Exotic states from LHCb

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On behalf of LHCb Collaboration

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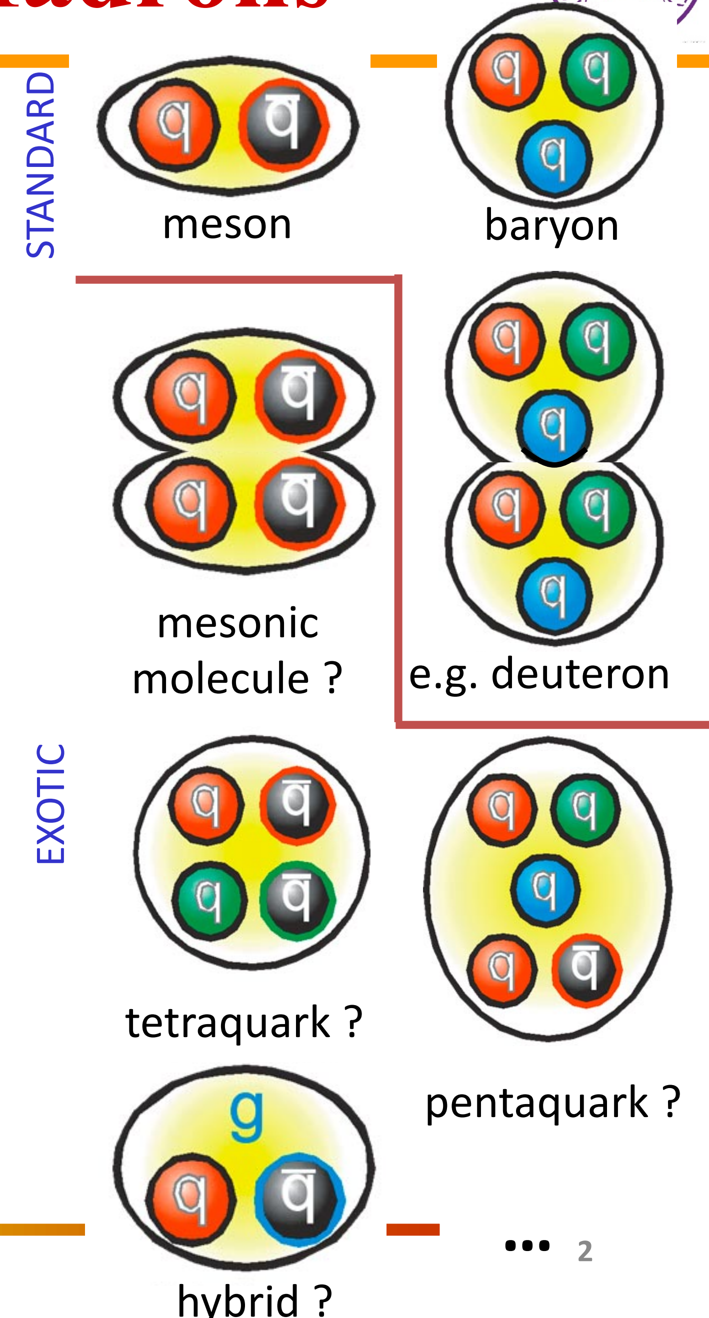
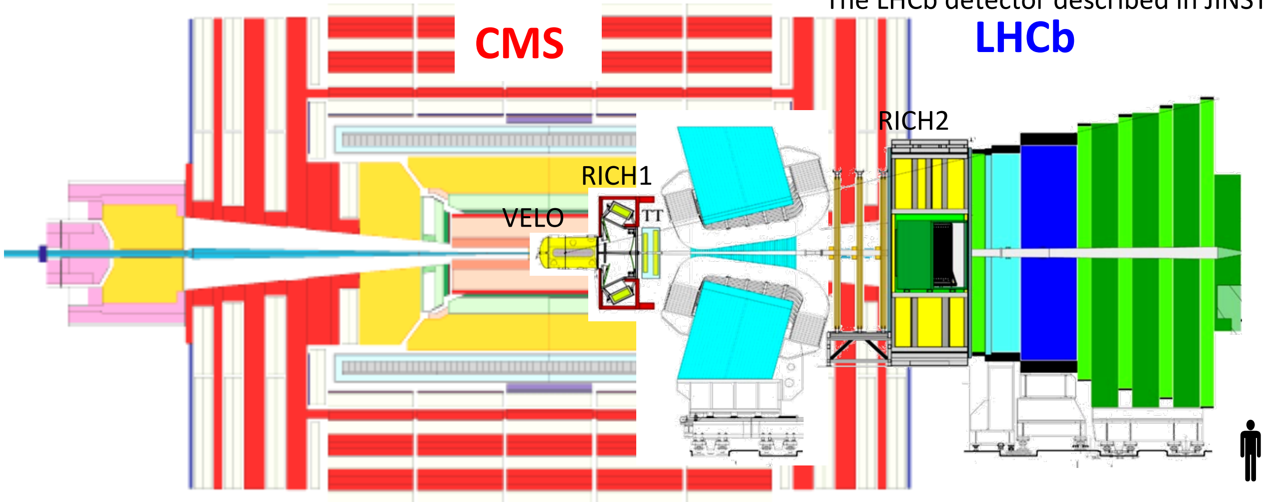
Standard and Exotic Hadrons

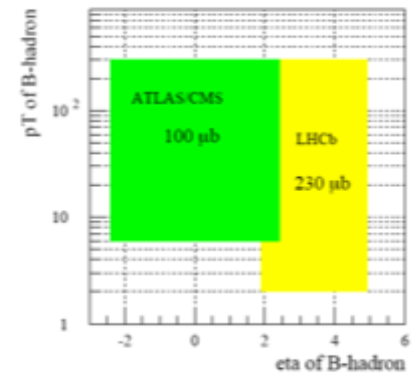
- Mesons beyond $q\bar{q}$ and baryons beyond three-quark configurations are called as exotic hadrons
- Their existence is not forbidden by QCD as long as they maintain color-singlet configurations
- Multiquark objects were proposed separately by Gell-Mann and Zweig in 1964
- Recent discoveries in heavy quark states have revived hopes for conclusive proofs for existence of exotic hadrons



Detectors and data sets

The LHCb detector described in JINST 3 (2008) S08005





- LHCb detector advantages:

Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$

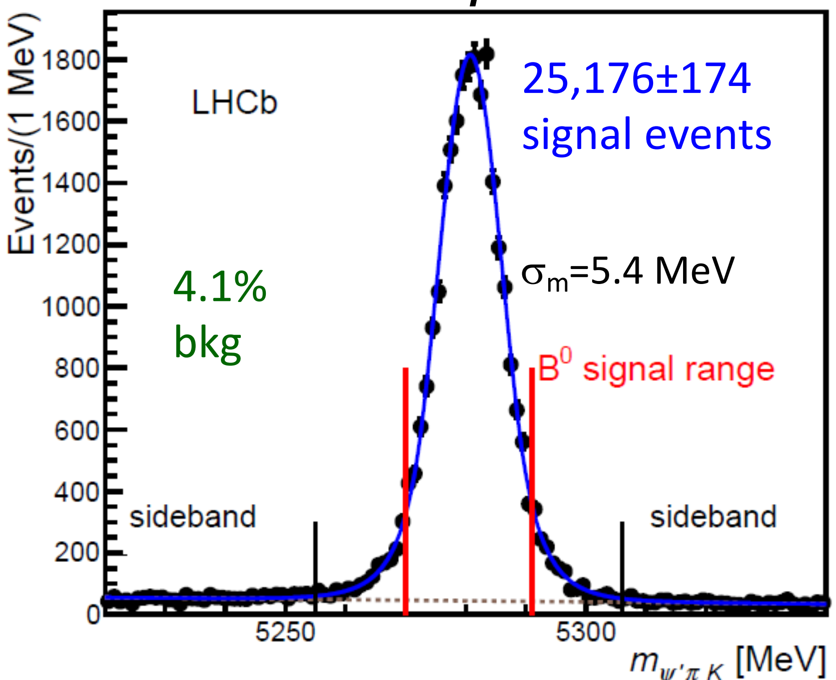
All LHCb results use total RUN-I data (3.0 fb^{-1})

$$Z_c(4430)^- \to \psi' \pi^- \ \text{and}$$
$$P_c(4380)^+ \, P_c(4450)^+ \to J/\psi \, p$$

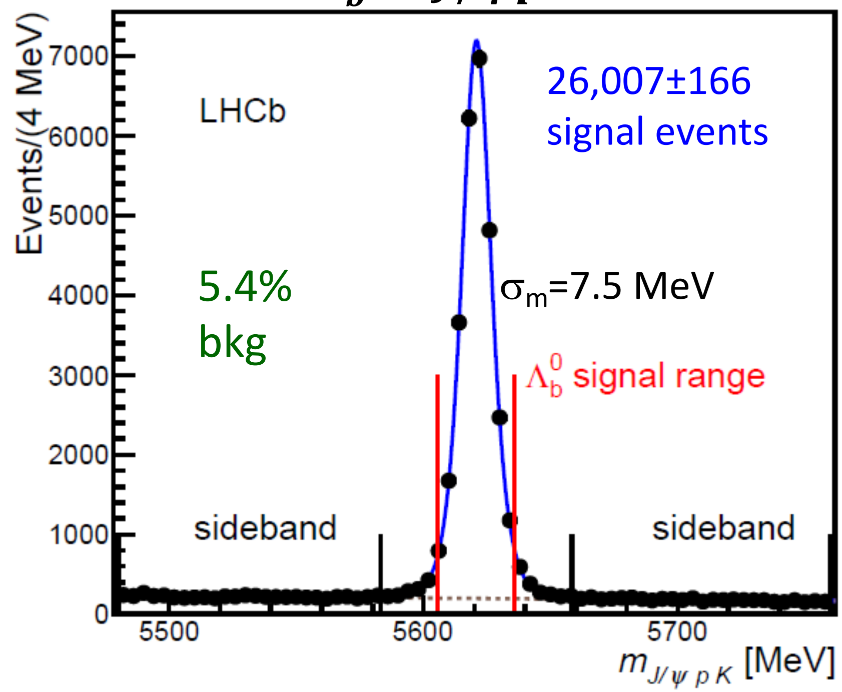
Full amplitude fits and
model-independent approaches

LHCb data samples (3 fb^{-1})

LHCb-PAPER-2014-014
PRL **112**, 222002 (2014)
$B^0 \to \psi'\pi^+K^-$



LHCb-PAPER-2015-029
PRL **115**, 07201 (2015)
$\Lambda_b^0 \to J/\psi p K^-$



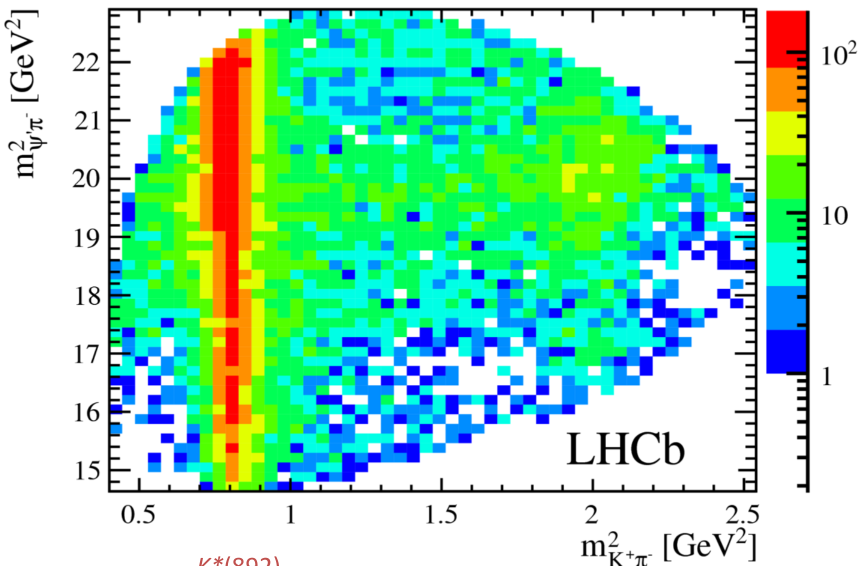
vs. bkg in
Belle: 7.8%

vs
Belle: 2,010±50 *[PRL **100**, 142001 (2008); PRD **88**, 074026 (2013)]*
BaBar: 2,021±53 *[PRD **79**, 112001 (2009)]*

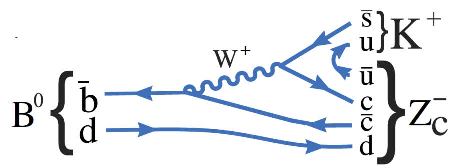
- > factor of 10 better statistics than at the B factories, at smaller bkg
- Comparable signal statistics and bkg levels between the B^0 and Λ_b data samples

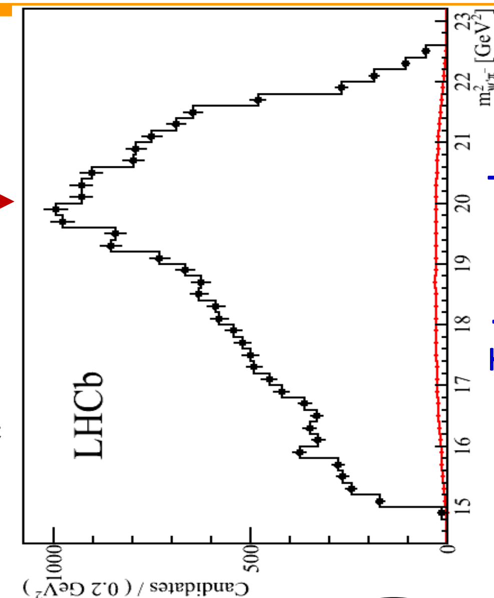
$B^0 \to J/\psi\pi^- K^+$

LHCb-PAPER-2014-014
PRL **112**, 222002 (2014)

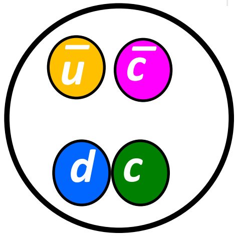


$Z_c(4430)^-$
$\to \psi'\pi^-$
?

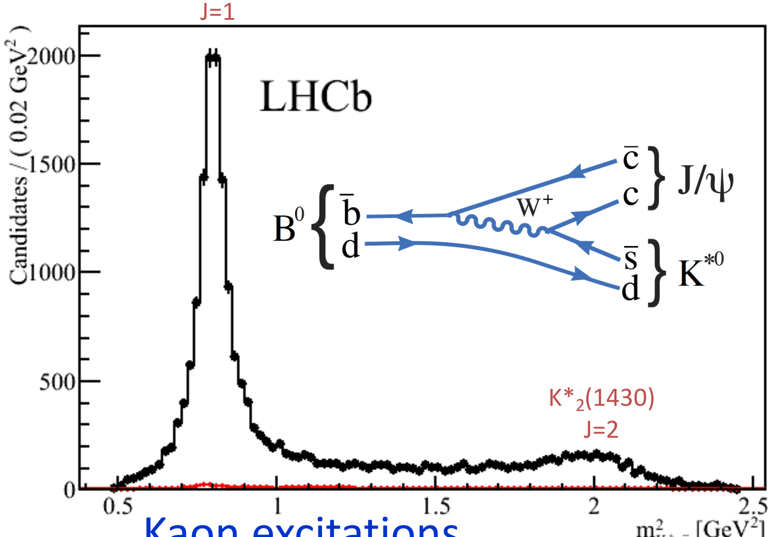




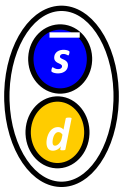
Tetraquark



$K^*(892)$
J=1

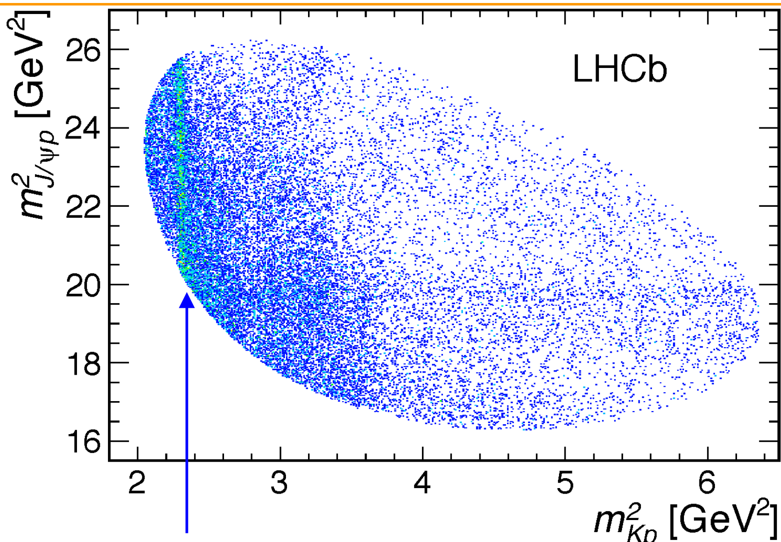


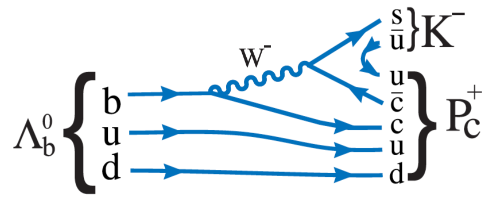
Kaon excitations



Is it a reflection of interfering K^*'s $\to \pi^- K^+$?
Proper amplitude analysis necessary to check

$\Lambda_b^0 \to J/\psi p K^-$: unexpected structure in $m_{J/\psi p}$

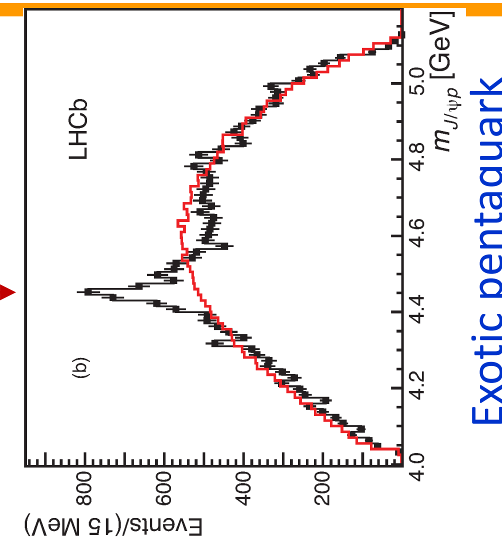




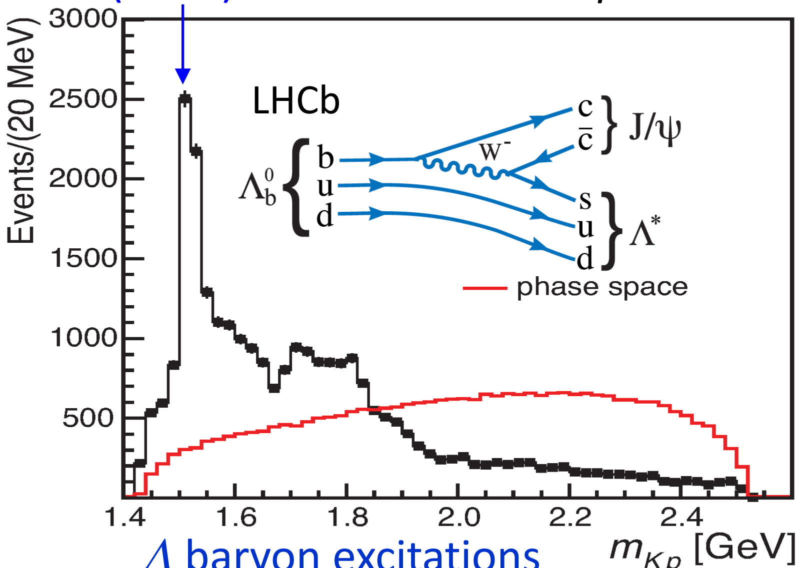
$P_c^+ \to J/\psi\, p$?

LHCb-PAPER-2015-029

PRL **115**, 07201 (2015)

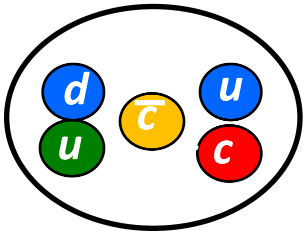


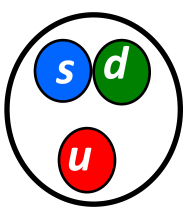
$\Lambda(1520)$ and other Λ^*'s $\to p K^-$



Λ baryon excitations

- Unexpected, narrow peak in $m_{J/\psi\, p}$



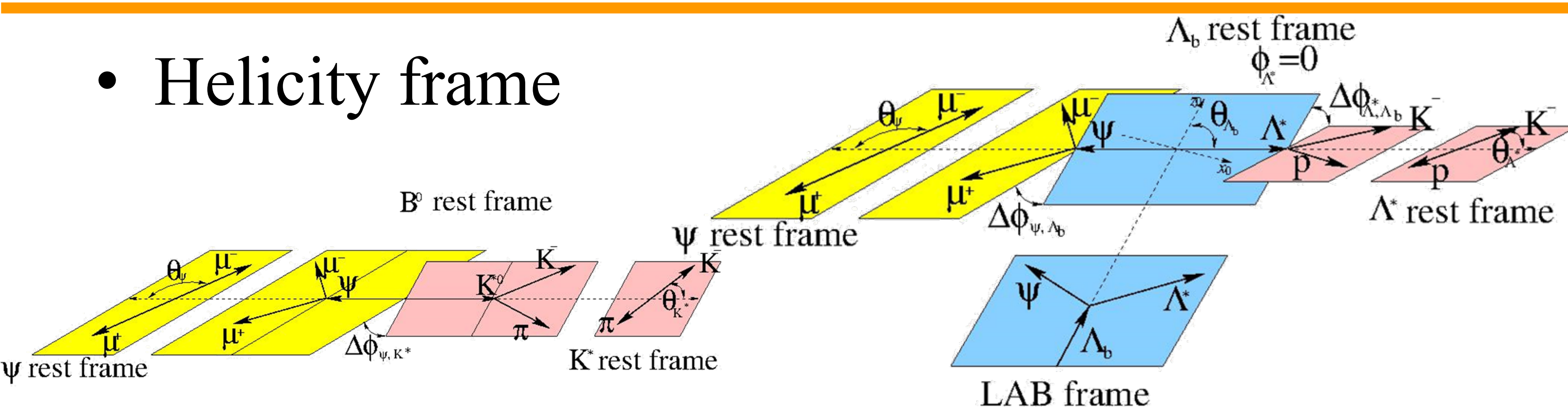


Is it a reflection of interfering Λ^*'s $\to pK^-$?

Proper amplitude analysis necessary to check

Full amplitude analyses

- Helicity frame



4D maximum likelihood fit

6D maximum likelihood fit

$$\Omega \equiv (\theta_{K^*}, \theta_{\psi}, \Delta\phi_{\psi,K^*})$$

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta\phi_{\Lambda^*,\Lambda_b}, \theta_{\psi}, \Delta\phi_{\psi,\Lambda_b})$$

$$\mathrm{PDF}(\mathrm{m}_{K\pi/Kp}, \Omega) = \left| MatrixEle(\mathrm{m}_{K\pi/Kp}, \Omega \mid J_R^P, M_R, \Gamma_R, H_R) \right|^2 \times \mathrm{eff}(\mathrm{m}_{K\pi/Kp}, \Omega) + \mathrm{PDF}_{\mathrm{bkg}}(\mathrm{m}_{K\pi/Kp}, \Omega)$$

Fitting parameters

M_R ,Γ_R fixed to known values, and varied within errors for systematics.

1-3 independent **complex** helicity couplings H_R per K^* resonance

4-6 independent **complex** helicity couplings H_R per Λ^* resonance

The decay angles greatly increase discrimination power between resonances of different J^P

Matrix elements for exotic decays are coherently added later to these for conventional resonance

Model of conventional resonances

Well established states from PDG

Only state wit P=(-1)^J decays to Kπ

No high-M_0 high-J^P

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# of complex couplings Red.	Ext.
NR	0^+	—	—	1	1
$K^*(800)^0$	0^+	682	547	1	1
$K^*(892)^0$	0^+	896	49	3	3
$K^*(1410)^0$	1^-	1414	232	3	3
$K^*(1430)^0$	0^+	1425	270	1	1
$K_2^*(1430)^0$	2^+	1432	109	3	3
$K^*(1680)^0$	1^-	1717	322	3	3
$K_3^*(1780)^0$	3^-	1776	159	0	3
Total # of free parameters				28	34

No high-M_0 high-J^P & limit L | All states all L

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# of complex couplings Red.	Ext.
$\Lambda(1405)$	$1/2^-$	1405	50	3	4
$\Lambda(1520)$	$3/2^-$	1520	16	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	2585	200	0	6
Total # of free parameters				64	146

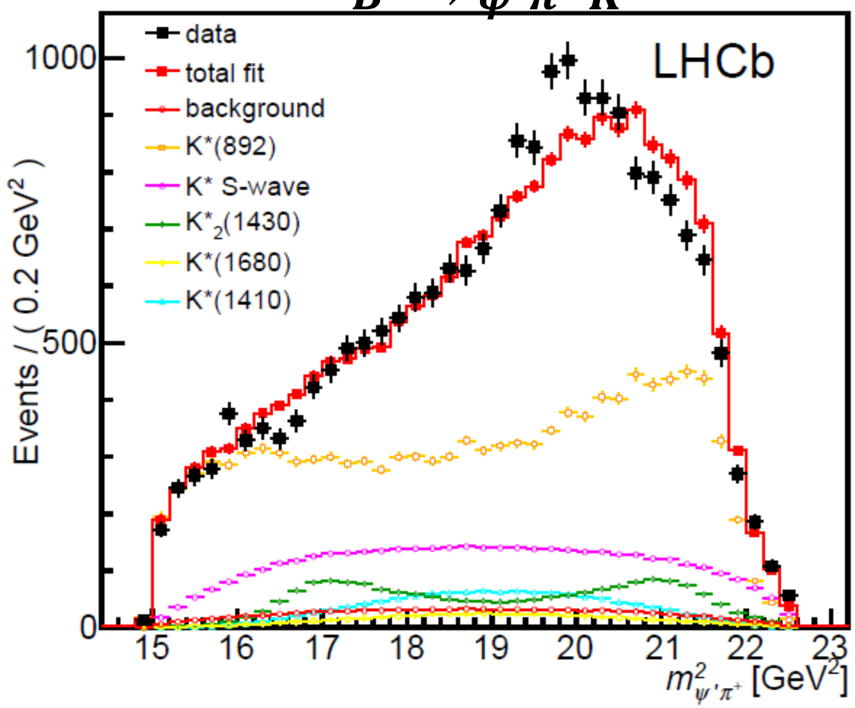
Using Extend model to set significance of exotic states

- Baryons have more than doubling of known states to include

Fits with conventional resonances only

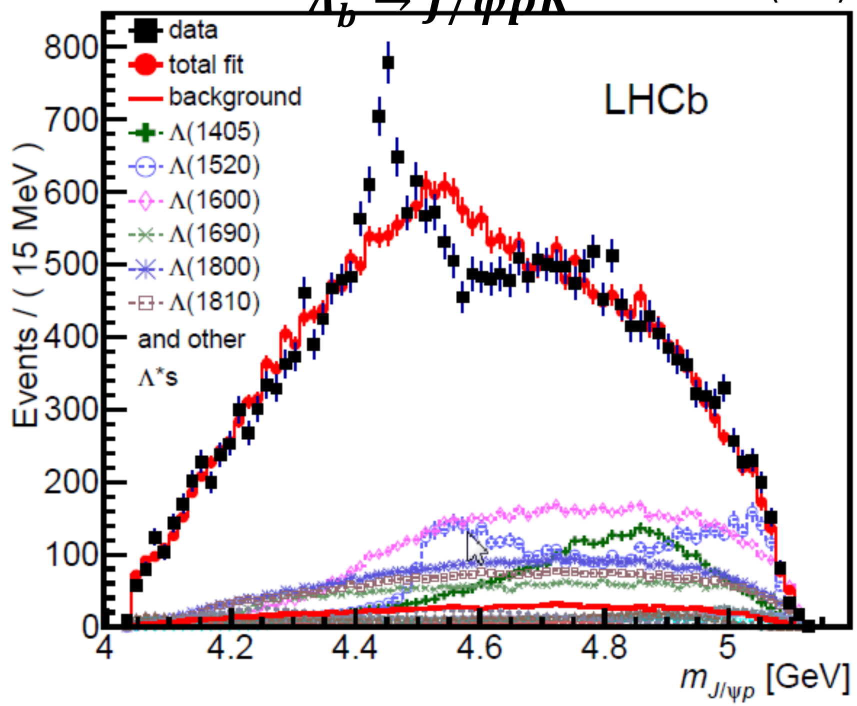
LHCb-PAPER-2014-014
PRL **112**, 222002 (2014)

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



LHCb-PAPER-2015-029
PRL **115**, 07201 (2015)

$\Lambda_b^0 \to J/\psi p K^-$ (Ext.)



