Pion-photon Reactions and Chiral Dynamics in Primakoff Processes at COMPASS

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for the COMPASS collaboration

XIth Quark Confinement and the Hadron Spectrum
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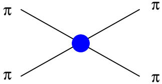
St. Petersburg 8.-12.9.2014

COMPASS

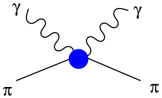
CERN

How to understand quark-gluon dynamics?

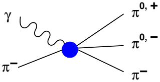
complicated system of interacting quarks and gluons $\xrightarrow{\text{ChPT}}$ effective degrees of freedom at low energy: mass, charge, spin, effective (self-)coupling



π only



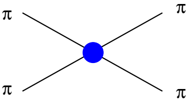
$\pi-$photon



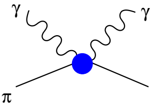
$\pi - \pi-$photon

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 our analysis)

More pion-photon reactions

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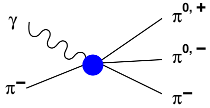
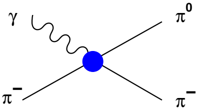
- Pion scattering including a real photon
  - Leading-order prediction from ChPT
    $\leftrightarrow$ pion scattering lengths
    combined with photon coupling
  - chiral loop contribution
    theory prediction available, no measurement



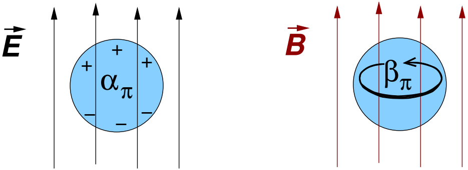
- Chiral anomaly $F_{3\pi}$
  - established on 10% level
  - further development: inclusion of the ρ resonance
    theoretical work by Kubis, Hoferichter, Sakkas
    PRD86(2012)116009



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±1.0 $\alpha_\pi + \beta_\pi =$ 0.16

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

ChPT prediction for the pion polarisability

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

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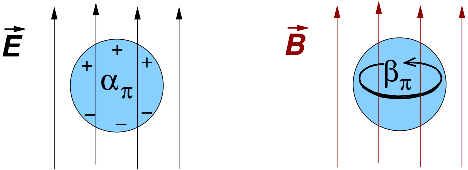

polarisabilities α_π, β_π [10^{-4} fm^3]

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

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

Polarisability effect in Primakoff technique

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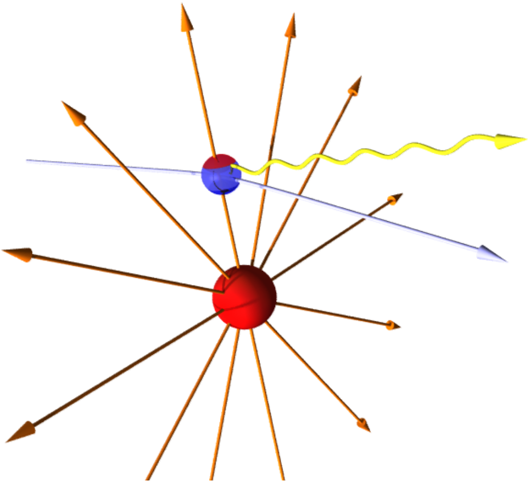
Primakoff measurement technique

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

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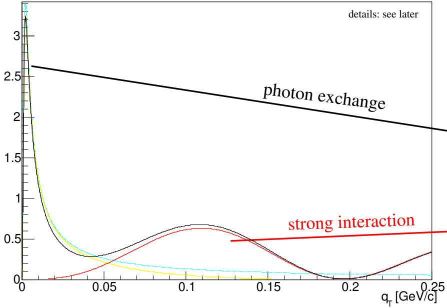

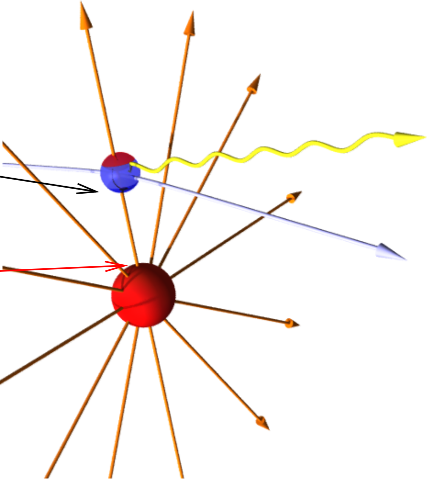

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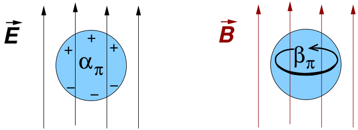
  - expected charge separation $\sim 10^{-5}$ fm $\cdot\, e$

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 $d\sigma/d\Omega_{cm}$

Pion Compton Scattering

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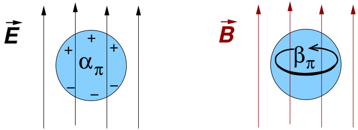

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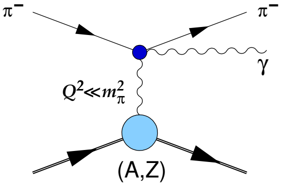
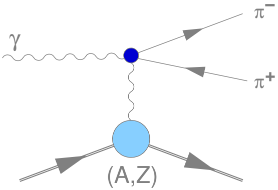
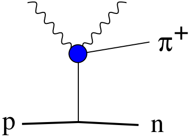
Pion Compton scattering: embedding the process

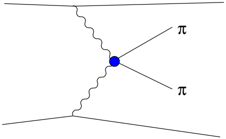




Primakoff processes



Radiative pion photoproduction



Photon-Photon fusion

Pion polarisability: world data before COMPASS

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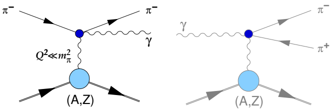

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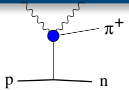

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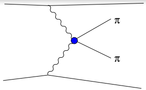

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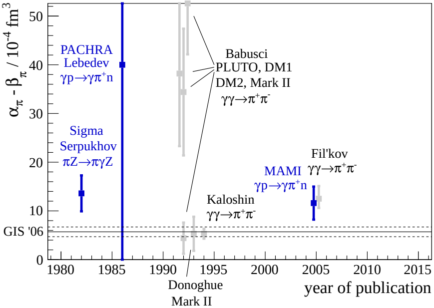

