Measurement of the pion polarisability

through the Primakoff effect

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TU München

COMPASS Collaboration Meeting
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A search for 30 years

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MEASUREMENT OF π^--MESON POLARIZABILITY IN PION COMPTON EFFECT

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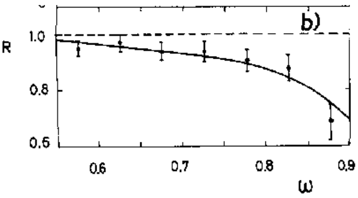
About 7×10^3 events of Compton effect on pion in the reaction $\pi^- A \to A\pi^-\gamma$ at 40 GeV/c were detected and for the first time the charged pion polarizability was obtained $\alpha_\pi = (6.8 \pm 1.4) \times 10^{-43}$ cm^3.



$x_\gamma = E_\gamma / E_{\text{Beam}}$

"Serpukhov value"

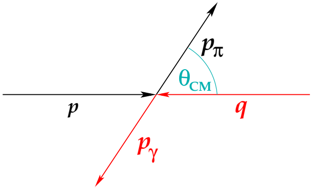
$\alpha_\pi \approx 7 \cdot 10^{-4}$ fm^3

from the pion bremsstrahlung spectrum

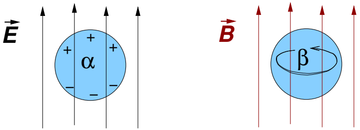
assuming $\alpha_\pi + \beta_\pi = 0$

Compton scattering and polarisability

$$\pi + \gamma \rightarrow \pi + \gamma$$



Low-energy LO deviation from pointlike particle ↔ em. polarisability



$[10^{-4}\ \mathrm{fm}^3]$	$\alpha_\pi - \beta_\pi$	$\alpha_\pi + \beta_\pi$
ChPT LO	6.0	0
NNLO	5.7±1.0	0.16
experiments	4 — 14	—

The constraint $\alpha_\pi + \beta_\pi = 0$

Coupling of scalar field to em. gauge field:

$$\mathcal{H}_{\text{int}} = g_1 \cdot \partial_\alpha \phi \partial_\beta \phi \; F^{\alpha\gamma} F^{\beta}_{\ \gamma} + g_2 \cdot \phi^2 F^2$$

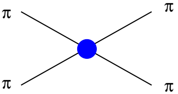
where

$$g_2 \cdot F^{\alpha\beta} F_{\alpha\beta} \sim g_2 \left(E^2 - B^2 \right) \stackrel{!}{=} \alpha_\pi \frac{E^2}{2} + \beta_\pi \frac{B^2}{2}$$

The term $g_1 = \frac{1}{2m}(\alpha_\pi + \beta_\pi)$ vanishes *to leading order* at low momenta.

ChPT and Experiment

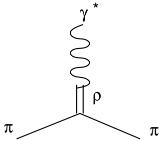
- Pion scattering lengths: 2-loop predictions
  - $a_0^0 m_{\pi^+} = 0.220 \pm 0.005$ confirmed in $K^+ \to \pi^+\pi^- e^+ \nu_e$ (E865)
  - $(a_0^0 - a_0^2) m_{\pi^+} = 0.264 \pm 0.006$ confirmed in $K^+ \to \pi^+\pi^\circ\pi^\circ$ (NA48: 0.268 ± 0.010)

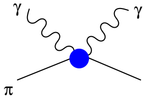


- Electromagnetic structure
  - Form factor described by coupling to $\rho(770)$ (resonance effect, VMD)
  - Polarisability
    accessible as contribution to Compton scattering; prediction obtained by the LEC relation to $\pi^+ \to e^+ \nu_e \gamma$

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

[Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]





Compton cross section

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

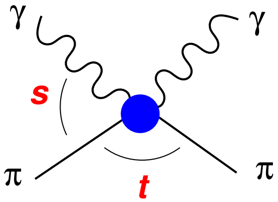
with (quadrupole polarisability $\alpha_2 - \beta_2$)

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

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

Measuring the differential cross section with high statistics allows to determine all three polarisability contributions

