Searching for

Doubly Charmed Baryon Ξ_{cc}^{+}

in High Energy Nuclear Collisions

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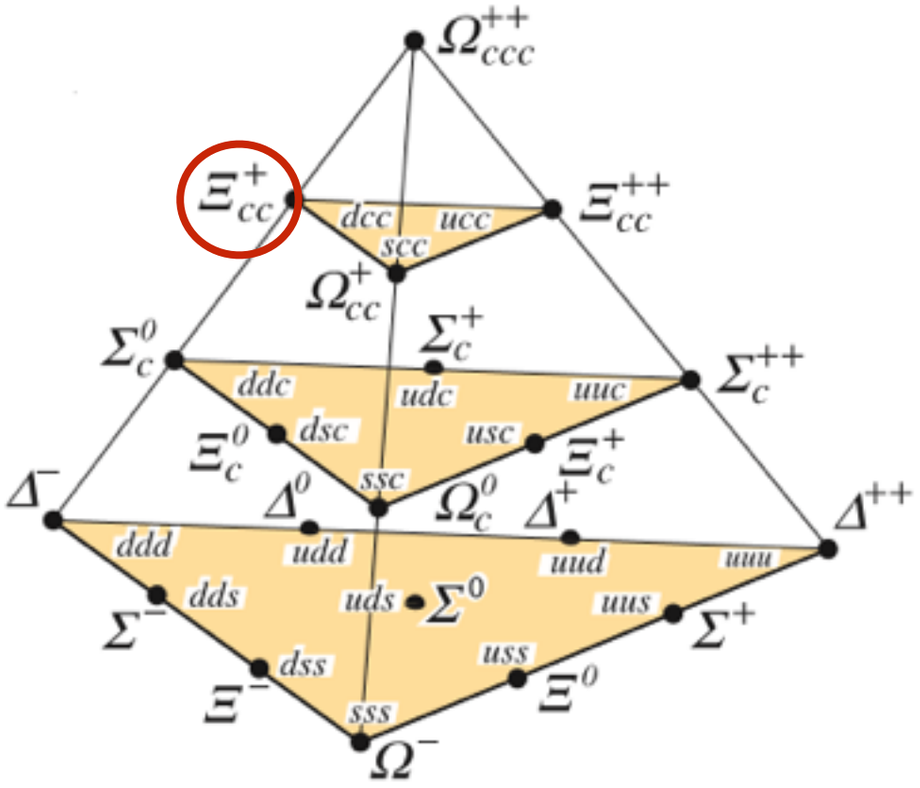
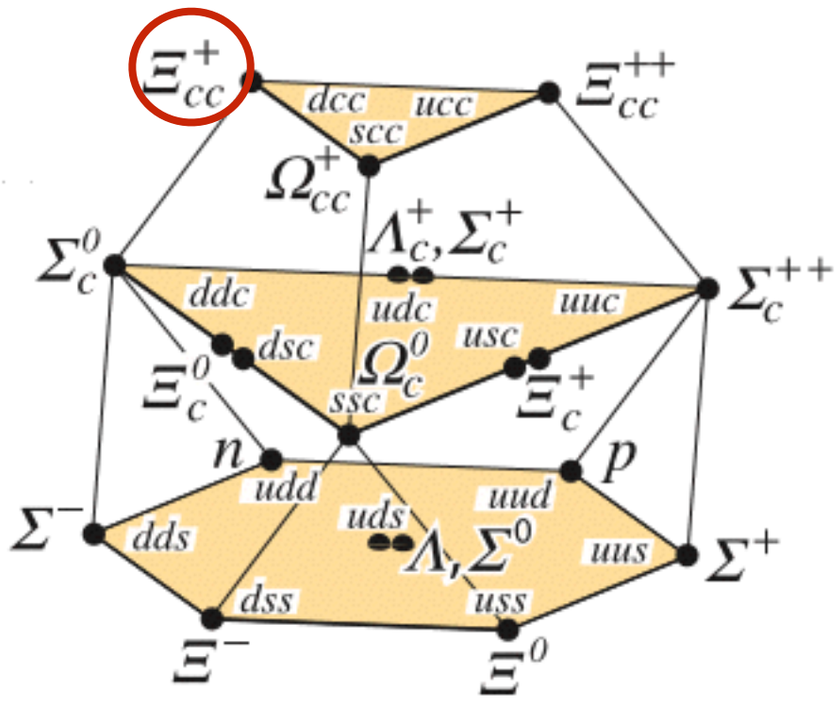
Based on : J. Zhao, H. He, P. Zhuang, arXiv: 1603.04524.

FCPPL Quarkonium Production Workshop (Peking University; 31, March)

Introduction

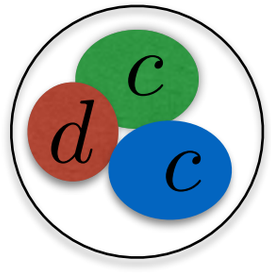


20-plet with SU(3) decuplet.



20-plet with SU(3) octet.

The flavor SU(4) quark model predicts 22 charmed baryons, but most of them are not yet discovered.



