Exotic Hadron Spectroscopy at LHCb

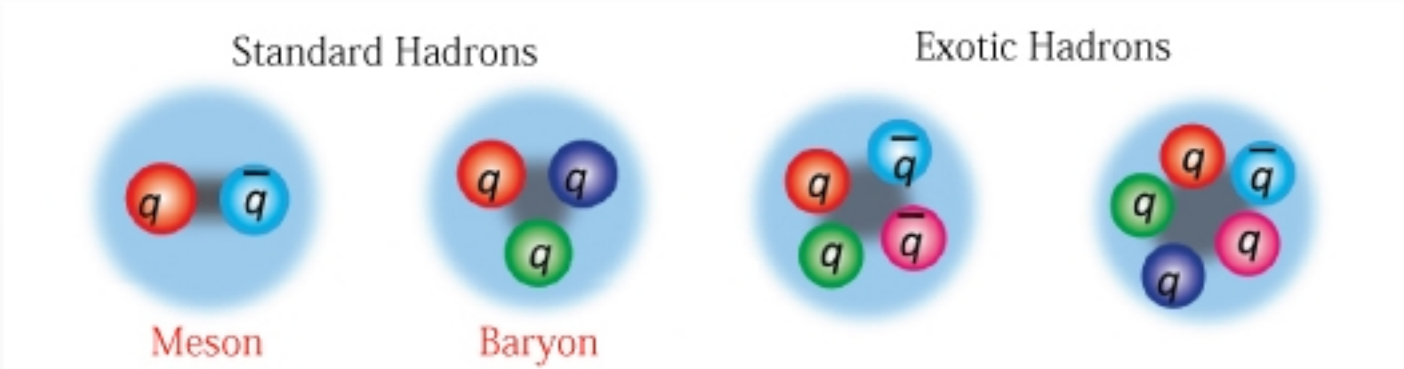
Marco Pappagallo

19 February, J-PARC, Japan

OUTLINE

- Introduction
  - Spectroscopy Techniques
  - Amplitude/Dalitz Analyses
- Confirmation of the $Z(4430)^+$
  - Model Independent Analysis
  - Amplitude Analysis of $B^0 \rightarrow \psi(2S)\, \pi^+ K^-$ Decay
- Observation of two Pentaquarks P_c^+
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\, p\, K^-$ Decay

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

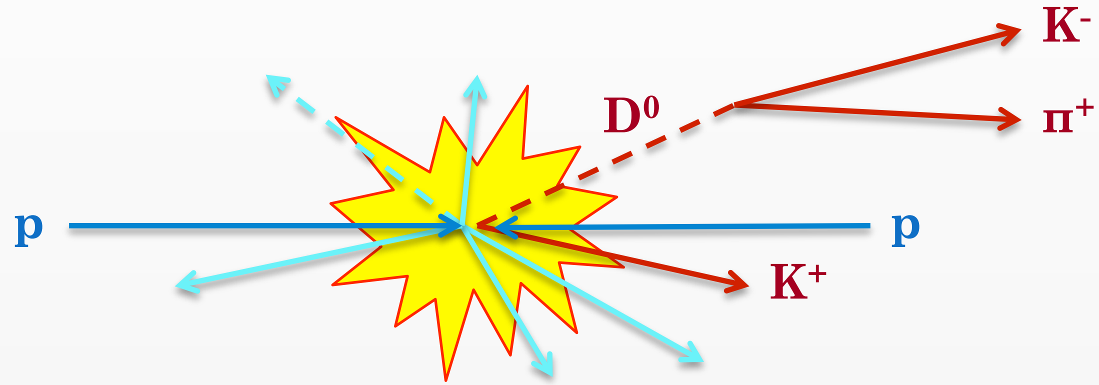
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$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".

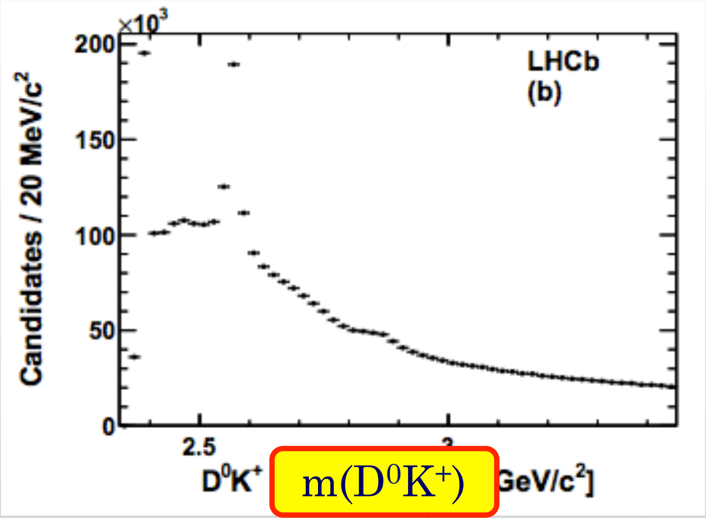
How to do spectroscopy?

"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"

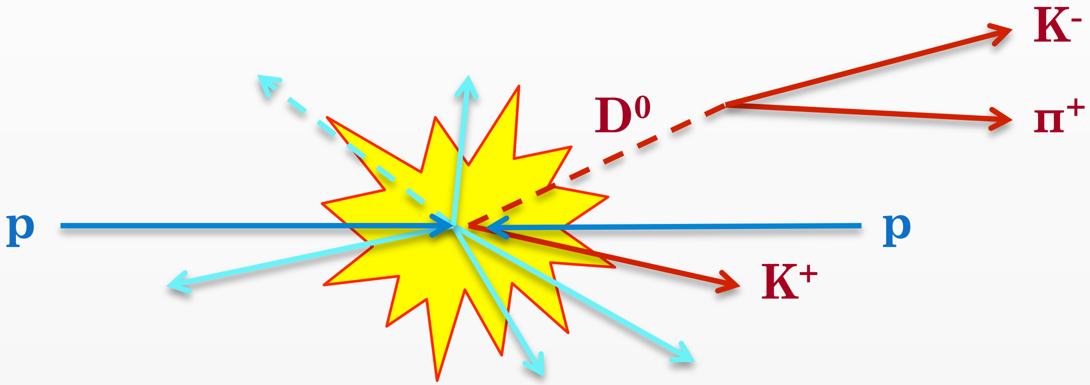


[LHCb: JHEP 10 (2012) 151]

HOW TO DO SPECTROSCOPY?

"Inclusive Analysis"

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



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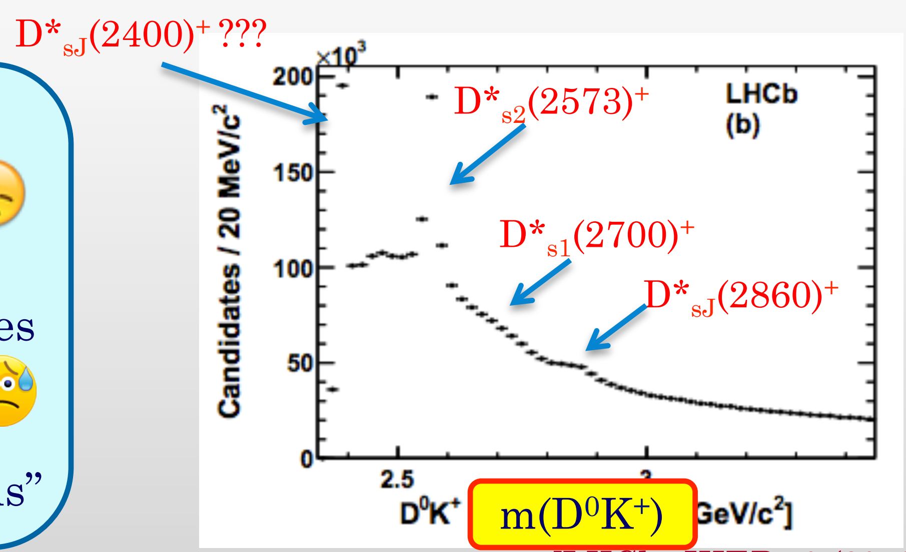

[LHCb: JHEP 10 (2012) 151]

How to do spectroscopy?

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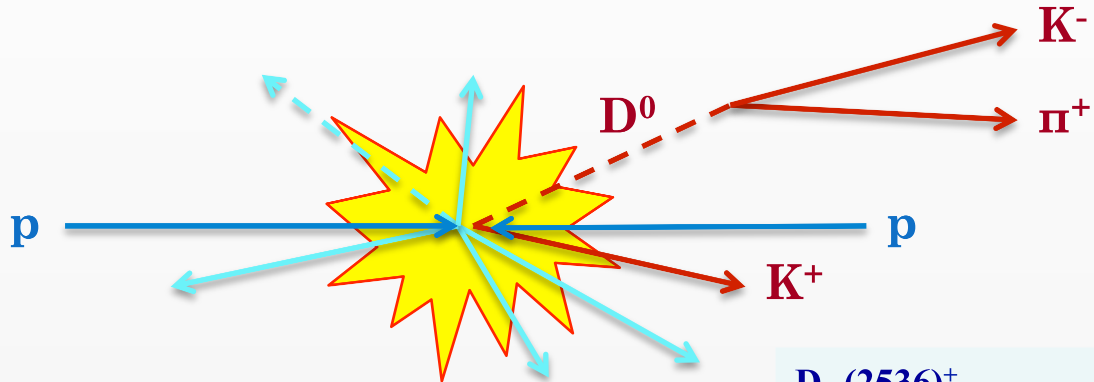

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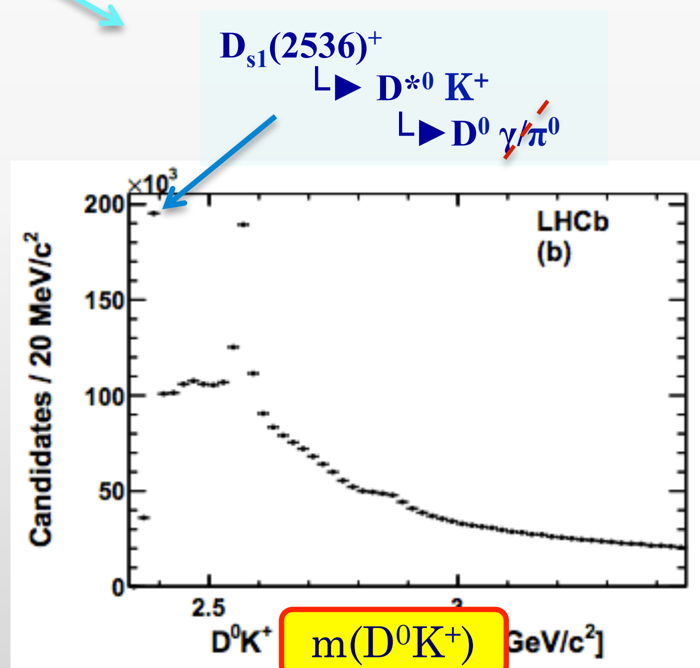
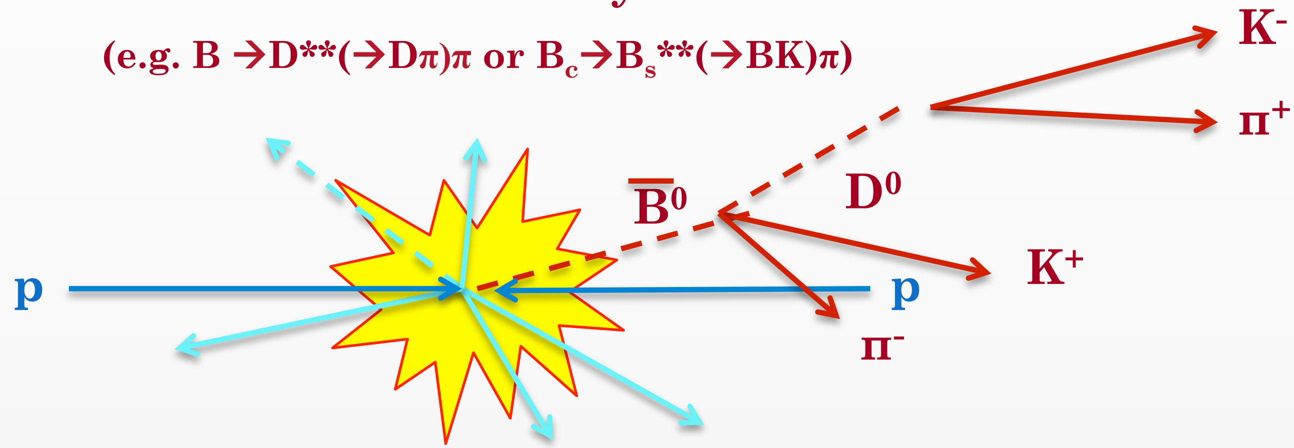


[LHCb: JHEP 10 (2012) 151]

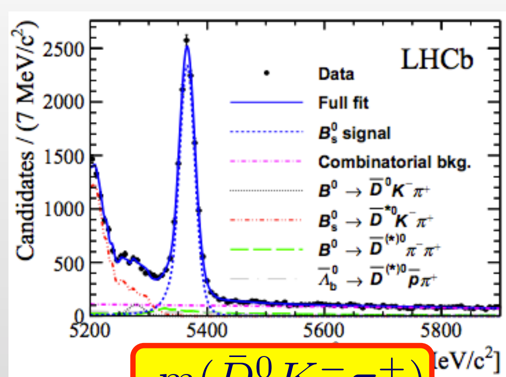
How to do spectroscopy?(II)

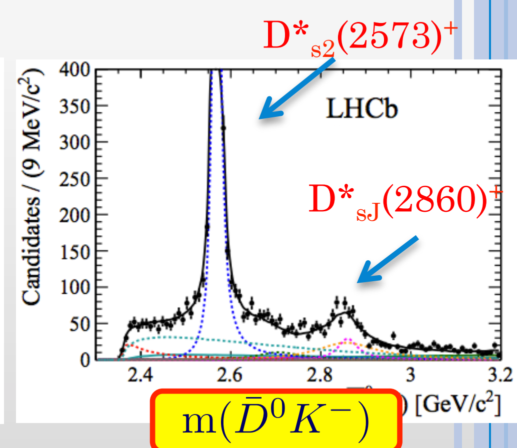
"Exclusive Analyses"

(e.g. $B \rightarrow D^{**}(\rightarrow D\pi)\pi$ or $B_c \rightarrow B_s^{**}(\rightarrow BK)\pi$)



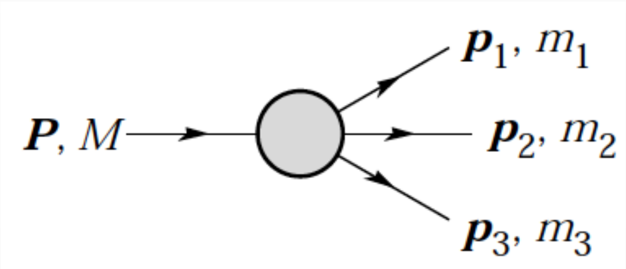
- Limited statistics
- Small background
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference)
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis





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

3-BODY DECAY WITH SPINLESS DAUGHTERS



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

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

Dalitz Plot

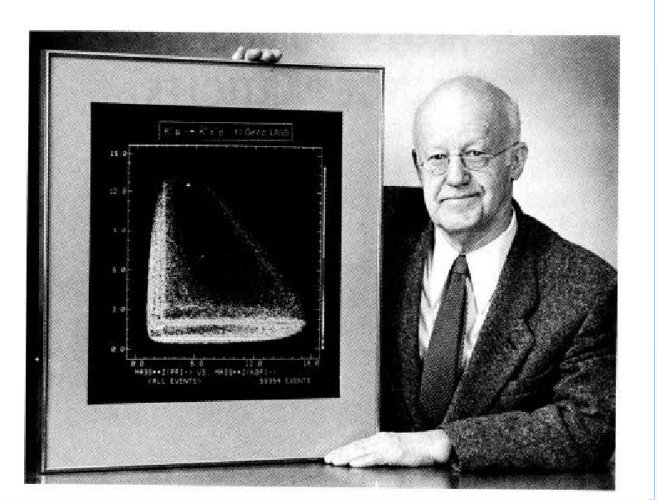
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$

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

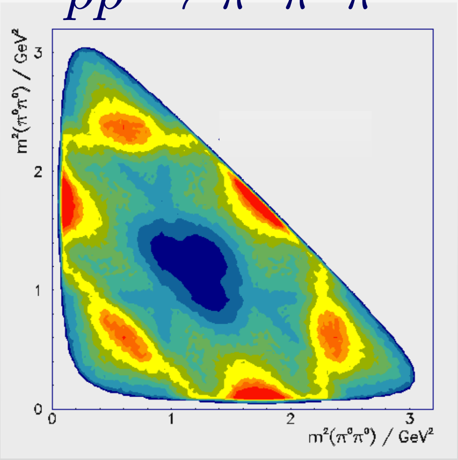
$\overline{|\mathcal{M}|^2} = Const \Rightarrow$ Dalitz uniformly populated

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

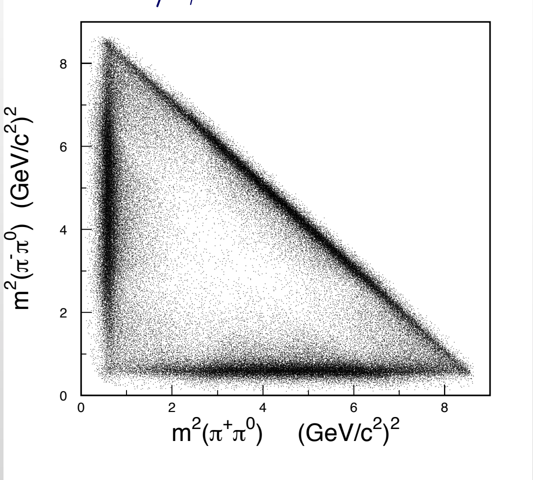
"I visualize geometry better than numbers."



