Stati Esotici (X, Y, Z, Pentaquark, …)

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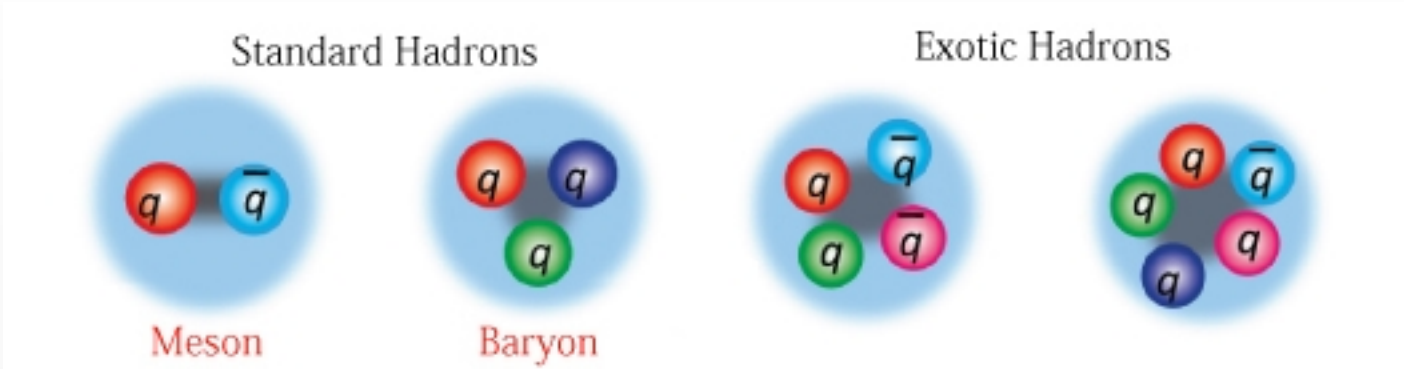
pp @ LHC
17 May 2016, Pisa, Italy

OUTLINE

- Introduction
- Search for $X_b \rightarrow Y(1S)\ \pi^+\ \pi^-$
- Evidence/Observation of X(4140)
- Search for $X(5568)^{\pm} \rightarrow B^0_s\ \pi^{\pm}$
- Observation of two Pentaquarks P_c^+
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$ Decay
  - Model Independent Analysis
- Prospects for RUN II and beyond

INTRODUCTION: "EXOTIC"



Tetra- and Penta-quarks conceived at the birth of the quark model

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

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. 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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

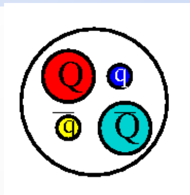
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig **)
CERN---Geneva

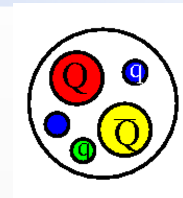
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

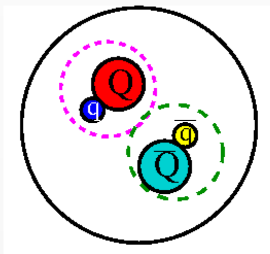
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

Models for Tetra- and Penta-quarks

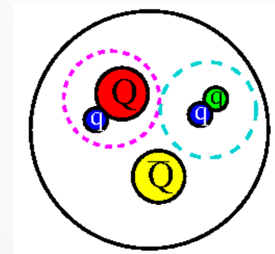


"plain"

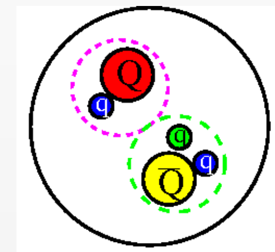


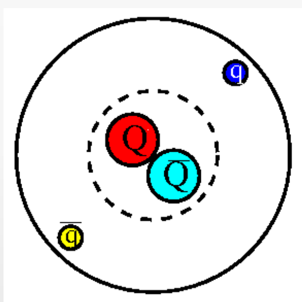


diquark model

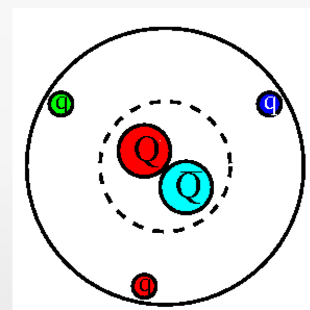


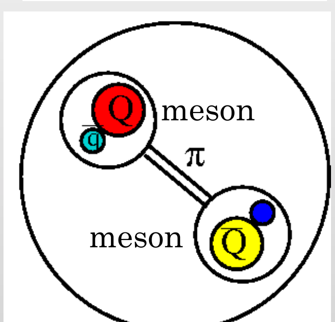
triquark model



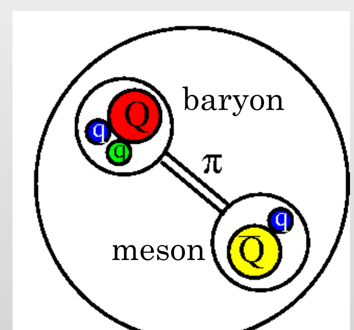


hydro-charmonium model





molecular model

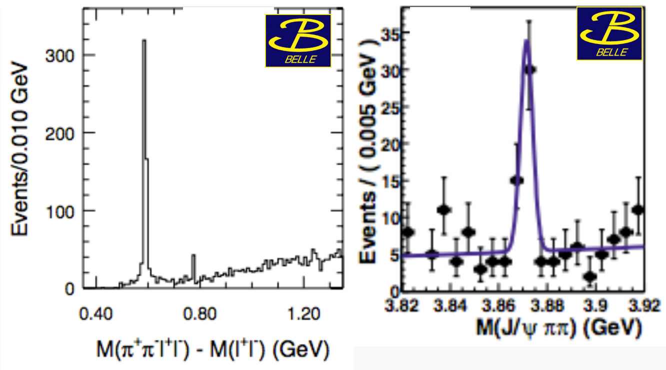


THE X(3872) STATE

Discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ decay where $X(3872) \to J/\psi\pi^+\pi^-$

- ⊛ Mass is roughly equal to $m(D^0) + m(D^{*0})$
- ⊛ Width is surprisingly narrow (< 1.2 MeV)
- ⊛ Large production rate in $p\bar{p}$ collisions

[Belle: PRL 91, 262001 (2003)]



LHC experiments are largely contributing to shed light on the nature of the X(3872) state

- ➢ Determination of the quantum numbers **[PRL 110, 222001 (2013)][PRD92, 011102 (2015)]**
- ➢ Measurement of $\mathcal{B}(X(3872) \to \psi(2S)\,\gamma)/\mathcal{B}(X(3872) \to J/\psi\,\gamma)$ **[Nucl.Phys.B886 (2014) 665]**
- ➢ Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

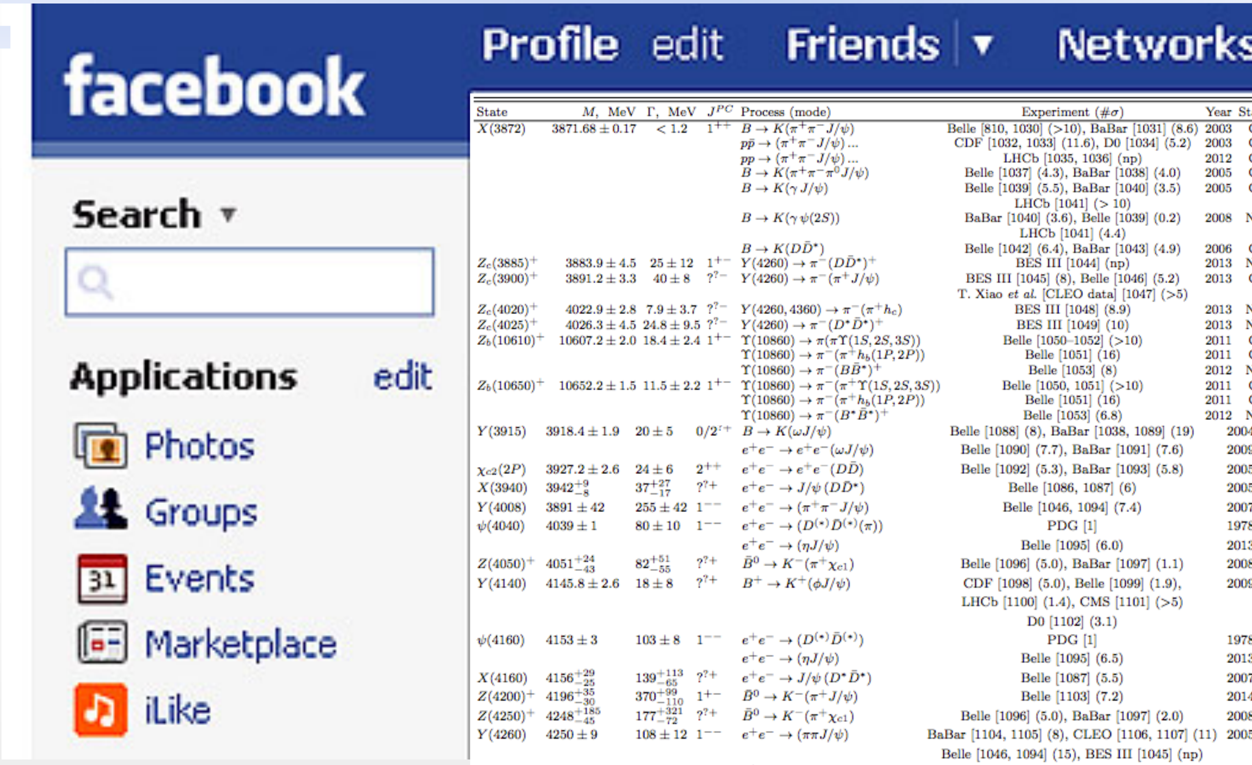
$$E_B = m(D^0\bar{D}^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV}/\mathrm{c}^2$$ ➡ *Loosely bound in the molecule scenario*

- ➢ Production cross-section in *pp* collisions at $\sqrt{s} = 7$ TeV **[EPJC 72 (2012) 1972, JHEP 1304, 154 (2013)]**
- ➢ Search for $X(3872) \to p\bar{p}$ **[EPJC 73 (2013) 2462]**

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

…And Friends

Eur.Phys.J. C74 (2014) 10, 2981



State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5)	2005	Ok
					LHCb [1041] (> 10)		
				$B \to K(\gamma \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2)	2008	NC!
					LHCb [1041] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
					T. Xiao *et al.* [CLEO data] [1047] (>5)		
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1050–1052] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1053] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1050, 1051] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1053] (6.8)	2012	NC!
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9),	2009	NC!
					LHCb [1100] (1.4), CMS [1101] (>5)		
					D0 [1102] (3.1)		
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11)	2005	Ok
					Belle [1046, 1094] (15), BES III [1045] (np)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0),	2011	NC!
					CMS [1101] (>3), D0 [1102] (np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4)	2007	Ok
					LHCb [1115] (13.9)		
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1051, 1052, 1117] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1051, 1052] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1051, 1052] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [986] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [986] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1118] (2.3)	2008	NC!

