

Production of T_{cc}

Qin Qin (秦臻)

Huazhong University of Science and Technology

华中科技大学

2008.08026; 2019.05678

In collaboration with Yin-Fa Shen, Fu-Sheng Yu
& Yi Jin, Shi-Yuan Li, Yan-Rui Liu, Zong-Guo Si



Workshop on Hadron Structure at High-Energy, High-Luminosity Facilities

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Contents

- It is important to study the double-charm tetraquark T_{cc}
- We predicted the correct discovery channel and the correct signal yield of T_{cc} at LHCb
- Further study of T_{cc} production properties can help probe its nature

The quark model

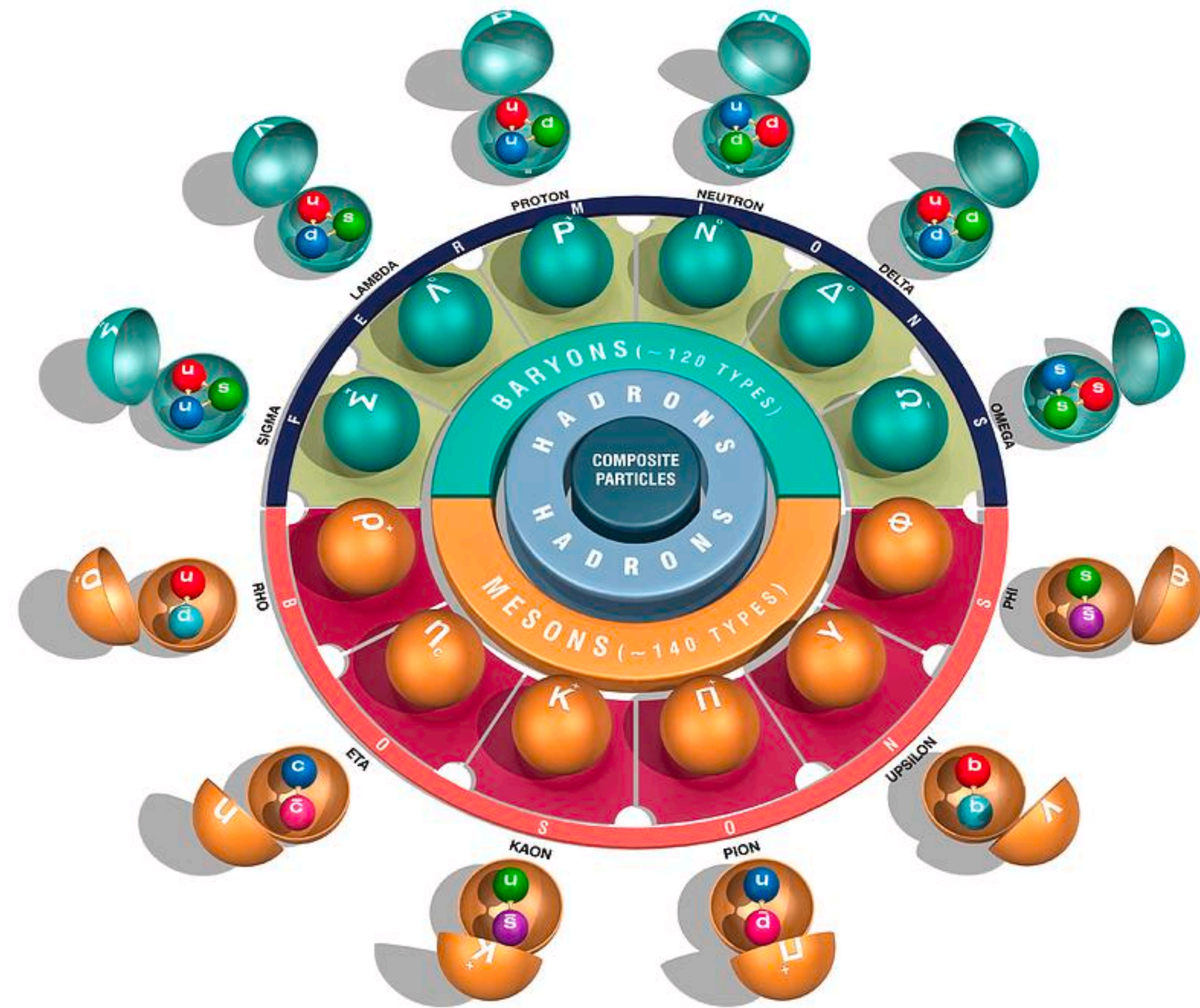
- Old myth
- New life



Murray Gell-Mann
1969 Nobel Prize for physics



George Zweig



Three new milestones

- Observation of tetraquarks

[BESIII, *Phys.Rev.Lett.* 110 (2013) 252001]

The *Physics* 2013 “Highlights of the Year” (rank 1st)

- Observation of pentaquarks

[LHCb, *Phys.Rev.Lett.* 115 (2015) 072001]

The *Physics World* 2015 “top-10 breakthroughs”

- Observation of a double-charm baryon Ξ_{cc}^{++}

[LHCb, *Phys.Rev.Lett.* 119 (2017) 112001]

国家科技部“2017年度中国科学十大进展”

“Periodic table of the hadrons”

Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003																				
3 Li Lithium 6.941	4 Be Beryllium 9.012															5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180																
11 Na Sodium 22.990	12 Mg Magnesium 24.305															13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948																
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798																				
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294																				
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018																				
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [293]	117 Ts Tennessine unknown	118 Og Oganesson unknown																				
																			57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967				
																			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]				
																			Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide									