Introduction

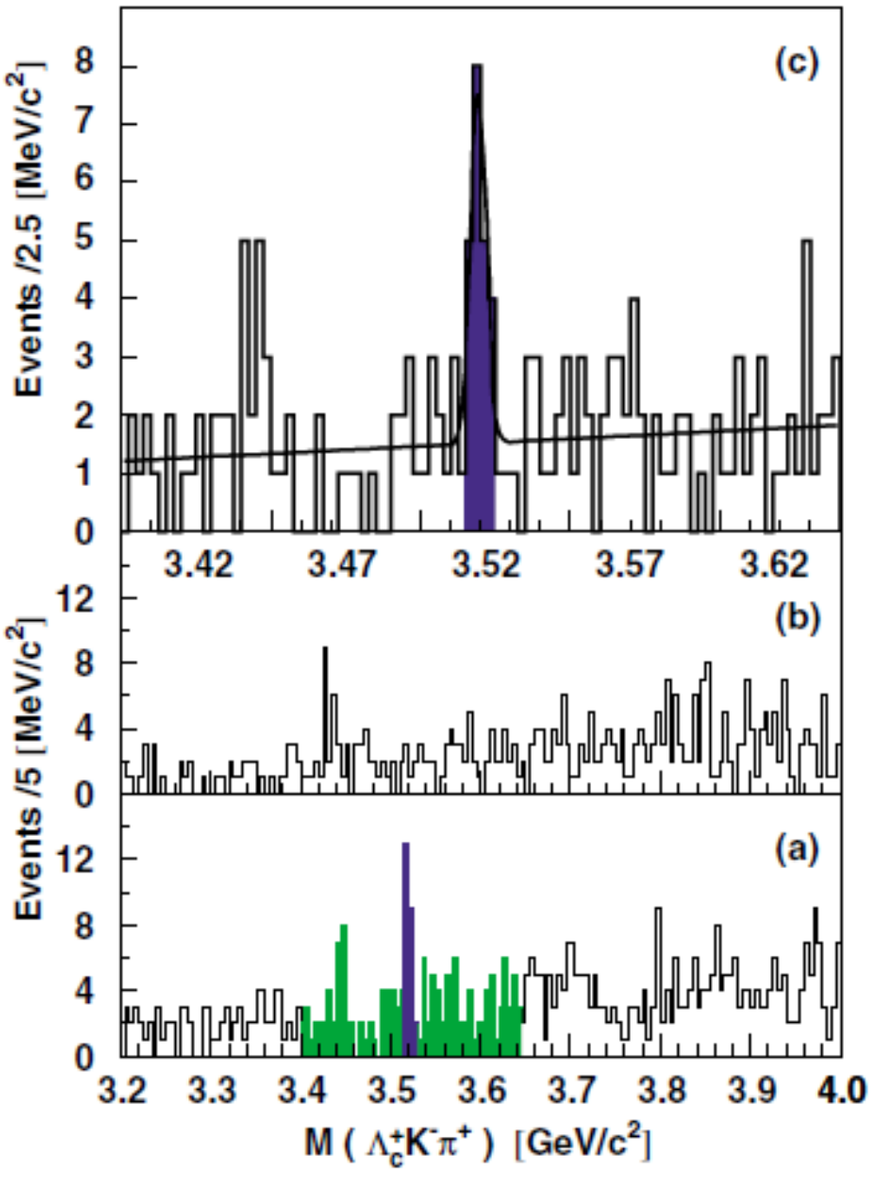
The experimental search for Ξ_{cc}^{+} lasts for decades.

1. SELEX Collaboration.

First observation of the doubly charmed baryon Ξ_{cc}^{+} and other five states like Ξ_{cc}^{++}.

Phys. Rev. Lett. 89, 112001(2002)

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



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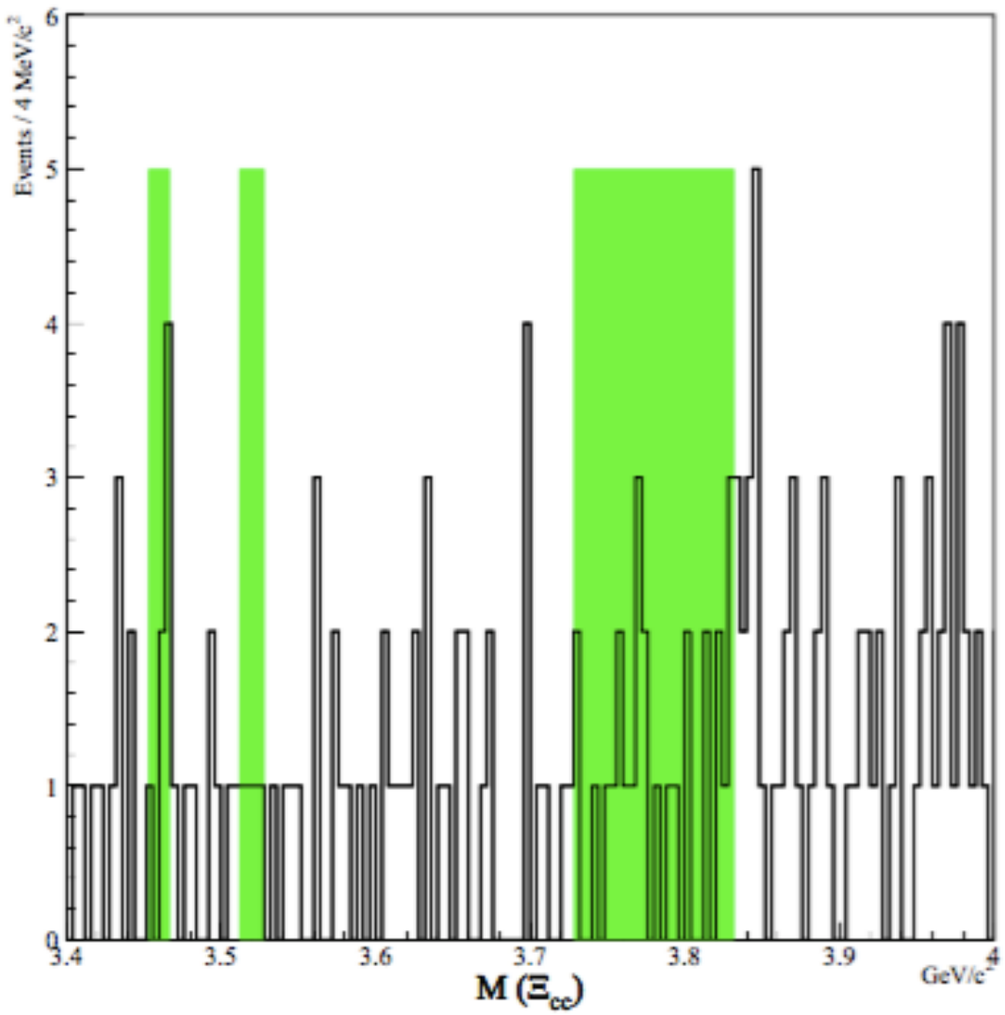