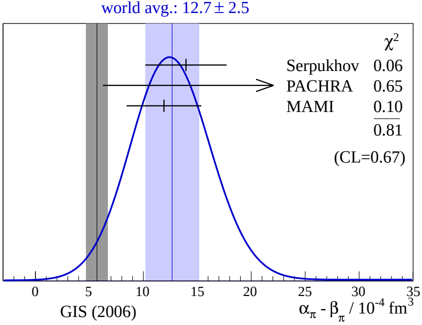

GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD
Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

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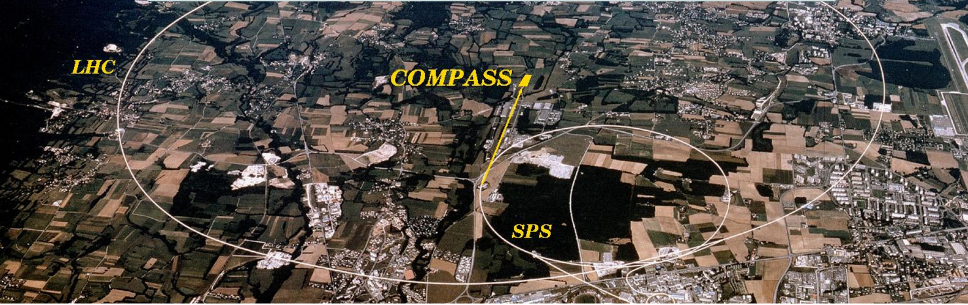
CERN SPS: protons ∼ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$ / s
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11: spin structure of the nucleon



COMPASS

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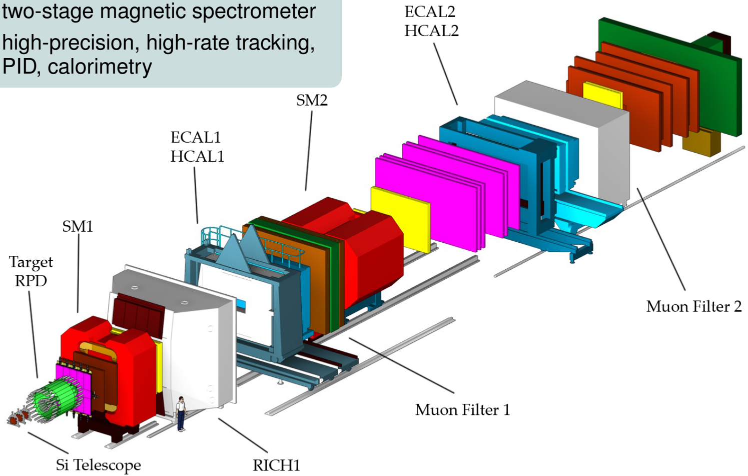
Experimental Setup

Fixed-target experiment

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



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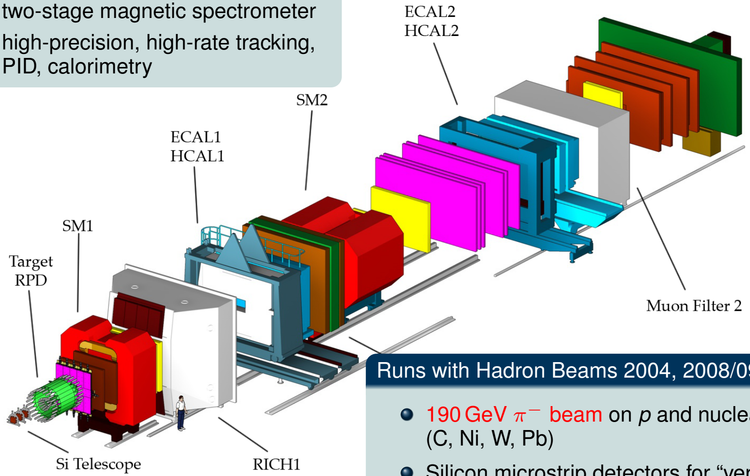
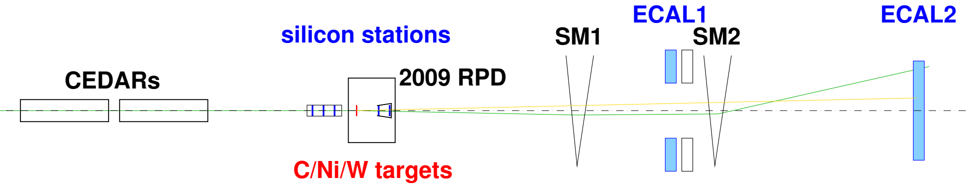


Runs with Hadron Beams 2004, 2008/09, 2012

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

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

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

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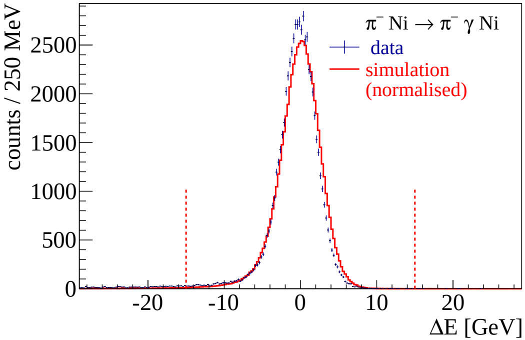
Identifying the $\pi\gamma \to \pi\gamma$ reaction

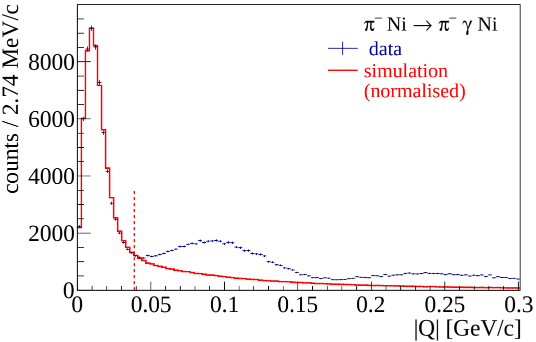
arxiv:1405.6377v1 subm. to PRL



- 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 $x_\gamma > 0.5$)

