Hadron Spectroscopy at COMPASS and ALICE plus related experiments

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Based on the slides provided by
Boris Grube, TU/München

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The 15th Conference on Elastic and Diffractive Scattering
Saariselkä, Finland; 09–13 September 2013

Prelude

- Breit-Wigner Form for $\{m_0, \Gamma_0\}$ for $X^0 \to \pi^+\pi^-$:
  Let the spin $J = \ell$, where $\ell =$ the orbital angular momentum

$$\Delta_\ell(m) = \frac{m_0\,\Gamma_\ell(m)}{m_o^2 - m^2 - i\,m_0\,\Gamma_\ell(m)} = \exp\left[i\,\delta_\ell(m)\right]\,\sin\delta_\ell(m)$$

$$\Gamma_\ell(m) = \Gamma_0\,\frac{F_\ell(m)}{F_\ell(m_0)}, \quad \Gamma_\ell(m_0) = \Gamma_0\,F_0(m) = F_0(m_0) = 1 \quad \text{for} \quad \ell = 0$$

At $m = m_0$,

$$\delta_\ell(m) = \frac{\pi}{2}$$

$$\frac{\mathrm{d}\delta_\ell(m)}{\mathrm{d}m} > 0 \qquad = \max \quad \longrightarrow \quad \text{the rising phase motion}$$

- Blatt-Weisskopf barrier factors for $F_\ell(m)$:

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- An introduction to quarkonia and beyond
- Diffractive Dissociation:
  Patial-wave analysis by COMPASS collaboration on $(3\pi)^-$
- Central Production:
  Future prospects for ALICE on $(2\pi)^0$, $(4\pi)^0$
- Concluding remarks

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Beyond the Constituent Quark Model

QCD: Gluonic d.o.f. should manifest themselves in hadron spectra

Hybrids $|q\bar{q}g\rangle$

- Resonances with excited glue
  - Definition of "excited glue" model dependent
- Angular momentum of glue component $\Longrightarrow$ *all* J^{PC} possible
- Lightest predicted hybrid: spin-exotic $J^{PC} = 1^{-+}$
  - Mass 1.3 to 2.2 GeV/c^2
  - Experimental candidates $\pi_1(1400, 1600, 2000)$

Glueballs $|gg\rangle$

- Bound states consisting purely of gluons
- Lightest predicted glueball: ordinary $J^{PC} = 0^{++}$
  - Will strongly mix with nearby conventional $J^{PC} = 0^{++}$ states
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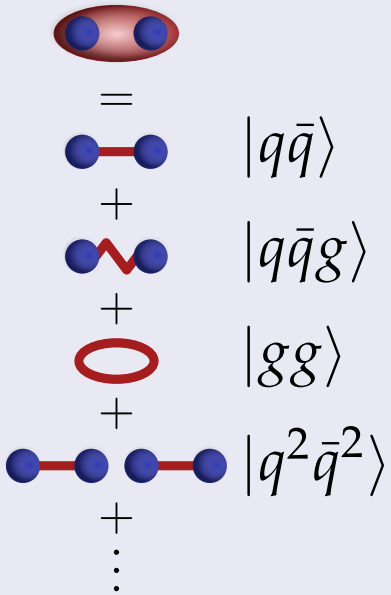
Beyond the Constituent Quark Model

Finding states beyond the CQM is difficult

- Physical mesons = linear superpositions of *all* allowed basis states: $|q\bar{q}\rangle$, $|q\bar{q}g\rangle$, $|gg\rangle$, $|q^2\bar{q}^2\rangle$, ...
  - Amplitudes determined by QCD interactions
- Resonance classification in quarkonia, hybrids, glueballs, tetraquarks, etc. assumes dominance of *one* basis state
  - In general "configuration mixing"
  - Disentanglement of contributions difficult



Special case: "exotic" mesons

- Have quantum numbers forbidden for $|q\bar{q}\rangle$
  - Discovery $\Longrightarrow$ unambiguous proof for meson states beyond CQM
- Especially attractive:
  "spin-exotic" states with $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

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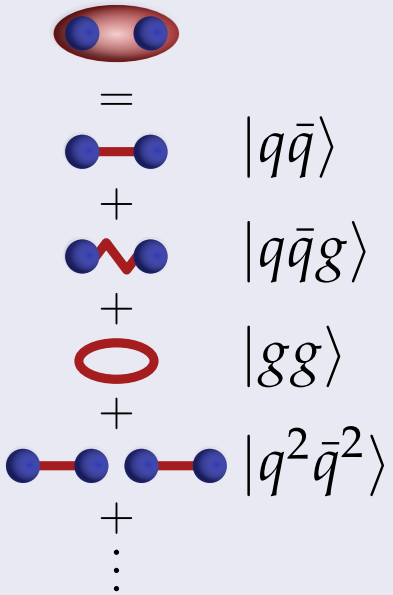

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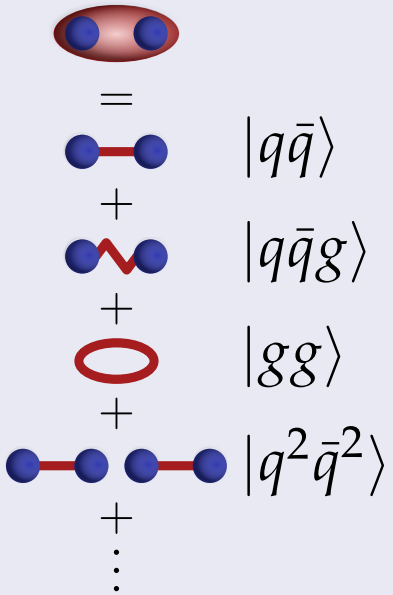

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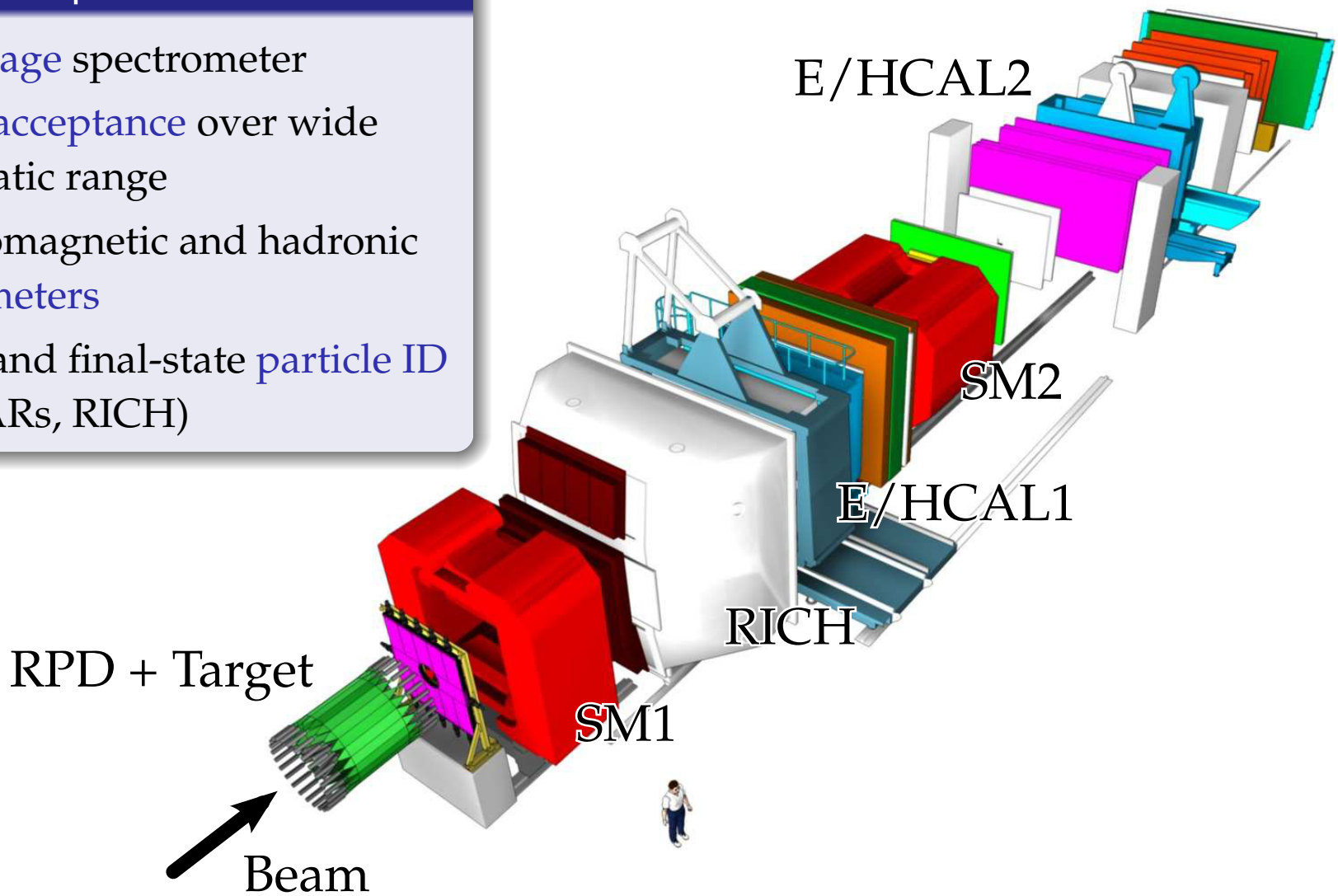
The COMPASS Experiment at the CERN SPS

