XYZ states at LHCb

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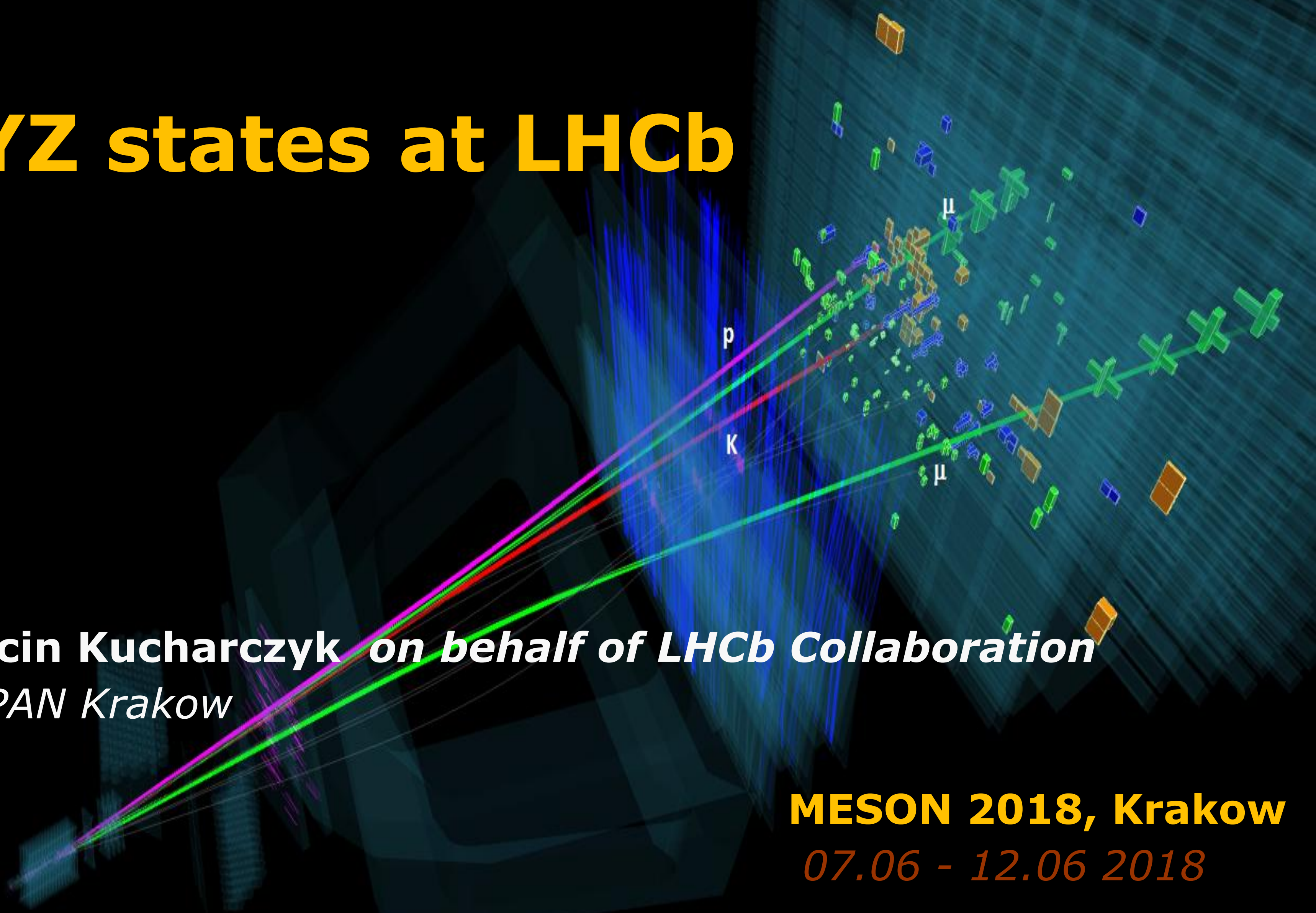


MESON 2018, Krakow
07.06 - 12.06 2018

Outline

XYZ states

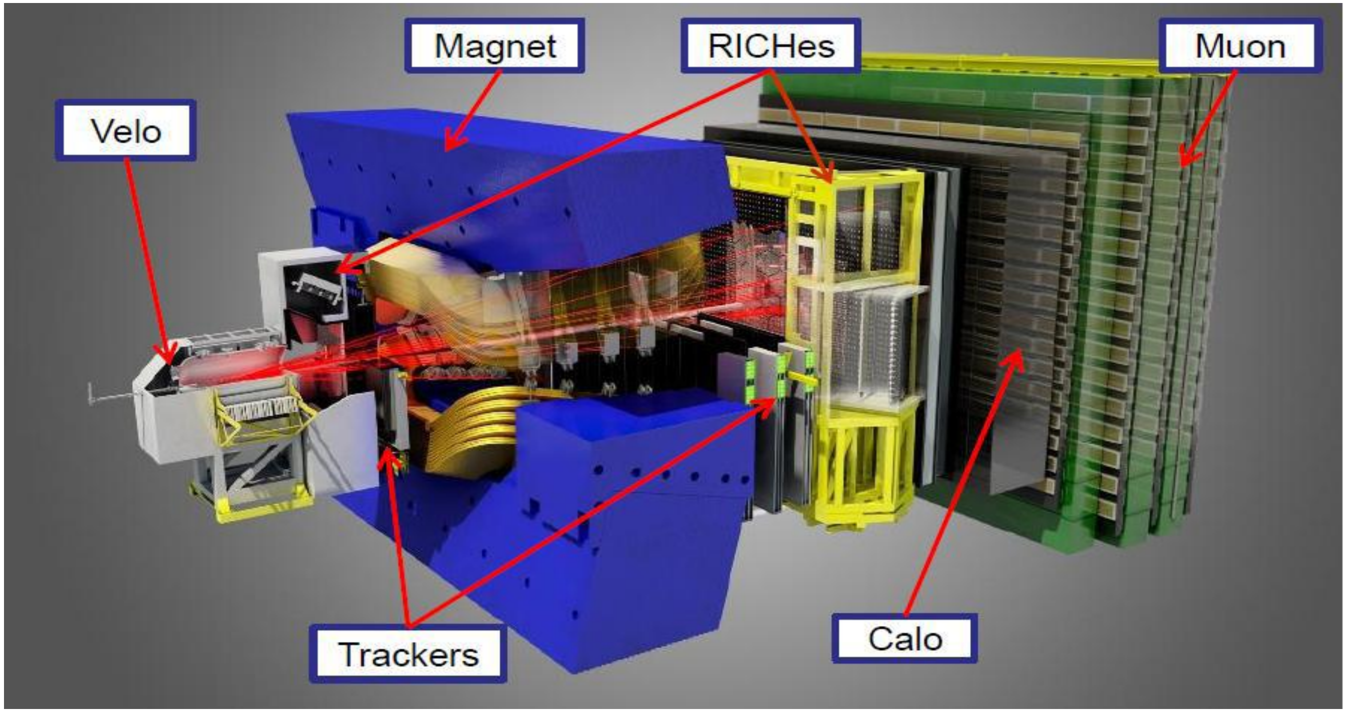
- Probing *X(3872)* composition
  - $\rightarrow$ quantum number confirmed 1^{++} [PRD 92 (2015) 011102]
- Enigmatic $X \rightarrow J/\psi\varphi$ states
  - $\rightarrow$ *X(4140), X(4270), X(4500), X(4700)* [PR D95 (2017) 012002] [PRL 118 (2017) 02203]
- Confirmation of resonant nature of *Z(4430)*
  - $\rightarrow$ 4D amplitude analysis [PRL 112 (2014) 222002]
  - $\rightarrow$ moment analysis [PRD 92 (2015) 112009]
- Tetraquark *X(5568)*?
  - $\rightarrow$ non-confirmation by LHCb [PRL 117 (2016) 152003]
  - $\rightarrow$ not seen by CDF
  - $\rightarrow$ seen again by D0
- Search for tetraquarks in *Υ(1S)* $\mu^+\mu^-$ system ***NEW!*** [LHCb-PAPER-2018-027]

see also Nicola's talk on pentaquarks

LHCb detector

[Int. J. Mod. Phys. A30 (2015) 1530022]

- forward spectrometer at LHC collider
- designed for CP violation & rare decays of heavy hadrons



- precision coverage unique for LHCb $2 < \eta < 5$ *(~40% of bb in forward region)*
- excellent tracking and vertexing *(σ(IP) ~ 20 μm for high-p_T tracks)*
- good hadron PID separation up to 100 GeV
- efficient trigger with *μ's*

