Hadron Spectroscopy in COMPASS

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for the COMPASS Collaboration

CERN

On leave of absence from
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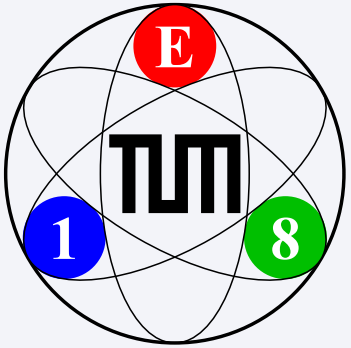
Technische Universität München,
Garching, Germany

Xth Quark Confinement and the Hadron Spectrum
Munich, 09.10.2012



The COMPASS Physics Program

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Goal

- Study non-perturbative QCD
- Probe structure and dynamics of hadrons

Very low Q^2: chiral dynamics

- π and K em. polarizabilities
- $\pi\gamma$ reactions (Primakoff)

J. M. Friedrich, Fri Session B7

Intermediate Q^2: spectroscopy

- Mass spectrum of hadrons
- Gluonic excitations

Large Q^2: nucleon structure

- Helicity, transversity PDFs
- Generalized PDFs

Outline

1. The experimental setup

2. Search for spin-exotic mesons in π^- diffraction
   - PWA of $\pi^-\pi^+\pi^-$ system
   - PWA of $\pi^-\eta$ and $\pi^-\eta'$ from final states
   - PWA of $\pi^-\pi^+\pi^-\pi^+\pi^-$ decay channel

3. Search for scalar glueballs in central production
   - PWA of $\pi^+\pi^-$ system

Outline

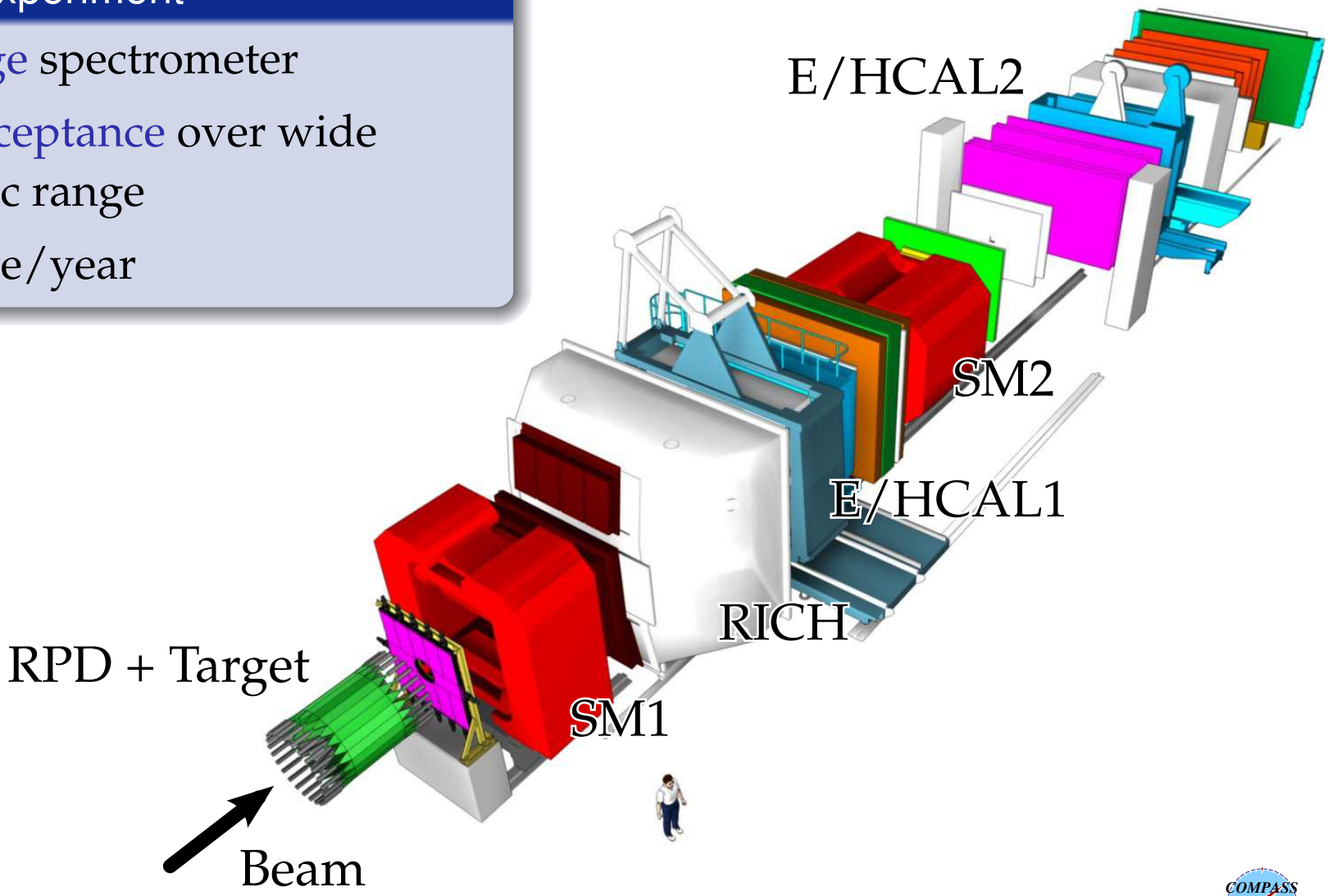
The COMPASS Experiment at the CERN SPS

Experimental Setup

NIM A **577**, 455 (2007)

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- > 1 PByte/year



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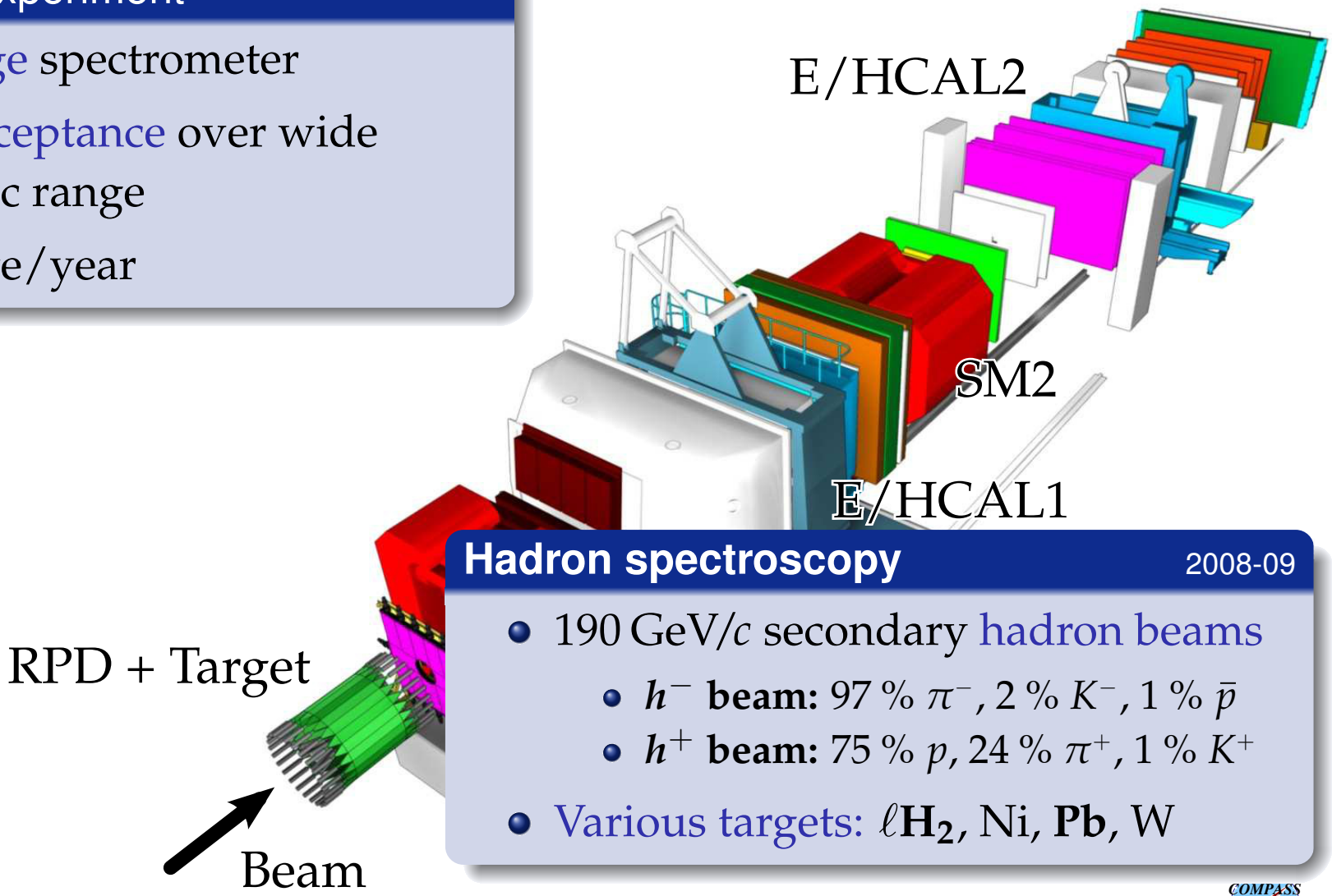


Hadron spectroscopy 2008-09

- 190 GeV/c secondary hadron beams
  - h^- **beam:** 97 % π^-, 2 % K^-, 1 % $\bar{p}$
  - h^+ **beam:** 75 % p, 24 % π^+, 1 % K^+
- Various targets: $\ell\mathbf{H_2}$, Ni, **Pb**, W

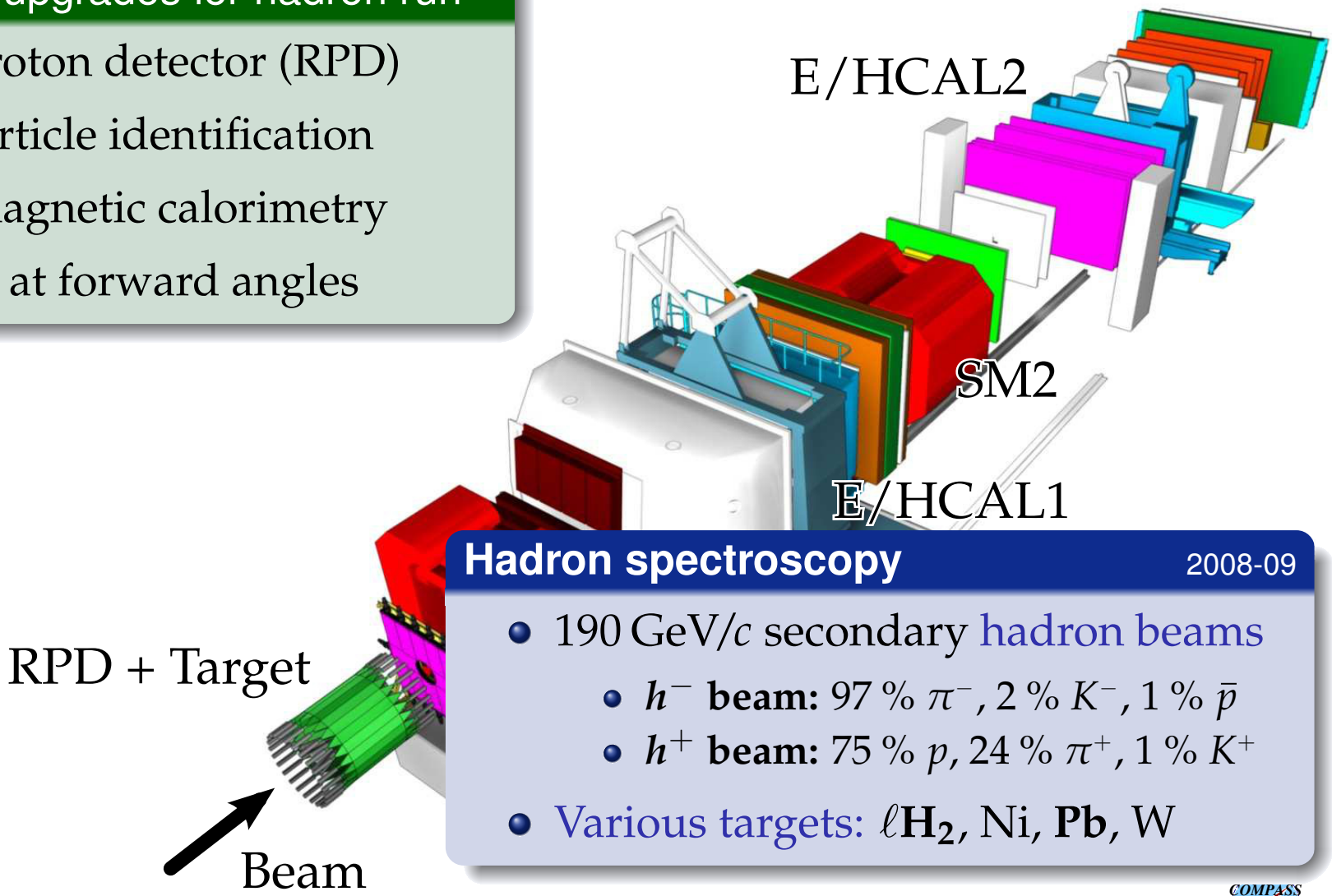
The COMPASS Experiment at the CERN SPS

Experimental Setup

NIM A **577**, 455 (2007)

Spectrometer upgrades for hadron run

- Recoil proton detector (RPD)
- Beam particle identification
- Electromagnetic calorimetry
- Tracking at forward angles



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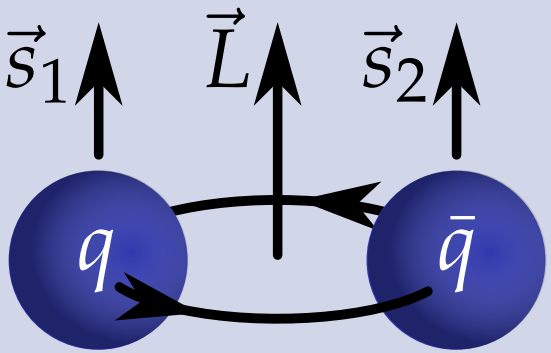
Mesons in the Constituent Quark Model

Spin-parity rules for bound $q\bar{q}$ system

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative orbital angular Momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- **Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$**
- Extension to charged mesons via G parity: $G = (-1)^{L+S+I}$



QCD allows for **states beyond the CQM**

- Hybrids $|q\bar{q}g\rangle$, glueballs $|gg\rangle$, multi-quark states $|q^2\bar{q}^2\rangle, \ldots$
- **Physical mesons:** superposition of all allowed basis states
- "Exotic" mesons have quantum numbers forbidden for $|q\bar{q}\rangle$
  - Particularly interesting: J^{PC}-exotic states

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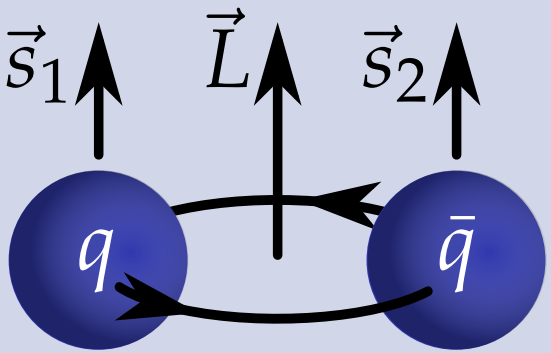

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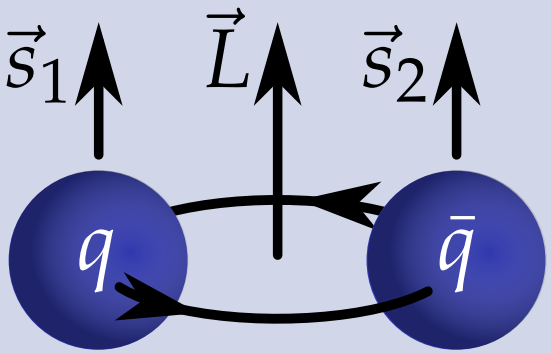

