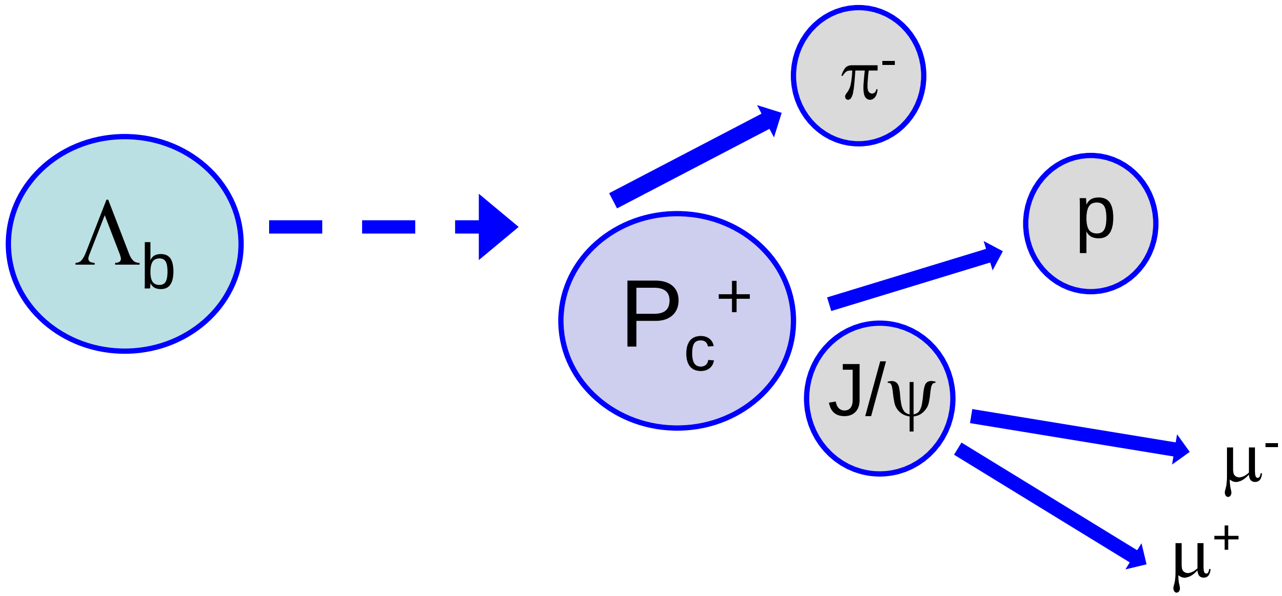
Exotic Hadron Spectroscopy at LHCb:
Candidates for Tetra- and Pentaquark States



Ulrich Uwer
Heidelberg University
On behalf of the LHCb Collaboration

Supported by Bundesministerium für Bildung und Forschung

Multi-Quark States in Quark Model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig *)
CERN - Geneva

Both papers mentioned explicitly the possibility for tetra and penta-quark states: $qq\bar{q}\bar{q}$, $qqqq\bar{q}$

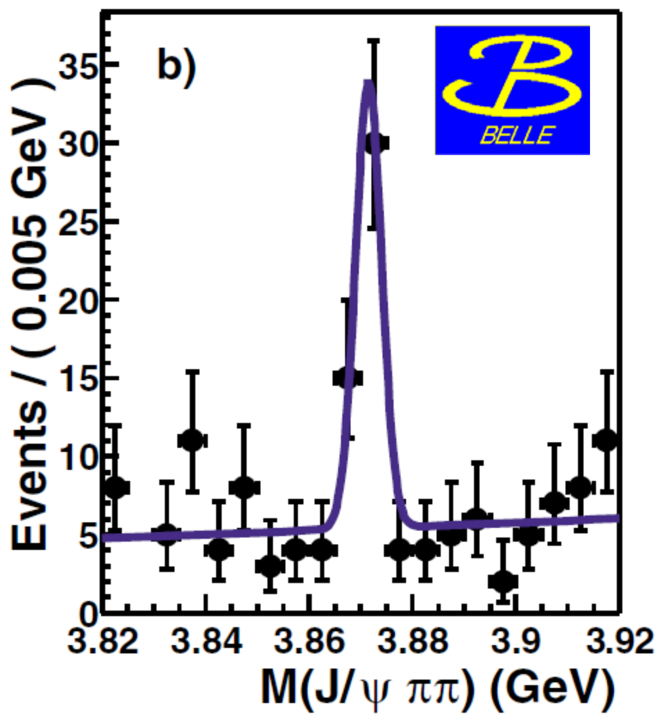
Multiquark states would be short-lived ~10^{-23}s "resonances" whose presences are detected by mass peaks & angular distributions showing unique J^{PC}.

Searches for such states made from light quarks (u,d,s) are ~50 years old, but no undisputed experimental evidence has been found.

Discovery of X(3872)

Belle 2003, Phys. Rev. Lett. 91, 262001

$$B^{\pm} \to K^{\pm} \underbrace{J/\psi\pi^{+}\pi^{-}}$$



- Very narrow resonance (Γ<1.2 MeV) close to $D^0 D^{0*}$ threshold.
- Nature unclear: conventional charmonium state, exotic state ($D^0 D^{0*}$ molecule, tetraquark), or a mixture
- Determination of J^{PC} important

PRL 110, 222001 (2013).

$B^+ \to X(3872)K^+$ w/ $X(3872) \to J/\psi\pi\pi$

$\to J^{PC} = 1^{++}$, $J^{PC} = 2^{-+}$ rejected w/ >8σ

(analysis assumed lowest possible L)

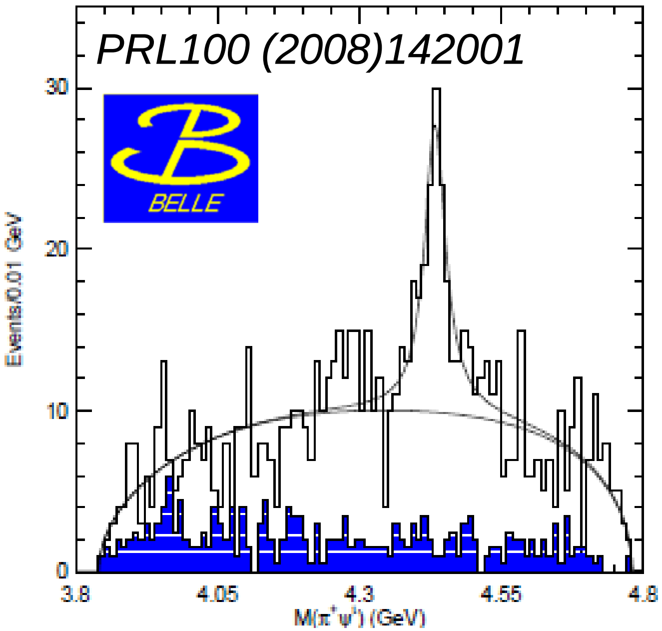
PR D 92, 011102 (2015).

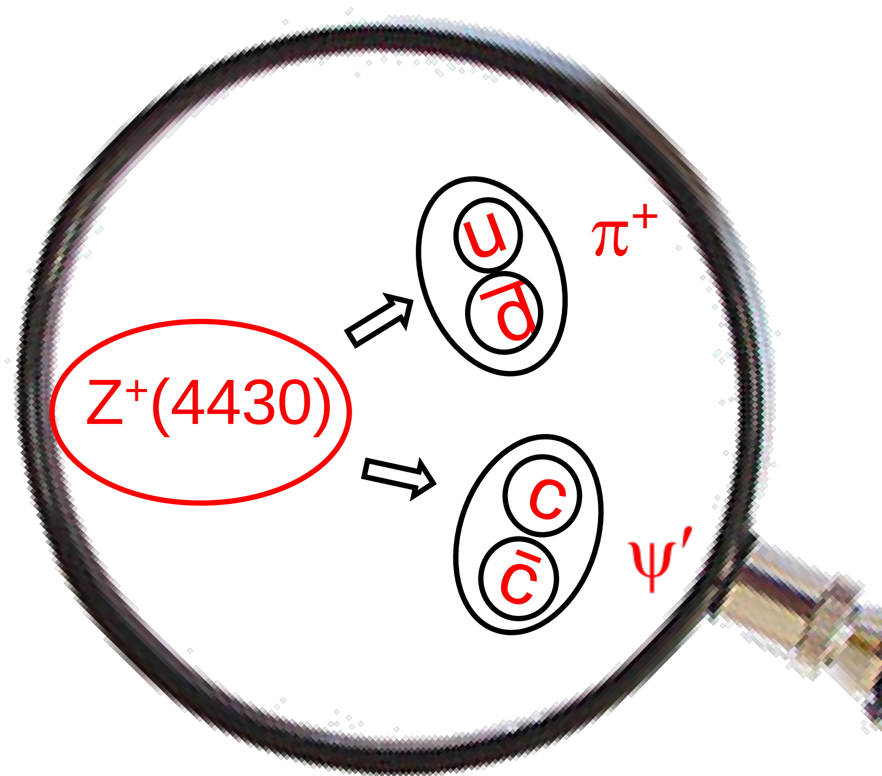
Update: w/o assumption on L

Confirms $J^{PC} = 1^{++}$

Tetra-Quark Candidate

$B \rightarrow \psi' \pi^+ K$

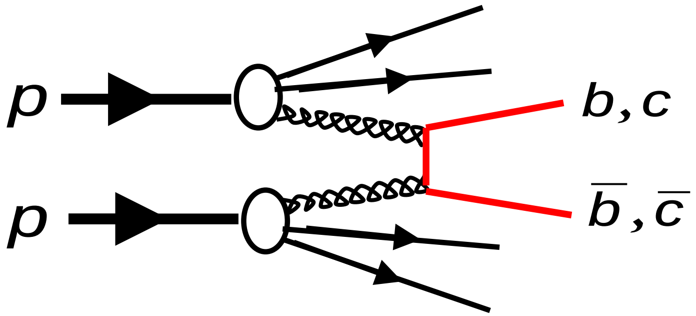




Smoking gun for 4-quark effect. Confirmed only recently by LHCb.
LHCb also provides evidence for the resonant character – see later.

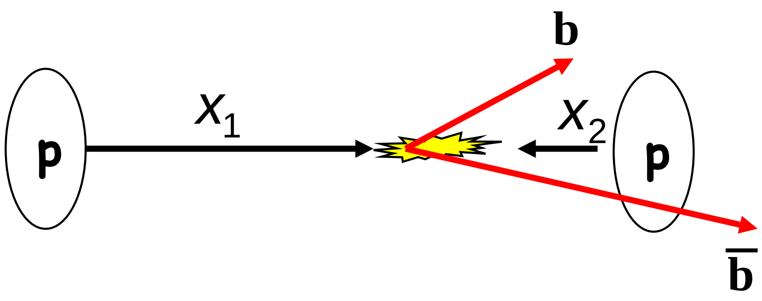
Supports the possibility for existence of pentaquark state.

LHCb-Experiment

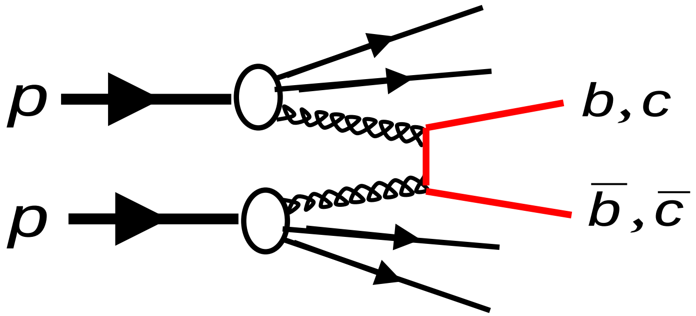


Run 2011-2012:		3 fb^{-1} (LHCb)
200 kHz $b\bar{b}$	$\rightarrow$	2.6×10^{11} $b\bar{b}$
4MHz $c\bar{c}$	$\rightarrow$	5.9×10^{12} $c\bar{c}$

$\times$O(5000) rates of B-factories.
Smaller background.