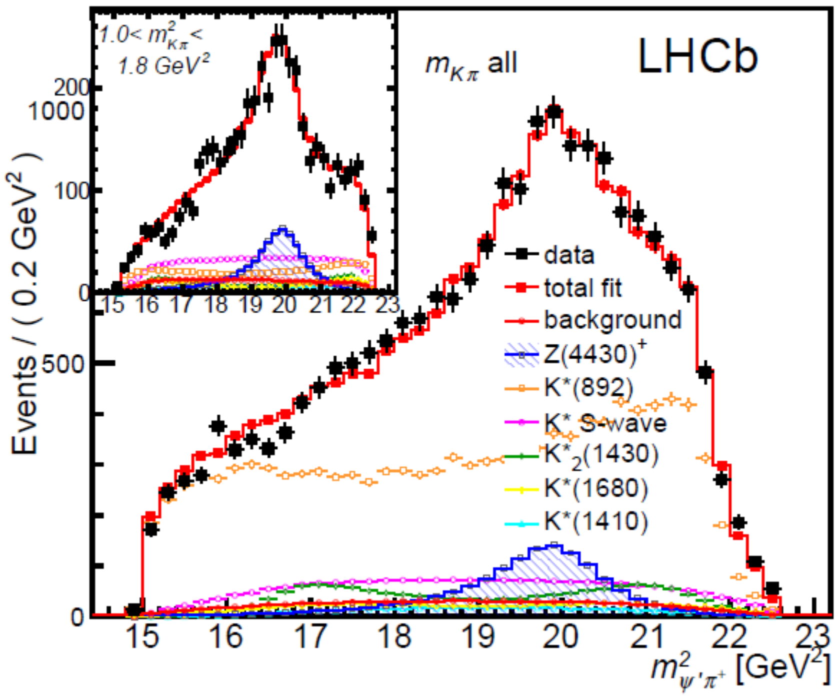
- Two models for conventional resonances: Extended and Reduced, cross-check with each other
- Extended uses all established resonances, for significances and syst.
- Reduced keeps only significant contributions

Cannot describe the data with the conventional resonances (Extended) alone

Fits including exotic hadrons

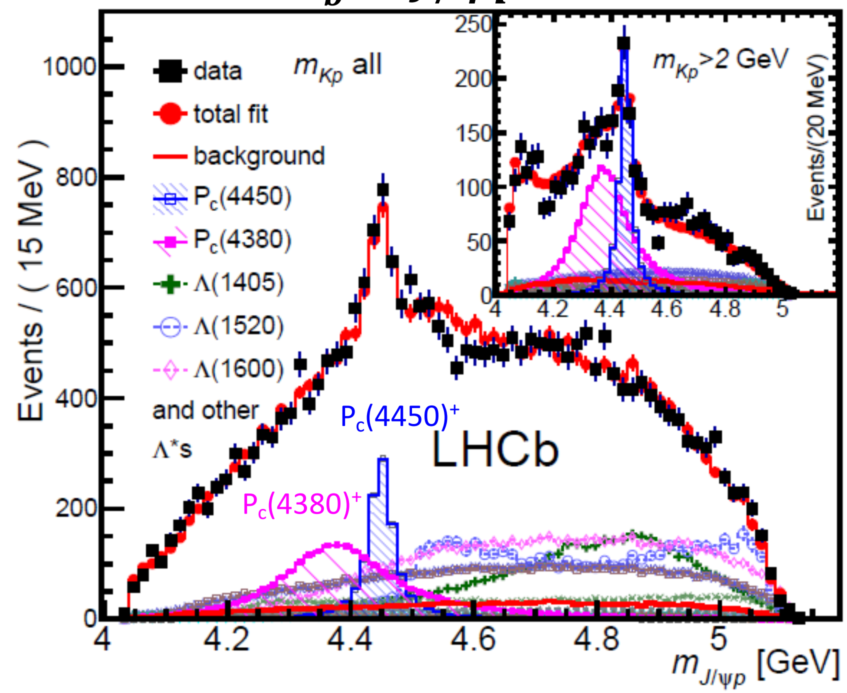
LHCb-PAPER-2014-014
PRL **112**, 222002 (2014)

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



LHCb-PAPER-2015-029
PRL **115**, 07201 (2015)

$\Lambda_b^0 \to J/\psi p K^-$ (Red.)



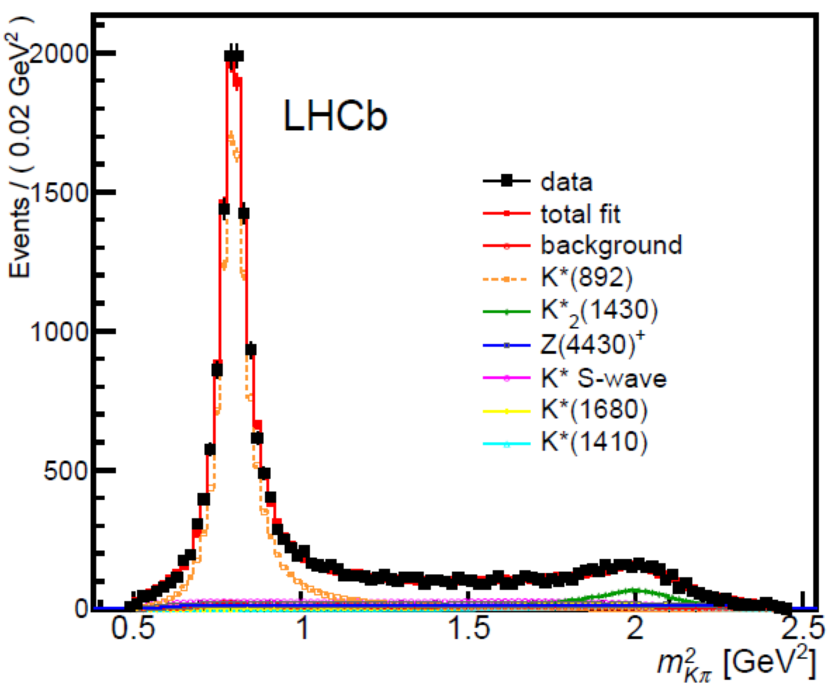
State	Mass (MeV)	Width (MeV)	Fit frac. (%)	Sig.
$Z_c(4430)^+$	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$	$5.9 \pm 0.9^{+1.5}_{-3.3}$	14σ
Belle	$4485 \pm 22^{+28}_{-11}$	$200 \pm 46^{+26}_{-35}$	$10.3 \pm 3.5^{+4.3}_{-2.3}$	5σ

State	Mass (MeV)	Width (MeV)	Fit frac. (%)	Sig.
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ

- $J^P=1^+$ at 9.7σ incl. syst. (in Belle at 3.4σ)
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ cannot be ruled out

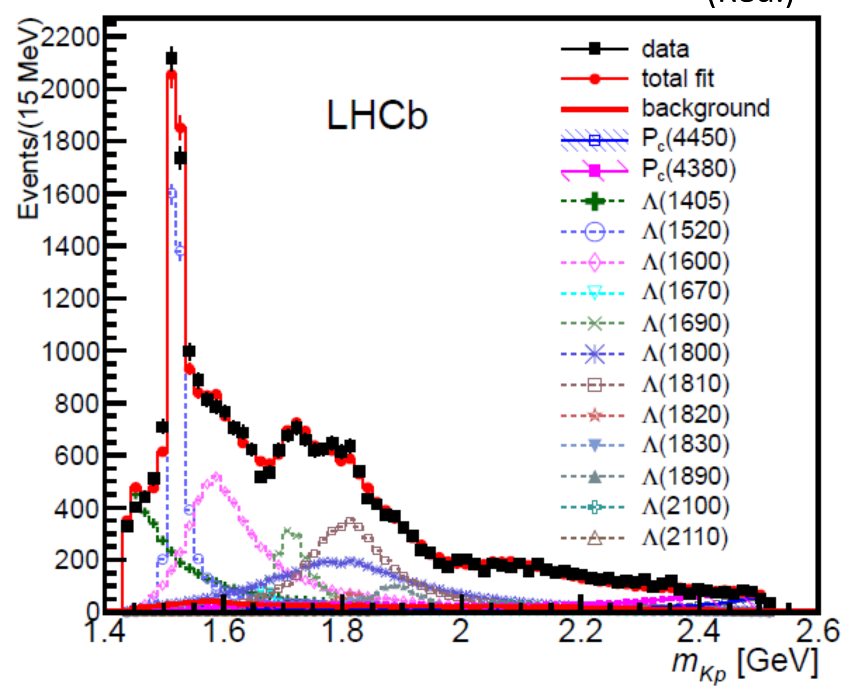
Fits including exotic hadrons

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



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

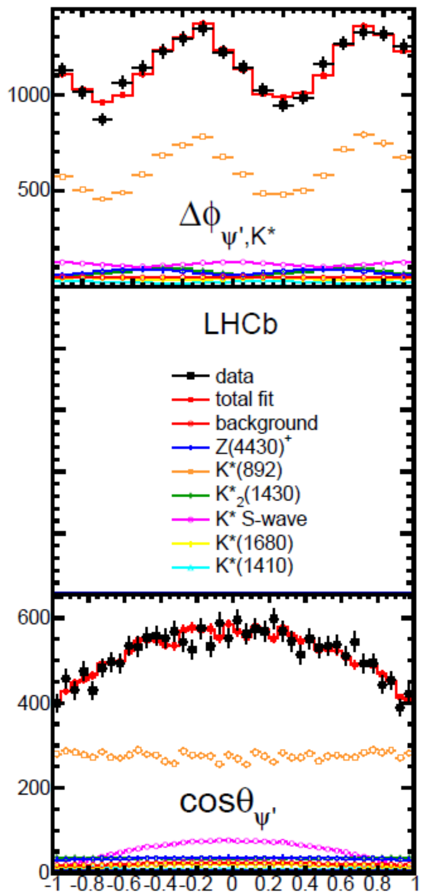
(Red.)



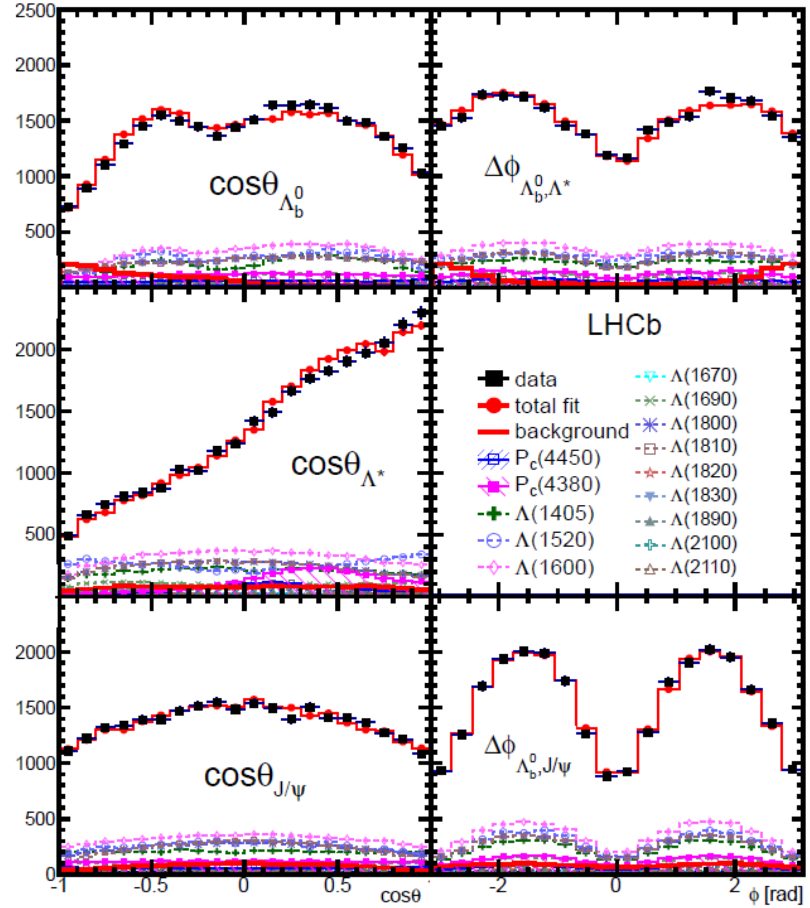
- Data are well described by the fits
- Conventional resonances dominate the rate
- Exotics spread across wide range of these masses

Decay angular projections

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



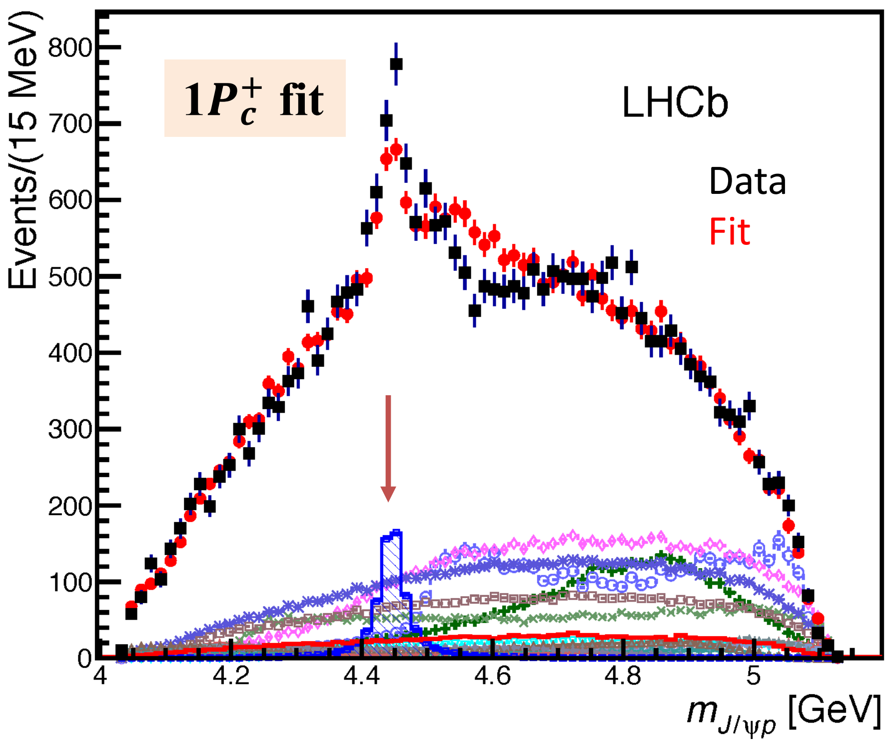
$\Lambda_b^0 \to J/\psi p K^-$

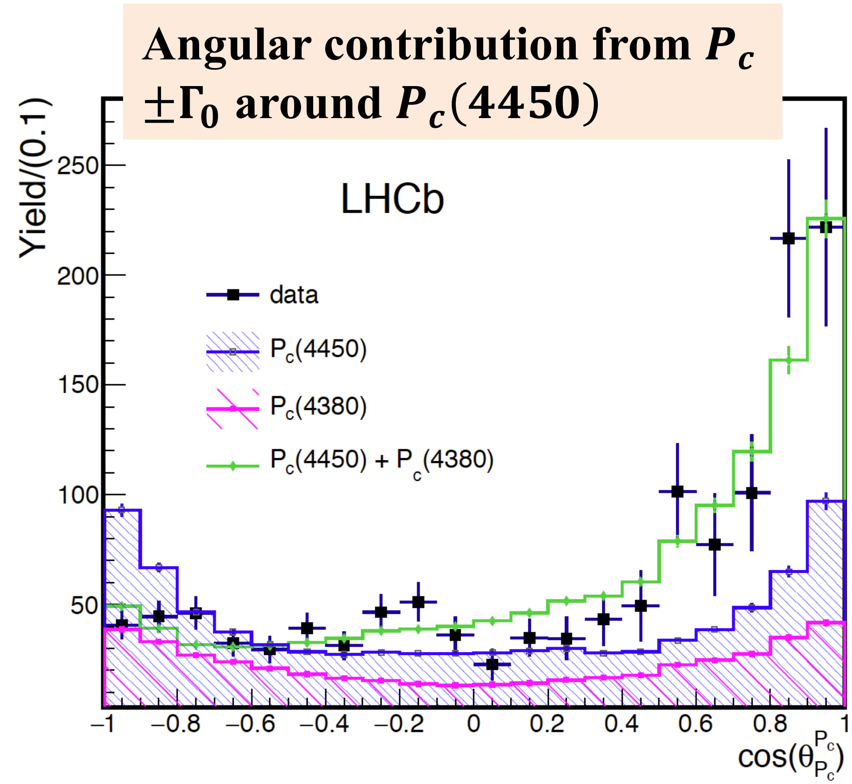


- They greatly increase discrimination power between resonances of different J^P
- Correctly describe interference

Why two P_c^+ with opposite parity

- 1 P_c^+ cannot fit well the peak
- Strong asymmetry angular distribution from P_c^+
- Can only be explained by interference two opposite parity P_c^+



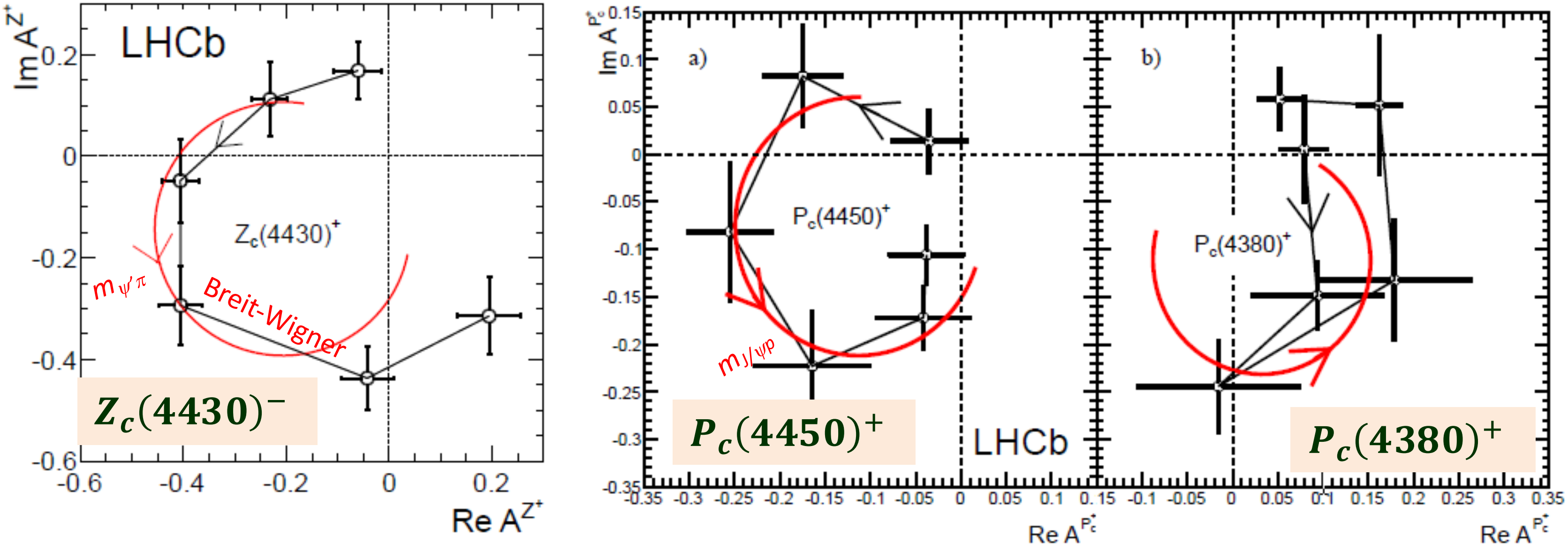


CERN-THESIS-2016-086

Argand diagrams for resonant behavior

LHCb-PAPER-2015-029
PRL **115**, 07201 (2015)

Exotic hadron amplitudes modelled by 6 complex coefficients near the peak mass, to compare with Breit-Wigner resonance amplitude



Good evidence for resonant character

Large errors: not conclusive

- The results are still dependent on the model of conventional hadrons
- Simultaneous PWA of the latter is not possible since exotics reflect into variables characterizing conventional hadrons
- However, we can assume exotics are not present and test for their presence in model-independent way - next 5 slides

Argand diagrams for resonant behavior

CERN-THESIS-2016-086

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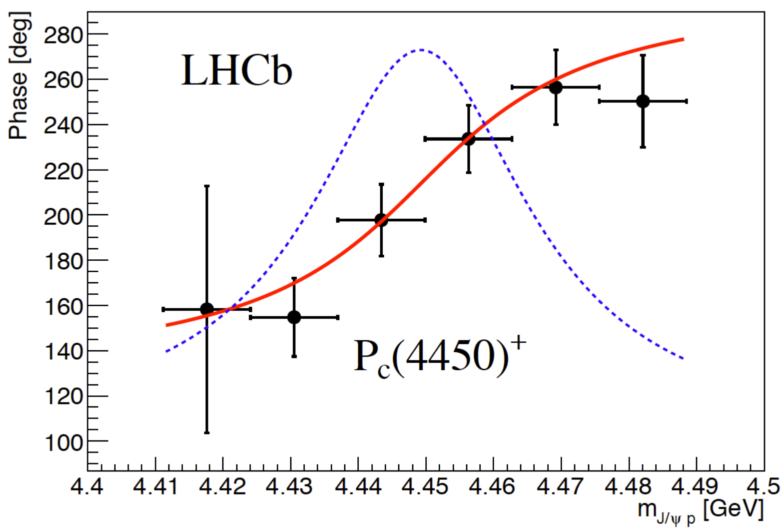

