Study of beautiful and/or charming particles at LHCb

Jibo HE (UCAS, Beijing)

Seminar at IJCLab, Orsay

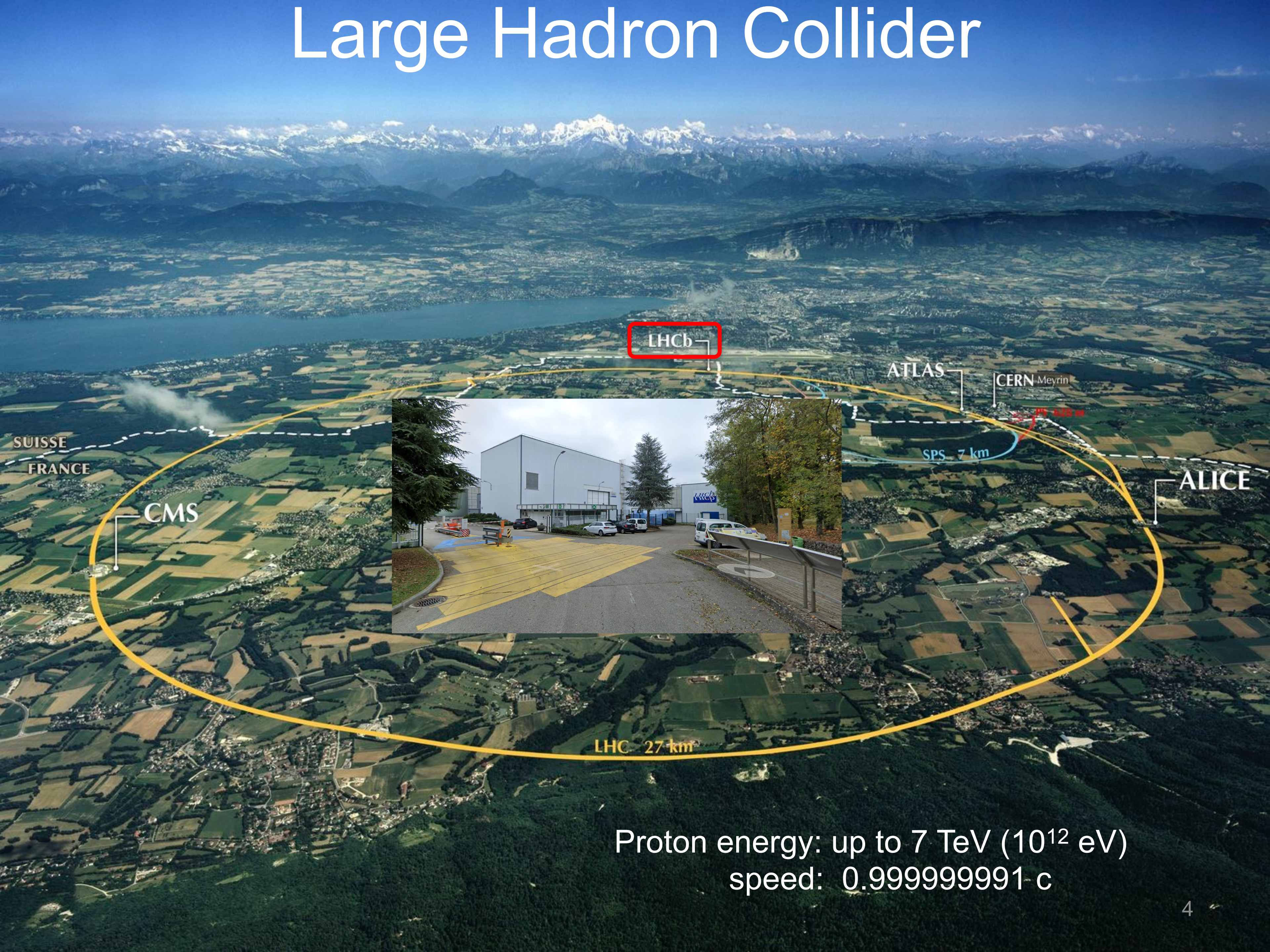
October 27, 2025

Outline

- Introduction to LHCb
- Indirect search for New Physics
  - $b \to s\ell^+\ell^-$, BR, LFU, angular analysis
  - $b \to c\tau\nu$, LFU
- Experimental study of QCD
  - Conventional hadrons
    - B_c^+ physics, Doubly heavy baryons
    - Quarkonium production
  - Exotic hadrons
    - Production
    - $X(5568)^+$

Le bestiaire

Large Hadron Collider



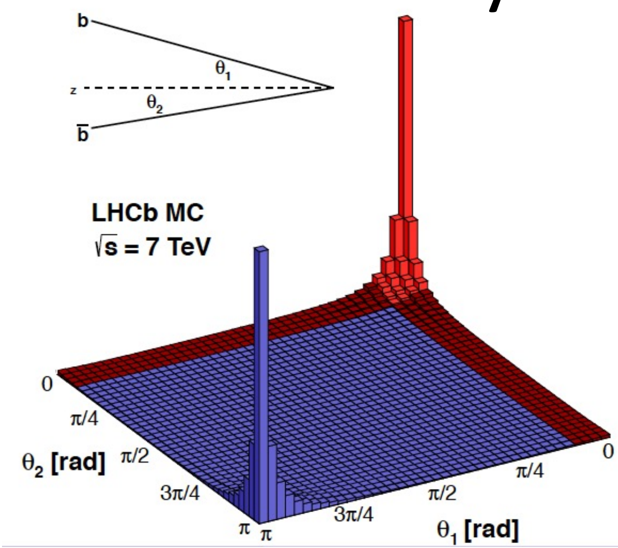
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

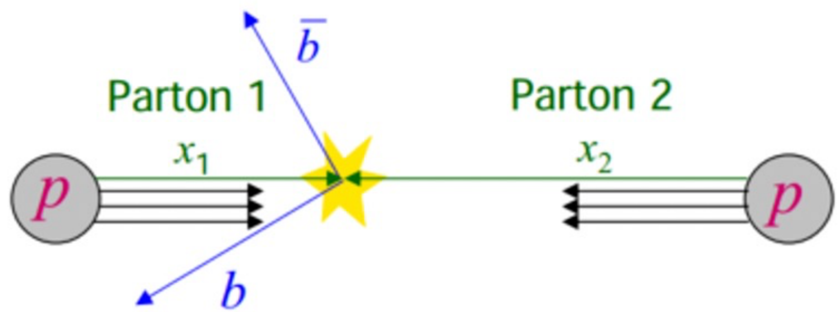
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb c.f. 1nb @$\Upsilon(4S)$

Flavour factory!

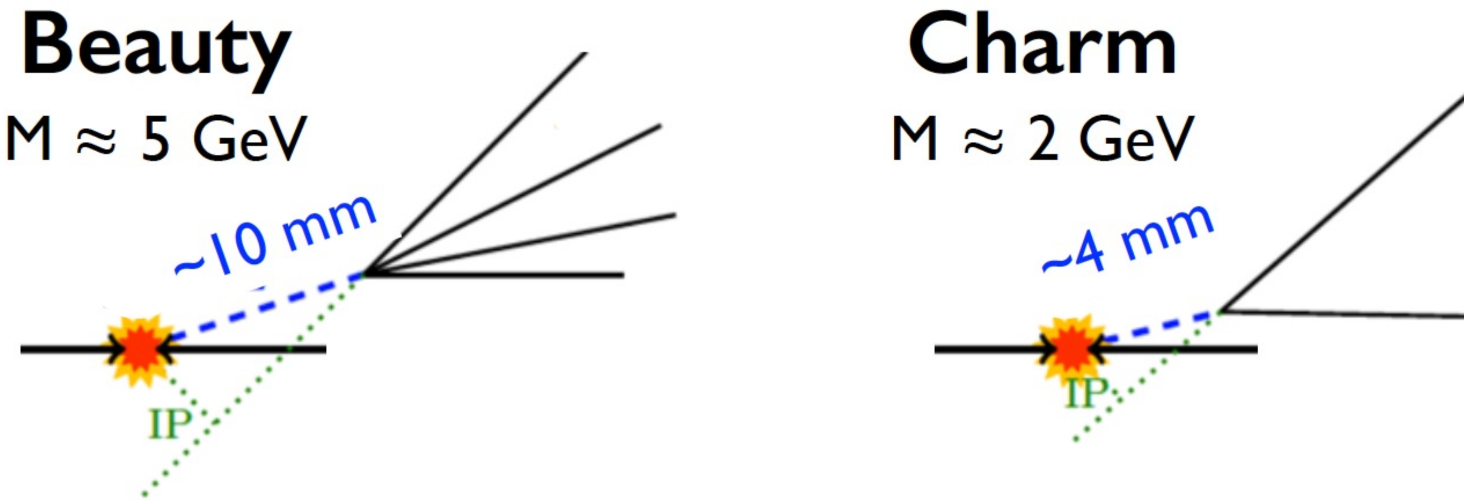
- Predominantly in forward/backward cones





Initial energy of $b\bar{b}$ not known

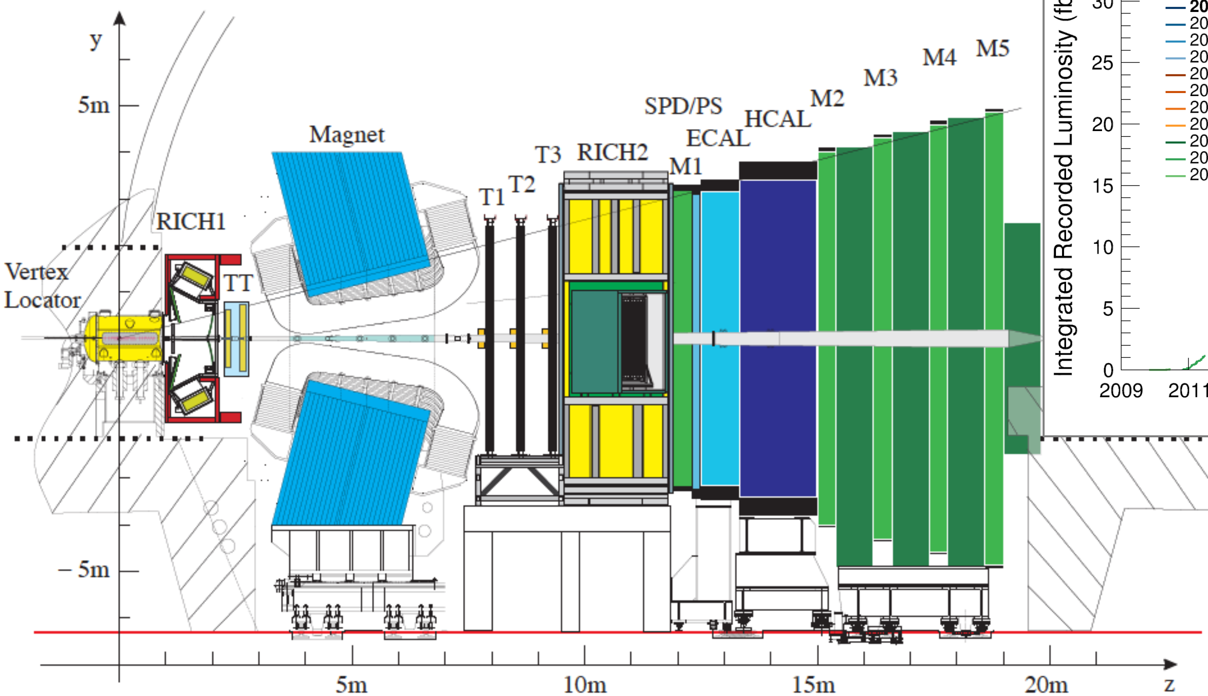
Beauty/charm signature

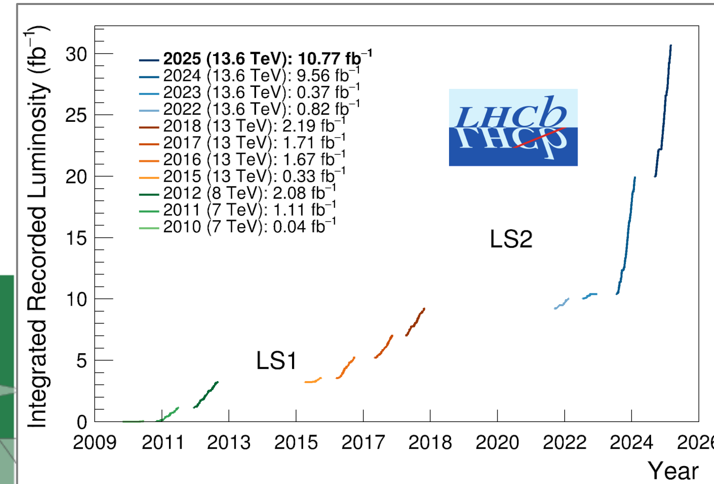


- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

The LHCb experiment

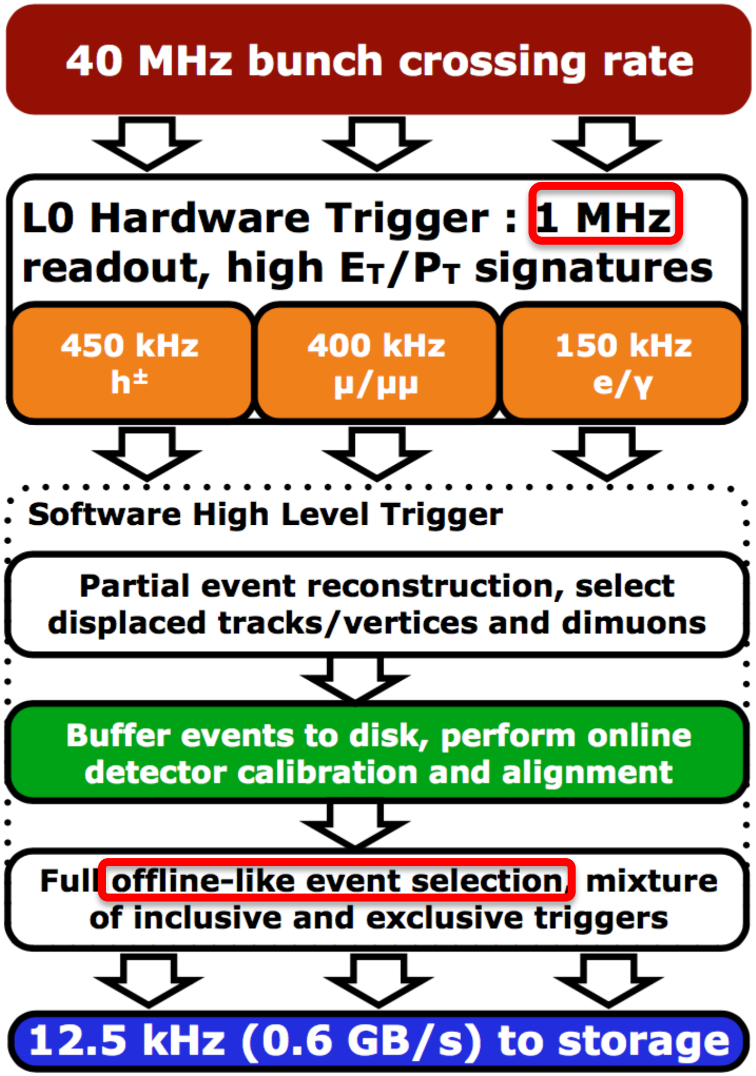
[JINST 3 (2008) S08005]





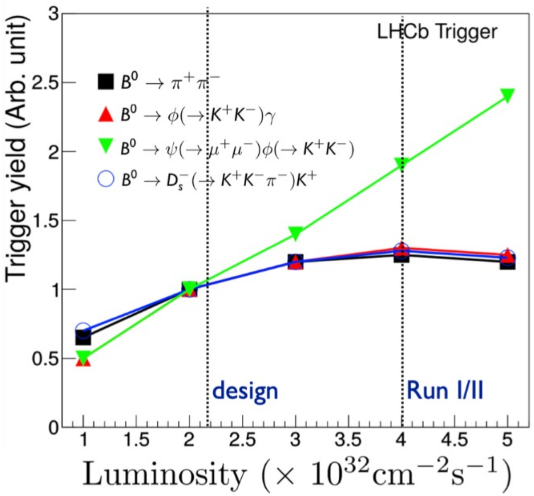
Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1-3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_T(\mu_1) \times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_T, IP
  - Stage2, full selection

The LHCb trigger (Run3)



Software High Level Trigger

- **Partial event reconstruction, select displaced tracks/vertices and dimuons**
- **Buffer events to disk, perform online detector calibration and alignment**
- **Full offline-like event selection, mixture of inclusive and exclusive triggers**

12.5 kHz (0.6 GB/s) to storage

L0 → removed

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

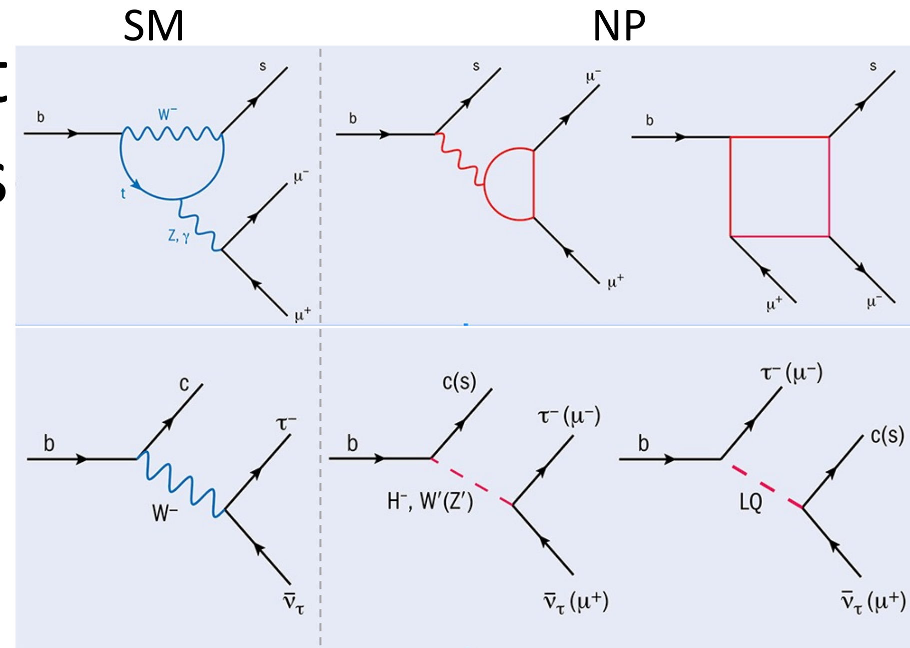
- **Full event reconstruction, inclusive and exclusive kinematic/geometric selections**
- **Buffer events to disk, perform online detector calibration and alignment**
- **Add offline precision particle identification and track quality information to selections**

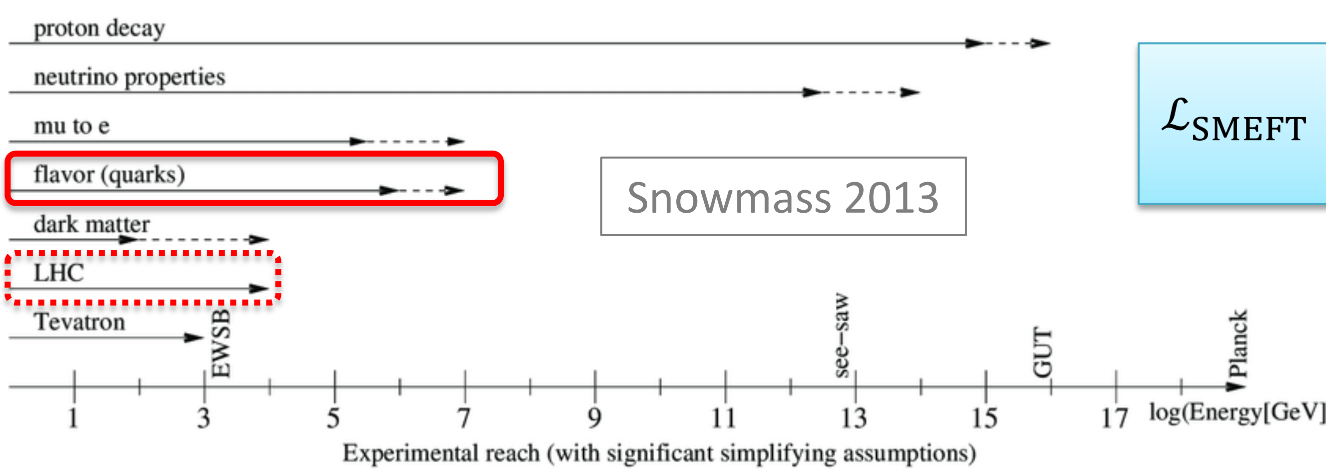
  Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

Indirect search for New Physics

- Precision measurement of heavy hadron decays
  - Flavour-Changing NC
  - Flavour-Changing CC
- Probe New Physics at high energy scale



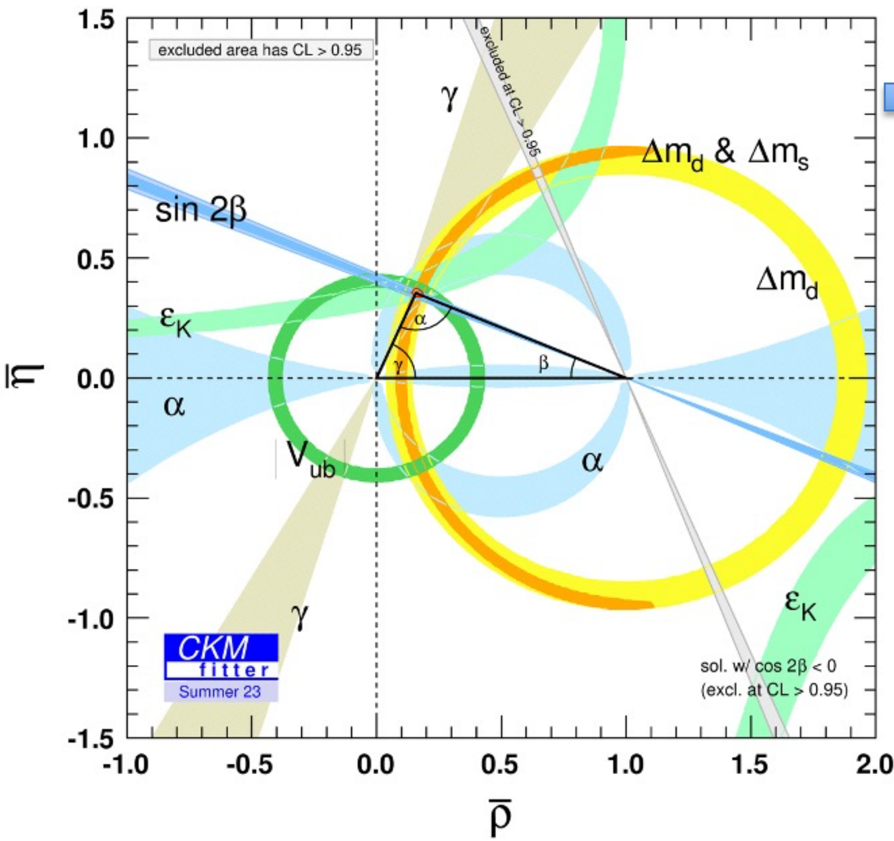


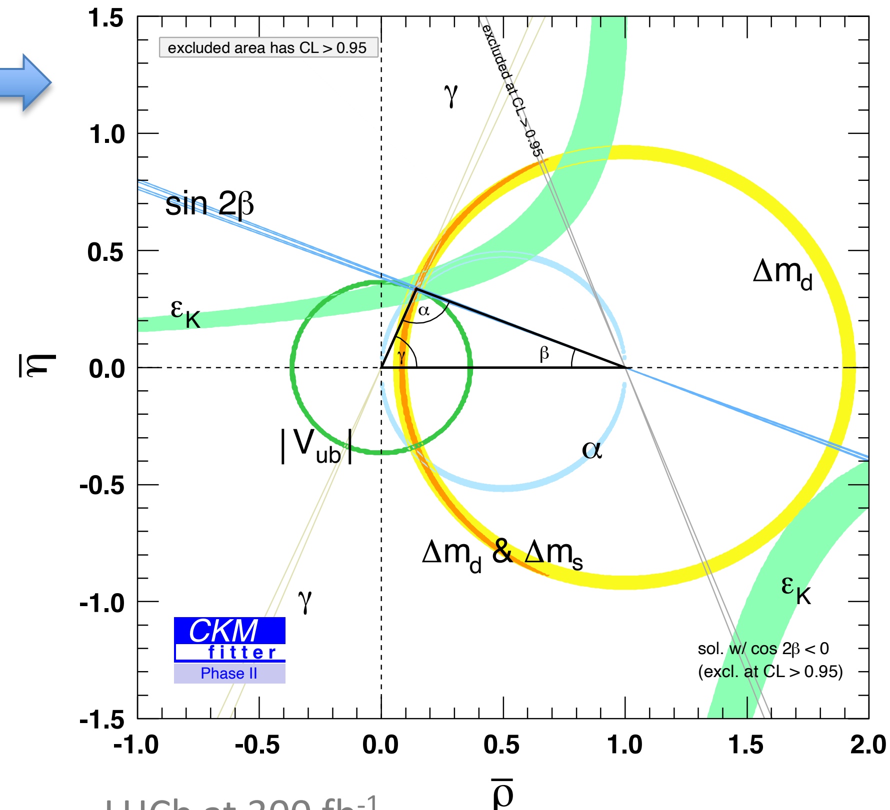
Snowmass 2013

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

Indirect search for NP (cont.)