LHCb-Experiment



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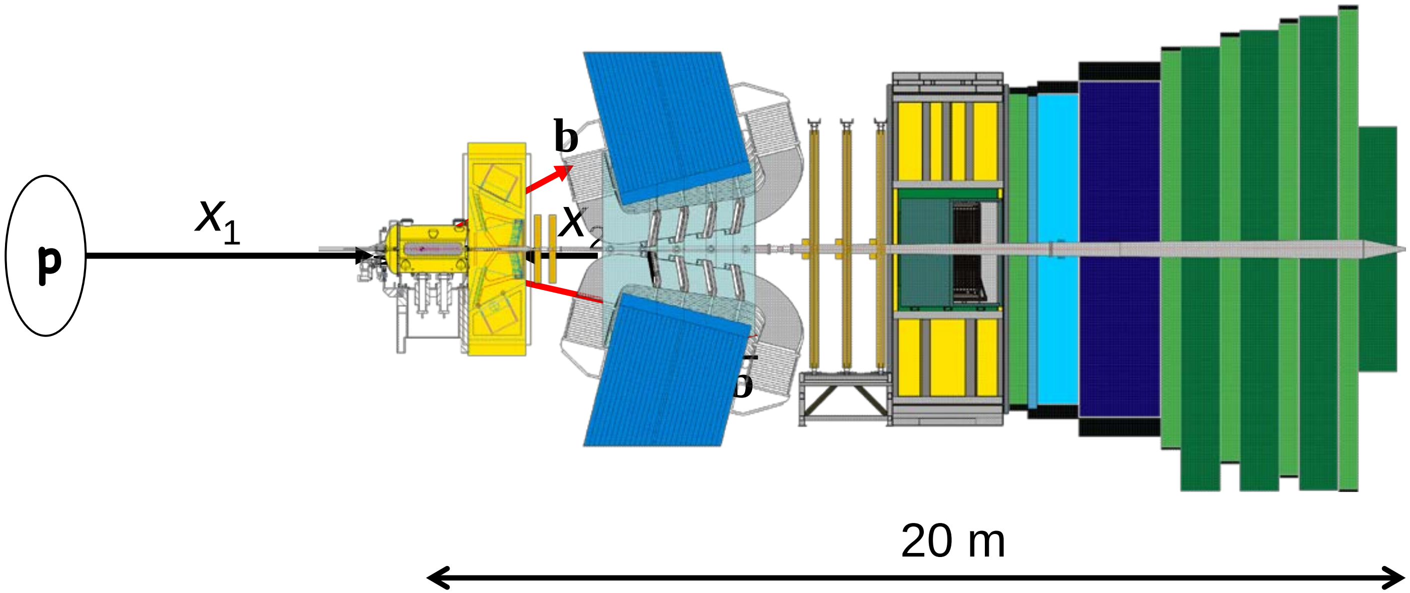
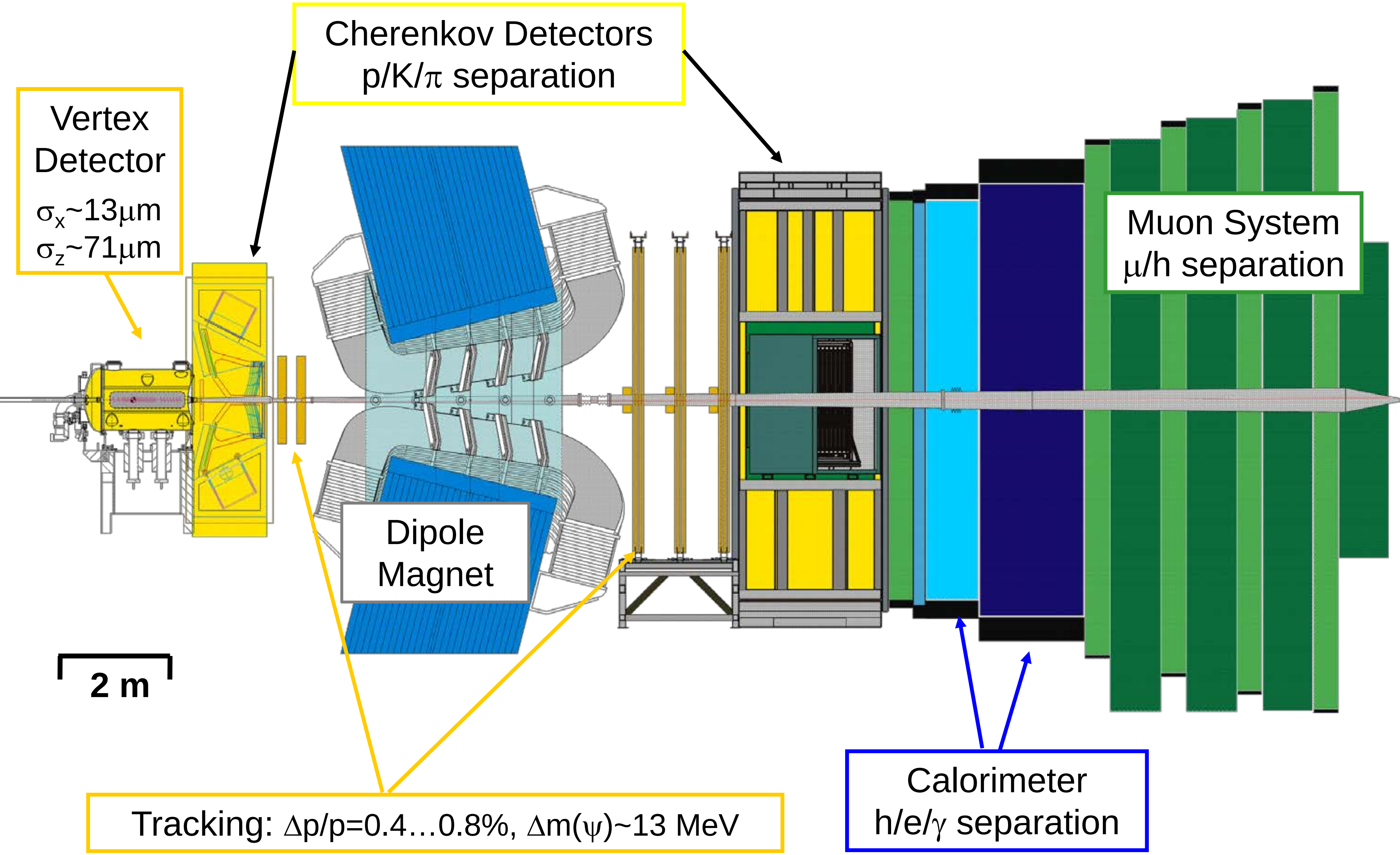
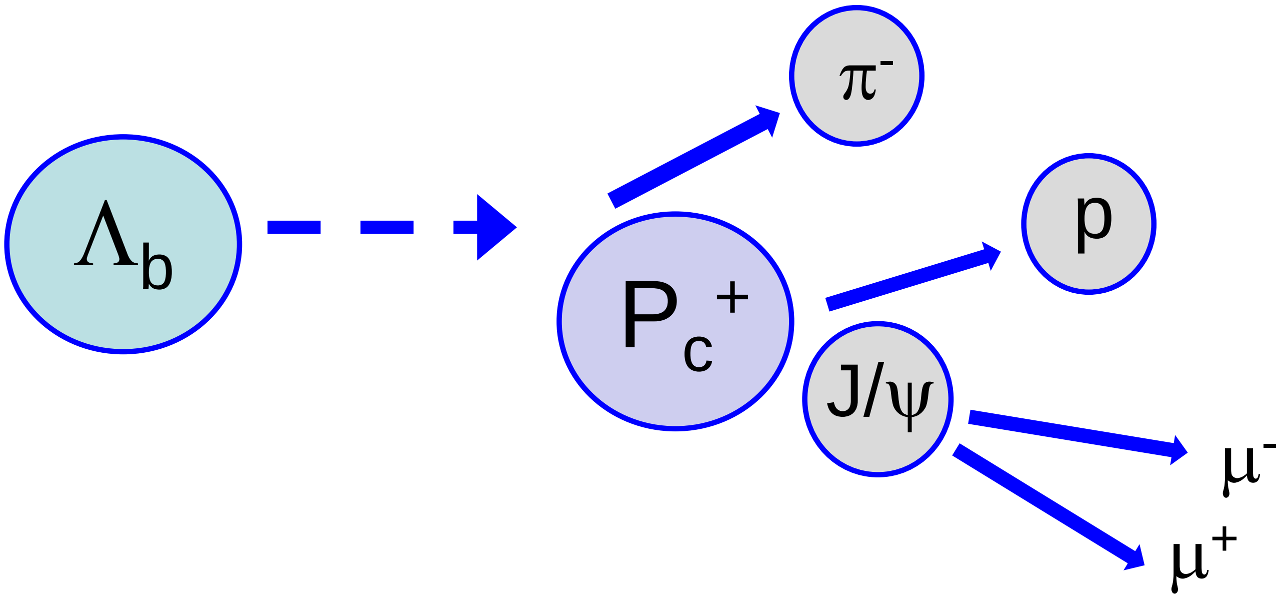


LHCb Detector



Observation of J/ψp resonances consistent with pentaquark states

PRL 115, 07201, arXiv:1507.03414

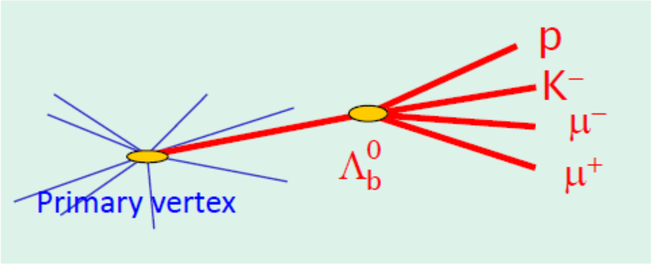


$\Lambda_b^0 \to J/\psi\ p\ K^-$ data sample

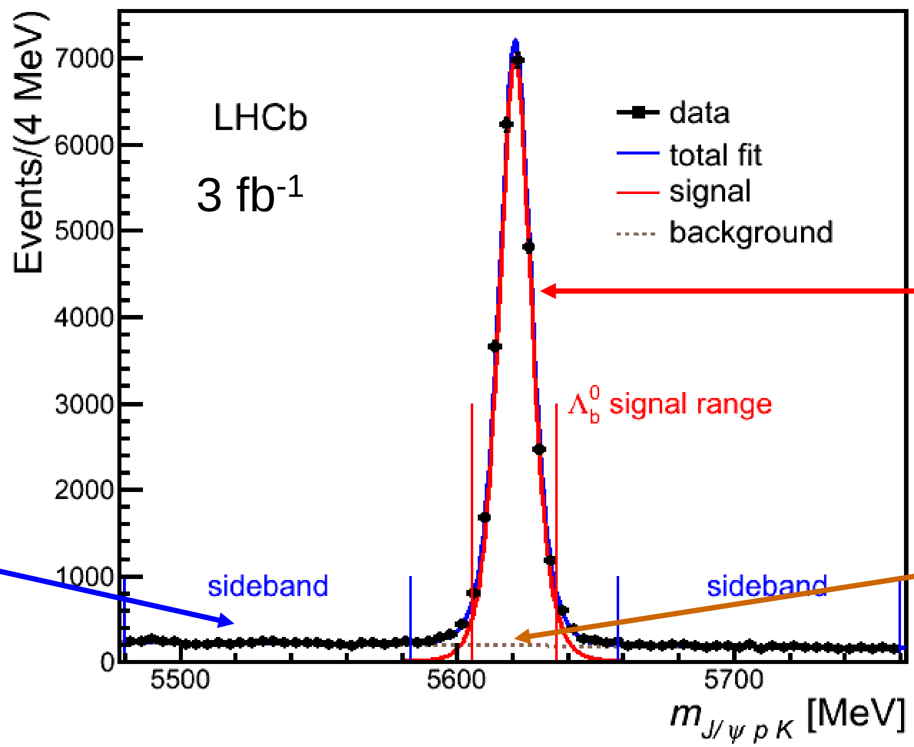
$\Lambda_b^0 \to J/\psi\ p\ K^-$ first observed by LHCb; used for Λ_b^0 lifetime.

$\mathcal{B}=(3.04\pm0.04\ ^{+0.55}_{-0.43})\times10^{-4}$

arXiv:1509.00292



PRL 115, 07201, arXiv:1507.03414

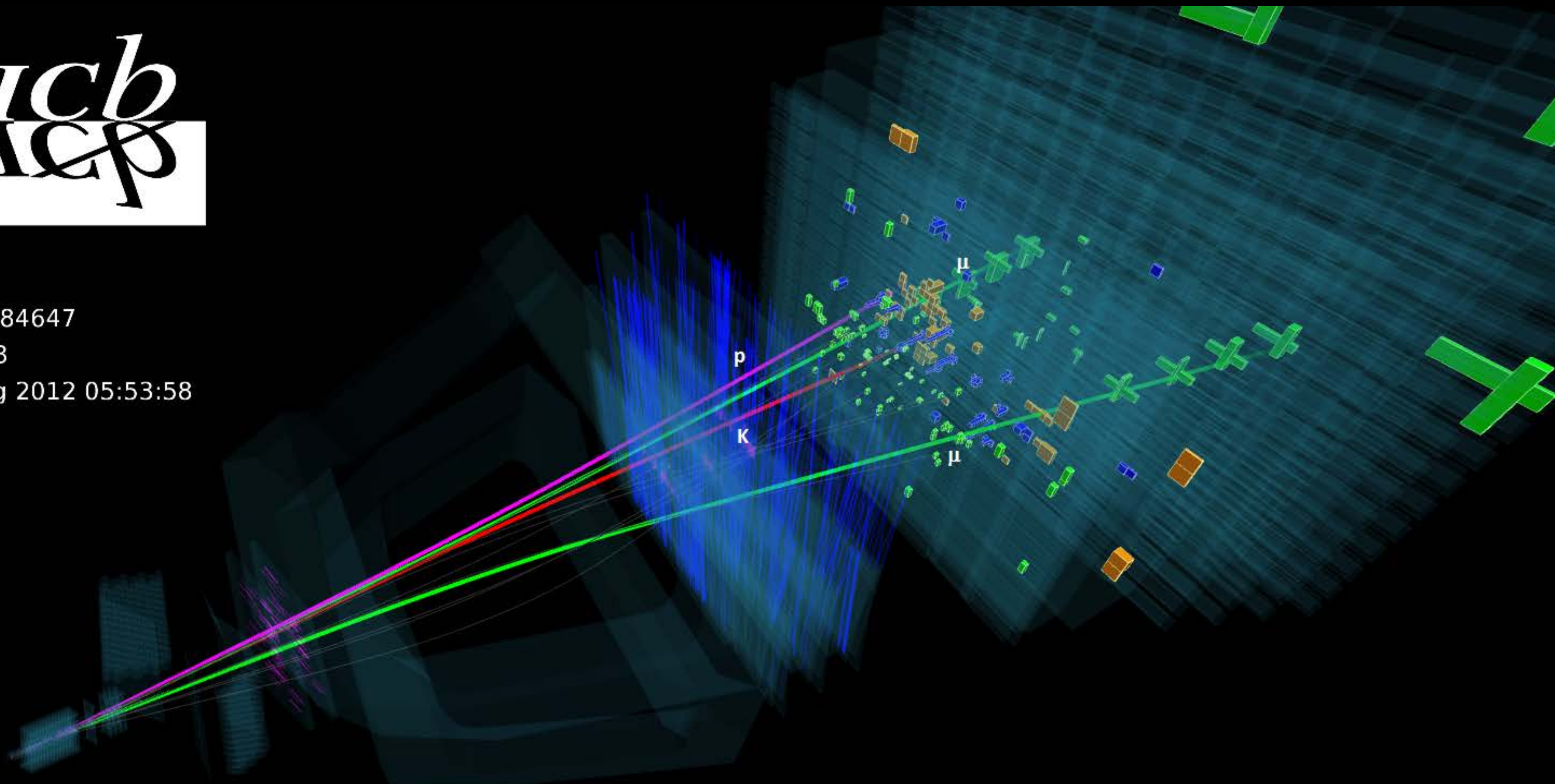


26000 Λ_b decays

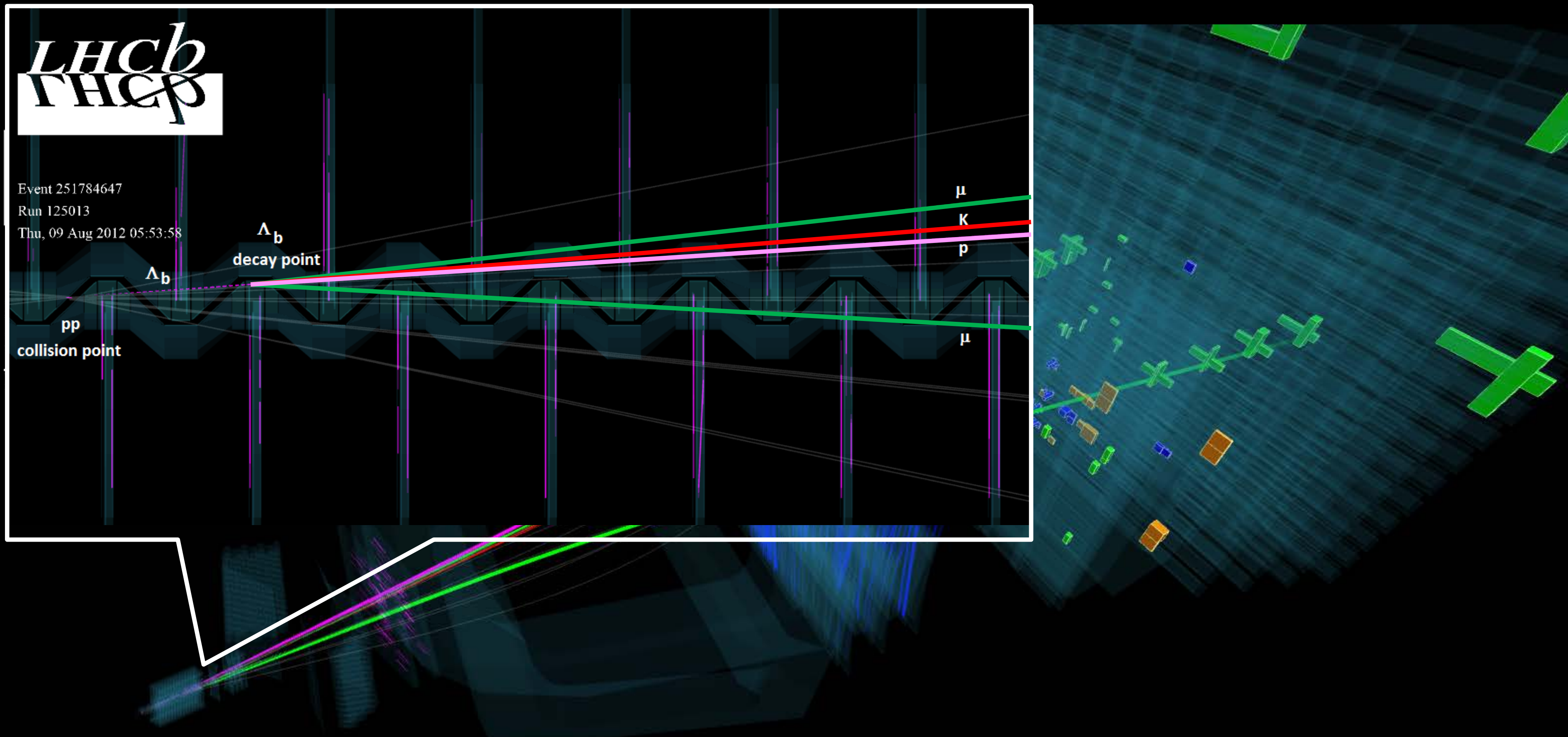
Flat sidebands → no major reflections from other b-hadrons

