# Production of pentaquarks in *pA*-collisions

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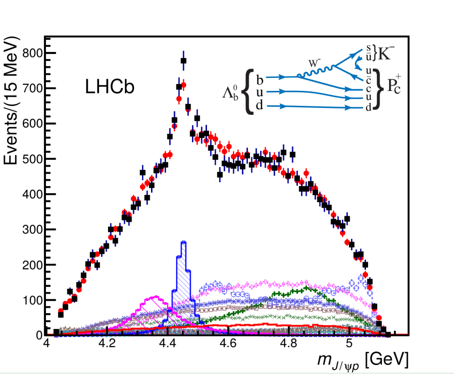
6th International Workshop on High Energy Physics in LHC era

# Pentaquark fact sheet

## LHCb discovery, $> 9\sigma$ significance

- PRL 115 (2015), 072001




- $P_c^+(4380), \Gamma = 205\,\mathrm{MeV}$
- $P_c^+(4450), \Gamma = 39\,\mathrm{MeV}$

## Possibility of pentaquarks

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

## Possibility of $\bar{c}c$ pentaquarks

S. J. Brodsky *et al*, PLB 93 (1980),451, PRL 64 (1990) 1011, PLB 411, 152 (1997)

- 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 M. Karliner

et. al, PRD 92 (2015), 074026

## $\bar{c}c$ in other exotics: tetraquarks

- $Z_c(3900)$
- X(3872)
- Z(4430)

# What is a pentaquark ?

## Molecule of $\bar{D}^{(*)}$ and $\Sigma_c$

- M. Karliner *et. al*, PRL 115 (2015), 122001
- H. X. Chen *et. al.*, PRL 115 (2015), 172001
- G. J. Wang *et. al.*, arXiv:1511.04845 [hep-ph].
- J. He, arXiv:1507.05200 [hep-ph].
- R. Chen *et. al.*, PRL 115 (2015), 132002
- N. N. Scoccola *et. al.*, PRD 92 (2015), 051501
- G. Yang *et. al.*, arXiv:1511.09053 [hep-ph].

## Not a hadronic molecule

- A. Mironov *et. al*, JETP Lett. 102 (2015), 271

## Common points of all models

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

(>100 papers since July'15)

## Molecule of $J/\psi p$ or $\psi(2S)p$

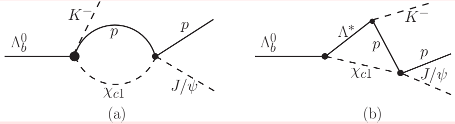
- D. E. Kahana *et. al*, arXiv:1512.01902
- M. I. Eides, *et. al*, arXiv:1512.00426

## Molecule of $\chi_c p$

- U. G. Meißner *et. al*, Phys. Lett. B 751, 59 (2015)

## Threshold singularity

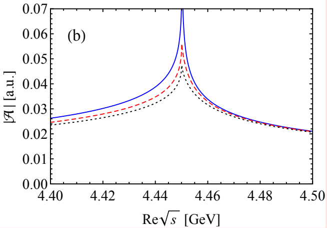
- F. K. Guo *et. al*, PRD 92 (2015), 071502
- Anisovich *et. al*, Mod. Phys. Lett. A 30, 1550212
- X-H. Liu *et al*, arXiv:1507.05359

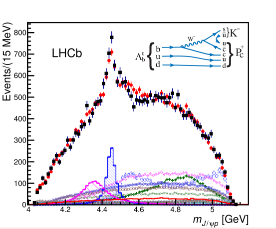


# Can we rule out a triangle singularity?

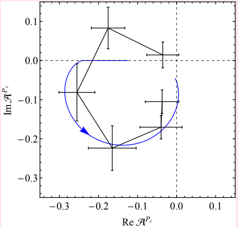
## Cusp vs LHCb peak

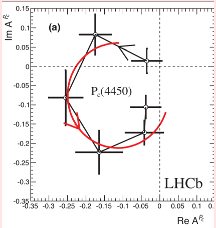
- F. K. Guo, U.-G. Meißner, W.Wang and Z. Yang, PRD 92 (2015), 071502
- $M_{P_c} - M_{\chi_{c1}} - M_p = 0.9 \pm 3.1\,\mathrm{MeV}$




