Pentaquark at LHCb

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on behalf of the LHCb Collaboration

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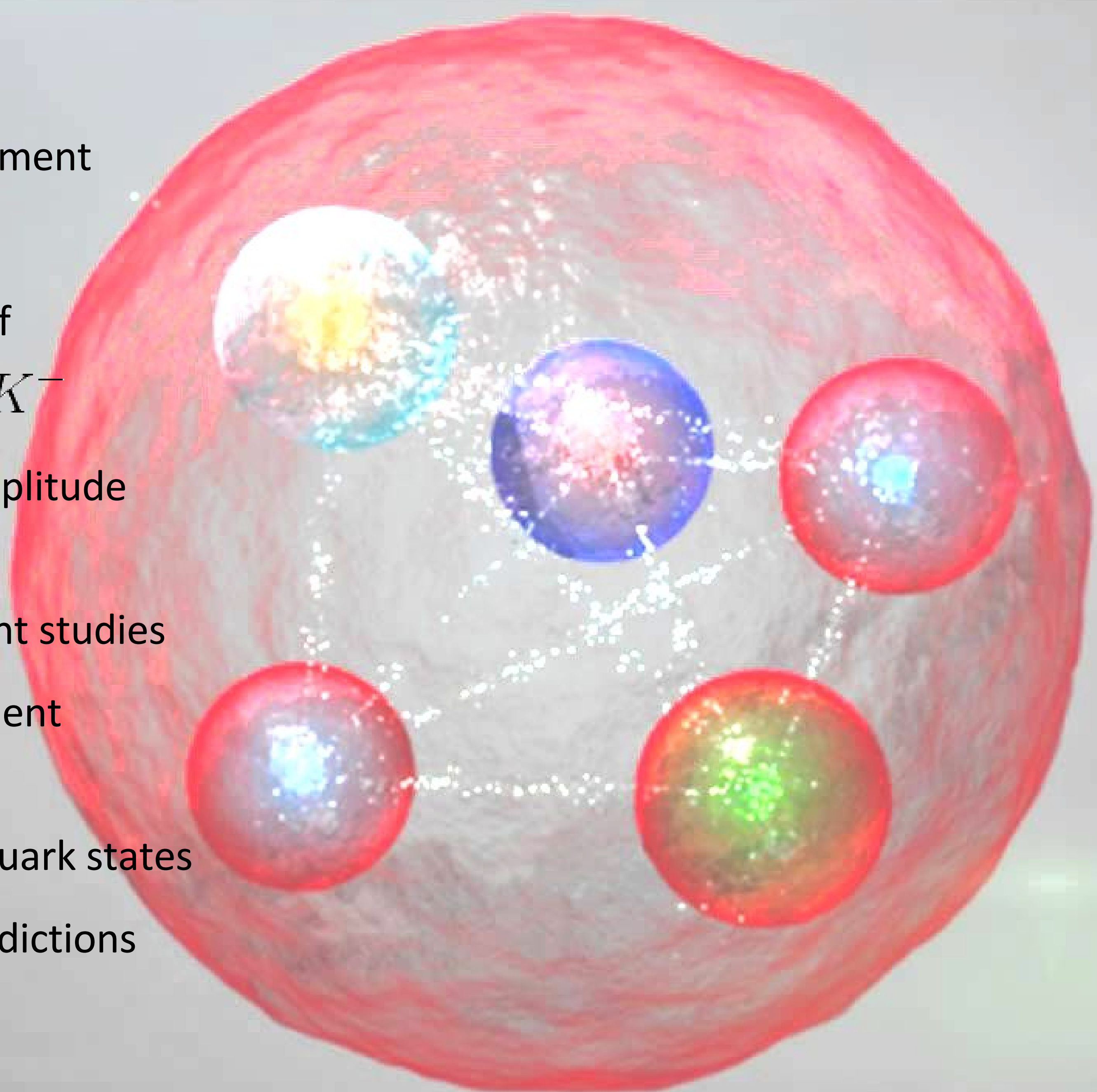
INFN Sezione di Firenze, Consiglio di Sezione 2016-04-05

Outline

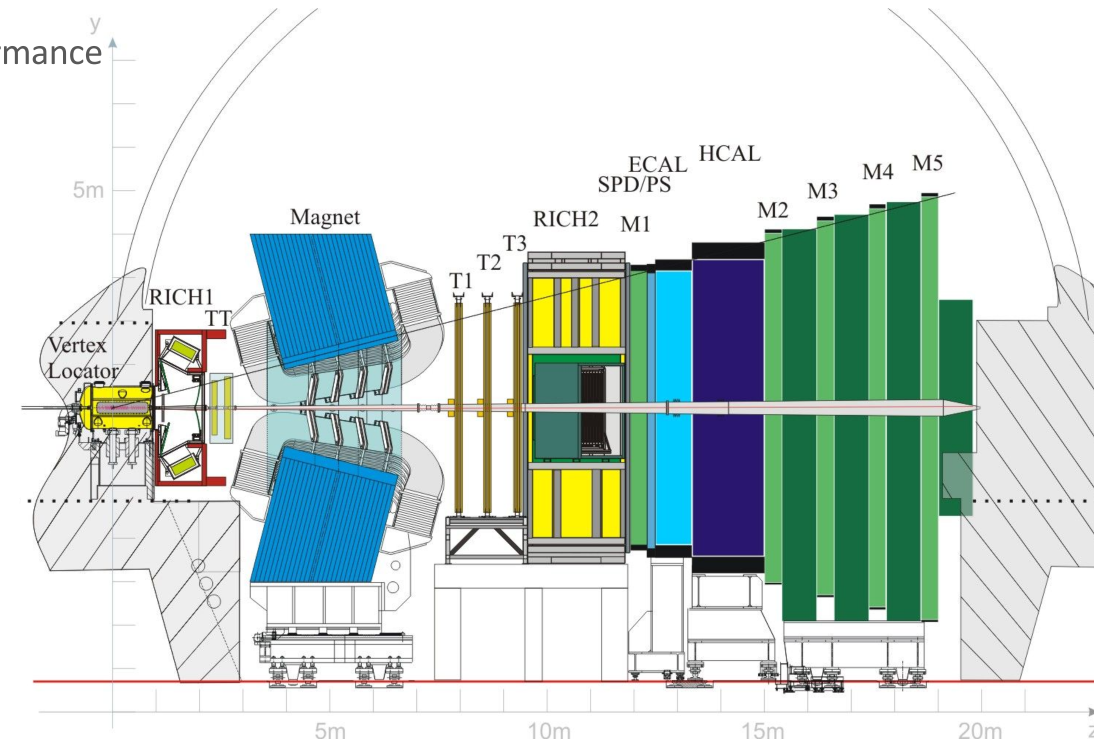
- The LHCb experiment
- The Λ_b baryon
- The Dalitz Plot of $\Lambda_b^0 \to J/\psi\, p\, K^-$
- The bases of Amplitude Analysis
- Model dependent studies
- Model independent confirmation
- The new pentaquark states
- Theoretical postdictions
- Conclusions



Introduction: the LHCb experiment

Originally designed to search indirect evidence of new physics in CP violating a rare *b* and *c* decays, LHCb is today a general purpose detector in the forward region.

- ➔ unique geometrical coverage
- ➔ outstanding track momentum and vertex resolution
- ➔ excellent Particle Identification performance
- ➔ unique trigger strategy



Tracking efficiency	> 96 %
Decay time resolution	45 fs
Momentum resolution	0.5 - 1.0 %
Software trigger input	10^6 events / s

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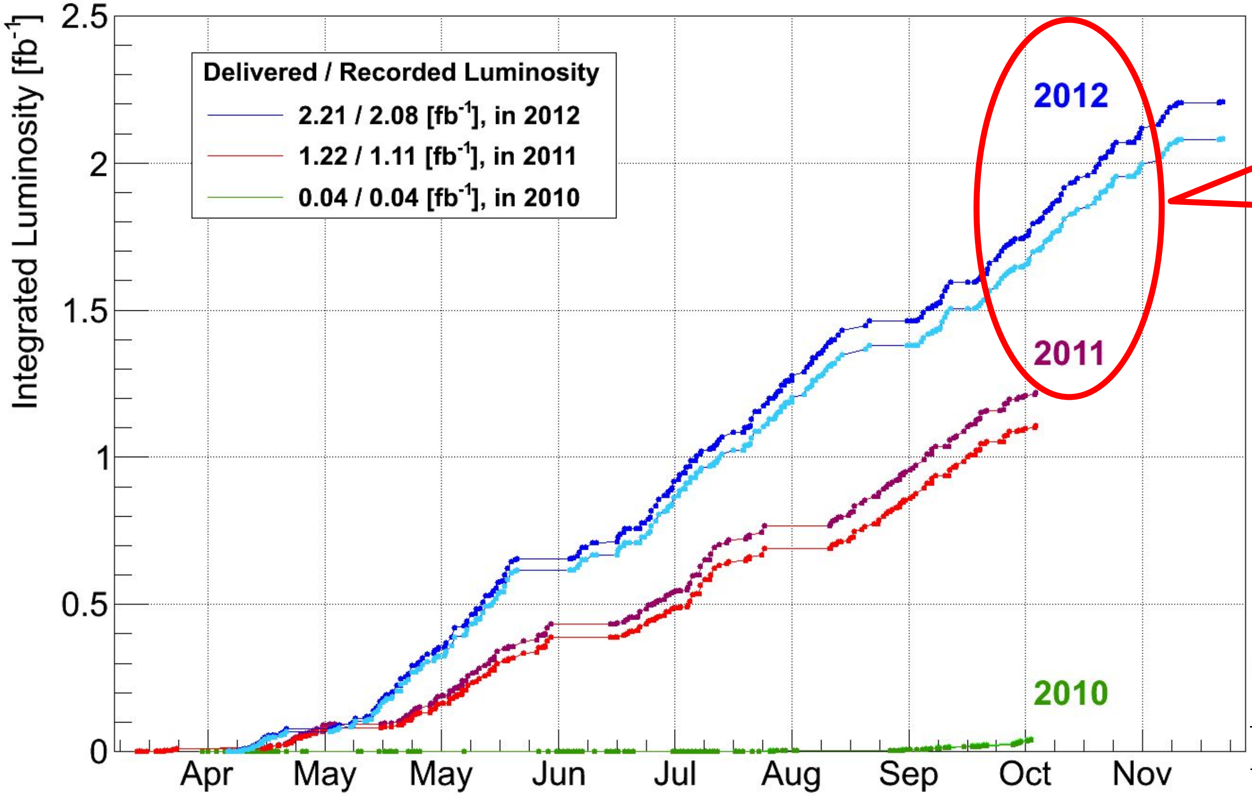
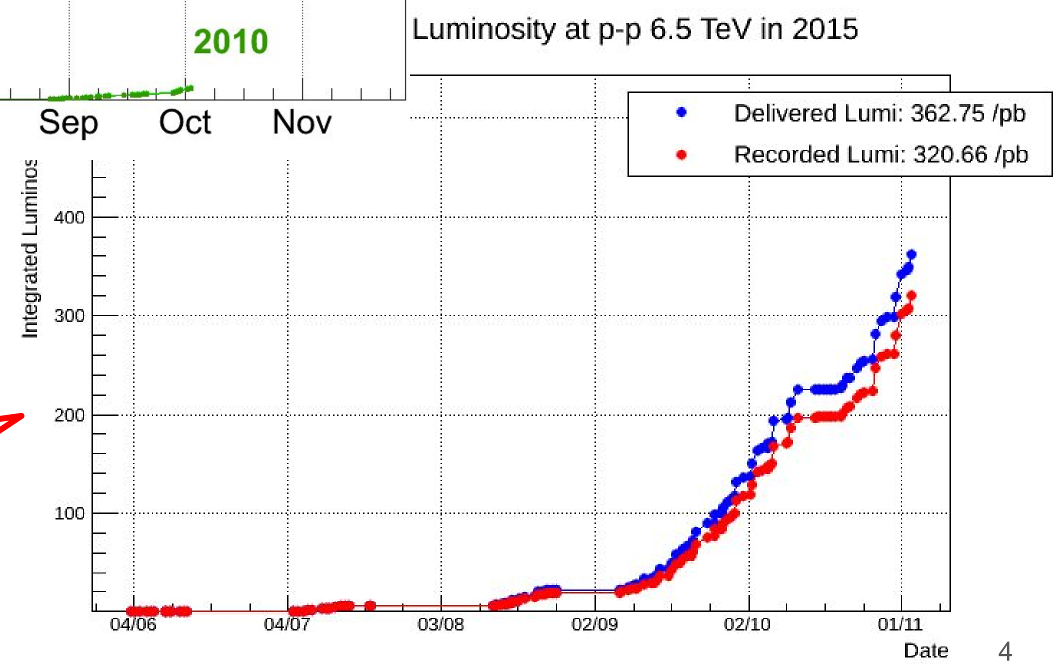


Used in the analyses presented **today**.

