重离子碰撞和强子对撞中奇特强子态的产生

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第九届XYZ研讨会，

西安交大，西安，2024年5月26日-30日

Outline

- A review of double charm tetraquark
- The production of the T_{cc}^{+} in HIC
- Revealing the nature of the T_{cc}^{+} in pp collision
- Summary and outlook

A review of double charm tetraquark

- 1964 Quark model

An SU(3) model for strong interaction symmetry and its breaking. Version 2 #1
G. Zweig (CERN) (Feb 21, 1964)
pdf cite claim reference search 657 citations

An SU(3) model for strong interaction symmetry and its breaking. Version 1 #2
G. Zweig (CERN) (Jan 17, 1964)
pdf cite claim reference search 818 citations

A Schematic Model of Baryons and Mesons #6
Murray Gell-Mann (Caltech) (1964)
Published in: *Phys.Lett.* 8 (1964) 214-215
DOI cite claim reference search 4,156 citations

- 1978 tetrquark in baryon-antibaryon system

PHYSICAL REVIEW D VOLUME 17, NUMBER 5 1 MARCH 1978

$Q^2\bar{Q}^2$ resonances in the baryon-antibaryon system

R. L. Jaffe
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 September 1977)

Two-quark–two-antiquark mesons which couple strongly to baryon-antibaryon channels are classified. The quantum numbers and masses of prominent states are predicted from the MIT bag model. The couplings of $Q^2\bar{Q}^2$ states to $B\bar{B}$ are estimated using the $^3P_0$ model and peripherality. Though most $Q^2\bar{Q}^2$ states do not couple strongly to $B\bar{B}$, many prominent resonances remain. Important $Q^2\bar{Q}^2$ resonances in the following processes are enumerated and discussed: elastic $N\bar{N}$ scattering, $N\bar{N}\to\pi^+\pi^-$, $N\bar{N}$ resonances at or below threshold, and exotic isotensor baryon-antibaryon resonances.

A review of double charm tetraquark

- 2002 the observation of the Ξ_{cc}^{+} $\quad ccq \leftrightarrow cc\bar{q}\bar{q}$

First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+} #1

SELEX Collaboration • M. Mattson (Carnegie Mellon U.) et al. (Aug, 2002)

Published in: *Phys.Rev.Lett.* 89 (2002) 112001 • e-Print: hep-ex/0208014 [hep-ex]

pdf links DOI cite claim reference search 501 citations

- 2003 the observation of the $X(3872)$ $\quad D\bar{D}^{*} \leftrightarrow DD^{*}$

- 2005 double charm tetraquarks by J.-M. Richard and Fl. Stancu

Double charm hadrons revisited #5

J.-M. Richard (LPSC, Grenoble), Fl. Stancu (Liege U.) (Nov, 2005)

Published in: *Bled Workshops Phys.* 6 (2005) 1, 25-31 • Contribution to: Mini-Workshop Bled 2005, 25-31 • e-Print: hep-ph/0511043 [hep-ph]

pdf links cite claim reference search 12 citations

A review of double charm tetraquark

2003—2020 double charm tetraquark in molecular picture

Coupled-channel analysis of the possible $D^{(*)}D^{(*)}$, $\overline{B}^{(*)}\overline{B}^{(*)}$ and $D^{(*)}\overline{B}^{(*)}$ molecular states

$D\bar{D}^* \leftrightarrow DD^*$

Ning Li, Zhi-Feng Sun, Xiang Liu, and Shi-Lin Zhu
Phys. Rev. D **88**, 114008 – Published 3 December 2013

Sanchez, Geng, Lu, Hyodo, Valderrama, PRD98(2018)054001,

Xu, Wang, Liu, Liu, PRD99(2019)014027, Wang, Liu, Liu, PRD99(2019)036007,

Yu, Zhou, Chen, Xiao, PRD101(2020)0740270, Ding, Jiang, He, EPJC80(2020)1179……

double charm tetraquark in compact tetraquark picture

$ccq \leftrightarrow cc\bar{q}\bar{q}$

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner and Jonathan L. Rosner
Phys. Rev. Lett. **119**, 202001 – Published 15 November 2017

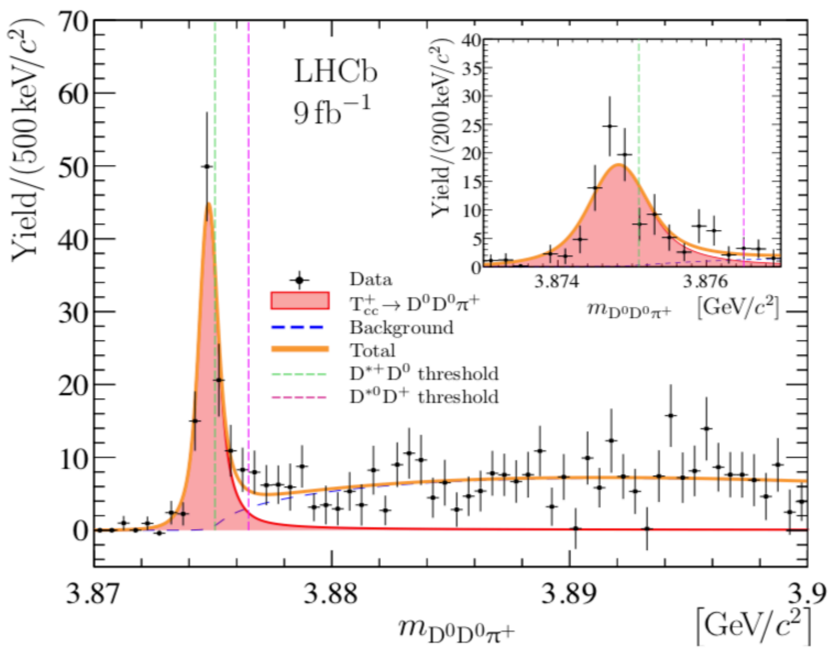
Karliner, Nussinov, JHEP07(2013)153, Cheng, Li, Si, Yao, CPC45(2021)043102,

Gelman, Nussinov, PLB551(2003)296-304, Luo, Chen, Liu, Liu, Zhu, EPJC77(2017)709……

A review of double charm tetraquark

- 2020 The observation of $T_{cc}^{+}(cc\bar{u}\bar{d})$

Breit-Wigner fit LHCb, Nature Phys.18(2022)751-754



$$\delta m \equiv m_{T_{cc}^{+}} - m_{D^{*+}} - m_{D^0}$$

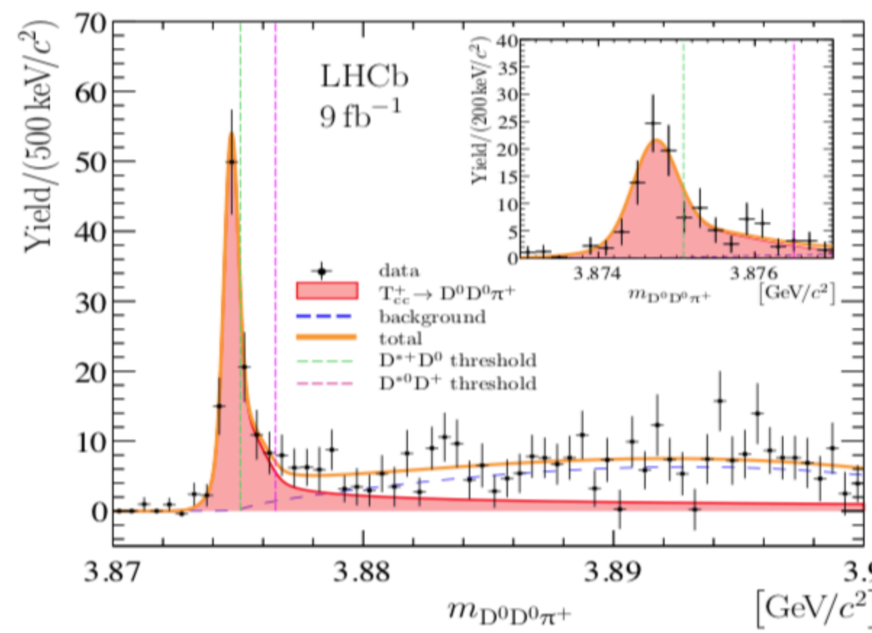
$$\delta m_{\mathrm{BW}} = -273 \pm 61 \ \mathrm{keV}$$

$$\Gamma_{\mathrm{BW}} = 410 \pm 165 \ \mathrm{keV}$$

No signal in $D^+D^0\pi^+, D^+D^+$

$\rightarrow$ I=0 isoscalar

Unitarized fit LHCb, Nature Commun. 13(2022)3351



$$\delta m_{\mathrm{pole}} = -360 \pm 40^{+4}_{-0} \ \mathrm{keV}$$

$$\Gamma_{\mathrm{pole}} = 48 \pm 2^{+0}_{-14} \ \mathrm{keV}$$

$$a = \left[-(7.16 \pm 0.51) + i(1.85 \pm 0.28)\right] \ \mathrm{fm}$$

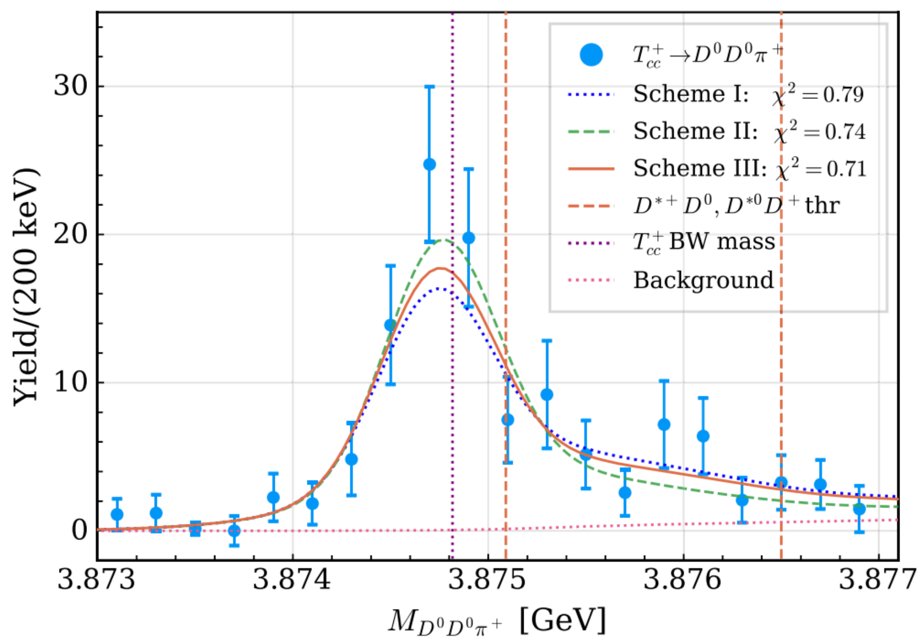
$$-r < 11.9(16.9) \ \mathrm{fm} \quad 90(95)\,\%\ \mathrm{CL}.$$

$$Z < 0.52(0.58) \quad 90(95)\,\%\ \mathrm{CL}.$$

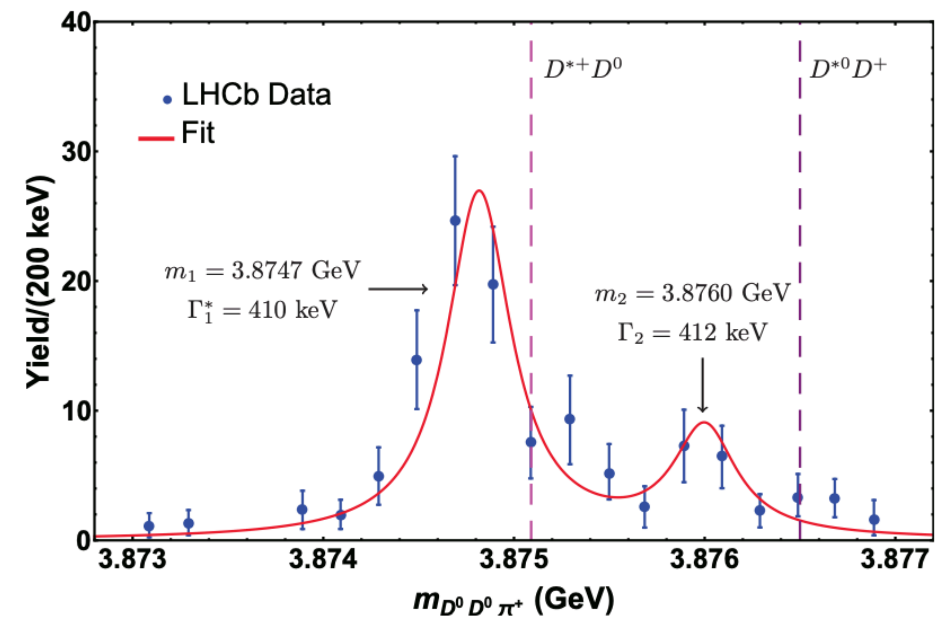
$Z = 0$ Composite $\quad Z = 1$ Elementary