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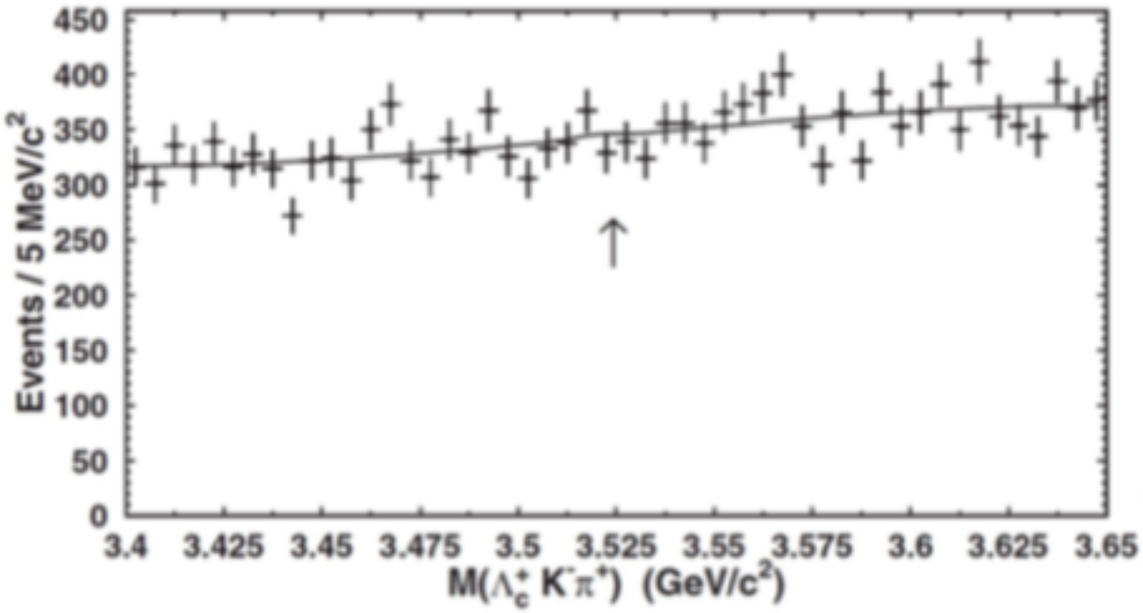

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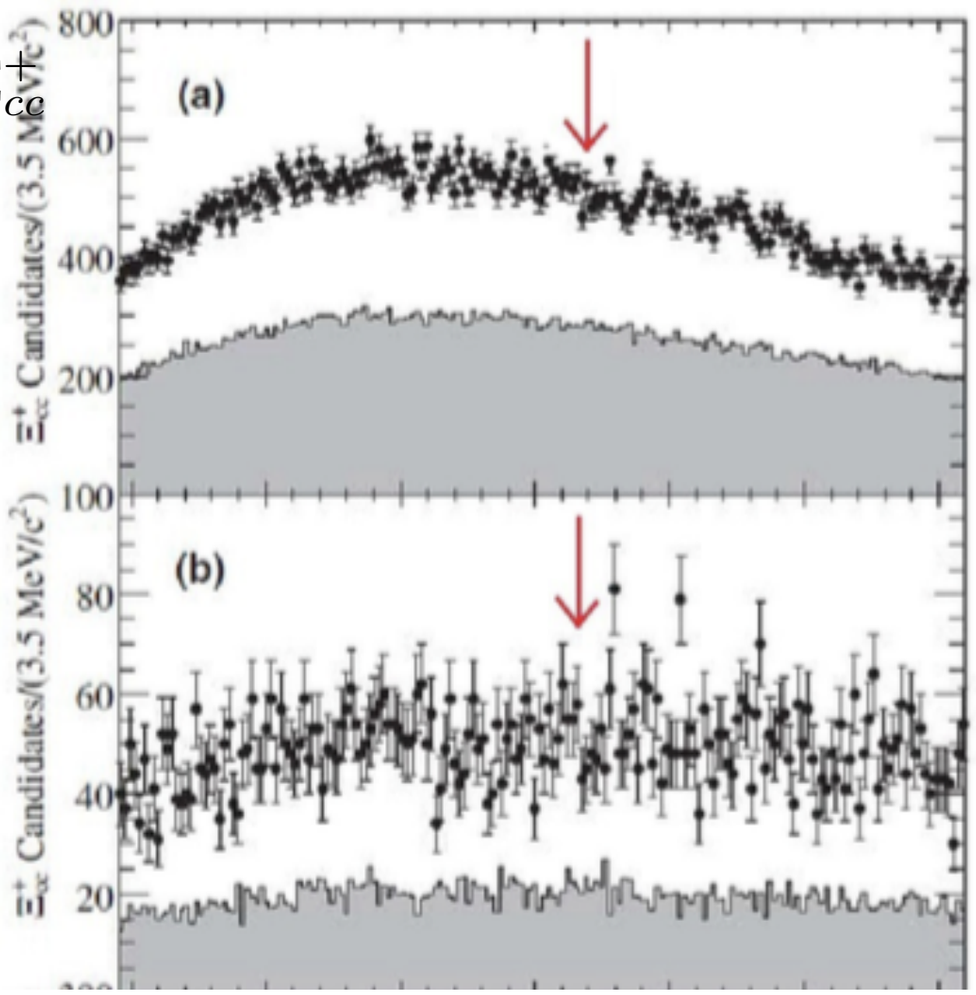

