Hadron Spectroscopy at COMPASS

and Related Experiments

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Erlangen, 23. July 2013

Outline

1. Introduction
   - QCD and constituent quark model
   - Beyond the constituent quark model
2. Hadron spectroscopy
   - Search for spin-exotic mesons in pion diffraction
   - Scalar mesons in central production
   - Baryon spectroscopy in proton diffraction
3. Conclusions and Outlook

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QCD: The Theory of Strong Interaction

Quantum chromodynamics describes interaction of quark and gluon fields

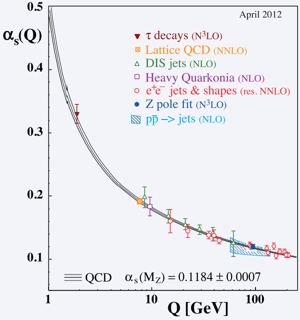
- Non-abelian gauge theory: gluons carry charge and self-interact
- Running coupling constant $\alpha_s(Q)$

Asymptotic freedom

- α_s small at short distances (high-energies)
  - Quarks and gluons relevant degrees of freedom
  - Lagrangian calculable by series expansion in α_s

Confinement of quarks and gluons into hadrons

- α_s large at distances $\mathcal{O}(1\text{ fm})$
  - Relevant d.o.f.: color-neutral hadrons
  - Series in α_s does not converge
    $\Longrightarrow$ non-perturbative regime
- Origin of confinement and connection to chiral symmetry breaking still not understood
- Explanation for 98 % of mass of visible matter in the universe
- Study of hadron spectra provides more insight



PDG 2012

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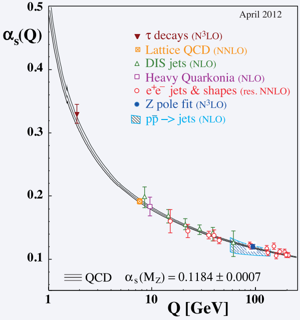

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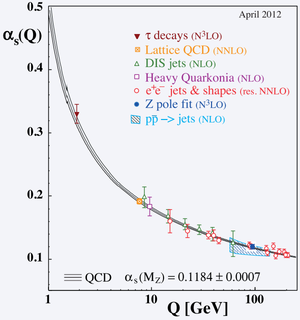

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Mesons in the Constituent Quark Model

Constituent Quark Model (CQM)

- Goes back over 40 years to Gell-Mann and Zweig
- **“Constituent” quarks:** quasi-particles with additional effective mass due to interaction with gluon field
  - E.g. for light-quark mesons $m_u = m_d = 310\ \text{MeV}/c^2$, $m_s = 485\ \text{MeV}/c^2$ Gasiorowicz *et al.*, AJP 49 (1981) 954
- Caveat: no connection to QCD

Mesons in CQM

- Color-singlet $|q\bar{q}'\rangle$ states, grouped into $\text{SU}(N)_{\text{flavor}}$ multiplets
- Meson masses are sum of constituent quark masses
- Together with hyperfine (spin-spin) interaction, meson spectrum is roughly described

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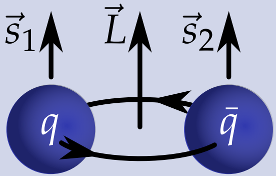
Mesons in the Constituent Quark Model

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: $G = C\,(-1)^I$
  - I isospin of meson
  - *Convention:* assign J^{PC} quantum numbers of neutral partner in isospin multiplet

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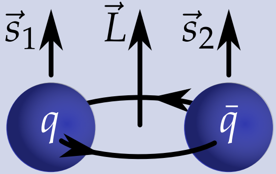

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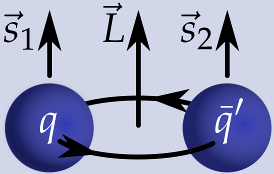
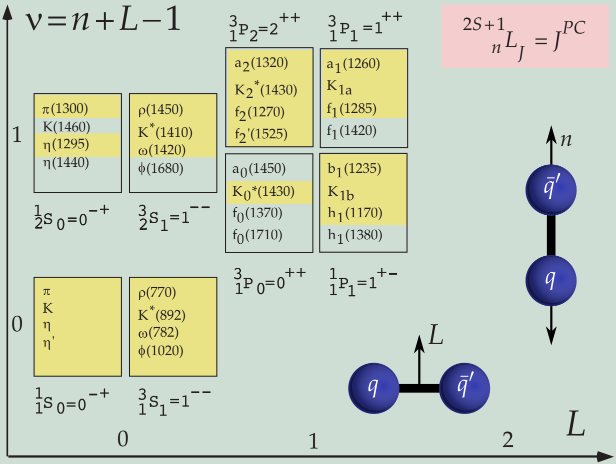


Mesons in the Constituent Quark Model

Light-quark meson spectrum



Amsler *et al.*, Phys. Rept. 389 (2004) 61

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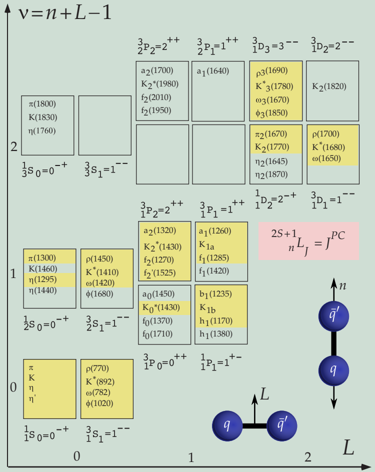
Light-quark meson spectrum (cont.)



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"Light meson frontier":

- Many missing and disputed states in mass region $m \approx 2\ \mathrm{GeV}/c^2$
- Identification of higher excitations becomes exceedingly difficult
  - Wider states + higher state density
  - More overlap and mixing

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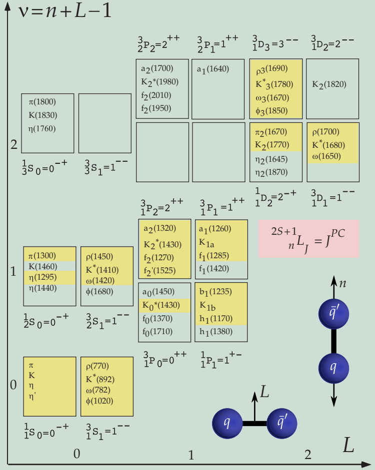

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***QCD:* Gluonic d.o.f. should manifest themselves in hadron spectra**

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 $\pi_1(1400, 1600, 2000)$ controversial

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

QCD in the confinement regime: $\alpha_s = \mathcal{O}(1)$

- QCD Lagrangian *not* calculable using perturbation theory

General *ab-initio* method: Lattice Gauge Theory

- Simulation of QCD Lagrangian on finite discreet space-time lattice using Monte Carlo techniques (computationally very expensive)
- *Challenge:* extrapolation to physical point
  - Heavier u and d quarks than in reality $\Longrightarrow$ extrapolation to physical quark masses
  - Extrapolation to infinite volume
  - Extrapolation to zero lattice spacing
    - Rotational symmetry broken due to cubic lattice
- Tremendous progress in past years
  - Finer lattices $\Longrightarrow$ spin-identified spectra
  - Larger operator bases $\Longrightarrow$ extraction of many excited states
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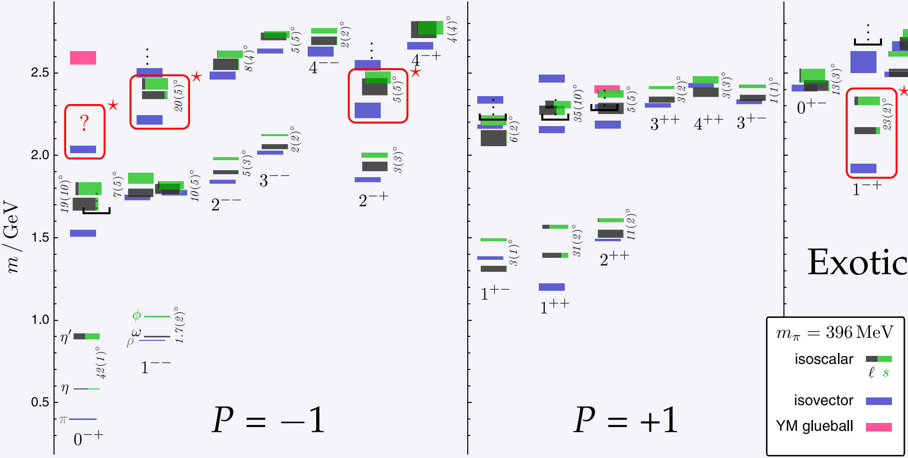
Light-Meson Spectrum in Lattice QCD

State-of-the-art light-meson spectrum

Dudek, PR D84 (2011) 074023

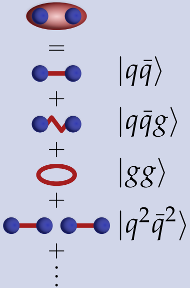


- Resonance widths and decay modes still very difficult

Beyond the Constituent Quark Model

Finding states beyond the CQM is difficult

- Physical mesons = linear superpositions of *all* allowed basis states: $|q\bar{q}\rangle, |q\bar{q}g\rangle, |gg\rangle, |q^2\bar{q}^2\rangle, \ldots$
  - 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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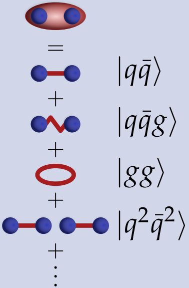

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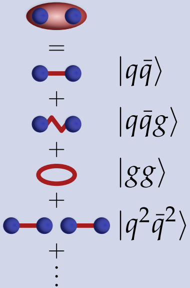

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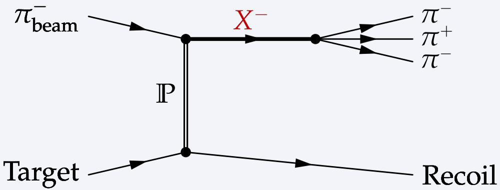
Production of Hadrons in Diffractive Dissociation

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': 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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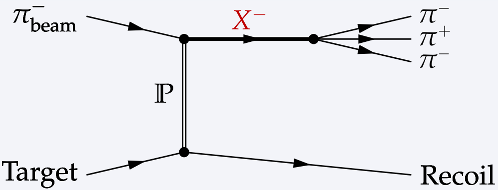

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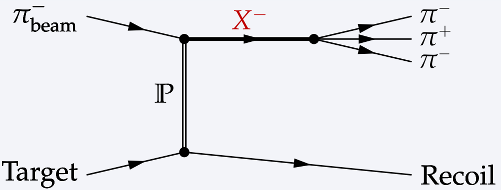