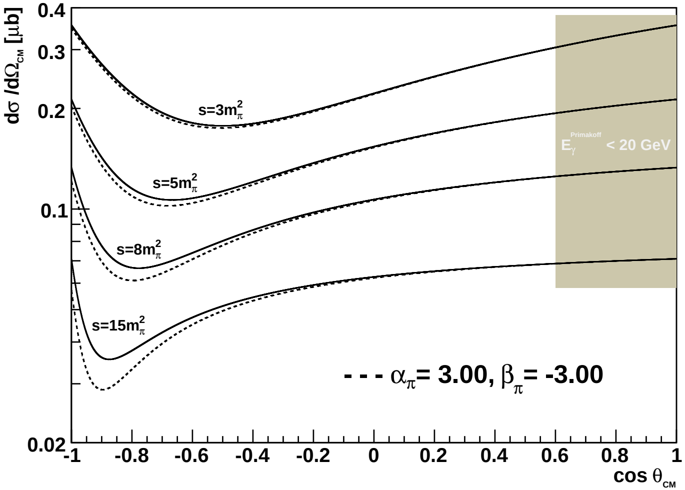
Compton cross section



- $s = (p + p_\gamma)^2$ (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

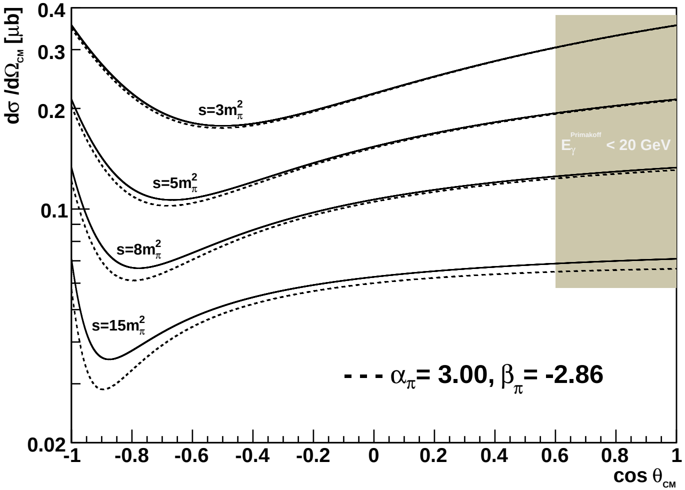
Polarisability effect (LO ChPT values)

loop effects not shown

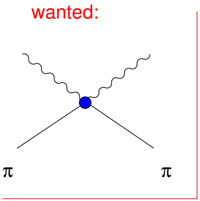


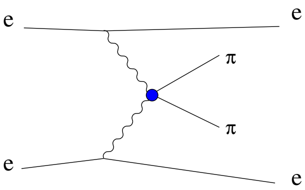
Polarisability effect (NLO ChPT values)

