Inclusive search for Ξ_{bc}

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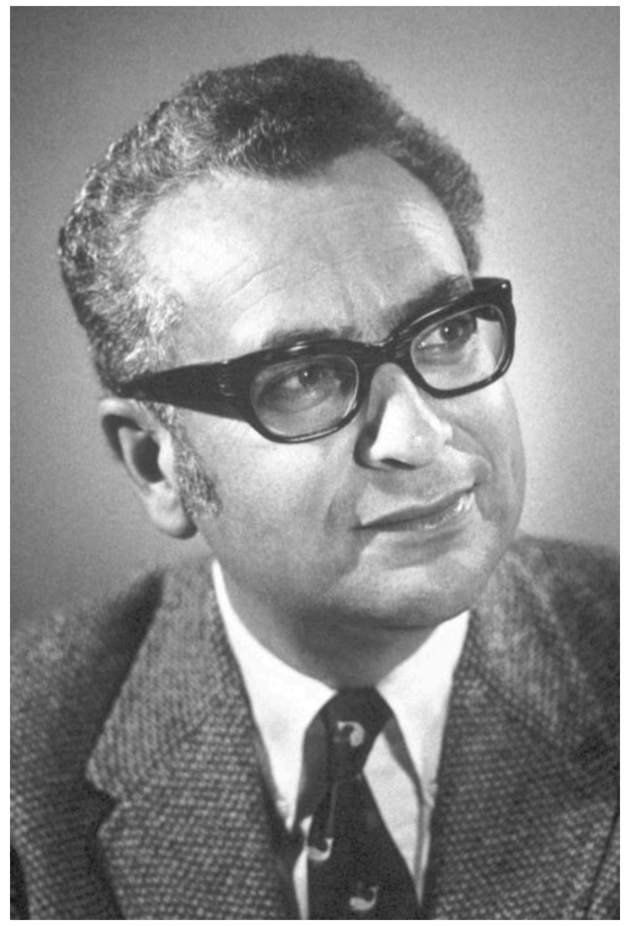
Contents

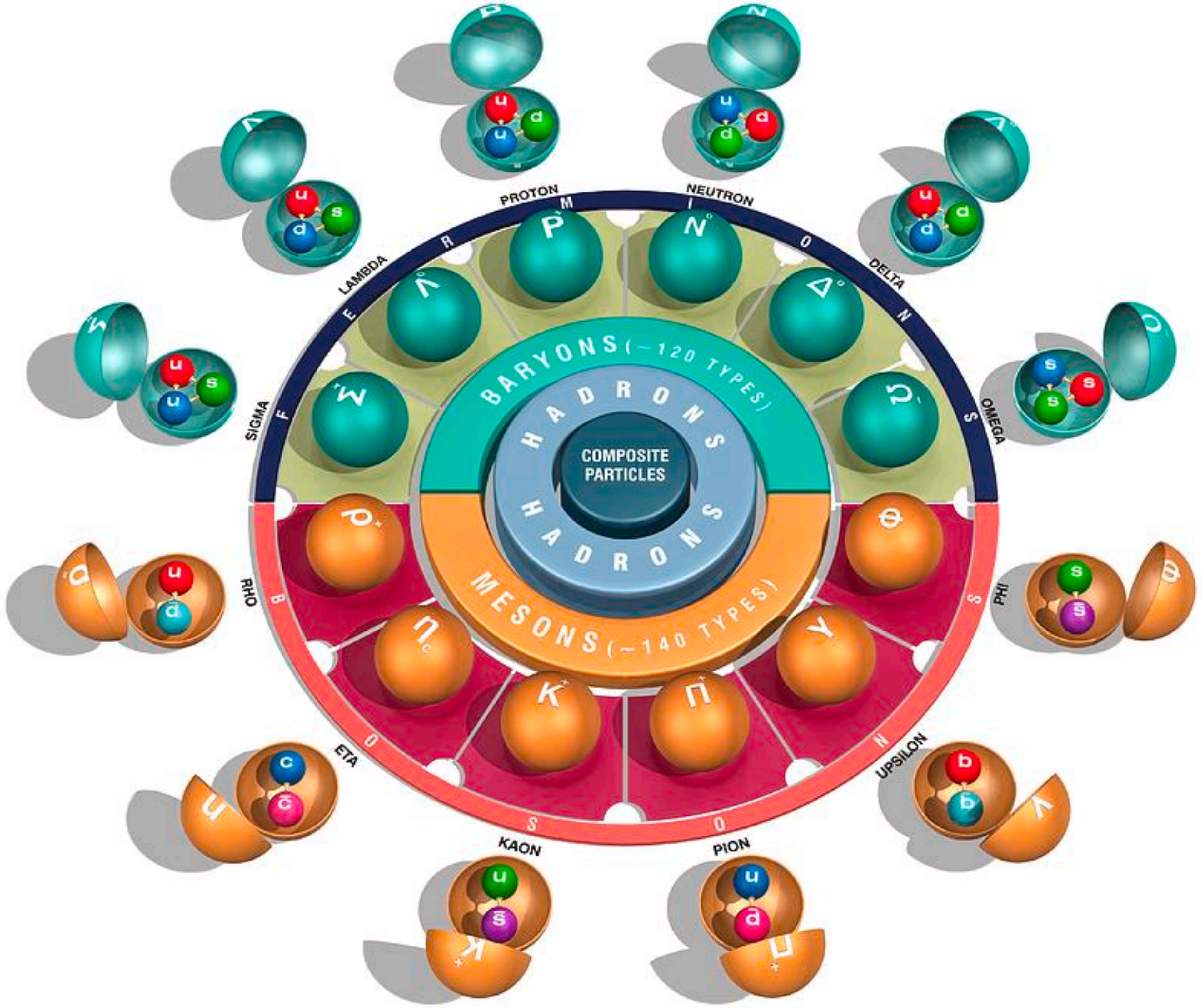
- It is important to study Ξ_{bc}
- We propose a inclusive strategy to find Ξ_{bc}
- We will show it is reachable at LHCb

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]