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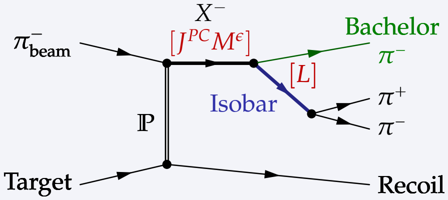

Isobar model: X^- decay is chain of successive two-body decays

- **"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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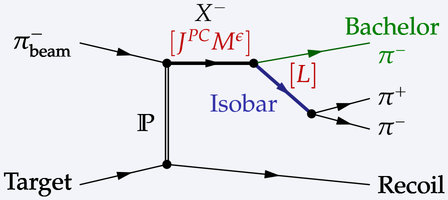

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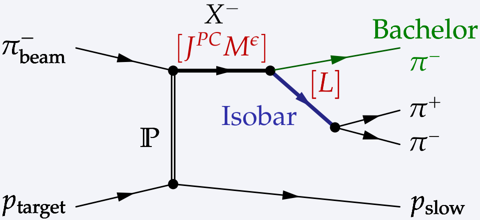
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

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
  - Model deficiencies become visible

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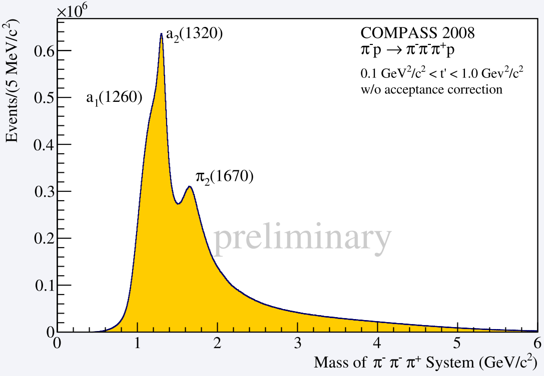
  - Needs precise understanding of apparatus
  - Model deficiencies become visible

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



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

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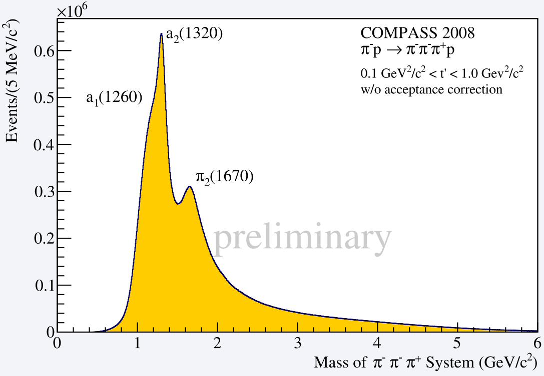
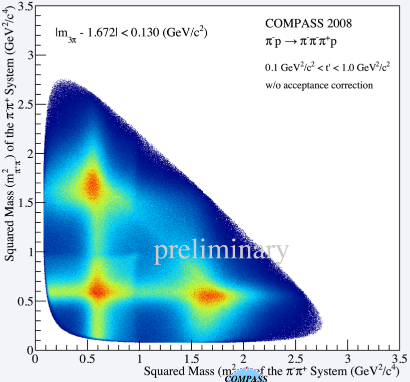
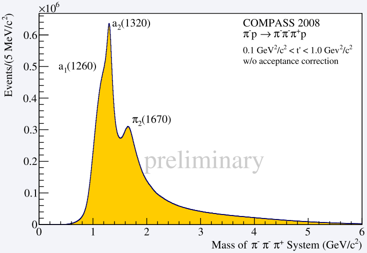


Dalitz plot for $\pi_2(1670)$ region



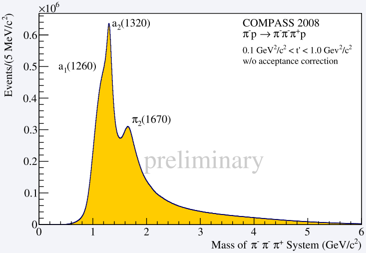
PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

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

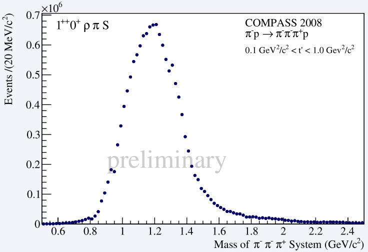


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

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



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



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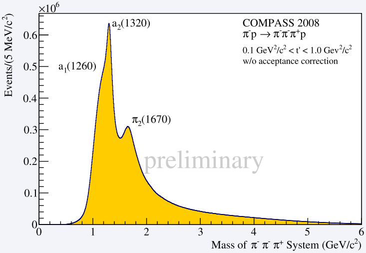

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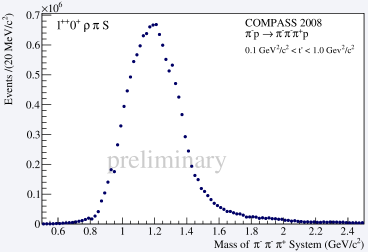
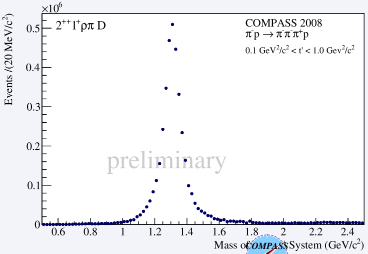


$2^{++}\,1^{+}\,[\rho\pi]D$: $a_2(1320)$



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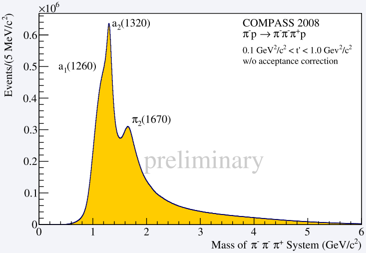

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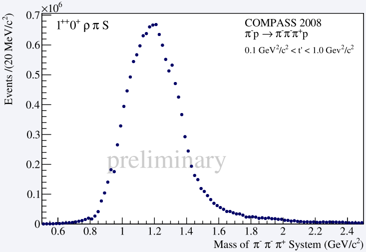
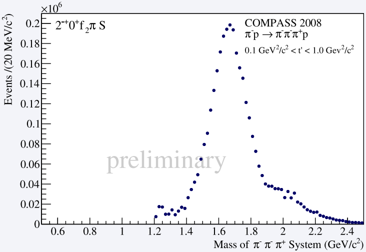
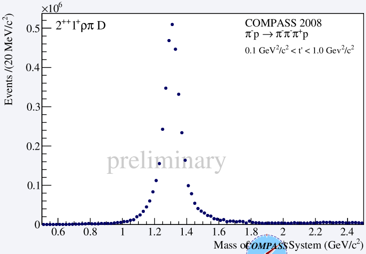


$2^{-+}\,0^+\,[f_2\pi]S$: $\pi_2(1670)$

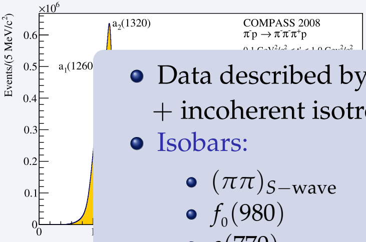


$2^{++}\,1^+\,[\rho\pi]D$: $a_2(1320)$



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

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



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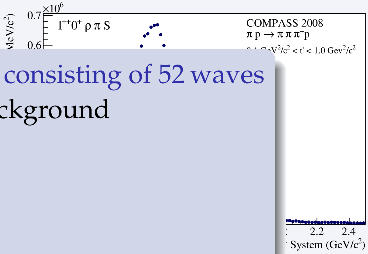
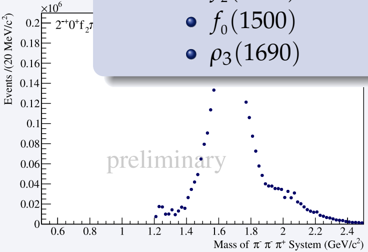
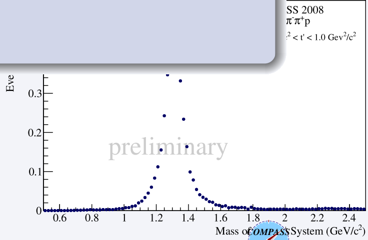


2^{-+}

20)

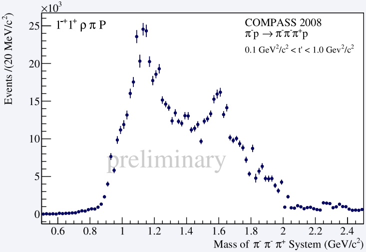




- Data described by model consisting of 52 waves + incoherent isotropic background
- Isobars:
  - $(\pi\pi)_{S-\text{wave}}$
  - $f_0(980)$
  - $\rho(770)$
  - $f_2(1270)$
  - $f_0(1500)$
  - $\rho_3(1690)$

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

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



- Structure around 1.1 GeV/c^2 unstable w.r.t. fit model
- Enhancement around 1.6 GeV/c^2
- Phase motion w.r.t. to tail of $a_1(1260)$
- Phase locked w.r.t. $\pi_2(1670)$
- Ongoing analysis

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

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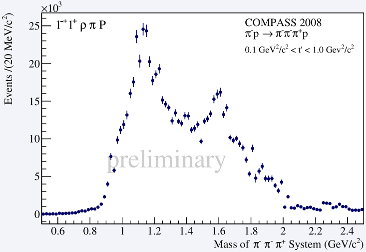

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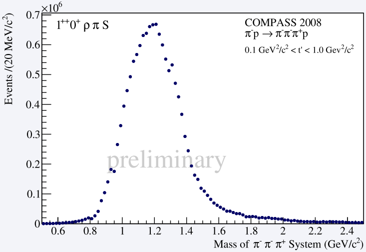
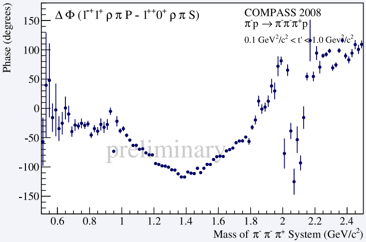


$1^{-+}1^+ [\rho\pi]P - 1^{++}0^+ [\rho\pi]S$



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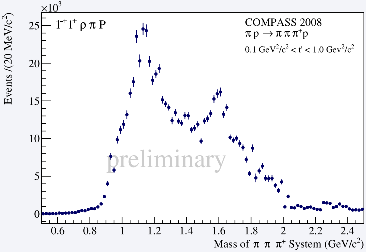
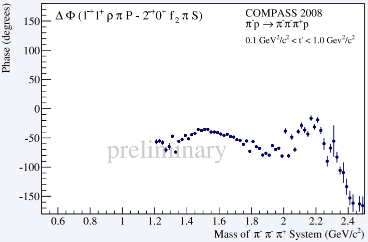
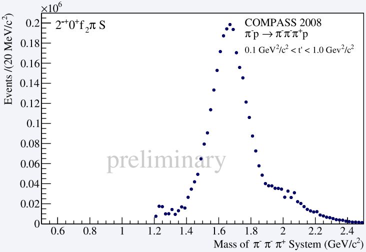


