Experimental and Theoretical Status of and Perspectives for XYZ States

In memory of Mikhail Voloshin (✝ March 20, 2020)

GSI Darmstadt, Germany, April 12-15, 2021

The properties and production of fully-heavy Tetraquarks in a strongly interacting medium

Jiaxing Zhao(赵佳星)

Tsinghua University

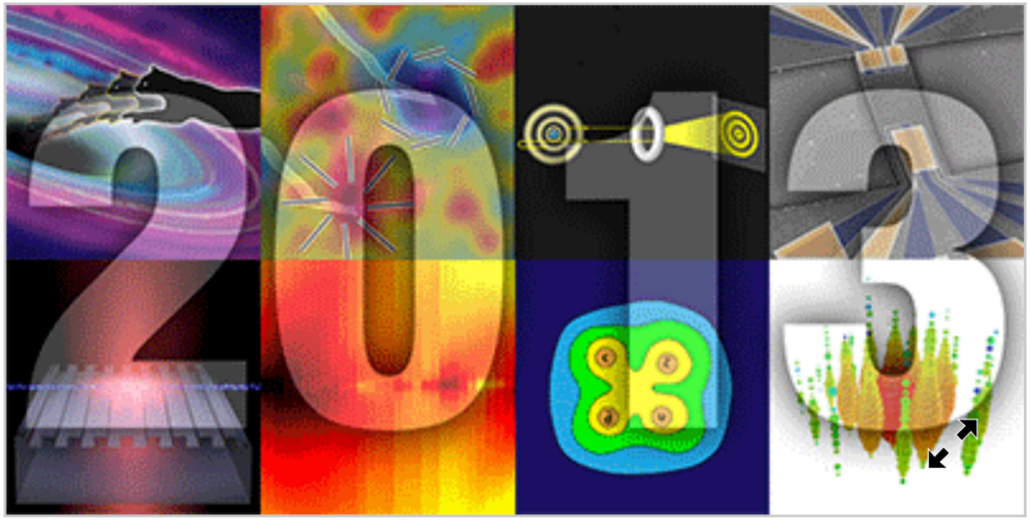
In collaboration with : Dr. Shuzhe Shi and Prof. Pengfei Zhuang

Email: jiaxingzhao@mail.tsinghua.edu.cn

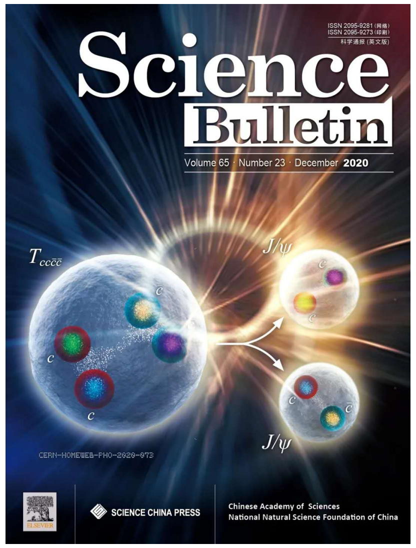
Outline

- *Brief review about heavy flavor exotic hadrons and heavy ion collisions*
- *Study the static properties of fully-heavy Tetraquarks in vacuum and finite temperature.*
- *Production of fully-heavy Tetraquarks in relativistic heavy ion collisions*
- *Summary and outlook*

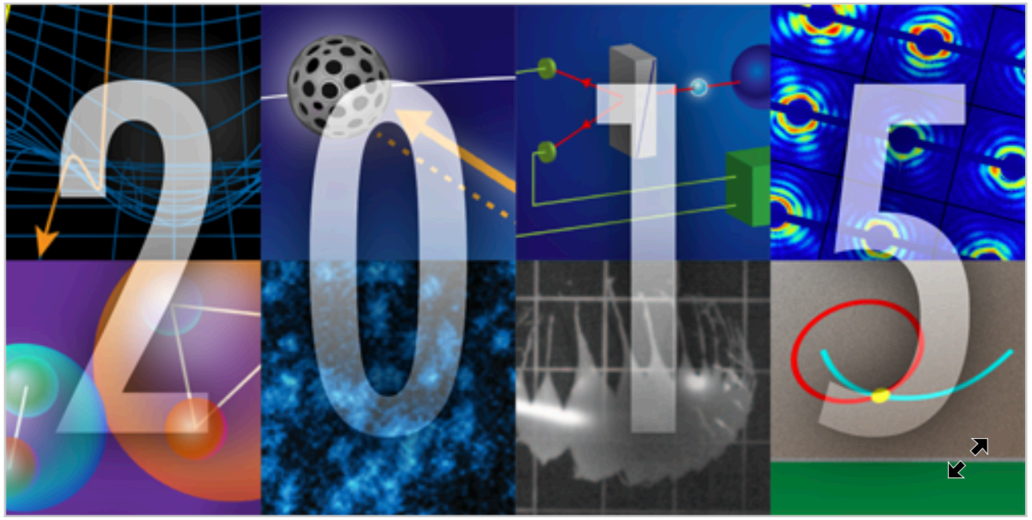
Heavy Flavor Exotic Hadrons



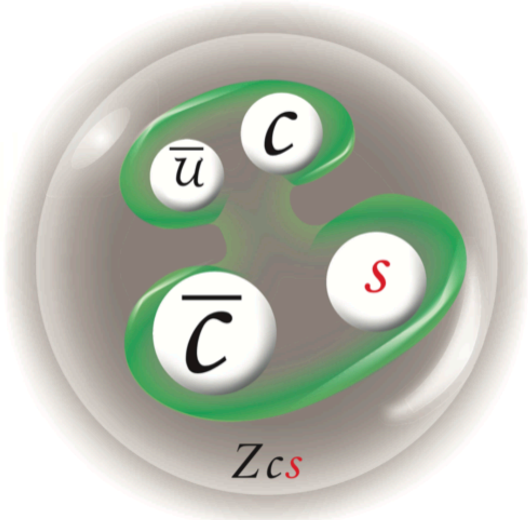
Research highlights of 2013:
Discovery of Zc(3900) at BESIII and Belle



2020: Discovery of Full-heavy Tetraquarks X(6900) at LHCb



Research highlights of 2015:
Discovery of Pentaquark at LHCb



2021: Discovery of Zcs(3985) at BESIII and Zcs(4000), Zcs(4220) at LHCb

A good platform to study the nature of strong interaction.
Deepen our understanding of low-energy dynamic behavior of QCD theory.

Heavy Flavor Exotic Hadrons in Exp.

- e+e- collisions: BESIII, Babar, Belle and CLEO

  Very clean experimental environment and various production mechanisms

- p-antiproton collisions: CDF, D0; pp collisions: LHCb, CMS, ATLAS…

  High statistic, decay of b hadrons (B and B_s mesons as well as the Λ_b baryon)

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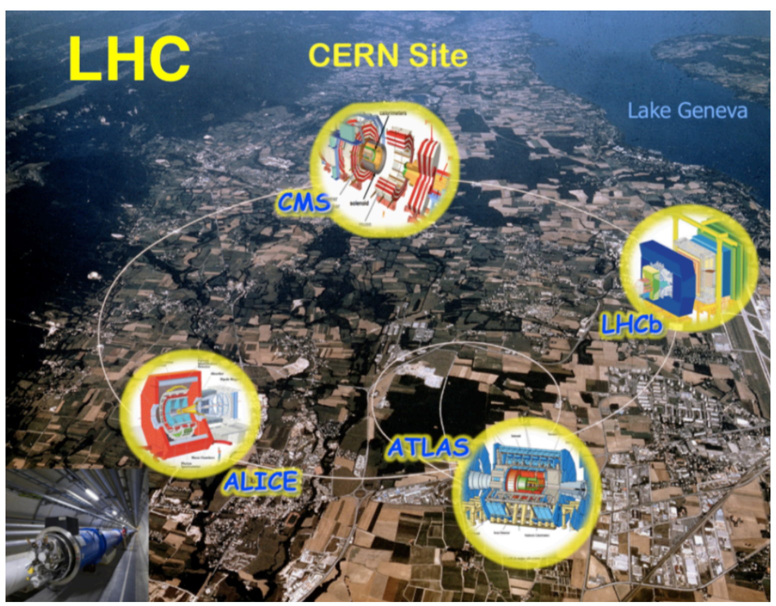
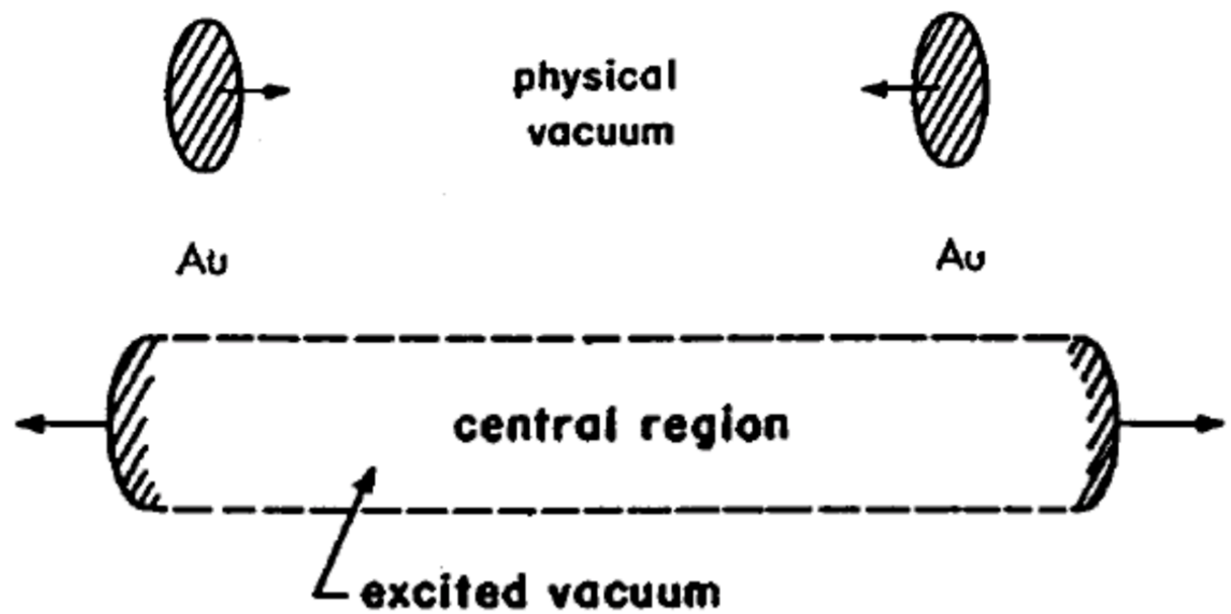
- Relativistic Heavy-ion Collisions at RHIC and LHC





T. D. Lee

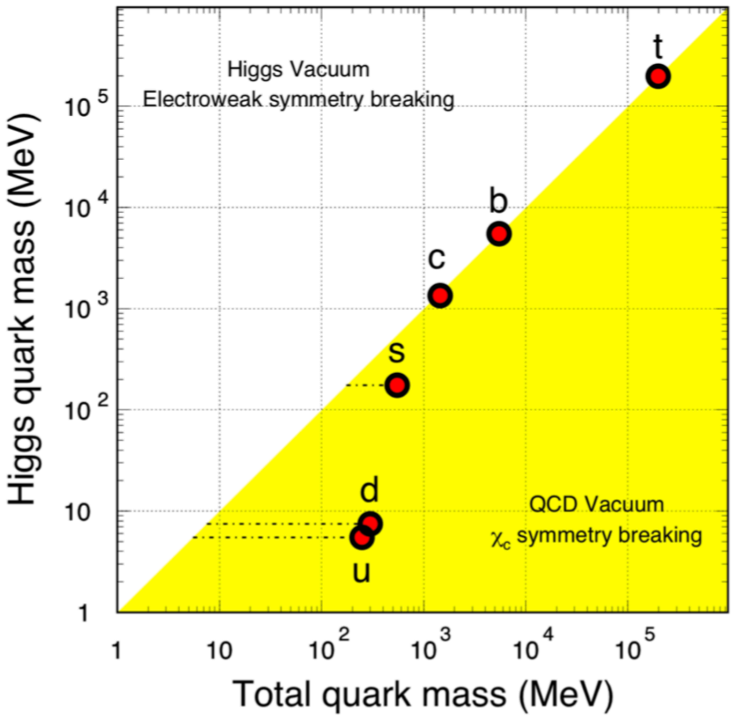
PbPb, $\sqrt{s_{NN}} \sim$ 2.76-5.02TeV

A new state of matter: Quark-Gluon Plasma(QGP) !

QGP: color deconfinement, chiral restoration, strong coupling(“prefect liquid”),…

Heavy Flavor: a sensitive probe of QGP

- *Heavy flavor can be used to probe and study the QGP !*



- *Mc, Mb >> Λ_{QCD}, produced by initial hard scattering and can be described by pQCD.*
- *Mass not change in QGP medium, number conserved. strong interaction with the hot medium.*
- *Heavy flavor hadrons produced on the boundary of QCD phase transition. Clear decay mode and easy to distinguish*

***JX. Zhao K. Zhou*, *ShL. Chen*, *PF. Zhuang*, *Prog. Part. Nucl. Phys.* 114 (2020) 103801.**

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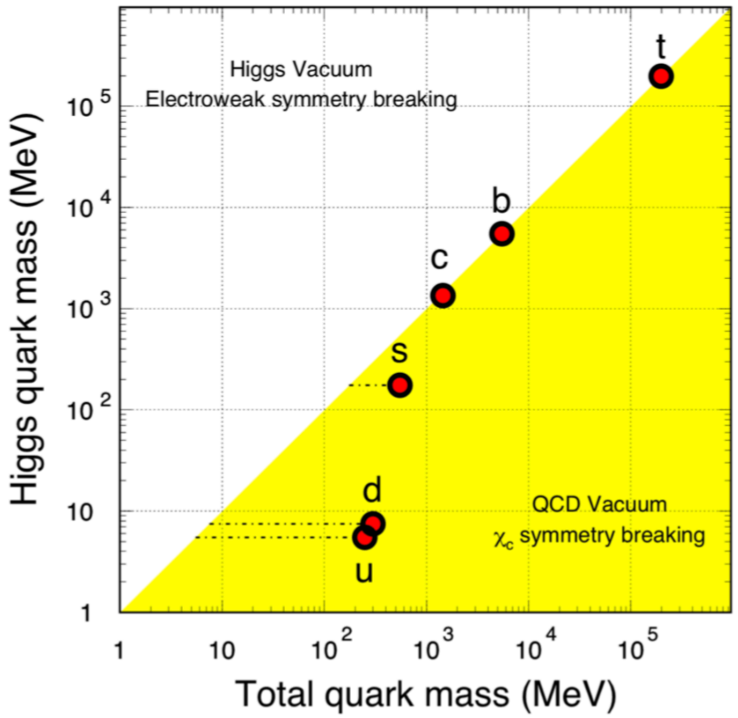

