Meson spectroscopy in diffractive dissociation of high-energetic pions at COMPASS

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for the COMPASS collaboration

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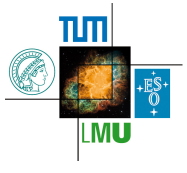
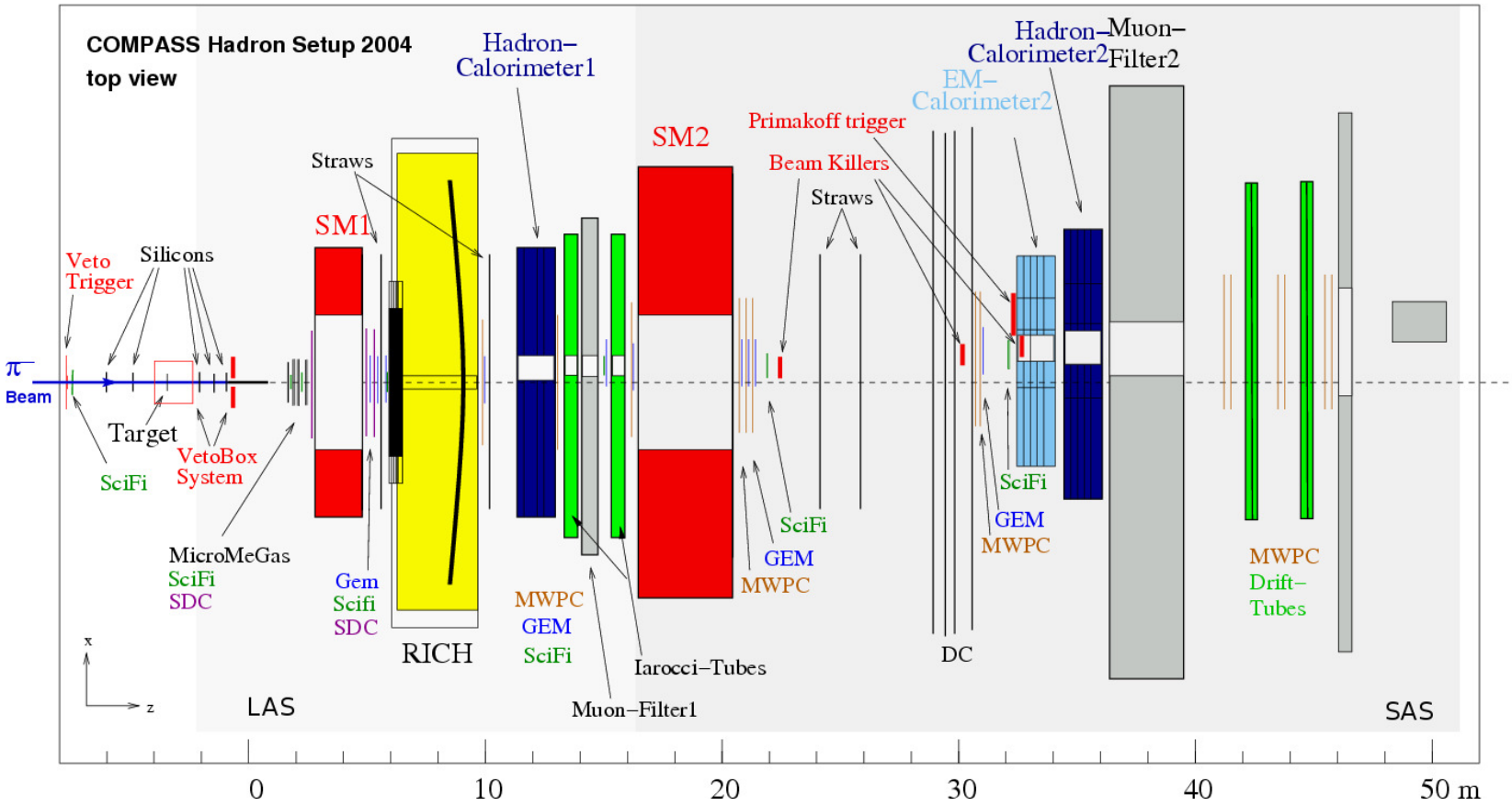


Hadron Beams at COMPASS

- Physics goals
  - Diffractive dissociation $\pi \to 3\pi,\ 5\pi,\ \ldots$
    mesonic resonances, exotics
  - Primakoff reactions $\pi + \gamma^* \to \pi\gamma,\ \ \pi\pi^0,\ 3\pi,\ \ldots$
    polarisability, chiral anomaly + diagrams, radiative couplings
  - Interference of strong and e.m. interaction

COMPASS – Pilot Hadron Run 2004

Experimental Setup (Nov 2004)



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    mesonic resonances, exotics
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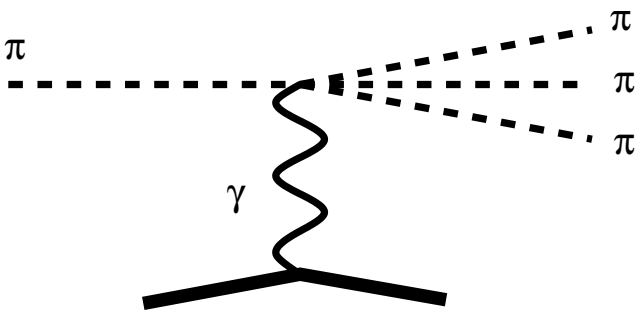
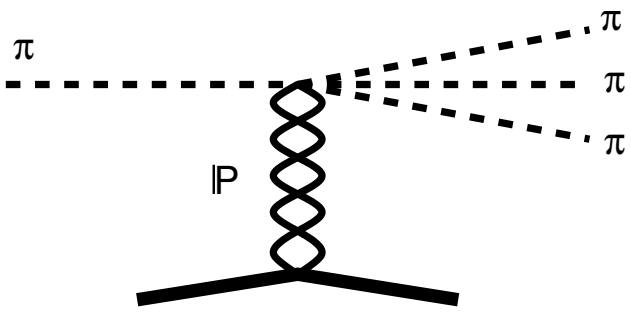
    polarisability, chiral anomaly + diagrams, radiative couplings
  - Interference of strong and e.m. interaction
- Major changes: muon $\rightarrow$ hadron setup ($\sim$ one month)
  - Pb, Cu, C solid disk targets
  - 3 silicon stations downstream of the target
    $\rightarrow$ high vertex / angular resolution
  - multiplicity trigger in the target region
  - analog trigger on the Ecal2 energy deposition

Production mechanisms



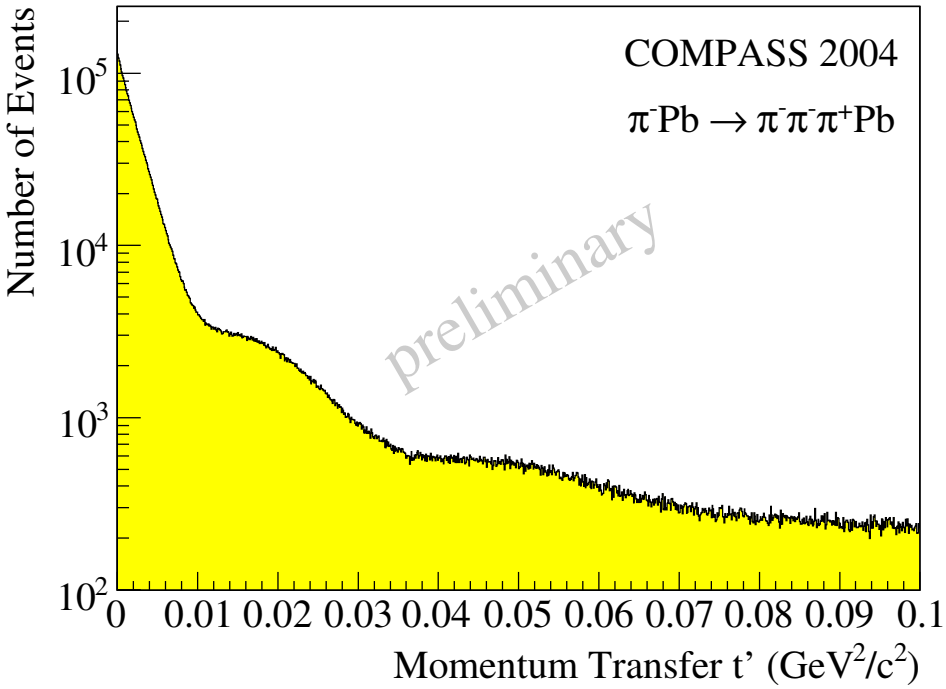


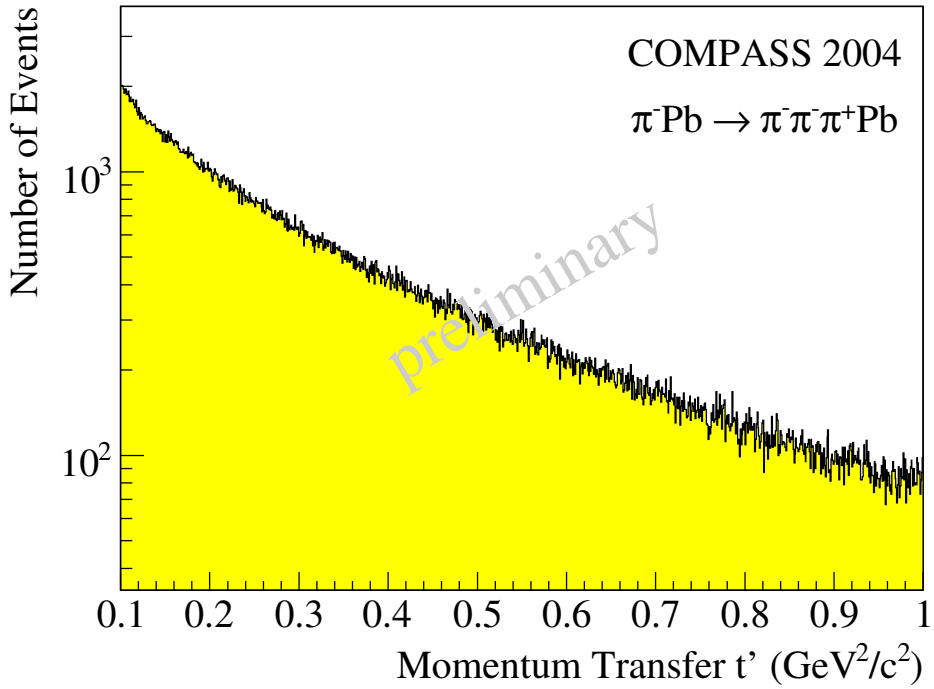
- Production via photon and strong (pomeron) exchange
  - separable by different $t-$dependence
- e.g. resonance $a_2(1320)$ is produced both ways
  - radiative width
  - phase between the photon and strong amplitudes
- low-mass region $\rightarrow$ ChPT