Search for X_b [Beauty partner of the X(3872)]

ATLAS: Phys. Lett. B 740, 199 (2015)

CMS: Phys. Lett. B 727 (2013) 57

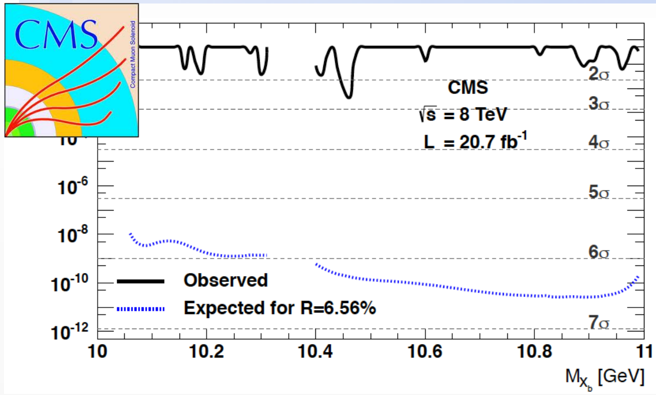
The beauty Partner of X(3872)

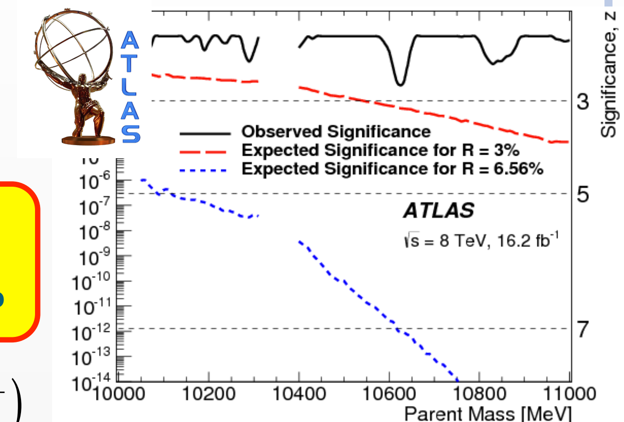
- Heavy quark symmetry suggests a hidden-beauty partner X_b analogous of X_c. Molecular (Swanson, 2004) and tetraquark models suggest to search it close to BB* threshold.

- CMS and ATLAS looked for $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ decay **seemingly analogous** to $X(3872) \to J/\psi\,\pi^+\pi^-$

  Analysis strategy: search for a peak other than known $\Upsilon(2S)$ & $\Upsilon(3S)$ in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum within 10-11GeV

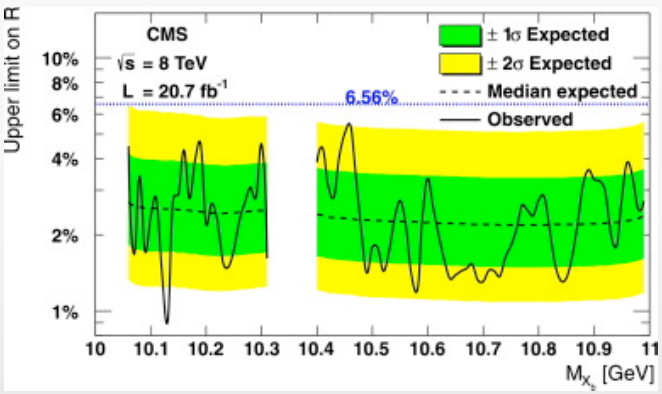
The beauty Partner of X(3872)

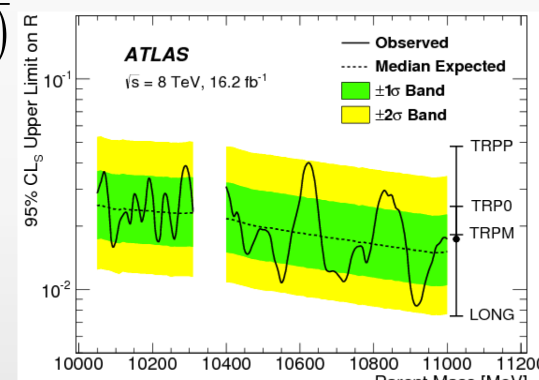




95% CL upper limits between ~ 1% and 5%

$$R \equiv \frac{\sigma\left(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{\sigma\left(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$





- According to Karliner & Rosner [**PRD91 (2015) 014014**], **this decay should be forbidden by G-parity conservation;** while for the *X(3872)* the isospin-conserving decay to $\omega J/\psi$ was kinematically suppressed, the same is not true for a bottomonium-like $J^{PC} = 1^{++}$ counterpart. The strategy for X_b observation should include search of $X_b \to \Upsilon(1S)\,\omega(\to\pi^+\pi^-\pi^0)$, $X_b \to \chi_{b1}(1P)\,(\to\Upsilon(1S)\,\gamma)\,\pi^+\pi^-$, $X_b \to \Upsilon(3S)\,\gamma$

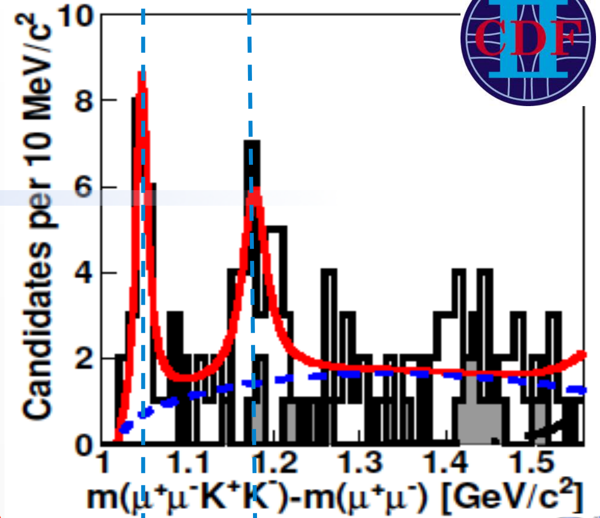
Observation of a peaking structure in the $J/\psi\ \phi$ mass spectrum from $B^+ \to J/\psi\ \phi\ K^+$ decays

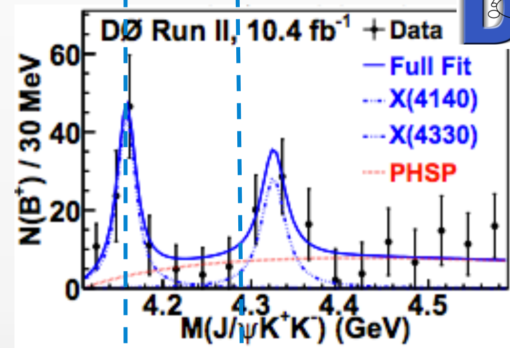
X(4140): A BIT OF HISTORY

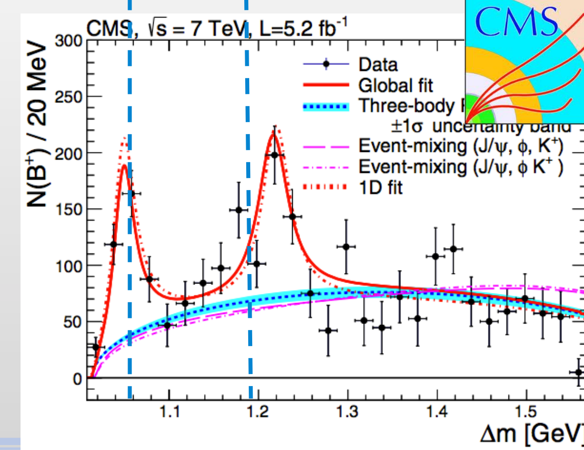
CDF: Evidence/"Observation" in $B^+ \rightarrow J/\psi\ \phi\ K^+$
[PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)	**X(4274)**
$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV	$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV
$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV	$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

- Belle: No evidence of X(4140) in $\gamma\gamma \rightarrow J/\psi\ \phi$. Observation of a new state X(4350) **[PRL 104, 112004 (2010)]**
- LHCb: No evidence of X(4140)/X(4274) in B decays but UL's don't disprove them **[PRD 85, 091103(R) (2012)]**
- D0: "Threshold enhancement consistent with the X(4140) (3.1σ) …Second structure consistent with X(4350)" **[PRD89 012004 (2014)]**
- CMS: Peak in $J\psi\ \phi$ consistent with X(4140). Evidence of a 2nd peak affected by reflections **[PLB 734 (2014) 261]**
- BaBar: No evidence of X(4140)/X(4274) **[PRD 91, 012003 (2015)]**
- D0: Evidence of X(4140) in prompt production **[PRL 115, 232001 (2015)]**



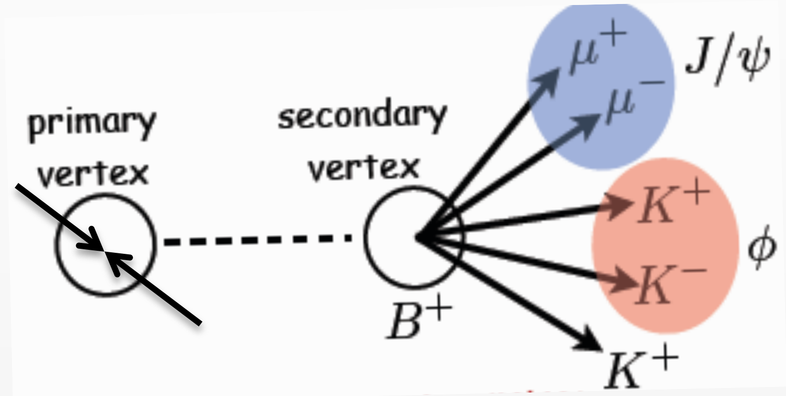




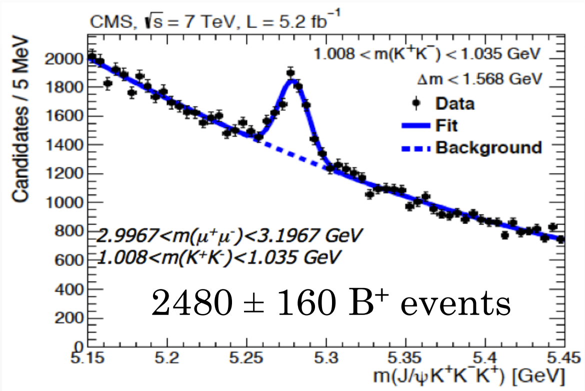
CMS SEARCH FOR X(4140)

[CMS: PLB 734 (2014) 261]

- Search performed with $5.2 fb^{-1}$ of collision at $7 TeV$

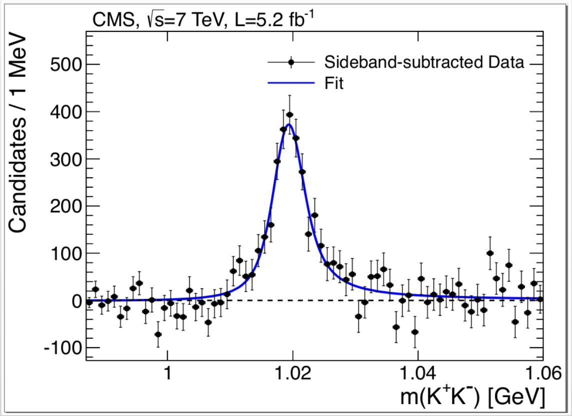


- **Signal extraction**:
  - $p_T > 1 GeV$ for any kaon
  - selection on common vertex probability and angular separation between J/ψ and kaons
  - $p_T(J/\psi) > 7 GeV$
  - transverse B^+ flight lenght significance > 3
- The $\Delta m = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$ spectrum is considered till $1.568 GeV$ to avoid reflections from $B_s \rightarrow \psi(2S)\varphi \rightarrow J/\psi\pi^+\pi^-\varphi$ (but whole spectrum also investigated)



