中国科学院大学
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Experimental review of pentaquarks and tetraquarks

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on behalf of the LHCb collaboration, including results from the Babar, Belle, BESIII, CMS, D0, CDF collaborations

University of Chinese Academy of Sciences (UCAS), Beijing

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Introduction

- Quark model proposed by Gell-Mann and Zweig in 1964
- Tetraquark and pentaquarks are not a priori excluded...

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

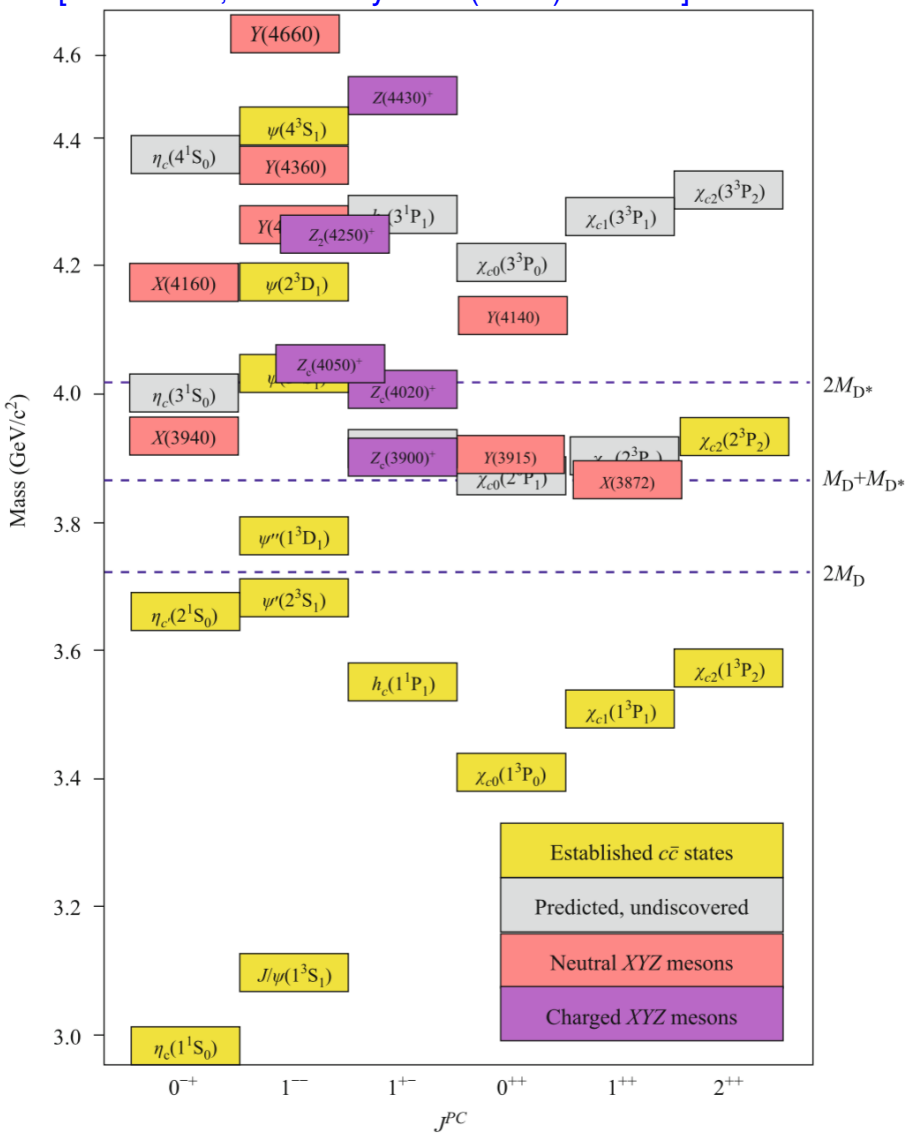
Experimental status

- *XYZ* keep appearing, continuous efforts to understand their nature

Not a complete list...

State	Experiment
$X(3872)$	Belle, CDF, D0, Babar, LHCb, BESIII, CMS
$X(3915)$	Belle, Babar
$X(3940)$	Belle
$G(3900)$	Babar, Belle
$Y(4008)$	Belle
$X(4140)$	CDF, LHCb, CMS, D0, Babar, Belle, BESIII
$X(4160)$	Belle
$Y(4260)$	Babar, CLEO, Belle
$X(4274)$	CDF, CMS, Babar, BESIII, LHCb
$X(4350)$	Belle
$Y(4360)$	Babar, Belle
$X(4630)$	Belle
$Y(4660)$	Belle
$Z_c^+(3900)$	BESIII, Belle, CLEO
$Z_c^+(4020)$	BESIII
$Z_1^+(4050)$	Belle, Babar
$Z^+(4200)$	Belle
$Z_2^+(4250)$	Belle, Babar
$Z^+(4430)$	Belle, Babar, LHCb
$Y_b(10890)$	Belle
$Z_b^+(10610)$	Belle
$Z_b^0(10610)$	Belle
$Z_b^+(10650)$	Belle
$P_c(4450)^+$	LHCb
$P_c(4380)^+$	LHCb

[S.L. Olsen, Front. Phys. 10 (2015) 101401]

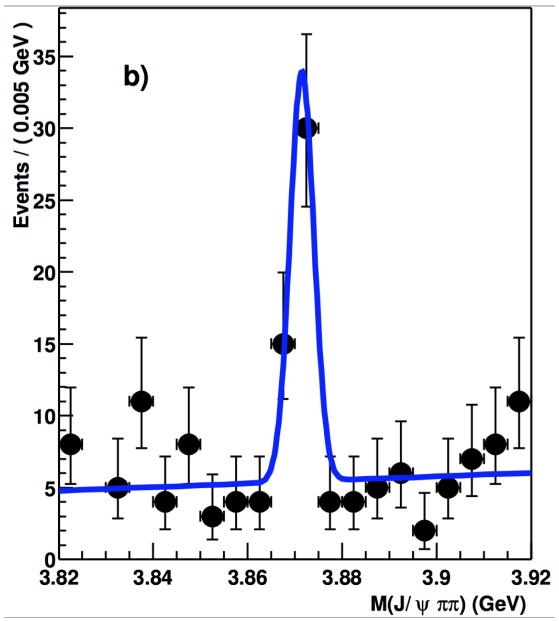


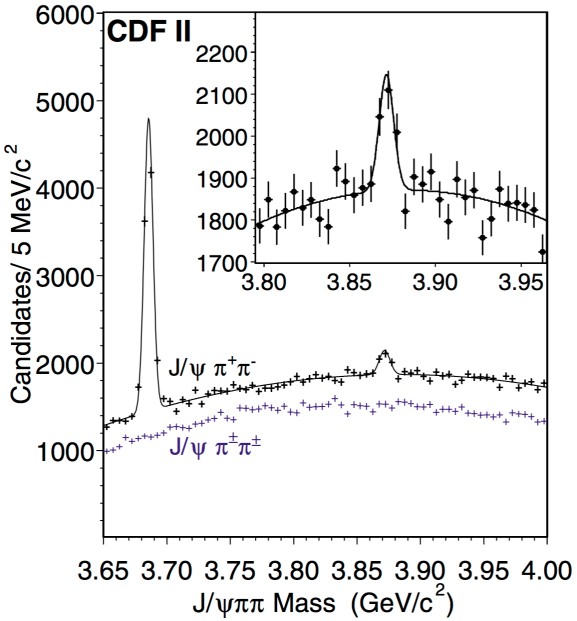
- Please see Dr. Estia Eichten's talk for theoretical discussions

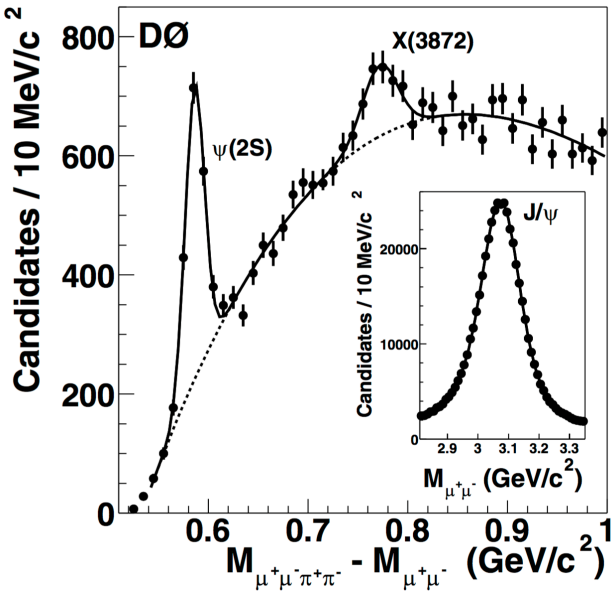
The $X(3872)$ $(c\bar{c}[u\bar{u}+d\bar{d}])$

[Belle, PRL 91 (2003) 262001] [CDF, PRL 93 (2004) 072001] [D0, PRL 93 (2004) 162002]

- $X(3872)$ discovered by Belle with $B^+ \to K^+ J/\psi \pi^+\pi^-$ in 2003, quickly confirmed by CDF and D0 in $p\bar{p}$ collisions





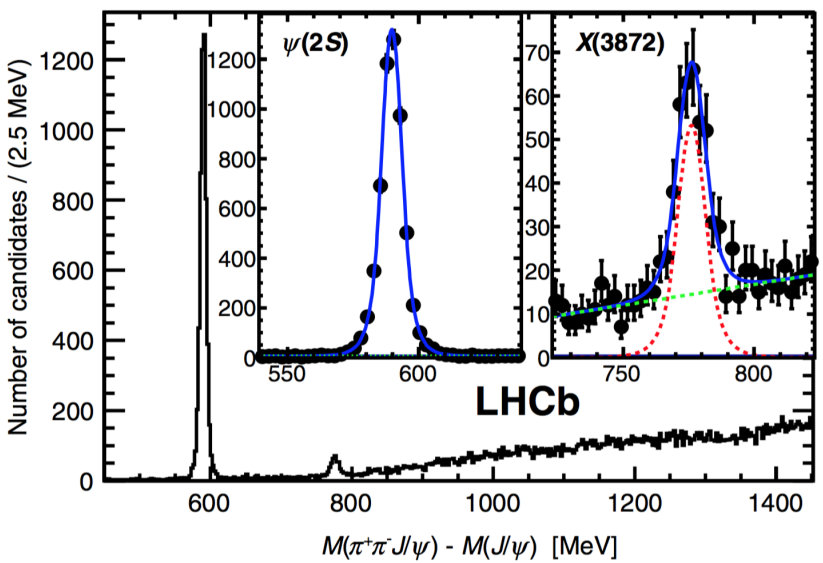


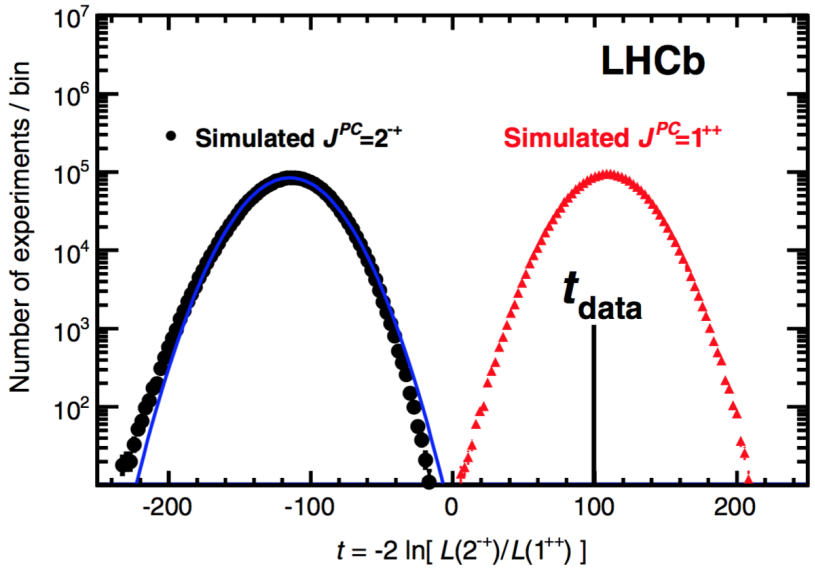
- Nature of $X(3872)$ still unclear
  - Molecular state, $D\bar{D}^{0*}$ threshold ($J^{PC} = 0^{-+}, 1^{++}$)
  - Tetraquark (1^{++})
  - $\chi_{c1}(2^3P_1)$ (1^{++}) or $\eta_{c2}(1^1D_2)$ (2^{-+})

Determining J^{PC} of $X(3872)$

[LHCb, PRL 110 (2013) 222001]

- Thanks to CDF, Belle and Babar, J^{PC} of $X(3872)$ narrowed to 1^{++} or 2^{-+}
- Full 5D angular analysis by LHCb, with ~ 310 $B^+ \to X(3872)K^+$ in 2011 data ($1\,\text{fb}^{-1}$), 2^{-+} rejected by 8σ



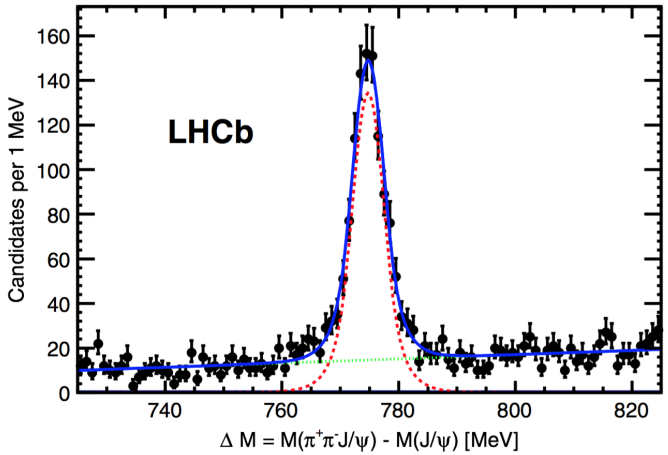


- All assumed the lowest orbital angular momentum $L_{\min}$ in $X(3872) \to J/\psi\rho$

