中国科学院大学

University of Chinese Academy of Sciences

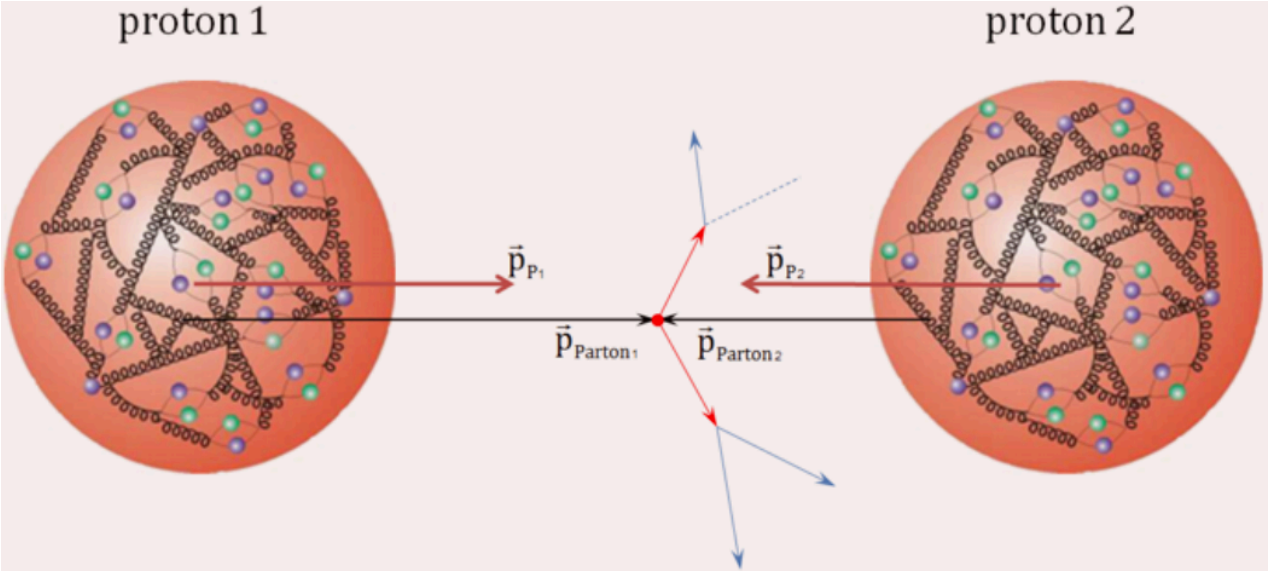
Results of hadron production & spectroscopy

Jibo HE (UCAS), for the LHCb collaboration, including results from ATLAS/CMS

Presented at 3rd CLHCP @NJU, 12/2017

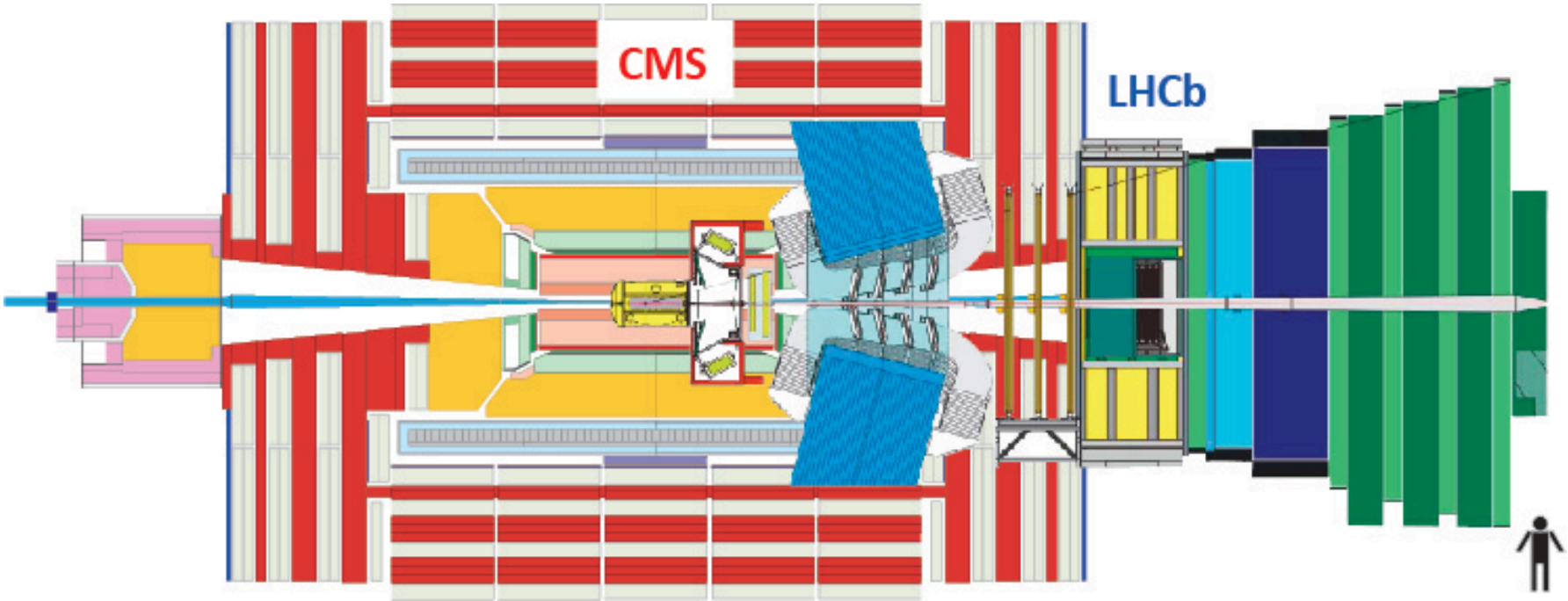
Introduction

- Study of hadron production & spectroscopy deepen our understanding of QCD
  - Production: Parton distribution function (PDF), hard parton scattering, hadronization
  - Spectroscopy



Experiments at LHC

- Two GPDs, ATLAS & CMS
- ALICE (Heavy-Ion Physics), LHCb (Beauty/Charm physics)



Contents of this talk

- Overview of hadron production & spectroscopy results in *pp* collisions released since last CLHCP
  - Please refer to Y.X. Mao's talk for results in heavy Ion
- Please refer to talks in parallel sessions for details

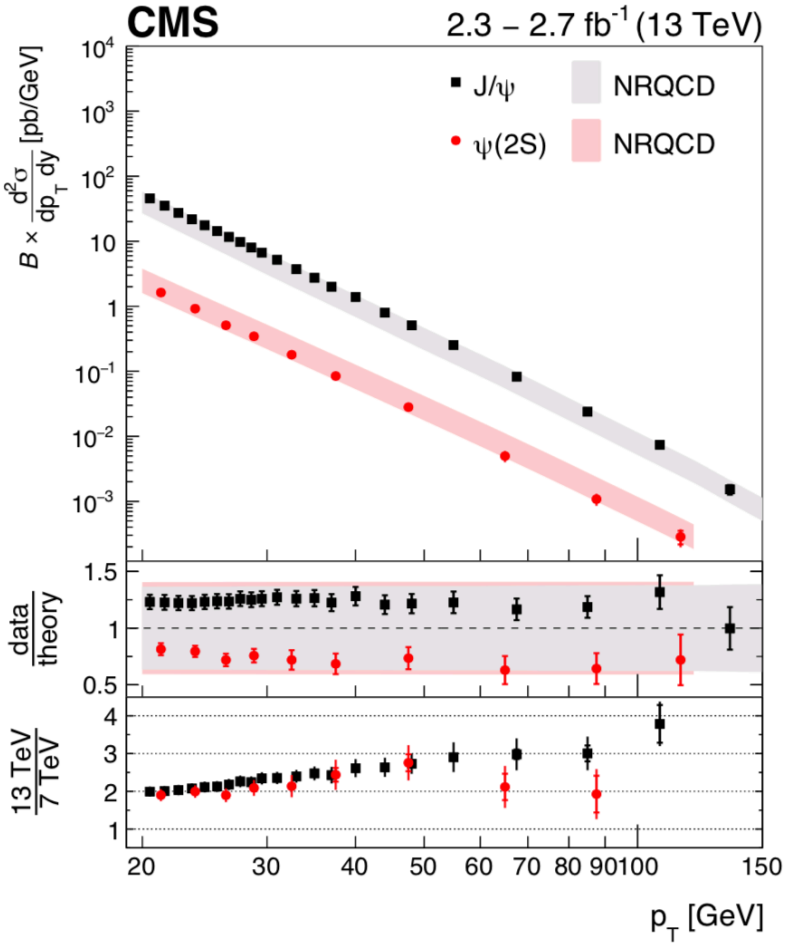
1.	B^+ production	Wenhua Hu
2.	Ξ_{cc}^{++} observation	Menglin Xu
3.	Pentaquarks	Mengzhen Wang
4.	B_c excited states	Liupan An
5.	pPb and PbPb	Jiayin Sun

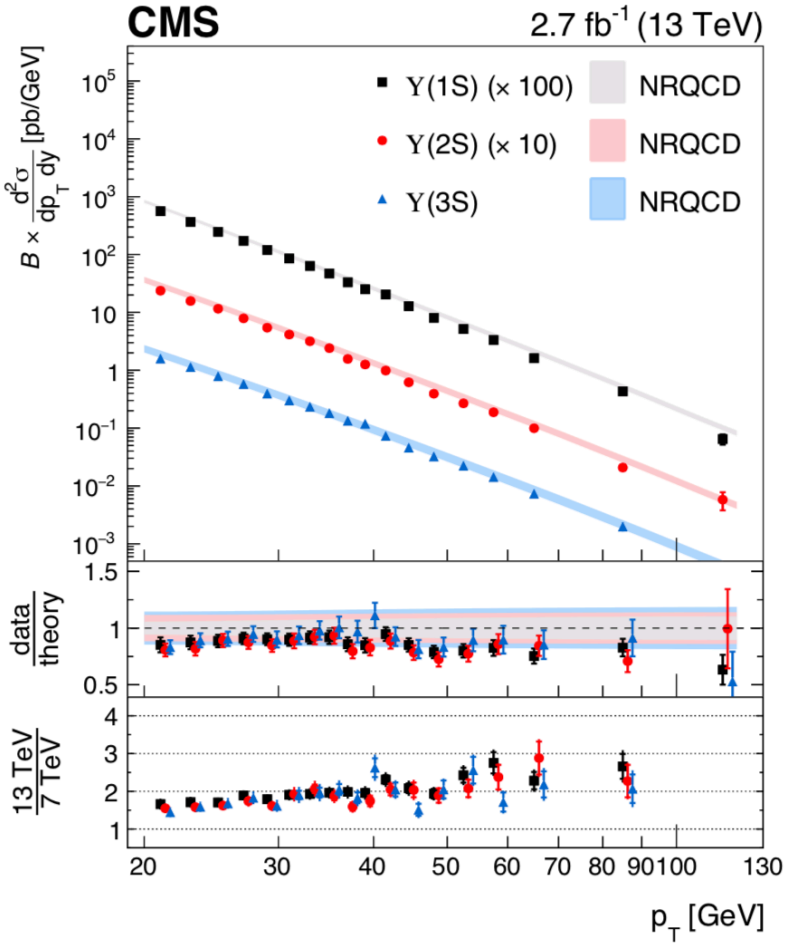
- My apologize if your favorites are not covered

Quarkonia production at 13 TeV

- NRQCD describes well cross-section

[K.T. Chao *et al.*, PRL 1026 (2011) 042002, PRD 94 (2016) 014028]



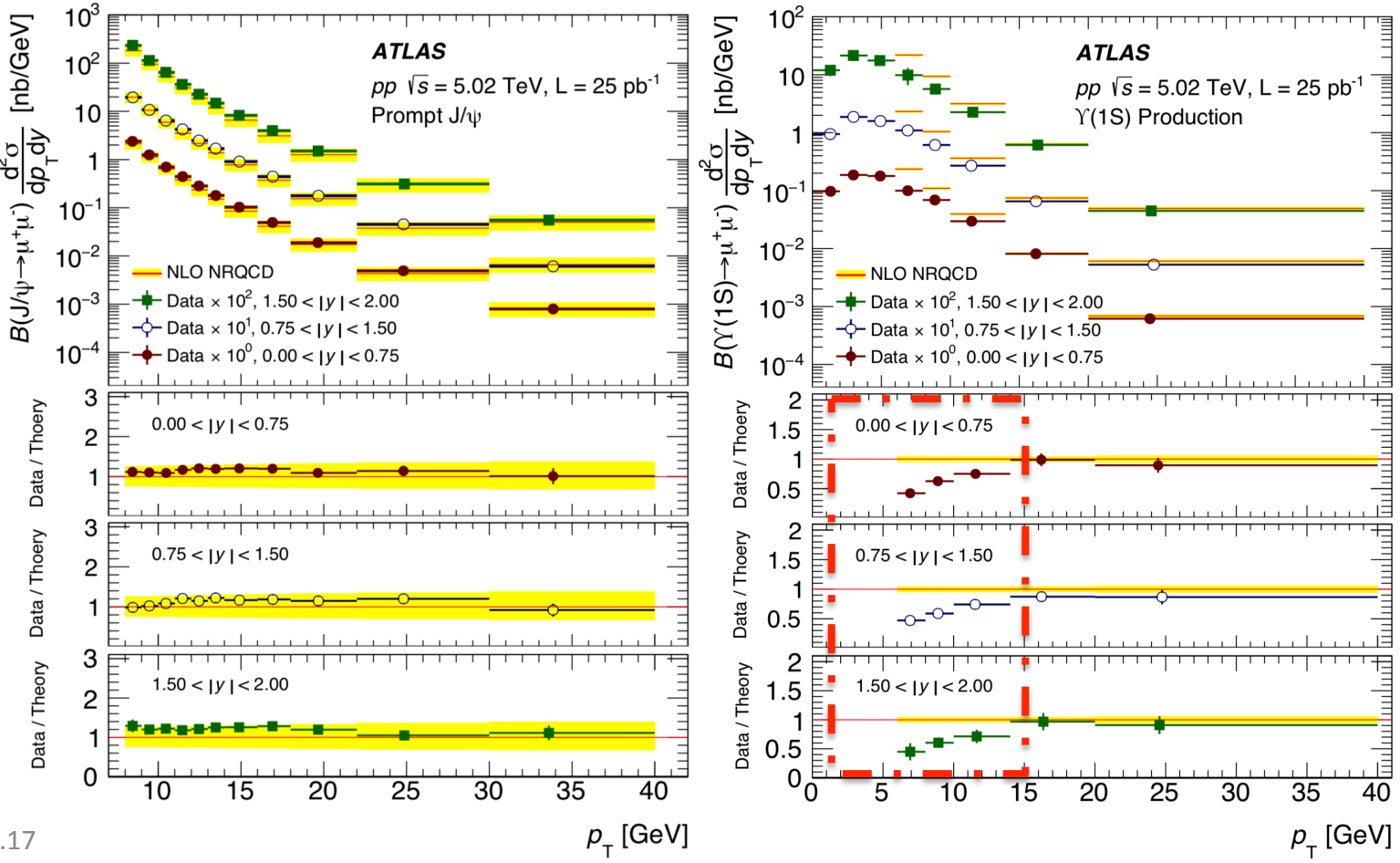


[CMS, arXiv:1710.11002]

