Study the nature of double charm tetraquark in proton-proton collisions

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The 23rd International Conference
on Few-Body Problems in Physics
Beijing, China 2024.9.22-27

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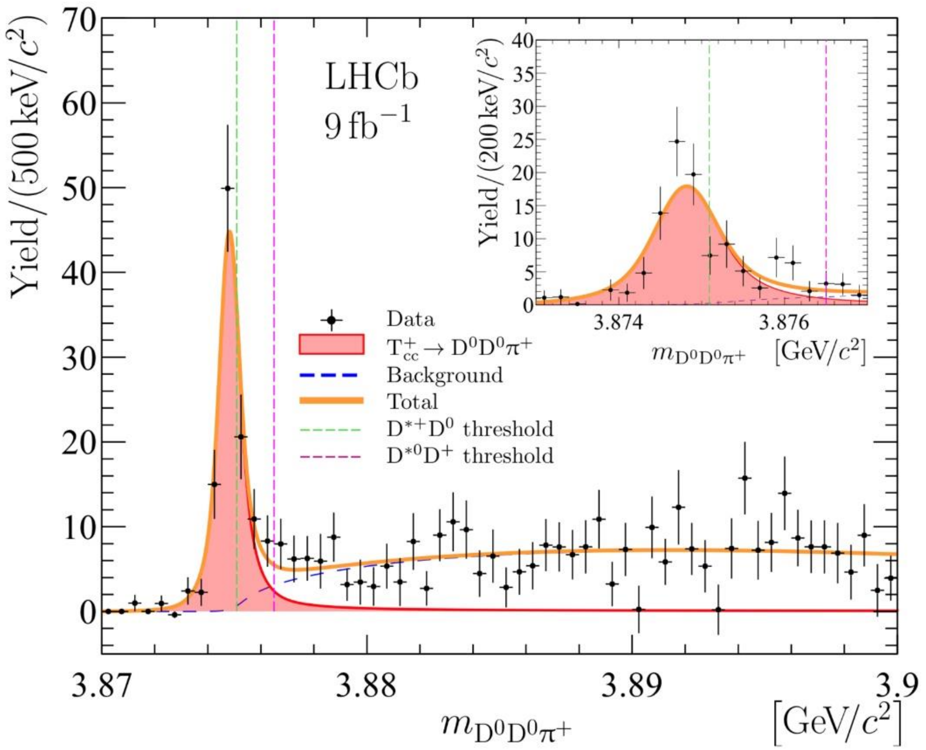
Eur. Phys. J. C 84 (2024) 8, 800

Background

The observation of T_{cc}^{+}

[LHCb, Nature Phys. 18(7) (2022) 751-754]



- Discovered in $\boldsymbol{pp \to D^0D^0\pi^+ + all}$ by LHCb
- The first double charm tetraquark candidate
- Quark content $cc\bar{u}\bar{d}$ and $I(J^P) = 0(1^+)$
- Close to (and below) $D^{*+}D^0$ threshold
- Well-established exotic hadron candidate

Simple BW

- $\delta_m = -273 \pm 61$ keV
- $\Gamma = 410 \pm 165$ keV
- 4.3σ for $\delta_m < 0$

[Nature Phys. 18(7) (2022) 751-754]

Unitarised 3-body BW

- $\delta_m = -359 \pm 40$ keV
- $\Gamma = 48 \pm 2$ keV
- 9σ for $\delta_m < 0$

[Nature Commun. 13 (2022) 1, 3351]

Background

Hadronic Molecular picture

- Obtain the line shape of T_{cc}^{+}
- Obtain the mass position and width of T_{cc}^{+}
- Predict the locations of $I = 1$ triplet partners of T_{cc}^{+}

[Xin et al, EPJA 58 (2022) 6, 110]
[Shi et al, PRD 106 (2022) 9, 096012]
[Albaladejo, PLB 829 (2022) 137052]
[Chen et al, PLB 833 (2022) 137391]
[Du et al, PRD 105 (2022) 1, 014024]
[Liu et al, PRD 107 (2023) 5, 054041]
[Lin et al, arXiv: 2205.14628 (2022)]
[Ke et al, PRD 105 (2022) 11, 114019]
[Chen et al, EPJC 82 (2022) 7, 581]
[Deng et al, PRD 105 (2022) 5, 054015]
[Wang et al, PRD 107 (2023) 9, 094002]
[Montesinos et al, PRC 108 (2023) 3, 035205]
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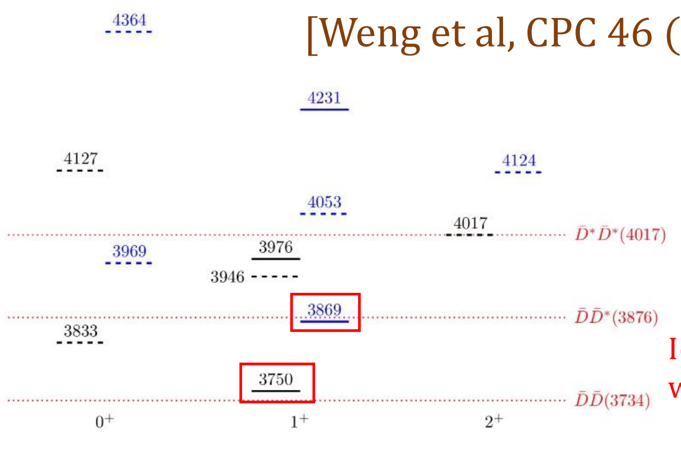
Compact Tetraquark picture

[Weng et al, CPC 46 (2022) 1 013102]



(a) $nn\bar{c}\bar{c}$ states

$I(J^P) = 0(1^+)$ state with different schemes

[Wu et al, PRD 107 (2023) 7, L071501]
[Simonov et al, Phys.Atom.Nucl. 86 (2023) 2, 147-152]
[Gao et al, Mod.Phys.Lett.A 37 (2022) 35n36, 2250223]
[Song et al, Commun.Theor.Phys. 75 (2023) 5, 055201]
[Noh et al, PRD 108 (2023) 1, 014004]
[Meng et al, PLB 846 (2023) 138221]
[Kim et al, PRD 105 (2022) 7, 074021]
......

Both HM and CT pictures can describe the mass position of T_{cc}^{+}!

Motivation

- A physical quantity to distinguish the internal structure of T_{cc}^{+}?
  (Hadronic Molecular & Compact Tetraquark)
- Can be achieved by current experiment?

