# Tests of $\chi$PT in Primakoff Reactions at COMPASS

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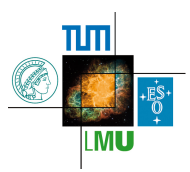


# Outline

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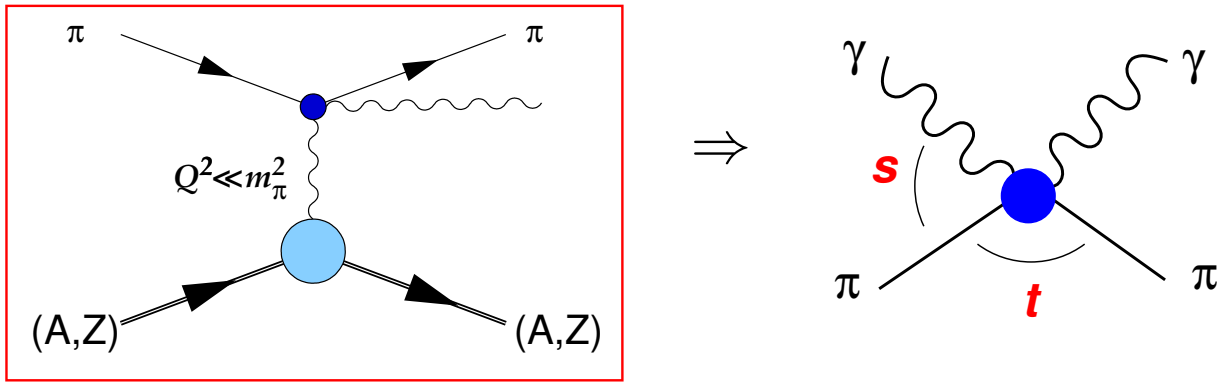
# Experimental Key to $\chi$PT: Primakoff Reactions



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

*At smallest momentum transfer* to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)




$$\pi^- + \gamma \to \begin{cases} \pi^- + \gamma & \text{(Compton reaction} \to \text{Polarisability)} \\ \pi^- + \pi^0 & \\ \pi^- + \pi^0 + \pi^0 & \text{(Absolute cross-section)} \\ \pi^- + \pi^- + \pi^+ & \text{(Absolute cross-section)} \\ \pi^- + \ldots & \end{cases}$$

*analogously possible at COMPASS: Kaon-induced reactions* $K^- + \gamma \to \cdots$

# Experimental Key to $\chi$PT: Primakoff Reactions

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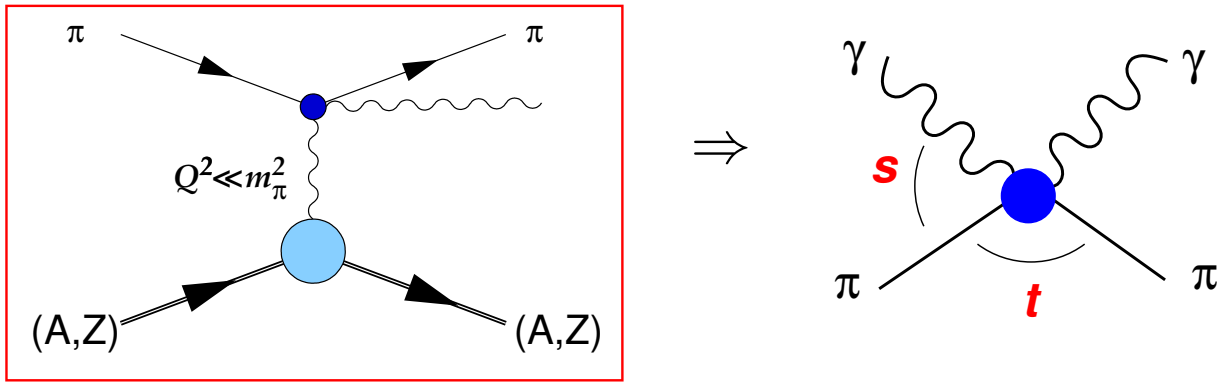
*At smallest momentum transfer* to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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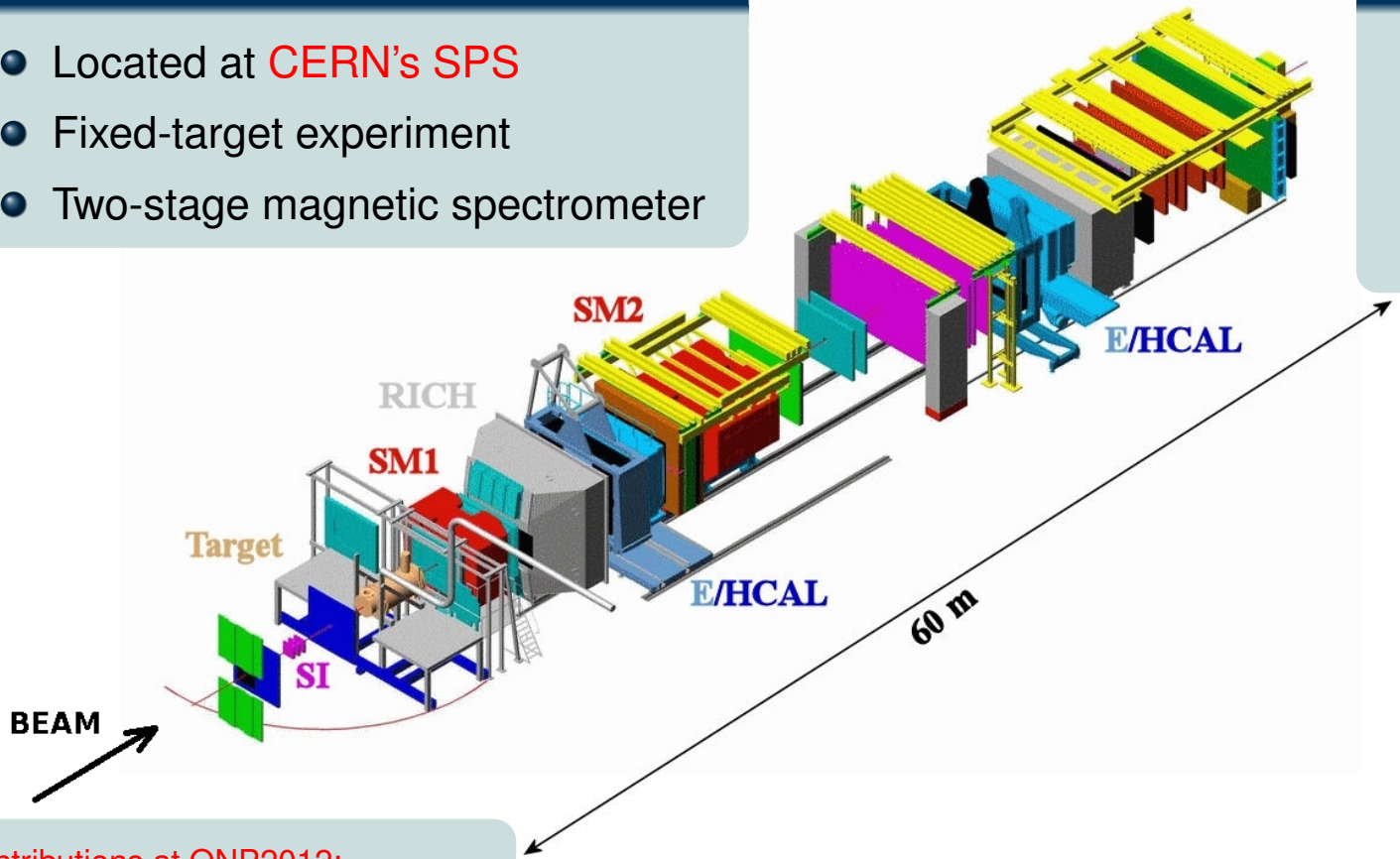
# COMPASS

Experimental Setup

Technische Universität München

## COmmon Muon and Proton Apparatus for Structure and Spectroscopy

- Located at CERN's SPS
- Fixed-target experiment
- Two-stage magnetic spectrometer




## Second./Tert. SPS Beams

- Muons: $4 \cdot 10^7 s^{-1}$
- Hadrons ($\pi$, $K$, $p$): up to $2 \cdot 10^7 s^{-1}$
- E: 100-250 GeV

Contributions at QNP2012:

G. Sbrizzai, K. Schmidt, T. Schlüter,

A. Austregesilo, B. Ketzer, S.G.

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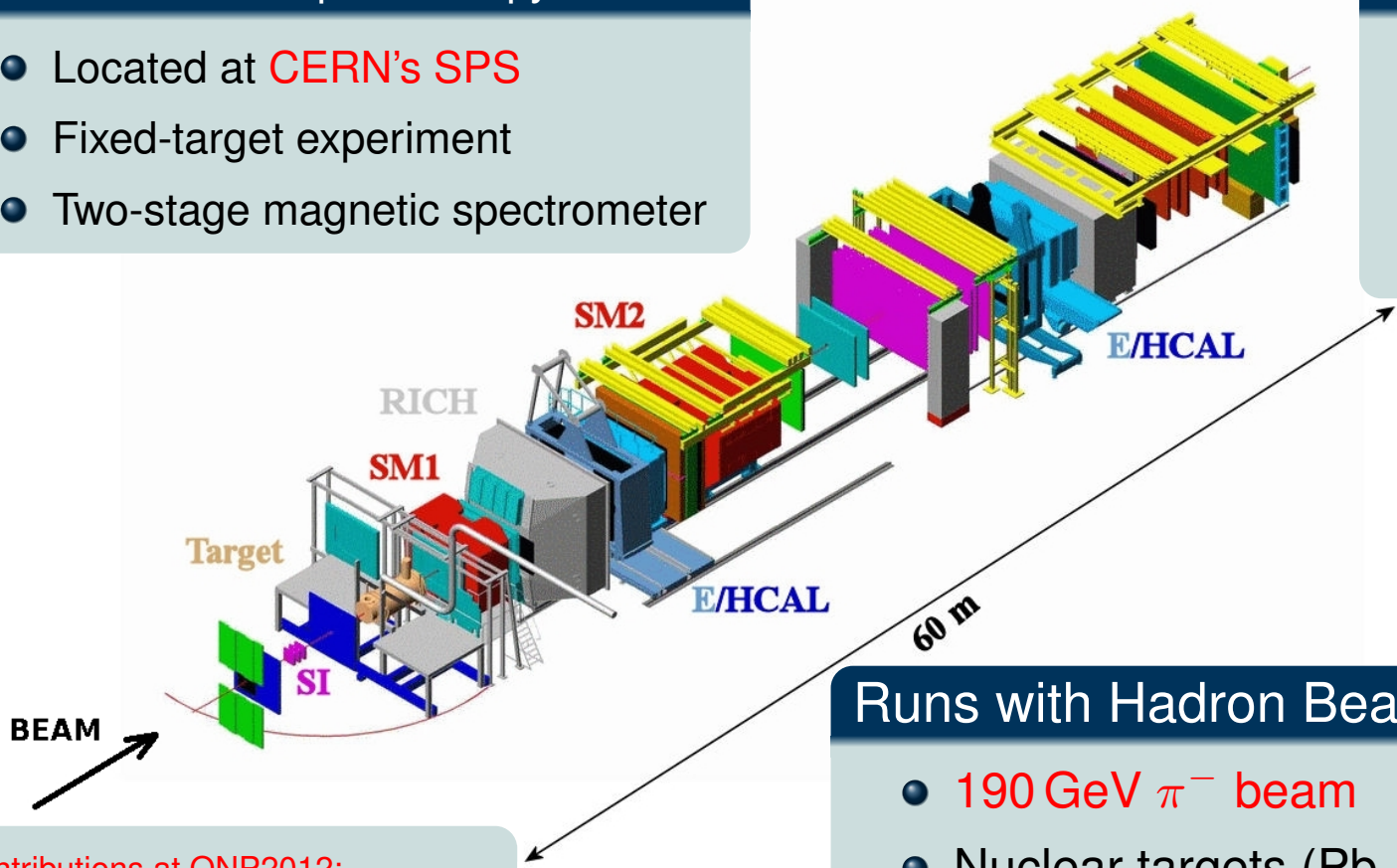


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- Hadrons ($\pi$, $K$, $p$): up to $2 \cdot 10^7 s^{-1}$
- E: 100-250 GeV

## Runs with Hadron Beams 2004, 2009

- 190 GeV $\pi^-$ beam
- Nuclear targets (Pb, Ni)
- Tracking: Silicons for vertexing
- Trigger: Multiplicity trigger, ECAL trigger