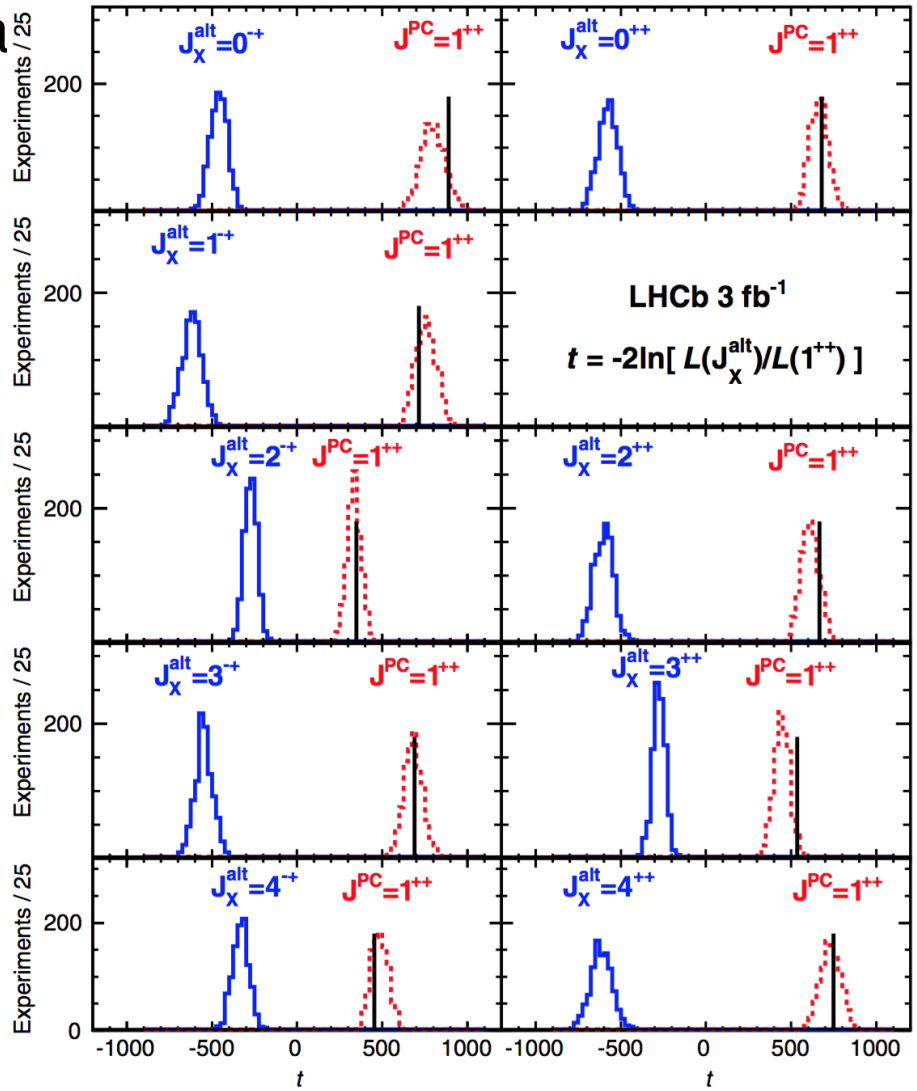
Determining J^{PC} of $X(3872)$, w/o assuming $L_{\rm min}$

- LHCb updated analysis without assuming $L_{\rm min}$, w/ 3 fb^{-1} data

[LHCb, PRD 92 (2015) 011102(R)]



J^{PC}	B_{LS} Any L value	Minimal L value
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

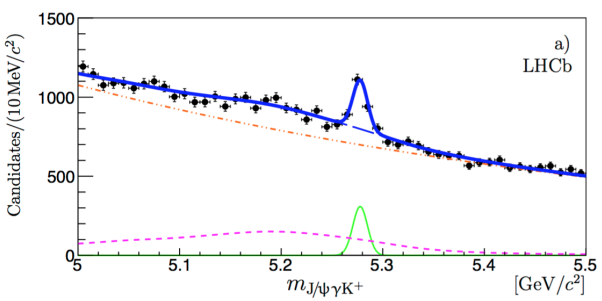


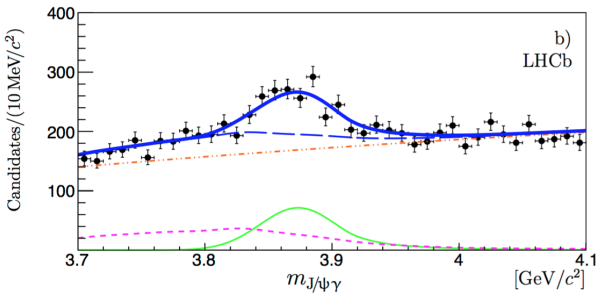
- $J^{PC} = 1^{++}$ confirmed, D-wave fraction <4% at 95% C.L.

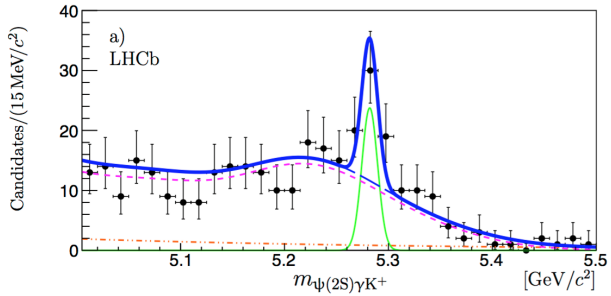
$X(3872) \to J/\psi\,\gamma,\ \psi(2S)\gamma$

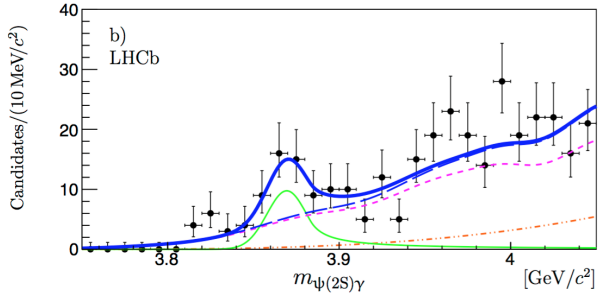
[LHCb, NPB 886 (2014) 665]

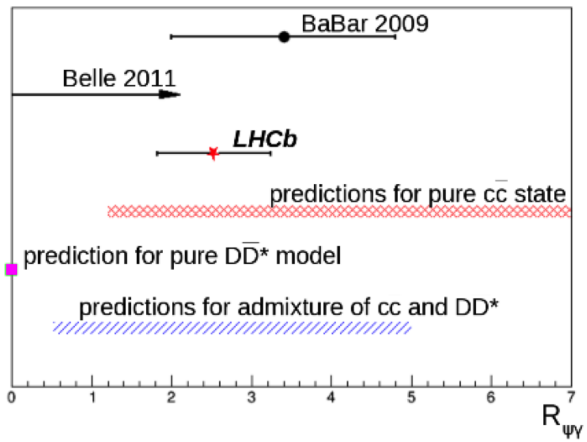
- $R_{\psi\gamma} \equiv \frac{\mathcal{B}(X\to\psi(2S)\gamma)}{\mathcal{B}(X\to J/\psi\,\gamma)}$ expected different for $c\bar{c}$ or $D\bar{D}^{*0}$ molecule
- Following Babar, Belle, LHCb also studied $X(3872) \to J/\psi\,\gamma$, $\psi(2S)\gamma$ with $3\,\text{fb}^{-1}$ of data
- Evidence of $X(3872) \to \psi(2S)\gamma$ found, 4.4 σ.
  Pure $D\bar{D}^{*0}$ molecule disfavored







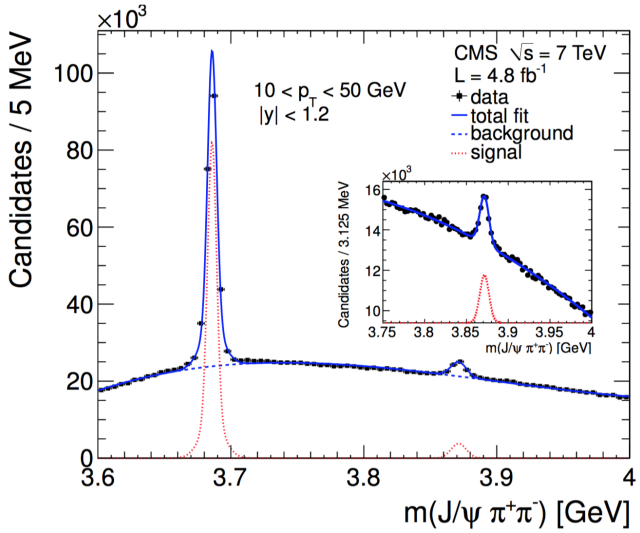


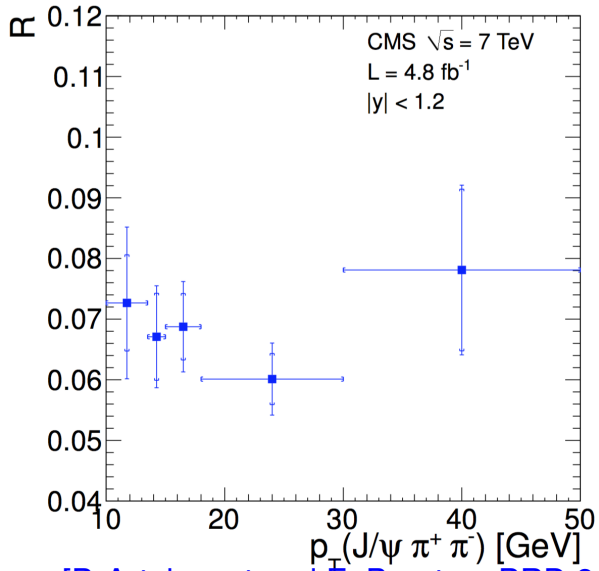


$X(3872)$ hadroproduction

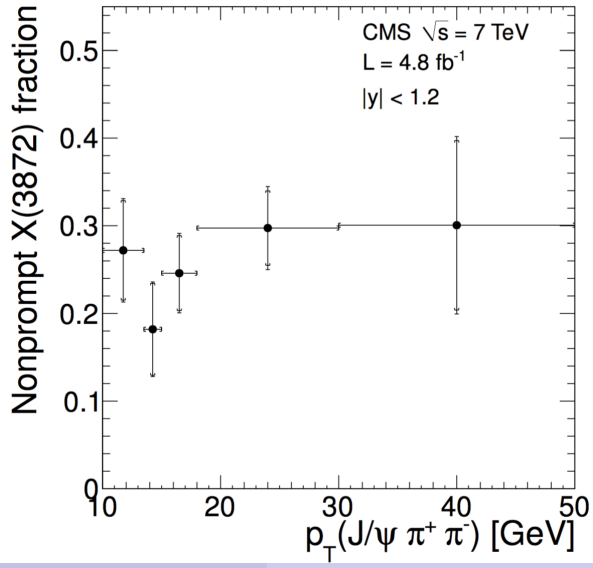
- Following CDF, LHCb, CMS also studied $X(3872)$ production at 7 TeV

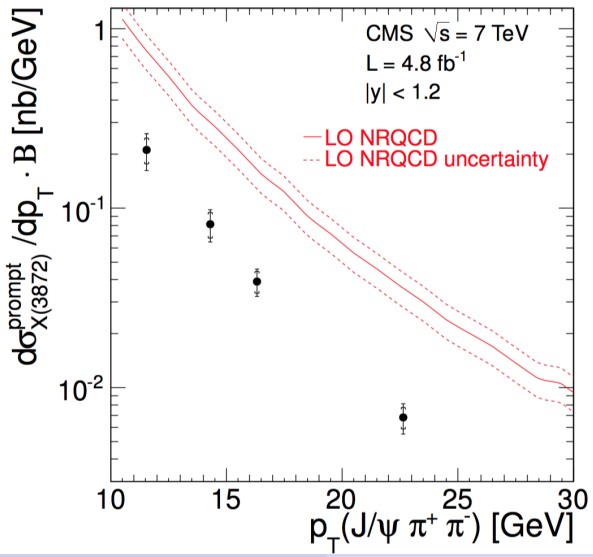
[CMS, JHEP 04 (2013) 154]





[P. Artoisenet and E. Braaten, PRD 81 (2010) 114018]

