Results on exotic spectroscopy at LHCb

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"Physics at the Terascale"
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1. Introduction
   - Motivation
   - The LHCb experiment
2. Tetraquark candidates at LHCb
   - $X(3872)$
   - $Z(4430)$
3. Pentaquark candidates at LHCb
   - $\Lambda_b^0 \to J/\psi p K^-$ Decays at LHCb
   - Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$
   - Results
   - Interpretations
   - Implications
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- Ongoing challenge: relate basic concepts of QCD to observed phenomena
  - **Effective Theories** make use of symmetries or phenomenologically motivated approximations - e.g. approximate $SU(3)_{\text{flavor}}$ symmetry

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Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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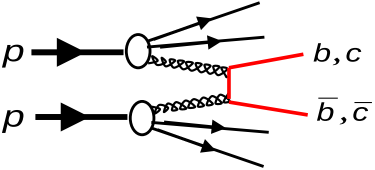
- QCD exotics (tetra-, penta-quarks, glueballs etc.) potentially provide invaluable insight to underlying dynamics of QCD
  - hadronization, binding mechanism, color structure ...

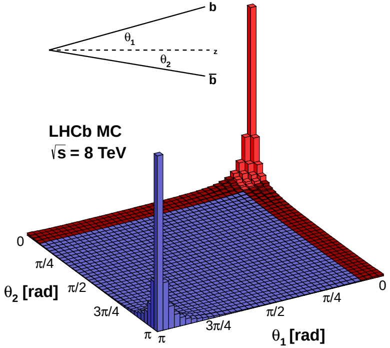
The LHCb Experiment

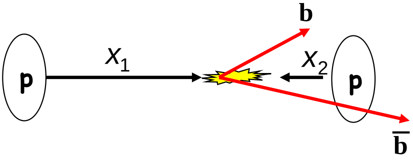


Run 2011-2012: 3 fb^{-1} (LHCb)

200 kHz $b\bar{b}$ $\rightarrow$ 2.6×10^{11} $b\bar{b}$

4MHz $c\bar{c}$ $\rightarrow$ 5.9×10^{12} $c\bar{c}$





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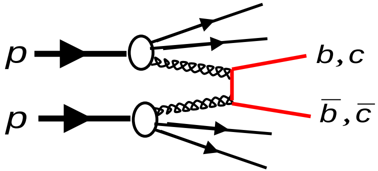

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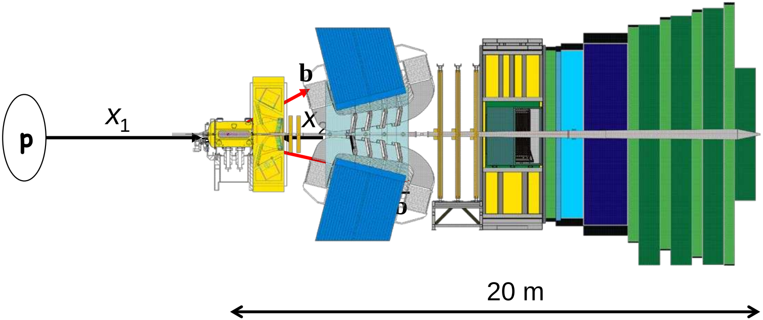
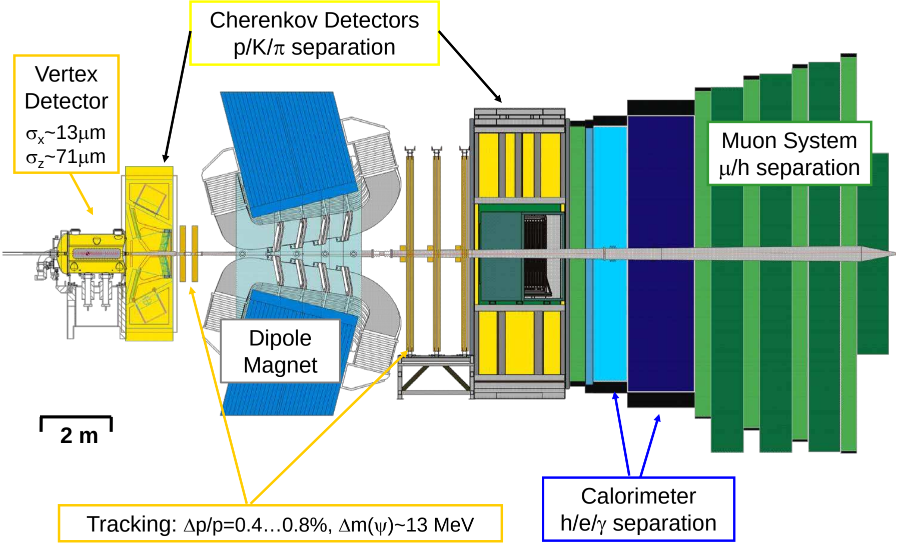


The LHCb Detector



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LHCb Results on the $X(3872)$

$X(3872)$ Properties

Discovered by Belle 2003 (PRL 91 262001)
in $B^{\pm} \to [J/\psi\pi^{+}\pi^{-}]_{X(3872)} K^{\pm}$ decays
significant isospin violation
$M_0 = 3871.69 \pm 0.17$ MeV
$\Gamma_0 < 1.2$ MeV @ 90% CL

- $\sigma(pp \to X(3872) + \text{anything})$
  $\times \mathcal{B}(X(3872) \to J/\psi\pi^{+}\pi^{-})$
  $= 5.4 \pm 1.3 \pm 0.8$ nb (EPJC 72 1972)

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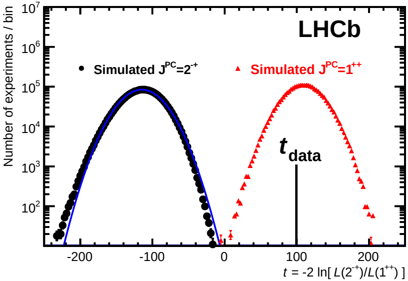

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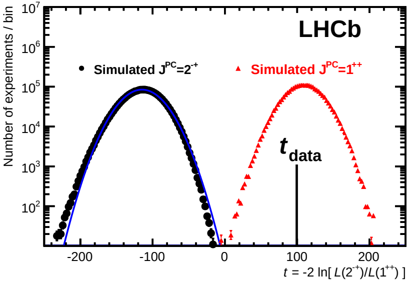
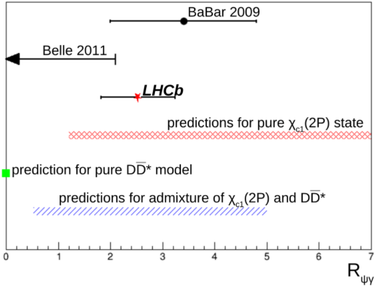
- Quantum numbers $I^G(J^{PC}) = 0^+(1^{++})$ (PRL 110 222001)
- $\dfrac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.5 \pm 0.6 \pm 0.3$ (NPB 886 665)
- D-wave fraction $f_D < 4\%$ @ 95% CL (PRD 92 011102(R))
- Results hint towards $c\bar{c}$-$D\bar{D}^*$ mixture or tetraquark pictures



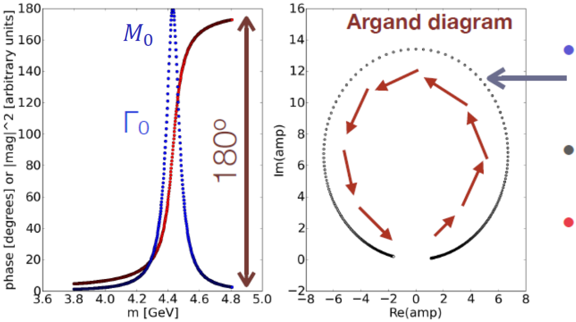


Phase Motion of a Breit-Wigner amplitude

- Resonances (R) parametrized by relativistic Breit-Wigner amplitude

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

$$\text{where } \Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L_R+1} \frac{M_0}{M} B'_{L_R}(q, q_0, d)^2$$



- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

LHCb Results on the $Z(4430)$ (PRL 112 222002) (arXiv:1510.01951)

$Z(4430)$ Properties

Discovered by Belle 2007 (PRL 100 142001)
Not confirmed by BaBar 2008 (PRD 79 112001)
dominant $K\pi$ reflections
$M_0 = 4478^{+15}_{-18}$ MeV
$\Gamma_0 = 181 \pm 31$ MeV
$I(J^P) = ?(1^+)$, decay to $\psi(2S)\pi^{\pm}$

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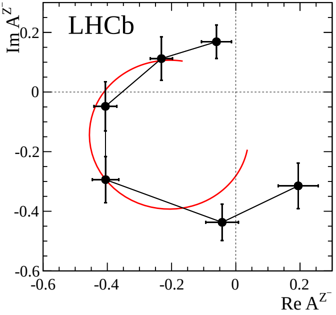
- 4D model-dependent amplitude analysis
  - extracted resonant character
  - J^P unambiguously 1^+
  - D-wave negligible



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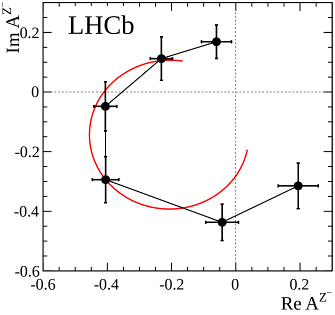
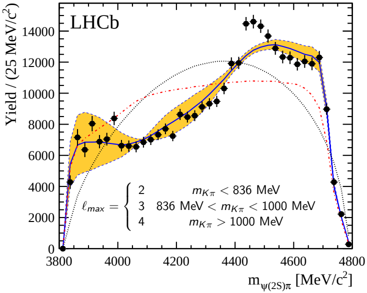


- 4D model-dependent amplitude analysis
  - extracted resonant character
  - J^P unambiguously 1^+
  - D-wave negligible
- Model-independent moment analysis
  - Test if $K\pi$ partial waves alone cause $\psi(2S)\pi$ shape
  - Exclude unphysical spin $\ell \geq 4$ $K\pi$ partial waves $\Rightarrow S(Z) = 8\,\sigma$
- Tetraquark picture most plausible



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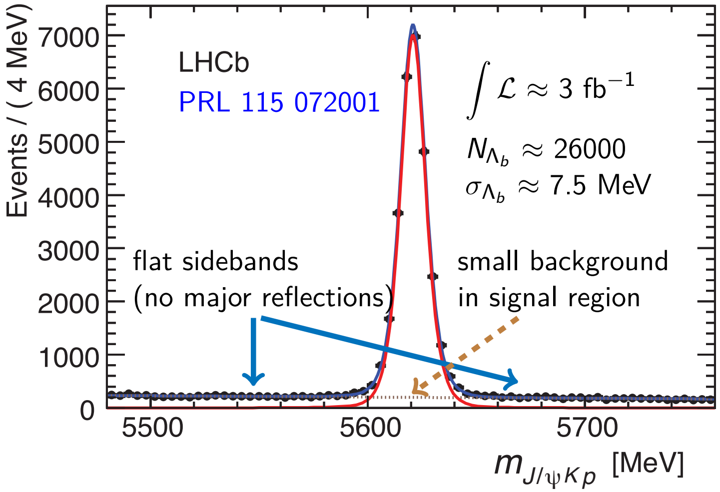
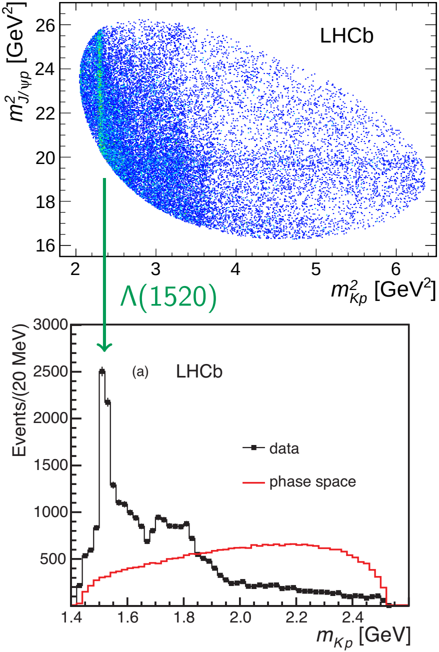
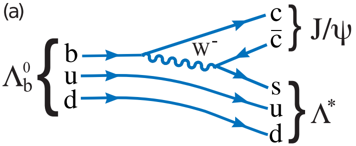
LHCb - The b-baryon Factory



- Initial goal: measurement of Λ_b lifetime (PRL 111 102003)
- $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.04^{+0.55}_{-0.43}) \times 10^{-4}$ (arXiv:1509.00292)

An Unexpected Structure in $m_{J/\psi p}$





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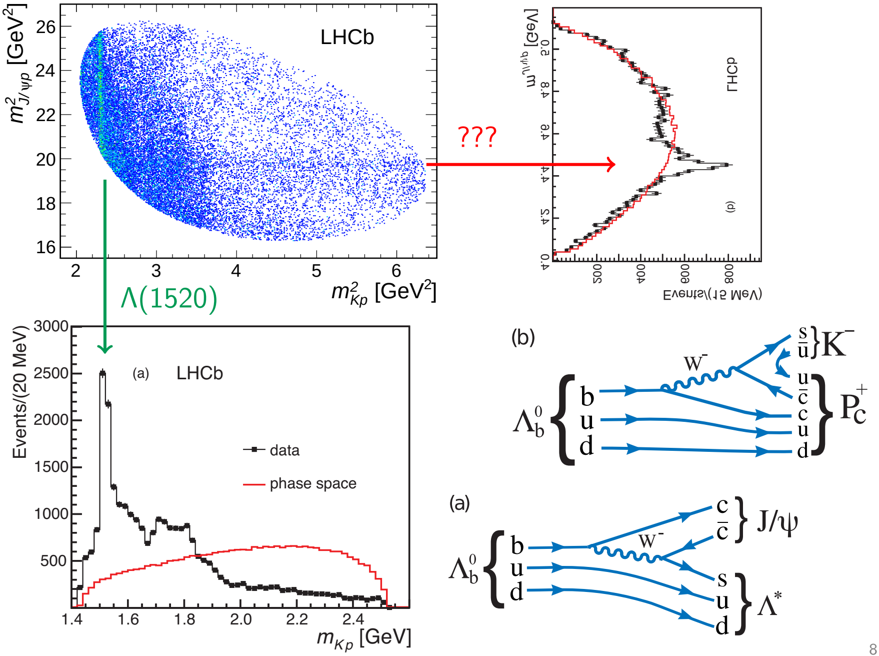
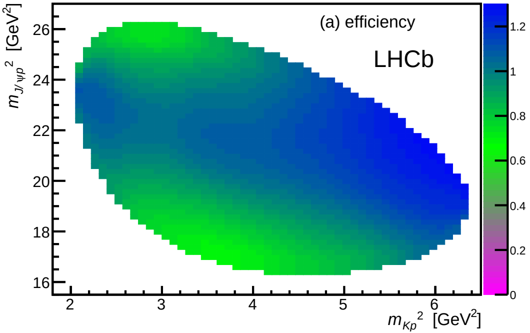


Is the Structure due to an Artefact?