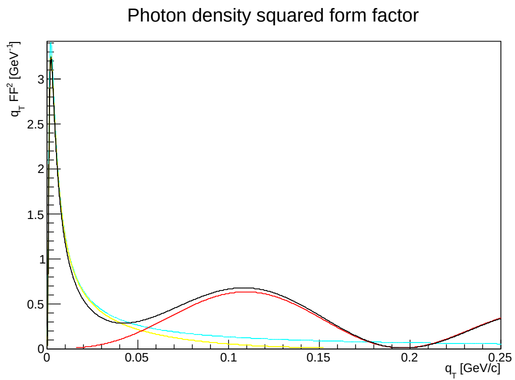
Primakoff peak

arxiv:1405.6377v1 subm. to PRL



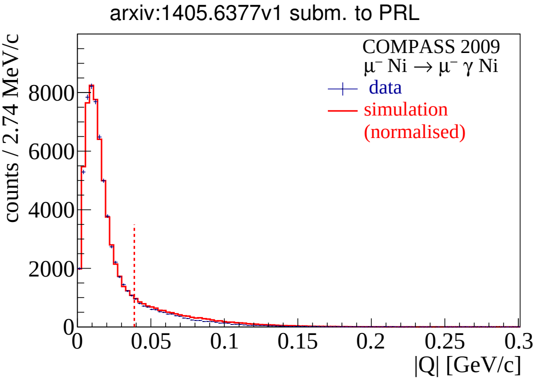
- $\Delta Q_T \approx$ 12 MeV/c (190 GeV/c beam $\rightarrow$ requires few-μrad angular resolution)
- first diffractive minimum on Ni nucleus at $Q \approx 190$ MeV$/c$

Coulomb-nuclear interference



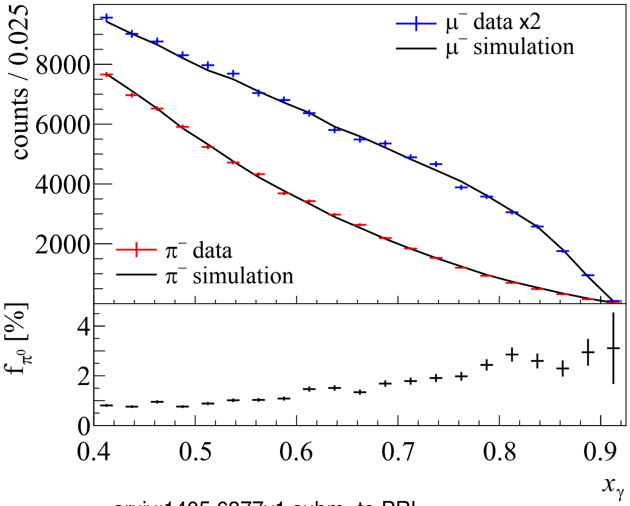
- calculation following G. Fäldt (Phys. Rev. C79, 014607)
- eikonal approximation: pions traverse Coulomb and strong-interaction potentials

Primakoff peak: muon data



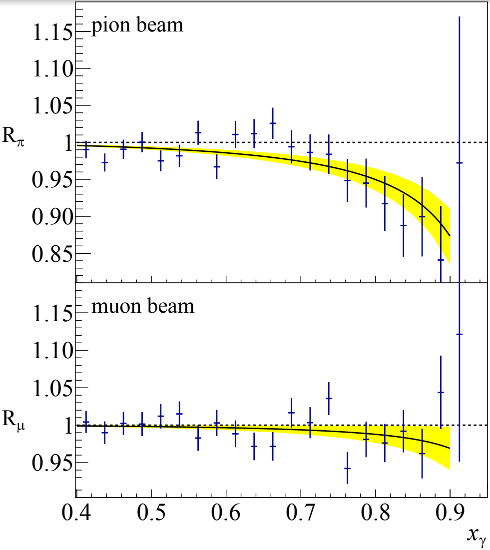
- muon control measurement: pure electromagnetic interaction

Photon energy spectra for muon and pion beam



arxiv:1405.6377v1 subm. to PRL

Pion polarisability: COMPASS result



$$\alpha_\pi = (\, 2.0 \pm 0.6_{\text{stat}} \,) \times 10^{-4}\,\text{fm}^3$$

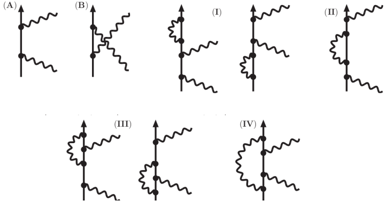
(assuming $\alpha_\pi = -\beta_\pi$)

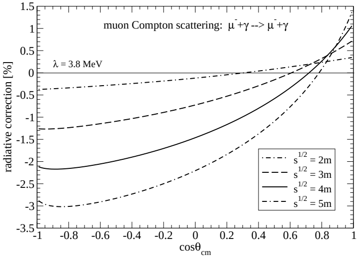
"false polarisability" from muon data:

$$(\, 0.5 \pm 0.5_{\text{stat}} \,) \times 10^{-4}\,\text{fm}^3$$

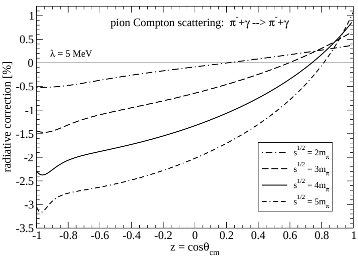
arxiv:1405.6377v1 subm. to PRL

Radiative corrections (Compton scattering part)





Nucl.Phys. A837 (2010)



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

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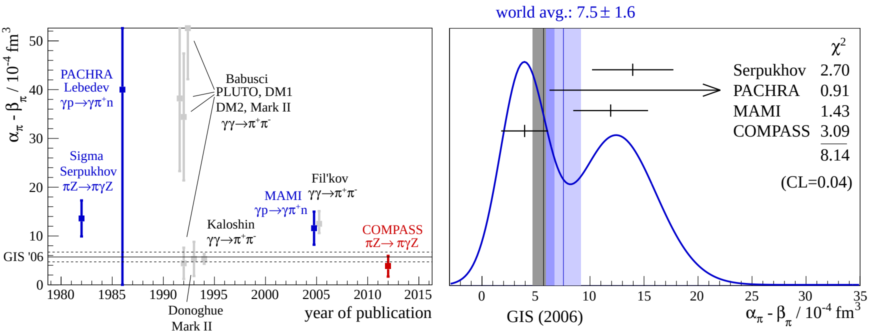
quadratic sum	0.8

COMPASS result for the pion polarisability:

$$\boldsymbol{\alpha_\pi = (\,2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}\,) \times 10^{-4}\,\text{fm}^3}$$