$1^{-+}1^+ [\rho\pi]P - 2^{-+}0^+ [f_2\pi]S$



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



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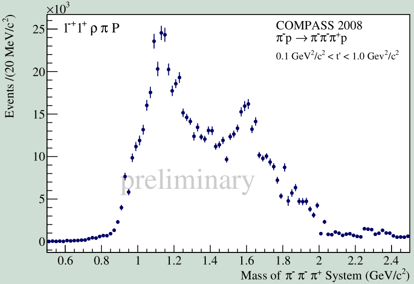
Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with BNL E852 and VES

COMPASS



- 190 GeV/c π beam
- p target
- $50 \cdot 10^6$ events
- $0.1 < t' < 1.0\ (\text{GeV}/c)^2$
- Rank-2 fit with 53 waves

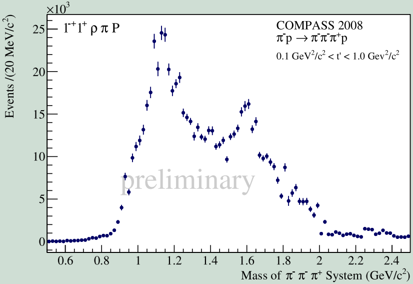
BNL E852 PR D73 (2006) 072001

- 18 GeV/c π beam
- $2.6 \cdot 10^6$ events
- $0.1 < t' < 0.5\ (\text{GeV}/c)^2$
- Rank-1 fit with 21/36 waves

Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with BNL E852 and VES

COMPASS



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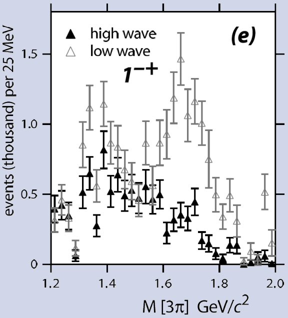
BNL E852 PR D73 (2006) 072001



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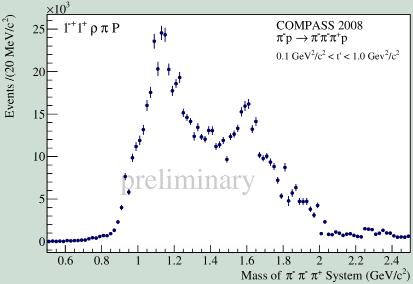

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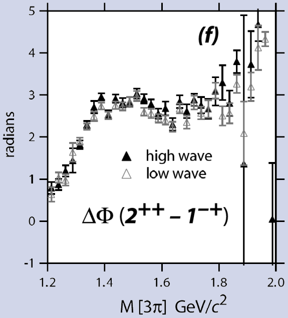
BNL E852 — PR D73 (2006) 072001



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Comparison with BNL E852 and VES

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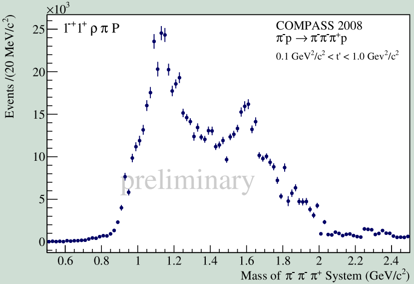
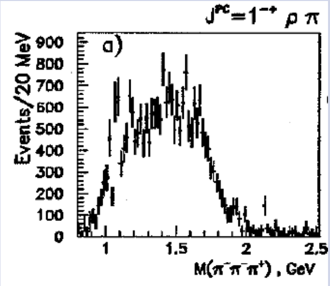


- $190\,\text{GeV}/c$ π beam
- p target
- $50 \cdot 10^6$ events
- $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Rank-2 fit with 53 waves

VES

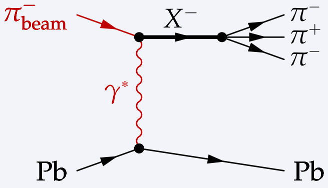
NP A675 (2000) 155



- $36.6\,\text{GeV}/c$ π beam
- Be target
- $9 \cdot 10^6$ events
- "Infinite"-rank fit with 44 waves

PWA of π^- Pb $\to \pi^-\pi^+\pi^-$ Pb at low t'

COMPASS

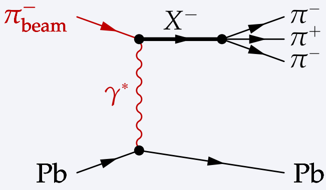


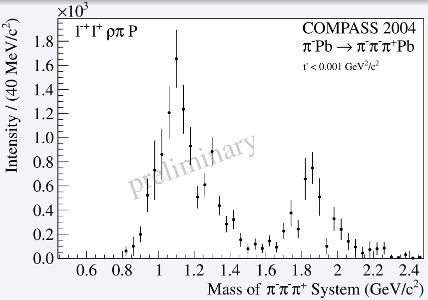
$\pi^-\pi^+\pi^-$ production in Primakoff reaction

- Very small momentum transfer: $t' < 0.001\ (\text{GeV}/c)^2$
- Photoproduction in Coulomb field of heavy target nucleus (Pb)
- For $M = 1$ waves diffractive contribution kinematically suppressed
- No intensity in 1.6 GeV/c^2 region in spin-exotic 1^{-+} wave

PWA of $\pi^- \mathrm{Pb} \to \pi^-\pi^+\pi^- \mathrm{Pb}$ at low t'

COMPASS





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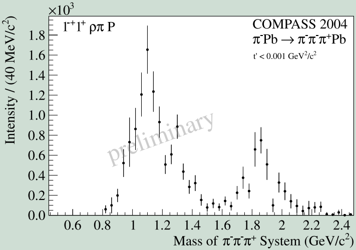
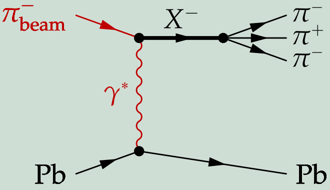
Photoproduction of Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with CLAS g12

COMPASS Primakoff





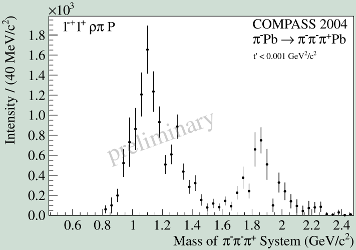
CLAS g12 C. Bookwalter, arXiv:1108.6112

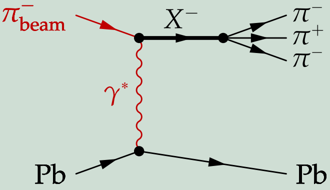
- Tagged photon beam
- $3.6 < E_\gamma < 5.5\,\text{GeV}$
- p target
- 502 000 events

Photoproduction of Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with CLAS g12

COMPASS Primakoff





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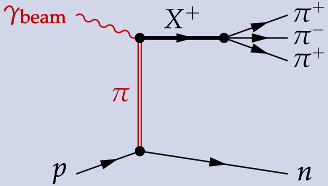

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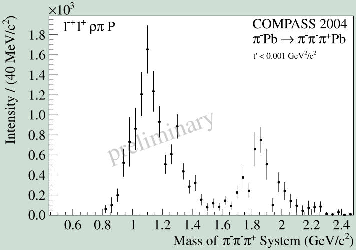

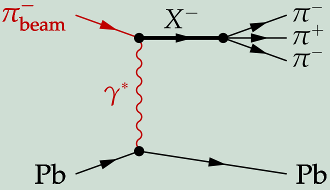

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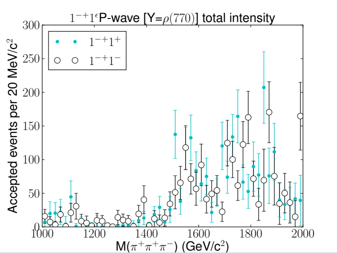

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PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

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
- Spin-exotic 1^{-+} also claimed in channels
  - $f_1(1285)\pi$ (E852, VES)
  - $b_1(1235)\pi$ (E852, VES, Crystal Barrel)
  - COMPASS will analyze these channels as well

- Improvements of wave set and isobar parameterization

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  - Inclusion into fit model
- Exploit t'-dependence of partial-wave amplitudes
  - PWA in narrow $m_{\pi^-\pi^+\pi^-}$ and t' bins
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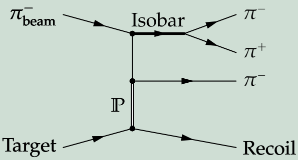

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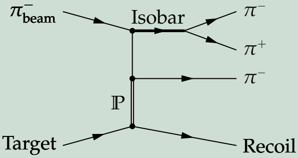
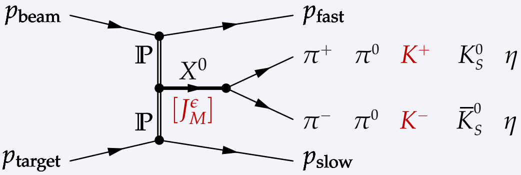


Central Production

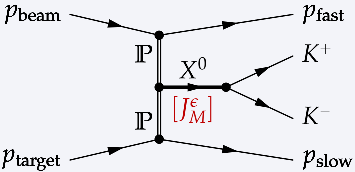
COMPASS, CERN Omega (WA76, WA91, WA102)



Search for **glueball candidates**

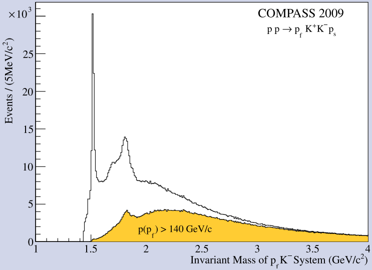
- *Glueballs:* mesonic states with no valence quarks
- Lattice QCD simulations predict lightest glueballs to be scalars
  - Glueball would appear as supernumerous state
  - Strong mixing with conventional scalar mesons expected
  - Difficult to disentangle
- Pomeron-Pomeron fusion well-suited to search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

