Inclusive search for Ξ_{bc}

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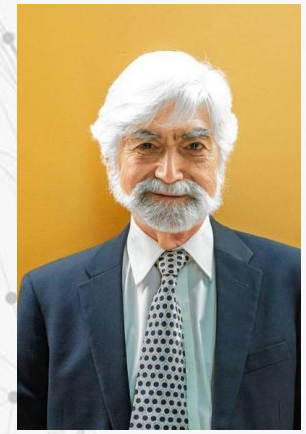
Content

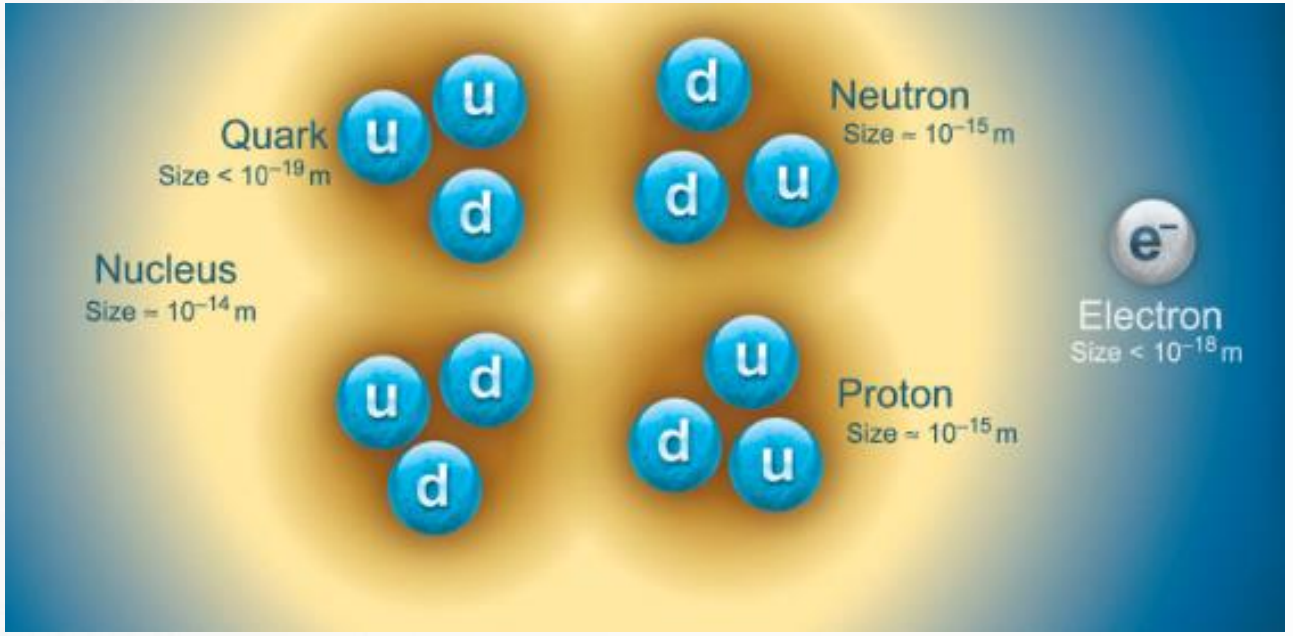
- It is important to study Ξ_{bc}
- We propose a inclusive strategy to find Ξ_{bc}
- We will show it is reachable at LHCb

The quark model

Murry Gell-Mann
1929,9,15—2019,5,24



George Zweig
1937,5,30---



‘Three quarks for muster mark’
《Finnegans wake》

The exotic state

- Observation of tetraquarks Zc(3900)

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

  The Physics 2013 "Highlights of the Year" (rank 1st)