## Argand plots [$\chi_c p$ vs. LHCb]



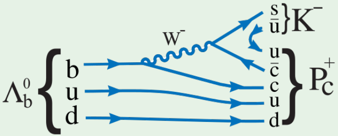



### How can we rule out a threshold cusp ?

- Confirm existence of a peak in other decay channels, like $\chi_c p$
- Study other production mechanisms

# What are the production mechanisms of $P_c^+$?

## $\Lambda_b$ decays [LHCb]

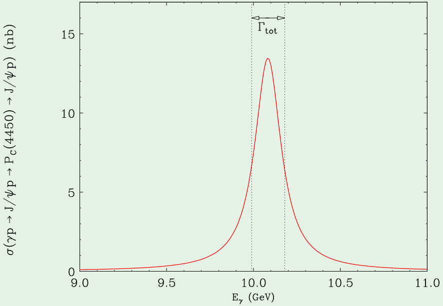



## $\pi N \to P_c \to J/\psi\, N$ [proposed]

- Q. F. Lu *et. al*, arXiv:1510.06271.
- J-PARC: $\pi$-beams up to 20 GeV.
- Can check existence of $P_c^0$.

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

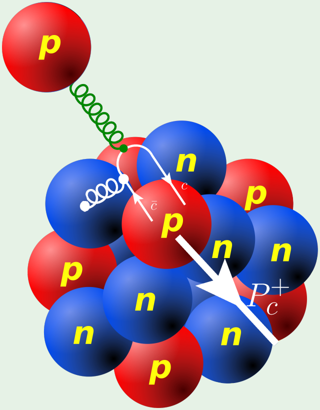
- Q. Wang *et al*, PRD 92 (2015) 034022
- V. Kubarovsky *et al*, PRD 92 (2015), 031502
- M. Karliner *et. al*, PLB 752 (2016), 329.




- Cross-section sizeable for JLAB 12 GeV.

# Our suggestion: pentaquark production in $pA$

## Nucleus rest frame




## Two-stage process

- Diffractive production of $\bar{c}c$ pair
- Formation of $P_c^+$ from $\bar{c}c$ and $p$

## $\bar{c}c$ properties

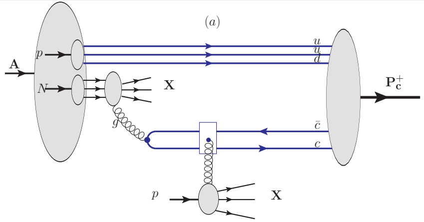
- Has small size $\sim m_c^{-1}$, $\alpha_s(m_c) \ll 1$
- $\bar{c}c$ production could be accompanied by extra gluon emissions to form correct state

## Kinematic constraint:

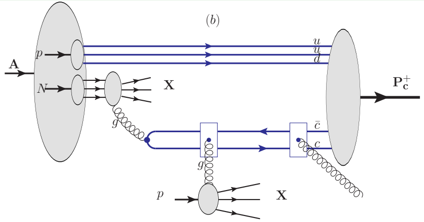
- $\bar{c}c$ should be slow in nucleus rest frame
- $\Rightarrow P_c^+$ in lab frame has forward rapidity

# $P_c^+$ production mechanisms in LO pQCD

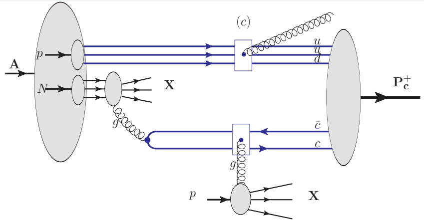
## $\bar{c}c = \mathbf{1}_c$, *P-wave* $[P_c^+ = \chi_c\, p\,]$