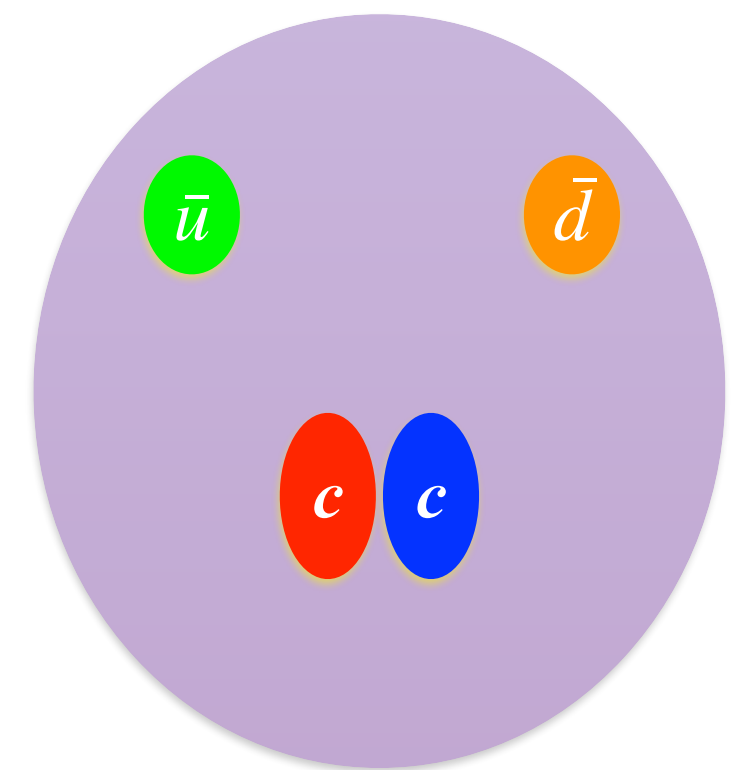
$\pi, K, \dots$	D	B	η_c	B_c	η_b				
p, n, ...	Λ_c	Λ_b				Ξ_{cc}	Ξ_{bc}	Ξ_{bb}	
	$X_{(2900)}$		Z_c			T_{cc}	T_{bc}	T_{bb}	$X_{(6900)}$
			P_c						

Z_c, P_c : a new period

$\Xi_{cc}, X_{(6900)}$: a new main group

Beyond stamp collecting

- Because of **color confinement**, properties of quarks are studied via hadrons
- New types of hadrons provide **new visual angles** into QCD and also electroweak dynamics
 - e.g., **doubly heavy baryons** have a unique structure, resembling a ‘double star’ with a ‘planet’ attached
 - analogous to a heavy meson, but also different: bosonic, sizable heavy element**
 - e.g., the **doubly heavy tetraquarks** help us probe the nature of exotic hadronic states, cusps or true resonances



Who is to be shot next?

$\pi, K, \dots$	D	B	η_c	B_c	η_b				
p, n, ...	Λ_c	Λ_b				Ξ_{cc}	Ξ_{bc}	Ξ_{bb}	
	$X_{(2900)}$		Z_c			T_{cc}	T_{bc}	T_{bb}	$X_{(6900)}$
			P_c						

Two targets in the talk @Nankai, 2nd May 2021.

T_{cc} : [QQ, Shen, Yu, 2008.08026] (this talk)

“Discovery potential of double-charm tetraquarks”

Three months later — — T_{cc} discovery was reported by LHCb on 28 July 2021.

Ξ_{bc} : [QQ, Shi, Wang, Yang, Yu, Zhu, 2108.06716]

Discovery of T_{cc}

[QQ,Shen,Yu,2008.08026]