3 fb^{-1} of data collected in 2011 and 2012

Soon new results using the data collected in Run2, with increased *b*-hadron production cross section



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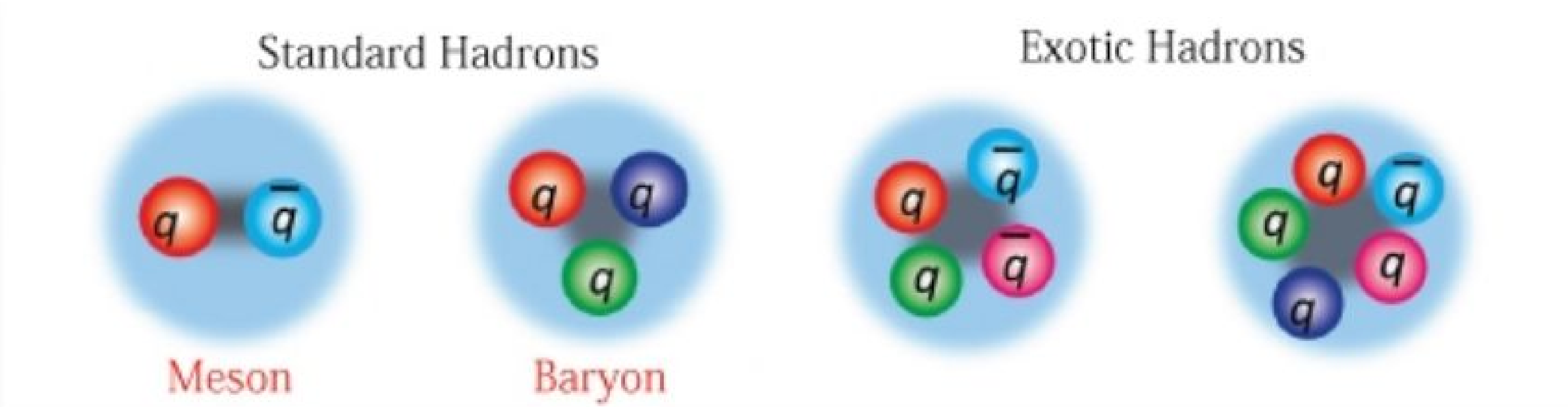
The pentaquark discovery

Exotic hadrons: *a story lasting half a century*



Stati composti da 4 o 5 quarks previsti sin dalla originaria formulazione del modello a quark

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".

Exotic hadrons: *prejudices*

- No convincing states 51 years after Gell-mann & Zweig proposed qqq and qqqq$\bar{q}$ states
- Previous “observations” of several pentaquark states have been refuted
- This includes:

$$\Theta^+ \to K^0 p, K^+ n \quad \text{(at 1.54 GeV/c)} \qquad \Gamma \sim 10\text{MeV}$$
$$\text{Resonances in } D^{*-}p \text{ at } 3.10 \text{ GeV}, \Gamma = 12\text{MeV}$$
$$\Xi^{--} \to \Xi^- \pi^-, \text{ mass } 1.862 \text{ GeV}, \Gamma < 18\text{MeV}$$

However, these states were found with bump-hunting which had many false-positive examples in light-flavour spectroscopy

- Cusp effects
- Opening of new thresholds
- ...

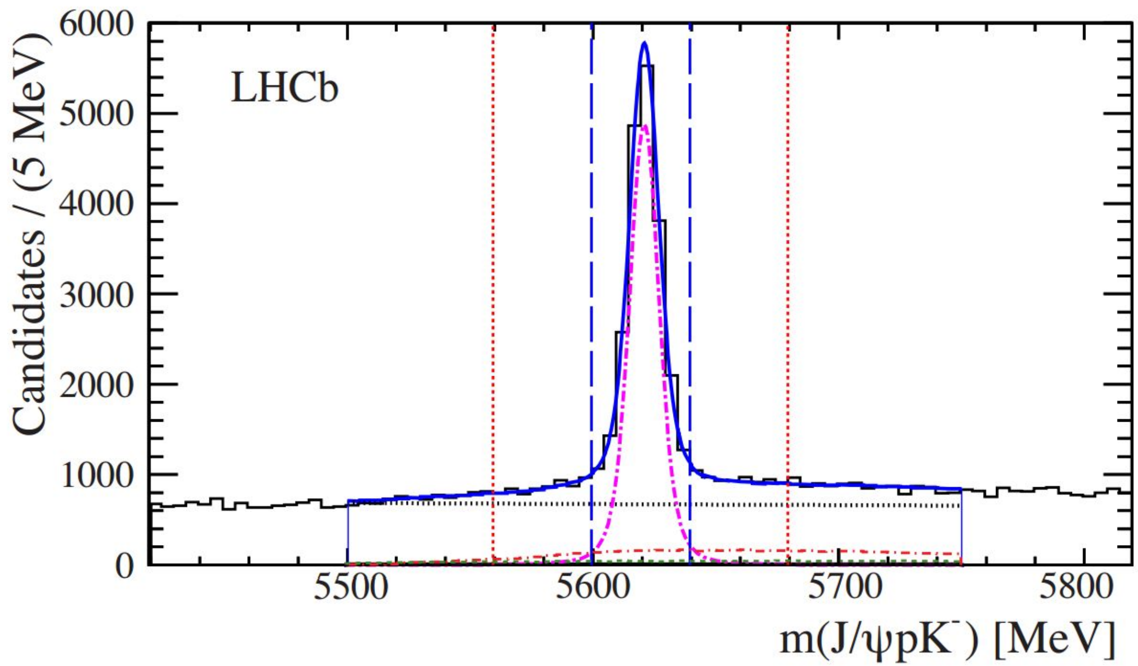
LHCb observed for the first time the decay $\Lambda_b^0 \to J/\psi\, p\, K^-$

July 9, 2013

Using 1.0 fb^{-1} of data collected in 2011

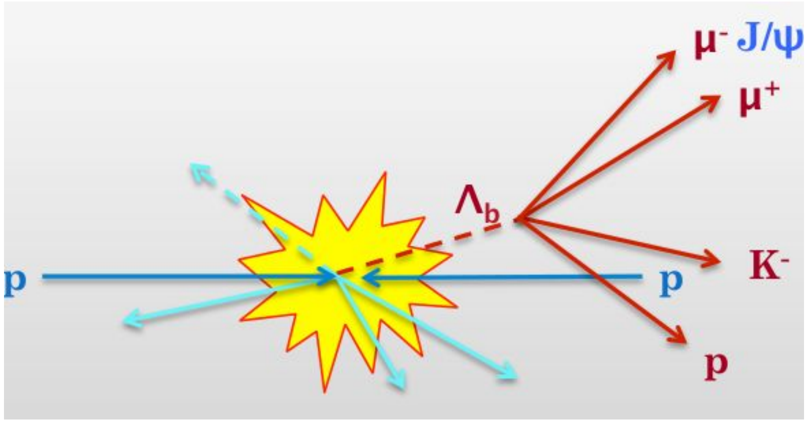
- First observation of the decay mode $\Lambda_b^0 \to J/\psi\, p\, K^-$
- Unprecedented precision in the lifetime measurement

$$\tau_{\Lambda_b} = 1.482 \pm 0.018 \pm 0.012 \text{ ps}$$



Λ_b production cross-section at Tevatron was modest, and production at ***b* factories in forbidden** (kinematics).
Very effective **trigger** on J/psi dimuons at LHCb.

Very few competitors for LHCb in this area.

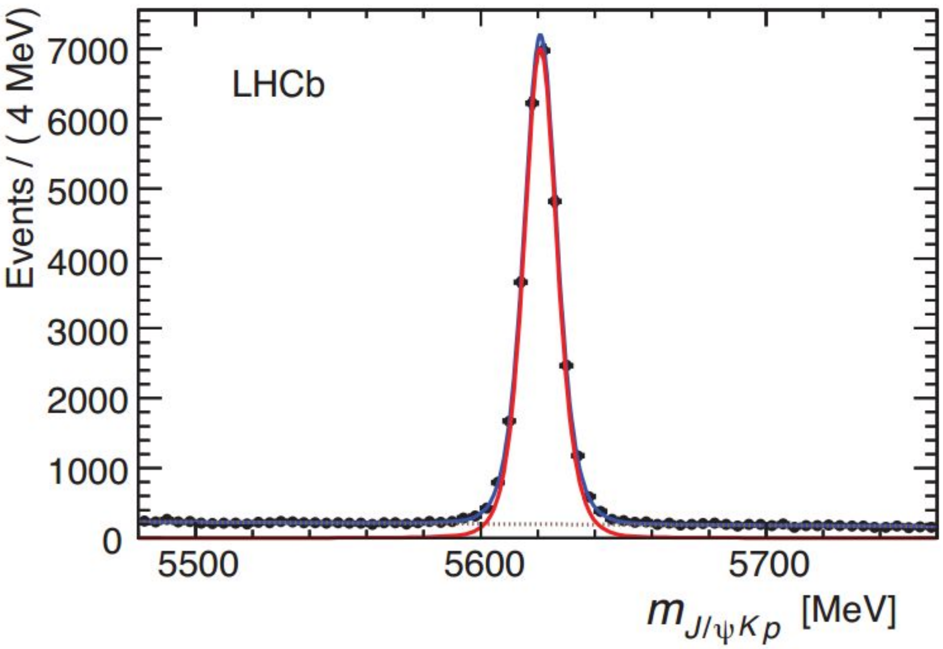


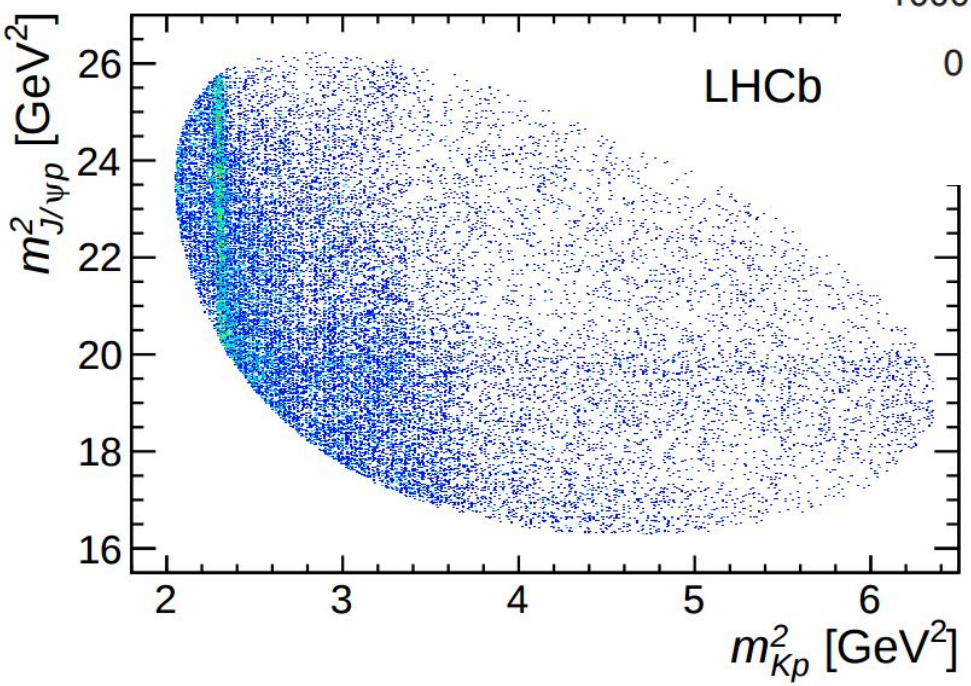
Reanalysis with the full Run1 dataset (3 fb^{-1})

July 13, 2015

~ 26 000 candidates

First look at the Dalitz plot





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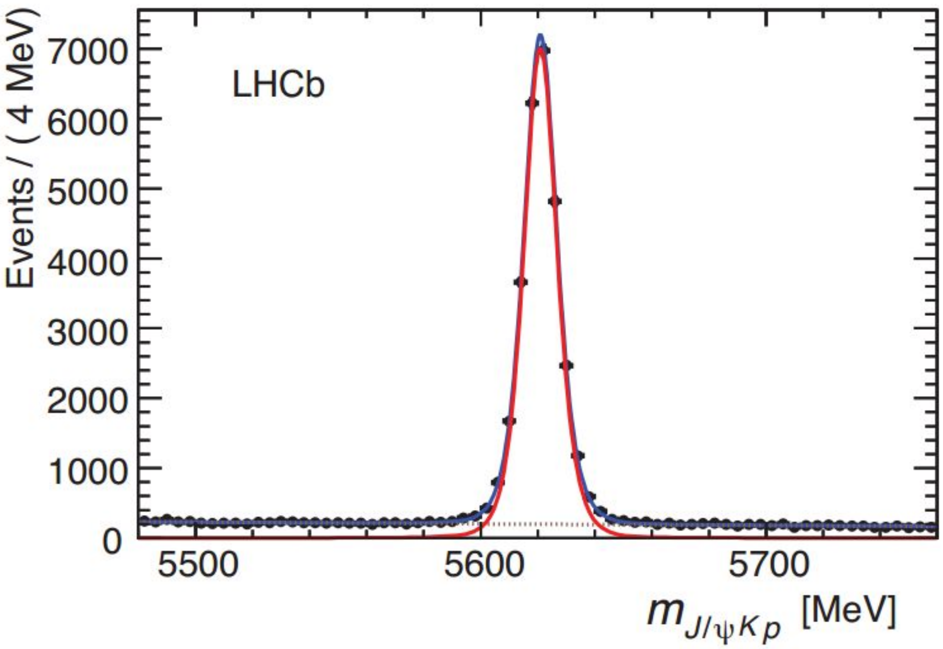

