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
Outline

1. Introduction
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2. Hadron spectroscopy
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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

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

Confinement of quarks and gluons into hadrons

- $\alpha_s$ large at distances $O(1 \text{ fm})$
  - Relevant d.o.f.: color-neutral hadrons
  - Series in $\alpha_s$ does not converge
    $\implies$ 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
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Asymptote freedom graph:
- $\alpha_s(Q)$ vs $Q$ [GeV]
- Data points and curves for various models like QCD, $\Lambda (3\text{LO})$, Lattice QCD (NNLO), DIS jets (NLO), Heavy Quarkonia (NLO), $e^+e^-$ jets & shapes (res. NNLO), $Z$ pole fit (N^3LO), $pp \rightarrow $ jets (NLO)

PDG 2012

Introduction
Hadron spectroscopy
Conclusions and Outlook
QCD and constituent quark model
Beyond the constituent quark model

Boris Grube, TU München
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Legend:
- $\tau$ decays (N3LO)
- Lattice QCD (NNLO)
- DIS jets (NLO)
- Heavy Quarkonia (NLO)
- $e^+e^-$ jets & shapes (res. NNLO)
- $Z$ pole fit (N3LO)
- $pp \rightarrow$ jets (NLO)

PDG 2012
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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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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# Mesons in the Constituent Quark Model

## Light-quark meson spectrum

<table>
<thead>
<tr>
<th>$\nu = n + L - 1$</th>
<th>$1\Sigma^+_0 = 0^{--}$</th>
<th>$\frac{3}{2}\Sigma_1^- = 1^{--}$</th>
<th>$\frac{3}{2}P_2 = 2^{++}$</th>
<th>$\frac{3}{2}P_1 = 1^{++}$</th>
<th>$2S + 1 \quad nL_J = J^{PC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi(1300)$</td>
<td>$\rho(1450)$</td>
<td>$a_2(1320)$</td>
<td>$a_0(1450)$</td>
<td>$nL_J = 1^{++}$</td>
<td></td>
</tr>
<tr>
<td>$K(1460)$</td>
<td>$K^*(1410)$</td>
<td>$K^*_2(1430)$</td>
<td>$K_0^*(1430)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta(1295)$</td>
<td>$\omega(1420)$</td>
<td>$f_2(1270)$</td>
<td>$f_0(1370)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta(1440)$</td>
<td>$\phi(1680)$</td>
<td>$f_{2'}(1525)$</td>
<td>$f_0(1710)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi$</td>
<td>$\rho(770)$</td>
<td>$a_1(1260)$</td>
<td>$b_1(1235)$</td>
<td>$nL_J = 1^{+-}$</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>$K^*(892)$</td>
<td>$K_1a$</td>
<td>$K_{1b}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td></td>
<td>$f_1(1285)$</td>
<td>$h_1(1170)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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**Introduction**

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**Conclusions and Outlook**

**QCD and constituent quark model**

**Beyond the constituent quark model**

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**Mesons in the Constituent Quark Model**

**Light-quark meson spectrum (cont.)**

```
\[ n = n + L - 1 \]
```

- **\( \pi(1800) \)**
- **\( K(1830) \)**
- **\( \eta(1760) \)**

**\( \frac{1}{2} S_0 = 0^- \)**

**\( 1 \)**

- **\( \frac{1}{2} S_1 = 1^- \)**

- **\( \frac{3}{2} S_0 = 0^- \)**

****

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- **\( \pi(770) \)**
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****

- **\( \frac{3}{2} S_0 = 0^+ \)**

****

- **\( \frac{3}{2} P_2 = 2^+ \)**
- **\( \frac{1}{2} P_1 = 1^+ \)**
- **\( \frac{3}{2} P_3 = 3^- \)**
- **\( 1^{D_2} = 2^{--} \)**

- **\( a_2(1320) \)**
- **\( K_2^*(1980) \)**
- **\( f_2(1270) \)**
- **\( f_2(1525) \)**
- **\( a_1(1640) \)**
- **\( K_2^*(1780) \)**
- **\( \pi_2(1690) \)**
- **\( K^*(1850) \)**

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- **\( \eta_2(1650) \)**
- **\( \eta_2(1870) \)**