Quarkonia production at 5.02 TeV

- NRQCD has some difficulty at p_T<15 GeV for ϒ

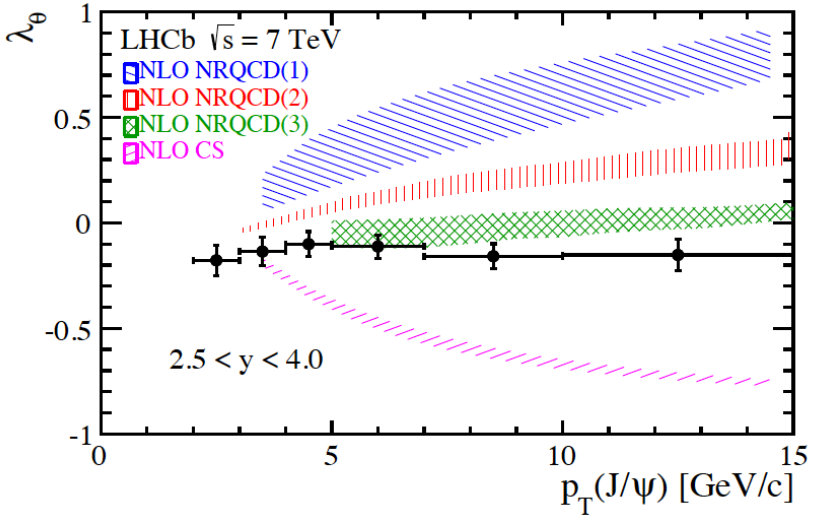
[K.T. Chao *et al.*, PRL 1026 (2011) 042002, PRD 94 (2016) 014028, JHEP 05 (2015) 103]

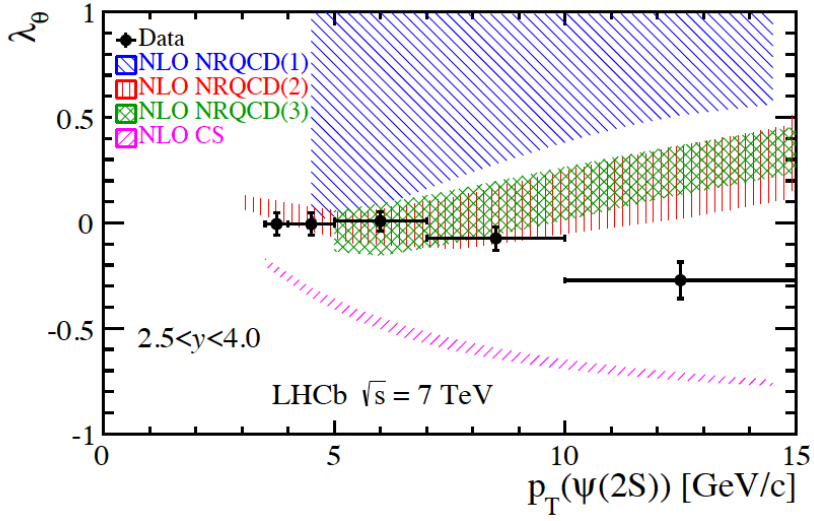


[ATLAS, arXiv:1709.03089]

J/ψ, ψ(2S) polarization by LHCb

- Disfavors NLO CSM
- Not well described by NRQCD predictions
  - NLO CS and NLO NRQCD(1) [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
  - NLO NRQCD(2) [B. Gong *et al.*, PRL 110 (2013) 042002]
  - NLO NRQCD(3) [K.-T. Chao *et al.*, PRL 108 (2012) 242004]

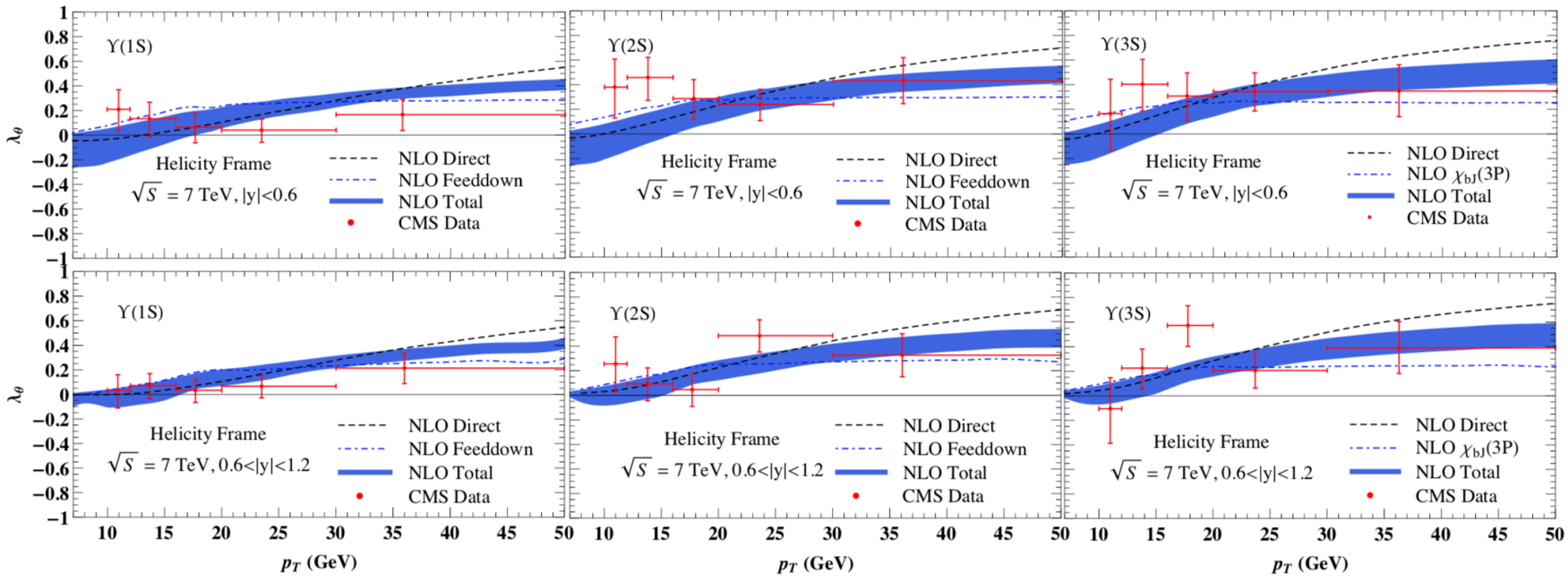




[LHCb, EPJC 73 (2013) 2631, EJPC 74 (2014) 2872]

ϒ polarization at 7 TeV by CMS

- Described by NRQCD?
  [K.T. Chao *et al.*, PRD 94 (2016) 014028]

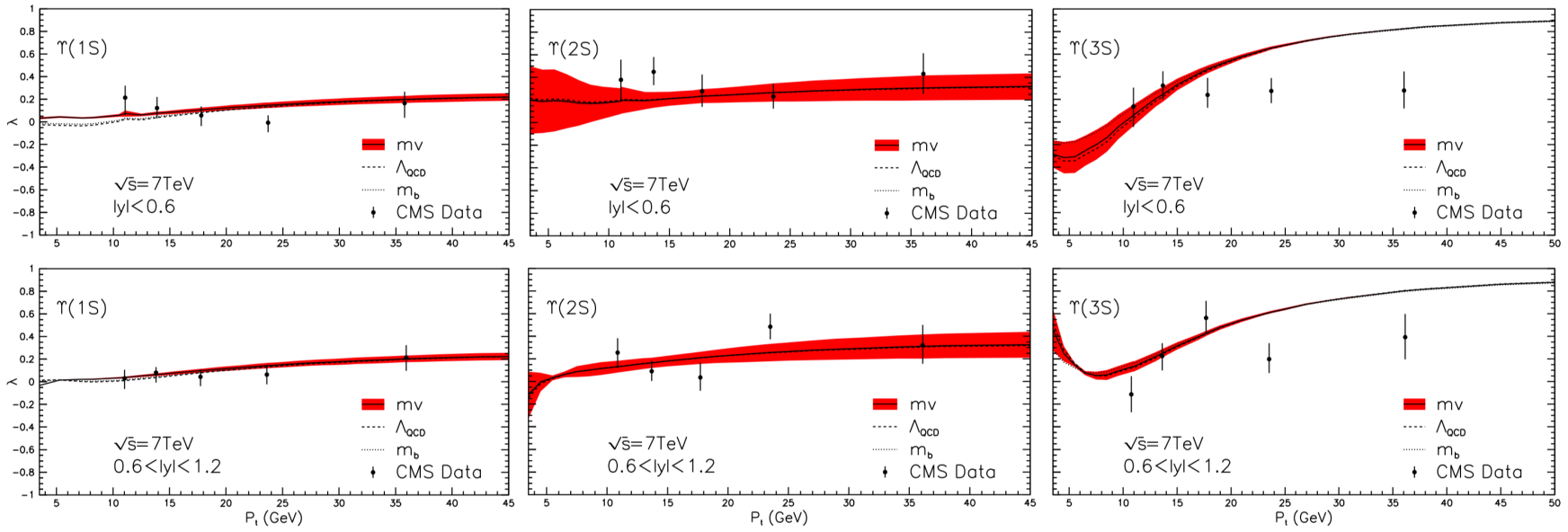


[CMS, PRL 110 (2013) 081802]

ϒ polarization at 7 TeV by CMS

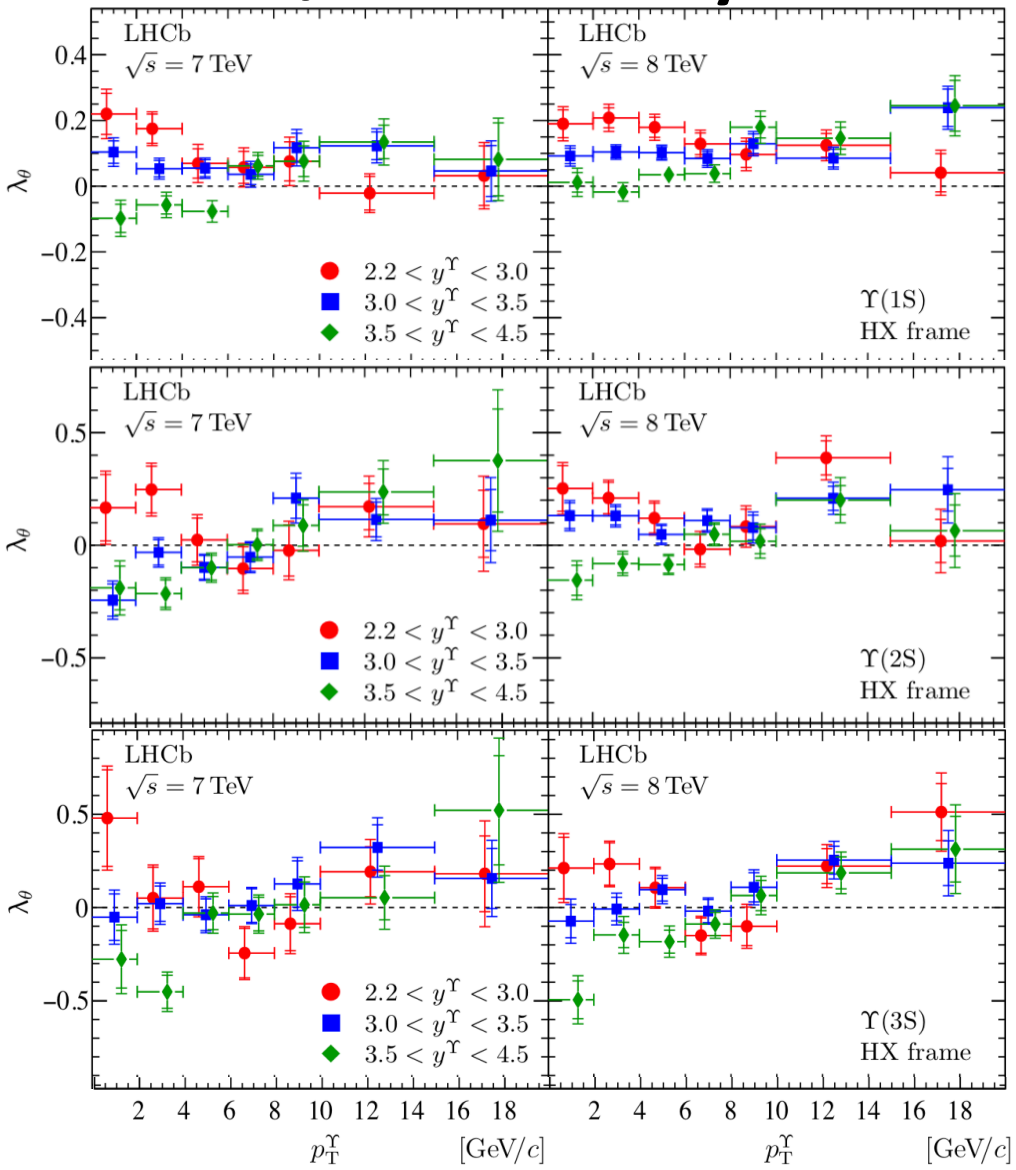
- Described by NRQCD?
  [J.X. Wang *et al.*, PRL 112 (2014) 032001]

[CMS, PRL 110 (2013) 081802]



ϒ polarization at 7/8 TeV by LHCb

- No large transverse or longitudinal polarization
- Consistent with CMS measurements