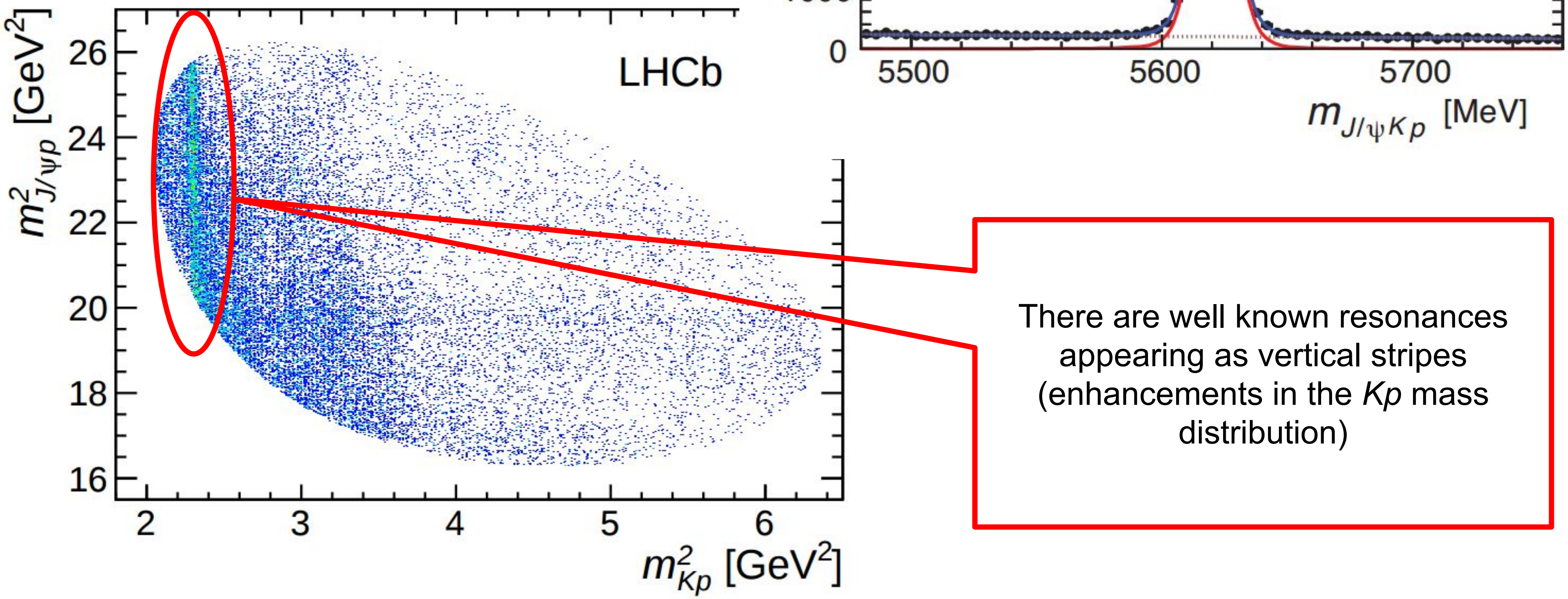

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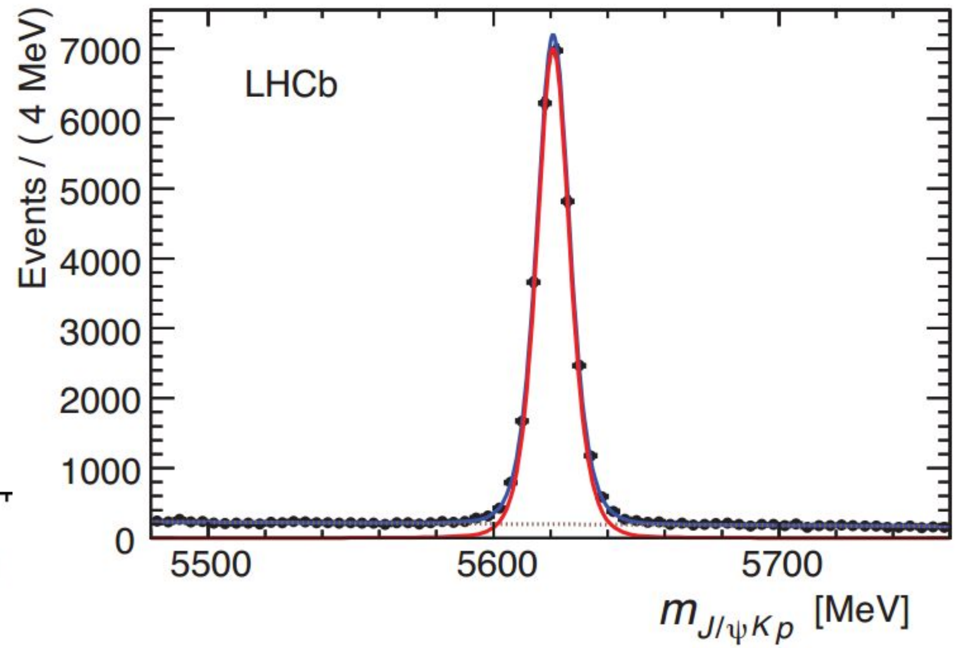
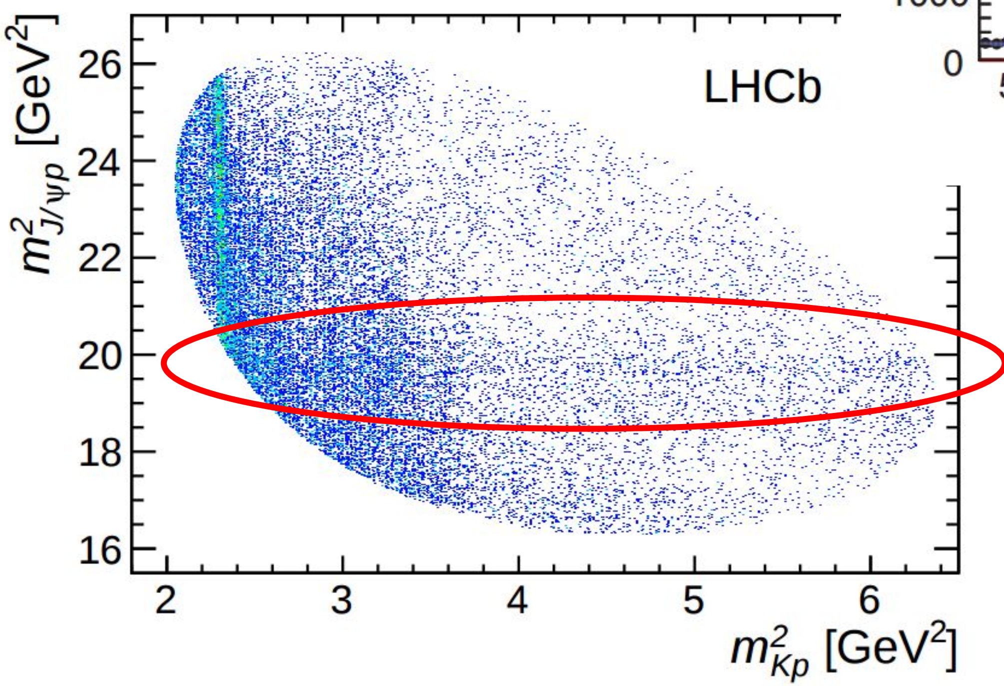




Observed an unusual structure in the Dalitz plot:

Could it be a J/ψ p resonance?

Possible "background" explanations

- Misidentified B meson decays?
  - $B_s \to J/\psi\, K^- K^+$
  - $B^0 \to J/\psi\, K^- \pi^+$
  - ...

  These decays are vetoed using the alternative Particle Identification hypothesis

- Clone tracks?
  - The structure is robust against different strategy of clone rejection

- Ghost tracks ?
  - No reason for being peaked, structure robust against very strict track quality requirements
- Cross-feed from Ξ_b decays checked and excluded.

Ok. Let's say it is an authentic Λ_b decay.
The peak can still be a QCD effect as in other pentaquark states in the past.

Amplitude Analysis

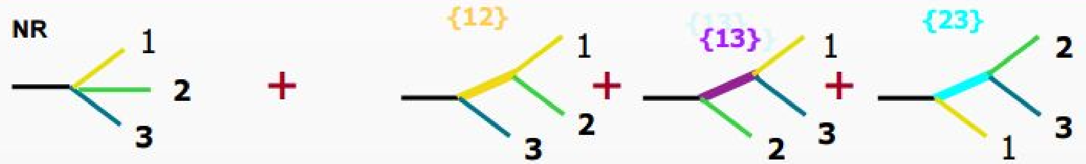
to exclude the Null Hypothesis

Amplitude Analysis

If this is a real resonance, it has to behave as a resonance not only in the mass distribution, but also under all the angular distributions!

We try to describe a set of angular distributions as known and expected resonances.

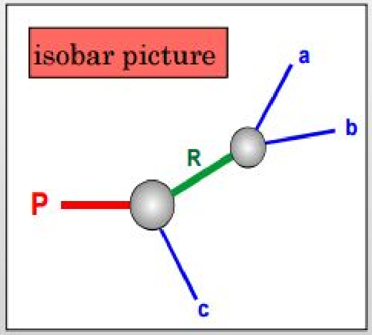
Isobar model: assume a three-body decay as made of non-resonant + quasi two body decay amplitudes.

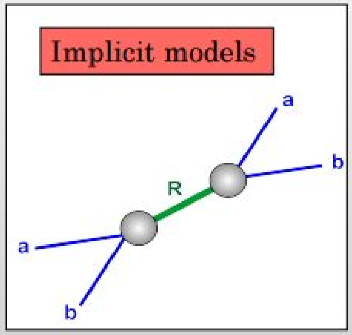


Three-body amplitude

$$\mathcal{A}_D(s_{12}, s_{13}) = a_0 e^{i\delta_0} + \sum_r a_r e^{i\delta_r} \mathcal{A}_r(s_{12}, s_{13})$$

NR term(direct 3 body decay)





Notice.

This is true for the **amplitude**. Since interference between resonances can be disruptive, it does not directly apply to the decay width (A^2).

When fitting the decay amplitudes, this makes the normalization of the total pdf ($\propto$ decay width) computationally expensive.

