Tests of Chiral Perturbation Theory in Primakoff Reactions at COMPASS

Jan Friedrich

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for the COMPASS collaboration

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Excellenzcluster: Origin and Structure of the Universe, BMBF

Outline

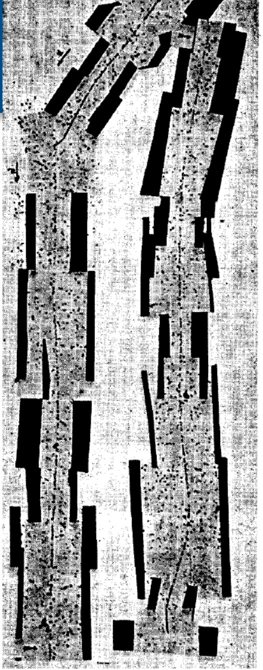
- Introduction: QCD and ChPT
- COMPASS at the CERN SPS
- Primakoff reactions
  - chiral anomaly
  - 3-pion final state
  - [pion polarisabilities $\rightarrow$ dedicated talk by Alexey Guskov]

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
- $\pi^+ \;\; \pi^\circ \;\; \pi^-$ (re-)appear as Goldstone bosons



NATURE October 4, 1947 Vol. 160

The strong force, the pion and χPT

- Yukawa's particle [illegible]
- development of [illegible]D: quarks [illegible]ons
- running coupling parameter, c[illegible]ent
- $m_q \approx 0 \rightarrow$ chiral symmetry (spontaneously broken)

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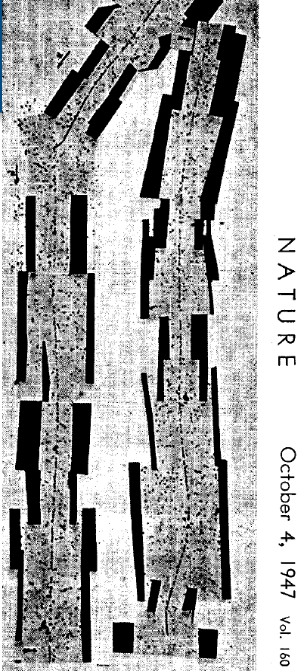

ChPT and Experiment

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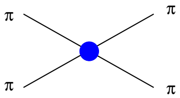
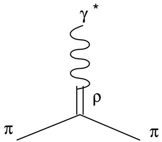
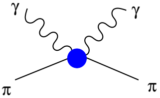
- Pion scattering lengths: 2-loop predictions
  - $a_0^0 m_{\pi^+} = 0.220 \pm 0.005$ confirmed in $K^+ \to \pi^+\pi^- e^+\nu_e$ (E865)
  - $(a_0^0 - a_0^2) m_{\pi^+} = 0.264 \pm 0.006$ confirmed in $K^+ \to \pi^+\pi^\circ\pi^\circ$ (NA48: 0.268 ± 0.010)
- Electromagnetic structure
  - Form factor described by coupling to $\rho(770)$ (resonance effect, VMD)
  - Polarisability
    accessible as contribution to Compton scattering;
    prediction obtained by the LEC relation to $\pi^+ \to e^+\nu_e\gamma$

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

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







COmmon Muon and Proton Apparatus for Structure and Spectroscopy

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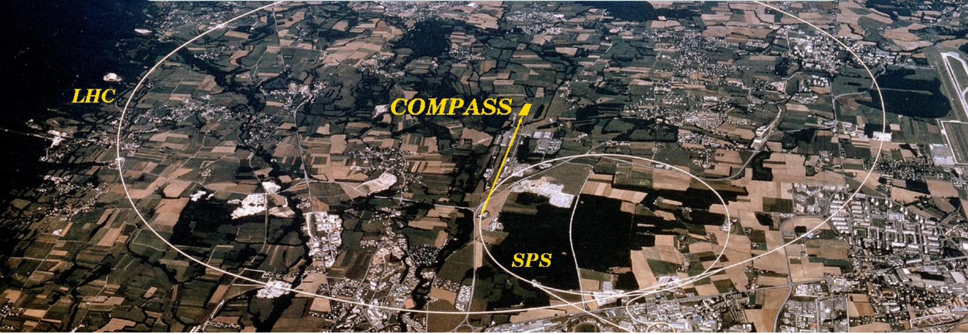
CERN SPS: protons $\sim$ 400 GeV

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



COMPASS

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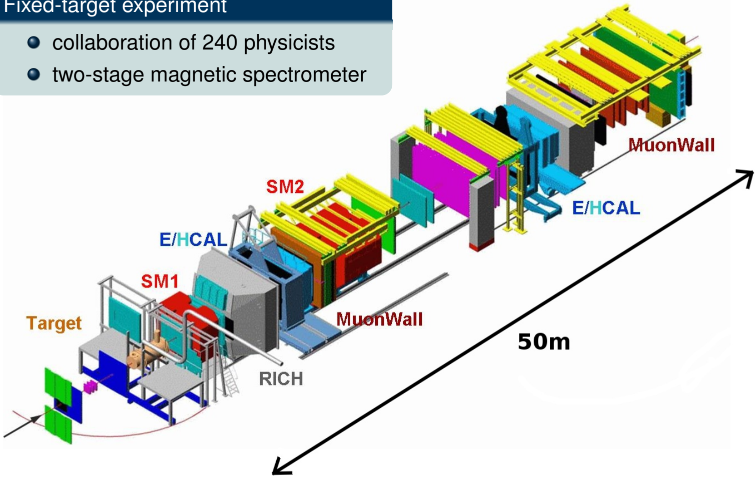
Experimental Setup

