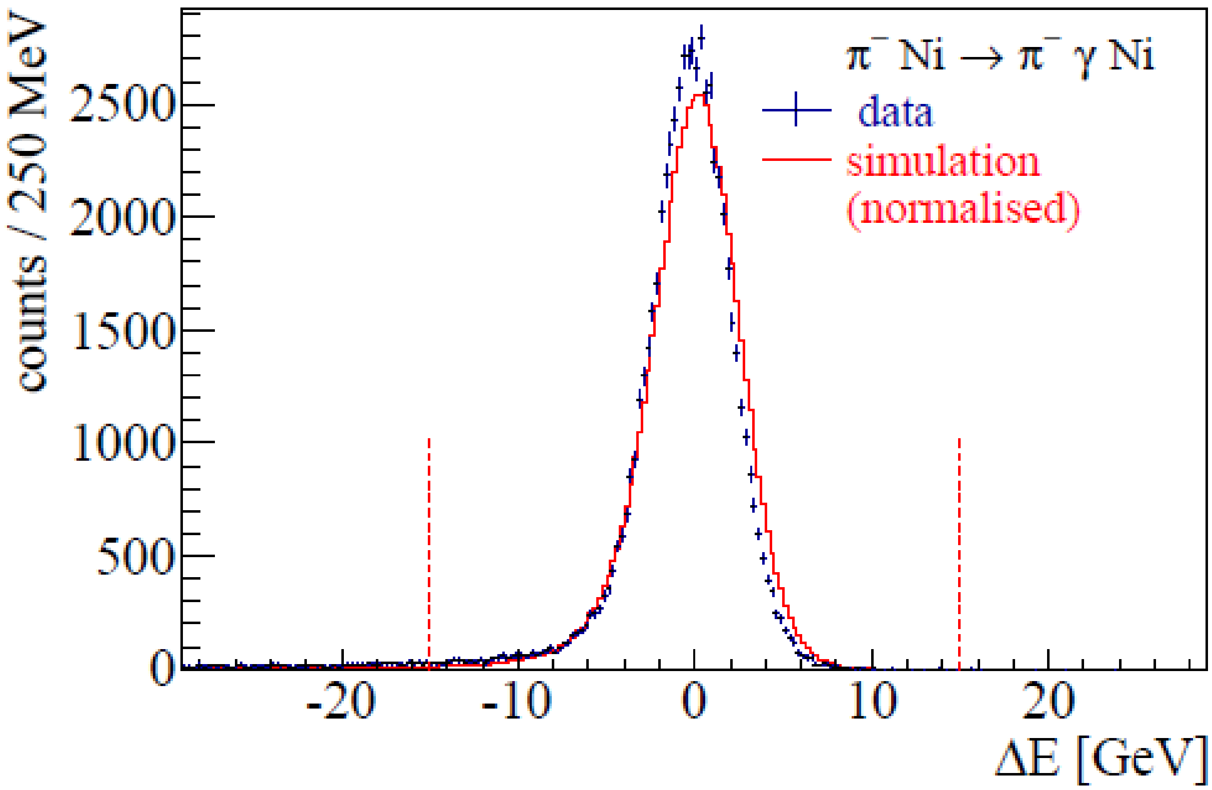
- 190 GeV π^- beam on p and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for "vertexing"
- recoil and (digital) ECAL triggers



[hep-ex/0703049, NIM A 577, 455 (2007)]

