

Inclusive search for Ξ_{bc}

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Contents

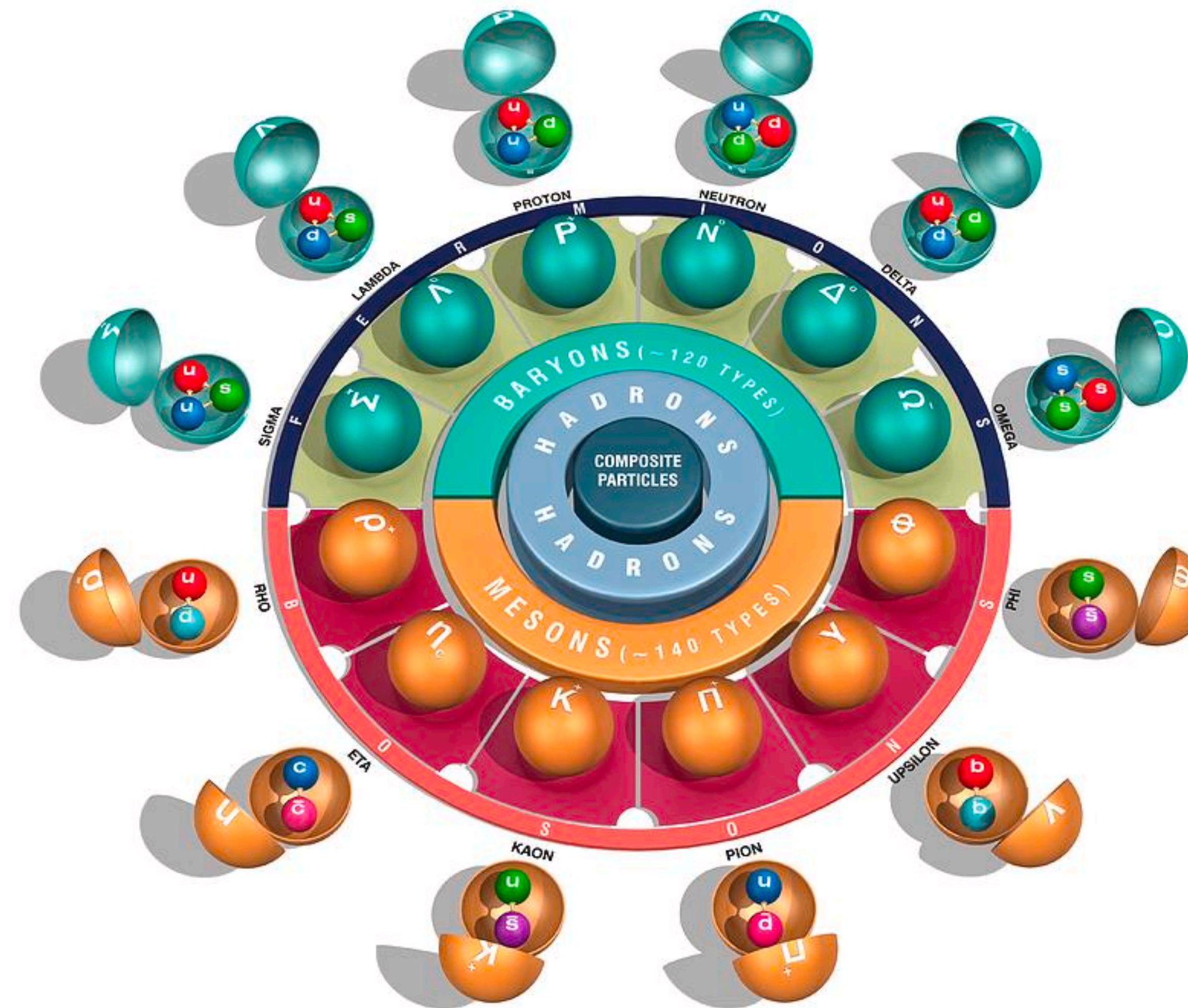
- It is important to study Ξ_{bc}
- We propose an inclusive approach to find Ξ_{bc}
- We will show it is feasible and timely for LHCb

The quark model

- Old myth
- New life



Murray 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”

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	

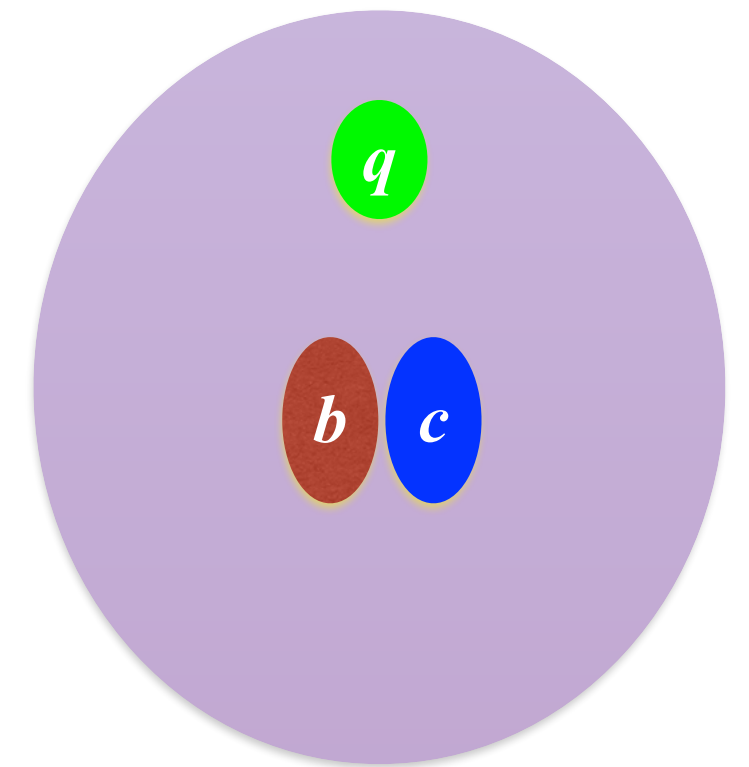
π, K, \dots	D	B	η_c	B_c	η_b				
p, n, ...	Λ_c	Λ_b				Ξ_{cc}	Ξ_{bc}	Ξ_{bb}	
	$X_{(2900)}$		Z_c			T_{cc}	T_{bc}	T_{bb}	$X_{(6900)}$
			P_c						