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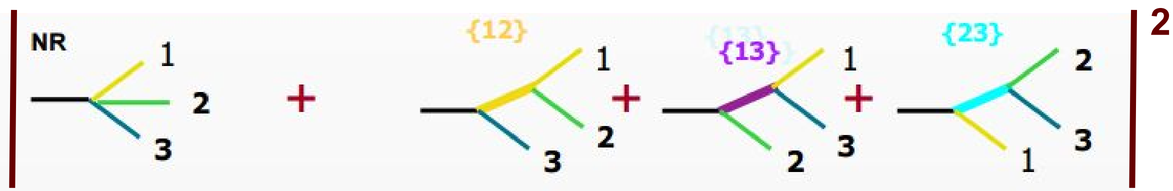
$\Gamma =$



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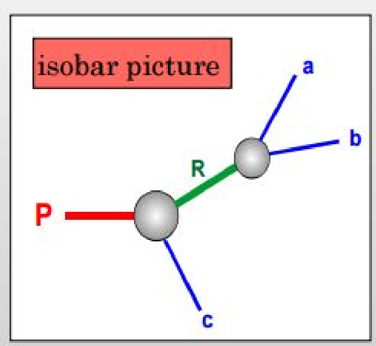

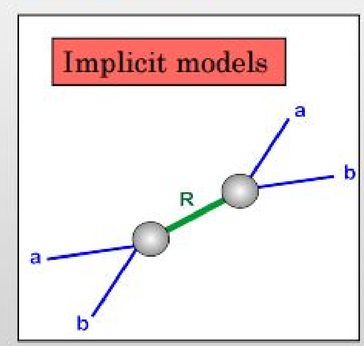

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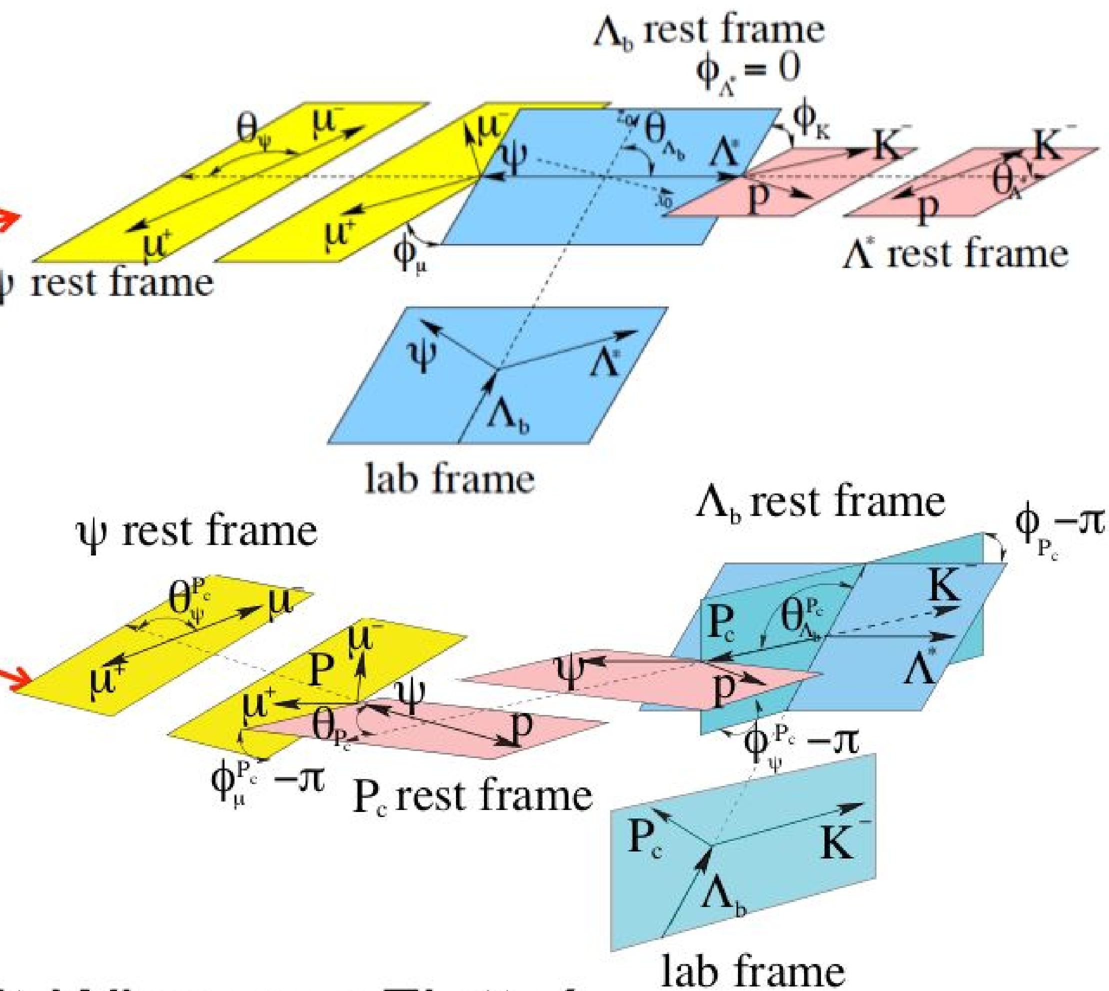
Definition of the constraining variables

- Two interfering channels:

$\Lambda_b \to J/\psi \Lambda^*$,
$\Lambda^* \to K^- p$

&

$\Lambda_b \to P_c^+ K^-$,
$P_c^+ \to J/\psi p$

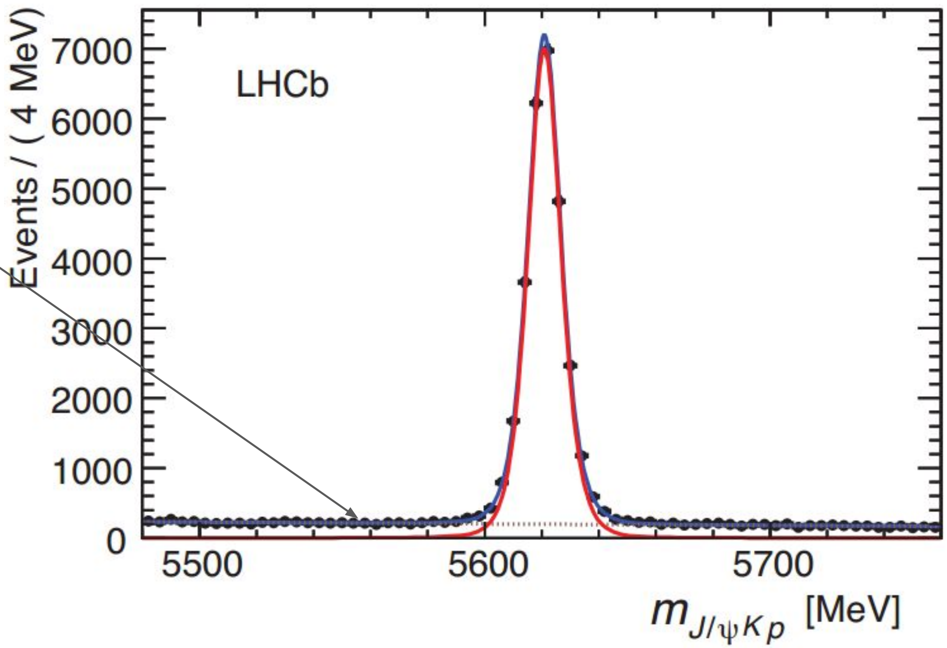


- Use m(K⁻p) & 5 decay ∠'s as fit parameters
- Mass shapes: Breit-Wigner or Flatte´

How to subtract the combinatorial background?

The combinatorial background distributes with respect to angular variables differently from signal:

it has to be subtracted.



Background subtraction with two alternative and complementary techniques:

cFit

Using mass sidebands to model the background components in all the angular variables (including correlations).

The background component is just another component of the full-amplitude fit.

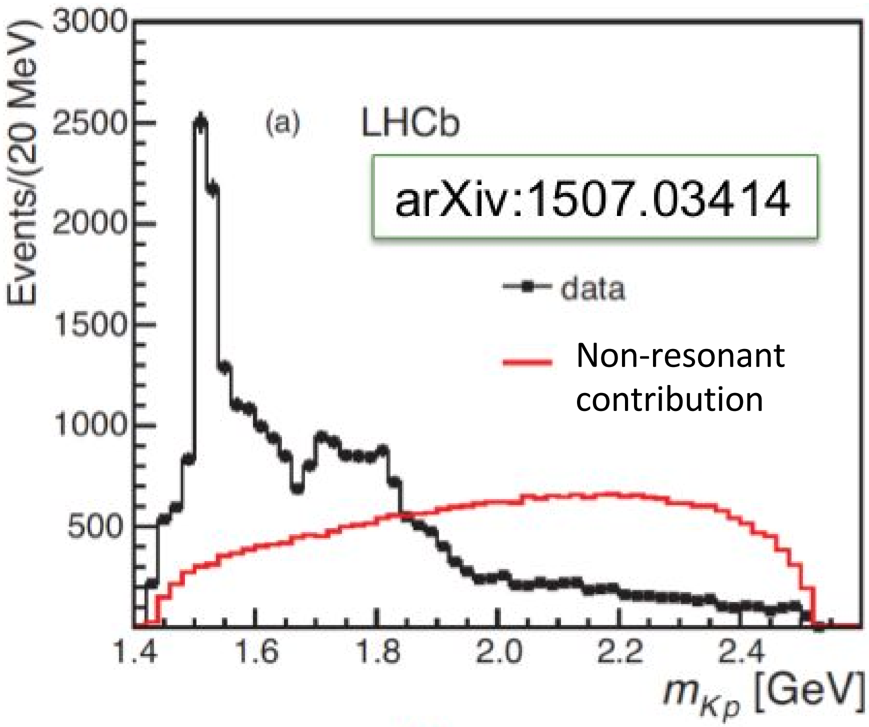
sFit

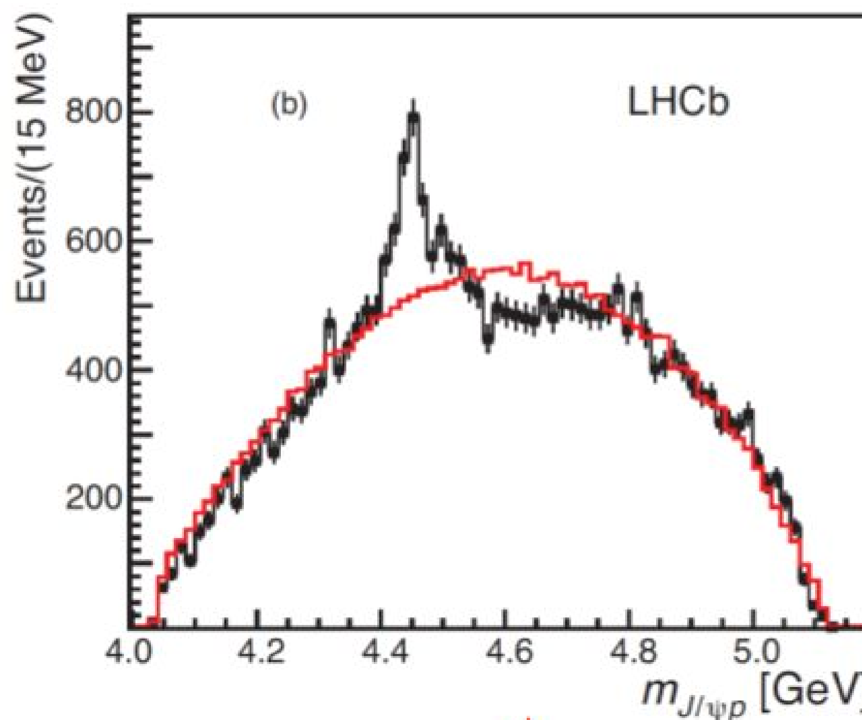
The background is statistically subtracted exploiting the covariance matrix of the normalizations of the components of the m(Λ_b) fit.

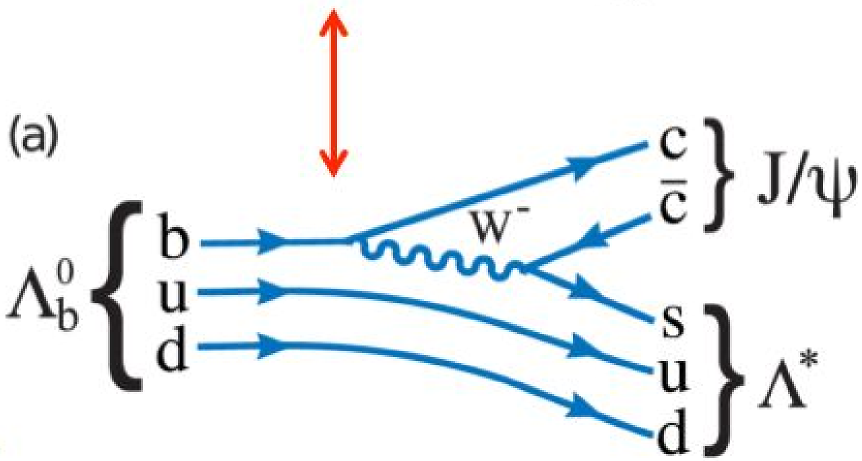
The sFit method doesn't require explicit parametrization of the background component, but needs additional care in the interpretation of the statistical uncertainties.

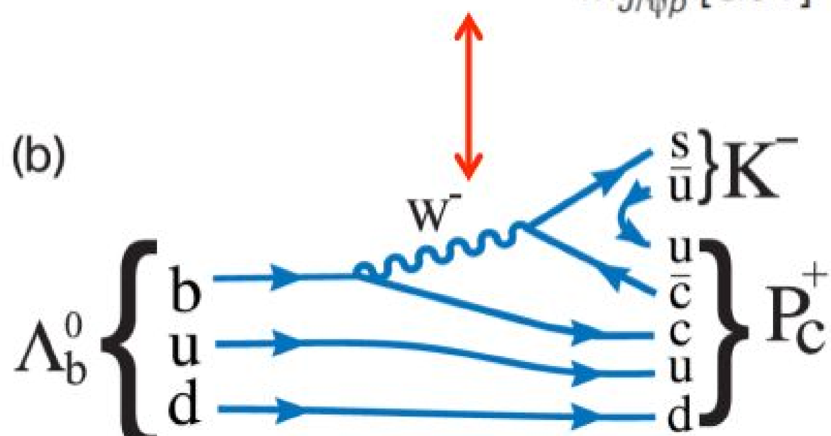
Both method were used and the results compared as an additional cross-check.