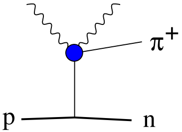
loop effects not shown

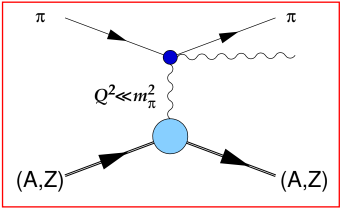


$\pi\gamma$ scattering: embedding the process



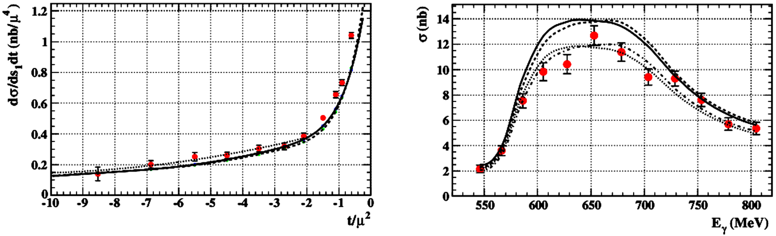


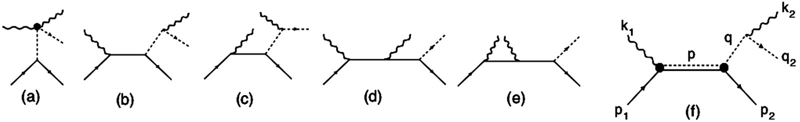




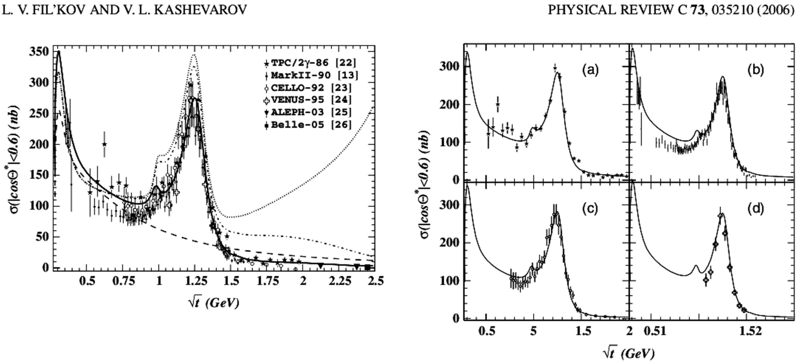
Radiative pion production on the proton

J. Ahrens *et al.*: Measurement of the π^+-meson polarizabilities via the $\gamma p \to \gamma \pi^+ n$ reaction 121





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



- $\gamma\gamma \to \pi\pi$ linked by crossing to $\gamma\pi \to \gamma\pi$
- this implementation of dispersion relations criticized *e.g.* by Drechsel, Pasquini, Scherer to be improperly done

Primakoff reactions

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 ($\sim Z^2$)

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$$\pi^- + \gamma \rightarrow \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 \;/\; \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + n \cdot (\pi^- + \pi^+) \\ \pi^- + \ldots \end{cases}$$

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

Pion Polarisability: Experimental Techniques

- $$\gamma^{(*)}\,\gamma^{(*)} \longrightarrow \pi^+\,\pi^- \qquad [\text{via } e^+e^- \to e^+e^-\,\pi^+\pi^-]$$

  PLUTO, MARKII,...: $\alpha_\pi - \beta_\pi = 4 - 20$

  rather insensitive to polarisability, dominated by loops

- Radiative π^+ production on the proton:

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

  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

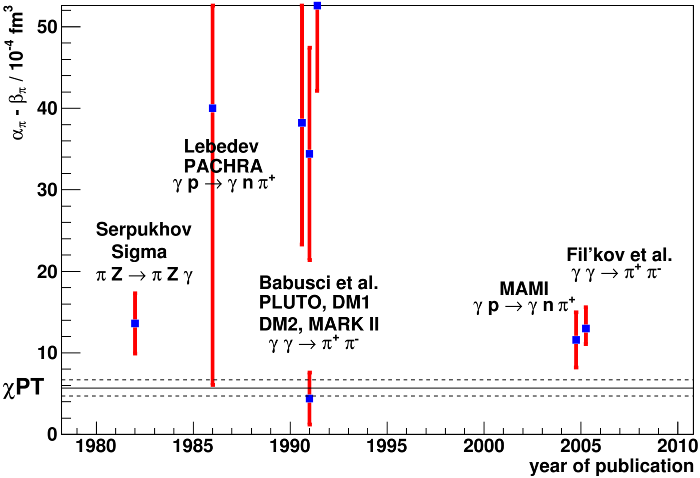
- Primakoff Compton reaction:

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

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

  fully under theoretical control

Pion Polarisability: Experimental Situation



Polarisability measurements at COMPASS

Nov. 2004

- eff. 3 days competitive to the Serpukhov measurement
- problems with the calorimeter (stability, trigger logic)
  $\rightarrow$ large estimated systematic error