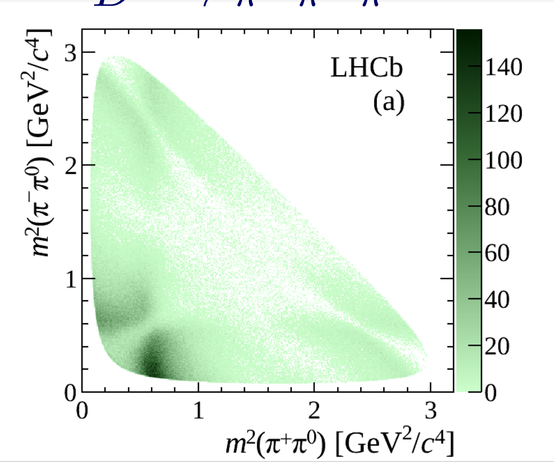
$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$



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



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



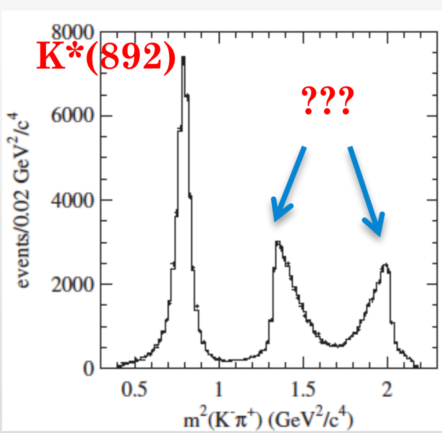
Kinematical Reflections/Shadows

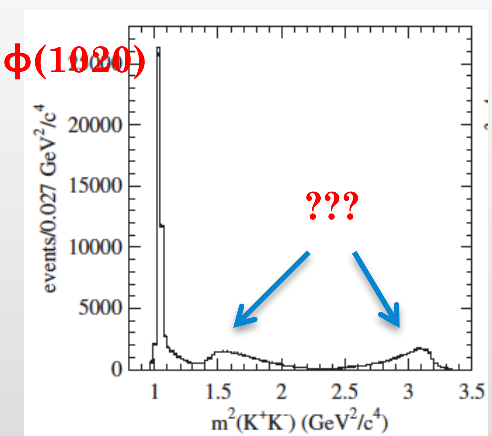
(e.g.) $D_s^+ \to K^+K^-\pi^+$

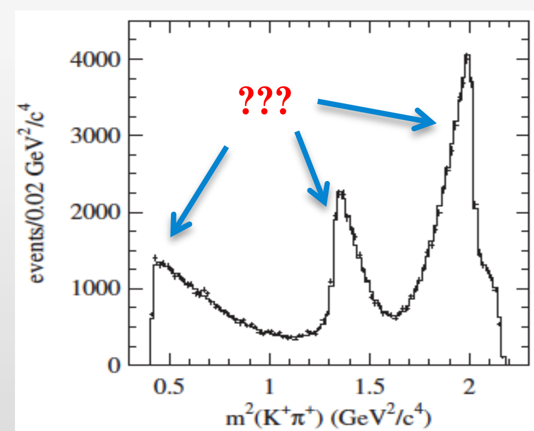
$$D_s^+ \to R\pi^+ \quad (R \to K^+K^-)$$

or

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







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

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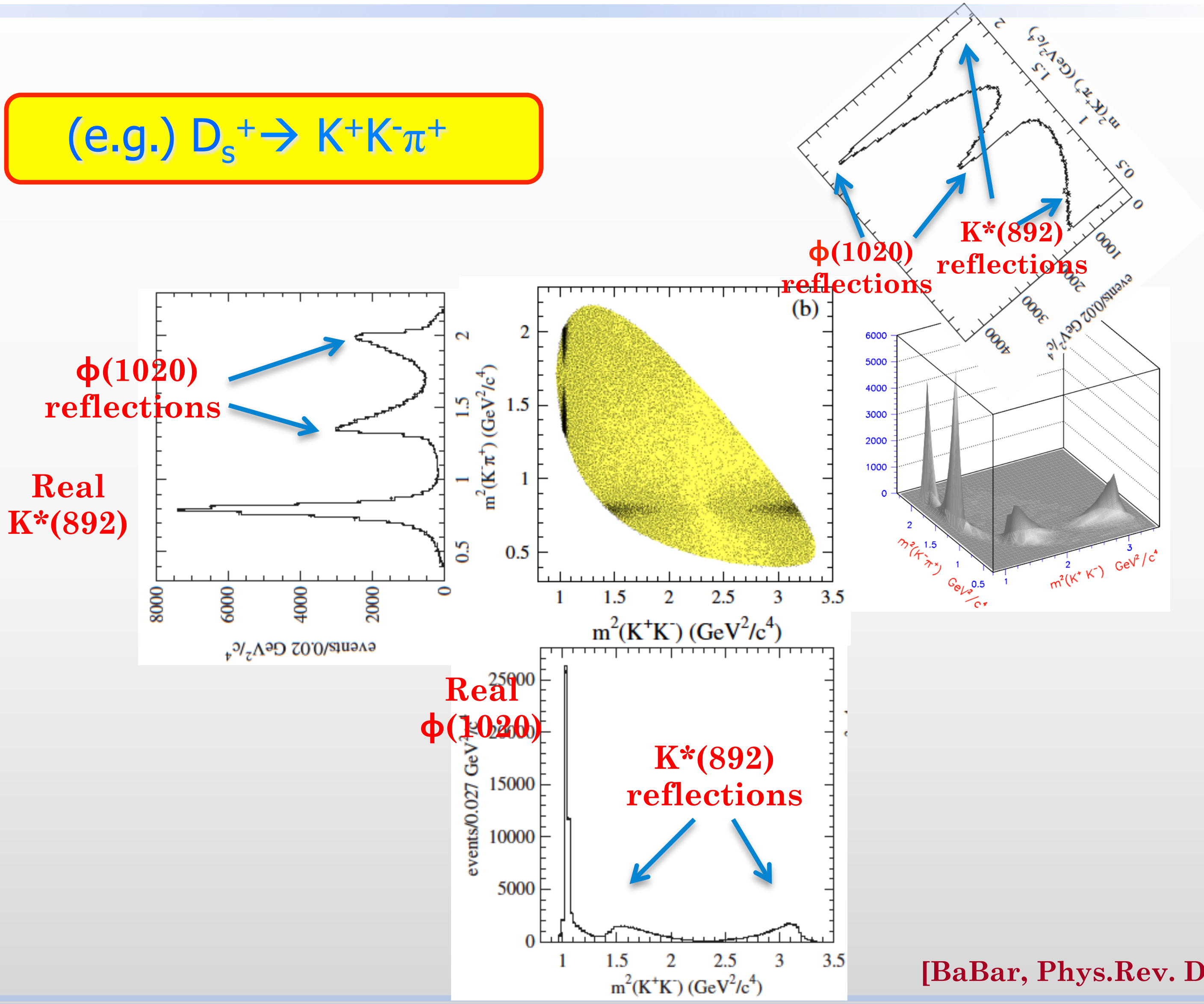
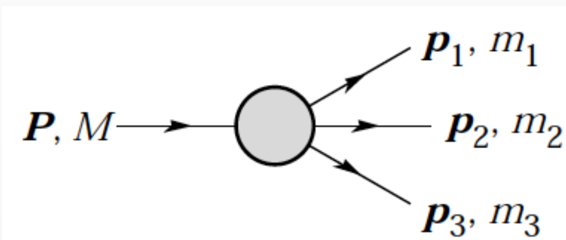


[BaBar, Phys.Rev. D83 (2011) 052001]

Confirmation of the $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ state (Amplitude analysis of $B^0 \rightarrow \psi(2S)\, K^- \pi^+$)

THE B→ψ(2S) K π DECAY

3-body decay with a vector state as a daughter



Constraints	Degree of freedom
3 four-vectors	12
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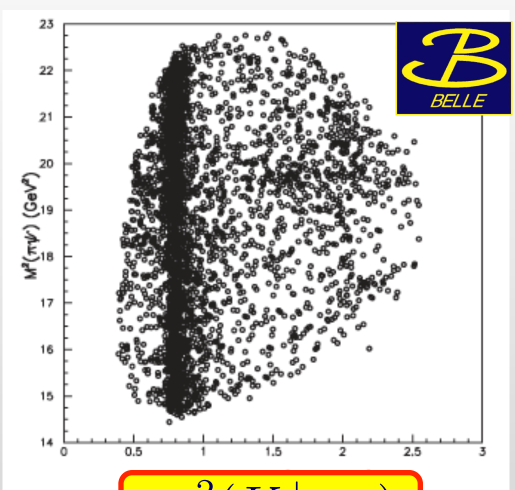
3 Euler angles	-3
Vector helicity	2
TOT	4

$m^2(\psi(2S)\pi^-)$



$m^2(K^+\pi^-)$

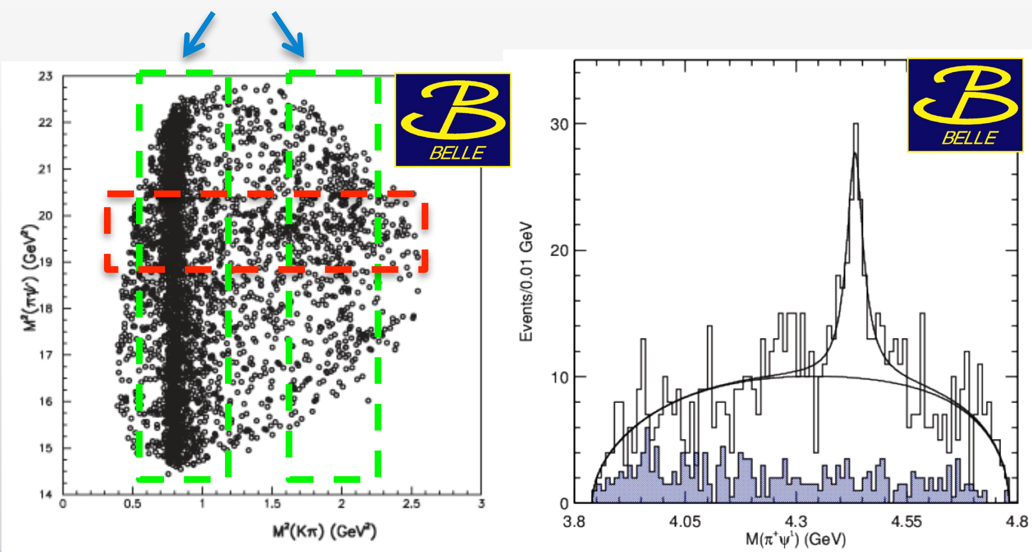
The "Dalitz" plot is itself a projection of a 4-D space

Any Reflection?

A BIT OF HISTORY: Z(4430)$^+$

- Observed in the $\psi(2S)\pi^+$ in $B^{0(+)} \to \psi(2S)\pi^+ K^{-(0)}$ decays by Belle
  [Belle, PRL100, 142001 (2008)]
- Clear signature of exotic:
  - Decay to charmonium $\to c\bar{c}$ pair content
  - Electric charged $\to$ at least 2 more light quarks $N_{quarks} >= 4$!
  - Tetraquark, D^*D_1 molecule?

VETOED



1-D fit of ψ(2S) π mass spectrum!