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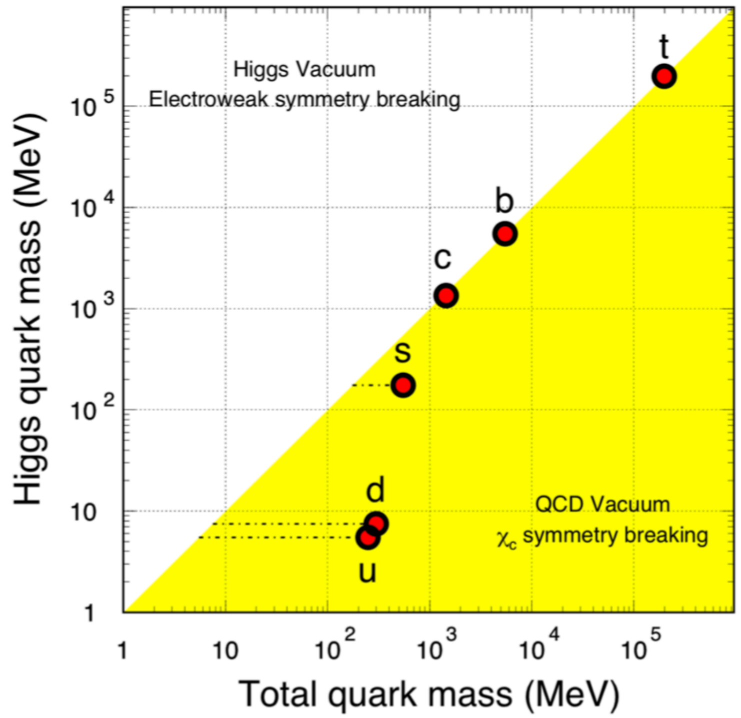

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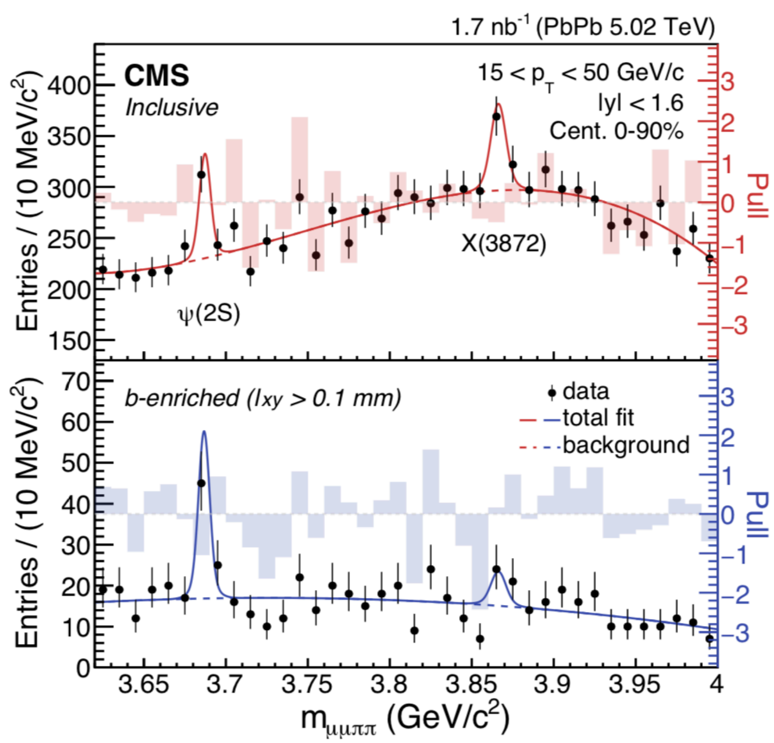

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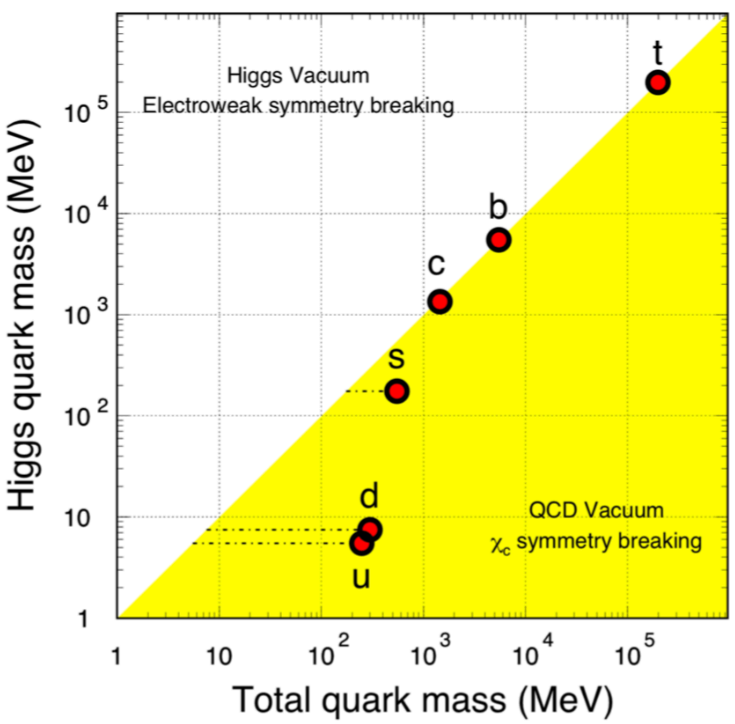

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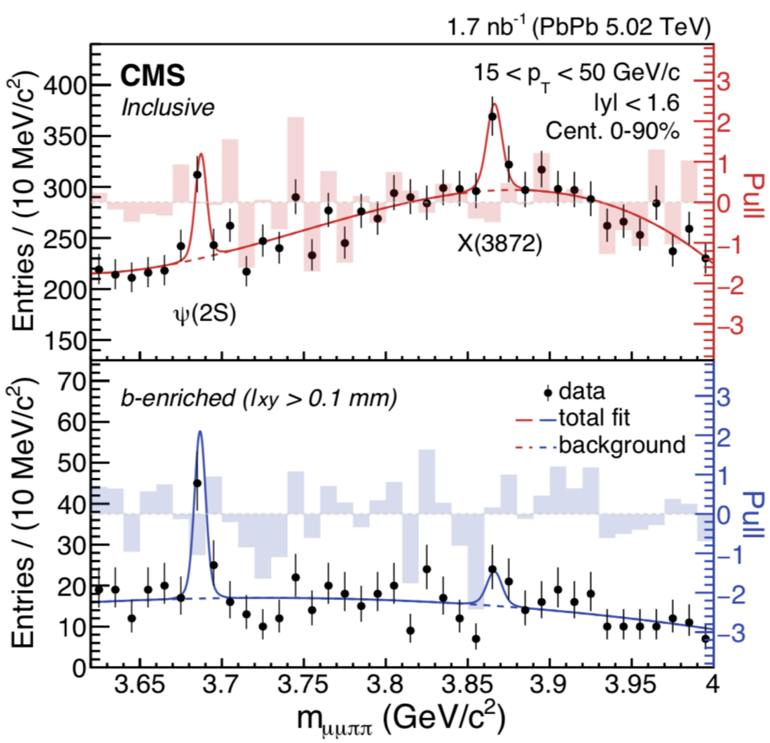

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*First evidence of **X(3872)** production in heavy ion collisions!*

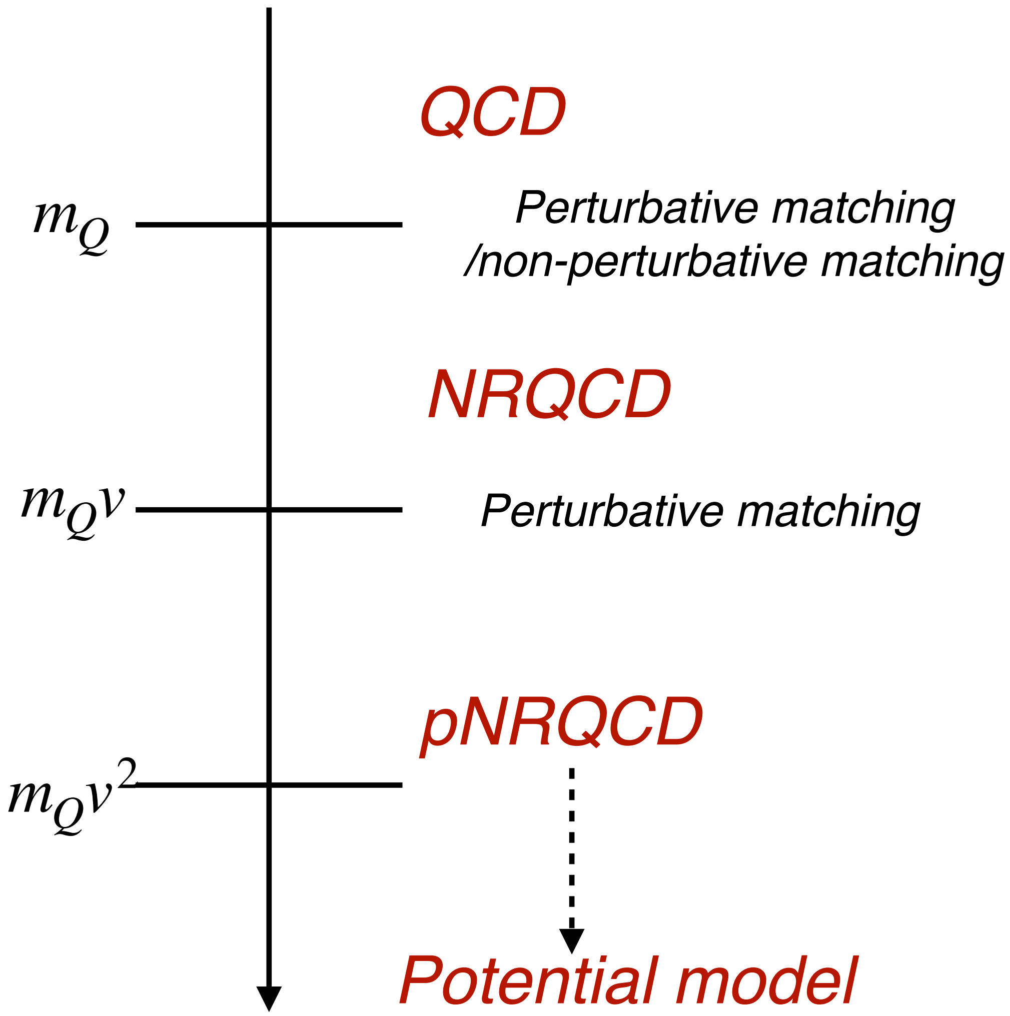
Fully-heavy Tetraquark properties and production in QGP !

Heavy Flavor Effective Theory

$$m_c \sim 1.5GeV, m_b \sim 4.7GeV$$

Separation of scales:

$$m_Q \gg m_Q v \gg m_Q v^2$$



"Top - down"

Nora Brambilla's talk in April.12

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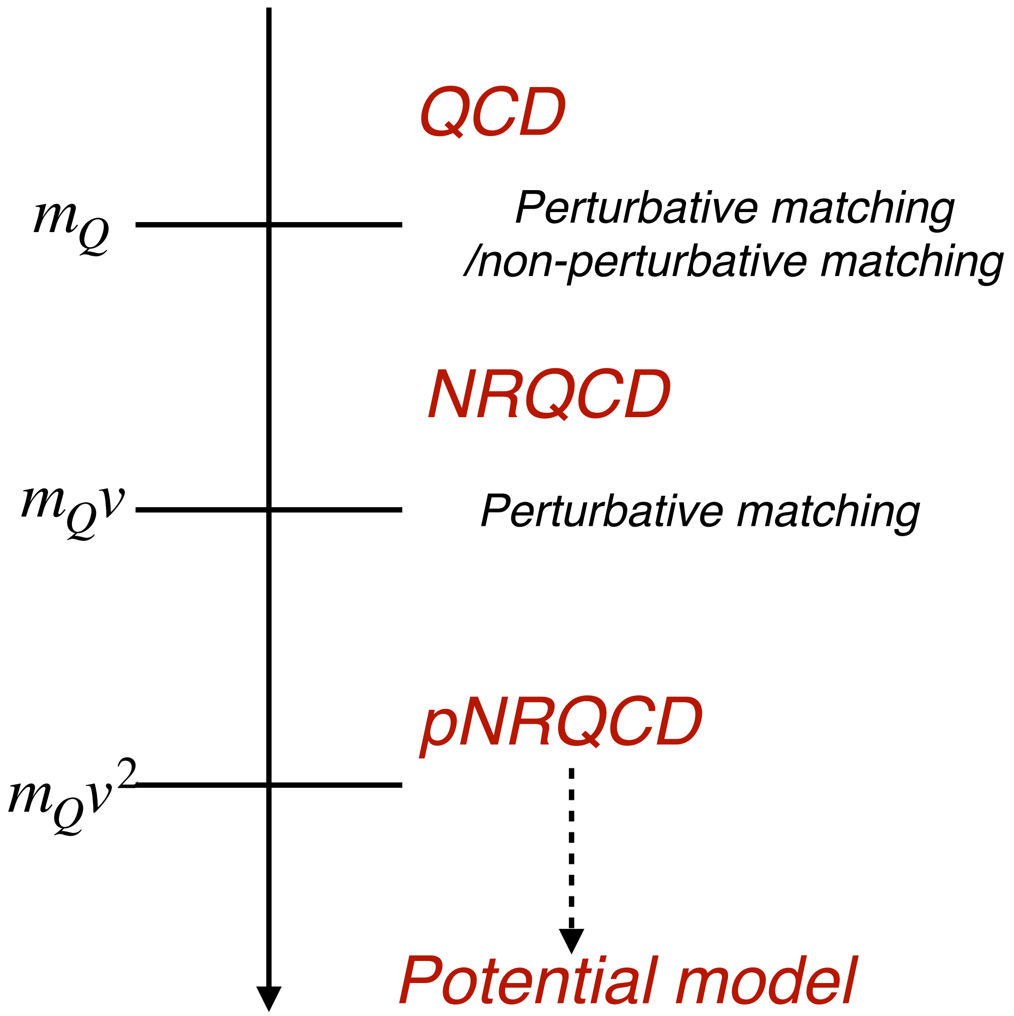

"Top - down"