Z_c, P_c : a new period

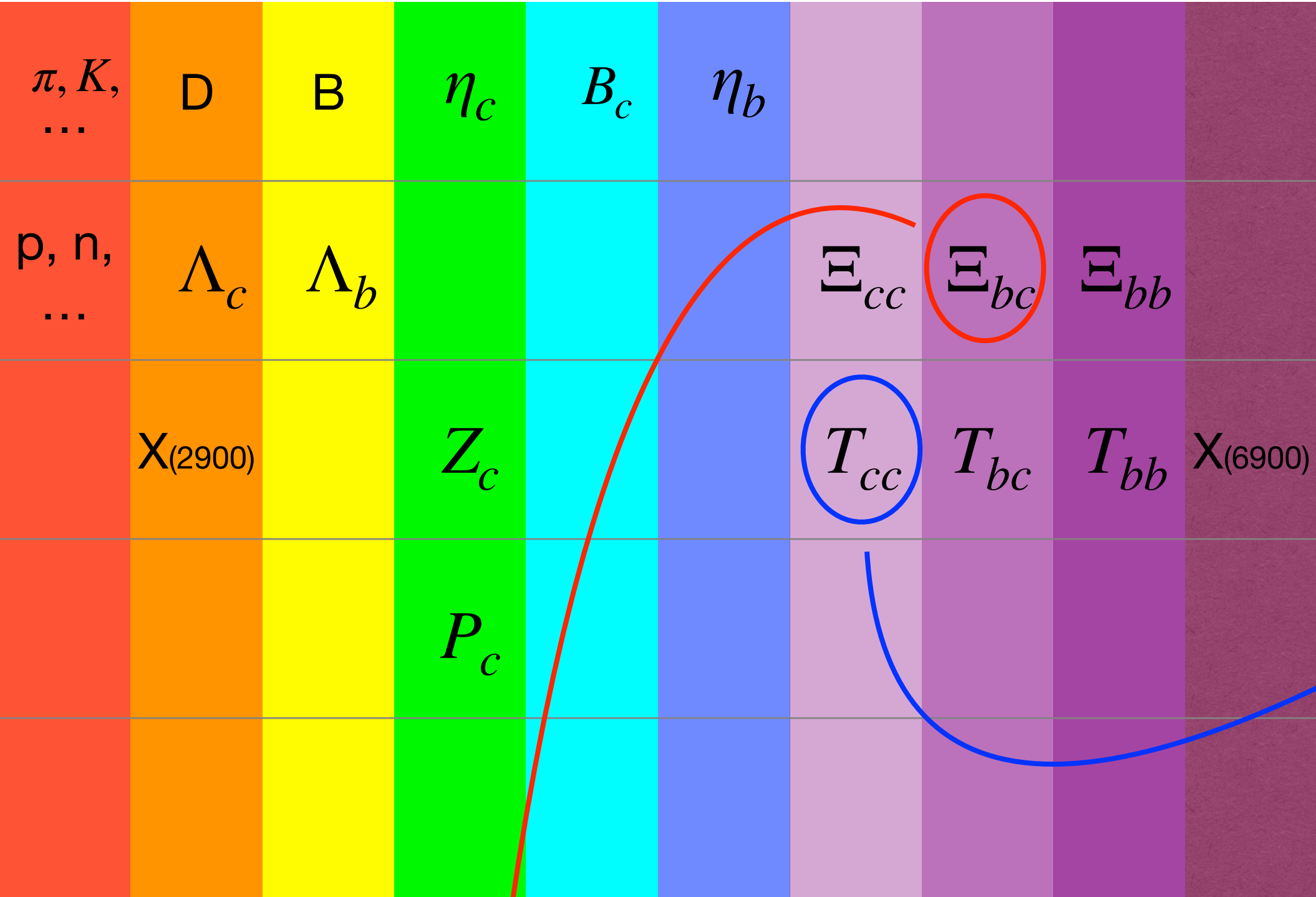
$\Xi_{cc}, X_{(6900)}$: a new main group

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?



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]