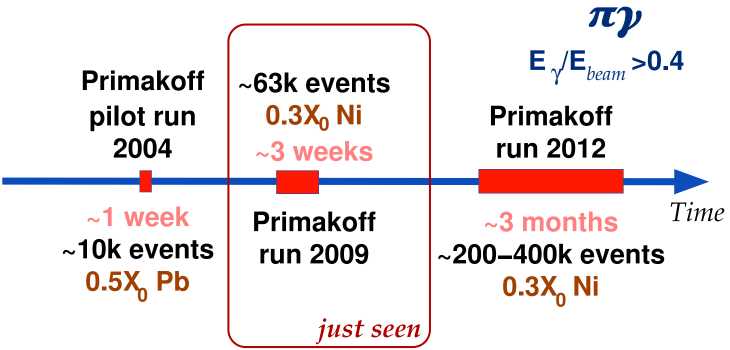
with $\alpha_\pi = -\beta_\pi$ assumed

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



Primakoff reactions accessible at COMPASS

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

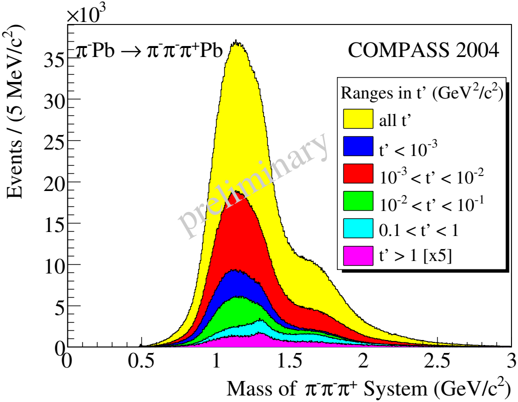
At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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

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

2004 Primakoff results

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



- "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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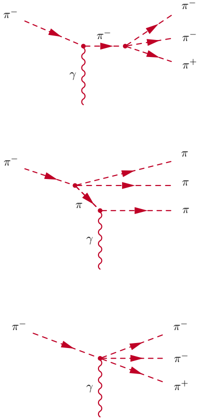
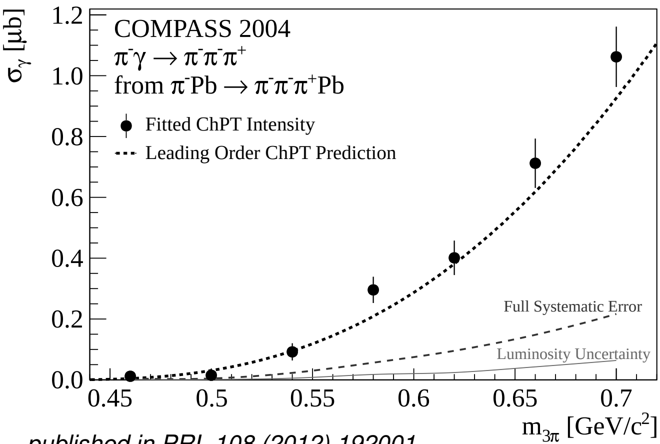


Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



published in PRL 108 (2012) 192001

Higher-order effects

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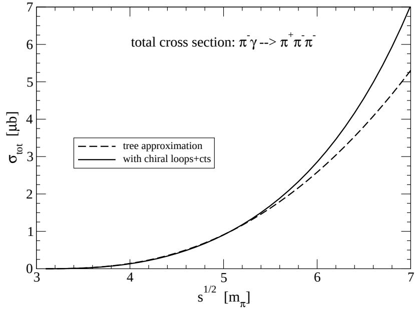
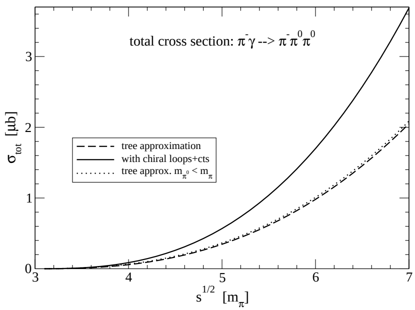
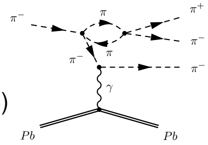
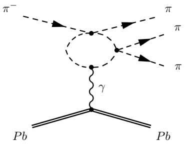




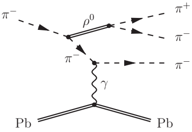
Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)



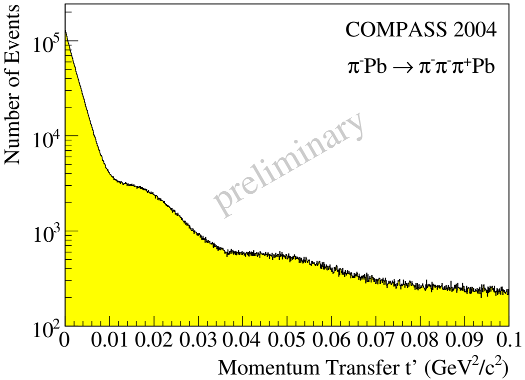


not (yet) included:



2004 Primakoff results

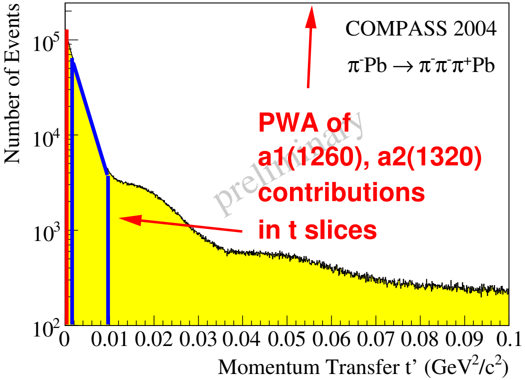
π^- Pb $\rightarrow$ Pb $\pi^-\ \pi^-\ \pi^+$