background only 5.4% in signal region

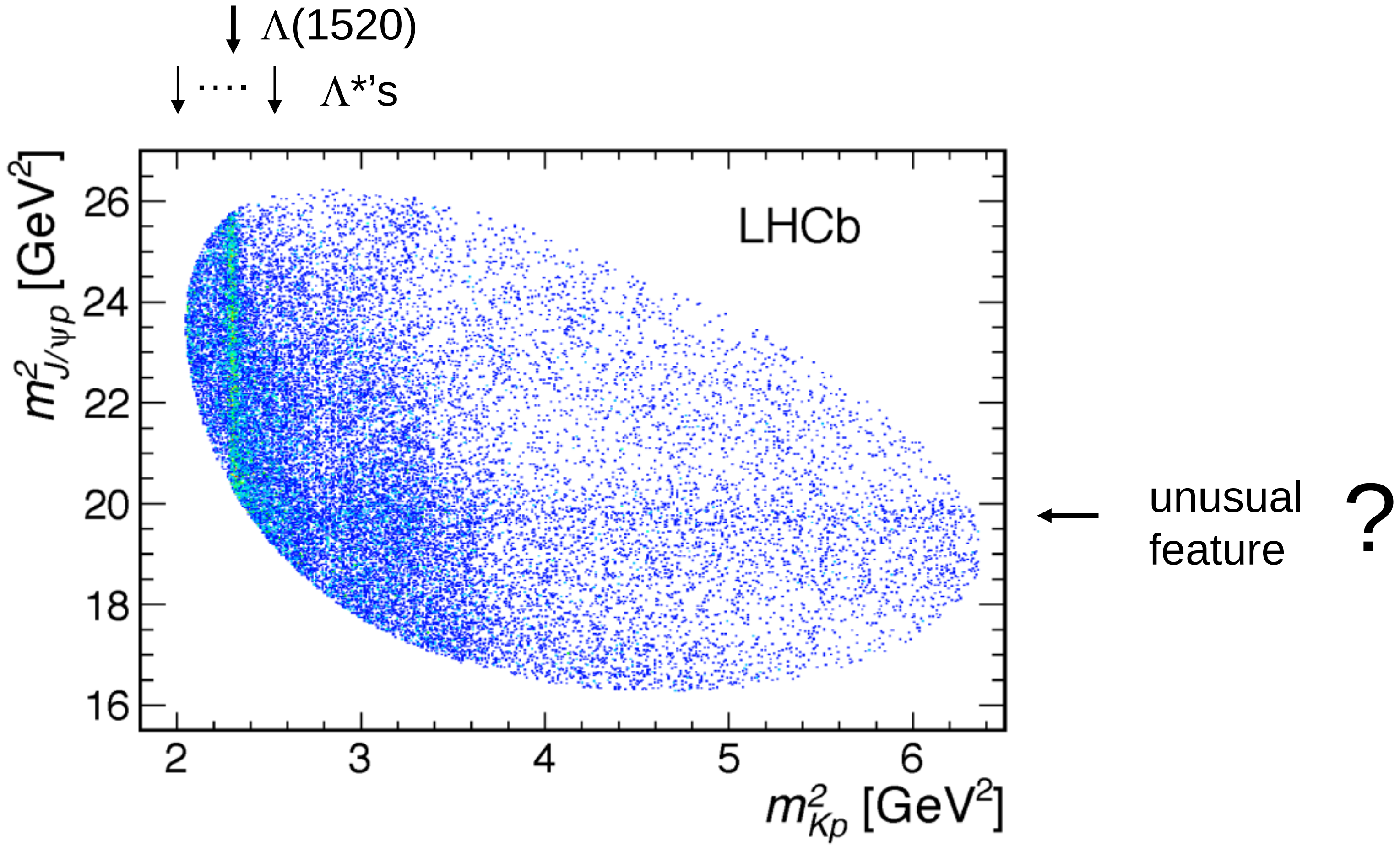
$\Lambda_b^0 \to J/\psi\ p\ K^-$ candidate



$\Lambda_b^0 \to J/\psi\ p\ K^-$ candidate

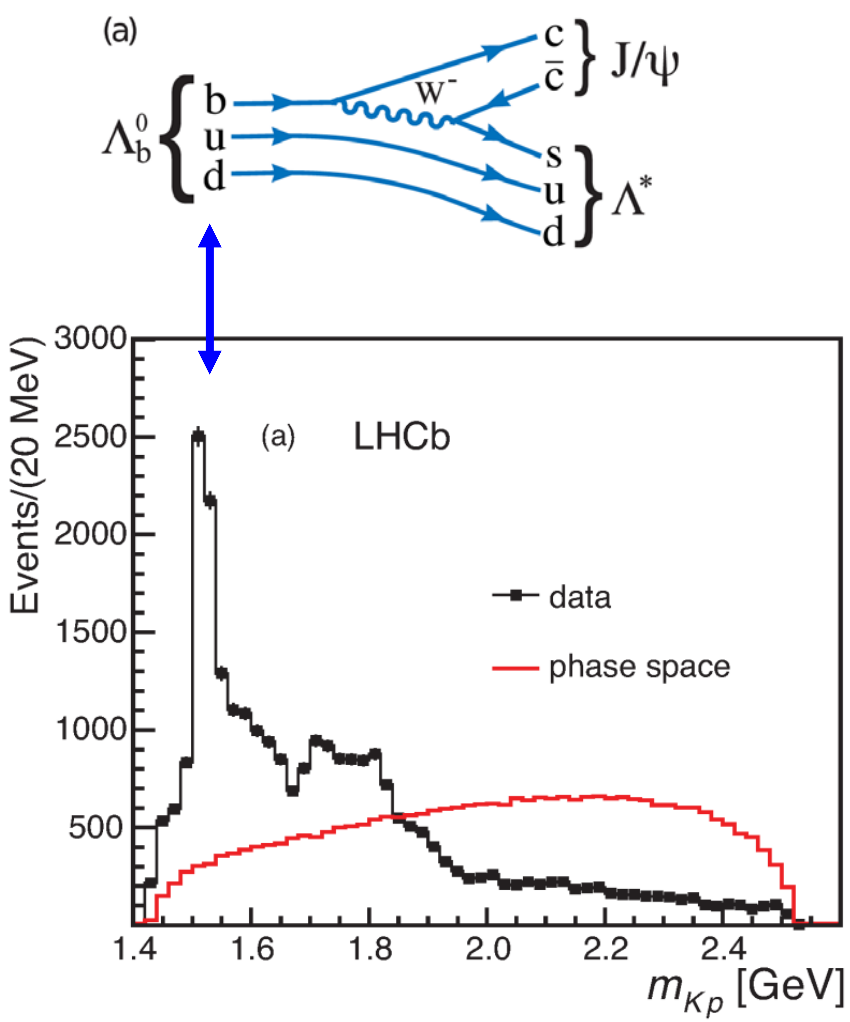


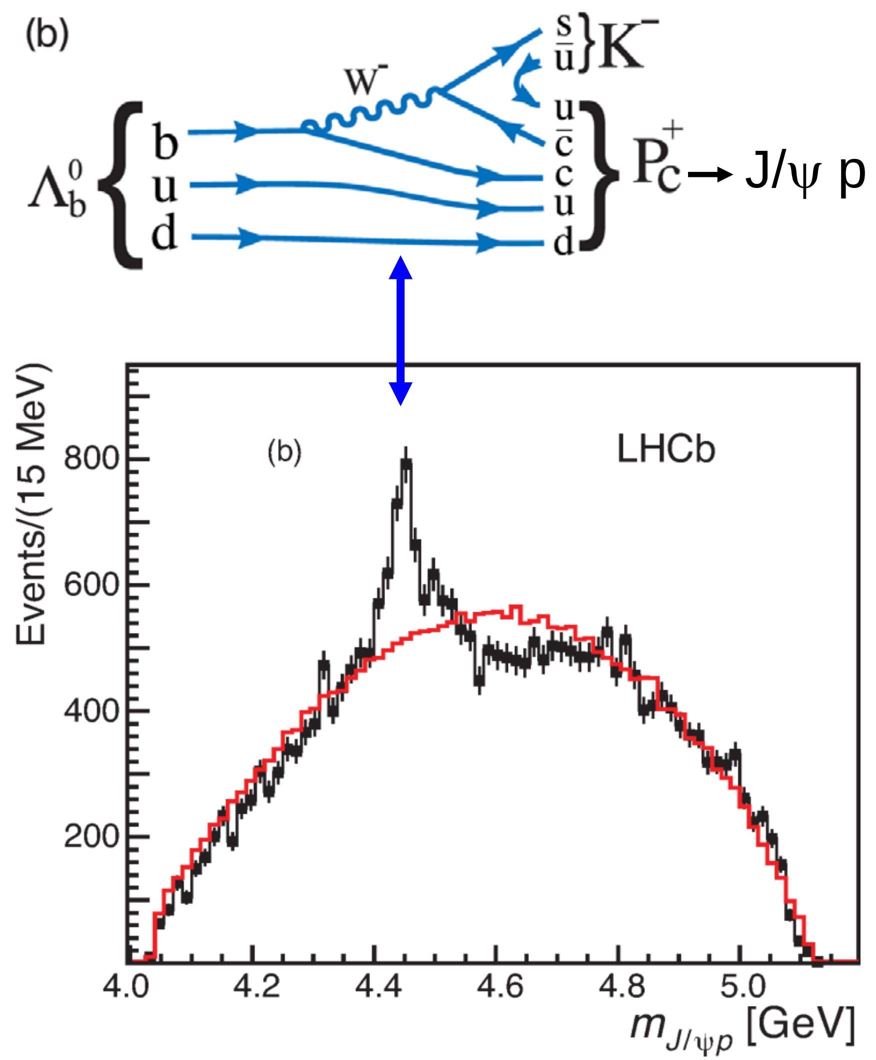
Dalitz-Plot


Λ(1520)
Λ*'s
LHCb
26
24
22
20
18
16
2
3
4
5
6
$m^2_{J/\psi p}$ [GeV^2]
m^2_{Kp} [GeV^2]
unusual feature ?

Projections

PRL 115, 07201, arXiv:1507.03414



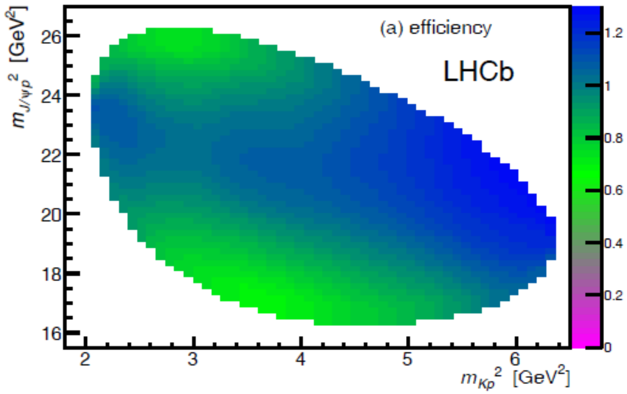


Origin of narrow peak in $m_{J/\psi p}$

PRL 115, 07201, arXiv:1507.03414

Checks to ensure that it is not an artifact of the selection:

- Reflections of $B^0 \to J/\psi K\pi$ & $B_s \to J/\psi KK$ are vetoed
- Ξ_b decays checked
- Efficiency is smooth, cannot create a peak
- Λ_b sideband background does not peak
- Clones and ghost tracks are eliminated



Can interference between Λ^* resonances generate peak in $(J/\psi p)$ mass?

If not, can data be described in all relevant kinematic variables with the addition of $(J/\psi\ p)$ resonances?

⇩

Full amplitude analysis using all known Λ^*'s .

Helicity formalism

Each sequential decay A→BC contributes to the amplitude:

$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C}\; D^{J_A}_{\lambda_A,\lambda_B-\lambda_C}(\phi_B,\theta_A,0)^* R_A(m_{BC})$$

Complex helicity coupling amplitude

Wigner D-matrices: rotation of quantization axis

Complex function for mass shape (BW)

Express helicity couplings via LS couplings (Clebsch-Gordon coeff.):

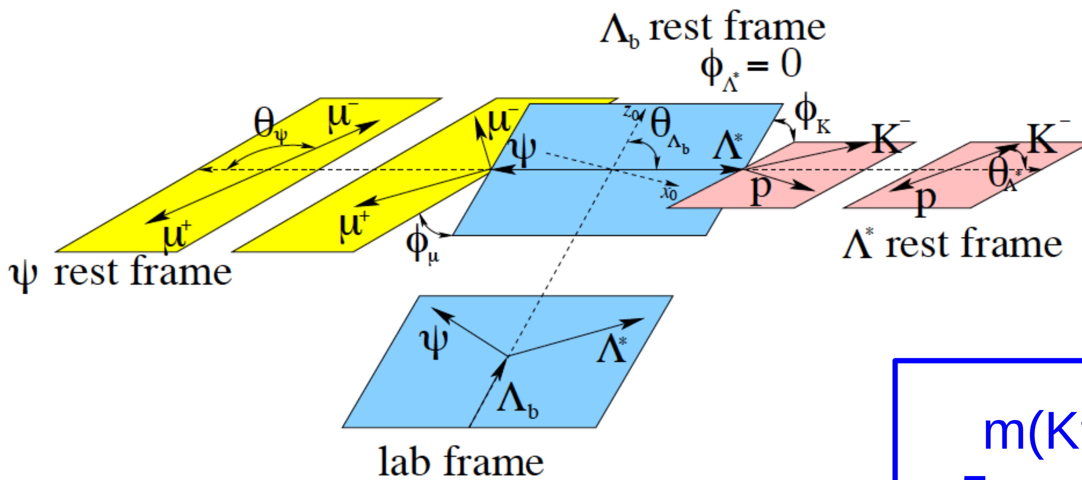
$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B-\lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B-\lambda_C & \lambda_B-\lambda_C \end{array} \right),$$

⇒ Easily consider parity conservation $P_A = P_B P_C (-1)^L$ and restrict L_{max}

Amplitude Analysis

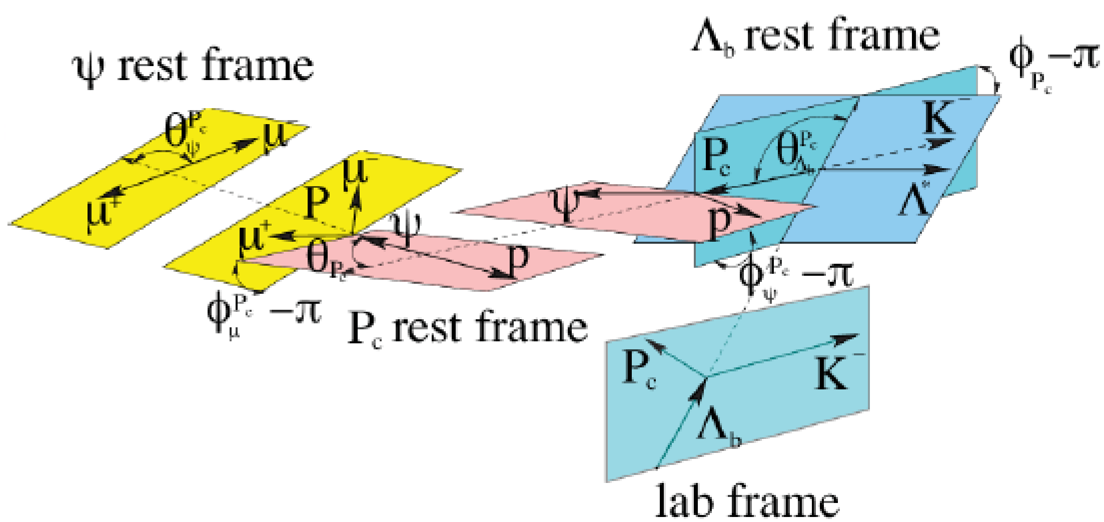
Consider two interfering processes with two distinct decay chains:

$\Lambda_b^0 \rightarrow J/\psi\ \Lambda^*$
$\Lambda^* \rightarrow p\ K^-$
$J/\psi \rightarrow \mu\mu$



m(K-p)
5 angles

$\Lambda_b^0 \rightarrow P_C^+\ K^-$
$P_C^+ \rightarrow J/\psi\ p$
$J/\psi \rightarrow \mu\mu$



Λ* resonance model

PRL 115, 07201, arXiv:1507.03414

Extended model:
- All known Λ* resonances. Masses and widths fixed to PDG.
- All possible L values.

