# Diffractive Pion Dissociation Into $3\pi$ and $5\pi$ Final States

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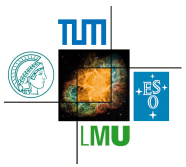




## Constituent Quark Model of Mesons – Spin Parity Rules

$$P = (-1)^{l+1} \qquad C = (-1)^{l+s}$$

$$\text{e.g. } P = (-1)^J \quad \Rightarrow \quad s = 1 \quad \Rightarrow \quad CP = +1$$

$J^{PC}$ Multiplets:
$0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
Forbidden:
$0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

## Spin Exotic States

- $J^{PC}$ forbidden in constituent quark model $\Rightarrow$ cannot be a $q\bar{q}$-state
- No mixing with quark model states

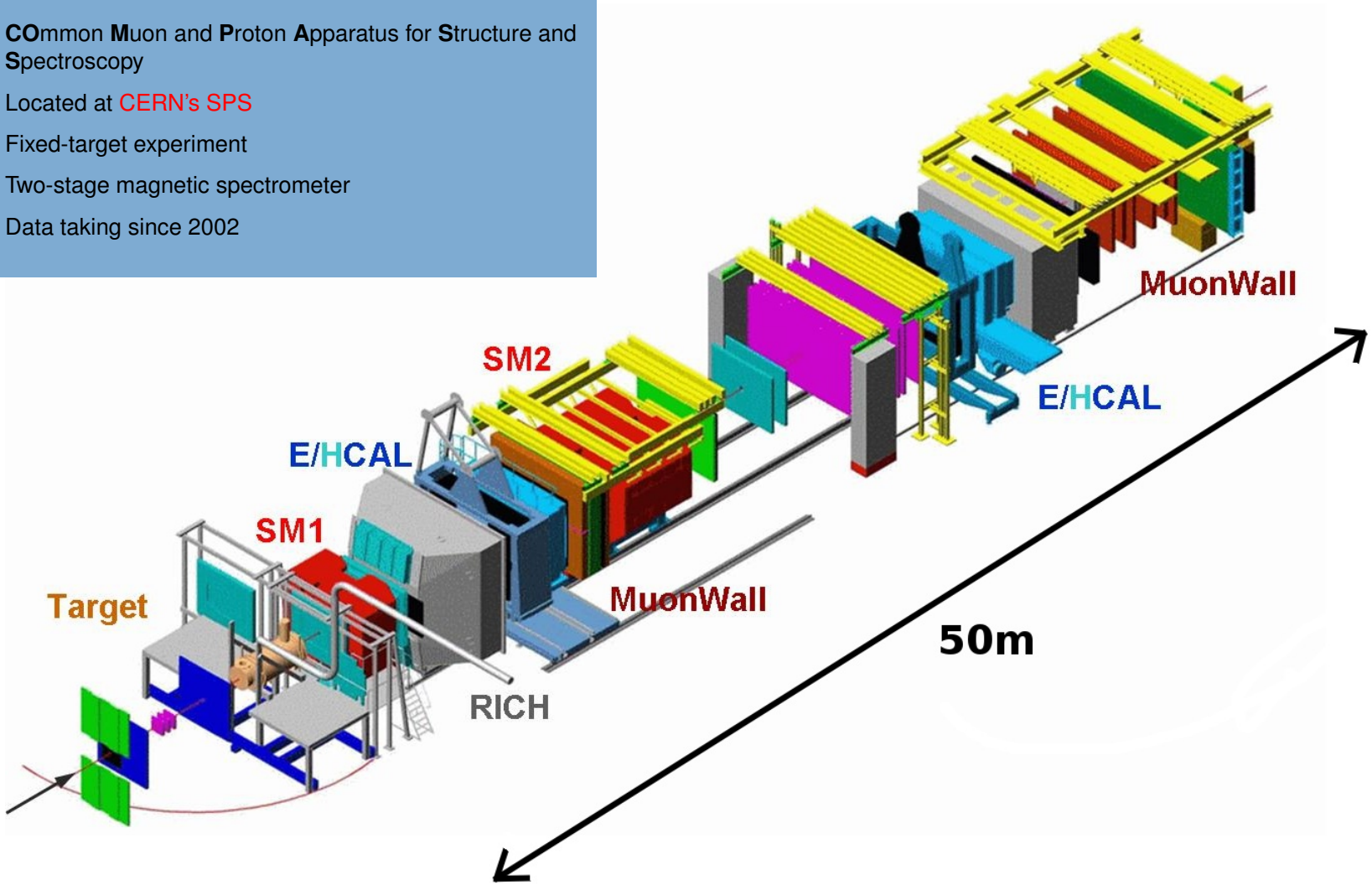
$$\underbrace{J^{PC} = 1^{-+}}_{\text{Smoking Gun}} + \underbrace{\text{Resonant Phase Motion}}_{\text{Bullet}} + \underbrace{\text{Quark Model}}_{\text{Victim}}$$

## Challenges and Opportunities in the light (u,d) Quark Sector

- High density of states; broad, overlapping states
- Exploit interference effects $\rightarrow$ phase motion
- Requires high statistics, complete PS coverage

## 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



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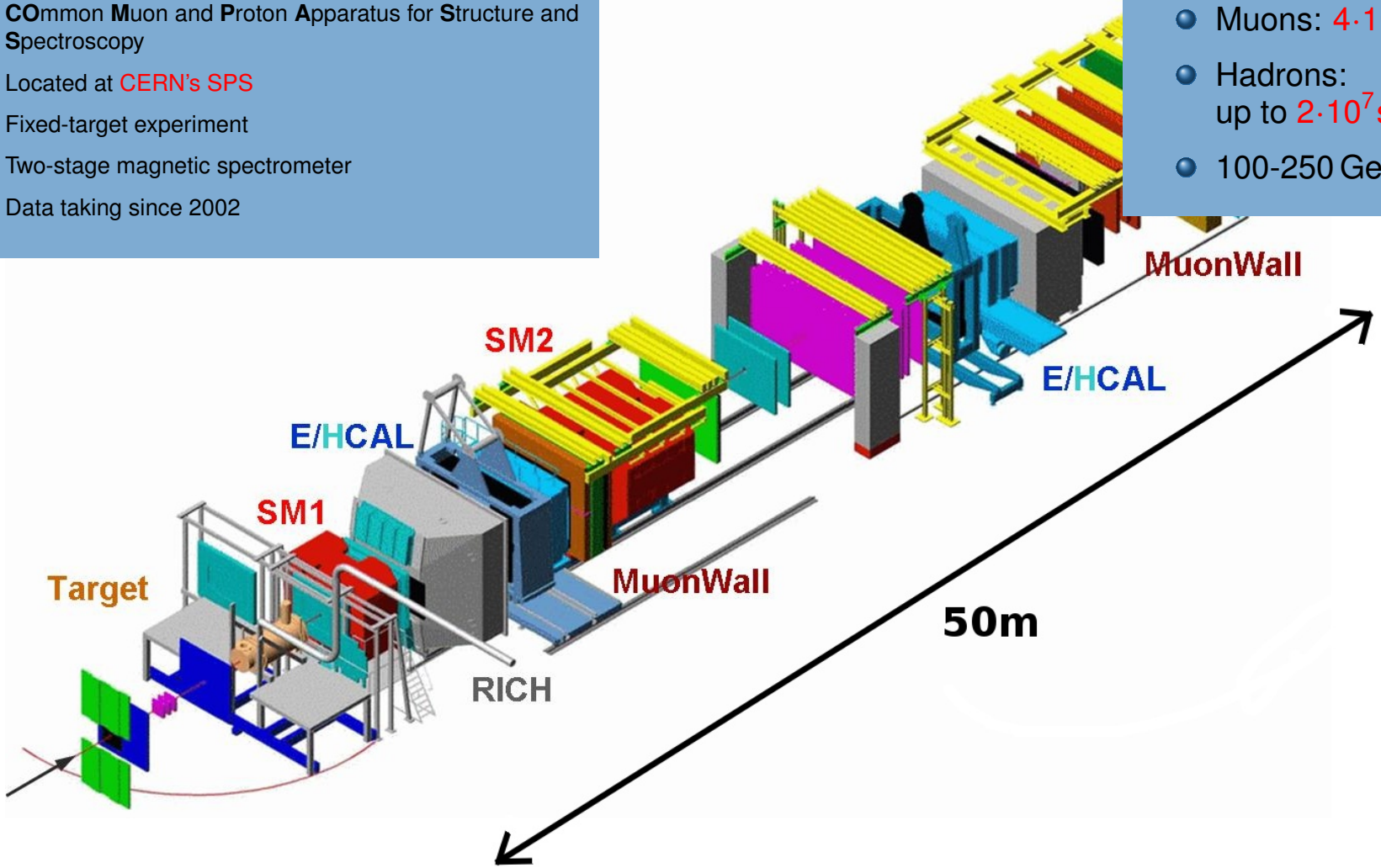
## Second./Tert. SPS Beams

- Muons: $4 \cdot 10^7 s^{-1}$
- Hadrons: up to $2 \cdot 10^7 s^{-1}$
- 100-250 GeV



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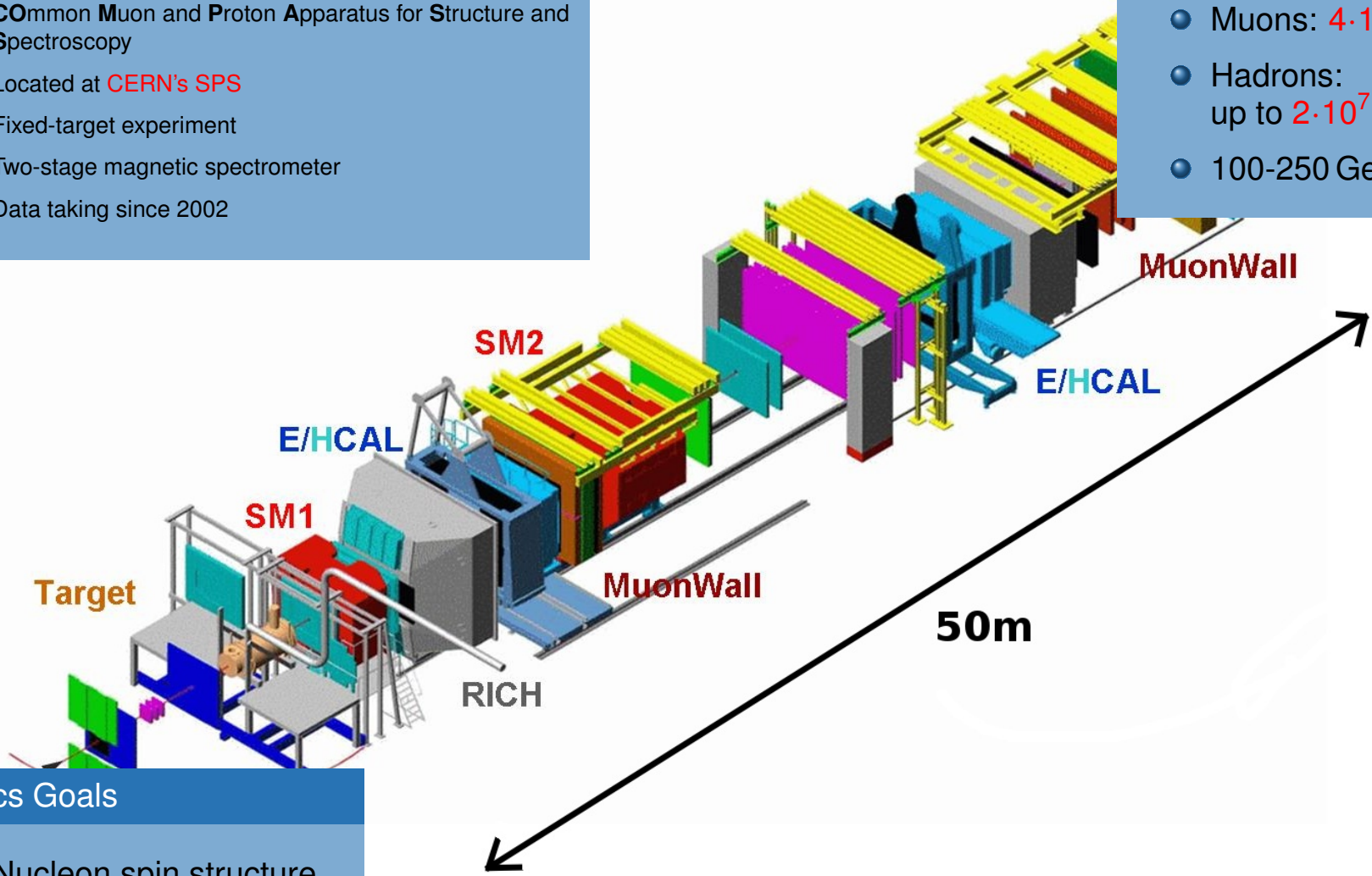


## Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

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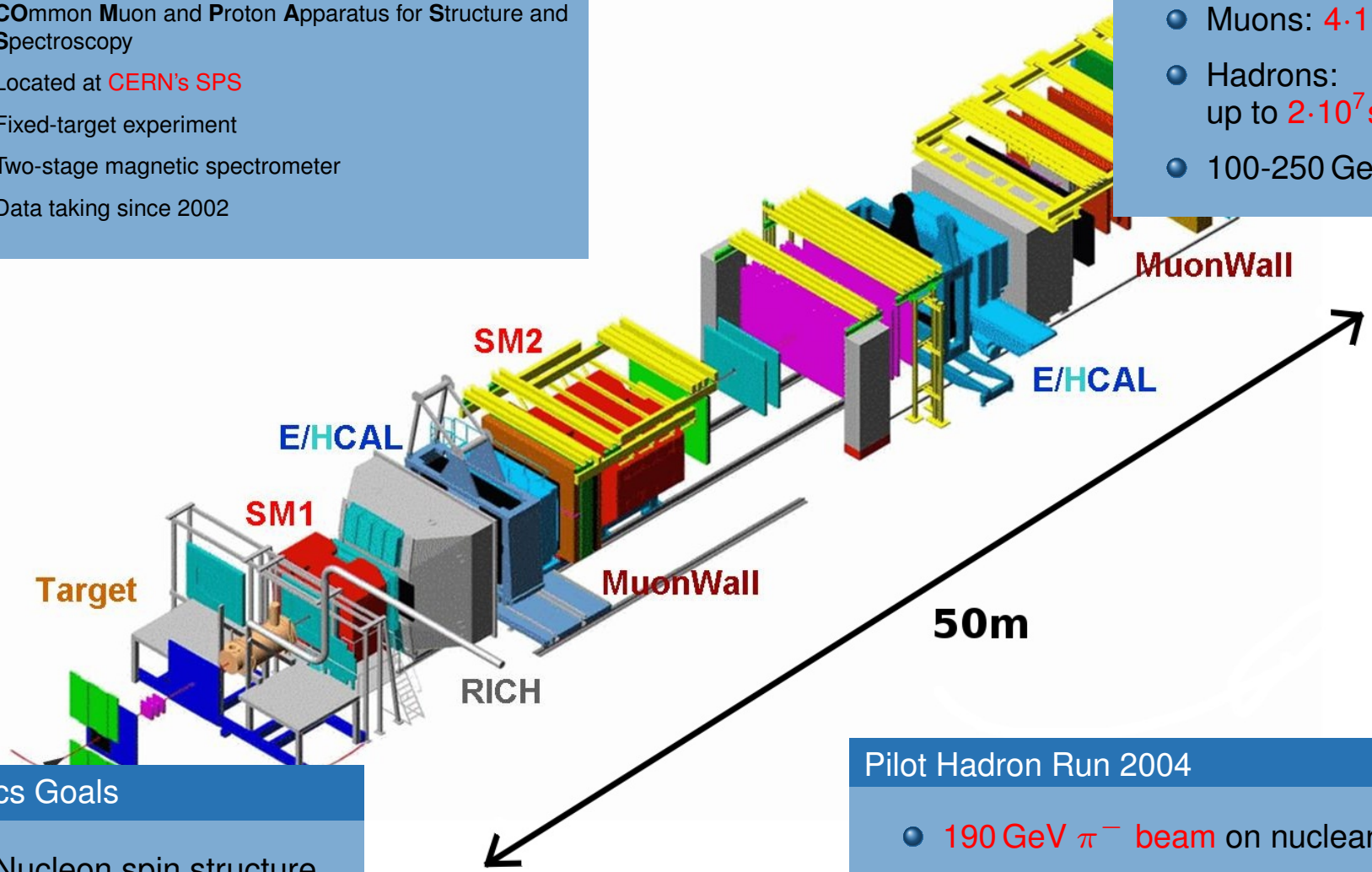


## Physics Goals

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## Pilot Hadron Run 2004

- 190 GeV $\pi^-$ beam on nuclear targets
- Tracking: Silicons, SciFis, GEMs, MicroMegas, MWPCs, Drift Chambers

# Diffractive Production of Mesons

- Diffraction: target particle remains intact
  Reggeon t-channel exchange
  Assumptions: Factorization of meson and Pb vertex, no final state interaction

- Dissociation: beam pion is excited to some resonance $X^-$, which subsequently decays
  $\Rightarrow$ e. g. $\pi^- \mathrm{Pb} \rightarrow X^- \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ \mathrm{Pb}$
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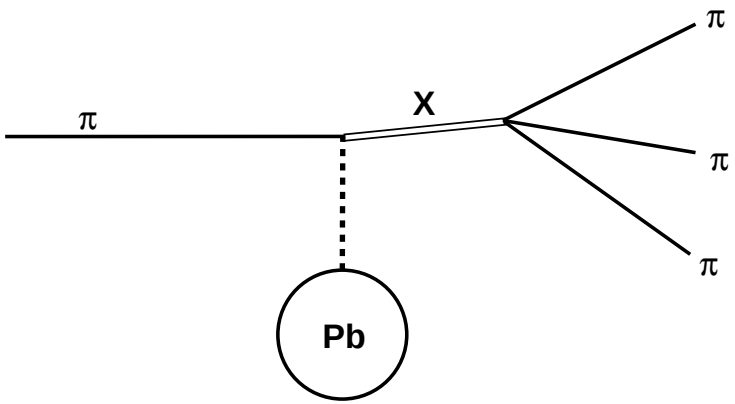

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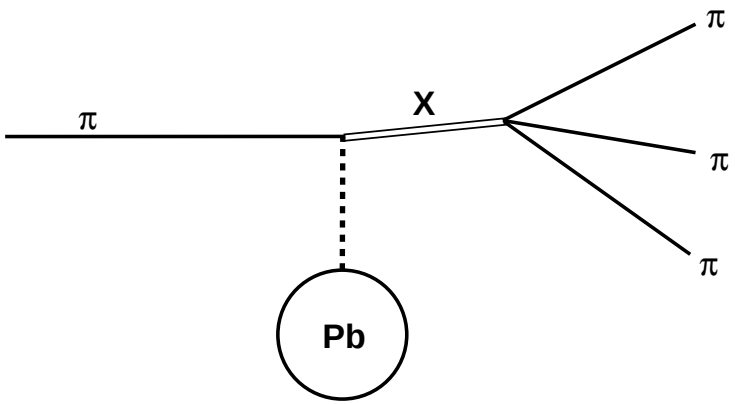


## Meson Spectroscopy and Search for **Exotic States** (non-$q\bar{q}$)

- Evidences for spin-exotic $\pi_1(1600)$ state with $J^{PC} = 1^{-+}$ in $\rho\pi^- \to \pi^-\pi^+\pi^-$ ?

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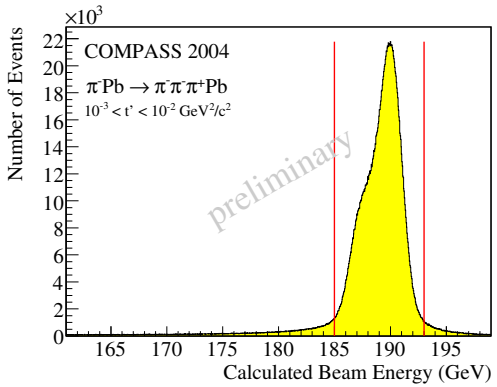


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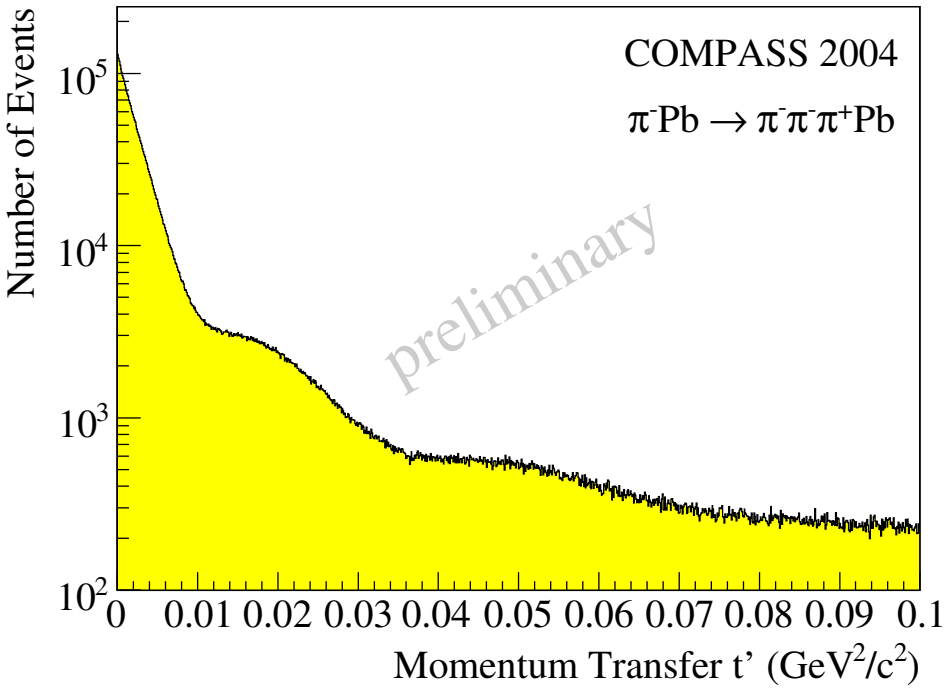
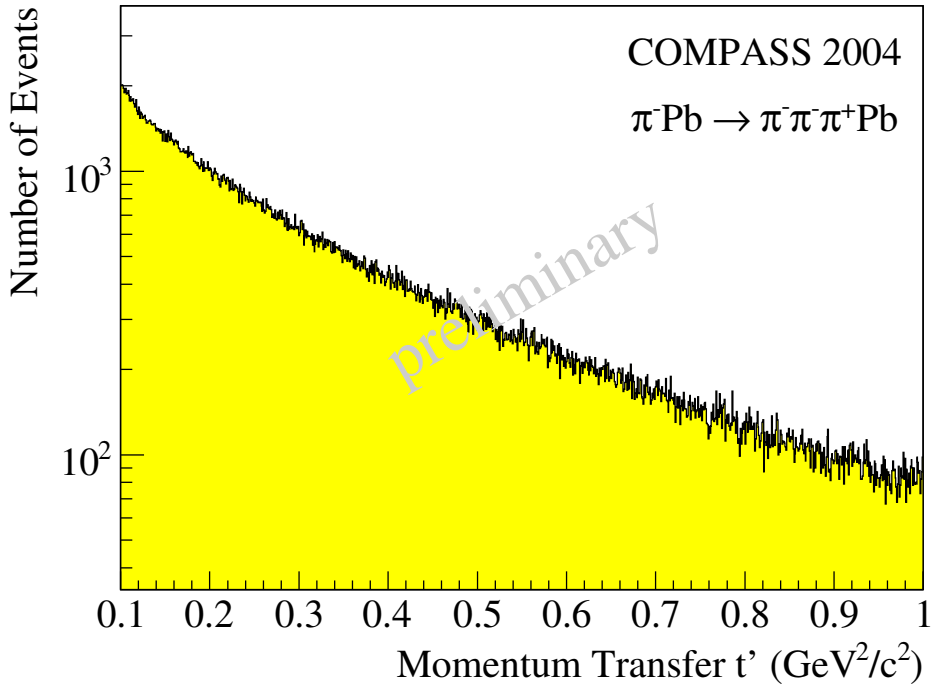
- Exclusive $3\pi$ or $5\pi$ final state events (pion hypothesis).
- COMPASS 2004 (few days of data taking):
  - $\sim$ 4 000 000 $3\pi$ events
    $\sim$ 400 000 events with $0.1 < t' < 1.0\ \mathrm{GeV}^2/c^2$
  - $\sim$ 380 000 $5\pi$ events

Momentum transfer from target: $-t = -(p_{\text{beam}} - p_{(\pi^-\pi^-\pi^+)})^2$