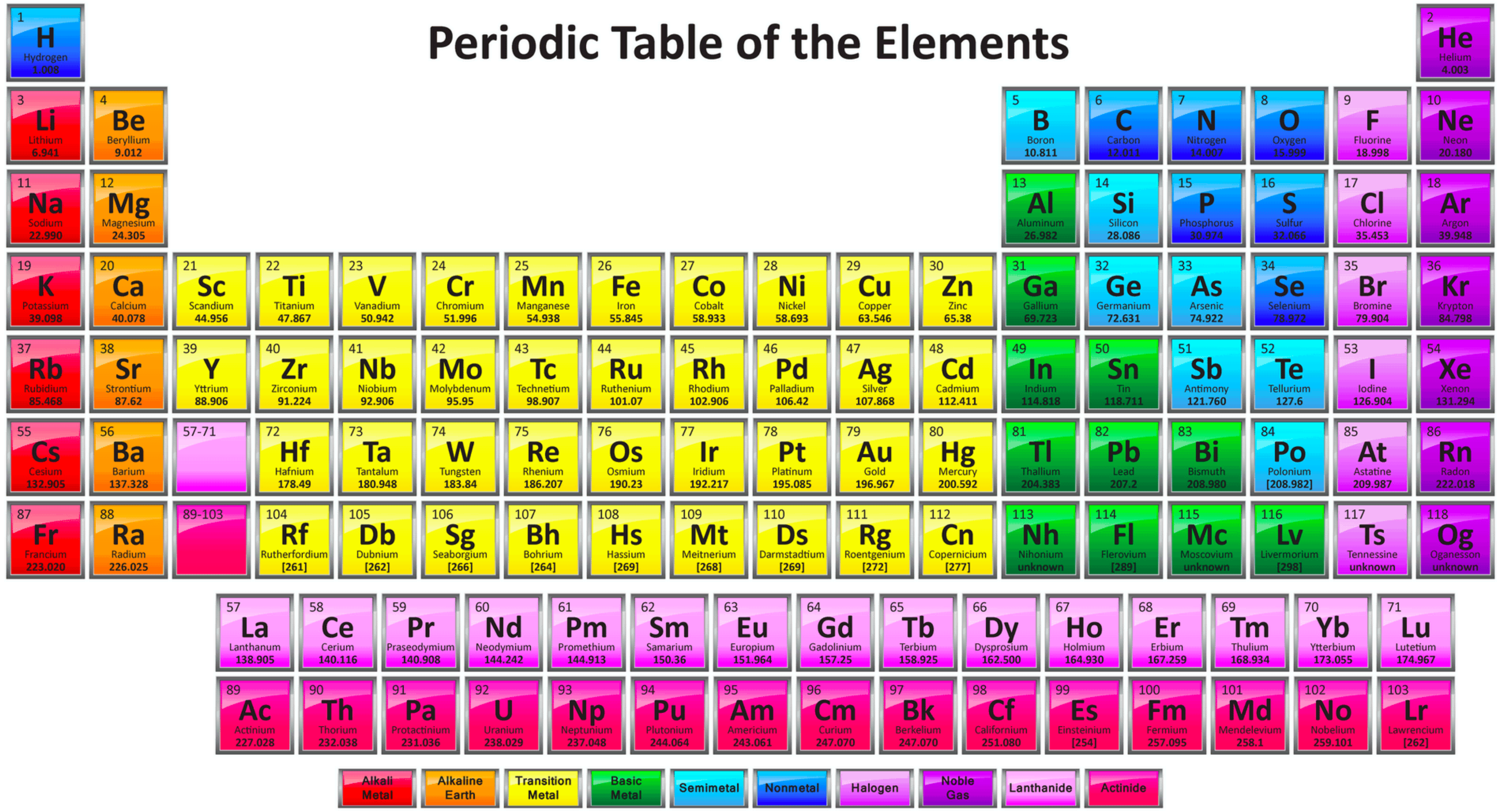
  The ***Physics World*** 2015 “top-10 breakthroughs”

- 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”



$\pi, K, \dots$	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}
			P_c					

Z_c, P_c: a new period

Ξ_{cc}: a new main group

Beyond stamp collecting

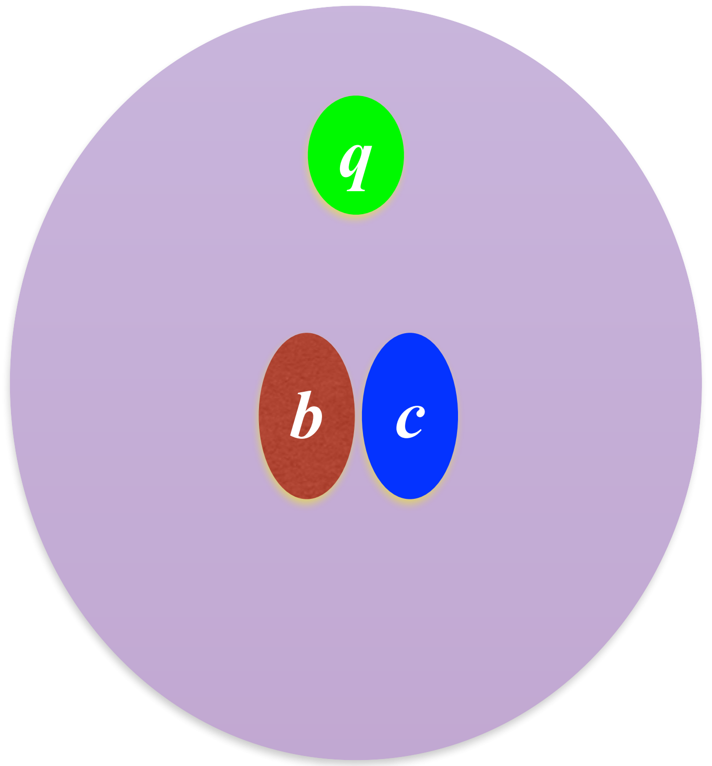
- Because of color confinement, properties of quarks are studied via hadrons

