Physics with Hadron Beam at COMPASS

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for the COMPASS collaboration

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Outline

- **Light meson spectroscopy**
  - 2008 data analysis ongoing
  - 2009 data taking about to start
  - depending on results → increase of statistics desirable

- **Primakoff reactions** (minor upgrades needed)
  - unique opportunity for new measurements at COMPASS
  - progress on theoretical understanding

- **Doubly charmed** baryons (requires new beam line)
  - evidence from SELEX to be checked
  - almost unexplored field
Goal of Primakoff program: Measure exclusive *pion-photon* reactions

\[ \pi + \gamma \rightarrow \begin{cases} 
\pi + \gamma & \text{Compton reaction} \\
\pi + \pi^0 & \text{neutral pion production} \\
\pi + \pi^0 + \pi^0 & \text{double pion production}
\end{cases} \]
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Compton reaction:
Leading deviation from pointlike \(\leftrightarrow\) e.m. polarisability

\[ \alpha_\pi \approx -\beta_\pi \]\n
for \(\alpha_\pi - \beta_\pi \, [10^{-4} \text{ fm}^3]\):

Theory: 5.7\pm1.0 \quad \text{Experiments: 4 \text{ --- } 14} \]
Pion Compton Scattering

Effect of $\alpha_\pi - \beta_\pi$ larger under backward CM angle

- - - - structureless pion, Born terms only

$\alpha_\pi = -\beta_\pi = 3.10^{-4}\text{ fm}^3$

full cross section with $\alpha_\pi = -\beta_\pi = 3.10^{-4}\text{ fm}^3$
Pion Compton Scattering

- \( s \)-dependence: polarisability ↔ ChPT loop effects

Effect of pion polarizabilities:

\[ \alpha_\pi = -\beta_\pi = 3.10^{-4}\text{fm}^3 \]

\( d\sigma / d\sigma_0 \) vs. \( s^{1/2} \) [\( m_\pi \)]
How to scatter photons on pions?

wanted:

\[ Q^2 \ll m_{\pi}^2 \]

\((A,Z) \rightarrow (A,Z)\)
How to scatter photons on pions?

wanted:

\[ Q^2 < < 2m_{\pi}^2 \]

▶ only Primakoff technique allows direct kinematical access to the pion polarisability
## Pion Polarisability: Theory and Data

<table>
<thead>
<tr>
<th></th>
<th>( \alpha_\pi + \beta_\pi ) [(10^{-4} \text{ fm}^3)]</th>
<th>( \alpha_\pi - \beta_\pi ) [(10^{-4} \text{ fm}^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bürgi/Gasser (ChPT)</td>
<td>0.2 (\pm) 0.1</td>
<td>5.7 (\pm) 1.0</td>
</tr>
<tr>
<td>(e^+ e^- \to e^+ e^- \pi^+ \pi^-)</td>
<td>0.22 (\pm) 0.07 (\pm) 0.04</td>
<td>4.8 (\pm) 4.0(??)</td>
</tr>
<tr>
<td>Mark II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CELLO</td>
<td>0.33 (\pm) 0.06 (\pm) 0.01</td>
<td></td>
</tr>
<tr>
<td>(\gamma p \to n \pi^+ \gamma)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAMI</td>
<td></td>
<td>11.6 (\pm) 1.5 (\pm) 3.0 (\pm) 0.5(??)</td>
</tr>
<tr>
<td>(\pi^- Z \to Z \pi^- \gamma)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serpukhov</td>
<td>1.8 (\pm) 3.1 (\pm) 2.5</td>
<td>12.3 (\pm) 2.6</td>
</tr>
<tr>
<td>COMPASS</td>
<td>XX</td>
<td>XX (\pm) 0.8 [30 days]</td>
</tr>
</tbody>
</table>
COMPASS Primakoff measurement

- **high resolution** for small $Q^2$
  - identify Primakoff events
  - tracking with SMDs, reduced material budget in the spectrometer
  - precise calorimetry and scattering angle of outgoing photons

- **(pointlike) muon** beam allows crucial systematic cross-check measurement

- **specific trigger** on high energy deposition in Ecal
  - implement sum of in-time signals in FPGA trigger electronics

- **high statistics** for full kinematical coverage
  - $\alpha_\pi - \beta_\pi$ is obtained with competitive precision in 30 days pion beam (assuming $\alpha_\pi = -\beta_\pi$)
  - Independent extraction of $\alpha_\pi$ and $\beta_\pi$ requires a factor 4 more statistics

- **$K^-$** polarisability via Primakoff mechanism (CEDARs)
Prospects for 4 weeks

\[
R(\omega) = \frac{N_{\exp}(\omega)}{N_{MC}(\omega)} = \frac{\frac{d\sigma^{\text{Prim}}}{d\sigma^{\text{Thomson}}}}{1 + \frac{3}{2} \frac{m_{\pi}^3}{\alpha} \frac{\omega^2}{1-\omega} \bar{\beta}_{\pi}}, \quad (\bar{\alpha}_{\pi} + \bar{\beta}_{\pi} = 0)
\]