A review of double charm tetraquark

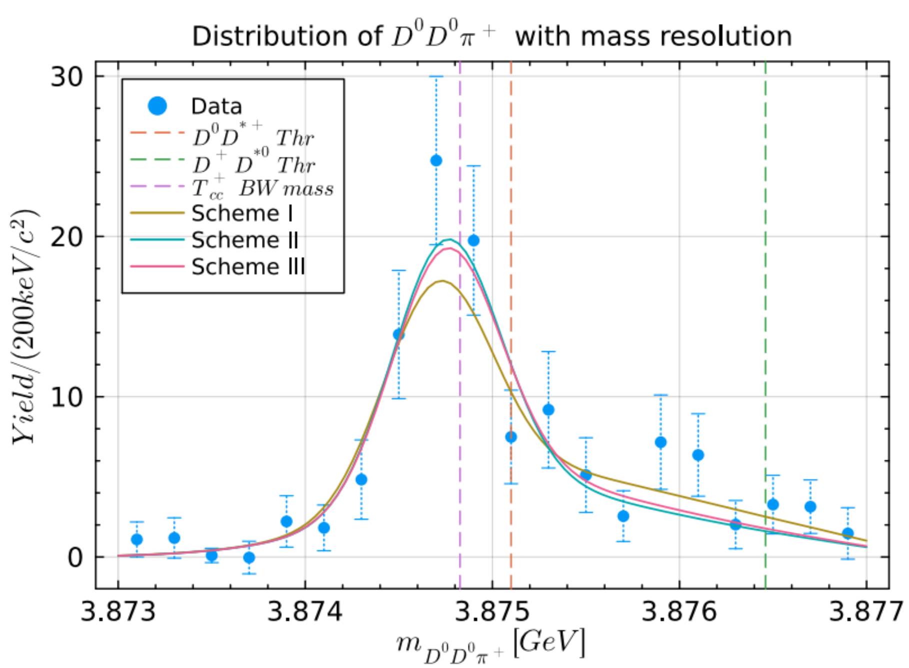
- 2020— double charm tetraquark in molecular picture



Du, et.al., PRD105(2022)014024



Chen, et.al., PRD104(2021)114042

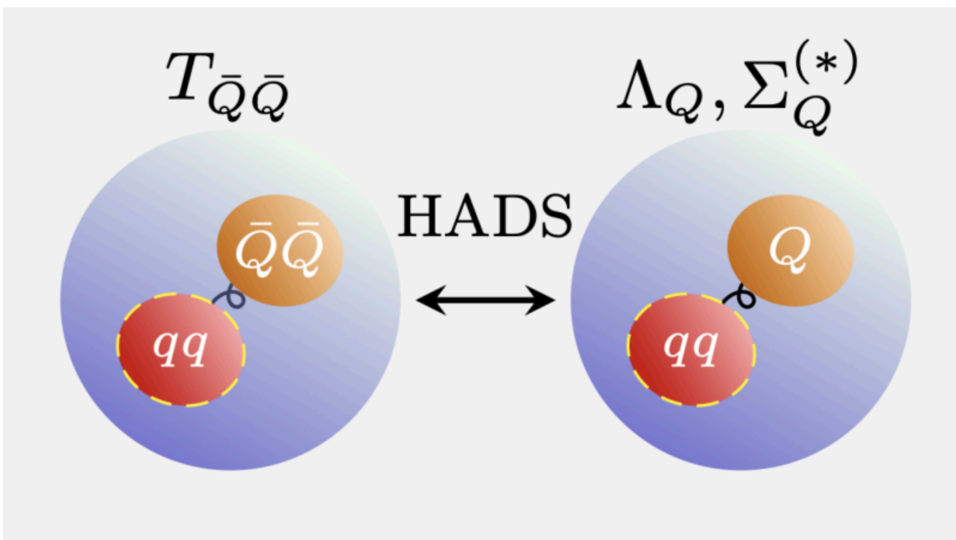


- Consider three-body unitarity
- Well describe the experimental data
- Confirm the molecular picture

Qiu, et.al., PRD109(2024)076016

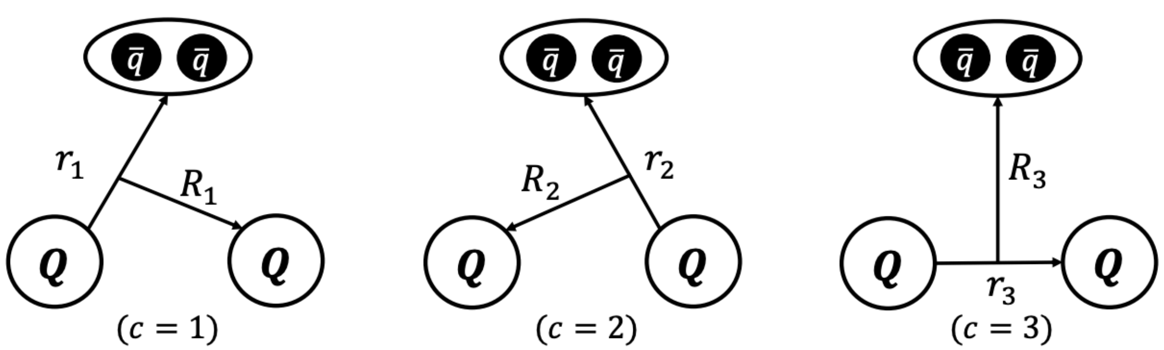
A review of double charm tetraquark

- 2020— double charm tetraquark in compact tetraquark picture

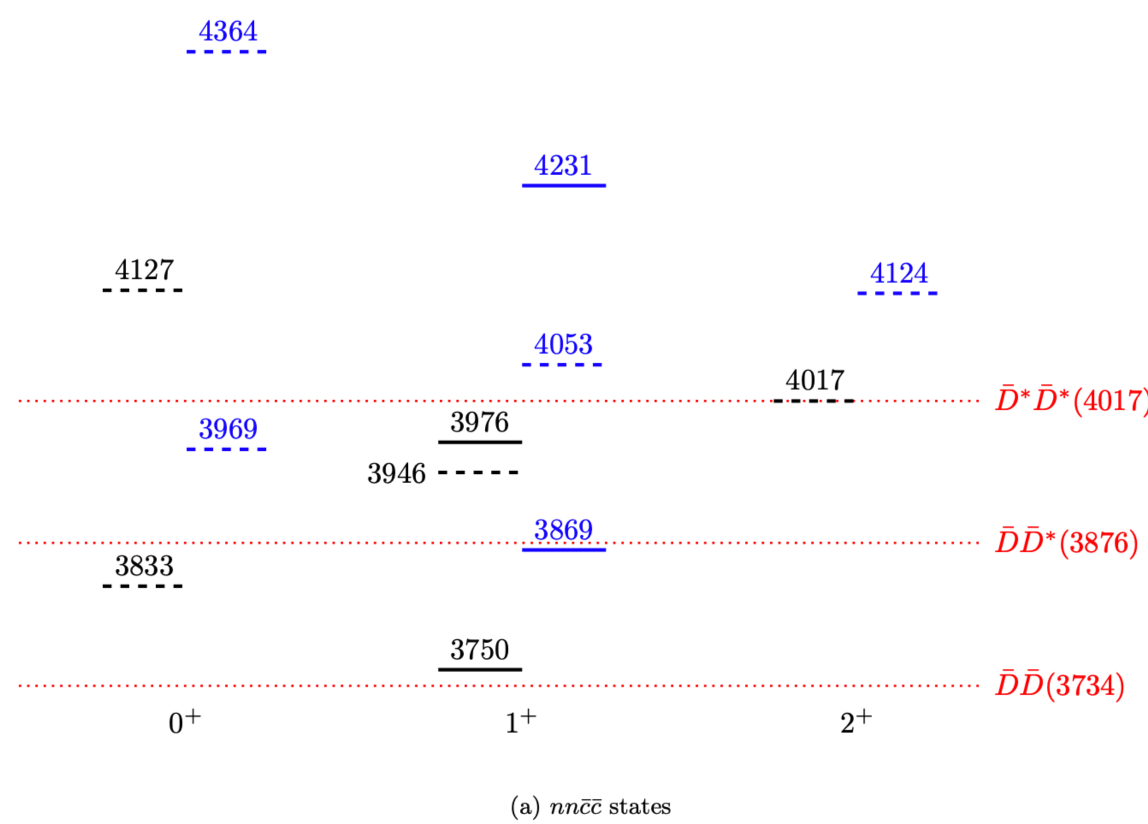


Wu. Ma, PRD107(2023)L071501

$$H = \sum_i m_i + H_{CE} + H_{CM}$$



Kim, et.al., PRD105(2022)074021



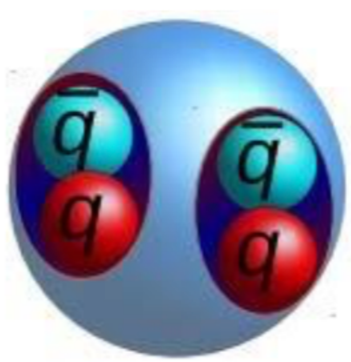
Weng, et.al., CPC46(2022)013102

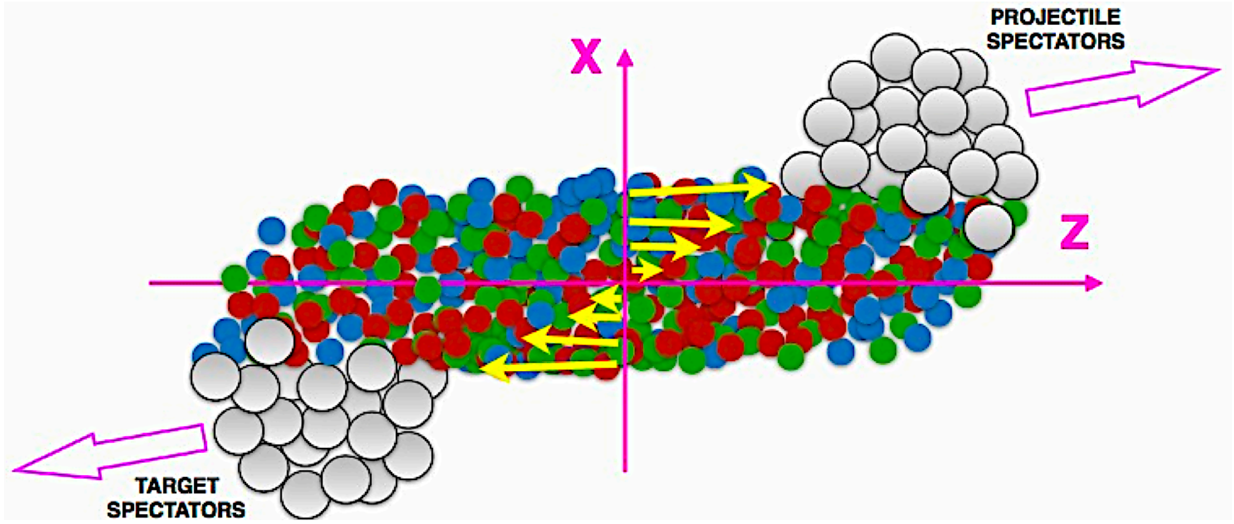
The production of Exotic hadrons in HIC

- Compact object ($r \sim 1$ fm)

Tetra quark　　Charmonium　　Hybrid　　…

- Loose hadronic molecule ($r \sim 10$ fm)



