Inclusive search for Ξ_{bc}

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第18届重味物理和CP破坏研讨会

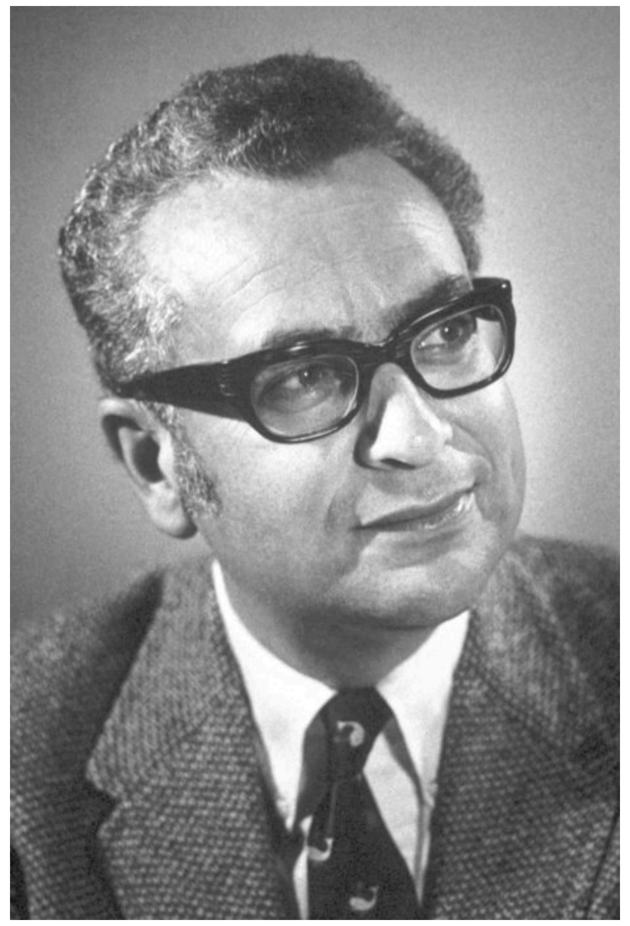
2021年11月10-14日，暨南大学，广州

Contents

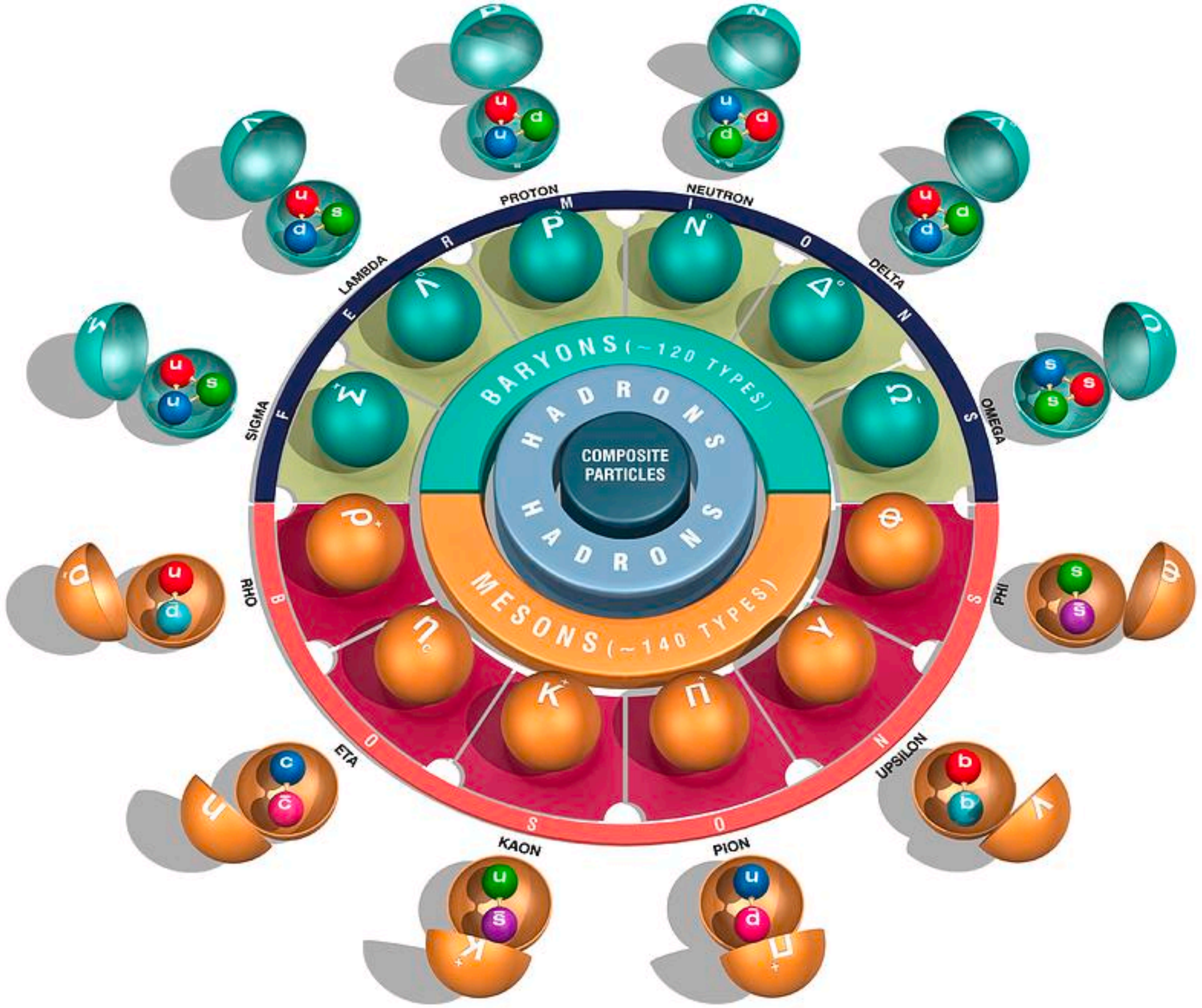
- It is important to study Ξ_{bc}
- We propose an inclusive approach to find Ξ_{bc}
- We will show it is feasible and timely for LHCb

The quark model

- Old myth
- New life



Murry Gell-Mann
1969 Nobel Prize for physics



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]