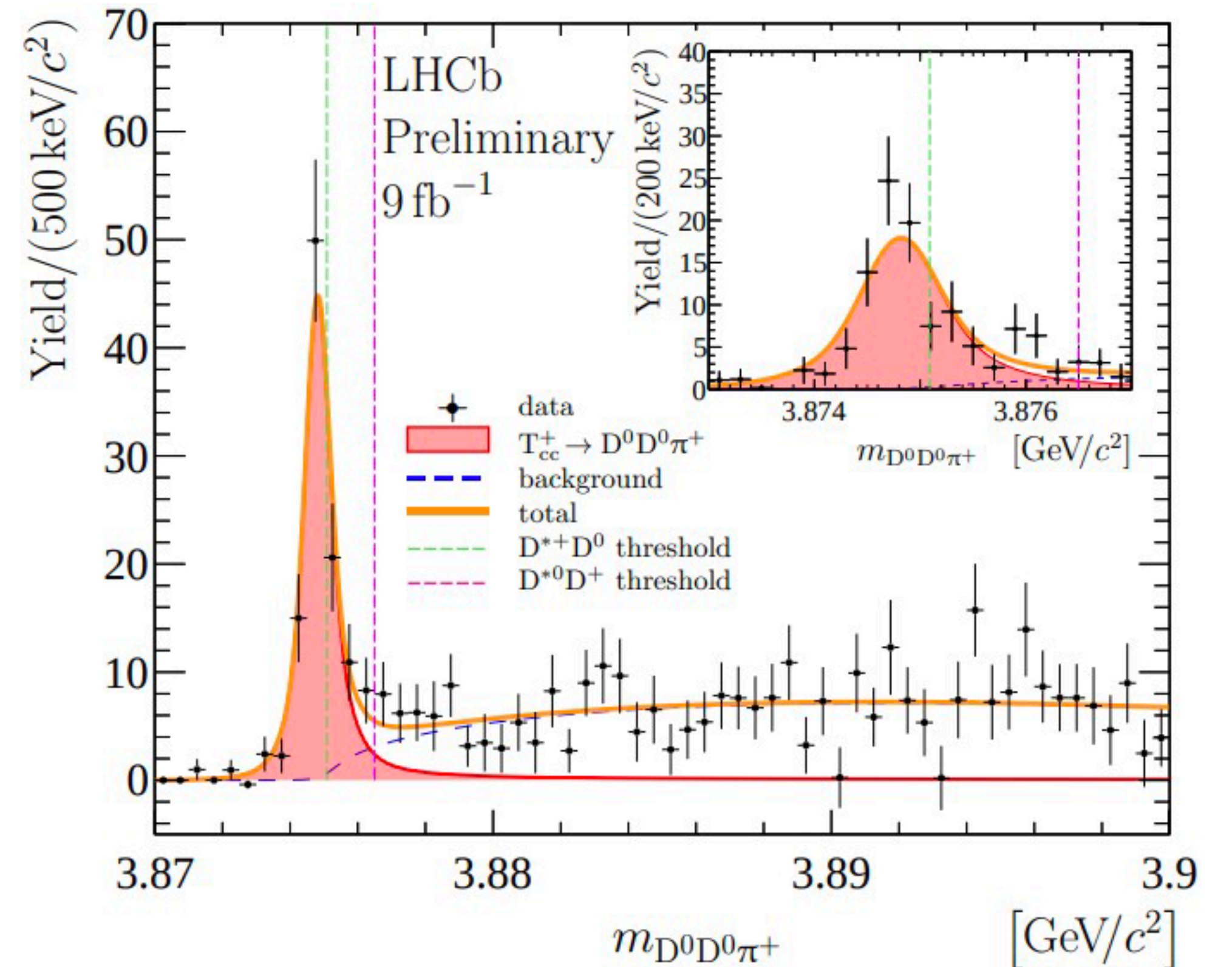
$$N_s = 117 \pm 16$$

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 $T_{[\bar{u}\bar{d}]}^{\{cc\}} \rightarrow D^+ K^- \pi^+$ 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]

Who is to be shot next?

π, 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}
			P_c					

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

[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

- First experimental attempts

(LHCb, 13 TeV, $\sim 5 \text{ fb}^{-1}$)

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

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

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

[LHCb, 2009.02481]

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \rightarrow \Lambda_c^+ \pi^-)}{B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} < [0.6, 3] \times 10^{-4}$$

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

[LHCb, 2104.04759]

A novel approach — — inclusive Ξ_{bc} search

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

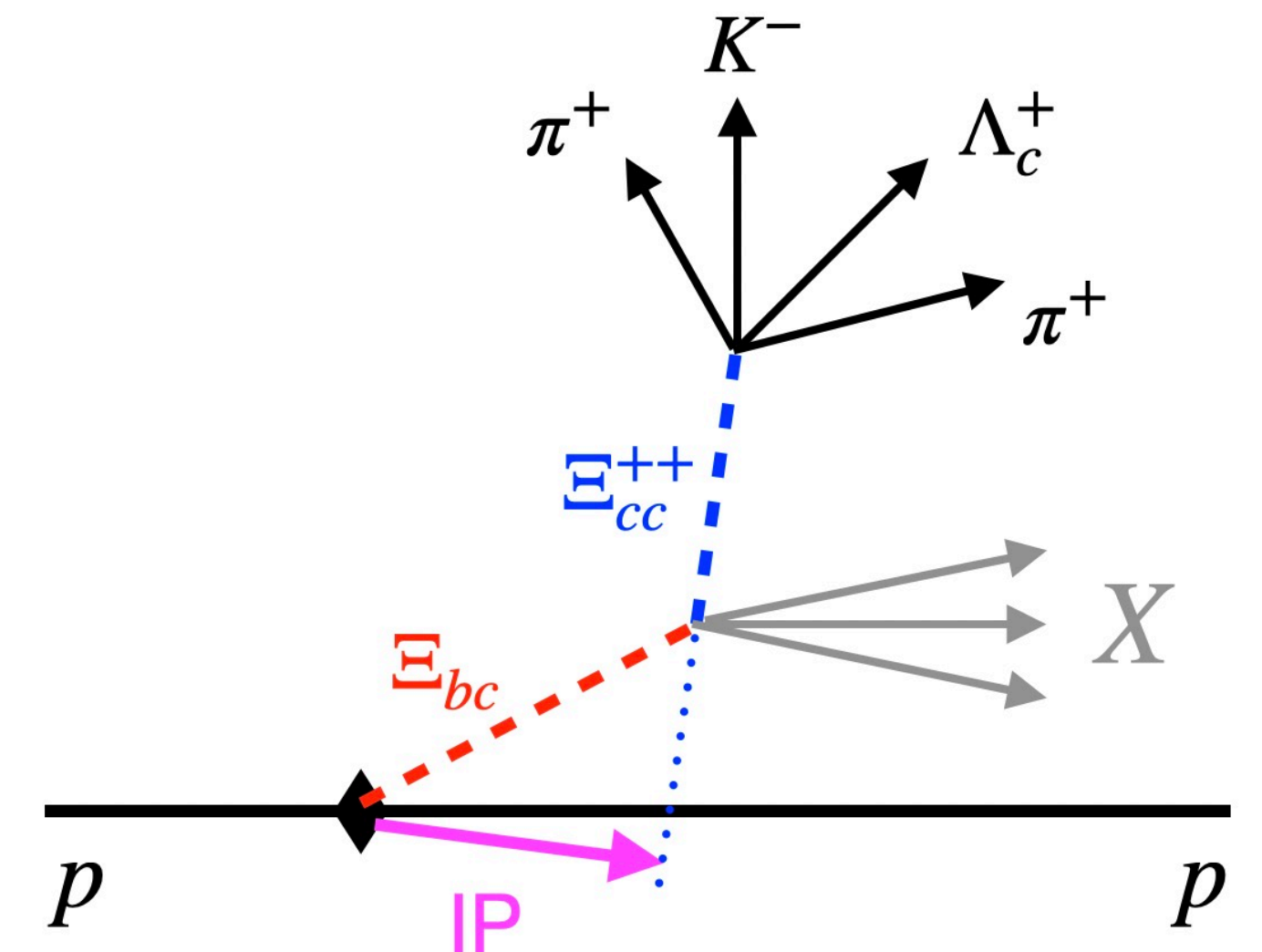
Basically impossible at hadron colliders

