A story of double charm tetraquark

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13th April 2024

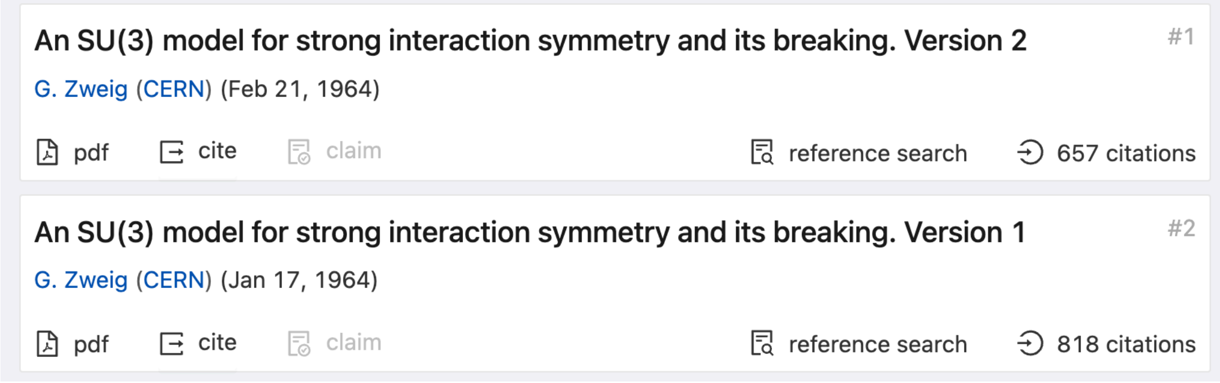
第二届超边缘碰撞物理研讨会，
合肥，科大，13th-15th April 2024

Outline

- A review of double charm tetraquark
- The molecular picture of the T_{cc}^{+}
- 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

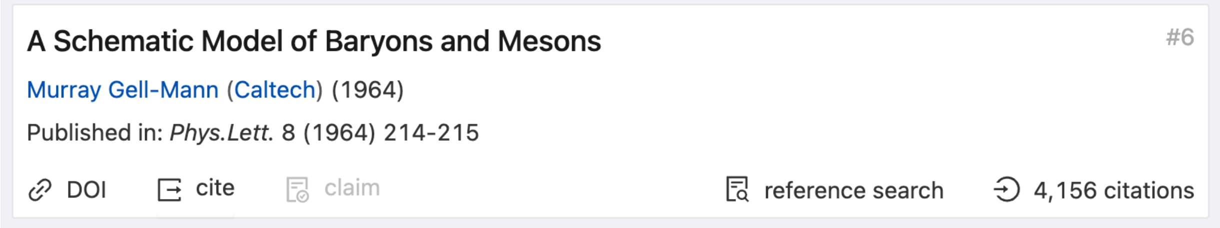


An SU(3) model for strong interaction symmetry and its breaking. Version 2 #1

G. Zweig (CERN) (Feb 21, 1964)

An SU(3) model for strong interaction symmetry and its breaking. Version 1 #2

G. Zweig (CERN) (Jan 17, 1964)

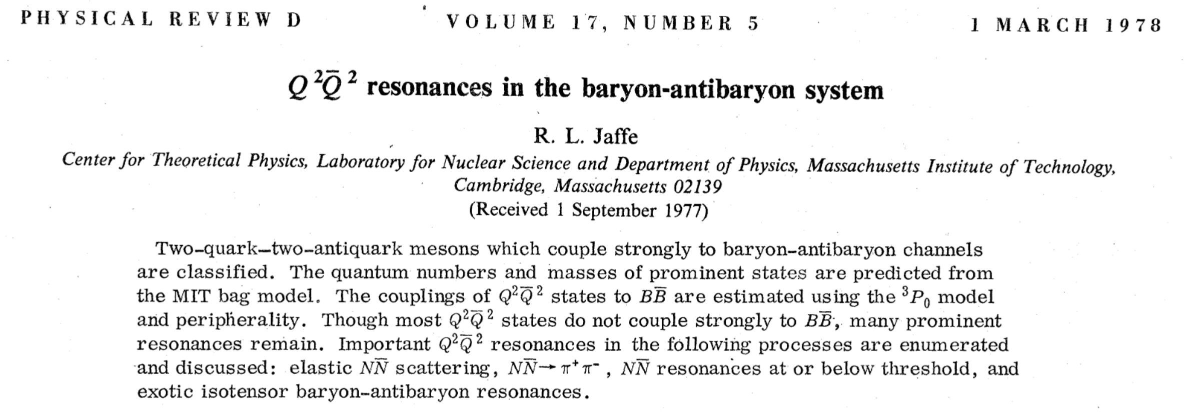


A Schematic Model of Baryons and Mesons #6

Murray Gell-Mann (Caltech) (1964)

Published in: *Phys.Lett.* 8 (1964) 214-215

- 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

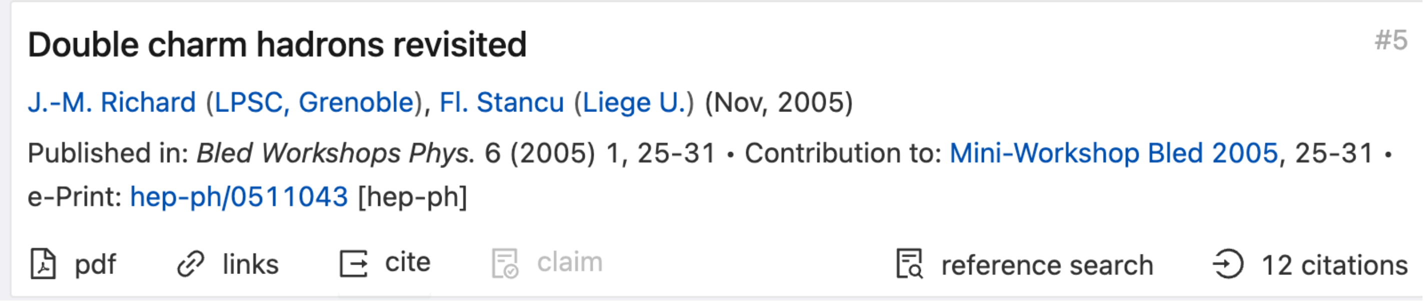
- 2002 the observation of the Ξ_{cc}^{+} $ccq \leftrightarrow cc\bar{q}\bar{q}$

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]

- 2003 the observation of the $X(3872)$ $D\bar{D}^{*} \leftrightarrow DD^{*}$
- 2005 double charm tetraquarks by J.-M. Richard and Fl. Stancu



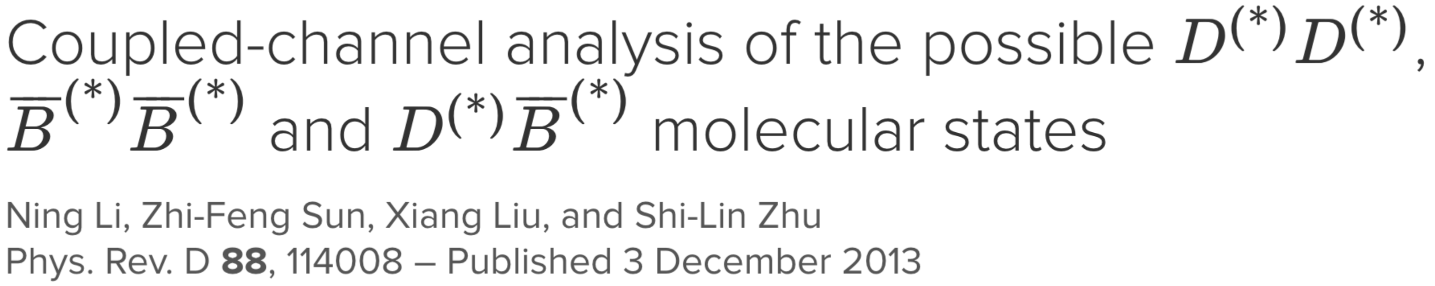
Double charm hadrons revisited #5

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]

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

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

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

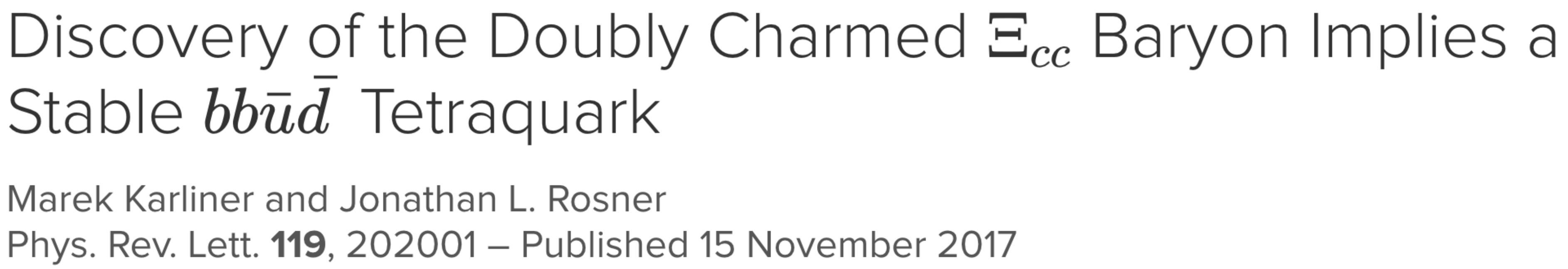
Sanchez, Geng, Lu, Hyodo, Valderrama, PRD98(2018)054001,

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

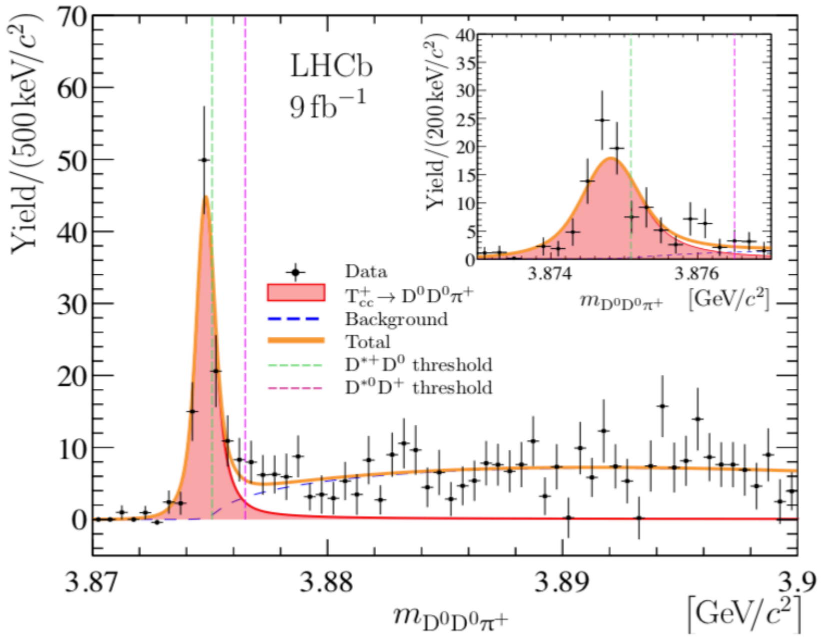
Karliner, Nussinov, JHEP07(2013)153, Cheng, Li, Si, Yao, CPC45(2021)043102,

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

A review of double charm tetraquark

2021 The observation of $T_{cc}^{+}(cc\bar{u}\bar{d})$

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



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

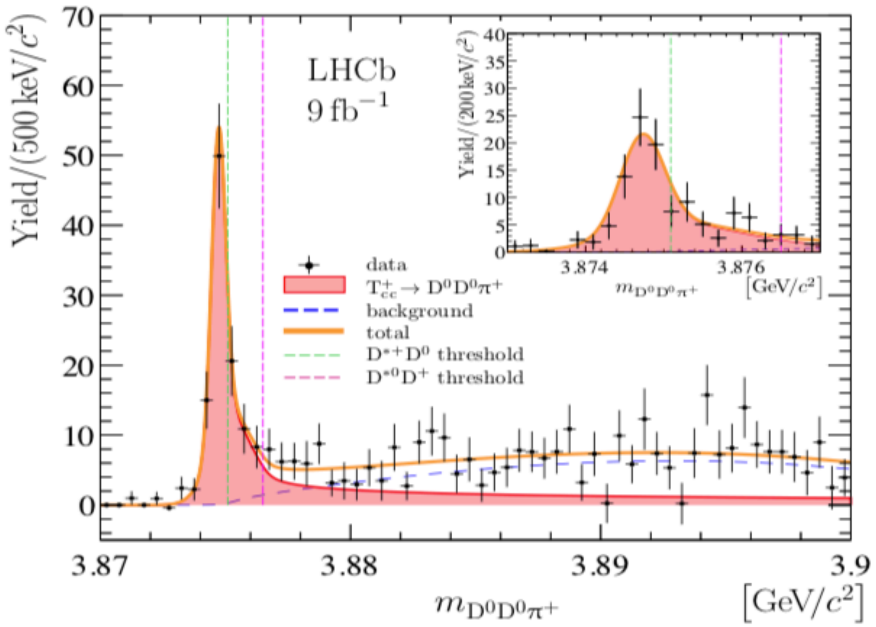
$$\delta m_{\text{BW}} = -273 \pm 61 \ \text{keV}$$

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

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

→ I=0 isoscalar

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



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

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

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

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

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

$Z = 0$ Composite $Z = 1$ Elementary

The molecular picture of the T_{cc}^{+}

Why the D^*D molecule?

