Hadron Spectroscopy at COMPASS

Bernhard Ketzer
Technische Universität München

International Workshop XXXIX on Gross Properties of Nuclei and Nuclear Excitations

Hirschegg
20 January 2011
Thank you very much for the dinner!
The Goal

Understand **hadrons** from the dynamics of quarks and gluons

⇒ **non-perturbative regime of QCD**

- Models: QM, bag, flux tube, ...
- Effective theories: $\chi$PT, ...
- Lattice-QCD
Experimental Tools

Deep Inelastic Lepton Scattering and related hard e.m. processes

Spectroscopy

QCD Bound States
- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Processes at low $Q^2$

Hadron Structure at Low Energies
- Polarizabilities
- Chiral anomaly

$\lambda = 1/\sqrt{Q^2}$
Experimental Tools

Deep Inelastic Lepton Scattering and related hard e.m. processes

Nucleon Structure
- Helicity
- Transversity
- GPDs

Spectroscopy
QCD Bound States
- Mass spectrum
- Gluonic excitations
- Multi-quark systems

Processes at low Q^2
Hadron Structure at Low Energies
- Photoproduction
- Polarizabilities
- Chiral anomaly

\[ \lambda = \frac{1}{\sqrt{Q^2}} \]
COMPASS at CERN

**COmmon Muon and Proton Apparatus for Structure and Spectroscopy**

- p up to 400 GeV
- secondary hadrons ($\pi, K, \ldots$): $2 \cdot 10^7$/s
- tertiary $\mu$ (polarized): $4 \cdot 10^7$/s
The COMPASS Experiment

Two-stage spectrometer
- large angular acceptance
- broad kinematical range
- ~250000 channels
- > 1000 TB/year

[COMPASS, P. Abbon et al., NIM A 577, 455 (2007)]
The COMPASS Experiment

Two-stage spectrometer
- large angular acceptance
- broad kinematical range
- ~250000 channels
- > 1000 TB/year

Data taking periods:
- 2002-2004: 160 GeV/c $\mu^+$
- 2004: 2 weeks 190 GeV/c $\pi^-$
- 2006-2007: 160 GeV/c $\mu^+$
- 2008-2009: 190 GeV/c $\pi^-$
- 2010: 160 GeV/c $\mu^+$

[COMPASS, P. Abbon et al., NIM A 577, 455 (2007)]
**QCD Bound States**

**Quark model:** bound state of $q\bar{q}$

**Quantum numbers:** $I^G (J^{PC})$

\[
P = (-1)^{L+1}, \quad C = (-1)^{L+S}, \quad G = (-1)^{I+L+S}
\]

**QCD:** other color-neutral configurations with same quantum numbers  $\Rightarrow$ mixing

- $(q\bar{q})_0$
- $(q\bar{q})(q\bar{q})$
- $(q\bar{q})_8 g$
- Hybrids
- $gg$ Glueballs
- $\ldots$

**Decoupling** only possible for
- narrow states
- vanishing leading $q\bar{q}$ term
  $\Rightarrow$ exotic $J^{PC}$: $0^--, 0^{+-}, 1^{++}, 2^{+-}, \ldots$
Glueballs

Quenched L-QCD prediction

Lightest glueballs:
- $M \sim 1.7 \text{ GeV}/c^2 \ (J^{PC} = 0^{++})$
- $M \sim 2.4 \text{ GeV}/c^2 \ (J^{PC} = 2^{++})$

Experimental candidate:
- $f_0(1500)$ (Crystal Barrel, WA102)
  $J^{PC}=0^{++} \Rightarrow$ mixing with isoscalar mesons!