Experimental Setup

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

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)



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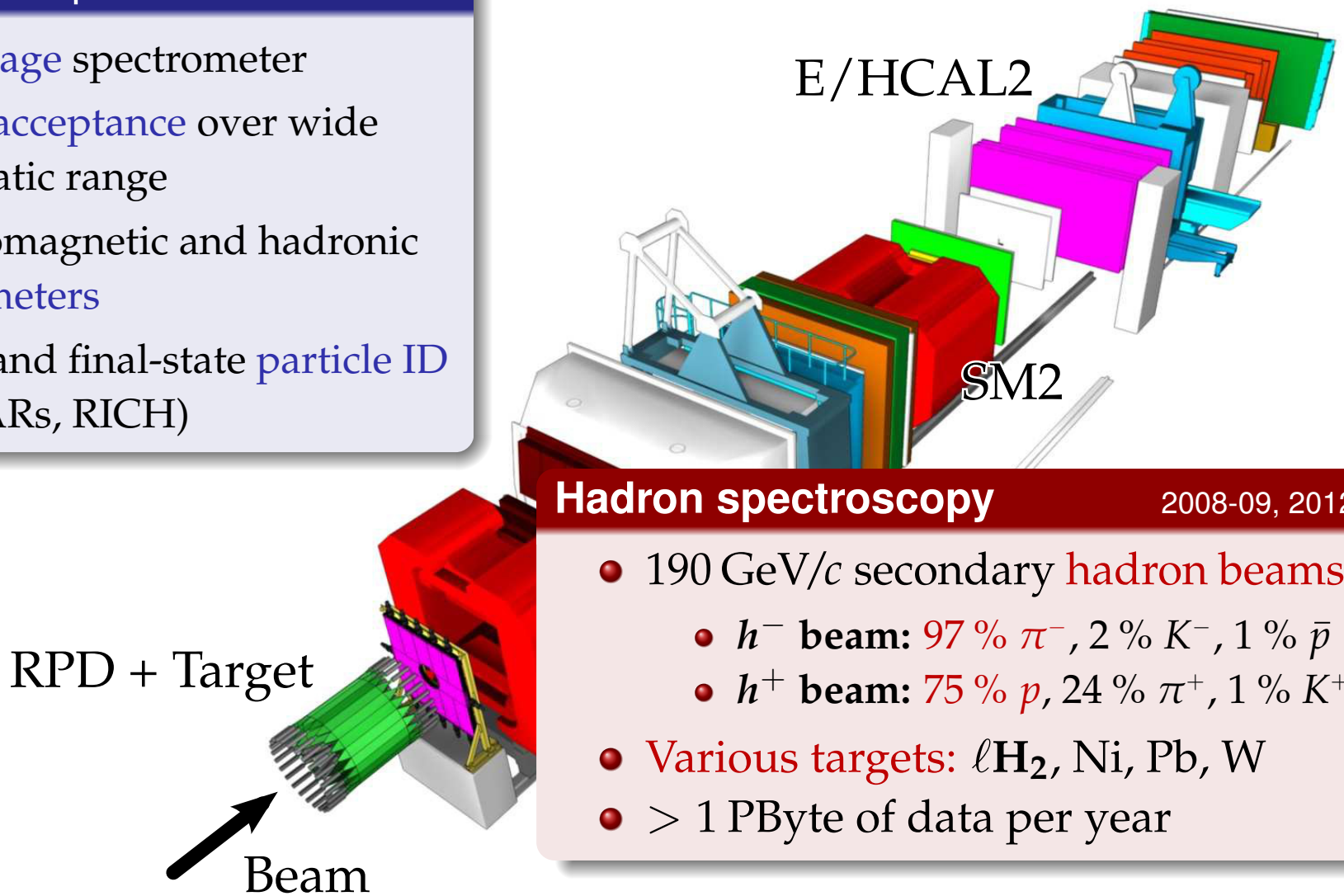
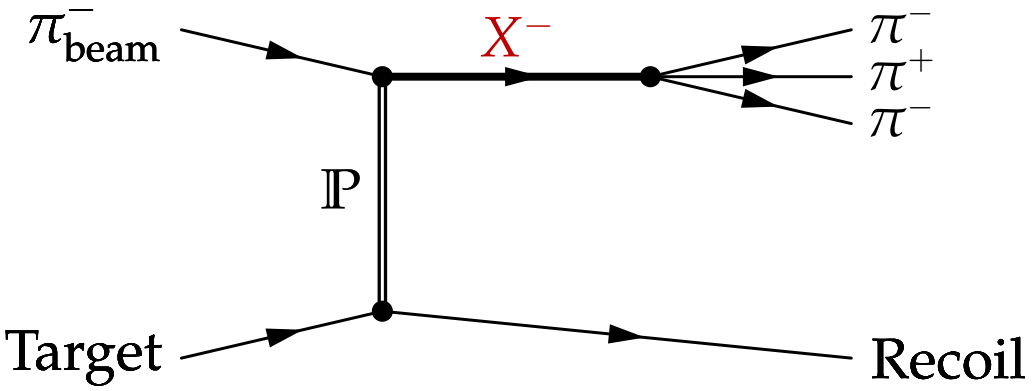


Hadron spectroscopy 2008-09, 2012

- 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
- $>$ 1 PByte of data per year

Production of Hadrons in Diffractive Dissociation

BNL E852, VES, COMPASS



- Soft scattering of beam hadron off nuclear target (remains intact)
  - Beam particle is excited into intermediate state X
  - X decays into n-body final state
- High $\sqrt{s}$, low $t' = |t| - |t|_{\text{min}}$: Pomeron exchange dominant
- 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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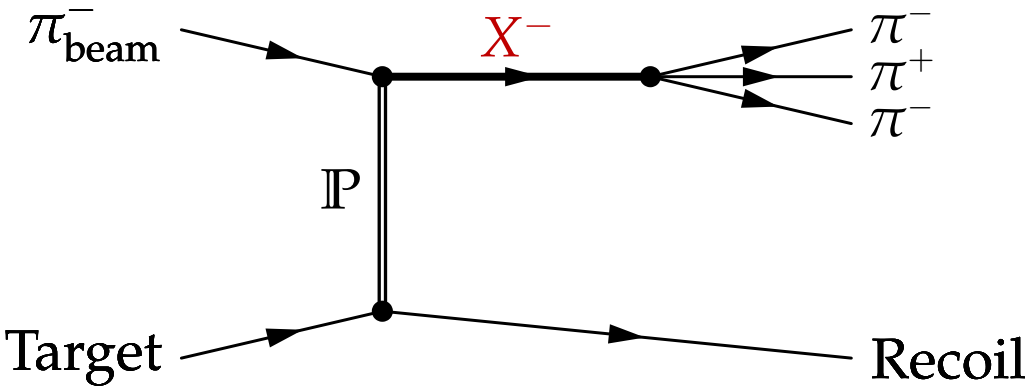