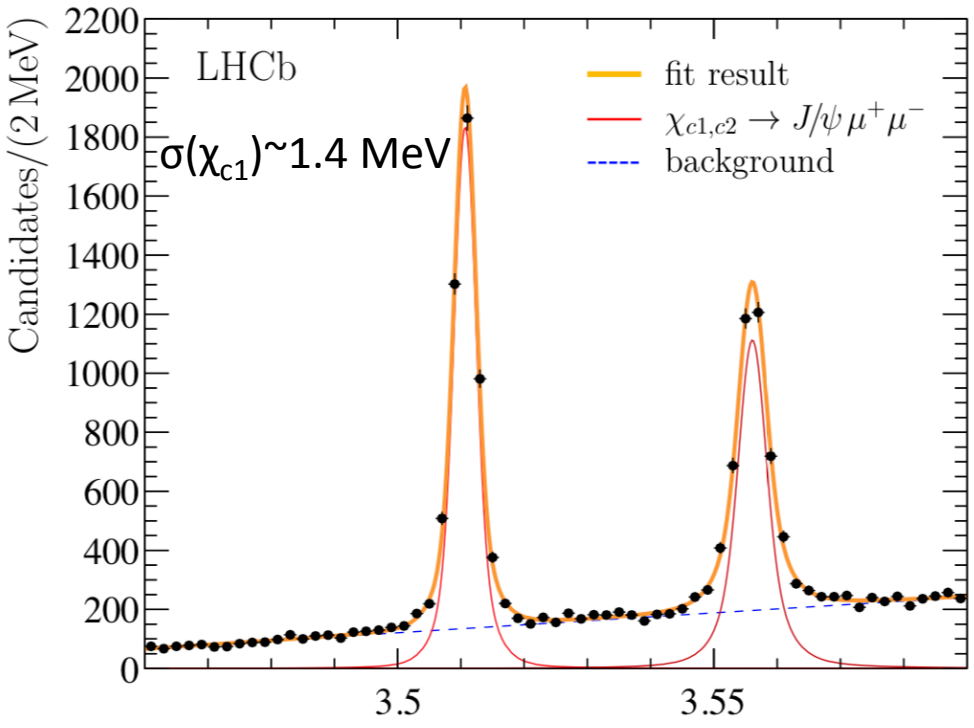


[LHCb, arXiv:1709.01301]

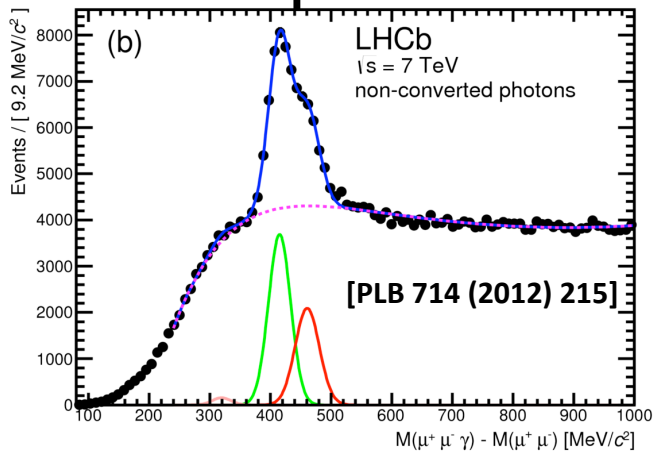
Observation of $\chi_{c1,c2}$->$J/\psi\mu^+\mu^-$

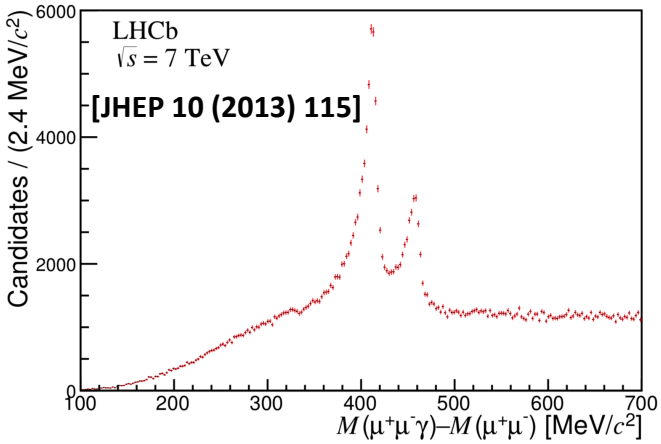
- First observation, resolution much better than $\chi_{c1,c2}$ rec'ed w/ photon or converted photon

[LHCb, PRL 119 (2017) 221801]



N(χ_{c1})=4755±81
N(χ_{c2})=3969±96

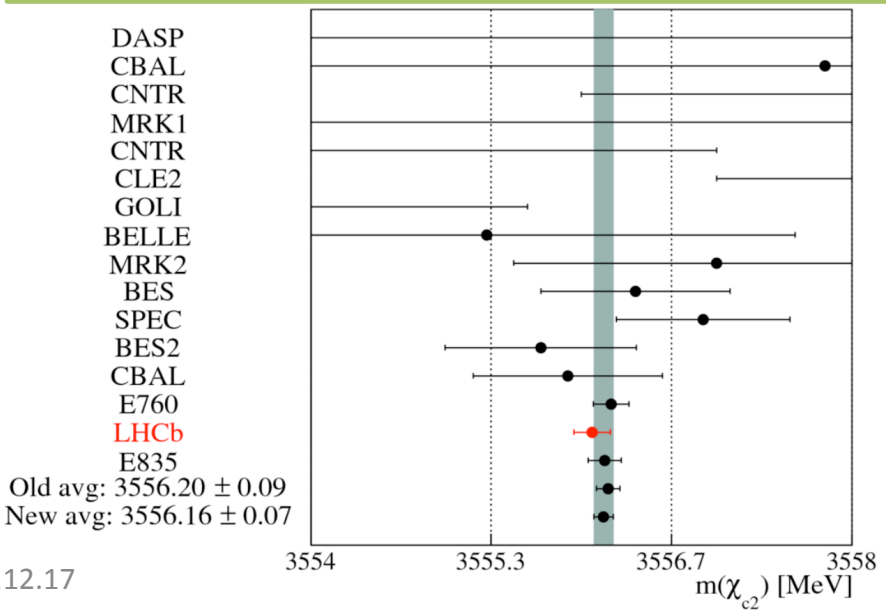


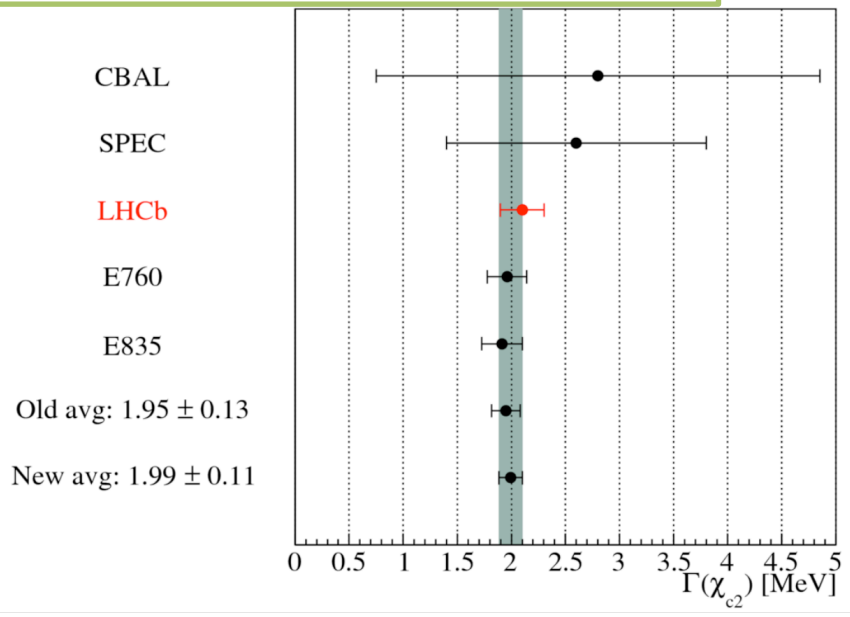


$\chi_{c1,c2}$ mass and width

- In good agreement w/ & have comparable precision to the current world average

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

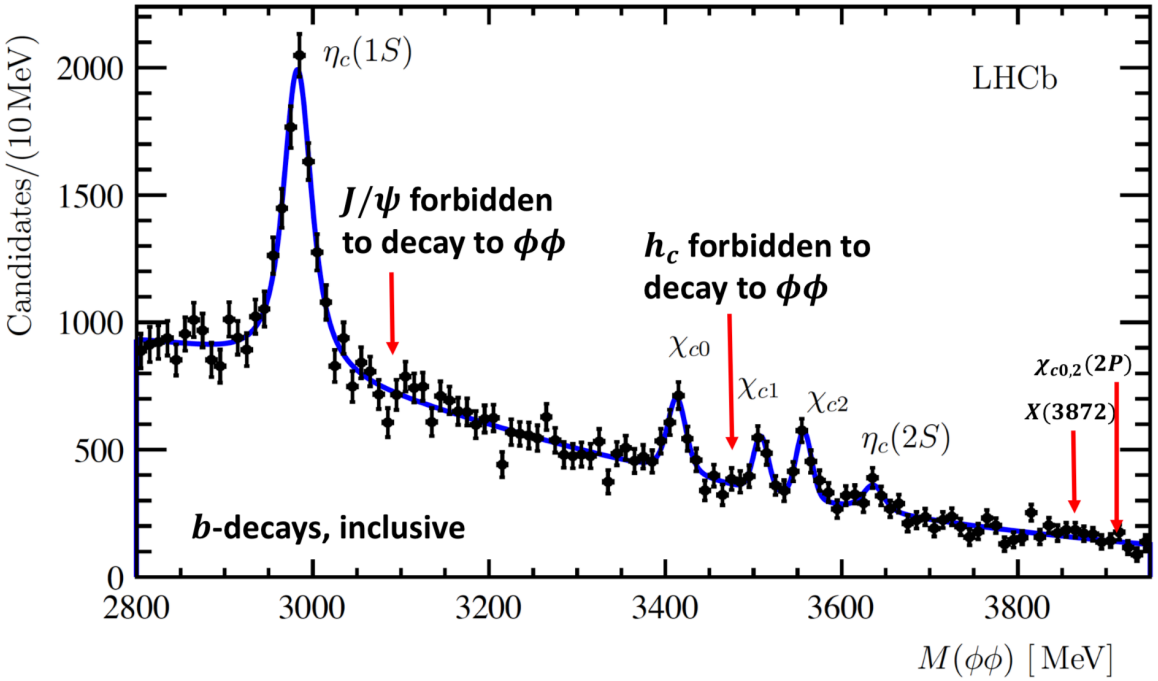


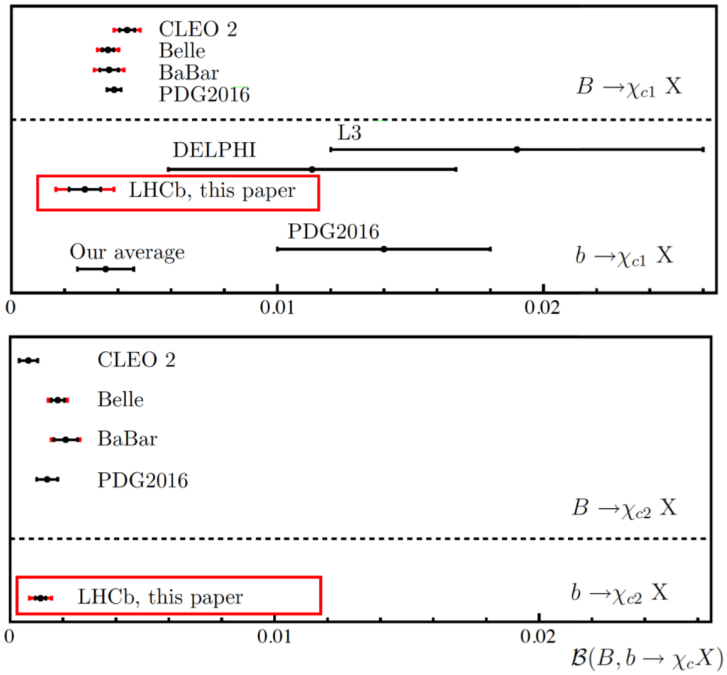


[LHCb, PRL 119 (2017) 221801]

Charmonium production in b-decays

- Using ϕϕ final states, measure b->charmonia + X in one go [LHCb, EPJC 77 (2017) 609]
- Possible to measure charmonia hadroproduction



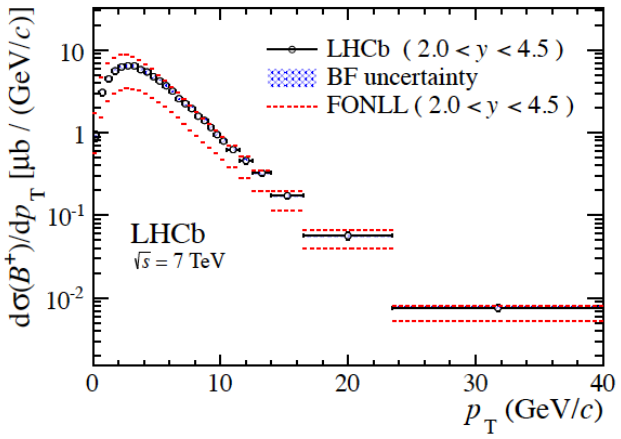


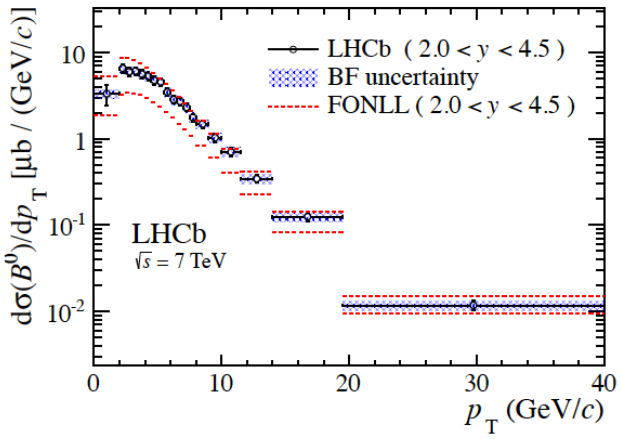
B mesons' production

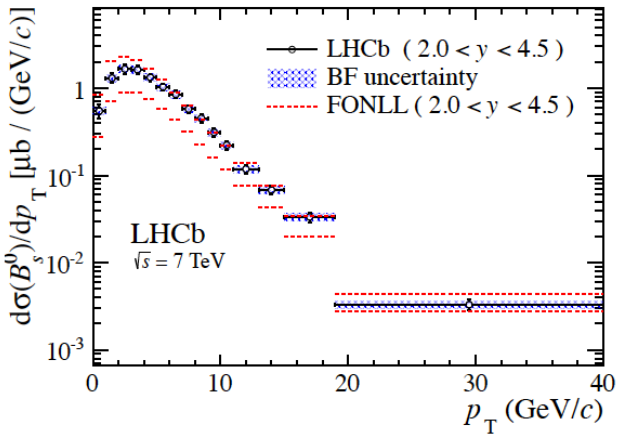
- Measured B mesons' production at 7 TeV, agree with FONLL (Fixed Order+Next-to-Leading Log)