[Y. Chen et al., Phys. Rev. D 73, 014516 (2006)]
Hybrids with $J^{PC} = 1^{--}$

### Mass

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass (GeV/c²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bag Model</td>
<td>1.0 – 1.4</td>
<td>[Barnes and Close, Jaffe et al., Vainshtein et al]</td>
</tr>
<tr>
<td>QSSR</td>
<td>1.0 – 1.9</td>
<td>[Balitsky et al., Latorre et al., Narison et al.]</td>
</tr>
<tr>
<td>Flux Tube</td>
<td>1.8 – 2.0</td>
<td>[Isgur et al.]</td>
</tr>
<tr>
<td>Hamiltonian</td>
<td>2.1 – 2.3</td>
<td>[Cotanch et al.]</td>
</tr>
</tbody>
</table>

### Decay

<table>
<thead>
<tr>
<th>Model</th>
<th>$b_1 \pi$</th>
<th>$f_1 \pi$</th>
<th>$\rho \pi$</th>
<th>$\eta \rho$</th>
<th>$\eta' \rho$</th>
<th>$\eta(1295) \pi$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux Tube, $^3P_0$</td>
<td>170</td>
<td>60</td>
<td>5 – 20</td>
<td>0 – 10</td>
<td>0 – 10</td>
<td></td>
<td>[Isgur et al., Close et al.]</td>
</tr>
<tr>
<td>Flux Tube, IKP m=1.6 GeV/c²</td>
<td>24</td>
<td>5</td>
<td>9</td>
<td>2</td>
<td></td>
<td></td>
<td>[Isgur et al.]</td>
</tr>
<tr>
<td>Flux Tube, PSS m=1.6 GeV/c²</td>
<td>59</td>
<td>14</td>
<td>8</td>
<td>1</td>
<td></td>
<td></td>
<td>[Page et al.]</td>
</tr>
<tr>
<td>L-QCD</td>
<td>66</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[McNeil and Michael]</td>
</tr>
</tbody>
</table>

[C. Mayer, arXiv: 1004.5516v2]
Hybrids

**Light meson sector exotics $J^{PC}=1^{-+}$:**
- $\pi_1(1400)$ (E852, VES, Crystal Barrel)
- $\pi_1(1600)$ (E852, VES, Crystal Barrel)
- $\pi_1(2000)$ (E852)

resonant nature controversial...

[S.U. Chung et al., PRD 65, 072001 (2002)]
[A.R. Dzierba et al., PRD 73, 072001 (2006)]

$1^{-+}1^{+}$ P-wave

$M(3\pi)$ (GeV/c$^2$)

Events / 0.04 GeV/c$^2$
Hadron Reactions at COMPASS

Three production mechanisms studied in parallel using proton, pion and kaon projectiles

Central production

- Double Reggeon exchange
- Rapidity gap between $p_{\text{slow}}$, $h_{\text{fast}}$, $X$
- Possible source of glueballs

Diffractive dissociation

- Reggeon (Photon) exchange
- Forward kinematics
- Study of $J^{PC}$-exotic mesons

$\Rightarrow$ Goal: 10× world statistics
Diffractive Reactions at COMPASS

Example:
\[ \pi^- + \text{Pb} \rightarrow \pi^- \pi^- \pi^+ + \text{Pb} \]
- 4\pi vertex in Pb target
- Exclusivity ⇒ target stays intact
- Momentum transfer

\[ -t \equiv Q^2 = -(p_a - p_c)^2 \]

Diffraction on Pb nuclei

COMPASS 2004
\[ \pi \text{Pb} \rightarrow \pi \pi \pi^+ \text{Pb} \]

\[ b = 400 \left( \frac{\text{GeV}^2}{c^2} \right)^{-1} \]

\[ R = 0.3 \sqrt{b} = 6 \text{ fm} \]
Diffractive Reactions at COMPASS

Example:

\[ \pi^- + \text{Pb} \rightarrow \pi^- \pi^- \pi^+ + \text{Pb} \]

- 4\pi vertex in Pb target
- Exclusivity \( \Rightarrow \) target stays intact
- Momentum transfer

\[ -t \equiv Q^2 = -(p_a - p_c)^2 \]