- Largest B^+ sample to date
  - 20 times CDF
  - 7 times LHCb

$m(J/\psi KKK) \in [m(B^\pm) - 3\sigma, m(B^\pm) + 3\sigma]$

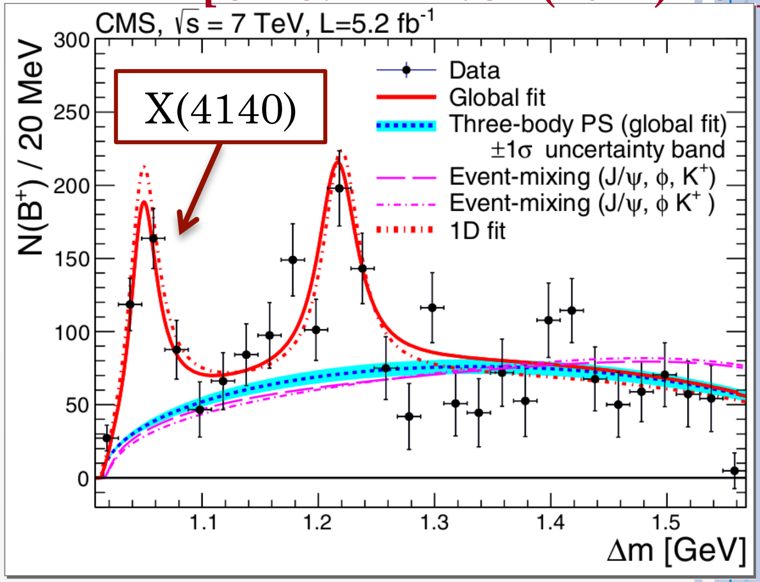


The J/Ψϕ mass spectrum

[CMS: PLB 734 (2014) 261]

- The $\Delta m = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$ spectrum is obtained:
  - dividing the dataset in $20 MeV$ Δm bins

    fitting every bin with:
    - Signal PDF: S-wave relativistic Breit-Wigner (BW) convoluted with mass resolution
    - Background PDF: 3-body Phase Space Shape (PS)
    - **1-D Fit**: Binned χ^2 fit to the extracted Δm spectrum using the BW and PS shape.
    - **Global 2-D Fit**: simultaneous fit of $m(B^+)$ and Δm with implicit background subtraction
  - extracting the number of B^+ signal in each Δm bin by fitting the spectrum



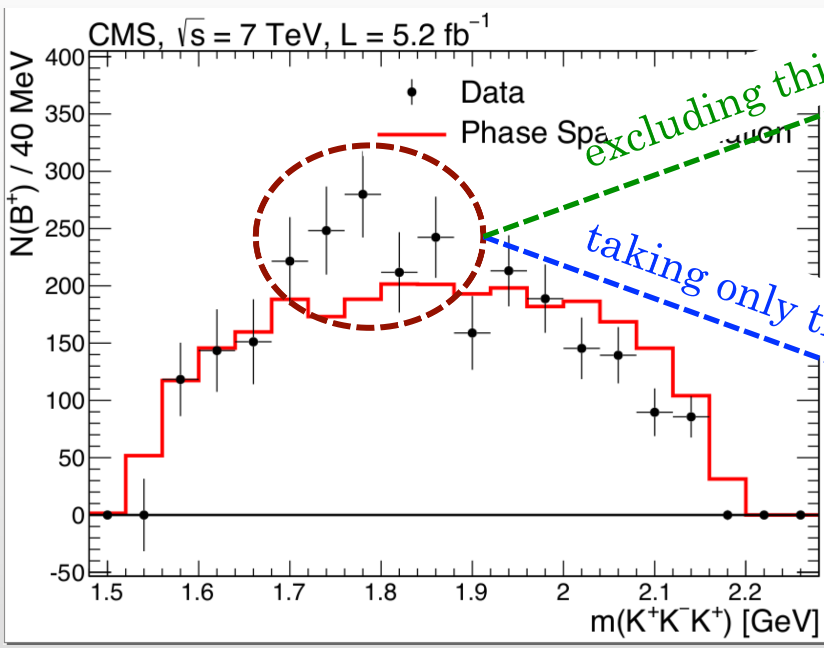
Yield	Mass [MeV]	Γ [MeV]
310 ± 70	4148.0 ± 2.4(stat) ± 6.3(syst)	28^{+15}_{-11}(stat) ± 19(syst)
418 ± 170	4313.8 ± 5.3(stat) ± 7.3(syst)	38^{+30}_{-15}(stat) ± 16(syst)

First structure is consistent with *X(4140)* of CDF observed with a stat. significance > 5σ!
There is evidence for a second structure in the same mass spectrum

- Naïve yields' ratio estimate: $\frac{BR(Y(4140))}{BR(J/\psi\phi K^\pm)} \approx 0.10 \pm 0.03\%$ consistent with CDF and LHCb UL

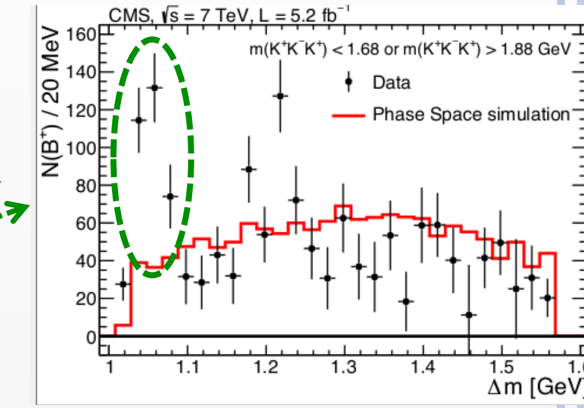
Next steps for X(4140)

- Understanding the nature of both structures needs further investigation
  - The φK^+ mass distribution shows an excess w.r.t. PHSP profile in the region where large resonances [$K_2(1770)$ & $K_2(1820)$] may appear; reflections studies are carried out:

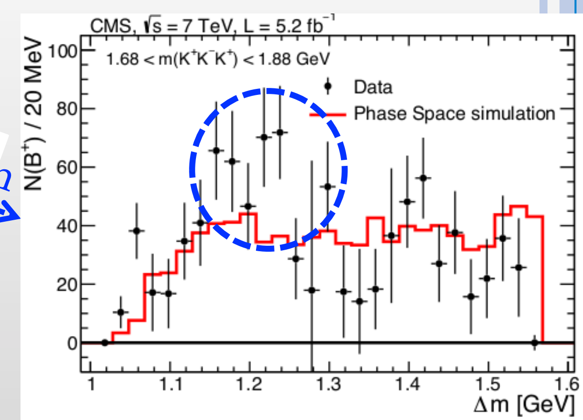


excluding this $m(K^+K^-K^+)$ region

taking only this $m(K^+K^-K^+)$ region



- ***Y(4140)*** **appears to be uncorrelated to φK^+ resonances**



- **Additional peak may be affected by them**

Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum

A New $B^0_s\pi^\pm$ State Claimed by DØ

[DØ: arXiv:1602.07588]

Claimed observation with 5.1 σ significance of an exotic state

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

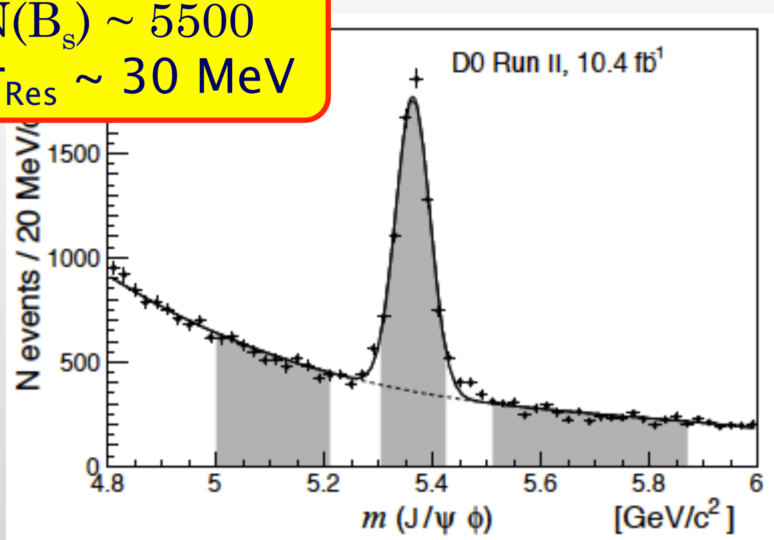
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$

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

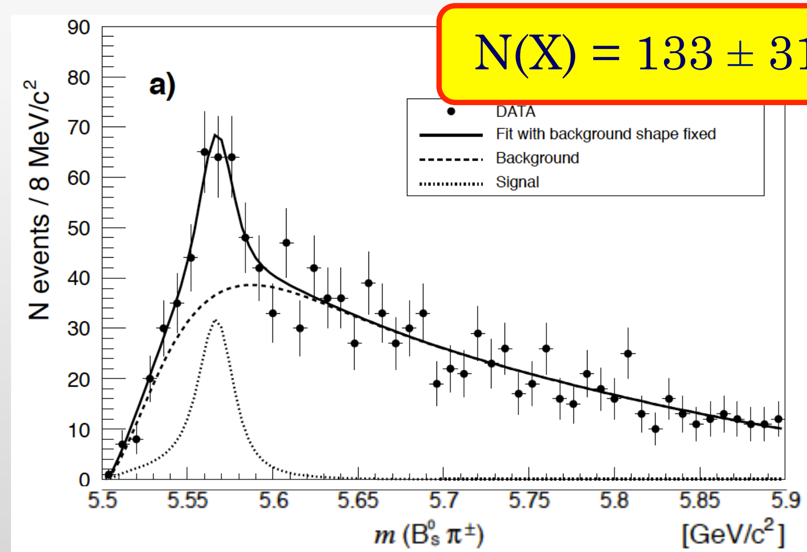
✓ Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\emptyset} = (8.6 \pm 1.9 \pm 1.4)\ \%$

"Cone" cut: $\mathbf{\Delta R} = \sqrt{(\mathbf{\Delta}\eta)^2 + (\mathbf{\Delta}\phi)^2} < 0.3$