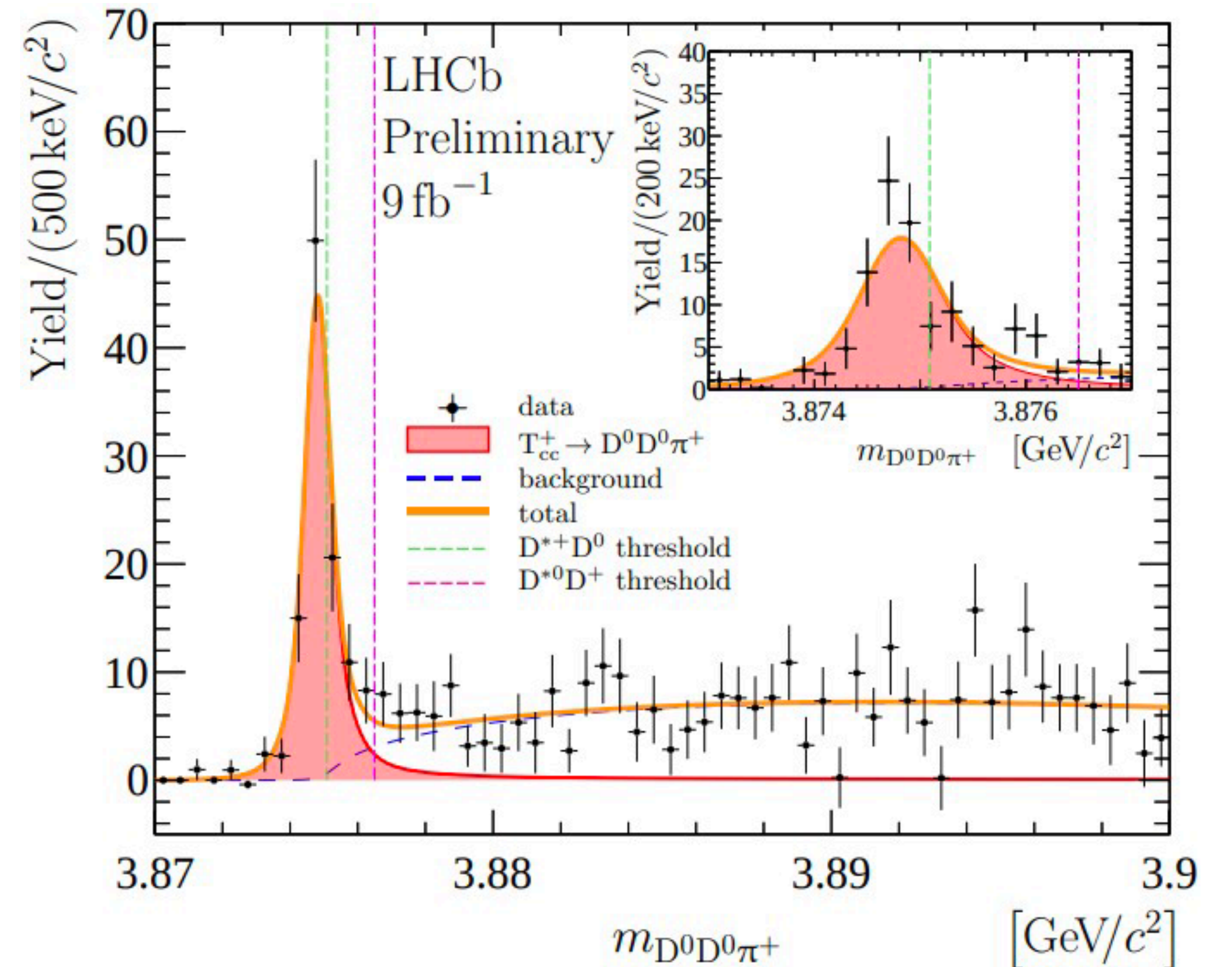
$$N_s = 117 \pm 16$$

Discovery potentials of double-charm tetraquarks

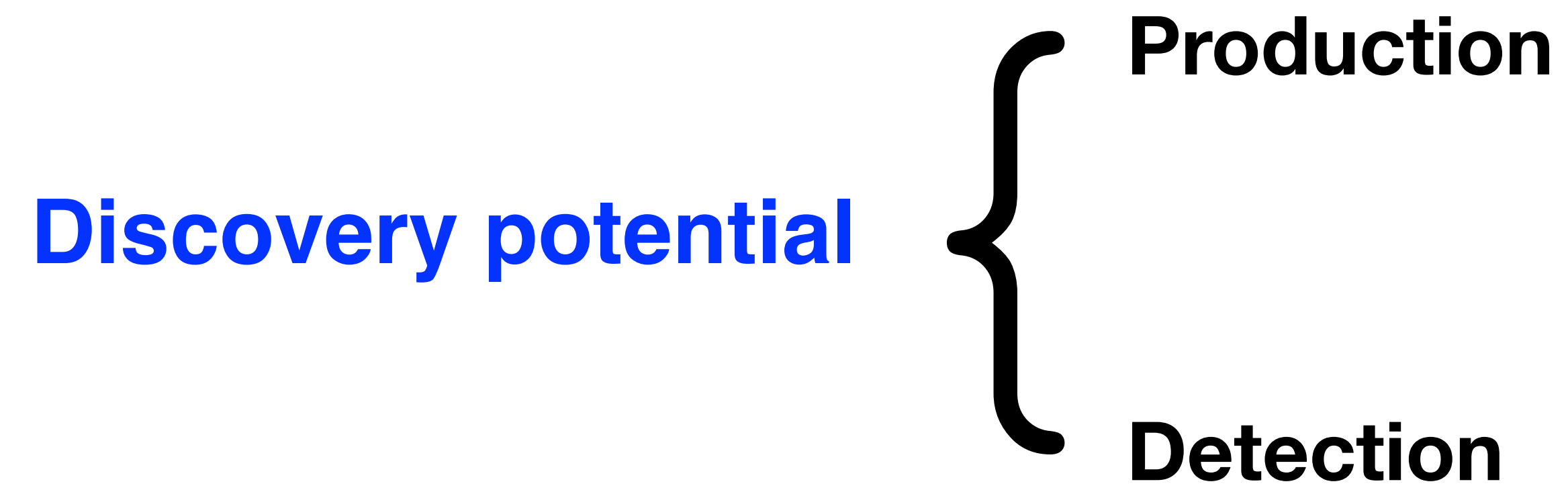
We find that their production cross sections at the LHCb with $\sqrt{s} = 13$ TeV reach $\mathcal{O}(10^4)$ pb, which indicate that the LHCb has collected $\mathcal{O}(10^8)$ such particles. Through the decay channels of $T_{[\bar{u}\bar{d}]}^{\{cc\}} \rightarrow D^+ K^- \pi^+$ or $D^0 D^+ \gamma$ (if stable) or $T_{[\bar{u}\bar{d}]}^{\{cc\}} \rightarrow D^0 D^{*+}$ (if unstable), it is highly hopeful that they get discovered at the LHCb in the near future. We also discuss the productions and decays of the double-charm tetraquarks at future Tera-Z factories.

branching fractions of $T_{[\bar{u}\bar{d}]}^{\{cc\}}$ decays is the same as the observed Ξ_{cc}^{++} . Comparing with the production rates between double-charm tetraquarks and baryons, and considering around 2×10^3 events of Ξ_{cc}^{++} with the current LHCb data, the signal yields of $T_{[\bar{u}\bar{d}]}^{\{cc\}}$ would be $\mathcal{O}(10^2)$ at LHCb, and will reach $\mathcal{O}(10^3)$ at LHCb Run III. Thus it is hopefully expected that the double-charm tetraquark will be observed in the near future. Although the production rates are smaller at the future Z factories, it is also expected to be observed at the Tera-Z factories due to the smaller backgrounds.

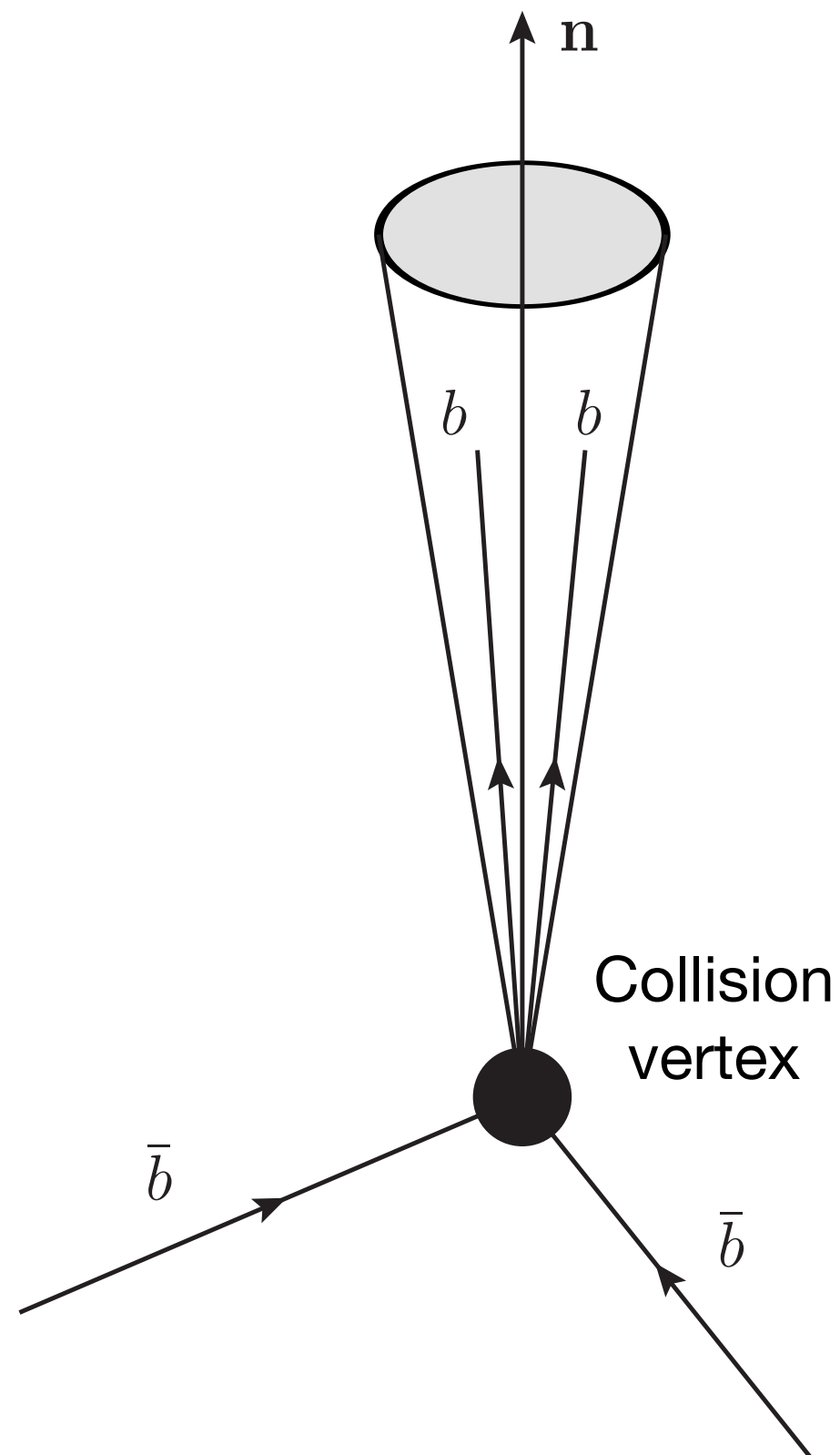
- [Correct discovery channel](#)
- [Correct signal yield](#)