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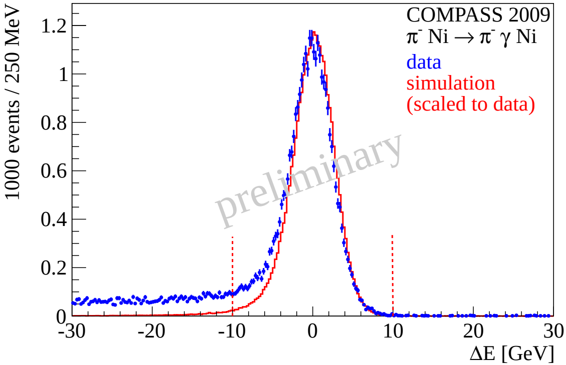
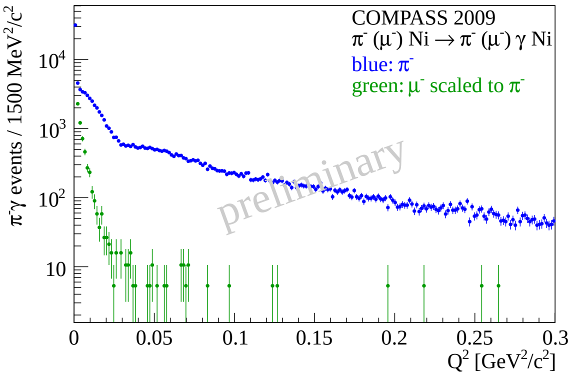
Identifying the $\pi\gamma \to \pi\gamma$ reaction



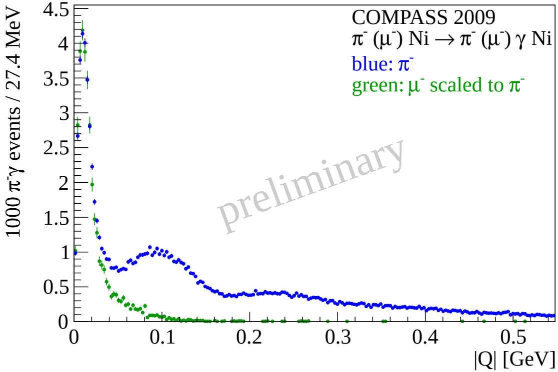
- Exclusivity peak $\sigma \approx 2.6$ GeV
- $\sim$ 30.000 exclusive events (Serpukhov $\sim$ 7000)

Primakoff peak



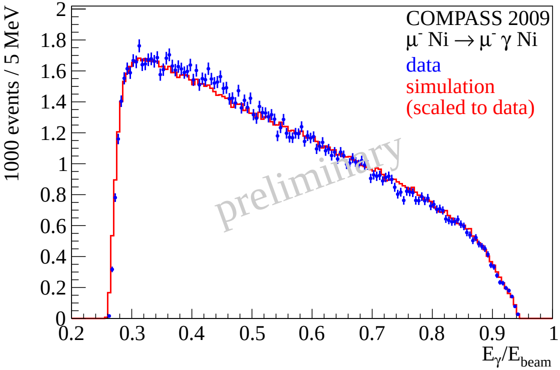
- Q^2-spectrum: photon-exchange peak in first bin
- muon control measurement:
  pure electromagnetic interaction, no polarisability effect

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 $Q \approx 170$ MeV/c

On the way to polarisability: Photon energy spectrum



- understanding of the photon spectrum on the few-% level
- pion data: [expected] 10 – 20% polarisability effect on x_γ =0.75 – 0.95 region, *not yet released*

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2012

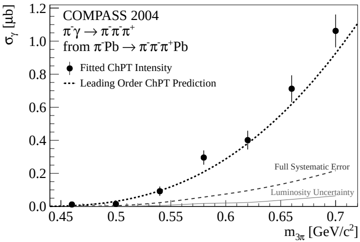
- COMPASS-II proposal for a high-statistics Primakoff run
- increase statistics by a factor > 30
- First measurement of polarisability sum $\alpha_\pi + \beta_\pi$

Proposal for the high-statistics Primakoff run

Days	π beam, days	μ beam, days	$\alpha_\pi - \beta_\pi$ σ_{tot}	$\alpha_\pi + \beta_\pi$ σ_{tot}	$\alpha_2 - \beta_2$ σ_{tot}
120	90	30	± 0.27	fixed	fixed
			± 0.26	± 0.016	fixed
			± 0.66	± 0.025	± 1.94
			ChPT prediction		
			5.70	0.16	4