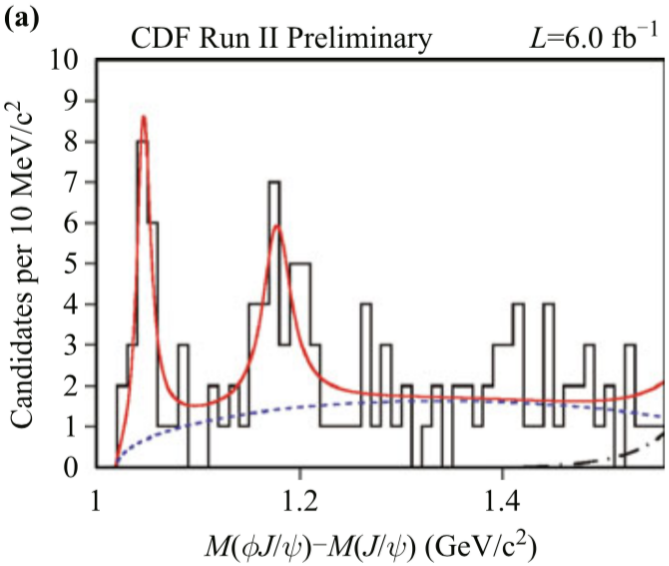


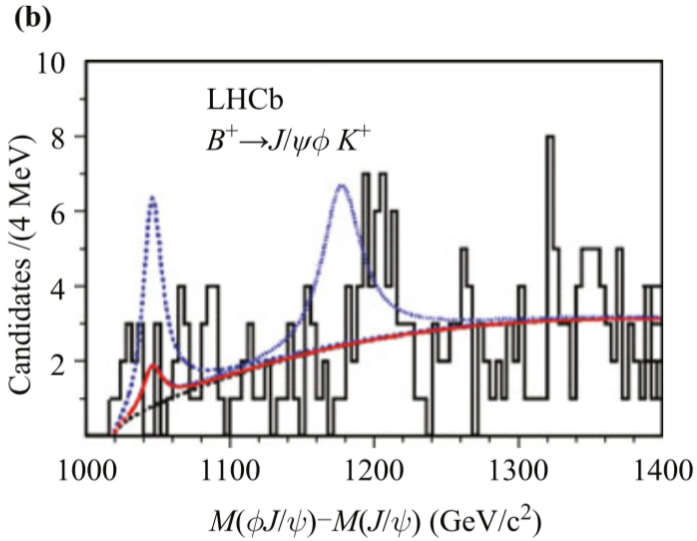


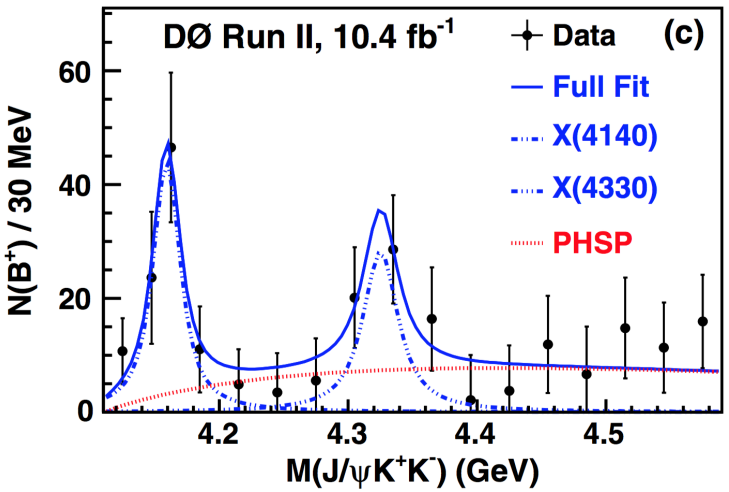
The $X(4140)$ and $X(4274)$ $(c\bar{c}s\bar{s})$

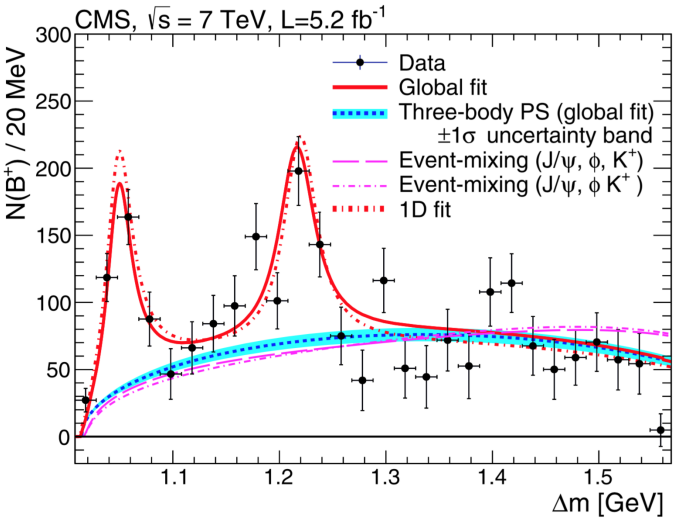
[CDF PRL 102 (2009) 242002, arXiv: 1101.6058] [LHCb, PRD 85 (2012) 091103(R)]
[D0, PRD 89 (2014) 012004] [CMS, PLB 734 (2014) 261]

- Seen by CDF in $B^+ \to K^+ J/\psi\,\phi$, not by LHCb... All 1D fits





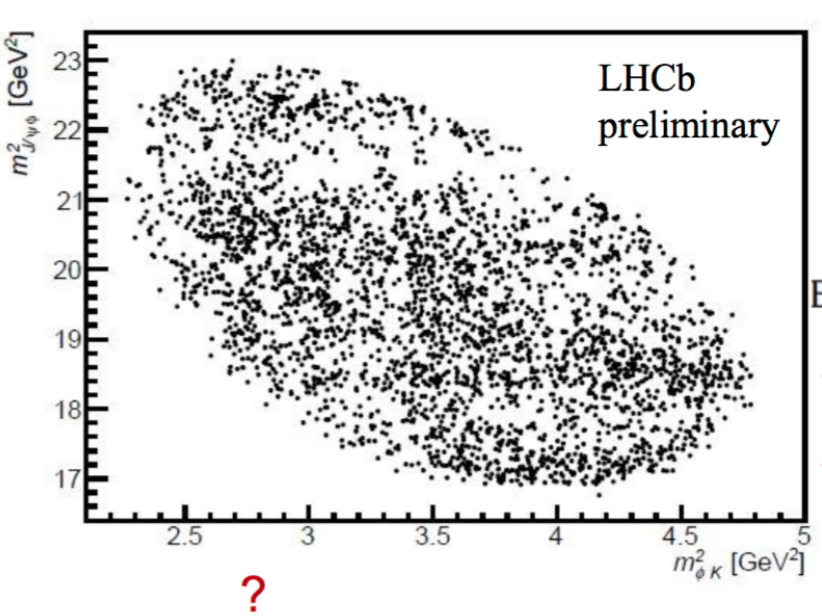




$B^+ \to J/\psi\,\phi\,K^+$ in LHCb full data set

New

[LHCb-Paper-2016-018, in preparation]



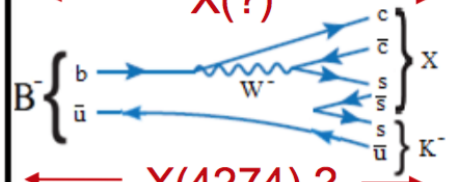
?

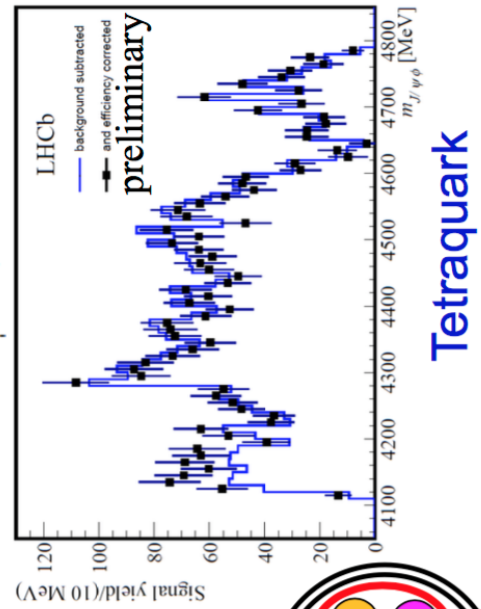
X(?)

X(?)

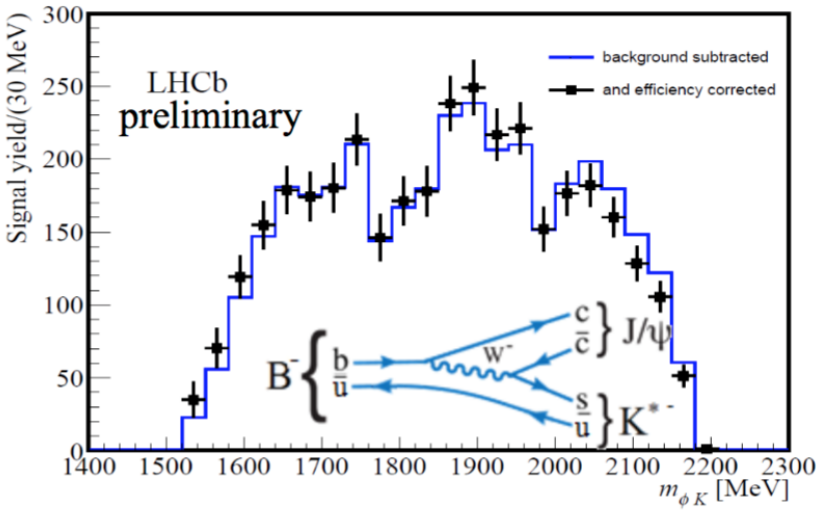
X(4274) ?

X(4140) ?
→ J/ψϕ





Tetraquark



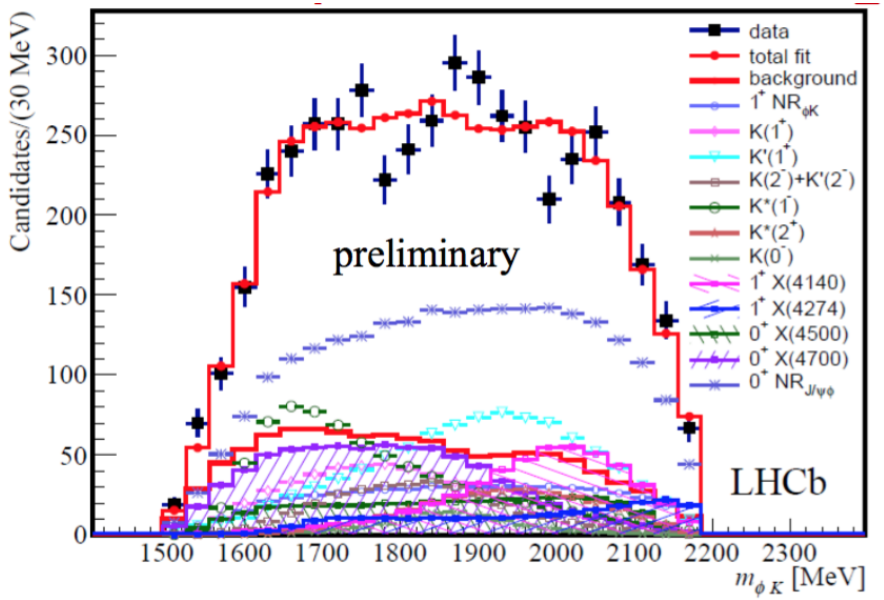
Kaon excitations

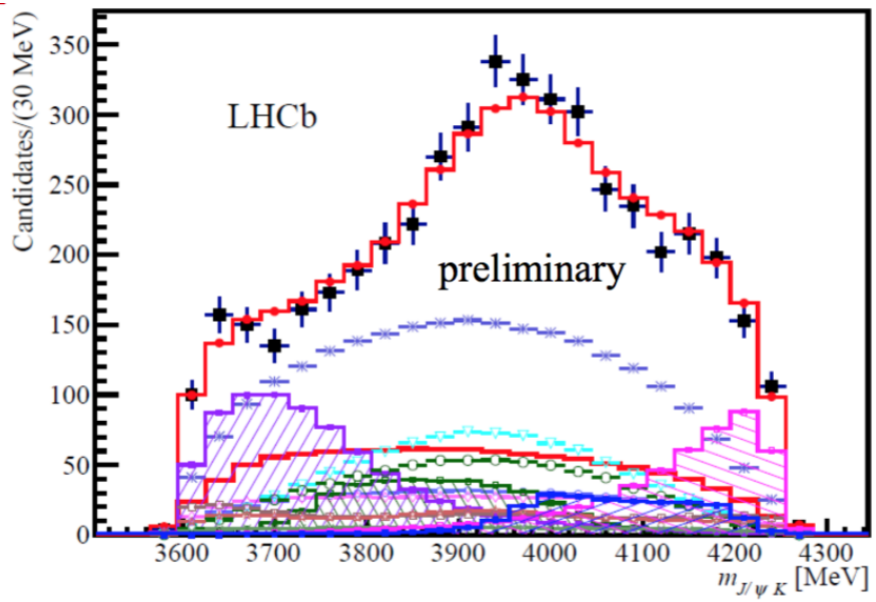
Are these reflections of interfering $K^{*-} \to \phi K^-$?

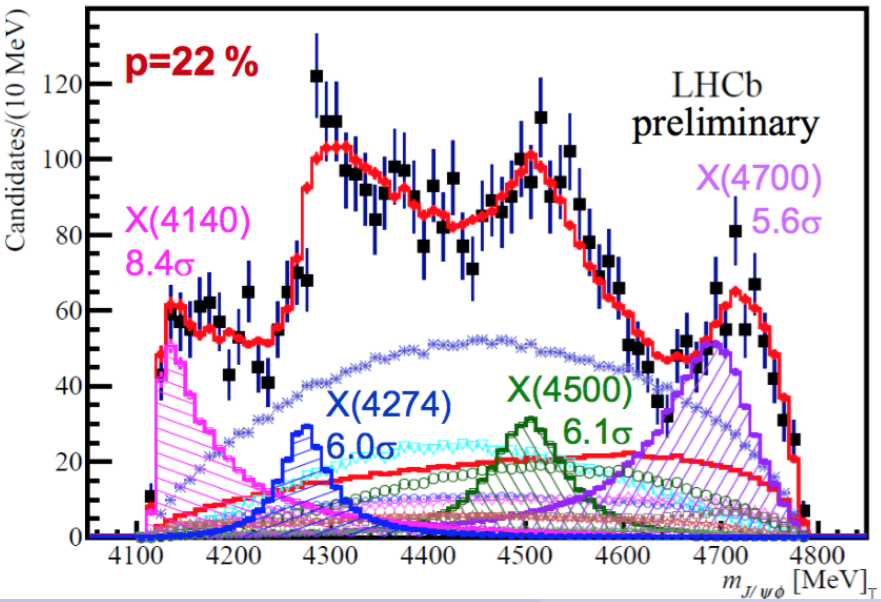
Proper amplitude analysis necessary to check

Amplitude fit including 4 exotic X New

[LHCb-Paper-2016-018, in preparation]



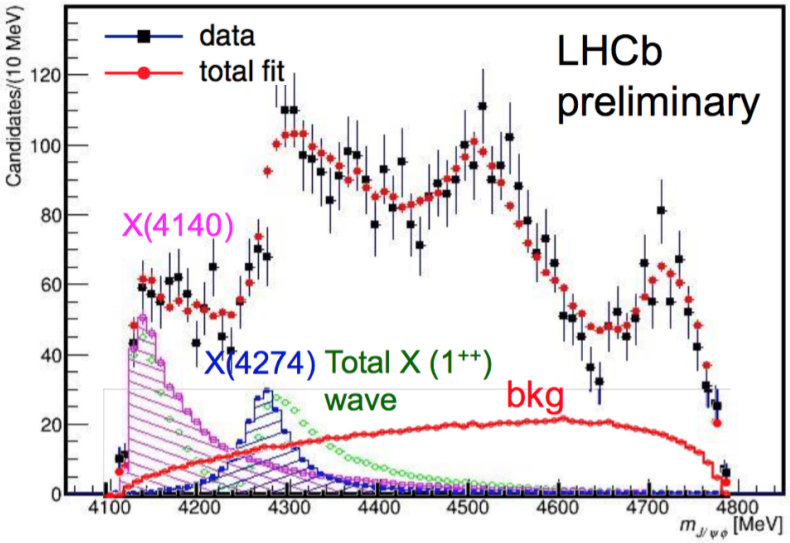




- We considered adding possible exotic $X \to J/\psi\,\phi$ and $Z^+ \to J/\psi\,K^+$ states as well as removing insignificant or implausible (Γ>1000 or <100 MeV) conventional $K^{*+} \to \phi\,K^+$ states leading us to a default model
- Only X states give very significant improvements in fit qualities over the models with K*s alone
- The default fit model is shown here.