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

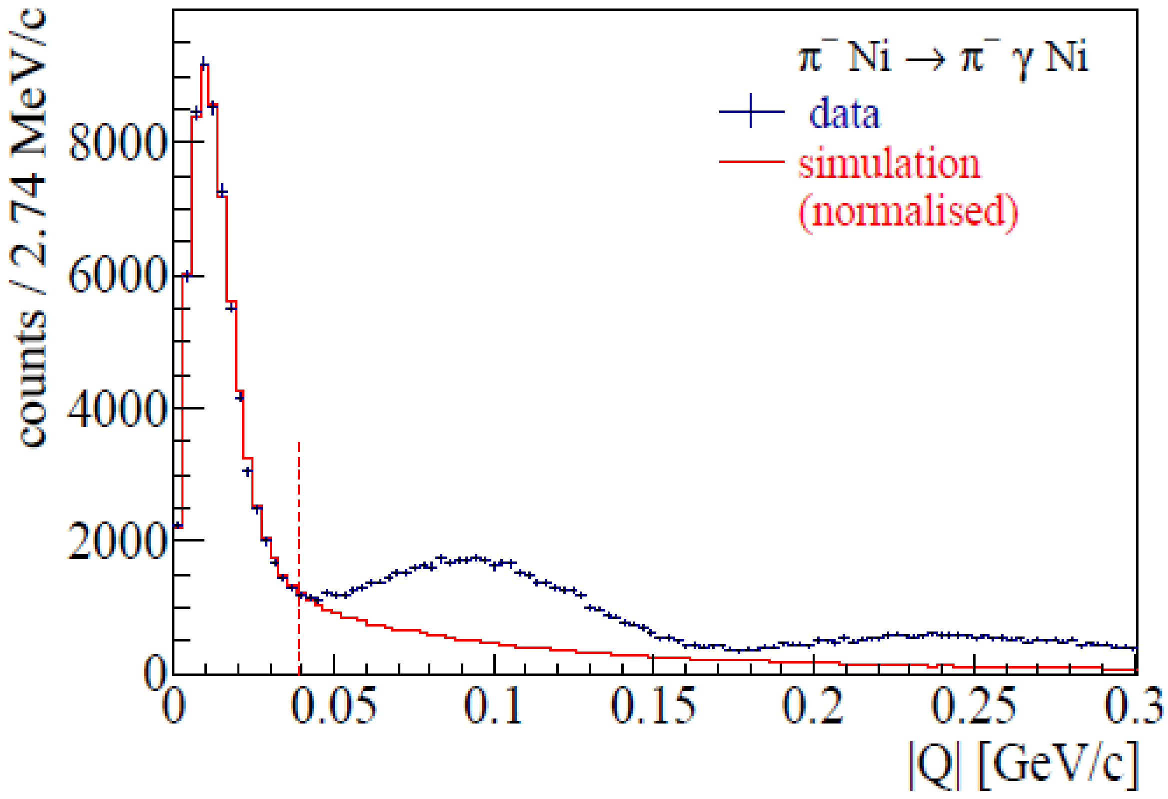
Phys. Rev. Lett. 114, 062002 (2015)



- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV (1.4%)
- $\sim$ 63.000 exclusive events ($x_\gamma > 0.4$) (Serpukhov $\sim$ 7000 for $x_\gamma > 0.5$)

Primakoff peak

Phys. Rev. Lett. 114, 062002 (2015)

