

$\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$ at Low Masses compared to ChPT Prediction at COMPASS

Stefanie Grabmüller, Dmitry Ryabchikov, Jan Friedrich
for the COMPASS collaboration

Physik Department E18
Technische Universität München

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Meson Spectroscopy at Low Momentum Transfer

Diagrams from ChPT

Absolute Cross-Section and ChPT Prediction

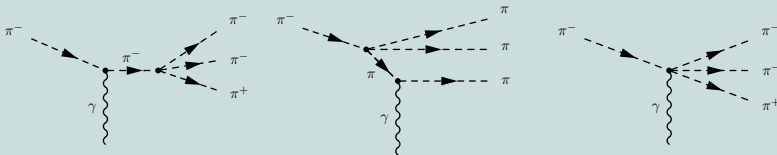


Motivation for Analysis

Meson spectrum at lowest momentum transfer:

Contribution of **photon-exchange**

- At low masses: **"pions only"** → predictions by **ChPT**



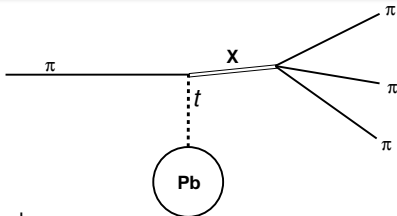
tree diagrams of 3π production in $\pi\gamma$ scattering

- At higher masses: **resonances**:
 - radiative coupling of $a_2(1320)$ / heavier mesons
 - interference between diffractive and Coulomb production



Interaction mechanisms

- **Diffraction:**
 - target particle remains intact
 - $l = 0$ **Reggeon t-channel exchange**
exchange particle: (mostly) Pomeron
 - **Assumptions:** Factorization of meson and Pb vertex, no final state interaction
- **Primakoff:** **photon** exchange ($J^{PC} = 1^{--}$)
dominant contribution at smallest momentum transfer
quasi-real $\gamma \rightarrow M = \pm 1$



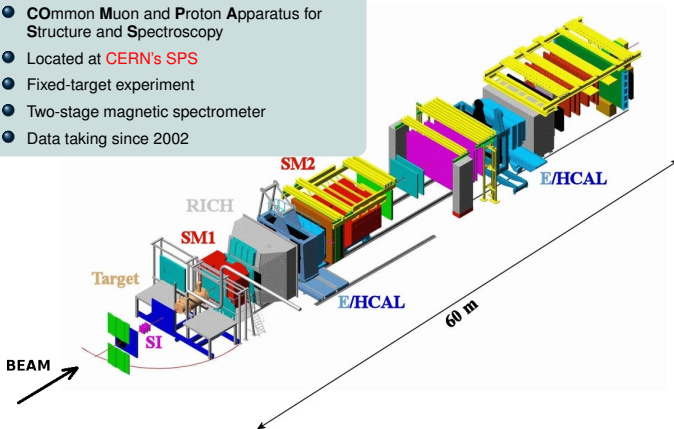


COMPASS 2004 Pilot Hadron Run

Experimental Setup

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at **CERN's SPS**
- Fixed-target experiment
- Two-stage magnetic spectrometer
- Data taking since 2002





COMPASS 2004 Pilot Hadron Run



Technische Universität München

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Pilot Hadron Run 2004

- **190 GeV π^- beam**
- Nuclear targets (Pb)
- Tracking: Silicons for vertexing
- Trigger: Multiplicity trigger, ECAL trigger



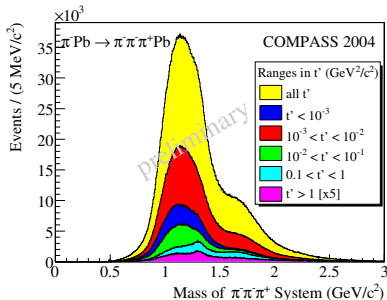
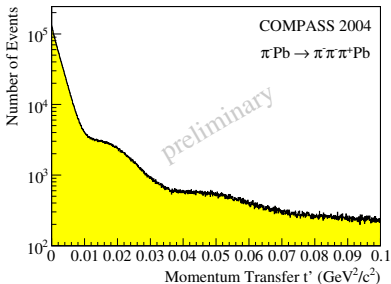
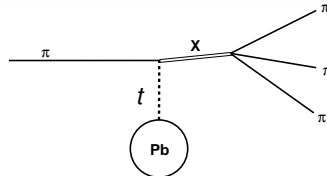
$\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$ Data

