Exotic Hadron Spectroscopy at LHC

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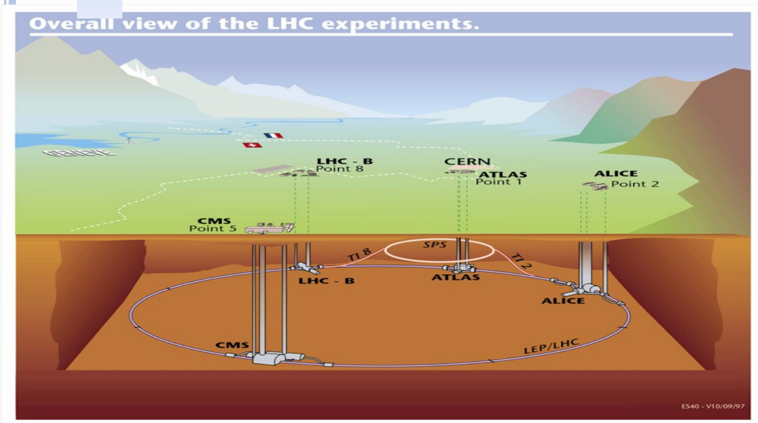
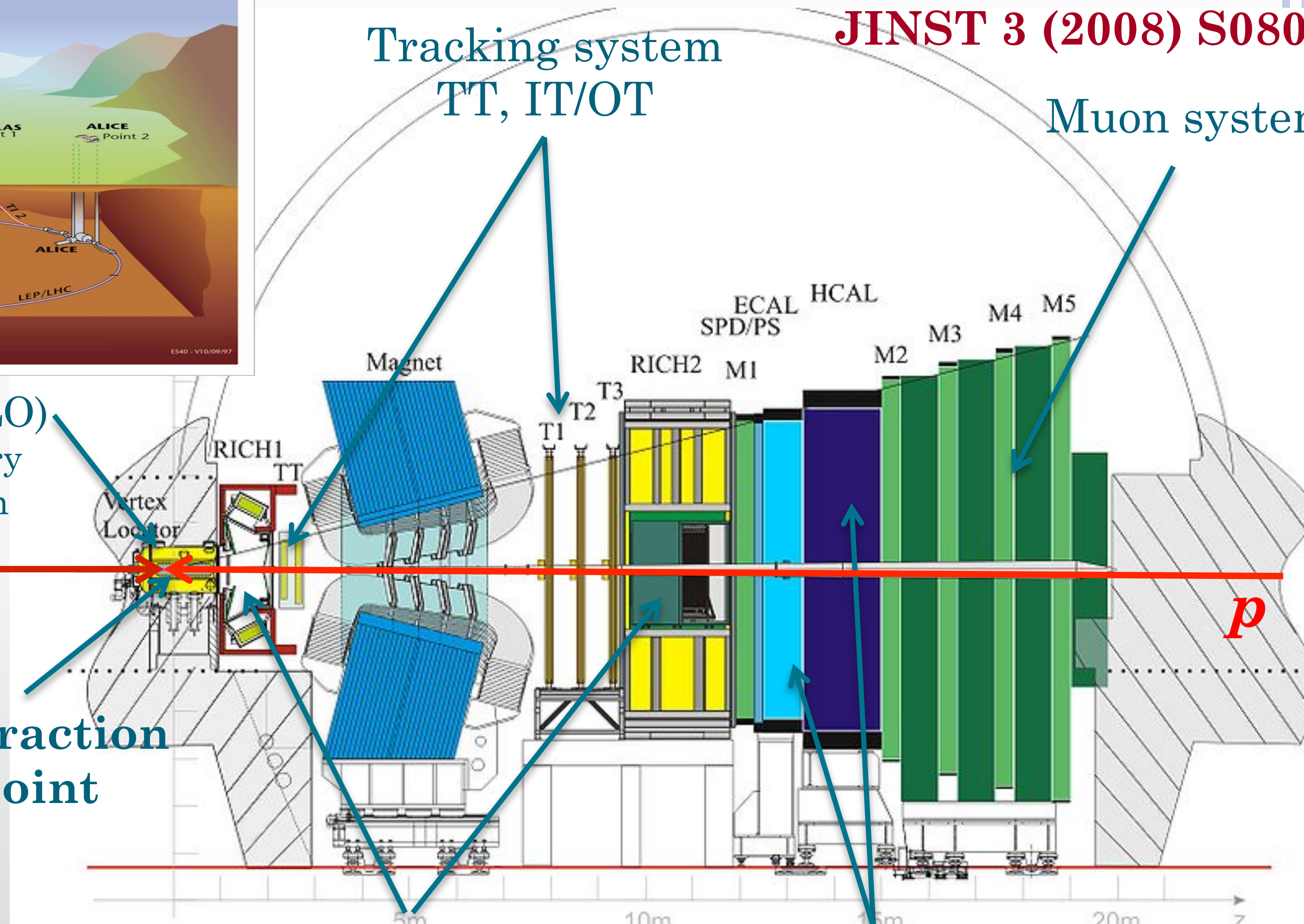
OUTLINE

- Introduction
  - Spectroscopy Techniques
  - Amplitude/Dalitz Analyses
- Search for Pentaquarks $P_c^+ \rightarrow J/\psi\ p$
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$ Decay
  - Model Independent Analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$ Decay
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\ p\ \pi^-$ Decay
- Search for a tetraquark $X(5568)^\pm \rightarrow B_s\ \pi^\pm$
- Amplitude Analysis for $B^+ \rightarrow J/\psi\ \phi\ K^+$

THE LHCb DETECTOR

Int. J. Mod. Phys. A 30 (2015) 1530022
JINST 3 (2008) S08005





Tracking system
TT, IT/OT

Muon system

Vertex Locator (VELO)
Primary and secondary
Vertex reconstruction

p

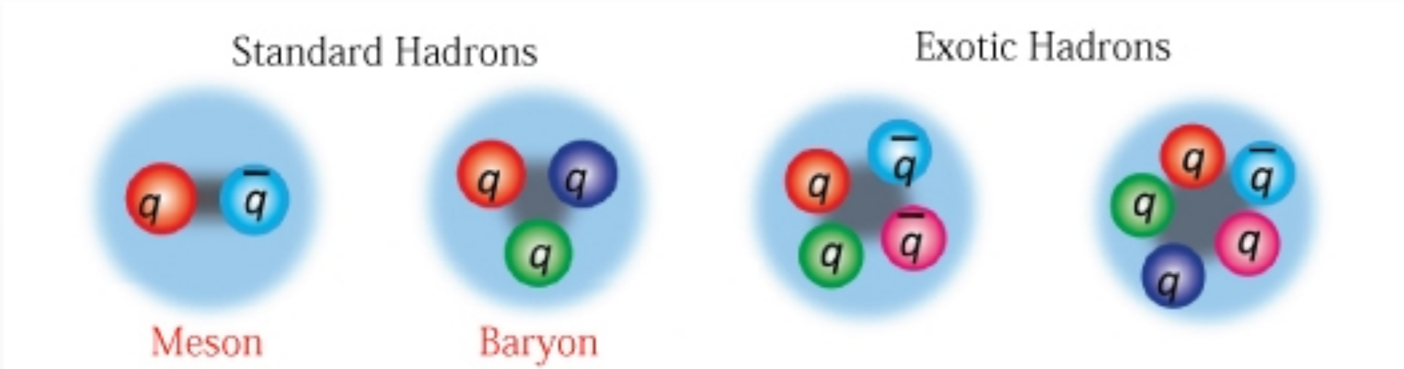
p

Interaction Point

RICH detector
PID p, K, π

Calorimeters
e, γ, π^0

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 (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 baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

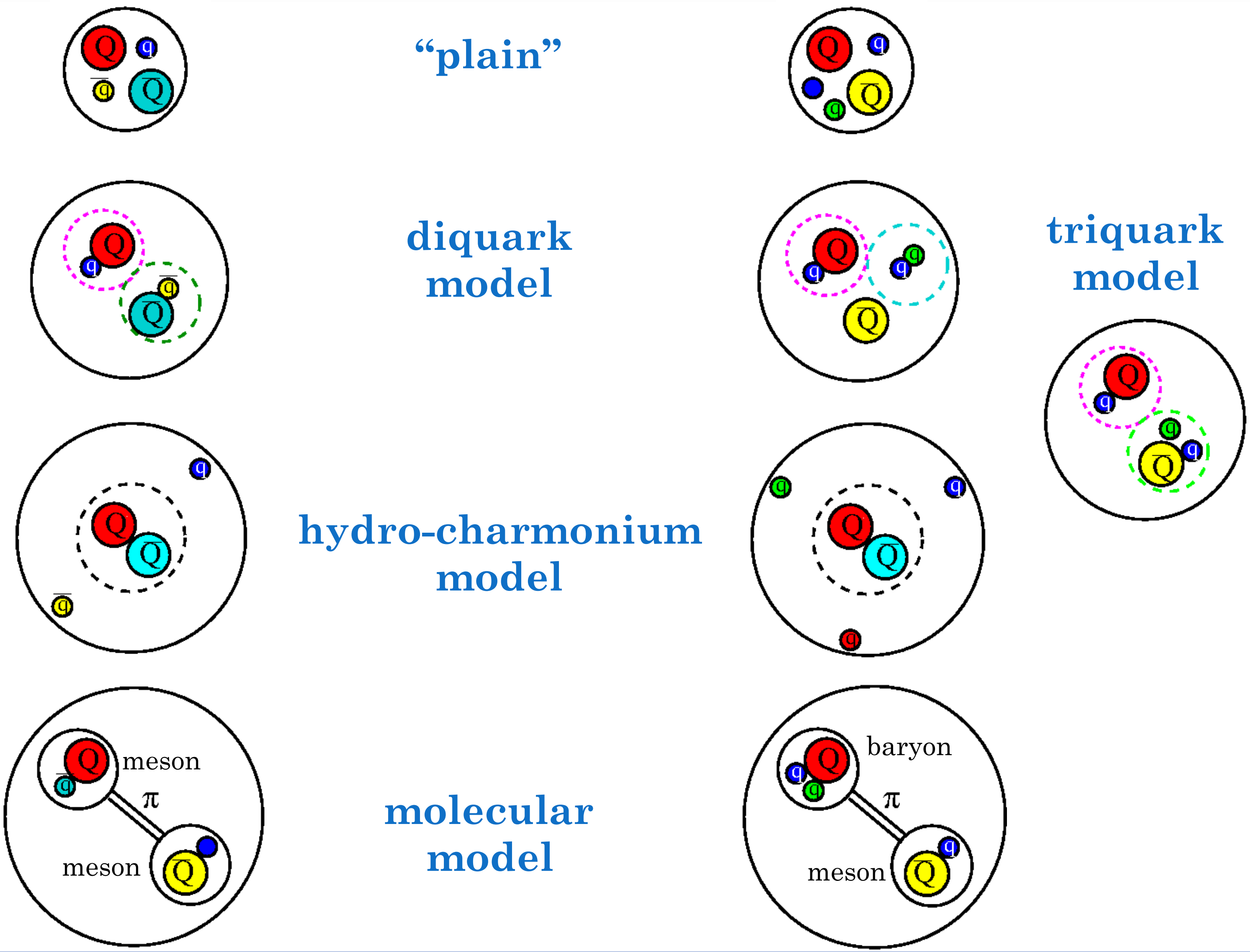
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig **)
CERN - Geneva

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

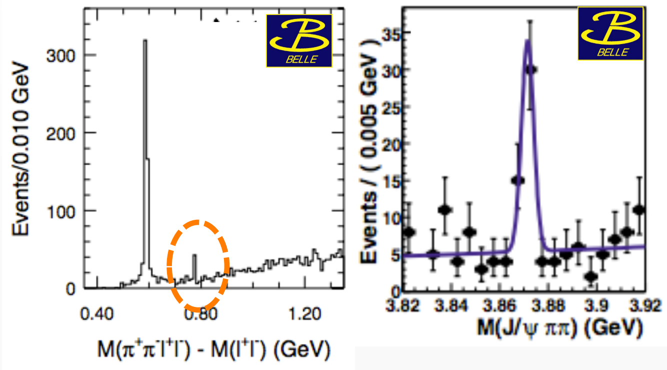
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons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

Models for Tetra- and Penta-quarks



THE X(3872) STATE

[Belle: PRL 91, 262001 (2003)]



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

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

- Determination of the quantum numbers $J^{PC} = 1^{++}$ **[PRL110 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]**

$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

➡ *Pure molecule scenario disfavored*

- Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0) + m(D^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV}/c^2$$

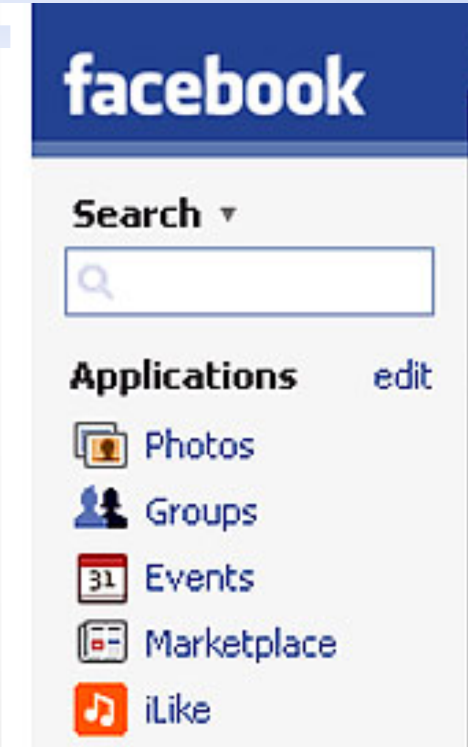
➡ *Loosely bound in the molecule scenario*

- Production cross-section in *pp* collisions at $\sqrt{s} = 7$ TeV **[EPJC 72 (2012) 1972,]**
- Search for new decay modes (e.g. $X(3872) \to p\bar{p}$) **[arXiv: 1607.06446]**

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2}\ @\ 95\%\ \mathrm{CL}$$

…AND FRIENDS

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

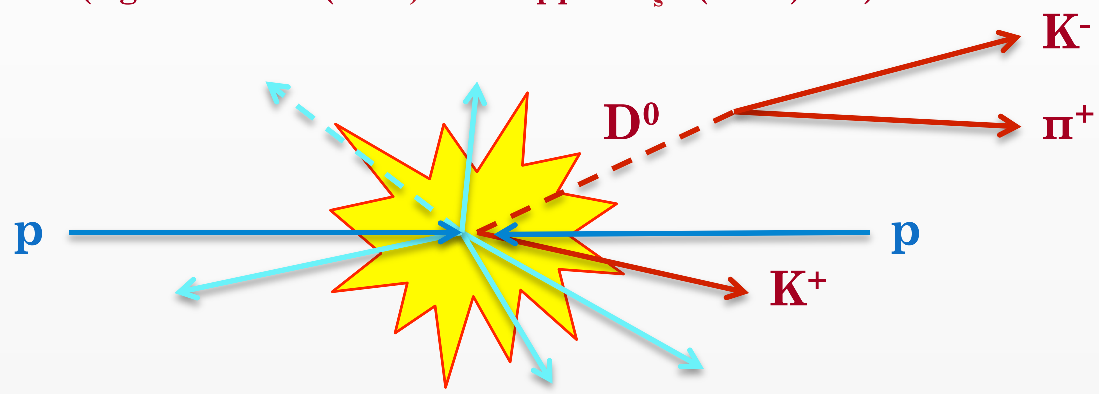


State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	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) LHCb [1041] (> 10)	2005	Ok
				$B \to K(\gamma \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2) LHCb [1041] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	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) T. Xiao *et al.* [CLEO data] [1047] (>5)	2013	Ok
$Z_c(4020)^+$	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), LHCb [1100] (1.4), CMS [1101] (>5) D0 [1102] (3.1)	2009	NC!
$\psi(4160)$	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) Belle [1046, 1094] (15), BES III [1045] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	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), CMS [1101] (>3), D0 [1102] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	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) LHCb [1115] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	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!

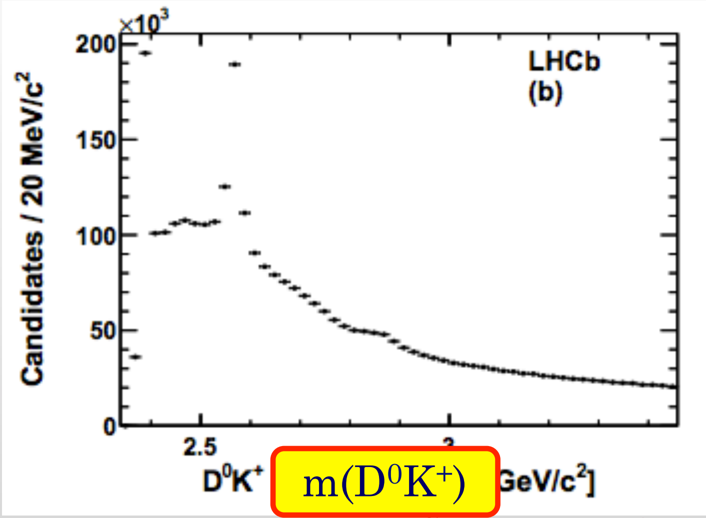
How to do spectroscopy?