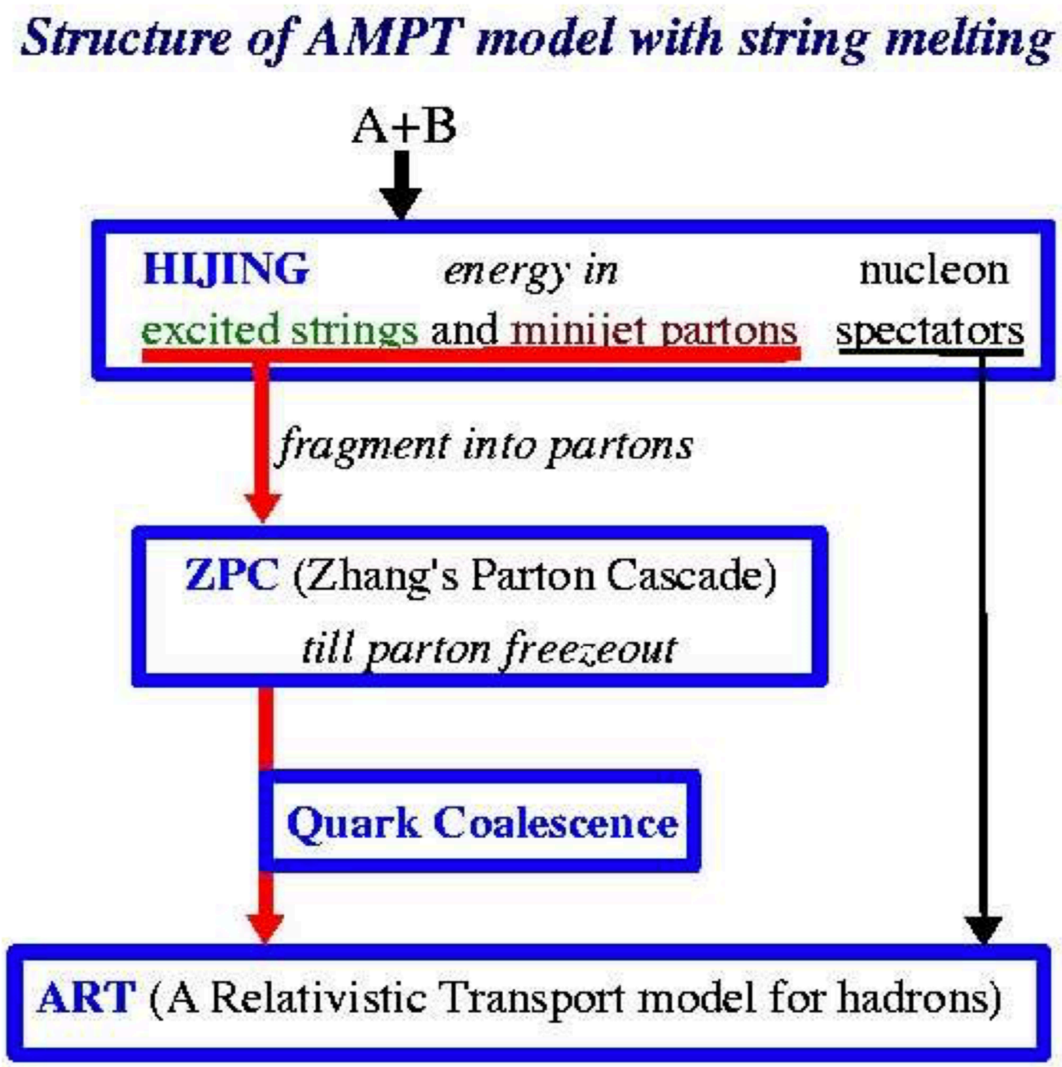


- Size effect
- Estimate the yield of X(3872) in HIC

Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

The production of Exotic hadrons in HIC

The multi-phase transport (AMPT) model



- Heavy Ion Jet Interaction Generator

Generate the initial conditions

- Zhang's Parton Cascade

Partonic scattering

- Diquark and antidiquark pairs in

"Quark Coalescence"

- $D^{(*)}$ and $\bar{D}^{(*)}$ in "ART"

Lin, et.al, PRC72(2005)064901

❖ The success of the AMPT model

Lin, et.al, PRC90(2014)1403,6321

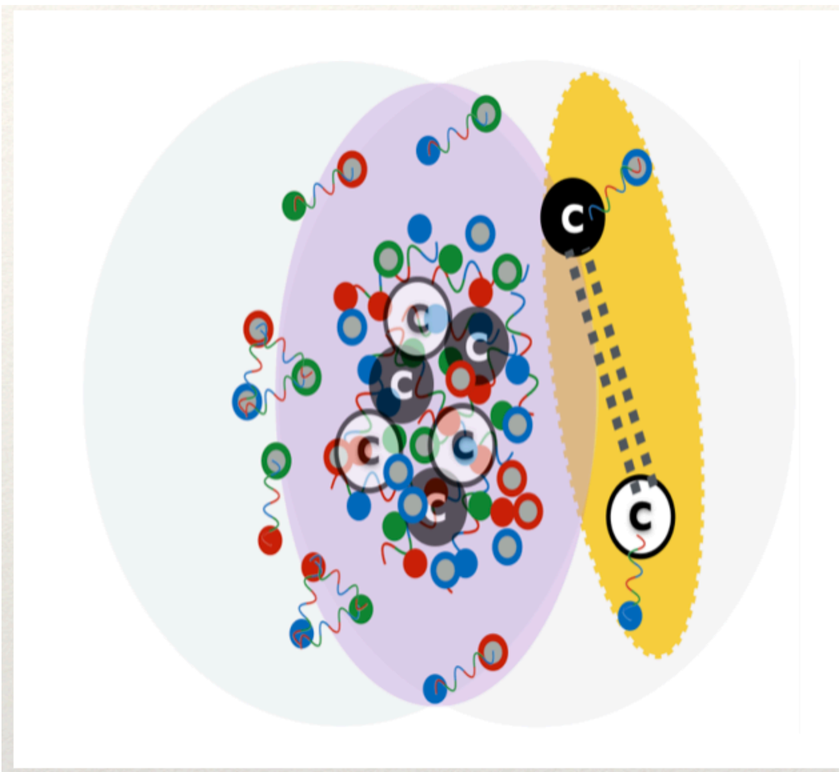
- Evolution of transverse flow and effective temperatures
- Pb+Pb Collisions@ 5.02 TeV   Ma, Lin, PRC93(2016)054911
- Two-particle angular correlations in pp and p-Pb collisions

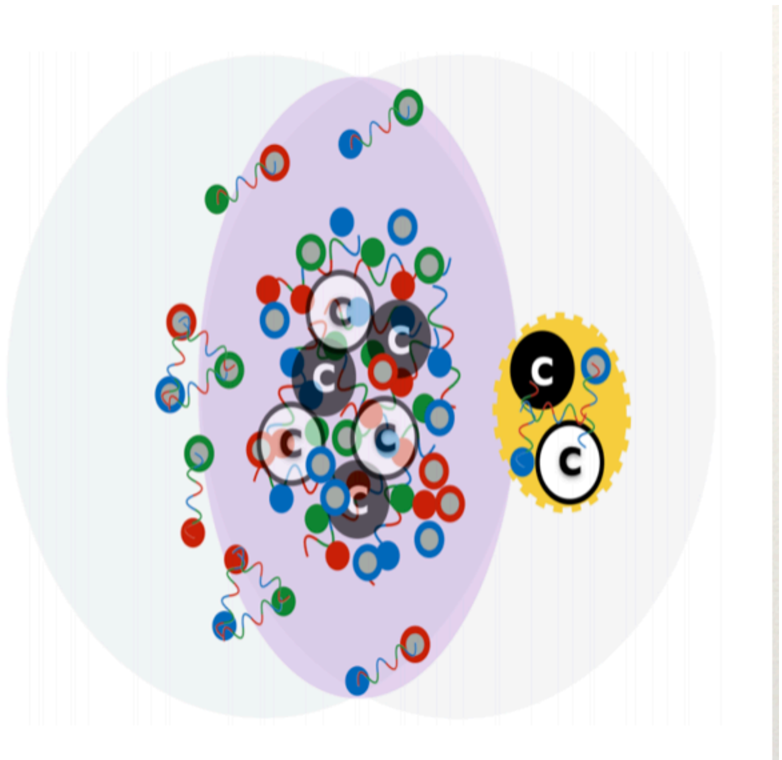
Zhang, et.al., PRC98(2018)034912

The production of the $X(3872)$ in HIC

The framework

- Molecular state
- Tetraquark





Molecular state:

- $D^{(*)}$ and $\bar{D}^{(*)}$ in "ART"
- $5\ \text{fm} < r_{D\bar{D}^*} < 7\ \text{fm}$
- $2M_D < M_X < 2M_{D^*}$

Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

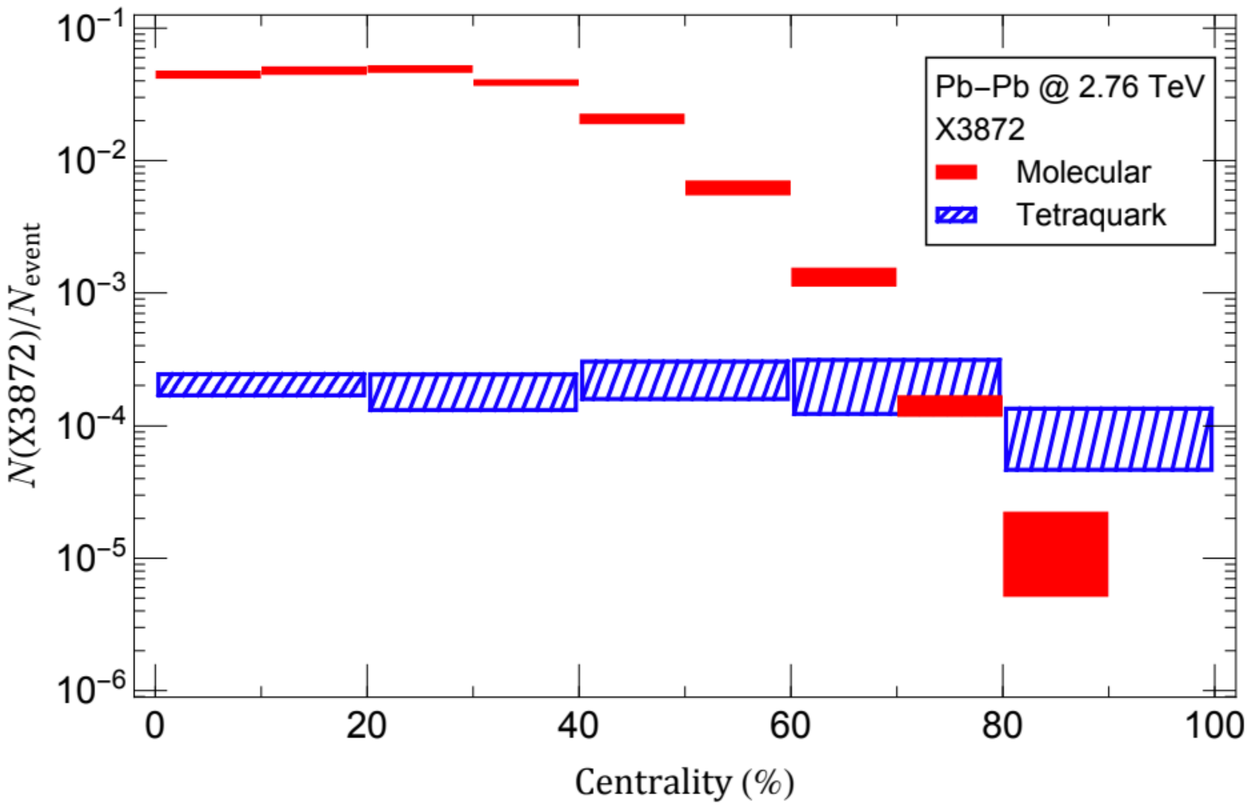
Tetraquark:

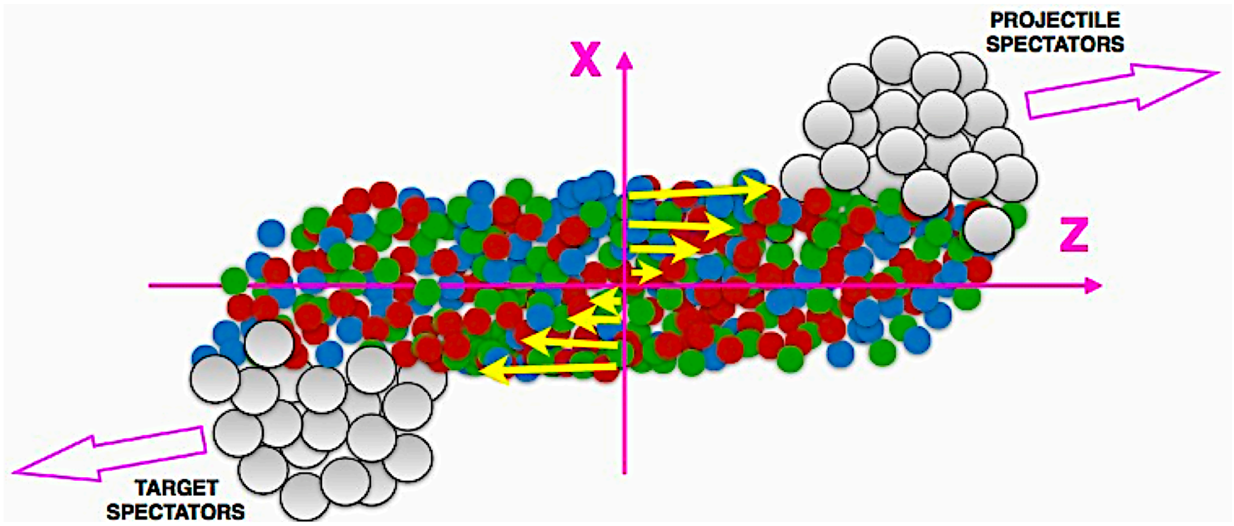
- Diquark $[cq]$ and antidiquark $[\bar{c}\bar{q}]$ pairs in partonic coalescence
- $r_{[cq][\bar{c}\bar{q}]} < 1\ \text{fm}$
- $M_{|00\rangle_0} < M_X < M_{|11\rangle_0}$