$N(B_s) \sim 5500$
$\sigma_{Res} \sim 30$ MeV



$N(X) = 133 \pm 31$

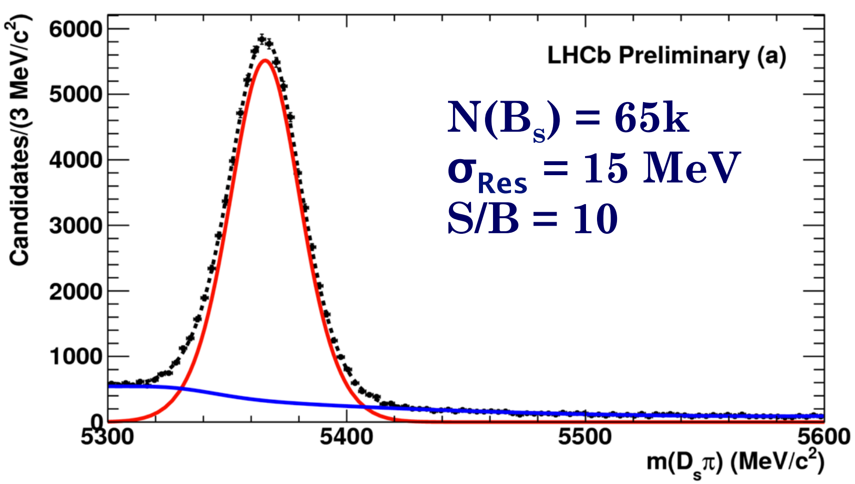


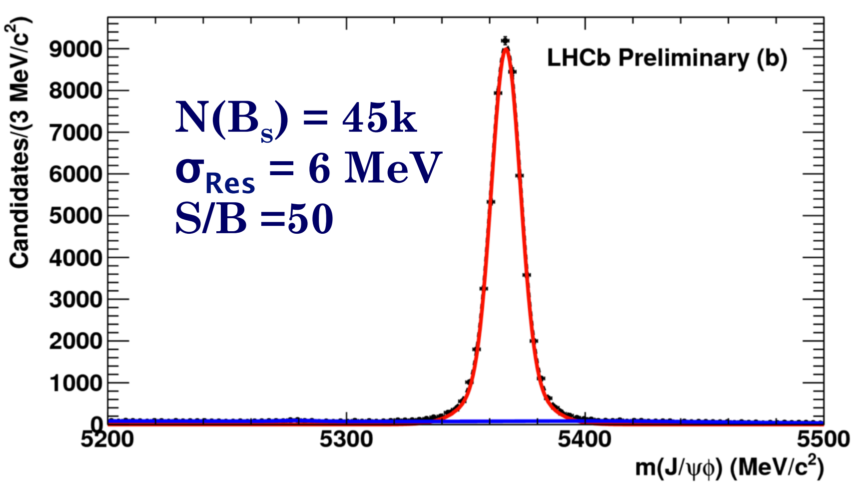
B_s SELECTION

LHCb-CONF-2016-004

- RUN I data ($3\ fb^{-1}$)
- Cut-based selections aiming to very clean B_s^0 samples
  - ✓ Both $B_s^0 \to D_s^- \pi^+$ and $J/\psi\ \phi$ (Mass constraints on the D_s and J/ψ)
  - ✓ Stick closely to tried and trusted analysis methods:

    $B^{**} \to B\pi$ e $B_s^{**} \to BK$
  - ✓ $p_T(\pi) > 500$ MeV/c
  - ✓ Baseline: $p_T(B_s^0) > 5$ GeV/c; Tight: $p_T(B_s^0) > 10$ GeV/c to match the DØ selection





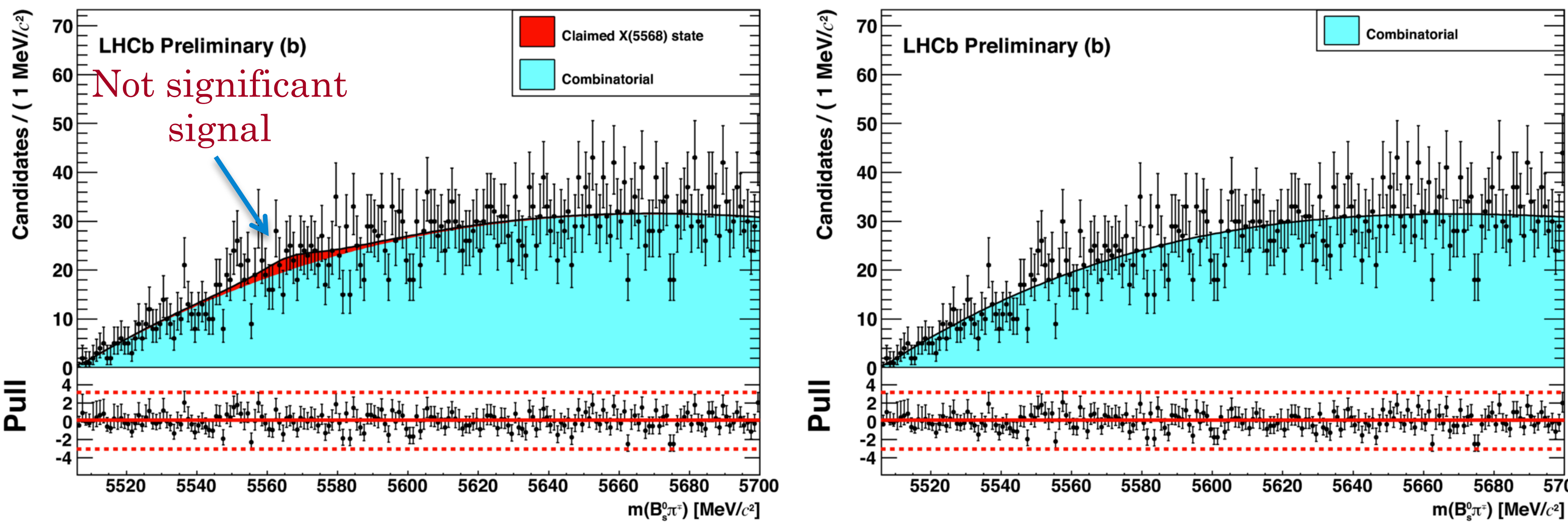
B_s sample 20x larger and much cleaner than DØ

Fit Result

LHCb-CONF-2016-004

Both modes combined (no "Cone" cut applied): $p_T(B_s) > 10$ GeV/c

Fit with signal component | Fit without signal component



$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 5\ \mathrm{GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 10\ \mathrm{GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$

JUST FOR CURIOSITY…

LHCb-CONF-2016-004

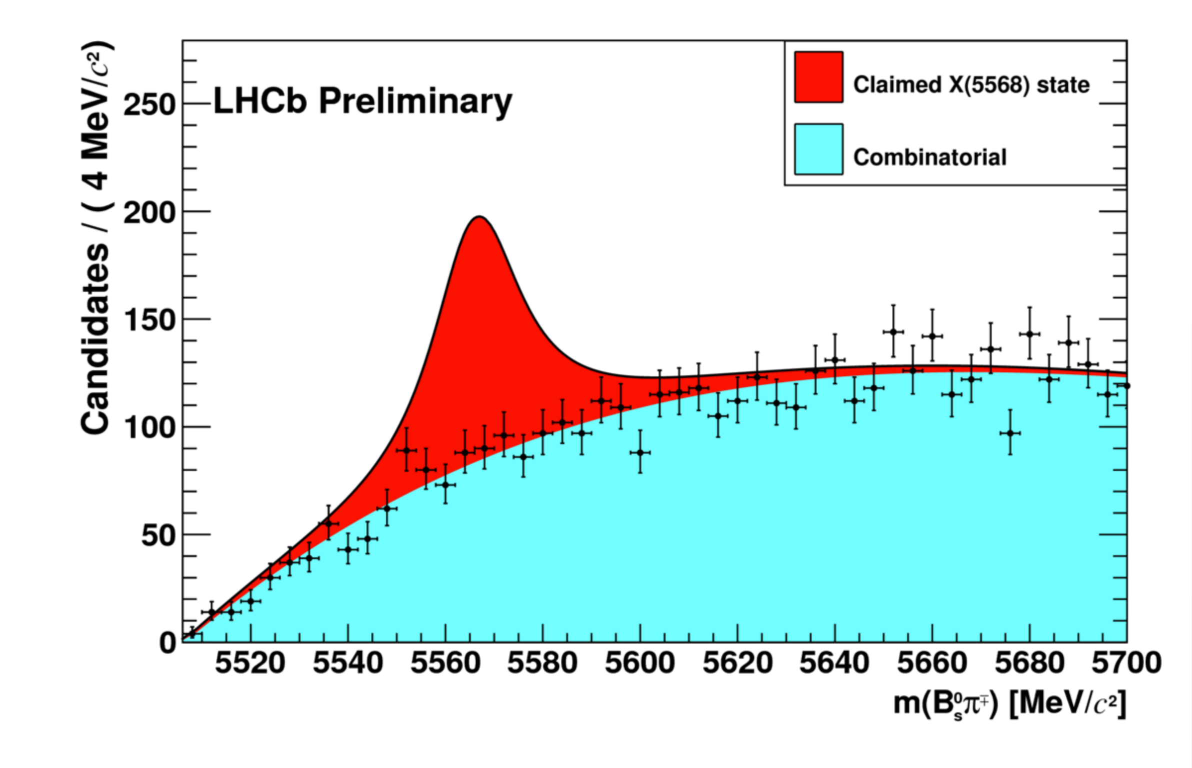
If $\rho_X^{\text{LHCb}} = \rho_X^{\text{DØ}} = 8.6\%$, how would the X(5568) signal look like?

JUST FOR CURIOSITY…

LHCb-CONF-2016-004

If $\rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D}\varnothing} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(B_s) > 10$ GeV/c)



Observation of two pentaquarks $P_c^+ \rightarrow J/\psi\ p$ (Amplitude analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$)

Pentaquark: The Return of the Living Dead

After 50 years no undisputed experimental evidence have been found for pentaquarks

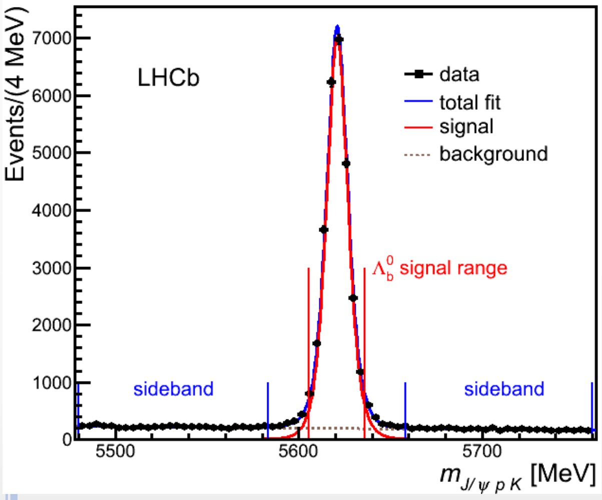
- Most famous candidates:
  - ✓ $\Theta^+ \to K^0 p$, $K^+ n$, m=1.54 GeV, Γ~10 MeV
  - ✓ Resonance in $D^{*-}p$ at 3.1 GeV, Γ=12 MeV
  - ✓ $\Xi^{--} \to \Xi^- \pi^-$, m=1.862 GeV, Γ<18 MeV
- <u>In general they were observed in "bump" searches</u>