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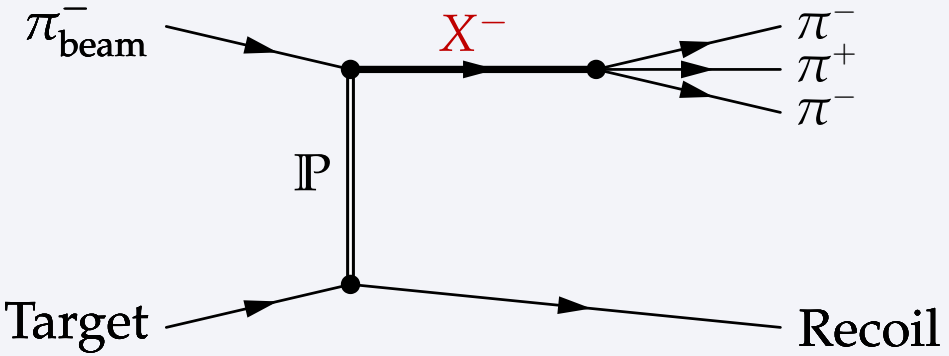
Production of Hadrons in Diffractive Dissociation



- Soft scattering of beam hadron off nuclear target (remains intact)
  - Beam particle is excited into some intermediate state X
  - X decays into n-body final state
- High $\sqrt{s}$ and low t': Pomeron exchange dominates strong interaction
- Rich spectrum: large number of overlapping and interfering X
- **Goal:** use kinematic distribution of final-state particles to
  - Disentangle all resonances X
  - Determine their mass, width, and quantum numbers
- **Method:** partial-wave analysis (PWA)

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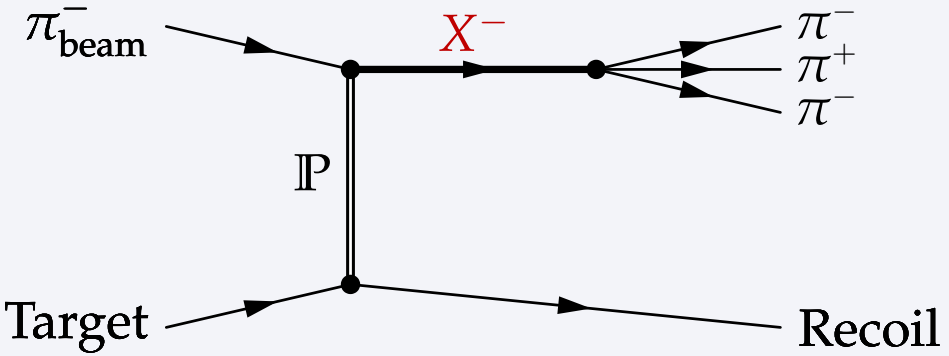

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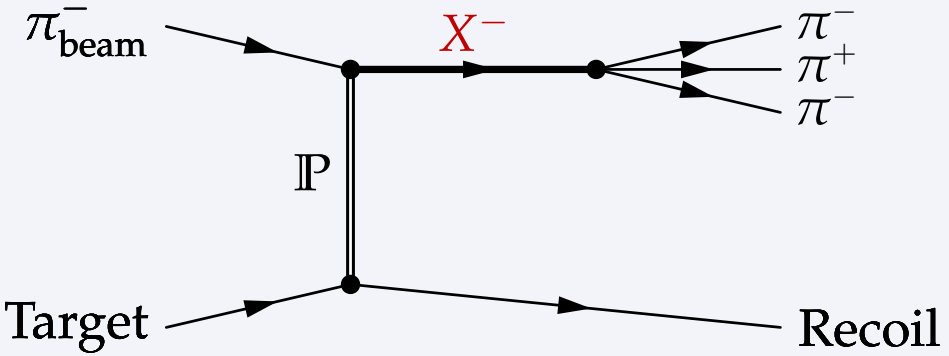

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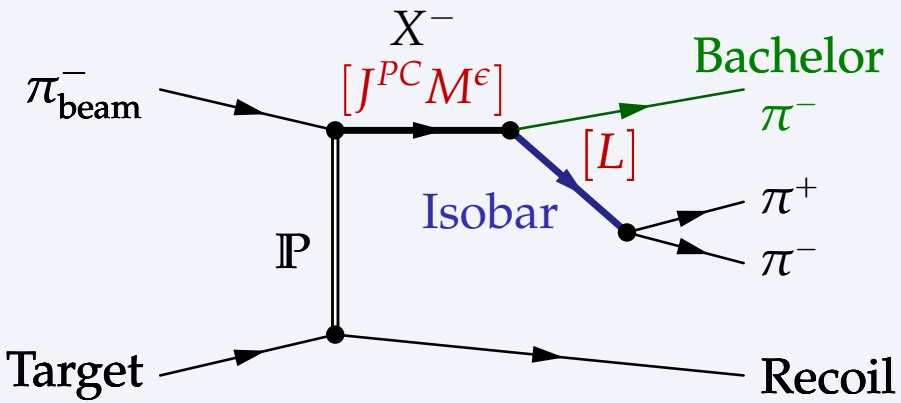
Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State



Isobar model: X^- decay is chain of successive two-body decays

- **"Wave":** unique combination of isobar and quantum numbers
- Full wave specification (in reflectivity basis): $J^{PC}M^{\epsilon}[\text{isobar}]L$

Fit model: $\sigma(m_X,\tau) = \sigma_0 \left|\sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(m_X,\tau)\right|^2$

- Calculable decay amplitudes $A_{\text{wave}}(m_X,\tau)$
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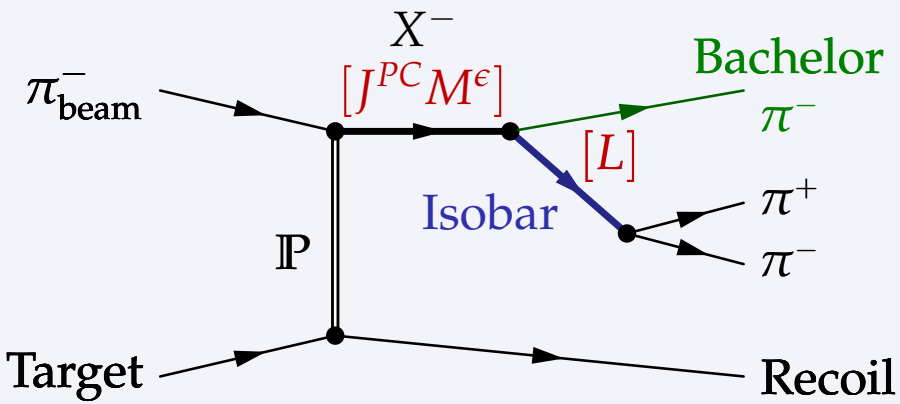

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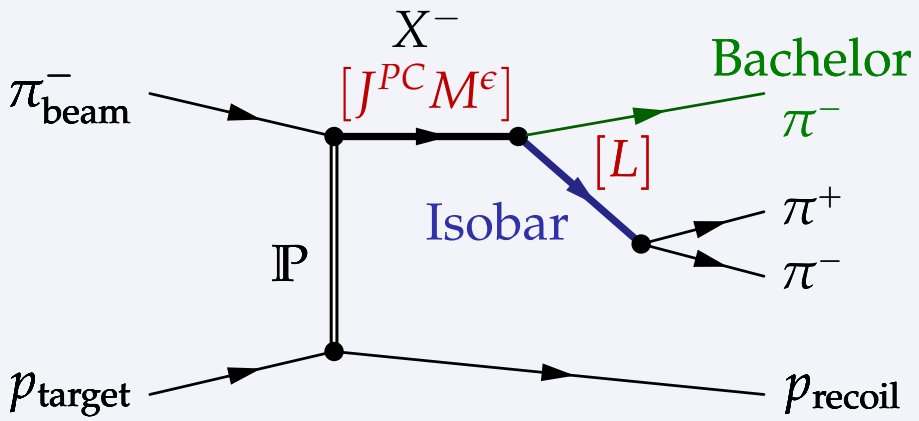
PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$



- 190 GeV/c negative hadron beam: 97 % π^-, 2 % K^-, 1 % $\bar{p}$
- Liquid hydrogen target
- Recoil proton p_{slow} measured by RPD
- Kinematic range $0.1 < t' < 1.0\ (\text{GeV}/c)^2$

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

World's largest 3π data set: $\approx$ 50 M exclusive events

- Challenging analysis
  - Needs precise understanding of apparatus
  - Model deficiencies become visible

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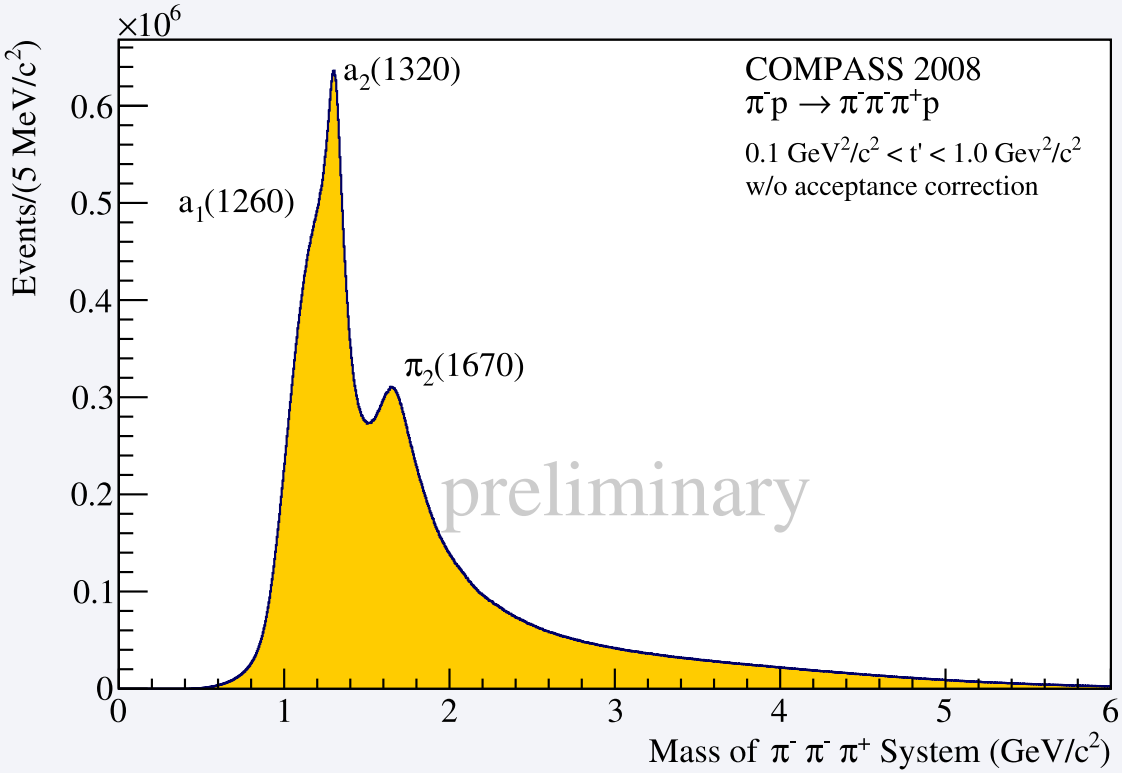
$\pi^-\pi^+\pi^-$ invariant mass distribution



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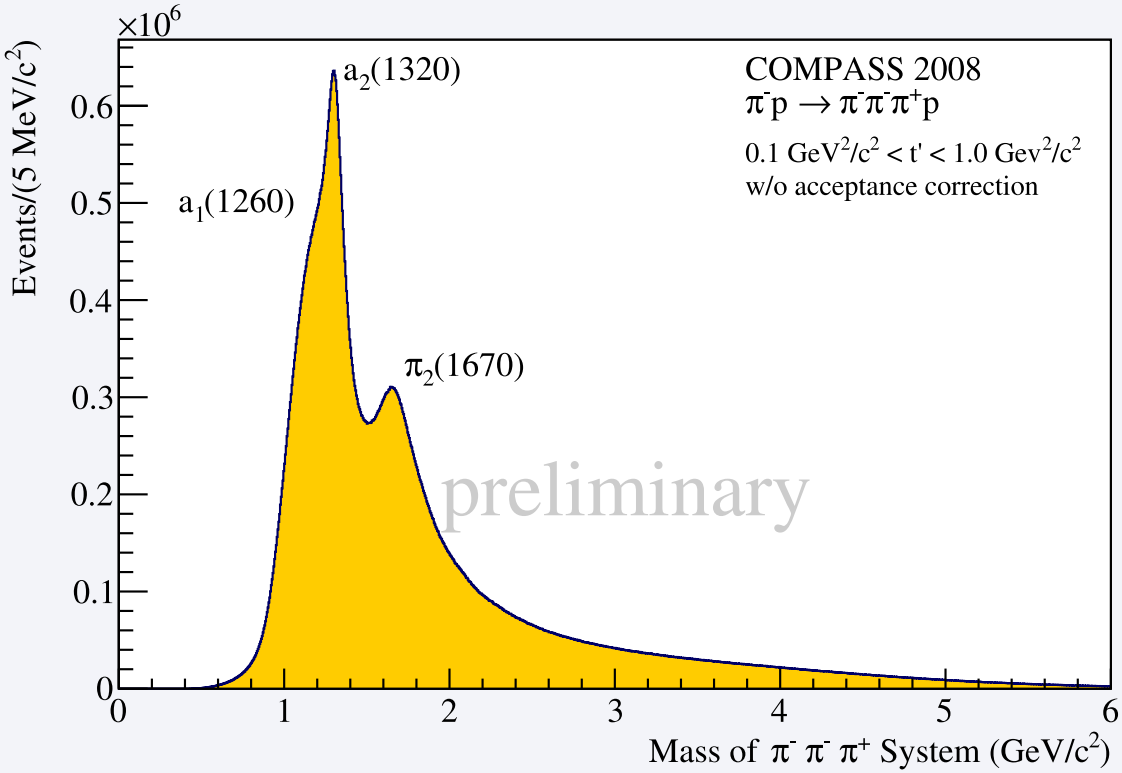
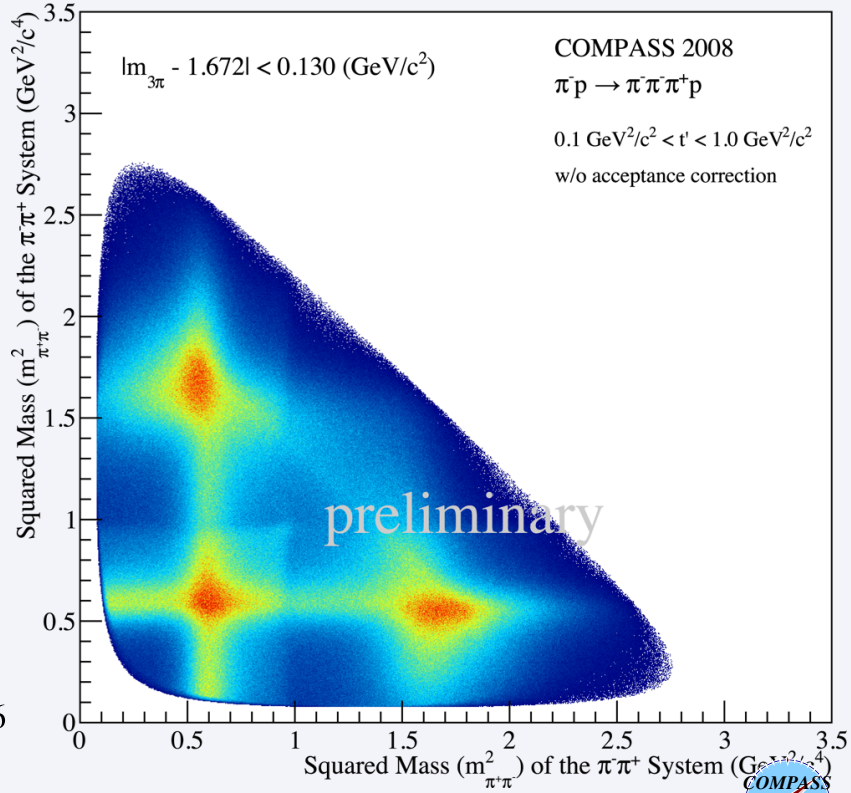


