Production of Tcc

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2008.08026; 2019.05678

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

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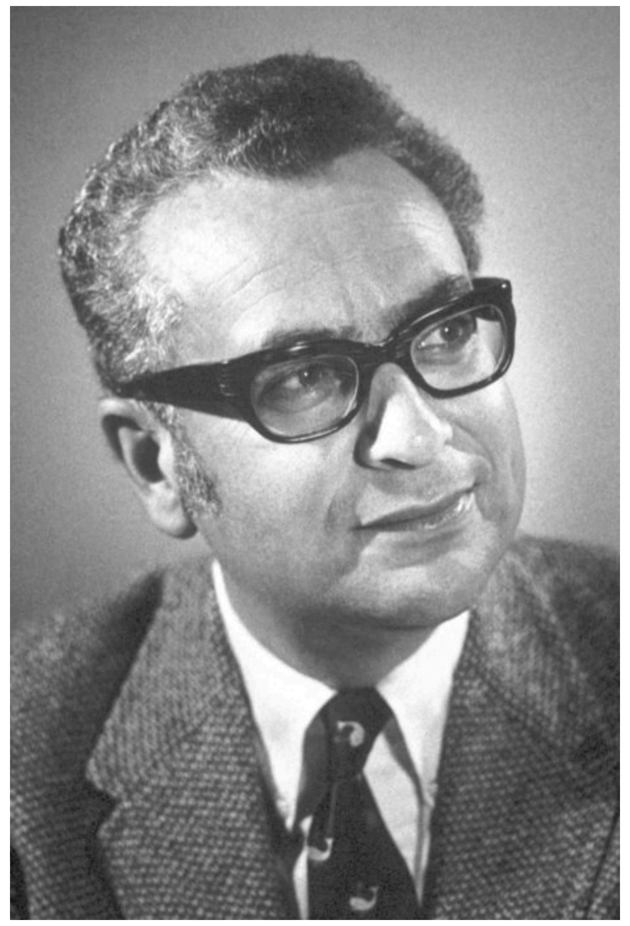
Contents

- 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

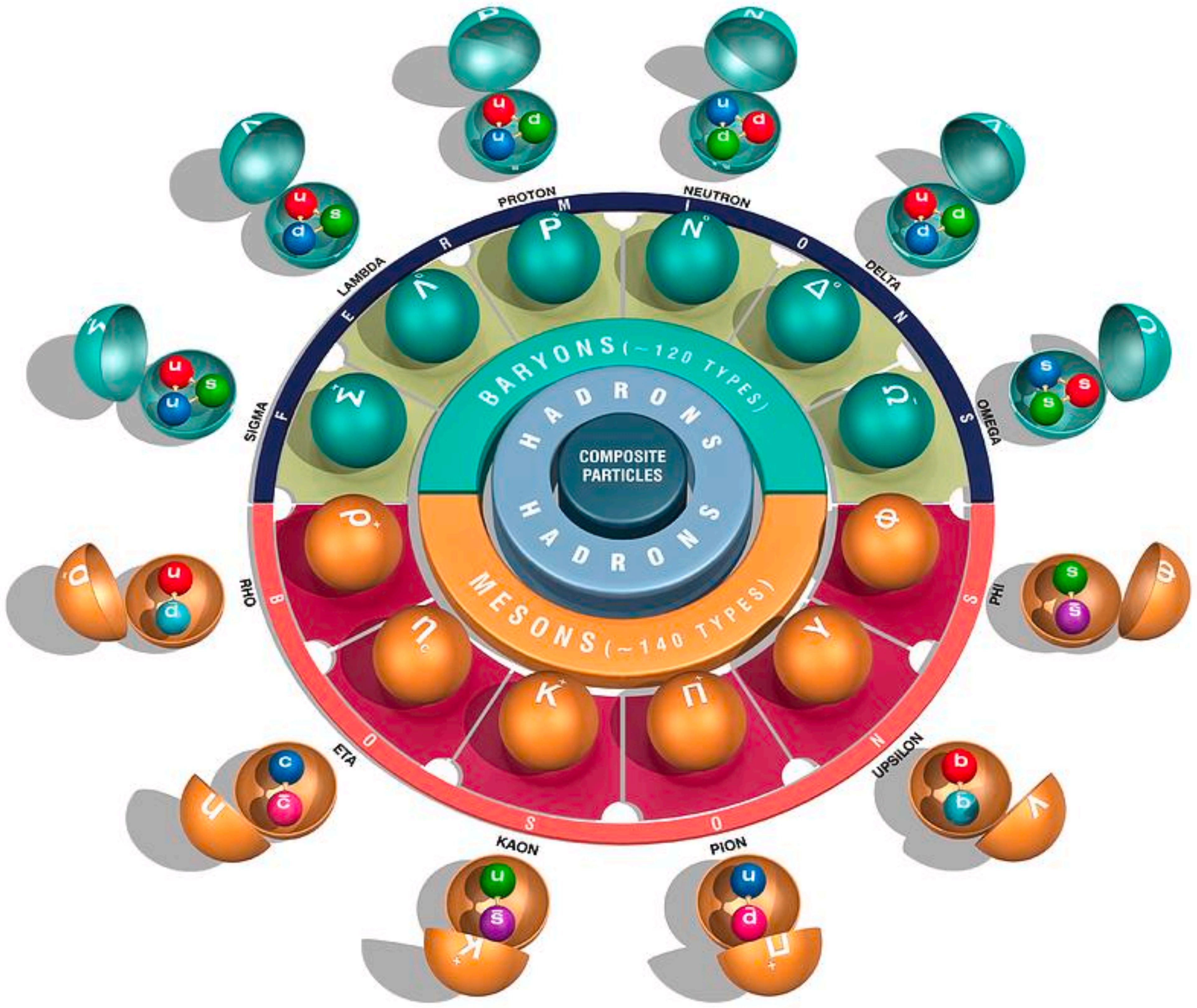
The quark model

- Old myth
- New life



Murry 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]