Data sample used

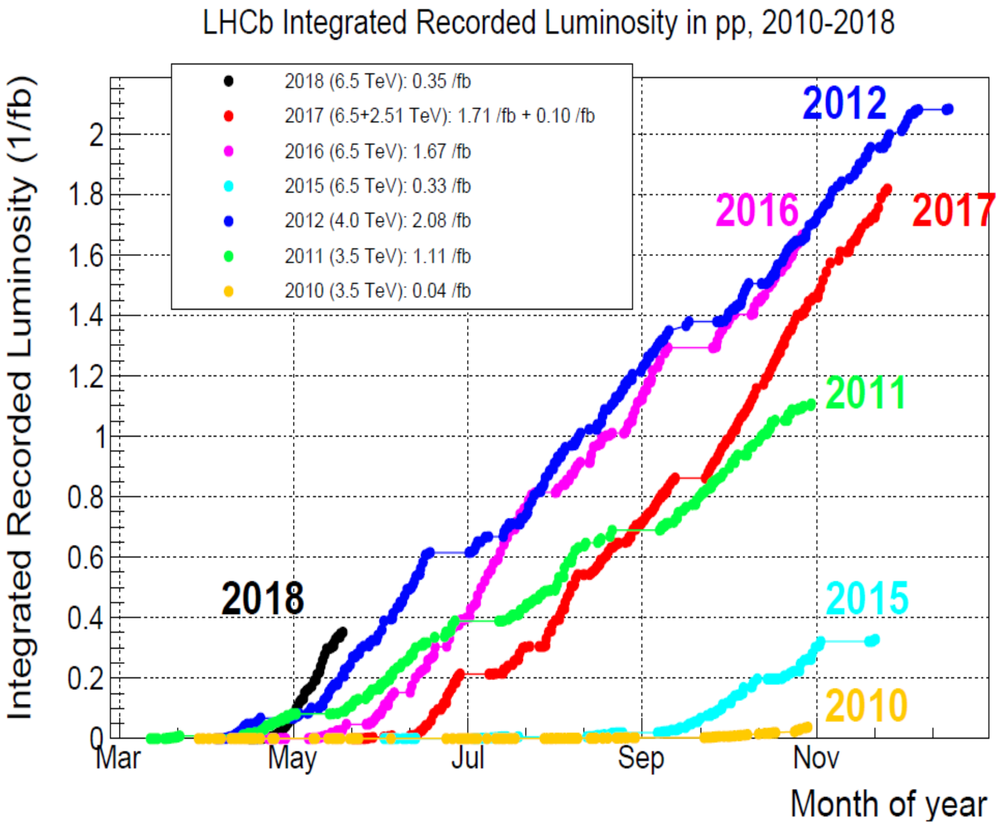
[Nucl. Phys. B871 (2013) 1]
[JHEP 03 (2016) 159]
[JHEP 09 (2016) 013]
[JHEP 03 (2017) 074]

All results in this talk correspond to 3 fb^{-1} Run 1 data

- 4 x 10^{12} *b*-hadrons produced in LHCb acceptance

Run 1 & Run 2

- Run 1: 3 fb^{-1} in 2011 and 2012 *($\sqrt{s}$ = 7, 8 TeV)*
- Run 2: > 4 fb^{-1} in 2015-2018 so far *($\sqrt{s}$ = 13 TeV)*
  - higher *b* cross section
  - improvements in trigger and selection efficiencies



Run	Years	Lumi [fb^{-1}]	$\sqrt{s}$ [TeV]	σ_{bb}^{th} [μb]	σ_{cc}^{th} [μb]
1	2011-2012	~3	7, 8	70	1400
2	2015-2018	>4	13	150	2400

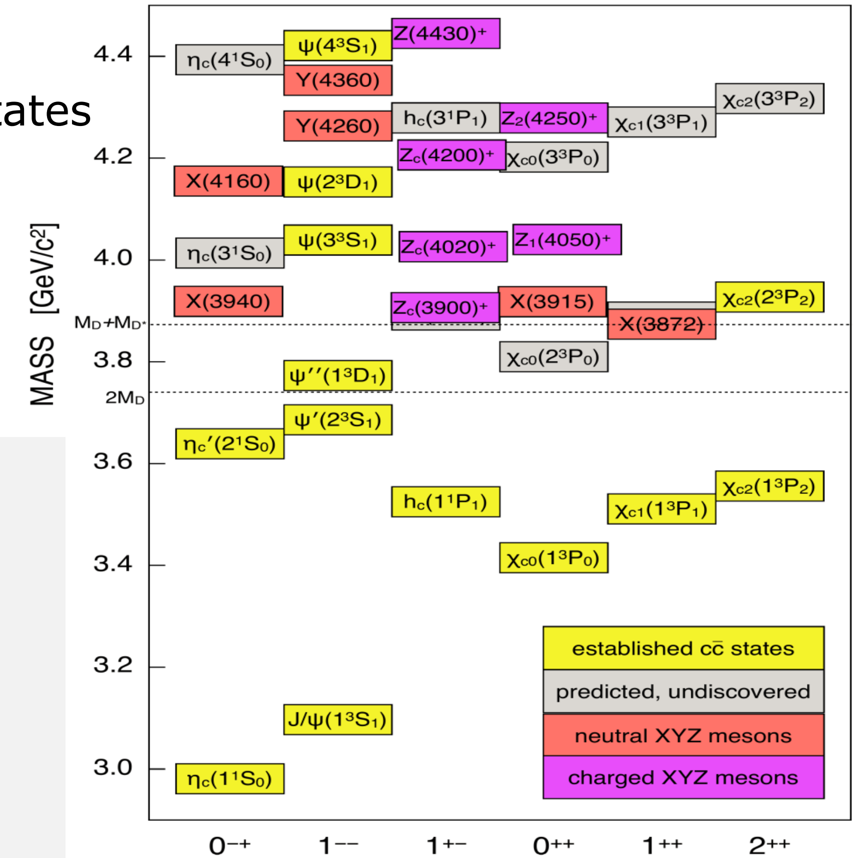
XYZ states

Bound states of quarks were first proposed in 1964 by Gell-Mann and Zweig

- many different exotic charmonium-like states has been seen so far
- CDF/D0, Belle/BaBar, LHC, BESIII
- properties do not fit very well to the quarkonia picture

[Olsen, arXiv:1403.1254]

charmonium & charmonium-like mesons



+2 P_c's + 4 new $J/\psi\varphi$

Many theoretical interpretations discussed

→ conventional quarkonia

→ multiquark states

→ meson molecules

→ hybrid mesons

→ threshold effects

No clear picture

→ *need experimental & theoretical effort to understand strong interaction dynamics that can cause their production and structure*

XYZ states: *production and taxonomy*

Charmonium *($c\bar{c}$)* or bottomonium *($b\bar{b}$)* states studied at LHCb in 2 regimes

→ *prompt production in pp collisions*

→ *weak decays of beauty hadrons*

~30 potentially exotic states observed since 2003

Tools

angular distributions, Dalitz and Argand plots

amplitude analysis, model independent approach

…

Commonly used nomenclature

P - pentaquarks

X - neutral resonances *(most observed in B decays),* positive parity

Y - states produced in the Initial State Radiation *(ISR)* processes, negative parity

Z - charmonium-like charged states *(and their isospin partners)*

X(3872): *1 fb^{-1}*

$B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\rho^0\ ,\ J/\psi \to \mu^+\mu^-,\ \rho^0 \to \pi^+\pi^-$ [PRL 110, 222001 (2013)]

(amplitude analysis assuming $J^{PC} = 1^{++}$)

- observed by Belle in 2003
  [PRL 91 (2003) 262001]

  → revolution in exotic meson/baryon

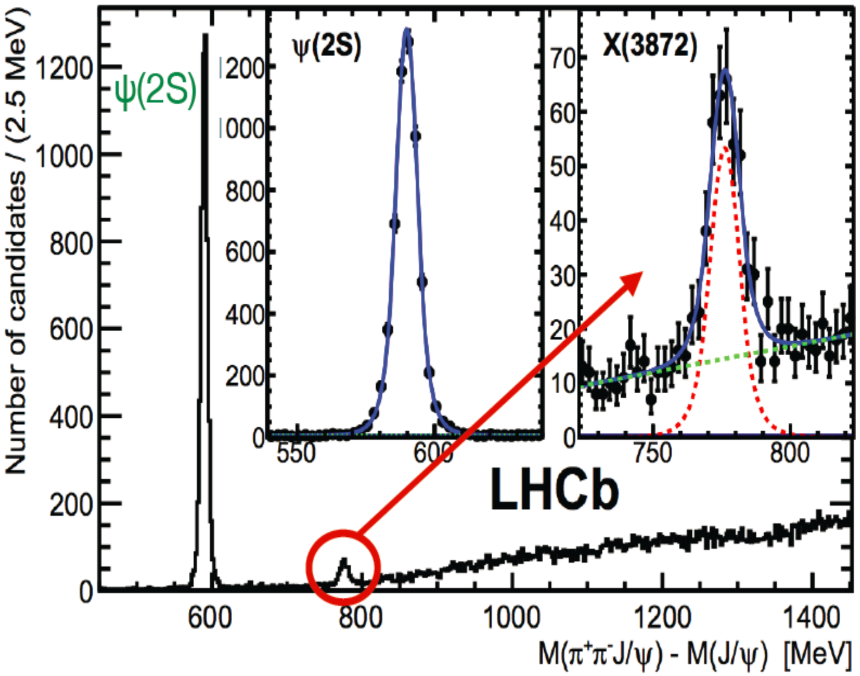
  → seen now at 7 experiments

  → mass close to DD^* threshold

- conventional charmonium?

