The charged-pion polarisability and more measurements on chiral dynamics at COMPASS

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Physik-Department, TU München

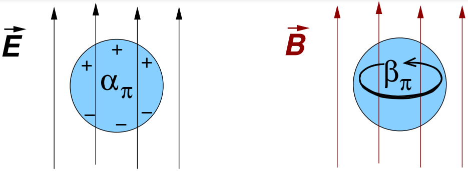
COMPASS collaboration

The 8th International Workshop on Chiral Dynamics, Pisa

1. July 2015

Bundesministerium für Bildung und Forschung

Pion polarisability and theoretical expectation



pion polarisabilities $\boldsymbol{\alpha_\pi}$, $\boldsymbol{\beta_\pi}$ in units of 10^{-4} fm^3

size of the pion $\sim$ 1 fm^3 [cf. atoms: polarisability $\approx$ size $\approx$ 1 Å^3]

Theory: ChPT (2-loop) prediction:

$$\begin{aligned} \alpha_\pi - \beta_\pi &= 5.7 \pm 1.0 \\ \alpha_\pi + \beta_\pi &= 0.16 \pm 0.1 \end{aligned}$$

Gasser, Ivanov, Saino Nucl. Phys. B 745, 84 (2006) [GIS]

relevant low-energy constants from the measurement of $\pi^+ \to e^+ \nu_e \gamma$
recent precision measurements: PIBETA PRL93(2004)181804, update
(and wangled "$\alpha_\pi = -\beta_\pi$" value) in PRL103(2009)051802)

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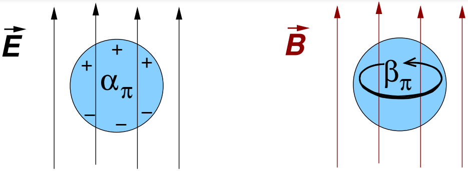

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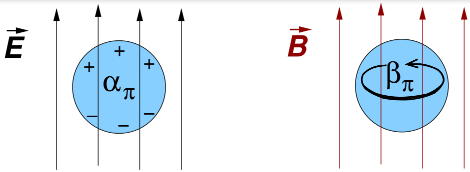

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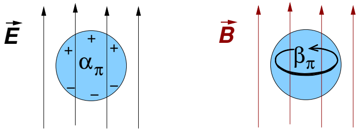
experimental value?

Pion Compton Scattering

$$\pi \quad \gamma \quad \rightarrow \quad \pi \quad \gamma$$



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

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

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

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

Pion Compton scattering: embedding the process

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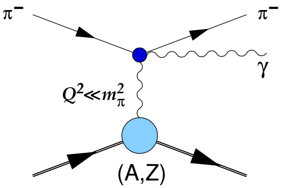
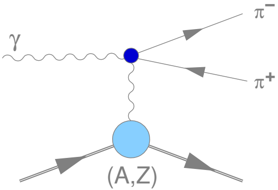
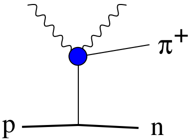
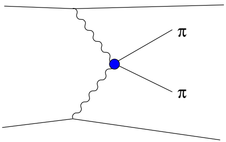




Primakoff processes



Radiative pion photoproduction



Photon-Photon fusion

Pion polarisability: world data before COMPASS

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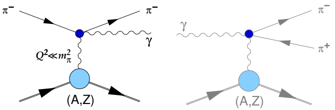

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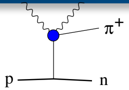

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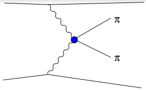

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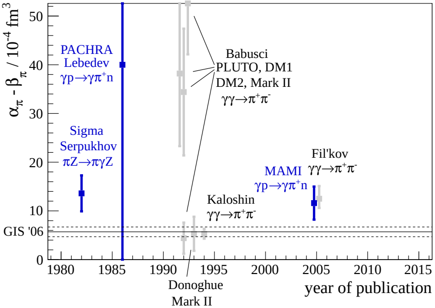
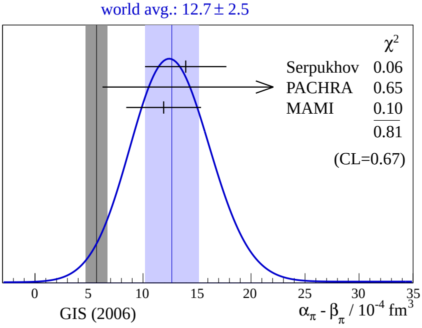
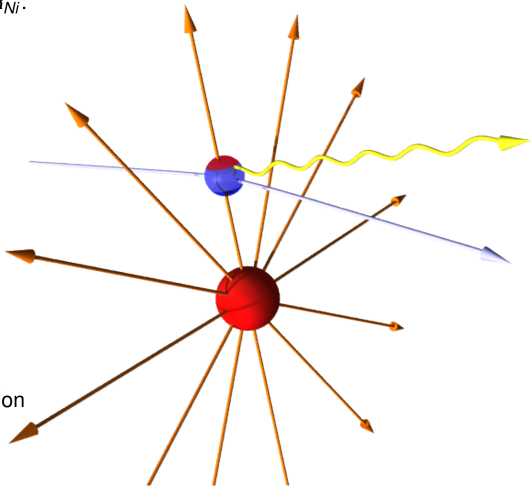




GIS'06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD
Fil'kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)

Polarisability effect in Primakoff technique

- Charged pions traverse the nuclear electric field
  - typical field strength at $d = 5R_{Ni}$: $E \approx 300\,\mathrm{kV/fm}$
- Bremsstrahlung process:
  - particles scatter 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
  - corresponding charge separation $\approx 10^{-5}\,\mathrm{fm} \cdot e$



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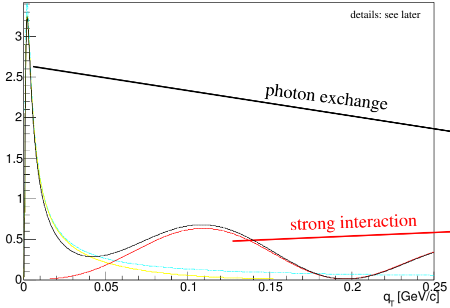

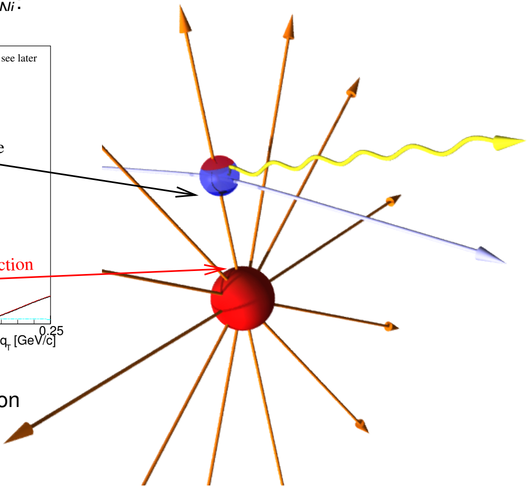

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  - corresponding charge separation $\approx 10^{-5}$ fm $\cdot\, e$

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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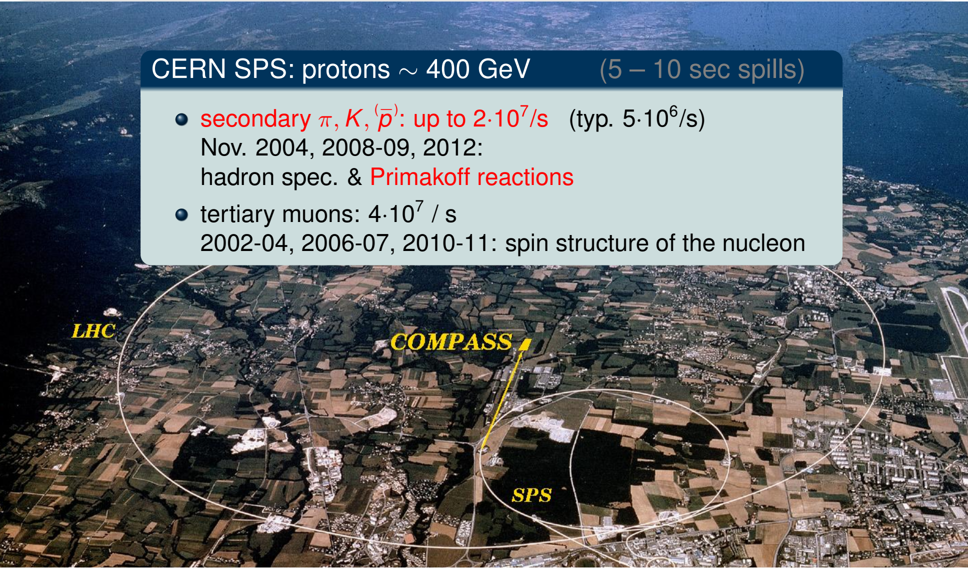
CERN SPS: protons $\sim$ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11: spin structure of the nucleon