**“Light meson frontier”:**

- Many missing and disputed states in mass region \( m \approx 2 \text{ GeV}/c^2 \)

- Identification of higher excitations becomes exceedingly difficult
  - Wider states + higher state density
  - More overlap and mixing

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Beyond the Constituent Quark Model

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

### Hybrids $|q\bar{q}g\rangle$
- Resonances with excited glue
  - Definition of “excited glue” model dependent
- Angular momentum of glue component $\implies all J^{PC}$ 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
  - Mass 1.5 to 2.0 GeV/$c^2$
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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
    $\Rightarrow$ 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 $\Rightarrow$ spin-identified spectra
  - Larger operator bases $\Rightarrow$ extraction of many excited states
  - Access to gluonic content of calculated states
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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: $|q\bar{q}\rangle$, $|q\bar{q}g\rangle$, $|gg\rangle$, $|q^2\bar{q}^2\rangle$, ...
  - 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 $\implies$ 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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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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Diffractive Dissociation of $\pi^-$ 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: $\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X) A_{\text{wave}}(m_X, \tau) \right|^2$
- 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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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

COMPASS

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

World’s largest diffractive $3\pi$ data set: $\approx 50$ M exclusive events

- Challenging analysis
  - Needs precise understanding of apparatus
  - Model deficiencies become visible
PWA of \( \pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}} \)

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\( \pi^- \pi^+ \pi^- \) invariant mass distribution

![Graph of invariant mass distribution](image)

- \( a_1(1260) \)
- \( a_2(1320) \)
- \( \pi_2(1670) \)

COMPASS 2008
\( \pi^- p \rightarrow \pi^- \pi^+ p \)

0.1 GeV\(^2/c^2\) < \( t' \) < 1.0 GeV\(^2/c^2\)

w/o acceptance correction

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

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

Dalitz plot for $\pi_2(1670)$ region

COMPASS 2008
$\pi p \rightarrow \pi \pi^+ p$
$0.1 \text{ GeV}^2/c^2 < t' < 1.0 \text{ GeV}^2/c^2$
w/o acceptance correction

$\text{Im}_m < 1.672 \times 0.130 (\text{GeV}/c^2)$

COMPASS 2008
$\pi p \rightarrow \pi \pi^+ p$
$0.1 \text{ GeV}^2/c^2 < t' < 1.0 \text{ GeV}^2/c^2$
w/o acceptance correction

$\text{Im}_m < 1.672 \times 0.130 (\text{GeV}/c^2)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

COMPASS 2008
$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$
$0.1 \text{ GeV}/c^2 < t' < 1.0 \text{ GeV}/c^2$
w/o acceptance correction

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

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

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

COMPASS 2008
$\pi^+ p \rightarrow \pi^+ \pi^- p$
$0.1 \text{ GeV}^2/c^2 < t < 1.0 \text{ GeV}^2/c^2$
no acceptance correction

COMPASS 2008
$\pi^- p \rightarrow \pi^- \pi^+ p$
$0.1 \text{ GeV}^2/c^2 < t < 1.0 \text{ GeV}^2/c^2$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

$\pi^- \pi^+ \pi^- \text{ invariant mass spectrum}$

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

$2^{++} 1^{+} [\rho \pi] D: a_2(1320)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

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

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

$2^{++} 1^+ [\rho \pi] D: a_2(1320)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

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

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

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

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

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  - Unstable w.r.t. fit model

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

![Graph showing preliminary data for spin-exotic $1^{-+} 1^{+} [\rho \pi] P$]

**Structure around 1.1 GeV/$c^2$$^\dagger$$^\ddagger$$^\S$**
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**$1^{-+} 1^{+} [\rho \pi] P - 2^{++} 0^{+} [f_2 \pi] S$**

![Graph showing preliminary data for $1^{-+} 1^{+} [\rho \pi] P - 2^{++} 0^{+} [f_2 \pi] S$]

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$^\dagger$ Boris Grube, TU München

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

Comparison with BNL E852 and VES

**COMPASS**

$1^{+} 1^{+} \rho \pi P$

$\pi p \to \pi \pi \pi^* p$

$0.1 \text{ GeV}^2/c^2 < t' < 1.0 \text{ GeV}^2/c^2$

- 190 GeV/c $\pi$ 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 $\pi$ 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