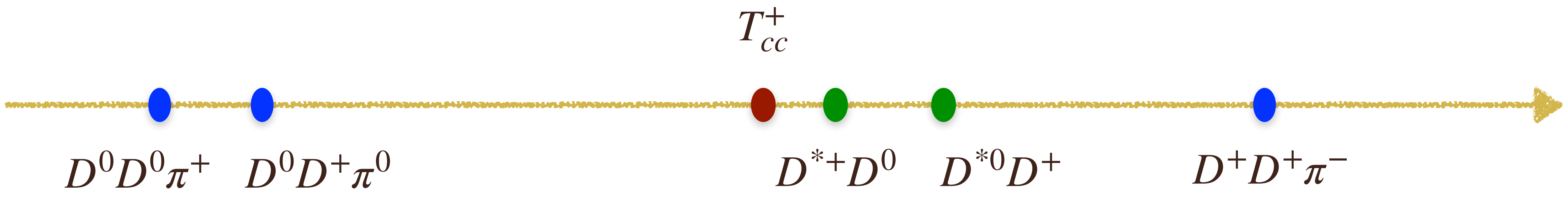
- Close to the D^*D thresholds
- Approximate 90% of $D^0D^0\pi^+$ events contain a D^{*+}
- Z<0.52

Wave functions for isospin singlet and triplet

$$|D^*D,\, I=0\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 - D^{*0}D^+\right) \qquad V_{\rm CT}^{I=0}(D^*D \to D^*D,\, J^P = 1^+) = v_0$$

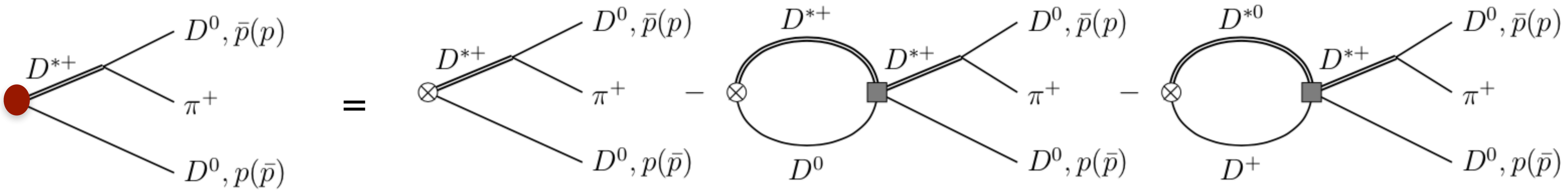
$$|D^*D,\, I=1\rangle = -\frac{1}{\sqrt{2}}\left(D^{*+}D^0 + D^{*0}D^+\right) \qquad V_{\rm CT}^{I=1}(D^*D \to D^*D,\, J^P = 1^+) = v_1$$

Three-body cut has to be considered

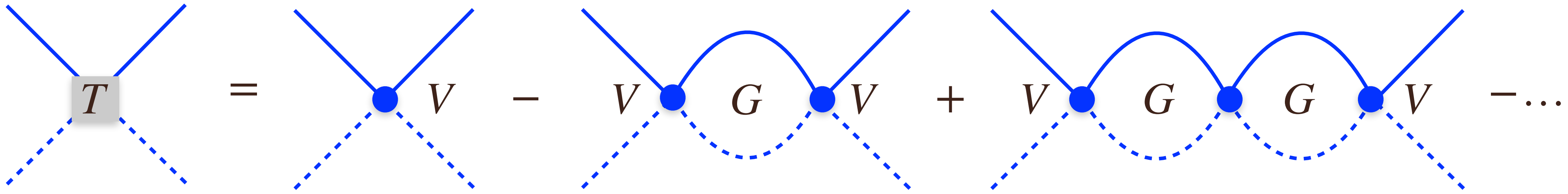


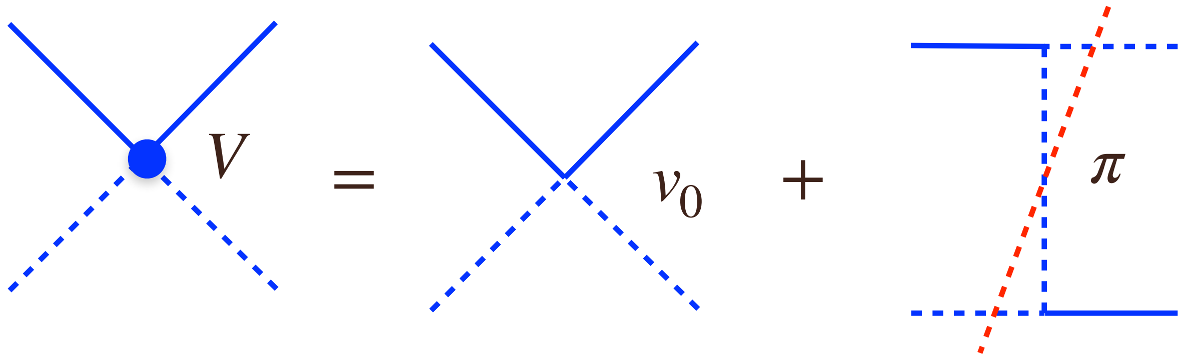
The molecular picture of the T_{cc}^+

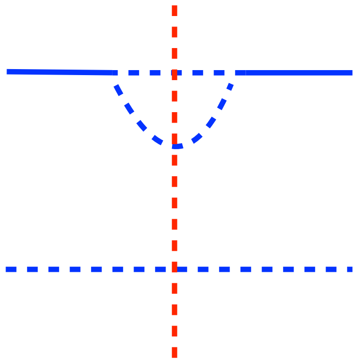
$D^0D^0\pi^+$ mass distribution



LSE





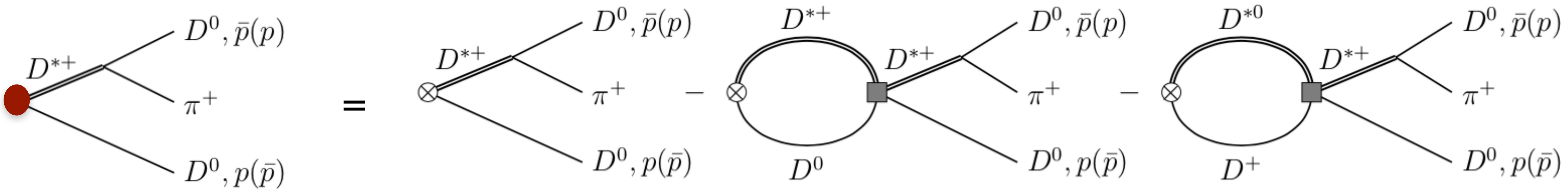


The calculation with full 3-body cut

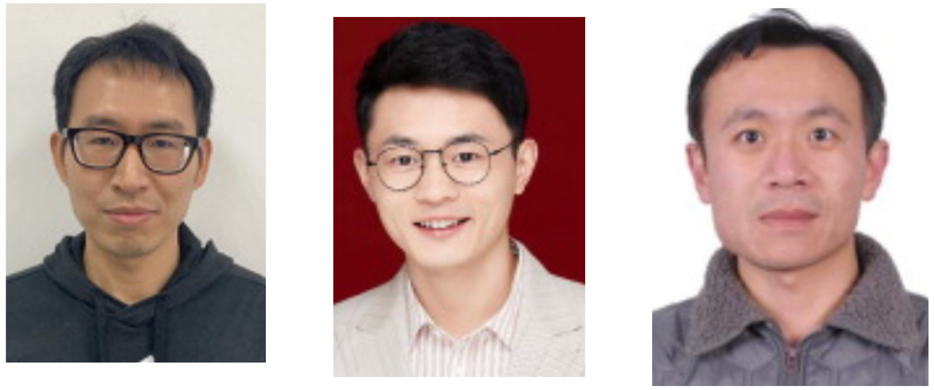
Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

The molecular picture of the T_{cc}^+

$D^0D^0\pi^+$ mass distribution



Schemes	Potential	Pole (keV)	Width (keV)
Scheme I	No OPE $\Gamma_{D^{*+}} = 82.5$ keV $\Gamma_{D^{*0}} = 53.7$ keV	$-368^{+43}_{-42} - i(37 \pm 0)$	74
Scheme II	No OPE Dynamical widths of D^*	$-333^{+41}_{-36} - i(18 \pm 1)$	36
Scheme III	OPE Dynamical widths of D^*	$-356^{+39}_{-38} - i(28 \pm 1)$	56



Width is not as large as 400keV.

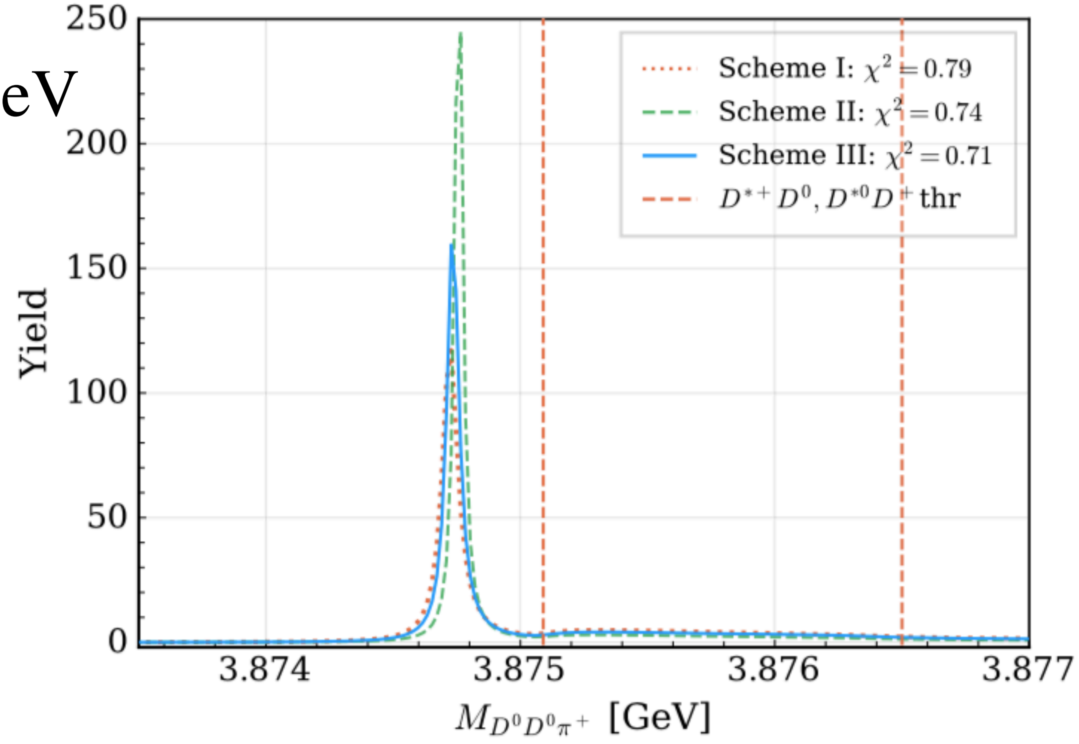
Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

