Pentaquark and tetraquark states at LHCb

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On behalf of the LHCb Collaboration

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  - Search for pentaquark states in $\Lambda_b^0 \to J/\psi p \pi^-$
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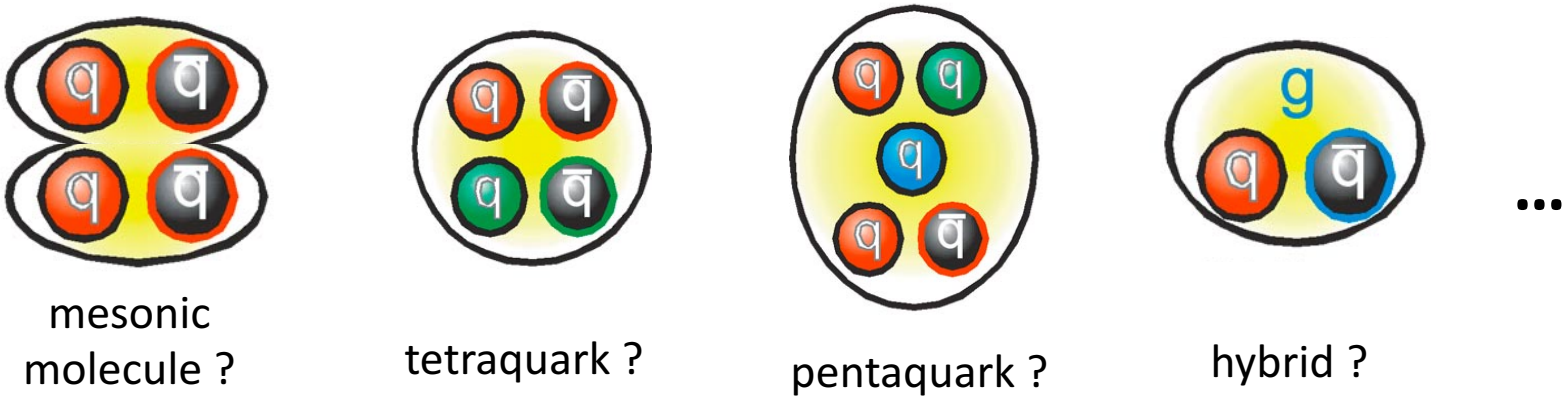
- Summary

Introduction

- Exotic states are important for understanding strong force in QCD
  - Prediced in quark model
  - Recent experimental results show strong evidence for their existence

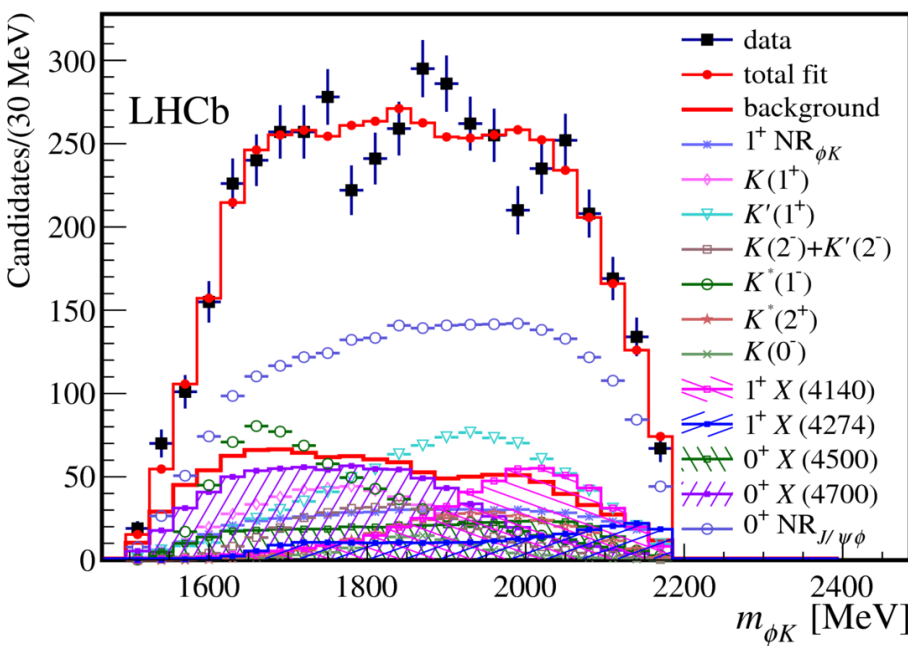


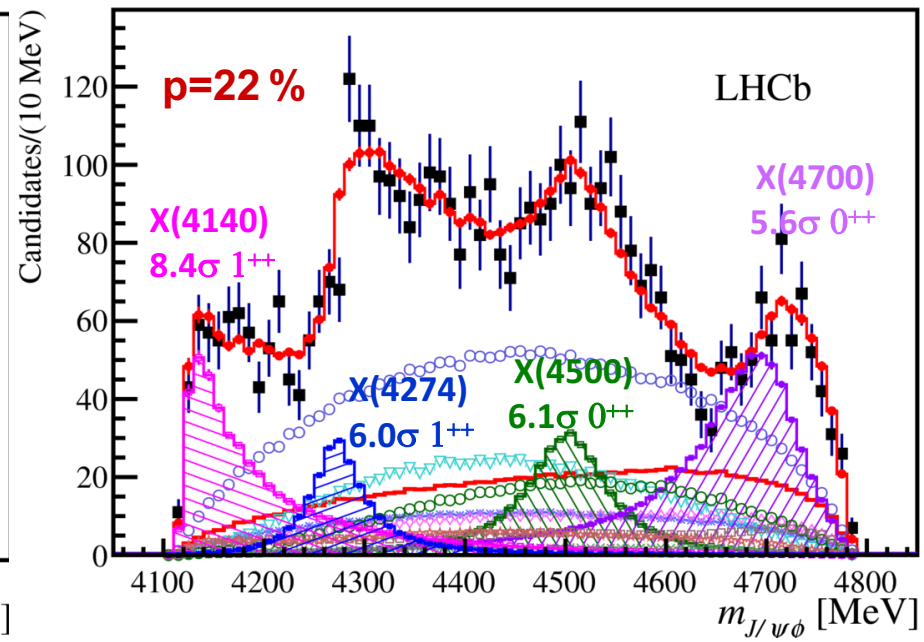
Tetraquark candidates

4 $X \to J/\psi\phi$ states in $B^+ \to J/\psi\phi K^+$

- $X(4140)$ first observed by CDF; evidence for $X(4274)$
- 1st full amplitude w/ world largest sample of 4300 signals at LHCb
- Good fit with **4 X** states + 7 $K^{*+} \to \phi K^+$ + NR's

PRL 118, 022003 (2017)





Results

PRL 118, 022003 (2017)

- J^{PC} are useful for interpretations of the states
- $X(4140)$ & $X(4274)$: identified as $J^{PC} = 1^{++}$ at $> 5\sigma$
- $X(4500)$ & $X(4700)$: $J^{PC} = 0^{++}$ at $> 4\sigma$

Contri-bution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				$16\pm3\ ^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
Average other experiments		4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-3.6}$	$56\pm11\ ^{+8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[28]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm5\pm7$
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm5\ ^{+9}_{-5}$

substantially larger

A new $B_s^0\pi^\pm$ state claimed by DØ

[DØ: arXiv:1602.07588, PRL 117, 022003 (2016)]

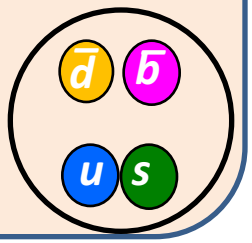
Claimed evidence of an exotic state

- $X(5568)^\pm \to B_s^0\pi^\pm,\ B_s^0 \to J/\psi\phi,\ J/\psi \to \mu^+\mu^-,\ \phi \to K^+K^-$

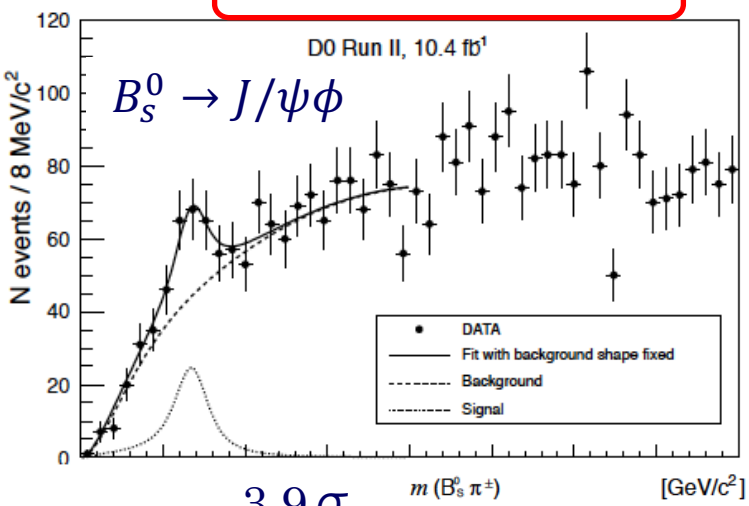
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV}$$

$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV}$$

- Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\emptyset} = (8.6 \pm 1.9 \pm 1.4)\ \%$
- **If confirmed, would be unique with 4 different flavours**