Contributions at QNP2012:

G. Sbrizzai, K. Schmidt, T. Schlüter, A. Austregesilo, B. Ketzer, S.G.

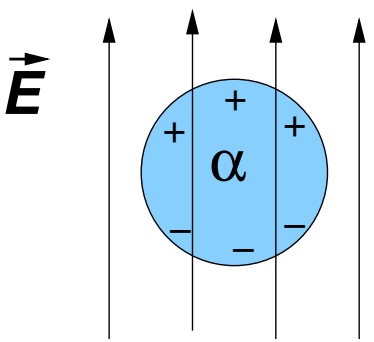
# Outline

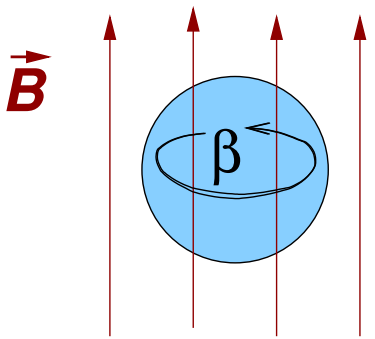
# Compton Scattering and Polarisability

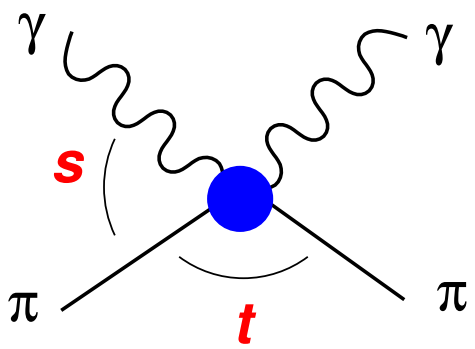


$$\pi\gamma \to \pi\gamma$$

Leading deviation from pointlike particle $\leftrightarrow$ electromagnetic polarisability:
Deformation of the $\pi$ in the electromagnetic field of the $\gamma$
$\to$ emission of $\gamma$: Compton scattering



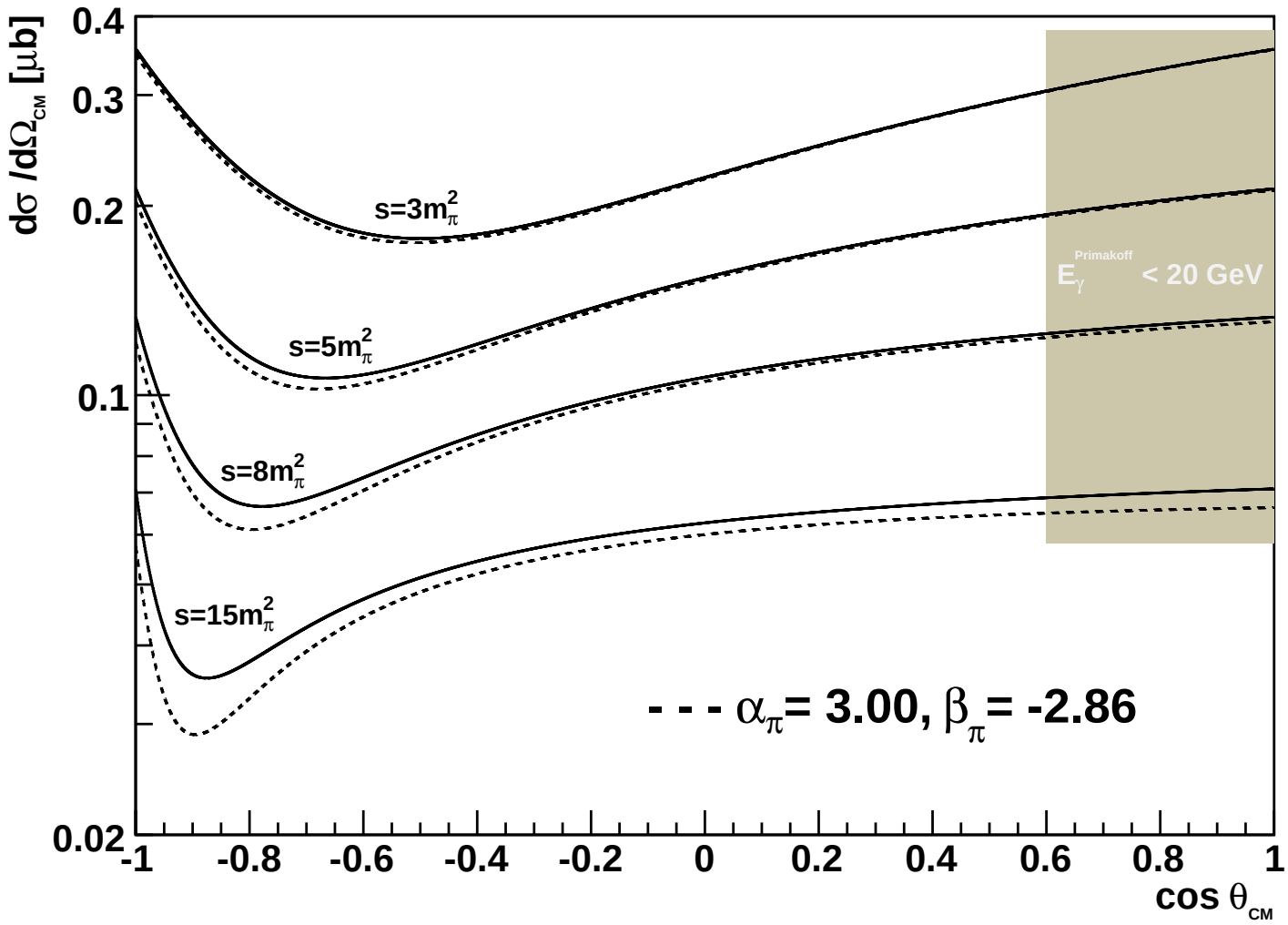




| | $\alpha_\pi - \beta_\pi$ | $\alpha_\pi + \beta_\pi$ | $[10^{-4}\,\mathrm{fm}^3]$ |
|---|---|---|---|
| $\chi$PT 2 loop: | $5.7 \pm 1.0$ | $0.2 \pm 0.1$ | |
| experiments: | $4 - 14$ | | |

# Polarisability effect (NLO ChPT values)



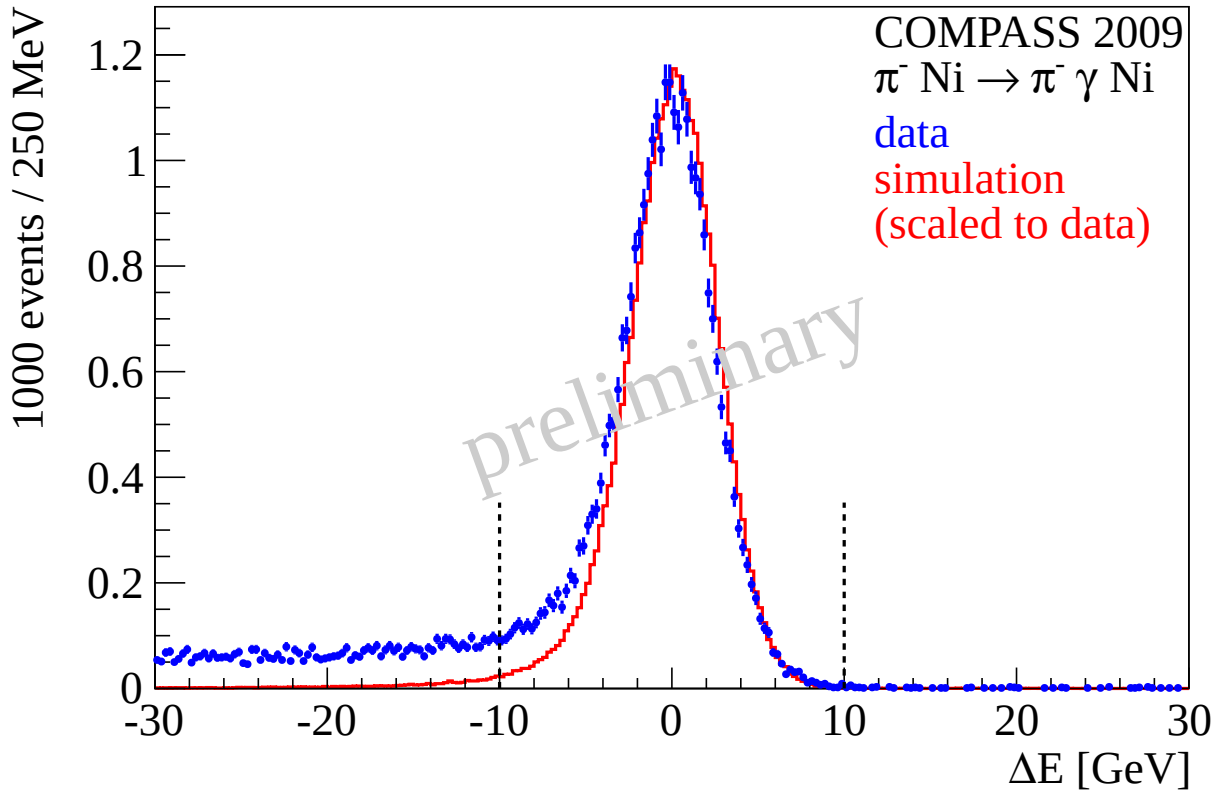
loop effects not shown



# Selection of the $\pi^-\gamma \to \pi^-\gamma$ reaction: Exclusivity

2009 Data



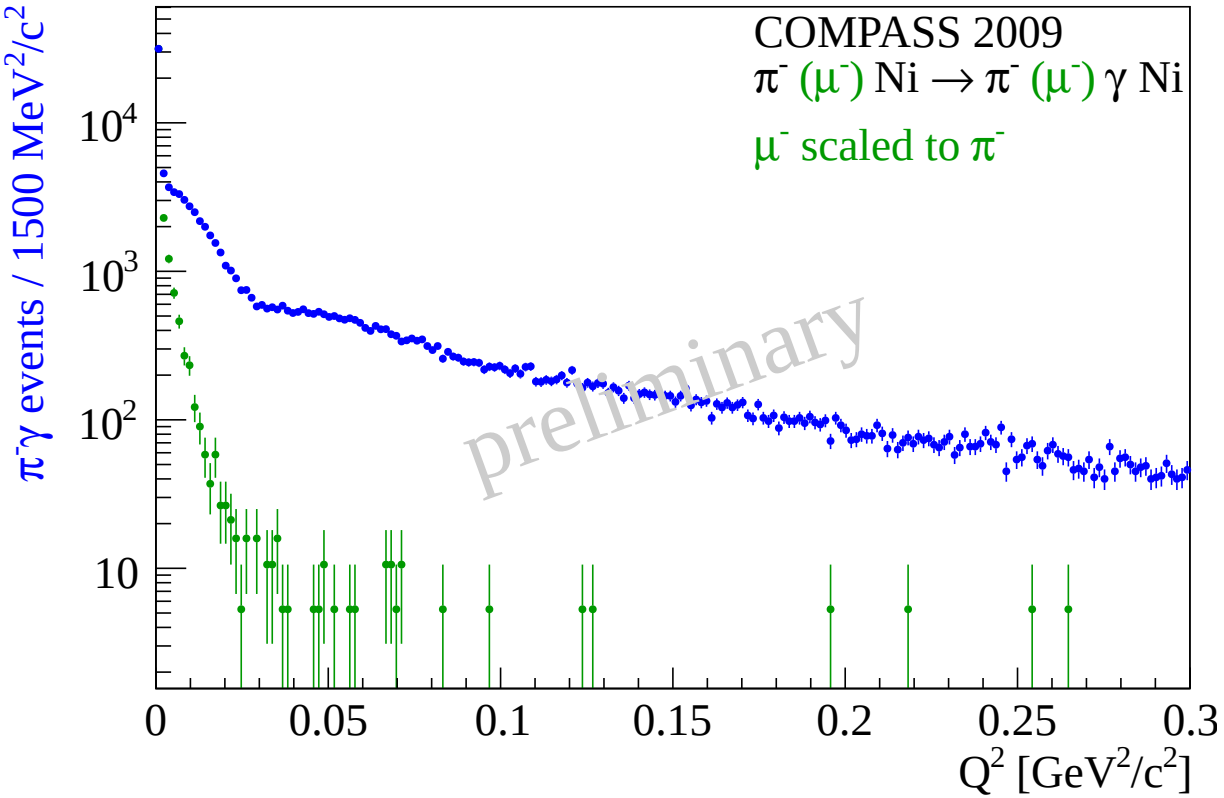



- Exclusivity peak $\sigma \approx 2.6\,\text{GeV}$
- $\sim$ 23 000 exclusive events (Serpukov: $\sim$ 7 000)

