

Spectroscopy of Exotic Hadrons

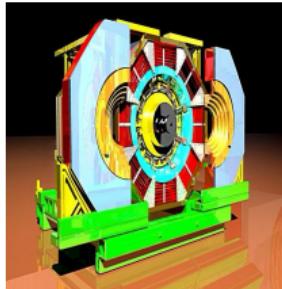
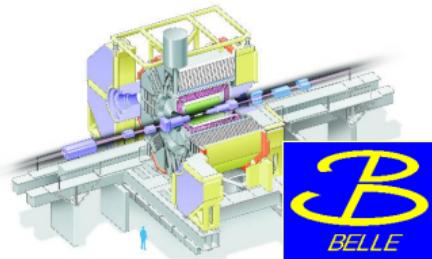
Sebastian Neubert

Heidelberg University

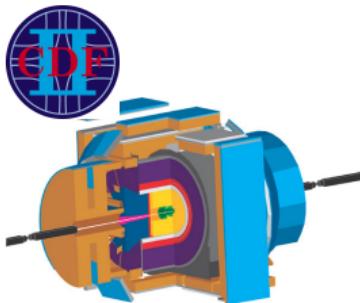
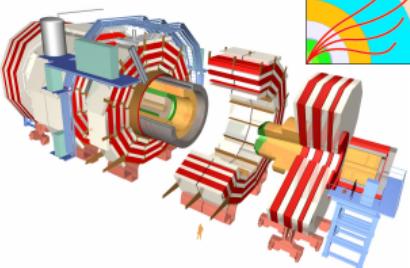
Confinement 2016, Aug 29th - Sept. 3rd, 2016, Thessaloniki



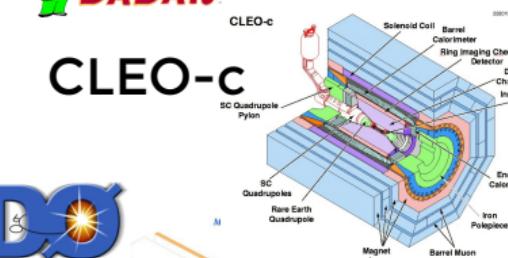
Experimental Efforts on Charmonium-like Exotics



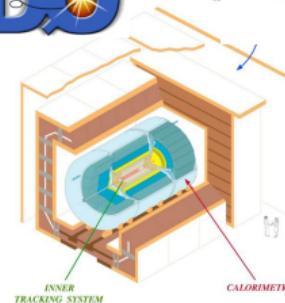
BES III



CDF



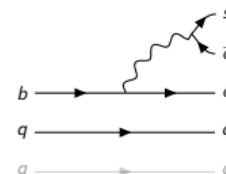
CLEO-c





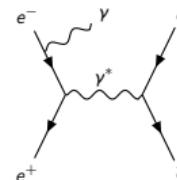
Production Processes

■ B decays

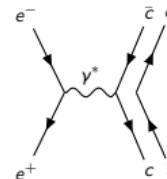


■ Initial state radiation/ e^+e^-

$$J^P = 1^-$$

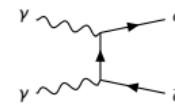


■ Double charmonium production

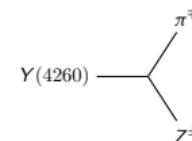


$$J^P = 0^+ \text{ or } 2^+$$

■ $\gamma\gamma$ -fusion



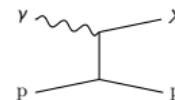
■ Decays of $Y(4260)$ and higher charmonia

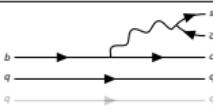
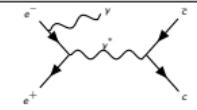
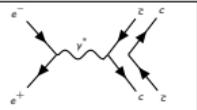
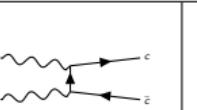
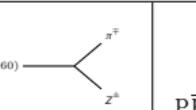


■ $p\bar{p}$ inclusive

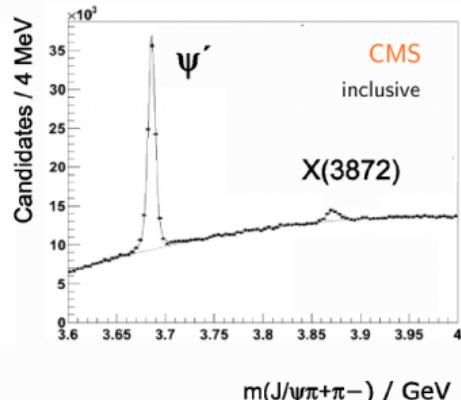
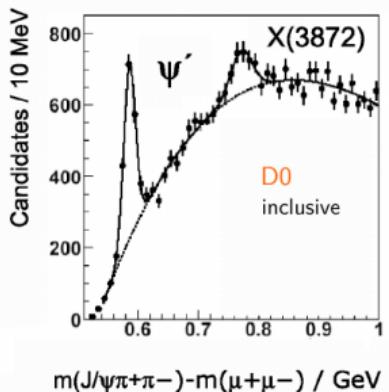
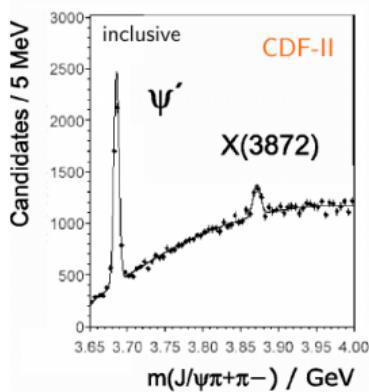
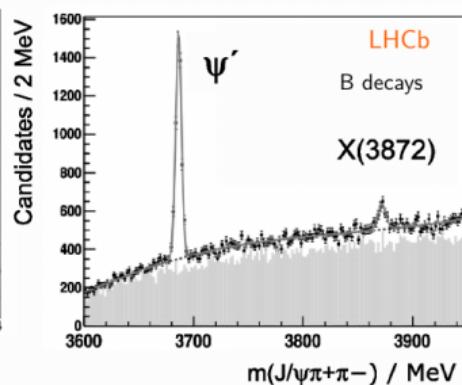
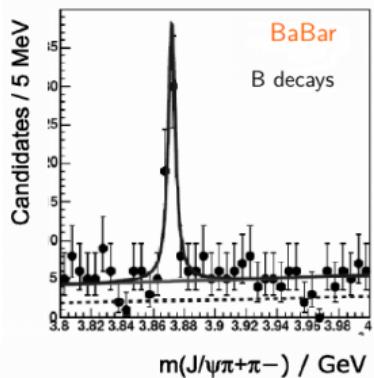
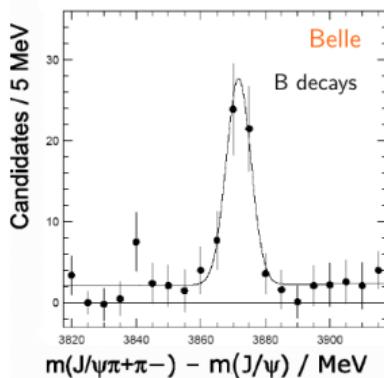
■ pp inclusive

■ (virtual) photo production



						p\bar{p} incl.	pp incl.
J/\psi \pi^+ \pi^-	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
\psi(2S) \pi^+ \pi^-		Y(4360) Y(4660)					
\Lambda_c \bar{\Lambda}_c		Y(4630)					
\psi \gamma	X(3872)						
\chi_{c1}(1P) \gamma	X(3832)						
\chi_{c1}(1P) \omega				Y(4220)			
J/\psi \omega	X(3872) Y(3940)			X(3915)			
J/\psi \phi	X(4140) X(4274) X(4500) X(4700)			X(4350)			
J/\psi \pi	Z(4430) Z(4200) Z(4240)				Z(3900)		
\psi(2S) \pi	Z(4430)						
\chi_{c1}(1P) \pi	Z(4051) Z(4248)						
h_c(1P) \pi					Z(4020)		
D\bar{D}				Z(3930)			
D\bar{D}^*	X(3872)		X(3940)		Z(3885)		
D^*\bar{D}^*			X(4160)		Z(4025)		
J/\psi p	P_c^+(4380) P_c^+(4430)						
B_s^0 \pi					X(5568)		-

The X(3872)





Status of the X(3872)

- $J^{PC} = 1^{++}$ established
LHCb [PRL110(2013)222001][PRD92(2015)011102]
- Mass $m = 3871.69 \pm 0.17 \text{ MeV}$ (in $X(3872) \rightarrow J/\psi X$ decays)
- $D\bar{D}^*$ threshold: $3871.81 \pm 0.09 \text{ MeV}$
- Mass difference $m_X - m_{J/\psi} = 775 \pm 4 \text{ MeV}$
- Width $\Gamma < 1.2 \text{ MeV}$ Belle [PRD84(2011)052004]
- Mass and decay mode disfavor $c\bar{c}$ state.
- $J^{PC} = 1^{++}$: $D^0 D^*$ molecule, Tetra-quark
- No charged partner, no $C = -1$ partner found
 - $X \rightarrow J/\psi \pi^+ \pi^0$ Belle[PRL111(2013)032001], BaBar[PRD71(2005)031501]
 - $X \rightarrow J/\psi \eta$ Belle[PTEP(2014)043C01], Belle[PRL111(2013)032001]



X(3872) decays

Approx. product branching fractions		
$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow D^{*0} \bar{D}^0)$	$\sim 1 \times 10^{-4}$	
$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \underbrace{\pi\pi}_{\rho})$	$\sim 1 \times 10^{-5}$	Isospin violation
$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \omega)$	0.6×10^{-5}	
$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \gamma)$	$\sim 2 \times 10^{-6}$	Allowed in molecule picture [PLB742(2015)394]
$\frac{\mathcal{B}(X \rightarrow \psi(2S) \gamma)}{\mathcal{B}(X \rightarrow J/\psi \gamma)}$	$\sim 2 - 3$	[EPJ C75(2015)26]
$\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow p\bar{p})$	$< 0.25 \times 10^{-2}$ @95% C.L.	NEW
$\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow p\bar{p})$		1607.06446
$\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow p\bar{p})$	$< 6 \times 10^{-9}$	

for a more details and precise values see the review arXiv:1601.02092

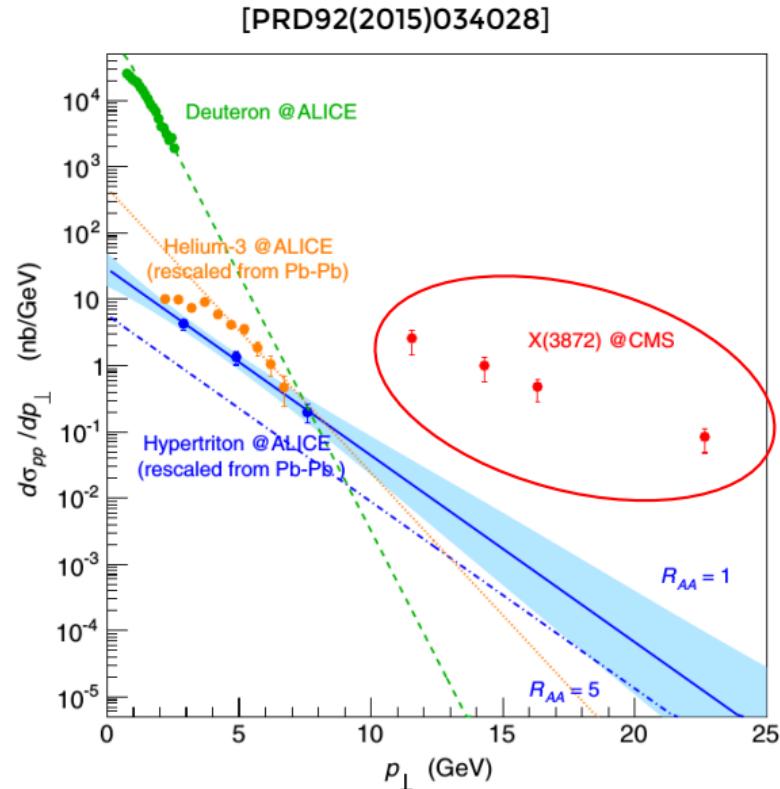
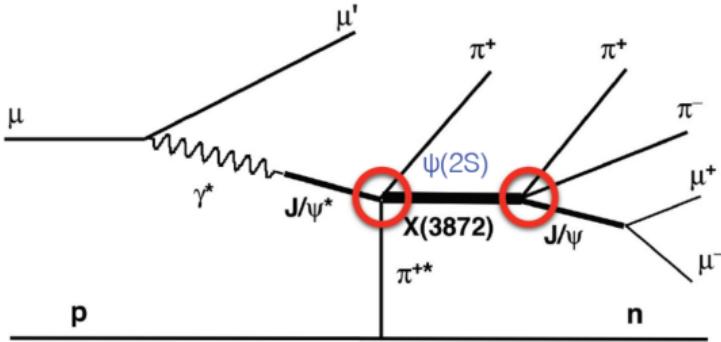