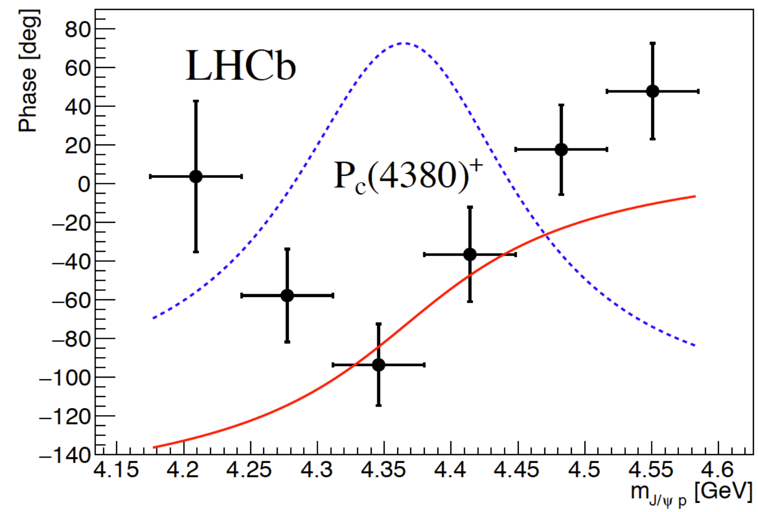

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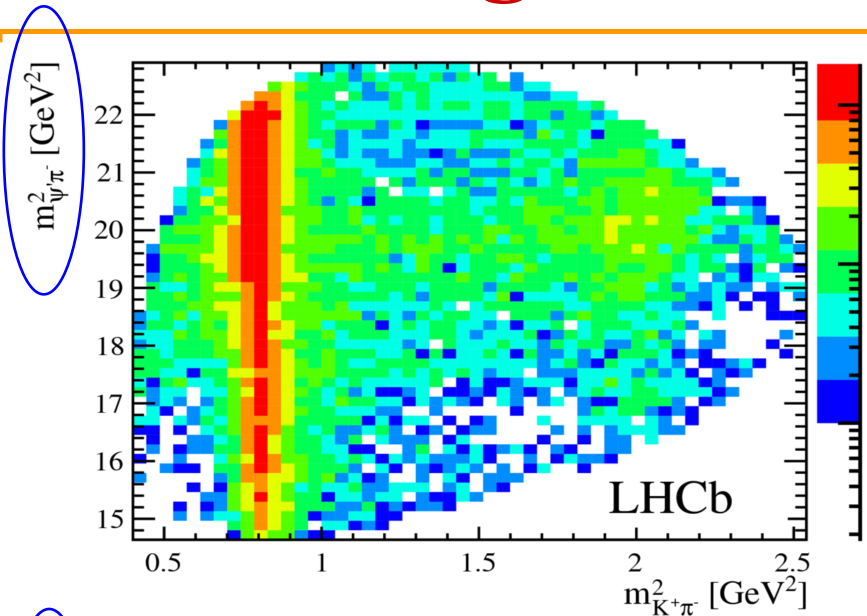
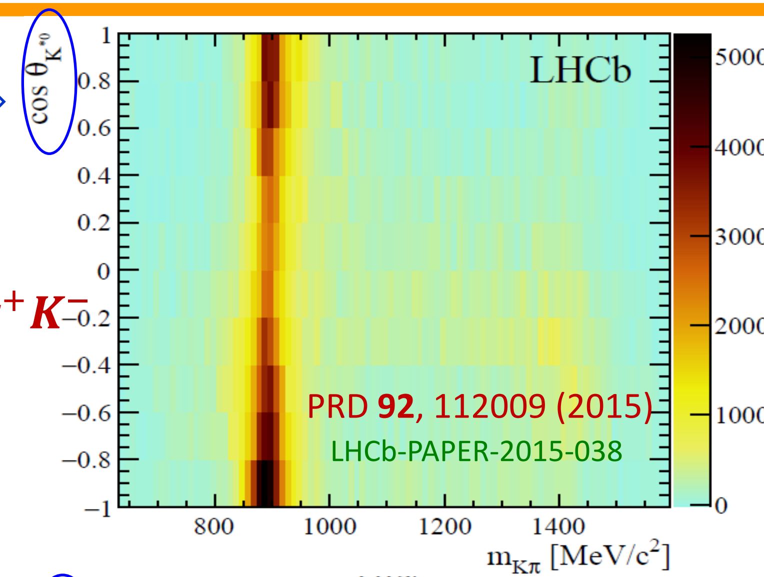
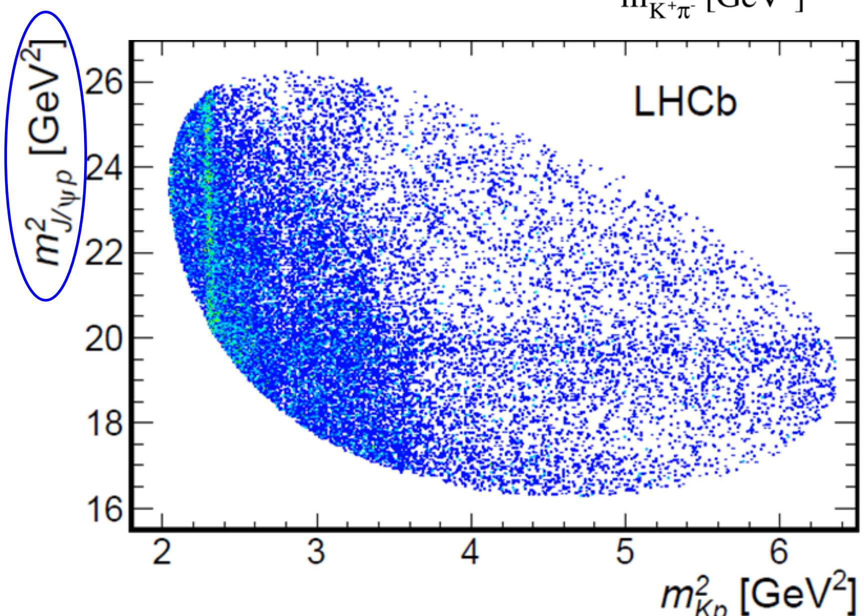
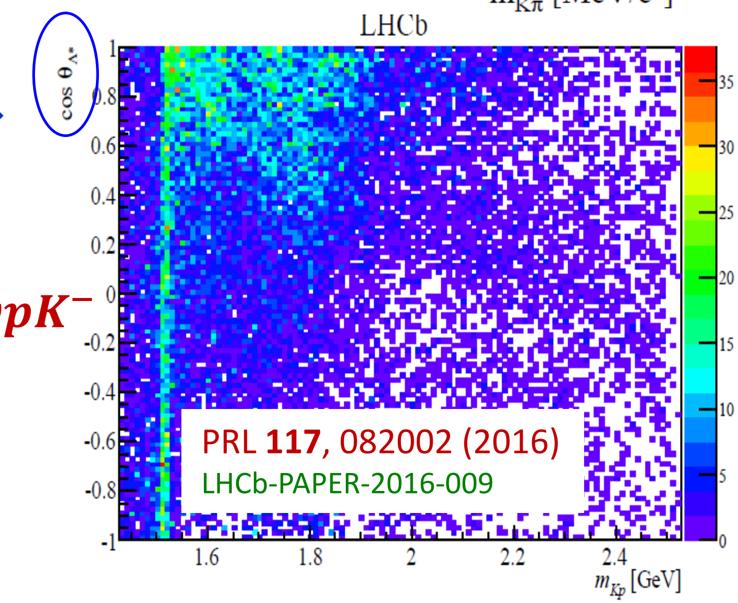
Rectangular Dalitz plane





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



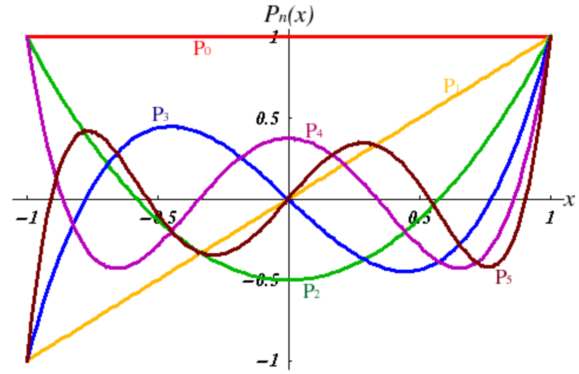


$\Lambda_b^0 \to J/\psi p K^-$

Legendre moments

$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{\max}} \left\langle P_l^U \right\rangle P_l(\cos\theta) \qquad \theta = \theta_{K^*} \quad \text{or} \quad \theta_{\Lambda^*}$$

$$\left\langle P_l^U \right\rangle = \int_{-1}^{+1} \frac{dN}{d\cos\theta} P_l(\cos\theta)\, d\cos\theta \propto \sum_{i=1}^{n_{events}} \frac{1}{\varepsilon_i} P_l(\cos\theta_i)$$



K^*/Λ^* can contribute only to low-order moments

K^*/Λ^*-only hypothesis called H_0

$$l_{\max} = 2J_{\max}$$

J_{max} is the highest spin of K^*/Λ^* resonance possible

Reflections of exotic hadrons can contribute to low **and high** order moments:

– Detecting non-zero moments above $2J_{max}$ signals presence of exotics

Setting l_{max} as function of $m_{K\pi}/m_{Kp}$

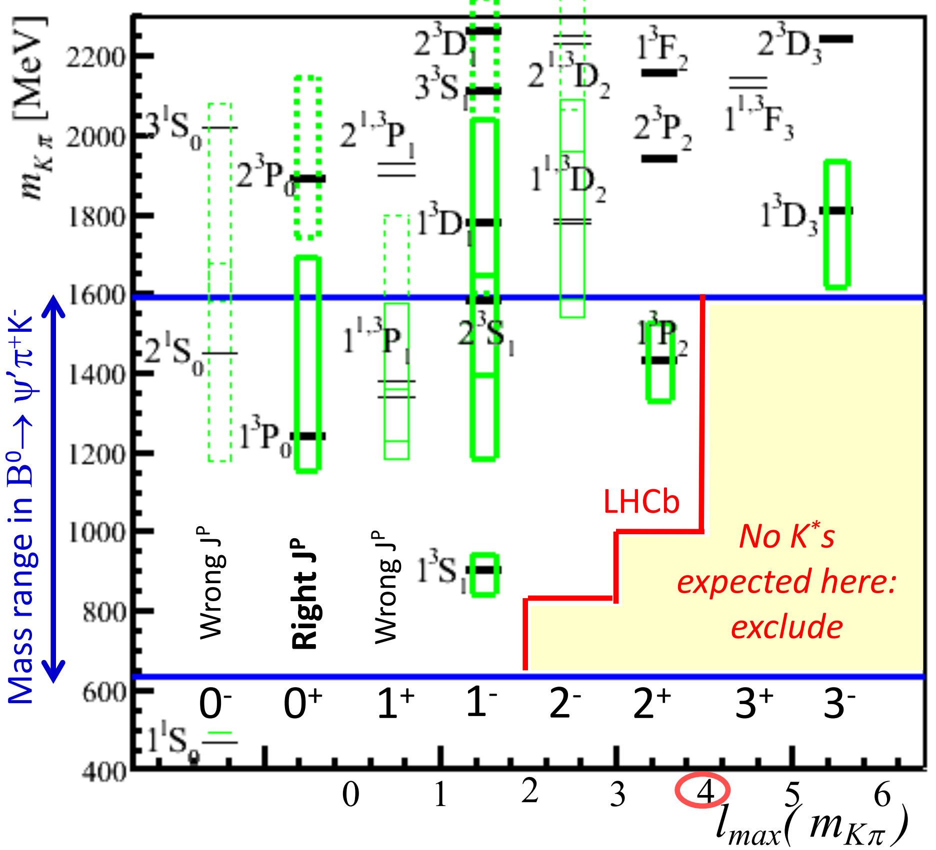
From **know K^*/Λ^* resonances**, **quark model predictions** as a guide

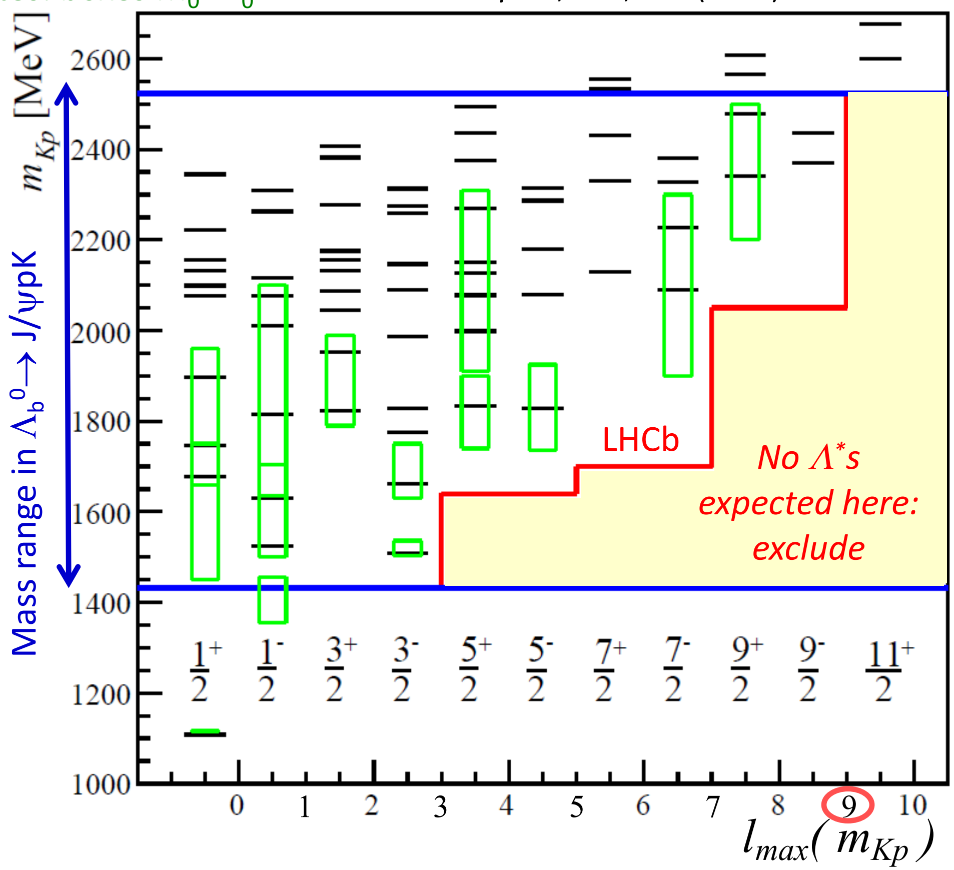
Much fewer known states than predicted!

K* mass predictions by Godfrey-Isgur, PRD 32, 189 (1985)

Known K* / Λ* states: boxes $M_0 \pm \Gamma_0$

Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)



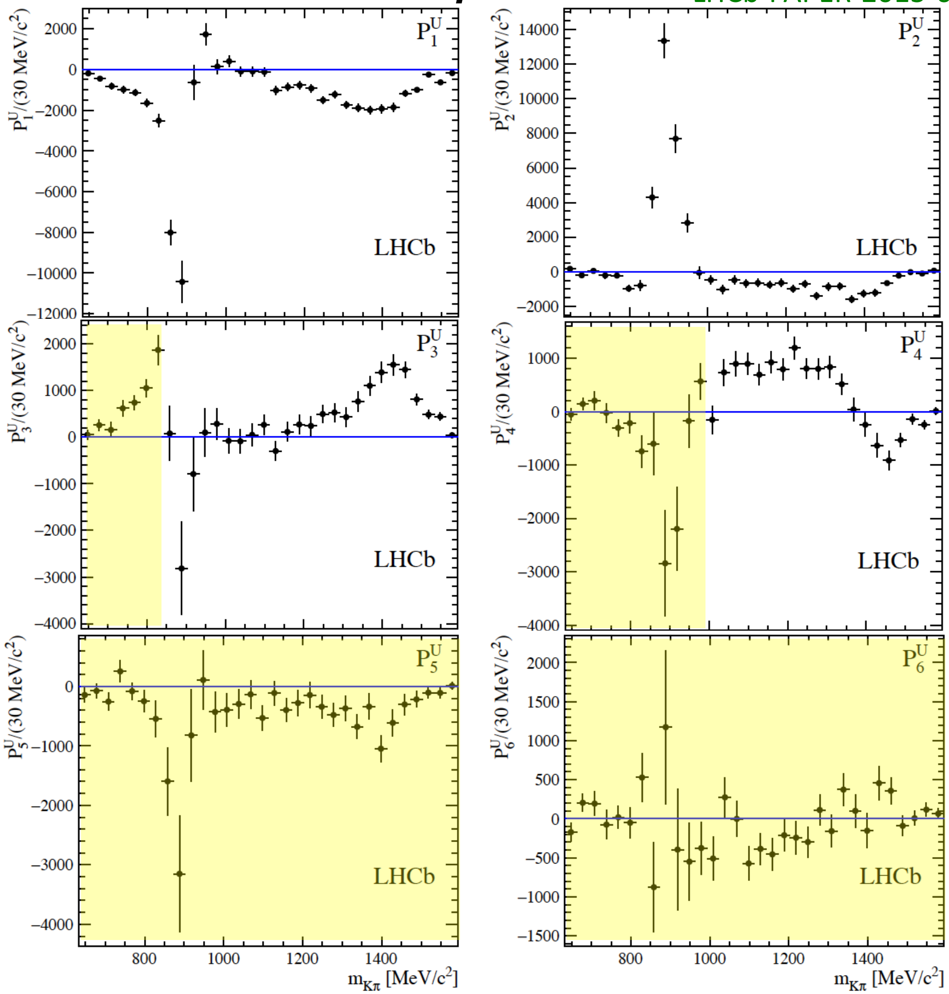


Moments coefficients

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

PRD **92**, 112009 (2015)

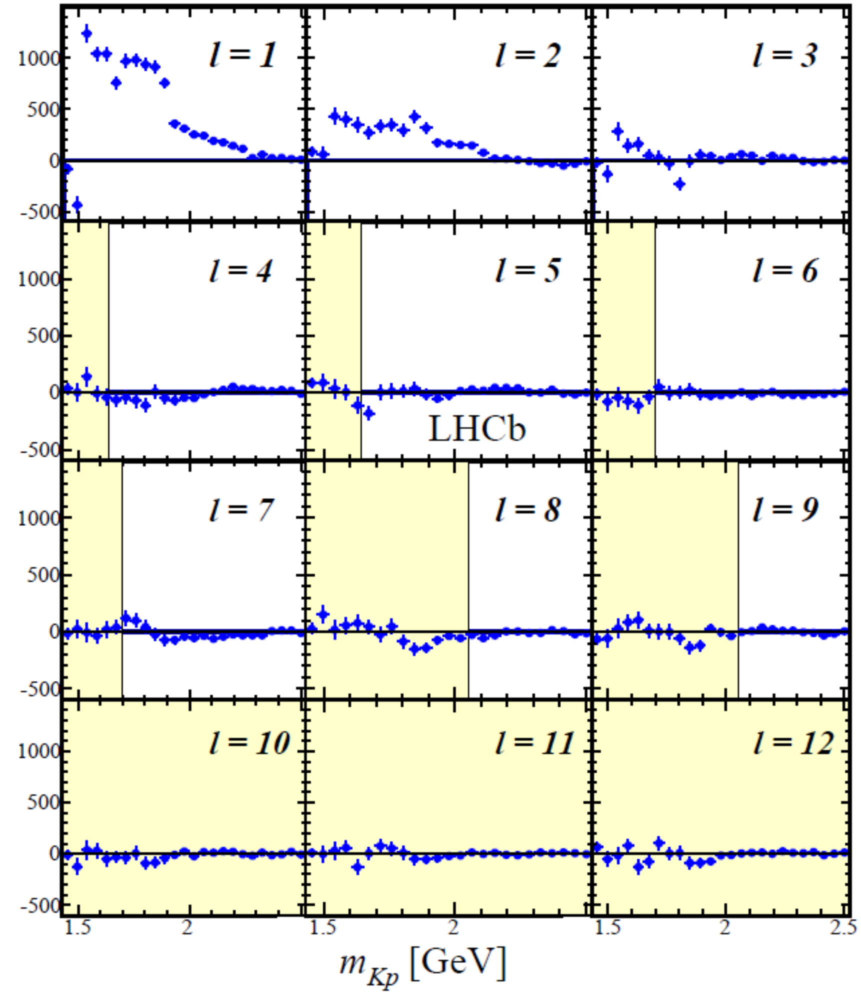
LHCb-PAPER-2015-038



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

PRL **117**, 082002 (201

LHCb-PAPER-2016-009



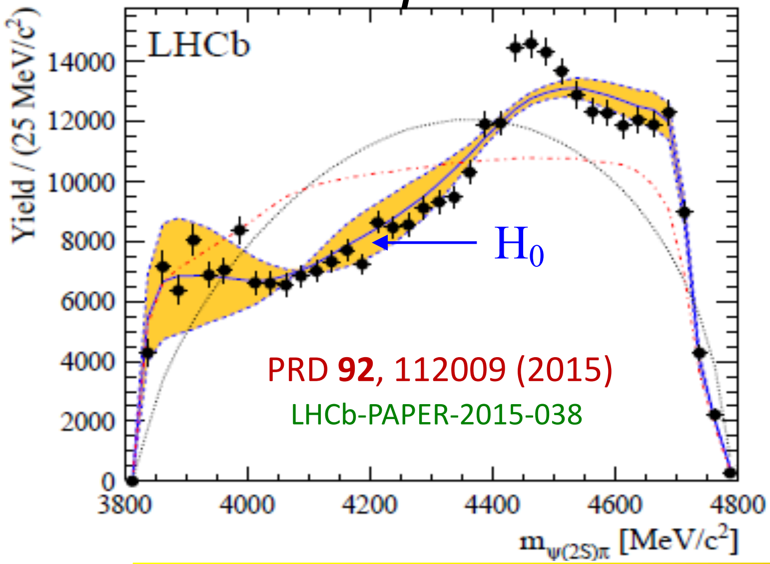
Non-zero values in the hatched area imply exotic contribution

Null exotic hypothesis (H_0) vs data

- Toy simulates the reflection of mass and angular structure of $K\pi/Kp$ onto $m_{\psi'\pi/\psi p}$
- Limits of l_{max} used (i.e. zero moments for > l_{max} order)
- $m_{\psi'\pi/\psi p}$ can not be explained by the reflections of conventional (non)resonances alone

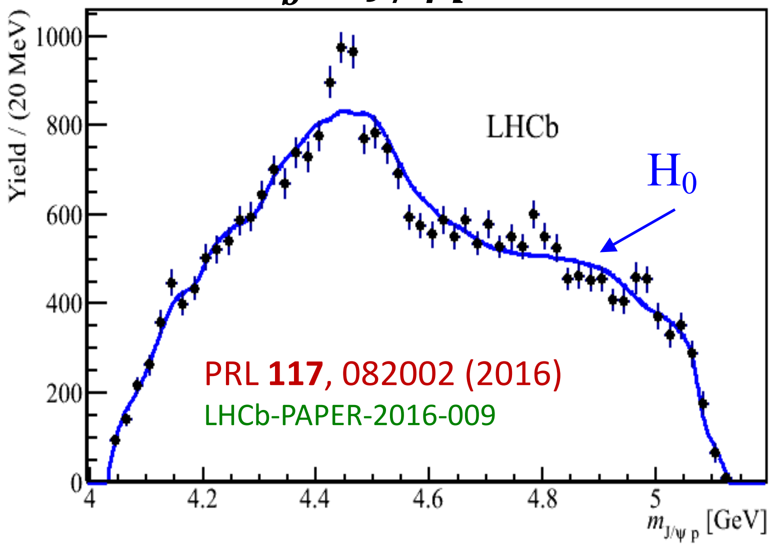
H_0 rejected by 15.2σ

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



H_0 rejected by 9.0σ

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



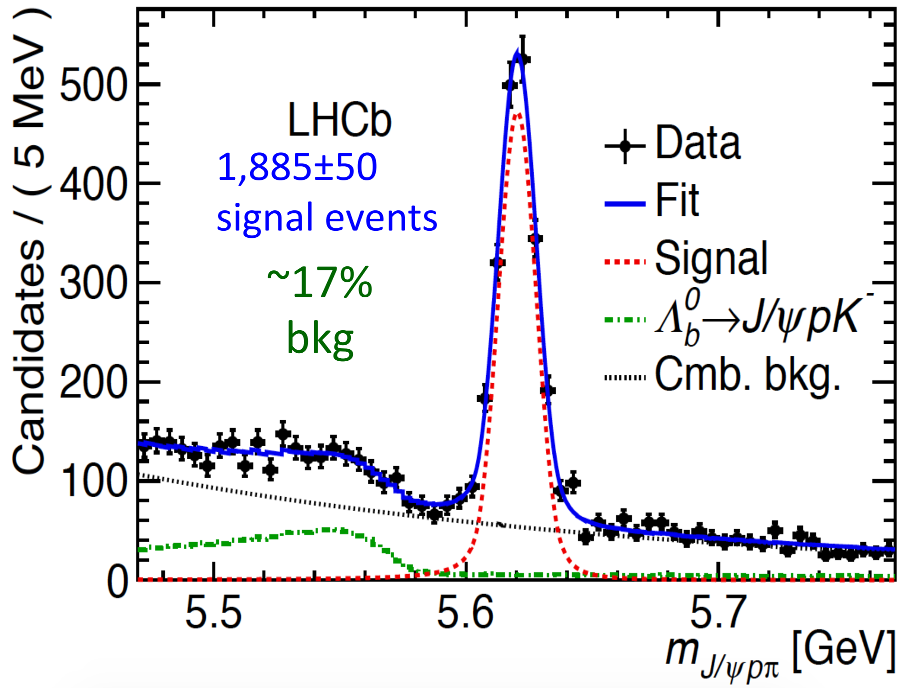
Exotic contributions in Cabibbo-suppressed decays $\Lambda_b^0 \to J/\psi p \pi^-$

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

LHCb-PAPER-2016-015

PRL **117**, 082003 (2016)

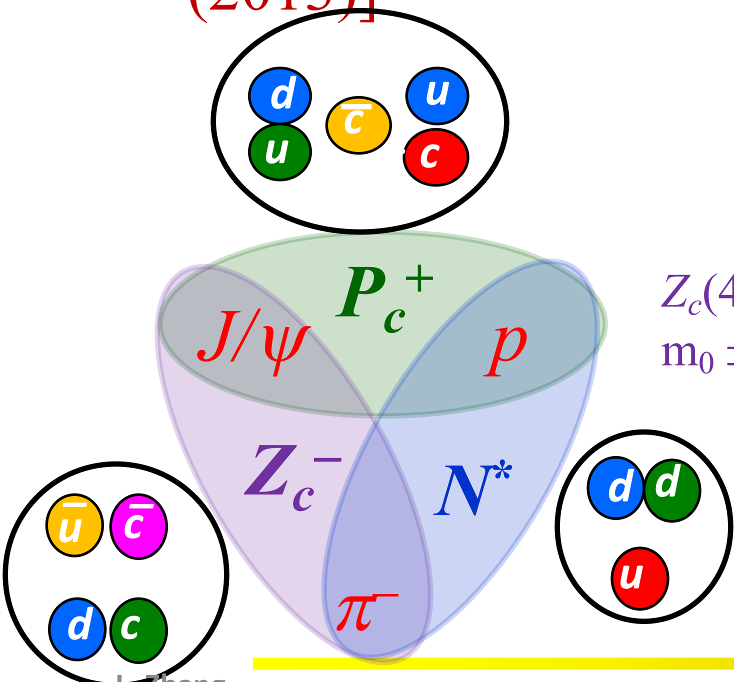
$\Lambda_b^0 \to J/\psi p \pi^-$



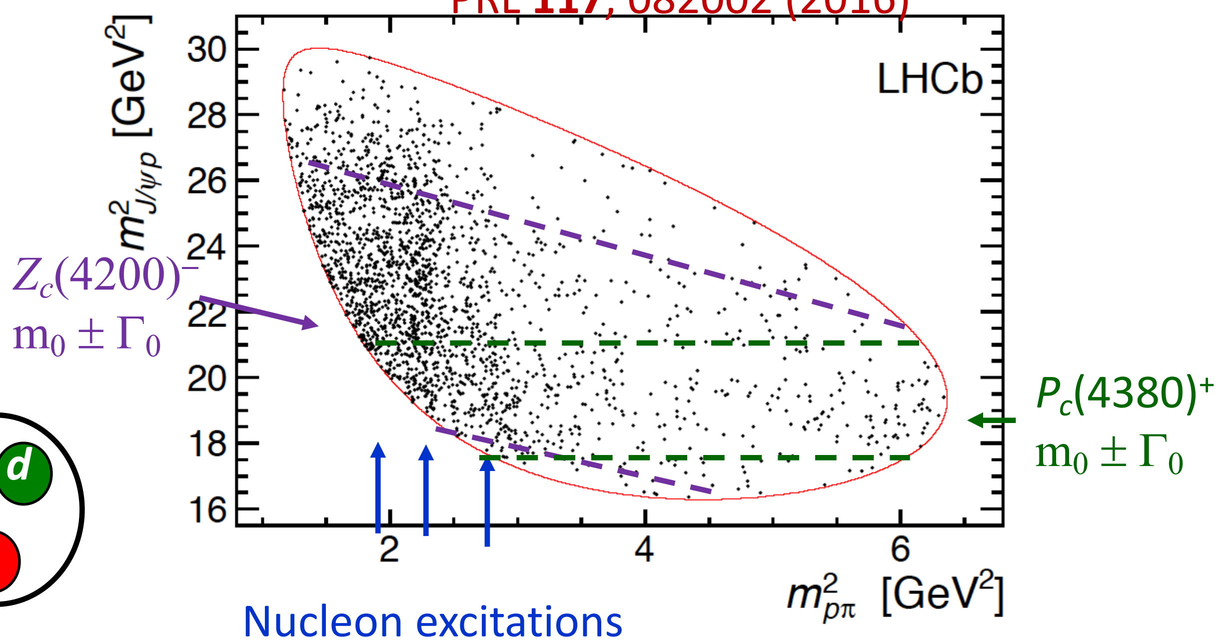
- More than a factor of 10 lower signal statistics in $\Lambda_b^0 \to J/\psi p \pi^-$ analysis than in $\Lambda_b^0 \to J/\psi p K^-$