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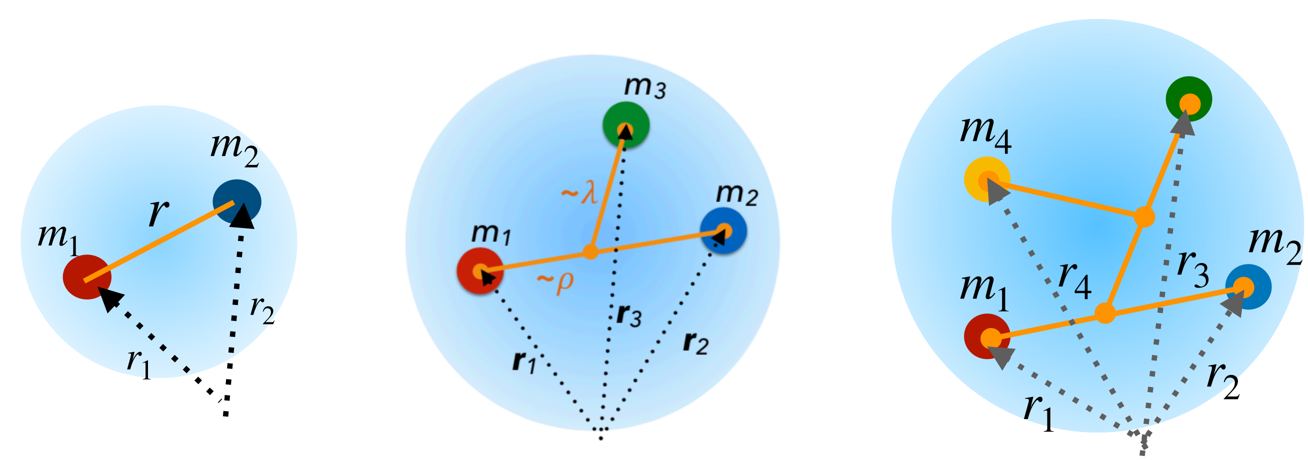
N-Body Schroedinger Equation Framework

$$\left(\sum_{i=1}^{N} \frac{\hat{p}_i^2}{2m_i} + \sum_{i<j} V_{ij} \right) \Psi(\mathbf{r}_1, \ldots, \mathbf{r}_N) = E \Psi(\mathbf{r}_1, \ldots, \mathbf{r}_N)$$

Jacobi coordinates :

$$\mathbf{R} = \frac{1}{M} \sum_{i=1}^{N} m_i \mathbf{r}_i,$$

$$\mathbf{x_j} = \sqrt{\frac{M_j m_{j+1}}{M_{j+1} \mu}} \left(\mathbf{r}_{j+1} - \frac{1}{M_j} \sum_{i=1}^{j} m_i \mathbf{r}_i \right)$$



Then, factorize the N-body motion into a center-of-mass motion and a relative motion

$$\Psi(\mathbf{r}_1, \ldots, \mathbf{r}_N) = \Theta(\mathbf{R}) \Phi(\mathbf{x}_1, \ldots, \mathbf{x}_{N-1}),$$

N-Body Schroedinger Equation Framework

Further, N-1 relative coordinates can be transformed to a single hyperradial coordinate and 3N-4 hyperangular coordinates.

$$(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{N-1}) \rightarrow (\rho, \alpha_{N-1}, \ldots, \alpha_2, \theta_1, \phi_1, \ldots, \theta_{N-1}, \phi_{N-1})$$

$$\rho = \sqrt{\mathbf{x}_1^2 + \ldots + \mathbf{x}_{N-1}^2} \qquad \sin\alpha_i = x_i/\rho_i \qquad \hat{x}_i = (\theta_i, \phi_i)$$

N. Barnea, et al. Phys. Rev. C 61.054001(2000)

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The relative motion is controlled by :

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$$\left[\frac{1}{2\mu} \left(-\frac{1}{\rho^{3N-4}} \frac{d}{d\rho} \rho^{3N-4} \frac{d}{d\rho} + \frac{\hat{K}_{N-1}^2}{\rho^2} \right) + V(\rho, \Omega) \right] \Phi(\rho, \Omega) = E_r \Phi(\rho, \Omega),$$

$$\hat{K}_{N-1}^2 = -\frac{\partial^2}{\partial \alpha_{N-1}^2} + \frac{(3N-9) - (3N-5)\cos(2\alpha_{N-1})}{\sin(2\alpha_{N-1})} \frac{\partial}{\partial \alpha_{N-1}} + \frac{1}{\cos^2 \alpha_{N-1}} \hat{K}_{N-2}^2 + \frac{1}{\sin^2 \alpha_{N-1}} \hat{l}_{N-1}^2,$$

$$\hat{K}_{N-1}^2 \mathcal{Y}_\kappa(\Omega) = K(K + 3N - 5) \mathcal{Y}_\kappa(\Omega).$$ *hyper-angular momentum operator*

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$$\Phi(\rho, \Omega) = \textstyle\sum_\kappa R_\kappa(\rho)\mathcal{Y}_\kappa(\Omega)$$ *hyper-spherical harmonic function expansion*

$$\left[\frac{1}{2\mu}\left(\frac{1}{\rho^{3N-4}}\frac{d}{d\rho}\rho^{3N-4}\frac{d}{d\rho} - \frac{K(K+3N-5)}{\rho^2}\right) + E_r\right]R_\kappa = \sum_{\kappa'} V_{\kappa\kappa'}R_{\kappa'}$$

Now, we apply this tool to deal with fully-heavy Tetraquark states !

Symmetric Analysis

Pauli exclusion principle requires the wave-function to be anti-symmetric when exchanging two identical fermions

$$\Psi = \psi \cdot \cancel{\phi_f} \cdot \chi_s \cdot \phi_c$$

Color $(3_c \otimes 3_c) \otimes (\bar{3}_c \otimes \bar{3}_c) = \bar{3}_c \otimes 3_c \oplus 6_c \otimes \bar{6}_c \oplus \bar{3}_c \otimes \bar{6}_c \oplus 6_c \otimes 3_c$

$$|\phi_1\rangle = |(QQ)_{\bar{3}_c}(\bar{Q}\bar{Q})_{3_c}\rangle, \quad |\phi_2\rangle = |(QQ)_{6_c}(\bar{Q}\bar{Q})_{\bar{6}_c}\rangle$$

Spin $2 \otimes 2 \otimes 2 \otimes 2 = 1 \otimes 1 \oplus 1 \otimes 3 \oplus 3 \otimes 1 \oplus 3 \otimes 3$

$$s = 0: \quad |\chi_1\rangle = |(QQ)_0(\bar{Q}\bar{Q})_0\rangle_0, \quad |\chi_2\rangle = |(QQ)_1(\bar{Q}\bar{Q})_1\rangle_0$$

$$s = 1: \quad |\chi_3\rangle = |(QQ)_0(\bar{Q}\bar{Q})_1\rangle_1, \quad |\chi_4\rangle = |(QQ)_1(\bar{Q}\bar{Q})_0\rangle_1, \quad |\chi_5\rangle = |(QQ)_1(\bar{Q}\bar{Q})_1\rangle_1$$

$$s = 2: \quad |\chi_6\rangle = |(QQ)_1(\bar{Q}\bar{Q})_1\rangle_2$$

So, for $cc\bar{c}\bar{c}$ *and* $bb\bar{b}\bar{b}$

$$J^{PC} = 0^{++}: \quad |\phi_1\chi_2\rangle \ \& \ |\phi_2\chi_1\rangle$$

$$J^{PC} = 1^{+-}: \quad |\phi_1\chi_5\rangle$$

$$J^{PC} = 2^{++}: \quad |\phi_1\chi_6\rangle$$

Solving the Coupled Equations

$J^{PC} = 0^{++}:$

$$\Phi(\rho,\Omega) = \sum_{\kappa} R_{\kappa}^{(1)}(\rho)\mathscr{Y}_{\kappa}(\Omega)\,|\,\phi_1\chi_2\rangle + R_{\kappa}^{(2)}(\rho)\mathscr{Y}_{\kappa}(\Omega)\,|\,\phi_2\chi_1\rangle$$

$$-\frac{1}{2\mu}\left(\frac{d^2}{d\rho^2}+\frac{8}{\rho}\frac{d}{d\rho}-\frac{K(K+7)}{\rho^2}\right)R_{\kappa}^{(1)} + \sum_{\kappa'} V_1^{\kappa\kappa'}R_{\kappa'}^{(1)} + \sum_{\kappa'} V_m^{\kappa\kappa'}R_{\kappa'}^{(2)} = E_r R_{\kappa}^{(1)}$$

$$-\frac{1}{2\mu}\left(\frac{d^2}{d\rho^2}+\frac{8}{\rho}\frac{d}{d\rho}-\frac{K(K+7)}{\rho^2}\right)R_{\kappa}^{(2)} + \sum_{\kappa'} V_2^{\kappa\kappa'}R_{\kappa'}^{(2)} + \sum_{\kappa'} V_m^{\kappa\kappa'}R_{\kappa'}^{(1)} = E_r R_{\kappa}^{(2)}$$

$J^{PC} = 1^{+-}\,,\ 2^{++}:$

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$$-\frac{1}{2\mu}\left(\frac{d^2}{d\rho^2}+\frac{8}{\rho}\frac{d}{d\rho}-\frac{K(K+7)}{\rho^2}\right)R_{\kappa} + \sum_{\kappa'} V^{\kappa\kappa'}R_{\kappa'} = E_r R_{\kappa}$$

$$V^{\kappa\kappa'} = \int V(\rho,\Omega)\mathscr{Y}_{\kappa}^{*}(\Omega)\mathscr{Y}_{\kappa'}(\Omega)d\Omega$$ *potential matrix element in angular momentum space*

- *Numerically solve the coupled differential equations with inverse power method*
- *Focus on the states with L=M=0, choose all hyperspherical harmonic functions with hyperangular quantum number K ≤ 3.*

Heavy Quark Potential

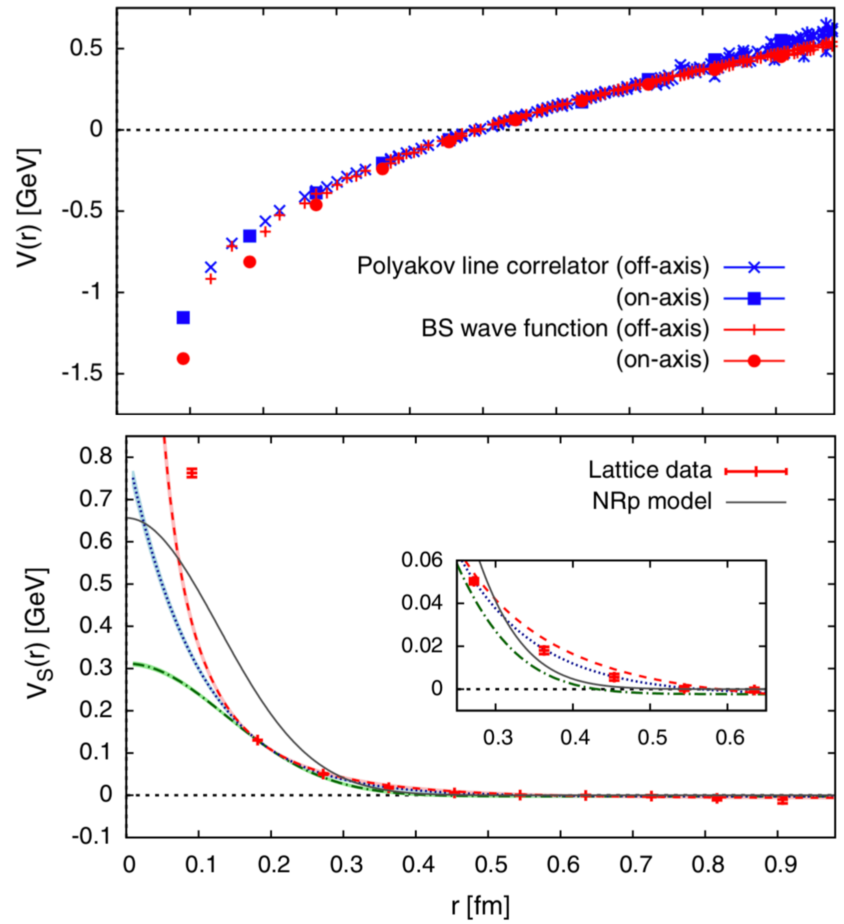
One-Gluon Exchange (OGE)

$$V_{ij}(|\mathbf{r}_{ij}|) = -\frac{1}{4}\lambda_i^a \cdot \lambda_j^a \left(V_{ij}^c(|\mathbf{r}_{ij}|) + V_{ij}^{ss}(|\mathbf{r}_{ij}|)\mathbf{s}_i \cdot \mathbf{s}_j\right)$$

$\lambda_i^a (a = 1,\ldots,8)$ *SU(3) Gell-Mann matrices*

Cornell potential

$$V_{ij}^c(|\mathbf{r}_{ij}|) = -\frac{\alpha}{|\mathbf{r}_{ij}|} + \sigma|\mathbf{r}_{ij}|$$



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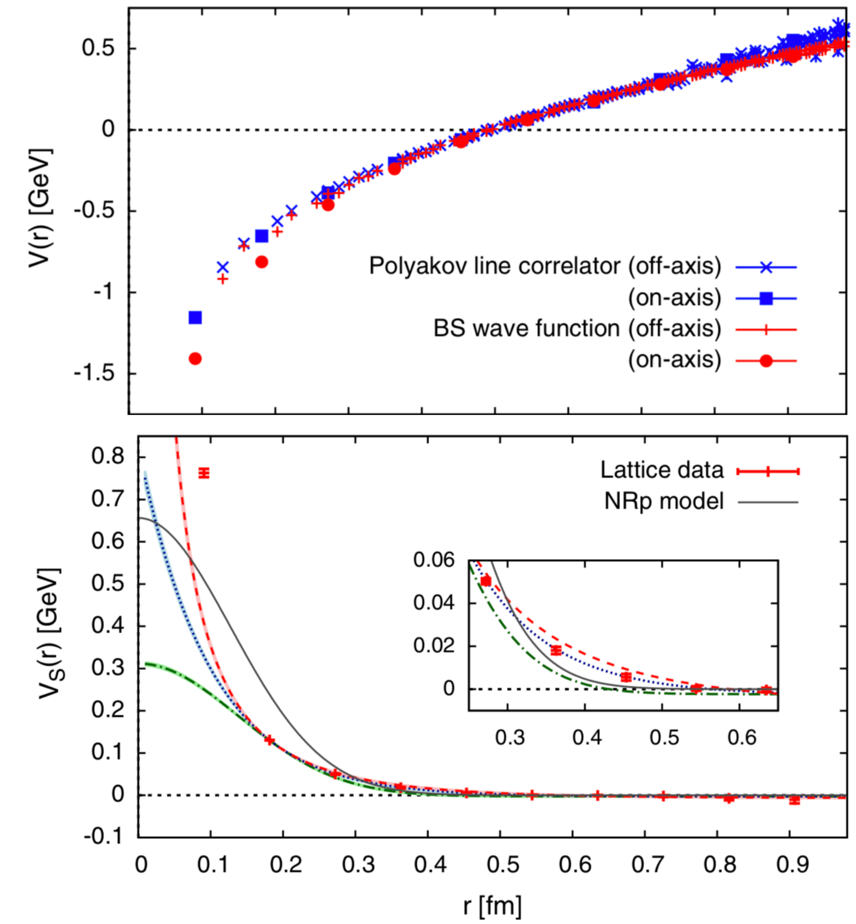

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Fixed by quarkonium mass in vacuum.

m_b	m_c	α	σ	γ	β_b	β_c
4.7 GeV	1.29 GeV	0.308	0.15 GeV^2	1.982 GeV	0.239 GeV	1.545 GeV