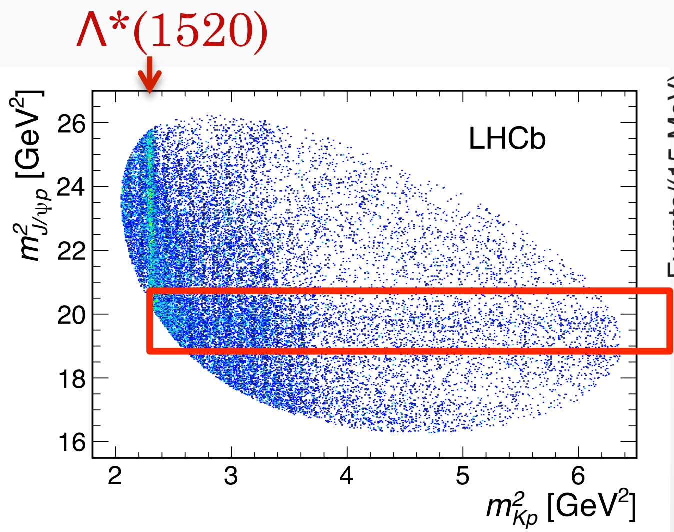
K.H. Hicks, "On the conundrum of the pentaquark", Eur.Phys.J. H37 (2012) 1

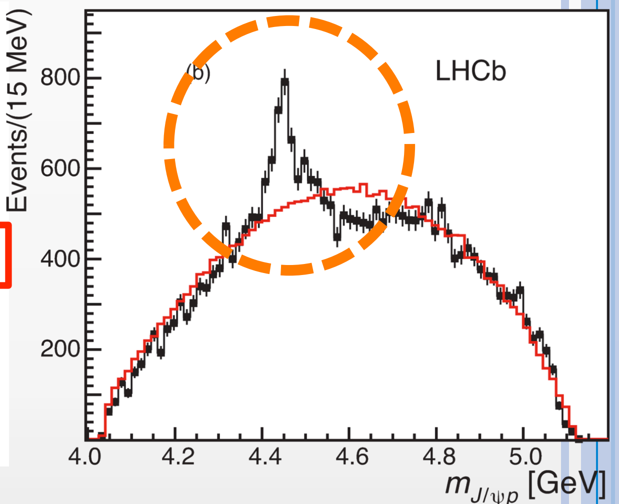
OBSERVATION OF A NARROW BAND IN THE Λ_b "DALITZ" PLANE

[LHCb: PRL 115, 07201 (2015)]

Selection based on the full Run I dataset ($3fb^{-1}$)
26k Λ_b^0 candidates. Background ~ 5.4%





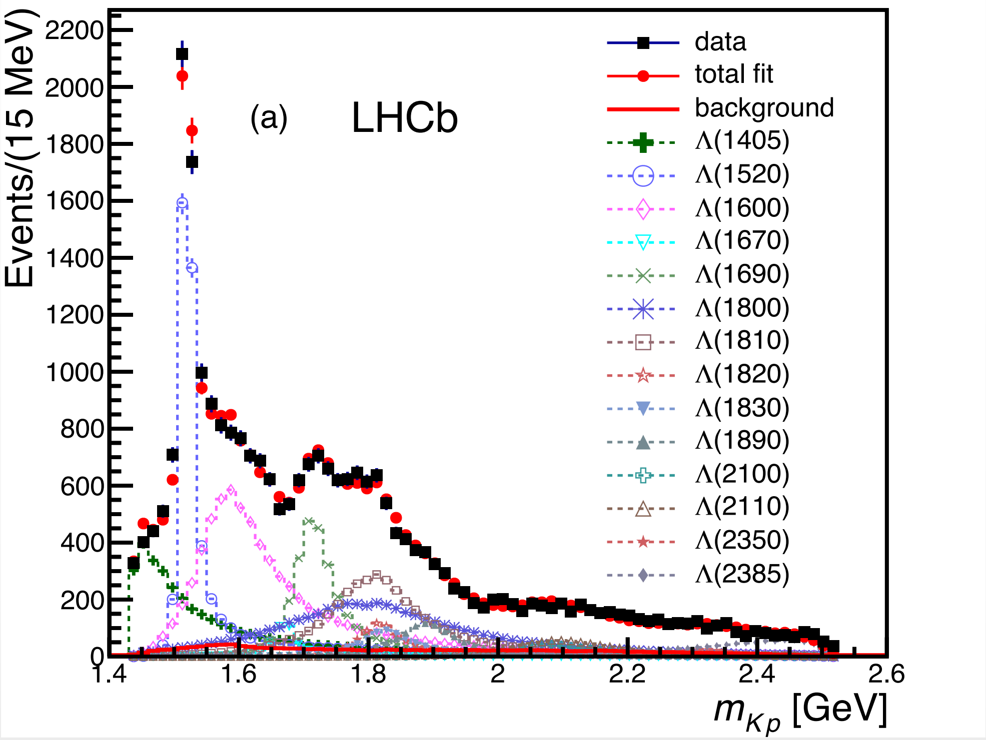


- The pK^- mass spectrum featured by several resonant states
- Could it be a reflection of the interfering excited $\Lambda^* \rightarrow pK^-$?

6D Amplitude analysis

Fit with Λ*→pK States only

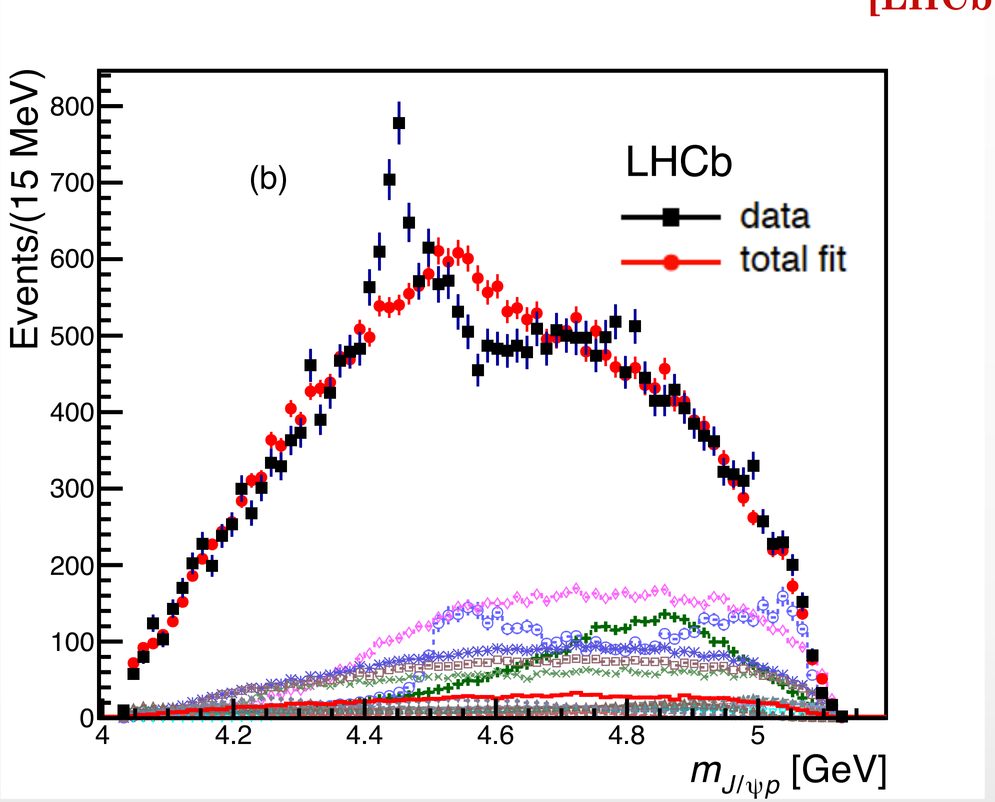
[LHCb: PRL 115, 07201 (2015)]



Use of extended model, so all possible known Λ* amplitudes: m_{Kp} projection looks fine, but…

FIT WITH Λ*→pK STATES ONLY

[LHCb: PRL 115, 07201 (2015)]

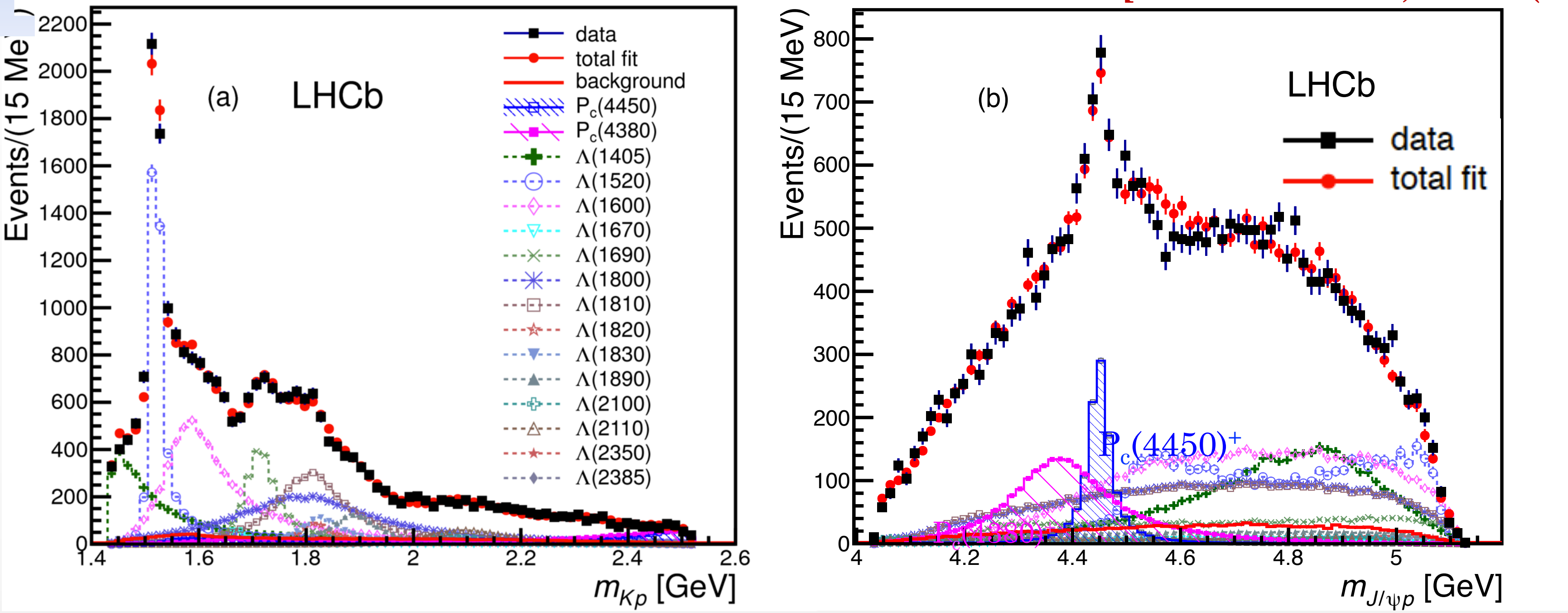


Extended Λ* model:

- …the fit projection can't reproduce the peaking structure in J/ψ p
- Adding non-resonant term, Σ*'s or extra unknown Λ*'s doesn't help

ADDING $P_c \rightarrow J/\psi\, p$ AMPLITUDES

[LHCb: PRL 115, 07201 (2015)]



