Heavy flavour spectroscopy at ATLAS, CMS and LHCb

Mat Charles (Sorbonne Université*/LPNHE)

* Previously Université Pierre et Marie Curie, previously Université de Paris, previously Université de France, previously Université de Paris

Topics for today

- The Ξ_{cc}^{++} discovery
- The ongoing X(5568) mystery
- Round-up of updates since La Thuile 2017
  - Five new narrow $\Omega_c^0 \to \Xi_c^+ K^-$ states
  - Search for weakly decaying b-flavoured pentaquarks
  - Excited B_c^+ states
  - Precise measurements of χ_{c1} and χ_{c2}
  - A promising first look at $\chi_b \to \Upsilon\gamma$ ($\Upsilon \to \mu^+\mu^-$)

No hope of covering all LHC spectroscopy results, sorry!

The Ξ_{cc}^{++} (ccu) discovery

Ξ_{cc}^{++} : Quark model

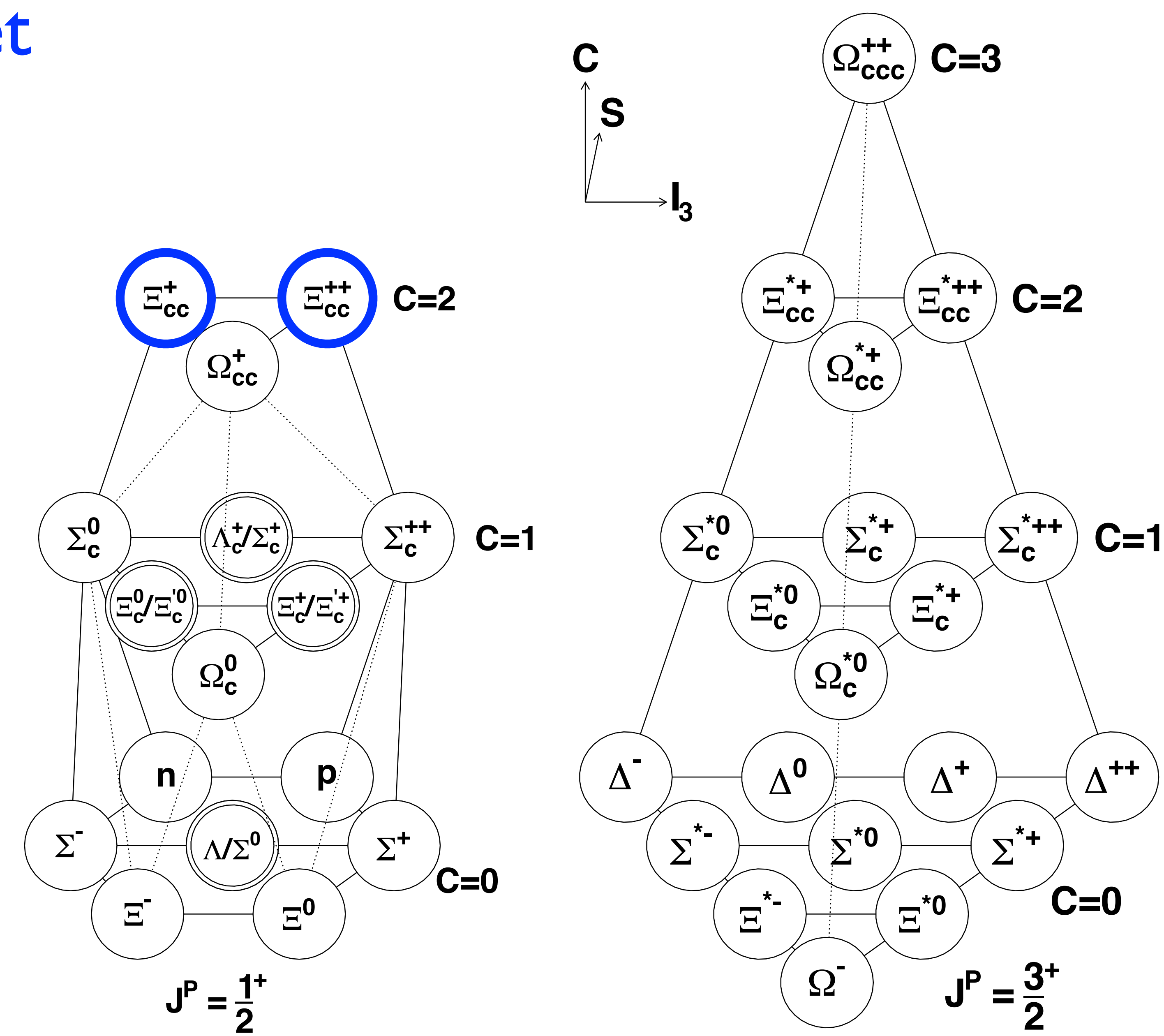
- In the quark model, expect baryons with > 1 heavy quark.
- Several of them should decay weakly, including:
  - ccu = Ξ_{cc}^{++} } Ξ_{cc} isospin doublet
  - ccd = Ξ_{cc}^{+}
  - ccs = Ω_{cc}^{++}
  - ccc = Ω_{ccc}^{++}
- At stupidly naive 0th order,

  m(p) = 938 MeV

  m(Λ_c) = 2286 MeV

  => m(Ξ_{cc}) ~ 3.6 GeV

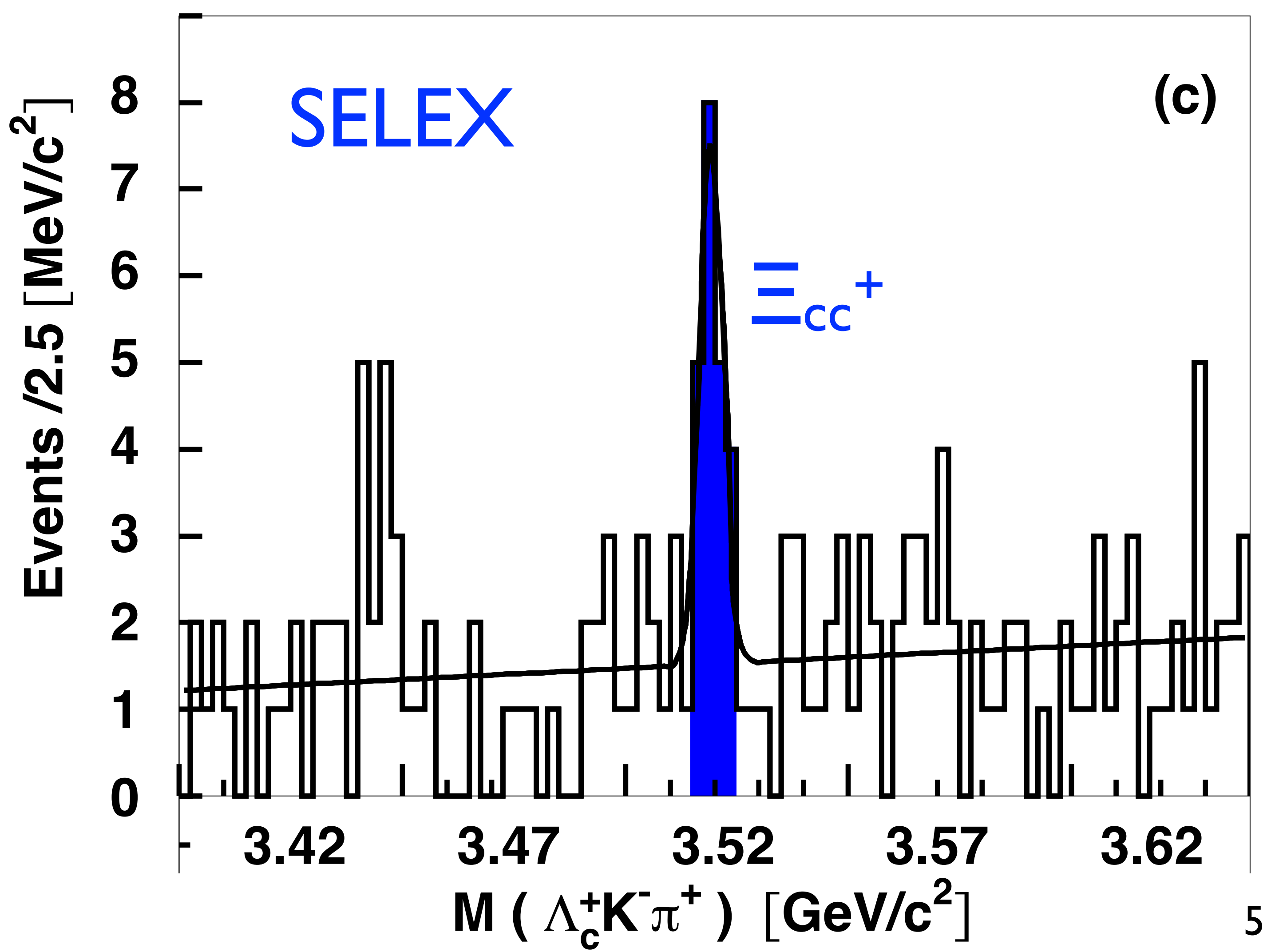
  => m(Ω_{ccc}) ~ 5.0 GeV
- Real calculations typically give 3.5 < m(Ξ_{cc}) < 3.7 GeV, $\tau(\Xi_{cc}^{++})$ ~ few hundred fs, $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^{+})$ ~ 3 to 4



See e.g. Kiselev & Likhoded [Phys. Usp. 45, 455 (2002)], Fleck & Richard [Prog. Theor. Phys. 82, 760 (1989)]. Full list of theory refs in backups.

Ξ_{cc}^{++} : History

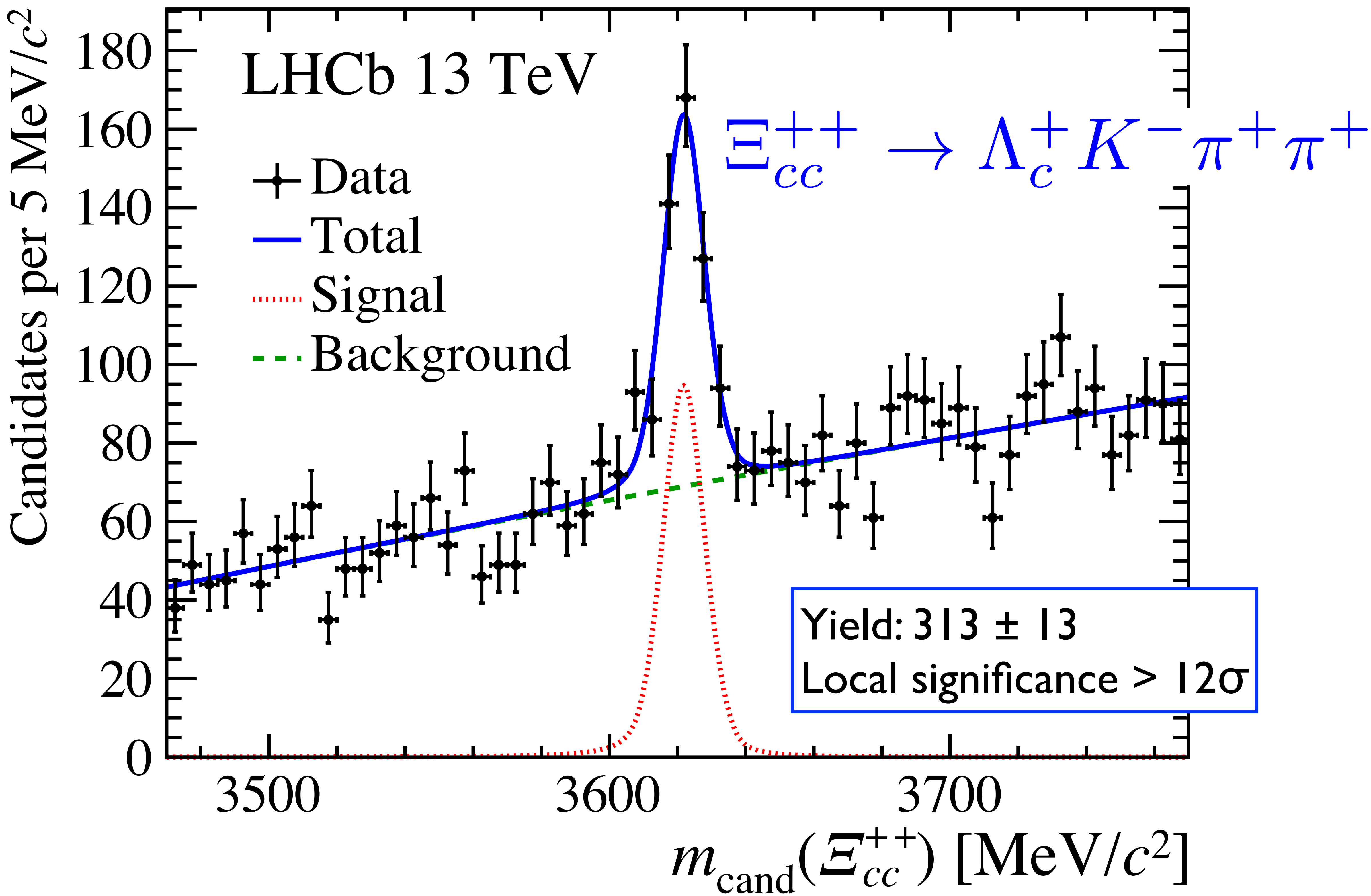
- Longstanding experimental puzzle: observations of Ξ_{cc}^{+} (ccd) claimed by SELEX in 2002, 2005 but never reproduced by other experiments.
- Various oddities with SELEX result... but because production environment was unique (hyperon beam on fixed target), other results didn't formally rule it out.
- Relevant points for today: SELEX reported
  - $m(\Xi_{cc}^{+})$ = 3519 ± 2 MeV
  - $\tau(\Xi_{cc}^{+})$ < 33 fs @ 90% CL



SELEX: PRL 89:112001 (2002)
SELEX: PLB B628:18-24 (2005)

Ξ_{cc}^{++} : Discovery

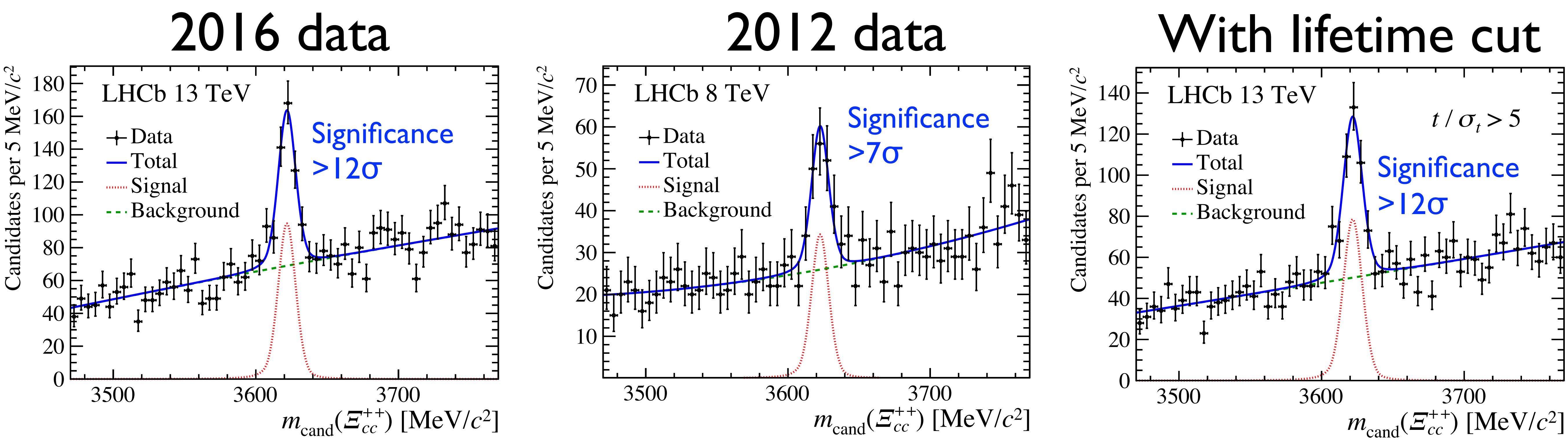
LHCb result, obtained with 2016 (Run 2) data:



LHCb: PRL 119, 112001 (2017)

Ξ_{cc}^{++} : Checks & tests

- Observation confirmed with 2012 sample (crosscheck).
- Lifetime significantly different from zero: observation persists when requiring $(t / \sigma_t) > 5$
  - σ_t varies event by event, but typical resolution ~ 40-50fs



Mass: $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \pm 0.14\,(\Lambda_c^+)\ \mathrm{MeV}/c^2$

Differs from SELEX Ξ_{cc}^{+} mass by 103±2 MeV => clearly not a conventional isodoublet.

LHCb: PRL 119, 112001 (2017)

Ξ_{cc}^{++} : What's next?

- Ξ_{cc}^{++} lifetime measurement! Crucial to the interpretation.
  - Will also give a clue about Ξ_{cc}^{+} lifetime.
- Ξ_{cc}^{++} production cross-section

veil of ignorance

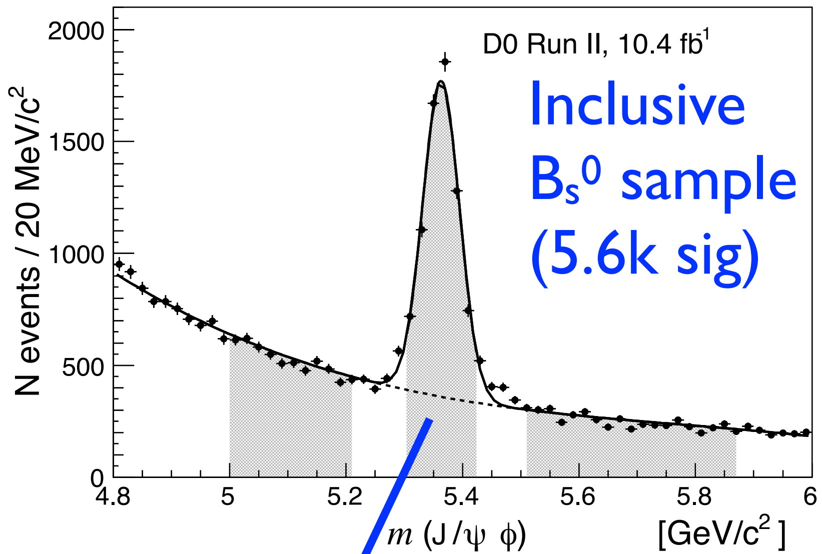
- Confirmation at ATLAS & CMS? Belle-II?
- More Ξ_{cc}^{++} decay modes! Ratios of branching fractions.
- Constraints on spin, parity
- Ξ_{cc}^{+} search
  - Tougher, due to shorter expected lifetime.
  - LHCb failed to find $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ with 0.65 fb^{-1} earlier... but now have better triggers, more modes, and much more data.
- Ξ_{cc}^{+} properties, production relative to Ξ_{cc}^{++}, etc
- Ω_{cc}^{+} search (tougher still)
- Excited states
  - Lowest expected to decay electromagnetically -- tough for LHCb
  - Add pions, kaon... see what's out there!

The ongoing X(5568) mystery

X(5568) : The D0 observation

Feb 2016: D0 reported a narrow structure in the $B_s^0 \pi^\pm$ spectrum (with $B_s^0 \to J/\psi\, \phi$).

Manifestly exotic $\bar{b}s\bar{q}q$ resonance.



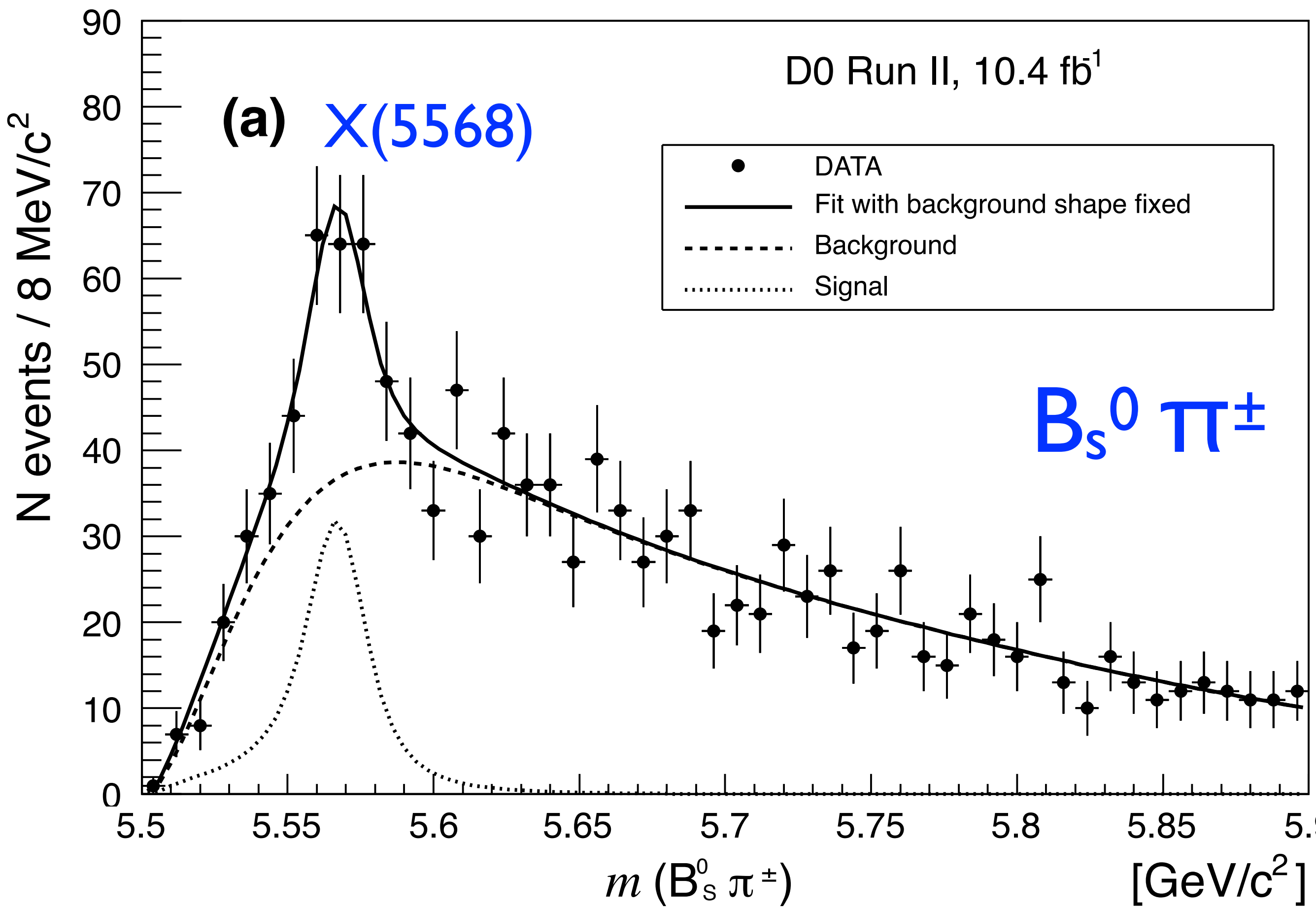
Yield: 133±31 events

Significance: 6.1σ stat, or 5.1σ stat+sys (inc LEE)

Eff-cor yield ratio $\rho(X/B_s^0)$:

$$10 < p_T(B_s^0) < 15\,\mathrm{GeV}/c : (9.1 \pm 2.6 \pm 1.6)\%$$
$$15 < p_T(B_s^0) < 30\,\mathrm{GeV}/c : (8.2 \pm 1.9 \pm 1.4)\%$$
$$\text{average} : (8.6 \pm 1.9 \pm 1.4)\%$$

This is a lot!