"Inclusive Analysis"

(e.g. $e^+e^- \rightarrow D^{**}(\rightarrow D\pi) + X$ or $pp \rightarrow B_s^{**}(\rightarrow BK) + X$)



- Large cross sections
- Large combinatorial background
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization
- Presence of "reflections"/"feed-downs"



[LHCb: JHEP 10 (2012) 151]

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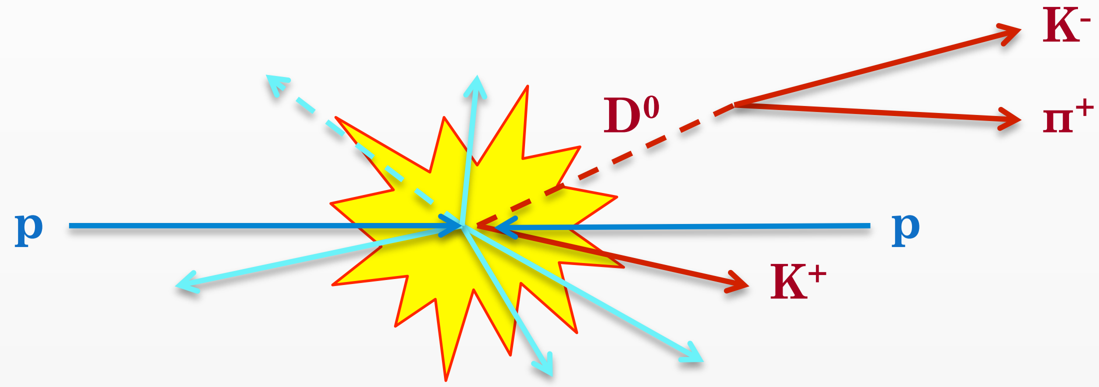
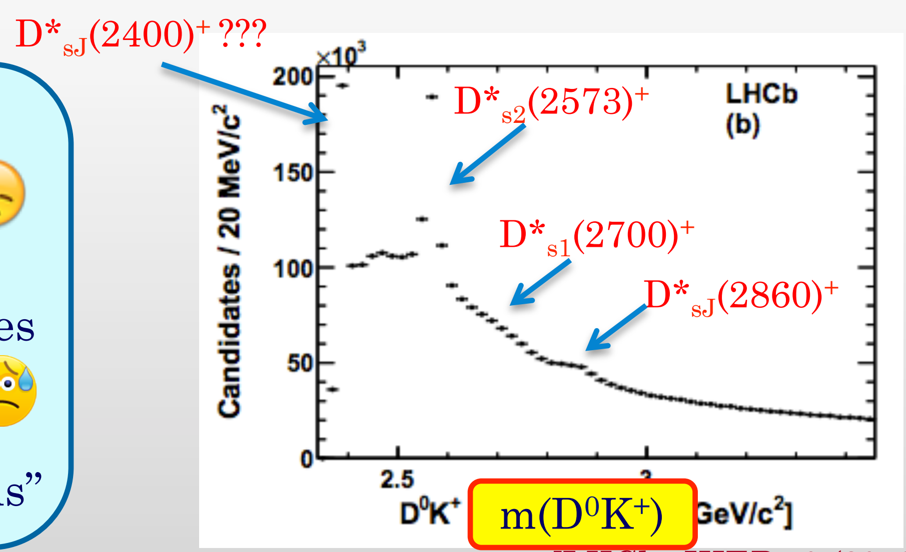


- Large cross sections 😄
- Large combinatorial background 😞
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization 😰
- Presence of "reflections"/"feed-downs"



[LHCb: JHEP 10 (2012) 151]

How to do spectroscopy?

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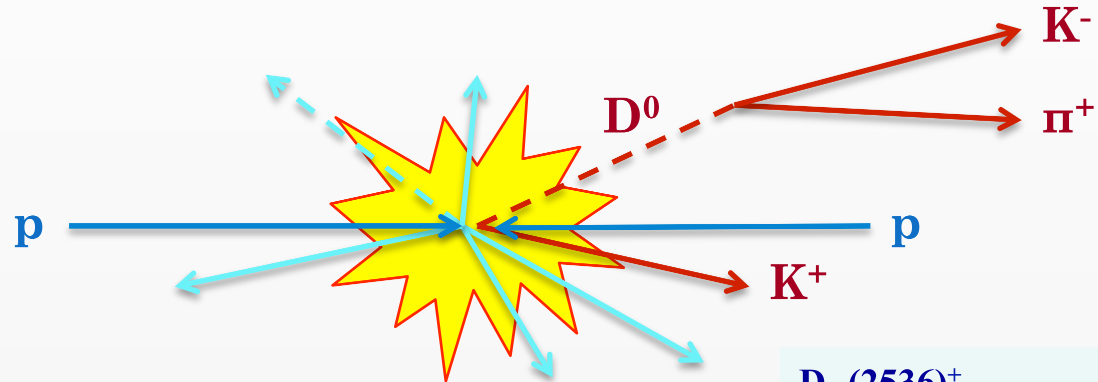
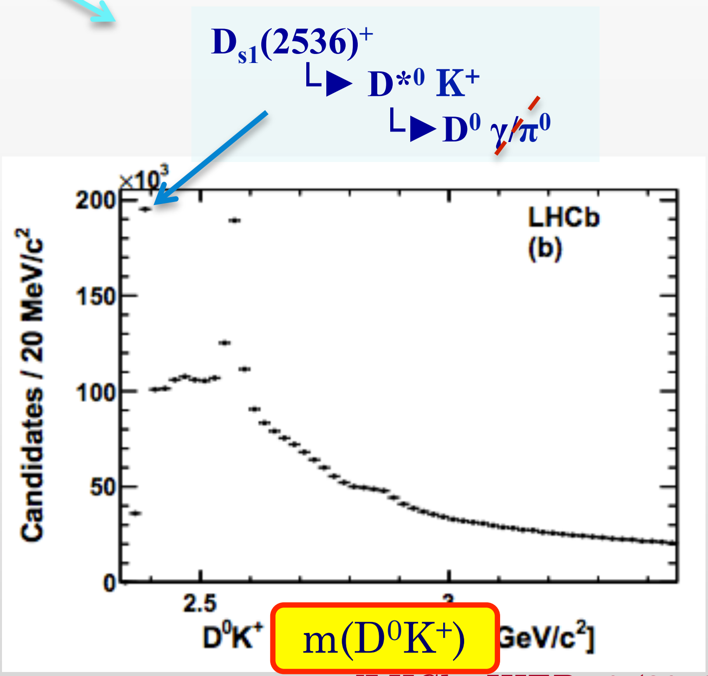




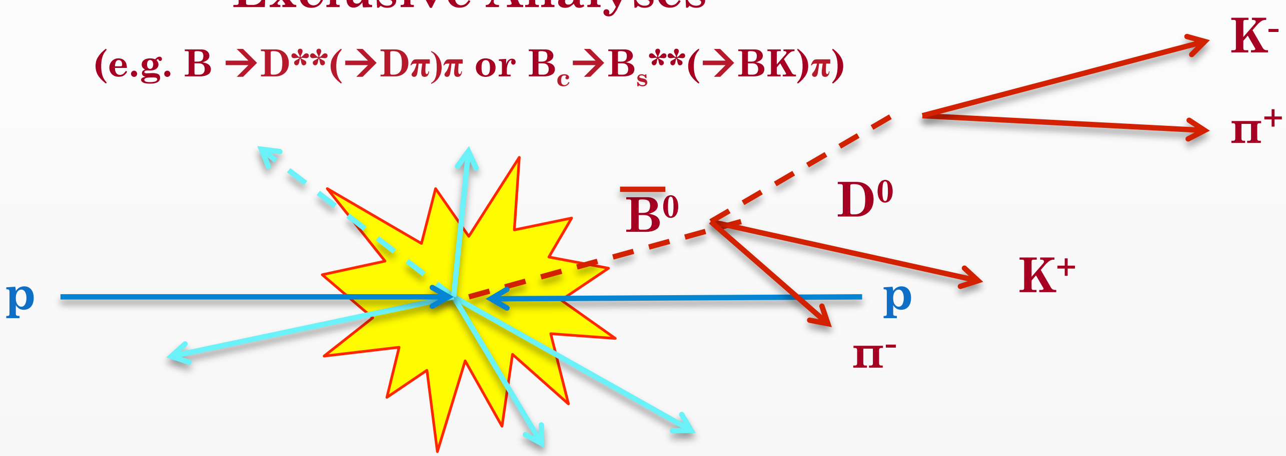
[LHCb: JHEP 10 (2012) 151]

- Large cross sections 😄
- Large combinatorial background 😞
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization 😰
- Presence of "reflections"/"feed-downs"

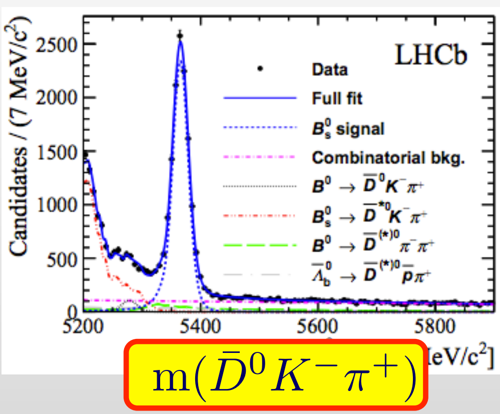
How to do spectroscopy?(II)

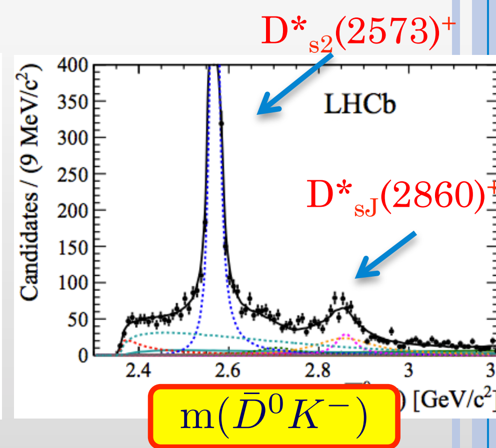
"Exclusive Analyses"

(e.g. B →D(→Dπ)π or B_c→B_s**(→BK)π)**



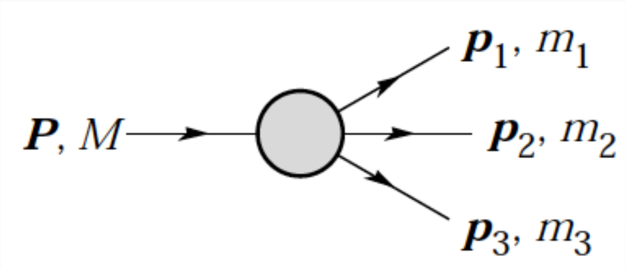
- Limited statistics 😞
- Small background 😄
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference) 😄
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis 😰





[LHCb: PRL 113 (2014) 162001, PRD 90 (2014) 072003]

3-body Decay with Spinless Daughters



Constraints	Degree of freedom
3 four-vectors	12
4-momentum conservation	-4
3 masses	-3
3 Euler angles	-3
TOT	2

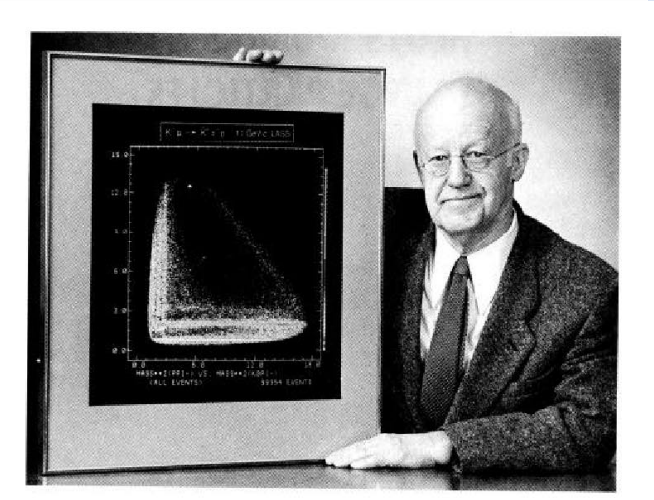
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2dm_{23}^2$$

DALITZ PLOT

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$

The scatter plot $m_{12}{}^2$ vs $m_{23}{}^2$ is usually called *Dalitz* plot

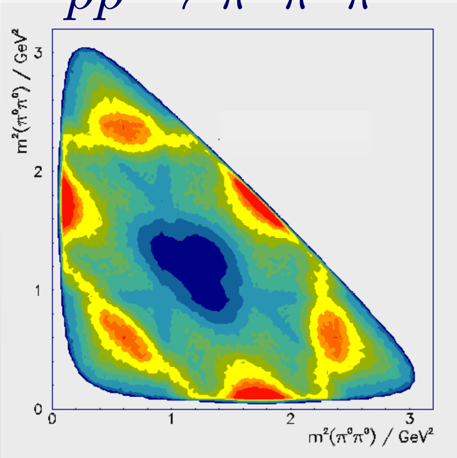
"I visualize geometry better than numbers."



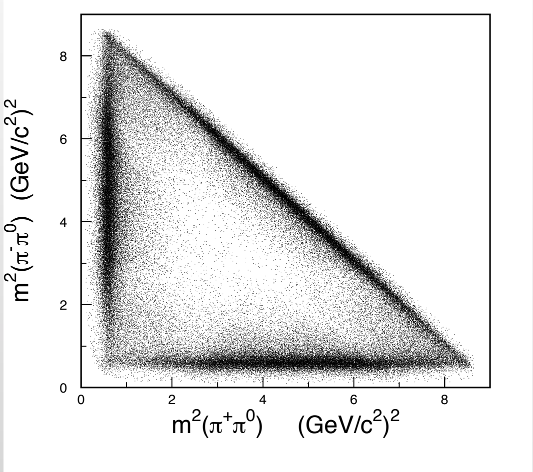
$\overline{|\mathcal{M}|^2} = Const \Rightarrow$ Dalitz uniformly populated

Nonuniformity $\Rightarrow$ Information on $\overline{|\mathcal{M}|^2}$

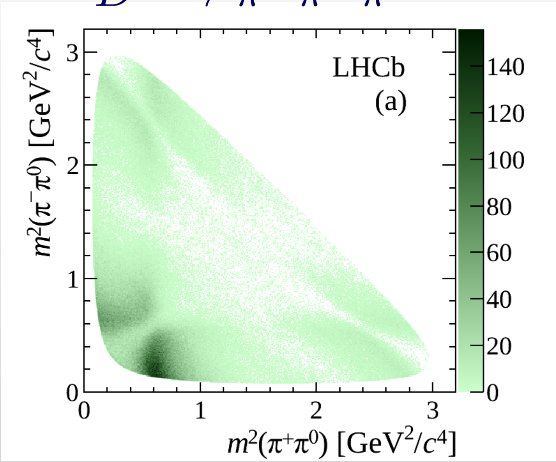
$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$



$J/\psi \rightarrow \pi^+\pi^-\pi^0$



$D^0 \rightarrow \pi^+\pi^-\pi^0$



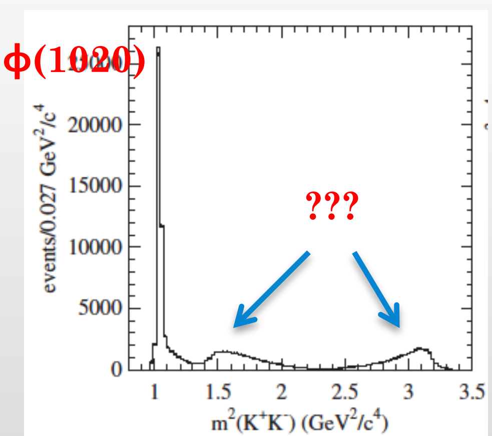
KINEMATICAL REFLECTIONS/SHADOWS

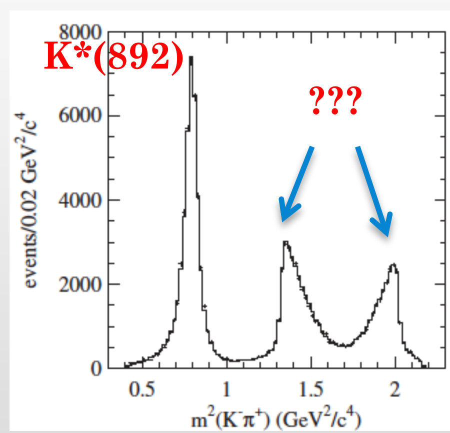
(e.g.) $D_s^+ \to K^+K^-\pi^+$

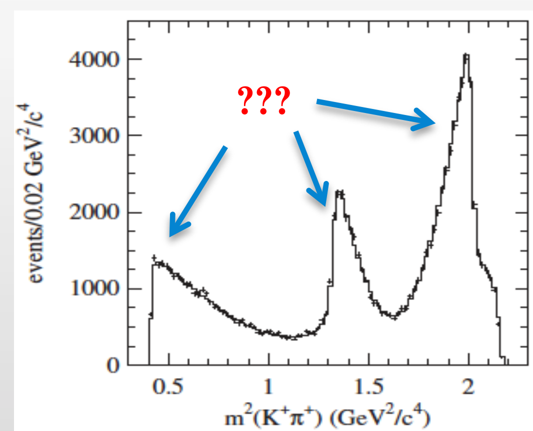
$$D_s^+ \to R\pi^+, \quad R \to K^+K^-$$

or

$$D_s^+ \to RK^+, \quad R \to K^-\pi^+$$



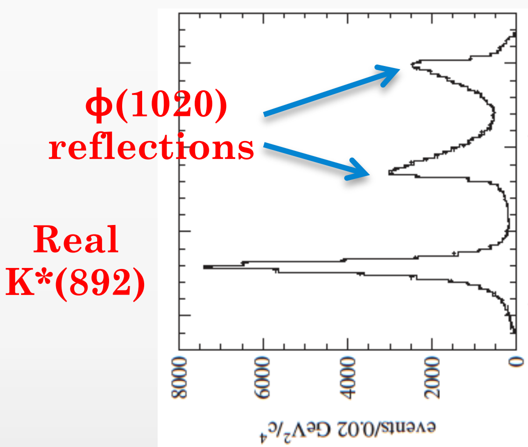


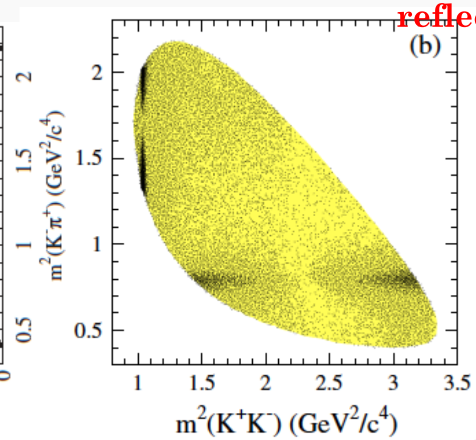


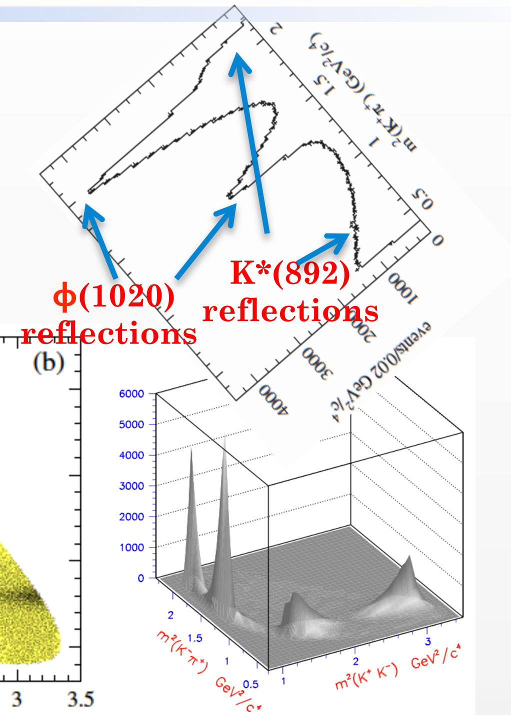
[BaBar, Phys.Rev. D83 (2011) 052001]