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

- Less statistics, more complex because of Z_c^-
- Here the exotic hadron contributions are examined for $P_c(4380)^+$, $P_c(4450)^+ \to J/\psi p$ and $Z_c(4200)^- \to J/\psi\pi^-$
- $Z_c(4200)^-$ $m_0 = 4196^{+35}_{-32}$ MeV, $\Gamma = 370^{+99}_{-149}$ MeV $J^P=1^+$ by Belle (6.2σ) in $B^0 \to J/\psi \pi^- K^+$ decays [PRD 88, 074026 (2013)]



LHCb-PAPER-2016-015
PRL **117**, 082002 (2016)



Model of N* and exotic states

Better established states from PDG

$\Lambda_b^0 \rightarrow J/\psi\, p\, \pi^-$

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

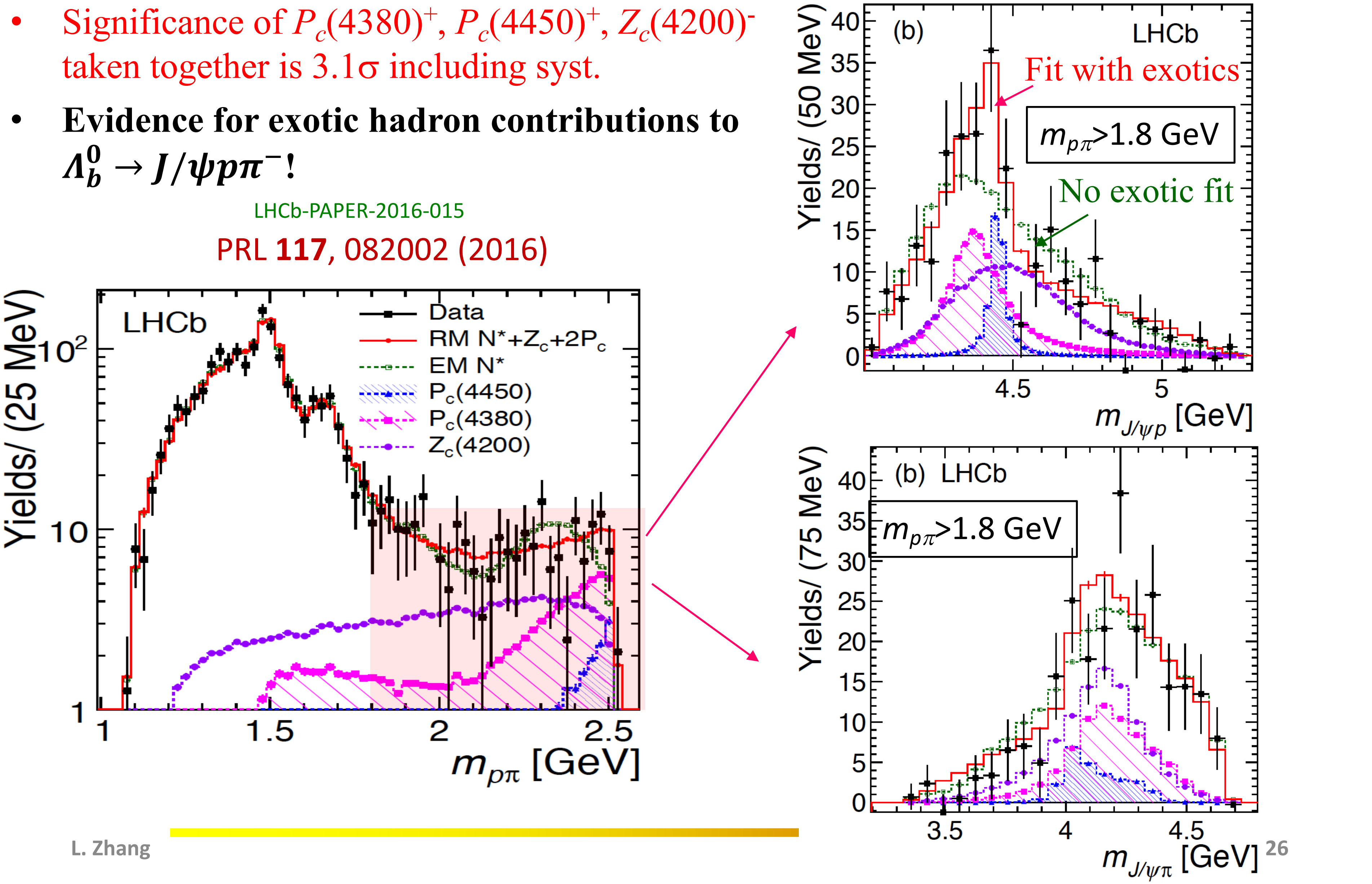
- Reduced model for central values
- Extended for significance and systematics
- Almost as many free parameters as in $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$
- Fixed m_0 and Γ_0 for the N* and exotic states
- $Z_c(4200)$: 10 free parameters
- Each P_c: 4 free parameters + 8 fixed to that from $\Lambda_b^0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

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

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ including syst.
- **Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$!**

LHCb-PAPER-2016-015

PRL **117**, 082002 (2016)



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

- Individual exotic hadron contributions are not significant if others are present. More data are needed
- Significance of two P_c is 3.3σ, if assume production of $Z_c(4200)^-$ is negligible. No independent confirmation of the P_c^+ states
- The data are consistent with the P_c states production rates expected from the $J/\psi p K^-$ measurement and Cabibbo suppression

LHCb-PAPER-2016-015

PRL **117**, 082002 (2016)

State	Fit fraction (%)	BR($\Lambda_b \to P_c^+\pi$)/BR($\Lambda_b \to P_c^+K^-$)
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$	---
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.6}_{-1.6}$	$0.050 \pm 0.016^{+0.026}_{-0.016} \pm 0.025$
$P_c(4450)^+$	$1.6\ {}^{+0.8}_{-0.6}\ {}^{+0.6}_{-0.5}$	$0.033\ {}^{+0.016}_{-0.014}\ {}^{+0.011}_{-0.010} \pm 0.009$

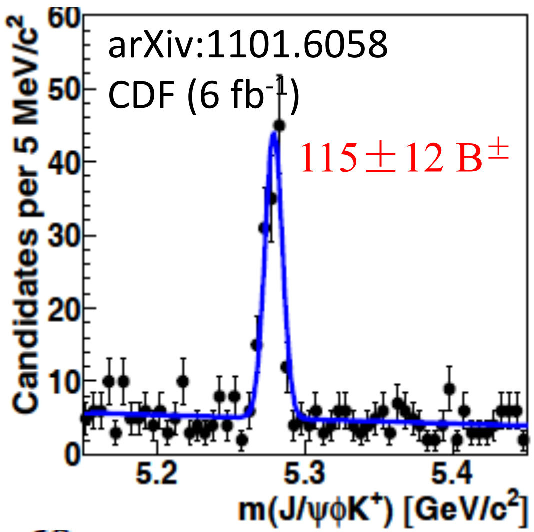
Expectation assuming the second diagram negligible: $0.07 \sim 0.08$

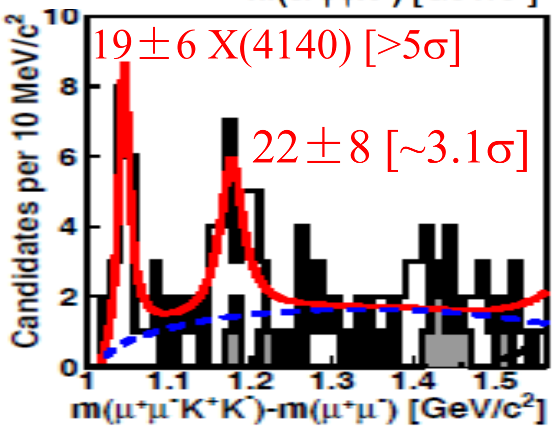
[Cheng and Chua, PRD **92**, 096009 (2015) arXiv:1509.03708]

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

X(4140) and X(4274)

- CDF observed a narrow $(J/\psi\phi)$ structure in $B^+ \to J/\psi\phi K^+$ 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 $D_s^+ D_s^-$ 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

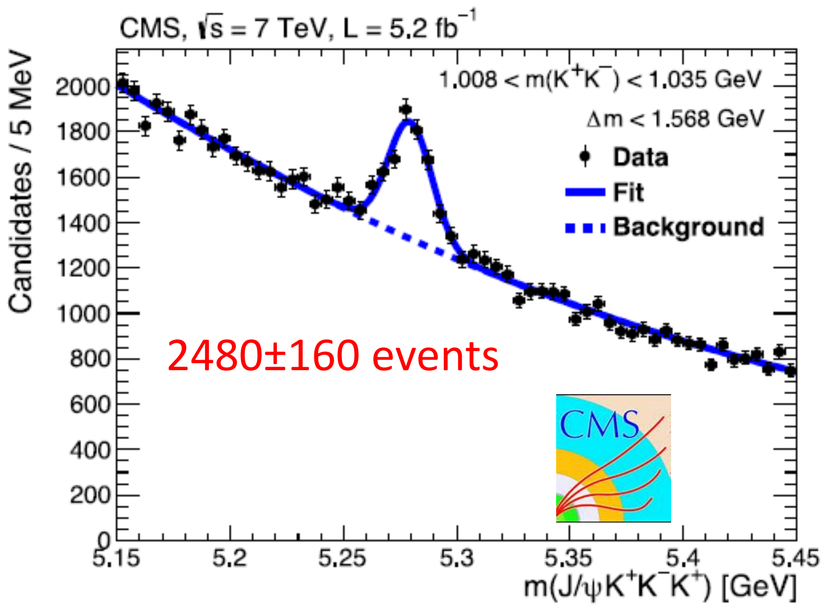


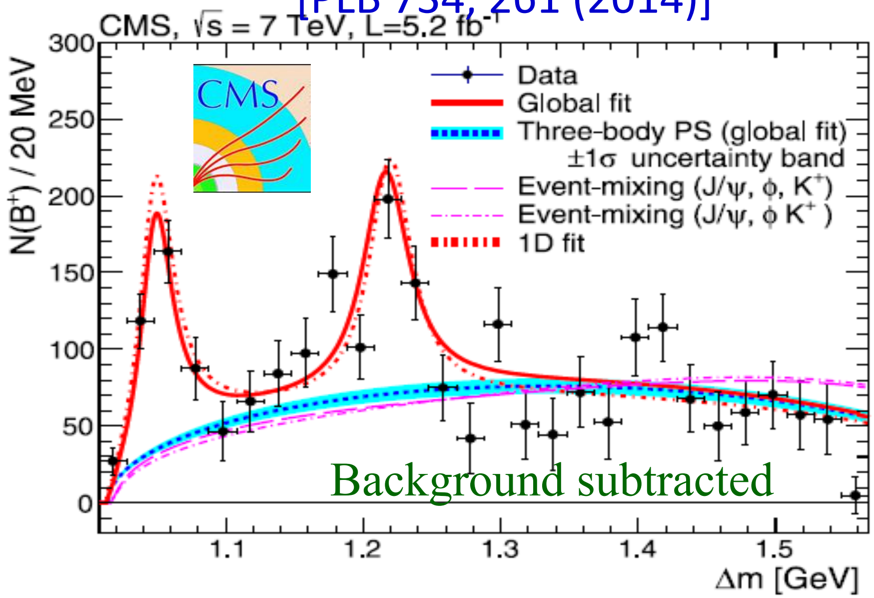


$X(4140)$ and $X(4274)$ from CMS

- Crucial to check by different experiments with larger statistics.

[PLB 734, 261 (2014)]

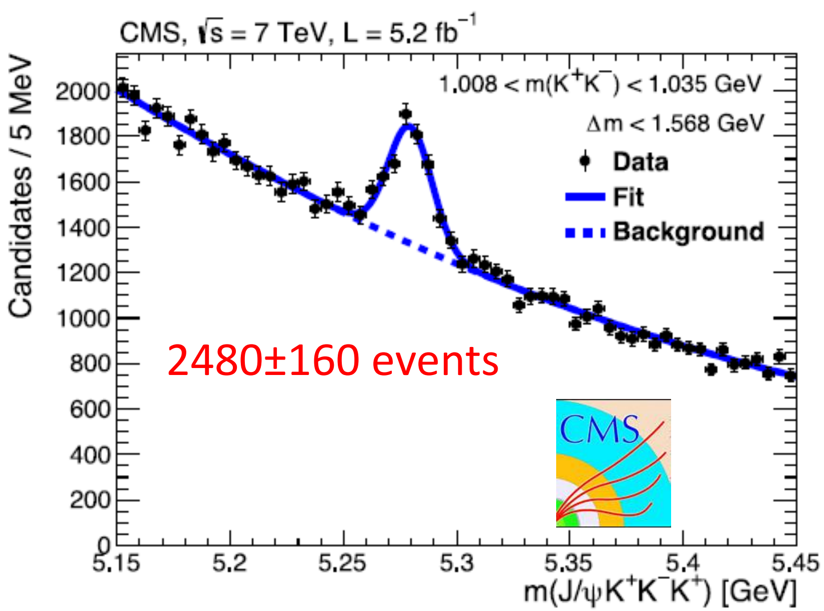




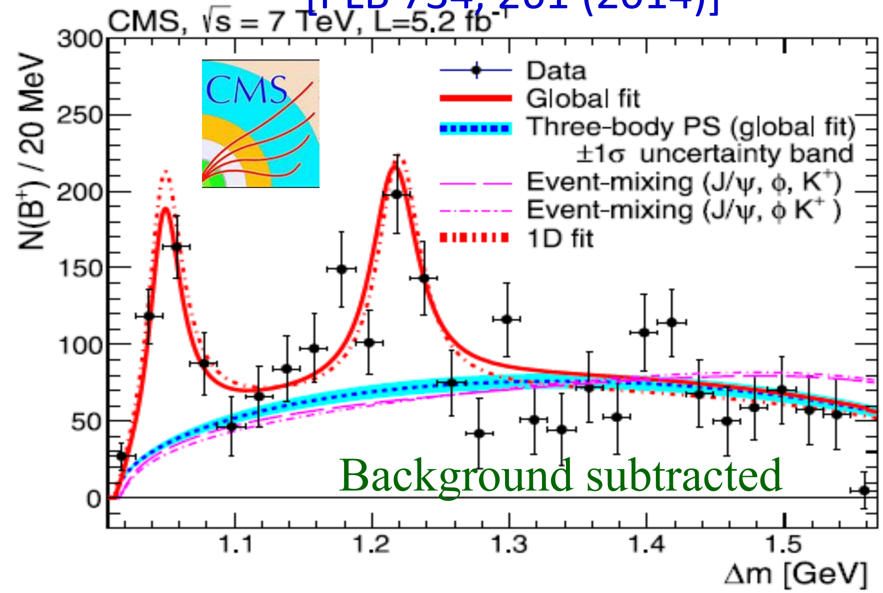
X(4140)	CDF [arXiv:1101.6058]	CMS [PLB 734, 261 (2014)]	DØ [PRD 89, 012004 (2014)]
Significance	>5σ	>5σ	3.1σ
M_0 (MeV)	$4143.4 \pm 3.0 \pm 0.6$	$4148.0 \pm 2.4 \pm 6.3$	$4159.0 \pm 4.3 \pm 6.6$
Γ_0 (MeV)	$15.3^{+10.4}_{-6.1} \pm 2.5$	$28^{+15}_{-11} \pm 19$	$19.9 \pm 12.6^{+1}_{-8}$

X(4140) and *X*(4274) from CMS

- Crucial to check by different experiments with larger statistics.



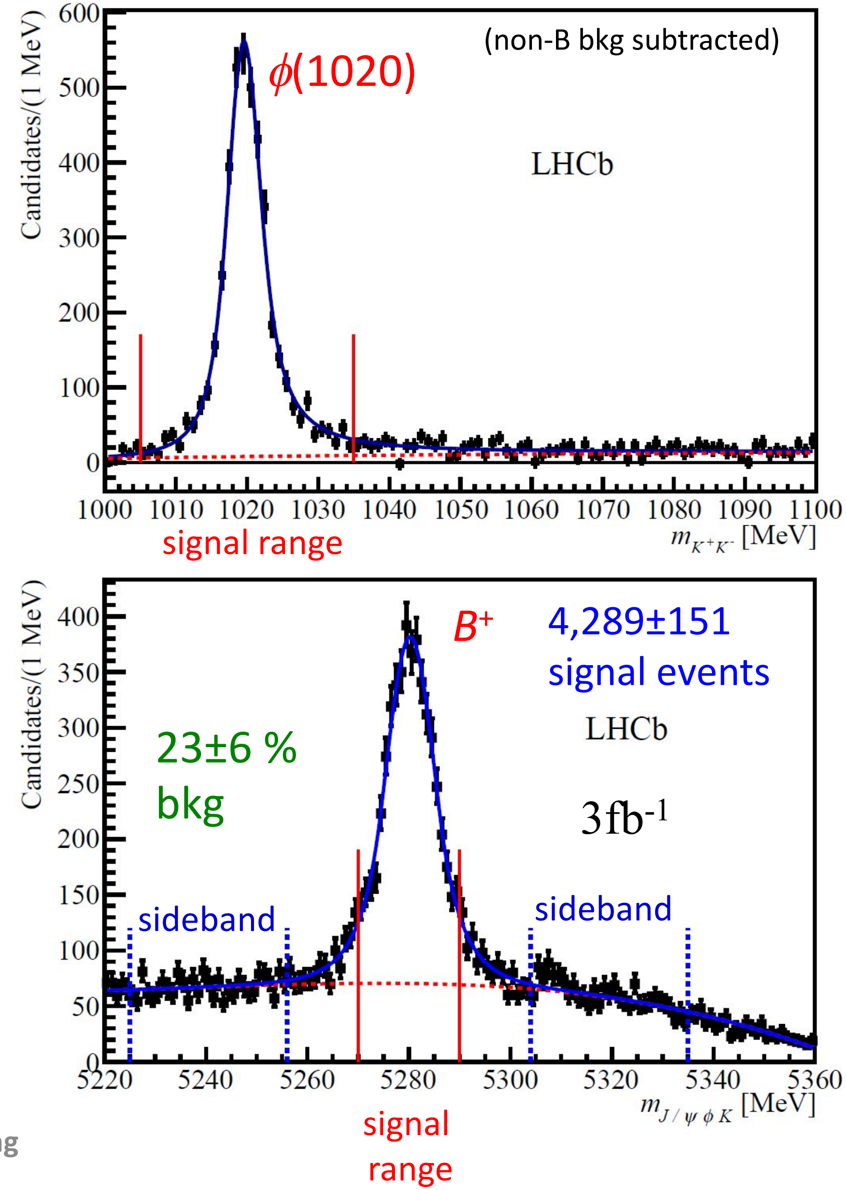
[PLB 734, 261 (2014)]



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

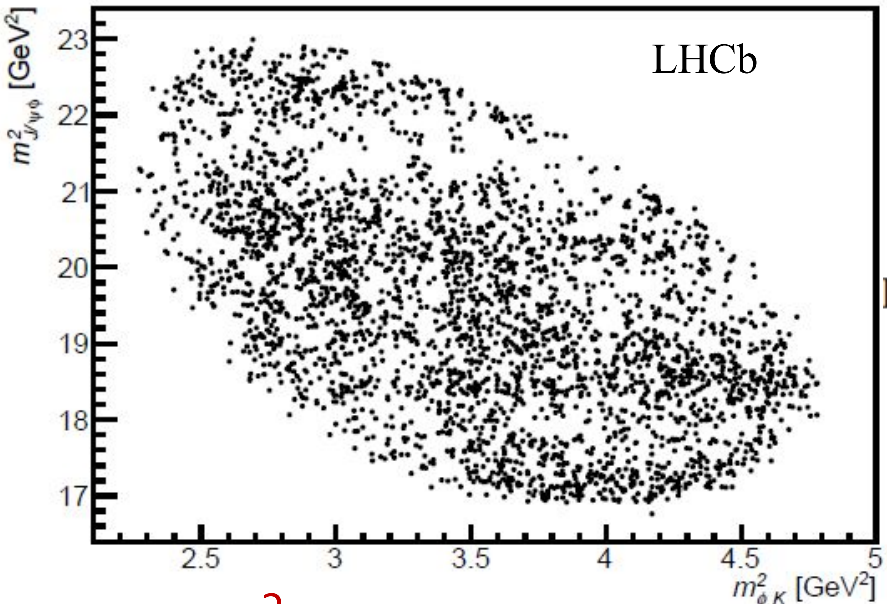
LHCb-PAPER-2016-018 arXiv: 1606.07895
LHCb-PAPER-2016-019 arXiv: 1606.07898



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

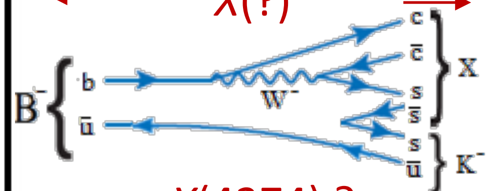
Use sidebands to subtract background

$B^+ \to J/\psi\phi K^+$



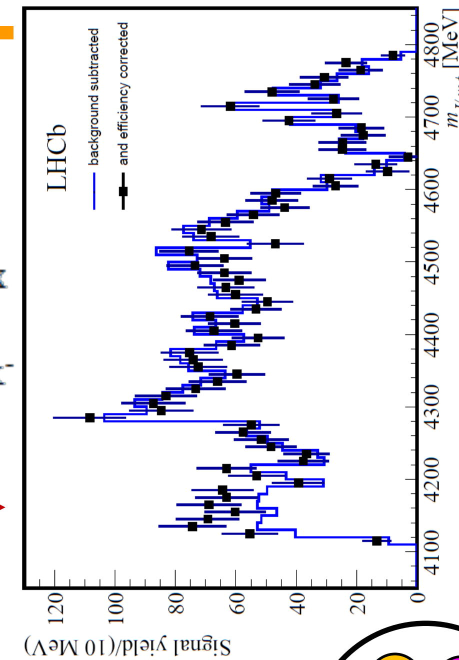
$X(?)$

$X(?)$

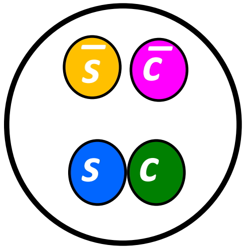


$X(4274)$?

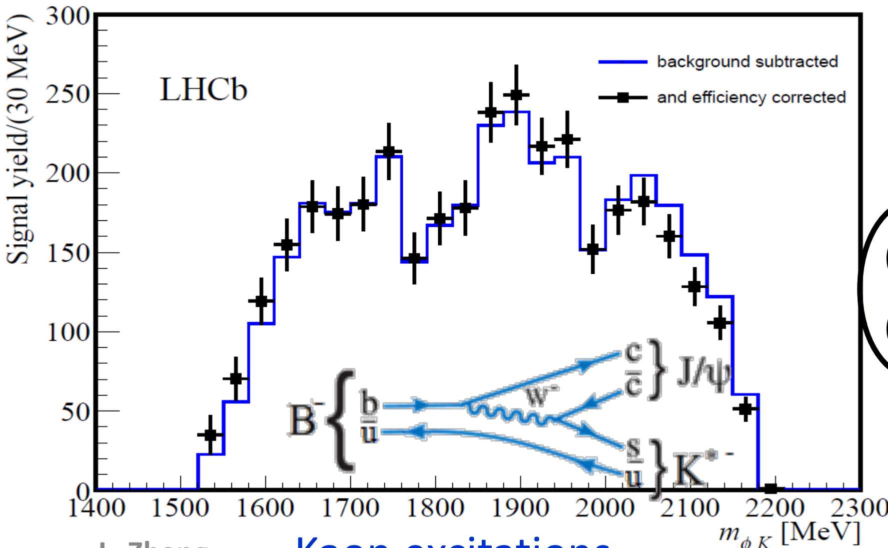
$X(4140)$? $\to J/\psi\phi$

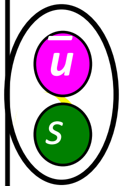


Tetraquark



?





Is it a reflection of interfering $K^{*-} \to \phi K^-$?