Fixed-target experiment

- collaboration of 240 physicists
- two-stage magnetic spectrometer



COMPASS

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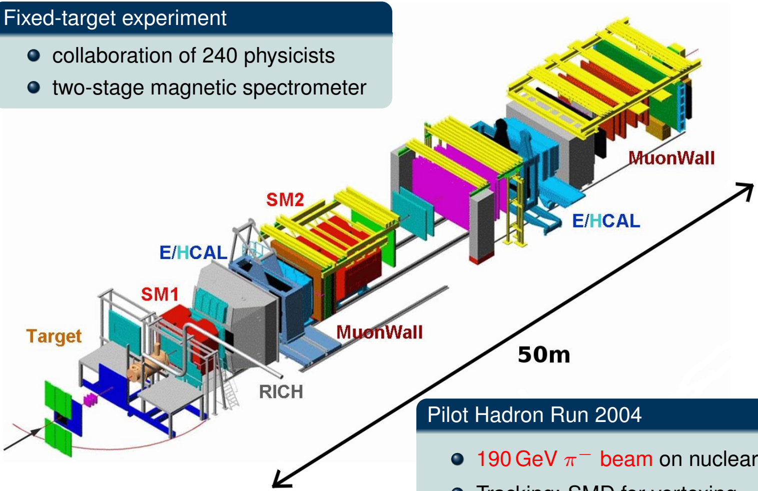
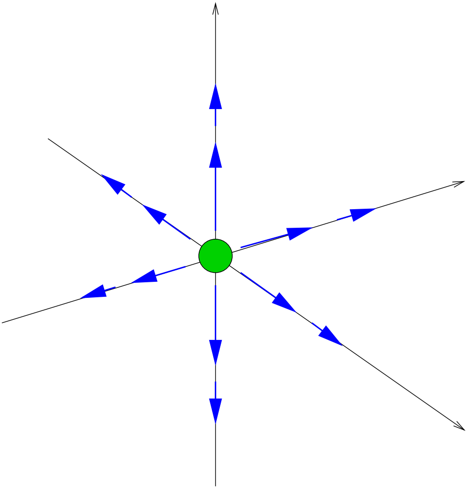


Pilot Hadron Run 2004

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

Weizsäcker-Williams Method

Electric charge at rest



Weizsäcker-Williams Method

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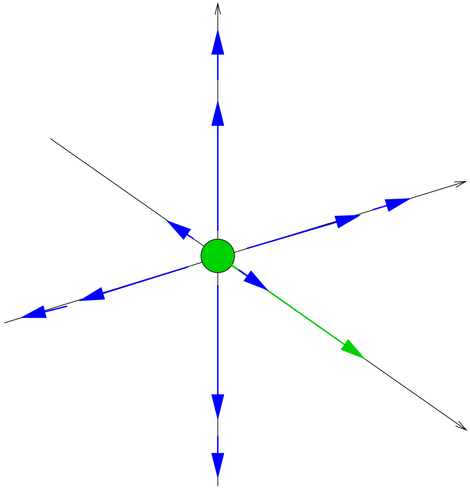
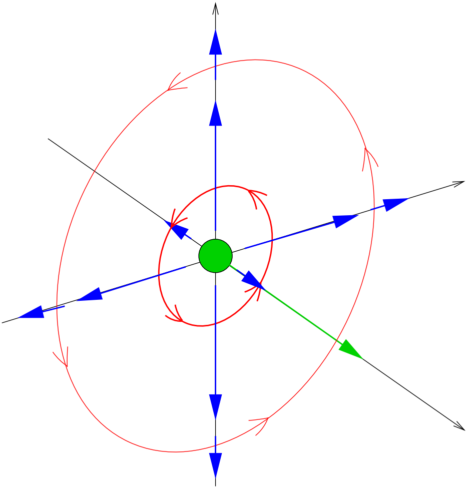
Electric charge moving



Weizsäcker-Williams Method

Electromagnetic field



Weizsäcker-Williams Method

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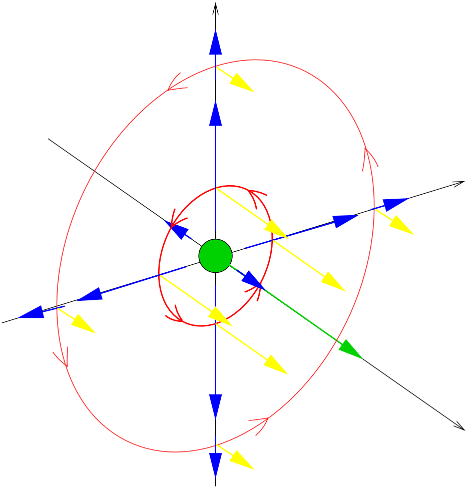
(almost) real photons



Key to ChPT: Primakoff reactions

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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 ($\sim Z^2$)

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

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

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Chiral anomaly $\pi^-\gamma \rightarrow \pi^-\pi^\circ$

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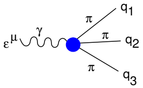
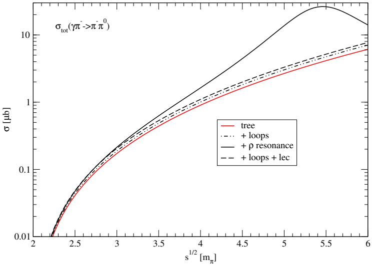


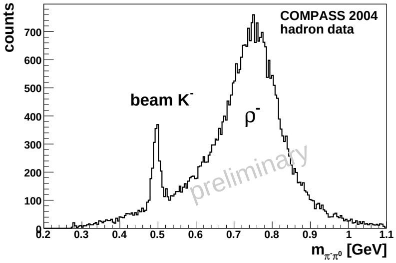
$$\rightarrow \quad \frac{e}{4\pi^2 f_\pi^3}\epsilon_{\mu\nu\alpha\beta}\, \varepsilon^\mu q_1^\nu q_2^\alpha q_3^\beta$$

$$F_{3\pi}^{\chi PT} = 9.72\ \text{GeV}^{-3} \qquad F_{3\pi}^{\text{Serpukhov}} = 12.9 \pm 1.4\ (10.7\pm1.2)\ \text{GeV}^{-3}$$

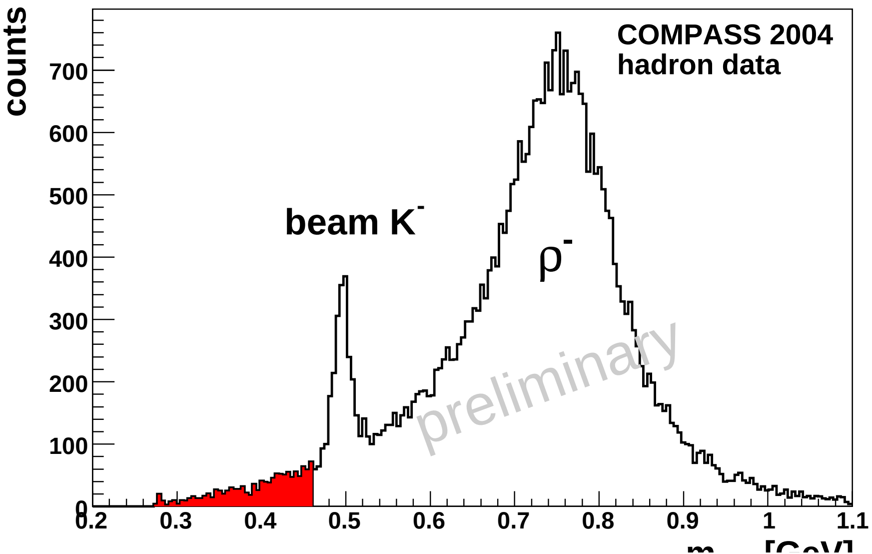
(theory: real photons)