K^+K^- Central Production

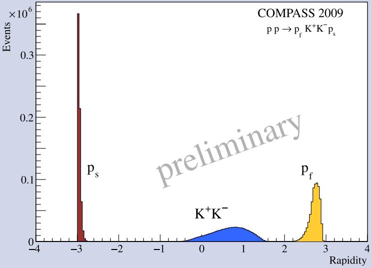


Suppression of diffractive background by cut $p(p_{fast}) > 140$ GeV/c

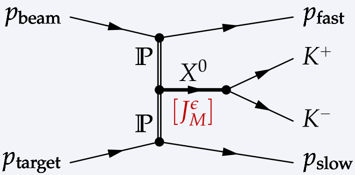
$p_{fast}K^-$ invariant mass



Rapidity in CM frame

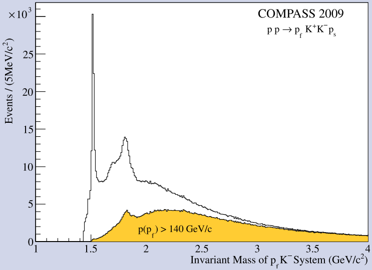


K^+K^- Central Production



Suppression of diffractive background by cut $p(p_{\text{fast}}) > 140$ GeV/c

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



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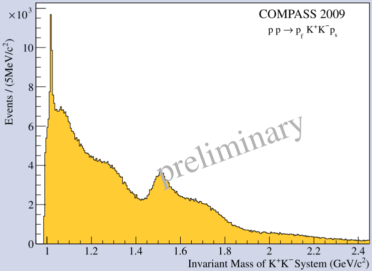
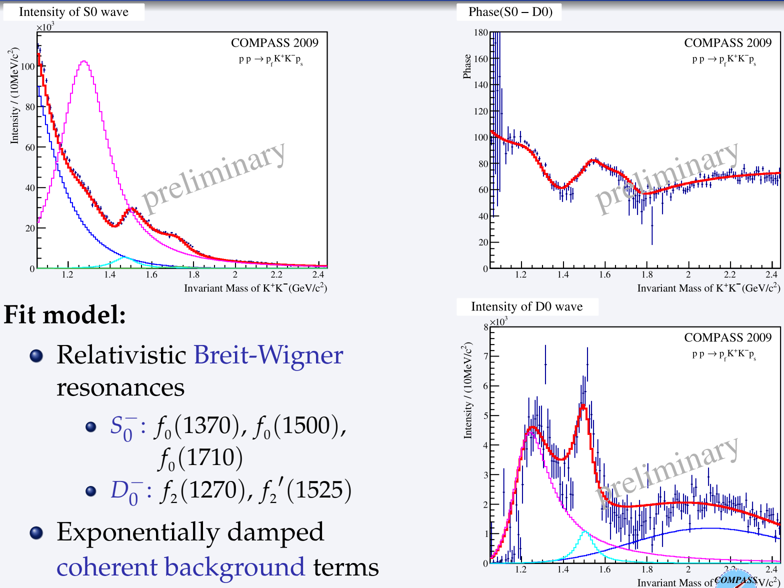


Fit of K^+K^- Mass Dependence



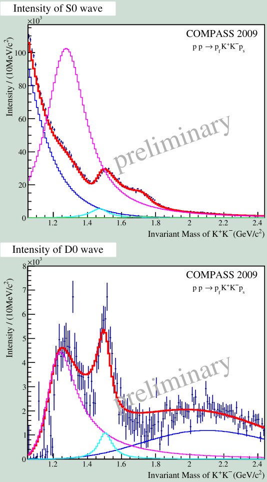
Fit model:

- Relativistic Breit-Wigner resonances
  - S_0^-: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
  - D_0^-: $f_2(1270)$, $f_2'(1525)$
- Exponentially damped coherent background terms

Fit of K^+K^- Mass Dependence

Comparison with WA102

COMPASS



WA102

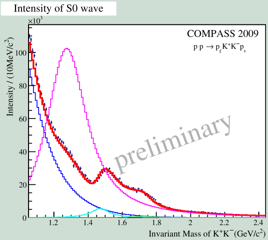
PL B453 (1999) 305

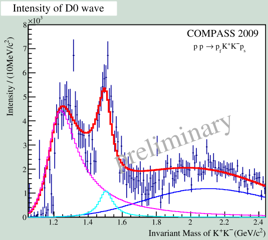
- 450 GeV/c p beam
- Fit of wave intensities only

Fit of K^+K^- Mass Dependence

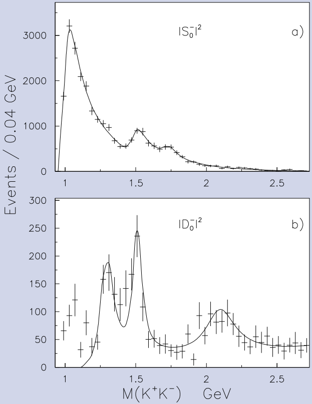
Comparison with WA102

COMPASS





WA102 PL B453 (1999) 305



- 450 GeV/c p beam
- Fit of wave intensities only

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

Summary

- Clean K^+K^- central-production sample
- PWA result similar to WA102
- Mass dependence can be described by model with three S_0^- and two D_0^- Breit-Wigner resonances
  - Extracted Breit-Wigner parameters mostly comparable to PDG values
- Surprisingly strong signal for $f_0(1370)$
  - $f_0(1370)$ resonance required by observed phase motion

Work in progress

- Simplistic fit model
  - Angular information of the two proton scattering planes not taken into account
  - Mass dependence parametrized by sum of relativistic Breit-Wigners
- *Goal:* combined analysis including $K^0_S K^0_S$, $\pi^+\pi^-$, $\pi^0\pi^0$, and $\eta\eta$

Baryon Spectroscopy

Search for

- "Missing" states
- Gluonic excitations (hybrids)

Worldwide experimental program

- ELSA, JLab, MAMI, J-PARC
- Excitation of baryon resonances using low-energy pion and photon beams
  - E.g. $\gamma + N \to N + \pi,\ \pi\pi,\ \pi\pi\pi,\ \eta,\ \pi\eta,\ \pi\omega,\ \eta\eta,\ \ldots$
- "Complete experiment"
  - Polarized beam *and* target + measurement of recoil polarization
  - 8 carefully selected double/single-spin observables
  - Well-defined quantum numbers of initial and final state
  - Unambiguous determination of scattering amplitude

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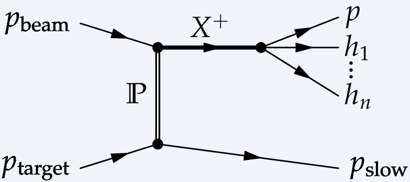
Baryon Spectroscopy in Proton Diffraction



- Large data set with 190 GeV/c positive hadron beam on liquid hydrogen target in kinematic range $0.1 < t' < 1.0\,(\text{GeV}/c)^2$
- Diffractive dissociation of beam p into various final states:
  - $p\pi^0$, $p\eta$, $p\eta'$, $p\omega$
  - $p\pi^+\pi^-$, $p\pi^0\pi^0$, pK^+K^-, $pK^0_S\bar{K}^0_S$, $p\eta\eta$
  - …
- Unpolarized beam and target; recoil polarization not measured
- J^P quantum numbers of initial state not fixed
- Quantization axis = beam direction (Gottfried-Jackson frame)
- $J^P M^\epsilon$ of intermediate state X deducible from kinematic distribution of final-state particles

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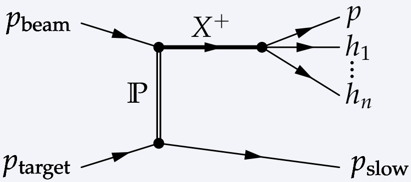

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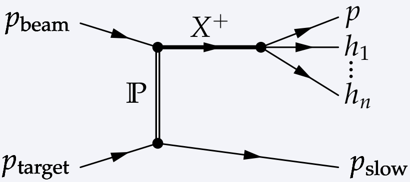

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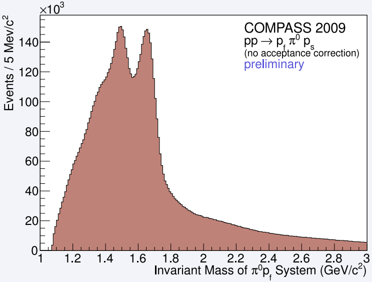
$pp \to p\pi^0\, p_{\text{slow}}$

$p\pi^0$ invariant mass



$\cos\theta_{GJ}$ of π^0 vs. $m_{p\pi^0}$

ϕ_{TY} of π^0 vs. $m_{p\pi^0}$

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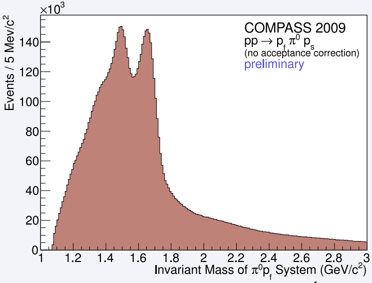

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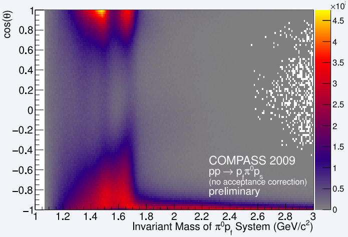

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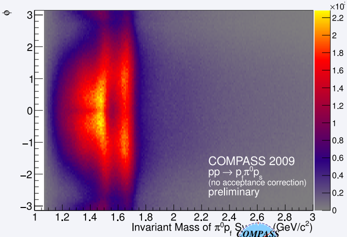
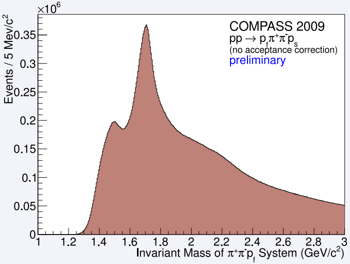


$pp \to p\pi^+\pi^- p_{\text{slow}}$

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



$p\pi^+$ subsystem

$p\pi^-$ subsystem

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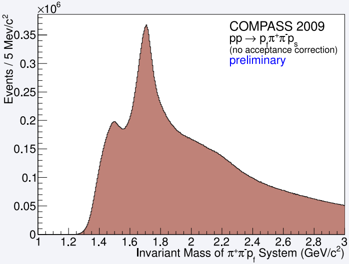

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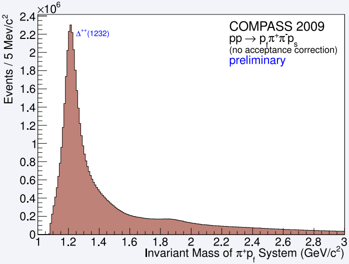

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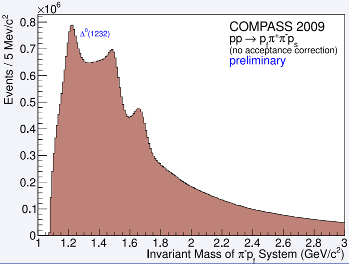