$\Rightarrow t' = |t| - |t|_{min}$

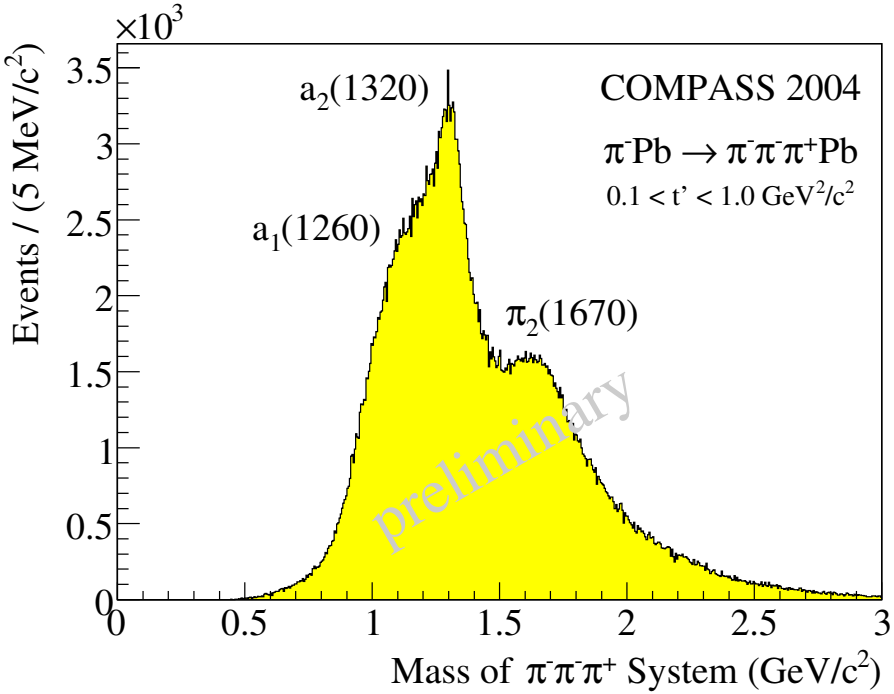


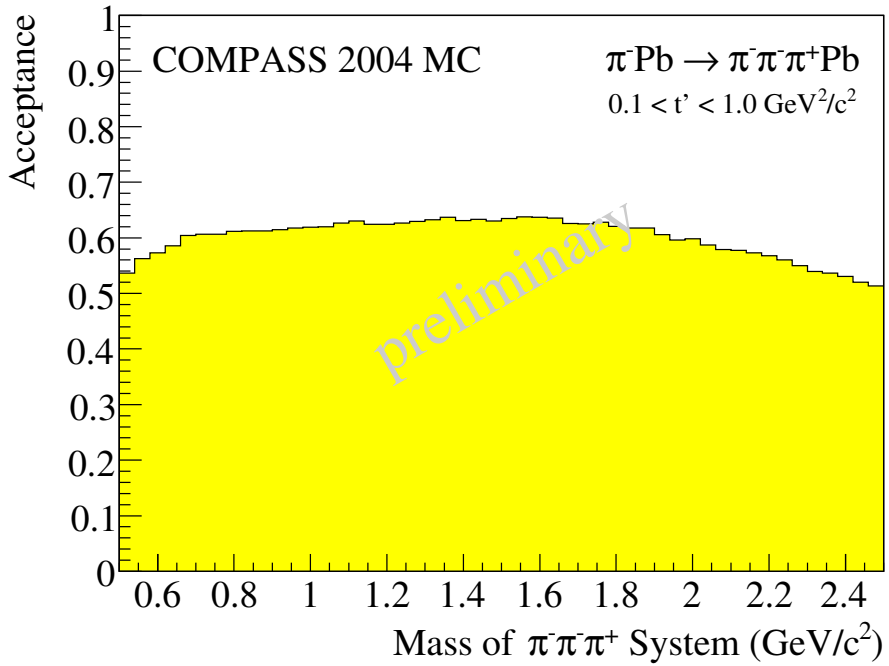

Diffraction pattern: Pb nucleus acts like "black disc" in optics

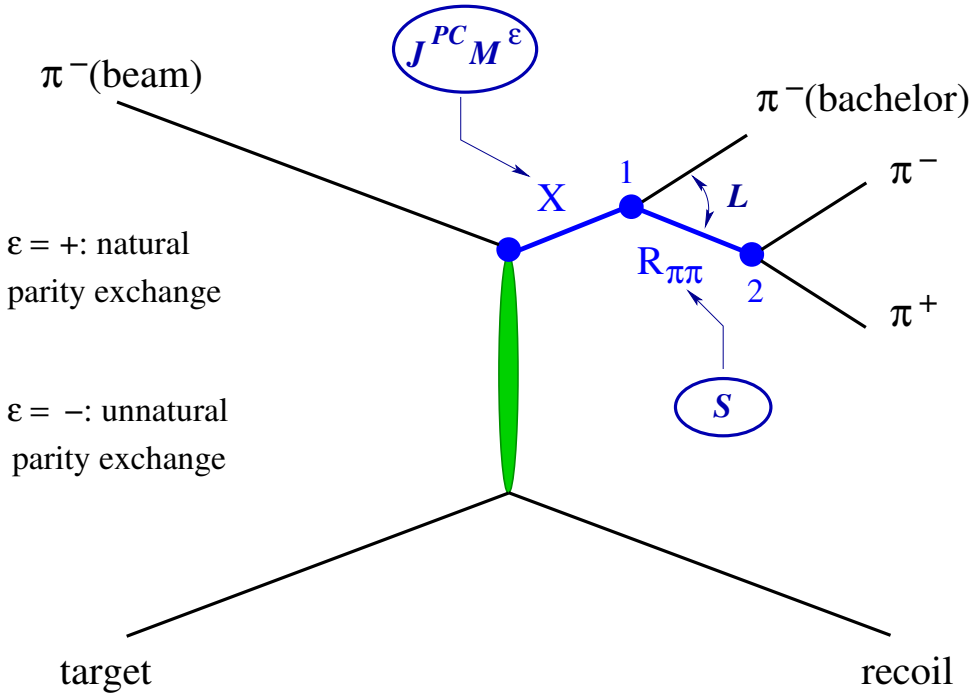
High-$t'$: scattering on single nucleons inside Pb nucleus

## High-$t'$ Spectrum




## Flat acceptance: 55-60%






- Isobar model: Intermediate 2-particle decays
- Zemach / Helicity formalism, reflectivity basis
- Reggeon exchange
- Partial wave: $J^{PC}M^{\epsilon}[isobar]L$
- Nucleon target $\Rightarrow$ rank 2

- Mass-independent PWA (40 MeV/$c^2$ mass bins): 42 waves
  - Extended log-likelihood method (Ascoli/Kachaev fitter)
  - Acceptance corrections included
  - $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$ from PDG, $(\pi\pi)_s$ with separated $f_0(980)$ from VES
  - Multiple solutions ($\Delta \ln L \leq 1$) added as additional error
- Mass-dependent $\chi^2$-fit: 6 waves
  - Only positive reflectivity waves (natural parity exchange dominant)
  - $X$ parameterized by Breit-Wigner (BW) functions
  - Coherent background added for some waves: $\exp(-\alpha p^2)$

# Partial Wave Set for Mass-Independent Fit (42 Waves)

Description of possible Decay Amplitudes

| $J^{PC}M^{\epsilon}$ | $L$ | Isobar $\pi$ | Thresh. [GeV] |
|---|---|---|---|
| $0^{-+}0^{+}$ | $S$ | $f_0\pi$ | 1.40 |
| $0^{-+}0^{+}$ | $S$ | $(\pi\pi)_S\pi$ | - |
| $0^{-+}0^{+}$ | $P$ | $\rho\pi$ | - |
| $1^{-+}1^{+}$ | $P$ | $\rho\pi$ | - |
| $1^{++}0^{+}$ | $S$ | $\rho\pi$ | - |
| $1^{++}0^{+}$ | $P$ | $f_2\pi$ | 1.20 |
| $1^{++}0^{+}$ | $P$ | $(\pi\pi)_S\pi$ | 0.84 |
| $1^{++}0^{+}$ | $D$ | $\rho\pi$ | 1.30 |
| $1^{++}1^{+}$ | $S$ | $\rho\pi$ | - |
| $1^{++}1^{+}$ | $P$ | $f_2\pi$ | 1.40 |
| $1^{++}1^{+}$ | $P$ | $(\pi\pi)_S\pi$ | 1.40 |
| $1^{++}1^{+}$ | $D$ | $\rho\pi$ | 1.40 |
| $2^{-+}0^{+}$ | $S$ | $f_2\pi$ | 1.20 |
| $2^{-+}0^{+}$ | $P$ | $\rho\pi$ | 0.80 |
| $2^{-+}0^{+}$ | $D$ | $f_2\pi$ | 1.50 |
| $2^{-+}0^{+}$ | $D$ | $(\pi\pi)_S\pi$ | 0.80 |
| $2^{-+}0^{+}$ | $F$ | $\rho\pi$ | 1.20 |
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| $4^{-+}0^{+}$ | $F$ | $\rho\pi$ | 1.20 |
| $4^{-+}1^{+}$ | $F$ | $\rho\pi$ | 1.20 |
| $4^{++}1^{+}$ | $F$ | $f_2\pi$ | 1.60 |
| $4^{++}1^{+}$ | $G$ | $\rho\pi$ | 1.64 |
| $1^{-+}0^{-}$ | $P$ | $\rho\pi$ | - |
| $1^{-+}1^{-}$ | $P$ | $\rho\pi$ | - |
| $1^{++}1^{-}$ | $S$ | $\rho\pi$ | - |
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| $2^{++}0^{-}$ | $D$ | $\rho\pi$ | - |
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## Waveset Features

- 41 Waves + Flat Background
- Isobars:
  - $\sigma(600)$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, $\rho_3$
- positive reflectivity dominates
- 7 negative reflectivity waves included
- More $M = 1$ waves than previous (e.g. BNL) analyses
- $2^{-+}$F waves included

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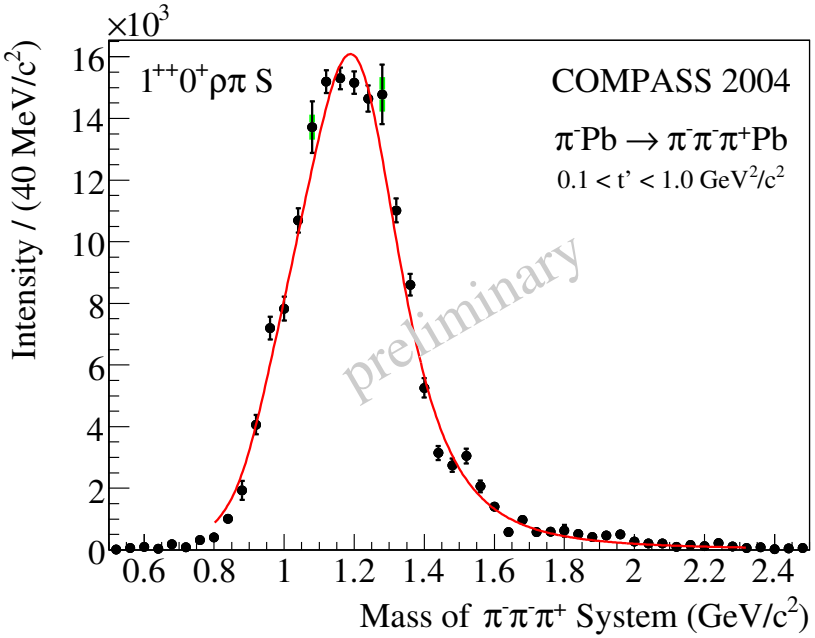
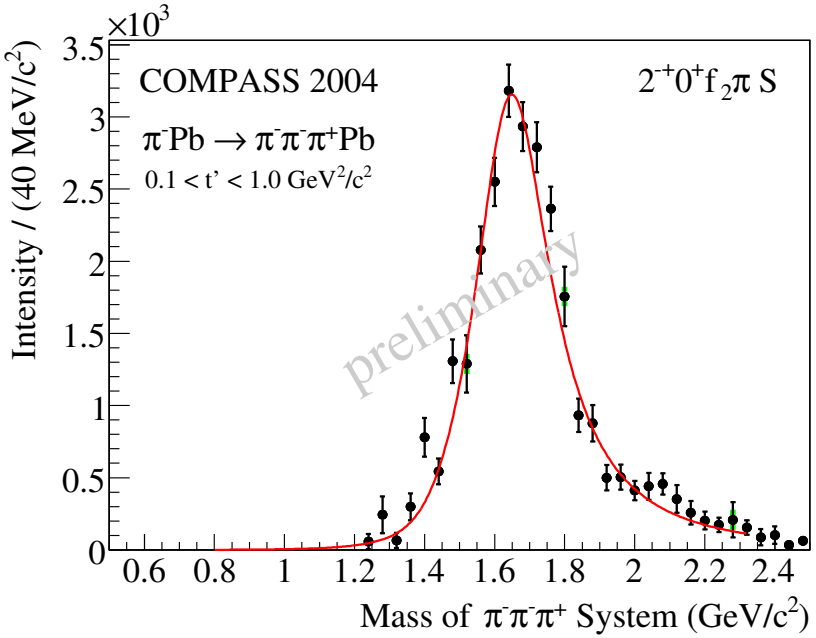
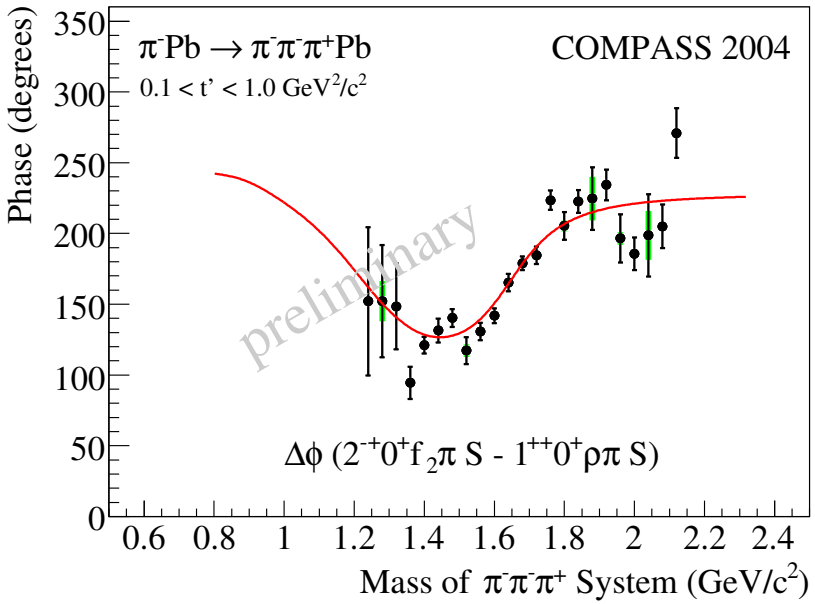



- BW for $a_1(1260)$ + background:

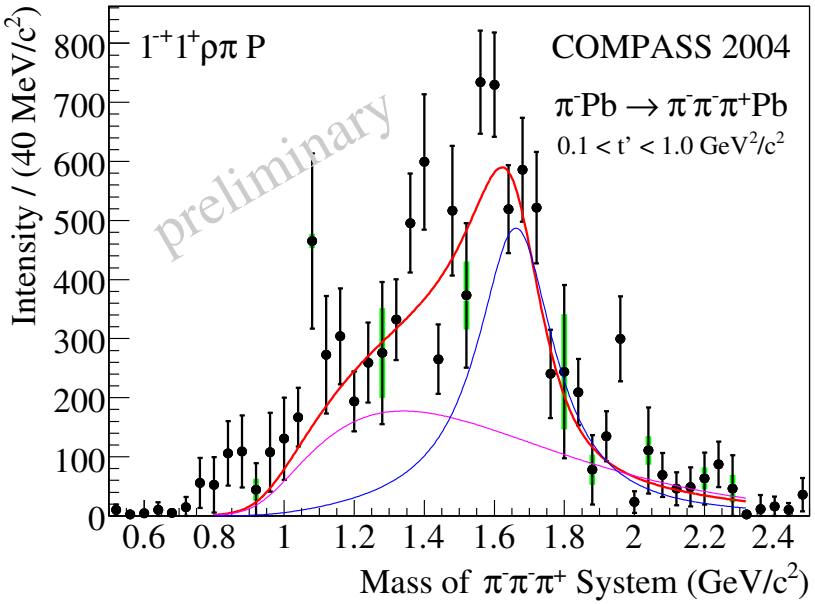
  $M = (1.255 \pm 0.006\ ^{+0.007}_{-0.017})\ \mathrm{GeV}/c^2$

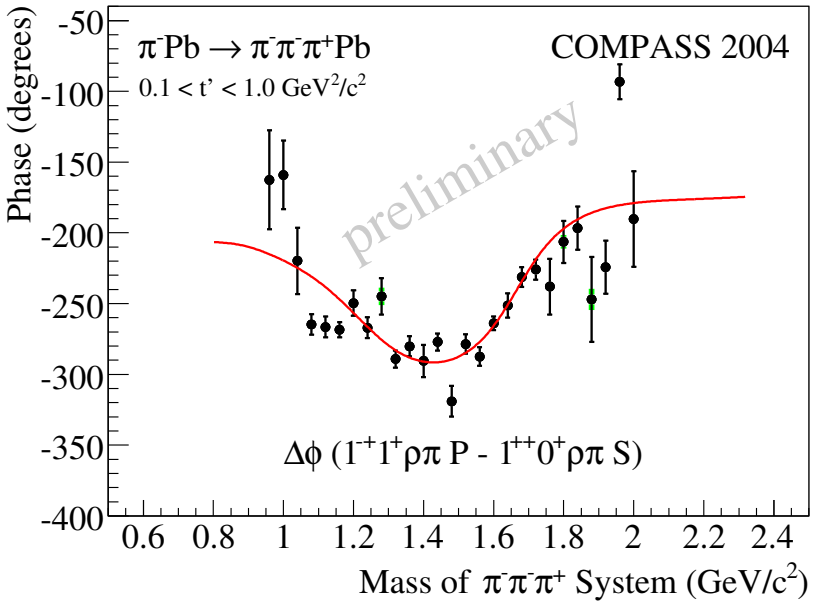
  $\Gamma = (0.367 \pm 0.009\ ^{+0.028}_{-0.025})\ \mathrm{GeV}/c^2$