(data: quasi-real)



Chiral anomaly - analysis of 2004 data



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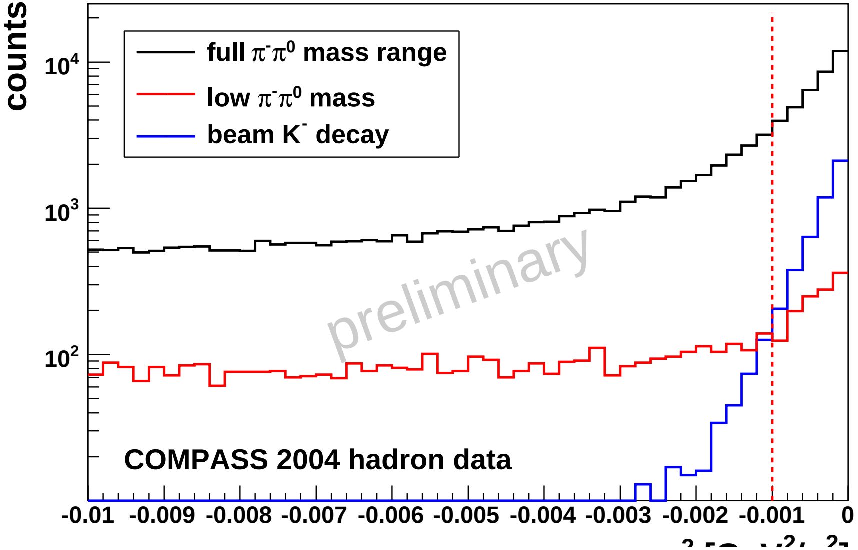

Low-t production mechanisms

- 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

2004 Primakoff results (diffractive trigger)

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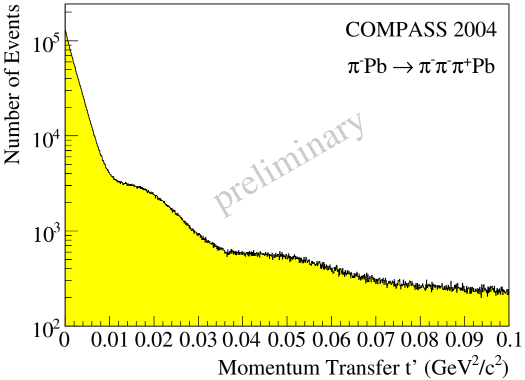
$$\pi^- \text{ Pb} \rightarrow \text{Pb } \pi^- \pi^- \pi^+$$



- "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

2004 Primakoff results (diffractive trigger)

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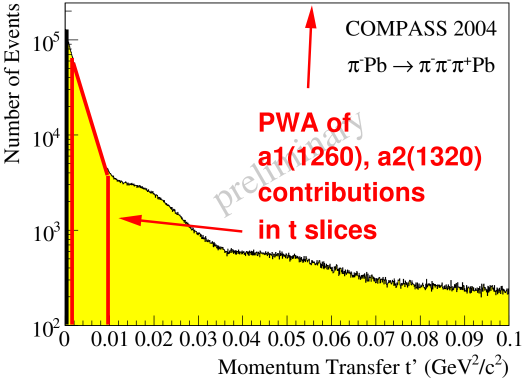

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PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

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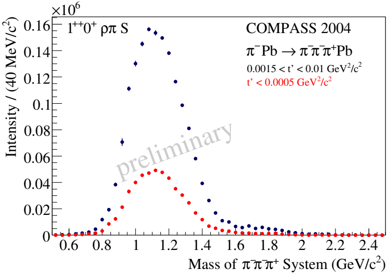
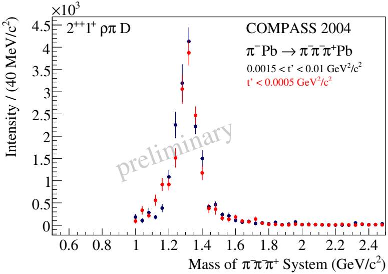
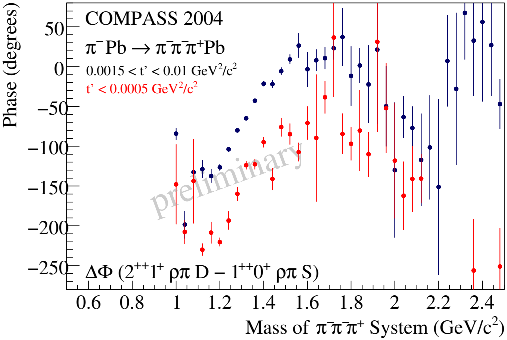
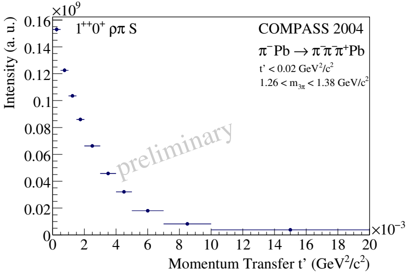
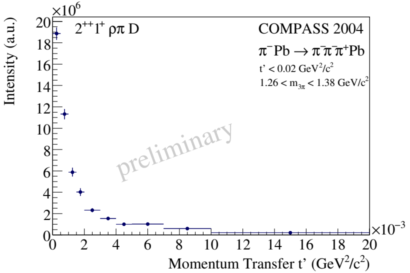


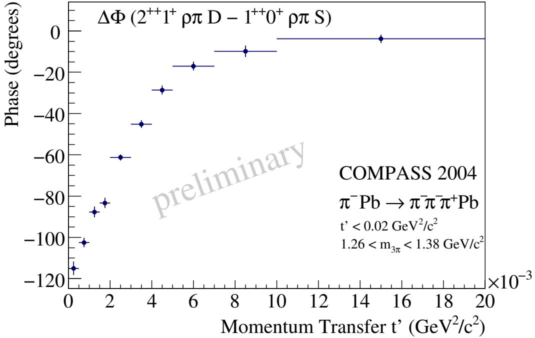




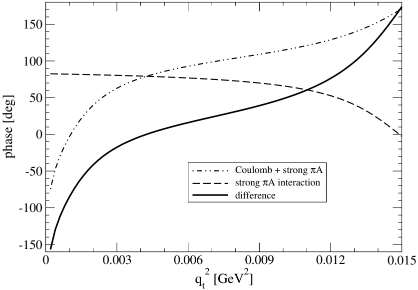
Phase $a_2 - a_1$ in detail: t' dependence