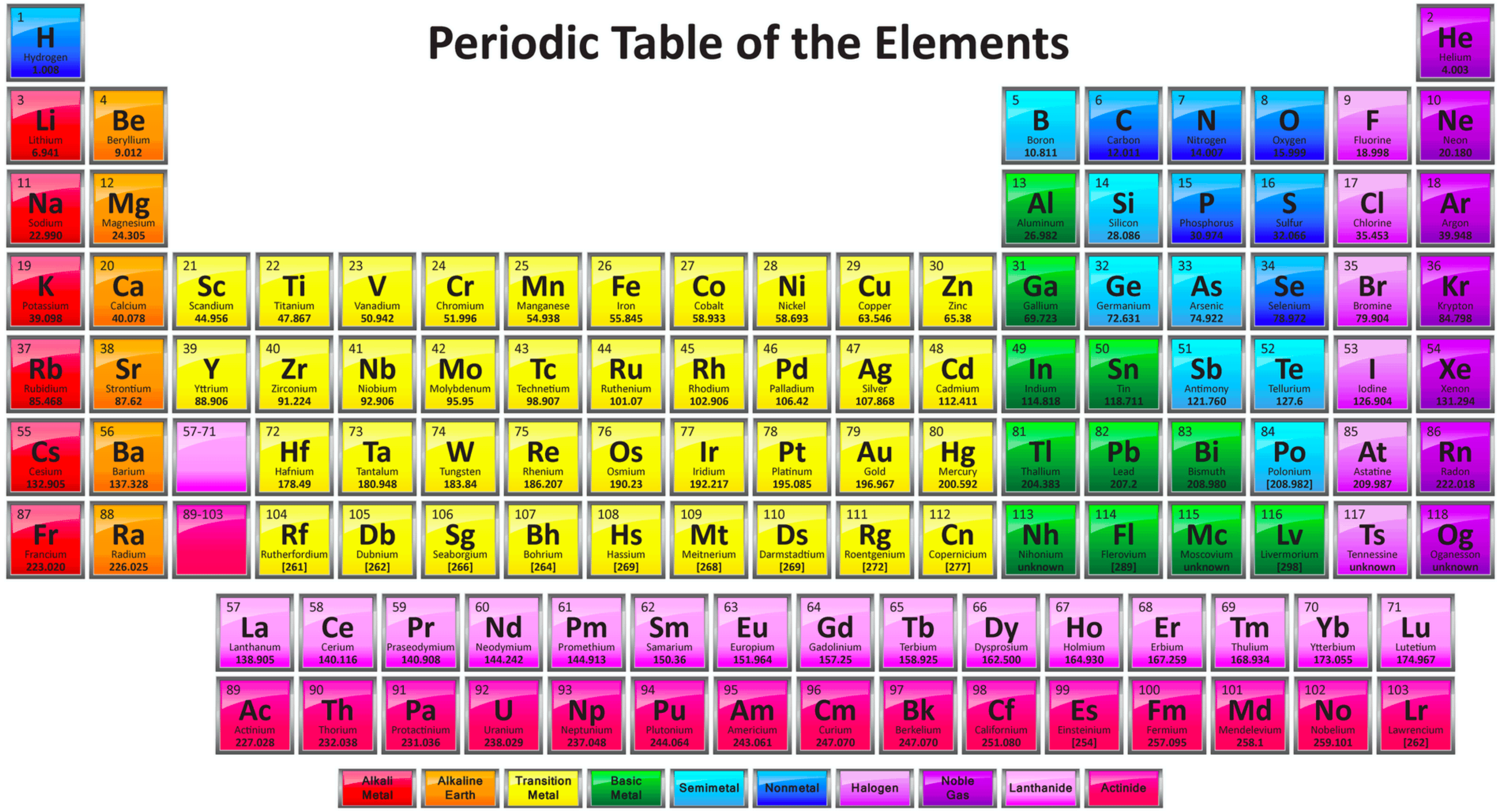
  The ***Physics World*** 2015 “top-10 breakthroughs”

- 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”



$\pi, K, \ldots$	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

Ξ_{cc}, X(6900): a new main group

Beyond stamp collecting

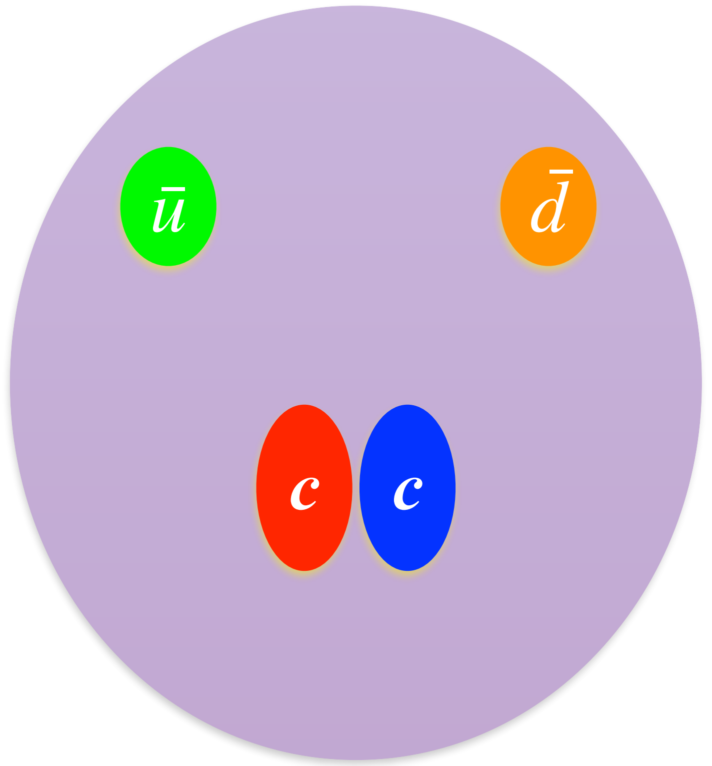
- Because of color confinement, properties of quarks are studied via hadrons

- 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?

$\pi, K,$ …	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						

<u>Two targets</u> in the talk @Nankai, 2nd May 2021.

