Heavy Flavor Production in QGP

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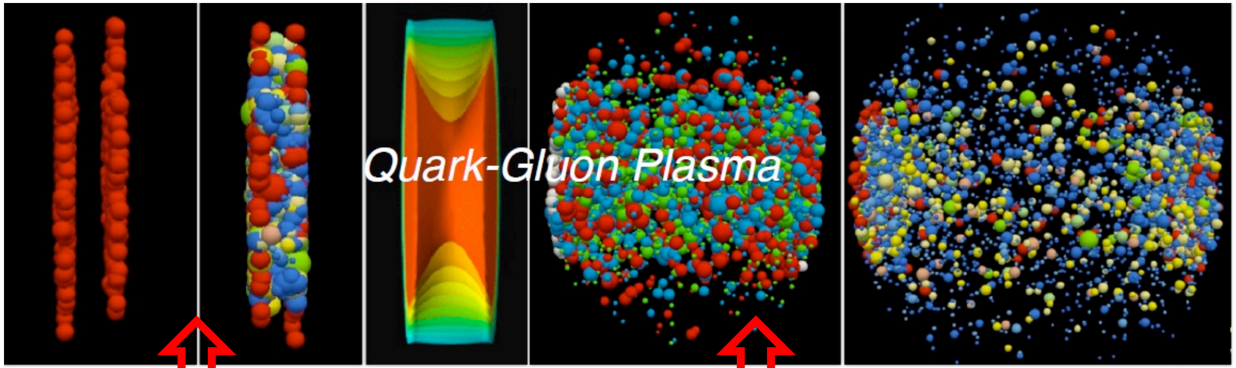


***Initial production** of heavy flavor quarks and their bound states*

***Thermal dissociation & Regeneration** of heavy flavor quarks and their bound states*

I will discuss Ω_{ccc} at LHC and J/ψ at FCC.

Ω_{ccc}: 3-body Schrodinger Equation

H.He, Y.Liu and PZ, PLB746, 59(2015)

Ω_{ccc} is hardly produced in pp collisions,

$\sigma(\Omega_{ccc})$ = 0.06~0.13 nb at 7 GeV and 0.1~0.2 nb at 14 GeV (Bjorken 1986 and Chen 2011)

However, coalescence among uncorrelated charm quarks in A+A may significantly enhance the production probability, Roughly speaking,

$N(\Omega_{ccc}) \sim N_c^3$, $N_c \sim 100$ at LHC !

If Ω_{ccc} is discovered in A+A collisions, it is a unique signal of QGP!

N-body Schroedinger Equation at finite temperature

$$\left[\sum_{i=1}^{N}\left(-\frac{\vec{\nabla}_i^2}{2m_i}\right)+V(\vec{r}_1,\dots\dots\vec{r}_N,T)\right]\Psi(\vec{r}_1,\dots\dots\vec{r}_N)=E_N\Psi(\vec{r}_1,\dots\dots\vec{r}_N)$$

$$V(\vec{r}_1,\dots\dots\vec{r}_N,T)=\sum_{i\neq j}^{N}\left[V_{ij}^c(|\vec{r}_{ij}|,T)+V_{ij}^s(|\vec{r}_{ij}|)\right]$$

Method to solve 3-body equation:
Hyperspherical method

$Casimir\ scaling\ potential$ $V_{ij}^c(|\vec{r}_{ij}|,T)$ from Lattice QCD, $V_{ij}^s(|\vec{r}_{ij}|)=\beta e^{-\gamma|\vec{r}_{ij}|}\vec{s}_i\cdot\vec{s}_j$

Wigner function (Ω_{ccc} formation probability)

$$W(\vec{x},\vec{p})=\int d^3\vec{y}e^{-i\vec{p}\cdot\vec{y}}\Psi(\vec{x}+\vec{y}/2)\Psi^+(\vec{x}-\vec{y}/2)$$

Ω_{ccc}: Significant Enhancement in AA at LHC

H.He, Y.Liu and PZ, PLB746, 59(2015)