- Smooth efficiency cannot create a peak



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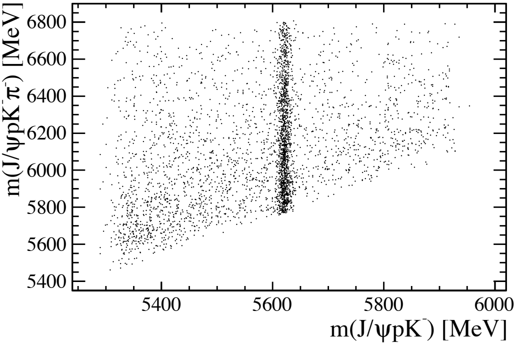

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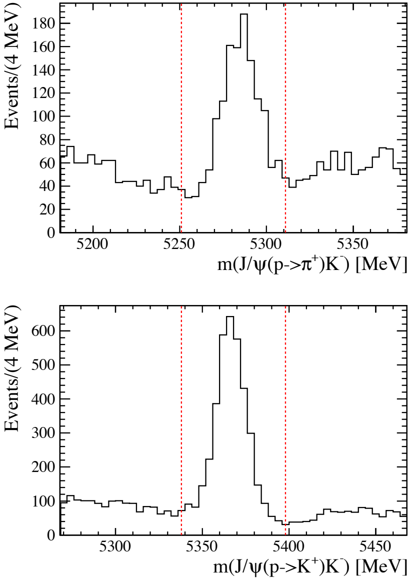
- Veto against $\overline{B}^0_s \to J/\psi K^- K^+$ and $\overline{B}^0 \to J/\psi K^- \pi^+$ candidates from $p \to K^+/\pi^+$ misID



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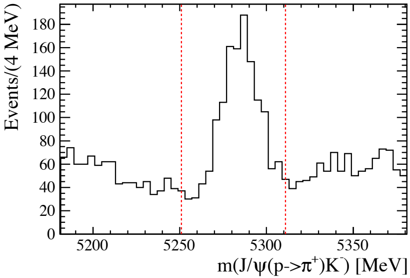
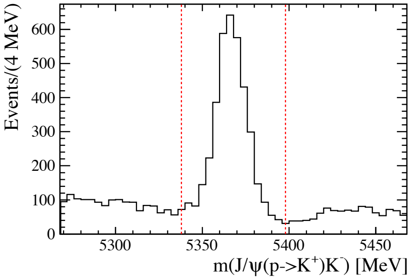
- ✓ Veto against $\overline{B}_s^0 \to J/\psi K^- K^+$ and $\overline{B}^0 \to J/\psi K^- \pi^+$ candidates from $p \to K^+/\pi^+$ misID
- Tested against selection artefacts
- Cross-checked by different analysis-teams
- Checked against clones/ghost-tracks





Fit Model

- Fit efficiency ϵ corrected PDF $\mathcal{P}$ in 1+5 dimensions m_{Kp}, Ω with parameters ω

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

Normalization integral

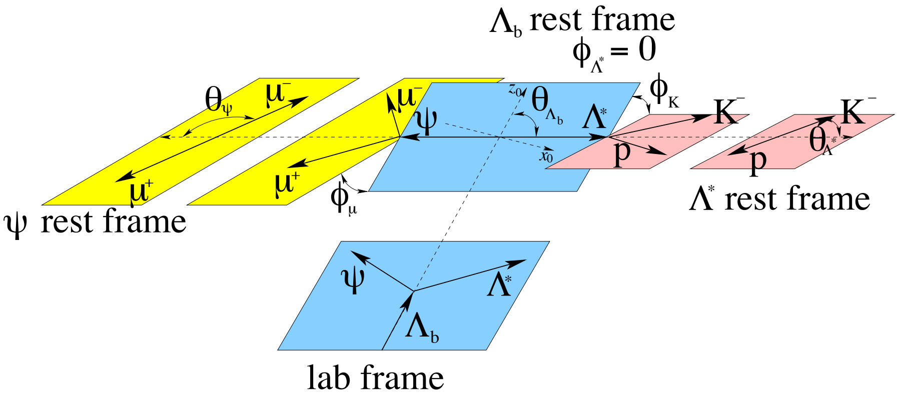
Matrix element for Λ_b decay (on next slides)

Phase space factor

- Background handled by conventional sideband subtraction: *cFit* or signal unfolding using ${}_s\mathcal{P}lot$ (NIM A 555, 356): *sFit*

- Fits coded independently for cross-check

$\Lambda_b \to J/\psi \Lambda^*$ Decay Chain in the Isobar Model



Fit observables: $m_{Kp}, \Omega = \{\theta_{\Lambda_b}, \phi_K, \phi_\mu, \theta_{\Lambda^*}, \theta_\Psi\}$

Isobar Model Helicity Amplitudes for $\Lambda_b \to J/\psi\Lambda^*$

The matrix element of the $\Lambda_b \to J/\psi\Lambda^*$ decay chain is given by:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n R_n(m_{Kp}) \; \mathcal{H}^{\Lambda^*_n \to Kp}_{\lambda_p} \; \sum_{\lambda_\psi} e^{i\,\lambda_\psi \phi_\mu} \; d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi) \; \times$$

$$\sum_{\lambda_{\Lambda^*_n}} \mathcal{H}^{\Lambda_b \to \Lambda^*_n \psi}_{\lambda_{\Lambda^*},\,\lambda_\psi} \; e^{i\,\lambda_{\Lambda^*}\phi_K} \; d^{\frac{1}{2}}_{\lambda_{\Lambda_b},\,\lambda_{\Lambda^*_n} - \lambda_\psi}(\theta_{\Lambda_b}) \; d^{J_{\Lambda^*_n}}_{\lambda_{\Lambda^*},\,\lambda_p}(\theta_{\Lambda^*_n})$$

- Λ^* resonant amplitudes (masses/widths): Breit-Wigner
- Helicity couplings for Λ^* and Λ_b decays (4-6 complex fit parameters per amplitude)
- Angular structure of Λ_b, J/ψ and Λ^* decays (no free parameters)

Λ^* Resonance Model

State	J^P	PDG class	Mass (MeV)	Γ (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
$\Lambda(1710)$	$1/2^+$	*	1713 ± 13	180 ± 40	0	0
$\Lambda(1800)$	$1/2^-$	***	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
$\Lambda(2000)$	?	*	≈2000	?	0	0
$\Lambda(2020)$	$7/2^+$	*	≈2020	?	0	0
$\Lambda(2050)$	$3/2^-$	*	2056 ± 22	493 ± 60	0	0
$\Lambda(2100)$	$7/2^-$	****	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	***	2110	200	1	6
$\Lambda(2325)$	$3/2^-$	*	≈2325	?	0	0
$\Lambda(2350)$	$9/2^+$	***	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	**	≈2585	200	0	6

- All established Λ^* resonances included in fit

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$\Lambda(1600)$	$1/2^+$	***	1600	150	3	[illegible]
$\Lambda(1670)$	$1/2^-$	****	1670	35	[illegible]	[illegible]
$\Lambda(1690)$	$3/2^-$	****	1690	60	[illegible]	6
$\Lambda(1710)$	$1/2^+$	*	1713 ± 13	[illegible]	[illegible]	0
$\Lambda(1800)$	$1/2^-$	***	1800	[illegible]	[illegible]	4
$\Lambda(1810)$	$1/2^+$	***	[illegible]	[illegible]	3	4
$\Lambda(1820)$	$5/2^+$	****	[illegible]	[illegible]	1	6
$\Lambda(1830)$	$5/2^-$	****	[illegible]	95	1	6
$\Lambda(1890)$	$3/2^+$	[illegible]	[illegible]	100	3	6
$\Lambda(2000)$	?	[illegible]	[illegible]	?	0	0
$\Lambda(2020)$	[illegible]	[illegible]	≈ 2020	?	0	0
$\Lambda(2050)$	[illegible]	[illegible]	2056 ± 22	493 ± 60	0	0
$\Lambda(2100)$	[illegible]	[illegible]	2100	200	1	6
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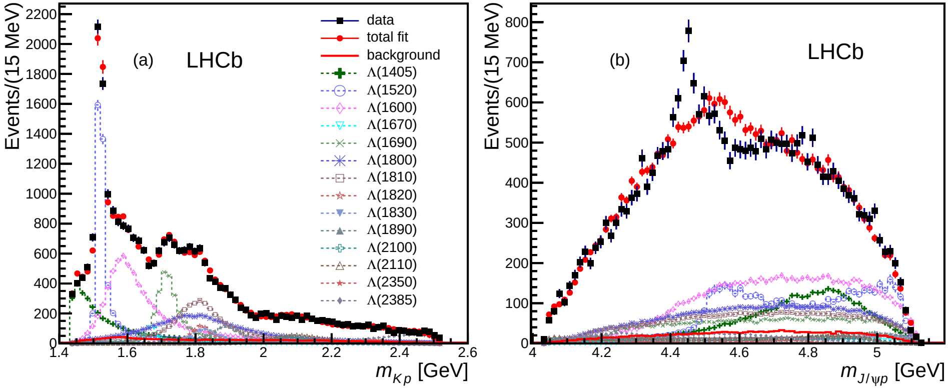
$\Lambda(2585)$	$5/2^-?$	**	≈ 2585	200	0	6

