Tests of ChPT with COMPASS

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for the COMPASS collaboration

Chiral'10
Valencia, June 22

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

Excellenzcluster: Origin and Structure of the Universe, BMBF

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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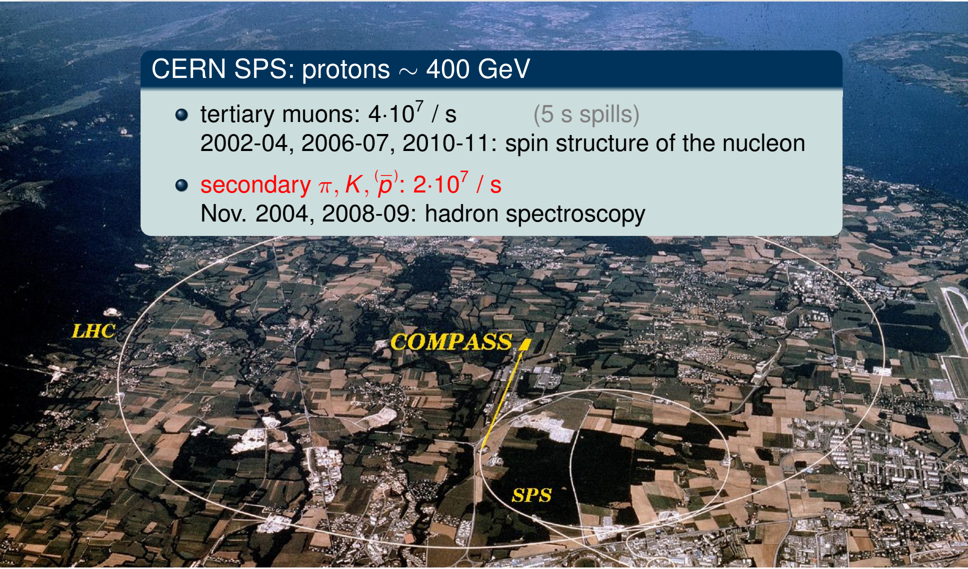
CERN SPS: protons $\sim$ 400 GeV

- tertiary muons: $4{\cdot}10^7$ / s (5 s spills)
  2002-04, 2006-07, 2010-11: spin structure of the nucleon
- secondary π, K, $\overset{(-)}{p}$: $2{\cdot}10^7$ / s
  Nov. 2004, 2008-09: hadron spectroscopy



COMPASS

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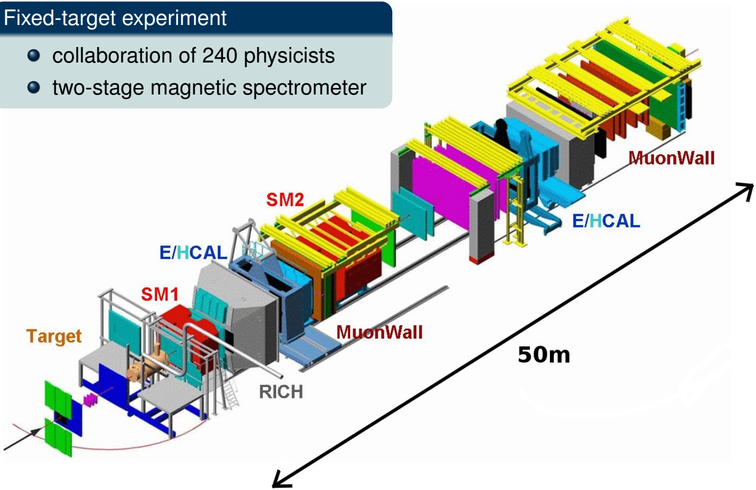
Experimental Setup