The $X(4140)$ and $X(4274)$ properties New

[LHCb-Paper-2016-018, in preparation]



LHCb preliminary

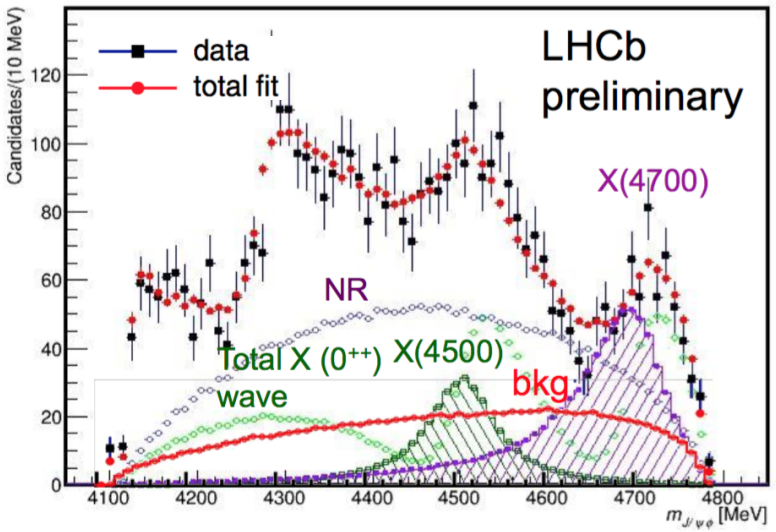
Contribution	sign. or Ref.	Fit results M_0 MeV	Fit results Γ_0 MeV	Fit results F.F. %
All $X(1^+)$				$16\pm3\,^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.8}_{-2.0}$
ave.		4146.9 ± 2.3	17.8 ± 6.8	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-3.6}$	$56\pm11\,^{+8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF		$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	

- $X(4140)$, significance 8.4σ
  - Mass consistent with previous measurements, width lager
  - $J^{PC} = 1^{++}$ determined at 5.7σ
- $X(4274)$, significance 6.0σ
  - Mass/width consistent with the CDF unpublished results
  - $J^{PC} = 1^{++}$ determined at 5.8σ

Observation of two new X states

New

[LHCb-Paper-2016-018, in preparation]



LHCb preliminary

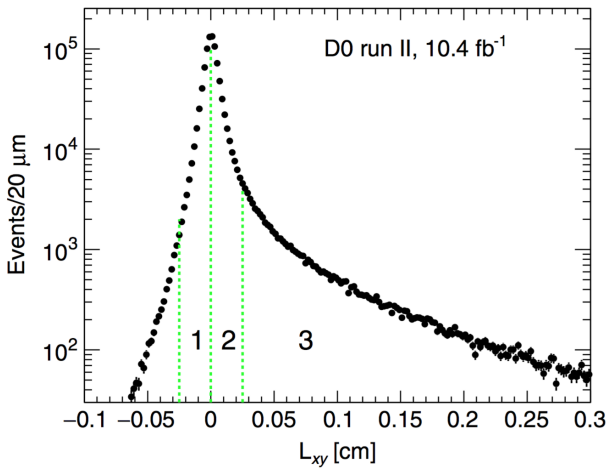
Contribution	sign.	Fit results M_0 MeV	Γ_0 MeV	F.F. %
All $X(0^+)$				$28\pm 5\,^{+7}_{-7}$
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46\pm 11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm 11\,^{+12}_{-15}$	$92\pm 21\,^{+21}_{-20}$	$6.6\pm 2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm 10\,^{+14}_{-24}$	$120\pm 31\,^{+42}_{-33}$	$12\pm 5\,^{+\ 9}_{-\ 5}$

- Significant structures at higher masses, best described by two new 0^{++} resonances $X(4500)$, $X(4700)$
  - Significance of 6.1σ, 5.6σ
  - $J^{PC} = 0^{++}$ determined at 4.0σ, 4.5σ

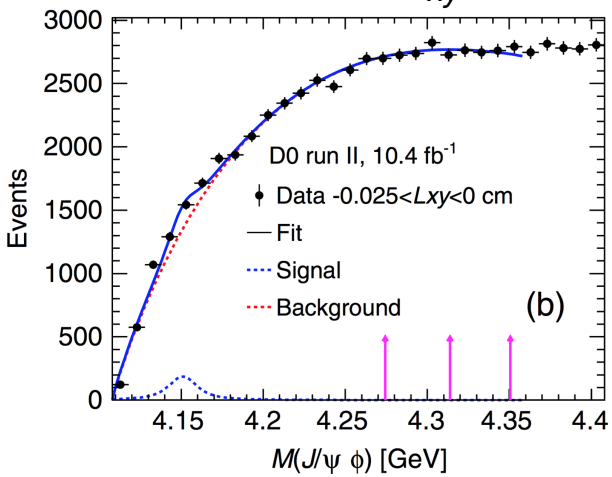
Hadroproduction of $X(4140)$

[D0, PRL 115 (2015) 231001]

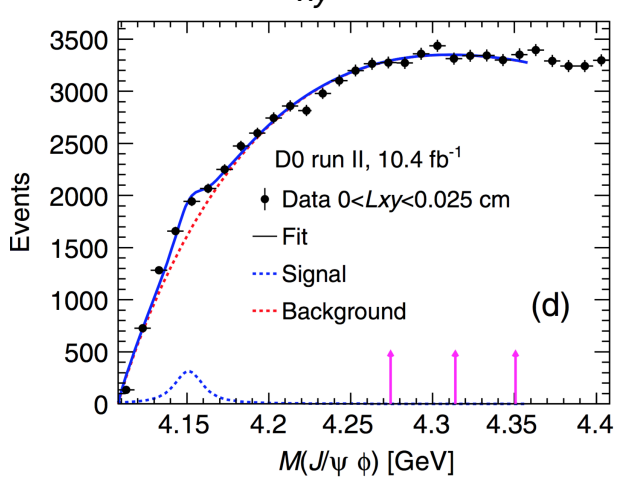
- First evidence of prompt production of $X(4140)$, 4.7σ
- Fraction of $X(4140)$ from b-decays $f_b = 0.39 \pm 0.07 \pm 0.10$



$-0.025 < L_{xy} < 0cm$



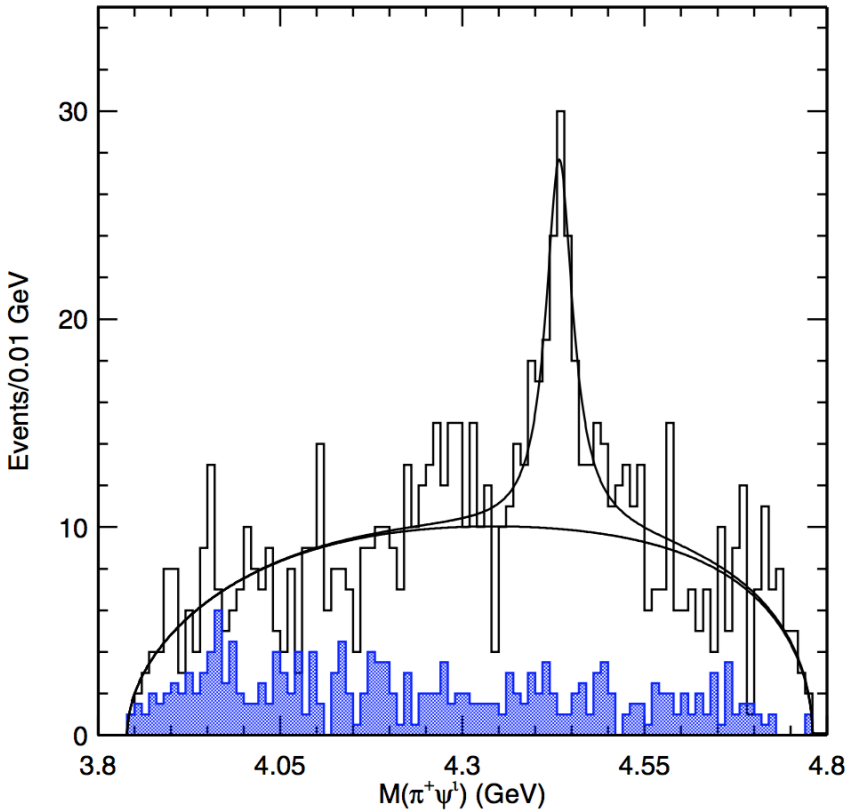
$0 < L_{xy} < 0.025cm$

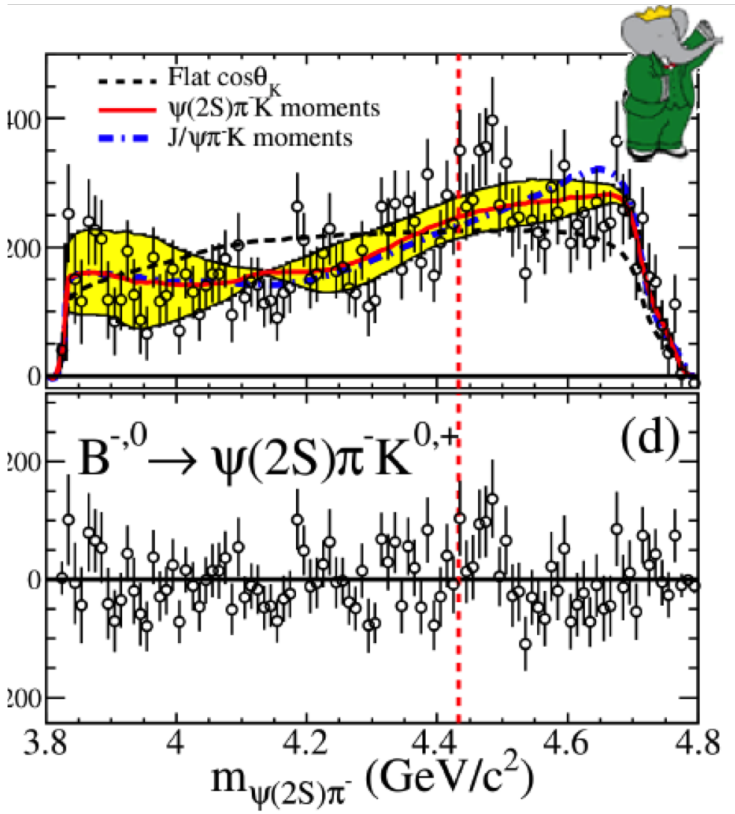


The $Z(4430)^-$ $(c\bar{c}d\bar{u})$

[Belle, PRL 100 (2008) 142001] [BaBar, PRD 79 (2009) 112001]

- Seen by Belle in $B^0 \to K^+\psi(2S)\pi^-$, with 605 fb^{-1} @ $\Upsilon(4S)$
  - $M = 4433 \pm 4 \pm 2$ MeV, $\Gamma = 45^{+18+30}_{-13-13}$ MeV
- Not confirmed by Babar with 413 fb^{-1} @ $\Upsilon(4S)$