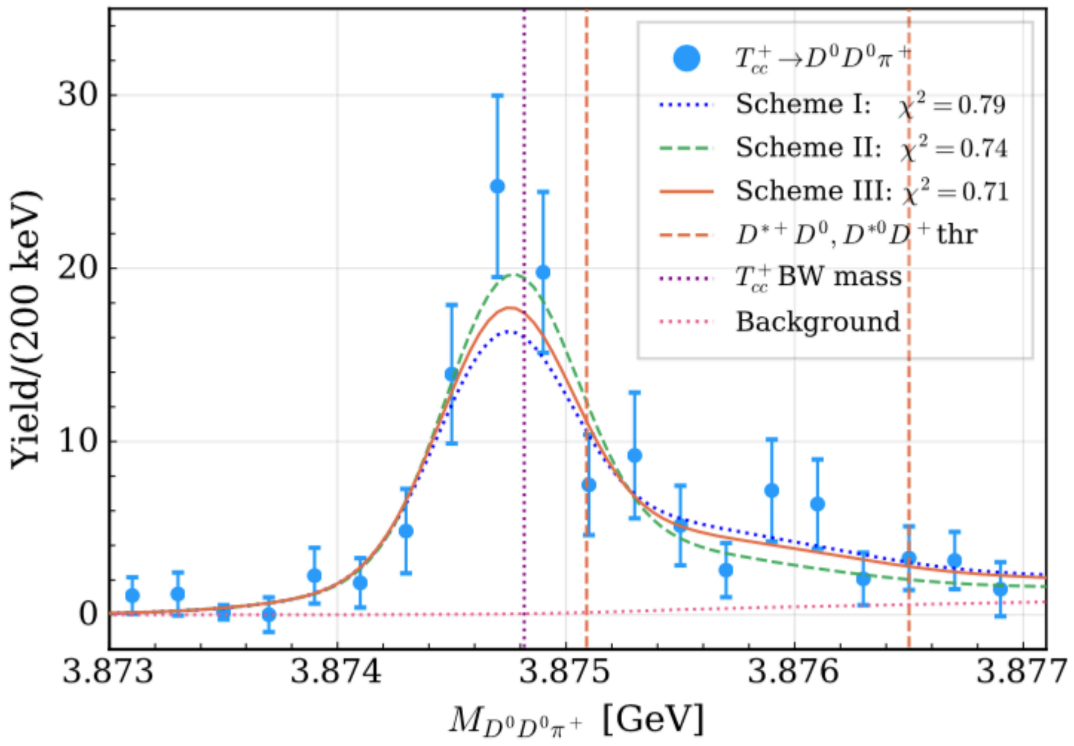
The molecular picture of the T_{cc}^{+}

$D^0D^0\pi^+$ mass distribution

Cutoff independent for $\Lambda = [0.3 - 1.2]$ GeV

$\Lambda = 0.5$ GeV

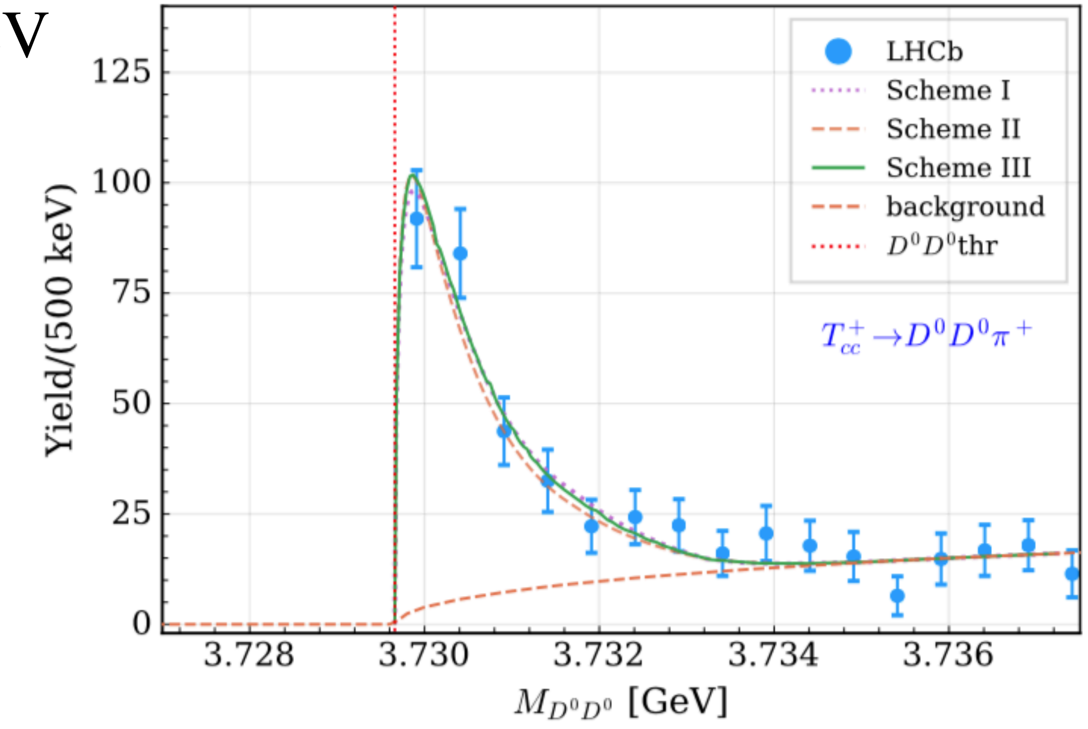


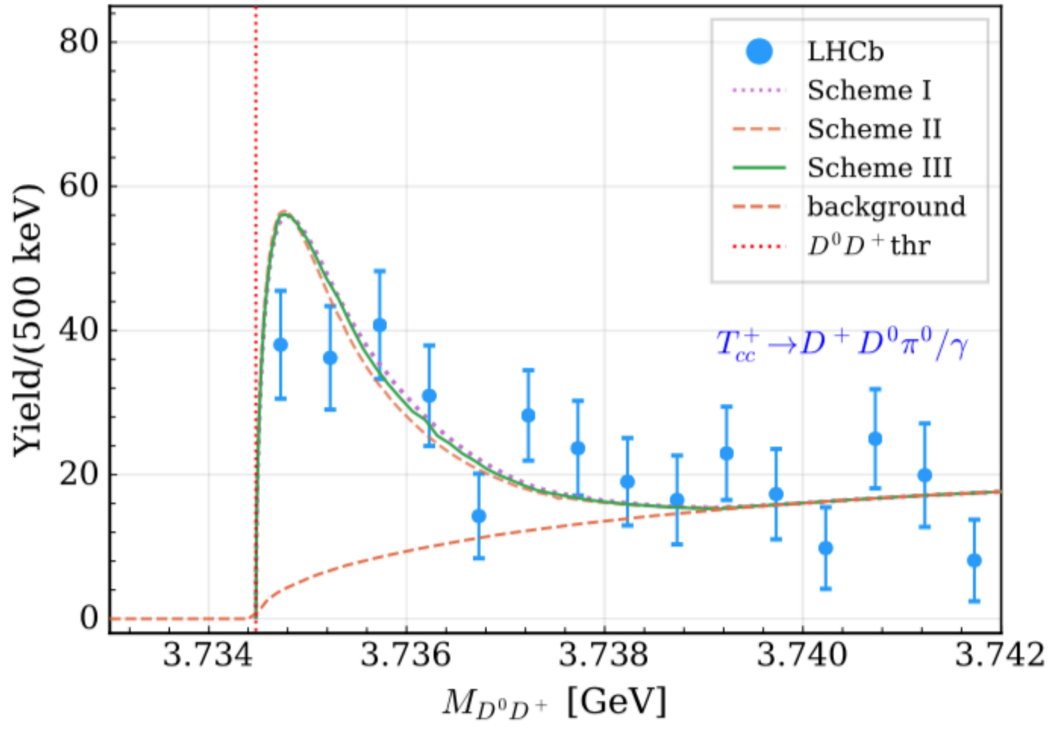


D^0D^0 and D^0D^+ mass distribution

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

$\Lambda = 0.5$ GeV





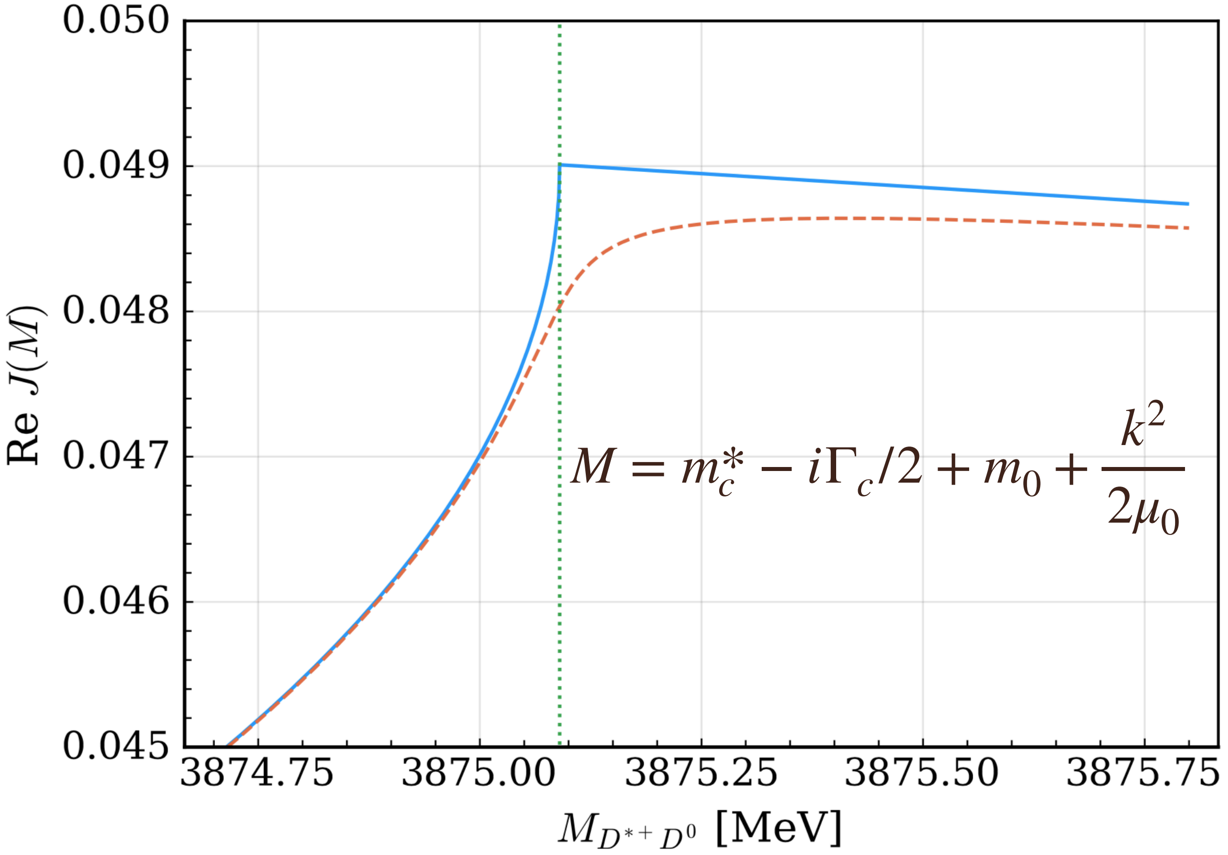
The molecular picture of the T_{cc}^+

Low energy expansion of the scattering amplitude

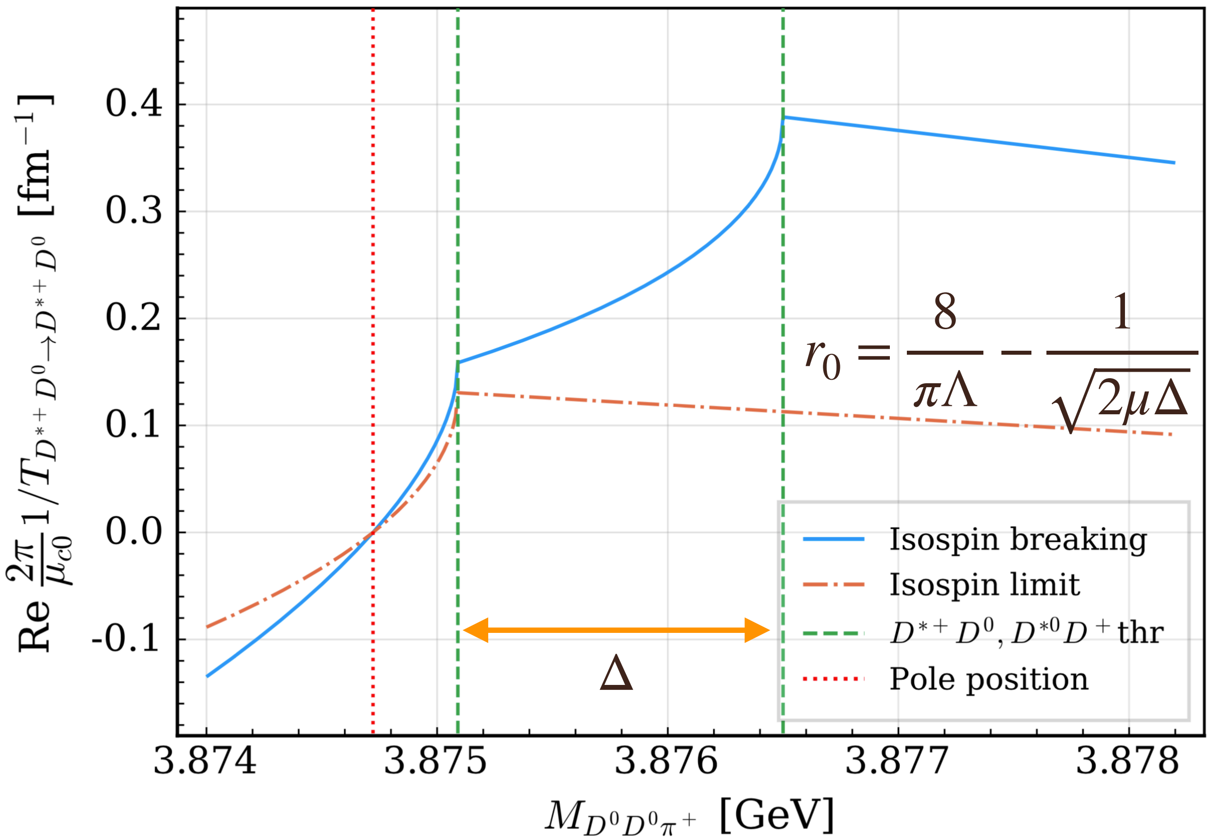
$$T_{D^{*+}D^0\to D^{*+}D^0}(k) = -\frac{2\pi}{\mu_{c0}}\left(\frac{1}{a_0}+\frac{1}{2}r_0k^2 - ik + \mathcal{O}(k^4)\right)$$