Dalitz plot for $\pi_2(1670)$ region



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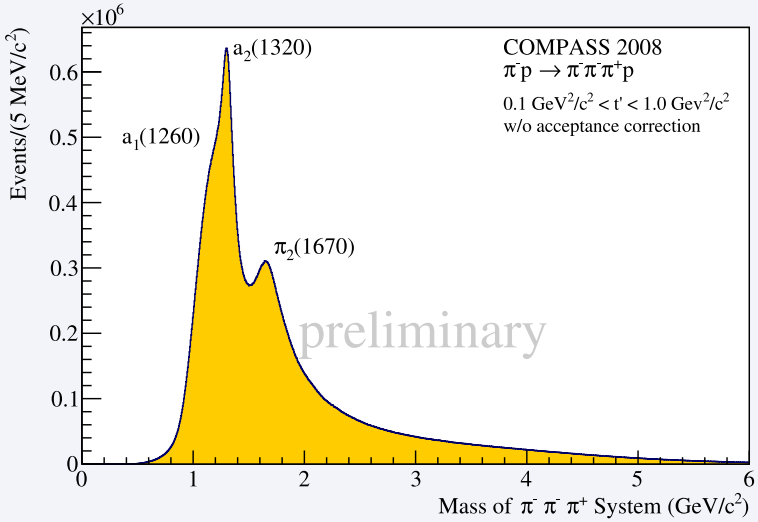

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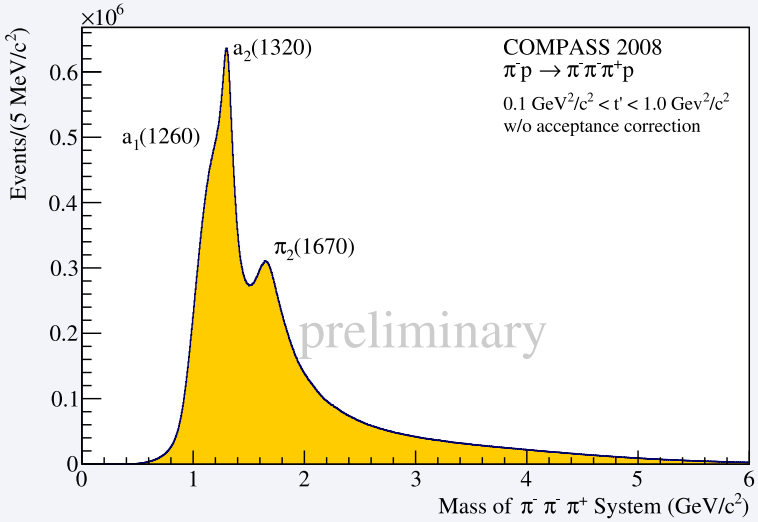
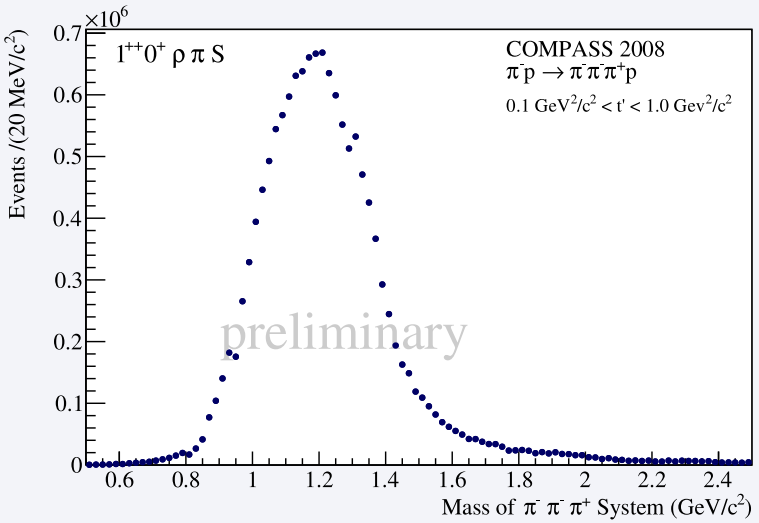


$1^{++}\,0^+\,[\rho\pi]S$: $a_1(1260)$



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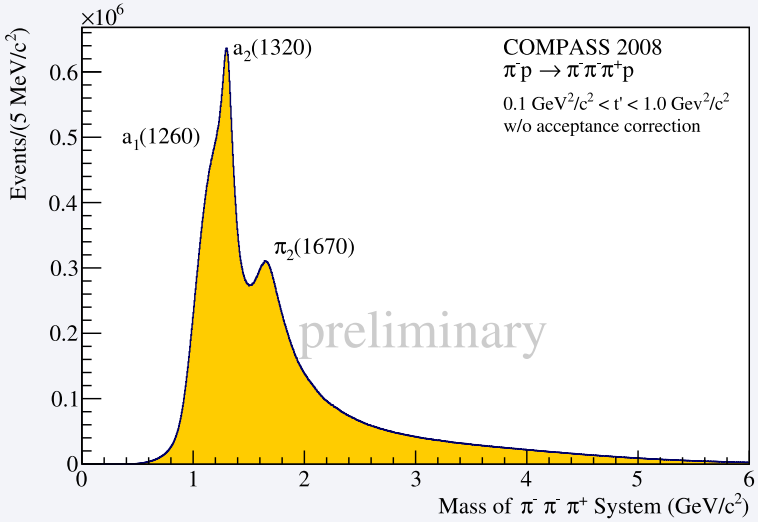

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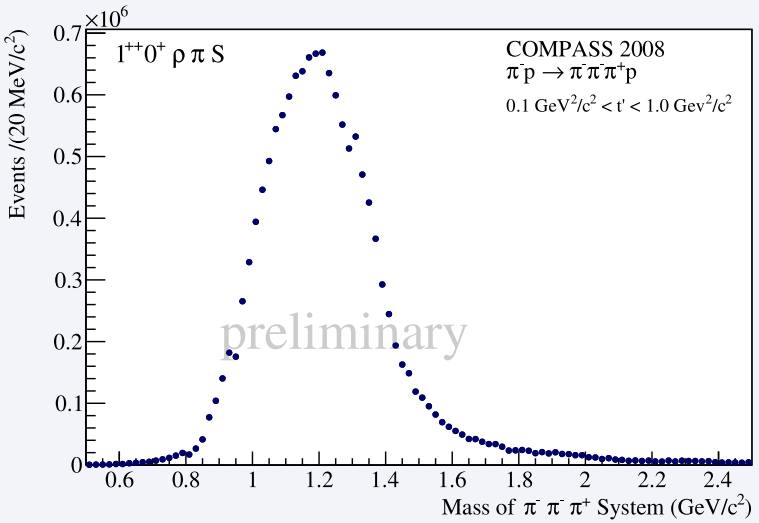
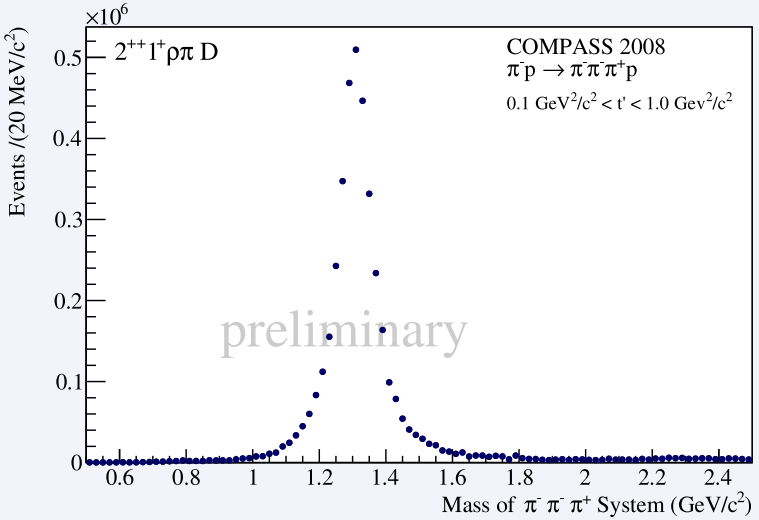


$2^{++}\,1^+\,[\rho\pi]D$: $a_2(1320)$



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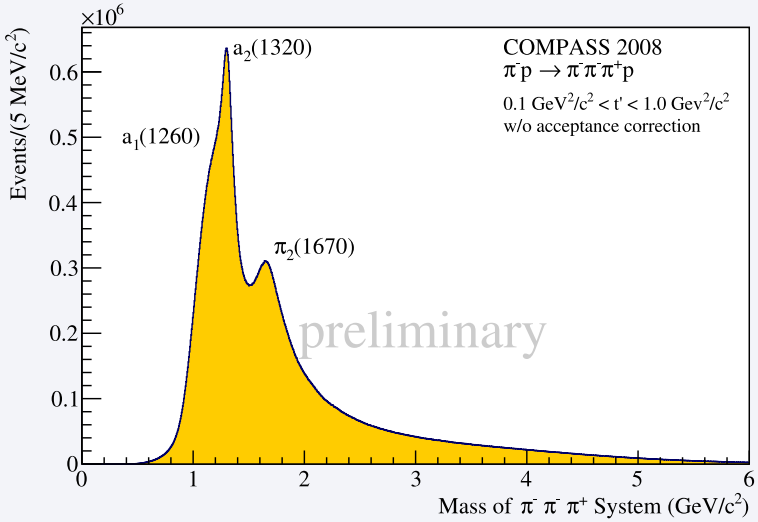

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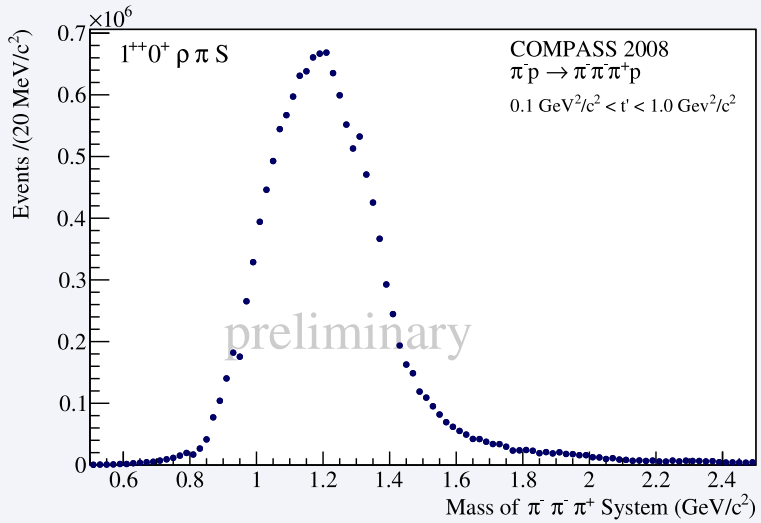
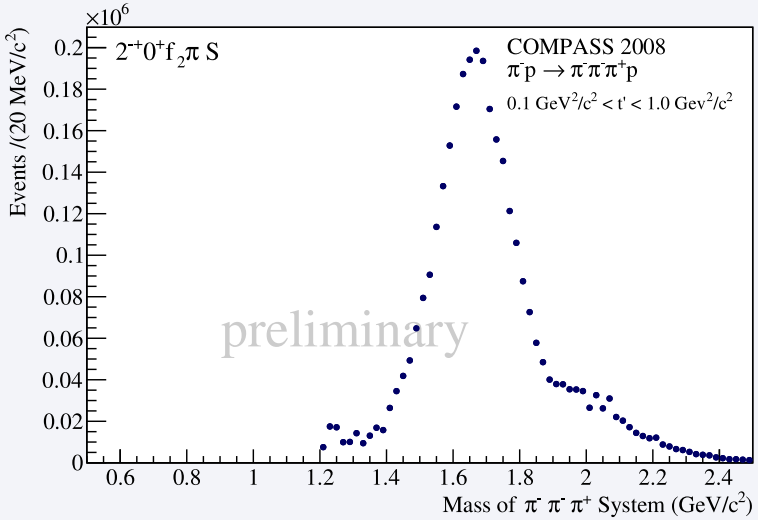


$2^{-+}\,0^+\,[f_2\pi]S$: $\pi_2(1670)$



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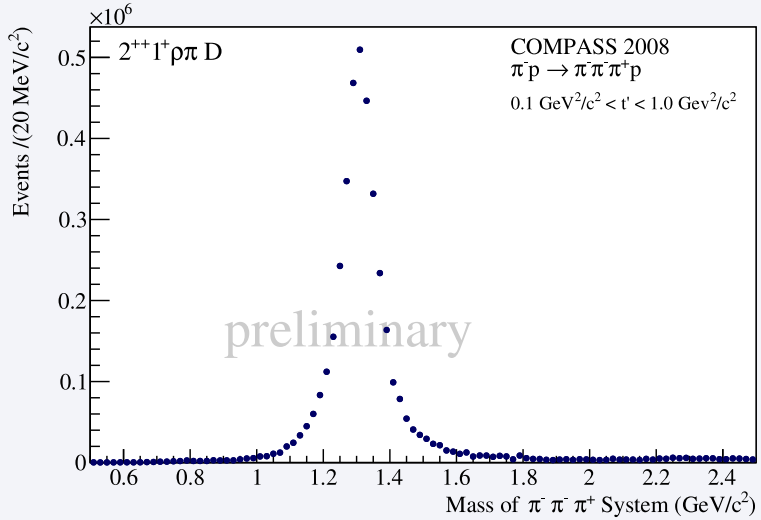

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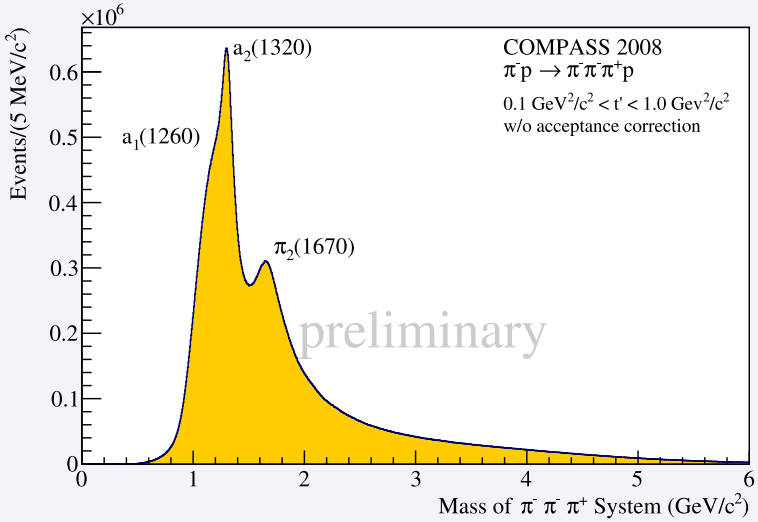
$\pi^-\pi^+\pi^-$ invariant mass spectrum



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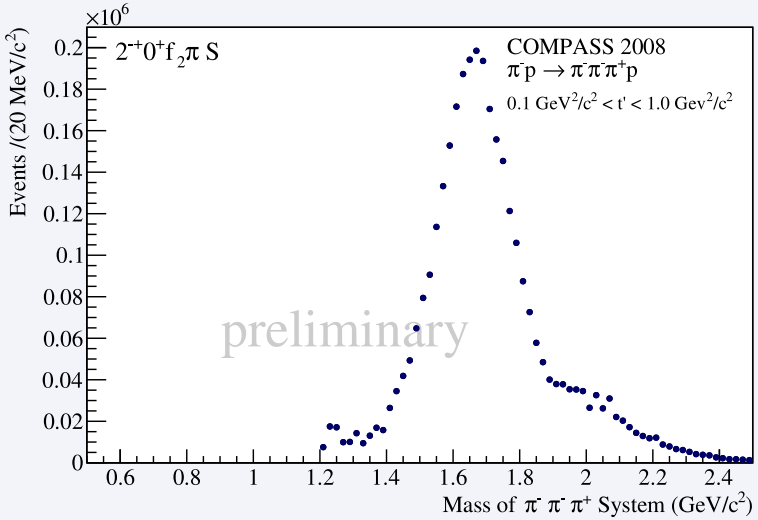