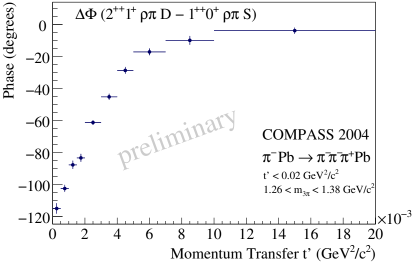






Theory: Phase a_2(strong+Coulomb)-a_1(strong)





Glauber model

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

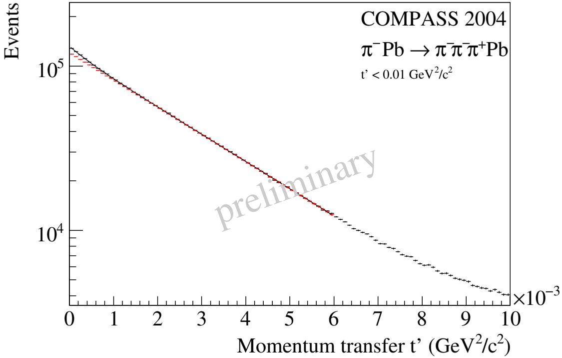
Plot: N. Kaiser (TU München)

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

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

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

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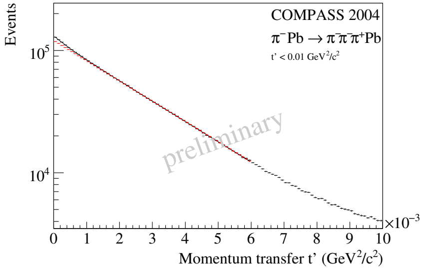
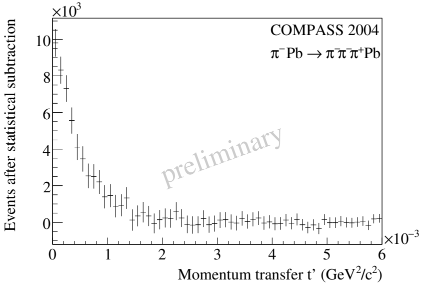
- Fit of t' spectrum with sum of both exponentials for $0 < t' < 0.006\,(\mathrm{GeV}/c)^2$ $(0.5 < m_{3\pi} < 2.5\,\mathrm{GeV}/c^2)$
- Subtraction of "diffractive" exponent from t' spectrum



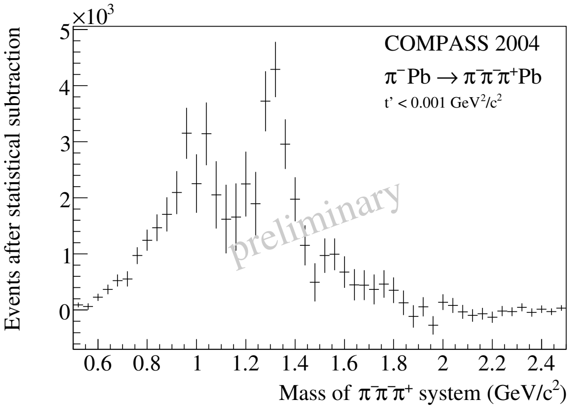


- Fit and subtraction in 3π mass bins:
  - $b_{\mathrm{Prim}} = 2050\,(\mathrm{GeV}/c)^{-2}$ fixed
  - b_{diff} as fit parameter

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

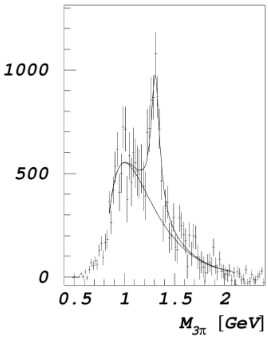
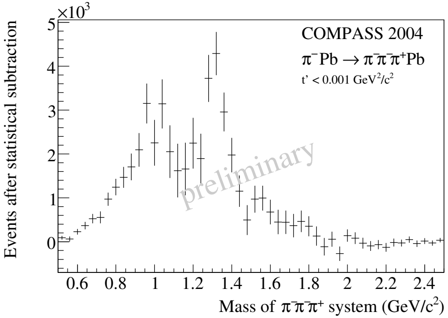
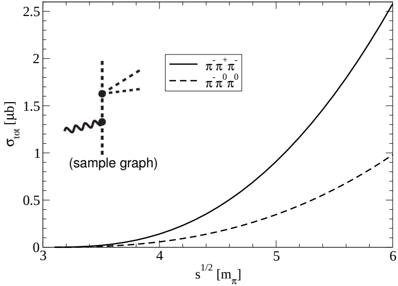


Fig. 3. $M_{3\pi}$ mass distribution for the Cu target after subtraction of diffractive background. The curve shows fit with a sum of pure Coulomb contribution and smooth background.

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

Chiral anomaly - contribution of loop graphs

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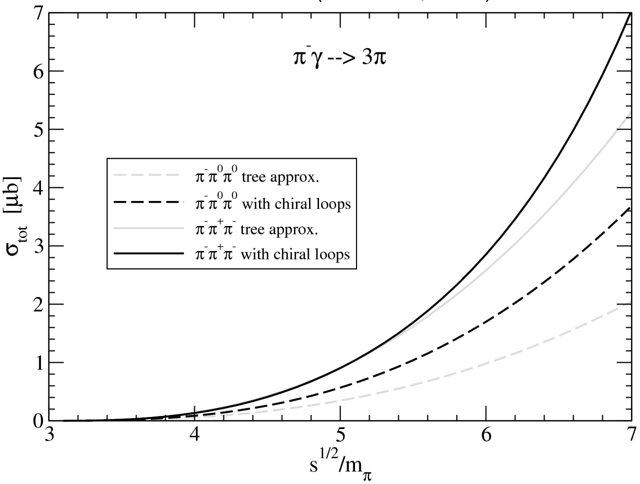
new calculation (N. Kaiser, TUM)