Projection: *the NR contribution alone is not enough*









Does this diagram exist?

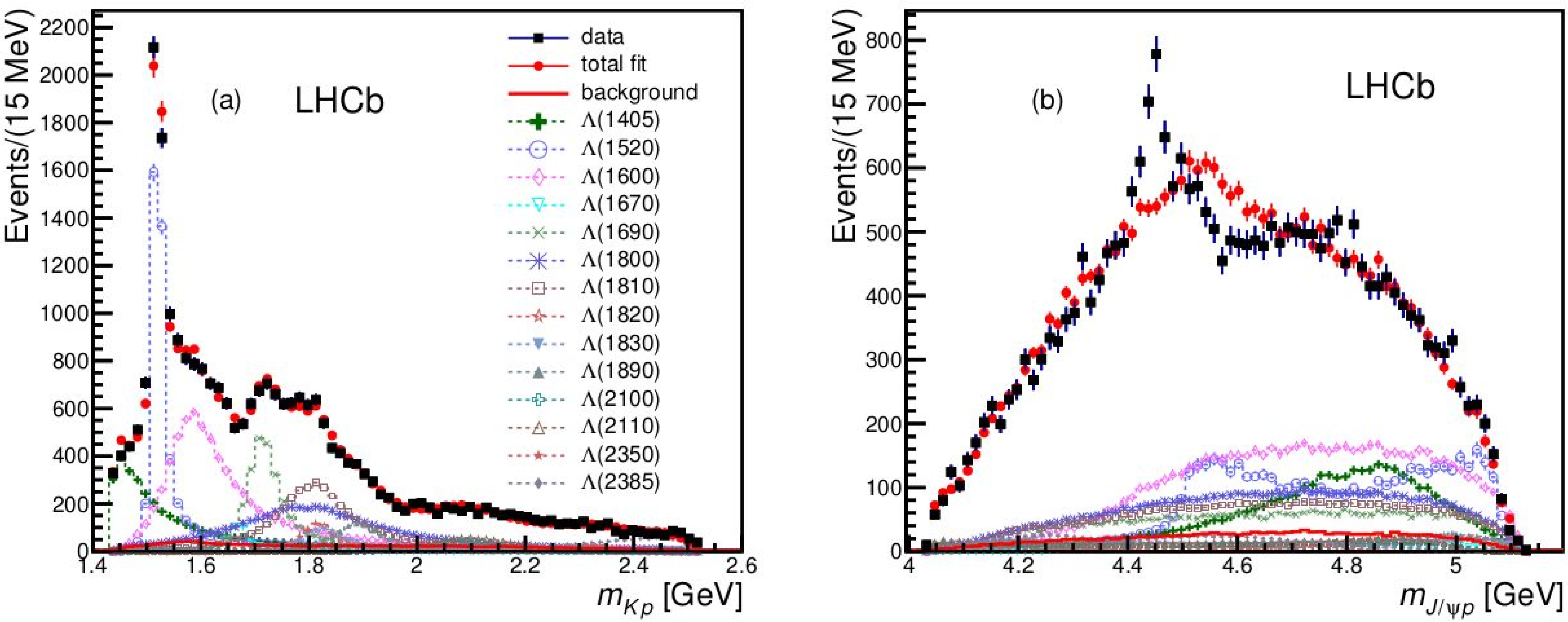
Let's say that the P_c^+ diagram does not exist

Two models defined, one extended model with all resonances one may think of, one reduced with a reasonable number of parameters.

	State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
Flatte´	$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
BW	$\Lambda(1520)$	$3/2^-$	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
				# parameters	64	146

Using the extended model, cannot reproduce the peak

Reminder: the extended model includes all the Kp resonances that one may expect.



Despite the large number of free parameters, a decay model without P_c fails to describe the data.

Model Independent Study

to exclude the Null Hypothesis

Intermezzo: *might we have missed a Kp resonance?*

A model independent analysis was performed by describing the decay as sum of partial wave contributions.

The steps are:

1. For each bin of m(pK) compute the decomposition in Legendre Polynomials of the helicity angle $\cos\theta_{\Lambda^*}$ exploiting orthonormality

Background subtraction

$$\langle P_l^U \rangle^k = \sum_{i=1}^{n_{\text{cand}}^k} (w_i / \epsilon_i) P_l(\cos\theta_{\Lambda^*}^i).$$

Efficiency correction

The polynomial serie is truncated at $l = l_{max}$ because contributions from resonances with angular momentum larger than l_{max} are considered unphysical.

l_{max} depends on the mass bin.

Assessing the statistical significance of the disagreement

Generate pseudo-experiments according to the null hypothesis ($l \leq 31$) and compute, for each experiment the difference in log-likelihood.

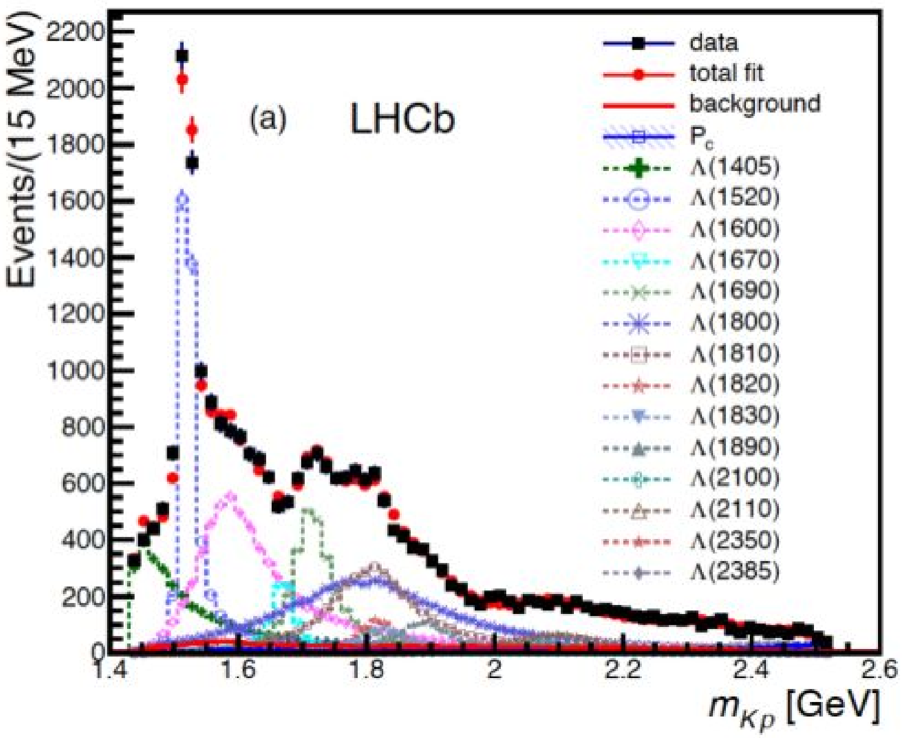
A fit of the filled histogram with a bifurcated Gaussian distribution is used to extrapolate the probability of description of a pure Kp system as poorly as in data, or worse.

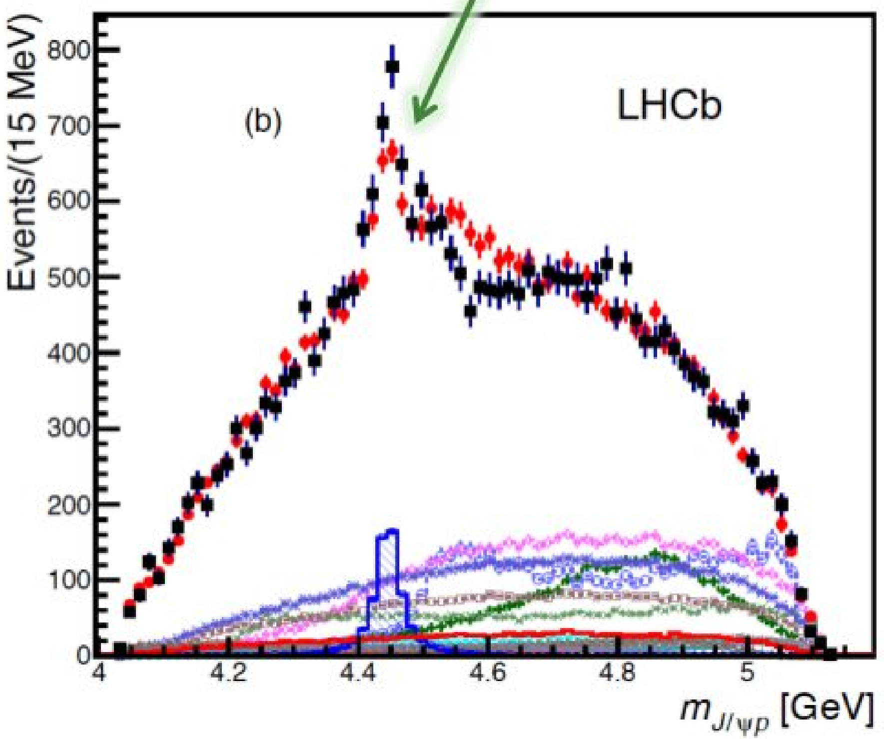
Amplitude Analysis

to study the Pentaquark(s) properties

Let's put in a P_c resonance (extended model)

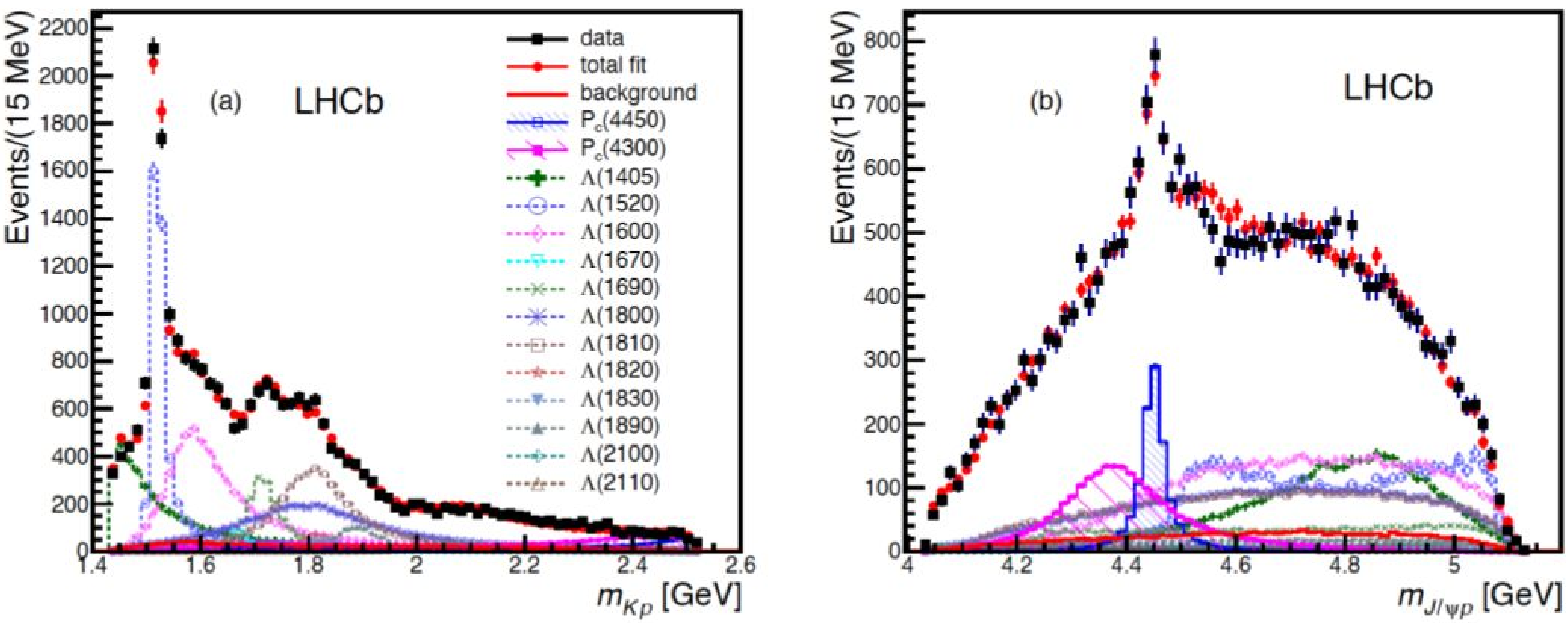
- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit