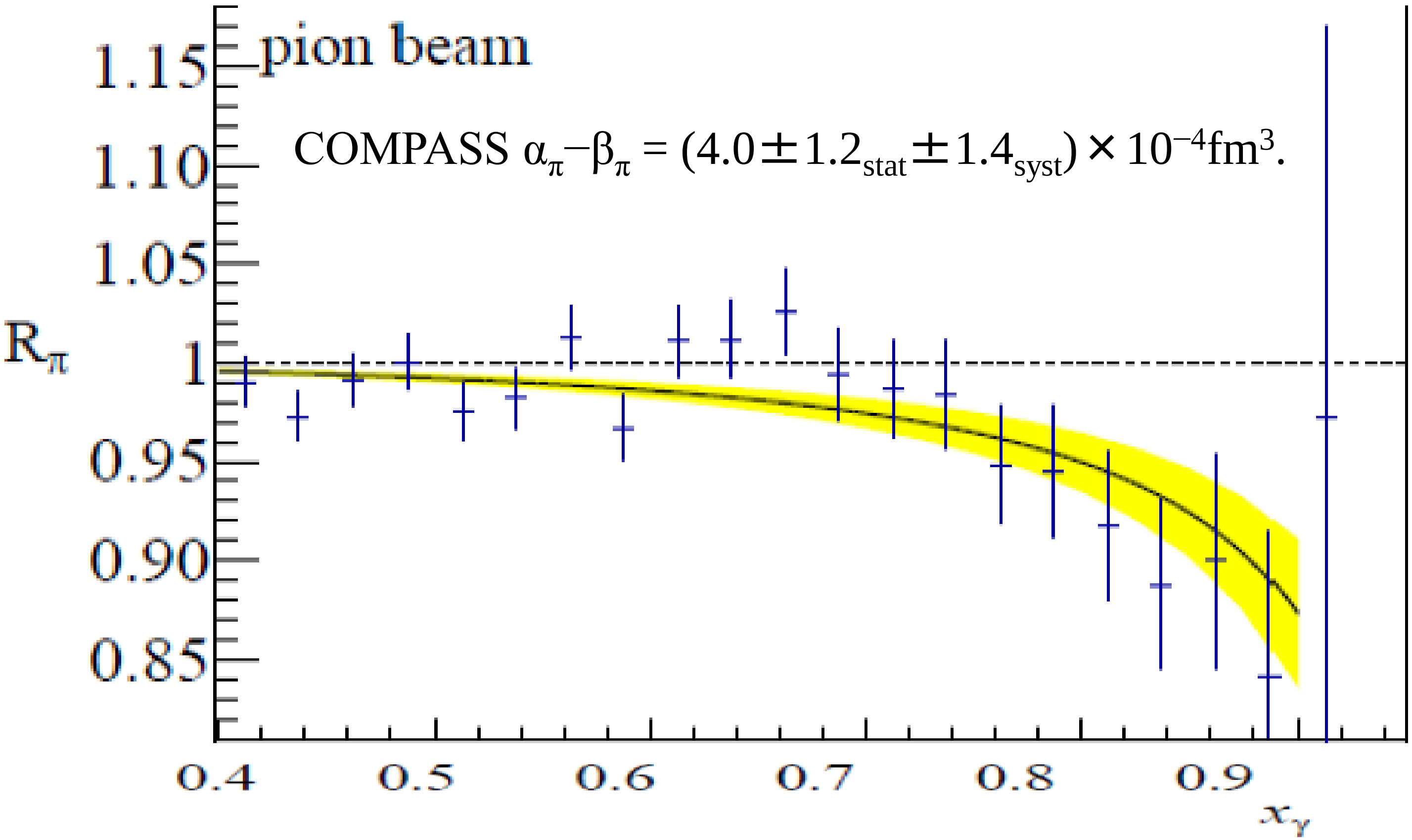


- $\Delta Q_T \approx 12$ MeV/c (190 GeV/c beam $\to$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$
- data a little more narrow than simulation $\to$ negative interference?

Determination of the pion polarizability by fitting the x_γ distribution of the Ratios $R_\pi=\sigma_E(x_\gamma,\alpha_\pi)/\sigma_{MC}(x_\gamma,\alpha_\pi=0)$ to the theoretical expression:

$$R_\pi = 1 - 72.7\,\frac{x_\gamma^2}{1-x_\gamma}\,\alpha_\pi.$$

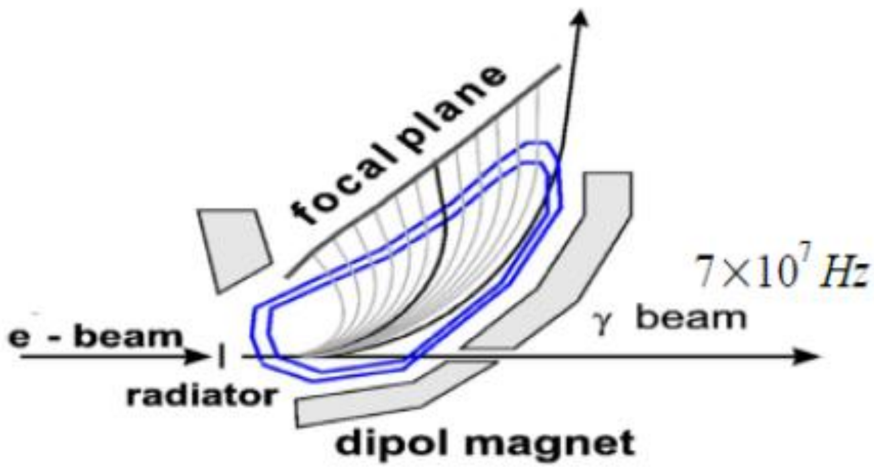
$x_\gamma=E_\gamma/E_\pi$ is the fraction of the beam energy carried by the final state γ.

