Photoproduction at COMPASS

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on behalf of the COMPASS collaboration

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The COMPASS experiment

**COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy)**

is a fixed target experiment on a secondary beam of **Super Proton Synchrotron** at CERN

13 countries,
24 institutions,
~220 physicists

1996 - Proposal
2002-now - Physical data taking
COMPASS: physics with muon and hadron beam

COMPASS \approx SPIN PHYSICS + SPECTROSCOPY

Study of spin structure of nucleon with muon beam and polarized target:
- (un)polarized and TMD PDFs and FFs
- Generalized PDFs

Study of hadron structure and hadron spectroscopy with hadron beam:
- Primakoff reactions
- diffractive and central production
- $k_T$-dependent PDFs via Drell-Yan process

Spectroscopy with muon beam:
XYZ-states
Outline of this talk

**COMPASS ≈ SPIN PHYSICS + SPECTROSCOPY**

Study of spin structure of nucleon with muon beam and polarized target:
- (un)polarized and TMD PDFs and FFs
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Study of hadron structure and hadron spectroscopy with hadron beam:
- Primakoff reactions
- Diffractive and central production
- 
  $k_T$-dependent PDFs via Drell-Yan process

Study of photon-meson scattering via low-$t$ (Primakoff) reactions

Muoproduction of exotic charmonia

XYZ-states

$q\bar{q}g$

$gg$

$qq\bar{q}$
The COMPASS setup

COMPASS layout for hadron program

- Muon (160-200 GeV/c) and hadron (190 GeV/c) beams
- CEDAR detectors for beam particle identification (for hadron beam)
- Set of nuclear targets (from H to Pb), polarized $^6$LiD and NH$_3$
QCD - true theory of strong interactions, but...

Since the constant of strong interactions $\alpha_s \sim 1$ at small energies, exact QCD formalism cannot make predictions with reasonable accuracy. Effective phenomenological models are needed.

**Chiral Perturbation Theory**

Mass of light quarks ($u,d$) is much smaller than the typical scale $M \approx 1$ GeV.

$$\mathcal{L}_{QCD} = \mathcal{L}^0 + \mathcal{L}_m$$

mass term - a small perturbation

**Chiral symmetric term**

$m_q/M$, $p/M$ - small parameters in expansion

Approximate chiral symmetry is in lagrangian but not in the mass spectrum of hadrons!

Pions are pseudo-Goldstone bosons in chiral theory.
Low-t reactions

Electromagnetic field of fast charged particle is similar to a field of electromagnetic wave

\[ \sigma_{x\gamma}(\omega, Q^2) \rightarrow \sigma_{x\gamma}(\omega, 0) \]

\[ d\sigma_{xA} = \int n_\gamma(\omega) d\sigma_{x\gamma}(\omega) d\omega \]

Density of equivalent photons:

\[ n_\gamma(\omega) \sim \frac{Z^2 \alpha}{\omega} \ln \frac{E}{\omega} \]
Polarizabilities of hadrons

**Compton amplitude:**

\[ A(\gamma X \rightarrow \gamma X) = \]

\[ \left( -\frac{\alpha}{m} \delta_{\omega \omega} + \alpha_X \omega_1 \omega_2 \right) \hat{e}_1 \cdot \hat{e}_2 + \]

\[ + \beta_X \omega_1 \omega_2 (\hat{e}_1 \times \hat{q}_1)(\hat{e}_2 \times \hat{q}_2) + \ldots \]

**The electric and magnetic polarizabilities of a hadron are the quantities characterizing the rigidity of QCD system**

\[ H = \ldots - \left( \alpha_X E^2 + \beta_X H^2 \right)/2 \]

**PDG data:**

<table>
<thead>
<tr>
<th></th>
<th>( \alpha_X, 10^{-4} \text{fm}^3 )</th>
<th>( \beta_X, 10^{-4} \text{fm}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>12.0±0.6</td>
<td>1.9±0.6</td>
</tr>
<tr>
<td>( n )</td>
<td>12.5±1.7</td>
<td>2.7±1.8</td>
</tr>
</tbody>
</table>

**Chiral theory 2-loop approximation \( (O(p^6)) \) for \( \pi \):**

\[ \alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4} \text{fm}^3 \]

\[ \alpha_\pi + \beta_\pi = (0.16 \pm 0.1) \times 10^{-4} \text{fm}^3 \]

**The most of other models:**

\[ 8 \times 10^{-4} \text{fm}^3 \leq \alpha_\pi - \beta_\pi \leq 14 \times 10^{-4} \text{fm}^3 \]
Polarizabilities and cross section

\[ \frac{d\sigma}{ds\,dt\,dQ^2} = \frac{Z^2\alpha}{\pi(s - m^2_\pi)} \cdot F^2_{\text{eff}}(Q^2) \cdot \frac{Q^2 - Q^2_{\text{min}}}{Q^4} \cdot \frac{d\sigma_{\pi\gamma}}{dt} \]

\[ Q_{\text{min}} = (s - m^2_\pi)/2E_{\text{beam}} \]