Pilot Hadron Run 2004

$\approx 4\,000\,000$ exclusive 3π events

$\approx 1\,000\,000$ with $t' < 10^{-3} \text{ (GeV}^2/\text{c}^2)$

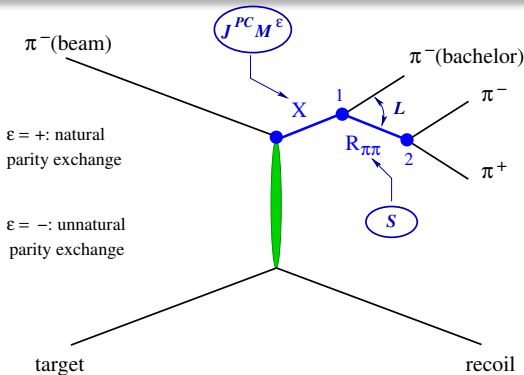
$\approx 2\,000\,000$ with $10^{-3} < t' < 10^{-2} \text{ (GeV}^2/\text{c}^2)$
 with $t' = |t| - |t|_{\min} (m_{3\pi})$





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/c² mass bins): **38 waves**
Fit of angular dependence of partial waves, interferences
- **Acceptance** corrections from MC
- (**Mass-dependent** χ^2 -fit)



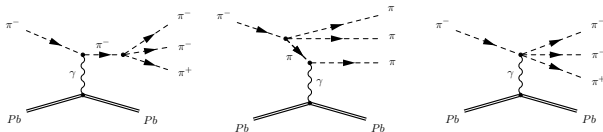
Meson Spectroscopy at Low Momentum Transfer

Diagrams from ChPT

Absolute Cross-Section and ChPT Prediction



- $t' < 10^{-3} (\text{GeV}/c)^2$: Coulomb production in $M = 1$ waves ($\pi\gamma \rightarrow 3\pi$)
- Low masses: no resonances, governed by pion-scattering
→ **tree diagrams** from ChPT prediction¹



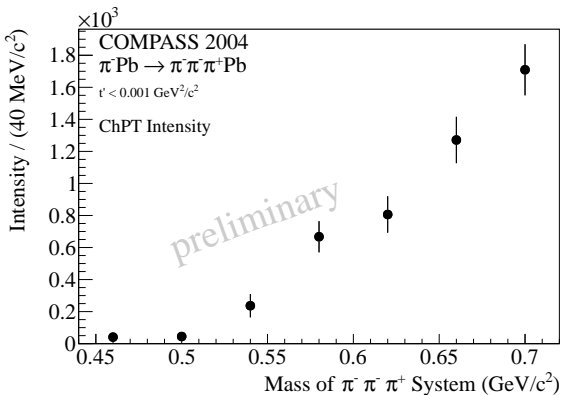
- **ChPT amplitude introduced as single partial wave**
 - not orthogonal to $M = 1$ waves in isobar model
 - replaces (up to 6) $(\pi\pi)_S\pi$ and $\rho\pi$ waves by a **single amplitude**
 - Fit quality in low mass region compatible
- ChPT valid for $3m_\pi \approx 0.42 \text{ GeV}/c^2 < m_{3\pi} < 0.7 \text{ GeV}/c^2$
- Higher masses: Isobaric decays

¹EPJ A36 (2008) 181



Total Intensity of Chiral Amplitude

Chiral amplitude at low masses equivalent to fit with 6 waves
but much less parameters (i.e. basically intensity)

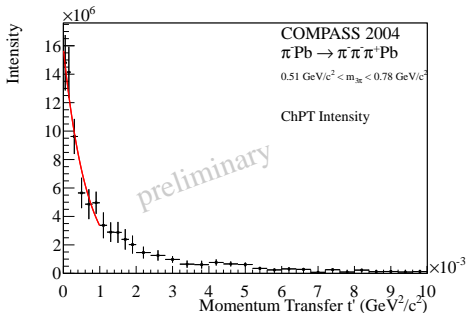


...is this really photon exchange?