Cf. data from 2004 pilot-run

PRL **104** (2010) 241803

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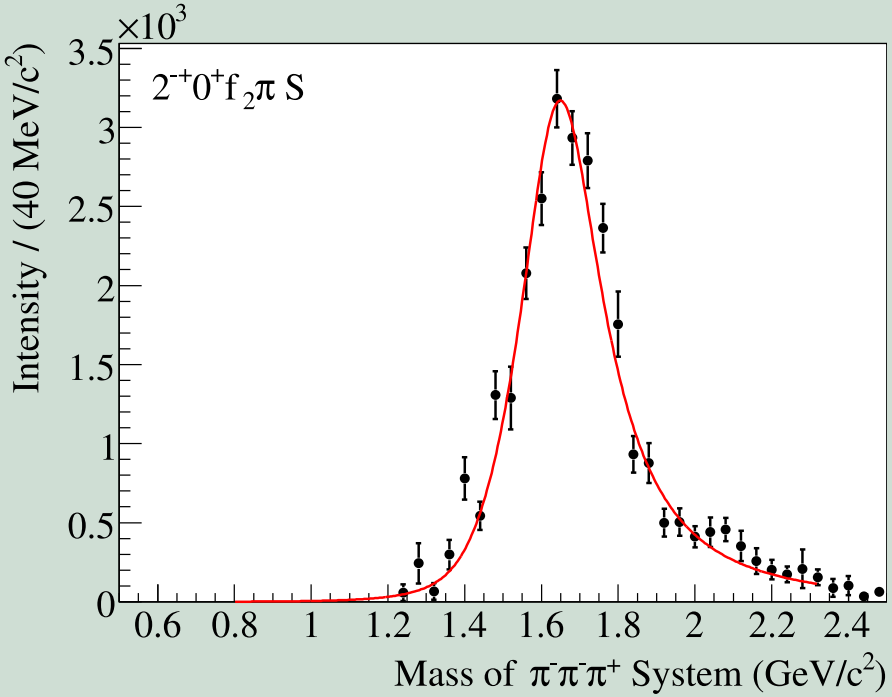
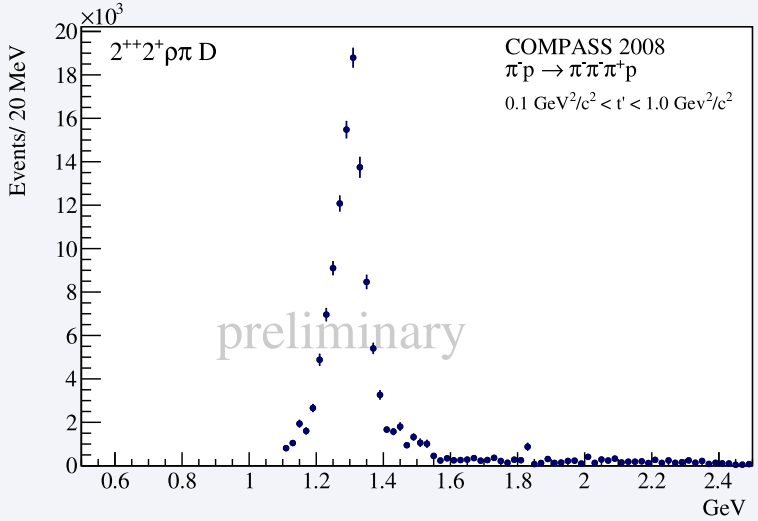


- 420 000 events
- Pb target

Mass of π⁻ π⁻ π⁺ System (GeV/c²)

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

$2^{++}\,2^+\,[\rho\pi]D$: $a_2(1320)$



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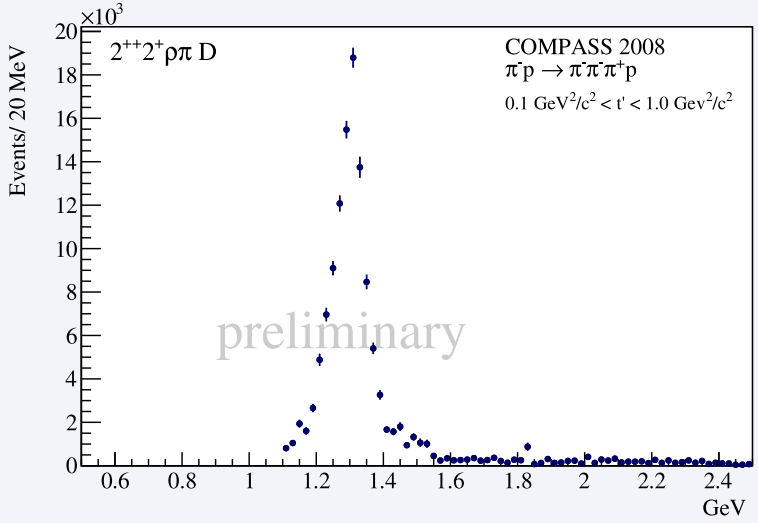
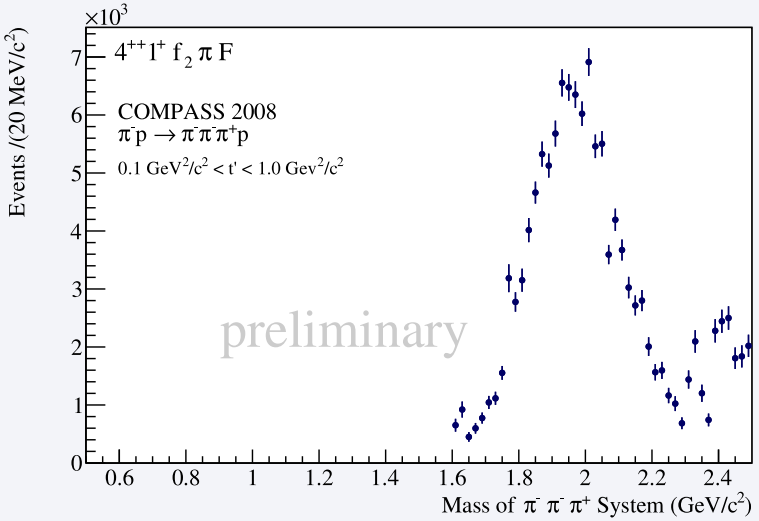


$4^{++}\,1^+\,[f_2\pi]F$: $a_4(2040)$



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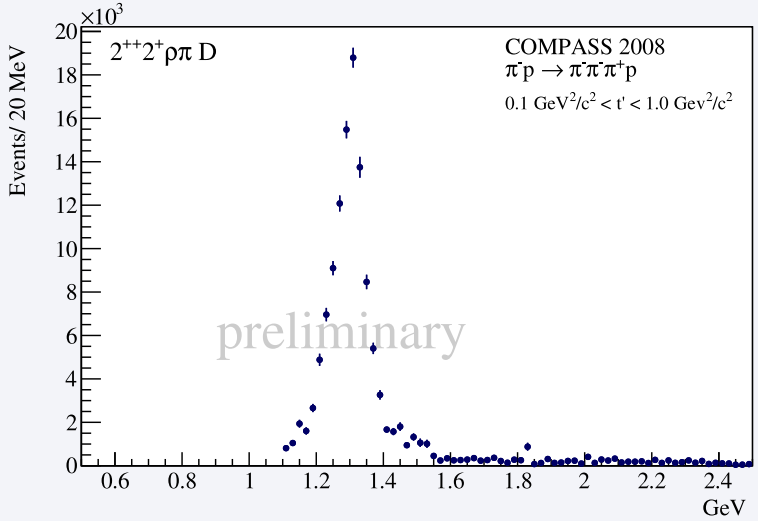

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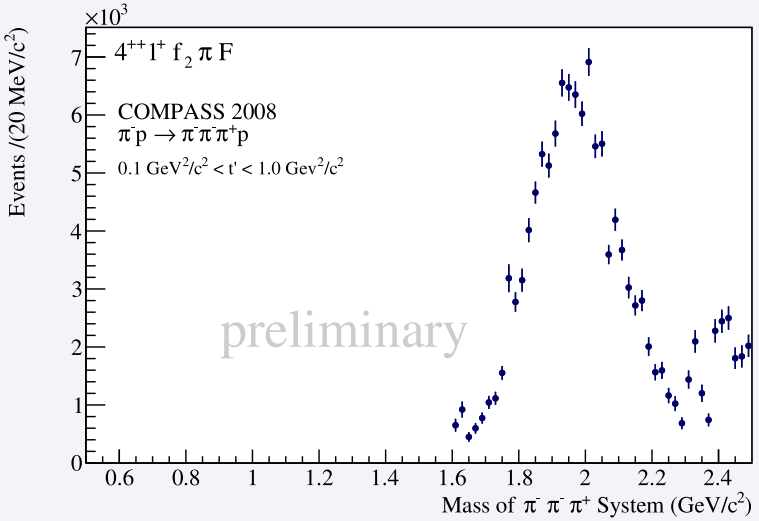
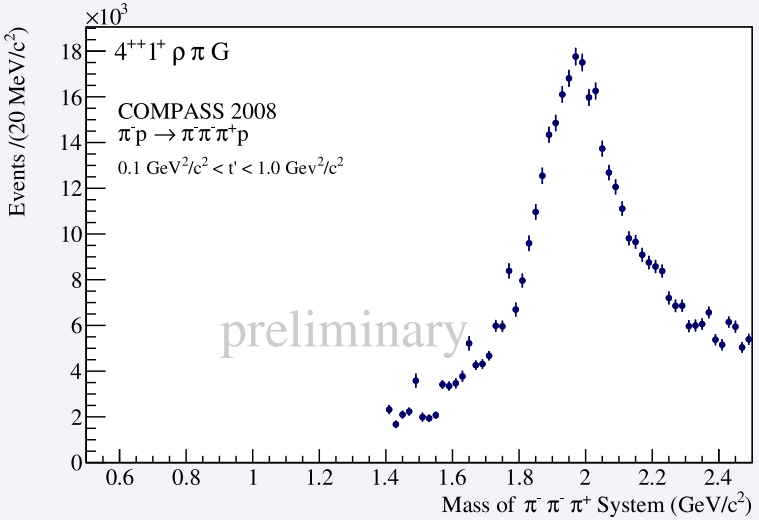


$4^{++}\,1^+\,[\rho\pi]G$: $a_4(2040)$



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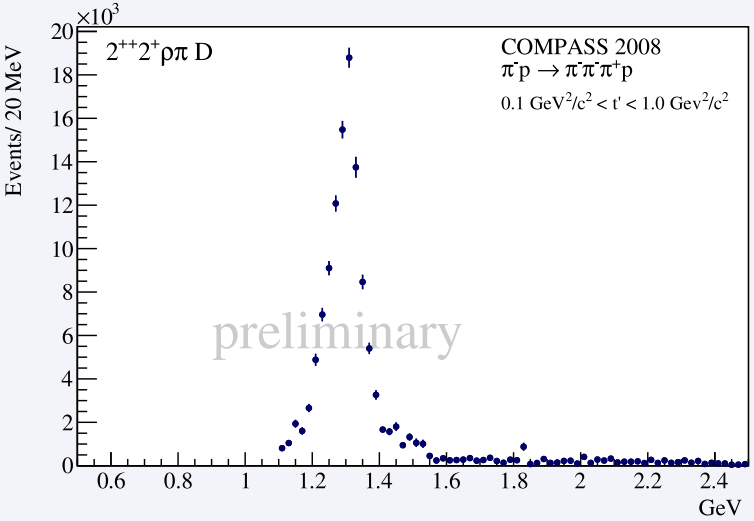
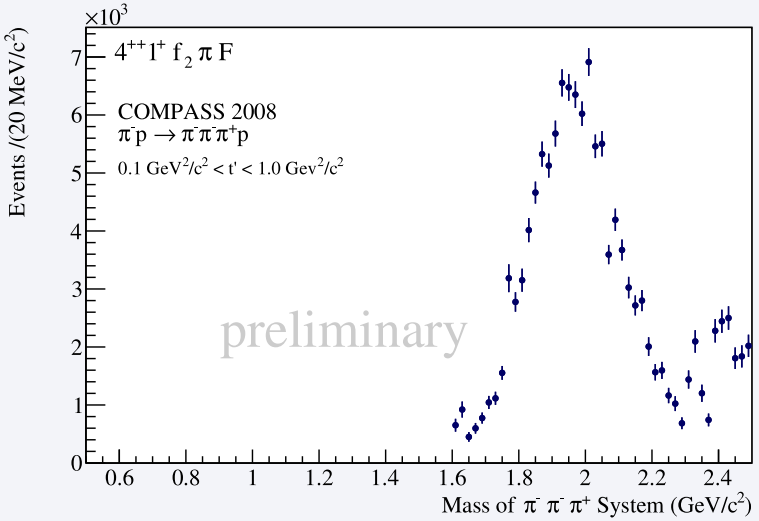
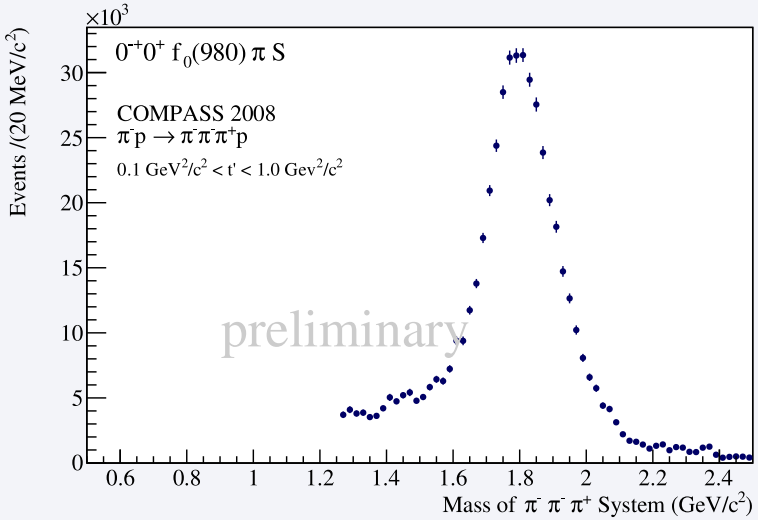


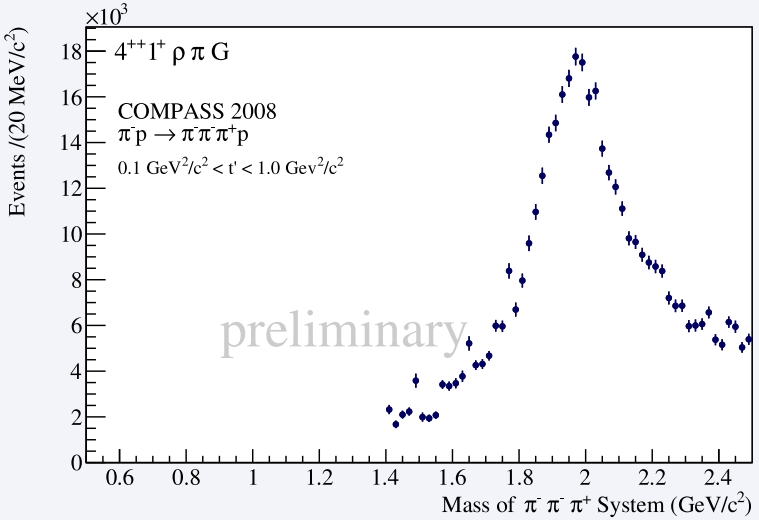
$4^{++}\,1^+\,[f_2\pi]F$: $a_4(2040)$



$0^{-+}\,0^+\,[f_0(980)\pi]S$: $\pi(1800)$



$4^{++}\,1^+\,[\rho\pi]G$: $a_4(2040)$



PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

- Data described by model consisting of 52 waves + incoherent isotropic background
  - Isobars: $(\pi\pi)_{S-\text{wave}}$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $f_0(1500)$ and $\rho_3(1690)$

Understanding of small waves is work in progress

- Wave set contains spin-exotic $1^{-+}\,1^+\,[\rho\pi]P$ wave
  - Interpretation in terms of resonances still unclear
- Significant contributions from non-resonant Deck-like processes
  - Inclusion into fit model
- Exploit t'-dependence of partial-wave amplitudes
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- Study of $\pi^-\gamma \to \pi^-\pi^+\pi^-$ using heavy nuclear targets