[LHCb,2109.01038;2109.01056]



Production Mechanism



- It was proposed for double-bottom hadron production

[Ali, Parkhomenko, **QQ**, Wang, 1805.02535; Ali, **QQ**, Wang, 1806.09288]

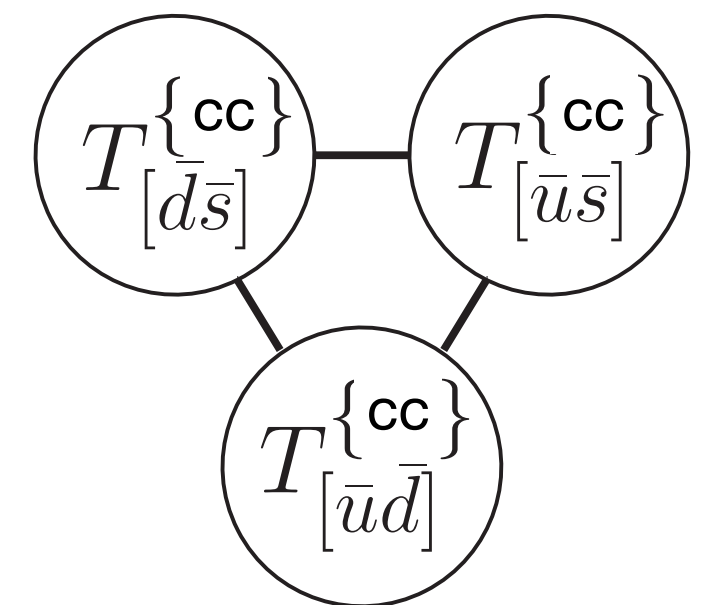
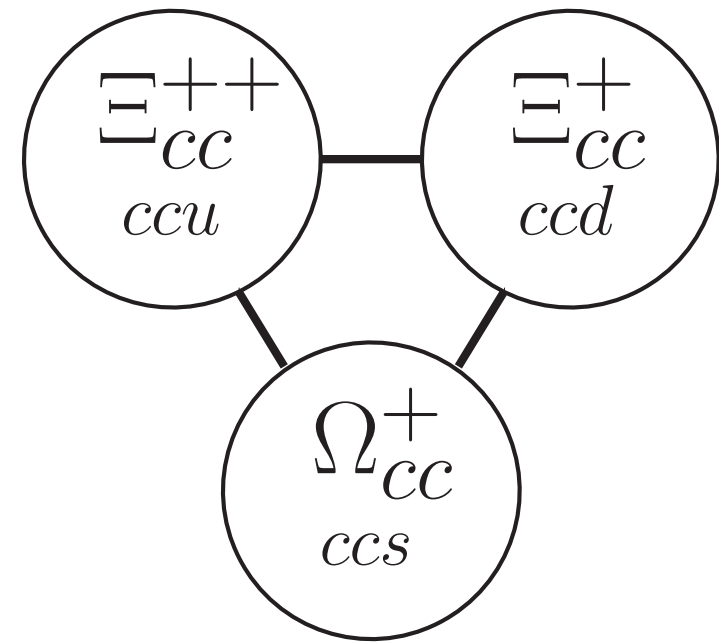
1. Two produced heavy quarks stay close enough to form a heavy diquark
2. The heavy diquark further fragments into doubly heavy hadrons

- Assuming T_{cc} a real tetraquark, the same mechanism applies
- Stay close enough? One parameter — —

$$\Delta M \equiv M_{cc} - 2m_c \leq (2.0^{+0.5}_{-0.4}) \text{ GeV}$$



Determined by matching the B_c production rate to $\bar{b}b\bar{c}c$



SU(3) triplets

Fragmentation of cc diquark

- Heavy quark symmetry

1. Heavy quark **flavor** symmetry; 2. Heavy quark **spin** symmetry

- Heavy quark-diquark symmetry

The cc diquark is just a static $\bar{3}$ color source

➔ Similar fragmentation with heavy quarks

All ratios determined!

$$\left[\frac{\Lambda_b^0}{B_d^0} \right] (p_T) = 0.151 + \exp \left[-0.57 - 0.095 p_T (\text{GeV}) \right]$$

[LHCb, 1405.6842]

$$\left[\frac{f_s}{f_d} \right] (p_T) = 0.263 - 17.6 \times 10^{-4} \cdot p_T (\text{GeV})$$

[LHCb, 2103.06810]

Ground
state ratio

$$r_g = 0.48 \pm 0.08$$

[Belle, 1706.06791]

$$\frac{T_{\bar{u}\bar{d}}^{\{cc\}}}{\Xi_{cc}^{+(+)}}$$

$$\frac{T_{\bar{u}\bar{s}}^{\{cc\}}}{T_{\bar{u}\bar{d}}^{\{cc\}}}, \frac{\Omega_{cc}^{+}}{\Xi_{cc}^{+}}$$

$$\frac{T_{\bar{u}\bar{d}}^{\{cc\}}}{T_{\bar{u}\bar{d}}^{\{cc\}} + \text{excited}}$$

Production of double-charm hadrons

With partonic simulation by MadGraph & Pythia, we obtain

- The cross section for all double-charm hadrons

$$\sigma(pp \rightarrow H_{cc} + X) = (310^{+170}_{-70}) \text{ nb};$$

- For double-charm baryons, e.g.