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- 190 GeV/c $\pi$ beam
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Comparison with BNL E852 and VES

**COMPASS**

- $1^{+} \rho \pi P$
- COMPASS 2008
  - $\pi p \rightarrow \pi \pi \pi^* p$
  - $0.1 \text{ GeV}^2/c^2 < t' < 1.0 \text{ GeV}^2/c^2$

**VES**

- $J^{PC} = 1^{-+} \rho \pi$
- NP A675 (2000) 155

- 36.6 GeV/c $\pi$ beam
- Be target
- 9 $\cdot$ 10$^6$ events
- “Infinite”-rank fit with 44 waves

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

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Boris Grube, TU München
Hadron Spectroscopy at and related experiments
PWA of $\pi^-\text{Pb} \rightarrow \pi^-\pi^+\pi^-\text{Pb}$ 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 $\pi^-\text{Pb} \rightarrow \pi^-\pi^+\pi^-\text{Pb}$ at low $t'$

**COMPASS**

$\pi^-\text{beam}$

**$\gamma^*$**

Pb

**Pb**

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

Comparison with CLAS g12

- Tagged photon beam
- $3.6 < E_\gamma < 5.5$ GeV
- $p$ target
- 502 000 events
Photoproduction of Spin-Exotic $1^{-} + 1^{+} \left[\rho\pi\right] P$ Wave

Comparison with CLAS g12

**COMPASS Primakoff**

- **Intake / (40 MeV/c^2)**
  - $1^{+} 1^{+} \rho\pi P$

**CLAS g12**

- C. Bookwalter, arXiv:1108.6112

- **Tagged photon beam**
- $3.6 < E_{\gamma} < 5.5$ GeV
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- 502,000 events
Photoproduction of Spin-Exotic $1^{-+} 1^{+} [\rho \pi] P$ Wave

Comparison with CLAS g12

**COMPASS Primakoff**

- Intensity / (40 MeV/c^2)
- Mass of $\pi \pi \pi^+$ System (GeV/c^2)

**CLAS g12**

- 3.6 $< E_\gamma < 5.5$ GeV
- $p$ target
- 502,000 events

C. Bookwalter, arXiv:1108.6112
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
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

Summary

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- Significant contributions from non-resonant Deck-like processes
  - Inclusion into fit model
  - Exploit $t'$-dependence of partial-wave amplitudes
    - PWA in narrow $m_{\pi^- \pi^+ \pi^-}$ and $t'$ bins
  - Improvements of wave set and isobar parameterization
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

Summary

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

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

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

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

- Intensity of S0 wave
- Intensity of D0 wave

**WA102**

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

**PL B453 (1999) 305**
Fit of $K^+K^-$ Mass Dependence
Comparison with WA102

**COMPASS**

- Intensity of S0 wave
- Intensity of D0 wave

**WA102**

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

**PL B453 (1999) 305**
PWA of $p p \rightarrow p_{\text{fast}} K^+ K^- p_{\text{slow}}$

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 $K_S^0 K_S^0$, $\pi^+ \pi^-$, $\pi^0 \pi^0$, 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. $\gamma + N \rightarrow N + \pi, \pi\pi, \pi\pi\pi, \eta, \pi\eta, \pi\omega, \eta\eta, \ldots$
- “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:
  - $p\pi^0, p\eta, p\eta', p\omega$
  - $p\pi^+\pi^-, p\pi^0\pi^0, pK^+K^-, pK^0\bar{K}^0, p\eta\eta$
  - ...  
- 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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$pp \rightarrow p\pi^0 p_{\text{slow}}$

$p\pi^0$ invariant mass

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

$\phi_{\text{TY}}$ of $\pi^0$ vs. $m_{p\pi^0}$
$pp \rightarrow p\pi^0 p_{\text{slow}}$

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

**$p\pi^0$ invariant mass**

```
pp → pπ⁰ p

Events / 5 MeV/c²
```

**COMPASS 2009**

pp → pπ⁰ p

(no acceptance correction)

preliminary

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

```
\cos \theta_{\text{GJ}} \text{ of } \pi^0 \text{ vs. } m_{p\pi^0}
```