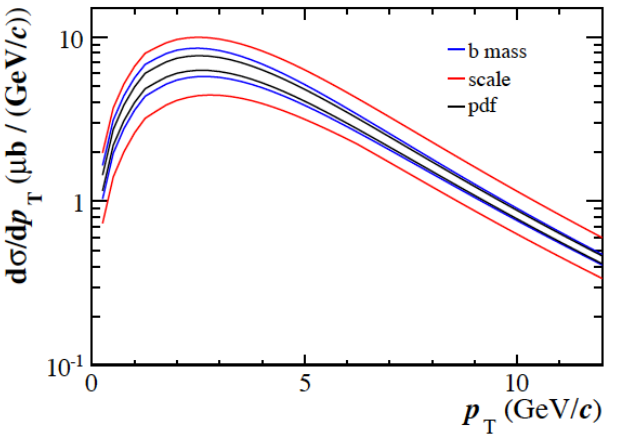
[M. Cacciari *et al.*, JHEP 10 (2012) 137]

[LHCb, JHEP 08 (2013) 117]



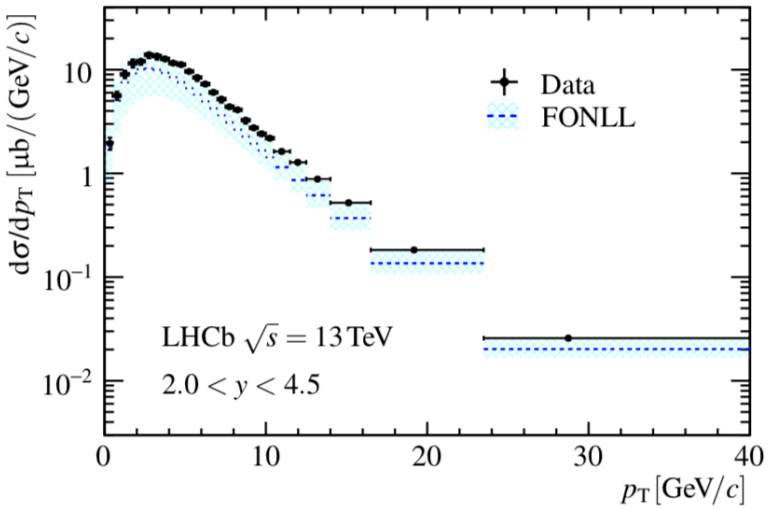


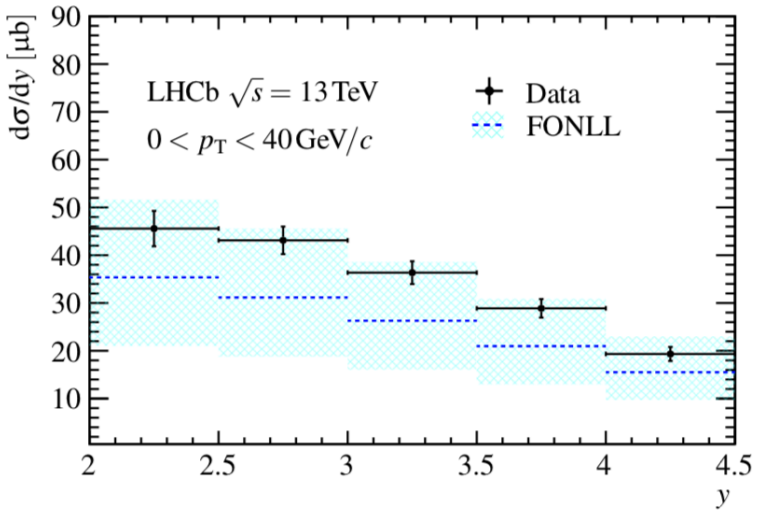


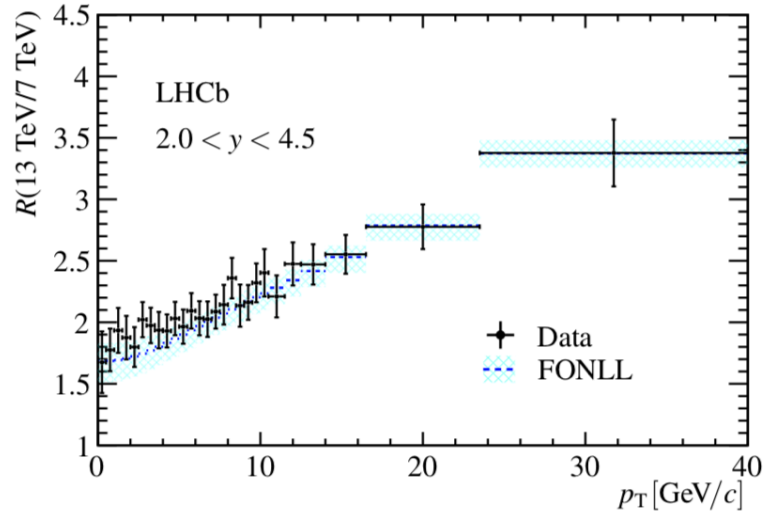


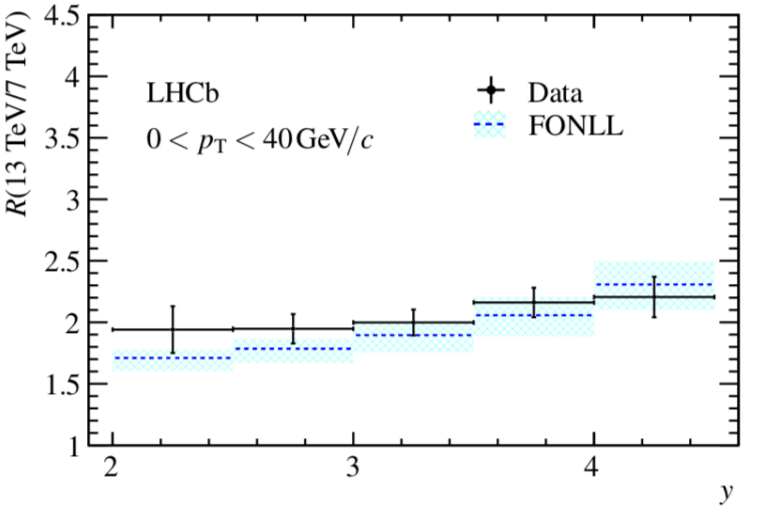
B^+ production at 13 TeV

- New energy, ratio 13/7 TeV





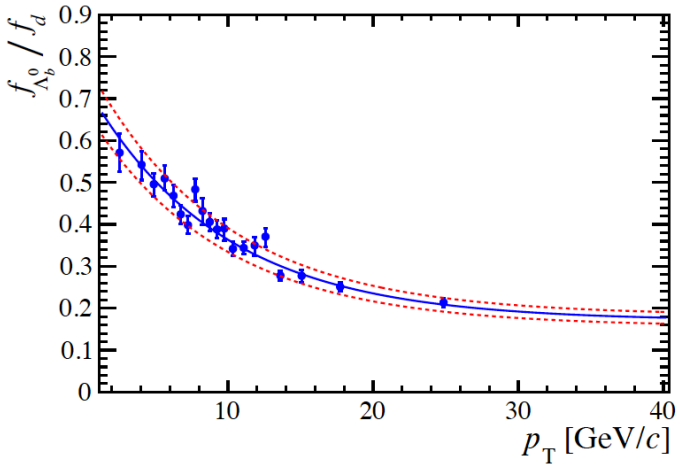


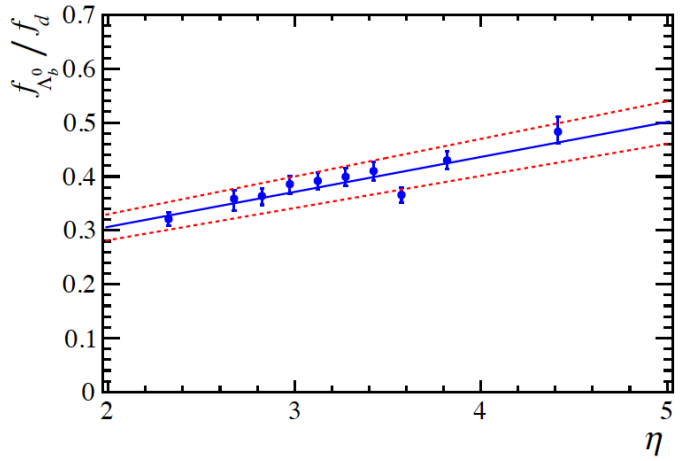


[LHCb, JHEP 12 (2017) 026]

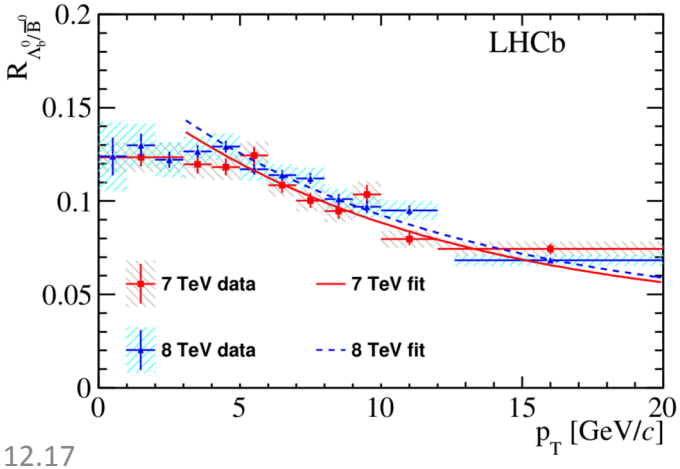
Λ_b^0 production at LHCb

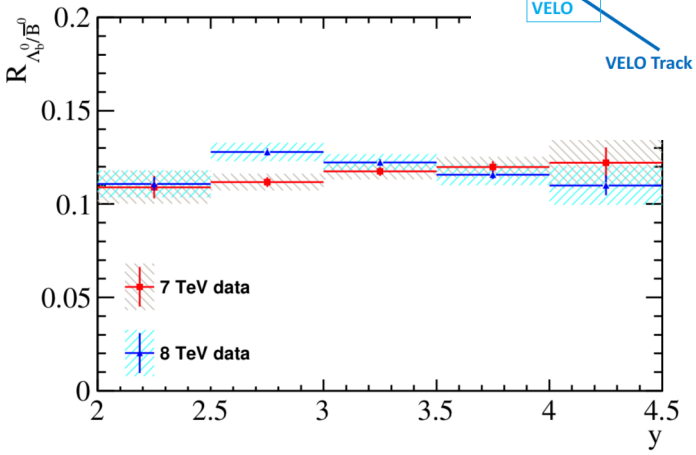
- p_T and η dependence, with $\Lambda_b^0 \to \Lambda_c \pi^+$

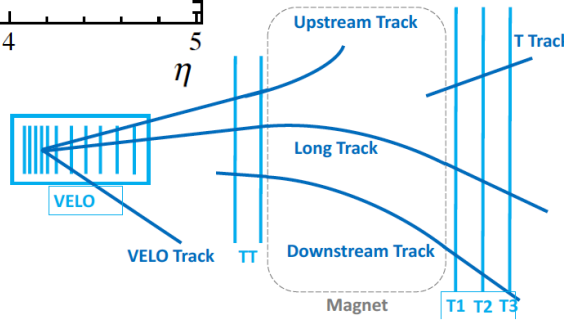




- Confirmed with $\Lambda_b^0 \to J/\psi p K^+$



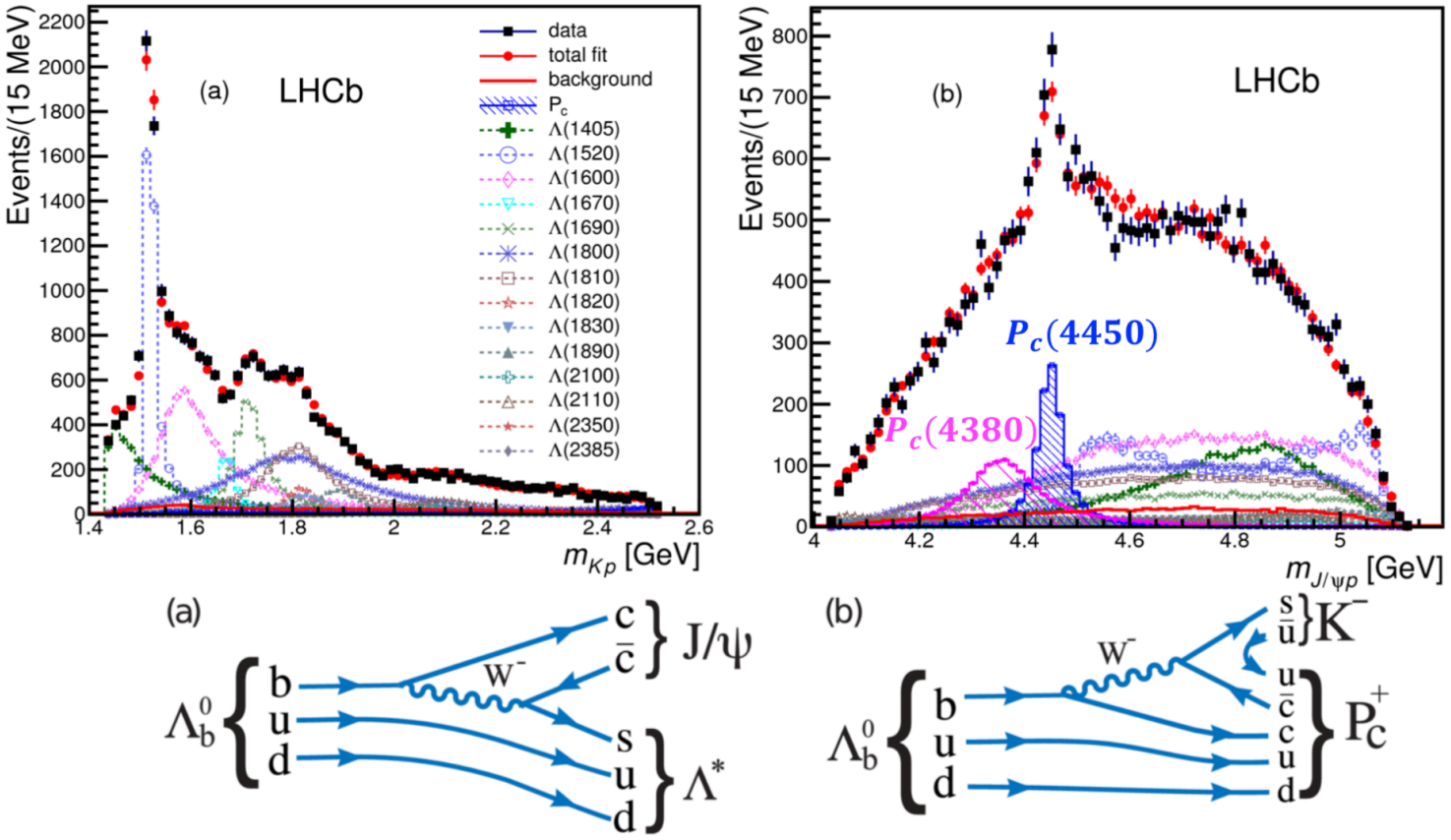




[LHCb, JHEP 03 (2014) 143, CPC 40 (2016) 011001]