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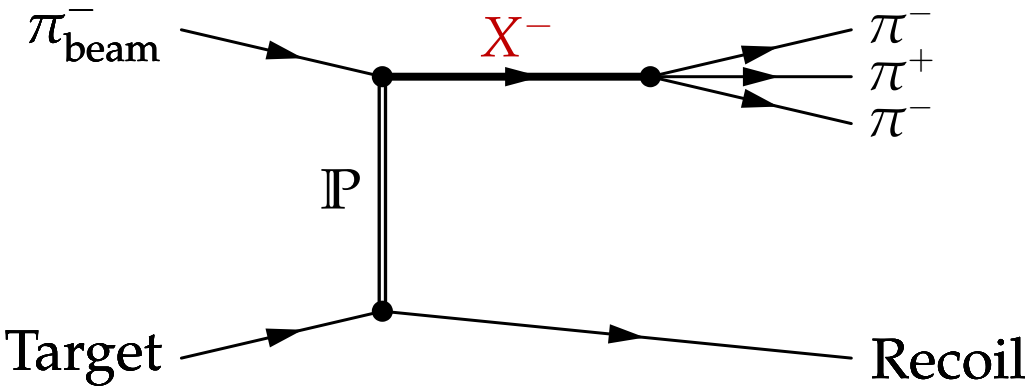

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Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State

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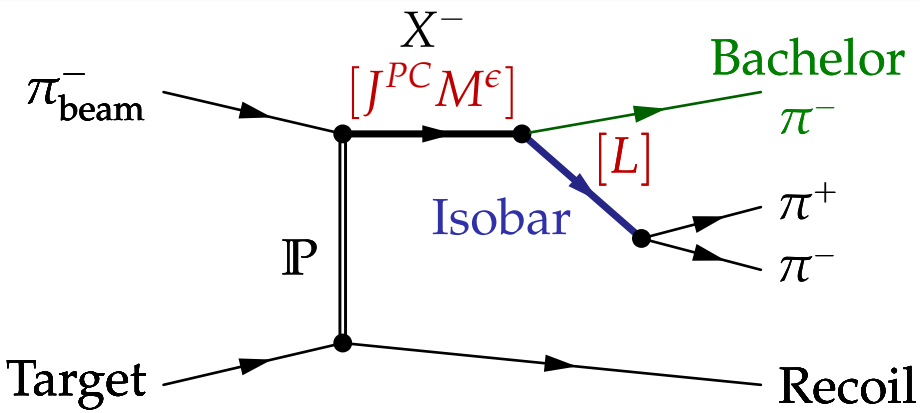

Isobar model: X^- decay is chain of successive two-body decays

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

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

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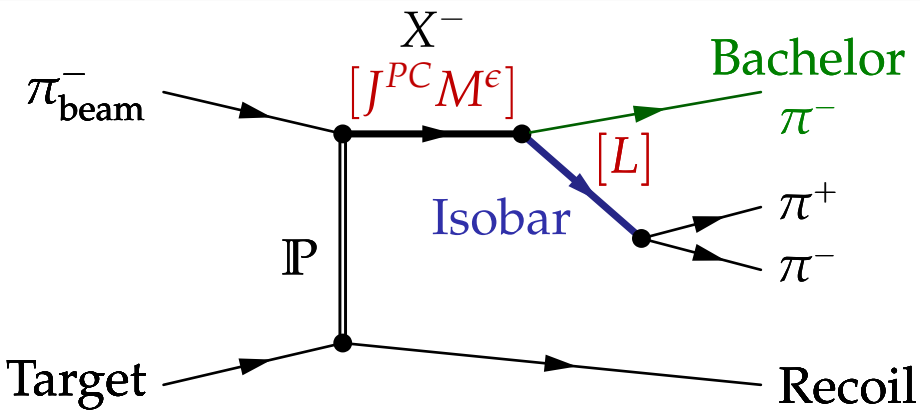

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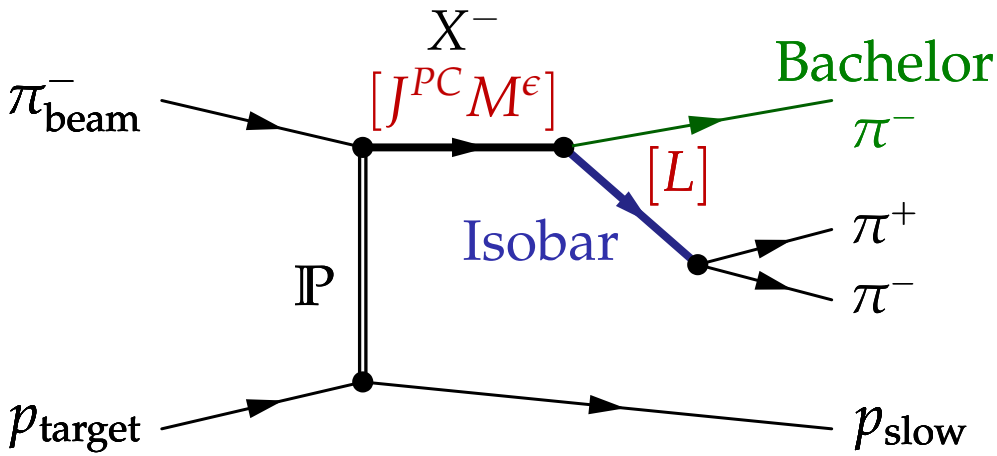
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

COMPASS



- 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 diffractive 3π data set: $\approx$50 M exclusive events

- Challenging analysis
  - Needs precise understanding of apparatus
  - Test of analysis Models

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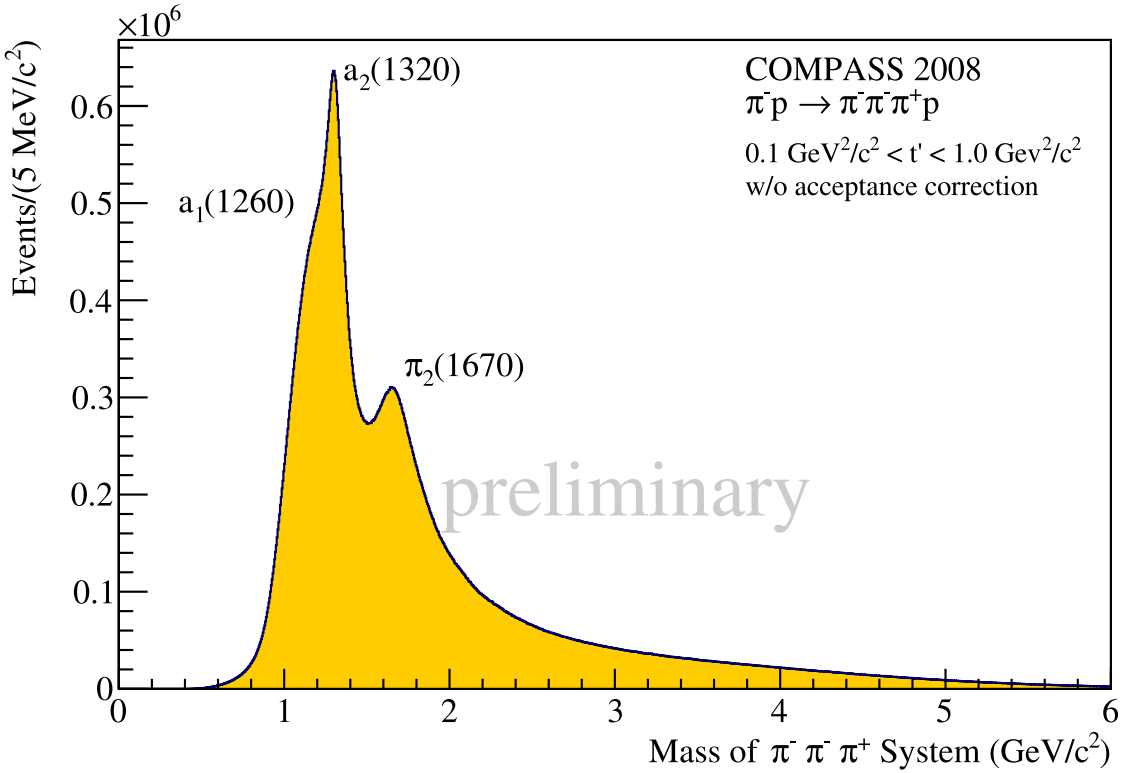