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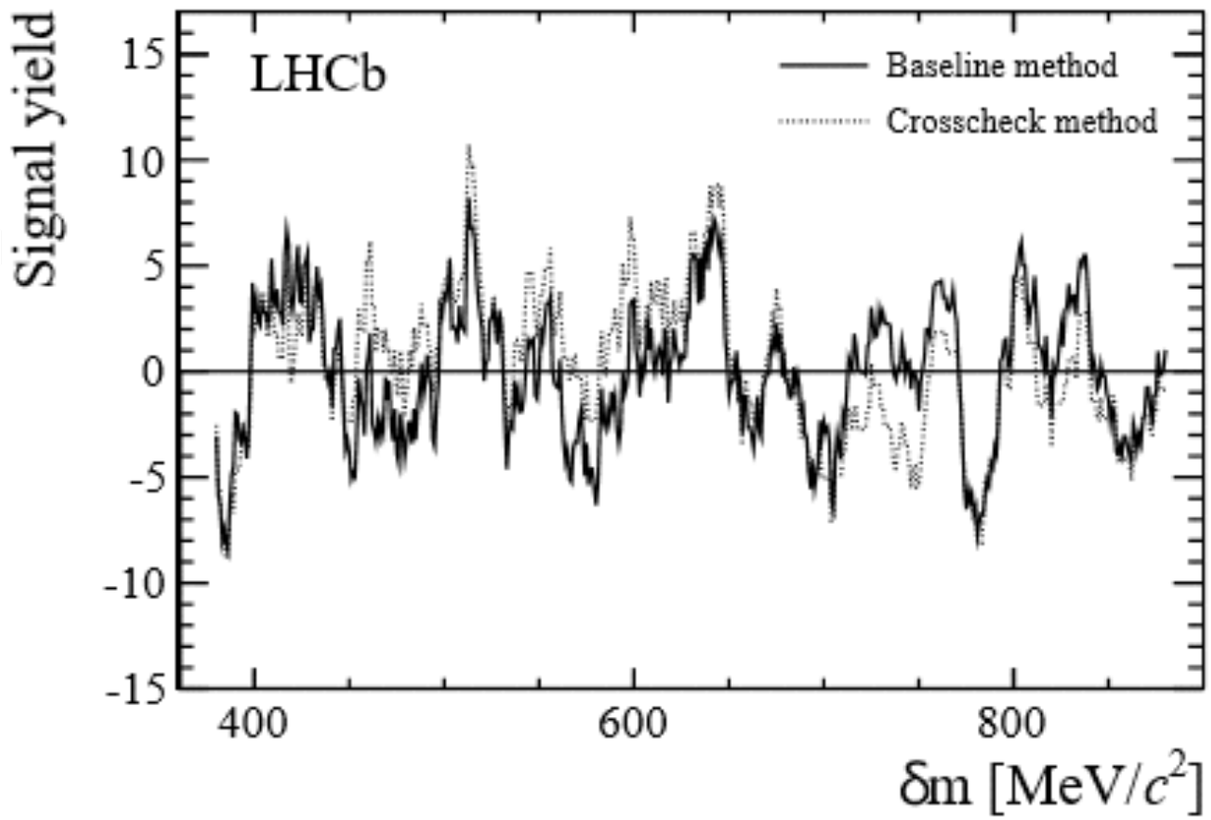
5. LHCb Collaboration.

No significant evidence is found (2013).



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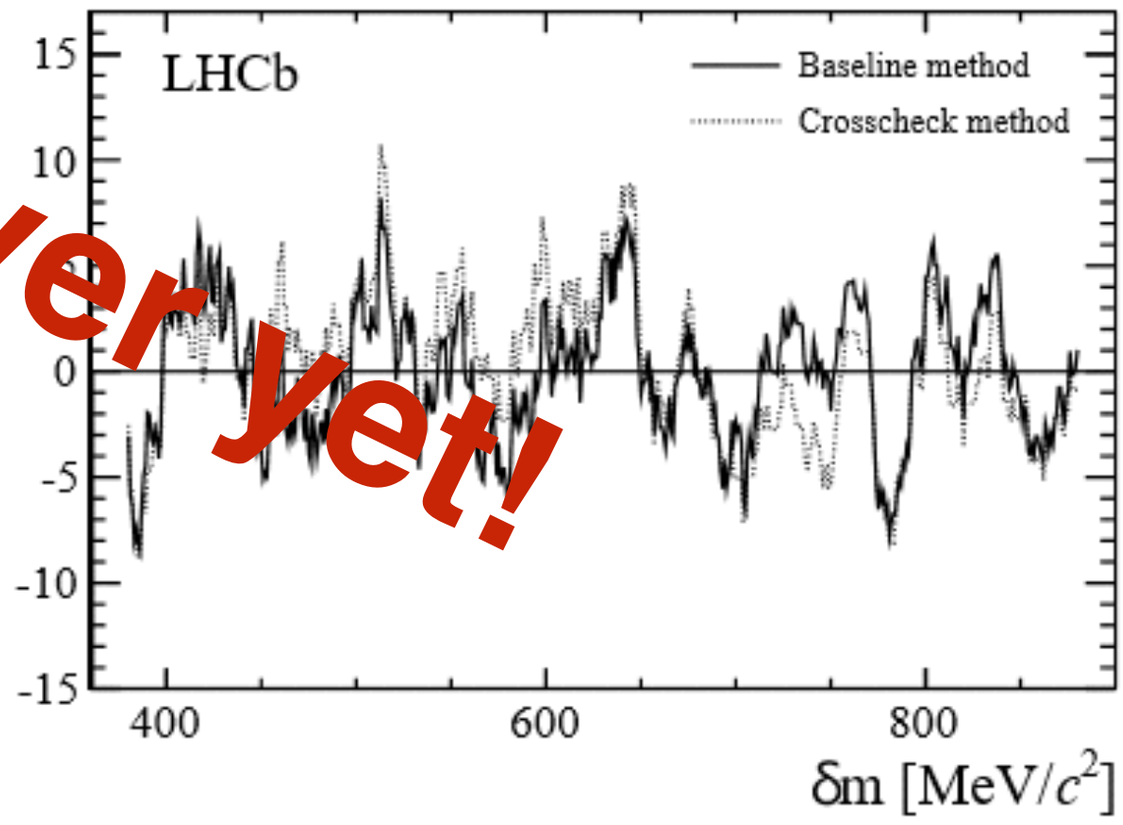
It's not over yet!



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

Introduction

SELEX Collaboration	Fixed target (π^-or proton beam with 600GeV)
FOCUS Collaboration	heavy flavor photo-production (200GeV)
Belle Collaboration	$e^+ + e^-$ collisions
BaBar Collaboration	$e^+ + e^-$ collisions
LHCb Collaboration	$p + p$ collisions (7TeV)

Rare production of charm quarks

Need at least two pairs of charm quarks in an event !

But their production in nuclear collisions will be largely enhanced due to the recombination of uncorrelated charm quarks in quark-gluon plasma !