- "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

π^- Pb $\rightarrow$ 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

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

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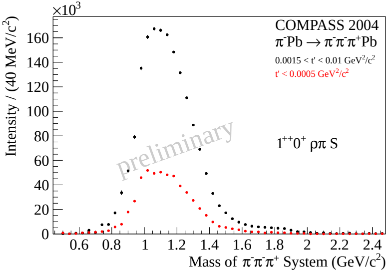
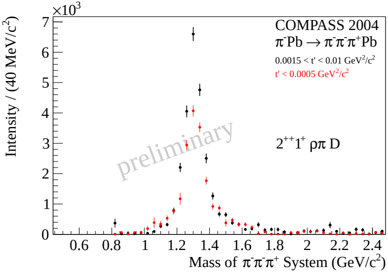
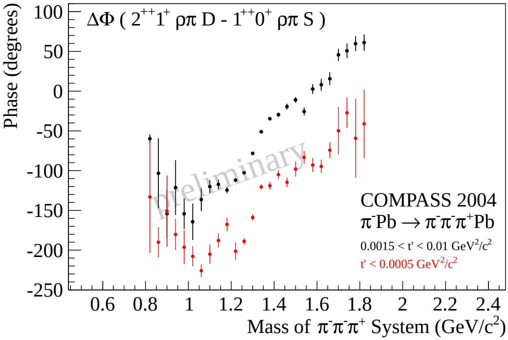
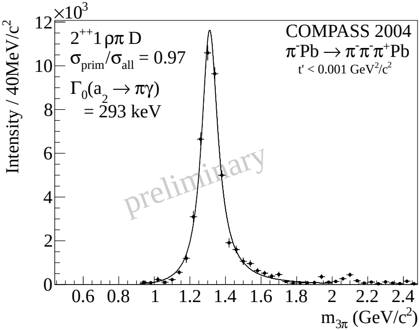
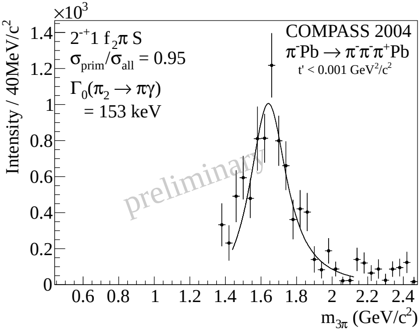






Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$





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

published in EPJ A50 (2014) 79

Summary and Outlook

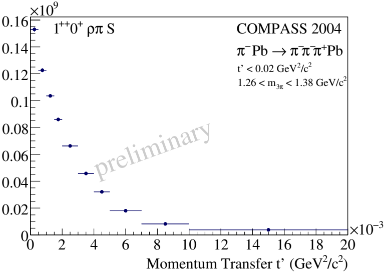
- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined

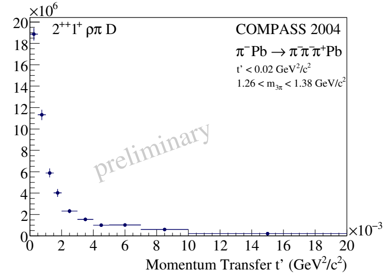
$$\boxed{\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}\,\text{fm}^3} \text{ assuming } \alpha_\pi + \beta_\pi = 0$$

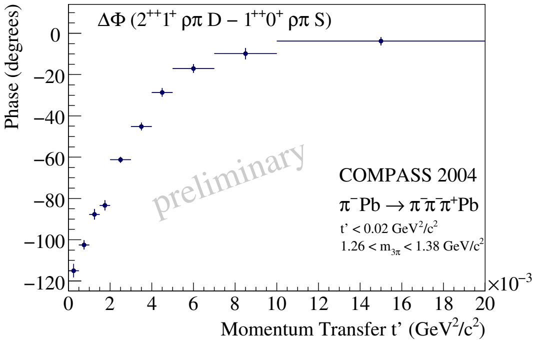
  - Most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma,\ K^- \to \pi^-\pi^0$
- Chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ reactions
  - Charged-channel $\pi\gamma \to \pi^-\pi^-\pi^+$ tree-level ChPT prediction confirmed
  - Neutral-channel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

Backup

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



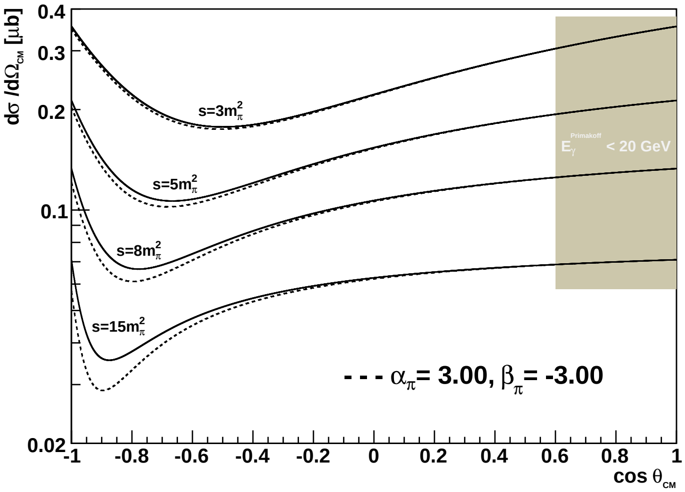




- transition of $\pi\gamma$ to $\pi I\!P \rightarrow a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

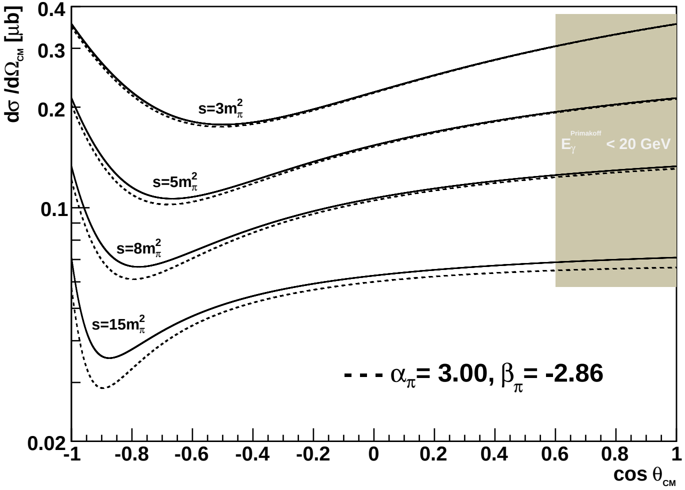
Polarisability effect (LO ChPT values)

loop effects not shown

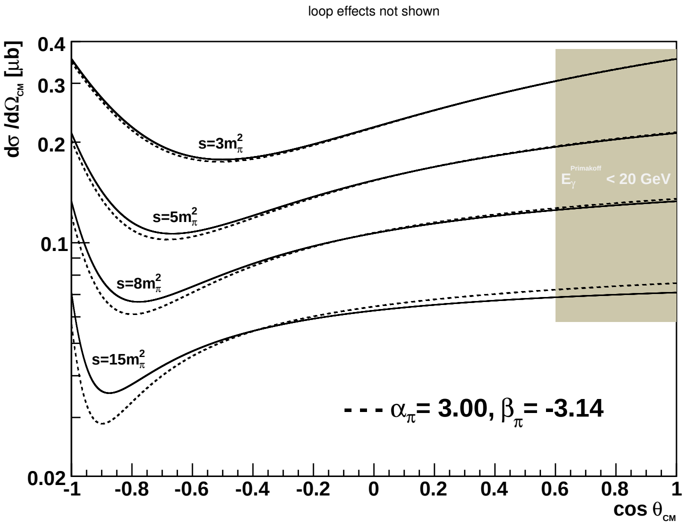


Polarisability effect (NLO ChPT values)