**$\phi_{\text{TY}}$ of $\pi^0$ vs. $m_{p\pi^0}$**

```
\phi_{\text{TY}} \text{ of } \pi^0 \text{ vs. } m_{p\pi^0}
```

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Scalar mesons in central production

Baryon spectroscopy in proton diffraction

CONCLUSIONS AND OUTLOOK

Search for spin-exotic mesons in pion diffraction

COMPASS 2009

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

$\Delta^+(1232)$

32 Boris Grube, TU München

HADRON SPECTROSCOPY AT COMPASS

and related experiments
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

- $\bar{p}p$ data complementary to $\gamma p$ and $\pi p$ 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
Baryon Spectroscopy in Proton Diffraction

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

Main focus: search for mesonic states beyond the CQM

- Huge diffractive $\pi^-\pi^+\pi^-$ data set: precision spectroscopy of light-quark isovector sector
- Spin-exotic $J^{PC} = 1^{-+}$ signals observed in $\pi^-$ diffraction
  - $\pi^-\eta$ and $\pi^-\eta'$ channels
  - $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ final states
  - Resonance interpretation still unclear
- Study of scalar mesons in central production of $\pi\pi$, $K\bar{K}$, and $\eta\eta$
- Further analyses
  - $\pi^-$ diffraction into $\pi^-\eta\eta$, $\pi^-\pi^+\pi^-\pi^+$, $(\pi\pi K\bar{K})^-$, $\ldots$
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  - Radiative couplings of $a_2(1320)$ and $\pi_2(1670)$
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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 $\pi^-$ 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
Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)
The COMPASS Experiment at the CERN SPS

Experimental Setup

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

**Hadron spectroscopy**
- 190 GeV/c secondary hadron beams
  - $h^-$ beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
  - $h^+$ beam: 75% $p$, 24% $\pi^+$, 1% $K^+$
- **Various targets**: $\ell$H$_2$, Ni, Pb, W
- > 1 PByte of data per year

**E/HCAL2**

**SM2**

**RPD + Target**

**Beam**
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
Meson Production in Diffractive Dissociation

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- "Intermediate-\(t'\)" region: diffraction pattern of Pb nucleus
- "High-\(t'\)" region: scattering on individual nucleons in nucleus

\[ t' \in [0, 0.1] \text{ (GeV/c)}^2 \]

COMPASS 2004
\( \pi^+ \text{Pb} \to \pi^- \pi^+ \pi^+ \text{Pb} \)

\begin{align*}
\text{Number of Events} \\
10^5 &\quad 10^4 &\quad 10^3 \quad 10^2 \\
0.1 &\quad 0.09 &\quad 0.08 &\quad 0.07 &\quad 0.06 &\quad 0.05 &\quad 0.04 &\quad 0.03 &\quad 0.02 &\quad 0.01 &\quad 0
\end{align*}

Momentum Transfer \(t'\) (GeV/c\(^2\))

I(\(\theta\))

\(\lambda\)

\(\lambda/2R_0\)

I(\(\theta\))

\(\theta\)

\(R_0\)
Meson Production in Diffractive Dissociation

Reaction similar to diffraction of light by black disk

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- “Intermediate-\( t' \)” region: diffraction pattern of Pb nucleus
- “High-\( t' \)” region: scattering on individual nucleons in nucleus

\[
t' \in [0, 0.1] \text{ (GeV/c)}^2
\]

\[
t' \in [0.1, 1] \text{ (GeV/c)}^2
\]
Gottfried-Jackson Coordinate System

\[
\begin{align*}
X_L & \quad \hat{p}_a \\
Y_L & \quad \hat{p}_d \\
Z_L & \quad \hat{p}_c \\
X_{GJ} & \quad \hat{p}'_b \\
Y_{GJ} & \quad \hat{p}'_a \\
Z_{GJ} & \quad \hat{p}'_d \\
GJF & \quad \hat{p}'_c
\end{align*}
\]
Canonical vs. Helicity Coordinate System

X RF

Isobar

\( \hat{z} \)

\( \hat{z}_c = \hat{z} \)

\( \hat{x}_c \)

\( \hat{y}_c = \hat{y} \)

