Production of double charmed baryons with excited diquark at LHC

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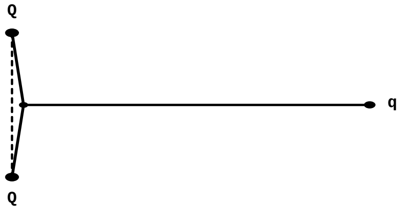
$\mathbf{QQ'q}-$ system:

$$\Xi_{QQ'} = QQ'q, \quad q = (u,d)$$
$$\Omega_{QQ'} = QQ'q, \quad q = s$$

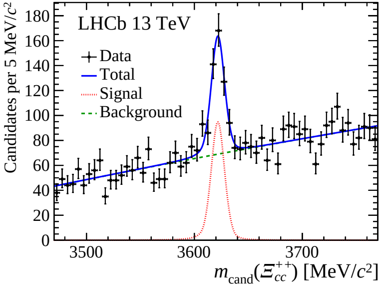


Key features:

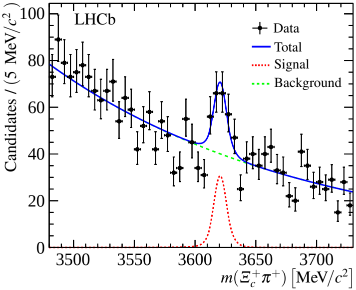
- Hierarchy of interaction scales: $\boxed{m_{Q,Q'} \gg m_{Q,Q'} \cdot v \gg \Lambda_{QCD}}$
- In the limit $m_Q \to \infty$ diquark acts as a local heavy source of gluon field
- Sequential interaction:
  - $[QQ']_{\bar{3}_c}$
  - $[QQ']_{\bar{3}_c} \ + \ q_{3_c}$

[V.V. Kiselev and A.K. Likhoded, Phys. Usp.45, 455 (2002)]

SEP 2017.
Observation of Ξ_{cc}^{++} in decay mode
$\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^+$



OCT 2018.
Observation of the decay
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



[R. Aaij et al. (LHCb), Phys. Rev. Lett. 119, 112001 (2017)
R. Aaij et al. 1807.01919 (2018)]

In case $Q = Q'$ wave function of a diquark is AS:

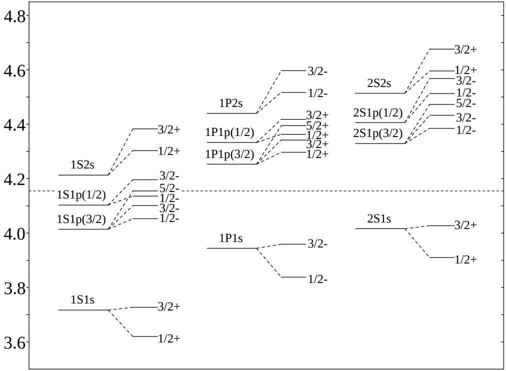
- S,D-wave $\quad S = 1$
- P-wave $\quad S = 0$

Metastable states:
$\Xi_{cc}(1P),\ \Xi_{cc}(2P)$

Transitions

$$1P1s \to 1S1s$$
$$2P1s \to 1S1s$$

require a simultaneous change of the diquark's spin and angular momentum



Mass spectrum of Ξ_{cc} baryon in GeV. Dashed line shows the $\Lambda_c D$ threshold.

[D.Ebert, R.N. Faustov et al., Phys. Rev.D66,014008 (2002)]

Several stages:

- Hard production of two heavy quark pairs
- Soft formation of the diquark in color antitriplet
- Hadronization into baryon

$$\mathbf{Q\bar{Q}Q'\bar{Q}'} \to \left[\mathbf{QQ'}\right]_{\bar{\mathbf{3}}_\mathbf{c}} \to \mathbf{QQ'q}$$