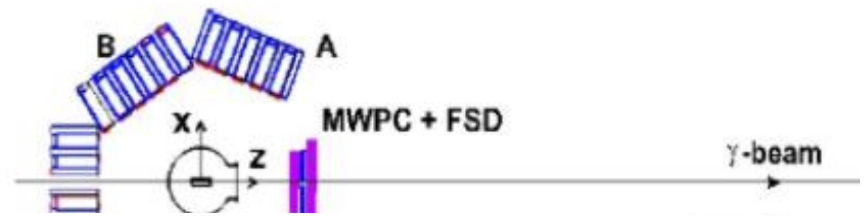


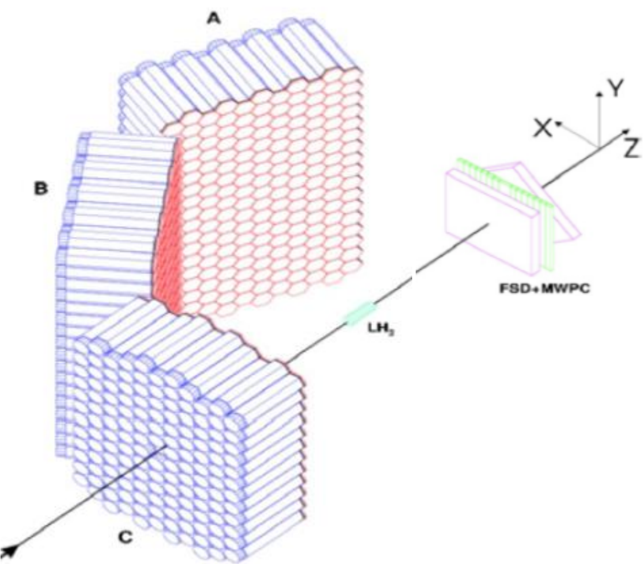
Systematic uncertainties were controlled by measuring $\mu^- Ni \rightarrow \mu^- Ni\ \gamma$ cross sections.
Statistics (63K events) 10X previously. Phys. Rev. Lett. 114, 062002 (2015)

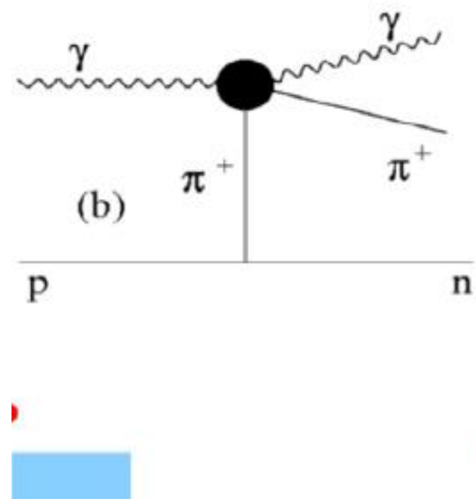
MEASUREMENT OF THE PI+ MESON POLARIZABILITIES VIA THE GAMMA P ---> GAMMA PI+ N REACTION.

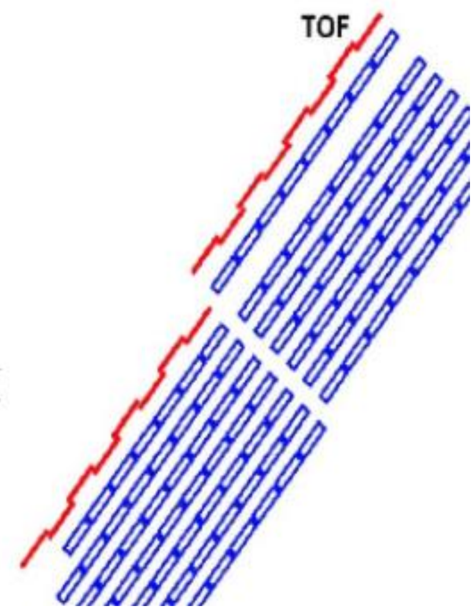
J. Ahrens et al.. Jul 2004. 34pp. Published in **Eur.Phys.J.A23:113-127,2005** e-Print Archive: **nucl-ex/0407011** .