Fixed-target experiment

- collaboration of 240 physicists
- two-stage magnetic spectrometer



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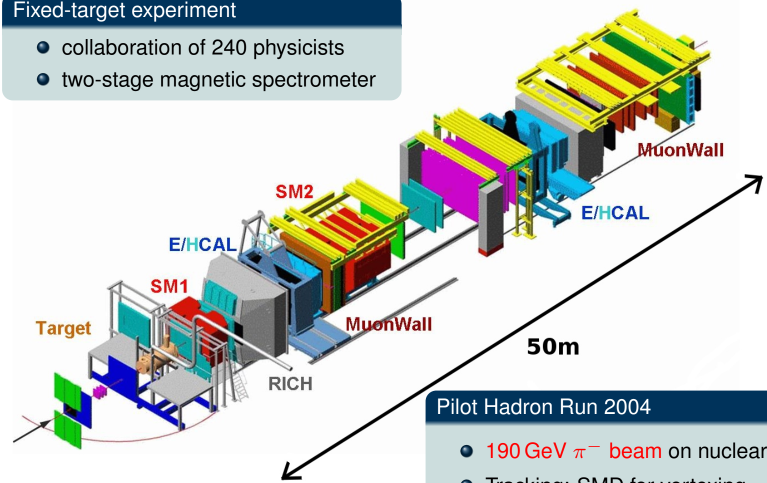

Pilot Hadron Run 2004

- 190 GeV π^- beam on nuclear targets
- Tracking: SMD for vertexing
- Trigger: Multiplicity trigger, ECAL trigger

Key to ChPT: Primakoff reactions

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

At small momentum transfer to the nucleus, high-energetic particles scatter predominantly off the el.mag. field quanta ($\sim Z^2$)

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

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

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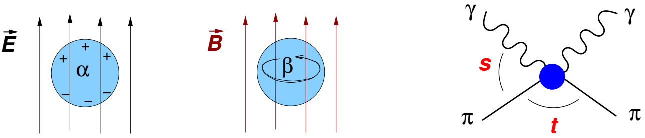
Low-t production mechanisms

- Production via photon and strong (pomeron) exchange
  - separable by different $t-$dependence
- e.g. resonance $a_2(1320)$ is produced both ways
  - radiative width
  - phase between the photon and strong amplitudes
- low-mass region $\rightarrow$ ChPT

Compton scattering and polarisability

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

Leading deviation from pointlike particle $\leftrightarrow$ e.m. polarisability

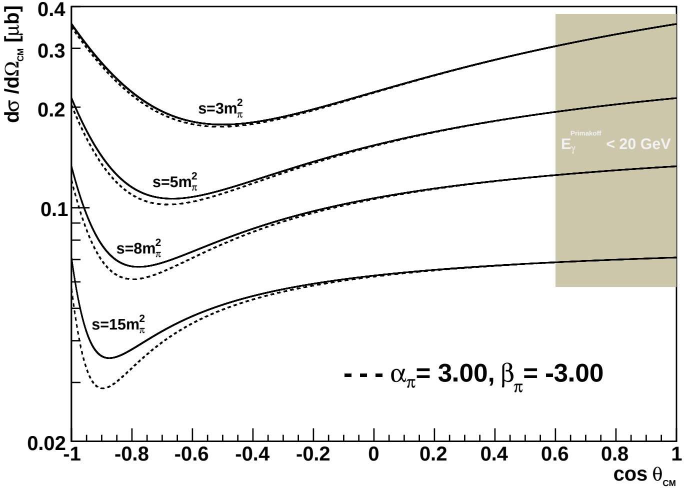


for $\alpha_\pi - \beta_\pi$ [10^{-4} fm^3]: $(\alpha_\pi \approx -\beta_\pi)$

ChPT: 5.7±1.0
experiments: 4 — 14

Polarisability effect (LO ChPT values)

loop effects not shown



Polarisability effect (NLO ChPT values)