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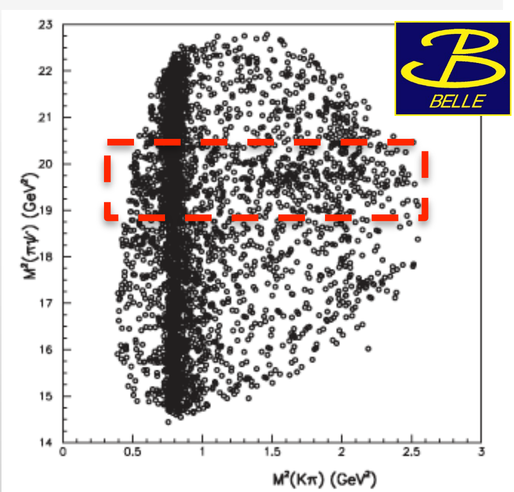
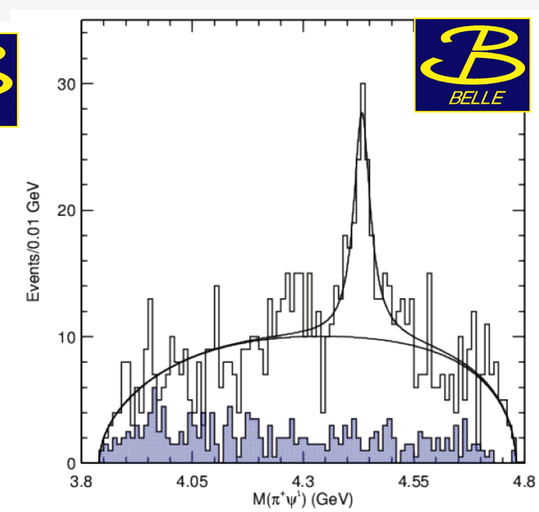
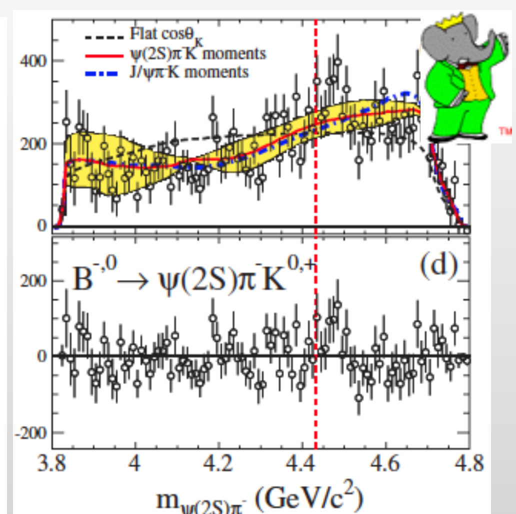
- $Z(4430)^+$ not confirmed (nor excluded) by BaBar **[BaBar, PRD 79, 112001 (2009)]**







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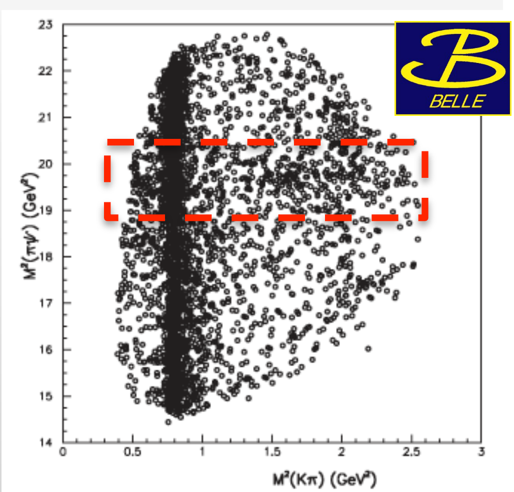
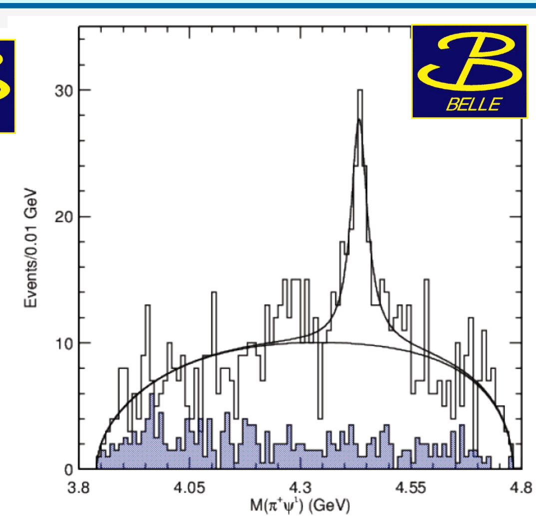
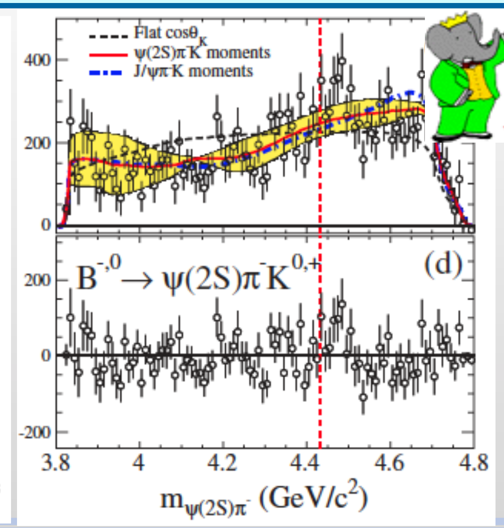
  Tetraquark, D^*D_1 molecule?
- $Z(4430)^+$ not confirmed (nor excluded) by BaBar **[BaBar, PRD 79, 112001 (2009)]**
- Later 2D "Dalitz" technique: $M^2(\psi(2S)\pi^+)$ vs $M^2(K^-\pi^+)$ **[Belle, PRD 80, 031104 (R) (2009)]**
- Belle: full 4D amplitude analysis. $J^P = 1^+$ favoured but $J^P = 0^-$ not excluded
  [Belle, PRD 88 (2013) 074026]



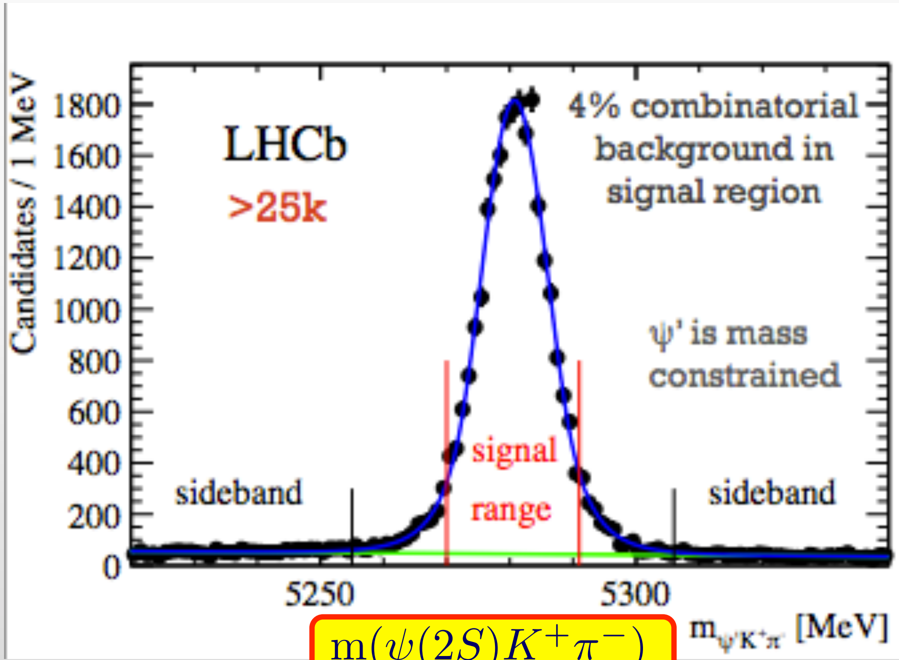


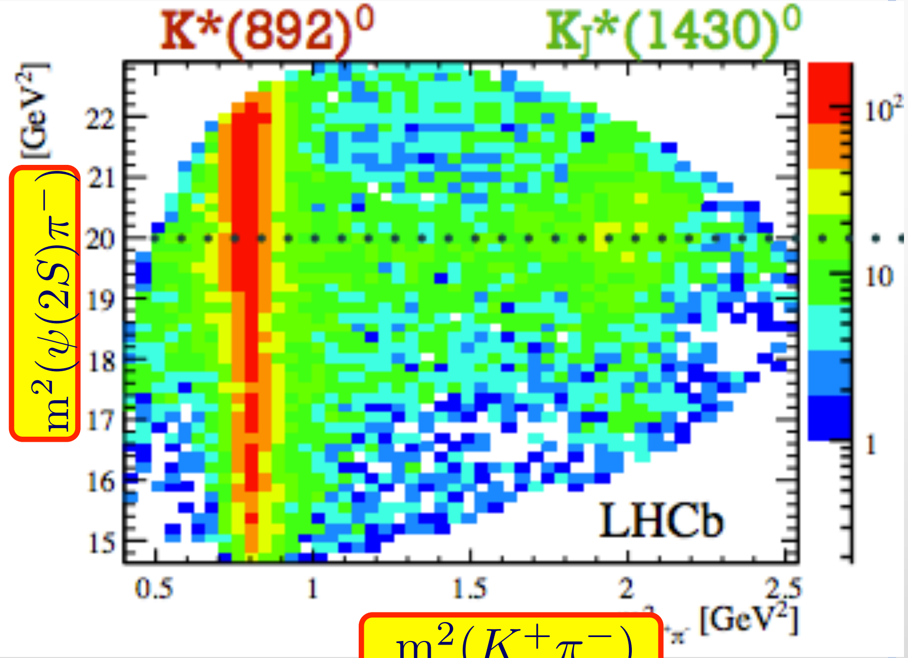


Search for Z(4430)$^+$ at LHCb

[LHCb: PRL 112, 222002 (2014)]

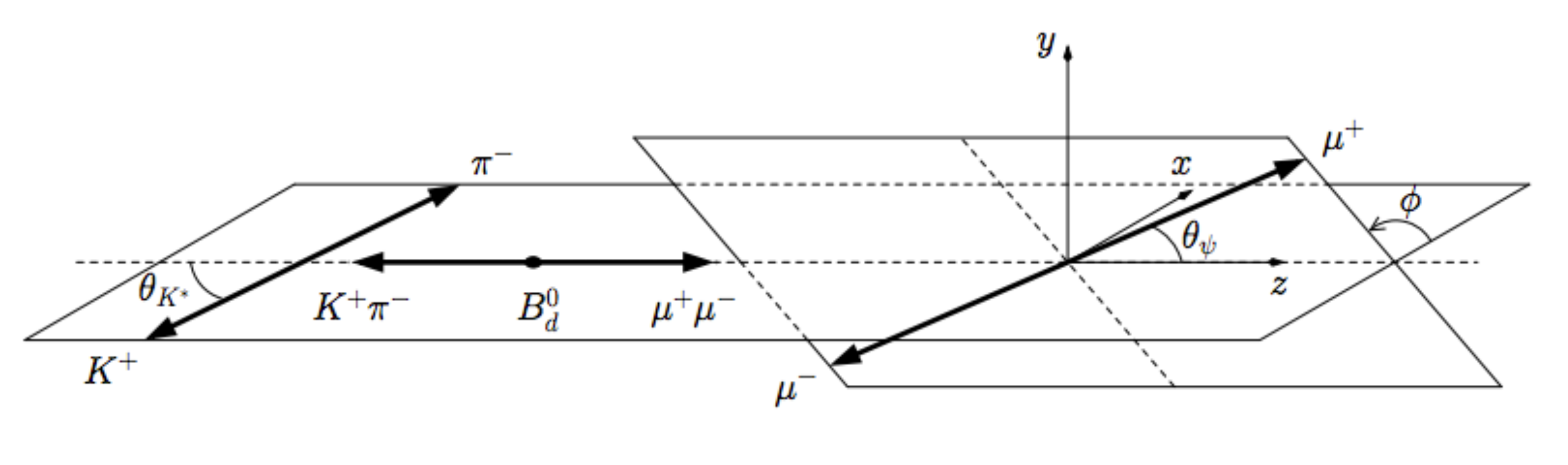
- 25k $B^0 \to \psi(2S)K^+\pi^-$ candidates in 3.0 fb^{-1} (x10 Belle/BaBar)
- Small combinatorial background
- Sidebands used to build 4D model of the combinatorial background





INDEPENDENT VARIABLES

LHCb: PRD92, 112009 (2015)



Amplitude Analysis

$$\vec{\Phi} = (m^2_{K\pi}, m^2_{\psi\pi}, \cos\theta_\psi, \phi) \Rightarrow \frac{d\Gamma}{d\vec{\Phi}} \propto |\mathcal{M}(\vec{\Phi})|^2$$

Model Independent Analysis

$$\vec{\Phi} = (m^2_{K\pi}, \cos\theta_{K*}, \cos\theta_\psi, \phi) \Rightarrow \frac{d\Gamma}{d\vec{\Phi}} \propto |\mathcal{M}(\vec{\Phi})|^2 p(\vec{\Phi}) q(\vec{\Phi})$$

MODEL INDEPENDENT APPROACH (*i.e.* A LA BABAR)

LHCb: PRD92, 112009 (2015)

Can the reflections of the structures in m(Kπ) and cos ϑ_{K^*} reproduce the m(ψ'π) distribution?

If no exotics in ψK and ψπ → Partial wave expansion in a given bin of m²(Kπ)

Legendre Polynomials

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \ldots$$

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

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

Model Independent Approach (*i.e.* à la BaBar)

LHCb: PRD92, 112009 (2015)

(e.g.) If only K* resonances up to J = 2

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \dots$$

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

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

Should it not happen →

There are K* resonances with J > 2
or
There are exotic(s) which make the high order terms non-zero!

The K* family

LHCb: PRD92, 112009 (2015)

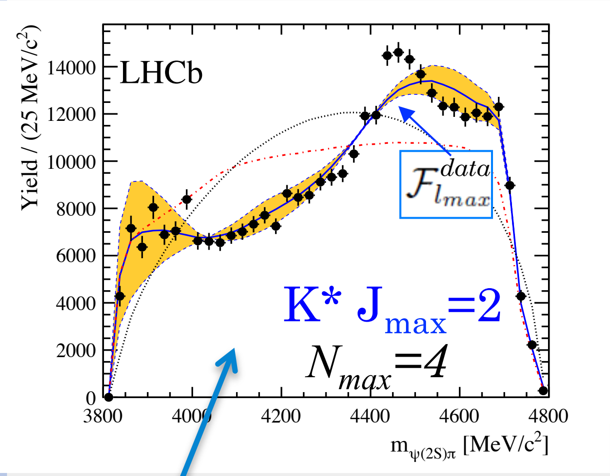
Resonance	Mass (MeV/c^2)	Γ (MeV/c^2)	J^P
$K^*(892)^0$	895.81 ± 0.19	47.4 ± 0.6	1^-
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit (1593 MeV)			
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-
$K_3^*(1780)^0$	1776 ± 7	159 ± 21	3^-
...	...	...	...
$K_4^*(2045)^0$	2045 ± 9	198 ± 30	4^+

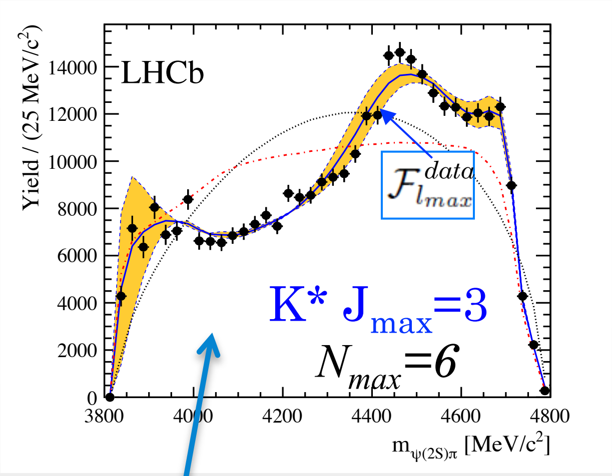
Unlikely a contribution from K* resonances with J > 3

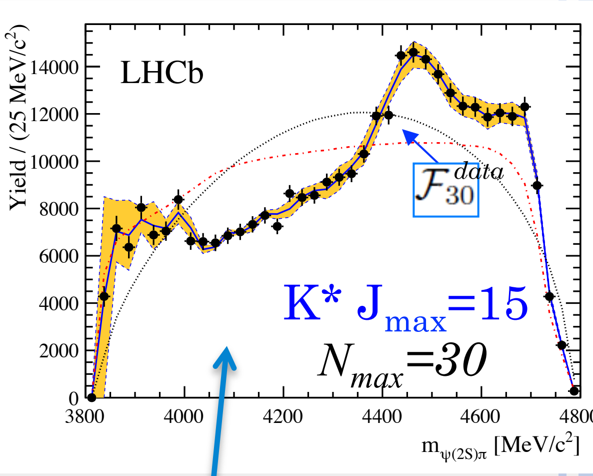
Results of the Model Independent Analysis

LHCb: PRD92, 112009 (2015)

Allows for K* states up to $K^*_2(1430)$	Allows for a tail of $K^*_3(1780)$	Allows implausible K* contributions







Clear discrepancy at ~4430 MeV

It may look OK but…

No discrepancy as expected

The yellow bands related to the uncertainty on normalized moments (due to the statistical uncertainty from the data)