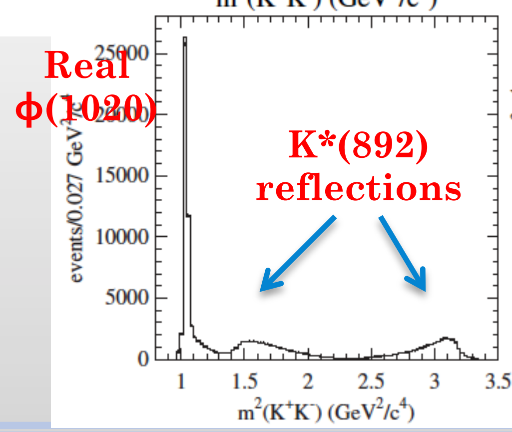
KINEMATICAL REFLECTIONS/SHADOWS

(e.g.) $D_s^+ \rightarrow K^+K^-\pi^+$









[BaBar: Phys.Rev. D83 (2011) 052001]

physicsworld
TOP 10 BREAKTHROUGH 2015

Observation of J/ψ p resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi\, p\, K^-$ decays

(Amplitude analysis of $\Lambda_b \rightarrow J/\psi\, p\, K^-$)

[LHCb: PRL 115 (2015) 072001]

PENTAQUARK:
THE RETURN OF THE LIVING DEAD

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

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

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

FIRST OBSERVATION OF $\Lambda_b \rightarrow J/\psi\ K^- p$

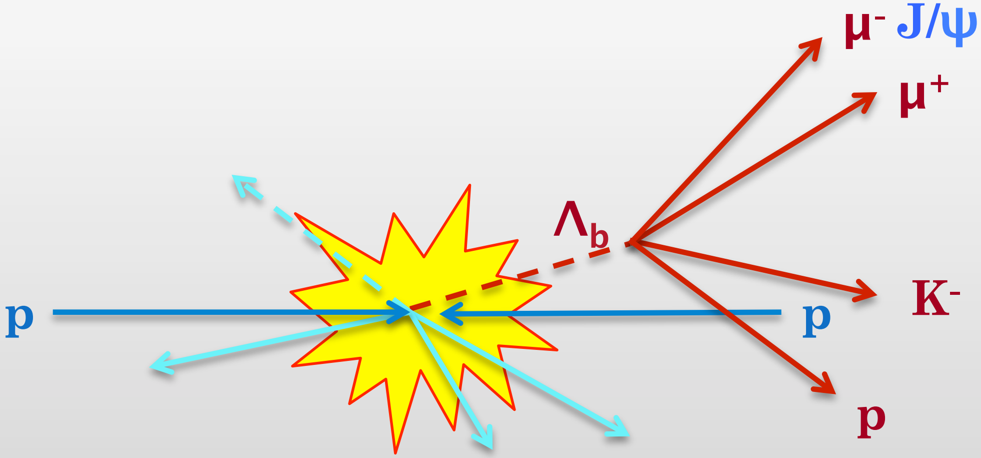
[LHCb: PRL 111 (2013) 102003]

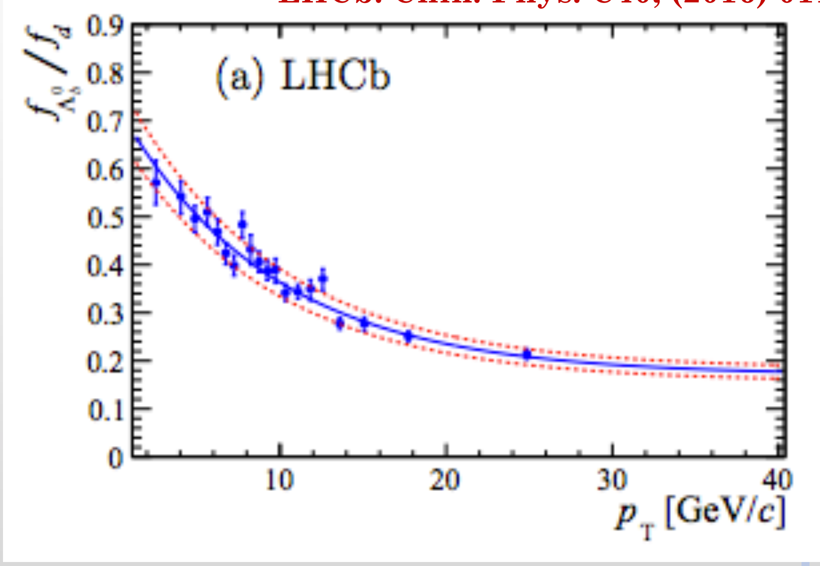
Why did LHCb arrive first? The decay was not observed before!

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

LHCb: JHEP 08(2014)143

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

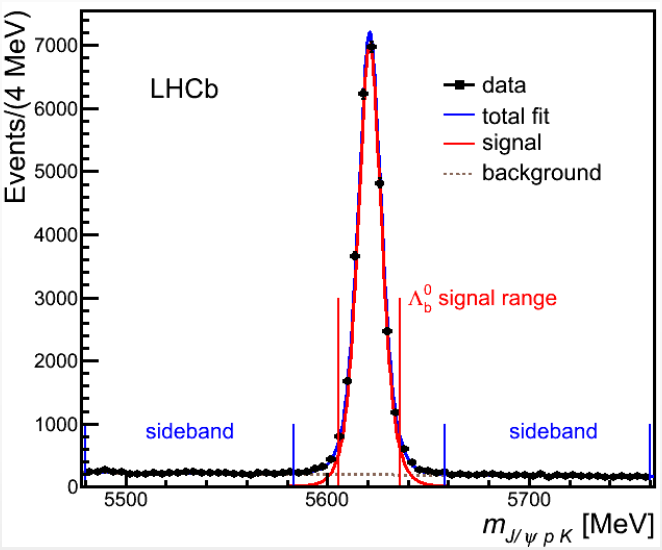


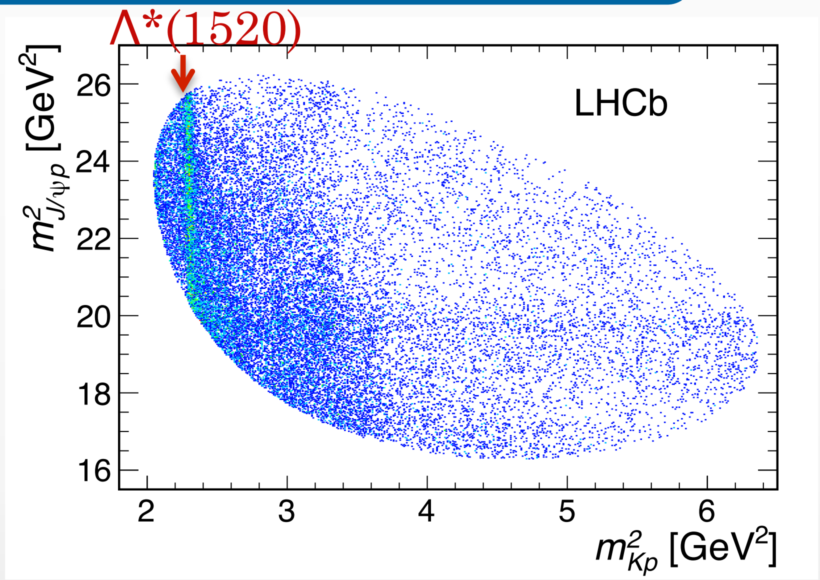


Observation of a Narrow Band in the Λ_b Dalitz plane

[LHCb: PRL 115, 072001 (2015)]

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





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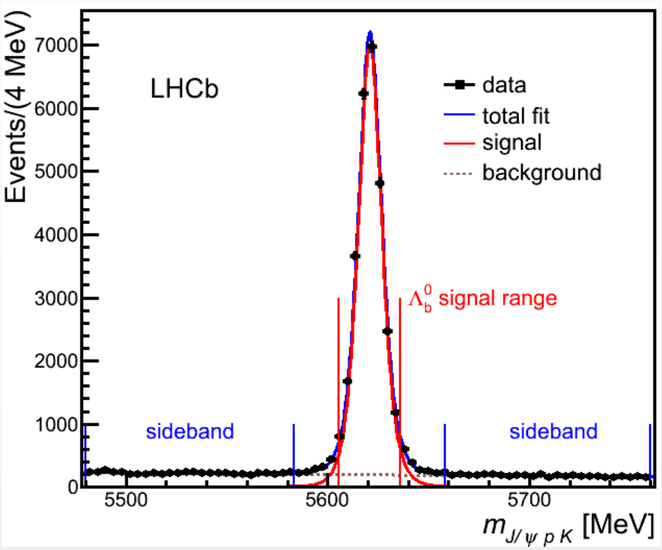
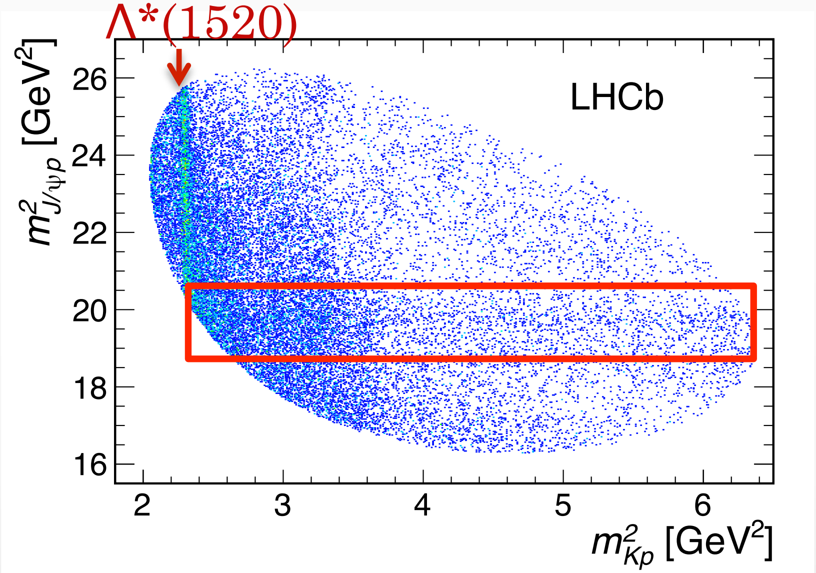
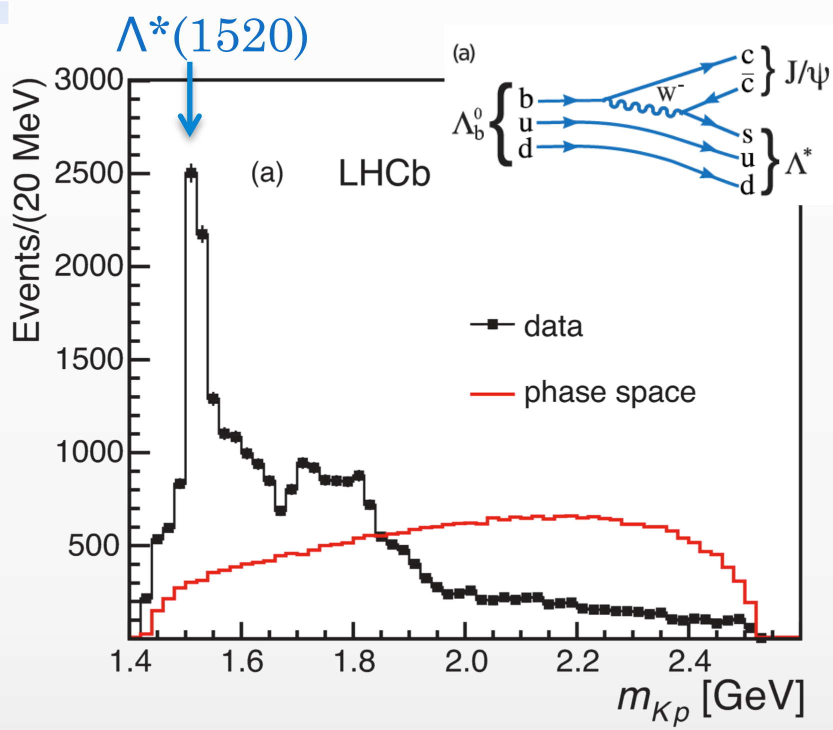


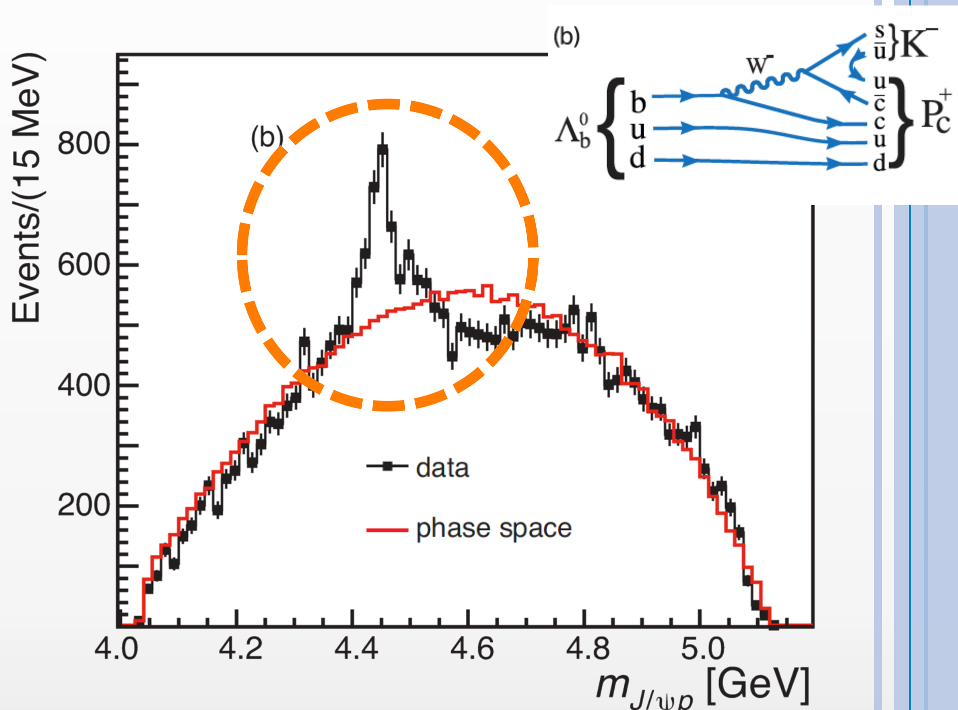


- Efficiency flat over the "Dalitz" plot
- Cross checks:
  - ✓ Veto $B_s \to J/\psi KK$ & $B^0 \to J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters: p ←→K or p ←→ π
  - ✓ Clone and ghost tracks carefully removed
  - ✓ Not a partially reconstructed Ξ_b decay

UNEXPECTED NARROW PEAK IN m(J/ψ p)

[LHCb: PRL 115, 072001 (2015)]



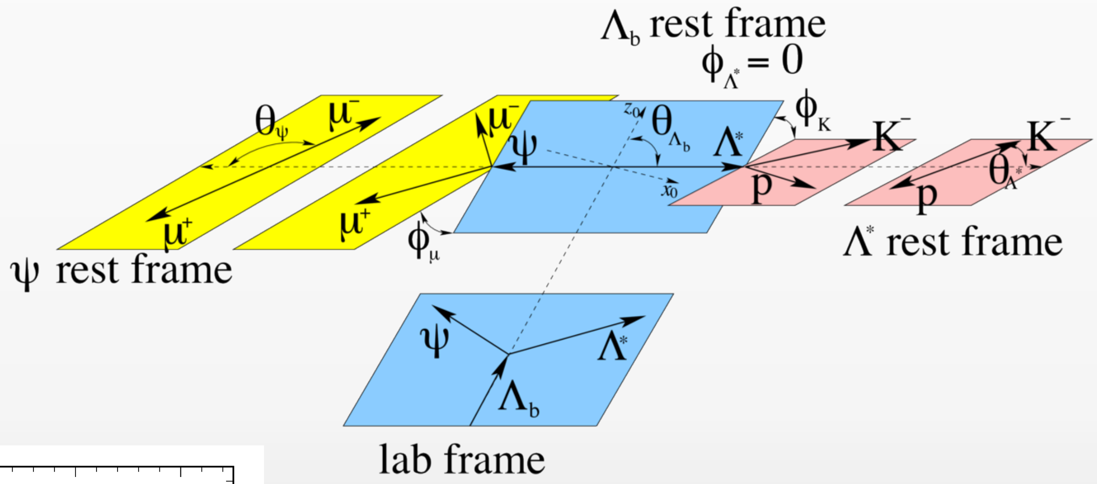


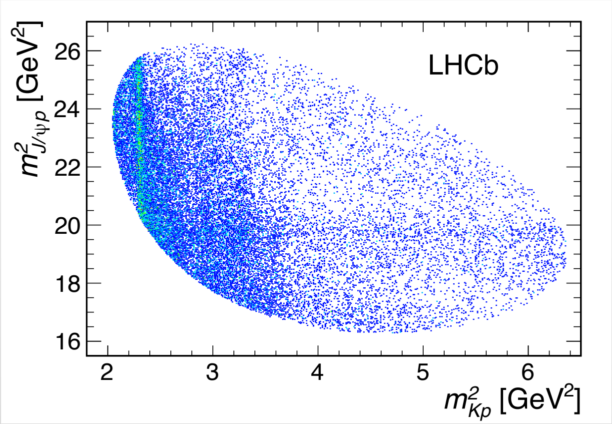
- A lot of structures in m(pK$^-$)!
- Could it be a reflection of the interfering Λ*'s→ pK$^-$?

