Pentaquarks at LHCb

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On behalf of the LHCb collaboration

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http://indico.ihep.ac.cn/event/4774/overview

Outline

➢ Introduction

➢ $\Lambda_b^0 \to J/\psi p K^-$ & peak structure in $J/\psi p$

➢ Full amplitude analysis

  • Observation of two $J/\psi p$ resonances

➢ Summary & prospects

Why pentaquarks?

➢ Pentaquarks are states of matter beyond simple quark picture
  - Could teach us a lot about QCD
➢ There is no reason that they should not exist
  - Predicted by M. Gell-Mann(1964), G. Zweig(1964), and other later in context of specific QCD models: Jaffe (1976), Strottman (1979)
➢ These multi-quark states would be short-lived $\sim 10^{-23}$ s "resonances", whose presences are detected by mass peaks & angular distributions showing the unique J^{PC} quantum numbers

Prejudices

➢ No convincing states 50 years after Gell-Mann paper proposing $qqqq\bar{q}$ states

➢ Previous "observations" of several pentaquark states have been refuted

- $\Theta^+ \to K^0 p, K^+ n, m = 1.54 \text{ GeV}, \Gamma \sim 10 \text{ MeV}$

- Resonance in $D^{*-}p$ at $3.10 \text{ GeV}, \Gamma = 12 \text{ MeV}$

- $\Xi^{--} \to \Xi^- \pi^-, m = 1.862 \text{ GeV}, \Gamma < 18 \text{ MeV}$

➢ Generally they were found/debunked by looking for "bumps" in mass spectra circa 2004

See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

LHCb detector
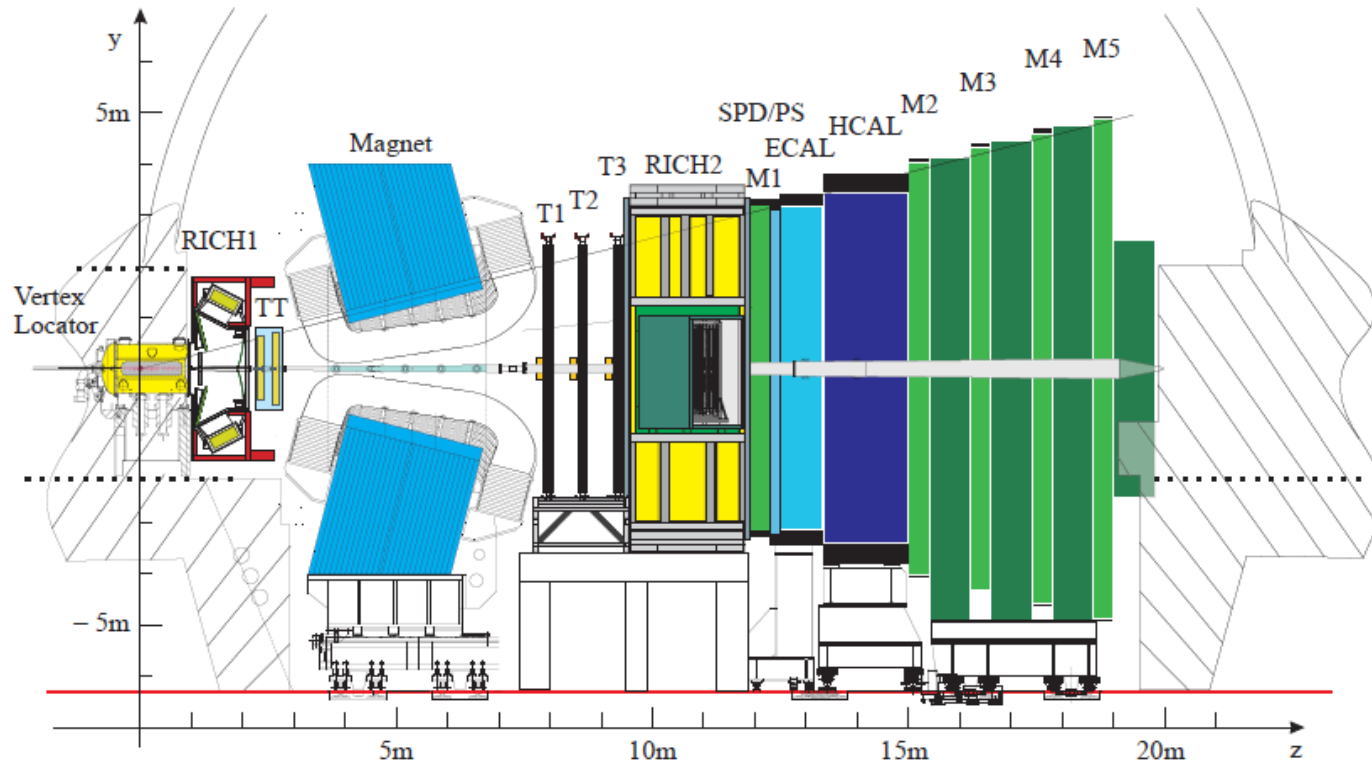
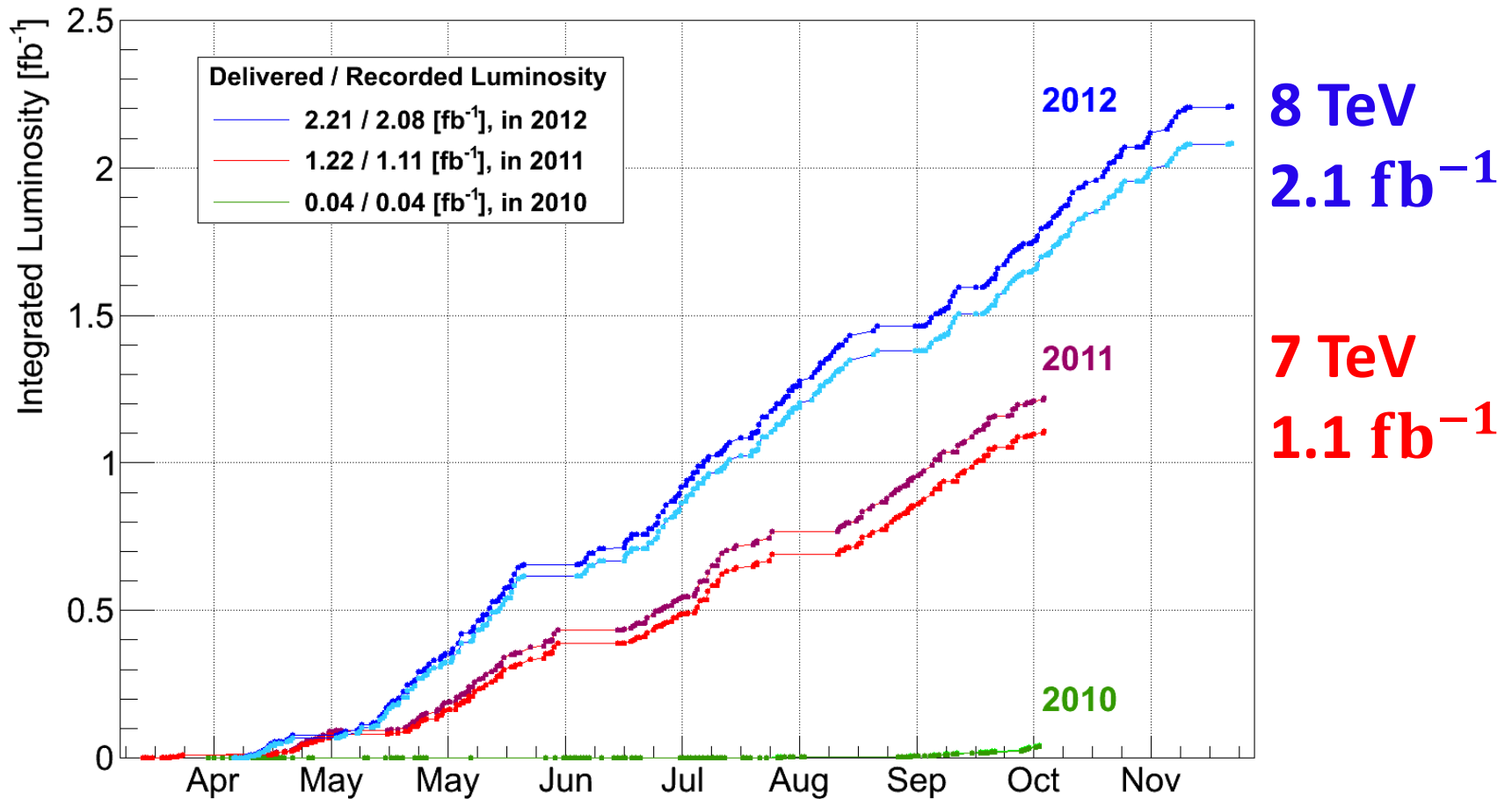|	
Impact parameter:	$\sigma_{IP} = 20$ μm
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \rightarrow J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\sigma_m = 8$ MeV/c^2 for $B \rightarrow J/\psi X$ (constrainted $m_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \rightarrow K) \sim 95\%$ mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$
Muon ID:	$\epsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