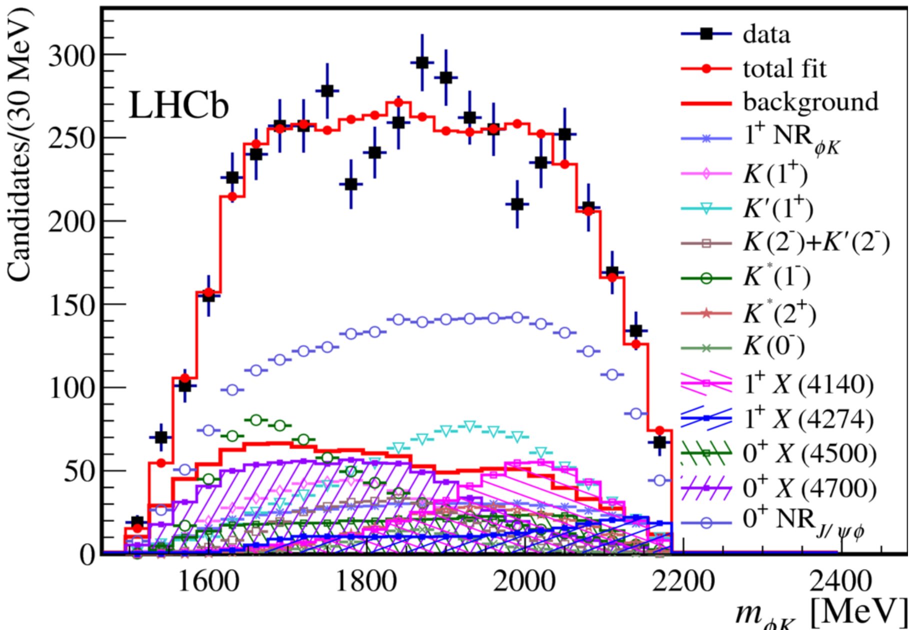
Proper amplitude analysis necessary to check

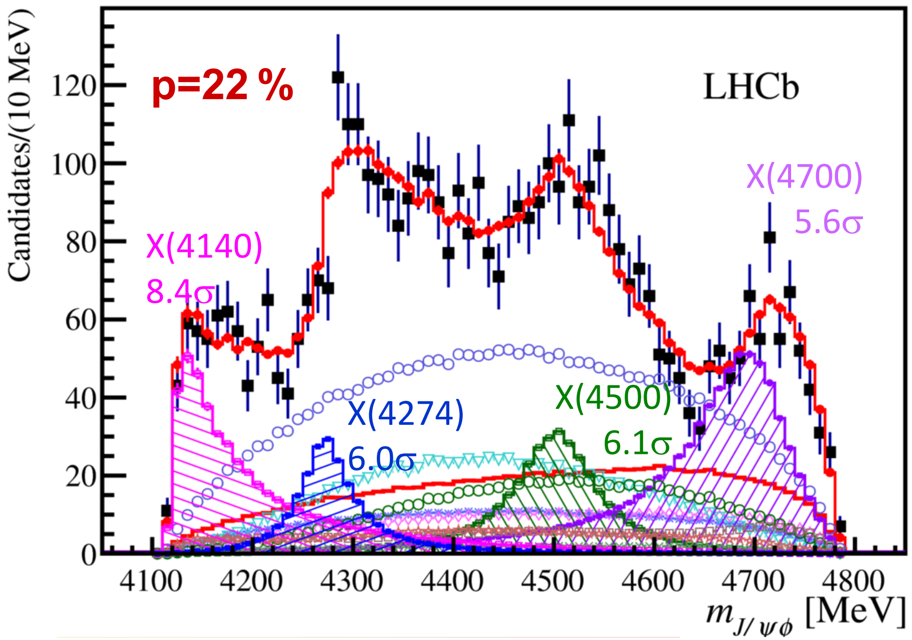
Kaon excitations

Amplitude fit including 4 exotic X

LHCb-PAPER-2016-019 arXiv: 1606.07898

- Four X states + NR $J/\psi\phi$ give very significant improvements over the models with K*s alone
- Default model also includes NR ϕK + 7 K^* (float M_0 and Γ_0) that are significant
- These results add significantly to the knowledge of K spectroscopy (results in the paper and backup)





Results

LHCb-PAPER-2016-019 arXiv: 1606.07898

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

Contri-bution	sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	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 $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\,\phi}$	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	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

substantially larger

Search for $B_s^0\pi^\pm$ state

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

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

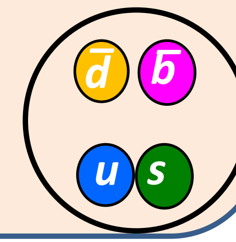
Claimed evidence of an exotic state

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

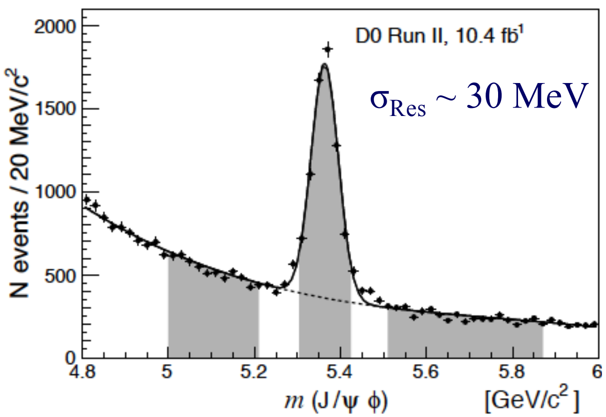
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV}$$

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

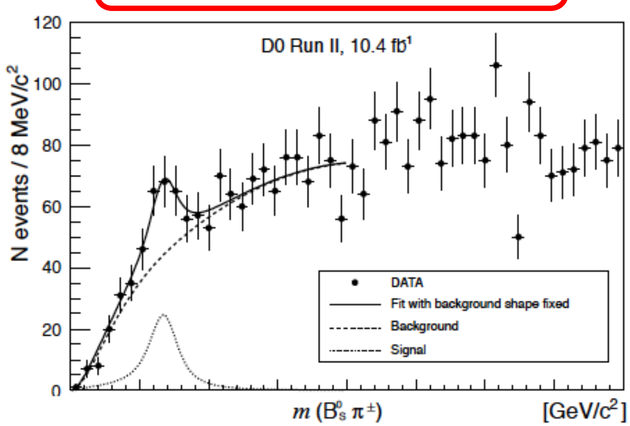
- Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)\ \%$
- **If confirmed, would be unique with 4 different flavours**



$N(B_s) \sim 5500$

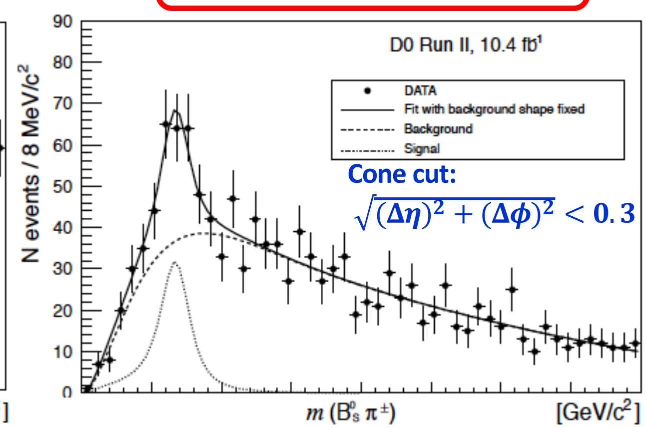


$N(X) = 106 \pm 23$



3.9 σ

$N(X) = 133 \pm 31$

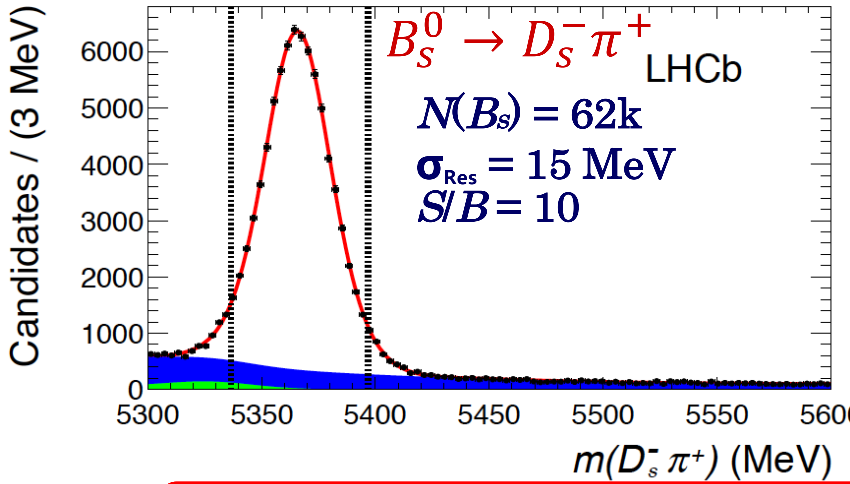


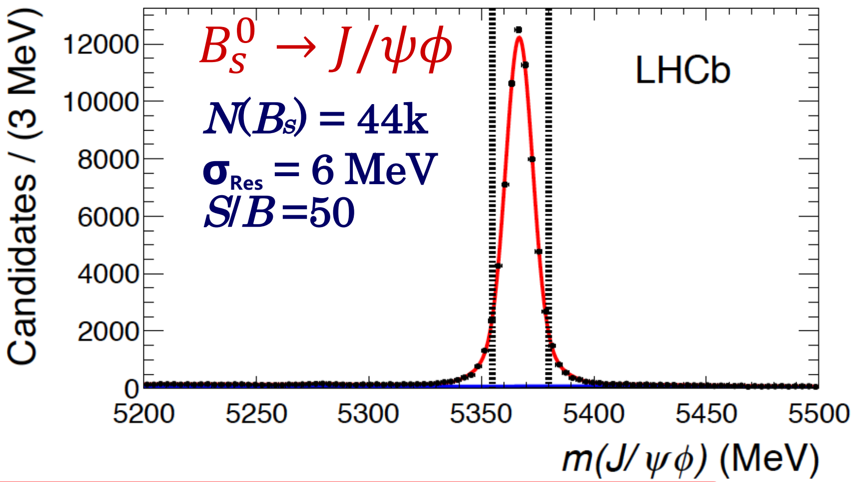
5.1 σ

Signal significance

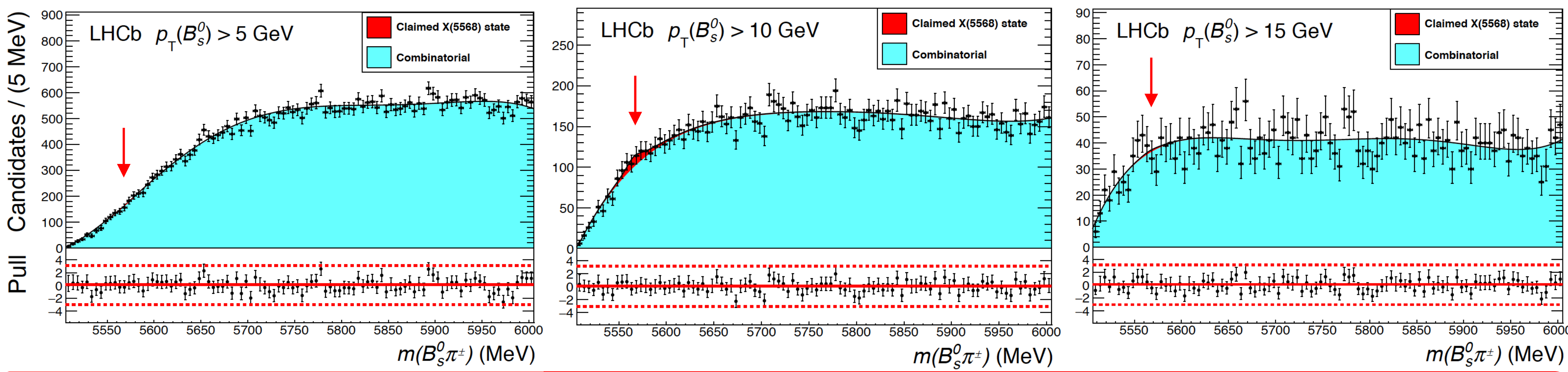
Samples from LHCb

LHCb-PAPER-2016-029
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

LHCb-PAPER-2016-029
PRL **117**, 152003 (2016)

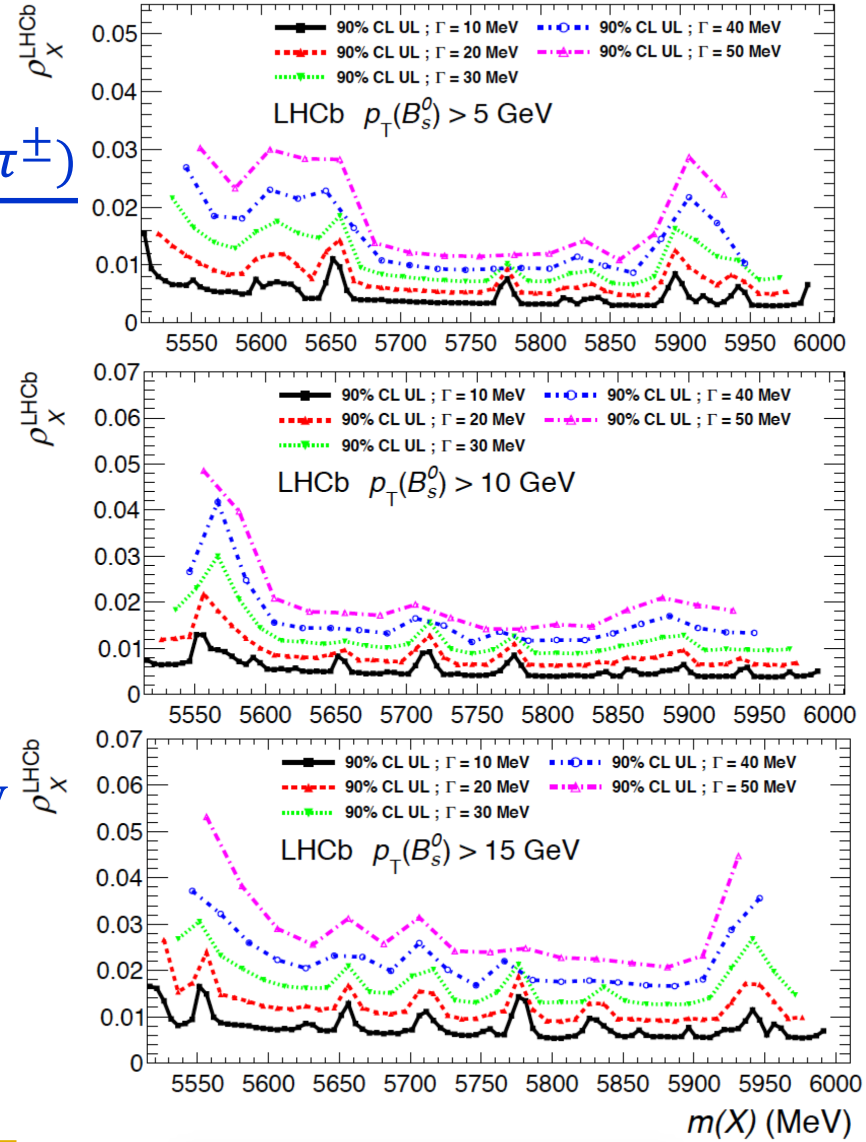
- At 90% (95%) CL

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

in LHCb acceptance

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

- No significant $B_s^0\pi^\pm$ states for any mass and width below 6 GeV
- Upper limit is set as a function of m(X) and Γ(X)



Summary

- No significant signal for a tetraquark of $B_s^0\pi^\pm$ for $m < 6$ GeV
- $Z_c(4430)$ state is confirmed, and two pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$ are observed
- Using amplitude analysis, 3.1σ evidence is seen for the exotic hadron contributions in $\Lambda_b^0 \to J/\psi p\pi^-$ (more data needed)
- Four $X \to J/\psi\phi$ observed in the 1st full amplitude analysis of $B^+ \to J/\psi\phi K^+$
- More studied can be made with Run-II data, in similar channels where J/ψ replaced by ψ', χ_{c1}, η_c etc.

LHCb-PAPER-2015-060

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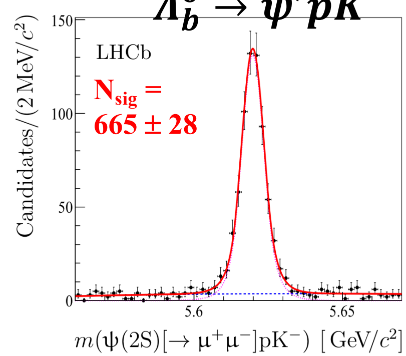
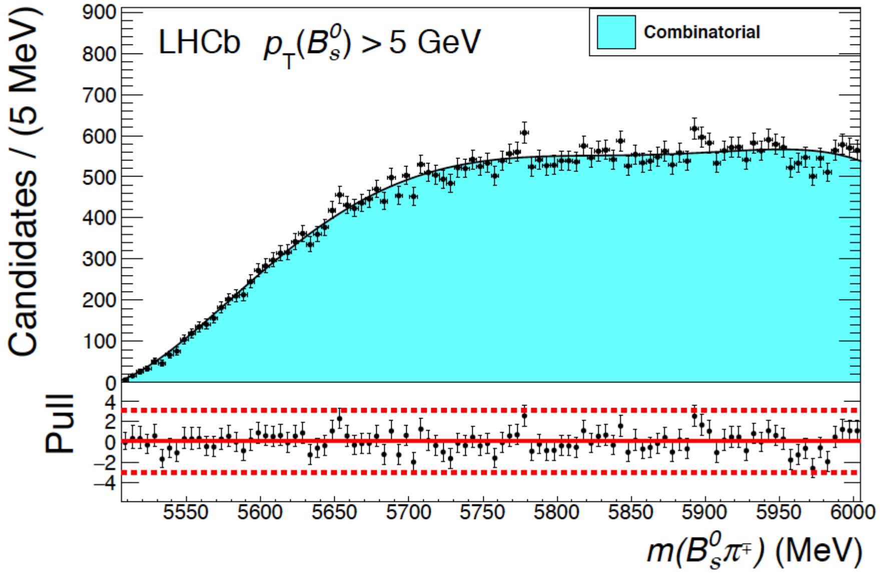
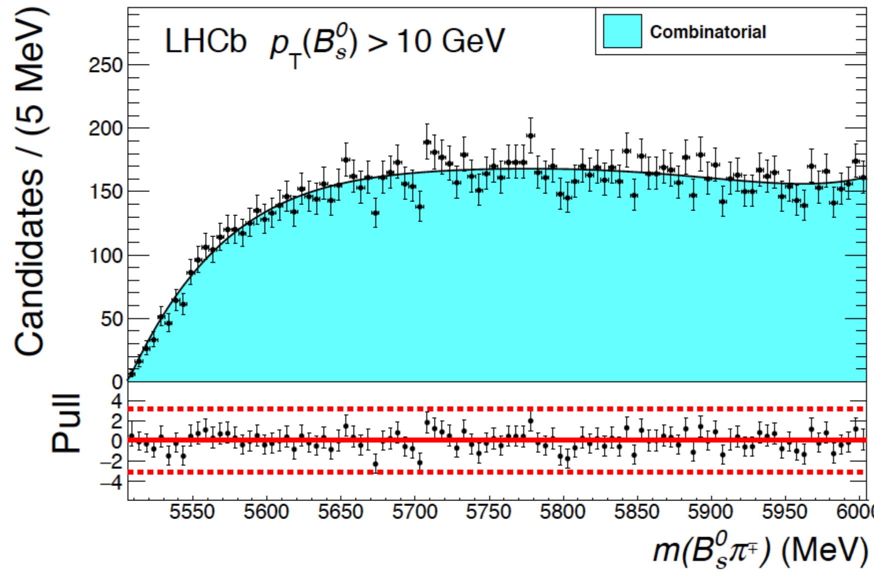
$\Lambda_b^0 \to \psi' p K^-$



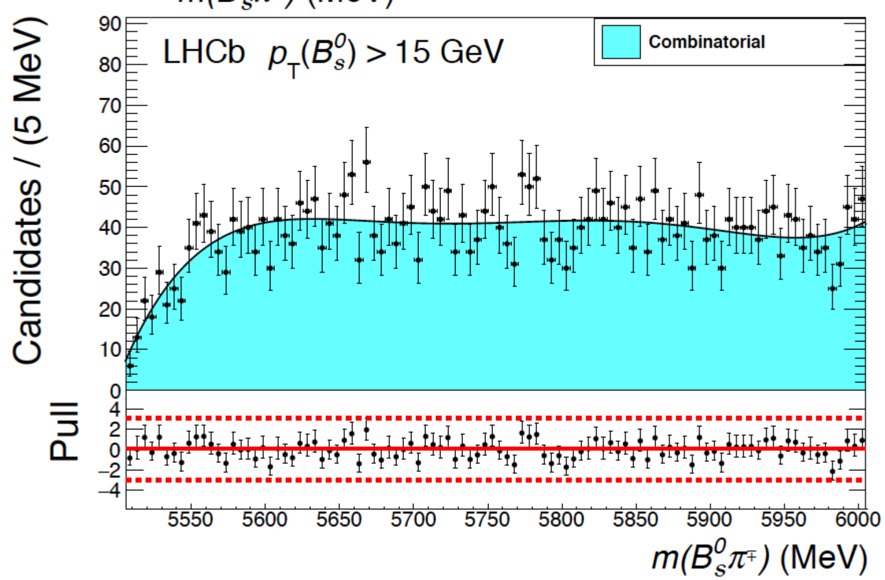
BACKUP

Search for $B_s^0\pi^\pm$ state: fits w/o signal





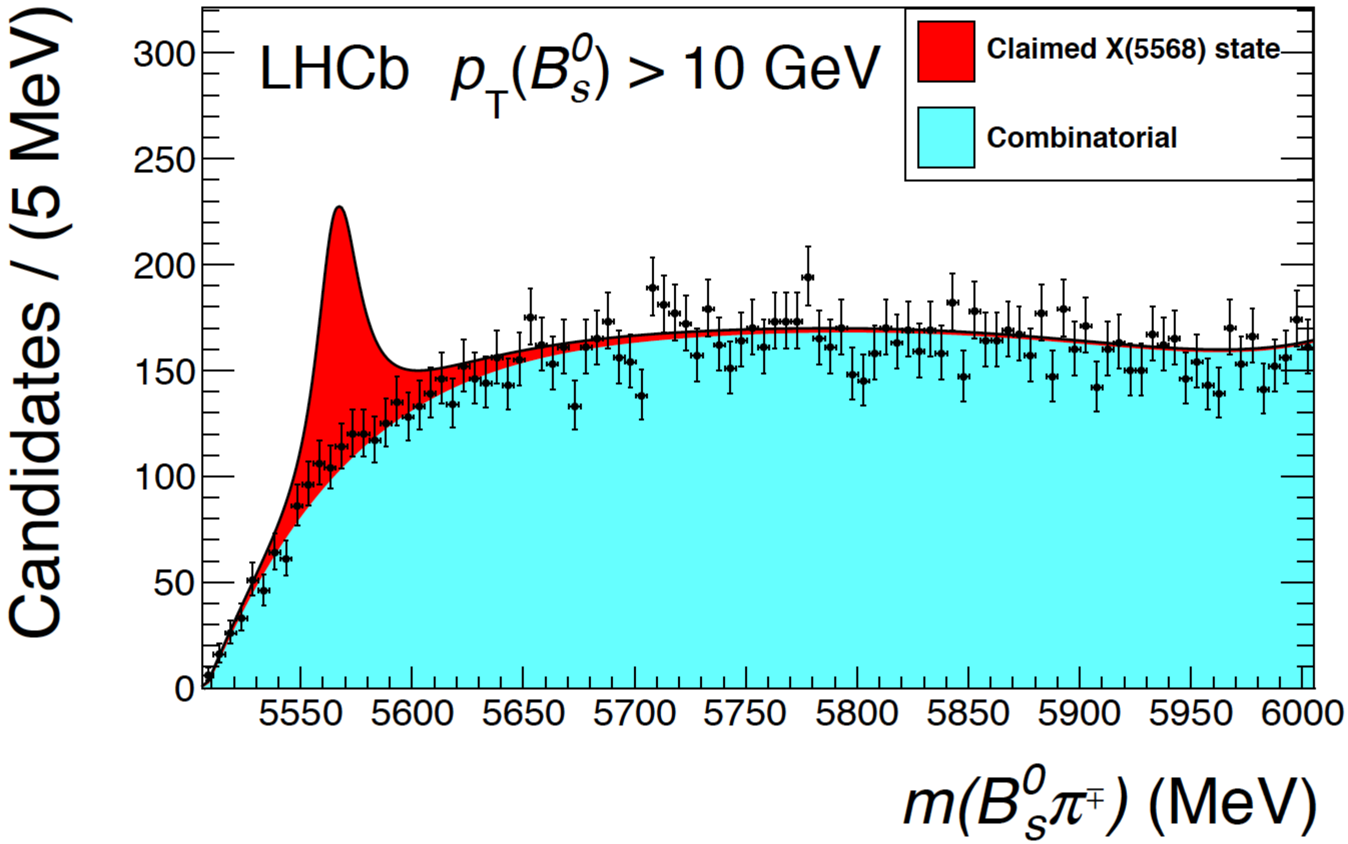
LHCb-PAPER-2016-029
arXiv:1608.00435



Search for $B_s^0\pi^\pm$ state

LHCb-PAPER-2016-029
arXiv:1608.00435

- Superimpose signal component assuming $\rho_X^{\text{LHCb}} = \rho_X^{\text{DØ}} = 8.6\%$



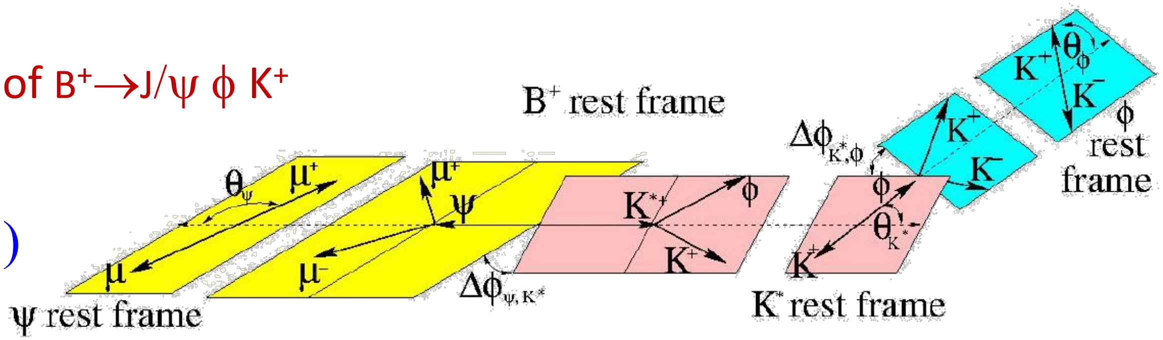
Amplitude analysis needed

- All previous analyses performed naïve 1D mass fits to $m_{J/\psi\phi}$
  - Ad hoc assumptions about kaon contributions (e.g. 3-body phase-space distribution, incoherent)
  - No sensitivity to J^{PC} of X structures