Amplitude analysis

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

6D unbinned maximum likelihood fit (m_{Kp}, $\theta_{\Lambda b}$, θ_{Λ^*}, ϕ_K, θ_ψ, ϕ_μ)

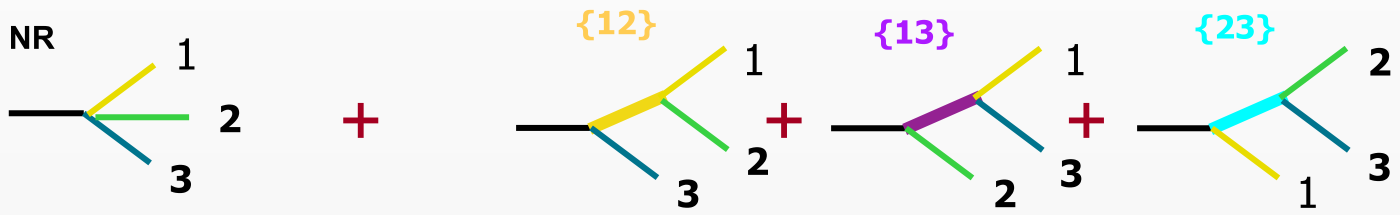




N.B. The "Dalitz" plot is itself a projection of a 6-D space

The Isobar Model

Isobar model: total decay amplitude as a coherent sum of processes where one daughter is spectator



Three-body amplitude for $\Lambda_b \to J/\psi\, p\, K$

Sum over all Λ^* resonances

P_c^+ components

$$|\mathcal{M}(\Phi)|^2 = \sum_{\lambda_{\Lambda_b}} \sum_{\lambda_p} \sum_{\Delta\lambda_u} \left| A^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_u}(m_{pK},\Omega) + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} A^{P_c}_{\lambda_{\Lambda_b},\lambda_p^{P_c},\Delta\lambda_u}(m_{J/\psi p},\Omega) \right|^2$$

Defined unless a phase and a constant

Rotation by α due to different helicity frame

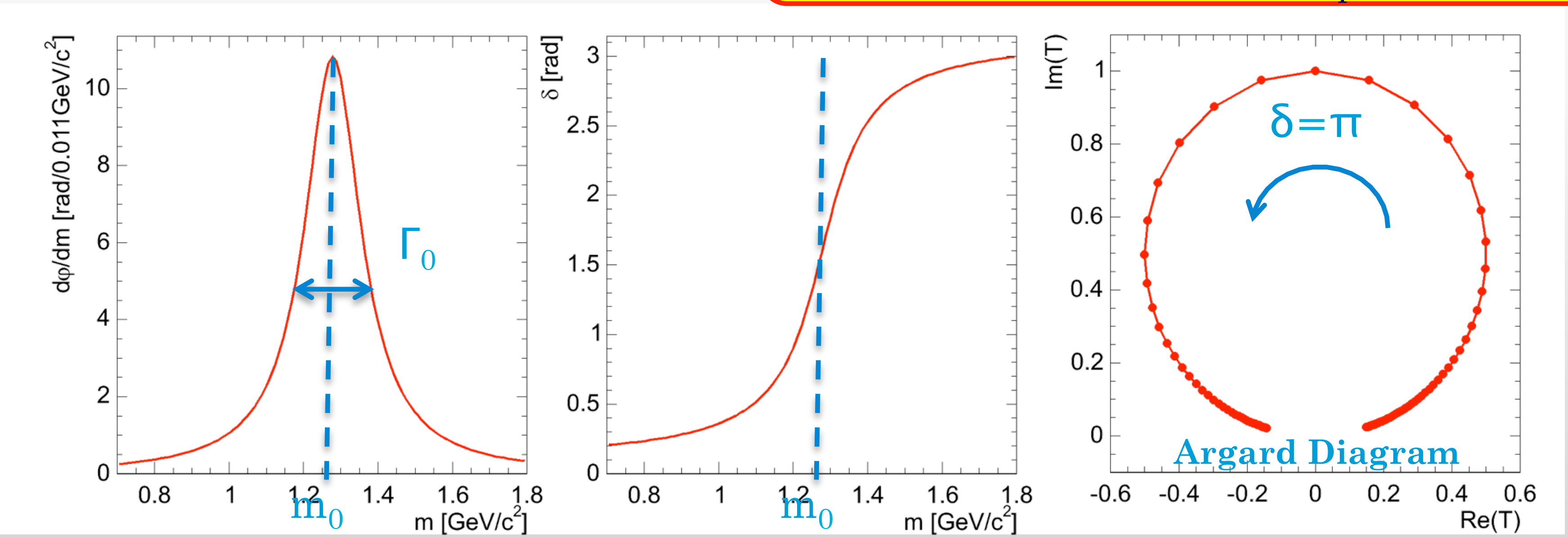
How to model a single term

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

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

Relativistic Breit-Wigner

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



Λ^* Decay Models

[LHCb: PRL 115, 072001 (2015)]

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

All known Λ^* states

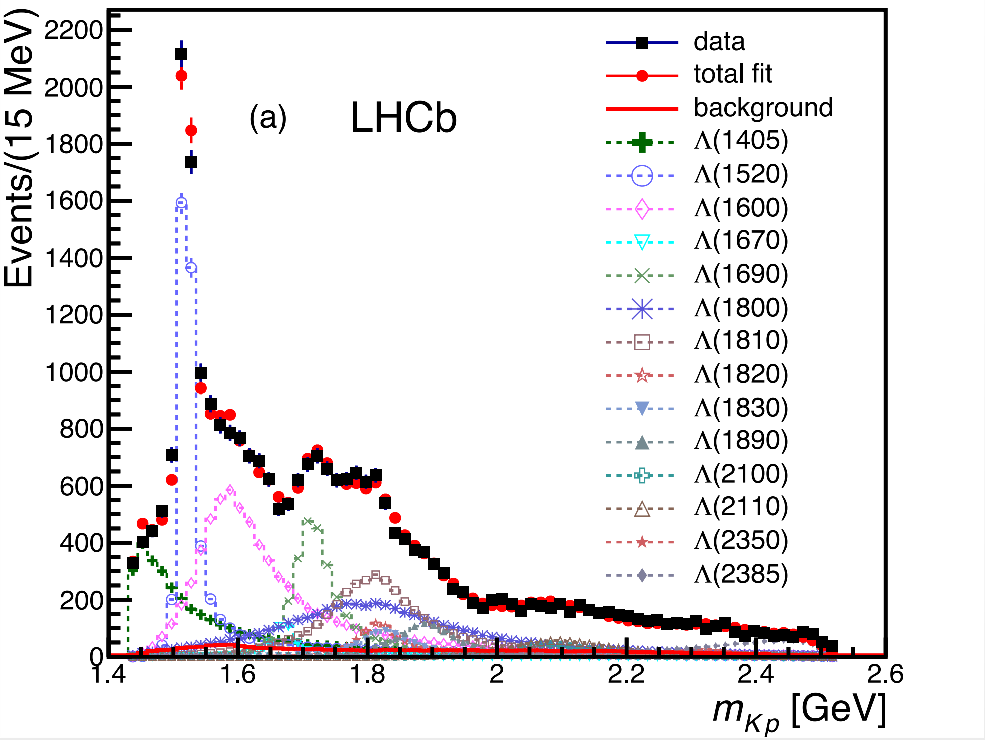
No high-J^P high-mass states, limited L

All states, all L

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 WITH $\Lambda^* \rightarrow pK$ STATES ONLY

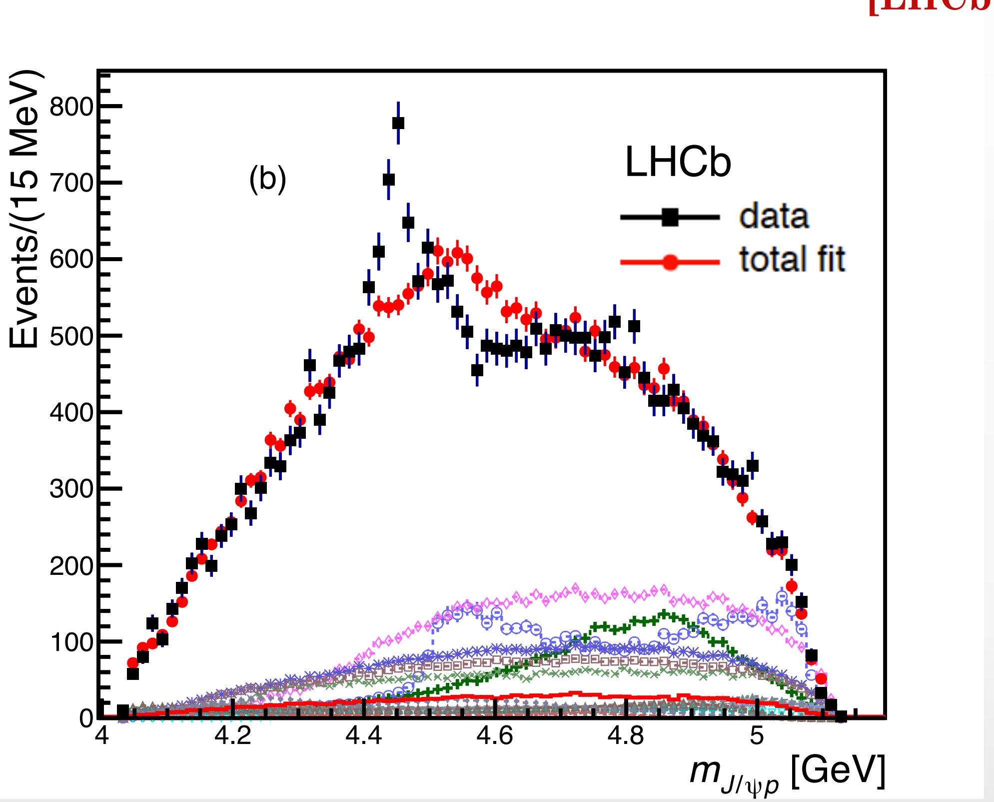
[LHCb: PRL 115, 072001 (2015)]



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, 072001 (2015)]

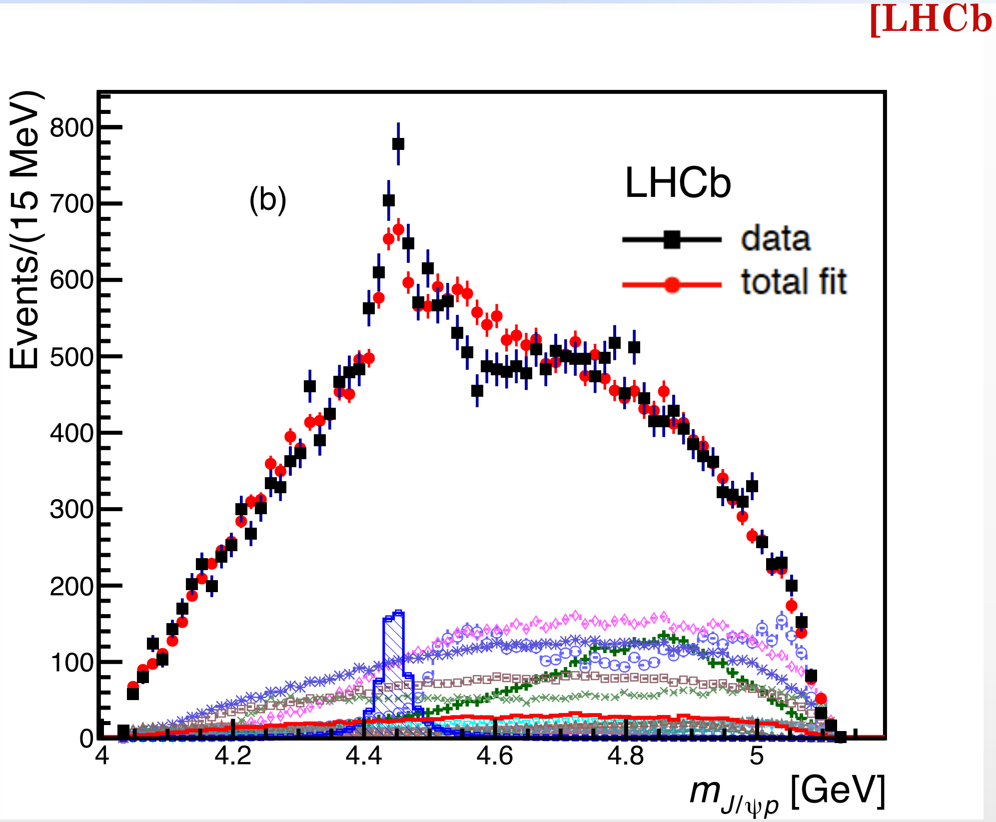


Extended Λ* model:

- …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, 072001 (2015)]

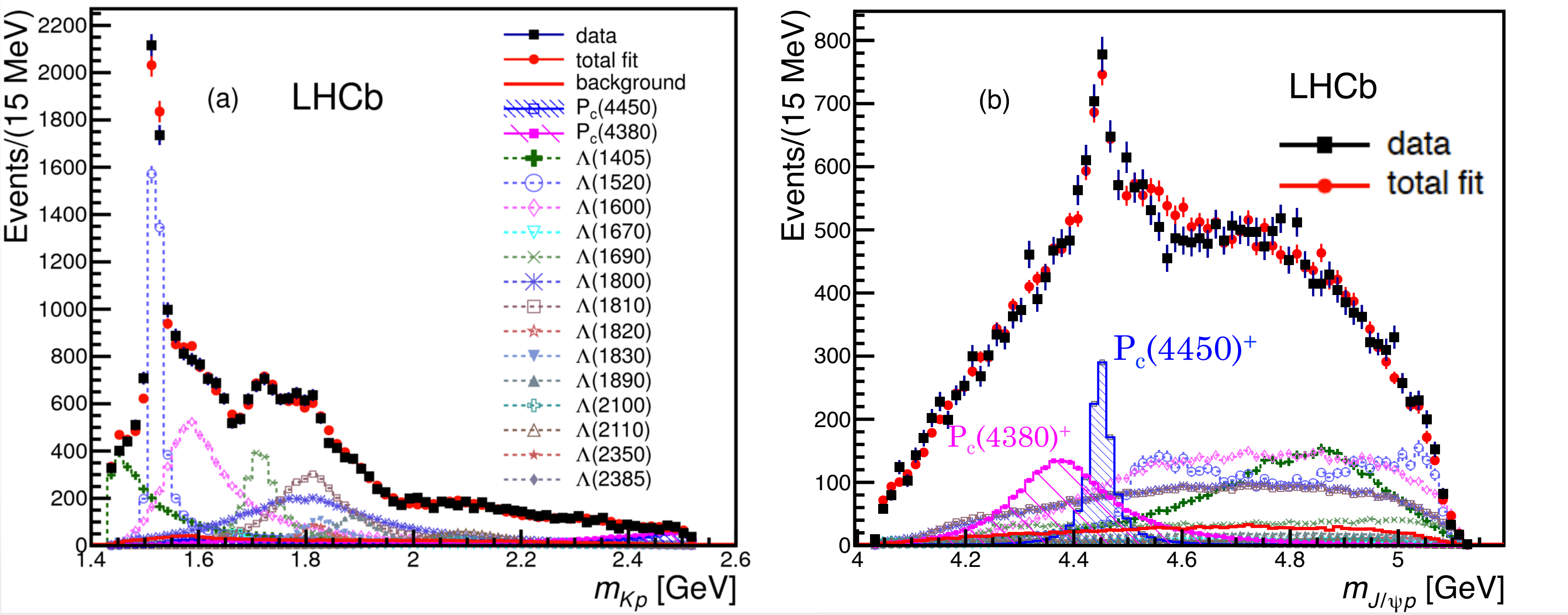


Extended Λ* model + 1 Pentaquark decaying to J/ψ p

- Try all J^P of P_c^+ up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

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

[LHCb: PRL 115, 072001 (2015)]

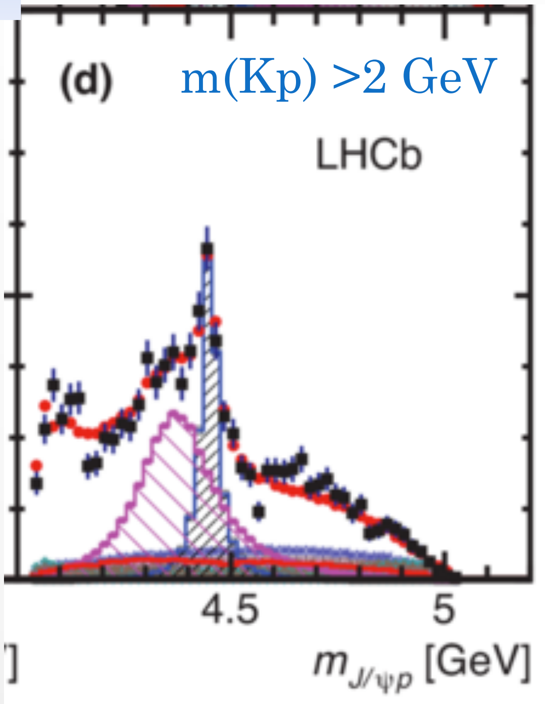


Reduced Λ* model + 2 Pentaquarks decaying to J/ψ p

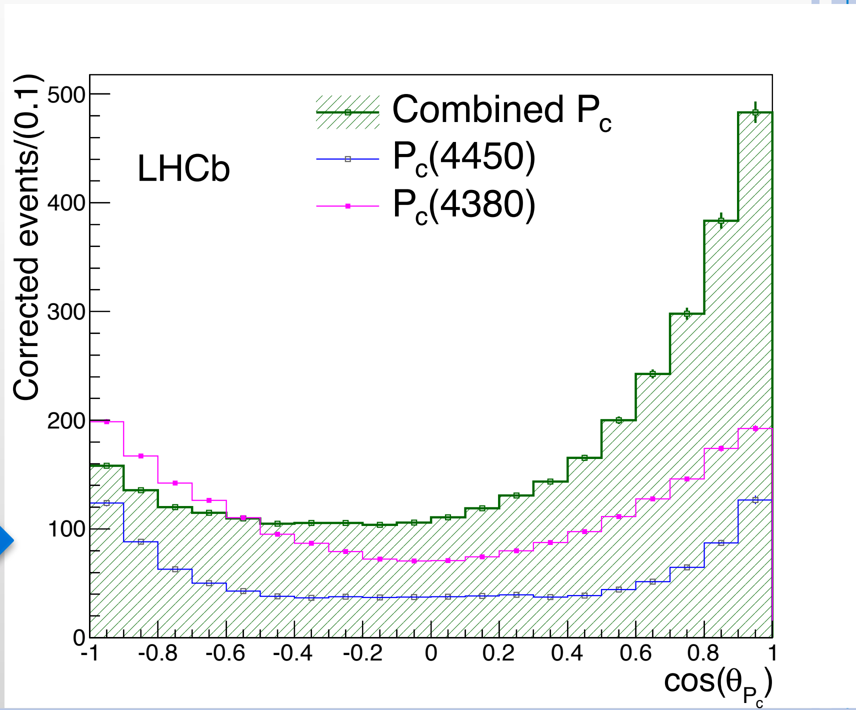
- Obtain good fits even with the reduced Λ* model
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred
- Adding more amplitudes doesn't improve the fit quality

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

[LHCb: PRL 115, 072001 (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

Significances and Results

[LHCb: PRL 115, 072001 (2015)]

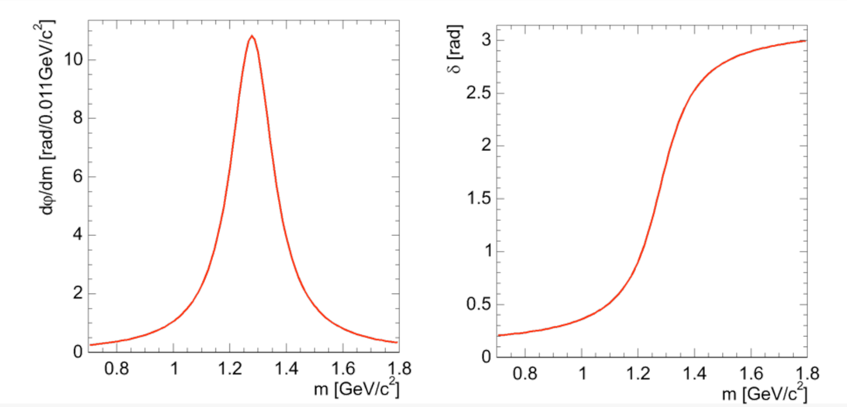
- Simulations of pseudo-experiments are used to quote the significances:
  - ✓ Significance of $P_c(4450)^+$ state is 12σ
  - ✓ Significance of $P_c(4380)^+$ state is 9σ
- Main systematic uncertainty: difference between extended and reduced fit models. Taken in account while computing the significances