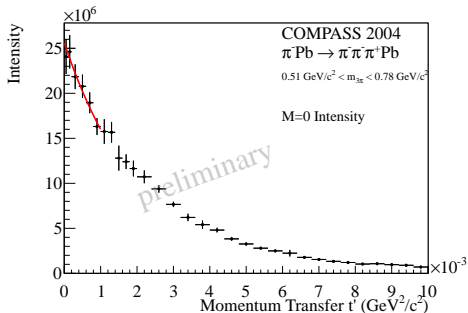
t' Dependence of Chiral Amplitude

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



$$b_{\text{chiral}} \approx 1560 \text{ (GeV}/c)^{-2}$$

→ Primakoff (Photon)

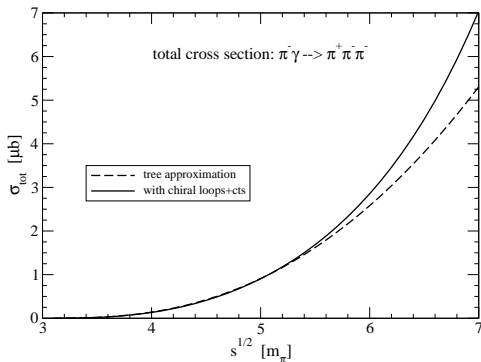


$$b_{M=0} \approx 400 \text{ (GeV}/c)^{-2}$$

→ diffractive (Pomeron)



- **Goal:** Compare to



[Nucl. Phys. A 848 (2010) 198]

- Experimental determination of absolute cross-section $\pi^- \gamma \rightarrow 3\pi$
- **Normalization** via $K^- \rightarrow \pi^+ \pi^- \pi^-$ decays in target region



Meson Spectroscopy at Low Momentum Transfer

Diagrams from ChPT

Absolute Cross-Section and ChPT Prediction



From Intensity to Cross-Section

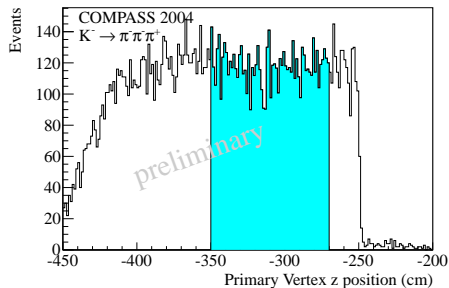
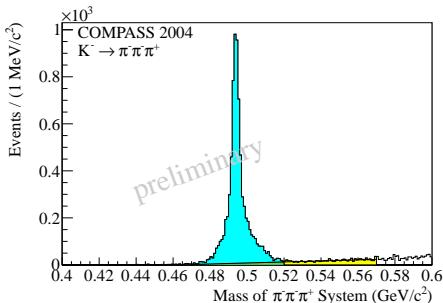
Beam K^- Decays from Data

In each bin of $m_{3\pi}$:

$$\text{Number of reactions (events)} = \epsilon_{\text{bin}} \cdot \int \mathcal{L} dt \cdot \sigma_{\text{abs}}$$

