Light Meson Spectroscopy with COMPASS

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on behalf of the COMPASS collaboration

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Outline

• The Compass Experiment
• Light Meson Spectroscopy with Compass
  • $3\pi$ channel: $a_1(1440)$, $\pi_1(1600)$
  • $\pi\eta'/\pi\eta$ channel
  • Central production ($K^+K^-$)
  • Radiative widths of $a_2(1320)$ and $\pi_2(1670)$
  • Pion polarisability
• Conclusions and Outlook
COMPASS - A facility to study QCD

Large $Q^2$:
Nucleon structure
- Helicity, transversity PDFs
- TMDs and GPDs (2015-17)

Low $Q^2$:
Spectroscopy
- Hadronic mass spectrum
- Gluonic excitations / spin-exotics

Very low $Q^2$:
Chiral dynamics
- $\pi$ and $K$ polarisibilities
- Radiative widths
The COMPASS experiment at CERN

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

13 countries 24 institutions 220 physicists
The COMPASS spectrometer

Hadron Set-up: [NIMA 779 (2015) 69]

• Data taking in 2008 and 2009 with 190 GeV/c hadron beam ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$)
• $5 \cdot 10^7$ particles/10 s SPS-spill on 40cm liquid hydrogen target
• Trigger: Recoil Proton Detector + beam (minimum bias on forward system)
Meson Spectroscopy

Constituent quark model: color neutral $q\bar{q}$ systems

- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, $G = (-1)^{I+L+1}$
- Allowed $J^{PC}$: $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, ...$
- Forbidden: $0^{--}, 0^{+-}, 1^{--}, ...$

Dudek et al. PRD 88, 094505 (2013)
Meson Spectroscopy

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Experiment (1.3 - 2.2 GeV/$c^2$):
hybrid candidates with exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852 \rightarrow \eta\pi
- $\pi_1(1600)$: E852, VES \rightarrow \rho\pi, \eta'\pi, f_1\pi, b_1\pi
  COMPASS (2004) \rightarrow \rho\pi
- $\pi_1(2000)$: E852 \rightarrow f_1(1285)\pi, b_1(1235)\pi
Meson Spectroscopy at COMPASS: 3π

Exclusive 3π events in πp -> πππ p_recoil

- channels: π−π+π−, π−π0π0
- high t' region: 0.1 (GeV/c)^2 < t' < 1 (GeV/c)^2
- large data set
  - 50 Million events for π−π+π−
    400 mass bins & 11 bins of t'
  - 3.5 Million events for π−π0π0
    200 mass bins & 8 bins of t'

J. Bernhard
Partial Wave Analysis 3π

- Isobar Model
- Acceptance correction
- Factorisation of process with production and decay amplitude
- Fit in two steps:
  - fit in mass and $t'$ bins -> production amplitudes
  - fit mass dependence of spin-density matrix -> resonance parameters
Partial Wave Analysis $3\pi$

- 87 waves + flat wave
- crosscheck: $\pi\pi^0\pi^0$ scaled to $\pi\pi^+\pi^-$
- good agreement between channels

Meson Spectroscopy with Compass – J. Bernhard
Partial Wave Analysis $3\pi$

- first observation of structure in $1^{++} f_0(980) \pi P$
- small intensity ($\sim 0.25\%$)
- $\pi\pi^0\pi^0$ scaled to $\pi\pi^+\pi^-$
New axial-vector meson

Mass dependent fit for $\pi^-\pi^+\pi^-$ reveals new resonance: $a_1(1420)$
- Mass $1414 \pm^{15}_{-13}$ MeV/$c^2$
- Width $153 \pm^{8}_{-23}$ MeV/$c^2$

PRL 115 (2015) 082001
New axial-vector meson

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>mass range (MeV/$c^2$)</th>
<th>width range (MeV/$c^2$)</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1(1260)$</td>
<td>1$^{++}$</td>
<td>1260 – 1290</td>
<td>360 – 420</td>
</tr>
<tr>
<td>$a_2(1320)$</td>
<td>2$^{++}$</td>
<td>1312 – 1315</td>
<td>108 – 115</td>
</tr>
<tr>
<td>$\pi_2(1670)$</td>
<td>2$^{-+}$</td>
<td>1635 – 1663</td>
<td>265 – 305</td>
</tr>
<tr>
<td>$a_4(2040)$</td>
<td>4$^{++}$</td>
<td>1928 – 1959</td>
<td>360 – 400</td>
</tr>
<tr>
<td>$\pi(1800)$</td>
<td>0$^{-+}$</td>
<td>1790 – 1807</td>
<td>212 – 230</td>
</tr>
<tr>
<td>$\pi_2(1880)$</td>
<td>2$^{-+}$</td>
<td>1900 – 1990</td>
<td>210 – 390</td>
</tr>
</tbody>
</table>

Nature of $a_1(1420)$ still to be understood:

- isospin partner of $f_1(1420)$?
- no quark model state expected at 1.4 GeV/$c^2$
- ground state $a_1(1260)$ close and wider
- only seen in decays to $f_0(980)\pi$, not in $\rho\pi$
- close to $K^*\bar{K}^*$ threshold