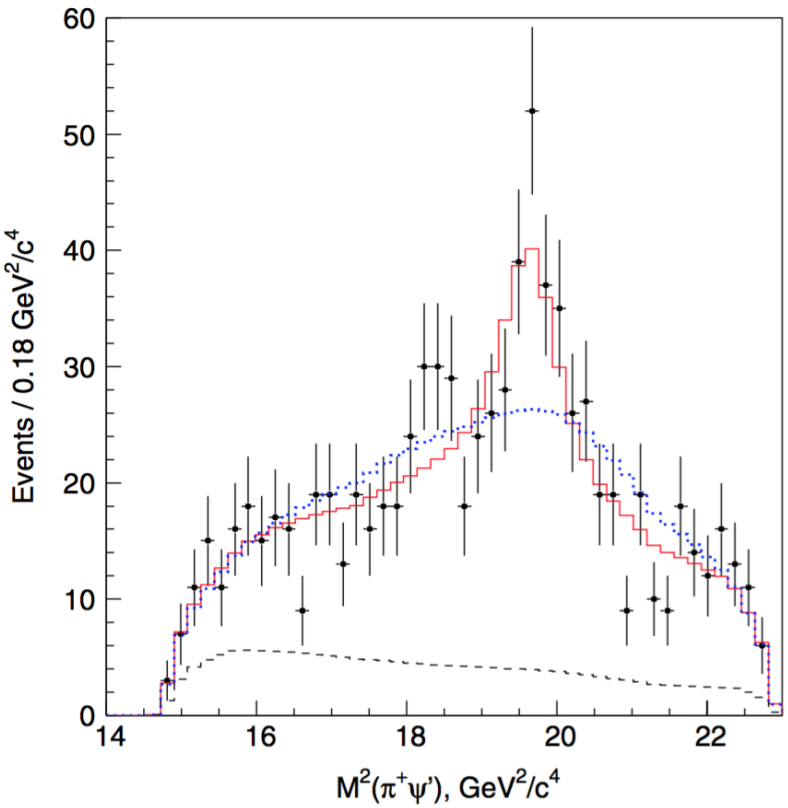


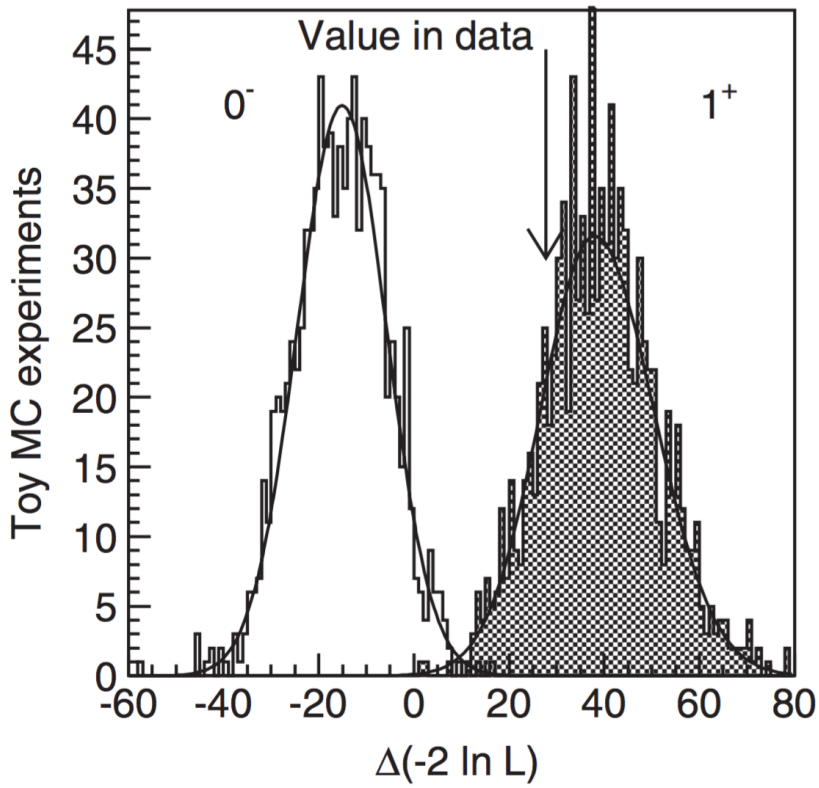


The $Z(4430)^-$, further studies by Belle

[Belle, PRD 80 (2009) 031104, PRD 88 (2013) 074026]

- Dalitz analysis (2D) in 2009 ($605\,\text{fb}^{-1}$)
  - $M = 4443^{+15+19}_{-12-13}$ MeV, $\Gamma = 107^{+86+74}_{-43-56}$ MeV
- Full 4D angular analysis in 2013 ($711\,\text{fb}^{-1}$), $N_{\text{sig}} \sim 2\text{k}$
  - $M = 4485^{+22+28}_{-22-11}$ MeV, $\Gamma = 200^{+41+26}_{-46-35}$ MeV
  - $J^P = 1^+$ favored by $> 3.4\sigma$

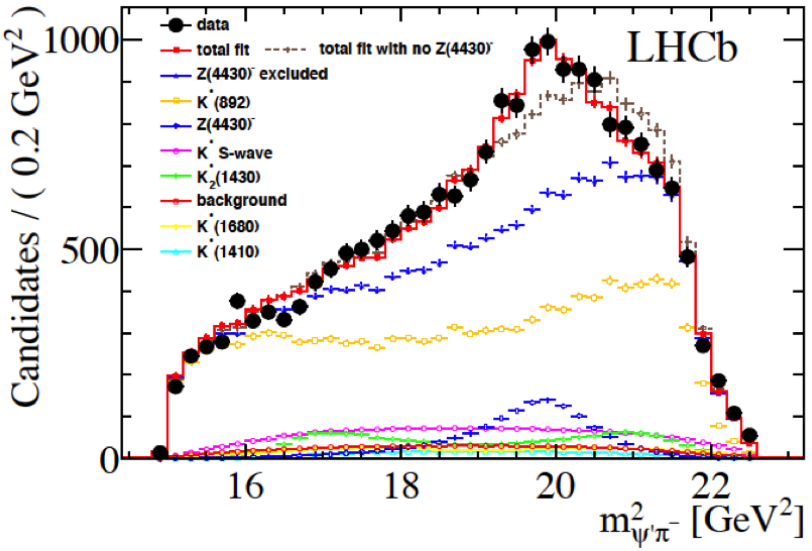


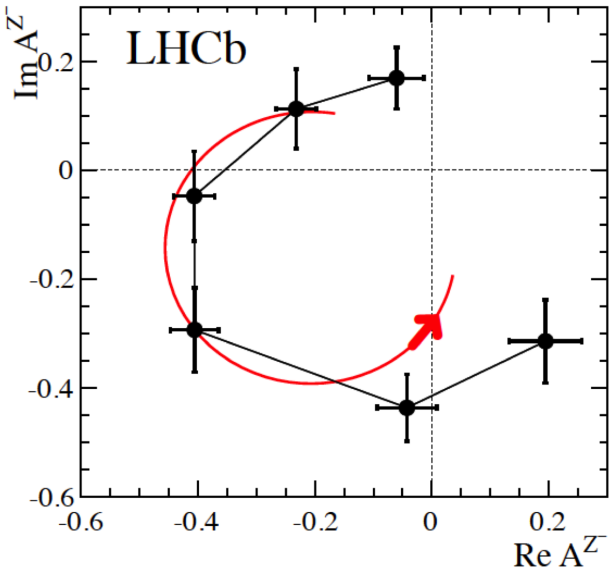


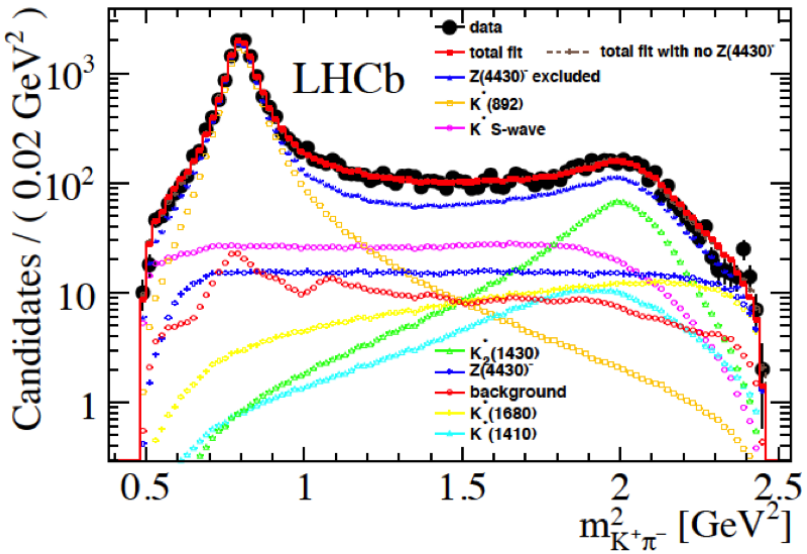
The $Z(4430)^-$, further studies at LHCb

[LHCb, PRL 112 (2014) 222002, PRD 92 (2015) 112009]

- LHCb did both full 4D angular analysis and model-independent analysis, with 10 times more signal $N_{\rm sig} \sim 25$k
  - $M = 4475 \pm 7^{+15}_{-25}$ MeV, $\Gamma = 172 \pm 13^{+37}_{-34}$ MeV
  - $J^P = 1^+$ established
- Argand plot shows clear resonance feature





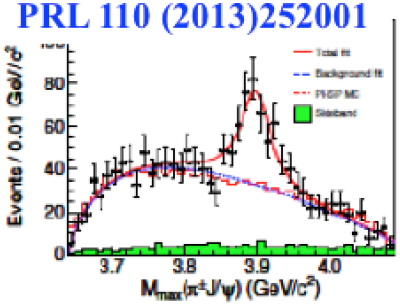


The Z_c family $(c\bar{c}u\bar{d}[u\bar{u}+d\bar{d}])$

- Several Z_c states found by BESIII, Belle, CLEO
- $Z_c(3900)$ & $Z_c(3885)$ the same? $Z_c(4020)$ & $Z_c(4025)$?

$Zc(3900)^+$

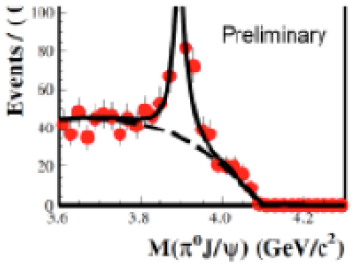
PRL 110 (2013)252001



$e^+e^- \to \pi^-\pi^+ J/\psi$

$Zc(3900)^0$

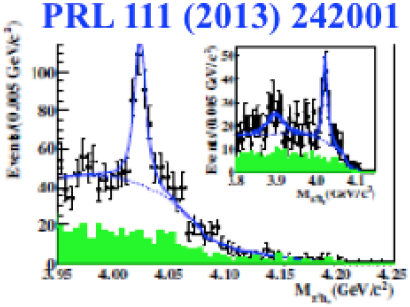
PRL 115 (2015) 112003



$e^+e^- \to \pi^0\pi^0 J/\psi$

$Zc(4020)^+$

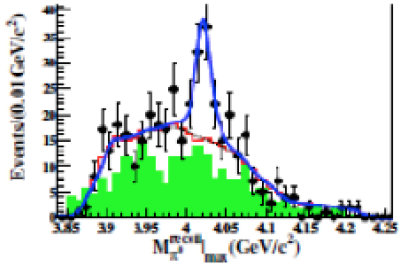
PRL 111 (2013) 242001



$e^+e^- \to \pi^-\pi^+ h_c$

$Zc(4020)^0$

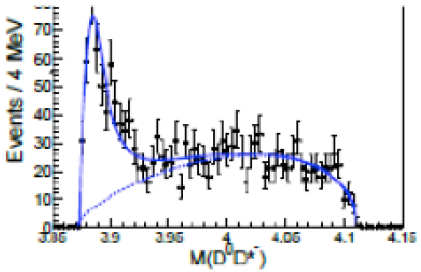
PRL113 (2014) 212002



$e^+e^- \to \pi^0\pi^0 h_c$

$Zc(3885)^+$

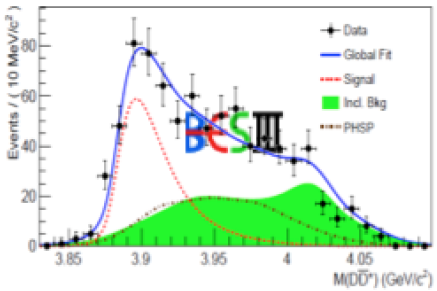
ST: PRL 112 (2014) 022001
DT: PRD 92 (2015) 092006



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

$Zc(3885)^0$

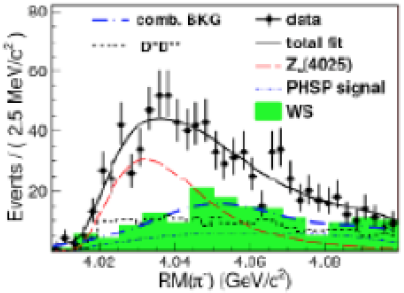
PRL115 (2015) 222002



$e^+e^- \to \pi^0(D\bar{D}^*)^0$

$Zc(4025)^+$

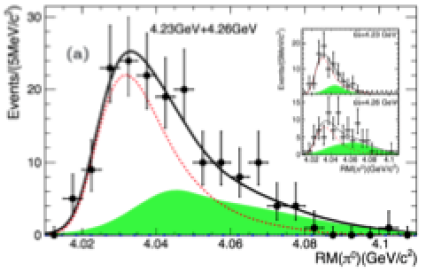
PRL 112 (2014) 132001



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Zc(4025)^0$

PRL115 (2015) 182002



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

The Z_c family (cont.)