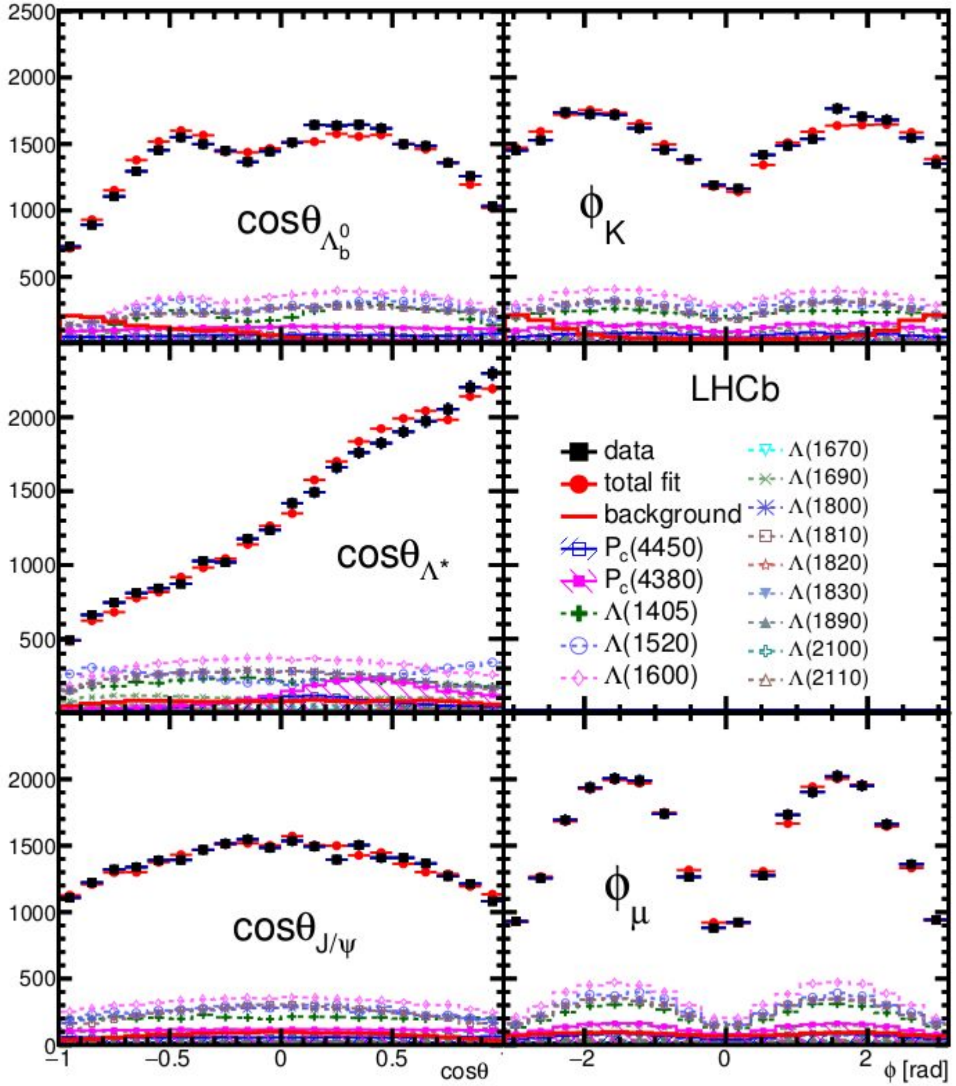


Let's put one another P_c state

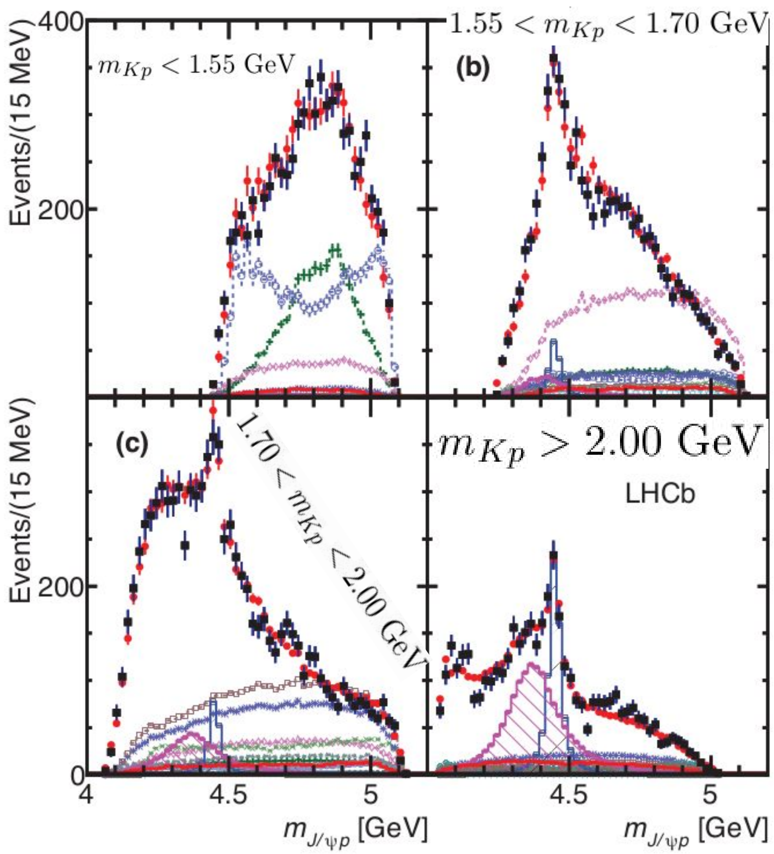
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred



It works well also for angular variables...



… and in bins of m_{Kp}



Fit results

Mass (MeV/c^2)	Width (MeV/c^2)	Fit fraction (%)	J^P	Significance
4380 ± 8 ± 29	205 ± 12 ± 86	8.4 ± 0.7 ± 4.2	$3/2^-$	9 σ
4449.8 ± 1.7 ± 2.5	39 ± 5 ± 19	4.1 ± 0.5 ± 1.1	$5/2^+$	12 σ

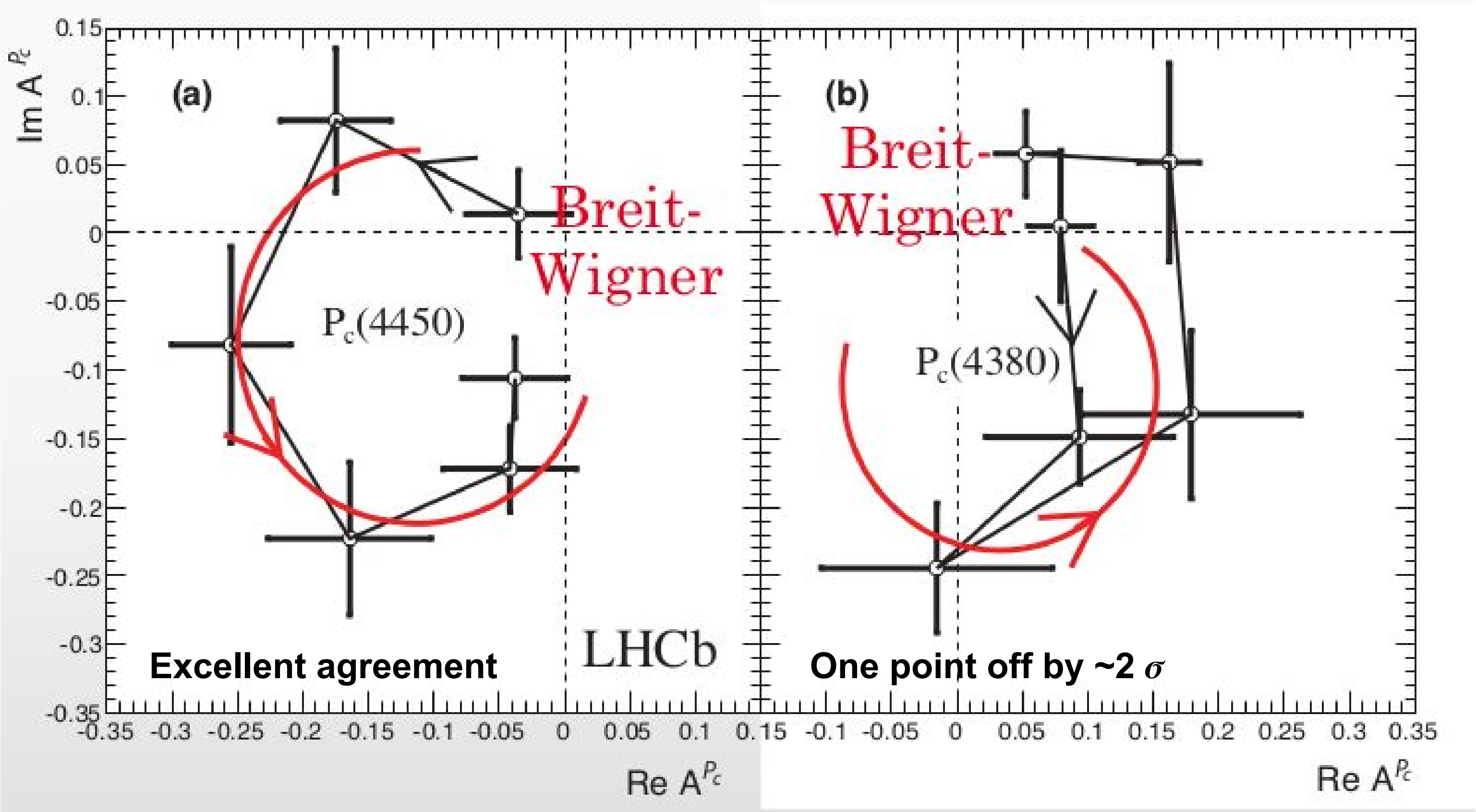
We cannot exclude solutions with J^P being ($3/2^+$, $5/2^-$) and ($5/2^+$, $3/2^-$)

Argand diagrams

Alternative parametrization of the complex amplitude of the two P_c^+ states.

12 free points in the complex plane: one point per $m(J/\psi\ p)$ bin.

For authentic resonances, the points distribute along a circular path.



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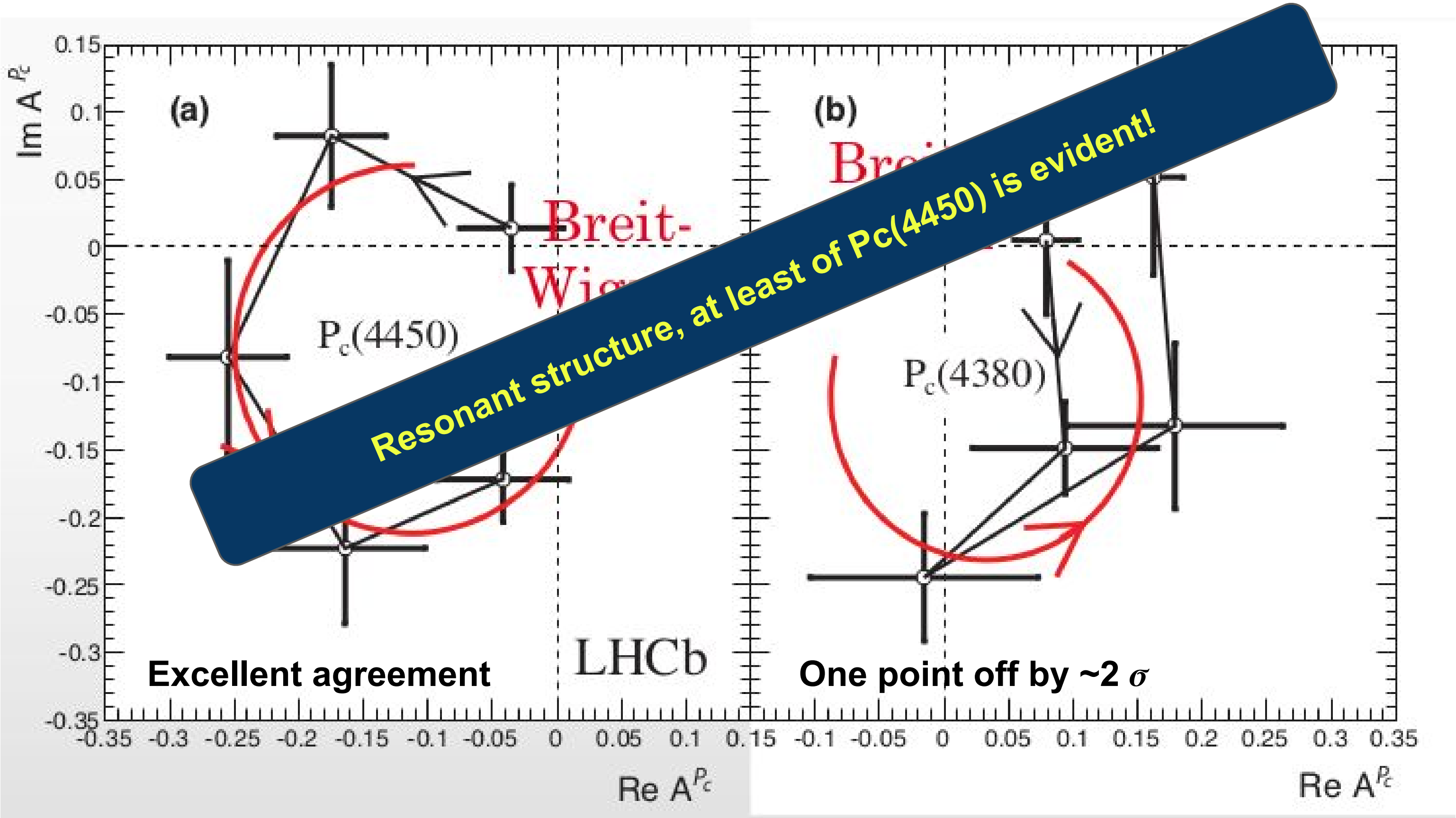