Effective range $\quad r_0 \propto -\,\mathrm{Re}\frac{dT^{-1}}{dM}\Big|_{M=M_{\rm thr}+0^+}$

Width effect



Isospin violation



Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

The molecular picture of the T_{cc}^+

Scheme I: Only contact potentials

$$T^{-1}_{D^{*+}D^0\to D^{*+}D^0}(M) = \frac{2}{v_0} + \left(J_1(M) + J_2(M)\right) \qquad E = M - M_{\mathrm{thr.1}}$$

$$J_1(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2\Lambda} + i\frac{\sqrt{2\mu E}\,\mu}{2\pi} + \mathcal{O}(E^2)$$

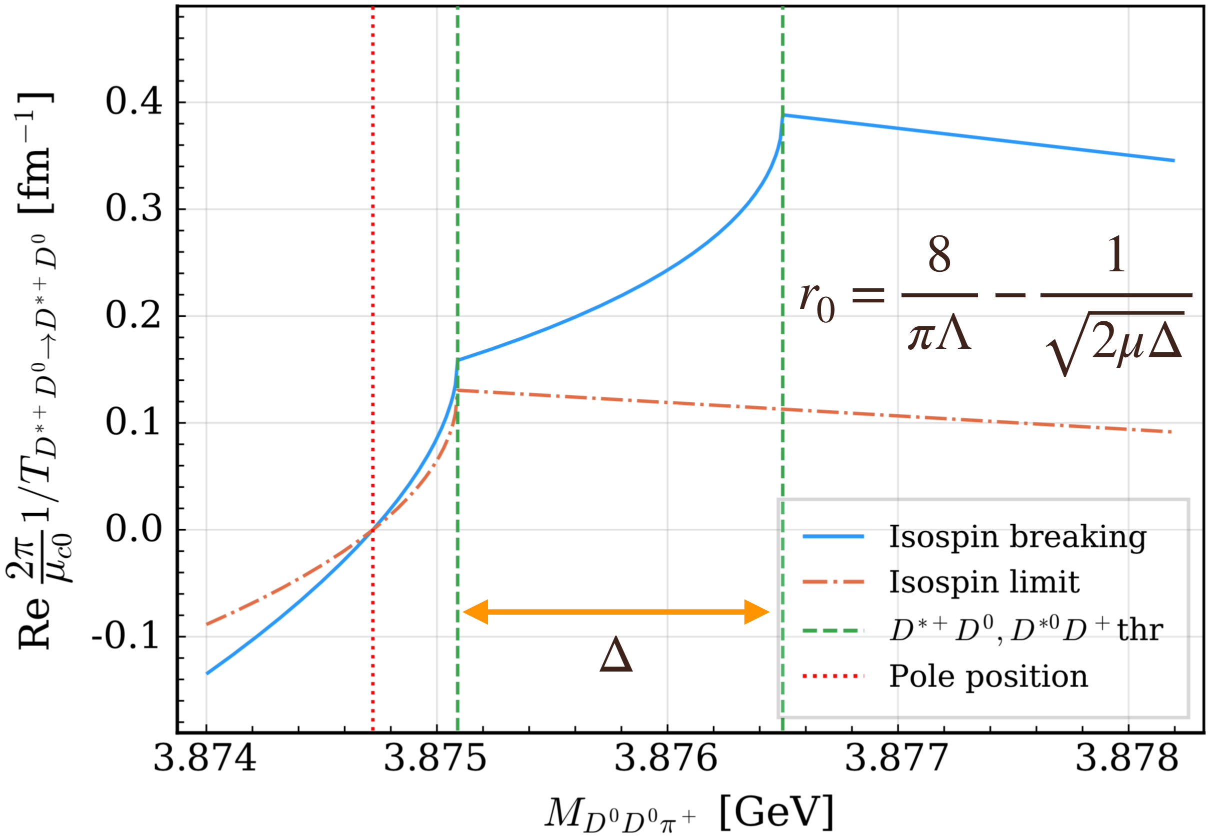
$$J_2(E) = \frac{\Lambda\mu}{\pi^2} - \frac{2\mu^2 E}{\pi^2\Lambda} + \frac{2\Delta\mu^2}{\pi^2\Lambda} - \frac{\mu\sqrt{2\mu\Delta}}{2\pi} + \frac{\mu E\sqrt{2\mu\Delta}}{4\pi\Delta} + \mathcal{O}(E^2)$$

Isospin violation

$$r_0 = -\frac{2\pi}{\mu^2}\frac{\mathrm{d}\left(J_1(M) + J_2(M)\right)}{\mathrm{d}M}\Big|_{M=M_{\mathrm{thr.1}}+0^+}$$

$$= -\frac{8}{\pi\Lambda} - \frac{1}{\sqrt{2\mu\Delta}}$$

$$\Delta r_{\mathrm{IV}} \equiv -\sqrt{\frac{1}{2\mu\Delta}} = -3.78\ \mathrm{fm}$$



Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

The molecular picture of the T_{cc}^{+}

Compositeness

$$\bar{X}_A = \left(1 + 2\left|\frac{r_0'}{\mathrm{Re}a_0}\right|\right)^{-1/2}, \quad r_0' = r_0 - \Delta r_{\mathrm{IV}}$$

$$\Delta r_{\mathrm{IV}} \equiv -\sqrt{\frac{1}{2\mu\Delta}} = -\,3.78\ \mathrm{fm}$$

Scattering length and effective range

Schemes	a (fm)	r_0 (fm)	r_0' (fm)	$\bar{X}_A$
Scheme I	$\left(-6.31^{+0.36}_{-0.45}\right) + i\left(0.05^{+0.01}_{-0.01}\right)$	-2.78 ± 0.01	1.00 ± 0.01	0.87 ± 0.01
Scheme II	$\left(-6.64^{+0.36}_{0.50}\right) - i\left(0.10^{+0.01}_{-0.02}\right)$	-2.80 ± 0.01	0.98 ± 0.01	0.88 ± 0.01
Scheme III	$\left(-6.72^{+0.36}_{-0.45}\right) - i\left(0.10^{+0.03}_{-0.03}\right)$	-2.40 ± 0.01	1.38 ± 0.01	0.84 ± 0.01

OPE contribute 0.40

Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, QW, PRD105(2022)014024

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

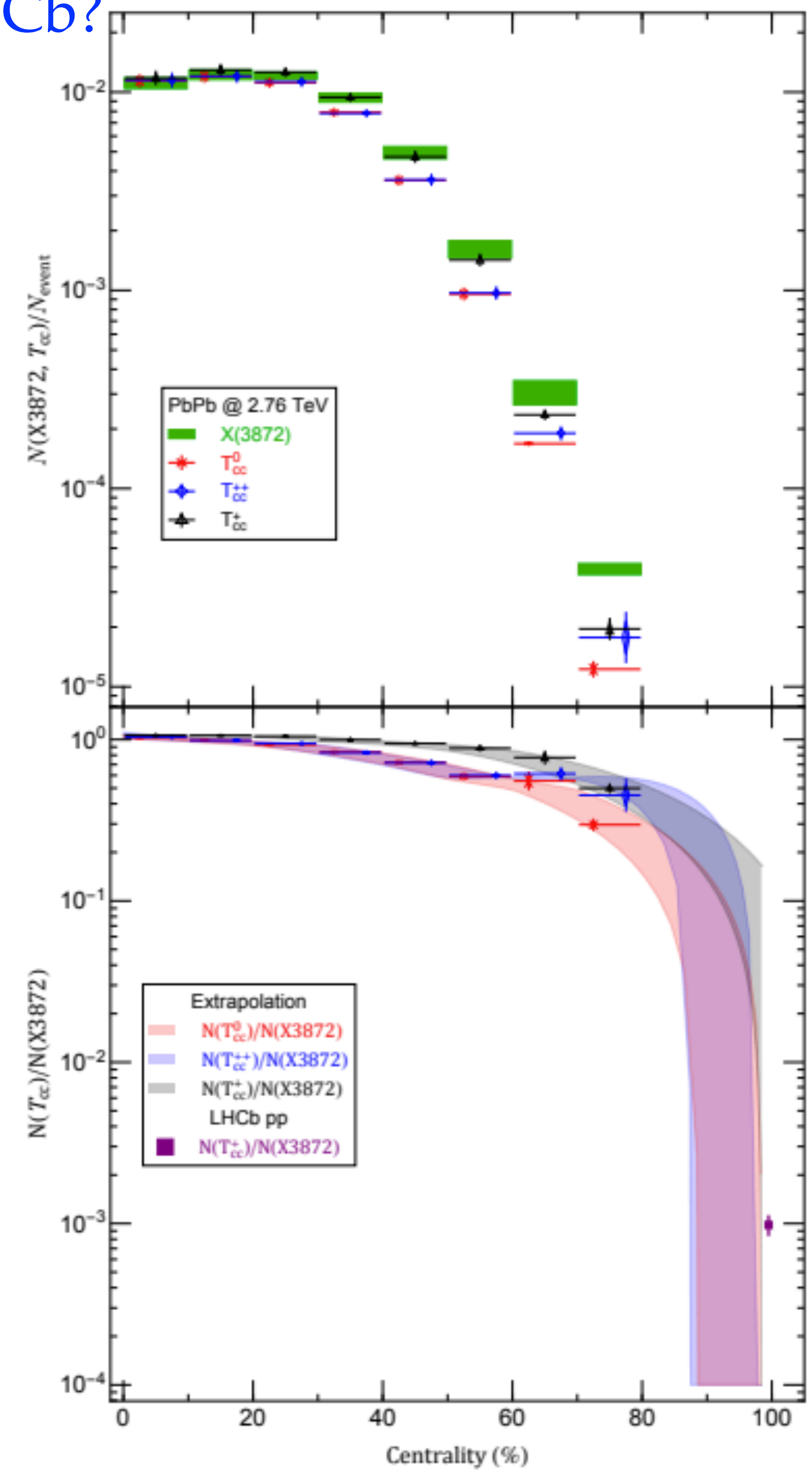
③ $R(T_{cc}^{0,+,++}) \equiv N(T_{cc}^{0,+,++})/N(X(3872))$

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}^{+}

$\mathrm{P_b - P_b @ 2.76\ TeV}$



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

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

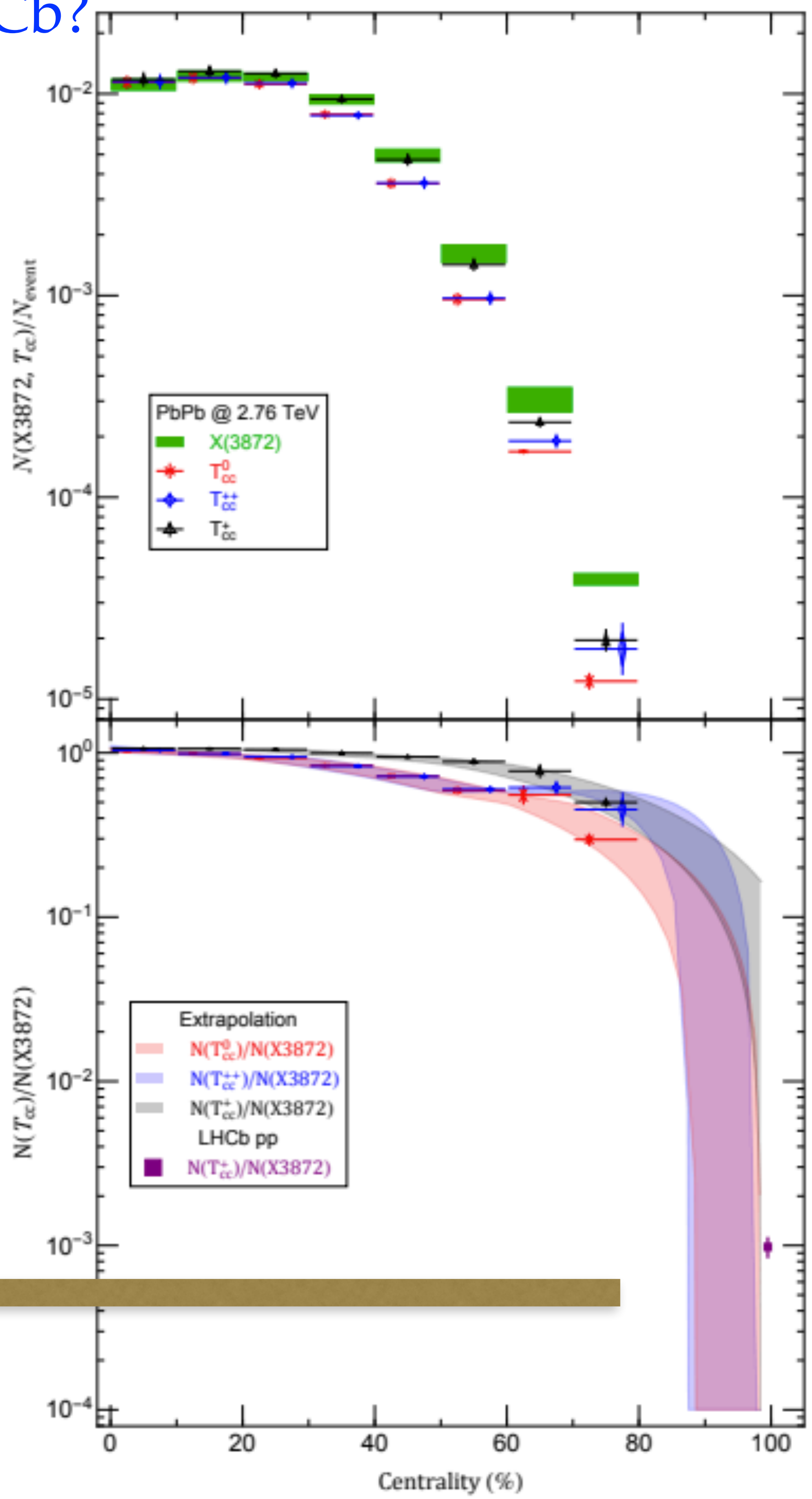
Why does the isospin triplet T_{cc} disappear in LHCb?