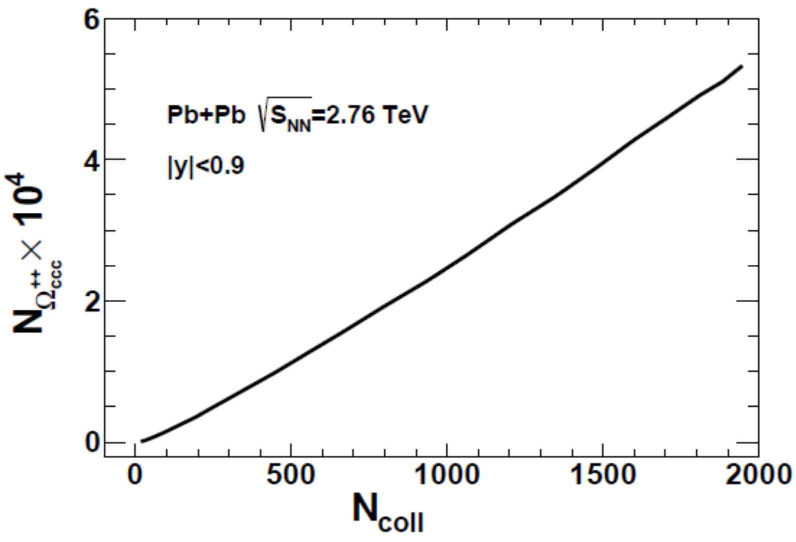
Static properties:

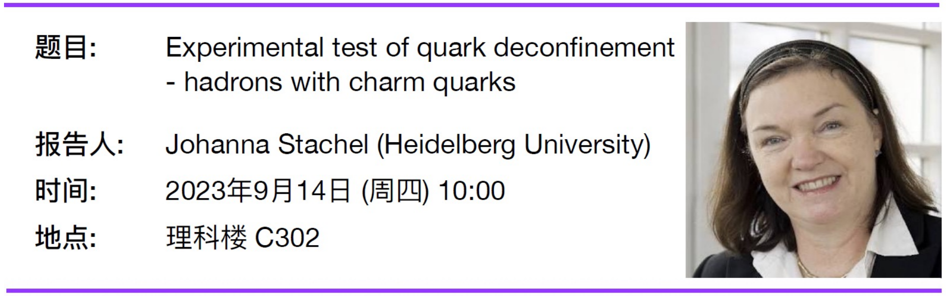
$m_\Omega = 4.75$ GeV (4.8 GeV from LQCD), $\epsilon_\Omega = 900\ MeV$, $\langle r_\Omega \rangle = 0.5\ fm \simeq \langle r_{J/\psi} \rangle$

Coalescence:

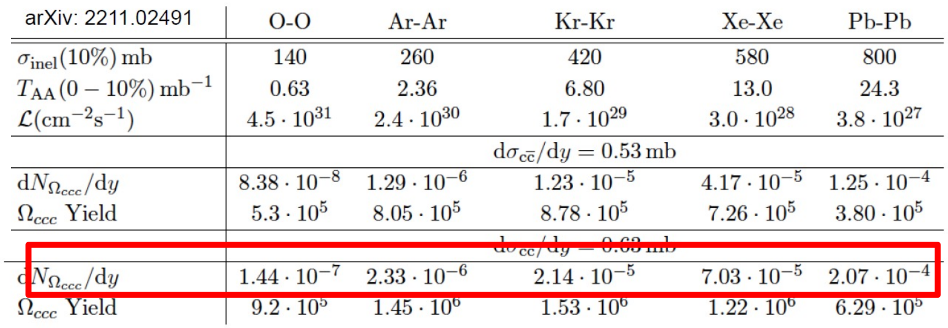
$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int_\Sigma \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\int \frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

The integration is on the hypersurface of phase transition by hydrodynamics.





