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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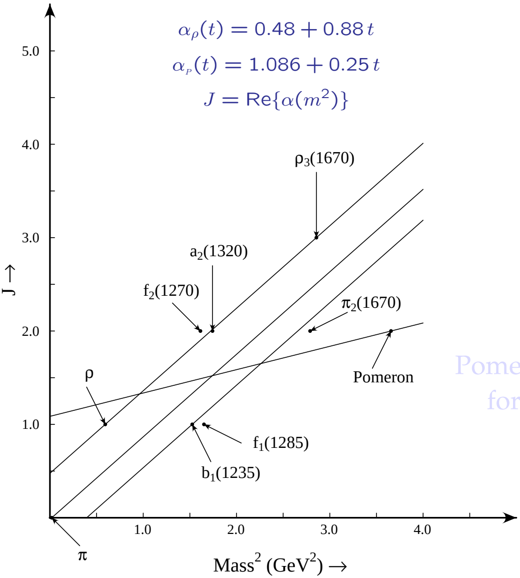
Heidelberg, 02–06 September 2013

Regge Trajectories

$$\alpha_\rho(t) = 0.48 + 0.88\,t$$

$$\alpha_{_P}(t) = 1.086 + 0.25\,t$$

$$J = \mathrm{Re}\{\alpha(m^2)\}$$



Pomeron mass for $J = 2$: 1.91 GeV

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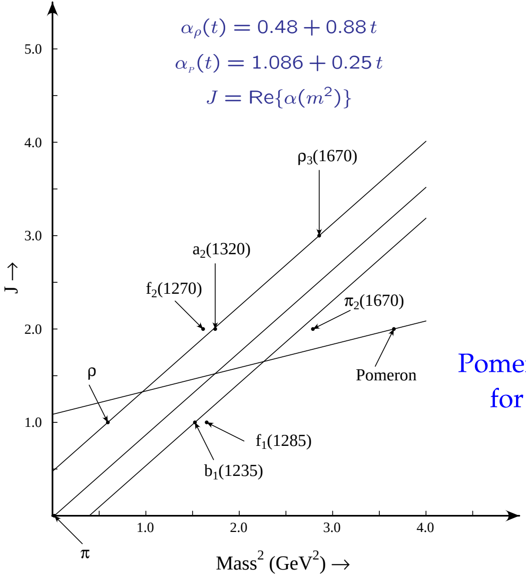

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Prelude

- 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

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

$$\Gamma_\ell(m) = \Gamma_0\,\frac{F_\ell(m)}{F_\ell(m_0)}, \quad \Gamma_\ell(m_0) = \Gamma_0$$

$$F_0(m) = F_0(m_0) = 1 \quad \text{for} \quad \ell = 0$$

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

F. von Hippel and C. Quigg, Phys. Rev. **5**, 624 (1972)

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Prelude—continued

PWA's two- and three-body systems

Two-body system:
2-dimentional in $\{\cos\theta, \phi\}$
$Y_\ell^m(\Omega)$ or $D^{\ell\,\star}_{m\,0}(\phi, \theta, 0)$
Ambiguous solutions:

Techniques of amplitude analysis for two-pseudoscalar systems
S. U. Chung, Phys. Rev. **D56**, 7299-7316 (1997)

Three-body system: 5-dimentional in $\{\alpha, \beta, \gamma\}$, m_{12}^2, m_{23}^2

$$D^{J\,\star}_{m\,\delta}(\alpha, \beta, \gamma), \quad \delta = \lambda_1 - \lambda_2$$

S. U. Chung, *Spin formalisms*,
CERN Yellow Report 71-8, 25 March 1971.

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

QCD: The Theory of Strong Interaction

Quantum chromodynamics describes interaction of quark and gluon fields

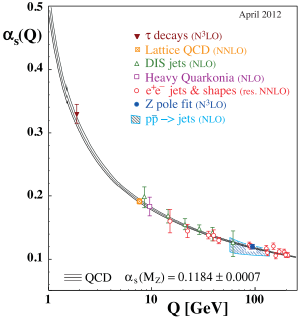
- Non-abelian gauge theory: gluons carry charge and self-interact
- Running coupling constant $\alpha_s(Q)$

Asymptotic freedom

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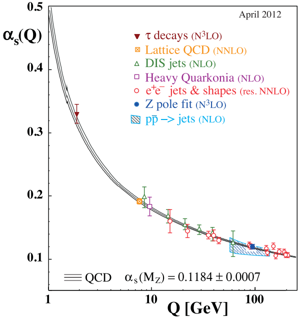

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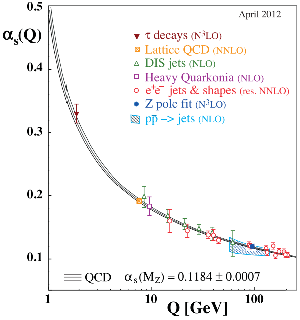

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Mesons in the Constituent Quark Model

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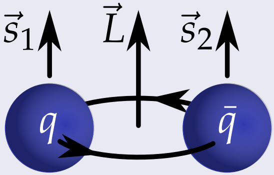
Spin-parity rules for bound $q\bar{q}$ system

- 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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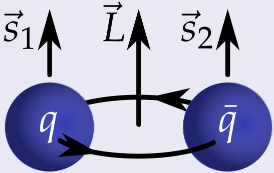

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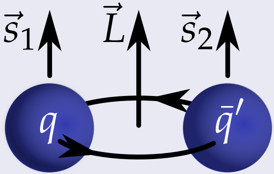