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

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

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

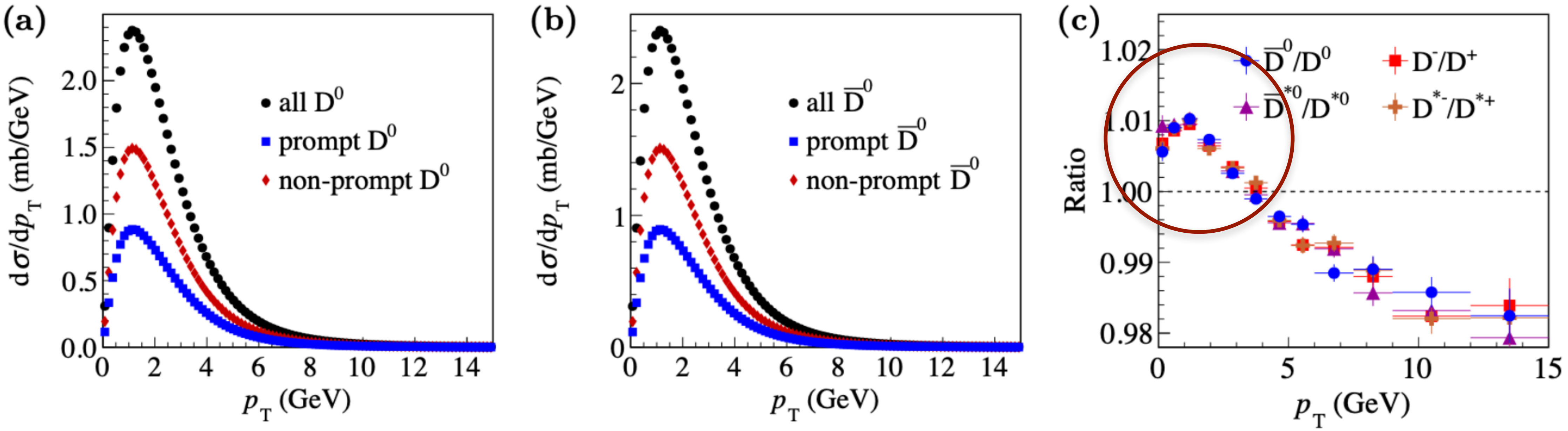
$\mathrm{P_b - P_b @ 2.76\ TeV}$



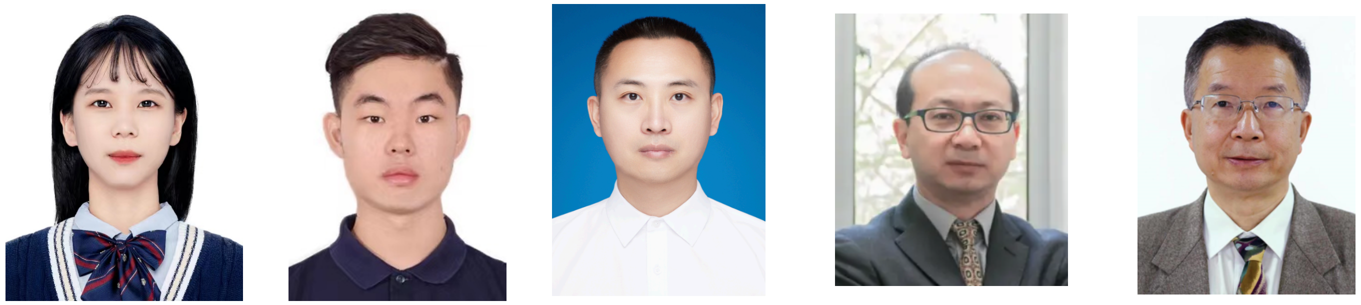
Hu, Liao, Wang, QW, Xing, Zhang, PRD104(2021)L111502

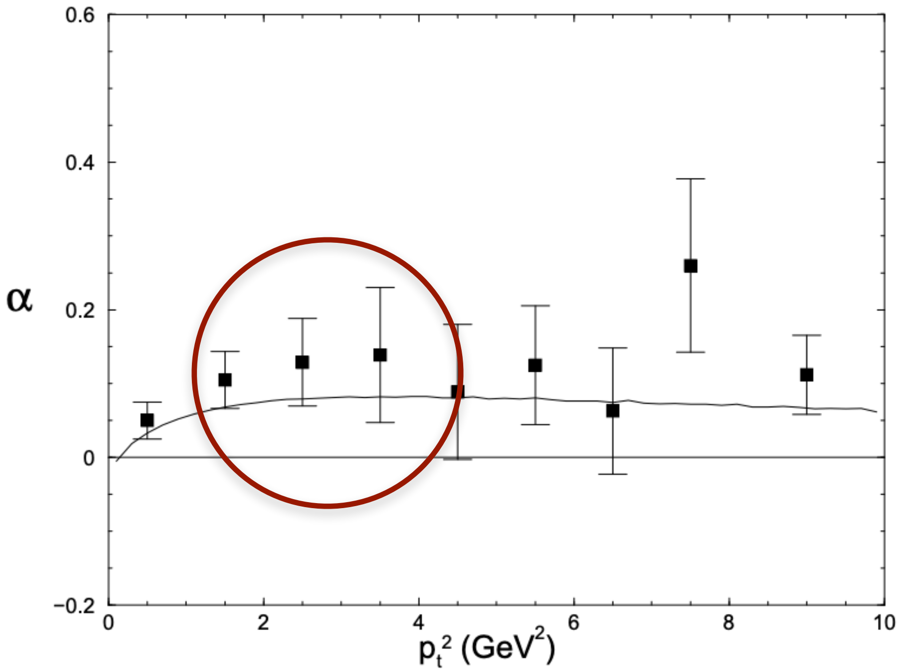
Revealing the nature of the T_{cc}^{+} in pp collision

The production of single charmed meson



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





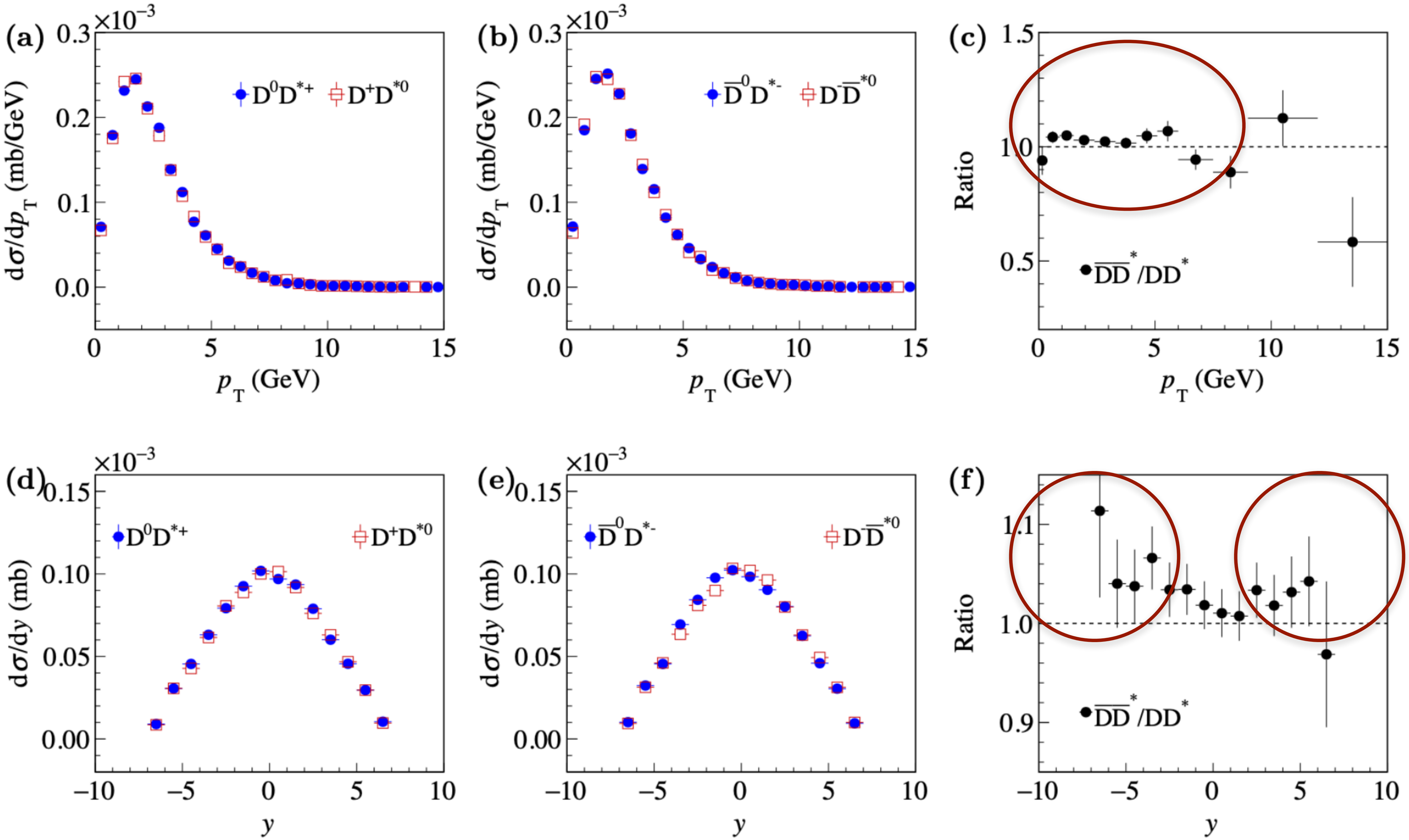
$$\alpha\left[D^{+}\right]=\frac{d\sigma\left[D^{-}\right]-d\sigma\left[D^{+}\right]}{d\sigma\left[D^{-}\right]+d\sigma\left[D^{+}\right]}$$