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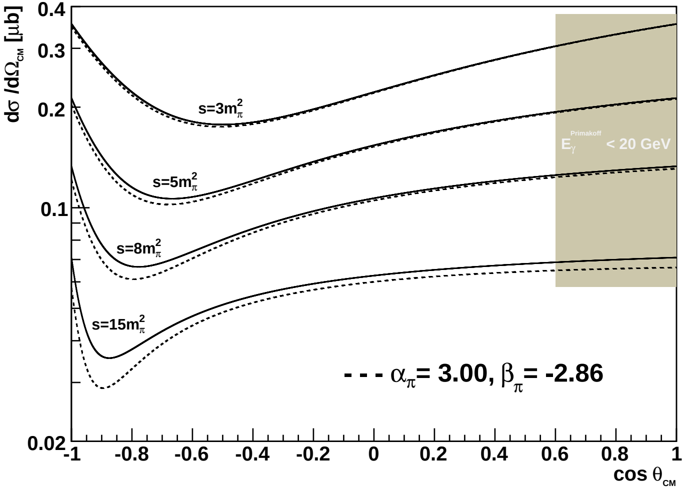
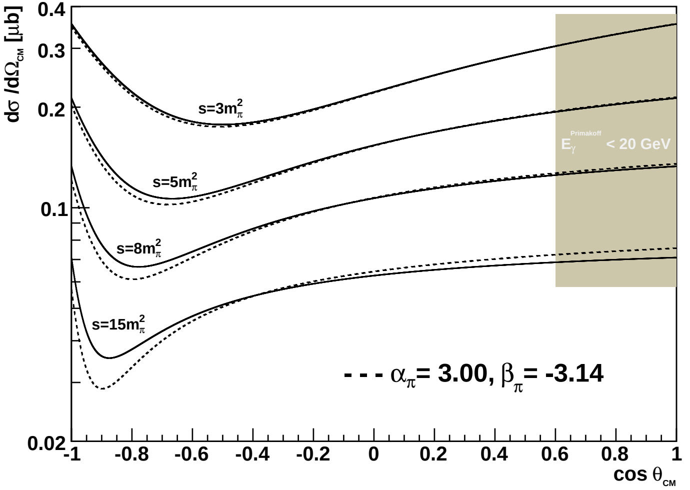
loop effects not shown



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

loop effects not shown



Polarisability effect (Serpukhov values)

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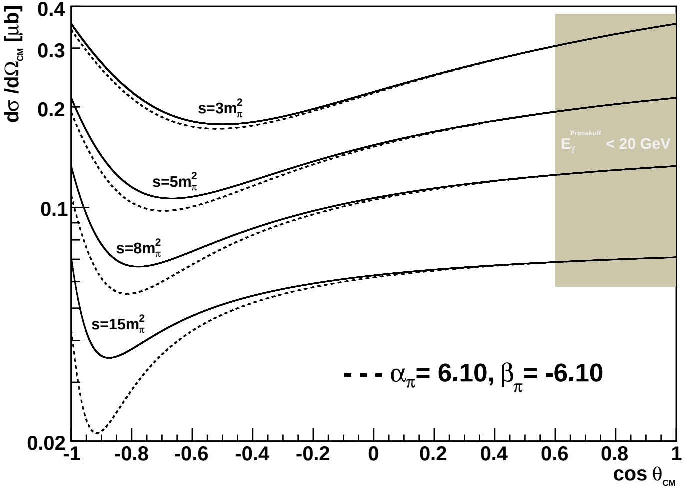
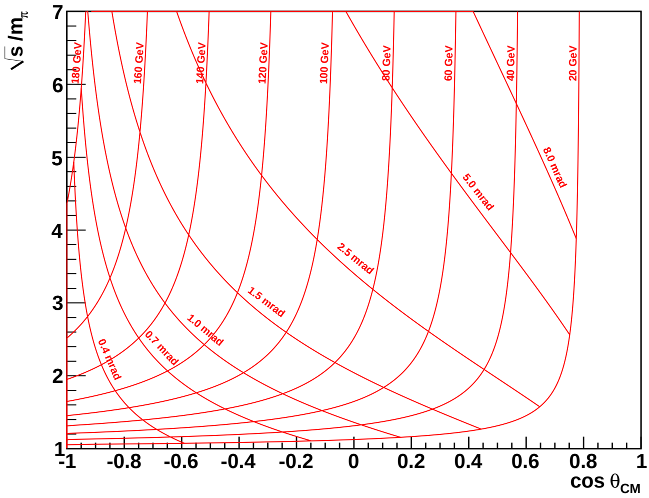
loop effects not shown