Reduced model:
- Drop Λ(2350) and Λ(2585)
- Remove high L contributions.

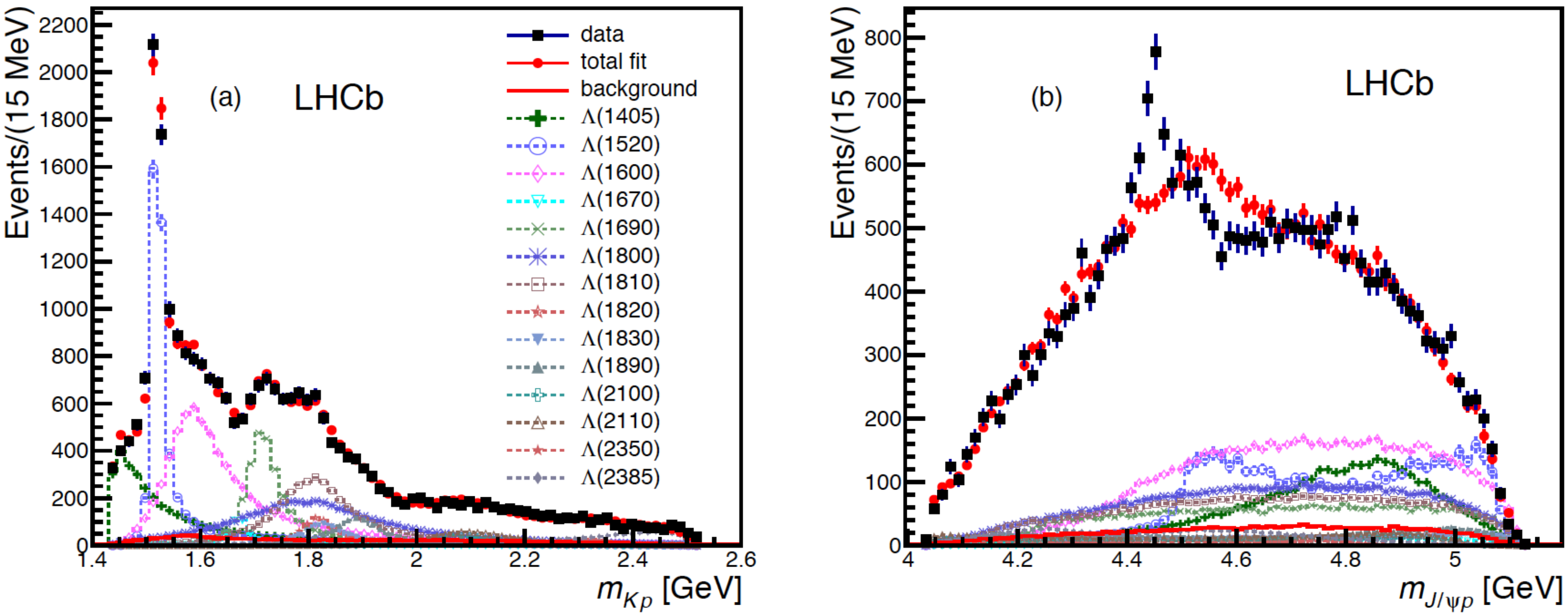
14 Λ* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	≈2585	200	0	6
				64	146

Fit parameters

Fit with extended Λ* model (no P_c^+)

PRL 115, 07201, arXiv:1507.03414

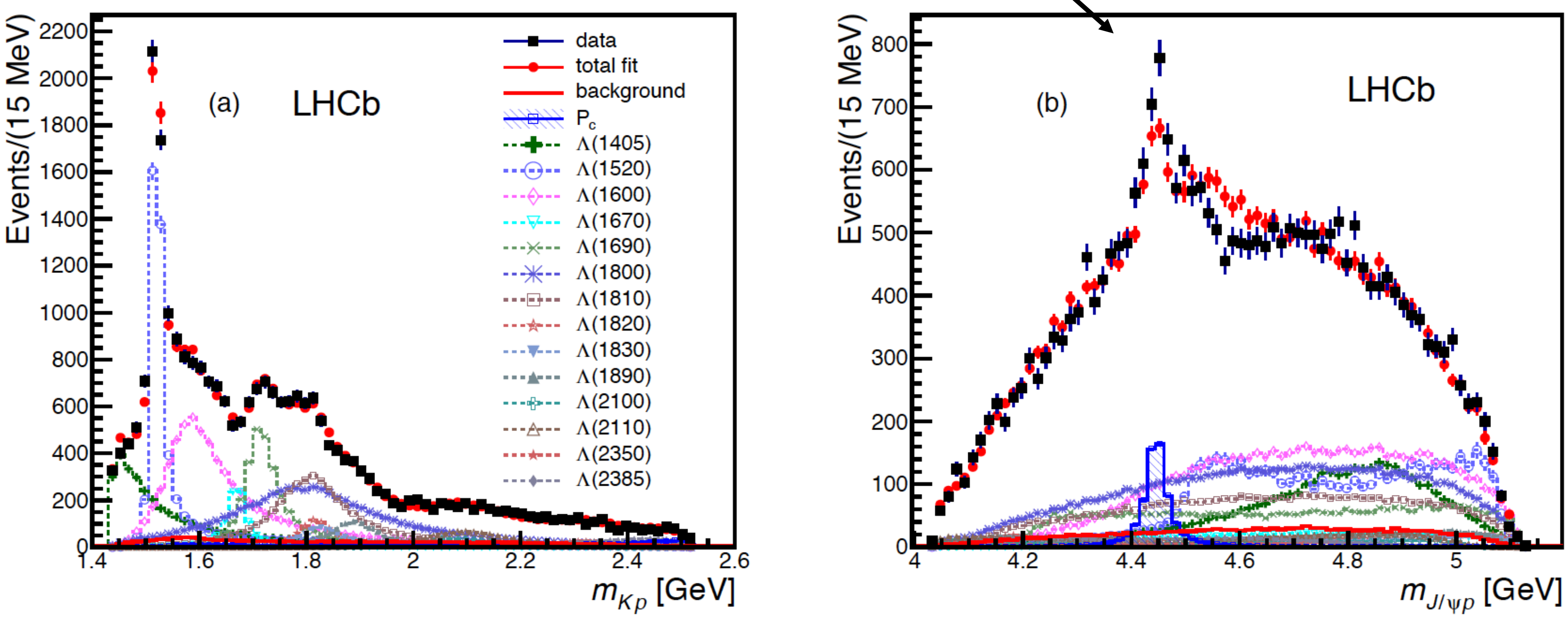


- m_{Kp} looks fine, $m_{J/\psi p}$ not described
- Additional terms do not help:
  - Σ*'s (expect small contribution: ΔI=1)
  - Λ* with free mass and widths
  - Non-resonant terms w/ $J^P=1/2^{\pm}$ $3/2^{\pm}$

Fit with one additional P_C^+ state

PRL 115, 07201, arXiv:1507.03414

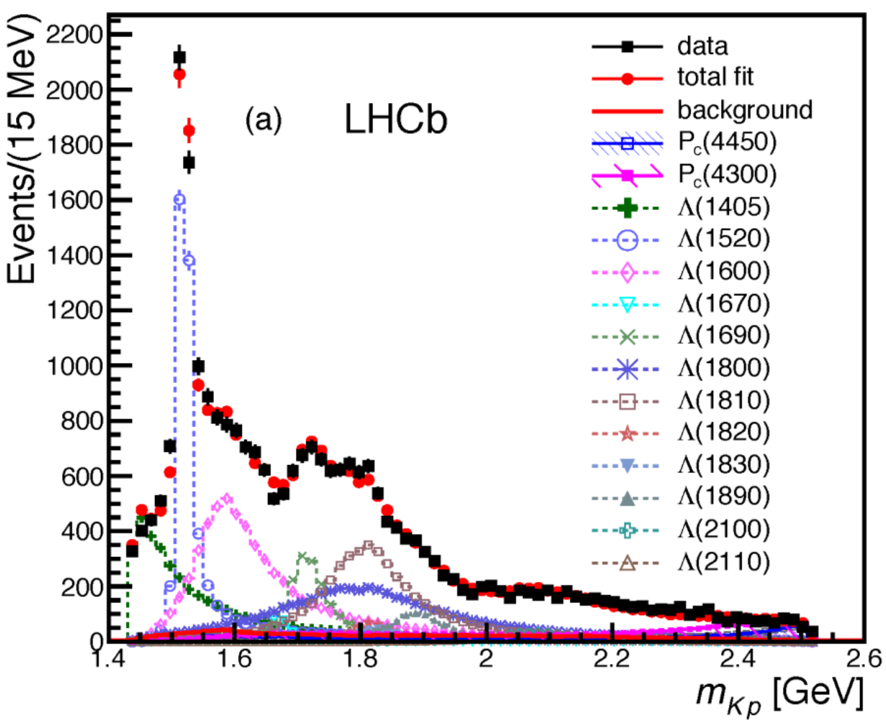
- Extended Λ^* model
- Try all J^P (P_C^+) up to $7/2^{\pm}$
- Best fit for $J^P(P_C^+)=5/2^{\pm}$. Still not a good fit.

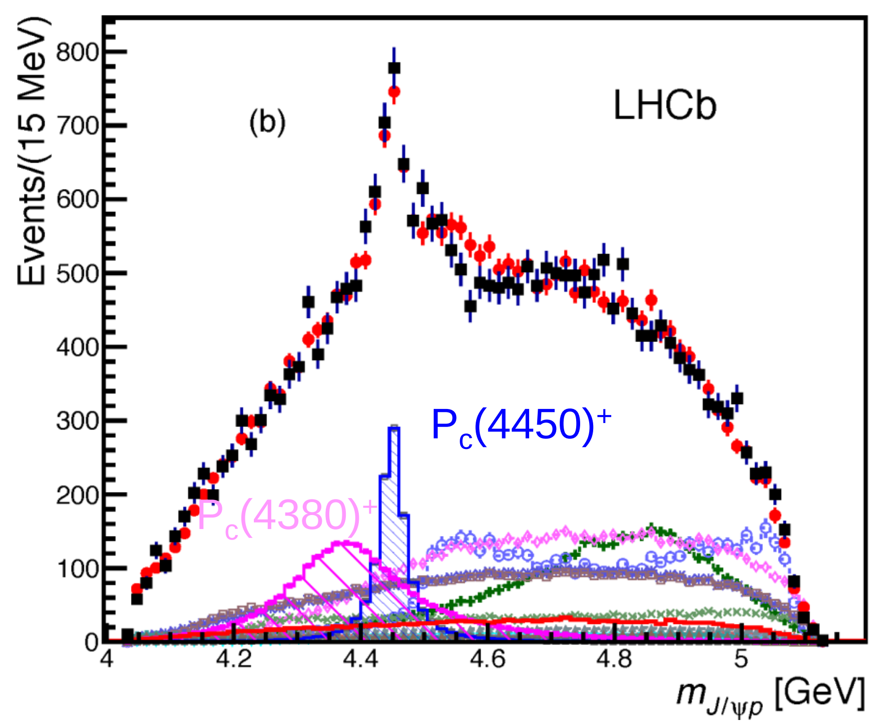


Fit with two additional P_C^+ states

PRL 115, 07201, arXiv:1507.03414

- Obtain good fits even with the reduced Λ* model
  (use reduce Λ* model when determining the P_C^+ parameters)
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $J^P=(3/2^+, 5/2^-)$ and $J^P=(5/2^+, 3/2^-)$ possible ($\Delta(-2\ln\mathcal{L})= 1, 2.3^2$). Other combinations up to 7/2 disfavored. Opposite paraity needed to explain P_c^+ decay angle distribution.