# Selection of the $\pi^-\gamma \to \pi^-\gamma$ reaction: Primakoff Peak



2009 Data




- $Q^2$ spectrum: photon exchange peak in first bin
- Muon control measurement:
  pure electromagnetic interaction, no polarisability effect

# Selection of the $\pi^-\gamma \to \pi^-\gamma$ reaction: Primakoff Peak

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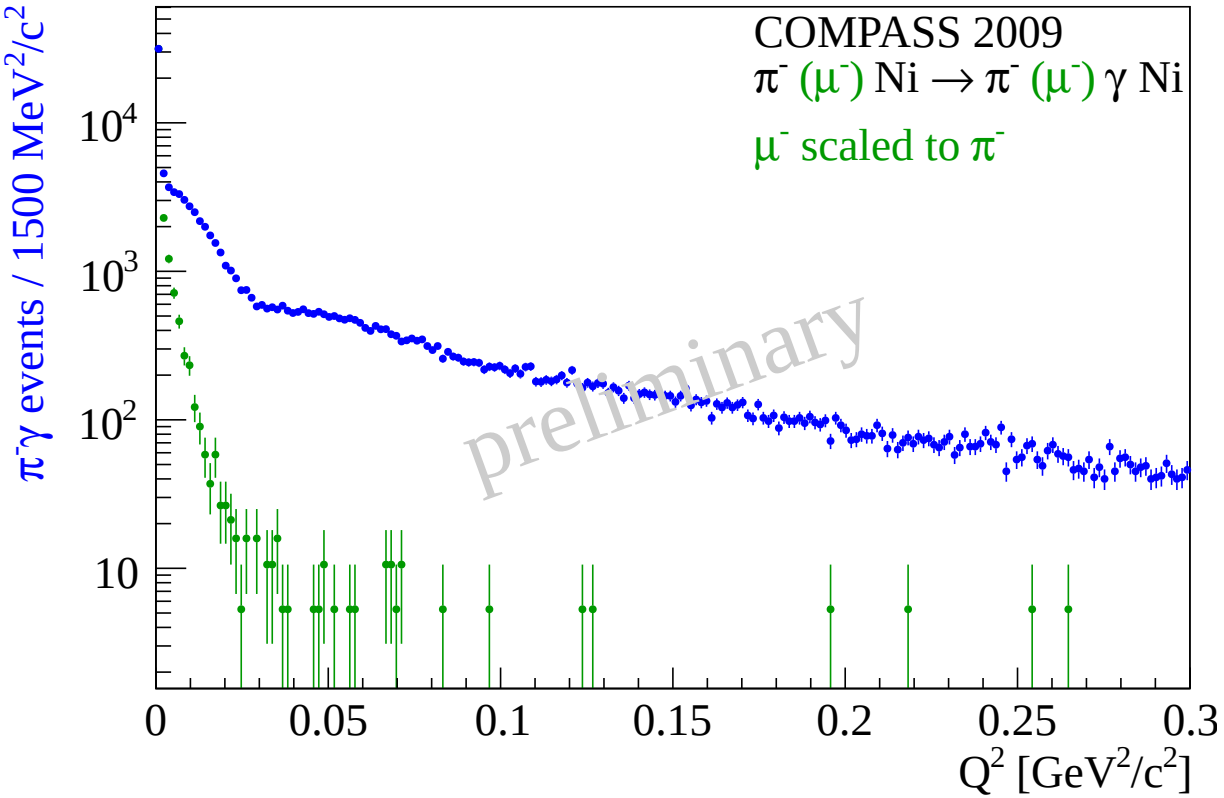
2009 Data



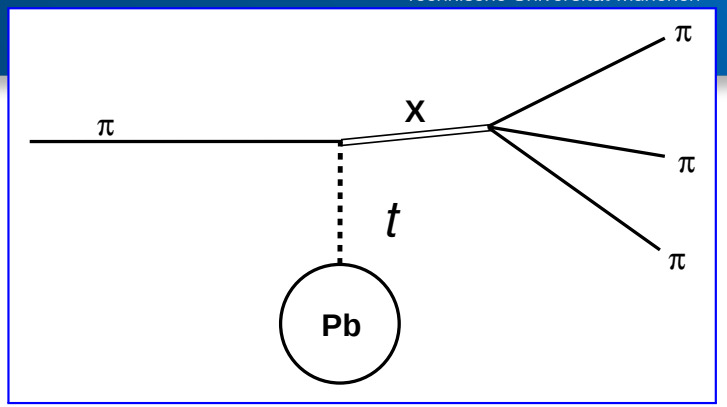

- $Q^2$ spectrum: photon exchange peak in first bin
- Muon control measurement:
  pure electromagnetic interaction, no polarisability effect

**Work on $\alpha_\pi - \beta_\pi$ in progress!** (using $\alpha_\pi + \beta_\pi = 0$)

# Outline

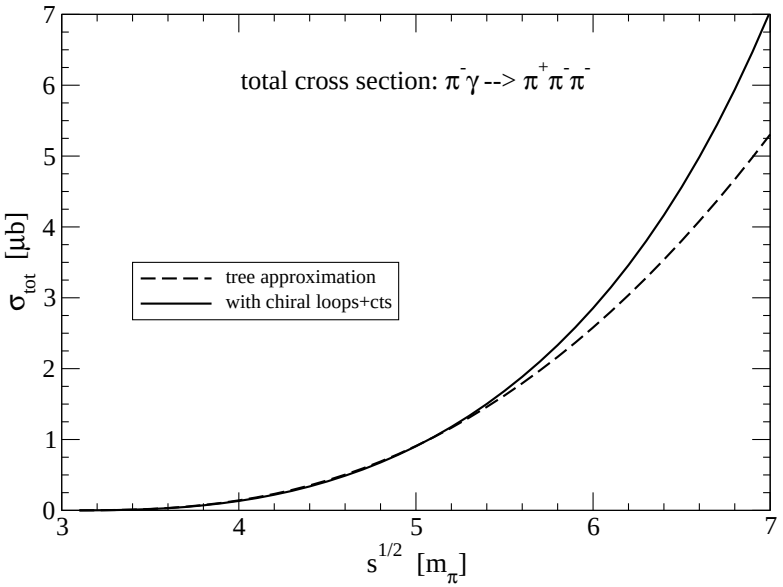
# $\pi^-\mathrm{Pb} \to \pi^-\pi^-\pi^+\mathrm{Pb}$ at very low $t'$






Two production mechanisms

- Diffractive dissociation (Pomeron exchange)
- Primakoff (photon exchange)
  At low masses: "pions only" $\to$ $\chi$PT




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

$\Rightarrow$ Leading Order (tree diagrams) sufficient for $\pi^-\pi^-\pi^+$ final state with $m_{3\pi} < 5m_\pi (\approx 0.7\,\mathrm{GeV}/c^2)$

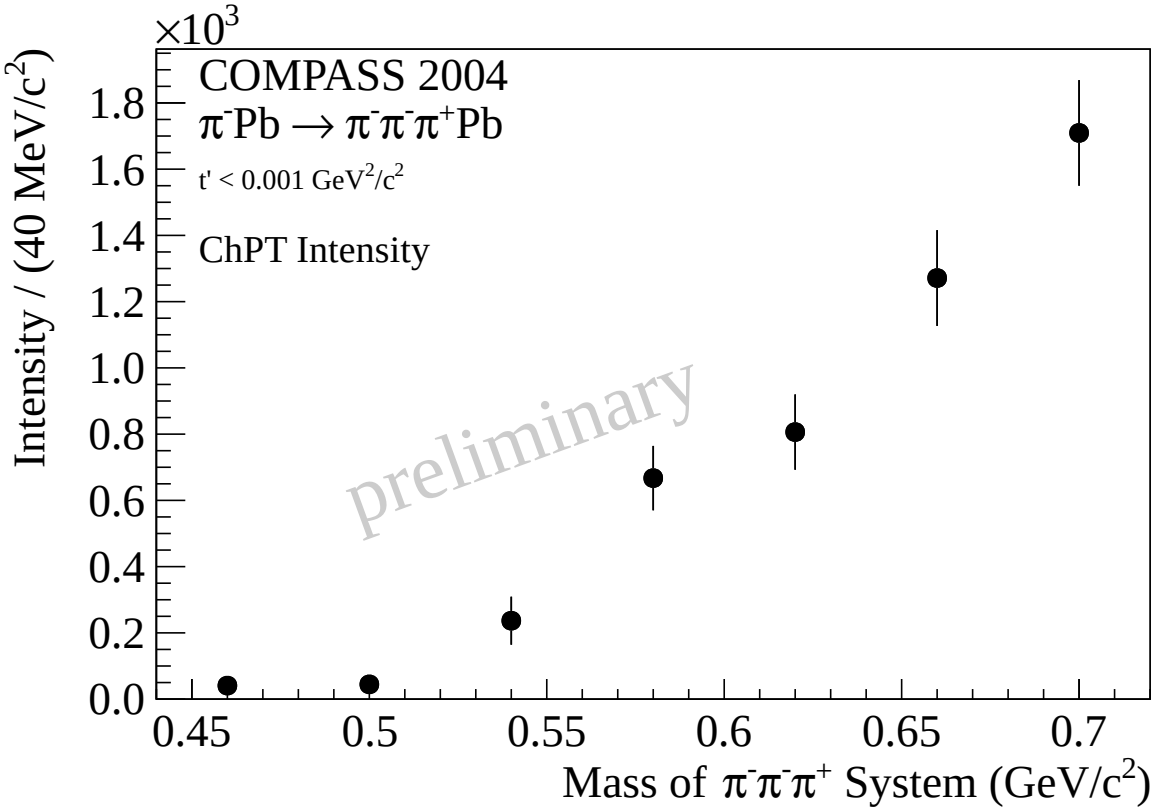
$\to$ implement "chiral amplitude" (fully differential form) into PWA