Diffraction on Pb nuclei

Diffraction on nucleons

Graphs showing the number of events vs. momentum transfer for Pb target interactions.
Example:

\[ \pi^- + \text{Pb} \rightarrow \pi^- \pi^- \pi^+ + \text{Pb} \]

- $4\pi$ vertex in Pb target
- Exclusivity $\Rightarrow$ target stays intact
- Momentum transfer

\[-t = Q^2 = -(p_a - p_c)^2\]

3$\pi$ invariant mass

\[\begin{align*}
\text{a}_2(1320) & \\
\text{a}_1(1260) & \\
\pi_2(1670) & 
\end{align*}\]

\[\begin{align*}
\text{COMPASS 2004} & \\
\pi \text{Pb} \rightarrow \pi \pi \pi^+ \text{Pb} & \\
0.1 < t' < 1.0 \text{ GeV}^2/c^2 & 
\end{align*}\]

\[\begin{align*}
\text{Number of Events} & \\
0.1 & \quad 0.2 & \quad 0.3 & \quad 0.4 & \quad 0.5 & \quad 0.6 & \quad 0.7 & \quad 0.8 & \quad 0.9 & \quad 1 \\text{ (GeV}/c^2) & 
\end{align*}\]

Diffraction on nucleons
Partial Wave Analysis

- Many different resonances are produced which decay into same final state
- Goal:
  - find and disentangle (all) contributing resonances
  - determine mass, width and quantum numbers $J^P$ of resonances
    - angular distributions of decay products
- Interference effects ⇒ small resonances may be enhanced
- Take into account experimental acceptance
Partial Wave Analysis

Isobar model:
• X decays via sequence of 2-body decays
• Intermediate resonances: isobars
• Partial wave: $\chi = J^{PC}M^\varepsilon[\text{isobar } R]L$
• Decay amplitudes $A_\chi(m, \tau)$ calculable
  • 3 variables for each 2-body vertex $m_{\text{mother}}, (\theta, \varphi)$ in mother r.f.
  • $3\pi$ decay: $m, \{\theta_{\text{GJ}}, \phi_{\text{GJ}}, m_R, \theta_H, \phi_H\} \equiv \tau$
  • contain angular distributions and isobar parameterizations

Reflectivity basis: linear combinations

$$\left| p_\varepsilon jm \right> = \theta(m) \left[ \left| p jm \right> - \varepsilon P(-1)^{j-m} \left| p j-m \right> \right]$$

$$\theta(m) = \begin{cases} 
1/\sqrt{2} & , \ m > 0 \\
1/2 & , \ m = 0 \\
0 & , \ m < 0 
\end{cases}$$
Real Life…

Example: $\pi_2(1670) \rightarrow f_2(1270) \pi$, $f_2(1270) \rightarrow \pi \pi$
PWA Technique

Illinois / Protvino / Munich Program – BNL / Munich Program

1. **PWA** of angular distributions in 40 MeV mass bins

   \[ I_{\text{indep}}(\tau, m) = \sum_{\varepsilon = \pm 1} \sum_{r=1}^{N_r} \left| \sum_{i} T_{\varepsilon}^{ir} A_i^{\varepsilon}(\tau, m) \right|^2 \]

   - Production amplitudes \( T_{ir}^{\varepsilon} \) \( \Rightarrow \) extended maximum likelihood fit
   - Decay amplitudes \( A_i^{\varepsilon}(\tau, m) \) (Zemach tensors, D functions)
   - 41 partial waves \( i = J^{PC} M^{\varepsilon} [...] L \)
     \[ [...] = (\pi\pi)_S, \rho(770), f_0(980), f_2(1270), \rho_3(1690) \]
   - Background wave added incoherently
   - No assumption on resonant behavior is made at this point!