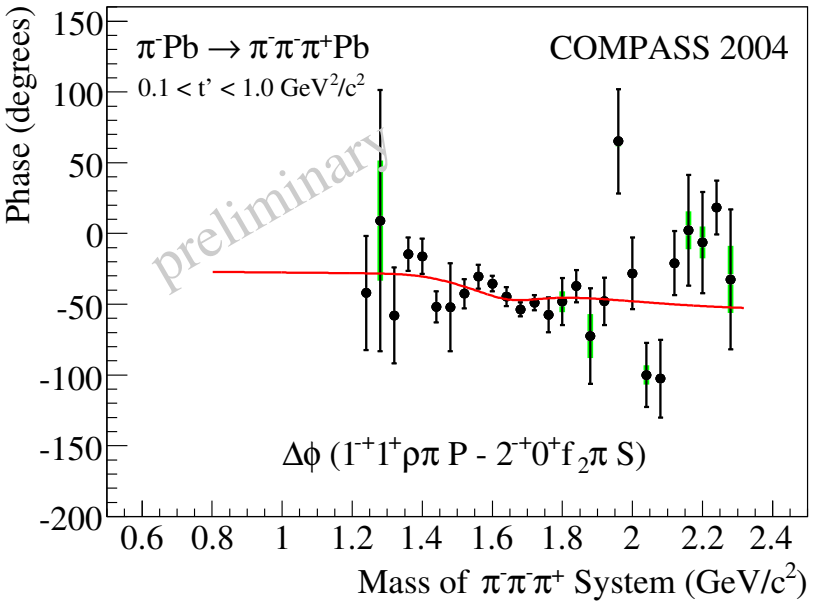
- BW for $\pi_2(1670)$:

  $M = (1.658 \pm 0.003\ ^{+0.024}_{-0.008})\ \mathrm{GeV}/c^2$

  $\Gamma = (0.271 \pm 0.009\ ^{+0.022}_{-0.024})\ \mathrm{GeV}/c^2$



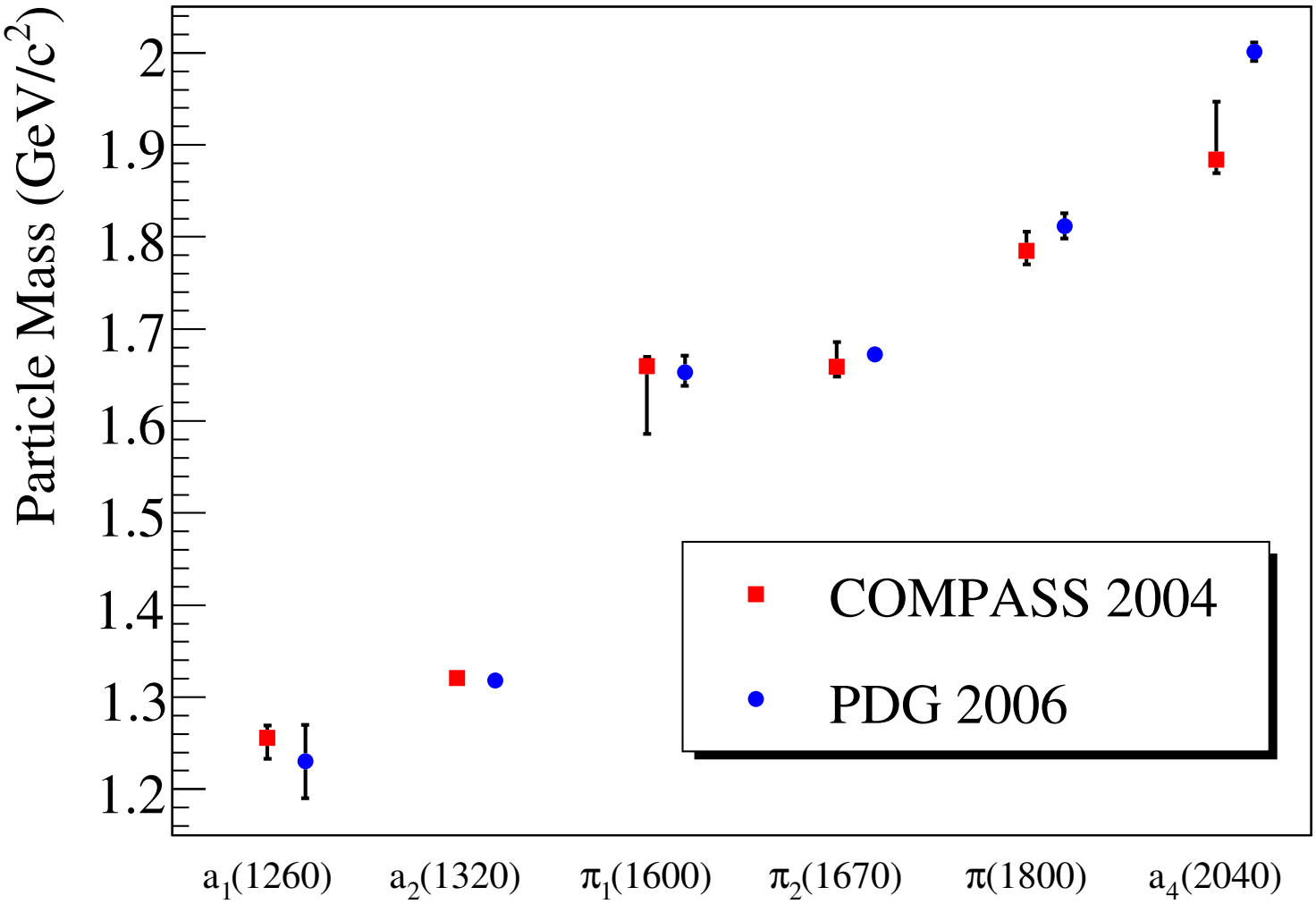

- Significant $1^{-+}$ amplitude consistent with resonance at $\sim 1.7\,\mathrm{GeV}/c^2$
- No leakage observed ($< 5\%$)
- BW for $\pi_1(1600)$ + background:

  $M = (1.660 \pm 0.010\ ^{+0.000}_{-0.064})\,\mathrm{GeV}/c^2$

  $\Gamma = (0.269 \pm 0.021\ ^{+0.042}_{-0.064})\,\mathrm{GeV}/c^2$

# Summary of Extracted States from $\pi^- \mathrm{Pb} \to X^- \mathrm{Pb} \to \pi^-\pi^-\pi^+ \mathrm{Pb}$

## Comparison with PDG values



**Motivation:**

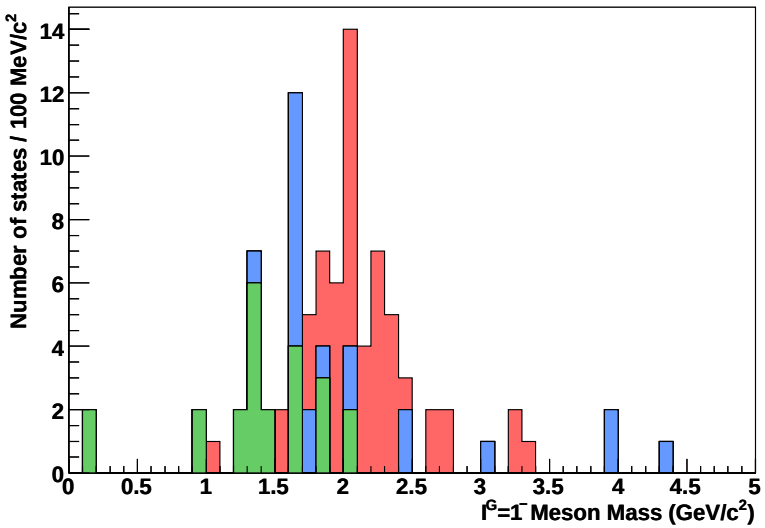
- Access to mass-range $> 2\,\mathrm{GeV}/c^2$
- Interesting accessible quantum numbers:
  - $1^-(1^{-+})$ spin exotic
  - $1^-(0^{++})$ not accessible in $3\pi$!
  - $1^-(3^{-+})$ high J spin exotic?
- BNL: $\pi^- p \longrightarrow f_1\pi \longrightarrow \eta\pi^+\pi^-\pi^-$
  2 exotic $1^{-+}$ states

  (Kuhn et al., Phys. Lett. B, 595(2004)109)
- Interesting decay modes $b_1\pi$, $f_1\pi$, $\rho'\pi$
- *Light meson frontier*:
  many disputed states in this region
  $(0^{-+})(1^{++})(2^{-+})$...