Maiani, et. al., PRD89(2014)114010

The production of the $X(3872)$ in HIC

The centrality distribution





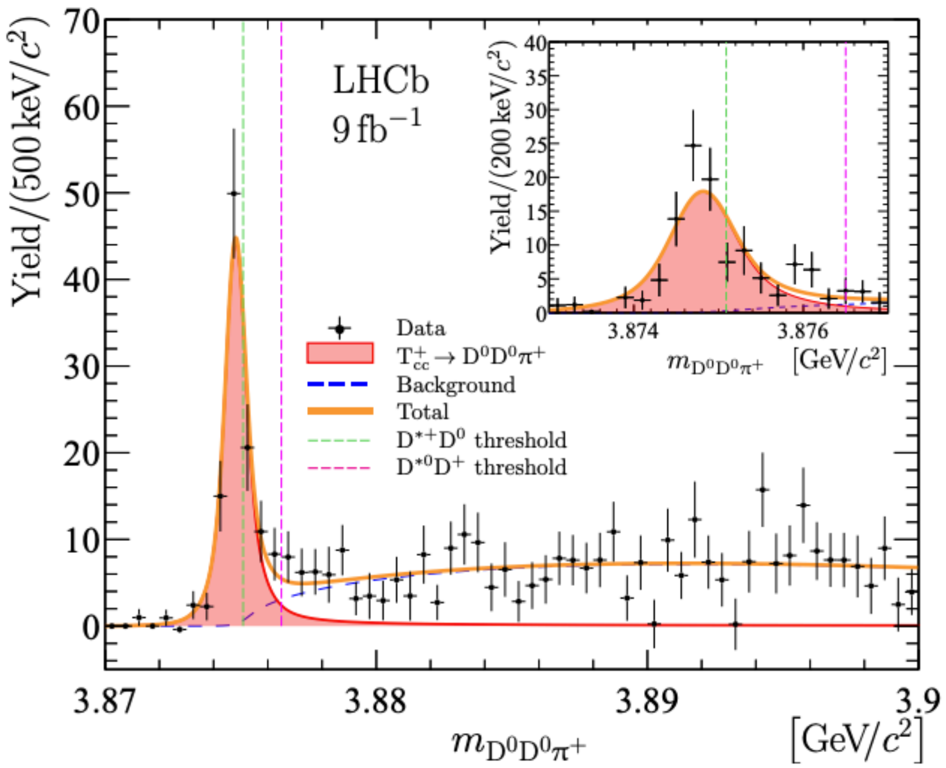
- Strongly decreasing for HM
- Mild change for compact tetra quark
- System size dependance could be a good probe to X(3872) inner structure
- The size dependance is universal for all the hadrons

Zhang, Liao, Wang, QW, Xing, PRL126(2021)012301

The production of the T_{cc}^+ in HIC

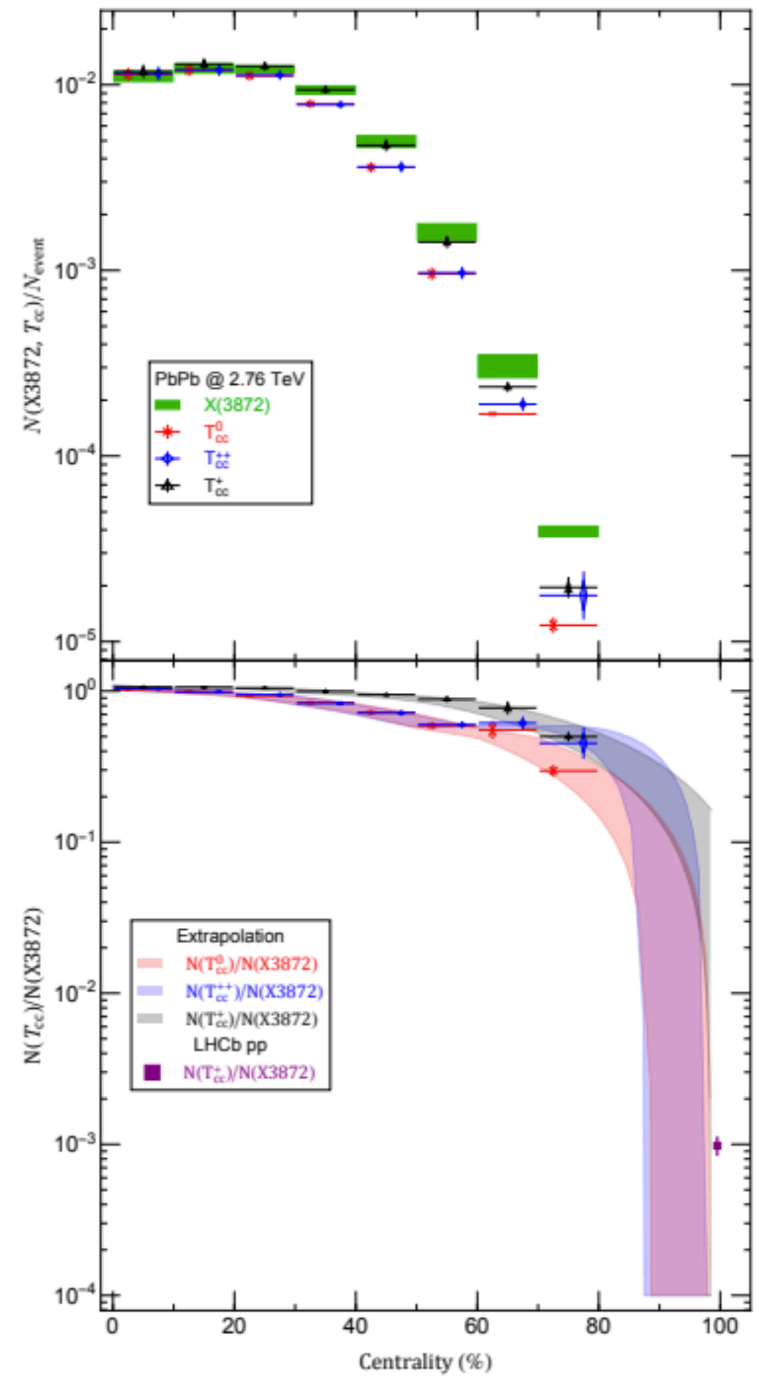
Production of T_{cc} in HIC

LHCb@2021



- $D^0D^0\pi^+$ channel
- Around $D^{*+}D^0$ threshold
- Isosinglet T_{cc}^+
- The $X(3872)$ partner in HM
- Estimate production of T_{cc} in HIC

The centrality distribution



Hu, Liao, Wang, QW, Xing, Zhang, PRD104(2021)L111502

The production of the T_{cc}^{+} in HIC

Why does the isospin triplet T_{cc} disappear in LHCb?

- Small production in pp collision
- Isotriplet DD^* state doesn't exist

① $I = 1:\quad T_{cc}^{\prime 0},\ T_{cc}^{\prime +},\ T_{cc}^{\prime ++}$

② $I = 0:\quad T_{cc}^{+}$

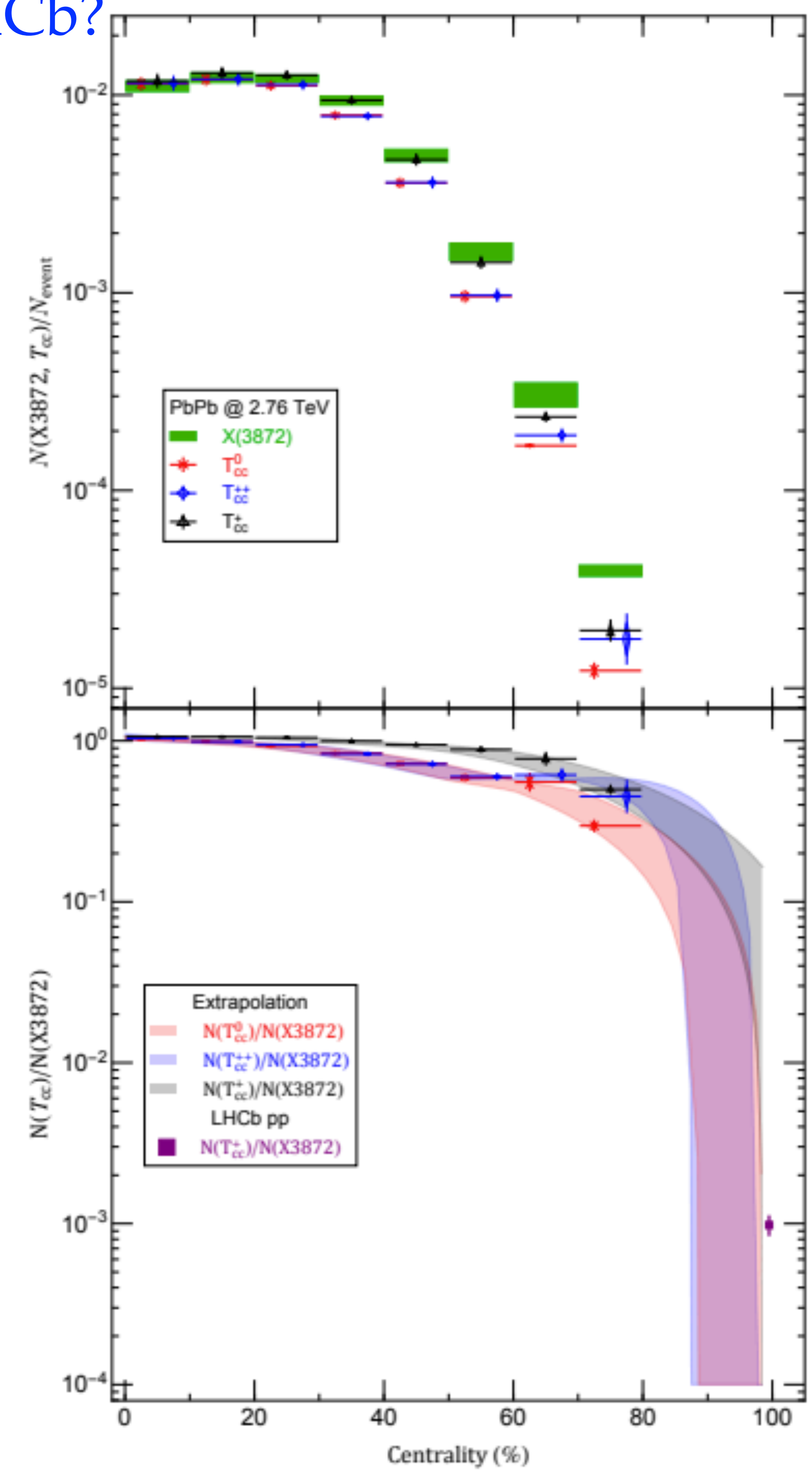
③ $R(T_{cc}^{0,+,++}) \equiv N(T_{cc}^{0,+,++})/N(X(3872))$

④ A third order polynomial function for the relative yield ratio

⑤ T_{cc}^{+} is about 3 orders smaller at UPC

⑥ Isotriplet partners is even smaller than that of T_{cc}^{+}

$P_b - P_b @ 2.76$ TeV



Hu, Liao, Wang, QW, Xing, Zhang, PRD104(2021)L111502

The production of the T_{cc}^{+} in HIC

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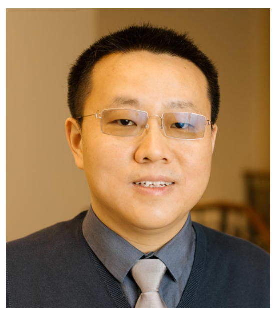
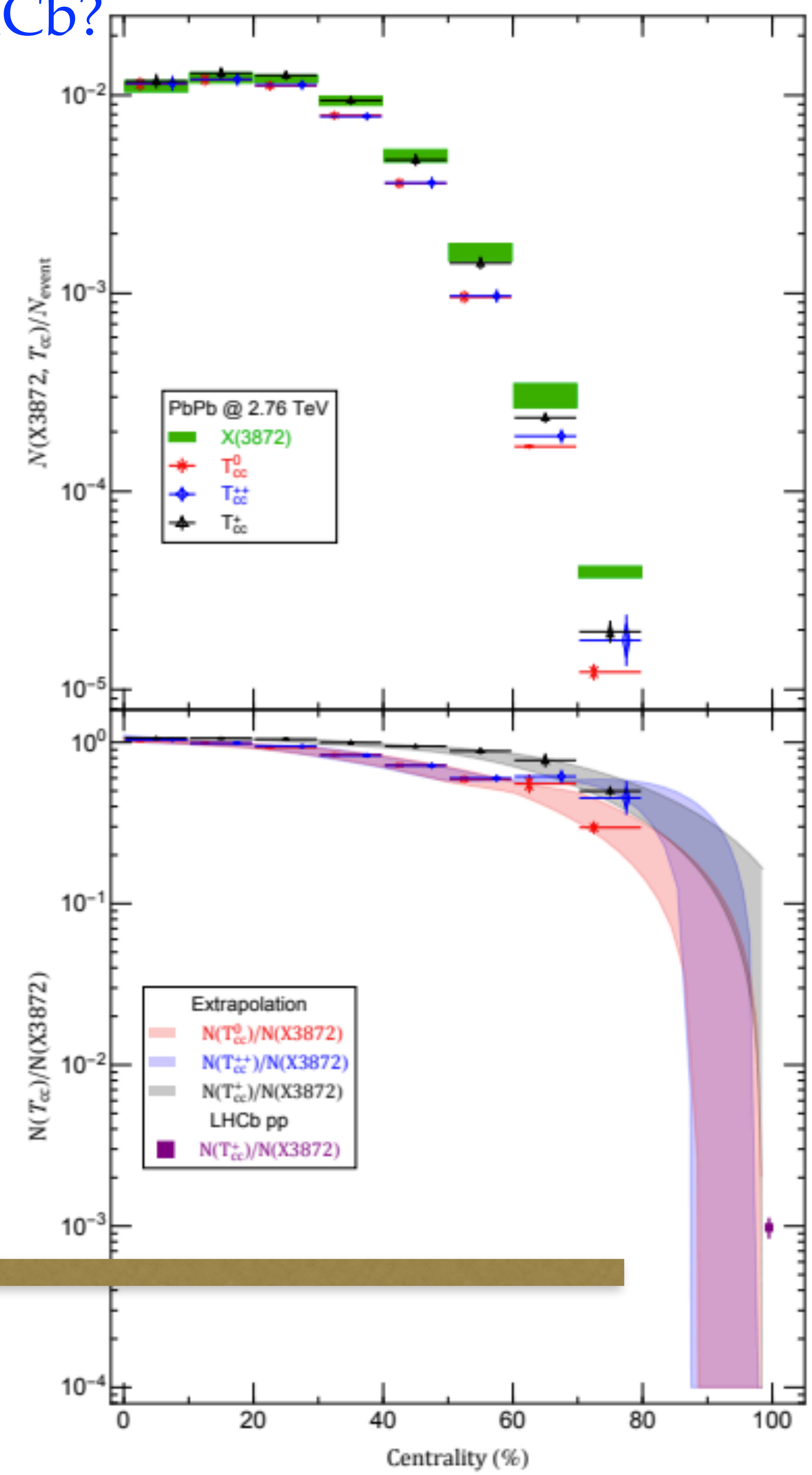