Study the natures of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in pp collision at $\sqrt{s}$=14 TeV

Hadronic Molecular picture

- Events generator: PYTHIA 8.3 (Statistic: 1 billion)
- Collect prompt $D^{-}, \bar{D}^{0}, D^{*-}, \bar{D}^{*0}$ in an event
- Make cone cut $R_{D-D^*} < \Lambda_{HM}$ of $D^{-}\&\bar{D}^{*0}$ or $D^{*-}\&\bar{D}^{0}$ ($\Lambda_{HM} = 0.5, 1, 1.5$ GeV)
- Form $\bar{D}^{*0}D^{-}\&D^{*-}\bar{D}^{0}$ and obtain $\sigma_{\bar{D}^{*0}D^{-}(D^{*-}\bar{D}^{0})}$
- Calculate the $\sigma_{T_{\bar{c}\bar{c}}^{-}}$ by factorization formula

The product of $T_{\bar{c}\bar{c}}^{-}$ by PYTHIA

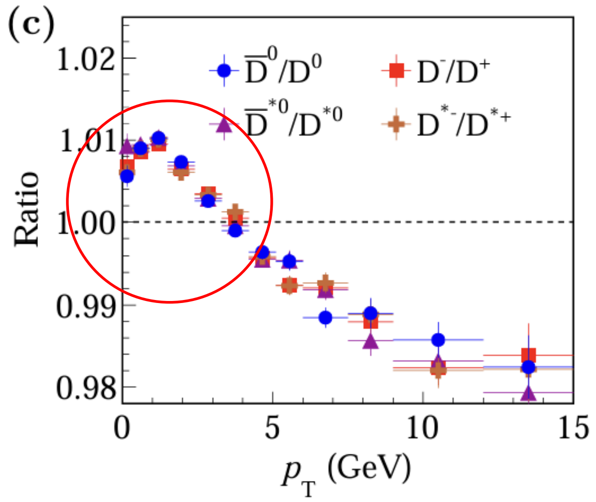
Compact Tetraquark picture

di-quark from Monte Carlo simulation directly, only for $T_{\bar{c}\bar{c}}^{-}$

- Events generator: PYTHIA 8.3 (Statistic: 100 billion)
- Collect $\bar{c}, u, d,$ $\boldsymbol{ud_0, ud_1}$ in an event
- Make cone cut of $\bar{c}\&\bar{c}$ or $u\&d$ ($R_{\bar{c}-\bar{c}}$ or $R_{u-d} < 1$GeV) to form $\bar{c}\bar{c}$ and ud (anti)di-quark
- Make cone cut of $\bar{c}\bar{c}\&ud$ to form $\bar{c}\bar{c}ud$ (select condition: $R_{\bar{c}\bar{c}-ud} < \Lambda_{CT}$, Λ_{CT}=0.5, 1 GeV)
- Calculate the $\sigma_{T_{\bar{c}\bar{c}}^{-}}$ by convolute wave function

T_{cc}^{+} in Hadronic Molecular picture

$P_{\rm T}$ distributions of $\bar{D}^{(*)}$&$D^{(*)}$ and their ratio

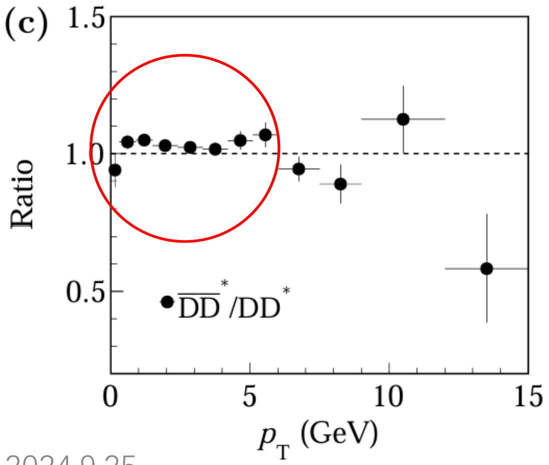


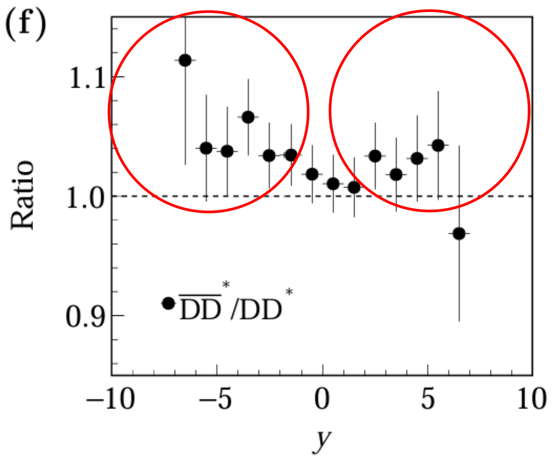
$$\text{Ratio} \equiv \frac{\sigma_{\bar{D}^{(*)}}}{\sigma_{D^{(*)}}}$$

- $\sigma_{\bar{D}^{(*)}}$ is lager than $\sigma_{D^{(*)}}$ at low $P_{\rm T}$
- Described by [Braaten, Jia, Mehen, PRL 89 (2002) 122002]

  with heavy quark recombination mechanism

$P_{\rm T}$, rapidity (y) distributions of $\bar{D}\bar{D}^{*}$ & DD^{*} pairs and their ratio





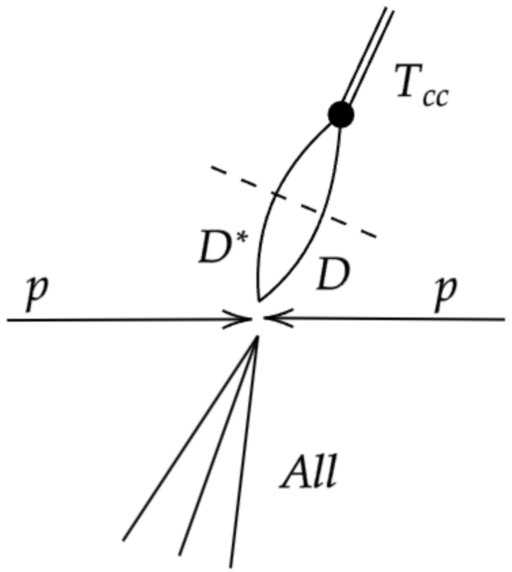
$$\text{Ratio} \equiv \frac{\sigma_{\bar{D}\bar{D}^{*}}}{\sigma_{DD^{*}}}$$