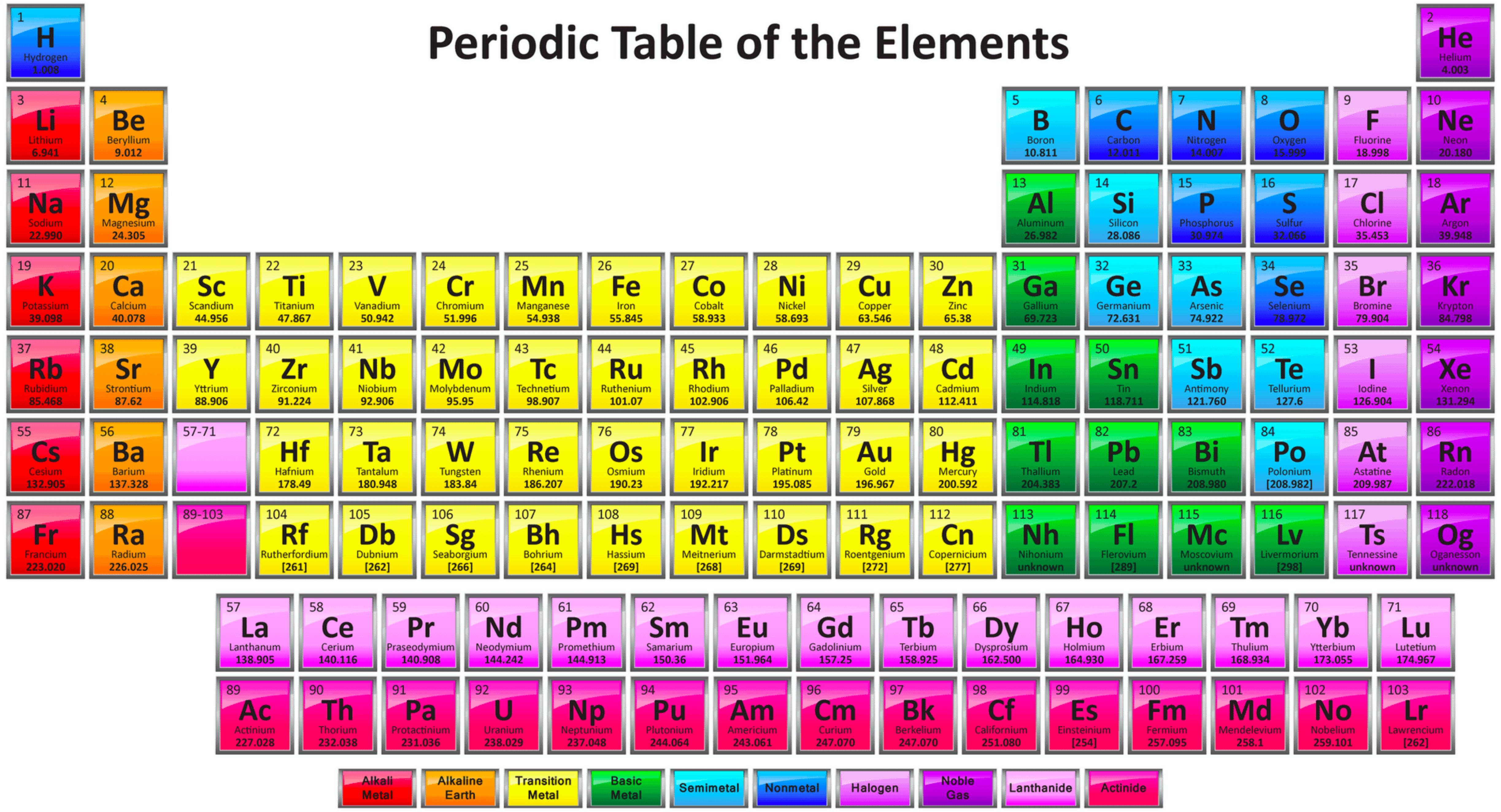
  The ***Physics World*** 2015 “top-10 breakthroughs”

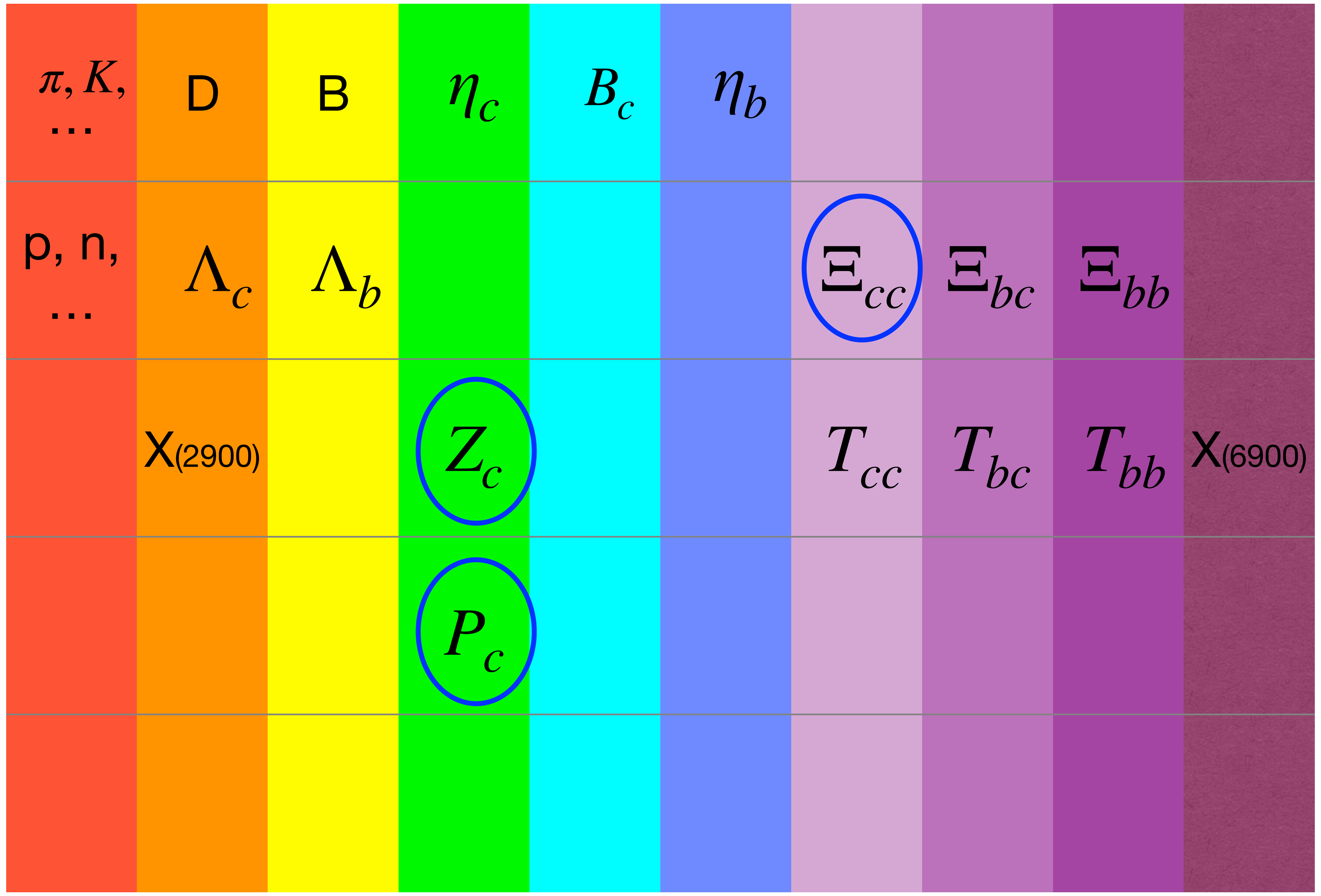
- Observation of a double-charm baryon Ξ_{cc}^{++}

  [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”





Z_c, P_c: a new period

Ξ_{cc}, X(6900): a new main group

Beyond stamp collecting

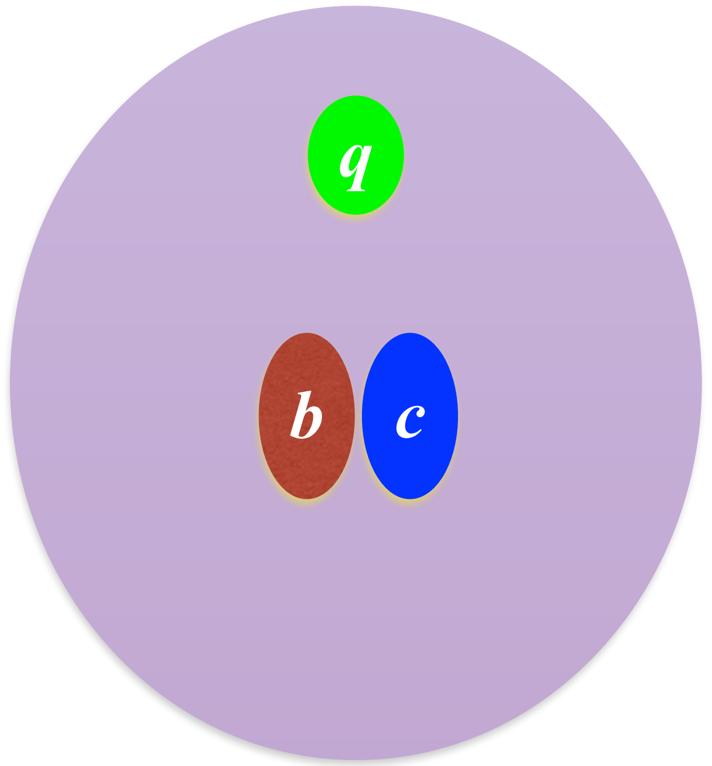
- Because of color confinement, properties of quarks are studied via hadrons

- 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?