COMPASS π^- beam features K^- component

→ beam flux from $K^- \rightarrow \pi^+ \pi^- \pi^-$ decays





Cross-section of $\pi^- \gamma \rightarrow \pi^-(q_1) \pi^-(q_2) \pi^+(q_3)$ from ChPT

$$\begin{aligned}
 d\sigma_r(s) = & \frac{8\pi\alpha \cdot s}{(s - m_\pi^2)^3 f_\pi^4} \cdot d\Phi_3(p + k, q_1, q_2, q_3) \cdot \\
 & \left[\frac{\vec{q}_1 \times \hat{k}}{\omega_1 - \vec{q}_1 \cdot \hat{k}} \left(p_0(\sqrt{s} - \omega_2) - \sqrt{s}\omega_1 - \vec{k} \cdot \vec{q}_2 \right) + \right. \\
 & \frac{\vec{q}_2 \times \hat{k}}{\omega_2 - \vec{q}_2 \cdot \hat{k}} \left(p_0(\sqrt{s} - \omega_1) - \sqrt{s}\omega_2 - \vec{k} \cdot \vec{q}_1 \right) + \\
 & \left. \frac{\vec{q}_3 \times \hat{k}}{\omega_3 - \vec{q}_3 \cdot \hat{k}} \left(\sqrt{s}k_0 - p_0\omega_3 - \vec{k} \cdot \vec{q}_3 \right) \right]^2
 \end{aligned}$$

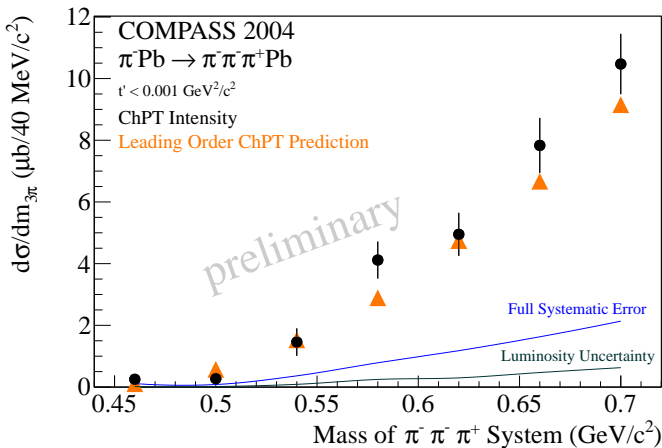
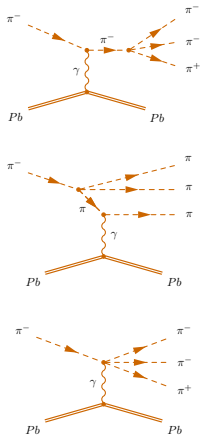
Cross-section of $\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

$$\frac{d\sigma}{ds dt'} = \underbrace{\frac{\alpha \cdot Z^2}{\pi(s - m_\pi^2)} \cdot F_{\text{eff}}^2(t')}_{\text{Weizsäcker-Williams photon density}} \cdot \frac{t'}{(t' + t_{\text{min}})^2} \cdot \sigma_r(s)$$



Measured Absolute Cross-Section

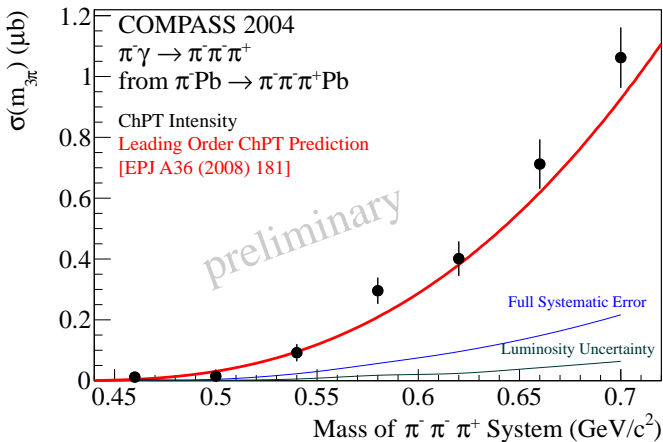
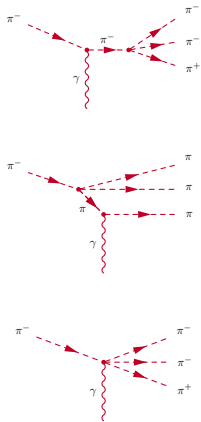
Absolute cross-section of $\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$
induced by γ exchange