loop effects not shown

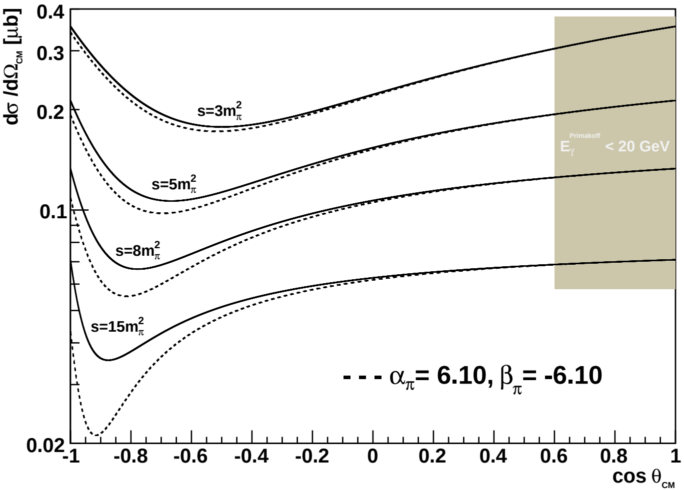


Polarisability effect (wrong sign $\alpha_\pi + \beta_\pi$)



Polarisability effect (Serpukhov values)

loop effects not shown



- Radiative π^+ production on the proton:

$$\gamma\,\pi^* \longrightarrow \pi\,\gamma \qquad [\text{via } \gamma\, p \rightarrow n\,\pi^+\,\gamma]$$

Mainz (2005) measurement: $\alpha_\pi - \beta_\pi = 11.6 \pm 1.5 \pm 3.0 \pm 0.5$

"± 0.5": model error *only within the used ansatz*,

full systematics not under control

- Primakoff Compton reaction:

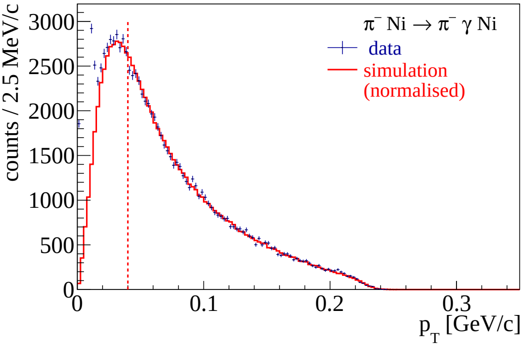
$$\gamma^*\,\pi \longrightarrow \pi\,\gamma \qquad [\text{via } \pi\, Z \rightarrow Z\,\pi\,\gamma]$$

tiny extrapolation $\gamma^* \rightarrow \gamma \;\; \mathcal{O}(10^{-3} m_\pi^2)$

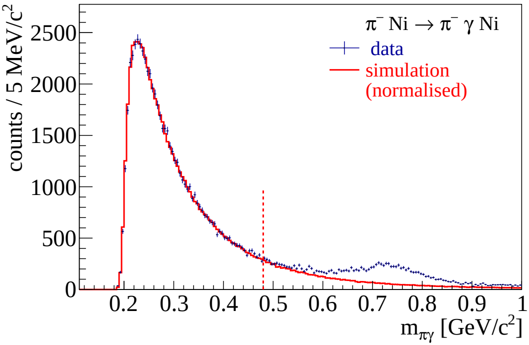
fully under theoretical control

[N. Kaiser, J.F., Nucl. Phys. A 812 (2008) 186]

Minimum transverse momentum of the charged particle

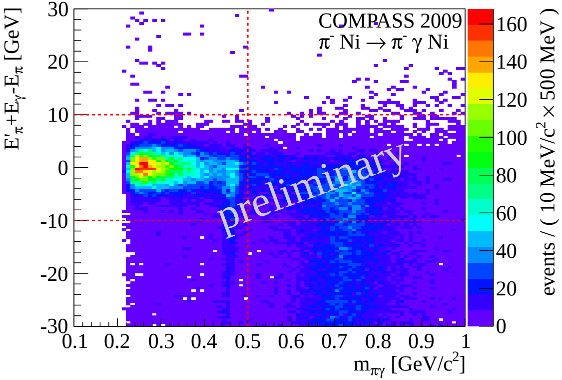


CM energy in $\pi\gamma \to \pi\gamma$



- ρ contribution from $\pi\gamma \to \pi\pi^0$

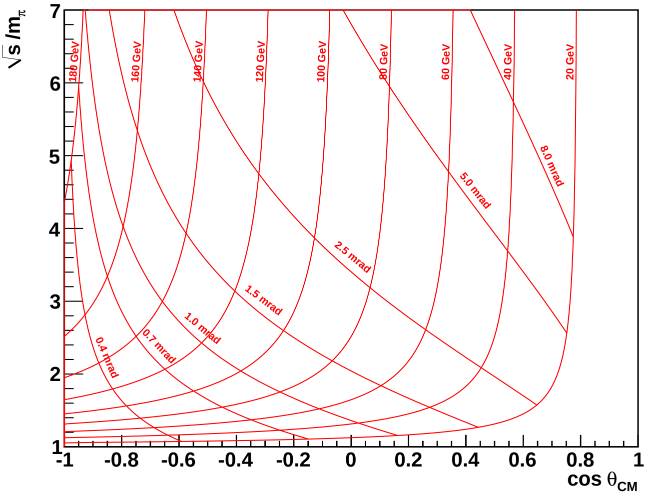
Exclusivity vs. $\sqrt{s}$



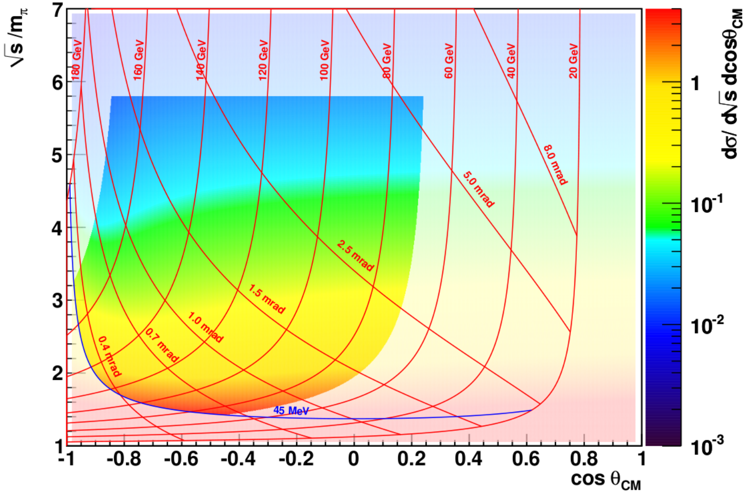
- ρ contribution from $\pi\gamma \to \pi\pi^0$