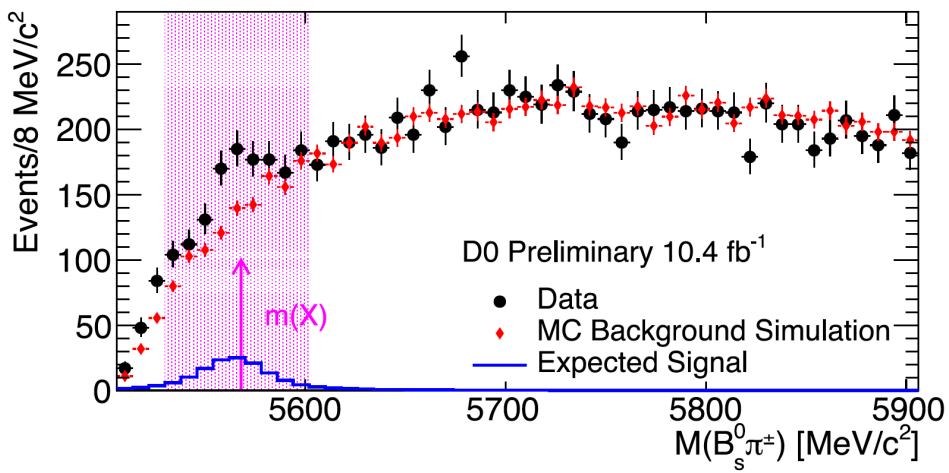
$N(X) = 106 \pm 23$



$3.9\,\sigma$

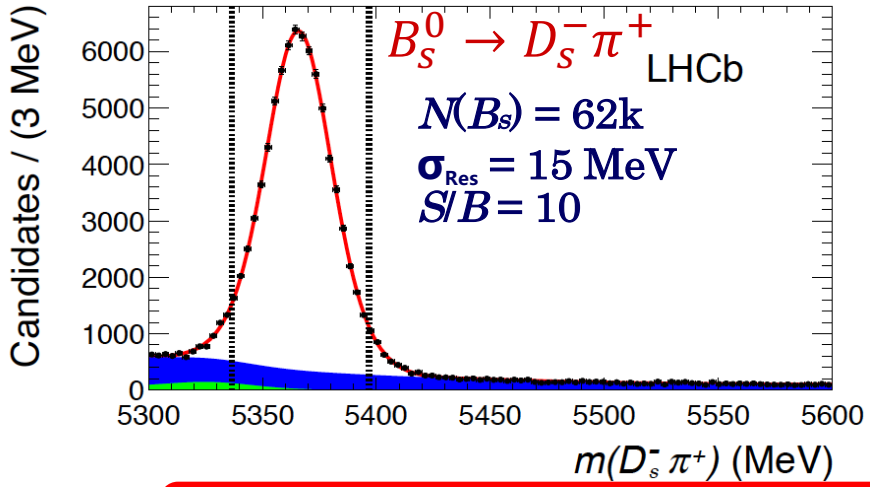
Signal significance

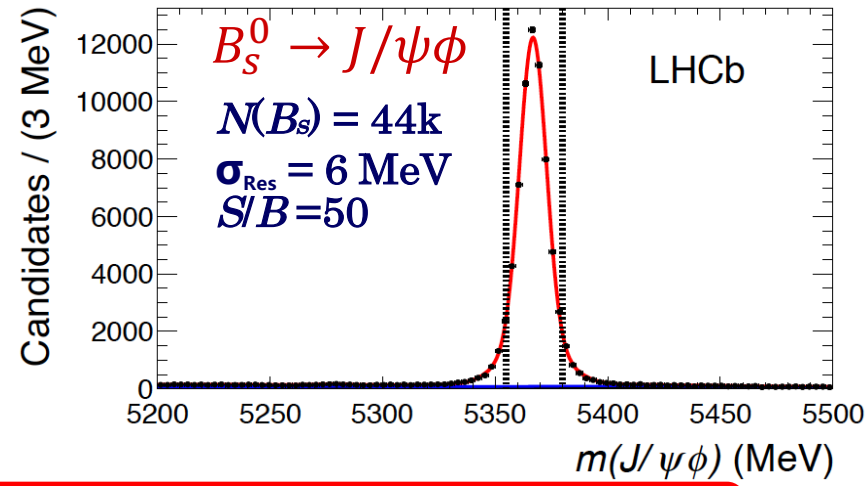
$B_s^0 \to D_s^-\mu^+\nu$



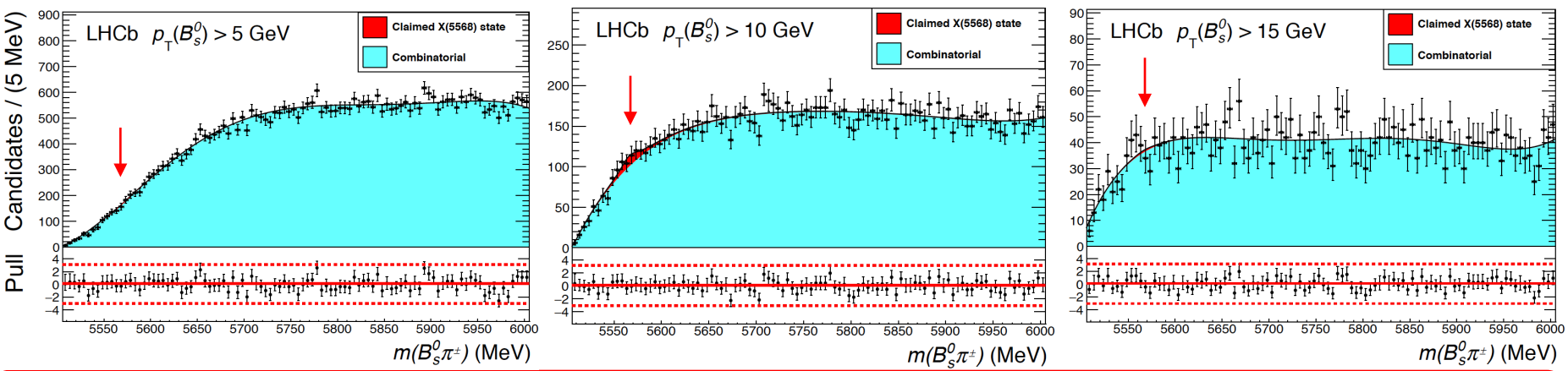
Samples from LHCb

PRL 117, 152003 (2016)





B_s^0 sample 20x larger and much cleaner than DØ



No evident $X(5568)$ in $B_s^0\pi^\pm$ sample for 3 different $p_T(B_s^0)$ cuts

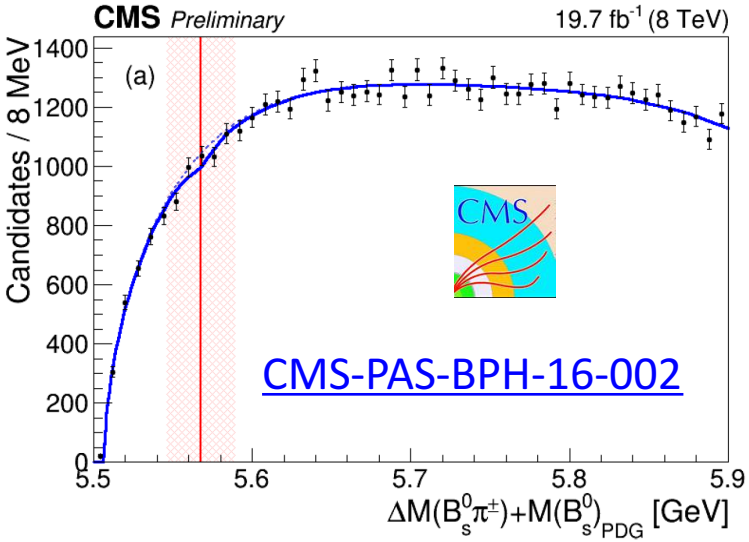
Upper limits

PRL 117, 152003 (2016)

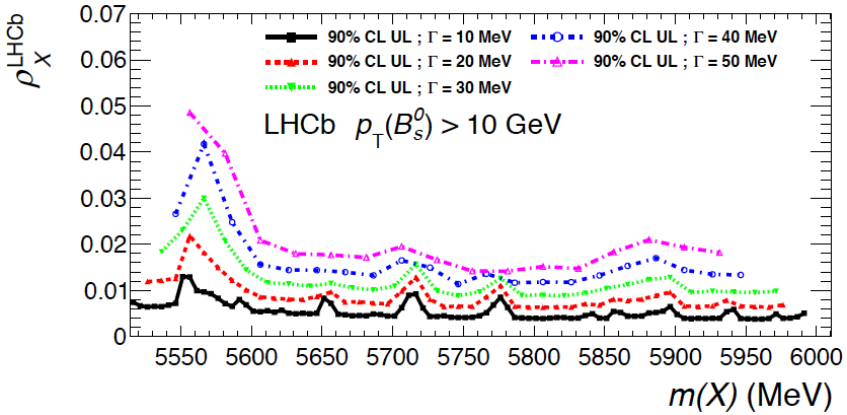
$$\rho_X^{\mathrm{LHCb}} = \frac{\sigma(pp \to X + \text{anything};\ X \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

in LHCb acceptance

ρ_X < 2.1% (LHCb) @90% $C.L.$ for $p_T(B_s^0) > 10$ GeV

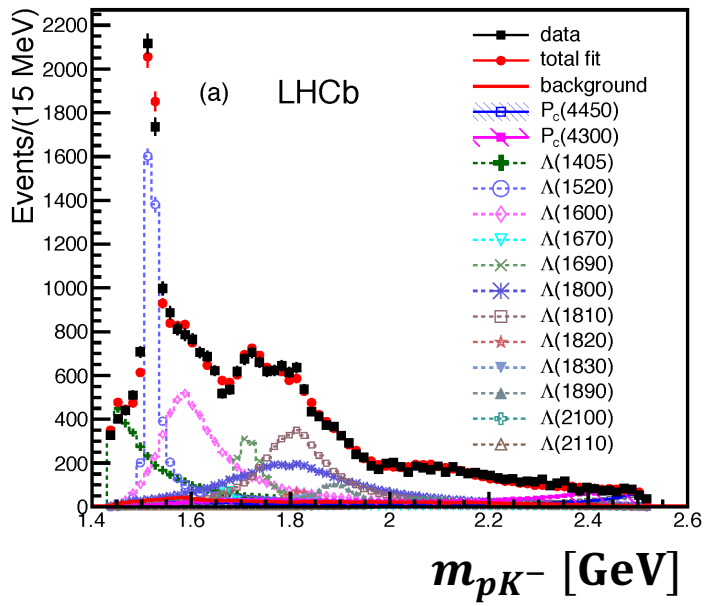


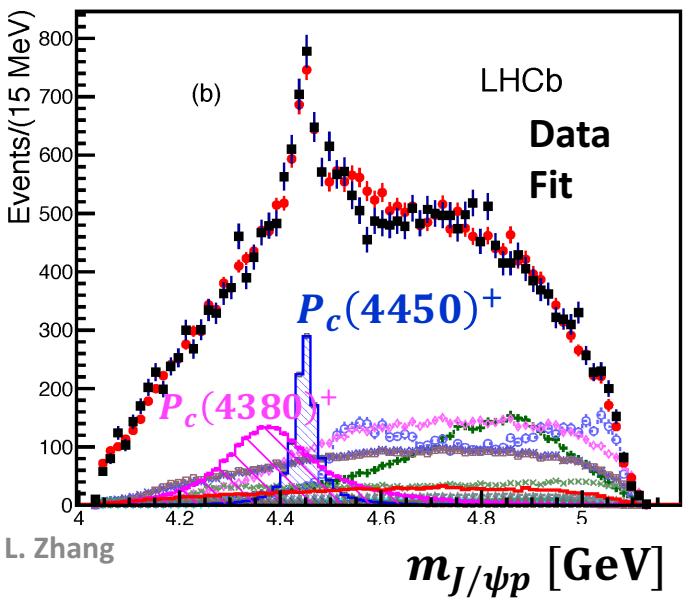
- No significant $B_s^0\pi^\pm$ states for any mass and width below 6 GeV