$$\sigma(\Xi_{cc}^{++}) = (103^{+56}_{-22}) \text{ nb}$$

- For double-charm tetraquarks, e.g.

$$\sigma(T_{cc}^{+}) = (24^{+14}_{-7}) \text{ nb}$$

The cuts are $4 < p_T < 15 \text{ GeV}$, $2 < \eta < 4.5$ @ 13 TeV LHCb

Comparison with theory

vs **62 nb** (NRQCD)

[Chang,Qiao,Wang,Wu,0601032]

Comparison with experiment

vs **[30, 130] nb**
(LHCb with theory inputs)

$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

[LHCb,1910.11316]

Detection of T_{cc}

Propose the golden channel $T_{cc}^+ \rightarrow D^0 D^{*+} \rightarrow D^0 D^0 \pi^+$

- Big branching ratio
- Big **detection efficiency** (all charged particles)

Compared with $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

Production

$$\sigma(\Xi_{cc}^{++}) = (103^{+56}_{-22}) \text{ nb} \quad \rightarrow \quad \frac{f_{T_{cc}}}{f_{\Xi_{cc}}} \sim \frac{1}{4}$$

$$\sigma(T_{cc}^+) = (24^{+14}_{-7}) \text{ nb}$$

Decay

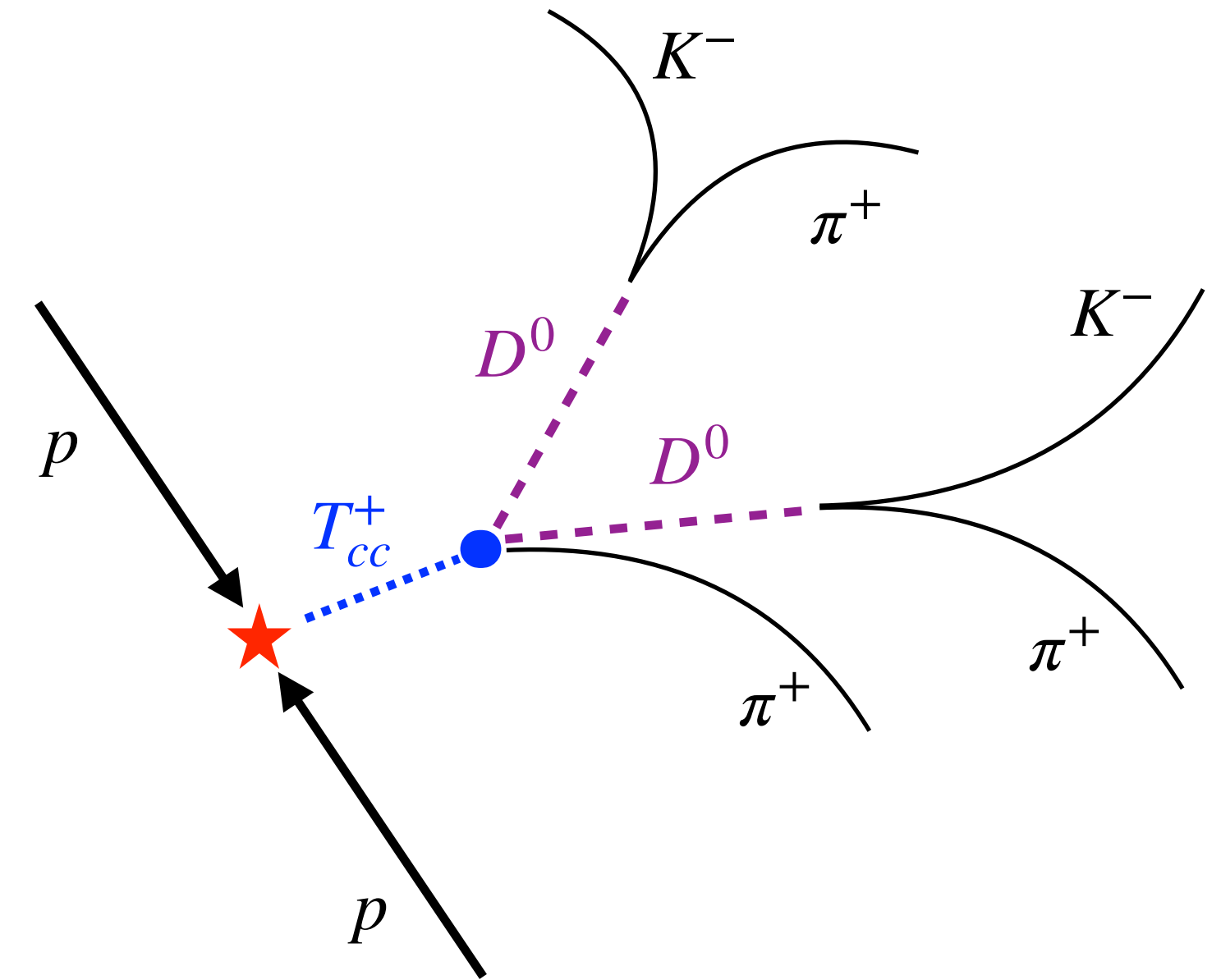
$$Br(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \quad Br(\Lambda_c^+ \rightarrow p K^- \pi^+) \quad \text{one more track}$$

$$10\% \quad 6\% \quad 1/3$$

$$Br(T_{cc} \rightarrow D^0 D^{*+}) \quad Br(D^{*+} \rightarrow D^0 \pi^+) \quad Br(D^0 \rightarrow K^- \pi^+)^2$$