LHCb data taking

Legend:
Delivered / Recorded Luminosity
- 2.21 / 2.08 [fb^{-1}], in 2012
- 1.22 / 1.11 [fb^{-1}], in 2011
- 0.04 / 0.04 [fb^{-1}], in 2010

2012 8 TeV 2.1 fb^{-1}

2011 7 TeV 1.1 fb^{-1}

2010
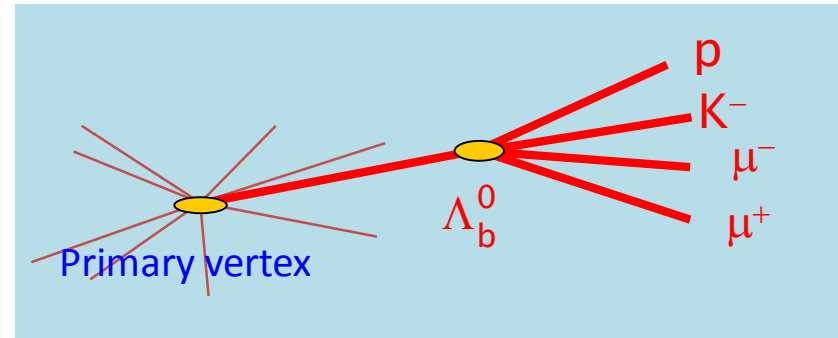
Stable and efficient (> 90%) data taking
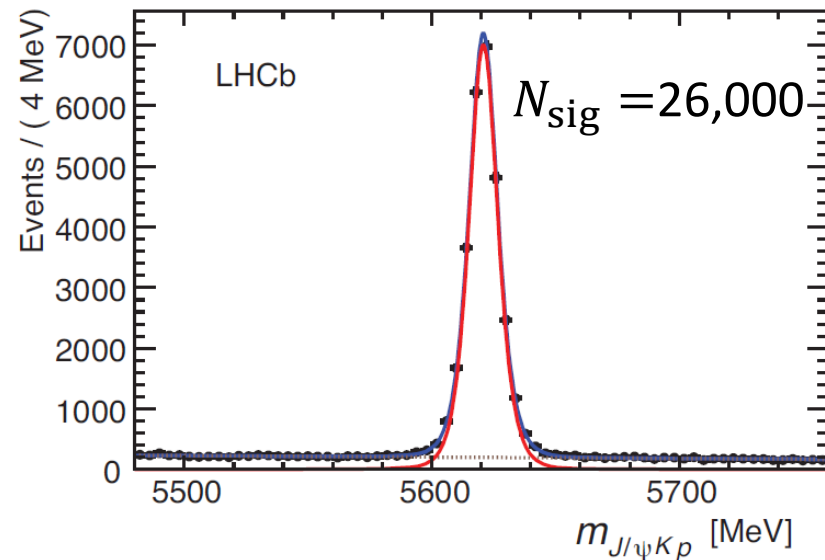
This analysis based on 2011 + 2012 data

$\Lambda_b^0 \to J/\psi p K^-$ and event selection

- First observed by LHCb as a potential background for
  $$B^0 \to J/\psi K^+ K^-$$

- Large signal yield found, used for Λ_b^0 lifetime measurement

Event selection:
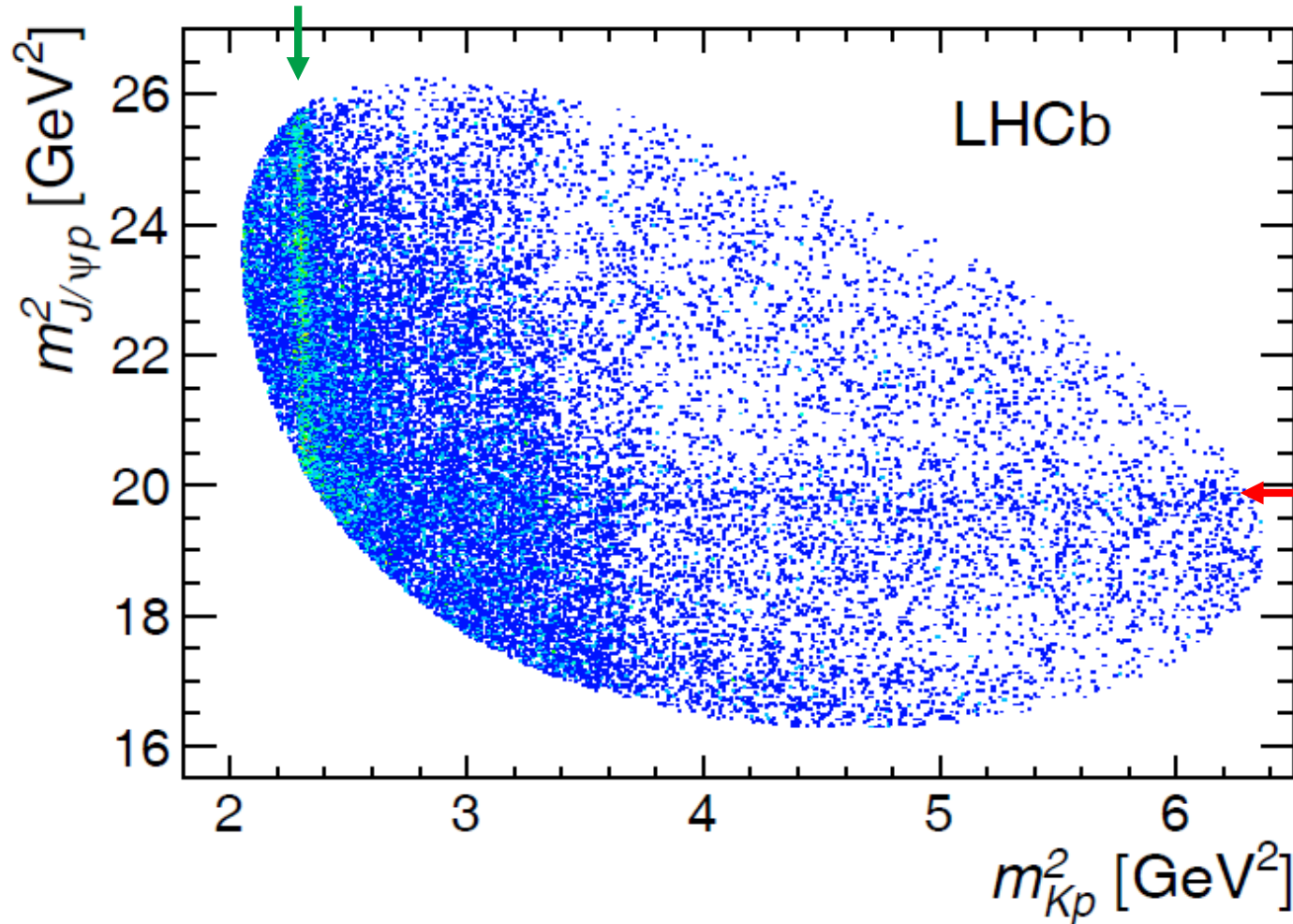
- Standard preselection

- Followed by selection with BDTG

- Veto $B_s^0 \to J/\psi K^+ K^-$ and
  $$B^0 \to J/\psi K^+ \pi^-$$
  reflections, where K^- and π^- are misidentified as proton

$N_{\text{sig}} = 26,000$

5.4% background in $\pm 2\sigma$

Unusual feature in "Dalitz plot"