Pentaquark candidates

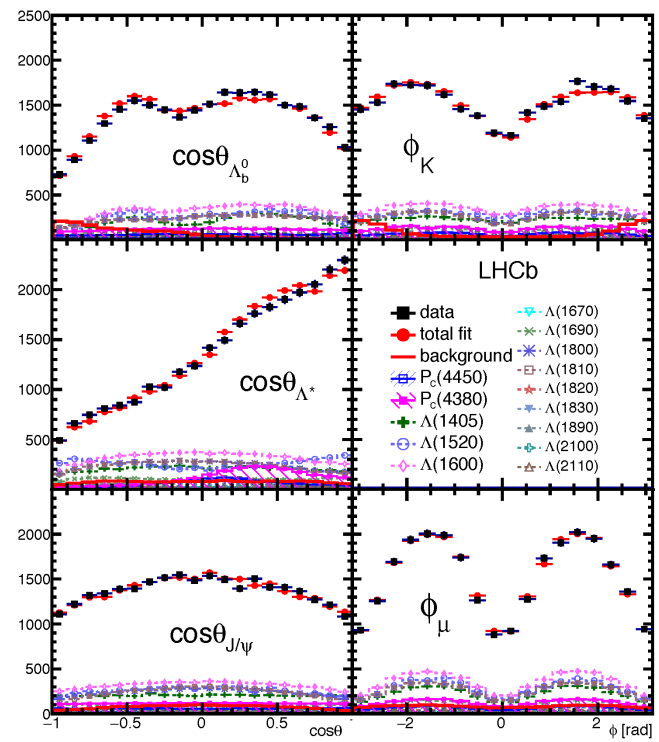
Observation of pentaquark states





- Observed two exotic states in $\Lambda_b^0 \to J/\psi p K^-$, consistent with charmonium pentaquarks $(uudc\bar{c})$
- Good fit in all dimensions

PRL 115, 072001 (2015)



Observation of pentaquark states

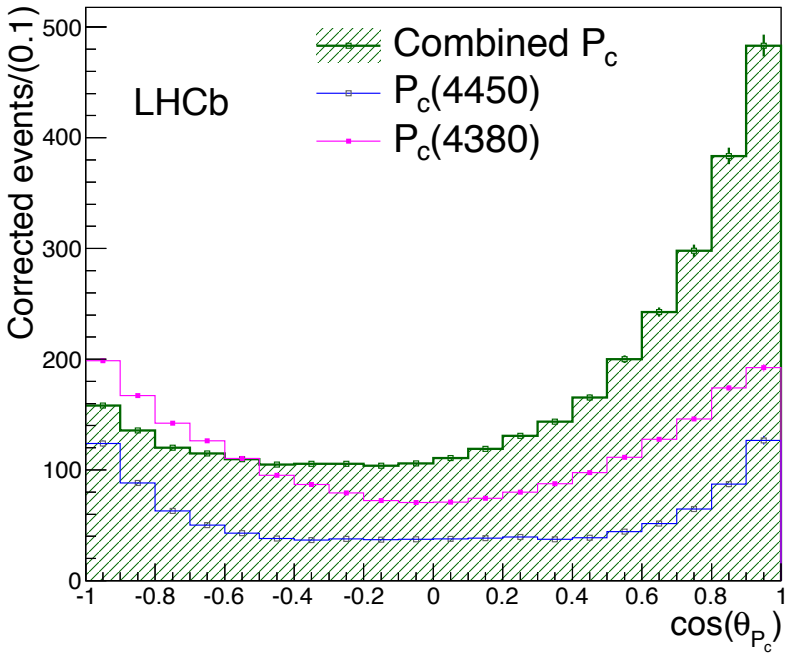
	$P_c(4380)^{\pm}$	$P_c(4450)^{\pm}$
Significance	9σ	12σ
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit fraction(%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-;$ $P_c^+ \to J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$

PRL 115, 072001 (2015)

$\mathcal{B}$ measurements reported in Chinese Physics C, 40, 011001 (2016)

J^P determination

- J^P are important for their interpretations
  - $(3/2^-, 5/2^+)$ is the best fit
  - $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are also possible
- Information from the angular distribution of P_c^+



arXiv:1509.04051

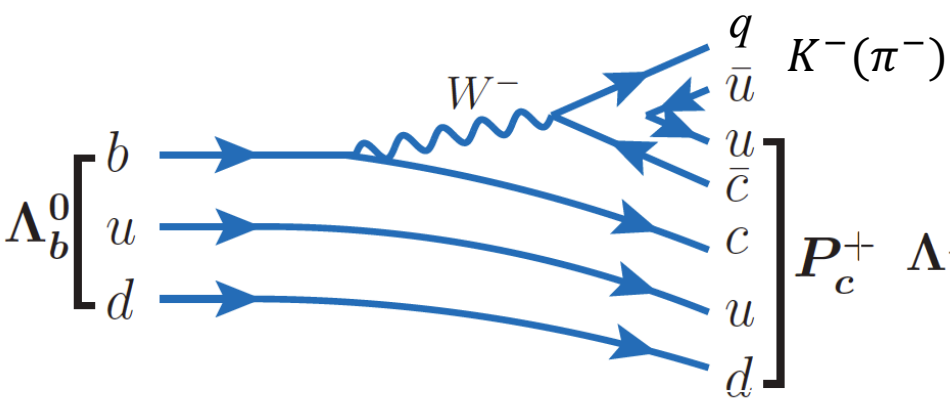
- Ongoing Run-II analysis, aim to identify J^P with improved Λ^* modellings **[PRD 93, 034029 (2016)]**

The discovery opened a gate to study pentaquarks

Cabibbo-suppressed decays

- Find the same P_c^+ in other channels is helpful to understand the production mechanism and internal structure
- $\Lambda_b^0 \to J/\psi p \pi^-$ is Cabibbo-suppressed w.r.t. $J/\psi p K^-$
- Two production mechanisms predicted:

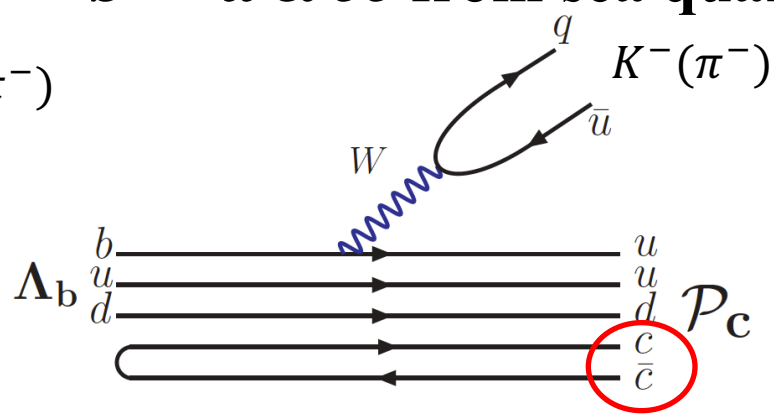
$b \to c$



$$R_{\pi/K} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} = 0.07 \sim 0.08$$

[Cheng, Phys. Rev. D 92, 096009 (2015)]

$b \to u$ & $c\bar{c}$ from sea quarks

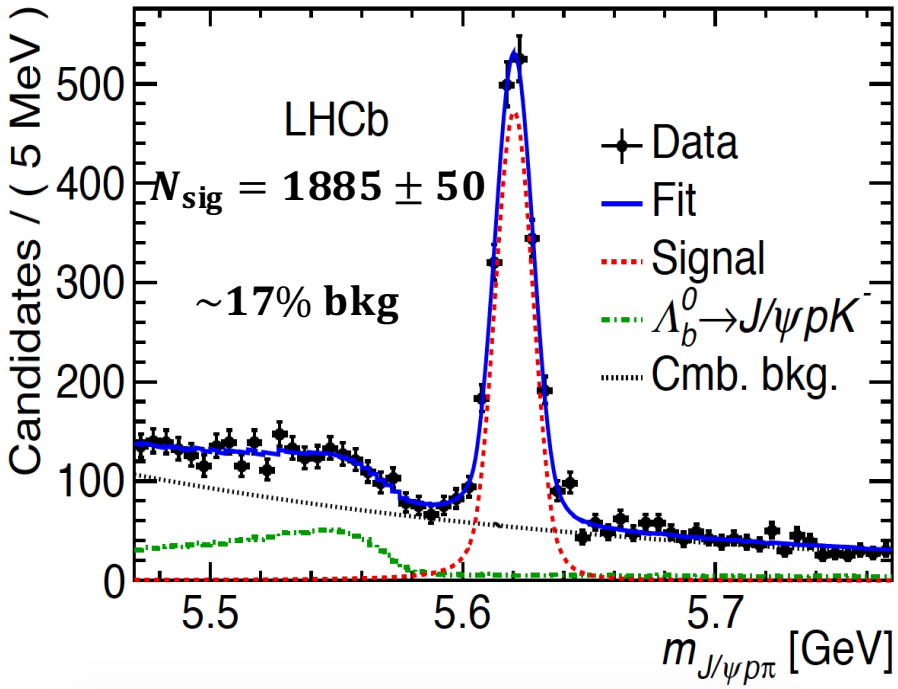


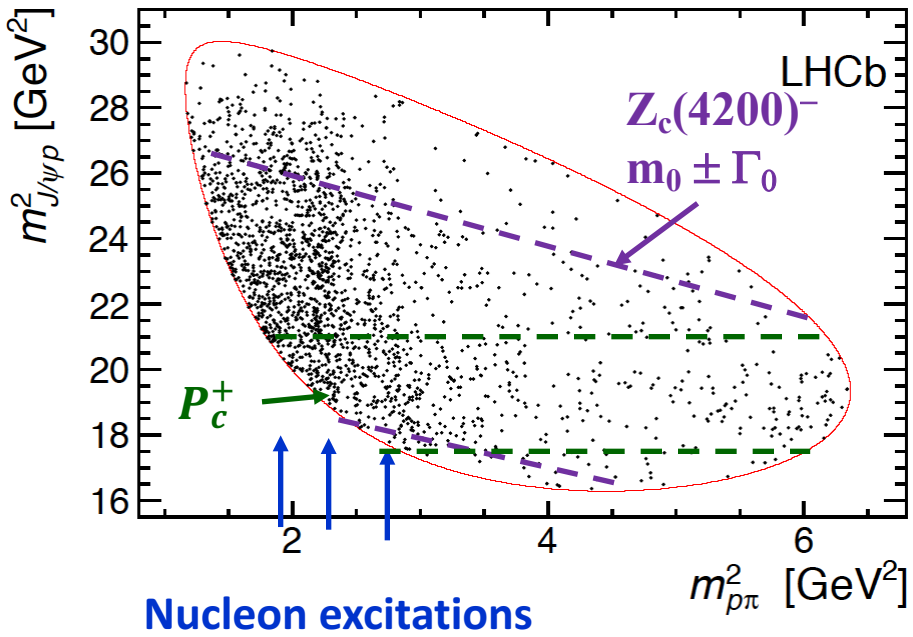
$$R_{\pi/K} = 0.58 \pm 0.05$$

[Hsiao, Phys. Lett. B 751, 572 (2015)]