Large number of free parameters (in 6D)
$\rightsquigarrow$ computationally expensive and challenging fit

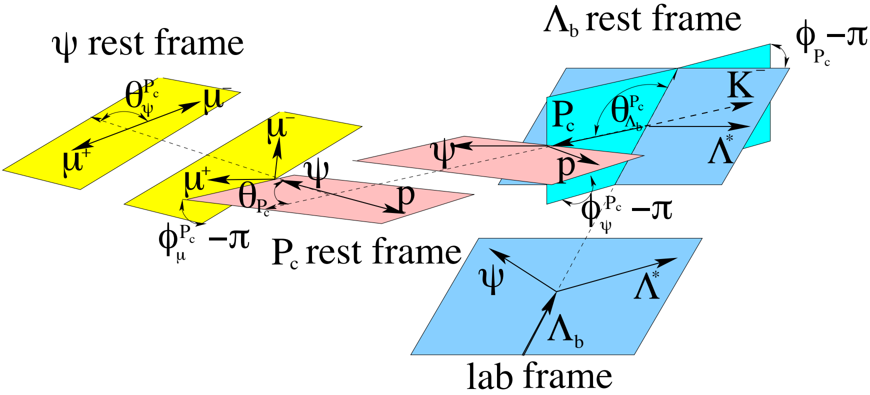
- All established Λ^* resonances included in fit

Fit with Λ^* States Only



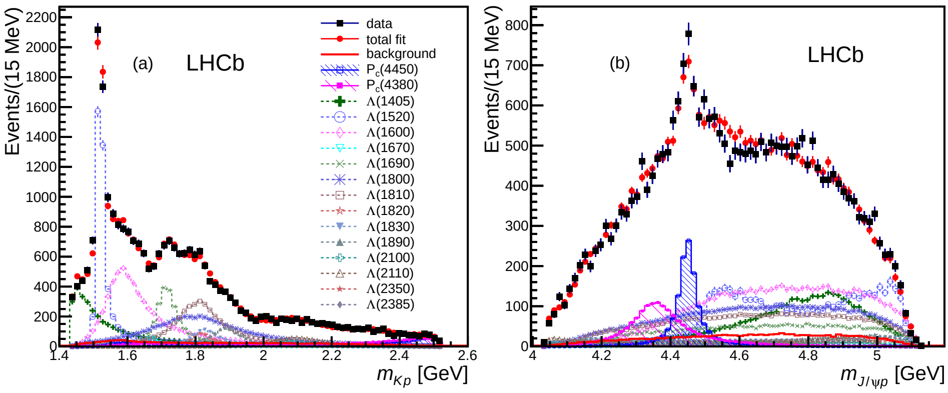
- Including non resonant components up to J^P=3/2$^\pm$, Σ^*'s and floating masses and widths of Λ^*'s can also not describe $m_{J/\psi p}$
- Next: attempt to obtain better fit by including $m_{J/\psi p}$ resonances

Adding the $\Lambda_b \to P_c^+ K^-$ Decay Chain



construct $\mathcal{M}^{P_c}_{\lambda_{\Lambda_b},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}}$ analogous to $\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu}$

Best Fit with Two P_c States



- Adding 2nd P_c gives good description of data in all observables
- $\Delta(2\ln\mathcal{L}) = 11.6^2$ from adding 2nd P_c vs. only 1 P_c
- Best fit has $J^P(P_c(4380), P_c(4450))$=$(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ reasonable

Results

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

- Syst. uncertainties on Λ^* model and J^P assignment dominate
- Significances calculated by fitting distribution of test-statistic ($\Delta(2\ln\mathcal{L})$) from toyMC experiments

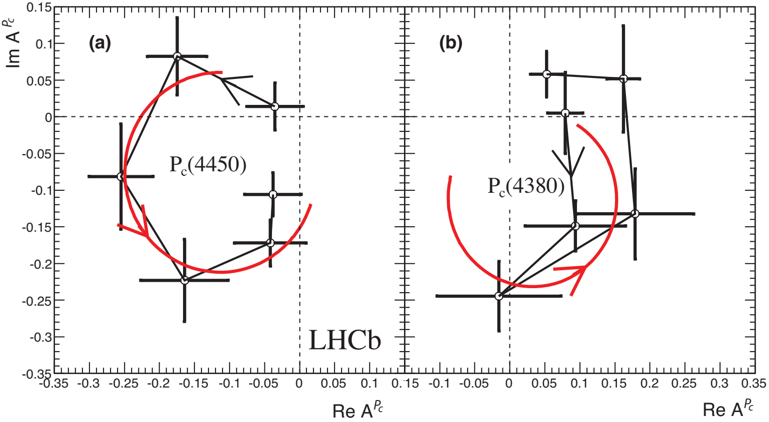
Null $\rightarrow$ Alternative Hypothesis	$\Delta(2\ln\mathcal{L})$	Significance
$0\ P_c \rightarrow 1\ P_c$	14.7^2	$12\,\sigma$
$1\ P_c \rightarrow 2\ P_c$'s	11.6^2	$9\,\sigma$
$0\ P_c \rightarrow 2\ P_c$'s	18.7^2	$15\,\sigma$

- In a separate paper, LHCb measured (arXiv:1509.00292)

$$\mathcal{B}(\Lambda_b \rightarrow P_c^+ K^-)\mathcal{B}(P_c^+ \rightarrow J/\psi p) = \begin{cases} (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} \text{ for } P_c(4380)^+ \\ (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} \text{ for } P_c(4450)^+ \end{cases}$$

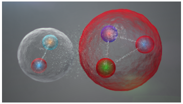
Phase Motion

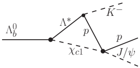
- Test resonant character of P_c's by plotting spline-interpolated amplitude in an Argand diagram
  - Scan $m_{J/\psi p}$ in 6 bins around $m_0 \pm \Gamma_0$ of P_c's
  - Fit data with full model but replace Breit-Wigner parametrization with cubic spline interpolating from 4 closest neighbouring points

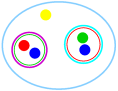


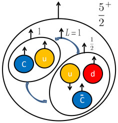
Theory Community Responding to P_c candidates

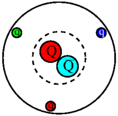
- Already 81 citations!