$\pi, K, \ldots$	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						

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

T_{cc}: [**QQ**,Shen,Yu,2008.08026]
"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}

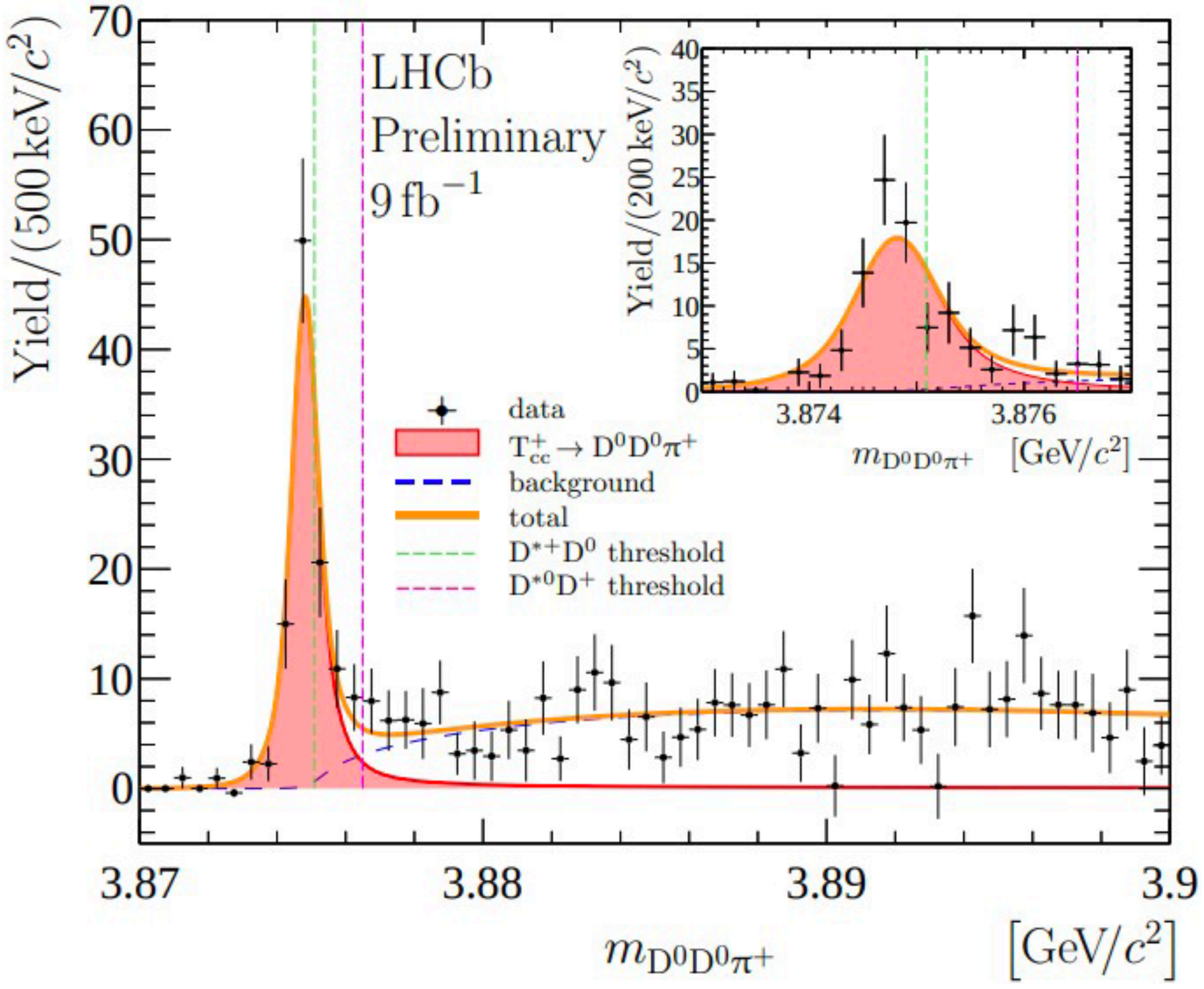
[**QQ**,Shen,Yu,2008.08026]

$N_s = 117 \pm 16$

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 $T^{\{cc\}}_{[\bar{u}\bar{d}]} \to D^+K^-\pi^+$ 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.



[LHCb,2109.01038;2109.01056]

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

@ European Physical Society Conference on high energy physics 2021

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}
			P_c					

$\sigma(\Xi_{bc})$ = 37 nb at 14 TeV LHCb

[X.G.Wu, et al 1101.1130]

	2011	2012	2018	2023	2029	2035
LHCb	Run I		Run II	Run III	Run IV	Run V
Integrated luminosity	1 fb^{-1}	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

Trillions of Ξ_{bc} will be produced @ LHCb Run3.

T_{cc}: [**QQ**, F.S.Yu,2008.08026]

Ξ_{bc}: this talk

Difficulties in experimental searches for Ξ_{bc}

- Detection efficiency —— small exclusive branching ratios

channels	Γ/ GeV	$\mathcal{B}$	channels	Γ/ GeV	$\mathcal{B}$
$\Xi_{bc}^0 \to \Lambda_c^+ \pi^-$	1.13×10^{-18}	1.60×10^{-7}	$\Xi_{bc}^0 \to \Lambda_c^+ \rho^-$	3.31×10^{-18}	4.68×10^{-7}
$\Xi_{bc}^0 \to \Lambda_c^+ a_1^-$	4.42×10^{-18}	6.24×10^{-7}	$\Xi_{bc}^0 \to \Lambda_c^+ K^-$	9.36×10^{-20}	1.32×10^{-8}
$\Xi_{bc}^0 \to \Lambda_c^+ K^{*-}$	1.70×10^{-19}	2.41×10^{-8}	$\Xi_{bc}^0 \to \Lambda_c^+ D^-$	2.27×10^{-19}	3.21×10^{-8}
$\Xi_{bc}^0 \to \Lambda_c^+ D^{*-}$	2.42×10^{-19}	3.42×10^{-8}	$\Xi_{bc}^0 \to \Lambda_c^+ D_s^-$	6.23×10^{-18}	8.80×10^{-7}
$\Xi_{bc}^0 \to \Lambda_c^+ D_s^{*-}$	5.82×10^{-18}	8.22×10^{-7}			
$\Xi_{bc}^0 \to \Sigma_c^+ \pi^-$	1.12×10^{-18}	1.58×10^{-7}	$\Xi_{bc}^0 \to \Sigma_c^+ \rho^-$	3.53×10^{-18}	4.99×10^{-7}
$\Xi_{bc}^0 \to \Sigma_c^+ a_1^-$	5.24×10^{-18}	7.41×10^{-7}	$\Xi_{bc}^0 \to \Sigma_c^+ K^-$	9.16×10^{-20}	1.29×10^{-8}
$\Xi_{bc}^0 \to \Sigma_c^+ K^{*-}$	1.86×10^{-19}	2.63×10^{-8}	$\Xi_{bc}^0 \to \Sigma_c^+ D^-$	1.96×10^{-19}	2.77×10^{-8}
$\Xi_{bc}^0 \to \Sigma_c^+ D^{*-}$	3.85×10^{-19}	5.44×10^{-8}	$\Xi_{bc}^0 \to \Sigma_c^+ D_s^-$	5.34×10^{-18}	7.55×10^{-7}
$\Xi_{bc}^0 \to \Sigma_c^+ D_s^{*-}$	9.73×10^{-18}	1.38×10^{-6}			

[W. Wang, F.S. Yu, Z.X. Zhao, 1707.02834]

- First experimental attempts

(LHCb, 13 TeV, ~ 5 fb^{-1})

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to D^0 p K^-)}{B(\Lambda_b^0 \to D^0 p K^-)} < [1.7,30]\,\%$$

[LHCb, 2009.02481]

$< [0.6, 3] \times 10^{-4}$

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to \Lambda_c^+ \pi^-)}{B(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} < [0.5,2.5] \times 10^{-4}$$