# Total Intensity of Chiral Amplitude

From 2004 Pb data



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



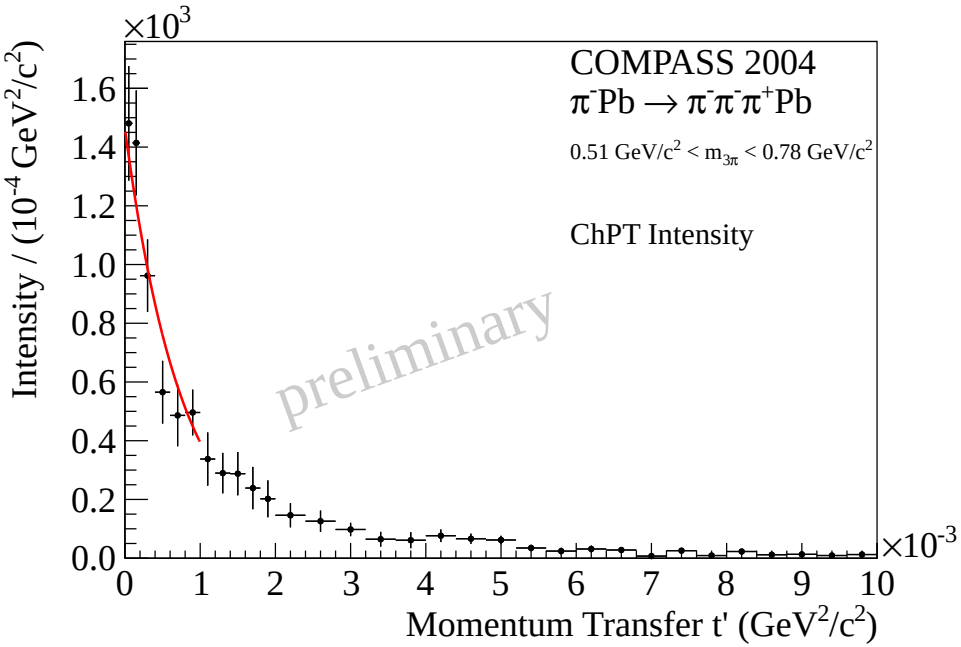

**...is this really photon exchange?**

# $t'$ Dependence of Chiral Amplitude

From 2004 Pb data

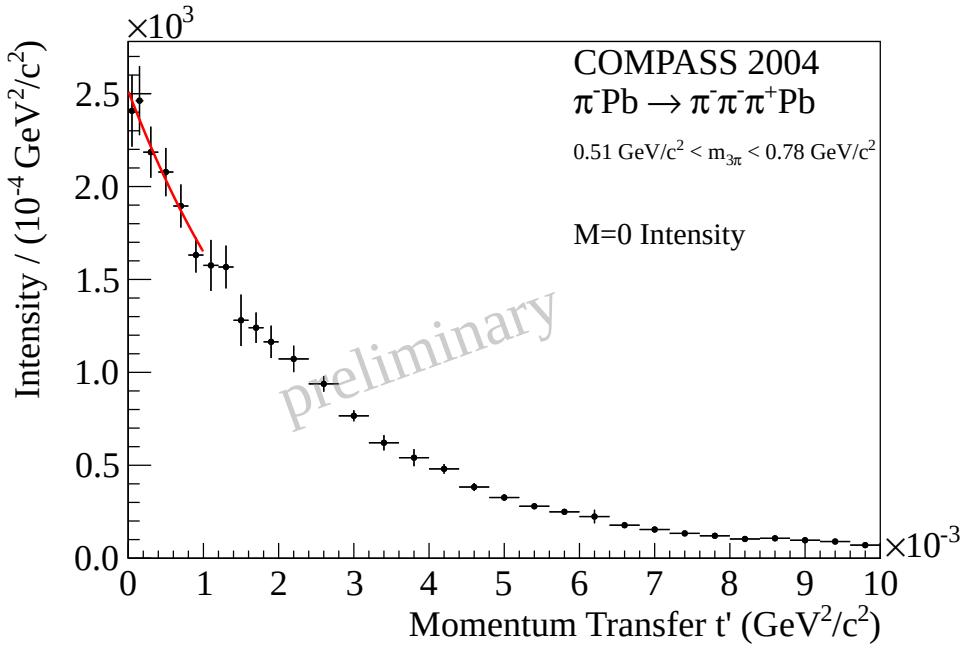


- Fits in small bins of $t'$, but only 1 mass bin $(0.51 < m_{3\pi} < 0.78)\,\mathrm{GeV}/c^2$
- $t'$ dependence of intensity $\sigma \propto e^{-bt'}$




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

$\to$ Primakoff (Photon)



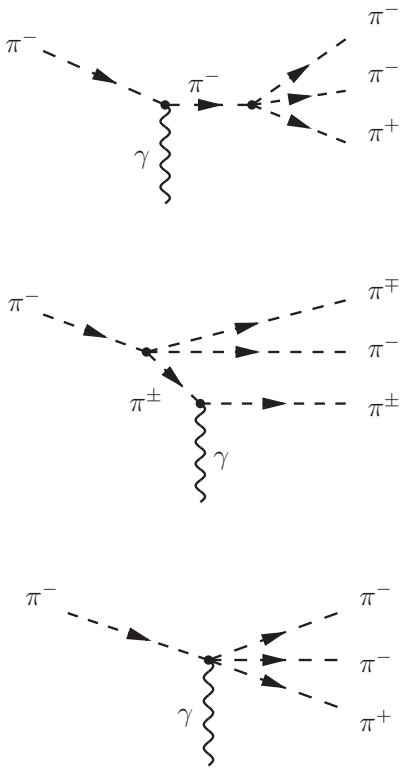

$b_{M=0} \approx 400\,(\mathrm{GeV}/c)^{-2}$

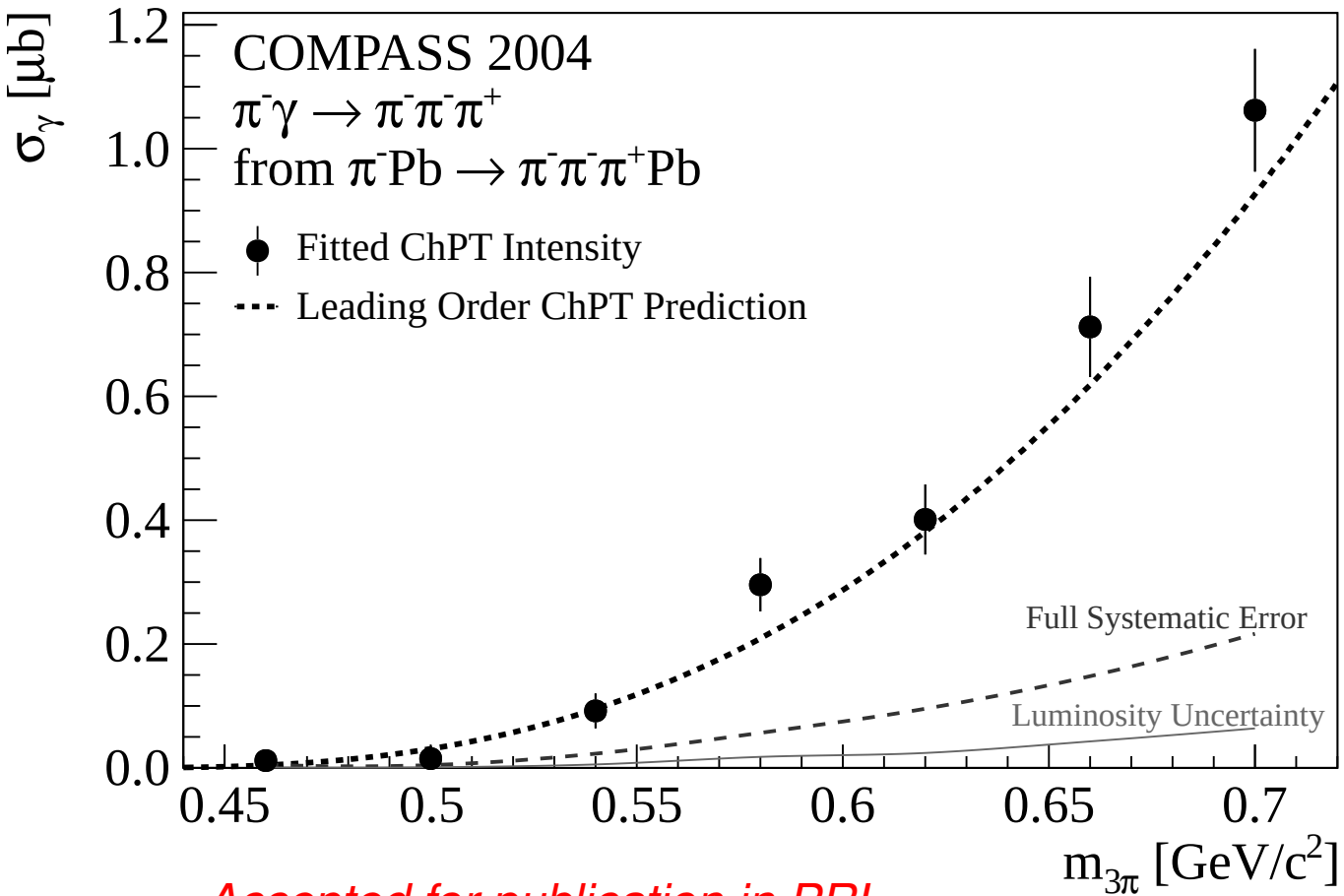
$\to$ diffractive (Pomeron)

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



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




*Accepted for publication in PRL*

arXiv:1111.5954 [hep-ex]

# Summary and Outlook



COMPASS: ideal experiment for Primakoff measurements

## Pion polarisability

- 2009 data with Ni target: $> 3\times$ Serpukov statistics
  $\Rightarrow$ expected uncertainty $< 10^{-4}\,\mathrm{fm}^3$
- 2012 high statistics run:
  - Separation of $\alpha_\pi$ and $\beta_\pi$
  - *s*-dependent quadrupole polarisabilities
  - First measurement of kaon polarisabilities

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

- 2004 data: Test of $\pi^-\gamma \to \pi^-\pi^-\pi^+$ $\chi$PT in low mass region ($m_{3\pi} < 0.72\,\mathrm{GeV}/c^2$)
- First Measurement of $\pi\gamma \to 3\pi$ absolute cross section in low mass region
- $\pi^-\gamma \to \pi^-\pi^0\pi^0$ from 2009 Primakoff data
- Higher order processes (loops, rho contributions) being added

## Further physics potential of $3\pi$ Primakoff data

- Radiative excitation of resonances ($a_2(1320)$) $\to$ radiative widths
- Interference between Primakoff and strong production



# BACKUP SLIDES

# BACKUP: Experimental Key to $\chi$PT: Primakoff Reactions

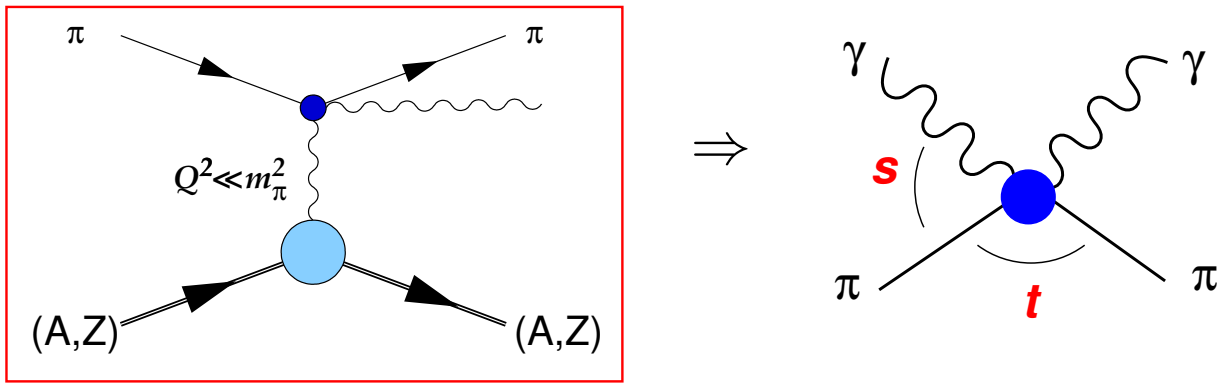


**Ch**iral **P**erturbation **T**heory:

- $\pi^+$, $\pi^0$, $\pi^-$: Goldstone bosons of the spontaneous breaking of chiral symmetry
- Effective theory for **Q**uantum **C**hromo**D**ynamics at low energies / long distances
  - scattering of bound systems
  - effective coupling in vertices
  - additionally QED interaction ($\pi\gamma$ scattering)

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

*At smallest momentum transfer* to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)



# BACKUP: Polarisability Measurements at COMPASS



## Nov. 2004

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

## Nov. 2009

- major upgrade of calorimeter readout, new digital trigger
- fine tuning / offline corrections ongoing
  $\to$ results expected soon

## 2012

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

# BACKUP: Compton Cross-Section

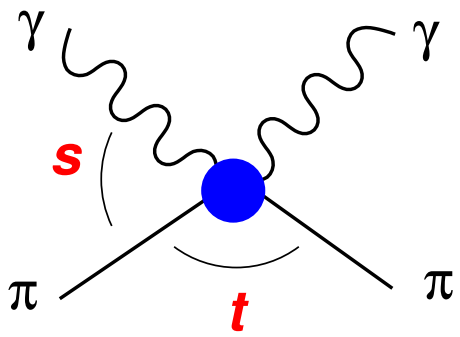


$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

with (quadrupole polarisability $\alpha_2 - \beta_2$)