  → $X \to J/\psi\ \rho/\omega$ violates isospin

  → $c\bar{c}$ not expected to have large BF to $(J/\psi\ \rho)$



$$M_{X(3872)} = 3871.69 \pm 0.17\ \mathrm{MeV}/c^2$$
$$\Gamma_{X(3872)} < 1.2\ \mathrm{MeV}/c^2$$

- **exotic interpretation**

  → $D^0D^{*0} = (c\bar{u})(\bar{c}u)$ molecular state, $c\bar{c}u\bar{u}$ tetraquark, $c\bar{c}g$ hybrid, glueball,...

- **crucial: unambiguous quantum number *J^{PC}***

CDF determined quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+} [PRL 98 (2007) 132002]

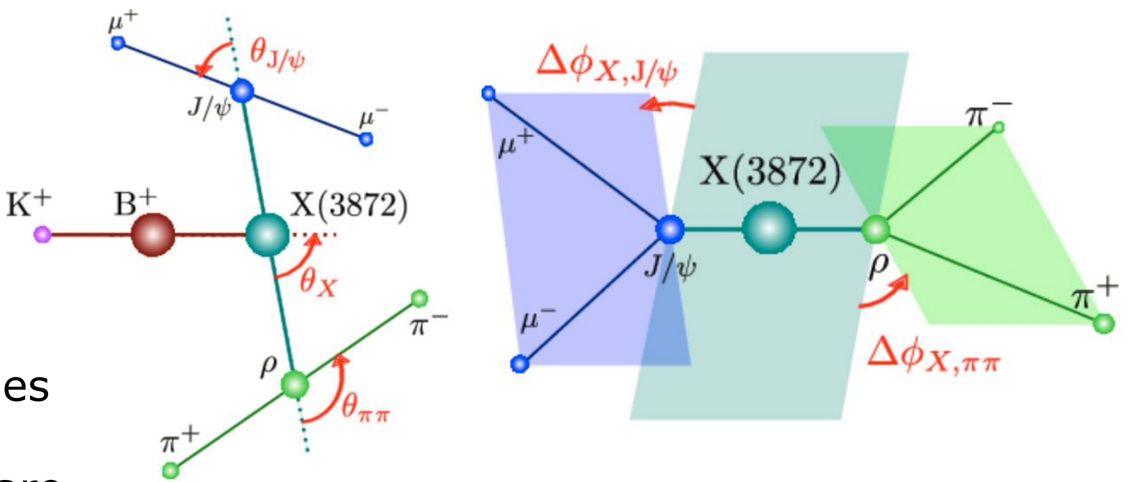
X(3872): *angular analysis with 3 fb^{-1}*

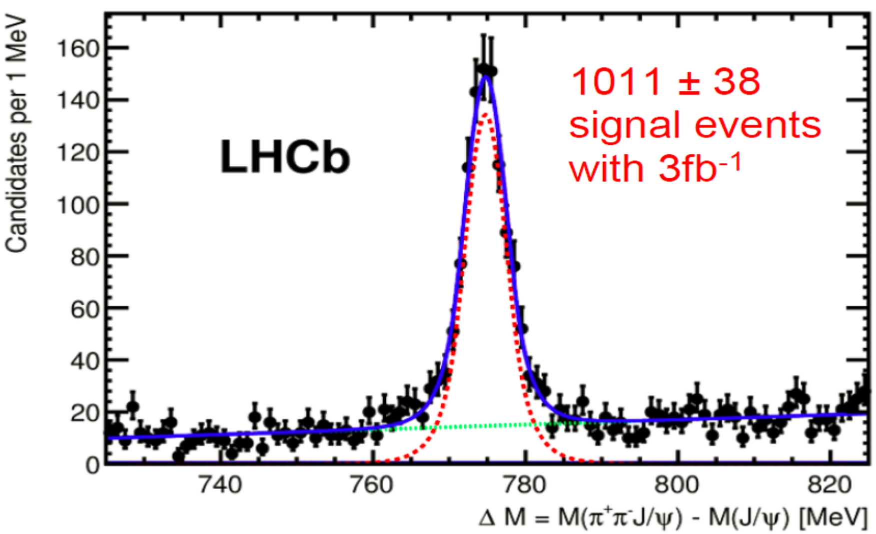
[PRD 92 (2015) 011102]

Full angular 5D analysis of
$B^+ \to K^+ (X(3872) \to \rho \, J/\psi)$

- ~1000 candidates at **3 fb^{-1}**
- helicity formalism
  → decay described by 5 angles
- likelihood ratio test to compare J^{PC} hypotheses
- fit with no assumptions on orbital angular momentum!

5 independent angles describing the decay





X(3872): *quantum numbers*

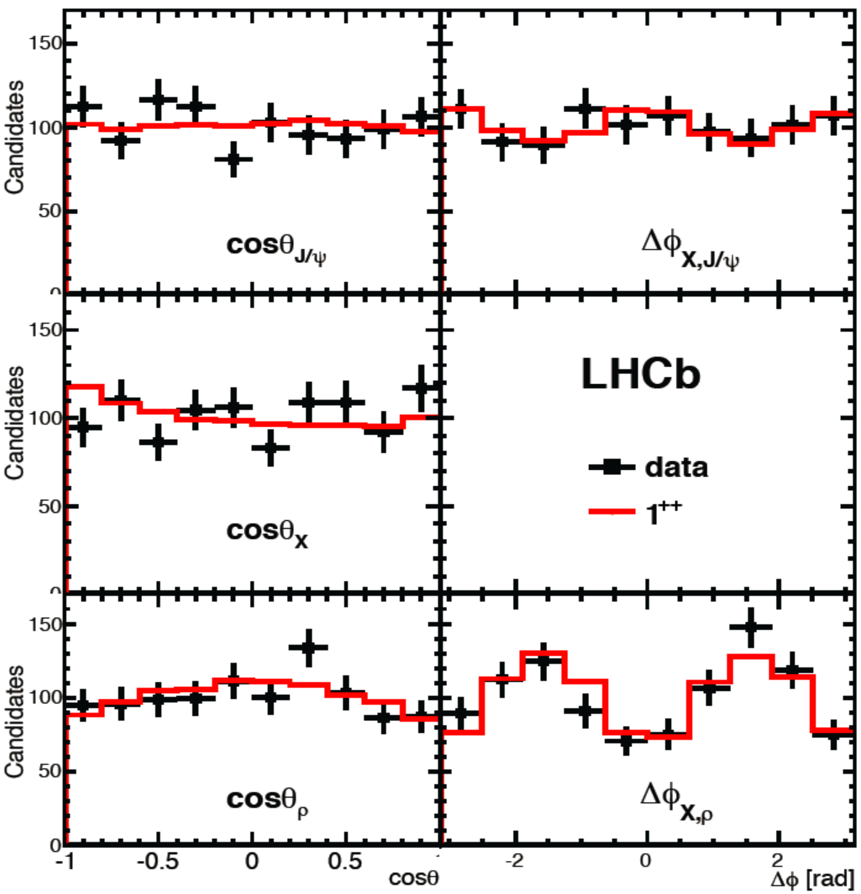
[PRD 92 (2015) 011102]

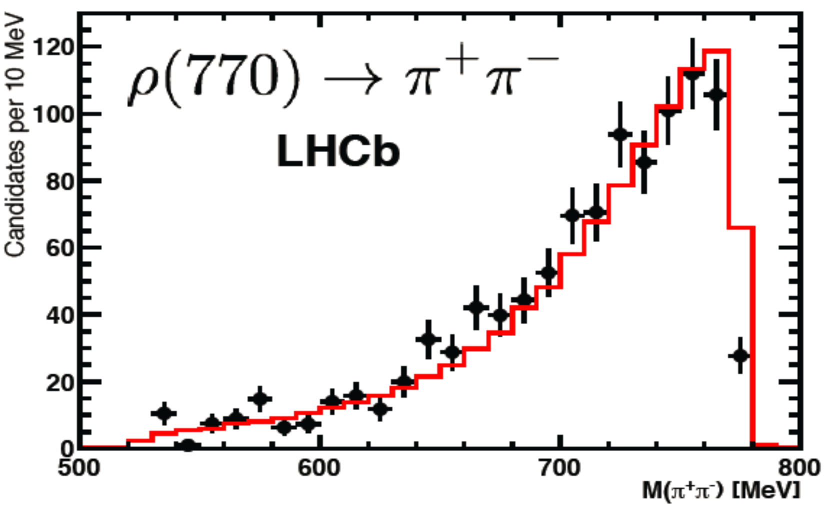
$J^{PC} = 1^{++}$ confirmed!