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to \Xi_c^+ \pi^-)}{B(\Lambda_b^0 \to \Xi_c^+ \pi^-)} < [1.4,6.9] \times 10^{-3}$$

[LHCb, 2104.04759]

$$\left(B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 4.9 \times 10^{-3}, \sigma(\Lambda_b^0) \sim 10\ \mu b, \sigma(\Xi_{bc}^0) \sim\ 40\ nb\right)$$

A novel approach —— inclusive Ξ_{bc} search

- Generally, inclusive decays have (1) larger branching ratios but (2) lower detection efficiencies

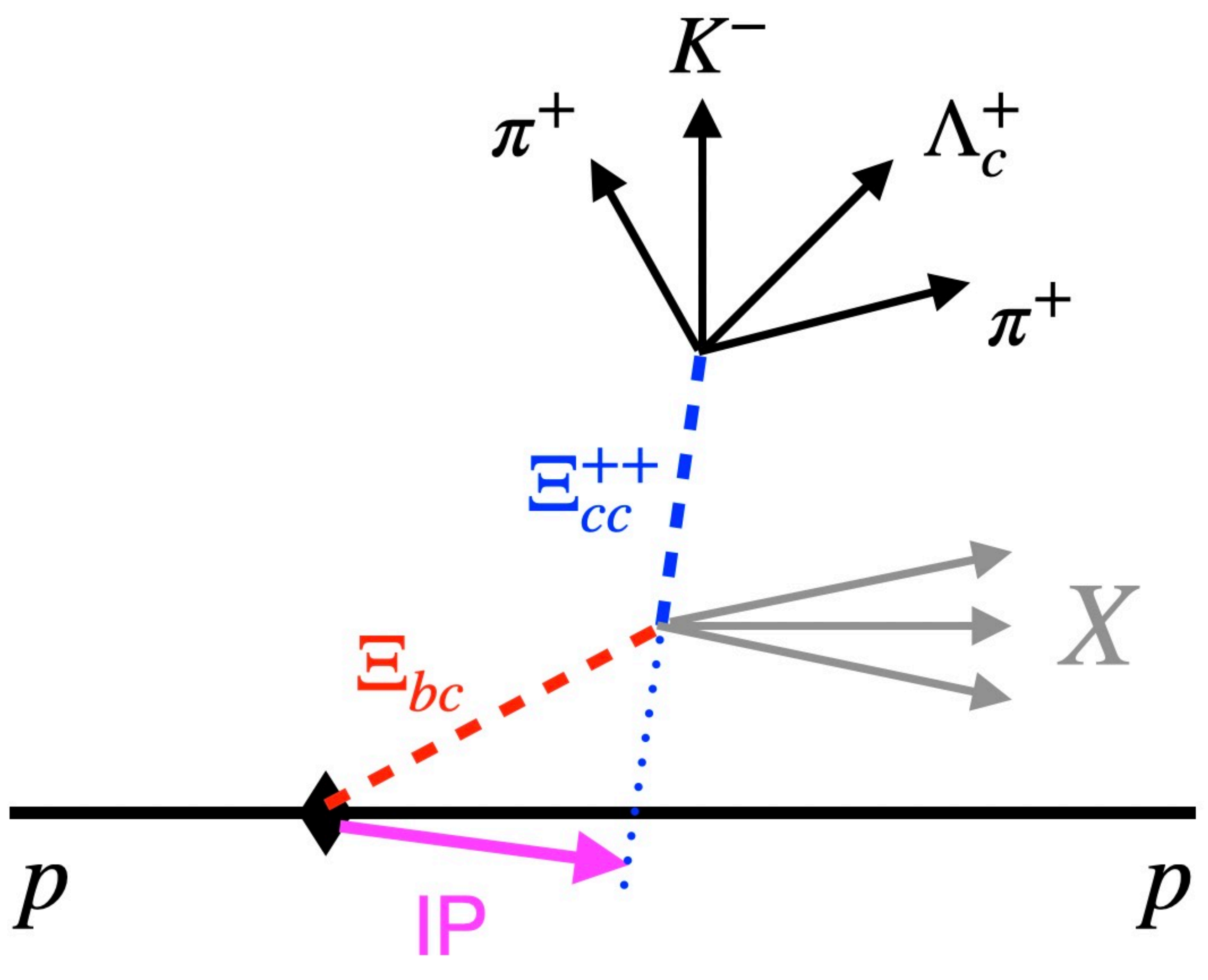
  Basically impossible at hadron colliders

- However, for $\Xi_{bc} \to \Xi_{cc}^{++} + X$, the efficiency can be large by making use of the inform of displaced vertex

  Inspired by the proposal to search for Ξ_{bb} via $\Xi_{bb} \to B_c + X$
  [Gershon,Poluektov,1810.06657]

- Ξ_{bc} is (almost) the only source for displaced Ξ_{cc}'s

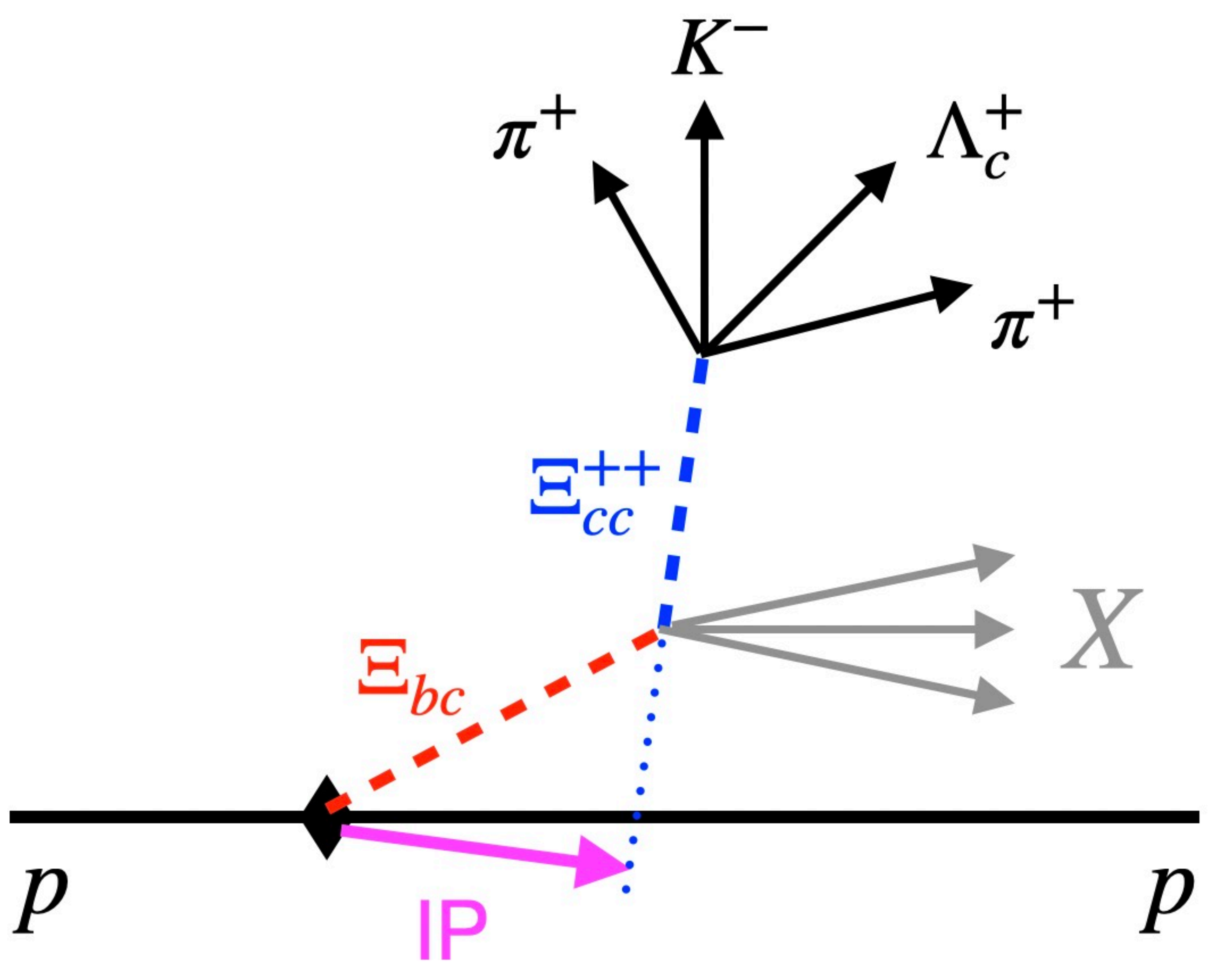
- The $B_c \to \Xi_{cc}^{++} + X$ decay is highly suppressed