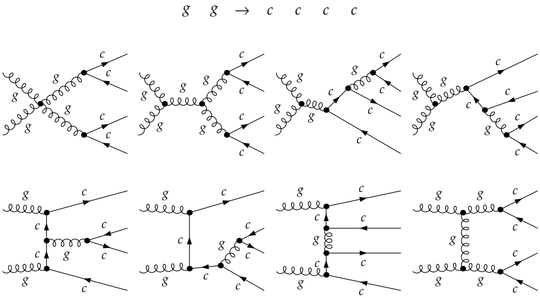
- DPS mechanism is not involved in production of QQ'
- In very rough approximation

$$P\left(\left[QQ'\right]_{\bar{3}_c} \to QQ'q\right) = 1$$

the probability of diquark dissociation is not accounted,
the whole momentum of the diquark is transmitted to the baryon

Hadronic production of $c\bar{c}c\bar{c}$

- gg contribution dominates towards $q\bar{q}$
- gq diagrams may be neglected given that $p_T \sim m_c$
- 36 diagrams of the 4th order by α_s in perturbative QCD



- FeynArts

  Generation and visualization of feynman diagrams

FeynArts: analytical expressions

[T. Hahn, Comput. Phys. Commun. 140, 418-431 (2001)]

- Spin selection for S-wave state:

$$\mathtt{N}(1,1) = |\uparrow\uparrow>$$

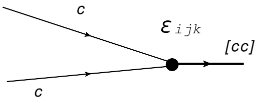
$$\mathtt{N}(1,0) = \frac{1}{\sqrt{2}}(|\uparrow\downarrow> + |\downarrow\uparrow>)$$

$$\mathtt{N}(1,-1) = |\downarrow\downarrow>$$

- Spin selection for P-wave state:

$$\mathtt{N}(0,0) = \frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$$

- Colour factor



- Convolution with the wave function of the diquark:

$$A^{SJj_z} = \int T^{Ss_z}_{c\bar{c}c\bar{c}}(p_i, k(\vec{q})) \cdot \left(\Psi^{Ll_z}_{cc}(\vec{q})\right)^* \cdot C^{Jj_z}_{s_z l_z} \frac{d\vec{q}}{(2\pi)^3}$$

$T\,(p_i, k(\vec{q}))$ — amplitude of the hard production of two $c\bar{c}$ pairs
$\Psi_{c\bar{c}}(\vec{q})$ — wave function of the diquark
p_i — four momenta of $[cc]_{\bar{3}_c}$, c_1, c_2
$\vec{q}$ — three momentum of c-quark in the diquark rest frame
$(0, \vec{q}) \to k\,(\vec{q})$ — boost from the diquark rest frame to the frame of $c\bar{c}c\bar{c}$ production
$C^{Jj_z}_{s_z l_z}$ — Clebsh-Gordon coefficients

Under assumption of small dependence of $T^{S s_z}_{c\bar{c}c\bar{c}}$ on $k\,(\vec{q})$:

$$A \sim \int d^3q\, \Psi(\vec{q}) \left\{ T(p_i, \vec{q})\big|_{\vec{q}=0} + \vec{q}\frac{\partial}{\partial \vec{q}} T(p_i, \vec{q})\big|_{\vec{q}=0} + \cdots \right\}$$

- For S-wave state:

$$A^{s_z} \sim R_s(0) \cdot T^{s_z}_{c\bar{c}c\bar{c}}(p_i)\big|_{\vec{q}=0}$$

- For scalar P-wave state:

$$A^{l_z} \sim R'_p(0) \cdot \mathcal{L}^{l_z} T_{c\bar{c}c\bar{c}}\,(p_i)\big|_{\vec{q}=0}$$

Differential operator:

$$\mathcal{L}^{l_z} = \begin{cases} \mathcal{L}^{-1} = \frac{1}{\sqrt{2}}\left(\frac{\partial}{\partial q_x} + i\frac{\partial}{\partial q_y}\right) \\ \mathcal{L}^{0} = \frac{\partial}{\partial q_z} \\ \mathcal{L}^{+1} = -\frac{1}{\sqrt{2}}\left(\frac{\partial}{\partial q_x} - i\frac{\partial}{\partial q_y}\right) \end{cases}$$