- Observation of pentaquarks Pc

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

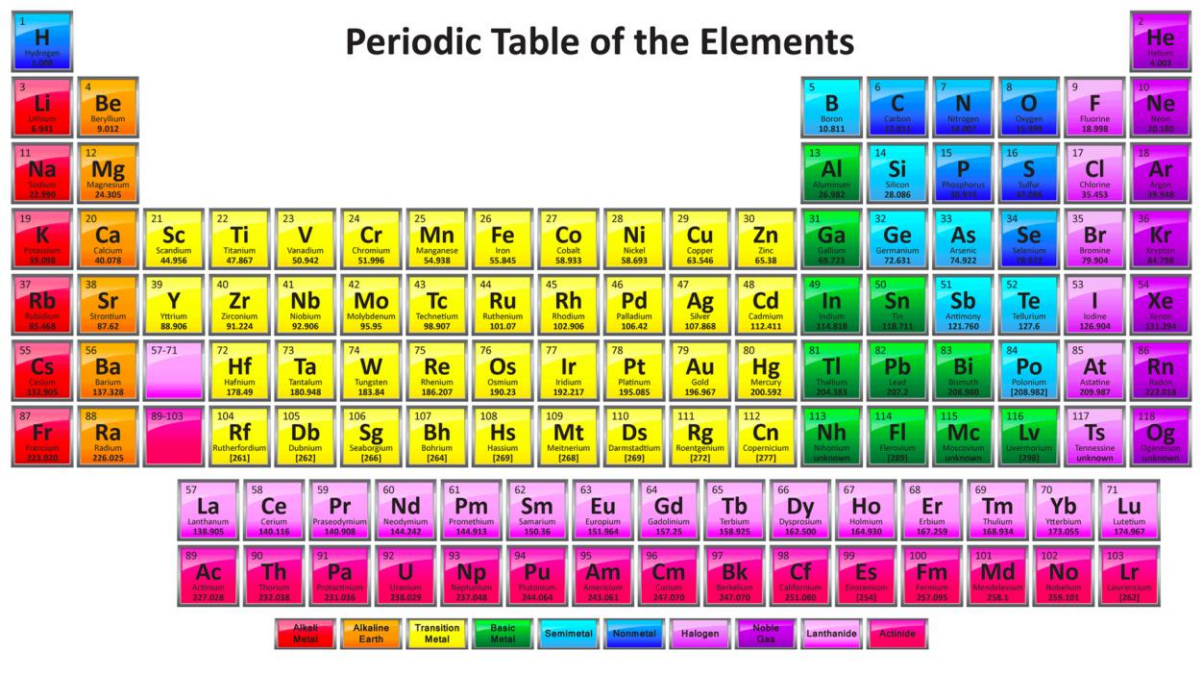
  The Physics World 2015 "top-10 breakthroughs"

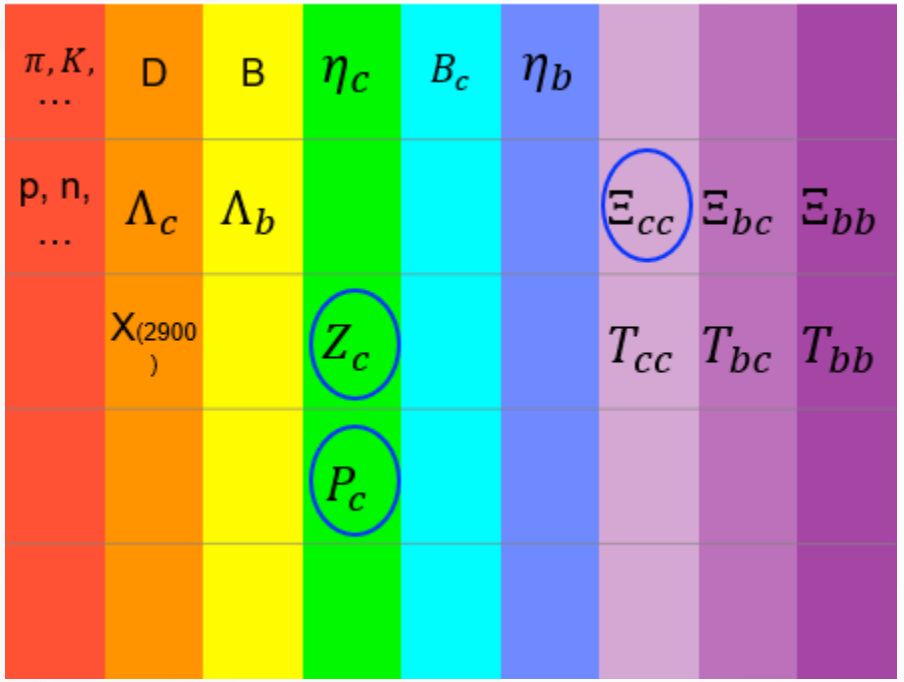
- Observation of a double-charm baryon Ξ_{cc}^{++}