**Compton cross section:**

\[ \frac{d\sigma_{\pi\gamma}}{d\Omega_{\text{cm}}} = \alpha^2(s^2z^2_+ + m^4_\pi z^-_+) \cdot \frac{\alpha m^3_\pi (s - m^2_\pi)^2}{s(sz_+ + m^2_\pi z^-_2) - 4s^2(sz_+ + m^2_\pi z^-_2)} \cdot \mathcal{P} \]

\[ z_\pm = 1 \pm \cos \theta_{\text{cm}} \]

\[ \mathcal{P} = z^-_2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m^4_\pi} z^2_+(\alpha_\pi + \beta_\pi) \]

**For the case** \( \alpha_\pi + \beta_\pi = 0 \):

\[ R = \frac{\sigma}{\sigma_{\text{p.l.}}} \approx 1 - \frac{3}{2} \cdot \frac{x^2_\gamma}{1 - x_\gamma} \cdot \frac{m^3_\pi}{\alpha} \cdot \alpha_\pi \]
The measured kinematic distributions

Background from the reaction $\pi^-\text{Ni} \rightarrow \pi^-\text{Ni} \pi^0$ is subtracted
The COMPASS result

Protvino: $\alpha_\pi = -\beta_\pi = (6.8 \pm 1.4_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-4} \text{ fm}^3$, $\chiPT$: $\alpha_\pi \approx 2.8 \times 10^{-4} \text{ fm}^3$

Under assumption $\alpha_\pi = -\beta_\pi$:
$\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3$


Larger statistics is under analysis. Separate precision extraction of $\alpha_\pi$ and $\beta_\pi$ is expected

Alexey Guskov, Joint Institute for Nuclear Research
QCD chiral anomaly

Chiral anomaly: chiral symmetry on the level of the lagrangian but non conservation of chiral current

\[ \pi^0 \rightarrow \gamma \gamma \quad \gamma \rightarrow 3 \pi \]

For \( \pi^- \gamma \rightarrow \pi^- \pi^0 \):

\[ F_{3\pi}(0,0,0) = \frac{F_{\pi}(0,0,0)}{e f^2} \]

Low-energy theorem:

\[ F_{3\pi} = \frac{e N_c}{12\pi^2 F_{\pi}^3} = (9.78 \pm 0.05) \text{ GeV}^{-3} \]

SIGMA (Protvino, 1987): 10.7±1.2 GeV⁻³
\( \pi^- \)–e scattering (2005): 9.6±1.1 GeV⁻³

For \( \pi^- \gamma \rightarrow \pi^- \eta \):

\[ F_{\eta\pi\pi\gamma}(0,0,0) = \frac{e}{4\pi^2} \left( \frac{f_{\pi} \cos \theta_p}{f_8} - \frac{f_{\pi}}{f_0} \sqrt{\frac{2}{3}} \sin \theta_p \right) \]

\[ F_{\eta\pi\pi\gamma}(0,0,0) = 6.5 \pm 0.3 \text{ GeV}^{-3} \]

VES (Protvino, 1998): 6.9±0.7 GeV⁻³
$\chi$PT prediction for $\gamma\pi \rightarrow 3\pi$ cross sections

Radiative widths of mesons

\[ \sigma_{\text{Primakoff}, X} = \int_{m_1}^{m_2} \int_0^{t_{\text{max}}} \frac{d\sigma}{dm \, dt'} \, dt' \, dm = \Gamma_0(X \rightarrow \pi\gamma) C_X. \]

Intensity \( \cdot 10^{-3} / (40 \text{ MeV/c}^2) \)