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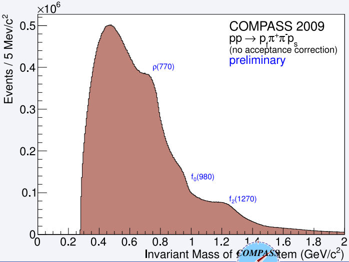

Baryon Spectroscopy in Proton Diffraction

Summary

- Large data sets from p diffraction
  - $p\pi^0$: $8.8 \cdot 10^6$ events
  - $p\eta$: 440 000 events
  - $p\pi^+\pi^-$: more than $50 \cdot 10^6$ events
  - …
- Interesting structures visible in kinematic distributions
- $\mathbb{P}p$ data complementary to γp and πp data
- Will start with PWA of two-body final states
  - Acceptance correction in preparation
  - Implementation of PWA model started
- Three-body final states require more work on PWA model

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Outline

1. Introduction
   - QCD and constituent quark model
   - Beyond the constituent quark model
2. Hadron spectroscopy
   - Search for spin-exotic mesons in pion diffraction
   - Scalar mesons in central production
   - Baryon spectroscopy in proton diffraction
3. Conclusions and Outlook

Conclusions and Outlook

COMPASS has acquired large data sets for many reactions

- Diffractive dissociation of p, π^-, and K^- on various targets
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- $\pi^-\gamma$ 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
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  - Resonance interpretation still unclear
- Study of scalar mesons in central production of $\pi\pi$, $K\bar{K}$, and $\eta\eta$
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Conclusions and Outlook

Running and upcoming experiments

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

Outline

4 Backup slides I
- Introduction
- Search for spin-exotic mesons in π^- diffraction
  - $\pi^-\pi^+\pi^-$ final state
  - $\eta'\pi^-$ final state
- PWA of $\pi^-\eta$ and $\pi^-\eta'$ from final states
  - PWA of $\pi^-\pi^+\pi^-\pi^+\pi^-$ decay channel

5 Backup Slides II
- Search for scalar glueballs in central production
  - PWA of $\pi^+\pi^-$ system

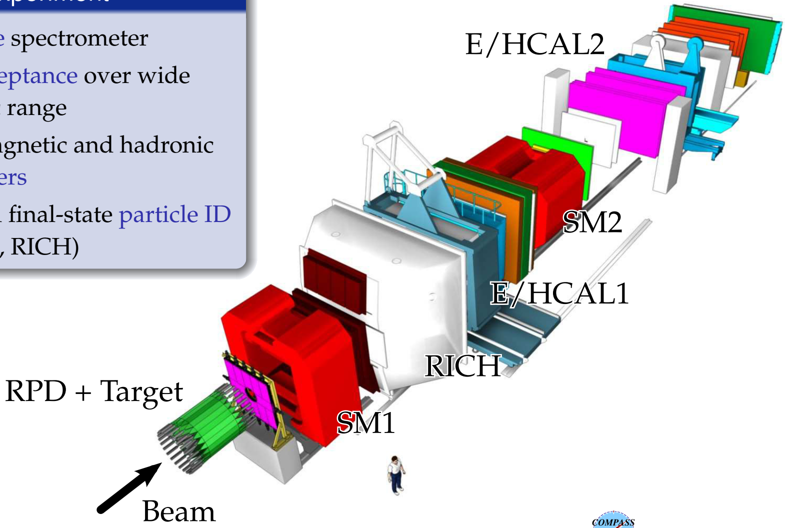
The COMPASS Experiment at the CERN SPS

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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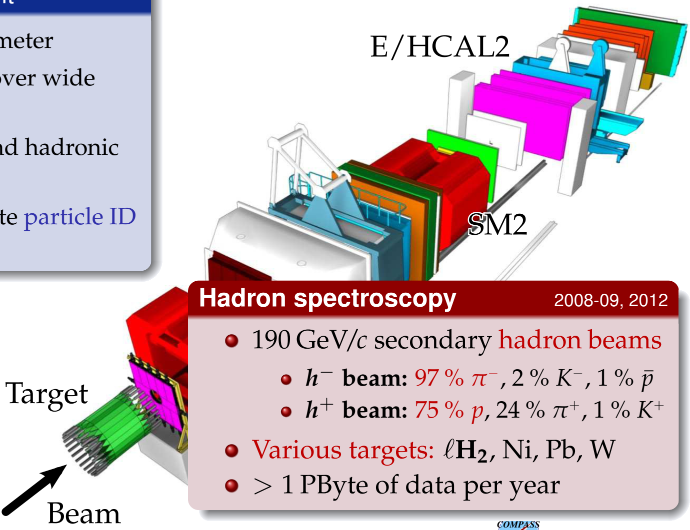


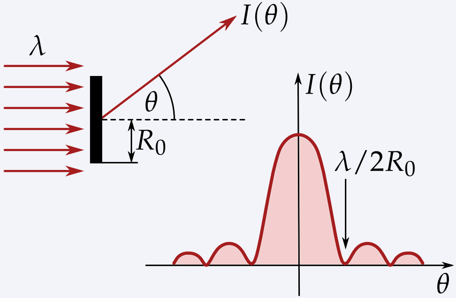
Hadron spectroscopy 2008-09, 2012

- 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

Meson Production in Diffractive Dissociation

Reaction similar to diffraction of light by black disk

- Relevant kinematic variable is squared four-momentum transfer $t = (p_{\text{beam}} - p_X)^2 < 0$; more practical $t' \equiv |t| - |t|_{\text{min}} > 0$
- **"Intermediate-t'"** region: diffraction pattern of Pb nucleus
- **"High-t'"** region: scattering on individual nucleons in nucleus



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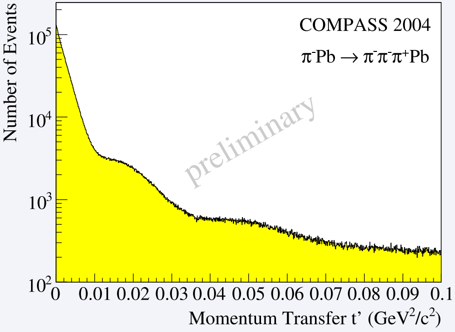

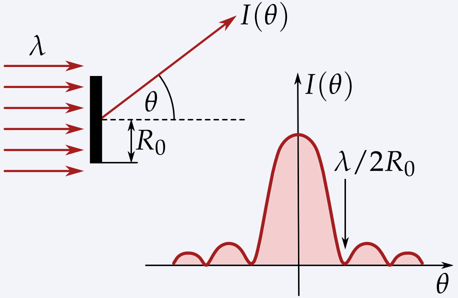

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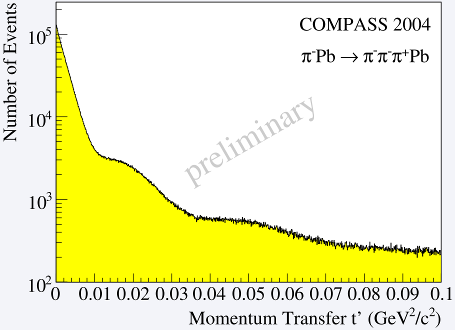
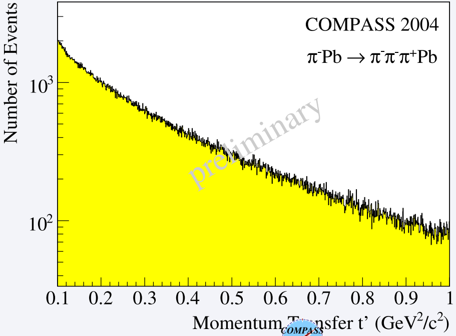
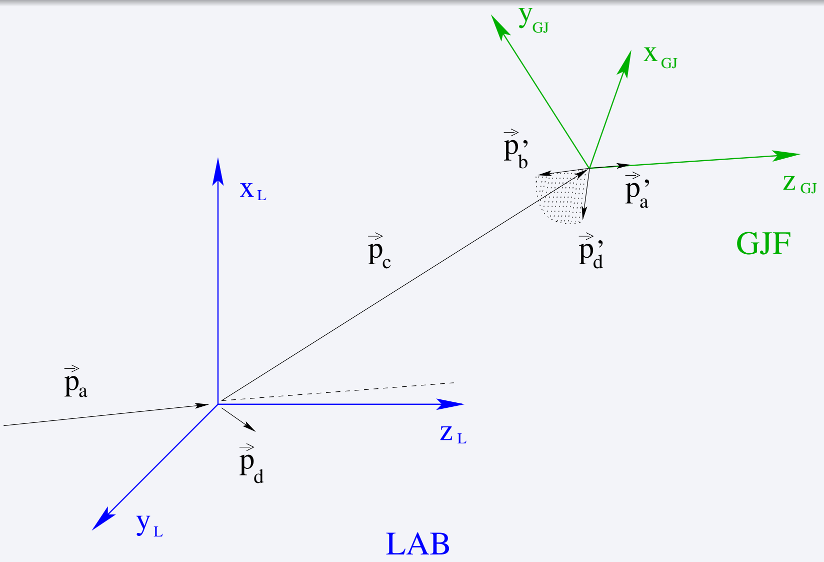


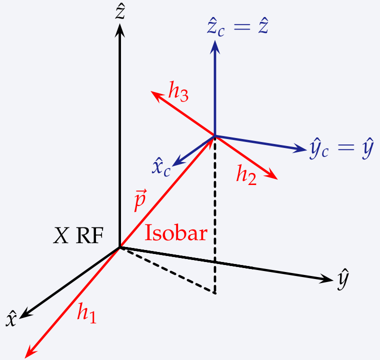
$t' \in [0.1, 1]$ (GeV/c)^2

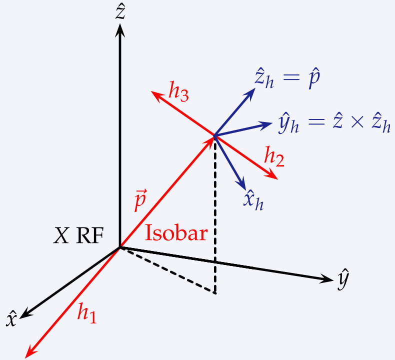


Gottfried-Jackson Coordinate System



Canonical vs. Helicity Coordinate System





Partial-Wave Analysis Formalism

Cross section parameterization in mass-independent PWA

$$\sigma(\tau; m_X) = \sigma_0 \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_{i}^{\text{waves}} T_i^{r\epsilon}(m_X)\, A_i^{\epsilon}(\tau) \right|^2$$

- ϵ, i: quantum numbers of partial wave ($J^{PC} M^{\epsilon}$ [isobar] L)
- $T_i^{r\epsilon}$: complex production amplitudes; fit parameters
- A_i^{ϵ}: complex decay amplitudes
- τ: phase space coordinates