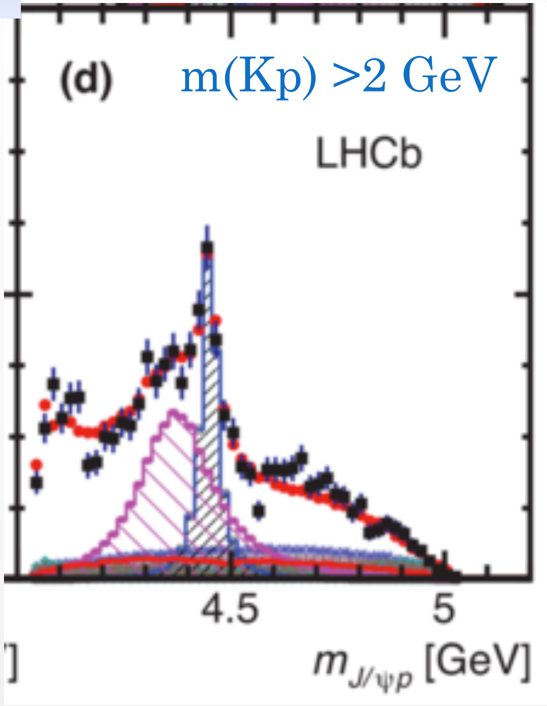
Reduced Λ* model + 2 Pentaquarks decaying to J/ψ p

- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred
- Adding more amplitudes doesn't improve the fit quality

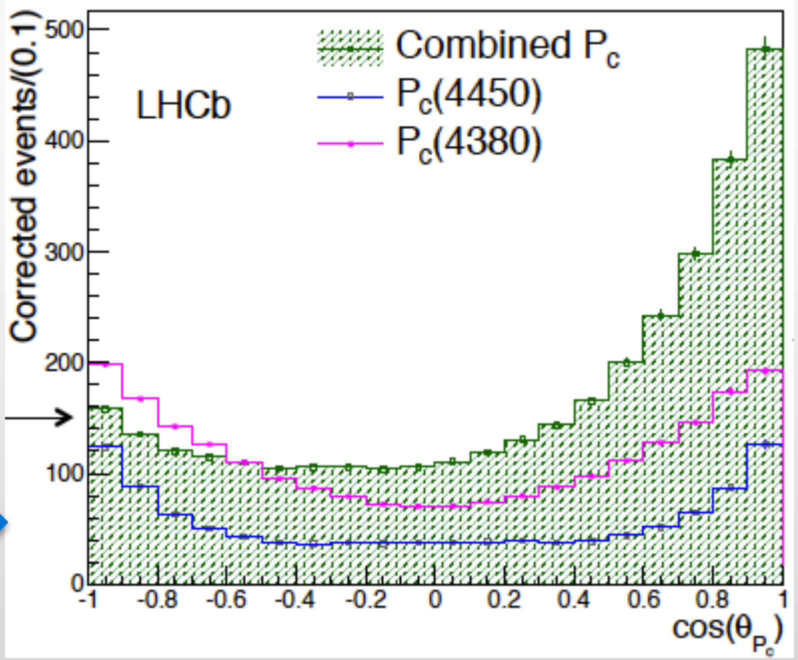
State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2
$P_c(4450)^+$	4449.8±1.7±2.5	39 ± 5±19	4.1±0.5±1.1

DO WE REALLY NEED 2 P_c^+'S? YES

[LHCb: PRL 115, 07201 (2015)]



Clear need for the 2nd broad P_c^+ where the $\Lambda^* \rightarrow pK^-$ contribution is the smallest

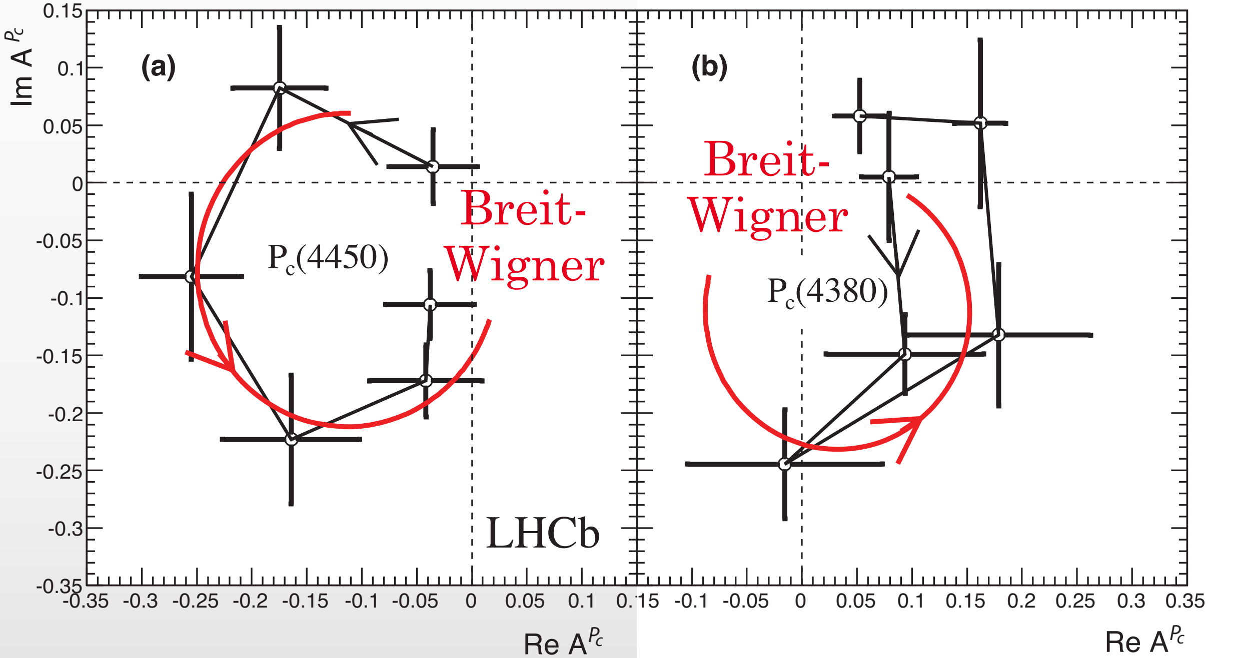


Evidence of an interference pattern in the angular distribution

Argard Diagrams

[LHCb: PRL 115, 07201 (2015)]

P_c^+ amplitudes for 6 m(J/ψ p) bins between +Γ & -Γ around the resonance mass



- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

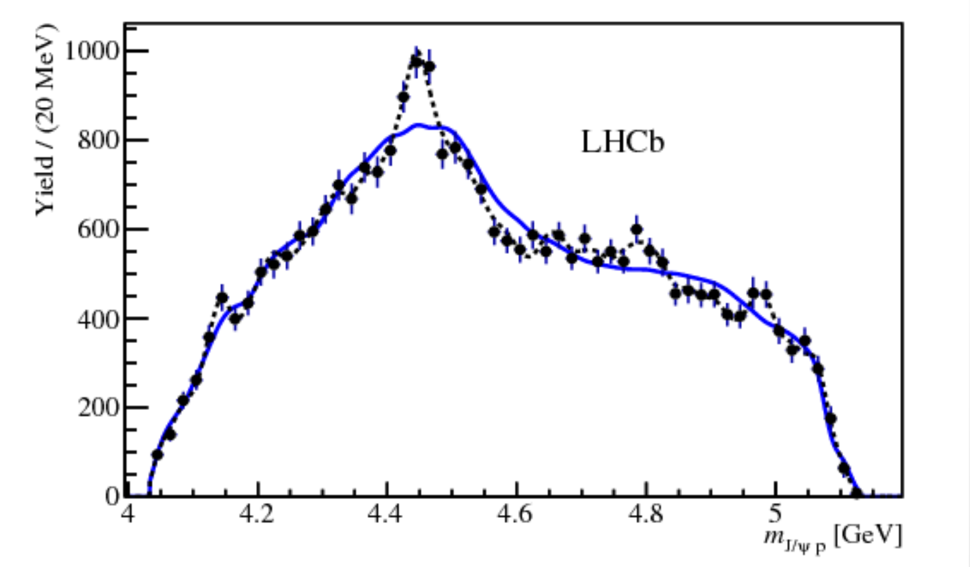
Model-independent evidence for J/ψ p contributions to $\Lambda_b \rightarrow J/\psi\ p\ K^-$

MODEL INDEPENDENT ANALYSIS

[arXiv:1604.05708]

Can the reflections of the structures in m(pK) and cos ϑ_{Λ^*} reproduce the m(J/ψ p) distribution?

If no exotics in J/ψK and J/ψ p → Decompose angular distribution into Legendre moments → Recombine the moments up to a certain order

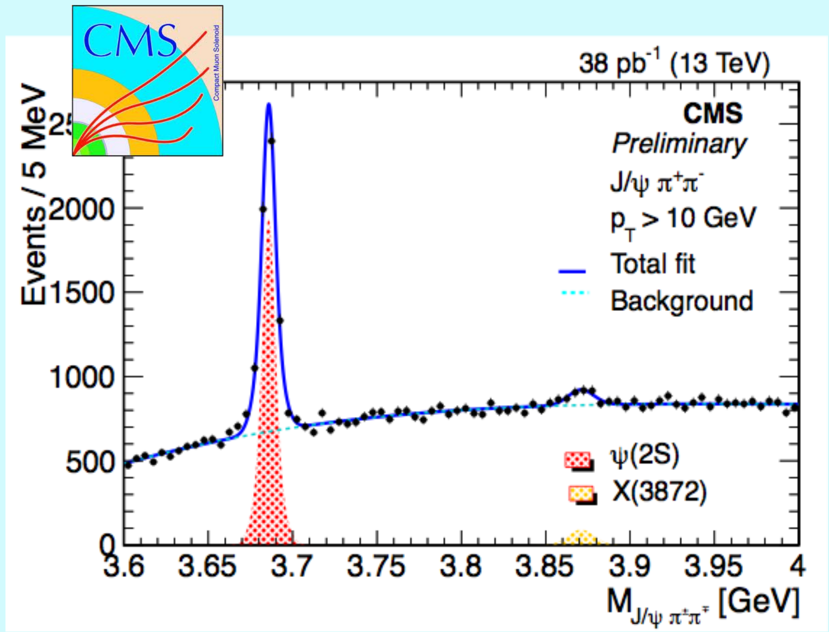


Explanation of the data with plausible Λ* contributions is ruled at high significance without assuming anything about Λ* resonance shapes or their interference patterns!

RUN II and Beyond

X(3872) & QUARKONIA-LIKE STATES

- X(3872)
  - Precise mass measurements. Why so close to $D^0\bar{D}^{*0}$ threshold?
  - Search for new decay modes: (e.g.) $\chi_{c1}\ \pi\ \pi$
  - Confirmation of $J/\psi\ \omega$ or $D^0\bar{D}^{*0}$ decay modes
  - Production measurements at 13 TeV (prompt and non-prompt)



X(3872) & QUARKONIA-LIKE STATES

- Charmonium-like states
  - Search for X(4140) → $J/\psi\ \phi$ in $B \to J/\psi\ \phi\ K$ and $B_s \to J/\psi\ \phi\phi$ decays
  - Search for the missing $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$
  - Exploration of $D_{(s)}\bar{D}_{(s)}$ mass spectra from B decays
  - Determination of spin-parity
  - Central Exclusive Production
- Search for X_b

Tetra/Pentaquarks

- Search for Z_c+
  - Study of B →J/ψ K π
  - Study of B →η_c K π
  - Study of B →ψ(2S) π π
  - Study of B →χ_{c1} K π
- Pentaquarks
  - Search for P_c^+'s in Λ_b →J/ψ p π decays
  - RUN II data will help to determine spin-parity of the two P_c^+'s
  - The hunt to the next pentaquark is open!
    - χ_{c1} p
    - Υ(1S)→J/ψ p $\bar{p}$
    - D Σ_c
    - Triple charged pentaquarks

Amplitude Analyses

- Many studies involved b-hadron decays with vectors into the final states ➔ Multidimensional phase-space

Why amplitude analysis are strongly recommended?