Perform first amplitude analysis of $B^+ \to J/\psi\, \phi\, K^+$

$$\Omega \equiv (\theta_{K^*}, \theta_{\psi}, \Delta\phi_{\psi,K^*}, \theta_{\phi}, \Delta\phi_{K^*,\phi})$$

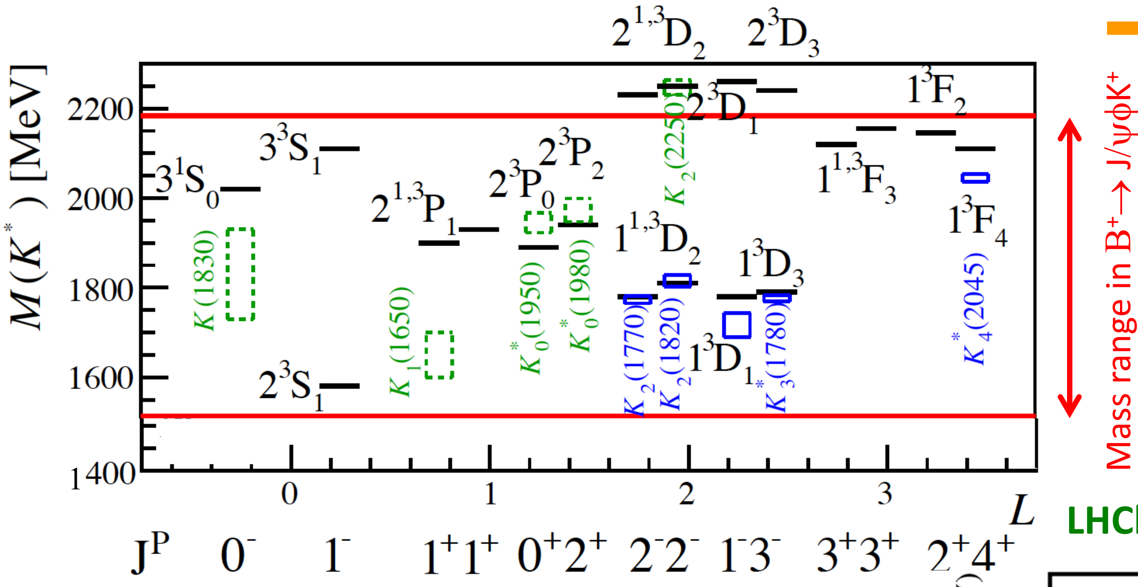
$$\left| MatrixEle(\mathrm{m}_{K\phi}, \Omega \,|\, J_R^P, M_R, \Gamma_R, H_R) \right|^2$$



6D maximum likelihood fit

1-4 independent **complex** helicity couplings H_R per K^* resonance

Amplitude fits with kaon excitations only



Guidance from quark model prediction

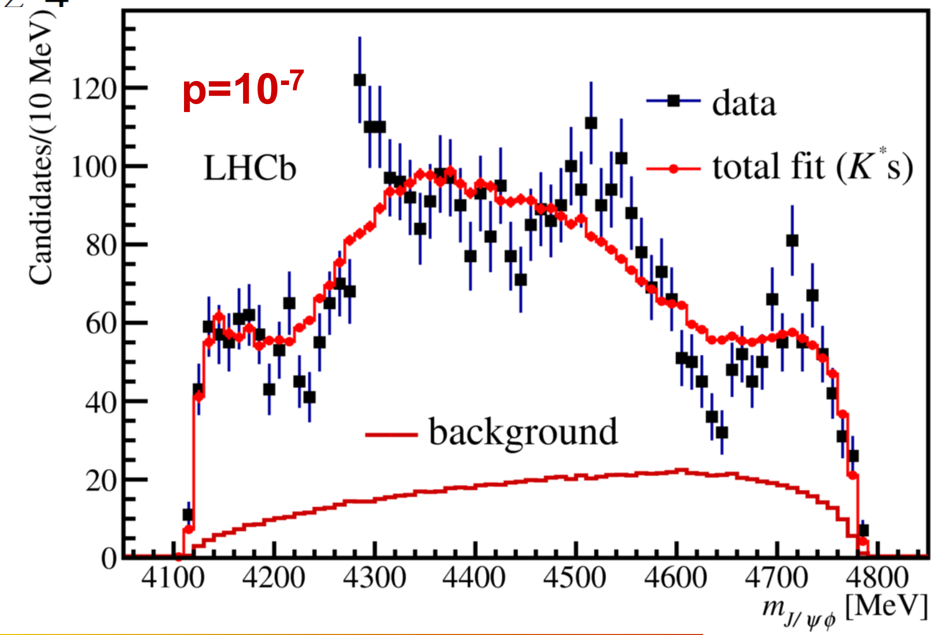
Godfrey-Isgur, PRD 32, 189 (1985)

Established

Unconfirmed

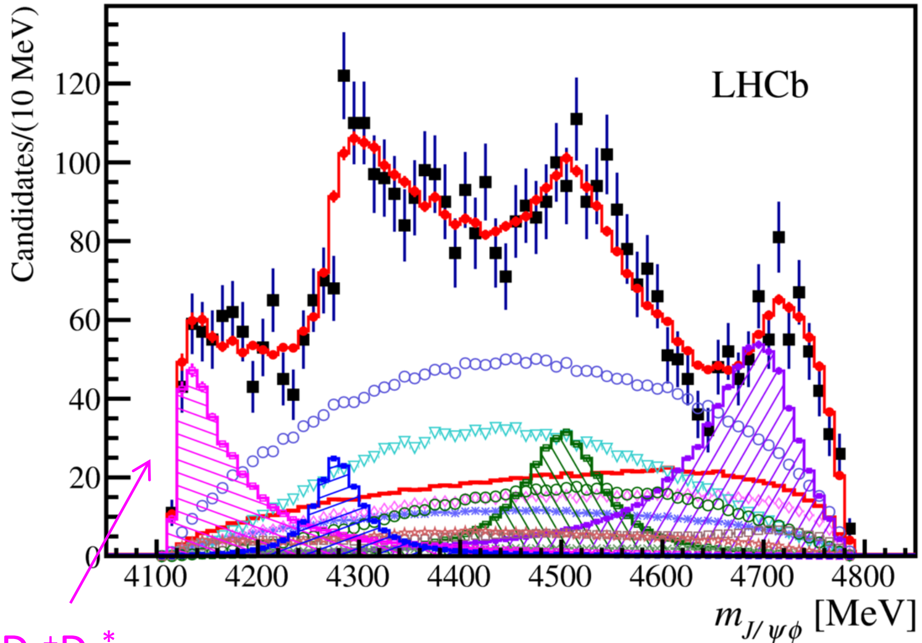
LHCb-PAPER-2016-019 arXiv: 1606.07898

- M_0 and Γ_0 of K^*s are kept float in the fits
- Data can not be described by K^* only
  - Example fit: 12 K^* + NR ϕK

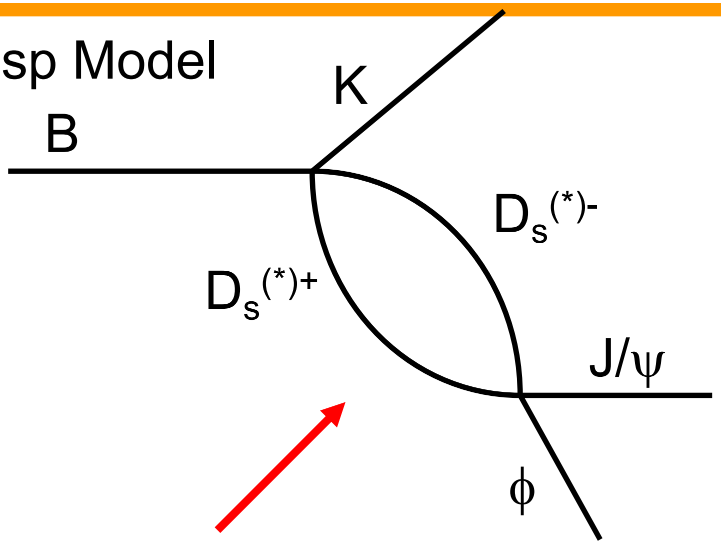


Is X(4140) a $D_s^+ D_s^{*-}$ cusp ?

LHCb-PAPER-2016-019 arXiv: 1606.07898



$D_s^+D_s^{*-}$ cusp



Cusp model by
E. S. Swanson, arXiv:1504.07952
(see also PRD91, 034009 (2015))

- The cusp is preferred by 1.6σ over the Breit-Wigner amplitude for X(4140) from the fit likelihood ratio
- No success in describing any other J/ψϕ mass structures as a cusp

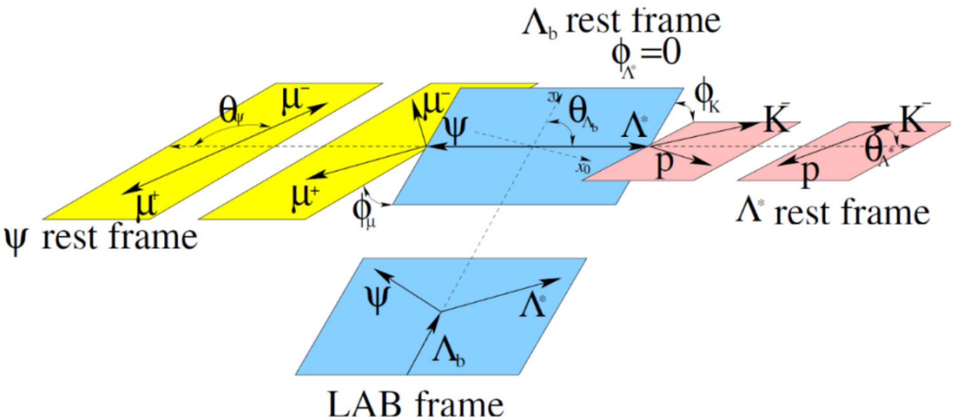
Amplitude Analysis Formalism

- Helicity formalism
  - Allows for the conventional $\Lambda^* \to pK$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$
  - Use m(K⁻p) & 5 decay angles as fit parameters.

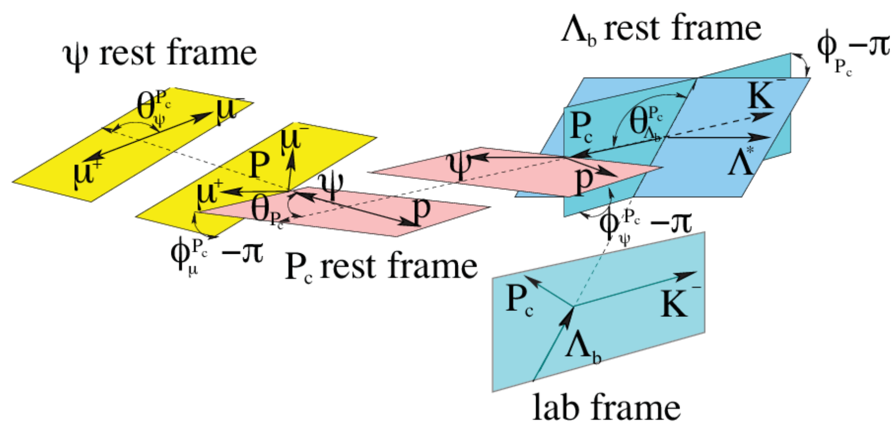
So 6D fit

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\, \lambda_p,\, \Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\, \lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\, \lambda_p^{P_c},\, \Delta\lambda_\mu} \right|^2$$

Λ^* Decay Chain



P_c^+ Decay Chain



Systematic uncertainty

LHCb-PAPER-2015-029
PRL 115, 07201 (2015)

$\Lambda_b^0 \to J/\psi\, pK^-$

Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	Fit fractions (%) $\Lambda(1405)$	Fit fractions (%) $\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L_{\Lambda_b^0}^{\Lambda_n^*}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Systematic uncertainty

LHCb-PAPER-2016-015
arXiv: 1606.06999, to appear in PRL

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

Source	$P_c(4450)^+$	$P_c(4380)^+$	$Z_c(4200)^-$
N^* masses and widths	±0.05	±0.23	±0.31
P_c^+, Z_c^- masses and widths	±0.32	±1.27	±1.56
Additional N^*	${}^{+0.08}_{-0.23}$	${}^{+0.59}_{-0.55}$	${}^{+0.71}_{-2.92}$
Inclusion of $Z_c(4430)^-$	$+0.01$	$+0.97$	$+2.87$
Exclusion of $Z_c(4200)^-$	-0.15	$+1.61$	-
Other J^P	${}^{+0.38}_{-0.00}$	${}^{+0.92}_{-0.28}$	${}^{+0.00}_{-2.16}$
Blatt–Weisskopf radius	±0.11	±0.17	±0.21
$L^{N^*}_{\Lambda_b^0}$ in $\Lambda_b^0 \to J/\psi\, N^*$	±0.07	±0.46	±0.04
$L^{P_c}_{\Lambda_b^0}$ in $\Lambda_b^0 \to P_c^+\pi^-$	-0.05	-0.17	$+0.09$
$L^{Z_c}_{\Lambda_b^0}$ in $\Lambda_b^0 \to Z_c^- p$	±0.07	±0.22	±0.53
K-matrix model	-0.03	$+0.11$	-0.02
P_c^+ couplings	±0.14	±0.31	±0.36
Background subtraction	-0.07	-0.13	-0.39
Total	${}^{+0.55}_{-0.48}$	${}^{+2.61}_{-1.58}$	${}^{+3.43}_{-4.04}$

Systematic uncertainty

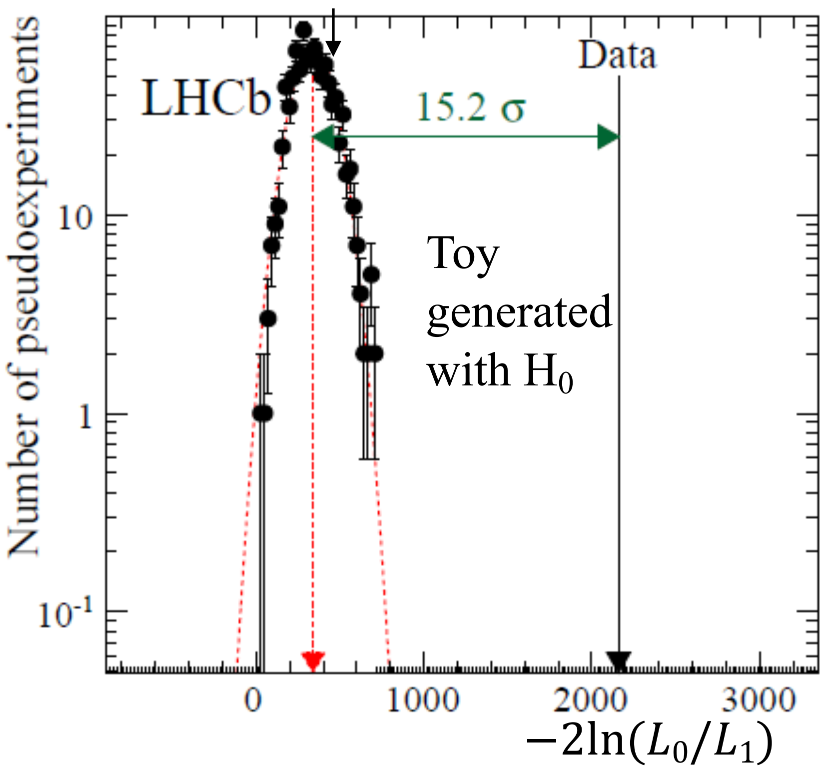
LHCb-PAPER-2016-019
arXiv: 1606.07898

sys.	1^+	$X(4140)$			$X(4274)$			0^+	$X(4500)$			$X(4700)$			NR
var.	FF	M_0	Γ_0	FF	M_0	Γ_0	FF	FF	M_0	Γ_0	FF	M_0	Γ_0	FF	FF
K^*	+2.0	+3.6	+17.1	+2.2	+11.2	+7.9	+1.4	+1.8	+9.3	+13.8	+2.0	+7.5	+38.6	+6.7	+8.0
model	−1.7	−2.6	−11.7	−1.9	−2.5	−8.5	−1.5	−11.0	−8.6	−16.6	−1.7	−18.9	−13.5	−4.8	−16.6
L	+3.2	+2.2	+7.3	+2.1	+10.6	+1.4	+1.0	+0.3	+1.3	+10.8	+1.7	+9.0	+12.4	+1.5	+1.2
var.	+0.0	−1.2	−6.2	−0.5	−0.8	−4.6	−1.2	−4.7	−9.6	−11.2	−1.6	−6.8	−24.9	−0.8	−8.5
NR exp.	+0.4	−0.2	−0.1	+0.4	−0.2	+0.6	+0.8	−1.7	+6.3	+0.3	+0.2	+7.1	−15.7	−1.7	−9.1
X cusp	+2.2			+0.9	+6.4	−5.4	−1.4	−1.2	+0.0	+1.2	+0.2	+1.9	−2.5	0.5	−1.6
$\Gamma_{\rm tot}$	−0.6	+0.2	+1.5	−0.4	+3.2	+0.2	−0.3	+0.1	+0.8	−0.1	−0.3	+0.9	−5.8	−0.9	−1.1
d=1.5	−0.9	+1.1	+5.3	−0.5	+2.2	+0.8	−0.4	+0.5	+1.7	+3.2	+0.1	−0.1	+1.7	+0.0	+1.1
d=5.0	+1.1	−0.2	−2.0	+0.6	+0.2	−0.8	+0.3	−0.5	−1.0	−3.1	−0.1	−1.2	−3.2	−0.7	−2.5
Left s.	+0.1	−0.4	−2.0	+0.1	+0.4	−0.8	+0.1	−0.5	−2.4	−2.6	−0.2	−1.5	−3.1	−0.7	−1.2
Right s.	−0.3	+0.3	+2.6	−0.2	−0.6	+1.0	+0.0	+0.5	+3.7	+3.4	+0.4	+1.2	+7.0	+0.8	+1.6
β	+1.2	−0.6	−3.6	+1.2	+1.7	−0.7	+0.9	−2.5	−4.6	−11.1	−0.5	−3.9	−6.1	−1.4	−1.4
No w^{MC}	+1.6	+0.0	+0.0	+0.1	+0.0	+0.0	+1.4	+1.7	+0.0	+0.2	+0.2	+0.1	+0.0	+1.2	+2.7
ϕ window	+2.5	+1.1	+4.7	+2.4	−1.6	+1.4	+1.8	+4.2	−4.3	+7.1	+1.2	−9.3	+5.8	+0.7	+4.7
Total	+5.9	+4.6	+20.7	+4.7	+17.2	+8.4	+3.5	+6.5	+12.0	+20.8	+3.2	+13.9	+42.0	+7.2	+11.0
sys.	−2.1	−2.8	−13.5	−2.0	−3.6	−11.1	−2.4	−6.7	−14.5	−20.4	−2.3	−24.1	−33.3	−5.3	−21.0
Stat.	2.8	4.5	20.7	3.2	8.3	10.9	2.5	5.1	11.1	21.2	2.4	10.1	30.7	4.9	10.7
${p_{\rm T}}^K$>500	−1.3	+1.6	+1.7	−2.7	+7.8	+12.2	+0.2	−9.6	−10.9	−18.6	−3.2	−4.7	−12.7	−6.6	−17.1

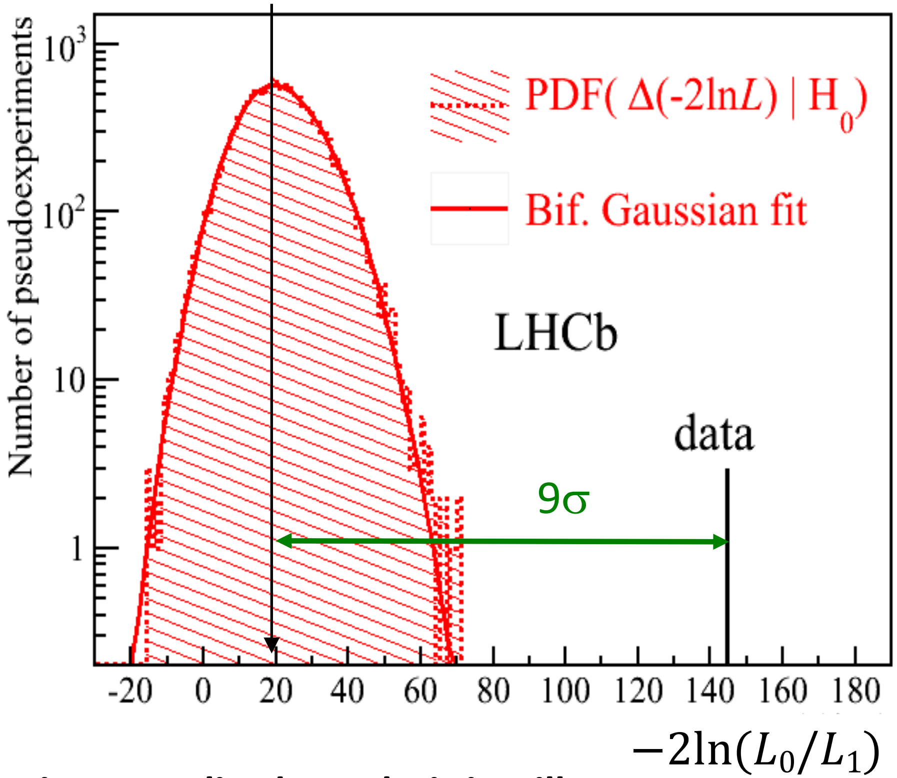
Log-likelihood ratio method

- 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

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



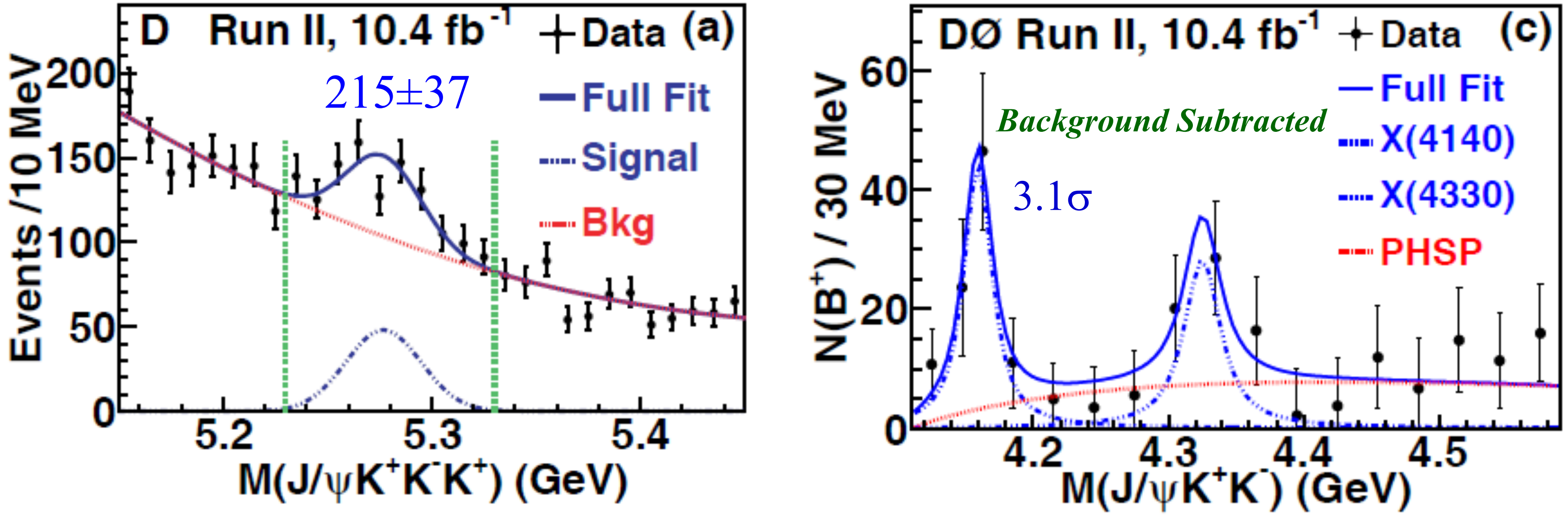
$\Lambda_b \to J/\psi\, p\, K^-$



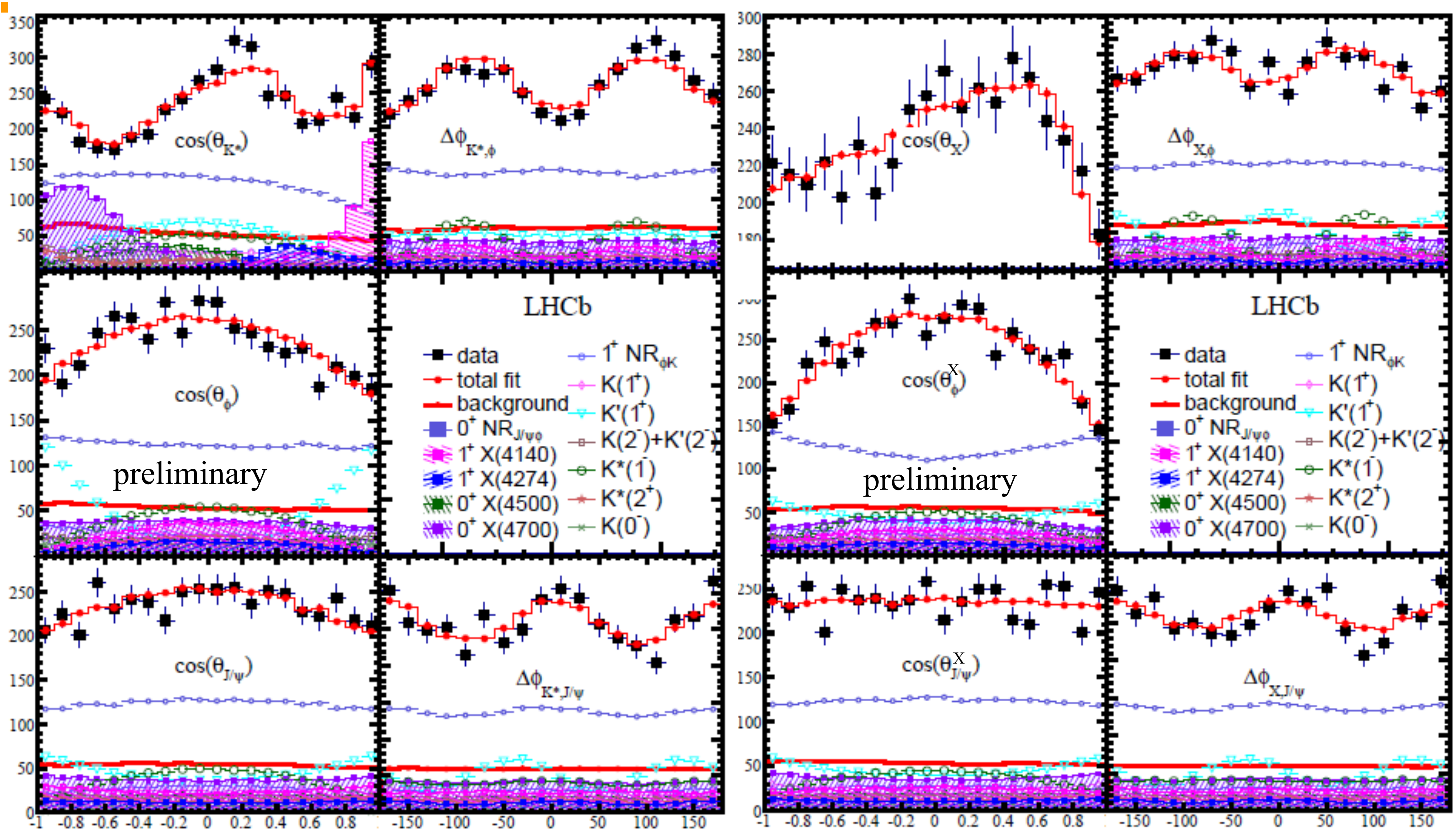
However, this approach cannot characterize exotics – amplitude analysis is still necessary