$\Lambda_b^0 \to J/\psi p \pi^-$ decays

PRL 117, 082003 (2016)



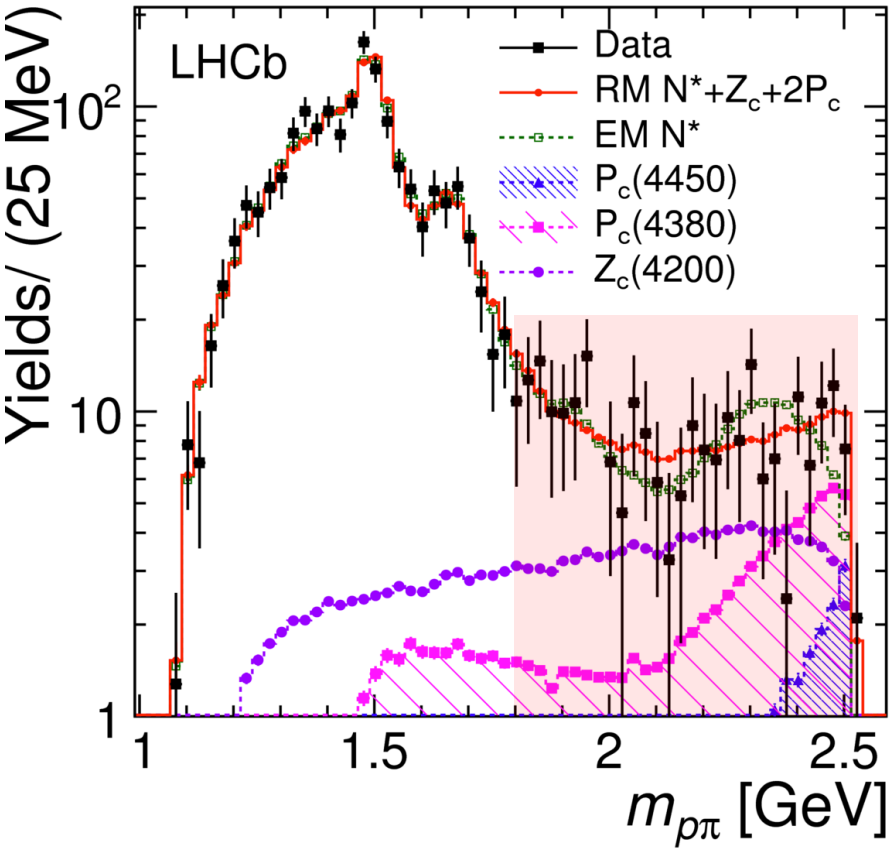


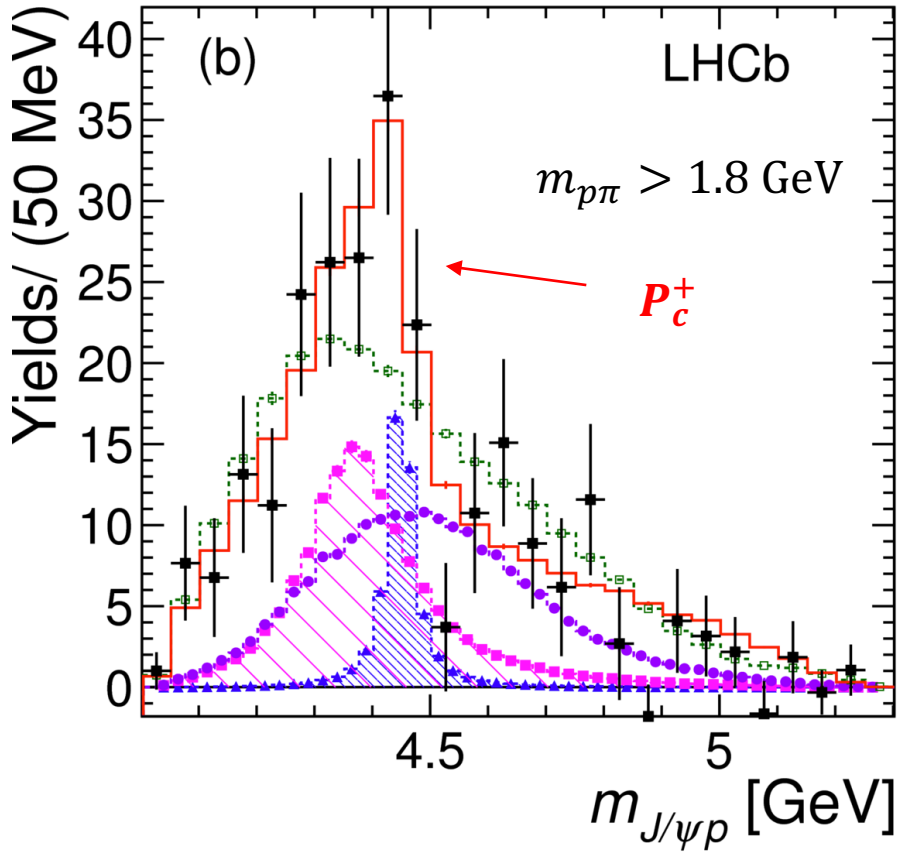
- >10 lower signal in $\Lambda_b^0 \to J/\psi p \pi^-$ than in $\Lambda_b^0 \to J/\psi p K^-$
- But more complex because of possible $Z_c^- \to J/\psi \pi^-$

Full amplitude fits to $\Lambda_b^0 \to J/\psi p \pi^-$

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ take together is 3.1 σ including syst.
- First evidence!

PRL 117, 082003 (2016)



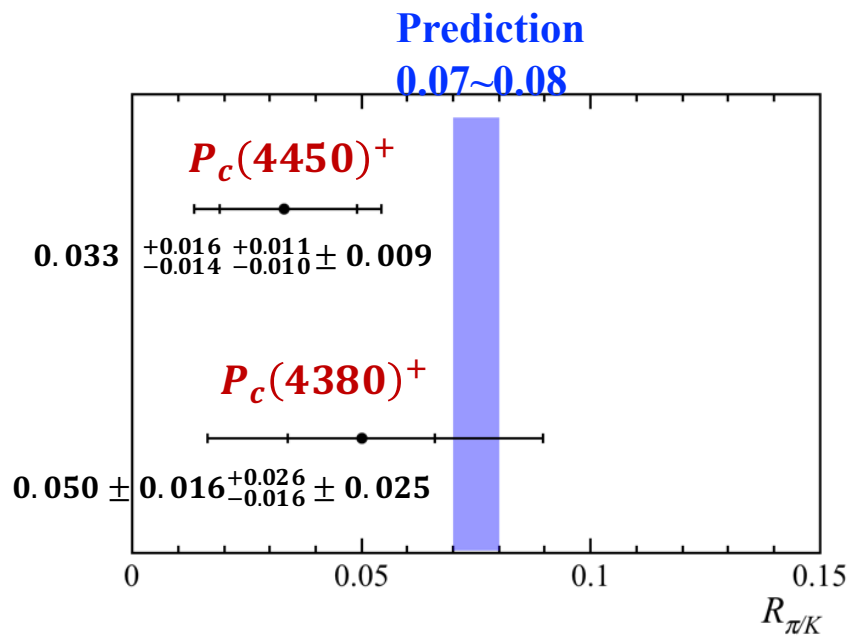


Further results for $\Lambda_b^0 \to J/\psi p \pi^-$

- Significance of two P_c is 3.3σ, if assuming production of $Z_c(4200)^-$ is negligible. **More data statistics are needed!**
- **Overall, P_c^+ productions are consistent between the two Λ_b^0 decays**

PRL 117, 082003 (2016)

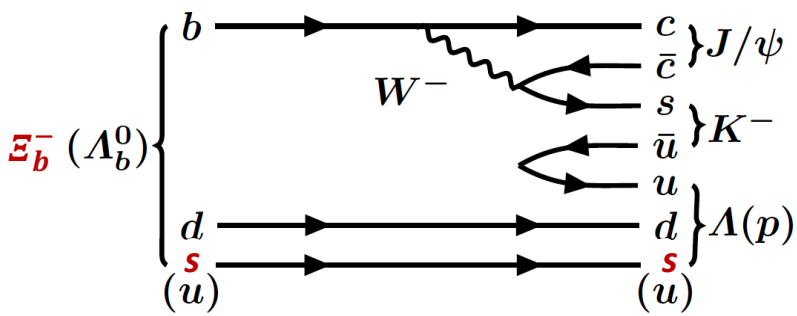
State	Fit fraction (%)
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.6}_{-1.6}$
$P_c(4450)^+$	$1.6\ ^{+0.8}_{-0.6}\ ^{+0.6}_{-0.5}$



✘ Another prediction $R_{\pi/K} = 0.58 \pm 0.05$ is ruled out ($b \to u$ & $c\bar{c}$ from sea quarks)

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

- Strange pentaquark ($udsc\bar{c}$) predicted in [PRL 105, 232001 (2010)]
- Can be searched for in the Ξ_b^- decay [PRC 93, 065203 (2016)]