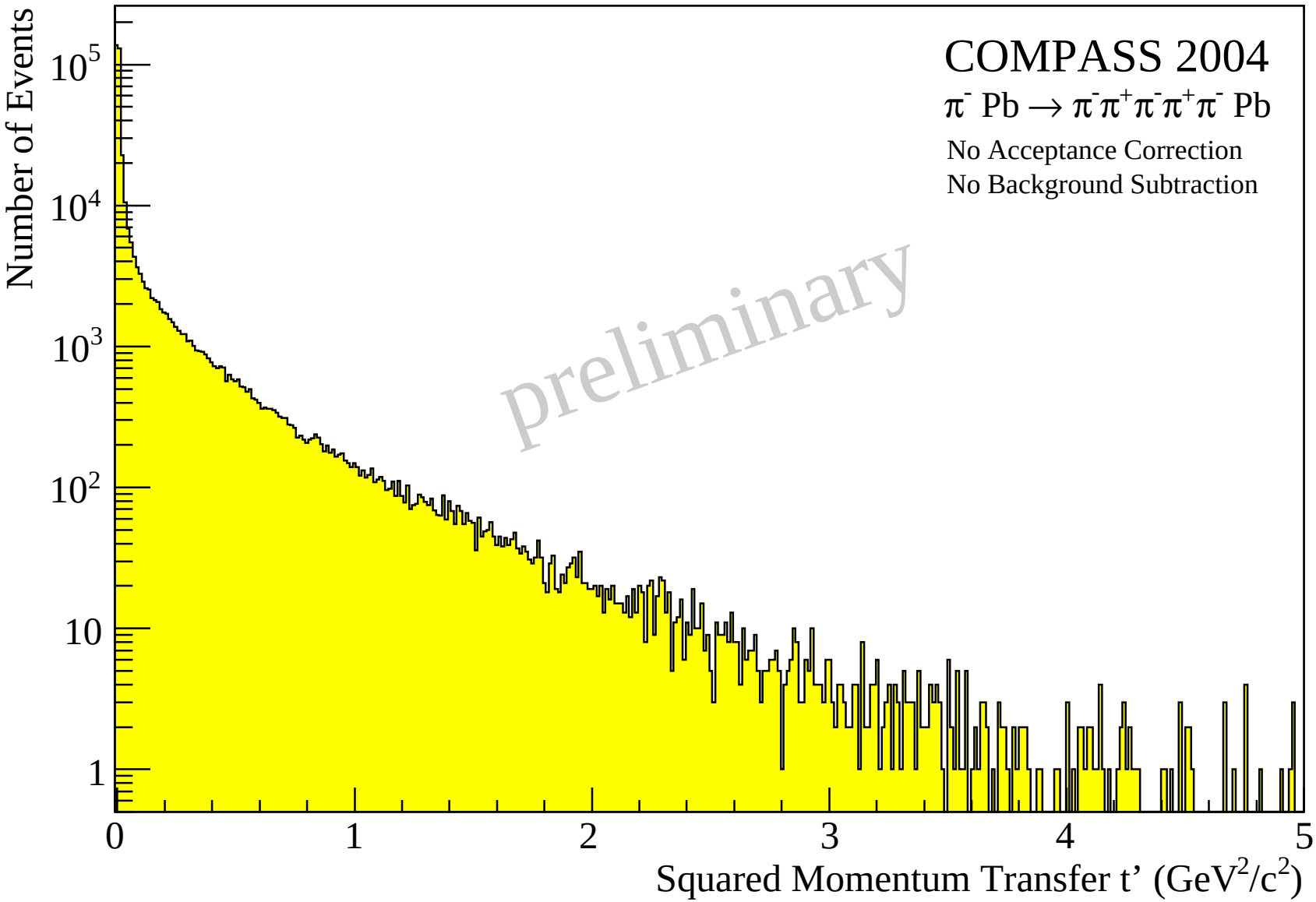
## $\pi_1(1^{-+})$ branching ratios

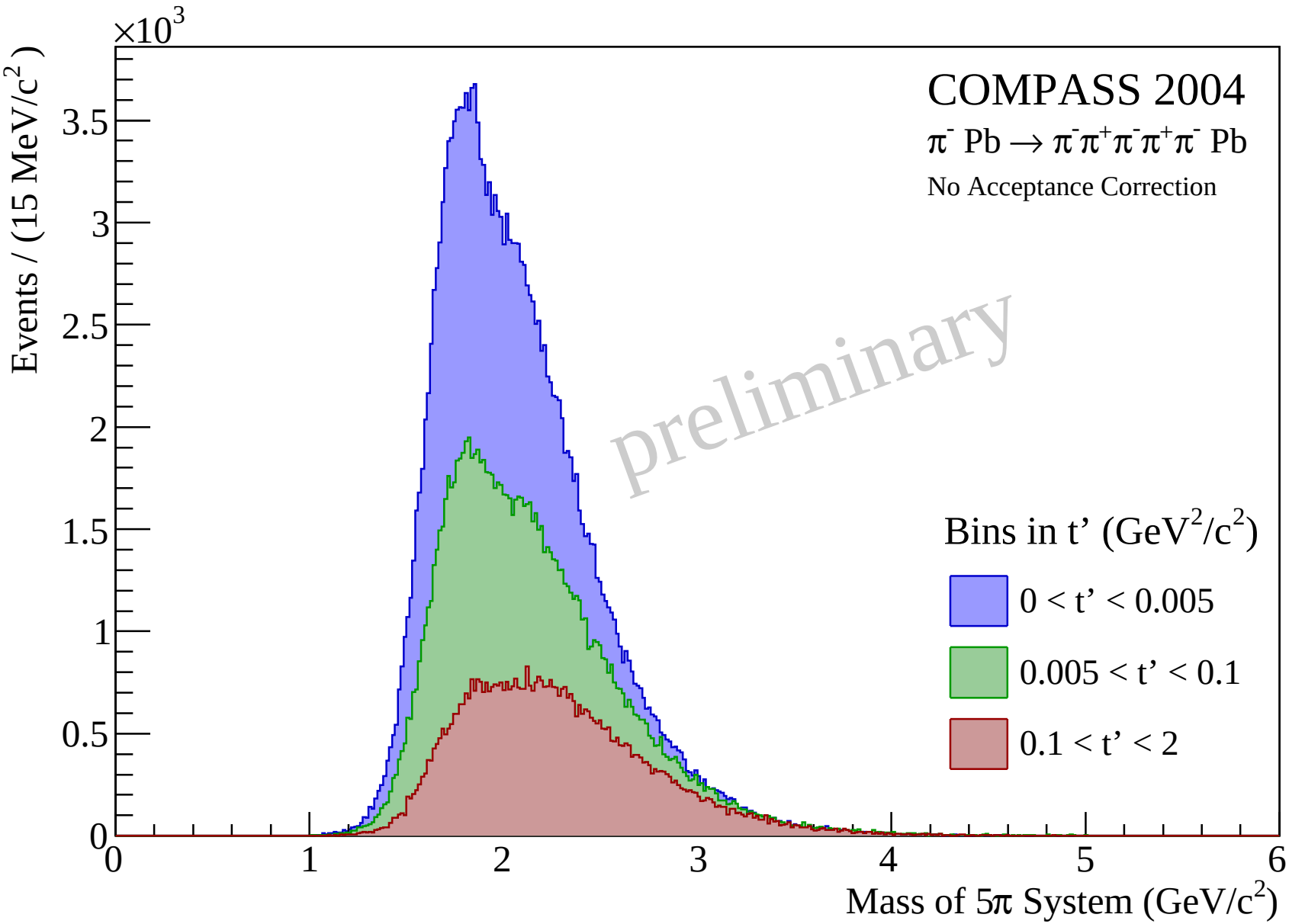
Flux-Tube model predictions:
(Page, Swanson, Szczepaniak, Phys. Rev. D59, 034016(1999))

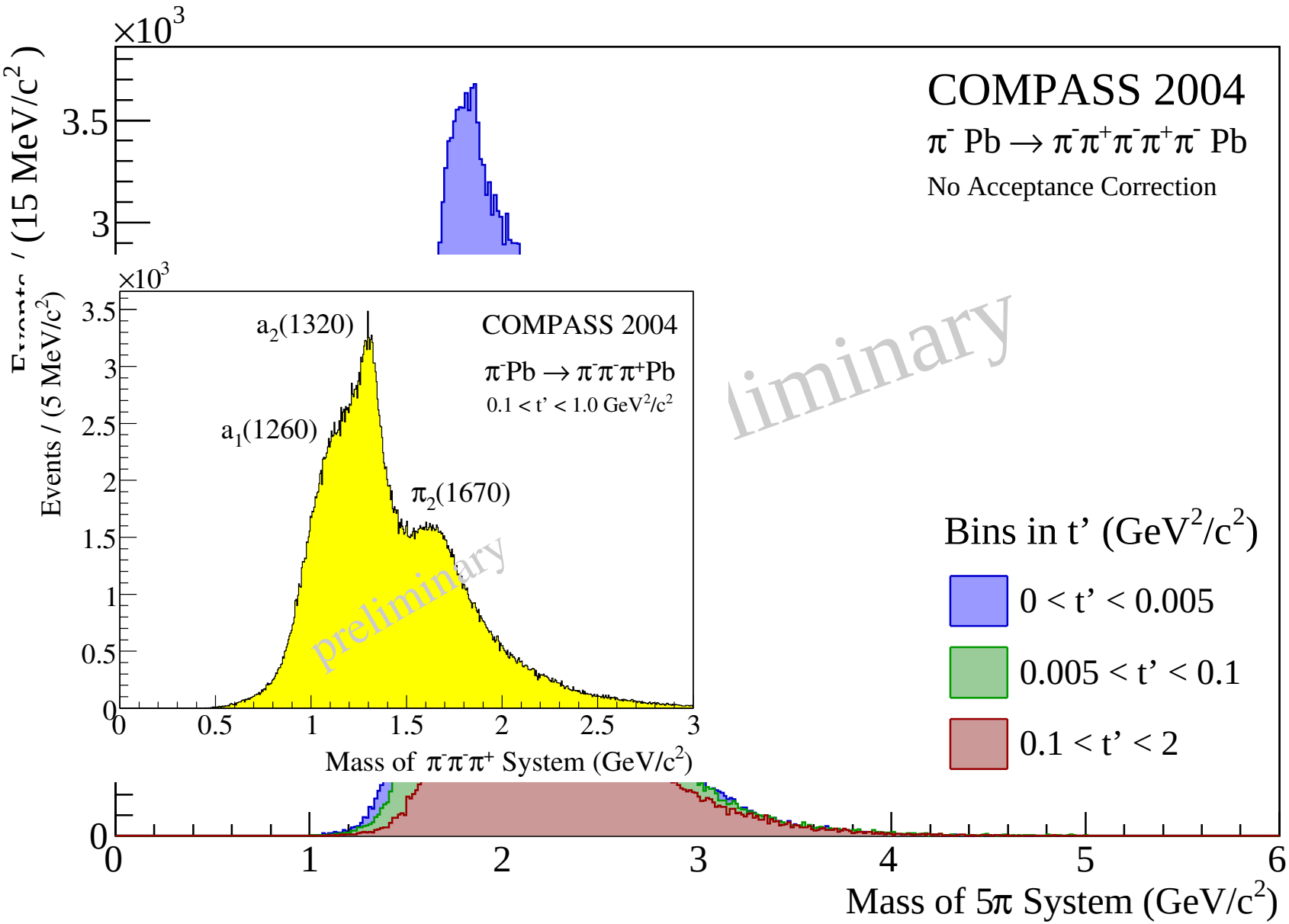
| $m_{\pi_1}$ | $b_1\pi$ | $f_1\pi$ | $\eta'\pi$ | $\rho(1450)\pi$ |
|---|---|---|---|---|
| $1.6\,\mathrm{GeV}/c^2$ | 24: | 5: | 2 | |
| $2.0\,\mathrm{GeV}/c^2$ | 43: | 10: | 27: | 12 |

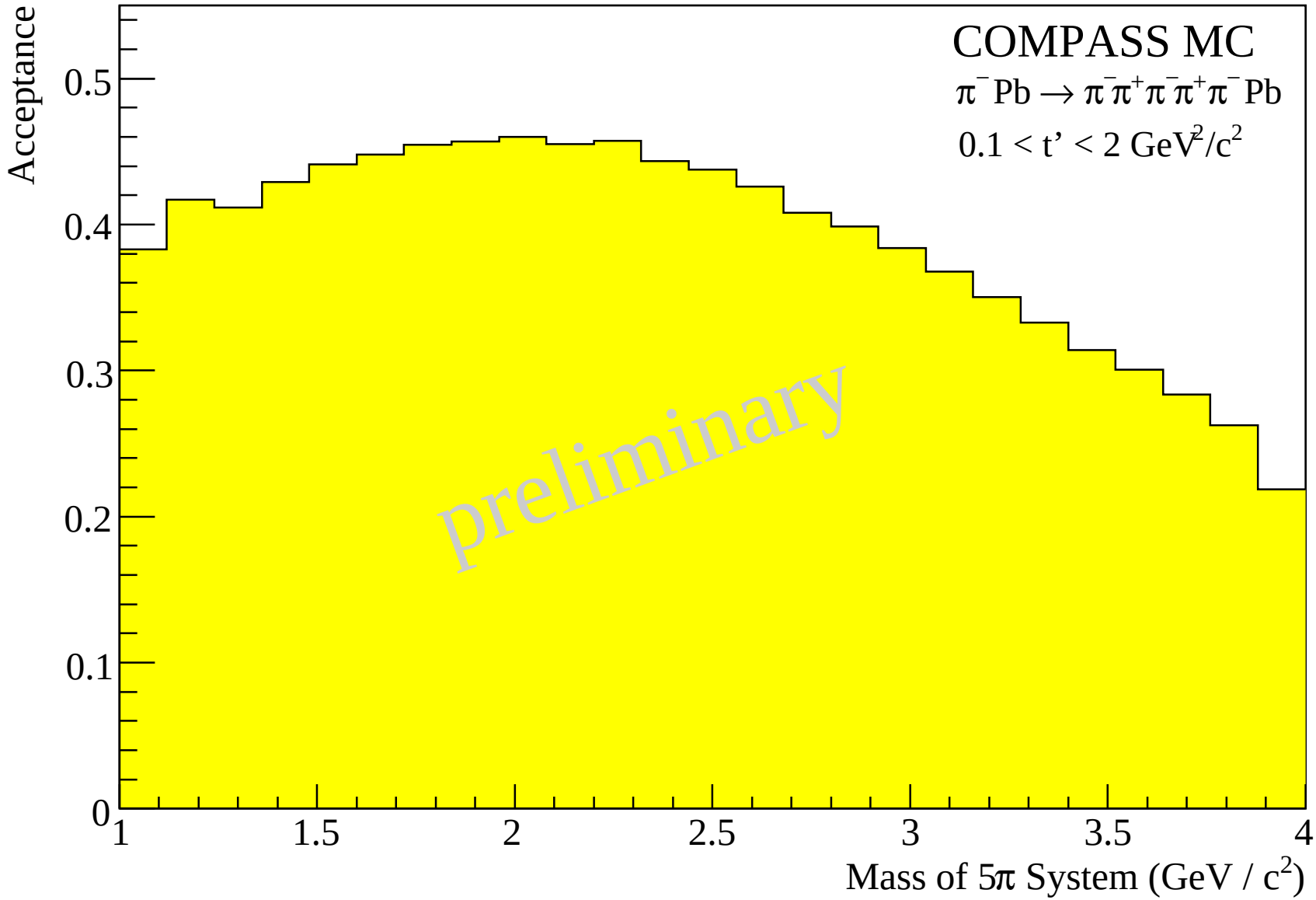



Meson states with $I^G = 1^-$ listed in the PDB.
Green = established, blue = need confirmation,
red = “further states”. The histogram is stacked.


COMPASS 2004
$\pi^- Pb \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- Pb$
No Acceptance Correction
No Background Subtraction
preliminary
Number of Events
$10^5$
$10^4$
$10^3$
$10^2$
10
1
0
1
2
3
4
5
Squared Momentum Transfer t' ($GeV^2/c^2$)

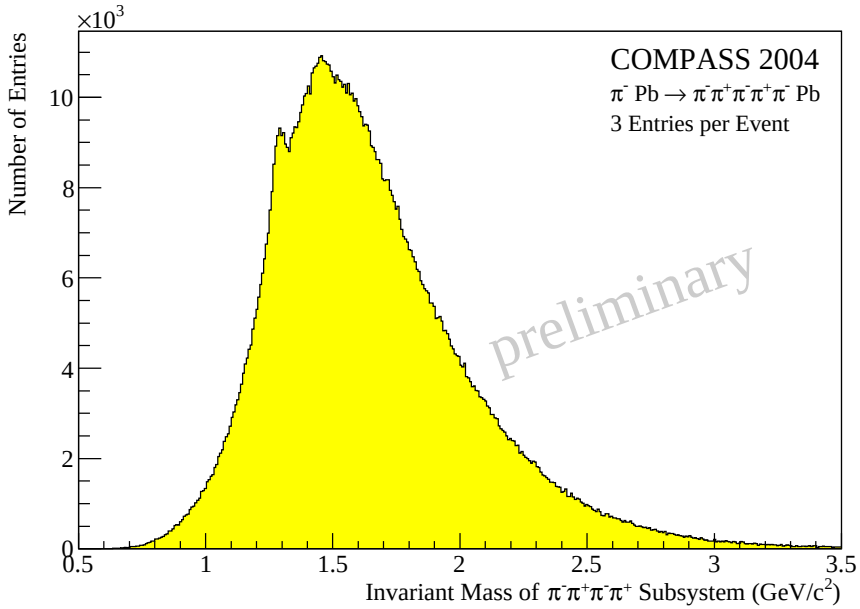

COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
No Acceptance Correction
preliminary
Bins in t' (GeV²/c²)
0 < t' < 0.005
0.005 < t' < 0.1
0.1 < t' < 2
Events / (15 MeV/c²)
×10³
Mass of 5π System (GeV/c²)

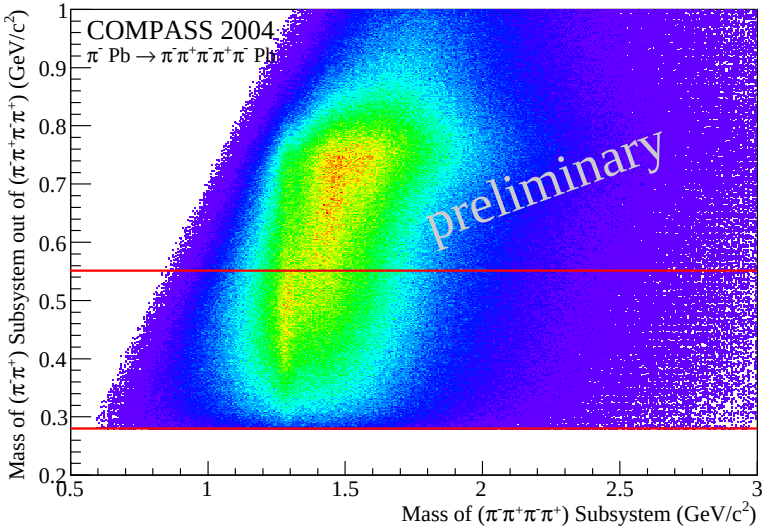

COMPASS 2004
π⁻ Pb → π⁻π⁺π⁻π⁺π⁻ Pb
No Acceptance Correction
Bins in t' (GeV²/c²)
0 < t' < 0.005
0.005 < t' < 0.1
0.1 < t' < 2
Mass of 5π System (GeV/c²)
Events / (15 MeV/c²)
×10³
3.5
3
a₂(1320)
a₁(1260)
π₂(1670)
COMPASS 2004
π⁻Pb → π⁻π⁻π⁺Pb
0.1 < t' < 1.0 GeV²/c²
Events / (5 MeV/c²)
2.5
2
1.5
1
0.5
0
Mass of π⁻π⁻π⁺ System (GeV/c²)
preliminary
preliminary