Diffraction 2004: $\pi^- \mathrm{Pb} \to \pi^-\pi^-\pi^+\mathrm{Pb}$

Momentum Transfer Distributions

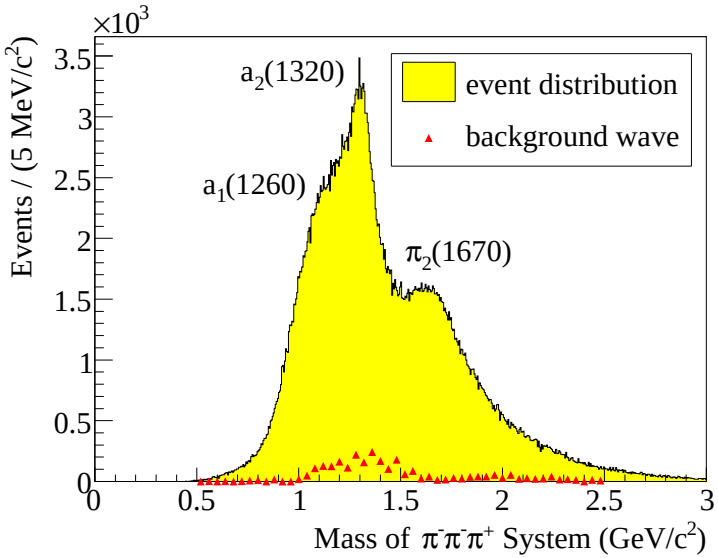
- 4-pion vertex in Pb target
- Exclusive in the total energy (within resolution)
- Momentum transfer: $-t = Q^2 = -(p_{\mathrm{beam}} - p_{(\pi^-\pi^-\pi^+)})^2, \quad t' = |t| - |t|_{\mathrm{min}}$

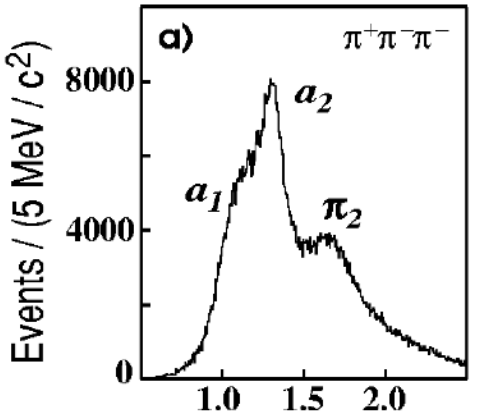




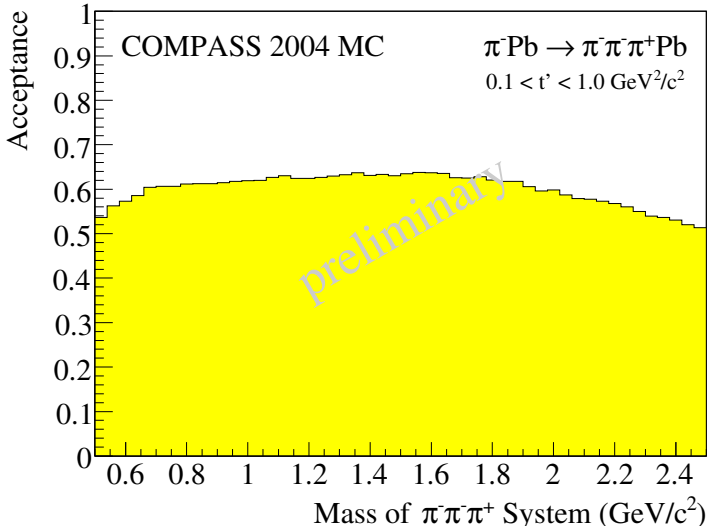
3π Data in the high-t range

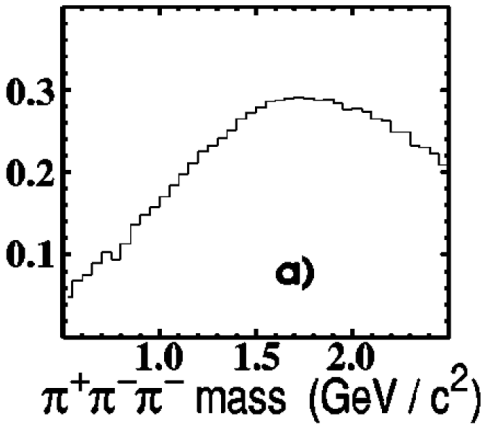
Phys. Rev. Lett. 104, 241803 (2010)





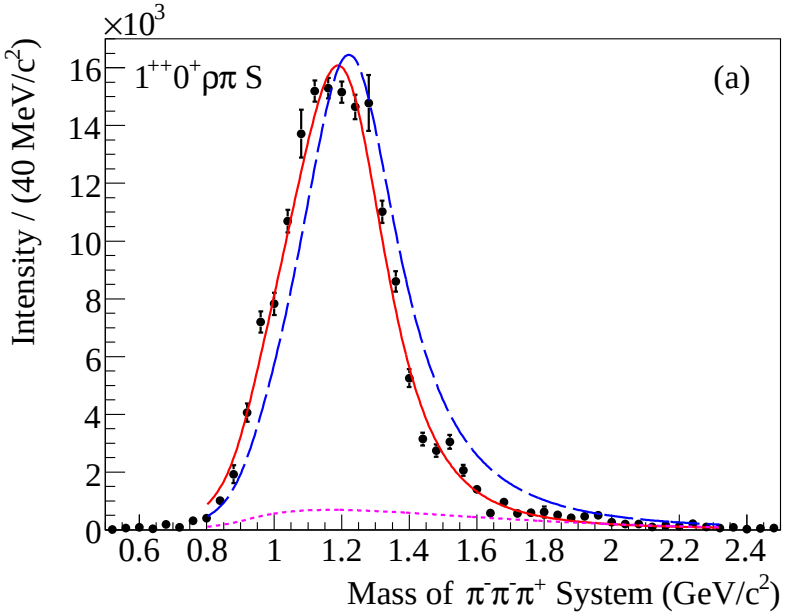
BNL-E852, Phys. Rev. **D65**, 072001, 2002

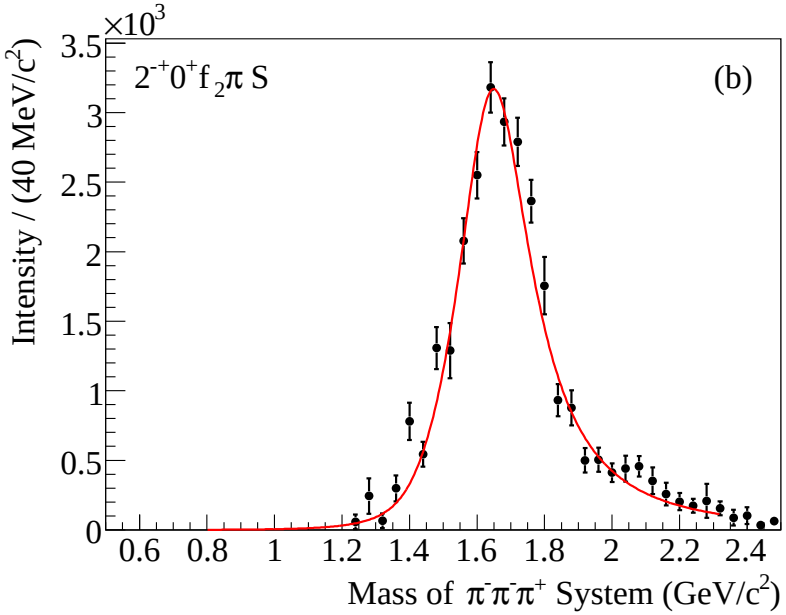


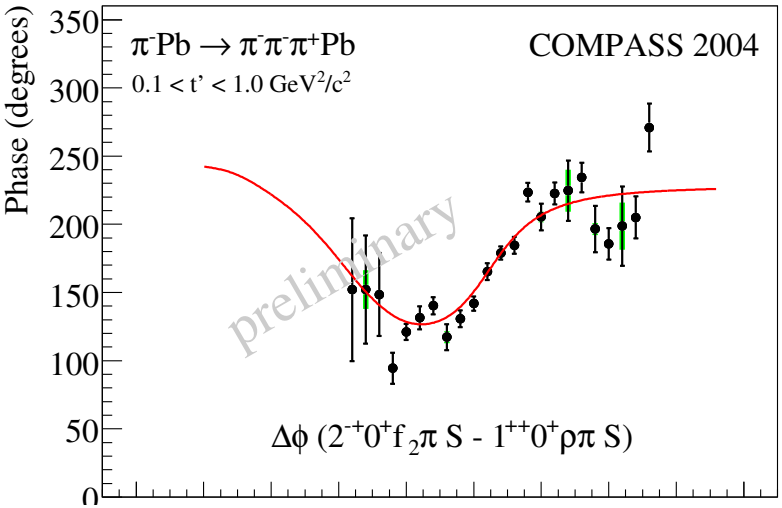


PWA Results

Phys. Rev. Lett. 104, 241803 (2010)







- BW for $a_1(1260)$:

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

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

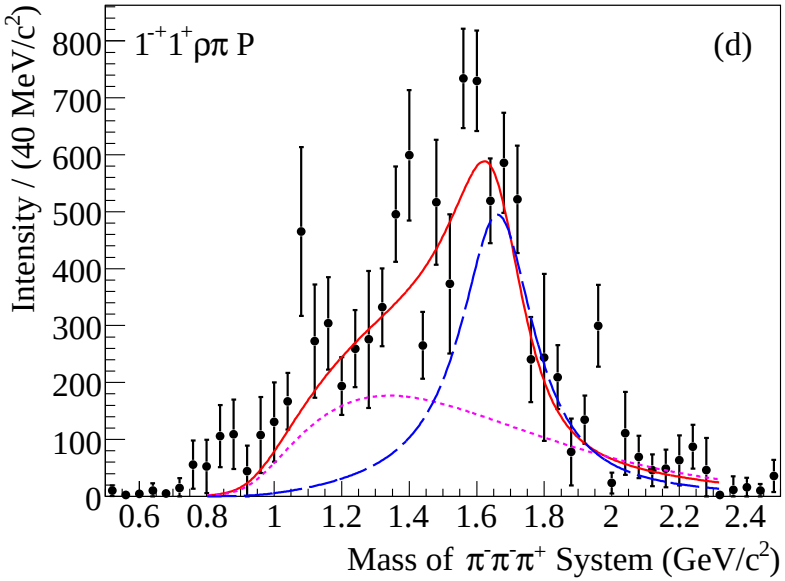
- BW for $\pi_2(1670)$:

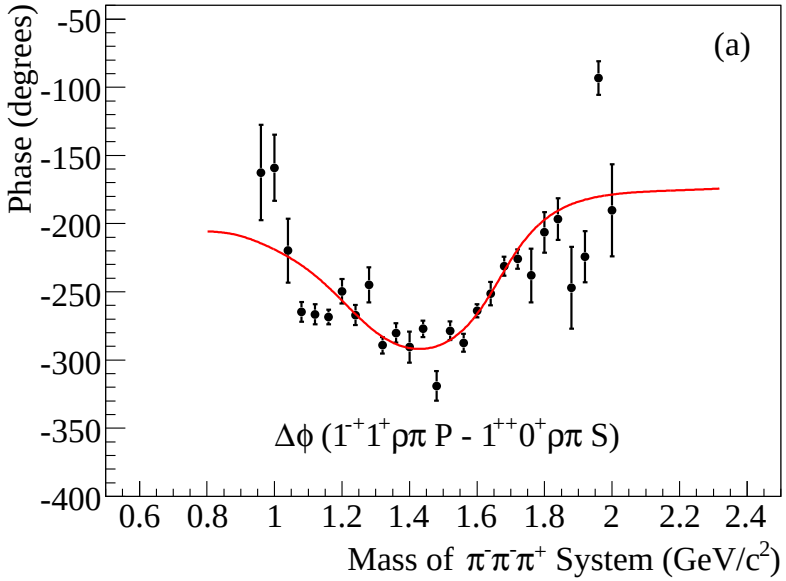
  $M = (1.659 \pm 0.003\ ^{+0.024}_{-0.008})$ GeV

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

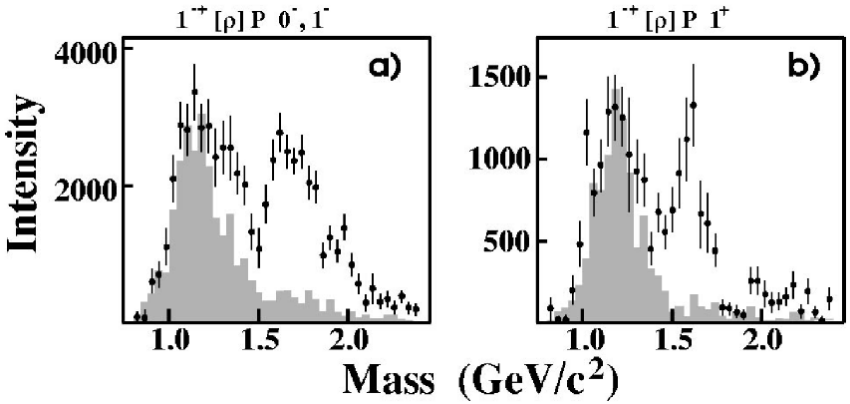
PWA Results

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





BNL E852 signal:



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

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

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

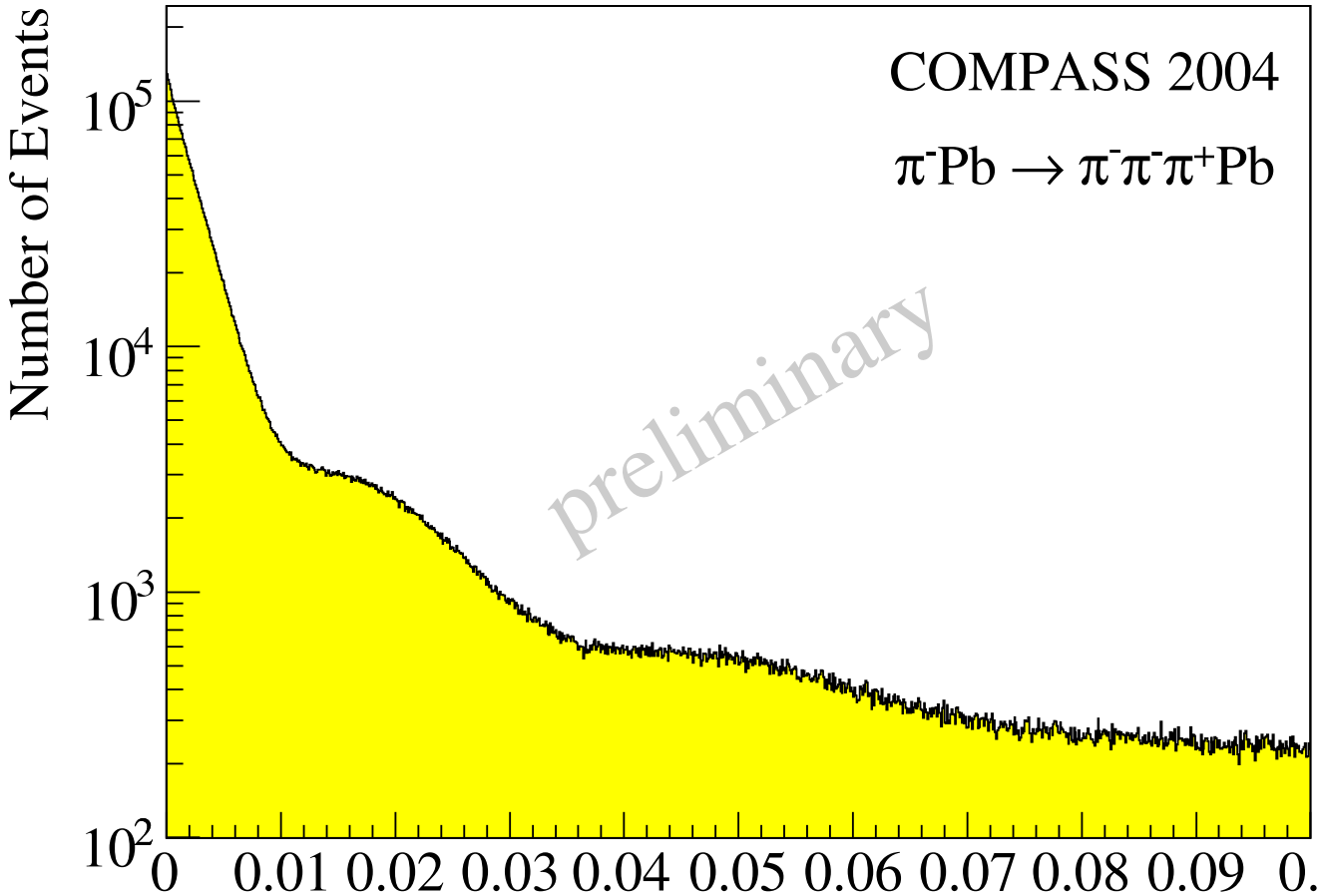
Diffraction 2004: conclusions on high-t

- 2004 π^- Pb $\rightarrow$ Pb $\pi^-\pi^-\pi^+$ at high-t: spin-exotic 1^{-+} observed
  - BW parameters similar to those of $\pi_2(1670)$
- 2008/2009 $\pi^- p$, pp, π^-Pb, π^-Ni data
  - analysis ongoing
  - acceptance corrections

next:

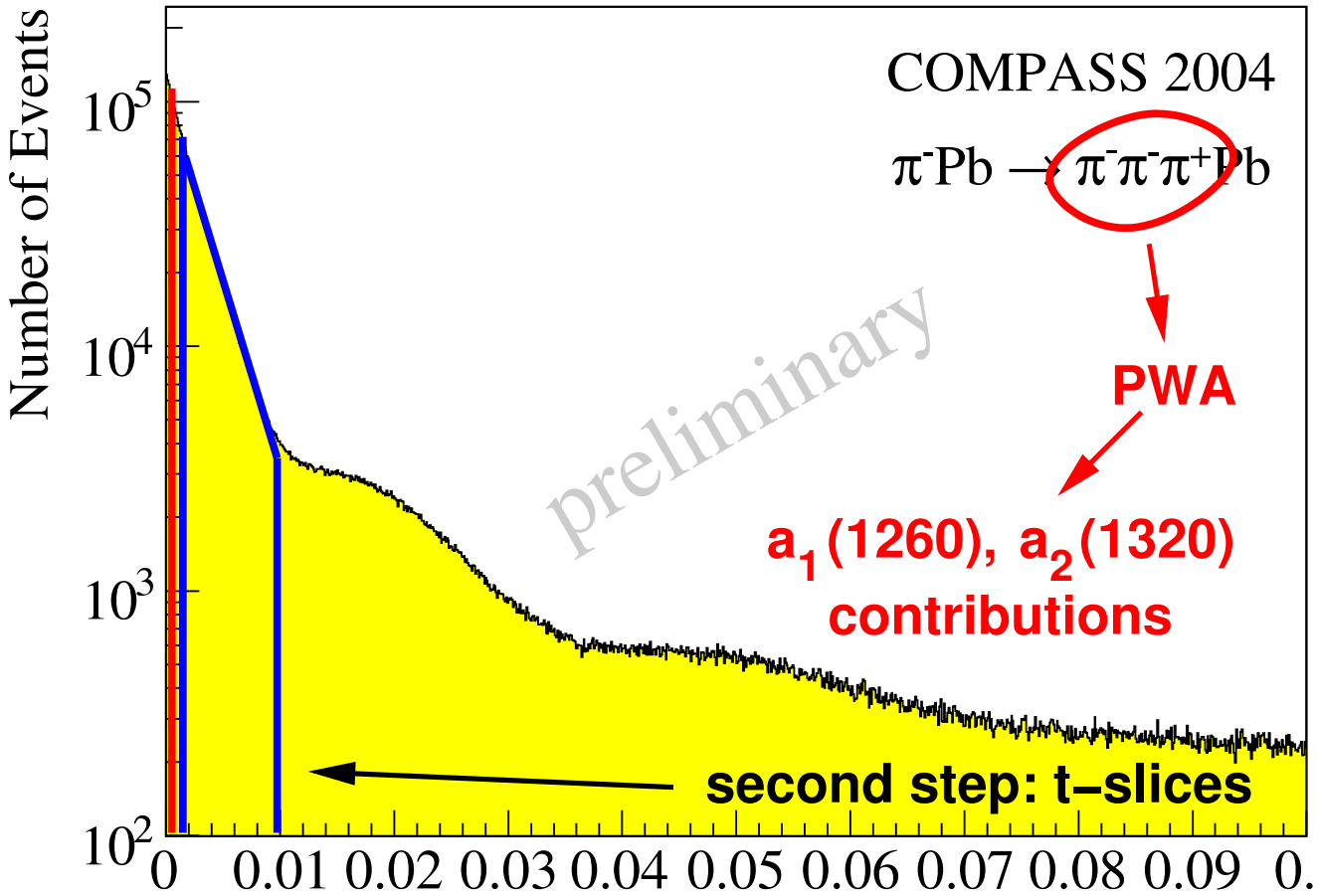
- 2004 π^- Pb $\rightarrow$ Pb $\pi^-\pi^-\pi^+$ at low-t
  - study main resonances: a_1, a_2
  - separate two t-regions: diffractive and Primakoff
  - interference in narrow t-slices