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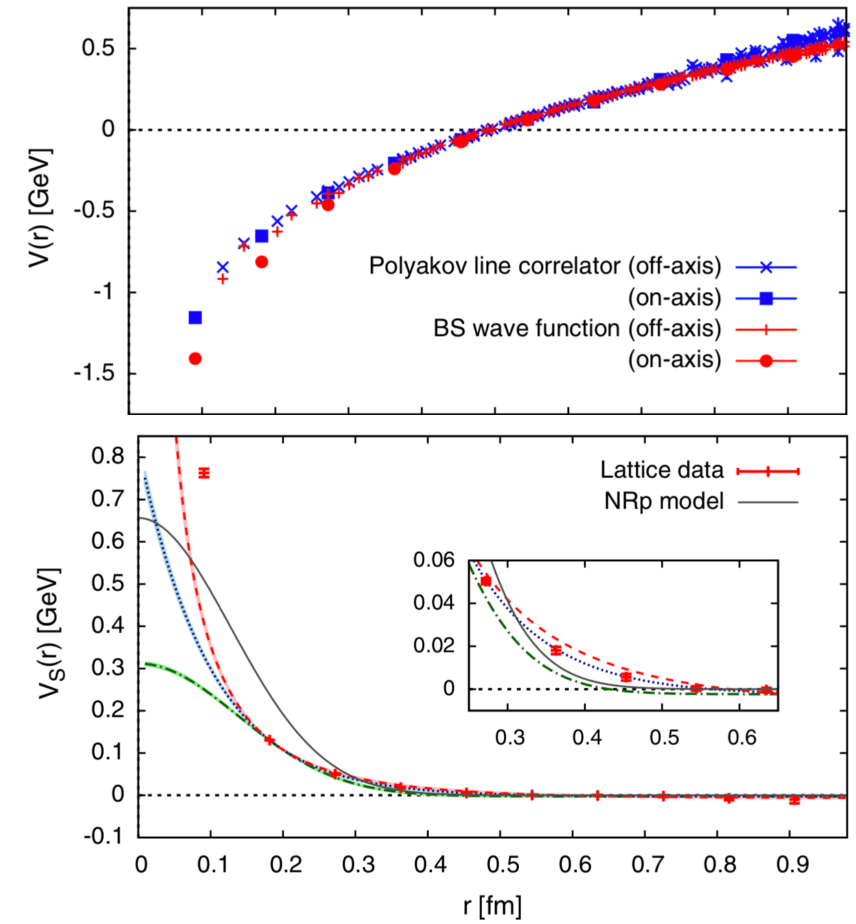

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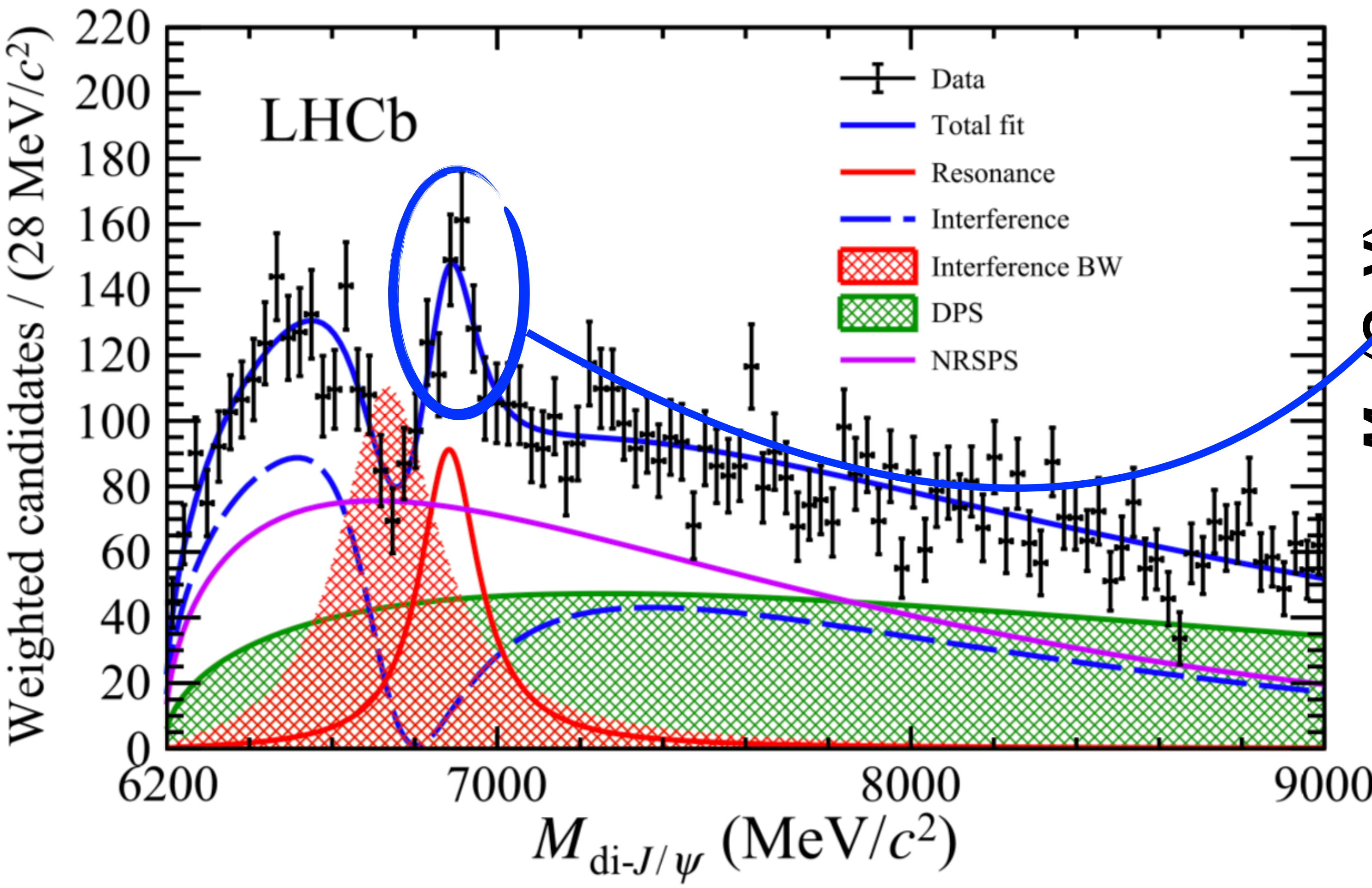
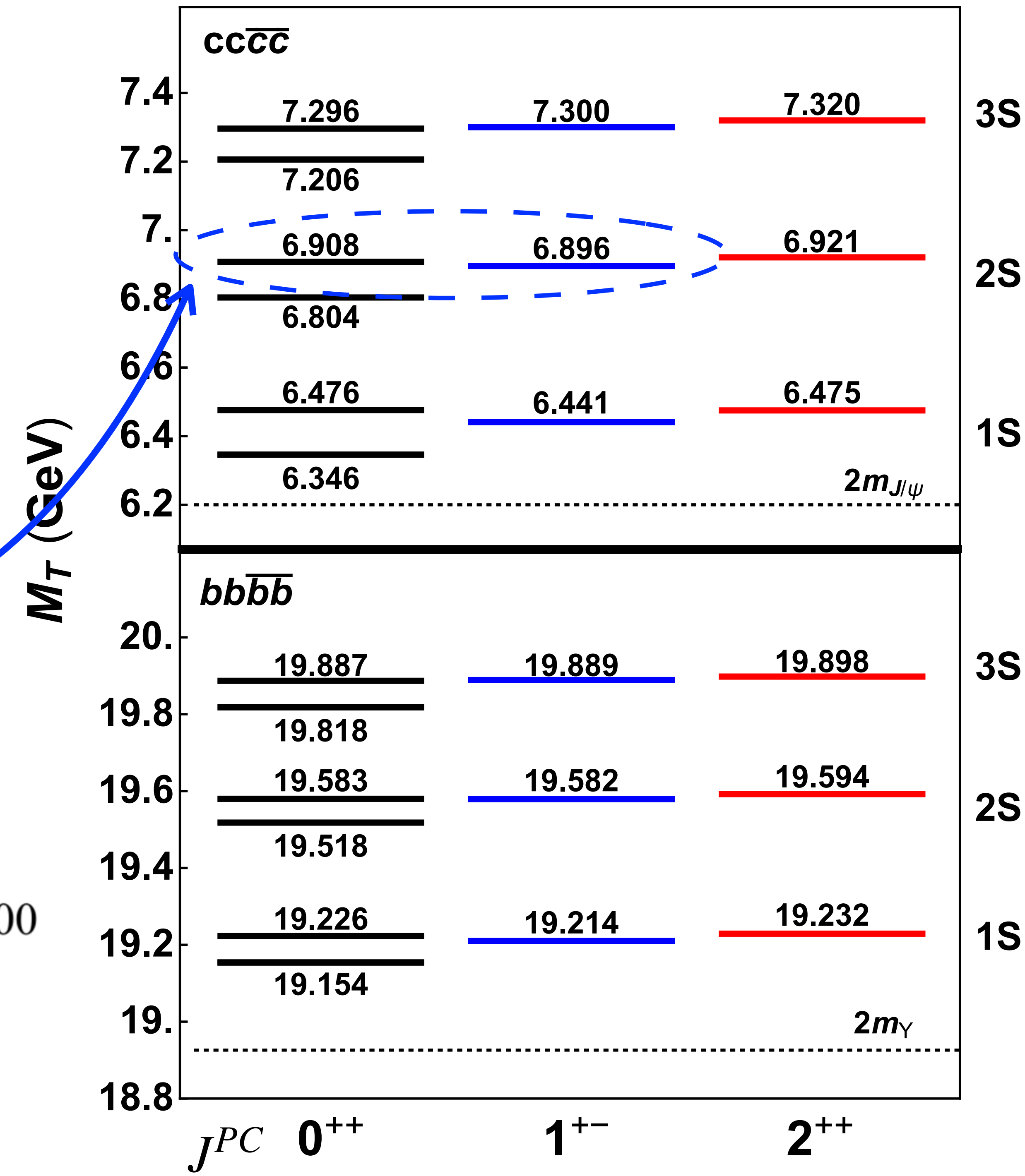
State	η_c	J/ψ	$h_c(1P)$	$\chi_c(1P)$	$\eta_c(2S)$	$\psi(2S)$	$\chi_c(2P)$
M_E (GeV)	2.981	3.097	3.525	3.556	3.639	3.696	3.927
M_T (GeV)	2.968	3.102	3.480	3.500	3.654	3.720	4.000

State	η_b	$\Upsilon(1S)$	$h_b(1P)$	$\chi_b(1P)$	$\eta_b(2S)$	$\Upsilon(2S)$	$\chi_b(2P)$
M_E (GeV)	9.398	9.460	9.898	9.912	9.999	10.023	10.269
M_T (GeV)	9.397	9.459	9.845	9.860	9.957	9.977	10.221

Agree very well with the experiment data !

Results





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

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

LHCb Collaboration, Science Bulletin, 2020, 65(23)1983-1993

- *The X(6900) is probably the 1st excited state of $cc\bar{c}\bar{c}$ with $J^{PC} = 0^{++} or\ 1^{+-}$*

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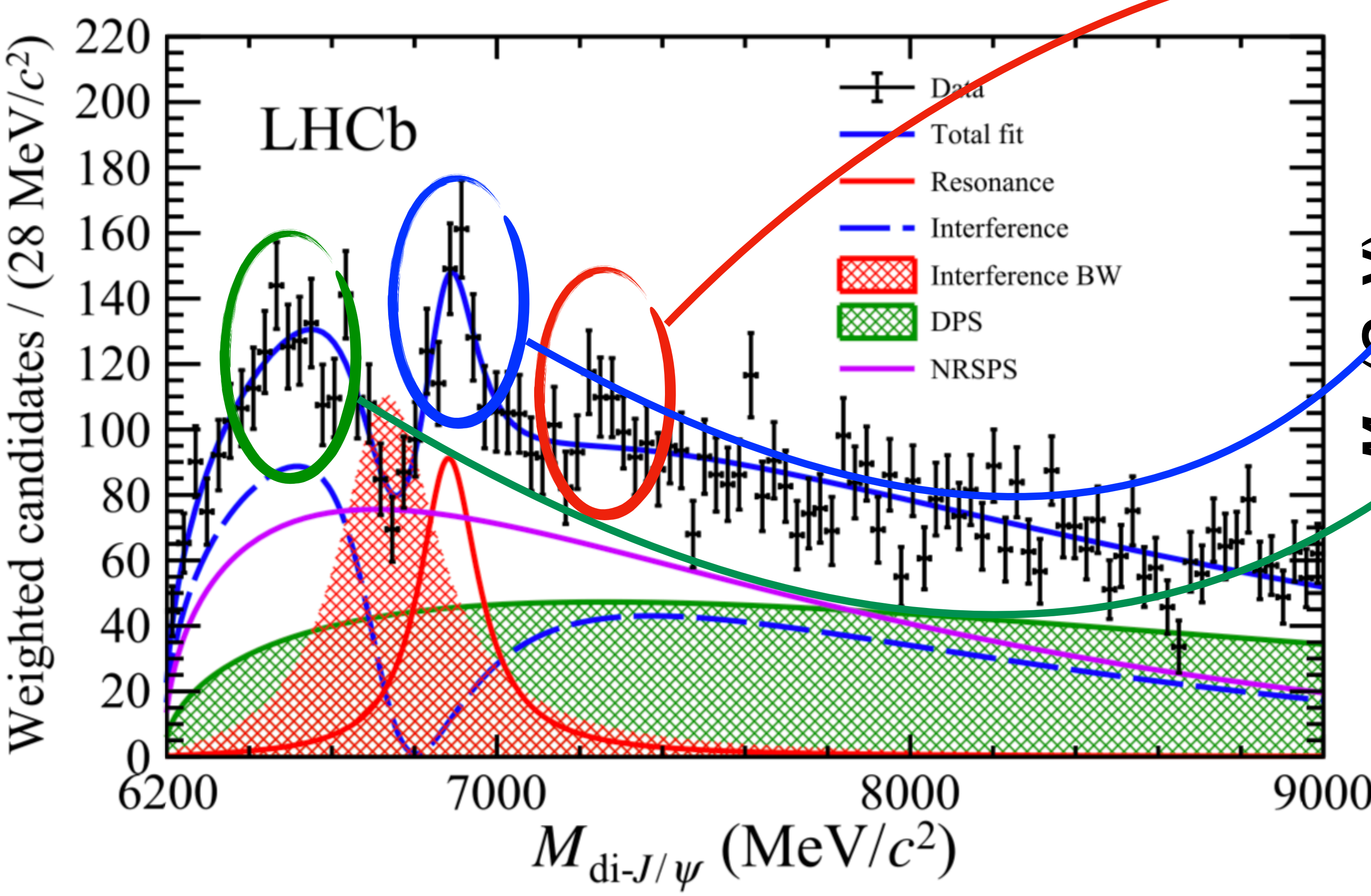