Diffraction 2004: $\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$

Momentum Transfer Distributions

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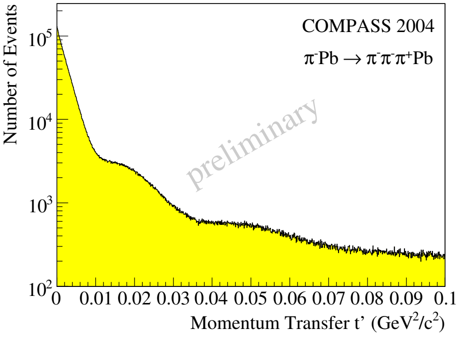
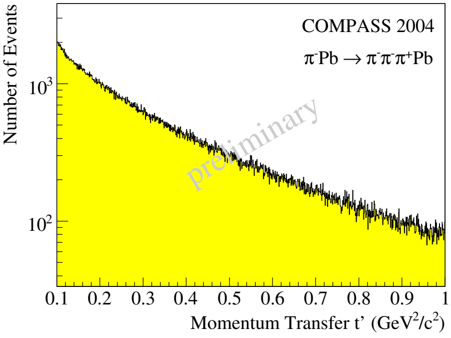
- 4-pion vertex in Pb target
- Exclusive in the energy within resolution
- Momentum transfer: $-t = Q^2 - (p_{beam} - p_{(\pi^-\pi^-\pi^+)})^2$





3π Data in the range $0.3 < t'/(\text{GeV}^2/c^2) < 1$

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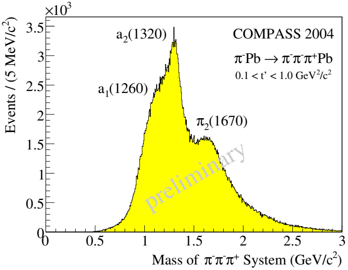
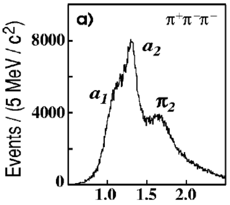
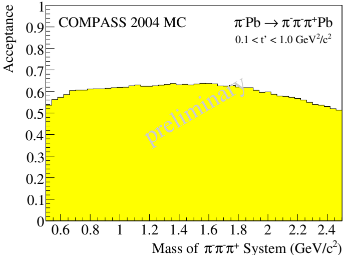
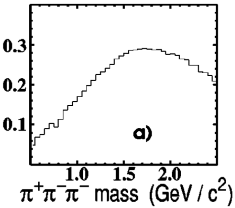
$\pi^-\pi^-\pi^+$ Mass Distributions and Acceptance





BNL-E852, Phys. Rev. **D65**, 072001, 2002





PWA Results

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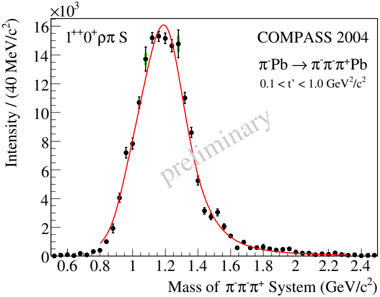
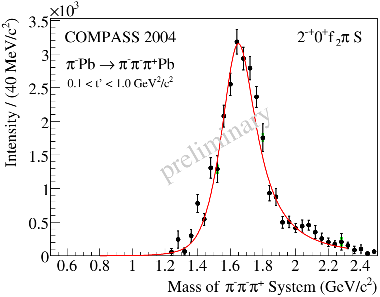
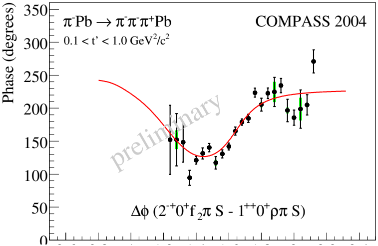
$1^{++}0^{+}\rho\pi S$ and $2^{-+}0^{+} f_2\pi S$







- BW for $a_1(1260)$ + background:

  $M = (1.256 \pm 0.006 \,^{+0.007}_{-0.017})$ GeV

  $\Gamma = (0.366 \pm 0.009 \,^{+0.028}_{-0.025})$ GeV

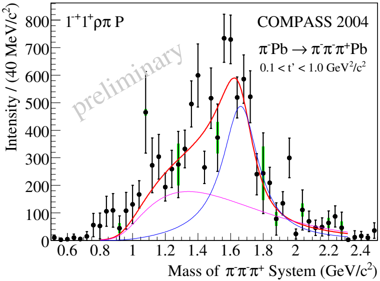
- BW for $\pi_2(1670)$:

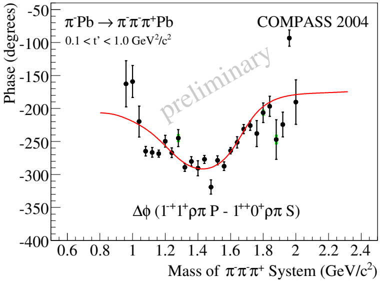
  $M = (1.659 \pm 0.003 \,^{+0.024}_{-0.008})$ GeV

  $\Gamma = (0.271 \pm 0.009 \,^{+0.022}_{-0.024})$ GeV

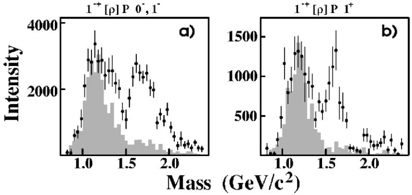
PWA Results

Exotic $1^{-+}1^{+}\rho\pi P$ Wave





BNL E852 signal:



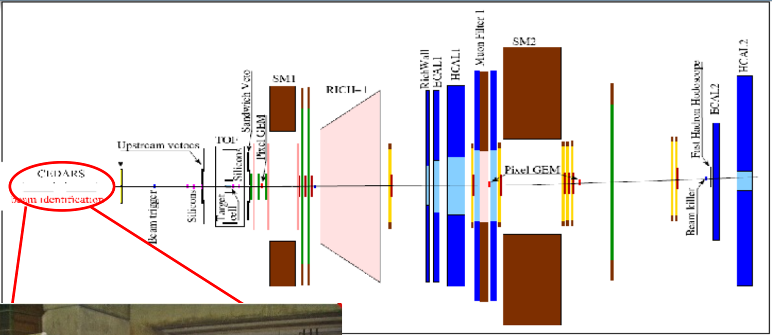
- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.6\,\mathrm{GeV}$
- No leakage observed
- BW for $\pi_1(1600)$ + background:

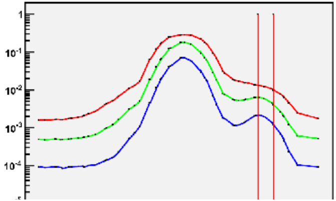
  $M = (1.660 \pm 0.010\ ^{+0.000}_{-0.064})\,\mathrm{GeV}$