Projections
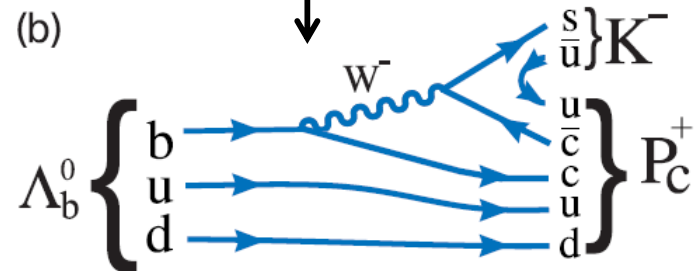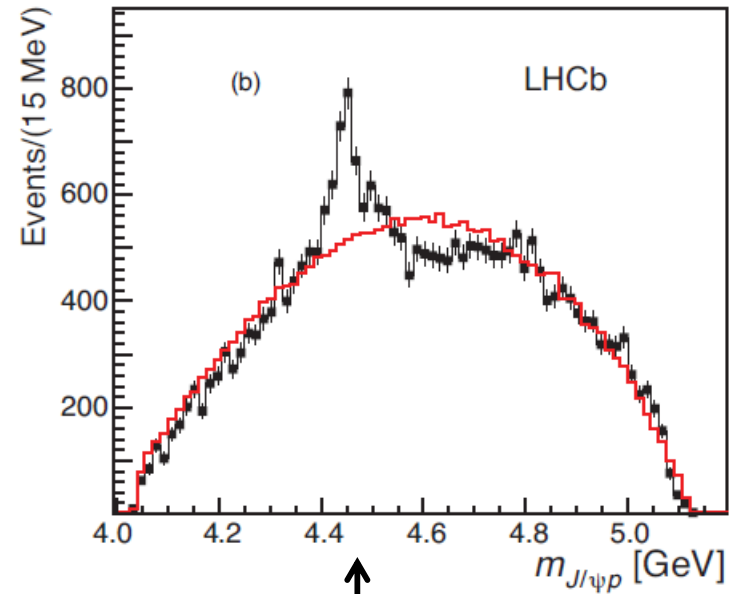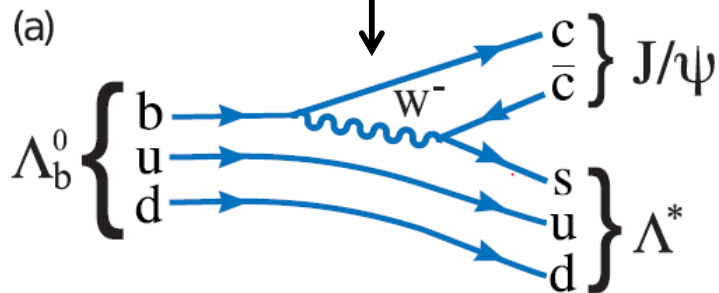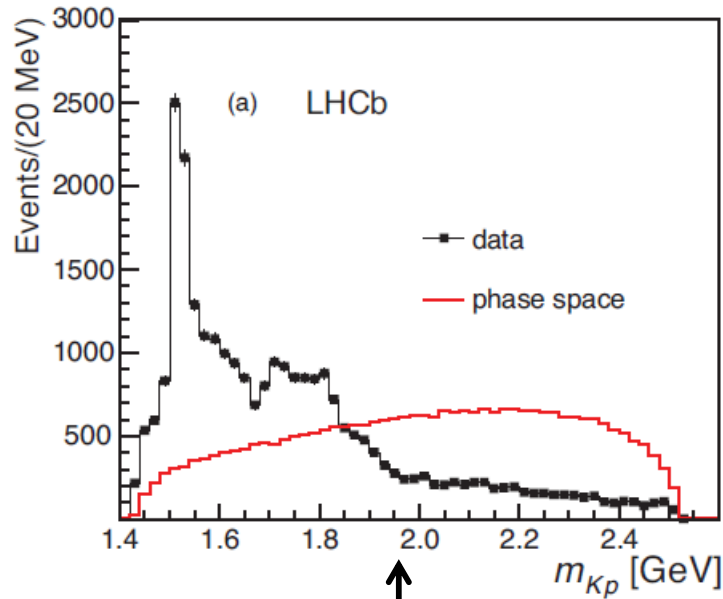
Is the peak "artifacts"?

> Many checks done

- Reflections of B^0 and B_s^0 are vetoed

Total Efficiency
LHCb

- Efficiency doesn't make narrow peak

- Clones & ghost tracks eliminated

- Ξ_b decays checked as a source

> Can interference between Λ^* resonances generate a peak in the $J/\psi p$ mass spectrum?

- A full amplitude analysis is performed using all known Λ^* resonances
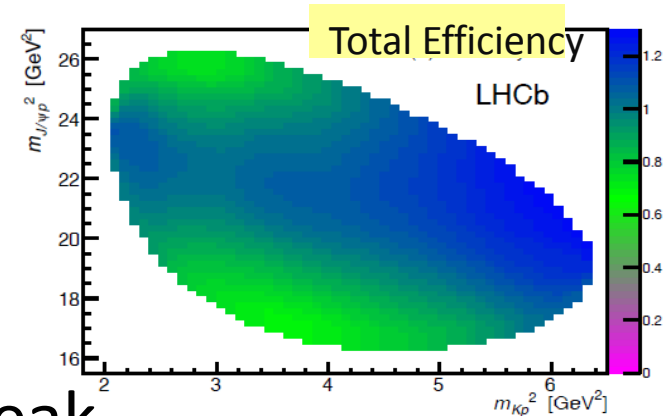
Amplitude analysis

➢ Allows for $\Lambda^* \to p K^-$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$

$$\Lambda_b^0 \to J/\psi \Lambda^*,$$
$$\Lambda^* \to p K^-$$

$$\Lambda_b^0 \to P_c^+ K^-,$$
$$P_c^+ \to J/\psi p$$

➢ Independent variables: $m(pK^-)$ and 5 angles ➔ 6D fit

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Λ^* resonances

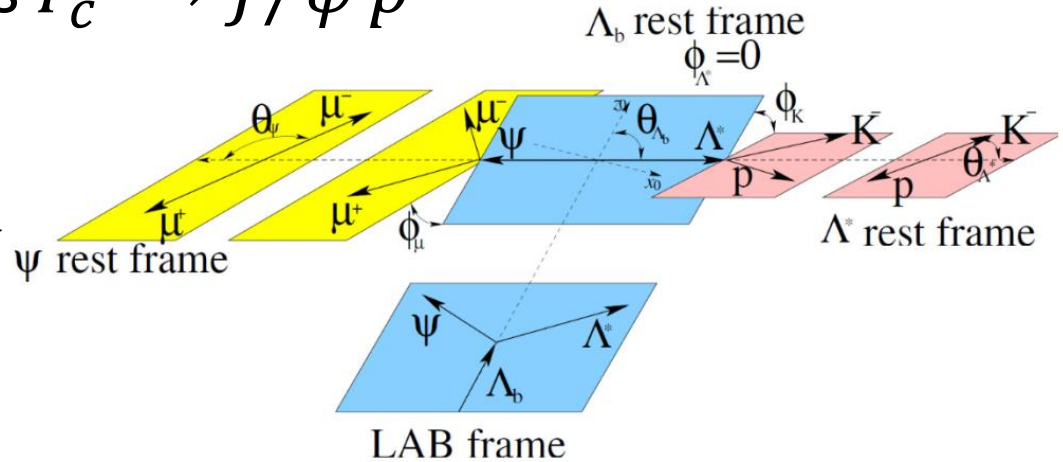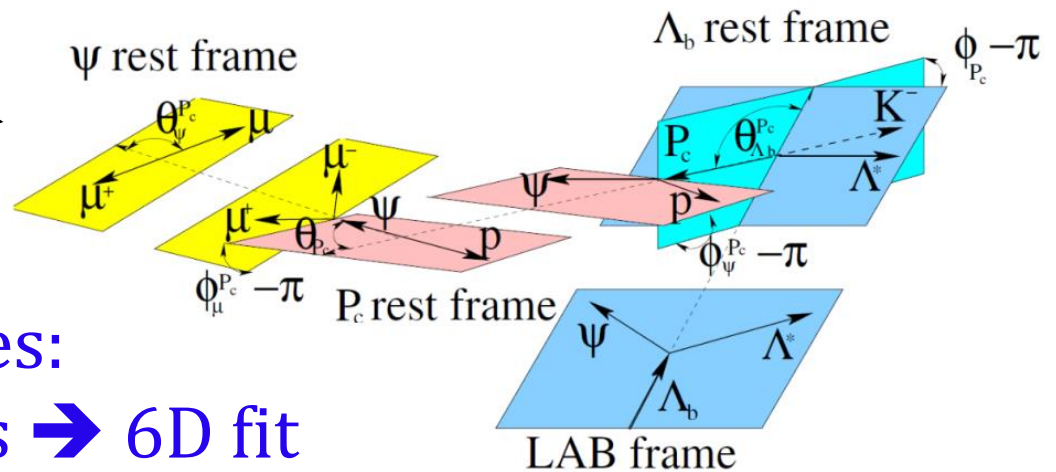➢ Each Λ^* resonance: $J = \frac{1}{2}$ ($> \frac{1}{2}$) has 4 (6) complex couplings