X(4140) from DØ

[Phys. Rev. D 89, 012004 (2014)]



Fitted angles in J/ψφK

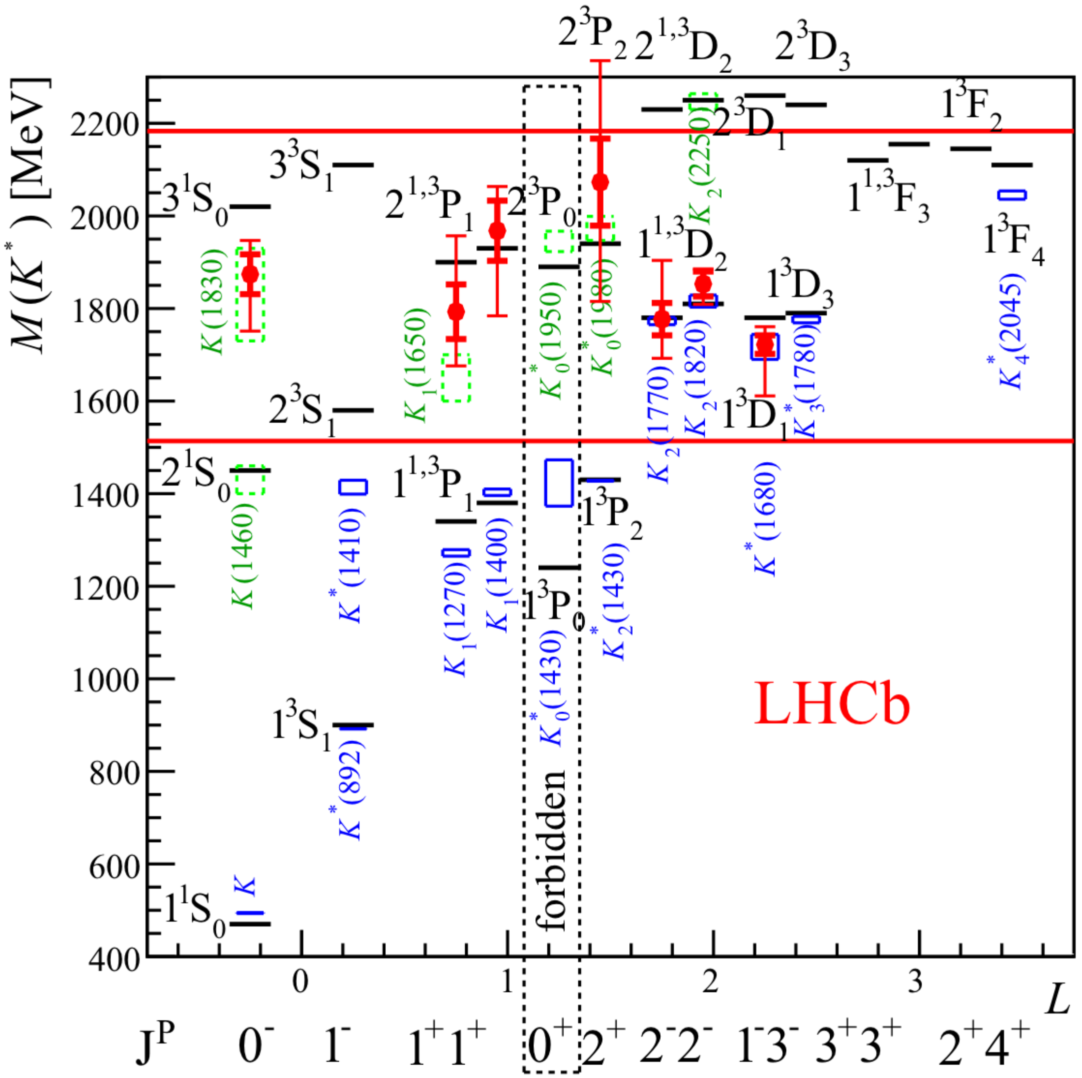


- Fit quality is good in all fitted variables

K* results

Default model: 6 K* resonances (of 4 different J^P) + 1 NR ϕK

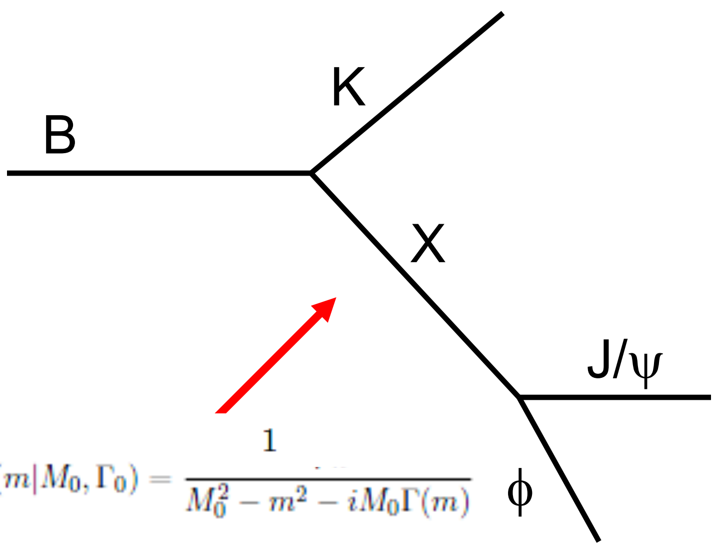
Our results are given by the red points with error bars



Excellent agreement between our results and both theory and previous experiments

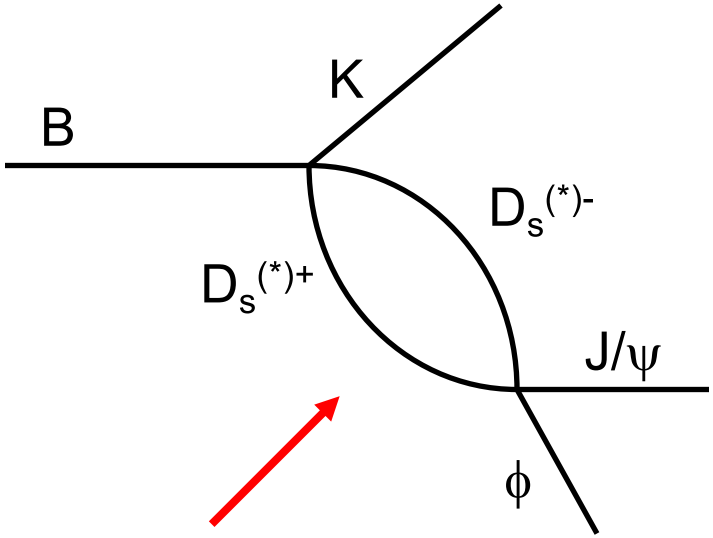
X exotics as $D_s^{(*)}\overline{D_s^{(*)}}$ cusps?

Breit-Wigner Model



$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

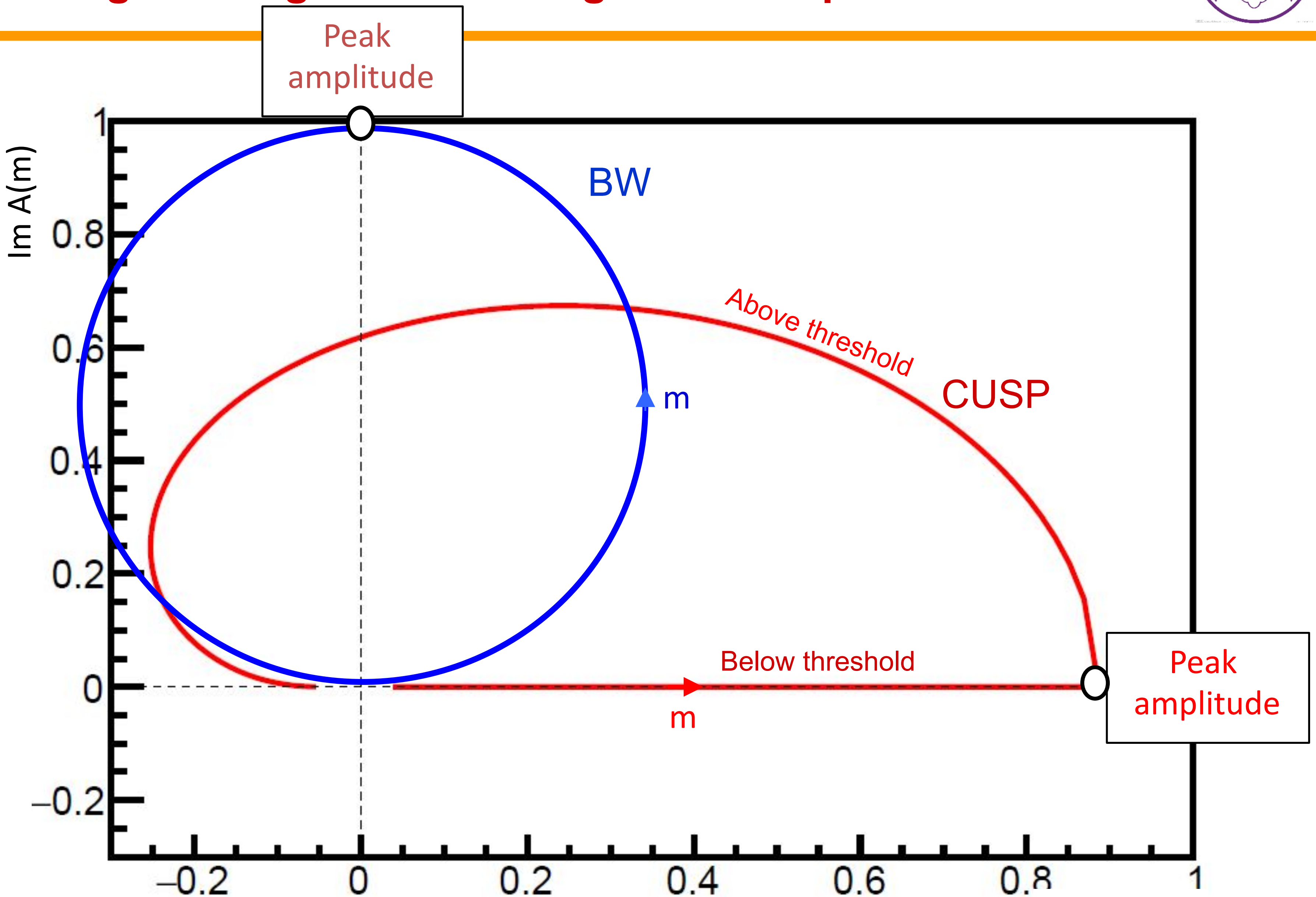
Cusps Model



$$\Pi(m|\beta_0) = \int \frac{d^3q}{(2\pi)^3} \frac{e^{-2q^2/\beta_0^2}}{m - M_A - M_B - \frac{q^2}{2\mu_{AB}} + i\epsilon}$$

Cusp model by
E. S. Swanson, arXiv:1504.07952
(see also PRD91, 034009 (2015))

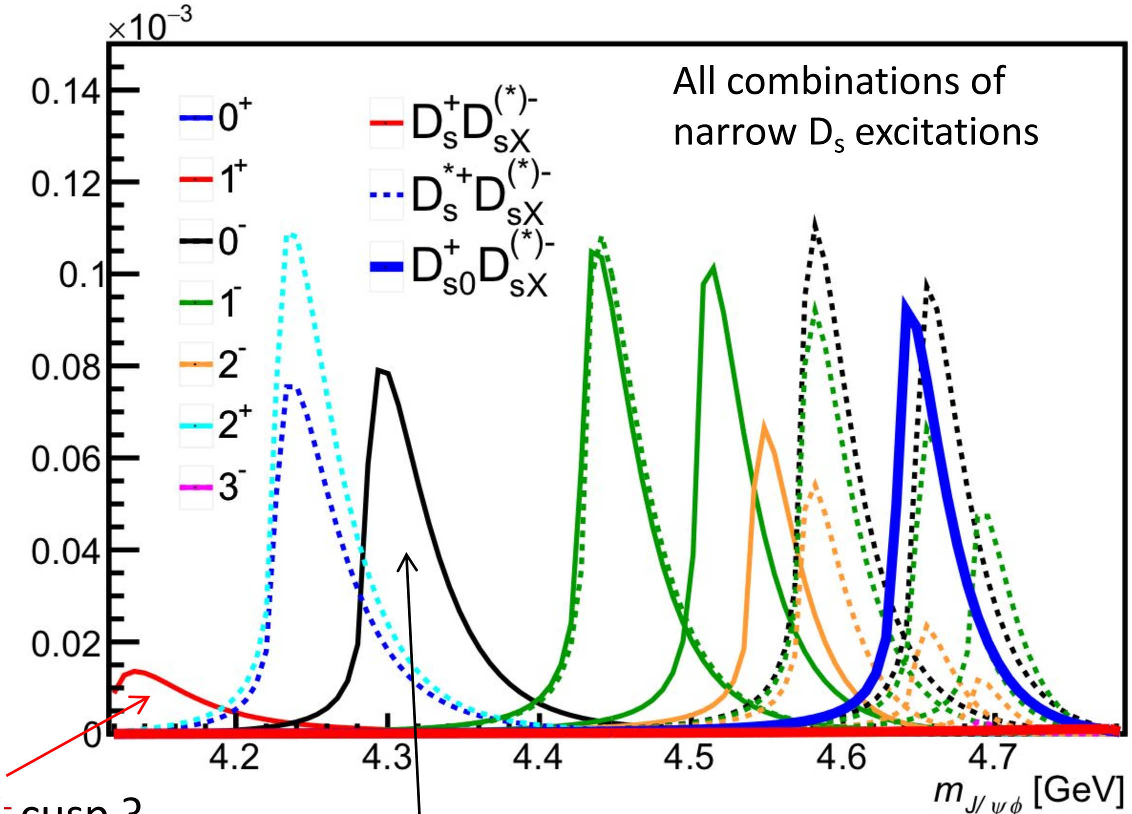
Argand diagram: Breit-Wigner vs cusp



Different shape and phase running with mass

Cusps

- Cusp peaks at the sum of masses of the virtual narrow-$D_{sX}^{(*)}$ pairs.
- Width of cusp in Swanson model is controlled with a free parameter (β_0)
- J^P of cusp determined by J^Ps of virtual D_s pairs (cusps occur in S-wave)



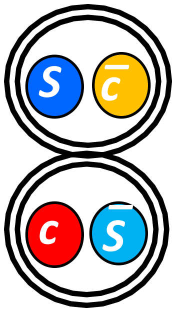
(β_0=0.3 GeV)

Is X(4140) a $D_s^+D_s^{*-}$ cusp ?
Right $J^P=1^+$

Is X(4274) a $D_s^+D_{s0}^{*-}$ cusp ?
Wrong $J^P=0^-$

Theoretical interpretations of X(4140),X(4274)

Molecular models

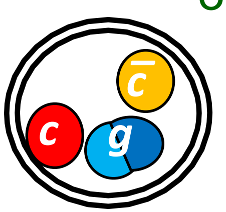


- The determination of the quantum numbers of X(4140) as $J^{PC}=1^{++}$ rules out many interpretations. Namely, 0^{++} or 2^{++} $D_s^*\overline{D_s}^*$ molecules. The large width is also not expected for true molecular bound states.

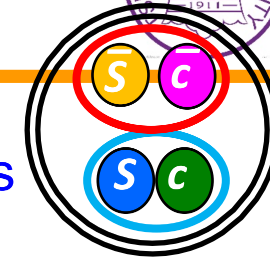
- However, X(4140) may be a 1^{++} $D_s\overline{D_s}^*$ cusp (form of rescattering)

Hybrid models

- Hybrid charmonium states proposed for X(4140) would have $J^{PC}=1^{-+}$. Thus they are also ruled out.



Tightly-bound tetraquark models



- There are tetraquark models which predict states with $J^{PC}=0^{-+}$, 1^{-+} or 0^{++}, 2^{++} near X(4140); these can be ruled out.

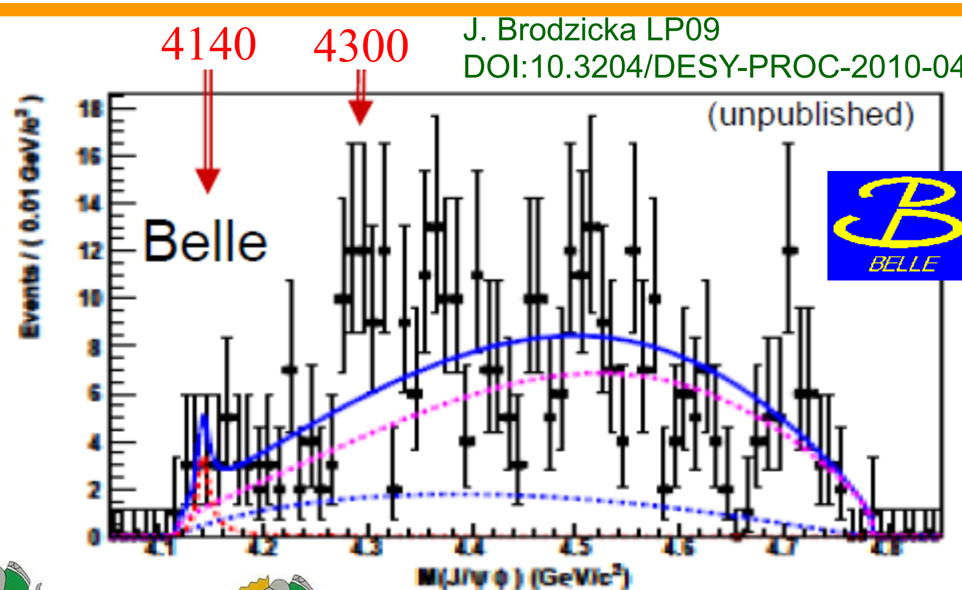
- A tetraquark model implemented by Stancu [JP G37, 075017 (2010), arXiv:0906.2485] correctly assigns 1^{++} to X(4140) and predicts a second 1^{++} state at a mass not much higher than X(4274)

- A Lattice calculation by Padmanth et al [PRD92, 034501 (2015)], based on a diquark tetraquark model, found no evidence for a 1^{++} tetraquark below 4.2 GeV

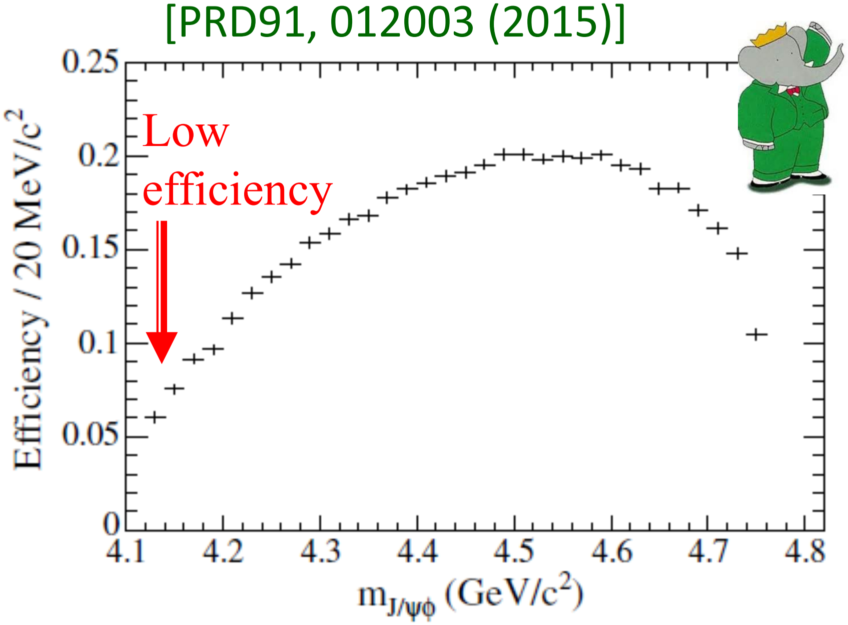
X(4140) from B-factories

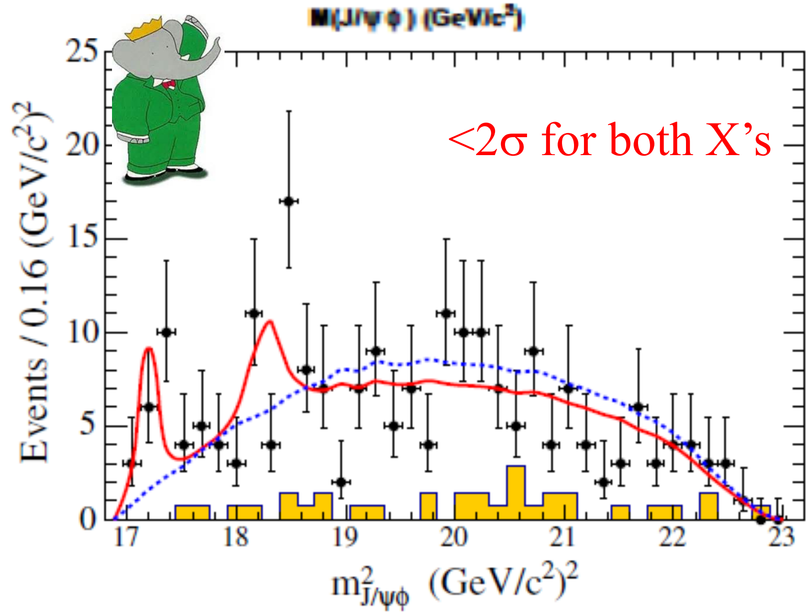
- No evidences reported by B-factories
  - Low efficiency at threshold region

J. Brodzicka LP09
DOI:10.3204/DESY-PROC-2010-04/38



[PRD91, 012003 (2015)]

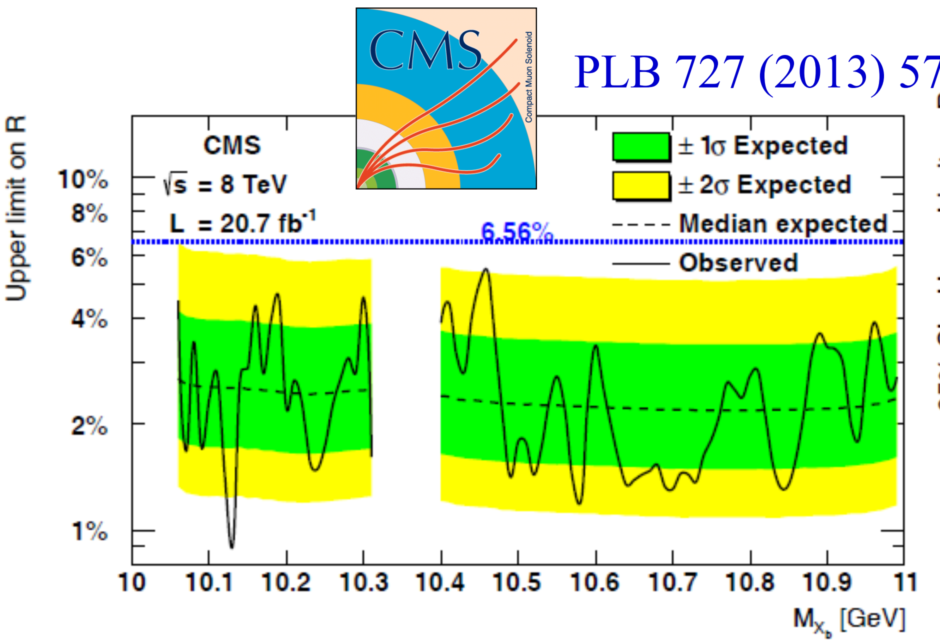




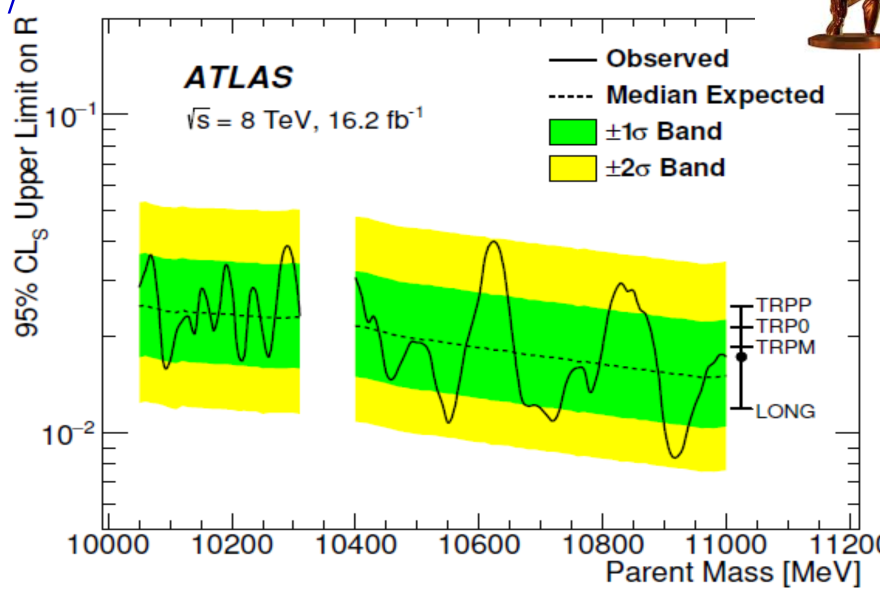
Search for X_b

- $X_b \to \Upsilon(1S)\pi^+\pi^-$: bottomonium counterpart of X(3872)
- Set 95% CL upper limit on $R = \frac{(\sigma\mathcal{B})_{X_b}}{(\sigma\mathcal{B})_{\Upsilon(2S)}}$ as a function of M_{Xb}