$$\frac{\#T_{cc}^{+}}{\#X(3872)}_{\text{Exp.}} \simeq 10^{-3}$$

$$\frac{\#T_{cc}^{++}}{\#X(3872)}_{\text{Theory}} \simeq 10^{-4}$$

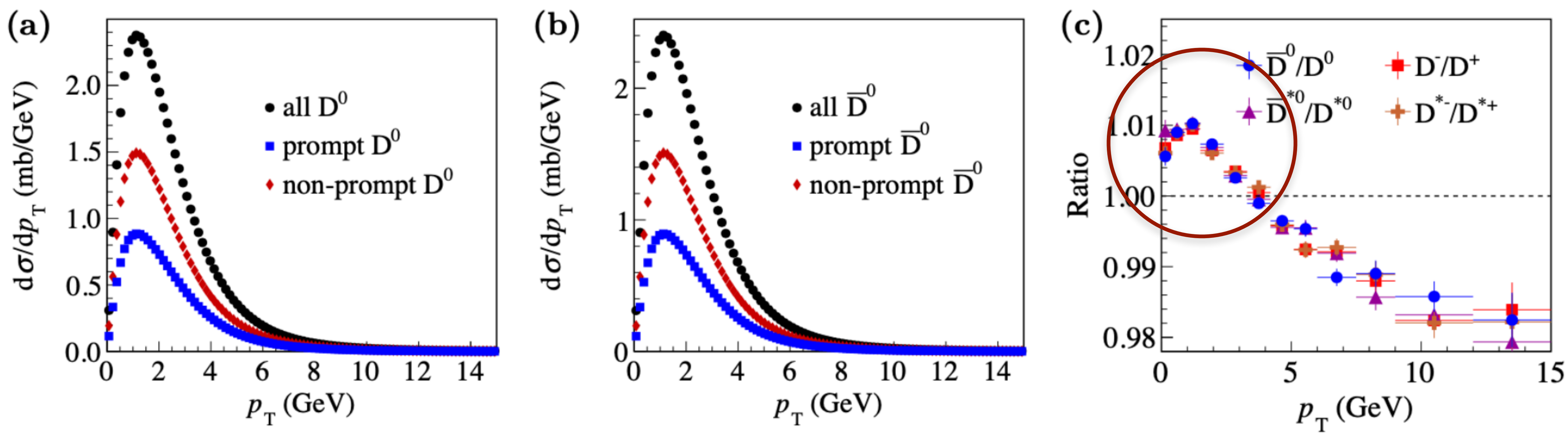
$P_b - P_b @ 2.76$ TeV

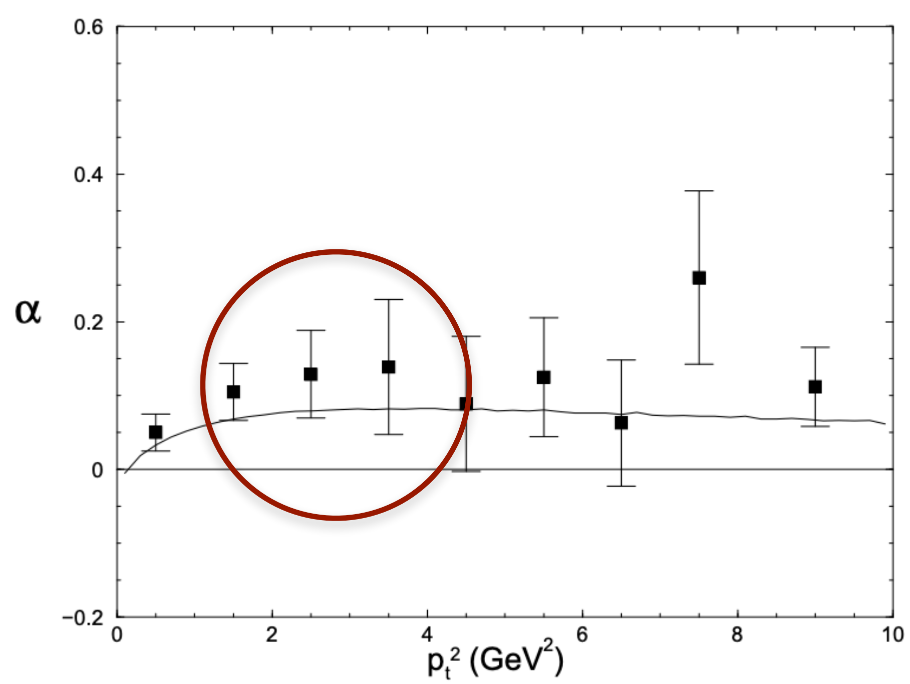


Hu, Liao, Wang, QW, Xing, Zhang, PRD104(2021)L111502

Revealing the nature of the T_{cc}^+ in pp collision

The production of single charmed meson





Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]





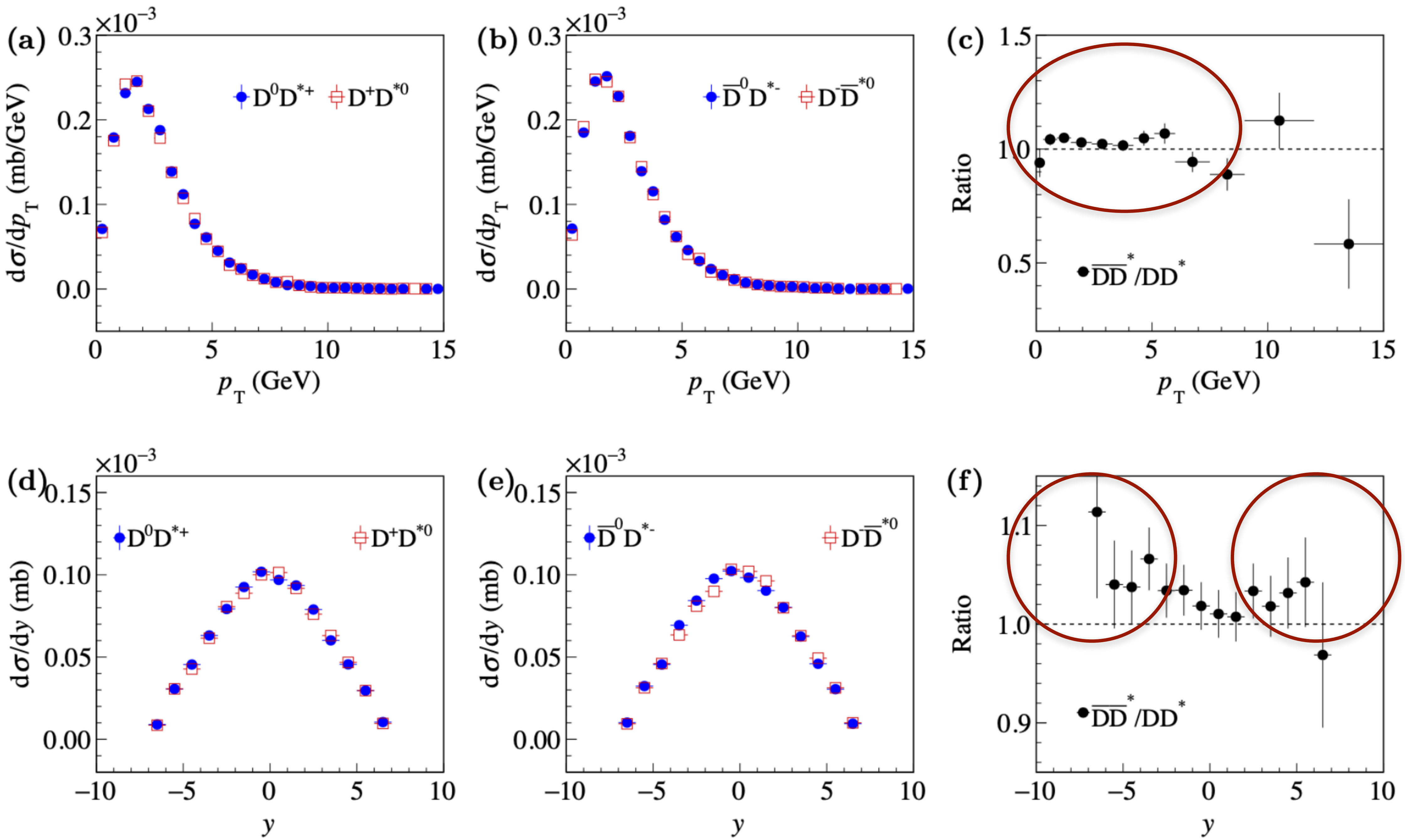
$$\alpha\left[D^+\right] = \frac{d\sigma\left[D^-\right] - d\sigma\left[D^+\right]}{d\sigma\left[D^-\right] + d\sigma\left[D^+\right]}$$

Heavy quark recombination mechanism

Braaten, Jia, Mehen, PRL89(2002)122002, Chang, Ma, Si, PRD68(2003)014018

Revealing the nature of the T_{cc}^{+} in pp collision

The production of prompt (anti)charmed meson pairs

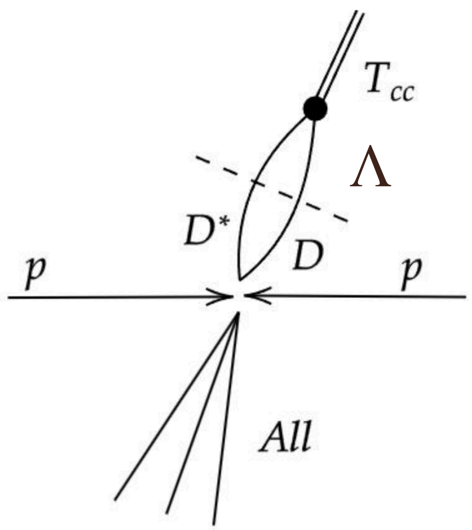


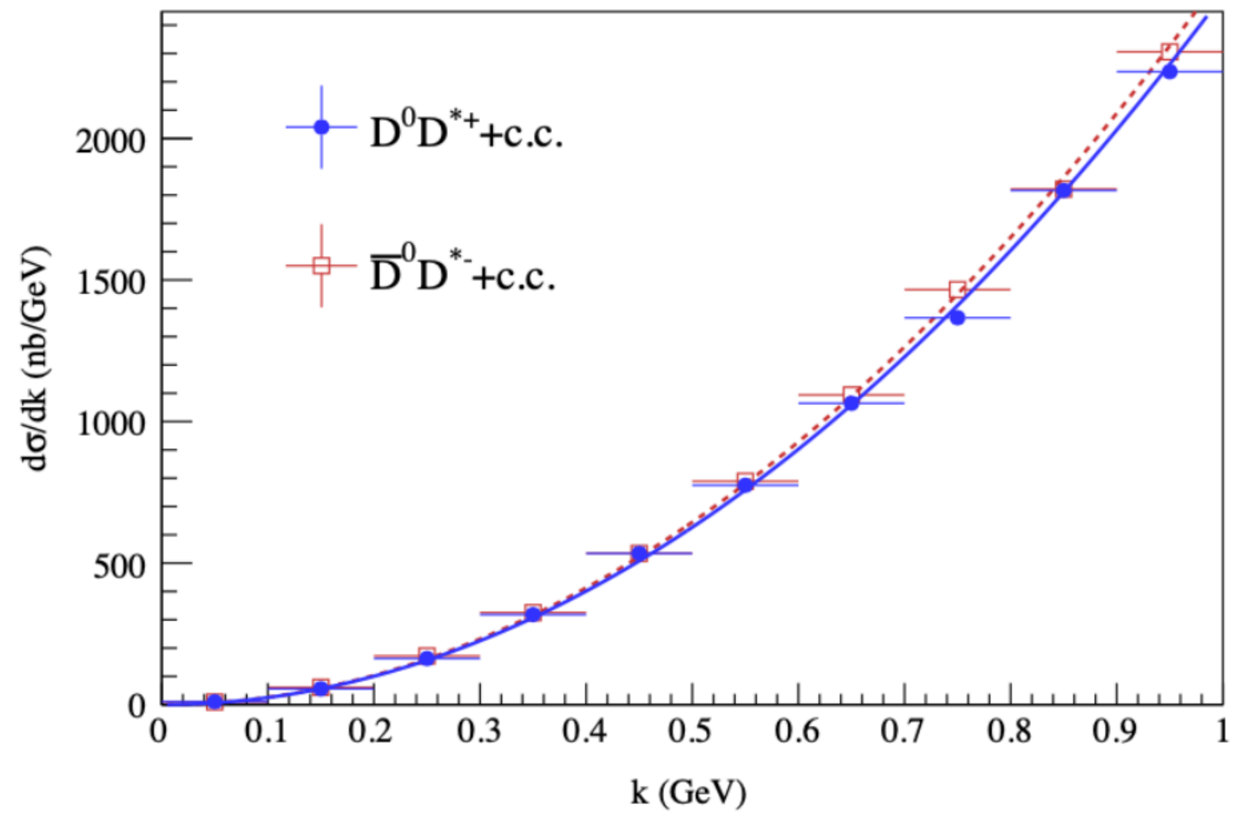
Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Revealing the nature of the T_{cc}^{+} in pp collision