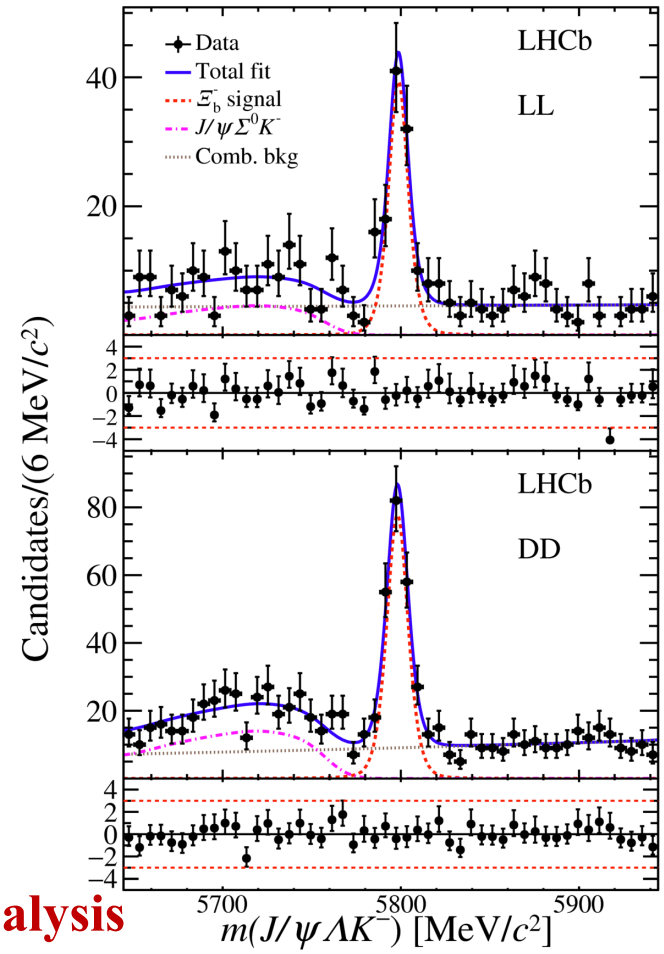
$N_{sig} = 308 \pm 21$ (21σ)

PLB 772 (2017) 265-273

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

$$M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47 \pm 0.16\ \mathrm{MeV}/c^2$$

One of two world best measurements!



Expect ~1500 signals after 2018 for amplitude analysis

Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \boxed{\chi_{c(1,2)} p} K^-$ decays
  ⇒Test hypothesis of kinematic rescattering effect

PRD 92 (2015) 071502

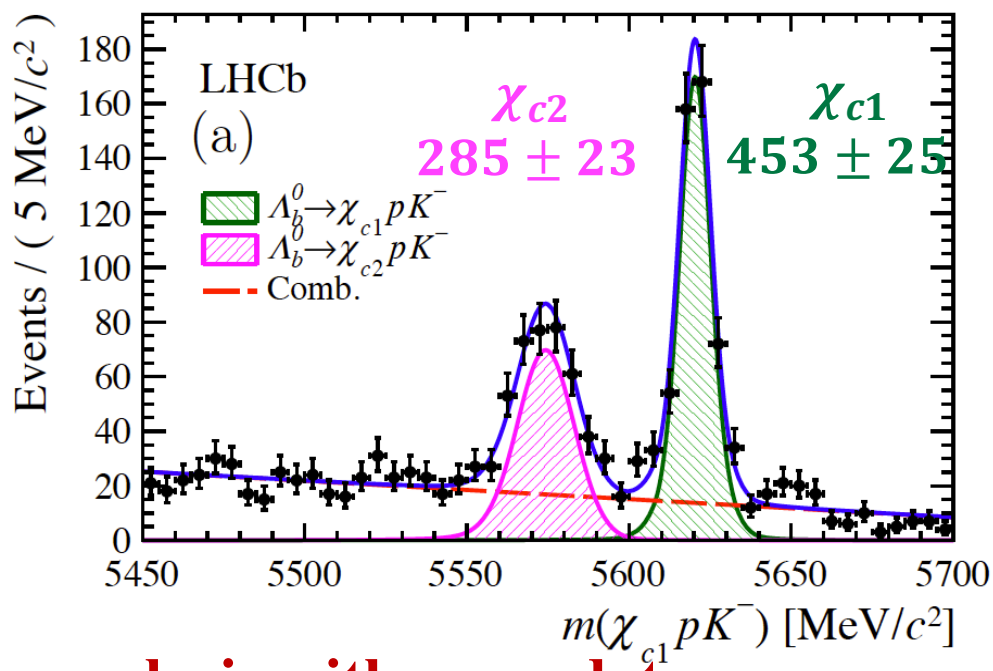
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

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

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

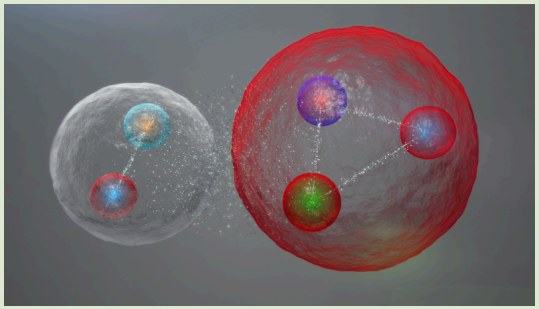
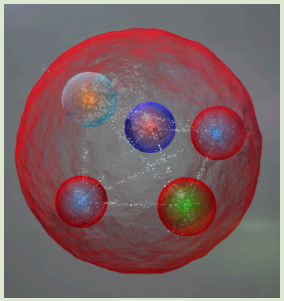
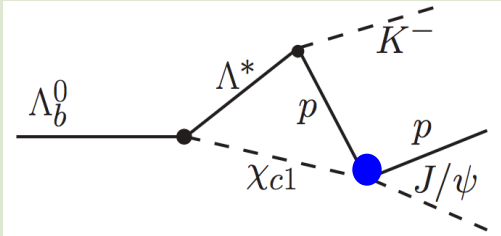
$\mathcal{B}(\chi_{cJ})$

LHCb-PAPER-2017-011



Next step: full amplitude analysis with more data

Interpretations and how to distinguish

Hadronic molecules	Tightly-bounded states	Abnormal kinematic effects
		 $\chi_{c1}p \rightarrow J/\psi p$
Close to two heavy hadron thresholds	Predicted more than 10 J^P states	Predicted no decay of $P_c(4450)^+ \rightarrow \chi_{c1}p$
Karliner&Rosner, PRL 115 (2015) 122001	Maiani et al, PLB 749 (2015) 289	Guo et al, PRD 92 (2015) 071502

Summary

- LHCb is an active laboratory to study many exotic states
- Other than updating these results with Run-II data, many ongoing analyses:
  - Tetraquark search in $B^0 \to J/\psi K^+\pi^-$, aka $Z_c(4200)^-$…
  - Search for P_c^+ in $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$
  - Search for J=1/2 P_c^+ in $\Lambda_b^0 \to \eta_c p K^-$
  - Search for pentaquarks with a single b quark and pentaquarks with a single c quark

Summary

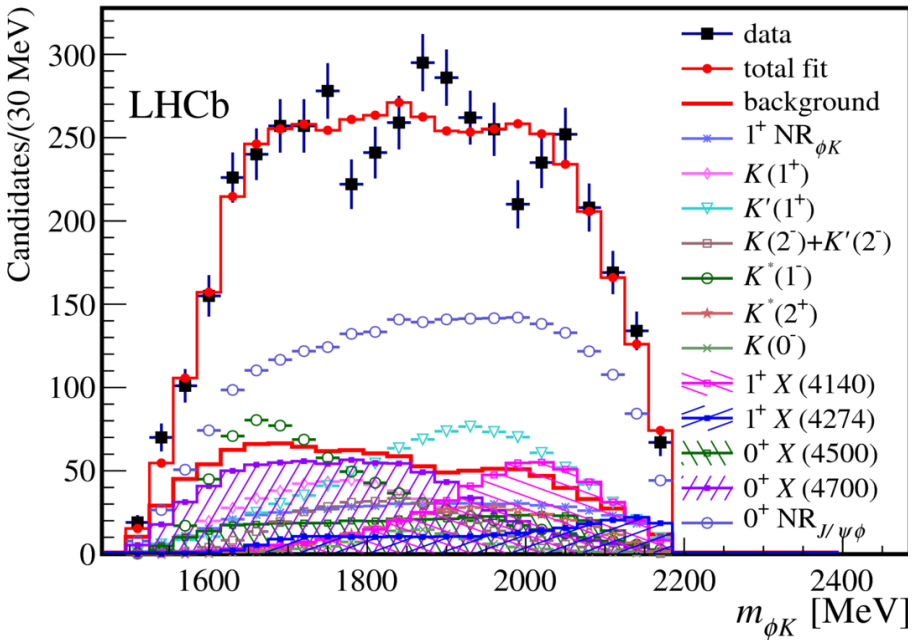
stay tuned!
future epic content
coming soon
Thanks for your attention!

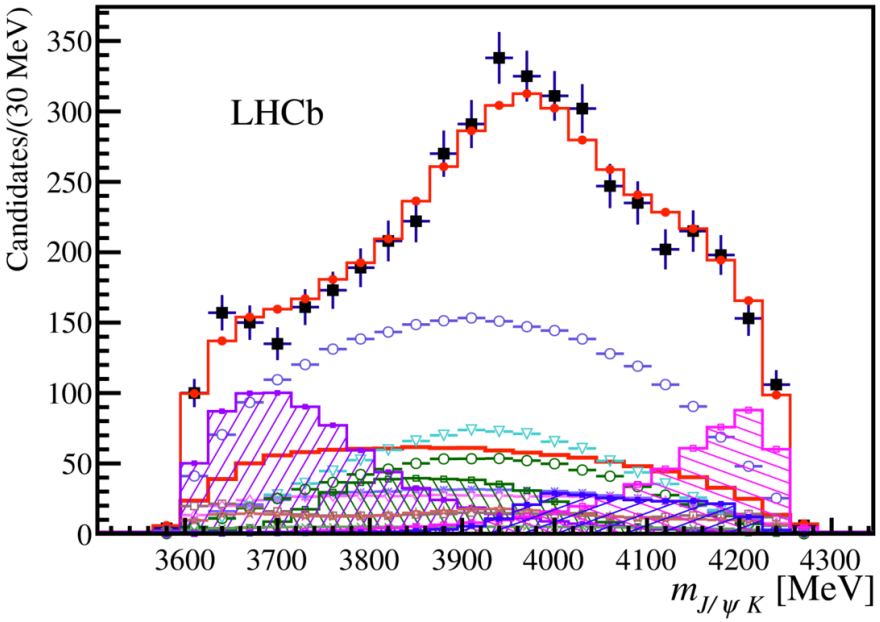
BACKUP

4 $X \to J/\psi\phi$ states in $B^+ \to J/\psi\phi K^+$

- $X(4140)$ first observed by CDF; evidence for $X(4274)$
- 1st full amplitude w/ world largest sample of 4300 signals at LHCb
- No obvious $J/\psi K^+$ strcture