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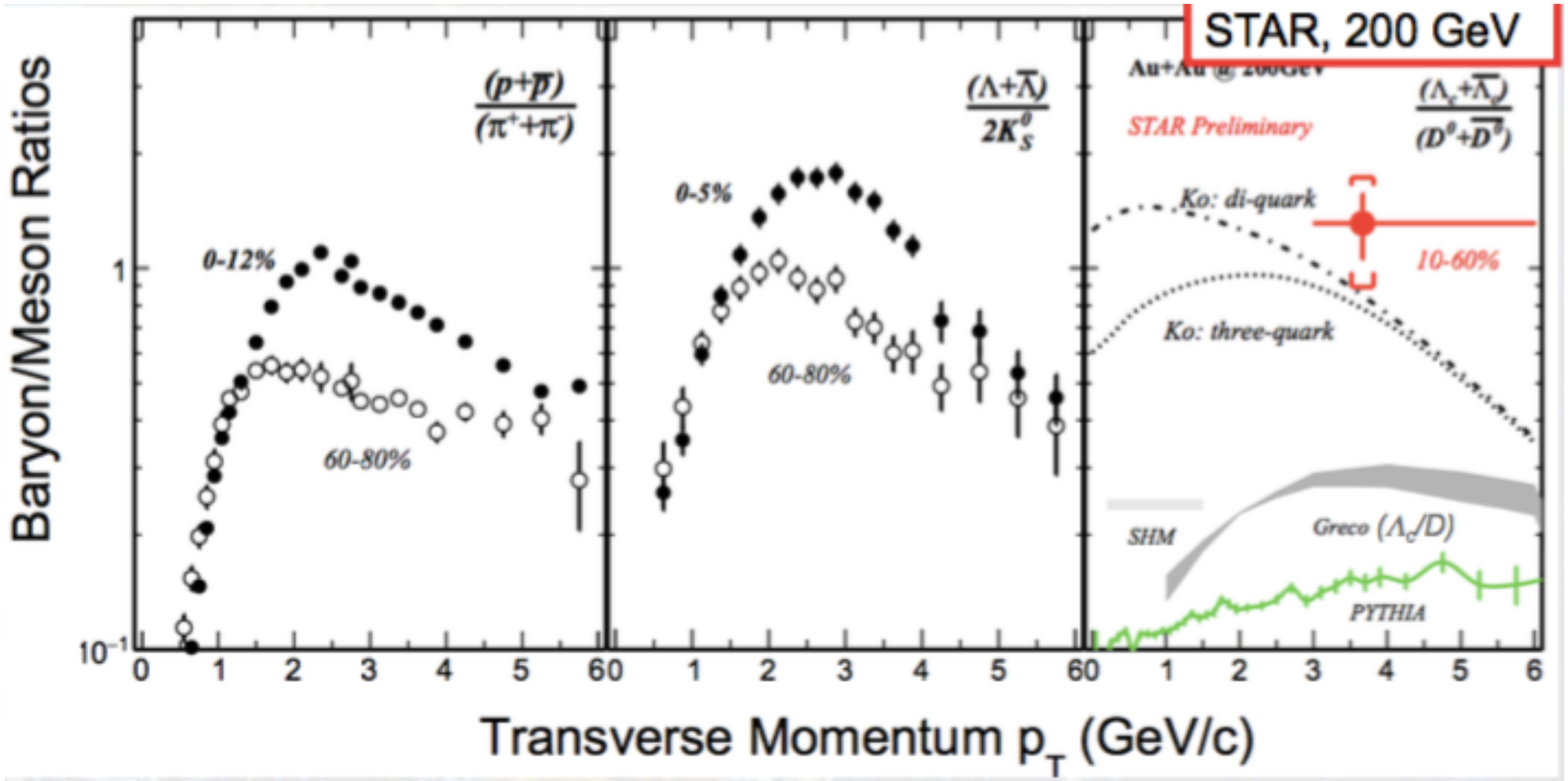


Significant enhancement in Λ_c/D ***compared to PYTHIA***

Consistent with Coalescence model + thermalized charm quarks

The cross section of per binary collision is at least two orders of magnitude larger than that in a p+p collision at LHC energy for Ω_{ccc}.

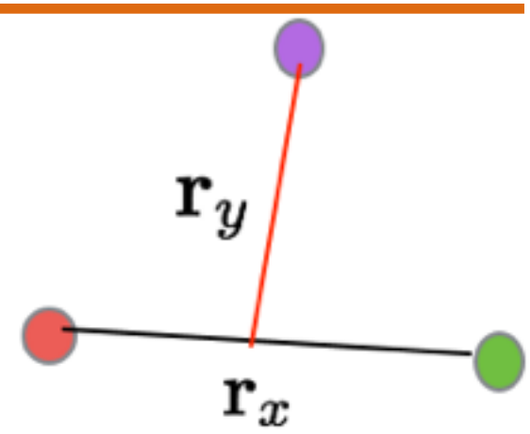
Xin. Dong's slide in QM2017.

H. He, Y. Liu, and P. Zhuang. Phys. Lett. B746,59(2015).

Method

$$\left[\sum_{i=1}^{3}\frac{\hat{p}_i^2}{2m_i}+V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\right]\Psi=E\Psi$$

$$V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)=\sum_{i<j}V_{qq}(r_i,r_j)$$



$$(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\to(\mathbf{R},\mathbf{r}_x,\mathbf{r}_y)\to(r,\alpha,\theta_x,\phi_x,\theta_y,\phi_y)$$

Hyperspherical method

$$\left[\frac{1}{2m_\mu}(-\frac{d^2}{dr^2}-\frac{5}{r}\frac{d}{dr}+\frac{\hat{\Lambda}^2}{r^2})+V(r,\Omega)\right]\Phi=E\Phi$$

$$\Phi(r,\Omega)=\sum_\kappa\phi_\kappa(r)Y_\kappa(\Omega).$$

$$\left[\frac{\partial^2}{\partial r^2}+\frac{5}{r}\frac{\partial}{\partial r}-\frac{L(L+4)}{r^2}+E\right]\phi_\kappa=\sum_{\kappa'}V_{\kappa\kappa'}\phi_{\kappa'}$$

$$V_{\kappa\kappa'}(r)=\int Y_\kappa^*(\Omega)V(r,\Omega)Y_{\kappa'}(\Omega)d\Omega$$

$$V_{Cornell}=-\frac{\alpha}{r_{ij}}+\sigma r_{ij}$$

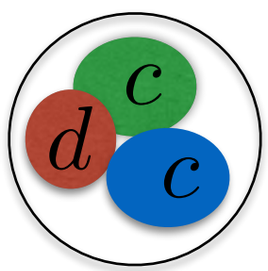
relativistic correction

$$\Delta\epsilon_0=\langle\Phi_0|\Delta\hat{H}|\Phi_0\rangle$$

$$\Delta\Phi_0(r,\Omega)=\sum_n\frac{\langle\Phi_n|\Delta\hat{H}|\Phi_0\rangle}{\epsilon_0-\epsilon_n}\Phi_n,$$

$$m_{\Xi_{cc}^+}=2m_c+m_q+\epsilon_0+\Delta\epsilon_0=3.584\ \text{GeV}$$

$$\langle r\rangle_{\Xi_{cc}^+}=\frac{\int drd\Omega r^6\,|\Phi_0+\Delta\Phi_0|^2}{\int drd\Omega r^5\,|\Phi_0+\Delta\Phi_0|^2}=0.41\ \text{fm}.$$