Diffraction 2004: low-t



- "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

Diffraction 2004: low-t



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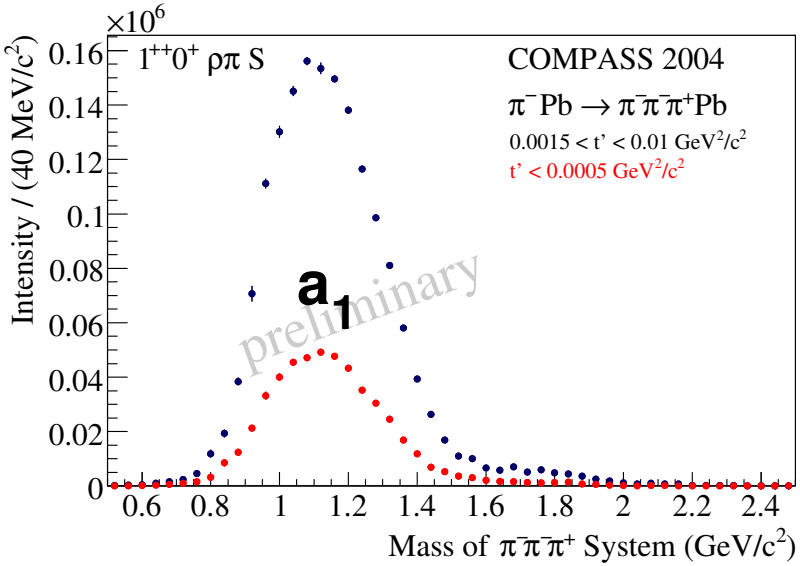
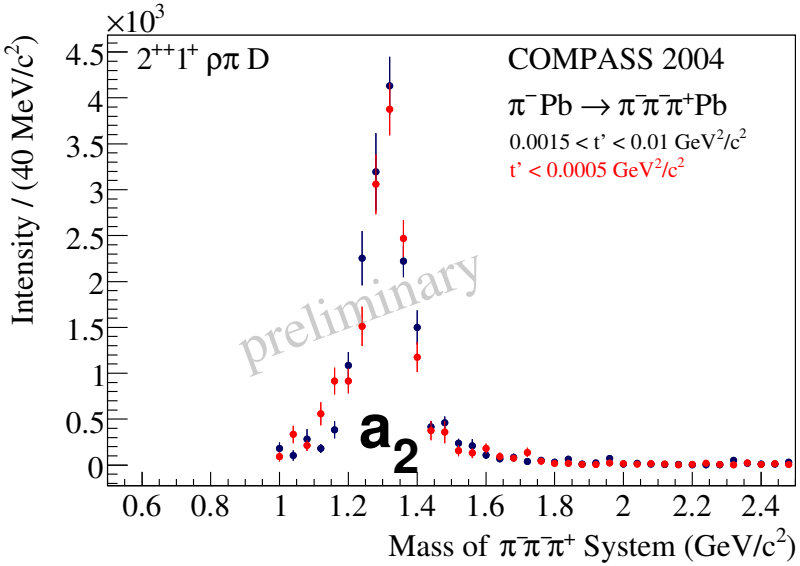
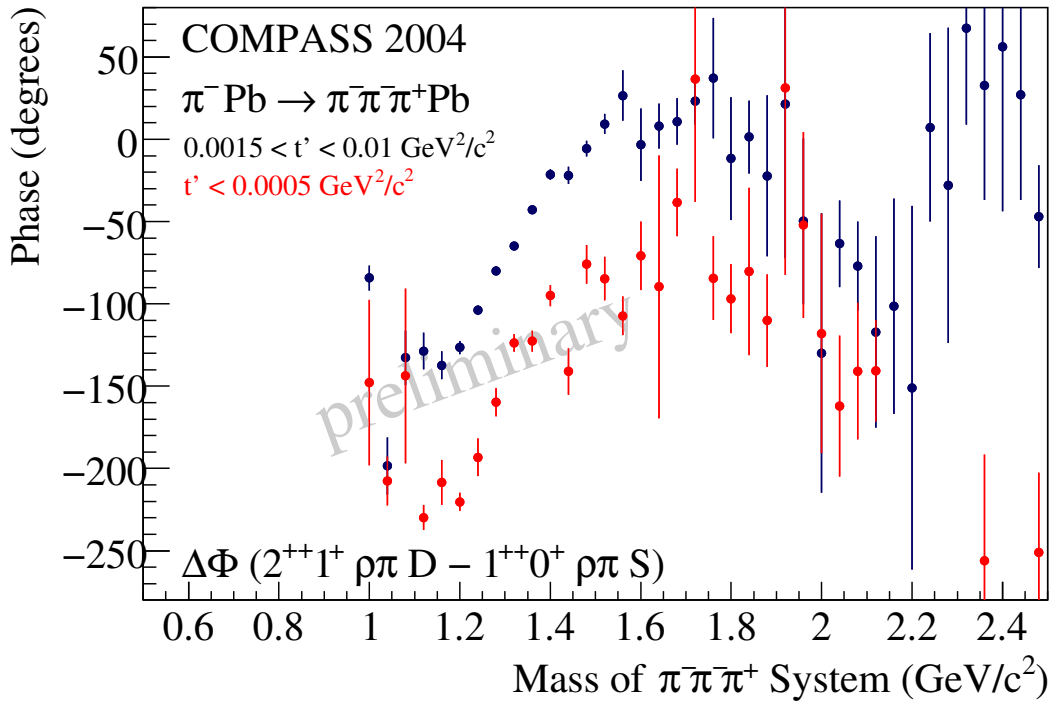
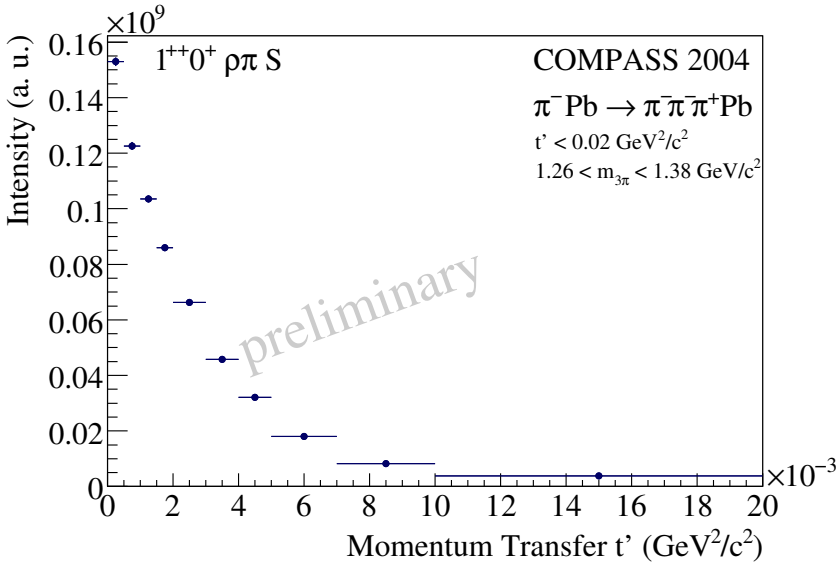
PWA: a_1, a_2 and $\Delta\Phi$ in separated t' regions

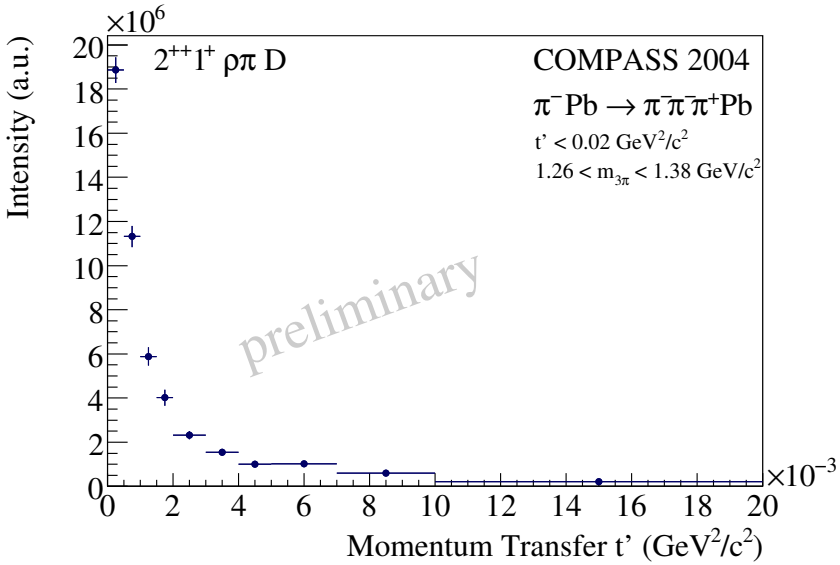


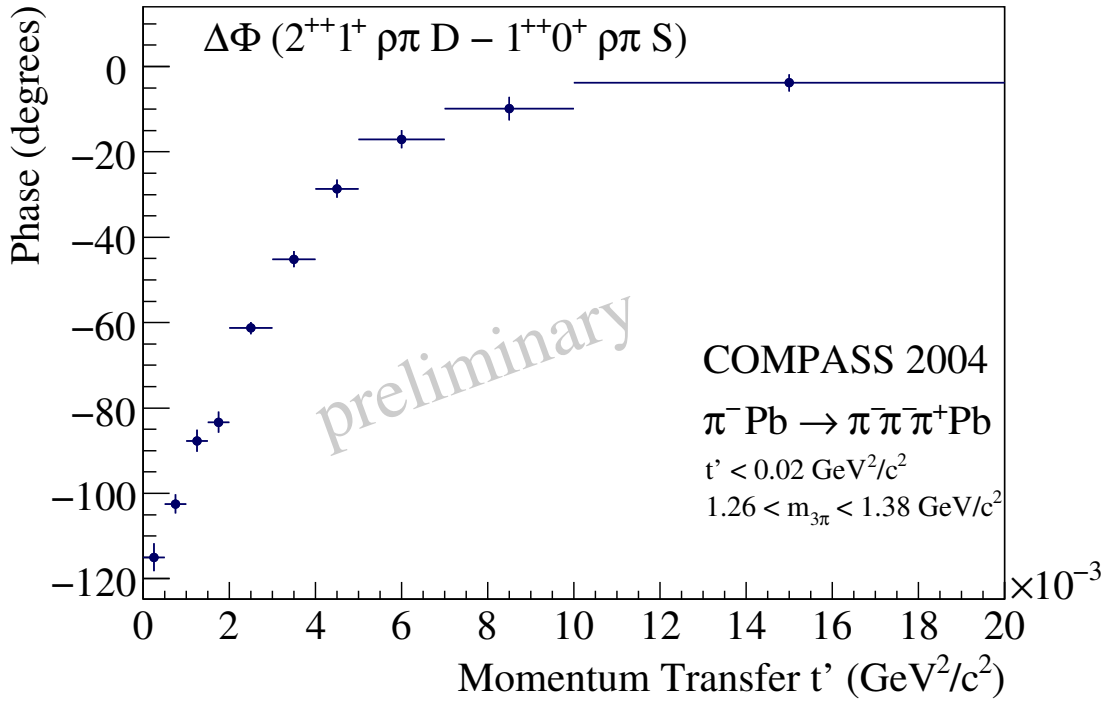




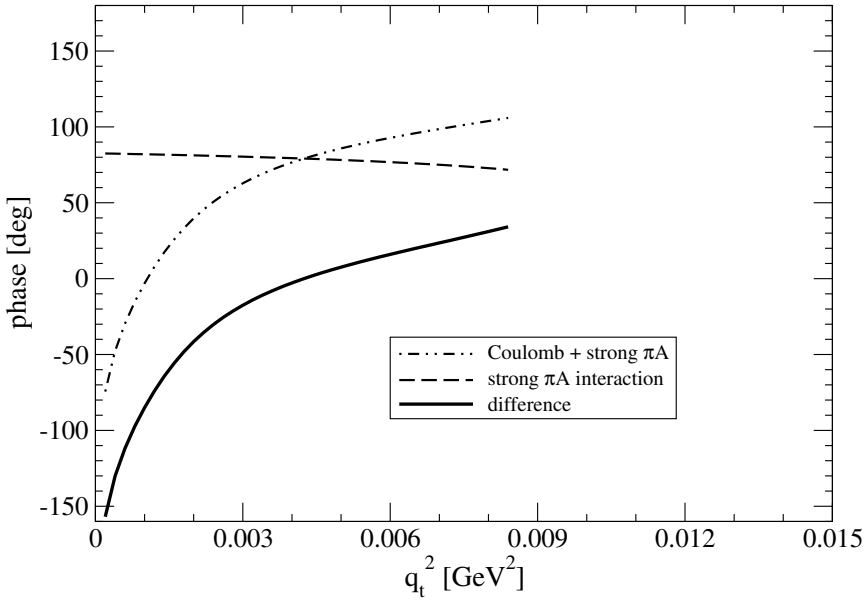
Phase $a_2 - a_1$ in detail: t' dependence