题目:	Experimental test of quark deconfinement - hadrons with charm quarks
报告人:	Johanna Stachel (Heidelberg University)
时间:	2023年9月14日 (周四) 10:00
地点:	理科楼 C302



arXiv: 2211.02491	O-O	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
$\sigma_{\rm inel}(10\%)$ mb	140	260	420	580	800
$T_{\rm AA}(0-10\%)$ mb^{-1}	0.63	2.36	6.80	13.0	24.3
$\mathcal{L}(\rm cm^{-2}s^{-1})$	$4.5 \cdot 10^{31}$	$2.4 \cdot 10^{30}$	$1.7 \cdot 10^{29}$	$3.0 \cdot 10^{28}$	$3.8 \cdot 10^{27}$
	$d\sigma_{c\bar{c}}/dy = 0.53$ mb				
$dN_{\Omega_{ccc}}/dy$	$8.38 \cdot 10^{-8}$	$1.29 \cdot 10^{-6}$	$1.23 \cdot 10^{-5}$	$4.17 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$
Ω_{ccc} Yield	$5.3 \cdot 10^5$	$8.05 \cdot 10^5$	$8.78 \cdot 10^5$	$7.26 \cdot 10^5$	$3.80 \cdot 10^5$
	$d\sigma_{cc}/dy = 0.63$ mb				
$dN_{\Omega_{ccc}}/dy$	$1.44 \cdot 10^{-7}$	$2.33 \cdot 10^{-6}$	$2.14 \cdot 10^{-5}$	$7.03 \cdot 10^{-5}$	$2.07 \cdot 10^{-4}$
Ω_{ccc} Yield	$9.2 \cdot 10^5$	$1.45 \cdot 10^6$	$1.53 \cdot 10^6$	$1.22 \cdot 10^6$	$6.29 \cdot 10^5$

$\sigma_\Omega \sim 3.5\times10^4\ nb$ in central Pb+Pb at 2.76 TeV ($\sigma_\Omega \sim$0.1 nb in p+p at 7 TeV)

current estimates for luminosities for LHC for lighter nuclei somewhat less optimisti
→ optimum for Xe-Xe with 3.9-6.5 10^5 Ω_{ccc} per year

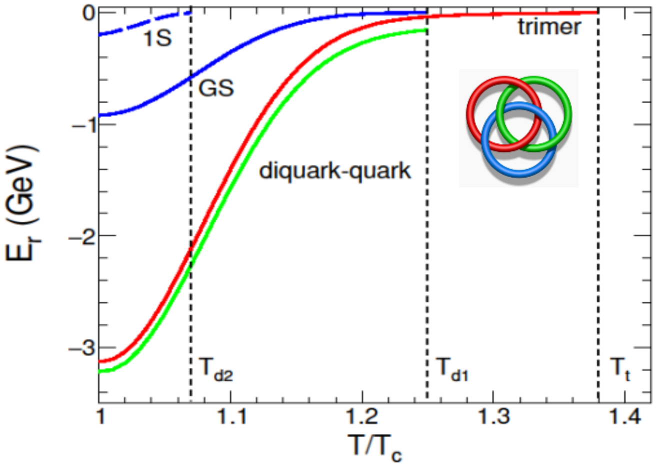
Conclusion: Ω_{ccc} in A+A is enhanced by 5-6 orders !

Ω_{ccc}: Exotic States

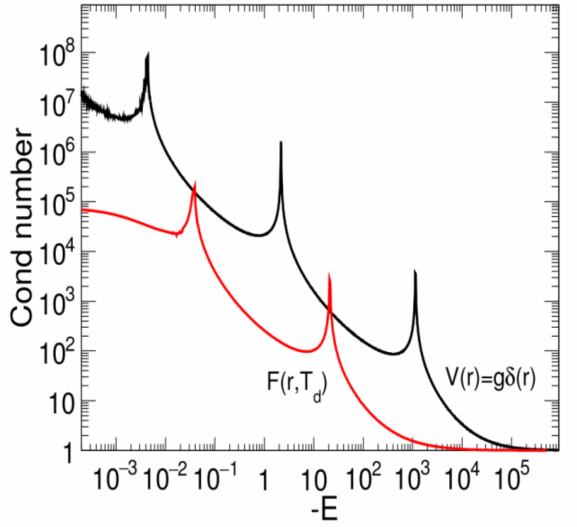
J.Zhao and PZ, PLB775,84(2017)