3.5~3.6GeV(IQCD)

Results 1

For the ground state (L=0) of Ξ_{cc}^{+} ,
we expand only with the first two hyperspherical harmonic function:

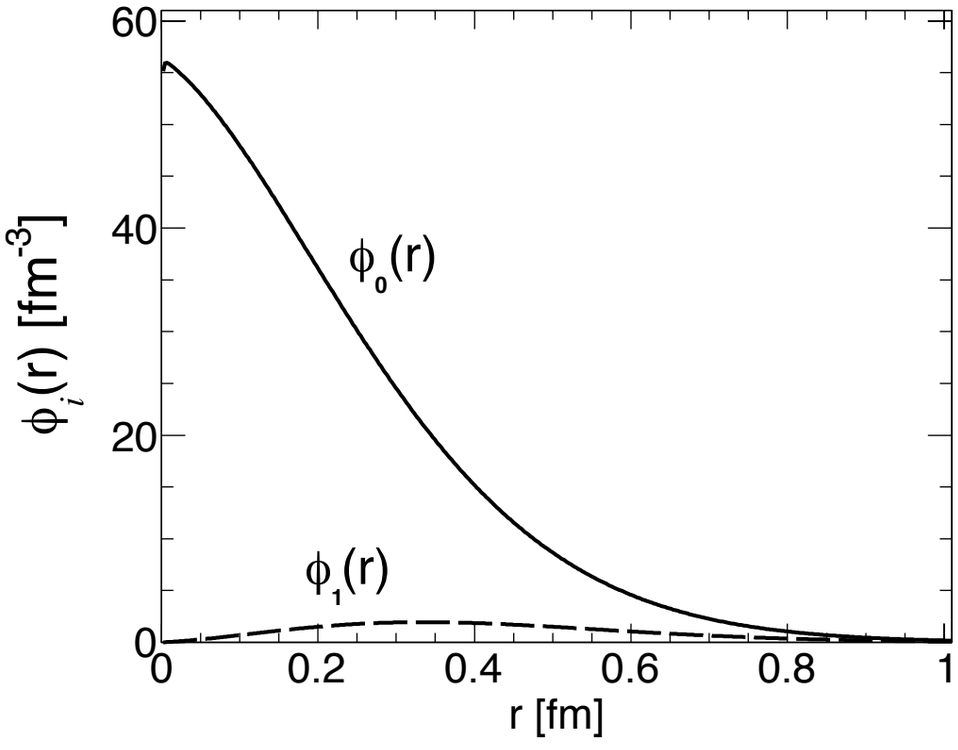
$$Y_0 = 1/\pi^{3/2} \qquad Y_1 = 2\cos(2\alpha)/\pi^{3/2}$$

So:

$$\Phi(r,\Omega) = \phi_0(r)Y_0 + \phi_1(r)Y_1$$

$$\left[-\frac{\partial^2}{\partial r^2} - \frac{5}{r}\frac{\partial}{\partial r} + V_{00} - \epsilon\right]\phi_0 + V_{01}\phi_1 = 0,$$

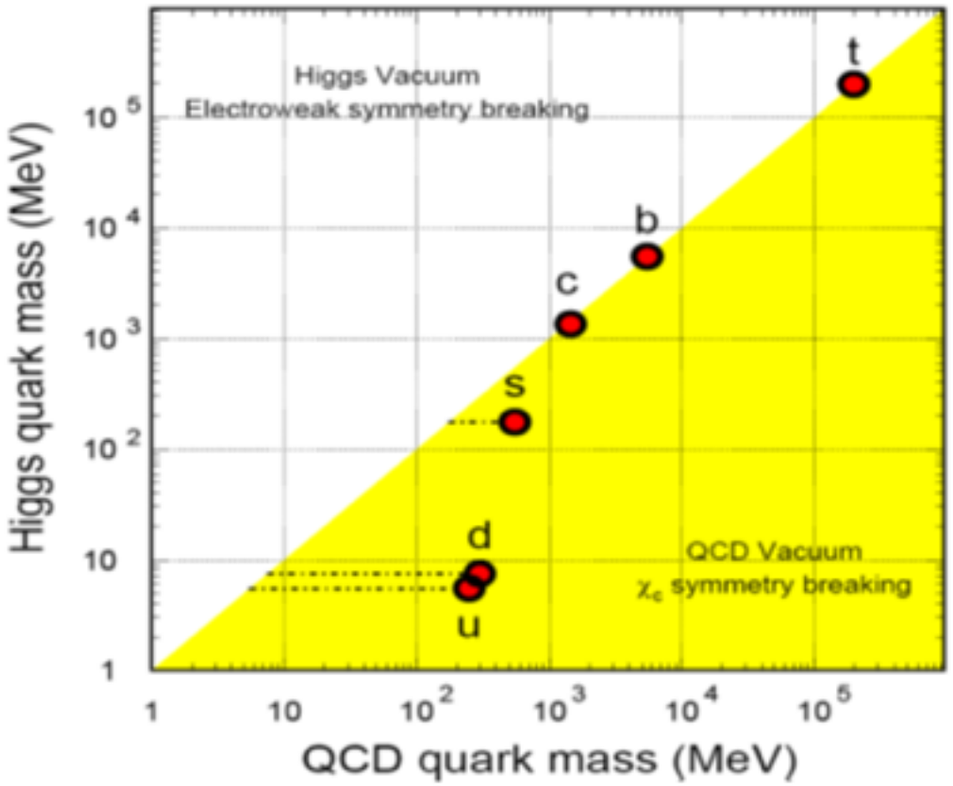
$$\left[-\frac{\partial^2}{\partial r^2} - \frac{5}{r}\frac{\partial}{\partial r} + \frac{12}{r^2} + V_{11} - \epsilon\right]\phi_1 + V_{10}\phi_0 = 0$$



Indicating that the truncation is good enough!