<table>
<thead>
<tr>
<th>( 2^{++} \rho[D]\pi )</th>
<th>( \sigma_{\text{prim}} / \sigma_{\text{all}} = 0.97 )</th>
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</thead>
<tbody>
<tr>
<td>( \pi \text{ Pb} \rightarrow \pi \pi \pi' \text{ Pb} )</td>
<td>( t' &lt; 0.001 (\text{GeV/c})^2 )</td>
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<tr>
<td>( \Gamma_0(a_2 \rightarrow \pi\gamma) = 358 \text{ keV} )</td>
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<thead>
<tr>
<th>( 2^{-+} f_2[S]\pi )</th>
<th>( \sigma_{\text{prim}} / \sigma_{\text{all}} = 0.86 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \text{ Pb} \rightarrow \pi \pi \pi' \text{ Pb} )</td>
<td>( t' &lt; 0.001 (\text{GeV/c})^2 )</td>
</tr>
<tr>
<td>( \Gamma_0(\pi_2 \rightarrow \pi\gamma) = 181 \text{ keV} )</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th><strong>This measurement</strong></th>
<th><strong>( a_2(1320) )</strong></th>
<th><strong>( \pi_2(1670) )</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>SELEX [21]</td>
<td>( 358 \pm 6 \pm 42 ) keV</td>
<td>( 181 \pm 11 \pm 27 ) keV ( \cdot (0.56/\text{BR}_{f_2\pi}) )</td>
</tr>
<tr>
<td>S. Cihangir et al. [24]</td>
<td>( 284 \pm 25 \pm 25 ) keV</td>
<td></td>
</tr>
<tr>
<td>E.N. May et al. [25]</td>
<td>( 295 \pm 60 ) keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( 0.46 \pm 0.11 ) MeV</td>
<td></td>
</tr>
<tr>
<td>VMD model [1]</td>
<td>( 375 \pm 50 ) keV</td>
<td></td>
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</tbody>
</table>

2 values: 335 keV and 521 keV

*EPJA 50 (2014) 79*
Kaon polarizabilities

**Theoretical predictions:**

χPT prediction $O(p^4)$:

\[ \alpha_K + \beta_K = 0 \]
\[ \alpha_K = \alpha_\pi \times \frac{m_\pi F_\pi^2}{m_K F_K^2} \approx \frac{\alpha_\pi}{5} \approx 0.6 \times 10^{-4} \text{fm}^3 \]

**Quark confinement model:**

\[ \alpha_K + \beta_K = 1.0 \times 10^{-4} \text{fm}^3 \]
\[ \alpha_K = 2.3 \times 10^{-4} \text{fm}^3 \]

**Exp. result:** $\alpha_K < 200 \times 10^{-4} \text{fm}^3$ (1973)

- from kaonic atoms spectra

Presently COMPASS has ~2.4% of kaons in hadron beam...

RF-separated hadron beam enriched by kaons is under discussion
Exotic charmonia

tetraquark

hybrid meson

hadro-quarkonium

 glueball

molecule

...
XYZ production mechanisms

direct production in $e^+e^-$ collisions;

COMPASS: photo-(muo-)-production off nucleon

We cover range of $\sqrt{s_{YN}}$ from 6 to 19 GeV
Muophoto)production of exotic charmonia: **X(3872)**

**First observation of exotic charmonia in photoproduction!**

\[ iG(J^{PC}) = 0^+(1++) \]

- Mass \( m = 3871.69 \pm 0.17 \text{ MeV} \)
- \( m_{X(3872)} - m_{J/\psi} = 775 \pm 4 \text{ MeV} \)
- \( m_{X(3872)} - m_{\psi(2S)} \)
- Full width \( \Gamma < 1.2 \text{ MeV}, \text{ CL} = 90\% \)

**COMPASS result for dipion mass spectrum is in tension with previous observations:**

\[ 13.2 \pm 5.2 \text{ X}(3872) \text{ events} \]

\[ \sigma_{\gamma N \rightarrow X(3872) \pi N'} \times B_{X(3872) \rightarrow J/\psi \pi \pi} = 71 \pm 28 \text{ (stat)} \pm 39 \text{ (syst)} \text{ pb} \]

**ATLAS:** \( \psi(2S) \) and \( X(3872) \)
Muo(photoproduction of exotic charmonia: $Z_c(3900)$

$X(3900)$

$I^G(J^{PC}) = 1^+(1^+-)$

Mass $m = 3886.6 \pm 2.4$ MeV  ($S = 1.6$)

Full width $\Gamma = 28.1 \pm 2.6$ MeV

7 years (2002-2011) of data taking with muon beam and nuclear target ($^6$LiD and NH$_3$)

$BR(Z_c^{\pm}(3900) \rightarrow J/\psi \pi^{\pm}) \times \sigma_{\gamma \rightarrow Z_c^{\pm}(3900)} < 52$ pb

$\sqrt{s_{\gamma N}} = 13.8$ GeV

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Low-t reactions provide unique possibility to study processes induced by photons. Study of such reactions is one of the main goals of the COMPASS experiment. Main directions of low-t studies at COMPASS are:

- pion and kaon polarizabilities;
- chiral anomaly study;
- meson radiative width;
- $\sigma_{\pi\gamma}$ dynamics for ChPT tests.

Exclusive photoproduction of exotic charmonia off a nuclear target is a new opportunity to clarify nature of the XYZ states. COMPASS performed:

- first search for exclusive photoproduction of the $Z_c(3900)$;
- first observation of photoproduction of the $X(3872)$;
- more results are expected.