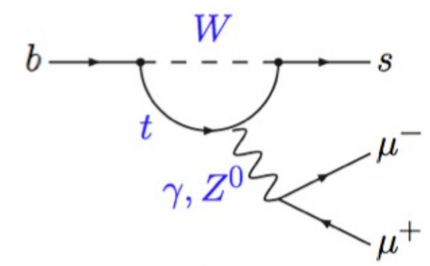
- Overconstrain the CKM triangle



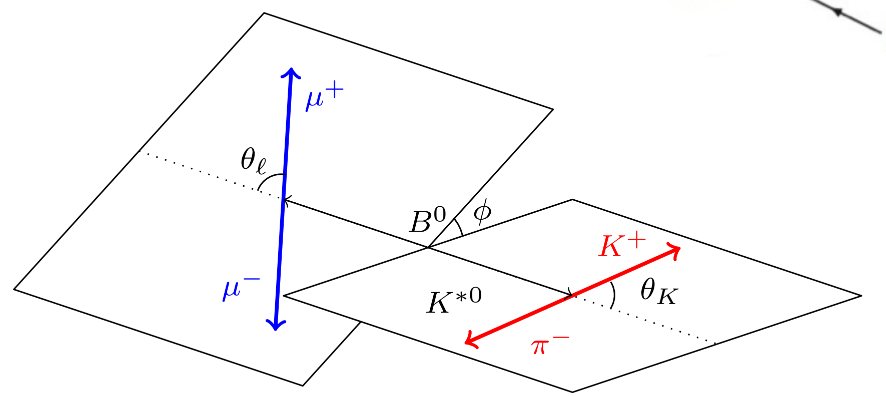


LHCb at 300 fb^{-1},
CMS/ATLAS at 3000 fb^{-1}, Belle II at 50 ab^{-1}.

$B^0 \to K^{*0}\mu^+\mu^-$



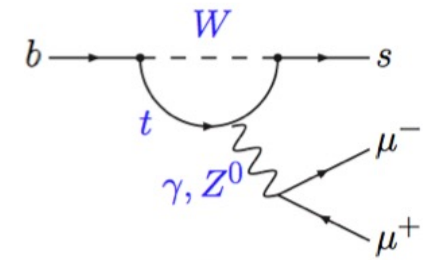
- Described by $q^2 = m^2(\ell^+\ell^-)$ and $\theta_\ell, \theta_K, \phi$
- Many observables!

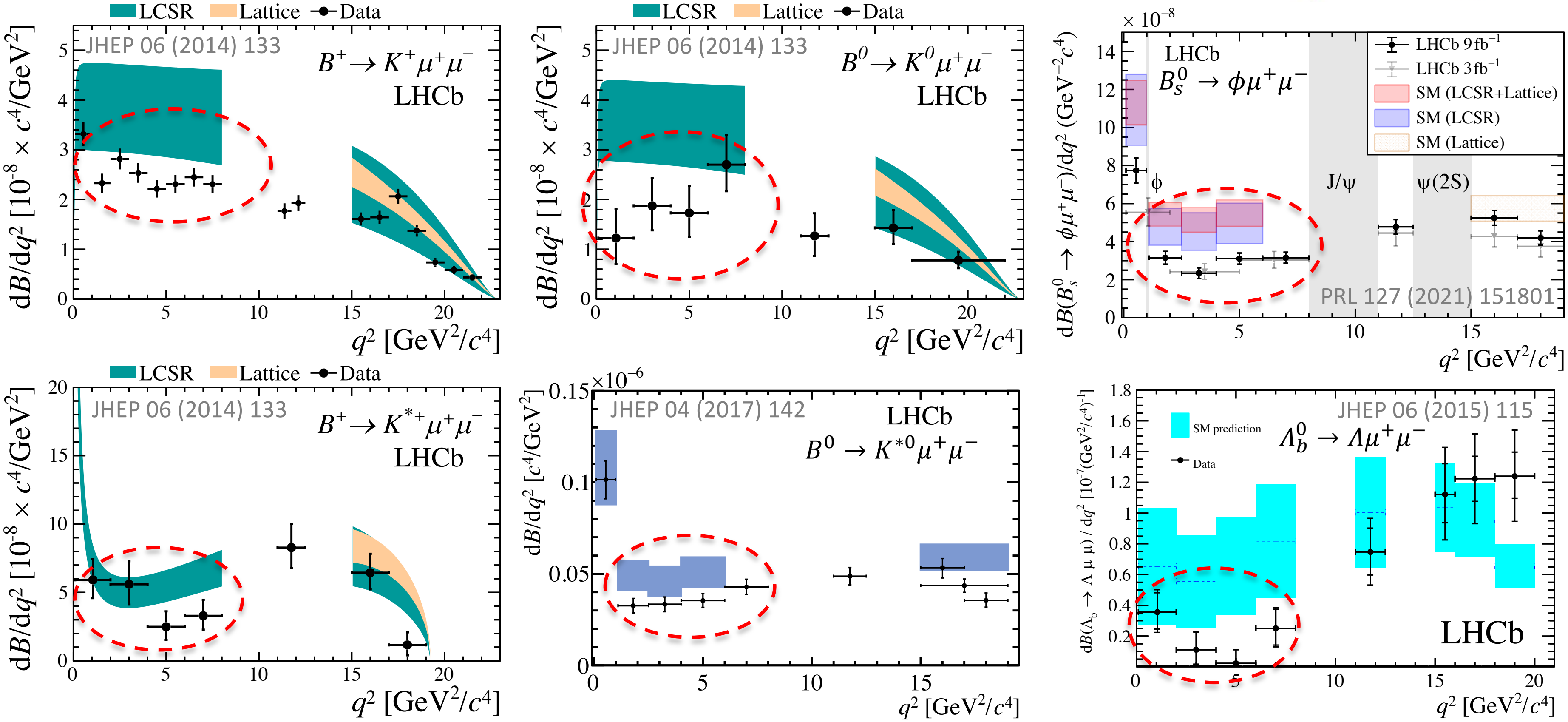


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Branching fraction of $b \to s\mu^+\mu^-$

- Pattern of tensions seen, theoretical uncertainty?

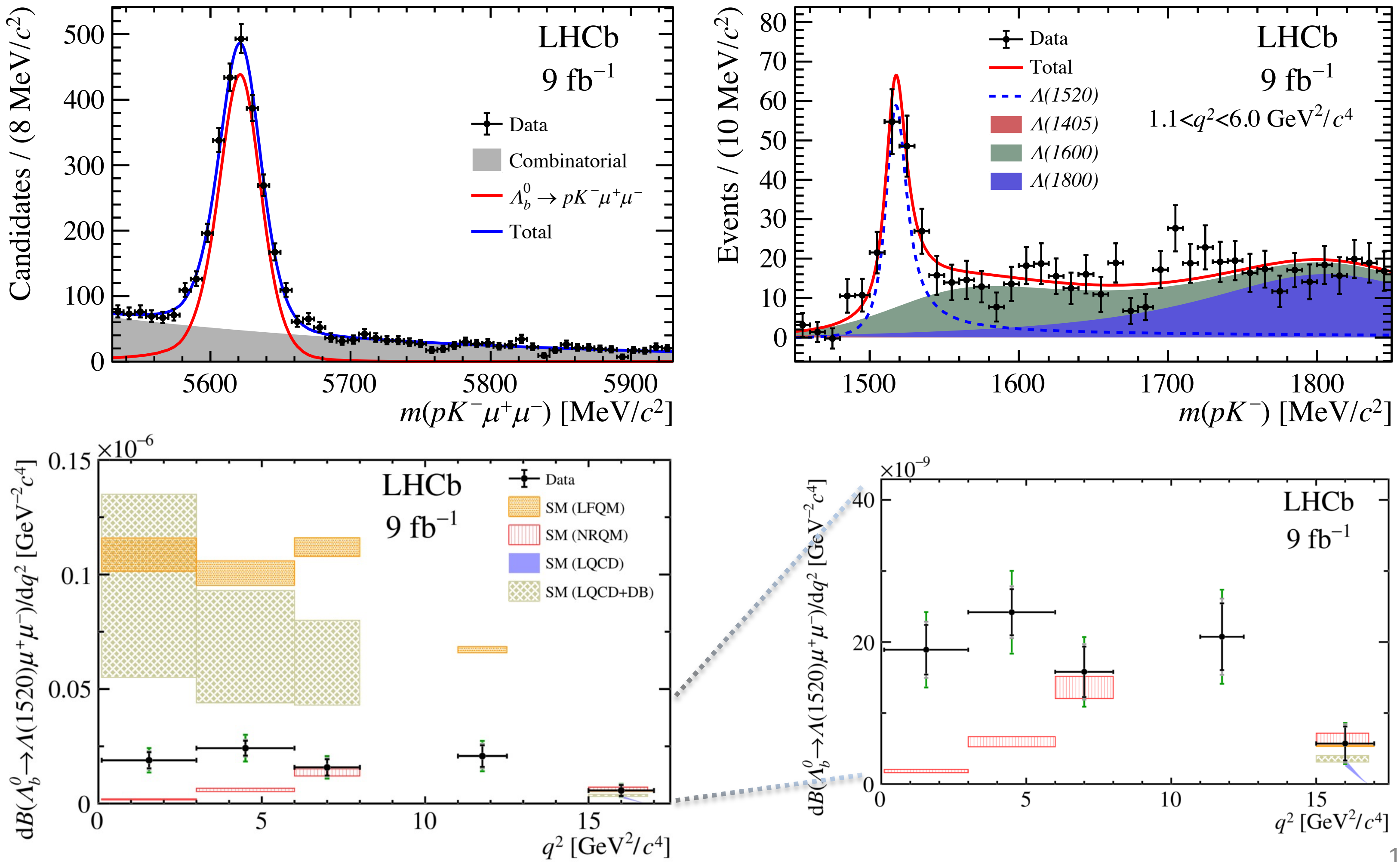




BR of $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$

- First measurement using excited baryon

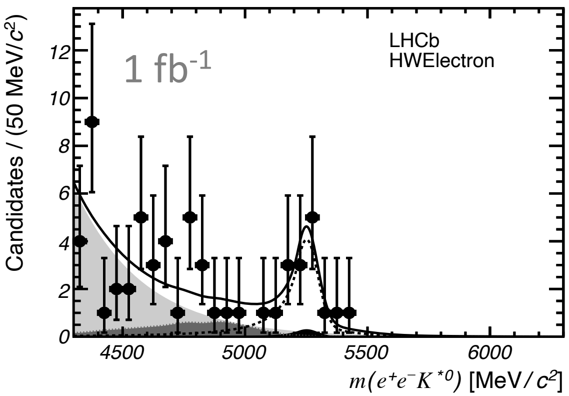
[PRL 131 (2023) 151801]

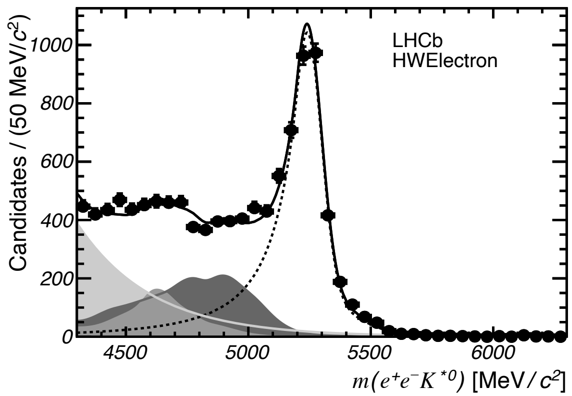


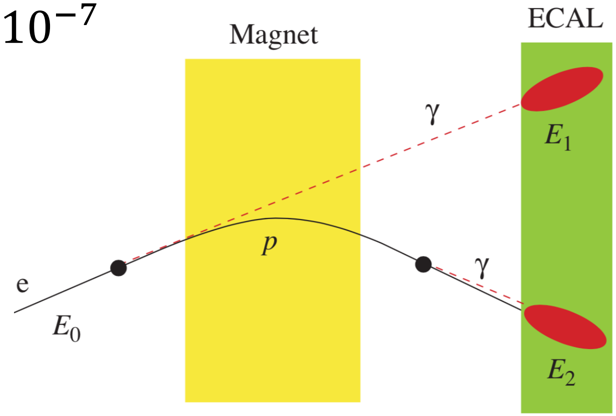
$B^0 \to K^{*0} e^+ e^-$

- First measurement using low-energy electron

$$\mathcal{B}(B^0 \to K^{*0} e^+ e^-)^{30-1000\ \mathrm{MeV}} = (3.1^{+0.9+0.2}_{-0.8-0.3} \pm 0.2)\times 10^{-7}$$

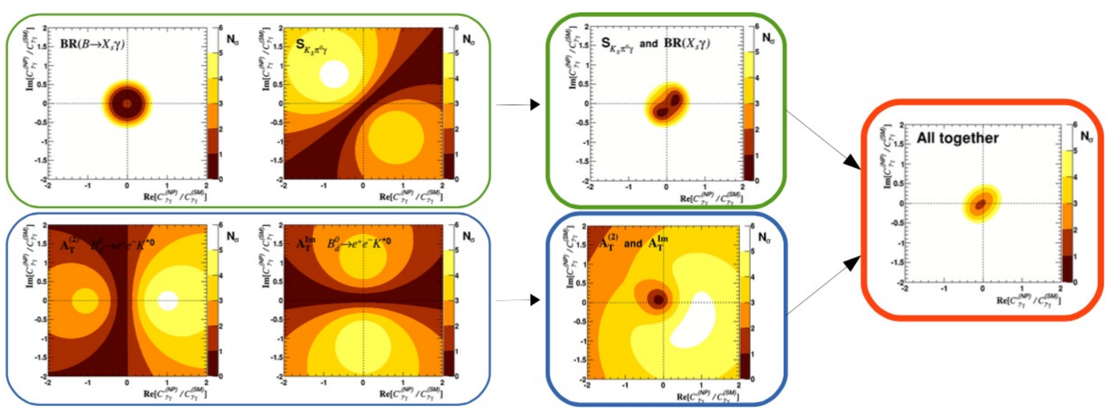




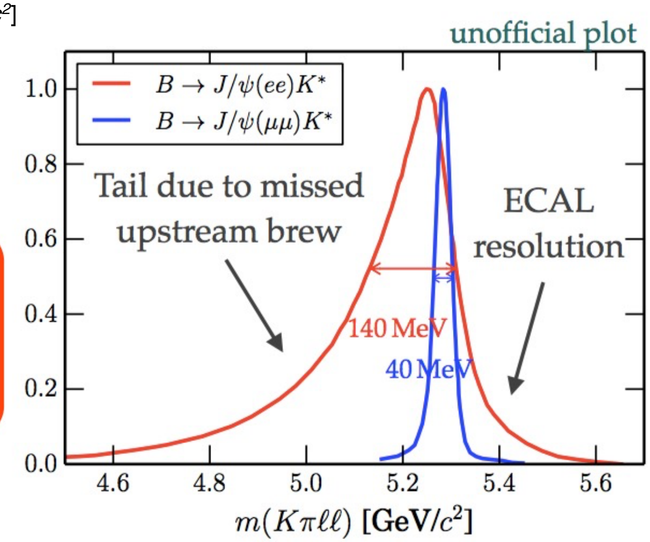


[JHEP 05 (2013) 159]

- Angular analysis in 2015

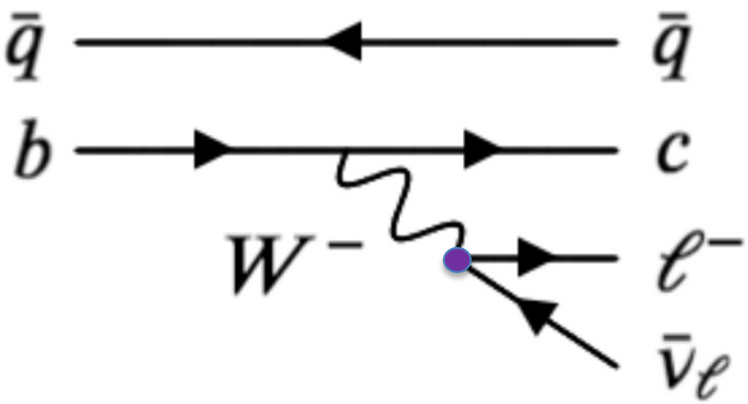


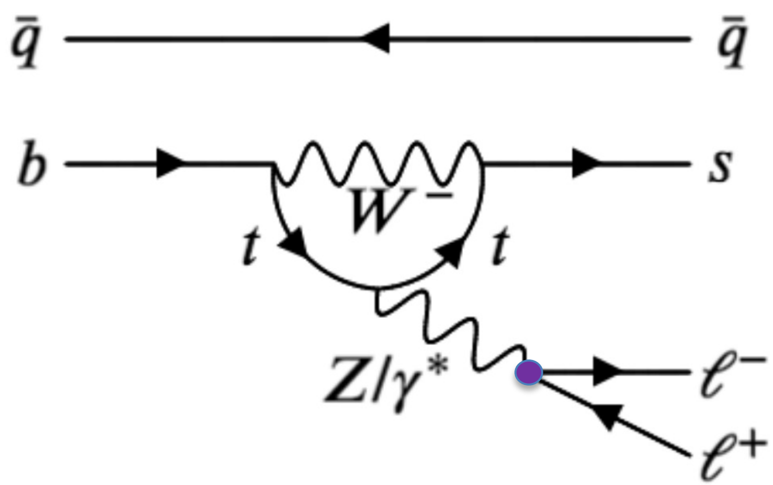
from M. H. Schune



Lepton flavour universality

- In SM, three lepton families (e, μ, τ) have identical couplings to the gauge bosons





  - which means, e.g.,

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \cong 1$$

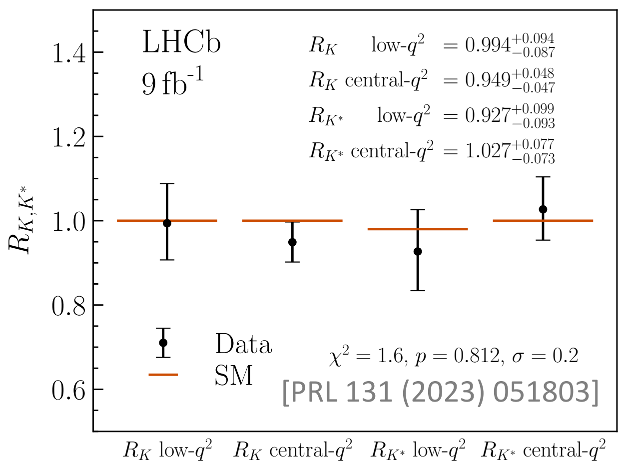
$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

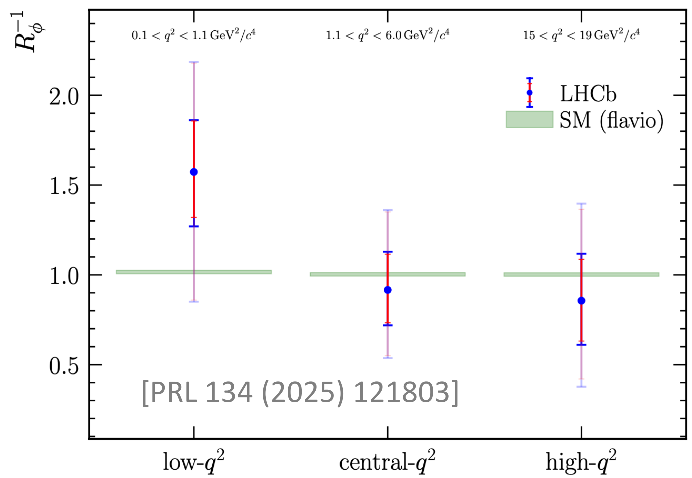
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

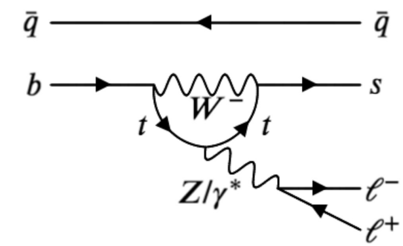
- Lepton flavour universality violation? New Physics!