X(3872) production

See talks by F. Navarra,
F. Carvalho and L. Cristello
in Sec. C, Thur. afternoon

- Expectation: Production of loosely bound hadronic molecules in high energy hadronic collisions suppressed [PRL103(2009)162001]
- COMPASS showed preliminary results for virtual photo production

J. Bernhard, @ Baryon2016



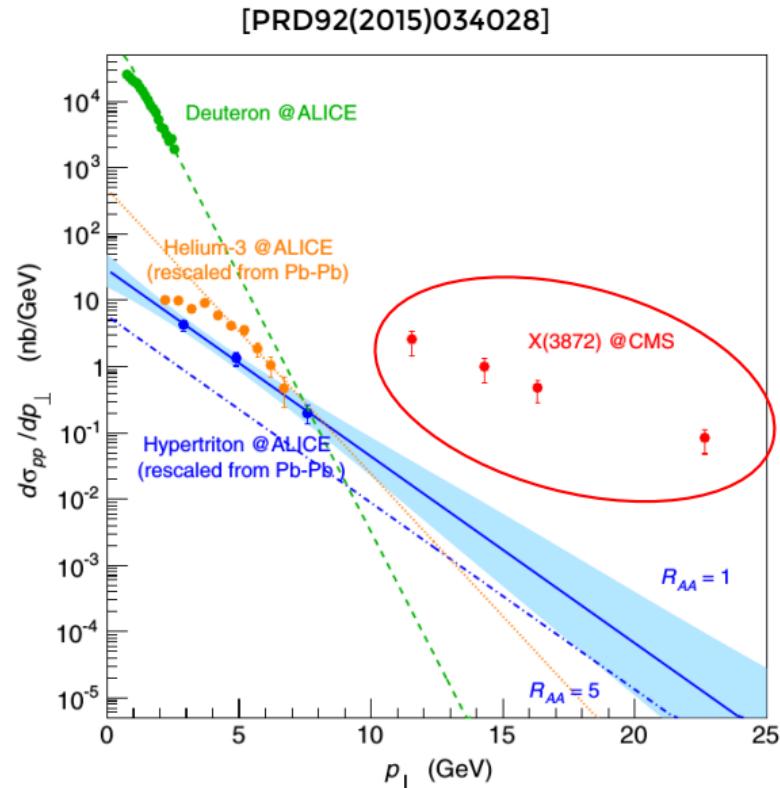
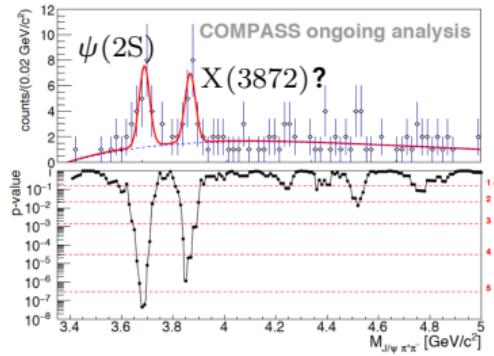


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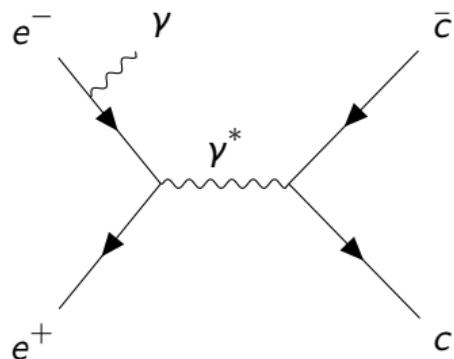
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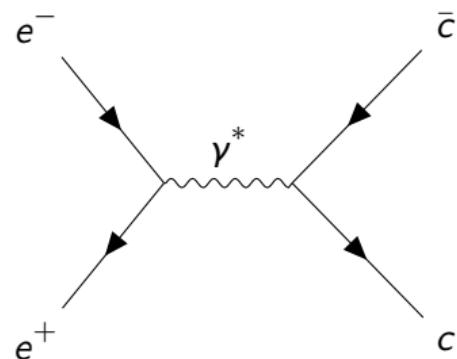


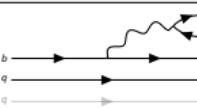
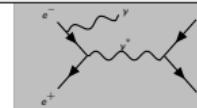
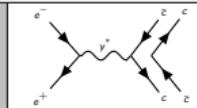
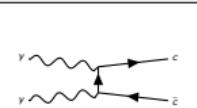
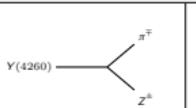
Exotic vector mesons

Belle, BaBar
(running on Υ resonance)



BESIII
(\sqrt{s} scan)

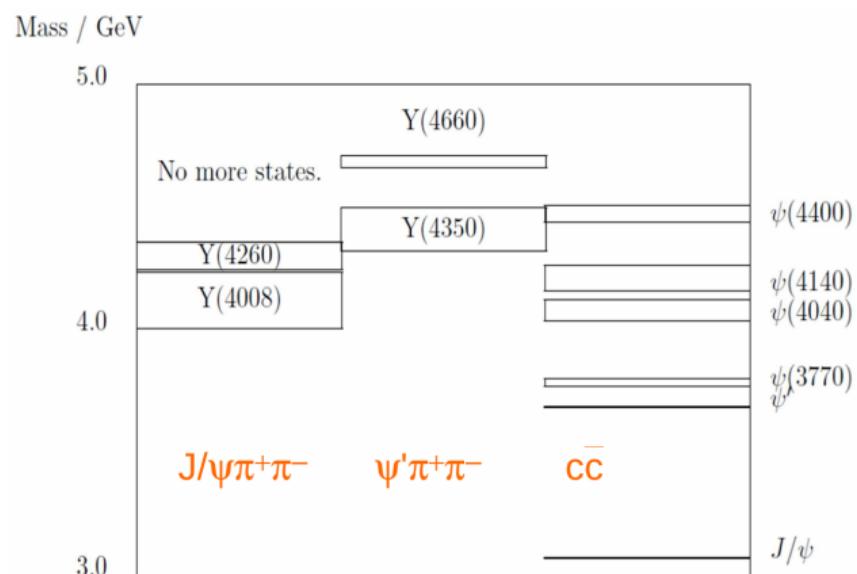


						p p̄ incl.	p p incl.
J/ψ π ⁺ π ⁻	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
ψ(2S) π ⁺ π ⁻		Y(4360) Y(4660)					
Λ̄ c̄		Y(4630)					
ψγ	X(3872)						
χ _{c1} (1P) γ	X(3832)						
χ _{c1} (1P) ω				Y(4220)			
J/ψ ω	X(3872) Y(3940)				X(3915)		
J/ψ φ	X(4140) X(4274) X(4500) X(4700)				X(4350)		
J/ψ π	Z(4430) Z(4200) Z(4240)					Z(3900)	
ψ(2S) π	Z(4430)						
χ _{c1} (1P) π	Z(4051) Z(4248)						
h _c (1P) π						Z(4020)	
D D̄				Z(3930)			
D D̄*	X(3872)		X(3940)			Z(3885)	
D * D̄*			X(4160)			Z(4025)	
J/ψ p	P _c (4380) P _c (4430)						
B _s ⁰ π						X(5568)	-



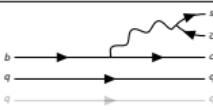
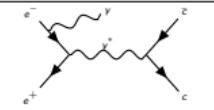
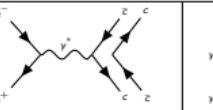
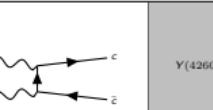
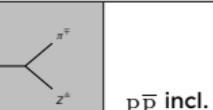
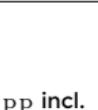
An overpopulation of $J^{PC} = 1^{--}$ states

- 7-9 vector states above $D\bar{D}$ threshold!
- $Y(4008)$ only seen by Belle
- All other states well established
- $Y(4260)$: no decay via $\psi'\pi\pi$
- $Y(4350)$: no decay via $J/\psi\pi\pi$
- $Y(4260)$ a source of exotic mesons (see later)
- Models: Tetraquark, Hadrocharmonium, Molecule, Hybrid



$Y(4630)$ in $\Lambda_c \bar{\Lambda}_c$

Charged exotic mesons - the Z states

								p anti-pbar incl.	pp incl.
J/\psi pi ⁺ pi ⁻	X(3872)	Y(4260) Y(4008)						X(3872)	X(3872)
psi(2S) pi ⁺ pi ⁻		Y(4360) Y(4660)							
Lambda_c anti-Lambda_c		Y(4630)							
psi gamma	X(3872)								
X_c1(1P) gamma	X(3832)								
X_c1(1P) omega				Y(4220)					
J/\psi omega	X(3872) Y(3940)				X(3915)				
J/\psi phi	X(4140) X(4274) X(4500) X(4700)				X(4350)				
J/\psi pi	Z(4430) Z(4200) Z(4240)					Z(3900)			
psi(2S) pi	Z(4430)								
X_c1(1P) pi	Z(4051) Z(4248)								
h_c(1P) pi						Z(4020)			
DD				Z(3930)					
D D-bar*	X(3872)		X(3940)			Z(3885)			
D * D-bar*			X(4160)			Z(4025)			
J/\psi P	P_c(4380) P_c(4430)								
B_s^0 pi							X(5568)	-	

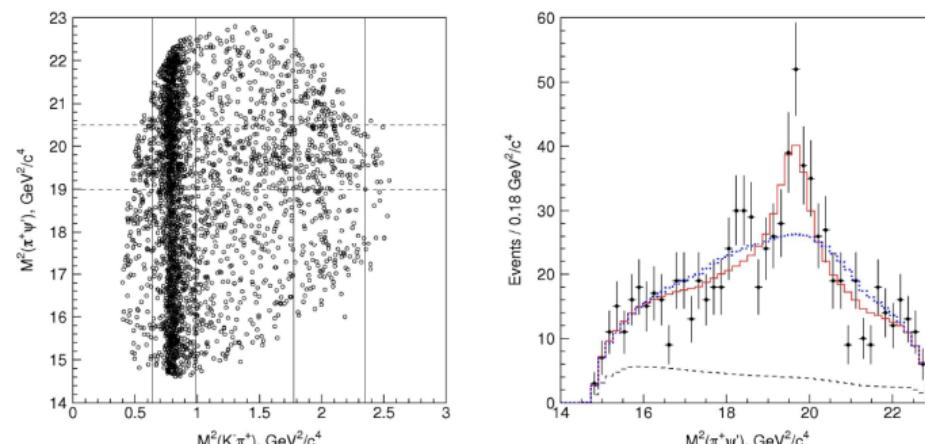




The $Z(4430)^-$

- $Z(4430)^-$ has first been claimed by Belle in $B \rightarrow K(\pi^-\psi(2S))$
- Minimal quark content: $c\bar{c}d\bar{u}$
- BaBar could explain this through reflections of the $K\pi$ system (K^*)
- Amplitude analysis by Belle confirms new state (assuming a resonant shape)

Belle data



PRL 100(2008)142001





$B \rightarrow K\pi^-\psi(2S)$ at LHCb

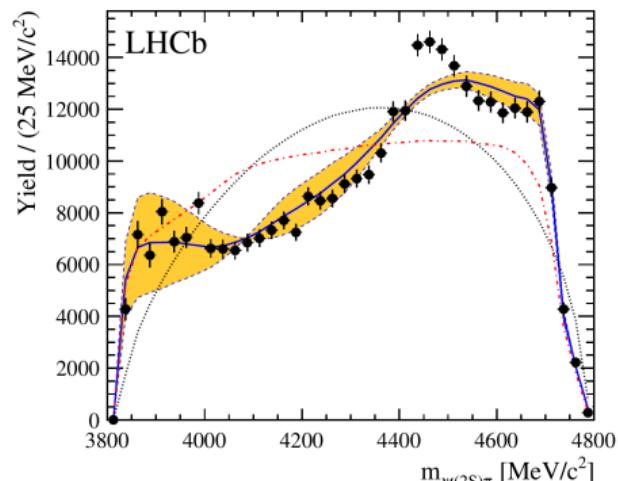
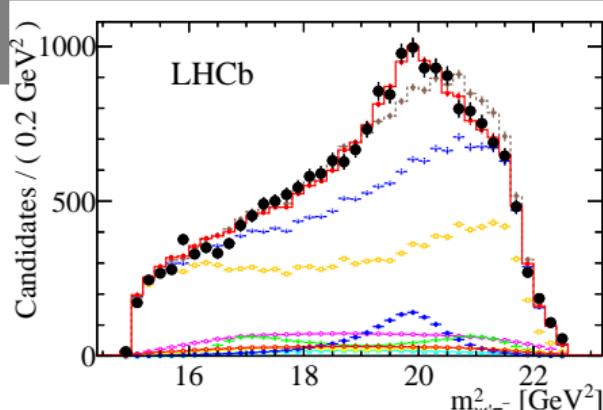
Data sample:

- ~ 25 000 $B \rightarrow K\pi^-\psi(2S)$ candidates in $3 fb^{-1}$ at LHCb

2 Analysis methods:

- 4D amplitude analysis a'la Belle extract resonant phase establish $J^P = 1^+$
[PRL112(2014)222002]

- Moments analysis a'la BaBar model independent confirms existence of Z(4430)
[PRD92(2015)112009]

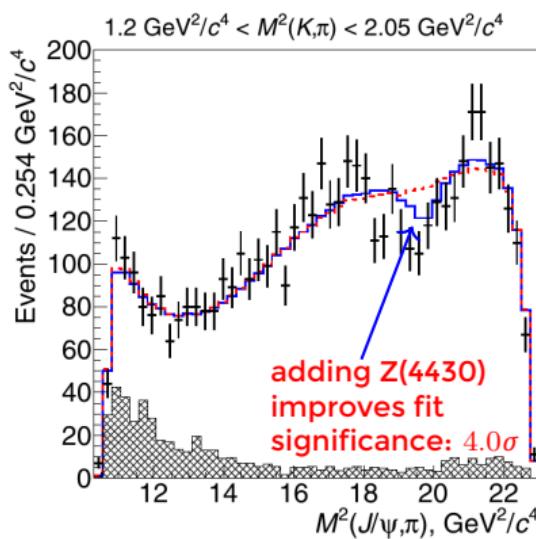




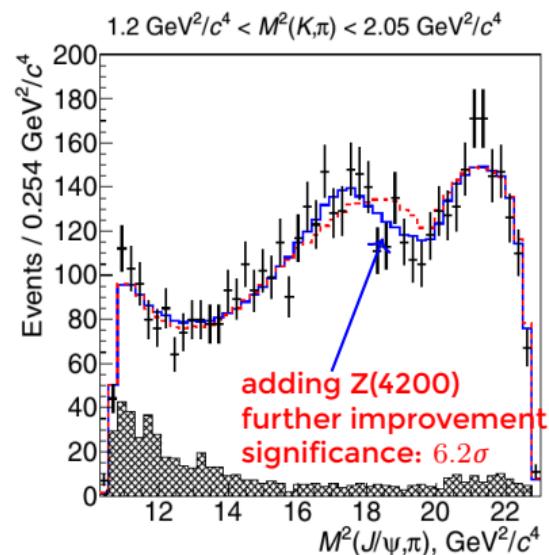
$\overline{B} \rightarrow K^- \pi^+ J/\psi$ at Belle

[PRD90(2014)112009]

- 30 000 $\overline{B} \rightarrow K^- \pi^+ J/\psi$ decays (711 fb^{-1})



- 4D amplitude analysis



- Z(4430) with $J^P = 1^+$ confirmed

- Z(4200) with $J^P = 1^+$ observed





Status of $Z(4430)$ and $Z(4200)$

- Resonant nature established

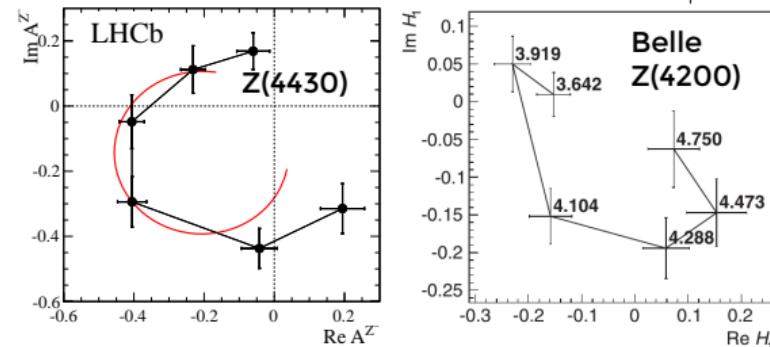
	M [MeV]	Γ [MeV]
LHCb	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$
Belle	$4485 \pm 22^{+28}_{-11}$	200^{+41+26}_{-46-35}
Belle	4196^{+31+17}_{-29-13}	$370^{+70+70}_{-70-132}$

- Both have $J^P = 1^+$

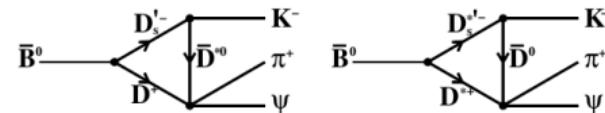
- positive parity rules out S-wave molecules
 $\bar{D}^*(2007)D_1^+(2420)$ and
 $\bar{D}^*(2007)D_2^+(2460)$

The $Z(4240)$ at LHCb

LHCb data can be fit including a second state with $J^P = 0^-$ and $M = 4239 \pm 18^{+45}_{-10}$ MeV
 But in this fit $\Gamma(Z(4430)) = 660 \pm 150$ MeV



- Candidate for a tetraquark
- Rescattering effect?



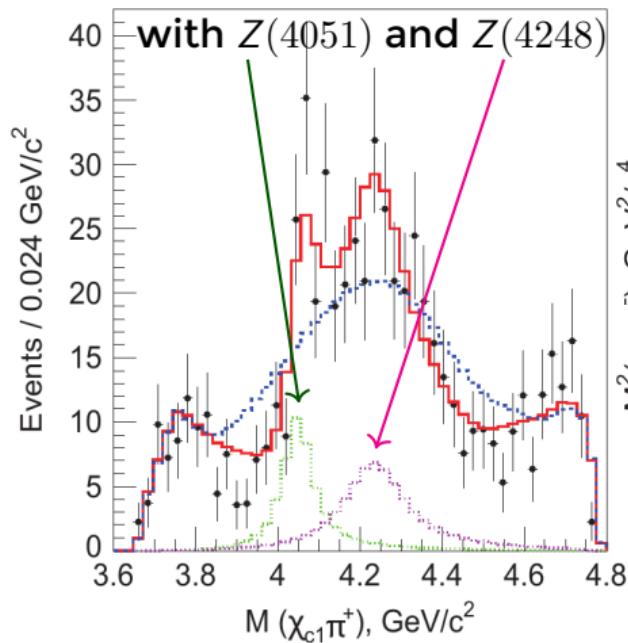
[PLB748(2015)183]

but: wrong sense of phasemotion

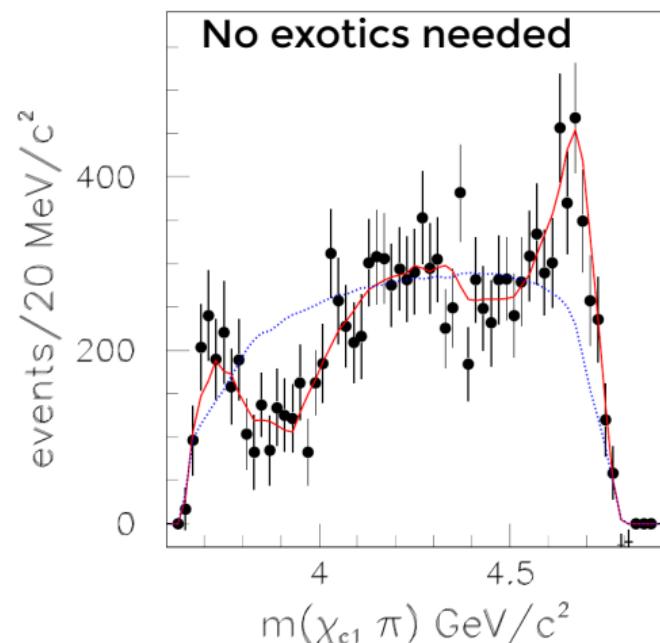


Charged exotics in $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}(1P)$?

Belle [PRD78(2008)072004]



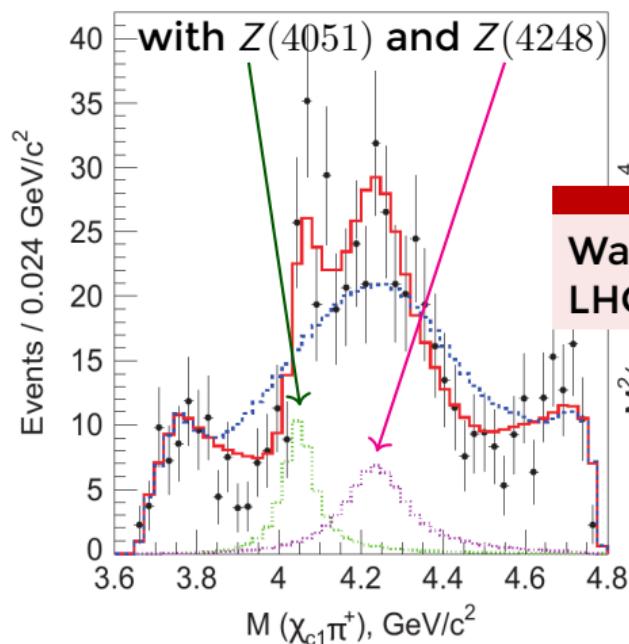
BaBar [PRD85(2012)052003]



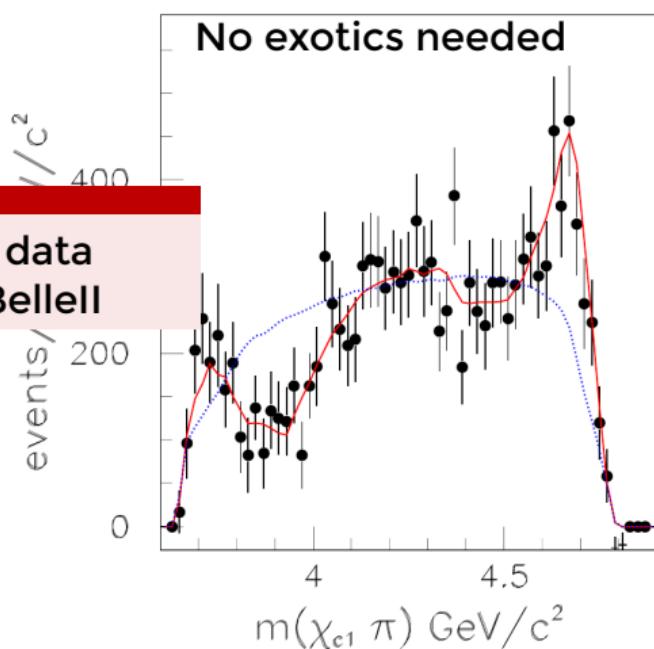


Charged exotics in $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}(1P)$?