J. M. Friedrich, Fri Session B7

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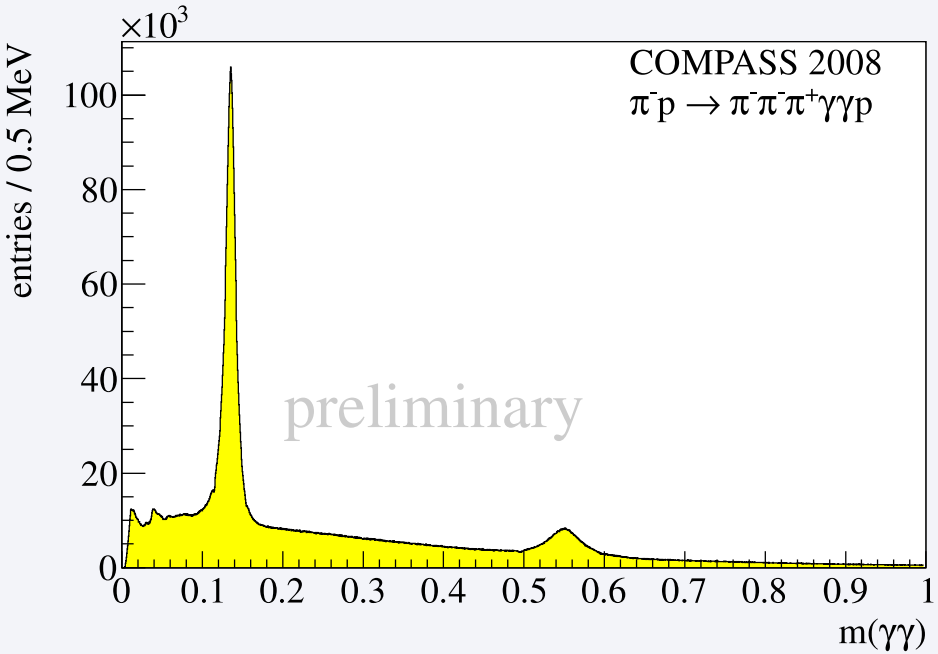
J. M. Friedrich, Fri Session B7

PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

Selection of exclusive events with 3 charged tracks + 2 photons

- Kinematic range $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- η reconstructed from $\eta \to \pi^+\pi^-\pi^0$
- η' reconstructed via $\pi^+\pi^-\eta$ decay with $\eta \to \gamma\gamma$

$\gamma\gamma$ invariant mass distribution



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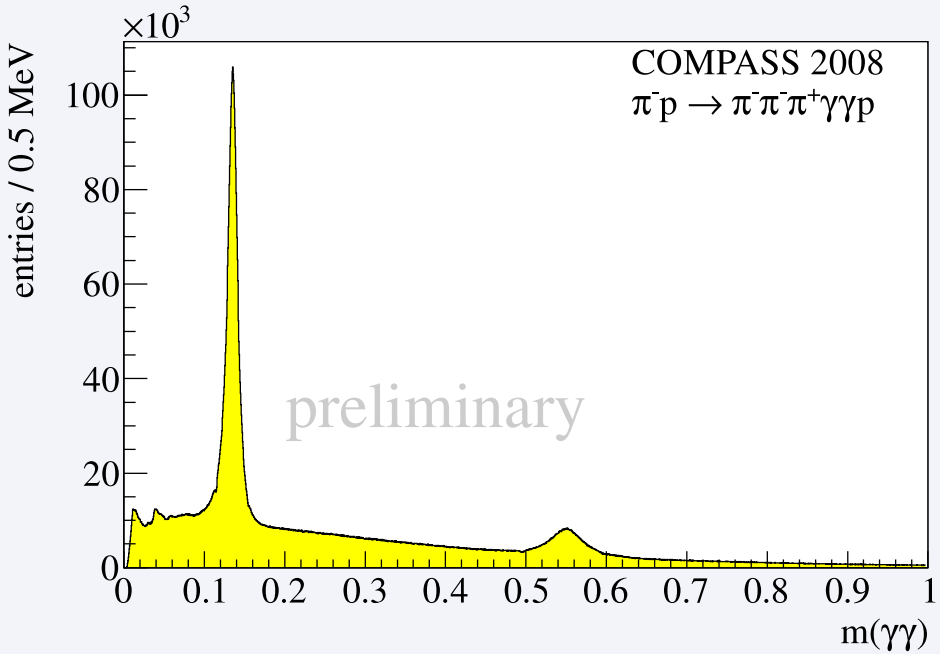
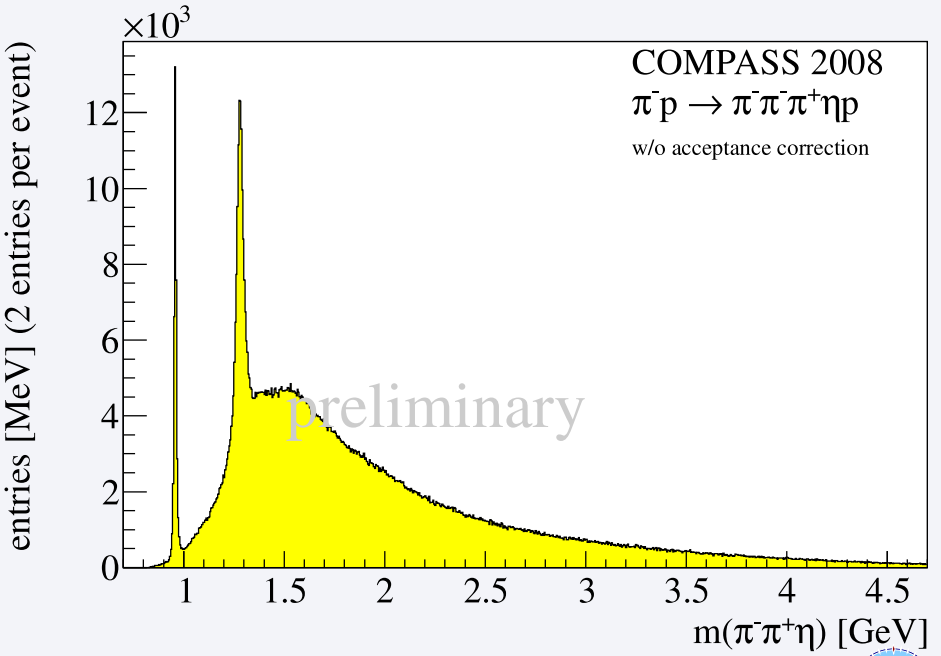
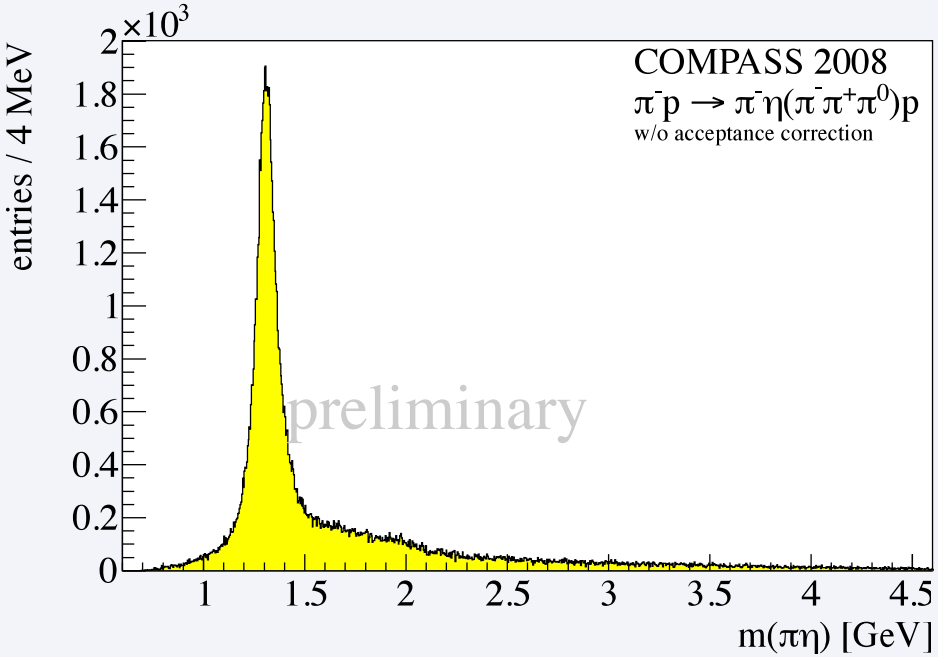


$\pi^+\pi^-\eta$ invariant mass distribution



PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

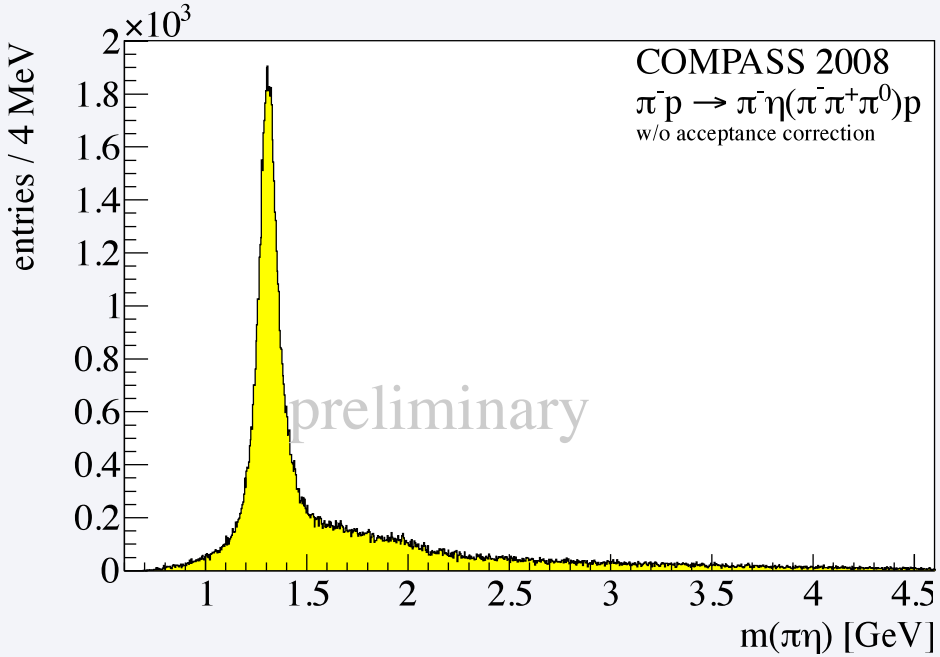
$\pi^-\eta$ invariant mass distribution



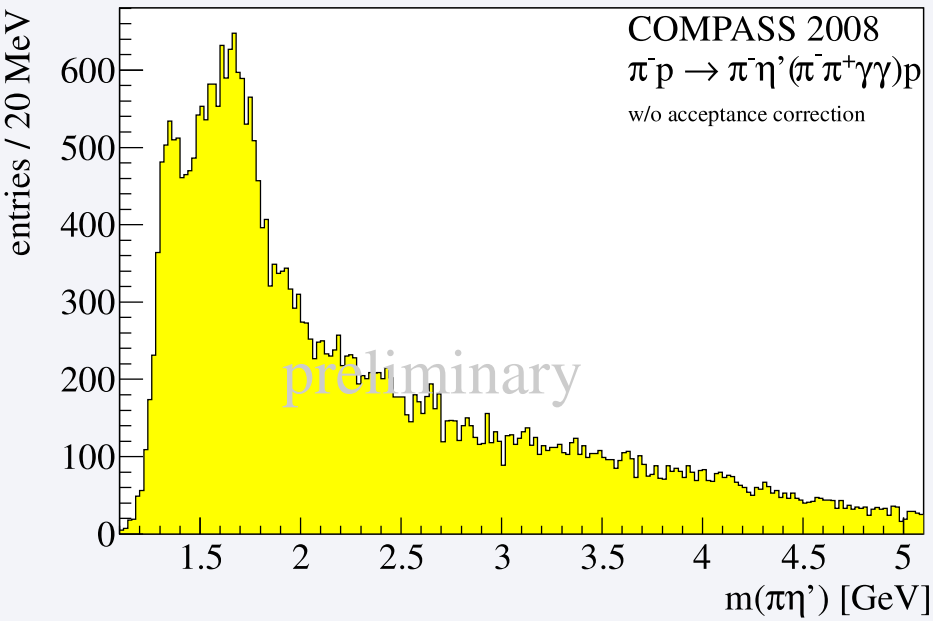
- $\pi^-\eta$: dominant $a_2(1320)$
- $\pi^-\eta'$: dominant broad structure around 1.7 GeV/c^2 and $a_2(1320)$ close to threshold
- Bulk of data described by 3 partial waves
  - $1^{-+}\,1^+$, $2^{++}\,1^+$, and $4^{++}\,1^+$

PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

$\pi^-\eta$ invariant mass distribution



$\pi^-\eta'$ invariant mass distribution



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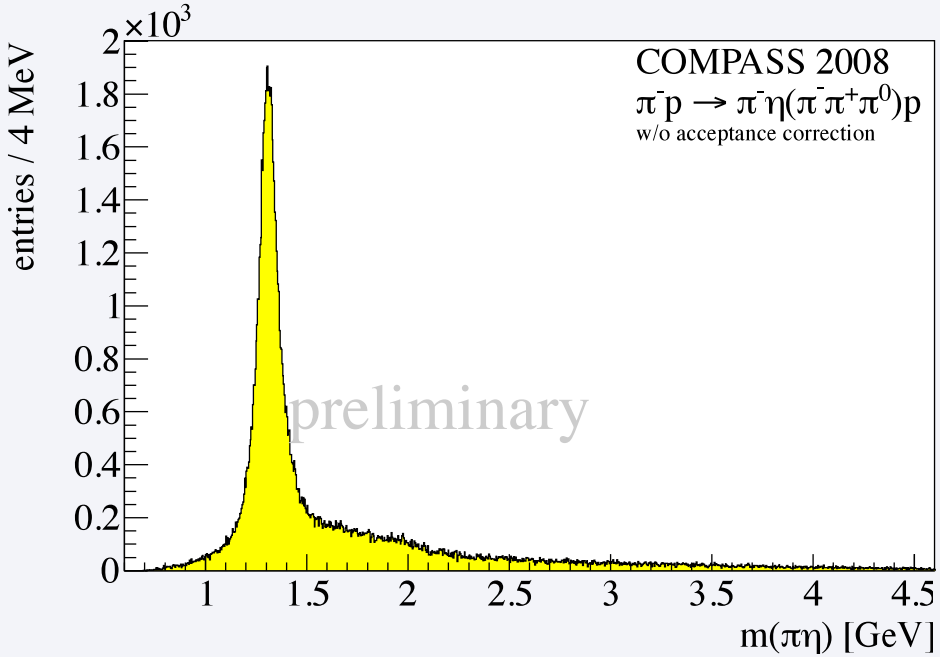

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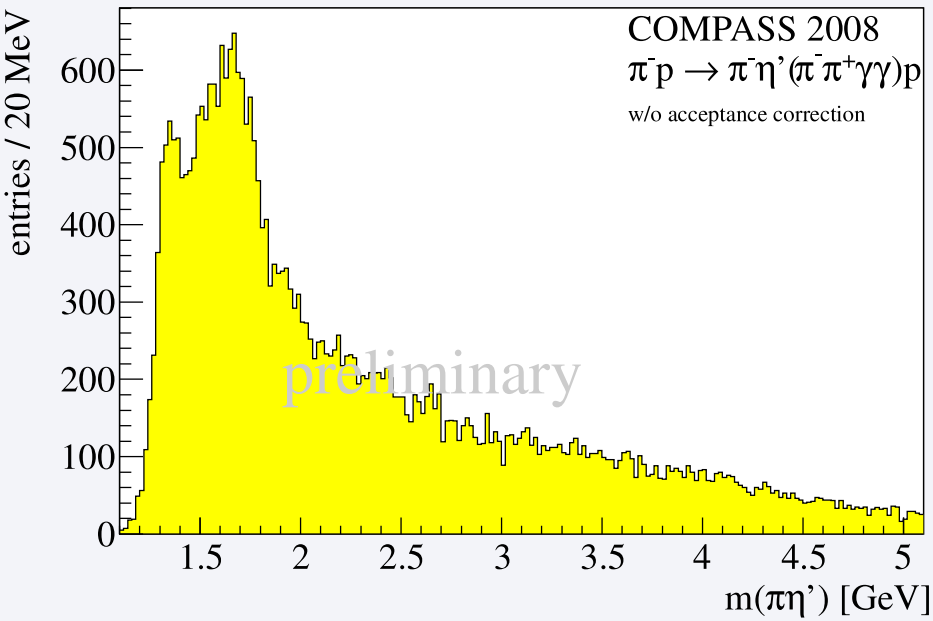