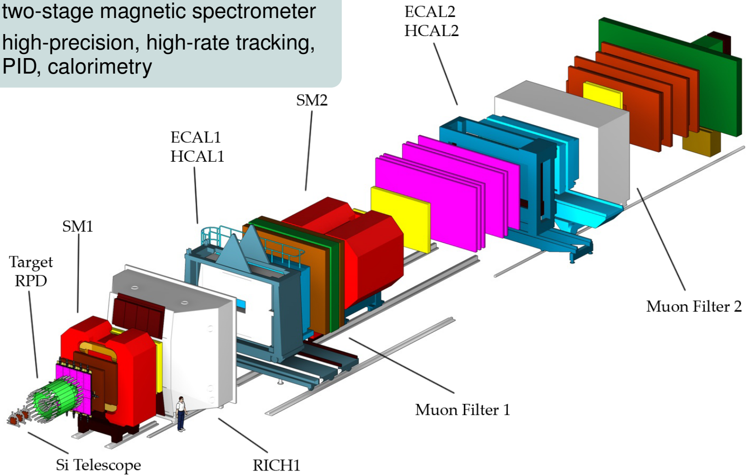


COMPASS

Experimental Setup

Fixed-target experiment

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



COMPASS

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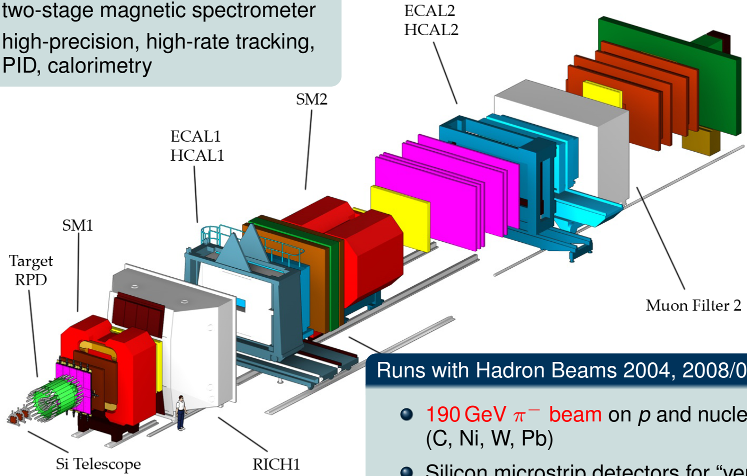
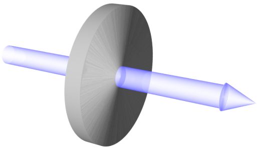


Runs with Hadron Beams 2004, 2008/09, 2012

- 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 COMPASS measurement

- high-energetic pion beam on 4mm nickel disk
- observe scattered pions in coincidence with produced hard photons
- study of cross-section shape



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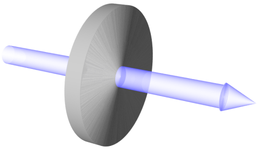

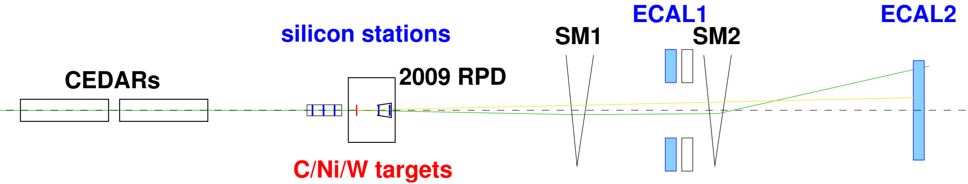

Extraction of the pion polarisability

- Identify exclusive reactions

$$\pi\gamma_{\{\mathrm{Ni}\rightarrow\mathrm{Ni}'\}} \rightarrow \pi\gamma$$

at smallest momentum transfer $< 0.001\ \mathrm{GeV}^2/c^2$

- Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

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

is derived, depending on $x_\gamma = E_{\gamma(lab)}/E_{Beam}$.
Measuring R the polarisability α_π can be concluded.

- Control systematics by

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

and

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

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latest publication on the pion polarisability

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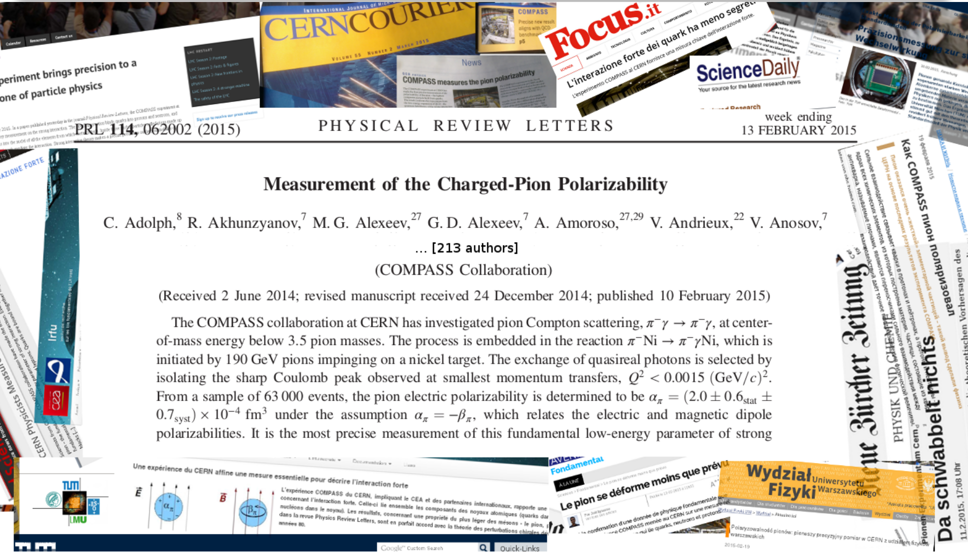


PRL 114, 062002 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

Measurement of the Charged-Pion Polarizability

C. Adolph,[8] R. Akhunzyanov,[7] M. G. Alexeev,[27] G. D. Alexeev,[7] A. Amoroso,[27,29] V. Andrieux,[22] V. Anosov,[7]

... [213 authors]

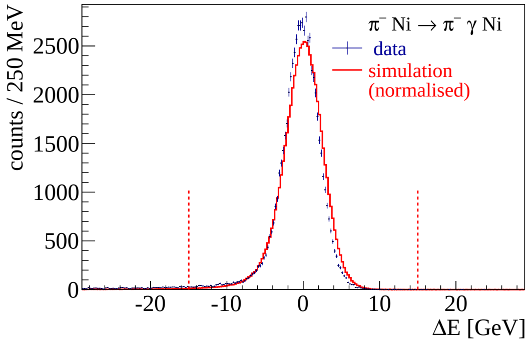
(COMPASS Collaboration)

(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \rightarrow \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \rightarrow \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong

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

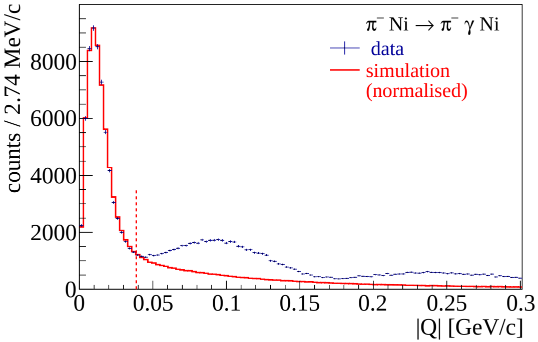
Phys. Rev. Lett. 114, 062002 (2015)



- 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 $x_\gamma > 0.5$)

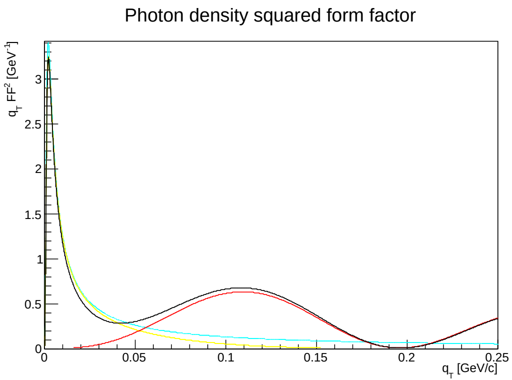
Primakoff peak

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



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

Coulomb-nuclear interference



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

Primakoff peak: muon data

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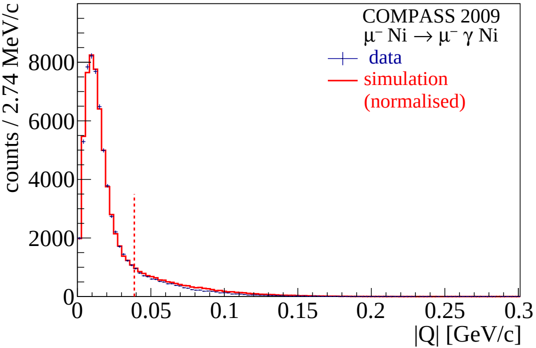
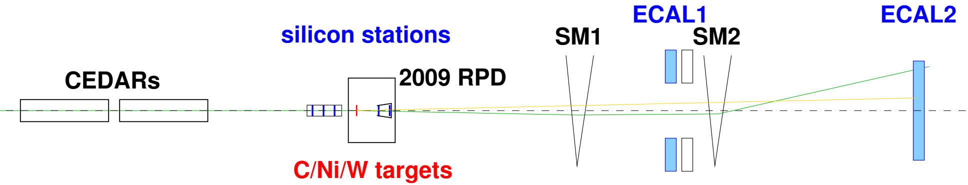
Phys. Rev. Lett. 114, 062002 (2015)



- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood

Principle of the measurement



ECAL2: 3000 cells of different types

ECAL2: the quest for precision

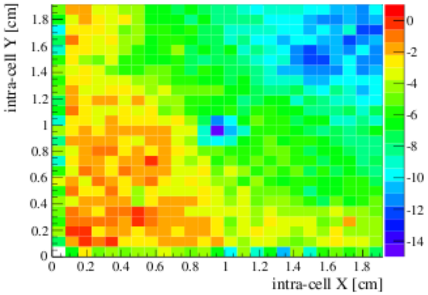


Figure 3.5: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range 133 GeV $< E_\gamma <$ 152 GeV .