- 3x larger sample than previous result
- decay mainly through S-wave
  (suggests compact state)
- D-wave negligible *(< 4% @ 95% CL)*
- *ρ(770)* → *ππ* dominates

  → decay violates isospin
  (unlikely to be ordinary $c\bar{c}$)

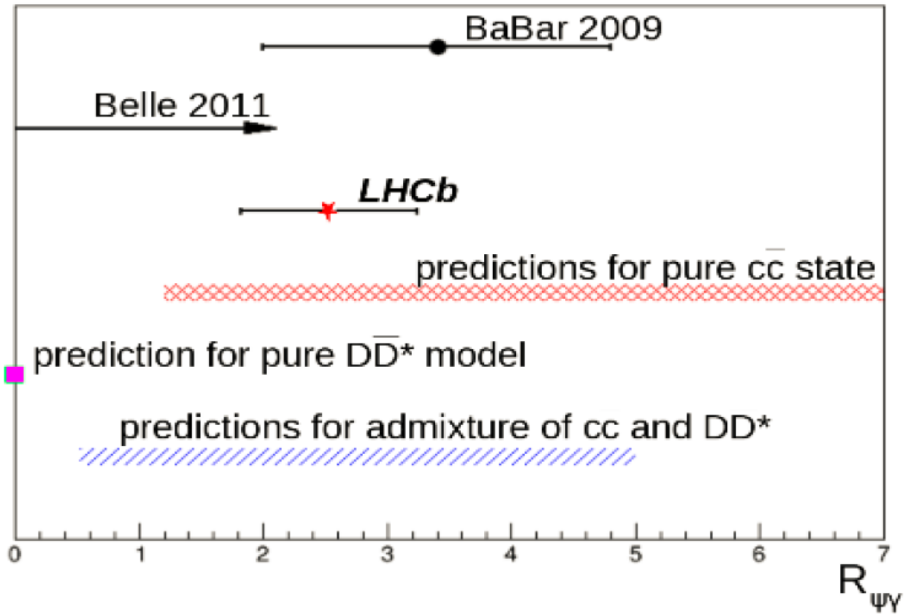
Best fit to data with 1^{++} hypothesis





X(3872): *radiative decays*

- $X(3872) \to J/\Psi\gamma$, $\Psi(2S)\gamma$ disfavors pure DD^* molecule by 4.4σ $(C = +1)$
  [LHCb, NP B886 (2014) 665]
- consistent with $c\bar{c}$ state where the presence of the threshold lowers the mass and width



[PRL 102 (2009) 132001]

[PRL 107 (2011) 091803]

[NP B886, (2014) 665]

$$R_{\psi\gamma} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi(2S)}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)},$$

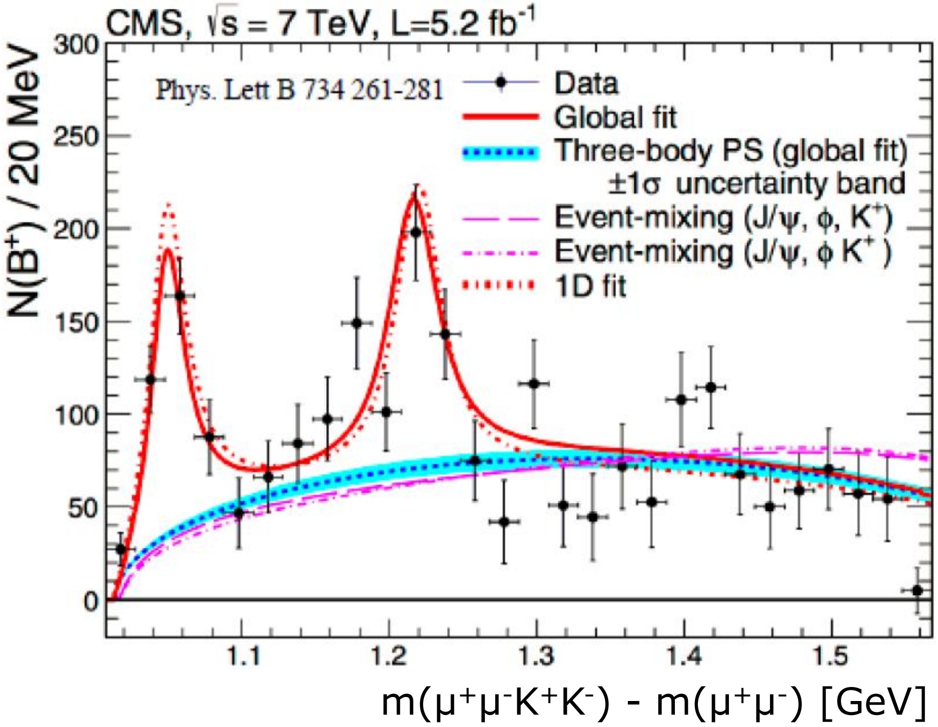
Charged partners of *X(3872)* predicted by some tetraquark models

- next step at LHCb
  → precision measurement of $m_{X(3872)}$ - $m_{\Psi(2S)}$ and widths

$X \to J/\psi\varphi$ states

[PRL 102 (2009) 242002, arXiv: 1101.6058] *CDF*
[PL 734 (2014) 261] *CMS*
[PR D89 (2014) 012004, PRL115 (2015) 232001] *D0*

- *X(4140)* - narrow near threshold structure in $B^+ \to (J/\psi\ \varphi)\ K^+$ *(CDF, D0, CMS)*
- *X(4274)* - second relatively narrow *$(J/\psi\ \varphi)$* state *(CDF, CMS)*



Non-confirmation from other experiments *(B-factories)*

$X \to J/\psi\varphi$ states

LHCb: Full amplitude fit to $B^+ \to J/\psi\ \varphi\ K^+$

[PRL 118 (2017) 02203]
[PR D95 (2017) 012002]

- Run 1, 3fb^{-1} *(4289 ± 151 candidates with minor background)*
- 6D phase space: $m(\varphi K)$, helicity angles and $\Delta\varphi$ angles
- includes interferences between $B \to J/\psi K^*$, $K^* \to \varphi K$ and $B \to X^0 K$, $X^0 \to J/\psi\varphi$

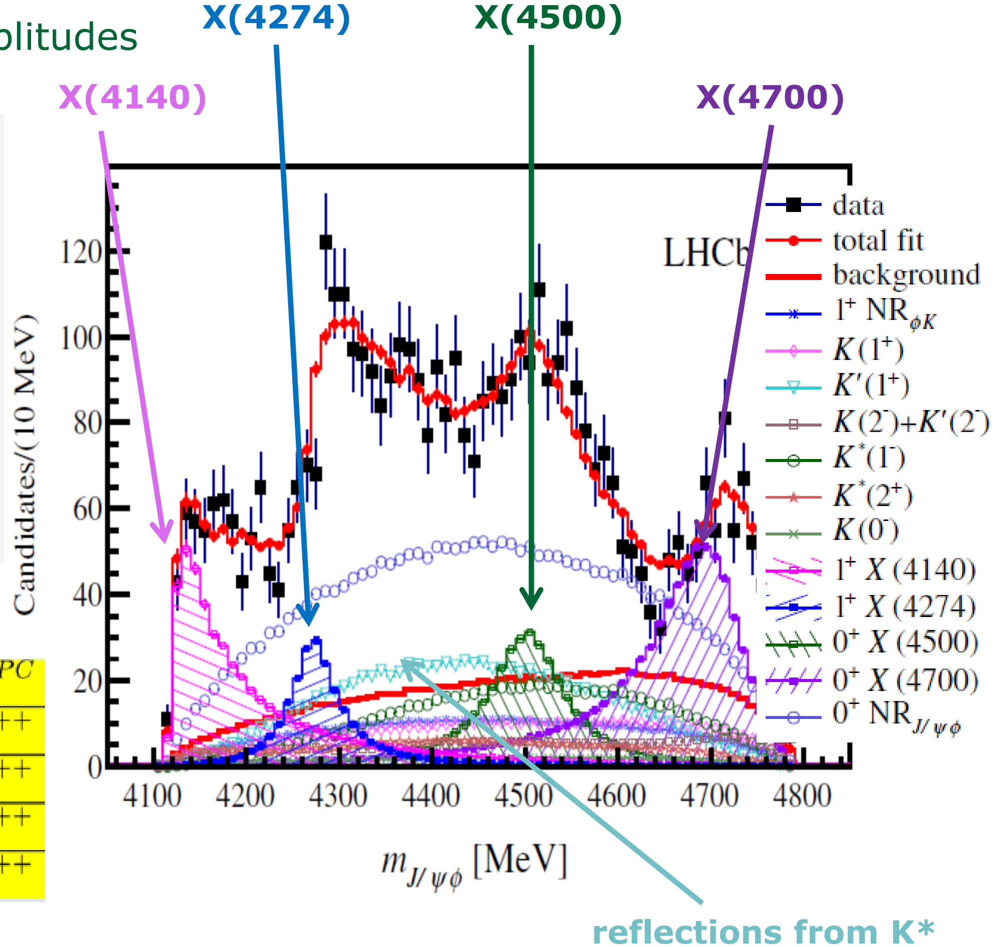
4 structures visible: fit with BW amplitudes

- model with $K^*(\to K\varphi)$ cannot describe data
- *X(4140)* width significantly larger than previously determined *(av. 15.7± 6.3 MeV)*
- *X(4140), X(4274)*: J^{PC} incompatible with cusps and molecular bound states