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

PROBING THE RESONANT CHARACTER OF P_c^+

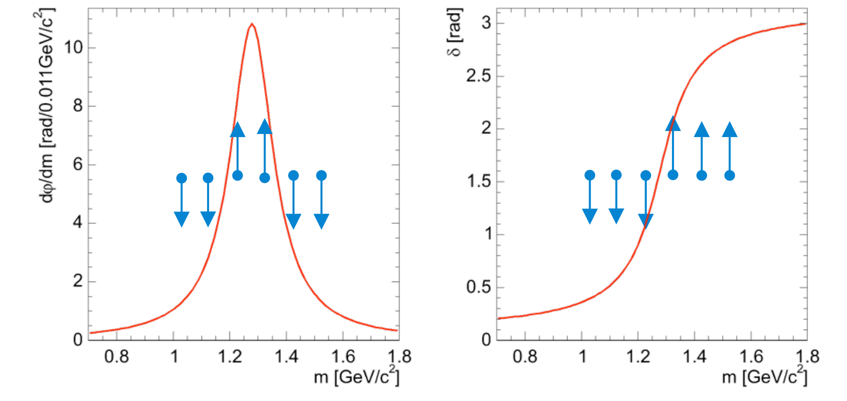
[LHCb: PRL 115, 072001 (2015)]

Nominal fit



4 free parameters:
m_0, Γ_0 + complex constant

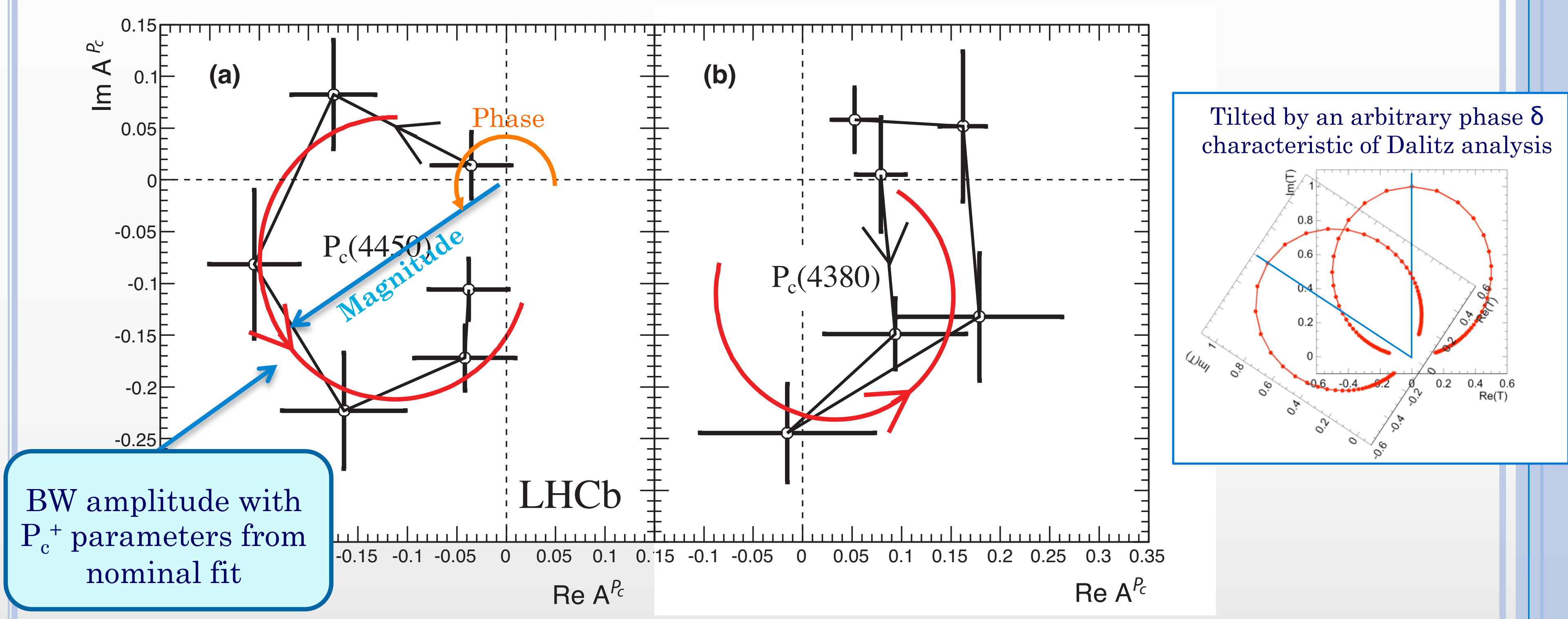
Alternative fit
Replace BW amplitude with 6 independent complex numbers in 6 bins of $m(J/\psi\, p)$ in region $m_0 \pm \Gamma_0$, where m_0 is the mass of P_c^+



12 free parameters

Argard Diagrams

[LHCb: PRL 115, 072001 (2015)]



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

[LHCb: PRL 117 (2016) 082003]

MODEL INDEPENDENT ANALYSIS

[LHCb: PRL 117 (2016) 082003]

- Amplitude analyses are powerful tools but they are intrinsically model dependent:
  - How many Λ^* should be taken in account? How to deal with unknown/not observed states predicted by the quark model?
  - Not trivial to model NR components. Any mass dependence?
  - Possible 3-body contribution?
  - Isobar model has well known limitation: unitarity violation when adding broad overlapping states. K-matrix formalism? How to deal with the couplings to the exotic sector?

While studying the Z(4430) state, the BaBar collaboration developed a model-independent approach

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

Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

H1: If no exotics in J/ψ K and J/ψ p

$(m_{pK}, \theta_{\Lambda b}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu) \rightarrow (m_{pK}, \theta_{\Lambda^*})$

Decompose angular distribution into Legendre moments

Legendre Polynomials

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0 \rangle P_0 + \langle P_1 \rangle P_1 + \langle P_2 \rangle P_2 + \langle P_3 \rangle P_3 + \langle P_4 \rangle P_4 + \langle P_5 \rangle P_5 + \langle P_6 \rangle P_6 + \ldots$$

where the moments $\langle P_l \rangle$ determined from data: $\langle P_l \rangle = \sum_{i=1}^{N_{data}} \frac{1}{\epsilon_i} P_l(\cos\theta^i_{K^*})$

Recombine the "meaningful" moments up to a certain order

(driven by physics arguments)

Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

H2: (e.g.) If only Λ* resonances up to J = 3/2

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0 \rangle P_0 + \langle P_1 \rangle P_1 + \langle P_2 \rangle P_2 + \langle P_3 \rangle P_3 + \langle P_4 \rangle P_4 + \langle P_5 \rangle P_5 + \langle P_6 \rangle P_6 + \ldots$$

Sum of the terms up to $P_{N_{max}}$, where N_{max} = 2*J(Λ*), has to describe the data projections

Should it not happen →

There are Λ* resonances with J > 3/2

or

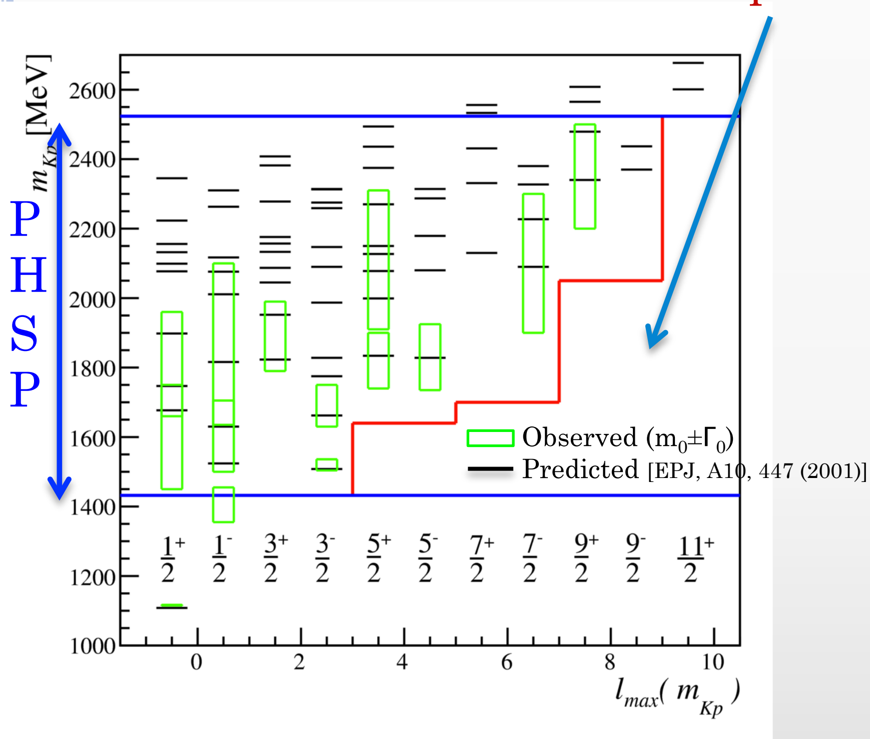
There are exotic(s) which make the high order terms non-zero!

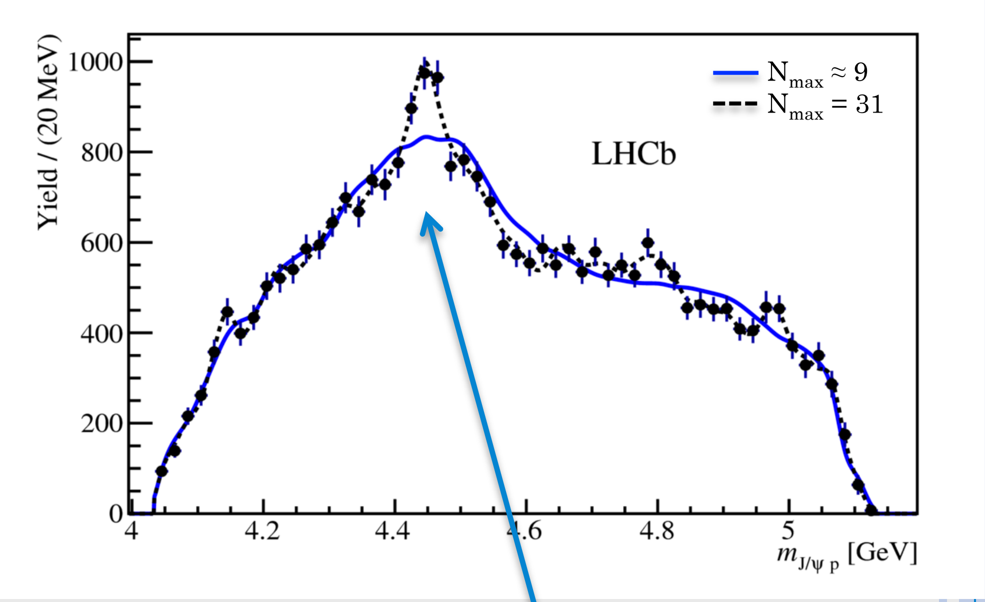
Qualitative Results from Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

$\Lambda^* \equiv$ excited Λ, excited Σ, NR

No Λ^* expected here





How much significant is the discrepancy after taking in account the statistical uncertainties?

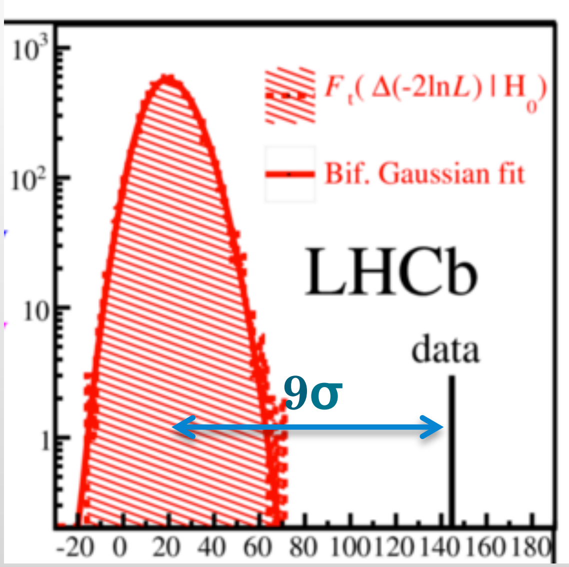
Quantitative Results from Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

Test significance of implausible $N_{max} < N < 31$ moments using the log-likelihood ratio:

$$\Delta(-2\mathrm{NLL}) = -2\ln\frac{\mathcal{L}_{\mathrm{N_{max}}}}{\mathcal{L}_{31}} = -2\ln\frac{\prod_i \mathcal{F}_{\mathrm{N_{max}}}(m^i_{\psi'\pi})}{\prod_i \mathcal{F}_{31}(m^i_{\psi'\pi})}$$

Statistical simulations of pseudo-experiments generated from the $N < N_{max}$ hypotheses



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

Evidence for the Exotic Hadron Contributions to $\Lambda_b \rightarrow J/\psi\, p\, \pi^-$ decays

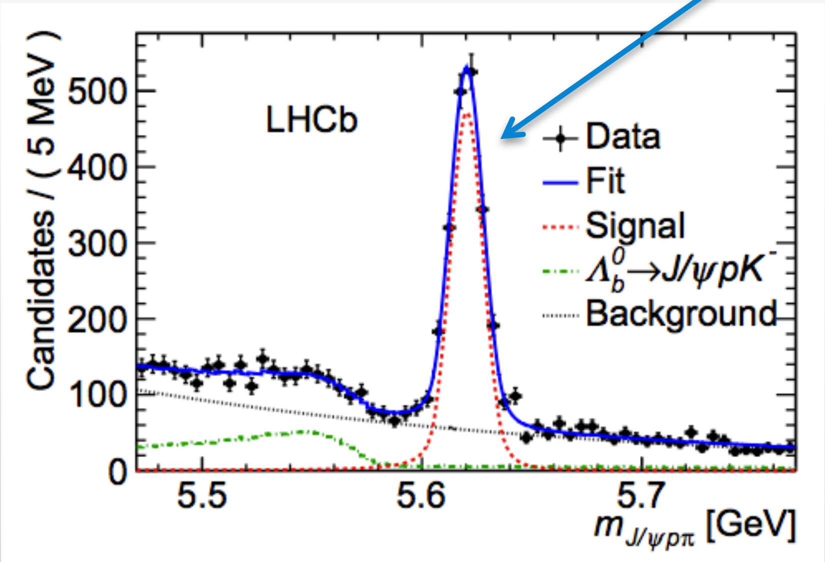
[LHCb: PRL 117 (2016) 082002]

How to Investigate the P_c^+ States Further?

[LHCb: PRL 117 (2016) 082002]

The confirmation of a new state passes through:

- Observation of a different decay:
  - $P_c^+ \rightarrow \chi_{c1}$ p (neutrals are involved)
  - $P_c^+ \rightarrow \Lambda_c$ D (long-lived hadrons → low efficiency, small BR's)
- Observation in a different environment:
  - Prompt production pp → P_c^+ + X (large track multiplicity at LHC)
  - $\Lambda_b \rightarrow J/\psi\ p\ \pi^-$: Cabibbo suppressed but feasible



Dataset: 3 fb^{-1}

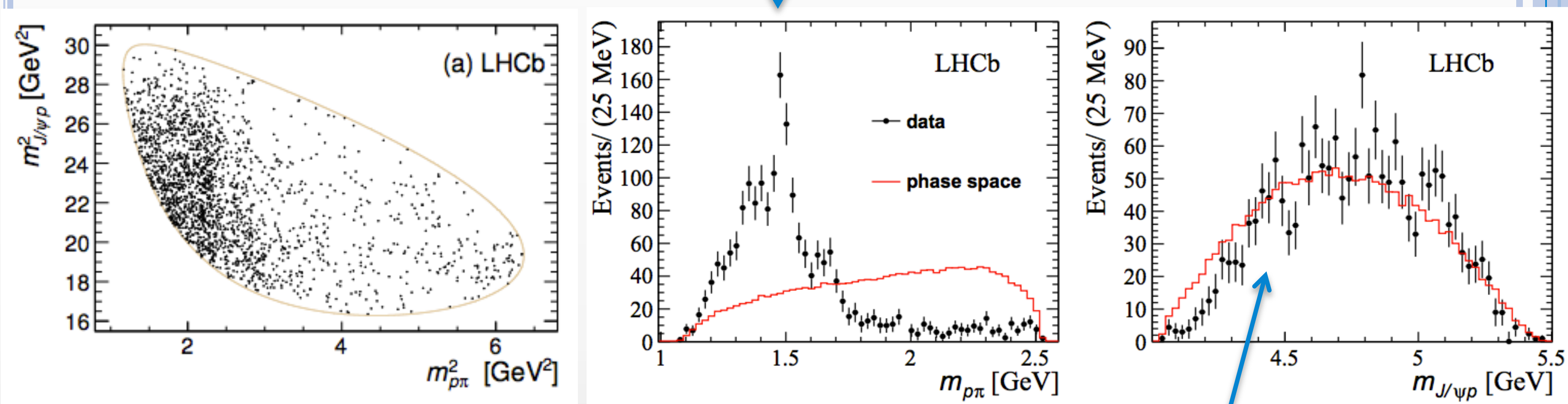
N_{events} = 1885 ± 50 (10x smaller than $\Lambda_b \rightarrow J/\psi$ p K)

Background ~ 20% (3x larger than $\Lambda_b \rightarrow J/\psi$ p K)

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

[LHCb: PRL 117 (2016) 082002]

N(1535)



No peaking structure in J/ψ p but P_c^+ 's could be still there

Amplitude Analysis

Amplitude Analysis of $\Lambda_B \rightarrow J/\psi\ p\ \pi^-$ Decay
Fit Model

[LHCb: PRL 117 (2016) 082002]

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

$N^* \rightarrow p\ \pi$

- Reduced model (RM) for central values, extended (EM) for systematics and significances
- Neglecting higher orbital angular momenta for most of the N* states