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



Cross section

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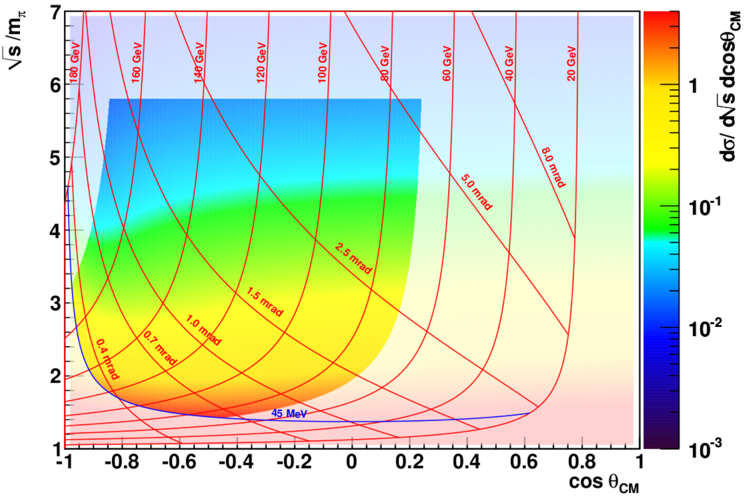

Polarisability measurements at COMPASS

Nov. 2004

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

Nov. 2009

- major upgrade of calorimeter readout, new digital trigger
- fine tuning / offline corrections ongoing

2012 `http://wwwcompass.cern.ch` $\rightarrow$ New proposal

- COMPASS-II proposal for a high-statistics Primakoff run
- increase statistics by a factor > 30, uncertainty on $\alpha_\pi - \beta_\pi$: ± 0.66 (ChPT: 5.7)
- First measurement of polarisability sum $\alpha_\pi + \beta_\pi$
  expected uncertainty ± 0.025 (ChPT: 0.16)

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2004 Primakoff results (diffractive trigger)

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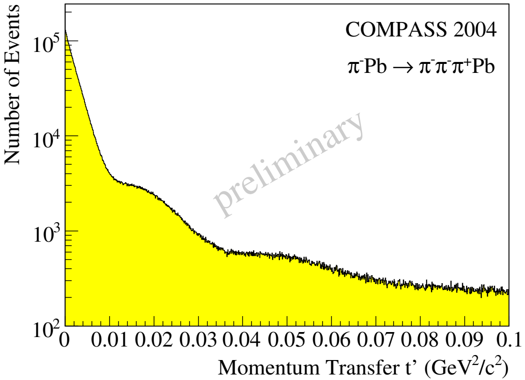
$$\pi^- \text{ Pb} \rightarrow \text{Pb } \pi^- \, \pi^- \, \pi^+$$



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

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

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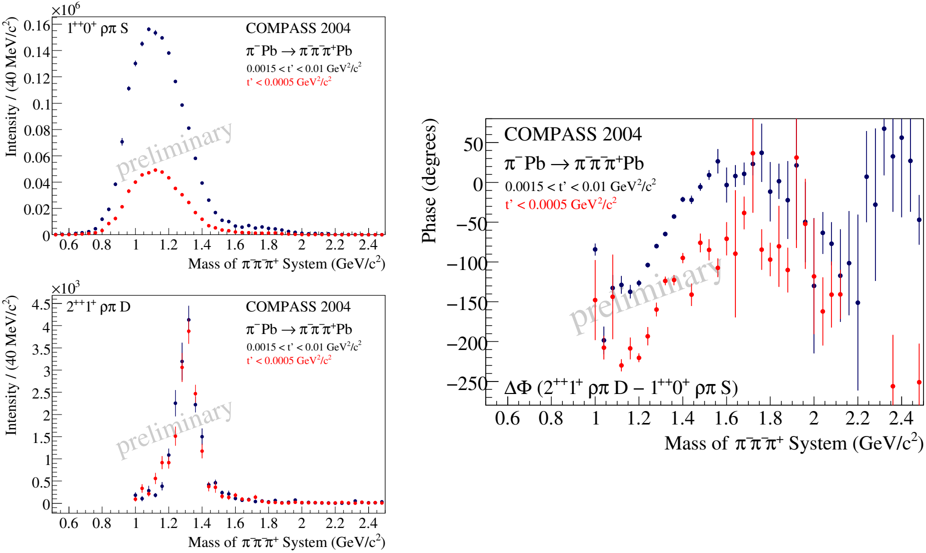
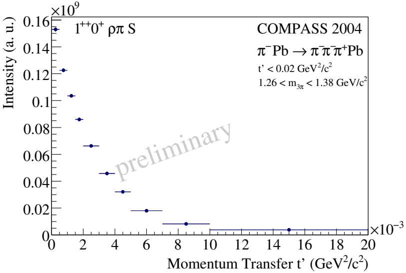
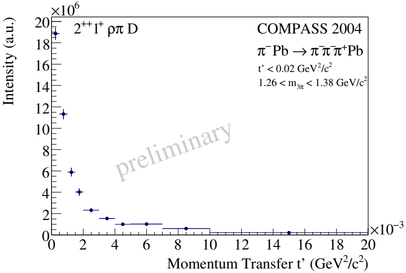
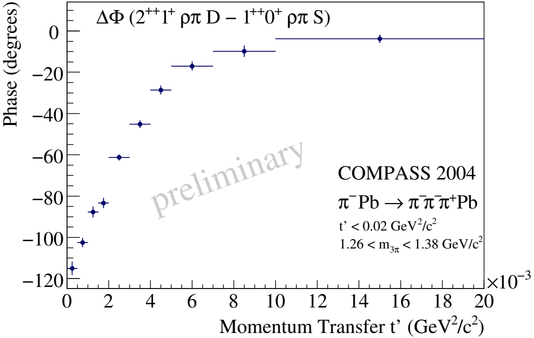