→ possible interpretation as tetraquark $c\bar{c}s\bar{s}$ *(no light valence quarks)* or χ_{c1}

- *X(4500), X(4700)*: D^{*+}_s-D^{*-}_s or $\chi_{c1}(4P)$, $\chi_{c1}(5P)$

State	Sign. [σ]	Mass [MeV]	Width [MeV]	J^{PC}
$X(4140)$	8.4	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
$X(4274)$	6.0	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++}
$X(4500)$	6.1	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
$X(4700)$	5.6	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

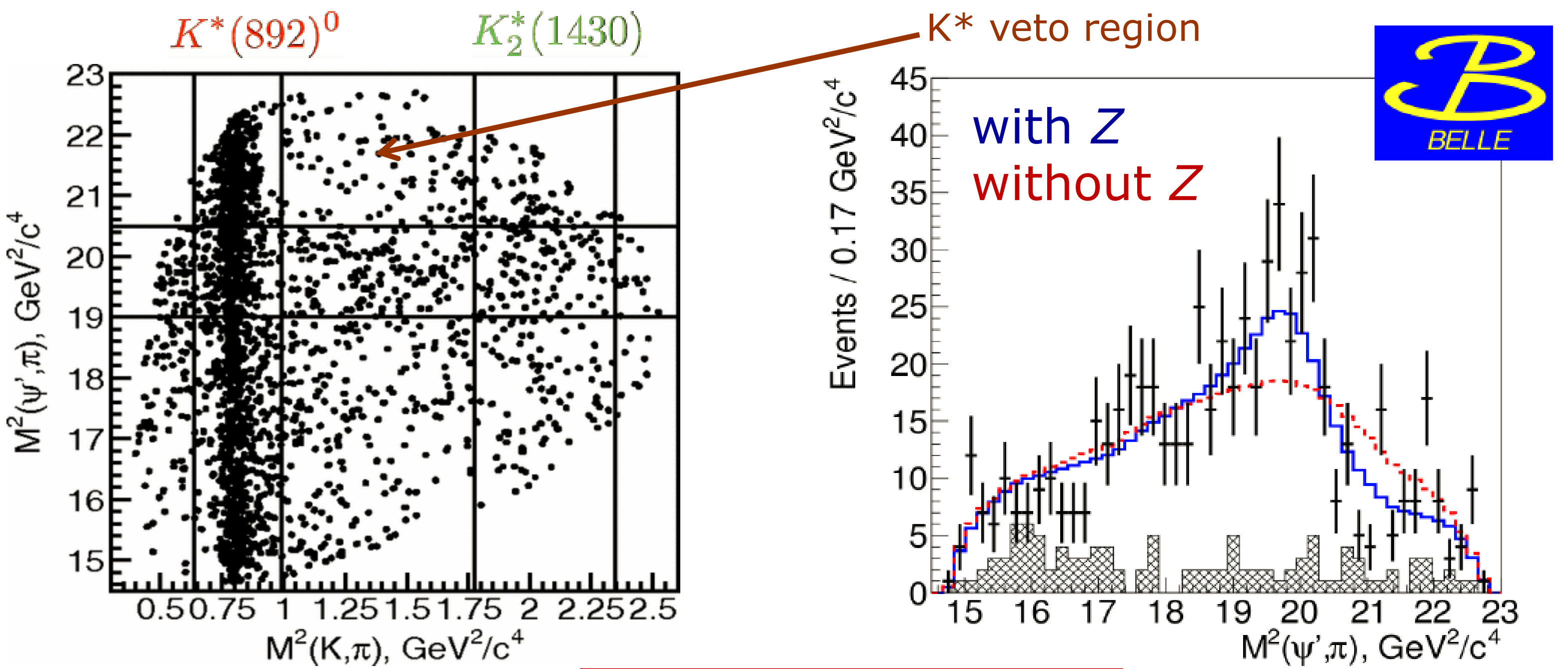


Z(4430)

[PRD 88 (2013) 074026]

Charged charmonium-like state in $B^0 \to \psi(2S)\pi K$

- originally found by Belle in $B \to (Z \to J/\psi\pi^-) K$ and $B \to (Z \to \psi(2S)\pi^-) K$
  [PRL 100(2008) 142001, PR D80(2009) 031104, PR D88(2013) 074026]
- not confirmed by BaBar [PR D79 (2009) 112001]



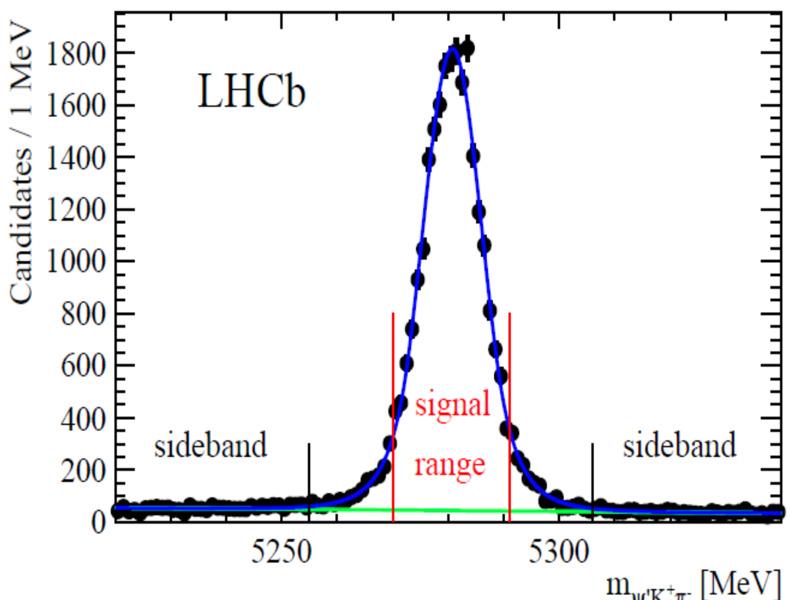
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}/c^2$$

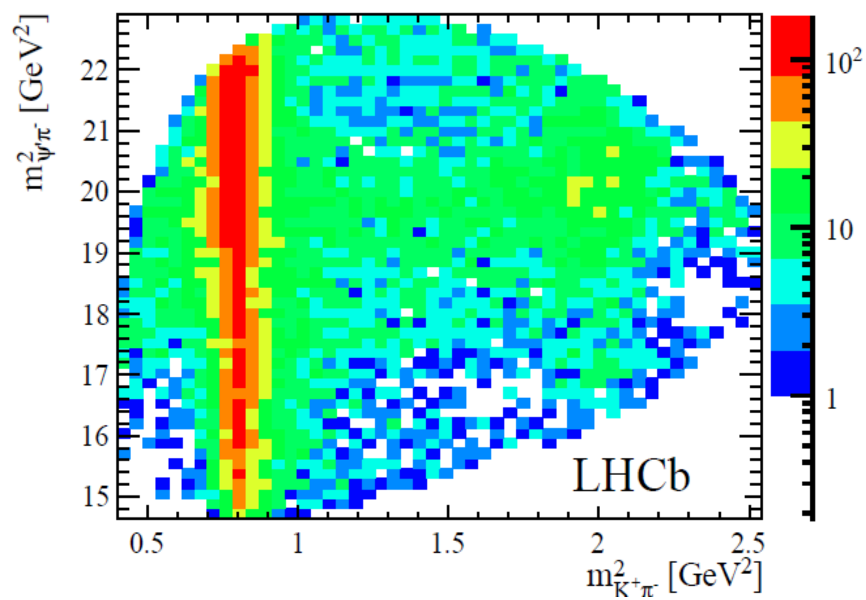
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}/c^2$$

Z(4430): *LHCb confirmation*

LHCb full amplitude analysis using 3 fb^{-1} [PRL 112 (2014) 222002]

- ~25K $B^0 \to K^+\psi(2S)\pi^-$ candidates (x10 Belle/BaBar)
- two different analysis approaches
  - → 4D amplitude analysis *(invariant masses, helicity and decay planes angles)* to measure resonance parameters and J^P
  - → model independent analysis based on the Legendre polynomial moments extracted from the *Kπ* system *(similar to what was done for pentaquark)*