$P_c^+ \rightarrow J/\psi\ p$

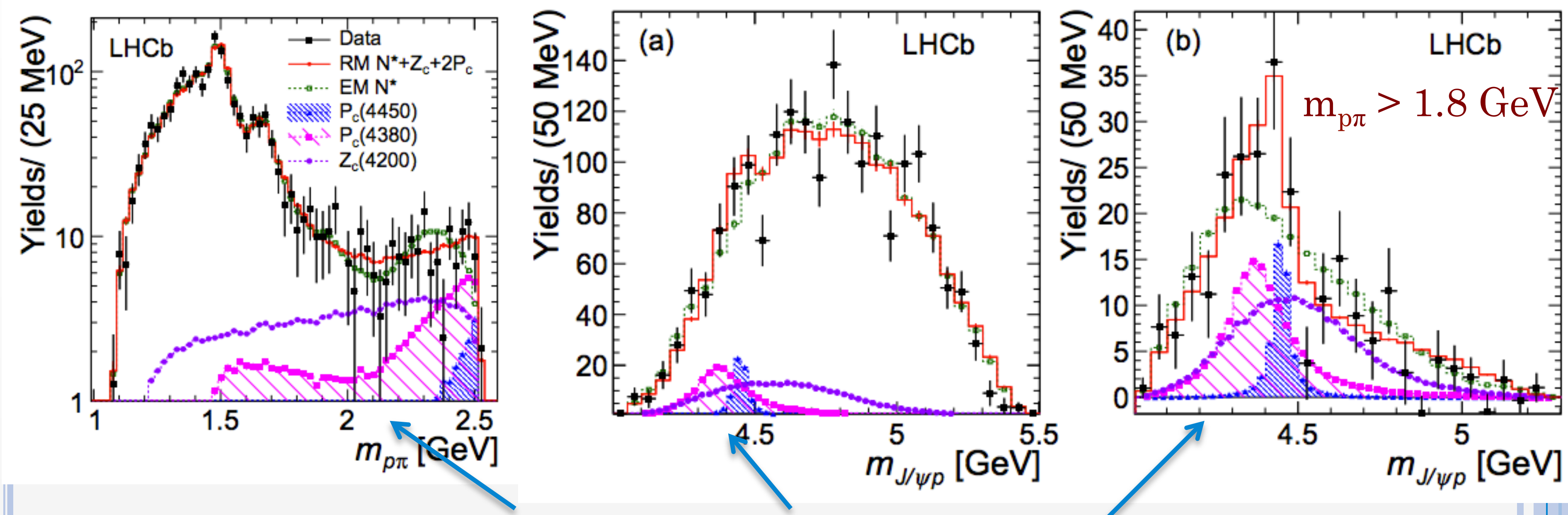
- Masses, widths and $J^P = (3/2^-, 5/2^+)$ fixed. Not possible to float them with the current statistic

$Z_c(4420)^+ \rightarrow J/\psi\ \pi$

- Observed by Belle [PRD, 90, 112009]
- Mass, width and $J^P = 1^+$ fixed

Amplitude Analysis of $\Lambda_B \rightarrow J/\psi\ p\ \pi^-$ Decay
Fit Results

[LHCb: PRL 117 (2016) 082002]



$P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ overlap each other

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ (including systematic uncertainty) → Evidence for exotic hadrons.
- Individual exotic hadron contributions are not significant.
- Fit fractions consistent with what expected for the Cabibbo suppressed decay

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

(Inclusive Analysis)

[Phys. Rev. Lett. 117 (2016) 152003]

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

[DØ: PRL 117 (2016) 022003]

Claimed observation/evidence of an exotic state ($\bar{b}s\bar{u}d$)

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

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

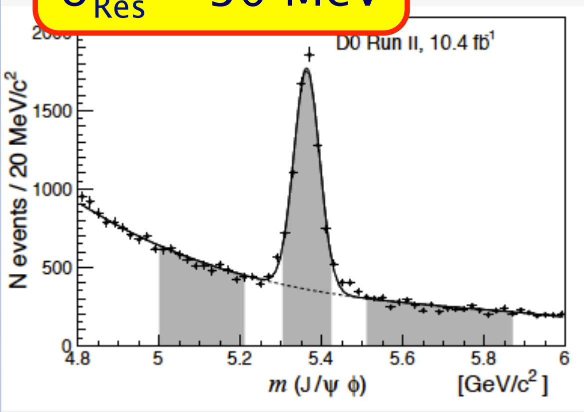
N.B. $m(\Xi_b) \sim 5790$ MeV

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

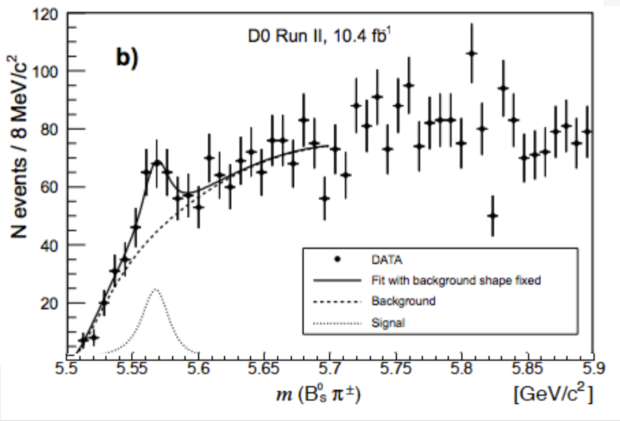
✓ Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)\ \%$

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

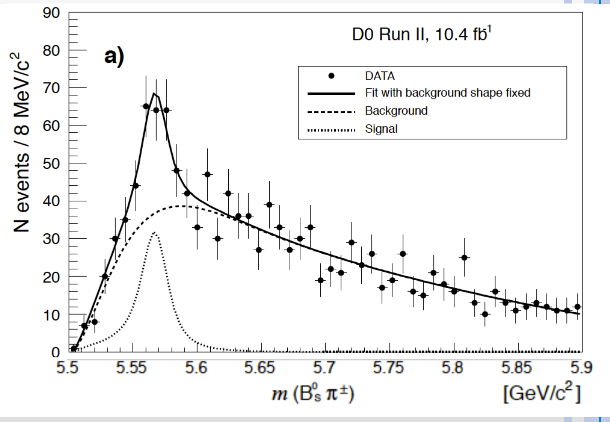
$N(B_s) \sim 5500$
$\sigma_{Res} \sim 30$ MeV



$N(X) = 106 \pm 23$



$N(X) = 133 \pm 31$



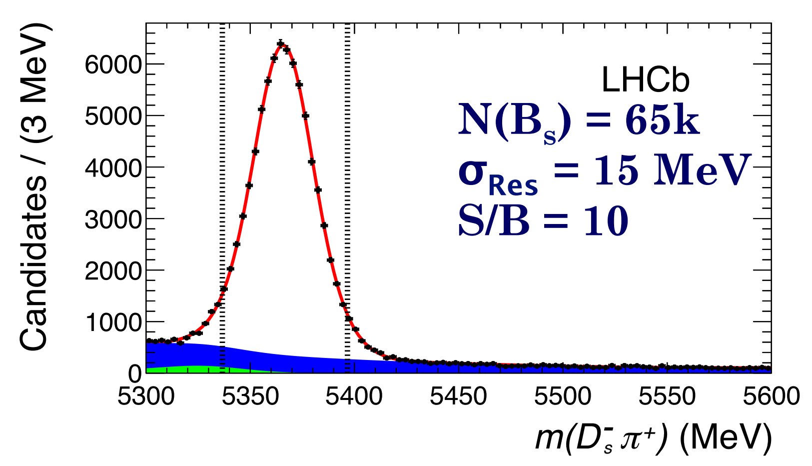
$3.9\,\sigma$ $5.1\,\sigma$

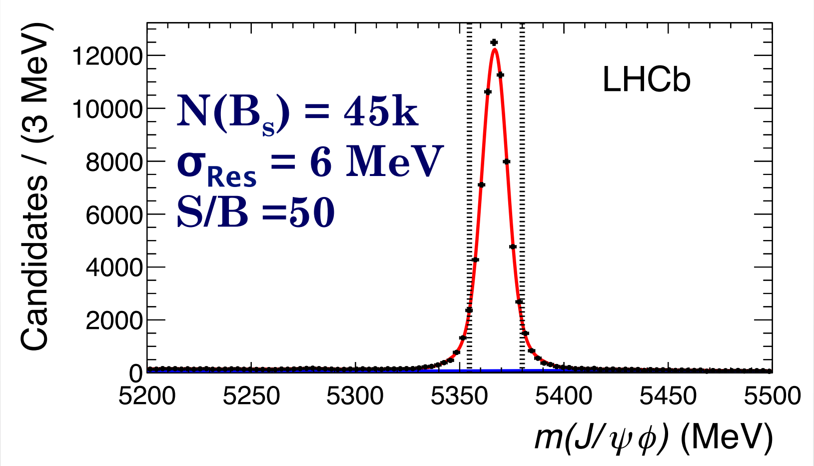
Signal significance

B_s SELECTION

[Phys. Rev. Lett. 117 (2016) 152003]

- 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:
    $B^{**} \to B\pi$ and $B_s^{**} \to BK$
  - ✓ $p_T(\pi) > 500$ 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



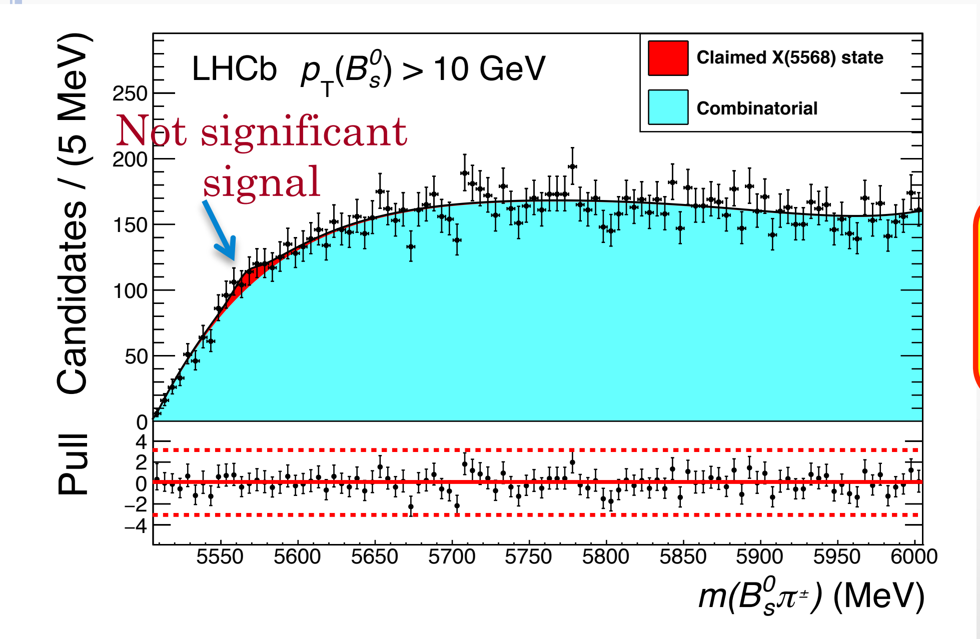


B_s sample 20x larger and much cleaner than DØ

Fit Result

[Phys. Rev. Lett. 117 (2016) 152003]

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



$$\rho_X^{\text{LHCb}}(B_s^0\ p_T > 5\ \text{GeV}/c) < 0.011\,(0.012)\ @\ 90\,(95)\,\%\ \text{CL}$$
$$\rho_X^{\text{LHCb}}(B_s^0\ p_T > 10\ \text{GeV}/c) < 0.021\,(0.024)\ @\ 90\,(95)\,\%\ \text{CL}$$
$$\rho_X^{\text{LHCb}}(B_s^0\ p_T > 15\ \text{GeV}/c) < 0.018\,(0.020)\ @\ 90\,(95)\,\%\ \text{CL}$$

Limits are also set as function of mass (up to 6 GeV) and width (up to 50 MeV)

JUST FOR CURIOSITY…

[Phys. Rev. Lett. 117 (2016) 152003]

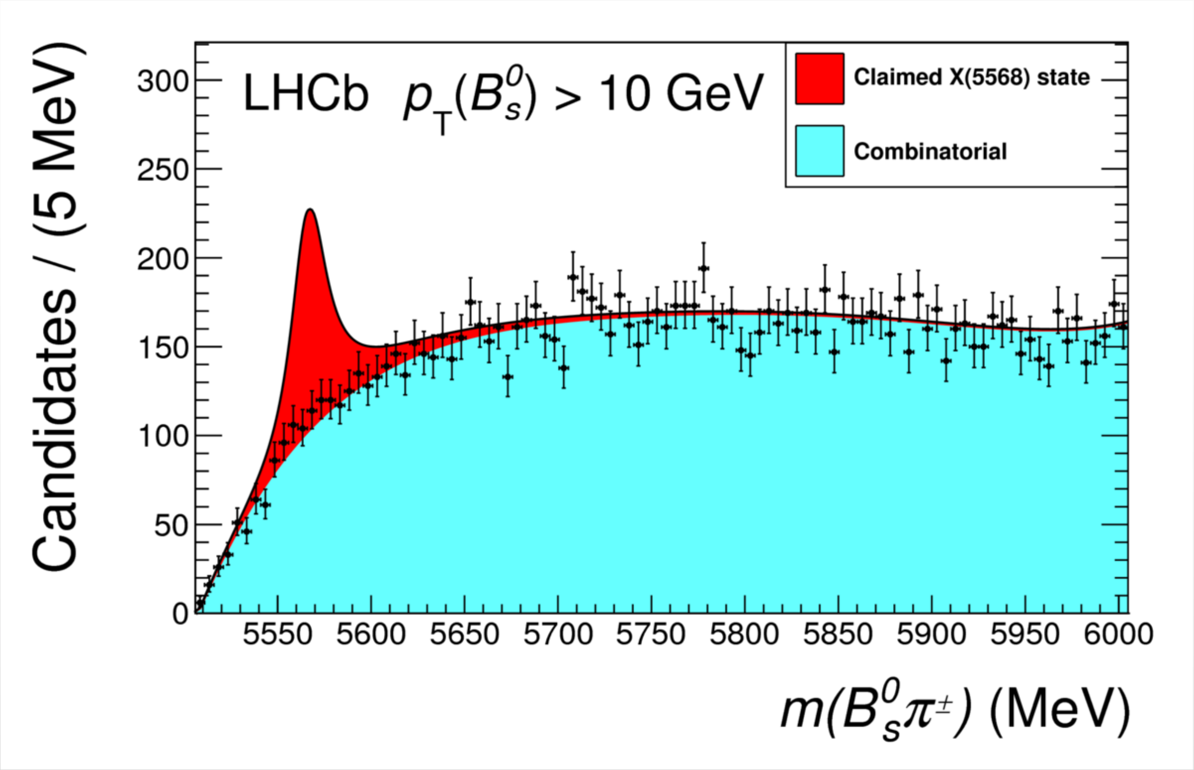
If $\rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D\emptyset}} = 8.6\%$, how would the X(5568) signal look like?

Just for curiosity…

[Phys. Rev. Lett. 117 (2016) 152003]

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

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

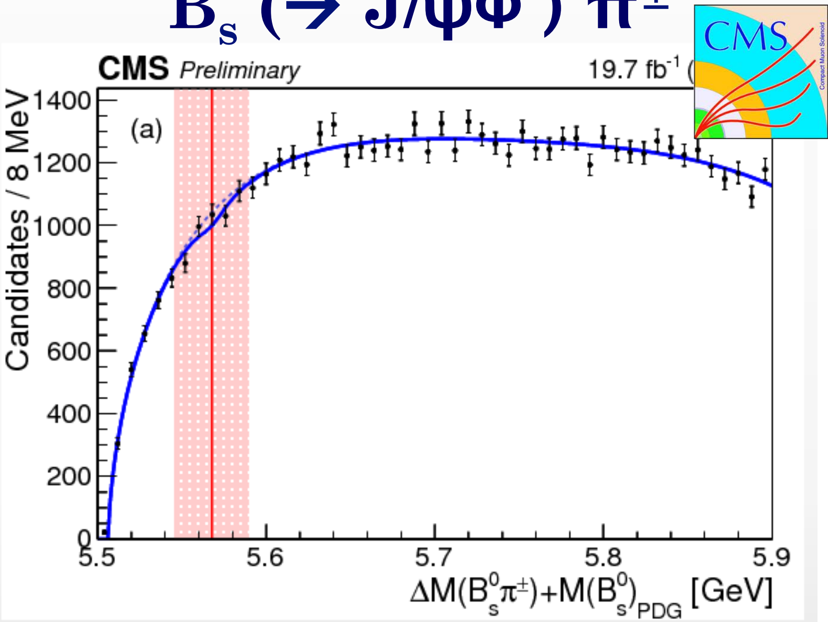


NEW RESULTS @ ICHEP

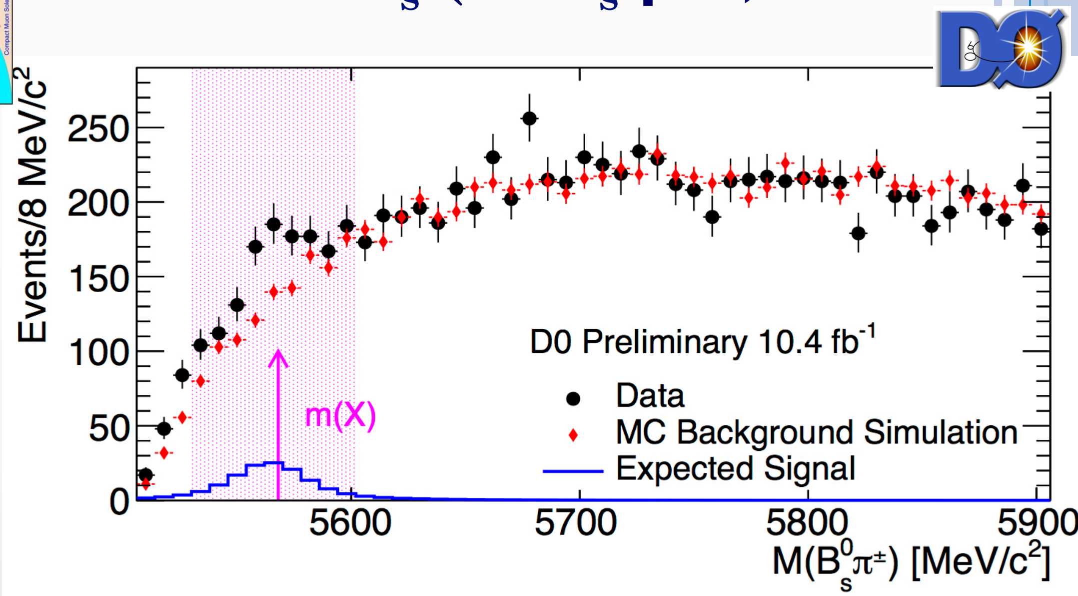
CMS-PAS-BPH-16-002

DØ Note 6488-CONF

B_s (→ J/ψΦ) $\pi^{\pm}$



B_s (→ D_s μ υ) $\pi^{\pm}$



$\rho_X < 3.9\%$ @95% C.L.