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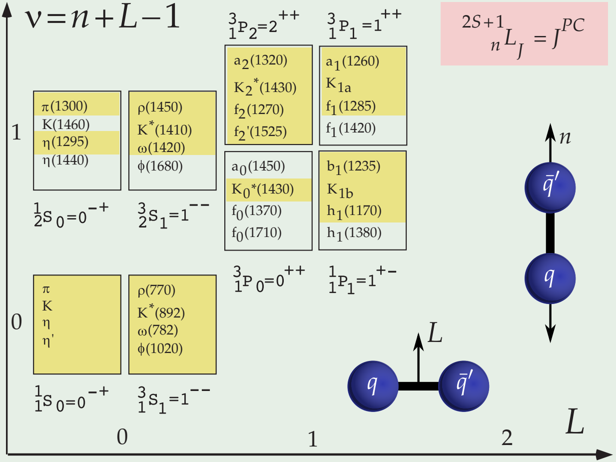
Light-quark meson spectrum



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

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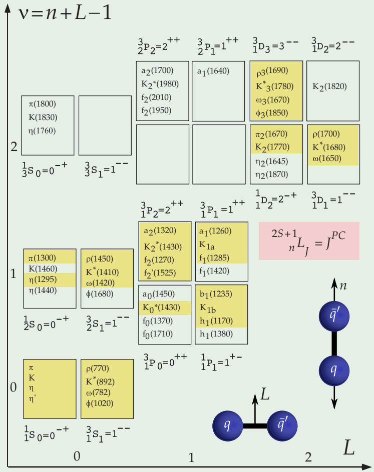
Light-quark meson spectrum (cont.)



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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
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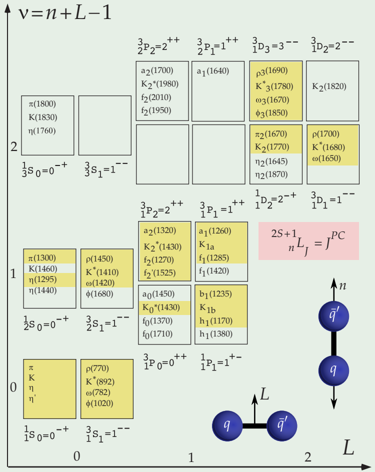

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QCD: **Gluonic d.o.f. should manifest themselves in hadron spectra**

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 $J^{PC} = 0^{++}$
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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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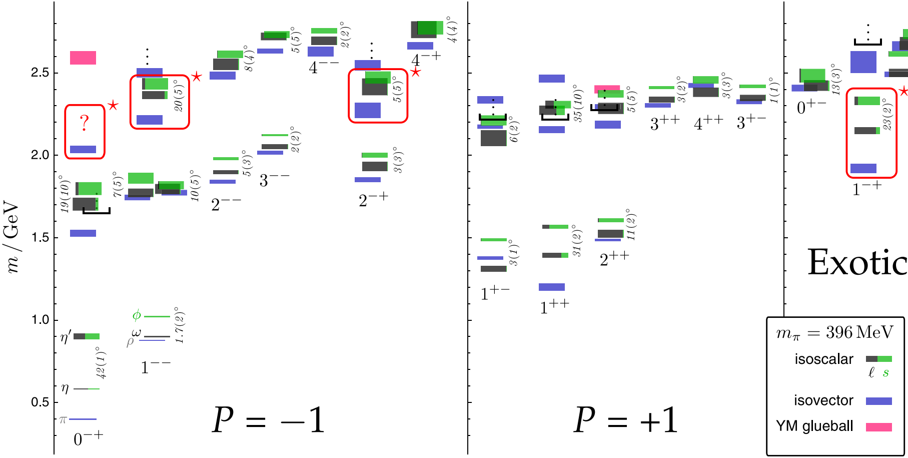
Light-Meson Spectrum in Lattice QCD

State-of-the-art light-meson spectrum Dudek, PR D84 (2011) 074023



- Resonance widths and decay modes still very difficult

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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
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  - In general "configuration mixing"
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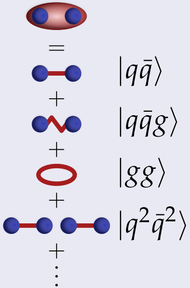

Special case: **"exotic" mesons**

- Have quantum numbers forbidden for $|q\bar{q}\rangle$
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- Especially attractive:
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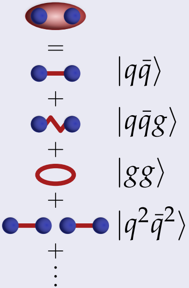

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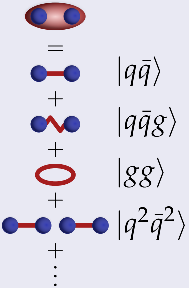