Molecular models:	
$P_c(4450)$ as $\Sigma_c \bar{D}^*$ molecule	PRL 115 122001
$P_c(4380)$ as $\Sigma_c \bar{D}^*$ and $P_c(4450)$ as $\Sigma_c^* \bar{D}^*$	PRL 115 132002
$P_c(4380)$ as $\Sigma_c \bar{D}^*$ and $P_c(4450)$ as $\Sigma_c^* \bar{D}$	PRL 115 172001
$P_c(4450)$ as $\Sigma_c \bar{D}^*$ and $\Sigma_c^* \bar{D}^*$ molecule	arXiv:1507.04249
P_c's not (colored) molecules	arXiv:1507.04694
$P_c(4380)$ as $\Sigma_c^* \bar{D}$ and $P_c(4450)$ as $\Sigma_c \bar{D}^*$	arXiv:1507.05200
$P_c(4450)$ as $\chi_{c1} p$ molecule (compositeness)	arXiv:1511.00870
Rescattering effects:	
$\chi_{c1} p$ rescattering, $\Lambda(1890)\chi_{c1} p$ triangle singularity	PRD 92 071502(R),PLB 751 59
ATS, cusp effect	arXiv:1507.05359
$D^* D_s^* \Sigma_c$ triangle singularity	arXiv:1507.06552
$P_c(4380)$ rescattering, $P_c(4450)$ diquark model	arXiv:1507.07652
Diquarks/Triquarks:	
Diquark-Diquark-Antiquark ($[qq][qq]\bar{q}$)	PLB 749 289
Dynamical Diquark-Triquark	PLB 749 454
Diquark-Diquark-Antiquark multiplets	arXiv:1507.08252
Quasi particle diquarks	arXiv:1508.00356
$[qq][qq]\bar{q}$ with QCD sum rules	arXiv:1508.01468
$P_c(4380)$ as $J/\psi K$ reflection, $P_c(4450)$ as $[qq][qq]\bar{q}$	arXiv:1509.04898
Dynamical Diquark-Triquark multiplets	arXiv:1510.08693
Other:	
Bound $\bar{D}$-soliton	PRD 92 051501(R)
Intrinsic charm in Λ_b decays	arXiv:1508.03910
Baryocharmonium	PRD 92 031502(R)
Phenomenology review	arXiv:1509.02460
$J/\psi K$ reflection	arXiv:1509.03028
$Z_{2,3}$ geometrical symmetries	arXiv:1509.06013

(List may be incomplete, not listing implications)

Implications for experiments

Concerning $P_c(4380)$ and $P_c(4450)$

- Most important: confirmation by other experiments needed!
- Observe $P_c \to J/\psi p$ as subsystems in different final states, e.g.:
  - $\Lambda_b \to J/\psi p \pi$
  - $\Upsilon \to J/\psi p \bar{p}$ (check for peaks at $\chi_{c0,1,2} p$ thresholds (PRD 92 071502(R)))
- Observe new decay modes of P_c's, e.g. in:
  - $\Lambda_b \to \chi_{c1} p K$ (decay of $P_c(4450)$ in this channel rules out $\chi_{c1} p$ rescattering (PRD 92 071502(R)))
  - $\Lambda_b \to \Lambda_c \bar{D}^0 K$

Search for other types of pentaquarks

- Hidden charm partners
- Open charm pentaquarks
- Triply charged baryons
- Bottom pentaquarks
- Hidden strangeness pentaquarks

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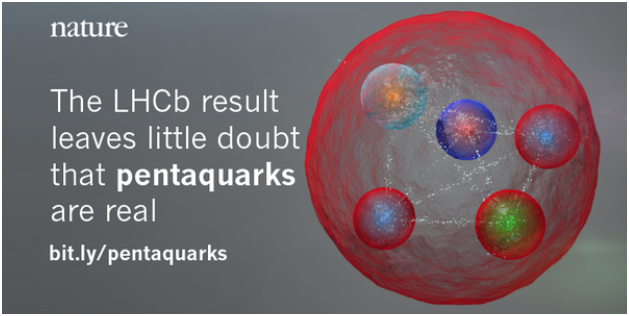
At distant horizons

- Dibaryons?
- Hexaquarks?
- Heptaquarks?
- ...

Summary

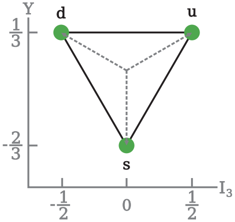
- LHCb confirmed and measures distinct properties of the exotic $X(3872)$ and $Z(4430)$
- First observation of two $J/\psi p$ resonances in amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$
- Resonant phase motion of pentaquark candidates extracted
  - Consistent with Breit-Wigner for $P_c(4450)^+$
  - More complicated for $P_c(4380)^+$ (motion counter-clockwise)
- Link between XYZ states and pentaquarks potentially provides key towards some fundamental principles of QCD phenomenology
- LHCb has a broad (exotic) spectroscopy programme in meson and baryon sector

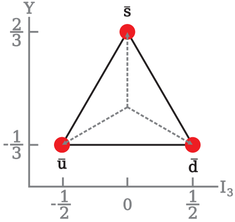

nature
The LHCb result leaves little doubt that **pentaquarks** are real
bit.ly/pentaquarks

Backup slides start here

Multiquark Exotic States from $SU(3)_{flavor}$ Symmetry

- Hadrons are physical observable color singlet bound states of quarks
- They can be labelled by their minimum (valence) quark content
  - so far $q_1q_2q_3$, $q_1\bar{q}_2$ and $q_1q_2\bar{q}_1\bar{q}_3$(?!)





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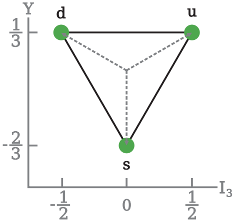

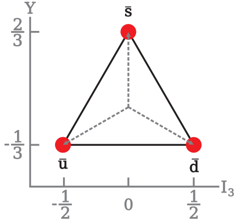

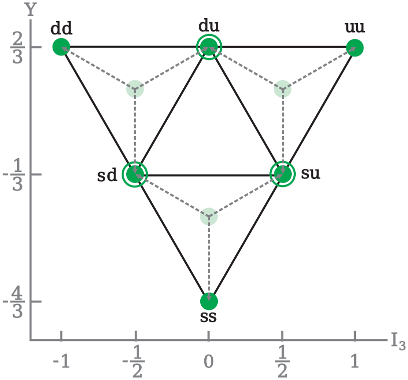

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \bar{\mathbf{3}}$$

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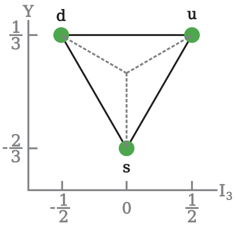

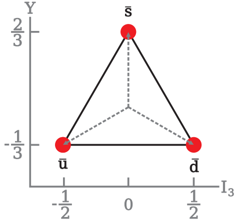

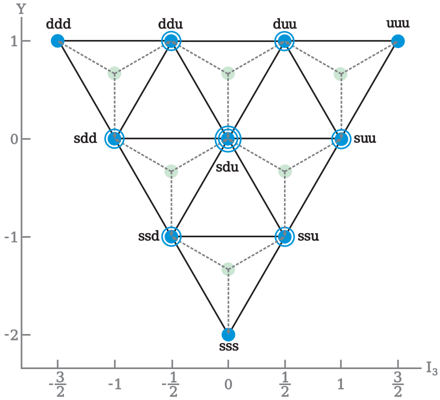

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8}^{(2)} \oplus \mathbf{1}$$

Multiquark Exotic States from SU(3)$_{flavor}$ Symmetry

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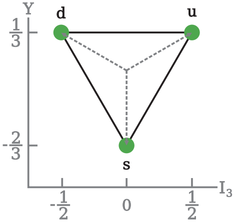
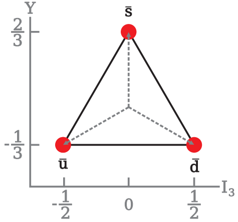
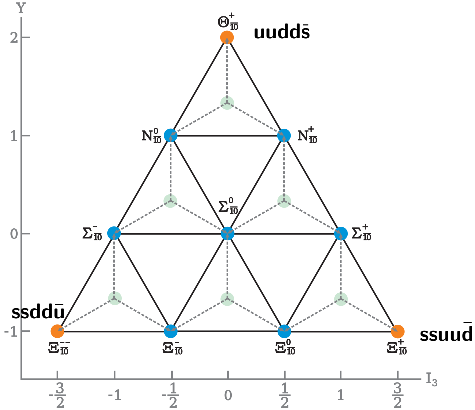