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

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

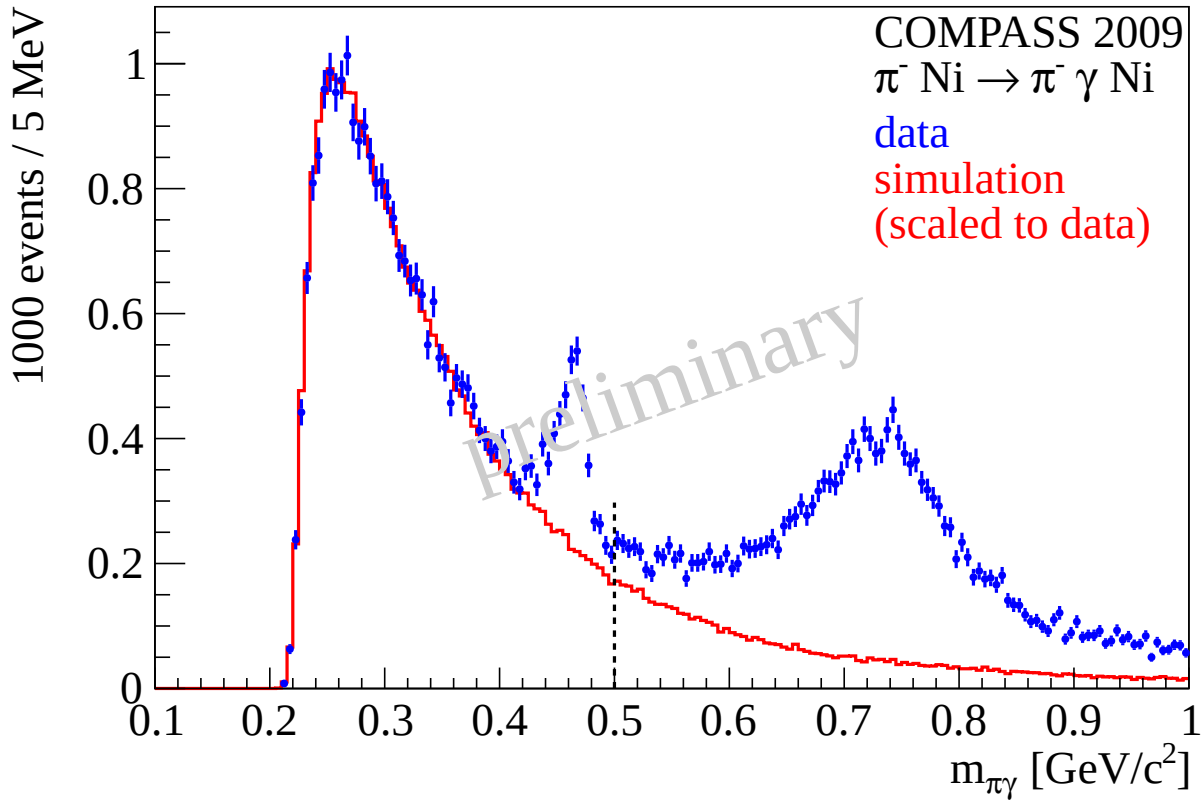



**Measuring the differential cross section with high statistics allows to determine all three polarisability contributions**

# BACKUP: CM Energy $\pi\gamma \to \pi\gamma$

## 2009 Data



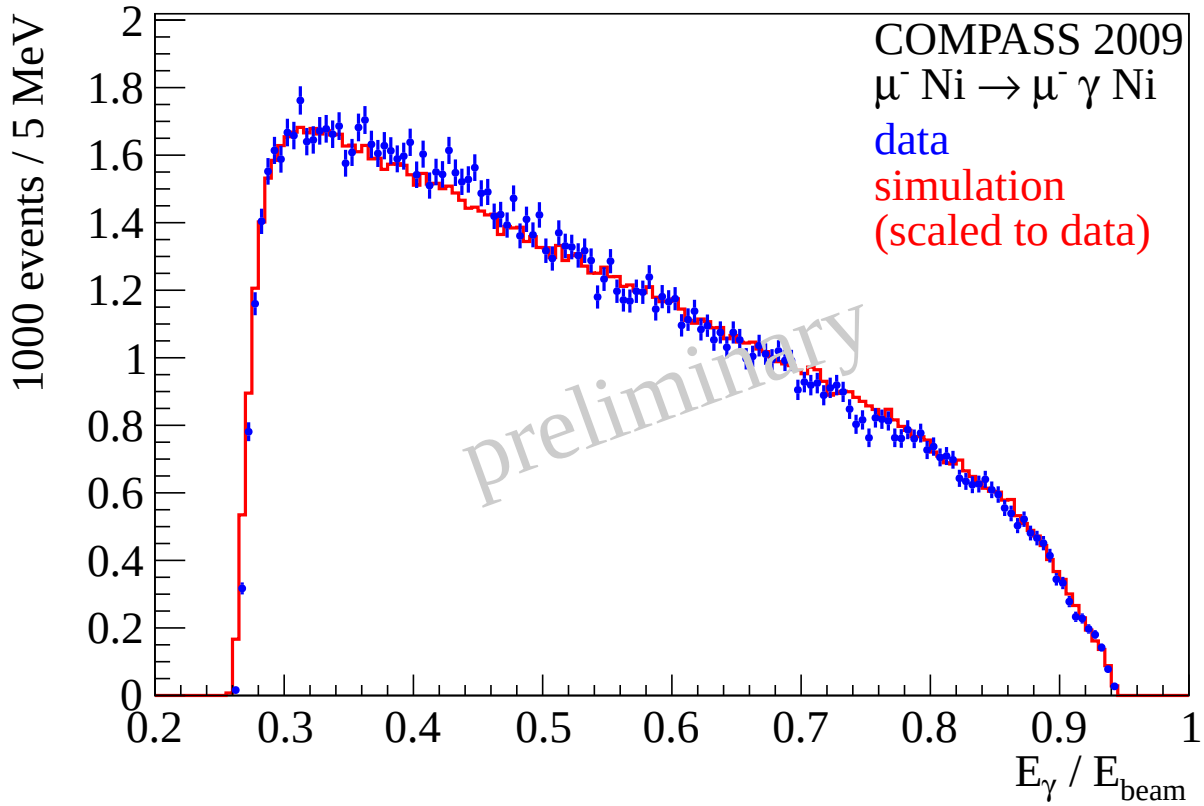



- $\rho$ contribution from $\pi\gamma \to \pi\pi^0$

# BACKUP: On the Way to Polarisability: $E_\gamma / E_{\text{beam}}$

2009 Data






- Muon control measurement: no polarisability effect
- $\Rightarrow$ Pion data: Extraction of $\alpha_\pi - \beta_\pi$ under the assumption $\alpha_\pi + \beta_\pi = 0$

**Work in progress!**

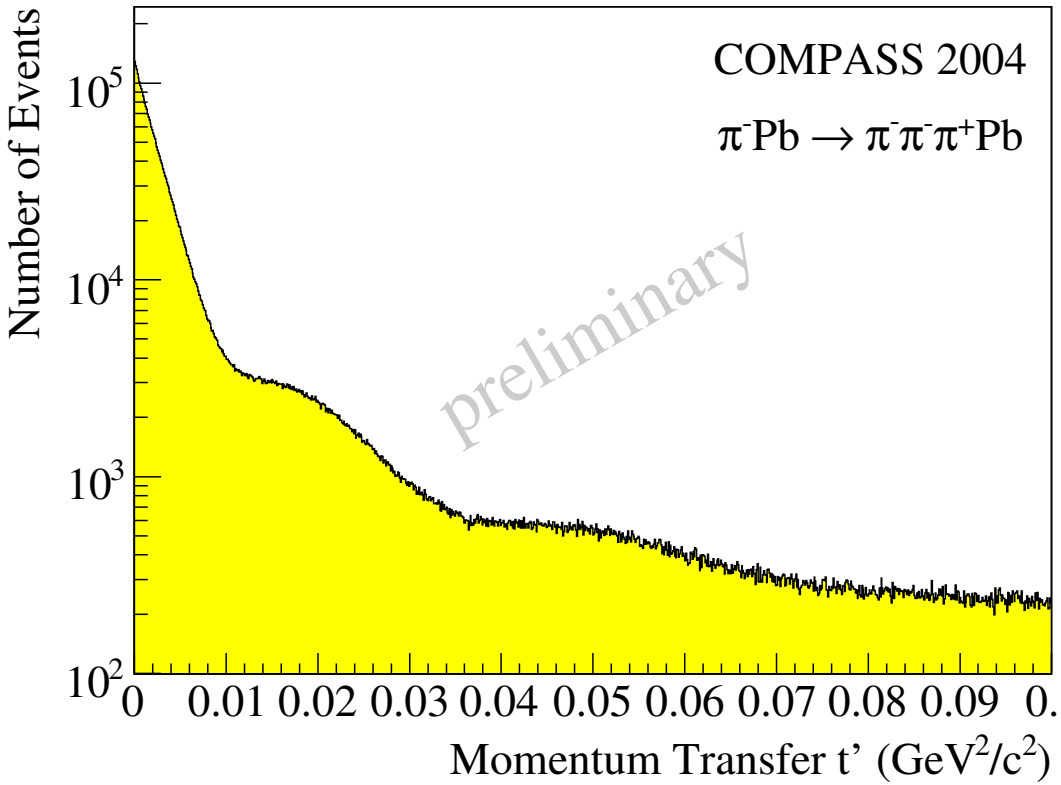
# BACKUP: $3\pi$ Data Sample (2004)

## 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

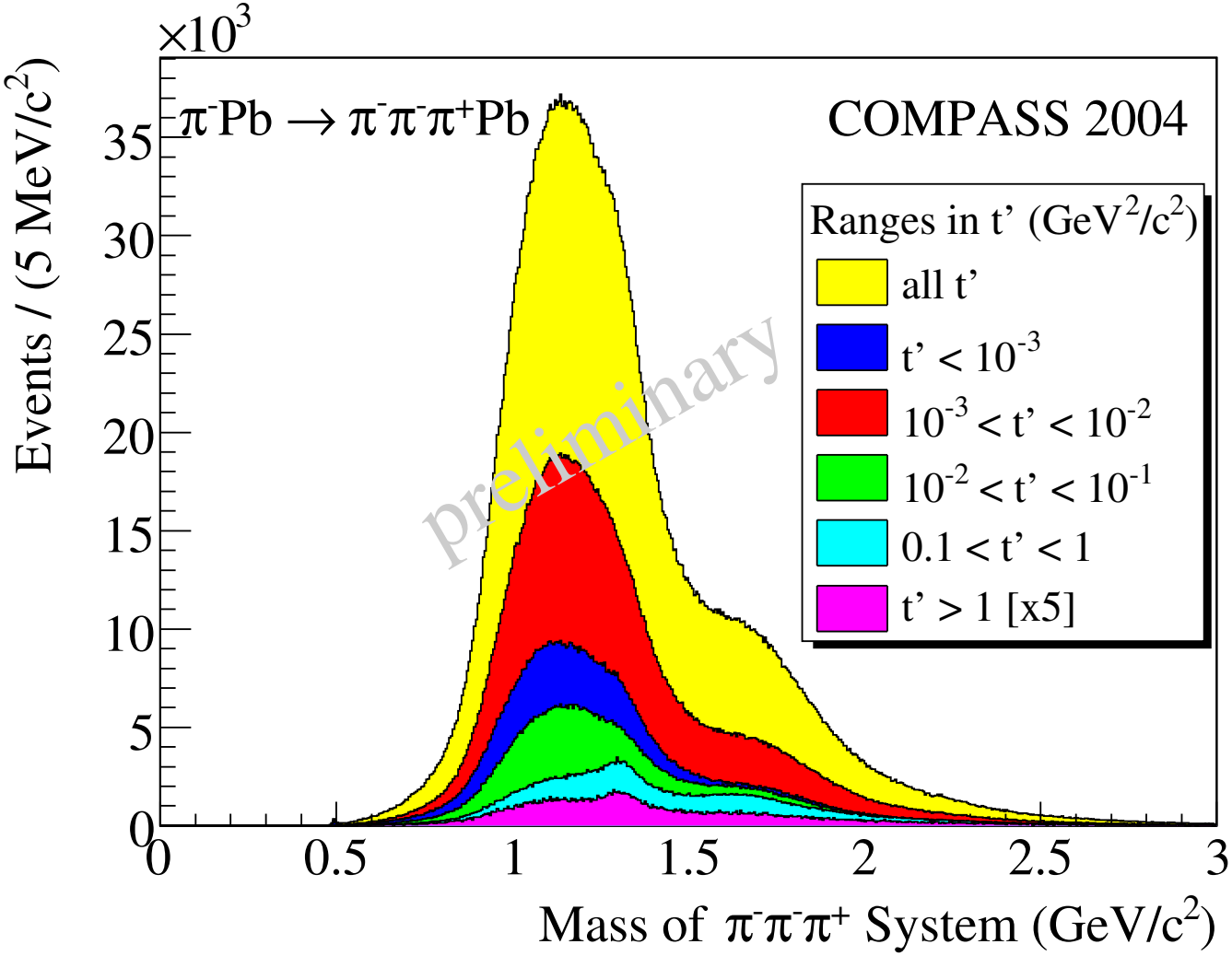
- "Low $t'$": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim 1\,000\,000$ events

