Production of pentaquarks in $pA$-collisions

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Pentaquark fact sheet

LHCb discovery, > 9σ significance
- PRL 115 (2015), 072001

Possibility of pentaquarks
- M. Gell-Mann, Phys. Lett. 8 (1964) 214

Possibility of \( \bar{c}c \) pentaquarks

Indirect evidence from \( \Lambda^0_b \rightarrow J/\psi \pi^- p \) (\( \sim 3\sigma \))
[arXiv:1606.06999]

Possibility of \( \bar{c}c \) pentaquarks
- Intrinsic charm of proton
- Attractive force between \( \bar{c}c \) and light baryons
- More exotic exotics: \( \bar{c}c - He^3 \) bound states
- Many new exotic states in \( \bar{c}c \) sector

\( P^+_c(4380), \Gamma = 205 \text{ MeV} \)
\( P^+_c(4450), \Gamma = 39 \text{ MeV} \)

\( \bar{c}c \) in other exotics: tetraquarks
- \( Z_c(3900) \)
- \( Z_c(3900)^+ ? \)
- \( X(3872) \)
- \( X(4140)? \)
- \( X(4274)? \)
- \( Z(4430) \)
- \( Z_c(4025)^+ ? \)
What is a pentaquark?

Molecule \((D_c, \bar{D}_c, \ldots) + \Sigma_c, \bar{\Sigma}_c\)

- M. Karliner et. al., PRL 115 (2015), 122001
- H. X. Chen et. al., PRL 115 (2015), 172001
- G. J. Wang et. al., PRD 93, 034031.
- [many developments in this direction ...]

Non-molecular structure

- A. Mironov et. al, JETP Lett. 102 (2015), 271
- S. Takeuchi et. al, arXiv:1608.05475

Common points of all models

- Should have other decay channels
- Should have siblings from multiplets

Threshold singularity

- F. K. Guo et. al, PRD 92 (2015), 071502
- Anisovich et. al, MPL. A 30, 1550212
Can we rule out a triangle singularity?

Cusp vs LHCb peak

- \( M_{Pc} - M_{\chi c_1} - M_P = 0.9 \pm 3.1 \text{ MeV} \)

\[
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\]

Argand plots \([\chi c_P \text{ vs. LHCb}]\)

- Argand plots [\(\chi c_P \text{ vs. LHCb}]\)
How can we rule out a threshold cusp?

Check for existence of a peak in other decay channels

- Observation in $\Lambda_b^0 \rightarrow J/\psi \pi^- p$: $\sim 3\sigma$
  
  [arXiv:1606.06999]

- Study other production mechanisms
What are the production mechanisms of $P_c^+$?

**$\Lambda_b$ decays [LHCb]**

- $\Lambda_b^0 \to b u c c d \to P_c^+ \to J/\psi p$
- $\Lambda_b \to W^+ s u c u c \to \Lambda_b^0 \to b u c c d \to P_c^+$

**$\gamma p \to P_c^+ \to J/\psi p$ [proposed]**

- V. Kubarovsky et al, PRD 92 (2015), 031502
- M. Karliner et. al, PLB 752 (2016), 329.

**$\pi N \to P_c \to J/\psi N$ [proposed]**

- J-PARC: $\pi$-beams up to 20 GeV.
- Can check existence of $P_c^0$.

**Cross-section sizeable for JLAB 12 GeV.**
Our suggestion: pentaquark production in $pA$

Two-stage process
- Production of $\bar{c}c$ pair
- Fusion $\bar{c}c + p \rightarrow P_c^+ + X$.

Coherence and formation time
$E_g \sim 10\text{GeV}$: [PLB206 (1988) 685-690]

$t_{\text{form}} \sim 0.2\text{fm}, \quad t_{\text{coh}} \sim 10\text{fm}$

$\Rightarrow$ Bare $\bar{c}c$ pair passes through the nucleus

Kinematic constraint
- $\bar{c}c$ should be slow in nucleus rest frame

Main advantage
- No electroweak intermediaries, expect higher cross-sections
Distributions of $\bar{c}c$ dipoles

Dipole size distribution

- Mild dependence on $\sqrt{s}$, $(\bar{c}c)$
- Exponential decrease with size
  - For reference: $\sigma_{tot}(J/\psi) \gtrsim 10^4$ nb

⇒ Expect significantly smaller cross-sections than for charmonium.