Primakoff (*pion*) program is broader: Measure exclusive *pion-photon* reactions

$$\pi+\gamma \rightarrow \begin{cases} \pi + \gamma & \text{Compton reaction: polarisabilities} \\ \pi + \pi^0 & \text{single pion production: chiral anomaly} \\ \pi + \pi^0 + \pi^0 & \text{double pion production: chiral trees + loops,} \\ \pi + n \cdot \pi^{\pm} & \quad \text{resonances, exotics} \end{cases}$$



Summary and Outlook

- Measurement of the pion polarisability
  - Long-standing demand by theory of QCD
  - Available data scarce and contradictory
  - Primakoff data taken in 2009 π^- on Ni: $> 4\times$ Serpukhov statistics
  - Systematic checks with $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
    $\Rightarrow$ uncertainty expected $< 1.0 \cdot 10^{-4}\text{fm}^3$
- 2004 few-days hadron run with 190 GeV π^- beam
  - Lower-mass region $\Rightarrow$ chiral dynamics in $\pi\gamma \to \pi^-\pi^-\pi^+$
    $\pi\gamma \to \pi^-\pi^0\pi^0$ from 2009 Primakoff data
- High-statistics run 2012
  - separation of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

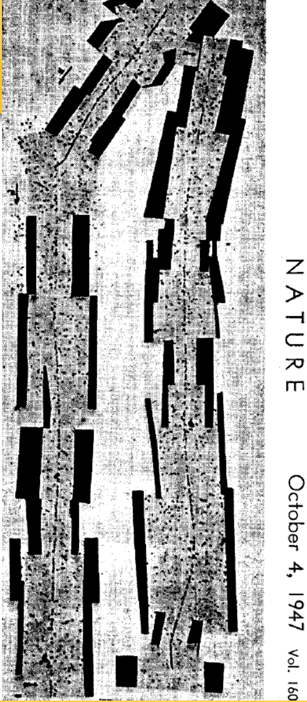
COMPASS: *unique apparatus for Primakoff measurements tackling a broad physics program*

The strong force, the pion and χPT

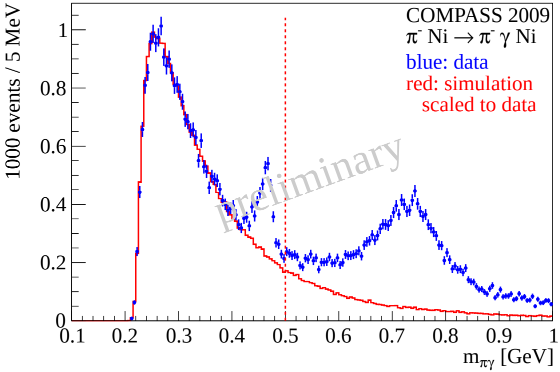
- Yukawa's particle of the strong force
- development of QCD: quarks and gluons
- running coupling parameter, confinement
- $m_q \approx 0 \rightarrow$ chiral symmetry (spontaneously broken)

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

- series expansion of QCD in particle momenta, inner d.o.f. are "condensed" into Low Energy Constants
- π^+ π° π^- (re-)appear as Goldstone bosons