$$1/2 \quad 2/3 \quad (4\%)^2$$

$$\rightarrow Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4$$



Detection of T_{cc}

$$f_{T_{cc}}/f_{\Xi_{cc}} \sim 1/4$$

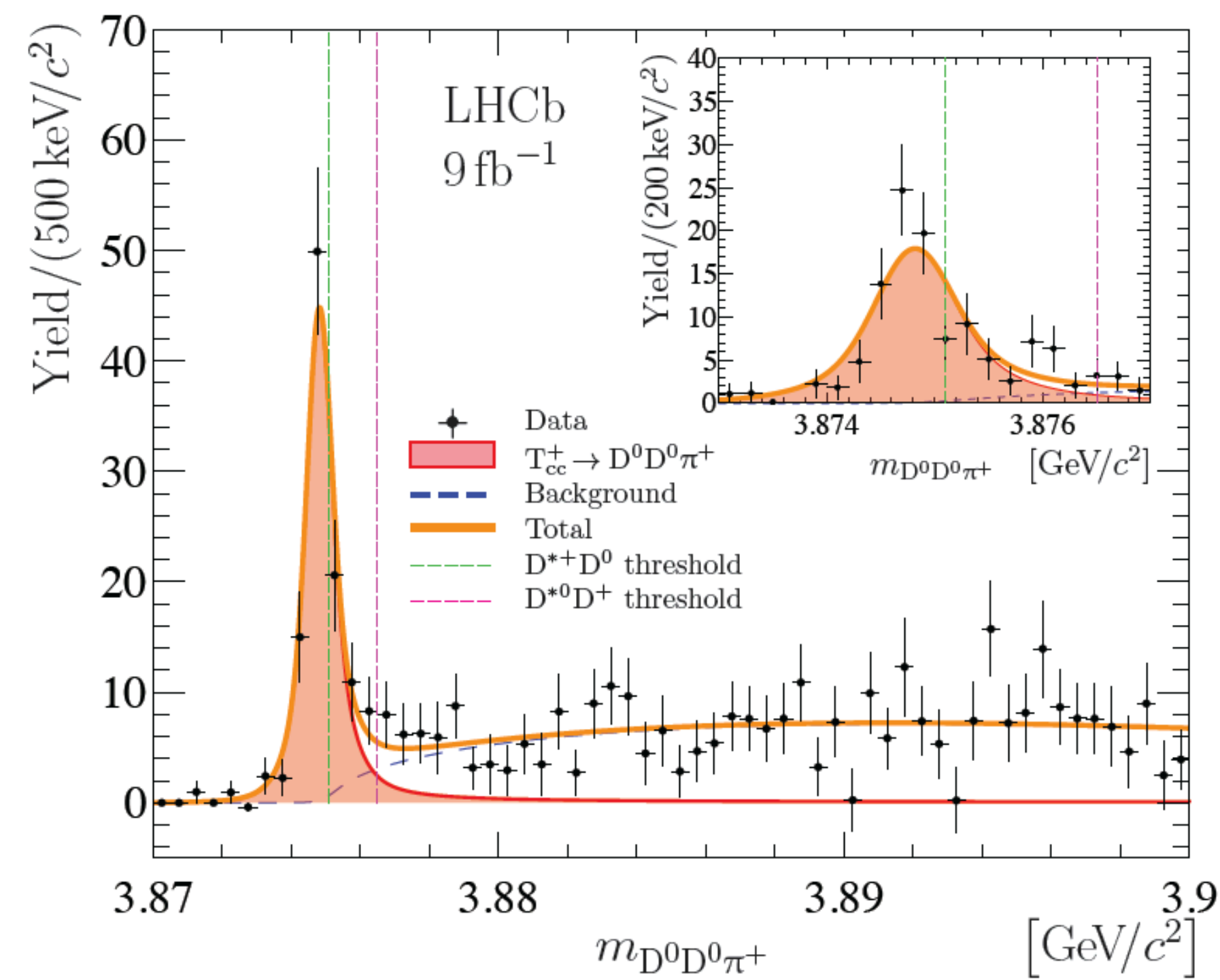
$$Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4$$

1500 events of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$



$$T_{cc}^+: N_s \sim 100$$

[QQ,Shen,Yu, 2008.08026]



Parameter	Value
N	117 ± 16
δm_{BW}	$-273 \pm 61 \text{ keV}/c^2$
Γ_{BW}	$410 \pm 165 \text{ keV}$

[LHCb,2109.01038;2109.01056]

Further production properties

— — To probe the nature of T_{cc}

[Jin,Li,Liu,QQ,Si,Yu,2019.05678]

Observables of T_{cc} to probe its nature

Molecule? Tetraquark?

- Static quantities [Dong,Guo,Zou,2108.02673, see also Prof. He's talk]

Tetraquark
 $M = (3.87 \pm 0.09) \text{ GeV}$
[Wang,Yan,1710.02810]

Mass, spin, parity, ...



Molecule
 $\delta M \approx -470 \text{ keV}$
[Li,Sun,Liu,Zhu,1211.5007]



- Dynamical quantities

1. Decay rates

2. Production observables

- Cross section
- Kinematic spectrum
- Production ratio
- ...



Cross section

- As a tetraquark
- As a molecule state



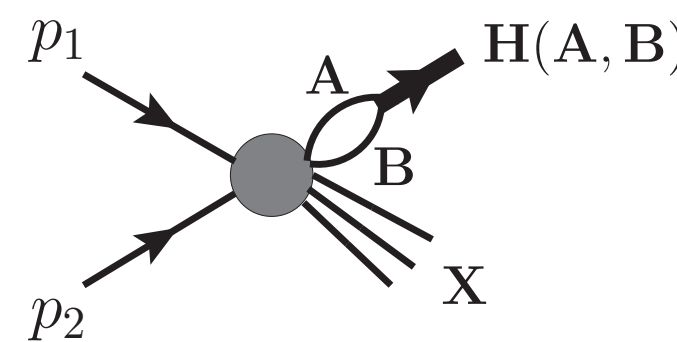
$$\sigma(T_{cc}^+) = (24_{-7}^{+14}) \text{ nb}$$

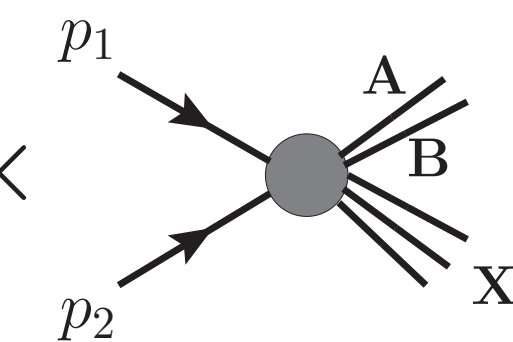
$$\sigma(T_{DD^*}) \approx 0.3 \text{ nb}$$

2 orders of magnitude lower!