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

Inspired by the proposal to search for Ξ_{bb} via $\Xi_{bb} \rightarrow B_c + X$

[Gershon, Poluektov, 1810.06657]

- Ξ_{bc} is (almost) the only source for displaced Ξ_{cc} 's
- The $B_c \rightarrow \Xi_{cc}^{++} + X$ decay is highly suppressed



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

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

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

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

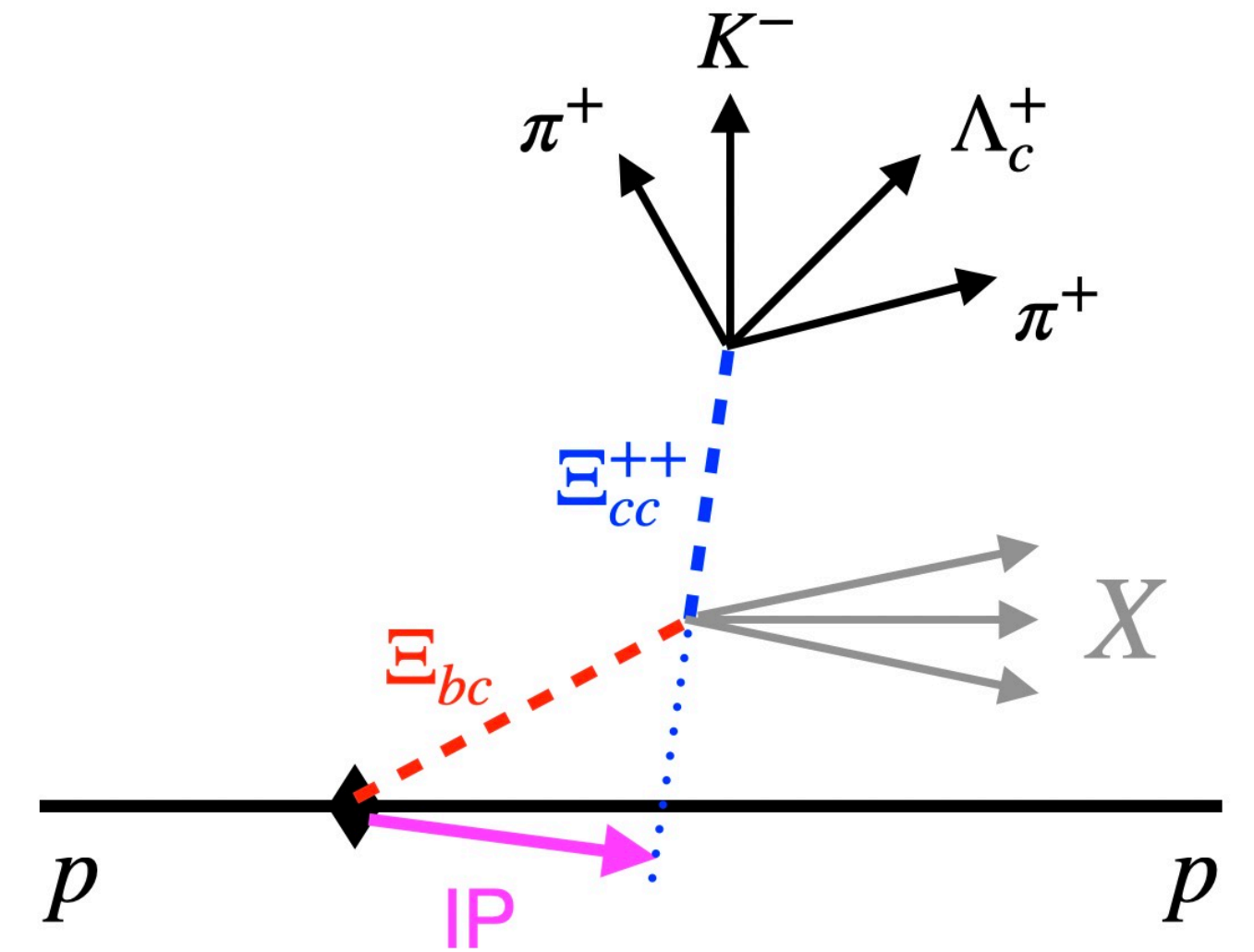
It is reasonable because $r_{QQ'} \sim 1/(m_Q v) \ll 1/\Lambda_{\text{QCD}}$ [e.g., Brodsky, Guo, Hanhart, Meissner, 1101.1983]