COMPASS MC
$\pi^- Pb \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^- Pb$
$0.1 < t' < 2\ GeV^2/c^2$
preliminary
Acceptance
0
0.1
0.2
0.3
0.4
0.5
1
1.5
2
2.5
3
3.5
4
Mass of 5π System (GeV / $c^2$)

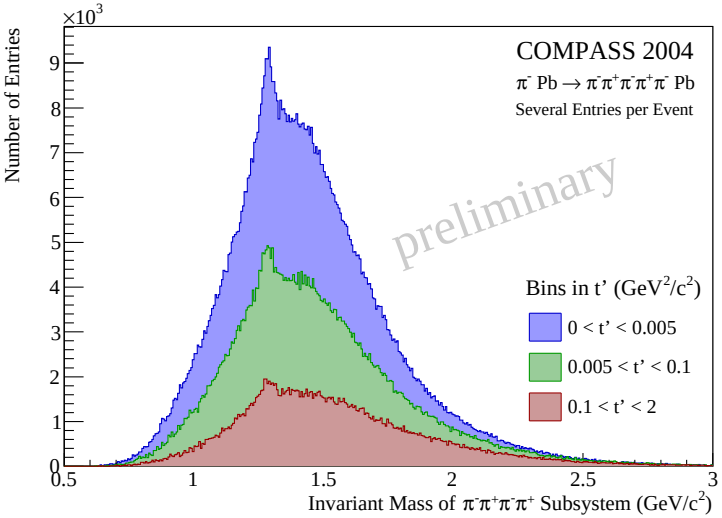
# $4\pi$ Subsystem – the $f_1$ and Friends

## Isobar Candidates




## Cut $4\pi$ spectrum:




## Isobar candidates:

| Name | Mass ($\mathrm{GeV}/c^2$) | $I^G(J^{PC})$ |
|---|---|---|
| $f_0$ | 1370 / 1700 | $0^+(0^{++})$ |
| $\eta'$ | 1403 | $0^+(0^{-+})$ |
| $\rho'$ | 1450 | $1^+(1^{--})$ |
| $b_1$ | 1235 / 1800 | $1^+(1^{+-})$ |
| $f_1$ | 1285 / 1450 | $0^+(1^{++})$ |
| $\eta_2'$ | 1645 | $0^+(2^{-+})$ |
| $f_2$ | 1565 | $0^+(2^{++})$ |
| $\rho_3$ | 1690 | $1^+(3^{--})$ |

# Summary

- COMPASS 2004 pilot run using a 190 GeV $\pi^-$ beam
  - Diffractive dissociation on lead targets exploited for meson production
  - $3\pi \sim 4\,000\,000$ events recorded within a few days of data taking
  - $5\pi \sim 370\,000$ events
  - Excellent acceptance for diffractive charged pion events ($\sim$ 55-60% for $3\pi$)

- Partial wave analysis on $\sim 400\,000$ $\pi^-\pi^-\pi^+$ events with $0.1 < t' < 1.0$ GeV$^2/c^2$
  - Dominant $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ states resolved
  - Excellent agreement with PDG
  - Also small, well-known resonances $\pi(1800)$ and $a_4(2040)$ can be fitted

- Spin-exotic $1^{-+}$ state observed in $\rho\pi$ decay channel both in intensity and phase motion
  - $\Rightarrow$ consistent with $\pi_1(1600)$ resonance
  - Publication about to be submitted

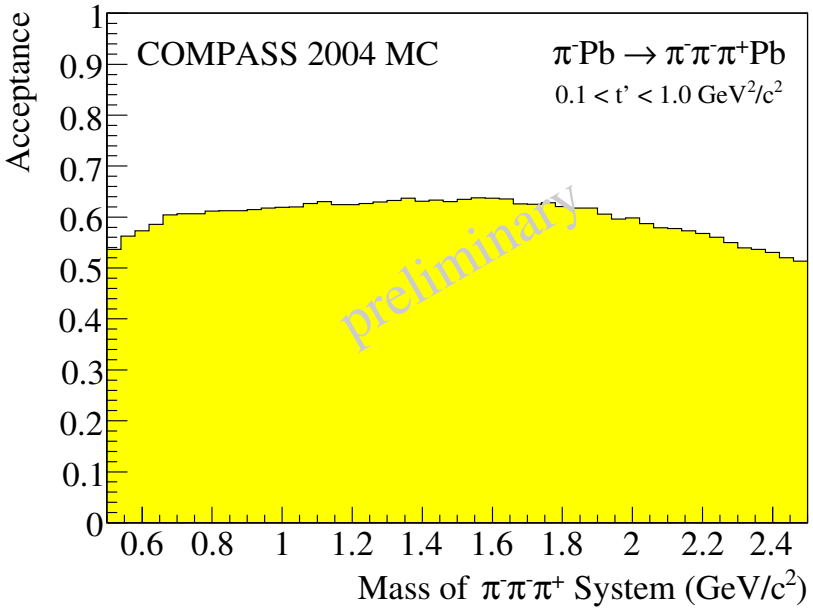
# Outlook

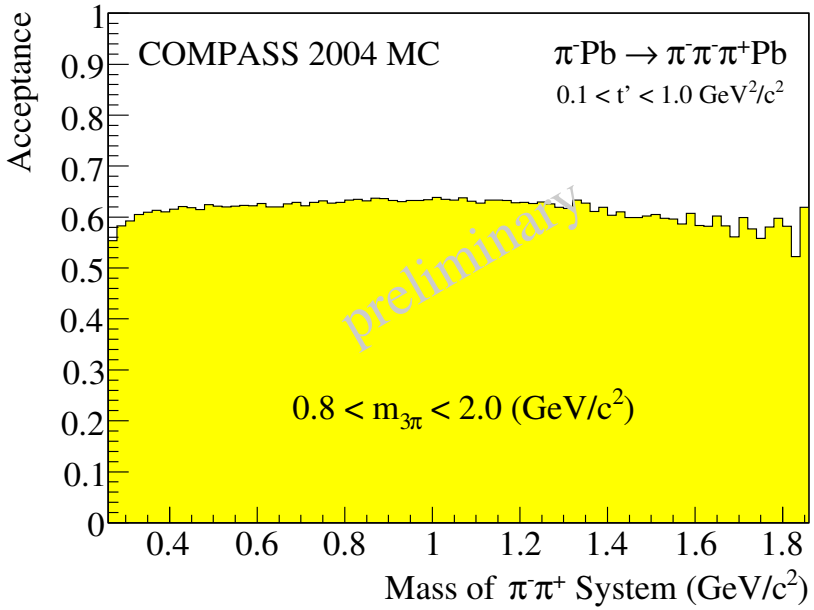
- Analysis of $5\pi^{\pm}$ final state in progress
- Clear $f_1$ signal in $4\pi$ subsystem
- New PWA software: `http://ospdev.org/projects/rootpwa`
  - Users or collaborators welcome!

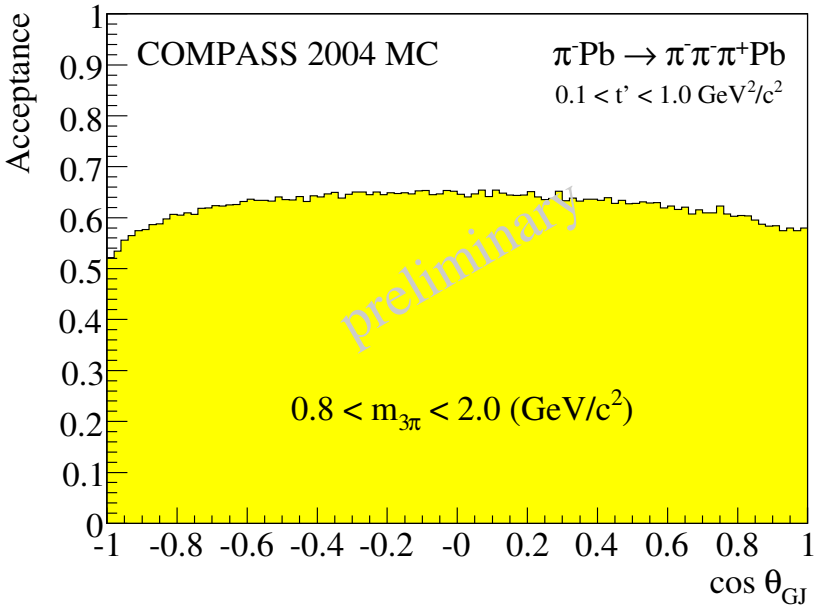
- COMPASS Hadron Run 2008
  - Change-over to liquid hydrogen target
  - Spectrometer upgrade (Recoil Detector, PID, ECAL ...)
  - $\sim$ 2 orders of magnitude more high-$t'$ statistics has been collected
  - Analysis in progress

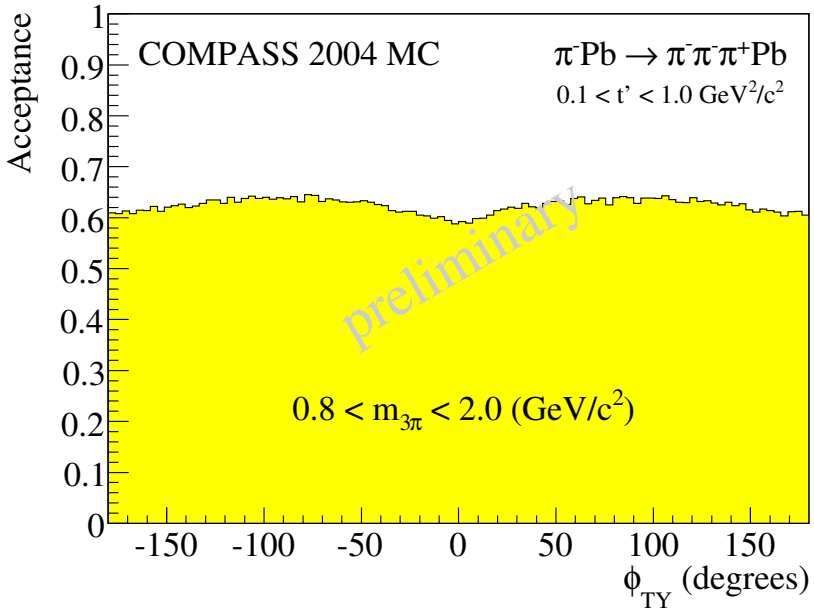
- COMPASS Hadron Run 2009 topics:
  - Central Production (proton and pion beam)
  - Diffractive Dissociation
  - Repeat measurements on Pb with upgraded spectrometer; more statistics
  - Primakoff

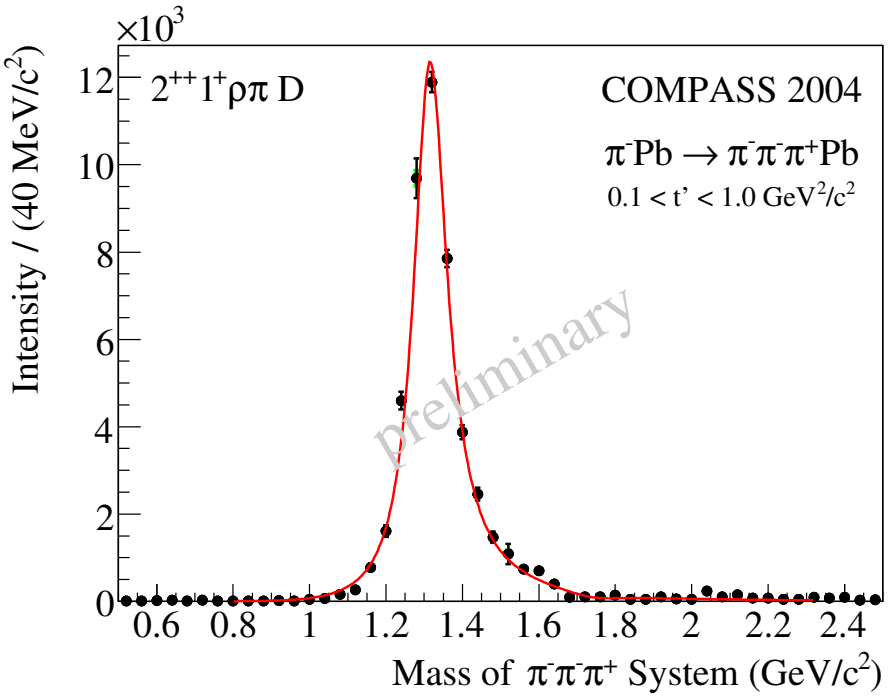
# Backup Slides: COMPASS Acceptance for $\pi^-\pi^-\pi^+$ Events