Observation of pentaquark states

- Two pentaquark states observed in $\Lambda_b^0 \to J/\psi p K^+$



[LHCb, PRL 115 (2015) 072001]

Observation of Ξ_b^-->J/ψΛK$^-$

- Looking for udsc$\bar{c}$ state
- First observation of ~300 events in Run-I

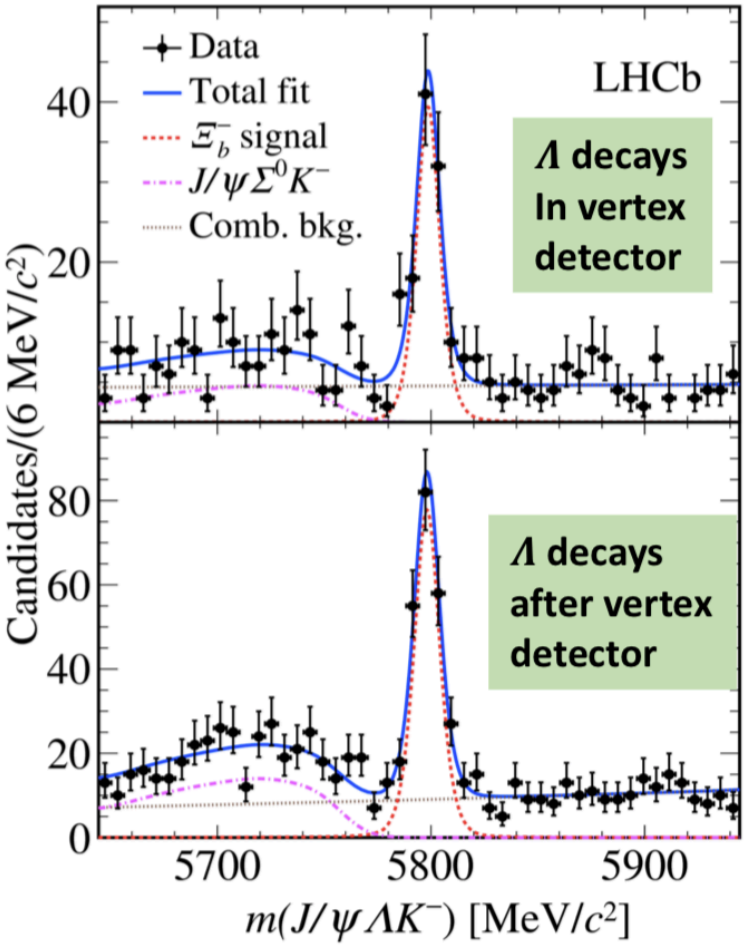
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b) = 177.08 \pm 0.47 \pm 0.16\,\mathrm{MeV}/c^2$$

(One of the two world best measurements)

- Full amplitude analysis foreseen with Run-I+II

[J.-J. Wu *et al.*, PRL 105 (2010) 232001]
[H.-X. Chen *et al.*, PRC 93 (2016) 082002]



[LHCb, PLB 772 (2017) 265]

Observation of $\Lambda_b^0 \to \chi_{c1,c2} p K^-$

- $P_c(4450)$ close to $\chi_{c1}p$ threshold, triangle singularity?

[F.-K. Guo *et al.*, PRD 92 (2015) 071502]
[M. Bayar *et al.*, PRD 94 (2016) 074039]

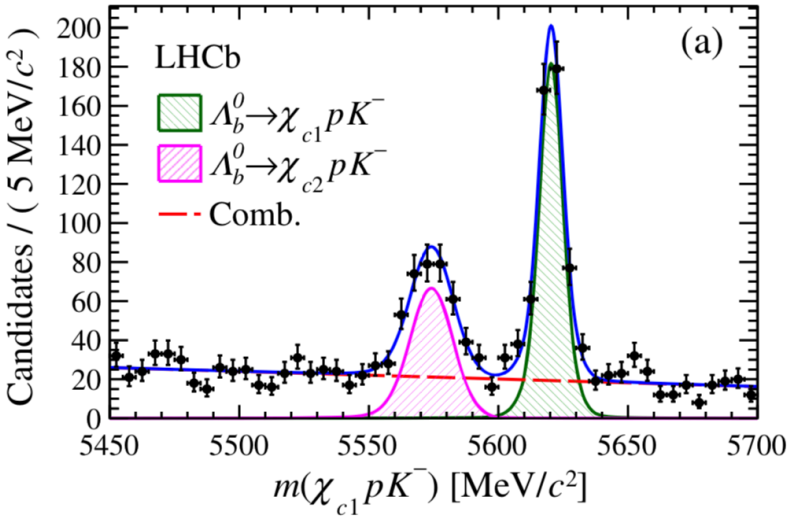
- First observation of these decay modes
  (~453 $\Lambda_b^0 \to \chi_{c1} p K^-$, ~285 $\Lambda_b^0 \to \chi_{c2} p K^-$)

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05,$$

χ_{c2} mode not suppressed as in $B \to \chi_{cJ} K$ decay



χ_{c1} mass constraint applied

- Full amplitude analysis foreseen with Run-I+II

[LHCb, PRL 119 (2017) 062001]

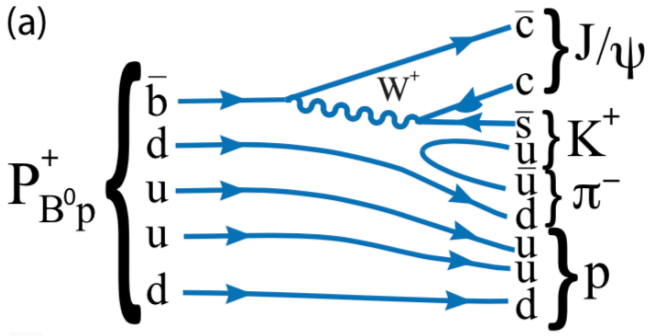
Search for b-flavored pentaquarks

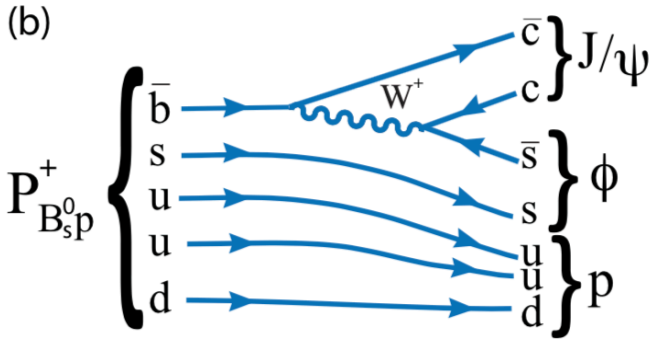
- Skyrme model: the heavier the constituent quarks, the more tightly bound the state

[T.H.R. Skyrme, Proc. Roy. Soc. Lond. A 260 (1961) 127] & other refs. in paper

[LHCb, arXiv:1712.08086]

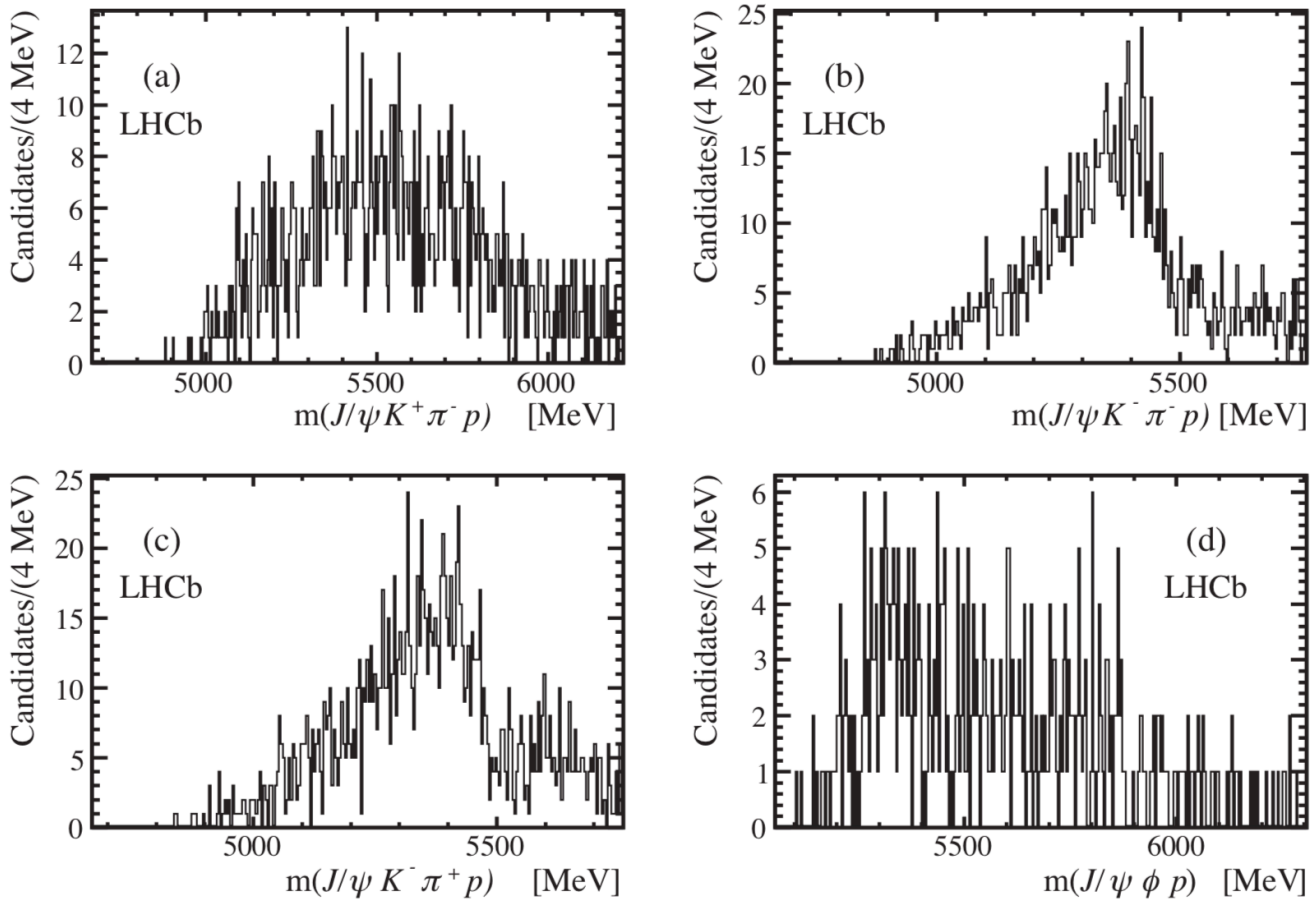
Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi\, K^+\pi^-p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda_b^0\pi^-} \to J/\psi\, K^-\pi^-p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda_b^0\pi^+} \to J/\psi\, K^-\pi^+p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B_s^0p} \to J/\psi\, \phi p$	5055–6305 MeV





Search for b-flavored pentaquarks

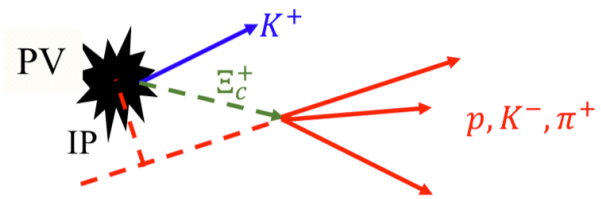
- No clear signal, set upper limits on their cross-section times BR relative to $\Lambda_b^0 \to J/\psi p K^+$, ~$10^{-3}$



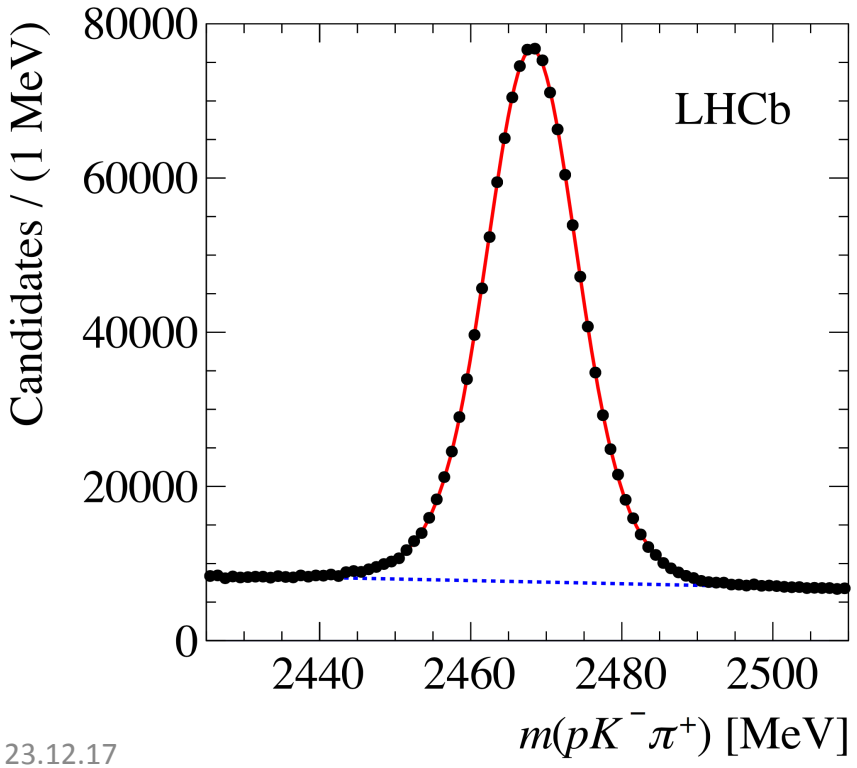
[LHCb, arXiv:1712.08086]