  [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}: a new main group

Beyond stamp collecting

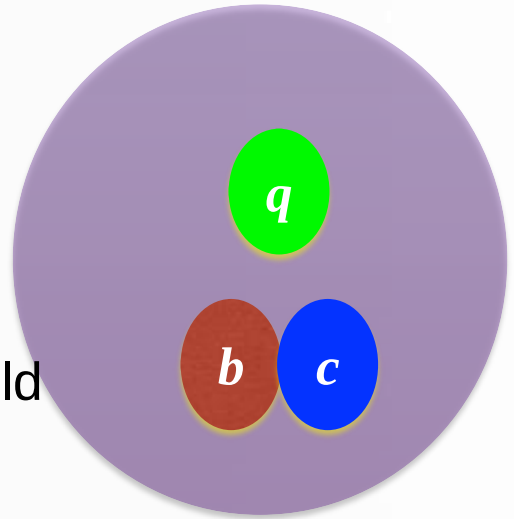
- Because of color confinement, properties of quarks are studied via hadrons

- 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



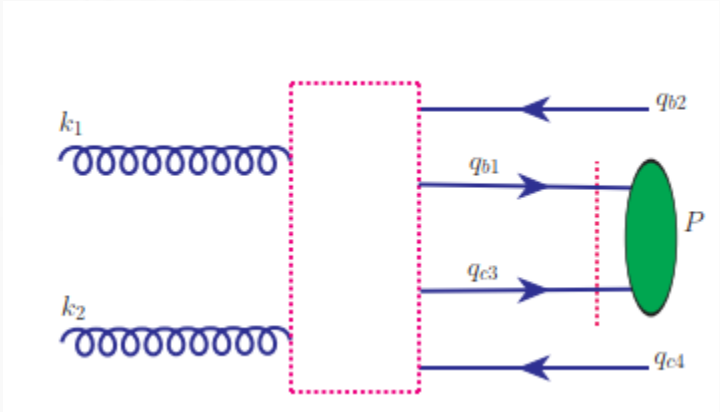
[Eichten,Quigg,1707.09575]

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					

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

Ξ_{bc}: this talk



$\sigma(\Xi_{bc})$ =35 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.

Difficulties in experimental searches

- Production rate

- Detection efficiency —— small exclusive branching ratios

channels	Γ/ GeV	$\mathcal{B}$	channels	Γ/ GeV	$\mathcal{B}$
$\Xi_{bc}^0 \to \Sigma_b^- \pi^+$	6.13×10^{-15}	8.66×10^{-4}	$\Xi_{bc}^0 \to \Sigma_b^- \rho^+$	2.58×10^{-14}	3.64×10^{-3}
$\Xi_{bc}^0 \to \Sigma_b^- K^{*+}$	1.29×10^{-15}	1.82×10^{-4}	$\Xi_{bc}^0 \to \Sigma_b^- K^+$	4.62×10^{-16}	6.53×10^{-5}
$\Xi_{bc}^0 \to \Xi_b^- \pi^+$	9.38×10^{-14}	1.33×10^{-2}	$\Xi_{bc}^0 \to \Xi_b^- \rho^+$	1.90×10^{-13}	2.68×10^{-2}
$\Xi_{bc}^0 \to \Xi_b^- K^{*+}$	7.47×10^{-15}	1.06×10^{-3}	$\Xi_{bc}^0 \to \Xi_b^- K^+$	8.12×10^{-15}	1.15×10^{-3}
$\Xi_{bc}^0 \to \Xi_b^{\prime -} \pi^+$	5.47×10^{-14}	7.73×10^{-3}	$\Xi_{bc}^0 \to \Xi_b^{\prime -} \rho^+$	2.01×10^{-13}	2.83×10^{-2}
$\Xi_{bc}^0 \to \Xi_b^{\prime -} K^{*+}$	8.53×10^{-15}	1.21×10^{-3}	$\Xi_{bc}^0 \to \Xi_b^{\prime -} K^+$	3.82×10^{-15}	5.40×10^{-4}