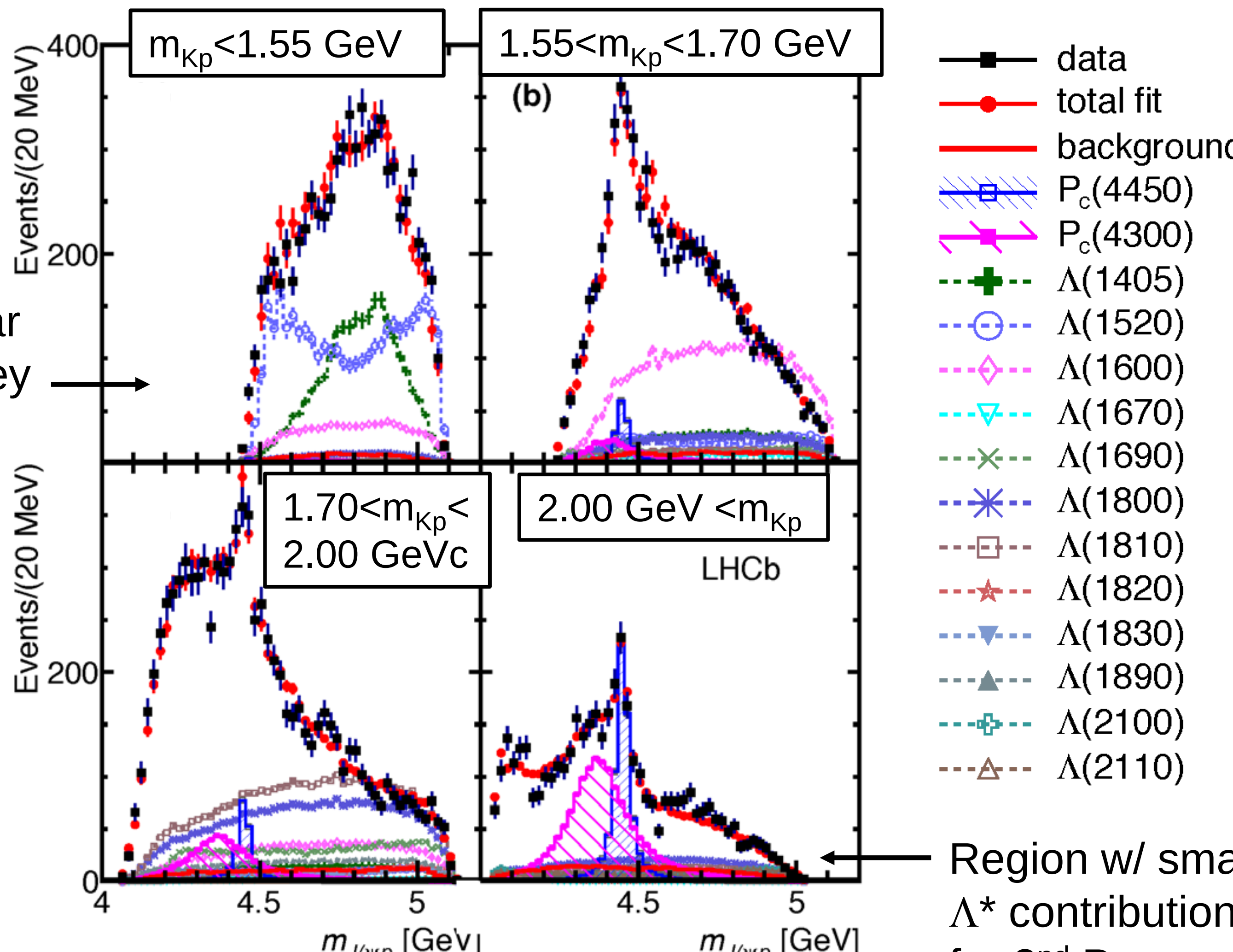




$m_{J/\psi p}$ projection for different m_{Kp} bins

PRL 115, 07201, arXiv:1507.03414

Pc's cannot appear in first interval: they would be outside Dalitz boundary

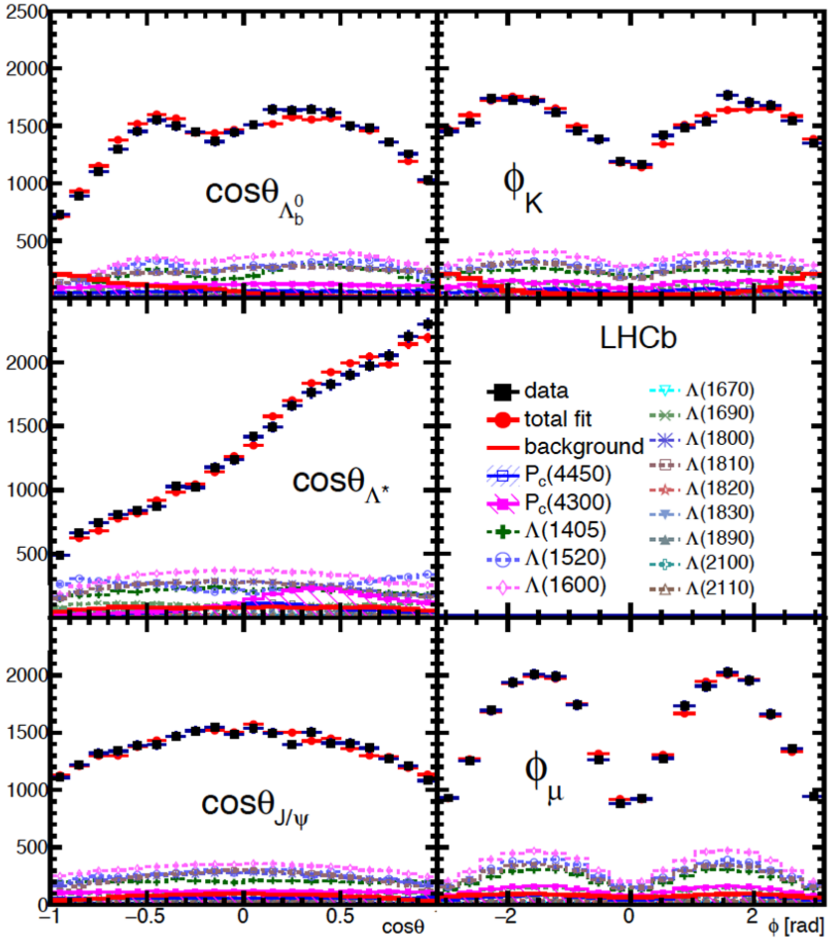


Region w/ smallest Λ^* contribution: need for 2^{nd} P_c apparent

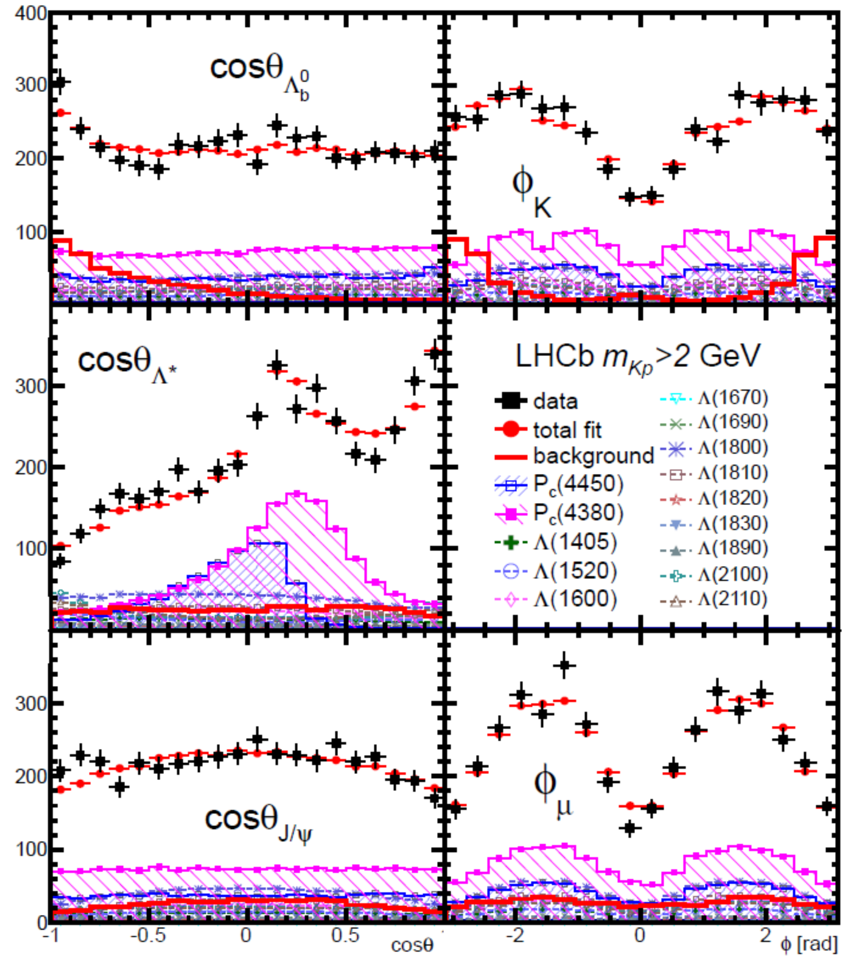
Angular distributions

PRL 115, 07201, arXiv:1507.03414

All data



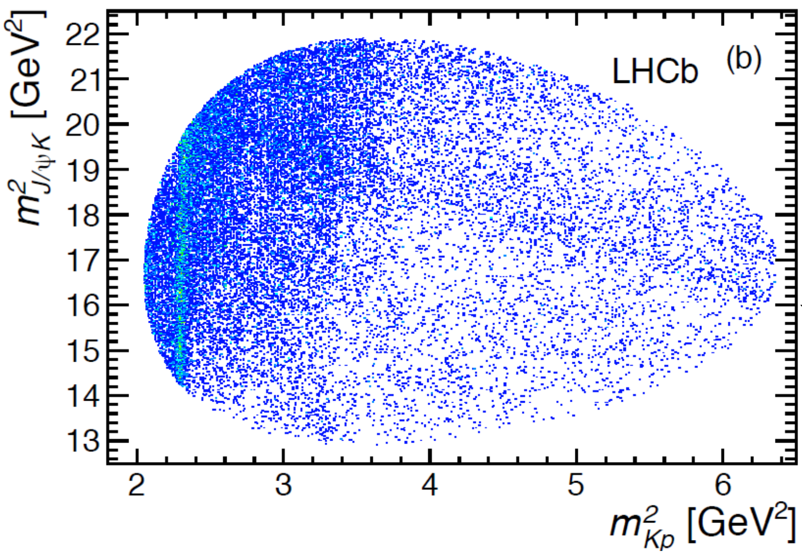
P_C^+ enriched (m_{Kp}>2 GeV)

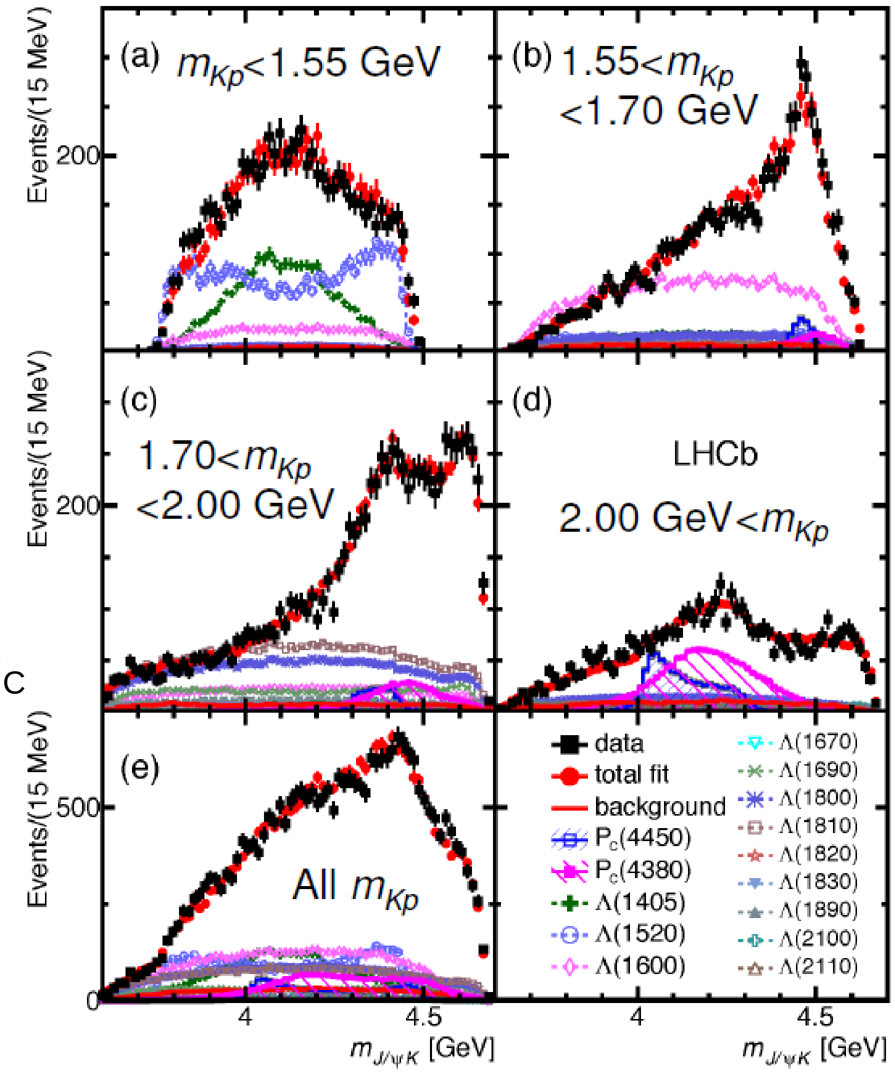


No need for exotic $J/\psi K^-$ contributions

PRL 115, 07201, arXiv:1507.03414

$J/\psi K^-$ structure well described by the Λ^* and P_c^+ reflections.





Significances and Fit Results

PRL 115, 07201, arXiv:1507.03414

Improvement of fit quality:

Fit w/ only Λ^* model

+ 1^{st} P_c^+

+ 2^{nd} P_c^+

$\Delta(-2\ln\mathcal{L}) = 14.7^2$

$\Delta(-2\ln\mathcal{L}) = 11.6^2$

$\Delta(-2\ln\mathcal{L}) = 18.7^2$

Simulation of pseudo-experiments used to turn $\Delta(-2\ln\mathcal{L})$ values into significances:

(includes dominant systematics: difference between extended and reduced Λ^* model)

$P_c(4450)^+$	12σ
$P_c(4380)^+$	9σ
$P_c(4450)$ & $P_c(4380)$	15σ

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**
$\Lambda(1405)$			15±1±6
$\Lambda(1520)$			19±1±4

PRL 115, 07201, arXiv:1507.03414

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
$L^{P_c}_{\Lambda^0_b}$ $\Lambda^0_b \to P_c^+$ (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^* modeling is largest uncertainty
- Fits w/ alternative J^P assignment
- Parameters for description of mass dependence

Cross checks

- Two independently coded max. log likelihood fitters using different background subtractions (cFit [default] & sFit):
  - Signal and background described by PDFs
  - background subtraction using sPlot technique*)

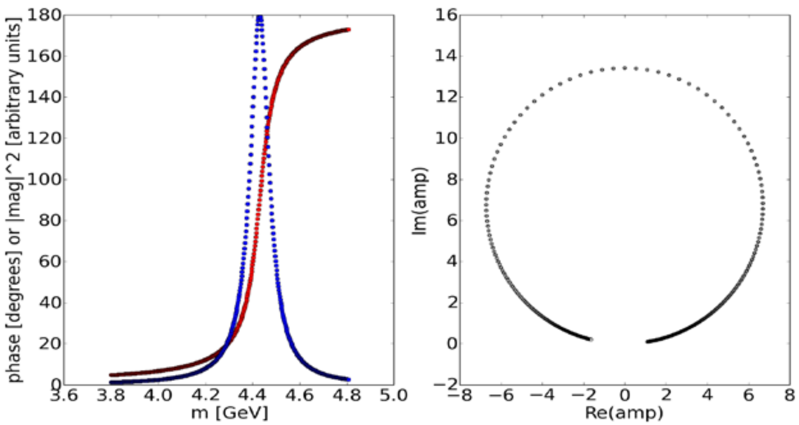
- Split data to check consistency: 2011/2012, magnet up/down, $\Lambda_b/\overline{\Lambda}_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$

- Extended model fits tried without P_c states, but two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

**) sPlot: M.Pivk and F.R. Le Diberder, NIM A555 (2005) 356.*

Phase motion across the resonance

For a Breit-Wigner resonance we expect a phase variation over the resonance:



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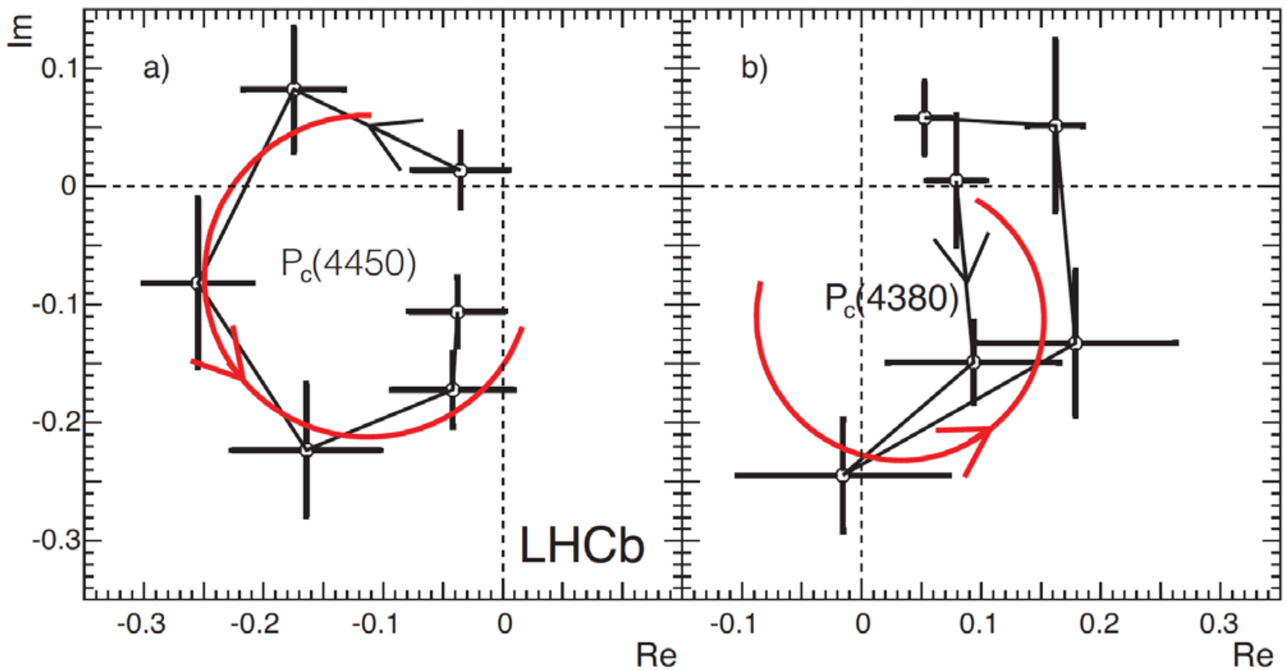
PRL 115, 07201, arXiv:1507.03414

Fit Re and Im part of amplitudes for 6 individual mass bins in $M_0 \pm \Gamma_0$

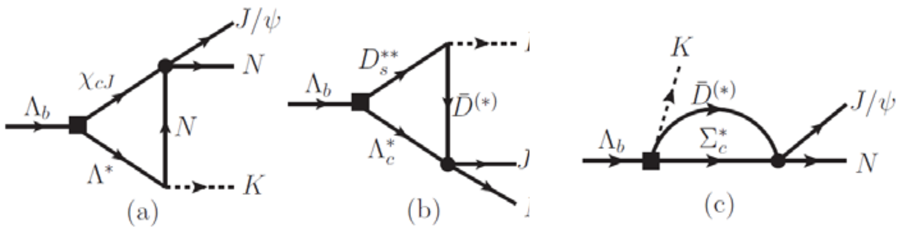


$P_c(4450)$: clock-wise phase change across pole.