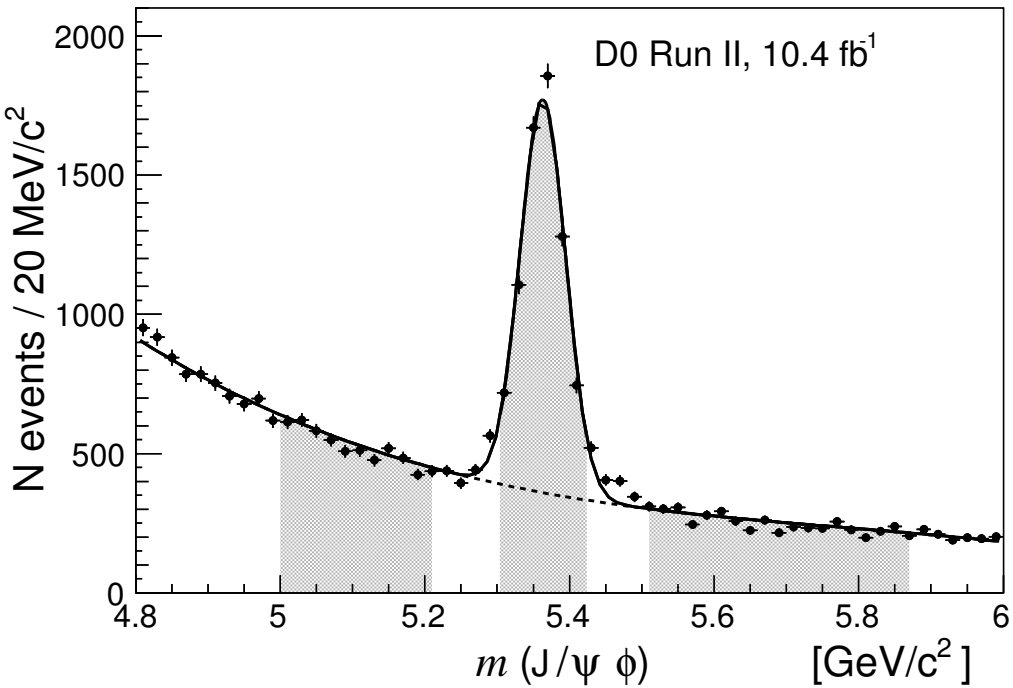
- $Z_c(3900)$ & $Z_c(3885)$ the same? $Z_c(4020)$ & $Z_c(4025)$?
  - Masses and widths consistent with each other within 2σ
  - Seem to favor the same J^P

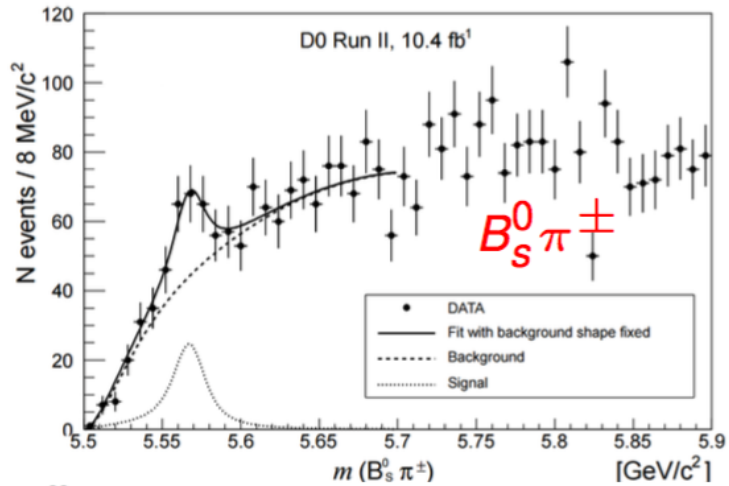
Z_c	Mass (MeV/c^2)	Width (MeV/c^2)	Decay mode	J^P
$Z_c(3900)^+$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^+ J/\psi$	1^+
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	
$Z_c(3885)^+$	$3882.3 \pm 1.1 \pm 1.9$	$26.5 \pm 1.7 \pm 2.3$	$(D\bar{D}^*)^+$	1^+
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	
$Z_c(4020)^+$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^+ h_c$	
$Z_c(4020)^0$	$4023.8 \pm 2.2 \pm 3.8$	7.9 (fixed)	$\pi^0 h_c$	
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$(D^*\bar{D}^*)^+$	
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$(D^*\bar{D}^*)^0$	

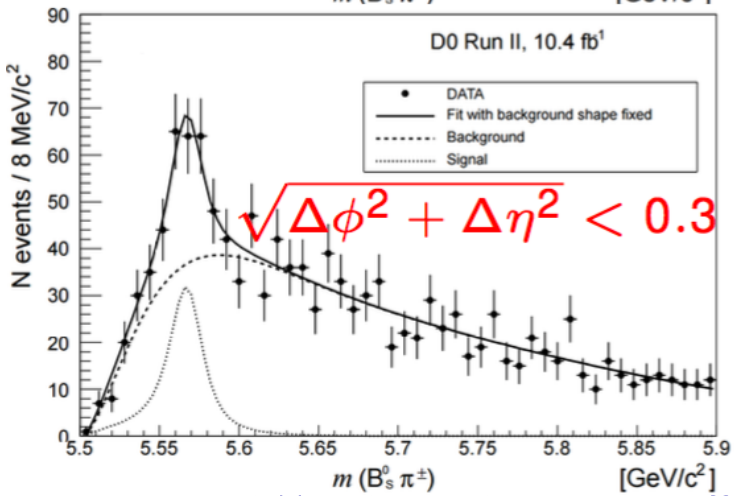
The $X(5568)^+$ by D0 $(\bar{b}su\bar{d})$

[D0, arXiv: 1602.07588]

- $X(5568)^+ \to B_s^0\pi^+$ observed by D0 with 5.1σ
  - $M = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV
  - $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV
  - $\rho_X^{\mathrm{D0}} \equiv \frac{\sigma(X)\mathcal{B}(X\to B_s^0\pi^+)}{\sigma(B_s^0)}\Big|_{\mathrm{D0Acc}}$
    $= (8.6 \pm 1.9 \pm 1.4)\%$
    for $p_{\mathrm{T}}(B_s^0) > 10$ GeV





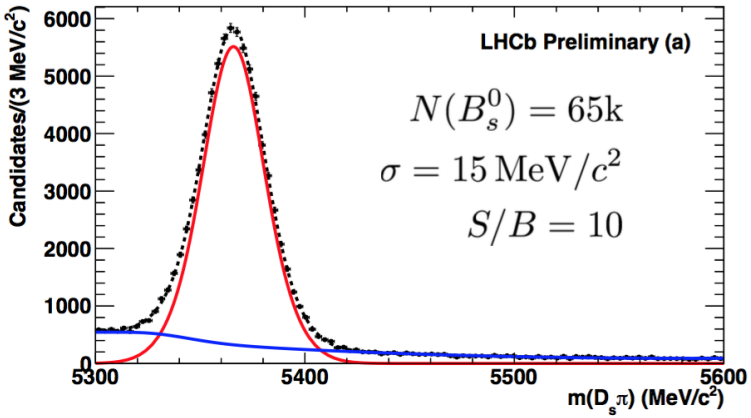


The $X(5568)^+$, not confirmed by LHCb

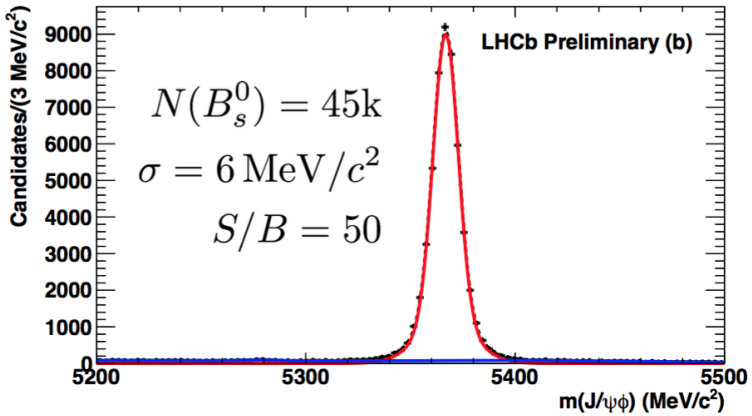
[LHCb-CONF-2016-004]

- Using both $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\,\phi$, cut based selection for clean B_s^0 samples, $N(B_s^0)$ 10 times more than D0

$B_s^0 \to D_s^- \pi^+$

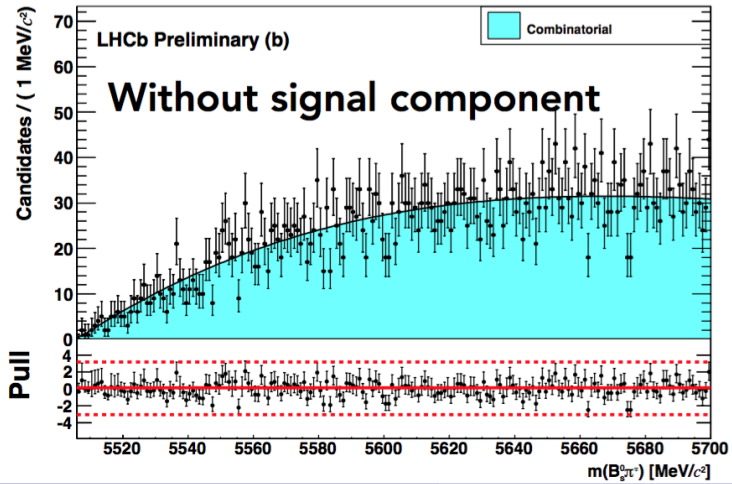


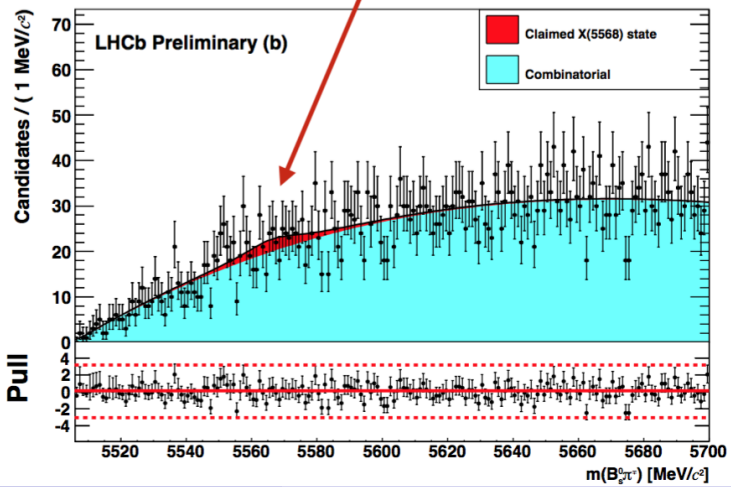
$B_s^0 \to J/\psi\phi$



$p_T(B_s^0) > 10\,\text{GeV}/c$

No significant signal

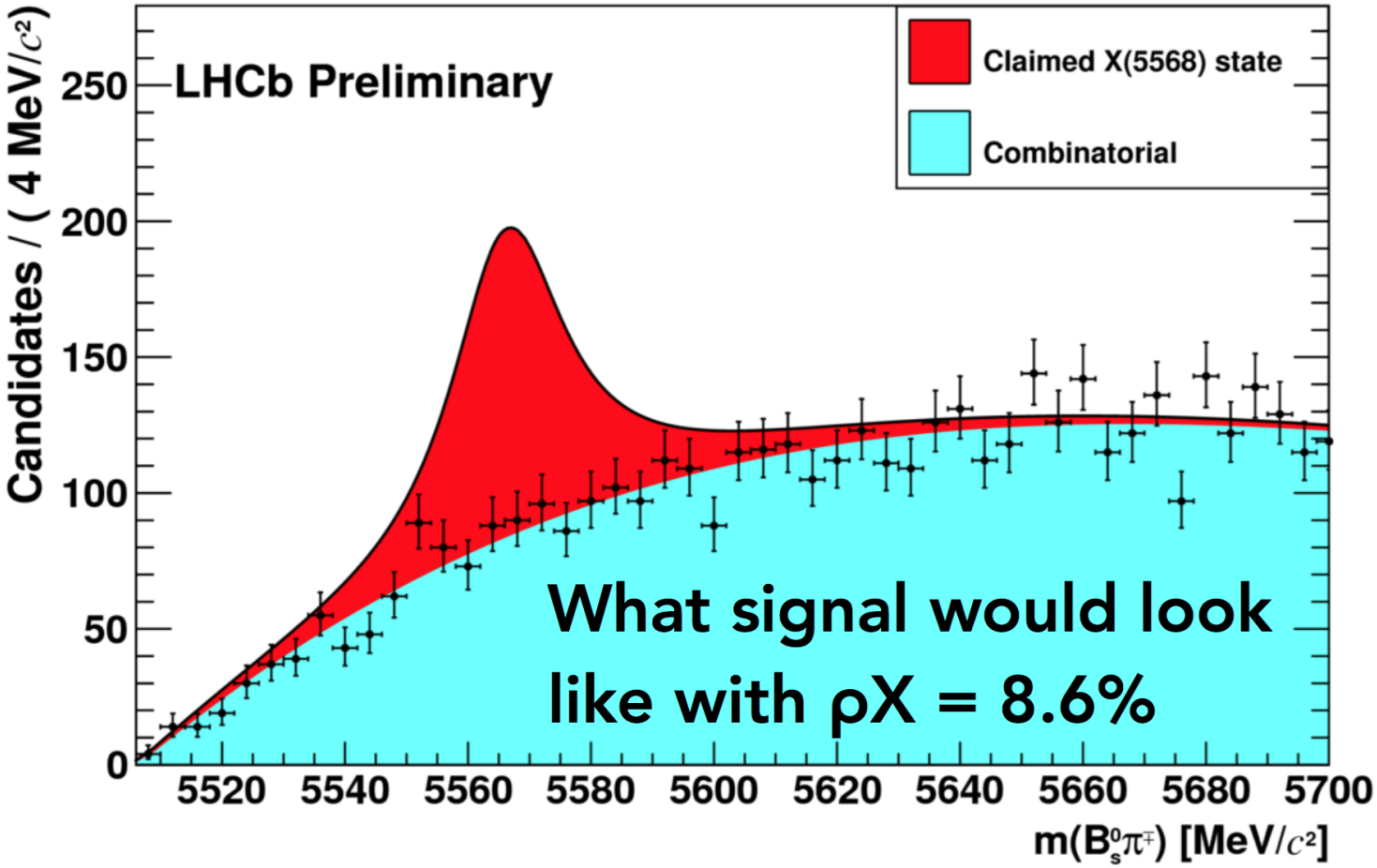




The $X(5568)^+$, upper limits on production rate

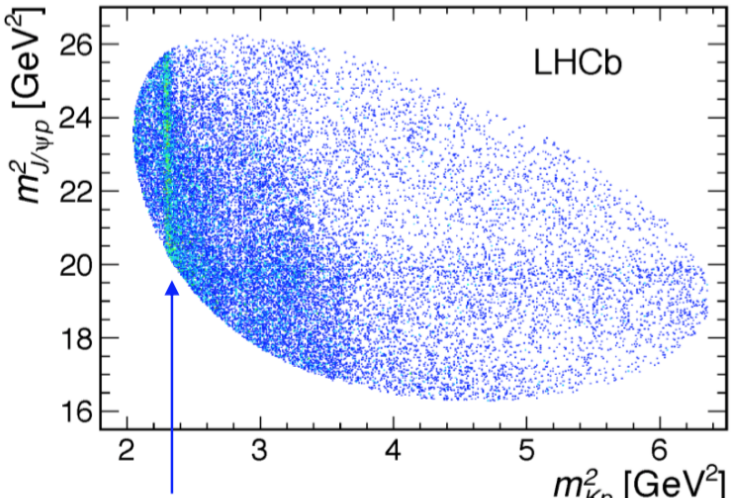
[LHCb-CONF-2016-004]

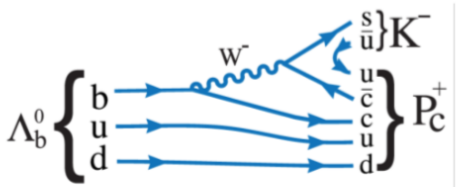
- Upper limits on $X(5568)^+$ production rate at LHC
  - $\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > \ 5\ \mathrm{GeV}) < 0.009(0.010)$ @ 90 (95)% C.L.
  - $\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\ \mathrm{GeV}) < 0.016(0.018)$ @ 90 (95)% C.L.