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

- First experimental attempt

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

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

[LHCb, 2104.04759]

A novel approach —— inclusive Ξ_{bc} search

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

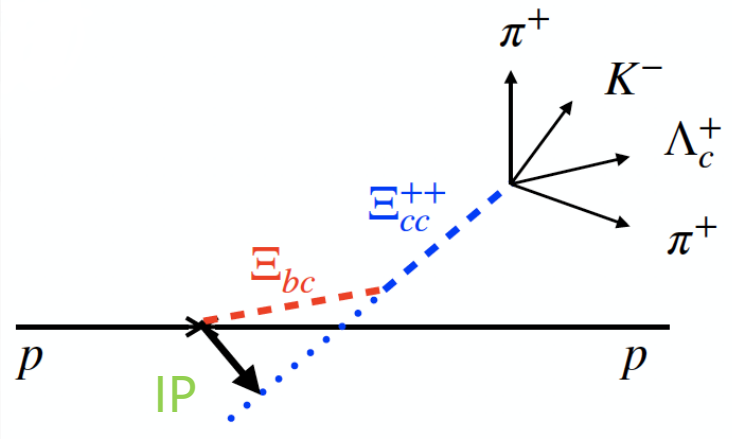
  Basically impossible at hadron colliders

- However, for $\Xi_{bc} \to \Xi_{cc} + X$, 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

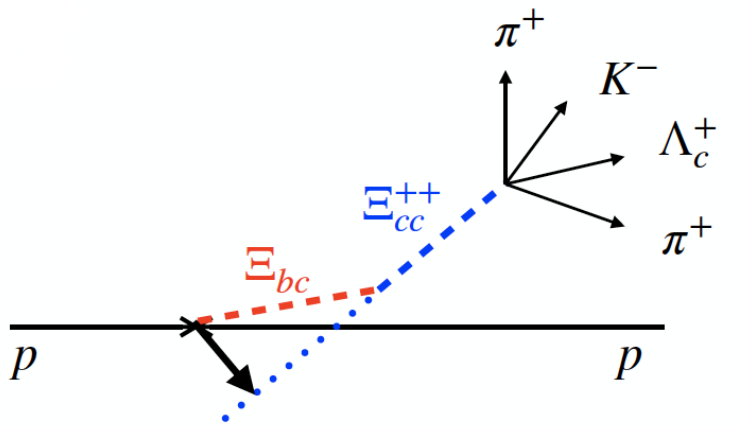
- The $B_c \to \Xi_{cc} + X$ decay is highly suppressed



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

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

  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

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

It is reasonable because $r_{QQ'} \sim 1/(m_Q v) \ll 1/\Lambda_{QCD}$ [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]