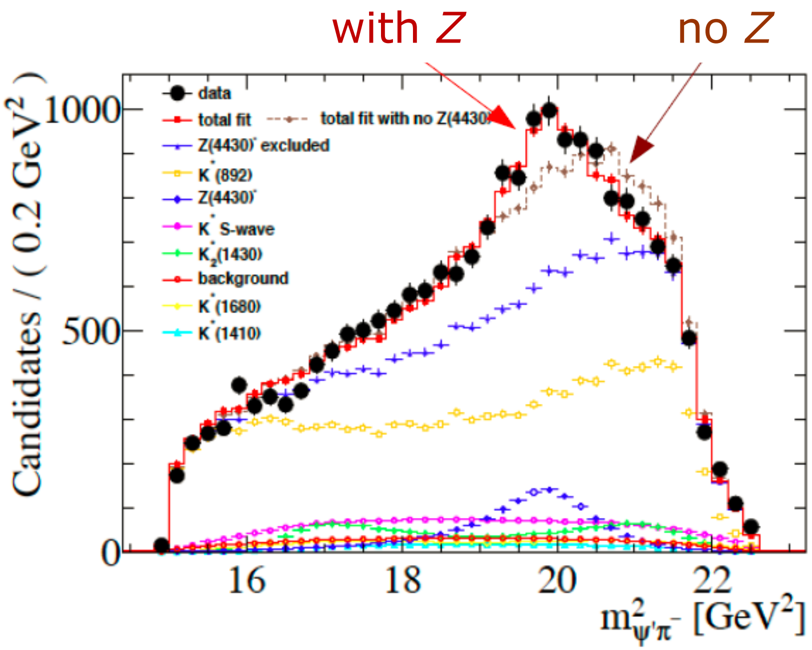


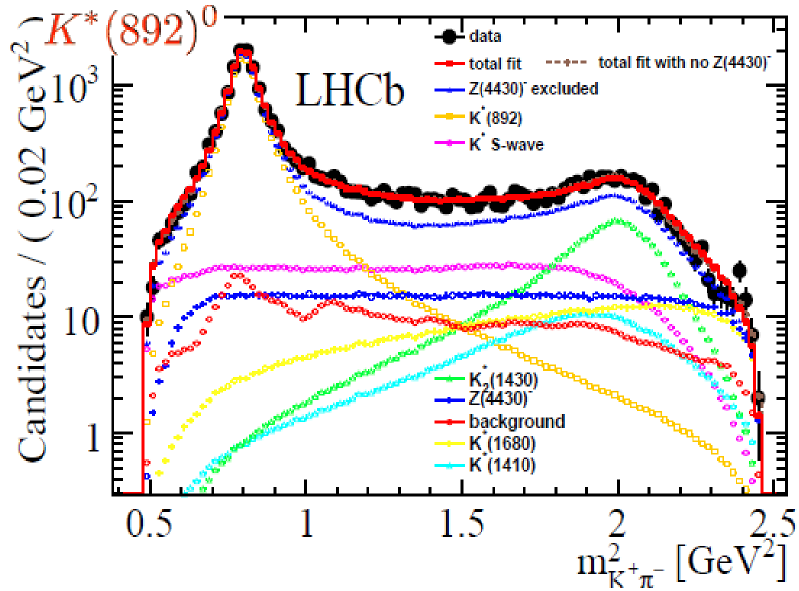


Background from sidebands (4% of combinatorial background in the signal region)

Z(4430): *amplitude fit*

[PRL 112 (2014) 222002]





4D amplitude analysis fit

- $J^P = 1^+$ confirmed
- others assignment excluded with large significance
- mass close to $D^*D_1(2420)$ threshold
- excellent agreement between LHCb & Belle

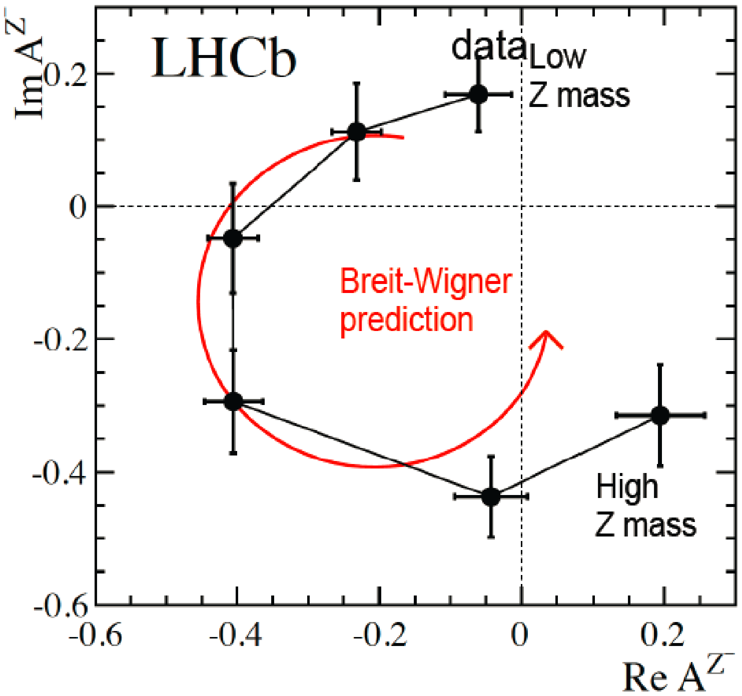
	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+

Z(4430): *resonant nature*

[PRL 112 (2014) 222002]

Argand plot shows a clear resonant behaviour

- additional fit: *Z amplitude with complex parameters in 6 $m_{\psi'\pi^-}$ bins*
- phase rotation as expected for Breit-Wigner resonance



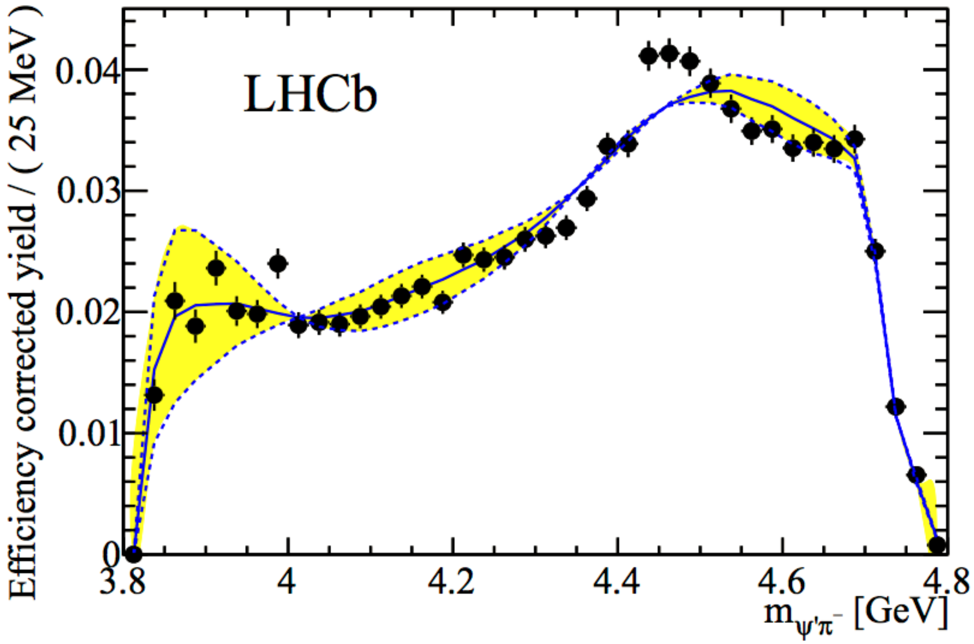
Results confirm *Z(4430)* with $J^P=1^+$ and its resonant behaviour

Z(4430): *model independent*

[PRD 92 (2015) 112009]

Can the *Z(4430)* be explained by K^* reflections?

- sideband subtract and efficiency correct $B^0 \to K^+\psi(2S)\pi^-$ sample
- no assumptions on the K^* resonances: *only its maximum J is limited*
- angular structure of the $K\pi$ system extracted with Legendre polynomial moments



K^* reflections cannot describe properly the Z(4430) region

Among all tetraquark candidates the *Z(4430)*$^-$ is special
→ *being charged it cannot be a $c\bar{c}$ state*

X(5568)?

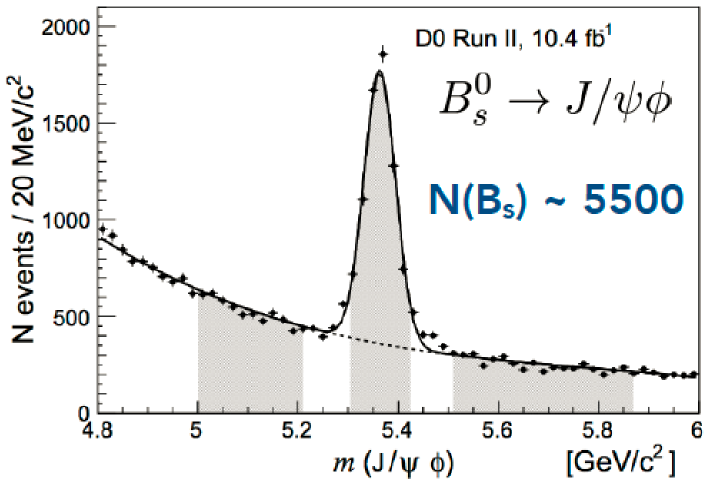
[PRL 117 (2016) 022003]