➢ Masses and widths fixed to PDG values

  • Uncertainties are considered as systematics

➢ Two models: "reduced" and "extended" to test dependence of the Λ^* model

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
$\Lambda(2585)$	?	≈ 2585	200	0	6

Extended Λ^* model

➤ The extended model allows all LS couplings of each resonance, and includes poorly motivated states

➤ First try extended model to describe the data

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
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$\Lambda(2585)$	?	≈ 2585	200	0	6

Total # of free parameters for Λ^* 64   146

Extended model without P_c^+

➢ $m(pK^-)$ looks fine, but not $m(J/\psi p)$

➢ Other possibilities:

 • All Σ^{*0} ($I = 1$), isospin violating decay

 • two new Λ^* with free m&Γ

 • 4 non-resonant Λ^* with $J^P = \frac{1}{2}^{\pm}$ and $\frac{3}{2}^{\pm}$

➢ Still fail to describe the data
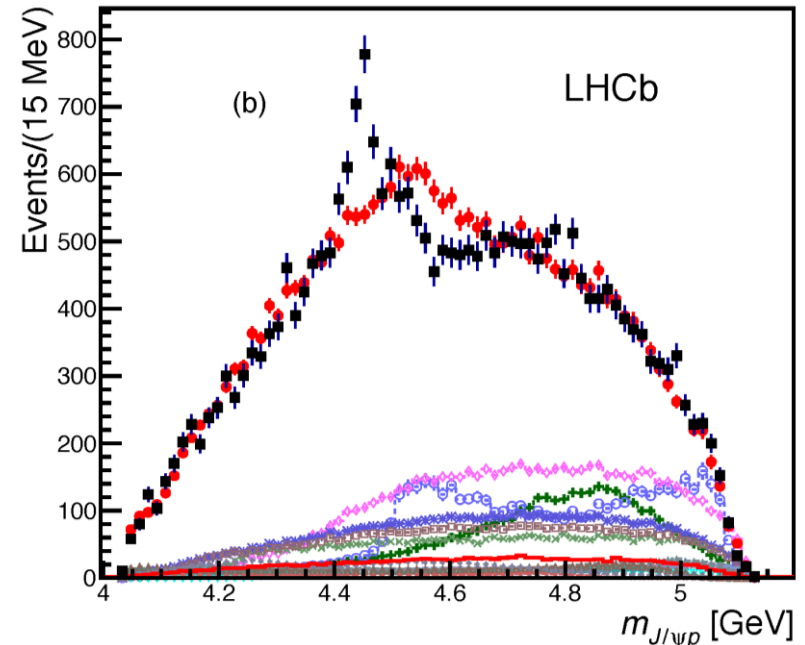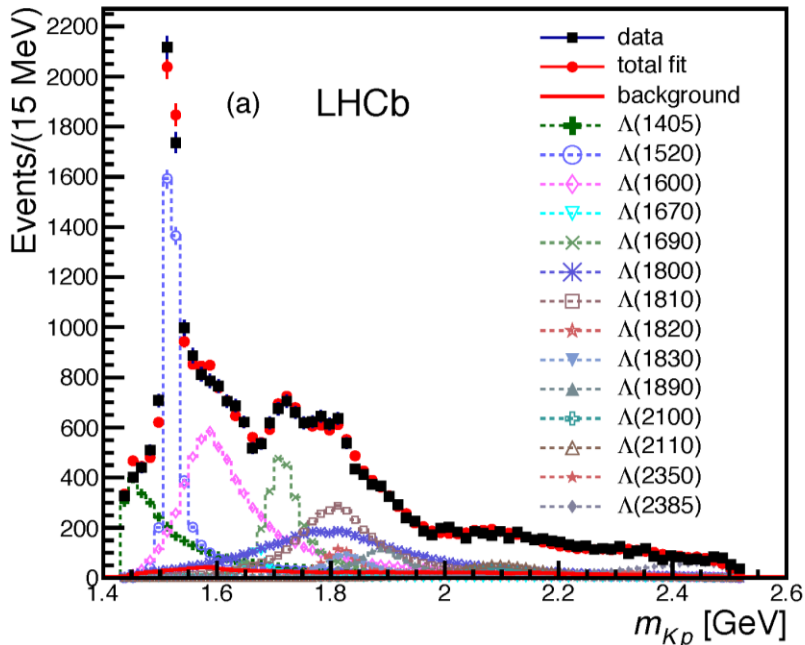
Extended model with one P_c^+

➢ Try all J^P up to $\frac{7}{2}^\pm$. Neither gives good fit

- 8 (10) free parameters for a P_c^+ of $J = \frac{1}{2} \left(> \frac{1}{2} \right)$

- Best fit has $J^P = \frac{5}{2}^\pm$
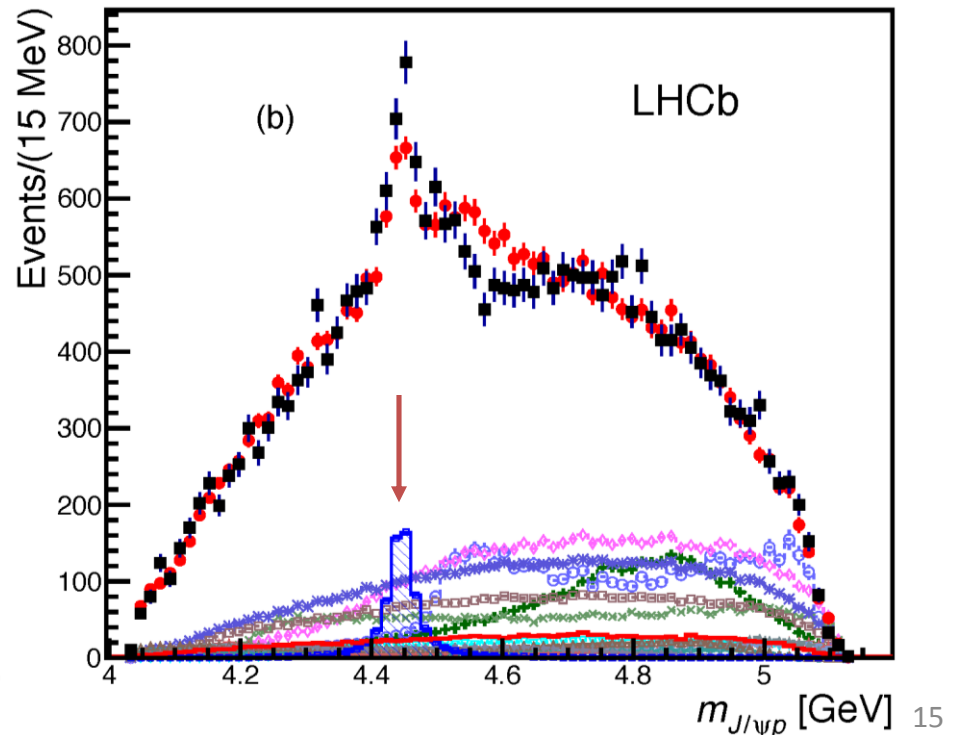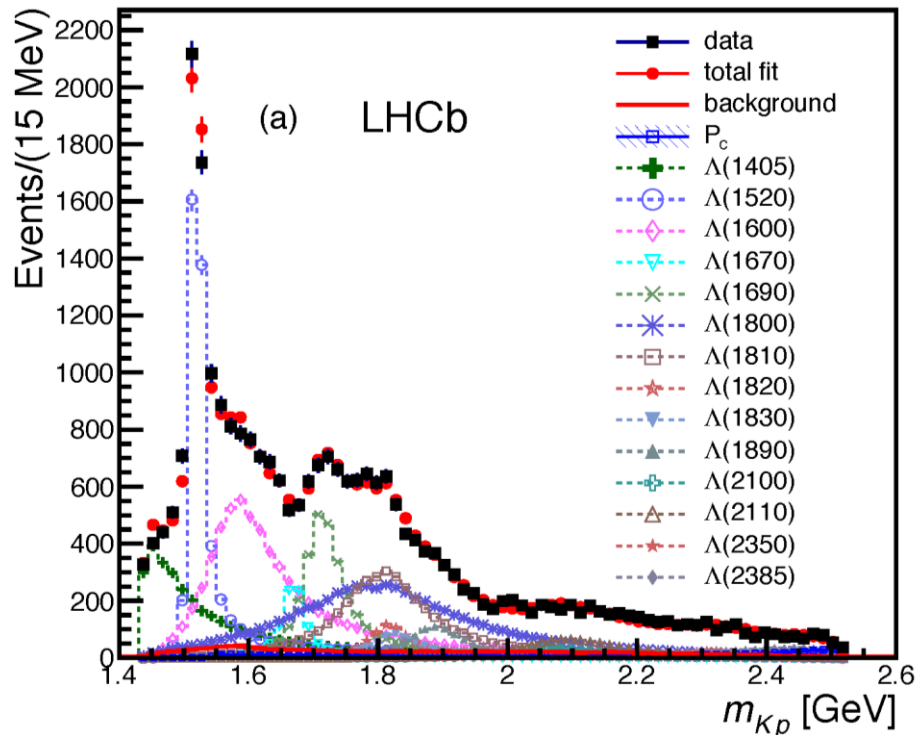
Extended model with two P_c^+'s