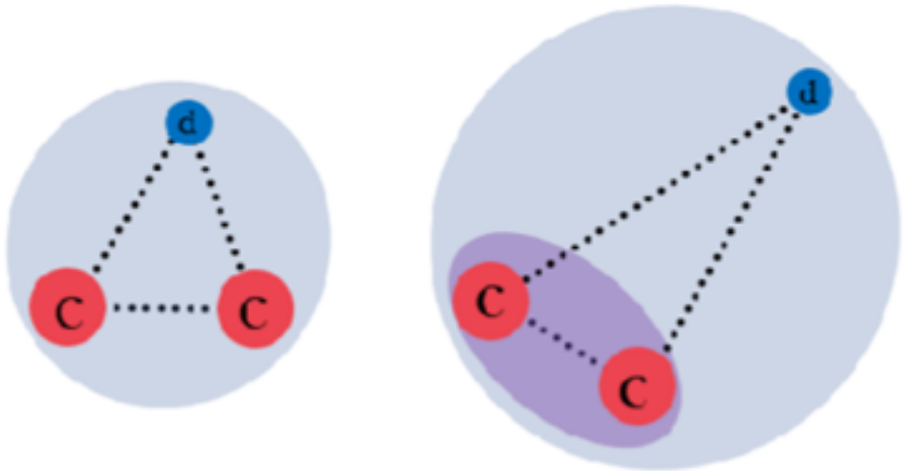
Results 2

Chiral symmetry and the structure of Ξ_{cc}^{+}



the coalescence happens at the hadronization hypersurface where the broken chiral symmetry is restored, and the light quark mass drops down significantly:

$$m_c(T_c) \simeq m_c(0),$$
$$m_q(T_c) \simeq 100\ \mathrm{MeV} < m_q(0) \simeq 300\ \mathrm{MeV}$$



Average r_i(fm)	Model 1 (m_d=0.3GeV)	Model 2 (m_d=0.1GeV)
$< r_{cc} >$	0.4437	0.4620
$< r_{(cc)-q} >$	0.5294	0.9662

Ξ_{cc}^{+} produced in heavy ion collisions is more like a quark-diquark state (cc-q)!

Method

Coalescence probability (Wigner function):

$$W(\mathbf{r},\mathbf{p}) = \int d^6\mathbf{y} e^{-i\mathbf{p}\cdot\mathbf{y}} \Phi(\mathbf{r}+\frac{\mathbf{y}}{2})\Phi^*(\mathbf{r}-\frac{\mathbf{y}}{2})$$

Momentum distribution:

$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} \times f_c(\tilde{r}_1,\tilde{p}_1) f_c(\tilde{r}_2,\tilde{p}_2) f_d(\tilde{p}_3,\tilde{p}_3) W(r_x,r_y,p_x,p_y)$$

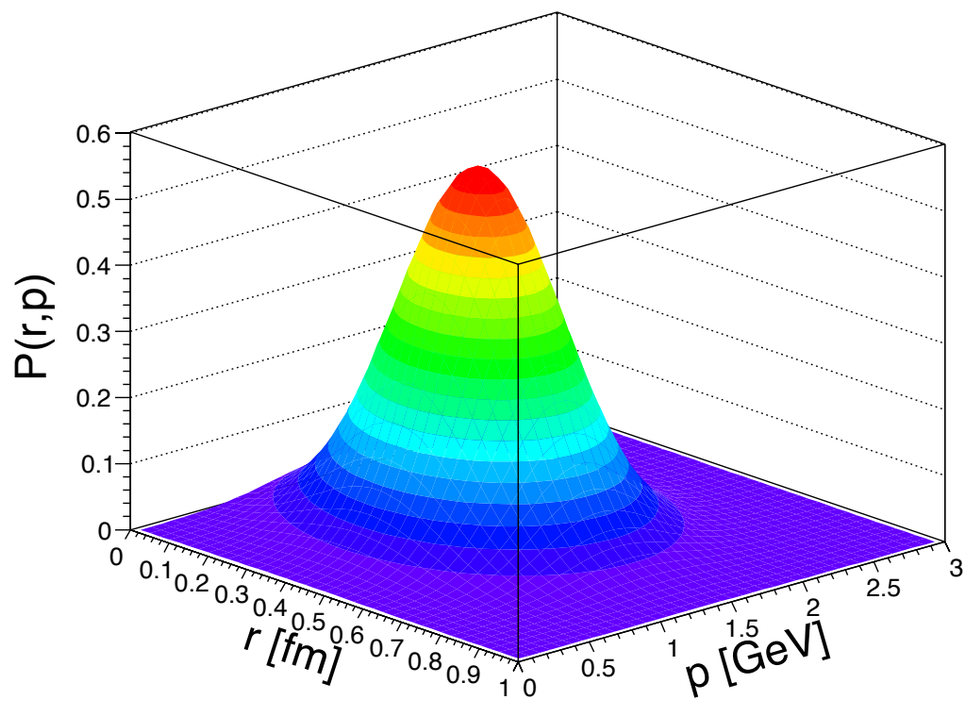
The integral hypersurface is defined through hydrodynamics

$$\partial_\mu T^{\mu v} = 0 \ \textbf{(+ EOS)}$$

$$T(R_\mu) = T_c$$

The charm quark distribution:

$$f(r_i,p_i) = \rho(r_i)\frac{N(r_i)}{e^{u^\mu(r_i)p_\mu/T(r_i)}+1}$$



Results 3

to eliminate the simple superposition of p+p collisions and focus on the hot medium effect, we introduce the effective cross section per binary collision at $\sqrt{s_{NN}} = 2.76$ TeV*:*