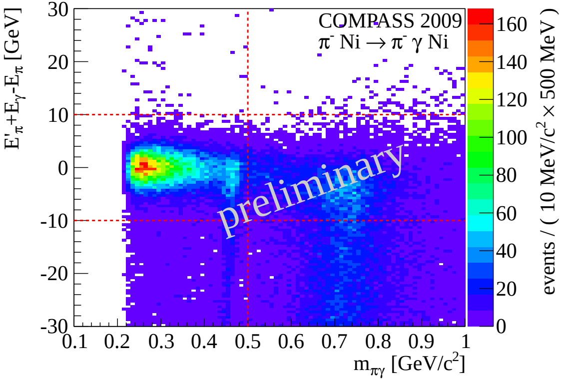


CM energy in $\pi\gamma \to \pi\gamma$



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

Exclusivity vs. $\sqrt{s}$



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

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

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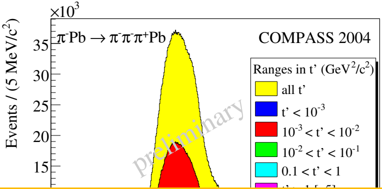
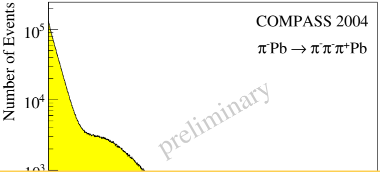
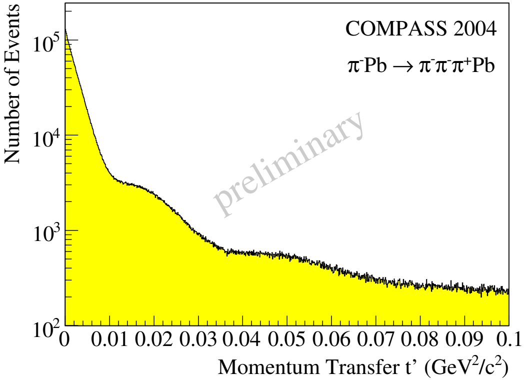
$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \end{cases}$$





2004 Primakoff results (diffractive trigger)

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



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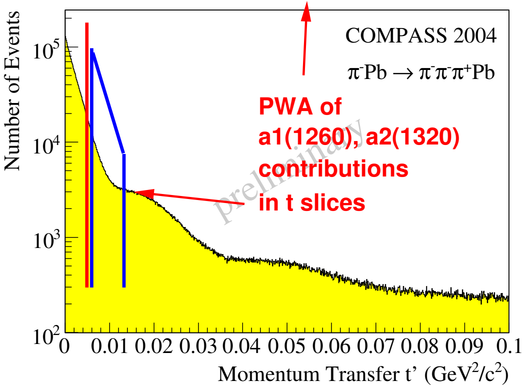
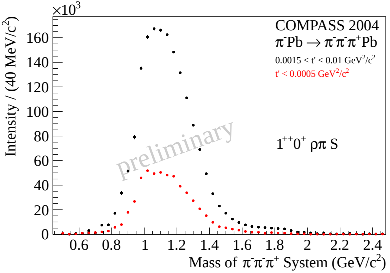
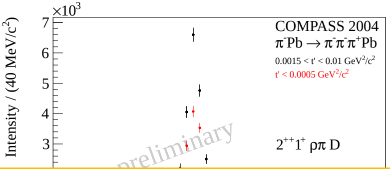
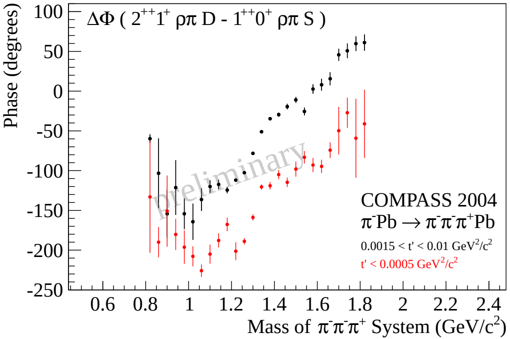
$\pi^- \text{ Pb} \to \text{Pb } \pi^- \pi^- \pi^+$



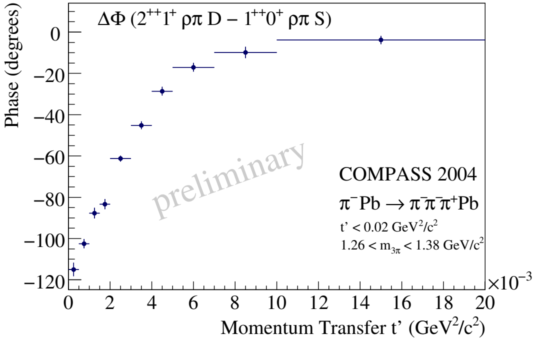
PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

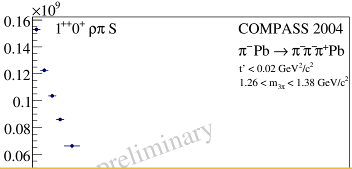






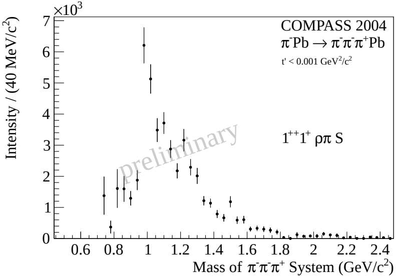
Phase $a_2 - a_1$ in detail: t' dependence