See Prof. Xiang Liu's talk

- Different types of hadrons provide different visual angles into QCD and also electroweak dynamics

  e.g., doubly-heavy baryons have a unique structure, a bound state of a heavy 'diquark' and a light quark

  analogous to a heavy meson, but also different: bosonic, sizable heavy element



  e.g., the double-bottom tetraquark $T^{\{bb\}}_{[qq']}$ is expected to be below threshold and thus decay weakly

  [Eichten,Quigg,1707.09575]

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

- Production rate
- Detection efficiency —— small exclusive branching ratios

channels	$\Gamma/$ GeV	$\mathcal{B}$	channels	$\Gamma/$ GeV	$\mathcal{B}$
$\Xi_{bc}^{+}\to\Lambda_b^0\pi^+$	5.74×10^{-15}	2.13×10^{-3}	$\Xi_{bc}^{+}\to\Lambda_b^0\rho^+$	1.55×10^{-14}	5.77×10^{-3}
$\Xi_{bc}^{+}\to\Lambda_b^0 a_1^+$	5.85×10^{-15}	2.17×10^{-3}	$\Xi_{bc}^{+}\to\Lambda_b^0 K^+$	5.21×10^{-16}	1.93×10^{-4}
$\Xi_{bc}^{+}\to\Lambda_b^0 K^{*+}$	7.32×10^{-16}	2.71×10^{-4}			
$\Xi_{bc}^{+}\to\Sigma_b^0\pi^+$	3.08×10^{-15}	1.14×10^{-3}	$\Xi_{bc}^{+}\to\Sigma_b^0\rho^+$	1.30×10^{-14}	4.81×10^{-3}
$\Xi_{bc}^{+}\to\Sigma_b^0 K^{*+}$	6.50×10^{-16}	2.41×10^{-4}	$\Xi_{bc}^{+}\to\Sigma_b^0 K^+$	2.32×10^{-16}	8.62×10^{-5}
$\Xi_{bc}^{+}\to\Xi_b^0\pi^+$	9.42×10^{-14}	3.49×10^{-2}	$\Xi_{bc}^{+}\to\Xi_b^0\rho^+$	1.91×10^{-13}	7.09×10^{-2}
$\Xi_{bc}^{+}\to\Xi_b^0 K^{*+}$	7.55×10^{-15}	2.80×10^{-3}	$\Xi_{bc}^{+}\to\Xi_b^0 K^+$	8.16×10^{-15}	3.03×10^{-3}
$\Xi_{bc}^{+}\to\Xi_b^{\prime 0}\pi^+$	5.47×10^{-14}	2.03×10^{-2}	$\Xi_{bc}^{+}\to\Xi_b^{\prime 0}\rho^+$	2.01×10^{-13}	7.44×10^{-2}
$\Xi_{bc}^{+}\to\Xi_b^{\prime 0} K^{*+}$	8.53×10^{-15}	3.16×10^{-3}	$\Xi_{bc}^{+}\to\Xi_b^{\prime 0} K^+$	3.82×10^{-15}	1.42×10^{-3}

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

- First experimental attempt

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)}\frac{B(\Xi_{bc}^0\to\Lambda_c^+\pi^-)}{B(\Lambda_b^0\to\Lambda_c^+\pi^-)} < [0.5,2.5]\times10^{-4}$$

$$\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)}\frac{B(\Xi_{bc}^0\to\Xi_c^+\pi^-)}{B(\Lambda_b^0\to\Xi_c^+\pi^-)} < [1.4,6.9]\times10^{-3}$$

[LHCb, 2104.04759]