- 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

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

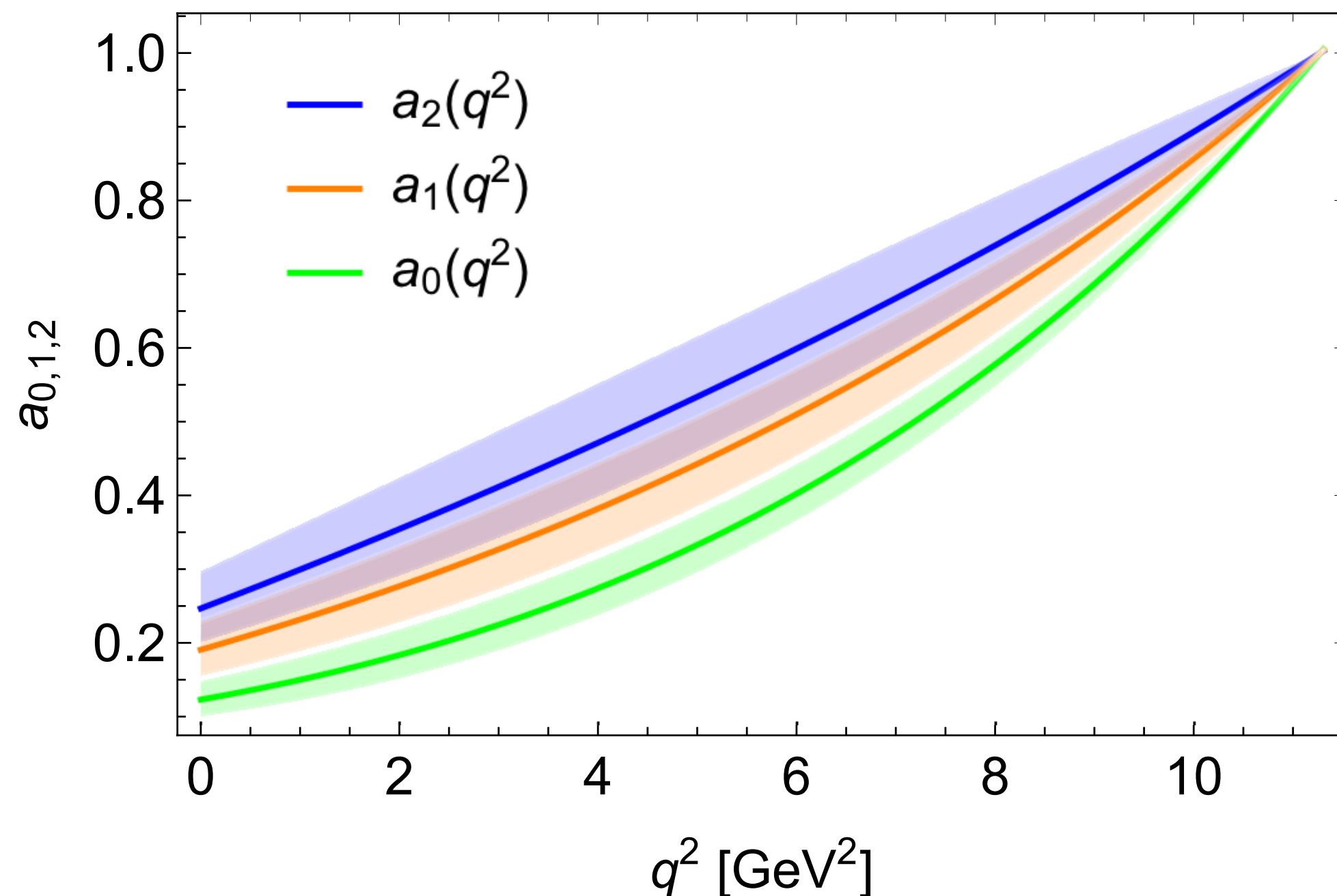
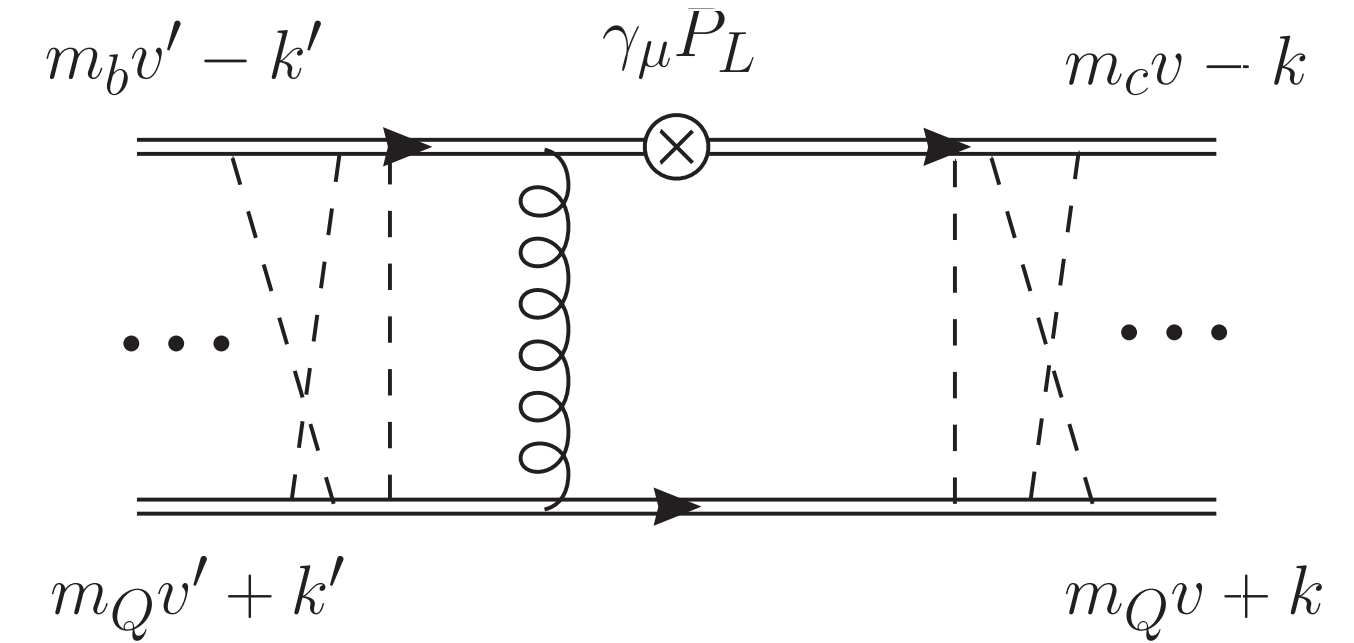