➢ Leads to a good fit

  ➢ The 2nd broad P_c^+ visible in other projections (shown later)

  ➢ It also modifies the narrow P_c^+'s decay angular distribution via interference to match the data
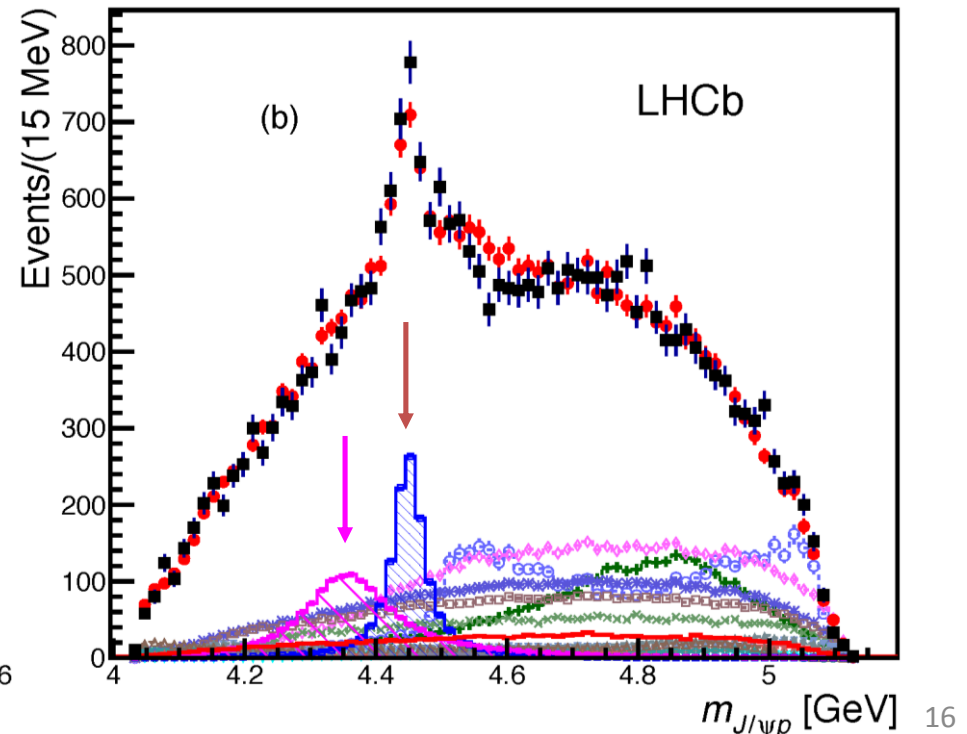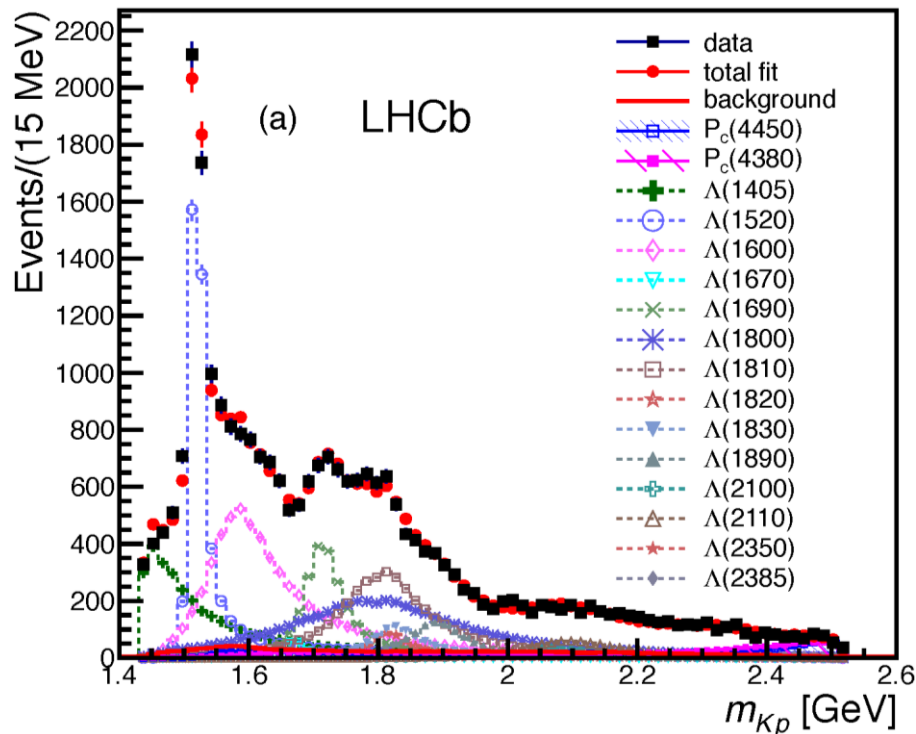
Reduced Λ^* model

➢ Too many free parameters in extended model

- Some high mass states with high L not likely present in data

➢ Use only well motivated contributions for final results

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$\Lambda(2350)$	$9/2^+$	2350	150	0	6
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Total # of free parameters for Λ^* 64   146