Flux energy dependence (nucleus rest frame)

- Suppression for onshell $\bar{c}c$ near endpoint
- Extra interactions/emissions of $\bar{c}c$

Higher $E_{\bar{c}c}$ permitted (smaller cross-section).
$P_c^+$ production mechanisms in LO pQCD

$\bar{c}c = 1_c, P$-wave $[P_c^+ = \chi_c p]$ $\bar{c}c = 1_c, S$-wave $[\psi(2S)p]$

$\bar{c}c = 8_c$ $[P_c^+ = \bar{D}^{(*)} + \Sigma_c]$ 

= sum over all diagrams with different gluon connections

Dipole model: gluons $\Rightarrow$ dipole cross-sections
Kinematics and choice of framework

\[ \bar{c}c = 1_c, P\text{-wave} \]

**Kinematic window**
- \( g(x_1) \) suppressed at \( x_1 \sim 1 \)
- WF \( \Psi_{P_c^+}(x_1, \ldots) \) suppressed at \( x_1 \sim 0 \)
- [\( \bar{c}c \) “slow” in the nucleus rest frame]
- \( \langle x_1 \rangle \sim 0.2 - 0.3 \) \( \langle x_2 \rangle \sim m_c^2/s \ll 1 \)

**Relation of \( x_1 \) to a rapidity of \( P_c^+ \)**

\[
y_{P_c} = \frac{1}{2} \ln \left( \frac{P_{c+}}{P_{c-}} \right) = \ln \left( \frac{(1 + x_1) \sqrt{s}}{\sqrt{M_{P_c}^2 + P_{\perp}^2}} \right),
\]

\( \Rightarrow \) Rapidity distribution of \( P_c^+ \) \( \Leftrightarrow \) access to l.c. fraction of \( \bar{c}c \) in \( P_c^+ \)
What should we take into account in evaluations?

\[ \bar{c}c = 1_c, P\text{-wave} \]

**2N correlator**
- Studied at SRC at SLAC, JLAB, ...
- Shape is similar to deuteron WF
- Normalization \( \sim AZ; \Phi_{2N} \equiv \rho_{2N}^{1/2} \)

**Gaussian param. for nucleon WF**
- \[ |\psi_p(\{\alpha_i, \vec{r}_i\})|^2 = |f_3(\alpha_1, \alpha_2, \alpha_3)|^2 \frac{1}{\pi^2 R_p^4} \exp \left(-\frac{1}{4 R_p^2} (r_1^2 + r_2^2 + r_3^2)\right) \bigg|_{\sum_i \vec{r}_i = 0} \]
- \[ f_n(\alpha_1, ..., \alpha_n) = \frac{N_n}{\left( M_B^2 - \sum_{i=1}^n m_i^2 \right) \prod_{i=1}^n \alpha_i} \bigg|_{\sum_i \alpha_i = 1} \]

From S. J. Brodsky et al. PLB 93 (1980), 451
What do we know about pentaquark WF?

Tightly bound state

- Superposition: \( |P^+_c\rangle = [\bar{c}c][uud] + [\bar{c}u][udc] + [\bar{c}d][uuc] + ... \)
- \( \langle r_{cc}\rangle \approx 1 - 2 \text{ fm} \)
- Should evaluate a wave function in some model

Charmonium molecule

- \( \bar{c}c \) in color singlet
- Small size, \( \langle r_{cc}\rangle \approx 0.4 - 0.7 \text{ fm} \)
- Far from center, \( \langle R_{cc}\rangle \gtrsim 1 \text{ fm} \)

\( \bar{D}(*)\Sigma_c \) molecule

- Colors of \( \bar{c}c \) uncorrelated
- \( \langle r_{cc}\rangle \approx 2 - 3 \text{ fm} \) (far)
- \( \langle R_{cc}\rangle \lesssim 0.5 \text{ fm} \)
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\[ \psi \left( \vec{r}_i, \vec{R}_{cc}, \vec{r}_{cc} \right) = \psi_{\text{baryon}}(\vec{r}_i) \times \psi_{\text{relative}}(\vec{R}_{cc}) \times \psi_{\text{meson}}(\vec{r}_{cc}) \]

\( \bar{D}^*(\Sigma_c) \) molecule

- Colors of \( \bar{c}c \) uncorrelated
- \( \langle r_{cc} \rangle \approx 2 - 3 \text{ fm (far)} \)
- Far from center, \( \langle R_{cc} \rangle \lesssim 0.5 \text{ fm} \)
How much are results sensitive to $\langle R_{cc}\rangle, \langle r_{cc}\rangle$?

Sensitivity of $\sigma_{P_c}$ [mb] on $\langle R_{cc}\rangle, \langle r_{cc}\rangle$

- Sensitivity is sizeable
- $\sigma_{P_c}$ peaks at $\langle R_{cc}\rangle \sim 3\,\text{fm}$
- $\Rightarrow$ Please consider all the following results as a factor-of-two estimates

Fix $\langle R_{cc}\rangle$ from experiment?