Belle [PRD78(2008)072004]



BaBar [PRD85(2012)052003]





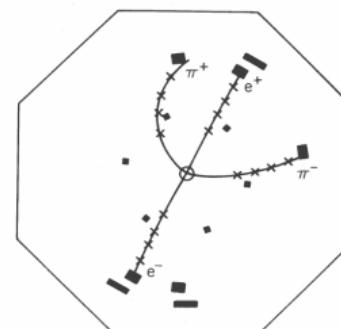
The Y(4260) as a source of exotic mesons at BESIII

MARK I, 1977

$$e^+e^- \rightarrow \psi'$$

$$\rightarrow J/\psi \pi^+ \pi^-$$

$\sqrt{s}=3868$ MeV

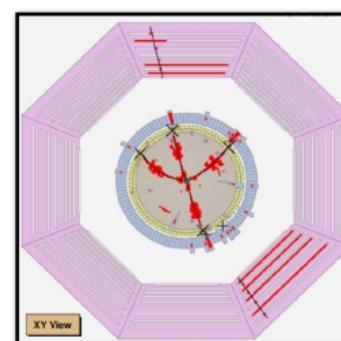


BESIII, 2013

$$e^+e^- \rightarrow Y(4260)$$

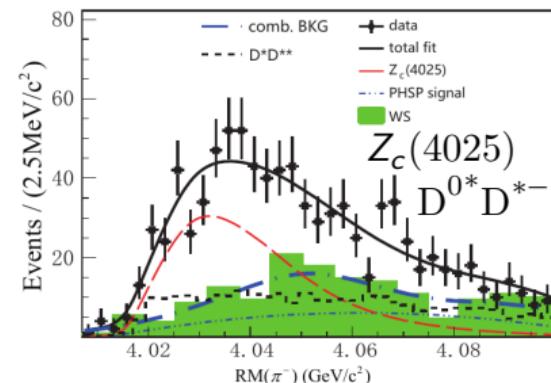
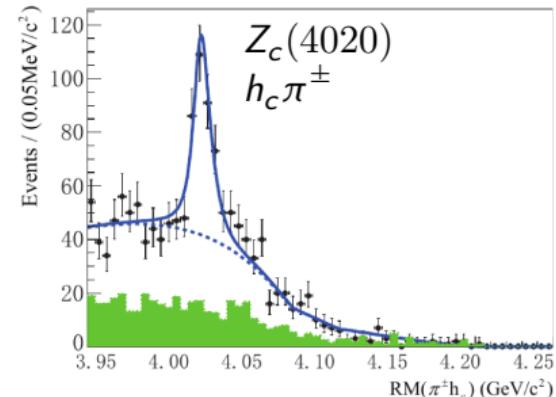
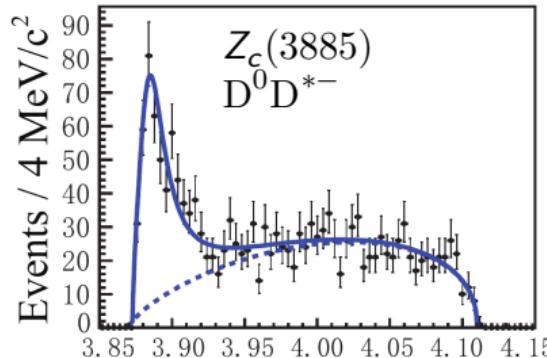
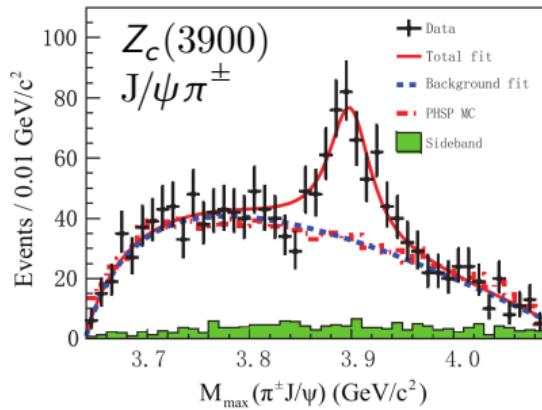
$$\rightarrow J/\psi \pi^+ \pi^-$$

$\sqrt{s}=4260$ MeV



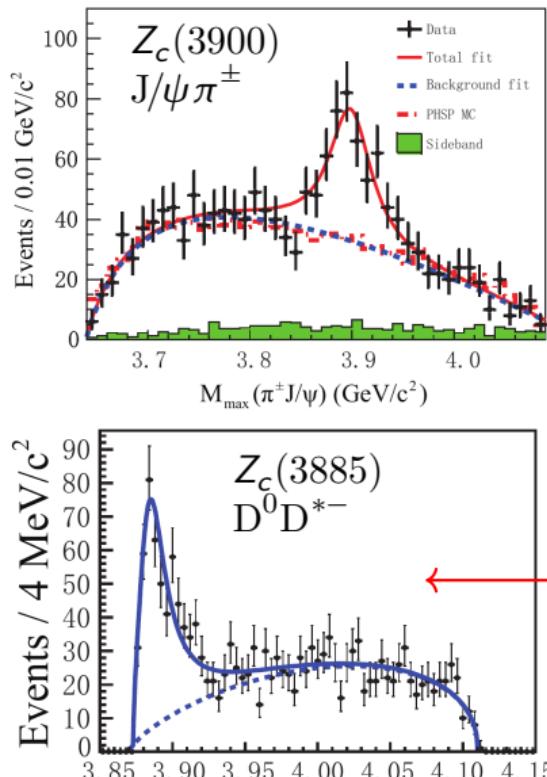


Z states in $e^+e^- \rightarrow Y(4260) \rightarrow Z\pi$ decays at BES III





Z states in $e^+e^- \rightarrow Y(4260) \rightarrow Z\pi$ decays at BES III



Are these one state?

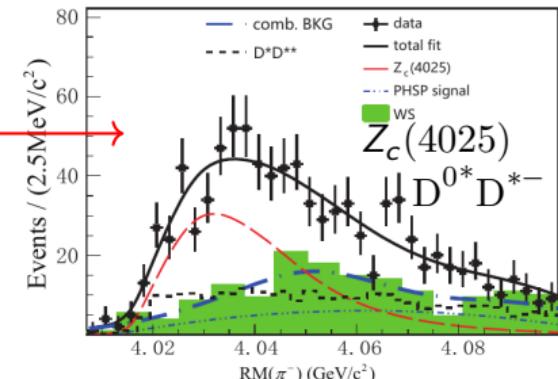
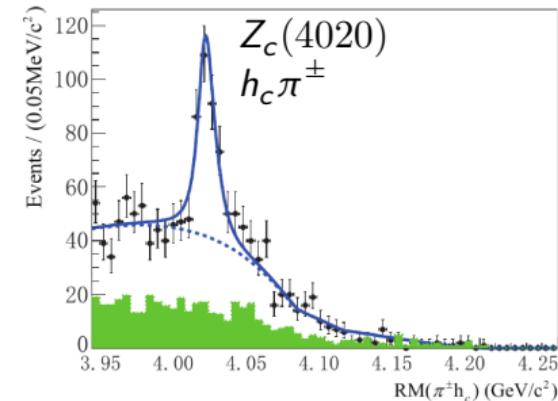
- Masses / widths match
- Right above DD^* threshold
- Decay into $D^0 D^{*-}$ favoured
 $R = 6.2 \pm 1.1 \pm 2.7$
similar to $X(3872)$
- Kinematic cusp effect?
excluded due to signal in elastic channel [PRD91(2015)051504]



Z states in $e^+e^- \rightarrow Y(4260) \rightarrow Z\pi$ decays at BES III

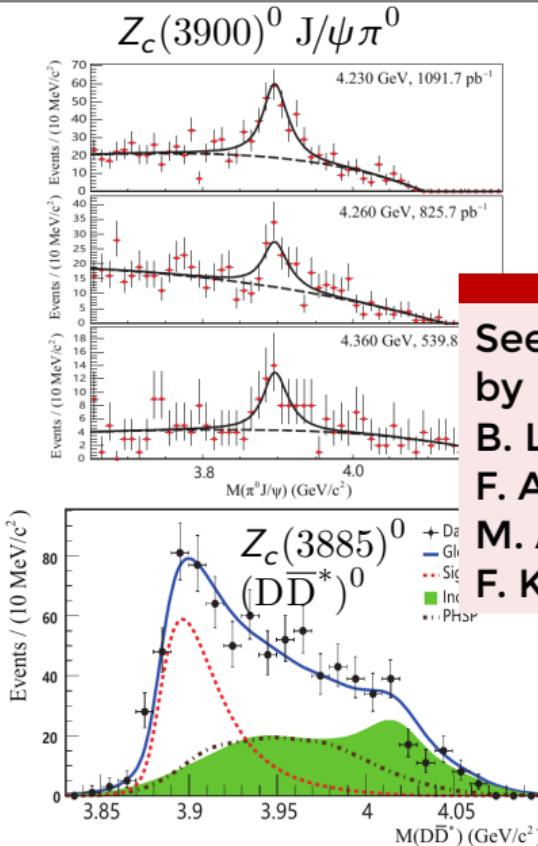
Are these one state?

- Masses / widths match
- Right above $D^*\bar{D}^*$ threshold
- Decay into $D^*\bar{D}^*$ favoured $R = 12 \pm 5$
- Kinematic cusp effect?
excluded due to signal in elastic
channel [PRD91(2015)051504]





There are neutral partners to the Z_c !



See talks in Sec. C.

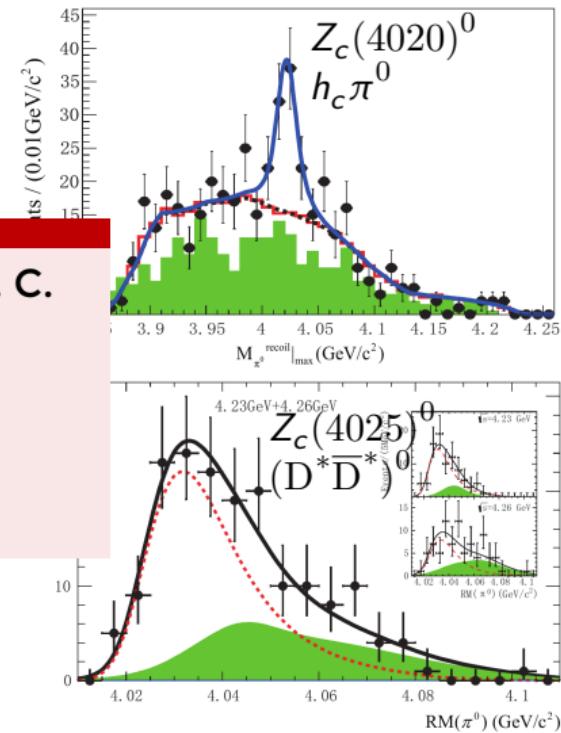
by

B. Liu's

F. Aceti

M. Albaladejo

F. K. Guo

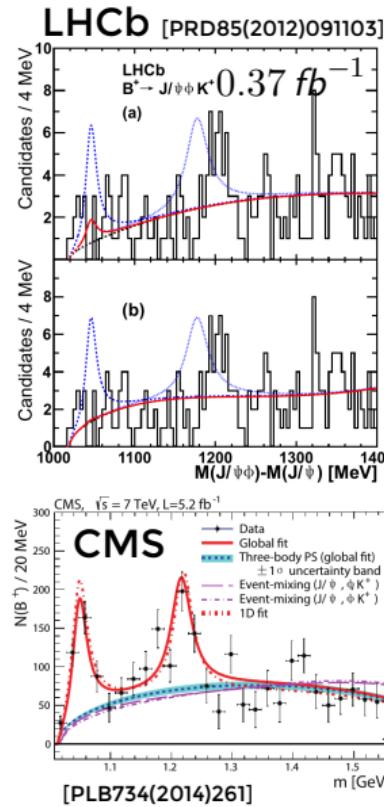
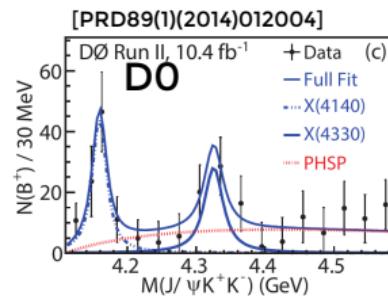
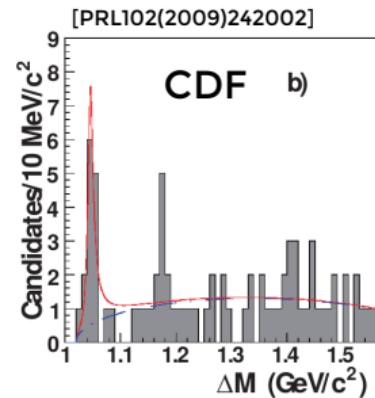


Resonances decaying to $J/\psi\phi$

						p \bar{p} incl.	pp incl.
$J/\psi\pi^+\pi^-$	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
$\psi(2S)\pi^+\pi^-$		Y(4360) Y(4660)					
$\Lambda_c\bar{\Lambda}_c$		Y(4630)					
$\psi\gamma$	X(3872)						
$\chi_{c1}(1P)\gamma$	X(3832)						
$\chi_{c1}(1P)\omega$				Y(4220)			
$J/\psi\omega$	X(3872) Y(3940)				X(3915)		
$J/\psi\phi$	X(4140)				X(4350)		
	X(4274)						
	X(4500)						
	X(4700)						
$J/\psi\pi$	Z(4430) Z(4200) Z(4240)					Z(3900)	
$\psi(2S)\pi$	Z(4430)						
$\chi_{c1}(1P)\pi$	Z(4051) Z(4248)						
$h_c(1P)\pi$						Z(4020)	
D \bar{D}				Z(3930)			
D \bar{D}^*	X(3872)		X(3940)			Z(3885)	
D $^*\bar{D}^*$			X(4160)			Z(4025)	
$J/\psi p$	$P_c(4380)$ $P_c(4430)$						
B $_s^0\pi$						X(5568)	-



Narrow resonances in $J/\psi\phi$ (from B-decays)



- **Narrow structures in $J/\psi\phi$ discovered by CDF in 2008**
- **Subsequent observations by D0 and CMS**
- **BaBar, Belle and LHCb (0.37 fb^{-1}): no significant signal**

[PRL104(2010)112004][PRD91(2015)012003][PRD85(2012)091103]