T_{cc}: [**QQ**,Shen,Yu,2008.08026] (this talk)
"<u>Discovery potential of double-charm tetraquarks</u>"

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}

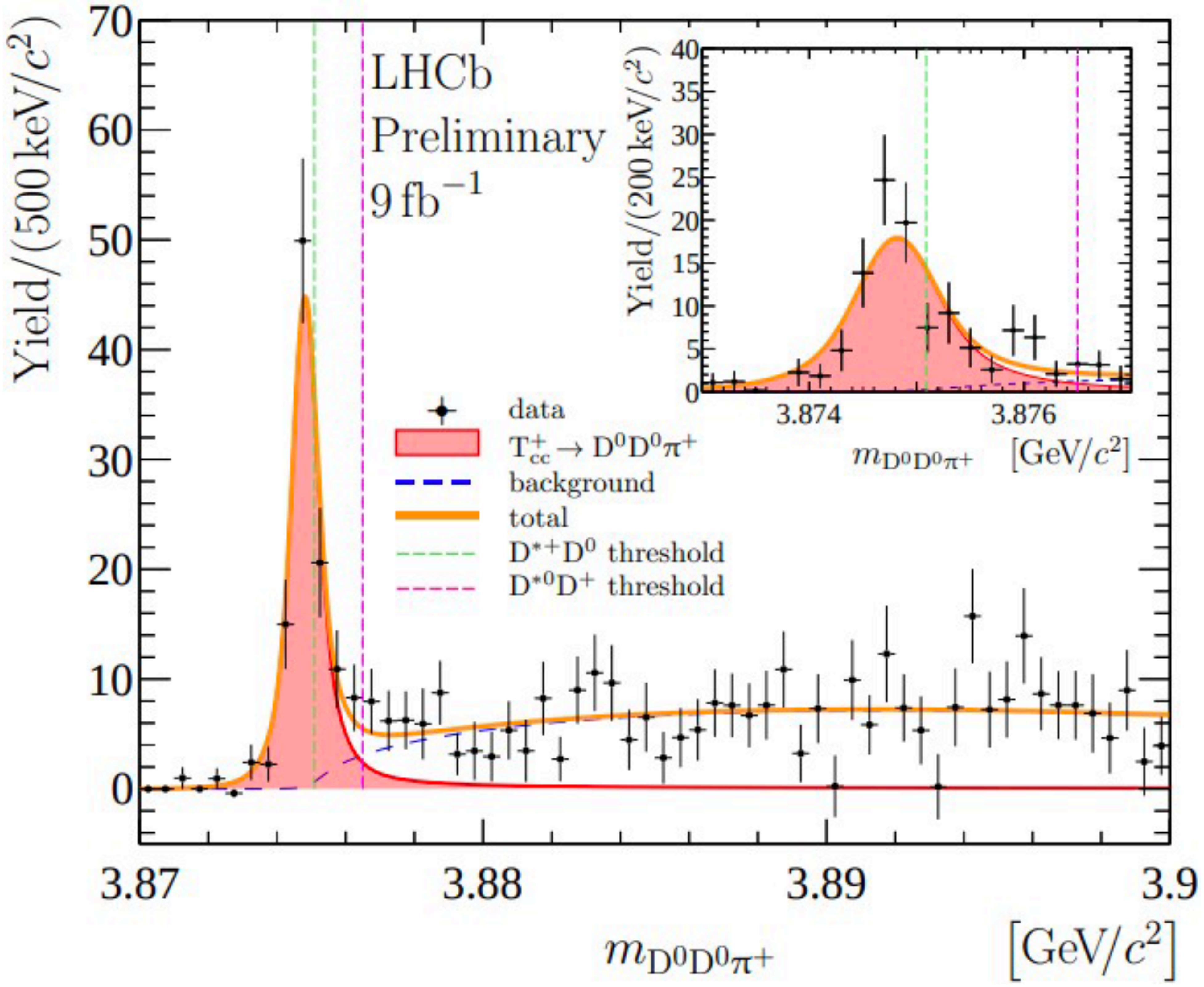
[**QQ**,Shen,Yu,2008.08026]

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 $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+K^-\pi^+$ or $D^0D^+\gamma$ (if stable) or $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^0D^{*+}$ (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 $T^{\{cc\}}_{[\bar{u}\bar{d}]}$ 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 $T^{\{cc\}}_{[\bar{u}\bar{d}]}$ 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.

$N_s = 117 \pm 16$



[LHCb,2109.01038;2109.01056]