Prefer a tetraquark...

$$pp \rightarrow D + D^* + X \rightarrow T(DD^*) + X$$



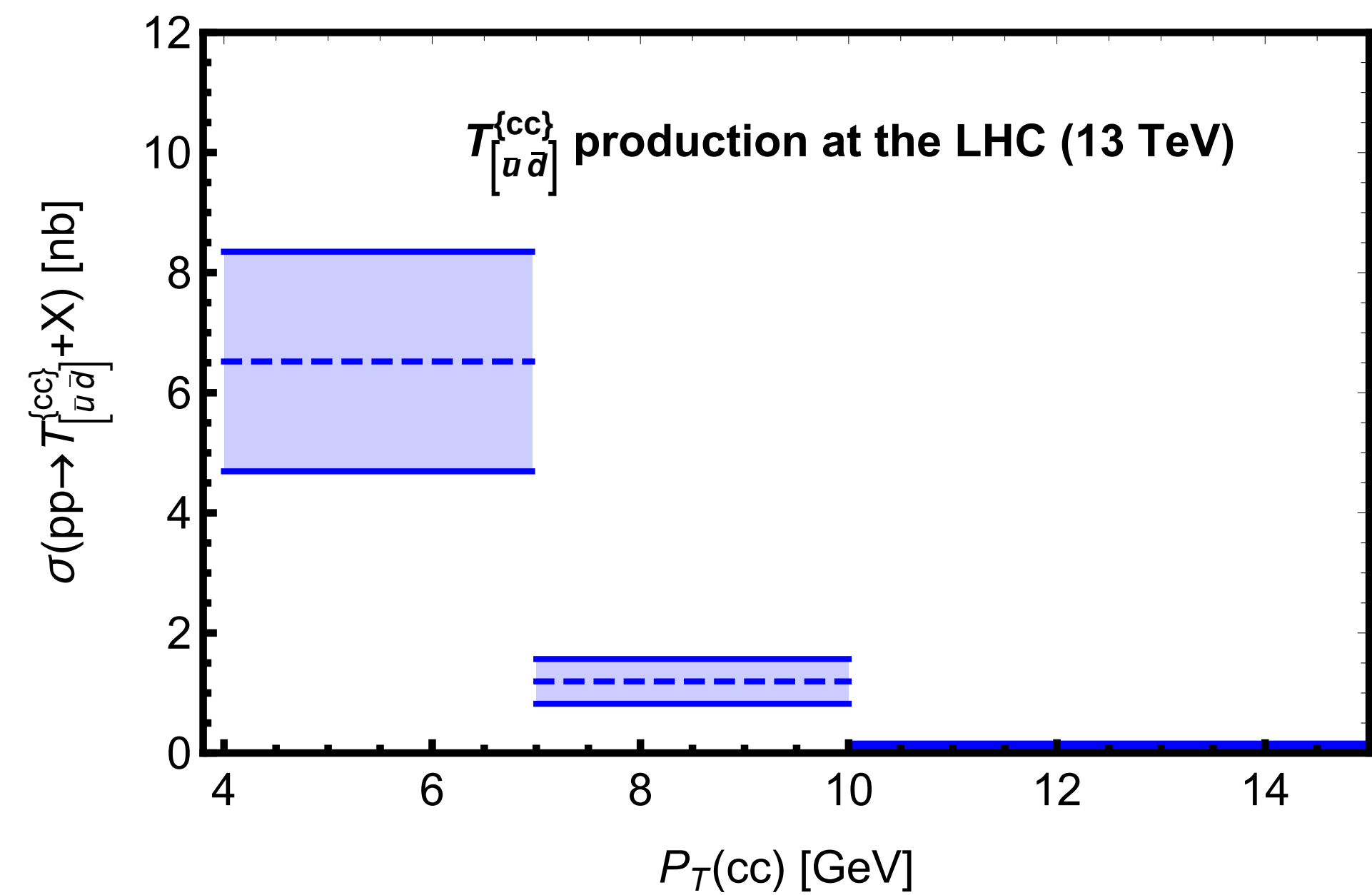
$$= \int \frac{d^3k}{(2\pi)^3} \Phi(\vec{k}) \times$$


$$\sim \Psi(0) \times A(pp \rightarrow D + D^* + X)$$

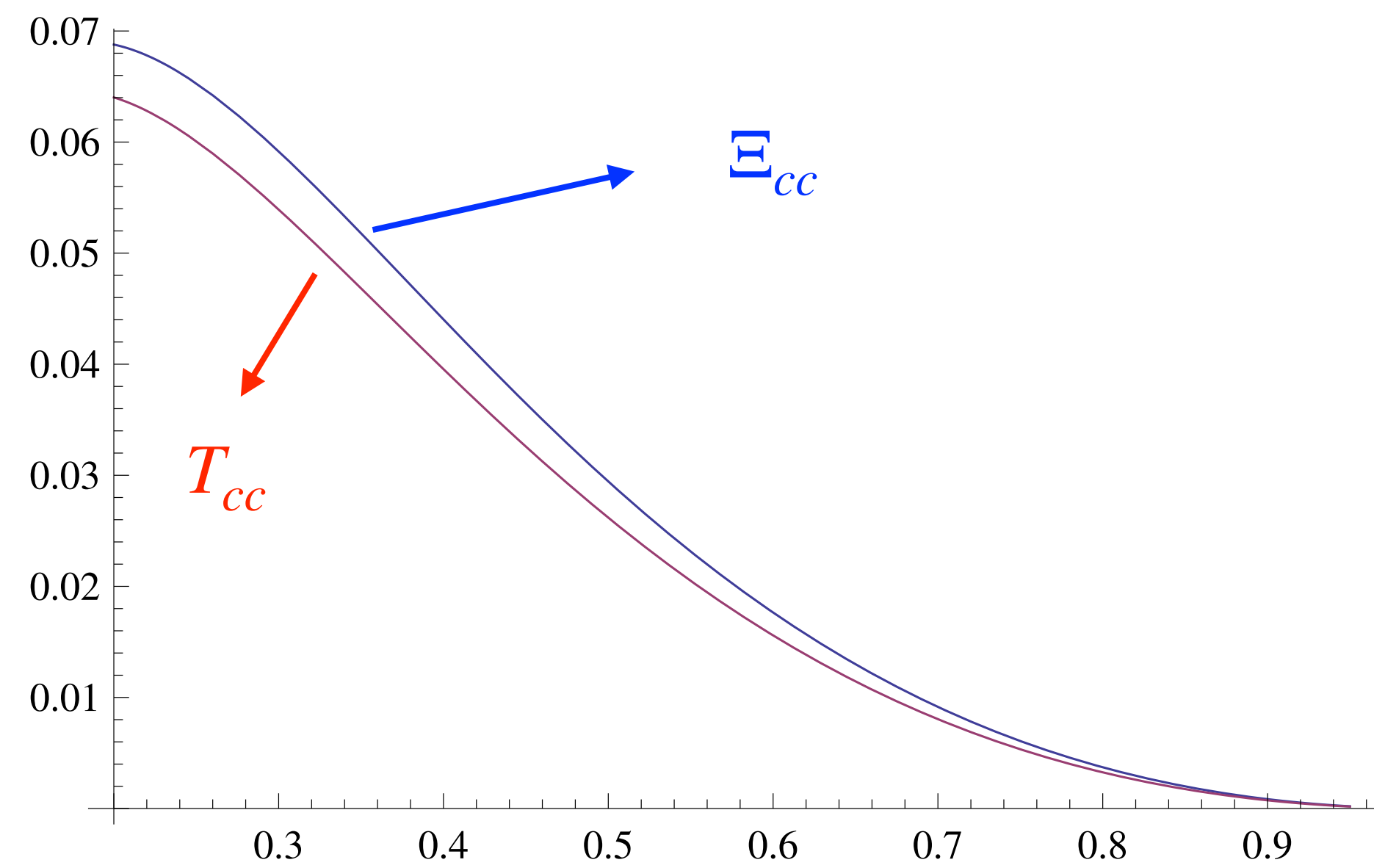
$$(\text{Input } \Psi(0) = 0.14 \text{ GeV}^{3/2})$$