2. **Mass-dependent \( \chi^2 \) fit** to results of step 1

   - 6 waves
   - Parameterized by Breit-Wigner
   - Coherent background for some waves
$a_1(1260)$ and $\pi_2(1670) - \pi^-\pi^-\pi^+$

- BW for $a_1(1260) + \text{bgr}$
  \[ M = \left( 1255 \pm 6^{+7}_{-17} \right) \text{MeV}/c^2 \]
  \[ \Gamma = \left( 367 \pm 9^{+28}_{-25} \right) \text{MeV}/c^2 \]

- BW for $\pi_2(1670)$
  \[ M = \left( 1658 \pm 3^{+24}_{-8} \right) \text{MeV}/c^2 \]
  \[ \Gamma = \left( 271 \pm 9^{+22}_{-24} \right) \text{MeV}/c^2 \]
\[ \pi(1800) - \pi^-\pi^-\pi^+ \]

- Constant width BW for \( \pi(1800) \) and low-mass background
- BW parameters

\[
M = \left( 1785 \pm 9^{+12}_{-6} \right) \text{ MeV}/c^2
\]

\[
\Gamma = \left( 208 \pm 22^{+21}_{-37} \right) \text{ MeV}/c^2
\]
$J^{PC}=1^{-+}$ Exotic Wave – $\pi^{-}\pi^{-}\pi^{+}$

- BW parameters for $\pi_1(1600)$
  
  $$M = (1660 \pm 10^{+0}_{-64}) \text{ MeV}/c^2$$
  
  $$\Gamma = (269 \pm 21^{+42}_{-64}) \text{ MeV} / c^2$$

- Leakage negligible: <5%

Diffractive Dissociation – $3\pi$

\[ \pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb} \quad 420k \text{ events} \]

\[ \pi^- \text{p} \rightarrow \pi^- \pi^- \pi^+ \text{p} \quad 96M \text{ events} \]

\[ \pi^- \text{p} \rightarrow \pi^- \pi^0 \pi^0 \text{p} \quad > 2.4M \text{ events} \]

- Target: (2+1) cm Pb
- Trigger: Multiplicity
- No RPD

- Target: 40 cm lH2
- Trigger: Recoil proton
- RPD

- Cross-check:
  - tracking vs ECAL
  - Isospin symmetry:
    - I=1 vs I=0 isobars
    - fulfilled
Nuclear Effect $- \pi^-\pi^-\pi^+$

- Compare intensities of $a_1(1260)$ and $\pi_2(1670)$ from Pb and H$_2$ targets
- Normalize to intensity of $a_2(1320)$ ($J^{PC}M^\varepsilon = 2^{++}1^+$)
- Pb target: enhancement of spin projection $M=1$
  suppression of spin projection $M=0$
- Total intensity (both spin projections) roughly the same

\[ J^{PC}M^\varepsilon = 1^{++}1^+ \]
\[ J^{PC}M^\varepsilon = 1^{++}0^+ \]
Nuclear Effect $- \pi^-\pi^-\pi^+$

- Compare intensities of $a_1(1260)$ and $\pi_2(1670)$ from Pb and H$_2$ targets
- Normalize to intensity of $a_2(1320)$ ($J^{PC}M^\varepsilon = 2^{++}1^+$)
- Pb target: enhancement of spin projection $M=1$
  suppression of spin projection $M=0$
- Total intensity (both spin projections) roughly the same

\[ J^{PC}M^\varepsilon = 2^{-+}1^+ \]

\[ J^{PC}M^\varepsilon = 2^{-+}0^+ \]
Multi-Particle (>3) Final States

Motivation:

• Clarify the hybrid nature of the $\pi_1 \Rightarrow$ branching ratios to different channels