Mass and width:

$$m = 5567.8 \pm 2.9\,(\mathrm{stat})^{+0.9}_{-1.9}\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

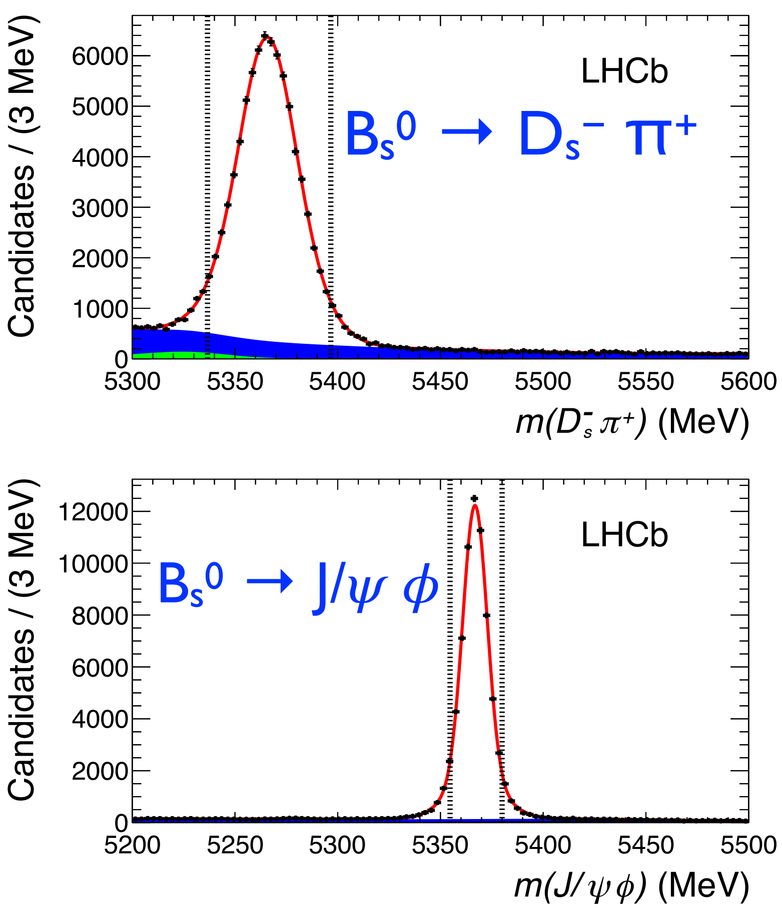
$$\Gamma = 21.9 \pm 6.4\,(\mathrm{stat})^{+5.0}_{-2.5}\,(\mathrm{syst})\,\mathrm{MeV}$$

But then...

D0: PRL 117, 022003 (2016)

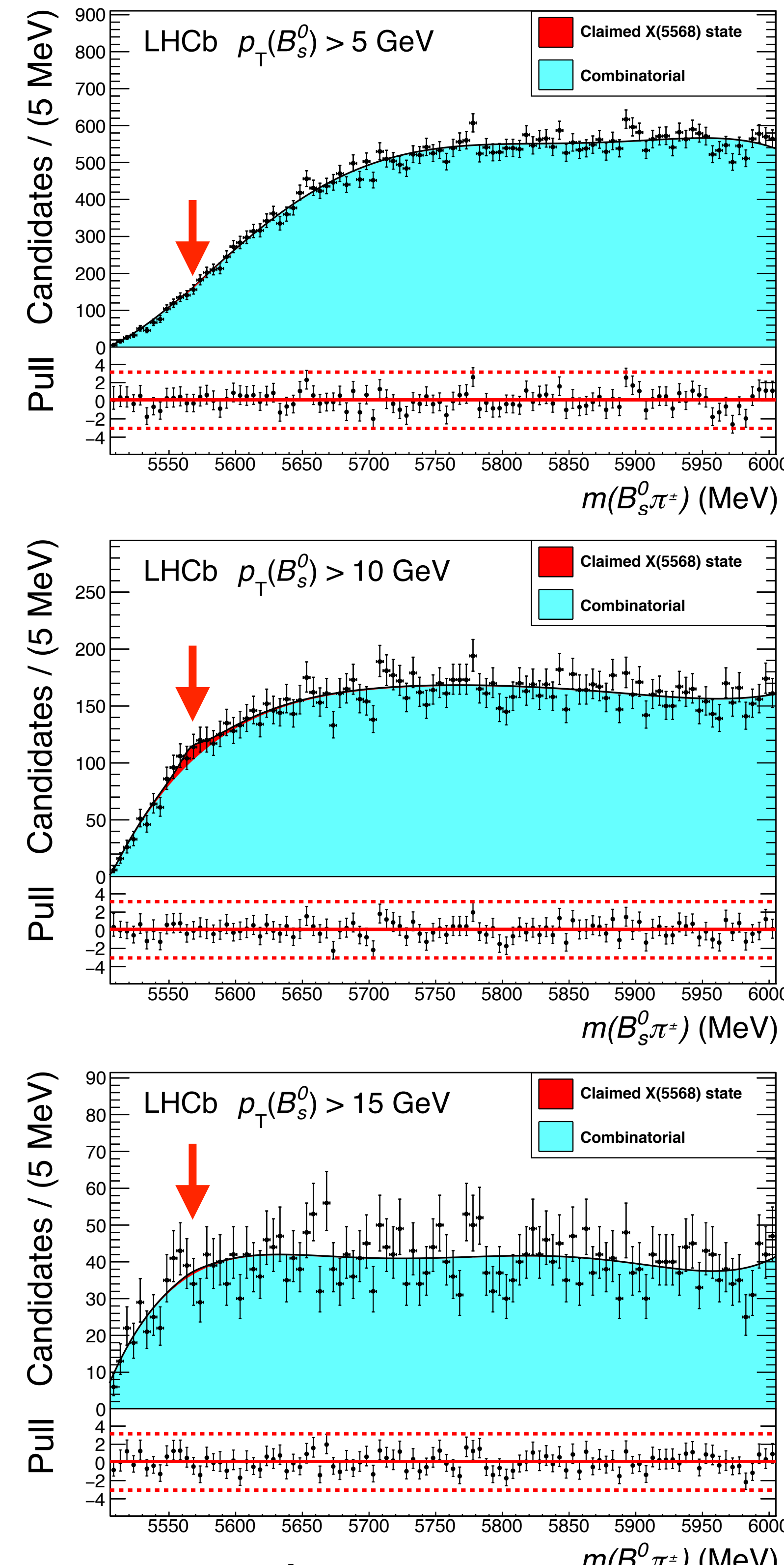
X(5568) : Not seen at LHCb

Aug 2016: LHCb tries to confirm peak, finds nothing despite larger B_s^0 sample, extra mode.



106k B_s^0

Add $\pi^\pm$, try various p_T cuts...



Upper limits set on (X/Bs) cor. yield ratio:

$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 5\,{\rm GeV}) < 0.011\ (0.012)$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 10\,{\rm GeV}) < 0.021\ (0.024)$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 15\,{\rm GeV}) < 0.018\ (0.020)$$

at 90% (95%) CL

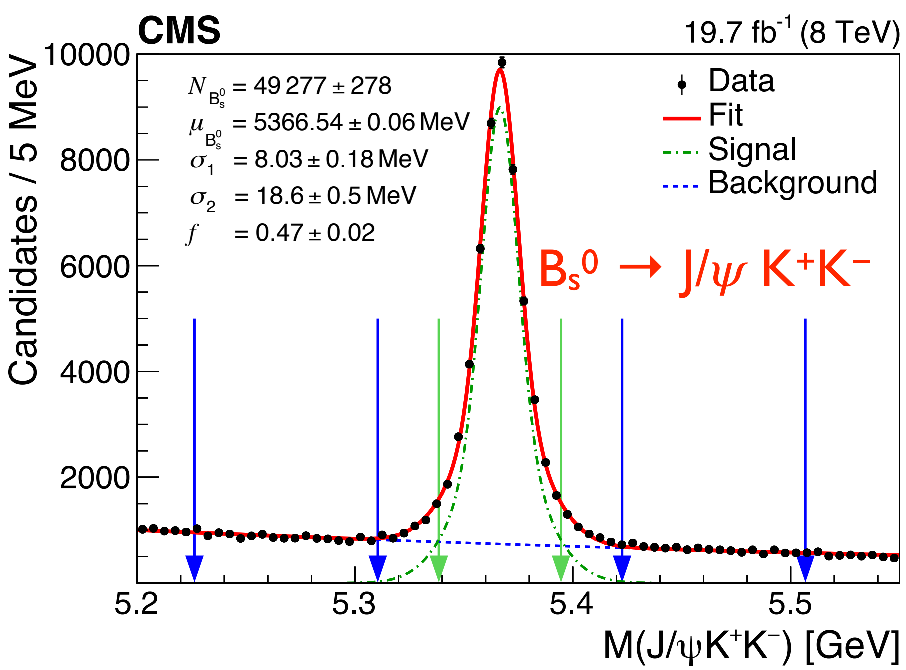
... vs (8.6 ± 1.9 ± 1.4)% at D0 (but different environment)

And then...

LHCb: PRL 117, 152003 (2016)

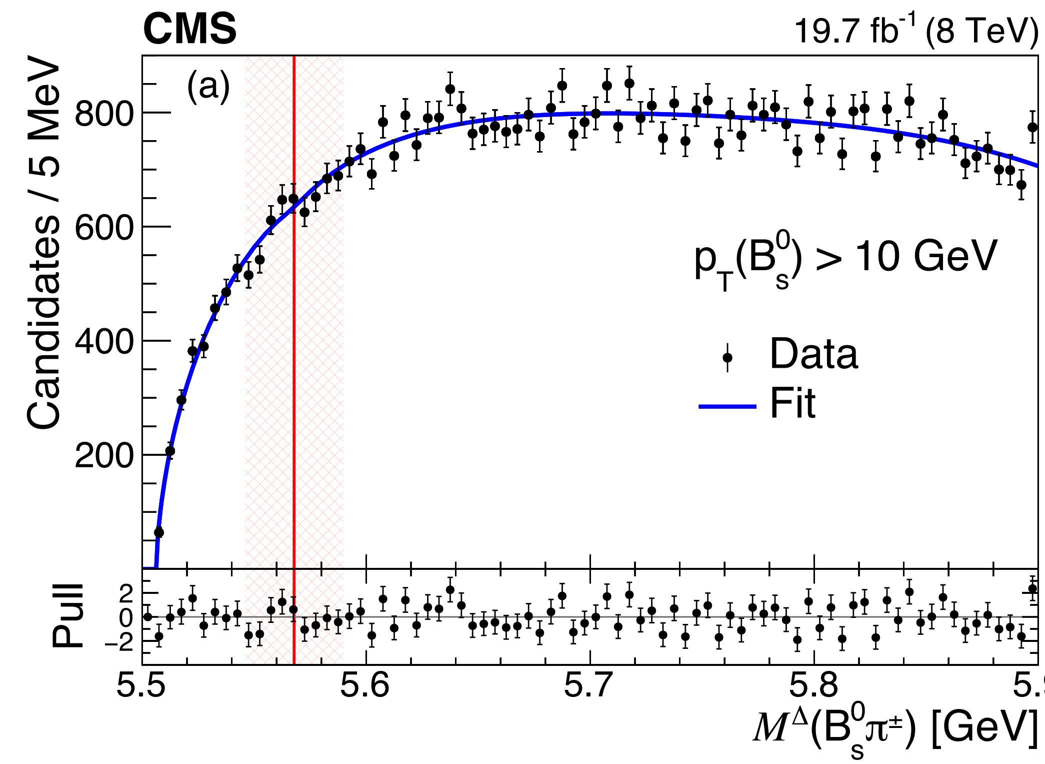
X(5568) : Nor at CMS

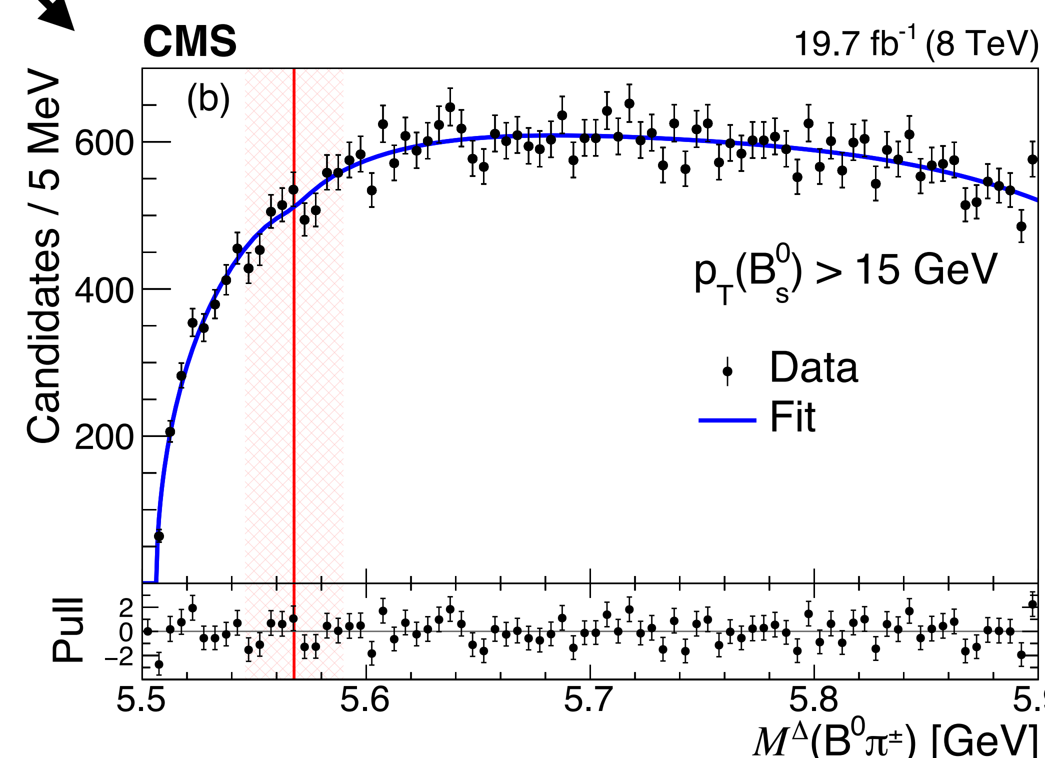
17 Dec 2017: CMS tries to confirm peak, also finds nothing.



49k B_s^0

Add $\pi^{\pm}$, try various p_T cuts...





$\rho_X < 1.1\%$ at 95% CL for $p_T(B_s^0) > 10\,\text{GeV}$ and

$\rho_X < 1.0\%$ at 95% CL for $p_T(B_s^0) > 15\,\text{GeV}$.

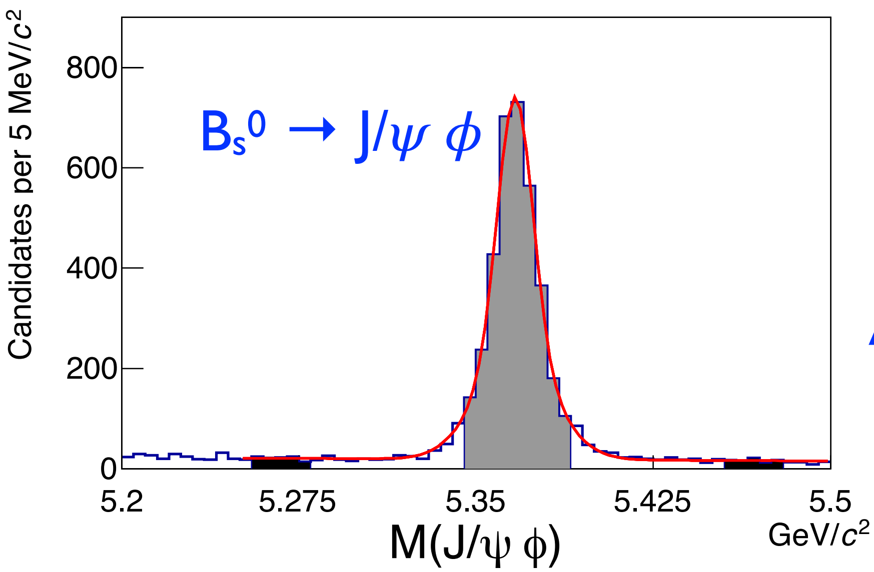
... vs (8.6 ± 1.9 ± 1.4)% at D0, but again different production environment.

And just 10 days later...

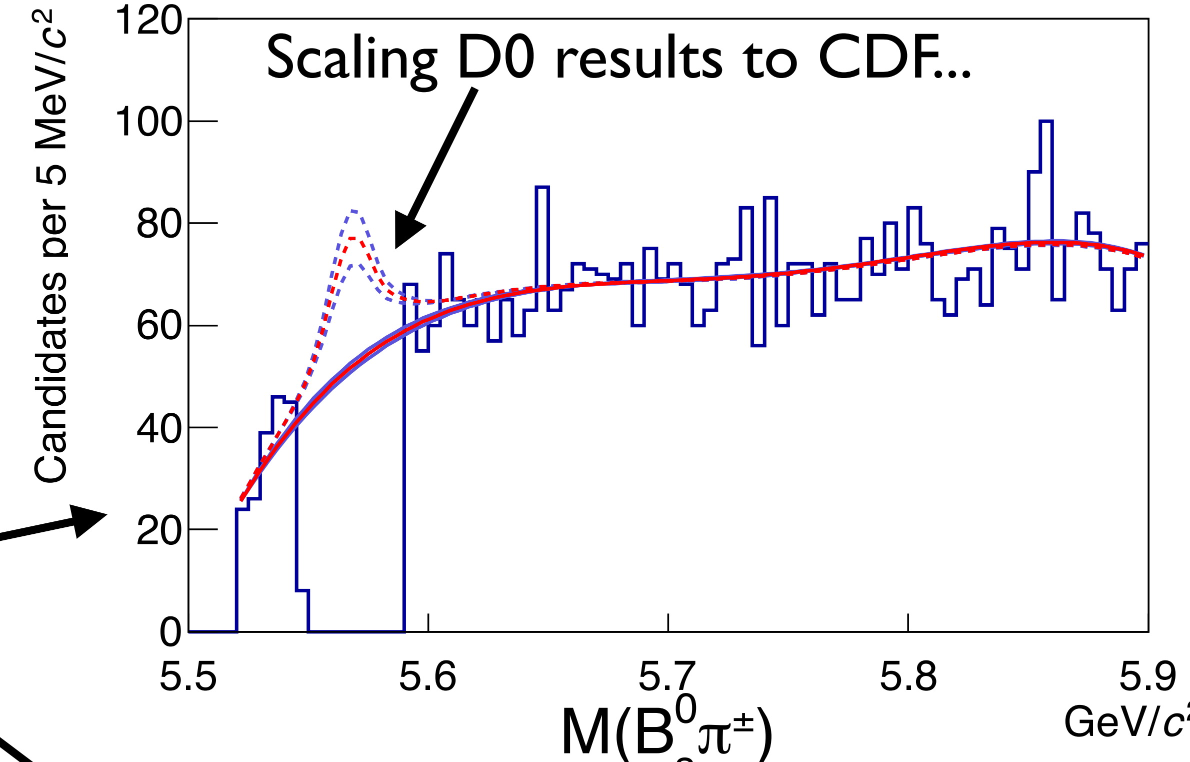
CMS: arXiv:1712.06144 (submitted to PRL)

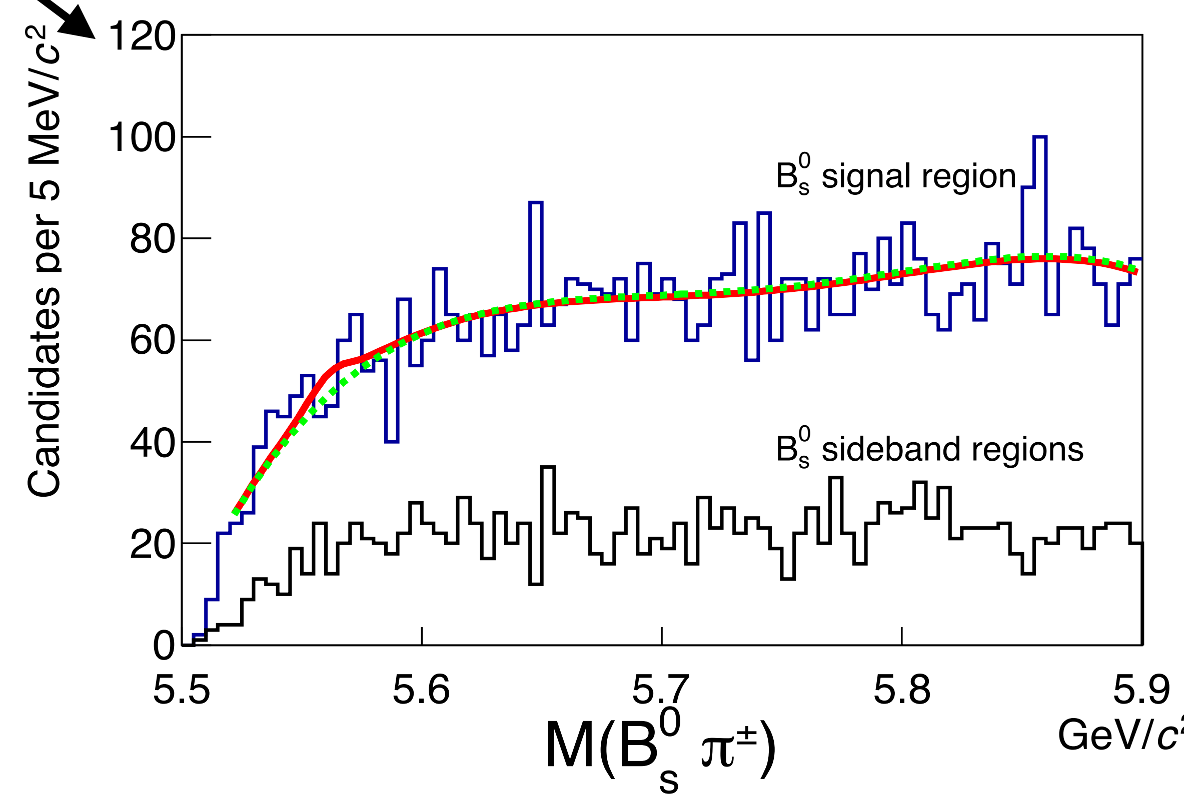
X(5568) : Nor at CDF

27 Dec 2017: CDF searches, finds nothing, sets UL.



3.6k B_s^0
Add $\pi^{\pm}$...