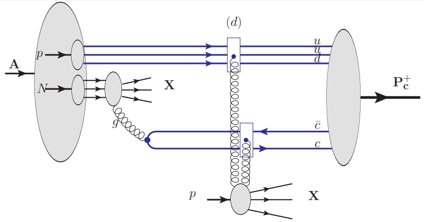



## $\bar{c}c = \mathbf{1}_c$, *S-wave* $[J/\psi\, p$ or $\psi(2S)p]$




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

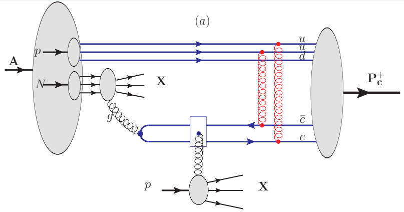



 = sum over all diagrams with different gluon connections

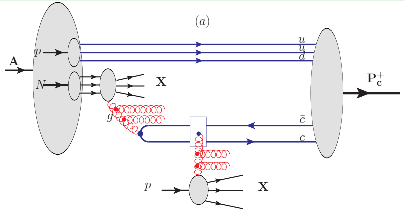
# $P_c^+$ production beyond LO pQCD

## WF corrections




- Gluons in red are part of the WF
- Suppressed by $\alpha_s(m_c)$
- Suppressed as $\langle r_{cc}\rangle \sim m_c^{-1}$ due to interference $c+\bar{c}$.
- Any other gluon connection to $\bar{c}c$ is also suppressed

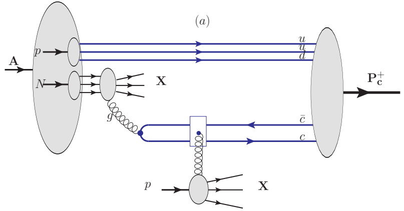
## Reggeization




- At high energies gluon reggeize
- Saturation at very small $x$
- $\Rightarrow$pQCD cannot be used for estimates

# Kinematics and choice of framework

## $\bar{c}c = \mathbf{1}_c, P$-wave




## Kinematics analysis [CM($NN$)]

- Suppression at $x_1 \sim 0$ from WF of $P_c^+$
- Suppression at $x_1 \sim 1$ due to $g(x_1)$
- $\langle x_1 \rangle \sim 0.2 - 0.3$ $\langle x_2 \rangle \sim m_c^2/s \ll 1$
- Gluon PDF $g(x_1)$ for projectile+color dipole model for $\bar{c}c$
- Kopeliovich et al. NPA 710 (2002), 180

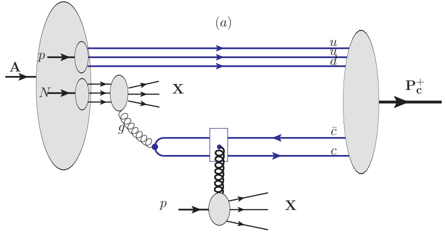
## Relation of $x_1$ to a rapidity of $P_c^+$

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

- There is a minimal value of rapidity $(y_{P_c})_{min}$
- Rapidity distribution of $P_c^+ \Leftrightarrow$access to l.c. fraction of $\bar{c}c$ in $P_c^+$

# What do we need for evaluations ?

## $\bar{c}c = \mathbf{1}_c, P$-wave




## Gaussian param. for nucleon WF

- $\left|\Psi_p\left(\{\alpha_i, \vec{r}_i\}\right)\right|^2 =$

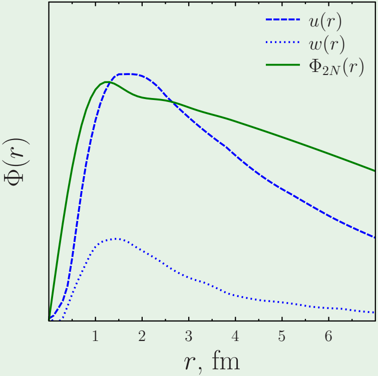
$$\left|f_3\left(\alpha_1, \alpha_2, \alpha_3\right)\right|^2 \frac{1}{\pi^2 R_p^4} \exp\left(-\frac{1}{4 R_p^2}\left(r_1^2 + r_2^2 + r_3^2\right)\right)\Big|_{\sum_i \vec{r}_i = 0},$$