Mandelstam $\{s,t\} \leftrightarrow$ Laboratory $\{E_\gamma, \theta_\gamma\}$

for $\pi\gamma \to \pi\gamma$



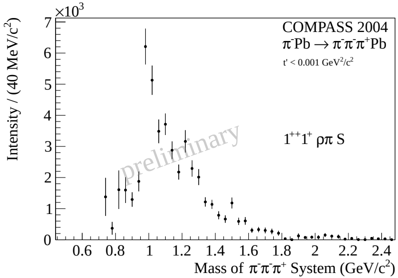
Cross section

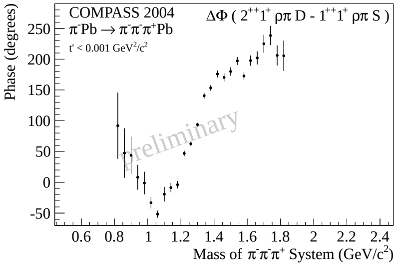


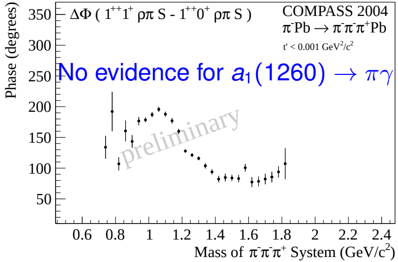
M.R. Pennington in the 2nd DAΦNE Physics Handbook,
"What we learn by measuring $\gamma\gamma \to \pi\pi$ at DAΦNE":

> All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \to \pi\pi$. Though the low energy $\gamma\gamma \to \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the *extrapolation* not very far, the dominance of the pion pole (...) means that the energy scale for this continuation is m_π. Thus the polarisabilities cannot be determined accurately from $\gamma\gamma$ experiments in a model-independent way and must be measured in the Compton scattering region.

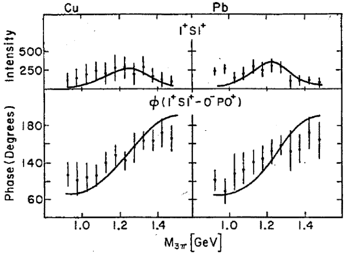
Primakoff production of a1(1260) vs. E272 result







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



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

- Mass-independent PWA (narrow mass bins):

$$\sigma_{\text{indep}}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |f_i^{\epsilon}(t')|^2 \mathrm{d}t'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2$$

  - Production strenght assumed constant in single bins
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$, with t' dependence $f_i^{\epsilon}(t')$
  - Production amplitudes T_{ir}^{ϵ} $\rightarrow$ Extended log-likelihood fit
  - Acceptance corrections included

- Spin-density matrix: $\rho_{ij}^{\epsilon} = \sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon *}$

$\rightarrow$ Physical parameters:

$$\mathrm{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

relative phase Φ_{ij}^{e}

$$\mathrm{Coh}\ _{i,j}^{\epsilon} = \sqrt{(\ \mathrm{Re}\ \rho_{ij}^{\epsilon})^2 + (\ \mathrm{Im}\ \rho_{ij}^{\epsilon})^2} \Big/ \sqrt{\rho_{ii}^{\epsilon} \rho_{jj}^{\epsilon}}$$

- Mass-dependent χ^2-fit (not presented here):
  - X parameterized by Breit-Wigner (BW) functions
  - Background can be added

Mass dependence of the diffractive slope

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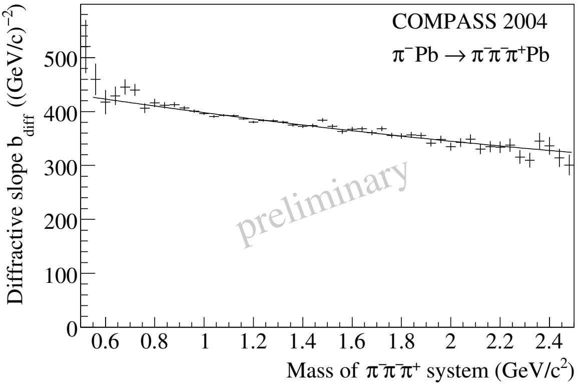
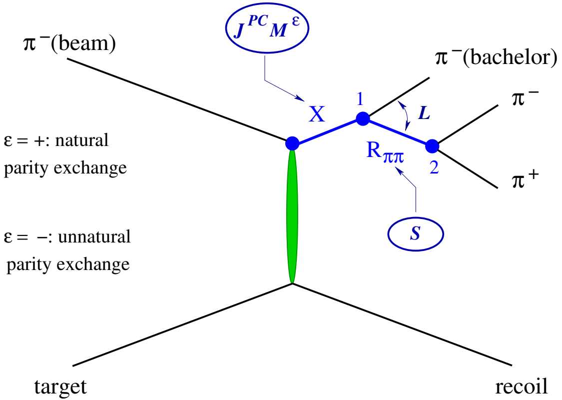