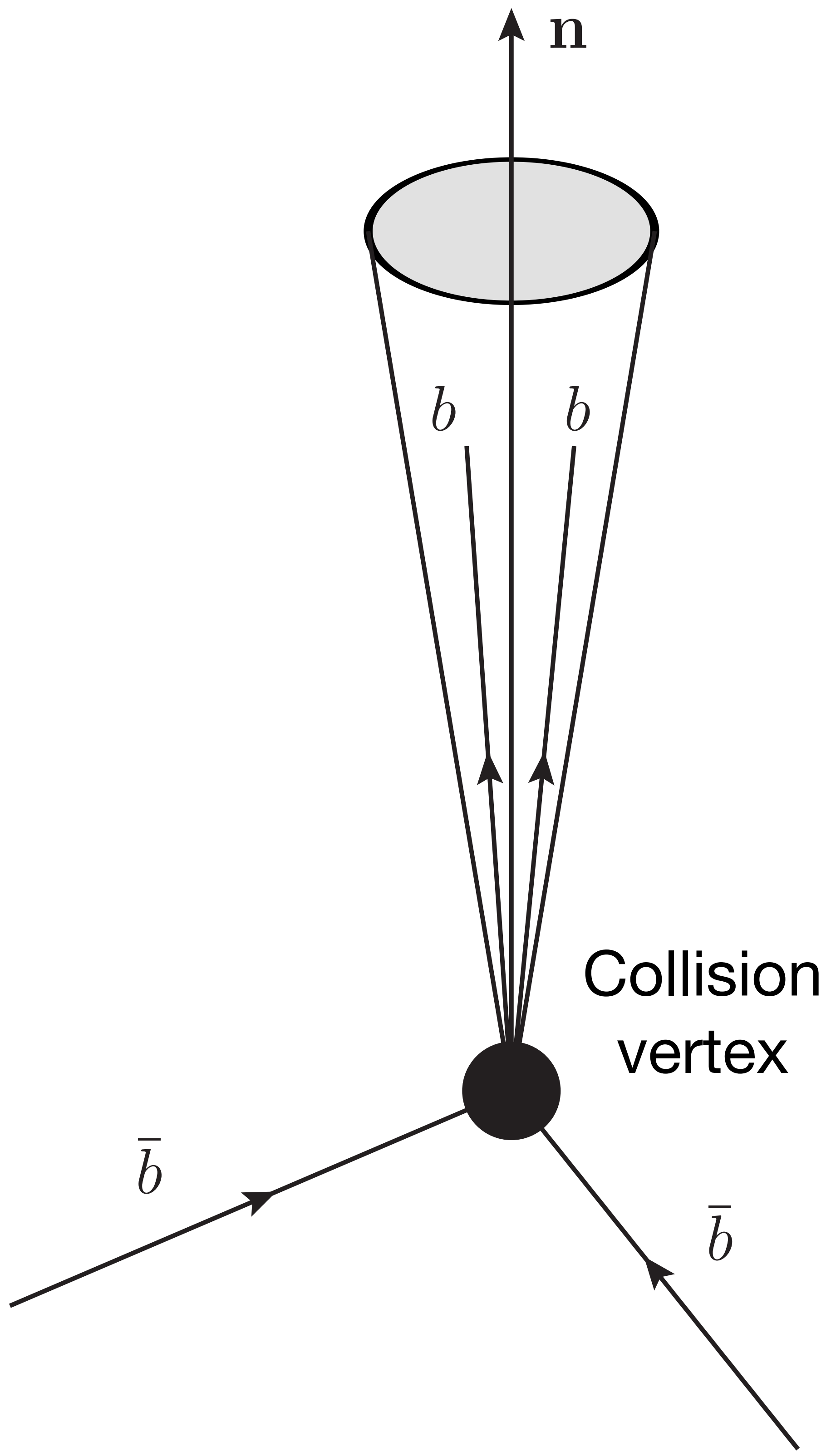
- **Correct discovery channel**
- **Correct signal yield**

@ European Physical Society Conference on high energy physics 2021

Discovery potential $\begin{cases} \text{Production} \\ \\ \text{Detection} \end{cases}$

[**QQ**,Shen,Yu,2008.08026]

Production Mechanism



- It was propose for double-bottom hadron production

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

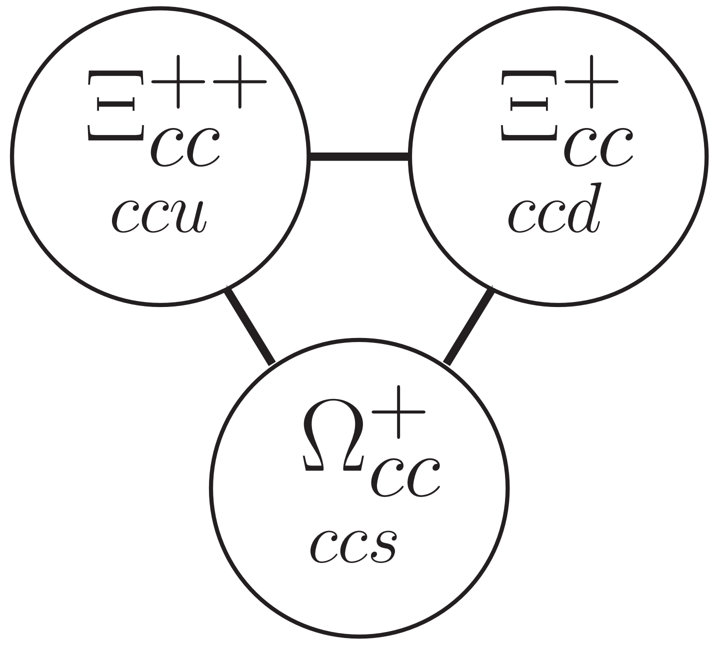
  1. Two produced heavy quarks stay close enough to form a heavy diquark
  2. The heavy diquark further fragments into doubly heavy hadrons

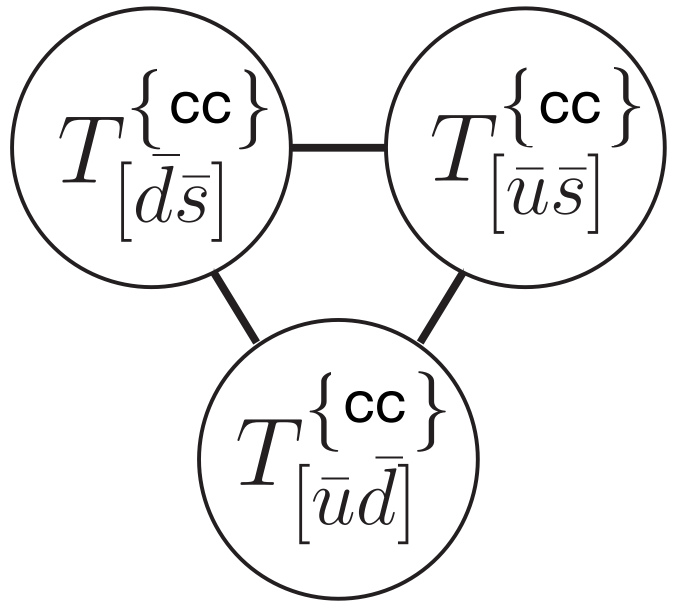
- Assuming T_{cc} a real tetraquark, the same mechanism applies

- 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!