$$f_n\left(\alpha_1, \ldots, \alpha_n\right) = \frac{N_n}{\left(M_B^2 - \sum_{i=1}^{n} \frac{m_i^2}{\alpha_i}\right)}\Bigg|_{\sum \alpha_i = 1}$$

from S. J. Brodsky *et.al.* PLB 93 (1980), 451

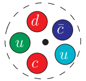
## $2N$ correlator

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



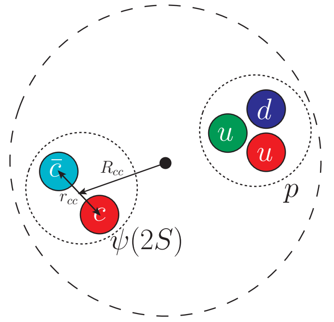
# What do we know about pentaquark WF?

## Tightly bound state



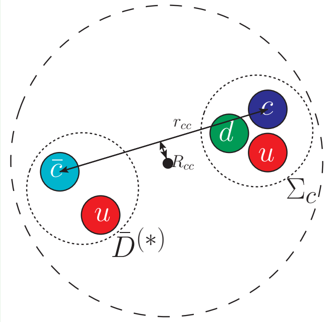

- Superposition: $|P_c^+\rangle = [\bar{c}c][uud] + [\bar{c}u][udc] + [\bar{c}d][uuc]$
- $\langle r_{cc}\rangle \approx 1 - 2\,\mathrm{fm}.$
- Should evaluate a wave function in some model

## Charmonium molecule



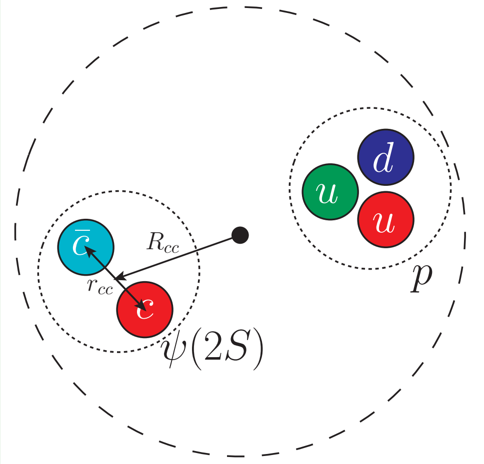

- $\bar{c}c$ in color singlet
- Small size, $\langle r_{cc}\rangle \approx 0.4 - 0.7$ fm
- Far from center, $\langle R_{cc}\rangle \gtrsim 1$ fm

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




- Colors of $\bar{c}c$ uncorrelated
- $\langle r_{cc}\rangle \approx 2 - 3$ fm (far)
- $\langle R_{cc}\rangle \lesssim 0.5$ fm

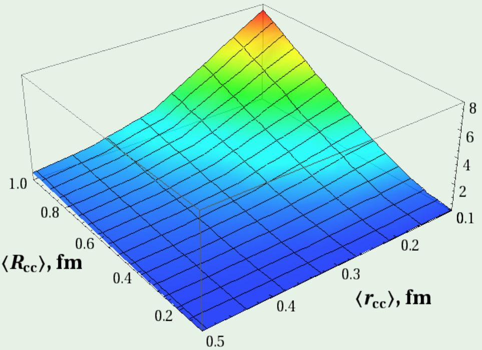
## For molecule can separate motion




- $\Psi\left(\vec{r}_i, \vec{R}_{cc}, \vec{r}_{cc}\right) = \psi_{baryon}\left(\vec{r}_i\right) \times \psi_{relative}\left(\vec{R}_{cc}\right) \times \psi_{meson}\left(\vec{r}_{cc}\right)$

# 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 $\langle R_{cc}\rangle \sim 3\,\mathrm{fm}$
- $\Rightarrow$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 $k_F$, $B_{\rm prot}$).