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

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





- Test of ChPT calculations in low mass region ($m_{3\pi} < 0.72 \text{ GeV}/c^2$)
- Intensity shows good agreement with predicted cross-section (tree diagrams)
- **First Measurement of $\pi\gamma \rightarrow 3\pi$ absolute cross section** in low mass region

- Next-order (chiral loop) contribution
- Extension to adjacent mass region, including (chiral) ρ contributions
- Radiative coupling of resonances, e.g. a_2 (see next talk)
- COMPASS 2009 data



BACKUP SLIDES



- **Mass-independent PWA** (narrow mass bins):

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

- Production strength 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

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

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



BACKUP: Chiral amplitude replacing other waves ($M=1$)

Waveset in low mass region

Comparison of two **fitting models** (for $m_{3\pi} < 0.7 \text{ GeV}/c^2$):

● Several $M = 0$ waves

- $1^{++}1^{\pm} \rho\pi S$
- $1^{++}1^{\pm} (\pi\pi)_S \pi P$
- $1^{-+}1^{\pm} \rho\pi P$
- $2^{++}1^{\pm} \rho\pi D$
- $2^{-+}1^{\pm} \rho\pi P$
- $2^{-+}1^{\pm} (\pi\pi)_S \pi D$

● Several $M = 0$ waves

● **ChPT amplitude**

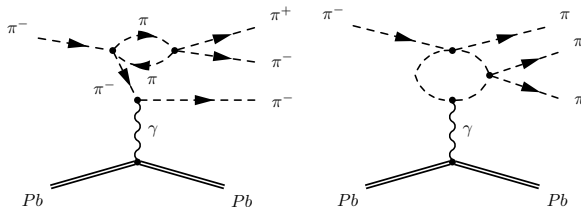
Both reflectivities are taken into account

● **Fit without chiral amplitude, but "other" waves starting at $0.5 \text{ GeV}/c^2$**

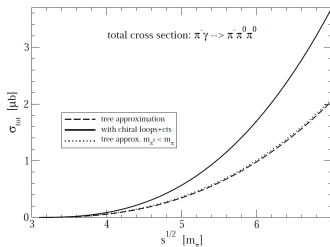
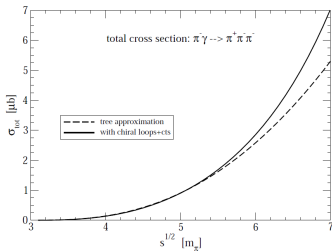
● Chiral amplitude starting at threshold (i.e. $0.5 \text{ GeV}/c^2$)
 $M=1$ $(\pi\pi)_S \pi$ and $\rho\pi$ waves thresholded as indicated



- Loop diagrams², e.g.



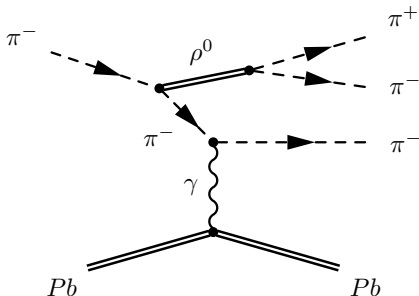
- Prediction of total cross-section ($\pi^- \pi^- \pi^+$ vs. $\pi^- \pi^0 \pi^0$):



²N. Kaiser, Nucl. Phys. A 848 (2010) 198



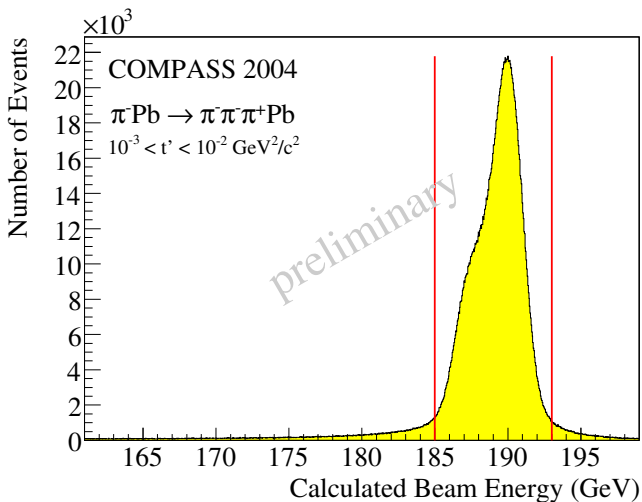
- explicit contribution from the ρ ($m_{3\pi} > 0.7 \text{ GeV}/c^2$), e.g.