Averages	$M [\text{MeV}]$	$\Gamma [\text{MeV}]$
$X(4140)$	4143.4 ± 1.9	15.7 ± 6.3
$X(4274)$	4293 ± 20	35 ± 16

- **No amplitude analysis so far**
- **CDF/CMS $X(4274)$ mass measurements disagree at 3.16σ**



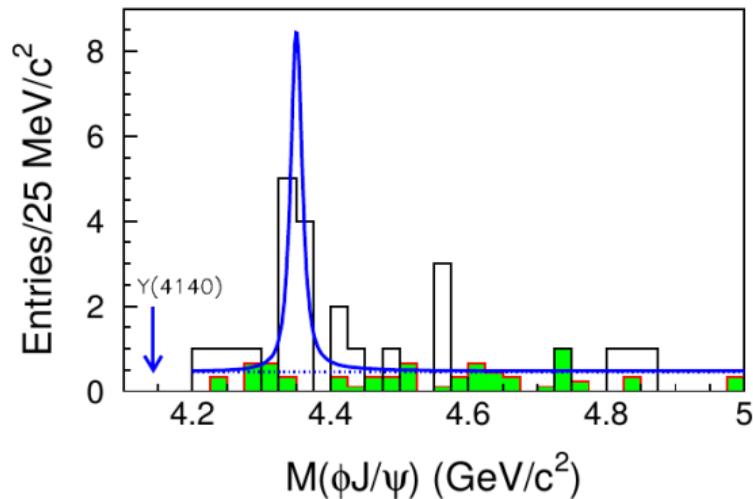


A $J/\psi\phi$ resonance in $\gamma\gamma$ fusion

[PRL104(2010)112004]

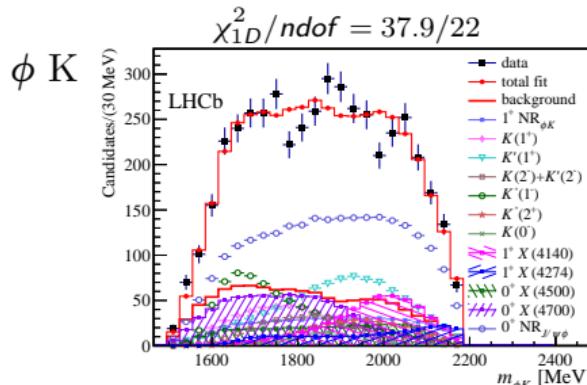
- Belle searched for the X(4140) in
 $\gamma\gamma \rightarrow J/\psi\phi$
- No events were found close to threshold
- Instead a peak with 3.2σ significance at
- $m = 4350.6^{+4.6}_{-5.1} \pm 0.7 \text{ MeV}$ and
 $\Gamma = 13^{+18}_{-9} \pm 4 \text{ MeV}$

J^P	$\Gamma_{\gamma\gamma}(X) \times \mathcal{B}(X \rightarrow J/\psi\phi) [\text{eV}]$
0^+	$6.7^{+3.2}_{-2.4} \pm 1.1$
2^+	$1.5^{+0.7}_{-0.6} \pm 0.3$

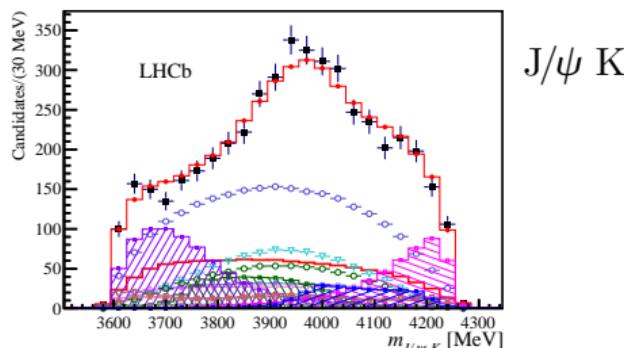
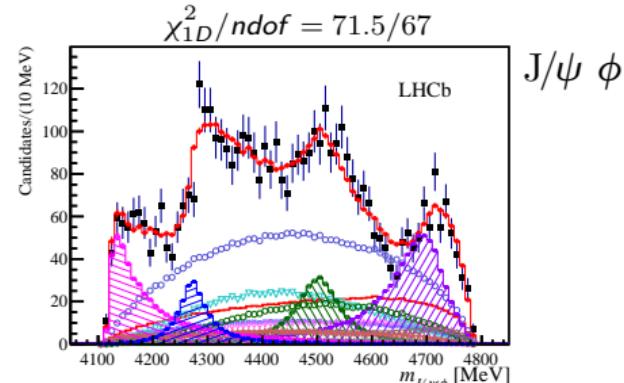




LHCb: $B^+ \rightarrow J/\psi\phi K^+$ amplitude analysis



- **3 fb^{-1} yield 4289 ± 151**
- **$B^+ \rightarrow J/\psi\phi K^+$ candidates**
- **7 K^* resonances**
+ non-resonant ϕK amplitude
- **4 exotic resonances in $J/\psi\phi$**
- **Fit quality on Dalitz-Plot: $p_{2D} = 17\%$**
- **No $J/\psi K$ resonances needed**





Results for X(4140), X(4274), X(4500) & X(4700)

[arXiv:1606.07898][arXiv:1606.07895]

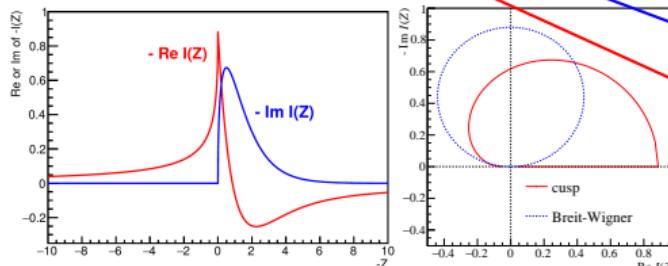
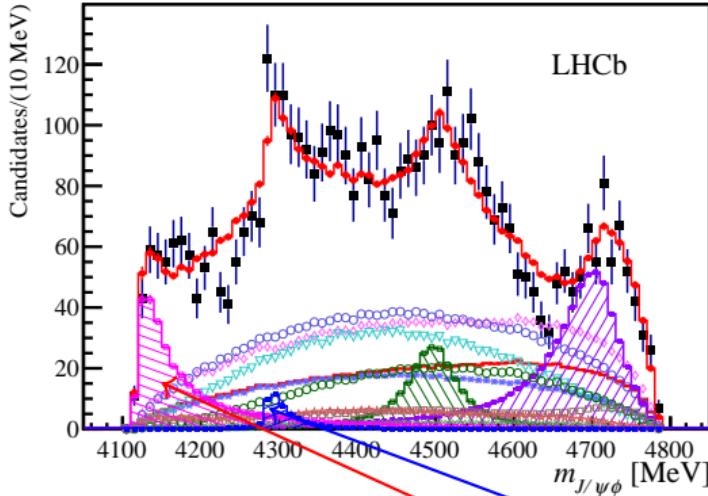
State	M [MeV]	Γ [MeV]	signi	J^{PC}	J^{PC} signi
X(4140)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	1^{++}	5.7σ
X(4274)	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	6.0σ	1^{++}	5.8σ
X(4500)	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	6.1σ	0^{++}	4.0σ
X(4700)	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	5.6σ	0^{++}	4.5σ

- X(4140) & X(4274) confirmed but with **larger width** than previous analyses
- First evidence of two new states X(4500) and X(4700)
- Large contribution from K^* resonances,
including first observation of $K^*(1680) \rightarrow K^+\phi$
- non-resonant contribution in 0^{++} amplitude.





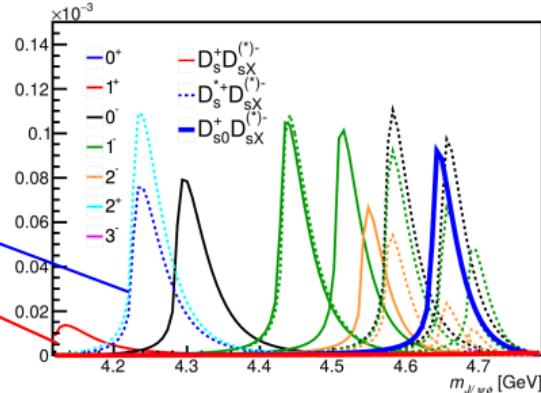
$D_s D_s^*$ cusp amplitudes



- $D_s^{(*)} D_s^{(*)}$ cusp-amplitudes included in fit

- X(4140) favours $D_s D_s^*$ cusp by $\Delta(-2 \ln \mathcal{L}) = 3.0^2$
- X(4274) resonance fav. over $J^P = 0^-$ cusp
- Many cusps at higher masses, needs future investigation

[PRD91(2015)034009]





Status of $J/\psi\phi$ resonances

State	M [MeV]	Γ [MeV]	M^{LHCb} [MeV]	Γ^{LHCb} [MeV]	$J^P C$
$X(4140)$	4143.4 ± 1.9	15.5 ± 6.3	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
$X(4274)$	4293 ± 20	35 ± 16	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	1^{++}
$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$			$0^+ \text{ or } 2^+$
$X(4500)$			$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
$X(4700)$			$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

- $J^P C = 1^{++}$ assignment of $X(4140)$ and $X(4274)$ consistent with non-observation in $\gamma\gamma$ fusion
- Are $X(4350)$ and $X(4500)$ the same state?
masses and widths don't match well
- $X(4140)$ consistent with $D_s D_s^*$ cusp

X(4140) at CMS
see L. Cristella,
Sec. C, Thu. 17:40

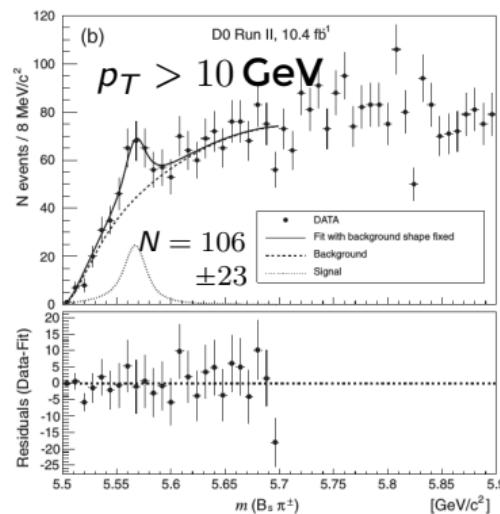
The $B_s^0 \pi^+$ System



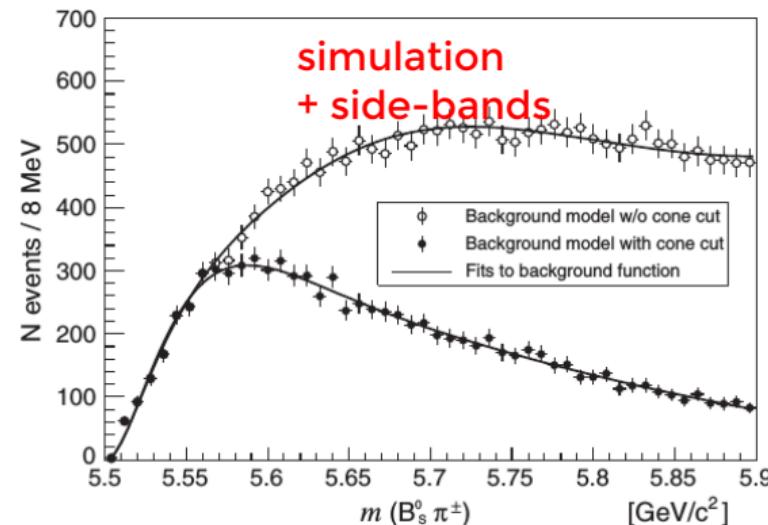
A resonance in $B_s^0 \pi^+$ at D0

[PRL117(2016)022003]

Peaking structure found by D0



Applying a cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$



- 5582 ± 100 $B_s^0 \rightarrow J/\psi \phi$ candidates
- significance: 3.9σ (incl. LEE)