Calculation of $\Xi_{bc} \rightarrow \Xi_{cc} + X$

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

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

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

- Numerical result for the decay width

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

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

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

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

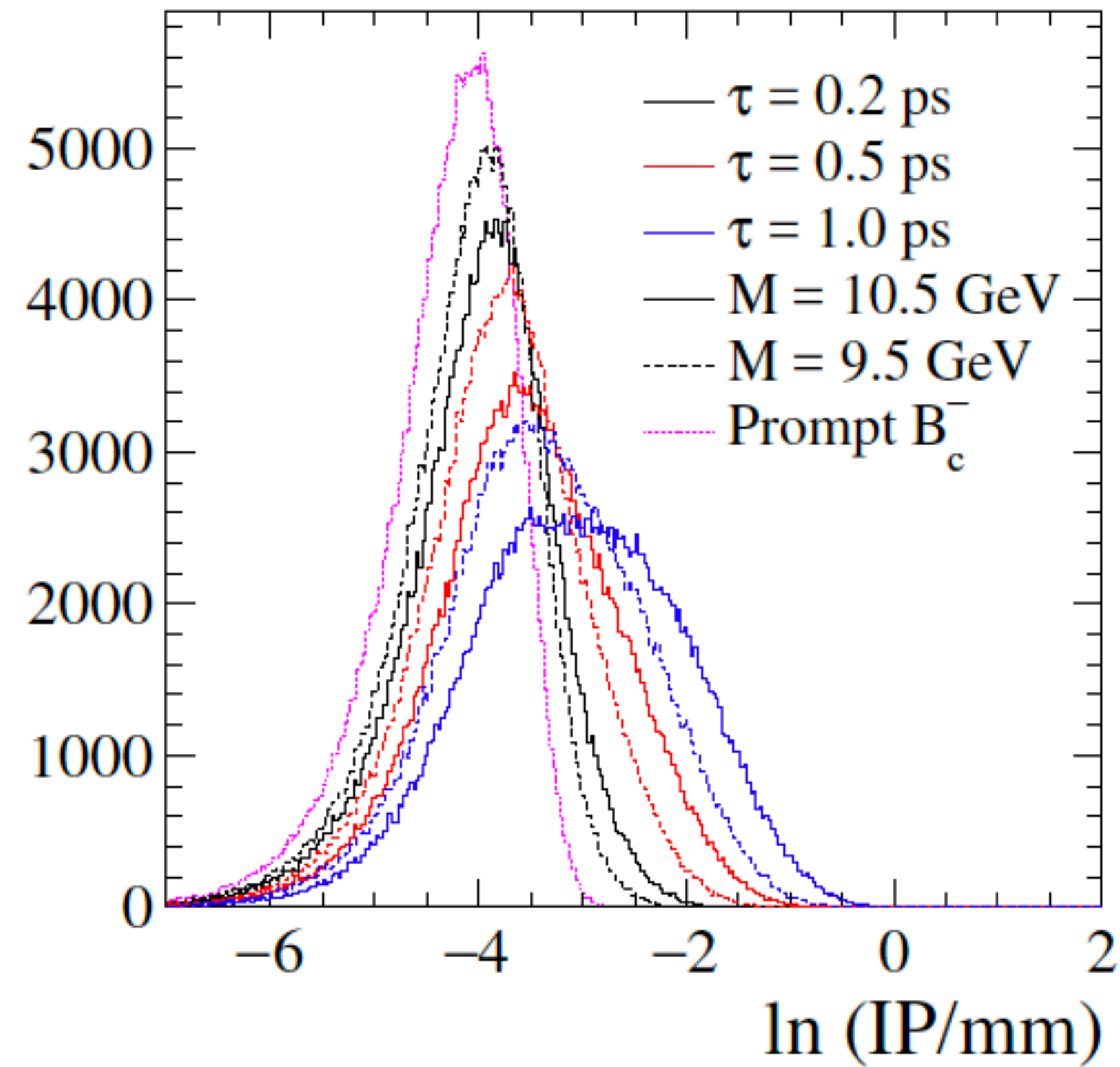
- The branching ratio is

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

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

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

IP resolution of LHCb



[Gershon, Poluektov, 1810.06657]

- Ξ_{bc}^+ is very promising.

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

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

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

- Estimated of signal signal events

$$\begin{aligned} N(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) &= N_p(\Xi_{bc}^+) \cdot B(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) \cdot \epsilon(\Xi_{cc}^{++}) \\ &= N_d(\Xi_{cc}^{++}) \cdot \frac{\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) \end{aligned}$$

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

Three ingredients:

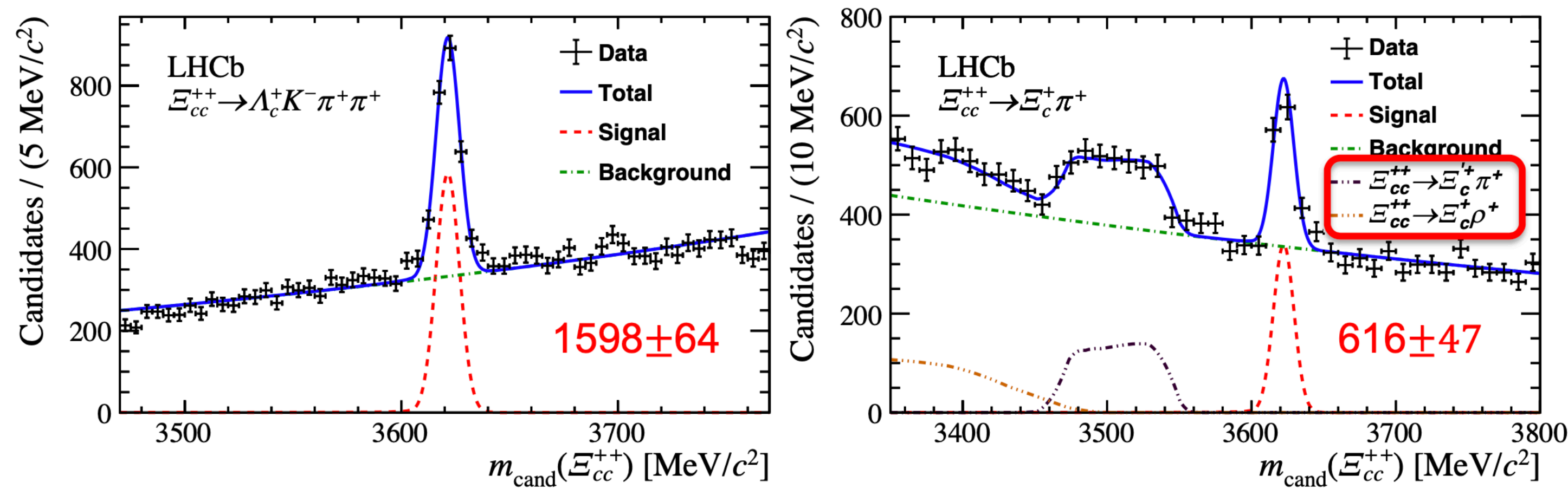
1. Number of signals of Ξ_{cc}^{++}

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

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

Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ 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	23 fb ⁻¹	LHCb		Belle II
		50 fb ⁻¹	300 fb ⁻¹	50 ab ⁻¹
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$	50	100	600	—