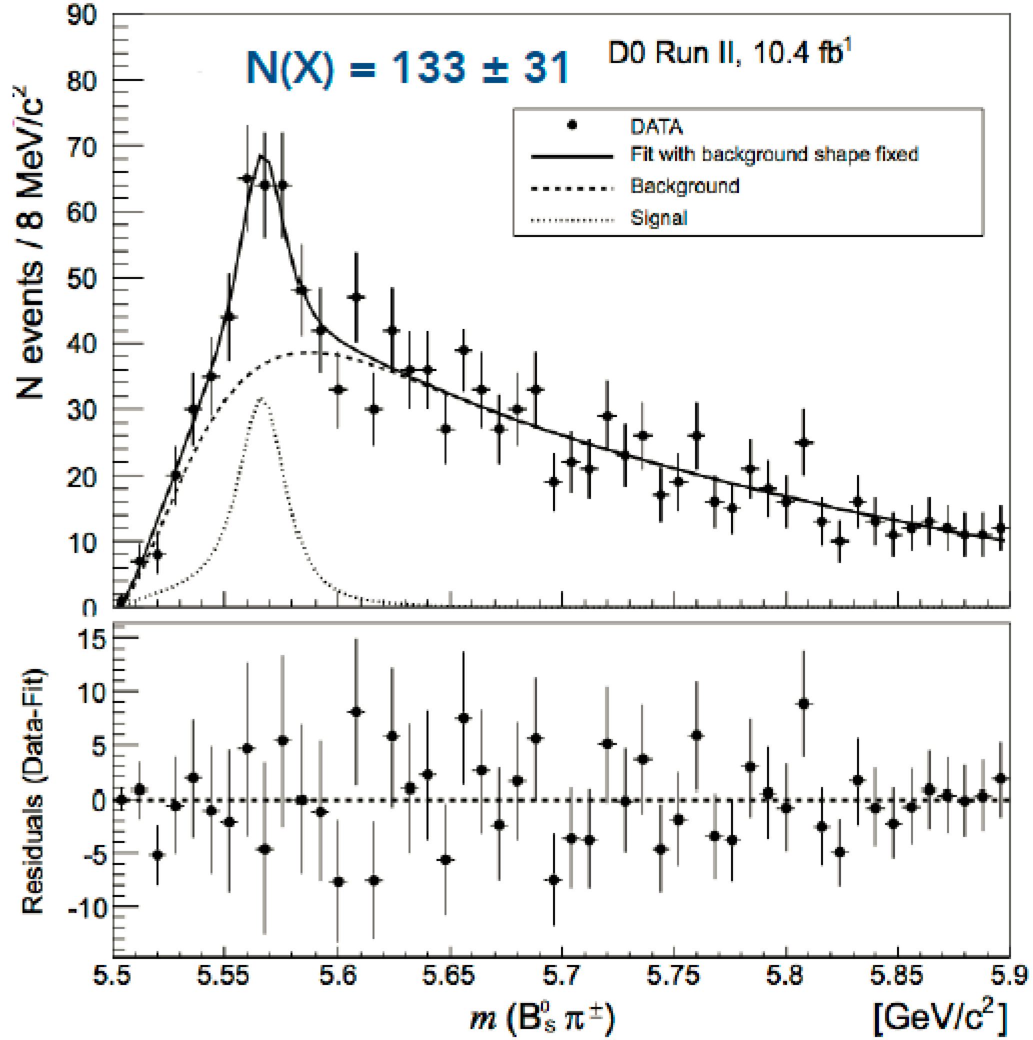
X(5568)$^{\pm} \to B^0_s\ \pi^{\pm}$ decay reported by D0 with significance of 3.9σ

[Phys. Rev. Lett. 117 (2016) 022003]

- large B_s production rate:
  $\rho^{D0}_X = (8.6 \pm 1.9 \pm 1.4)\%$
- minimal quark content $\bar{b}su\bar{d}$

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9} \mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5} \mathrm{MeV}/c^2$$





X(5568): *CDF and D0 again*

Not seen by CDF

(27 Dec 2017)

[Phys. Rev. Lett. 120 (2018) 202006]

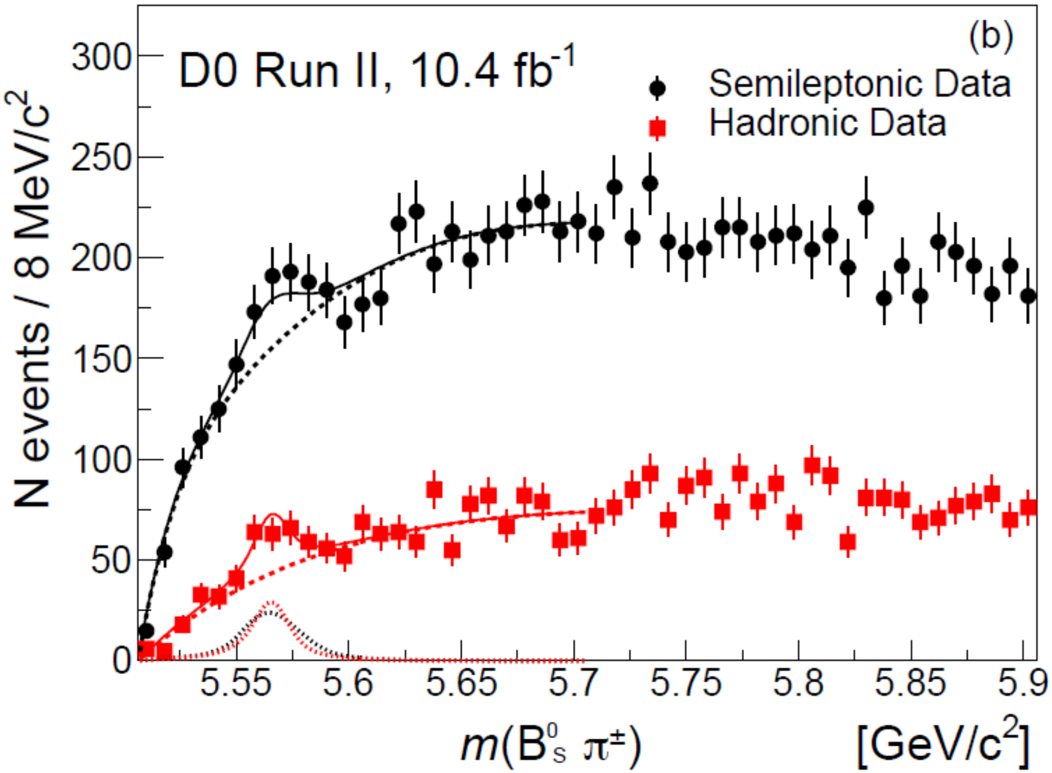
Seen again by D0

(29 Dec 2017)

[Phys. Rev. D97 (2018) 092004]

$$X^{\pm}(5568) \rightarrow B_s^0\pi^{\pm}$$

$$B_s^0 \rightarrow \mu^{\mp} D_s^{\pm}\,\mathrm{X}, \quad D_s^{\pm} \rightarrow \phi\pi^{\pm}$$



$$m = 5566.9^{+3.2}_{-3.1}\,(\mathrm{stat})^{+0.6}_{-1.2}\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

$$\Gamma = 18.6^{+7.9}_{-6.1}\,(\mathrm{stat})^{+3.5}_{-3.8}\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