LFU in $b \to s\ell^+\ell^-$ decays

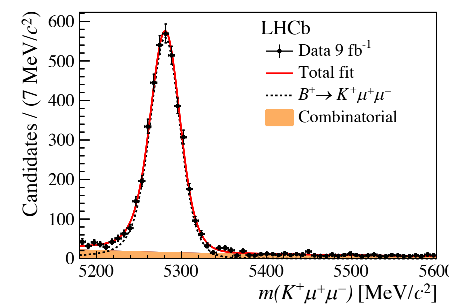
- All consistent with SM for now

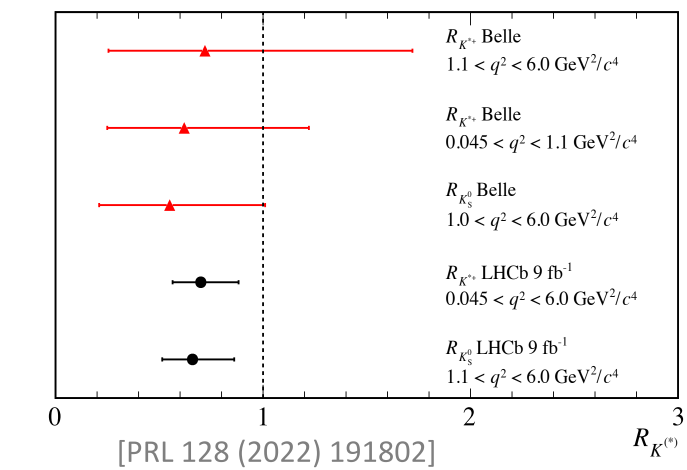


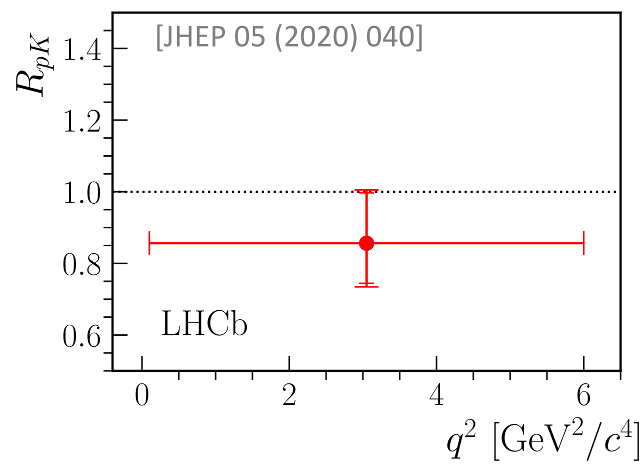


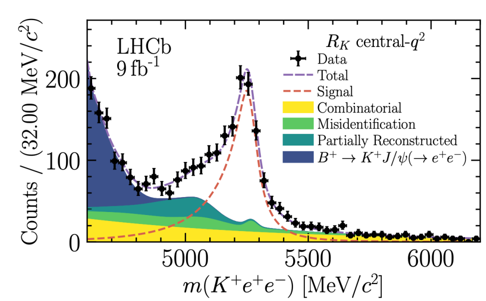


$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$



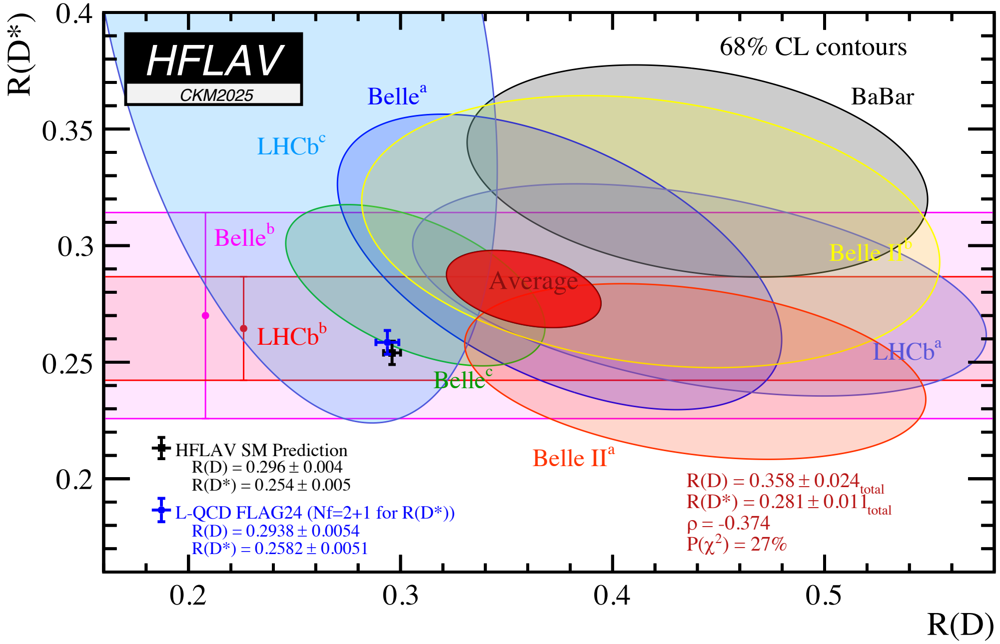


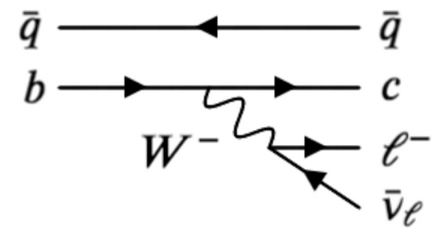




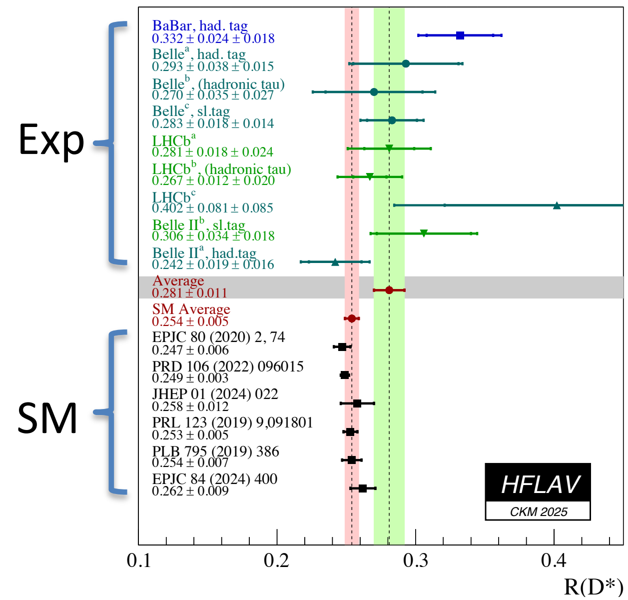
LFU in $b \to c\ell\nu$ decays

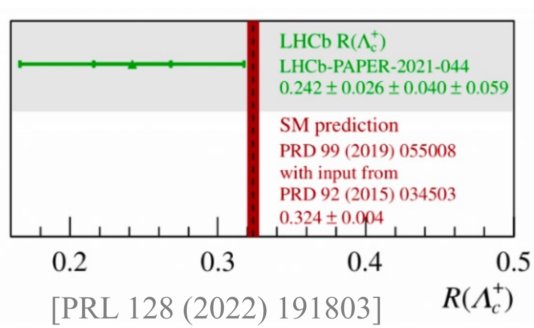
- Deviations from SM seen by Babar/Belle/LHCb



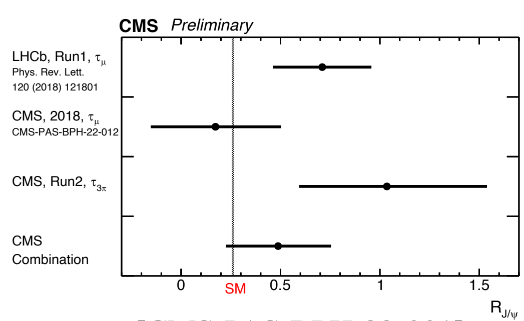


$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$



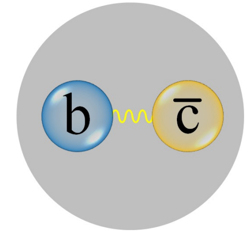


[PRL 128 (2022) 191803]



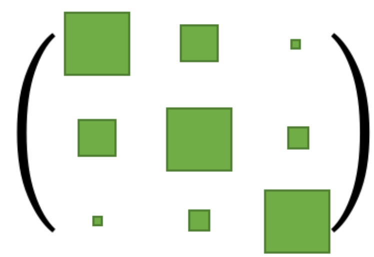
[CMS-PAS-BPH-23-001]

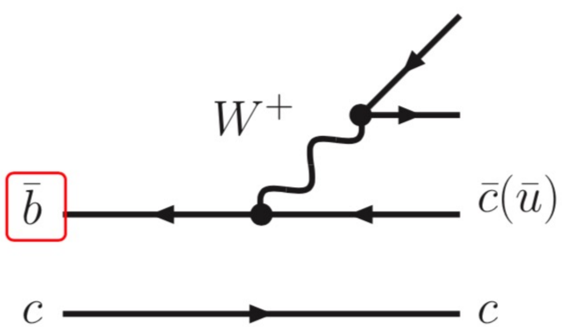
B_c meson

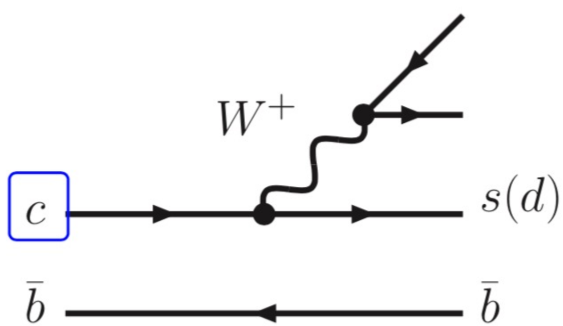


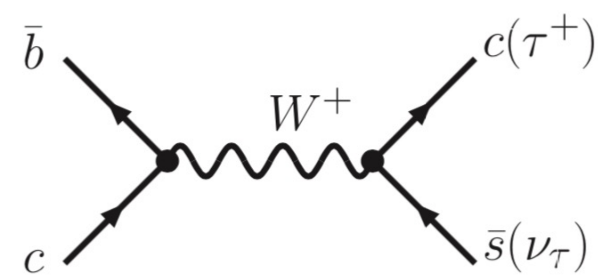
- Formed by two different heavy quarks, unique in the Standard Model. Both *b*- & *c*-quark can decay, or annihilate
  - $\bar{b} \to \bar{c}W^+$, 20%, e.g., $J/\psi\ell^+\nu_\ell$
  - $c \to sW^+$, 70%, e.g., $B_s^0\pi^+$
  - $c\bar{b} \to W^+$, 10%, e.g., $\tau^+\nu_\tau$

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



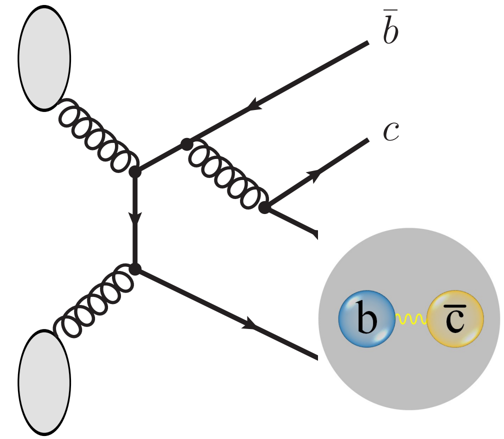






B_c production

- Difficult to produce at e^+e^- machine. Mainly through $gg \to B_c + b + \bar{c}$ at LHC



- Production rate
  - Theoretical prediction (in nb)

[C.-H. Chang, *et al.*, PRD 71 (2005) 074012]

-	$\vert({}^1S_0)_{\mathbf{1}}\rangle$	$\vert({}^3S_1)_{\mathbf{1}}\rangle$	$\vert({}^1S_0)_{\mathbf{8}}g\rangle$	$\vert({}^3S_1)_{\mathbf{8}}g\rangle$	$\vert({}^1P_1)_{\mathbf{1}}\rangle$	$\vert({}^3P_0)_{\mathbf{1}}\rangle$	$\vert({}^3P_1)_{\mathbf{1}}\rangle$	$\vert({}^3P_2)_{\mathbf{1}}\rangle$
LHC†	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

    - Color octet contribution is small
  - $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)| \approx 0.6$
  - $\sigma(B_c^+) \sim 0.9$ μb for $\sqrt{s} = 14$ TeV

Before LHC started

CHIN. PHYS. LETT. Vol. 27, No. 6 (2010) 061302

Experimental Prospects of the B_c Studies of the LHCb Experiment *

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(Received 3 February 2010)

The experimental prospects of the B_c studies of the LHCb experiment are discussed. Production rates of B_c mesons at different center-of-mass energies are estimated with the dedicated generator BCVEGPY. Theoretical estimates and experimental measurements of the $B_c^\pm$ inclusive production cross section at $\sqrt{s} = 1.96$ TeV are compared. The possibilities of studying B_c production, B_c spectroscopy, B_c decays and CP violation in B_c decays in the LHCb experiment are evaluated.

identify, as discussed above. A fast simulation shows that the mass of the $B_c(2^3S_1)$ state would be shifted down by the mass difference of $M(B_c^{*+}) - M(B_c^+)$ and the mass resolution is not affected much when the $B_c(2^3S_1)$ state is reconstructed only with $B_c^+\pi^+\pi^-$ and the photon is missing. Thus the $2S$ states will probably be observed at the LHCb experiment, and it will also be possible to distinguish the 2^3S_1 state from the 2^1S_0 state if the mass difference between the B_c^{*+} and B_c^+ mesons is sufficiently larger than that between the 2^3S_1 and 2^1S_0 states.

LHCb experiment. Taking the inclusive cross section of the B_c^+ meson as 0.9 μb and the branching ratio $\mathcal{B}(B_c^+ \to B_s^0\pi^+)$ as 16.4%[1] and assuming the efficiency of reconstructing B_c^+ from $B_s^0\pi^+$ as 30%, we will be able to observe about 100 $B_c^+ \to B_s^0\pi^+$ events with $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ and about 120 $B_c^+ \to B_s^0\pi^+$ events with $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$ from 1 fb^{-1} of data, which may be not very interesting for the CP violation studies of the B_s^0 meson, but we can at least measure the branching ratios of such decays and test the theoretical predictions of their branching ratios.

Progress in the past 17 years

2008

$B_c^{\pm}$ $I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

$B_c^{\pm}$ MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
6.276 ±0.004 OUR AVERAGE				
6.2756±0.0029±0.0025	[1] AALTONEN	08M	CDF	$p\bar{p}$ at 1.96 TeV
6.4 ±0.39 ±0.13	[2] ABE	98M	CDF	$p\bar{p}$ at 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.2857±0.0053±0.0012	[1] ABULENCIA	06C	CDF	Repl. by AALTONEN 08M
6.32 ±0.06	[3] ACKERSTAFF	98O	OPAL	$e^+e^- \to Z$

[1] Measured using a fully reconstructed decay mode of $B_c \to J/\psi\pi$.
[2] ABE 98M observed $20.4^{+6.2}_{-5.5}$ events in the $B_c^+ \to J/\psi(1s)\ell\nu_\ell$ with a significance of > 4.8 standard deviations. The mass value is estimated from $m(J/\psi(1S)\ell)$.
[3] ACKERSTAFF 98O observed 2 candidate events in the $B_c \to J/\psi(1S)\pi^+$ channel with an estimated background of 0.63 ± 0.20 events.

$B_c^{\pm}$ MEAN LIFE

VALUE (10^{-12} s)	DOCUMENT ID		TECN	COMMENT
0.46 ±0.07 OUR AVERAGE				
$0.463^{+0.073}_{-0.065}\pm0.036$	[4] ABULENCIA	06O	CDF	$p\bar{p}$ at 1.96 TeV
$0.46\ ^{+0.18}_{-0.16}\ \pm0.03$	[4] ABE	98M	CDF	$p\bar{p}$ 1.8 TeV

[4] The lifetime is measured from the $J/\psi(1S)e$ decay vertices.

B_c^+ DECAY MODES × B($\bar{b} \to B_c$)

B_c^- modes are charge conjugates of the modes below.

The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times$ B($\bar{b} \to B_c$).

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$anything	$(5.2^{+2.4}_{-2.1}) \times 10^{-5}$	
Γ_2	$J/\psi(1S)\pi^+$	$< 8.2 \times 10^{-5}$	90%
Γ_3	$J/\psi(1S)\pi^+\pi^+\pi^-$	$< 5.7 \times 10^{-4}$	90%
Γ_4	$J/\psi(1S)a_1(1260)$	$< 1.2 \times 10^{-3}$	90%
Γ_5	$D^*(2010)^+\bar{D}^0$	$< 6.2 \times 10^{-3}$	90%

2025

B_c^+ $I(J^P) = 0(0^-)$ I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.

Expand/Collapse All

B_c^+ MASS	6274.47 ± 0.32 MeV
$m_{B_c^+} - m_{B_s^0}$	907.8 ± 0.5 MeV
B_c^+ MEAN LIFE	$(0.510 \pm 0.009) \times 10^{-12}$ s

POLARIZATION IN B_c^+ DECAY

Γ_L/Γ in $B_c^+ \to J/\psi D_s^{*+}$	0.34 ± 0.09
$A_P(B_c^+)$	-0.010 ± 0.010

B_c^+ DECAY MODES × B($\bar{b} \to B_c$)

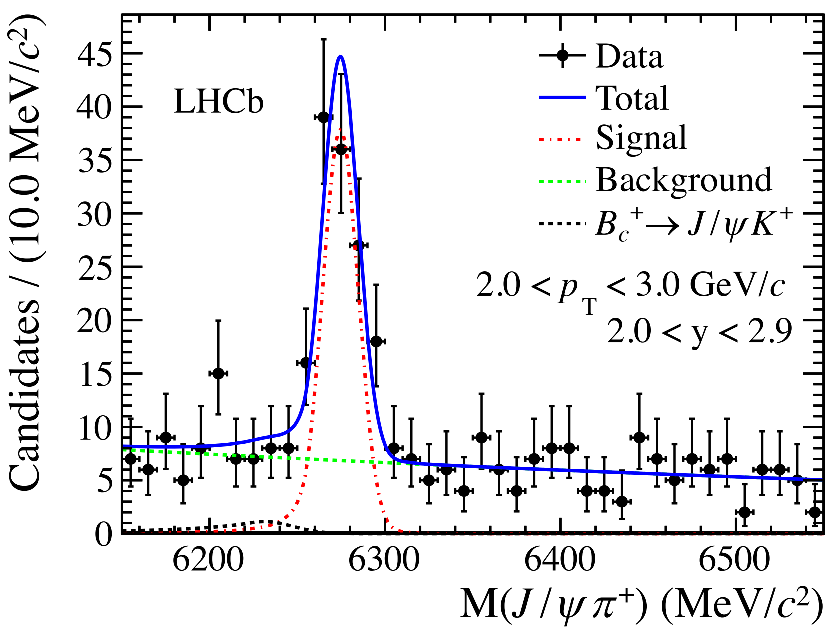
The following quantities are not pure branching ratios; rather the fractions $\Gamma_i/\Gamma \times$ B($\bar{b} \to B_c$). B_c^- modes are charge conjugates of the modes below.

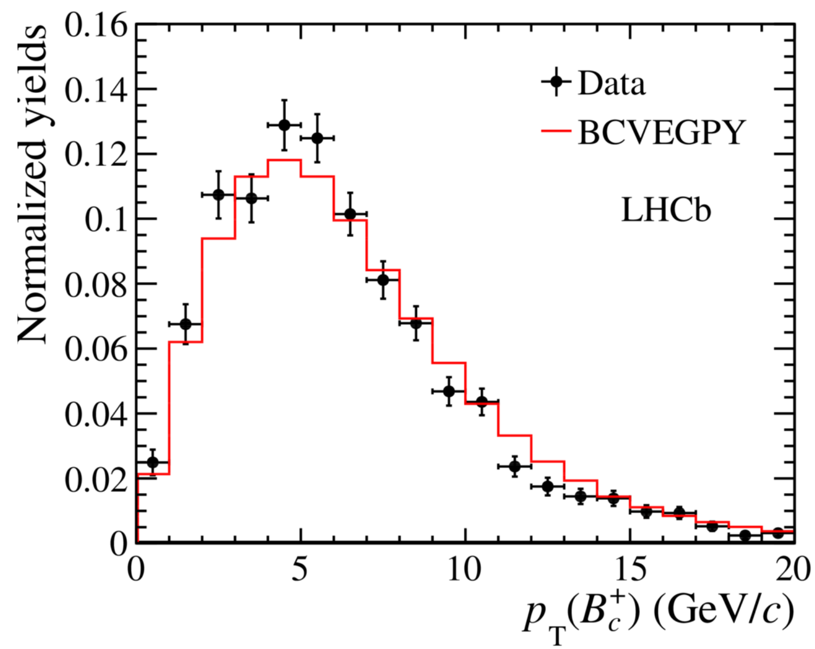
	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	[1] seen		
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$	seen		2372
Γ_3	$J/\psi(1S)\tau^+\nu_\tau$	seen		1932
Γ_4	$J/\psi(1S)\pi^+$	seen		2370
Γ_5	$J/\psi(1S)K^+$	seen		2341
Γ_6	$J/\psi(1S)\pi^+\pi^0$			2363
Γ_7	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen		2350
Γ_8	$J/\psi(1S)K^+\pi^-\pi^+$			2294
Γ_9	$J/\psi(1S)K^+K^-K^+$			2073
Γ_{10}	$J/\psi(1S)a_1(1260)$	not seen		2169
Γ_{11}	$J/\psi(1S)K^+K^-\pi^+$	seen		2203
Γ_{12}	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen		2309
Γ_{13}	$\psi(2S)\pi^+$	seen		2051
Γ_{14}	$\psi(2S)\pi^+\pi^-\pi^+$			2026
Γ_{15}	$\psi(2S)K^+K^-\pi^+$			1838
Γ_{16}	$J/\psi(1S)D^0K^+$	seen		1539
Γ_{17}	$J/\psi(1S)D^*(2007)^0K^+$	seen		1411
Γ_{18}	$J/\psi(1S)D^*(2010)^+K^{*0}$	seen		919
Γ_{19}	$J/\psi(1S)D^+K^{*0}$	seen		1122
Γ_{20}	$J/\psi(1S)D_s^+$	seen		1821
Γ_{21}	$J/\psi(1S)D_s^{*+}$	seen		1727
Γ_{22}	$J/\psi(1S)p\bar{p}\pi^+$	seen		1791
Γ_{23}	$\chi_{c0}\pi^+$			2205
Γ_{24}	$\chi_{c1}\pi^+$			2152
Γ_{25}	$\chi_{c2}\pi^+$			2126
Γ_{26}	$p\bar{p}\pi^+$	not seen		2970
Γ_{27}	D^0K^+	seen		2837
Γ_{28}	$D^0\pi^+$	not seen		2858
Γ_{29}	$D^{*0}\pi^+$	not seen		2814
Γ_{30}	$D^{*0}K^+$	not seen		2792
Γ_{31}	$D_s^+\bar{D}^0$	$< 7.2 \times 10^{-4}$	CL=90%	2483
Γ_{32}	$D_s^+D^0$	$< 3.0 \times 10^{-4}$	CL=90%	2483
Γ_{33}	$D^+\bar{D}^0$	$< 1.9 \times 10^{-4}$	CL=90%	2521
Γ_{34}	D^+D^0	$< 1.4 \times 10^{-4}$	CL=90%	2521
Γ_{35}	$D_s^{*+}\bar{D}^0$	$< 5.3 \times 10^{-4}$	CL=90%	2425
Γ_{36}	$D_s^+\bar{D}^*(2007)^0$	$< 4.6 \times 10^{-4}$	CL=90%	2427
Γ_{37}	$D_s^{*+}D^0$	$< 9 \times 10^{-4}$	CL=90%	2425
Γ_{38}	$D_s^+D^*(2007)^0$	$< 6.6 \times 10^{-4}$	CL=90%	2427
Γ_{39}	$D^*(2010)^+\bar{D}^0$	$< 3.8 \times 10^{-4}$	CL=90%	2467
Γ_{40}	$D^*(2010)^+\bar{D}^0$, $D^{*+} \to D^+\pi^0$ / γ	not seen		

B_c^+ production

- Double-differential production as (p_{T}, y), w/ 2 fb^{-1} data at 8 TeV
- p_{T} distribution well described by BcVegPy

[PRL 114 (2015) 132001]



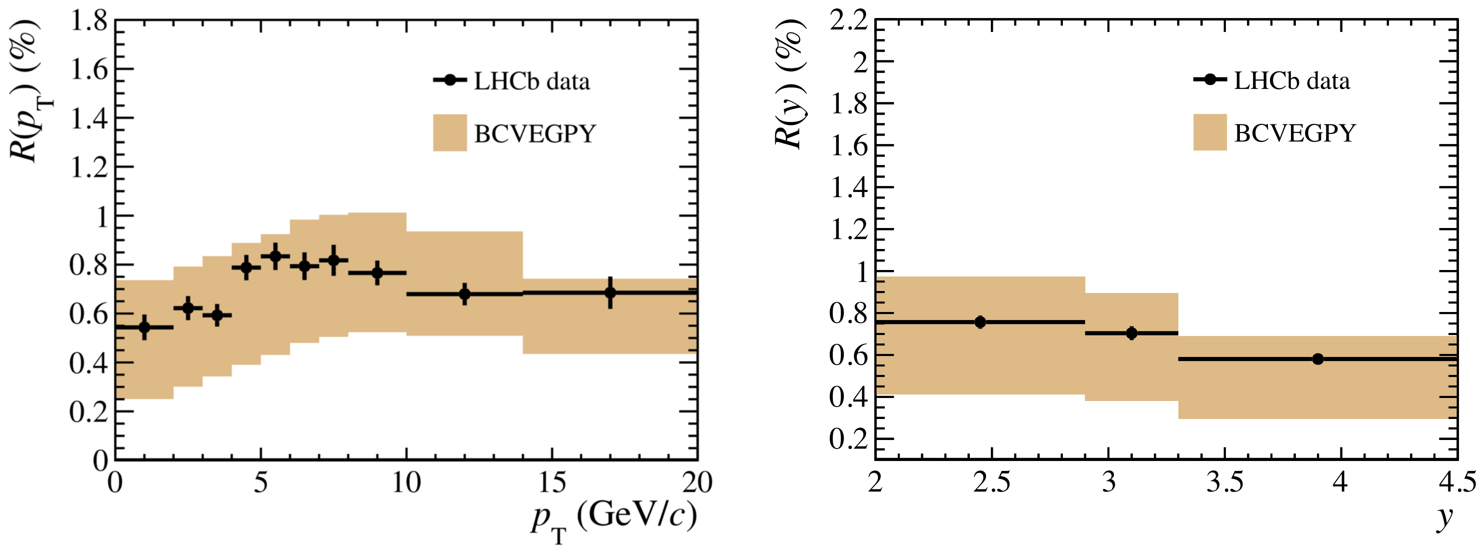


B_c^+ production

- $\mathcal{R} = \frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} = (0.683 \pm 0.018 \pm 0.009)\%$
  for $p_\mathrm{T} < 20$ GeV, $y \in [2, 4.5]$