Z.W.Yang

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

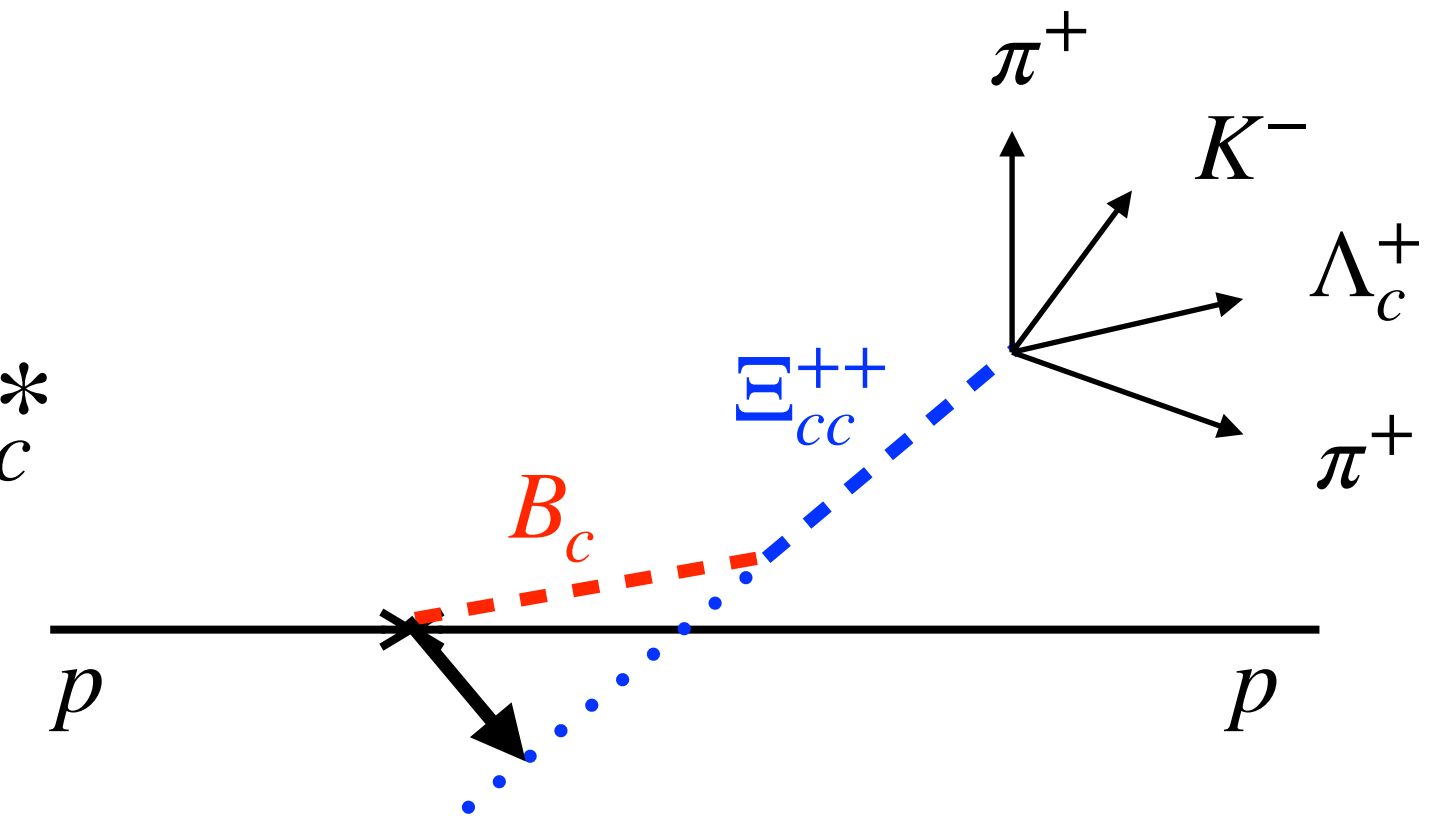
- Final number of estimated signal events @ LHCb Run3

$$\begin{aligned} N(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) &= N(\Xi_{cc}^{++}) \cdot \frac{\sigma(\Xi_{bc}^+)}{\sigma(\Xi_{cc}^{++})} \cdot B(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) \\ &\approx 10^4 \times 40\% \times 7\% \\ &\approx 280 \end{aligned}$$