Spin-density matrix

$$\rho_{ij}^{\epsilon} = \sum_{r=1}^{N_r} T_i^{r\epsilon}\, T_j^{r\epsilon *} \qquad \sigma(\tau; m_X) = \sigma_0 \sum_{\epsilon=\pm1} \sum_{i,j}^{\text{waves}} \rho_{ij}^{\epsilon}(m_X)\, A_i^{\epsilon}(\tau)\, A_j^{\epsilon *}(\tau)$$

- Diagonal elements ρ_{ii}: intensities
- Off-diagonal elements ρ_{ii}, $i \neq j$: interference terms

Partial-Wave Analysis Formalism

Two-body decay amplitude in helicity formalism

- Decay $X(w, J, \lambda) \to 1(J_1, \lambda_1)\ [L, S]\ 2(J_2, \lambda_2)$

$$A_X^{\text{hel}} = \sqrt{2L+1} \sum_{\lambda_1, \lambda_2} (J_1\,\lambda_1\; J_2\, -\lambda_2 | S\, \delta)\,(L\,0\,S\,\delta | J\,\delta)\; D_{\lambda\delta}^{J*}(\theta, \phi, 0)\, F_L(q)\, \Delta(w)\, A_1\, A_2$$

- $\delta = \lambda_1 - \lambda_2$
- $D_{\lambda\delta}^{J*}(\theta, \phi, 0)$ — Wigner D-function describes rotational properties of helicity states
- θ, ϕ — polar angles of decay daughter 1 in X rest frame (GJ or helicity frame)
- $F_L(q)$ — Blatt-Weisskopf barrier factor
- $\Delta(w)$ — amplitude that describes resonance shape of X
- $A_{1,2}$ — decay amplitudes of (unstable) daughter particles 1 and 2

Partial-Wave Analysis Formalism

Two-body decay amplitude in canonical formalism

- Decay $X(w, J, M) \to 1(J_1, M_1)\ [L, S]\ 2(J_2, M_2)$

$$A_X^{\text{can}} = \sqrt{2J+1} \sum_{M_1, M_2} (J_1\, M_1\ J_2\, M_2 | S\, M_S) \sum_{M_L} (L\, M_L\ S\, M_S | J\, M) \sqrt{\frac{4\pi}{2L+1}} Y_{M_L}^L(\theta, \phi)\, F_L(q)\, \Delta(w)\, A_1\, A_2$$

- $Y_{M_L}^L(\theta, \phi)$ — Spherical harmonic describes rotational property of $|L\, M_L\rangle$ state
- θ, ϕ — polar angles of decay daughter 1 in X rest frame (reached by simple boost, no rotations)
- $F_L(q)$ — Blatt-Weisskopf barrier factor
- $\Delta(w)$ — amplitude that describes resonance shape of X
- $A_{1,2}$ — decay amplitudes of (unstable) daughter particles 1 and 2

Partial-Wave Analysis Formalism

Extended maximum-likelihood method

- Likelihood $\mathcal{L}$ to observe N events distributed according to $\sigma(\tau; m_X)$ and acceptance $\mathrm{Acc}(\tau; m_X)$

$$\mathcal{L} = \underbrace{\left[\frac{\overline{N}^N}{N!}\, e^{-\overline{N}}\right]}_{\text{Poisson likelihood}} \prod_{i=1}^{N} \underbrace{\left[\frac{\sigma(\tau_i; m_X)\,\mathrm{Acc}(\tau_i)}{\int \mathrm{d}\Phi_n(\tau)\,\sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)}\right]}_{\text{Likelihood of event } n}$$

with $\overline{N} \propto \int \mathrm{d}\Phi_n(\tau)\,\sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)$

$$\mathcal{L} \propto \left[\frac{\overline{N}^N}{N!}\, e^{-\overline{N}}\right] \left[\frac{1}{\overline{N}^N} \prod_{i=1}^{N} \sigma(\tau_i; m_X)\right]$$

$$\mathcal{L} \propto e^{-\int \mathrm{d}\Phi_n(\tau)\,\sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)} \prod_{i=1}^{N} \sigma(\tau_i; m_X)$$

Partial-Wave Analysis Formalism

Extended maximum-likelihood method (cont.)

- Insert parameterization of cross section for $\sigma(\tau_i; m_X)$

$$\mathcal{L} \propto e^{-\int \mathrm{d}\Phi_n(\tau)\,\sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)} \prod_{i=1}^{N} \sum_{r=1}^{N_r} \left| \sum_{\text{waves}} T^r_{\text{wave}}(m_X)\, A_{\text{wave}}(\tau_i; m_X) \right|^2$$

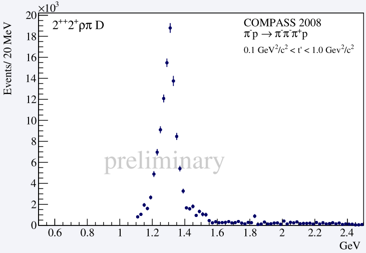
- Make expression less unwieldy by taking logarithm

$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln \left[\sum_{r=1}^{N_r} \left| \sum_{\text{waves}} T^r_{\text{wave}}(m_X)\, A_{\text{wave}}(\tau_i; m_X) \right|^2 \right] - \underbrace{\int \mathrm{d}\Phi_n(\tau)\,\sigma(\tau; m_X)\,\mathrm{Acc}(\tau; m_X)}_{\text{Normalization integral}}$$

- Normalization integral estimated using phase space Monte Carlo

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

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



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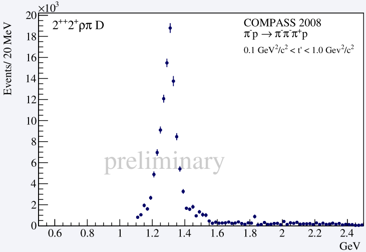
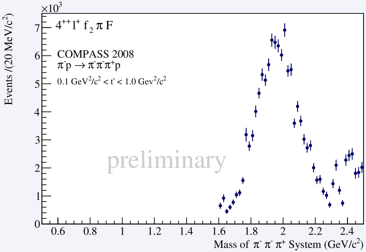


$4^{++}\,1^+\,[f_2\pi]F$: $a_4(2040)$



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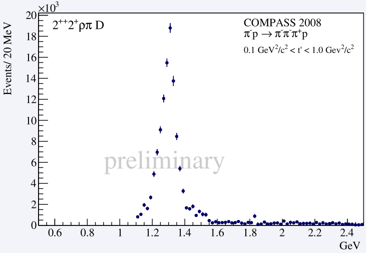

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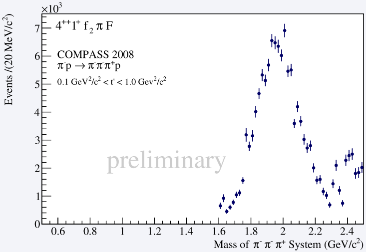
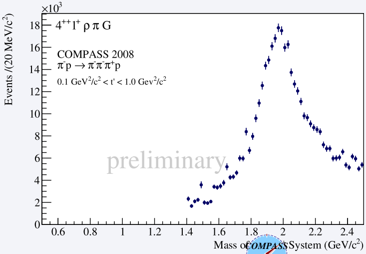
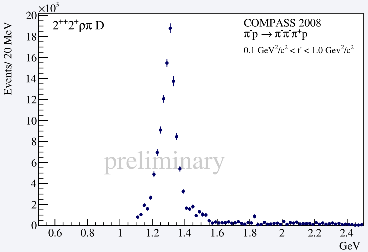


$4^{++}\,1^+\,[\rho\pi]G$: $a_4(2040)$

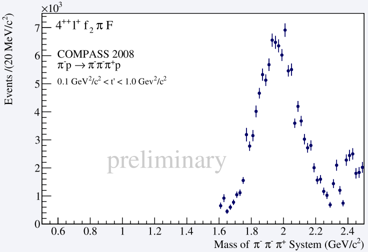


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

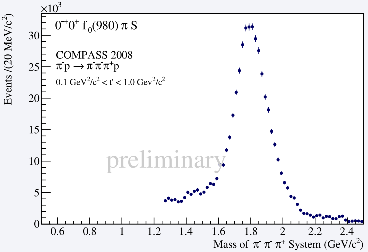
$2^{++}\,2^+\,[\rho\pi]D$: $a_2(1320)$



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



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



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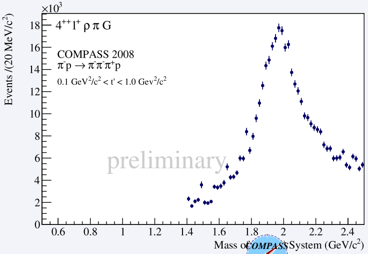
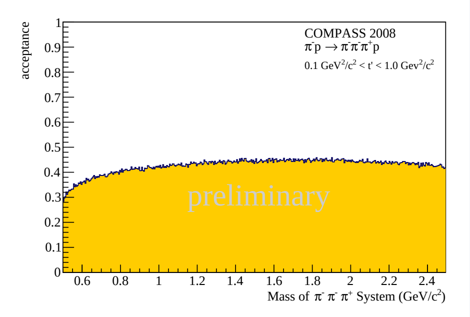


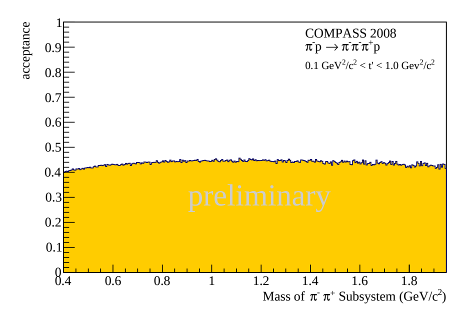
$\pi^-\pi^+\pi^-$ Final State

Acceptance (p Target)

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



$\pi^+\pi^-$ mass



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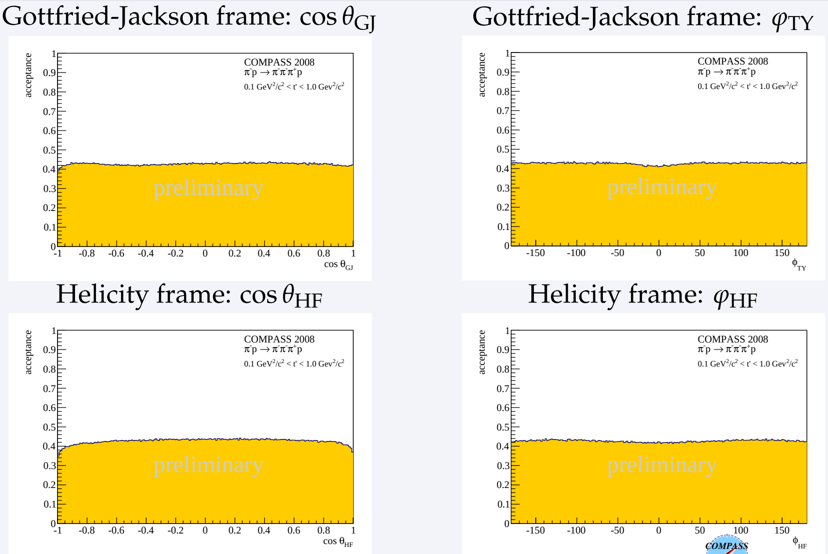
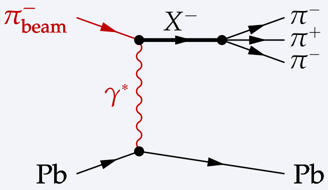