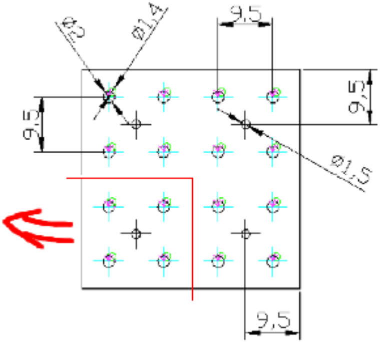


Figure 3.6: Technical drawing of a full shashlik cell to be compared with the figure to the left.

from: Th. Nagel, PhD thesis TUM 2012

Photon energy spectra for muon and pion beam

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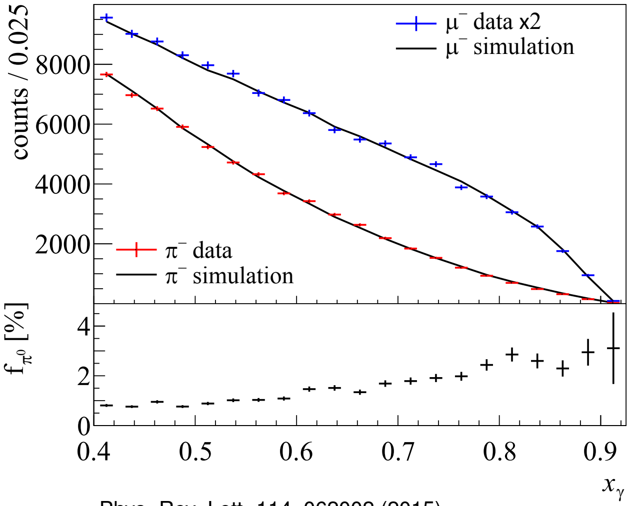
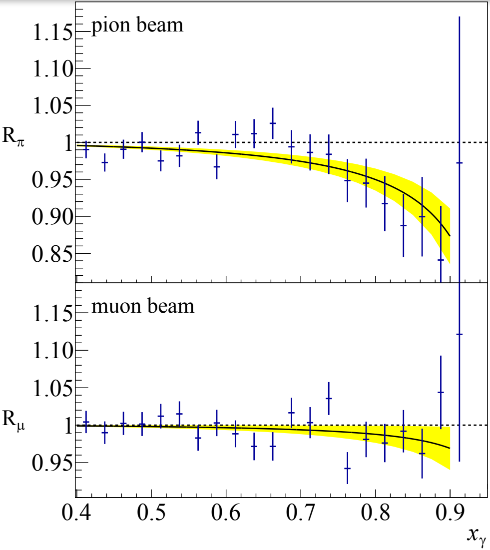


Phys. Rev. Lett. 114, 062002 (2015)

Pion polarisability: COMPASS result



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

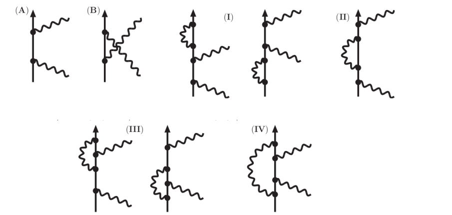
(assuming $\alpha_\pi = -\beta_\pi$)

“false polarisability” from muon data:

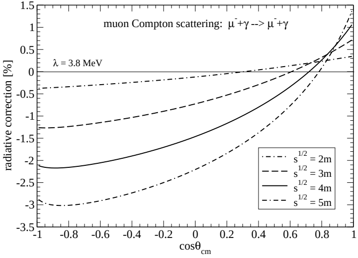
$$(\,0.5 \pm 0.5_{\text{stat}}\,) \times 10^{-4}\,\text{fm}^3$$

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

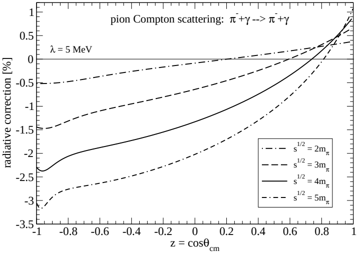
Radiative corrections (Compton scattering part)



implemented on the level of the COMPASS Monte Carlo simulation, including soft photon emission



Nucl.Phys. A837 (2010)



Eur.Phys.J. A39 (2009) 71

source of systematic uncertainty	estimated magnitude $\mathrm{CL} = 68\,\%$ $[10^{-4}\,\mathrm{fm}^3]$
determination of tracking-detector efficiencies	0.5
treatment of radiative corrections	0.3
subtraction of π^0 background	0.2
strong interaction background	0.2
pion-electron elastic scattering	0.2
contribution of muons in the beam	0.05
quadratic sum	0.7

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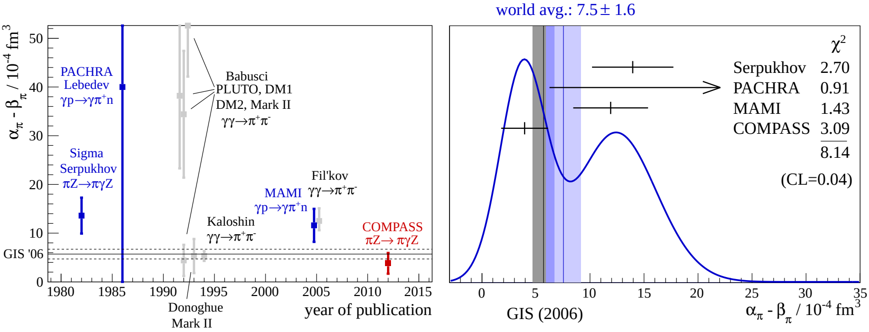
COMPASS result for the pion polarisability:

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

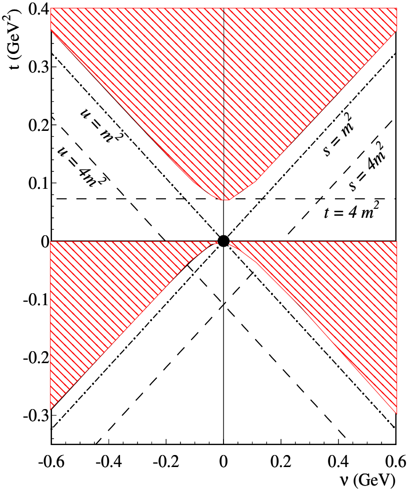
with $\alpha_\pi = -\beta_\pi$ assumed

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

About crossing



from: D. Drechsel, talk at IWHSS 2011 Paris

- red hatched: physical regions
  $\gamma + \gamma \to \pi + \pi$
  $\gamma + \pi \to \gamma + \pi$
- two-pion thresholds at $s = 4m_\pi^2$, $u = 4m_\pi^2$, $t = 4m_\pi^2$
- DR integration paths
  $t = 0$ (forward),
  $\theta = 180^\circ$ (backward)
  $u = m_\pi^2$, $s = m_\pi^2$, ...