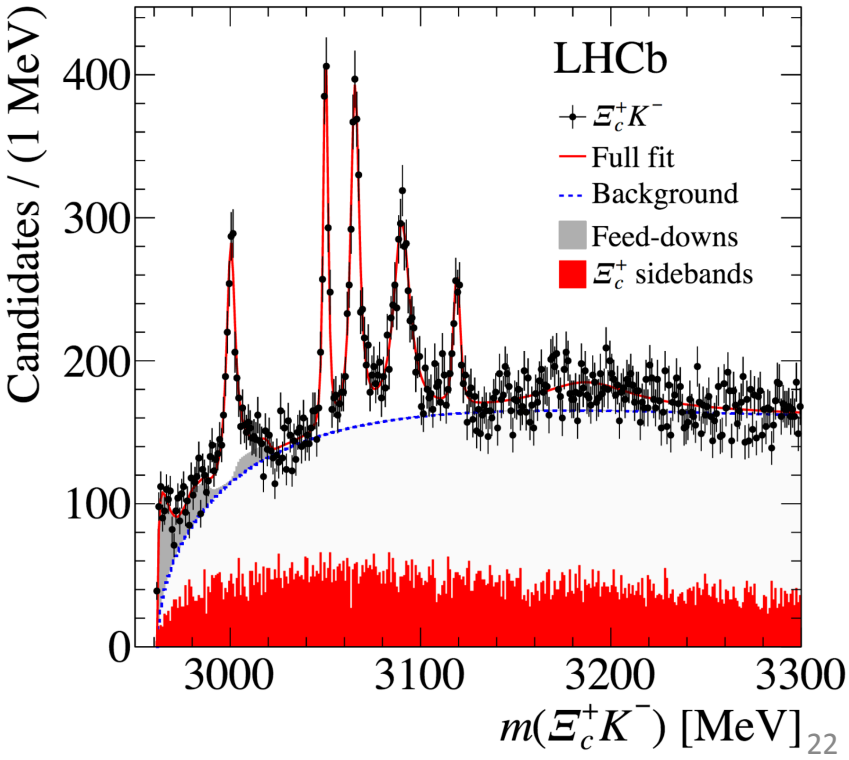
Observation of excited Ω_c states

- Searched with $\Xi_c^+ K^-$, $\Xi_c^+ \to p K^- \pi^+$
- 5 narrow states + evidence of a broader one



[LHCb, PRL 118 (2017) 182001]



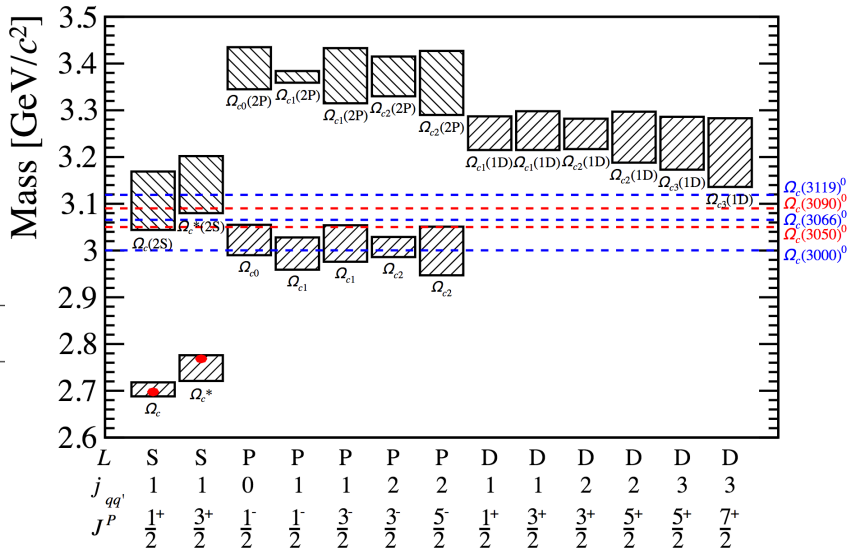


Observation of excited Ω_c states (cont.)

- Matching between observed peaks and predictions requires spin-parity info

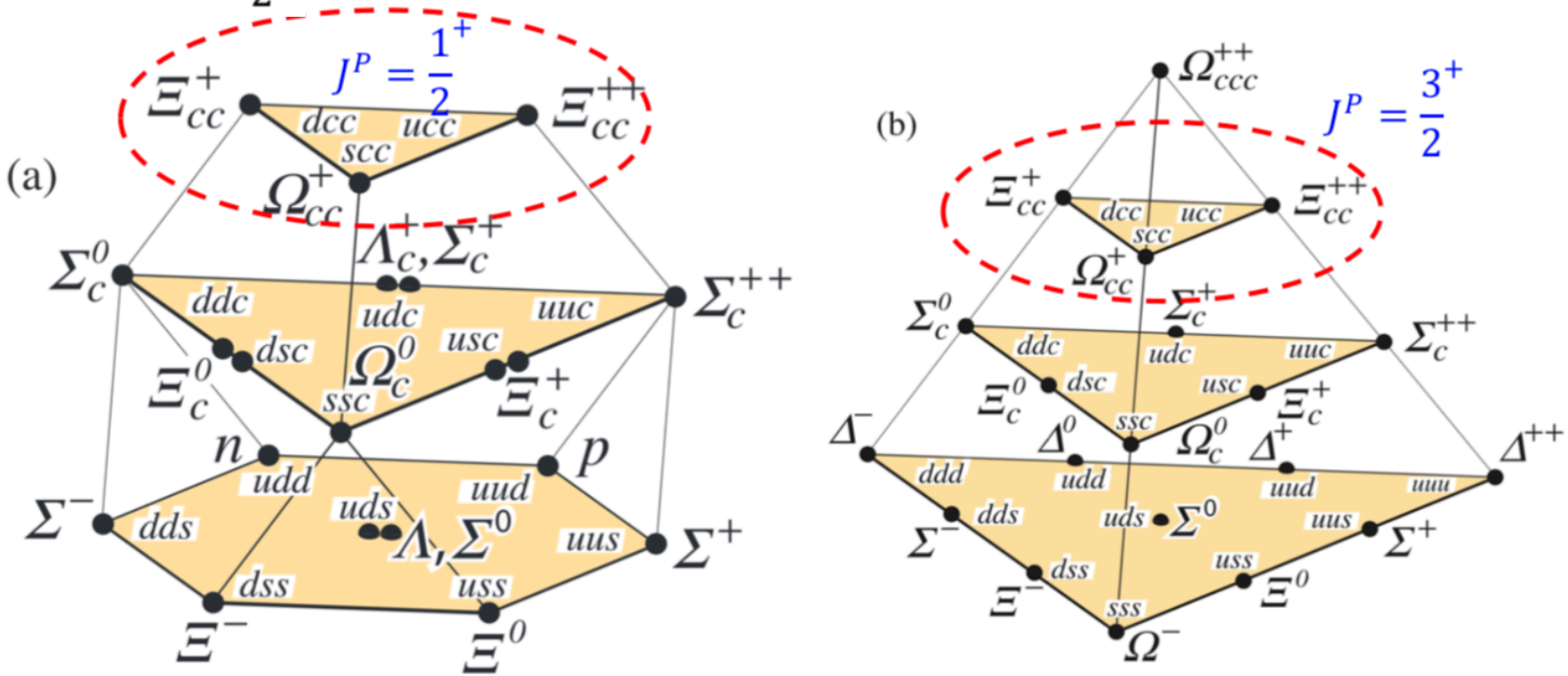
[LHCb, PRL 118 (2017) 182001]

Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		$< 1.2\,\text{MeV}, 95\%\ \text{CL}$	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		$< 2.6\,\text{MeV}, 95\%\ \text{CL}$	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4



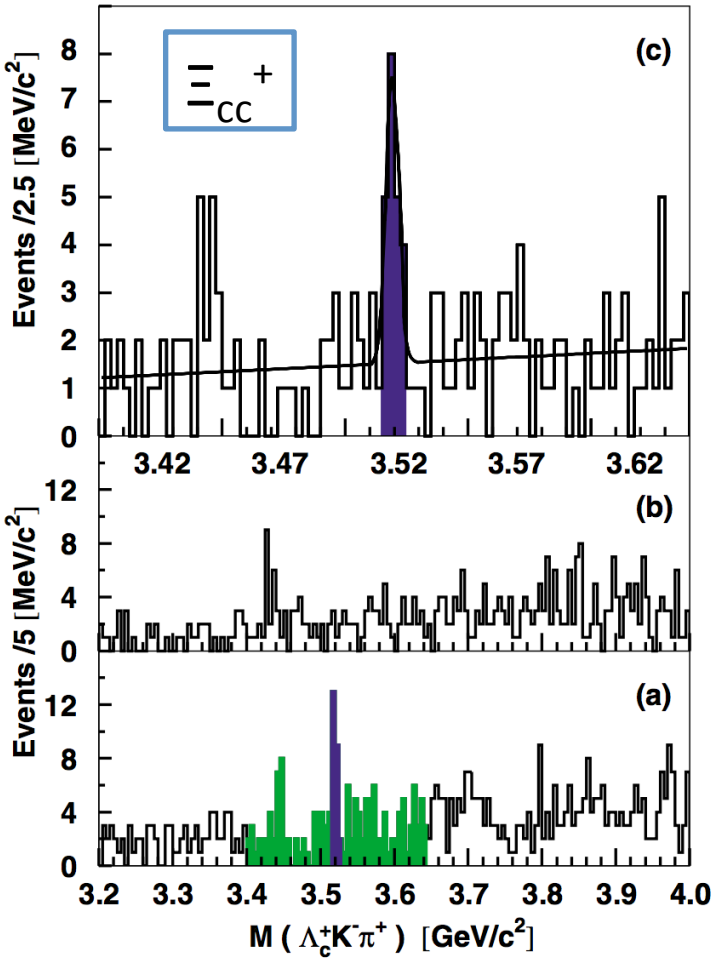
Doubly charmed baryons

- Two SU(4) 20-plets
  - $J^P = \frac{3}{2}^+$ decays via EM/strong interactions to $\frac{1}{2}^+$
  - $J^P = \frac{1}{2}^+$ decays weakly

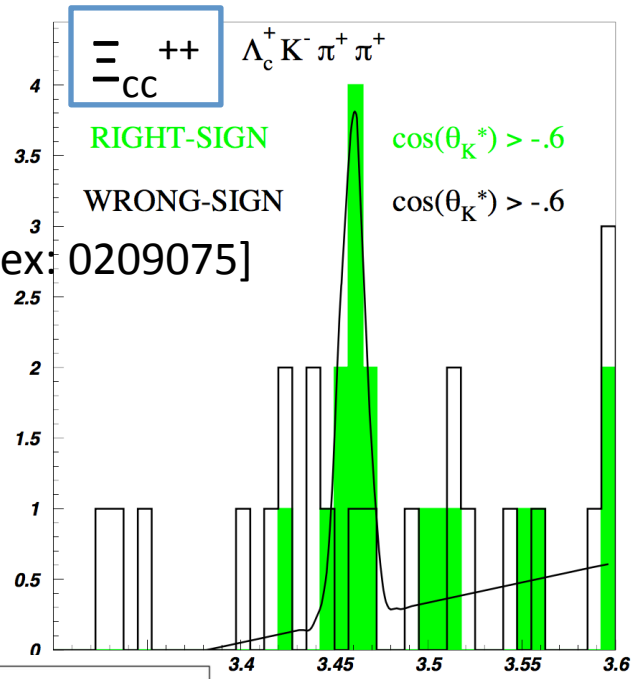


Ξ_{cc} @ SELEX

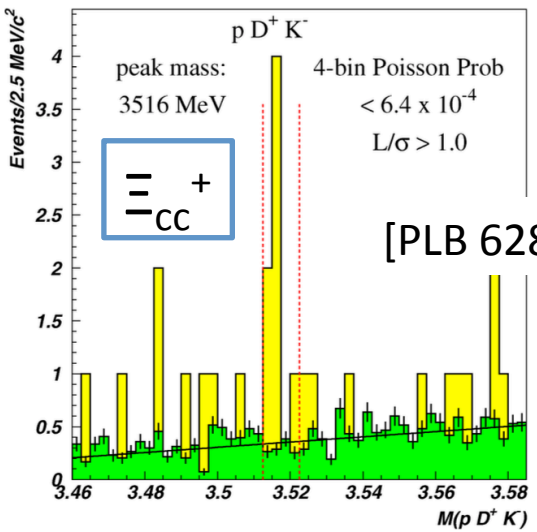
[PRL 89 (2002) 112001]



[hep-ex: 0209075]



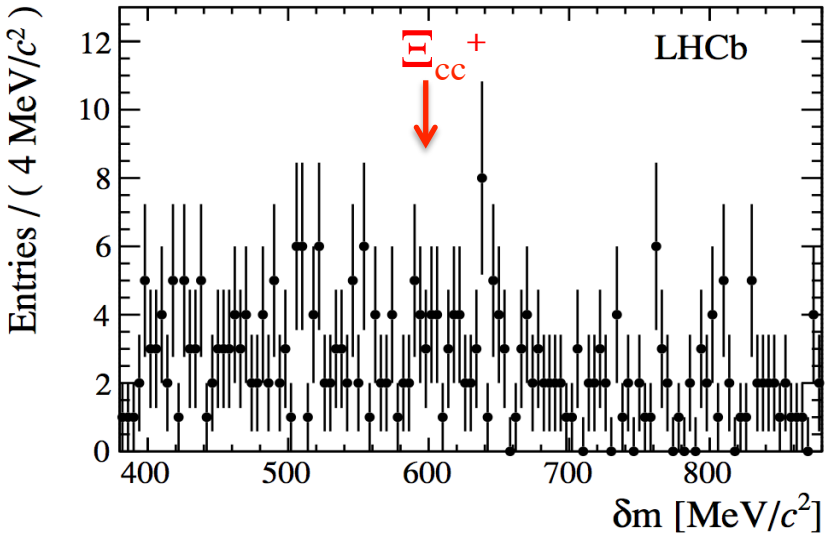
[PLB 628 (2005)18]