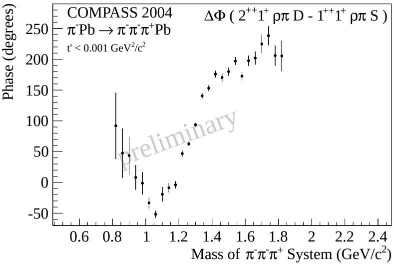


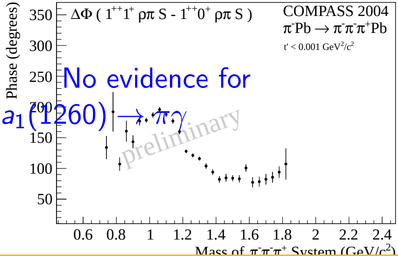


- transition of $\pi\gamma$ to $\pi IP \rightarrow a_2$ productio
- work in progress
- interference can be used to map details of resonances and production

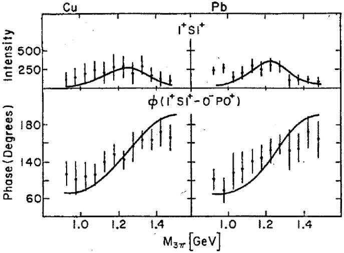
Primakoff production of a1(1260) vs. E272 result





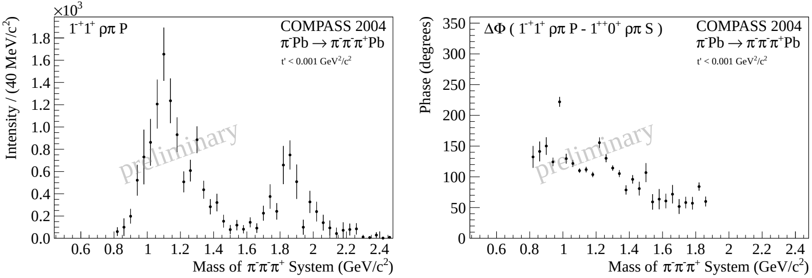


No evidence for $a_1(1260) \to \pi\gamma$



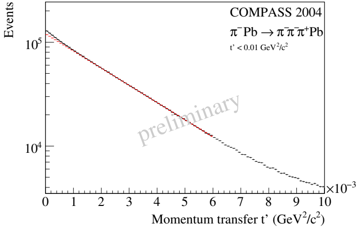
M. Zielinski et al. Phys.Rev.Lett.vol.52, 14.

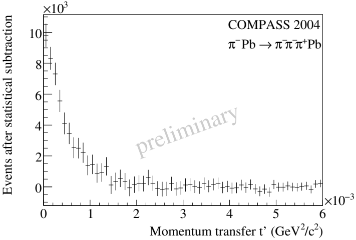
Spin-exotic 1^{-+}

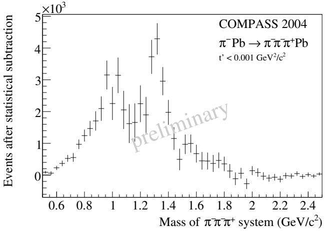


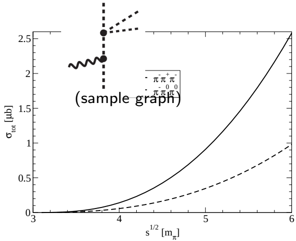
No evidence for $\pi_1(1600)$ Primakoff production