Limit on corrected yield ratio:
$\rho(X/Bs) < 6.7\%$ at 95% CL
... vs $(8.6 \pm 1.9 \pm 1.4)\%$ at D0.
NB same environment

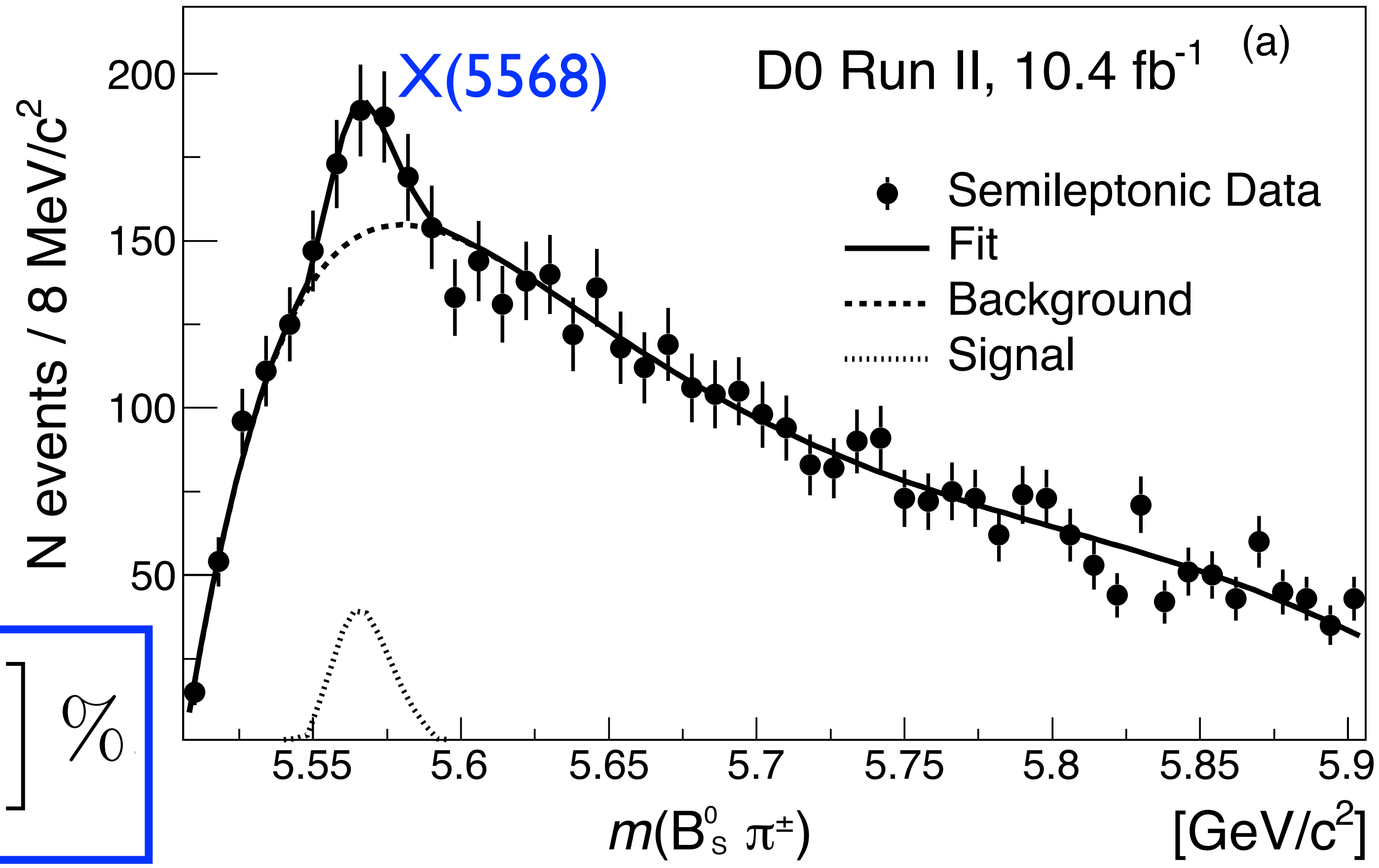
And then just two days later...

CDF: arXiv:1712.09620

X(5568) : D0 still sees it!

29 Dec 2017: D0 publishes second analysis with different decay mode: semileptonic $B_s^0 \rightarrow D_s^- \mu^+ X$... 3.2σ signal!

$$\rho(X/Bs) = \left[7.3^{+2.8}_{-2.4}\,(\text{stat})^{+0.6}_{-1.7}\,(\text{syst})\right]\%$$



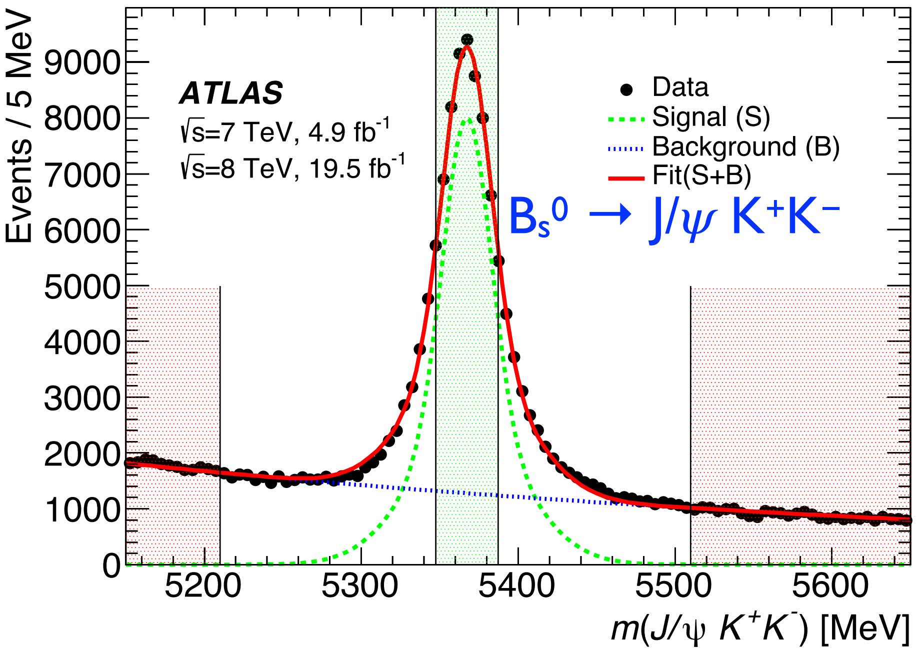
	Semileptonic		Hadronic (from Ref. [15])	
	Cone cut	No cone cut	Cone cut	No cone cut
Fitted mass, MeV/c^2	$5566.4^{+3.4}_{-2.8}\,^{+1.5}_{-0.6}$	$5566.7^{+3.6}_{-3.4}\,^{+1.0}_{-1.0}$	$5567.8 \pm 2.9^{+0.9}_{-1.9}$	5567.8
Fitted width, MeV/c^2	$2.0^{+9.5}_{-2.0}\,^{+2.8}_{-2.0}$	$6.0^{+9.5}_{-6.0}\,^{+1.9}_{-4.6}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	21.9
Fitted number of signal events	$121^{+51}_{-34}\,^{+9}_{-28}$	$139^{+51}_{-63}\,^{+11}_{-32}$	$133 \pm 31 \pm 15$	106 ± 23 (stat)
Local significance	$4.3\,\sigma$	$4.5\,\sigma$	$6.6\,\sigma$	$4.8\,\sigma$
Significance with systematics	$3.2\,\sigma$	$3.4\,\sigma$	$5.6\,\sigma$	-
Significance with LEE+systematics	-	-	$5.1\,\sigma$	$3.9\,\sigma$

But a few weeks afterwards...

D0: arXiv:1712.10176

X(5568) : But ATLAS does not

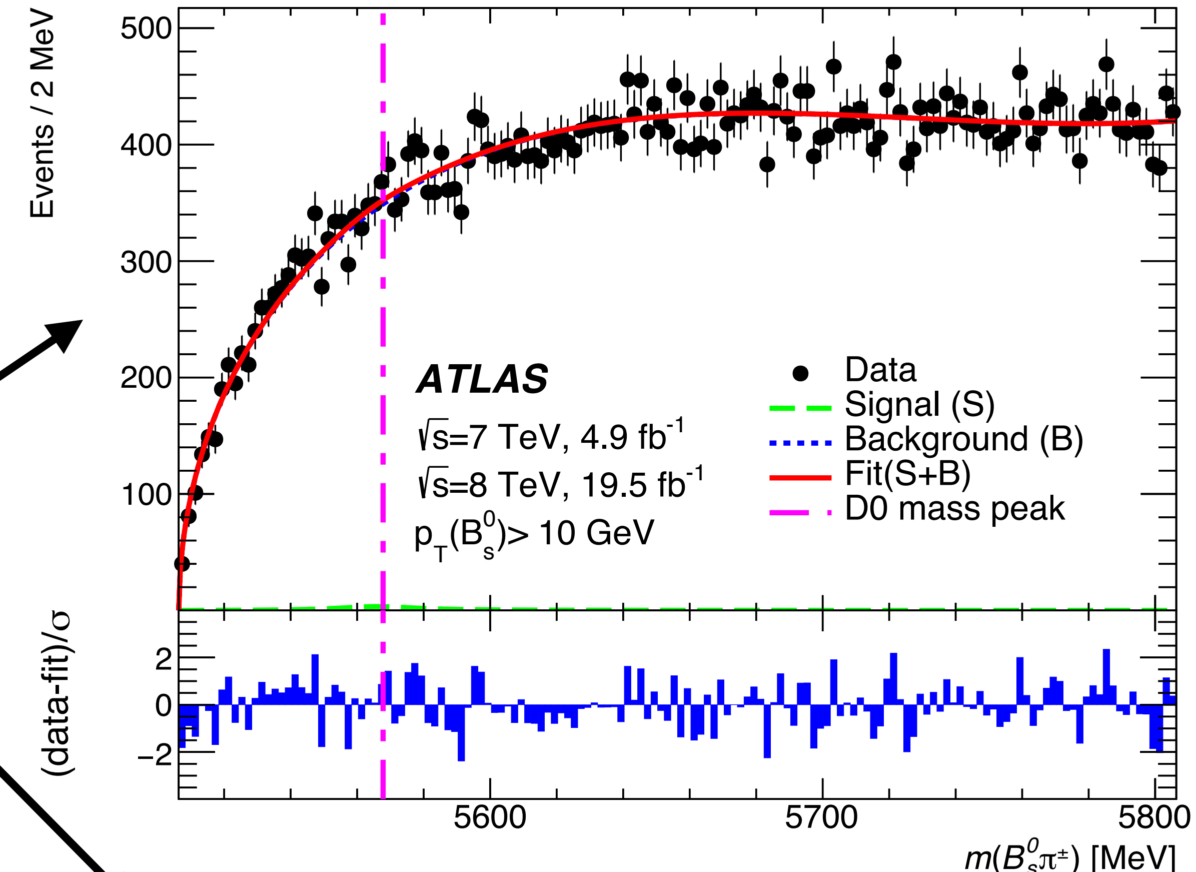
6 Feb 2018: ATLAS joins the fray!

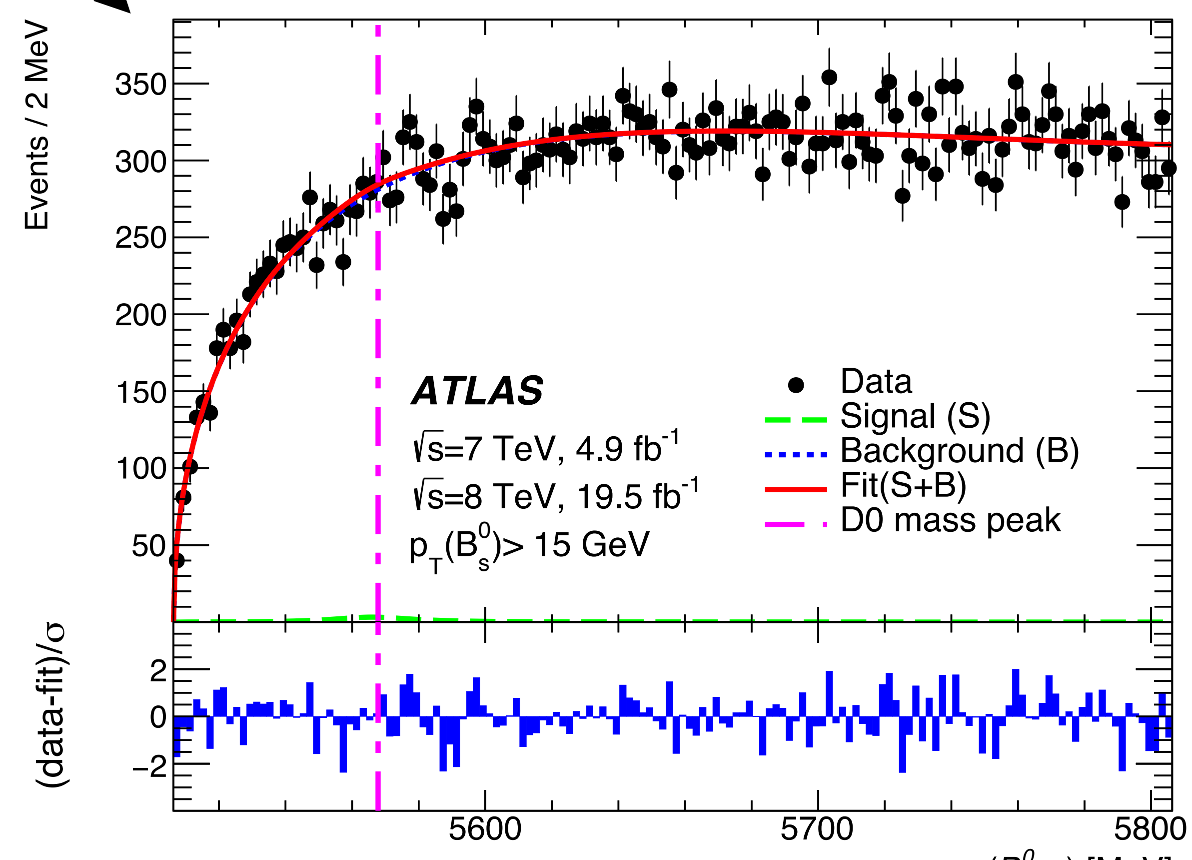


$B_s^0 \to J/\psi\, K^+K^-$

53k B_s^0

Add $\pi^{\pm}$, try various p_T cuts...





Limit on corrected yield ratio:

$$\rho(X/B_s^0) < 1.5\% \text{ at } 95\% \text{ CL for } p_T(B_s^0) > 10\,\mathrm{GeV}/c$$

$$\rho(X/B_s^0) < 1.6\% \text{ at } 95\% \text{ CL for } p_T(B_s^0) > 15\,\mathrm{GeV}/c$$

Wow.

ATLAS: arXiv:1802.01840

The ongoing X(5568) mystery

- This remains a mystery.
- LHC samples have much larger B_s^0 stats and disfavour D0 result assuming conventional heavy quark production.
- ... but cannot rule it out absolutely due to different production environments.
- CDF has the same environment as D0 and does not confirm it... but lower stats => the UL does not fully rule it out.
  - But perhaps by adding more decay modes, this might be resolved.

- LHCb was quicker off the mark (data model is better optimised for B physics) but ATLAS and CMS Run1 data samples had comparable statistics in the end.
- Bodes well for future spectroscopy studies at the big detectors!

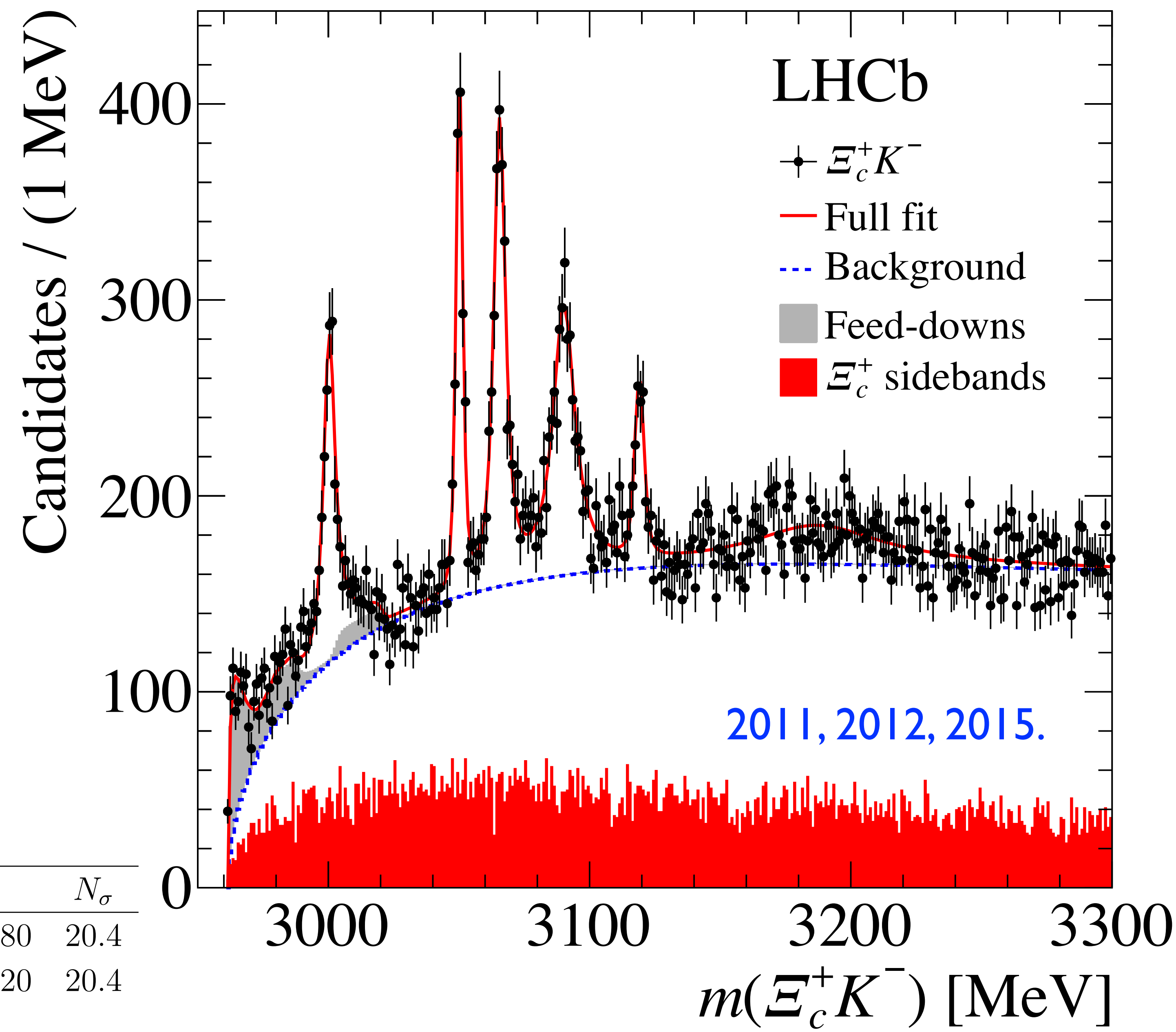
Round-up of other updates since La Thuile 2017

- Five new narrow $\Omega_c^0 \rightarrow \Xi_c^+ K^-$ states
- Search for weakly decaying b-flavoured pentaquarks
- Excited B_c^+ states
- Precise measurements of χ_{c1} and χ_{c2}
- A promising first look at $\chi_b \rightarrow \Upsilon\gamma$ ($\Upsilon \rightarrow \mu^+\mu^-$)

Five new narrow $\Omega_c^0 \rightarrow \Xi_c^+ K^-$ states

- Fit takes into account feed-down from $\Omega_c^0 \rightarrow \Xi_c'^+ K^-$, $\Xi_c'^+ \rightarrow \Xi_c^+ \gamma$ with missing photon
- Exotic interpretations possible for unusually narrow states (3050, 3119)
  - e.g. Montaña et al: arXiv:1709.08737
  - e.g. Debastiani et al: arXiv:1710.04231
- Broad structure ~ 3200 MeV

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ < 1.2 MeV, 95% CL	$970 \pm 60 \pm 20$	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ < 2.6 MeV, 95% CL	$480 \pm 70 \pm 30$	10.4
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	



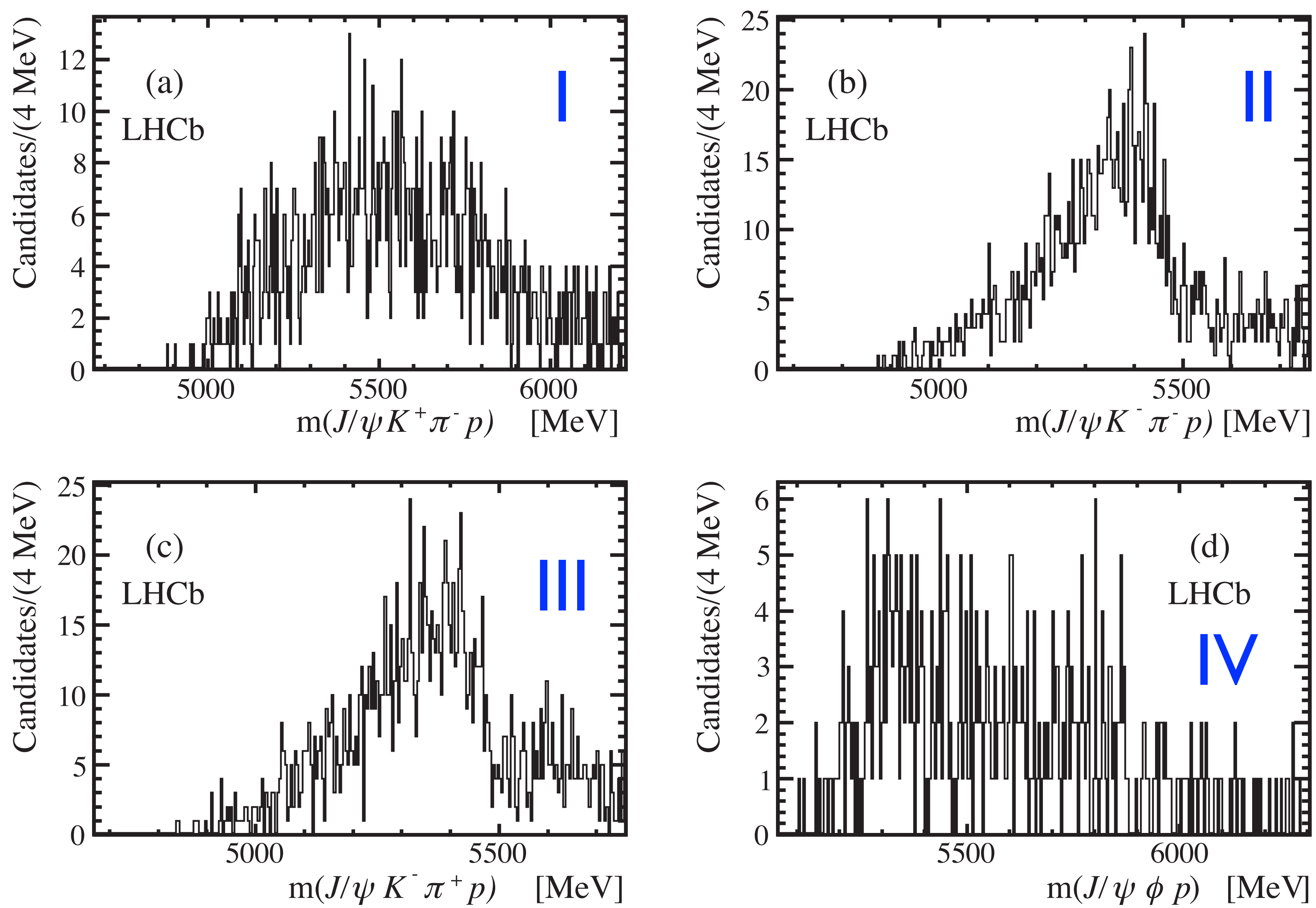
Belle confirms 4/5 states.