Amplitude analysis of $B^+ \rightarrow J/\psi\ \phi\ K^+$ decays

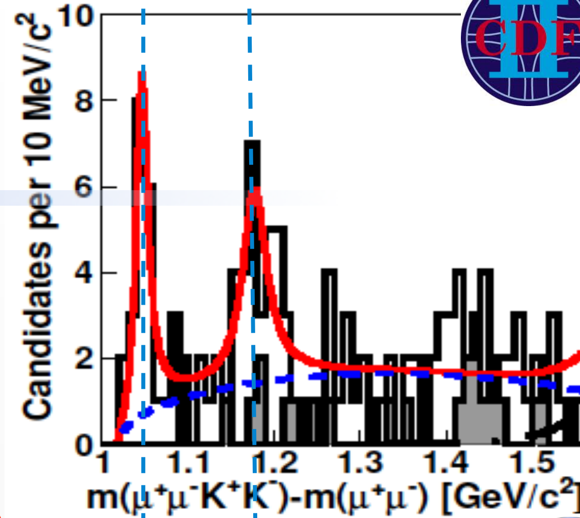
[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

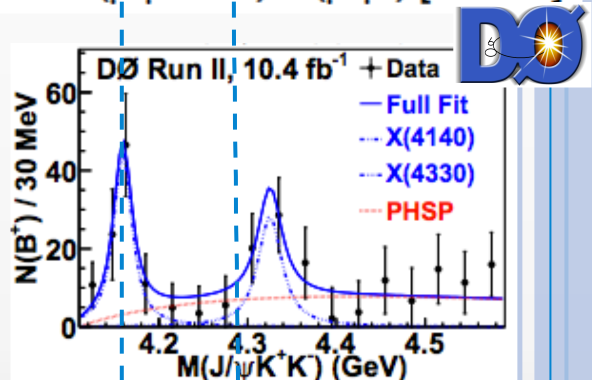
X(4140): A BIT OF HISTORY

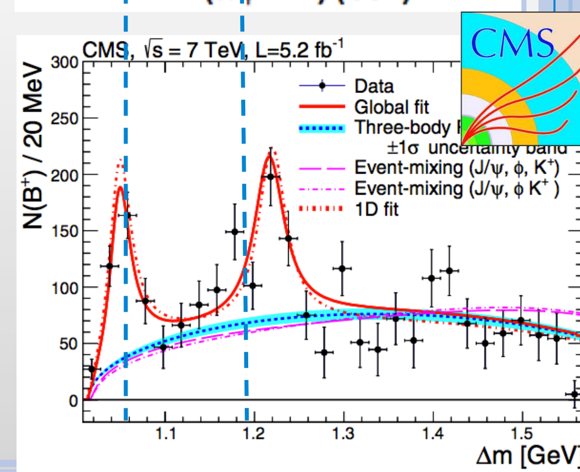
CDF: Evidence/“Observation” in $B^+ \rightarrow J/\psi\ \phi\ K^+$
[PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)	**X(4274)**
$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV	$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ 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)]**
- DØ: “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)]**
- DØ: Evidence of X(4140) in prompt production **[PRL 115, 232001 (2015)]**



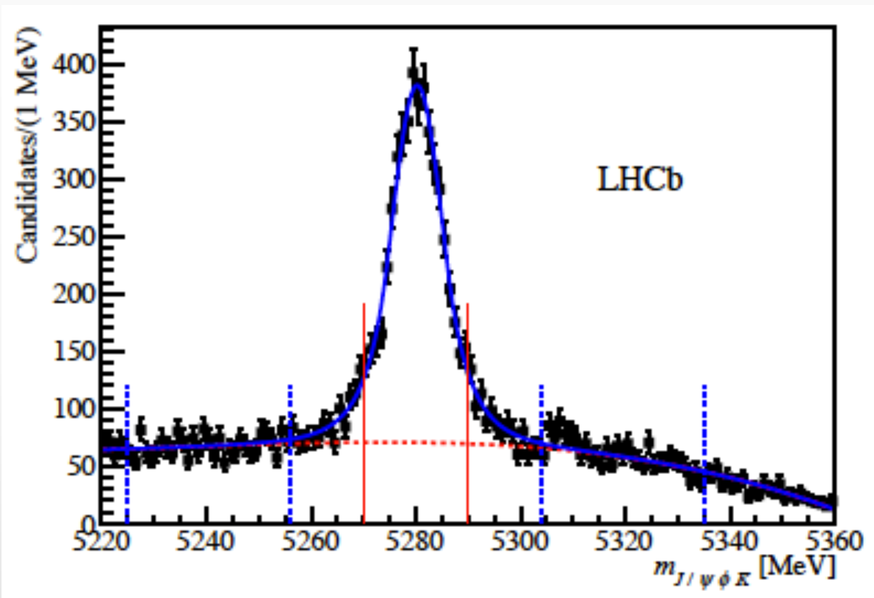


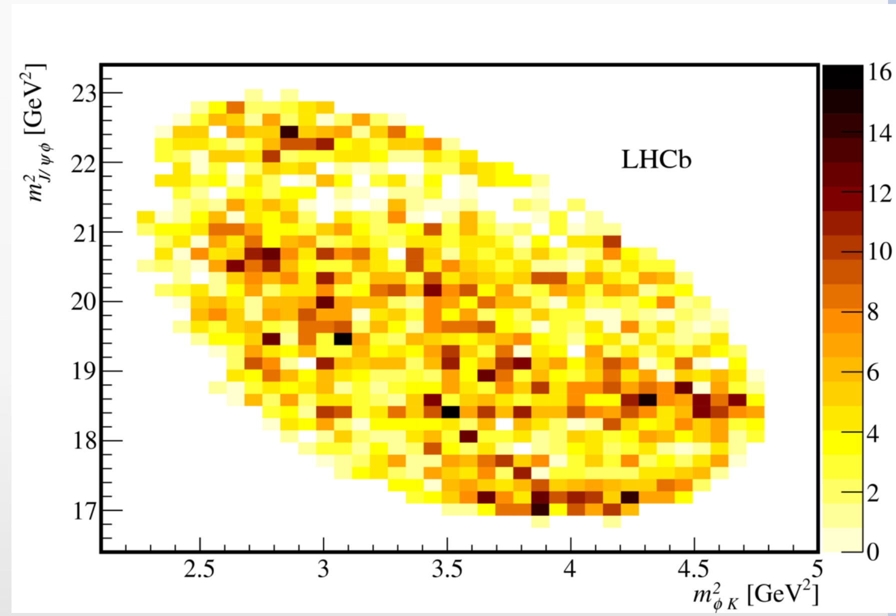


THE $B^+ \rightarrow J/\psi\ \phi\ K^+$ SAMPLE

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

Run I data (3 fb^{-1})
N_{Events} = 4289 ± 151
Background ~ 20%

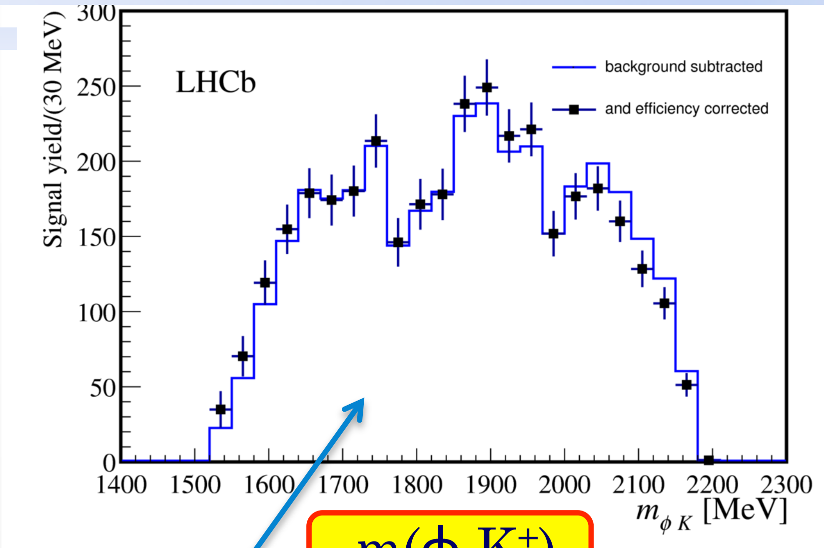




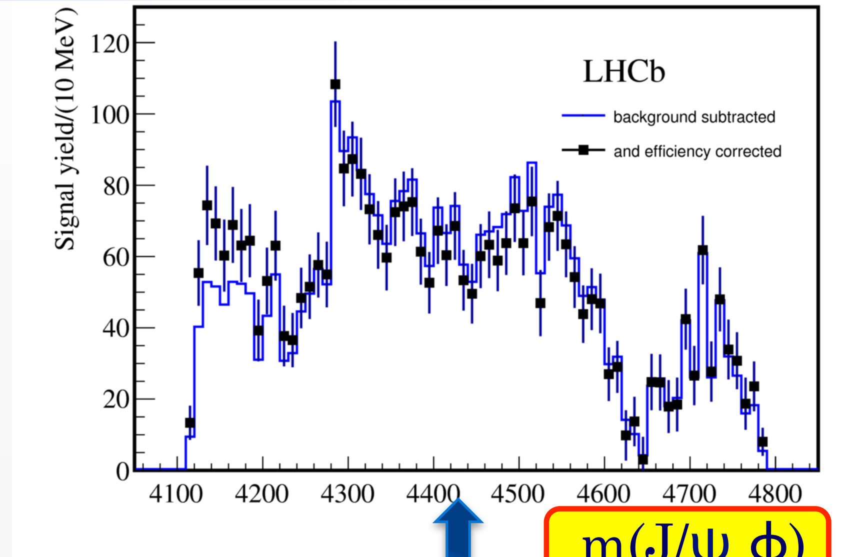
Statistically, the most powerful $B^+ \rightarrow J/\psi\ \phi\ K$ sample analyzed so far
First 6D amplitude analysis

Mass Projections

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

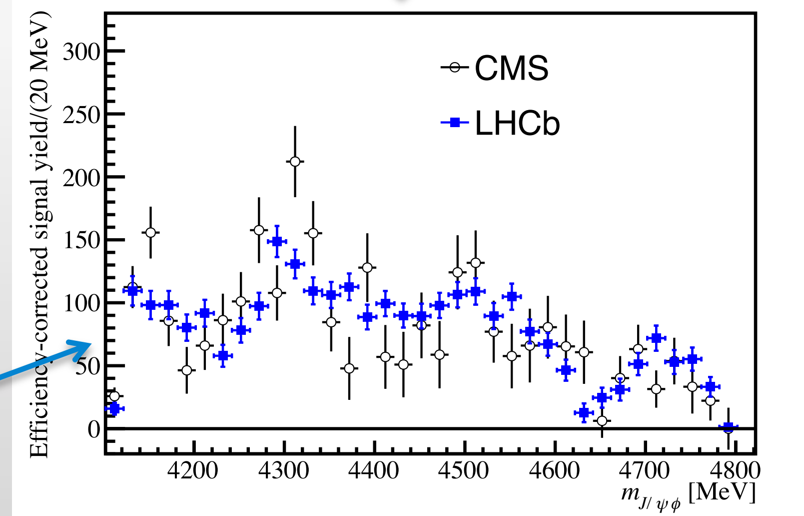


$m(\phi\ K^{+})$



$m(J/\psi\ \phi)$

Smooth plot without any sharp structure but K* ‘s in such mass region have widths 150 < Γ < 400 MeV



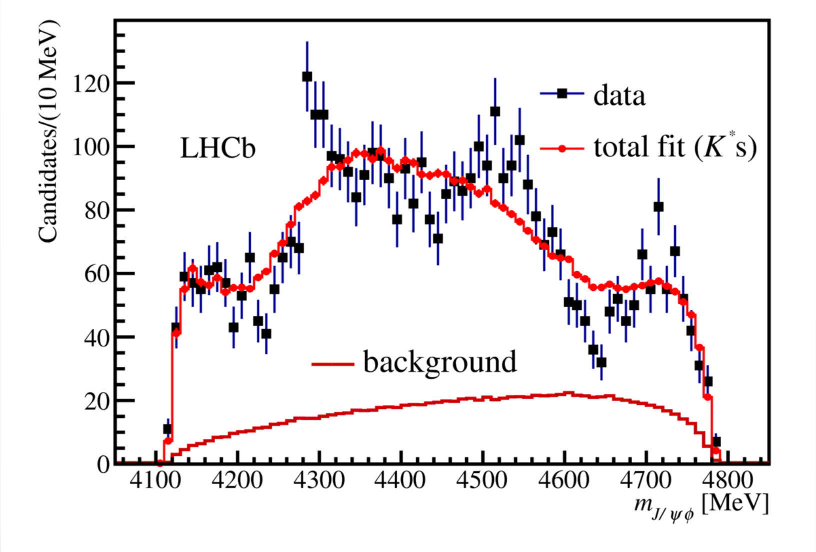
Qualitative agreement over the full mass range

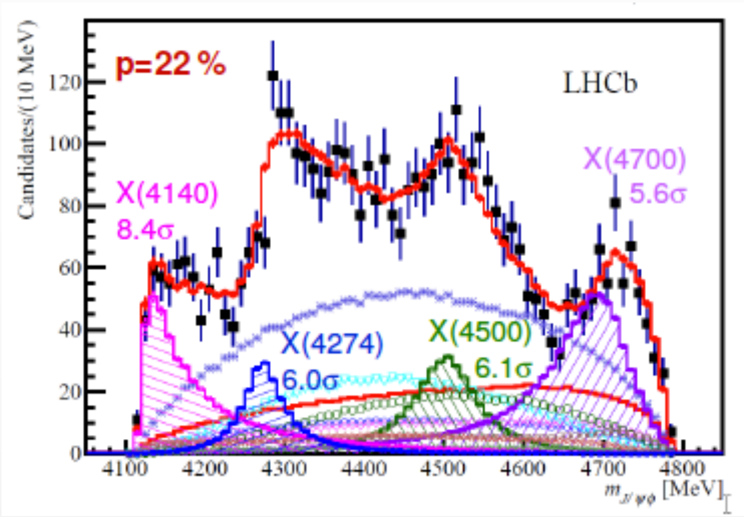
FIT RESULTS

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

Fit with K* only

Fit with K* + 4 X's!





	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	$4146.5 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$
$X(4274)$	$4273.3 \pm 8.3\,^{+17.2}_{-\ \ 3.6}$	$56 \pm 11\,^{+\ \ 8}_{-11}$
$X(4500)$	$4506 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$
$X(4700)$	$4704 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$

X(4140) ($J^{PC} = 1^{++}$)
- Mass consistent with the previous measurements but <u>the width substantially larger</u>

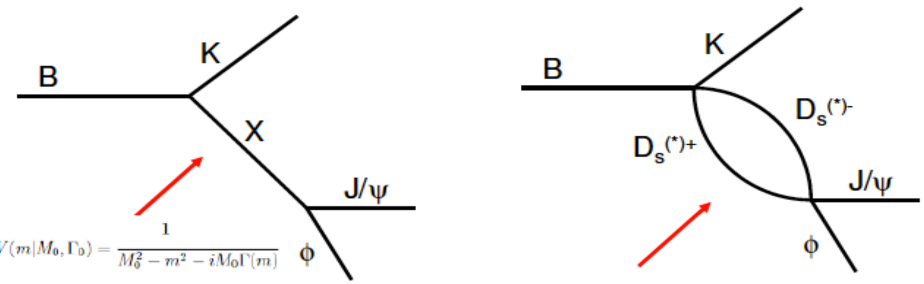
X(4274) ($J^{PC} = 1^{++}$)
- Consistent with the unpublished CDF results.

Two new states : **X(4500)** and **X(4700)** with ($J^{PC} = 0^{++}$)

EXOTIC STATES AS CUSPS?

X(4140)

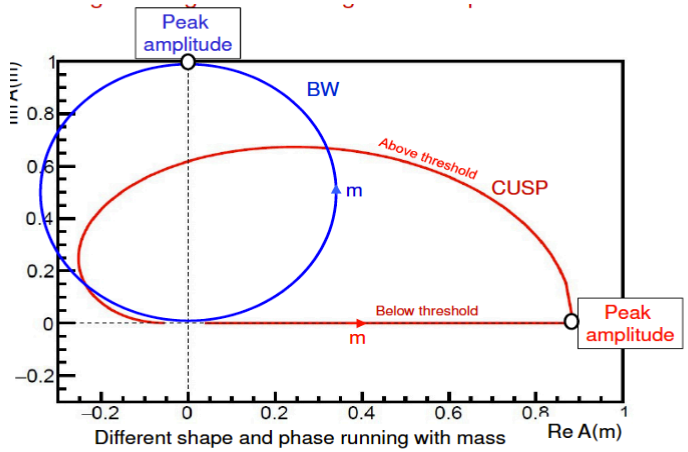
The cusp is preferred over the Breit-Wigner amplitude for X(4140) from the fit likelihood ratio



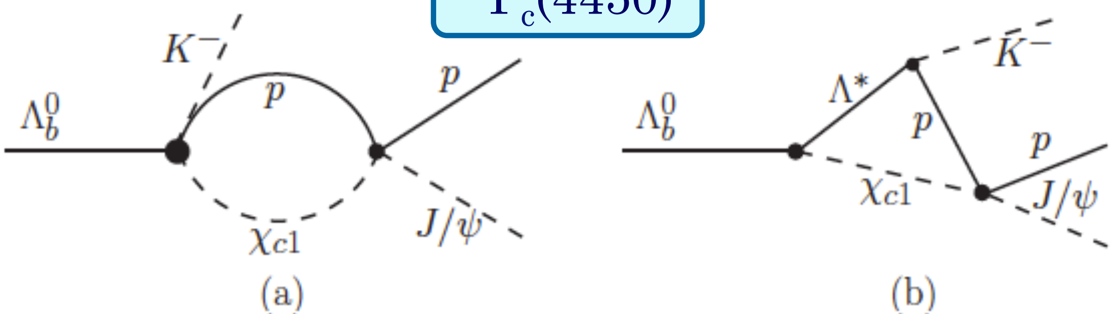
$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

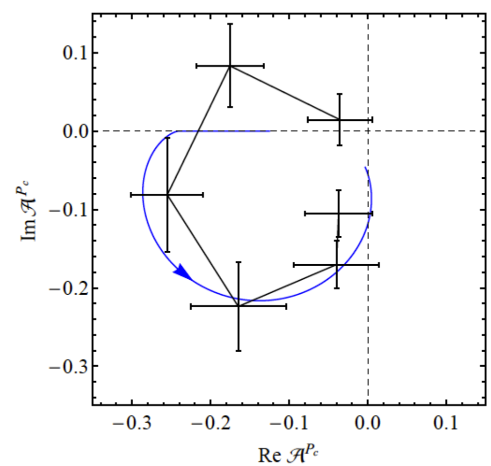
$$\Pi(m|\beta_0) = \int \frac{d^3q}{(2\pi)^3} \frac{e^{-2q^2/\beta_0^2}}{m - M_A - M_B - \frac{q^2}{2\mu_{AB}} + i\epsilon}$$