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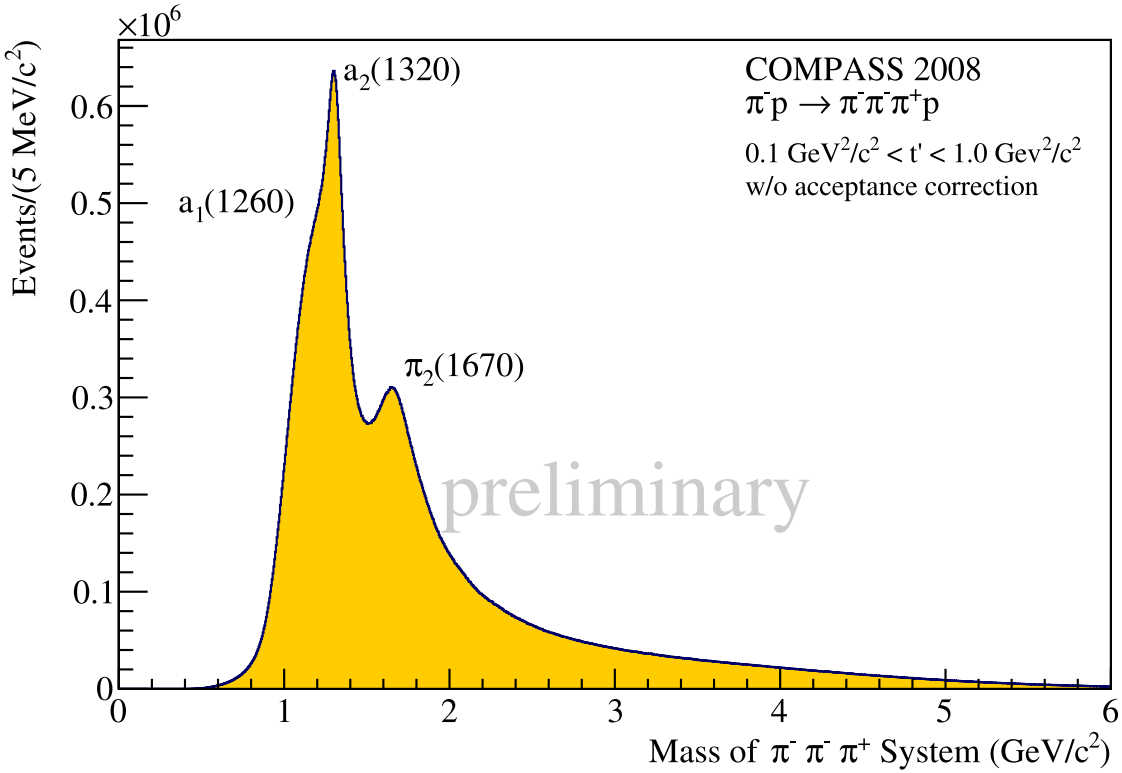
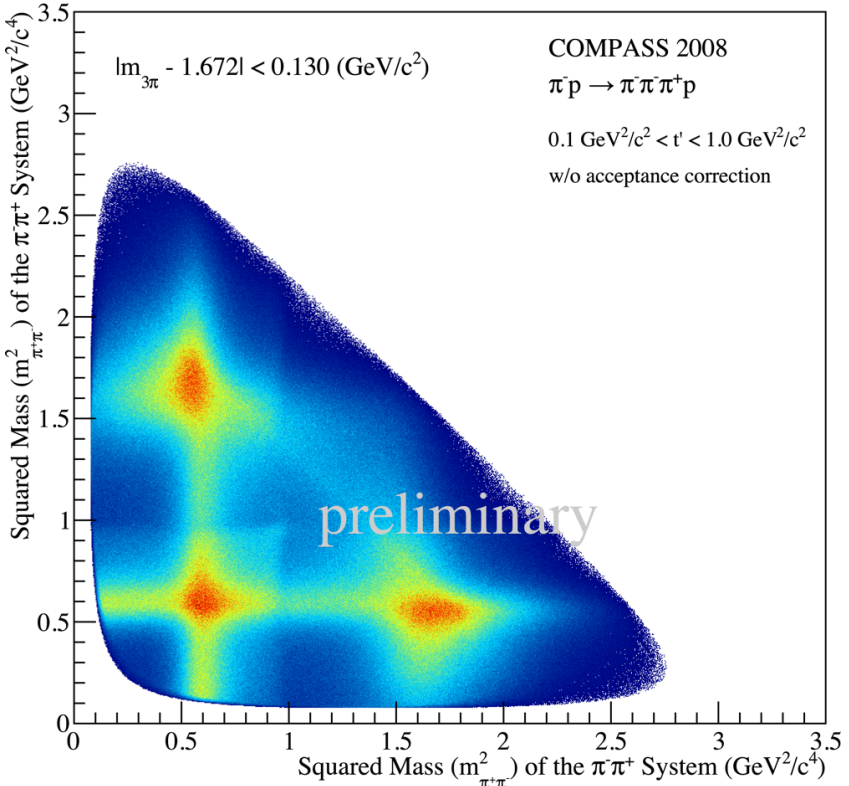


Dalitz plot for $\pi_2(1670)$ region



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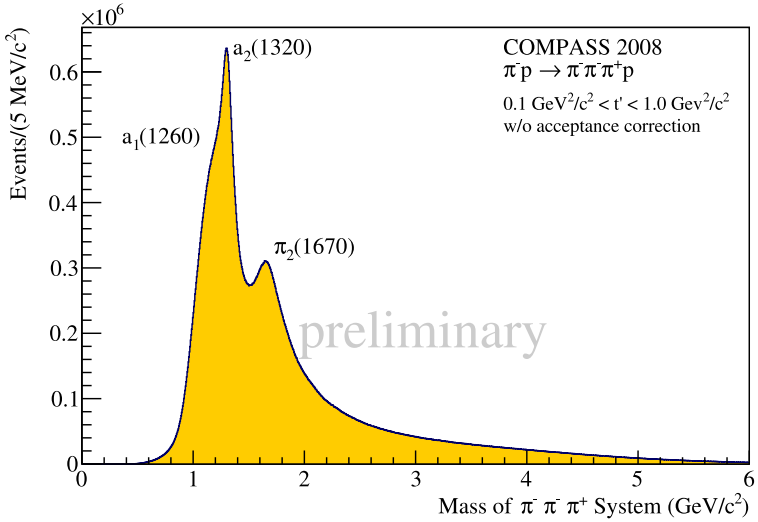