LHCb: PRL 118, 182001 (2017)
Belle: arXiv:1711.07927

Search for weakly decaying b-flavoured pentaquarks

- So far, observed pentaquarks contain charm and decay strongly.
- Skyrme: ($b\bar{q}qqq/\bar{b}qqqq$) may be tightly bound and decay weakly.
- LHCb search up to strong threshold in suitable final states: →

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



No signal => scan in steps and set upper limits relative to Λ_b^0:

$$R = \frac{\sigma(pp \to P_B X)\cdot \mathcal{B}(P_B \to J/\psi\, X)}{\sigma(pp \to \Lambda^0_b X)\cdot \mathcal{B}(\Lambda^0_b \to J/\psi\, K^- p)}$$

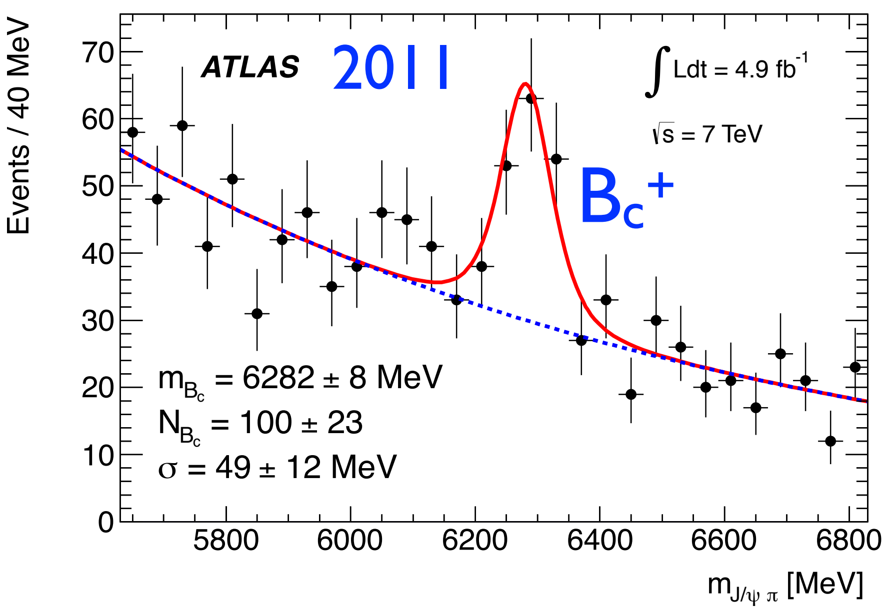
Upper limits typically $R <$ few x 10^{-3} (see backup)

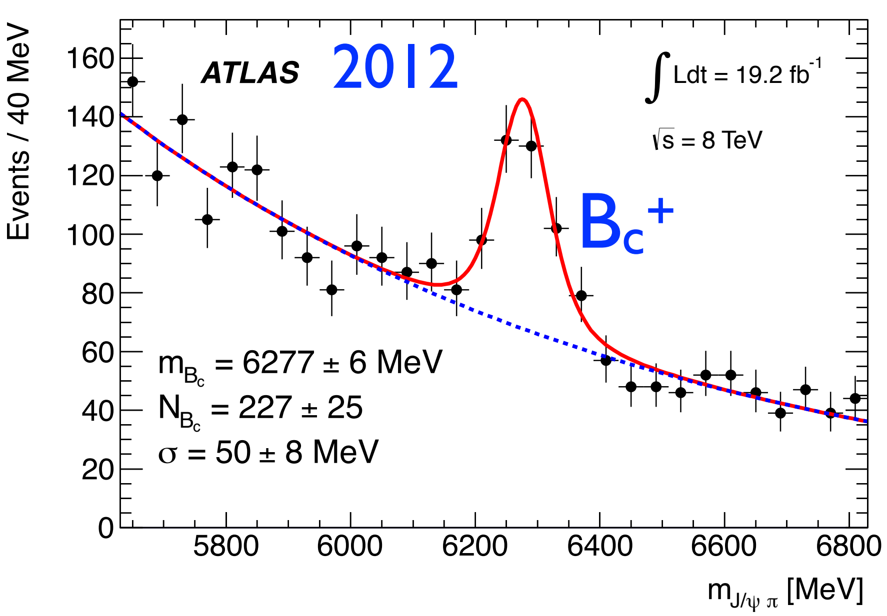
Skyrme, Proc. Roy. Soc. Lond. A260 (1961) 127

LHCb: arXiv:1712.08086, submitted to PRD

Excited B_c^+ states

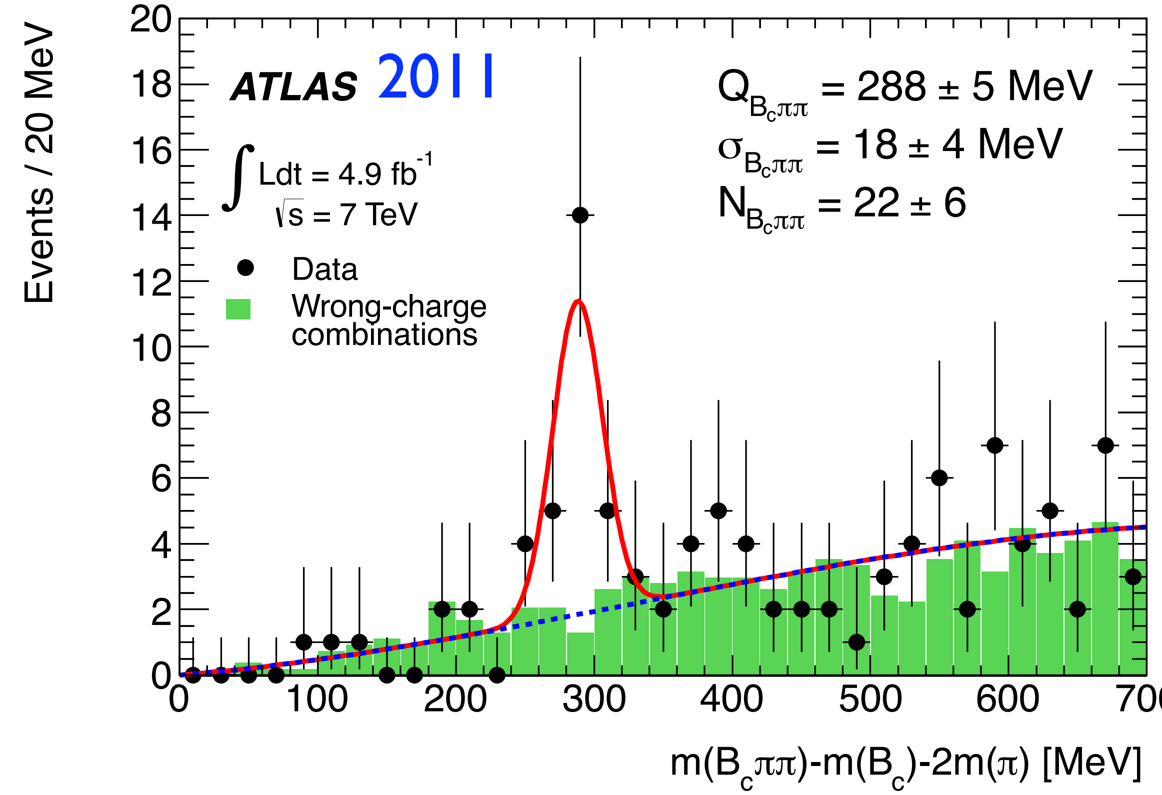
In 2014, ATLAS observes structure in $(B_c^+ \pi^+ \pi^-)$:

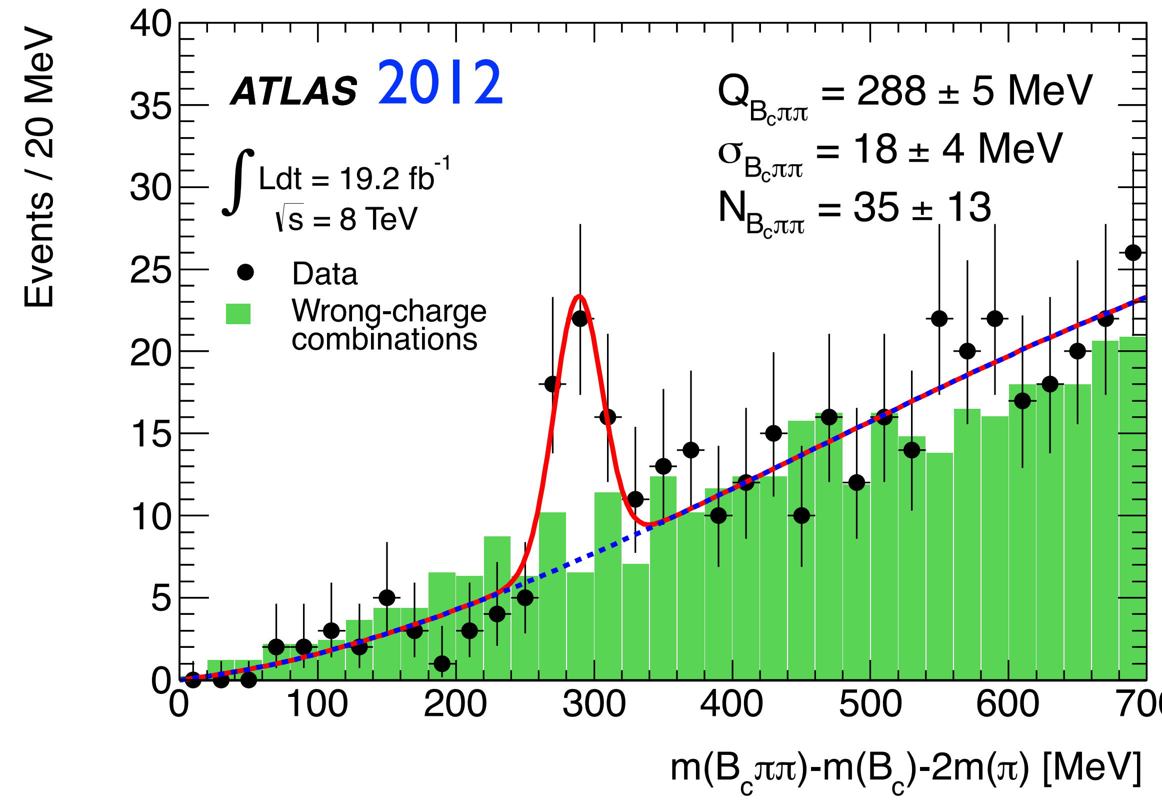




$B_c^+ \rightarrow J/\psi\, \pi^+$
(327 ± 34)

add $\pi^+ \pi^-$



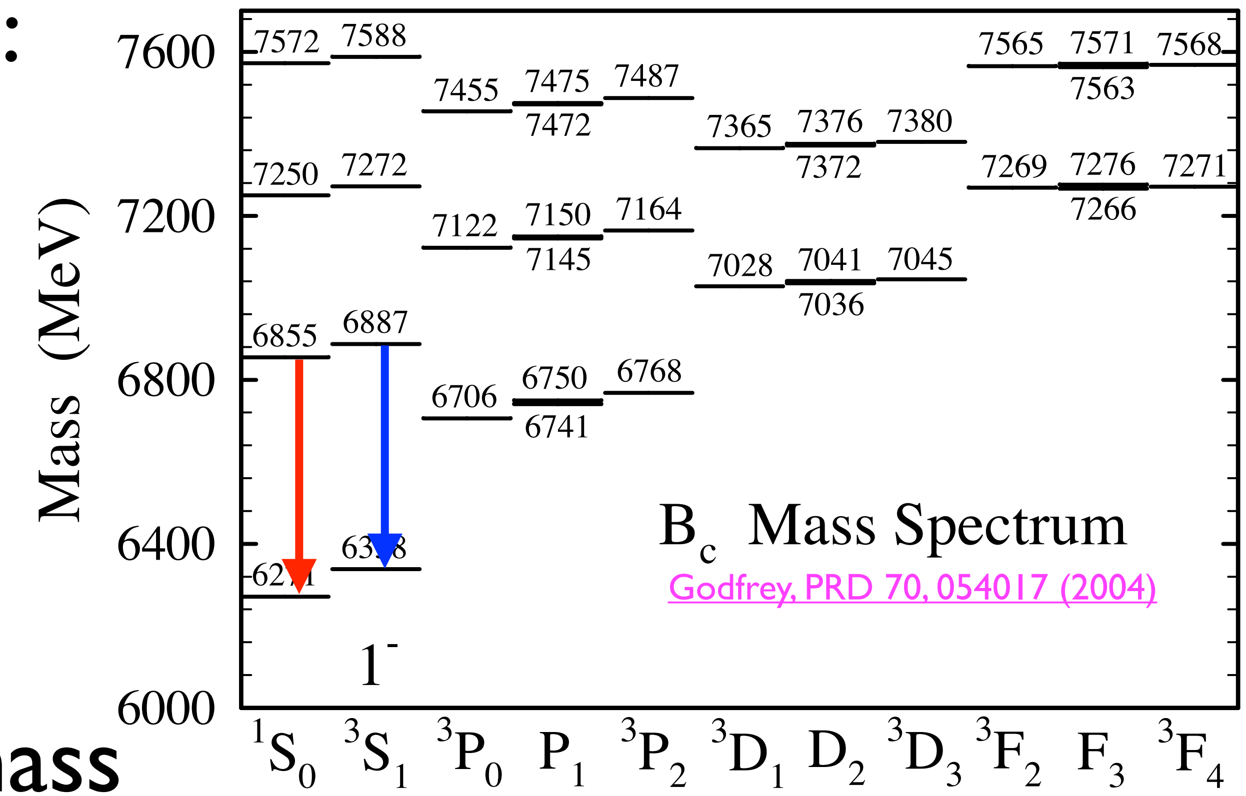


$B_c^+(2S) \rightarrow B_c^+ \pi^+ \pi^-$
(57 ± 14): 5.2σ inc LEE

ATLAS: PRL 113, 212004 (2014)

Excited B_c^+ states

- Expect **two** structures in $B_c^+ \pi^+ \pi^-$:
  - $B_c(2^1S_0)^+ \rightarrow B_c^+ \pi^+ \pi^-$
  - $B_c(2^3S_1)^+ \rightarrow B_c^{*+} \pi^+ \pi^-$, $B_c^{*+} \rightarrow B_c^+ \gamma$
- Higher production rate of $B_c(2^3S_1)^+$
- $B_c(2^1S_0)^+$ peak at its mass, predicted to be ~ [6830,6890] MeV



- $B_c(2^3S_1)^+$ peak offset from its true mass by missing photon; separation between the two peaks is

$$\Delta M \equiv \left[M(B_c^{*+}) - M(B_c^+)\right] - \left[M(B_c^*(2S)^+) - M(B_c(2S)^+)\right]$$

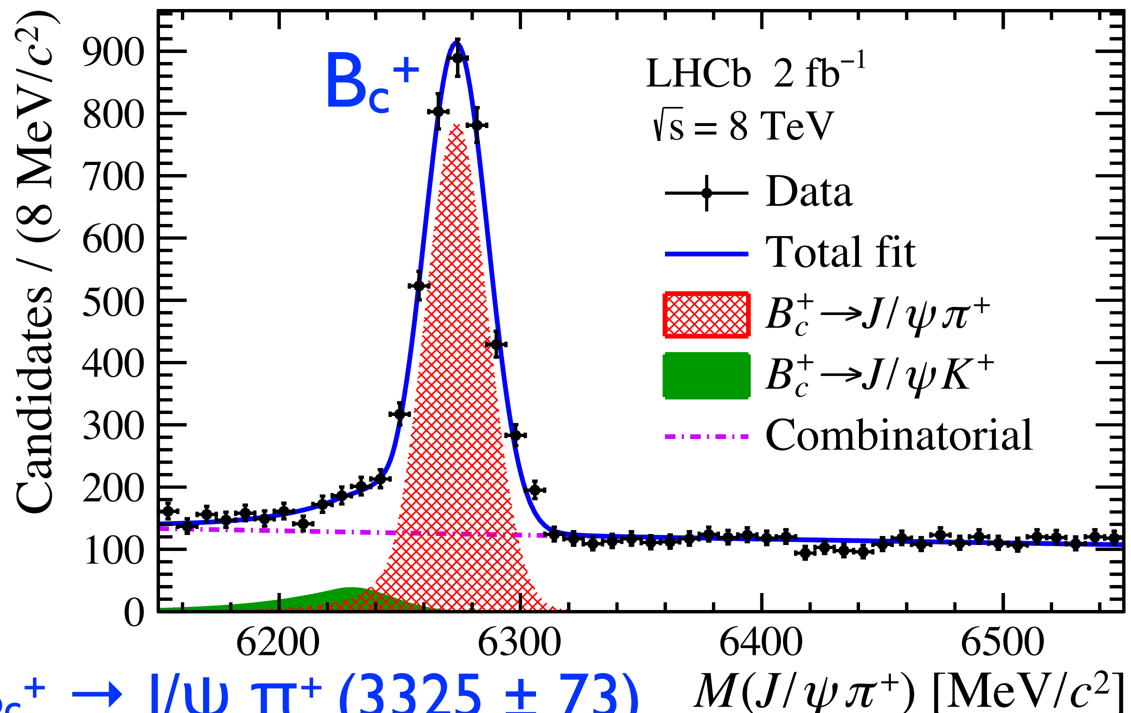
  and is predicted to be [0, 35] MeV

- So ATLAS may be seeing
  - Just $B_c(2^1S_0)^+$
  - Just $B_c(2^3S_1)^+$ with missing photon
  - Mixture of $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$

Gershtein et al., Sov. J. Nucl. Phys. 48, 327 (1988)
Chen & Kuang, PRD 46, 1165 (1992)
Eichten & Quigg, PRD 49, 5845 (1994)
Kiselev et al, PRD 51, 3613 (1995)
Gupta & Johnson, PRD 53, 312 (1996)
Fulcher, PRD 60, 074006 (1999)
Ebert et al, PRD 67, 014027 (2003)
Godfrey, PRD 70, 054017 (2004)
Wei & Guo, PRD 81, 076005 (2010)
Rai & Vinodkumar, Pramana 66, 953 (2006)
Abd El-Hady et al, PRD 71, 034006 (2005)
Gouz et al, Phys.Atom.Nucl. 67, 1559 (2004); Yad.Fiz. 67, 1581 (2004)

Excited B_c^+ states

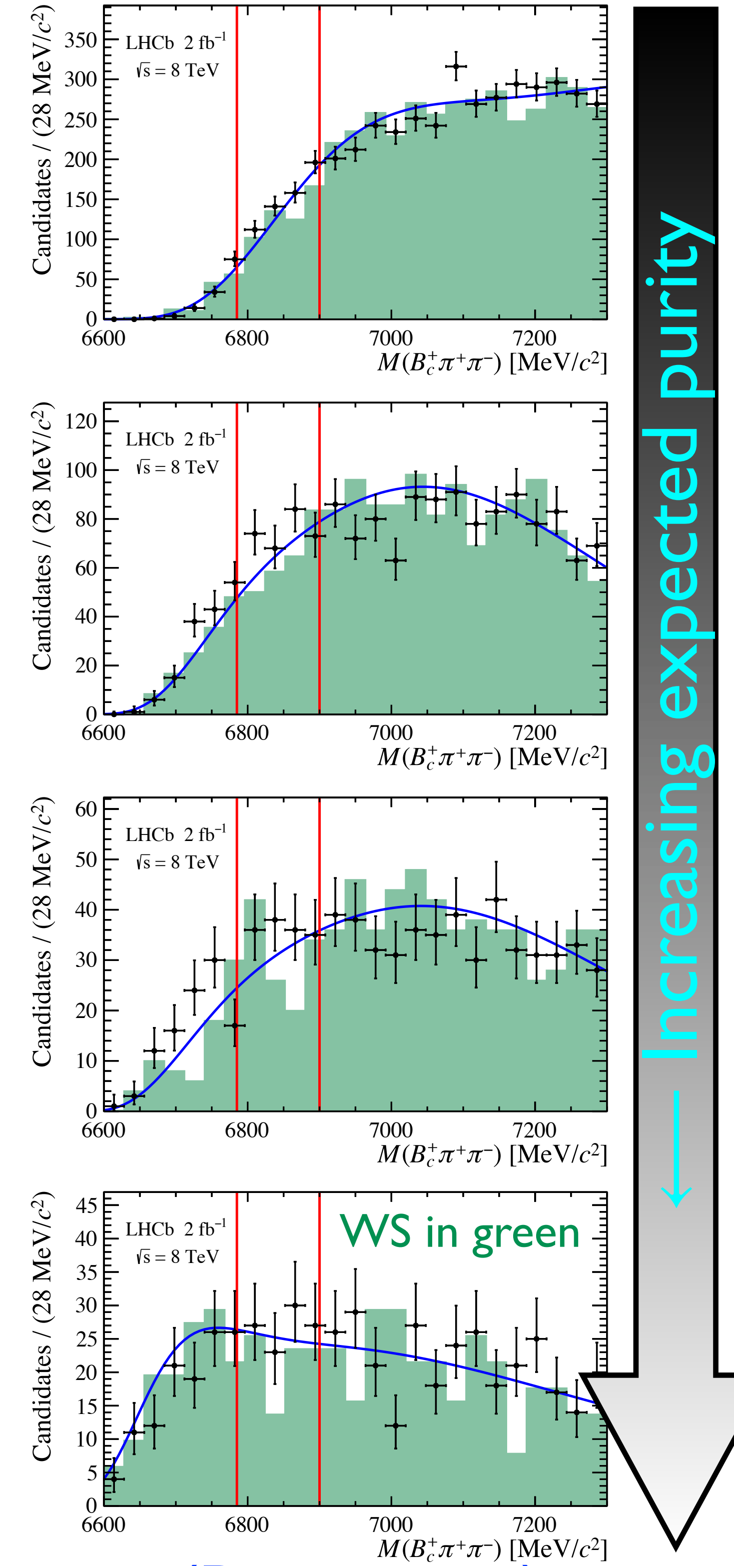
In 2017: LHCb doesn't confirm the observation with a larger B_c^+ sample