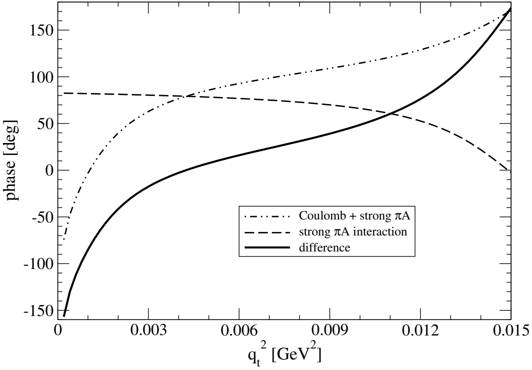
Phase $a_2 - a_1$ in detail: t' dependence

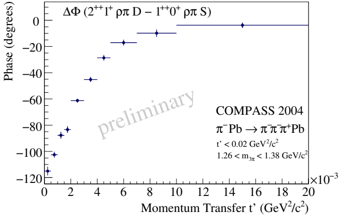






Theory: Phase a_2(strong+Coulomb)-a_1(strong)





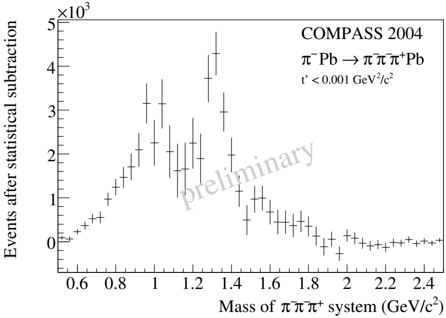
Glauber modell

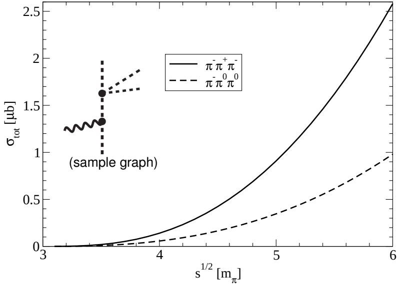
G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

Plot: N. Kaiser (TU München)

$\Rightarrow$ indicates confirmation of interference Coulumb-interaction - strong interaction
$\Rightarrow$ detailed studies of the nature of resonances

Another look at the mass spectrum: threshold region





- Simple approach: look at Primakoff mass spectrum by statistical subtraction
- Chiral Perturbation Theory prediction: tree diagrams calculation 2008
- Formula for (absolute) total cross section: N. Kaiser, JF, EPJA 36 (2008) 181