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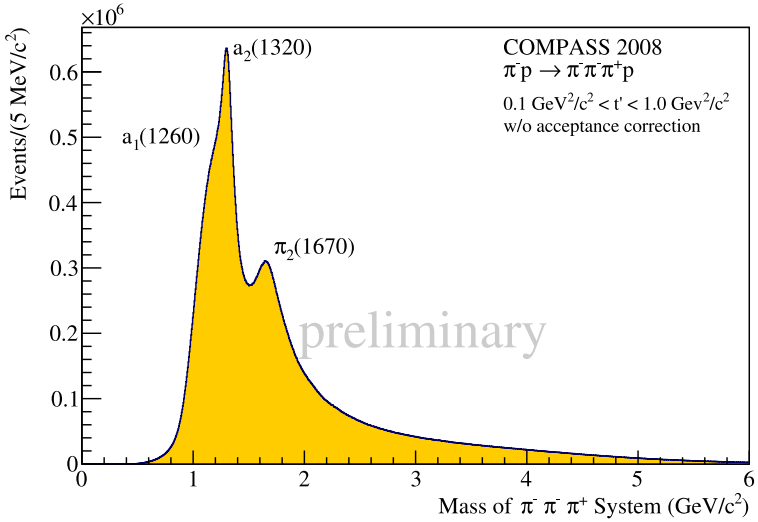
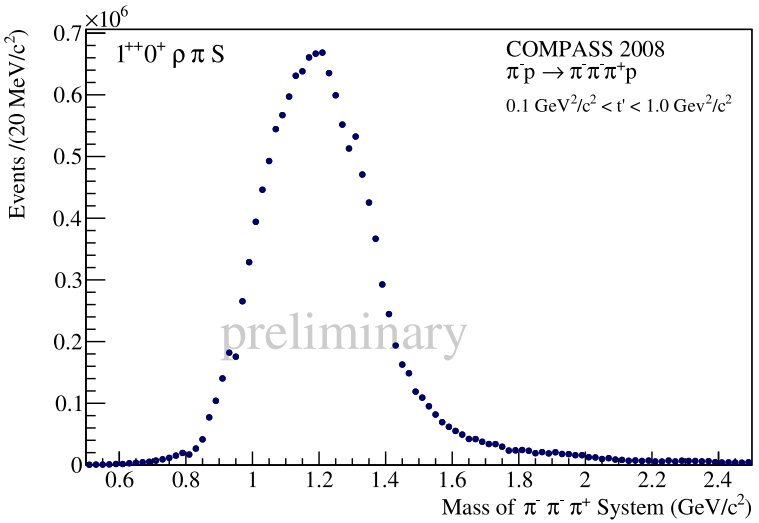


$1^{++}\,0^+\,[\rho\pi]S$: $a_1(1260)$



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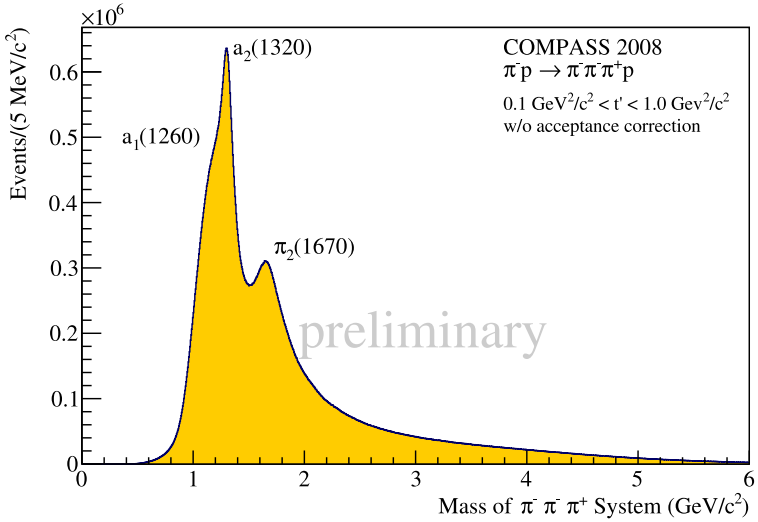

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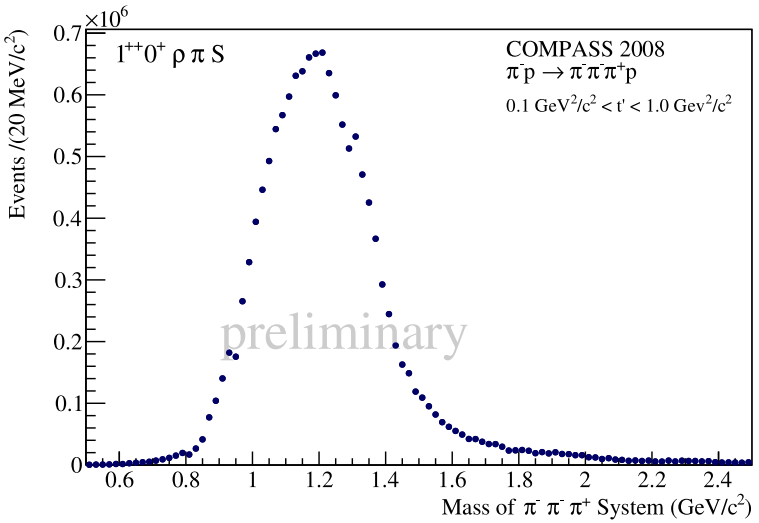
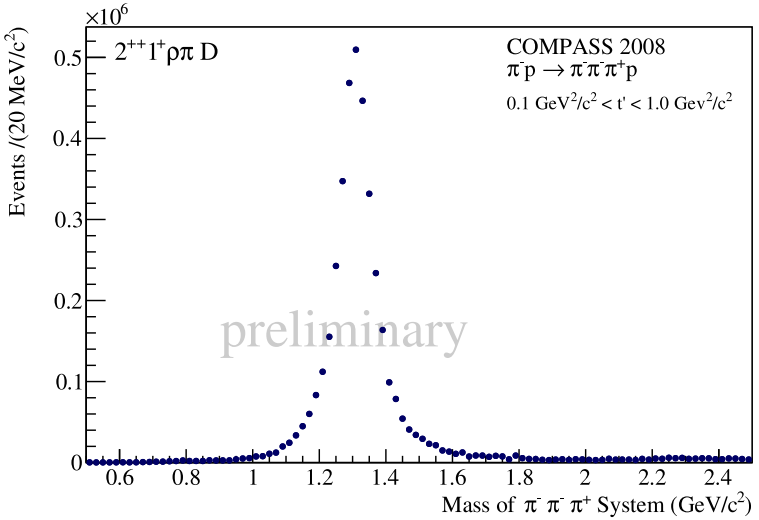


$2^{++}\,1^+\,[\rho\pi]D$: $a_2(1320)$



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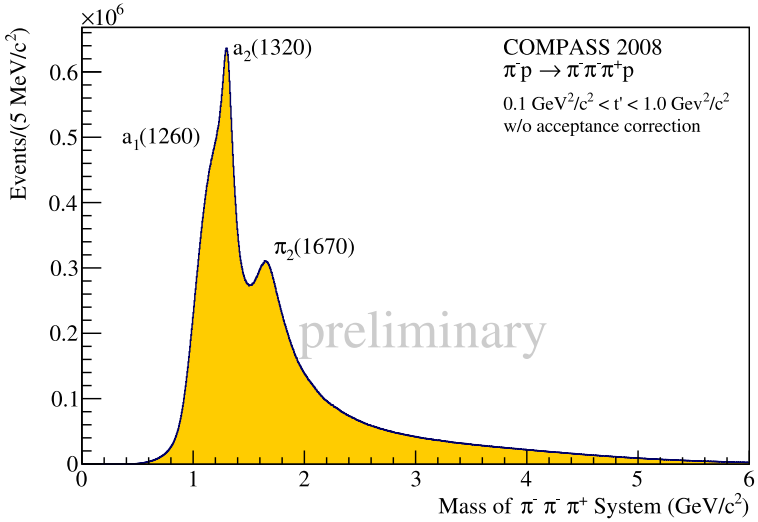

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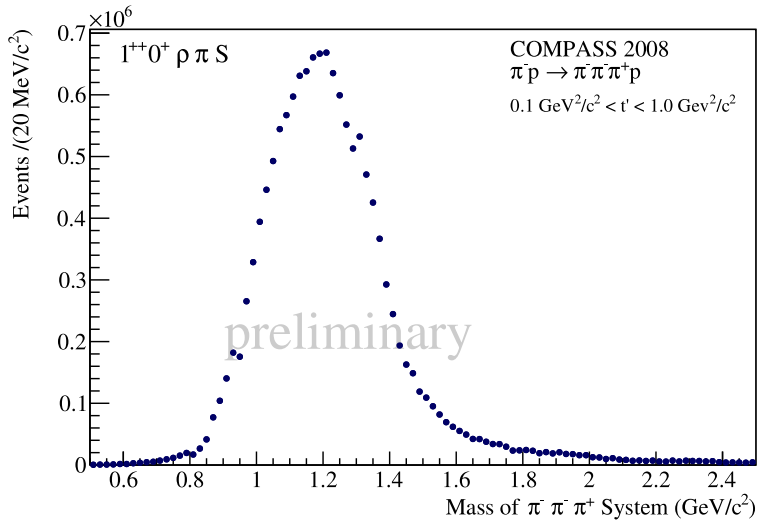