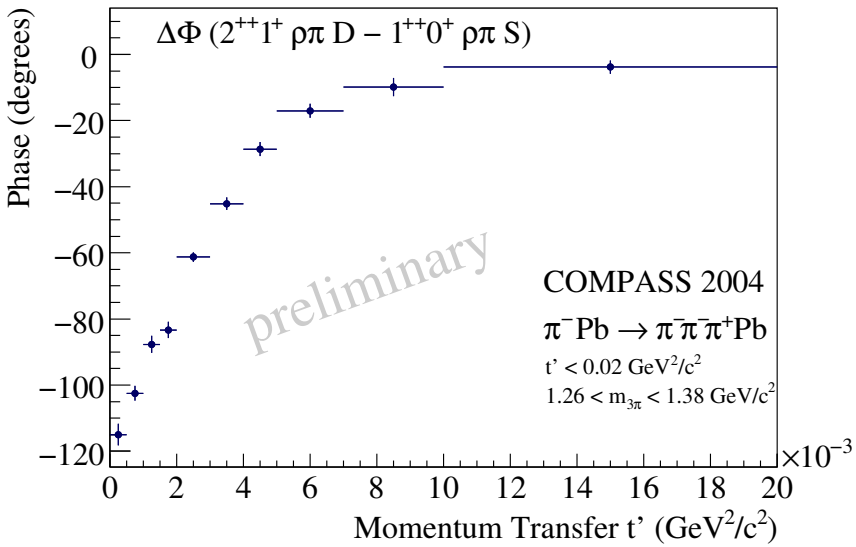






Theory: Phase a_2(strong+Coulomb)-a_1(strong)





Glauber modell

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

Plot: N. Kaiser (TU München)

- indicates confirmation of the Coulomb/strong interference
- detailed study of the nature of resonances and exchange mechanism

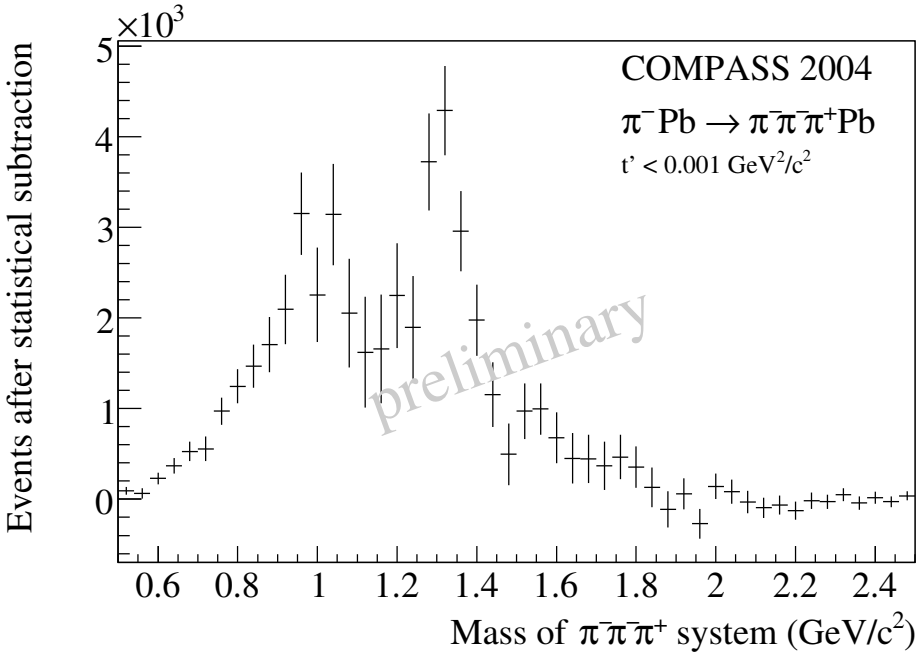
Diffraction 2004: conclusions on low-t

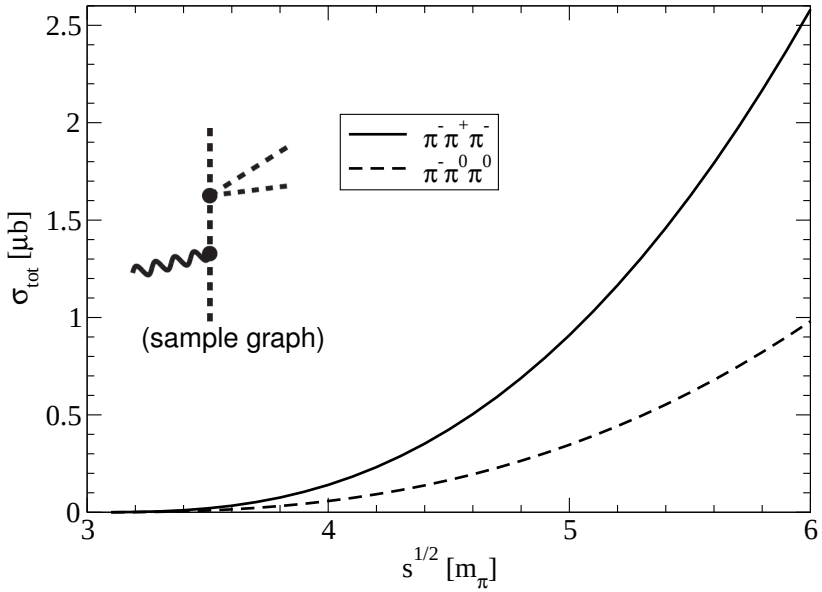
- π^- Pb at low-t: resonances
  - study the main resonances: a_1, a_2
  - a_2 radiative coupling
  - phase $\geq 90^\circ$ between Coulomb and strong amplitude
  - other resonances: *coming up*

next:

- π^- Pb at low-t: low mass region of the 3π f.s. system
  - extraction of the Primakoff signal: $\pi\gamma \to 3\pi$
  - low-energetic "tail" of the a_1

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
  new calculation of loop contributions: arXiv:1007.5277

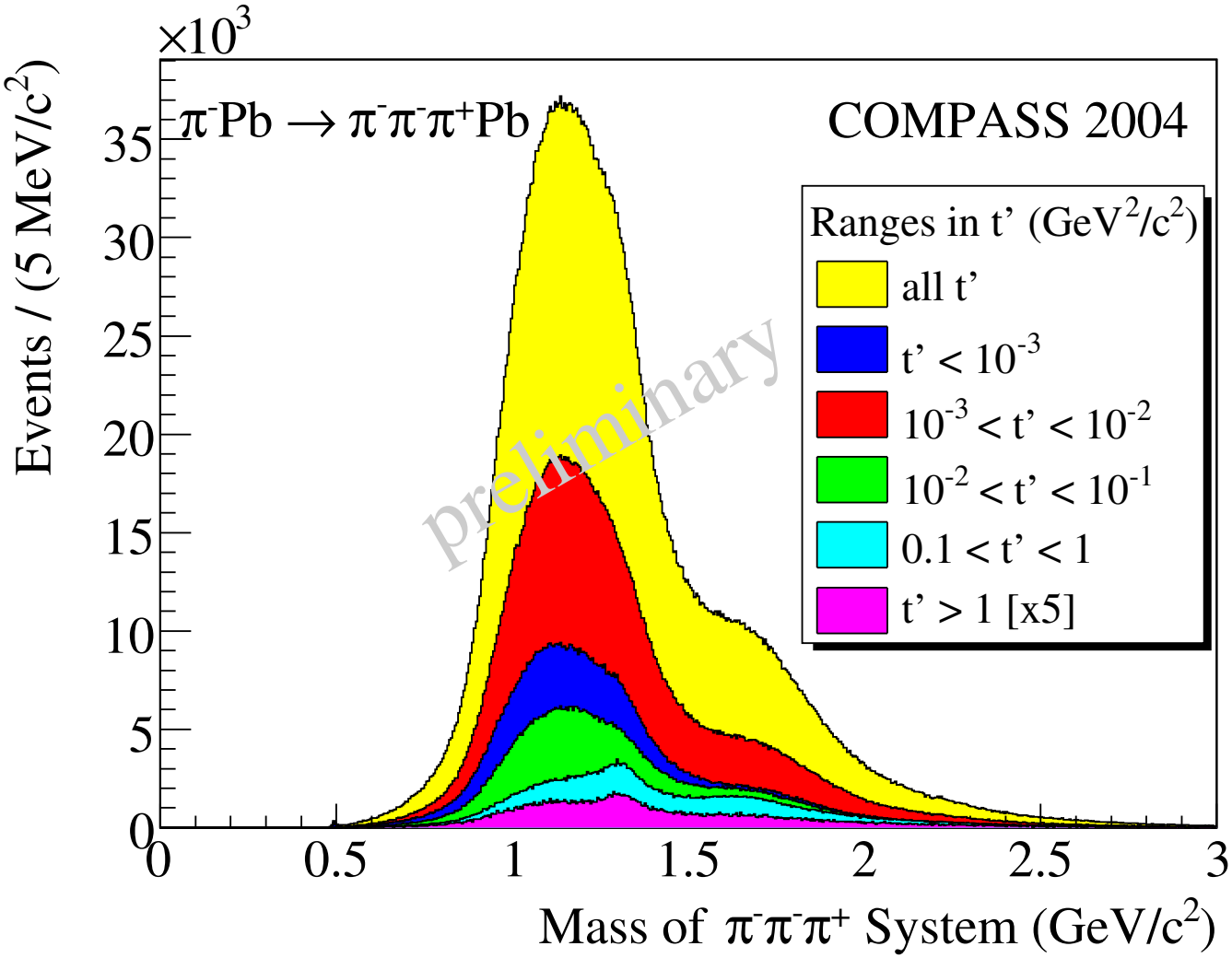
Summary and Outlook

- COMPASS 2004 hadron run (few days) using a 190 GeV π^- beam
  - diffractive dissociation in the $0.3 < -t/\text{GeV}^2 < 1$ range: 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*
- 2008/2009 data with extended spectrometer
  - diffractive on H, Pb, Ni
  - Primakoff on Ni
- High-statistics Primakoff run proposed for 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):

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

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

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

  $\rightarrow$ Physical parameters:

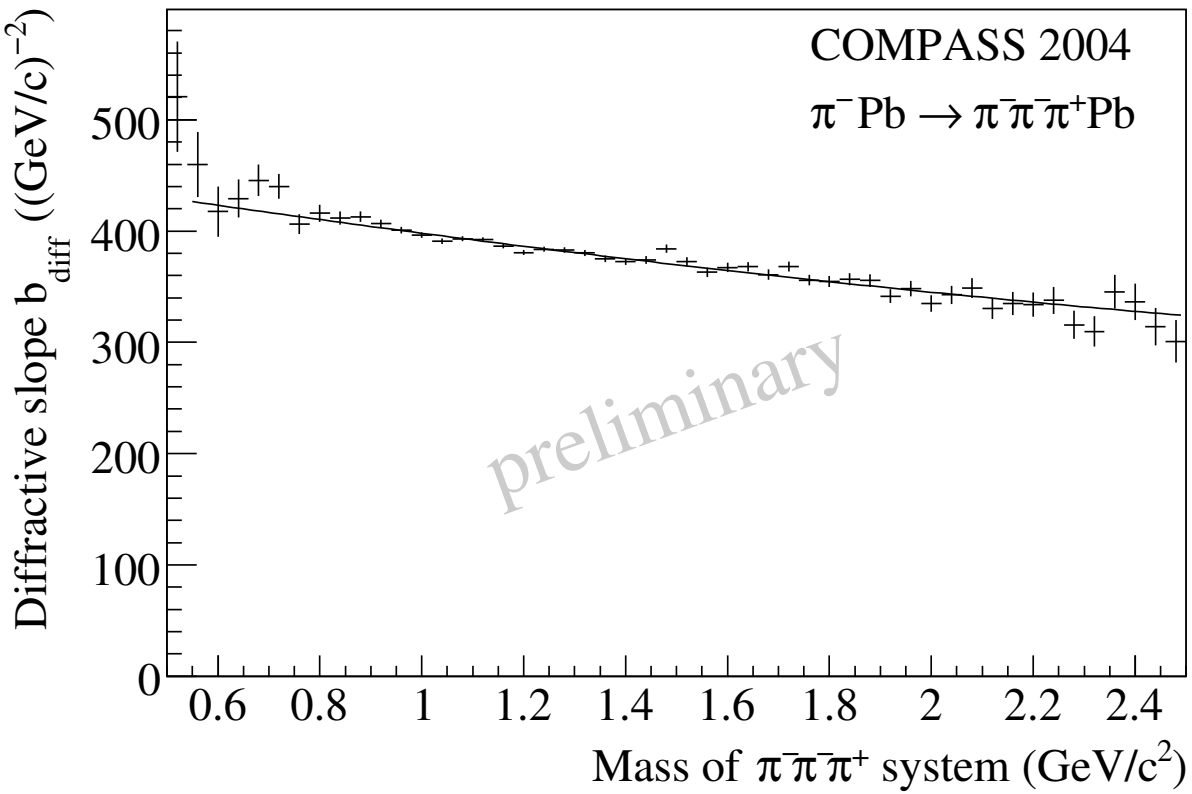
$$\text{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

relative phase Φ_{ij}^{e}

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

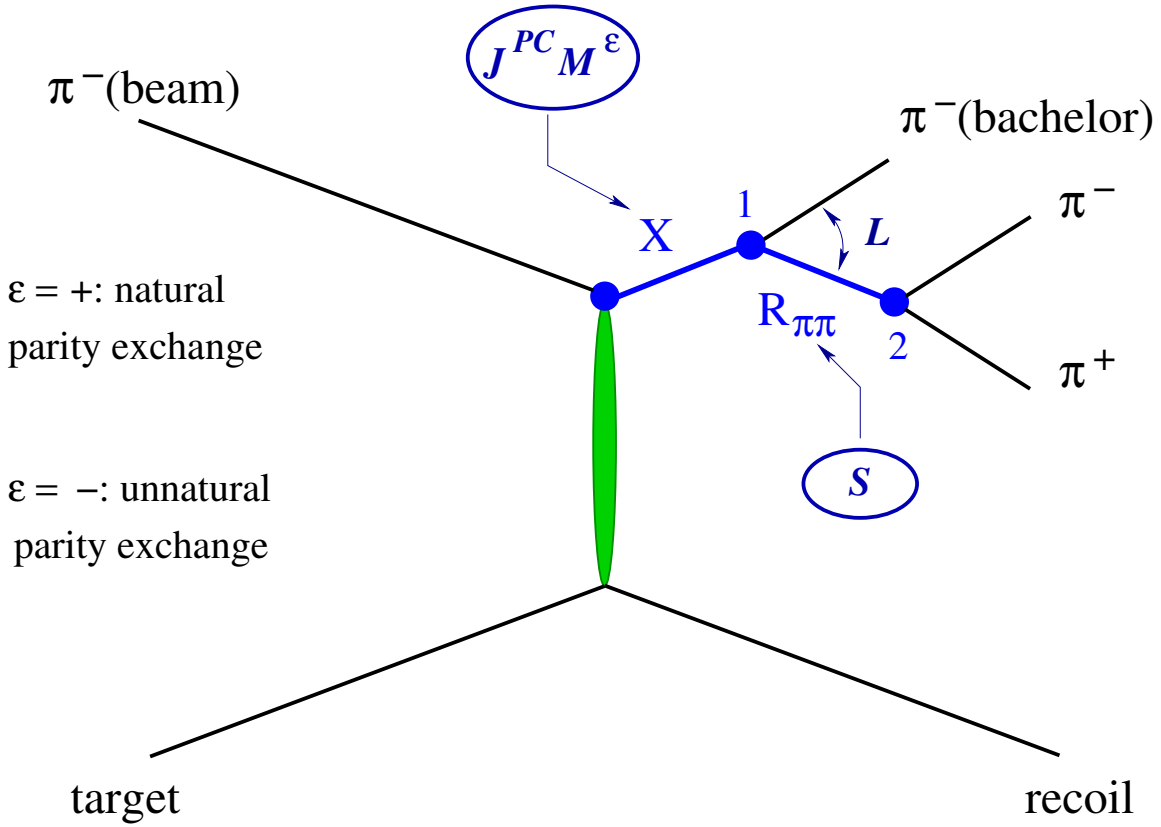
- Mass-dependent χ^2-fit (not presented here):
  - X parameterized by Breit-Wigner (BW) functions
  - Background can be added

Mass dependence of the diffractive slope



Partial Wave Analysis Formalism

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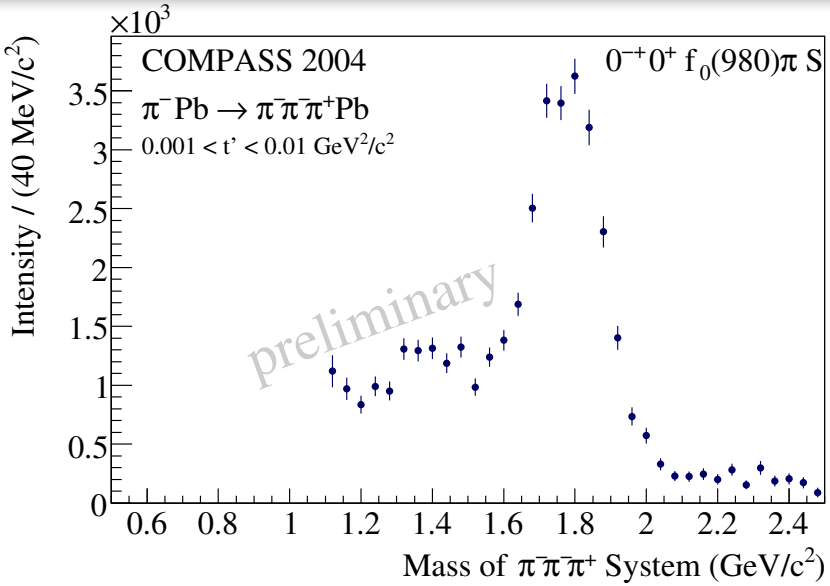
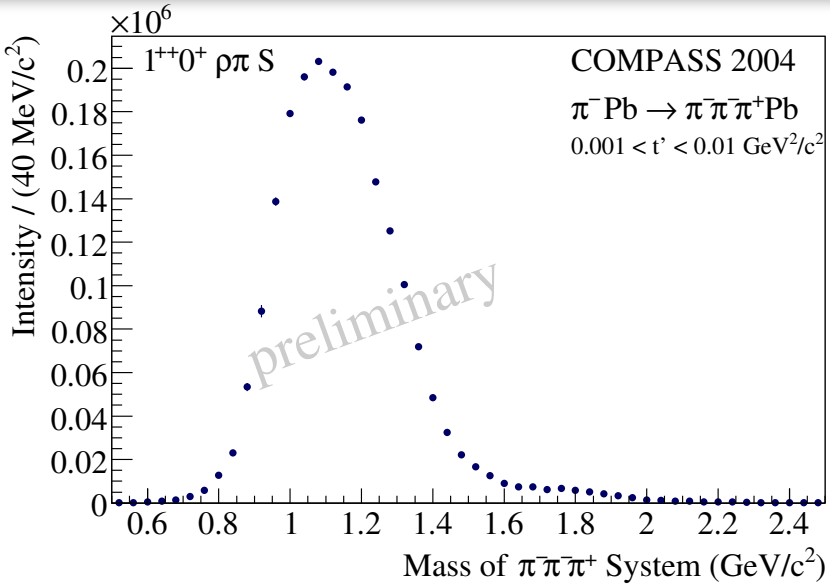
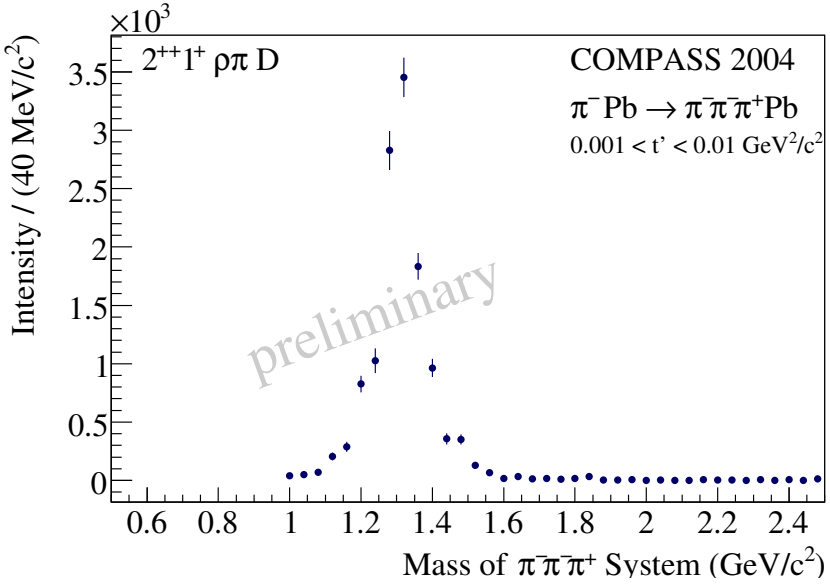
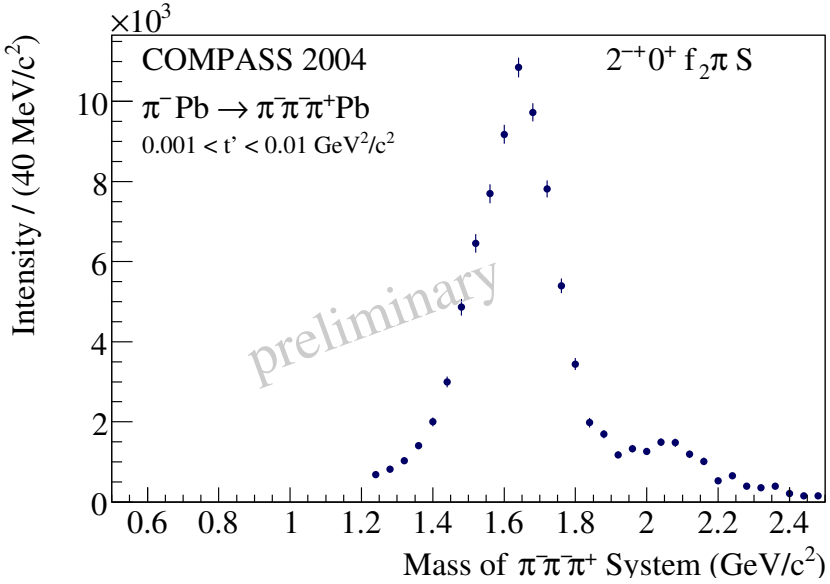
Intensity of selected waves: $0^{-+}0^{+}f_0(980)\pi S$, $1^{++}0^{+}\rho\pi S$, $2^{++}1^{+}\rho\pi D$, $2^{-+}0^{+}f_2(1270)\pi S$