- Maximum at $P_{\rm T} \approx 2\text{GeV}$ and $y \approx 0$
- Similar $P_{\rm T}$ and y behaviors
- $\sigma_{\bar{D}\bar{D}^{*}}$ is lager than $\sigma_{DD^{*}}$ at low $P_{\rm T}$ and large $|y|$

T_{cc}^{+} in Hadronic Molecular picture

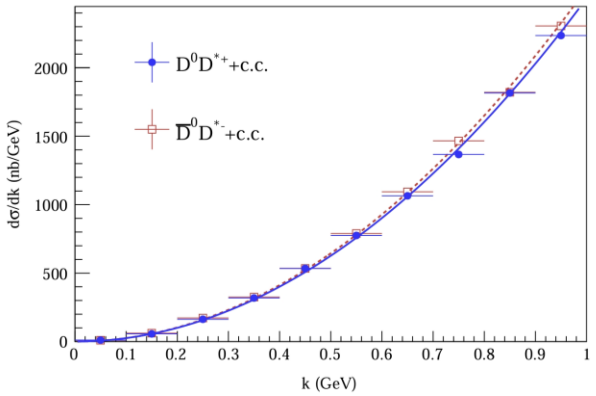
The cross section of the T_{cc}^{+}

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



The amplitude of the production of DD^* should be a constant without considering the FSI:

$$\frac{d\sigma_{DD^*}}{dk} \sim k^2$$



Successfully apply to:

$\boldsymbol{X(3872)}$: [Guo et al, EPJC 74 (2014) 9, 3063], [Shi et al, PRD 106 (2022) 11, 114026], [Albaladejo et al, CPC 41 (2017) 12, 121001], [Yang et al, CPC 45 (2021) 12, 123101]

$\boldsymbol{P_c s}$: [Ling et al, EPJC 81 (2021) 9, 819]

$\boldsymbol{Z_b s}$: [Cao et al, PRD 101 (2020) 7, 074010]

$\boldsymbol{D_{s0}(2317)}$: [Guo et al, JHEP 05 (2014) 138]

T_{cc}^{+} in Hadronic Molecular picture

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

$A + \delta_{sta} + \delta_{sys}$

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

statistic error (→ 0.70)

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 $\sigma_{T_{cc}^+}$ ($\sigma_{T_{\bar{c}\bar{c}}^-}$)	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

A: the weighted average of $A_{0.5\text{GeV}}$, $A_{1\text{GeV}}$ and $A_{1.5\text{GeV}}$

$$A \equiv \omega_1 A_1 + \omega_2 A_2 + \omega_3 A_3$$

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

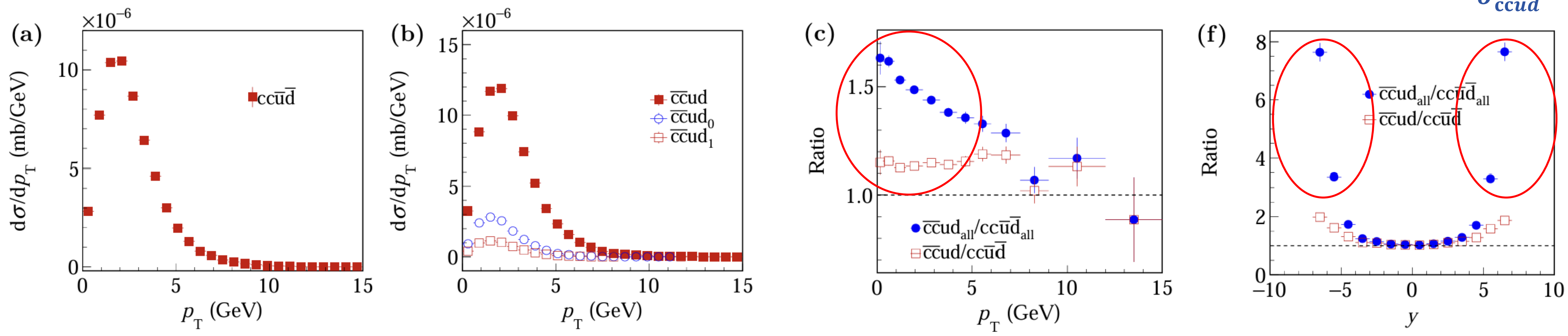
$$\omega_i \equiv \frac{\frac{1}{\delta_i^2}}{\frac{1}{\delta_1^2} + \frac{1}{\delta_2^2} + \frac{1}{\delta_3^2}}$$

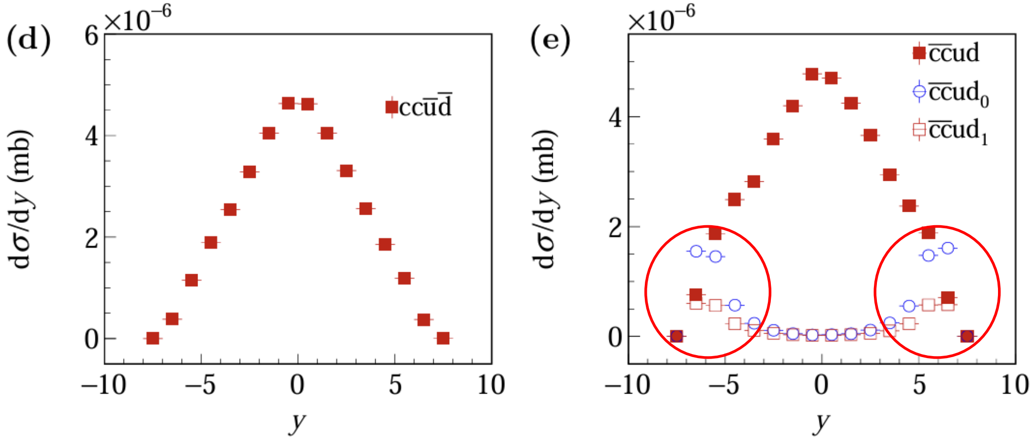
$$\delta_{sys} \equiv \sqrt{\frac{\sum_i (A_i - A)^2}{3}}$$

T_{cc}^{+} in Compact Tetraquark picture

P_{T}, rapidity (y) distributions of $cc\bar{u}\bar{d}$ & $\bar{c}\bar{c}ud$ and their ratio

$\text{Ratio} \equiv \frac{\sigma_{\bar{c}\bar{c}ud}}{\sigma_{cc\bar{u}\bar{d}}}$





$cc\bar{u}\bar{d}$ & $\bar{c}\bar{c}ud$: hand-made diquark pairs

$\bar{c}\bar{c}ud_0$ & $\bar{c}\bar{c}ud_1$: MC diquark pairs consist of ud_0, ud_1