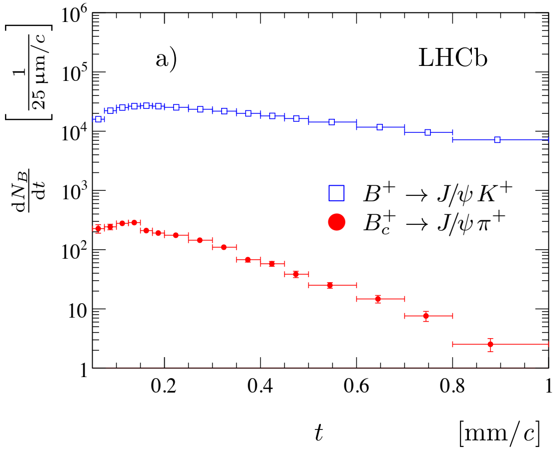
- Using
  $\sigma(B_c^+) = 0.47$ μb, theoretical prediction by BcVegPy
  $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
  $\sigma(B^+, p_\mathrm{T}(B) < 40\ \mathrm{GeV}/c, 2.0 < y < 4.5) = 38.9$ μb at $\sqrt{s} = 7$ TeV, measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
  $\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12

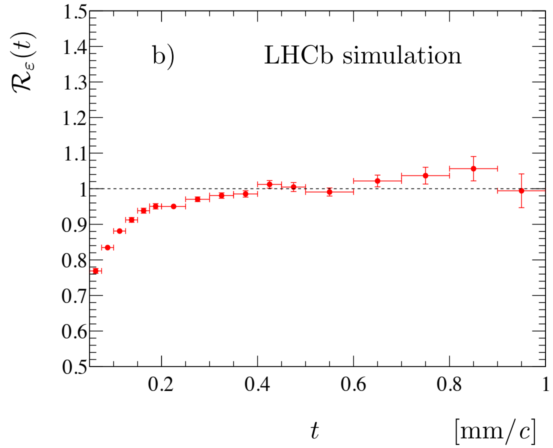
[PRL 114 (2015) 132001]



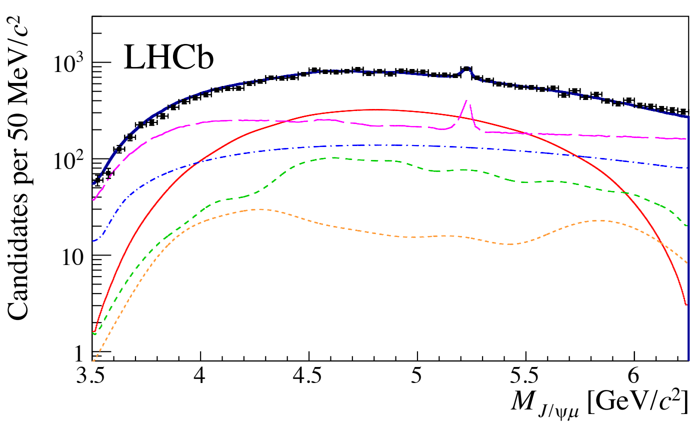
B_c^+ lifetime

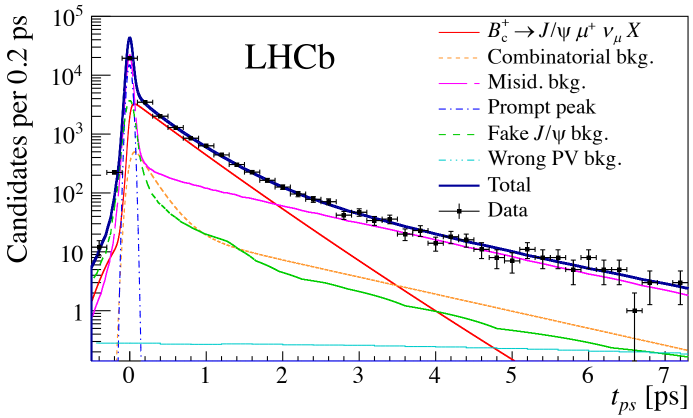
- $B_c^+ \to J/\psi\pi^+, \quad \tau = 513 \pm 11 \pm 6$ fs [PLB 742 (2015) 39]





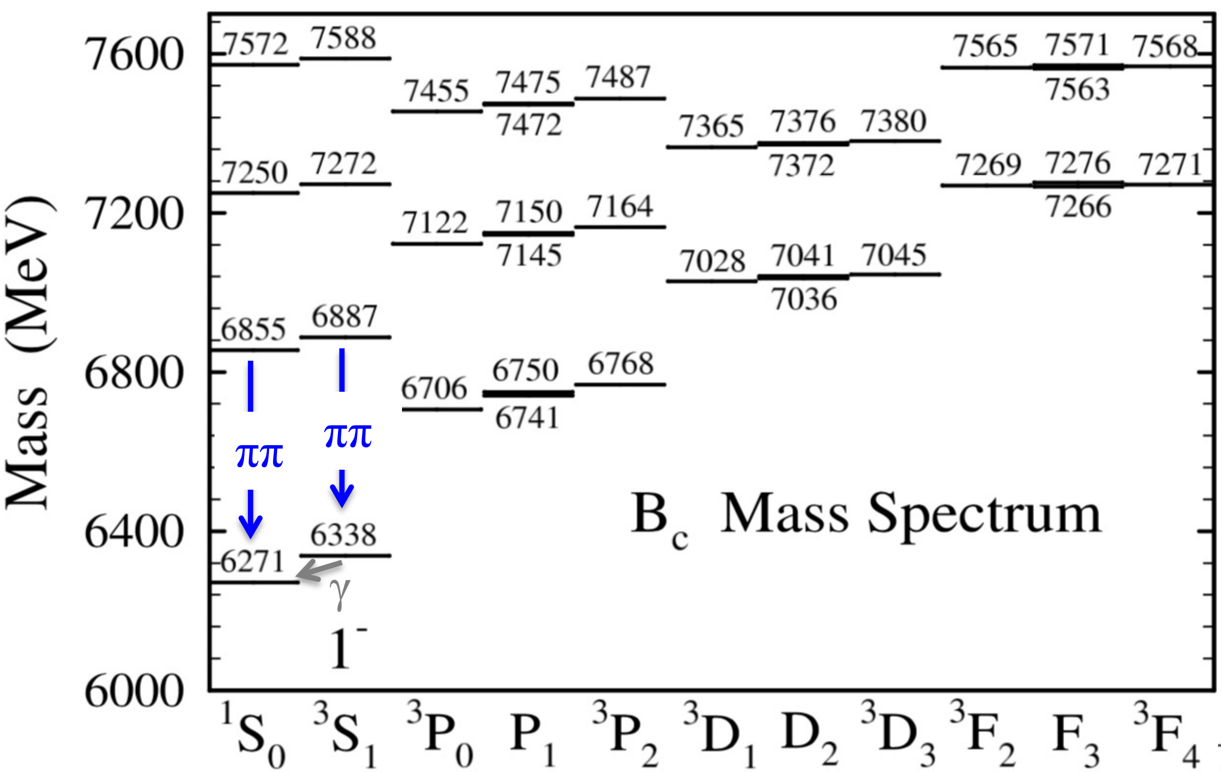
- $B_c^+ \to J/\psi\mu^+X, \ \tau = 509 \pm 8 \pm 12$ fs [EPJC 74 (2014) 2839]





Excited B_c^+ states

- B_c has a rich spectrum



[S.Godfrey, PRD 70 (2004) 054017]

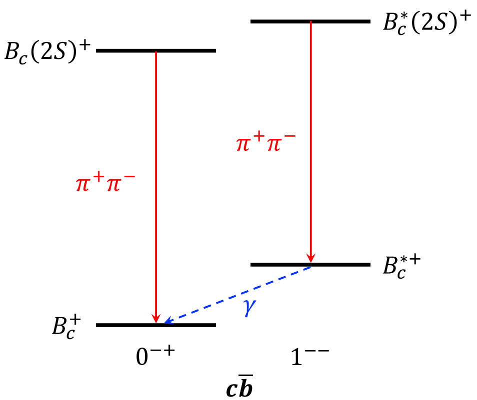
State	Decay	GKLRY *	Godfrey †
1^3S_1	$1^1S_0+\gamma$	100	100
1^3P_2	$1^3S_1+\gamma$	100	100
$1P'_1$	$1^3S_1+\gamma$	6	12.1
	$1^1S_0+\gamma$	94	87.9
$1P_1$	$1^3S_1+\gamma$	87	82.2
	$1^1S_0+\gamma$	13	17.8
1^3P_0	$1^3S_1+\gamma$	100	100
2^1S_0	$1^1S_0+\pi\pi$	74	88.1
	$1P'_1+\gamma$		9.4
	$1P_1+\gamma$		2.0
	$1^3S_1+\gamma$		0.5
2^3S_1	$1^3S_1+\pi\pi$	58	79.6
	$1^3P_2+\gamma$		8.0
	$1P'_1+\gamma$		1.0
	$1P_1+\gamma$		6.6
	$1^3P_0+\gamma$		4.0
	$2^1S_0+\gamma$		0.01
	$1^1S_0+\gamma$		0.8

* [I. P. Gouz, *et al.*, Phys. Atom. Nucl. 67 (2004) 1559]

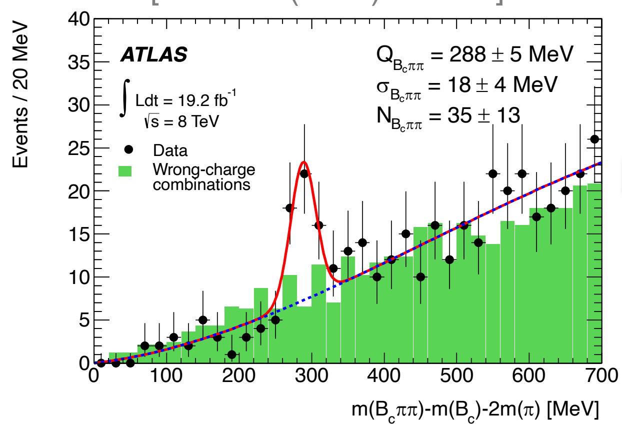
† [S.Godfrey, PRD 70 (2004) 054017]

Observation of $B_c^{(*)}(2S)^+$

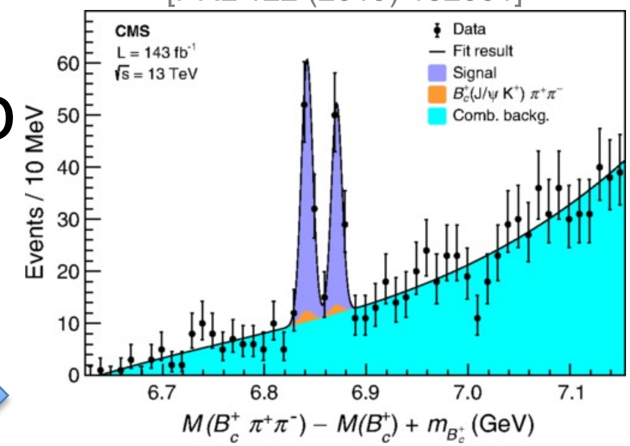
- Mixture (?) by ATLAS, then both states by CMS and LHCb

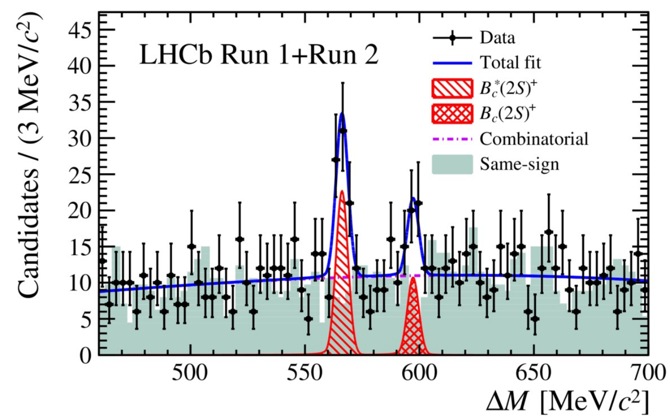


[PRL 113 (2014) 212004]



[PRL 122 (2019) 132001]





[PRL 122 (2019) 232001]

LHCb

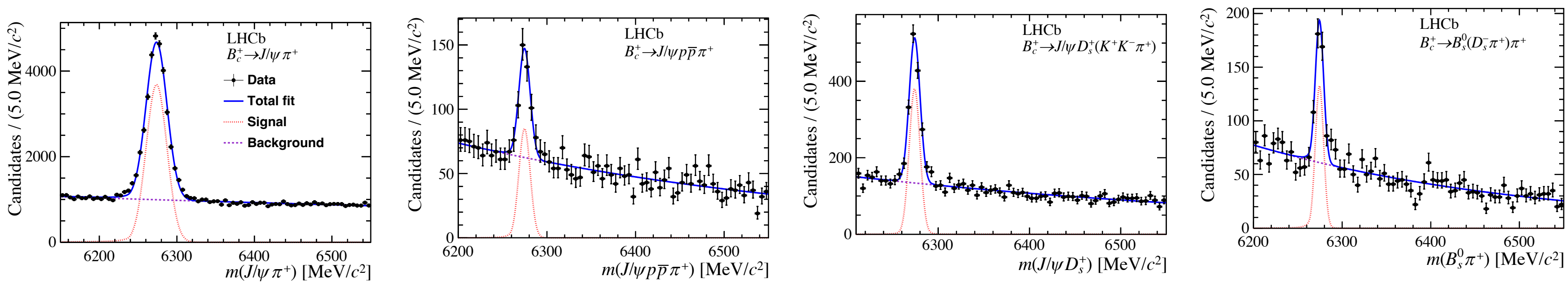
$$M(B_c(2^3S_1)^+)_{\rm rec} = 6841.2 \pm 0.6({\rm stat}) \pm 0.1({\rm syst}) \pm 0.8(B_c^+)\ {\rm MeV}/c^2$$
$$M(B_c(2S)^+) = 6872.1 \pm 1.3({\rm stat}) \pm 0.1({\rm syst}) \pm 0.8(B_c^+)\ {\rm MeV}/c^2$$
$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} = 31.0 \pm 1.4({\rm stat}) \pm 0.0({\rm syst})\ {\rm MeV}/c^2$$

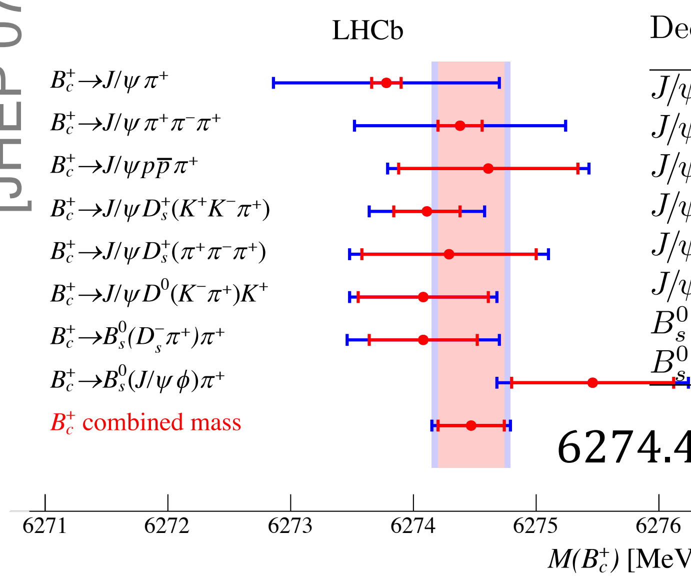
CMS

$$M(B_c(2^3S_1)^+)_{\rm rec} = 6842.0 \pm 1.0({\rm stat}) \pm 0.0({\rm syst}) \pm 0.8(B_c^+)\ {\rm MeV}/c^2$$
$$M(B_c(2S)^+) = 6871.0 \pm 1.2({\rm stat}) \pm 0.8({\rm syst}) \pm 0.8(B_c^+)\ {\rm MeV}/c^2$$
$$M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\rm rec} = 29.0 \pm 1.5({\rm stat}) \pm 0.7({\rm syst})\ {\rm MeV}/c^2$$

B_c^+ mass measurement

- Six decay modes, with all Run1+2 data, precision improved by a factor of 2



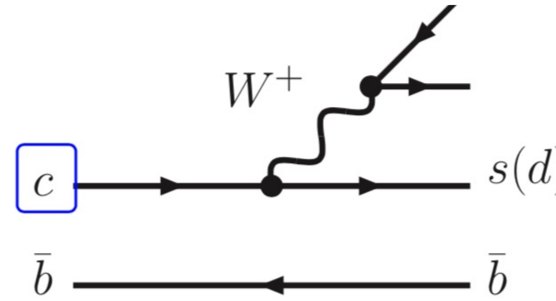


Decay mode	Yield	Fitted mass [MeV/c^2]	Corrected mass [MeV/c^2]	Resolution [MeV/c^2]
$J/\psi\,\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\,\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi\,p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 0.76
$J/\psi\,D_s^+(K^+K^-\pi^+)$	1135 ± 49	6274.09 ± 0.27	6274.11 ± 0.27	5.93 ± 0.30
$J/\psi\,D_s^+(\pi^+\pi^-\pi^+)$	202 ± 20	6274.57 ± 0.71	6274.29 ± 0.71	6.63 ± 0.67
$J/\psi\,D^0(K^-\pi^+)K^+$	175 ± 21	6273.97 ± 0.53	6274.08 ± 0.53	3.87 ± 0.57
$B_s^0(D_s^-\pi^+)\pi^+$	316 ± 27	6274.36 ± 0.44	6274.08 ± 0.44	4.67 ± 0.48
$B_s^0(J/\psi\,\phi)\pi^+$	299 ± 37	6275.87 ± 0.66	6275.46 ± 0.66	5.32 ± 0.74

$6274.47 \pm 0.27 \pm 0.17$ MeV, taken as WA by PDG

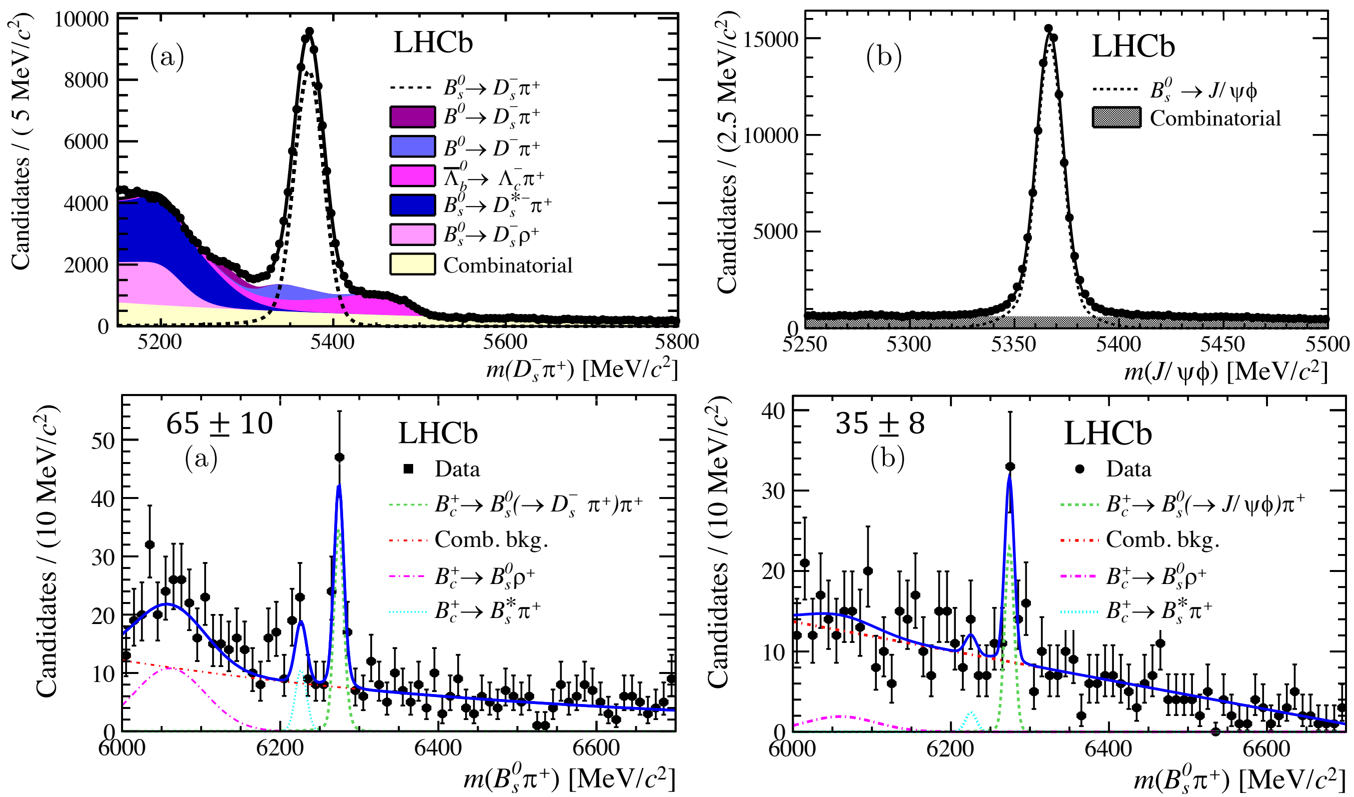
[JHEP 07 (2020) 123]

$B_c^+ \to B_s^0 \pi^+$



- Observed w/ Run1 data, production ratio for $\eta \in [2, 5]$

$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31 \pm 0.11^{+0.17}_{-0.13}\,(\tau_{B_c})\right) \times 10^{-3}$$

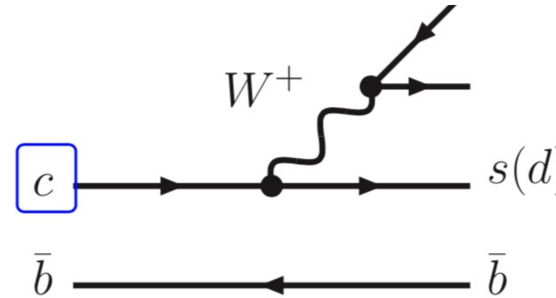


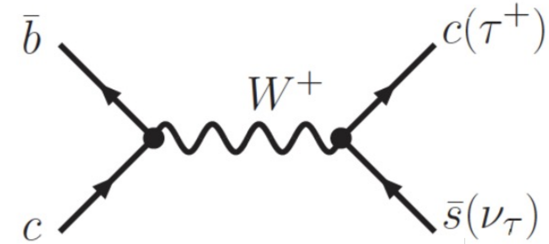
[PRL 111 (2013) 181801]

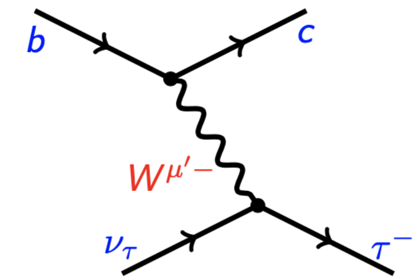
UROP

[JHEP 07 (2023) 066]