Calculation of $\Xi_{bc} \to \Xi_{cc} + X$

- First important fact: $\Xi_{bc} \to \Xi_{cc} + X$ = $\Xi_{bc} \to H_{cc} + X$

  H_{cc} include excited states of Ξ_{cc}, which still decay into Ξ_{cc}



- Regarding the heavy diquarks χ_{bc} and χ_{cc} as point-like particles, the decay at the quark-diquark diquark level is

$$\chi_{bc} \to \chi_{cc} + \ell^- \bar{\nu},\ \chi_{cc} + \bar{q} q'$$

  It is reasonable because $r_{QQ'} \sim 1/(m_Q v) \ll 1/\Lambda_{\mathrm{QCD}}$ [e.g.,Brodsky,Guo,Hanhart,Meissner,1101.1983]

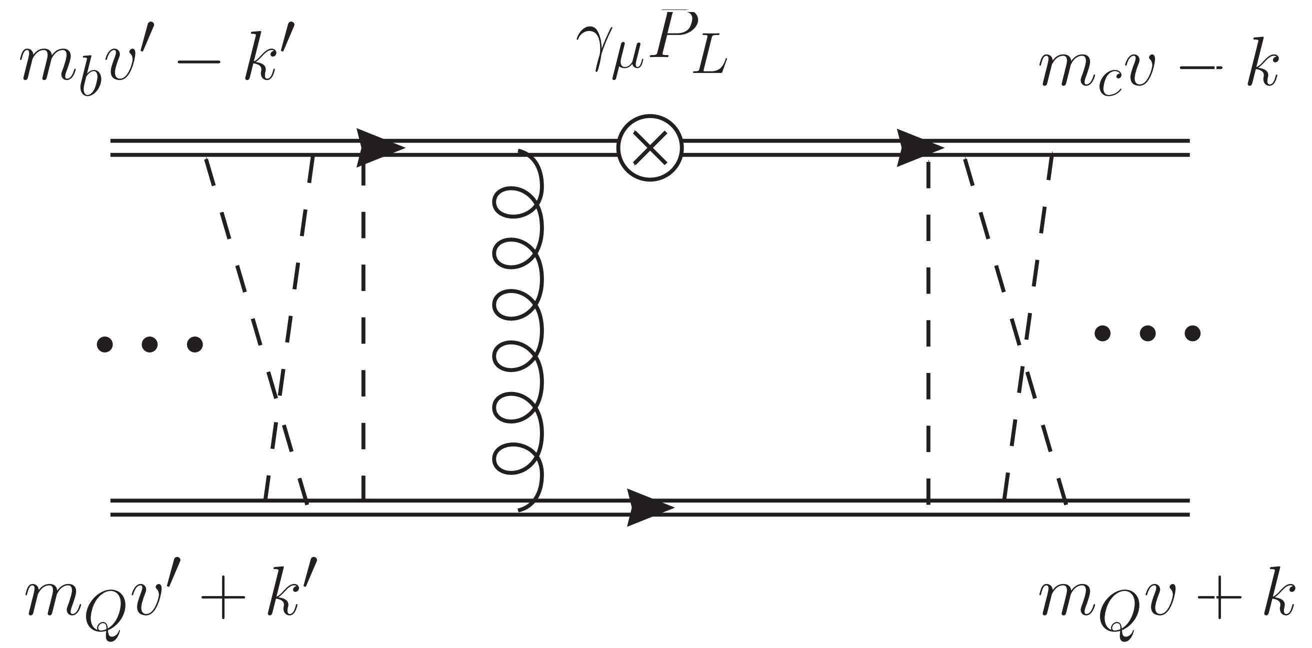
- By making use of OPE, the inclusive decay rate is expanded by powers of $1/M_{QQ'}$ within the Heavy Diquark Effective Theory

  [Y.J.Shi, W.Wang, Z.X.Zhao,Meissner,2002.02785]

- At the leading power

$$B(\Xi_{bc} \to \Xi_{cc} + X) = B(\chi_{bc} \to \chi_{cc} + \ell^- \bar{\nu},\ \chi_{cc} + \bar{q} q') + \mathcal{O}(1/M_{QQ'})$$

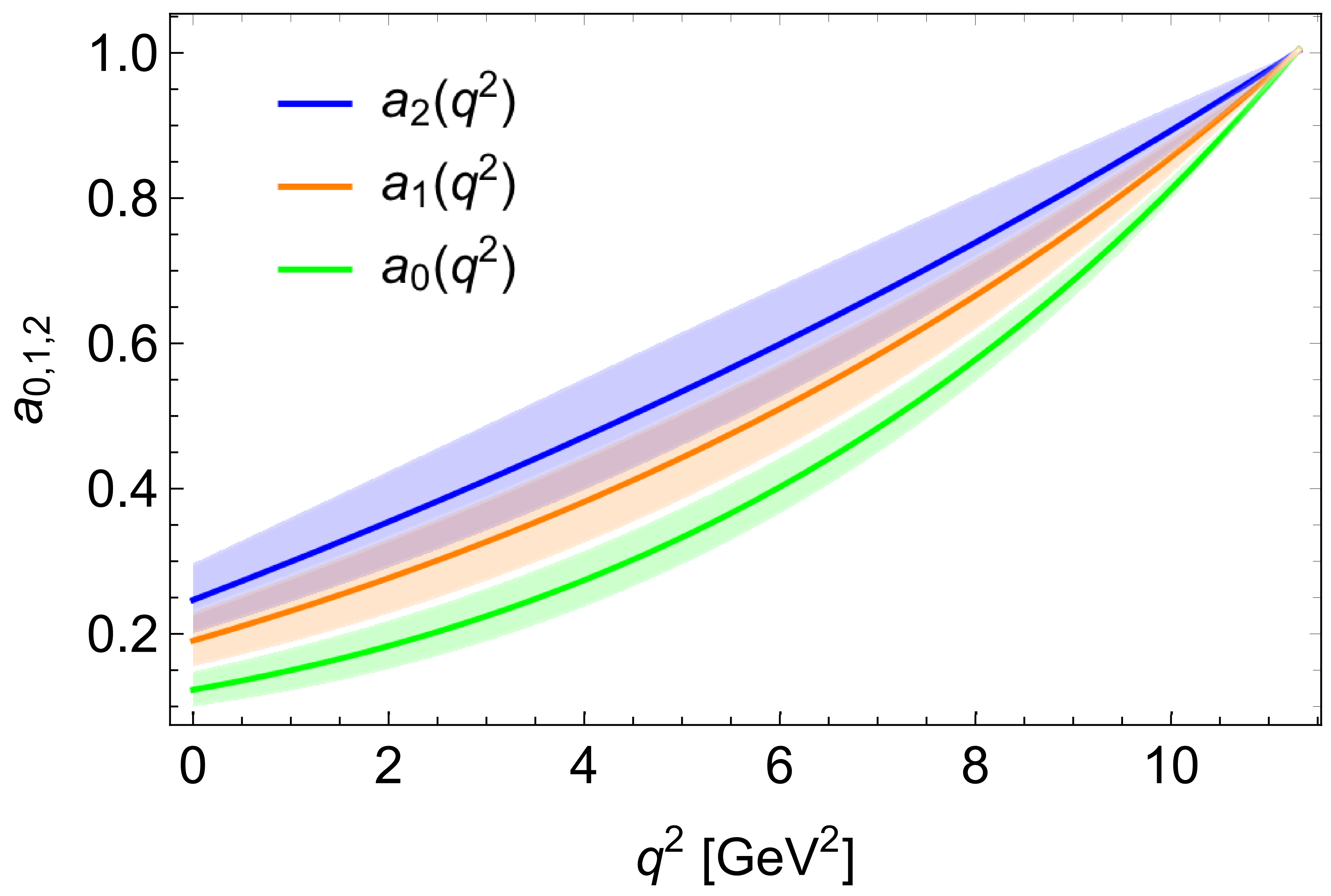
Calculation of $\Xi_{bc} \to \Xi_{cc} + X$