# BACKUP: $3\pi$ Data Sample (2004)

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



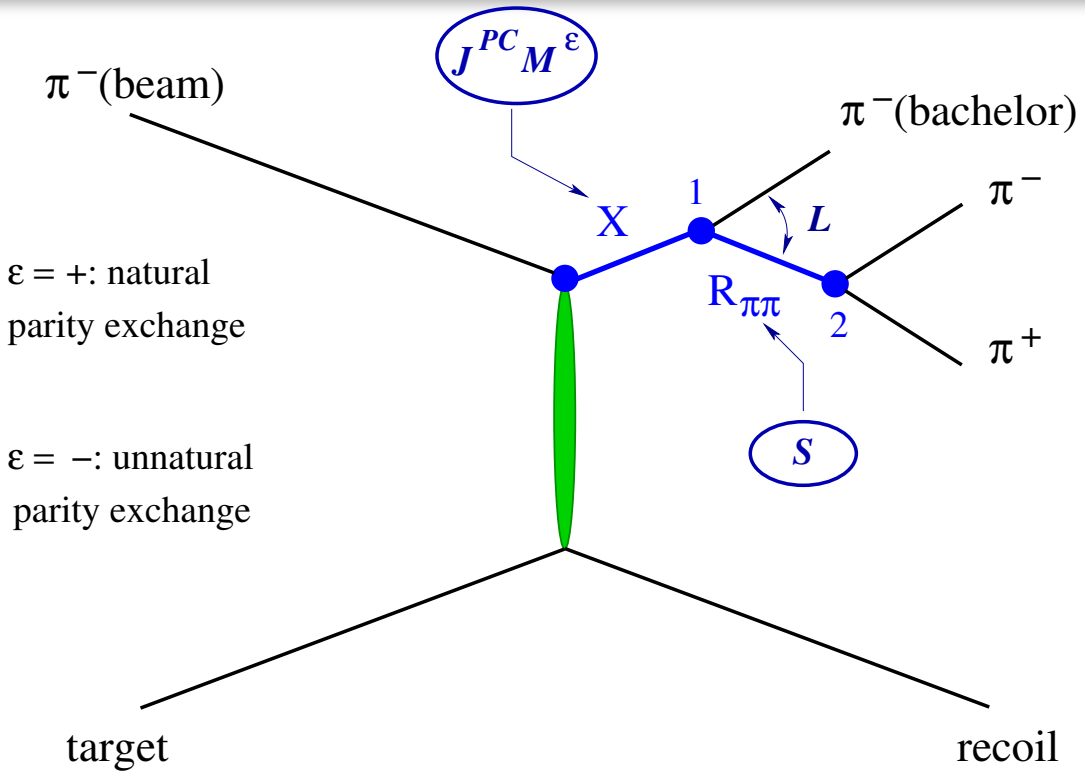
Different $t'$ ranges:



# BACKUP: 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
- Acceptance corrections from MC
- (Mass-dependent $\chi^2$-fit)

# 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 $T_{ir}^{\epsilon} \to$ Extended log-likelihood fit
  - Acceptance corrections included

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

  $\to$ Physical parameters:

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

relative phase $\Phi_{ij}^{e}$

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

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

# BACKUP: Total Intensities for $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

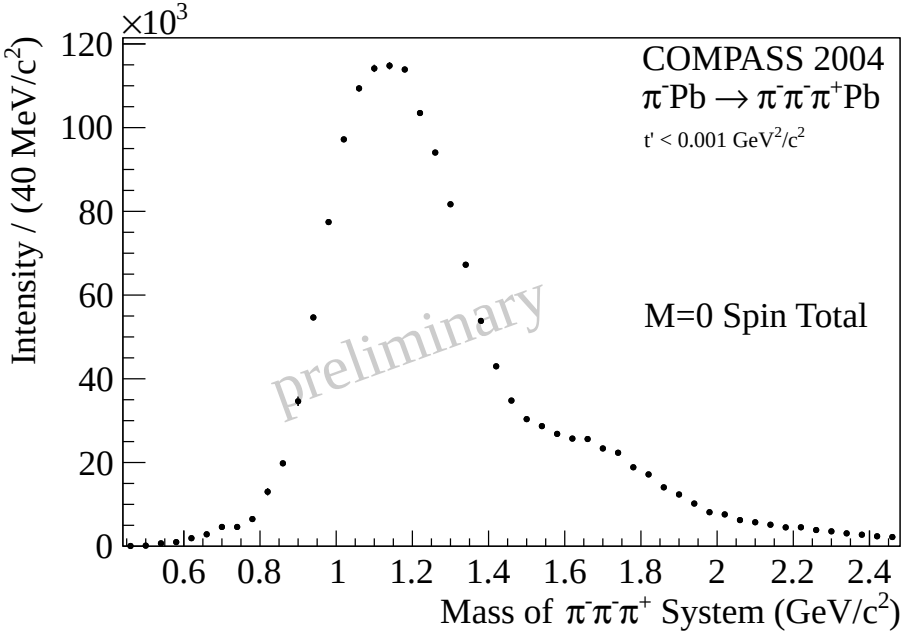


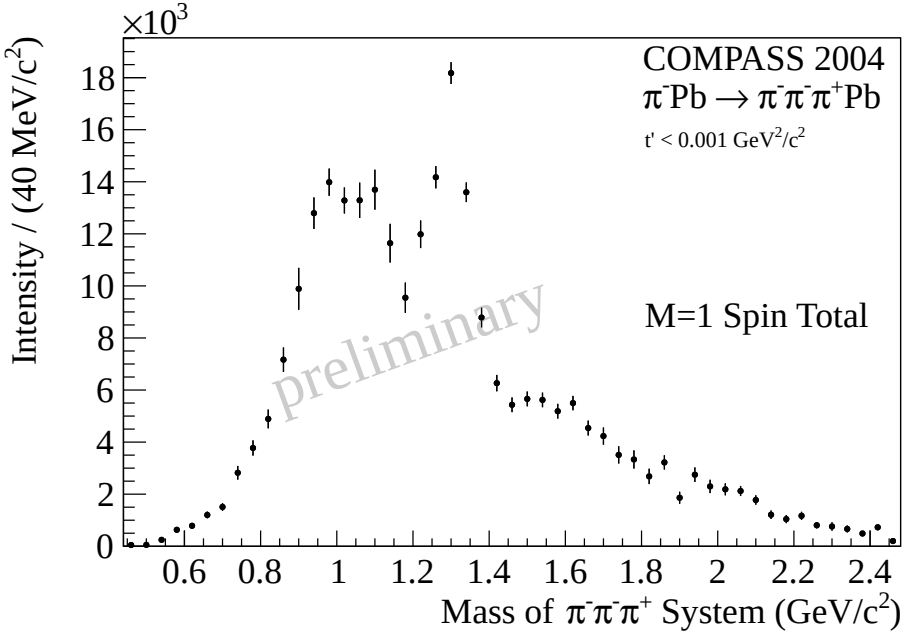
$t'$ dependent amplitudes:

Primakoff production: M=1: $\mathrm{e}^{-b_{prim(m)}t'} \to$ arises for $t' \approx 0$

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

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



# BACKUP: $\pi\gamma \to 3\pi$

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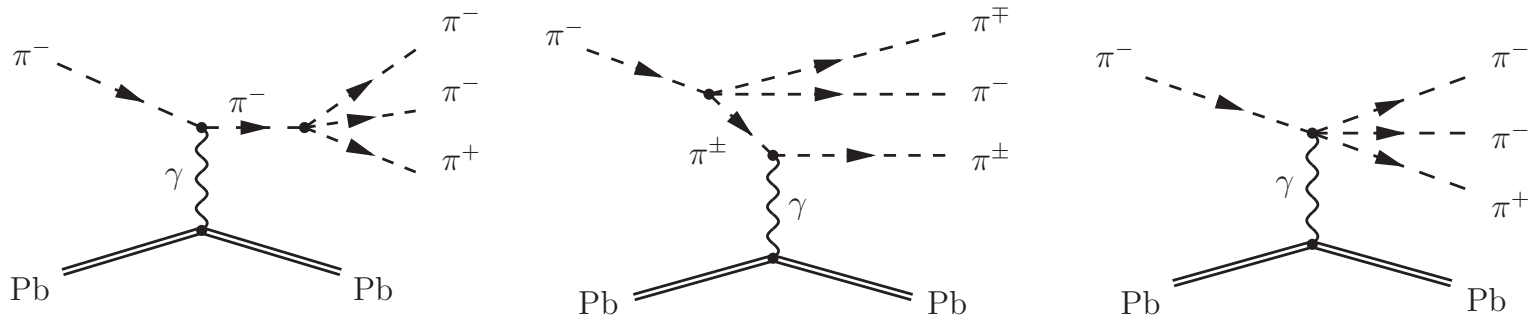
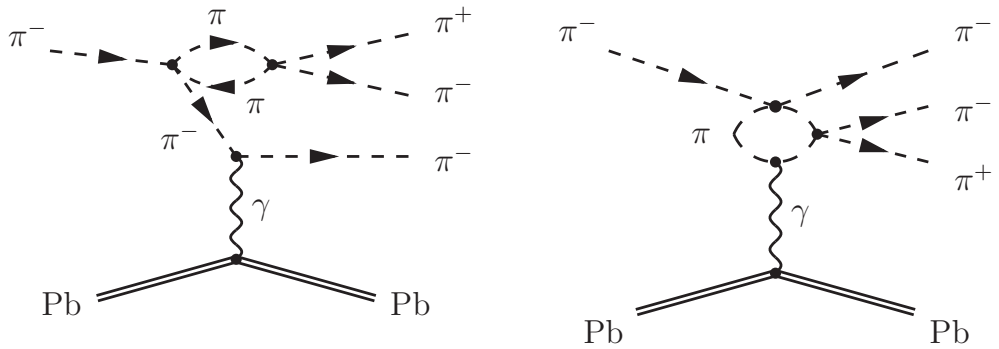
## Contribution of photon-exchange to meson spectrum

- At low masses: ”pions only”




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




examples for loop diagrams of $3\pi$ production in $\pi\gamma$ scattering

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

# BACKUP: ChPT Prediction of $\pi^-\gamma \to \pi^-\pi^-\pi^+$ Cross-Section



## Leading Order Calculation

Cross-section of $\pi^-\gamma \to \pi^-(q_1)\pi^-(q_2)\pi^+(q_3)$ 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 $\pi^-\mathrm{Pb} \to \pi^-\pi^-\pi^+\mathrm{Pb}$

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

# BACKUP: Dalitz-Plot of $\pi^-\pi^-\pi^+$ $\chi$PT Cross-Section

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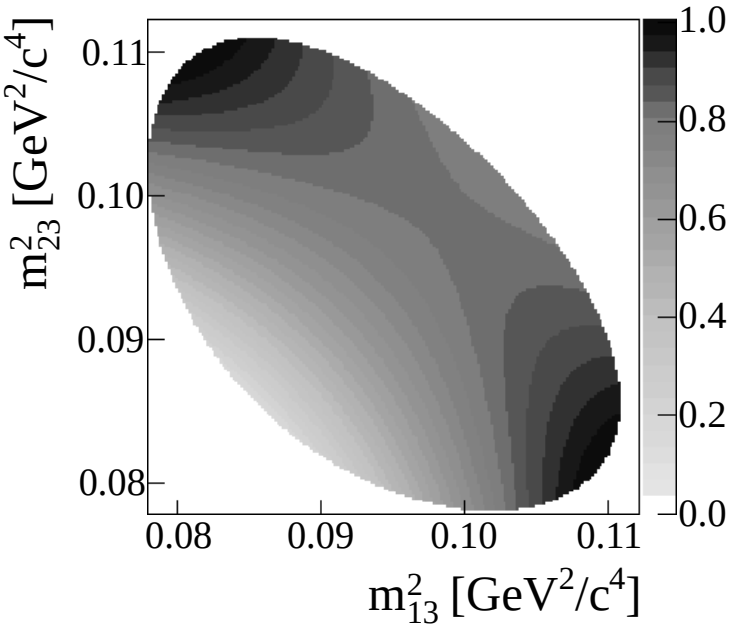
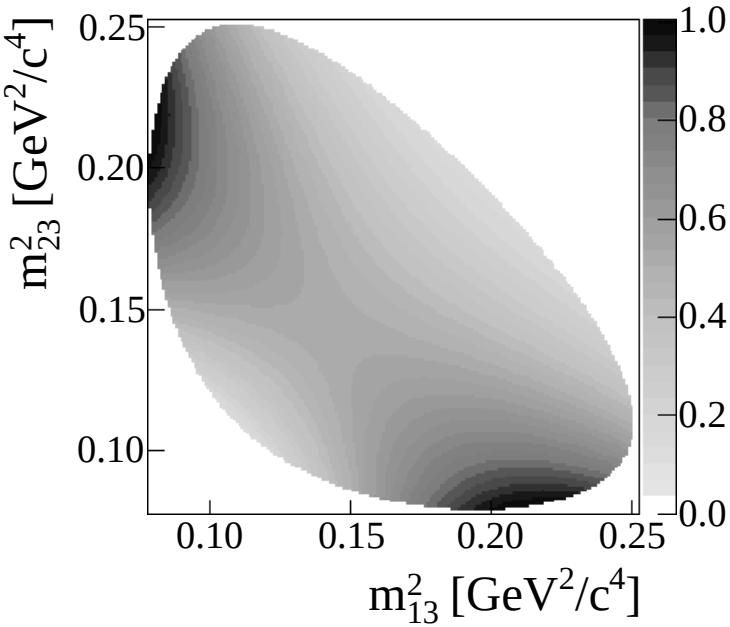
## Leading Order Calculation