$$\left[\frac{\Lambda_b^0}{B_d^0}\right](p_{\mathrm{T}}) = 0.151 + \exp\left[-0.57 - 0.095 p_{\mathrm{T}}(\mathrm{GeV})\right] \quad \Rightarrow \quad \frac{T_{\bar{u}\bar{d}}^{\{cc\}}}{\Xi_{cc}^{+(+)}}$$

[LHCb,1405.6842]

$$\left[\frac{f_s}{f_d}\right](p_{\mathrm{T}}) = 0.263 - 17.6 \times 10^{-4} \cdot p_{\mathrm{T}}(\mathrm{GeV}) \quad \Rightarrow \quad \frac{T_{\bar{u}\bar{s}}^{\{cc\}}}{T_{\bar{u}\bar{d}}^{\{cc\}}}, \frac{\Omega_{cc}^{+}}{\Xi_{cc}^{+}}$$

[LHCb,2103.06810]

Ground state ratio → $r_g = 0.48 \pm 0.08$ $\quad \Rightarrow \quad \dfrac{T_{\bar{u}\bar{d}}^{\{cc\}}}{T_{\bar{u}\bar{d}}^{\{cc\}} + \text{excited}}$

[Belle,1706.06791]

Production of double-charm hadrons

With partonic simulation by MadGraph & Pythia, we obtain

- The cross section for all double-charm hadrons

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

- For double-charm baryons, e.g.

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

- For double-charm tetraquarks, e.g.

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

The cuts are $4 < p_T < 15$ 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)

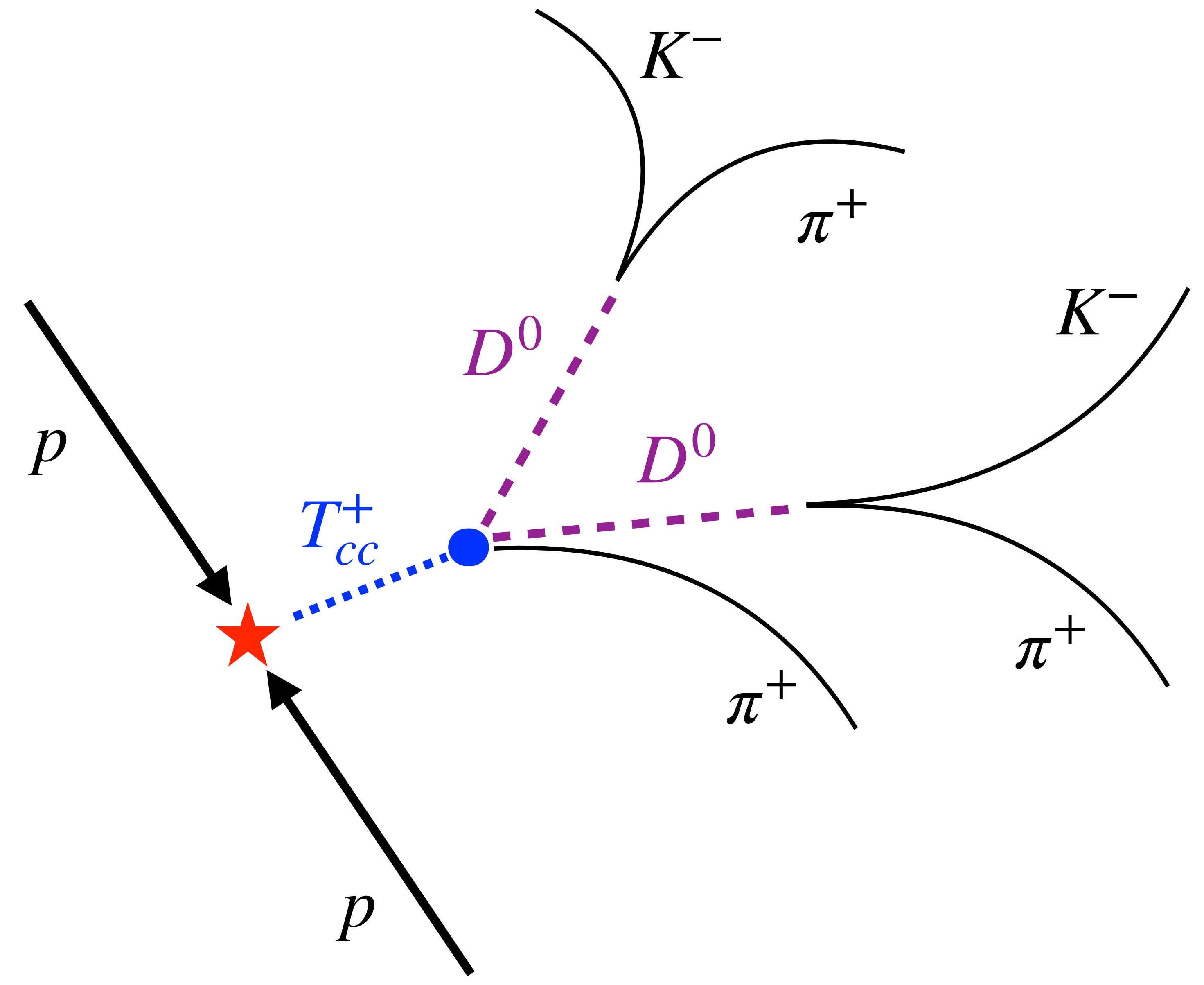
$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

[LHCb,1910.11316]

Detection of T_{cc}

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

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



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

Production $\sigma(\Xi_{cc}^{++}) = (103^{+56}_{-22})$ nb
$\sigma(T_{cc}^+) = (24^{+14}_{-7})$ nb
$\Rightarrow \dfrac{f_{T_{cc}}}{f_{\Xi_{cc}}} \sim \dfrac{1}{4}$