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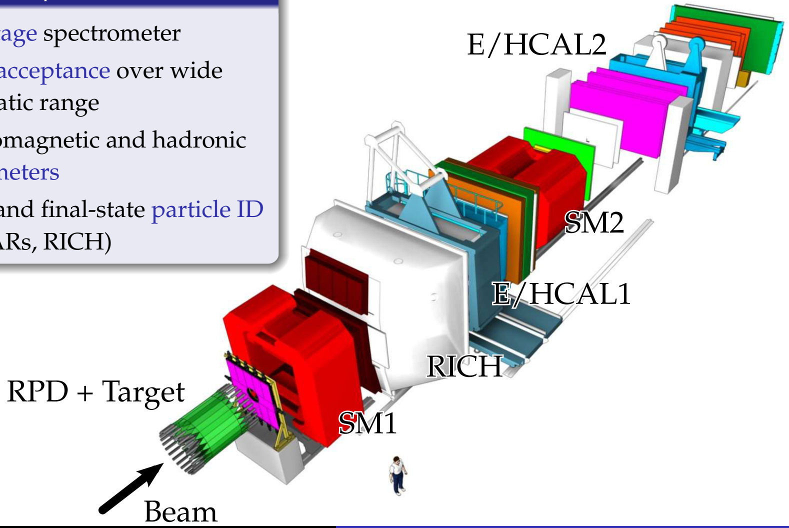
The COMPASS Experiment at the CERN SPS

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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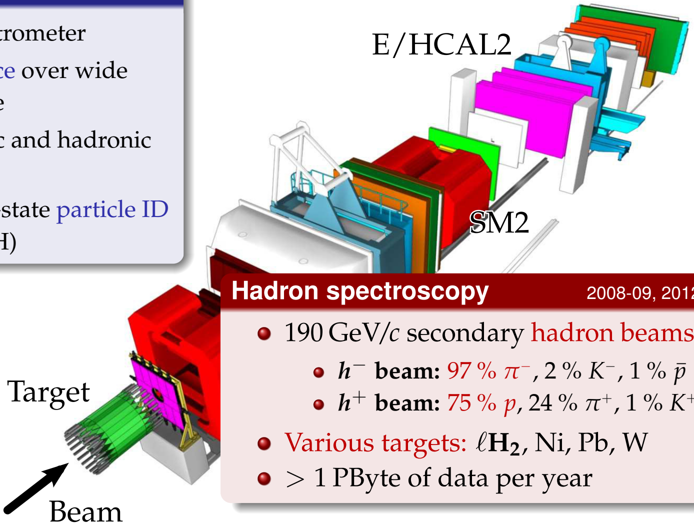


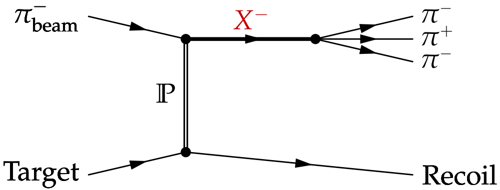
Hadron spectroscopy

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': Pomeron exchange dominant
- Rich spectrum: large number of overlapping and interfering X
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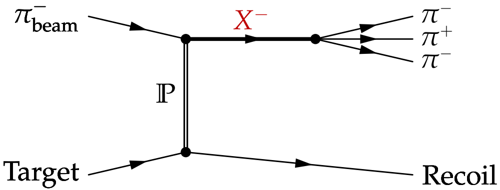
  - Determine their mass, width, and quantum numbers
- **Method:** partial-wave analysis (PWA)

Production of Hadrons in Diffractive Dissociation

BNL E852, VES, COMPASS



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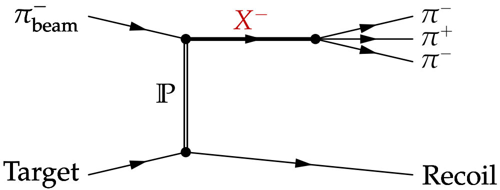

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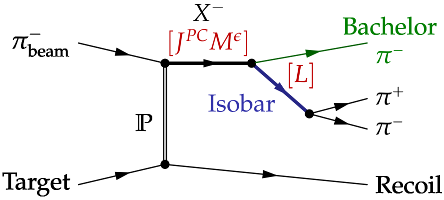
Diffractive Dissociation of π^- into $\pi^-\pi^+\pi^-$ Final State

BNL E852, VES, COMPASS



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 $A_{\text{wave}}(m_X,\tau)$
- Transition amplitudes $T_{\text{wave}}(m_X)$ determined from multi-dimensional fit to final-state kinematic distributions taking into account interference effects

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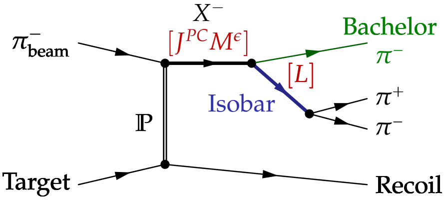

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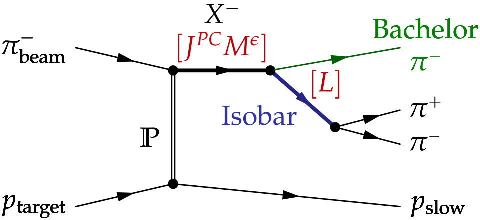
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

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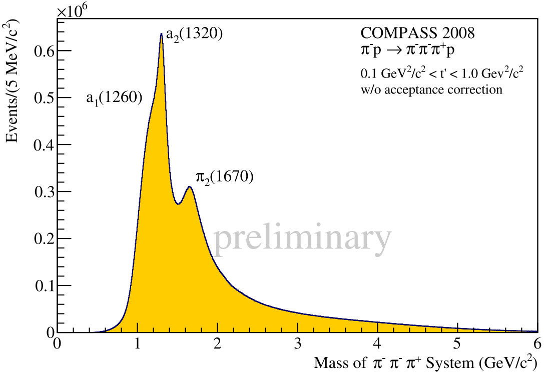
$\pi^-\pi^+\pi^-$ invariant mass distribution