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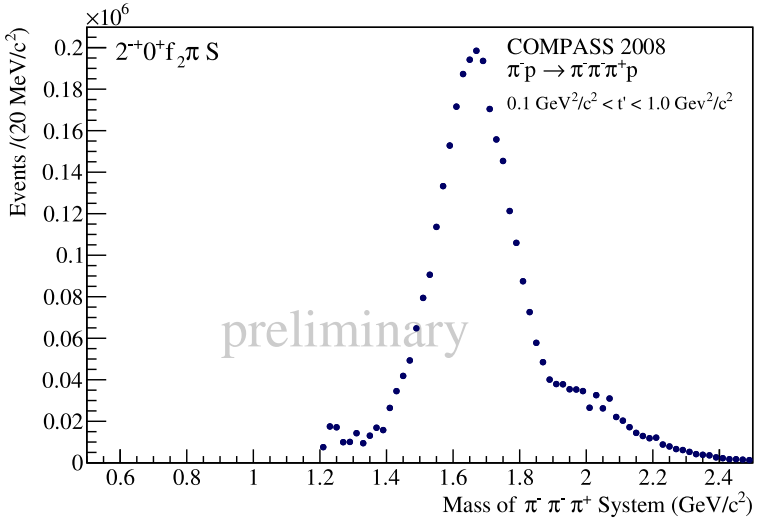

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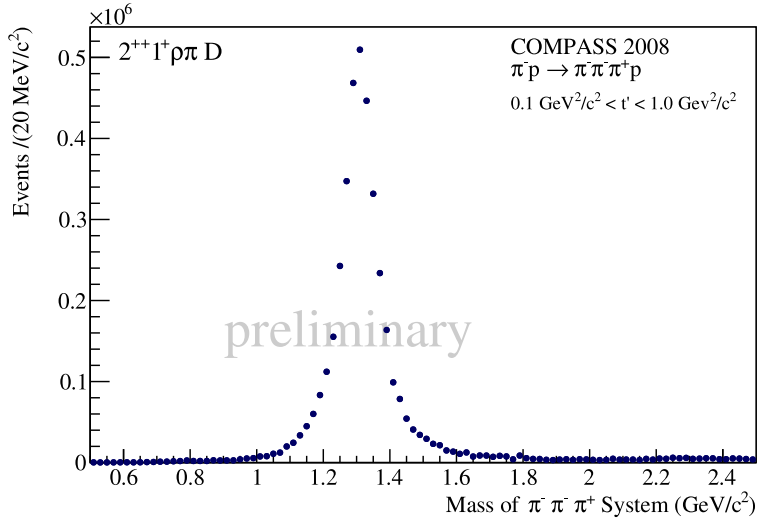

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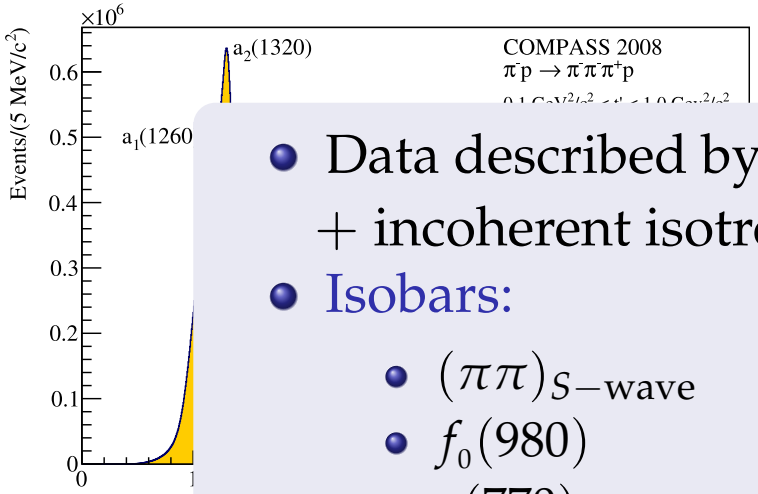

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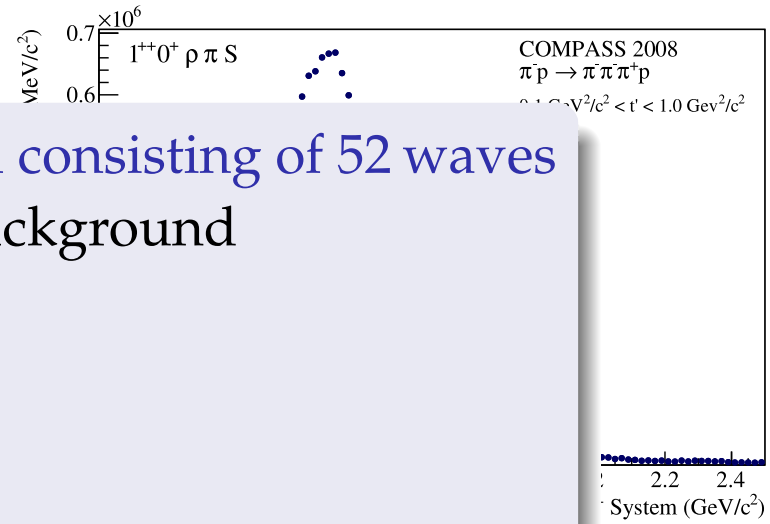
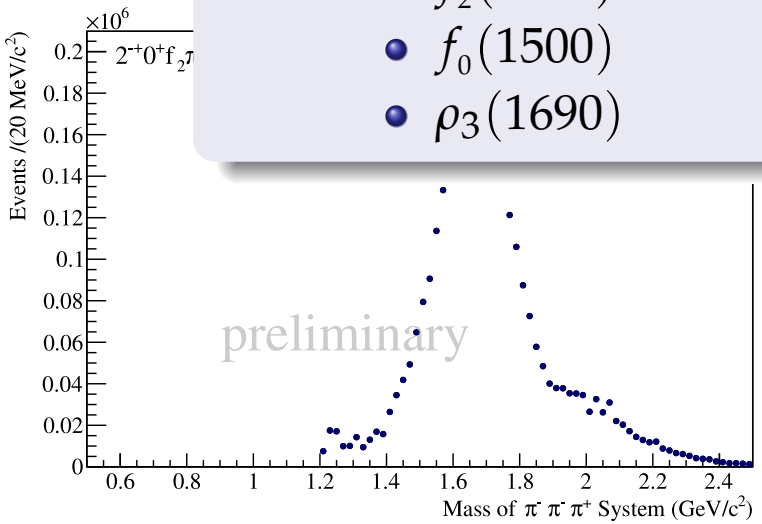
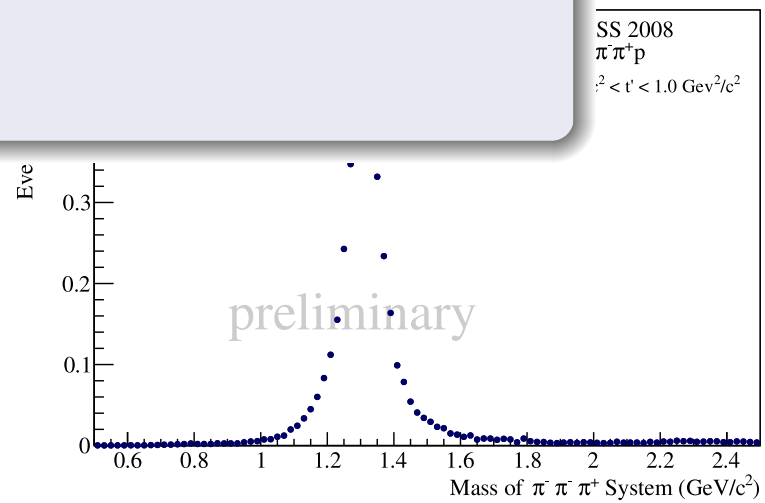


- Data described by model consisting of 52 waves + incoherent isotropic background
- Isobars:
  - $(\pi\pi)_{S-\text{wave}}$
  - $f_0(980)$
  - $\rho(770)$
  - $f_2(1270)$
  - $f_0(1500)$
  - $\rho_3(1690)$