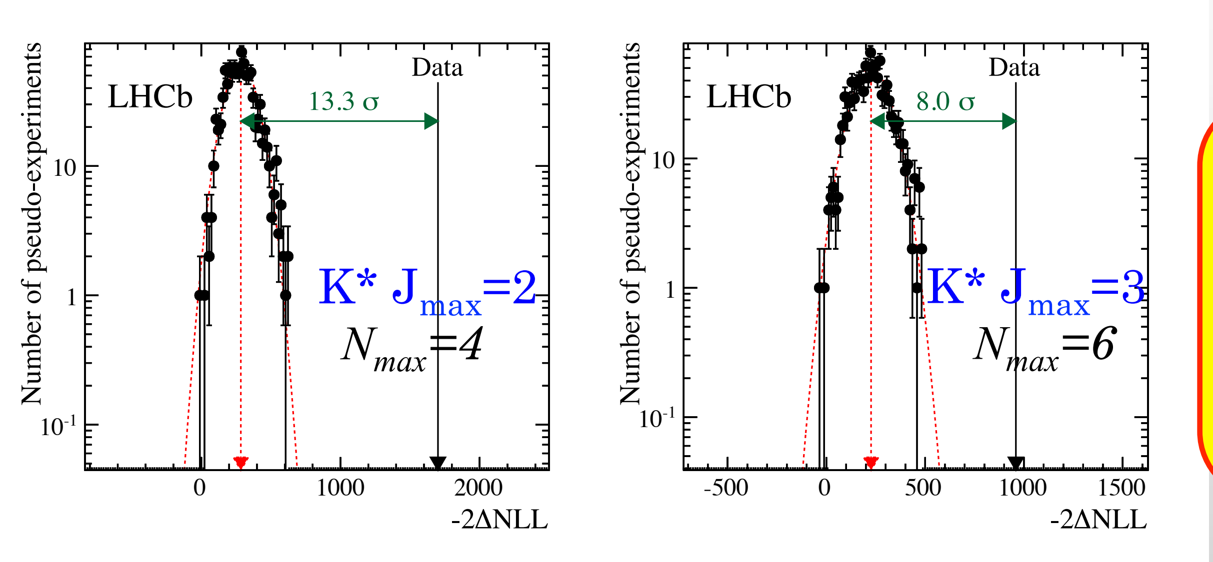
Quantitative Results from Model Independent Approach

LHCb: PRD92, 112009 (2015)

Test significance of implausible $N_{max} < N < 30$ moments using the log-likelihood ratio:

$$\Delta(-2\mathrm{NLL}) = -2\log\frac{\mathcal{L}_{N_{max}}}{\mathcal{L}_{30}} = -2\log\frac{\prod_i \mathcal{F}_{N_{max}}(m^i_{\psi'\pi})}{\prod_i \mathcal{F}_{30}(m^i_{\psi'\pi})}$$

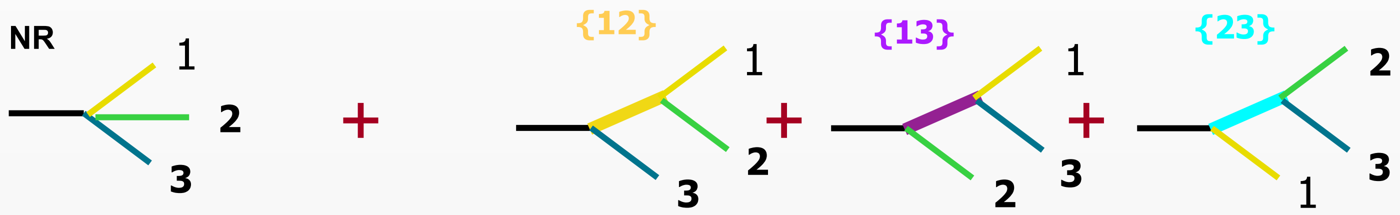
Statistical simulations of pseudo-experiments generated from the $N < N_{max}$ hypotheses



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

The Isobar Model

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



Three-body amplitude for $B^0 \to \psi(2S) K \pi$

Sum over all K* resonances

Z(4430) component

$$|\mathcal{M}(\Phi)|^2 = \sum_{\Delta\lambda_\mu = 1,-1} \left| \sum_{\lambda_\psi = -1,0,1} \sum_{K^*} A^{K^*}_{\lambda_\psi \Delta\lambda_\mu}(m_{K\pi}, \Omega) + \sum_{\lambda^Z_\psi = -1,0,1} A^Z_{\lambda^Z_\psi \Delta\lambda_\mu}(m_{\psi\pi}, \Omega^Z) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

Defined unless a phase and a constant

Rotation by α due to different helicity frame

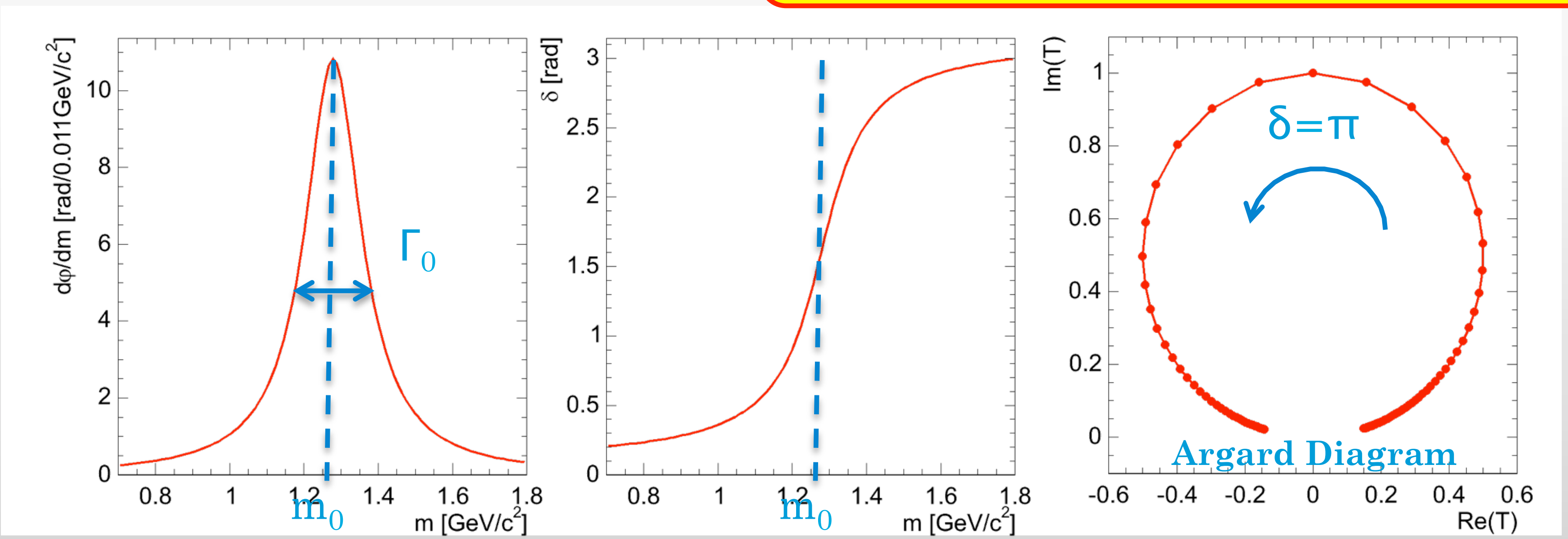
How to model a single term

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

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

Relativistic Breit-Wigner

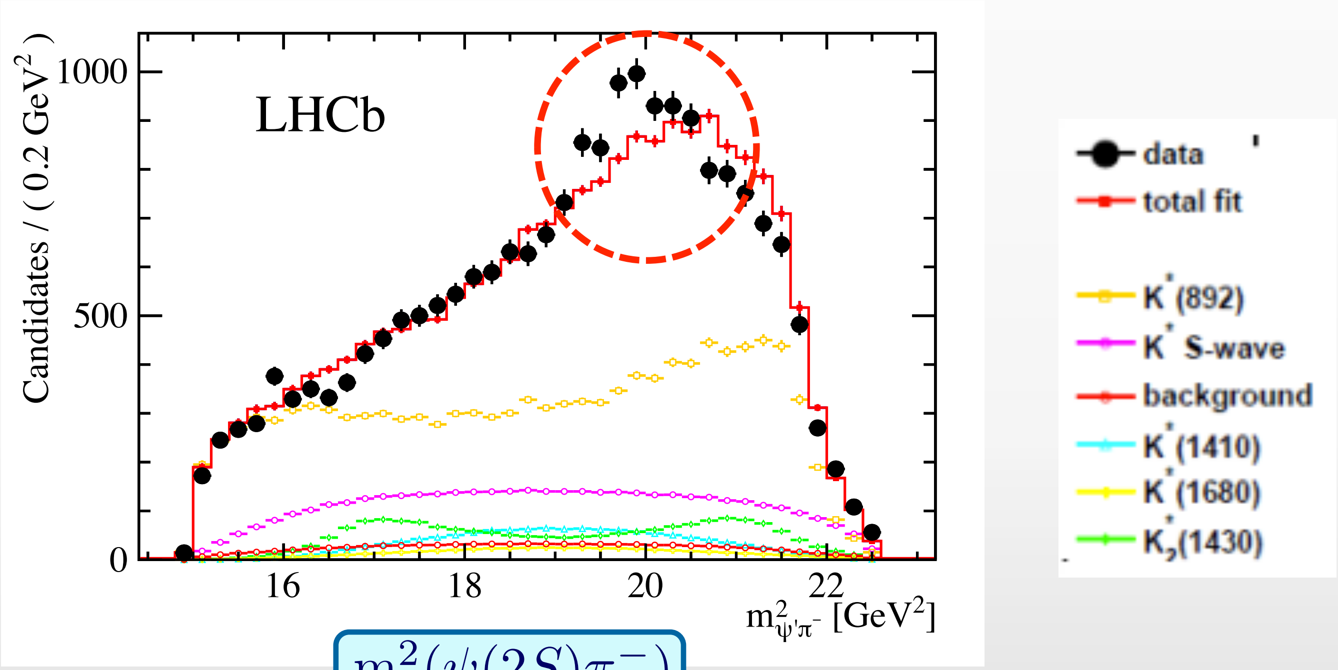
$$A^{K^*}(m_{K\pi}) = \frac{1}{m_0^2 - m_{K\pi}^2 - i m_o \Gamma_0}$$



RESULTS OF A FIT WITHOUT Z(4430)$^+$

[LHCb: PRL 112, 222002 (2014)]

Can the reflections of K* resonances describe the m(ψ'π) distribution?

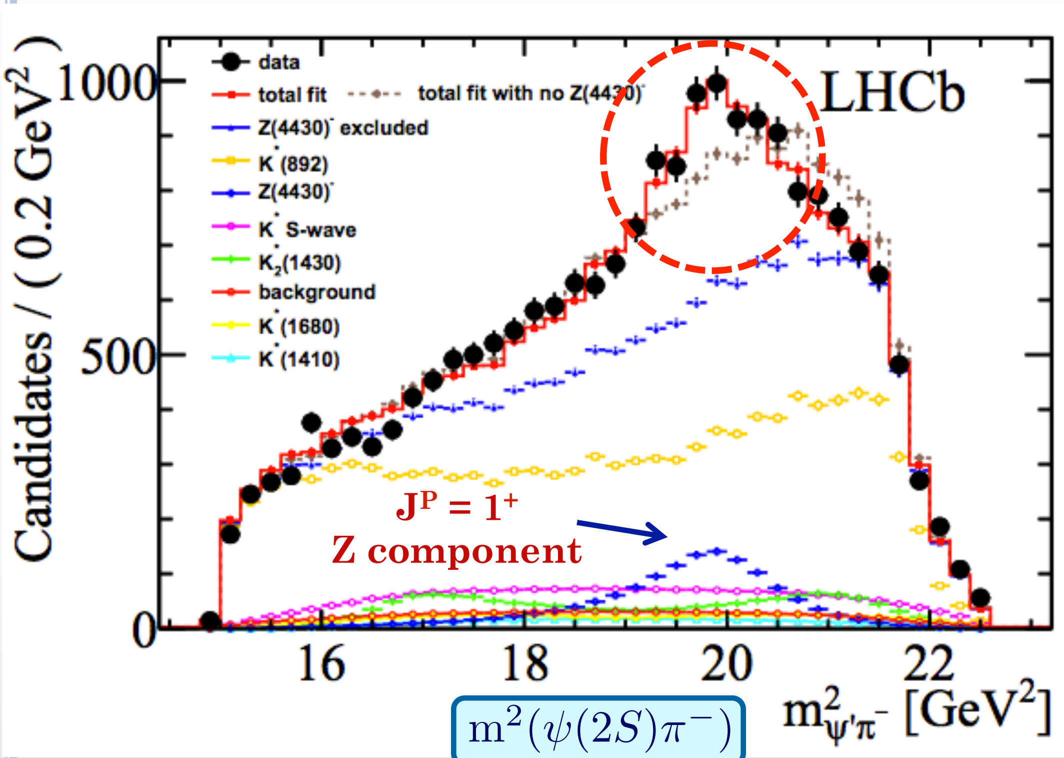


$m^2(\psi(2S)\pi^-)$

The data cannot be adequately described only using J ≤ 3 K* contributions.

4D Amplitude Fit and confirmation of Z(4430)$^+$

[LHCb: PRL 112, 222002 (2014)]



	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

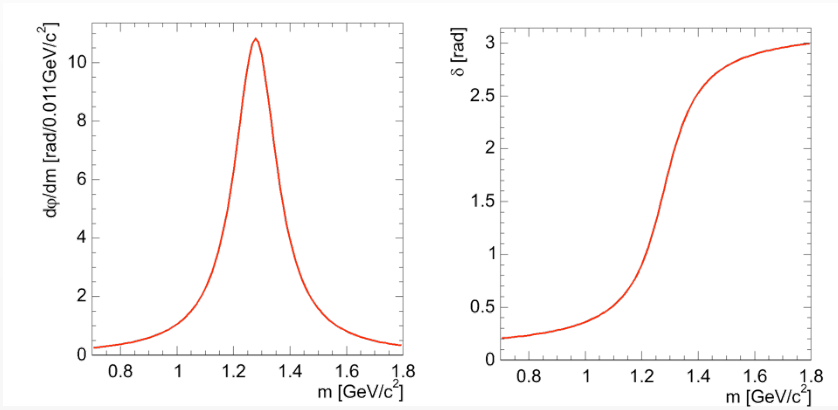
	LHCb	Belle
Mass (MeV)	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
Width (MeV)	$172 \pm 13^{+37}_{-34}$	$200\ ^{+41}_{-46}\ ^{+26}_{-35}$

- Large interference between Z(4430) and K* resonances
- Very good agreement between LHCb/Belle results

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

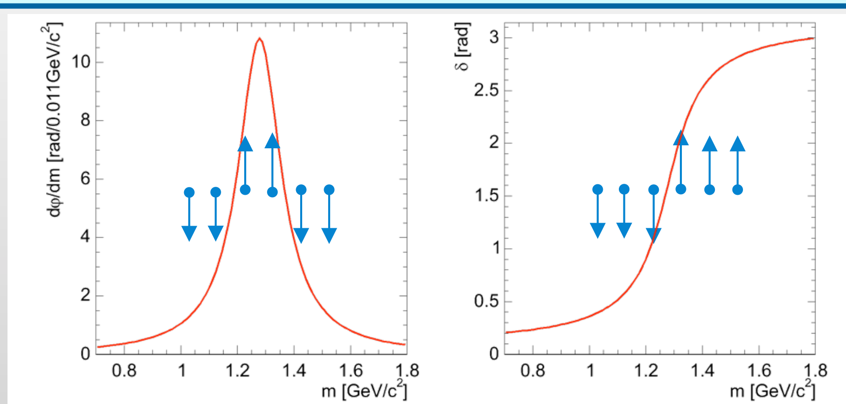
[LHCb: PRL 112, 222002 (2014)]

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 $m(\psi(2S)\pi)$ in region $m_0 \pm \Gamma_0$, where m_0 is the mass of Z(4430)