Reduced model with two P_c^+'s

➤ Fits are good in all 6 dimensions (see next slide)!
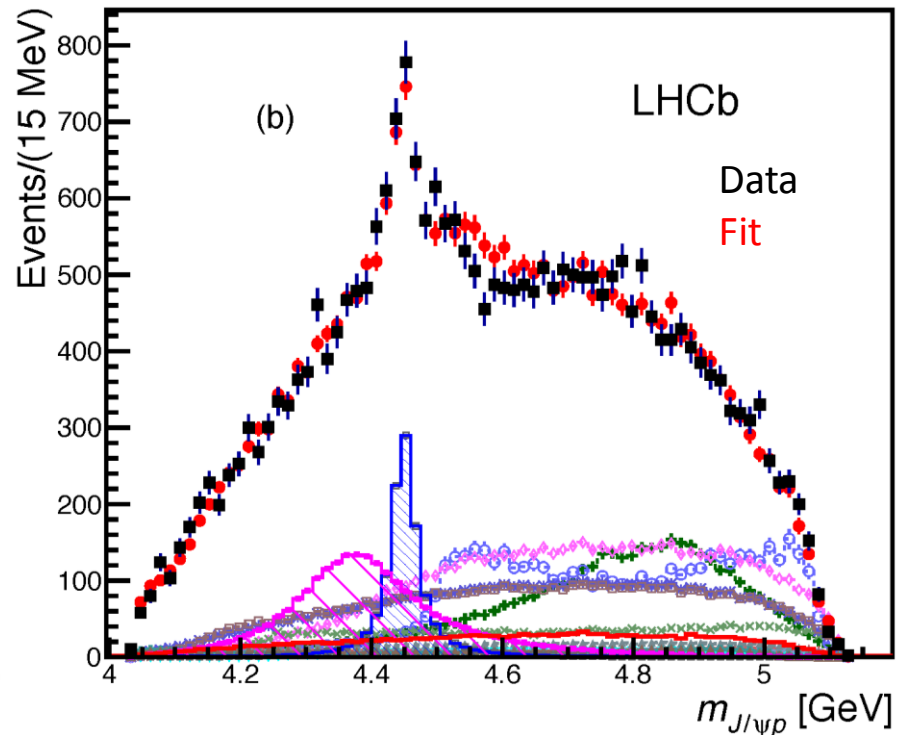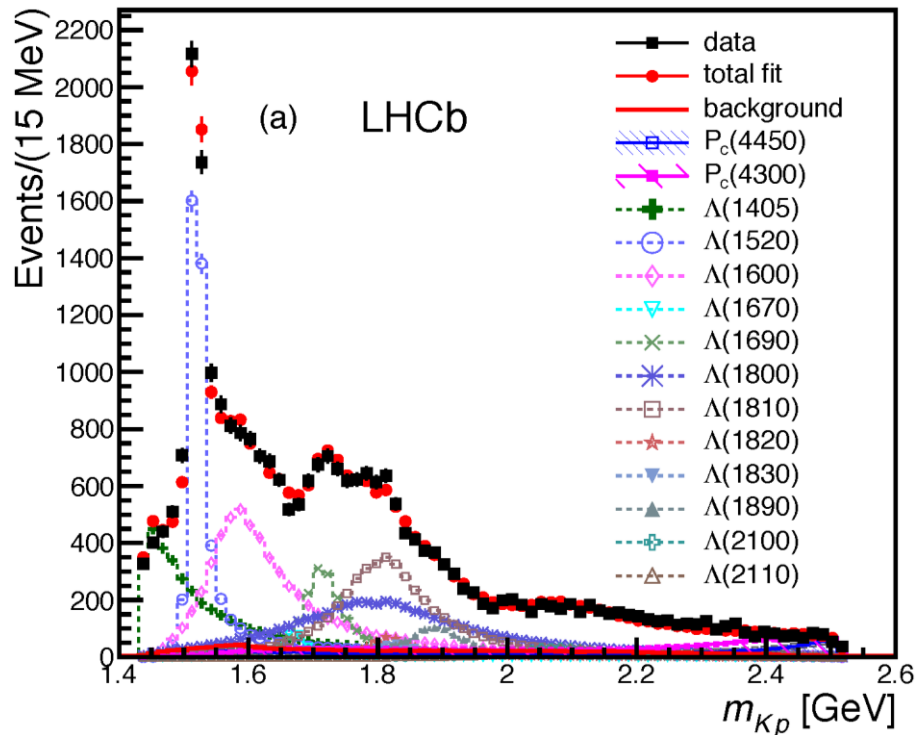
Angular distributions
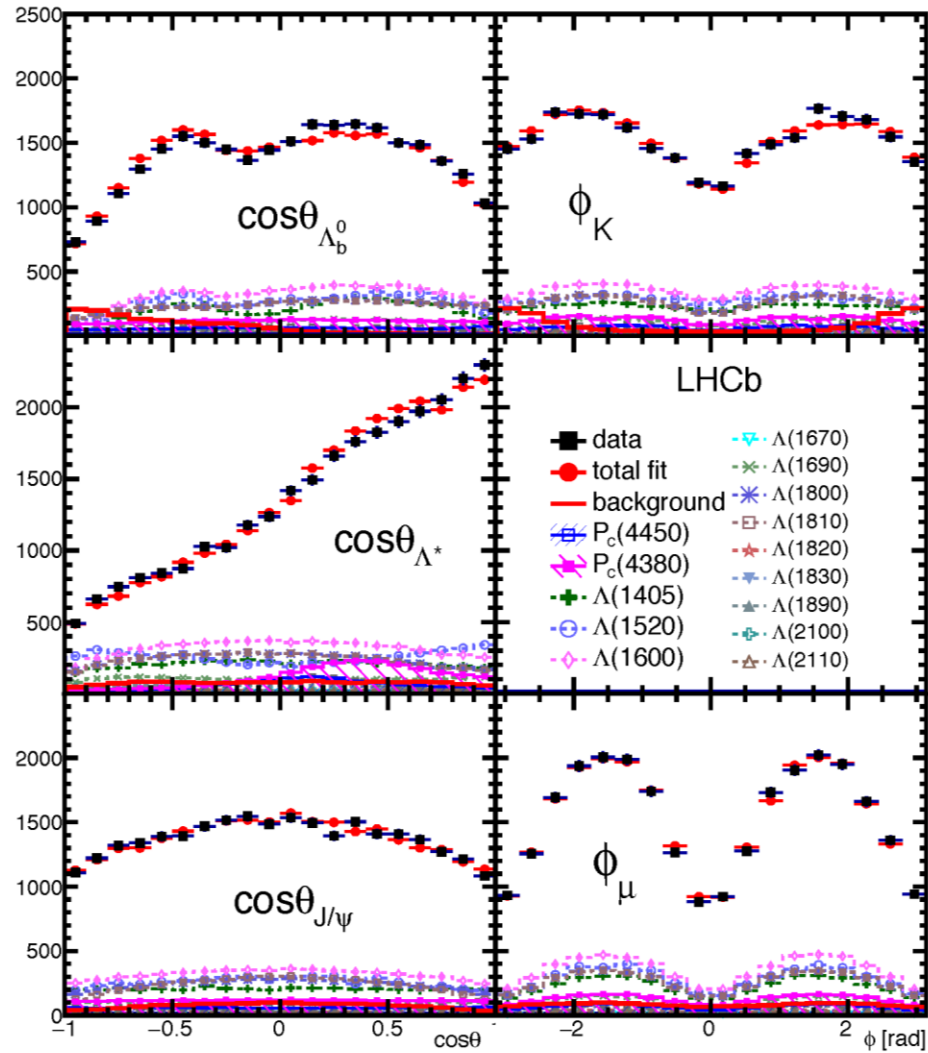
$M(J/\psi\,p)$ in $M(Kp)$ Slices

> P_c^+'s cannot appear in first interval as they would be outside of the Dalitz plot boundary

Legend:
- data
- total fit
- background
- $P_c(4450)$
- $P_c(4380)$
- $\Lambda(1405)$
- $\Lambda(1520)$
- $\Lambda(1600)$
- $\Lambda(1670)$
- $\Lambda(1690)$
- $\Lambda(1800)$
- $\Lambda(1810)$
- $\Lambda(1820)$
- $\Lambda(1830)$
- $\Lambda(1890)$
- $\Lambda(2100)$
- $\Lambda(2110)$

(a) < 1.55 GeV

(b) 1.55-1.7 GeV

(c) 1.7-2.0 GeV

(d) > 2.0 GeV — LHCb — 2nd P_c now obvious!