Summary and Outlook

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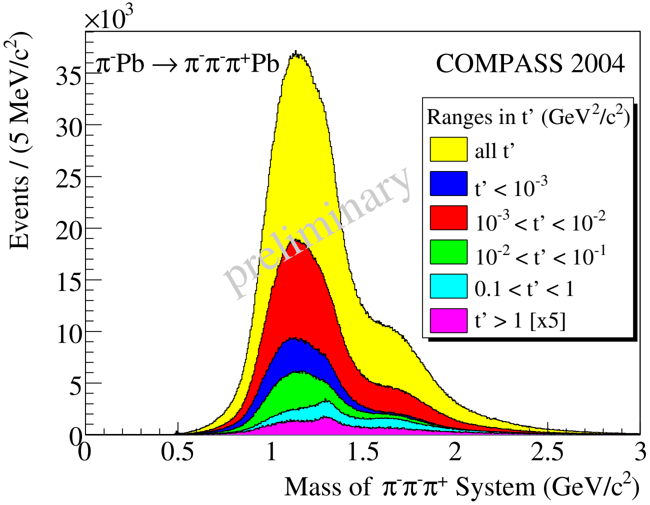
- COMPASS 2004 hadron run (few days) using a 190 GeV π^- beam
  - Primakoff: calorimetry problems
  - diffractive: spin-exotic π_1 observation (PRL104), more results coming
- $\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$ at (very) low momentum transfer
- Production phase of $a_2(1320)$ dependent on t' shows interference of contributions from Coulomb and strong interaction
- Test of chiral diagrams in threshold mass region *coming up*
- 2009 data with extended spectrometer
  - diffractive on H, Pb, Ni
  - Primakoff on Ni
- High-statistics run 2012

BACKUP: 3π Data Sample (2004)

$\pi^-\pi^-\pi^+$ mass distribution

Different t' ranges:



BACKUP: Partial Wave Analysis Formalism

- Mass-independent PWA (narrow mass bins):

$$\sigma_{\mathrm{indep}}(\tau, m, t') = \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |f_i^{\epsilon}(t')|^2 \mathrm{d}t'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2$$

  - Production strenght assumed constant in single bins
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$, with t' dependence $f_i^{\epsilon}(t')$
  - Production amplitudes $T_{ir}^{\epsilon} \rightarrow$ 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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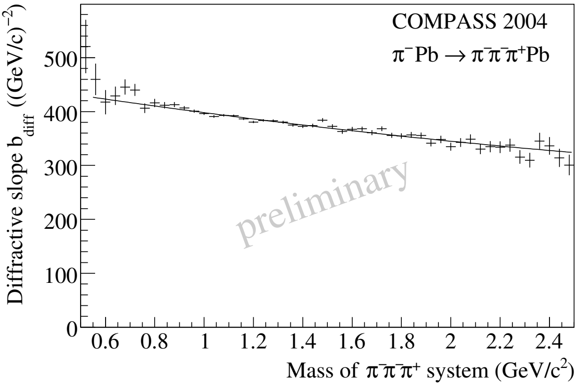
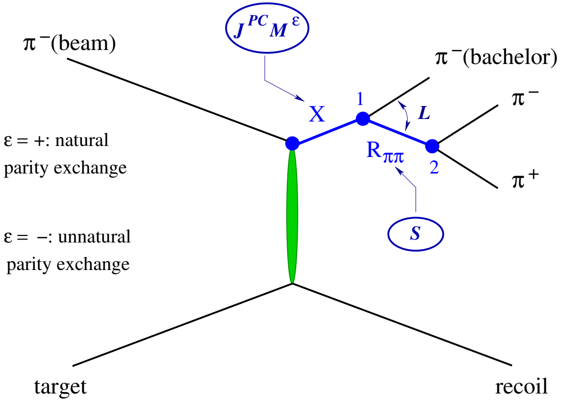


Partial Wave Analysis Formalism

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)

PWA of data with low t'