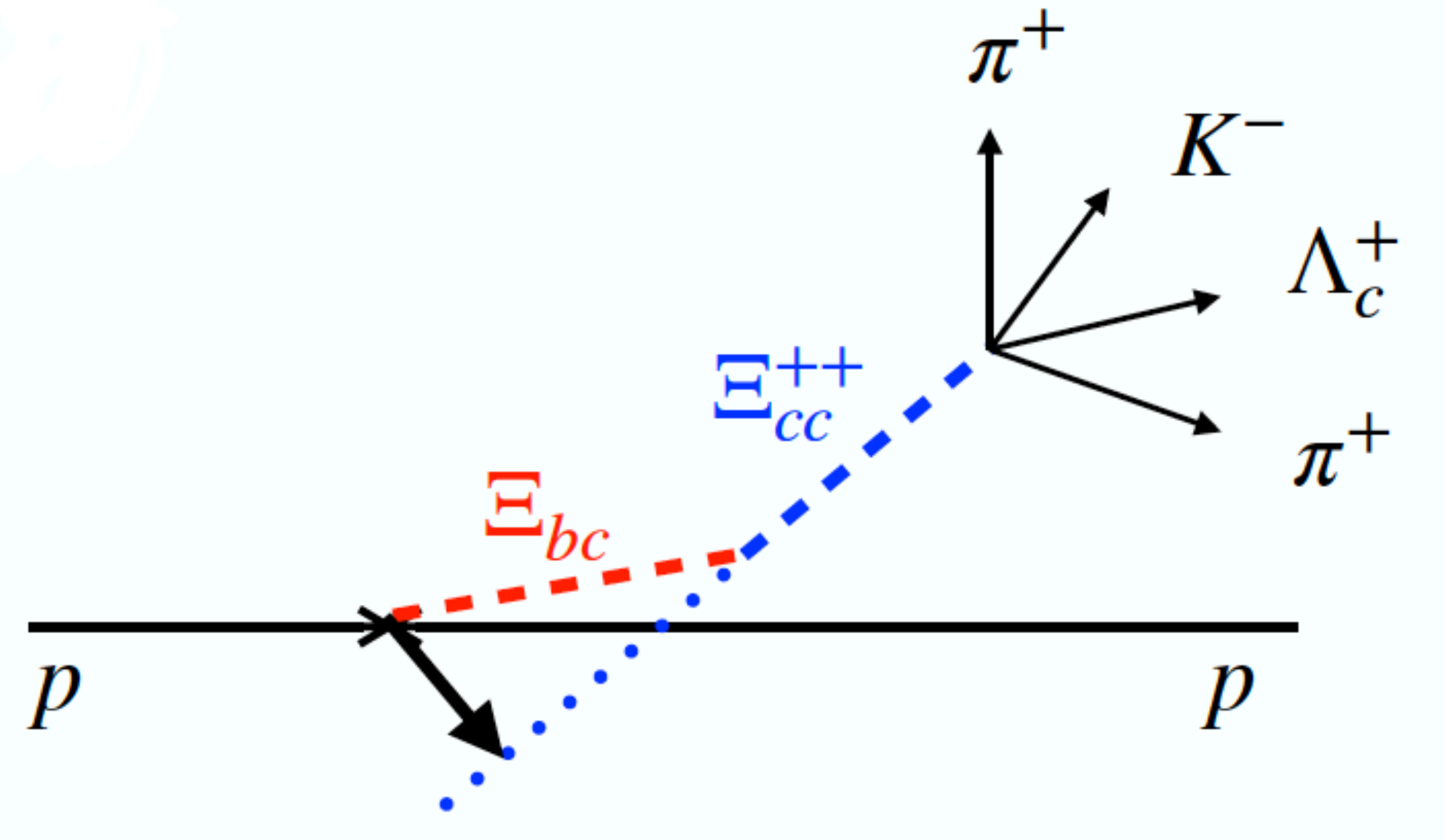
See Prof. Yuehong Xie's talk

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

See Prof. Xiaolong Wang's talk



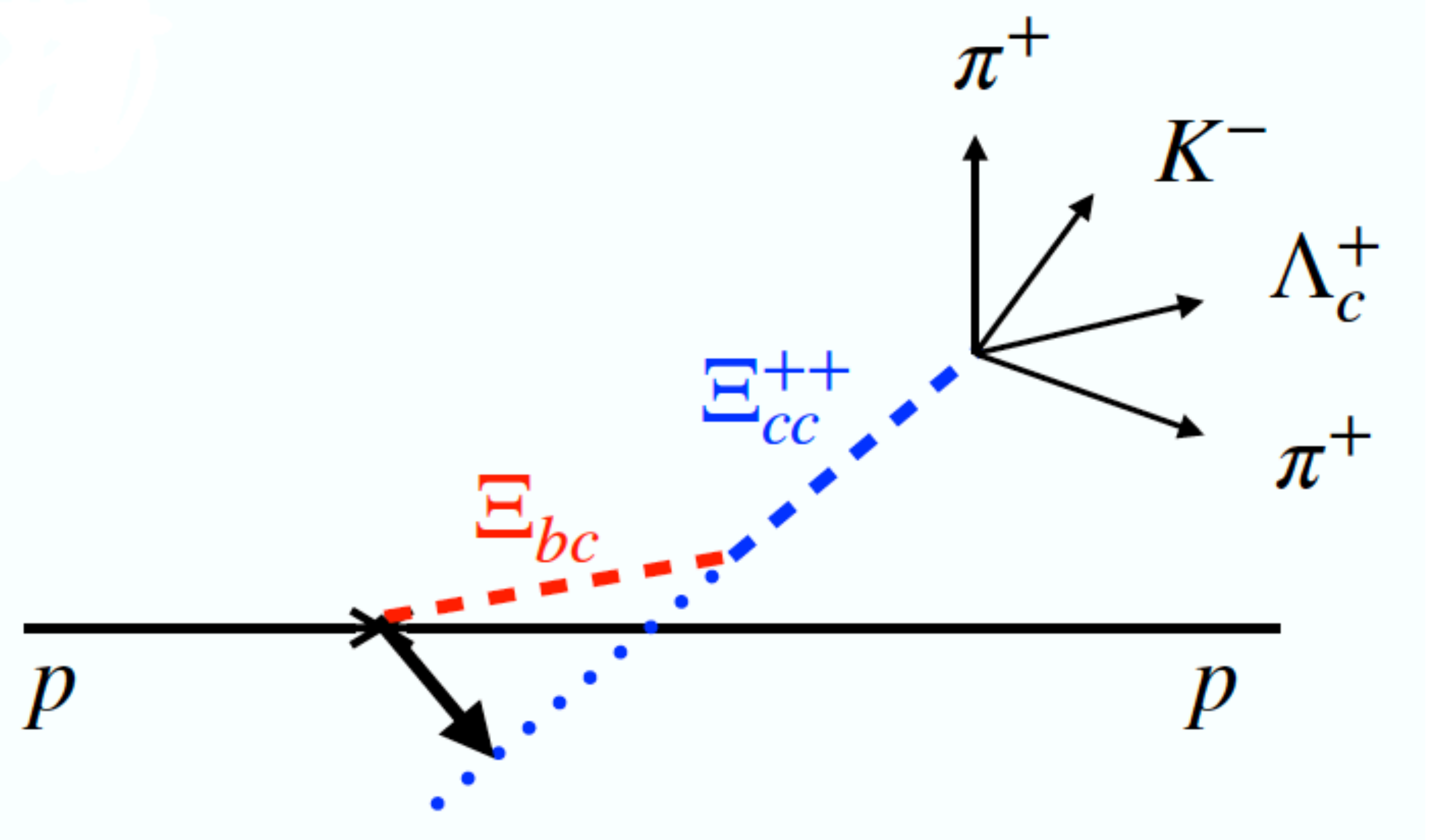
- However, for $\Xi_{bc} \to \Xi_{cc} + X$, the efficiency can be large by making use of the inform of displaced vertex, because Ξ_{bc} can only decay weakly

  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: $\Xi_{bc} \to \Xi_{cc} + X$ = $\Xi_{bc} \to X_{cc}$

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

- If we regard the heavy diquarks χ_{bc} and χ_{cc} as elementary objects, 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 $r_{QQ'} \sim 1/(m_Q v) \ll 1/\Lambda_{\text{QCD}}$ [e.g.,Brodsky,Guo,Hanhart,Meissner,1101.1983]

- By making use of OPE, the inclusive decay width can be 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