Decay

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

10% 6% $1/3$

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

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

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

Detection of T_{cc}

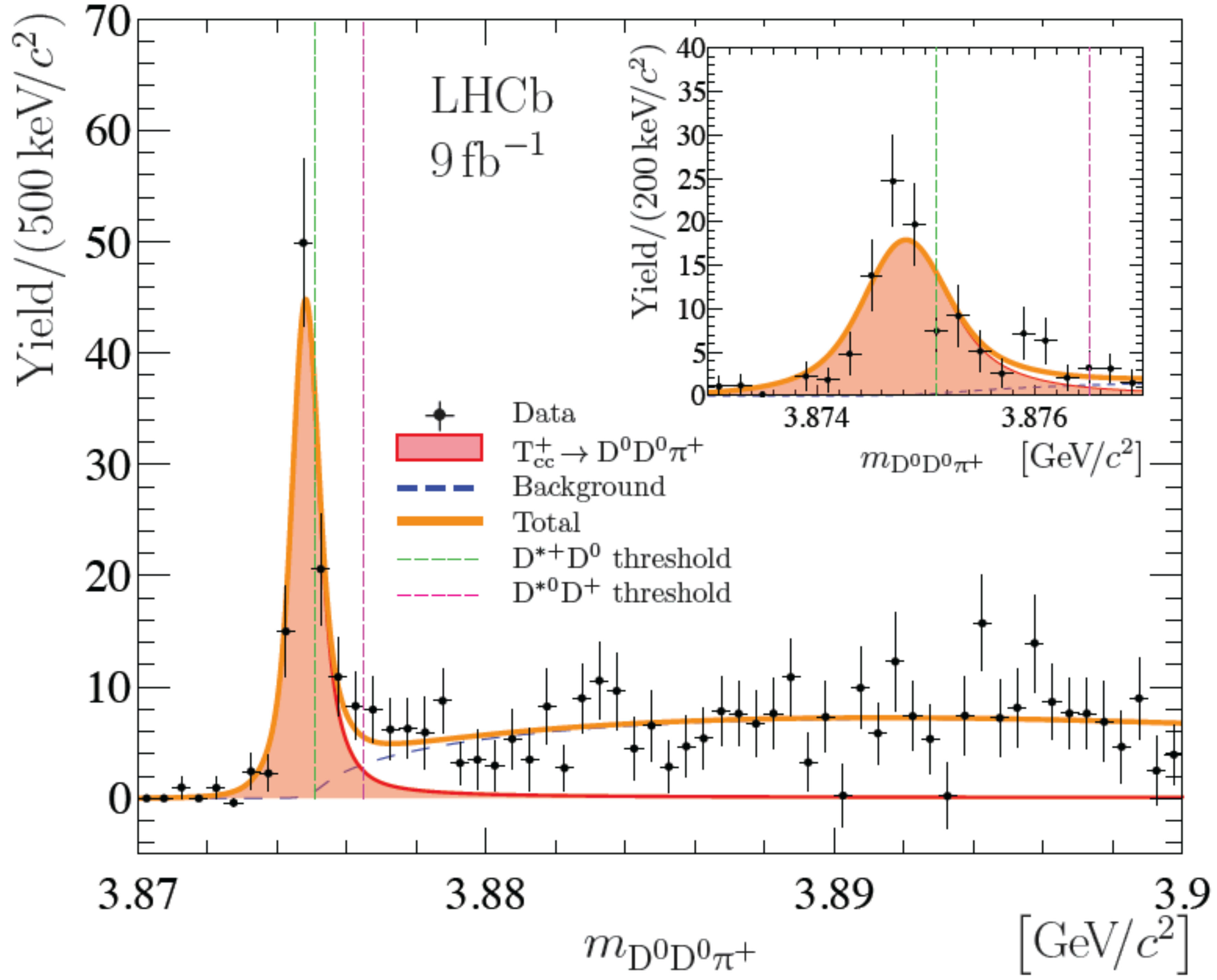
$f_{T_{cc}}/f_{\Xi_{cc}} \sim 1/4$

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

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

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

[**QQ**,Shen,Yu, 2008.08026]



Parameter	Value
N	117 ± 16
$\delta m_{\rm BW}$	-273 ± 61 keV/c^2
$\Gamma_{\rm BW}$	410 ± 165 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

$M = (3.87 \pm 0.09)$ GeV

[Wang,Yan,1710.02810]

Mass, spin, parity, …

Molecule

$\delta M \approx -470$ keV

[Li,Sun,Liu,Zhu,1211.5007]

- Dynamical quantities

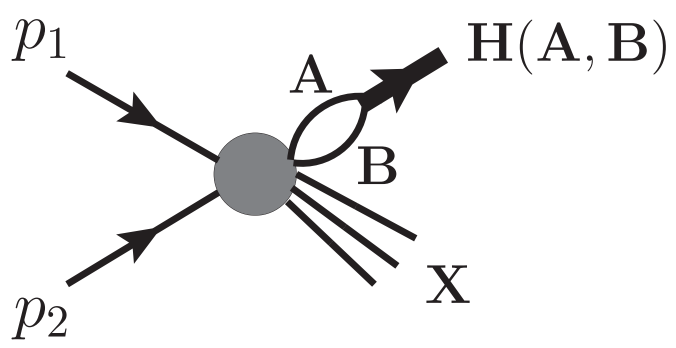
1. Decay rates

2. Production observables
    - Cross section
    - Kinematic spectrum
    - Production ratio
    - …

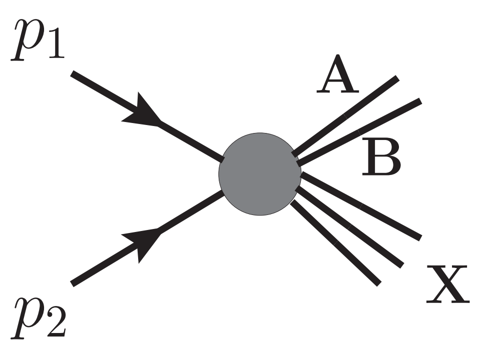
Cross section

- As a tetraquark → $\sigma(T_{cc}^{+}) = (24^{+14}_{-7})$ nb
- As a molecule state → $\sigma(T_{DD*}) \approx 0.3$ nb