$\mathcal{B}(B_c^+ \to B_s^0 \pi^+)$



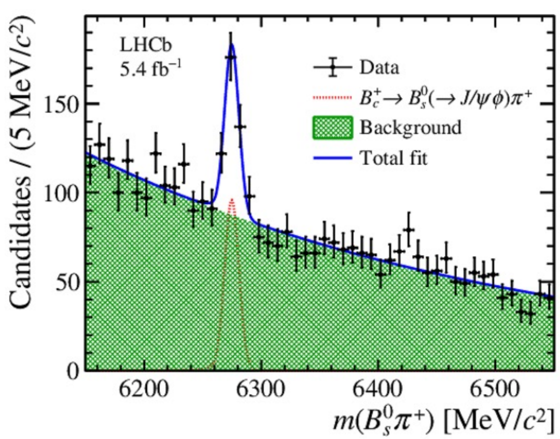


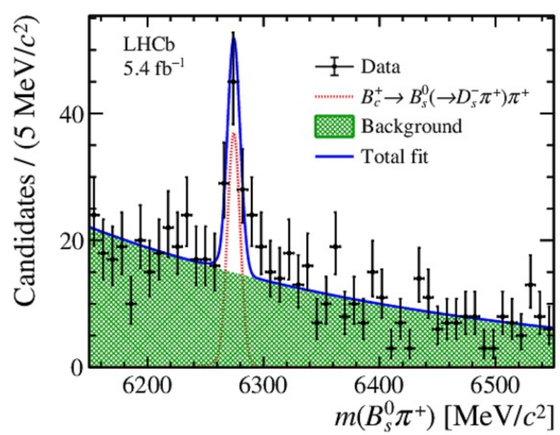


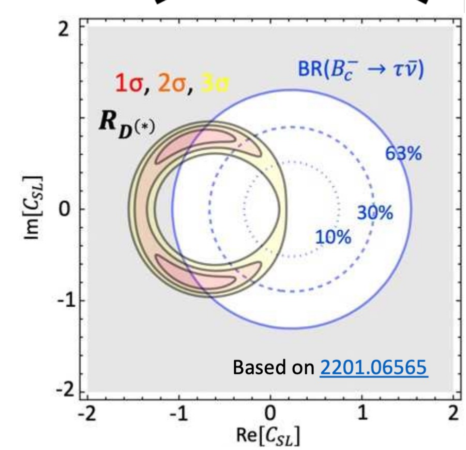
- Measured w/ Run2 data, helps constrain $\Gamma(b \to c\tau\nu)$

$$\frac{\mathcal{B}(B_c^+ \to B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 91 \pm 13$$

$\Longrightarrow$ $\mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ is 8% - 30% depending on $\mathcal{B}(B_c^+ \to J/\psi \pi^+)$



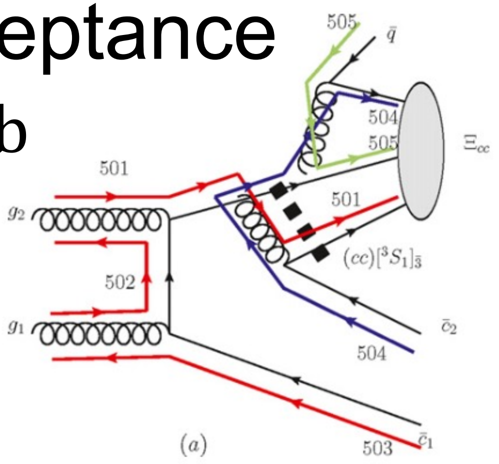




Credit: R. Watanabe

Doubly heavy baryons

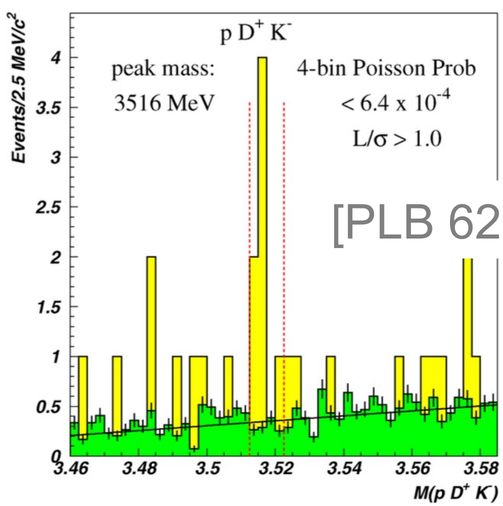
- Production @ 13 TeV, in LHCb acceptance
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+})\sim 40$ nb, $\sigma(\Omega_{cc}^{+})\sim 13$ nb
  - $\sigma(\Xi_{bc}^{+}) = \sigma(\Xi_{bc}^{0})\sim 17$ nb, $\sigma(\Omega_{bc}^{0})\sim 5$ nb



- Mass
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$: 3.5-3.7 GeV, $M(\Omega_{cc}^{+})$, +0.1-0.2 GeV
  - $M(\Xi_{bc}^{+}) \approx M(\Xi_{bc}^{0})$: 6.8-7.1 GeV, $M(\Omega_{bc}^{0})$, +0.05-0.1 GeV
- Lifetime
  - $\tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+}) \approx \frac{1}{3}\tau(\Xi_{cc}^{++})$, $\tau(\Xi_{cc}^{++})$: 0.2-1.05 ps
  - Ξ_{bc}^{+}, Ξ_{bc}^{0}, Ω_{bc}^{0}: 0.1-0.5 ps

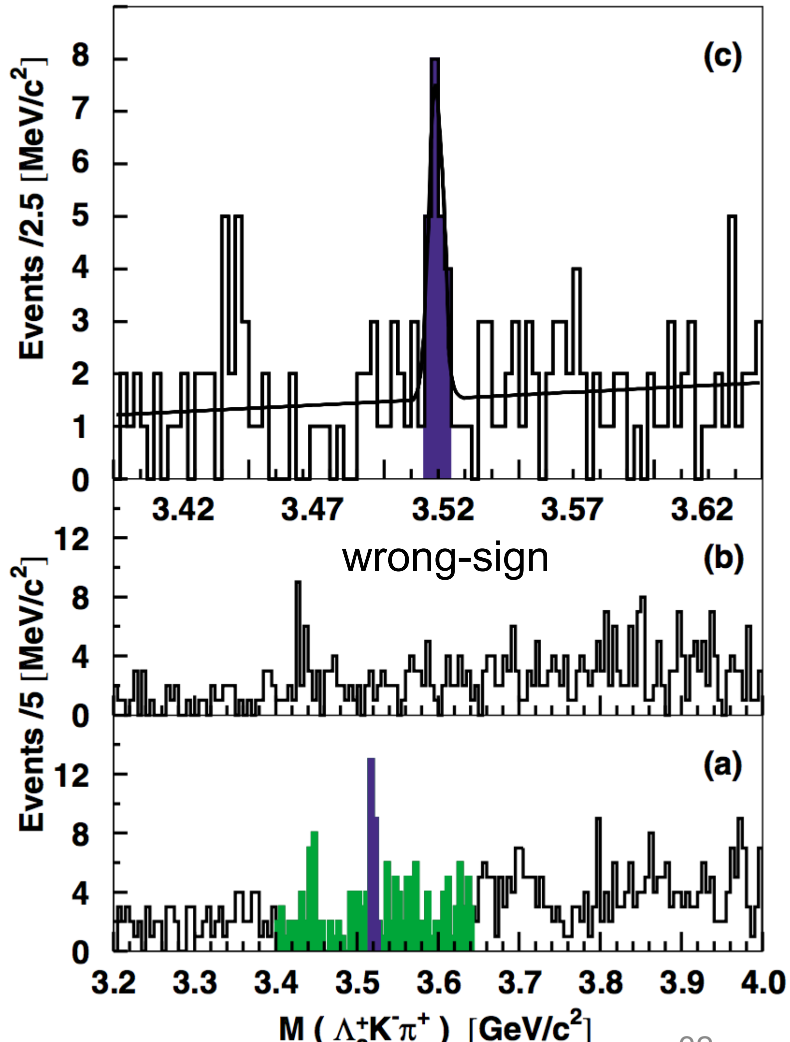
Ξ_{cc}^{+} @ SELEX

- SELEX claimed $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (6.3σ)
  - M, 3519±1 MeV
  - τ, <33 fs @90%CL
  - σ_{prod}, 20% Λ_c^{+} from Ξ_{cc}^{+}
- Also $\Xi_{cc}^{+} \to p D^{+} K^{-}$



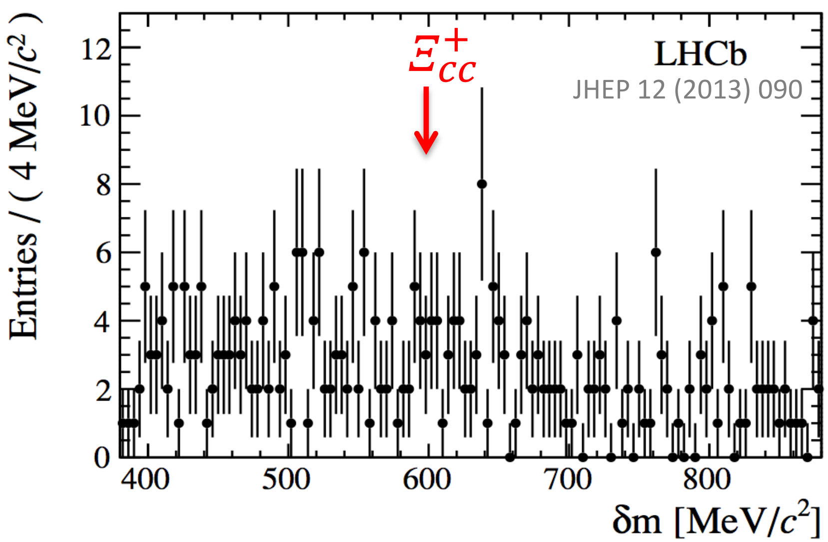
[PLB 628 (2005)18]

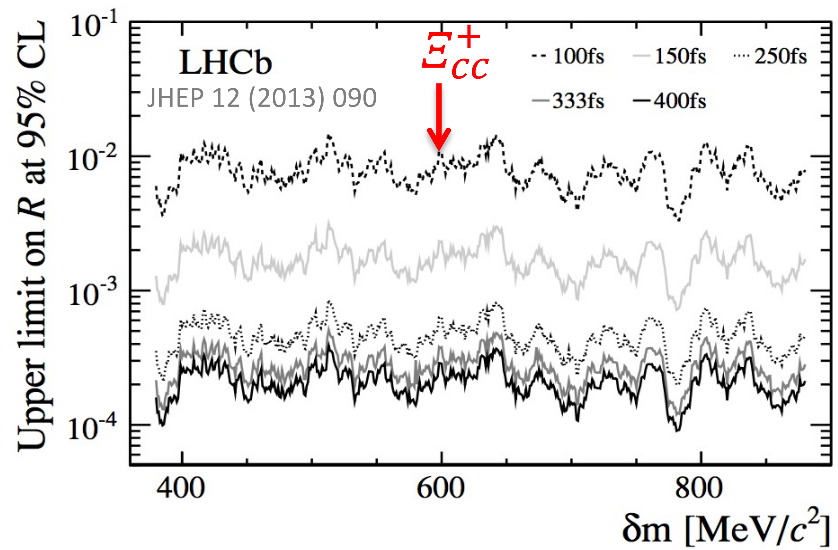
[PRL 89 (2002) 112001]



Ξ_{cc} @ LHCb & others

- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+}$ searched by LHCb w/ 2011 data

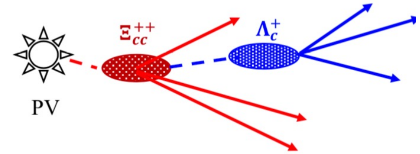


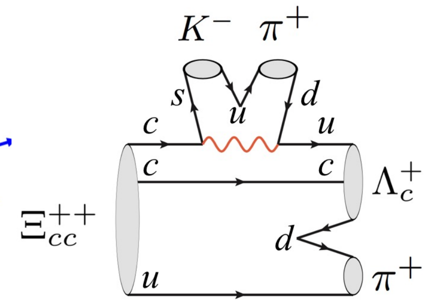


- However, LHCb already had lots of B_c^+ events, and double-charm events…

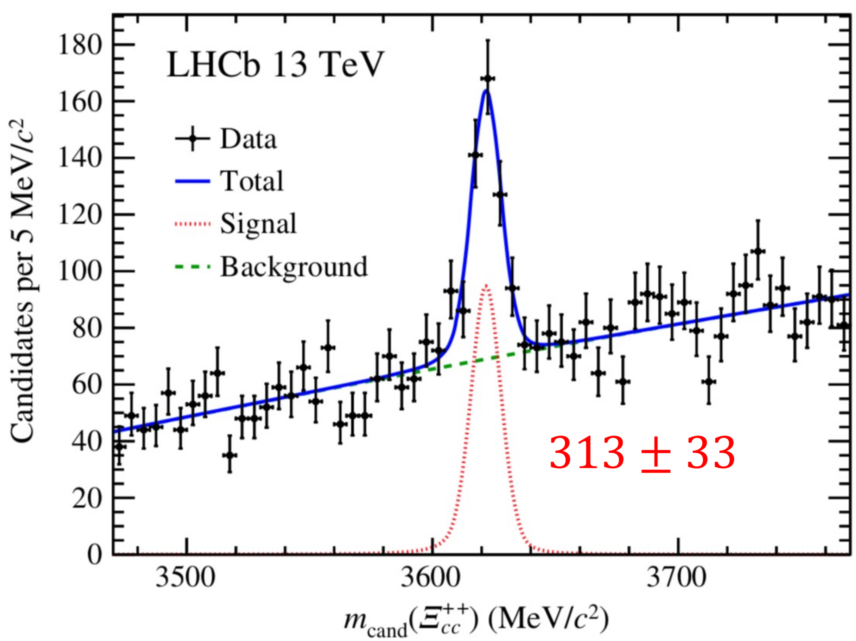
Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

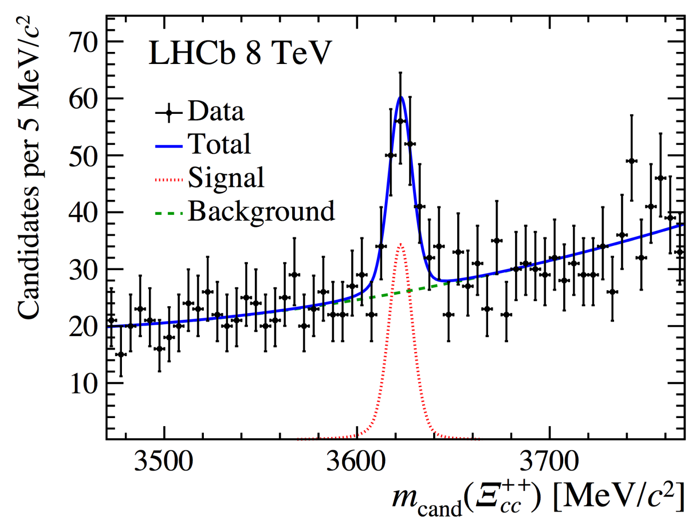
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]





- First observation, in 2016 (>12σ) & Run-I (>7σ)





[PRL 119 (2017) 112001]

Ξ_{cc}^{++} properties

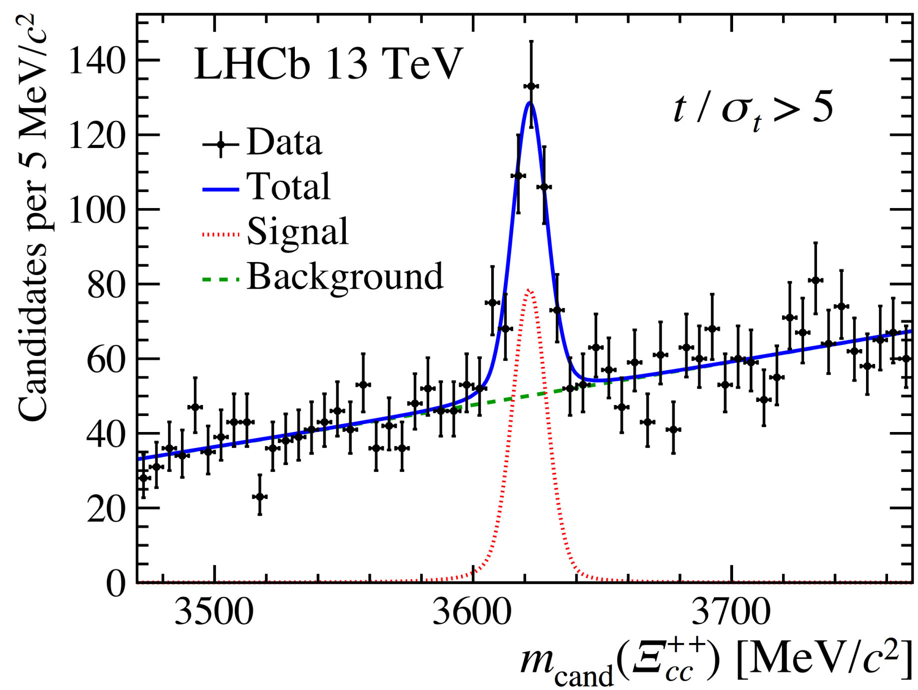
- Ξ_{cc}^{++} mass measured:
$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

SELEX: $M(\Xi_{cc}^{+})$=3519±1 MeV

Isospin partner?

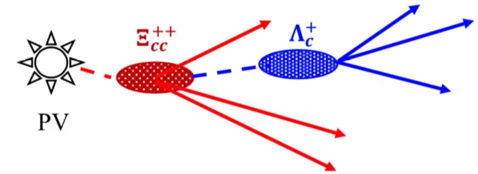
- Decay weakly, mass peak remains after lifetime cut

$\Rightarrow$Measurement of $\tau(\Xi_{cc}^{++})$ needed

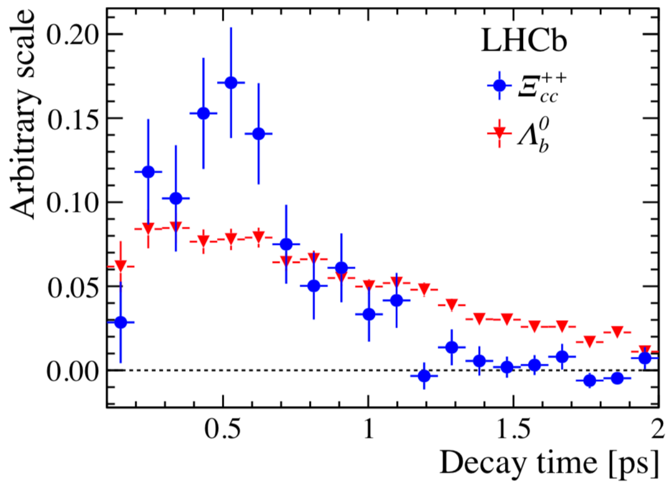


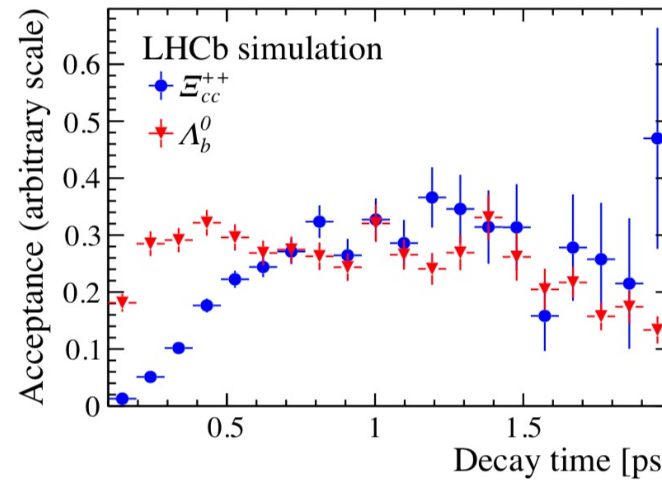
[PRL 119 (2017) 112001]

Ξ_{cc}^{++} lifetime



- Control mode, $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

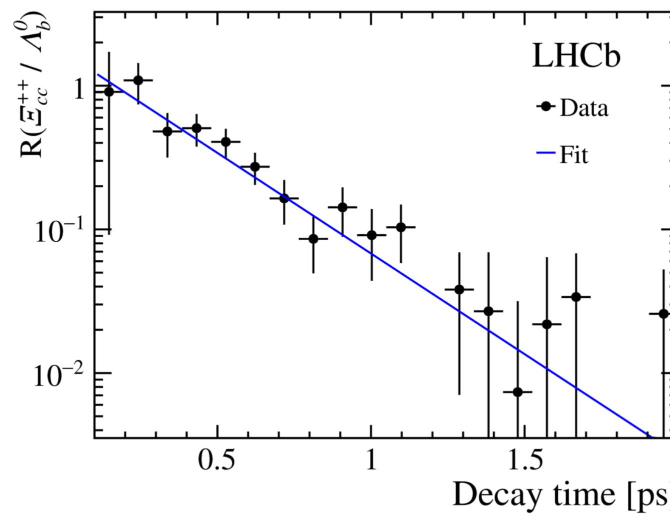




- $\tau(\Xi_{cc}^{++})$

  $= 0.256^{+0.024}_{-0.022} \pm 0.014$ ps

  at lower side prediction: 0.2-1.05ps



- Weakly decay nature established!