PRL 118, 022003 (2017)

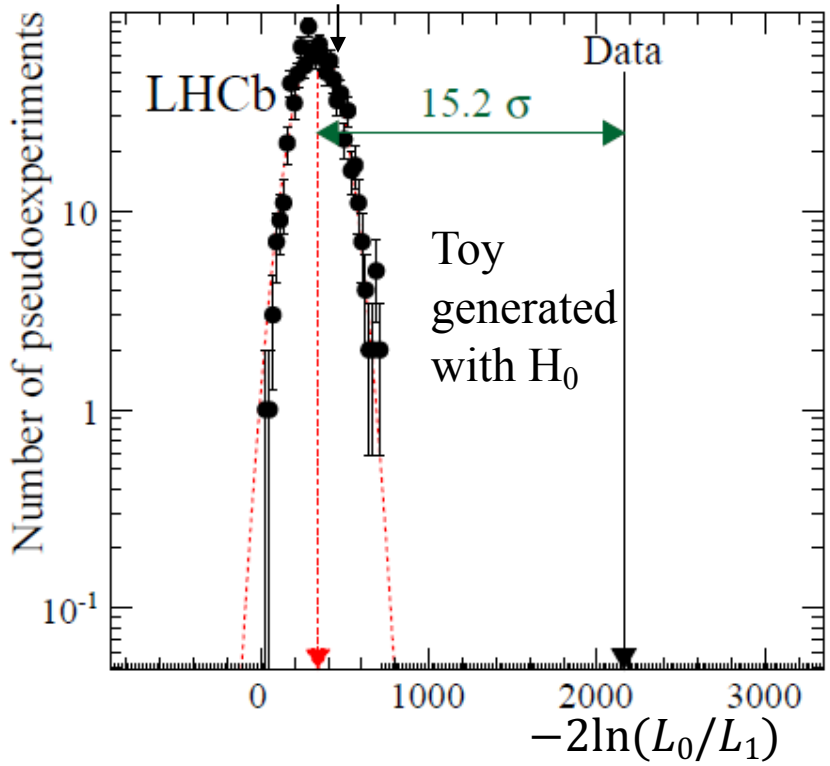




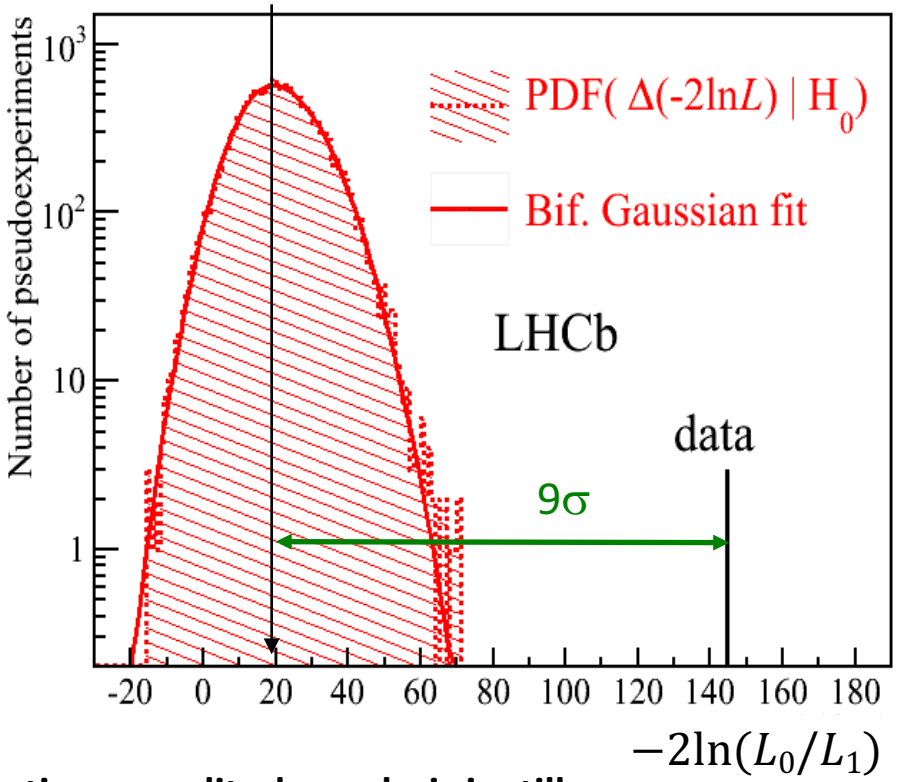
Log-likelihood ratio method

- Likelihood ratio for PDF($m_{\psi'\pi/\psi p}$|H_0) and PDF($m_{\psi'\pi/\psi p}$|H_1)
- H_1 can well present $m_{\psi'\pi/\psi p}$ spectrum in data using l_{max}=30/31

$B^0 \rightarrow \psi'\pi^-K^+$

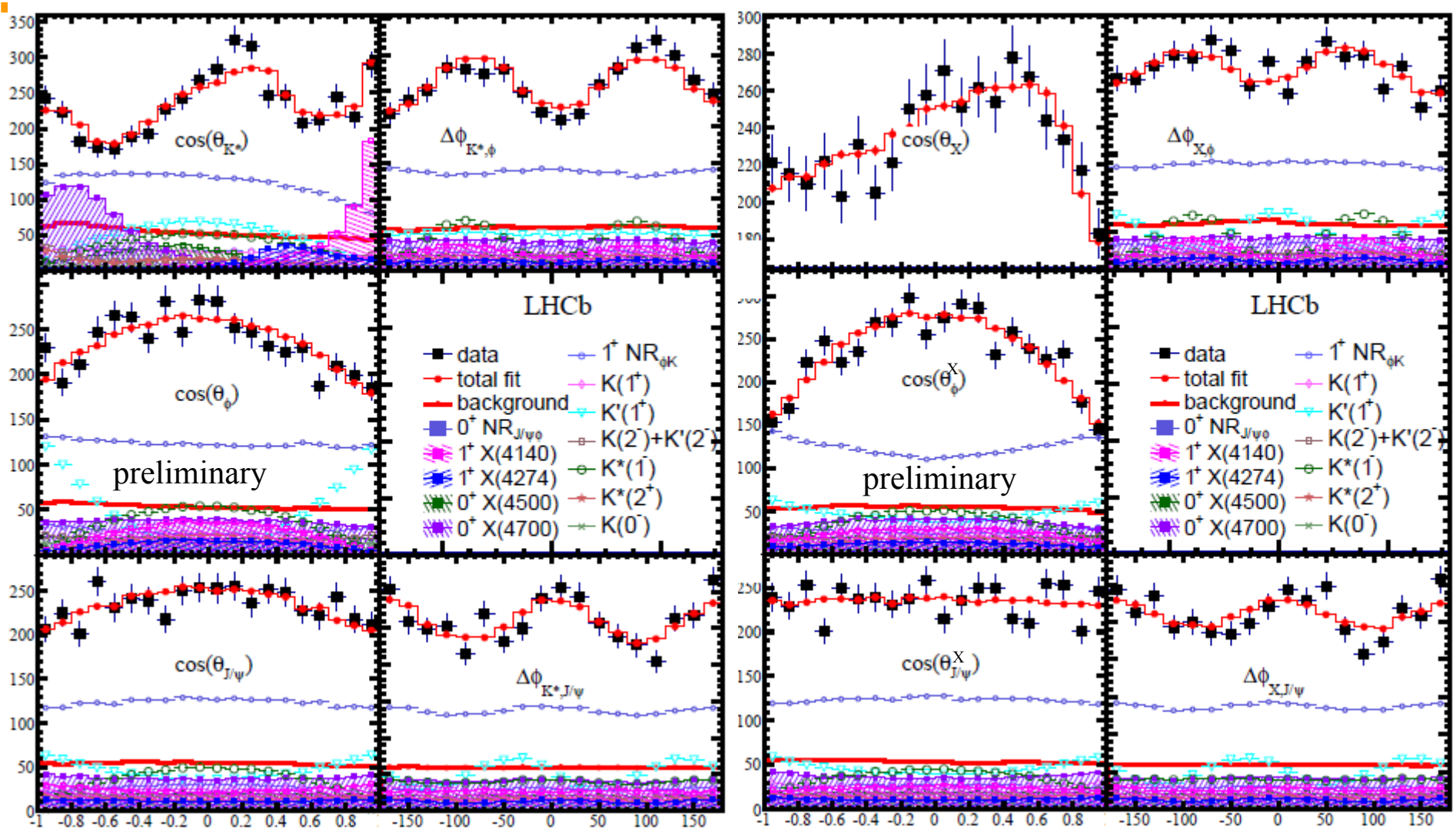


$\Lambda_b \rightarrow J/\psi\ p\ K^-$



However, this approach cannot characterize exotics – amplitude analysis is still necessary