- The key issue is the 2-diquark-2-fermion interaction vertex, i.e. the $\chi_{bc} \to \chi_{cc}$ diquark current

$$\langle \chi_{cc}(v,\epsilon)\,|\,\bar{c}\gamma^\mu b\,|\,\chi_{bc}(v',\epsilon')\rangle \propto -\, a_0\epsilon^* \cdot \epsilon' v'^\mu - \, a_1\epsilon^* \cdot \epsilon' v^\mu + \, a_2\epsilon^* \cdot v' \epsilon'^\mu + \, a_3 v \cdot \epsilon' \epsilon^{*\mu}$$

$$\langle \chi_{cc}(v,\epsilon)\,|\,\bar{c}\gamma^\mu\gamma_5 b\,|\,\chi_{bc}(v',\epsilon')\rangle \propto -\, ib_0\epsilon^{\epsilon'\epsilon^* v'\mu} - ib_1\epsilon^{\epsilon'\epsilon^* v\mu}$$



- The large-recoil diquark current calculated via NRQCD

$$a_{2,3}(q^2) = \frac{\alpha_s}{2(1-w)^2\sqrt{w}} \frac{N_c+1}{N_c} \frac{1}{m_c^3} R_{bc}(0) R_{cc}^*(0)$$

- The small-recoil diquark current determined by heavy quark symmetry

$$a_{0,1,2,3}(q^2_{\max}) = b_{0,1}(q^2_{\max}) = 1$$

Calculation of $\Xi_{bc} \to \Xi_{cc} + X$

- Numerical result for the decay width

$$\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (1.9 \pm 0.1 \pm 0.3 \pm 0.4) \times 10^{-13}\ \text{GeV}$$

Uncertainties from quark mass, wave function at origin, scale dependence

- Lifetime [H.Y.Cheng, F.R.Xu, 1903.08148]

$$93\text{fs} < \tau(\Xi_{bc}^0) < 108\ \text{fs},\ 409\ \text{fs} < \tau(\Xi_{bc}^+) < 607\ \text{fs}$$

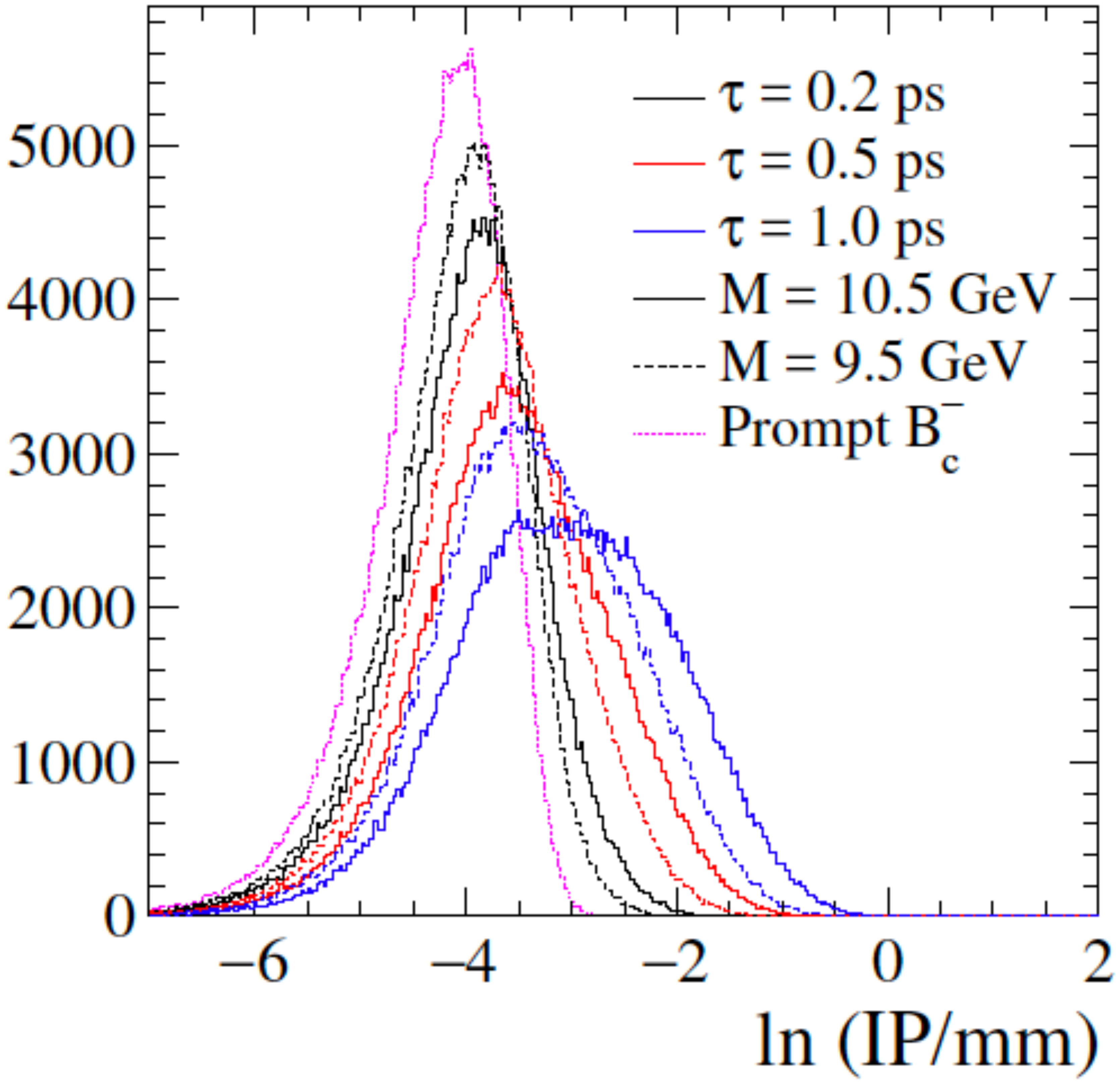
- The branching ratio is

$$B(\Xi_{bc}^+ \to \Xi_{cc} + X) \approx 14\,\%\,, \quad B(\Xi_{bc}^0 \to \Xi_{cc} + X) \approx 3\,\%$$

- Ξ_{cc}^{++} fragmentation suffers a factor of 1/2

$$B(\Xi_{bc}^+ \to \Xi_{cc}^{++} + X) \approx 7\,\%\,, \quad B(\Xi_{bc}^0 \to \Xi_{cc}^{++} + X) \approx 1.5\,\%$$

IP resolution of LHCb



[Gershon,Poluektov,1810.06657]

- Ξ_{bc}^{+} is very promising.