(e.g.) Natural width of Z(4430) (MeV)

State	1D	2D	4D
Belle	$45\,^{+18}_{-13}\,^{+30}_{-13}$	$107^{+86}_{-43}\,^{+74}_{-56}$	$200\,^{+41}_{-46}\,^{+26}_{-35}$
LHCb			$172 \pm 13\,^{+37}_{-34}$

- Broad structures may look narrow(er) in 1D mass projections.
- Amplitude analysis is a powerful tool to probe the quantum numbers and resonant character of the intermediate states.

Back-up slides

First Observation of $\Lambda_b \rightarrow J/\psi\ K^- p$

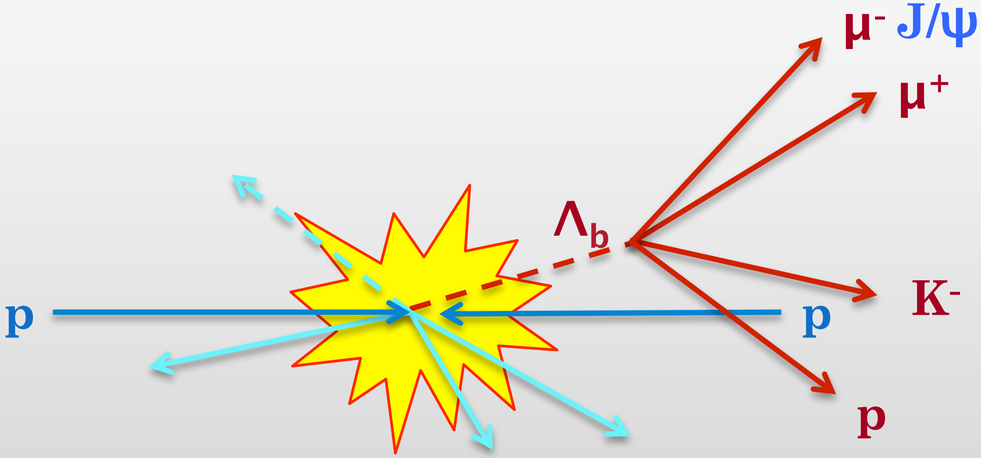
[LHCb: PRL 111 (2013) 102003]

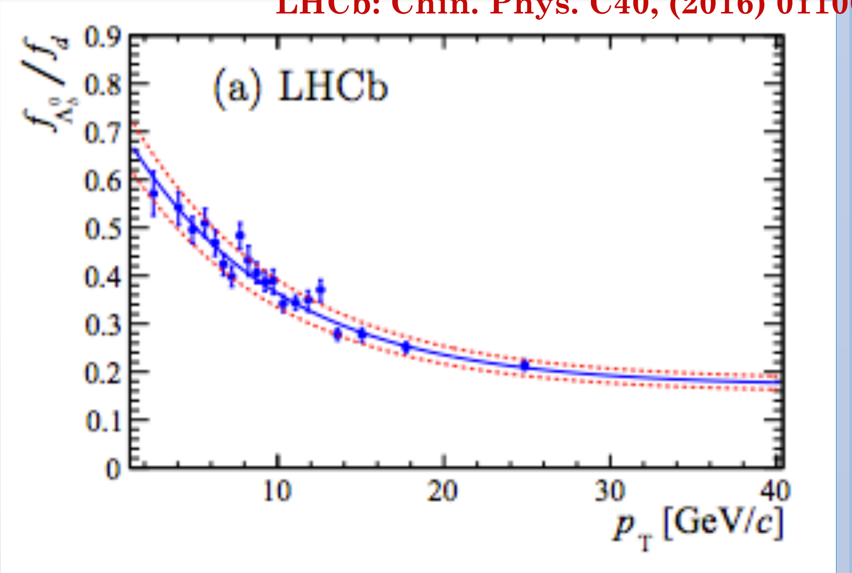
Why did LHCb arrive first? The decay was not observed before!

- ✓ J/ψ into final state → Large trigger efficiency
- ✓ 4 Tracks → Large detection efficiency
- ✓ Large Λ_b production

LHCb: JHEP 08(2014)143

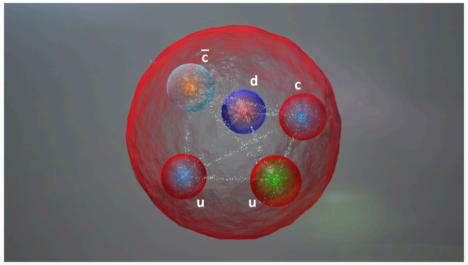
LHCb: Chin. Phys. C40, (2016) 011001

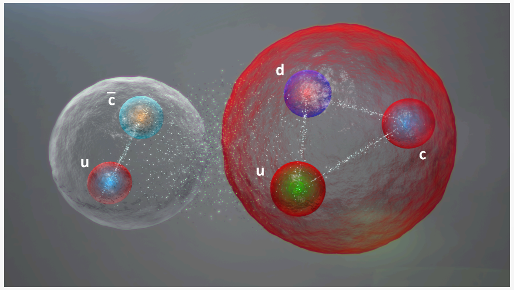




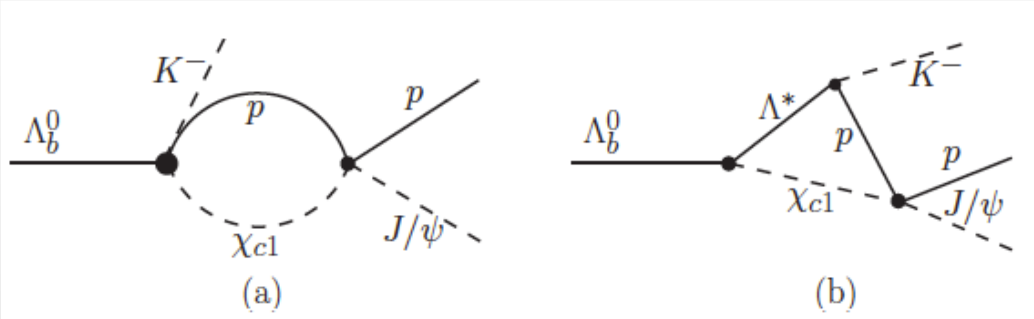
PENTAQUARK P_c^+

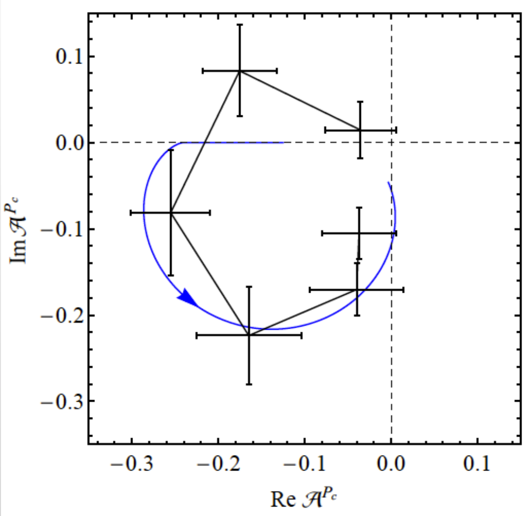
- Tightly bound
  - ✓ Jaffe, PRD15(1977) 267
  - ✓ Strottman, PRD20(1979) 748
  - ✓ Maiani et al. PRD71(2005)014028
- Molecular model with meson exchange for binding
  - ✓ Törnqvist, Z.Phys.C61(1994) 525
- Others (postdictions):
  - ✓ Rescattering, "Cusps"





A narrow pentaquark state challenges many models





PRD 92 (2015) 7, 071502

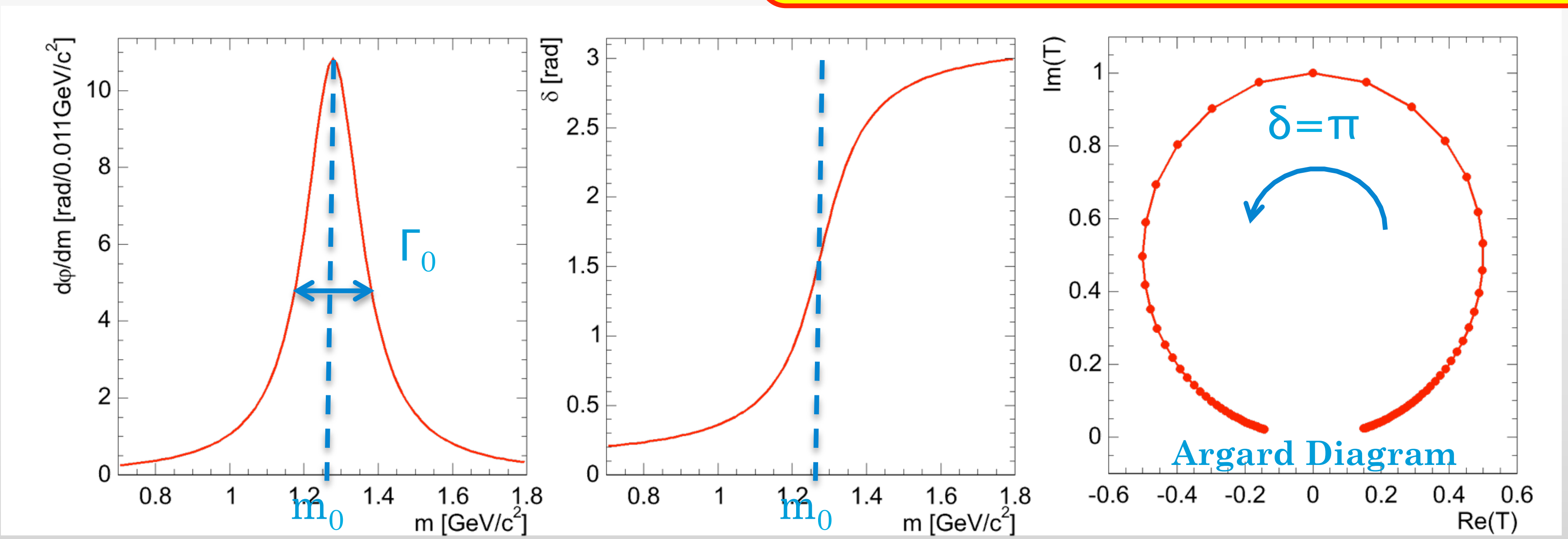
How to model a single term

$$A^{K^*}_{\lambda_\psi,\Delta\lambda_\mu}(m_{K\pi},\Omega) = H^{K^*}_{\lambda_\psi} A^{K^*}(m_{K\pi}) d^{J(K^*)}_{\lambda_\psi,0}(\theta_{K^*}) \times e^{i\lambda_\psi\phi} d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$

Free parameters
+
m_0, Γ_0 (in case of a new state)