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

Small possibility from B_c decays

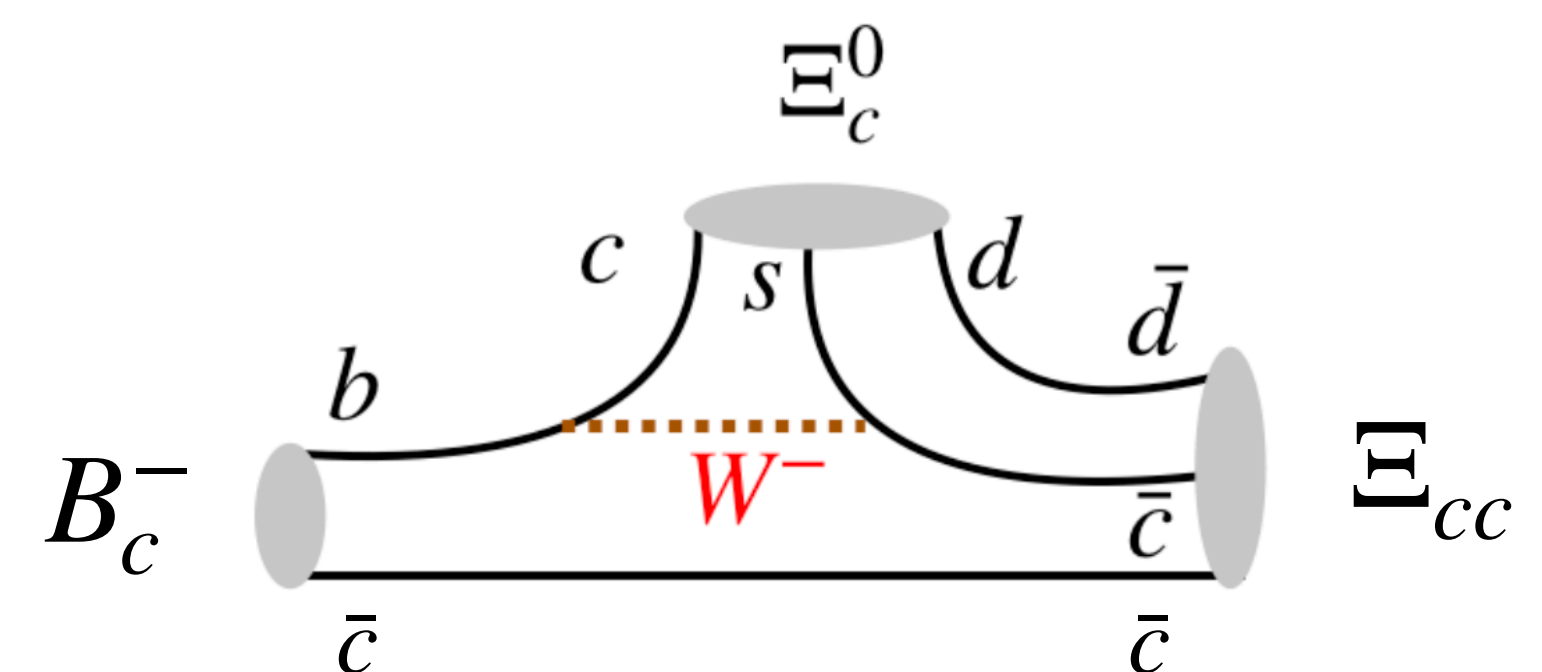
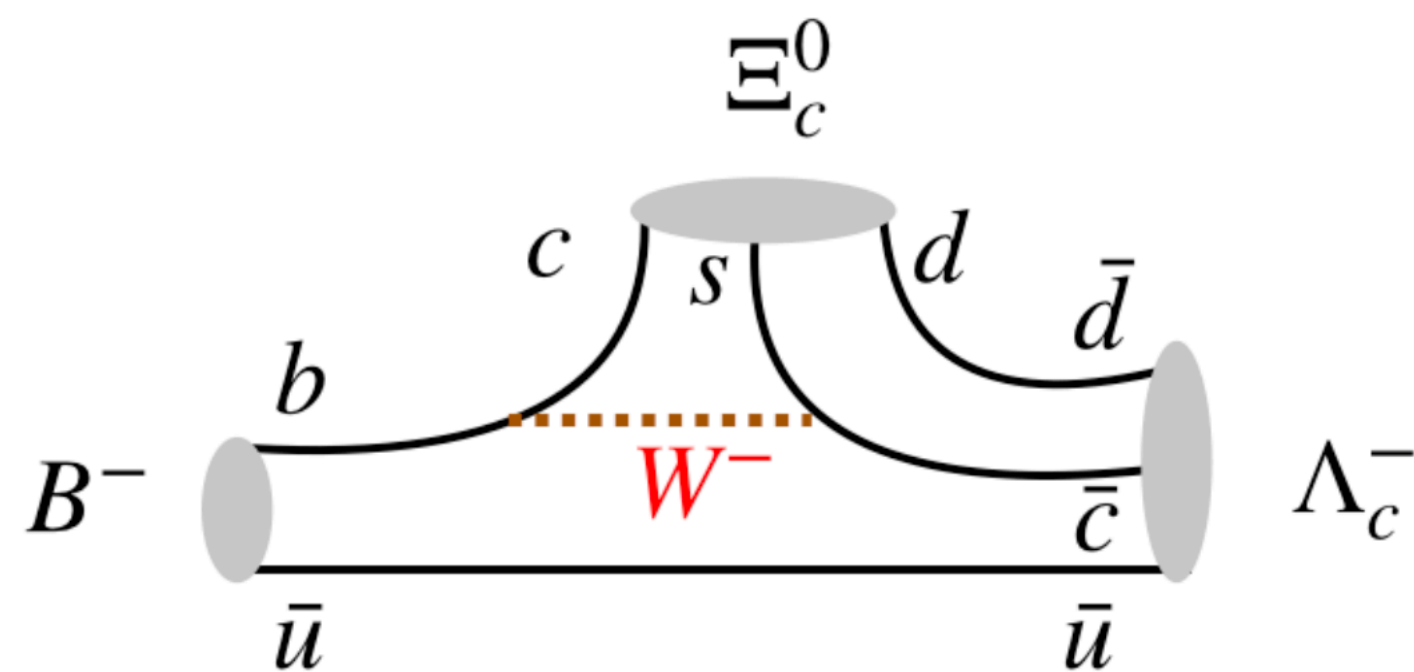
- The **small phase space** (0.18 GeV for $\Xi_{cc}\Xi_c$) only allows the processes of $B_c \rightarrow \Xi_{cc}\Xi_c$, or $\Xi_{cc}\Xi_c\gamma$, or $\Xi_{cc}\Xi_c\pi$, or $\Xi_{cc}^*\Xi_c$, or $\Xi_{cc}\Xi_c^*$
- Similar process but with a light spectator quark:



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

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

(0.5 GeV phase space)



Conclusion

- We propose to search for Ξ_{bc} via **inclusive** $\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X$ with a **displaced** Ξ_{cc}^{++} .
- We calculate $\Gamma(\Xi_{bc} \rightarrow \Xi_{cc} + X) = (1.9 \pm 0.1 \pm 0.3 \pm 0.4) \times 10^{-13}$ GeV.
- We estimate about **280** signal events to be observed @ LHCb Run 3.
- We hope it is useful.

Thank you!