Systematic uncertainties

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L_{\Lambda_b^0}^{\Lambda_n^*}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Other cross-checks

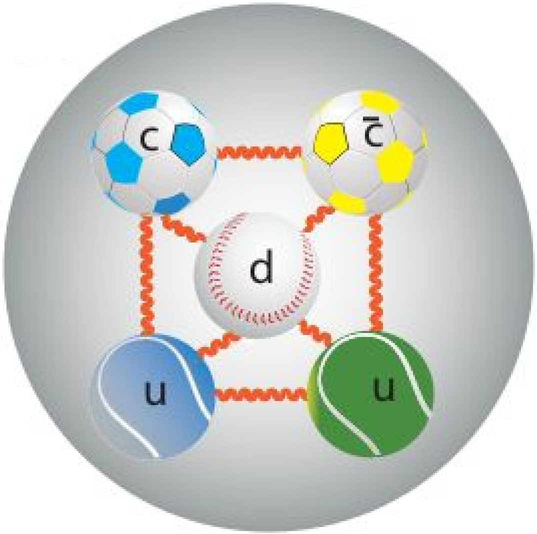
- *Many... not all listed here*
- Signal found using independent selections
- Two independent analyses within the collaboration using different code (sFit & cFit)
- Check data consistency in different "time bins": MagUp / MagDown, and 2011/2012
- ...

Few Words on Theory

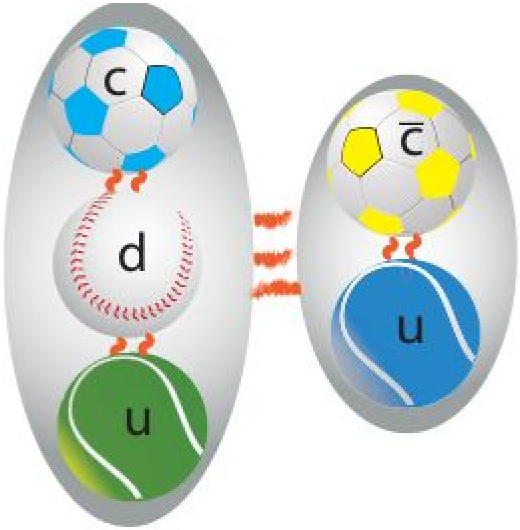
many more postdiction than prediction

Pentaquarks: *theoretical models*

Tight pentaquarks



Molecular models



Maiani, arXiv:1750.04980
Ibid, PRD 20 (1979) 748
Lebed, arXiv:1507.05867
Strings, NPB B123 (1977) 507

Generally, using meson exchange for binding
Tornqvist, Z. Phys C 61 (1994) 525

Difficult to predict two states using only π exchange, but can use ρ

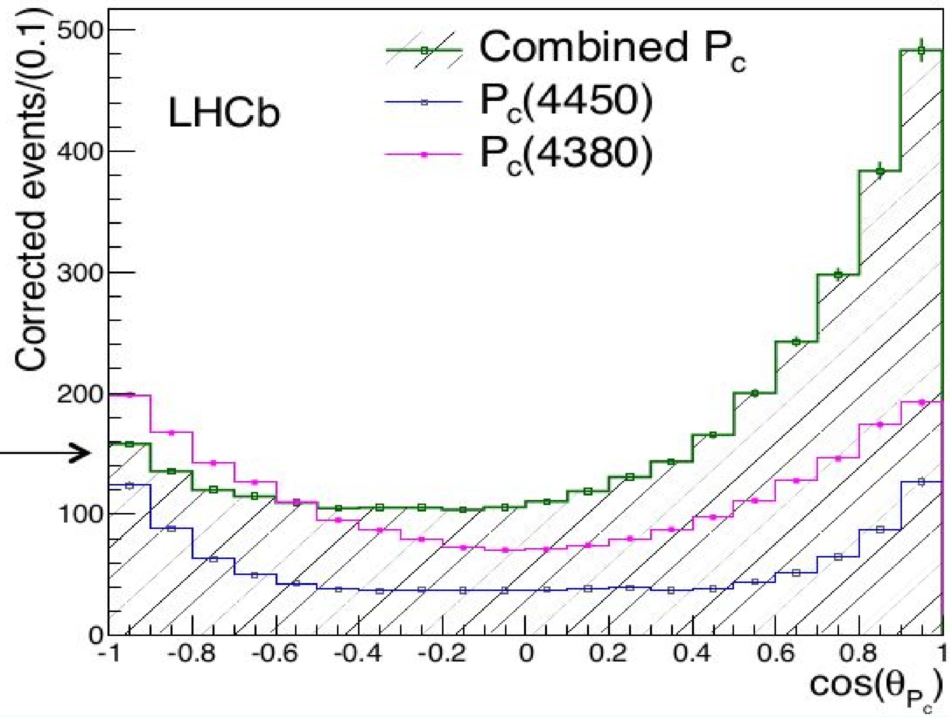
Pentaquarks: *other QCD effects, rescattering*

Rescattering effects of the final state may explain enhancements in the mass distributions, but they can hardly motivate the resonant structure.

Besides it is difficult to predict two states, and two states and their interference is needed to describe the data.

- Fit projections

Large m(Kp) region negative interference



Small m(Kp) region positive interference

Conclusions

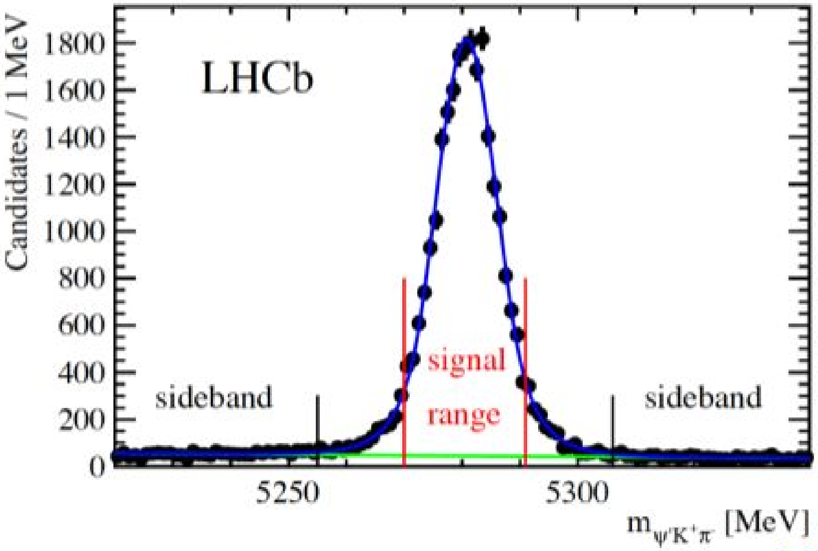
- LHCb has found two resonances decaying into $J/\Psi\ p$ with pentaquark content of $uudc\bar{c}$
- Determination of their internal binding mechanism will require more study. The preferred J^P configurations are $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$, or $(5/2^+, 3/2^-)$.
- Other exotic states have appeared containing the ccbar quarks:
  - The $Z_c(4430)^+ \rightarrow \Psi(2S)\ K^- \pi^+$ appears to be a tetraquark with $J^P = 1^+$.
- Lattice calculations providing masses would be welcome
- We look forward to search for new states and establish their internal structure.

Thank you!

Backup slides

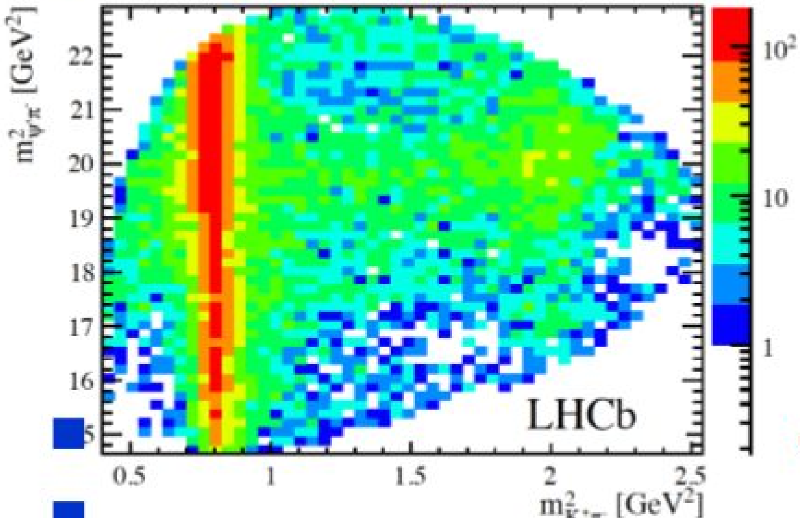
$Z(4430)^+$ tetraquark

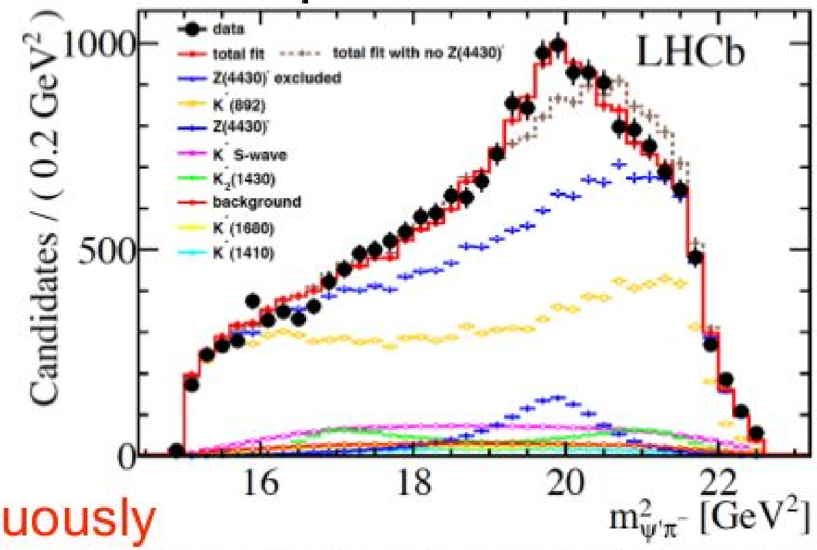
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 MeV, 1^+ preferred but 0^- & 1^- not excluded [arXiv:1306.4894]
- LHCb analysis also uses full amplitude fit
  - M= $4475 \pm 7^{+15}_{-25}$ MeV
  - Γ=172 MeV [arXiv:1404.1903]



Amplitude analysis of the Zc(4430)

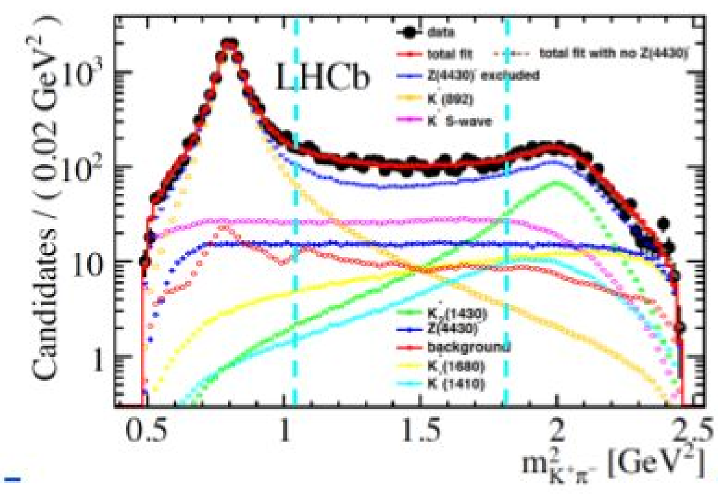
- Full 4D fit to both $K^* \to K^- \pi^+$ & $Z \to \psi' \pi^-$ states