Fitted angles in J/ψϕK



- Fit quality is good in all fitted variables

Model of N* and exotic states

Better established states from PDG

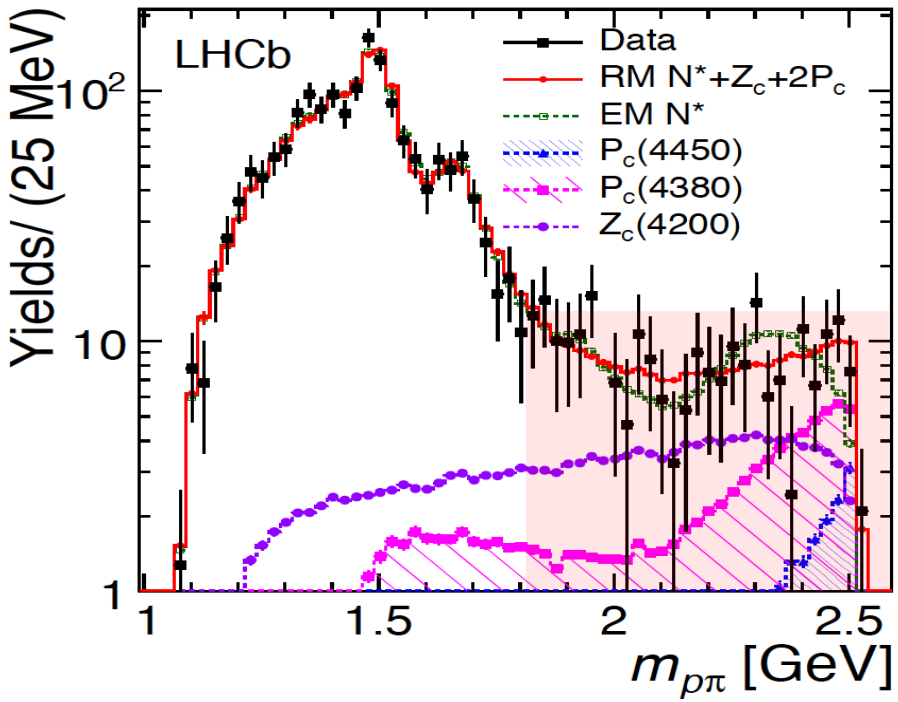
$\Lambda_b^0 \to J/\psi\ p\ \pi^-$

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# of complex couplings Red. (Only significant states limit L)	# of complex couplings Ext. (All states limit L)
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	0	3
$N(1700)$	$3/2^-$	1700	150	0	3
$N(1710)$	$1/2^+$	1710	100	0	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	0	3
$N(1900)$	$3/2^+$	1900	200	0	3
$N(2190)$	$7/2^-$	2190	500	0	3
$N(2300)$	$1/2^+$	2300	340	0	3
$N(2570)$	$5/2^-$	2570	250	0	3
Total # of free parameters				40	106

- Reduced model for central values
- Extended for significance and systematics
- Almost as many free parameters as in $\Lambda_b^0 \to J/\psi\ p\ K^-$
- Fixed m_0 and Γ_0 for the N* and exotic states
- $Z_c(4200)$: 10 free parameters
- Each P_c: 4 free parameters + 8 fixed to that from $\Lambda_b^0 \to J/\psi\ p\ K^-$

Full amplitude fits to $\Lambda_b^0 \to J/\psi p\pi^-$

- 14 $N^* \to p\pi^-$ states included to get significances of exotic states
- High mass N^* are important for exotic study
  - since exotic contribution is more visible in large $m(p\pi^-)$



PRL 117, 082003 (2016)

Included $N(2300)$, $N(2700)$ reported by BESIII in $\psi' \to p\bar{p}\pi^0$ [PRL 110, 022001 (2013)]

If without them, exotic significance is > 5σ

Model-independent confirmation

- $m_{J/\psi p}$ can not be explained by the reflections of K^-p alone
- Angular distribution of K^-p can be decomposed by $P_l(\cos\theta)$

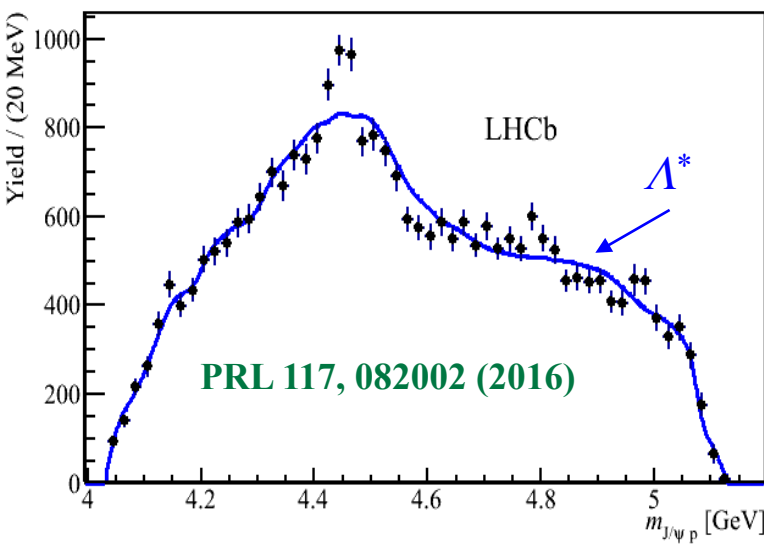
$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{\max}} \boxed{\left\langle P_l^U \right\rangle} P_l(\cos\theta)$$

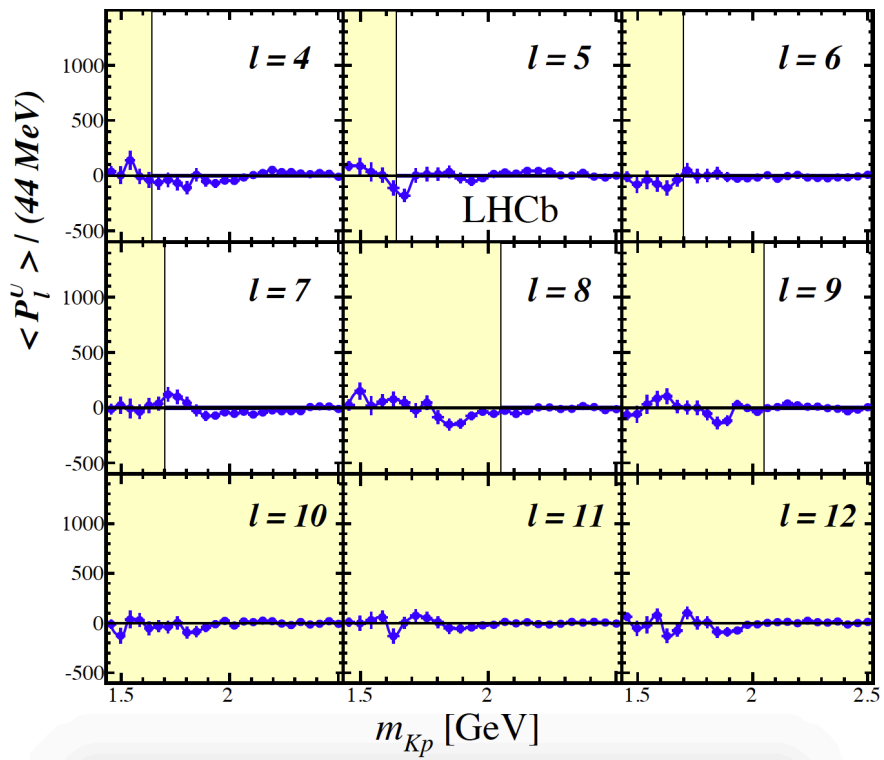
Legendre moments

$$\boxed{l_{\max} = 2J_{\max}}$$ for Λ^*-only

Non-zero-moments in the yellow region mean exotic contribution

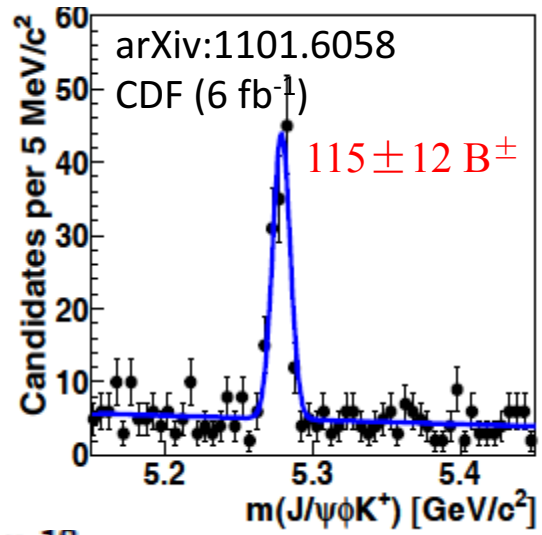
Λ^*-only rejected by 9.0σ
Exotic contribution confirmed

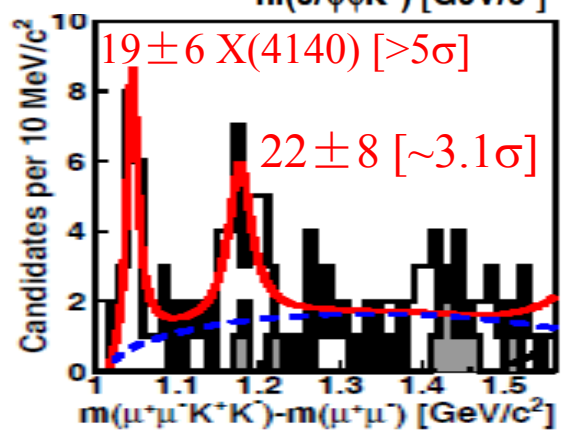




X(4140) and X(4274)

- CDF observed a narrow ($J/\psi\ \phi$) structure in $B^+ \rightarrow J/\psi\ \phi\ K^+$ decays [Initial publication on 2.7 fb^{-1} PRL102, 242002 (2009)]
  - $M=4143.4 \pm 3.0 \pm 0.6$ MeV
  - $\Gamma=15.3^{+10.4}_{-6.1} \pm 2.5$ MeV
  - Necessarily exotic since it is narrow and above the DsDs threshold
  - $[cs\bar{c}\bar{s}]$ tetraquark ?
  - Hint of a second structure: X(4274)
- Not confirmed by B-factories and LHCb with 0.37fb^{-1} data