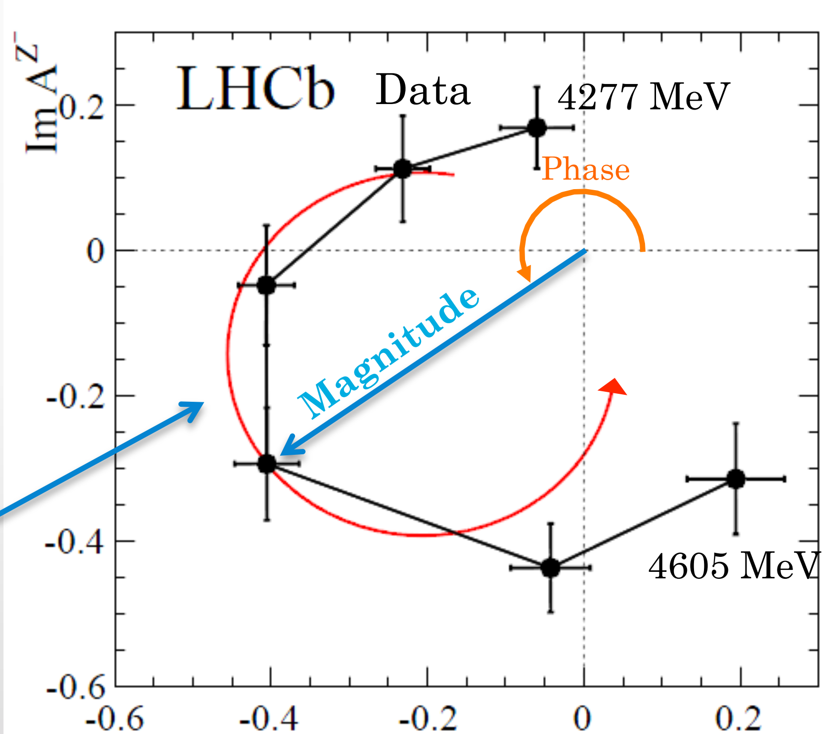


12 free parameters

RESONANT BEHAVIOR OF Z(4430)$^{+}$

[LHCb: PRL 112, 222002 (2014)]

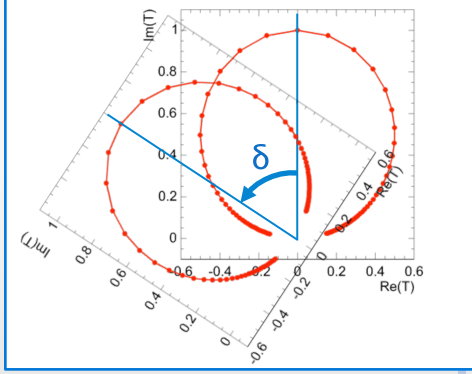
Observation of a rapid change of phase near maximum of magnitude ⇒ resonance!



Argand diagram

BW amplitude with Z(4430) parameters from nominal fit

Tilted by an arbitrary phase δ characteristic of Dalitz analysis



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:
  - ✓ $\Theta^+ \rightarrow K^0 p$, $K^+ n$, 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

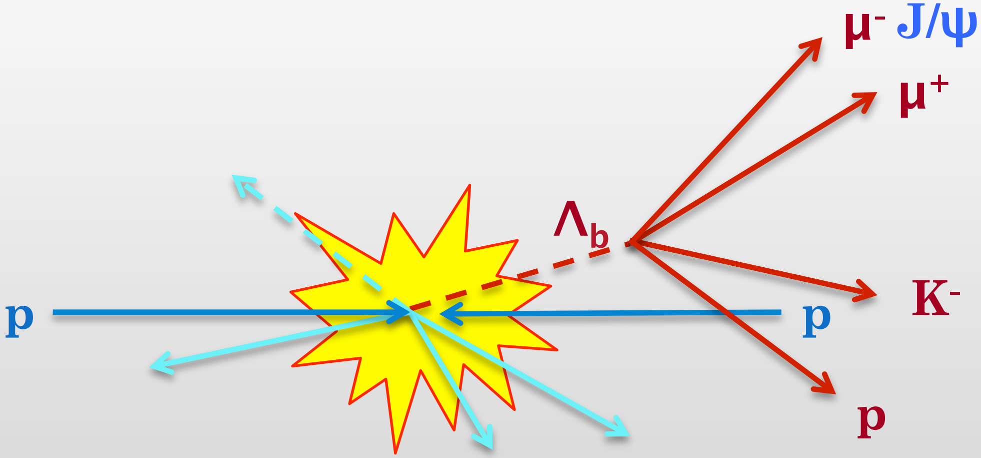
K.H. Hicks, "On the conundrum of the pentaquark", Eur.Phys.J. H37 (2012) 1

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

[LHCb: PRL 111 (2013) 102003]

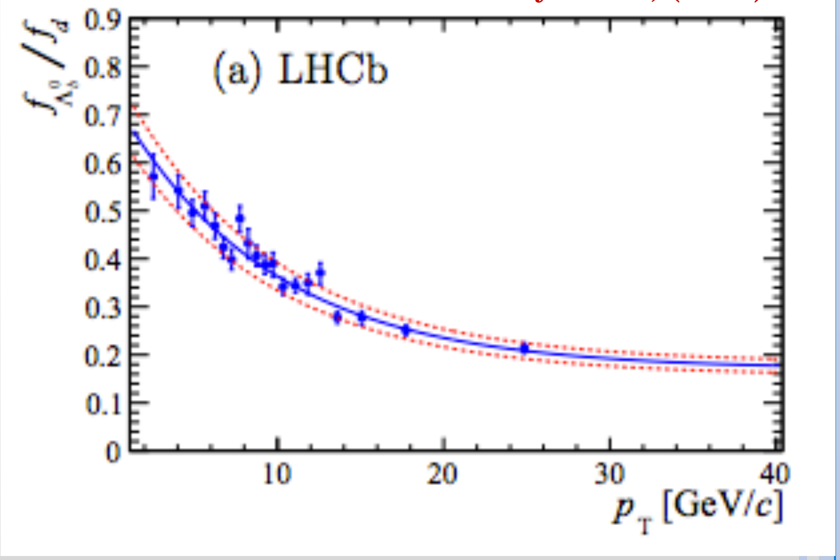
Why did LHCb arrive first? The decay was not observed before!

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



LHCb: JHEP 08(2014)143

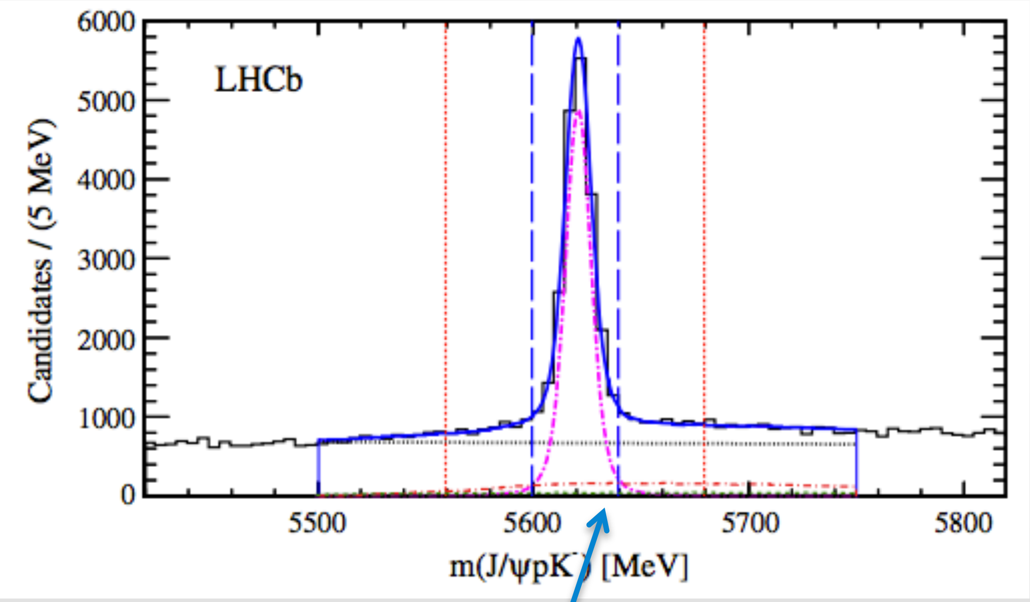
LHCb: Chin. Phys. C40, (2016) 011001



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!
- Measurement of the Λ_b lifetime with $L=1\ fb^{-1}$



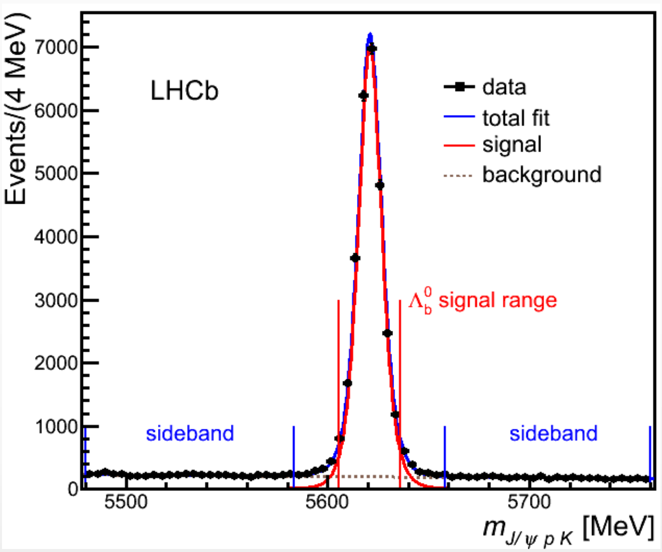
$\tau = 1.482 \pm 0.018 \pm 0.012$ ps

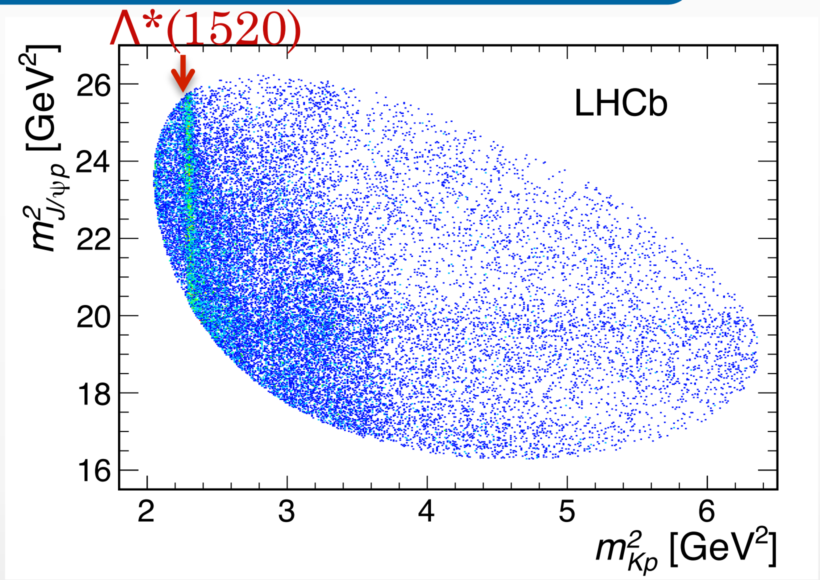
Small contaminations of $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$
where p ←→ K or p ←→ π

Observation of a Narrow Band in the Λ_b Dalitz plane

[LHCb: PRL 115, 07201 (2015)]

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

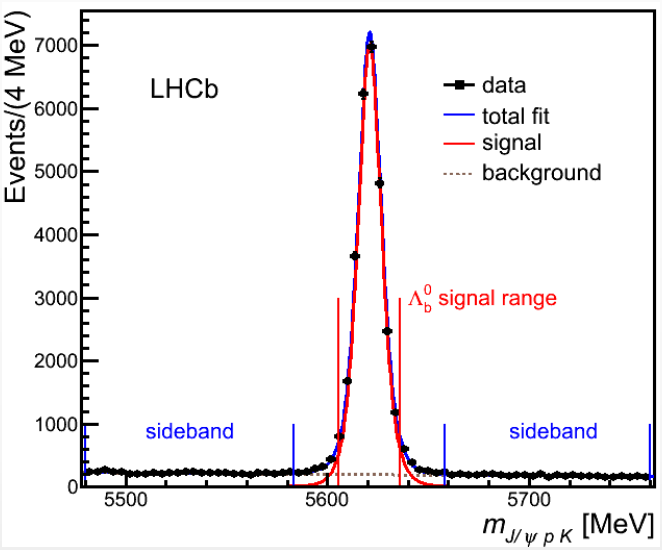


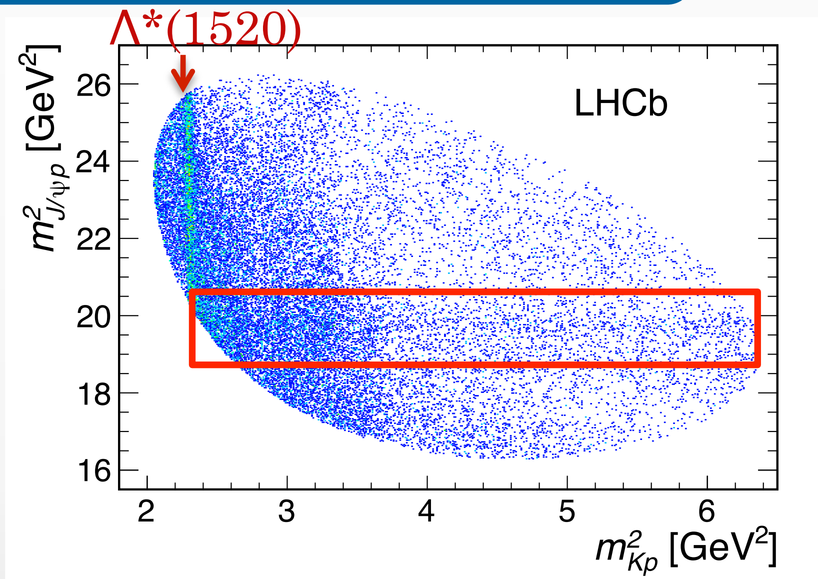


OBSERVATION OF A NARROW BAND IN THE Λ_b DALITZ PLANE

[LHCb: PRL 115, 07201 (2015)]

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

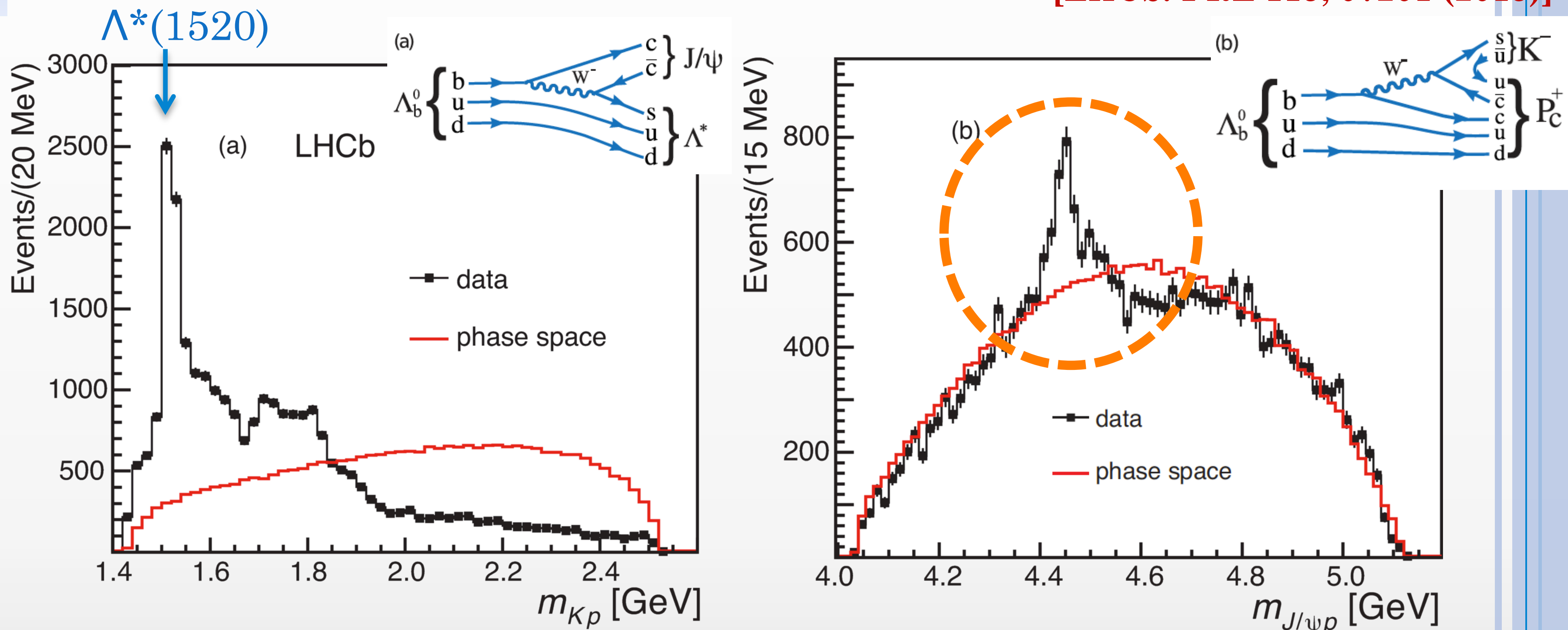




- Efficiency flat over the "Dalitz" plot
- Cross checks:
  - ✓ Veto $B_s \to J/\psi KK$ & $B^0 \to J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters: p ←→K or p ←→ π
  - ✓ Clone and ghost tracks carefully removed
  - ✓ Not a partially reconstructed Ξ_b decay