Exotic States of Ω_{ccc} at Finite Temperature

Borromean rings



Efimov states

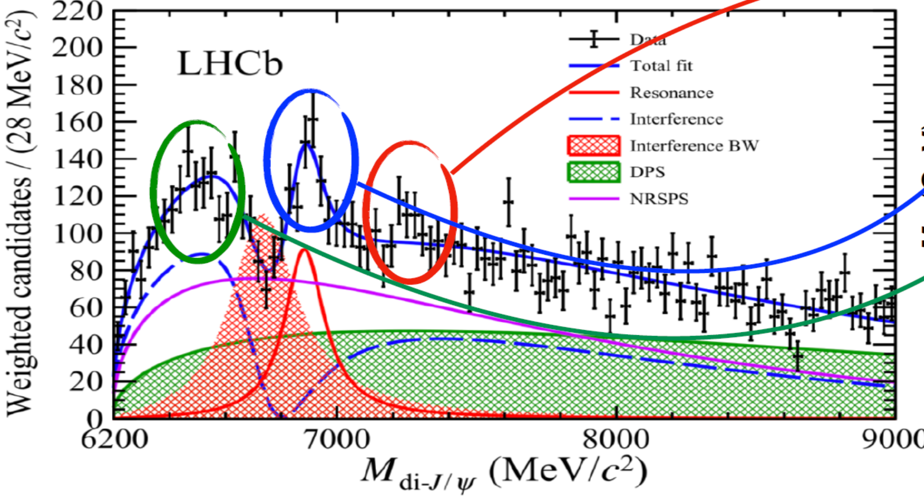


$$\frac{E_n}{E_{n+1}} = e^{2\pi/s_0} = 515$$

Can the exotic states be realized in A+A collisions?

$(QQ\bar{Q}\bar{Q})$

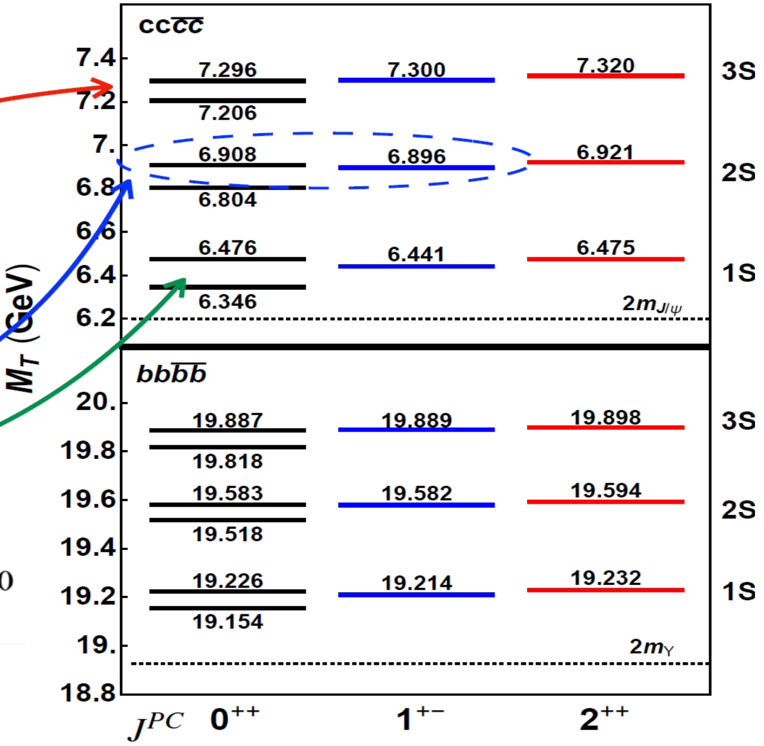
LHCb Collaboration, Science Bulletin 65, 1983(2020)



$m[X(6900)] = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$

$\Gamma[X(6900)] = 80 \pm 19 \pm 33\ \text{MeV}$

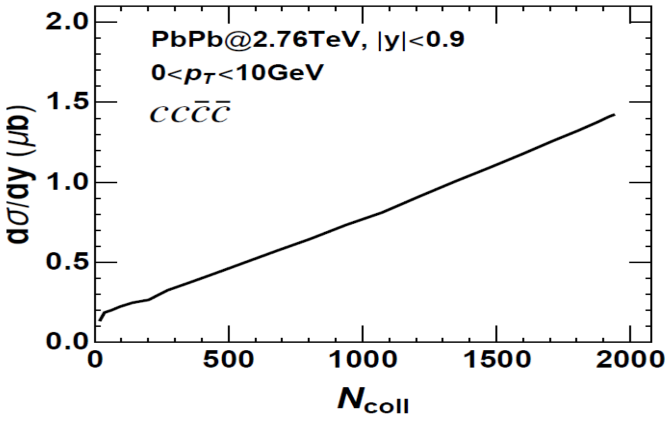
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)



$$\left.\frac{d\sigma}{dy}\right|_{pp} = 78pb$$ *in pp at 7TeV*

Marek Karliner el al, Phys.Rev.D 95 (2017) 3, 034011.
Ruilin Zhu, arXiv: 2010.09082.