Relativistic Breit-Wigner

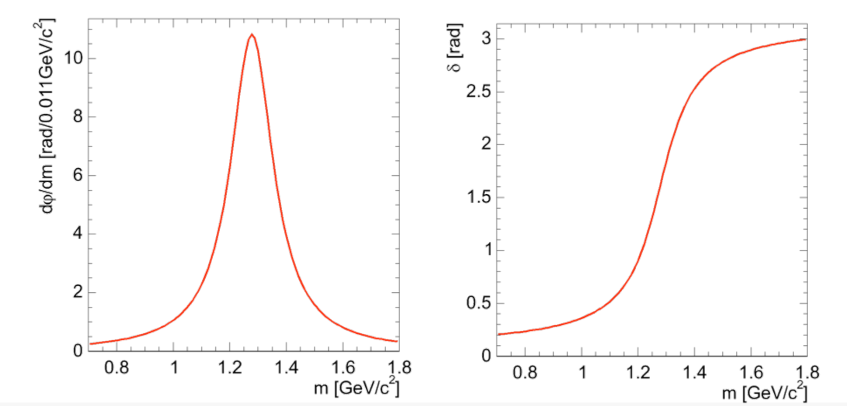
$$A^{K^*}(m_{K\pi}) = \frac{1}{m_0^2 - m_{K\pi}^2 - i m_o \Gamma_0}$$



Probing the Resonant Character of Z(4430)$^+$

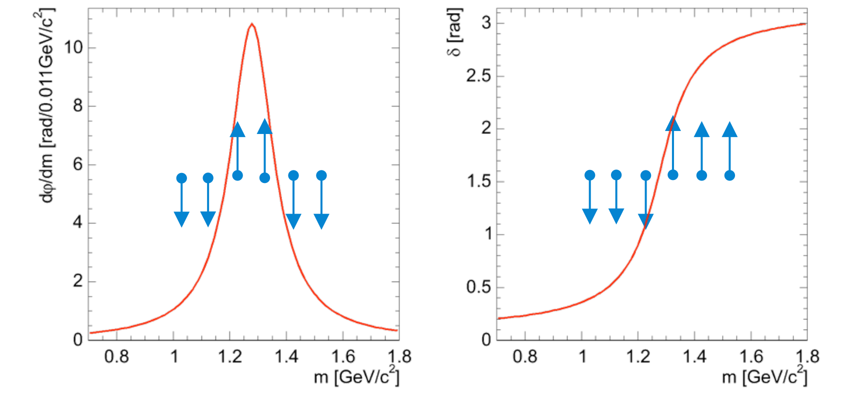
[LHCb: PRL 112, 222002 (2014)]

Nominal fit



4 free parameters:
m_0, Γ_0 + complex constant

Alternative fit
Replace BW amplitude with 6 independent complex numbers in 6 bins of m(ψ(2S)π) in region $m_0 \pm \Gamma_0$, where m_0 is the mass of Z(4430)



12 free parameters

Λ* Decay Models

[LHCb: PRL 115, 07201 (2015)]

Two models: Reduced and Extended
L = angular momentum between J/ψ and Λ*

No high-J^P high-mass states, limited L

All states, all L

All known Λ* states

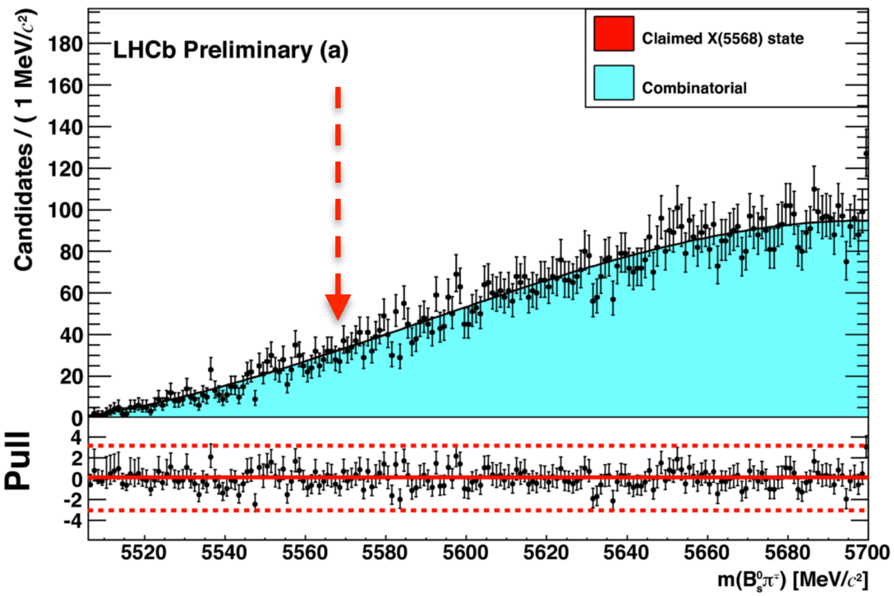
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	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
$\Lambda(2585)$	?	$\approx$2585	200	0	6
# of fit parameters:				64	146

Fit Result (I)

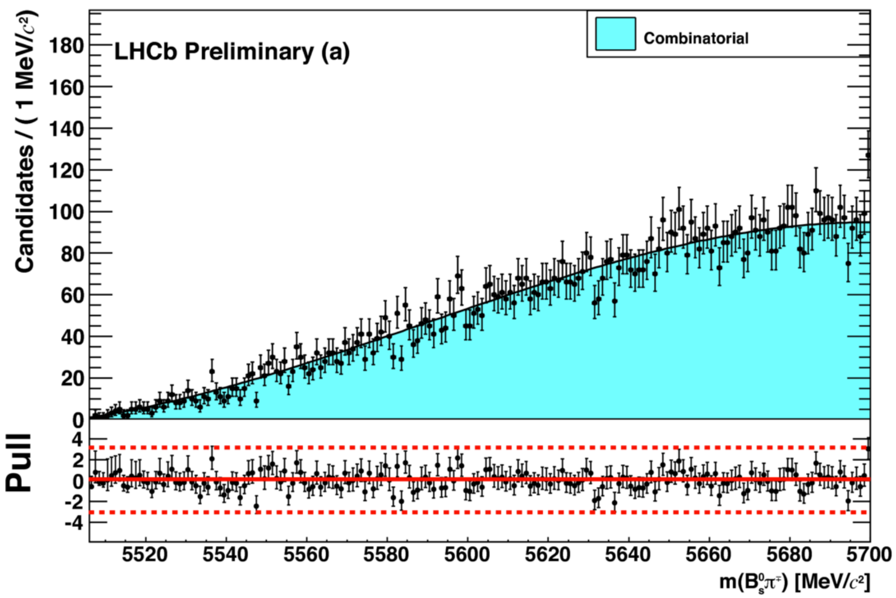
LHCb-CONF-2016-004

(Both modes combined: $p_T(B_s) > 5$ GeV/c)

Fit <u>with</u> signal component

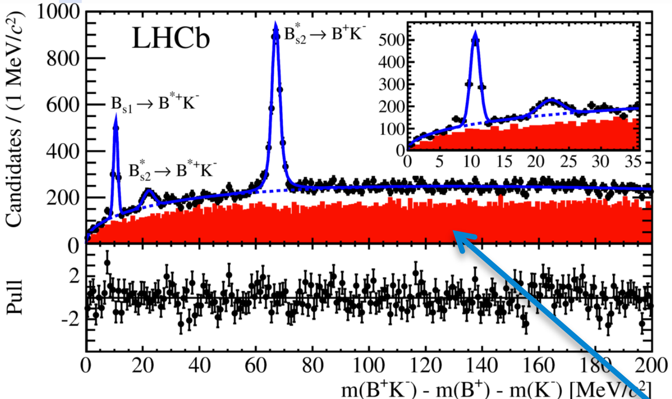


Fit <u>without</u> signal component



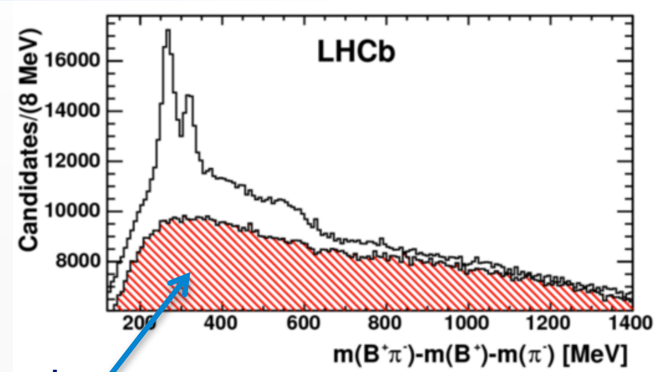
No “Cone” cut applied

OTHER "IMPLICIT" SEARCHES



PRL 110 (2013) 151803

B^+K^+

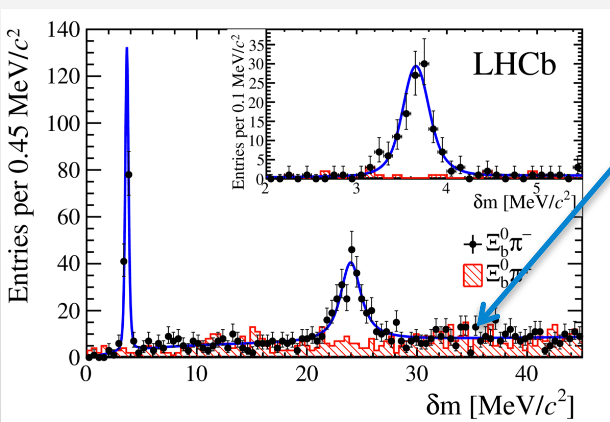


$B^+\pi^+$

JHEP 1504 (2015) 024

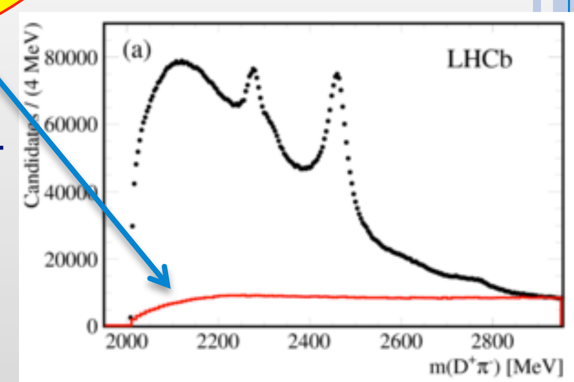
The red histograms, referred as Wrong Sign plots, are implicitly searches for tetra/ pentaquark

$\Xi_b{}^0\pi^+$



PRL 114 (2015) 062004

$D^+\pi^+$



JHEP 09 (2013) 145

Significances and Results

[LHCb: PRL 115, 07201 (2015)]

- Simulations of pseudo-experiments are used to quote the significances:
  - ✓ Significance of $P_c(4450)^+$ state is 12σ
  - ✓ Significance of $P_c(4380)^+$ state is 9σ

- Main systematic uncertainty: difference between extended and reduced fit models. Taken in account while computing the significances

State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2
$P_c(4450)^+$	4449.8±1.7±2.5	39 ± 5±19	4.1±0.5±1.1
Λ(1405)			15±1±6
Λ(1520)			19±1±4