Axis labels: Events/(20 MeV), $m_{J/\psi p}$ [GeV]
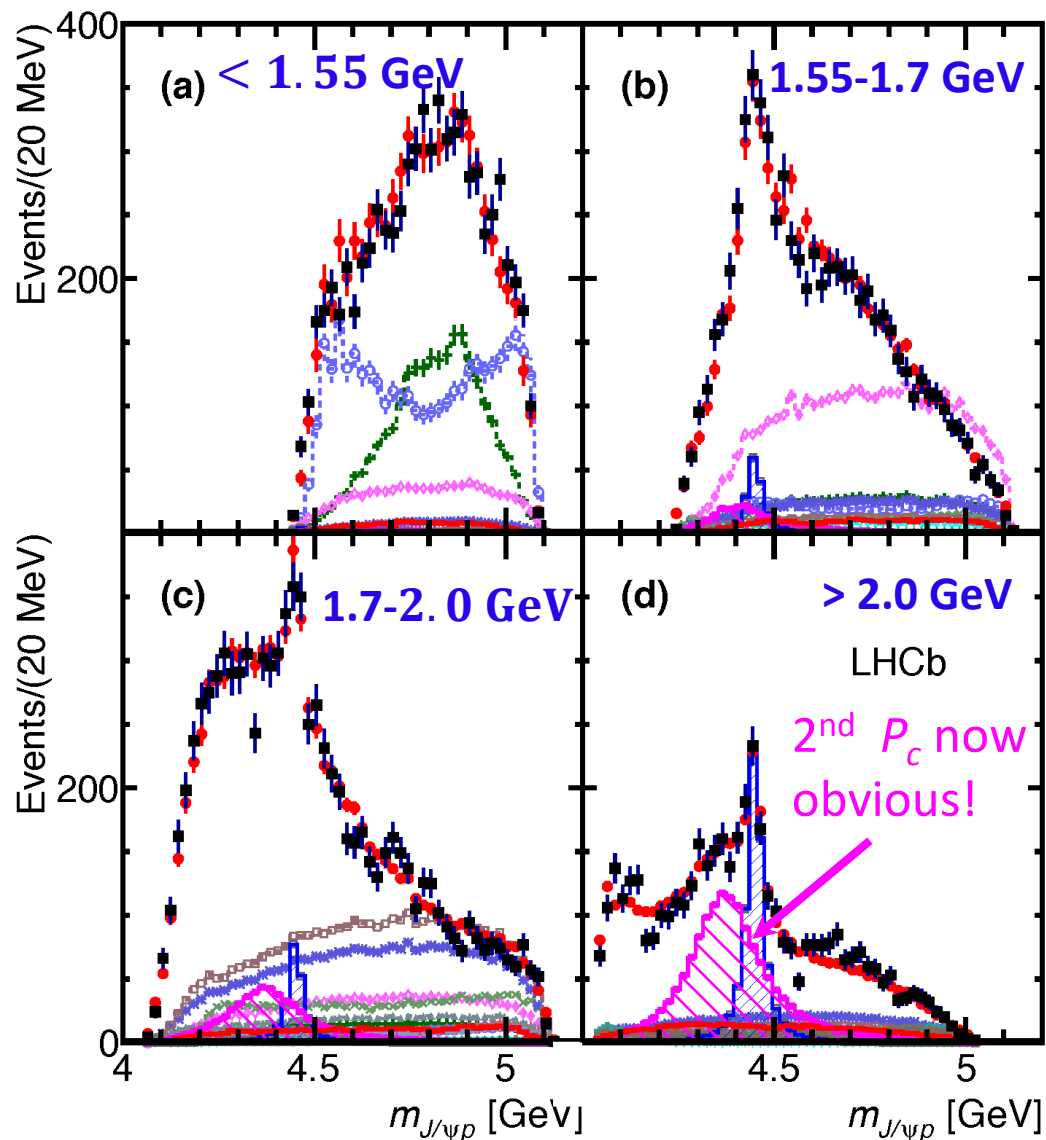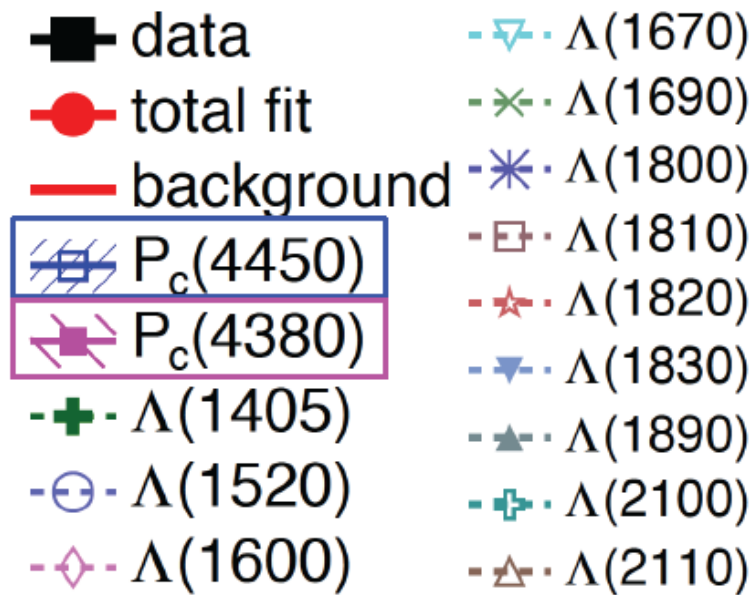
Quantum numbers

➢ Tested all J^P combinations up to spin $\frac{7}{2}$

➢ **Best fit has $J^P = \left[\frac{3}{2}^- (\textbf{low}), \frac{5}{2}^+ (\textbf{high}) \right]$**

- Plots shown correspond to this combination

➢ $\left[\frac{3}{2}^+ (\text{low}), \frac{5}{2}^- (\text{high}) \right]$ & $\left[\frac{5}{2}^+ (\text{low}), \frac{3}{2}^- (\text{high}) \right]$
are also possible: $\Delta(-2\ln\mathcal{L}) < 3^2$

➢ All others are ruled out: $\Delta(-2\ln\mathcal{L}) > 5.9^2$

Fit results

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

Systematic uncertainty discussed in next slide

Significances

➢ Fit improves greatly, for 1 P_c^+ Δ(-2ln$L$)=14.7^2, adding the 2nd P_c^+ improves by 11.6^2

➢ Toy MCs are used to obtain significances based on Δ(-2ln$L$)

➢ To include systematic uncertainty, the extended model fits are used:

- 1st P_c (4450)$^+$: 12σ
- 2st P_c (4380)$^+$: $9\,\sigma$

Systematic Uncertainties

Source	M_0 (MeV) low	high	Γ_0 (MeV) low	high	low	high	Fit fractions (%) $\Lambda(1405)$	$\Lambda(1520)$
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
$L^{P_c}_{\Lambda^0_b} \Lambda^0_b \to P^+_c$ (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		
$L^{\Lambda^*_n}_{\Lambda^0_b} \Lambda^0_b \to J/\psi\, \Lambda^*$	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

Λ* modelling contributes the largest

$J/\psi K^-$ system

> $J/\psi K$ system is well described by the Λ^* and P_c reflections
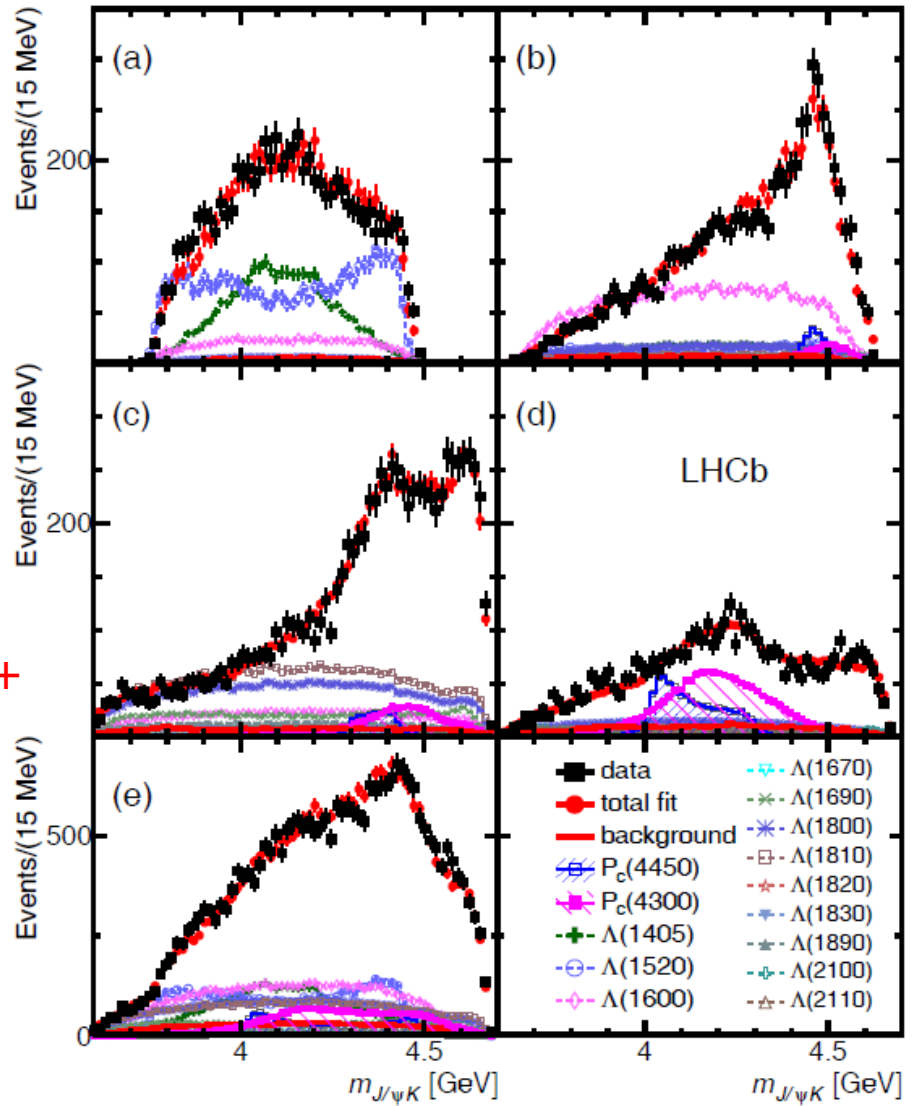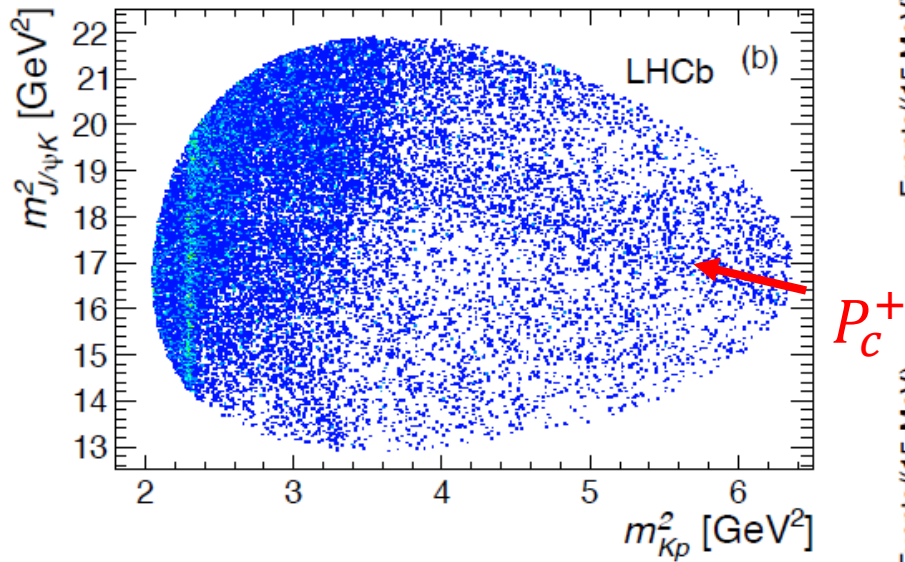
Cross-checks