- Similar P_{T} behaviors between all diquark pairs
- MC diquark pairs show different y behaviors
- $\sigma_{\bar{c}\bar{c}ud}$ is larger than $\sigma_{cc\bar{u}\bar{d}}$ at low P_{T} and large $|y|$

$$\sigma_{T_{cc}^{+}} = \sigma_{cc\bar{u}\bar{d}} \left|\phi\left(\vec{k}, a\right)\right|^2 \Longrightarrow \phi^{h.o.}\left(\vec{k}, a\right) = \left(\frac{1}{\pi}\right)^{\frac{3}{4}} \left(\frac{1}{a}\right)^{\frac{3}{2}} e^{\frac{-|\vec{p}|^2}{2a^2}} \qquad \phi^{St}\left(\vec{k}, a\right) = 2\sqrt{2}\,\frac{1}{\pi} \left(\frac{1}{a}\right)^{\frac{3}{2}} \left(\frac{|\vec{p}|^2}{a^2} + 1\right)^{-2}$$

T_{cc}^{+} in Compact Tetraquark picture

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

Range(GeV)		$\sigma_{T_{cc}^{+}}(\sigma_{T_{\bar{c}\bar{c}}^{-}})$			$\mathcal{A}(\%)$
		$r = 0.2\text{fm}$	$r = 0.5\text{fm}$	$r = 1\text{fm}$	
Full	$\boldsymbol{\sigma_{T_{cc}^{+}}}$ ($\boldsymbol{\sigma_{T_{\bar{c}\bar{c}}^{-}}}$)	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)	$18.73\pm0.25\pm0.14$
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)	$7.35\pm1.48\pm5.24$
$p_T > 0$ [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)	$11.42\pm0.60\pm0.17$

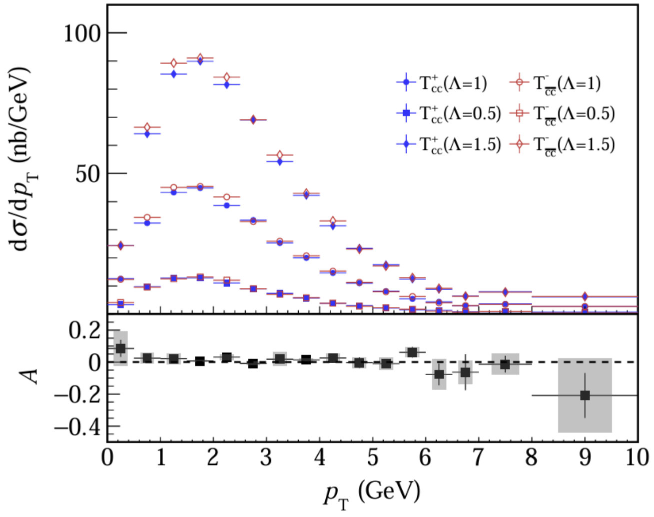
$$A \equiv \frac{\sigma^{-} - \sigma^{+}}{\sigma^{-} + \sigma^{+}}$$

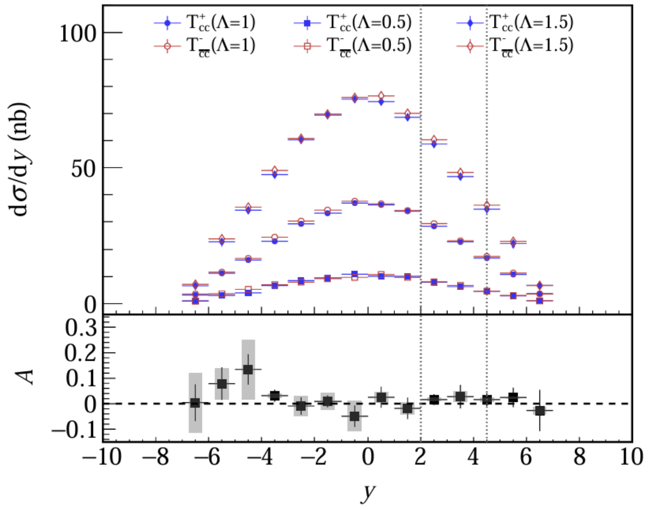
- $\Lambda_{CT} = 1\text{GeV}$
- Wave function: $\phi^{h.o.}$

A (%)	$\Lambda_{CT} = 1\text{GeV}$ & $\phi^{h.o.}$	$\Lambda_{CT} = 0.5\text{GeV}$ & $\phi^{h.o.}$	$\Lambda_{CT} = 1\text{GeV}$ & ϕ^{St}	$\Lambda_{CT} = 0.5\text{GeV}$ & ϕ^{St}	HM
Full	$18.73\pm0.25\pm0.14$	$18.71\pm0.67\pm0.17$	$18.70\pm0.25 \pm 0.08$	$18.70\pm0.67\pm0.11$	$1.24\pm0.30\pm0.20$
$2<y<4.5$ $4<P_T < 20$ GeV	$7.35\pm1.48 \pm 5.24$	$3.53\pm4.15\pm2.99$	$6.71\pm1.48 \pm 5.17$	$2.59\pm4.15\pm3.43$	$2.53\pm2.01\pm1.79$
$2<y<4.5$ $P_T>0$ GeV	$11.42\pm0.60 \pm 0.17$	$10.65\pm1.64 \pm 0.42$	$11.38\pm0.60 \pm 0.16$	$10.69\pm1.64\pm0.36$	$1.64\pm1.03\pm0.52$

The asymmetry A is stable!

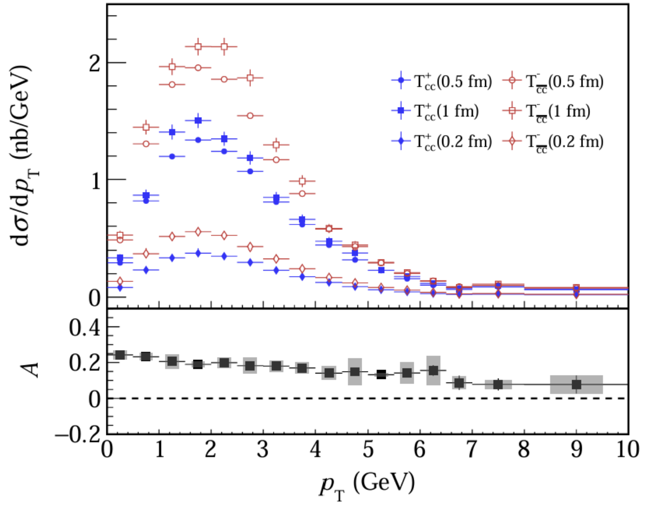
P_T, rapidity distributions of the cross section and A