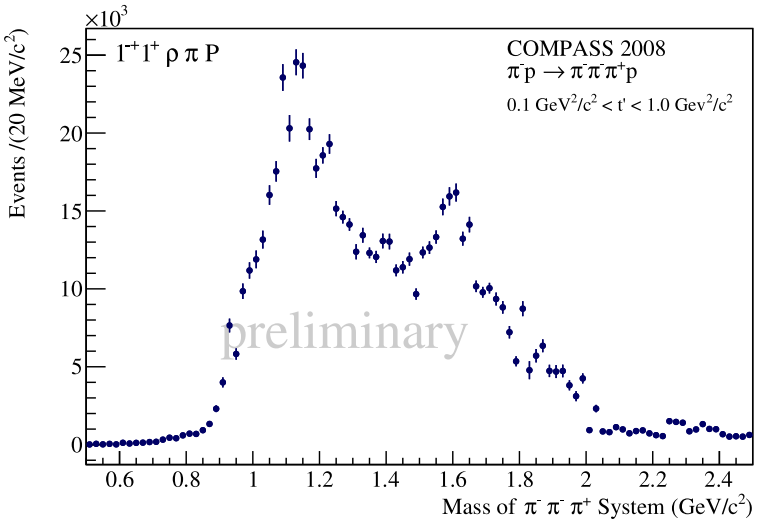
2^{-+} … 20)





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

Spin-exotic $1^{-+}\,1^+\,[\rho\pi]P$



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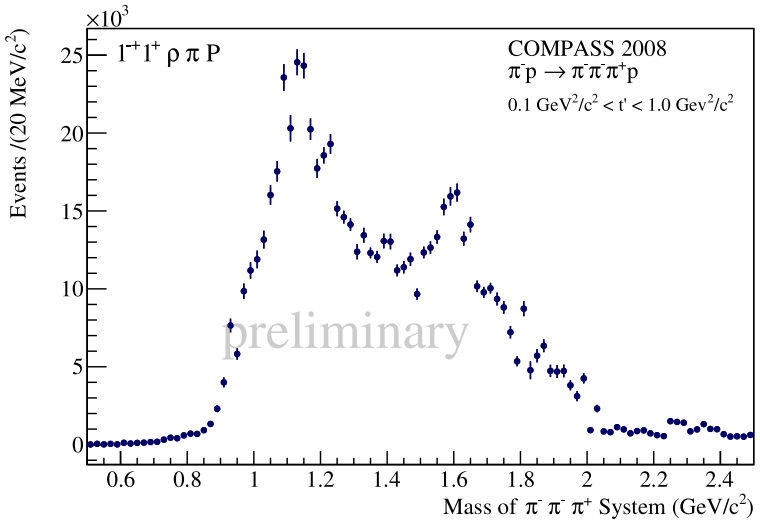

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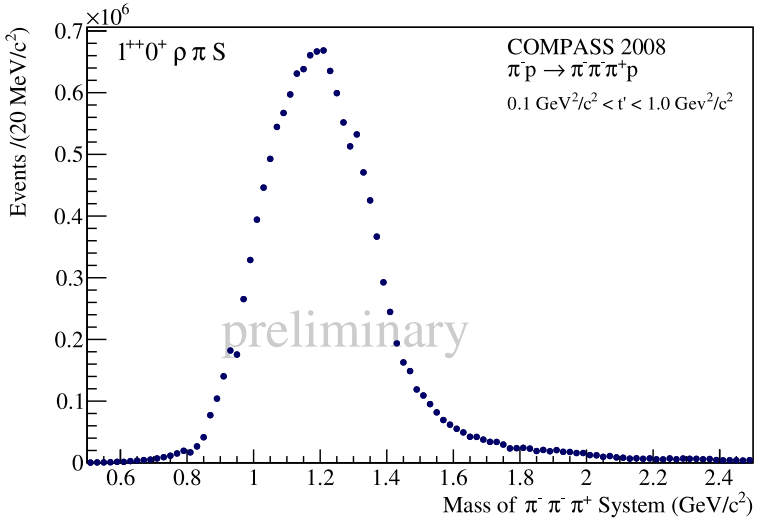

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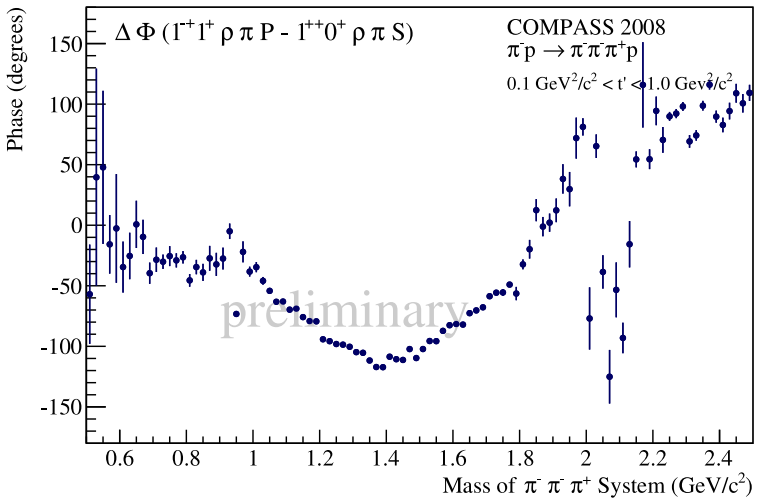

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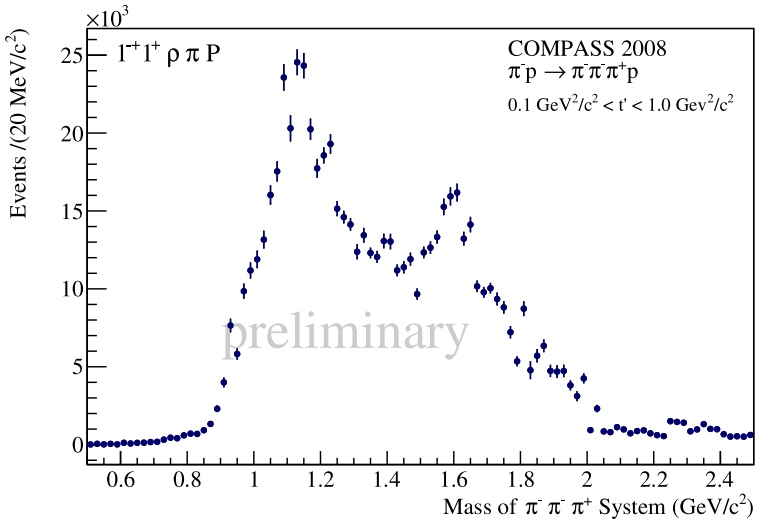
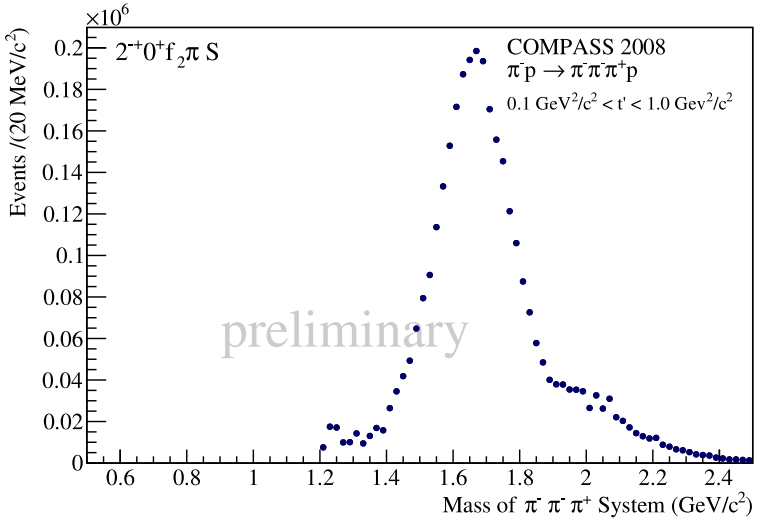