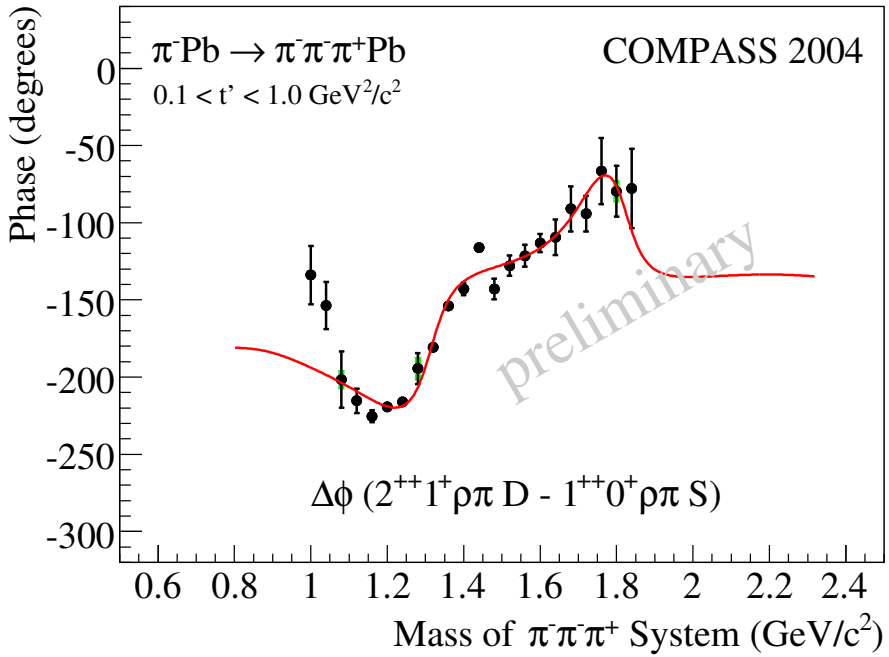





- Two Breit-Wigners needed to describe $2^{++}1^{+}\rho\pi D$ phase motion:
  BW1 for $a_2(1320)$ + BW2 for $a_2(1700)$
- $M = (1.321 \pm 0.001\ ^{+0.000}_{-0.007})\,\text{GeV}, \quad \Gamma = (0.110 \pm 0.002\ ^{+0.002}_{-0.015})\,\text{GeV}$
- $a_2(1700)$ parameters fixed to PDG values: $M = 1.732\,\text{GeV}, \quad \Gamma = 0.194\,\text{GeV}$

## Mass-Independent Cross-Section and Spin Density Matrix

$$\sigma_{\text{indep}}(\tau) = \sum_{\epsilon} \sum_{r} \left| \sum_{i} T^{\epsilon}_{ir} \psi^{\epsilon}_{i}(\tau) \Big/ \sqrt{\int |\psi^{\epsilon}_{i}(\tau')|^2 \mathrm{d}\tau'} \right|^2 \quad , \quad \rho^{\epsilon}_{ij} = \sum_{r} T^{\epsilon}_{ir} T^{\epsilon *}_{jr}$$

- $\epsilon$: reflectivity, r: rank of density matrix, $i$: different partial waves
- $T$: complex production amplitudes (fit parameters!)
- $\psi$: complex decay amplitudes
- $\tau$: phase space coordinates (5 parameters for 3-body decay)

## Likelihood Function

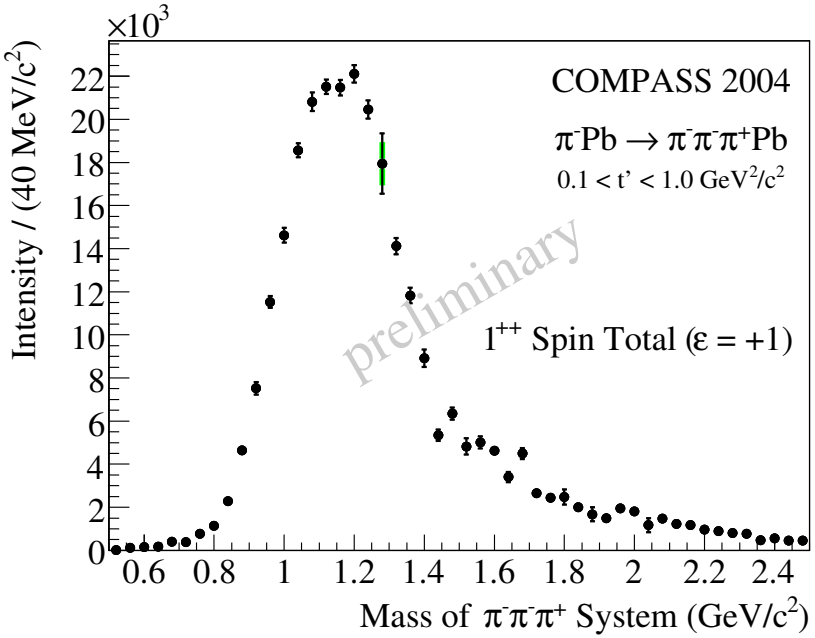
$$\ln L = \sum_{n} \ln \sigma_{\text{indep}}(\tau_n) - \int \sigma_{\text{indep}}(\tau') \text{Acc}(\tau') \mathrm{d}\tau'$$

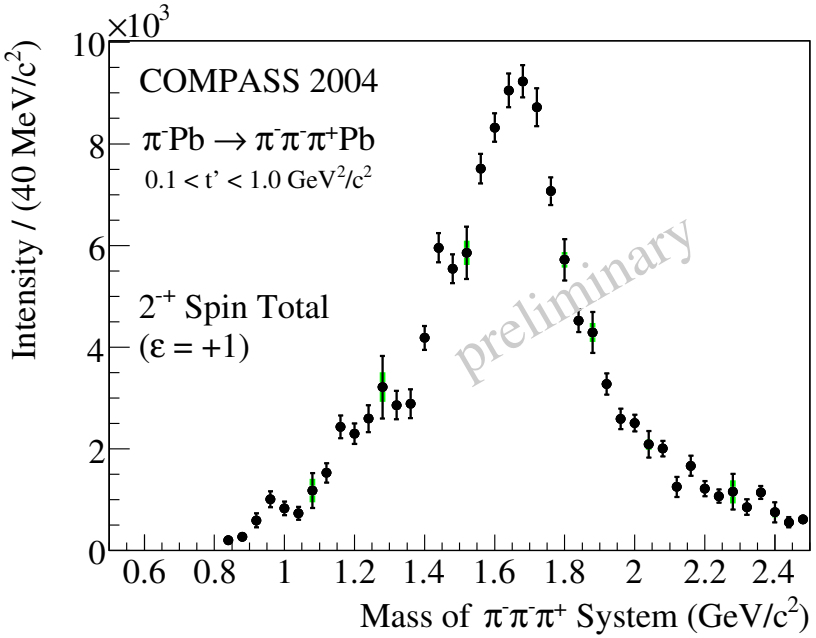
- n: analyzed events, Acc: Acceptance

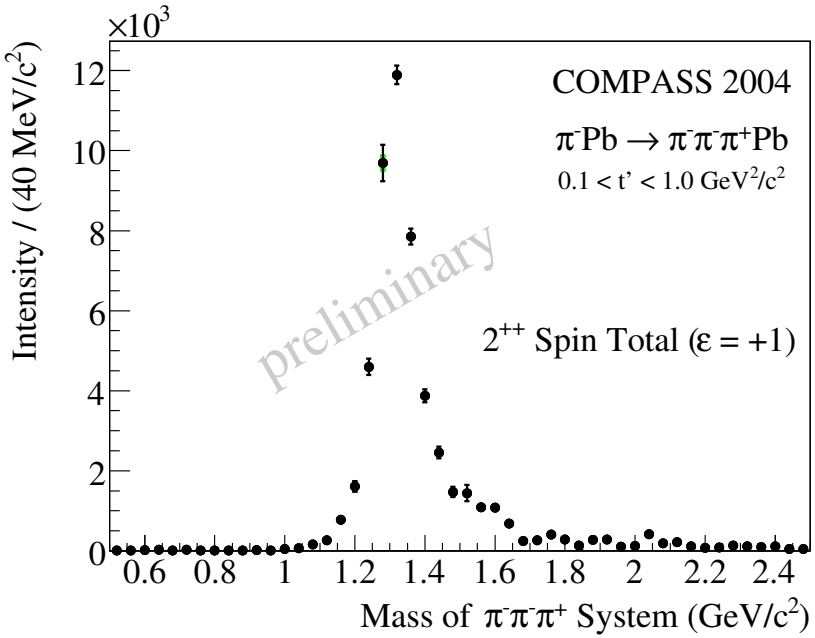
## Mass-Dependent Fit

$$\rho^{\epsilon}_{ij} = \sum_{r} \left( \sum_{k} C^{\epsilon}_{ikr} \text{BW}_k(m) \sqrt{\int |\psi^{\epsilon}_{i}(\tau)|^2 \mathrm{d}\tau} \right) \left( \sum_{l} C^{\epsilon}_{jlr} \text{BW}_l(m) \sqrt{\int |\psi^{\epsilon}_{j}(\tau)|^2 \mathrm{d}\tau} \right)^*$$