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



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



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

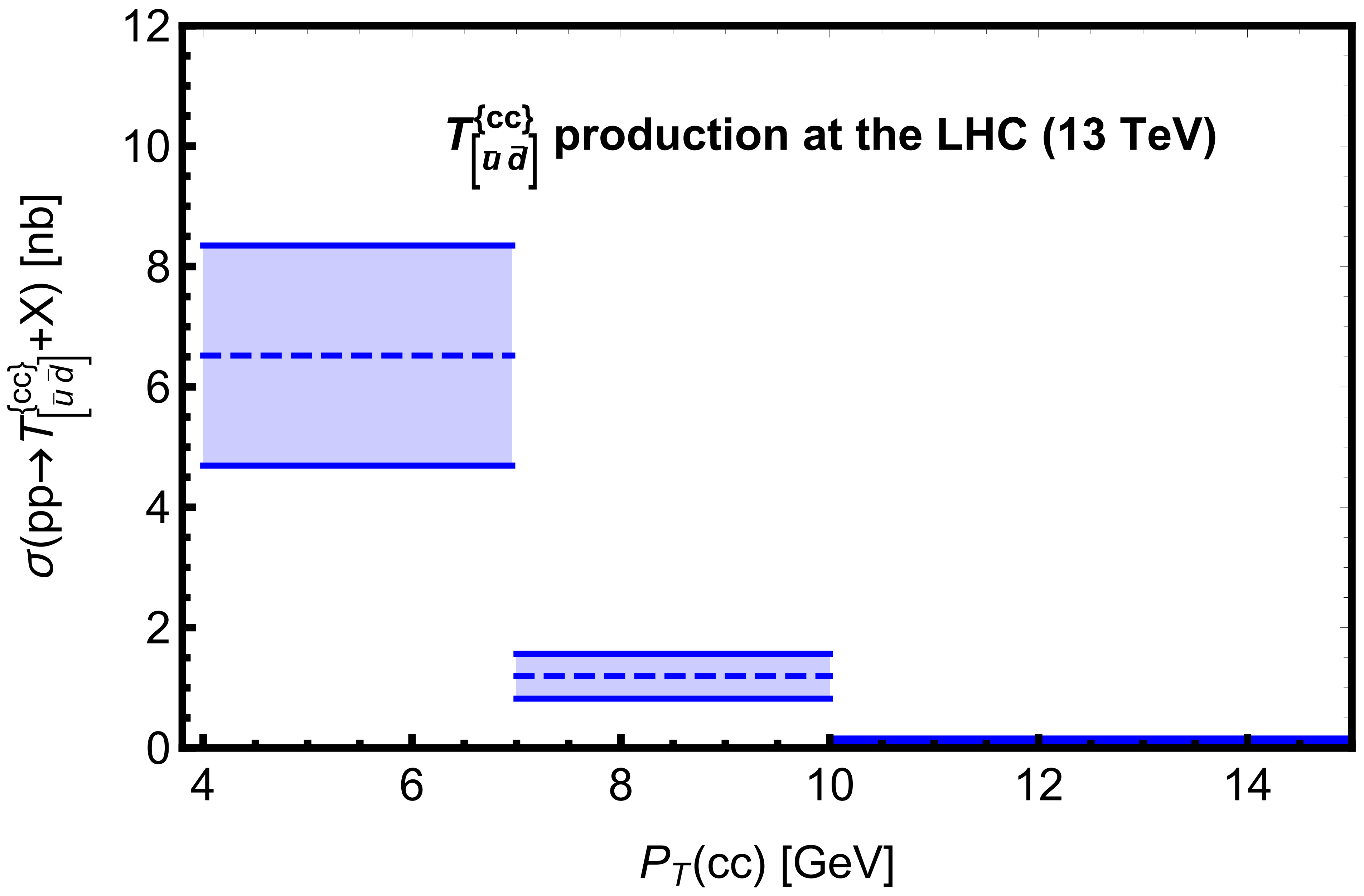
(Input $\Psi(0) = 0.14$ GeV$^{3/2}$)

2 orders of magnitude lower!