  $\Gamma = (0.269 \pm 0.021\ ^{+0.042}_{-0.064})\,\mathrm{GeV}$

COMPASS Setup 2008

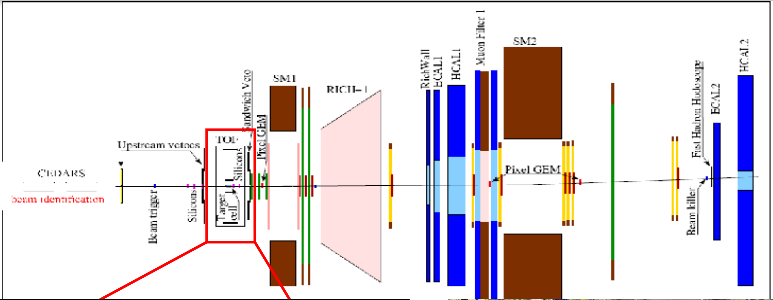
CEDARs

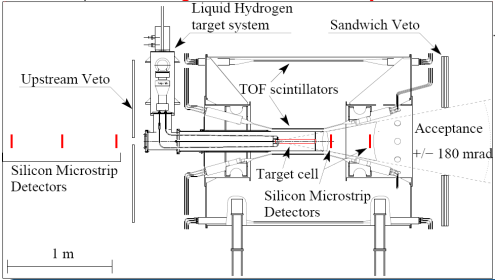




COMPASS Setup 2008

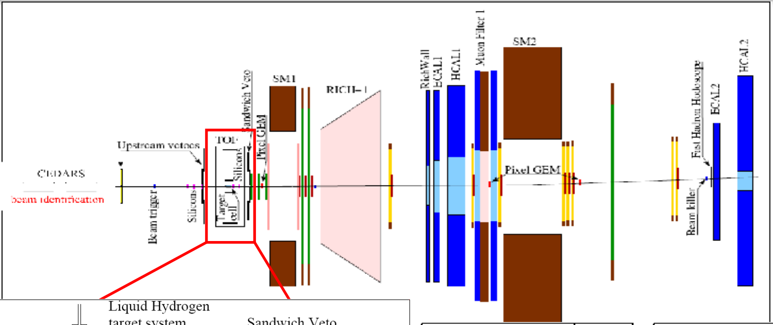
Target region: Recoil Proton Detector

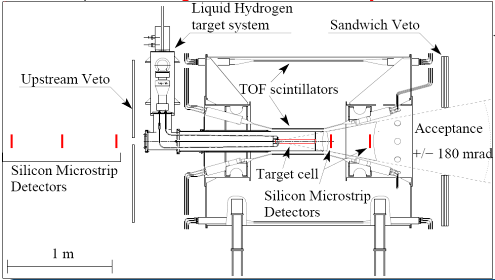


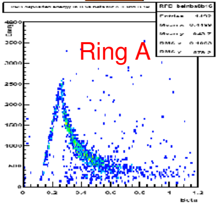


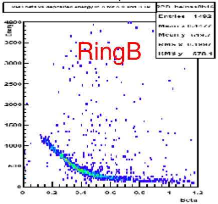
COMPASS Setup 2008

Target region: RPD Signals



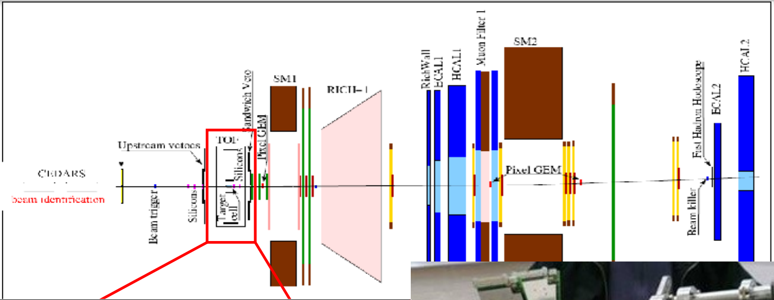


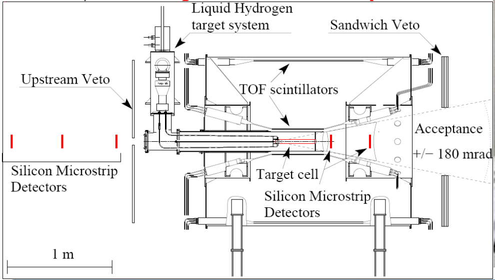


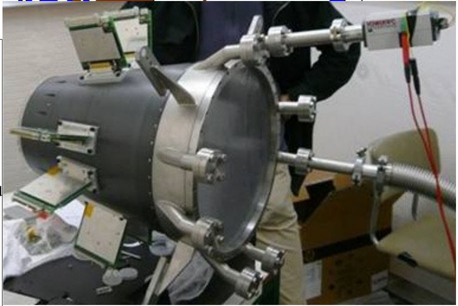


COMPASS Setup 2008

Target region: Silicon detectors







COMPASS Setup 2008

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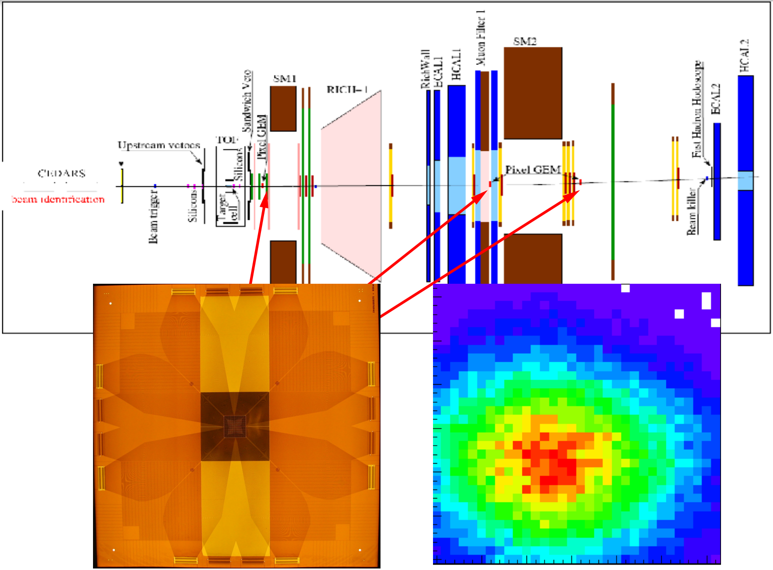
Target region: Pixel GEM detectors