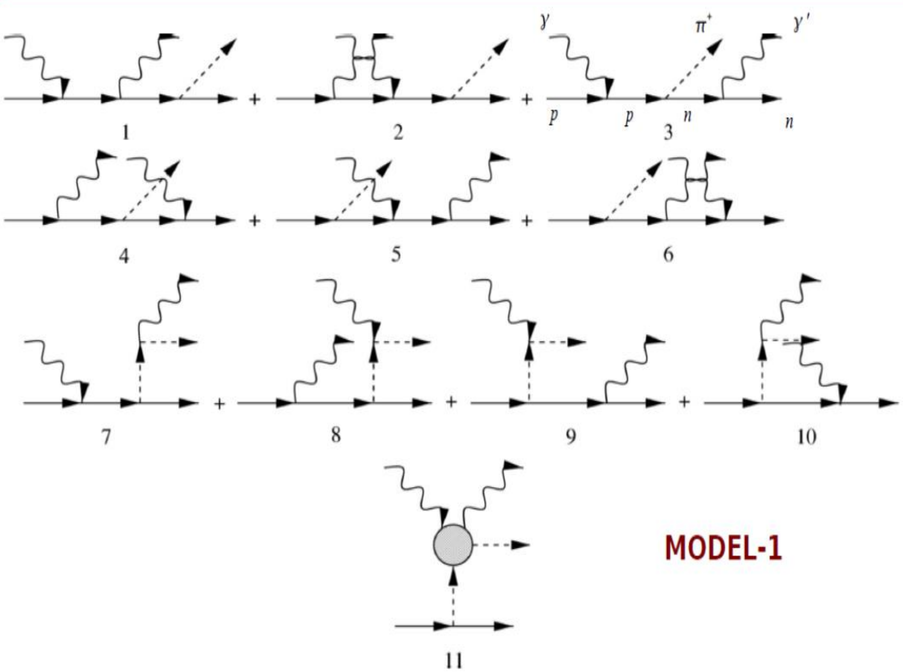
Radiative Pion Photoproduction

In the first model (model-1) the contribution, of all the pion and nucleon pole diagrams is taken into account.

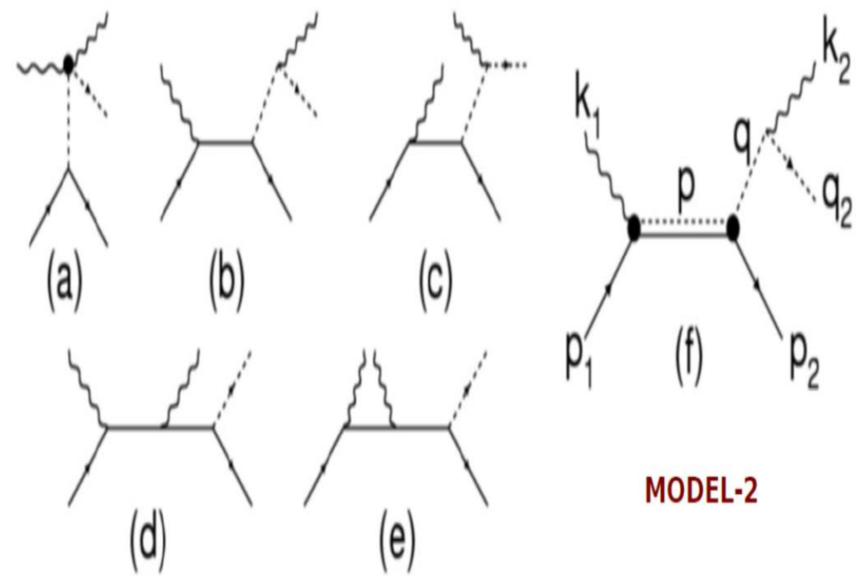
C. Unkmeir, PhD Thesis, Mainz University, (2000)

In the second model (model-2), in additional to the nucleon and the pion pole diagrams the contribution of the Δ **(1232)**, $\mathbf{P_{11}(1440)}$, $\mathbf{S_{11}(1535)}$, and $\mathbf{\Delta_{13}(1520)}$ resonances is considered.

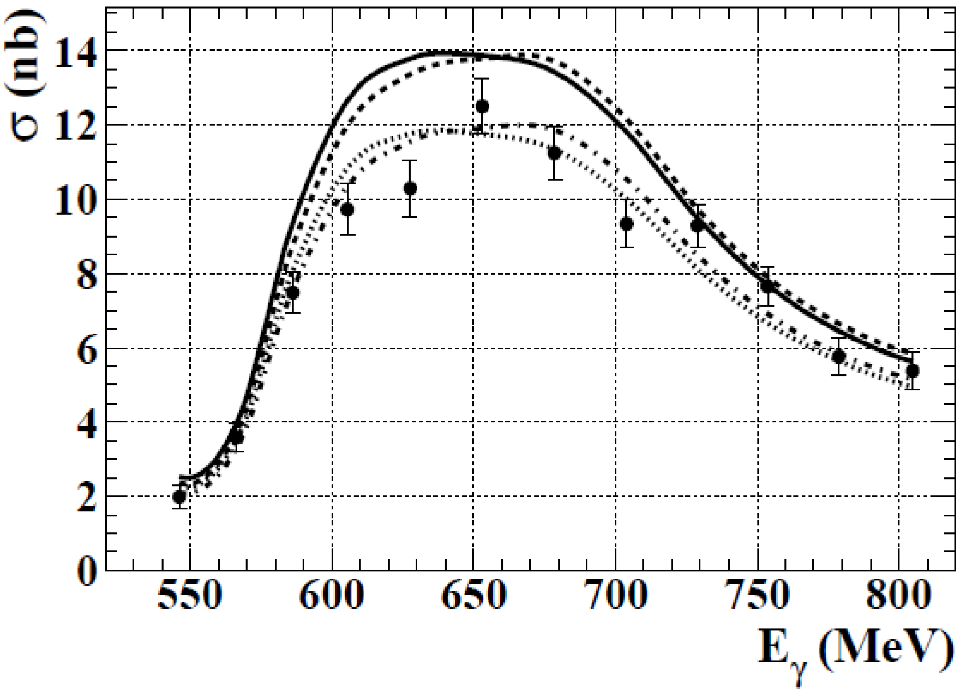
D. Drechsel, L. V. Fil'kov, Z. Phys. **A349**, 177 (1994)