$2^{-+}\,0^+\,[f_2\pi]S$: $\pi_2(1670)$



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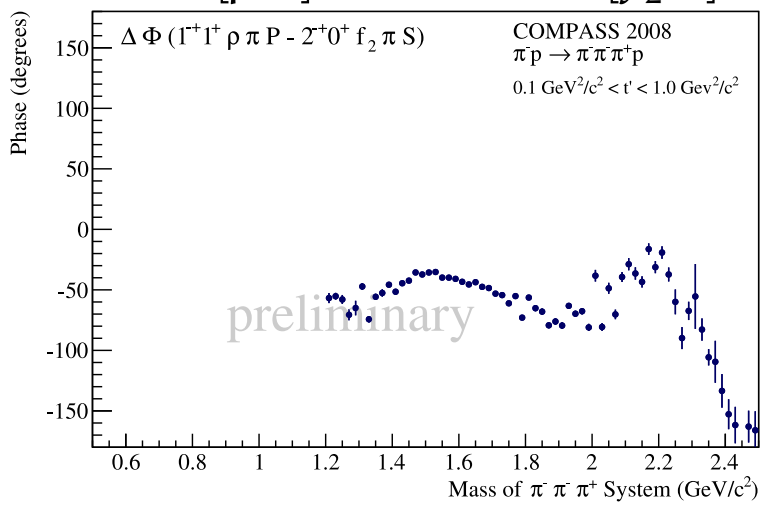

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Summary

Understanding of spin-exotic 1^{-+} wave is work in progress

- COMPASS: intensity in $\rho\pi$ and $\eta'\pi$ channels
  - Similar to BNL E852 and VES
  - Resonance interpretation still unclear
  - As CLAS: no signal in photoproduction
- Other spin-exotic 1^{-+} seen in channels
  - $f_1(1285)\pi$ (E852, VES)
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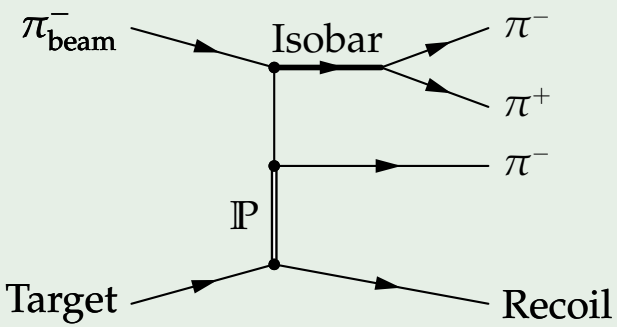

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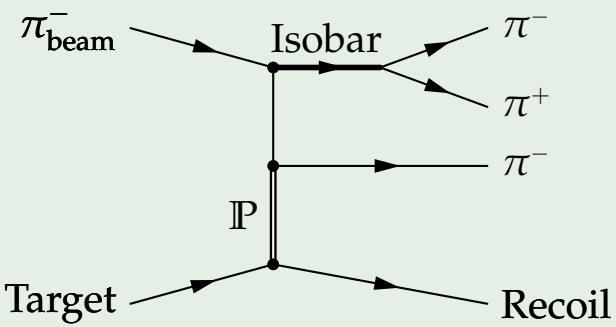
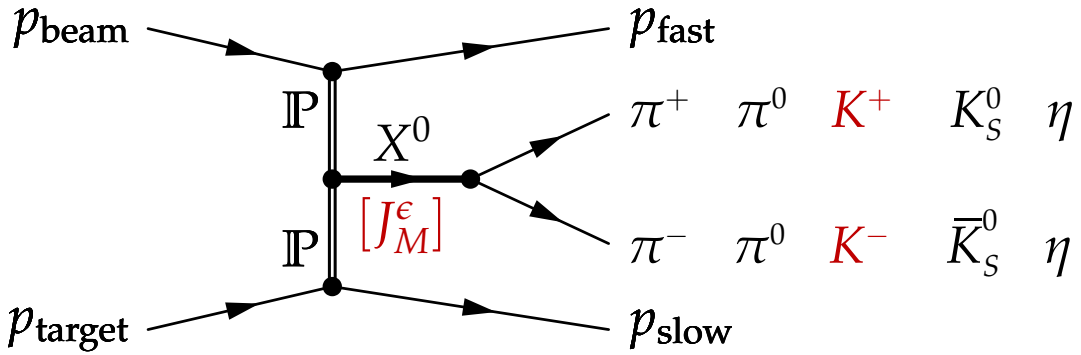


Central Production

COMPASS, CERN Omega (WA76, WA91, WA102)



Search for **glueball candidates**

- *Glueballs:* mesonic states with no valence quarks
- Lattice QCD simulations predict lightest glueballs to be scalars
  - Glueball would appear as supernumerous state
  - Strong mixing with conventional scalar mesons expected
  - Difficult to disentangle
- Pomeron-Pomeron fusion well-suited to search for glueballs
  - Isoscalar mesons produced at central rapidities
  - Scalar mesons dominant in this channel
  - Gluon-rich environment

Conclusions and Outlook

COMPASS has acquired large data sets for many reactions

- Diffractive dissociation of p, π^-, and K^- on various targets
- Central production with p and π^- beams on proton target
- $\pi^-\gamma$ and $K^-\gamma$ Primakoff reactions on heavy targets

Main focus: search for mesonic states beyond the CQM

- Huge diffractive $\pi^-\pi^+\pi^-$ data set: precision spectroscopy of light-quark isovector sector
- Spin-exotic $J^{PC} = 1^{-+}$ signals observed in π^- diffraction
  - $\pi^-\eta$ and $\pi^-\eta'$ channels
  - $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ final states
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  - π^- diffraction into $\pi^-\eta\eta$, $\pi^-\pi^+\pi^-\pi^+\pi^-$, $(\pi\pi K\bar{K})^-$, ...
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Conclusions and Outlook

Running and upcoming experiments

- VES
- BESIII
- Belle II
- GlueX, CLAS12
- PANDA
- ...

COMAPSS Conclusion

Establish an exotic meson $J^{PC} = 1^{-+}$:

$$\pi_1^-(1600) \to \rho^0 + \pi^-$$

consistent with previous publications
by BNL E852 and by COMPASS (2004 data).

Central Productions: COMPASS and ALICE

- Reaction:

$$a + b \to 1 + 3 + 2$$

$$a \to 1 + c(\text{space-like})$$
$$b \to 2 + d(\text{space-like})$$
$$c + d \to 3(\text{time-like})$$

A good approximation for ALICE:

Regge Domain: $\boxed{s_{13}s_{23} \simeq s\, w_3^2 = s\,(m_3^2 + \kappa_3^2)}$

w_3 = Transverse mass
κ_3 = Transverse momentum
(2-dimensional, normal to the beam direction)

Central Productions—continued

Lorentz-invariant phase-space element in the 3RF:
The plane$(a,1)$ is the $x-z$ plane; the plane$(b,2)$ is arbitrary;
the z-axis is along $\vec{c}-\vec{d}$ (note $\vec{c}=-\vec{d}$):

$$\mathrm{d}\Phi_3 = \left(\frac{1}{2E_1}\right) p_1^2 \mathrm{d}p_1\, \mathrm{d}\cos\theta_1 \left(\frac{1}{2E_2}\right) p_2^2 \mathrm{d}p_2\, \mathrm{d}\cos\theta_2\, \mathrm{d}\phi$$

Central Production at COMPASS and ALICE
S. U. Chung
—- to be an ALICE internal note

ALICE: PWA planned for 2-, 4- and 6-body final states

Final states for PWA:

- $\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^- K^+K^-$, $K_S\,K^\pm\pi^\mp$, $K_S \to \pi^+\pi^-$

Manpower available at ALICE:

- Jan Figiel and Lidia Goerlich / PAN Cracow, Poland
- Jeewon SEO (temporarily unavailable), Konkuk Univ., Korea
  Beomkyu KIM and Taesoo KIM / Yonsei Univ., Seoul, Korea
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$$p^\mu \; \varepsilon_\mu(m) = 0$$

Lorentz factors:

$$\frac{E_\rho}{m_\rho} \geq 1 \quad \text{for the } \rho(760) \quad \text{where } J = \ell = 1$$

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