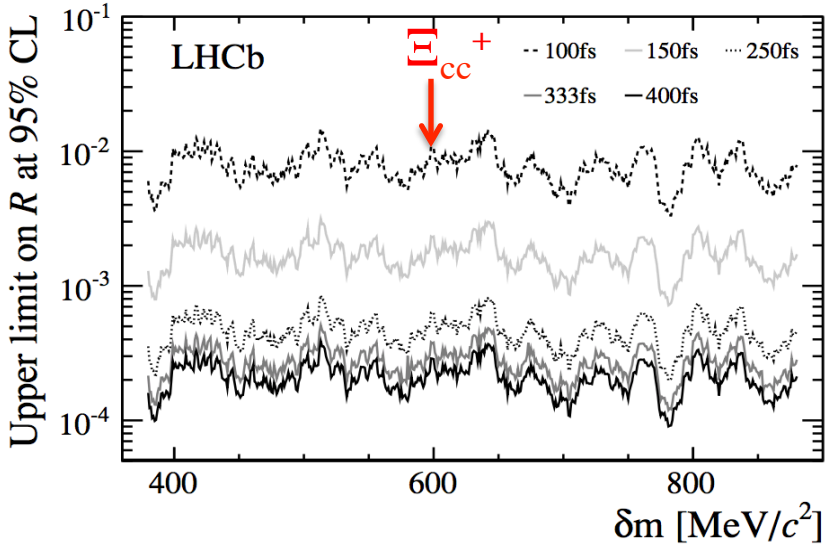


Ξ_{cc} @ LHCb & others

- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- Ξ_{cc}^{+}->$\Lambda_c^{+}K^{-}\pi^{+}$ searched by LHCb w/ 2011 data

[LHCb, JHEP 12 (2013) 090]

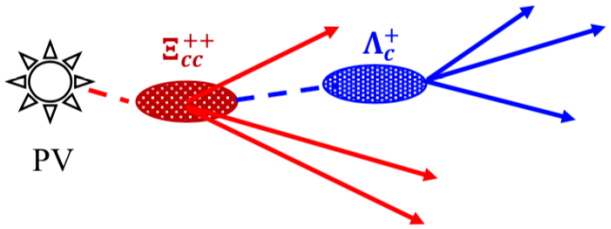




Observation of $\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+$

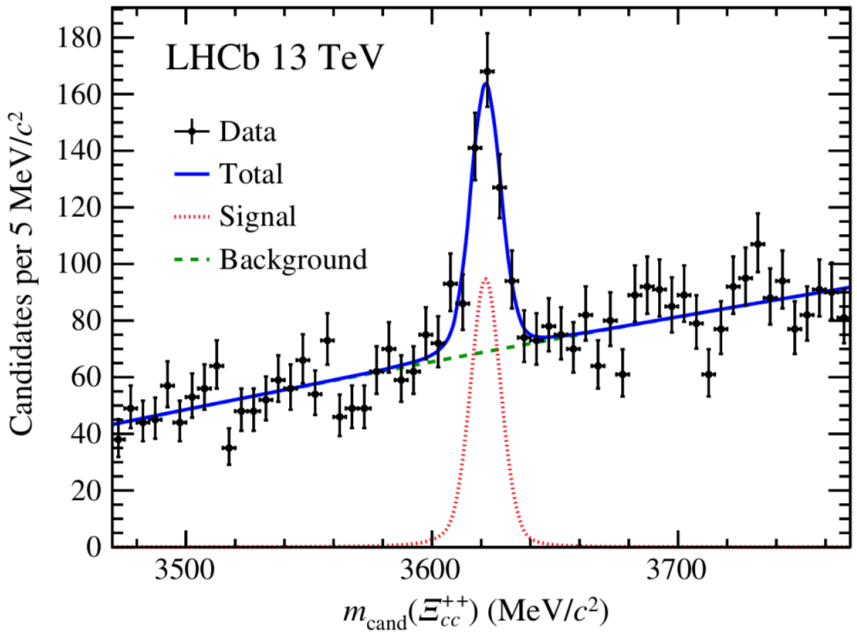
- $\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+$ identified as the most promising channel

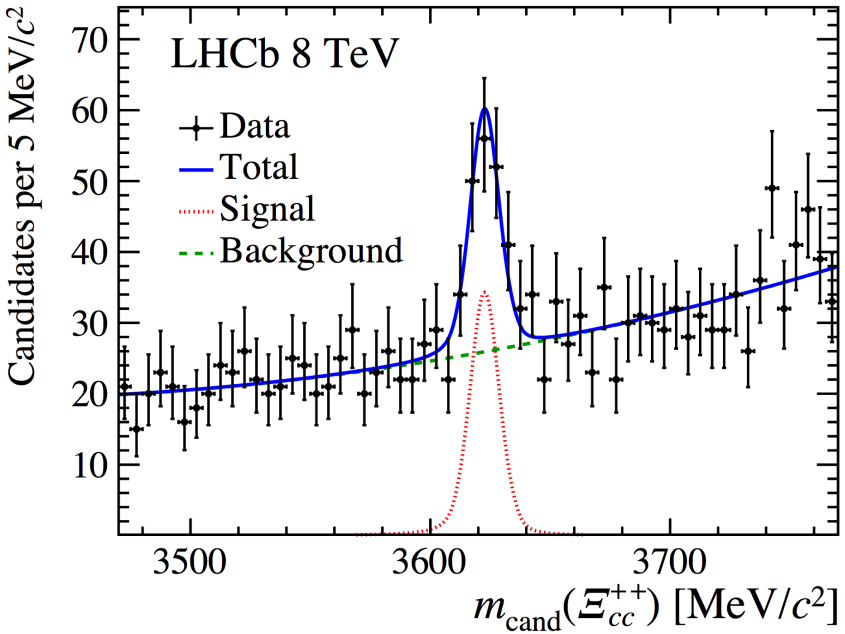
  [F.-S. Yu *et al.*, arXiv:1703.09086]



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

[LHCb, PRL 119 (2017) 112001]





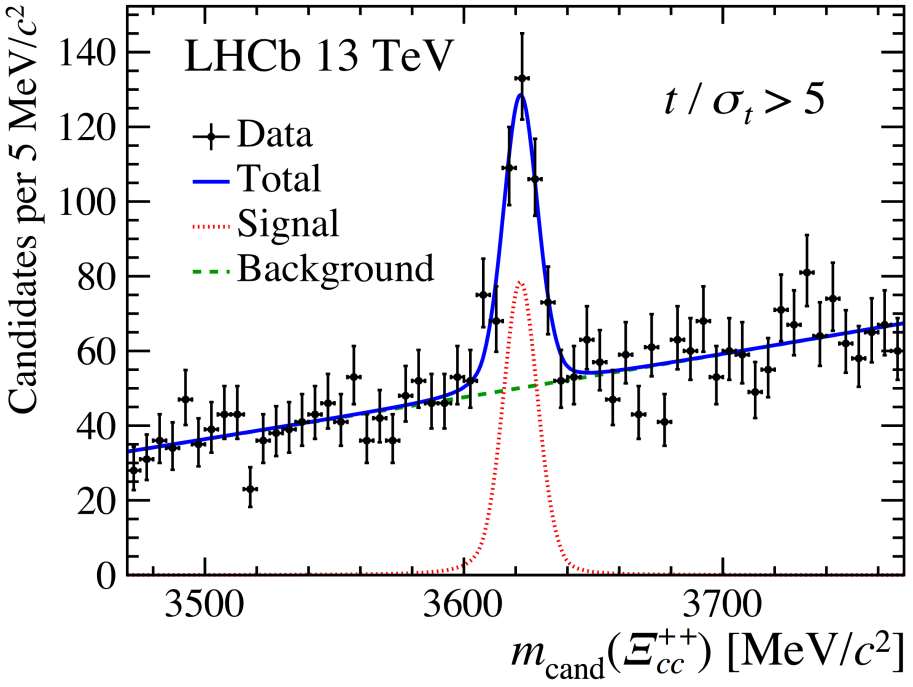
Ξ_{cc}^{++} properties

- 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

- Decay weakly, mass peak remains after lifetime cut

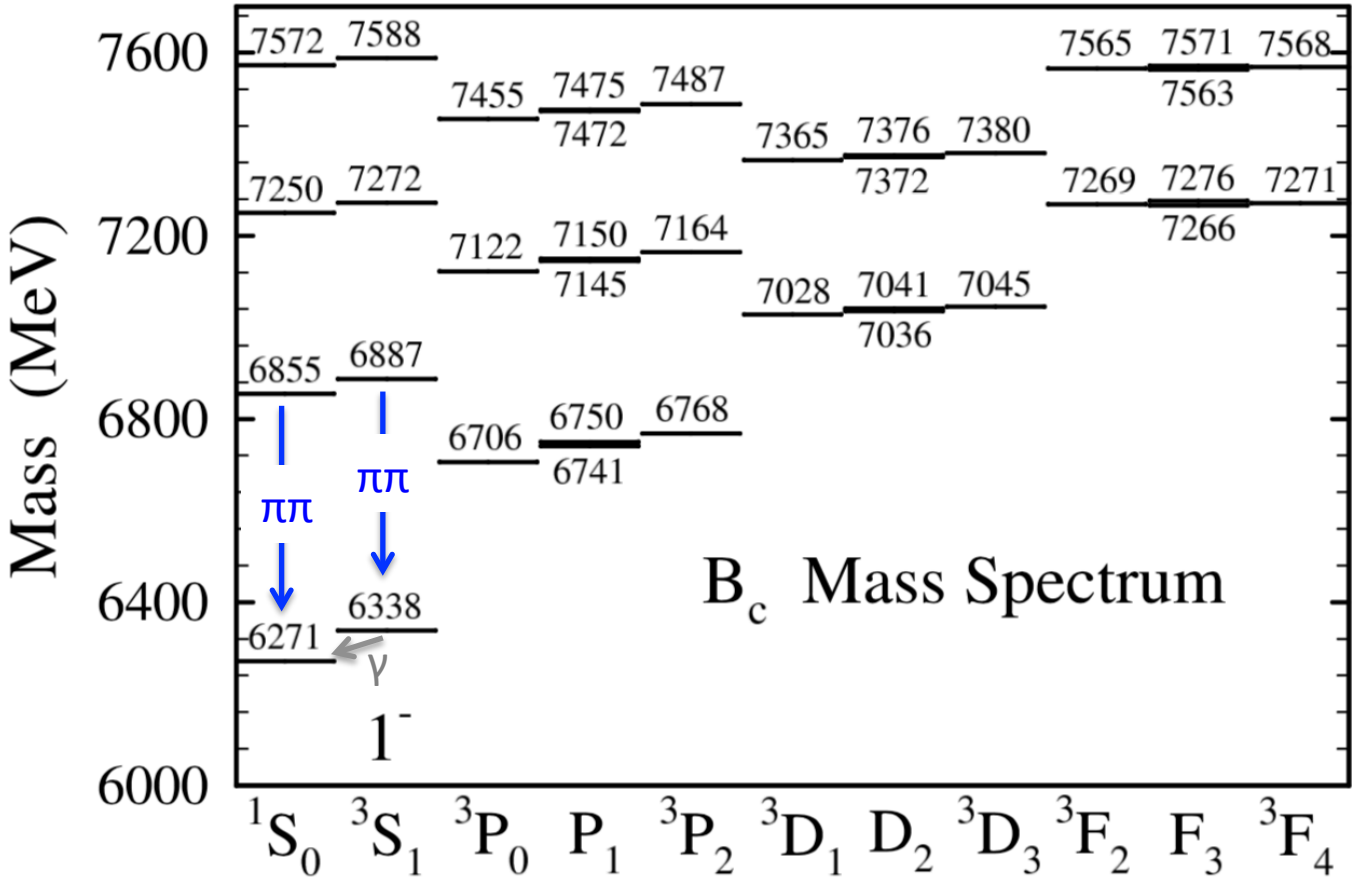
- Results on lifetime, production, other decay modes will be released soon



[LHCb, PRL 119 (2017) 112001]

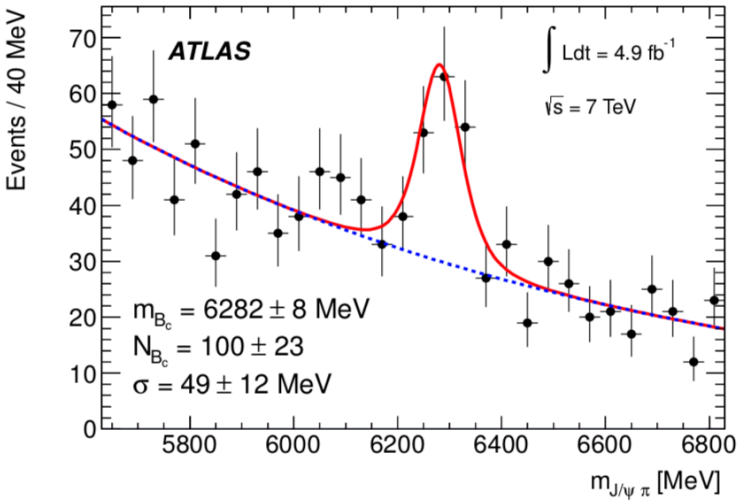
B_c spectrum

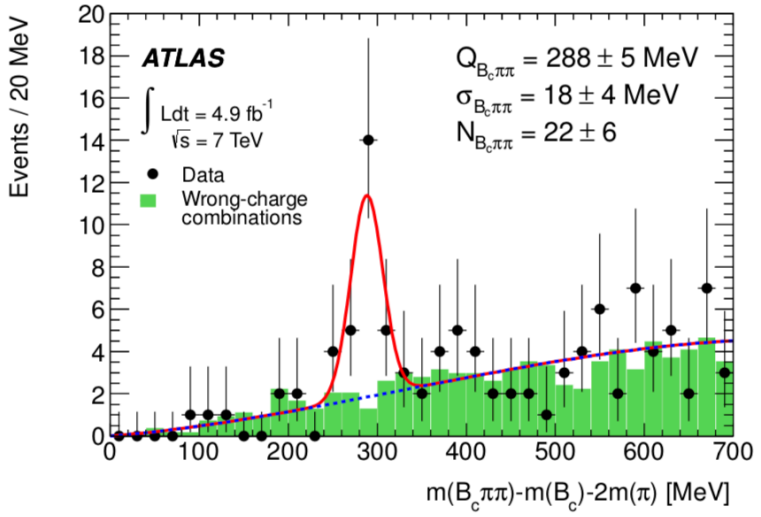
- B_c, doubly heavy meson, rich spectrum