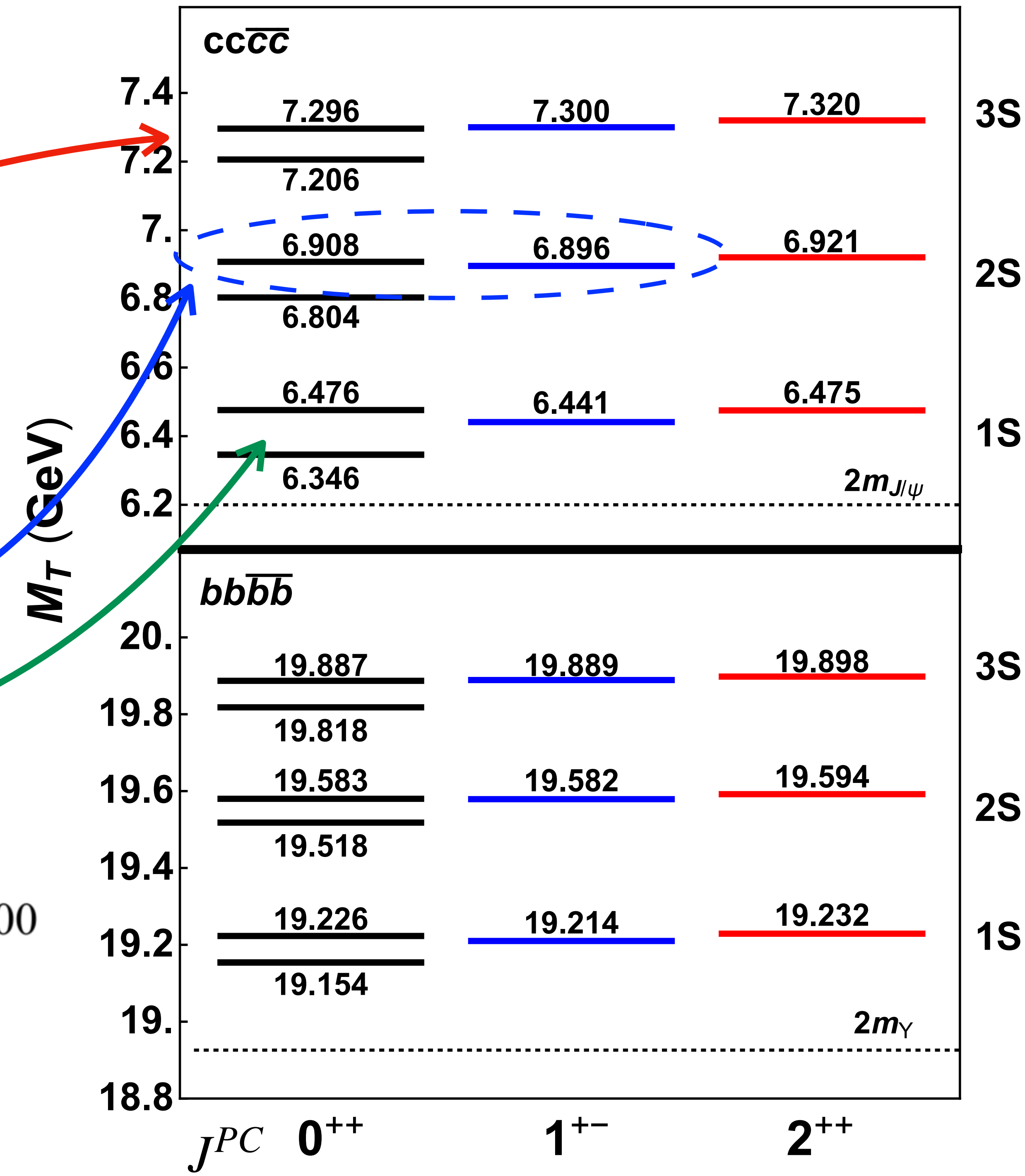

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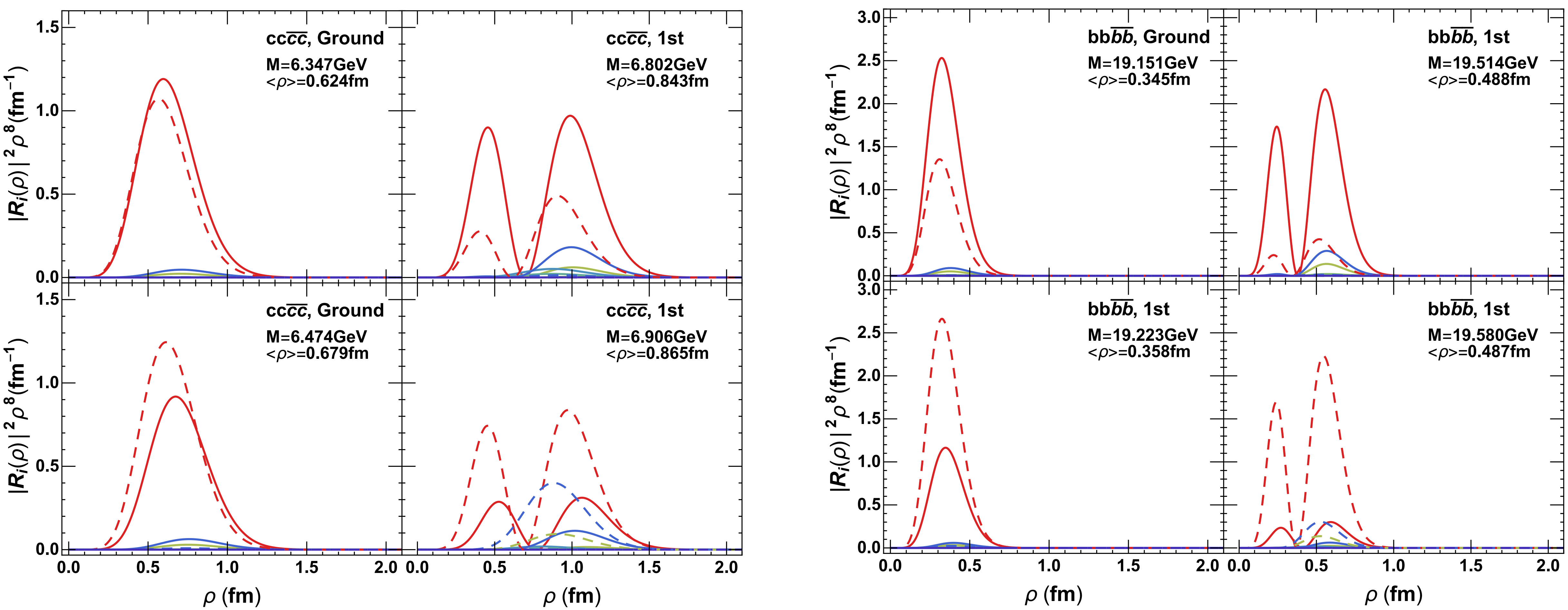
- *The X(6900) is probably the 1st excited state of* $cc\bar{c}\bar{c}$ *with* $J^{PC} = 0^{++} or\ 1^{+-}$
- *The potential states(~6.4GeV and ~7.2GeV) might be the ground and 2nd excited states.*

Results

JX Zhao, ShZh. shi, and Pf. Zhuang, Phys.Rev.D 102 (2020) 11, 114001

J^{PC}		0^{++}						1^{+-}			2^{++}		
State		$1S$		$2S$		$3S$		$1S$	$2S$	$3S$	$1S$	$2S$	$3S$
$cc\bar{c}\bar{c}$	M_T (GeV)	6.346	6.476	6.804	6.908	7.206	7.296	6.441	6.896	7.300	6.475	6.921	7.320
	r_{rms} (fm)	0.323	0.351	0.445	0.457	0.550	0.530	0.331	0.446	0.547	0.339	0.452	0.552
$bb\bar{b}\bar{b}$	M_T (GeV)	19.154	19.226	19.518	19.583	19.818	19.887	19.214	19.582	19.889	19.232	19.594	19.898
	r_{rms} (fm)	0.180	0.186	0.259	0.259	0.328	0.325	0.181	0.257	0.324	0.183	0.259	0.326



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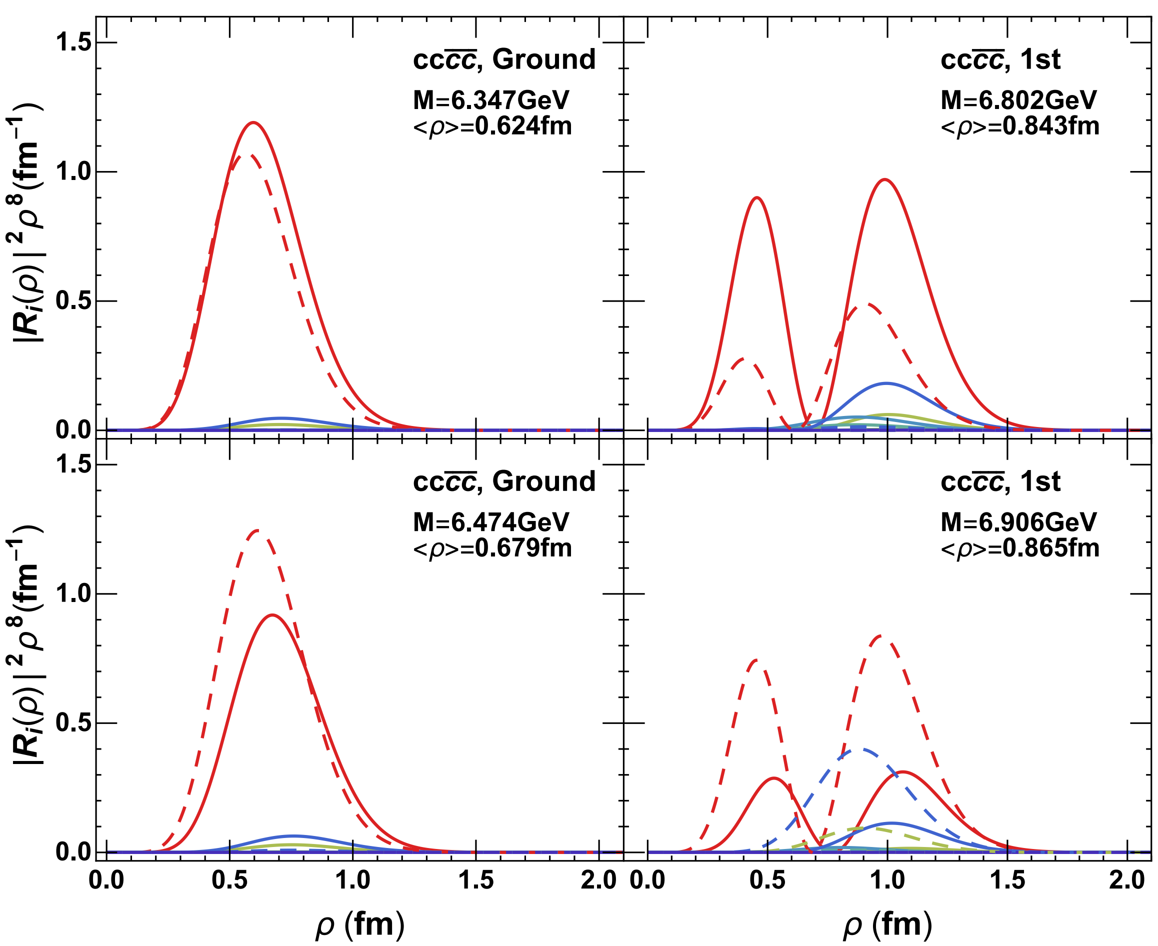
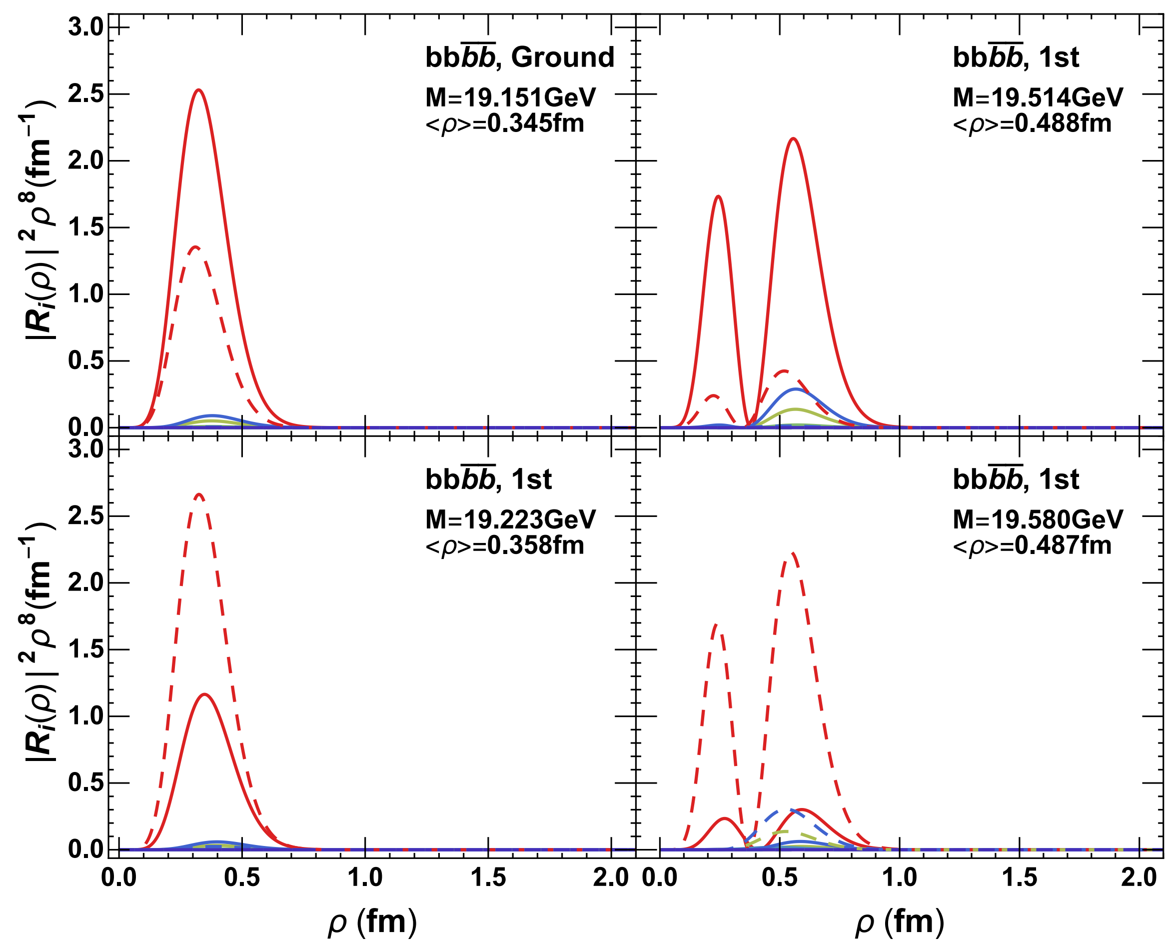