$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{3}} =$

$\mathbf{35} \oplus \mathbf{27}^{(3)} \oplus \overline{\mathbf{10}}^{(2)} \oplus \mathbf{10}^{(4)} \oplus \mathbf{8}^{(8)} \oplus \mathbf{1}^{(3)}$

Searches for S =+1 Baryons

- Broad exotic KN resonances predicted 1976 (SLAC-PUB-1774)
- Resonant partial waves claimed in 70's and early 80's

  (PDG, RPP 1992)
- Lig
  Θ
  in
- Se
  ex
  in
  "U
  subsequently

  (PDG, RPP 2008)

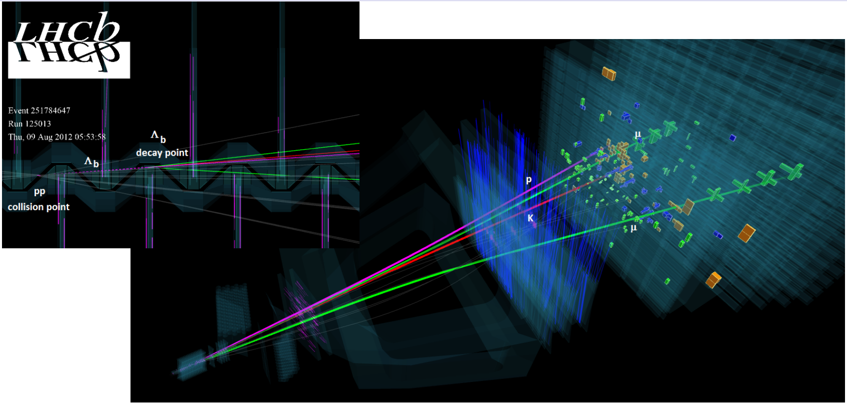
Z BARYONS
($S = +1$)

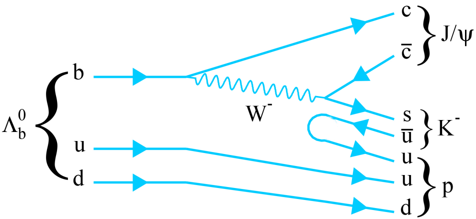
… New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel

that find weak
, but there is
overwhelming
xist. The only
mention in the
n 2003" was a
hemselves, the
enologists that
followed, and the eventual "undiscovery" —is a curious episode in the history of science.

- current consensus: Θ^+ faked by kinematic cuts, t-channel exchanges or experimental artefacts
- LEPS II result and amplitude analysis needed to settle the Θ^+ issue for good
- Amplitude analysis needs fully exclusive events or exclusive decay chain (e.g. $\psi \to \Theta^+ \bar{N}\bar{K}$ or $\Lambda_b^0 \to \Theta^+ \bar{K}^0 \pi^-$)

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





- "Standard" selection including decay chain fitting (NIM A 552 566) and Multi-Variate-Analysis (arXiv:0703039)

Fit Model

- Fit efficiency ϵ corrected PDF $\mathcal{P}$ in 1+5 dimensions m_{Kp}, Ω

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

Normalization integral

Matrix element for Λ_b decay (on next slides)

Phase space factor

- Background handled by conventional sideband subtraction *cFit* or signal unfolding using ${}_s\mathcal{P}lot$ (NIM A 555, 356) *sFit*

$$\mathcal{P}(m_{Kp,i}, \Omega_i|\omega) = (1-\beta)\mathcal{P}_{\text{sig}}(m_{Kp}, \Omega|\omega) + \beta \, \mathcal{P}_{\text{bkg}}(m_{Kp}, \Omega)$$

$$-2\ln\mathcal{L}(\omega) = -2\frac{\sum_i w_i}{\sum_i w_i^2} \sum_i w_i \ln \mathcal{P}(m_{Kp,i}, \Omega_i|\omega)$$

$w_i = 1$

$\beta = 5.4\%$

- Fits coded independently for cross-check

Λ^* Resonance Model

Dynamical terms $R_n(m_{pK})$ parametrized by

- Relativistic single-channel Breit-Wigner amplitudes
- (dressed) Blatt-Weisskopf barrier factors (PRD 5 624)

$$R_n(m_{Kp}) = \tilde{B}^{\Lambda_b}_{L_{\psi\Lambda^*}} \times BW(m_{Kp}|m_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*}) \times \tilde{B}^{\Lambda^*}_{L_{pK}}$$

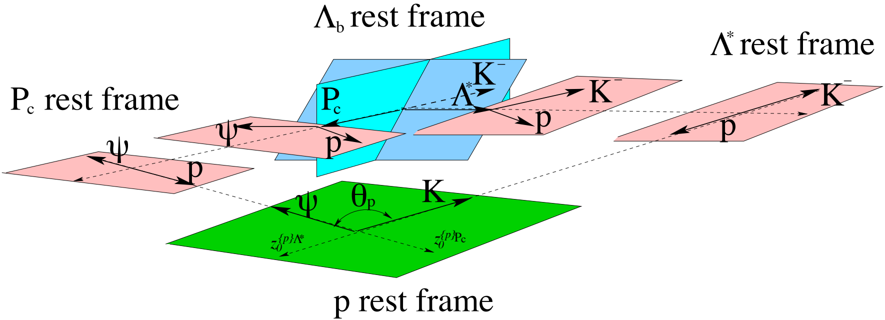
with $BW(m|m_0\Gamma_0) = \dfrac{1}{m_0^2 - m^2 - im_0\Gamma(m)}$

and $\Gamma(m) = \Gamma_0 \left(\dfrac{q}{q_0}\right)^{2L_{\Lambda^*}+1} \dfrac{m_0}{m} B'_{L_{\Lambda_n^*}}(q, q_0, d)^2$

where $p(q)$ are momenta of daughters in CM frame of mother

and subscript-0 denotes evaluation at nominal resonance parameters (PDG)

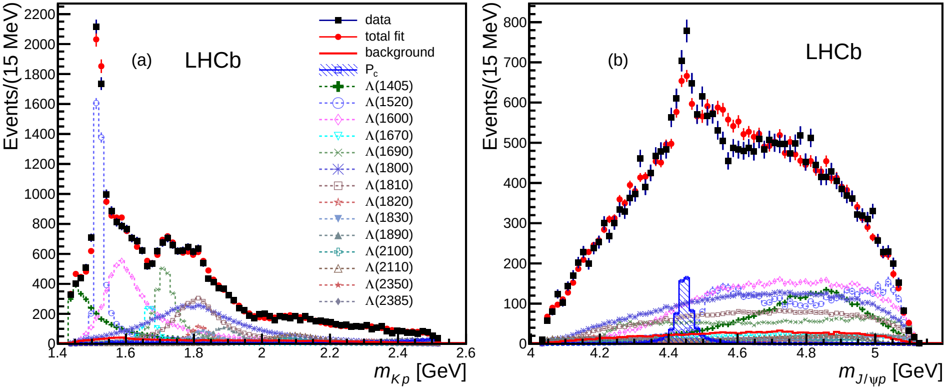
- Exception: sub-threshold $\Lambda(1405)$ described by Flatté-like parametrization (PLB 63 224)