The formation of hadronic double charm tetraquark

$$\sigma(T_{cc}) = \frac{1}{4m_D m_{D*}} g^2 |\mathcal{G}|^2 \left(\frac{d\sigma(DD^*)}{dk}\right) \frac{4\pi^2\mu}{k^2}$$





Successfully apply to

$X(3872)$: Guo et.al., EPJC74(2014)3063, Albaladejo et.al., CPC41(2017)121001, Yang et.al., CPC45(2021)123101, Shi et.al., PRD106(2022)114026

$P_c s$: Ling et.al., EPJC81(2021)319

$Z_b s$: Cao et.al., PRD101(2020)074010

$D_{s0}(2317)$: Guo et.al., JHEP05(2014)138

- Differential cross section behaves as k^2
- Total cross section depends on Λ
- Propose a model independent quantity $\mathscr{A}$

Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Revealing the nature of the T_{cc}^+ in pp collision

The cross sections and asymmetry in the molecular picture

$\mathscr{A} \pm \delta_{sys} \pm \delta_{sta}$

Range(GeV)	$\sigma_{T_{cc}^+}(\sigma_{T_{\bar{c}\bar{c}}^-})$			$\mathcal{A}(\%)$
	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	$\Lambda = 1.5$ GeV	
Full	43.30±0.70 nb (44.13±0.71 nb)	152.42±0.89 nb (156.81±0.91 nb)	313.74±1.03 nb (321.14±1.04 nb)	1.24±0.30±0.20
LHCb ($2 < y < 4.5$)				
$4 < p_T < 20$ [112]	1.46±0.15 nb (1.45±0.15 nb)	5.27±0.20 nb (5.63±0.20 nb)	11.46±0.23 nb (11.87±0.24 nb)	2.53±2.01±1.79
$p_T > 0$ [11]	8.26±0.44 nb (8.69±0.46 nb)	29.93±0.57 nb (30.82±0.58 nb)	62.28±0.66 nb (64.30± 0.67 nb)	1.64±1.03±0.52
CMS ($\lvert y\rvert < 1.2$)				
$10 < p_T < 50(30)$ [113]	0.05±0.02 nb (0.03±0.02 nb)	0.28±0.04 nb (0.20±0.03 nb)	0.55±0.04 nb (0.44±0.04 nb)	−13.42±8.44±2.18
ATLAS ($\lvert y\rvert < 0.75$)				
$10 < p_T < 70$ [114]	0.03±0.02 nb (0.03±0.02 nb)	0.20±0.03 nb (0.13±0.03 nb)	0.38±0.04 nb (0.28±0.03 nb)	−16.87±9.33±10.10

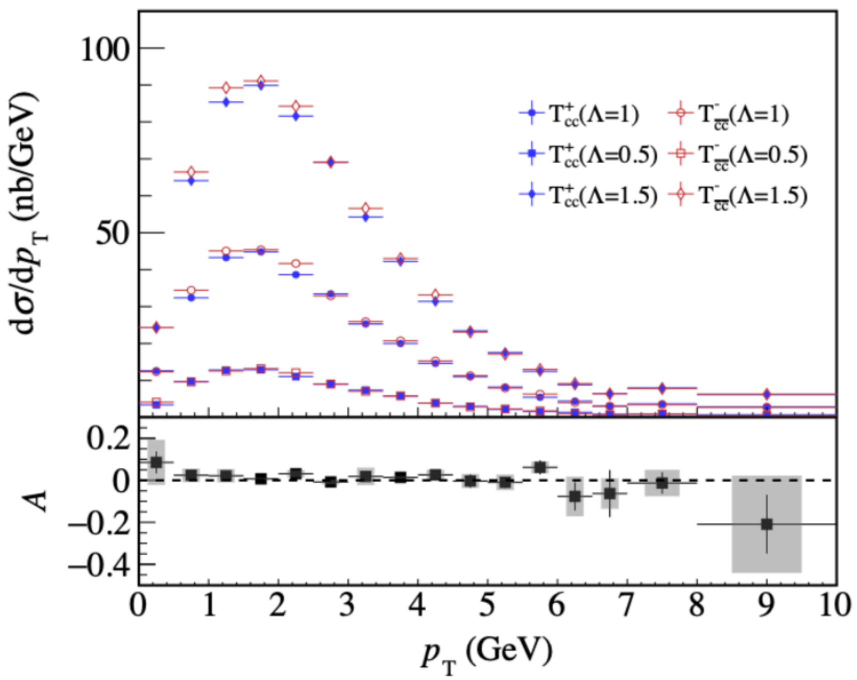
$$\mathscr{A} \equiv \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+} \qquad \mathscr{A} \equiv \omega_1\mathscr{A}_1 + \omega_2\mathscr{A}_2 + \omega_3\mathscr{A}_3 \qquad \omega_i = \frac{\frac{1}{\delta_i^2}}{\frac{1}{\delta_1^2}+\frac{1}{\delta_2^2}+\frac{1}{\delta_3^2}}$$

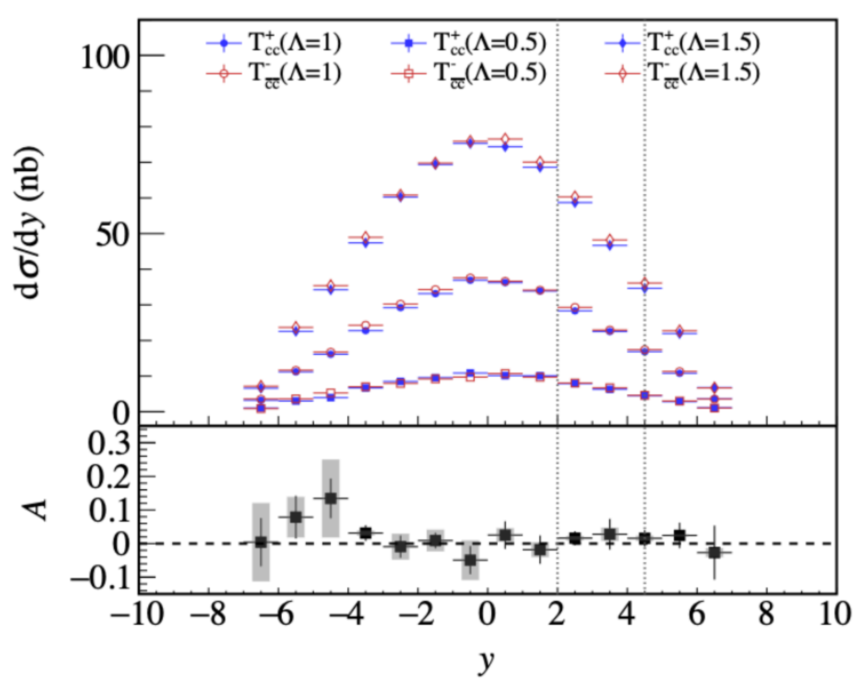
$$\delta_{sta} \equiv \omega_1\delta_1 + \omega_2\delta_2 + \omega_3\delta_3 \qquad \delta_{sys} \equiv \sqrt{\frac{\sum_i(\mathscr{A}_i - \mathscr{A})^2}{3}}$$

Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Revealing the nature of the T_{cc}^{+} in pp collision

The p_T and y distributions in the molecular picture



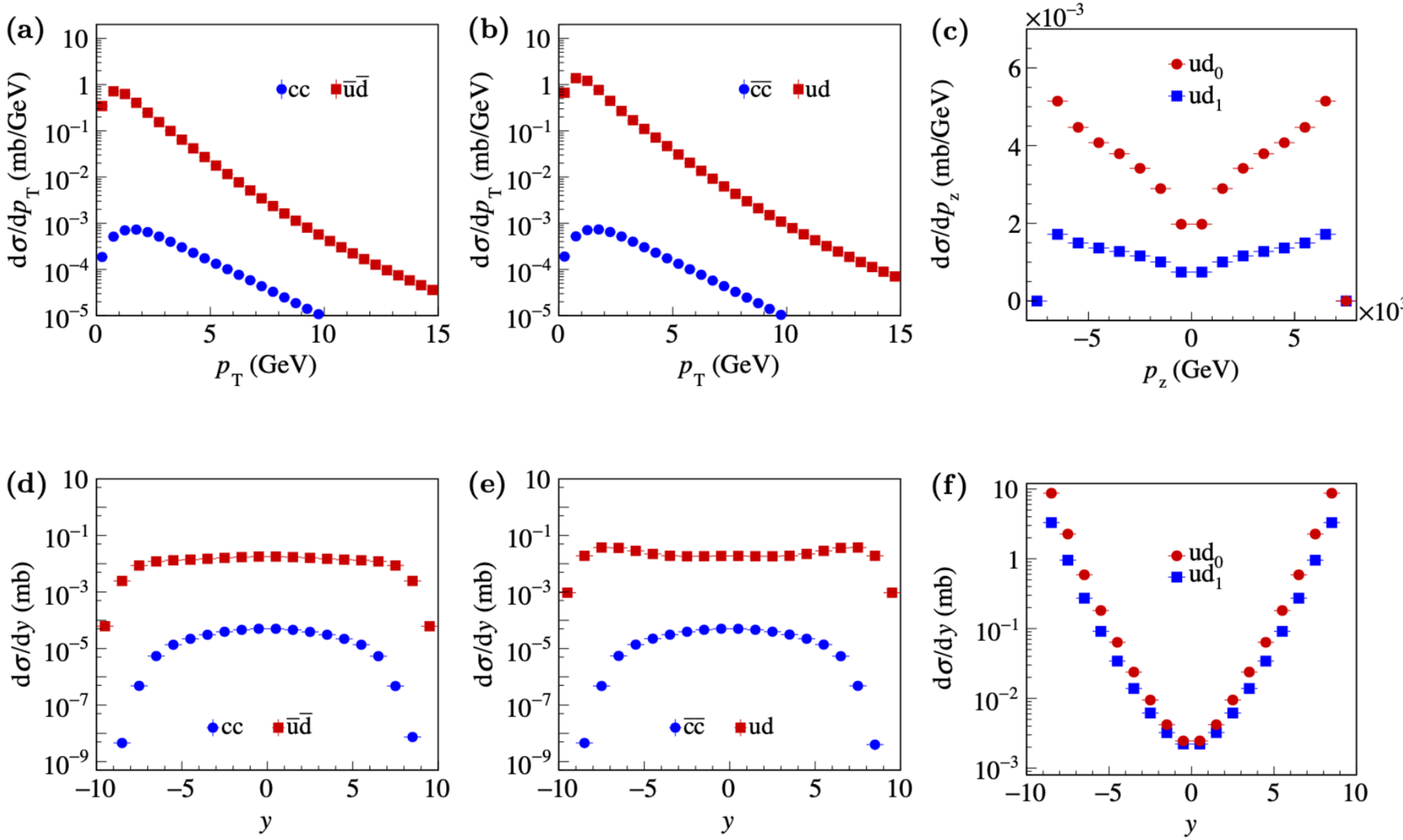


- Cross section increase with the increasing Λ
- Reach maximum value at $p_T = 2$ GeV
- Reach maximum value at $y = 0$
- The asymmetry is positive at low p_T
- The asymmetry is positive at large y
- Cross section depends on the parameter Λ

Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Revealing the nature of the T_{cc}^{+} in pp collision