  93fs < $\tau(\Xi_{bc}^{0})$ < 108 fs, 409 fs < $\tau(\Xi_{bc}^{+})$ < 607 fs

[H.Y.Cheng, F.R.Xu, 1903.08148]

Search for $\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

- Estimated of signal signal events

$$N(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X) = N_p(\Xi_{bc}^{+}) \cdot B(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X) \cdot \epsilon(\Xi_{cc}^{++})$$

$$= N_d(\Xi_{cc}^{++}) \cdot \frac{\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X)$$

(The detection efficiency is identical to that of Ξ_{cc}^{++})

Three ingredients:

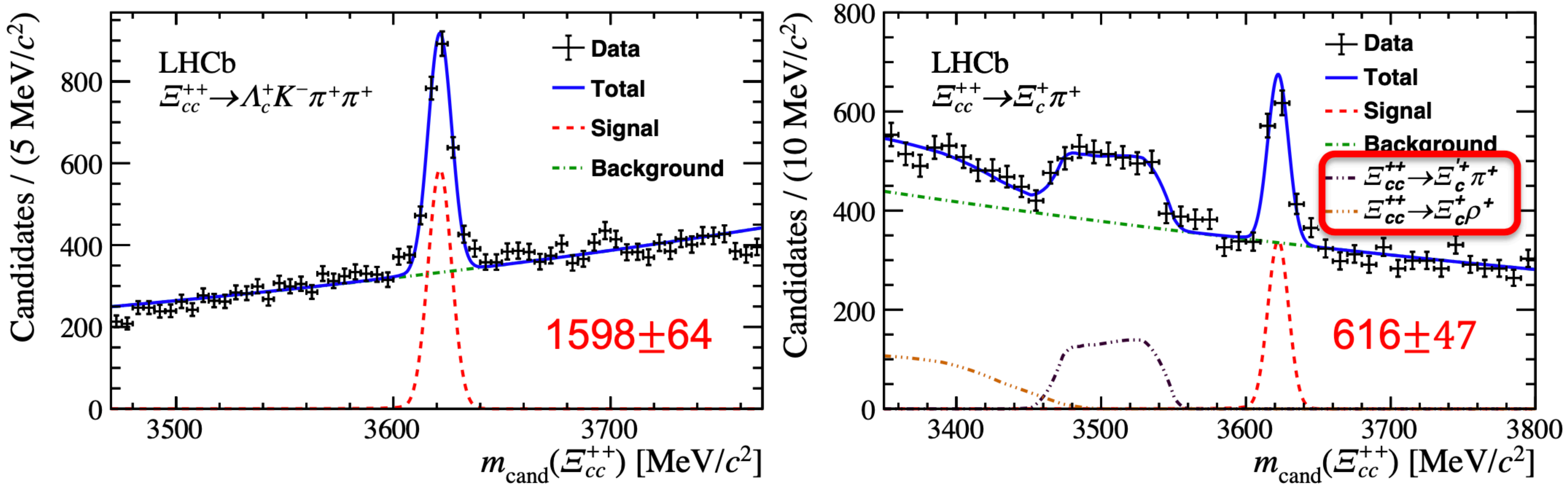
1. Number of signals of Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

3. Branching fraction of inclusive decay of $\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X$

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

1.Number of signals of Ξ_{cc}^{++}



J.B.He

- Data of 9 fb^{-1} Run 1+2

	2011	2012	2018	2023	2029	2035
LHCb	Run I		Run II	Run III	Run IV	Run V
Integrated luminosity	1 fb^{-1}	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

- Events estimated for 23 fb^{-1} (Run III)

$$\frac{7000}{1600} \times (1600 + 600) \approx 10000$$

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^{+} \to J/\psi\, \Xi_c^+$	50	100	600	—

Z.W.Yang

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

[X.G.Wu et al, 1101.1130]

TABLE VI. Comparison of the total cross section (in units nb) for the hadronic production of Ξ_{cc}, Ξ_{bc}, and Ξ_{bb} at $\sqrt{S} = 7.0$ TeV and $\sqrt{S} = 14.0$ TeV, where $[^3S_1]$ and $[^1S_0]$ stand for the combined results for the diquark in spin-triplet and spin-singlet states, respectively. In the calculations, we adopt $p_T > 4$ GeV and $|y| < 1.5$.

	Ξ_{cc}		Ξ_{bc}		Ξ_{bb}	
	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV	$\sqrt{S} = 7.0$ TeV	$\sqrt{S} = 14.0$ TeV
$[^3S_1]$	38.11	69.40	16.7	28.55	0.503	1.137
$[^1S_0]$	9.362	17.05	3.72	6.315	0.100	0.226
Total	47.47	86.45	20.42	34.87	0.603	1.363

$$\sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \approx 40\,\%$$

Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

- Final number of estimated signal events @ LHCb Run3

$$N(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X) = N(\Xi_{cc}^{++}) \cdot \frac{\sigma(\Xi_{bc}^{+})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X)$$

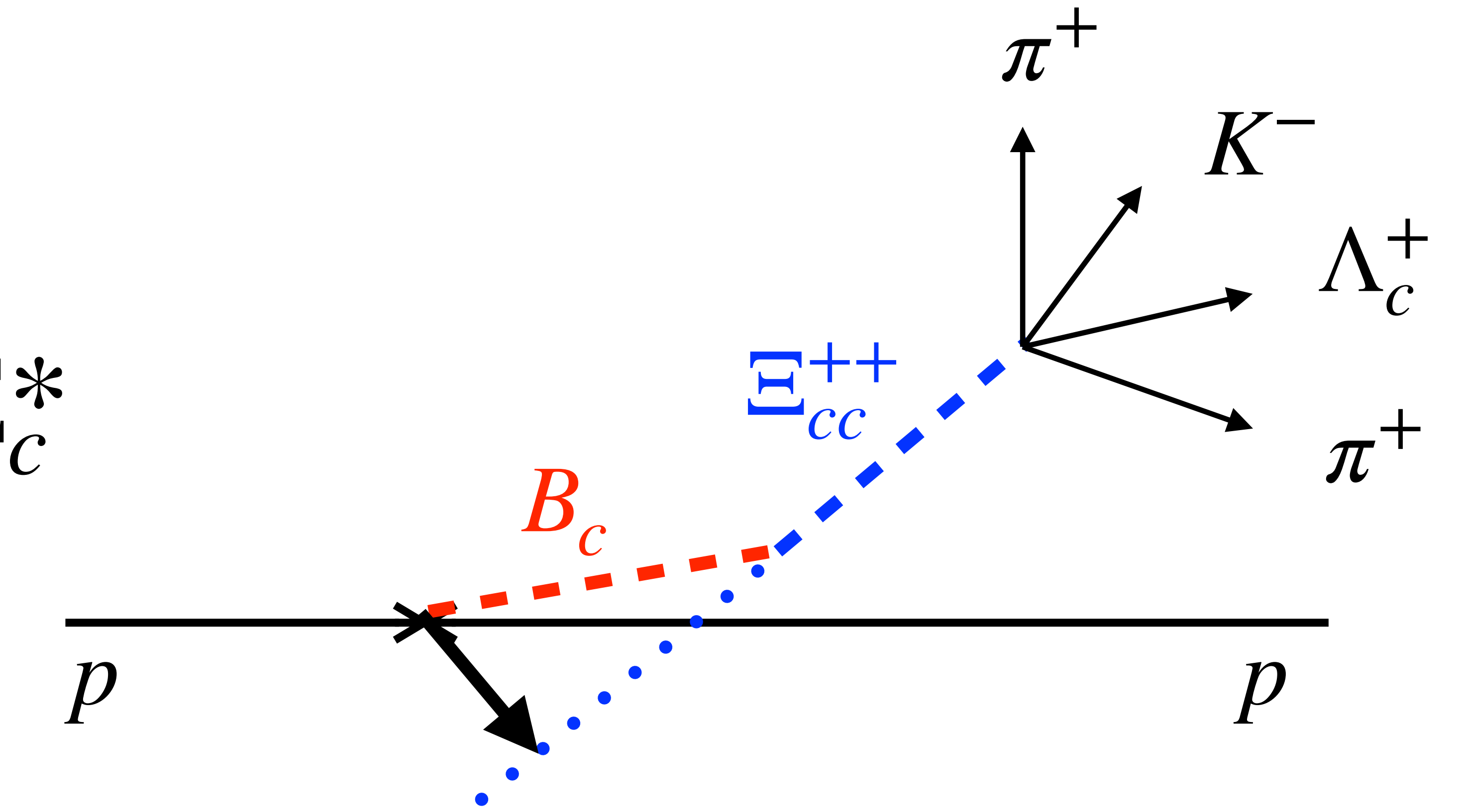
$$\approx 10^{4} \times 40\% \times 7\,\%$$

$$\approx 280$$

- With possible efficiency lost, it should still be detectable @ LHCb Run3

Small possibility from B_c decays

- The small phase space (0.18 GeV for $\Xi_{cc}\Xi_c$) only allows the processes of $B_c \to \Xi_{cc}\Xi_c$, or $\Xi_{cc}\Xi_c\gamma$, or $\Xi_{cc}\Xi_c\pi$, or $\Xi^*_{cc}\Xi_c$, or $\Xi_{cc}\Xi^*_c$