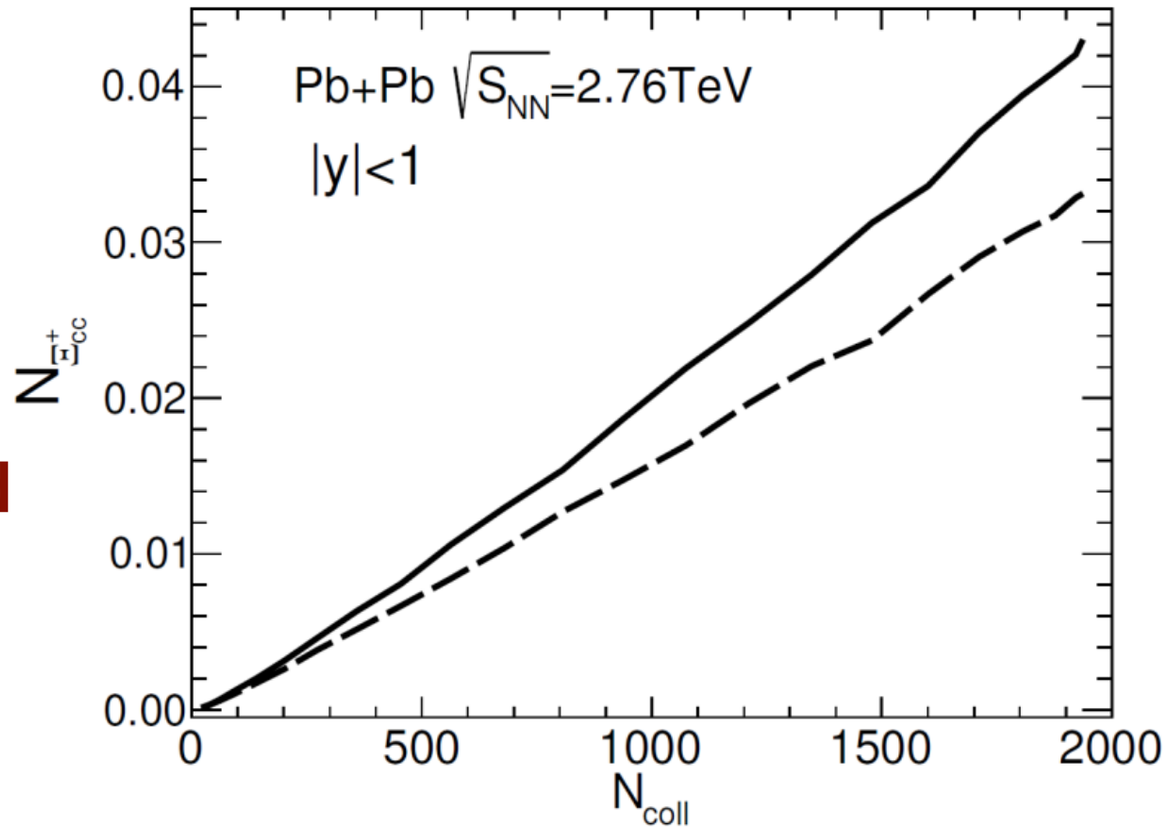
$$\tilde{\sigma}_{AA}^{\Xi_{cc}^+} = N_{\Xi_{cc}^+}/\Delta y \sigma_{pp} \qquad \tilde{\sigma}_{pp}^{\Xi_{cc}^+} = \tilde{\sigma}_{AA}^{\Xi_{cc}^+}/N_{coll}$$

$$\sigma_{pp} = 62\,mb \;\rightarrow\; \tilde{\sigma}_{pp}^{\Xi_{cc}^+} = 412 \text{ nb}$$

it is much larger than

$$\sigma_{pp}^{\Xi_{cc}^+} = 61 \text{ nb}$$

in p+p at $\sqrt{s_{NN}} = 14$ TeV



Ξ_{cc}^+ production is extremely enhanced in nuclear collisions !

Summary I

The reasonable decay modes of Ξ_{cc}^{+}

- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$
- $\Xi_{cc}^{+} \to D^{0} p K^{-} \pi^{+}$
- $\Xi_{cc}^{+} \to D^{+} p K^{-}$
- $\Xi_{cc}^{+} \to \Xi_c^{+} \pi^{+} \pi^{-}$
- $\Xi_{cc}^{+} \to \Xi_c^{0} \pi^{+}$

The lifetime calculated via optical theorem is between 110 and 250 fs.

Nucl. Phys. B. Proc. Suppl 115, 33(2003); Phys. Rev. Lett. 97, 162001(2006).
Phys. Rev. D 74, 011103(2006); JHEP 12, 090(2013); Phys. Rev. D60,014007(1999).
Eur. Phys. J. C9(1999).

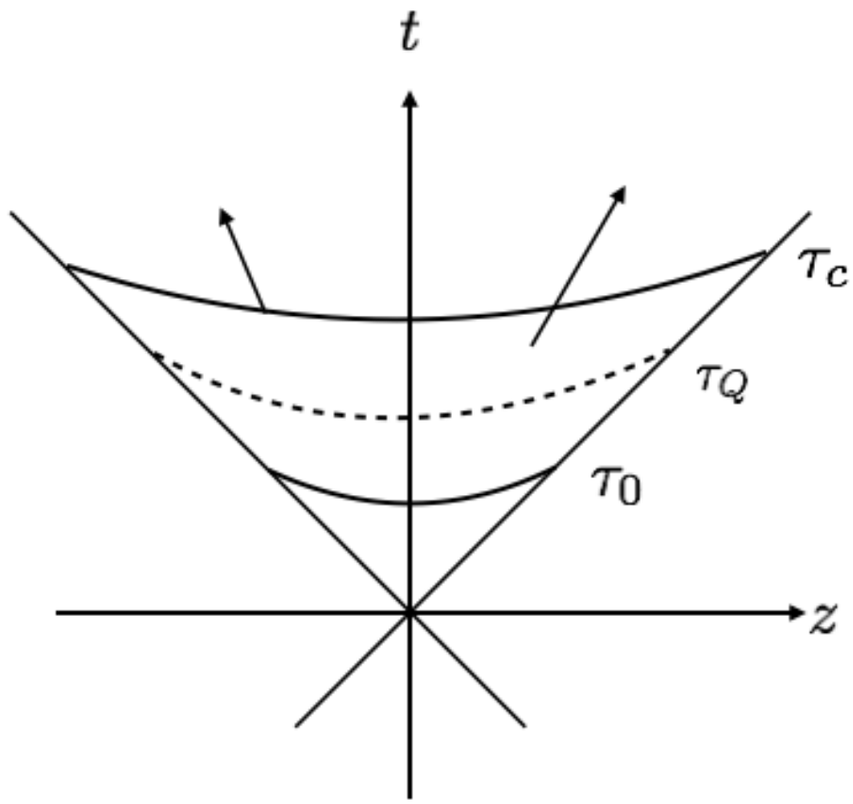
Summary 2

1. ***It is most probable to discover the new particle Ξ_{cc}^{+} in heavy ion collisions at RHIC and LHC.***
2. ***The discovery of Ξ_{cc}^{+} is unique signals of QGP!***
3. ***Due to the chiral symmetry restoration, the Ξ_{cc}^{+} is more like a quark-diquark state.***

Thank you !

Backup

$$\alpha = \arctan(r_x/r_y)$$

$$\mathbf{r_x} \to (r_x, \theta_x, \varphi_x)$$

$$\Delta\hat{H} = -\sum_i \frac{\hat{p}^4}{8m_i^3}$$