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

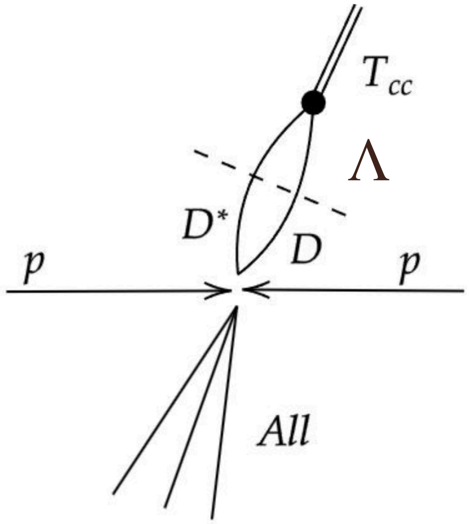


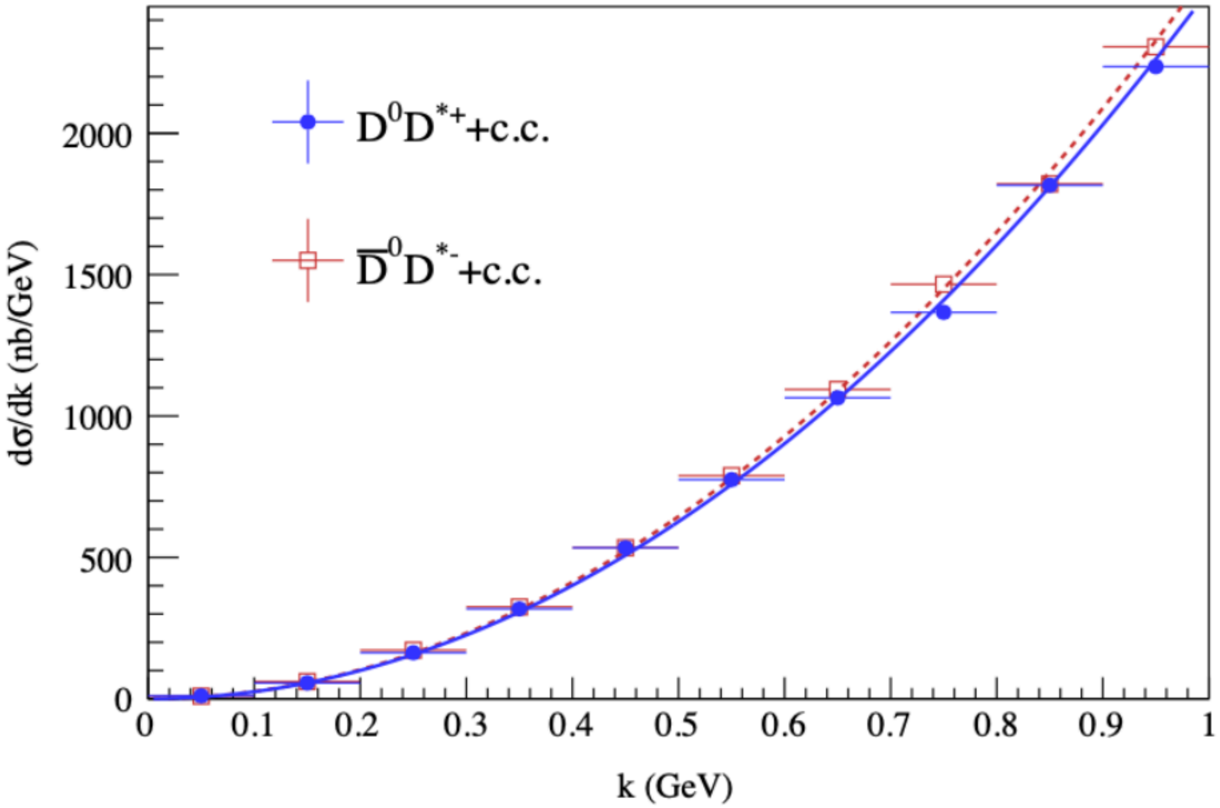
Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

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

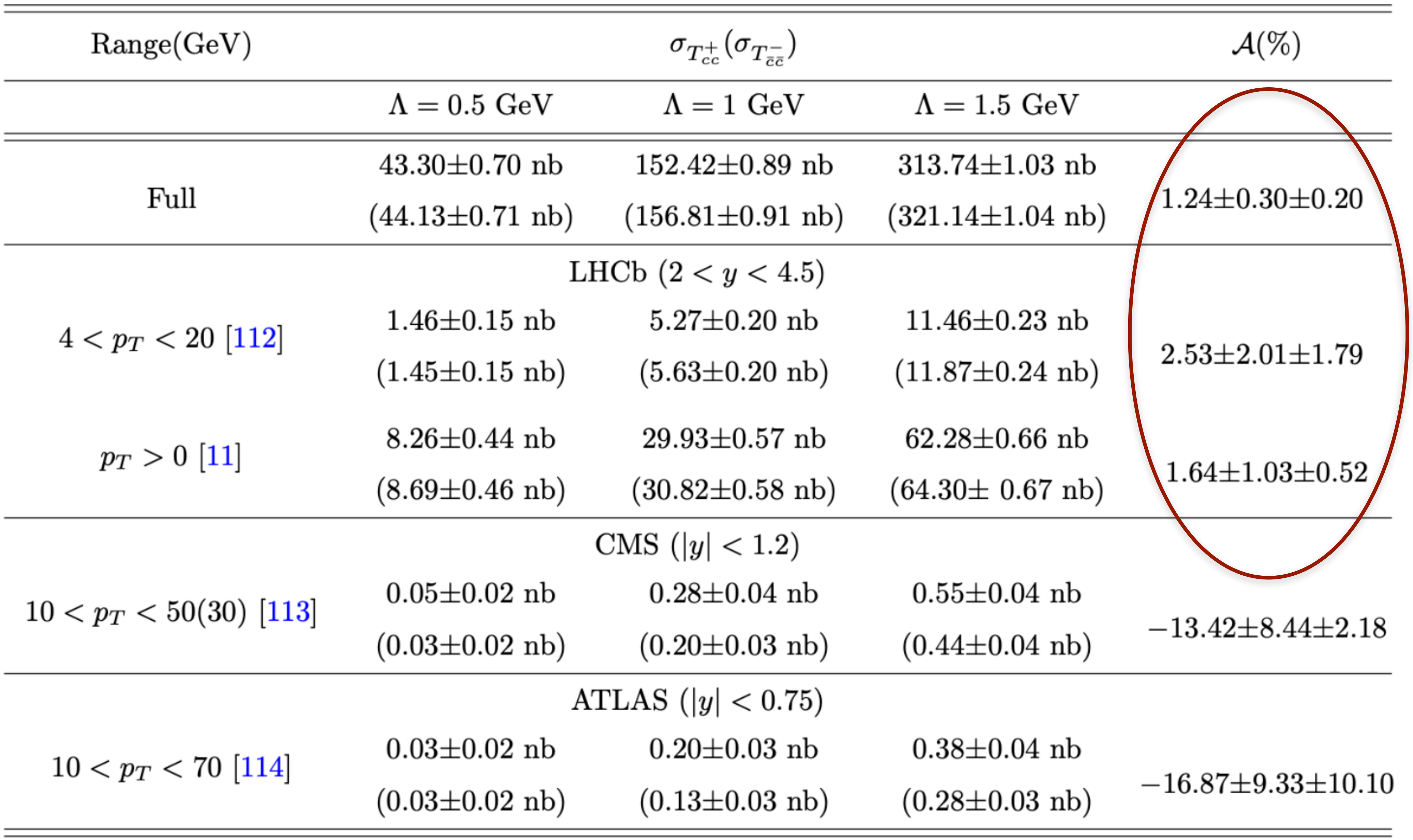
- Differential cross section behaves as k^2
- Total cross section depends on Λ
- Propose a model independent quantity $\mathscr{A}$

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

$$\mathscr{A} \equiv \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$$

$$\mathscr{A} \equiv \omega_1 \mathscr{A}_1 + \omega_2 \mathscr{A}_2 + \omega_3 \mathscr{A}_3$$

$$\omega_i = \frac{\frac{1}{\delta_i^2}}{\frac{1}{\delta_1^2} + \frac{1}{\delta_2^2} + \frac{1}{\delta_3^2}}$$

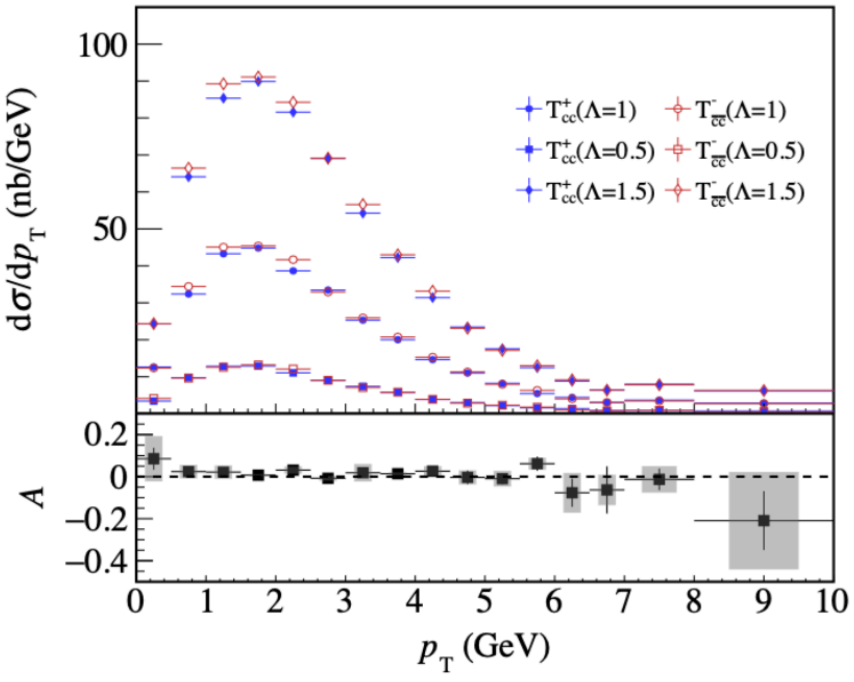
$$\delta_{sta} \equiv \omega_1 \delta_1 + \omega_2 \delta_2 + \omega_3 \delta_3$$

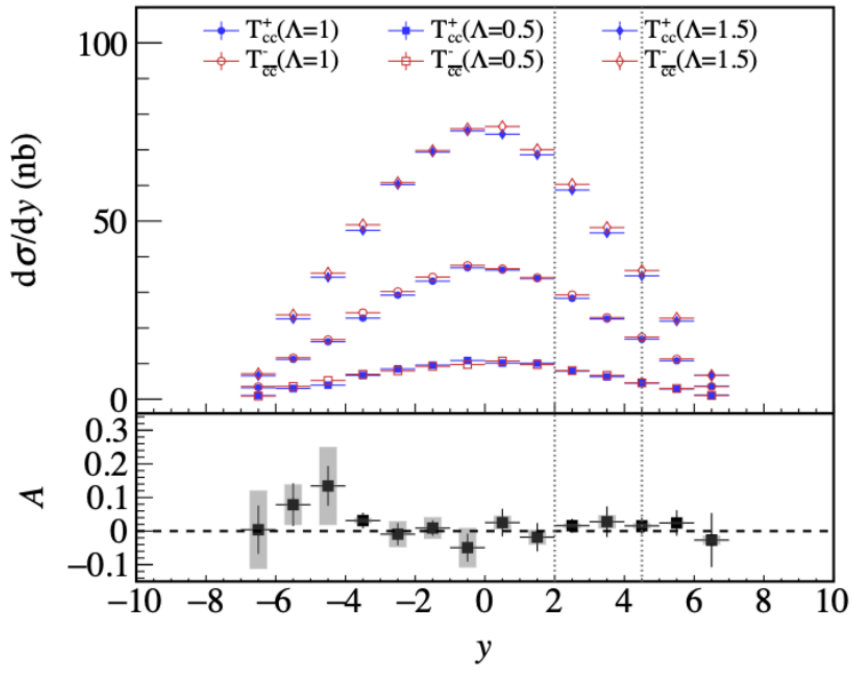
$$\delta_{sys} \equiv \sqrt{\frac{\sum_i (\mathscr{A}_i - \mathscr{A})^2}{3}}$$

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 $p_\mathrm{T} = 2$ 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

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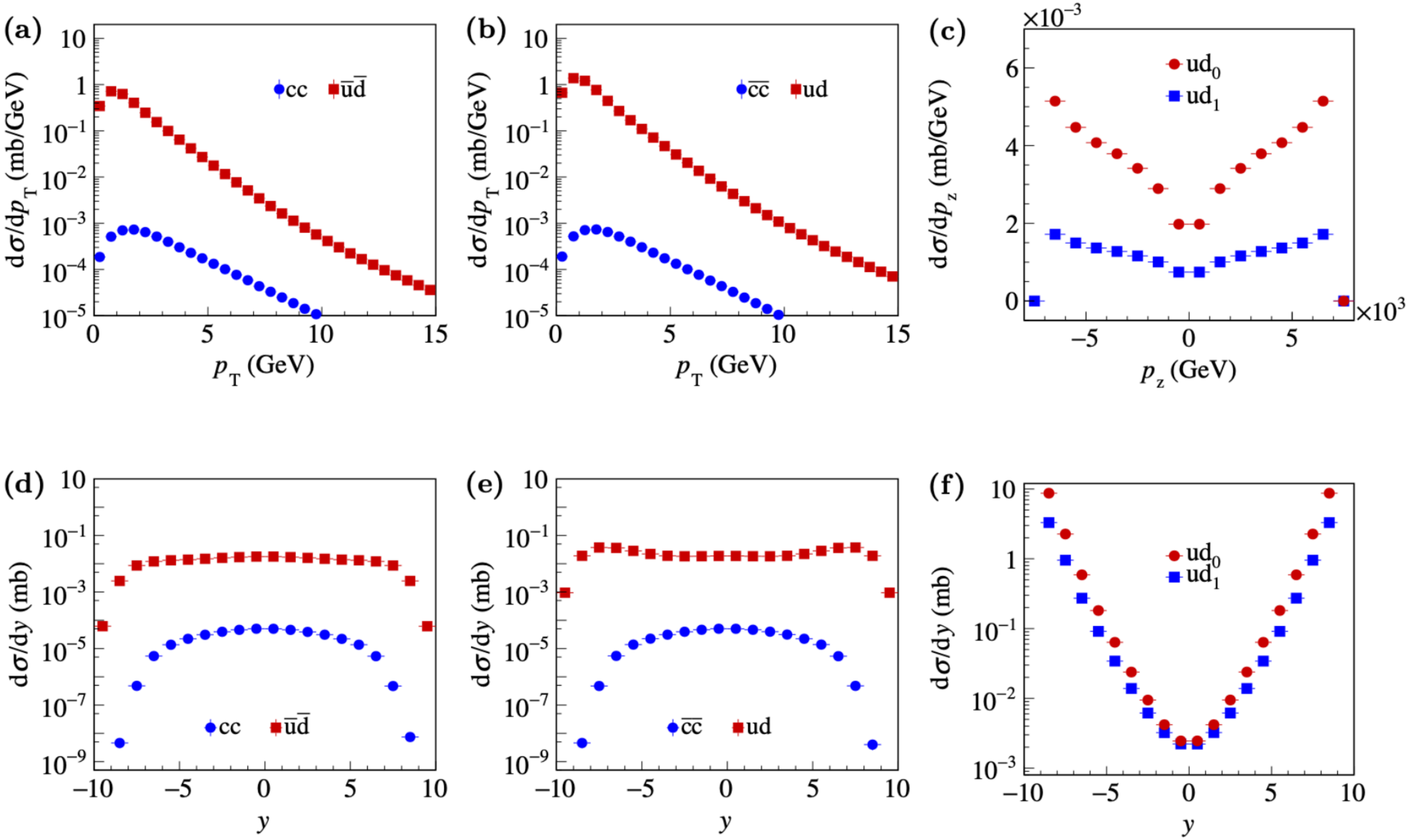
Revealing the nature of the T_{cc}^{+} in pp collision