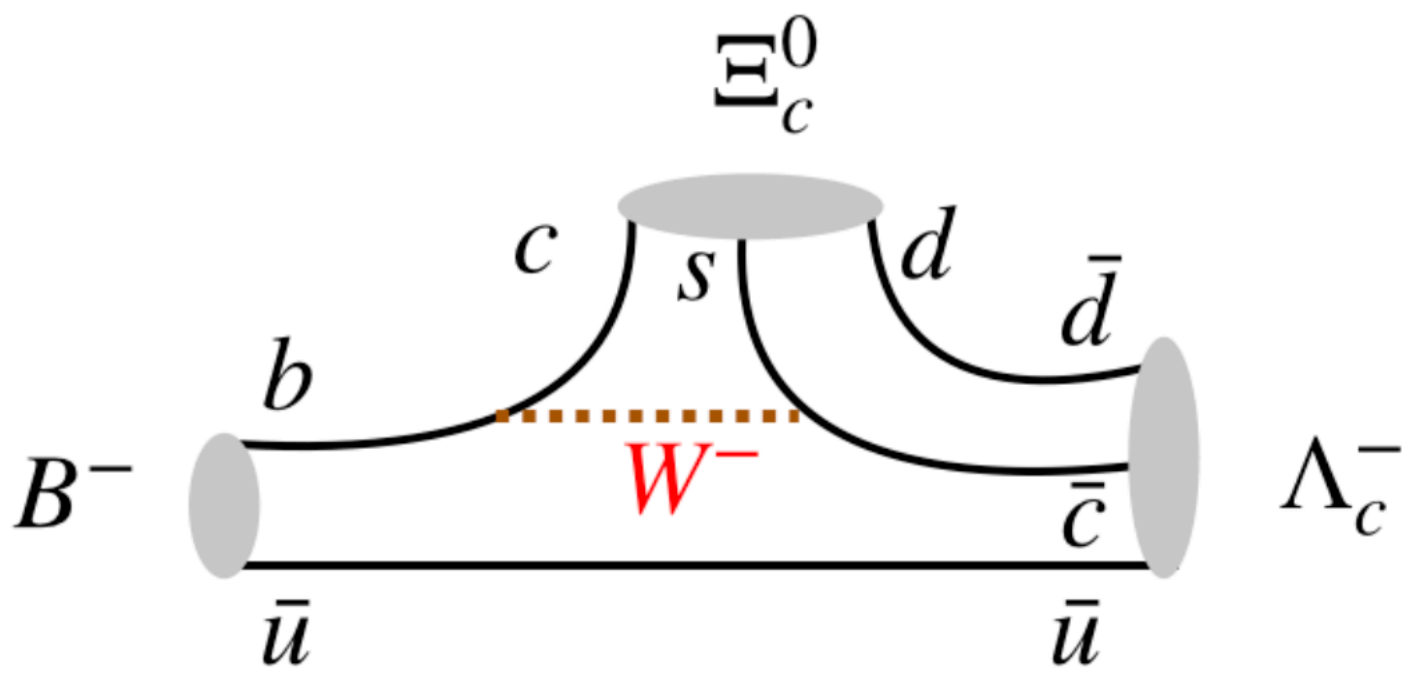


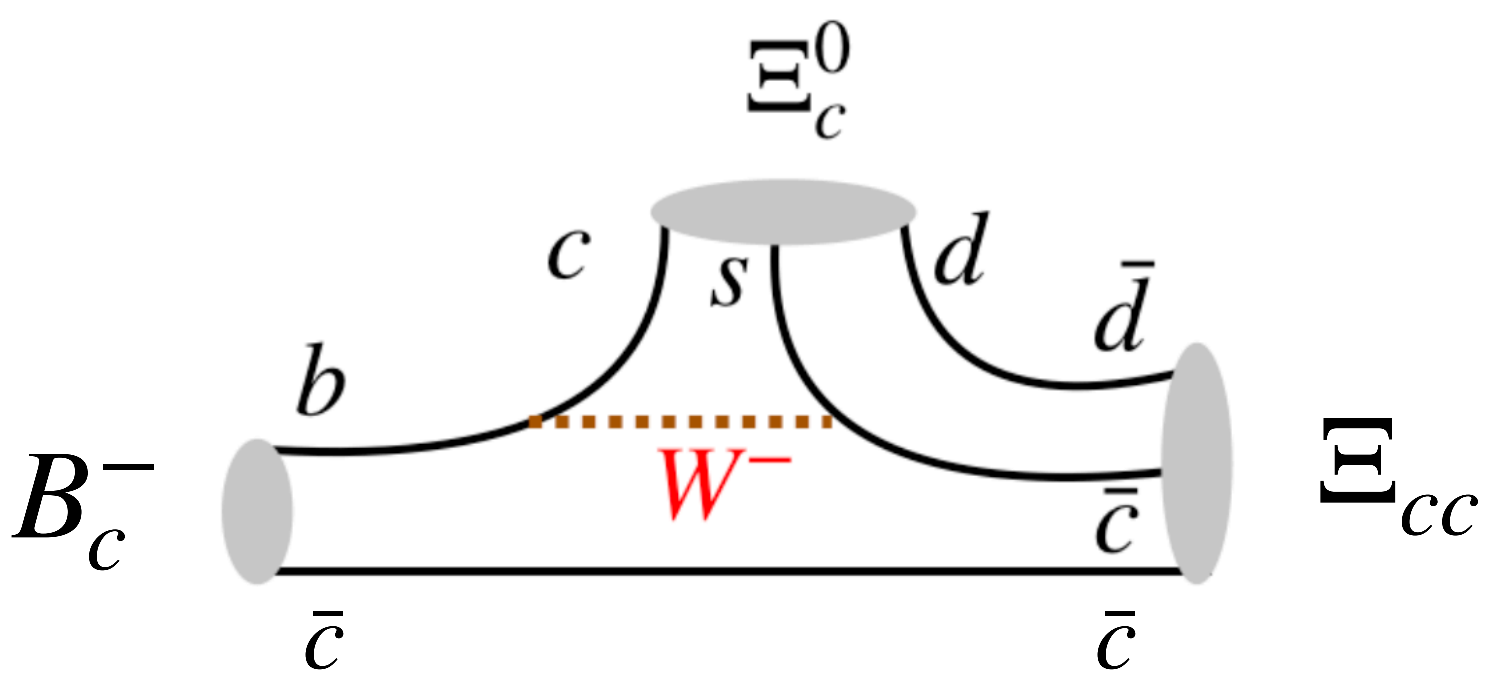
- Similar process but with a light spectator quark:

$$Br(B^0 \to \Xi_c^- \Lambda_c^+) = (1.2 \pm 0.8) \times 10^{-3}$$

$$Br(B^- \to \Xi_c^0 \Lambda_c^-) = (0.95 \pm 0.23) \times 10^{-3}$$

(0.5 GeV phase space)





Conclusion

- We propose to search for Ξ_{bc} via inclusive $\Xi_{bc}^{+} \to \Xi_{cc}^{++} + X$ with a displaced Ξ_{cc}^{++}.

- We calculate $\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (1.9 \pm 0.1 \pm 0.3 \pm 0.4) \times 10^{-13}$ GeV.

- We estimate about 280 signal events to be observed @ LHCb Run 3.

- We hope it is useful.

Thank you!