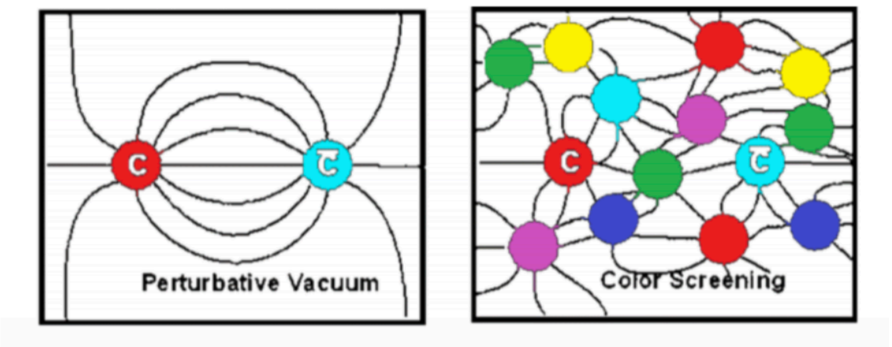
Yield and decay width:

F. Feng, Y. Huang, Y. Jia, WL. Sang, X. Xiong, J-Y. Zhang, arXiv: 2009.08450.

C. Becchi, A. Giachino, L. Maiani, E. Santopinto, arXiv: 2006.14388.

Heavy Quark Potential at Finite-temperature

Color Screening in hot dense medium：



Hard Thermal Loop (HTL)：

$$-\frac{\alpha}{r} \to -\frac{\alpha}{r}e^{-m_D r} \qquad m_D^2 = \frac{1}{3}g^2T^2\left(N_c + \frac{N_f}{2}\right)$$

N. Brambilla, J. Ghiglieri, A. Vairo, and P. Petreczky, Phys. Rev. D 78, 014017 (2008).

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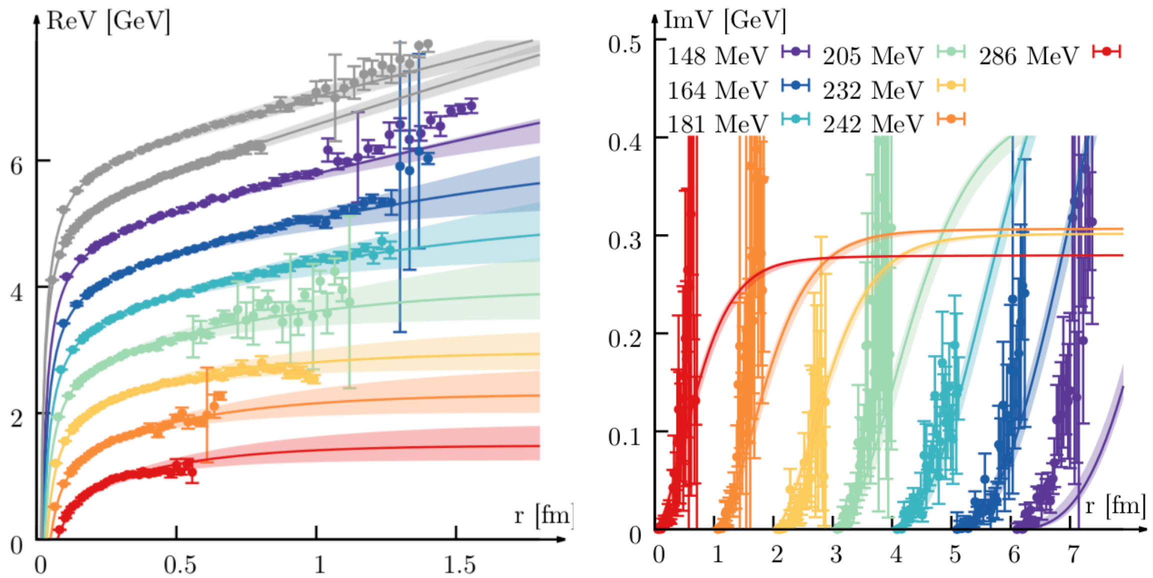

Burnier Y, Kaczmarek O, Rothkopf A. JHEP, 2015, 12:101.

D. Lafferty, A. Rothkopf, Phys.Rev.D 101 (2020) 5, 056010 .

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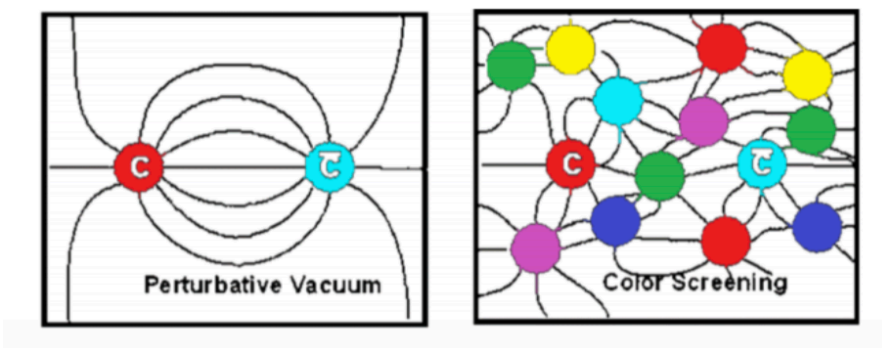

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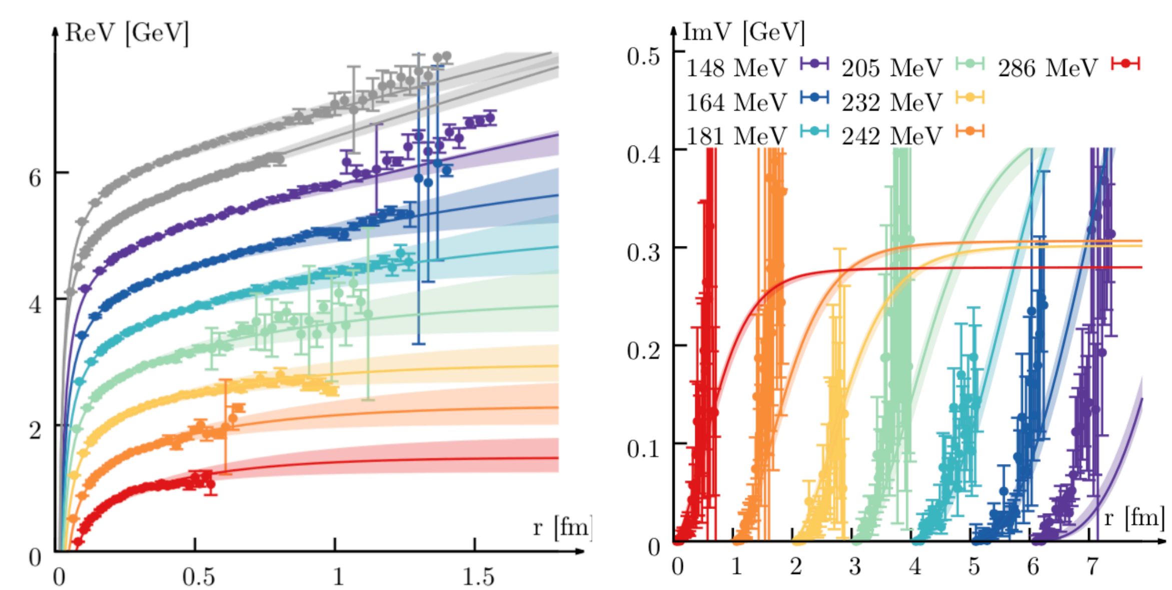

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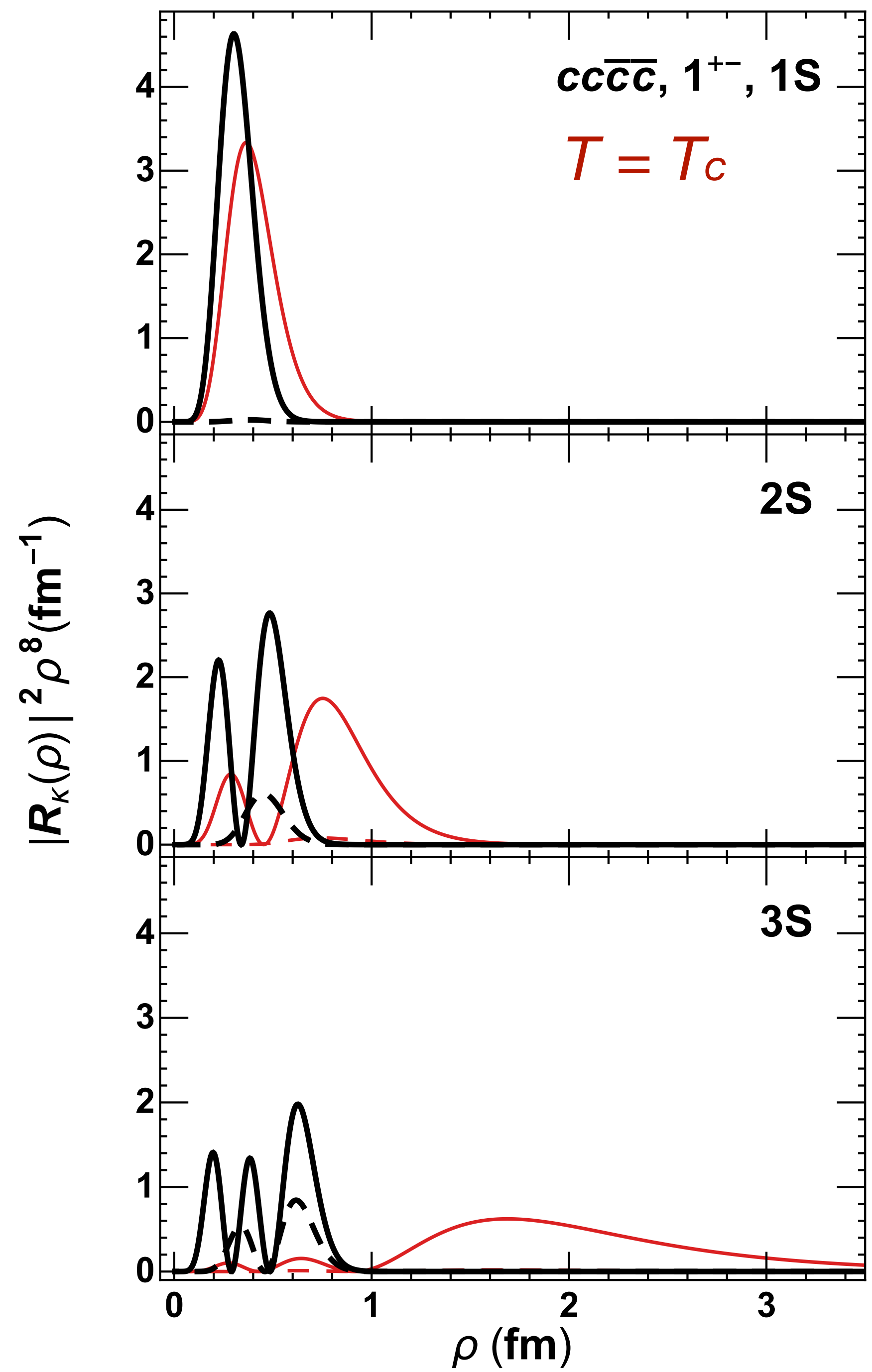
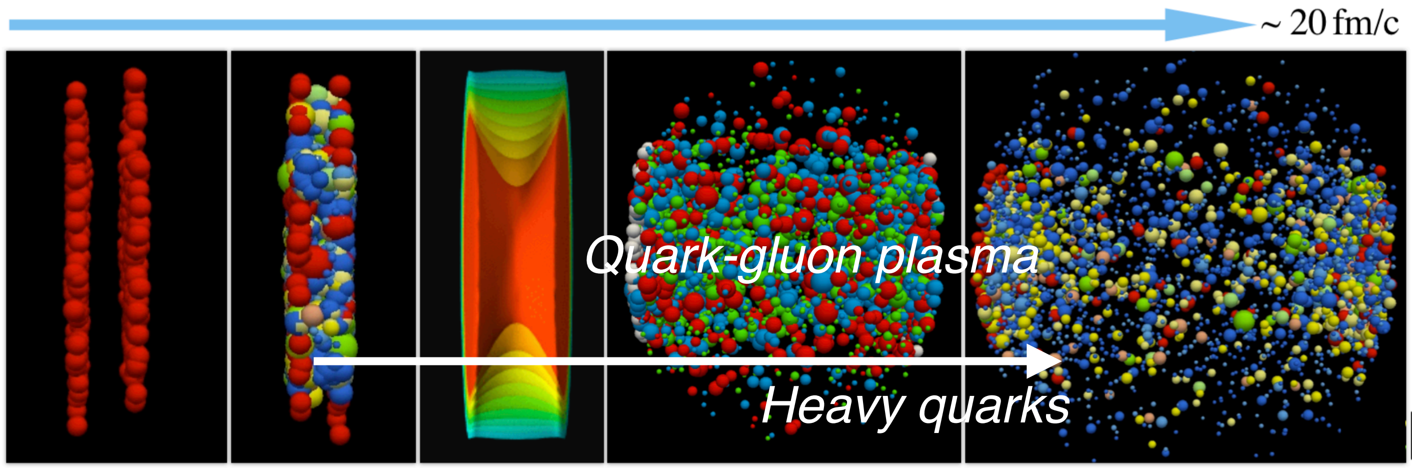
Wave function at QCD phase transition temperature T_c



Dissociation temperature

	$cc\bar{c}\,\bar{c}$			$bb\bar{b}\,\bar{b}$		
	1S	2S	3S	1S	2S	3S
T_d/T_c	1.08	1.02	1.0	2.40	1.85	1.30

Dynamical production (color recombination on the phase boundary)



Heavy flavor initial production: pQCD

Evolve in the QGP medium: Langevin equation

Dynamic production: Coalescence model

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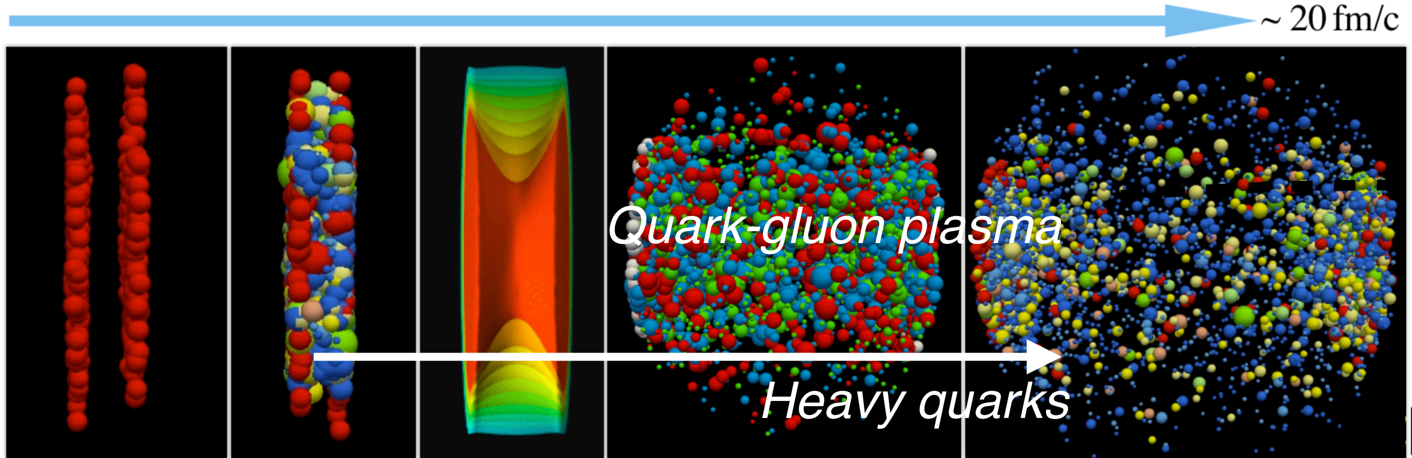