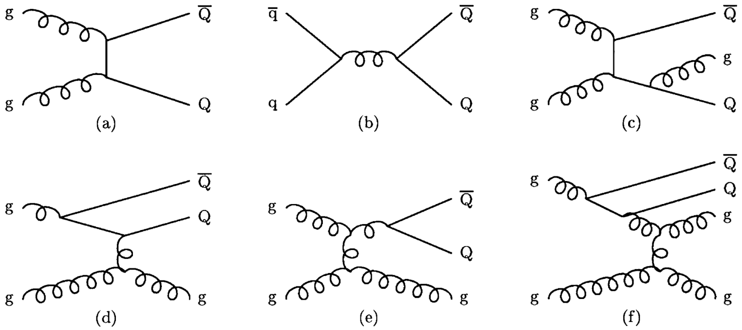
$$\left.\frac{d\sigma}{N_{coll}dy}\right|_{AA} \approx 770pb$$ *in AA at 5.02TeV*



Heavy Quark Production in QGP

Thermal charm production in QGP becomes important at high energies:

P.Levai, B.Muller and X.Wang, PRC51, 3326(1995).
B.Kaempfer and O.Pavlenko, PLB391, 185(1997).
J.Uphoff, O.Fochler, Z.Xu and C.Greiner, PRC82, 044906(2010).
B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)



(a) gluon fusion, (b) quark-antiquark annihilation, (c) pair creation with gluon emission,
(d) flavor excitation, (e) gluon splitting, (f) together gluon splitting and flavor excitation.

Question: Contribution to quarkonium regeneration ?

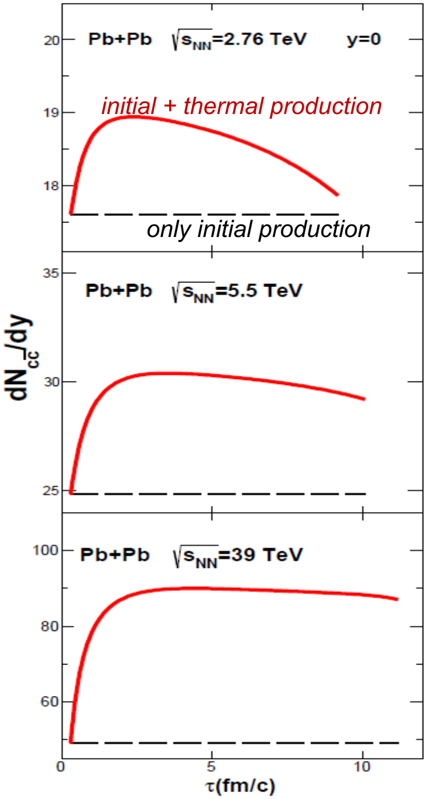
Charm Quark Evolution in QGP

K.Zhou, Z.Chen, C.Greiner, and PZ,. Phys.Lett. B758, (2016)434

$$\frac{1}{\cosh\eta}\partial_\tau n_c + \nabla_T \cdot (n_c \mathbf{v}_T) + \frac{1}{\tau\cosh\eta} n_c = r_{gain} - r_{loss}$$

gain rate:

$$r_{12} = \frac{dn}{d^4x} = \frac{1}{\nu}\int \frac{d^3\mathbf{p}_1}{(2\pi)^3 2E_1}\frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12} f_1 f_2,$$



**NLO production cross section*

P.Nason, S.Dawson, and R.Ellis, NPB 303, 607(1988); 327, 49(1989).
M.L.Mangano, P.Nason and G.Ridolfi, NPB373, 295(1992).