<table>
<thead>
<tr>
<th>Model</th>
<th>$b_1\pi$</th>
<th>$f_1\pi$</th>
<th>$\rho\pi$</th>
<th>$\eta p$</th>
<th>$\eta' p$</th>
<th>$\eta(1295)p$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux Tube, $^{3}P_0$</td>
<td>170</td>
<td>60</td>
<td>5 - 20</td>
<td>0 - 10</td>
<td>0 – 10</td>
<td></td>
<td>[Isgur et al., Close et al.]</td>
</tr>
<tr>
<td>Flux Tube, IKP m=1.6 GeV/c²</td>
<td>24</td>
<td>5</td>
<td>9</td>
<td></td>
<td>2</td>
<td></td>
<td>[Isgur et al.]</td>
</tr>
<tr>
<td>Flux Tube, PSS m=1.6 GeV/c²</td>
<td>59/14</td>
<td>14/8</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td>[Page et al.]</td>
</tr>
<tr>
<td>L-QCD</td>
<td>66/15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[McNeil and Michael]</td>
</tr>
</tbody>
</table>

• Higher masses accessible $\Rightarrow$ many disputed states: 0−+, 1++, 2++, ...

Under investigation in COMPASS:

• $\pi^- \pi^- \pi^- \pi^+ \pi^+$
• $\pi^- \eta$, $\eta \rightarrow \gamma \gamma$
• $\pi^- \eta$, $\eta \rightarrow \pi^- \pi^0 \pi^+$

• $\pi^- \eta'$, $\eta' \rightarrow \pi^- \pi^+ \eta$, $\eta \rightarrow \gamma \gamma$
• $\pi^- \eta'$, $\eta' \rightarrow \pi^- \pi^+ \eta$, $\eta \rightarrow \pi^- \pi^0 \pi^+$
• $\pi^- f_1$, $f_1 \rightarrow \pi^- \pi^+ \eta$, $\eta \rightarrow \gamma \gamma$
• $\pi^- f_1$, $f_1 \rightarrow \pi^- \pi^+ \eta$, $\eta \rightarrow \pi^- \pi^0 \pi^+$
$\pi^-\pi^-\pi^+\eta$ Final State

$\eta \rightarrow \pi^-\pi^+\pi^0$

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

$\eta \rightarrow \gamma\gamma$

Select $\eta'$

Hybrid $\pi_1(1600)$ expected in this channel
PWA - $\eta'\pi$ final state

- Preliminary PWA
- No optimization for COMPASS (acceptance, resolution)

VES results (38 GeV pions, Be target)

Coherent production on Pb nucleus

Contributions at very low \( t' \):

- **Diffraction:** \( \sigma(t') \propto e^{-b_{\text{Diff}} t'} \), \( b_{\text{Diff}} \approx 400 \text{(GeV/c)}^{-2} \)
- **Photoprod.:** \( \sigma(t') \propto e^{-b_{\text{Prim}} t'} \), \( b_{\text{Prim}} \approx 2050 \text{(GeV/c)}^{-2} \)

- Fit of 2 exponentials for \( t' < 0.006 \text{ GeV}^2/c^2 \)
- Steep fall-off for photoproduced events dominated by experimental resolution
- Statistical subtraction of diffractive contribution
Partial Wave Analysis

Two clearly separated regions: \( t' < 0.5 \cdot 10^{-3} \, \text{GeV}^2/c^2 \)

\[ 0.0015 < t' < 0.01 \, \text{GeV}^2/c^2 \]

\( a_2(1320) \) (M=1) present in both t’-ranges \( \Rightarrow \) different production mechanisms

- **Diffraction** \( \sigma(t') \propto t' e^{-bt'} \), vanishes for \( t' \rightarrow 0 \)
- **Photoproduction** \( \sigma(t') \propto e^{-b_{\text{prim}} t'} \)

Phase difference \( a_2(1320) - a_1(1260) \): offset for two t’-regions!
Phase Difference $a_2-a_1$

PWA in $t'$ bins for single mass bin $1.26 < m_{3\pi} < 1.38 \text{ GeV}/c^2$ ($a_2$ region)

**Experiment**

- Smooth transition from $a_2$ photoproduction to diffractive production with increasing $t'$
- Possibility to cleanly separate photoproduction from diffraction
- Determination of radiative width of $a_2(1320), \pi_2(1670)$