PLB 727 (2013) 57

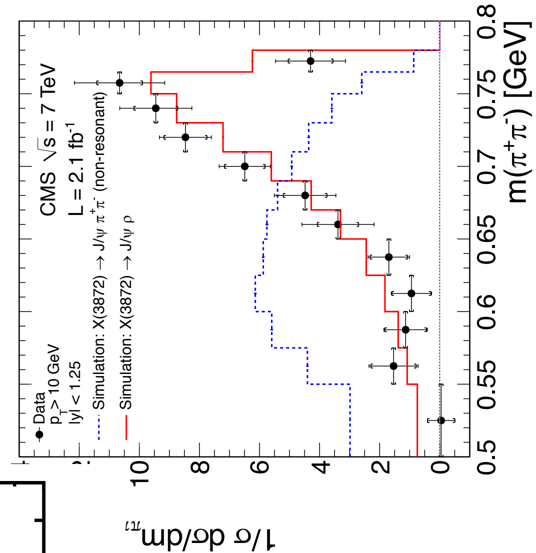


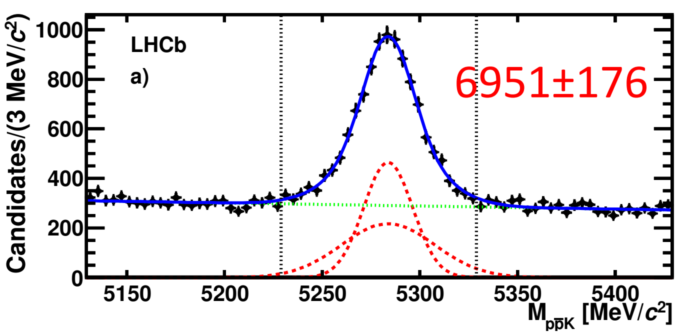
PLB 740 (2015) 199

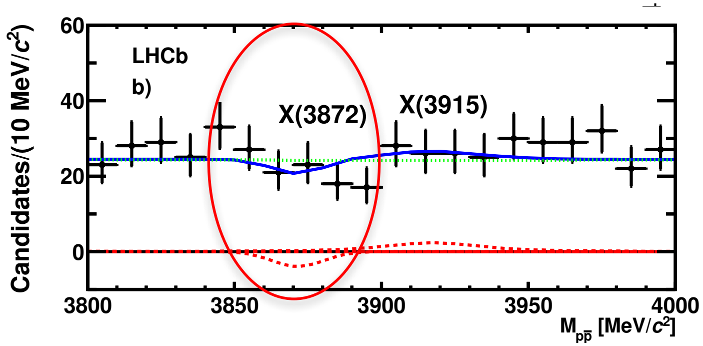


X(3872) decay

- CMS: $\pi^-\pi^+$ spectrum in X(3872) → J/ψ $\pi^+\pi^-$ decays, consistent with ρ^0 [JHEP 1304, 154 (2013)]
- LHCb: search for X(3872)→$\bar{p}p$ decays, in $B^+\to K^+\bar{p}p$ with 1 fb^{-1} [EPJC73, 2642 (2013)]





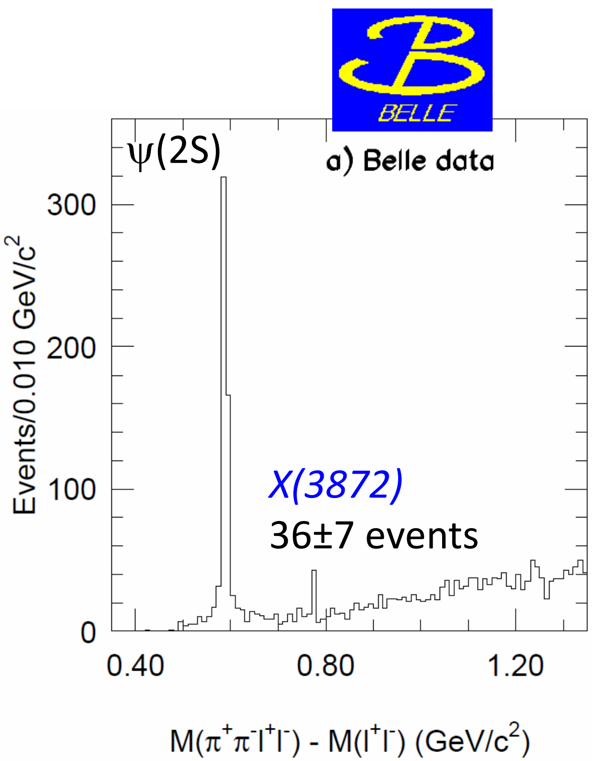


- Upper limit:

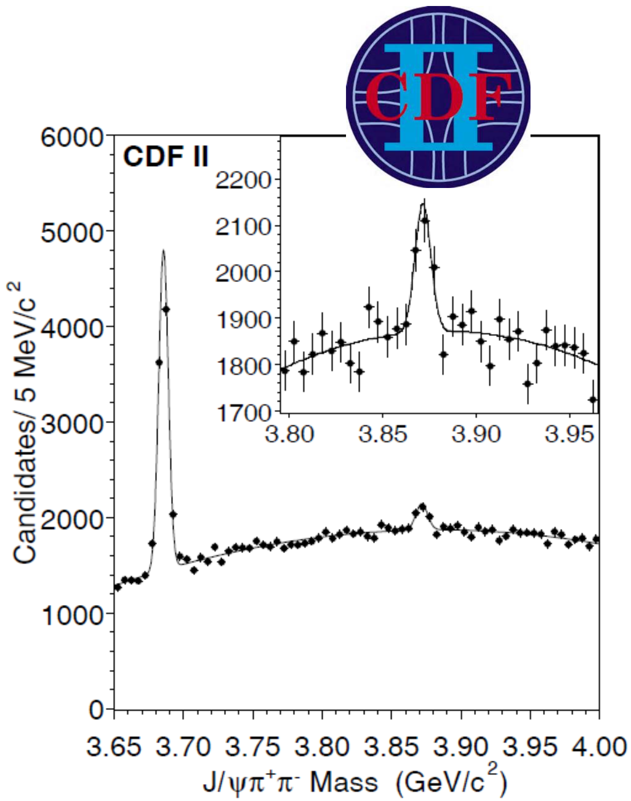
$$\frac{BR(X(3872)\to p\bar{p})}{BR(X(3872)\to J/\psi\pi^+\pi^-)} < 2.0\times 10^{-3}$$

X(3872)

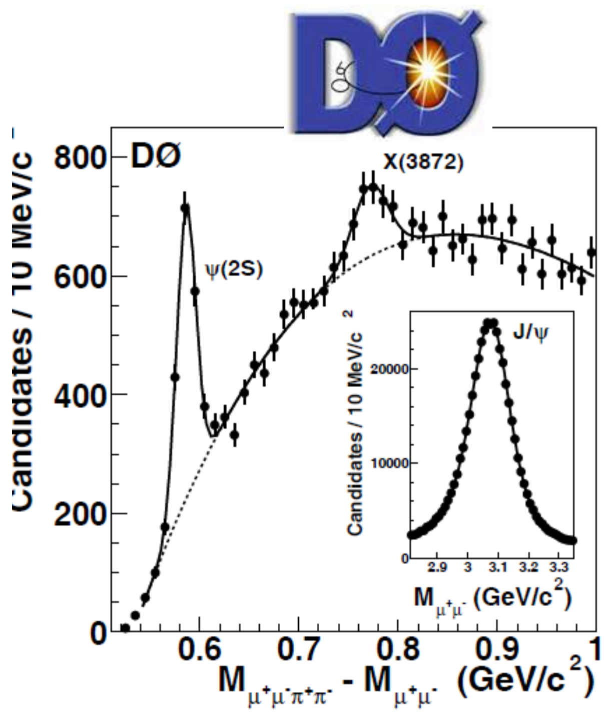
- First exotic observed by Belle in 2003, and then confirmed by CDF and other experiments



PRL 91, 262001, (2003)



PRL 93, 072001 (2004)

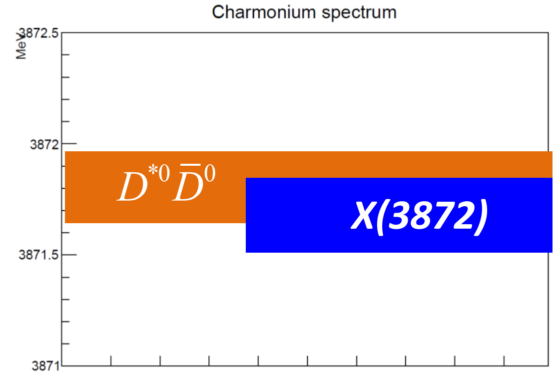


PRL 93, 162002 (2004)

X(3872)

- Studied now in details:
  - Mass = 3871.69 ± 0.17 MeV [PDG], Width < 1.2 MeV

    $m_{X(3872)} - (m_{D^{*0}} + m_{D^0}) = -0.11 \pm 0.22$ MeV [PDG]



  - Decays: open charm, charmonium ($J/\psi\pi^+\pi^-$, …)
  - Production both in *B* decays and hadron collisions

    Like conventional charmonium state

  - It also decays with strong isospin violation

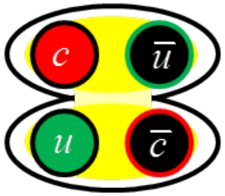
$$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to \rho J/\psi)} \approx 1$$

Comparable with a $D^{*0}\bar{D}^0$ molecular interpretation

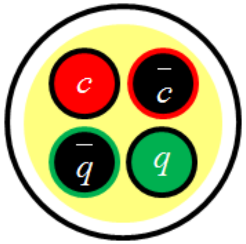
X(3872) J^{PC}: Motivation

X(3872) quantum numbers will help to better understand the state.

- $D^{*0}\bar{D}^0$ molecule, i.e. a $((u\bar{c})(c\bar{u}))$ system?
  - Requires $J^{PC} = 1^{++}$

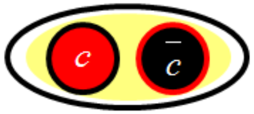


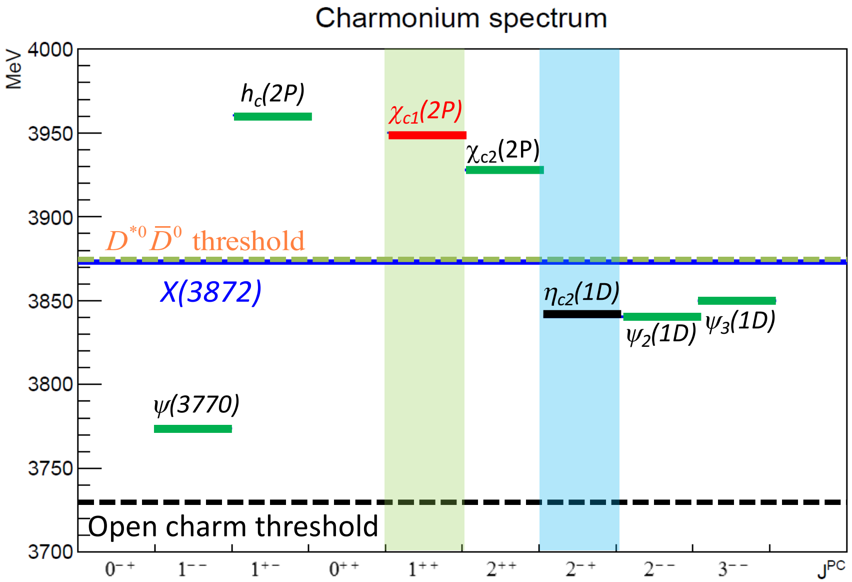
- Tetraquark?
  - Allows with $J^{PC} = 1^{++}$



- Conventional charmonium states?
  - $\chi_{c1}(2^3P_1)$ requires $J^{PC} = 1^{++}$
  - $\eta_{c2}(1^1D_2)$ requires $J^{PC} = 2^{-+}$

$(n^{2s+1}L_J)$

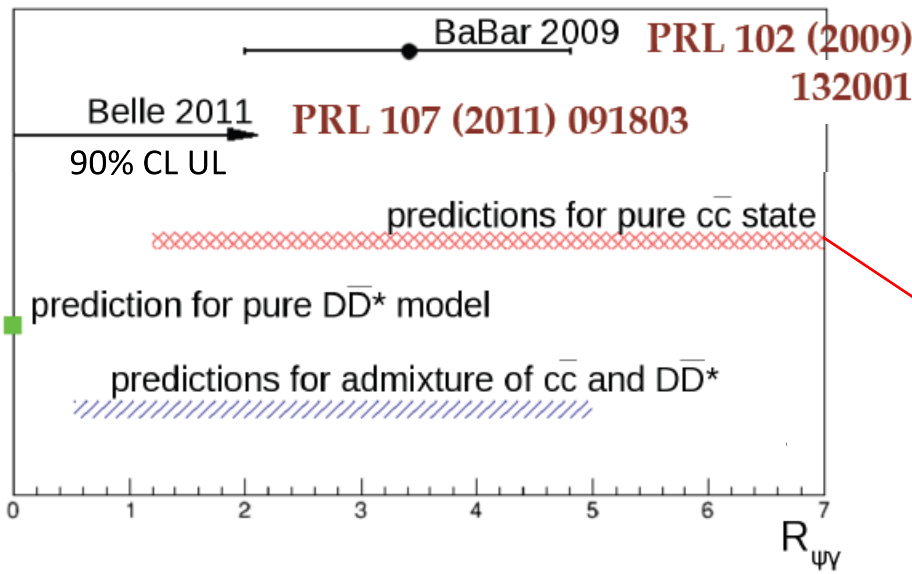




Radiative decays of X(3872)

- Measurement of $R_{\psi\gamma} = \dfrac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)}$

  a good probe for internal structure of X(3872)



efficiency($\psi(2S)\gamma$) / efficiency($J/\psi\gamma$) ~ 1

$\psi(2S)\gamma$ disfavored by phase-space
but enhanced by E1 matrix element:
$|\langle 2S|r|2P\rangle|^2$ ⛷ $|\langle 1S|r|2P\rangle|^2$

For theory predictions, see references in Nucl.Phys. B886, 665 (2014)

- Previous measurements by BaBar and Belle barely consistent and favoring the opposite conclusions

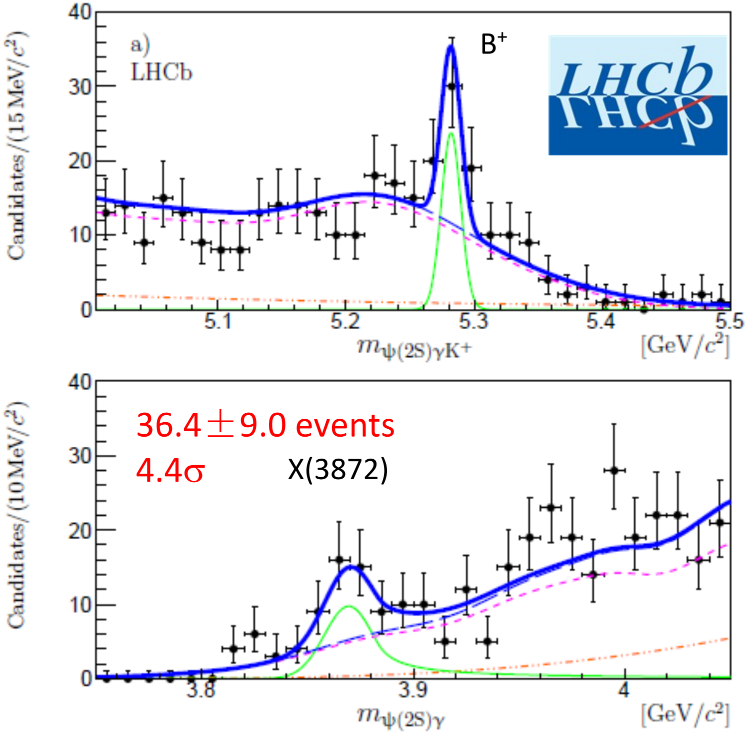
Radiative decays of X(3872)@LHCb

Nucl.Phys. B886, 665 (2014)

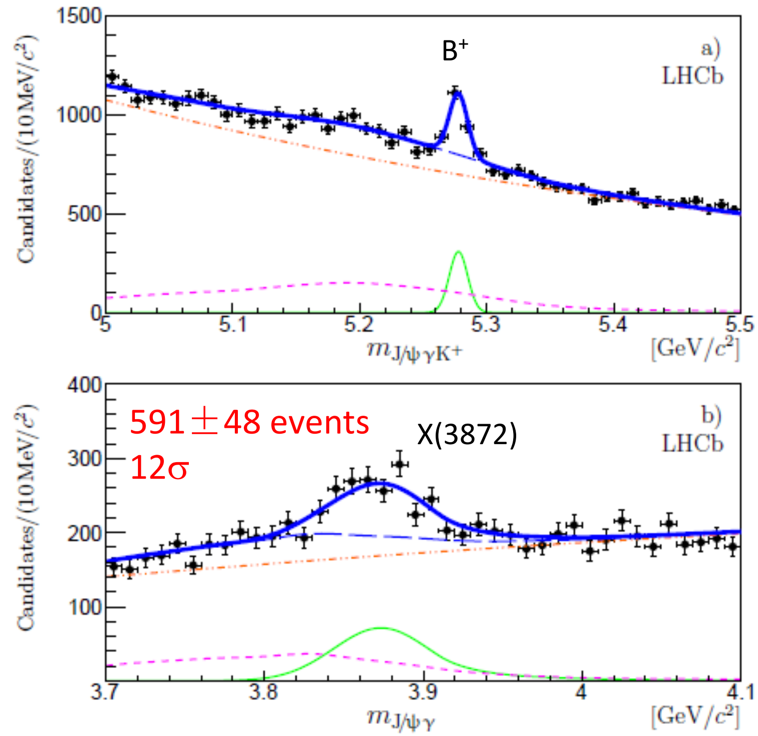
Projections of 2D fit to $m_{\psi\gamma K+}$ vs $m_{\psi\gamma}$

3fb^{-1}

$B^+ \to X(3872)K^+$,
$X(3872) \to \psi(2S)\gamma$



$B^+ \to X(3872)K^+$,
$X(3872) \to J/\psi\gamma$

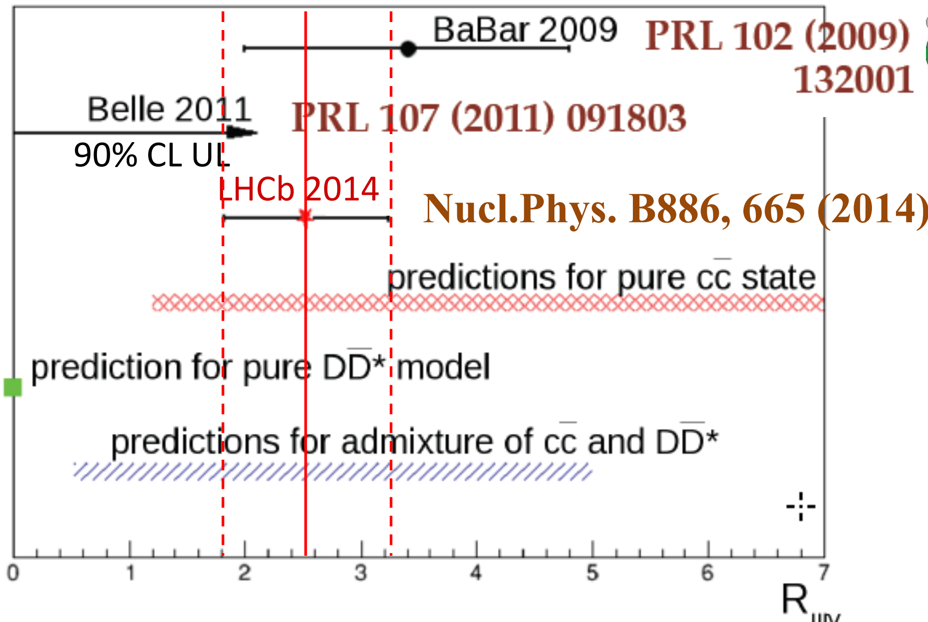


The most significant evidence for $X(3872) \to \psi(2S)\gamma$ to date!

efficiency($\psi(2S)\gamma$) / efficiency($J/\psi\gamma$) ~ 0.2

Detecting soft photons at hadron collider is hard.

Radiative decays of X(3872)@LHCb



	Signal events: $B^+ \to X(3872)K^+$, $X(3872) \to \psi(2S)\gamma$, $J/\psi\gamma$	Signal significance: $\psi(2S)\gamma$, $J/\psi\gamma$
	25.4 ± 7.3, 23.0 ± 6.4	3.6σ, 3.5σ
BELLE	$5.0^{+11.9}_{-11.0}$, $30.0^{+8.2}_{-7.4}$	0.4σ, 4.9σ
LHCb	36.4 ± 9.0, 591.0 ± 48.0	4.4σ, 12σ

$R_{\psi\gamma} = 2.48 \pm 0.64 \pm 0.29$ (LHCb)

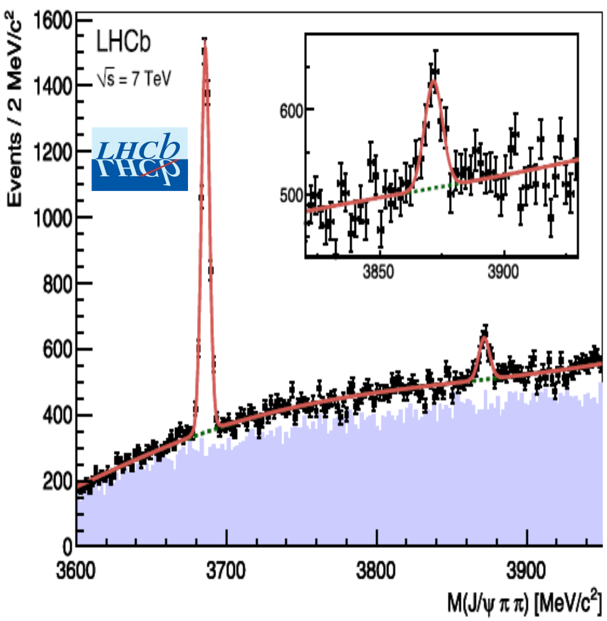
- The LHCb results are consistent with, but more precise than, the BaBar and Belle results
- The results are not consistent with the expectations for pure molecular X(3872)
- The favorite X(3872) interpretation is a mixture of a $\chi_{c1}(2^3P_1)$ charmonium state and of $D^{*0}\bar{D}^0$ molecule or cusp [arXiv:1404.3723]

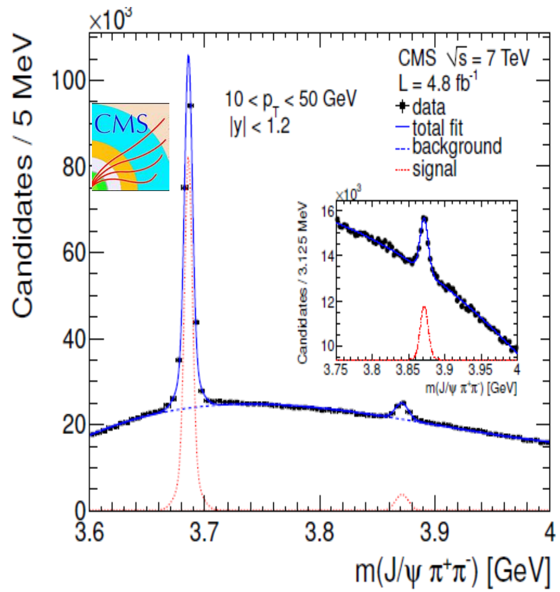
X(3872) production

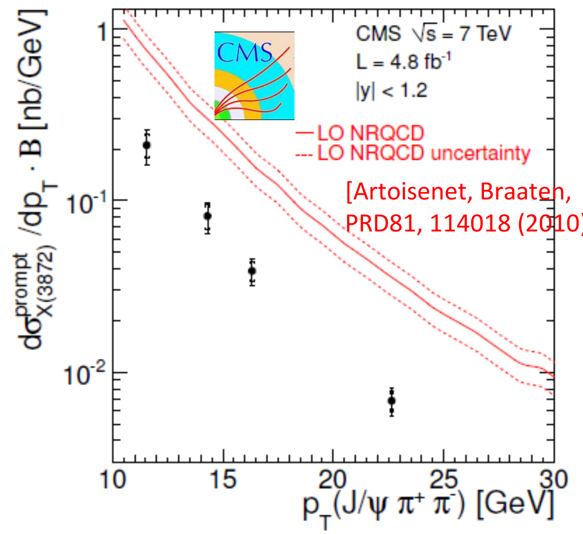
- All hadron collisions reported X(3872)

  CDF [PRL93, 072001 (2004)], D0 [PRL93, 162002 (2004)], LHCb [EPJC72, 1972 (2012)] and CMS [JHEP 1304, 154 (2013)].

- Study regions: central (CMS, $|y|<1.2$) or forward (LHCb, $2.5<y<4.5$)







LHCb: $\sigma_{inclusive}\mathcal{B}(X(3872)\rightarrow J/\psi\pi^+\pi^-)$ [2.5<y<4.5, pT>5 GeV] = 5.4±1.3±0.8 nb

CMS: $\sigma_{prompt}\mathcal{B}(X(3872)\rightarrow J/\psi\pi^+\pi^-)$ [|y|<1.2, pT>10 GeV] = 1.06±0.11±0.15 nb

CMS: Fraction of X(3872) from *B* hadron = (26.3±2.3±1.6)%