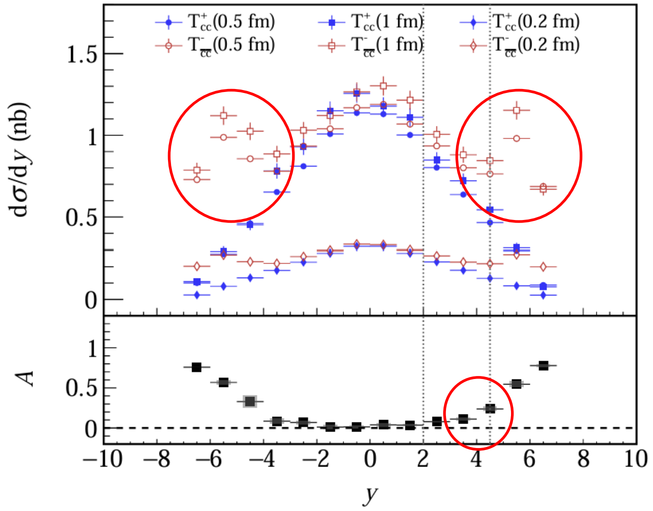




Hadronic Molecular picture

- Maximum at $P_T \approx 2$GeV and $y \approx 0$
- $A > 0$ at low P_T and large y
- Similar P_T and y behaviors



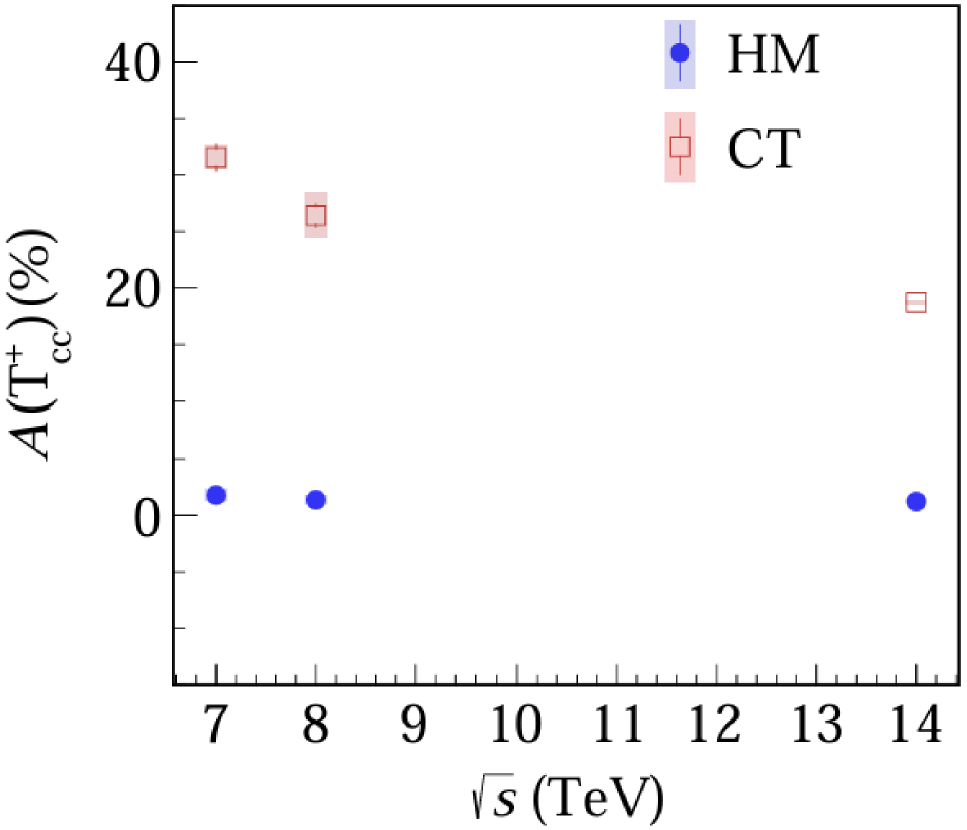


LHCb kinematic range: $2 < y < 4.5$

Compact Tetraquark picture

- Maximum at $P_T \approx 2$GeV and $y \approx 0$
- $A > 0$ at $P_T \approx 2$GeV and $y \approx \pm 6$
- Similar P_T behaviors
- Significantly different y behaviors for $T_{\bar{c}\bar{c}}^-$

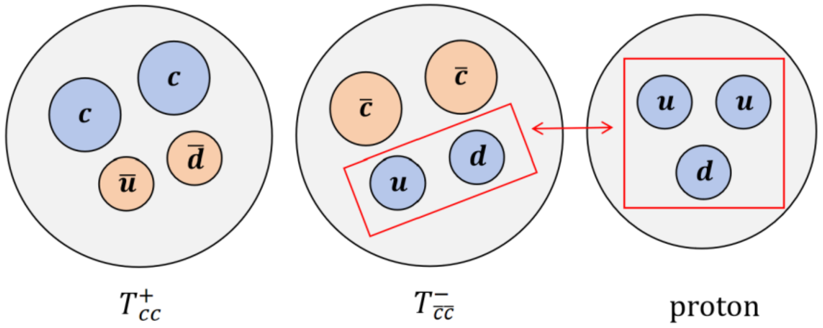
Asymmetry with different c.m. energy



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

- $A > 0$ in all energy region
- $A_{CT} > A_{HM}$ in all energy region
- Both A_{CT} and A_{HM} decrease when $\sqrt{s}$ increase
  - Larger asymmetry at RHIC energy region?

valence quarks contribute the asymmetry



Summary

Study the nature of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in pp collision at $\sqrt{s}$=14TeV

- Propose a physical quantity $A \equiv \frac{\sigma^{-}-\sigma^{+}}{\sigma^{-}+\sigma^{+}}$ to distinguish HM and CT picture
  - A_{CT} is significantly larger than A_{HM}
  - Both A_{CT} and A_{HM} decrease with the increasing c.m. energy
- These asymmetry can be observed at LHCb kinematic range
- We expect a larger asymmetry at RHIC energy region
- Can be applied to other double heavy tetraquark candidates

Thank you very much for your attention!