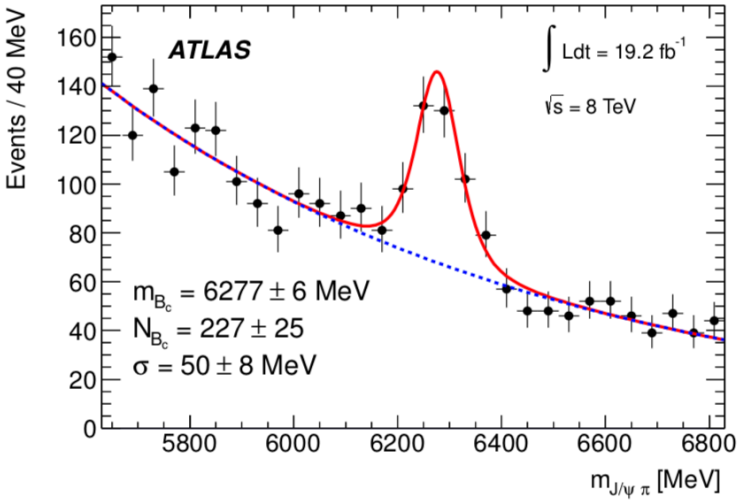


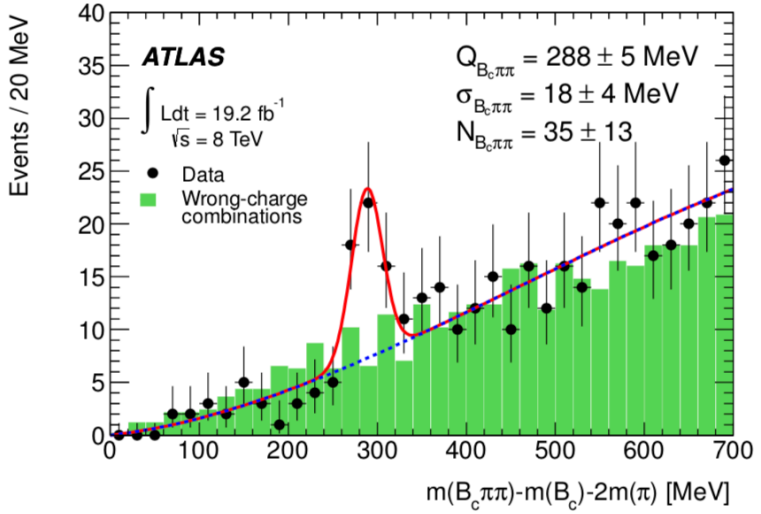
[S.Godfrey, PRD 70 (2004) 054017]

Observation of $B_c(2S)$ by ATLAS







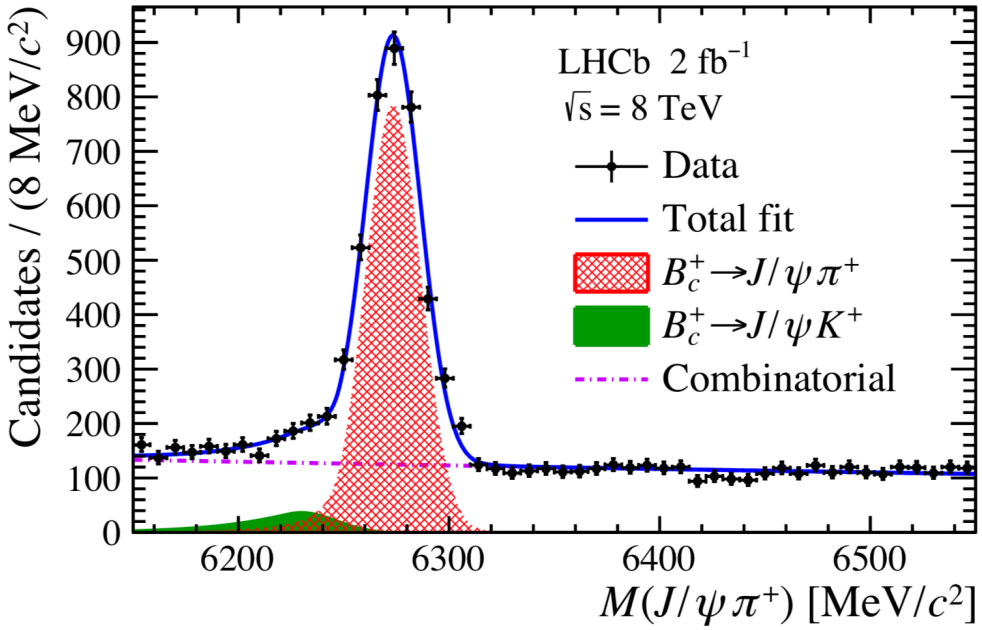


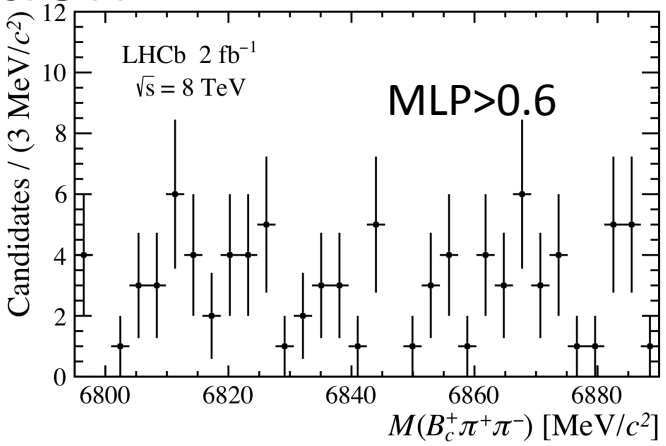
[ATLAS, PRL 113 (2014) 12004]

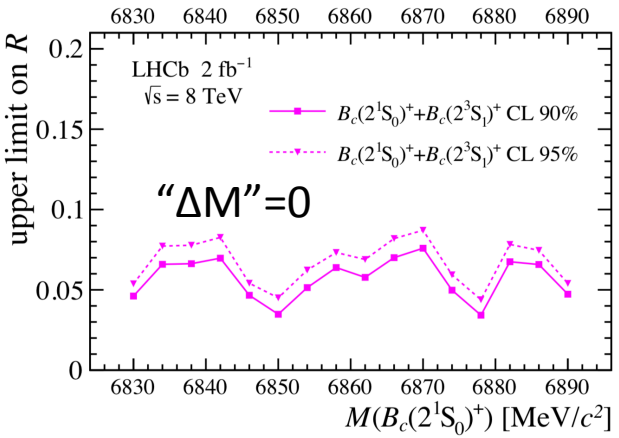
Search for $B_c(2S)$ by LHCb

- LHCb has the largest (low p_T) B_c^+ sample, not-yet confirming ATLAS observation
- Setting upper limits

[LHCb, arXiv: 1712.04094]

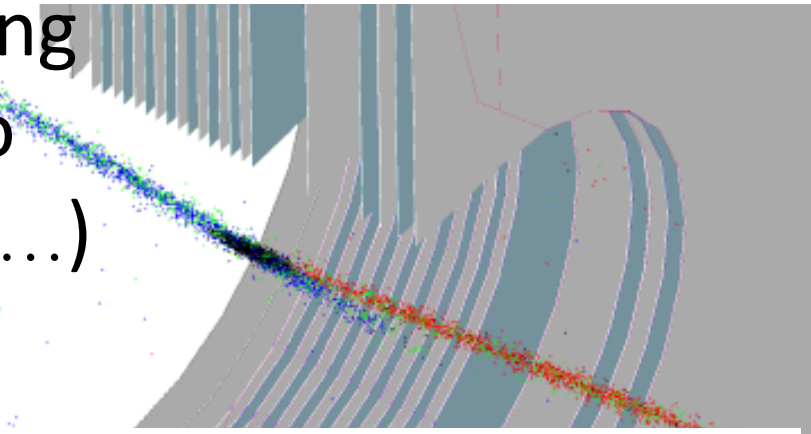


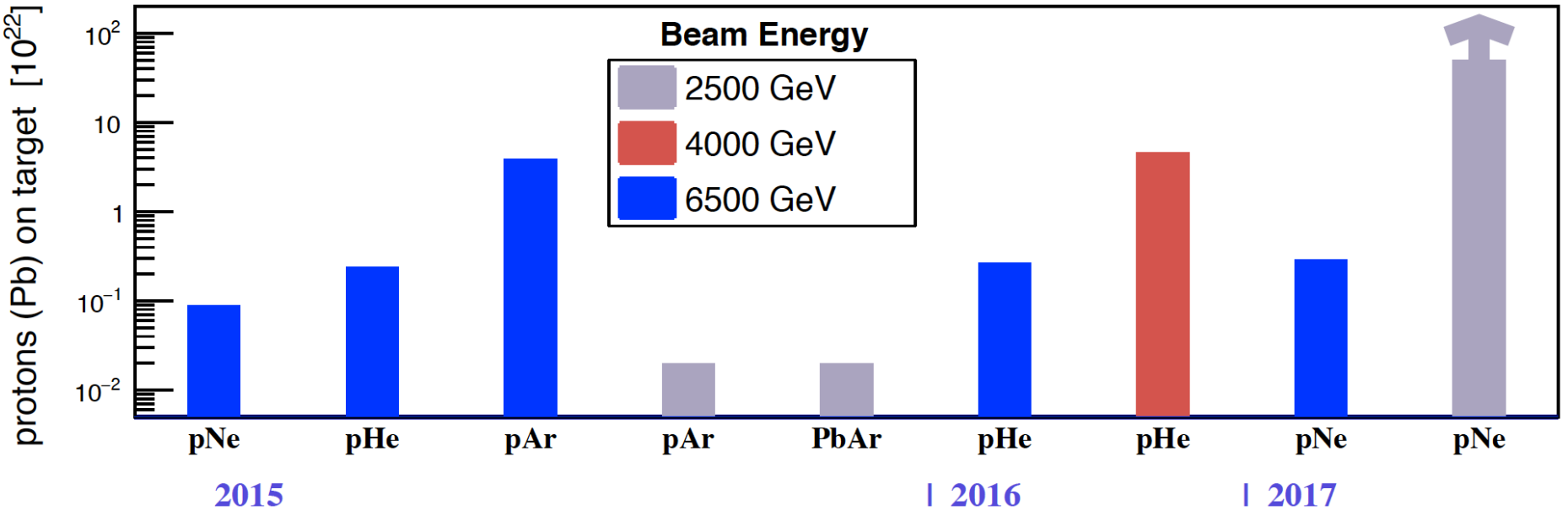




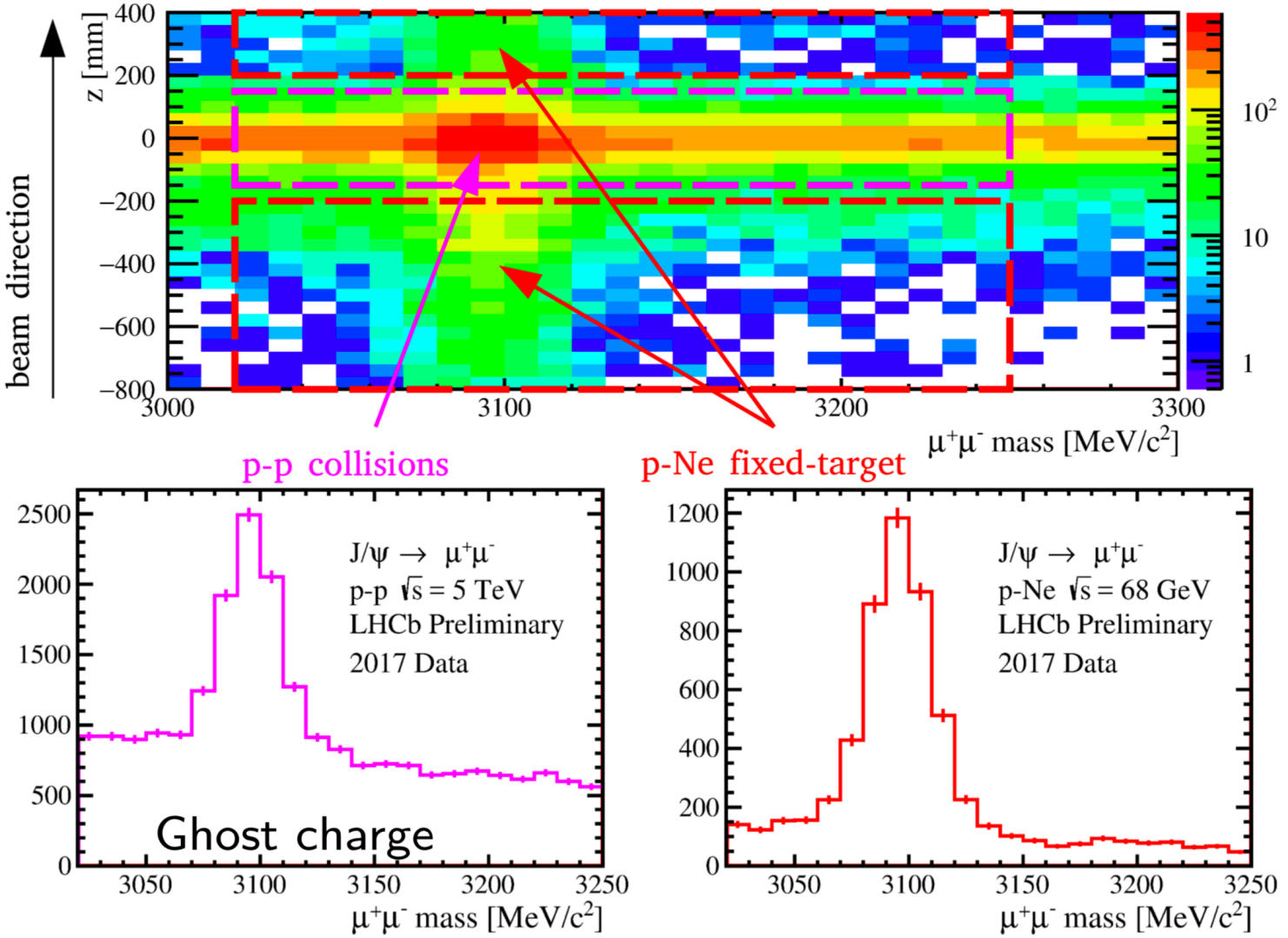
Fixed target program thanks to SMOG

- SMOG: System for Measuring Overlap With Gas, allows to inject noble gas (He, Ne, Ar…) around LHCb ~2x10^{-7} mbar





pNe: J/ψ from online monitoring



Summary

- LHC(b) is a flavor factory, an ideal place to study hadron production & spectroscopy
- Many interesting results in the past year:
  - Production: Quarkonia/B at 13 TeV, …
  - Spectroscopy: Ξ_{cc}^{++}, excited Ω_c, …
- Strong & continued supports from theory community greatly appreciated
- More will be released soon, stay tuned!