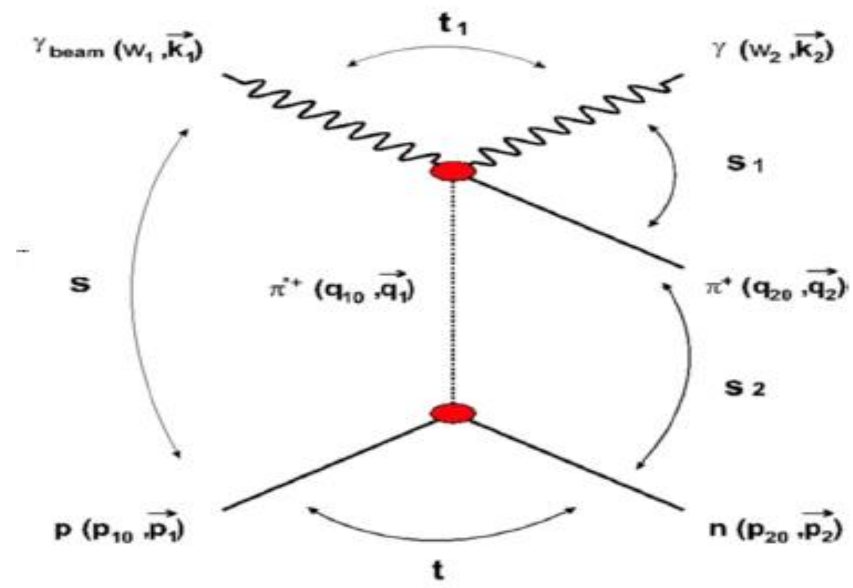


MODEL-1



MODEL-2

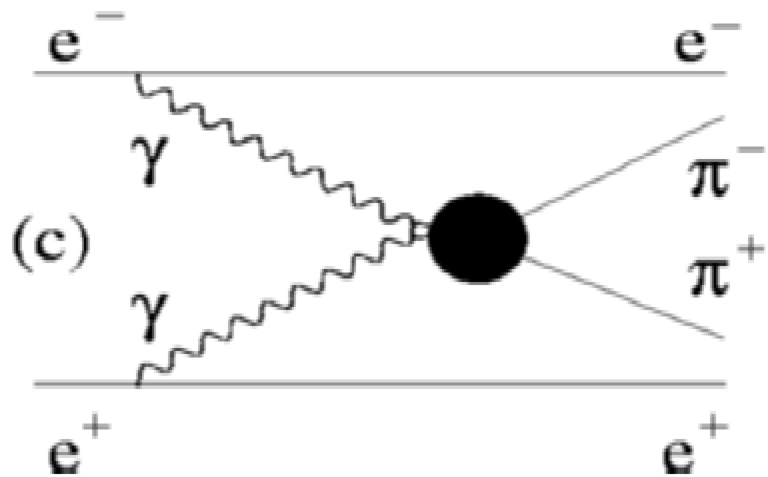




$$\alpha_\pi - \beta_\pi = (11.6 \pm 1.5_{stat} \pm 3.0_{syst} \pm 0.5_{model}) \times 10^{-4} fm^3$$