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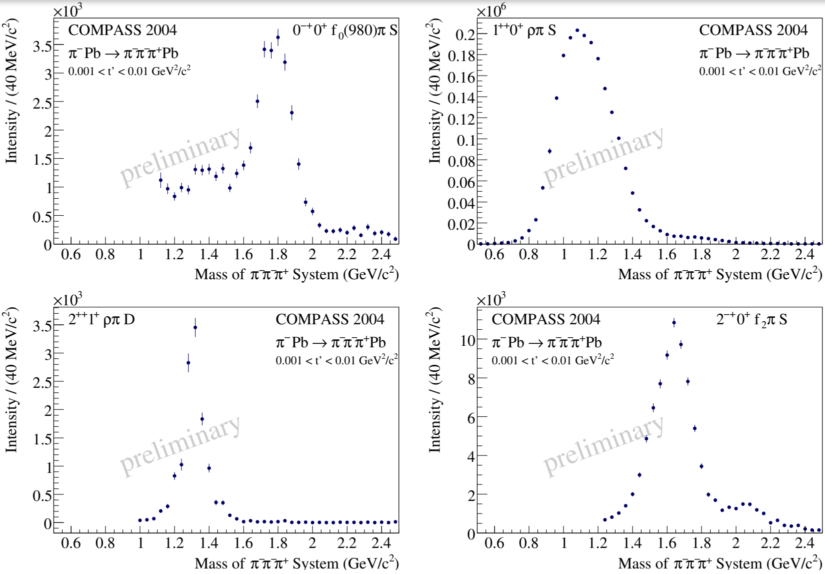
Intensity of selected waves: $0^{-+}0^{+} f_0(980)\pi S$, $1^{++}0^{+} \rho\pi S$, $2^{++}1^{+} \rho\pi D$, $2^{-+}0^{+} f_2(1270)\pi S$



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

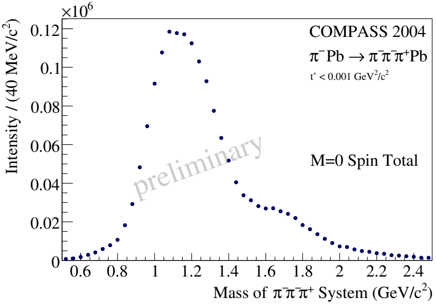
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

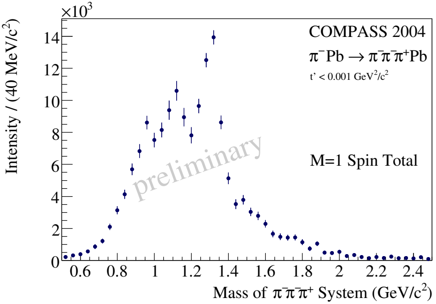
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'} \rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

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



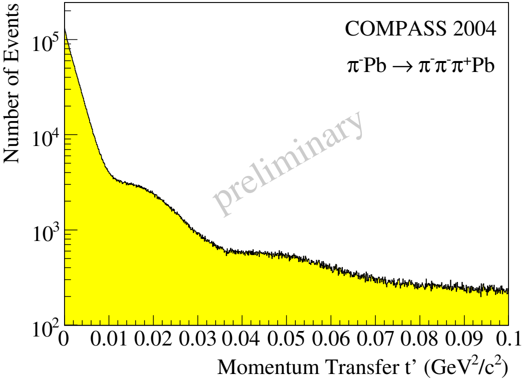
M=1

2004 Primakoff results (diffractive trigger)

Momentum Transfer

Momentum transfer to target:

$$-t = -(p_{\text{beam}} - p_{(\pi^-\pi^-\pi^+)})^2 \quad \Rightarrow t' = |t| - |t|_{\text{min}}$$



with

$$|t|_{\text{min}} = \frac{(m_{3\pi}^2 - m_\pi^2)^2}{4|\vec{p}_{\text{beam}}|_{\text{lab}}^2}$$

Diffraction pattern:
Pb nucleus acts like "black disc" in optics

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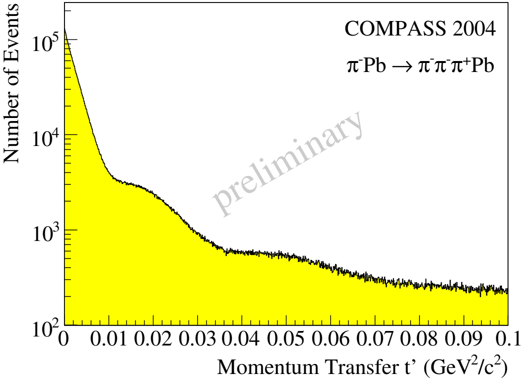