[PRL 121 (2018) 052002]

Observation of $\Xi_{cc}^{++} \to \Xi_c^{+} \pi^{+}$

[PRL 121 (2018) 162002]

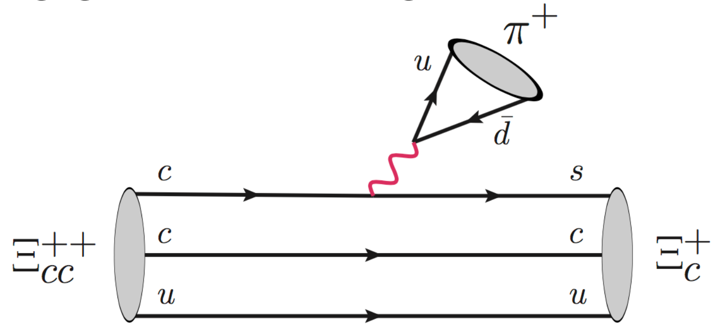
- $\Xi_{cc}^{++} \to \Xi_c^{+} \pi^{+}$ expected to have large BR

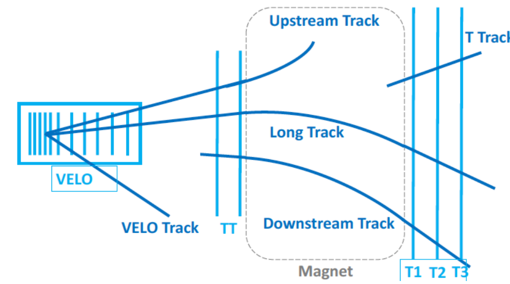
  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]

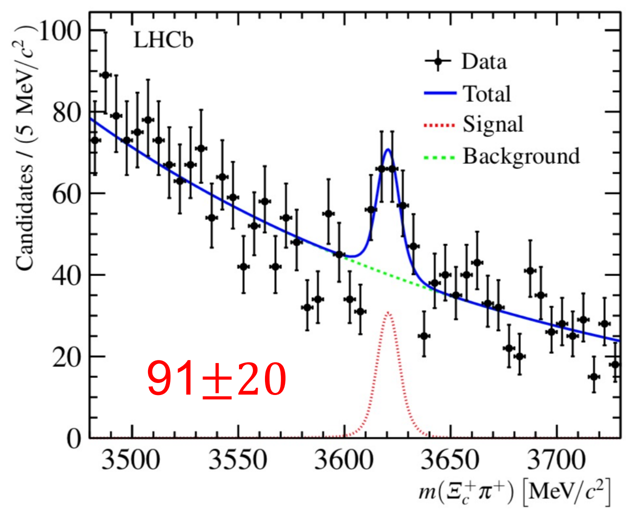
- Re-discovery with 2016 data, 5.9σ
- BR ratio measured

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}) \cdot \mathcal{B}(\Xi_c^{+} \to pK^{-}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}) \cdot \mathcal{B}(\Lambda_c^{+} \to pK^{-}\pi^{+})}$$

$$= 0.035 \pm 0.009 \pm 0.003$$



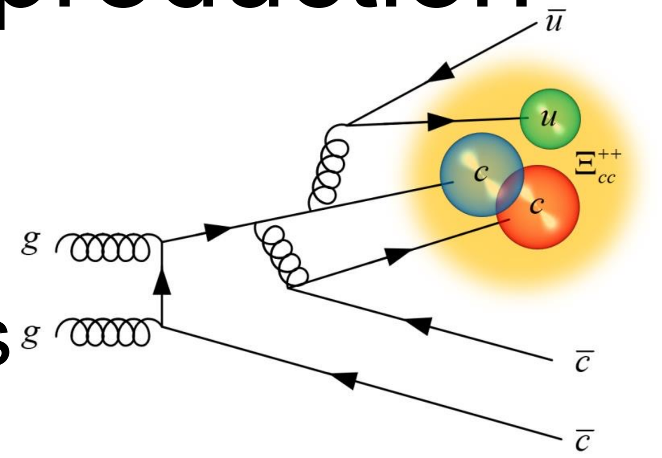




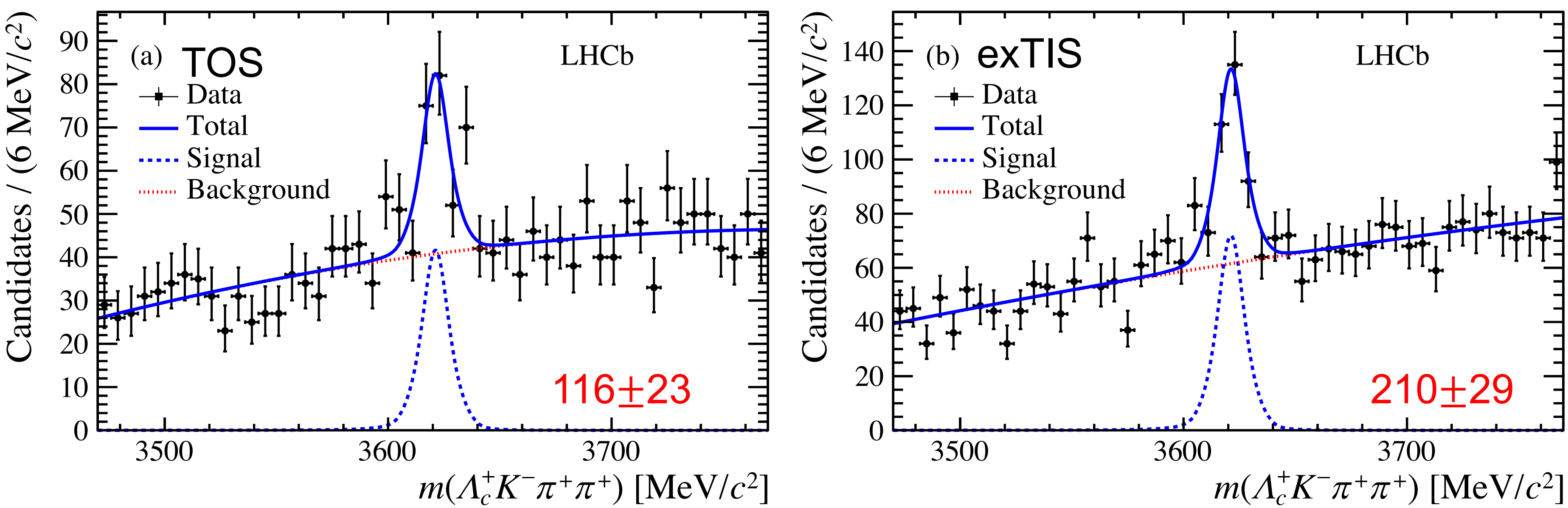
Measurement of Ξ_{cc}^{++} production

- Measured w/ 2016 data

$$N = \sigma_{\text{prod}} \cdot \mathcal{L} \cdot \mathcal{B} \cdot \varepsilon, \quad \sigma_{\text{prod}} \cdot \mathcal{B} = \frac{N}{\varepsilon \mathcal{L}}$$

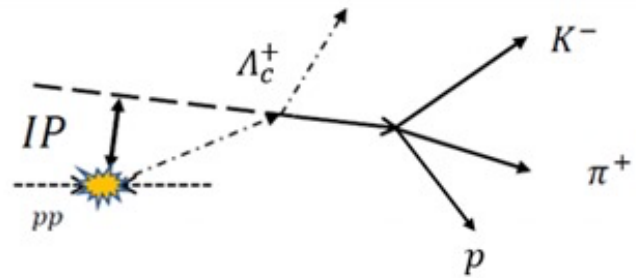


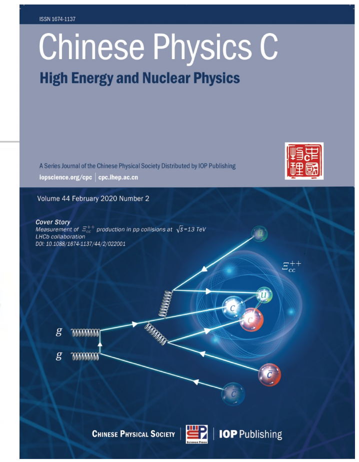
- Accompanying $\bar{c}\bar{c}$ dominates in trigger



Measurement of Ξ_{cc}^{++} production

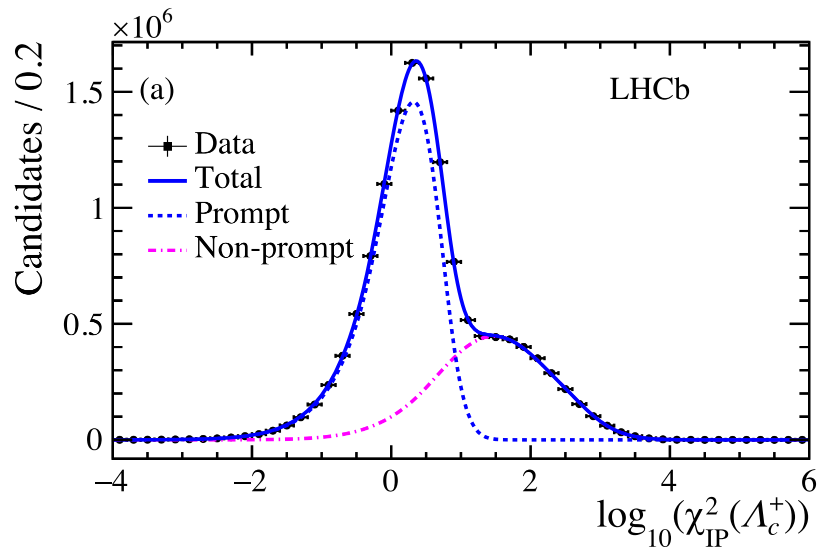
- Relative to Λ_c^+, in
  $4 < p_T < 15$ GeV,
  2<y<4.5





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

SELEX, 20% Λ_c^+ from Ξ_{cc}^+?



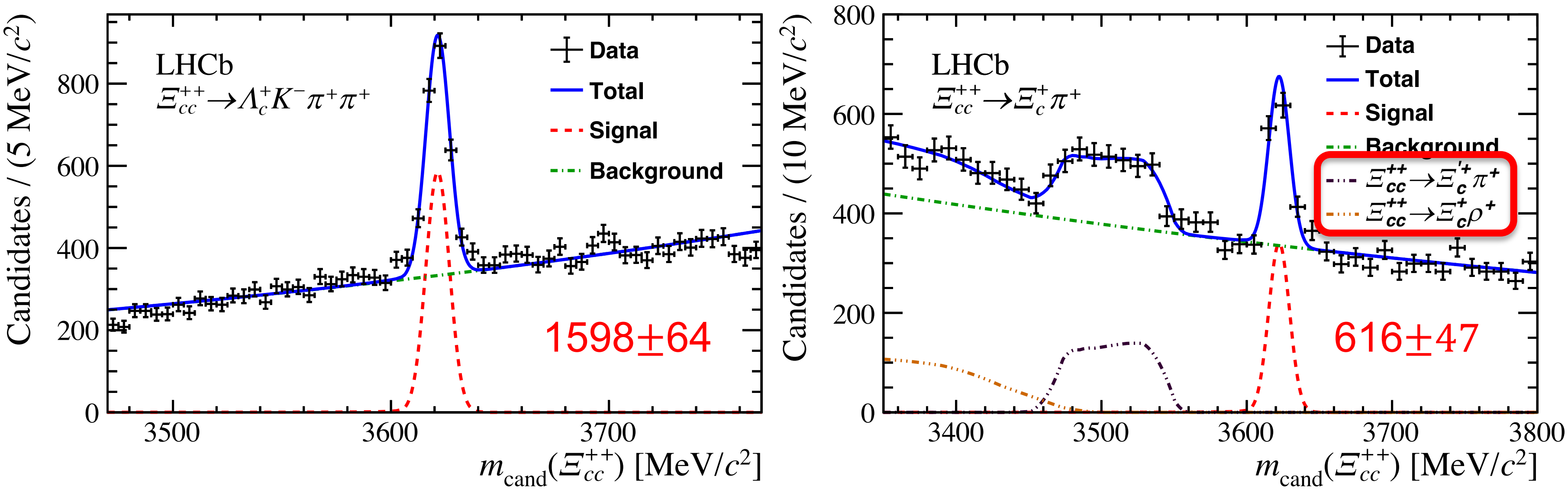
[CPC 44 (2020) 022001]

UROP

Precision measurement of $m(\Xi_{cc}^{++})$

- Preparing to search for excited states, event-selection re-optimised

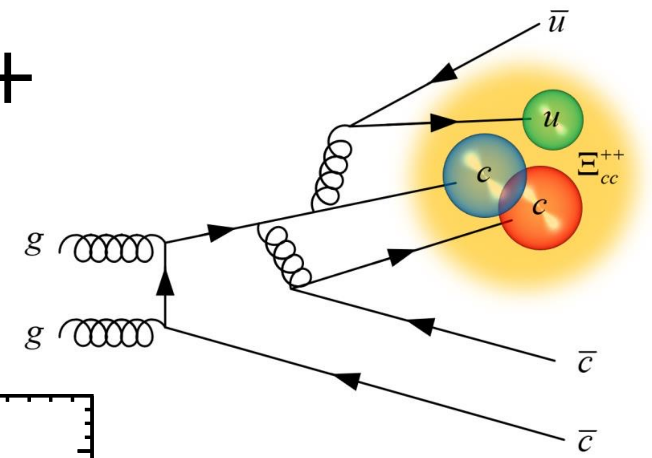
[JHEP 02 (2020) 049]



$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \mathrm{MeV}/c^2$ taken as WA by PDG

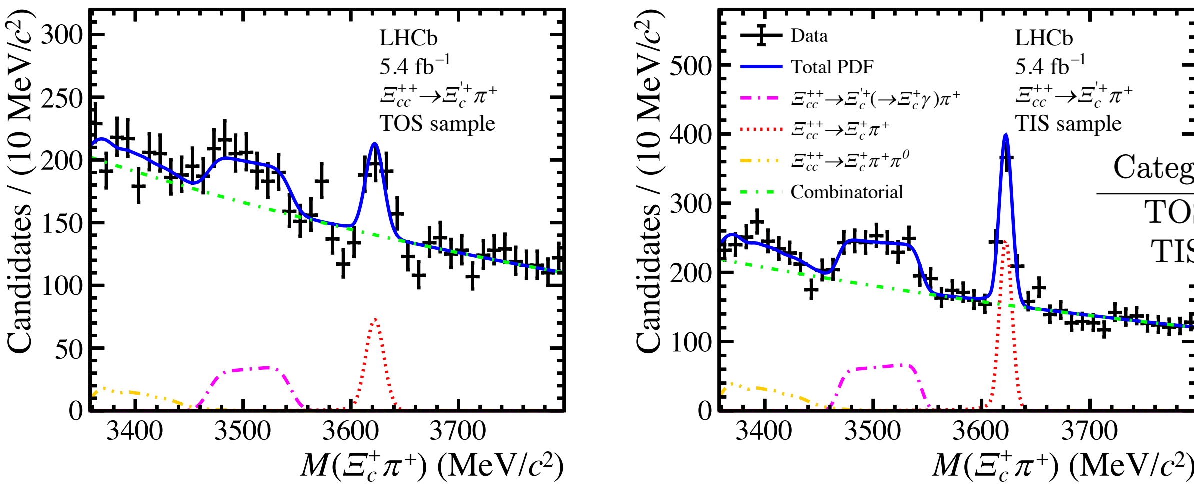
c.f., $3620.6 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$

$\Xi_{cc}^{++} \rightarrow \Xi_c'^{+}\pi^{+}$



[JHEP 05 (2022) 038]

- 2016-2018 data, $\Xi_{cc}^{++} \rightarrow \Xi_c'^{+}(\rightarrow \Xi_c^{+}\gamma)\pi^{+}$



Category	$\Xi_{cc}^{++} \rightarrow \Xi_c'^{+}\pi^{+}$	$\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$
TOS	262 ± 53	159 ± 32
TIS	494 ± 63	379 ± 32

- Branching fraction ratio

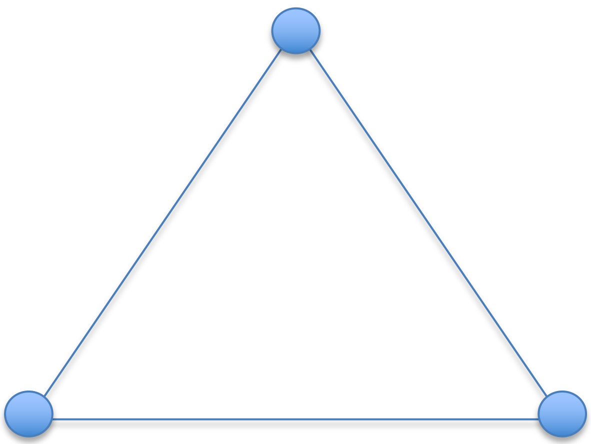
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+})} = 1.41 \pm 0.17 \pm 0.10$$

  – some tension with existing predictions

Summary of DHB studies

First search, Hint[SCPMA 64 (2021) 101062]

$\Omega_{cc}^{+}\ (ccs)$



$\Xi_{cc}^{++}\ (ccu)$

Observation[PRL 119 (2017) 112001]

Mass[JHEP 02 (2020) 049]

Lifetime[PRL 121 (2018) 052002]

Production[CPC 44 (2020) 022001]

Decay $\Xi_{c}^{+}\pi^{+}$ [PRL 121 (2018) 162002]

$\Xi_{c}^{\prime +}\pi^{+}$ [JHEP 05 (2022) 038]

$\Xi_{c}^{0}\pi^{+}\pi^{+}$ [JHEP 10 (2025) 136]

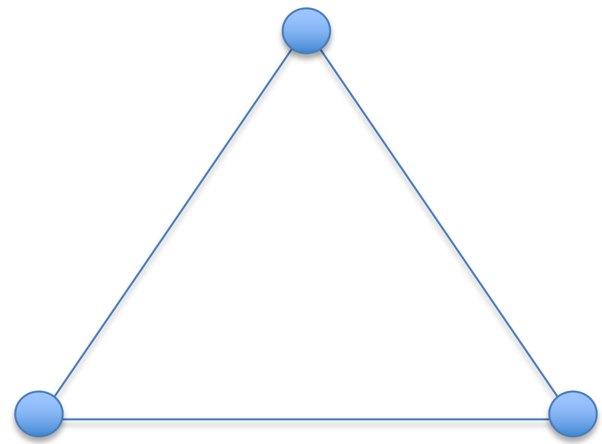
$\Xi_{cc}^{+}\ (ccd)$

Hint/Evidence

[SCPMA 63 (2020) 221062, JHEP 12 (2021) 107]

First search[CPC 45 (2021) 093002]

$\Omega_{bc}^{0}\ (bcs)$



$\Xi_{bc}^{+}\ (bcu)$

First search

Hint

[CPC 47 (2023) 093001]

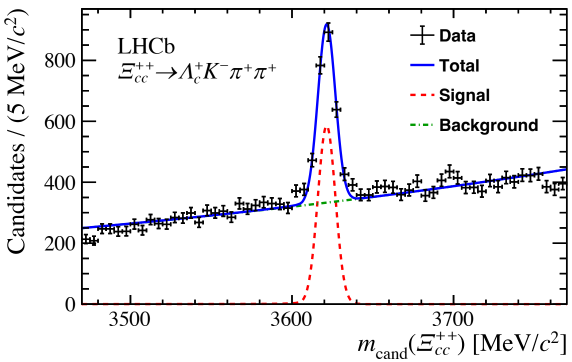
$\Xi_{bc}^{0}\ (bcd)$

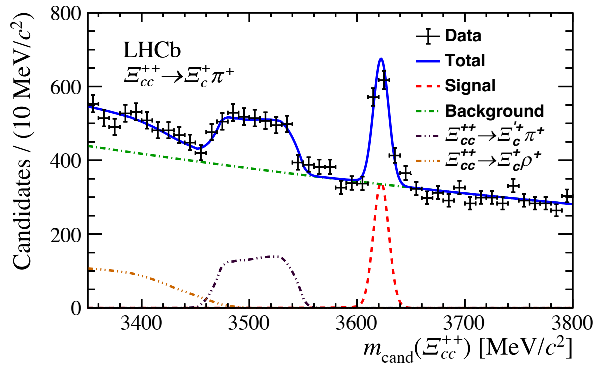
First search

[JHEP 11 (2020) 095]

Summary of DHB studies

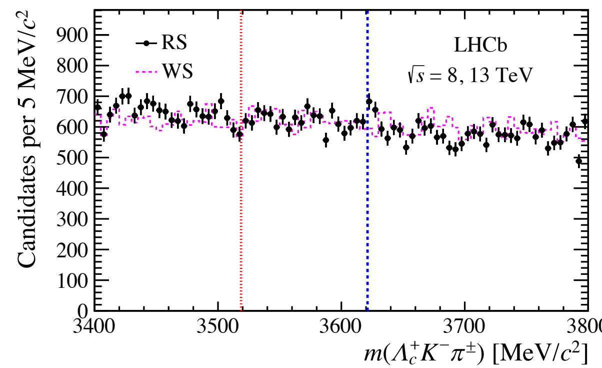
$\Xi_{cc}^{++}(ccu)$





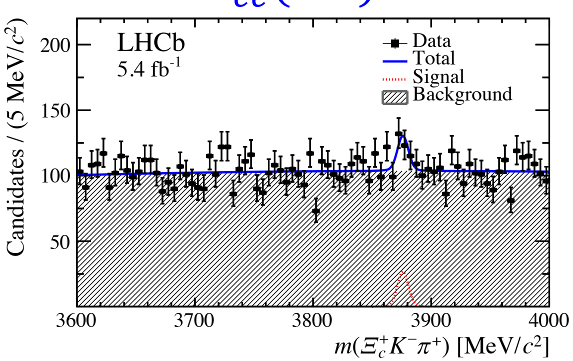
PRL 119 (2017) 112001, PRL 121 (2018) 052002, PRL 121 (2018) 162002,
CPC 44 (2020) 022001, JHEP 02 (2020) 049, JHEP 05 (2022) 038

$\Xi_{cc}^{+}(ccd)$



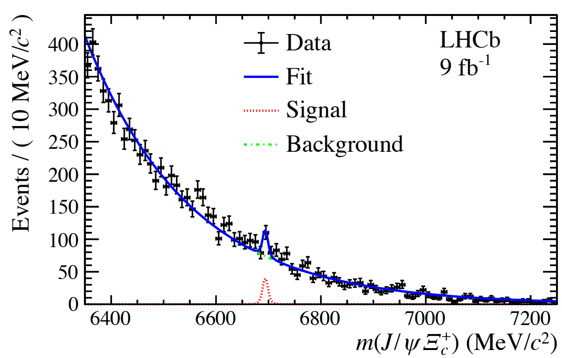
SCPMA 63 (2020) 221062

$\Omega_{cc}^{+}(ccs)$



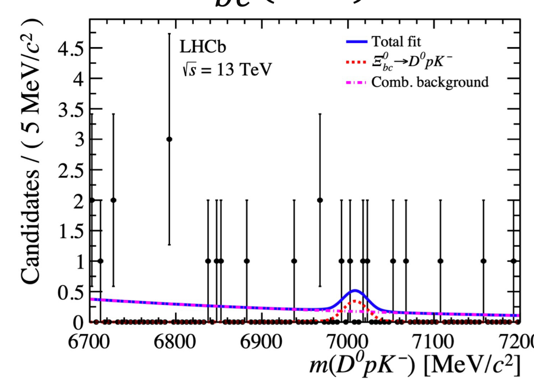
SCPMA 64 (2021) 101062

$\Xi_{bc}^{+}(bcu)$



CPC 47 (2023) 093001

$\Xi_{bc}^{0}(bcd)$



JHEP 11 (2020) 095

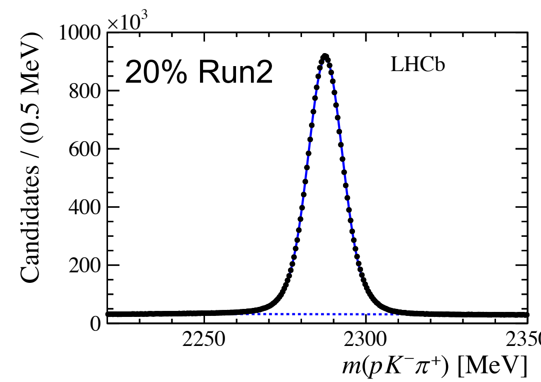
UROP

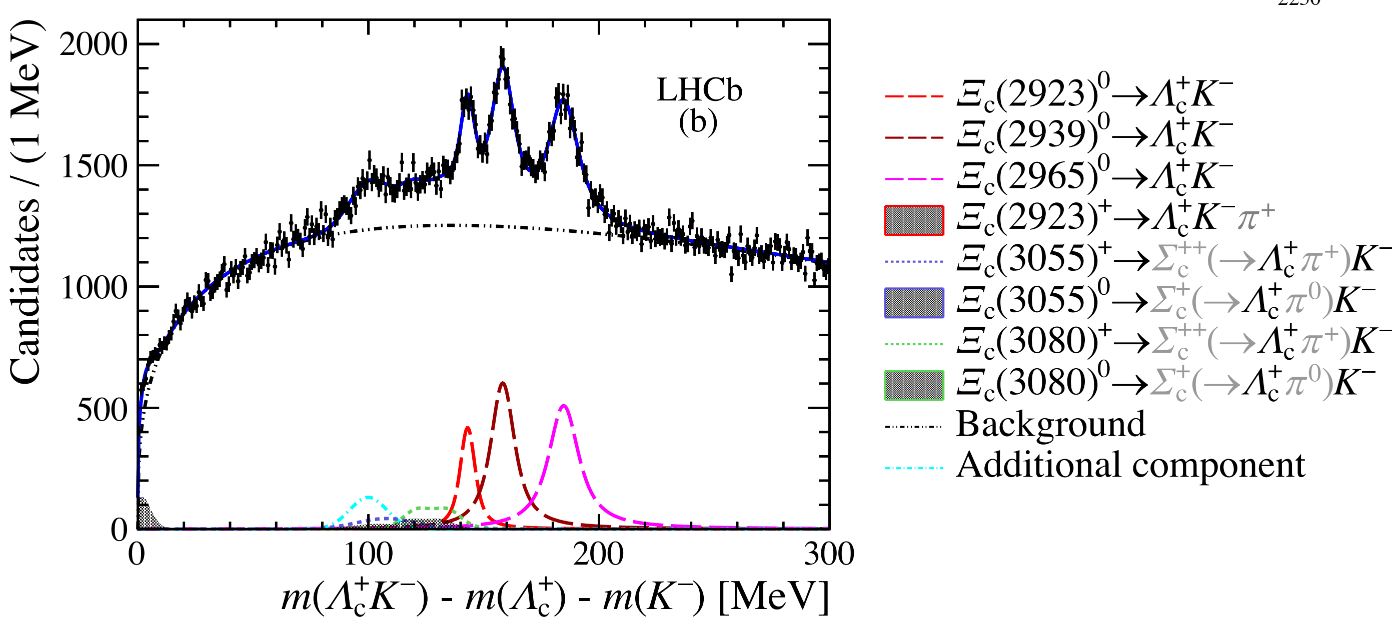
Excited Ξ_c^0 states

(csd)