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



$P_c(4450)$

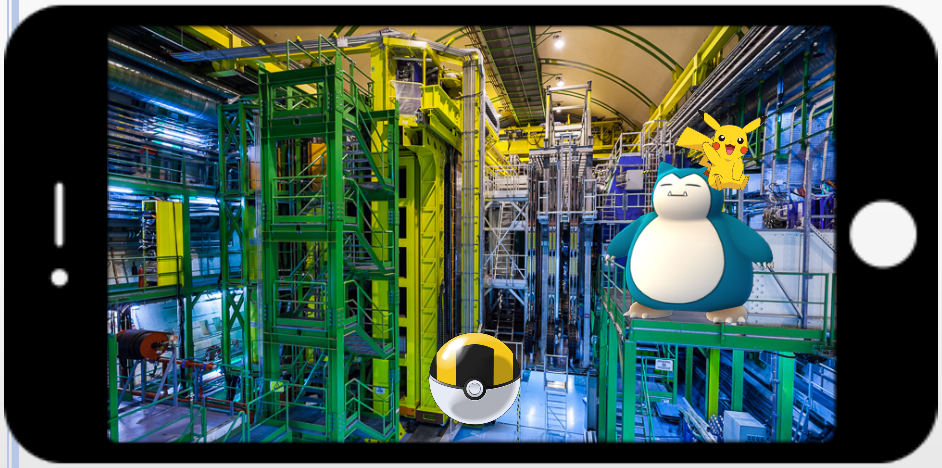




PRD 92 (2015) 7, 071502

SUMMARY & PROSPECT

- ✓ Two unexpected pentaquark appeared in the LHCb data
- ✓ Masses and widths measured precisely. Quantum numbers still to be fixed



SUMMARY & PROSPECT

- ✓ Two unexpected pentaquark appeared in the LHCb data
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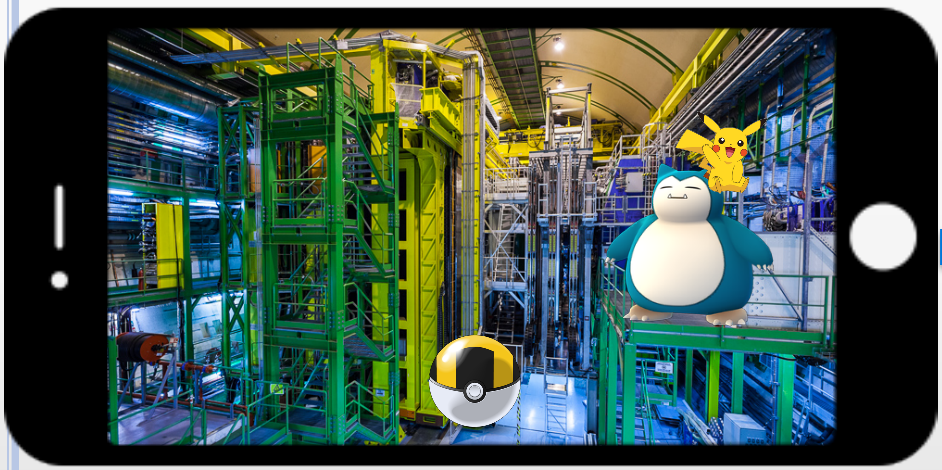
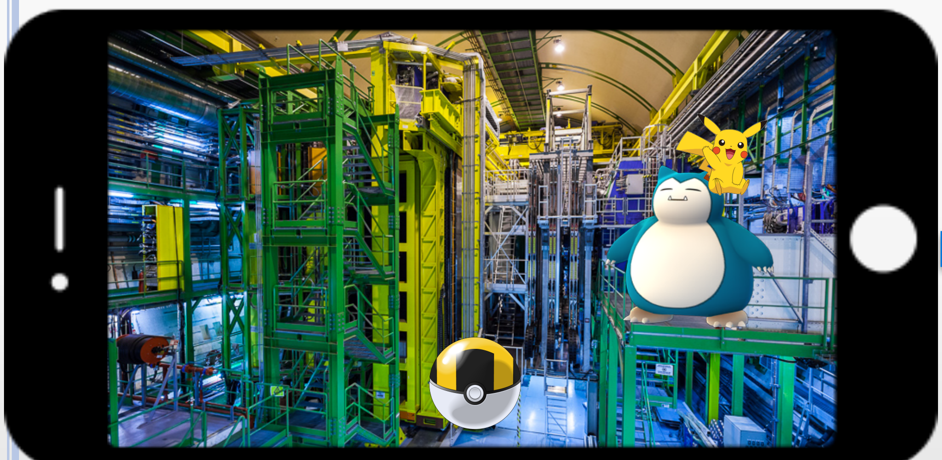
- ✓ Family of pentaquarks expected



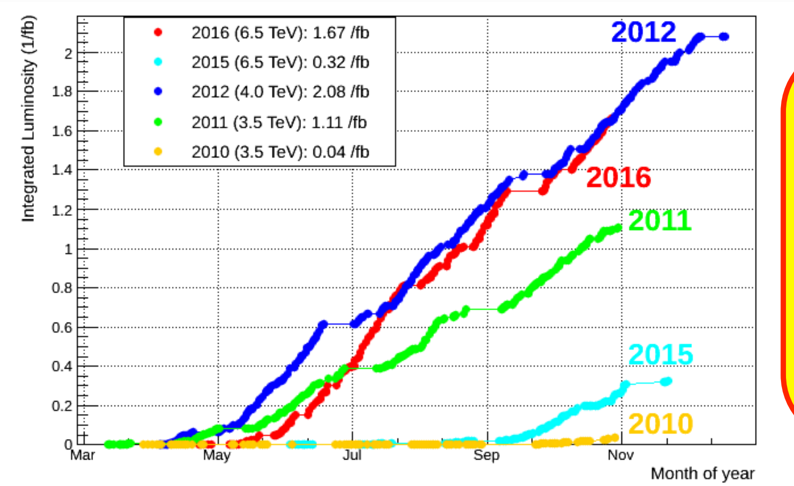
Summary & Prospect

- ✓ Two unexpected pentaquark appeared in the LHCb data
- ✓ Masses and widths measured precisely. Quantum numbers still to be fixed
- ✓ Family of pentaquarks expected
- ✓ Where are they?



Pokémon® Gotta catch 'em all!™

2016 DATA TAKING AND BEYOND

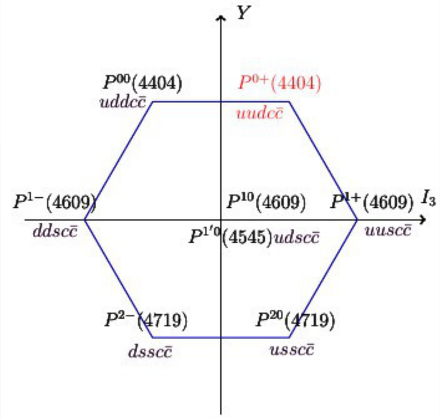


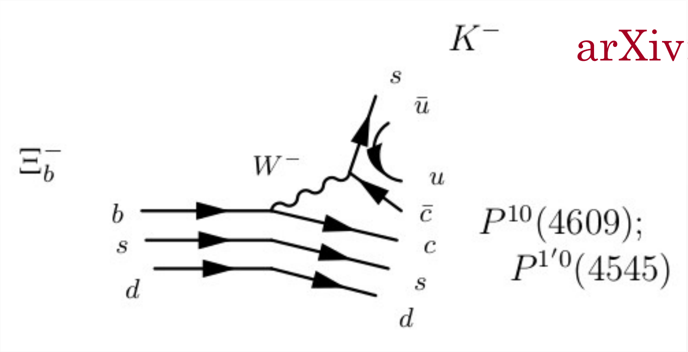
RUN II

2015: 0.3 fb^{-1}
2016: 1.7 fb^{-1} (corresponding to a larger *b-bbar* sample than collected in 2012, given larger collision energy/cross-sections)

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1}
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

SUMMARY & PROSPECT (II)

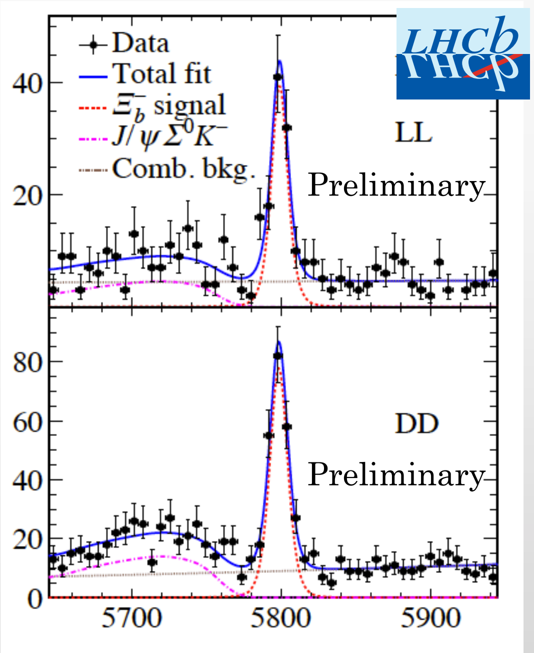




arXiv:1604.03769

LHCb-PAPER-2016-053 in preparation

300 candidates of
$\Xi_b^- \to J/\psi\, \Lambda K^-$ (3 fb^{-1})



Summary & Prospect (III)

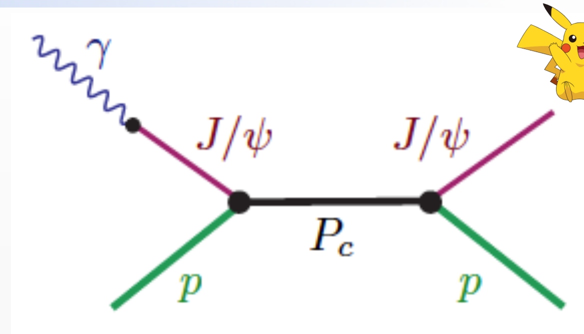
- *The hunt to the next pentaquark is open!*
  - χ_{c1} p (Observation of P_c would rule out the cusp scenario)
  - $\Upsilon(1S) \to J/\psi \; p \, \bar{p}$
  - D Σ_c
  - Triple charged pentaquarks

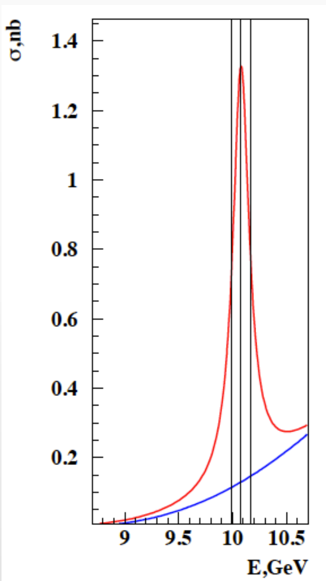
Interplay between light and heavy quark spectroscopy: the poor knowledge of N*, Λ*, etc baryons has a large impact. PANDA, J-PARC, JLab and other hadron facilities could help into improving the current status

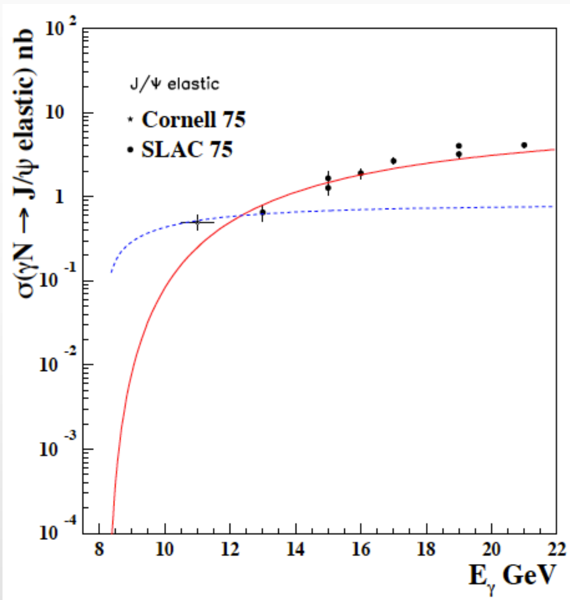
Photoproduction of Hidden-Charm Pentaquark in CLAS

arXiv:1609.00050
arXiv:1609.00676

The photoproduction of pentaquarks proceeds as an s-channel resonance





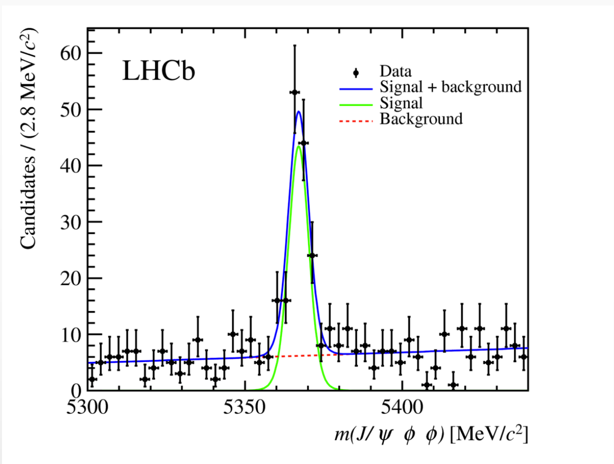


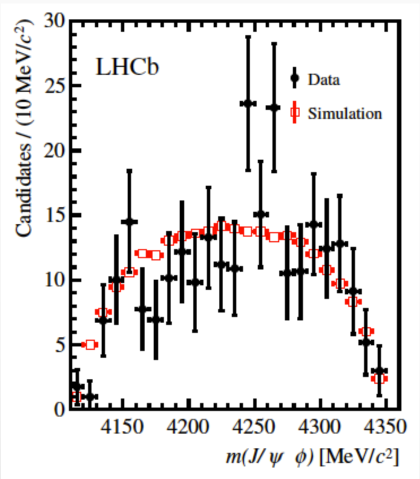
The lowest published energy is at E_γ = 11 GeV

With CLAS12 and 11 GeV electron beam, the threshold region can be studied in great details E12-12-001

SUMMARY & PROSPECT (IV)

- Measurement of mass (~0.1 MeV) and width (~0.3 MeV) of X(3872)
- Search for new decays mode for X(3872): (e.g.) χ_{c1} π π, $\bar{p}p$
- Search for X(4140) & X(4274) → J/ψ ϕ in B_s → J/ψ ϕϕ decays





[LHCb: JHEP 03 (2016) 040]

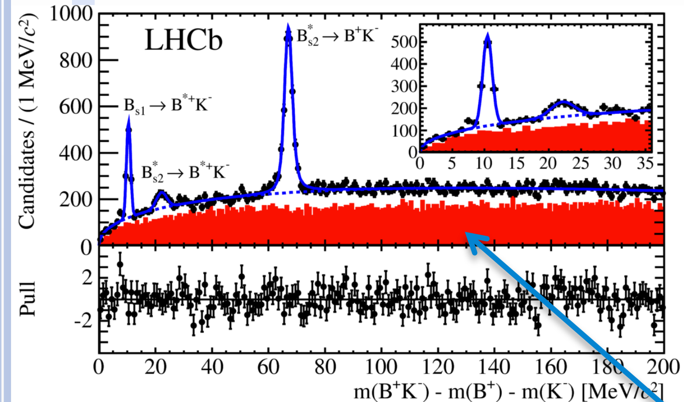
- Exploration of $D_{(s)}\bar{D}^{(*)}_{(s)}$ mass spectra from B decays & Central Exclusive Production

X_b

- Search for Y(1S) ω (→π π π^0, μμ)

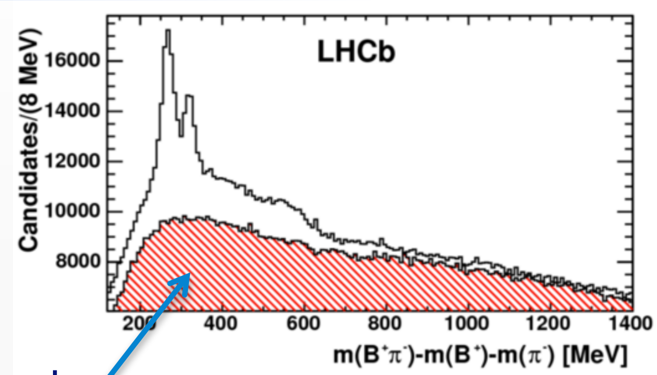
Back-up slides

Other "Implicit" Searches



PRL 110 (2013) 151803

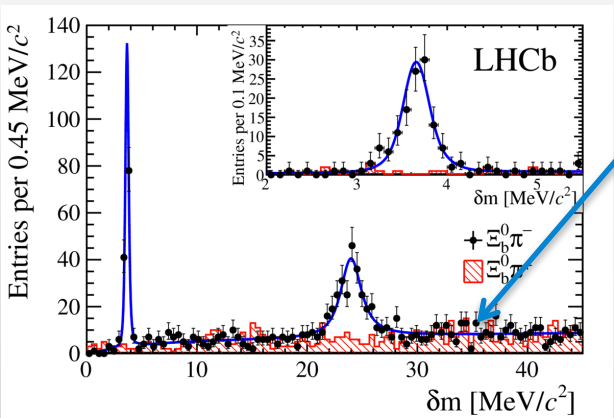
B^+K^+



$B^+\pi^+$

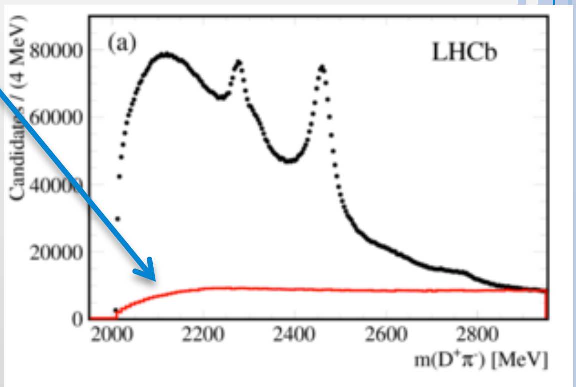
JHEP 1504 (2015) 024

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

INTERMEZZO: PRECISION INTO DETERMINING THE VALUE OF π

Arcsine [edit]

Observing an equilateral triangle and noting that

$$\sin\left(\frac{\pi}{6}\right) = \frac{1}{2}$$

yields

$$\pi = 6\sin^{-1}\left(\frac{1}{2}\right) = 6\left(\frac{1}{2} + \frac{1}{2\cdot 3\cdot 2^3} + \frac{1\cdot 3}{2\cdot 4\cdot 5\cdot 2^5} + \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7\cdot 2^7} + \cdots\right)$$

$$= \frac{3}{16^0\cdot 1} + \frac{6}{16^1\cdot 3} + \frac{18}{16^2\cdot 5} + \frac{60}{16^3\cdot 7} + \cdots = \sum_{n=0}^{\infty} \frac{3\cdot\binom{2n}{n}}{16^n(2n+1)}$$

$$= 3 + \frac{1}{8} + \frac{9}{640} + \frac{15}{7168} + \frac{35}{98304} + \frac{189}{2883584} + \frac{693}{54525952} + \frac{429}{167772160} + \cdots$$

with a convergence such that each additional five terms yields at least three more digits.

3.141

Amplitude Analyses are the way

Why amplitude analysis are strongly recommended?

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			$172 \pm 13\ ^{+37}_{-34}$

Natural width of X(4140) [MeV]

State	1D	6D
CDF	$15.3\ ^{+10.4}_{-6.1} \pm 2.5$	
LHCb		$83 \pm 21\ ^{+21}_{-14}$

- 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.
- Limitation: poor knowledge of the light spectroscopy!