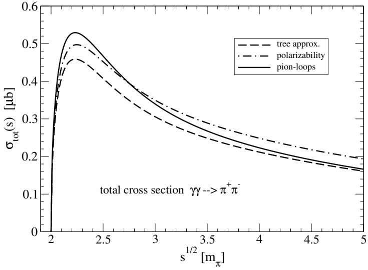
Photon-photon fusion process $\gamma\gamma \to \pi^+\pi^-$

- Planned measurements at ALICE and JLab

$$\sigma_{tot}(s) = \frac{2\pi\alpha^2}{\hat{s}^3 m_\pi^2}\Big\{\big[4+\hat{s}+\hat{s}|C(\hat{s})|^2\big]\sqrt{\hat{s}(\hat{s}-4)}$$

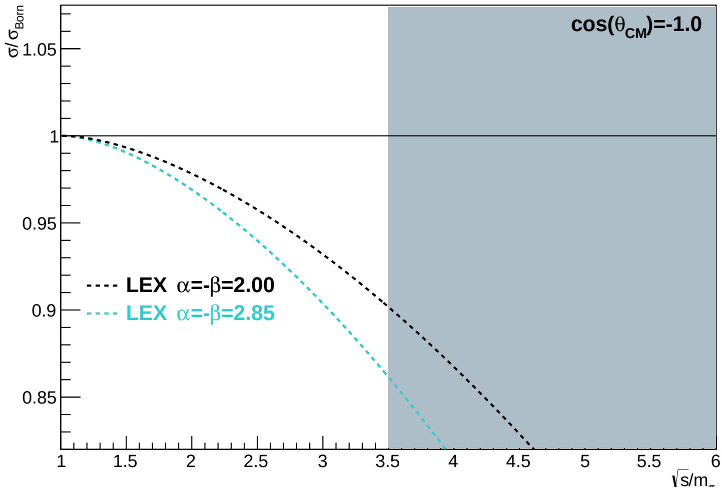
$$+8\big[2-\hat{s}+\hat{s}\,\mathrm{Re}\,C(\hat{s})\big]\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}\Big\},$$

$$C(\hat{s}) = -\beta_\pi\frac{m_\pi^3}{2\alpha}\hat{s} - \frac{m_\pi^2}{(4\pi f_\pi)^2}\left\{\frac{\hat{s}}{2}+2\left[\ln\frac{\sqrt{\hat{s}}+\sqrt{\hat{s}-4}}{2}-\frac{i\pi}{2}\right]^2\right\}$$

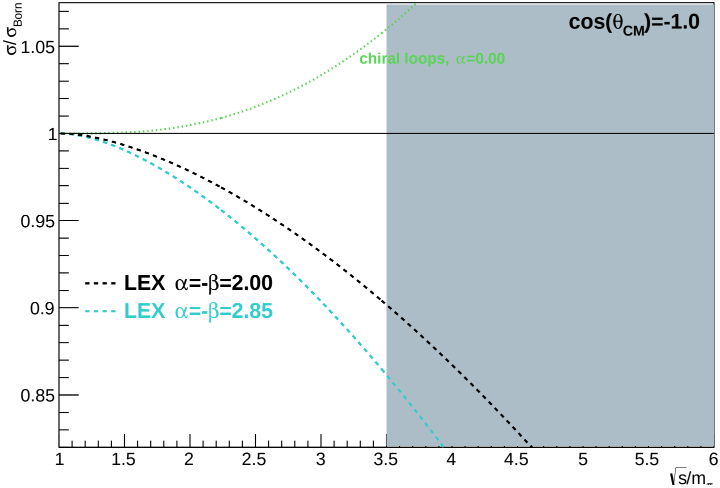


courtesy Norbert Kaiser (TUM)

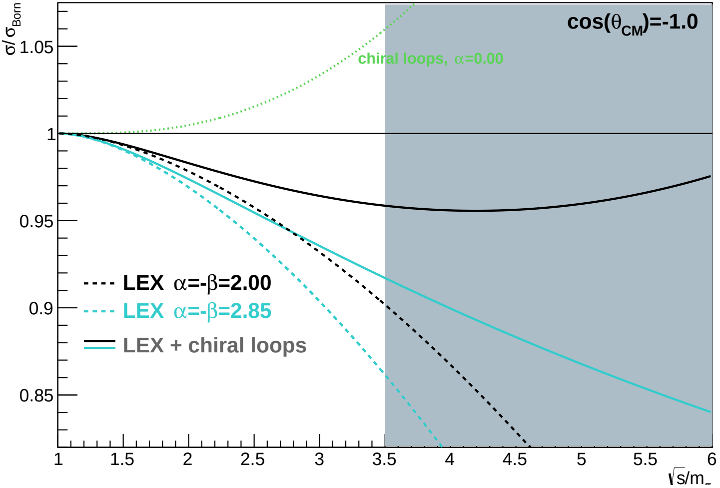
Polarisability, loop contributions, dispersion relations



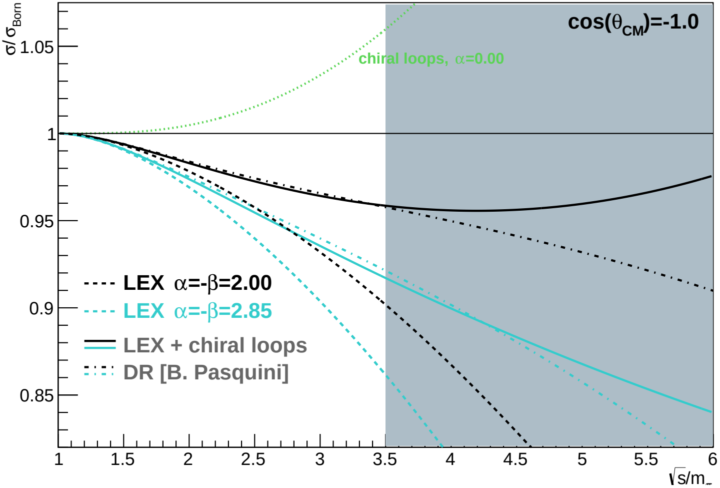
Polarisability, loop contributions, dispersion relations



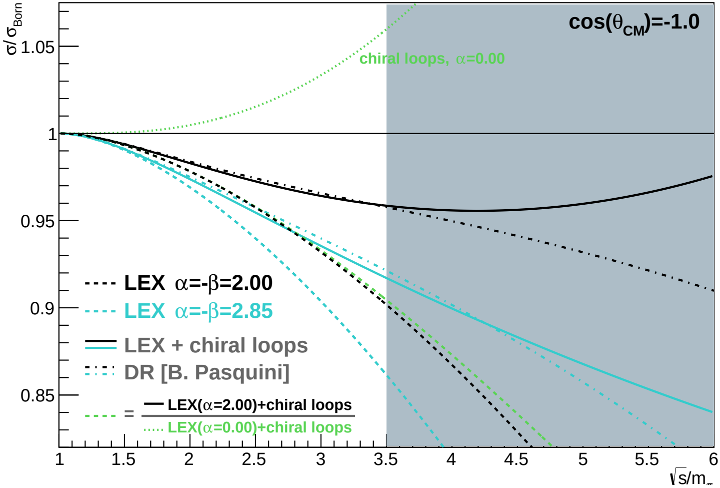
Polarisability, loop contributions, dispersion relations



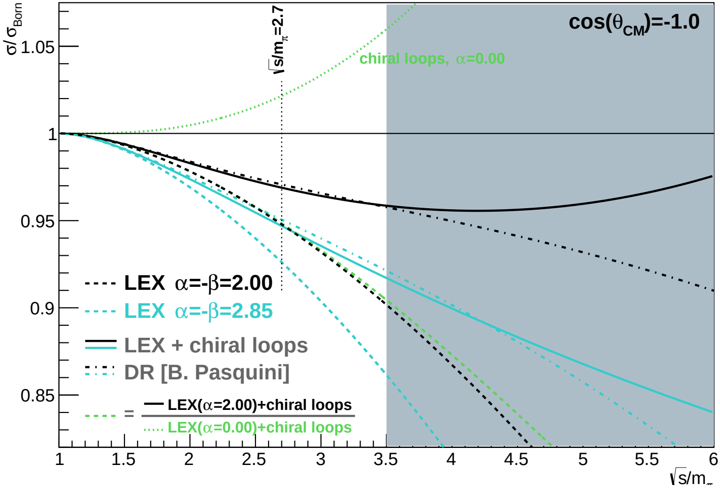
Polarisability, loop contributions, dispersion relations



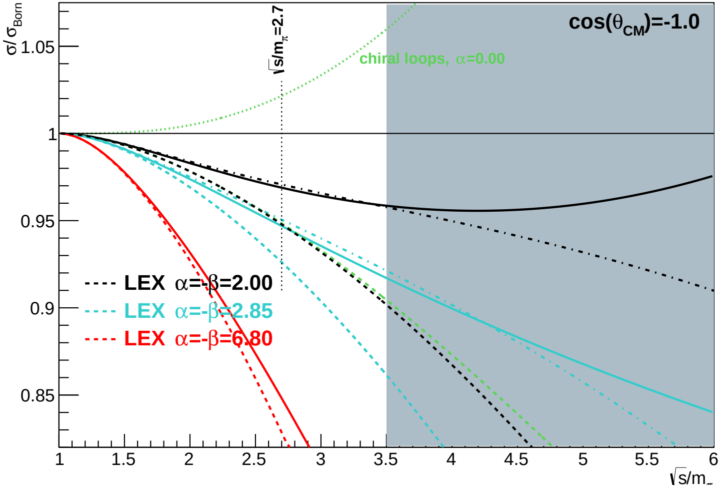
Polarisability, loop contributions, dispersion relations



Polarisability, loop contributions, dispersion relations



Polarisability, loop contributions, dispersion relations



Pion polarisability on the lattice

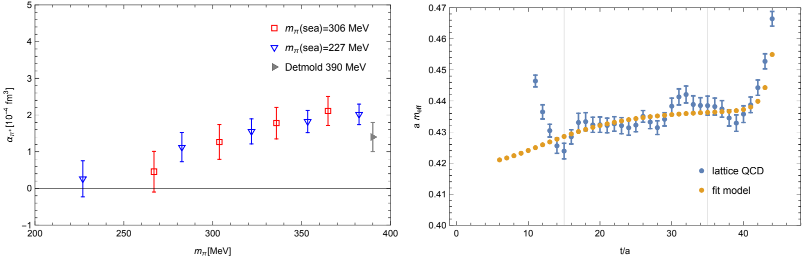


FIGURE 3. Left: electric polarizability for the charged pions as a function of the valence quark mass. The data for $m_\pi = 390\,\mathrm{MeV}$ is taken from [5]. Right: effective mass for a charged pion correlator together with the scalar particle correlator determined from the fit. The fitting range is indicated by the vertical bars.