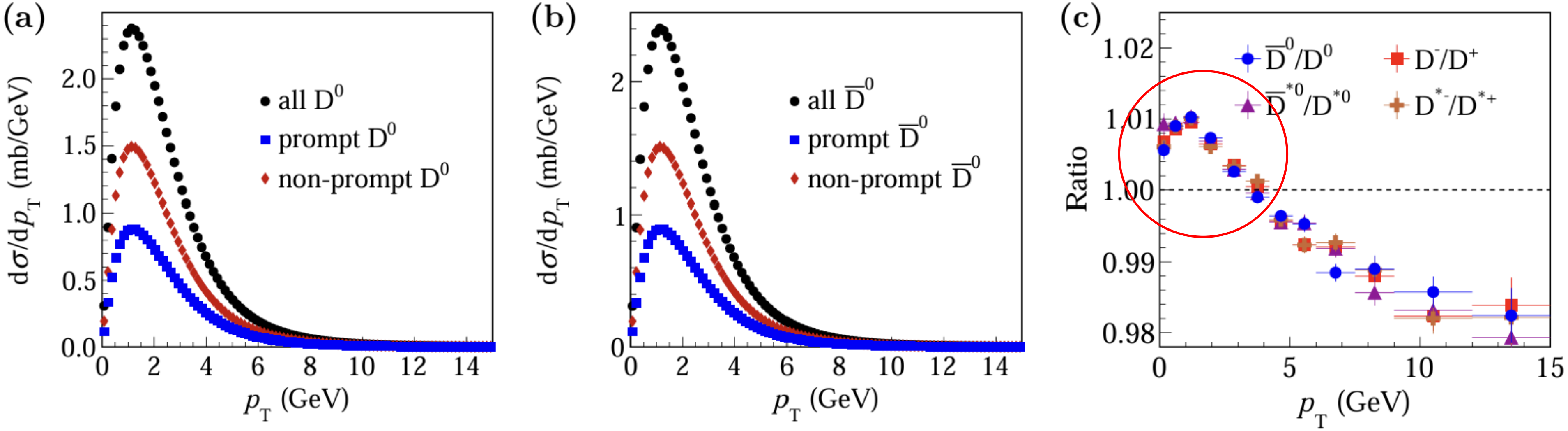
Back up

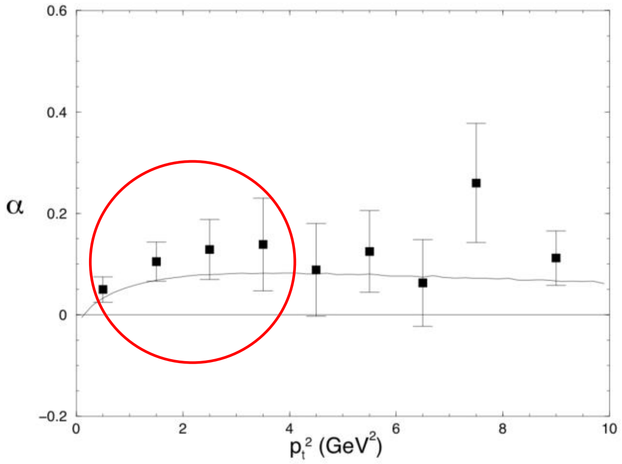
Picture	$\sigma_{T_{cc}^{+}}$	$\sigma_{T_{\bar{c}\bar{c}}^{-}}$	A (%)
HM	152.42±0.89 nb	156.81±0.91 nb	1.24±0.30
diquark-antidiquark	4.43±0.02 nb	6.46±0.02 nb	18.73±0.25
$(c\bar{u})_8(c\bar{d})_8$	2.79±0.04 nb	3.26±0.04 nb	7.91±0.94

Back up

P_T distributions of $D^{(*)}$ and $\overline{D}^{(*)}$

prompt $D(\overline{D})$ mesons





Heavy quark recombination mechanism

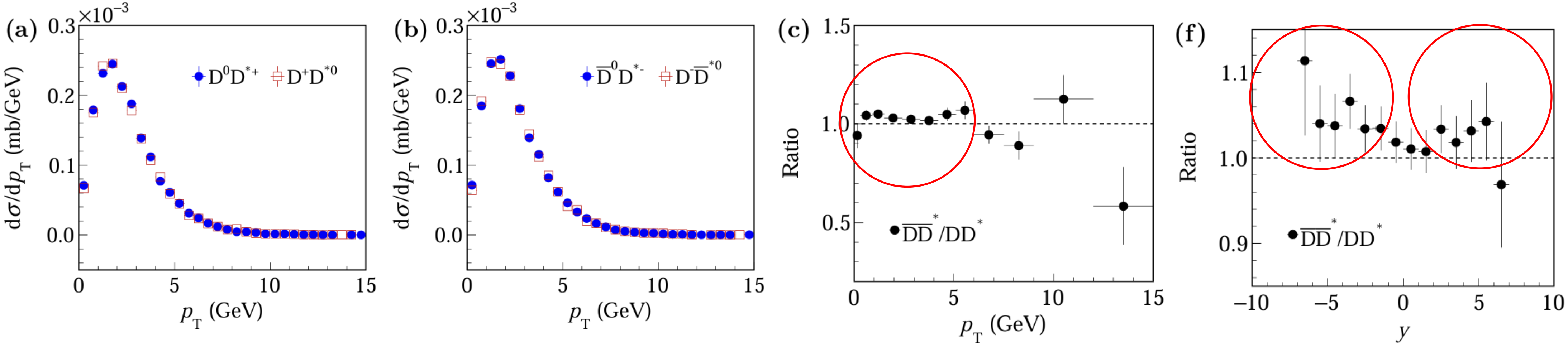
$$\alpha[D^+] = \frac{d\sigma[D^-] - d\sigma[D^+]}{d\sigma[D^-] + d\sigma[D^+]}$$

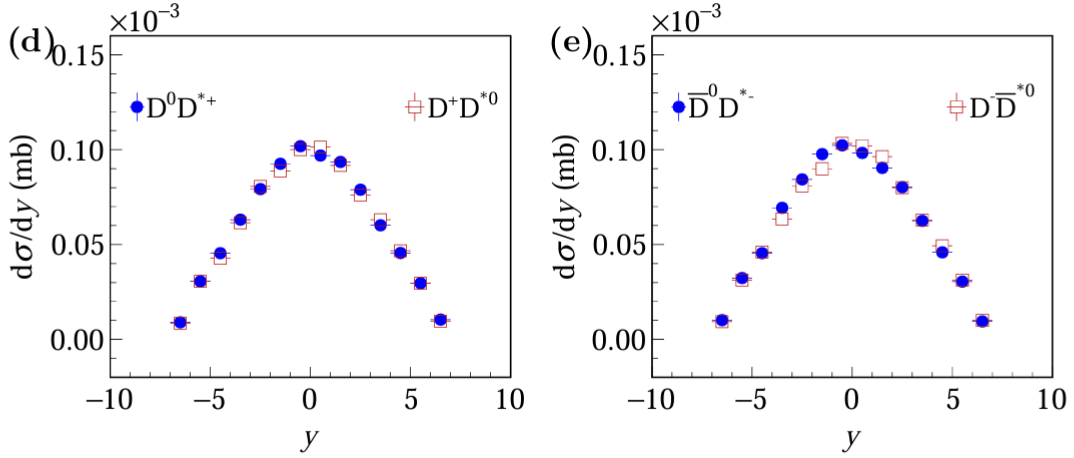
[Braaten, Jia, Mehen, PRL 89 (2002) 122002]