Another look at the mass spectrum: threshold region







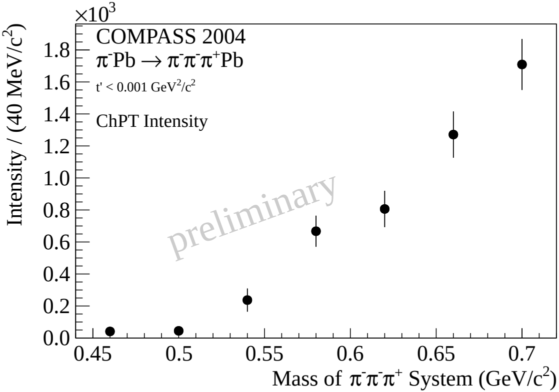


→ *implement "chiral amplitude" in PWA*

Total Intensity of Chiral Amplitude

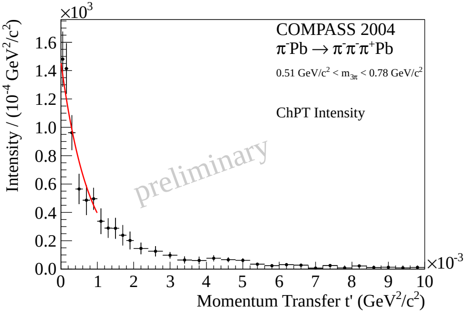
Chiral amplitude at low masses equivalent to fit with 6 waves

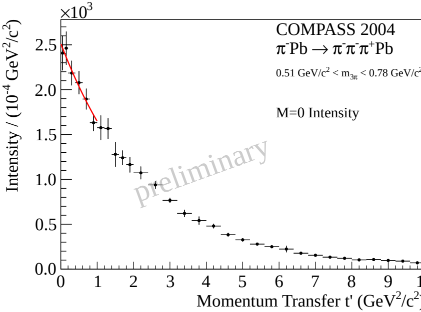
but much less parameters (i.e. basically intensity)



t' Dependence of Chiral Amplitude

- Fits in small bins of t', but only 1 mass bin $(0.51 < m_{3\pi} < 0.78)\,\mathrm{GeV}/c^2$
- t' dependence of intensity $\sigma \propto e^{-bt'}$

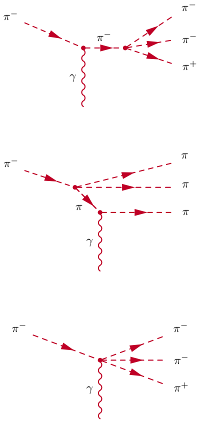




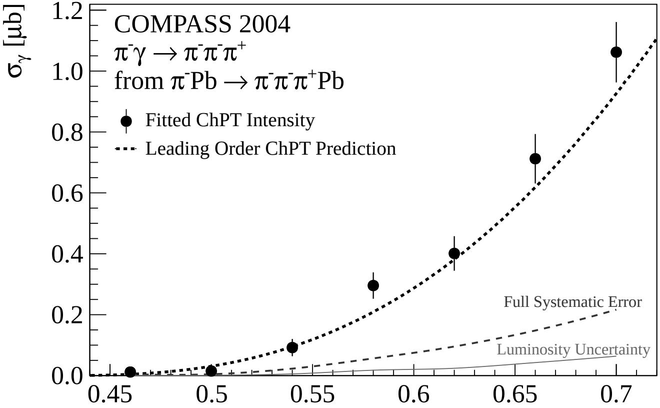
$$b_{chiral} \approx 1560\,(\mathrm{GeV}/c)^{-2}$$
$$b_{M=0} \approx 400\,(\mathrm{GeV}/c)^{-2}$$

$\leftrightarrow$ Primakoff (Photon) $\leftrightarrow$ diffractive

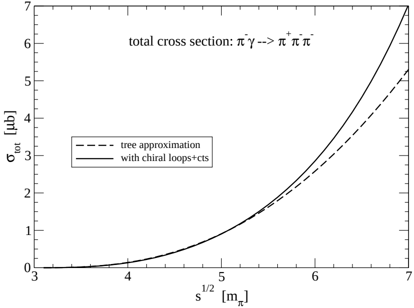
First Measurement of $\pi\gamma \to 3\pi$ Absolute Cross-Section

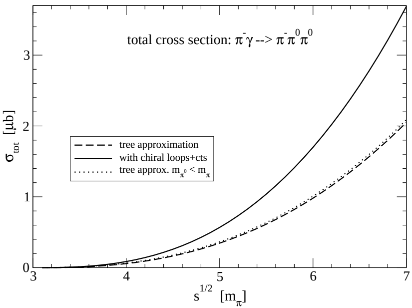


Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$



Higher-order effects





Chiral loops, e.g.

(N. Kaiser, NPA848 (2010) 198)

not (yet)