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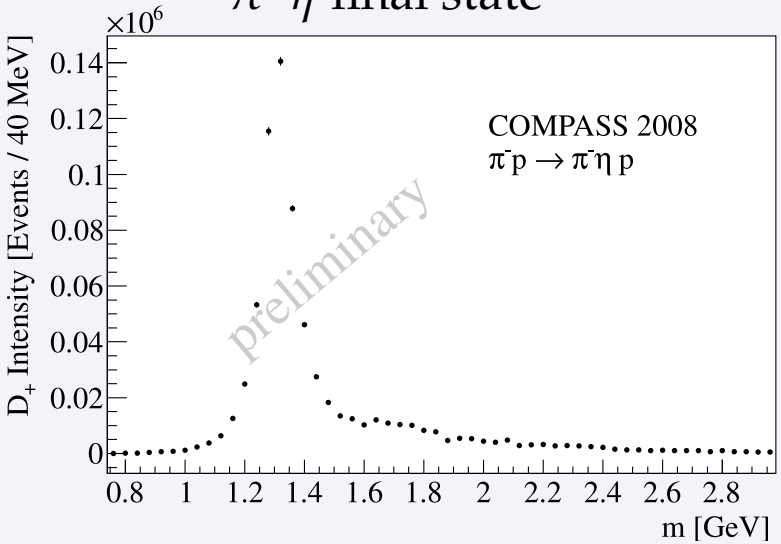
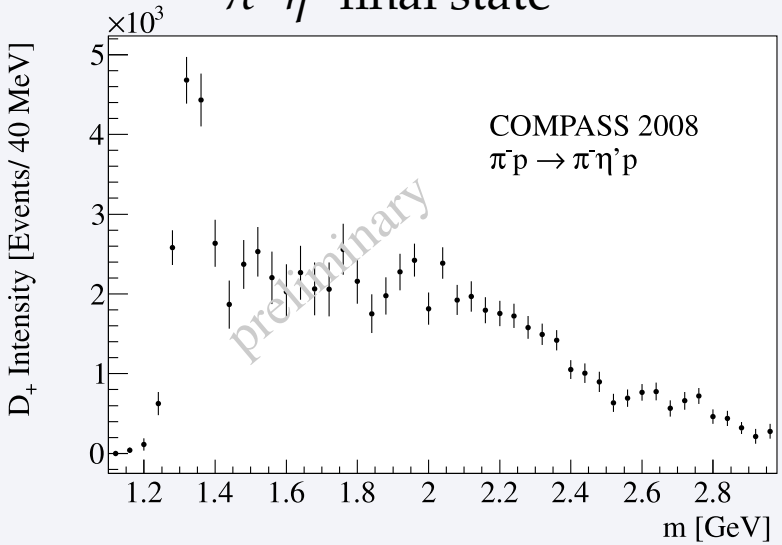
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

$a_2(1320)$ in $2^{++}\,1^+$ Partial Wave

$\pi^-\eta$ final state



$\pi^-\eta'$ final state



PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

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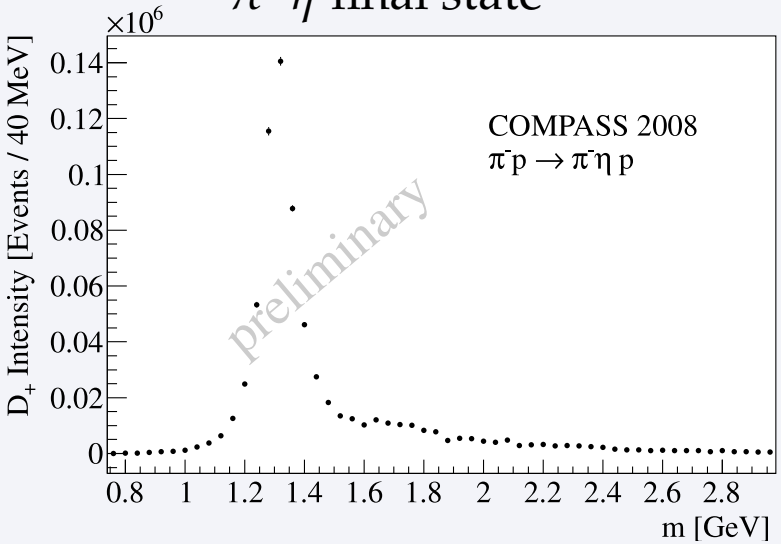

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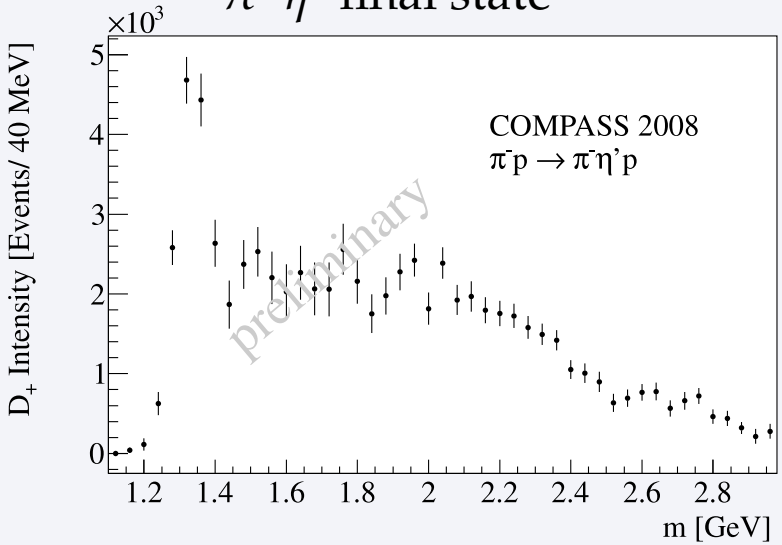


η-η' mixing together with OZI rule

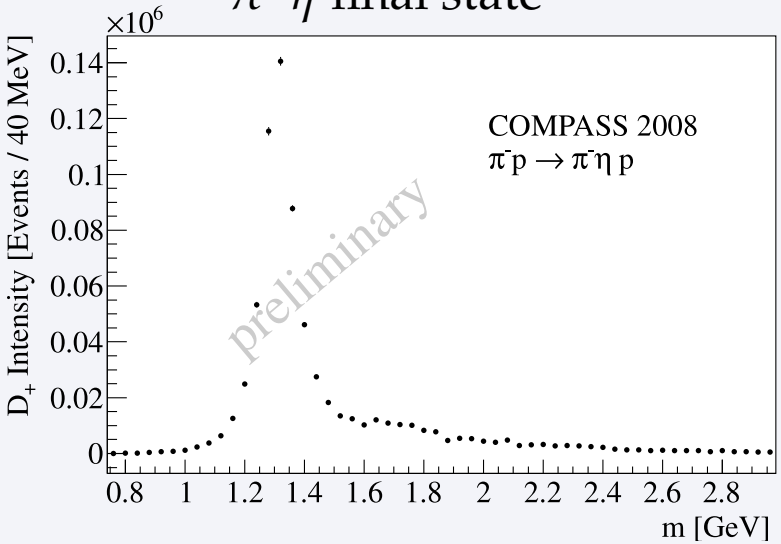
- Partial-wave amplitudes for spin J related by mixing angle ϕ, phase space, and barrier factors (q = breakup momentum)

$$\frac{T_J^{\pi\eta'}(m)}{T_J^{\pi\eta}(m)} = \tan\phi \left[\frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)}\right]^{J+1/2}$$

PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

$a_2(1320)$ in $2^{++}\,1^+$ Partial Wave

$\pi^-\eta$ final state



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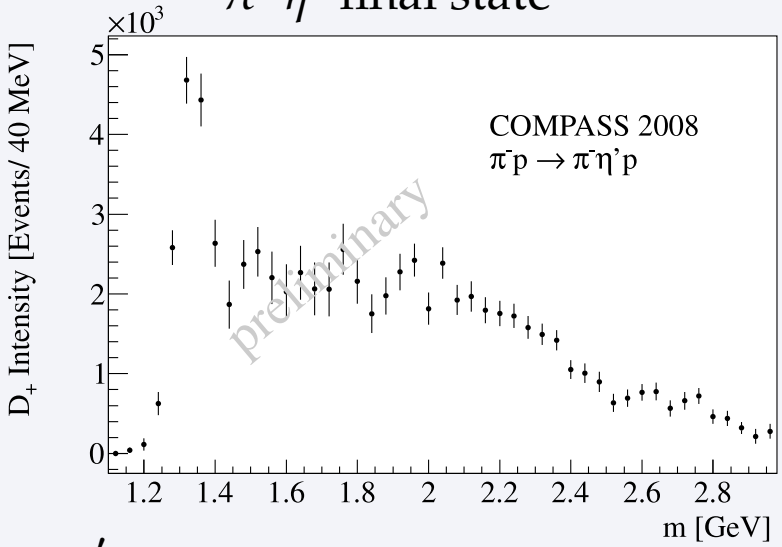
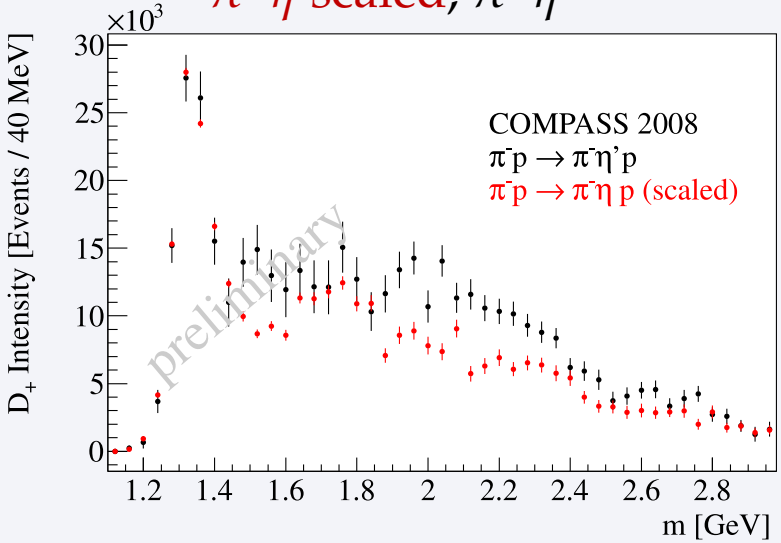
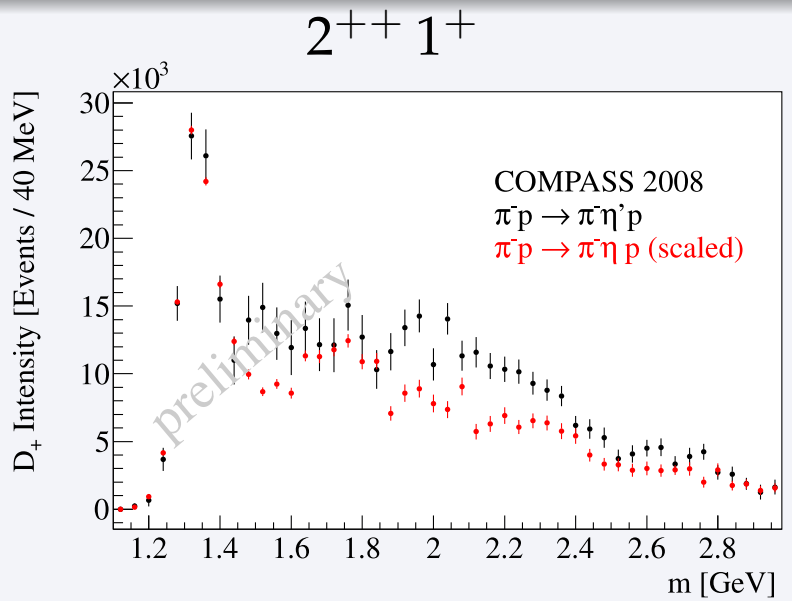


$\pi^-\eta$ scaled, $\pi^-\eta'$



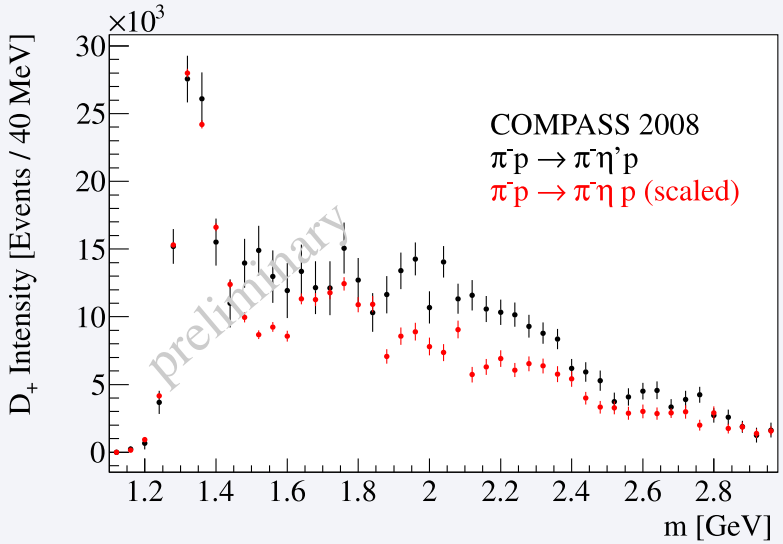
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$



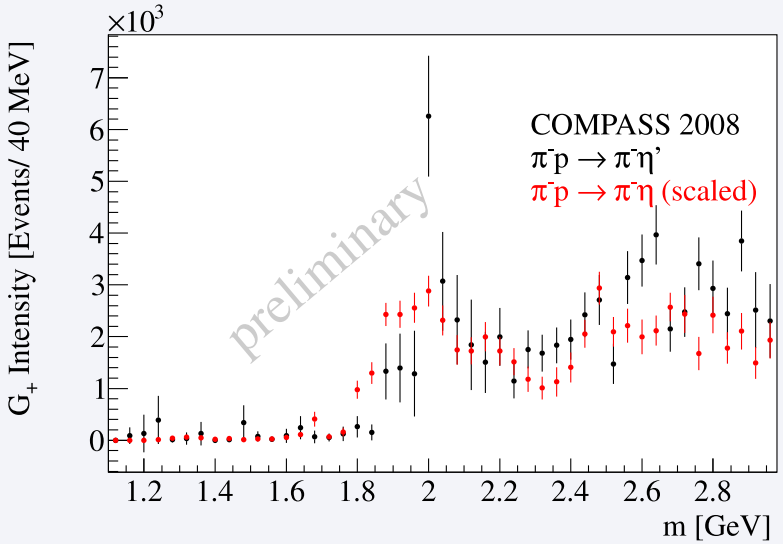
- Very similar even-spin waves
- Expected for $n\bar{n}$ resonances (OZI rule)
- Similar physical content also in non-resonant high-mass region

PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

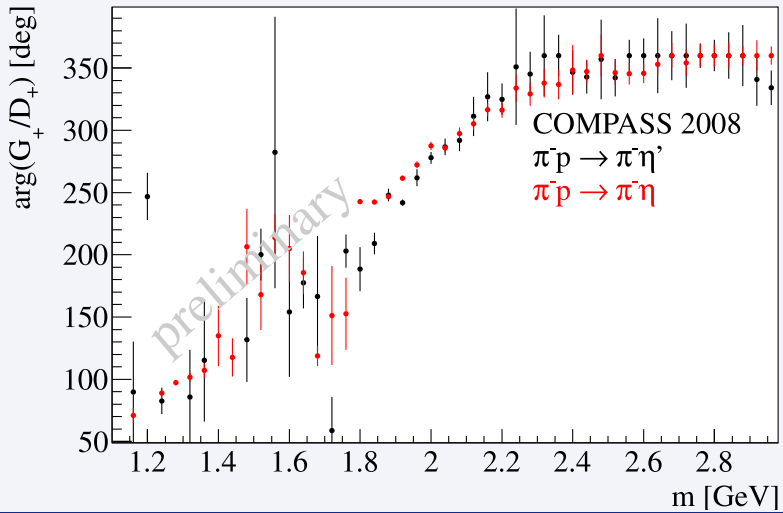
$2^{++}\,1^+$



$4^{++}\,1^+$



Phase: $4^{++}\,1^+ - 2^{++}\,1^+$



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PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