align Λ^* and P_c chain μ and p helicity frames to write full matrix element as

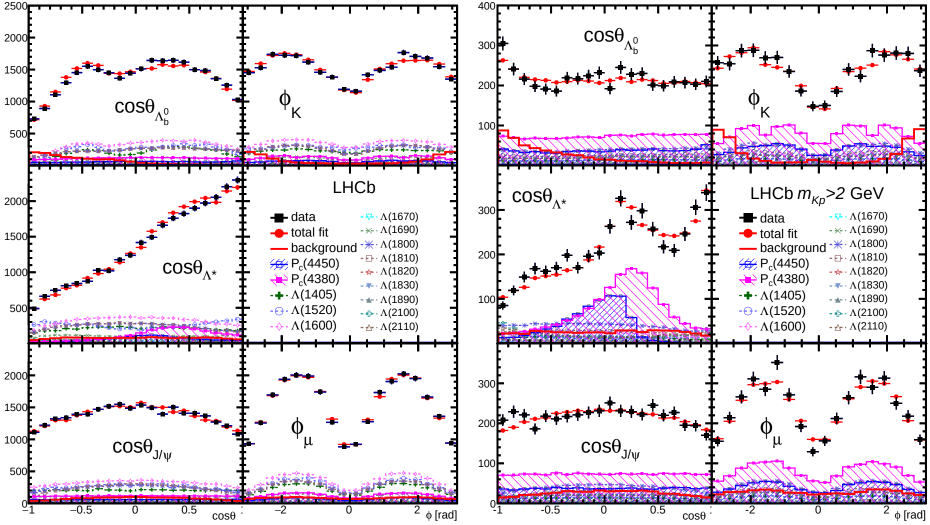
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} + \underbrace{e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)}_{\Lambda^*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

Best Fit with Single P_c State

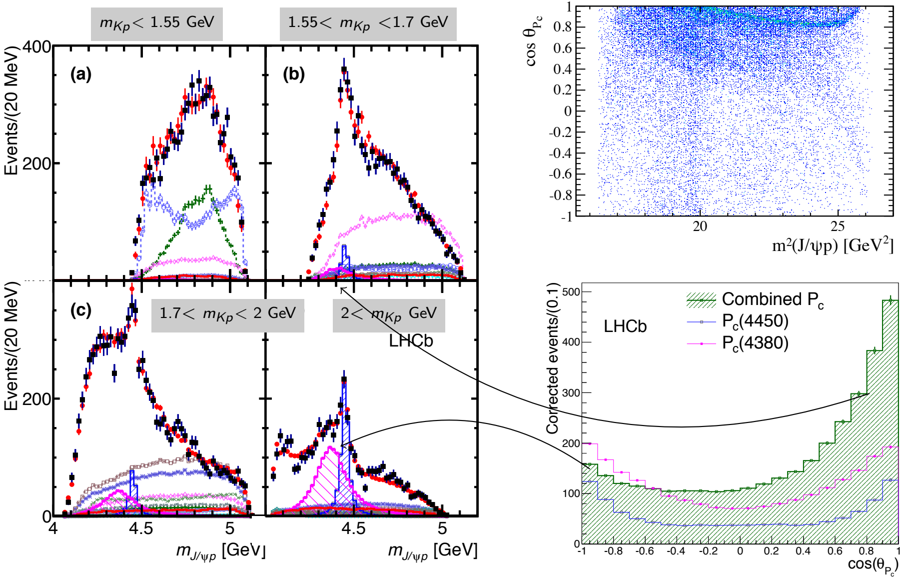


- P_c of best fit has $J^P = 5/2^+$ (tried up to $J^P = 7/2^{\pm}$)
- $\Delta(2\ln\mathcal{L}) = 14.7^2$ when adding single P_c vs. Λ^* only
- Likelihood significantly improved, but still discrepancies in $m_{J\psi p}$

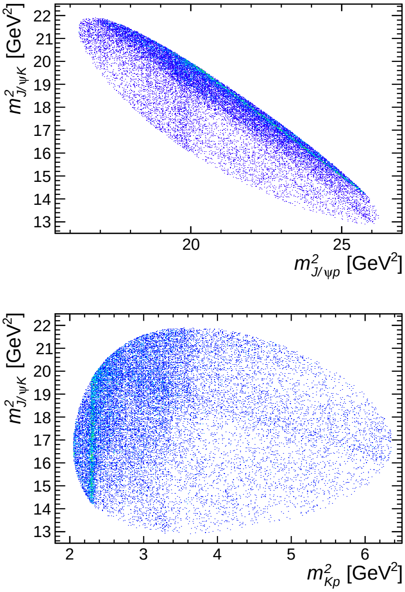
Angular Distributions

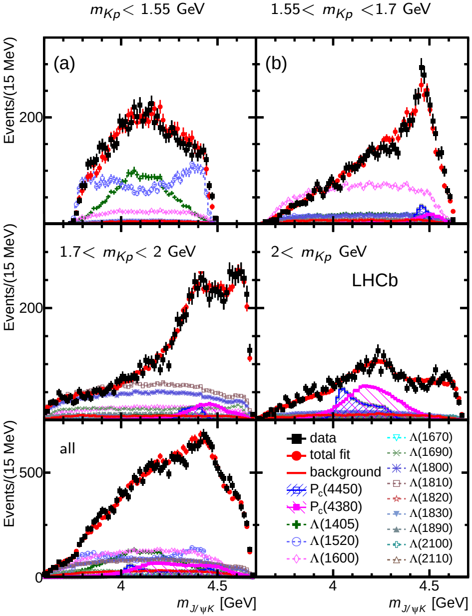


Preference of Opposite Parity P_c States



No Need for $m_{J/\psi K}$ Resonance





J^P Assignment

Table : Changes in fit quality using cFit from the baseline two P_c fit for different combinations of J^P states in terms of the difference $-2\ln\mathcal{L}$, where zero is set from cFit for the $(3/2^-, 5/2^+)$ case. The first column is for the low mass, wider width P_c and the second for the narrower higher mass state.