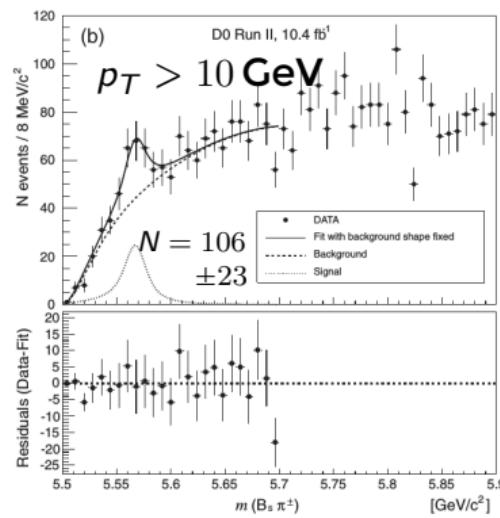




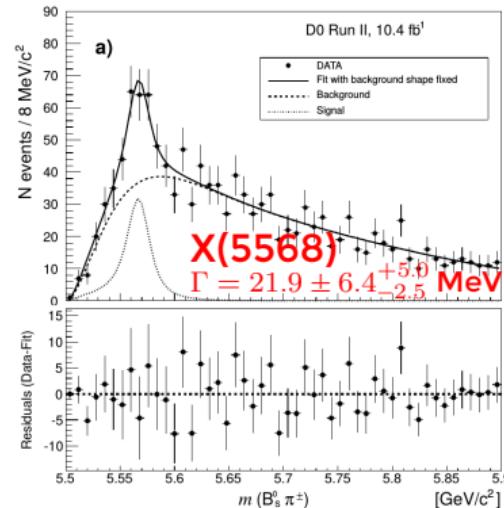
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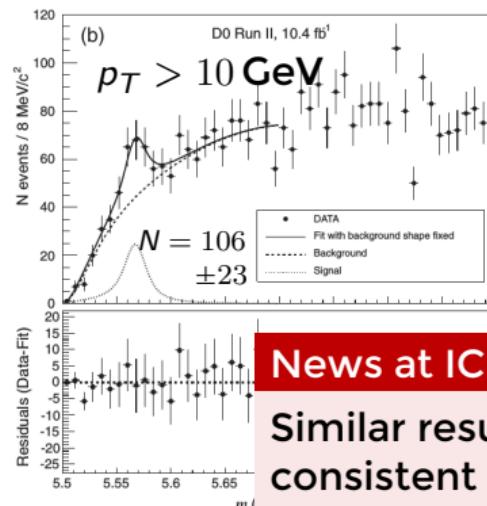
- 5.1σ significance after "cone"-cut
- $(8.6 \pm 1.9 \pm 1.4)\%$ of B_s^0 from $X(5568)$



A resonance in $B_s^0 \pi^+$ at D0

[PRL117(2016)022003]

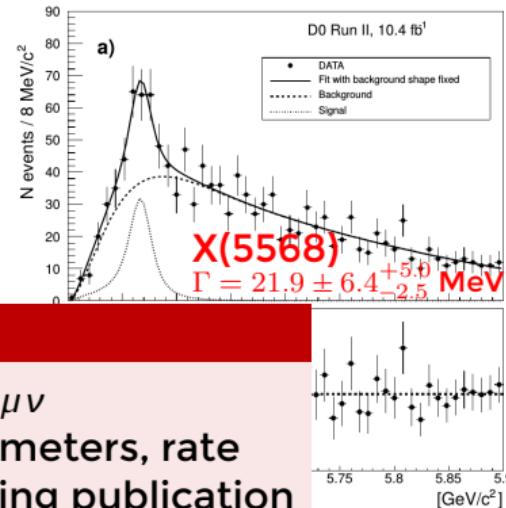
Peaking structure found by D0



News at ICHEP

Similar result with $B_s^0 \rightarrow D_s \mu \nu$
consistent resonance parameters, rate
awaiting publication

Applying a cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$

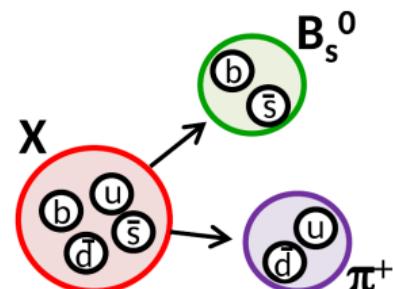


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- $(8.6 \pm 1.9 \pm 1.4)\%$ of B_s^0 from X(5568)

A four-flavour Tetraquark?

- Valence quark content $b\bar{s}u\bar{d}$
- How would such a state be generated/composed?
 - Tetraquark
 - $B_s^0 \pi$, BK molecule
 - $B_s^* \pi$ cusp,
 - Nearest 2-body threshold: $B_s^* \pi^-$ @ 5555 MeV
 - All models have troubles explaining the X(5568)
[CTP65(2016)593][PLB760(2016)627]
- Can it be confirmed by other experiments?

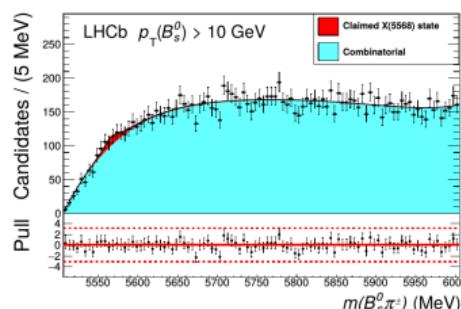
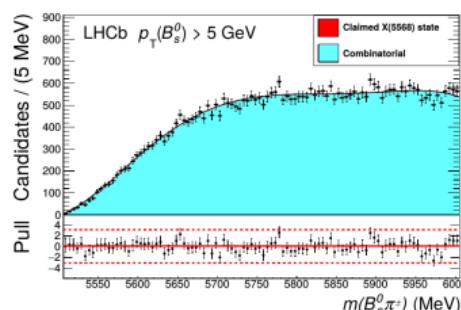




Search for X(5568) at the LHC

[arXiv:1608.00435]

LHCb: 50k $B_s^0 \rightarrow J/\psi \phi$ combined with
70k $B_s^0 \rightarrow D_s^- \pi^+$ candidates



Limit on cross-section times branching fraction ratio at 90(95)% C.L.

$$\rho_X = \frac{\sigma(pp \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_s^0 \pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})}$$

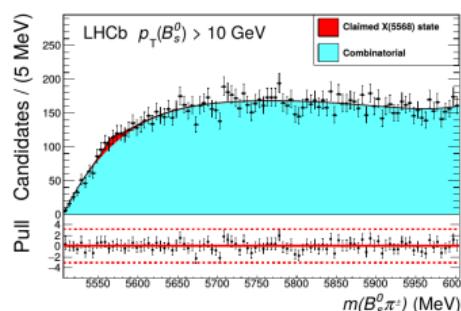
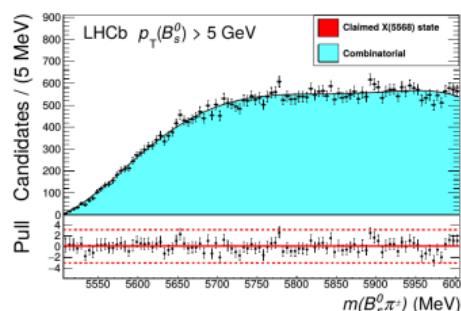
$$\rho_X^{LHCb}(p_T > 10 \text{ GeV}) < 0.021(0.024)$$



Search for X(5568) at the LHC

[arXiv:1608.00435]

LHCb: 50k $B_s^0 \rightarrow J/\psi \phi$ combined with
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Limit on cross-section times branching fraction ratio at 90(95)% C.L.

$$\rho_X = \frac{\sigma(\text{pp} \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_s^0 \pi^\pm)}{\sigma(\text{pp} \rightarrow B_s^0 + \text{anything})}$$

$$\rho_X^{LHCb}(p_T > 10 \text{ GeV}) < 0.021(0.024)$$

News from CMS at ICHEP

$$\rho_X^{CMS} < 0.039 \quad @95\% \text{C.L.}$$

see L. Cristella, Sec. C, Thu. 17:40



X(5568) Experimental Status

■ Seen by D0 in $p\bar{p} \rightarrow (B_s^0 \pi) + anything$

- with $B_s^0 \rightarrow J/\psi \phi$
- with $B_s^0 \rightarrow D_s \mu \nu$
- $\rho_X^{p\bar{p}} = (8.6 \pm 1.9 \pm 1.4)\%$

[PRL 117(2016)022003]

(presented at ICHEP)

■ Not seen at the LHC $pp \rightarrow (B_s^0 \pi) + anything$

- LHCb in $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow D_s \pi$
- CMS in $B_s^0 \rightarrow J/\psi \phi$
- $\rho_X^{pp} < 2.4\% @ 95\% C.L. (LHCb)$

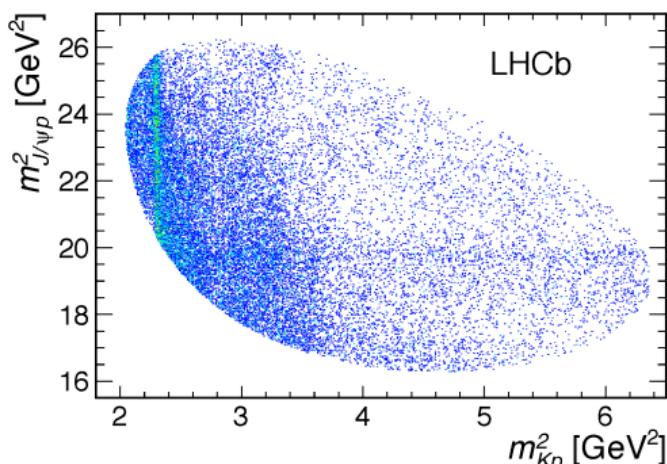
arXiv:1608.00435

(see L. Christella, Section C, Thu. 17:40)

■ A word from CDF?

Baryon Resonances with Hidden Charm

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





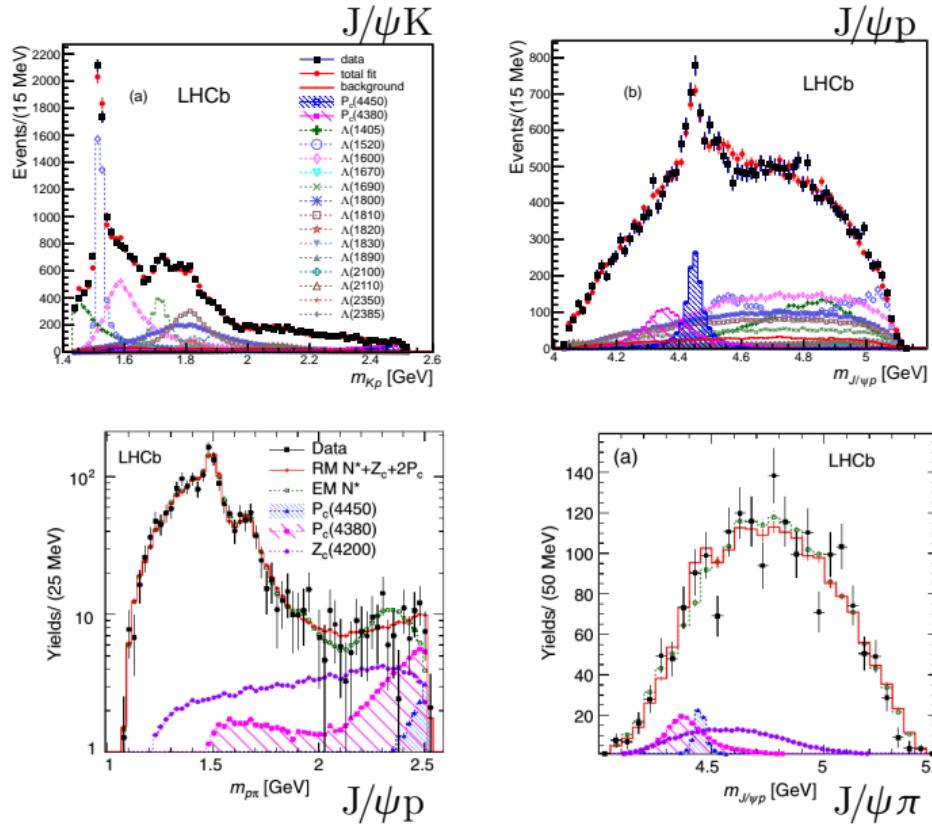
Discovery of $J/\psi p$ baryon resonances at LHCb

Three analyses performed:

- $\Lambda_b \rightarrow J/\psi p K$
 - 26 000 Λ_b candidates
 - 6D amplitude analysis
[PRL115(2015)072001]

- moments analysis
[PRL117(2016)082002]

- $\Lambda_b \rightarrow J/\psi p \pi$
 - 1 900 Λ_b candidates
 - 6D amplitude analysis
[PRL117(2016)082003]