\( h_1 \)

\( h_2 \)

\( h_3 \)

\( \hat{p} \)

\( \hat{z}_h = \hat{p} \)

\( \hat{y}_h = \hat{z} \times \hat{z}_h \)

\( \hat{x}_h \)
### Partial-Wave Analysis Formalism

#### Cross section parameterization in mass-independent PWA

\[
\sigma(\tau; m_X) = \sigma_0 \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{re}(m_X) A_i^\epsilon(\tau) \right|^2
\]

- \( \epsilon, i \): quantum numbers of partial wave \((J^{PC} M^\epsilon[\text{isobar}] L)\)
- \( T_{ir}^{re} \): complex production amplitudes; fit parameters
- \( A_i^\epsilon \): complex decay amplitudes
- \( \tau \): phase space coordinates

#### Spin-density matrix

\[
\rho_{ij}^\epsilon = \sum_{r=1}^{N_r} T_{ir}^{re} T_{jr}^{re*} \quad \sigma(\tau; m_X) = \sigma_0 \sum_{\epsilon=\pm 1} \sum_{i,j} \rho_{ij}^\epsilon(m_X) A_i^\epsilon(\tau) A_j^\epsilon(\tau)
\]

- Diagonal elements \( \rho_{ii} \): intensities
- Off-diagonal elements \( \rho_{ij}, i \neq j \): interference terms
Partial-Wave Analysis Formalism

Two-body decay amplitude in helicity formalism

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

$$A^\text{hel}_X = \sqrt{2L+1} \sum_{\lambda_1, \lambda_2} (J_1 \lambda_1 J_2 - \lambda_2 |S \delta) (L 0 S \delta |J \delta)$$

$$D^{J*}_{\lambda \delta}(\theta, \phi, 0) F_L(q) \Delta(w) A_1 A_2$$

- $\delta = \lambda_1 - \lambda_2$
- $D^{J*}_{\lambda \delta}(\theta, \phi, 0)$ — Wigner $D$-function describes rotational properties of helicity states
- $\theta, \phi$ — 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 $X(w, J, M) \rightarrow 1(J_1, M_1) [L, S] 2(J_2, M_2)$

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

- $Y_{M_L}^{L}(\theta, \phi)$ — Spherical harmonic describes rotational property of $|L M_L\rangle$ state
- $\theta, \phi$ — 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 $\text{Acc}(\tau; m_X)$

$$\mathcal{L} = \left[ \frac{\bar{N}^N}{N!} e^{-\bar{N}} \right] \prod_{i=1}^{N} \frac{\sigma(\tau_i; m_X) \text{Acc}(\tau_i)}{\int d\Phi_n(\tau) \sigma(\tau; m_X) \text{Acc}(\tau; m_X)}$$

Poisson likelihood

Likelihood of event $n$

with

$$\bar{N} \propto \int d\Phi_n(\tau) \sigma(\tau; m_X) \text{Acc}(\tau; m_X)$$

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

$$\mathcal{L} \propto e^{-\int d\Phi_n(\tau) \sigma(\tau; m_X) \text{Acc}(\tau; m_X)} \prod_{i=1}^{N} \sigma(\tau_i; m_X)$$
Partial-Wave Analysis Formalism

Extended maximum-likelihood method (cont.)

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

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

- Make expression less unwieldy by taking logarithm

$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln \left[ \sum_{r=1}^{N_r} \sum_{\text{waves}} T_{\text{wave}}^r(m_X) A_{\text{wave}}(\tau_i; m_X) \right]^2$$

$$- \int d\Phi_n(\tau) \sigma(\tau; m_X) \text{Acc}(\tau; m_X)$$

**Normalization integral** estimated using phase space Monte Carlo
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

Events/20 MeV

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi' p$
$0.1 \text{ GeV}/c^2 < t < 1.0 \text{ GeV}/c^2$

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

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

<table>
<thead>
<tr>
<th>Events/20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi' p$
$0.1 \text{ GeV}/c^2 < t < 1.0 \text{ GeV}/c^2$

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

<table>
<thead>
<tr>
<th>Events/(20 MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi' p$
$0.1 \text{ GeV}/c^2 < t < 1.0 \text{ GeV}/c^2$
PWA of $\pi^− p \rightarrow \pi^− \pi^+ \pi^− p_{\text{slow}}$