[A.V. Berezhnoy, V.V. Kiselev, A.K. Likhoded, Phys. Lett. B 381 (1996) 341–347]

Input parameters: $\boxed{m,\ M,\ R_s\left(0\right),\ R_p'\left(0\right),\sqrt{s}_{pp}}$

Fortran code:

- Calculation of matrix elements with spin selection
- Differentiation:

$$\frac{\partial T\left(p_i,k(\vec{q})\right)}{\partial q_j}\Big|_{\vec{q}=0}\approx\frac{T\left(p_i,k(\varepsilon^j)\right)-T\left(p_i,0\right)}{\varepsilon}$$

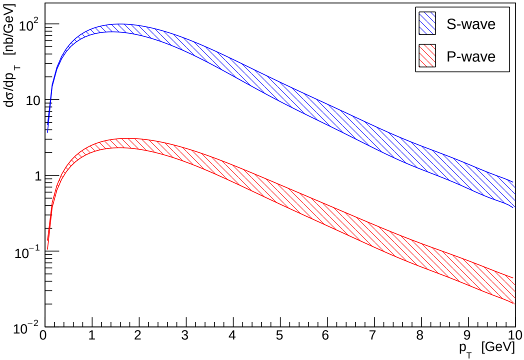
- Integration over phase space within RAMBO generator
- Convolution with proton distribution functions CT14 at varied scale:

$$\sigma_{pp}=\int\hat{\sigma}_{gg}\left(\hat{s}_{gg}\right)f_{g1}\left(x_1\right)f_{g2}\left(x_2\right)dx_1dx_2$$

[S. Dulat, T.J. Hou, J. Gao et al., EPJ Web Conf. 120, 07003 (2016)]

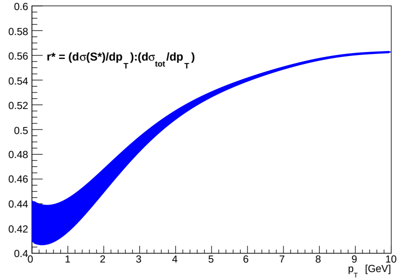
Cross sections for Ξ_{cc} excitations at $\sqrt{s} = 13$TeV

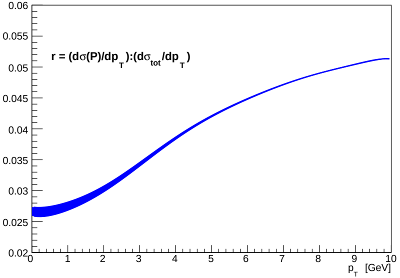
state	σ, [nb]
$1S$	$120 \div 170$
$2S$	$60 \div 90$
$3S$	$40 \div 70$
$1P$	$4 \div 6$
$2P$	$4 \div 5$



Relative yields $r\left(\Xi_{cc}^{*}\right) = \sigma\left(\Xi_{cc}^{*}\right)/\sigma\left(\Xi_{cc}\right)$ for Ξ_{cc} excitations

state	r, %
$1S$	$49 \div 52$
$2S$	$26 \div 27$
$3S$	$18 \div 20$
$1P$	2
$2P$	$1 \div 2$





- Relative yields for production of S-wave and P-wave excitations of Ξ_{cc} have been estimated in LHCb' kinematics:

$$\sigma\left(\Xi_{cc}^{P}\right)/\sigma\left(\Xi_{cc}\right) \approx 3\%$$
$$\sigma\left(\Xi_{cc}^{S*}\right)/\sigma\left(\Xi_{cc}\right) \approx 45\%$$

- Nowadays LHCb collaboration observes hundreds of events for Ξ_{cc} ground state. 313 ± 33 particles are identificated in decay:

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

- It is worth expecting that the excited states of Ξ_{cc} will be extracted at Run 3 in single pion transitions:

$$\Xi_{cc}^{P\ +} \to \ \Xi_{cc}^{++}\pi^-$$
$$\Xi_{cc}^{S*\ +} \to \ \Xi_{cc}^{++}\pi^-$$

Thank you for attention!

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