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

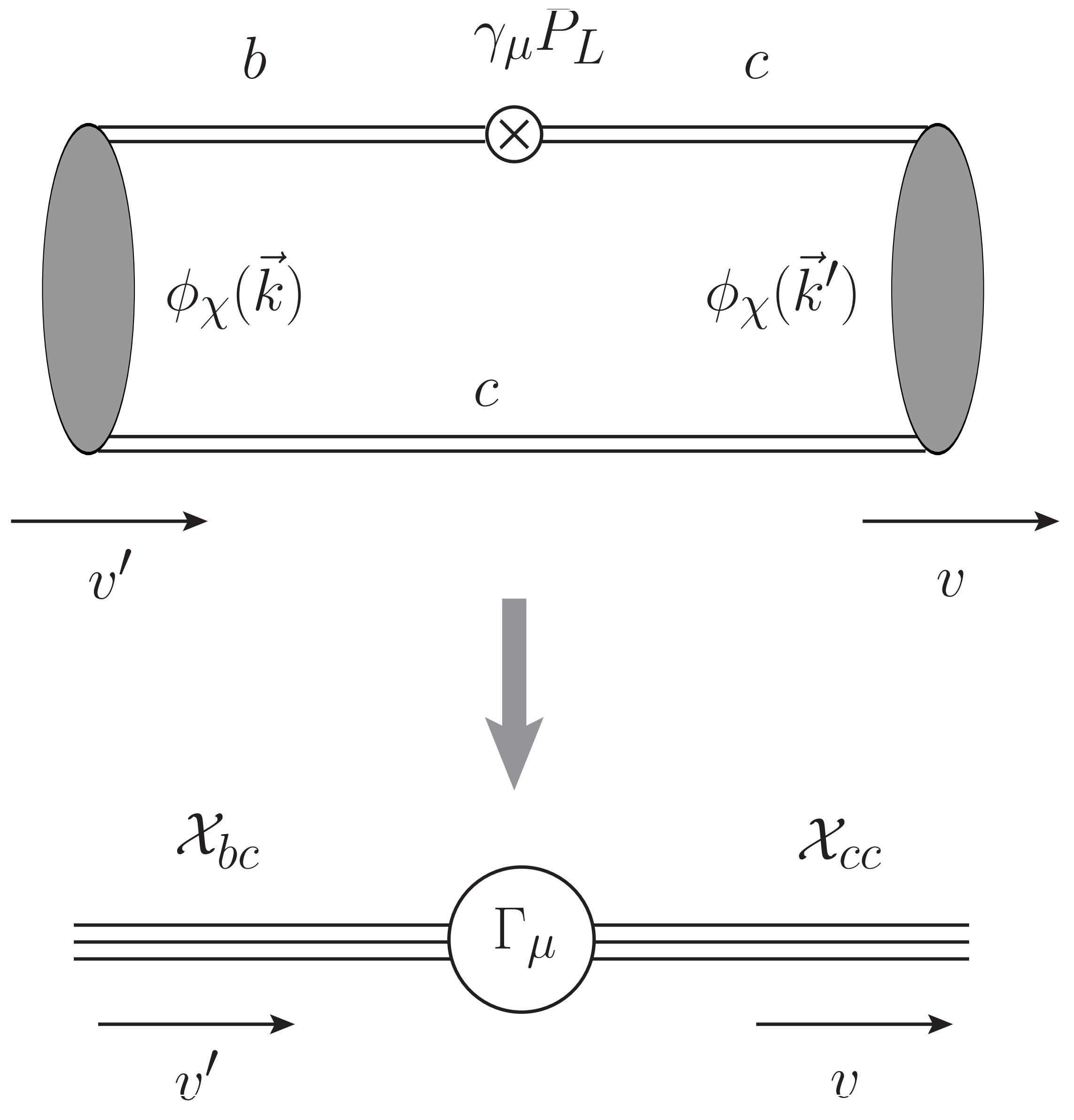
Calculation of $\Xi_{bc} \to \Xi_{cc} + X$

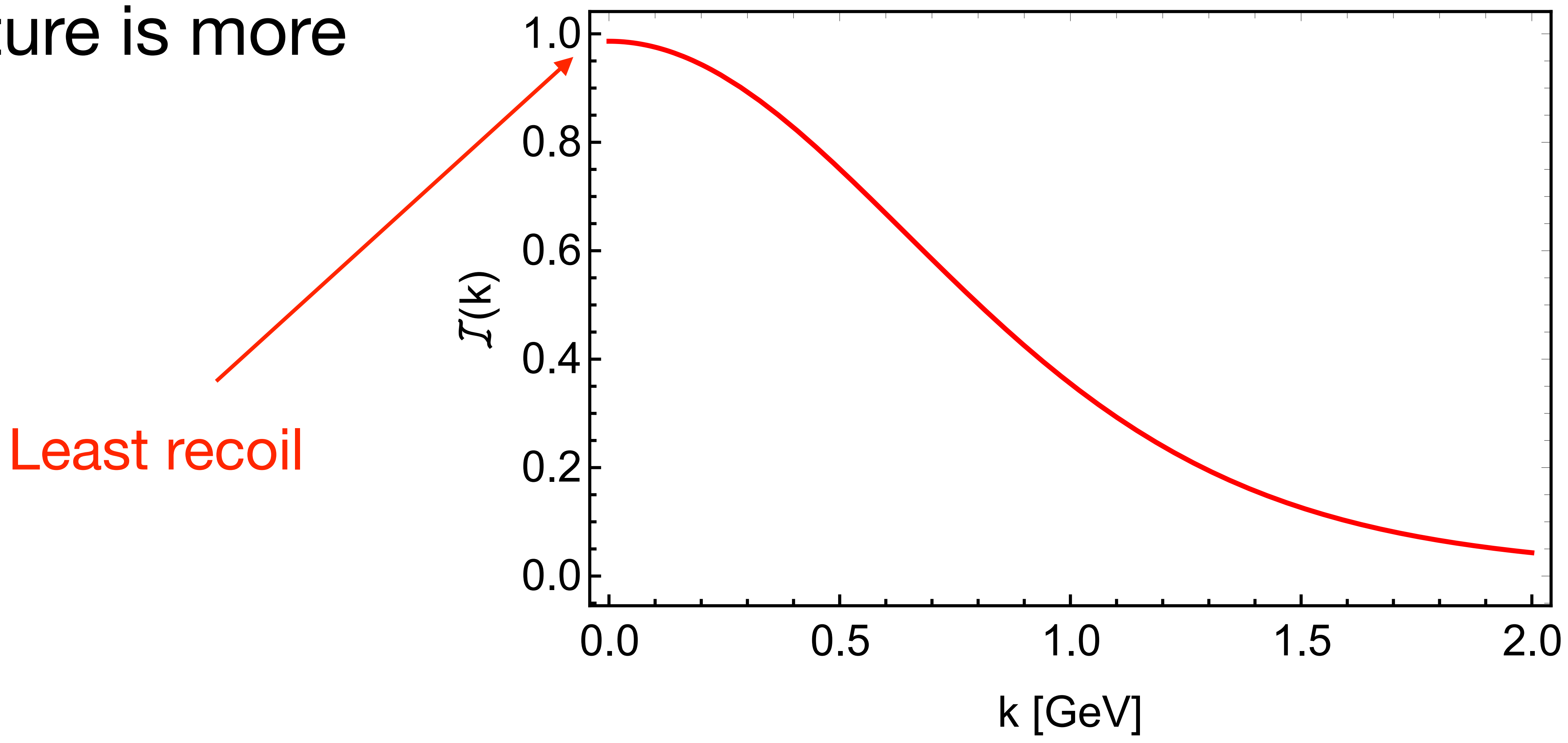
- The key issue is the 2-diquark-2-fermion interaction vertex, i.e. the $\chi_{bc} \to \chi_{cc}$ diquark current