[Li,Sun,Liu,Zhu,1211.5007]

Kinematic spectrum



p_T distribution

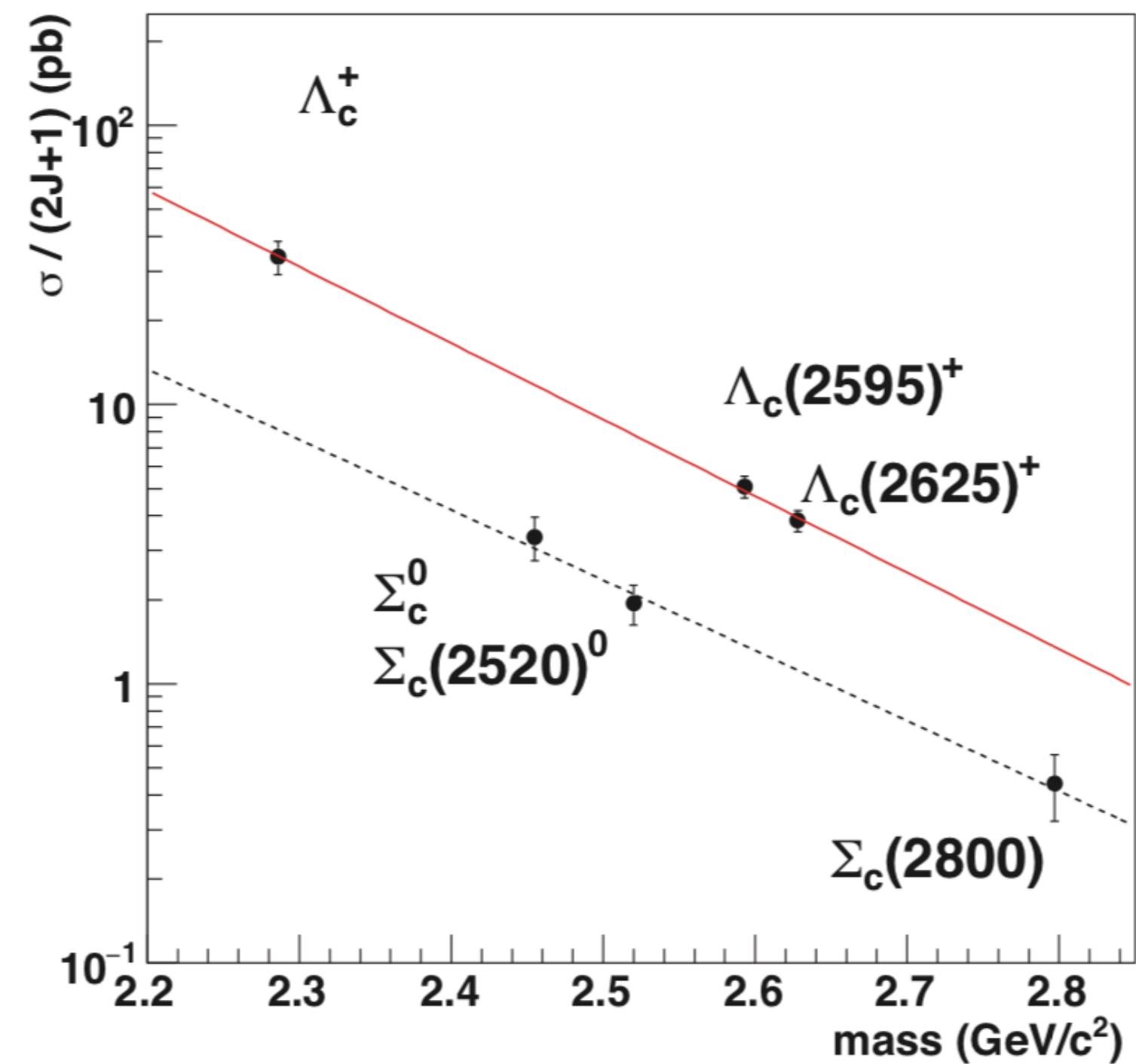


$z \equiv p_+^{\text{hadron}} / p_+^{\text{cluster}}$ distribution

Similarity between Ξ_{cc} and T_{cc} !

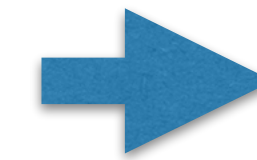
Production ratio

If experiments find an isospin triplet T'_{cc} , e.g. $T_{[\bar{u}\bar{u}]}^{\{cc\}}$, **compare their production cross sections.**



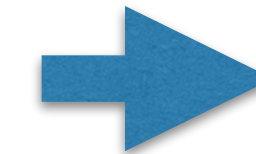
[Belle, 1706.06791]

Tetraquark picture



$$\frac{\sigma(T'_{cc})}{\sigma(T_{cc})} \sim \frac{\sigma(\Sigma_c)}{\sigma(\Lambda_c)} \sim \frac{1}{10}$$

Molecule picture



$$\sigma(T'_{cc}) \sim \sigma(T_{cc})$$

Summary

- We studied the discovery potential of T_{cc}^+ in **2020**, suggesting the golden channel $T_{cc}^+ \rightarrow D^0 D^{*+} \rightarrow D^0 D^0 \pi^+$, which has just been confirmed by the discovery in **2021** at the LHCb

- Considering the production and detection, we predicted the correct signal yield

$$N_s \sim 100 \text{ vs } N_s = 117 \pm 16$$

- We further propose to probe the nature of T_{cc}^+ by its production properties, including the production (1) cross section, (2) kinematic spectrum and (3) production rate

- An observable $\frac{\sigma(pp \rightarrow T_{cc} X) * B(T_{cc} \rightarrow D^0 D^0 \pi^+)}{\sigma(pp \rightarrow X(3872) X) * B(X(3872) \rightarrow D^0 \bar{D}^0 \pi^0)}$ to be studied

Thank you!