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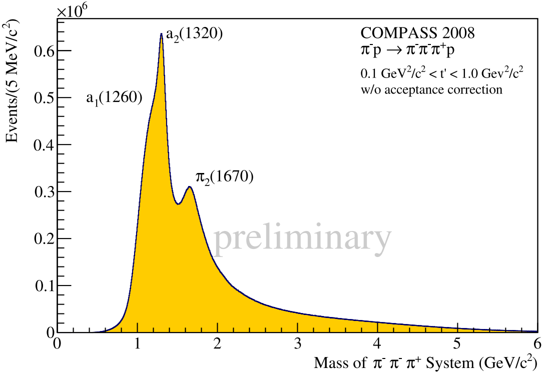
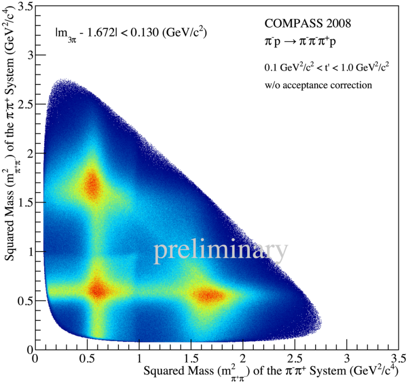
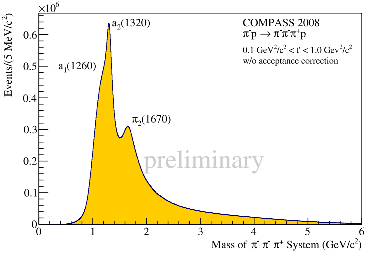


Dalitz plot for $\pi_2(1670)$ region



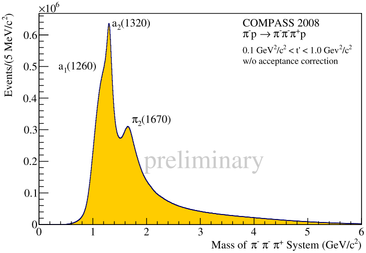
PWA of $\pi^- p \to \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

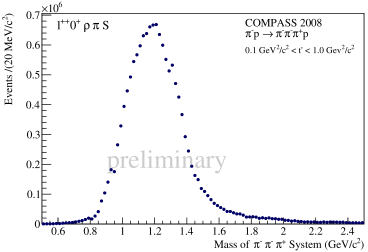


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

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



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



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

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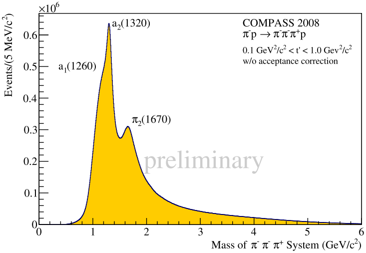

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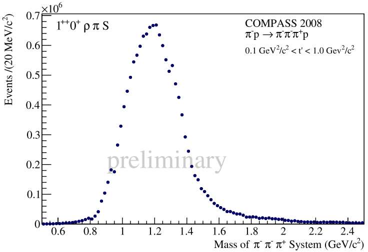
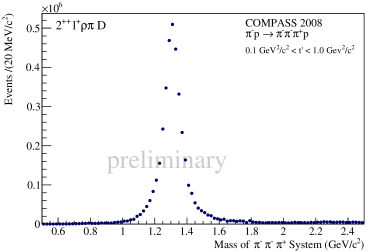
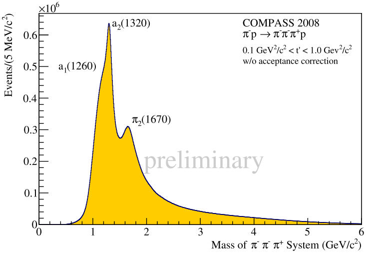


$2^{++}\,1^+\,[\rho\pi]D$: $a_2(1320)$

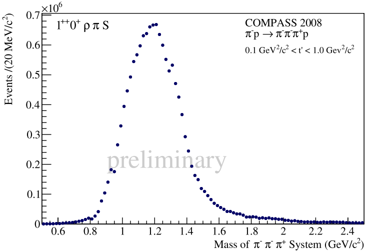


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

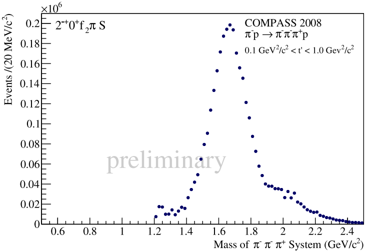
$\pi^-\pi^+\pi^-$ invariant mass spectrum



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



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



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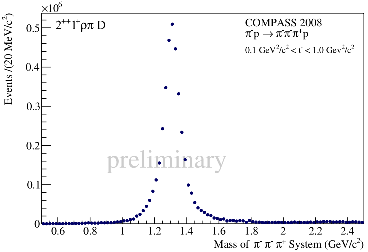
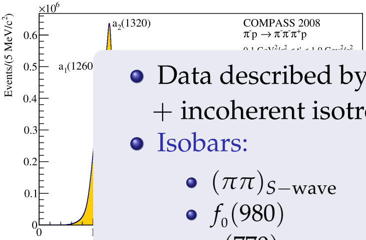
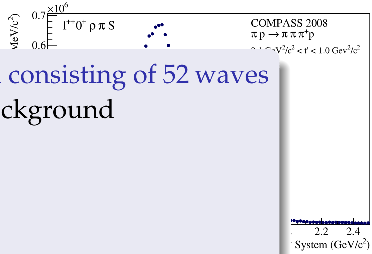


PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{slow}}$

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

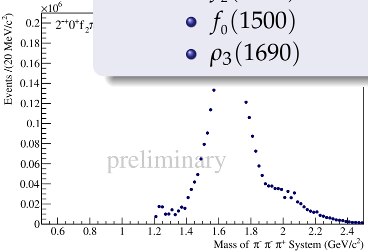


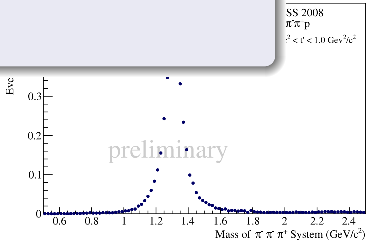
$1^{++}0^+[\rho\pi]S$: $a_1(1260)$



2^{-+}

20)

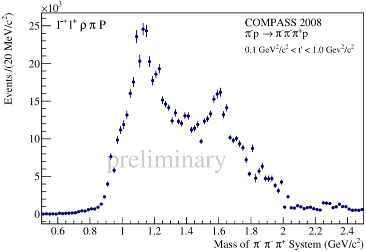




- Data described by model consisting of 52 waves + incoherent isotropic background
- Isobars:
  - $(\pi\pi)_{S-\text{wave}}$
  - $f_0(980)$
  - $\rho(770)$
  - $f_2(1270)$
  - $f_0(1500)$
  - $\rho_3(1690)$

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. $\pi_2(1670)$
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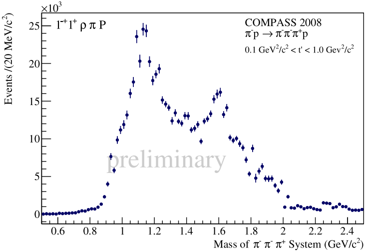

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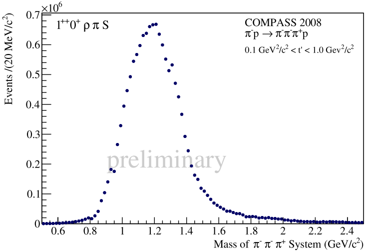
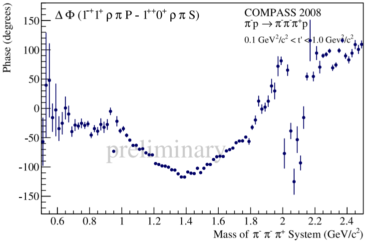


$1^{-+}\,1^+\,[\rho\pi]P - 1^{++}\,0^+\,[\rho\pi]S$



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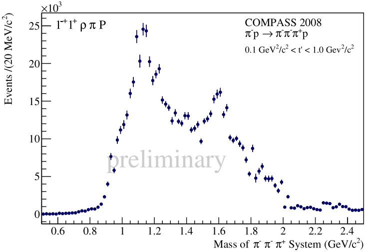
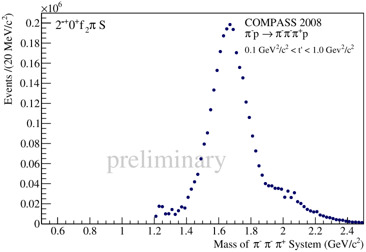
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

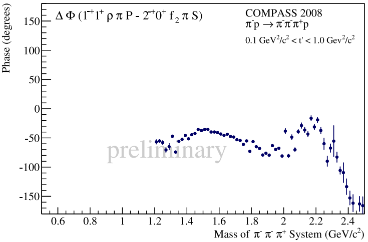
Spin-exotic $1^{-+} 1^+ [\rho\pi] P$



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



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



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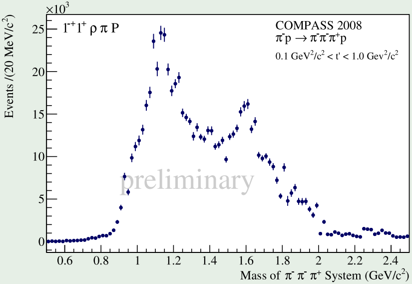
Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with BNL E852 and VES

COMPASS



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

BNL E852 PR D73 (2006) 072001

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

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

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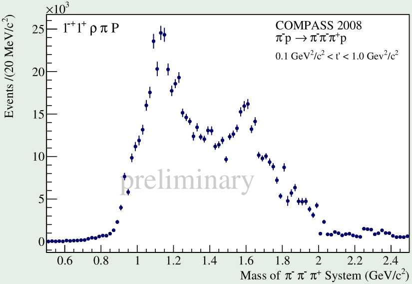
COMPASS



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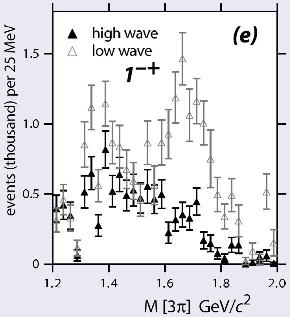
BNL E852 PR D73 (2006) 072001



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

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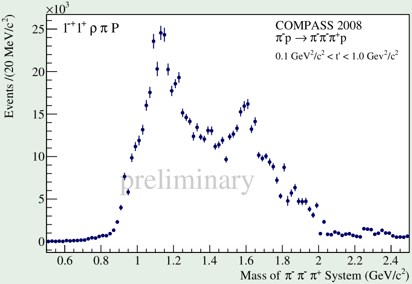