**temperature dependent parton masses and coupling constant*

E.Braaten and R.Pisarski, PRD45, 1827(1992).
S.Plumari, W.M.Alberico, V.Greco and C.Ratti, PRD84, 094004(2011)

**hydrodynamics for QGP evolution*

**detailed balance between loss and gain terms*

**shadowing effect on initial distribution (EPS09s NLO)*

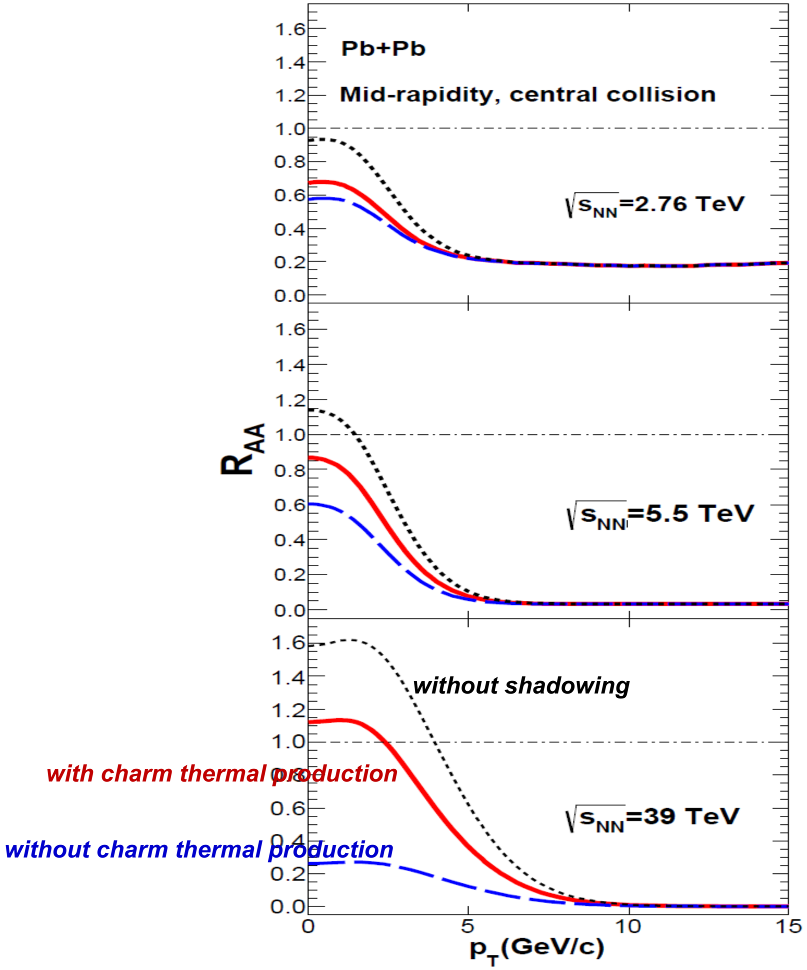
significant charm enhancement (~80%) at FCC !

Charmonia at FCC

K.Zhou, Z.Chen, C.Greiner, and PZ, PLB758 (2016) 434

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi\cdot\nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi .$$

Heavy flavors under extreme conditions in high energy nuclear collisions, J.Zhao, K.Zhou, S.Chen and PZ, Prog.Part.Nucl.Phys. 114 (2020)103801.



significant J/ψ enhancement at low p_T: $R_{AA}(p_t) < 1 \quad \rightarrow \quad R_{AA}(p_t) > 1$

Summary

1) It is most probable to discover Ω_{ccc} in AA collisions at LHC!

2) Charm quark thermal production changes significantly the J/ψ yield: it goes from suppression at SPS, RHIC and LHC to enhancement at FCC.

Thank you for your attention!

decay modes of Ω_{ccc}

Decay through weak interaction, for instance

nonleptonic cascade decay mode (Chen 2011):

$$\begin{array}{cccc} \Omega_{ccc}^{++} \rightarrow & \Omega_{ccs}^{+} & + & \pi^{+} \\ & \downarrow & & \\ & \Omega_{css}^{0} & + & \pi^{+} \\ & \downarrow & & \\ & \Omega_{sss}^{-} & + & \pi^{+} \end{array}$$

semileptonic decay mode (Bjorken, 1986):

$$\Omega_{ccc}^{++} \rightarrow \Omega_{sss}^{-} + 3\mu^{+} + 3v_{\mu}$$