\(R(\omega)\) for different values of \(\alpha_{\pi} (\beta_{\pi})\)  

Cross check with \(\mu\) beam
Primakoff neutral pion production

\[ F_{\gamma 3\pi} \sim \frac{e}{4\pi^2 f^3_\pi} \] (chiral anomaly)

\[ F_{\gamma 4\pi} \sim a_{IJ} \]

"\[ F_{2\gamma 2\pi} \]" \sim \alpha_\pi, \beta_\pi


all channels test QCD at low energy (Chiral Perturbation Theory)
Doubly Charmed Baryons

- B-like ground state ("heavy-light" system)
- excitation in c-c binding (molecular like)
- Mass spectrum calculable rather reliably
- First evidence of cc-systems
  - SELEX: fixed-target experiment at Fermilab
  - $\Sigma^-, \pi^-, p$ beams at 600 GeV

\[ \Xi^{+}_{cc} (ccd) \rightarrow pD^+ K^-, \Lambda_c K^-\pi^+, \Xi^+_c \pi^-\pi^+ \text{ M}=3519 \text{ MeV/c}^2 \]

\[ \Xi^{++}_{cc} (ccu) \rightarrow \Lambda_c K^-\pi^+\pi^+ \text{ M}=3460 \text{ MeV/c}^2 \]

\[ \Xi^{++*}_{cc} (ccu) \rightarrow \Lambda_c K^-\pi^+\pi^+ \text{ M}=3780 \text{ MeV/c}^2 \]
Properties of \( cc \)-Baryons: Mass and Lifetime

- Decay of baryons governed by three processes (W-exchange, spectator decay, quark interference)
- Lifetime: SELEX \( \tau(\Xi_{cc}^+) \sim 30 \text{ fs} \)
- Production observed in \( \Sigma^- \) beam, yield accounts for 50% of total \( \Lambda_c \) production (threshold effect?)
- No other experiment has observed these states (\( p, \pi \) beams)

needs clarification!
Doubly Charmed Baryons in COMPASS

- fixed-target experiment:
  - decay chain spatially resolvable
- use 450 GeV proton beam
- vertex detector system
- trigger
  - multiplicity $> 5$ charged tracks
  - high-$p_t$ muons
    - ($\sim 35\%$ of decays)
  - transverse energy $E_T$
- CPU-farm
  - (secondary vertex finding)
- yield (from SELEX signals):
  - 10-17k events
  - incoherent $cc$-production:
    - Factor 100-500 less
Beam for cc-baryon spectroscopy

- First trial with proton beam of highest possible energy → 450 GeV
- New beam line
- Best option: Hyperon beam (à la WA89):
  \[ p(450\text{GeV}) + \text{Be} \rightarrow \Sigma^-(350\text{GeV}) + \chi \]
Hadron spectroscopy at COMPASS is an open field:

- Continue the search for exotics in the light meson sector
- Primakoff reactions
  - unique potential to clarify pion polarisability
  - Data for $F_{\gamma 3\pi}$ and $F_{\gamma 4\pi}$ allow test of low-energy QCD (ChPT)
  - First value for Kaon polarisability
- Spectroscopy of doubly charmed baryons
  - COMPASS hardware
    - More silicon stations (possibly 25 µm pitch)
    - online filtering, HCAL / ECAL trigger
  - Beam
    - 450 GeV protons to COMPASS
    - (re)build of hyperon beam
Backup
Pion-nucleus reaction mechanisms

Diffractive dissociation
- projectile excitation
- exclusive reaction
- meson (exotic) spectrum

Central production
- target recoil
- projectile at high rapidity
- glueball search
$3\pi$ Data in the range $0.3 < t'/\text{(GeV}^2/\text{c}^2) < 1$

$\pi^- \pi^- \pi^+$ Mass Distributions and Acceptance

COMPASS 2004

$\pi^+ \pi^- \pi^+$ System (GeV/c)

Acceptance

J.M. Friedrich (TU München)

BNL-E852, Phys. Rev. D65, 072001, 2002
PWA Results

$1^{++}0^{+}\rho\pi S$ and $2^{-+}0^{+}f_2\pi S$

- **$1^{++}0^{+}\rho\pi S$**
  - COMPASS 2004
  - $\pi Pb \rightarrow \pi\pi\pi^+Pb$
  - $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

- **$2^{++}0^{+}f_2\pi S$**
  - COMPASS 2004
  - $\pi Pb \rightarrow \pi\pi\pi^+Pb$
  - $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