$B_c^+ \to J/\psi\, \pi^+$ (3325 ± 73)

add $\pi^+ \pi^-$

Bins of MVA classifier output



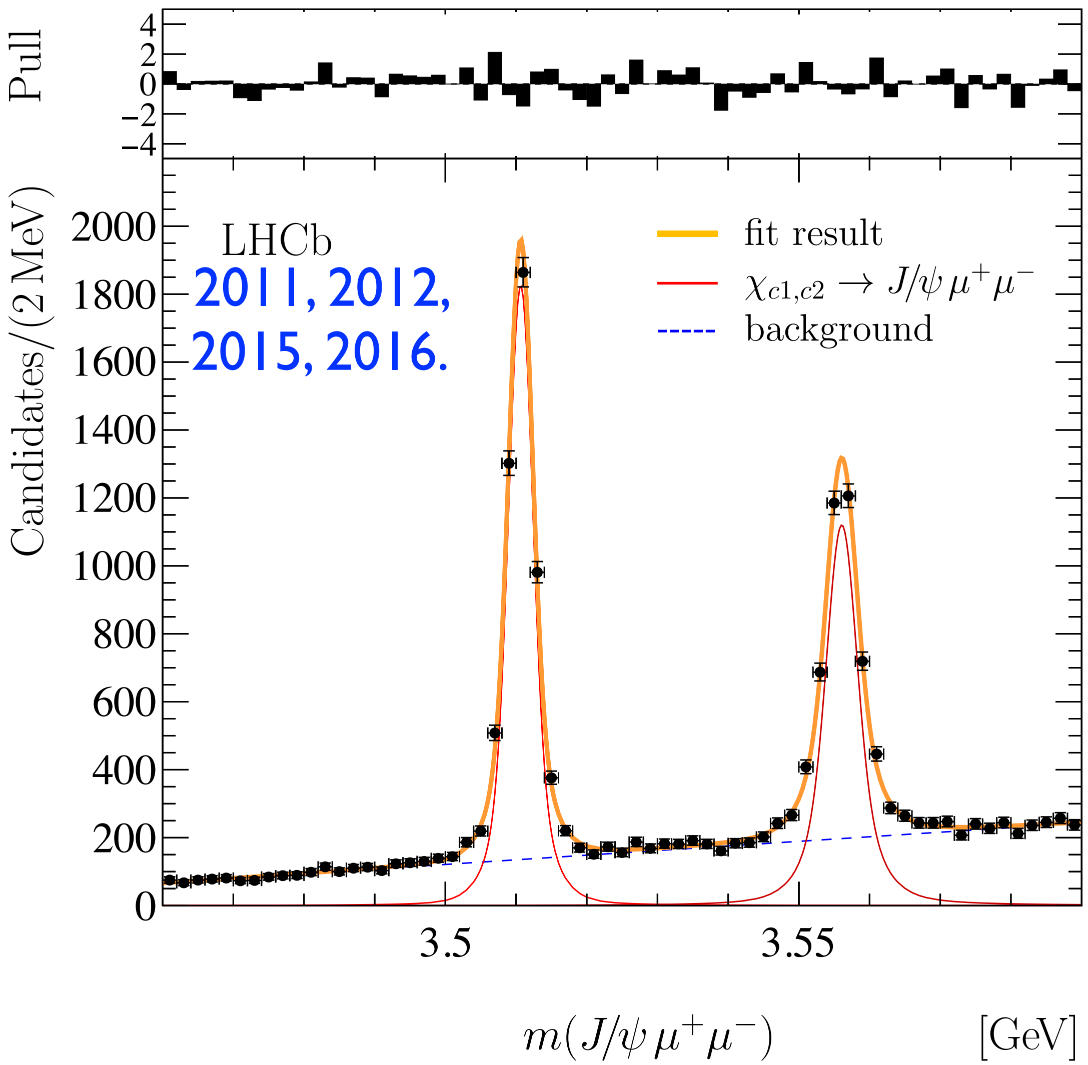
$m(B_c^+ \pi^+ \pi^-)$

- UL on yield ratio (resonance/B_c^+) set as function of mass for different hypotheses, see backups.
- LHCb & ATLAS results in mild tension but not incompatible given uncertainties & different kinematics, efficiencies (low vs high p_T).
- LHC experiments should be able to clear this up with Run2 data.

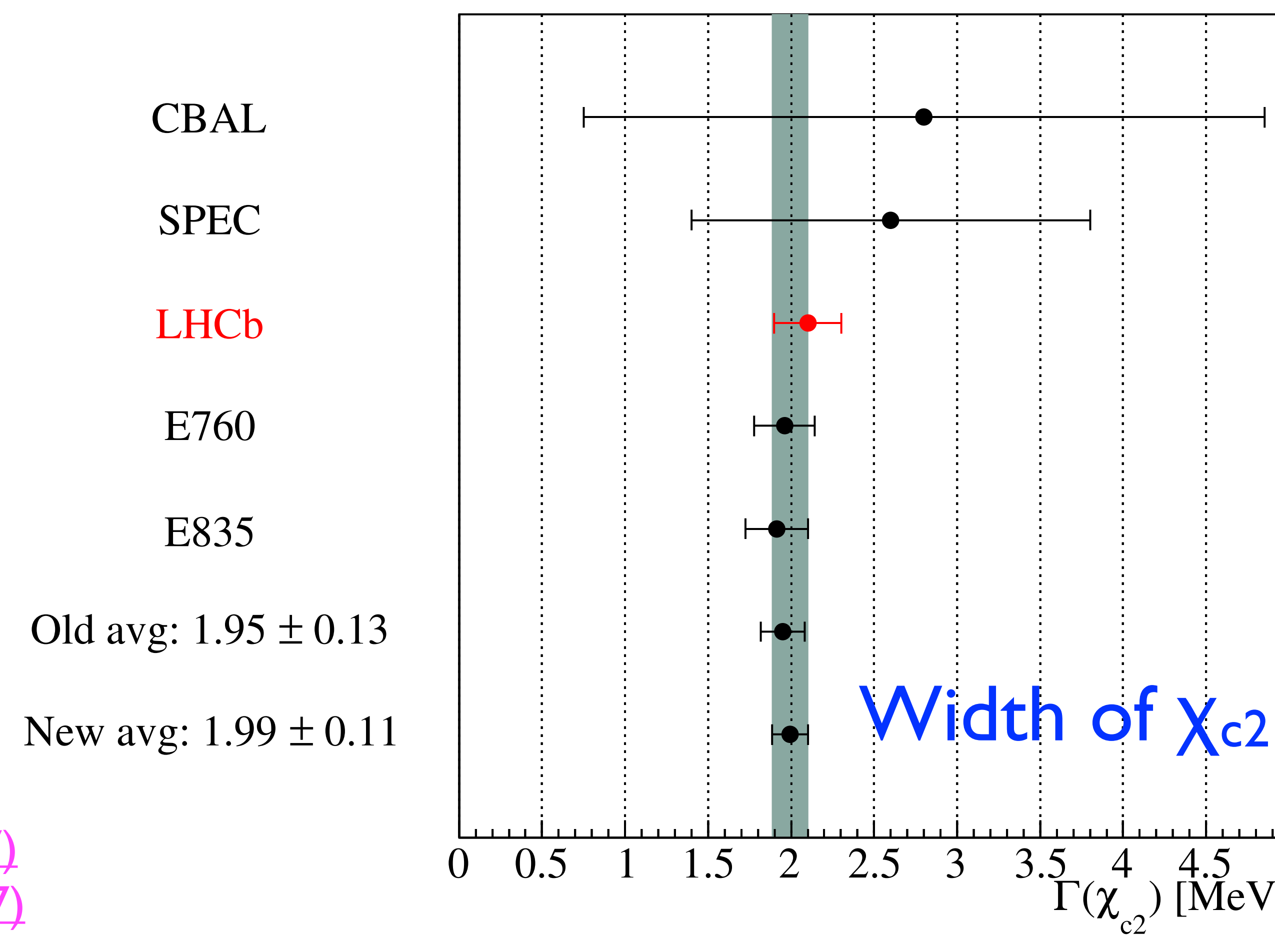
LHCb: JHEP (2018) 2018: 138

Precise measurements of χ_{c1} and χ_{c2}

- χ_{c1} and χ_{c2} states well known
- Recently, BESIII observed $\chi_{c(0,1,2)} \rightarrow J/\psi\, e^+ e^-$
- LHCb: first observation of $\chi_{c(1,2)} \rightarrow J/\psi\, \mu^+ \mu^-$
- Competitive with world-best measurements of mass, width.



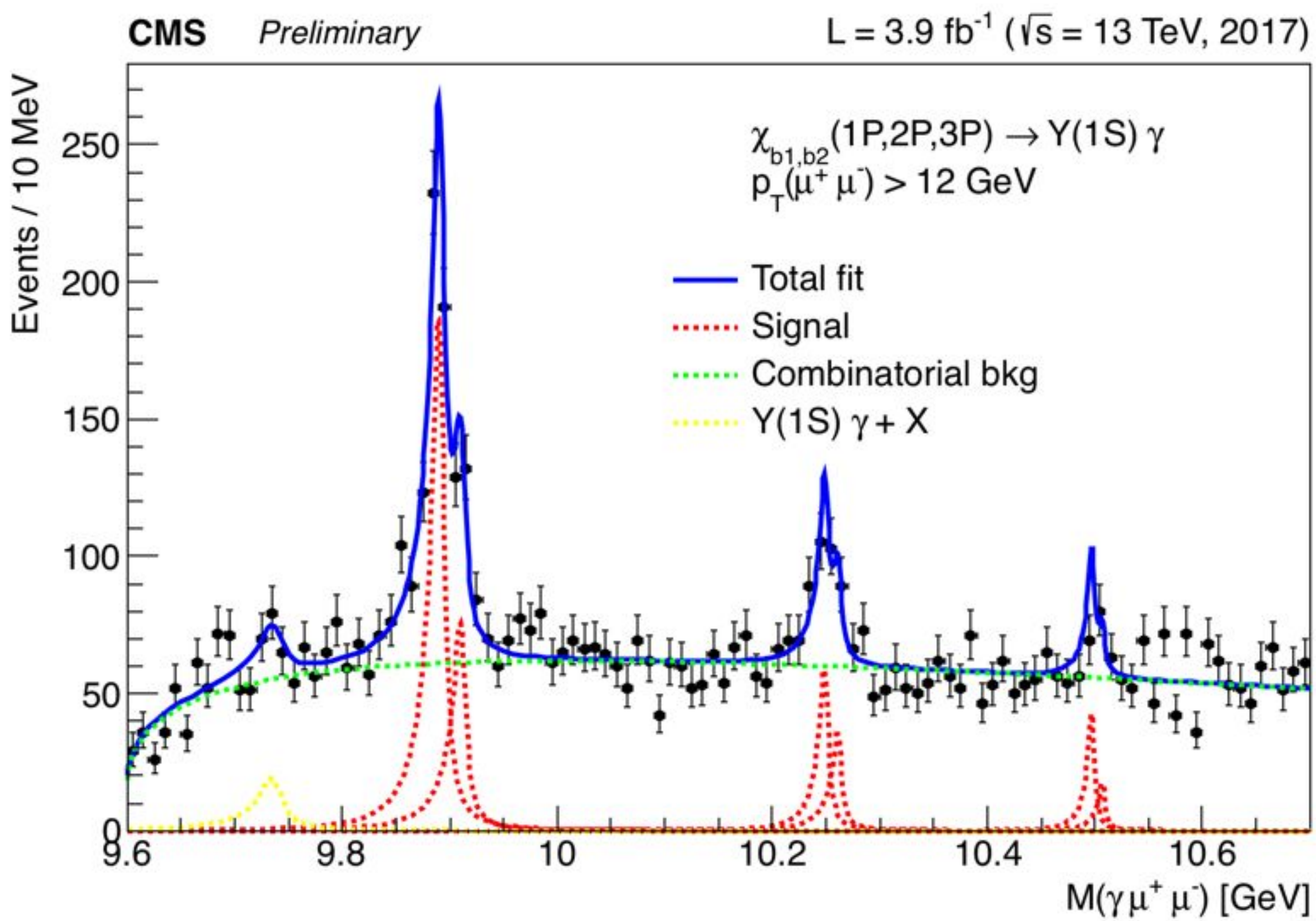
Quantity [MeV]	LHCb measurement	[E760/E835] Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11



E760: Nucl. Phys. B373, 35 (1992)
E835: Nucl. Phys. B717, 34 (2005)
BESIII: PRL 118, 221802 (2017)
LHCb: PRL 119, 221801 (2017)

$\chi_b \to \Upsilon\gamma$ ($\Upsilon \to \mu^+\mu^-$)

- Preliminary look at 2017 data by CMS.
- Reconstruct γ from converted photons
- Possibility to improve WA with full analysis (esp. for 3P states)

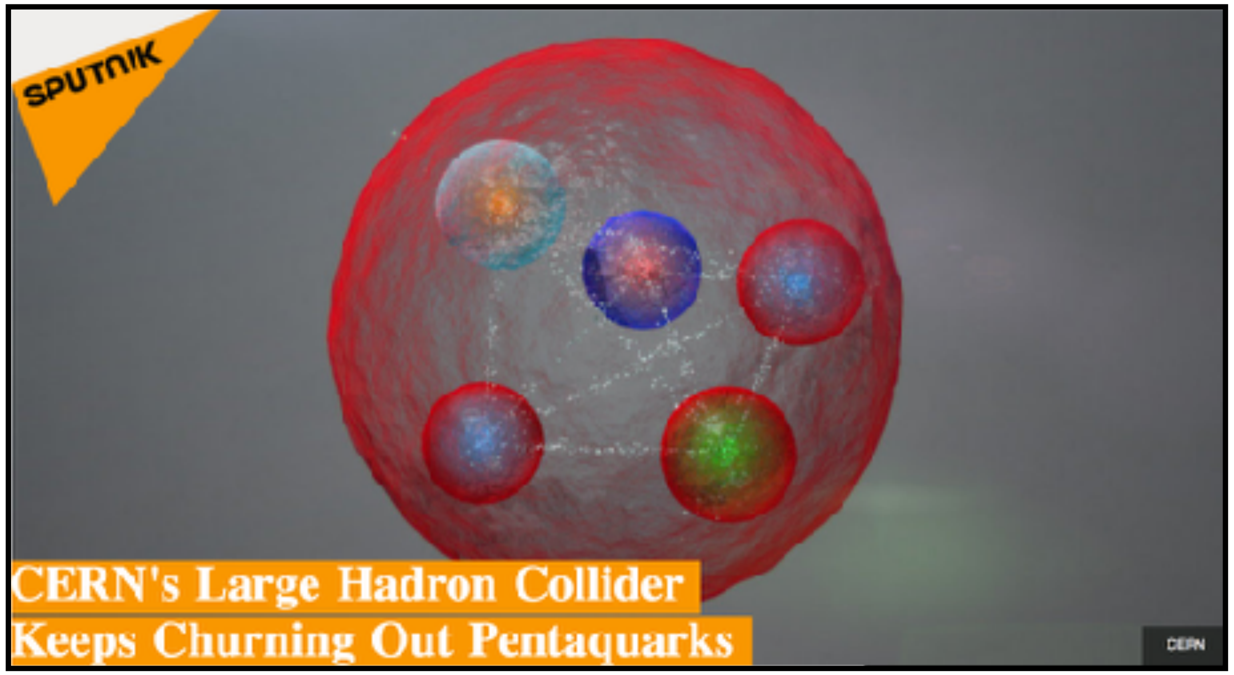


Yellow peak is misreconstructed
$\chi_{bX}(2P) \to \Upsilon(2S)\gamma$, $\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-$

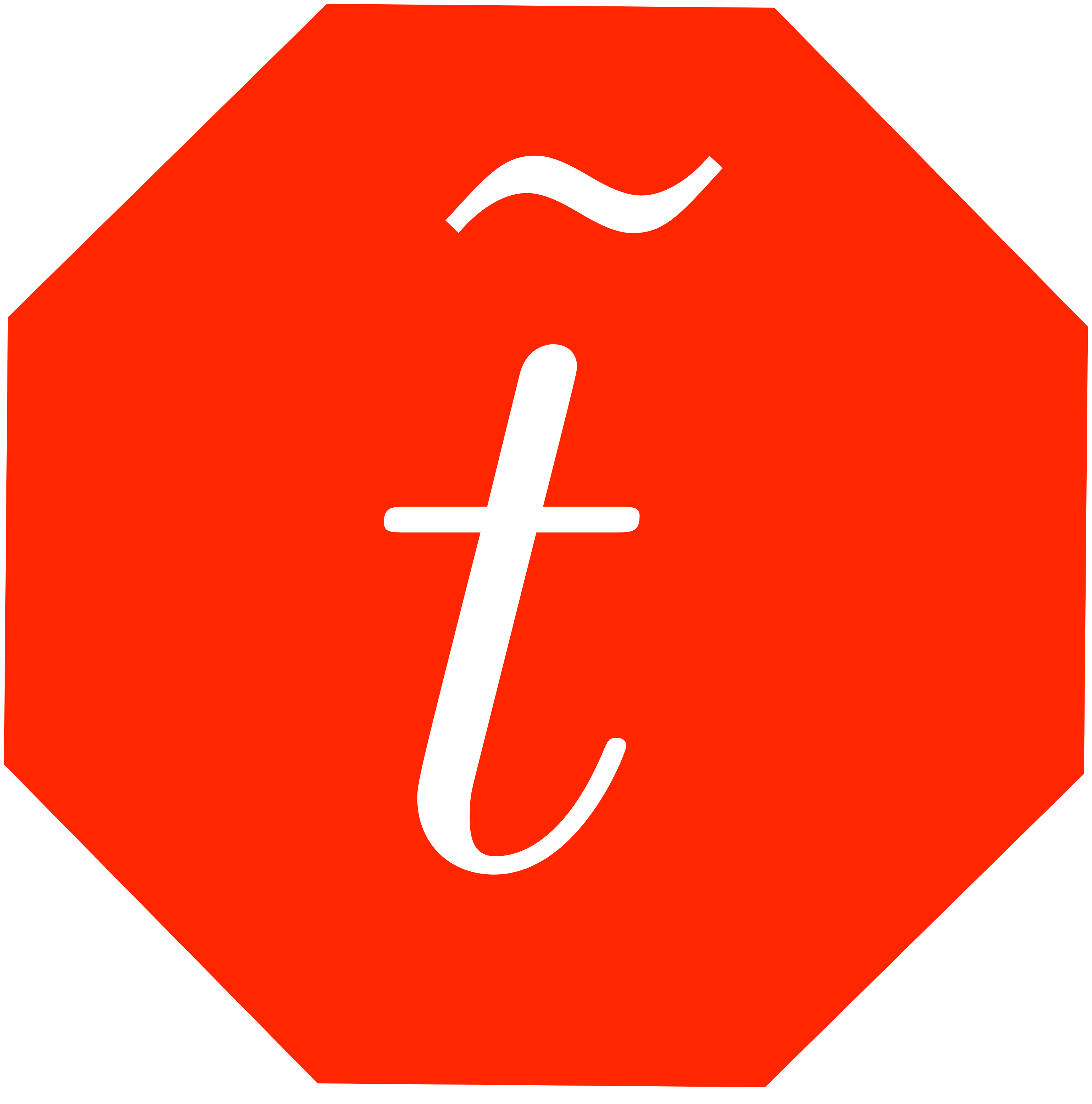
CMS-DP-2017-029

Summary

- Lots and lots of spectroscopy work ongoing at LHC, in many areas
- Things we didn't have time to talk about include
  - Pentaquark discovery
  - Exotic tetraquark-like states
  - Charmonia X family
  - More singly heavy baryon resonances
  - More bottomonia
  - and surely more



- Heavy flavour physics is LHCb's bread and butter--but important contributions from ATLAS & CMS too.
- Look forward to more analyses with the big Run2 dataset!


$\tilde{t}$

Backup stuff

- Too many references
- More on X(5568) cone cut
- Limits for weakly decaying b-flavoured PQ
- Limits for excited Bc states under different hypotheses
- More info on CMS 2017 plot
- SELEX Ξ_{cc} results
- ...