$P_c(4380)$: large changes, not conclusive

Interpretation

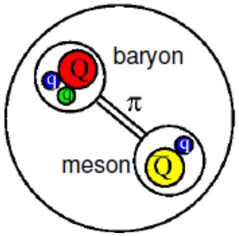
from arXiv:1507.05359



- Kinematic effects in non-perturbative rescattering processes (cusps)

  e.g. arXiv:1507.04950, 1507.05359, 1507.06552, 1507.07478

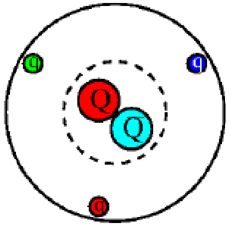
- bound states (or resonances) formed from open-charm baryon and meson constituents



  e.g. arXiv:1507.03717, 1507.03704, 1507.05200, 1507.04249, 1508.00924

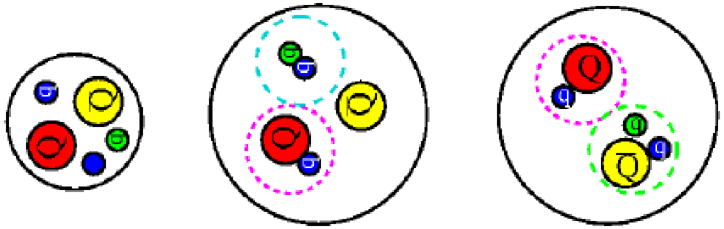
- Baryocharmonia

  e.g. arXiv:1508.00888



- Tightly bound pentaquark states

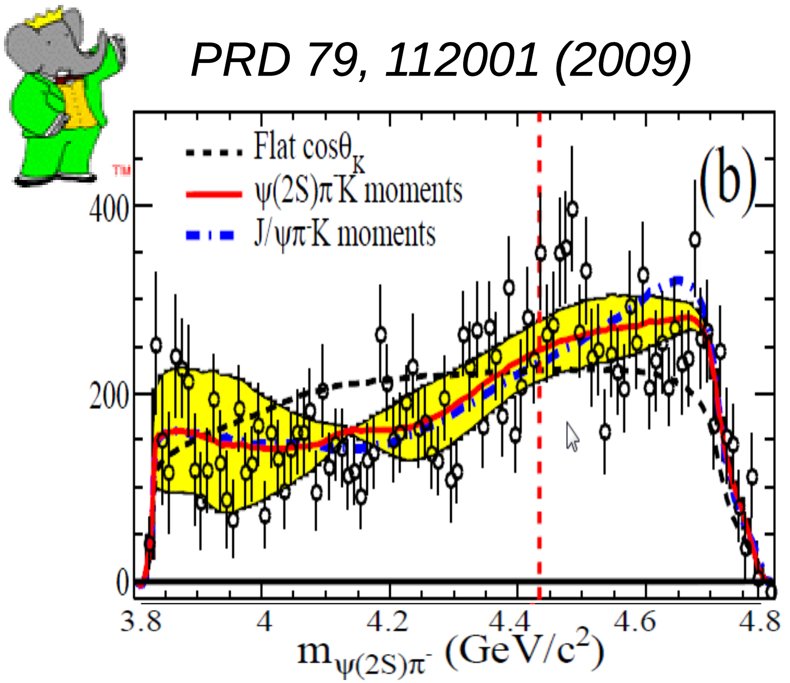
  e.g. arXiv:1201.0807, 1507.04980, 1507.07652, 1508.00356, 1507.05867, 1507.08252, 1508.01468, 1508.04189



The $Z^+(4430)$ – a Tetraquark Candidate

After the first observation by Belle in 2008 using simple 1D mass fit:

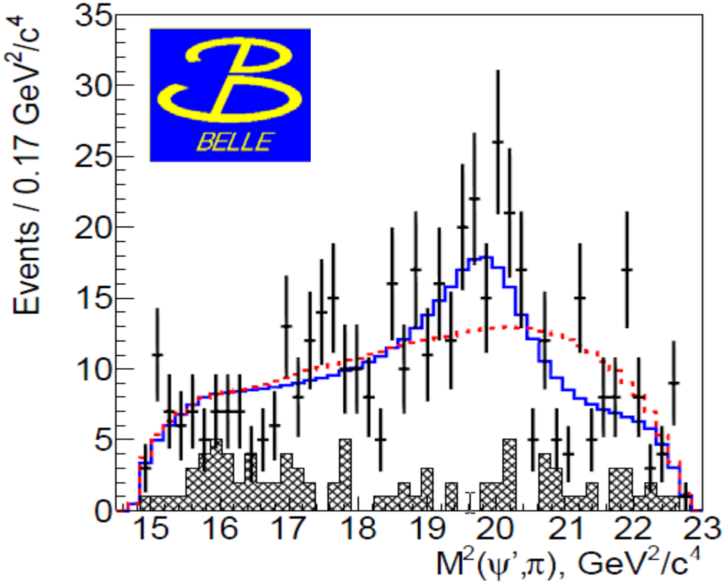
PRD 79, 112001 (2009)



2D analysis. Harmonic moments for K* reflected to $m(\psi'\pi^+)$: model independent description of $K^*\to K\pi$

BaBar did not confirm $Z(4430)^+$

PRD 88, 074026 (2013)



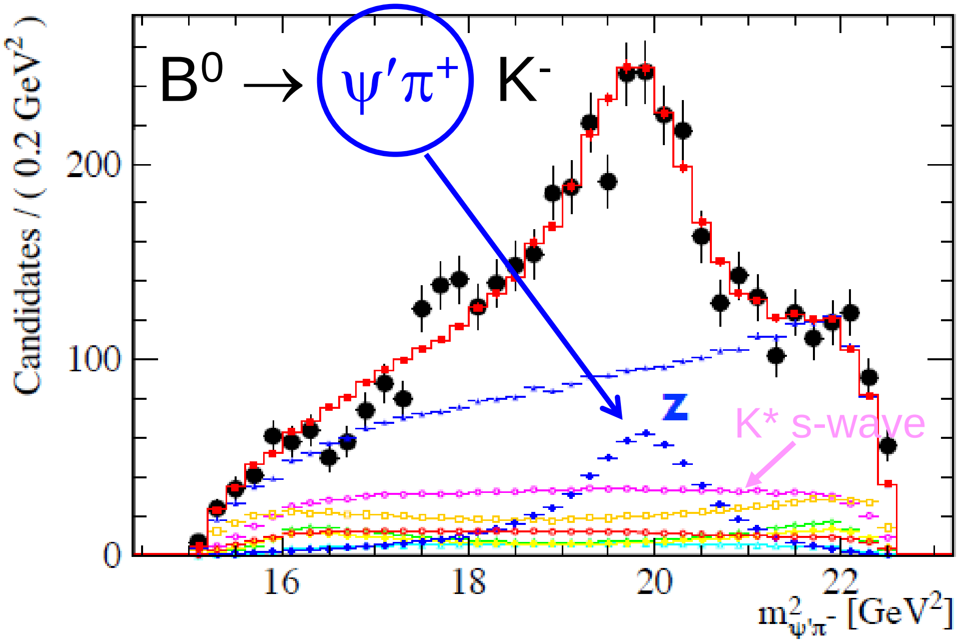
4D amplitude fit: model dependent description of $K^*\to K\pi$ resonances.

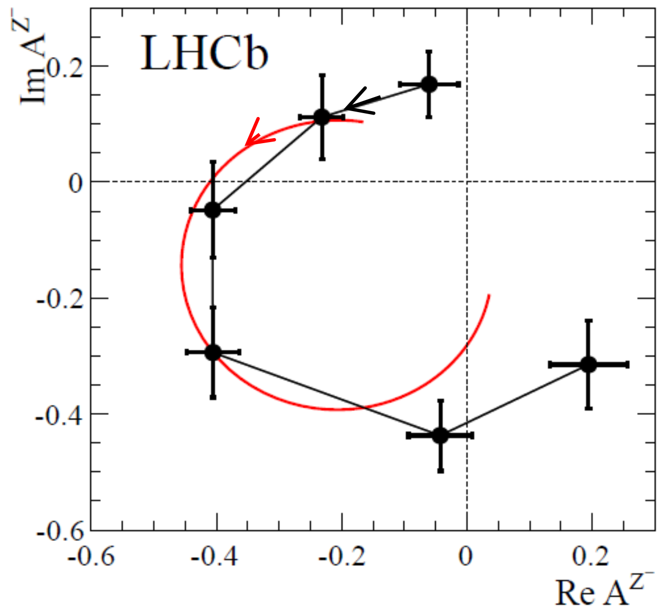
6.4σ (5.6σ w/ syst.) observation, $J^P=1^+$ preferred by $>3.4\sigma$

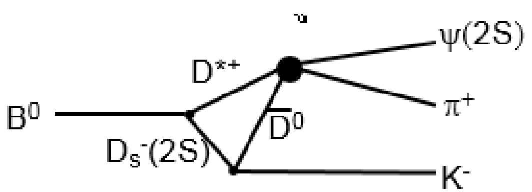
Z(4430)$^+$ confirmation by LHCb

PRL 112, 222002 (2014), arXiv;1404.1903

LHCb: more data and smaller backgrounds







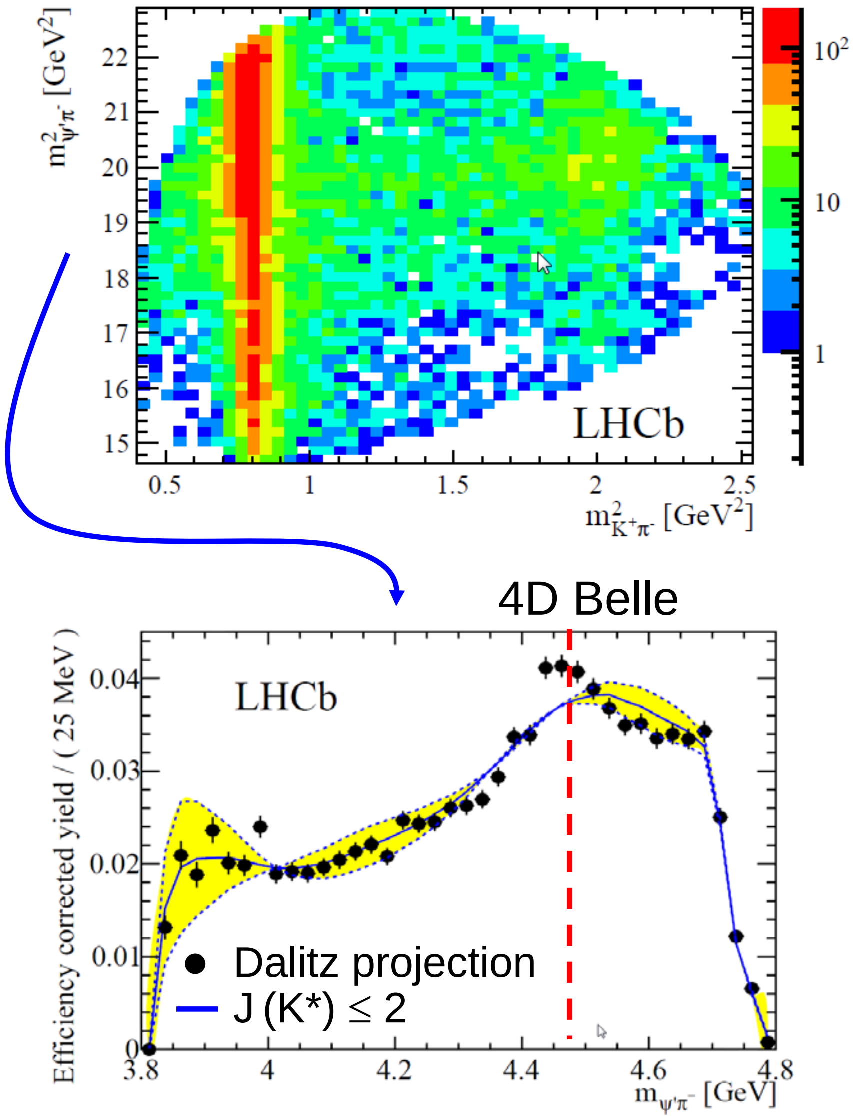
<u>4D amplitude analysis:</u>

- Clear confirmation of Z(4430)$^+$
- Resonance phase motion
- Quantum number: $J^P = 1^+$
- Rescattering →diff. phase behavior

P. Pakhlov, T. Uglov
PLB 748,183 (2015)

2D model independent analysis

PRL 112, 222002 (2014), arXiv;1404.1903



Describe the K* angular distribution ($\cos\theta_{K^*}$) and thus the reflection in $m_{\psi'\pi}$ using Legendre polynoms.

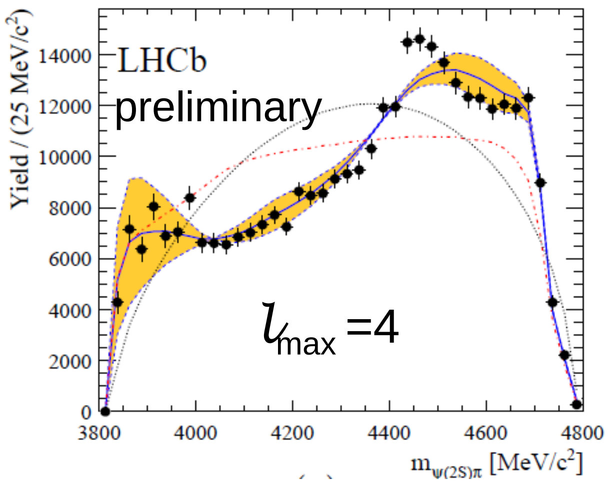
The maximum moment l_{max} of the Legendre polynoms depends on max. J(K*).