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

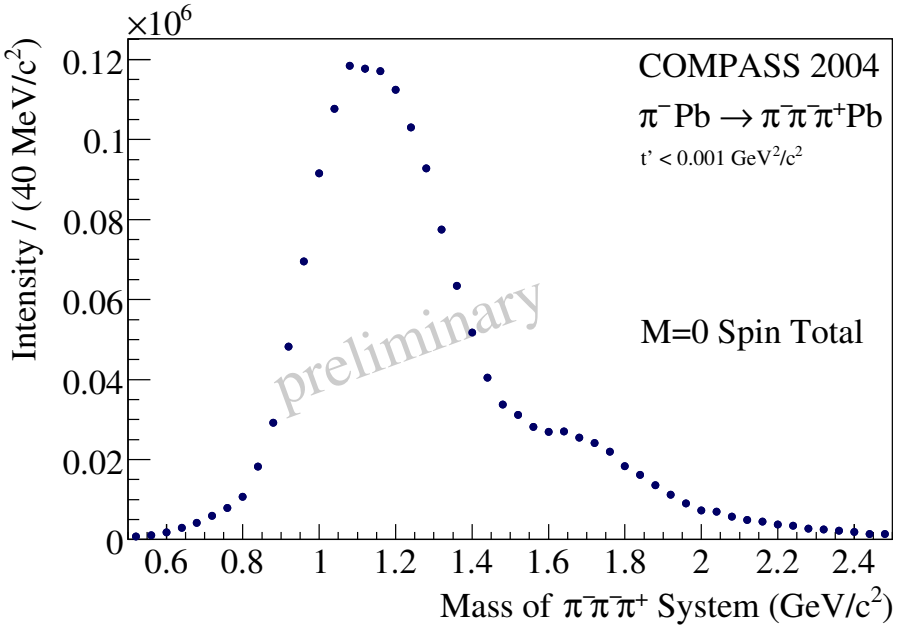
”Spin Totals”: Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

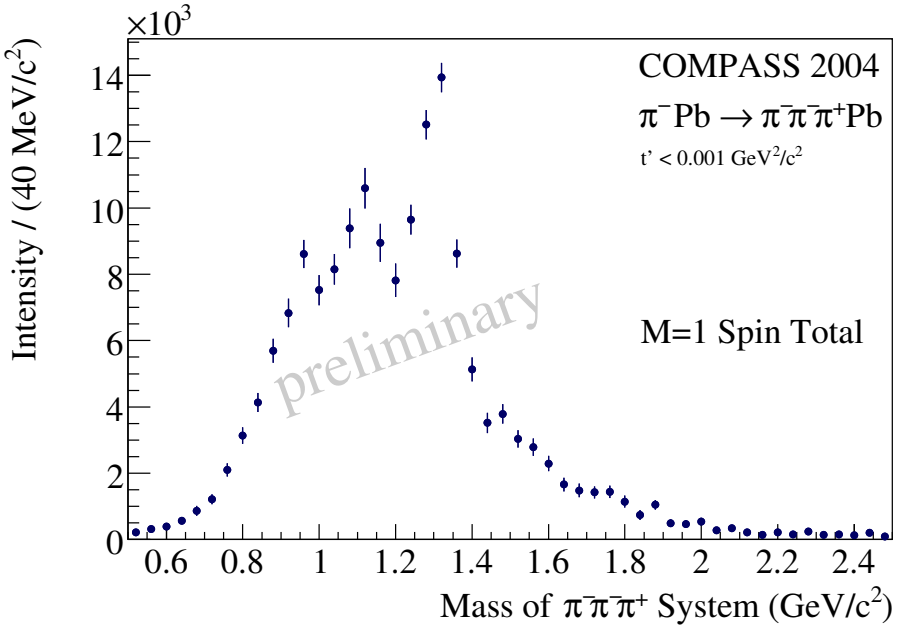
Primakoff production: M=1: $\sigma(t') \propto \mathrm{e}^{-b_{\mathrm{Prim}} t'} \rightarrow$ arises at $t' \approx 0$ (resoluted shape!)

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

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



M=0



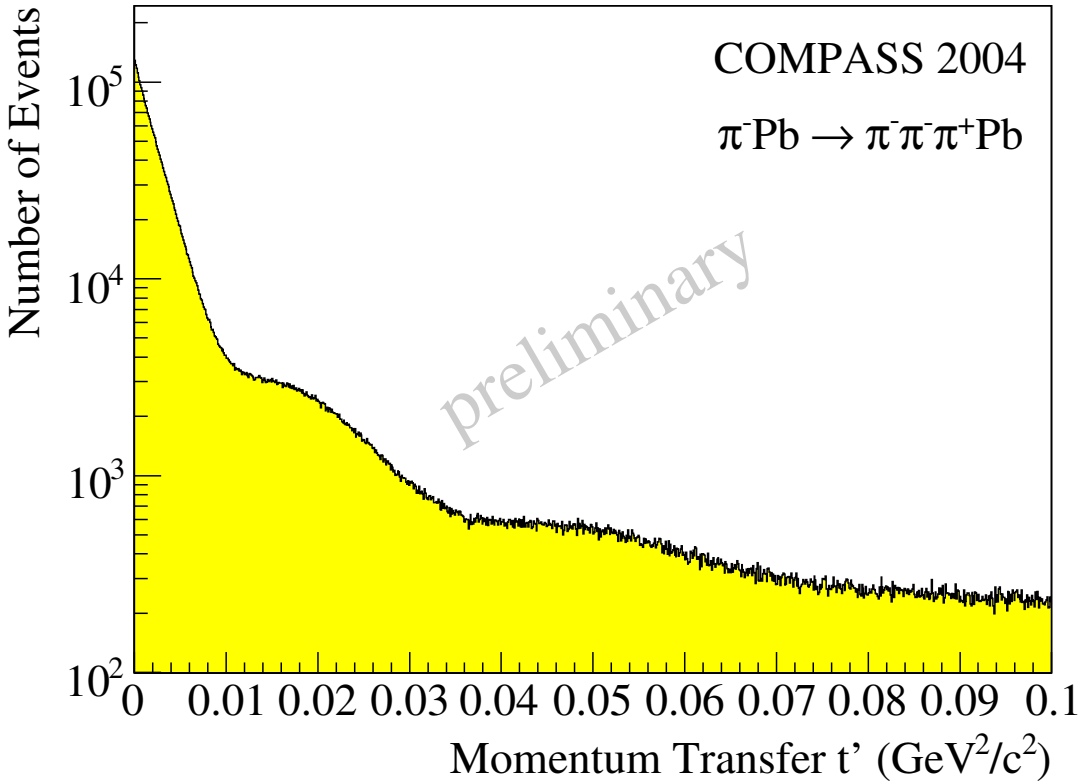
M=1

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

2004 Primakoff results (diffractive trigger)

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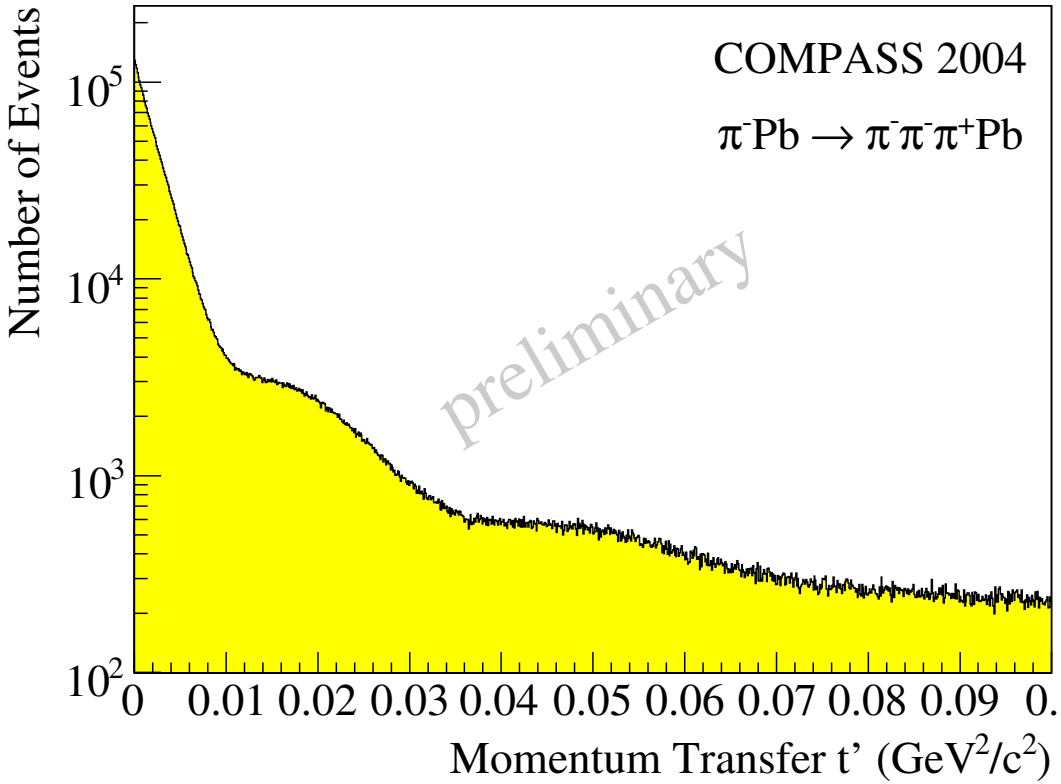

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- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim 1\,000\,000$ events