LHCb references: manifest exotics

- LHCb-PAPER-2017-043 : arXiv:1712.08086 :A search for weakly decaying b-flavored pentaquarks
- LHCb-PAPER-2017-011 : arXiv:1704.07900 : Observation of the decays $\Lambda_b^0 \to \chi_{c1} p K^-$ and $\Lambda_b^0 \to \chi_{c2} p K^-$
- LHCb-PAPER-2016-053 : arXiv:1701.05274 : Observation of the $\varXi^{-}_{b}\to J/\psi\varLambda K^{-}$ decay
- LHCb-PAPER-2016-029 : arXiv:1608.00435 : Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum
- LHCb-PAPER-2016-019 ; arXiv:1606.07898 :Amplitude analysis of $B^+\to J/\psi \phi K^+$ decays
- LHCb-PAPER-2016-018 ; arXiv:1606.07895 : Observation of $J/\psi\phi$ structures consistent with exotic states from amplitude analysis of $B^+\to J/\psi \phi K^+$ decays
- LHCb-PAPER-2016-015 : arXiv:1606.06999 : Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ decays
- LHCb-PAPER-2016-009 : arXiv:1604.05708 : Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0\to J/\psi p K^-$ decays
- LHCb-PAPER-2015-038 ; arXiv:1510.01951 : Model-independent confirmation of the $Z(4430)^-$ state
- LHCb-PAPER-2015-029 : arxiv:1507.03414 : Observation of $J/\psi p$ resonances consistent with pentaquark states in ${\Lambda_b^0\to J/\psi K^-p}$ decays
- LHCb-PAPER-2014-014 ; arXiv:1404.1903 : Observation of the resonant character of the $Z(4430)^-$ state
- LHCb-PAPER-2011-033 : arXiv:1202.5087 : Search for the $X(4140)$ state in $B^+\to J/\psi\phi K^+$ decays

Blue: covered in main slides

Orange: Result new since La Thuile 2017 and not covered in main slides

LHCb references: mesons

- LHCb-PAPER-2017-042 ; arXiv:1712.04094 : Search for excited B_c^+ states
- LHCb-PAPER-2017-036 : arXiv:1709.04247 : Precise measurement of the χ_{c1} and χ_{c2} resonance parameters with the decays $\chi_{c1,c2}\to J/\psi\mu^+\mu^-$
- LHCb-PAPER-2017-007 : arXiv:1706.07013 : Study of charmonium production in ${b}$-hadron decays and first evidence for the decay ${{{B}} ^0_{{s}}} \!\rightarrow \phi \phi \phi $
- LHCb-PAPER-2016-016 : arXiv:1607.06446 : Observation of $\eta_{c}(2S) \to p \bar p$ and search for $X(3872) \to p \bar p$ decays
- LHCb-PAPER-2015-015 : arXiv:1504.06339 : Quantum numbers of the $X(3872)$ state and orbital angular momentum in its $\rho^0 J/\psi$ decays
- LHCb-PAPER-2013-001 : arXiv:1302.6269 : Determination of the $X(3872)$ meson quantum numbers

LHCb references: baryons

- LHCB-PAPER-2017-023 ; arXiv:1708.05808 : Search for baryon-number-violating Ξ_b^0 oscillations
- LHCb-PAPER-2017-016 ; arXiv:1709.01920 : Measurement of the shape of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu$ differential decay rate
- LHCB-PAPER-2017-018 ; arXiv:1707.01621 : Observation of the doubly charmed baryon Ξ_{cc}^{++}
- LHCB-PAPER-2017-002 ; arXiv:1703.04639 : Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$
- LHCB-PAPER-2016-061 ; arXiv:1701.07873 : Study of the $D^0 p$ amplitude in $\Lambda_b^0 \rightarrow D^0 p \pi^-$ decays
- LHCB-PAPER-2016-010 ; arXiv:1604.03896 : Measurement of the properties of the Ξ_b^{*0} baryon
- LHCB-PAPER-2016-008 ; arXiv:1604.01412 : Measurement of the mass and lifetime of the Ω_b^- baryon
- LHCB-PAPER-2015-060 ; arXiv:1603.06961 : Observation of $\Lambda_b^0 \rightarrow \psi(2S) p K^-$ and $\Lambda_b^0 \rightarrow J/\psi \pi^+ \pi^- p K^-$ decays and a measurement of the Λ_b^0 baryon mass
- LHCB-PAPER-2015-047 ; arXiv:1510.03829 : Evidence for the strangeness-changing weak decay $\Xi_b^- \rightarrow \Lambda_b^0 \pi^-$
- LHCB-PAPER-2014-061 ; arXiv:1411.4849 : Observation of two new Ξ_b^- baryon resonances
- LHCB-PAPER-2014-048 ; arXiv:1409.8568 : Precision measurement of the mass and lifetime of the Ξ_b^- baryon
- LHCB-PAPER-2014-021 ; arXiv:1405.7223 : Precision measurement of the mass and lifetime of the Ξ_b^0 baryon
- LHCb-PAPER-2014-010 ; arXiv:1405.1543 : Measurement of the Ξ_b^- and Ω_b^- baryon lifetimes
- LHCB-PAPER-2014-003 ; arXiv:1402.6242 : Precision measurement of the ratio of the Λ_b^0 to $\bar{B}^0$ lifetimes
- LHCB-PAPER-2014-002 ; arXiv:1403.3606 : Study of beauty hadron decays into pairs of charm hadrons
- LHCB-PAPER-2013-056 ; arXiv:1311.4823 : Studies of beauty baryon decays to $D^0 p h^-$ and $\Lambda_c^+ h^-$ final states
- LHCB-PAPER-2013-049 ; arXiv:1310.2538 : Search for the doubly charmed baryon Ξ_{cc}^+
- LHCB-PAPER-2012-048 ; arXiv:1302.1072 : Measurement of the Λ_b^0, Ξ_b^- and Ω_b^- baryon masses
- LHCB-PAPER-2012-012 ; arXiv:1205.3452 : Observation of excited Λ_b^0 baryons
- LHCB-PAPER-2011-035 ; arXiv:1112.4896 : Measurement of b-hadron masses

ATLAS references

- BPHY-2017-02 : arXiv:1802.01840 : Search for a Structure in the B0sπ± Invariant Mass Spectrum with the ATLAS Experiment
- BPHY-2015-03 : arXiv:1610.09303 : Measurements of $\psi(2S)$ and $X(3872) \to J/\psi\pi^+\pi^-$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
- BPHY-2013-07 : arXiv:1410.4409 : Search for the Xb and other hidden-beauty states using the π+π-Υ(1S) channel at ATLAS
- BPHY-2012-04 : arXiv:1407.1032 : Observation of an Excited $B_c^{\pm}$ Meson State with the ATLAS Detector
- BPHY-2013-05 : arXiv:1404.7035 : Measurement of chi_c1 and chi_c2 production with sqrt(s) = 7 TeV pp collisions at ATLAS
- BPHY-2011-07 : arXiv:1112.5154 : Observation of a new chi_b state in radiative transitions to Upsilon(1S) and Upsilon(2S) at ATLAS
- ATLAS-CONF-2011-136 : Observation of the χc1(1P) and χc2(1P) charmonium states in $\sqrt{s}$ = 7 TeV pp collisions at the ATLAS experiment

- See also: ATLAS B Physics and Light States publications

CMS references

- CMS-BPH-16-002 : arXiv:1712.06144 : Search for the X(5568) state decaying into $\mathrm{B}^{0}_{\mathrm{s}} \pi^{\pm}$ in proton-proton collisions at $\sqrt{s} = $ 8 TeV
- CMS-BPH-13-008 : arXiv:1710.08949 : Measurement of b hadron lifetimes in pp collisions at $\sqrt{s} = $ 8 TeV
- CMS-BPH-12-001 : arXiv:1204.5955 : Observation of a New Ξ_{b} Baryon
- CMS-BPH-11-026 : arXiv:1309.6920 : Observation of a peaking structure in the J/psi phi mass spectrum from B(+/-) to J/psi phi K(+/-) decays
- CMS-BPH-11-016 : arXiv:1309.0250 : Search for a new bottomonium state decaying to Upsilon(1S) pi+ pi- in pp collisions at sqrt(s) = 8 TeV
- CMS-BPH-11-011 : arXiv:1302.3968 : Measurement of the X(3872) production cross section via decays to J/psi pi pi in pp collisions at sqrt(s) = 7 TeV
- CMS-DP-2017-029 : Heavy Flavour distributions from CMS with 2017 data at $\sqrt{s} = 13$ TeV

- See also: CMS B Physics and Quarkonia Publications

Other experimental references

- Belle : arXiv:1711.07927 : Observation of Excited Ωc Charmed Baryons in e+e− Collisions
- Belle : arXiv:1408.6457 : Observation of a new charged charmoniumlike state in B -> J/psi K pi decays
- CDF : arXiv:1712.09620 :A search for the exotic meson X(5568) with the Collider Detector at Fermilab
- CDF : arXiv:0903.2229 : Evidence for a Narrow Near-Threshold Structure in the J/ψφ Mass Spectrum in B+→J/ψφK+ Decays
- D0 : arXiv:1712.10176 : Study of the X±(5568) state with semileptonic decays of the B0s meson
- D0 : arXiv:1602.07588 : Evidence for a B0sπ± State
- D0 : arXiv:1508.07846 : Inclusive production of the X(4140) state in ppbar collisions at D0
- D0 : arXiv:1309.6580 : Search for the X(4140) state in B+->J/psi phi K+ decays with the D0 detector

Ξ_{cc} theory refs

[6] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Spectroscopy of doubly heavy baryons*, Phys. Atom. Nucl. **63** (2000) 274, arXiv:hep-ph/9811212, [Yad. Fiz. 63, 334 (2000)].

[7] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Spectroscopy of doubly charmed baryons: Ξ_{cc}^{+} and Ξ_{cc}^{++}*, Mod. Phys. Lett. **A14** (1999) 135, arXiv:hep-ph/9807375.

[8] C. Itoh, T. Minamikawa, K. Miura, and T. Watanabe, *Doubly charmed baryon masses and quark wave functions in baryons*, Phys. Rev. **D61** (2000) 057502.

[9] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Spectroscopy of doubly heavy baryons*, Phys. Rev. **D62** (2000) 054021.

[10] K. Anikeev *et al.*, *B physics at the Tevatron: Run II and beyond*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999*, 2001. arXiv:hep-ph/0201071.

[11] V. V. Kiselev and A. K. Likhoded, *Baryons with two heavy quarks*, Phys. Usp. **45** (2002) 455, arXiv:hep-ph/0103169.

[12] D. Ebert, R. N. Faustov, V. O. Galkin, and A. P. Martynenko, *Mass spectra of doubly heavy baryons in the relativistic quark model*, Phys. Rev. **D66** (2002) 014008, arXiv:hep-ph/0201217.

[13] D.-H. He *et al.*, *Evaluation of the spectra of baryons containing two heavy quarks in a bag model*, Phys. Rev. **D70** (2004) 094004, arXiv:hep-ph/0403301.

[14] C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, *Estimate of the hadronic production of the doubly charmed baryon Ξ_{cc} in the general-mass variable-flavor-number scheme*, Phys. Rev. **D73** (2006) 094022, arXiv:hep-ph/0601032.

[15] W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

[16] A. Valcarce, H. Garcilazo, and J. Vijande, *Towards an understanding of heavy baryon spectroscopy*, Eur. Phys. J. **A37** (2008) 217, arXiv:0807.2973.

[17] J.-R. Zhang and M.-Q. Huang, *Doubly heavy baryons in QCD sum rules*, Phys. Rev. **D78** (2008) 094007, arXiv:0810.5396.

[18] Z.-G. Wang, *Analysis of the $\frac{1}{2}^{+}$ doubly heavy baryon states with QCD sum rules*, Eur. Phys. J. **A45** (2010) 267, arXiv:1001.4693.

[19] M. Karliner and J. L. Rosner, *Baryons with two heavy quarks: masses, production, decays, and detection*, Phys. Rev. **D90** (2014) 094007, arXiv:1408.5877.

[20] K.-W. Wei, B. Chen, and X.-H. Guo, *Masses of doubly and triply charmed baryons*, Phys. Rev. **D92** (2015) 076008, arXiv:1503.05184.

[21] Z.-F. Sun and M. J. Vicente Vacas, *Masses of doubly charmed baryons in the extended on-mass-shell renormalization scheme*, Phys. Rev. **D93** (2016) 094002, arXiv:1602.04714.

[22] C. Alexandrou and C. Kallidonis, *Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical pion mass*, Phys. Rev. **D96** (2017) 034511, arXiv:1704.02647.

[23] B. O. Kerbikov, M. I. Polikarpov, and L. V. Shevchenko, *Multiquark masses and wave functions through a modified Green function Monte Carlo method*, Nucl. Phys. **B331** (1990) 19.

[24] S. Fleck and J.-M. Richard, *Baryons with double charm*, Prog. Theor. Phys. **82** (1989) 760.

[25] S. Chernyshev, M. A. Nowak, and I. Zahed, *Heavy hadrons and QCD instantons*, Phys. Rev. **D53** (1996) 5176, arXiv:hep-ph/9510326.

[26] T. M. Aliev, K. Azizi, and M. Savcı, *Doubly heavy spin-1/2 baryon spectrum in QCD*, Nucl. Phys. **A895** (2012) 59, arXiv:1205.2873.

[27] Z.-F. Sun, Z.-W. Liu, X. Liu, and S.-L. Zhu, *Masses and axial currents of the doubly charmed baryons*, Phys. Rev. **D91** (2015) 094030, arXiv:1411.2117.

[28] N. Mathur, R. Lewis, and R. M. Woloshyn, *Charmed and bottom baryons from lattice nonrelativistic QCD*, Phys. Rev. **D66** (2002) 014502, arXiv:hep-ph/0203253.

[29] PACS-CS collaboration, Y. Namekawa *et al.*, *Charmed baryons at the physical point in 2+1 flavor lattice QCD*, Phys. Rev. **D87** (2013) 094512, arXiv:1301.4743.

[30] Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, *Charmed bottom baryon spectroscopy from lattice QCD*, Phys. Rev. **D90** (2014) 094507, arXiv:1409.0497.

[31] M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, *Spectroscopy of doubly charmed baryons from lattice QCD*, Phys. Rev. **D91** (2015) 094502, arXiv:1502.01845.

[32] P. Pérez-Rubio, S. Collins, and G. S. Bali, *Charmed baryon spectroscopy and light flavor symmetry from lattice QCD*, Phys. Rev. **D92** (2015) 034504, arXiv:1503.08440.

[33] Y. Liu and I. Zahed, *Heavy baryons and their exotics from instantons in holographic QCD*, Phys. Rev. **D95** (2017) 116012, arXiv:1704.03412; Y. Liu and I. Zahed, *Heavy and strange holographic baryons*, arXiv:1705.01397.

[34] C.-W. Hwang and C.-H. Chung, *Isospin mass splittings of heavy baryons in heavy quark symmetry*, Phys. Rev. **D78** (2008) 073013, arXiv:0804.4044.

[35] S. J. Brodsky, F.-K. Guo, C. Hanhart, and U.-G. Meißner, *Isospin splittings of doubly heavy baryons*, Phys. Lett. **B698** (2011) 251, arXiv:1101.1983.

[36] M. Karliner and J. L. Rosner, *Isospin splittings in baryons with two heavy quarks*, Phys. Rev. **D96** (2017) 033004, arXiv:1706.06961.

[37] B. Guberina, B. Melić, and H. Štefančić, *Inclusive decays and lifetimes of doubly charmed baryons*, Eur. Phys. J. **C9** (1999) 213, Erratum ibid. **C13** (2000) 551, arXiv:hep-ph/9901323.

[38] V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Lifetimes of doubly charmed baryons: Ξ_{cc}^{+} and Ξ_{cc}^{++}*, Phys. Rev. **D60** (1999) 014007, arXiv:hep-ph/9807354.

[39] C.-H. Chang, T. Li, X.-Q. Li, and Y.-M. Wang, *Lifetime of doubly charmed baryons*, Commun. Theor. Phys. **49** (2008) 993, arXiv:0704.0016.

[40] A. V. Berezhnoy and A. K. Likhoded, *Doubly heavy baryons*, Phys. Atom. Nucl. **79** (2016) 260, [Yad. Fiz. 79, 151 (2016)].

D0 X(5568): Cone cut

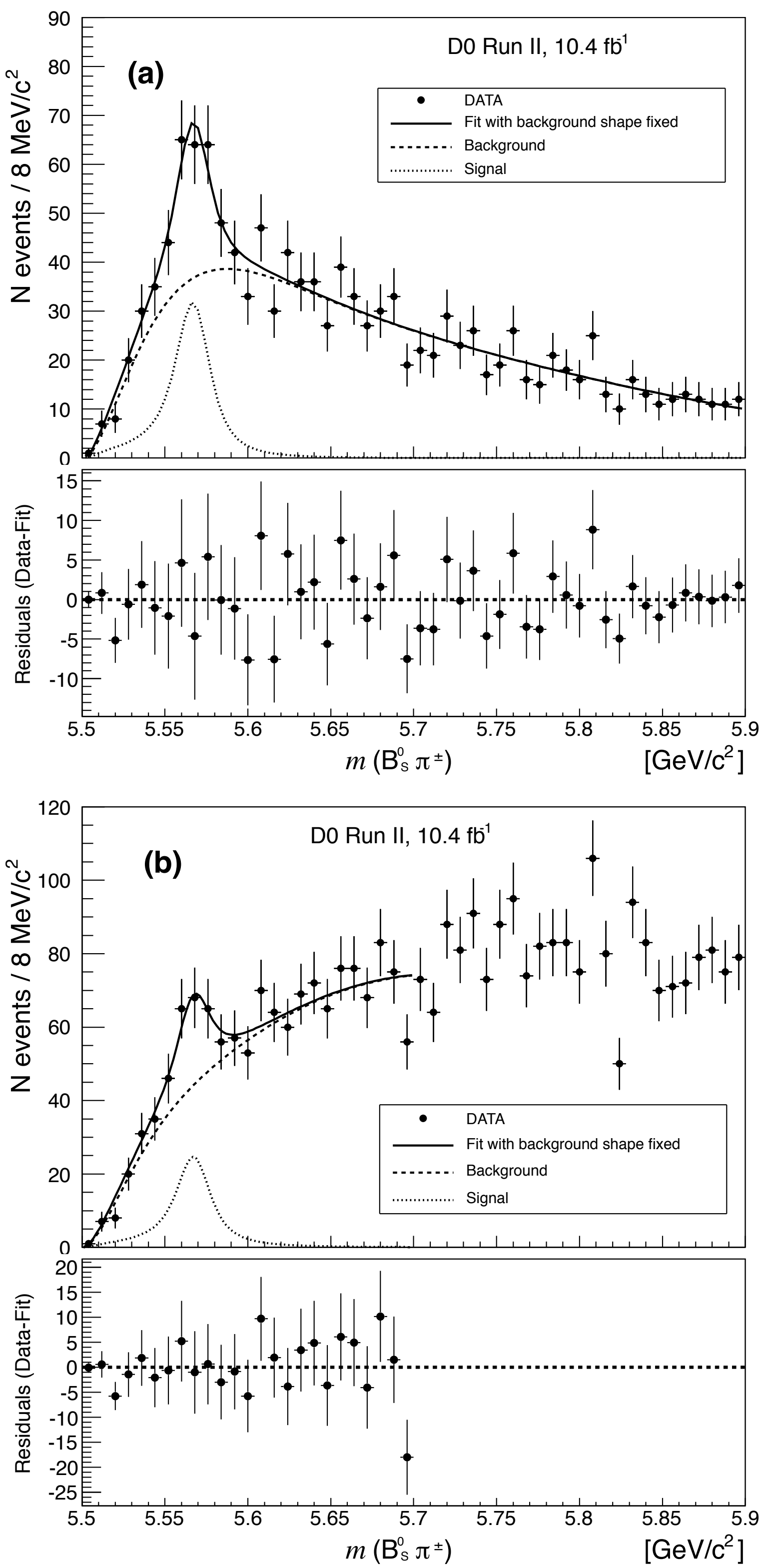


FIG. 3: The $m(B_s^0\pi^\pm)$ distribution together with the background distribution and the fit results (a) after applying the $\Delta R < 0.3$ cone cut and (b) without the cone cut.

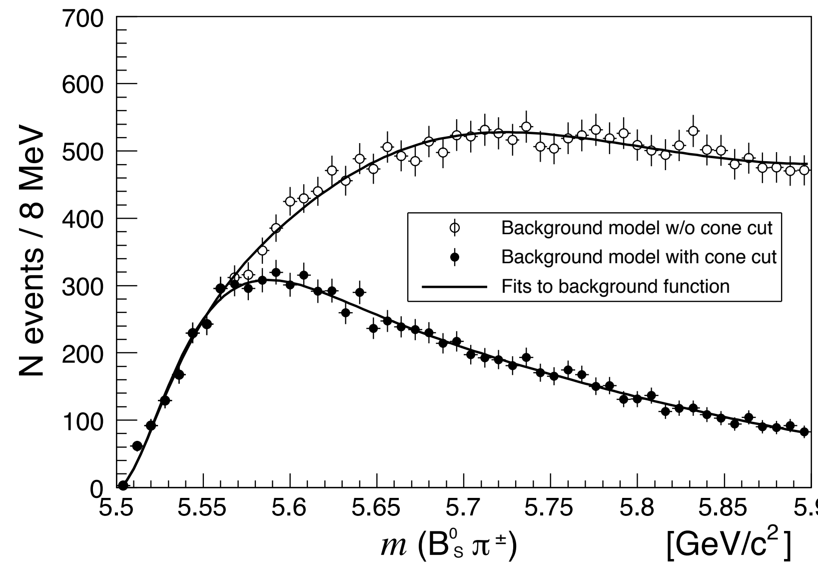


FIG. 2: The combined background for the $m(B_s^0\pi^\pm)$ distribution described in the text and the fit to that distribution with the $\Delta R < 0.3$ cone cut and without the cone cut.

D0: PRL 117, 022003 (2016)

D0 X(5568): Cone cut

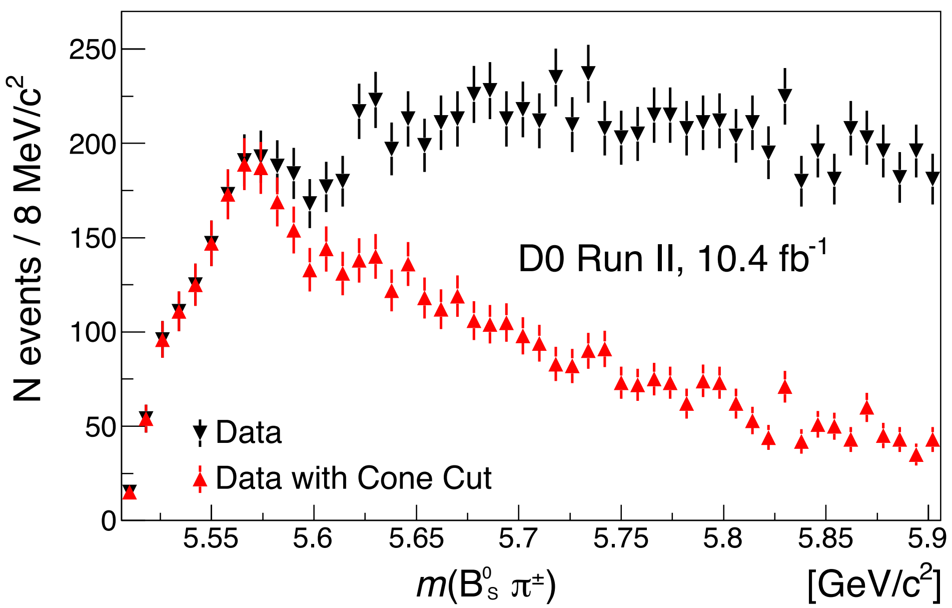


FIG. 3. The $m(B_s^0\pi^\pm)$ distribution for the semileptonic data with (red upward triangles) and without (black downward triangles) the cone cut (color online). Below $5.56\,\mathrm{GeV}/c^2$ the red and black points have the same values.