- Assuming the heavy quark symmetry, the diquark current is matched from the quark current to be
$$\Gamma^{\mu}_{\rho\sigma} = \left[i\left(g_{\rho\sigma}\overleftarrow{\partial}^{\mu} - g^{\mu}_{\rho}\overleftarrow{\partial}_{\sigma} - g_{\rho\sigma}\partial^{\mu} + \partial_{\rho} g^{\mu}_{\sigma} \right) + \epsilon^{\mu}{}_{\nu\rho\sigma}\left(\overleftarrow{\partial}^{\nu} - \partial^{\nu} \right) \right] \sqrt{\frac{1}{2}} \mathcal{I}\left(m_c |\mathbf{v}' - \mathbf{v}| \right)$$
with $\mathcal{I}(\ldots) \equiv 1$

- If we consider the heavy quark mass effects, the structure is more complicated, and $\mathcal{I}(\ldots)$ is given by the right curve

- The model matching is to be improved





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

- Numerical result for the decay width

$$\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (3.9 \pm 0.1 \pm 1.0 \pm 1.2) \times 10^{-13}\ \text{GeV}$$

Uncertainties from Quark mass, model independence, power correction

- The branching ratio is

$$B(\Xi_{bc} \to \Xi_{cc} + X) \approx 12\% \times \frac{\tau_{\Xi_{bc}}}{200\text{fs}}$$

- Ξ_{cc}^{++} fragmentation suffers a factor of 1/2 (Assuming the u and d quark saturate the fragmentation)

$$B(\Xi_{bc} \to \Xi_{cc}^{++} + X) = 6\% \times \frac{1}{2}\left(\frac{\tau_{\Xi_{bc}^{+}}}{200\text{fs}} + \frac{\tau_{\Xi_{bc}^{0}}}{200\text{fs}}\right) = 6\% \times \left(\frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^{0}}}{400\text{fs}}\right)$$

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

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

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

- Estimated of signal signal events

$$N(\Xi_{bc} \to \Xi_{cc}^{++} + X) = N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X)$$

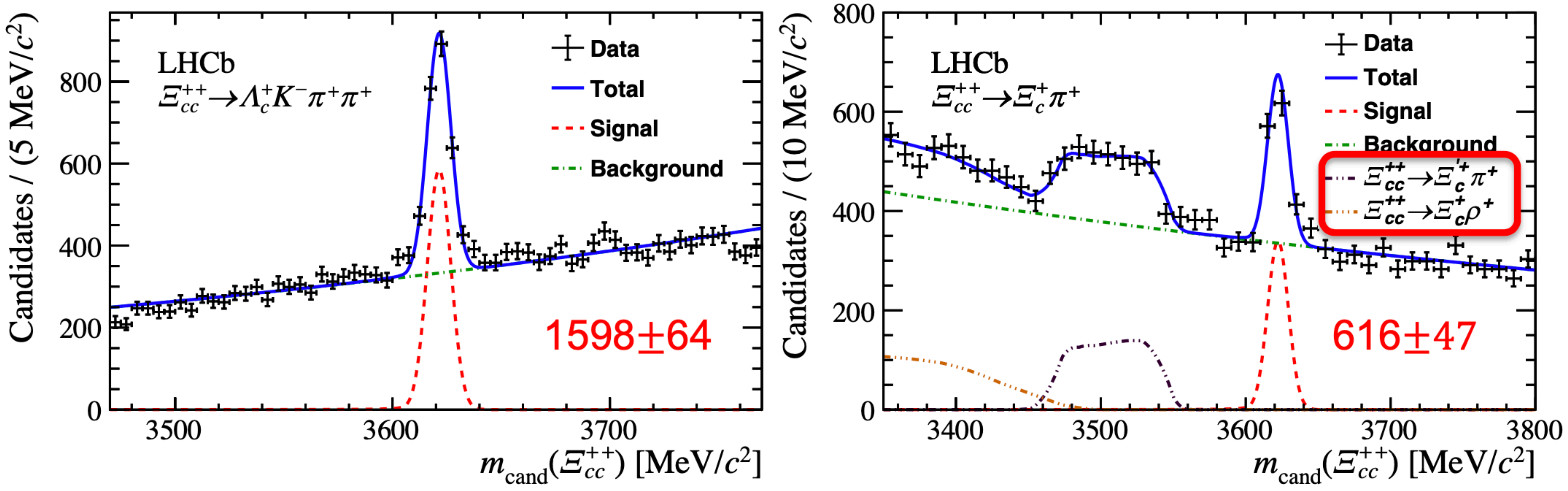
(Both Ξ_{bc}^{0} and Ξ_{bc}^{+} decay equally to Ξ_{cc}^{++} and thus Identical detection efficiency)