## Hints from models

- Size of molecule $R \sim 3\,\mathrm{fm}$
- Size of $\bar{c}c$ meson [Cornell]:

| State | 1S | 1P | 2S |
|---|---|---|---|
| $\langle r\rangle$, fm | 0.47 | 0.74 | 0.96 |

## Choice of $\langle R_{cc}\rangle$, $\langle r_{cc}\rangle$

- $\langle R_{cc}\rangle \approx \frac{M_{P_c - 2m_c}}{M_{P_c}} R$
- $\langle r_{cc}\rangle$ same as for $\bar{c}c$ meson

# How large are the cross-sections ?

## Cross-sections for $p\,Pb \to P_c^+$ [nb]

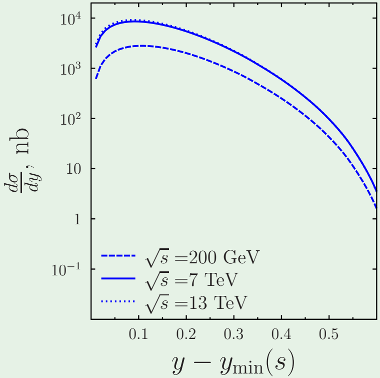
| $\sqrt{s_{NN}}$ | $(a)$ | $(b)$ | $(c)$ | $(d)$ |
|---|---|---|---|---|
| 200 GeV | $0.6\,\mu$b | 4.8 | 6.5 | 2.9 |
| 7 TeV | $1.9\,\mu$b | 34 | 137 | 19 |
| 13 TeV | $2\,\mu$b | 44 | 208 | 21 |

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

## Rough estimate of cross-sections

- $\frac{d\sigma_{pA\to P_c^+}}{dy_{P_c}} \sim |\mathscr{M}_{fi}|^2 \frac{d\sigma_{pp\to M_{\bar{c}c}}}{dy_{P_c}}$
- $M_{\bar{c}c}$-charmonium [$\chi_c$ for (a), $\psi(2S)$ for (b)], $\mathscr{M}_{fi}$-overlap integral
- Reasonable agreement if experimental cross-sections are used

## Rapidity distribution[$\bar{c}c = \mathbf{1}_c, 1P$]




- Suppression at $y \to y_{min}$ due to $\Psi_{P_c}$
- Suppression at $y \gg y_{min}$ due to $g(x_1)$

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

$$\left.\frac{d\sigma}{dy}\right|_{pp\to J/\psi} \approx 3\,\mu\text{b}$$

# Summary

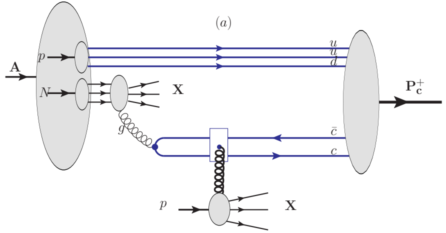
### $P_c^+$ can be produced in $pA$ collisions at forward rapidities

- The cross-sections are sizeable
  - 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
- We call experimentalists to analyse mass distributions of possible decay products of $P_c^+$($\underline{J/\psi + p}$, $\chi_c p$, $\bar{D}$ and charmed baryon) in order to study $P_c^+$ properties
- If $P_c^+$ has neutral "siblings" with structure $udd\bar{c}c$, these should be also produced via $\bar{c}c + n \to P_c^0$ subprocess in $pA$ collisions