Alexandru *et al.*, Pion electric polarizability from lattice QCD, arXiv:1501.06516

Pion polarisability measurements at COMPASS

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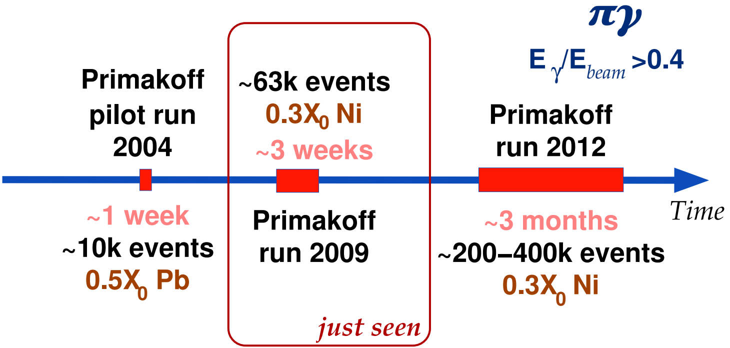
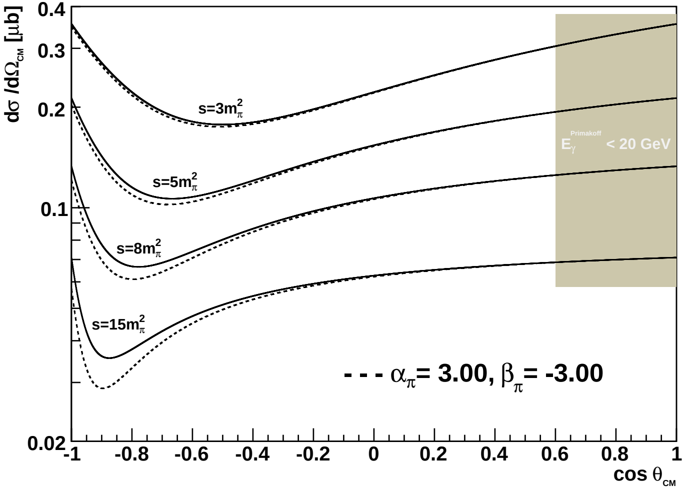


$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

Polarisability effect (LO ChPT values)

loop effects not shown



Polarisability effect (NLO ChPT values)

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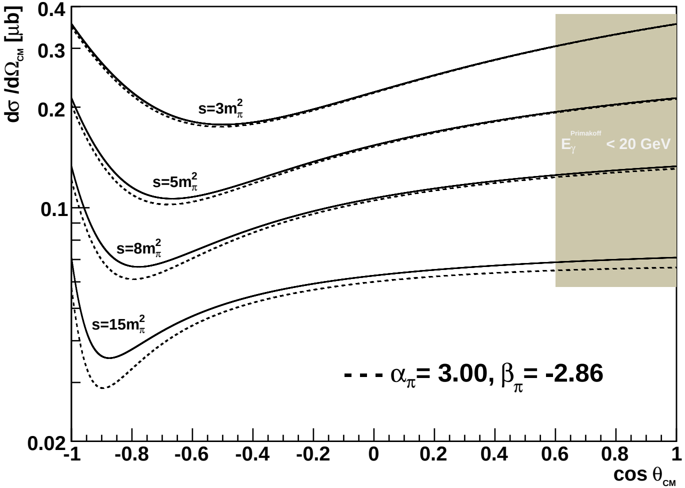
loop effects not shown



Polarisability effect with "wrong-sign" $\alpha_\pi + \beta_\pi < 0$

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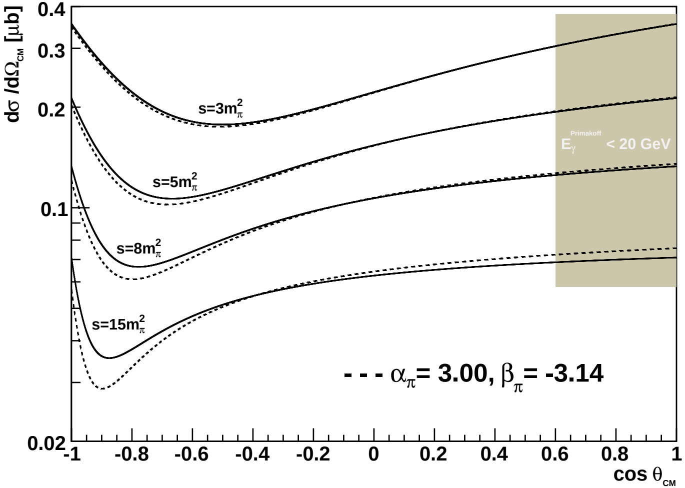
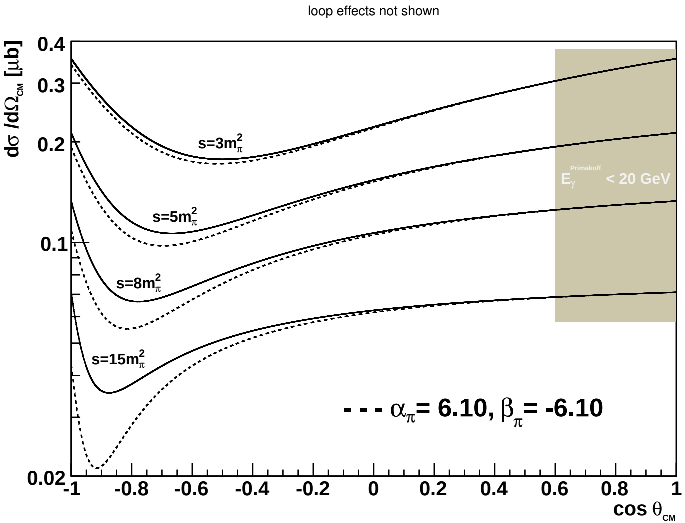
loop effects not shown



Polarisability effect (Serpukhov values)



Primakoff reactions accessible at COMPASS

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

chiral anomaly, delayed

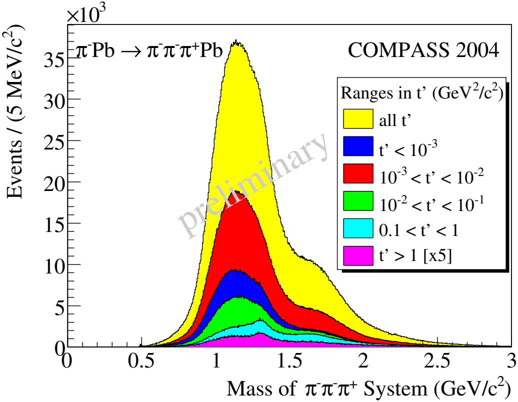
$\Longleftarrow$

$\Longleftarrow$

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

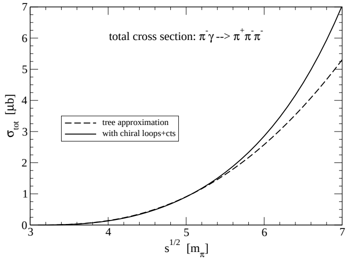
2004 Primakoff results

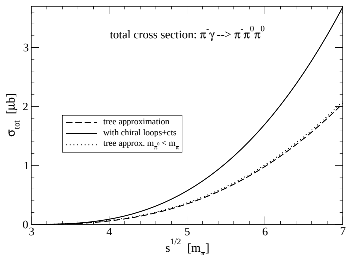
π^- Pb $\to$ Pb π^- π^- π^+

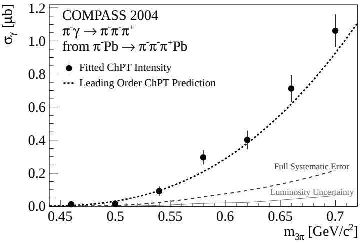


- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim$ 1 000 000 events

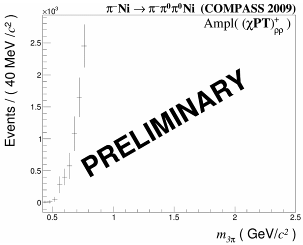
Chiral dynamics in $\pi\gamma \to 3\pi$







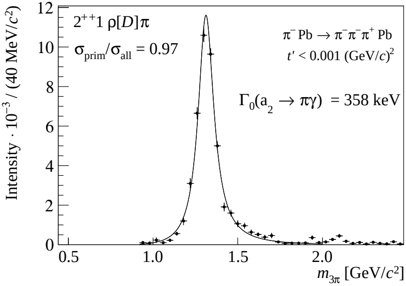
published in PRL 108 (2012) 192001

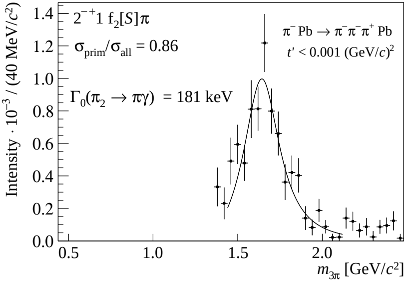


normalization: analysis ongoing

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

Technische Universität München





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

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

- radiative width for $a_2(1320)$: $358\pm6\pm42$ keV larger than PDG value (287 ± 30 keV)
- first measurement for $\pi_2(1670)$