The diquark and antidiquark distributions

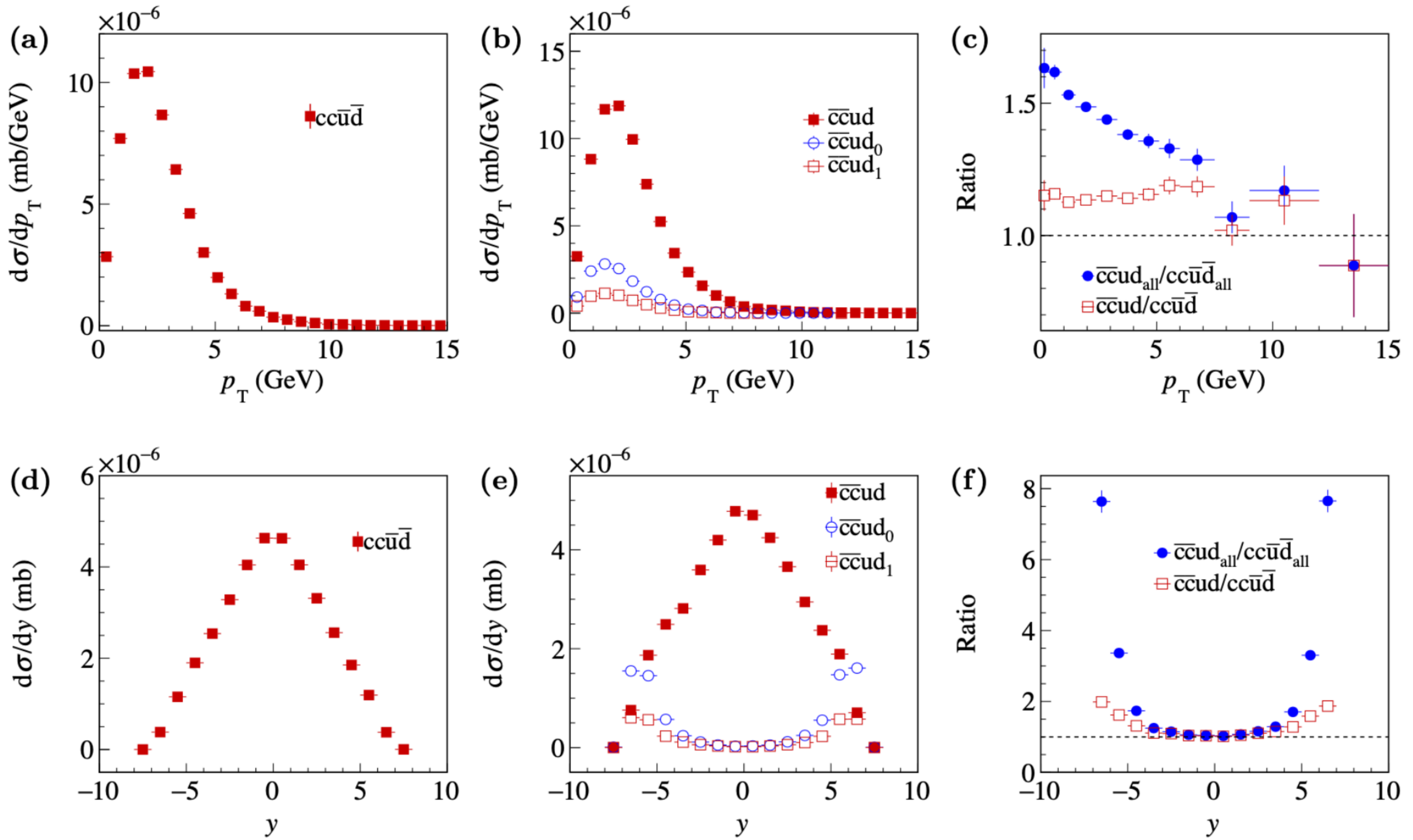


Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Revealing the nature of the T_{cc}^+ in pp collision

The diquark-antidiquark pair distributions

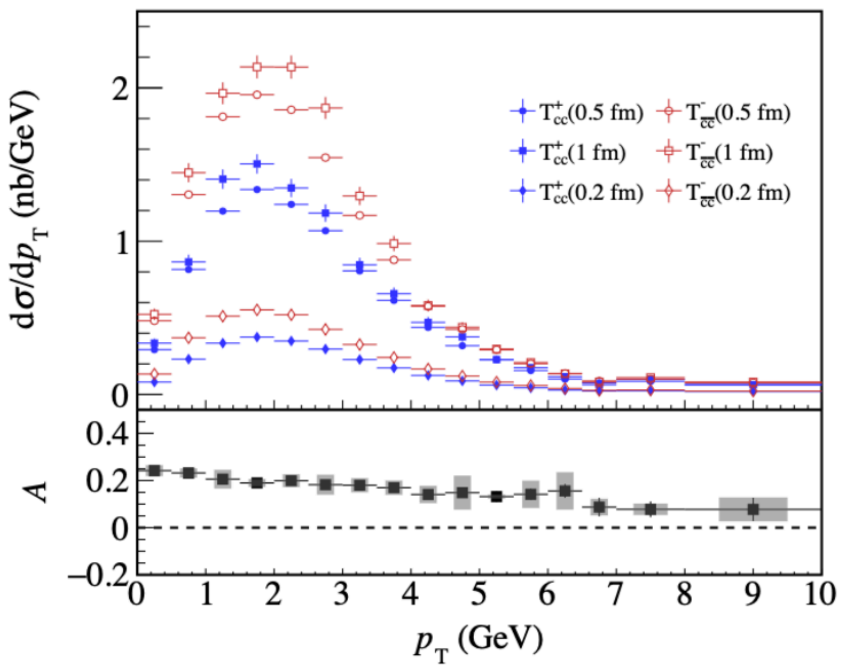
Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

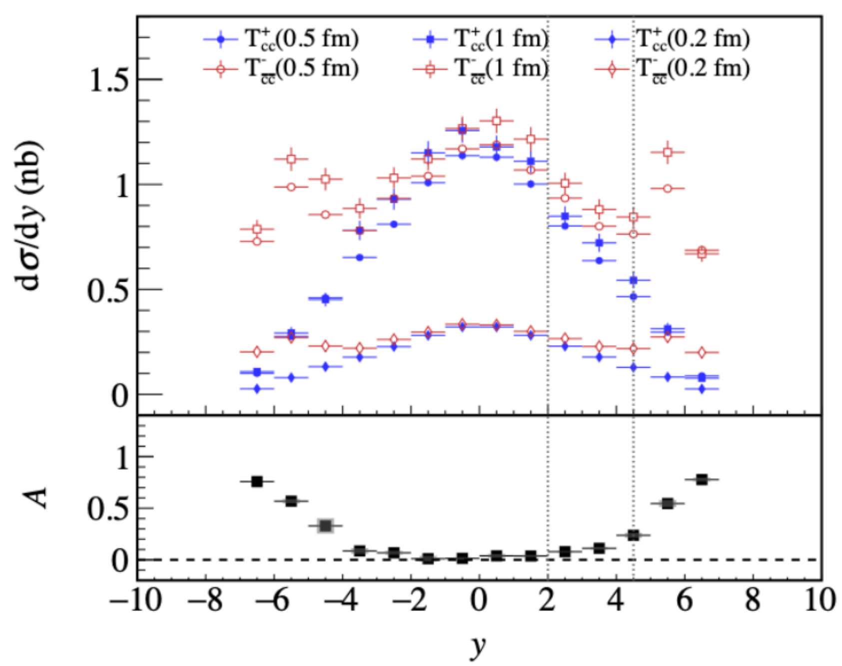


Gaussian Type $\phi(\overrightarrow{p}, a) = (\frac{1}{\pi})^{\frac{3}{4}}(\frac{1}{a})^{\frac{3}{2}}e^{\frac{-p^2}{2a^2}}$ Saturmian Type $\psi(\overrightarrow{p}, b) = 2\sqrt{2}(\frac{1}{\pi})(\frac{1}{b})^{\frac{3}{2}}\frac{1}{(\frac{p^2}{b^2}+1)^2}$

Revealing the nature of the T_{cc}^{+} in pp collision

The p_{T} and y distributions in the compact tetraquark picture





- Cross section increases with the size
- Reach maximum value at $p_{\mathrm{T}} = 2$ GeV
- Reach maximum value at $y = 0$ and $y = \pm 6$
- The asymmetry is positive at low p_{T} and large y
- The asymmetry is more significant
- The large difference region moves to smaller y with smaller c.m. energy

Heavy diquark symmetry

$cc\bar{u}\bar{d} \leftrightarrow \bar{c}\bar{u}\bar{d}$

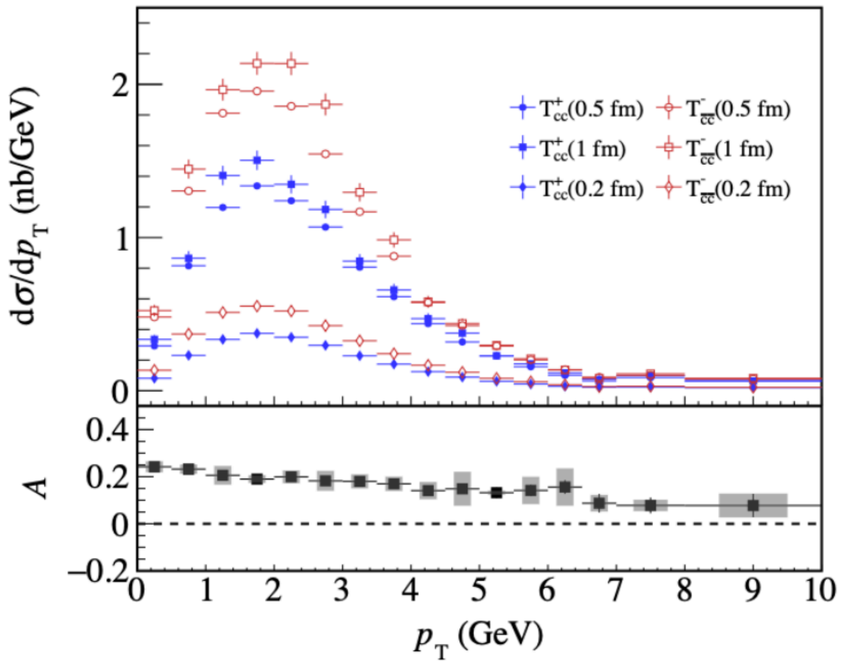
$\bar{c}\bar{c}ud \leftrightarrow cud$

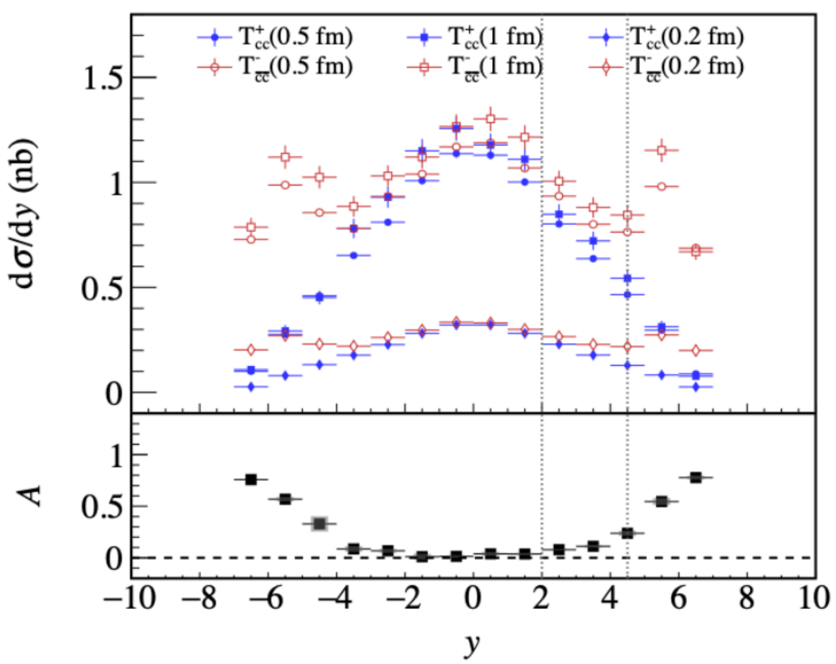
The asymmetry of Λ_c, Λ_b?

Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

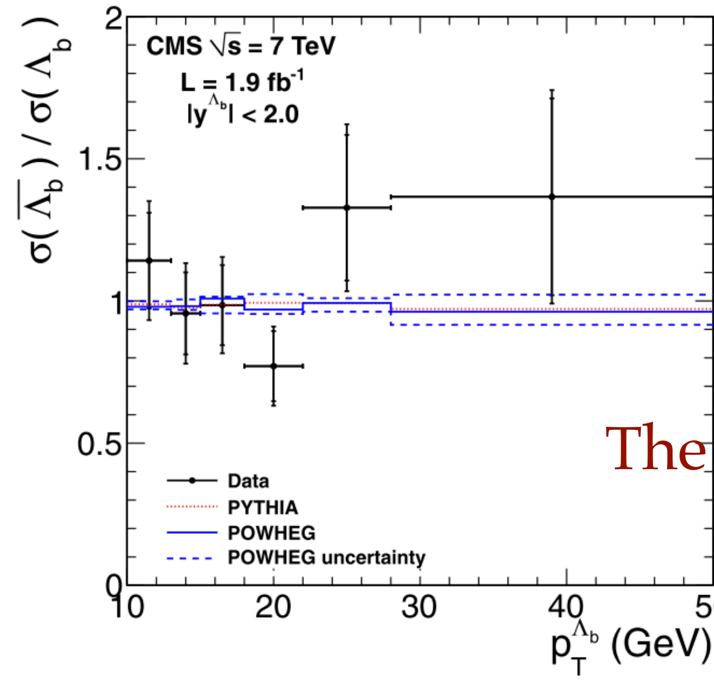
Revealing the nature of the T_{cc}^{+} in pp collision

The p_T and y distributions in the compact tetraquark picture

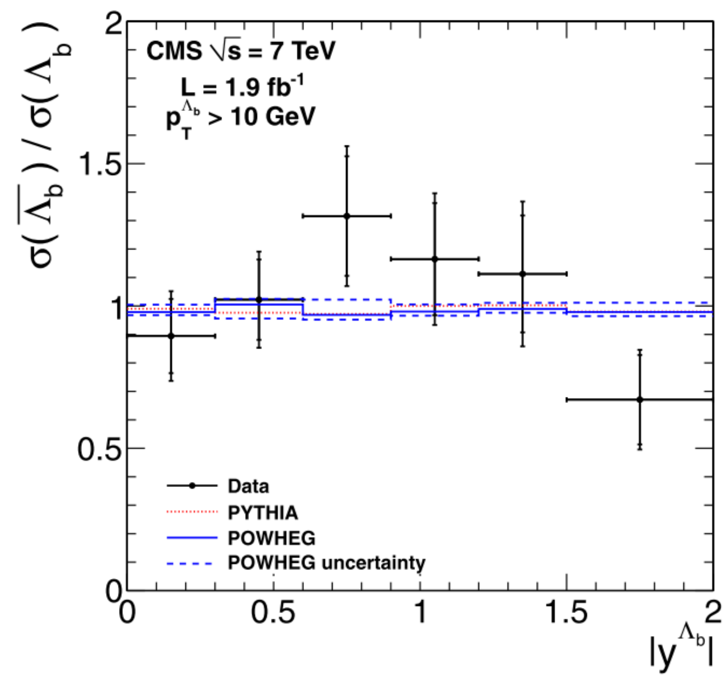




Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]



The statistic is too low



CMS, PLB714(2012)136-157

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The cross sections and asymmetry in the compact tetraquark picture

Gaussian Type+1GeV

Range(GeV)	$\sigma_{T_{cc}^{+}}(\sigma_{T_{\bar{c}\bar{c}}^{-}})$			$\mathcal{A}(\%)$
	$r = 0.2$ fm	$r = 0.5$ fm	$r = 1$ fm	
Full	1.25±0.005 nb (1.82±0.01 nb)	4.43±0.02 nb (6.46±0.02 nb)	4.88±0.02 nb (7.16±0.02 nb)	18.73±0.25±0.14
LHCb ($2 < y < 4.5$)				
$4 < p_T < 20$ [112]	39.75±0.89 pb (50.57±1.00 pb)	139.88±3.11 pb (171.16±3.38 pb)	163.77±3.65 pb (163.83±3.23 pb)	7.35±1.48±5.24
$p_T > 0$ [11]	0.24±0.002 nb (0.30±0.002 nb)	0.84±0.01 nb (1.05±0.01 nb)	0.91±0.01 nb (1.14± 0.01 nb)	11.42±0.60±0.17
CMS ($\lvert y\rvert < 1.2$)				
$10 < p_T < 50(30)$ [113]	3.77±0.51 pb (1.09±0.15 pb)	4.73±0.56 pb (3.77±0.51 pb)	4.51±0.53 pb (4.94±0.67 pb)	−6.62±8.86±7.96
ATLAS ($\lvert y\rvert < 0.75$)				
$10 < p_T < 70$ [114]	0.92±0.14 pb (0.69±0.12 pb)	3.15±0.46 pb (2.83±0.49 pb)	3.11±0.46 pb (4.88±0.84 pb)	0.98±11.04±15.37

Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

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The stability of asymmetry

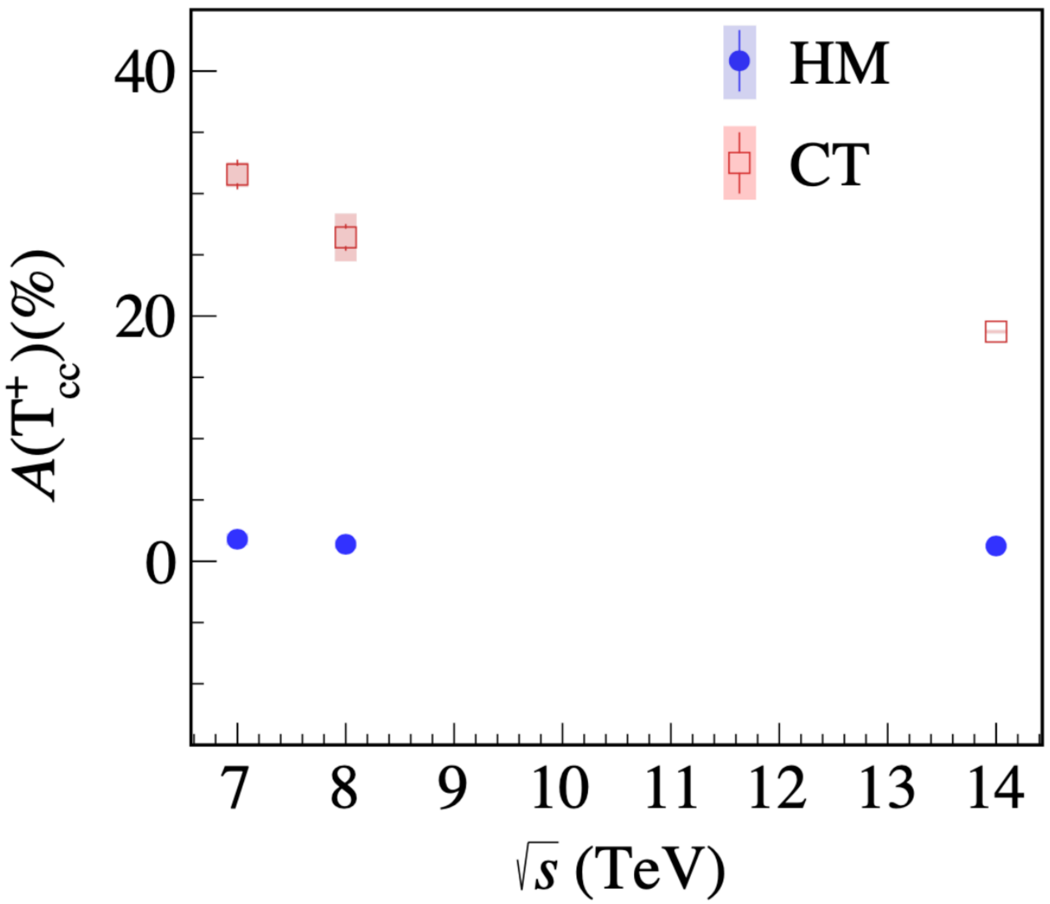
Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

$\mathscr{A}(\%)$	Gaussian 1GeV	Gaussian 0.5GeV	Saturmian 1GeV
Full	$18.73 \pm 0.25 \pm 0.14$	$18.71 \pm 0.67 \pm 0.17$	$18.70 \pm 0.25 \pm 0.08$
4<pT<20GeV	$7.35 \pm 1.48 \pm 5.24$	$3.53 \pm 4.15 \pm 2.99$	$6.71 \pm 1.48 \pm 5.17$
pT>0GeV	$11.42 \pm 0.60 \pm 0.17$	$10.65 \pm 1.64 \pm 0.42$	$11.38 \pm 0.60 \pm 0.16$

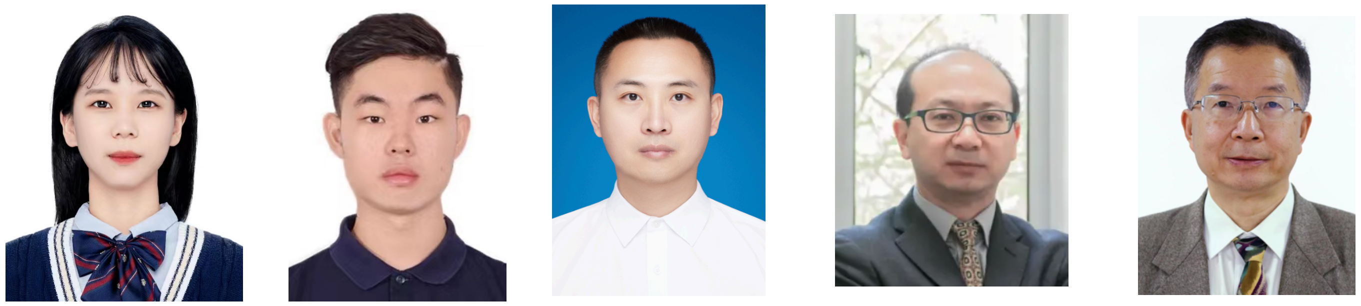
- The asymmetry is stable, i.e. the three asymmetries are consistent with each other with uncertainties
- The LHCb acceptance region has the ability to measure the asymmetry

Revealing the nature of the T_{cc}^{+} in pp collision

The asymmetries at three different c.m. energies



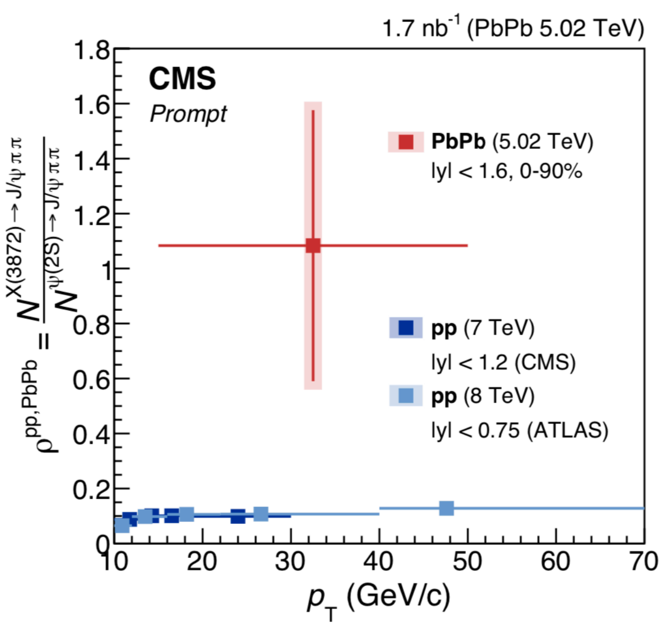
- Both asymmetries are positive
- The asymmetry of compact tetraquark is larger than that of hadronic moleculee
- The asymmetry decrease with the increasing c.m. energy

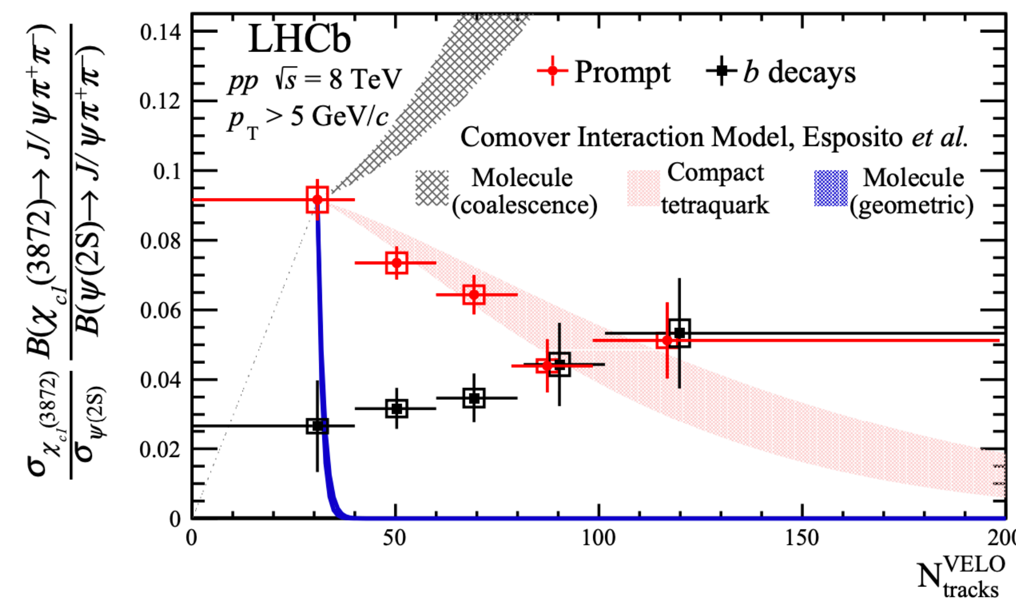


Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

Summary and outlook

- In the DD^* molecular picture, estimate the yield of T_{cc}^+ and its isospin partners in $Pb-Pb@2.76$ TeV.
- Propose asymmetry for distinguishing HM and CT pictures





- Whether it is possible to measure the T_{cc}^+ in HIC or UPC?
- We would naively expect that the asymmetry would decrease with the increasing impact parameter b

Thank you very much for your attention!