The diquark and antidiquark distributions



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

The diquark-antidiquark pair distributions

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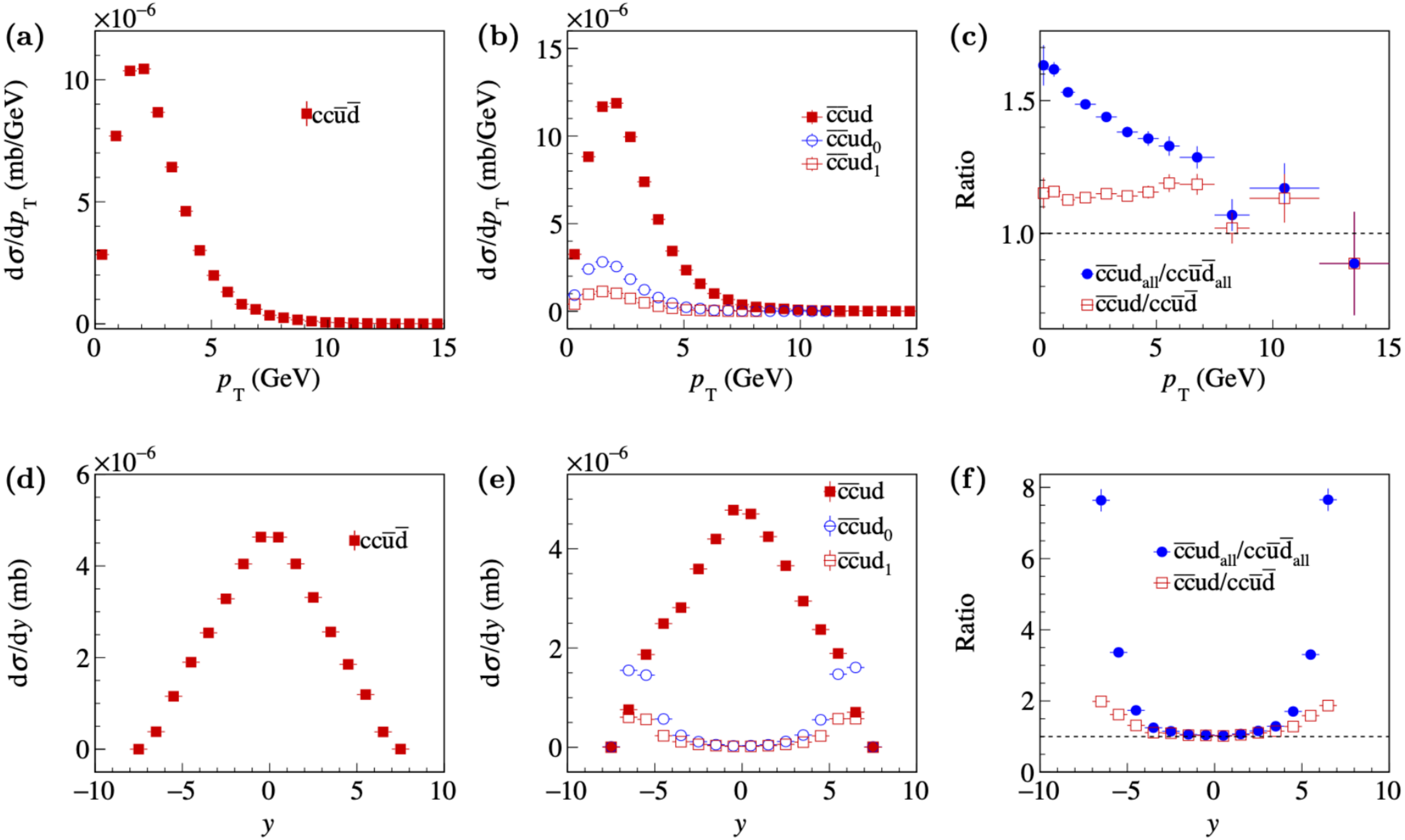
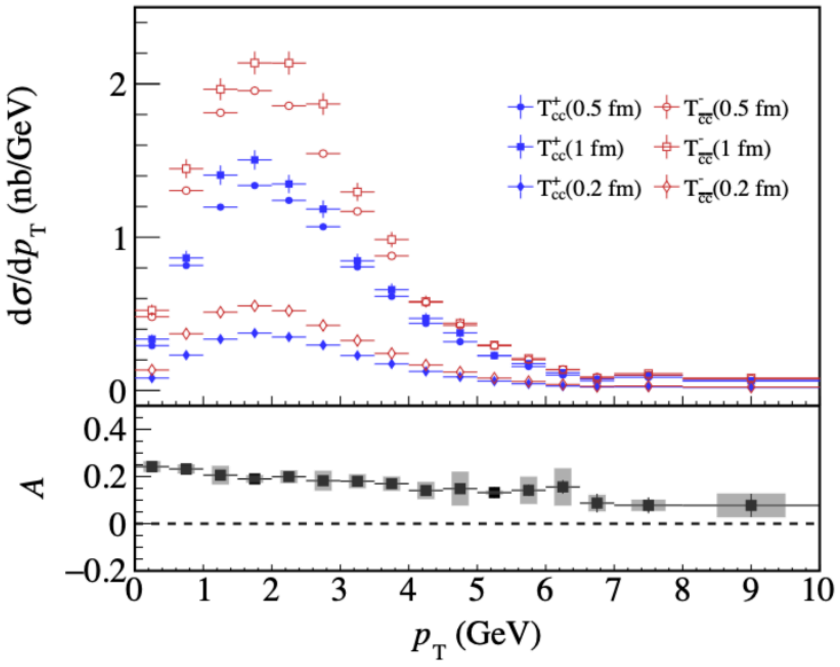
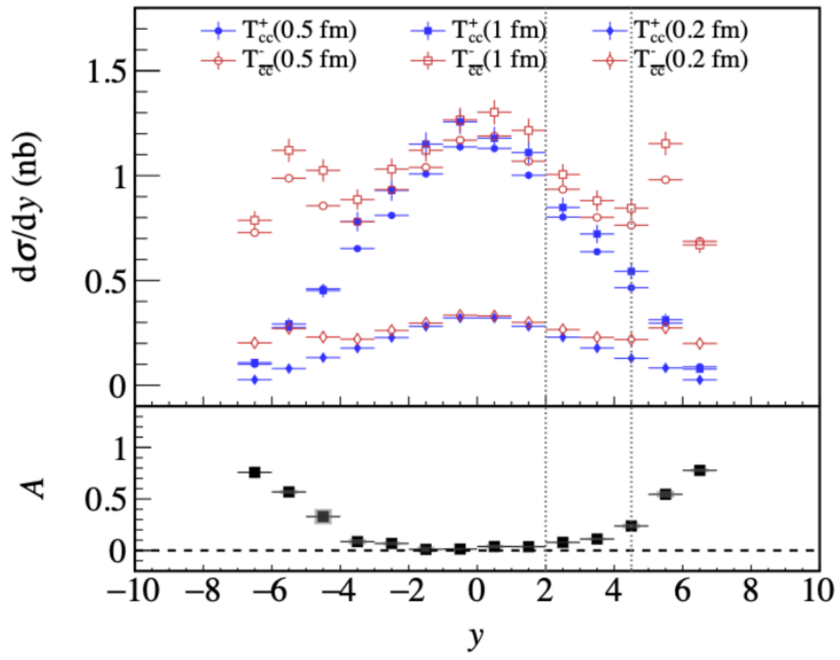


Gaussian Type $\phi(\overrightarrow{p}, a) = (\frac{1}{\pi})^{\frac{3}{4}}(\frac{1}{a})^{\frac{3}{2}}e^{\frac{-p^2}{2a^2}}$ Saturmian Type $\psi(\overrightarrow{p}, b) = 2\sqrt{2}(\frac{1}{\pi})(\frac{1}{b})^{\frac{3}{2}}\frac{1}{(\frac{p^2}{b^2}+1)^2}$

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?