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

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

$4^{++} 1^+ [\rho \pi] G: \ a_4(2040)$
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p_{\text{slow}}$

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

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

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

$4^{++} 1^+ [\rho\pi] G: a_4(2040)$
**π⁻ π⁺ π⁻ Final State**

Acceptance (p Target)

**π⁻ π⁺ π⁻ mass**

COMPASS 2008

\[ \pi p \rightarrow \pi \pi \pi^* p \]

0.1 GeV/c² < t' < 1.0 GeV/c²

preliminary

![Mass Distribution](image)

**π⁺ π⁻ mass**

COMPASS 2008

\[ \pi p \rightarrow \pi \pi \pi^* p \]

0.1 GeV/c² < t' < 1.0 GeV/c²

preliminary

![Mass Distribution](image)
**Final State**

Acceptance ($p$ Target)

**Gottfried-Jackson frame: $\cos \theta_{GJ}$**

**Helicity frame: $\cos \theta_{HF}$**

**Gottfried-Jackson frame: $\phi_{TY}$**

**Helicity frame: $\phi_{HF}$**
PWA of $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \text{Pb}$ at low $t'$ (Pilot Run)

$\pi^- \text{beam}$

$X^-$

$\gamma^*$

$\text{Pb}$

$\text{Pb}$

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

\[\times 10^3\]
\[\text{Intensity / (40 MeV/c^2)}\]

COMPASS 2004
$\pi\text{Pb} \rightarrow \pi\pi\pi^+\text{Pb}$
$t' < 0.001 \text{ GeV}^2\text{c}^2$

Mass of $\pi\pi\pi^+$ System (GeV/$c^2$)

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4

Graph showing intensity distribution for mass of $\pi\pi\pi^+$ system.
PWA of $\pi^- p \rightarrow \pi^- \eta p_{\text{slow}}$ and $\pi^- \eta' p_{\text{slow}}$

Selection of exclusive events with 3 charged tracks + 2 photons

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

$\gamma\gamma$ invariant mass distribution

\[ m(\gamma\gamma) \text{ [GeV]} \]

COMPASS 2008
$\pi^+ p \rightarrow \pi^- \pi^+ \gamma\gamma p$

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

Selection of exclusive events with 3 charged tracks $+$ 2 photons

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

$\gamma \gamma$ invariant mass distribution

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

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi^+ \gamma \gamma p$

COMPASS 2008
$\pi p \rightarrow \pi \pi \pi^+ \eta p$

w/o acceptance correction

preliminary
PWA of $\pi^- p \rightarrow \pi^- \eta \ p_{\text{slow}}$ 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
  - $1^{-+}$, $1^{++}$, $1^+$, and $4^{++}$ $1^+$
PWA of $\pi^- p \rightarrow \pi^- \eta \ p_{\text{slow}}$ and $\pi^- \eta' \ p_{\text{slow}}$

$\pi^- \eta$ invariant mass distribution

COMPASS 2008
$\pi^- p \rightarrow \pi^- \eta (\pi^+ \pi^- \pi^0) p$

entries / 4 MeV

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

COMPASS 2008
$\pi^- p \rightarrow \pi^- \eta' (\pi^+ \pi^- \gamma) p$

entries / 20 MeV

- $\pi^- \eta$: 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
  - $1^{-+}$, $1^+$, $2^{++}$, and $4^{++}$
PWA of $\pi^- p \rightarrow \pi^- \eta \, p_{\text{slow}}$ and $\pi^- \eta' \, p_{\text{slow}}$

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

$\pi^- \eta$ final state

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

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

**$\pi^- \eta$ final state**

**$\pi^- \eta'$ final state**

$\eta^-\eta'$ mixing together with OZI rule

- Partial-wave amplitudes for spin $J$ related by mixing angle $\phi$, phase space, and barrier factors ($q = \text{breakup momentum}$)

$$\frac{T_J^{\pi\eta'}(m)}{T_J^{\pi\eta}(m)} = \tan \phi \left[ \frac{q^{\pi\eta'}(m)}{q^{\pi\eta}(m)} \right]^{J+1/2}$$
PWA of $\pi^- p \rightarrow \pi^- \eta \, p_{\text{slow}}$ and $\pi^- \eta' \, p_{\text{slow}}$