K* contribution filtered w/ J(K*)≤ 2 (l_{max} ≤4):
Cannot describe the “Z(4430) region”

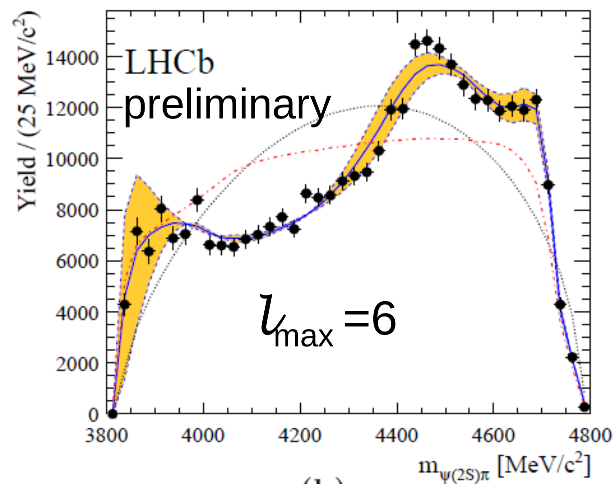
Quantitative Analysis

LHCb-Paper-2015-038
(in preparation)

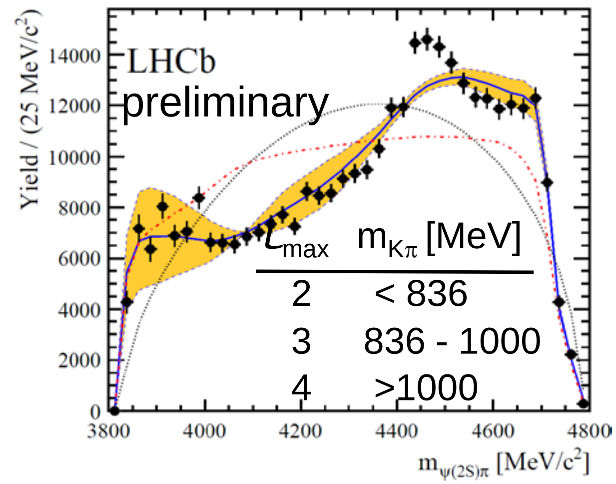
phase space
$m_{K\pi}$ weighting
experimental (stat.) uncertainty of moments



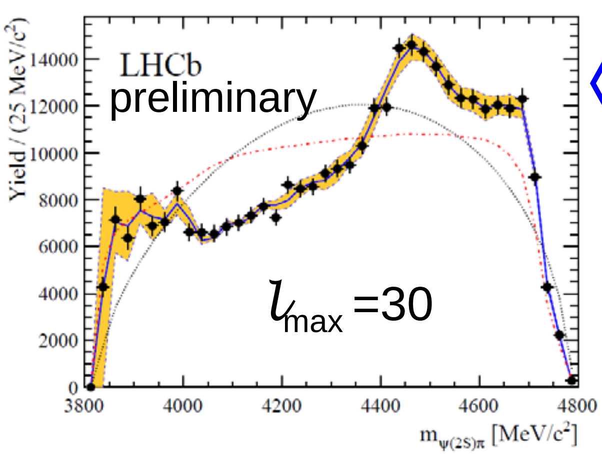
Significance 13.3σ



Significance 8.0σ



Significance 15.2σ



To calculate significance from pseudo-experiments we compare to test-statistics obtained with implausible high l_{max} = 30.

Explanation of data by plausible K* contributions is ruled out with >8.0σ w/o assuming anything about the K* model.

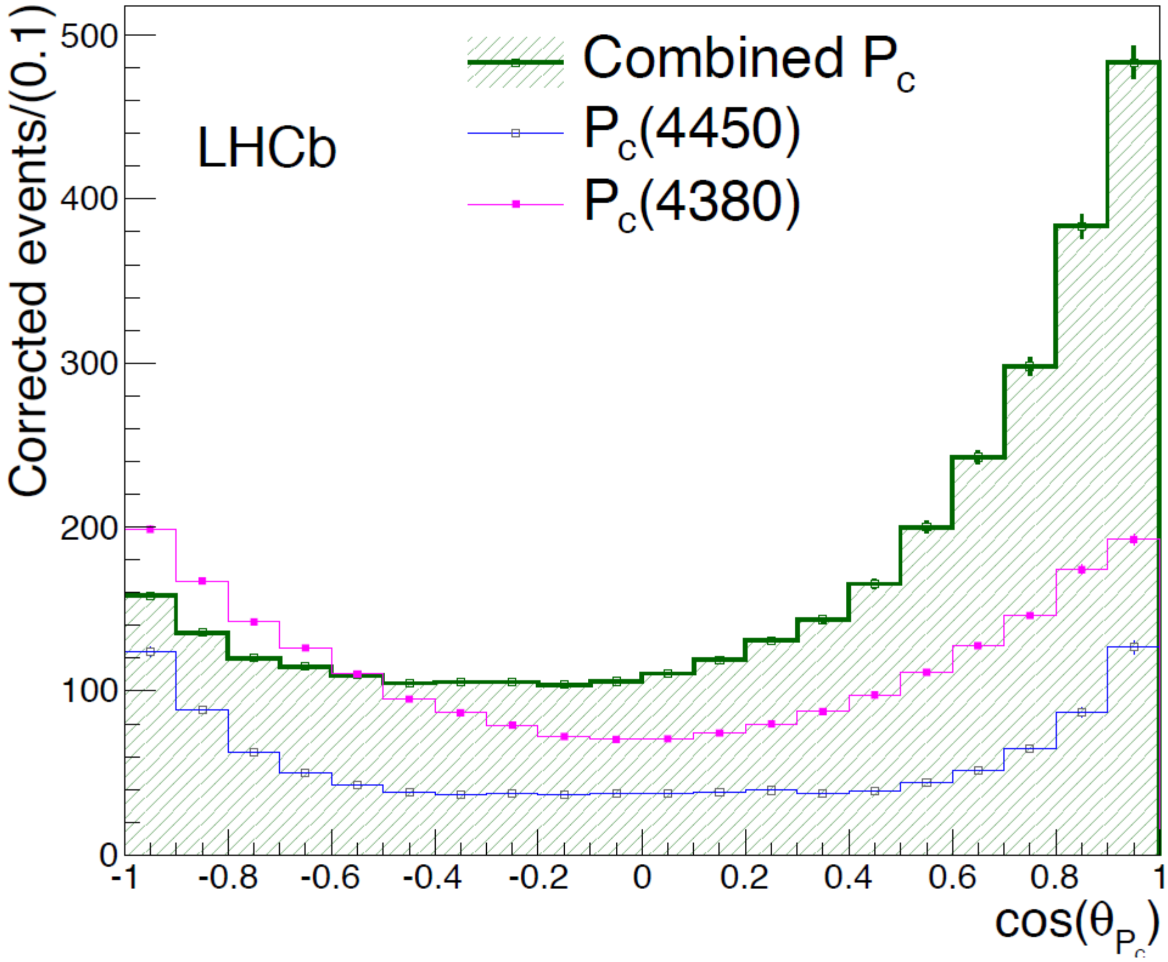
Conclusion

- Two states decaying to $J/\psi p$ have been observed in Λ_b decays which are consistent with pentaquarks. To better understand the origin:
  - Search for diff. final-states (e.g. $\Lambda_b \to J/\psi p \pi^-$, $\chi_c p K^-$, $\eta_c p K^-$, $\Lambda_c^+ D^0 K^-$)
  - Look in different b-hadron decays (e.g. Ξ_b)
  - Look for isospin partners (e.g. $\Lambda_b \to$ [ccddu] K^0)
  - Study $\chi_c \Lambda^*$, $\Sigma_c{}^*D$,… to check rescattering

- The 2014 model dependent amplitude analysis confirmed the Z(4430) tetraquark state from Belle and established its resonance character via the phase behavior.
  A new model independent analysis also demonstrates the need of an exotic tetraquark contributions with significances >8σ.

- We look forward to the discovery of more exotic hadrons and learning about their internal structure.

P_c^+ Angular distribution



Helicity Formalism

$D-$matrix,

$$|J_A, m_A >= \sum_{m'_A} D^{J_A}_{m_A, m'_A}(\alpha, \beta, \gamma)^* \, |J_A, m'_A >,$$

where,

$$D^J_{m, m'}(\alpha, \beta, \gamma)^* =< J, m|\mathcal{R}(\alpha, \beta, \gamma)|J, m' >^*= e^{i m \alpha} \; d^J_{m,m'}(\beta) \; e^{i m' \gamma},$$

$$D^j_{m'm}(\alpha, \beta, \gamma) \equiv \langle jm'|\mathcal{R}(\alpha, \beta, \gamma)|jm\rangle = e^{-im'\gamma} d^j_{m'm}(\beta) e^{-im\alpha}.$$

Amplitude Analysis II

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^*$$

$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^*$$

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\ \ D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

$$R_X(m) = B'_{L^X_{\Lambda_b^0}}(p,p_0,d)\left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}} \mathrm{BW}(m|M_{0X},\Gamma_{0X})\, B'_{L_X}(q,q_0,d)\left(\frac{q}{M_{0X}}\right)^{L_X}.$$

Orbital momentum barrier factor (Blatt-Weisskopf functons)

Amplitude Analysis III

- They are added together as:

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0}, \lambda_p, \Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c}, \lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu} \right|^2$$

- α_μ and θ_p are rotation angles to align the final state helicity axes of the μ and p, as helicity frames used are different for the two decay chains.

cFit

- cFit uses events in ±2σ window (σ=7.52MeV)
- Total PDF $\mathcal{P}(m_{Kp}, \Omega|\vec{\omega}) = (1-\beta)\,\mathcal{P}_{\rm sig}(m_{Kp}, \Omega|\vec{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{Kp}, \Omega)$
- Background is described by sidebands 5σ-13.5σ
- cFit minimizes

Background fraction β=5.4%

$$-\ln \mathcal{L}(\vec{\omega}) = \sum_i \ln \left[|\mathcal{M}(m_{Kp\ i}, \Omega_i|\vec{\omega})|^2 + \frac{\beta\, I(\vec{\omega})}{(1-\beta) I_{\rm bkg}} \frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ i}, \Omega_i)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i}, \Omega_i)} \right] + N \ln I(\vec{\omega}) + \text{constant},$$

$$I_{\rm bkg} \propto \sum_j w_j^{\rm MC} \frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ j}, \Omega_j)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ j}, \Omega_j)}$$

Signal efficiency parameterization becomes part of background parameterization,
effects only a tiny part of total PDF because of small β

sFit

- Signal PDF

$$\mathcal{P}_{\rm sig}(m_{Kp},\Omega|\vec{\omega}) = \frac{1}{I(\vec{\omega})}\left|\mathcal{M}(m_{Kp},\Omega|\vec{\omega})\right|^2 \Phi(m_{Kp})\epsilon(m_{Kp},\Omega)$$

$\vec{\omega}$: fitting parameters
Φ : phase-space = pq
ϵ : efficiency

$$I(\vec{\omega}) \propto \sum_j^{N_{\rm MC}} w_j^{\rm MC} \left|\mathcal{M}(m_{Kp\,j},\Omega_j|\vec{\omega})\right|^2$$

- Normalization calculated using simulated PHSP MC ($\Phi\epsilon$ included)
- $w^{\rm MC}$ discuss later

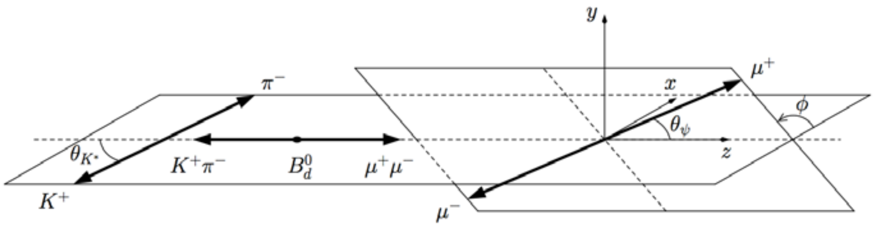
- sFit minimizes

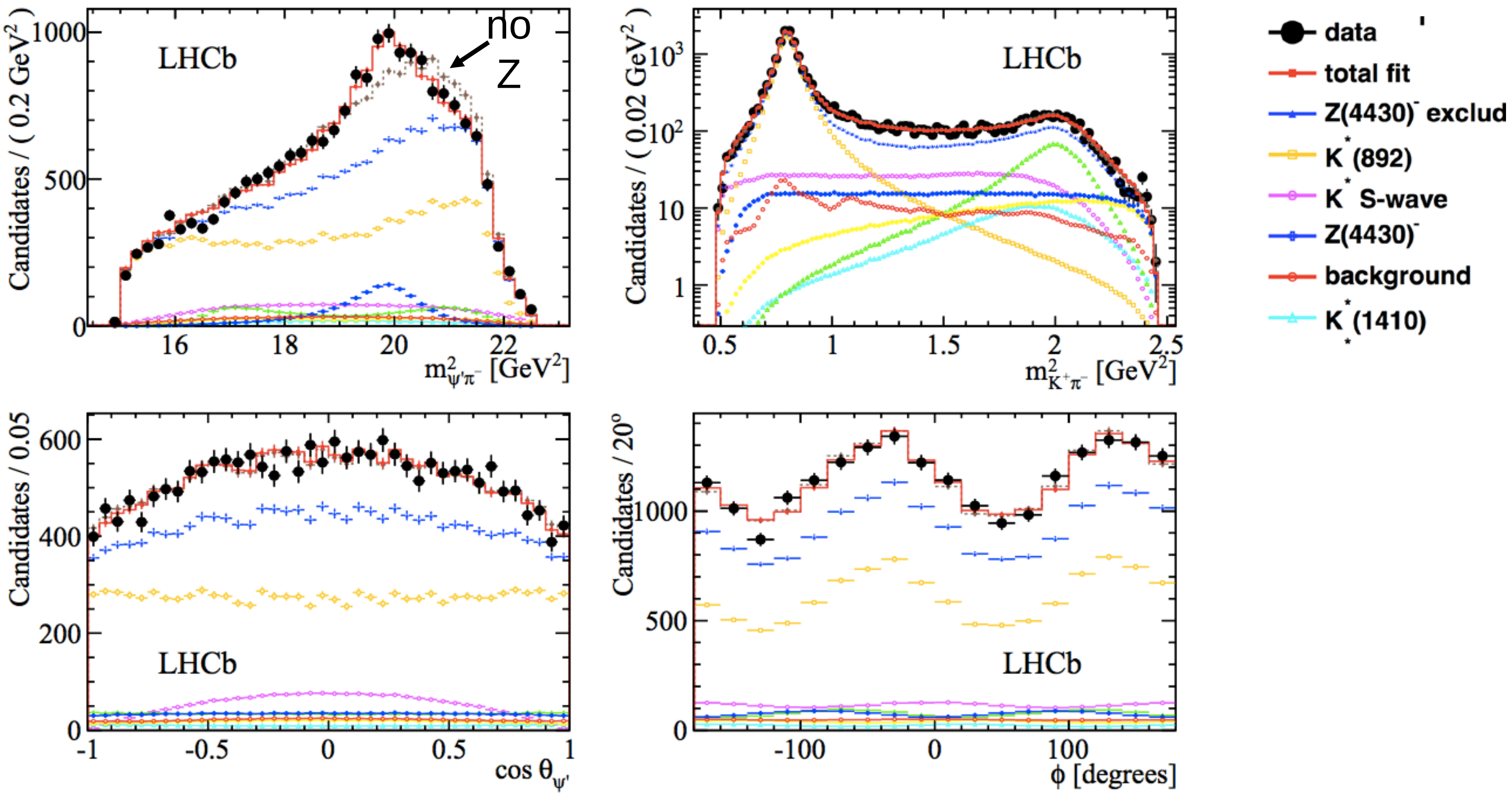
$$\begin{aligned}-2\ln\mathcal{L}(\vec{\omega}) &= -2s_W\sum_i W_i \ln\mathcal{P}_{\rm sig}(m_{Kp\,i},\Omega_i|\vec{\omega})\\ &= -2s_W\sum_i W_i\ln\left|\mathcal{M}(m_{Kp\,i},\Omega_i|\vec{\omega})\right|^2 + 2s_W\ \ln I(\vec{\omega})\sum_i W_i\\ &\quad -2s_W\sum_i W_i\ln[\Phi(m_{Kp\,i})\epsilon(m_{Kp\,i},\Omega_i)].\end{aligned}$$

W_i is sWeighs from m(J/ψKp) fits
$s_W = \Sigma_i W_i \,/\, \Sigma_i W_i^2$ constant factor to correct uncertainty