published in EPJ A50 (2014) 79

Summary and Outlook

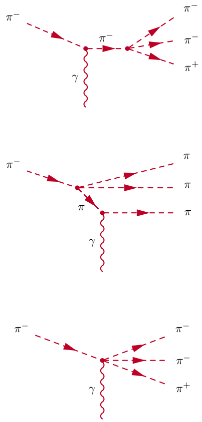
- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined

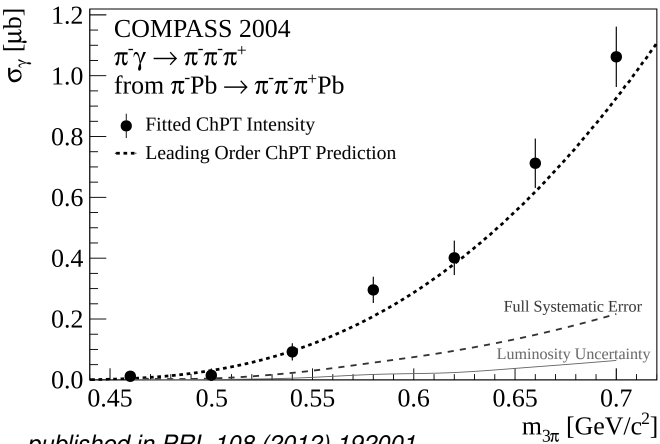
$$\boxed{\alpha_\pi \;=\; (\;2.0\;\pm\;0.6_{\text{stat}}\;\pm\;0.7_{\text{syst}}\;)\;\times 10^{-4}\,\text{fm}^3} \quad \text{assuming } \alpha_\pi + \beta_\pi = 0$$

  - most direct access to the $\pi\gamma \to \pi\gamma$ process
  - most precise experimental determination
  - Systematic control: $\mu\gamma \to \mu\gamma,\; K^- \to \pi^-\pi^0$
- COMPASS measures more aspects of chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$ reactions
- High-statistics run 2012
  - separate determination of α_π and β_π
  - $s-$dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability

Backup

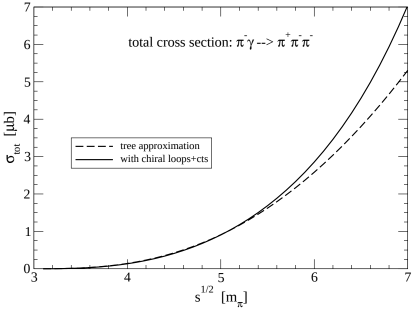
Measured absolute cross-section of $\pi^-\gamma \to \pi^-\pi^-\pi^+$

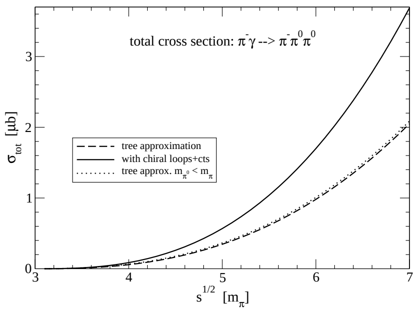




published in PRL 108 (2012) 192001

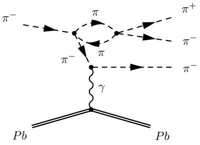
Higher-order effects

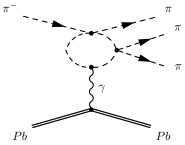




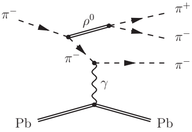
Chiral loops, e.g.

(N. Kaiser,
NPA848 (2010) 198)



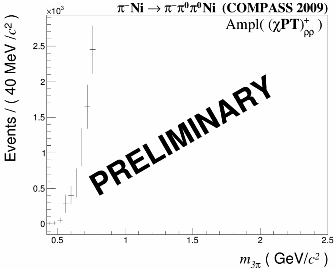


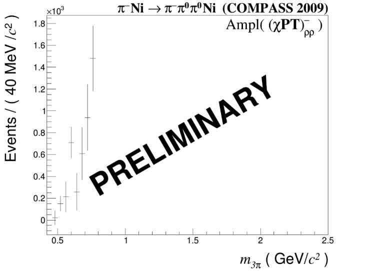
ρ terms:



Partial Wave Analysis

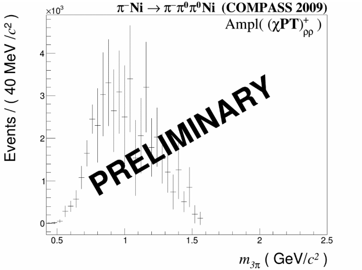
Isobaric Model – Chiral Wave

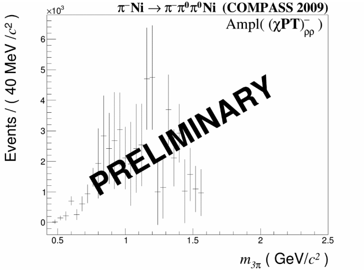




Partial Wave Analysis

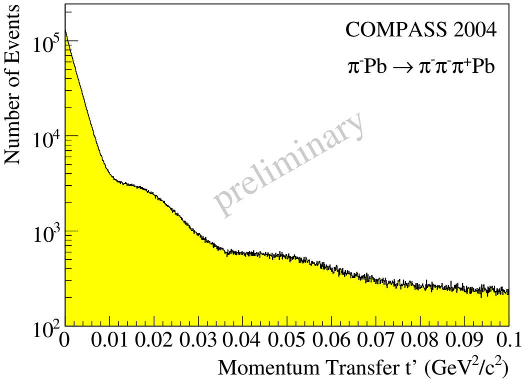
Chiral Model - Amplitudes





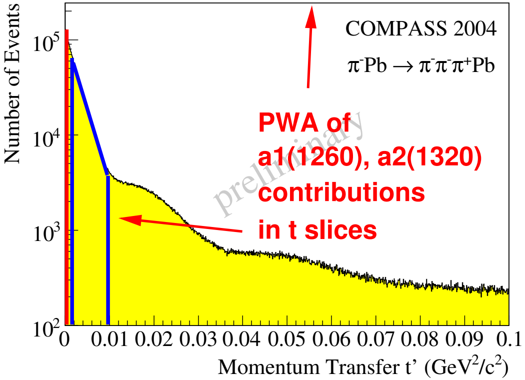
2004 Primakoff results

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



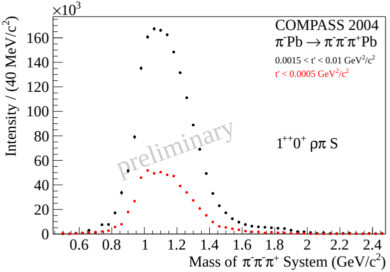
- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

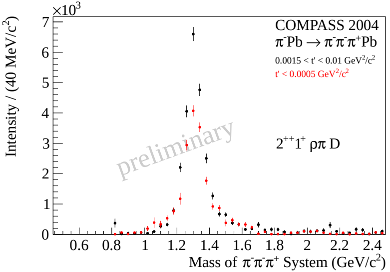
$$\pi^- \text{ Pb} \rightarrow \text{Pb } \pi^- \ \pi^- \ \pi^+$$