BACKUP: 3π Data Sample (2004)

Reconstructed beam energy distribution



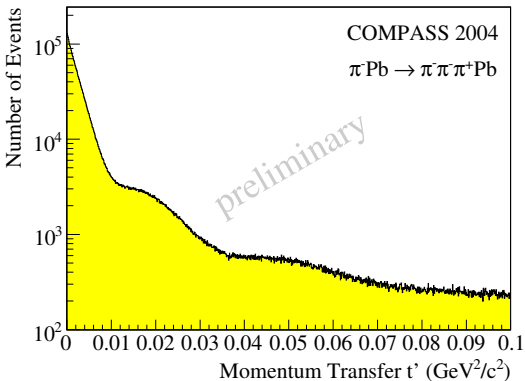


BACKUP: 3π Data Sample (2004)

Momentum Transfer

Momentum transfer to target:

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



with

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

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



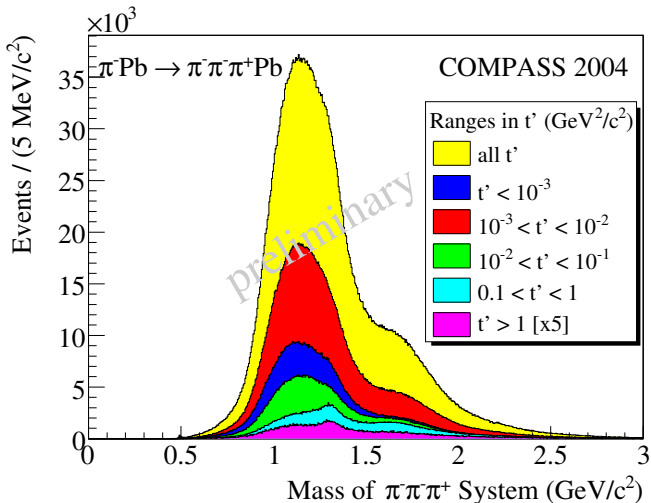
BACKUP: 3π Data Sample (2004)

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



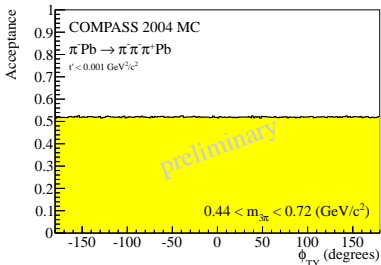
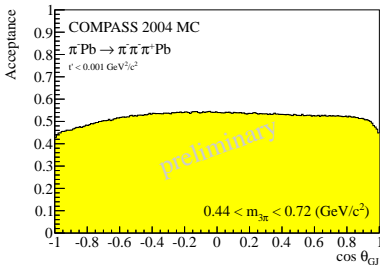
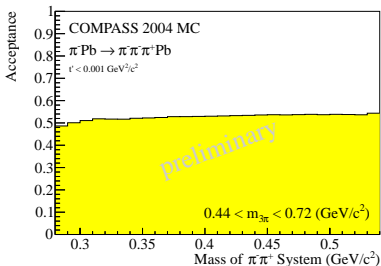
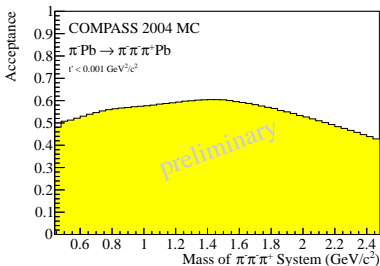
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Different t' ranges:





Acceptance of $\pi^- \pi^- \pi^+$ events ($t' < 0.001 \text{ (GeV/c)}^2$)