COMPASS Setup 2008

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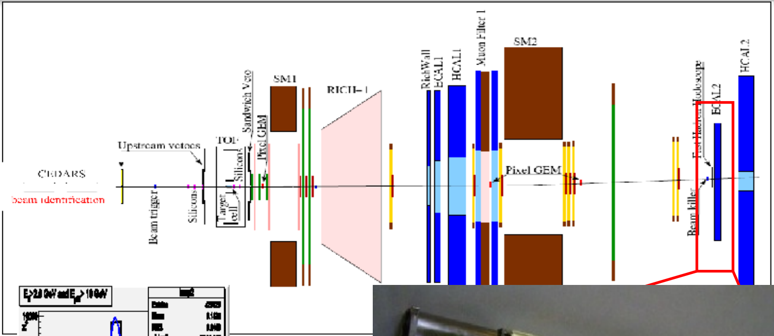
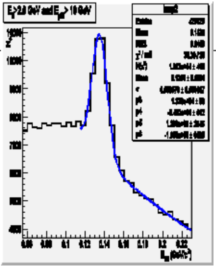
Calorimetry:

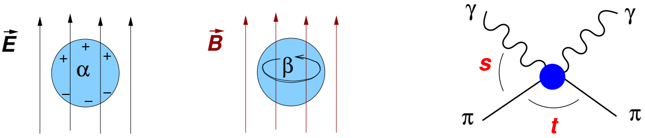




Compton scattering and polarisability

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

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

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 $\alpha_2 - \beta_2$)

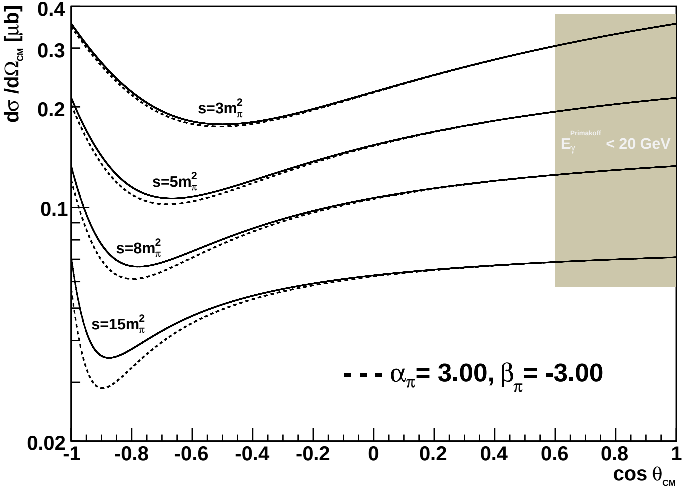
$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

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

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

Polarisability effect (LO ChPT values)

loop effects not shown



Polarisability effect (NLO ChPT values)

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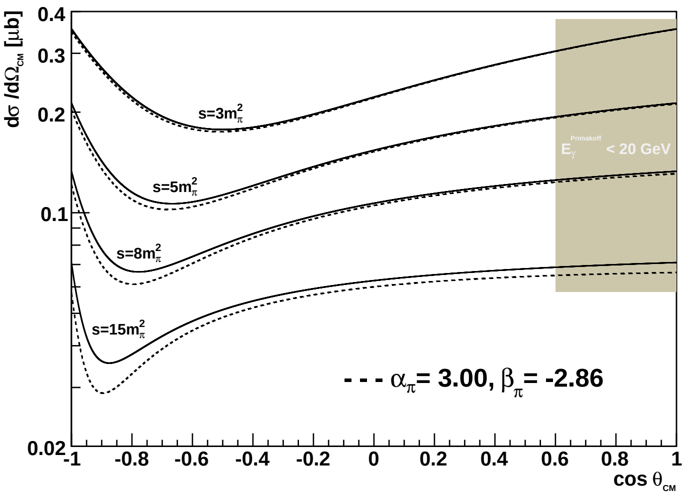
loop effects not shown



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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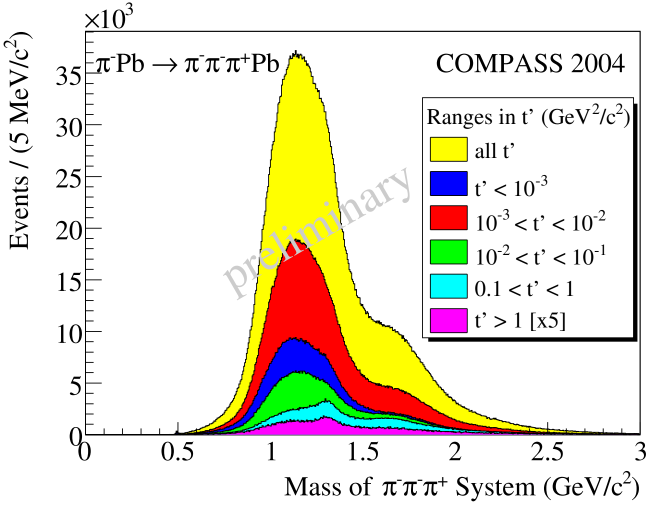
Summary and Outlook

- 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
- $\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$ 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

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- 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:

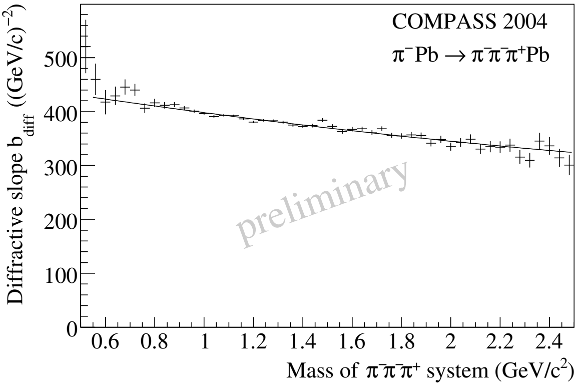
$$\mathrm{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

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



Partial Wave Analysis Formalism

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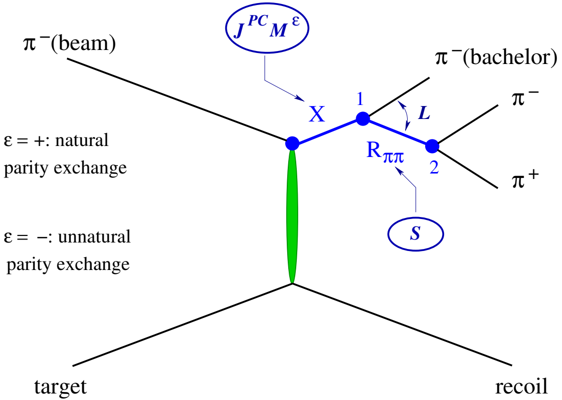
Isobar Model