**Theory**

Plot by N. Kaiser, TUM
Kaonic Final States

- Access to exotics, glueballs
- Clarify flavor content of resonances
- $K^\pm \Rightarrow$ RICH particle identification
- $K_S \Rightarrow \pi^+\pi^-$ decay
- $K$ beam $\Rightarrow$ CEDAR tagging
  $\Rightarrow$ extend knowledge on $K$ spectrum

Diffractive states at 1.7 GeV/c$^2$ and 2.2 GeV/c$^2$, decaying to $K^*(892)$ and $K^*(1430)$
Data with Proton Beam

- Beam: 190 GeV/c, 71.5% p, 25.5% $\pi$, 3.0% K
- CEDARs tagging protons
- Trigger: Recoil proton
- ~10% of total 2008/2009 statistics
- Baryon spectroscopy:
  - $pp \rightarrow p_f \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f K^+ K^- p_s$
- Central Production
  - $pp \rightarrow p_f \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f \pi^+ \pi^- \pi^+ \pi^- p_s$
  - $pp \rightarrow p_f K\bar{K} p_s$
Baryon Spectroscopy

\[ pp \rightarrow p_f \pi^+ \pi^- p_s \]

\[ pp \rightarrow p_f K^+ K^- p_s \]

- final states containing charged and neutral particles
- Masses up to \(~3\) GeV/c² accessible
Central Production

\[ \pi^- p \rightarrow \pi_f K^+ K^- p_s \]

\[ \pi^- p \rightarrow \pi_f K_S^0 K_S^0 p_s \]
Conclusions

- High statistics: 10 × world data sample on diffractive and central production
- High and uniform acceptance for charged and neutral final states
- Clear $\pi_1(1600)$ signal in $\pi^-\pi^-\pi^+$ for Pb target
- Signal also seen for H$_2$ target in $\pi^-\pi^-\pi^+$, $\pi^-\pi^0\pi^0$, $\eta'\pi$, $f_1\pi$
- Nuclear effect: production of M=1 states enhanced for larger A
- Kaonic final states $\Rightarrow$ resonance coupling to strangeness
- Kaon beam $\Rightarrow$ study Kaon spectrum
- Proton beam
  - central production of (glue-rich) states
  - baryon resonances
- PWA: two different programs: Illinois-Protvino-Munich, BNL-Munich
Outlook

- Production of large-statistics Monte Carlo sample
- Production mechanism \( \Rightarrow \) study \( t \)-dependence
- Optimization of wave set for \( \text{H}_2 / \text{Pb} / \text{Ni} \) data \( \Rightarrow \) genetic algorithm
- Improvement of model
  - Deck amplitude
  - Rescattering effects
- Development of PWA for baryons and central production
- Future data taking \( \Rightarrow \) addendum to COMPASS II proposal
  - higher beam energy / beam energy scan
  - dedicated trigger for neutral channels and higher masses
COMPASS Future Plans

|------|------|------|------|------|------|------|------|

**Spectroscopy**
- $p, \pi, K$ beam

**Transversity**
- $\mu$ beam: Collins, Sivers
- $\mu$ beam: $\Delta q$ at low $x$, high precision
- $\pi, K$ beam
- $\mu$ beam
- $\pi$ beam

**DIS / SIDIS**
- $p, K$ Polarizability
- GPDs: DVCS, HEMP
- Transversity: Drell-Yan

**Spectroscopy**
Deck Effect

Resonant production

\[ \pi \xrightarrow{\alpha_1} \rho \xrightarrow{\pi} R \]
\[ p \xrightarrow{R} p \]

Non-resonant production

\[ \pi \xrightarrow{\pi} \rho \xrightarrow{\pi} R \]
\[ p \xrightarrow{R} p \]

- Generate pure Deck-like events
- Pass through Monte Carlo & PWA
- Examine exotic wave
Resonant production

\[ \pi \rightarrow \alpha_1 \rightarrow \rho \]

Non-resonant production

\[ \pi \rightarrow \rho \]

- Generate pure Deck-like events
- Pass through Monte Carlo & PWA
- Examine exotic wave