[PRL 124 (2020) 222001]

- Lots of singly charmed baryons
- New excited Ξ_c^0 states in $m(\Lambda_c^+ K^-)$

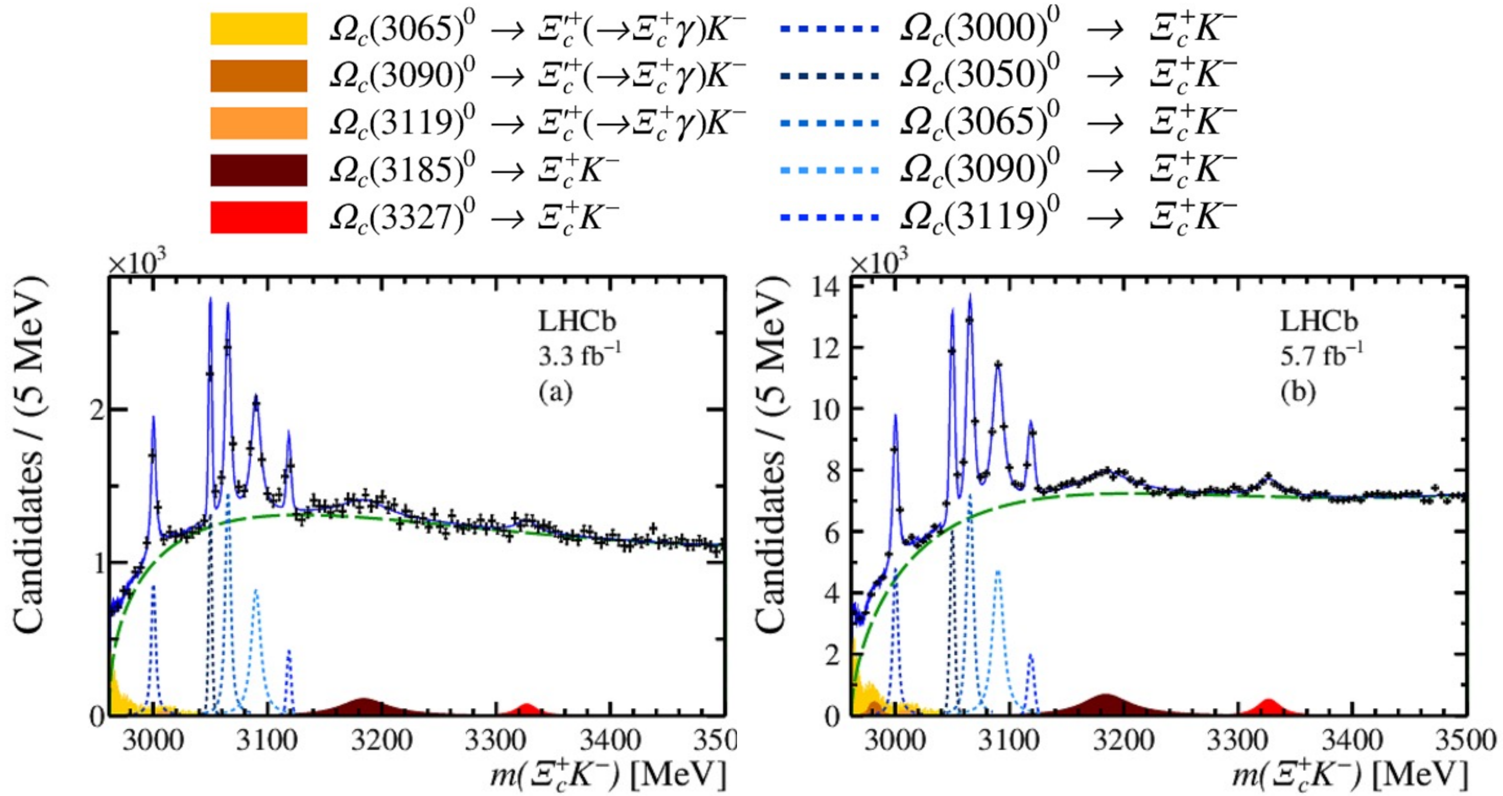




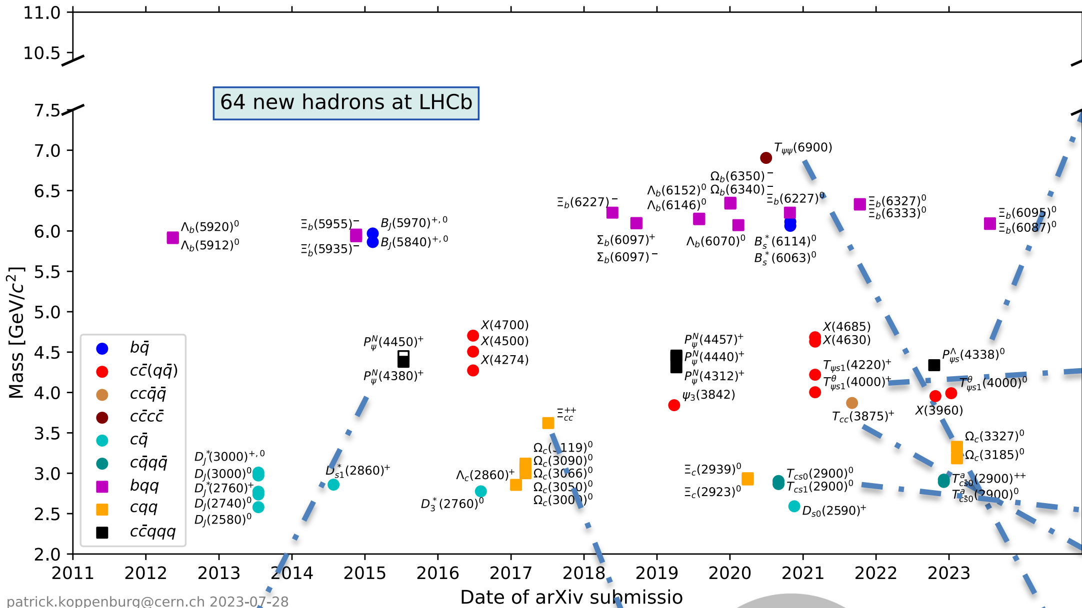
Two new charmed hadrons

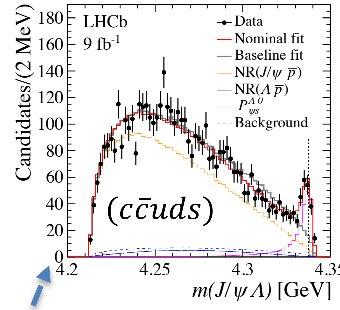
- Five states observed in $m(\Xi_c^+ K^-)$ in 2017, two new $\Omega_c(3185)^0, \Omega_c(3327)^0$ in 2023, nature unclear
  - Excited Ω_c^0 (css), molecular, pentaquark ($cssq\bar{q}$)?

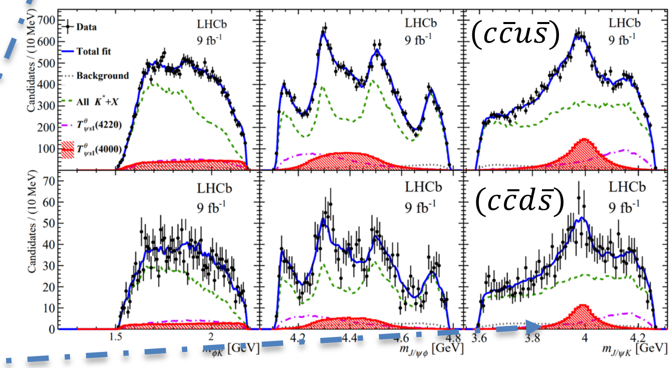
[PRL 131 (2023) 131902]

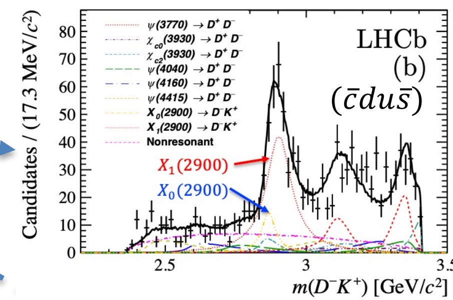


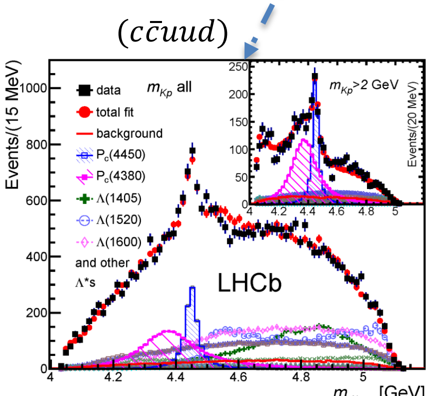
Spectroscopy at LHCb

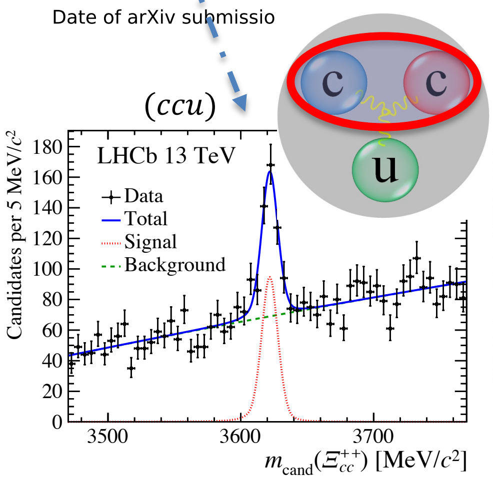


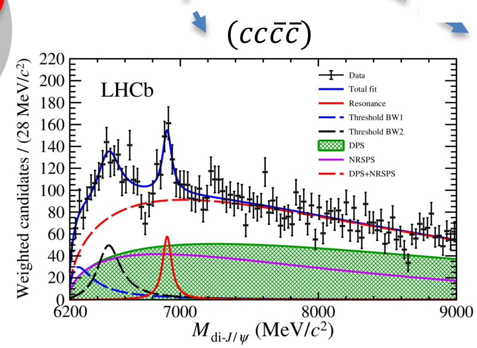


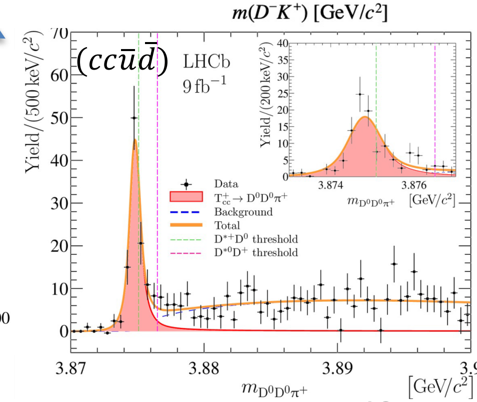






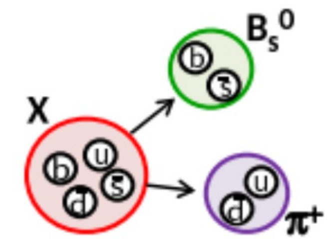






$$X(5568)^+ \rightarrow B_s^0 \pi^+ \qquad (b\bar{s}u\bar{d})$$

- D0 @ Tevatron (Fermi) claimed observation
- First tetraquark with open-bottom？



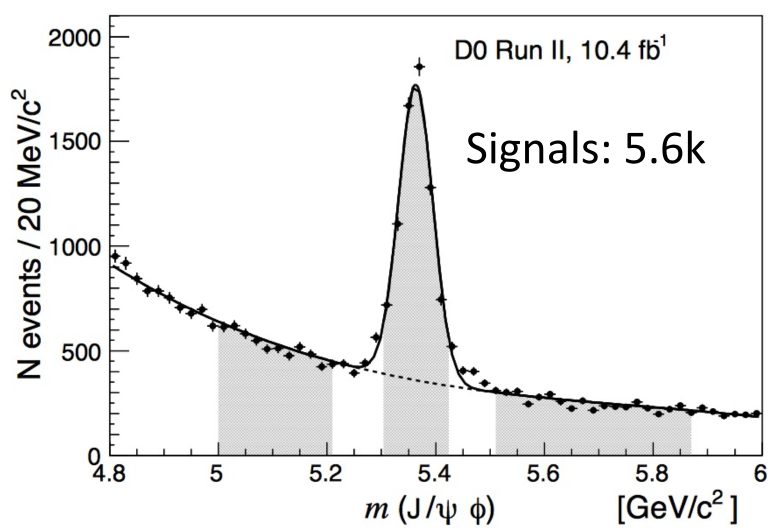
arXiv.org > hep-ex > arXiv:1602.07588v1

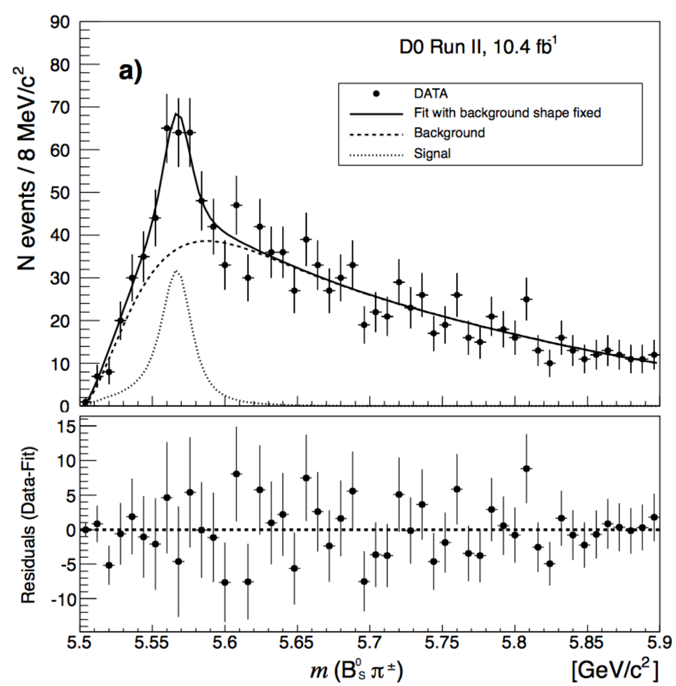
High Energy Physics – Experiment

Observation of a new $B_s^0\pi^\pm$ state

D0 Collaboration   PRL 117 (2016) 022003

(Submitted on 24 Feb 2016 (this version), **latest version 18 Aug 2016** *(v4))*

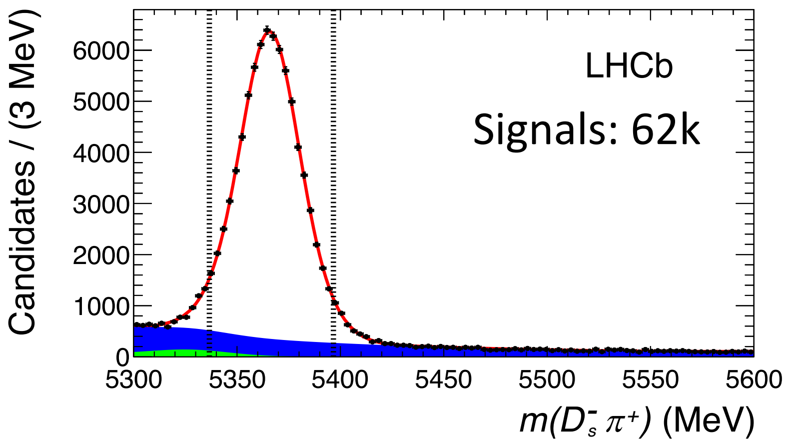


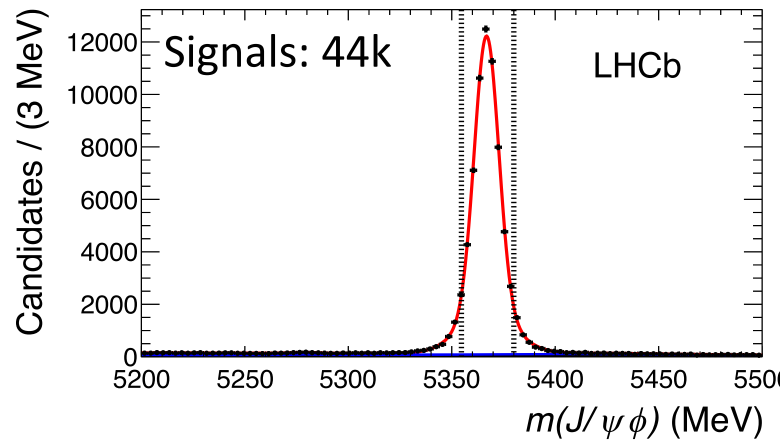


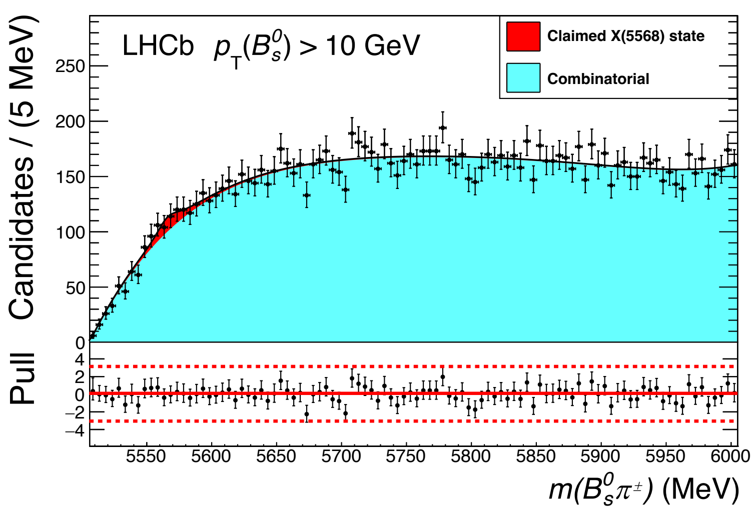
$X(5568)^+ \to B_s^0\pi^+$ $(b\bar{s}u\bar{d})$

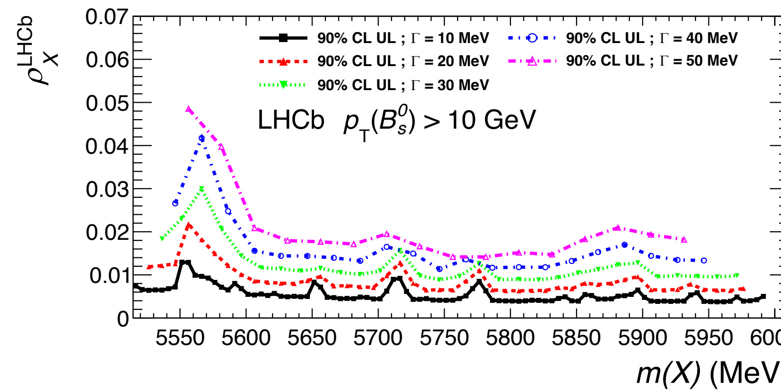
- Not confirmed by LHCb, ATLAS, CMS

[PRL 117 (2016) 152003]



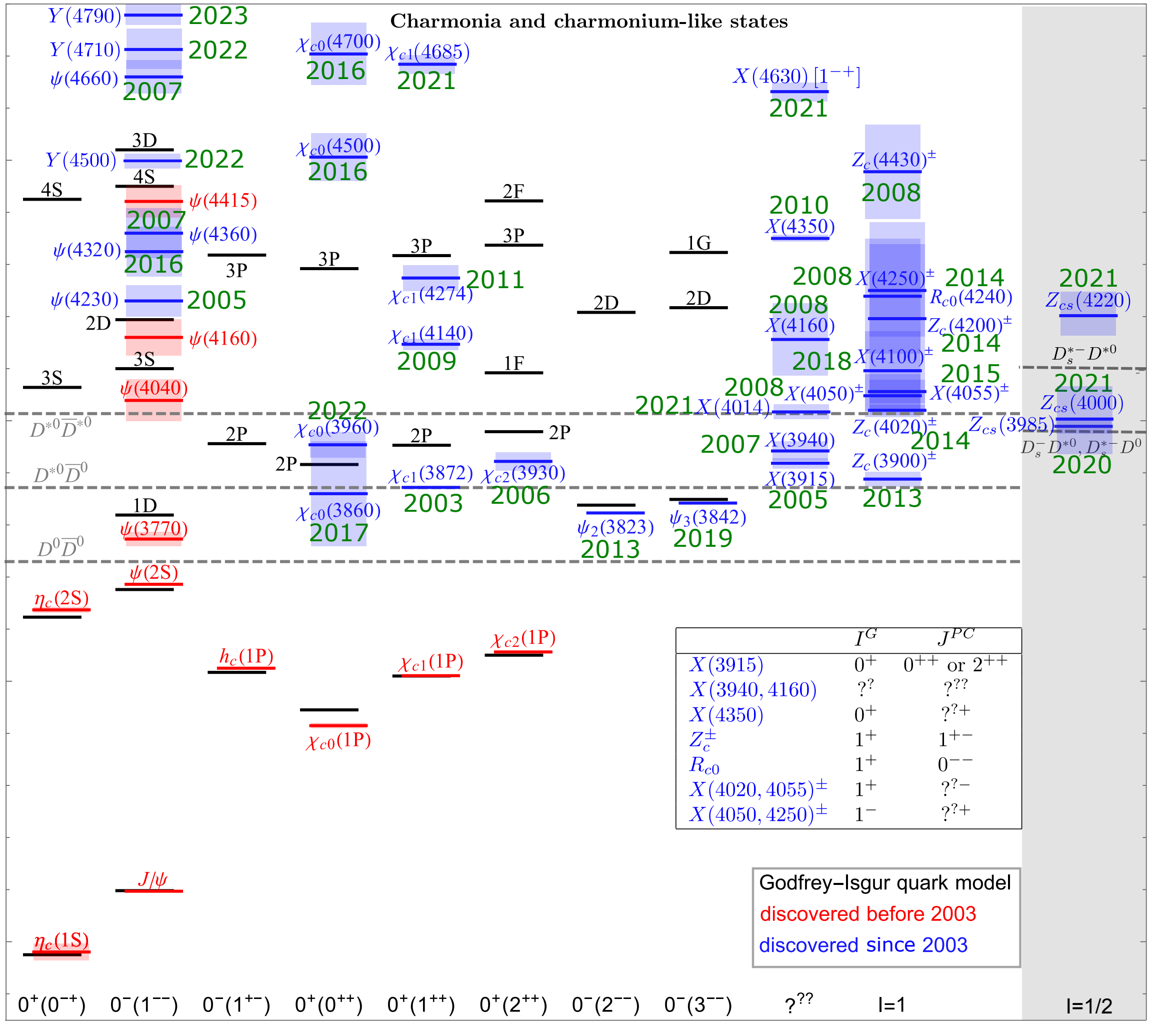






$$\rho_X^{\mathrm{LHCb}} \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

Charmonium(like) states



[F.-K. Guo (郭奉坤), PoS LATTICE 2022 (2023) 232]

$X(3872)$?