- Mild sensitivity of $p_T$-slope (interplay with $k_F$, $B_{\text{prot}}$).

Rapidity distribution

- $y \rightarrow y_{\text{min}}$: suppression from $\Psi_{P_c}$
- $y \gg y_{\text{min}}$: suppression from $g(x_1)$
How large are the cross-sections?

Cross-sections for $pPb \rightarrow P_c^+$ [nb]

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$</th>
<th>$(a)$</th>
<th>$(b)$</th>
<th>$(c)$</th>
<th>$(d)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV</td>
<td>0.6 $\mu$b</td>
<td>16</td>
<td>6.5</td>
<td>2.9</td>
</tr>
<tr>
<td>7 TeV</td>
<td>1.9 $\mu$b</td>
<td>120</td>
<td>137</td>
<td>19</td>
</tr>
<tr>
<td>13 TeV</td>
<td>2 $\mu$b</td>
<td>163</td>
<td>208</td>
<td>21</td>
</tr>
</tbody>
</table>

- $(a) = 1_c, 1P$
- $(b) = 1_c, 2S$
- $(c) = 8_c$, with $g$ emission
- $(d) = 8_c$, with multiple interaction

Rough estimate of cross-sections

- $\frac{d\sigma_{pA\rightarrow P_c^+}}{dy_{Pc}} \sim |M_{fi}|^2 \frac{d\sigma_{pp\rightarrow M_{cc}}}{dy_{Pc}}$
- Charmonium cross-section $d\sigma_{pp\rightarrow M_{cc}}$ from experiment, $M_{fi}$-overlap integral
- Reasonable agreement if experimental cross-sections are used

ALICE @forward rapidities [PLB 704 (2011), 442]:

$$\left| \frac{d\sigma}{dy}_{pp\rightarrow J/\psi} \right| \approx 3 \mu b \Rightarrow \left| \frac{d\sigma}{dy}_{pA\rightarrow J/\psi} \right| \approx 600 \mu b$$
How do we compare with other mechanisms?

**Cross-section “per nucleon” [nb]**

<table>
<thead>
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<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV</td>
<td>2.9</td>
<td>0.08</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>7 TeV</td>
<td>9</td>
<td>0.58</td>
<td>0.66</td>
<td>0.09</td>
</tr>
<tr>
<td>13 TeV</td>
<td>9.6</td>
<td>0.78</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- (a) = 1<sub>c</sub>, 1P
- (b) = 1<sub>c</sub>, 2S
- (c) = 8<sub>c</sub>, with $g$ emission
- (d) = 8<sub>c</sub>, with multiple interaction

**LHCb mechanism**

Suppression $\sim m_b^2 m_s^2 G_F^2$

Full production rate very small:

$$\sigma_{\text{tot}} \sim \frac{10^3 \text{events}}{3 \text{fb}^{-1}} \sim 300 \text{fb} \sim 3 \times 10^{-4} \text{nb}$$

**Cross-sections at least not smaller!**

**Electroproduction cross-sections**

- V. Kubarovsky et al, PRD 92 (2015), 031502
- M. Karliner et. al, PLB 752 (2016), 329.

$$\sigma_{ep \rightarrow e P_c^+ X} \sim \frac{d^2 n}{dE_\gamma dQ^2} \otimes \sigma_{\gamma p \rightarrow P_c^+ X}, \quad \frac{d^2 n}{dE_\gamma dQ^2} \sim \frac{\alpha_{em}}{\pi}$$
Summary

$P_c^+$ can be produced in $pA$ collisions

- The cross-sections are sizeable, contain important information about $P_c^+$ internal structure
  - Rapidity distribution $\Leftrightarrow$ access to light-cone fraction of $\bar{c}c$ in $P_c^+$
  - Slope of $p_T$ distribution $\Rightarrow$ mild sensitivity to average distance between $\bar{c}c$ and center of mass

- Suggested $P_c^+$ production occurs in the following kinematics:
  - Collider kinematics (RHIC, LHC, ...): very forward rapidities
  - Fixed-target experiments (AFTER@LHC, PANDA, ...): central rapidities

Outlook

- If $\exists P_c^0 = udd\bar{c}c$ (neutral “sibling” of $P_c^0$), this should be also produced via $\bar{c}c + n \rightarrow P_c^0$ subprocess in $pA$ collisions.
- If there are heavier pentaquark states, can also see them!
Thank You for your attention!