PRL 115 (2015) 082001
Status of exotic $1^{-+}$ wave

- again, $\pi\pi^0\pi^0$ scaled to $\pi\pi^+\pi^-$
- some differences between channels
- study in different $t'$ bins:
  - peak in high $t'$ region
  - structure in low $t'$, non-resonant
Status of exotic $1^{-+}$ wave

- **MC data** generated with Deck-amplitude
- analysed like real data and scaled to integrated intensity of each $t'$ bins
- to be included in PWA

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Partial wave analysis $\pi\eta / \pi\eta'$

- Disputed findings in odd-L waves
  - $\pi(1400)$ claimed in $\pi\eta$
  - $\pi(1600)$ claimed in $\pi\eta'$
- Comparison of channels yields information about flavour structure

Partial wave analysis $\pi \eta / \pi \eta'$

- Even-L waves: similar intensity distributions in $\eta$ and $\eta'$
- Odd-L waves: suppressed in $\eta\pi$ by factor 5-10
- mass dependent fits highly model dependent
Central Production

- “glue-rich” process: search for glueballs
- mass-dependent fits with phases available
- $f_0(980), f_0(1500), f_0(1710)$ found, hints for further states beyond 2 GeV/$c^2$
- analysis to be improved (handling of ambiguities, model dependence)
Very low $t'$ region

- study resonances with electromagnetic probes, but "inverted": Coulomb field of heavy target (Pb) becomes photon target
- $t' < 0.001 \text{ (GeV/c)}^2$

Analysis:
- photo-production (Primakoff): cross section proportional to $e^{-a t'}$
- diffractive production: cross section proportional to $(t')^M e^{-b t'}$
- distinguish by spin projection $M$ with partial wave analysis
- include chiral amplitude in PWA instead of isobars for very low masses
Radiative widths

$\Gamma_0(a_2(1320) \rightarrow \pi\gamma) = 358$ keV

$\sigma_{\text{prim}}/\sigma_{\text{all}} = 0.97$

$\Gamma_0(\pi_2 \rightarrow \pi\gamma) = 181$ keV

First E2 transition observed for mesons

$\pi_2(1670)$

M2 transition
Pion polarisability

- $\chi$PT prediction (2-loop):
  - $\alpha - \beta = (5.7 \pm 1.0) \times 10^{-4}$ fm$^3$
  - $\alpha + \beta = (0.2 \pm 0.1) \times 10^{-4}$ fm$^3$
  - Experimental results vary: $\alpha - \beta = (4...14) \times 10^{-4}$ fm$^3$ (assuming $\alpha + \beta = 0$)

- Compass study with Primakoff production
- Cross section proportional to $\alpha - \beta$ in LO
- Compare $\pi$ and $\mu$ beam data to search for deviation from cross section of point-like particle
Pion polarisability

\[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat.}} \pm 0.7_{\text{sys.}}) \times 10^{-4} \text{ fm}^3 \]

\[ \alpha_\mu = (0.5 \pm 0.5_{\text{stat.}}) \times 10^{-4} \text{ fm}^3 \]

- Result confirms \( \chi \text{PT} \) prediction
- In tension with former experiments
Conclusions and Outlook

• COMPASS high precision spectroscopy program
• Unchallenged data sets (e.g. \( \pi^-\pi^+\pi^- \)) with access to charged and neutral channels
• Partial wave analyses extended to \( m \) and \( t' \) bins
• Found new axial-vector meson \( a_1(1420) \), interpretations:
  • Tetra-quark state [Hua-Xing Chen et al., arXiv:1503.02597], [Zhi-Gang Wang, arXiv:1401.1134]
  • Dynamic effect of interference with Deck [Basdevant et al., arXiv:1501.04643]
  • Triangle singularity [Mikhasenko et al., arXiv:1501.07023]
• Precision study of exotic \( 1^-+ \) wave, \( \pi_1(1600) \)
• Several improvements coming up (e.g. integrate Deck amplitude to \( 1^-+ \), include de-isobaring: fit isobars with step-wise functions from data)
• \( \pi \) polarisability and tests of \( \chi PT \) with Primakoff production [PRL 114 (2015) 062002]
• more analyses published and ongoing, but not shown here: study of production mechanisms via OZI violation [NPB 886 (2014) 1078], \( 5\pi \) channel, etc.
• XYZ studies started
Search for $Z_c^{\pm}(3900)$

- sizable cross section [Q.-Y. Lin et al., PRD 88 114009 (2013)]
- branching ratio seems to be small
- search with exclusive $J/\psi \pi^\pm$, $J/\psi \rightarrow \mu\mu$ production in muon beam data
- normalise to $\mu N \rightarrow J/\psi N$ cross section (acceptances cancel largely, only acceptance for $\pi^\pm$ left)
Search for $Z_c^{\pm}(3900)$

- $\frac{BR(Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}) \times \sigma_{\gamma N \rightarrow Z_c^{\pm}(3900)N}}{\sigma_{\gamma N \rightarrow J/\psi N}} < 3.7 \times 10^{-3}$

- Use NA14 cross section for $\mu N \rightarrow J/\psi N$ for normalisation:
  $BR(Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}) < 52 \text{ pb}$

- Conclusion: $Z_c^{\pm}(3900) \rightarrow J/\psi \pi^{\pm}$ not dominant decay mode