Back up

P_{T}, rapidity (y) distributions of DD^* and $\bar{D}\bar{D}^*$ pairs

$\Lambda_{HM} = 1\mathrm{GeV}$



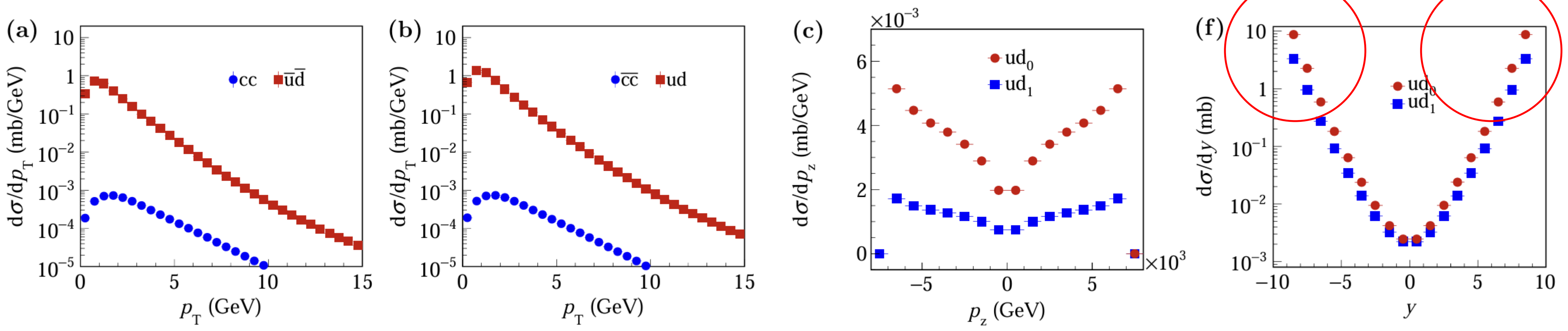


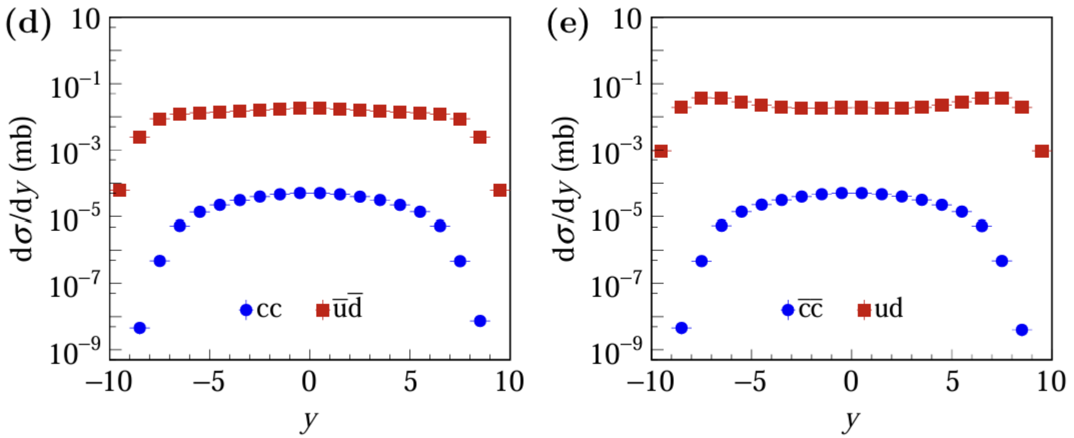
- Maximum at $P_{\mathrm{T}} \approx 2\mathrm{GeV}$ and $y \approx 0$
- Similar P_{T} and y behaviors
- $\sigma_{\bar{D}\bar{D}^*}$ is lager than σ_{DD^*} at low P_{T} and large $|y|$

Back up

P_T, P_z, rapidity (y) distributions of diquark and anti-diquark

hand-made diquark　　　　　　　　　　MC diquark





- Maximum at $P_T \approx 2$GeV and $y \approx 0$ for hand-made diquark
- Maximum at large $|P_z|$ and large $|y|$ for ud_0 and ud_1
- Different y behaviors between two kinds of diquark

Back up

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

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 ($\|y\| < 1.2$)			
$10 < p_T < 50(30)$ [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 ($\|y\| < 0.75$)			
$10 < p_T < 70$ [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

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

$$A + \delta_{sta} + \delta_{sys}$$

Back up

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

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

- $\Lambda_{CT}=1$GeV
- Wave function: $\phi^{h.o.}$

Back up

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

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	0.23±0.002 nb (0.34±0.003 nb)	2.20±0.02 nb (3.21±0.03 nb)	4.72±0.05 nb (6.92±0.06 nb)	18.71±0.67±0.17
LHCb ($2<y<4.5$)				
$4<p_T<20$ [114]	7.18±0.44 pb (8.15±0.46 pb)	69.86±4.24 pb (77.10±4.38 pb)	158.77±9.63 pb (156.83±8.91 pb)	3.53±4.15±2.99
$p_T>0$ [11]	0.04±0.001 nb (0.05±0.001 nb)	0.41±0.01 nb (0.51±0.01 nb)	0.88±0.02 nb (1.10± 0.02 nb)	10.65±1.64±0.42
CMS ($\|y\|<1.2$)				
$10<p_T<50(30)$ [115]	0.24±0.08 pb (0.16±0.07 pb)	2.25±0.75 pb (1.65±0.67 pb)	4.34±1.45 pb (4.82±1.97 pb)	−9.84±25.79±10.79
ATLAS ($\|y\|<0.75$)				
$10<p_T<70$ [116]	0.16±0.06 pb (0.16±0.07 pb)	1.51±0.62 pb (1.65±0.67 pb)	3.00±1.22 pb (4.82±1.97 pb)	9.44±28.33±9.92