PWA of π^- Pb $\rightarrow \pi^-\pi^+\pi^-$ Pb at low t' (Pilot Run)



$\pi^-\pi^+\pi^-$ production in Primakoff reaction

- Very small momentum transfer: $t' < 0.001\ (\text{GeV}/c)^2$
- Photoproduction in Coulomb field of heavy target nucleus (Pb)
- For $M = 1$ waves diffractive contribution kinematically suppressed
- No intensity in 1.6 GeV/c^2 region in spin-exotic 1^{-+} wave
  - Consistent with CLAS result

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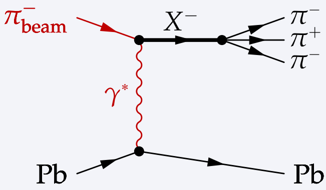

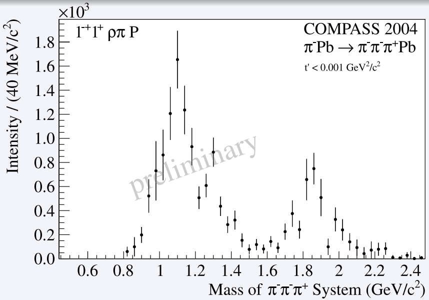

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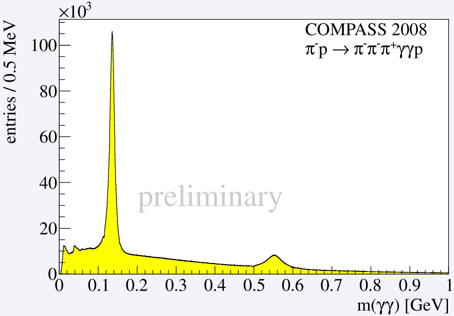
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

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



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

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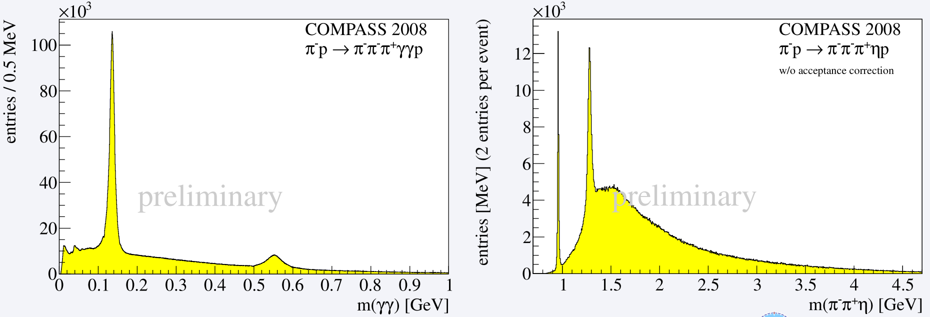
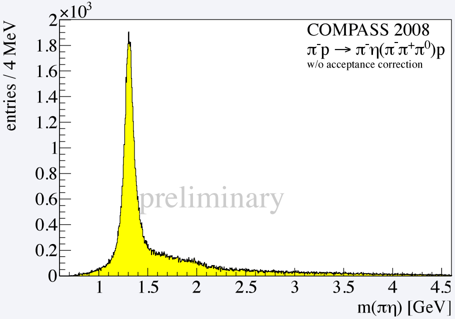
$\gamma\gamma$ invariant mass distribution

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



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

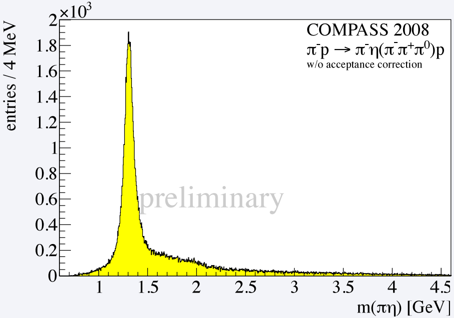
$\pi^-\eta$ invariant mass distribution



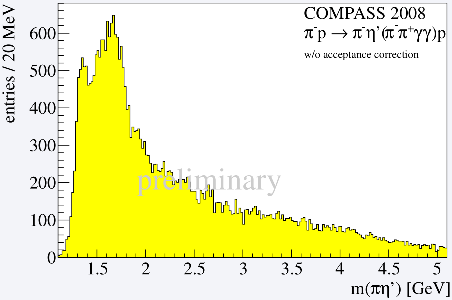
- $\pi^-\eta$: dominant $a_2(1320)$
- $\pi^-\eta'$: dominant broad structure around 1.7 GeV/c^2 and $a_2(1320)$ close to threshold
- Bulk of data described by 3 partial waves
  - $1^{-+}1^+$, $2^{++}1^+$, and $4^{++}1^+$

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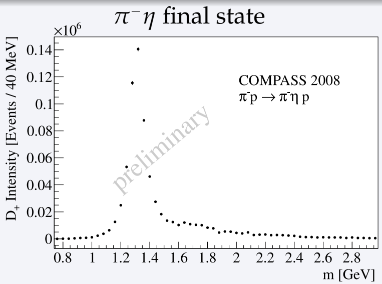
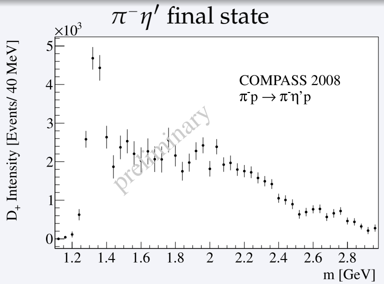
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

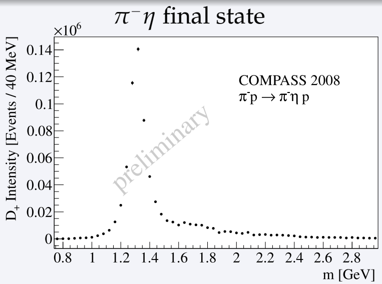
$a_2(1320)$ in $2^{++}1^+$ Partial Wave

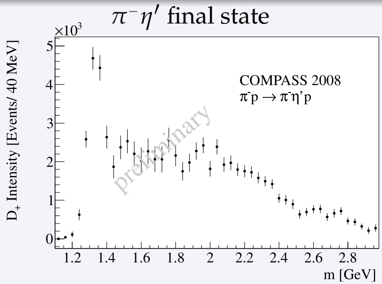




PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

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





η-η' mixing together with OZI rule

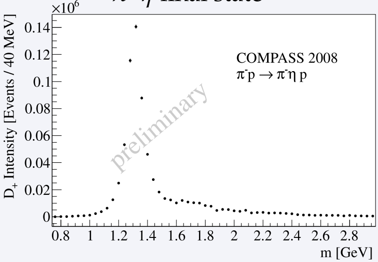
- Partial-wave amplitudes for spin J related by mixing angle ϕ, phase space, and barrier factors (q = breakup momentum)

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

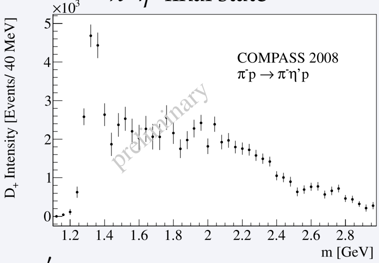
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

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

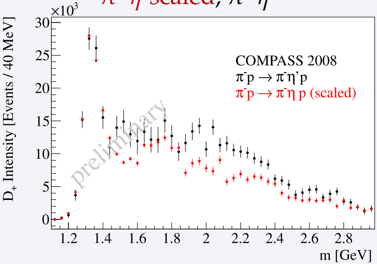
$\pi^-\eta$ final state



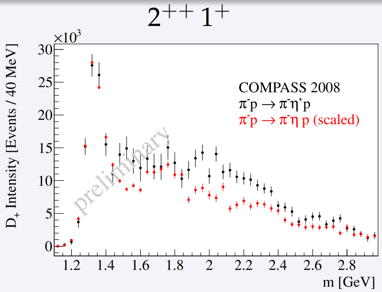
$\pi^-\eta'$ final state



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

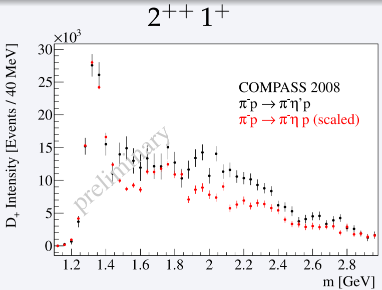


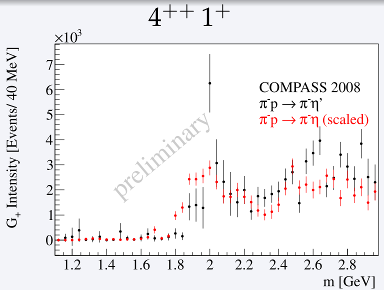
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$

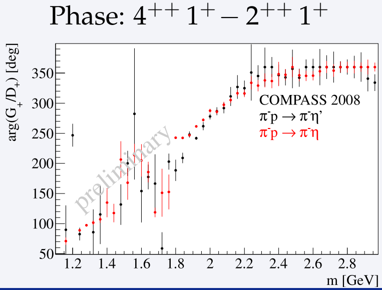


- Very similar even-spin waves
- Expected for $n\bar{n}$ resonances (OZI rule)
- Similar physical content also in non-resonant high-mass region