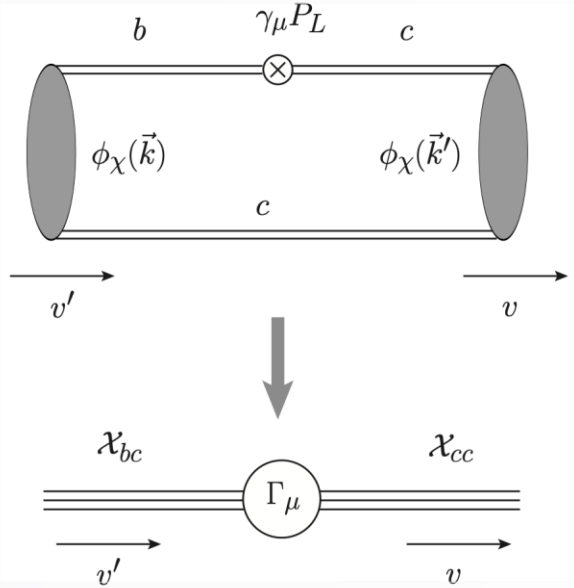
- At the leading power

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

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

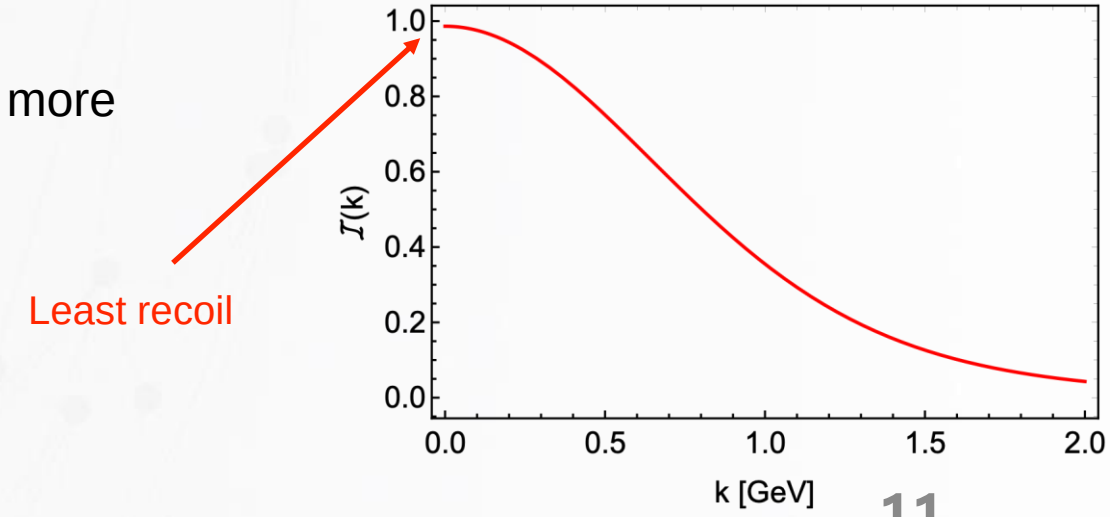
$$\langle 0|X_{cc}(v,\epsilon)\ \bar{c}\gamma^{\mu}P_L b(0)\ X_{bc}^{\dagger}(v',\epsilon')|0\rangle = \langle 0|X_{cc}(v,\epsilon)\ X_{cc}^{\dagger}\Gamma^{\mu}X_{bc}(0)\ X_{bc}^{\dagger}(v',\epsilon')|0\rangle$$



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

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

Uncertainties from Quark mass, model dependence, 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

93fs < $\tau(\Xi_{bc}^{0})$ < 118 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 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 $\Xi_{bc} \to \Xi_{cc}^{++} + X$

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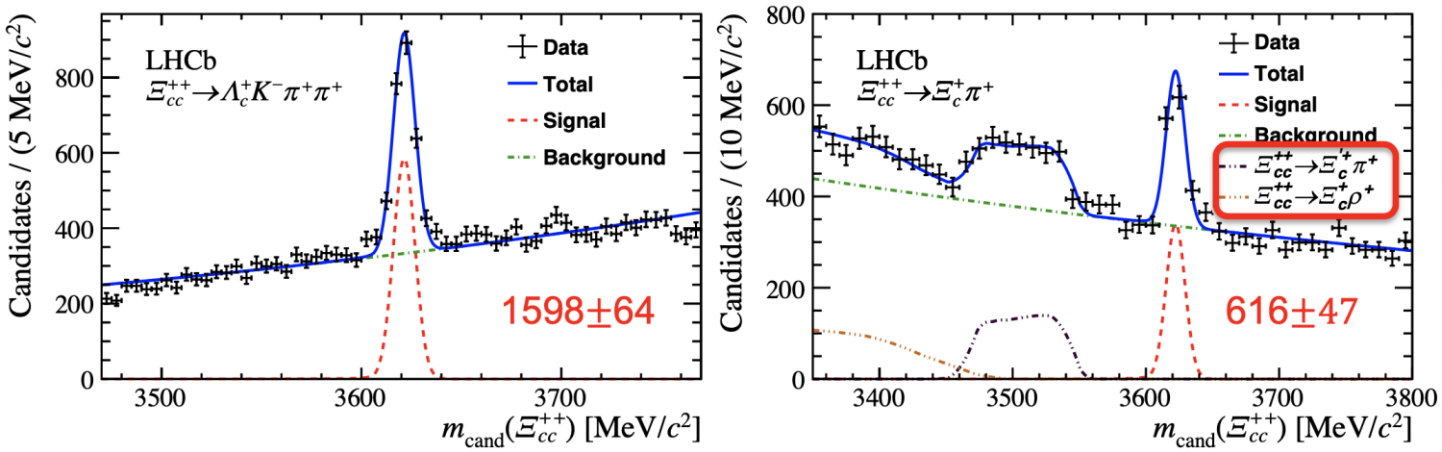
Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