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

\[ \pi^- \eta \text{ final state} \]

\[ \pi^- \eta' \text{ final state} \]
**PWA of** $\pi^- p \rightarrow \pi^- \eta p_{\text{slow}}$ **and** $\pi^- \eta' p_{\text{slow}}$

2$^++$ 1$^+$

- 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 $\pi^- p \rightarrow \pi^- \eta \, p_{\text{slow}}$ and $\pi^- \eta' \, p_{\text{slow}}$

2$^{++}$ 1$^+$

4$^{++}$ 1$^+$

**Phase:** $4^{++} 1^+ - 2^{++} 1^+$

- **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 $\pi^- p \rightarrow \pi^- \eta \, p_{\text{slow}}$ and $\pi^- \eta' \, p_{\text{slow}}$

**2++ 1+**

**Spin-exotic 1−− 1+**

- Completely different intensity of 1−− wave
- Suppression in $\pi\eta$ channel predicted for intermediate $|q\bar{q}g\rangle$ state
- Different phase motion in 1.6 GeV/c^2 region
PWA of $\pi^- p \rightarrow \pi^- \eta \, p_{\text{slow}}$ 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
PWA of $\pi^- p \rightarrow \pi^- \eta \ p_{\text{slow}}$ and $\pi^- \eta' \ p_{\text{slow}}$

**Summary**

- Found **significant intensity in spin-exotic $1^{-+}$ wave** in $\pi\eta$ and $\pi\eta'$
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- Found **significant intensity in spin-exotic $1^{-+}$ wave** in $\pi \eta$ and $\pi \eta'$
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**Non-resonant contributions**

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

**Summary**

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- **Final goal:** combined analysis of both channels
$\eta' \pi^-$ Final State

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

COMPASS 2008

$\pi^- p \rightarrow \pi^- \eta' p$

w/o acceptance correction

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

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 $\pi^-$ 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: $(\pi\pi)_S$-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 $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

- $0^{-+} \pi^- f_0(1500) S$
- $0^{-+} \rho a_1(1260) S$
- $1^{++} \pi^- f_0(1370) P$
- $1^{++} \pi^- f_1(1285) P$
- $1^{++} \rho \pi(1300) S$
- $1^{++} (\pi\pi) S a_1 D$
- $2^{-+} \pi^- f_2(1270) S$
- $2^{-+} \rho a_1(1260) S$
- $2^{-+} \rho a_2(1320) S$
- $2^{-+} \rho a_1(1260) D$
PWA of $\pi^-\,\text{Pb} \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-\,\text{Pb}$

COMPASS 2004

$\pi^-\,\text{Pb} \rightarrow \pi^+\pi^-\pi^+\pi^-$

width (GeV/c²)

mass (GeV/c²)

$\pi(1300)$

$\pi_2(1670)$

$\pi(1800)$

$a_1(1900)$

$\pi_2(1880)$

$\pi_2(2100)$

$a_1(2200)$

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

**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 $0.1 < t' < 1 (\text{GeV}/c)^2$
- Improvement of fit models
  - Analysis of $(4\pi)^0$ subsystem
PWA of $\pi^-\text{Pb} \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-\text{Pb}$

**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
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**Work in progress**

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  - Proton target, kinematic range $0.1 < t' < 1$ (GeV/c)^2
- Improvement of fit models
  - Analysis of $(4\pi)^0$ subsystem
PWA of $p\ p \rightarrow p_{\text{fast}} \pi^+ \pi^- \ p_{\text{slow}}$

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

Selected central events

$x_F$ distribution

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

COMPASS 2009
$p p \rightarrow p_f \pi^+ \pi^- p_s$,
$M(\pi \pi) > 1.5 \text{ GeV/c}^2$
PWA of $p\,p \rightarrow p_{\text{fast}}\,\pi^+\,\pi^-\,p_{\text{slow}}$

COMPASS 2009

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

### 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 $K_S^0K_S^0$, $\pi^0\pi^0$, and $\eta\eta$ final states on tape
PWA of $p p \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$

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