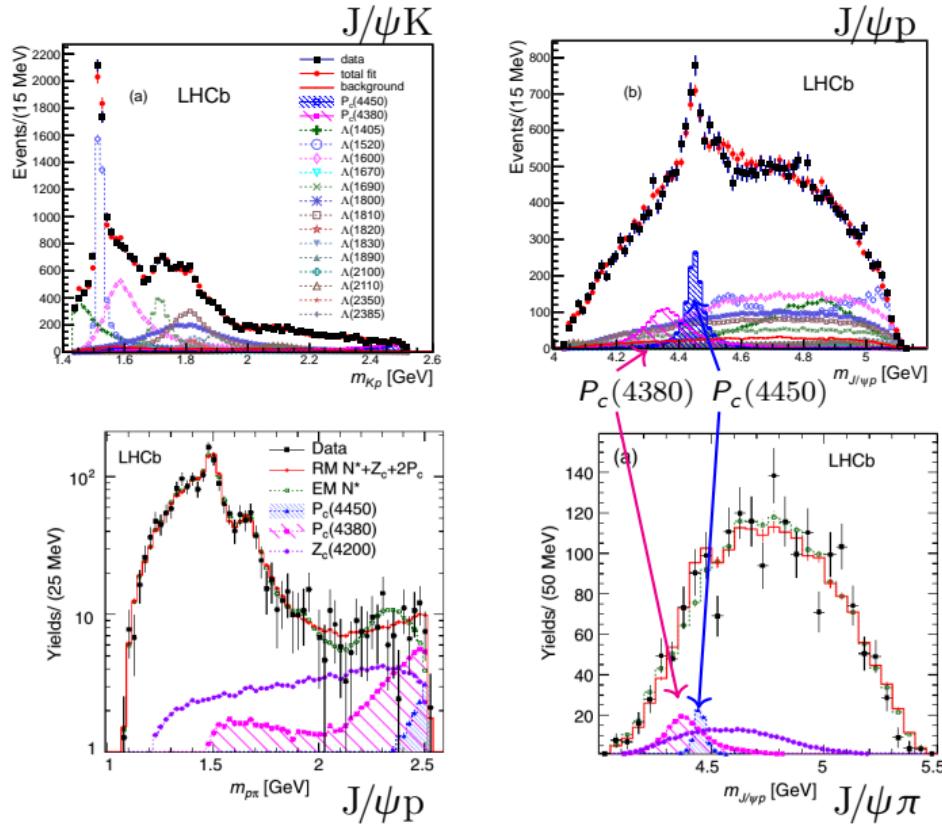
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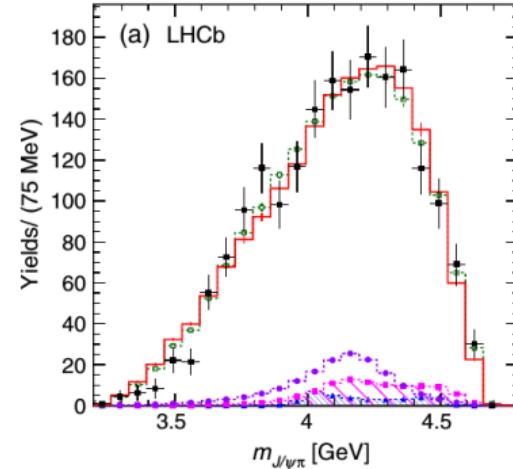
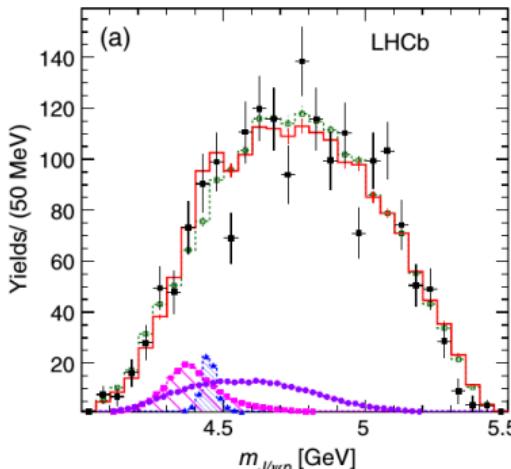




Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p \pi^-$

Challenges:

- Cabibbo suppr.
 $\mathcal{B}(\Lambda_b \rightarrow J/\psi p \pi) \approx 8\%$
 $\mathcal{B}(\Lambda_b \rightarrow J/\psi p K)$ [JHEP 07(2014)103]
- Need to deal with N^* resonances
- 6 N^* states needed
- Up to 14 used for systematic studies
- Bonn-Gatchina model for systematics
[EPJ A48(2012)15]
- Possibility in $J/\psi \pi$:
 $Z(4200)$





Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p \pi^-$

Challenges:

■ Cabibbo suppr.

$$\frac{\mathcal{B}(\Lambda_b \rightarrow J/\psi p\pi)}{\mathcal{B}(\Lambda_b \rightarrow J/\psi pK)} \approx 8\% \\ [\text{JHEP } 07(2014)103]$$

■ Need to deal with N^* resonances

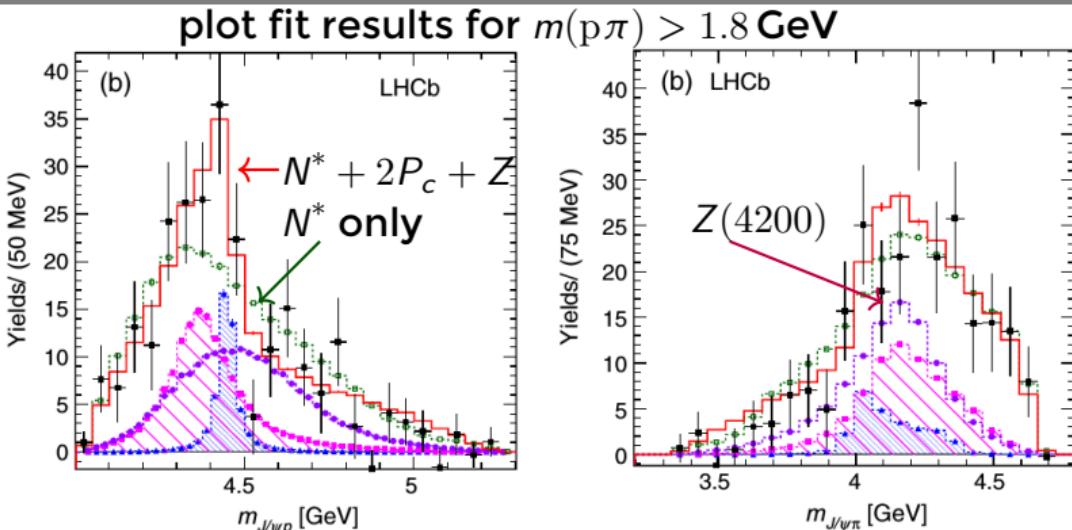
■ 6 N^* states needed

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■ Bonn-Gatchina model for systematics

[EPJ A48(2012)15]

■ Possibility in $J/\psi\pi$: $Z(4200)$





Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p \pi^-$

Challenges:

■ Cabibbo suppr.

$$\frac{\mathcal{B}(\Lambda_b \rightarrow J/\psi p\pi)}{\mathcal{B}(\Lambda_b \rightarrow J/\psi pK)} \approx 8\% \\ [\text{JHEP } 07(2014)103]$$

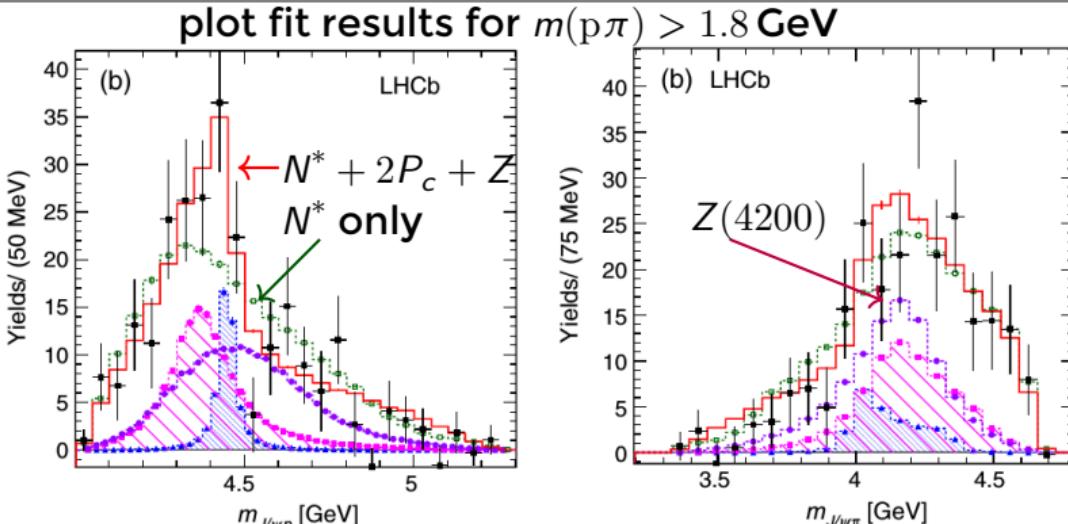
■ Need to deal with N^* resonances

■ 6 N^* states needed

■ Up to 14 used for systematic studies

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■ Possibility in $J/\psi\pi$: $Z(4200)$



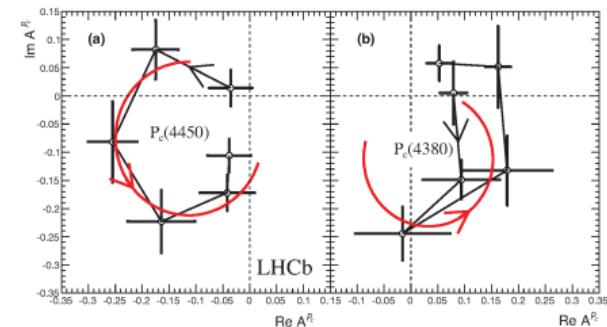
- Both types of exotics: significance 3.1σ
- Two P_c have a significance of 3.3σ
Assuming $Z(4200)$ negligible
- Exotic contributions needed,
can't distinguish scenarios



Parameters from $\Lambda_b \rightarrow J/\psi p K$ amplitude analysis

State	Mass [MeV]	Width [MeV]	fav. J^P	Fit fraction	Signi.
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	$(8.4 \pm 0.7 \pm 4.2)\%$	9σ
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$	$(4.1 \pm 0.5 \pm 1.1)\%$	12σ

- Interference of two states of **opposite parity** required by forward-backward asymmetry in P_c helicity angle



- Spin-parity assignment not conclusive:

Fit	$\Delta(-2 \ln \mathcal{L})$	P_c (Low) Mass	P_c (Low) Γ	P_c (High) Mass	P_c (High) Γ
$3/2^-, 5/2^+$	0	4.3799 ± 0.0064	0.205 ± 0.011	4.4498 ± 0.0017	0.0387 ± 0.0037
$3/2^+, 5/2^-$	0.9^2	4.3696 ± 0.0063	0.211 ± 0.012	4.4504 ± 0.0017	0.0492 ± 0.0040
$5/2^+, 3/2^-$	2.3^2	4.3770 ± 0.0098	0.239 ± 0.024	4.4486 ± 0.0018	0.0444 ± 0.0053

⋮



Nature of $P_c(4380)$ and $P_c(4450)$

- Valence quark content: $uudc\bar{c}$
- What are the relevant degrees of freedom?
- Are there more of their kind?