Radiative π^+-meson photoproduction from the proton **($\gamma p \rightarrow \gamma\pi^+ n$)** was studied at the Mainz Microtron in the kinematic region 537 MeV < E_γ < 817 MeV, $140^\circ \leq \theta_{\gamma\gamma'} \leq 180^\circ$, where $\theta_{\gamma\gamma}'$ is the polar angle between incident and final state gammas in the c.m. system of the outgoing γ and pion. The experimental challenge is that **the incident γ-ray is scattered from an off-shell pion**, and the polarizability contribution to the Compton cross section from the pion pole diagrams is only a small fraction of the measured cross section. The cross section of the process $\gamma p \rightarrow \gamma\pi^+ n$ **integrated over s1 and t** in the region where the contribution of the pion polarizability is largest. The dashed and dashed-dotted lines are predictions of model-1 and the solid and dotted lines of model-2 for $\alpha_\pi - \beta_\pi = 0$ and $14\times10^{-4} fm^3$, respectively.

First use of $\gamma\gamma \rightarrow \pi^+\pi^-$ data used to deduce pion polarizabilities



The MARK-II experiment was carried out via the reaction $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ at a center-of-mass energy of 29 GeV for invariant pion-pair masses $M_{\pi\pi}$ between 350 MeV/c^2 and 1.6 GeV/c^2. The dominant two-prong leptonic background reactions $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ were carefully eliminated. Previous experiments did not sufficiently eliminate these backgrounds.

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North-Holland

PHYSICS LETTERS B

Chiral symmetry and pion polarizabilities

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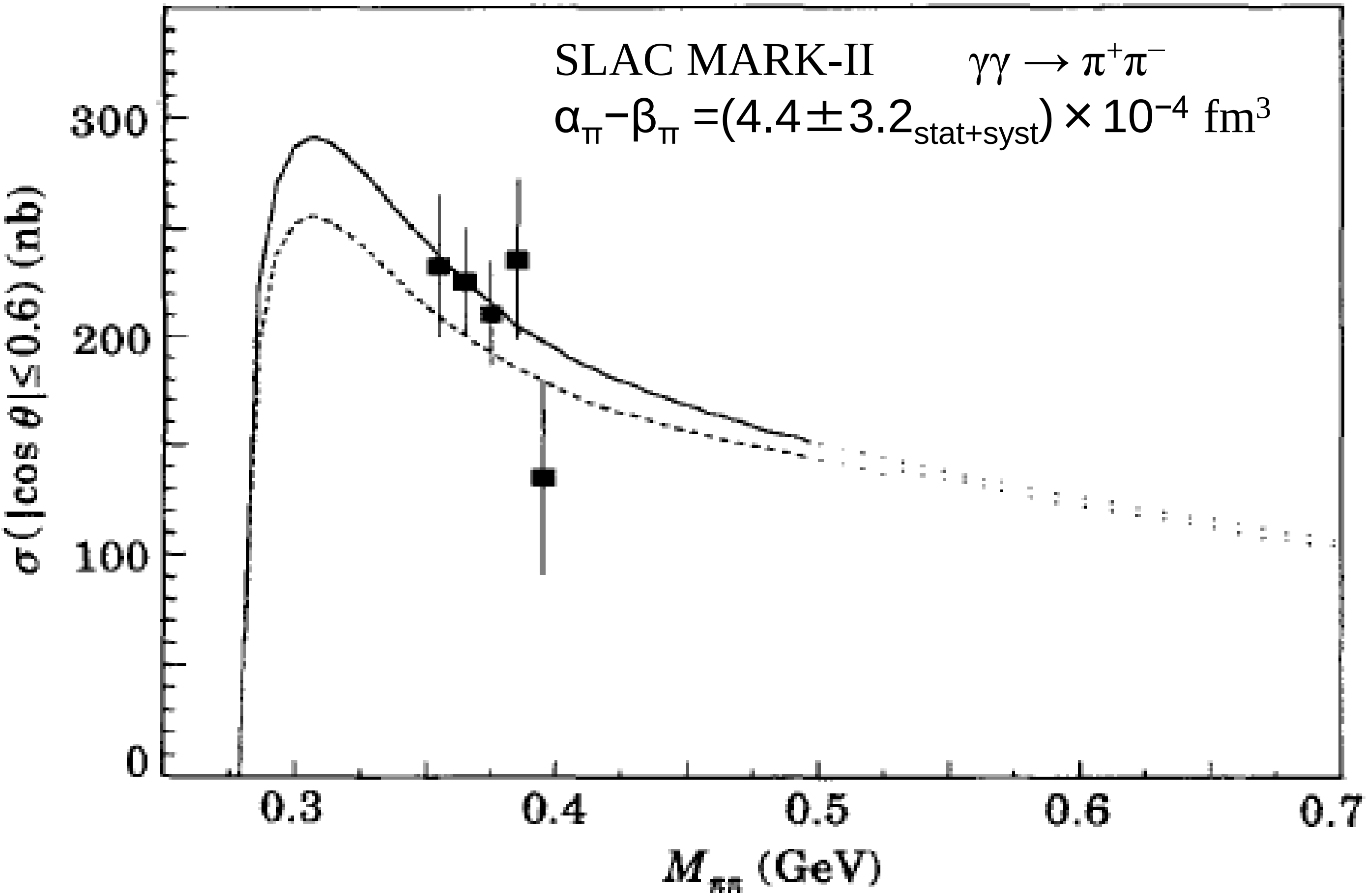
We use chiral perturbation theory including one-loop contribution to derive formulae needed to deduce pion polarizabilities for $\gamma\pi\to\gamma\pi$ and $\gamma\gamma\to\pi\pi$ data We deduce for the first time values for the $\pi^{\pm}$ and π^{0} polarizabilities from $\pi\pi$ production data, and compare these new results to chiral symmetry predictions