- $\Lambda_{CT}=0.5$GeV
- Wave function: $\phi^{h.o.}$

Back up

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

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	1.50±0.01 nb (2.18±0.01 nb)	4.16±0.02 nb (6.07±0.02 nb)	4.84±0.02 nb (7.09±0.02 nb)	18.70±0.25±0.08
LHCb ($2 < y < 4.5$)				
$4 < p_T < 20$ [114]	47.53±1.06 pb (60.31±1.19 pb)	132.57±2.95 pb (157.59±3.11 pb)	159.48±3.55 pb (158.35±3.13 pb)	6.71±1.48±5.17
$p_T > 0$ [11]	0.29±0.003 nb (0.36±0.003 nb)	0.79±0.01 nb (0.99±0.01 nb)	0.90±0.01 nb (1.13± 0.01 nb)	11.38±0.60±0.16
CMS ($\lvert y\rvert < 1.2$)				
$10 < p_T < 50(30)$ [115]	1.69±0.20 pb (1.31±0.18 pb)	4.37±0.52 pb (3.57±0.48 pb)	4.02±0.47 pb (5.44±0.73 pb)	−2.69±8.81±12.52
ATLAS ($\lvert y\rvert < 0.75$)				
$10 < p_T < 70$ [116]	1.10±0.16 pb (0.85±0.15 pb)	2.92±0.43 pb (2.83±0.49 pb)	2.79±0.41 pb (5.26±0.90 pb)	5.44±10.89±18.41

- $\Lambda_{CT} = 1\text{GeV}$
- Wave function: ϕ^{St}

Back up

The cross sections and asymmetry of T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ in different kinematic range

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	0.34±0.004 nb (0.49±0.004 nb)	2.39±0.03 nb (3.49±0.03 nb)	4.42±0.05 nb (6.47±0.06 nb)	18.70±0.67±0.11
LHCb ($2<y<4.5$)				
$4<p_T<20$ [114]	10.48±0.64 pb (11.83±0.67 pb)	76.95±4.67pb (83.02±4.72 pb)	146.22±8.87 pb (140.27±7.97 pb)	2.59±4.15±3.43
$p_T>0$ [11]	0.06±0.002 nb (0.08±0.002 nb)	0.45±0.01 nb (0.56±0.01 nb)	0.82±0.02 nb (1.03± 0.02 nb)	10.69±1.64±0.36
CMS ($\lvert y\rvert<1.2$)				
$10<p_T<50(30)$ [115]	0.34±0.11 pb (0.24±0.10 pb)	2.41±0.80 pb (1.91±0.78 pb)	3.57±1.19 pb (5.06±2.06 pb)	−4.32±25.67±15.52
ATLAS ($\lvert y\rvert<0.75$)				
$10<p_T<70$ [116]	0.23±0.09 pb (0.24±0.10 pb)	1.63±0.66 pb (1.91±0.78 pb)	2.49±1.02 pb (5.06±2.06 pb)	14.44±27.69±14.09

- $\Lambda_{CT}=0.5$GeV
- Wave function: ϕ^{St}

Back up

Events generator: PYTHIA 8.3

```
! 1) Settings used in the main program.
Main:numberOfEvents = 1000000          ! number of events to generate
Main:timesAllowErrors = 3              ! how many aborts before run stops
!Main:outputLog = on                 ! Put all printed output to a log file.

! 2) Settings related to output in init(), next() and stat().
!Init:showChangedSettings = on        ! list changed settings
!Init:showChangedParticleData = off ! list changed particle data
!Next:numberCount = 1000               ! print message every n events
!Next:numberShowInfo = 2              ! print event information n times
!Next:numberShowProcess = 1           ! print process record n times
!Next:numberShowEvent = 2             ! print event record n times
!Init:showAllSettings = on
!Init:showAllParticleData = on
!Stat:showPartonLevel = on            ! additional statistics on MPI

! 4) Beam parameter settings. Values below agree with default ones.
Beams:idA = 2212                     ! first beam, p = 2212, pbar = -2212
Beams:idB = 2212                     ! second beam, p = 2212, pbar = -2212
Beams:eCM = 14000.                    ! CM energy of collision

! 5) Settings for the hard-process generation.
!HardQCD:hardccbar = on             ! Sum of g g → c cbar and q qbar → c cbar.
!SoftQCD:all = on
SoftQCD:nonDiffractive = on         ! The inelastic nondiffrative part of the total cross section,
!HardQCD:all = on                     ! switch on all QCD jet + jet processes
!PhaseSpace:pTHatMin = 0.5          ! minimal pT scale in process
```

→ Set total event numbers of simulation

→ Set collision's beams (proton's ID: 2212)

→ Set collision's c.m. energy: 14TeV

→ Set collision type

$\sigma_{pp\ minibias} = 57.17\text{mb}$

Back up

Events generator: PYTHIA 8.3

Statistic in **Hadronic Molecular** picture: 1 billion

$\sigma_{pp\ minibias} = 57.17\text{mb}$

T_{cc}^{+}

$D^{+}, D^{0}, D^{*+}, D^{*0}$ → relative momentum cut $|\vec{k}| < \Lambda_{HM}$ → $D^{*0}D^{+} \& D^{*+}D^{0}$ → T_{cc}^{+}

$T_{\bar{c}\bar{c}}^{-}$

$D^{-}, \bar{D}^{0}, D^{*-}, \bar{D}^{*0}$ → relative momentum cut $|\vec{k}| < \Lambda_{HM}$ → $\bar{D}^{*0}D^{-} \& D^{*-}\bar{D}^{0}$ → $T_{\bar{c}\bar{c}}^{-}$

Back up

Events generator: PYTHIA 8.3

Statistic in **Compact Tetraquark** picture: 100 billion

$\sigma_{pp\ minibias} = 57.17mb$

T_{cc}^{+}

$c, \bar{u}, \bar{d}$ → relative momentum cut, $|\vec{q}| < 1\text{GeV}$ → cc & $\bar{u}\bar{d}$ → relative momentum cut, $|\vec{k}| < \Lambda_{CT}$ → $cc\bar{u}\bar{d}$ → T_{cc}^{+}

$T_{\bar{c}\bar{c}}^{-}$

$\bar{c}, u, d$, $\boldsymbol{ud_0, ud_1}$ → relative momentum cut, $|\vec{q}| < 1\text{GeV}$ → $\bar{c}\bar{c}$ & ud → relative momentum cut, $|\vec{k}| < \Lambda_{CT}$ → $\bar{c}\bar{c}ud$ → $T_{\bar{c}\bar{c}}^{-}$

ud_0, ud_1: di-quark from Monte Carlo simulation directly