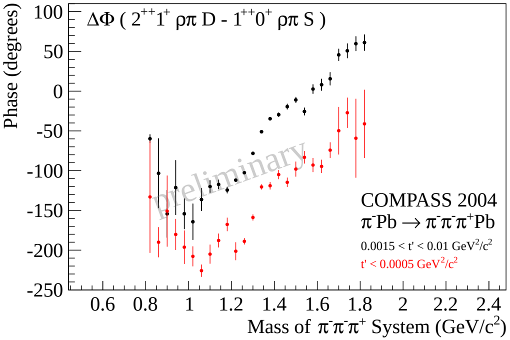


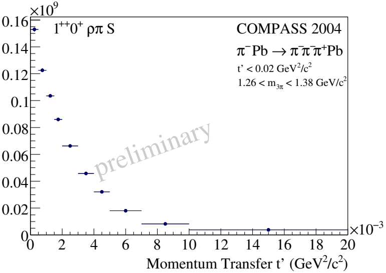
- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

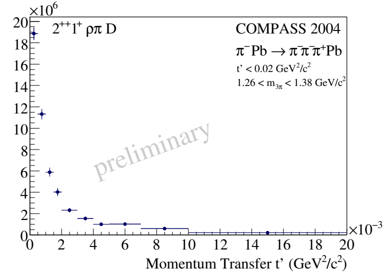
PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

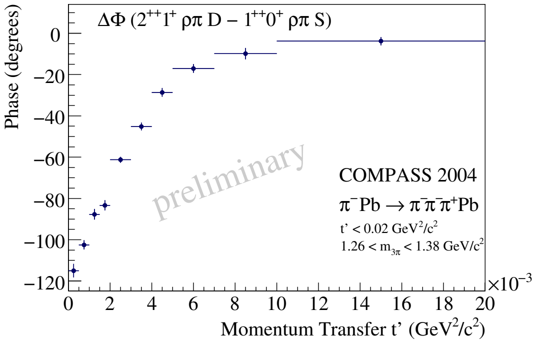












- transition of $\pi\gamma$ to $\pi I\!P \to a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

- Radiative π^+ production on the proton:

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

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:

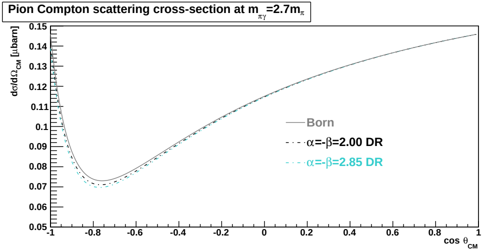
$$\boldsymbol{\gamma^{*}\, \pi \longrightarrow \pi\, \gamma} \qquad [\text{via } \pi\, Z \to Z\, \pi\, \gamma]$$

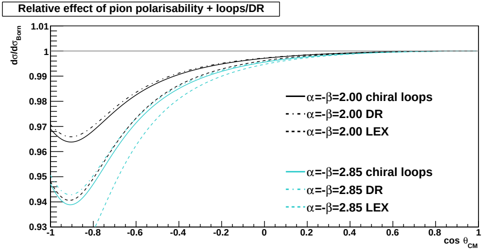
tiny extrapolation $\gamma^* \to \gamma$ $\mathcal{O}(10^{-3} m_\pi^2)$

fully under theoretical control

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

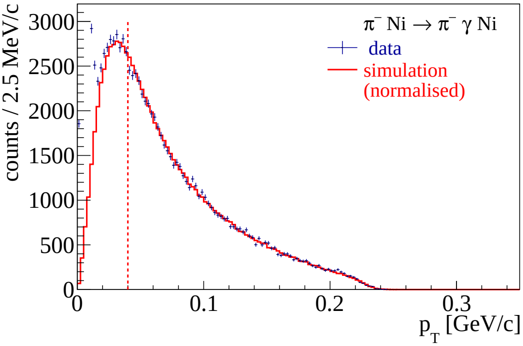
DR vs. chiral loops



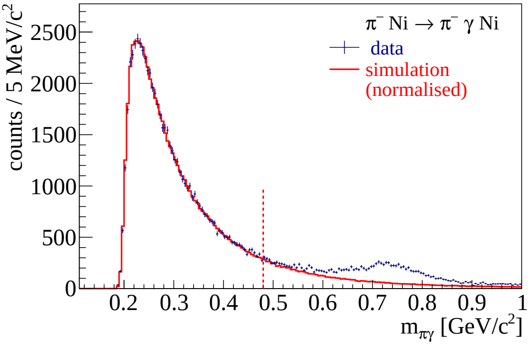


tially to our $\pi_{e2\gamma}$ data set. Our best-fit value of F_A agrees well with ChPT calculations, tending to the top of the reported range [7–9]. However, a more precise measurement of $\tau_{\pi 0}$ is needed in order that the sensitivity of our data, expressed in Eq. (2), be put to full use in determining F_A. We use our form factor results to evaluate the pion polarizability α_E and the ChPT parameter sum $L_9^r + L_{10}^r$ at leading order as follows: Using the one-parameter fit, we obtain $\alpha_E = -\beta_M = 2.78(2)_{\rm expt}(10)_{F_V} \times 10^{-4}\ {\rm fm}^3$, and $L_9^r + L_{10}^r = 0.001\,45(1)_{\rm expt}(5)_{F_V}$, where the first uncertainty comes from the fit and the second from the current CVC-derived value of F_V. Alternatively, we get $\alpha_E = 2.7(^{+6}_{-5}) \times 10^{-4}\ {\rm fm}^3$ and $L_9^r + L_{10}^r = 0.0014(^{+3}_{-2})$ based on our unconstrained fit of F_A and F_V. In addition, we use the

Minimum transverse momentum of the charged particle

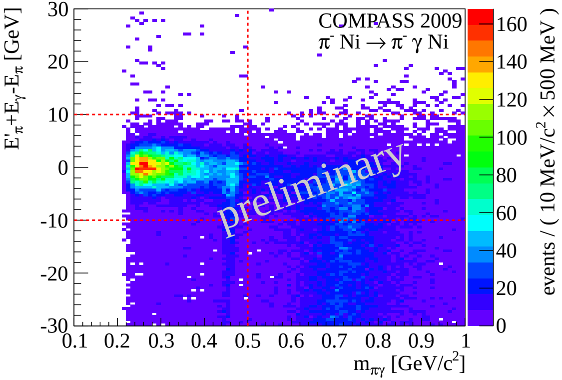


CM energy in $\pi\gamma \to \pi\gamma$



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

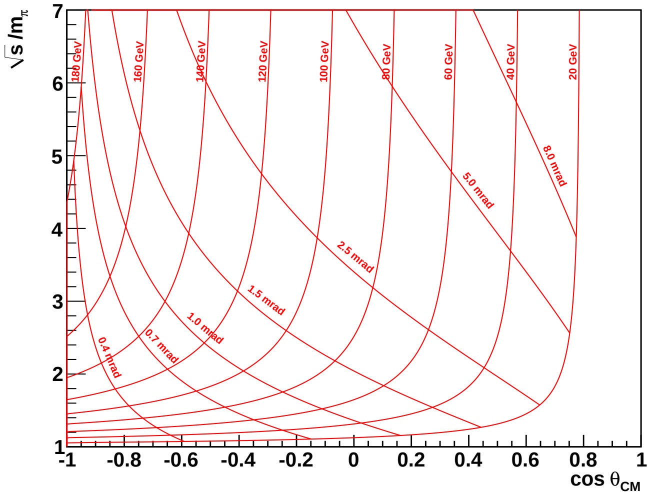
Exclusivity vs. $\sqrt{s}$



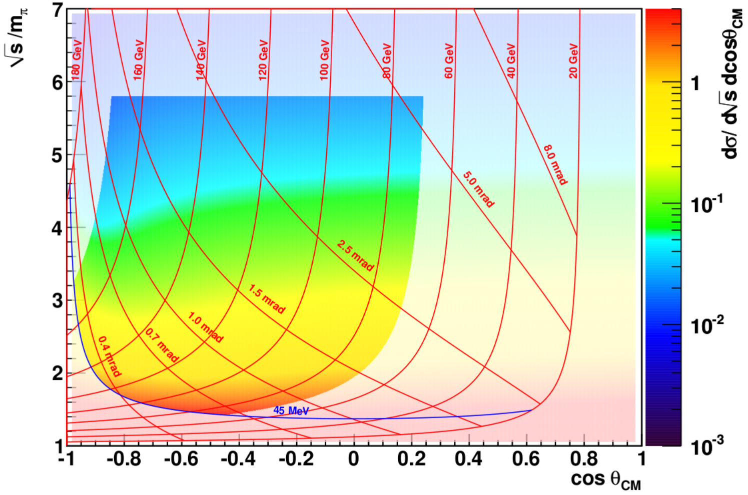
- ρ contribution from $\pi\gamma \rightarrow \pi\pi^0$

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

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



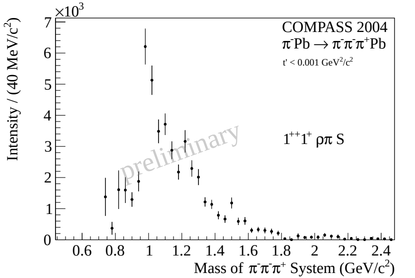
Cross section

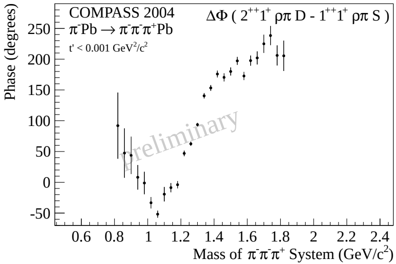


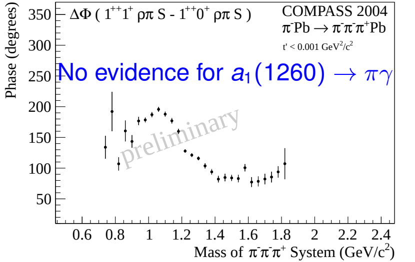
M.R. Pennington in the 2nd DAΦNE Physics Handbook,
"What we learn by measuring $\gamma\gamma \to \pi\pi$ at DAΦNE":

> 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.