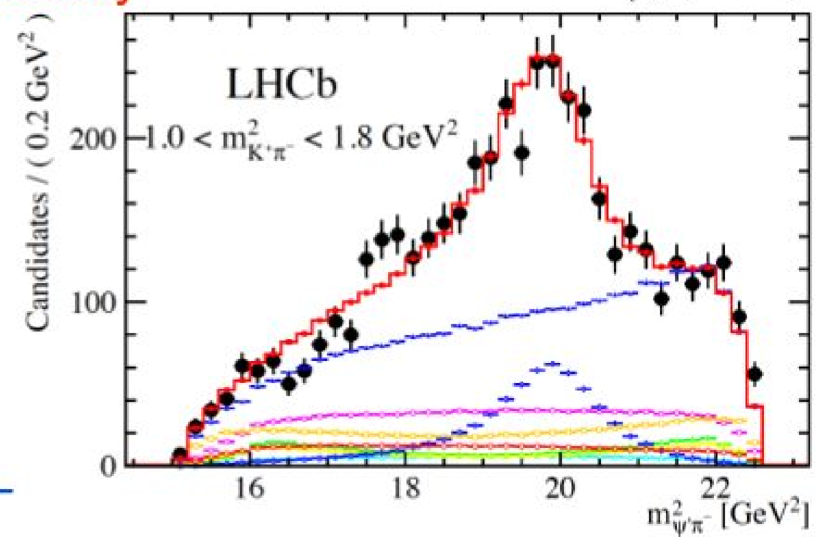




$J^P = 1^+$

Unambiguously





$X(5568)^{\pm} \rightarrow B^0_s\pi^{\pm}$

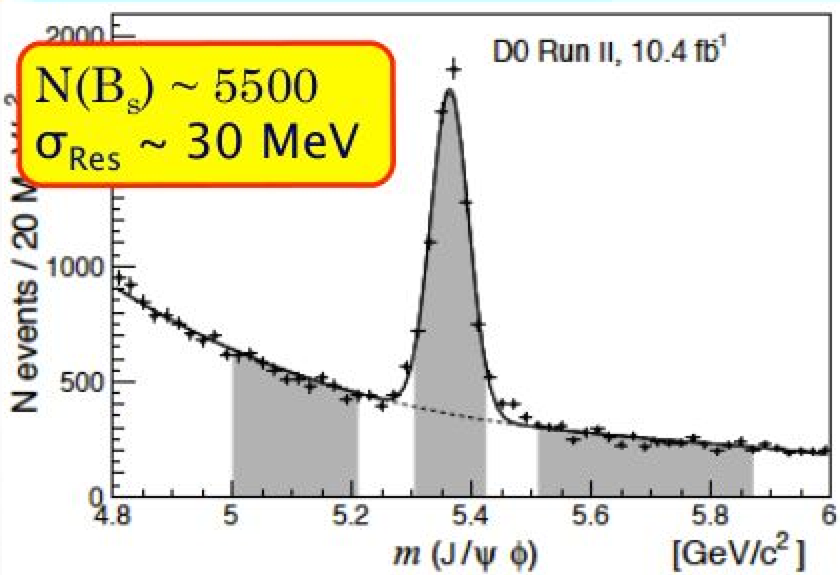
[DØ: arXiv:1602.0758

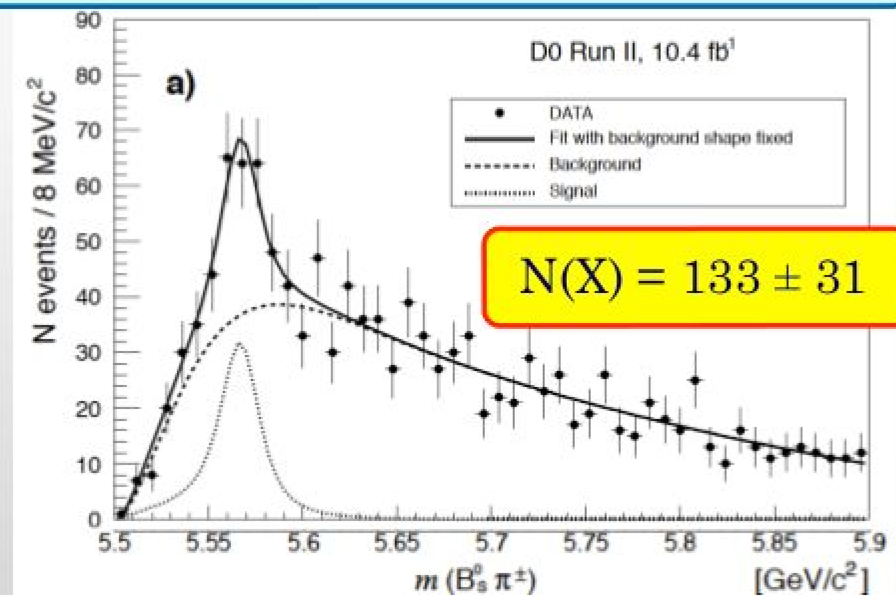
Il 24/02/2016, la collaborazione DØ annuncia l'osservazione (5.1σ) di un nuovo tetraquark:

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

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

✓ Frazione di B_s^0 dal decadimento di $X^{\pm}$: $\rho_X^{D\emptyset} = (8.6 \pm 1.9 \pm 1.4)\ \%$





Spettro di Massa $B^0_s\pi^\pm$

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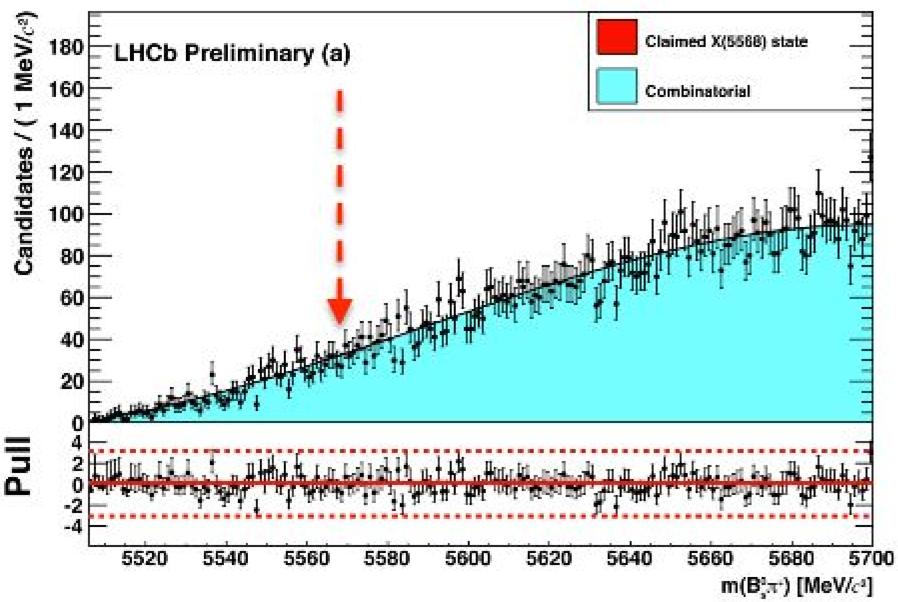
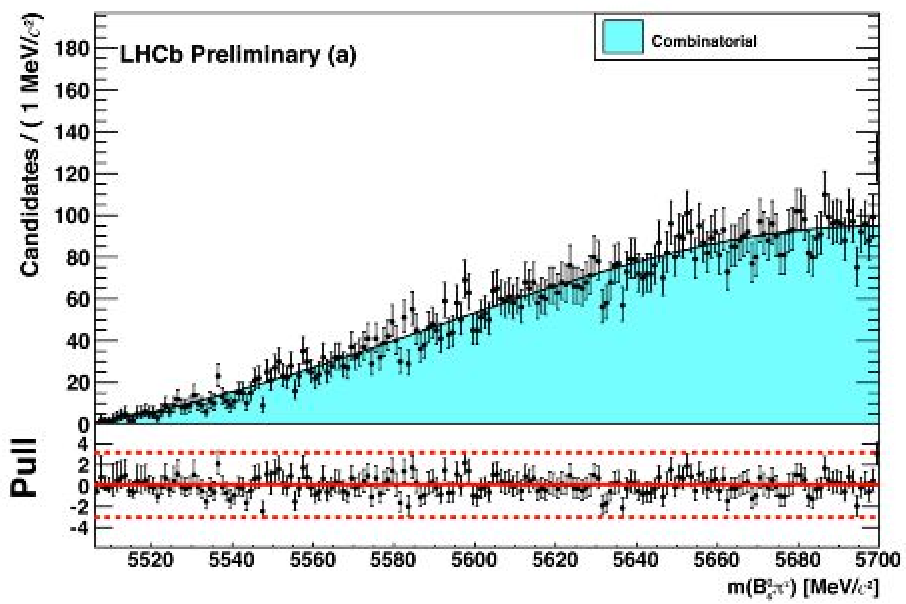
$p_T(B_s) > 5$ GeV/c

Risultati di un fit con funzione di segnale

Risultati di un fit senza funzione di segnale





Spettro di Massa $B^0{}_s\pi^\pm$ (II)

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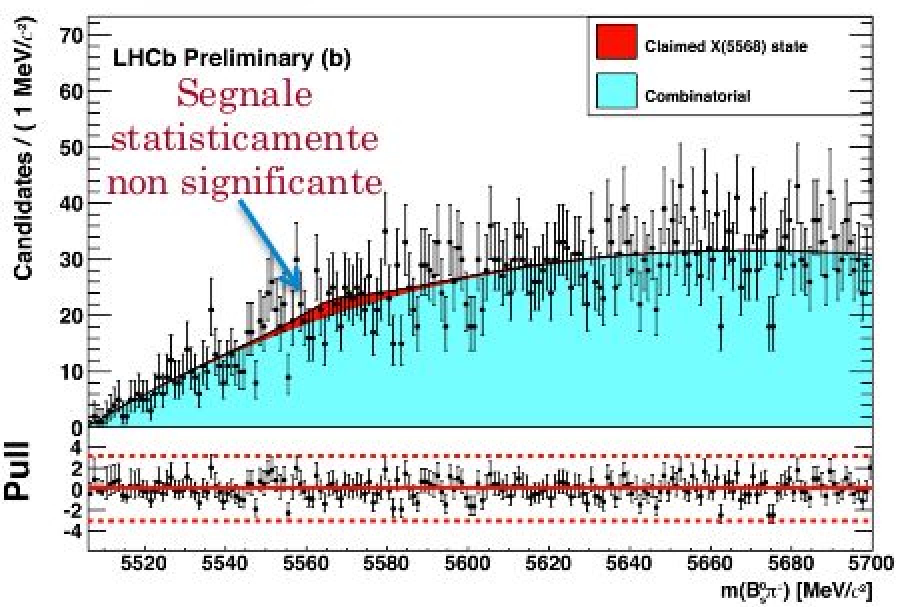
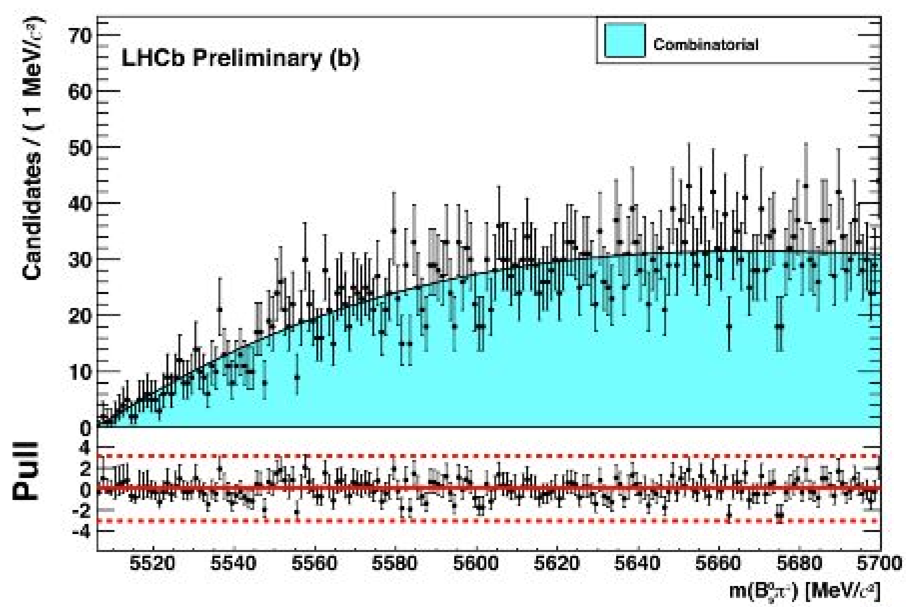
$(p_T(B_s) > 10\ \mathrm{GeV}/c)$

Risultati di un fit <u>con</u>
funzione di segnale



Risultati di un fit <u>senza</u>
funzione di segnale



Come Dovrebbe Apparire l'Ipotetico Segnale se….

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$$\ldots\ \rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D\O}} = 8.6\% \quad ?$$

($p_T(B_s) > 10$ GeV/c)