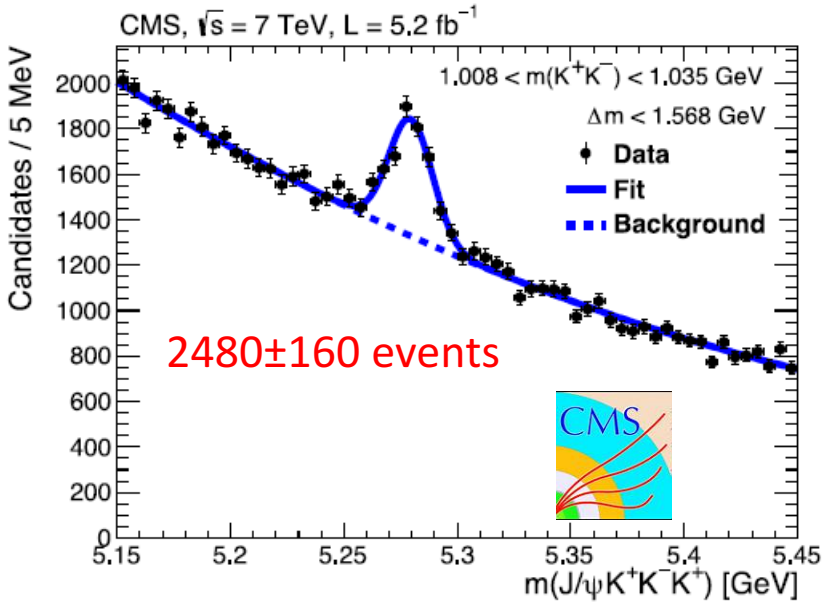


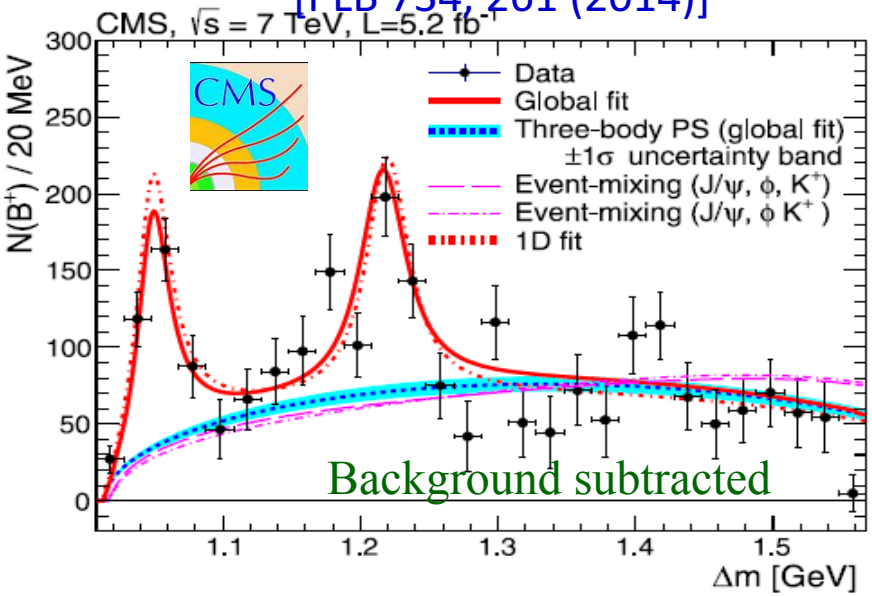


X(4140) and X(4274) from CMS

- Crucial to check by different experiments with larger statistics.

[PLB 734, 261 (2014)]



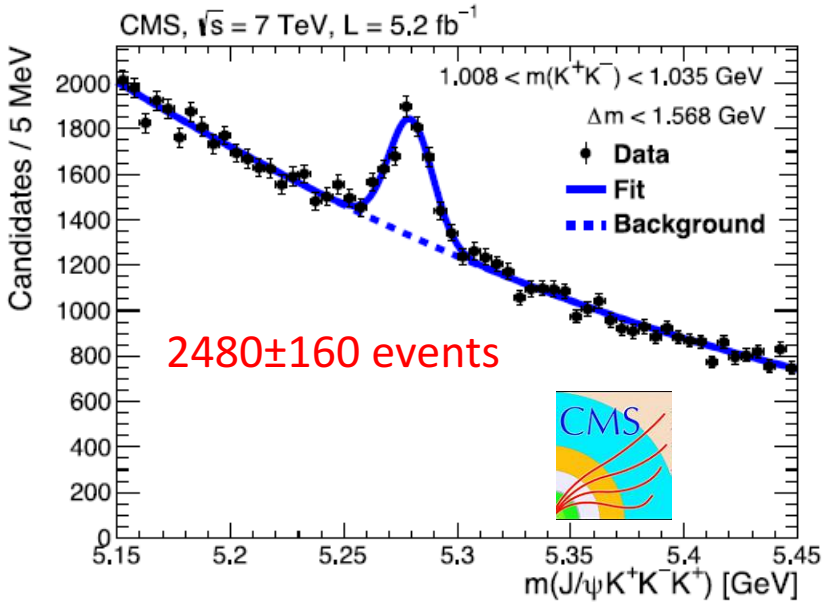


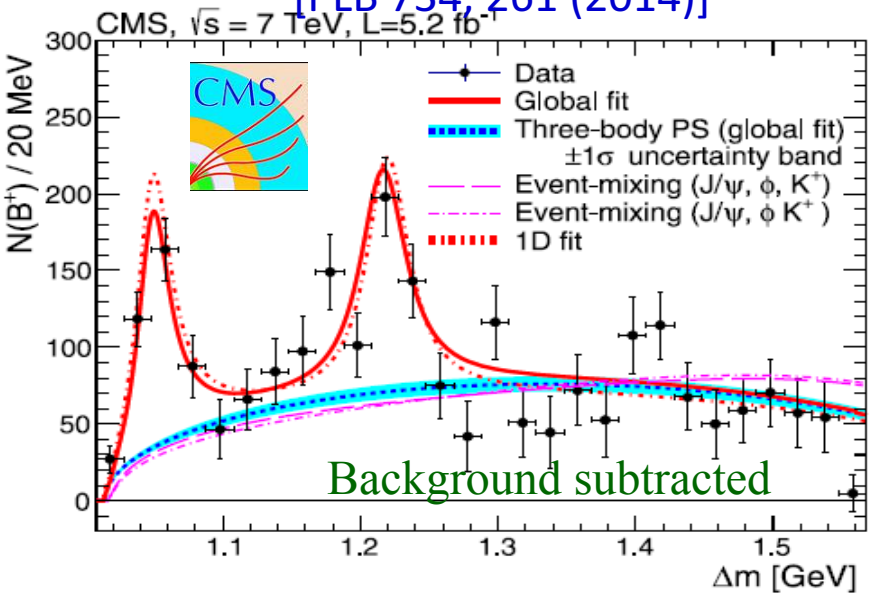
X(4140)	CDF [arXiv:1101.6058]	CMS [PLB 734, 261 (2014)]	DØ [PRD 89, 012004 (2014)]
Significance	>5σ	>5σ	3.1σ
M_0 (MeV)	4143.4±3.0±0.6	4148.0±2.4±6.3	4159.0±4.3±6.6
Γ_0 (MeV)	$15.3^{+10.4}_{-6.1} \pm 2.5$	$28^{+15}_{-11} \pm 19$	$19.9 \pm 12.6^{+1}_{-8}$

X(4140) and X(4274) from CMS

- Crucial to check by different experiments with larger statistics.

[PLB 734, 261 (2014)]

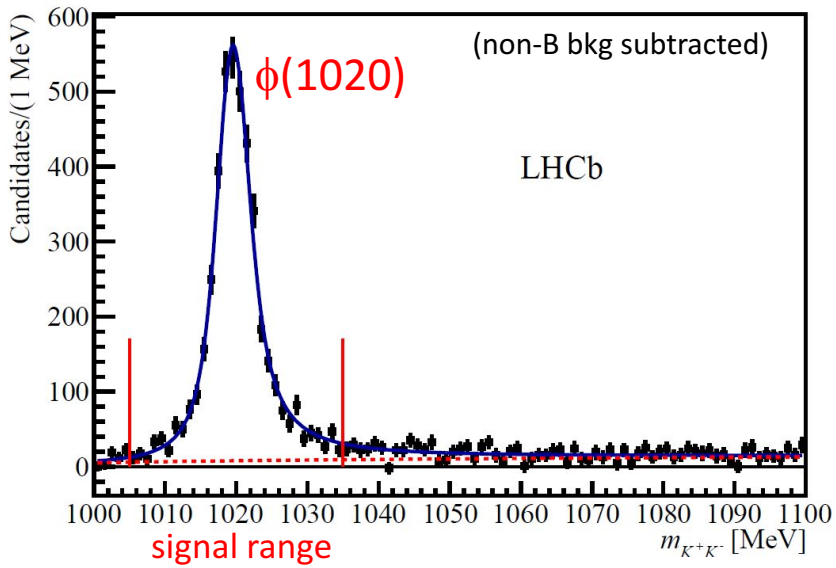


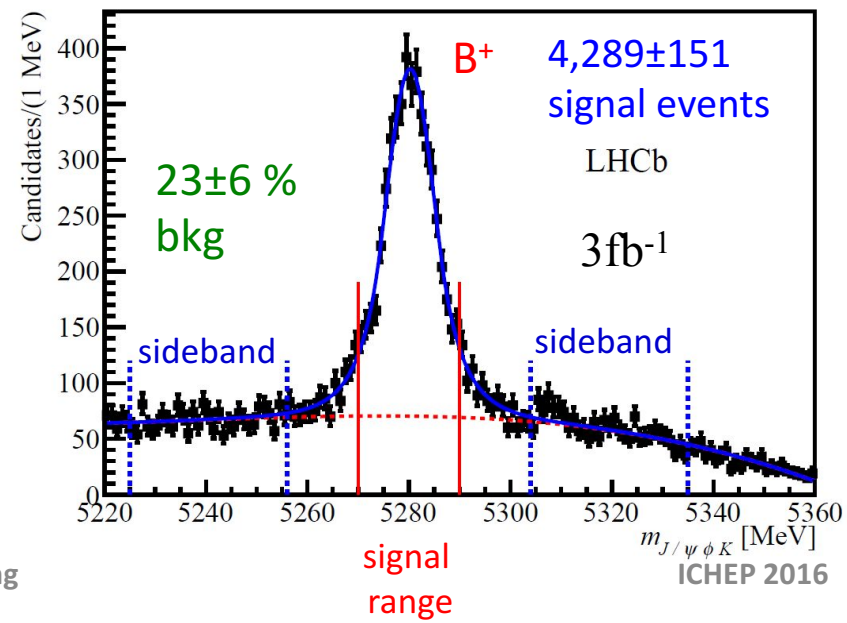


X(4274-4351)?	CDF [arXiv:1101.6058]	CMS [PLB 734, 261 (2014)]	DØ [PRD 89, 012004 (2014)]
Significance	3.1σ	>3σ	
M_0 (MeV)	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$4313.8 \pm 5.3 \pm 7.3$	4328.5 ± 12.0
Γ_0 (MeV)	$32.3^{+21.9}_{-15.3} \pm 7.6$	$28^{+15}_{-11} \pm 19$	

LHCb $B^+ \to J/\psi\ \phi\ K^+$ data samples

LHCb-PAPER-2016-018 arXiv: 1606.07895
LHCb-PAPER-2016-019 arXiv: 1606.07898





- Statistically, the most powerful $B \to J/\psi\ \phi\ K$ sample analyzed so far

Use sidebands to subtract background