Unexpected Narrow Peak in m(J/ψ p)

[LHCb: PRL 115, 07201 (2015)]

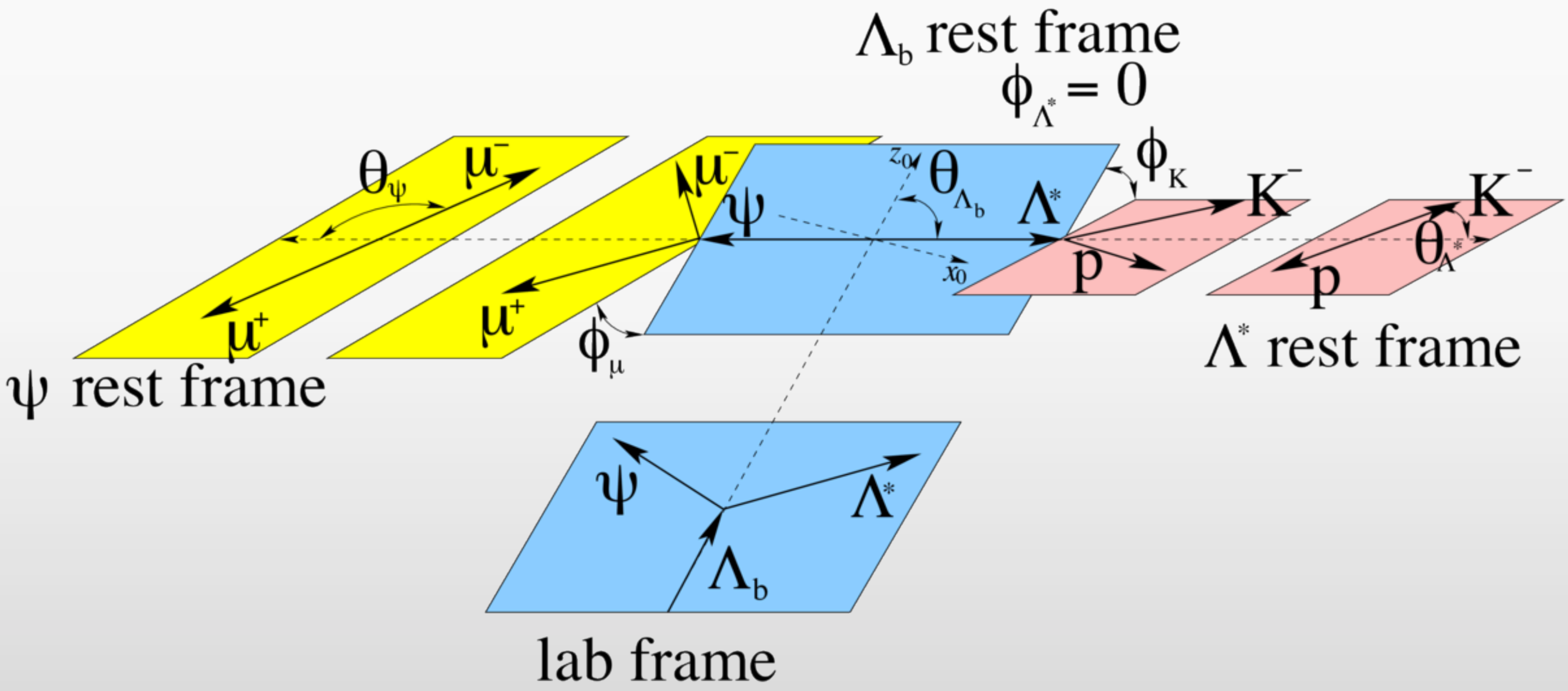


- ➢ A lot of structures in m(pK⁻)!
- ➢ Could it be a reflection of the interfering Λ*'s→ pK⁻?

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)



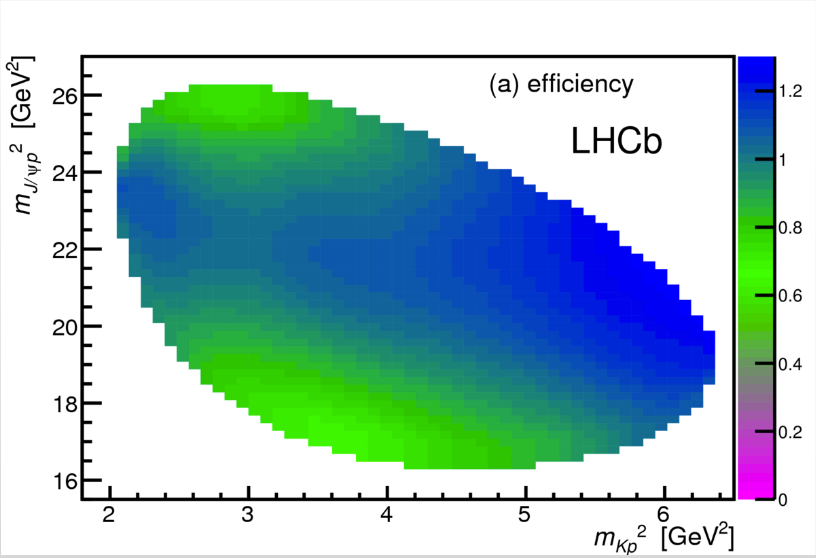
2 FITTERS AT WORK

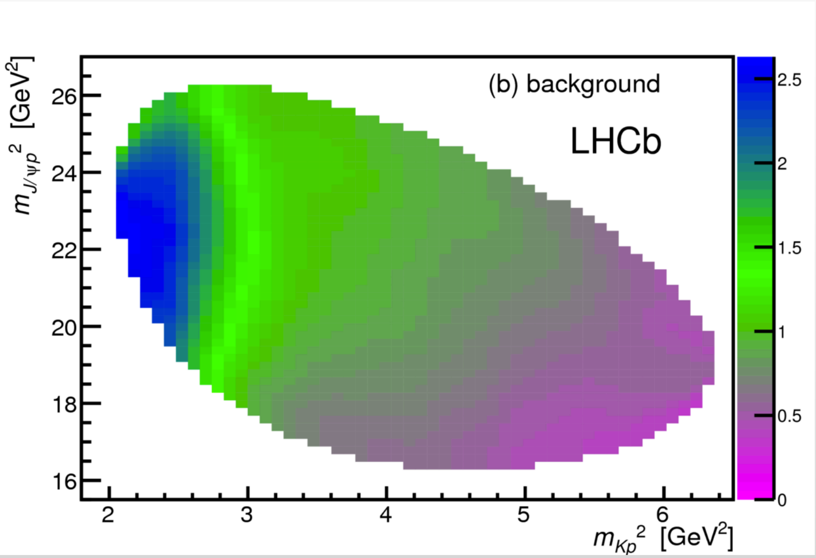
[LHCb: PRL 115, 07201 (2015)]

- Implementation of 2 fitters.
- Background treated differently

cFit (default)

sFit





Λ* Decay Models

[LHCb: PRL 115, 07201 (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

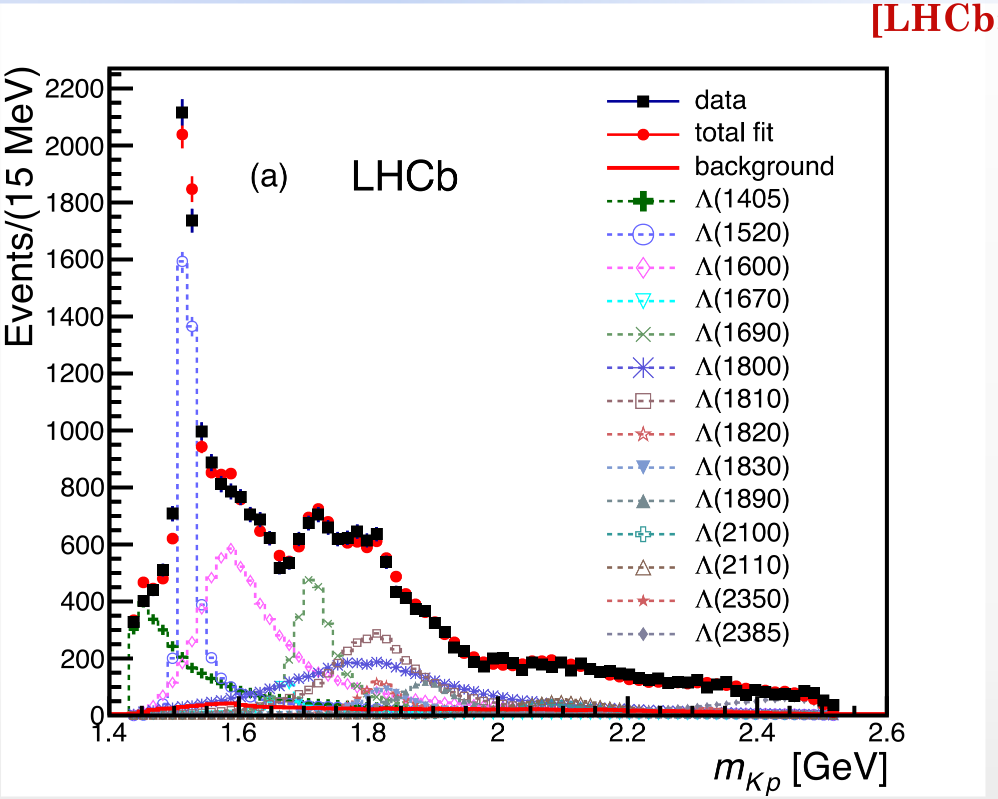
All states, all L

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 Λ*→pK STATES ONLY

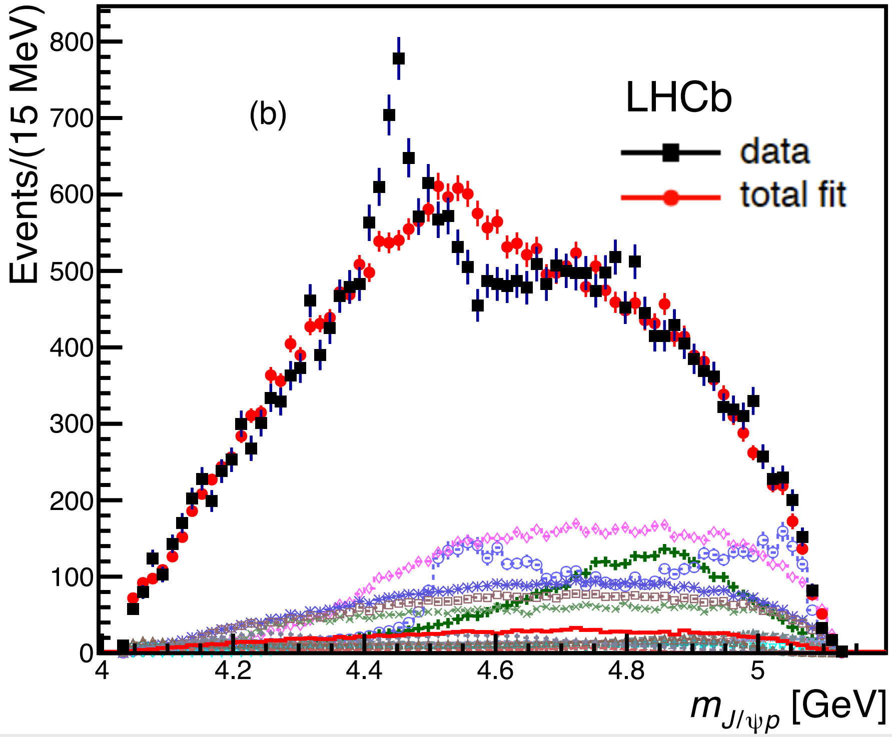
[LHCb: PRL 115, 07201 (2015)]



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)]

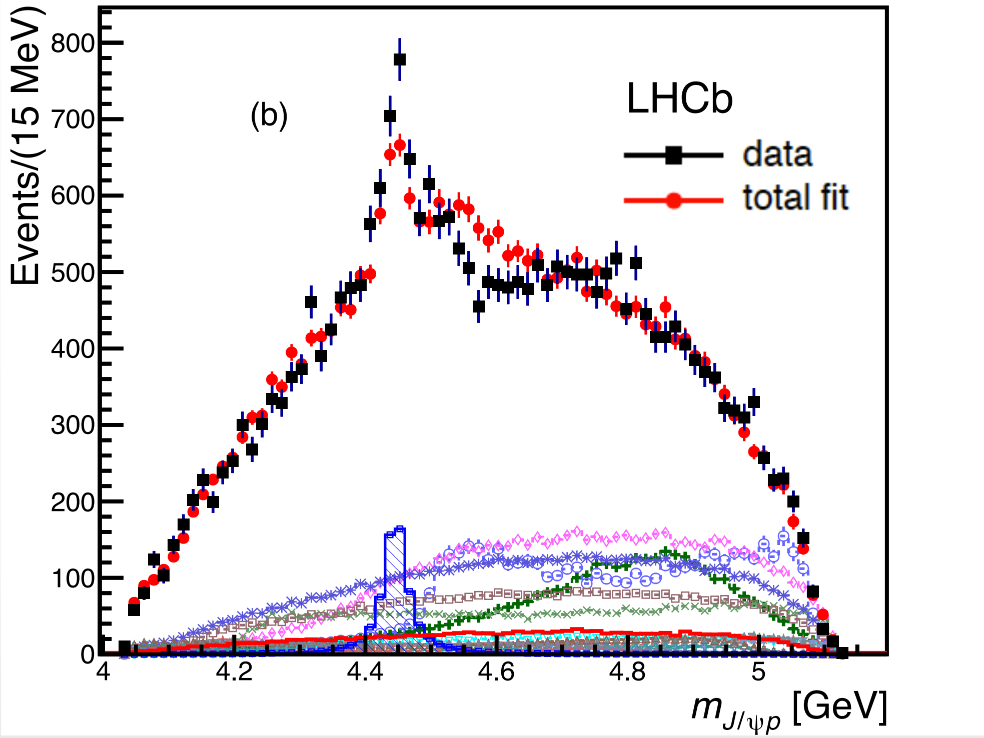


Extended Λ* model:

- …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)]

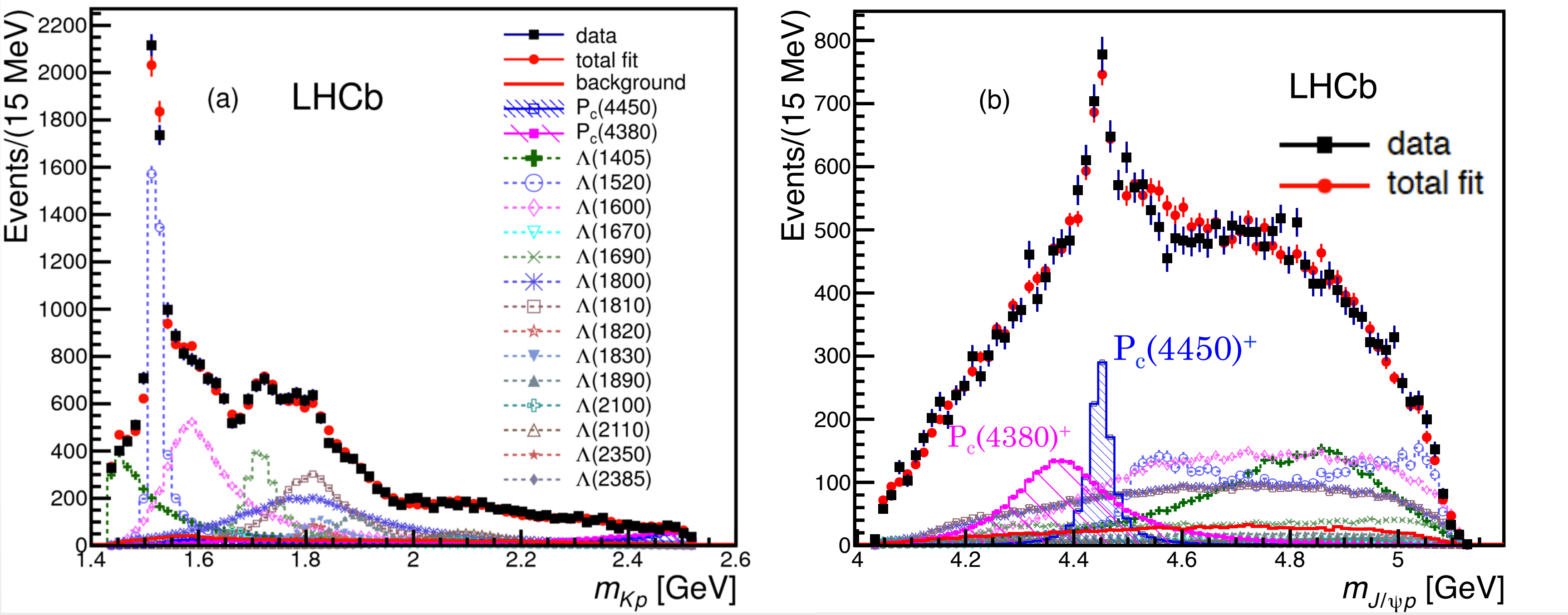


Extended Λ* model + 1 Pentaquark decaying to J/ψ p

- 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 $P_c \to J/\psi\, p$ amplitudes

[LHCb: PRL 115, 07201 (2015)]

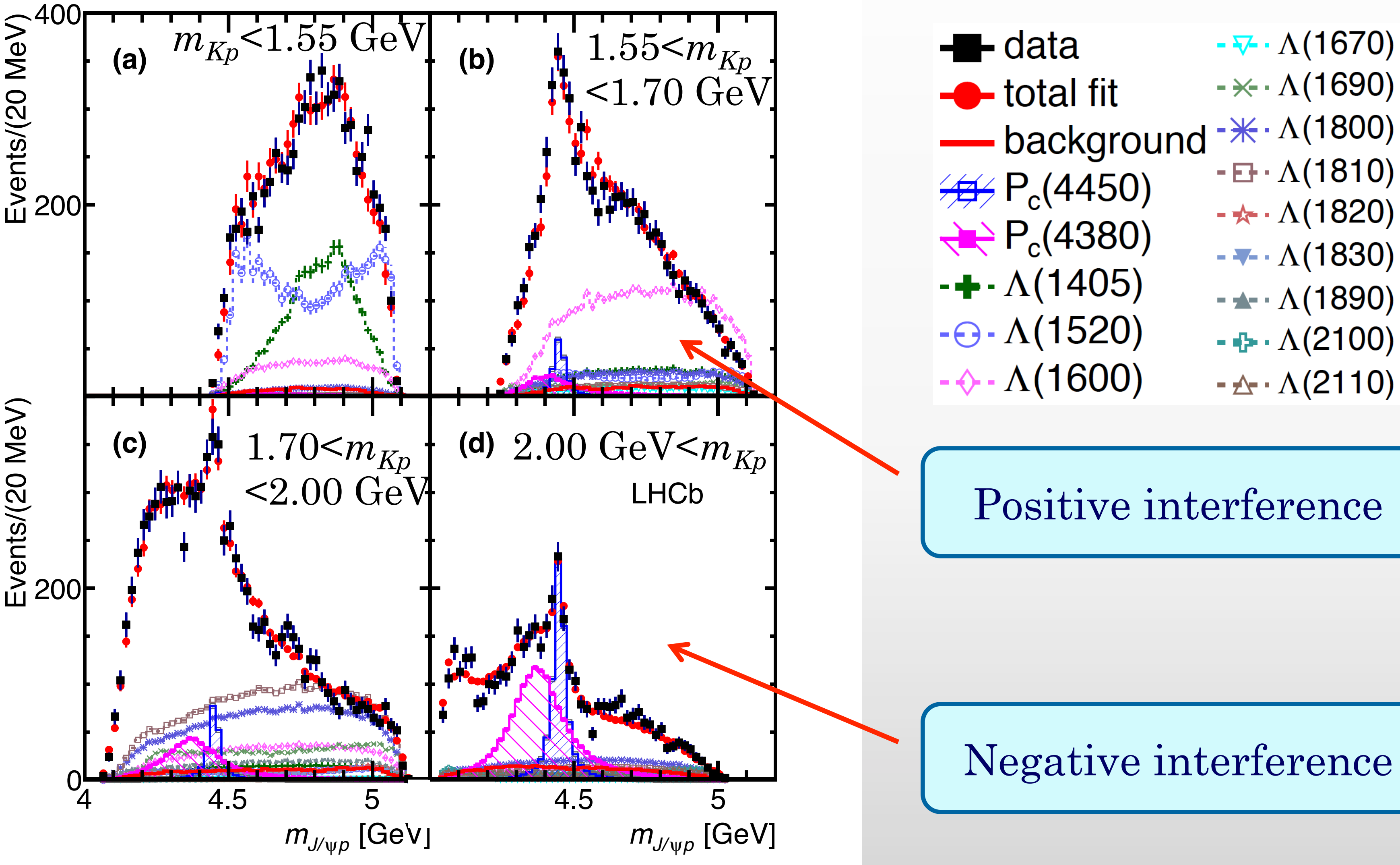


Reduced Λ* model + 2 Pentaquarks decaying to J/ψ p

- 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

Fit Projections

[LHCb: PRL 115, 07201 (2015)]

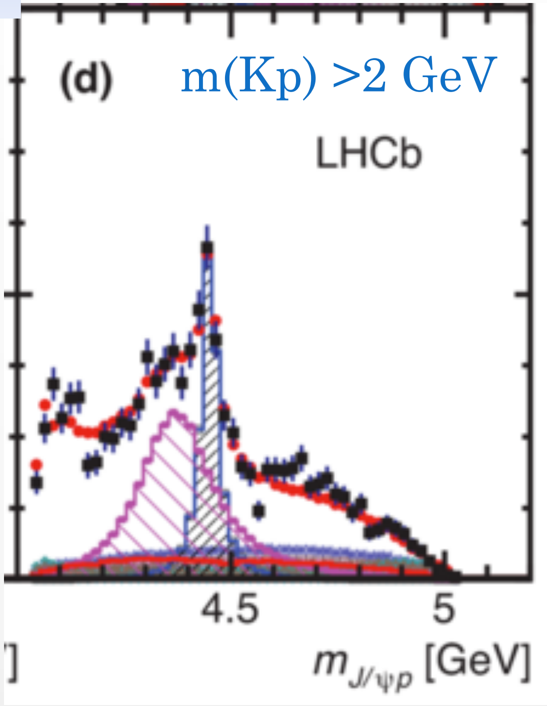


Positive interference

Negative interference

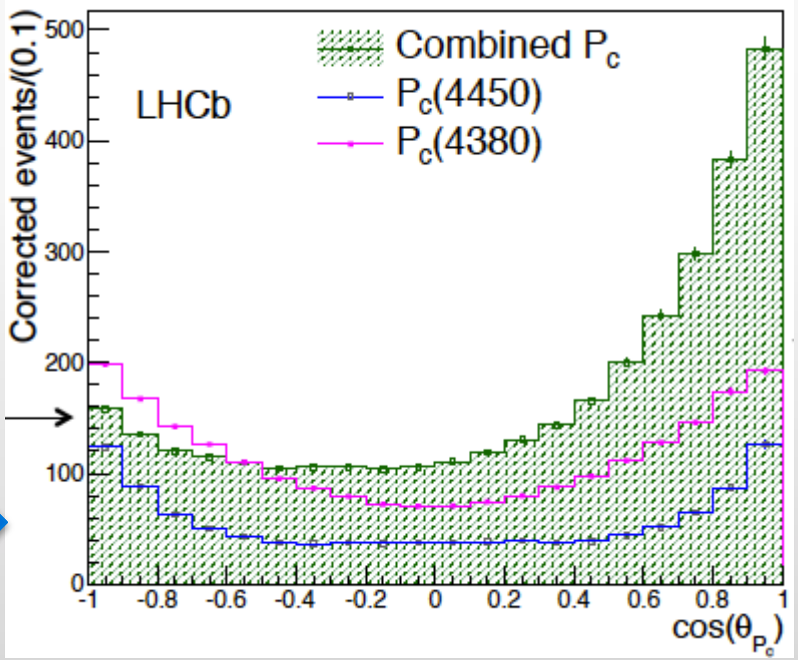
Do We really Need 2 P_c^+'s? YES

[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



SIGNIFICANCES AND RESULTS

[LHCb: PRL 115, 07201 (2015)]

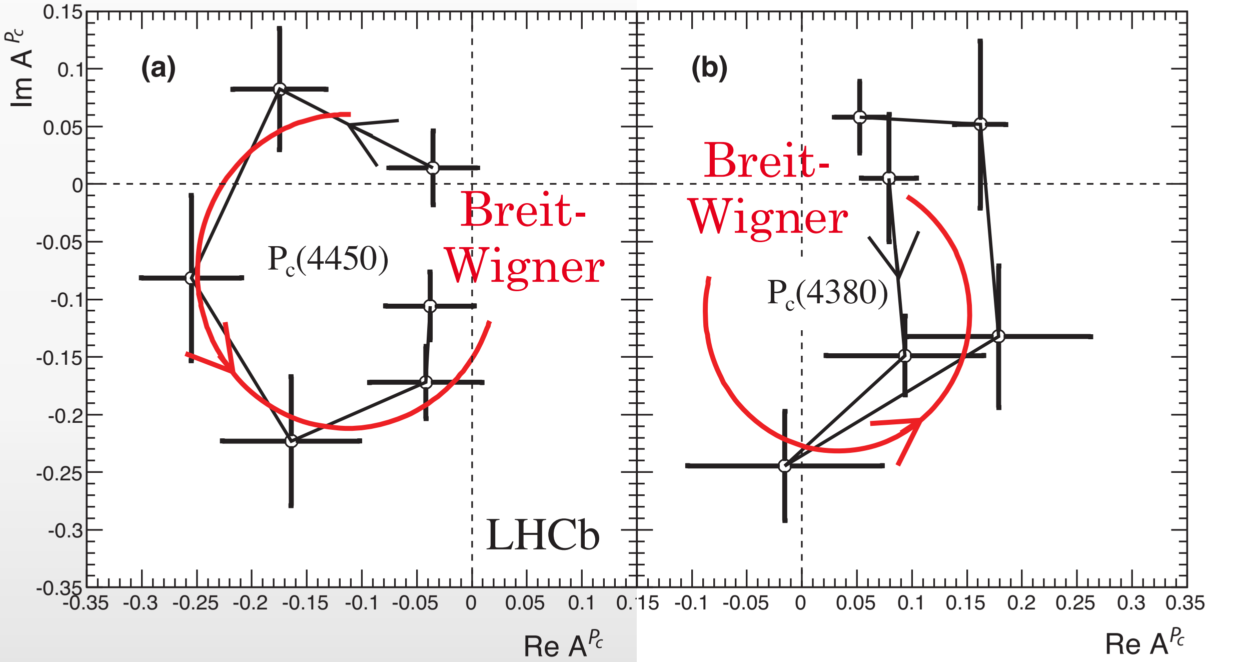
- Simulations of pseudo-experiments are used to quote the significances:
  - ✓ Significance of $P_c(4450)^+$ state is 12σ
  - ✓ Significance of $P_c(4380)^+$ state is 9σ
- Main systematic uncertainty: difference between extended and reduced fit models. Taken in account while computing the significances

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

ARGARD DIAGRAMS

[LHCb: PRL 115, 07201 (2015)]

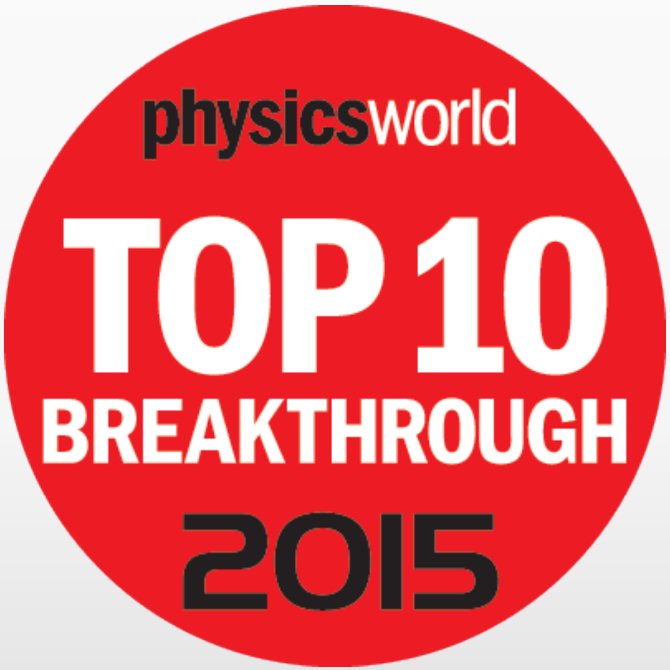
P_c^+ amplitudes for 6 m(J/ψ p) bins between +Γ & -Γ around the resonance mass



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

Pentaquarks on the Media

[LHCb: PRL 115, 07201 (2015)]

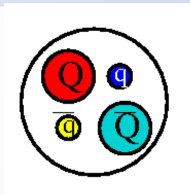


…AND FRIENDS

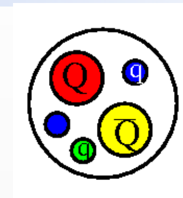
Eur.Phys.J. C74 (2014) 10, 2981

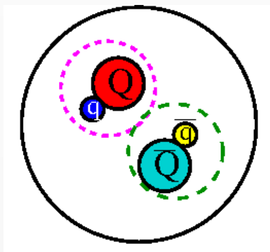
State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	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!