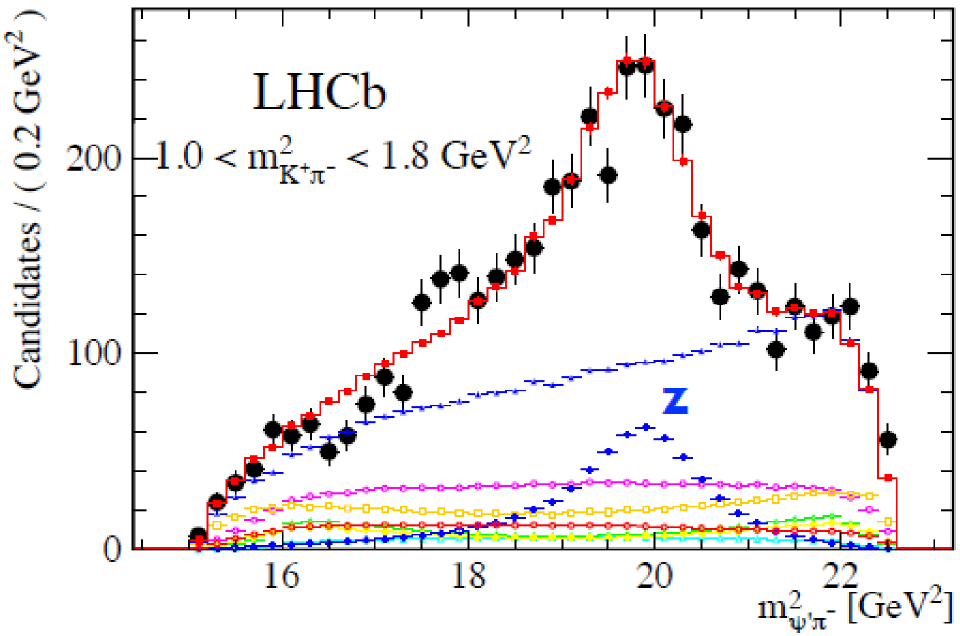
Constant (invariant of $\vec{\omega}$), is dropped
No need to know $\Phi\varepsilon$ paramerizaiton

4D Dalitz-Fit



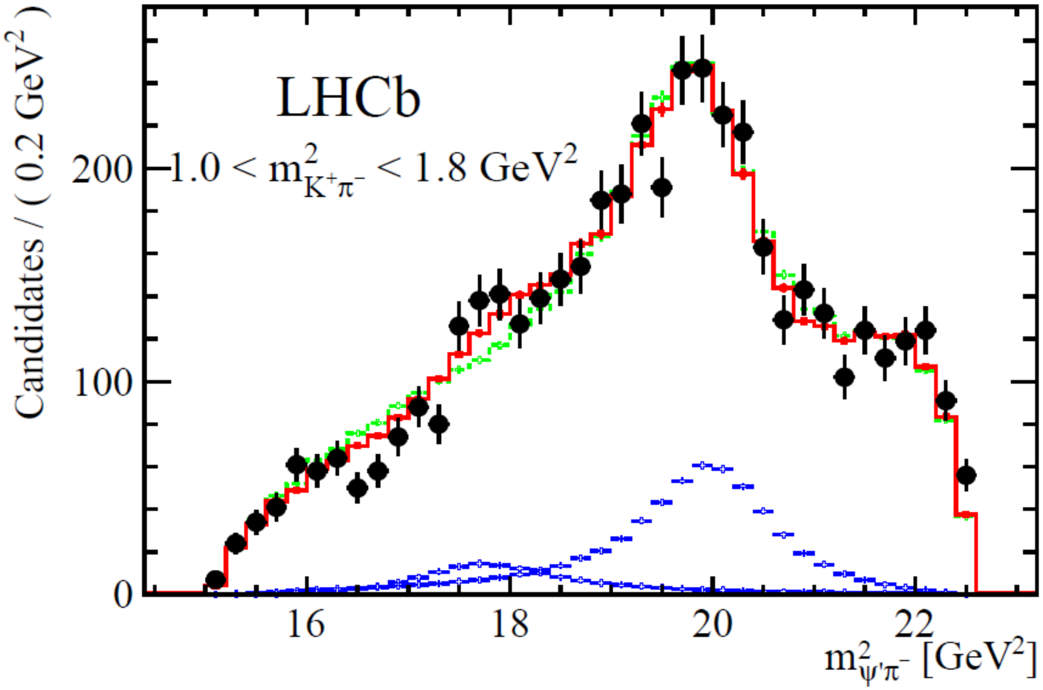


Resonances



State	Mass (MeV)	Width (MeV)	Fit Fraction (%)
$Z_1^{\ +}$	$4475 \pm 7\ ^{+15}_{-25}$	$172 \pm 13\ ^{+37}_{-34}$	$5.9 \pm 0.9^{+1.5}_{-3.3}$

Allowing two resonances



2 resonances: $J^p = 0^-$ and 1^+

1 resonance: $J^p = 1^+$

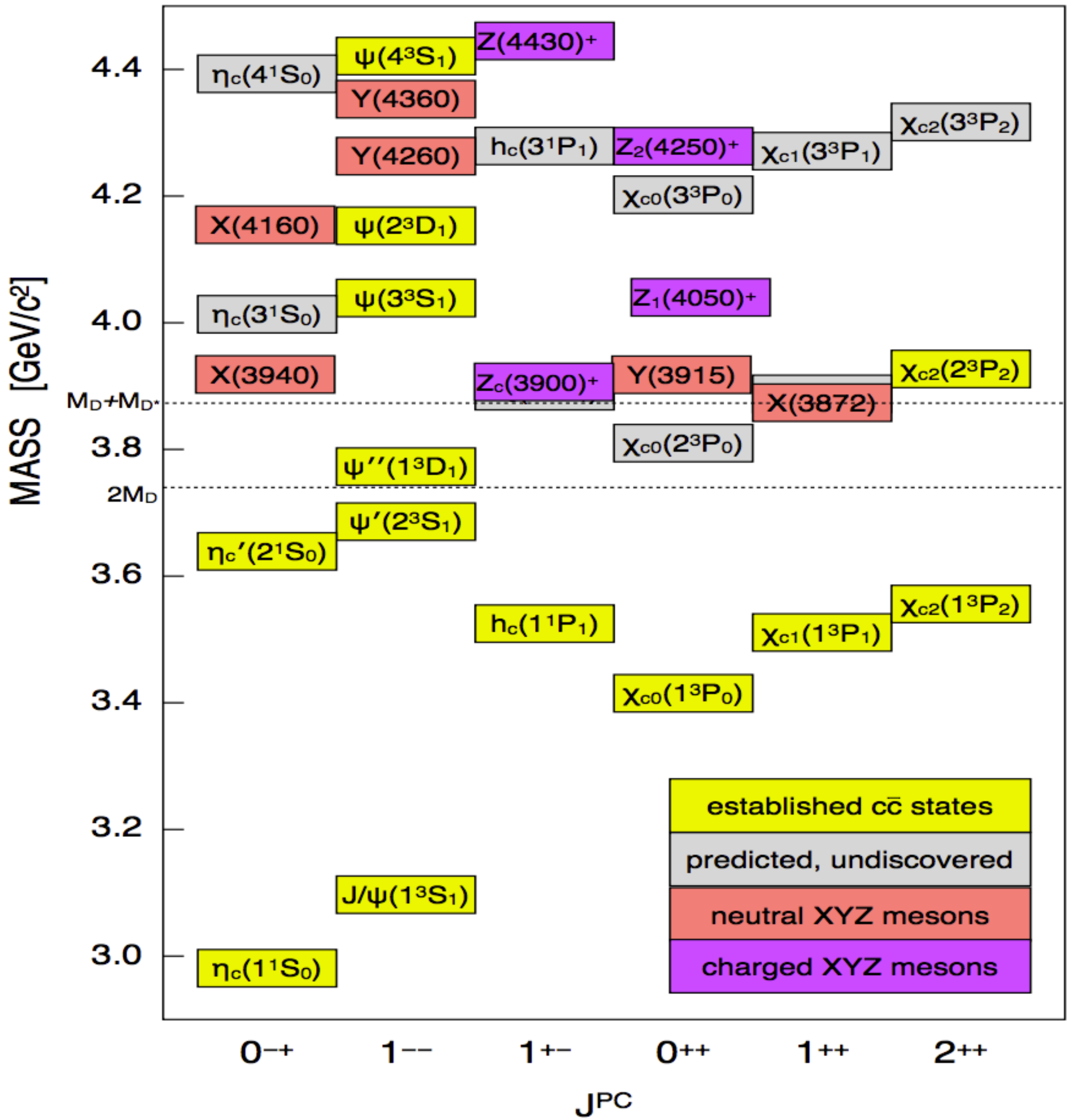
State	Mass (MeV)	Width (MeV)	Fit Fraction (%)
Z_0^+	$4239 \pm 18\,^{+45}_{-10}$	$220 \pm 47\,^{+108}_{-74}$	$1.6 \pm 0.5^{+1.9}_{-0.4}$

Open questions $Z^+(4430)$

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

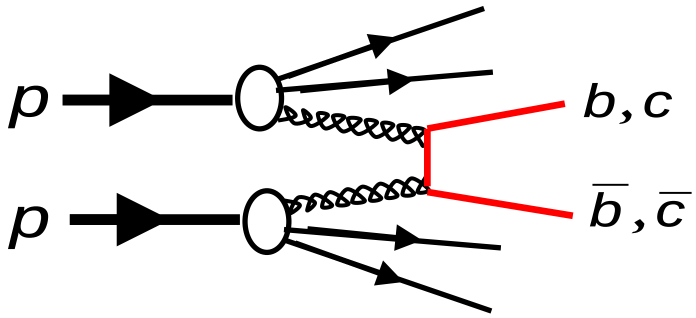
- P=+ rules out interpretation in terms of **$\bar{D}^*$(2010)D*1(2420)**molecule or threshold effect (cusp).
- Potential neutral **isospin partner?** Z(4430)0 in B+ ⟶ $\psi'\pi^0K^+$
- No clear picture of the complex system of charmonium-like exotic resonances.
- Further constraints will come from observing Z(4430)± and other exotics in alternative decay modes and/or production mechanisms.
- Look for synergies with the **$s\bar{s}$** and **$b\bar{b}$** sectors.

$c\bar{c}$ states



B-Physics at the Intensity Frontier

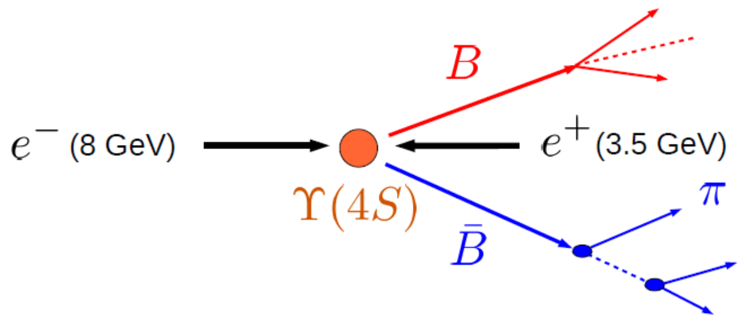
LHC @ 14 (13) TeV



$\sigma_{bb}(14\ TeV) \approx 500\ \mu b$

$\rightarrow 10^{10}\ b\bar{b}$ events/fb^{-1}

SuperKEKB & Belle II



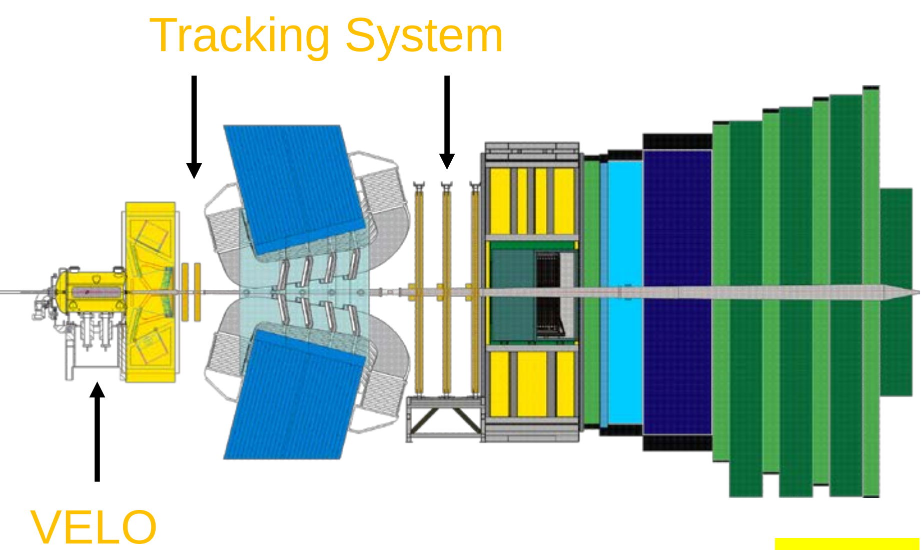
$\sigma_{BB} \approx 1\ nb$

$\rightarrow 10^{9}\ B\bar{B}$ events/ab^{-1}

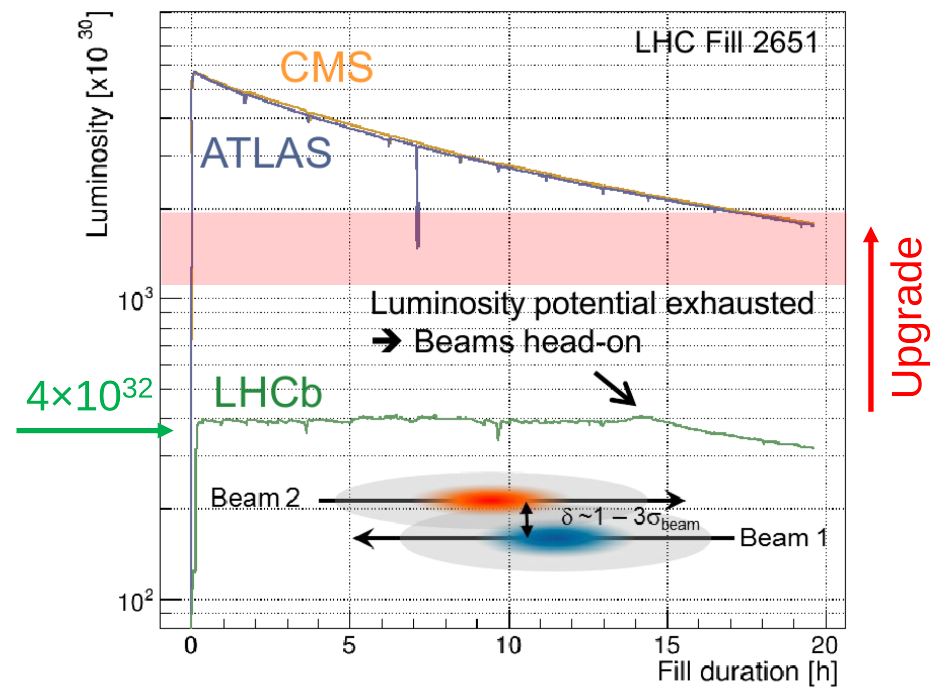
	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Upgrade-Project

CERN-LHCC-2012-007



40 MHz readout for RICHs, Calo, Muon System



See also talk by Wander Baldini

LHCb Upgrade:

- Increase levelled luminosity up to 2×10^{33} $cm^{-2}s^{-1}$ (pile-up ~8):
- Fully flexible & efficient software trigger up to 40 MHz input
- Record 20 – 100 kHz
- Upgrade VELO and Tracker (adapt to higher occupancy and radiation load)

Physics Complementarity*)

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \rightarrow \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B \rightarrow \tau\nu$, $D\tau\mu$,
- $B \rightarrow K^*\nu\nu$
- τ-physics

(Gluonic penguins, EW penguins:) Some only LHCb, some only Belle II

On-going

Belle II

*) Caveat: I am probably missing "your" favored channel/field

Typical bb ēvent