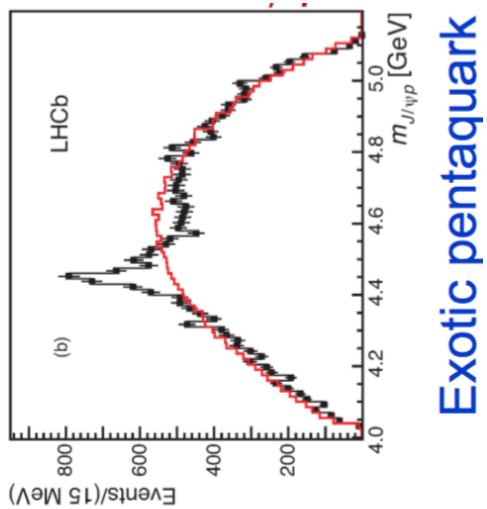
$\Lambda_b \to J/\psi\, p K^+$, unexpected structure in $m_{J/\psi\, p}$

[LHCb, PRL 115 (2015) 072001]

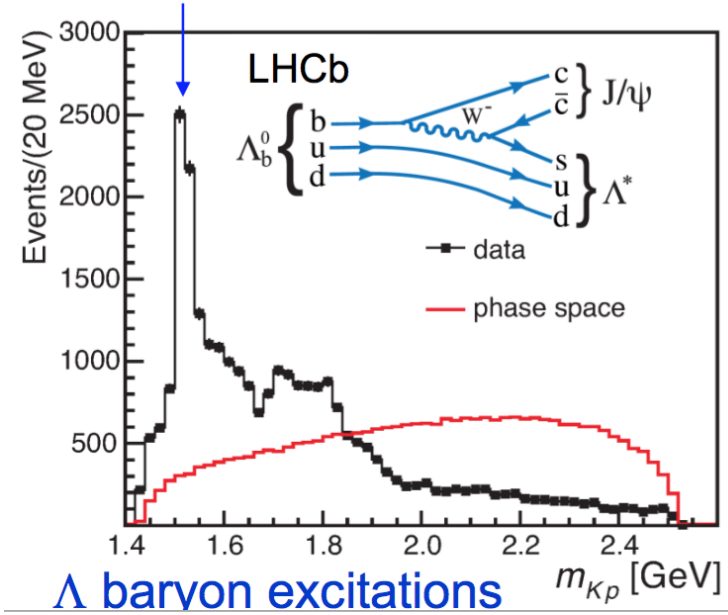




$P_c^+ \to J/\psi\, p$?



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



Λ baryon excitations

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

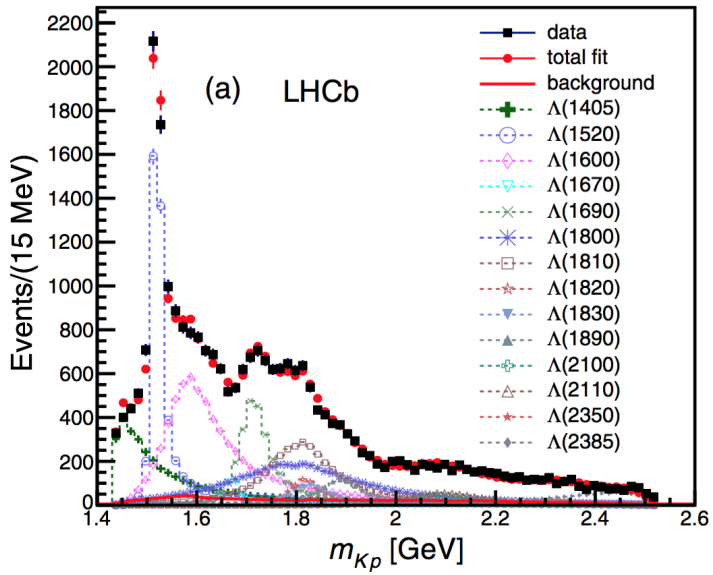
Is it a reflection of interfering Λ^*'s $\to$ p K$^-$?

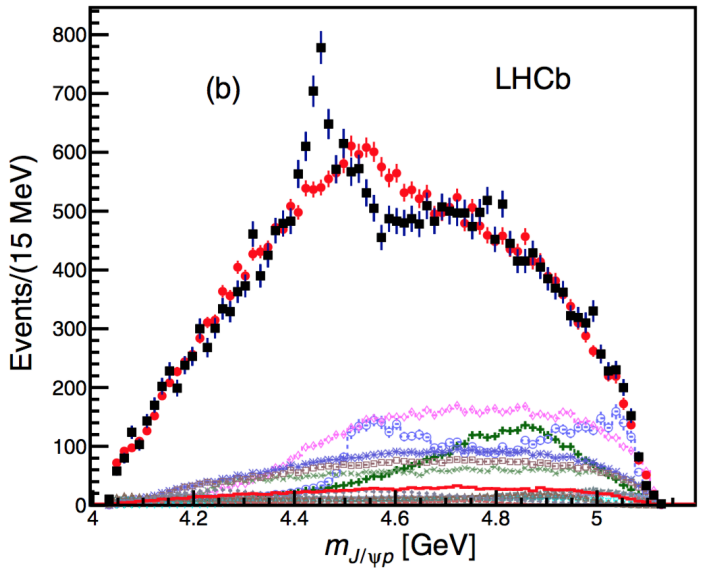
Proper amplitude analysis necessary to check

Observation of $P_c(4450)^+$ and $P_c(4380)^+$ $(c\bar{c}uud)$

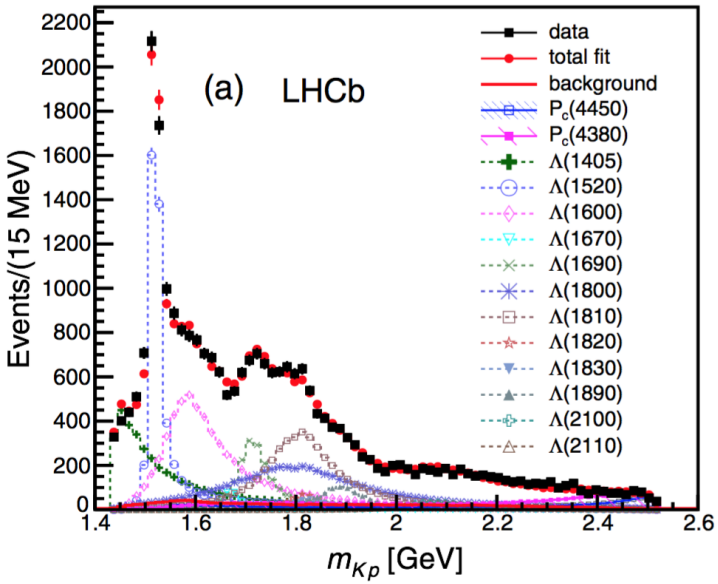
[LHCb, PRL 115 (2015) 072001]

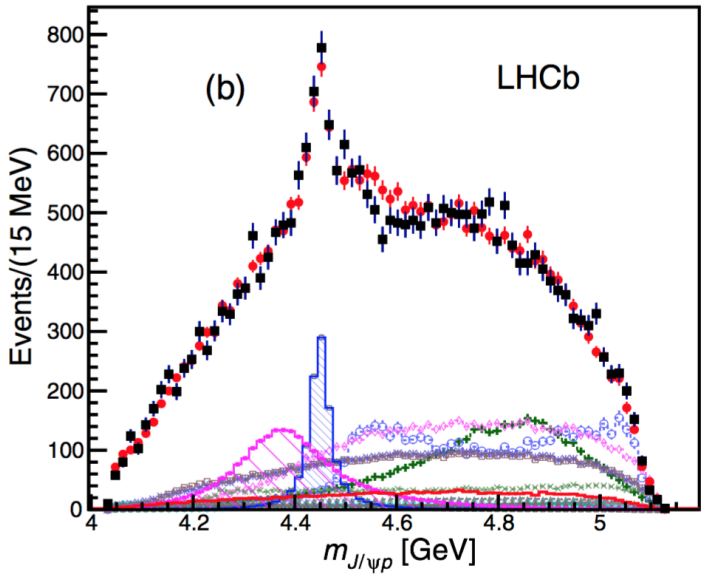
w/o P_c's





w/ P_c's





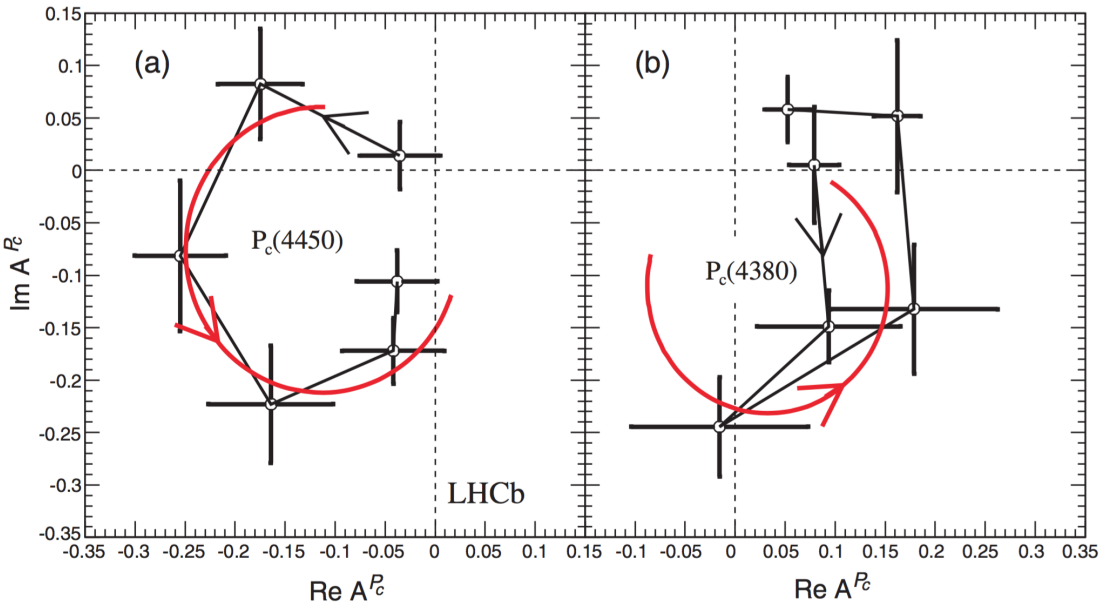
Observation of $P_c(4450)$ and $P_c(4380)$ (cont.)

[LHCb, PRL 115 (2015) 072001, Chin. Phys. C 40 (2016) 011001]

- Two new states needed to describe the data

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

- Argand plots



- Branching fractions also measured

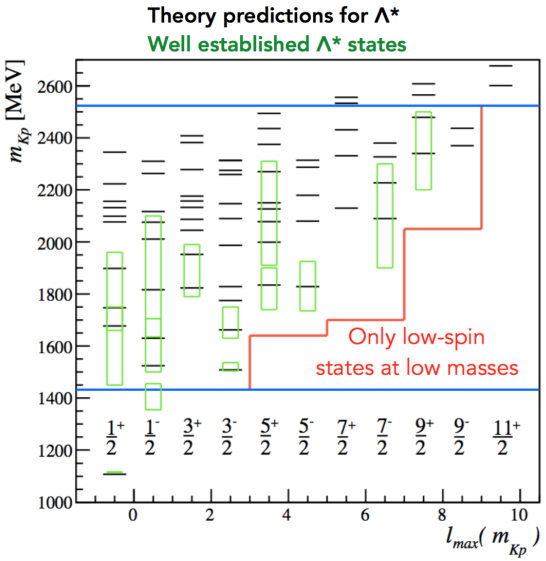
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+0.46}_{-0.36}\right) \times 10^{-5}$$

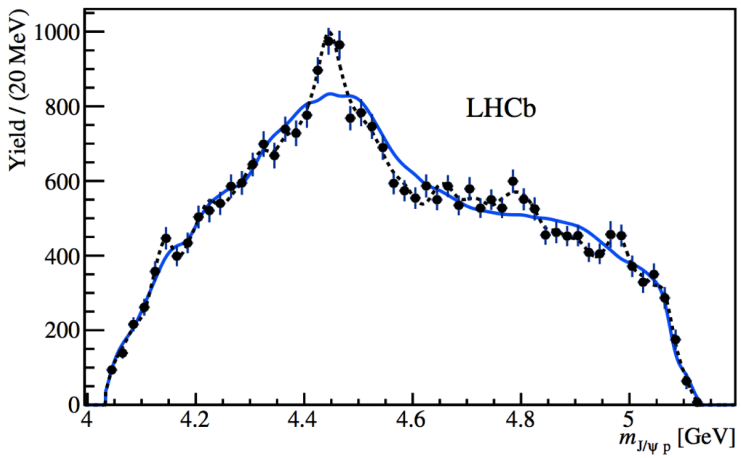
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+0.22}_{-0.18}\right) \times 10^{-5}$$