- 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)

Summary of Extracted States

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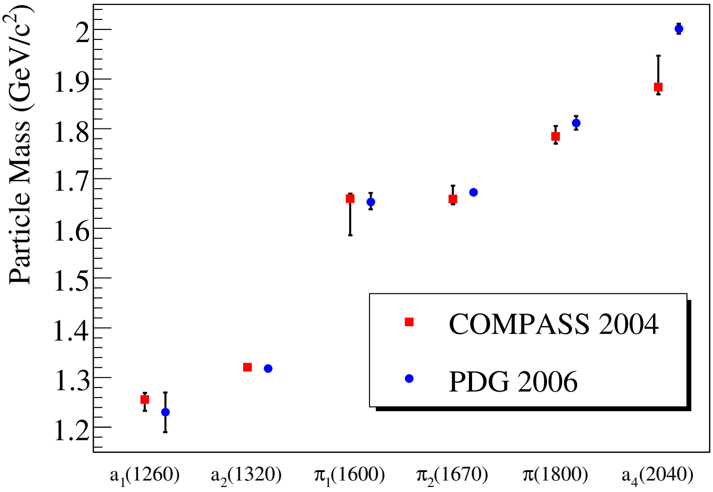
Comparison with PDG values



PWA of data with low t'

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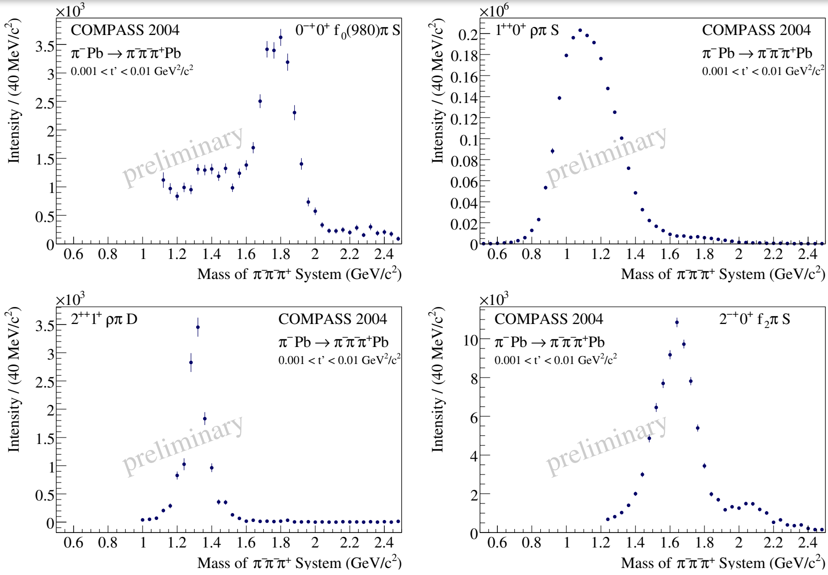
Intensity of selected waves: $0^{-+}0^{+} f_0(980)\pi S$, $1^{++}0^{+} \rho\pi S$, $2^{++}1^{+} \rho\pi D$, $2^{-+}0^{+} f_2(1270)\pi S$



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

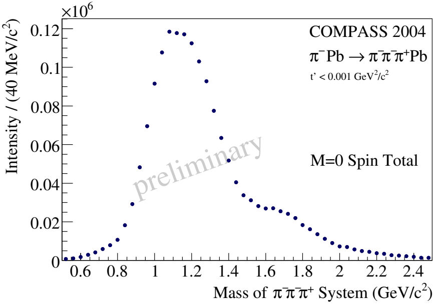
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

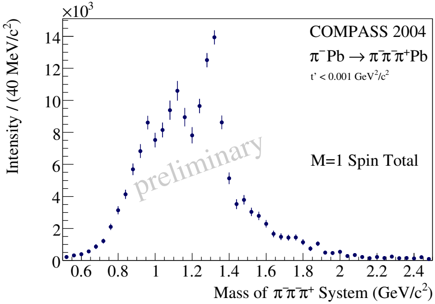
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'} \rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

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



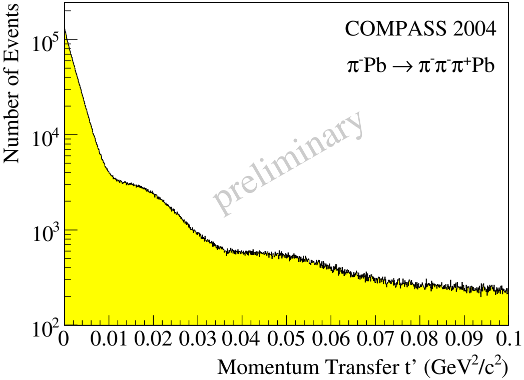
M=1

2004 Primakoff results (diffractive trigger)

Momentum Transfer

Momentum transfer to target:

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



with

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

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

2004 Primakoff results (diffractive trigger)

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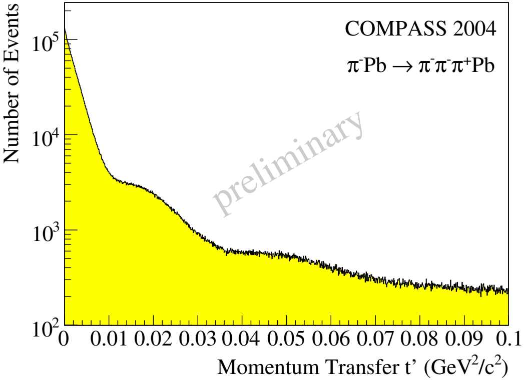

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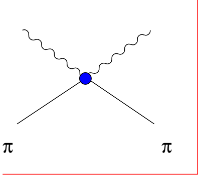
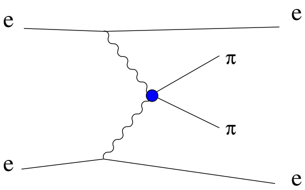
Diffraction pattern: Pb nucleus acts like "black disc" in optics

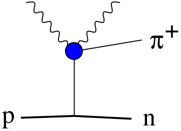
- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

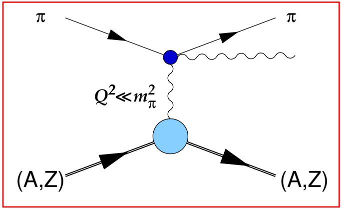
$\pi\gamma$ scattering: embedding the process

wanted:









$\gamma\gamma \to \pi\pi$ and the pion polarisability

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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.