Table 1
Values for α_π from data and theory

PLUTO	19 1	±4 8(stat)±5 7(syst)
DM1	17 2	±4 6(stat)
DM2	26 3	±7 4(stat)
LEBEDEV	20	±12 (stat)
MARK II	2 2	±1 6(stat +syst)



Charged pion polarizabilities were determined by comparing total cross section data ($\gamma\gamma \rightarrow \pi^+\pi^-$) with a ChPT one-loop calculation. Theoretical curves are shown for Born (dash-dotted line) and ChPT with $\alpha_\pi - \beta_\pi$. The cross section excess below $M\pi\pi$ = 0.5 GeV compared to the Born calculation was interpreted as due to pion polarizabilities, with best fit value

$\alpha_\pi - \beta_\pi = (4.4 \pm 3.2_{stat+syst}) \times 10^{-4}\ \text{fm}^3$.

Dispersion Relations and Pion Polarizabilities

Pion polarizabilities are determined by how the $\gamma\pi\rightarrow\gamma\pi$ Compton scattering amplitudes approach threshold. By crossing symmetry, the $\gamma\pi\rightarrow\gamma\pi$ amplitudes are related to the $\gamma\gamma\rightarrow\pi\pi$ amplitudes. Dispersion relations (DRs) provide the method to continue the $\gamma\gamma$ amplitudes analytically to the Compton scattering threshold.

Dai and Pennington DR calculations use COMPASS $\alpha_\pi-\beta_\pi = 4.0\times10^{-4}\ \mathrm{fm}^3$ and Mainz $\alpha_\pi-\beta_\pi = 11.6\times10^{-4}\ \mathrm{fm}^3$ to calculate $\gamma\gamma\rightarrow\pi^+\pi^-$ and $\gamma\gamma\rightarrow\pi^0\pi^0$ cross sections. For COMPASS, they find agreement for $\gamma\gamma\rightarrow\pi^+\pi^-$ and $\gamma\gamma\rightarrow\pi^0\pi^0$. But Mainz value is excluded by the $\gamma\gamma\rightarrow\pi^0\pi^0$ data. Also considering the large difference between Mainz and COMPASS-MARK-II values, the Mainz polarizability value is excluded from the summary here.

Summary

The pion polarizability combination (α_π-β_π) was measured by:

(1) CERN COMPASS via radiative pion Primakoff scattering (pion Bremsstrahlung) in the nuclear Coulomb field, $\pi Z \rightarrow \pi Z\gamma$, equivalent to $\gamma\pi \rightarrow \gamma\pi$ Compton:

$$\boldsymbol{\alpha_\pi - \beta_\pi = (4.0 \pm 1.2_{stat} \pm 1.4_{syst}) \times 10^{-4} fm^3}$$

(2) SLAC PEP Mark-II via two-photon production of pion pairs, $\gamma\gamma \rightarrow \pi^+\pi^-$: $\boldsymbol{\alpha_\pi - \beta_\pi = (4.4 \pm 3.2_{stat+syst}) \times 10^{-4}\ fm^3}$

They are in good agreement with the two-loop ChPT prediction $\boldsymbol{\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}\ fm^3}$,
thereby strengthening the identification of the pion with the Goldstone boson of QCD.