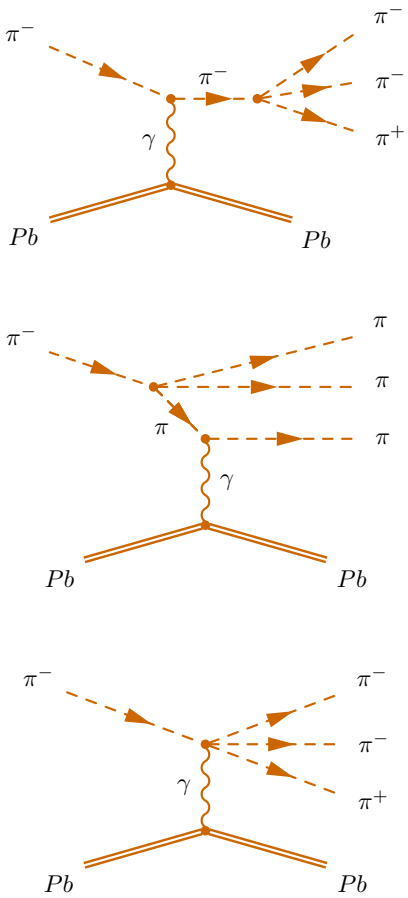

$m_{3\pi} = 3.4\, m_\pi = 0.475\,\text{GeV}/c^2$



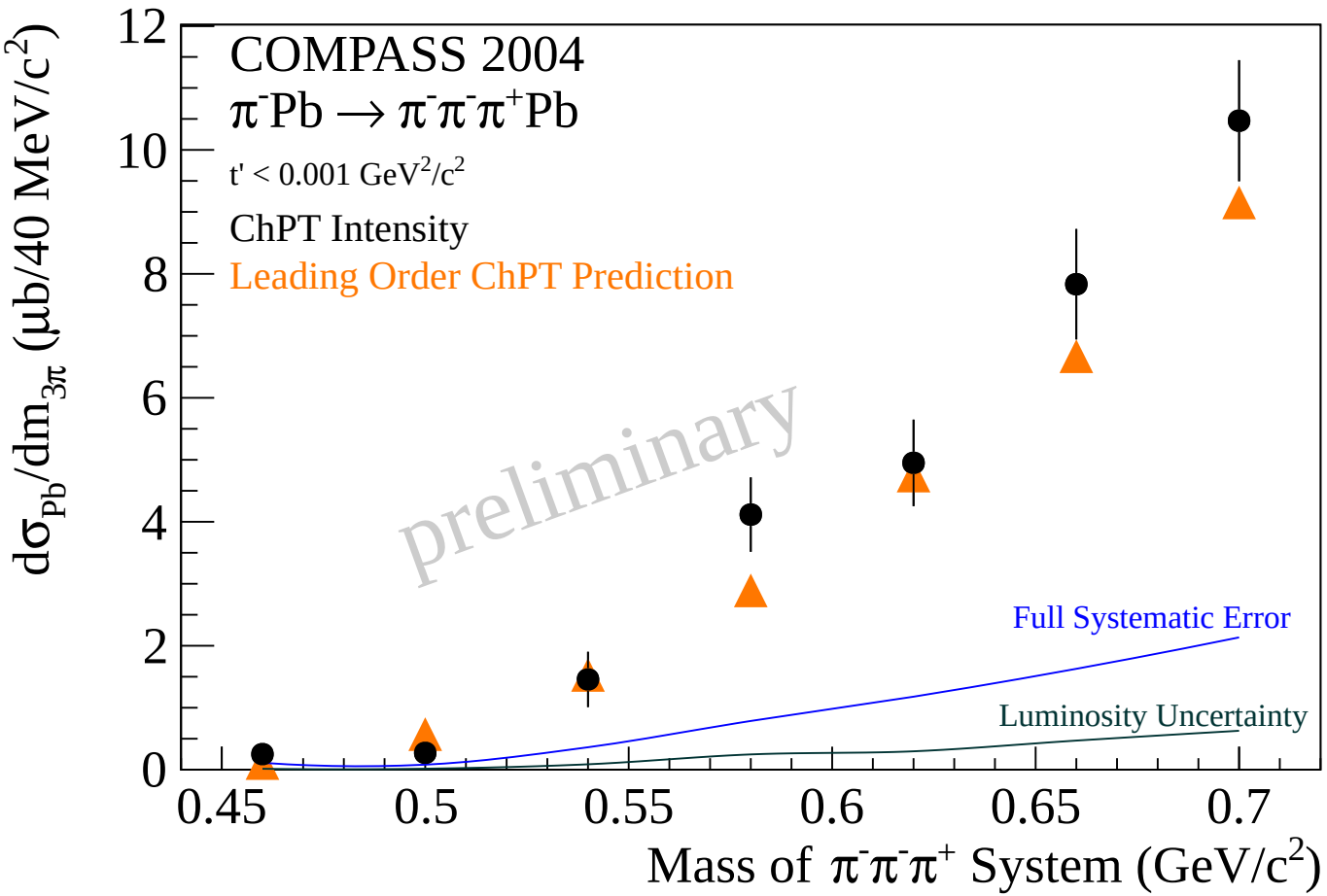

$m_{3\pi} = 4.6\, m_\pi = 0.642\,\text{GeV}/c^2$

# Measured Absolute Cross-Section






Absolute cross-section of $\pi^- Pb \to \pi^- \pi^- \pi^+ Pb$ induced by $\gamma$ exchange



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



## Waveset in low mass region

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

- 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

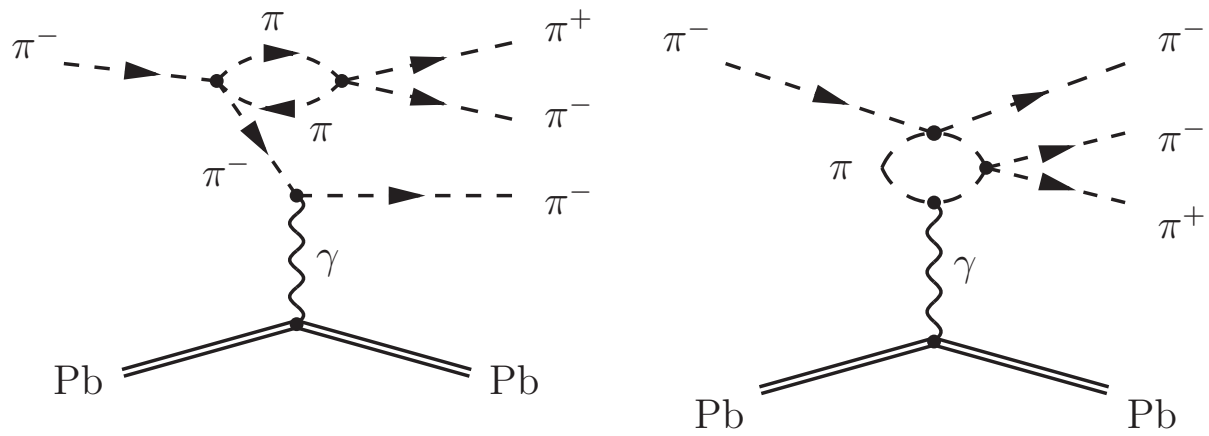
- Fit without chiral amplitude, but "other" waves starting at $0.5\,\mathrm{GeV}/c^2$

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

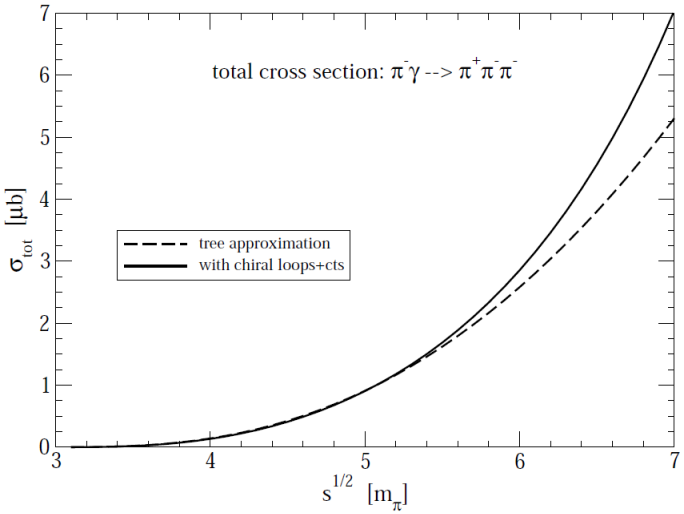
# BACKUP: Additional contributions to chiral processes

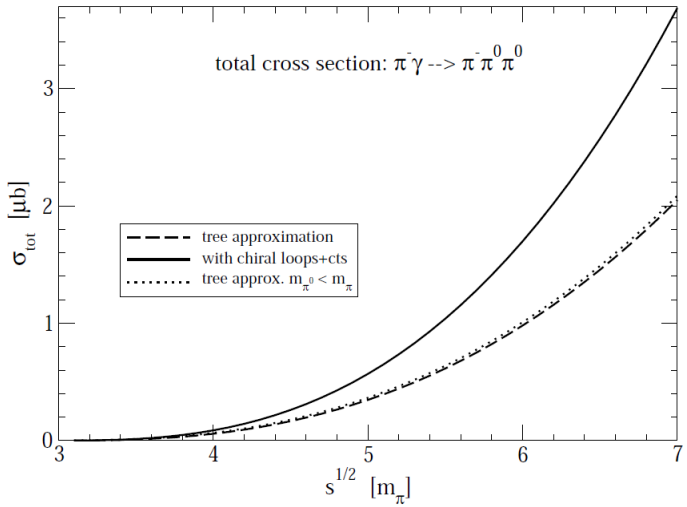


- Loop diagrams[1], e.g.