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







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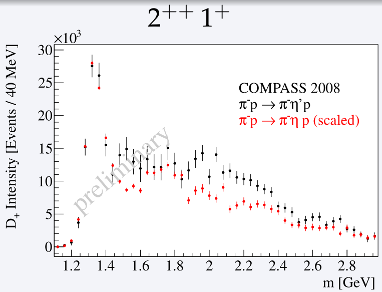
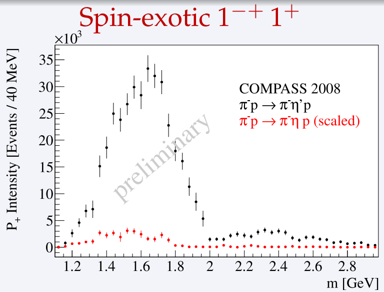
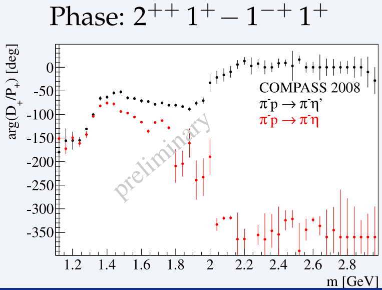
PWA of $\pi^- p \to \pi^- \eta\, p_{\text{slow}}$ and $\pi^- \eta'\, p_{\text{slow}}$







- Completely different intensity of 1^{-+} wave
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in $1.6\,\text{GeV}/c^2$ 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 Breit-Wigner 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
- **Final goal:** combined analysis of both channels

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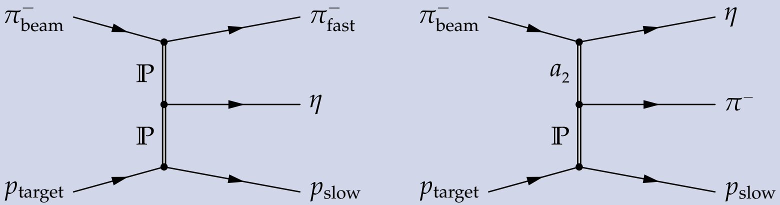
Non-resonant contributions



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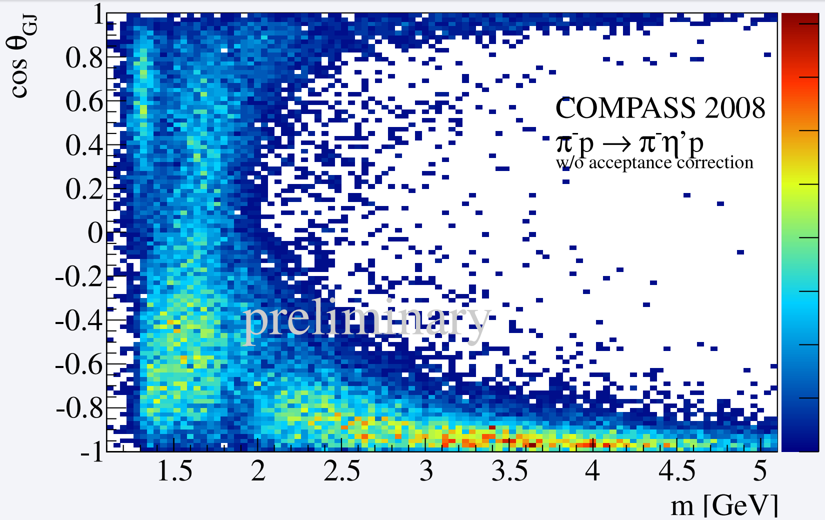
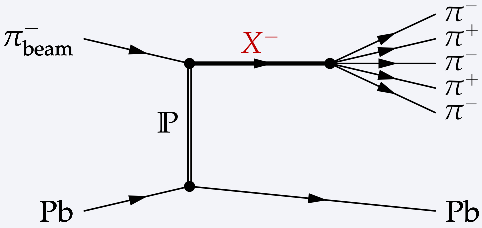
$\eta'\pi^-$ Final State

$\cos\theta_{GJ}$ vs. $\eta'\pi^-$ Invariant Mass



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

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

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

PWA of $\pi^- \mathrm{Pb} \to \pi^-\pi^+\pi^-\pi^+\pi^- \mathrm{Pb}$

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

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

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

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

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

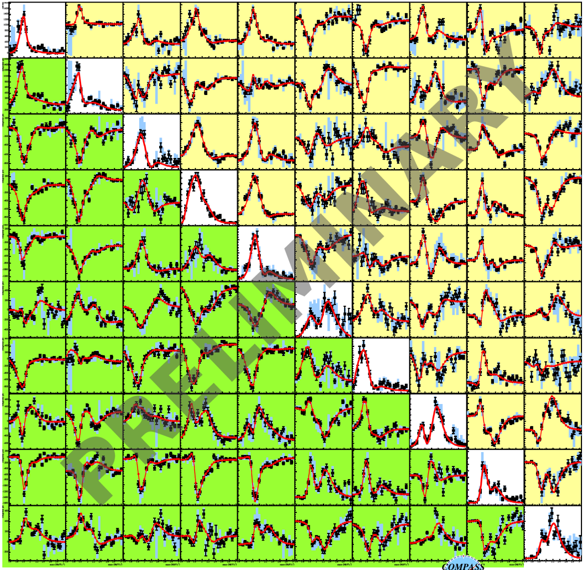
$1^{++}(\pi\pi)_S a_1\ D$

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

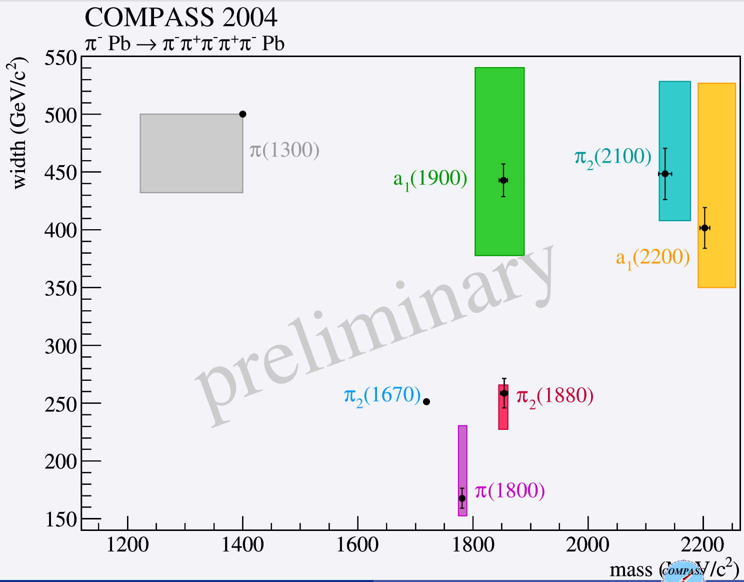
$2^{-+}\rho a_1(1260)\ S$

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

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



PWA of $\pi^- \text{Pb} \to \pi^-\pi^+\pi^-\pi^+\pi^- \text{Pb}$



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

Proof of Principle: First mass-dependent 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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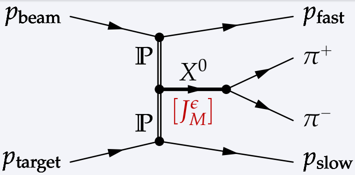
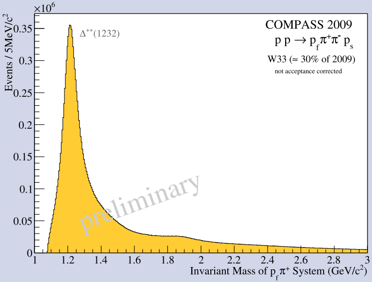
PWA of $p\, p \to p_{\text{fast}}\, \pi^+ \pi^- \, p_{\text{slow}}$

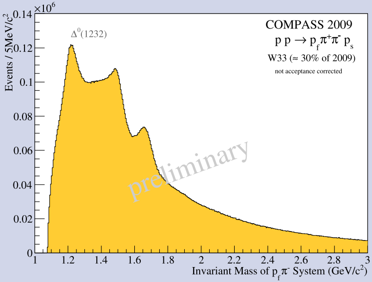


Suppression of diffractive background with $m(p_{\text{fast}}\pi^\pm) > 1.5\ \text{GeV}/c^2$

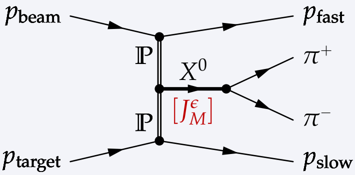
$p_{\text{fast}}\pi^+$ invariant mass



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

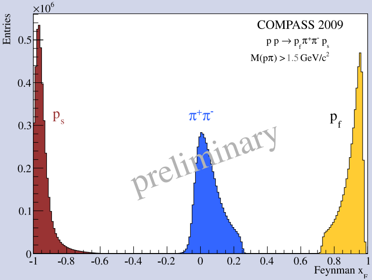


PWA of $p\,p \to p_{\text{fast}}\,\pi^+\pi^-\,p_{\text{slow}}$

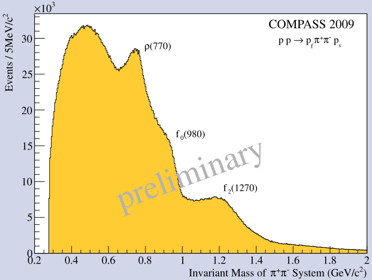


Selected central events

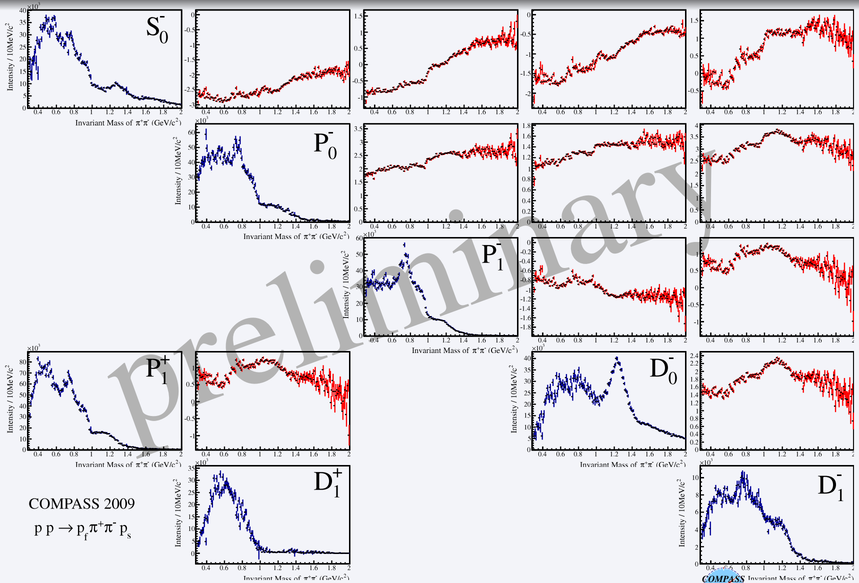
x_F distribution



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



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



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

Work in progress

- 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
- Data for $K^0_S K^0_S$, $\pi^0\pi^0$, and $\eta\eta$ final states on tape

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