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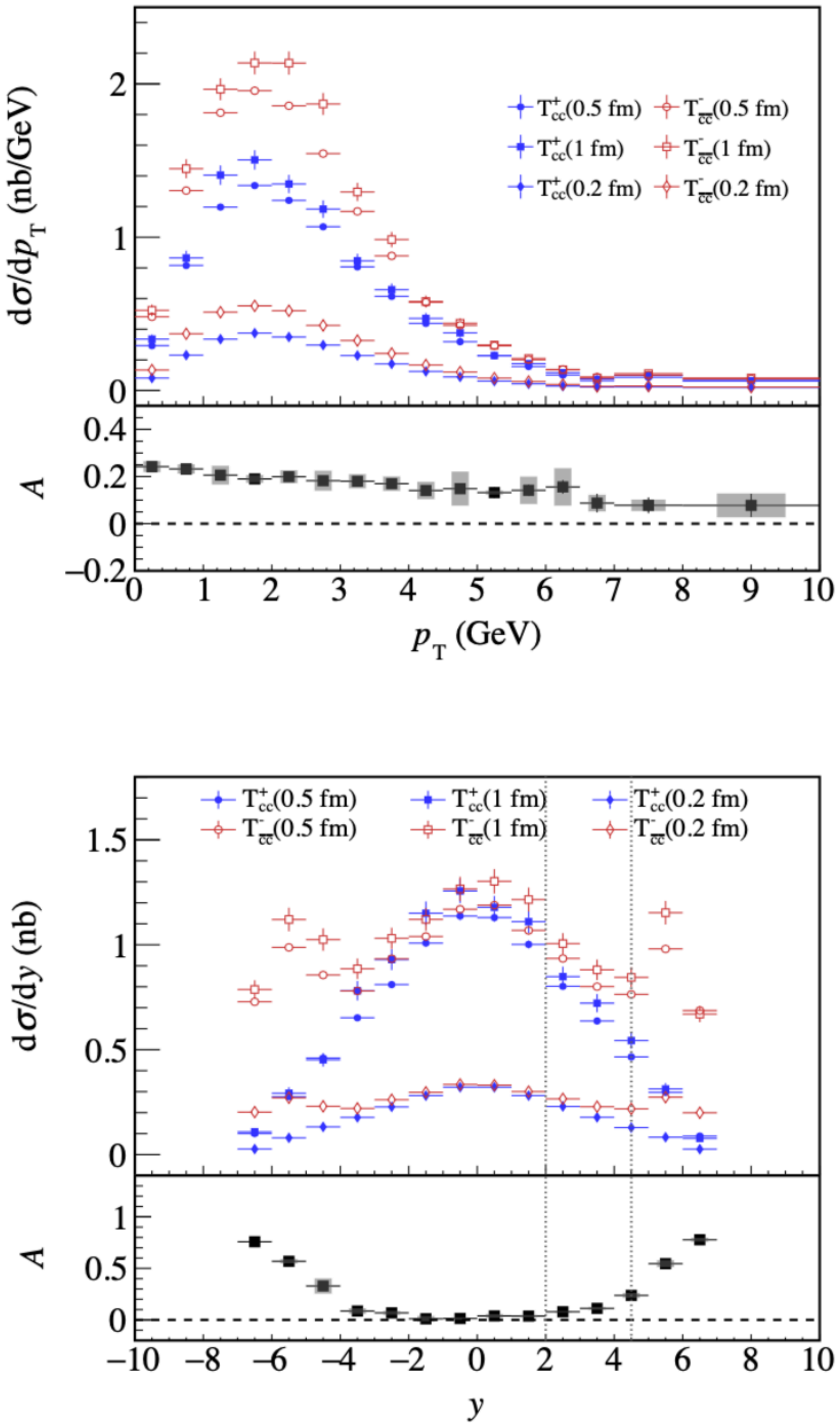
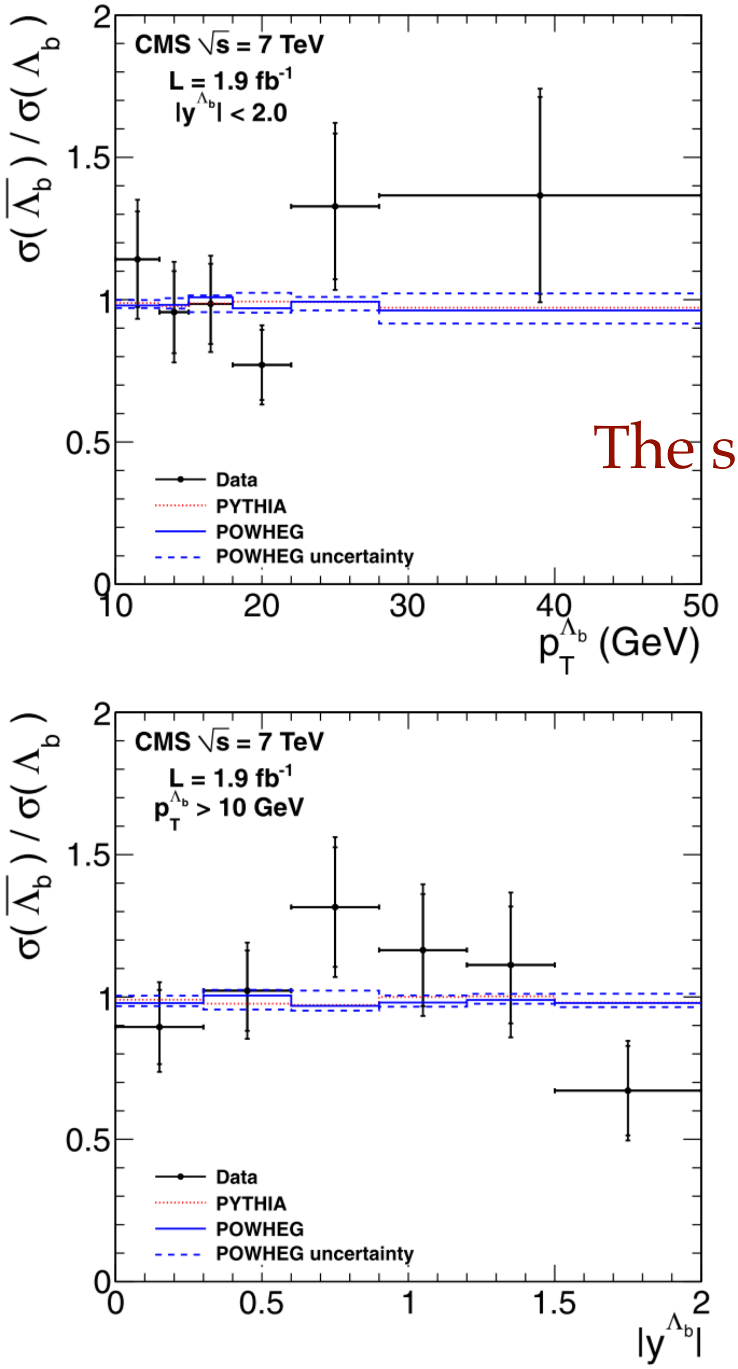
The p_T and y distributions in the compact tetraquark picture





The statistic is too low

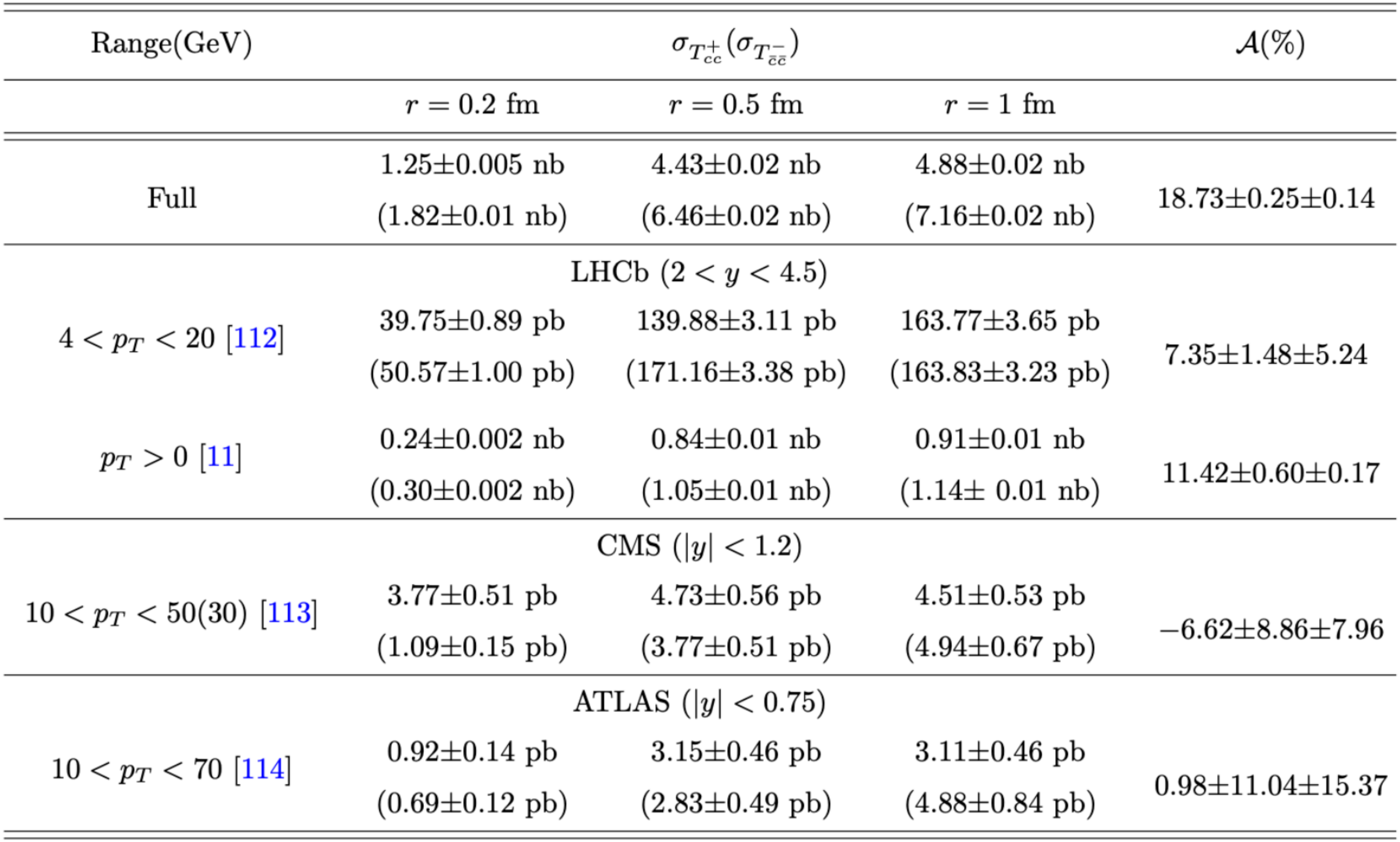
Hua, Li, QW, Yang, Zhao, Zou, arXiv:2310.04258[hep-ph]

CMS, PLB714(2012)136-157

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

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

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

The stability of asymmetry

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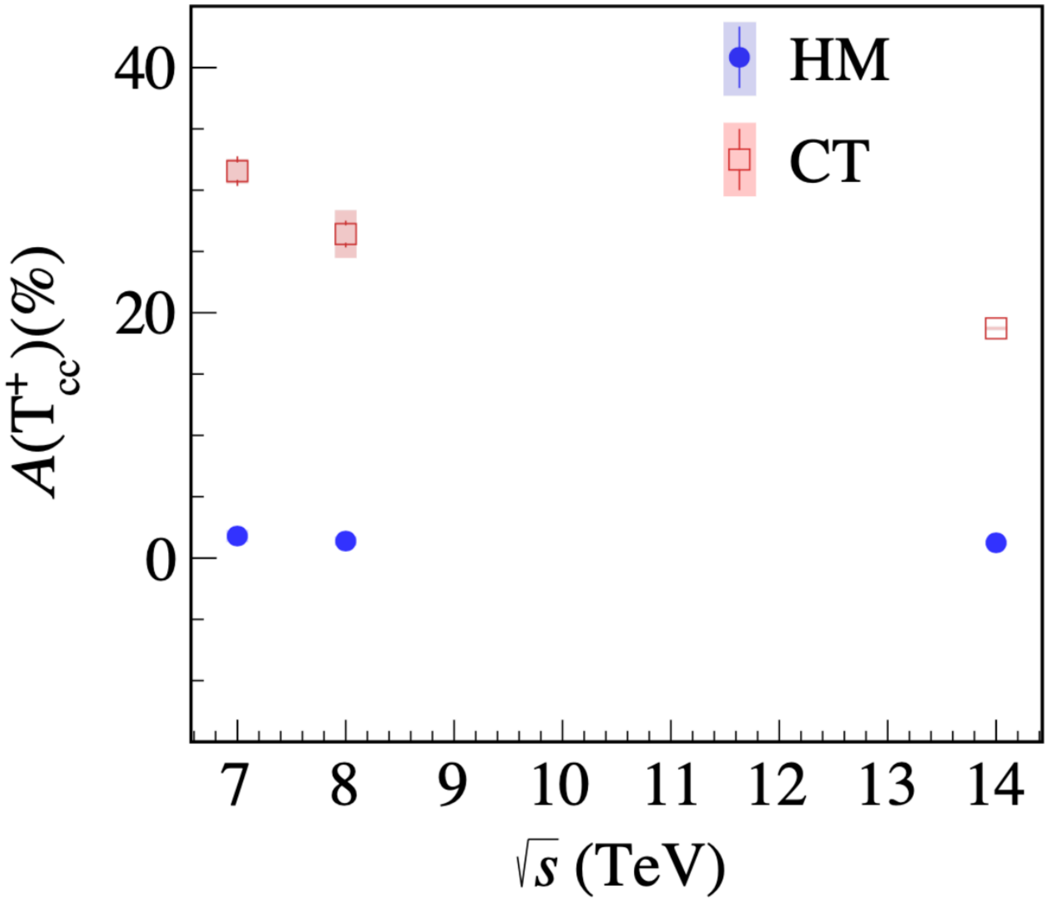
$\mathscr{A}(\%)$	Gaussian 1GeV	Gaussian 0.5GeV	Saturmian 1GeV
Full	$18.73 \pm 0.25 \pm 0.14$	$18.71 \pm 0.67 \pm 0.17$	$18.70 \pm 0.25 \pm 0.08$
4<pT<20GeV	$7.35 \pm 1.48 \pm 5.24$	$3.53 \pm 4.15 \pm 2.99$	$6.71 \pm 1.48 \pm 5.17$
pT>0GeV	$11.42 \pm 0.60 \pm 0.17$	$10.65 \pm 1.64 \pm 0.42$	$11.38 \pm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

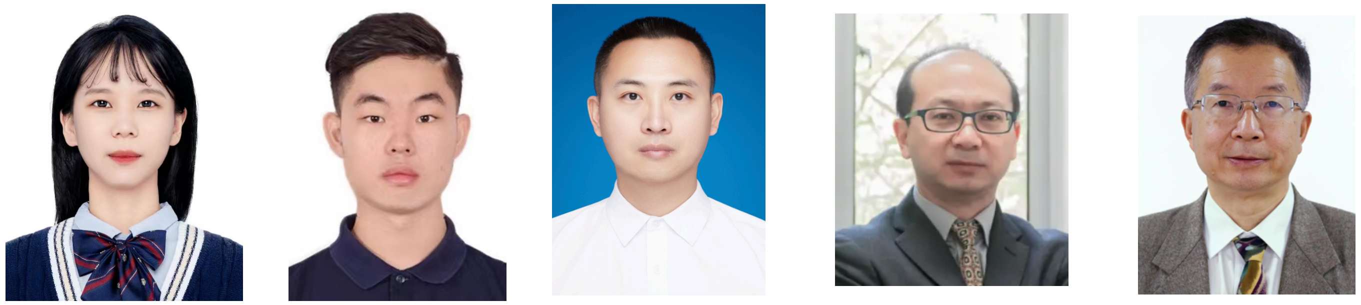
- The asymmetry is stable, i.e. the three asymmetries are consistent with each other with uncertainties
- The LHCb acceptance region has the ability to measure the asymmetry

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



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Summary and outlook

- Explore the hadronic molecular nature of the T_{cc}^{+} via its line shape
- 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

UPC or HIC?

- 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!