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



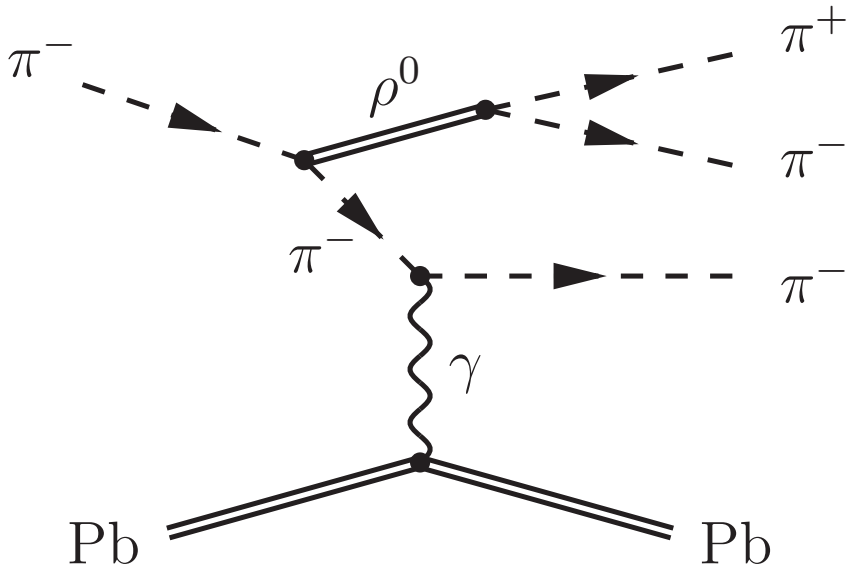

[1] N. Kaiser, Nucl. Phys. A 848 (2010) 198

# BACKUP: Additional contributions to chiral processes



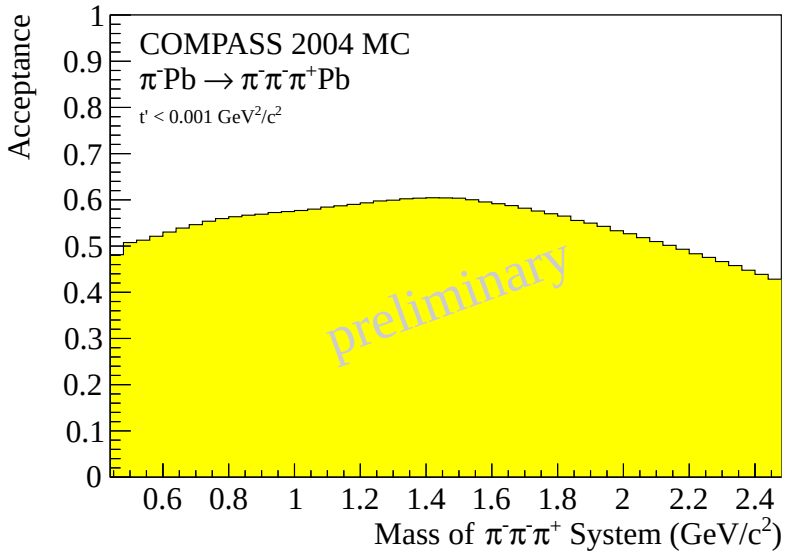
## Contributions from $\rho$ exchange

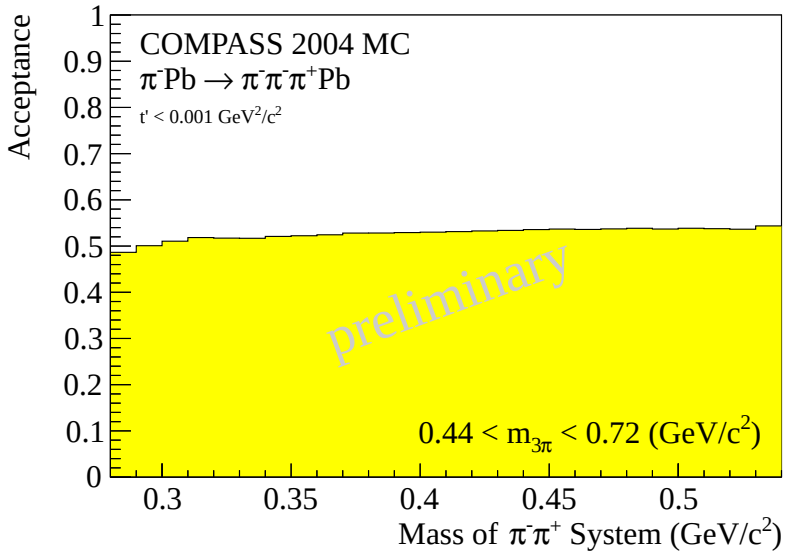
- explicit contribution from the $\rho$ ($m_{3\pi} > 0.7\,\mathrm{GeV}/c^2$), e.g.

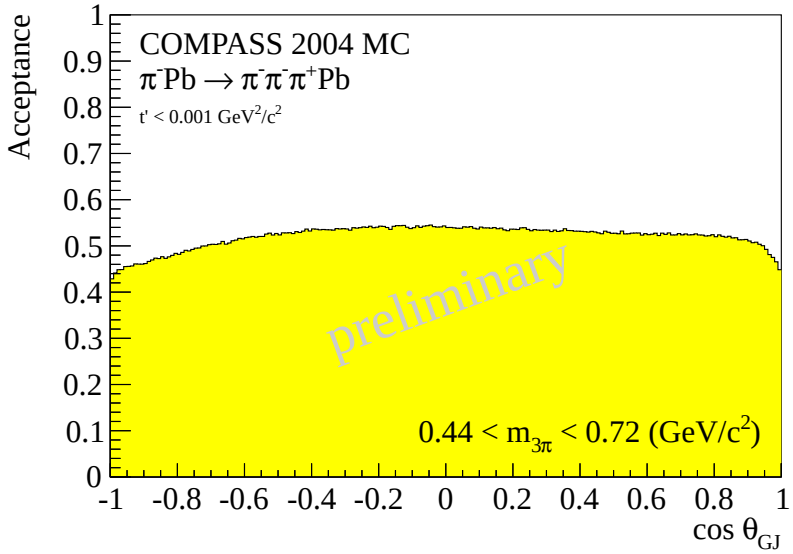


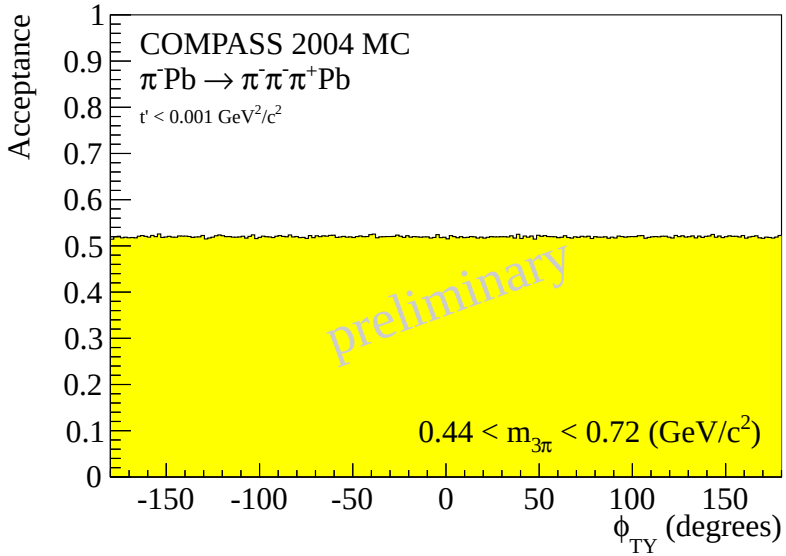
# BACKUP: Acceptance of $\pi^-\pi^-\pi^+$ events ($t' < 0.001$ (GeV/c)$^2$)





# BACKUP: Kaon mass resolution and vertex distribution

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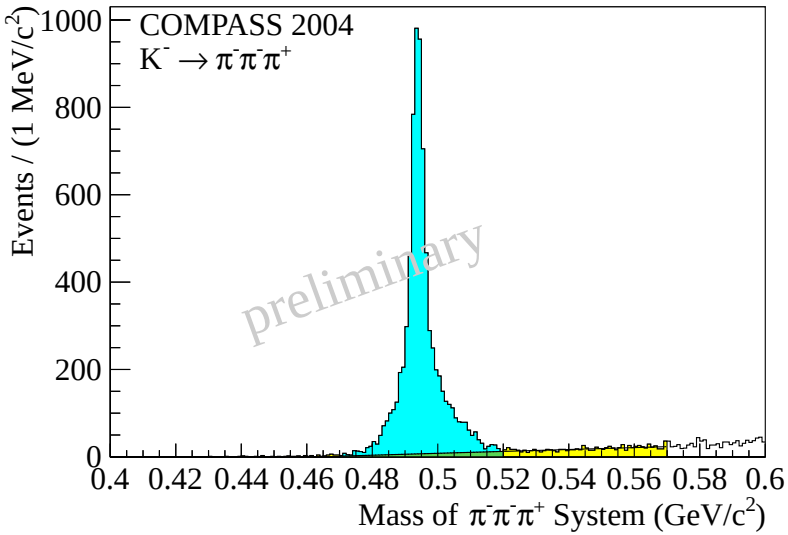
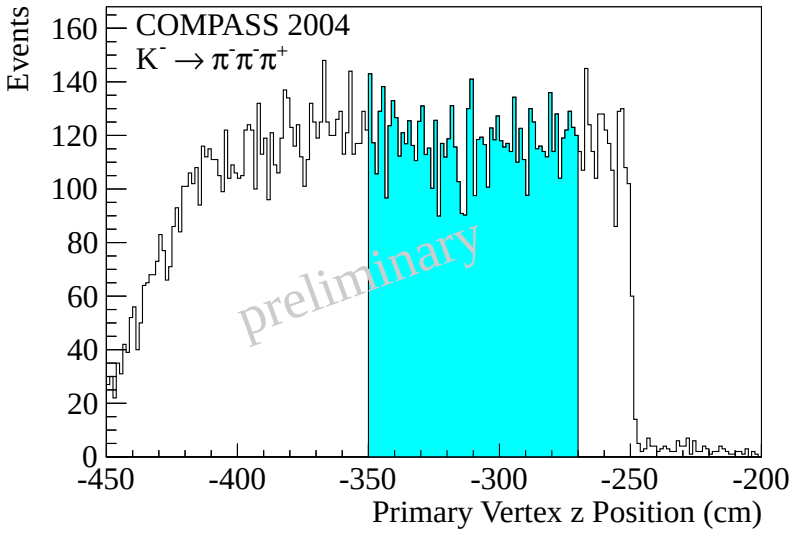
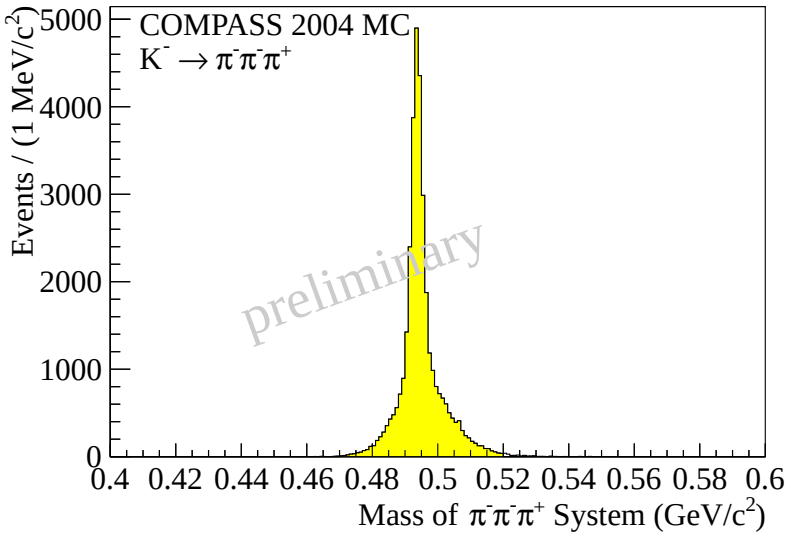
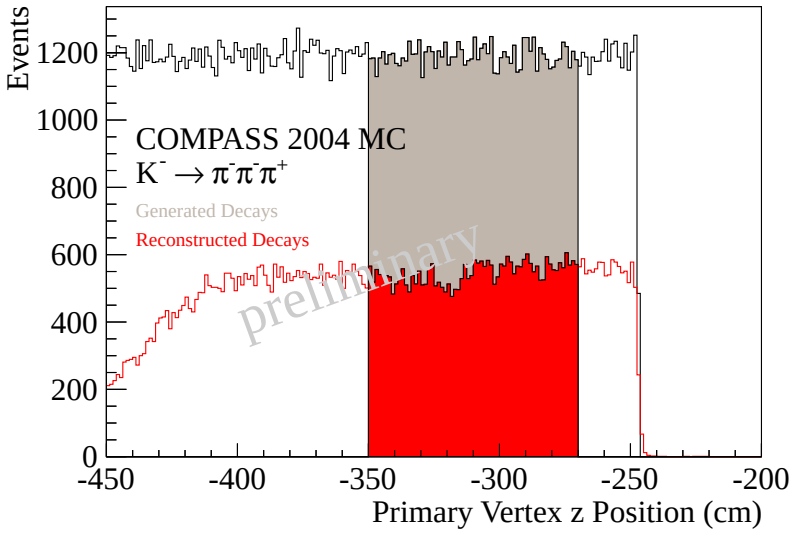
## Data vs. MC



# BACKUP: From Intensity to Cross-Section



In each bin of $m_{3\pi}$:
Number of reactions (events) = $\epsilon_{bin(3\pi)} \cdot \int \mathcal{L} \mathrm{d}t \cdot \sigma_{abs}$

COMPASS $\pi^-$ beam is contaminated with $K^-$
$\to$ beam flux from $K^-$ decays!

## Calculation of Integrated Flux

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

| | |
|---|---|
| $\epsilon$ | acceptance (from MC of kaon decay) |
| $\int \Phi \mathrm{d}t$ | integrated beam flux |
| $s$ | length of decay volume |
| $\beta\gamma\tau$: | $K^-$ decay length (1429 m at 190 GeV) |
| $BR$: | $K^- \to \pi^+ \pi^- \pi^-$ branching ratio (5.59%) |
| $\frac{K^-}{\pi^- K^- \bar{p}}$: | $K^-$ fraction at COMPASS target (2.43%, estimated relative uncertainty 5%) |