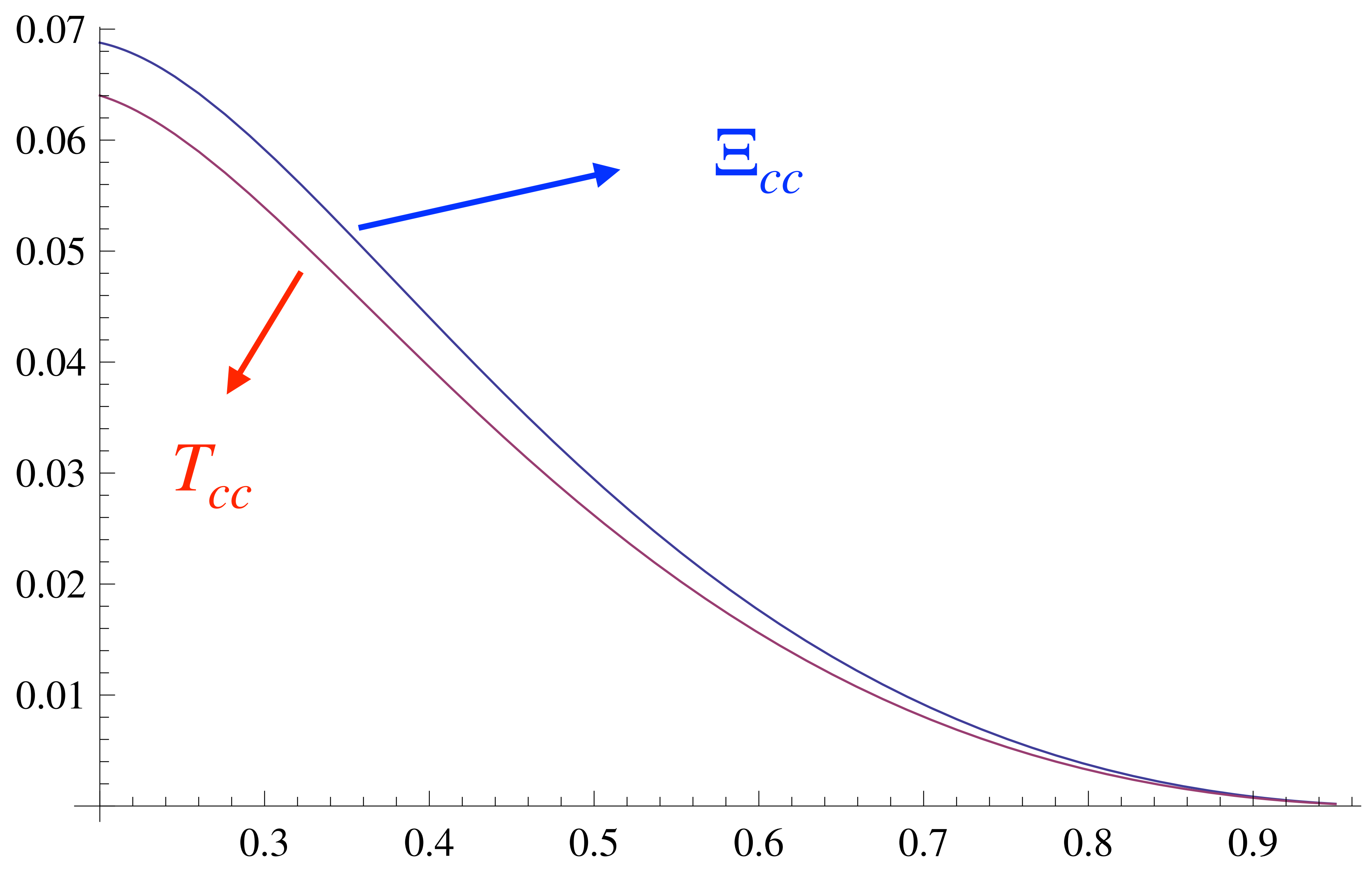
Prefer a tetraquark…

[Li,Sun,Liu,Zhu,1211.5007]

Kinematic spectrum



p_{T} distribution

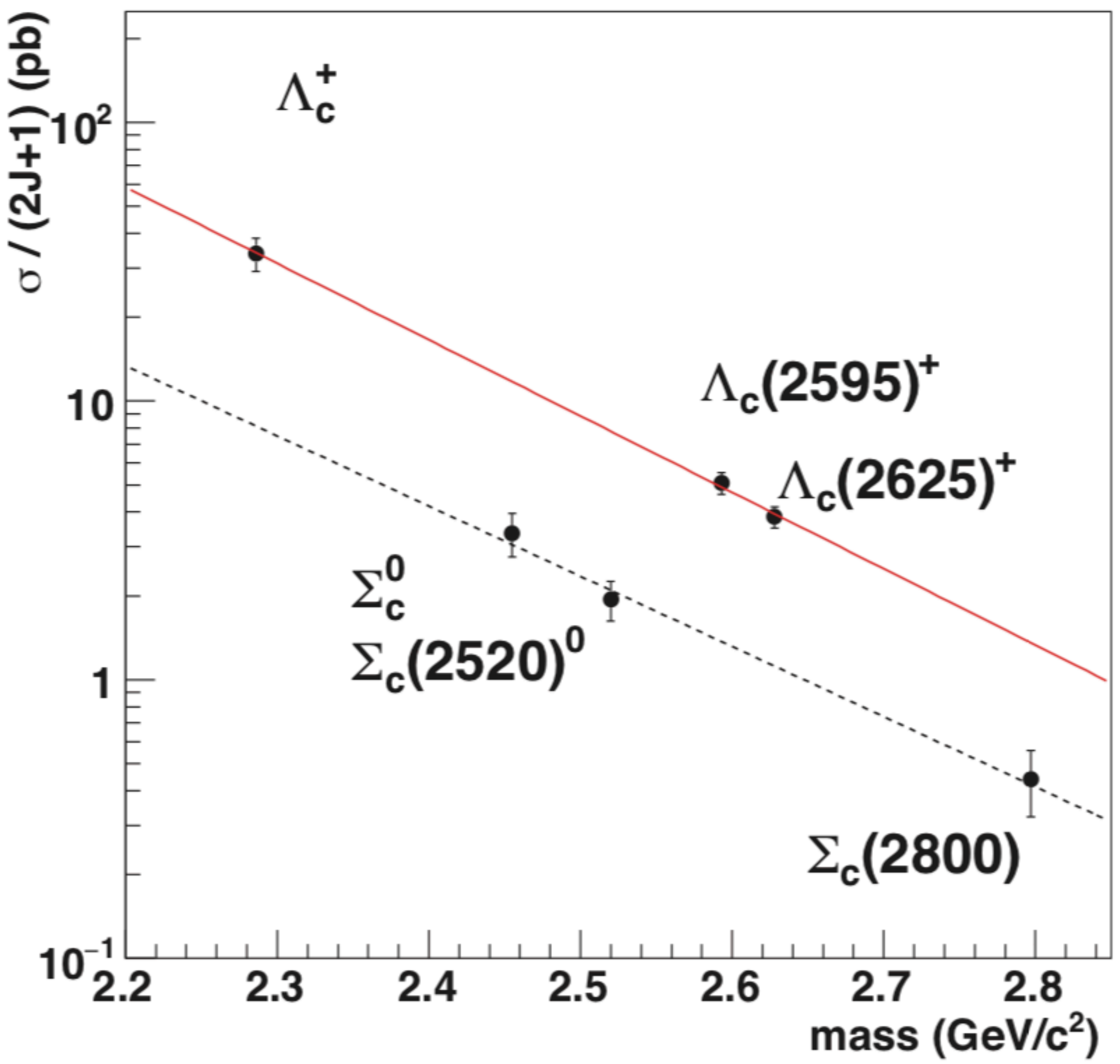


$z \equiv p_+^{\text{hadron}}/p_+^{\text{cluster}}$ distribution

Similarity between Ξ_{cc} and T_{cc}!

Production ratio

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



[Belle,1706.06791]

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

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

Summary

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

- Considering the production and detection, we predicted the <u>correct signal yield</u>

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

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

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

Thank you!