Partial Wave Analysis Formalism

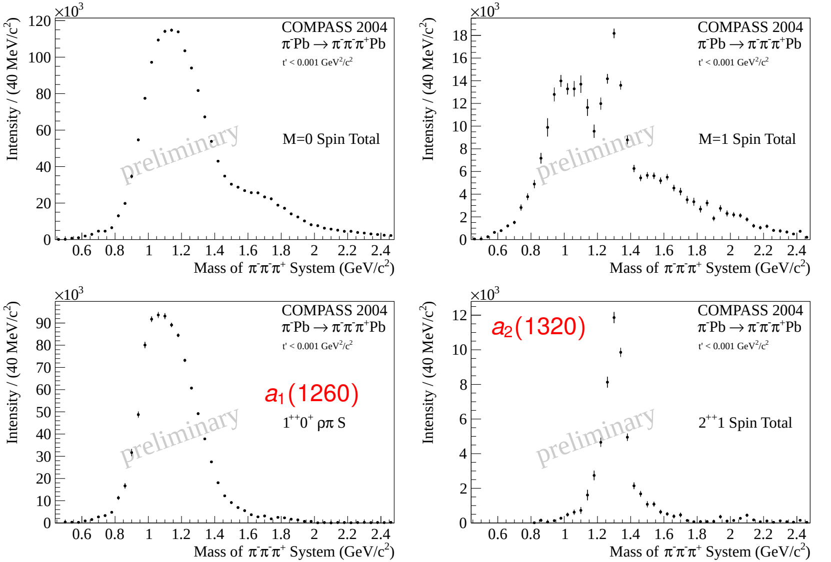
Isobar Model



- Isobar model: Intermediate 2-particle decays
- Partial wave in reflectivity basis: $J^{PC}M^{\epsilon}[isobar]L$

- Mass-independent PWA (40 MeV/c^2 mass bins): 38 waves
  Fit of angular dependence of partial waves, interferences
- Mass-dependent χ^2-fit (Not presented here)

Major intensities in m(3π)-bins (acceptance corrected)



PWA of data with low t'

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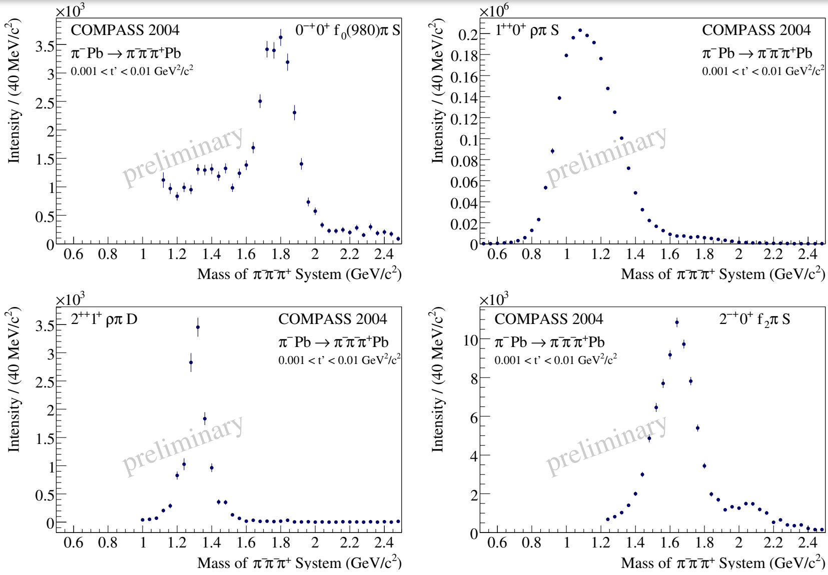
Intensity of selected waves: $0^{-+}0^+ f_0(980)\pi S$, $1^{++}0^+ \rho\pi S$, $2^{++}1^+ \rho\pi D$, $2^{-+}0^+ f_2(1270)\pi S$



Spin Totals for $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

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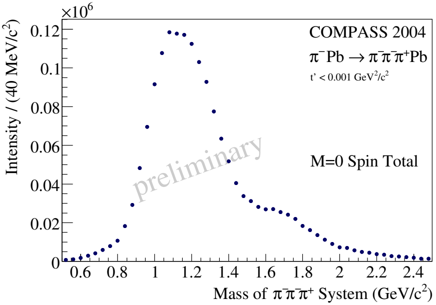
”Spin Totals”: Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

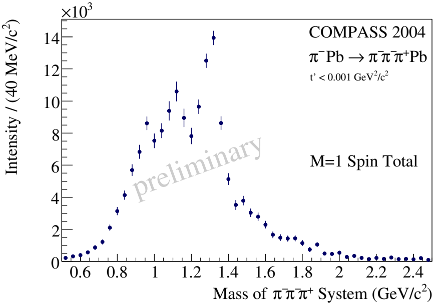
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$ $\rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

Diffractive production: M=0: $\sigma(t') \propto e^{-b_{\mathrm{diff}}(m) t'}$

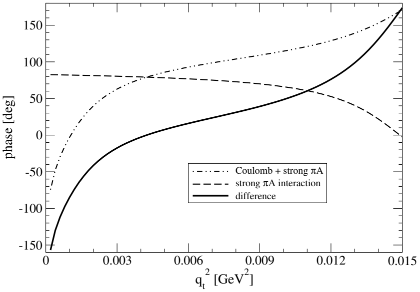
M=1: $\sigma(t') \propto t' e^{-b_{\mathrm{diff}}(m) t'}$ $\rightarrow$ vanishes for $t' \approx 0$

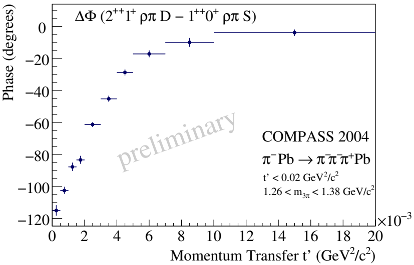


M=0



M=1





Glauber modell

G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

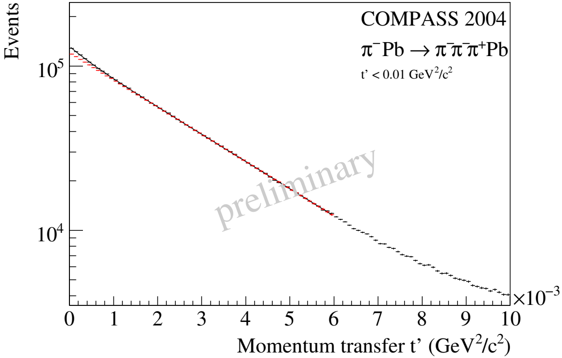
Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulomb-interaction - strong interaction

⇒ detailed studies of the nature of resonances

Primakoff contribution at $t' < 10^{-3}\,(\text{GeV}/c)^2$

Primakoff: $\sigma(t') \propto e^{-b_{\text{Prim}} t'}$, $b_{\text{Prim}} \approx 2000\,(\text{GeV}/c)^{-2}$ (mainly resolution)
Diffractive: $\sigma(t') \propto e^{-b_{\text{diff}} t'}$, $b_{\text{diff}} \approx 400\,(\text{GeV}/c)^{-2}$ for lead target



(Mass) spectrum of this Primakoff contribution?
⇒ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)