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Primakoff contribution at $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

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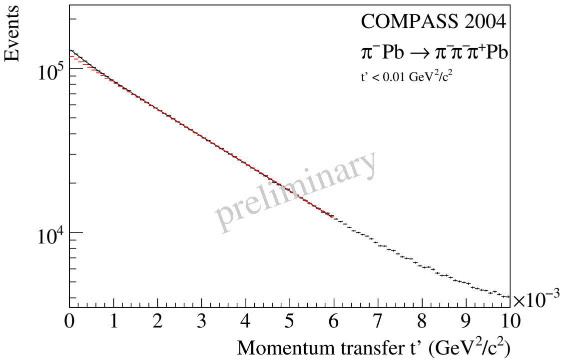
Primakoff: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$, $b_{\mathrm{Prim}} \approx 2000\,(\mathrm{GeV}/c)^{-2}$ (mainly resolution)

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

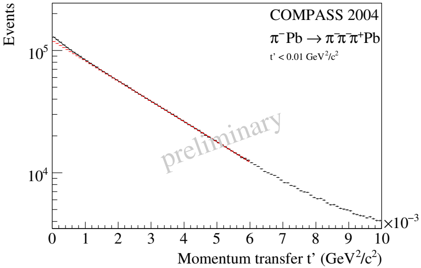


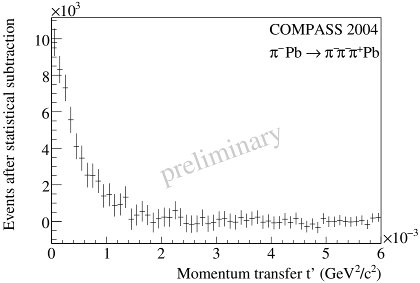
(Mass) spectrum of this Primakoff contribution?

$\Rightarrow$ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)

Basic features of the statistical subtraction

- Fit of t' spectrum with sum of both exponentials for $0 < t' < 0.006\,(\mathrm{GeV}/c)^2$ $(0.5 < m_{3\pi} < 2.5\,\mathrm{GeV}/c^2)$
- Subtraction of "diffractive" exponent from t' spectrum



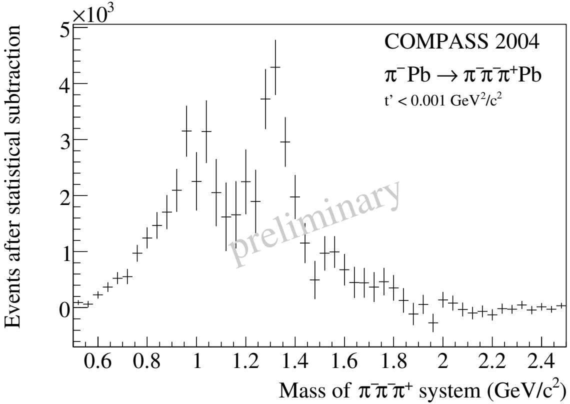


- Fit and subtraction in 3π mass bins:
  - $b_{\mathrm{Prim}} = 2050\,(\mathrm{GeV}/c)^{-2}$ fixed
  - b_{diff} as fit parameter

Primakoff contribution

Mass spectrum from statistical subtraction

- Statistical subtraction separately in 40 MeV/c^2 mass bins
- Integrate Primakoff contribution of the t' spectra for $t' < 10^{-3}$ (GeV/c)^2



Selex, Phys. Lett. B 521(2001), 171-180

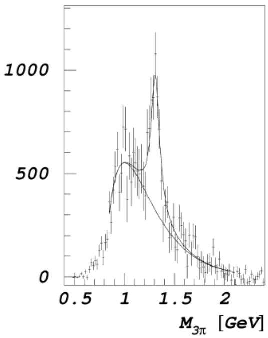


Fig. 3. $M_{3\pi}$ mass distribution for the Cu target after subtraction of diffractive background. The curve shows fit with a sum of pure Coulomb contribution and smooth background.