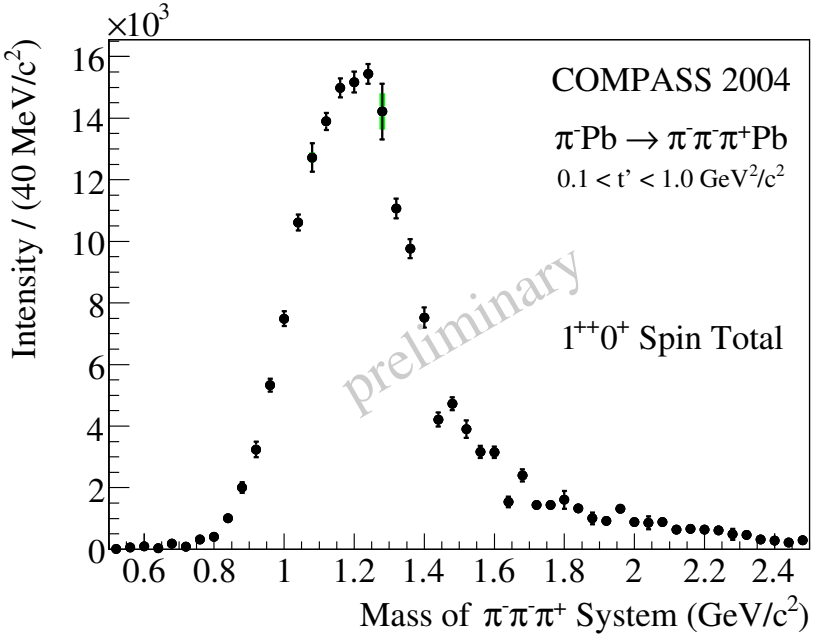
# Backup Slides: Spin Totals

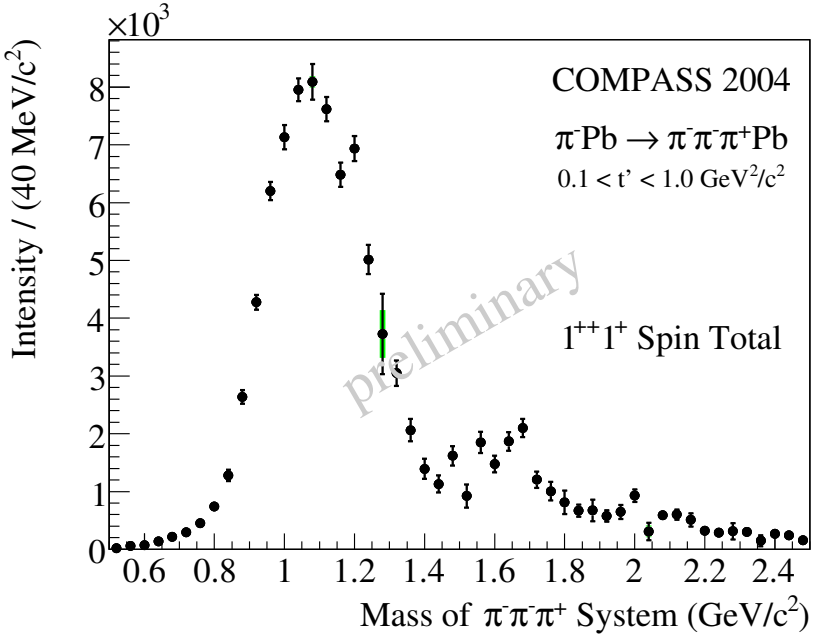


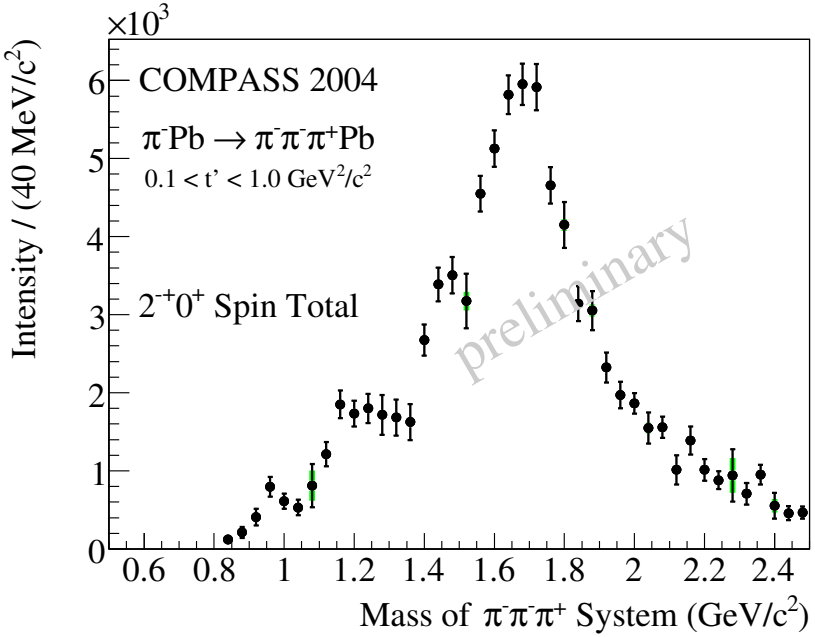



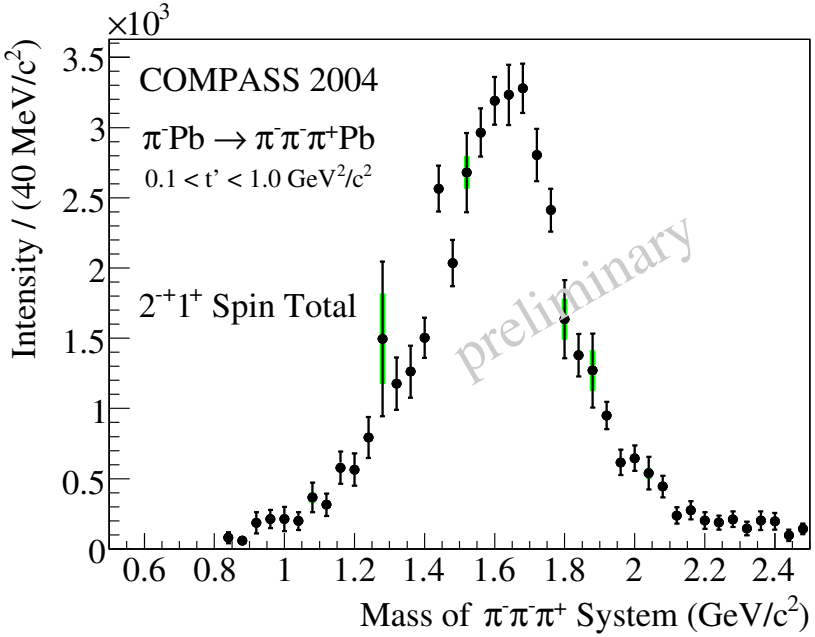



# Backup Slides: $M = 0$ and $M = 1$ Spin Totals



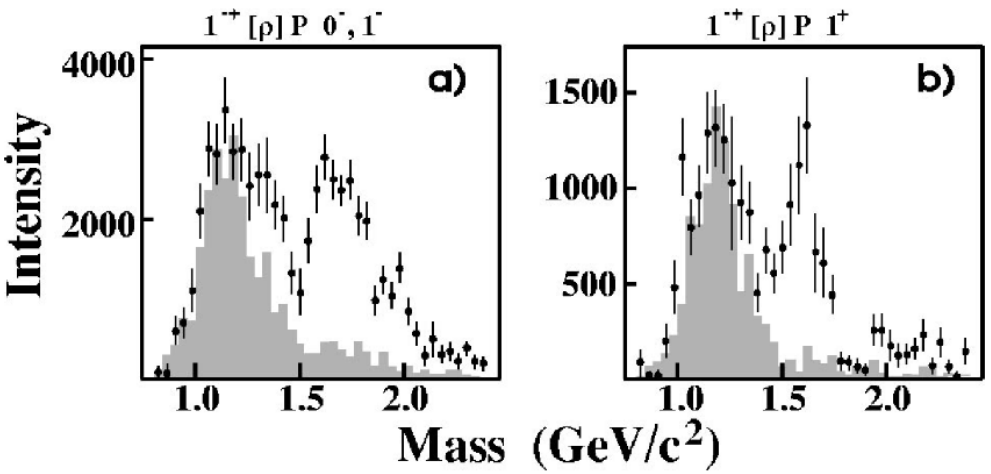



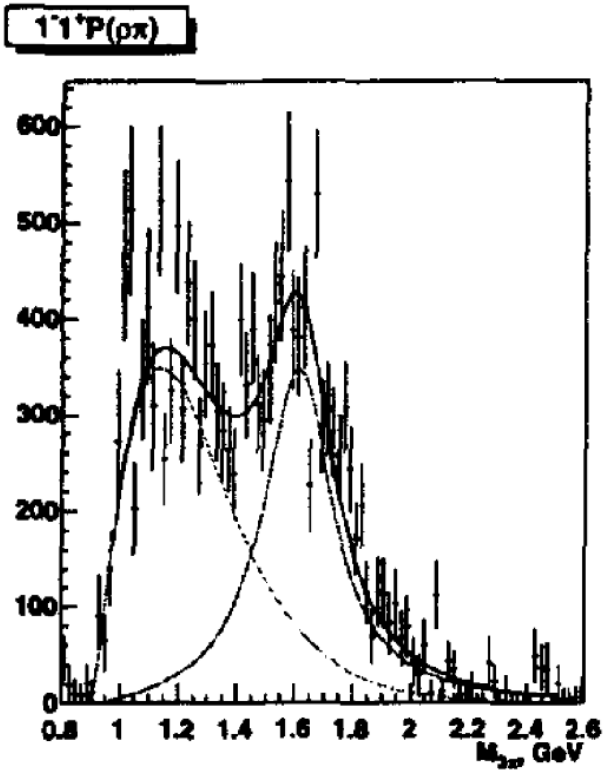
# Summary of Results and Comparison to PDG (2006)

| State | (GeV) | COMPASS ± stat ± syst | PDG |
|---|---|---|---|
| $a_1(1260)$ | $M$ | 1.256 ± 0.006 + 0.007 - 0.017 | 1.230 ± 0.040 |
| | $\Gamma$ | 0.366 ± 0.009 + 0.028 - 0.025 | 0.250 to 0.600 |
| $a_2(1320)$ | $M$ | 1.321 ± 0.001 + 0.000 - 0.007 | 1.3183 ± 0.0006 |
| | $\Gamma$ | 0.110 ± 0.002 + 0.002 - 0.015 | 0.107 ± 0.005 |
| $\pi_1(1600)$ | $M$ | 1.660 ± 0.010 + 0.000 - 0.064 | $1.653^{+0.018}_{-0.015}$ |
| | $\Gamma$ | 0.269 ± 0.021 + 0.042 - 0.064 | $0.225^{+0.045}_{-0.028}$ |
| $\pi_2(1670)$ | $M$ | 1.659 ± 0.003 + 0.024 - 0.008 | 1.6724 ± 0.0032 |
| | $\Gamma$ | 0.271 ± 0.009 + 0.022 - 0.024 | 0.259 ± 0.009 |
| $\pi(1800)$ | $M$ | 1.785 ± 0.009 + 0.012 - 0.006 | 1.812 ± 0.014 |
| | $\Gamma$ | 0.208 ± 0.022 + 0.021 - 0.037 | 0.207 ± 0.013 |
| $a_4(2040)$ | $M$ | 1.884 ± 0.013 + 0.050 - 0.002 | 2.001 ± 0.010 |
| | $\Gamma$ | 0.295 ± 0.024 + 0.046 - 0.019 | 0.313 ± 0.031 |

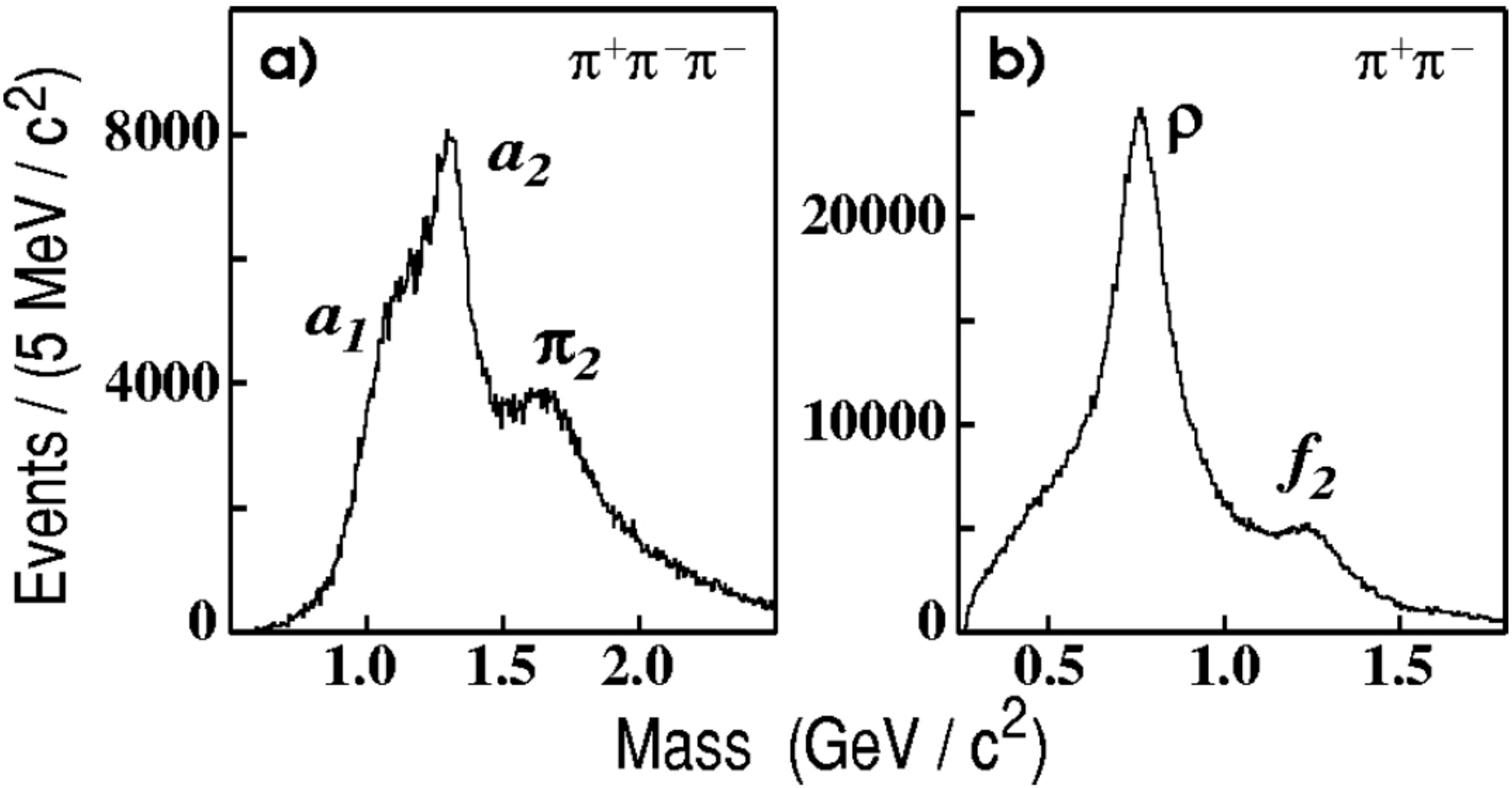
# Backup Slides: BNL-E852 and VES $1^{-+}$ Signal




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

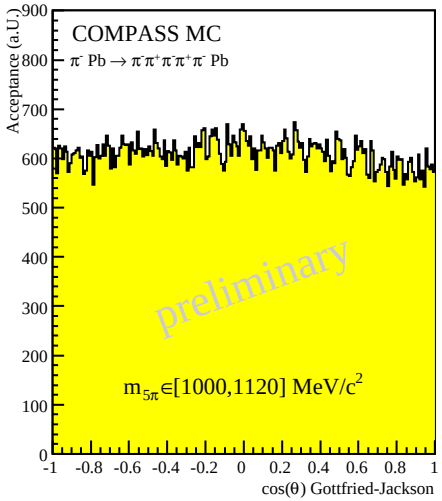


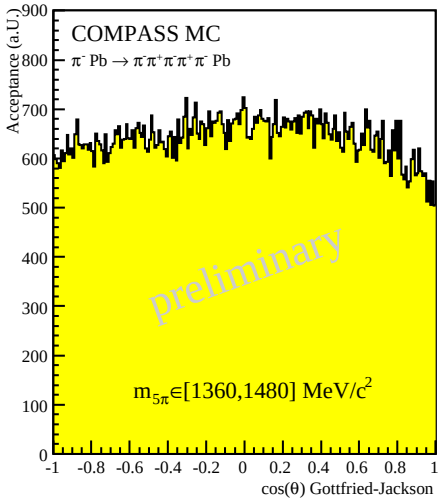

VES, Nucl. Phys. **A663**, 596, 2000

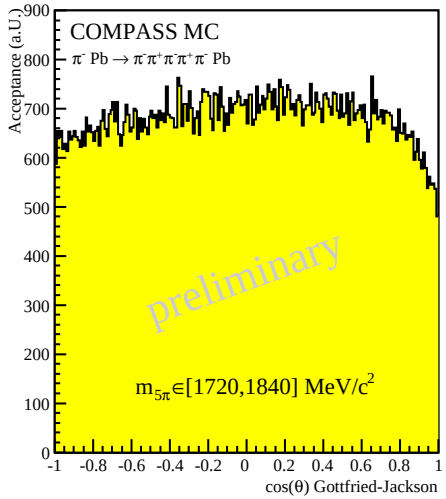


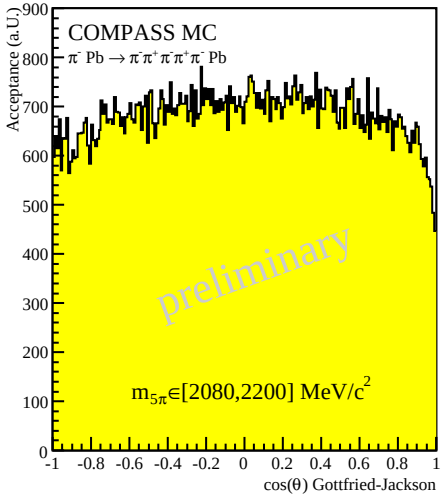

Phys. Rev. **D65**, 072001, 2002

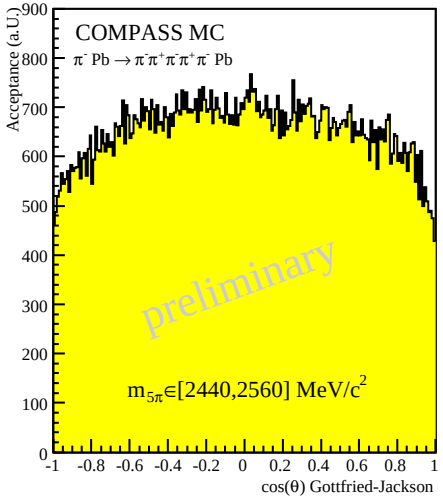
Single pion decay angle in $X^-$ rest frame (Gottfried-Jackson frame).

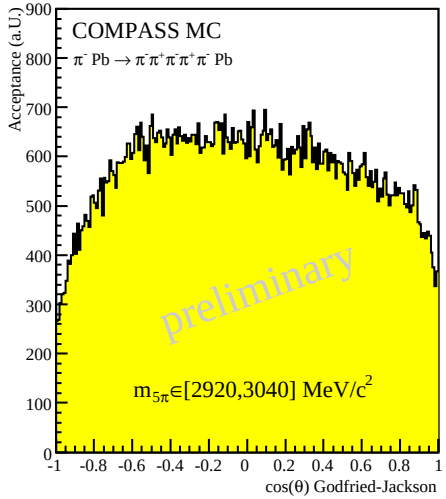


# Backup Slides: 3 and $2\pi$ Subsystems