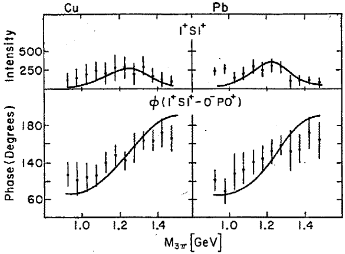
Primakoff production of a1(1260) vs. E272 result







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



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

BACKUP: Partial Wave Analysis Formalism

- Mass-independent PWA (narrow mass bins):

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

  - 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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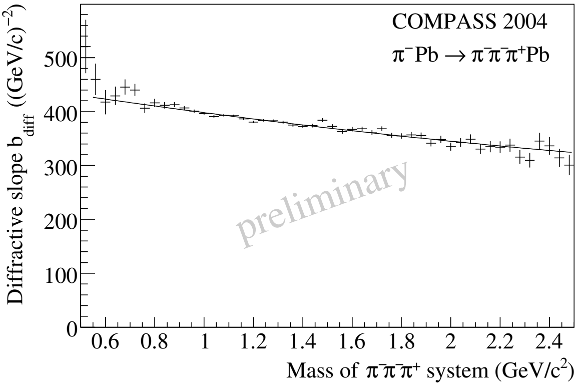
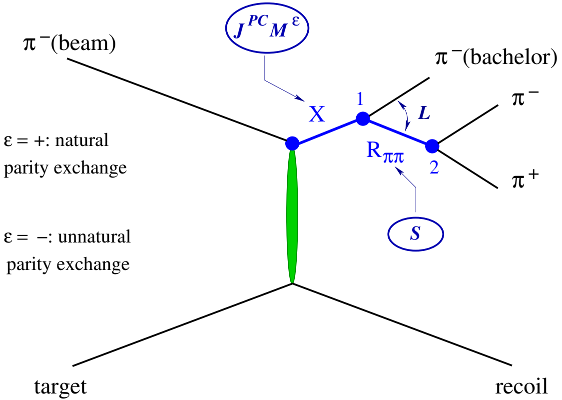


Partial Wave Analysis Formalism

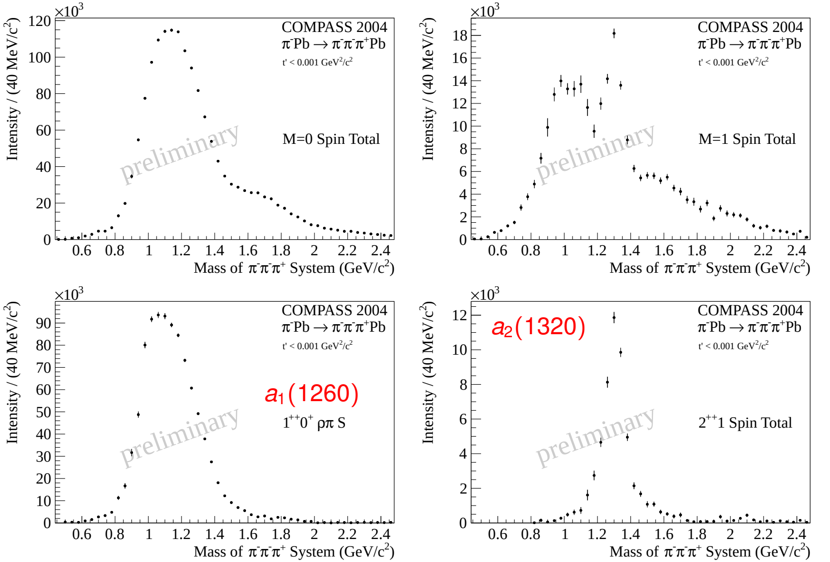
Isobar Model



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

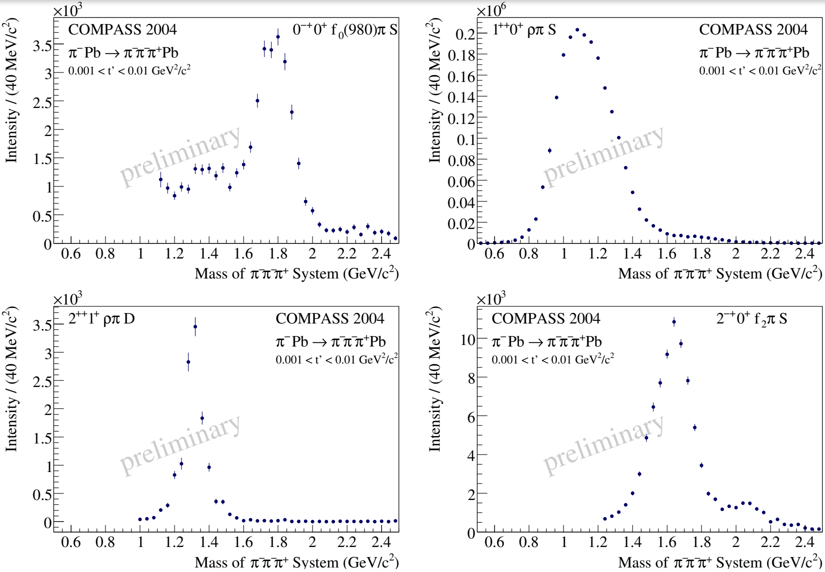
- Mass-independent PWA (40 MeV/c^2 mass bins): 38 waves
  Fit of angular dependence of partial waves, interferences
- Mass-dependent χ^2-fit (Not presented here)

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



PWA of data with low t'

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

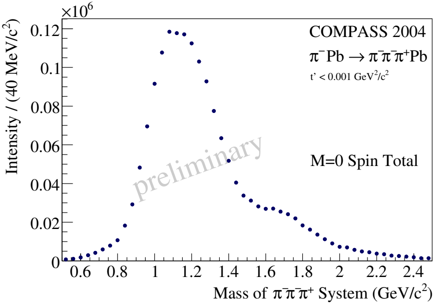
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

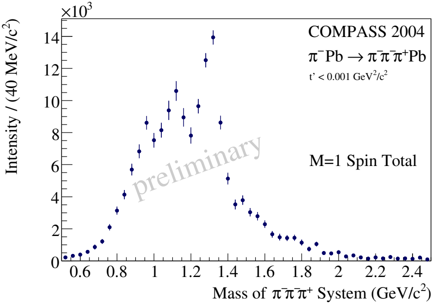
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$ $\rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

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

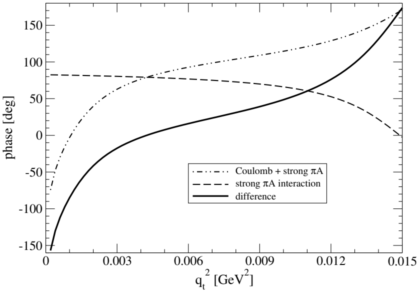
M=1: $\sigma(t') \propto t' e^{-b_{\mathrm{diff}}(m) t'}$ $\rightarrow$ vanishes for $t' \approx 0$

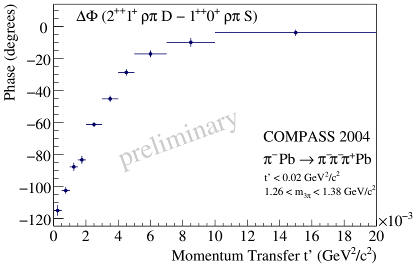


M=0



M=1





Glauber modell

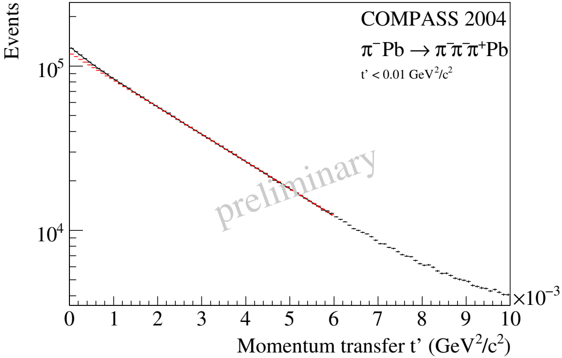
G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulomb-interaction - strong interaction
⇒ detailed studies of the nature of resonances

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

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



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