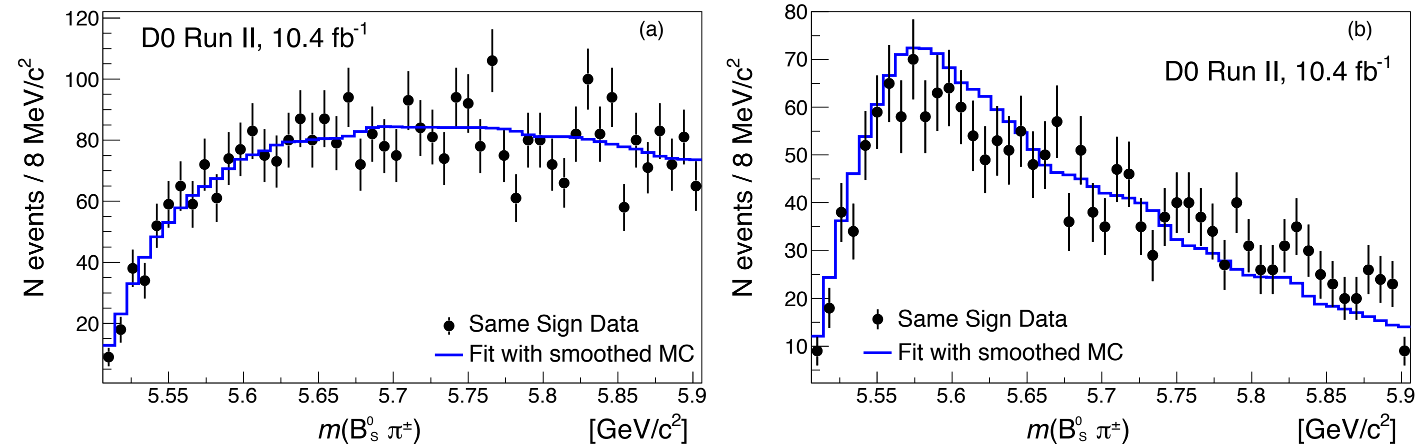


FIG. 6. The comparison of the $m(B_s^0\pi^\pm)$ background only distributions a) without the cone cut and b) with the cone cut, obtained using the weighted MC (histogram) and from the same sign data samples (points with error bars). The fluctuations in the number of MC events with the cone cut are due to the weighting procedure and the size of the sample.

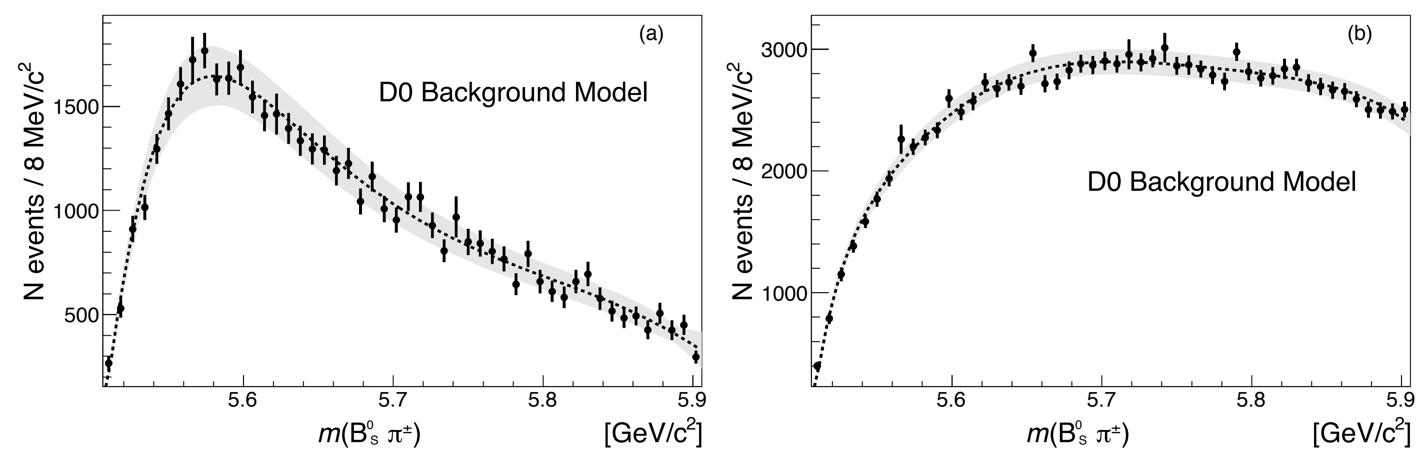


FIG. 7. The background model produced according to the procedure described in the text is showm along with background function (1) (a) with and (b) without the cone cut. The grey band shows the systematic uncertainties on the background model (see Section VI D).

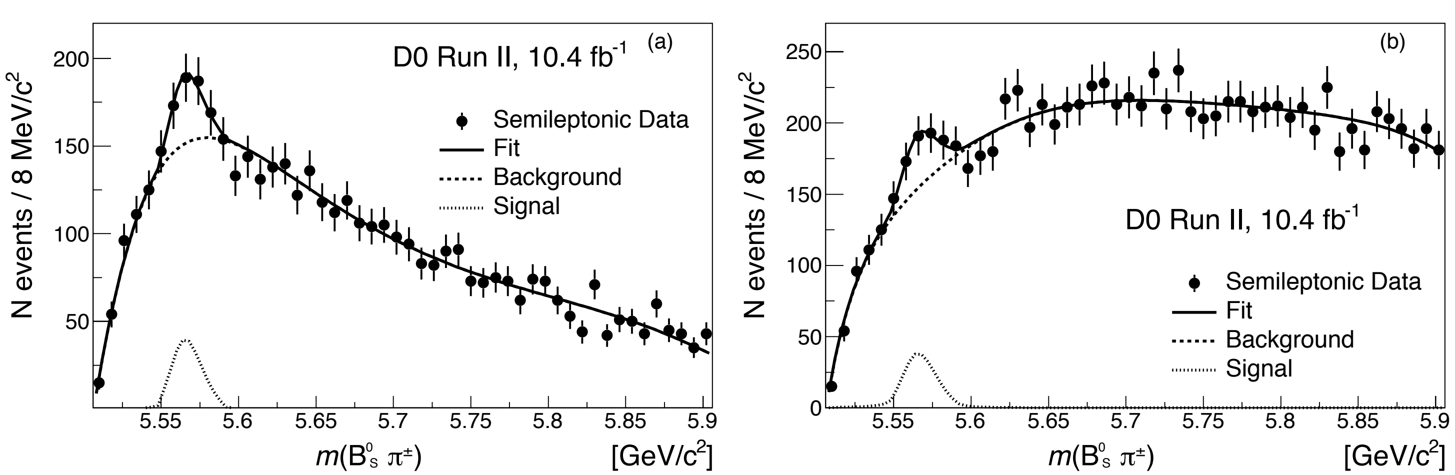


FIG. 9. The $m(B_s^0\pi^\pm)$ distribution (a) with and (b) without the cone cut. The fitting function is superimposed (see text for details).

D0: arXiv:1712.10176

D0 X(5568): Cone cut

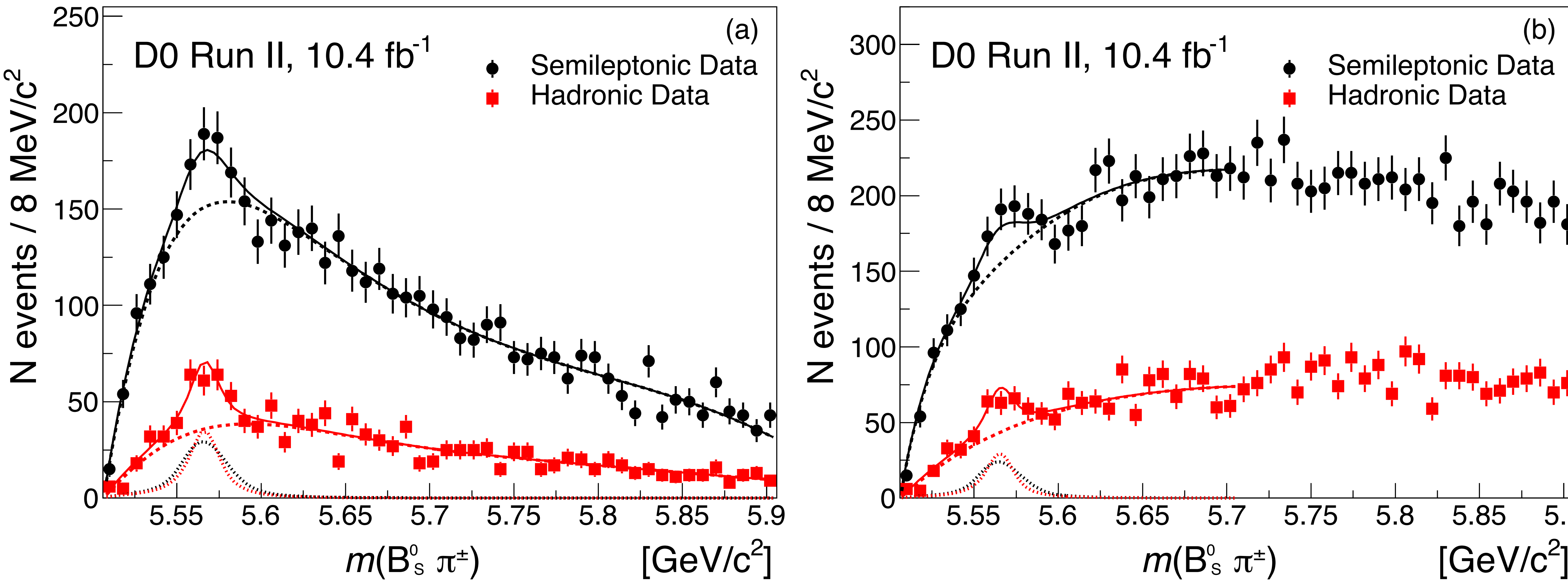
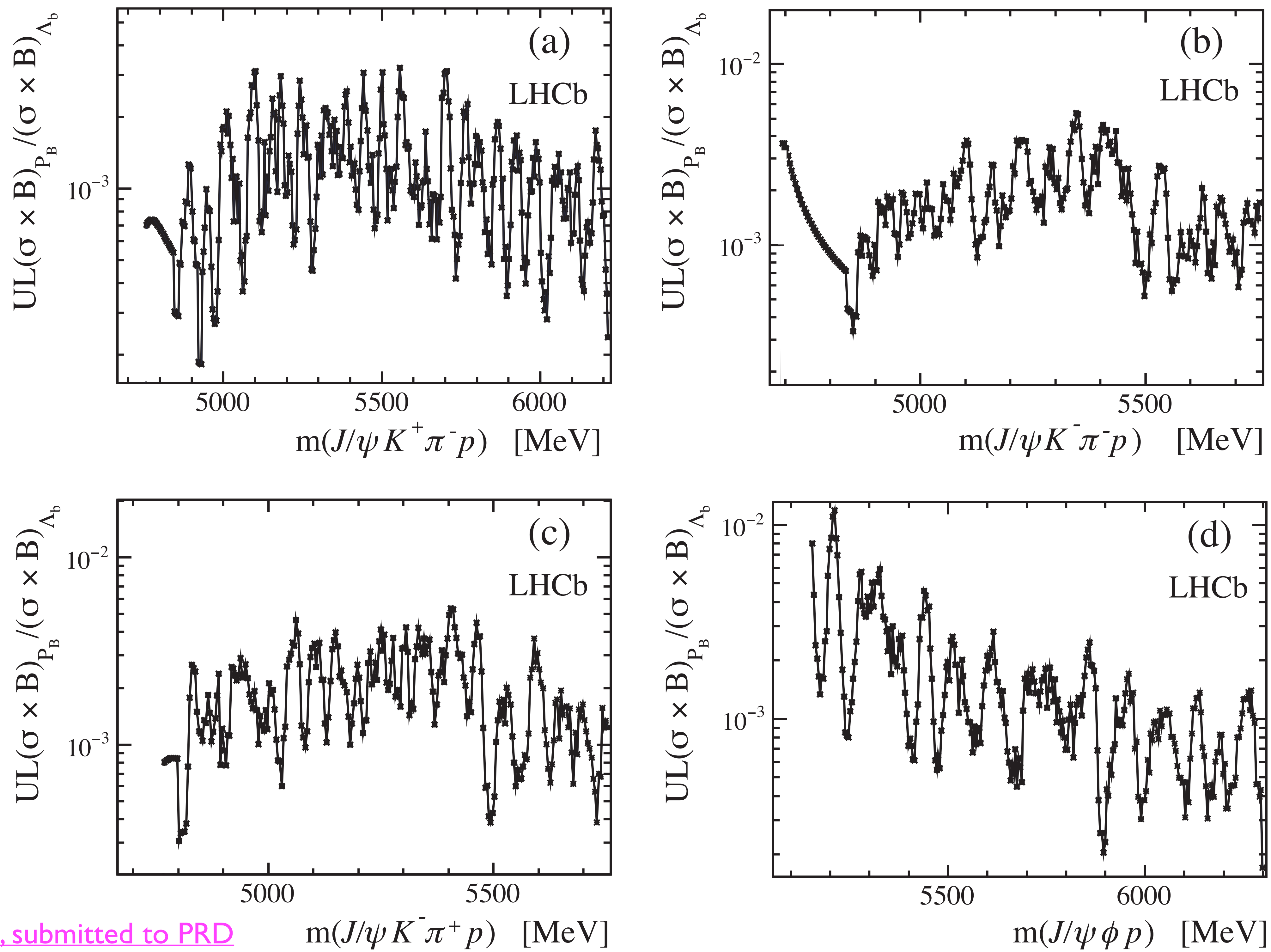


FIG. 11. The $m(B_s^0\pi^\pm)$ distribution for the hadronic (red squares) and semileptonic (black circles) data with the combined fitting function superimposed (a) with and (b) without the cone cut. (see text for details, the resulting fit parameters are given in Table VIII). The background parametrization function is taken from Eq. 1.

Search for weakly decaying b-flavoured pentaquarks

$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi\, X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi\, K^- p)}$$

Upper limits at 90% CL



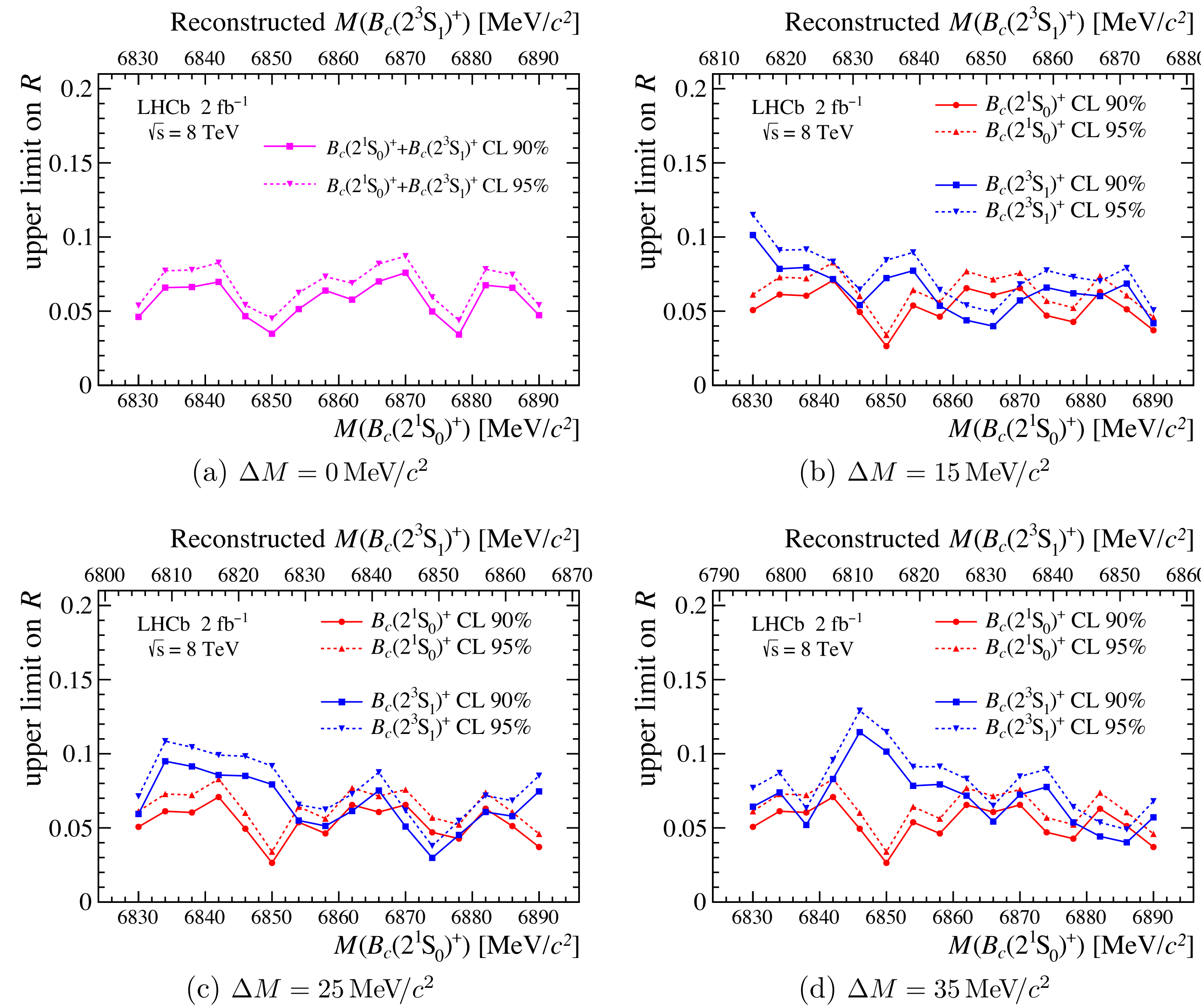
LHCb: arXiv:1712.08086, submitted to PRD

Excited B_c^+ states

R is ratio of excited vs ground-state B_c^+ yields, corrected for effic:

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$

$$= \frac{N_{B_c^{(*)}(2S)^+}}{N_{B_c^+}} \cdot \frac{\varepsilon_{B_c^+}}{\varepsilon_{B_c^{(*)}(2S)^+}},$$



	$\sqrt{s} = 7\,\mathrm{TeV}$	$\sqrt{s} = 8\,\mathrm{TeV}$
ATLAS	$(0.22 \pm 0.08\,(\mathrm{stat}))/\varepsilon_7$	$(0.15 \pm 0.06\,(\mathrm{stat}))/\varepsilon_8$
LHCb	–	$< [0.04, 0.09]$

95% CL UL on R

Figure 4: The upper limits on the ratio $\mathcal{R}(B_c^{(*)}(2S)^+)$ at 95% and 90% confidence levels under different mass splitting ΔM hypotheses.

$$\Delta M \equiv \left[M(B_c^{*+}) - M(B_c^+)\right] - \left[M(B_c^*(2S)^+) - M(B_c(2S)^+)\right]$$

LHCb: JHEP (2018) 2018: 138

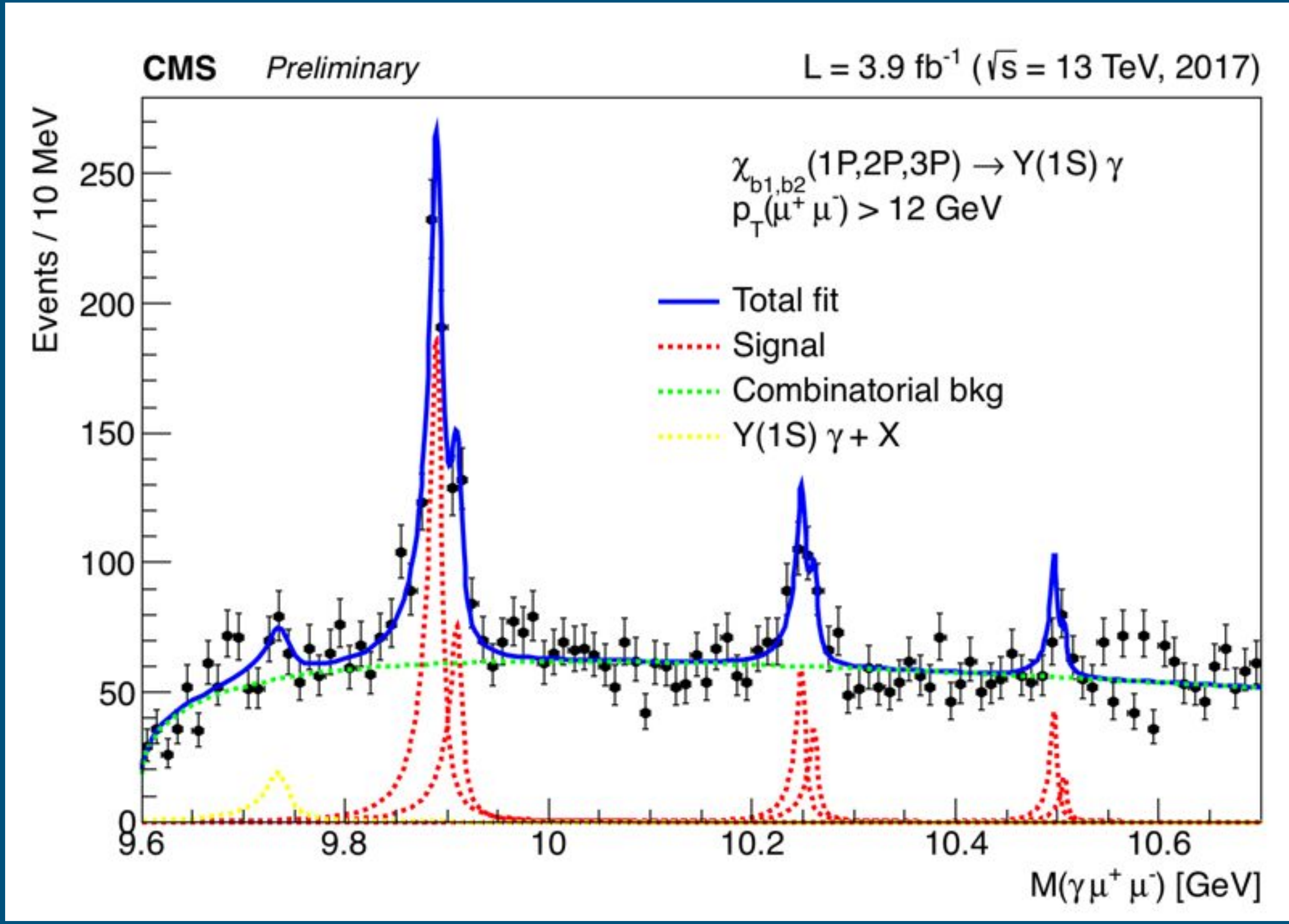
$\chi_b \to \Upsilon\gamma \ (\Upsilon \to \mu^+\mu^-)$