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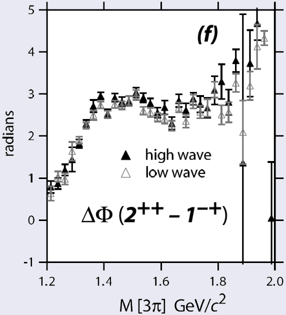
BNL E852 PR D73 (2006) 072001



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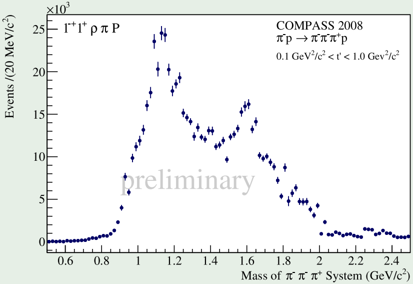
Comparison with BNL E852 and VES

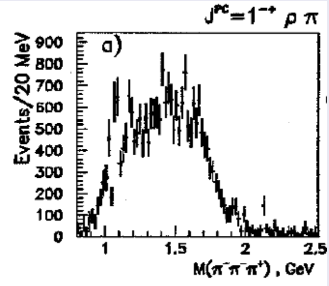
COMPASS



- 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

VES

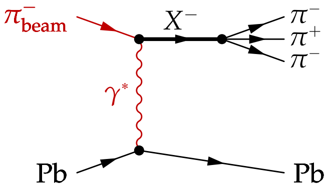
NP A675 (2000) 155



- 36.6 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

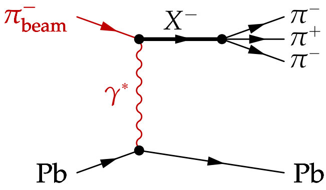


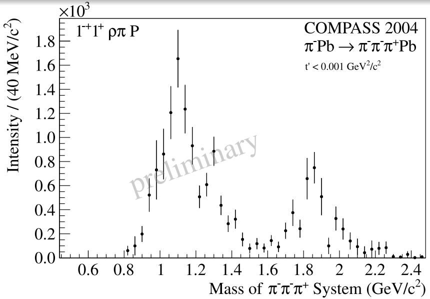
$\pi^-\pi^+\pi^-$ production in Primakoff reaction

- 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 $\pi^- \text{Pb} \to \pi^-\pi^+\pi^- \text{Pb}$ at low t'

COMPASS





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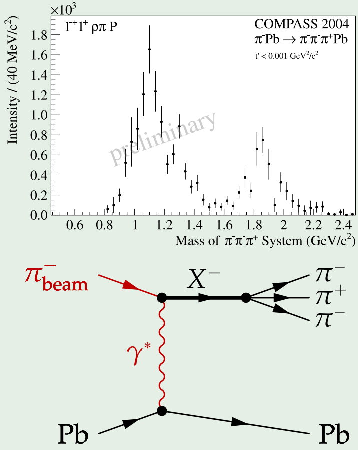
Photoproduction of Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with CLAS g12

COMPASS Primakoff



CLAS g12

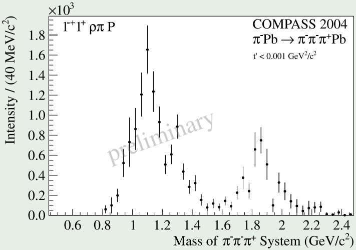
C. Bookwalter, arXiv:1108.6112

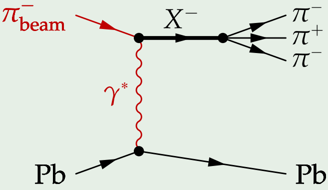
- Tagged photon beam
- $3.6 < E_\gamma < 5.5\,\text{GeV}$
- p target
- 502 000 events

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

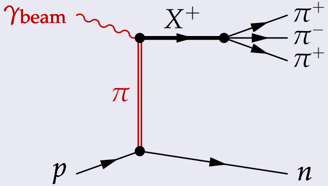
Comparison with CLAS g12

COMPASS Primakoff





CLAS g12 — C. Bookwalter, arXiv:1108.6112



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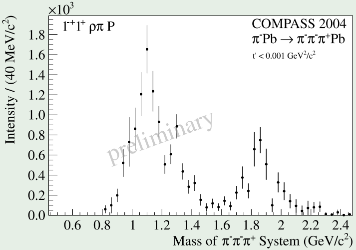
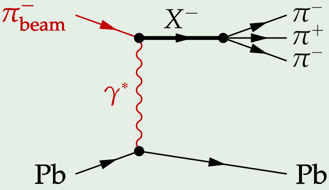
Photoproduction of Spin-Exotic $1^{-+}1^{+}[\rho\pi]P$ Wave

Comparison with CLAS g12

COMPASS Primakoff





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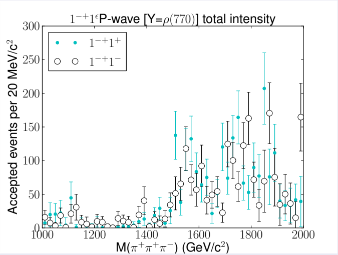

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- p target
- 502 000 events

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)
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- 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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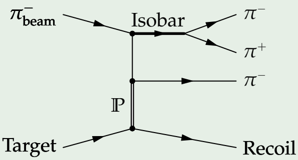