- **Phase (degrees)**
  - $\pi Pb \rightarrow \pi\pi\pi^+Pb$
  - $0.1 < t' < 1.0 \text{ GeV}^2/c^2$

BW for $a_1(1260)$ + background:

- $M = (1.256 \pm 0.006 \pm 0.007) \text{ GeV}$
- $\Gamma = (0.366 \pm 0.009 \pm 0.028) \text{ GeV}$

BW for $\pi_2(1670)$:

- $M = (1.659 \pm 0.003 \pm 0.024) \text{ GeV}$
- $\Gamma = (0.271 \pm 0.009 \pm 0.022) \text{ GeV}$
PWA Results
Exotic $1^{-+} 1^{++}$ P Wave

BNL E852 signal:

- Significant $1^{-+}$ amplitude consistent with resonance at $\sim 1.6$ GeV
- No leakage observed
- BW for $\pi_1(1600)$ + background:
  
  $M = (1.660 \pm 0.010 ^{+0.000} _{-0.064})$ GeV
  
  $\Gamma = (0.269 \pm 0.021 ^{+0.042} _{-0.064})$ GeV
Summary of Extracted States
Comparison with PDG values

Particle Mass (GeV/c^2)

- COMPASS 2004
- PDG 2006

a_1(1260) a_2(1320) π_1(1600) π_2(1670) π(1800) a_4(2040)
COMPASS Setup 2008
Target region: Silicon detectors

Liquid Hydrogen target system
Sandwich Veto

Upstream Veto
TOF scintillators
Target cell
Silicon Microstrip Detectors

Acceptance +/- 180 mrad

1 m

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Hadron Beams at COMPASS

2009-03-19
Primakoff $\pi\gamma$ reactions

Photon exchange (hadronic interference)

COMPASS 2004 $\pi^{-}$ data

- Coulomb peak
- Diffractive background
- Empty target background

$E_\pi = 190$ GeV
$E_\gamma = 90$ GeV
Pion physics and $\chi$PT

Pion scattering lengths: 2-loop predictions

- $a_0^0 m_{\pi^+} = 0.220 \pm 0.005$ confirmed in $K^+ \to \pi^+ \pi^- e^+ \nu_e$ (E865)
- $(a_0^0 - a_0^2) m_{\pi^+} = 0.264 \pm 0.006$ confirmed in $K^+ \to \pi^+ \pi^0 \pi^0$ (NA48: 0.268 ± 0.010)

Electromagnetic structure

- Form factor described by coupling to $\rho(770)$ (resonance effect, VMD)

- **Polarisability**
  accessible as contribution to Compton scattering; prediction obtained by the LEC relation to $\pi^+ \to e^+ \nu_e \gamma$
  $$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1) \cdot 10^{-4} \text{fm}^3$$
  $$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4} \text{fm}^3$$
  [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]
Details of Primakoff measurement

- s-dependence $\alpha_\pi(s)$ (as ChPT loop effect)
- interference with $\pi^- \pi^0$ Primakoff production
- e.m. radiative corrections, Coulomb corrections
- Beyond the Weizsäcker-Williams factorization

Effect of pion polarizabilities: $\alpha_\pi = -\beta_\pi = 3 \times 10^{-4} \text{fm}^3$

$N. Kaiser, J.F.
Pion Compton Scattering

- $s$-dependence: polarisability ↔ ChPT loop effects

Effect of pion polarizabilities: $\alpha_\pi = -\beta_\pi = 3.10^{-4}\text{fm}^3$

Born approx.
Mandelstam \(\{s,t\} \leftrightarrow \) Laboratory \(\{E_\gamma, \theta_\pi\}\)
All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \rightarrow \pi\pi$. Though the low energy $\gamma\gamma \rightarrow \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the extrapolation not very far, the dominance of the pion pole (...) means that the energy scale for this continuation is $m_\pi$. Thus the polarisabilities cannot be determined accurately from $\gamma\gamma$ experiments in a model-independent way and must be measured in the Compton scattering region.
Update on the status - SELEX data
Perspectives for the yield

- **Resolution**
  - mass resolution $\Xi_{cc}$: 13 MeV/c$^2$
  - lifetime $\Leftrightarrow$ few 100 $\mu$m flight path

- **Production**
  - $10^8$ p/spill on 2% i.l. target (segmented diamond foils) – 100 effective days
  - Acceptance $x_F > -0.1$
  - Total acceptance $\times$ efficiency: 0.8%

- from SELEX yield (50% of all $\Lambda_c$ from $\Xi_{cc}$) ($\sigma_{\Xi_{cc}} \sim 2\mu$b)
  - $50 \cdot 10^6$ (ccq) produced
  - Expectation for COMPASS: 10-17k events

- Incoherent production: assuming $\sigma_{\Xi_{cc}} \sim \sigma_{tot} \cdot (10^{-3})^2$
  - $\sim 2$-10 nb