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

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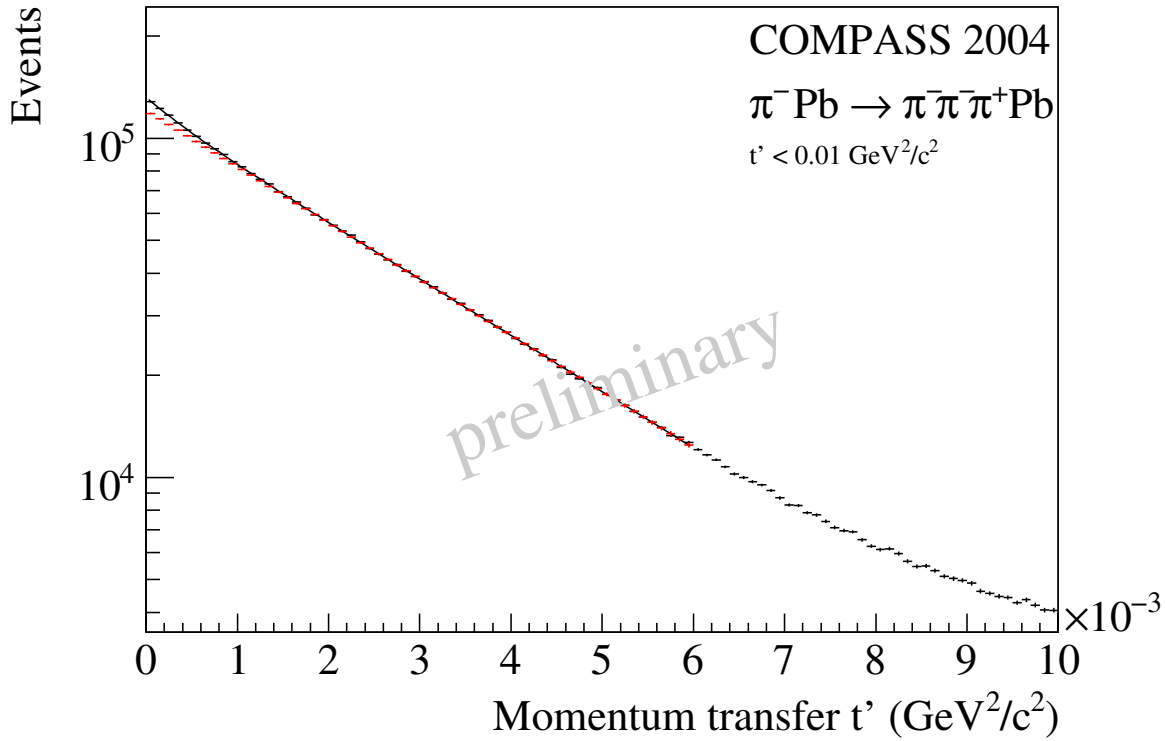
Primakoff: $\sigma(t') \propto \mathrm{e}^{-b_{\mathrm{Prim}}\,t'}$, $b_{\mathrm{Prim}} \approx 2000\,(\mathrm{GeV}/c)^{-2}$ (mainly resolution)

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

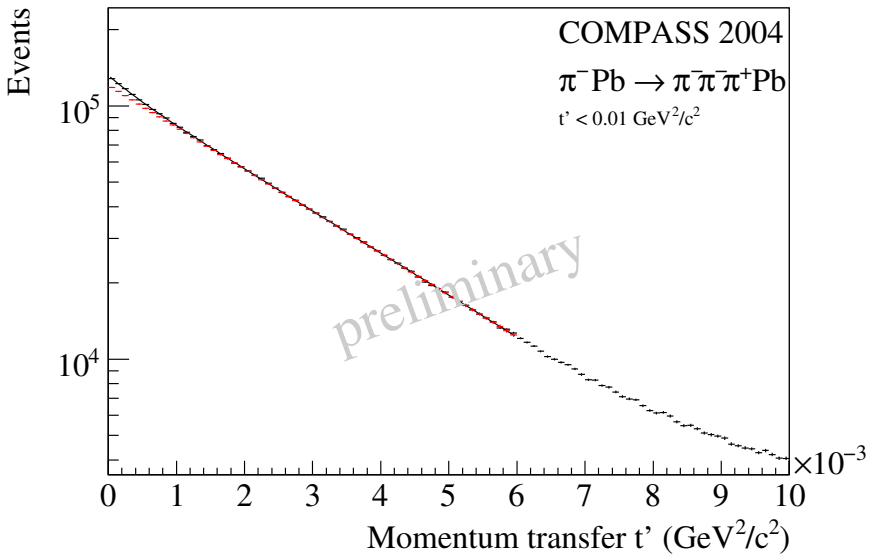


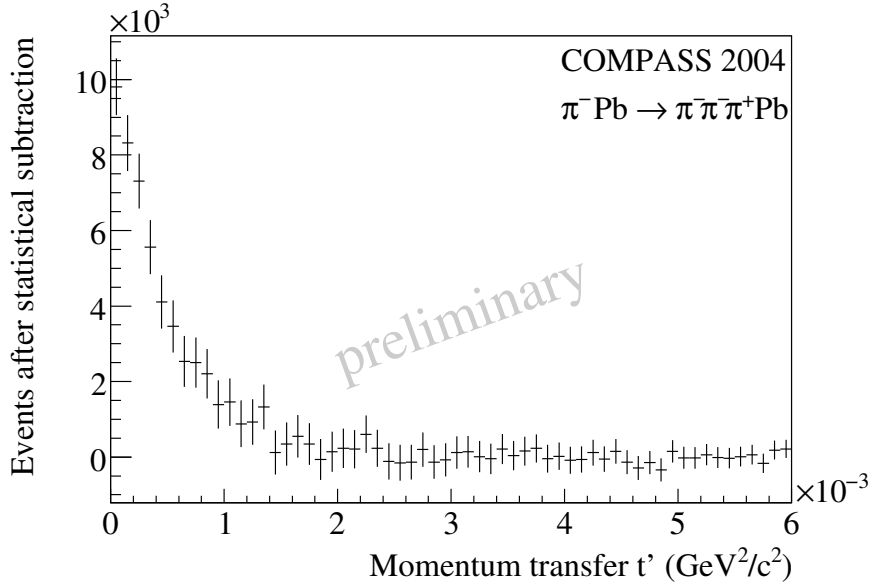
(Mass) spectrum of this Primakoff contribution?

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

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



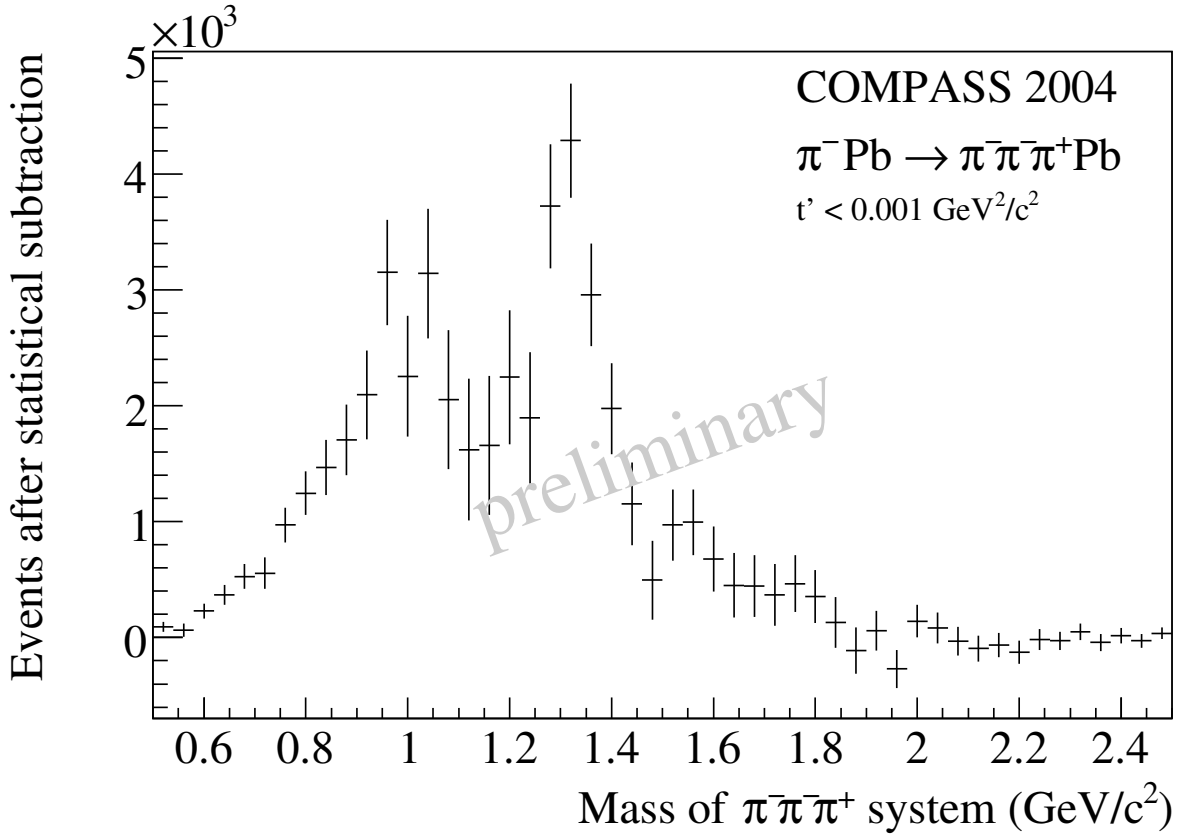


- Fit and subtraction in 3π mass bins:
  - $b_{\mathrm{Prim}} = 2050\,(\mathrm{GeV}/c)^{-2}$ fixed
  - b_{diff} as fit parameter

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



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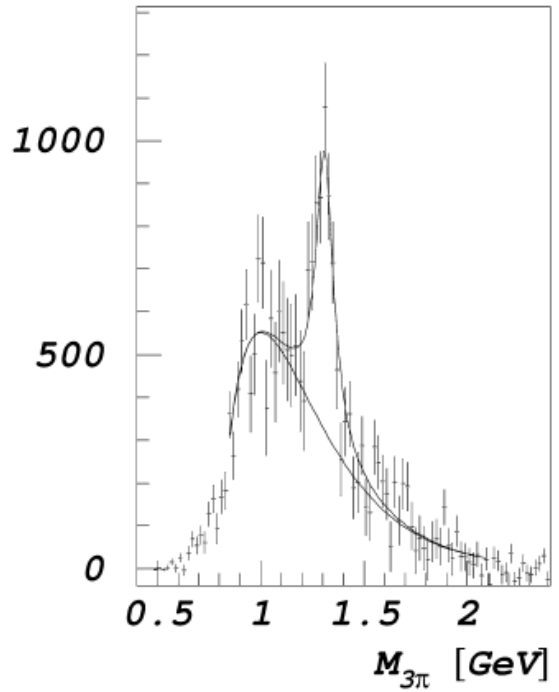

Fig. 3. $M_{3\pi}$ mass distribution for the Cu target after subtraction of diffractive background. The curve shows fit with a sum of pure Coulomb contribution and smooth background.