Fit	$\Delta(-2\ln\mathcal{L})$	P_c (Low) Mass	P_c (Low) Γ	P_c (High) Mass	P_c (High) Γ
$\frac{3}{2}^-, \frac{5}{2}^+$	0	4.3799 ± 0.0064	0.205 ± 0.011	4.4498 ± 0.0017	0.0387 ± 0.0037
$\frac{3}{2}^+, \frac{5}{2}^-$	0.9^2	4.3696 ± 0.0063	0.211 ± 0.012	4.4504 ± 0.0017	0.0492 ± 0.0040
$\frac{5}{2}^+, \frac{3}{2}^-$	2.3^2	4.3770 ± 0.0098	0.239 ± 0.024	4.4486 ± 0.0018	0.0444 ± 0.0053
$\frac{1}{2}^-, \frac{3}{2}^+$	5.9^2	4.3703 ± 0.0085	0.252 ± 0.022	4.4477 ± 0.0019	0.0367 ± 0.0043
$\frac{5}{2}^-, \frac{3}{2}^+$	5.9^2	4.3505 ± 0.0058	0.163 ± 0.012	4.4458 ± 0.0017	0.0553 ± 0.0042
$\frac{7}{2}^+, \frac{5}{2}^-$	6.3^2	4.3762 ± 0.013	0.253 ± 0.051	4.4484 ± 0.0019	0.0520 ± 0.0050
$\frac{3}{2}^-, \frac{1}{2}^+$	6.3^2	4.3580 ± 0.0115	0.186 ± 0.026	4.4469 ± 0.0019	0.0438 ± 0.0057
$\frac{3}{2}^+, \frac{3}{2}^-$	6.4^2	4.3421 ± 0.0071	0.141 ± 0.016	4.4452 ± 0.0019	0.0492 ± 0.0048
$\frac{7}{2}^-, \frac{1}{2}^+$	6.8^2	4.3394 ± 0.0080	0.136 ± 0.022	4.4460 ± 0.0020	0.0563 ± 0.0063
$\frac{5}{2}^-, \frac{7}{2}^+$	6.8^2	4.3862 ± 0.0095	0.252 ± 0.027	4.4483 ± 0.0019	0.0420 ± 0.0042
$\frac{7}{2}^+, \frac{3}{2}^-$	7.2^2	4.3643 ± 0.0135	0.222 ± 0.052	4.4460 ± 0.0019	0.0514 ± 0.0056
$\frac{5}{2}^-, \frac{5}{2}^+$	7.3^2	4.3526 ± 0.0076	0.165 ± 0.021	4.4461 ± 0.0018	0.0438 ± 0.0449
$\frac{3}{2}^+, \frac{1}{2}^-$	7.4^2	4.3422 ± 0.0082	0.152 ± 0.019	4.4468 ± 0.0019	0.0499 ± 0.0059
$\frac{5}{2}^+, \frac{1}{2}^-$	7.6^2	4.3423 ± 0.0063	0.112 ± 0.014	4.4459 ± 0.0019	0.0536 ± 0.0054
$\frac{1}{2}^-, \frac{1}{2}^+$	7.7^2	4.3580 ± 0.0087	0.183 ± 0.020	4.4455 ± 0.0020	0.0451 ± 0.0065
$\frac{5}{2}^-, \frac{1}{2}^+$	8.0^2	4.3648 ± 0.0139	0.226 ± 0.040	4.4446 ± 0.0020	0.0451 ± 0.0055
$\frac{3}{2}^-, \frac{3}{2}^+$	8.3^2	4.3493 ± 0.0067	0.150 ± 0.016	4.4463 ± 0.0017	0.0467 ± 0.0042
$\frac{7}{2}^+, \frac{1}{2}^-$	8.5^2	4.3443 ± 0.0098	0.148 ± 0.031	4.4447 ± 0.0021	0.0632 ± 0.0073
$\frac{1}{2}^-, \frac{5}{2}^+$	8.6^2	4.3709 ± 0.0087	0.199 ± 0.019	4.4477 ± 0.0018	0.0355 ± 0.0048
$\frac{7}{2}^+, \frac{7}{2}^-$	8.6^2	4.4066 ± 0.0165	0.379 ± 0.080	4.4466 ± 0.0018	0.0382 ± 0.0040
$\frac{7}{2}^-, \frac{5}{2}^+$	8.9^2	4.3500 ± 0.0081	0.142 ± 0.019	4.4462 ± 0.0020	0.0568 ± 0.0054
$\frac{7}{2}^-, \frac{3}{2}^+$	8.9^2	4.3396 ± 0.0098	0.138 ± 0.025	4.4451 ± 0.0020	0.0510 ± 0.0056
$\frac{1}{2}^+, \frac{3}{2}^-$	8.9^2	4.3332 ± 0.0085	0.118 ± 0.022	4.4434 ± 0.0020	0.0563 ± 0.0074
$\frac{1}{2}^+, \frac{1}{2}^-$	9.0^2	4.3320 ± 0.0087	0.134 ± 0.023	4.4463 ± 0.0022	0.0588 ± 0.0072
$\frac{1}{2}^-, \frac{7}{2}^+$	9.4^2	4.3762 ± 0.0081	0.204 ± 0.016	4.4487 ± 0.0019	0.0339 ± 0.0048
$\frac{5}{2}^+, \frac{7}{2}^-$	9.6^2	4.3645 ± 0.0090	0.157 ± 0.019	4.4496 ± 0.0020	0.0479 ± 0.0051
$\frac{3}{2}^+, \frac{7}{2}^-$	9.6^2	4.3671 ± 0.0010	0.193 ± 0.023	4.4470 ± 0.0019	0.0348 ± 0.0046
$\frac{5}{2}^+, \frac{5}{2}^-$	9.9^2	4.3583 ± 0.0066	0.201 ± 0.013	4.4465 ± 0.0019	0.0421 ± 0.0031
$\frac{3}{2}^-, \frac{7}{2}^+$	9.9^2	4.3823 ± 0.0099	0.222 ± 0.021	4.4476 ± 0.0021	0.0407 ± 0.0061
$\frac{7}{2}^-, \frac{7}{2}^+$	10.5^2	4.3397 ± 0.0068	0.114 ± 0.015	4.4459 ± 0.0019	0.0507 ± 0.0055
$\frac{1}{2}^+, \frac{5}{2}^-$	10.9^2	4.3642 ± 0.0091	0.168 ± 0.019	4.4482 ± 0.0019	0.0425 ± 0.0057
$\frac{1}{2}^+, \frac{7}{2}^-$	11.6^2	4.3587 ± 0.0099	0.172 ± 0.020	4.4488 ± 0.0020	0.0376 ± 0.0049

Systematic Uncertainties

Source	m_0 (MeV) low	m_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	Fit fractions (%) $\Lambda(1405)$	Fit fractions (%) $\Lambda(1520)$
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
$L_{\Lambda_b}^{P_c}$ $\Lambda_b \to P_c^+(\text{low/high})K^-$	6	0.7	4	8	0.37	0.16		
L_{P_c} $P_c^+(\text{low/high}) \to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L_{\Lambda_b}^{\Lambda_n^*}$ $\Lambda_b \to J/\psi \Lambda^*$	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

Uncertainties in Λ^* model dominate

Sizeable uncertainties from J^P assignment and resonance parametrization

The Dynamical Diquark-Triquark Picture (PLB 749 454), (PRL 113 112001)

- Model provides qualitative information about tetraquark decay-widths, implies broad (or absence of) open charm tetraquarks and can incorporate hidden charm pentaquarks
- Quarks couple as $\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \bar{\mathbf{3}}$ to diquarks δ in color-space
  - Evidence for 0^+ $\bar{\mathbf{3}}$ diquark from LQCD (PRL 97 222002)
- $\bar{\mathbf{3}}$ is attractive color-channel (coupling half as strong as color-singlet)
  - Triquark: $[qq]_{\bar{\mathbf{3}}}\bar{q}_{\bar{\mathbf{3}}} \equiv \bar{\theta}$ is $\bar{\mathbf{3}} \otimes \bar{\mathbf{3}} = \bar{\mathbf{6}} \oplus \mathbf{3}$ in color-space

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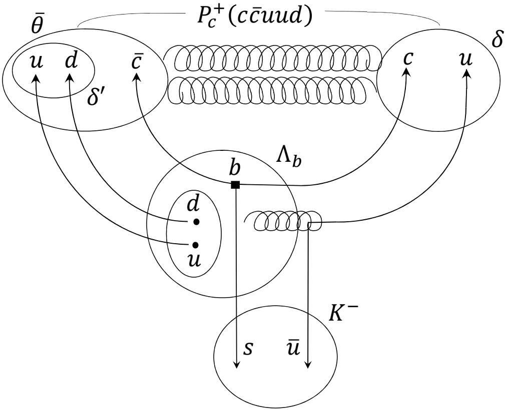
- Kinetic energy between δ and $\bar{\delta}$ gradually converted in potential energy of color flux tube due to confinement



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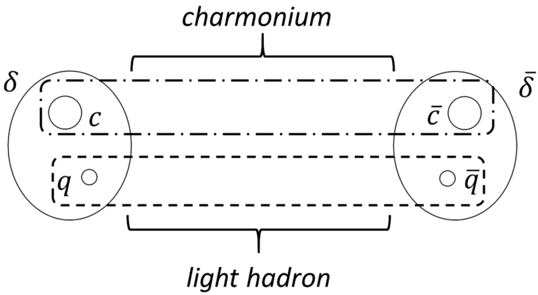

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- Kinetic energy between δ and $\bar{\delta}$ gradually converted in potential energy of color flux tube due to confinement
- Hadronization via large r tails of mesonic wave functions, which suppresses decay widths
- Key ingredients for pentaquarks in this model
  - compact (in size r) di-/triquarks (estimate slightly larger than mesonic r (PRD 91 094025))
  - high energy release to separate di-/triquarks
  - wave function overlap across spatially separated di-/triquarks
- Model provides qualitative information about tetraquark decay-widths, implies broad (or absence of) open charm tetraquarks and can incorporate hidden charm pentaquarks