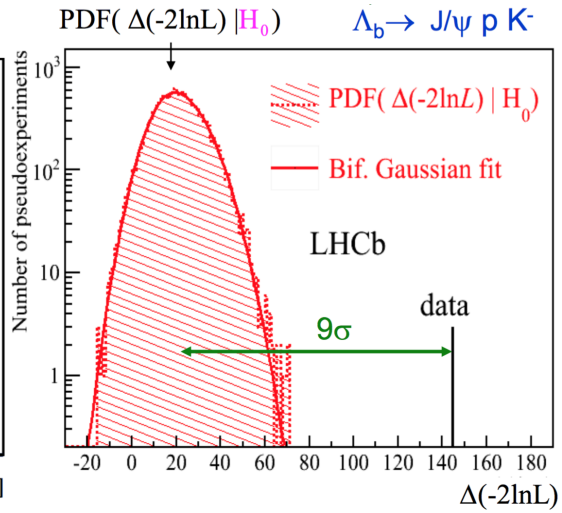
Pentaquark, model-independent analysis

[LHCb, arXiv:1604.05708]

- Model-independent approach: not assume anything about Λ^*, Σ^* or NR compositions, spin, masses, widths or mass-shape
- Only restrict maximal spin of allowed Λ^* at given m_{Kp}
- Null hypothesis (H_0) rejected at 9σ



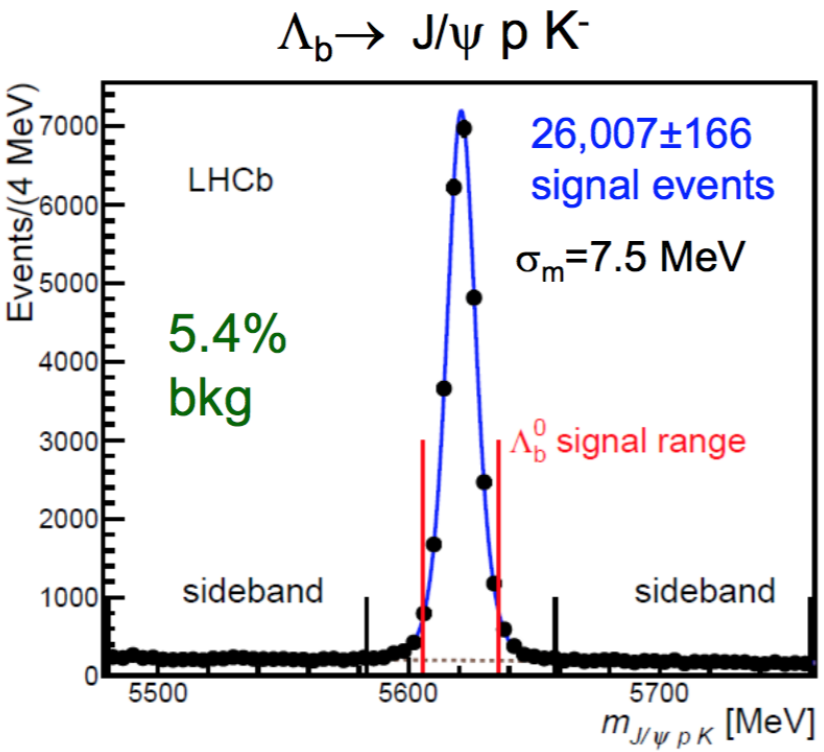


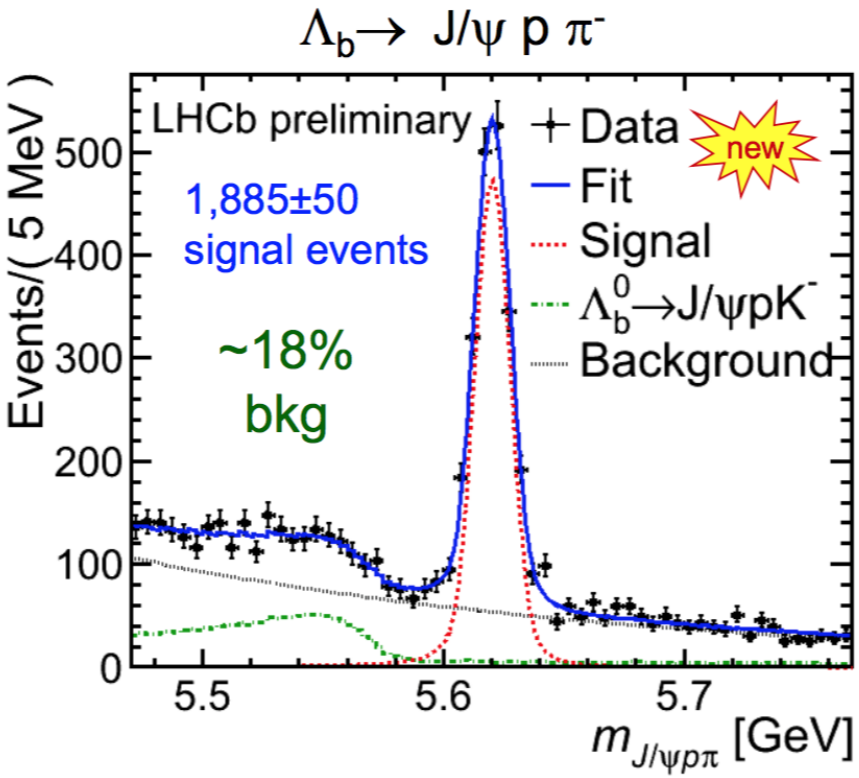


Cabbibo suppressed vs favored Λ_b decay

[LHCb, PRL 115 (2015) 072001] [LHCb-Paper-2016-015, in preparation]

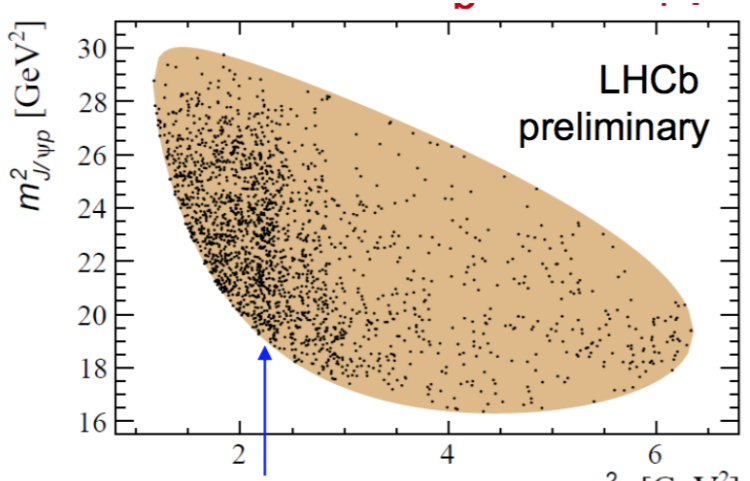
- Cabbibo suppressed $\Lambda_b \to J/\psi\, p\pi^+$, signal yields 10 times smaller than $\Lambda_b \to J/\psi\, pK^+$
- Relatively higher background...



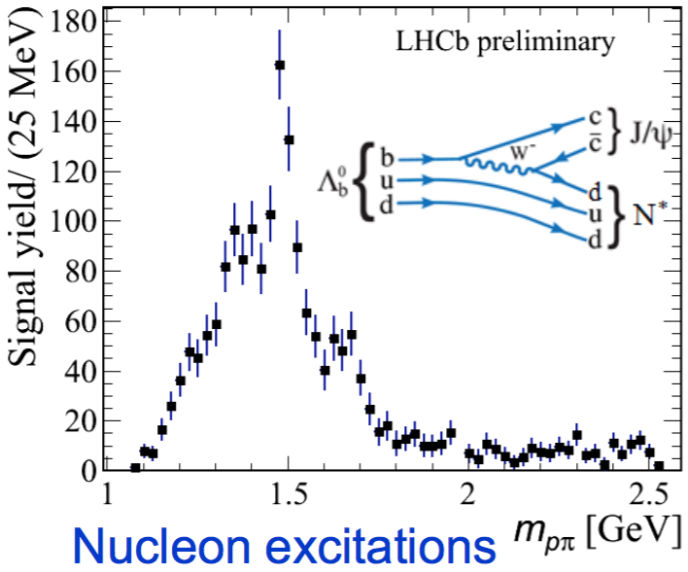


Cabbibo suppressed $\Lambda_b \to J/\psi\, p\pi^+$

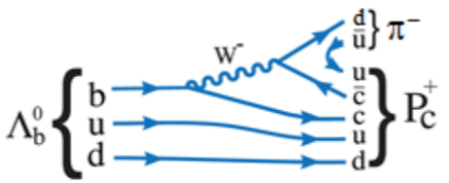
[LHCb-Paper-2016-015, in preparation]



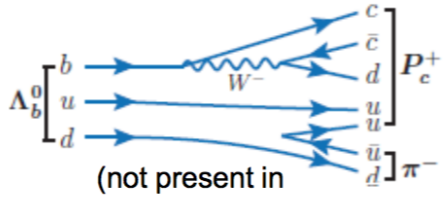
N(1535) and other N*'s → p π^-



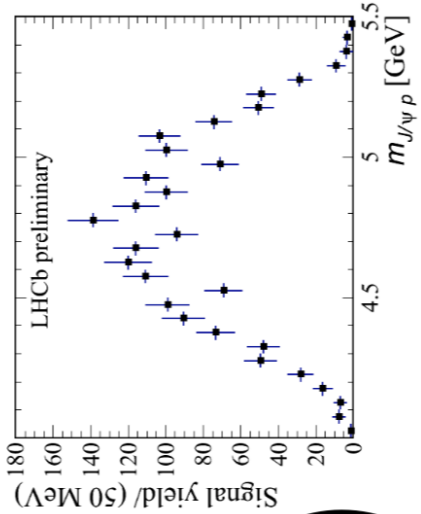
Nucleon excitations



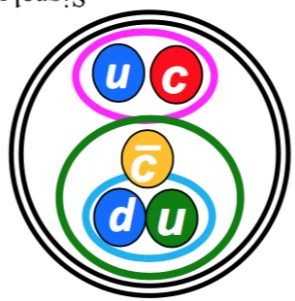
$P_c^+ \to J/\psi\, p$?



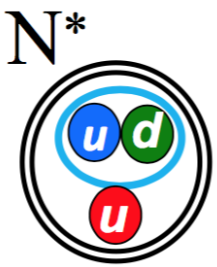
(not present in Cabibbo favored case)



Exotic pentaquark



- No obvious structure in $m_{J/\psi p}$



Statistics is low.

Proper amplitude analysis necessary to check for consistency with Cabibbo favored $\Lambda_b^0 \to J/\psi p K^-$

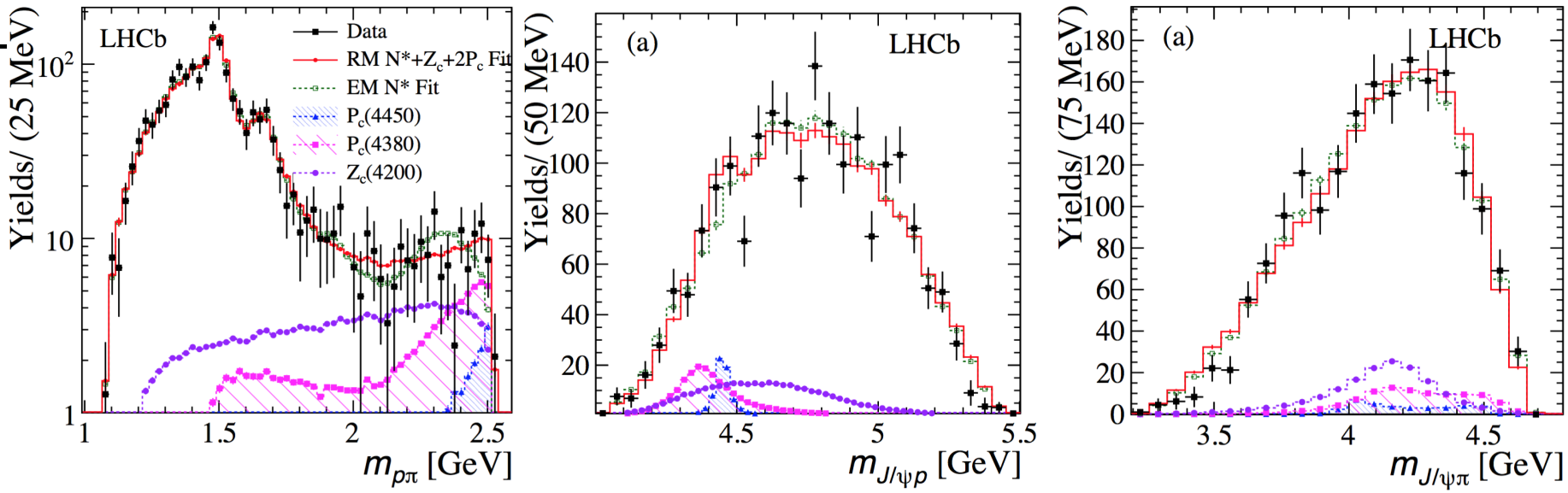
Pentaquarks in $\Lambda_b \to J/\psi\, p\pi^+$ decay

New

[LHCb-Paper-2016-015, in preparation]

- Not enough statistics to do open-ended analysis of $J/\psi\, p$, $J/\psi\, \pi^-$ contributions, check data for previously observed states
- Combined significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ together, 3.1σ

LHCb preliminary



Summary

- Many charmonium-like and bottomonium-like XYZ states found in the past decade, their nature remains unclear
  - Pentaquarks, tetraquarks; molecule; $c\bar{c}/b\bar{b}$?
- Great progress made to help understand their nature
  - J^{PC}, $X(3872)$, $Z(4430)^{-}$, $X(4140)$, ...
  - New decay modes, $X(3872) \to \psi(2S)\gamma$, ...
  - Hadroproduction, $X(3872)$, $X(4140)$
- Tensions between results of different experiments resolved, e.g., $Z(4430)^{-}$, $X(4140)$; new tension appears, $X(5568)^{+}$
- Your suggestions on high-priority analysis are always welcome