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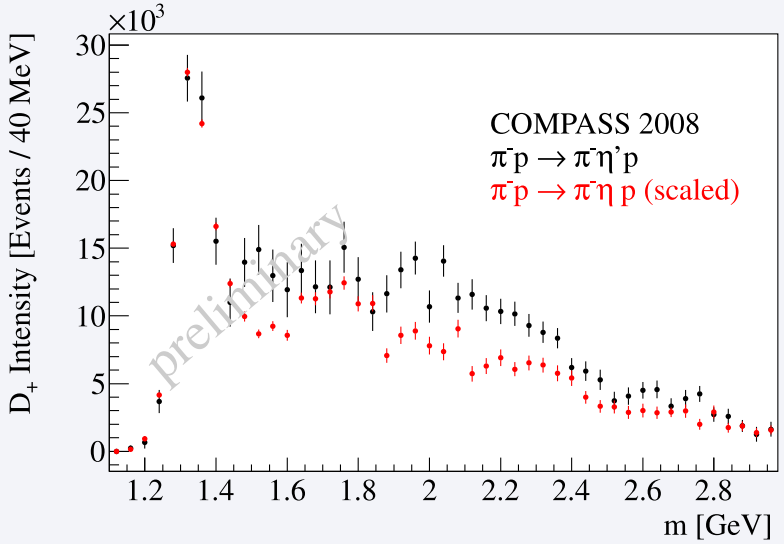
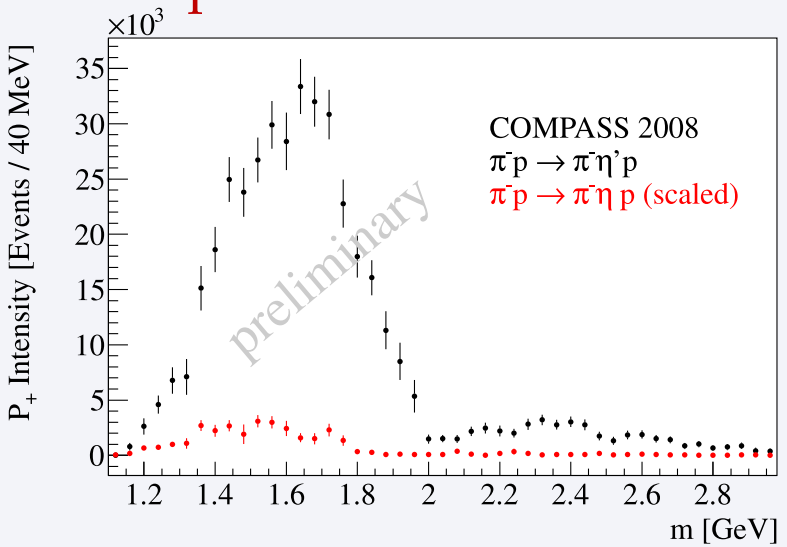


Spin-exotic $1^{-+}\,1^+$



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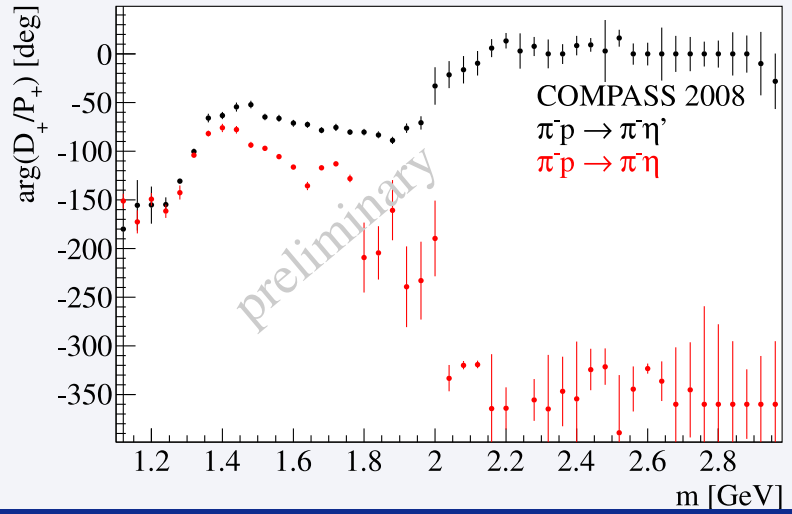


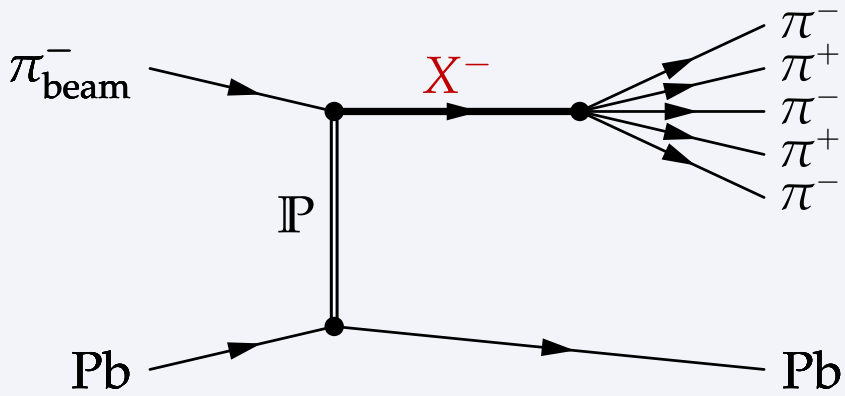
- Completely different intensity of 1^{-+} wave
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in 1.6 GeV/c^2 region

PWA of $\pi^- p \to \pi^- \eta p_{\text{slow}}$ and $\pi^- \eta' p_{\text{slow}}$

Summary

- Found significant intensity in spin-exotic 1^{-+} wave in $\pi\eta$ and $\pi\eta'$
- 2^{++} and 4^{++} waves very similar in both channels
- 1^{-+} wave enhanced in $\pi\eta'$
- First mass-dependent fits describe data in terms of resonances and backgrounds
  - $a_2(1320)$ and $a_4(2040)$ resonance parameters consistent in both channels
  - Description of 1^{-+} wave by Breit-Wigner requires large interfering background and additional 2^{++} resonance
- Resonance interpretation of 1^{-+} wave requires
  - Better understanding of resonance structure of 2^{++} and 4^{++} waves
  - Inclusion of non-resonant contributions from double-Regge processes in high-mass region (V. Mathieu, Tue Session B4)
- **Final goal:** combined analysis of both channels

PWA of π^- Pb $\rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-$ Pb



First mass-dependent PWA of this reaction

- **Light-meson frontier:** access to mesonic states in 2 GeV/c^2 region
- Little information from previous experiments

Data from pilot run

- Pb target
- Recoil not measured
- Kinematic range $t' < 5 \cdot 10^{-3}$ (GeV/c)^2

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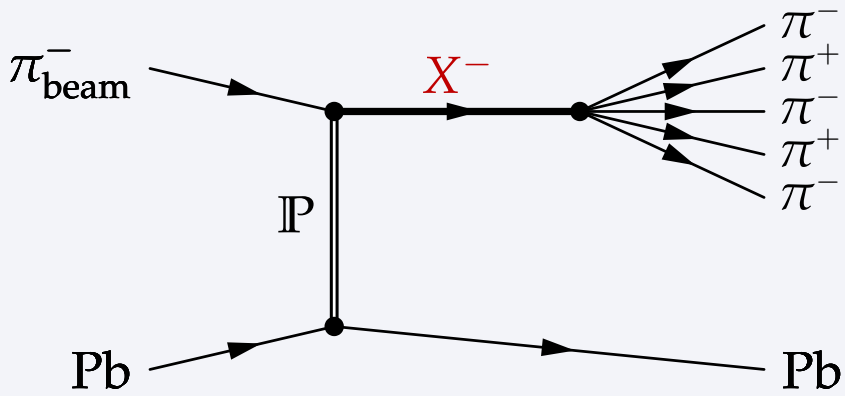

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Fit model

- Complicated isobar structure
  - Large number of possible waves
  - Data exhibit no dominant waves
- Exploration of model space using evolutionary algorithm based on goodness-of-fit criterion
  - 284 waves tested
  - Also provides estimate for systematic uncertainty from fit model
- Best model: 31 waves + incoherent isotropic background
- Isobars
  - $(2\pi)^0$ isobars: $(\pi\pi)_{S-\text{wave}}$, $\rho(770)$
  - $(3\pi)^\pm$ isobars: $a_1(1260)$, $a_2(1320)$
  - $(4\pi)^0$ isobars: $f_2(1270)$, $f_1(1285)$, $f_0(1370, 1500)$, and $\rho'(1450, 1700)$
    - Only few information available for $(4\pi)^0$ isobars

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PWA of π^- Pb $\rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-$ Pb

$0^{-+}\pi^- f_0(1500)\ S$

$0^{-+}\rho a_1(1260)\ S$

$1^{++}\pi^- f_0(1370)\ P$

$1^{++}\pi^- f_1(1285)\ P$

$1^{++}\rho\pi(1300)\ S$

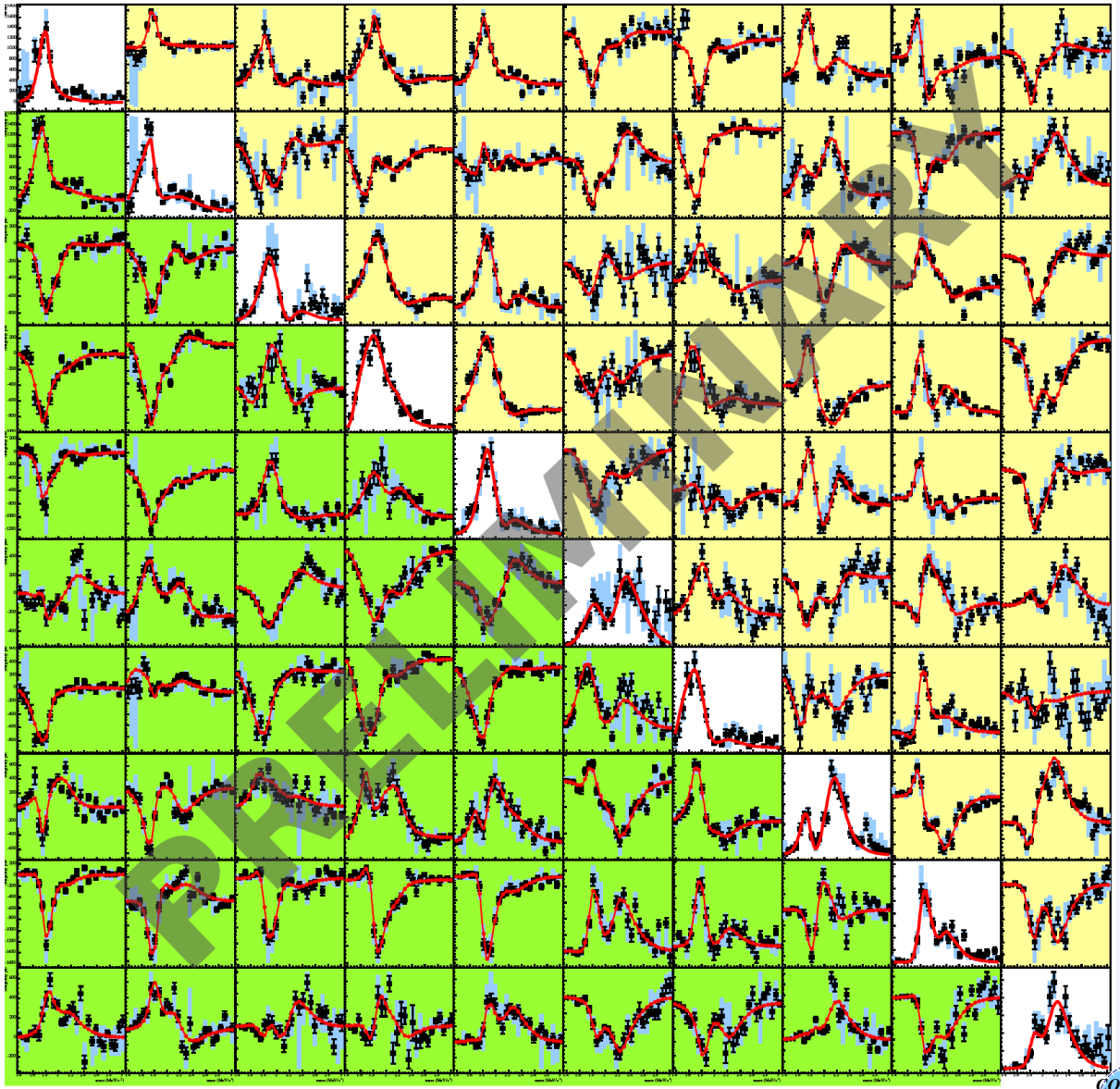
$1^{++}(\pi\pi)_S a_1\ D$

$2^{-+}\pi^- f_2(1270)\ S$

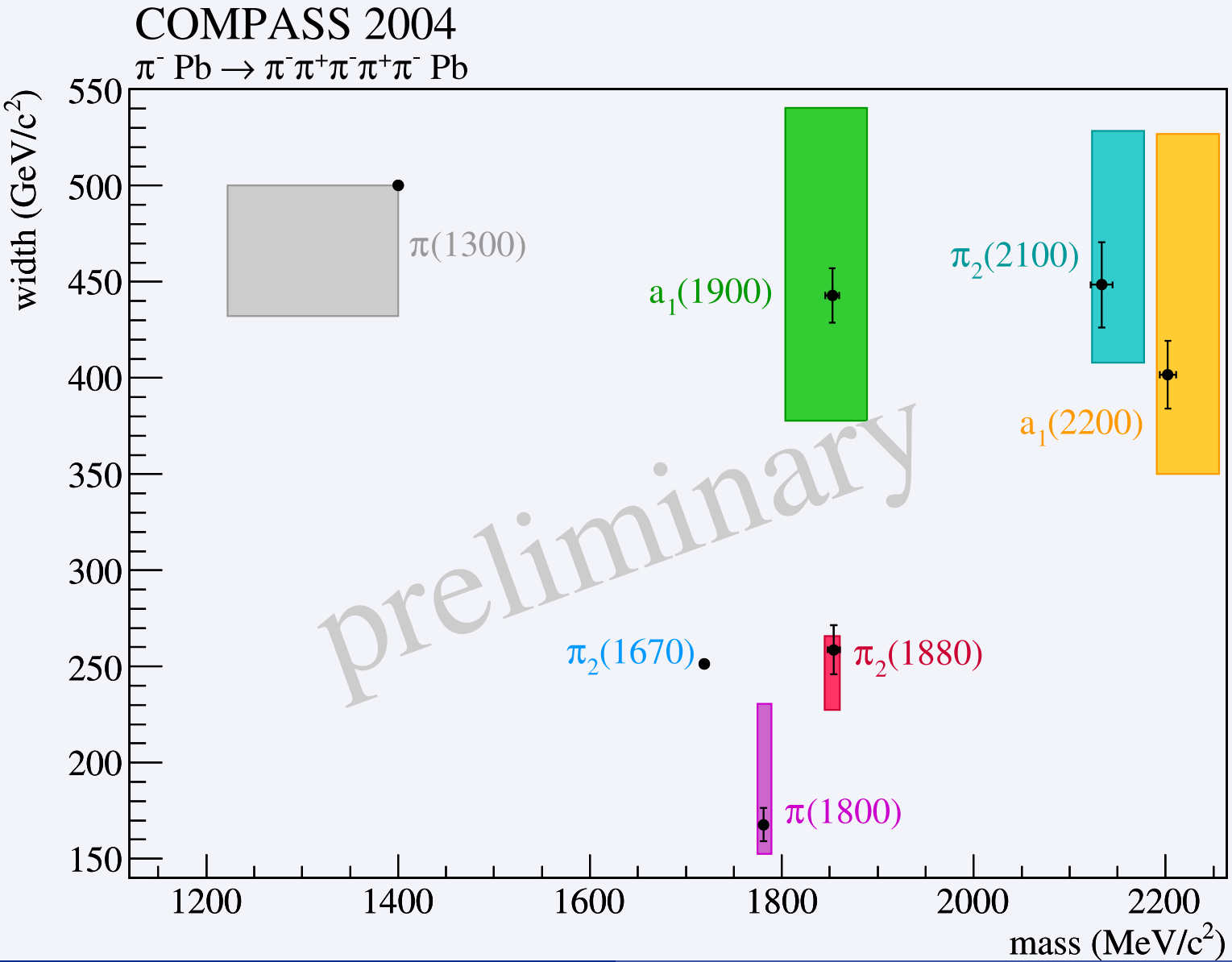
$2^{-+}\rho a_1(1260)\ S$

$2^{-+}\rho a_2(1320)\ S$

$2^{-+}\rho a_1(1260)\ D$



PWA of π^- Pb $\rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-$ Pb



PWA of π^- Pb $\rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-$ Pb

Proof of Principle: First mass-dependent full five-body PWA

- Spin-density sub-matrix of 10 waves described using 7 resonances + background terms
- Rather simplistic fit model
  - Parameterization by sum of relativistic constant-width Breit-Wigners
  - Mixing and coupled-channel effects neglected
  - Multi-peripheral processes (Deck-effect) not taken into account
- Good description of data