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}^{++} (Preliminary)

- Final number of estimated signal events @ LHCb Run3

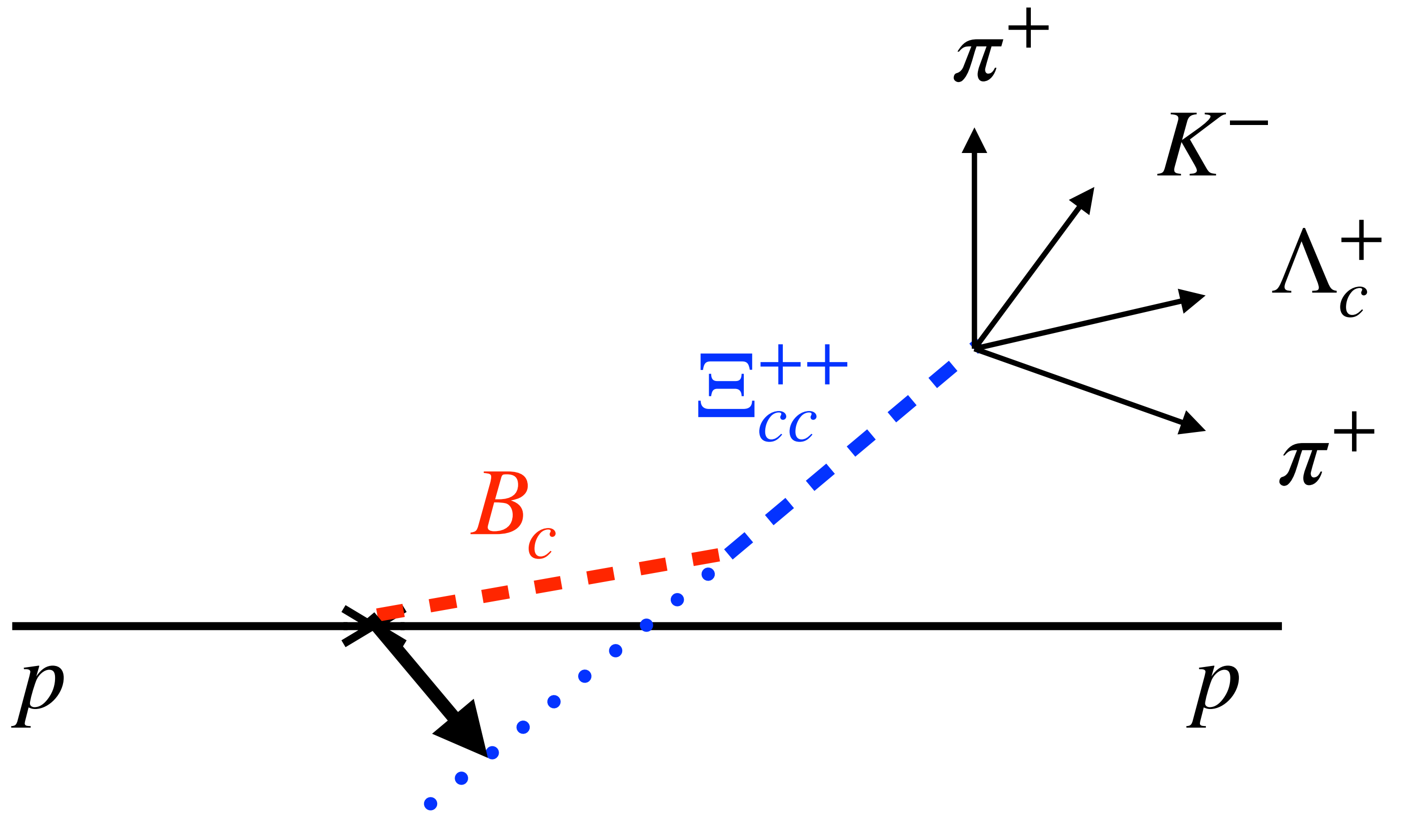
$$N(\Xi_{bc} \to \Xi_{cc}^{++} + X) = N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X)$$

$$= 10^4 \cdot \frac{N(\Xi_{cc}^{++})}{10^4} \times 40\% \cdot \frac{2\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\ \%} \times 6\% \cdot \left(\frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^{0}}}{400\mathrm{fs}}\right)$$

$$= \mathbf{480} \times \frac{N(\Xi_{cc}^{++})}{10^4} \cdot \frac{\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\ \%} \cdot \left(\frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^{0}}}{400\mathrm{fs}}\right)$$

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 $\Xi_{cc}\Xi_c\pi$, or $\Xi^*_{cc}\Xi_c$, or $\Xi_{cc}\Xi^*_c$