Models for Tetra- and Penta-quarks

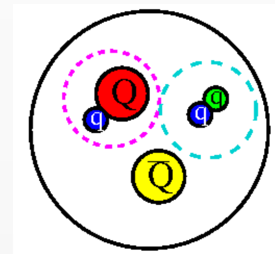


"plain"

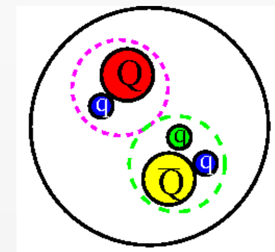


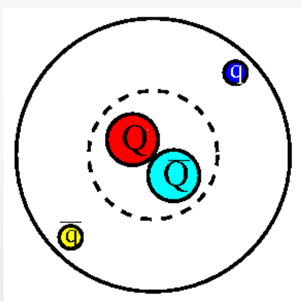


diquark model

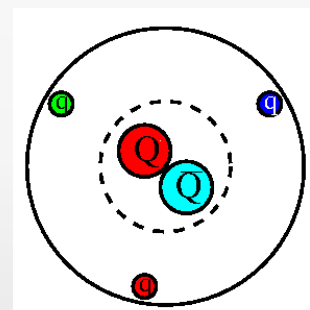


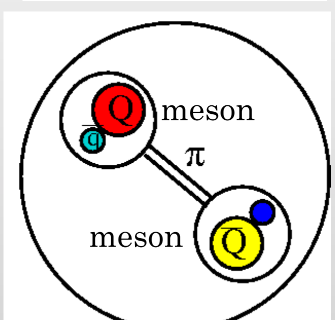
triquark model



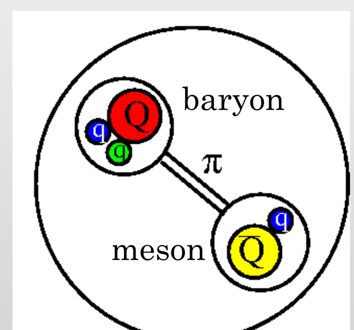


hydro-charmonium model





molecular model



Z(4430)$^+$

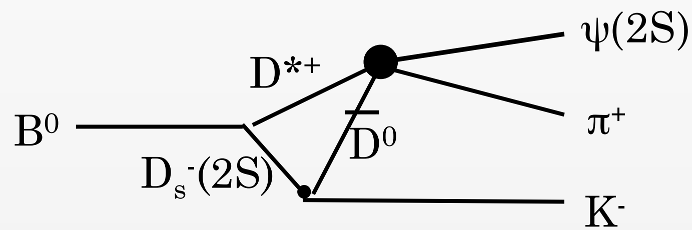
Molecular model

- Positive parity rules out interpretation in terms of $\overline{D}^*(2010)D_1(2420)$ molecule or threshold effect (cusp) [Rosner, PRD76(2007)114002][Bugg, J.Phys.G35(2008)075005]

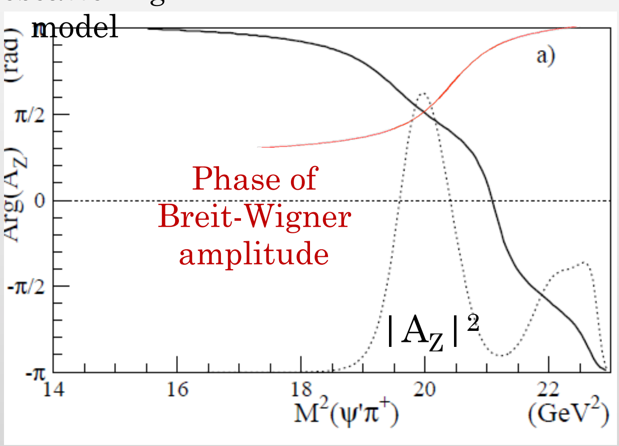
- $D\overline{D}^*(2S)$ molecule? [T. Barnes, F. E. Close, E. S. Swanson, Phys. Rev. D 91, 014004 (2015)]

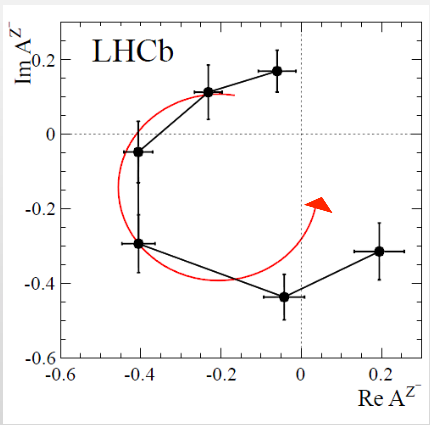
Rescattering Effect

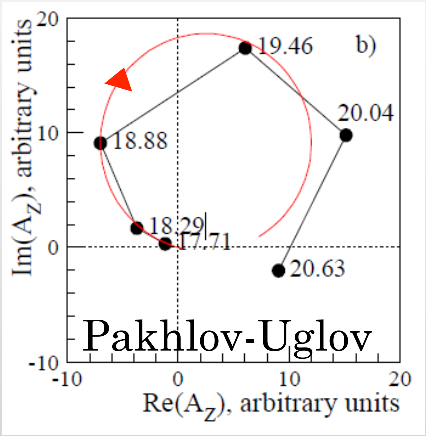
P. Pakhlov, T. Uglov Phys. Lett. B748 (2015) 183



Phase in the rescattering model



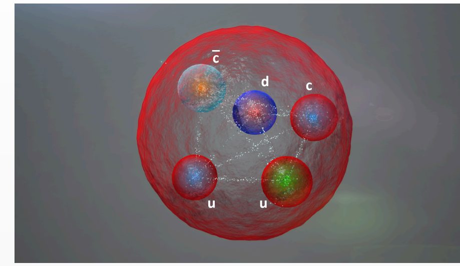


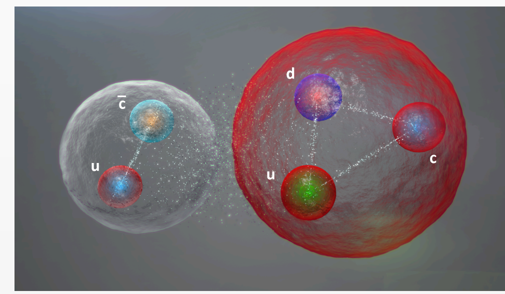


Phase runs in opposite direction

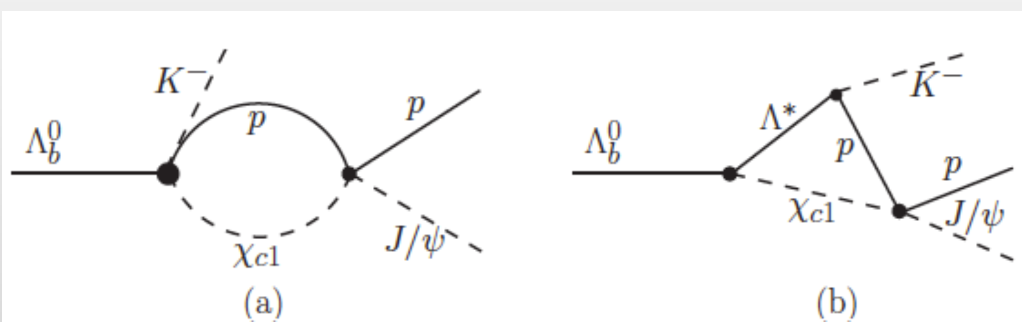
PENTAQUARK P_c^+

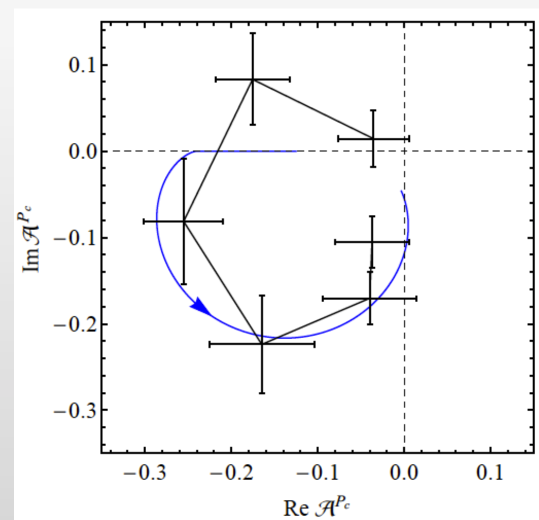
- Tightly bound
  - ✓ Jaffe, PRD15(1977) 267
  - ✓ Strottman, PRD20(1979) 748
  - ✓ Maiani et al. PRD71(2005)014028
- Molecular model with meson exchange for binding
  - ✓ Törnqvist, Z.Phys.C61(1994) 525
- Others (postdictions):
  - ✓ Rescattering, "Cusps"





A narrow pentaquark state challenges many models





PRD 92 (2015) 7, 071502

Summary & Prospect

- *Confirmation of $Z(4430)^+$*
  - $J^P = 1^+$
  - Resonance character shown
  - Molecule or tetraquark? **[Maiani et al, PRD 89, 114010 (2015)]**
- *Observation of two Pentaquarks P_c^+*
  - More data required to determine J^P
  - Resonance character shown

What's next?

- Search for new decay modes or in different system: (e.g.) $\Lambda_b \rightarrow J/\psi\ p\ \pi$
- Search for the isospin partners
- Search for other (distinctive) states: (e.g.) $cc\overline{du}$ or triple charged pentaquarks
- Confirmation of many charmonium-like states

Back-up slides

Feed-Downs of $D_1/D_2^* \to D^*\pi$ Decays into $D\pi$ Mass Spectrum

Inclusive analysis
$pp \to D^{(*)+} \pi^- + X$
[LHCb: JHEP 09 (2013) 145]

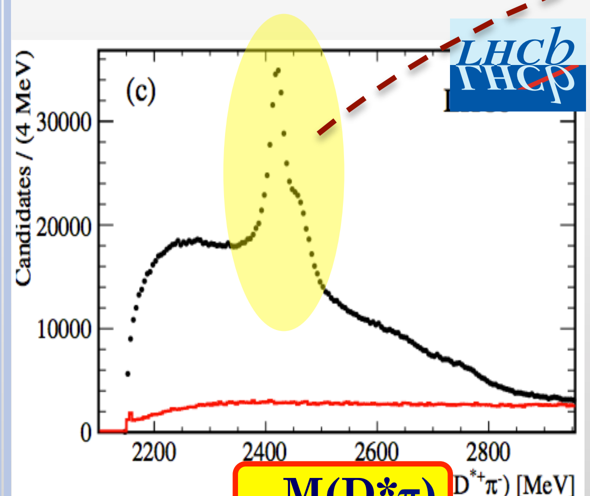
j_q=3/2 doublet

- 3 peaks in $D\pi$
  - ✓ $D_2^* \to D\pi$
  - ✓ $D_1 \to D^*\pi$ feed-down
  - ✓ $D_2^* \to D^*\pi$ feed-down
- 2 peaks in $D^*\pi$

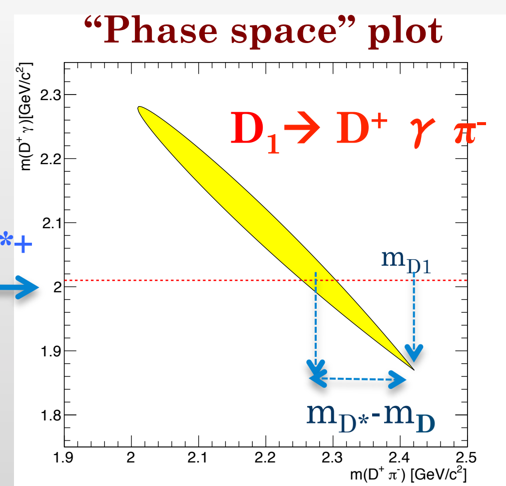
overlapped if $\Gamma > m(D^*)-m(D)$

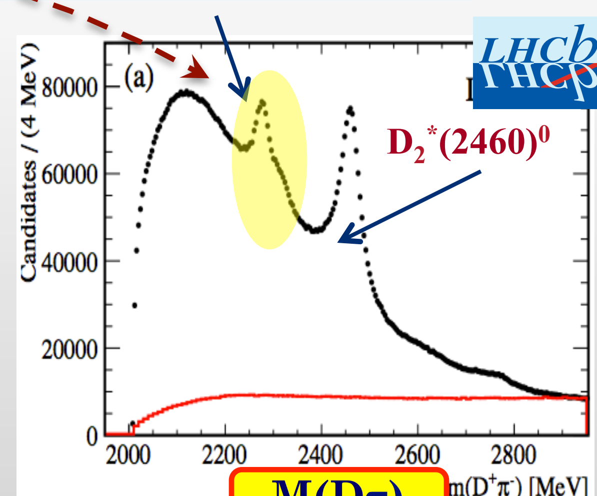
	j_q	J^P	Allowed decay mode $D\pi$	$D^*\pi$
D_0^*	1/2	0^+	yes	no
D_1'	1/2	1^+	no	yes
D_1	3/2	1^+	no	yes
D_2^*	3/2	2^+	yes	yes

$D_1(2420)^0 / D_2^*(2460)^0$ feed-down
└▶ $D^{*+} \pi^-$
└▶ $D^+ \gamma/\pi^0$



M(D*π)





M(Dπ)

Second Exotic Z^+?

[PRL 112, 222002 (2014)]

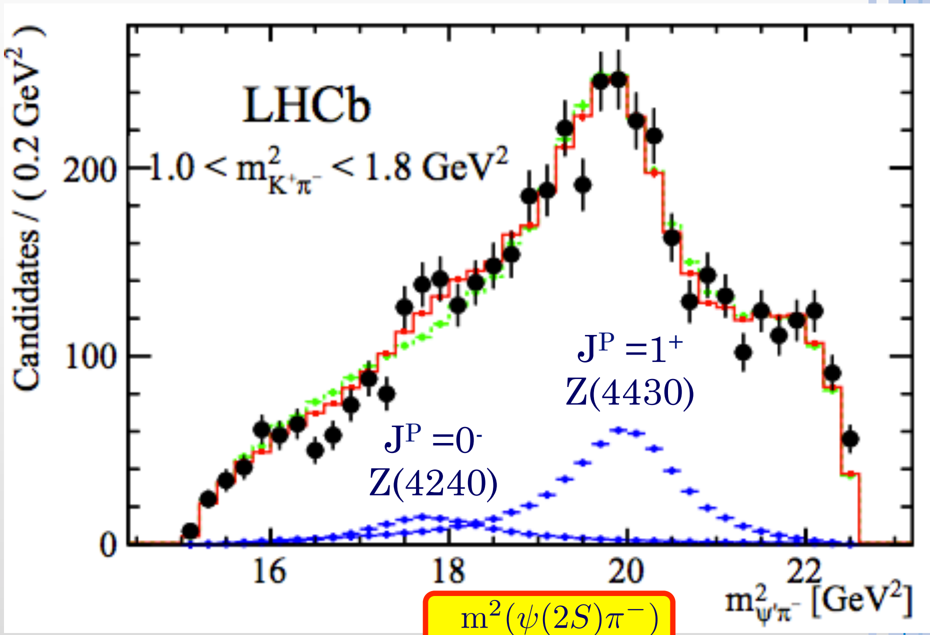
Fit confidence level increases with a second exotic ($J^P=0^-$) component, but…

- No evidence for Z_0 in model independent approach.
- Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterize this state.

$$M_{Z_0} = 4239 \pm 18^{+45}_{-10}\text{MeV}$$
$$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}\text{MeV}$$
$$f_{Z_0} = (1.6 \pm 0.5^{+1.9}_{-0.4})\%$$

Mass and width consistent with other Z's observed by Belle:

- $Z^- \rightarrow \chi_{c1}\pi^-$ ($J^P \neq 0^-$) **[PRD 78 (2008) 072004]**
- $Z^- \rightarrow J/\psi\pi^-$ **[arXiv: 1408.6457]**



$m^2(\psi(2S)\pi^-)$