➢ Two independently coded fitters using different background subtractions (sFit & cFit)

➢ Split data show consistency:

- 2011/2012

- magnet up/down

- $\Lambda_b^0/\overline{\Lambda}_b^0$

- $\Lambda_b^0(\text{low } p_\text{T})/\Lambda_b^0(\text{high } p_\text{T})$

➢ Selection varied

- BDTG>0.5 instead of 0.9 (default)

- B^0 and B_s^0 reflections modelled in the fit instead of veto

Argand diagram

➢ Replace the Breit-Wigner amplitude for either one P_c^+ by 6 independent amplitudes in range of $\pm\Gamma_0$ around M_0

➢ $P_c(4450)^+$ shows resonance behavior: a rapid contour-clockwise change of phase when cross pole mass

➢ $P_c(4380)^+$ does show large phase change, but is not conclusive
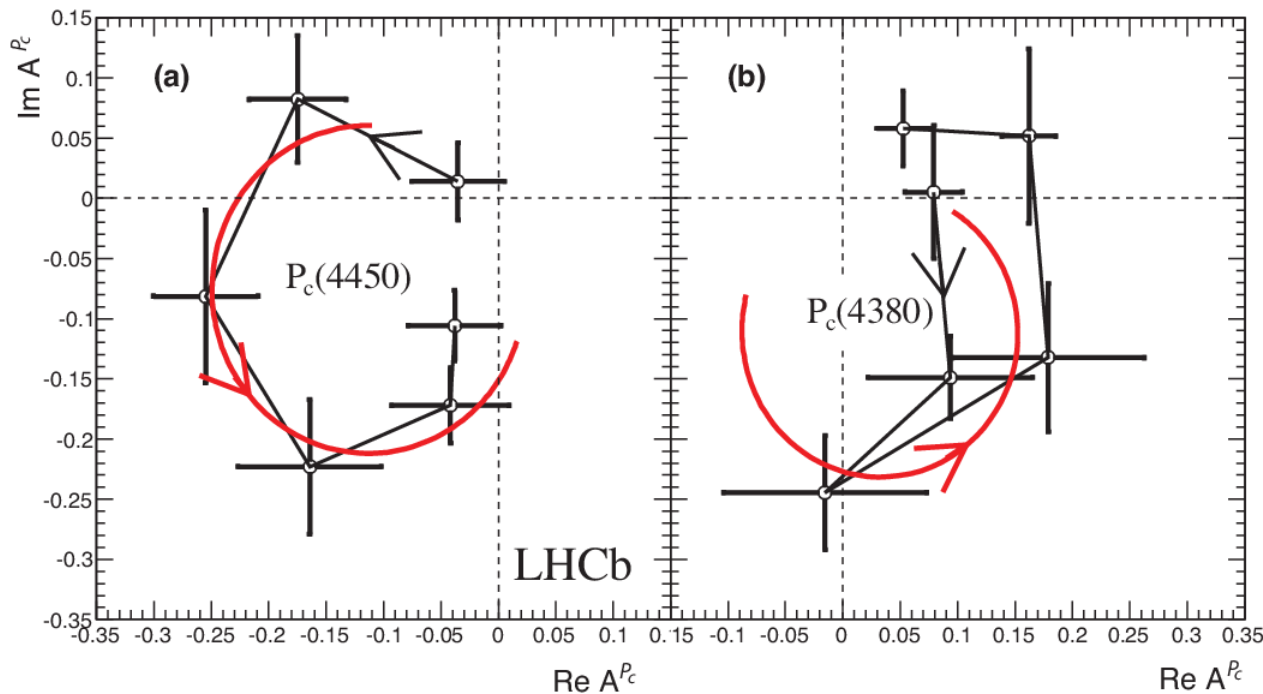
Breit-Wigner expectation
Fitted values

Intepretation

➢ Different binding mechanisms are possible

- Tightly-bound
- Weakly bound "molecules" of baryon-meson
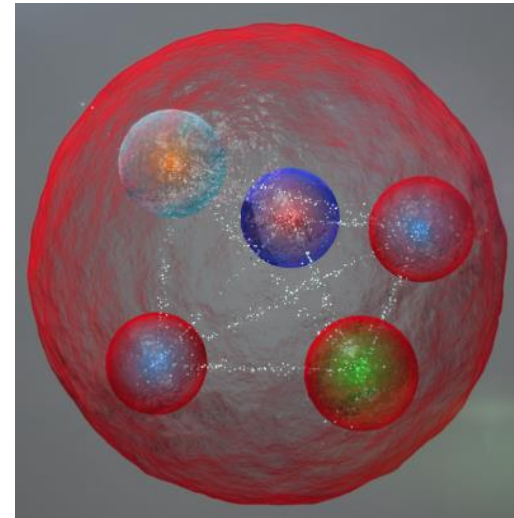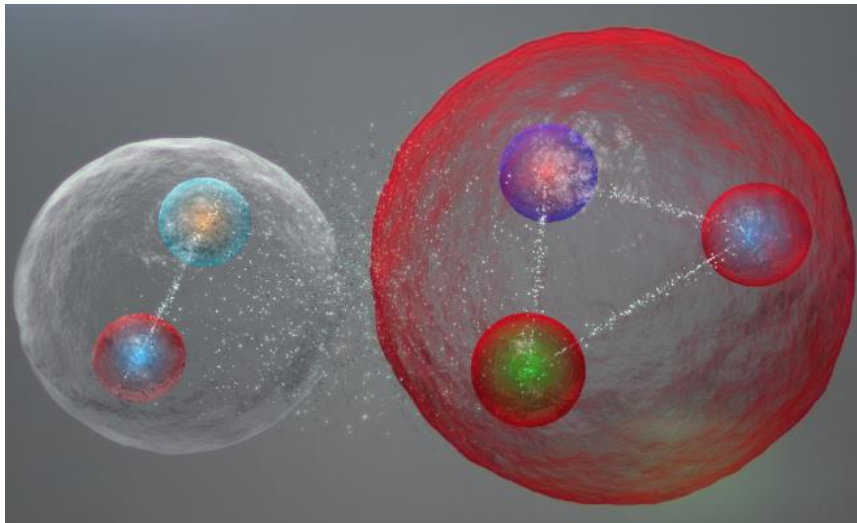
Summary

➢ Have performed a full amplitude fit to $\Lambda_b^0 \to J/\psi\, pK^-$

➢ Two Breit-Wigner shaped resonances in $J/\psi p$ mass are observed, with minimal quark content of $c\bar{c}uud$, therefore called pentaquark-charmonium states

- The preferred J^P are of opposite parity, with one state having $J = \frac{3}{2}$ and the other $J = \frac{5}{2}$

	$P_c(4380)^+$	$P_c(4450)^+$
Significance	9σ	12σ
Mass (MeV)	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width (MeV)	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction(%)	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$

Outlook

➢ Determination their internal binding mechanism will require more study

➢ We look forward to establishing the structure of many other states or other decay modes

➢ Run II data provides good opportunities

Thank you!

Multi-quark states were discussed when the quark model was proposed

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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 the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

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➤ Threshold ("cusps") [Swanson arXiv:1504.07952, 1409.3291, Bugg 1105.5492] has obvious difficulties

- The closest threshold 4457.1 ± 0.3 MeV $(\Lambda_c(2595)D^0)$ is somehow above the measured mass

- And it would give $J^P = \frac{1}{2}^+$, disfavored by our data

- No threshold close to the low state