*Thank You for your attention!*

# Appendix

## $\bar{c}c = \mathbf{1}_c, P$-wave




- [NPA 710 (2002), 180]

$$\frac{d\sigma^{(a)}}{dy} = \frac{1+x_1}{x_1} x_1 g(x_1) \int d^2R^{(1)}_{cc} d^2R^{(2)}_{cc} d\alpha^{(1)}_c d^2r^{(1)}_{cc} d\alpha^{(2)}_c d^2r^{(2)}_{cc} \Phi^{\bar{\mu}\mu}_{\bar{c}c}\left(\alpha^{(1)}_c, \vec{r}^{(1)}_{cc}\right) \Phi^{\bar{\nu}\nu*}_{\bar{c}c}\left(\alpha^{(2)}_c, \vec{r}^{(2)}_{cc}\right)$$

$$\times \Phi_D\left(-\frac{M_{P_c}}{M_{P_c}-2m_c}\vec{R}^{(1)}_{cc}\right)\Phi^*_D\left(-\frac{M_{P_c}}{M_{P_c}-2m_c}\vec{R}^{(2)}_{cc}\right)\mathscr{H}^{\bar{\mu}\mu}\left(\alpha^{(1)}_c, x_1, \vec{r}^{(1)}_{cc}, \vec{R}^{(1)}_{cc}\right)\mathscr{H}^{\bar{\nu}\nu}\left(\alpha^{(2)}_c, x_1, \vec{r}^{(2)}_{cc}, \vec{R}^{(2)}_{cc}\right)^*$$

$$\times \frac{1}{16}\left[\sigma\left(\alpha^{(1)}_c\vec{r}^{(1)}_{cc} + \bar{\alpha}^{(2)}_c\vec{r}^{(2)}_{cc}\right) + \sigma\left(\bar{\alpha}^{(1)}_c\vec{r}^{(1)}_{cc} + \alpha^{(2)}_c\vec{r}^{(2)}_{cc}\right) - \sigma\left(\alpha^{(1)}_c\vec{r}^{(1)}_{cc} - \alpha^{(2)}_c\vec{r}^{(2)}_{cc}\right) - \sigma\left(\bar{\alpha}^{(1)}_c\vec{r}^{(1)}_{cc} - \bar{\alpha}^{(2)}_c\vec{r}^{(2)}_{cc}\right)\right]$$

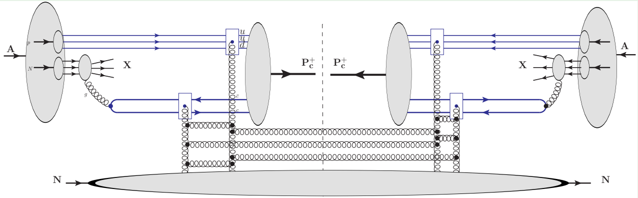
$$\mathscr{H}^{\bar{\mu}\mu}\left(\alpha_c, \xi, \vec{r}_{cc}, \vec{R}_{cc}\right) = \int \prod_{i=1}^{3}(d\alpha_i dr_i)\,\delta^2\left(\sum_i \vec{r}_i\right)\delta\left(1-\sum_i \alpha_i\right)d\alpha_c$$

$$\times \Psi^{\nu_1\nu_2\nu_3\bar{\mu}\mu\dagger}_{P_c}\left(\frac{\alpha_i}{1+\xi}, \vec{r}_i + \vec{R}_l;\ \frac{\alpha_c\xi}{1+\xi}, \vec{R}_{\bar{c}c} - \alpha_c\vec{r}_{\bar{c}c}, \frac{\bar{\alpha}_c\xi}{1+\xi}, \vec{R}_{\bar{c}c} + \bar{\alpha}_c\vec{r}_{\bar{c}c}\right)\Psi^{\nu_1\nu_2\nu_3}_p(\alpha_i, r_i),$$

## Reggeization in diagram (d)

### $\bar{c}c = \mathbf{8}_c$

- General multipomeron configuration cannot be expressed as a dipole cross-section




- The largest intercept has a two-pomeron configuration