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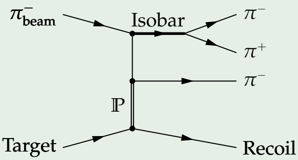
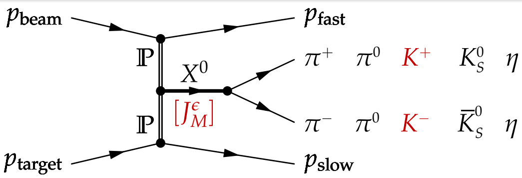


- Improvements of wave set and isobar parameterization

Central Production

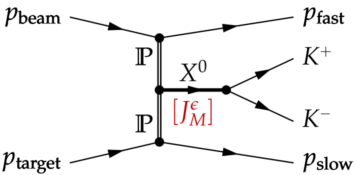
COMPASS, CERN Omega (WA76, WA91, WA102)



Search for **glueball candidates**

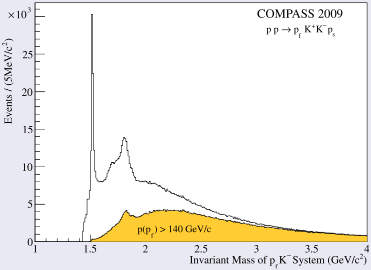
- *Glueballs:* mesonic states with no valence quarks
- Lattice QCD simulations predict lightest glueballs to be scalars
  - Glueball would appear as supernumerous state
  - Strong mixing with conventional scalar mesons expected
  - Difficult to disentangle
- Pomeron-Pomeron fusion well-suited to search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

K^+K^- Central Production

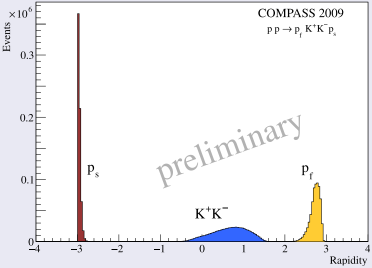


Suppression of diffractive background by cut $p(p_{\text{fast}}) > 140$ GeV/c

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



Rapidity in CM frame



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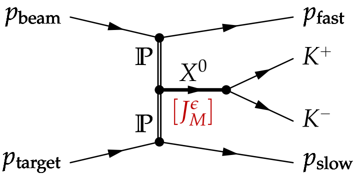

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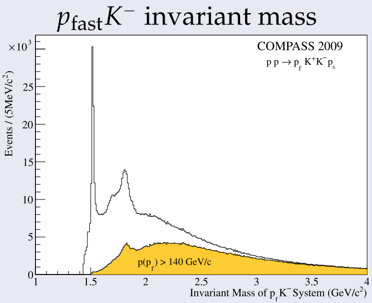
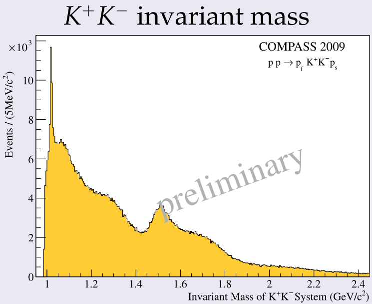
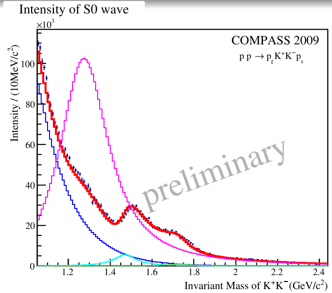
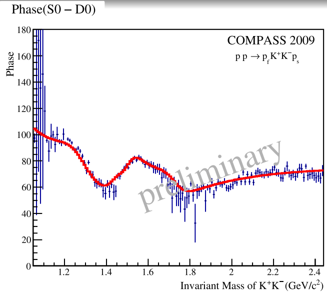




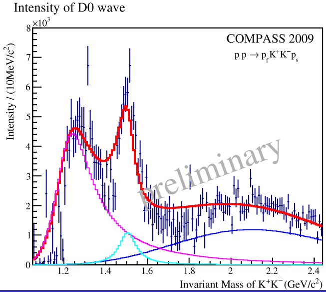
Fit of K^+K^- Mass Dependence





Fit model:

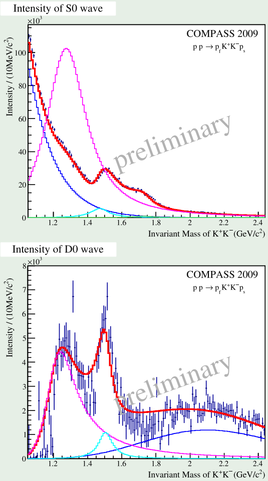
- Relativistic Breit-Wigner resonances
  - S_0^-: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
  - D_0^-: $f_2(1270)$, $f_2'(1525)$
- Exponentially damped coherent background terms



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

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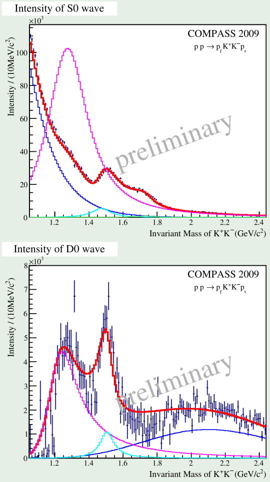

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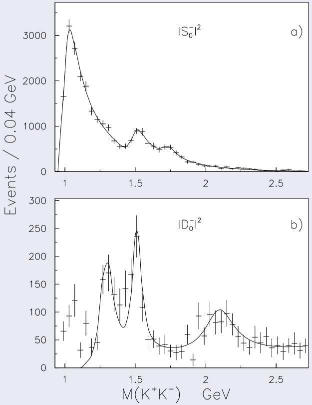