$\chi_b \longrightarrow \gamma\ \Upsilon\ (\longrightarrow \mu^+\mu^-)$

- Trigger conditions: opposite-sign muon pair with invariant mass in range 8.5-11.5 GeV, p_T > 12 GeV, single muons $|\eta|$ < 1.5 and vertex-fit probability > 0.5%
- The Υ has p_T > 12 GeV
- The γ is a converted photon
- The distance between the Υ and the γ vertices along the beam direction is < 1 mm
- The $\Upsilon\ \gamma$ system has a vertex-fit probability > 1%
- Fit method: unbinned extended maximum likelihood
  - Signal: double side Crystal Ball for each peak with common n, α
    - $m(\chi_{b2})$ - $m(\chi_{b1})$ fixed to previous CMS results
    - first peak corresponds to the misreconstructed decay $\chi_b(2P) \rightarrow \gamma\ \Upsilon(2S)\ (\rightarrow \Upsilon(1S)\pi^+\pi^-)$
  - Background: exponential times power law

$\chi_b \to \Upsilon\gamma\ (\Upsilon \to \mu^+\mu^-)$

$\chi_b \to \gamma\, \Upsilon\, (\to \mu^+\mu^-)$



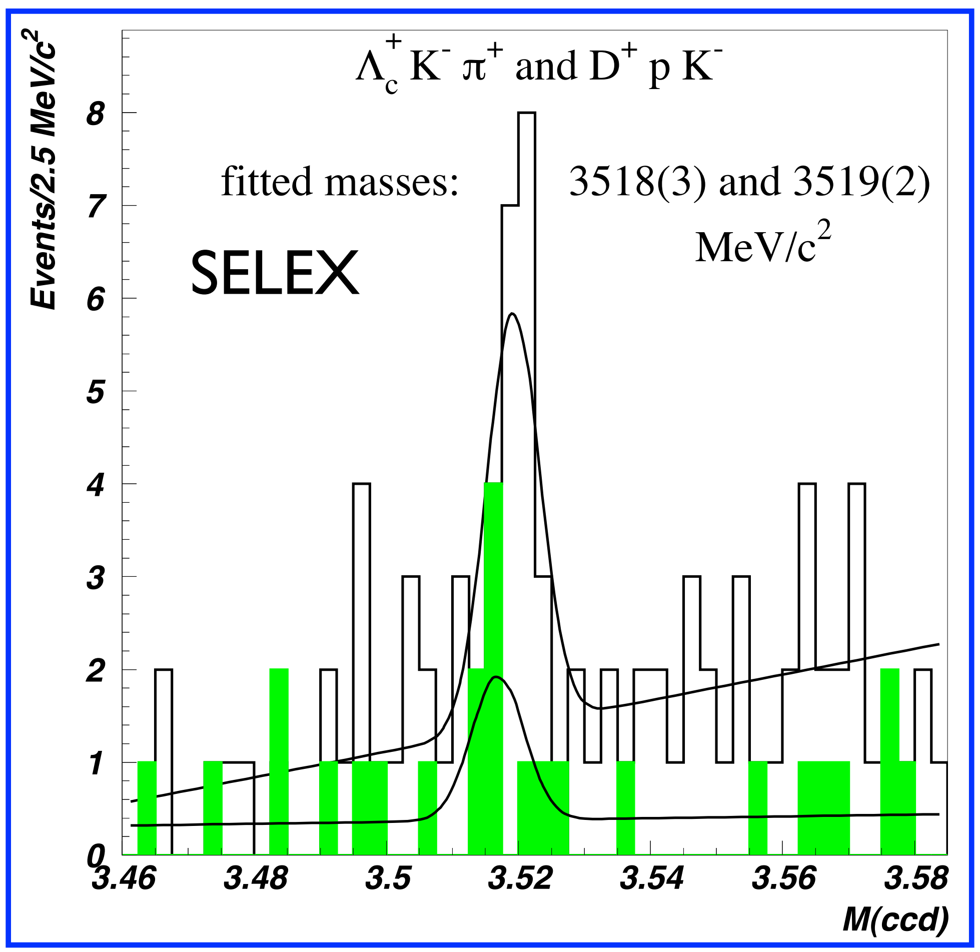
Mass[χ_{b1}(1P)] = 9.890 ± 0.001 (stat.) GeV, Mass[χ_{b2}(1P)] = 9.910 ± 0.001 (stat.) GeV
Mass[χ_{b1}(2P)] = 10.248 ± 0.001 (stat.) GeV, Mass[χ_{b2}(2P)] = 10.260 ± 0.001 (stat.) GeV
Mass[χ_{b1}(3P)] = 10.497 ± 0.001 (stat.) GeV, Mass[χ_{b2}(3P)] = 10.507 ± 0.001 (stat.) GeV

37

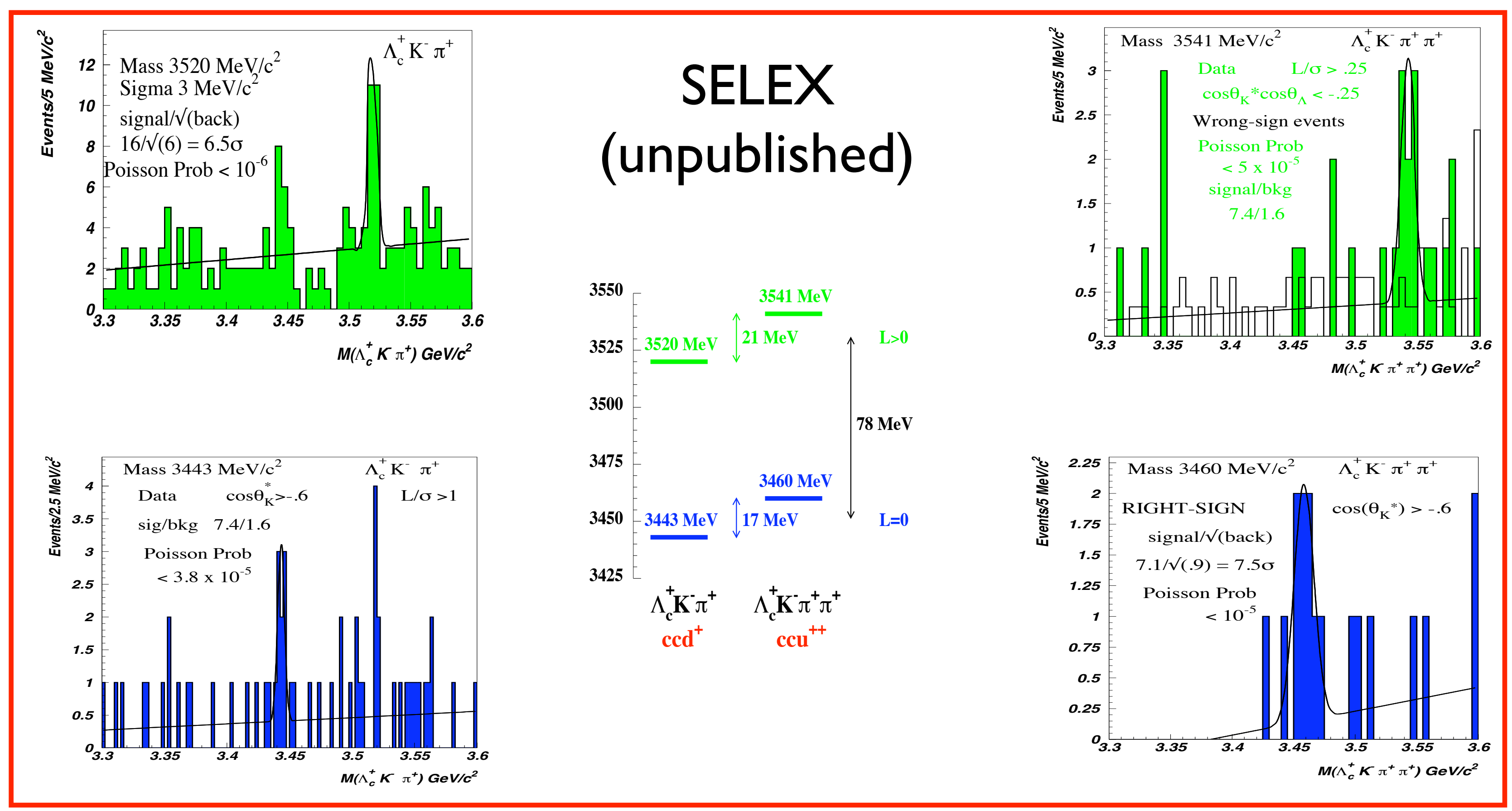
CMS-DP-2017-029

SELEX Ξ_{cc} results

- In 2002 and 2004, SELEX published results on a weakly-decaying Ξ_{cc}^+ at 3518 MeV/c^2
  - $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$: 15.9 events over background of 6.1 ± 0.5 => 6.3σ
  - $\Xi_{cc}^+ \rightarrow p\, D^+ K^-$: 5.62 events over background of 1.38 ± 0.13 => 4.8σ
  - ... and also unpublished results on 4 other claimed Ξ_{cc} states
- These observations were not been confirmed.
  - Searches by BABAR, Belle, FOCUS, LHCb-(0.65/fb)
  - SELEX used O(1600) Λ_c^+, FOCUS O(20k), BaBar+Belle O(1M)



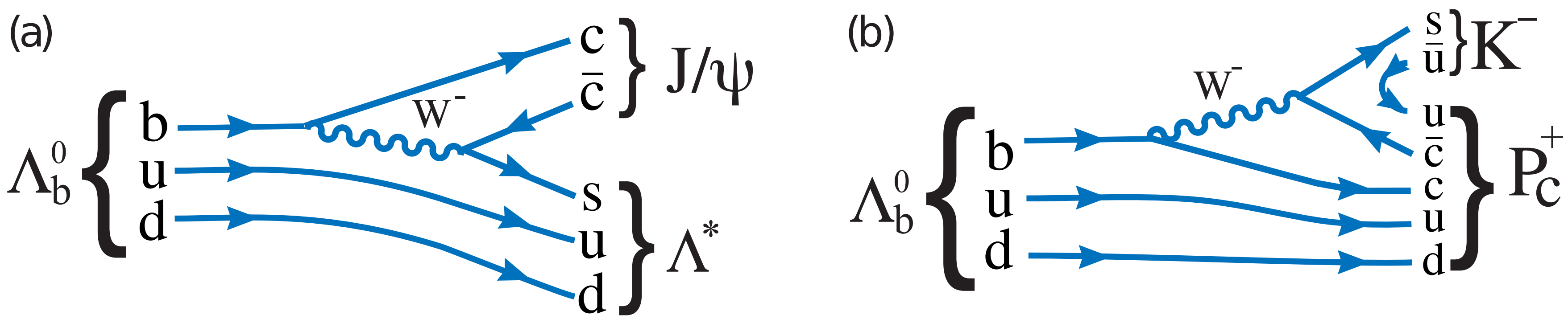
PRL 89:112001 (2002) and PLB 628:18 (2005)



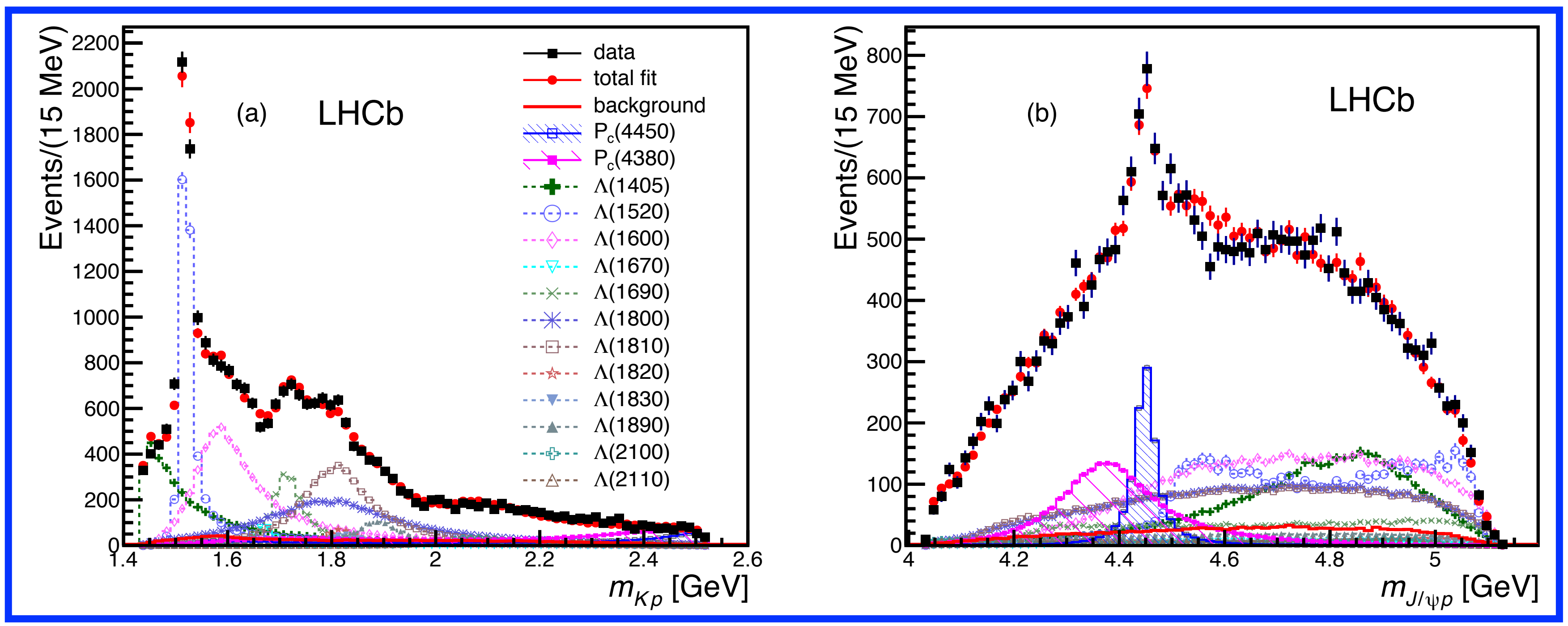
Fermilab - Joint Experimental and Theoretical Physics Seminar - June 13, 2003

See also: hep-ex/0212029

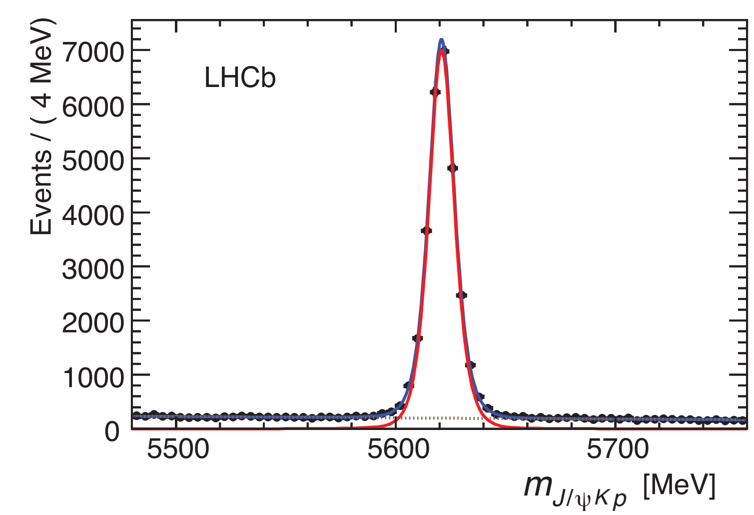
Pentaquark recap: $\Lambda_b \to J/\psi\, p\, K^-$

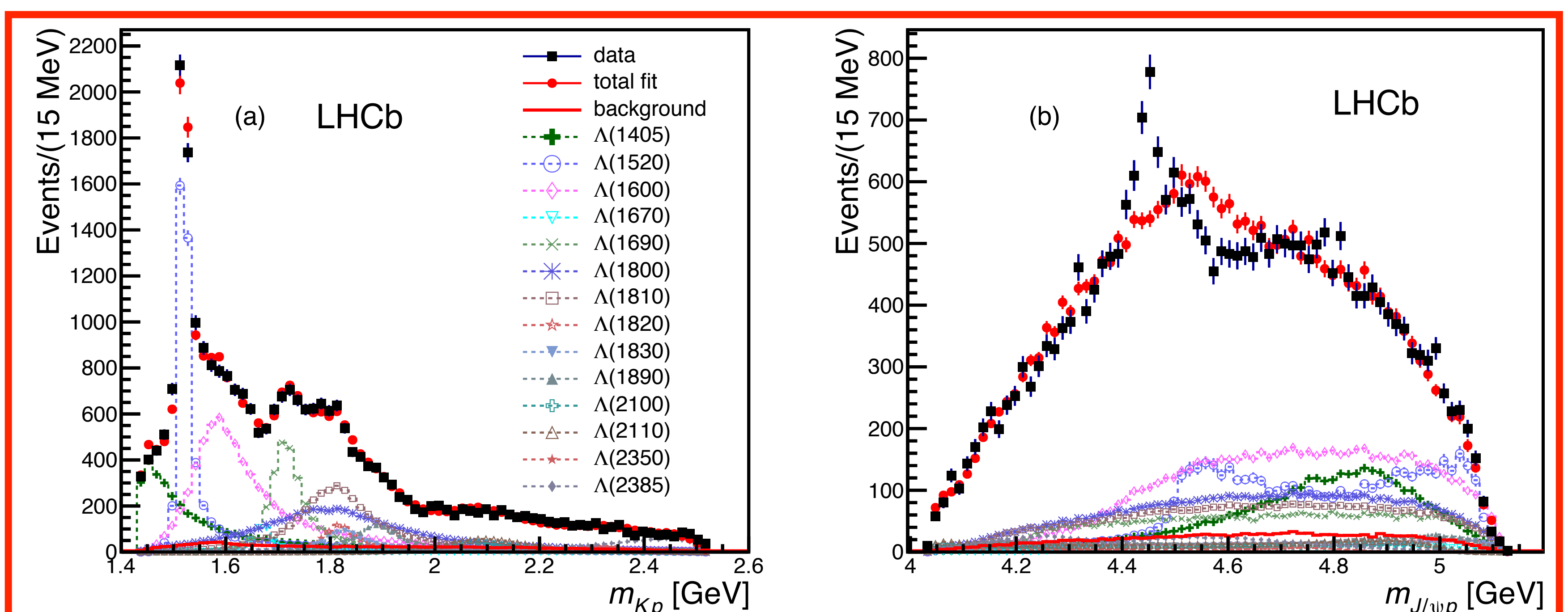


PRL 115 (2015) 072001
[LHCb-PAPER-2015-029]



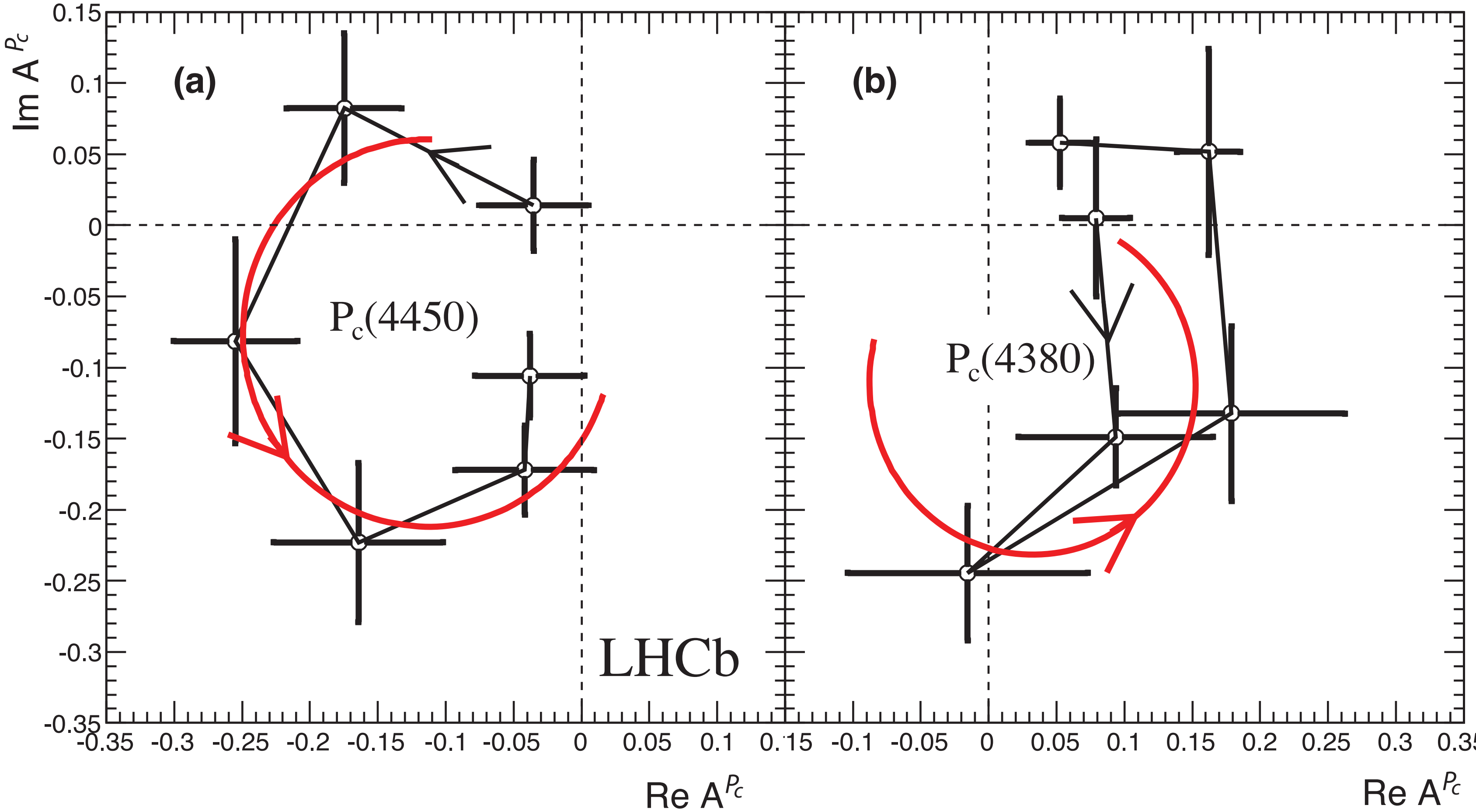
Fit with PQ





Fit sans PQ

Pentaquark recap: $\Lambda_b \to J/\psi\ p\ K^-$



- Combined significance (vs no P_c) ~ 15σ
- $P_c(4380)^+$: m=4380±8±29 MeV, Γ=205±18±86 MeV, ~9σ
- $P_c(4450)^+$: m=4449.8±1.7±2.5 MeV, Γ=39±5±19 MeV, ~12σ
- Preferred J^P: $3/2^-$ and $5/2^+$ for lower and heavier
  - Also compatible with reversed parity: $3/2^+$ and $5/2^-$