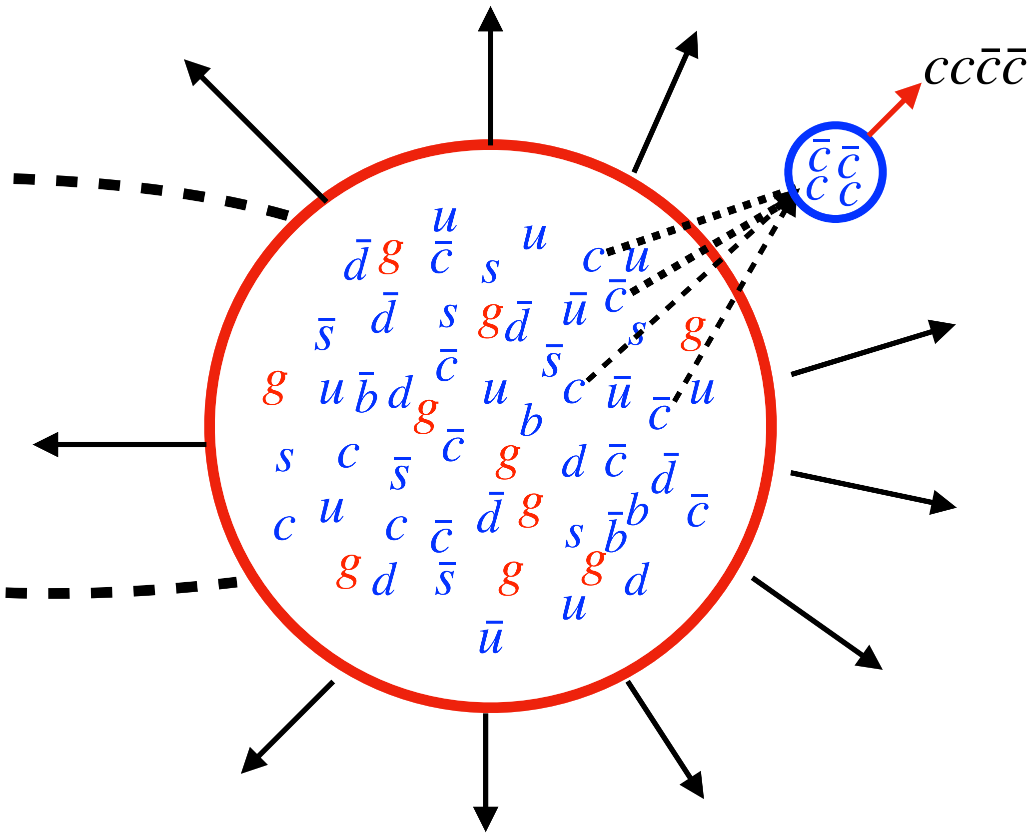

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$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int_{\Sigma} \frac{P_\mu d\sigma_\mu}{(2\pi)^3} \int \frac{d^9\mathbf{x} d^9\mathbf{y}}{(2\pi)^9} F(r_1, r_2, r_3, r_4, p_1, p_2, p_3, p_4) W(\mathbf{x}, \mathbf{p})$$

V. Greco, C. M. Ko and R. Rapp, Phys. Lett. B 595, 202 (2004).
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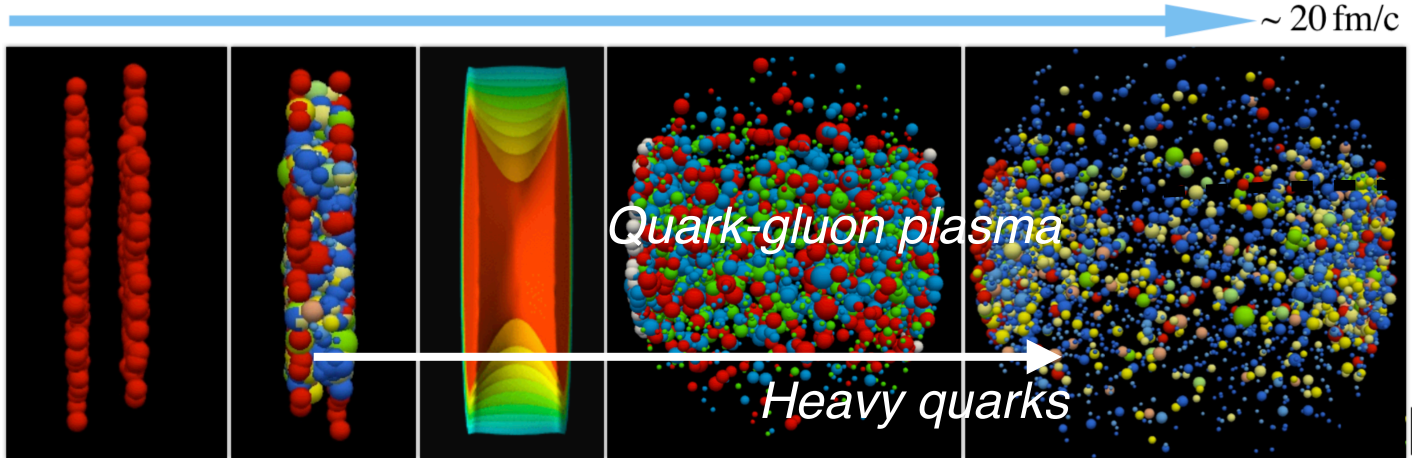

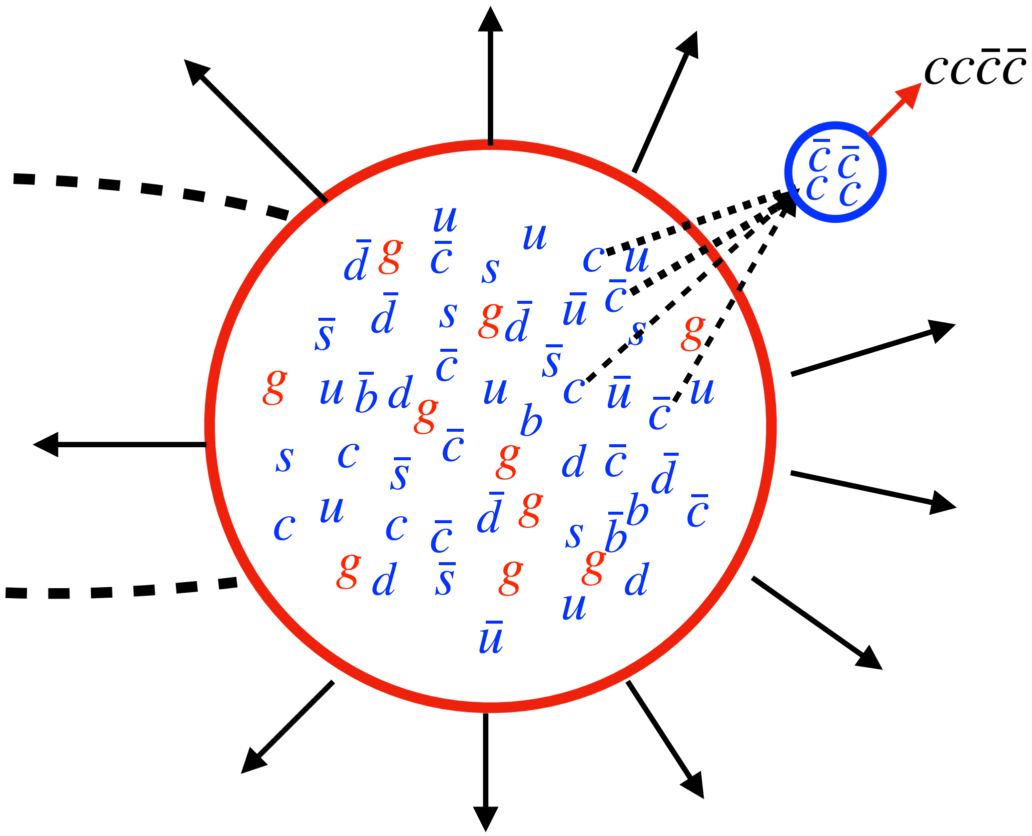

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- *The hadronization hypersurface is determined by the hydrodynamics.*
- *The Wigner function can self-consistently be determined by the wavefunction.*

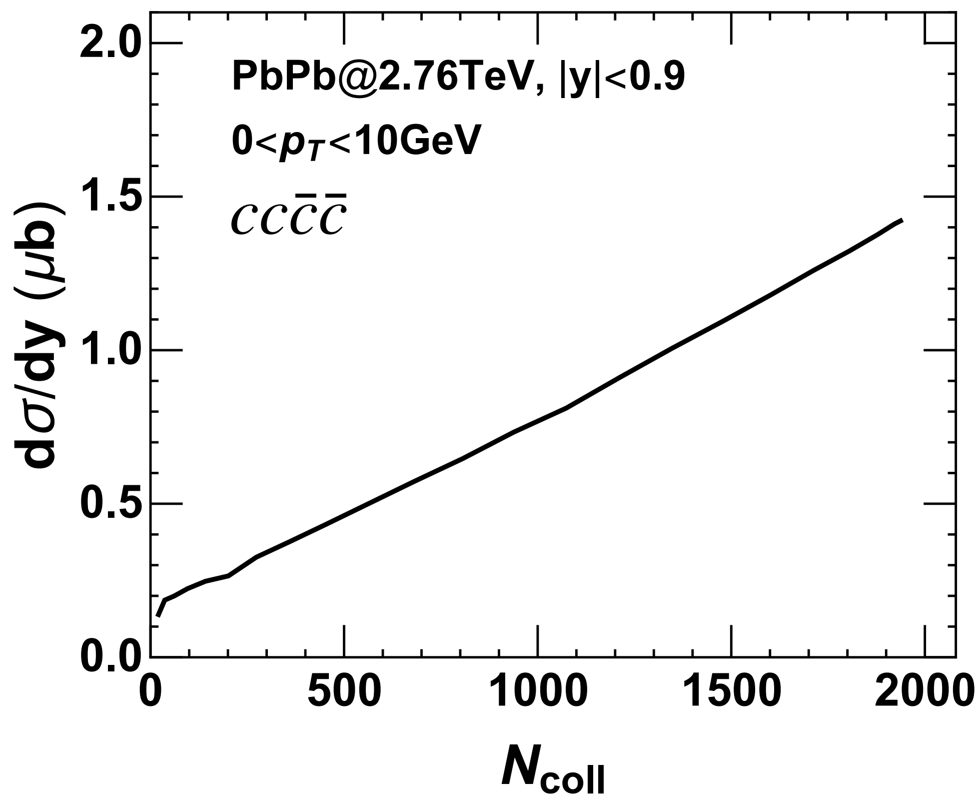
$$W(\mathbf{x},\mathbf{p},T) = \int d^9\mathbf{y}e^{-i\mathbf{p}\cdot\mathbf{y}}\Phi\left(\mathbf{x}+\frac{\mathbf{y}}{2},T\right)\Phi\left(\mathbf{x}-\frac{\mathbf{y}}{2},T\right).$$

- *Heavy quark distribution functions*

$$F(r_1,r_2,r_3,r_4,p_1,p_2,p_3,p_4) = \frac{1}{4} f_Q(r_1,p_1)\, f_Q(r_2,p_2)\, f_{\bar{Q}}(r_3,p_3)\, f_{\bar{Q}}(r_4,p_4)$$

Results

Fully-heavy Tetraquark state production in heavy-ion collisions!



1 Pb+Pb collisions ≈ 2000 p+p collisions.

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

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

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

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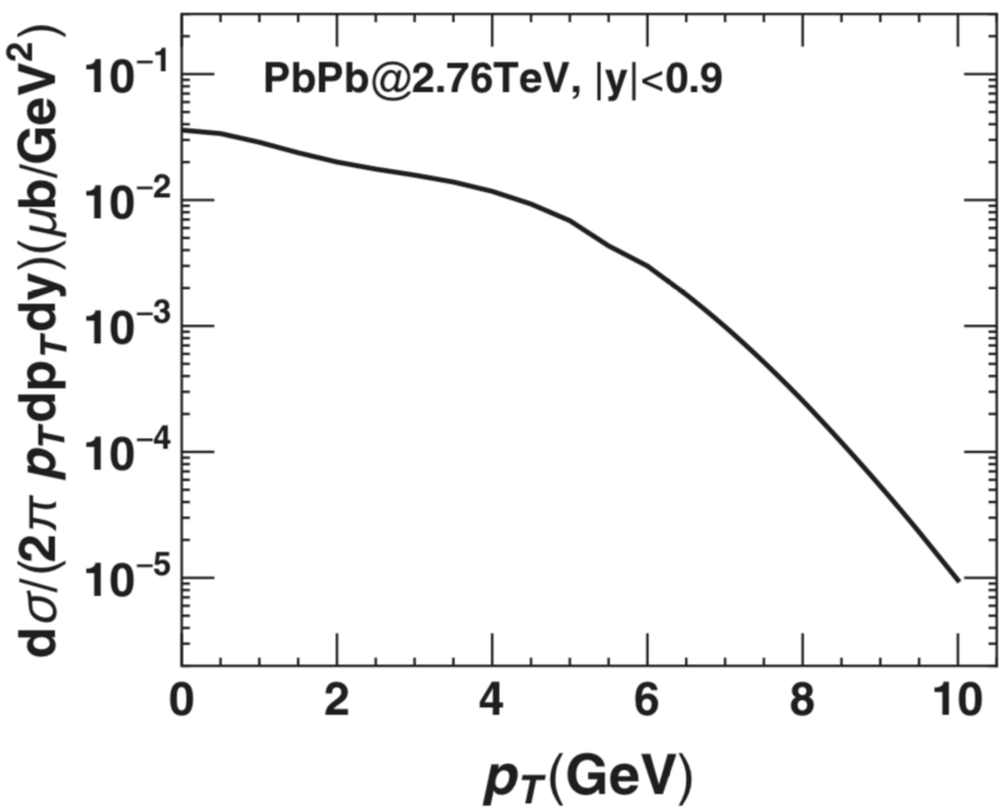