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PWA of $p\,p \to p_{\text{fast}}\,K^+K^-\,p_{\text{slow}}$

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 $K_S^0K_S^0$, $\pi^+\pi^-$, $\pi^0\pi^0$, 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
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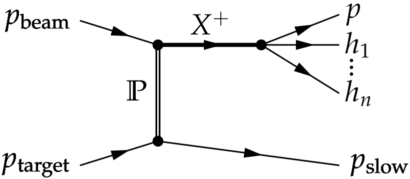
Baryon Spectroscopy in Proton Diffraction



- 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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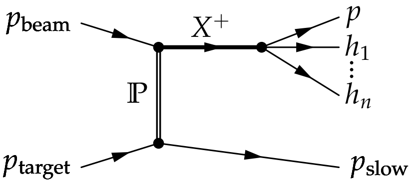

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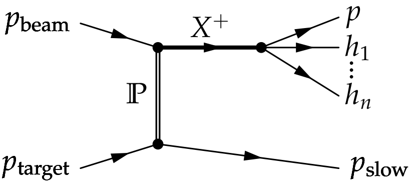

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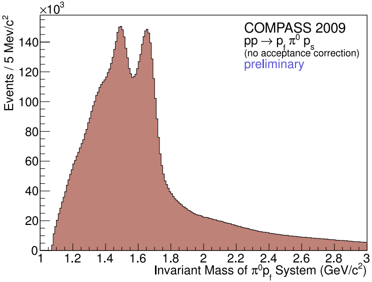
$pp \to p\pi^0\, p_{\text{slow}}$

$p\pi^0$ invariant mass



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

ϕ_{TY} of π^0 vs. $m_{p\pi^0}$

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

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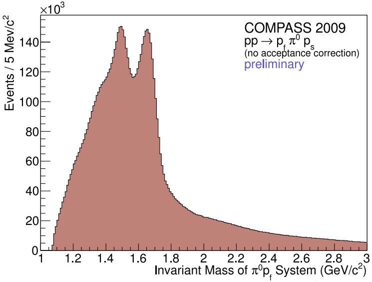

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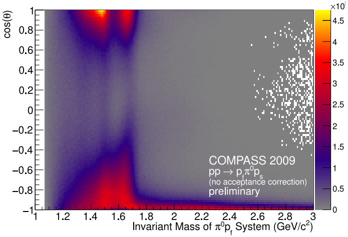

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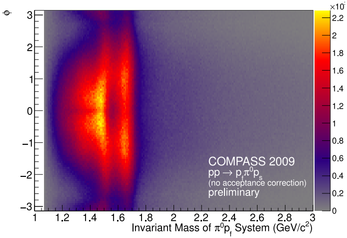
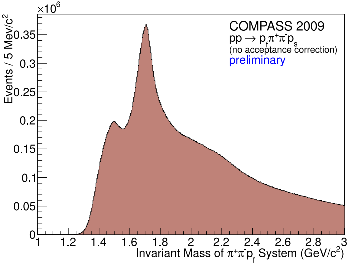


$pp \to p\pi^+\pi^- p_{\text{slow}}$

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



$p\pi^+$ subsystem

$p\pi^-$ subsystem

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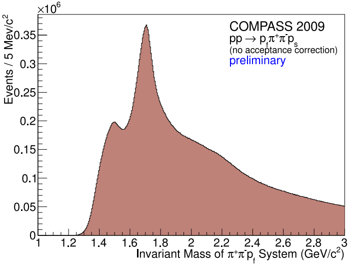

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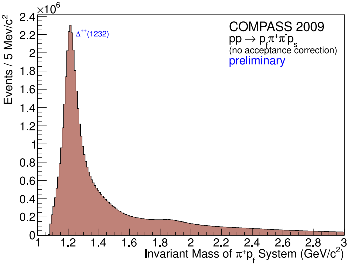

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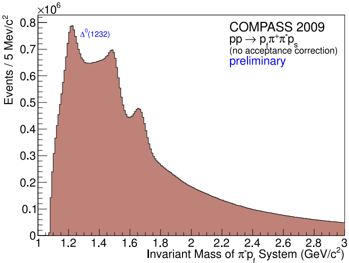

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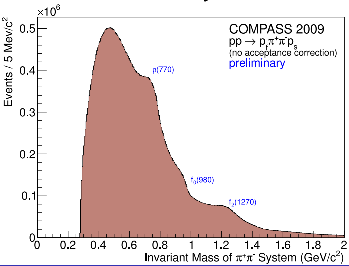

Baryon Spectroscopy in Proton Diffraction

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

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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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).

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

Final states for PWA:

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

Manpower available at ALICE:

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- Jan Figiel and Lidia Goerlich / PAN Cracow, Poland
- Jeewon SEO (temporarily unavailable), Konkuk Univ., Korea
  Beomkyu KIM and Taesoo KIM / Yonsei Univ., Seoul, Korea
- Sergey Evdokimov, IHEP Protvino, Russia

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

Final states for PWA:

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- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^- K^+ K^-$
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Finale

- Lorentz factors for $X^- \rightarrow \rho^0 + \pi^-$ and $\rho^0 \rightarrow \pi^+\pi^-$:

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

in the X^- rest frame.

- Reference:

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  S. U. Chung, BNL/TUM/PNU and Jan Friedrich, TUM
  Phys. Rev. **D78**, 074027 (2008).

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