1.Number of signals of Ξ_{cc}^{++}



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- 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

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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

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

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

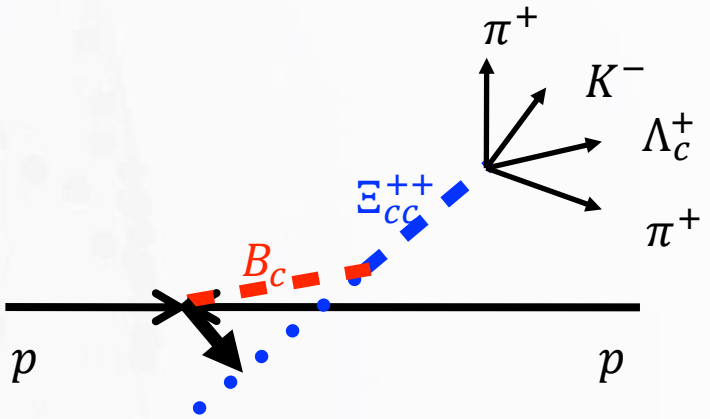
$$= \mathbf{480} \times \frac{N(\Xi_{cc}^{++})}{10^4} \cdot \frac{\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\%} \cdot \left(\frac{\tau_{\Xi_{bc}^+} + \tau_{\Xi_{bc}^0}}{400\text{fs}}\right)$$

Small possibility from B_c decays

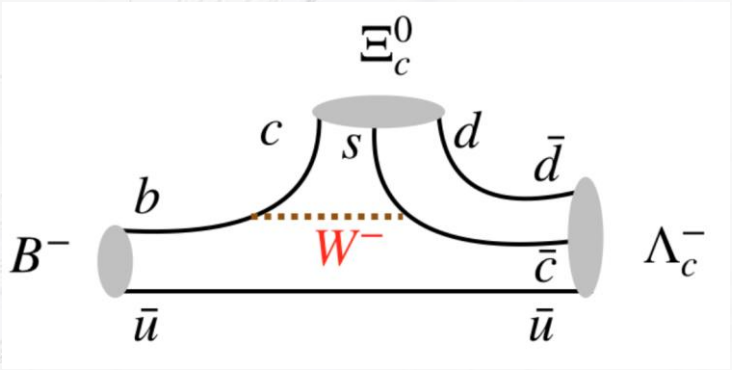
- The small phase space (0.18 GeV for $\Xi_{cc}\Xi_c$) only allows the processes of B_c
  $\rightarrow \Xi_{cc}\Xi_c, \text{or}\Xi_{cc}\Xi_c\pi, \text{or}\Xi_{cc}^*\Xi_c, \text{or}\Xi_{cc}\Xi_c^*$
- Similar process but with a light spectator quark:

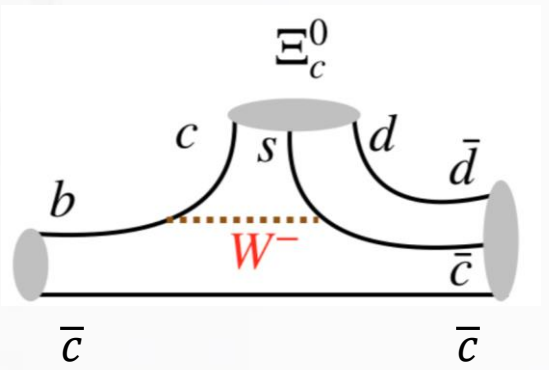
$$Br(B^0 \rightarrow \Xi_c^-\Lambda_c^+) = (1.2 \pm 0.8) \times 10^{-3}$$

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



(0.5 GeV phase space)





Conclusion

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