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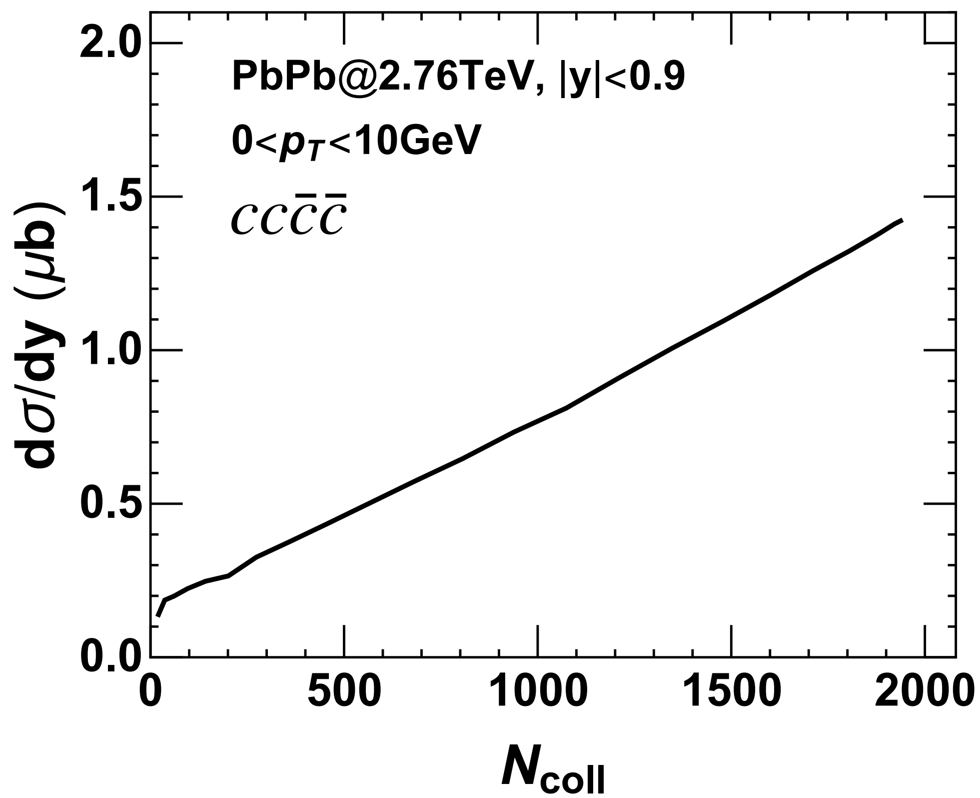

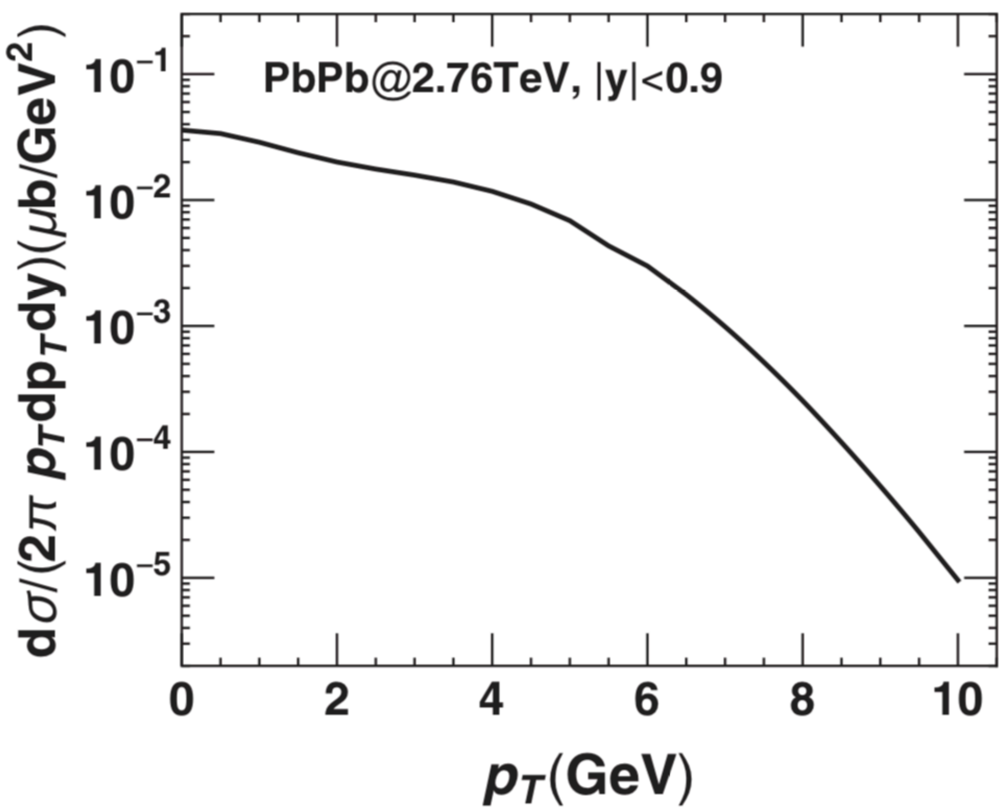

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$$X(cc\bar{c}\bar{c}) \rightarrow l_1^+ l_2^- l_3^+ l_4^-$$

can be well separated from the bulk back ground and makes it possible to find such exotic states in heavy-ion collision even in low pt region!

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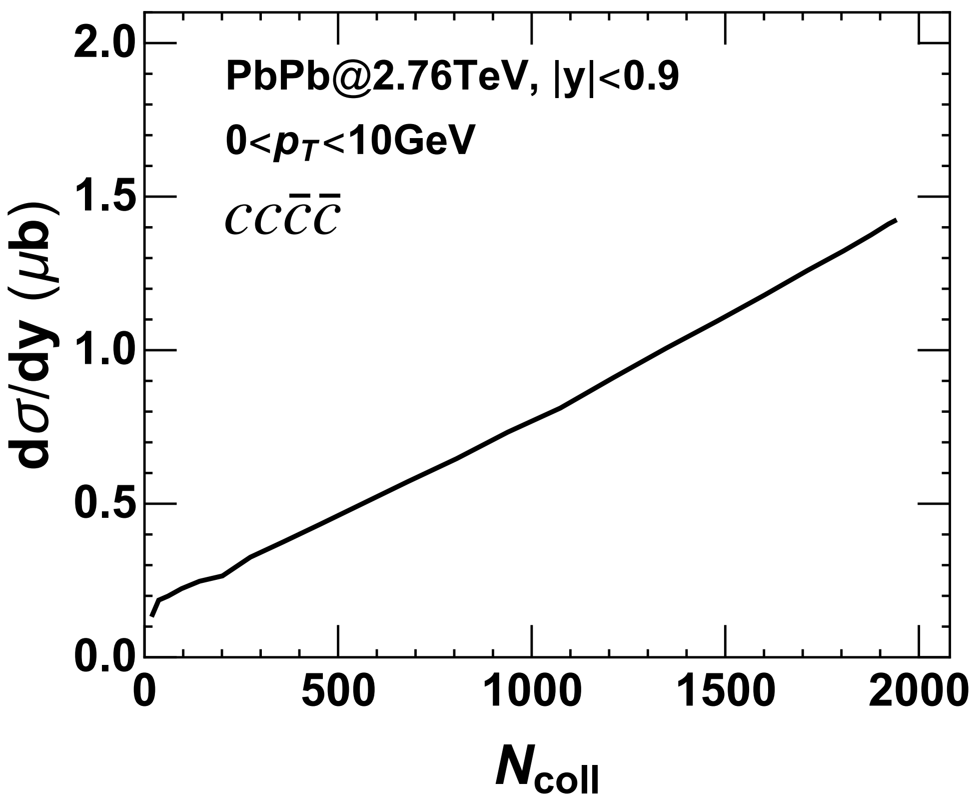

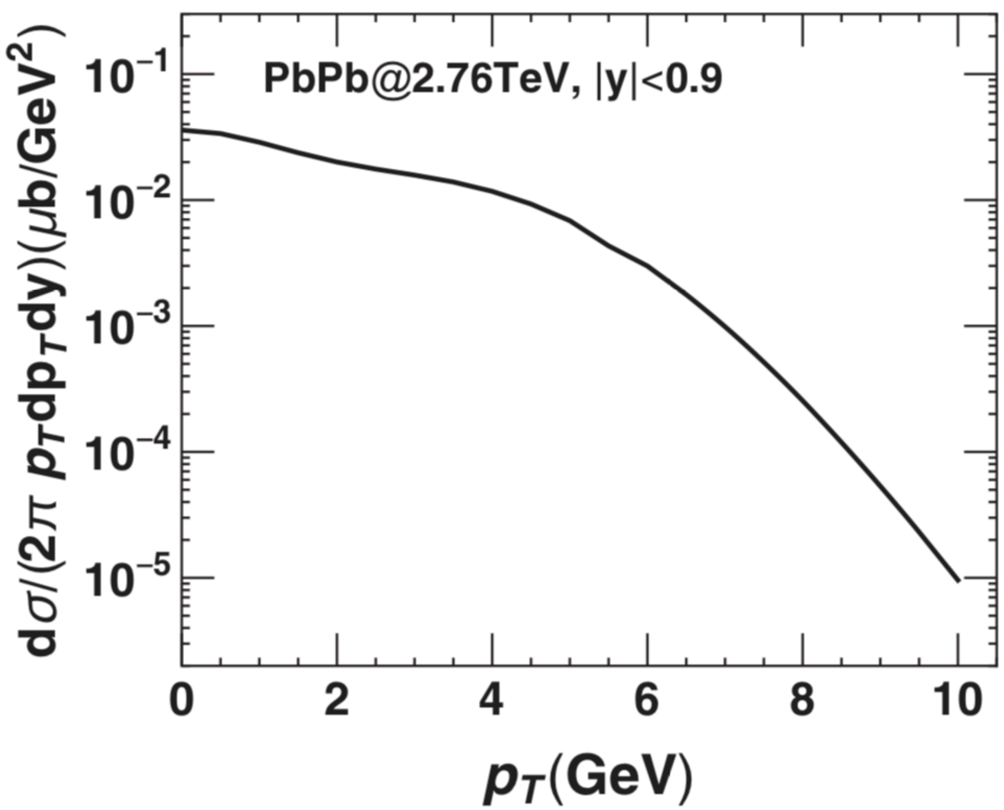

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CMS

Summary

- *We studied fully-heavy Tetraquark in vacuum and finite-temperature via 4-body Schroedinger equation.*

Finite temperature properties → *Dynamic production in relativistic heavy ion collisions!*

- *Due to the color recombination of uncorrelated charm quarks, the yield significantly enhanced comparing with p+p collisions !*

This supply a way to searching for more fully-heavy Tetraquark states in the experiment.

Outlook

- *The angle excited(L=1, 2…) states of fully-heavy Tetraquark states.*
- *Searching for new observables of fully-heavy Tetraquark states in heavy-ion collisions.*

Thanks for your attention!

Backup

hyper-spherical harmonic function expansion
(L = M = 0)

$$\mathcal{Y}_1 = \sqrt{\frac{105}{32}}\frac{1}{\pi^2},$$

$$\mathcal{Y}_2 = \sqrt{\frac{385}{6}}\frac{3}{16\pi^2}(3\cos(2\alpha_3) - 1),$$

$$\mathcal{Y}_3 = \sqrt{\frac{385}{2}}\frac{3}{8\pi^2}\cos(2\alpha_2)\cos^2(\alpha_3),$$

$$\mathcal{Y}_4 = -\sqrt{\frac{385}{2}}\frac{3}{4\pi^2}\cos\alpha_2\sin\alpha_2\cos^2\alpha_3 \times [\cos\theta_1\cos\theta_2 + \cos(\phi_1 - \phi_2)\sin\theta_1\sin\theta_2],$$

$$\mathcal{Y}_5 = -\sqrt{\frac{385}{2}}\frac{3}{4\pi^2}\cos\alpha_2\cos\alpha_3\sin\alpha_3 \times [\cos\theta_1\cos\theta_3 + \cos(\phi_1 - \phi_3)\sin\theta_1\sin\theta_3],$$

$$\mathcal{Y}_6 = -\sqrt{\frac{385}{2}}\frac{3}{4\pi^2}\sin\alpha_2\cos\alpha_3\sin\alpha_3 \times [\cos\theta_2\cos\theta_3 + \cos(\phi_2 - \phi_3)\sin\theta_2\sin\theta_3],$$

$$\mathcal{Y}_7 = i\sqrt{5005}\frac{3}{8\pi^2}\sin\alpha_2\cos\alpha_2\sin\alpha_3\cos^2\alpha_3 \times [\cos\theta_3\sin\theta_1\sin\theta_2\sin(\phi_1 - \phi_2) - \sin\theta_3\cos\theta_2\sin\theta_1\sin(\phi_1 - \phi_3) + \sin\theta_3\cos\theta_1\sin\theta_2\sin(\phi_2 - \phi_3)].$$

$$V_1 = \langle\phi_1\chi_2|\sum_{i<j}V_{ij}|\phi_1\chi_2\rangle = \frac{2}{3}(V^c_{12} + V^c_{34}) + \frac{1}{3}(V^c_{13} + V^c_{14} + V^c_{23} + V^c_{24}) + \frac{1}{6}(V^{ss}_{12} + V^{ss}_{34}) - \frac{1}{6}(V^{ss}_{13} + V^{ss}_{14} + V^{ss}_{23} + V^{ss}_{24}),$$

$$V_2 = \langle\phi_2\chi_1|\sum_{i<j}V_{ij}|\phi_2\chi_1\rangle = -\frac{1}{3}(V^c_{12} + V^c_{34}) + \frac{5}{6}(V^c_{13} + V^c_{14} + V^c_{23} + V^c_{24}) + \frac{1}{4}(V^{ss}_{12} + V^{ss}_{34}),$$

$$V_m = \langle\phi_1\chi_2|\sum_{i<j}V_{ij}|\phi_2\chi_1\rangle = \langle\phi_2\chi_1|\sum_{i<j}V_{ij}|\phi_1\chi_2\rangle = -\frac{\sqrt{6}}{8}(V^{ss}_{13} + V^{ss}_{14} + V^{ss}_{23} + V^{ss}_{24}),$$

$$V = \langle\phi_1\chi_5|\sum_{i<j}V_{ij}|\phi_1\chi_5\rangle = \frac{2}{3}(V^c_{12} + V^c_{34}) + \frac{1}{3}(V^c_{13} + V^c_{14} + V^c_{23} + V^c_{24}) + \frac{1}{6}(V^{ss}_{12} + V^{ss}_{34}) - \frac{1}{12}(V^{ss}_{13} + V^{ss}_{14} + V^{ss}_{23} + V^{ss}_{24}),$$

Many excellent review papers :

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E. Klempt, JM. Richard, Rev. Mod. Phys. 82 (2010) 1095–1153.

YR Liu, HX Che, W. Chen, X. Liu, SL Zhu. Phys. Rept. 639 (2016) 1–121.

A. Ali, JS. Lange, S. Stone. Prog. Part. Nucl. Phys. 97 (2017) 123–198.

FK. Guo, C. Hanhart, U. Meißner, Q. Wang, Q. Zhao. Rev. Mod. Phys. 90 (2018) 015004.

YR. Liu, HX. Chen, W. Chen, X. Liu, SL. Zhu. Prog. Part. Nucl. Phys. 107 (2019) 237–320.

N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, CP. Shen, CE. Thomas, A. Vairo, ChZh. Yuan. Phys. Rept. 873 (2020) 1-154.

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