- Tetraquark
- $\chi_{c1}(2P)$
- Molecule
- Mixture

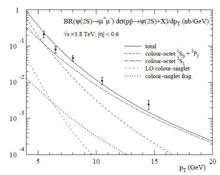
Samuel C.C.Ting

Quarkonium production

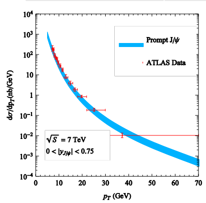
CO mechanism

➢ Nicely explain ψ' surplus by CO contributions

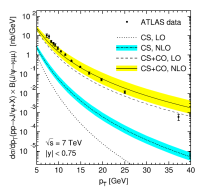
States	p_T behavior at LO
$^3S_1^{[1]}$	p_T^{-8}
$^3S_1^{[8]}$	p_T^{-4}
$^1S_0^{[8]}$	p_T^{-6}
$^3P_J^{[8]}$	p_T^{-6}



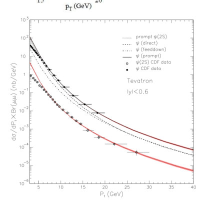
Kramer, 0106120



YQM, Wang, Chao, 1012.1030



Butenschoen, Kniehl, 1105.0820



Gong, Wan, Wang, Zhang, 1205.6682

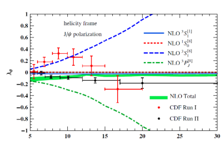
马滟青

25/62

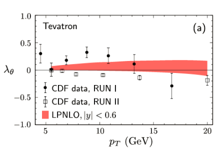
Credits: Y.Q. MA

Polarization puzzle at NLO

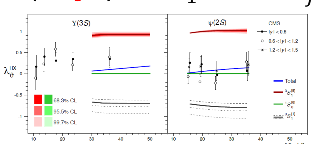
➢ J/ψ: transverse polarization canceled (*why?*) in $^3S_1^{[8]}$ and $^3P_J^{[8]}$



Chao,YQM,Shao,Wang, Zhang,1201.2675

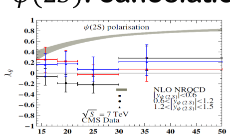


Bodwin, Chung, Kim, Lee, 1403.3612

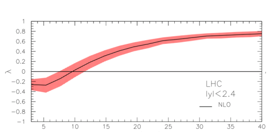


Faccioli,Knunz,Lourenco, Seixas,Wohri,1403.3970

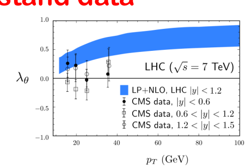
➢ $\psi(2S)$: cancelation weak, hard to understand data



Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



Gong, Wan, Wang, Zhang, 1205.6682



Bodwin et al., 1509.07904

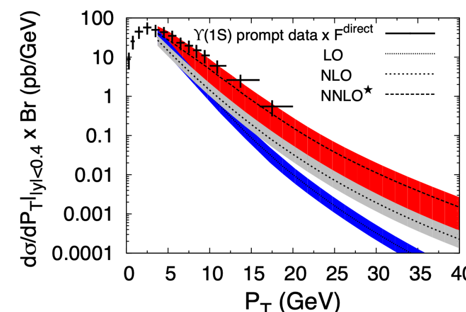
马滟青

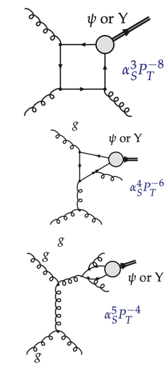
33/62

Credits: Y.Q. MA

QCD corrections to the CSM for Υ at colliders

J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)





Attention: the NNLO★ is not a complete NNLO
See a recent study by H.S. Shao JHEP 1901 (2019) 112

The current situation in one slide ...

For an up-to-date review, see JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)

- Colour-Singlet Model (CSM) long thought to be insufficient
  ... not as clear now

[large NLO and NNLO correction to the P_T spectrum ; but not perfect → need a full NNLO]

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, PRL 101, 152001 (2008); JPL EPJC 61 (2009) 693; H.S. Shao JHEP 1901 (2019) 112

- CSM is doing well for the P_T-integrated yield

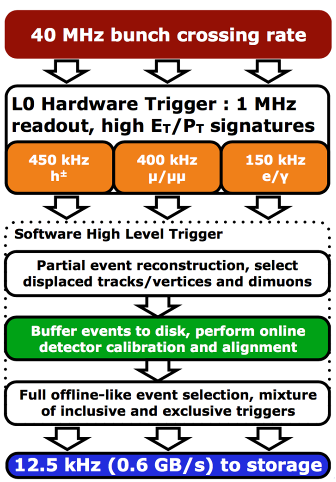
S.J. Brodsky, JPL PRD 81 (2010) 051502;A. Colpani Serri, Y. Feng, C. Flore, JPL, M.A. Ozcelik, H.S. Shao, Y. Yedelkina PLB 835 (2022) 137556

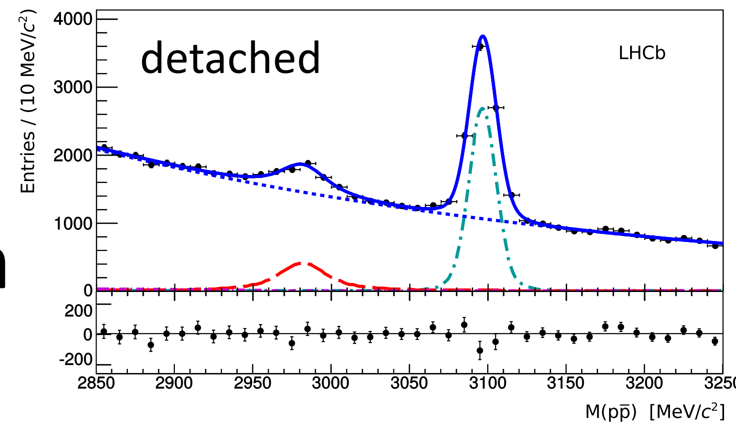
- Colour-Octet Mechanism (COM) helps in describing the P_T spectrum
- Yet, the COM NLO fits differ a lot in their conclusions owing to their assumptions (data set, P_T cut, polarisation fitted or not, etc.)
- Colour-Evaporation Mechanism (CEM) ↔ quark-hadron duality tends to overshoot the data at large P_T – issue shared by some COM fits

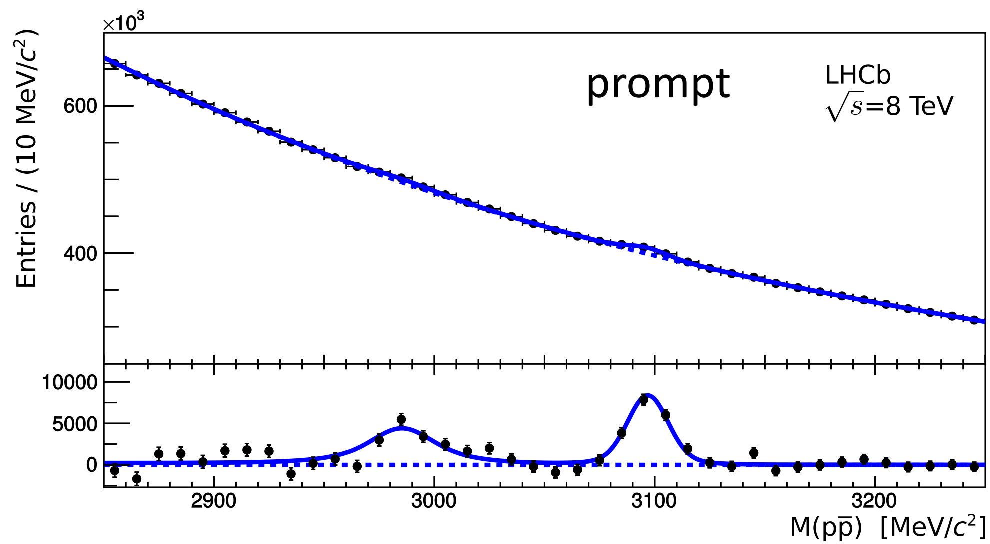
All approaches have troubles with ep, ee or pp polarisation and/or the η_c data

$\eta_c(1S)$ production

- $\eta_c(1S)$ hadroproduction firstly measured by LHCb
- Prompt signal suffers from high background
- Dedicated trigger

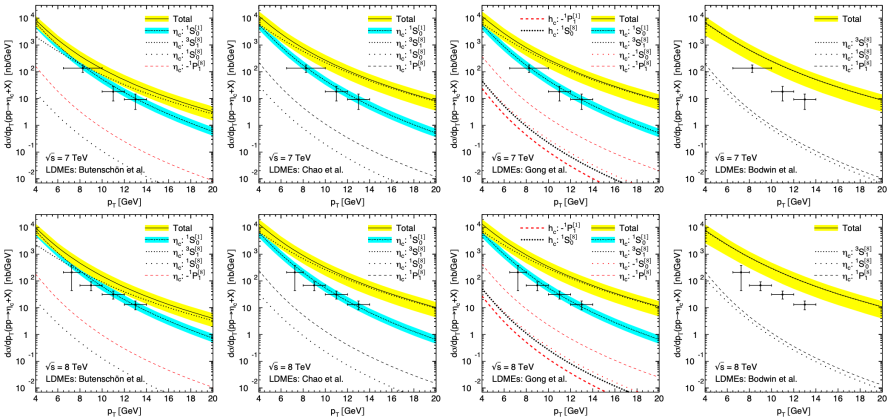






[EPJC 75 (2015) 311]

$\eta_c(1S)$ production



[M. Butenschoen, et al., PRL 114 (2015) 092004]

- **LHCb data + HQSS helps to constrain** $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$

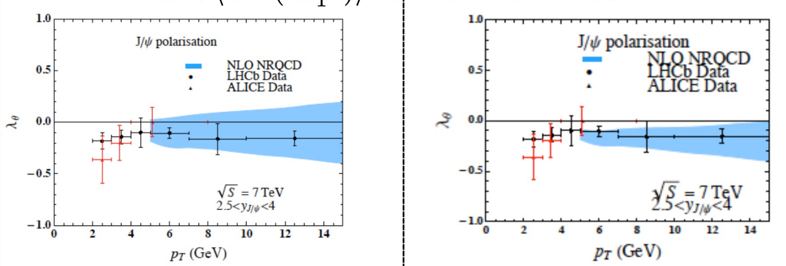
$$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle$$

- **A conservative upper limit was set via**

$$\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle \hat{\sigma}(c\bar{c}\left[^3S_1^{[8]}\right]) = \sigma_{\text{LHCb data}}$$

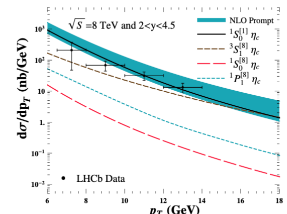
Before | After | Han et al. (2014)

$$0 < \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \text{GeV}^3$$



Tuesday, May 7, 19

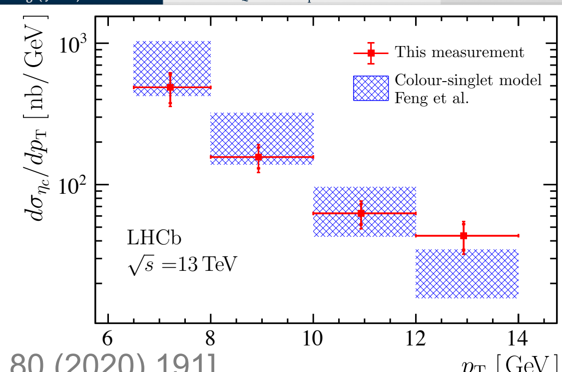
The last piece in the puzzle: the η_c



Data LHCb : EPJC 75 (2015) 311 (plot from H. Han *et al.* PRL 114 (2015) 092005)

- η_c x-section measured by LHCb very well described by the CS contribution (Solid Black Curve)
- Any CO contribution would create a surplus
- Even *neglecting* the *dominant* CS, this induces constraints on CO J/ψ LDMEs via Heavy-Quark Spin Symmetry : $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}$ GeV^3
- Rules out the fits yielding the $^1S_0^{[8]}$ dominance to get unpolarised yields
- Even the PKU fit has now troubles to describe CDF polarisation data
- Yet, the constraints actually is $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle \lesssim 5 \times 10^{-3}$ GeV^3 when the CS contribution is appropriately accounted for
- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out (Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006

[Additional relations: $\langle \mathcal{O}^{\eta_c}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle/3$ and $\langle \mathcal{O}^{\eta_c}(^1P_1^{[8]})\rangle = 3 \times \langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$]



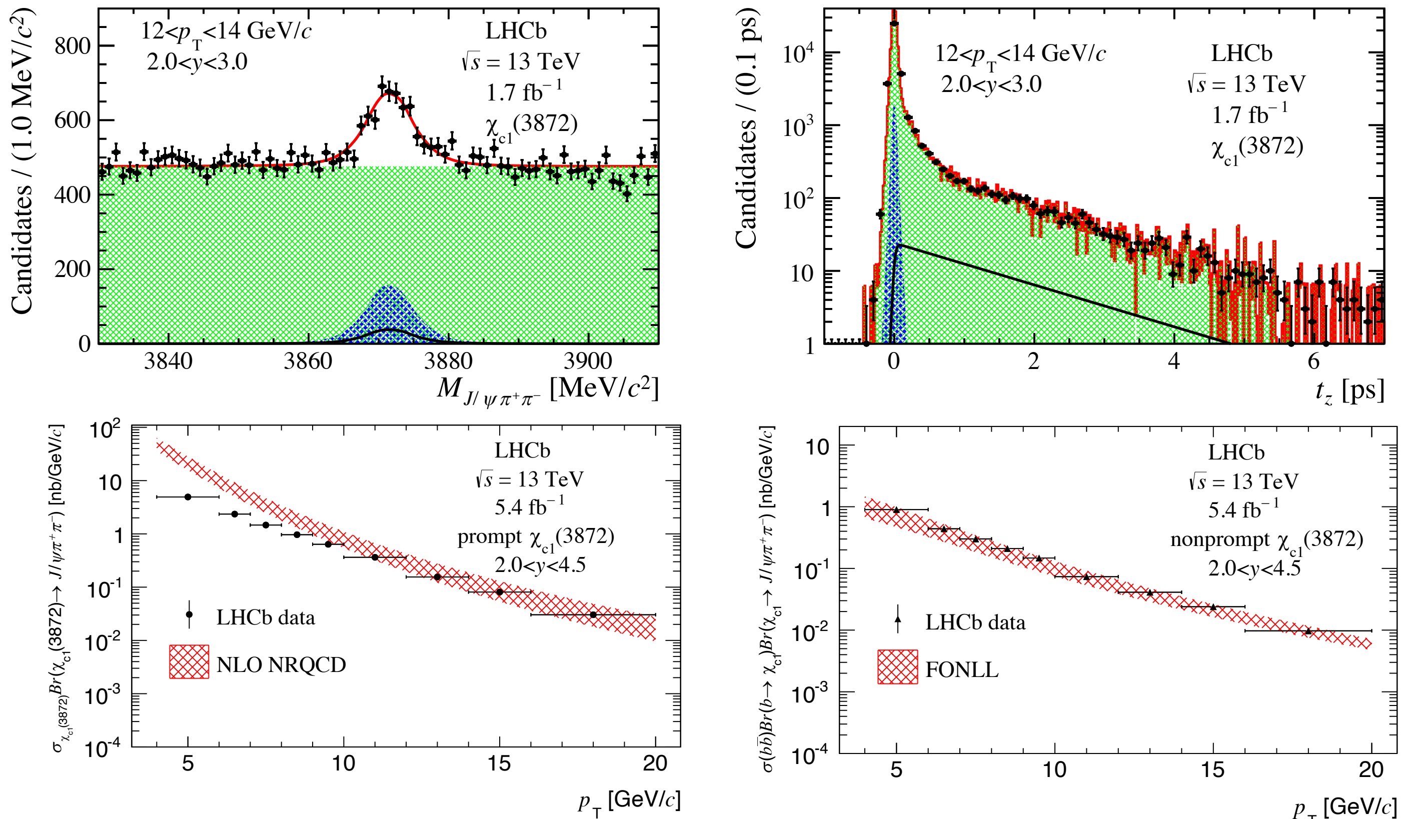
[EPJC 80 (2020) 191]

Results confirmed with 13 TeV data

$X(3872)$ production

- First double-differential cross-section
- Consistent with $\chi_{c1}(2P) + D^0\overline{D}^{*0}$ mixture

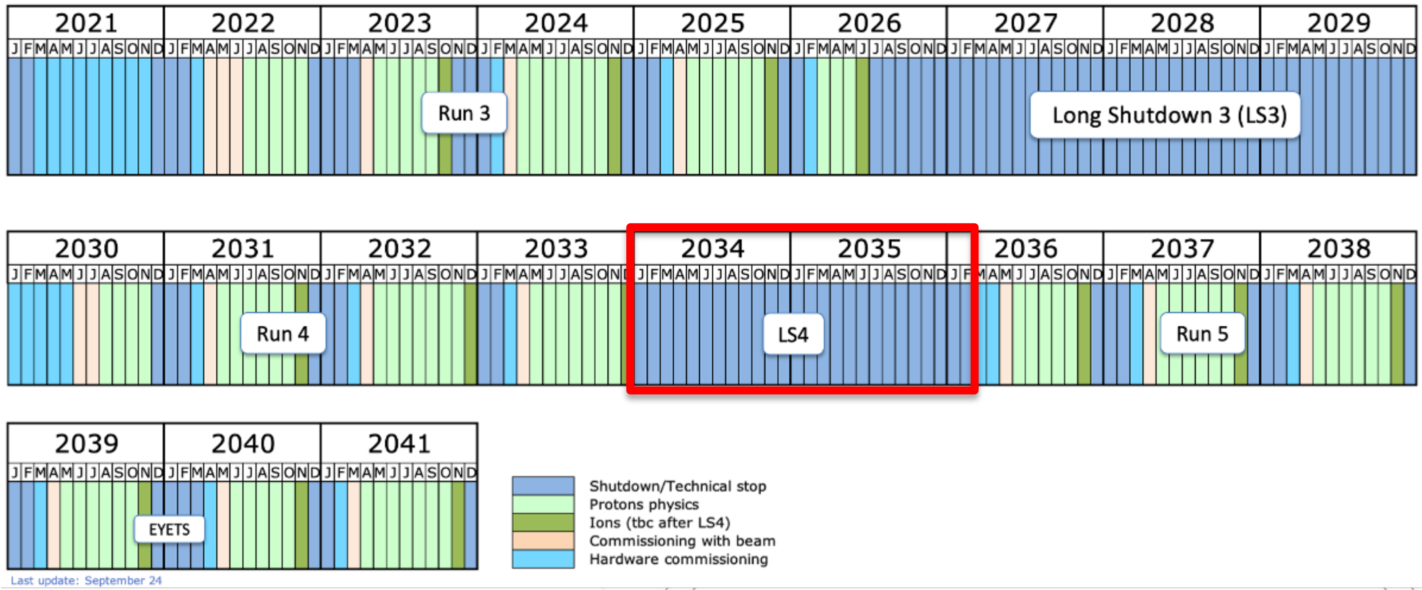
[JHEP 01 (2022) 131]

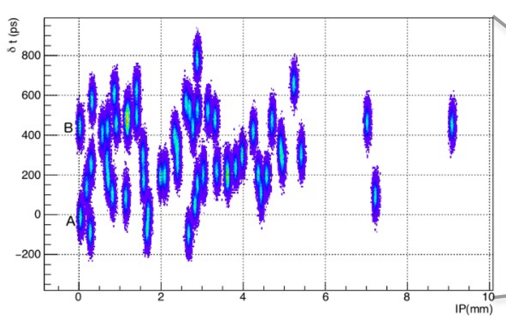


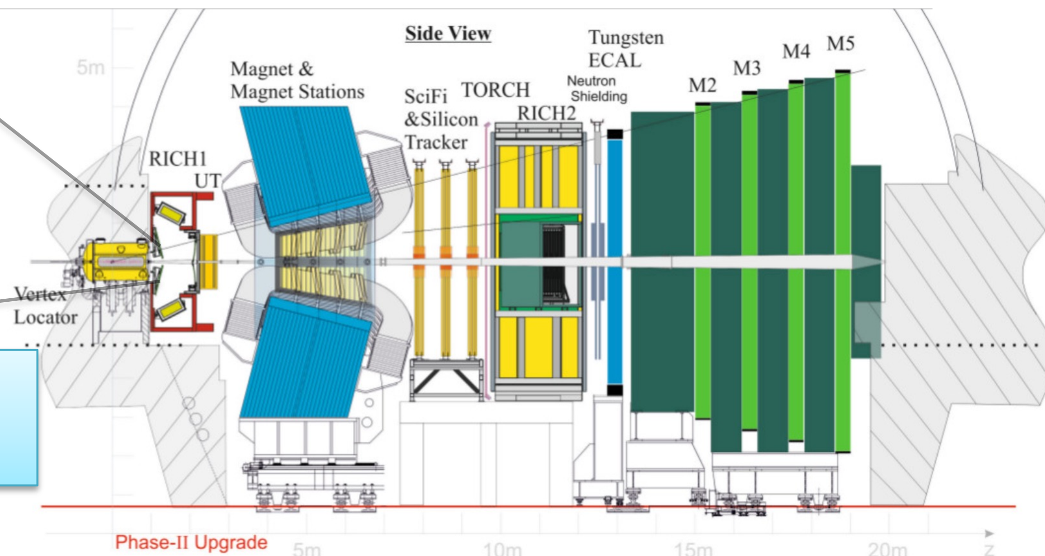
In pipeline: $J/\psi p$, $J/\psi\Lambda$, $J/\psi\phi$, $J/\psi\pi^+$...

The LHCb upgrades

[CERN-LHCC-2018-027, 2021-012]







Upgrade II, 4D detector
Timing, $\mathcal{O}(10\text{ ps})$, is essential

[CERN-LHCC-2018-027, 2021-012]

Prospects

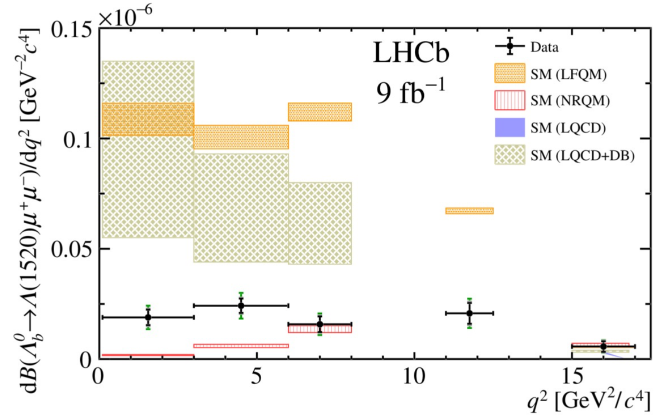
- LHCb upgrades

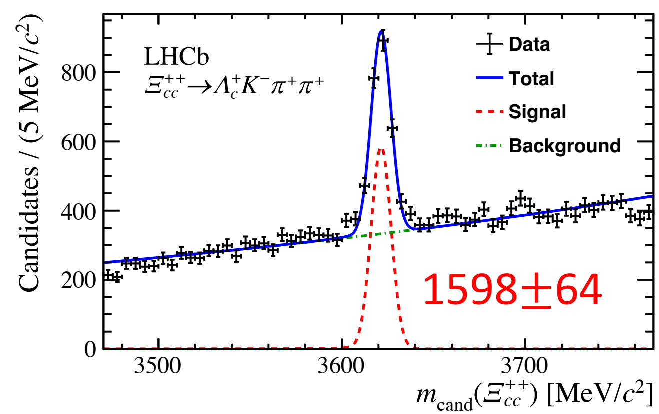
(2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- Indirect search for New Physics
  - $b \rightarrow s\ell^+\ell^-$, BR, LFU
  - $b \rightarrow c\tau\nu$, LFU
- Experimental study of QCD
  - Conventional hadrons
    - B_c^+ physics, Doubly heavy baryons
    - Quarkonium production
  - Exotic hadrons
    - Production
    - $X(5568)^+$





Your strong & continued supports always appreciated!