Work in progress

- Much more data on tape
  - Proton target, kinematic range $0.1 < t' < 1\,(\mathrm{GeV}/c)^2$
- Improvement of fit models
  - Analysis of $(4\pi)^0$ subsystem

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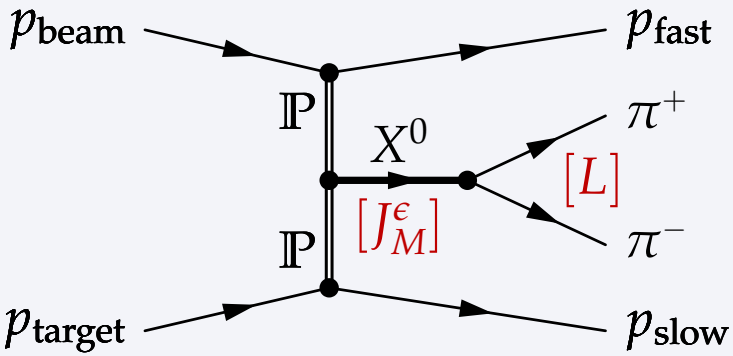
Outline

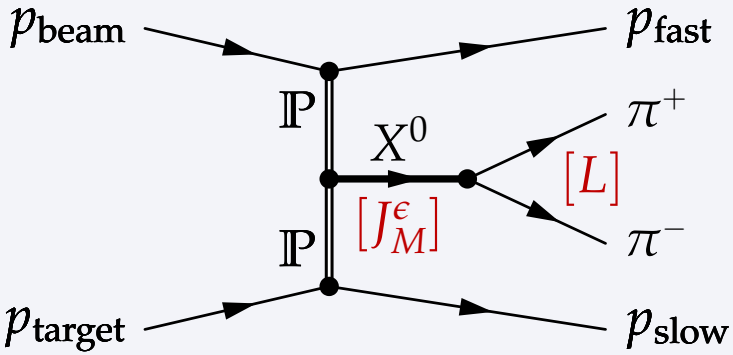
PWA of $p\,p \to p_{\text{fast}}\,\pi^+\pi^-\,p_{\text{slow}}$



Search for **glueballs**

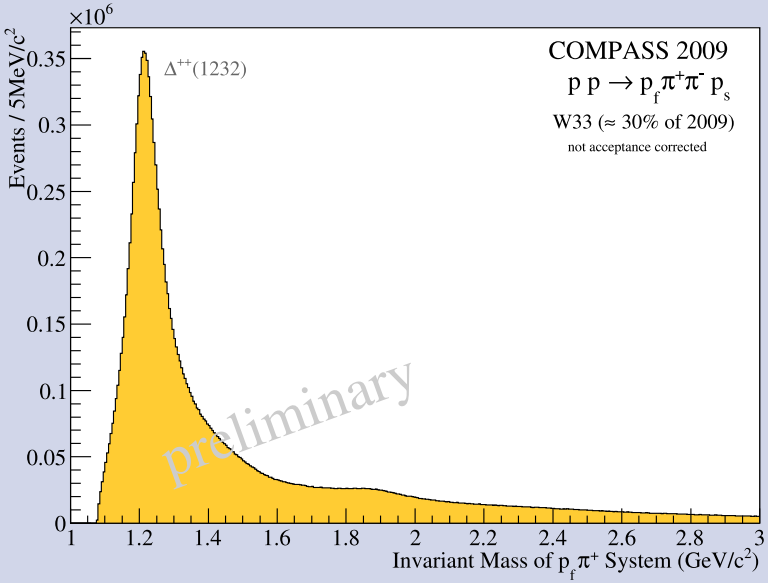
- Mesonic state with no valence quarks
- Lattice QCD simulations predict lightest glueballs to be scalars
  - Strong mixing with conventional scalar mesons expected
  - Difficult to disentangle
- Pomeron-Pomeron fusion well-suited to study scalar mesons
  - Mesons produced at central rapidities

PWA of $p\,p \to p_{\text{fast}}\,\pi^+\pi^-\,p_{\text{slow}}$

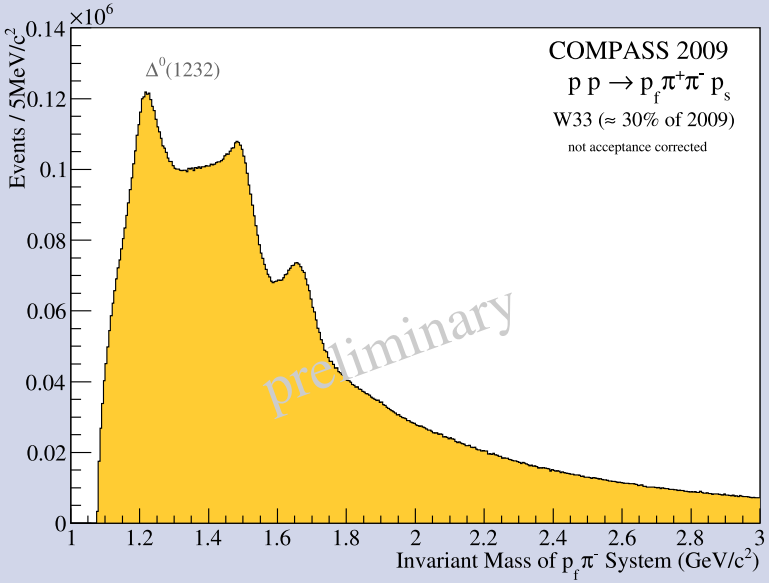


Suppression of diffractive background: require $m(p\pi^{\pm}) > 1.5$ GeV/c^2

$p_{\text{fast}}\pi^+$ invariant mass



$p_{\text{fast}}\pi^-$ invariant mass



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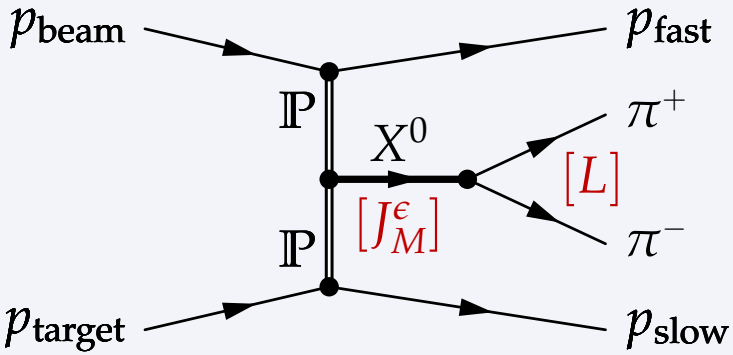
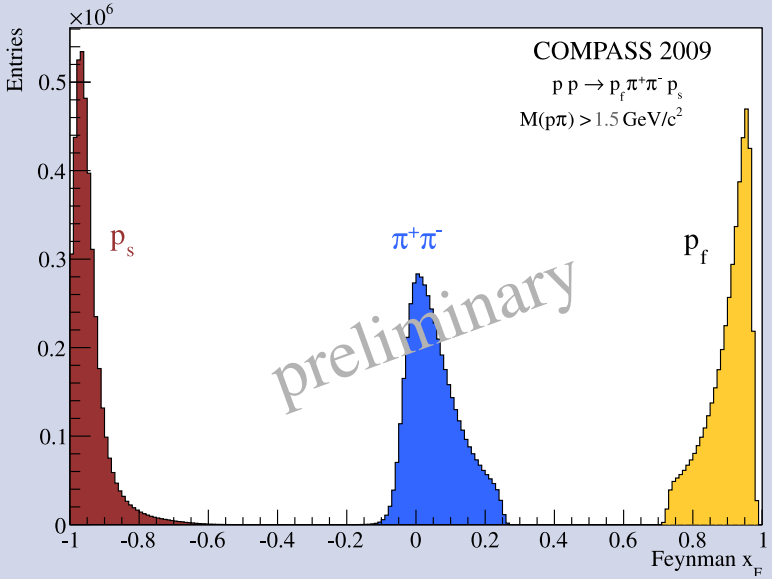
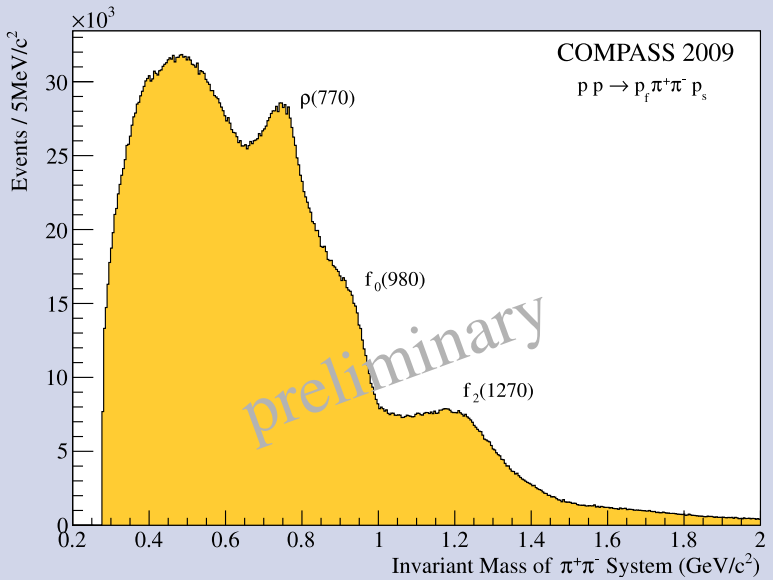


Selected central events

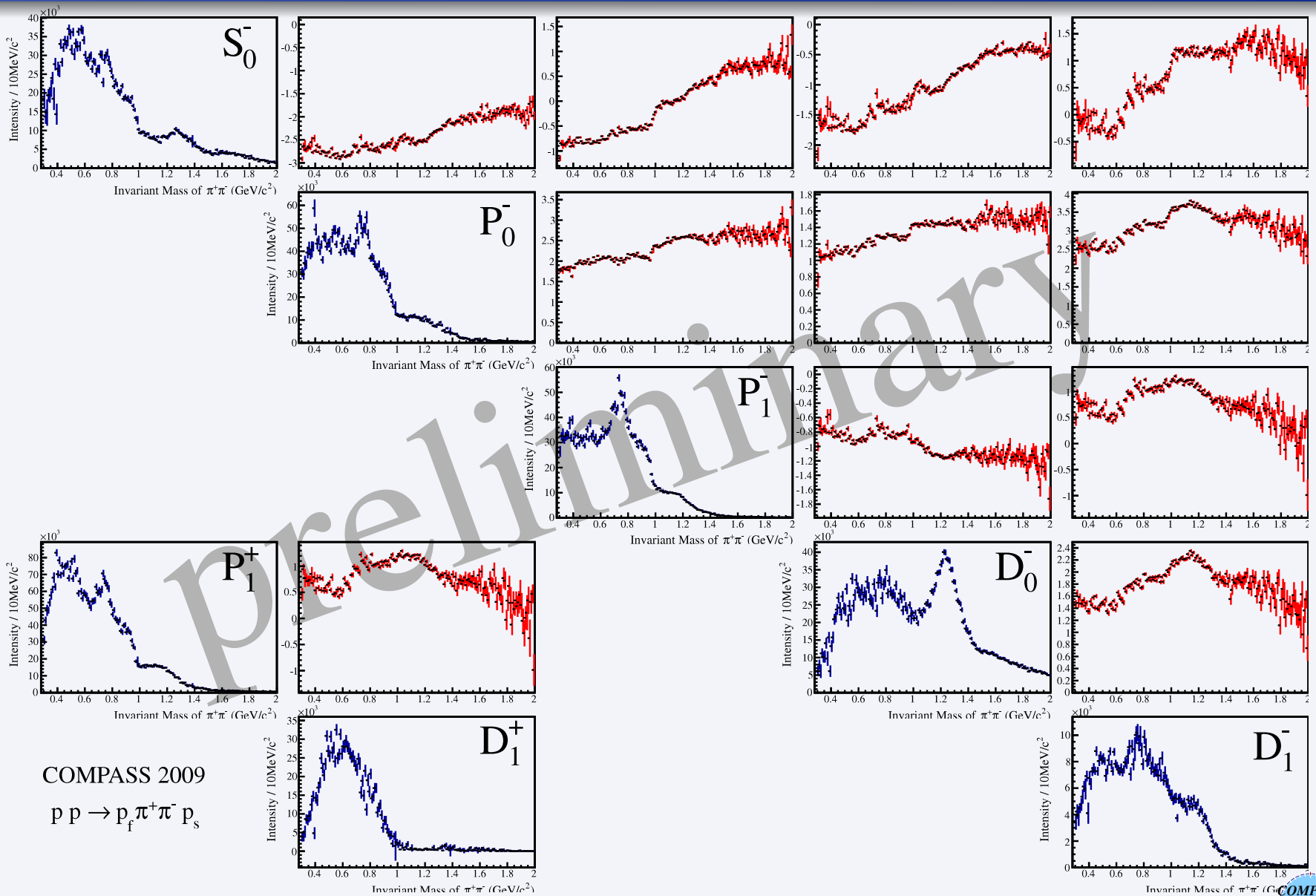
x_F distribution



$\pi^+\pi^-$ invariant mass



PWA of $p\,p \rightarrow p_{\text{fast}}\,\pi^+\pi^-\,p_{\text{slow}}$



preliminary

PWA of $p\,p \to p_{\text{fast}}\,\pi^+\pi^-\,p_{\text{slow}}$

Proof of concept

- Analysis similar to WA102 experiment
  - Comparable results
- Simplistic fit model
  - Angular information of the two proton scattering planes not taken into account
- 8 different mathematically ambiguous solutions
  - Additional constraints needed to select physical solution

Next steps

- Fit of mass dependence
- Analysis of K^+K^- final state

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Conclusions and Outlook

COMPASS has acquired large data sets for many final states

- Main focus on search for J^{PC}-exotic mesons
  - Pilot run: significant $J^{PC} = 1^{-+}$ signal consistent with $\pi_1(1600)$ seen in $\pi^-\pi^+\pi^-$ data on Pb target PRL **104** (2010) 241803
  - Detailed study of $\pi^-\pi^+\pi^-$ final state
    - 1^{-+} signal diluted by non-resonant Deck-like background
    - Full two-dimensional analysis in $m_{\pi^-\pi^+\pi^-}$ and t'
    - Consistency check with $\pi^-\pi^0\pi^0$
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    - Well-known $\pi(1800)$ and $\pi_2(1670)$ seen
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