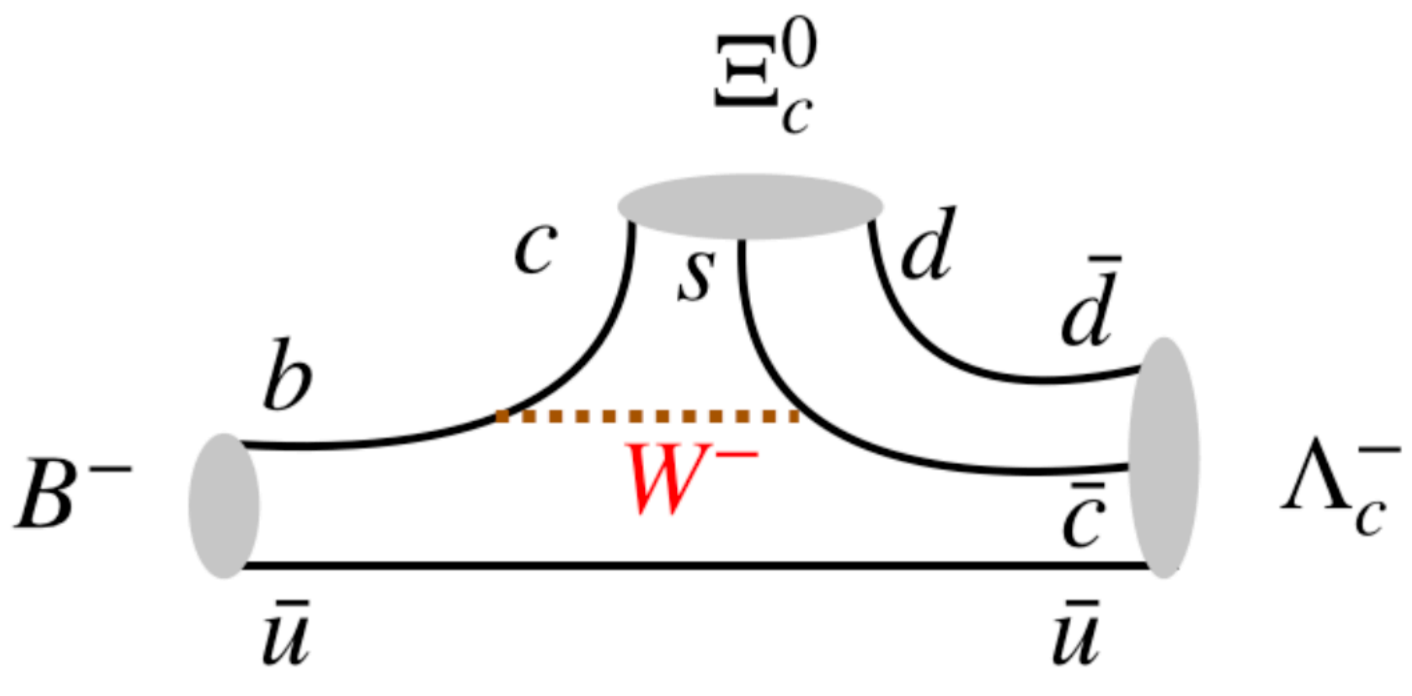


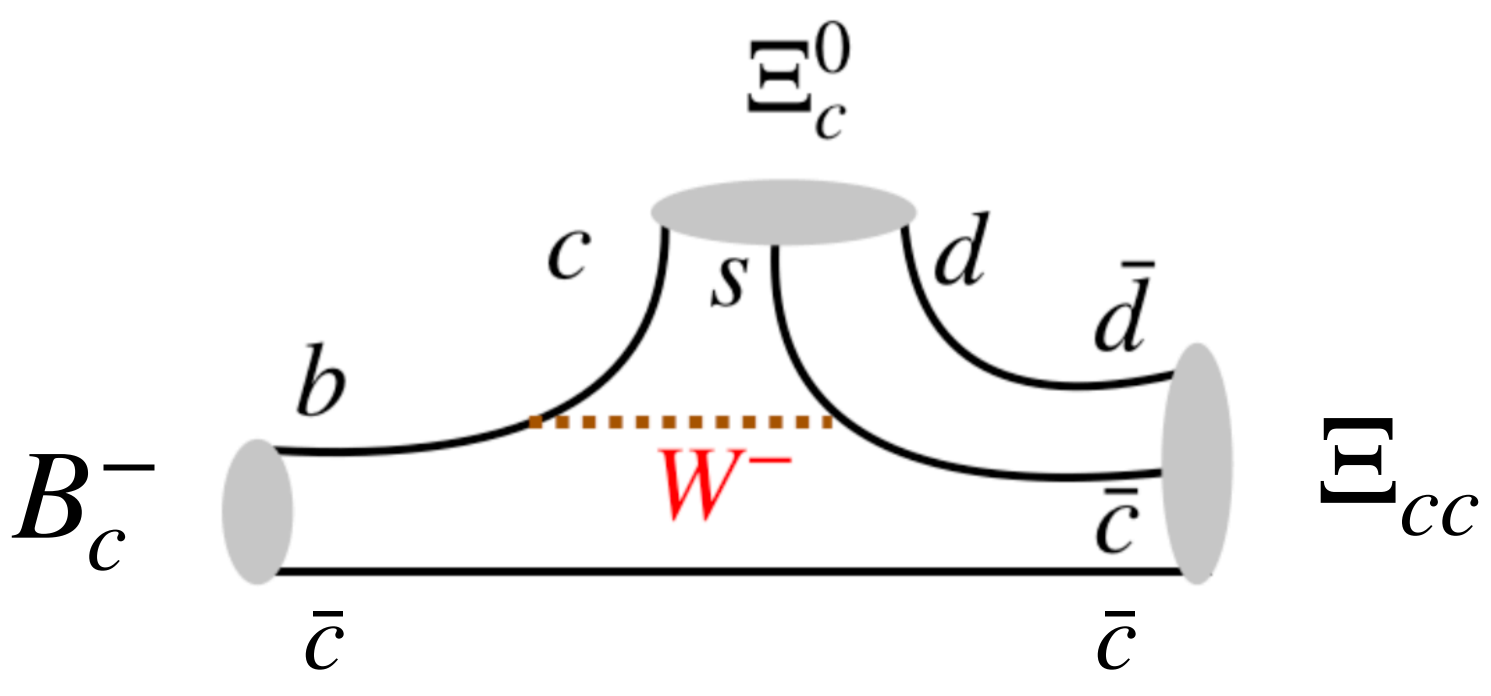
- Similar process but with a light spectator quark:

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

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

(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 $\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (3.9 \pm 0.1 \pm 1.0 \pm 1.2) \times 10^{-13}$ GeV.

- We estimate about 480 signal events to be observed @ LHC Run 3.

- We hope it is useful.

Thank you!