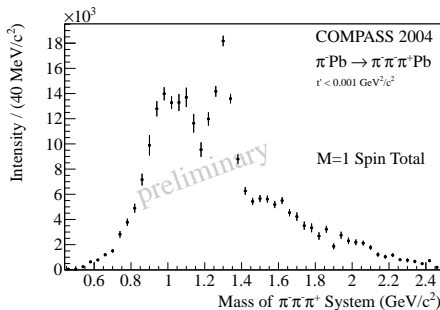
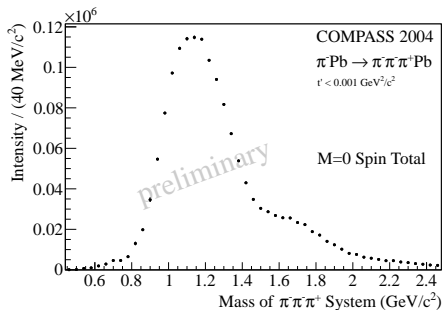
BACKUP: Spin Totals for $t' < 10^{-3} \text{ (GeV/c}^2\text{)}^2$

t' dependent amplitudes:

Primakoff production: **M=1**: $e^{-b_{prim}t'}$ → arises for $t' \approx 0$

Diffractive production: **M=0**: $e^{-b(m)t'}$

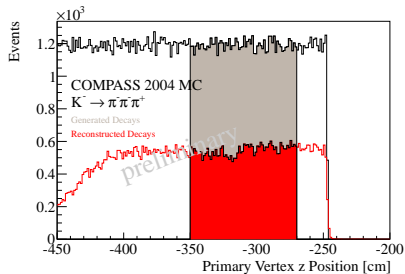
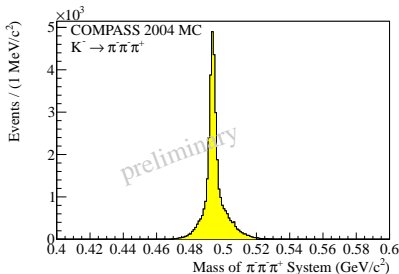
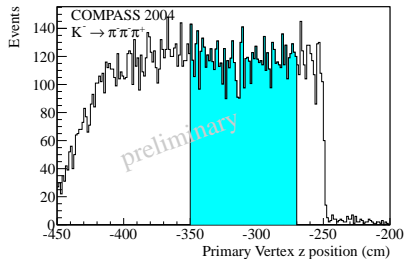
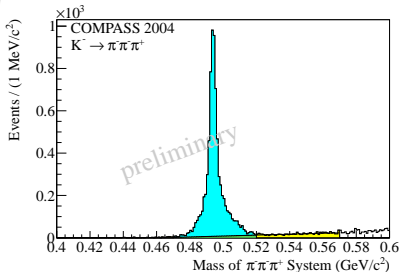
M=1: $t'e^{-b(m)t'}$ → vanishes for $t' \approx 0$





BACKUP: Kaon mass resolution and vertex distribution

Data vs. MC





BACKUP: From intensity to cross-section

In each bin of $m_{3\pi}$:

$$\text{Number of reactions (events)} = \epsilon_{bin(3\pi)} \cdot \int \mathcal{L} dt \cdot \sigma_{abs}$$

COMPASS π^- beam is contaminated with K^-

→ beam flux from K^- decays!

Calculation of Integrated Flux

$$\epsilon \cdot \int \Phi dt = \frac{N(K^- \text{ decays})}{(1 - e^{-s/\beta\gamma\tau}) \cdot BR \cdot \left(\frac{K^-}{\pi^- K^- \bar{p}}\right)}$$

ϵ acceptance (from MC of kaon decay)

$\int \Phi dt$ integrated beam flux

s length of decay volume

$\beta\gamma\tau$: K^- decay length (1429 m at 190 GeV)

BR : $K^- \rightarrow \pi^+ \pi^- \pi^-$ branching ratio (5.59%)

$\frac{K^-}{\pi^- K^- \bar{p}}$: K^- fraction at COMPASS target (2.43%, estimated relative uncertainty 5%)