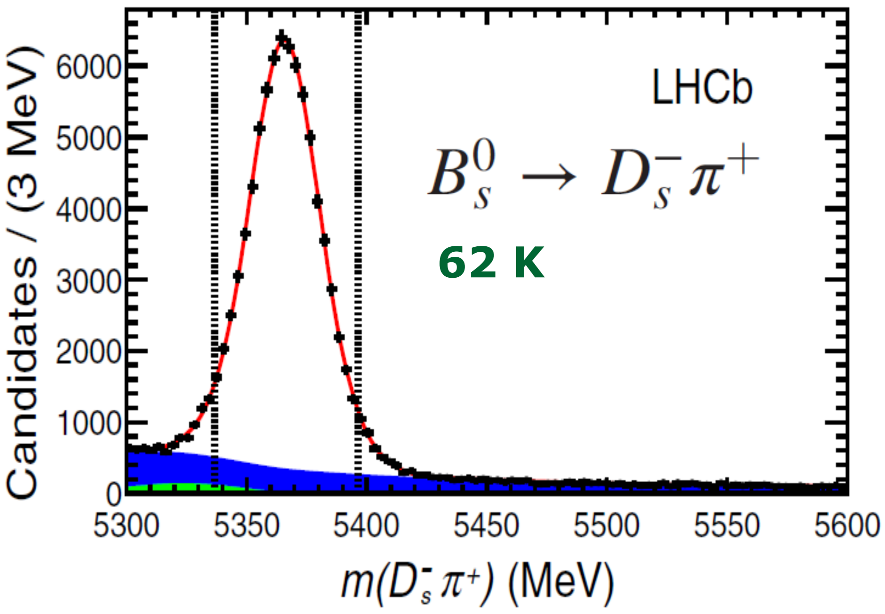
6.7σ

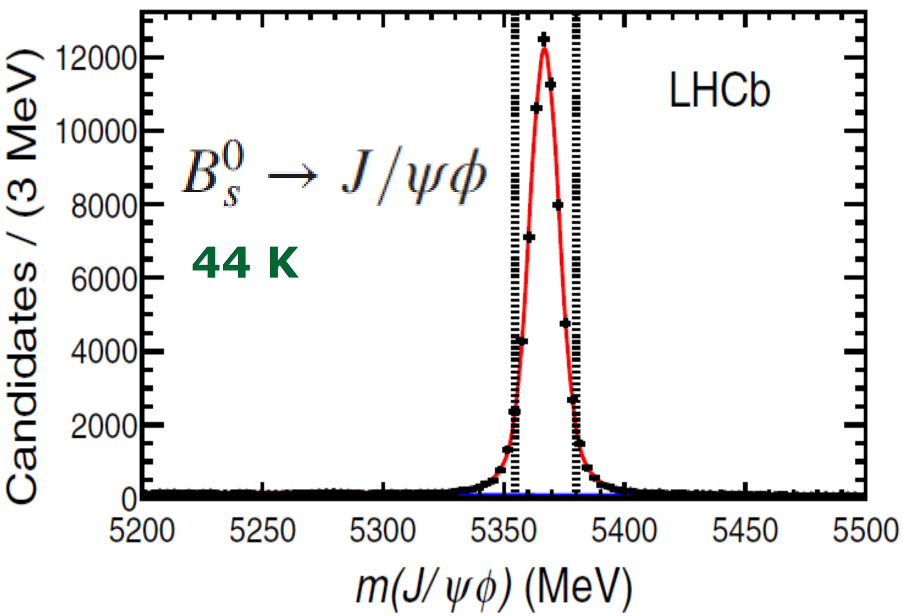
LHCb data sample of B^0_s

[PRL 117 (2016) 152003]

Very large and clean B^0_s sample at LHCb (3 fb^{-1})

- 20x the D0 sample
- cut-based selection to clean B^0_s sample
- mass constraints on J/ψ and D_s to improve mass resolution





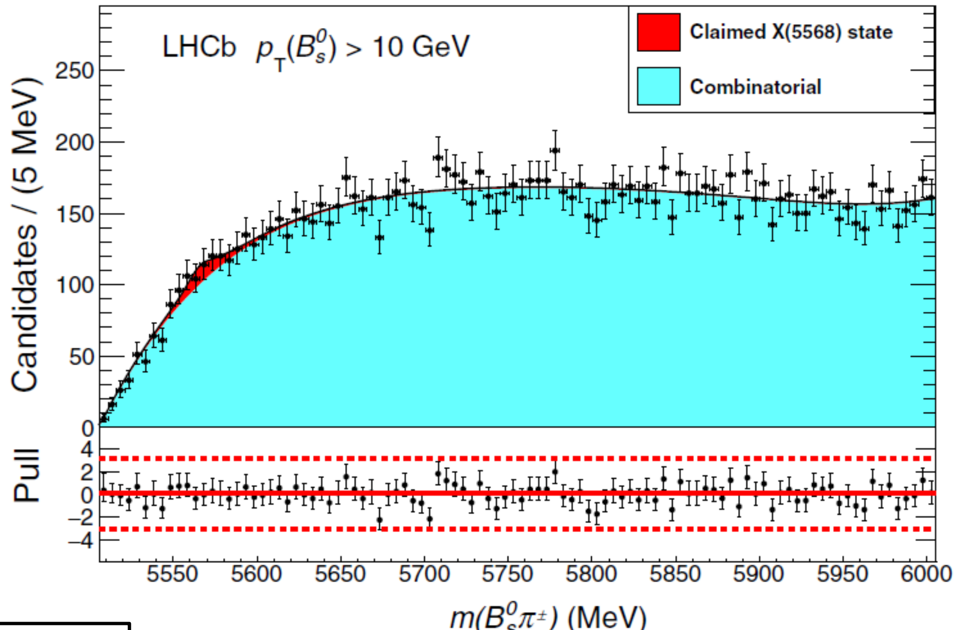
$B_s \pi$ mass spectrum

[PRL 117 (2016) 152003]

- B_s and π required to come from same PV
- signal shape is S-wave Breit-Wigner with parameters from D0
- polynomial for background

LHCb sees nothing!

$\rightarrow$ upper limit by integrating likelihood in physical *(non-negative ρ)* region



$\rho_X < 2\%$ (95% CL)

- similar result from CMS: CMS-PAS-BPH-16-002 (2016)

Search for tetraquarks in $\Upsilon(1S)\mu^+\mu^-$ NEW!

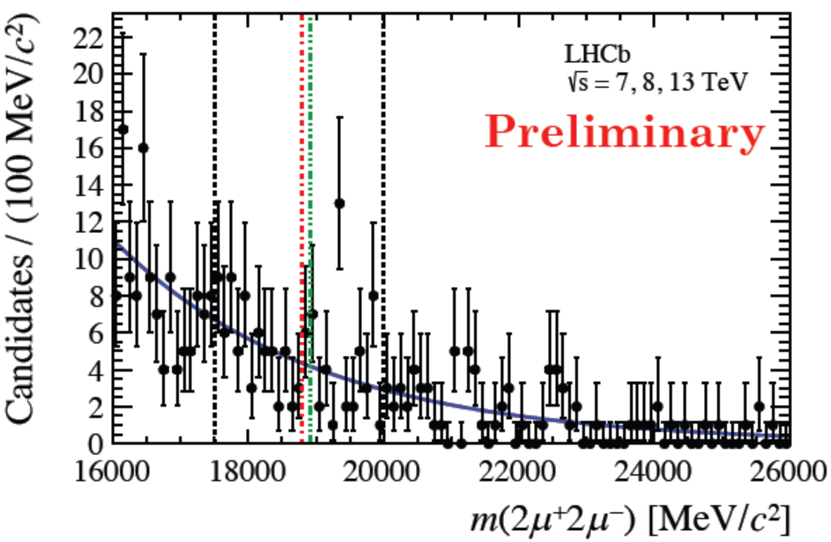
- predictions on exotic state $b\bar{b}b\bar{b}$ with mass < 2 × m(η_b) threshold
  - → $X_{b\bar{b}b\bar{b}}$ may decay into $\Upsilon(1S)\ \mu^+\mu^-$
  - → 4 muons in the final state
  - → high sensitivity at LHCb!

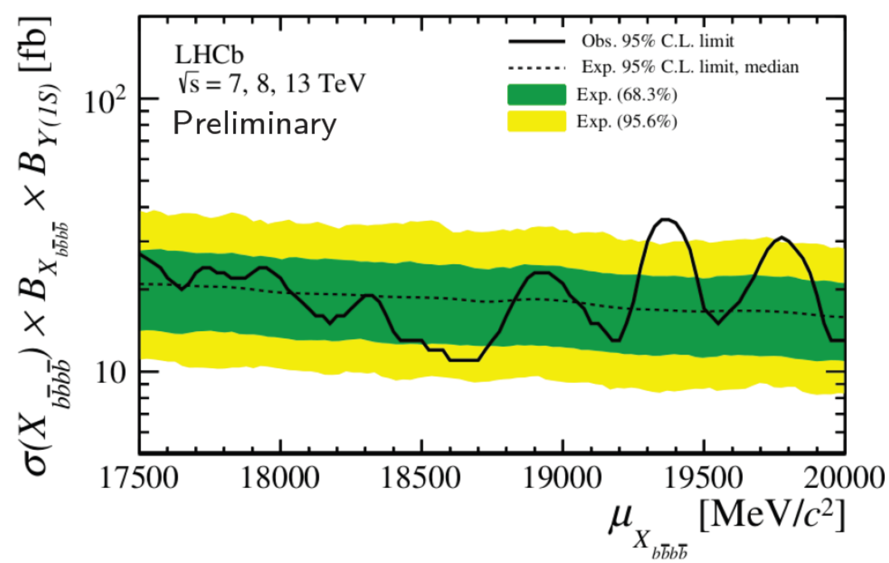
[LHCb-PAPER-2018-027]

- lattice QCD calculations do not find evidence in hadronic spectrum
  [PRD 97 (2018) 054505]
- first LHCb result with 2017 data

LHCb uses a dataset of 6.3 fb^{-1} *(2011-2017)*

m(4μ) resolution ~65 MeV





No significant enhancement at any mass hypothesis in (17.5-20) GeV region

Conclusions

- LHCb has made great progress in exotic spectroscopy
- Many new states discovered since the first observation of the *X(3872)*
- 1^{++} confirmed for *X(3872)*
- Other exotic containing *cc* (or *bb*) quarks

  → *Z(4430)* in $B^0 \rightarrow \Psi(2S)\, K^- \pi^+$ is now well established tetraquark

  → recent LHCb results on 4 new $J/\psi\varphi$ states
- Amplitude analysis crucial to interpret data

  → *establish quantum numbers*

  → *exclude some production mechanisms, e.g. threshold, rescattering,…*
- D0 claims a $\bar{b}su\bar{d}$ state, but we do not!
- Data sample will be tripled in RUN II
- Other tetraquark candidates *(no amplitude analysis so far)*

  → *Y(3940), Y(4260), Y(4350), Y(4660),… (Belle, BaBar, BES)*

Backup

Search for tetraquarks in $\Upsilon(1S)\mu^+\mu^-$

[LHCb-PAPER-2018-027]