Challenges to theory:

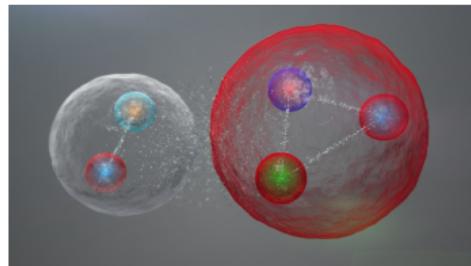
- Why two states with opposite parity?
- Small mass gap ≈ 100 MeV
- Narrow width of $P_c(4450)$

See talks by
V. Magas
in Sec. C, Thu. afternoon
F. Guo
T. Burns
in Sec. C, Fri. afternoon

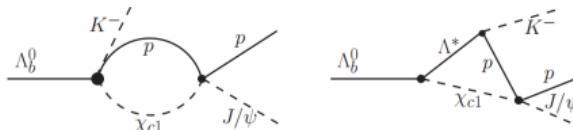


Meson-Baryon degrees of freedom following [EPJ A51(2015)11,152]

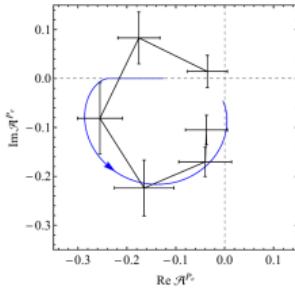
- Proximity of 2-body thresholds
→ need to be taken into account

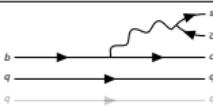
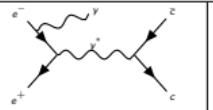
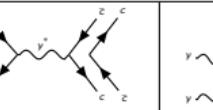
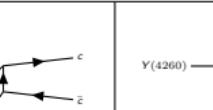
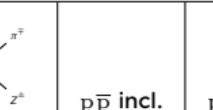


	Closeby thresholds	
[MeV]	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
$\Sigma_c^{*+} \bar{D}^0$	4382.3 ± 2.4	
$\chi_{c1}(1P)p$		4448.93 ± 0.07
$\Lambda_c^{+*} \bar{D}^0$		4457.09 ± 0.35
$\Sigma_c \bar{D}^{0*}$		4459.9 ± 0.5
$\Sigma_c \bar{D}^0 \pi^0$		4452.7 ± 0.5



- Guo et al [PRD92(2015)071502]
- can explain $P_c(4450)$ phase motion
But $P_c(4380)$?
- Rescattering would not explain a narrow enhancement
in $\chi_{c1}(1P)p$ ⇔ can be checked at LHCb



						p\bar{p} incl.	pp incl.
J/\psi \pi^+ \pi^-	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
\psi(2S) \pi^+ \pi^-		Y(4360) Y(4660)					
\Lambda_c \bar{\Lambda}_c		Y(4630)					
\psi \gamma	X(3872)						
\chi_{c1}(1P) \gamma	X(3832)						
\chi_{c1}(1P) \omega				Y(4220)			
J/\psi \omega	X(3872) Y(3940)			X(3915)			
J/\psi \phi	X(4140) X(4274) X(4500) X(4700)			X(4350)			
J/\psi \pi	Z(4430) Z(4200) Z(4240)				Z(3900)		
\psi(2S) \pi	Z(4430)						
\chi_{c1}(1P) \pi	Z(4051) Z(4248)						
h_c(1P) \pi					Z(4020)		
D\bar{D}				Z(3930)			
D\bar{D}^*	X(3872)		X(3940)		Z(3885)		
D^*\bar{D}^*			X(4160)		Z(4025)		
J/\psi p	P_c(4380) P_c(4430)						
B_s^0 \pi					X(5568)		-



Conclusion

- Patterns among the XYZ are getting clearer
- Unified description of phenomena lacking
- Case-to-case treatment of kinematic and coupled-channel effects
- More data in the analysis pipelines
- Exotics with hidden charm in the baryon sector!
- There is more! Sorry if I left out your favourite topic.

More Section C talks:

A. Pilloni
A. Nefediev
J. T. Castella
J. Soto

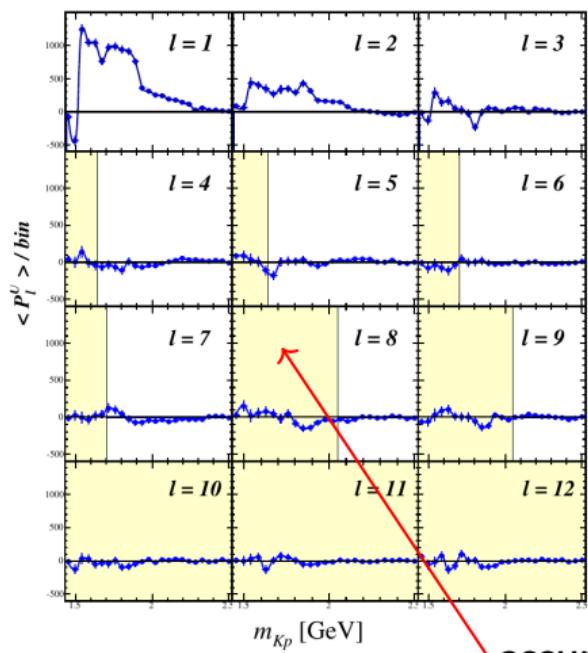
Very useful review article: arXiv:1601.02092
Many thanks to Soeren Lange for inspiration!

Backup

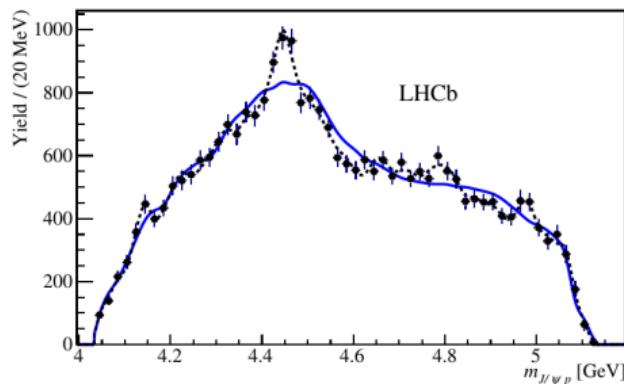


Model-independent analysis of $\Lambda_b \rightarrow J/\psi p K$

Legendre-moments of pK decay angle distribution



From moments construct toy MC:
Reflections of pK-system into $J/\psi p$



- Hypo "only Λ^* " rejected with $> 9\sigma$
- Confirms findings of amplitude analysis

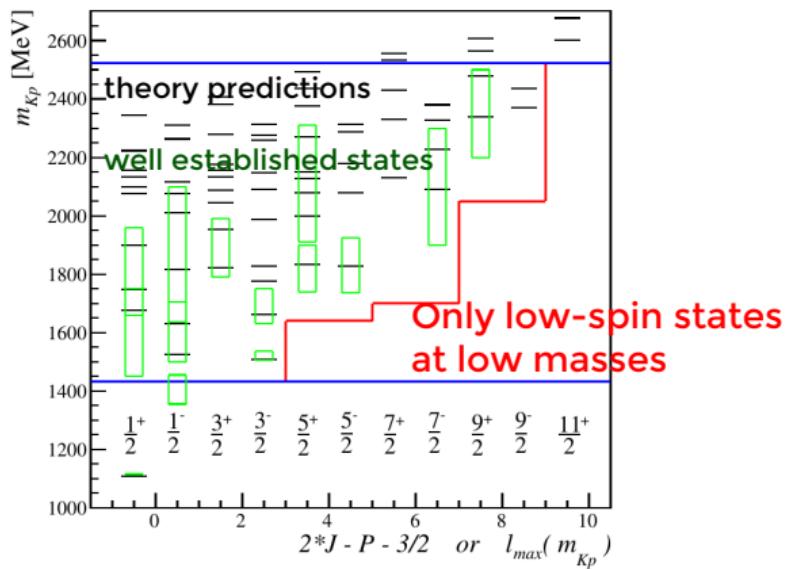
assume: at low mass only low-spin Λ^*



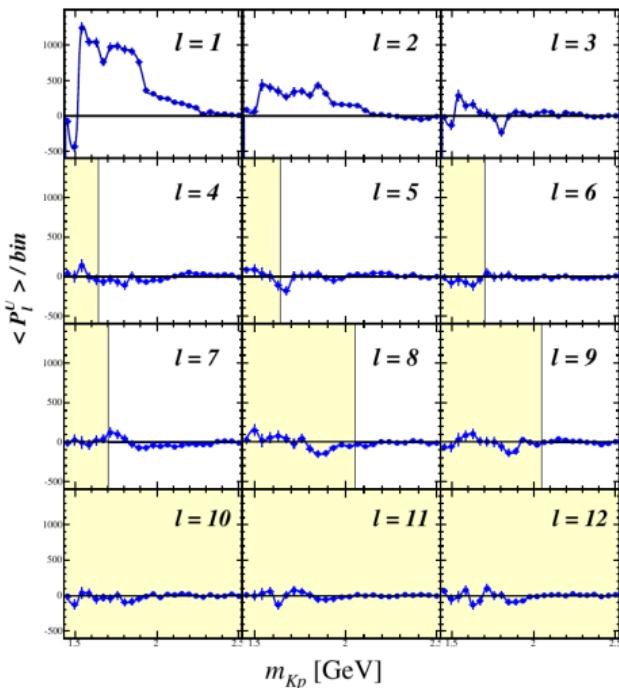


Model-independent analysis of $\Lambda_b \rightarrow J/\psi pK$

- Observation of the $P_c(4380)$ and $P_c(4450)$ used a model for the decay matrix element
- Λ^* spectrum biggest uncertainty



In bins of $m(pK)$: decompose decay-angle distribution into Legendre-moments



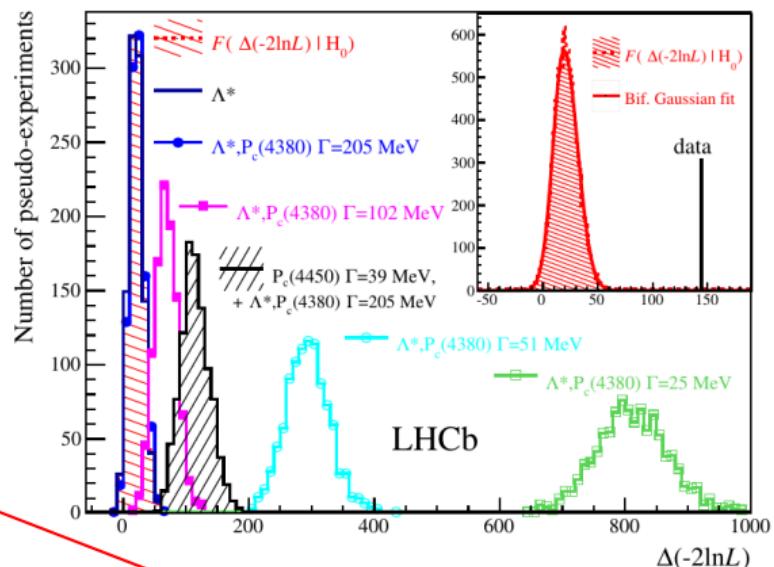
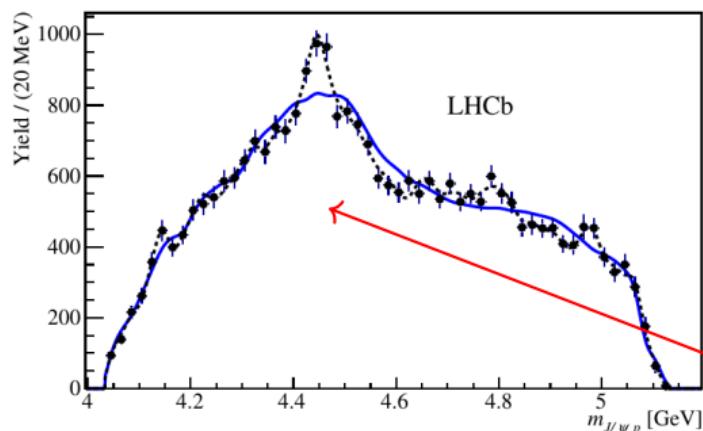


Model-independent analysis of $\Lambda_b \rightarrow J/\psi p K$

Testing sensitivity on MC for various models:

Construct ℓ_{max} -filtered toy MC:
Reflections of p K-system into J/ψ

p

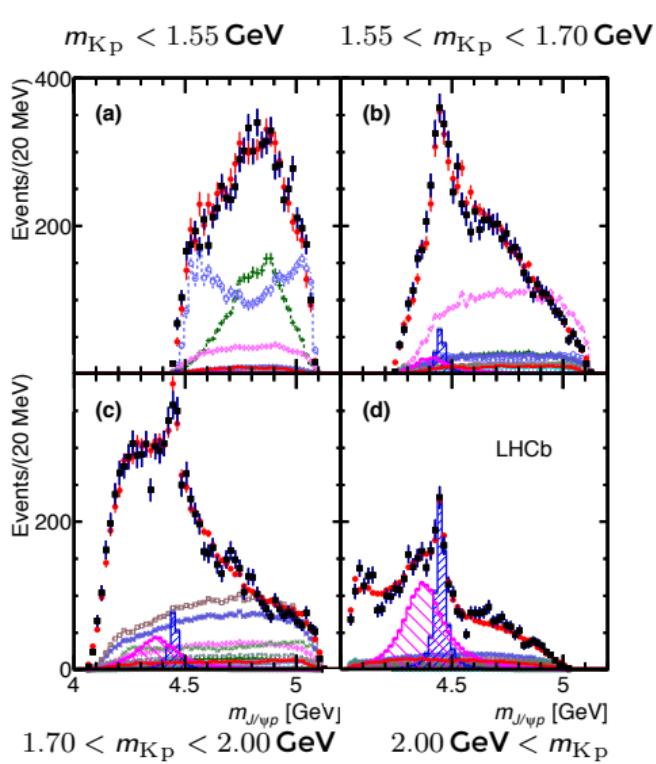


- p K-reflections cannot explain the narrow structure in $J/\psi p$

- Hypothesis "only Λ^* " rejected with $> 9\sigma$
- Confirms findings of amplitude analysis



Why a second state with opposing parity?



- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of m_{Kp} (or $\cos \theta_{P_c}$)
- This can be explained by interference of two states with opposing parity

