Resonant Structures in J/ψ p

The LHCb Pentaquark Candidates

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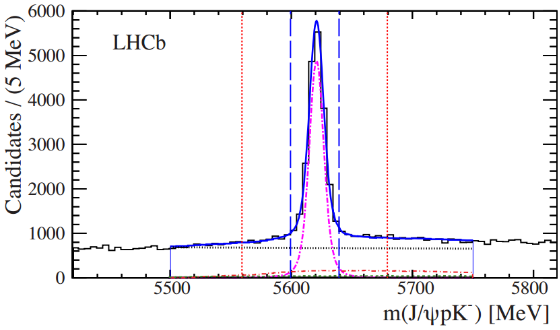
Workshop Resonances in QCD
October 14th 2015

- Initial goal: a precise measurement of the Λ_b lifetime
- $1\,fb^{-1}$ of $\Lambda_b \to J/\psi pK$ + previous measurements: $\tau = 1.482 \pm 0.018 \pm 0.012\,ps$
  ↪ PRL111(2013)102003



A Surprise in Λ_b Decays

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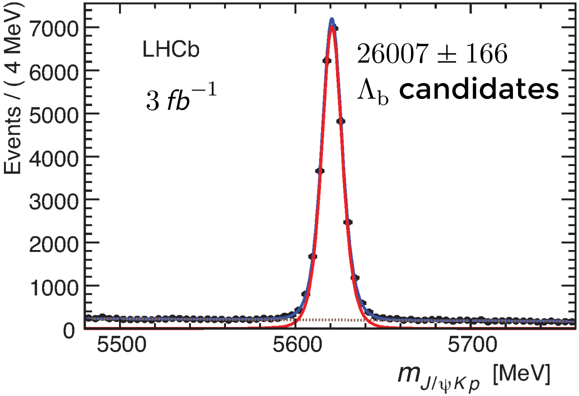

↪ `arXiv:1509.00292`

(submitted to Chin. Phys. C)

$\sigma(\Lambda_b)\mathcal{B}(\Lambda_b \to J/\psi pK) =$
$6.12 \pm 0.10 \pm 0.25 nb$ @7 TeV
$7.51 \pm 0.08 \pm 0.31 nb$ @8 TeV

$\mathcal{B}(\Lambda_b \to J/\psi pK) =$
$3.04 \pm 0.04 \pm 0.06 \pm 0.33^{+0.34}_{-0.27}$

(additional systematic uncertainties from $B \to J/\psi K^*$ and f_{Λ_b}/f_d)

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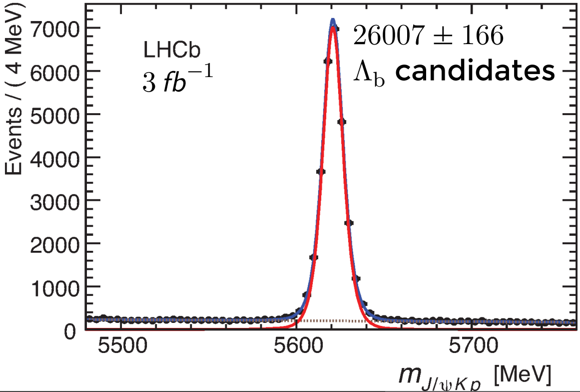
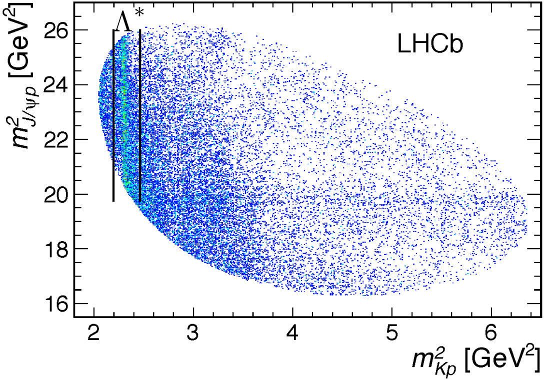
- But looking closer at the J/ψ p K Dalitz-Plot with a dataset of $3\,fb^{-1}$ (Run I)





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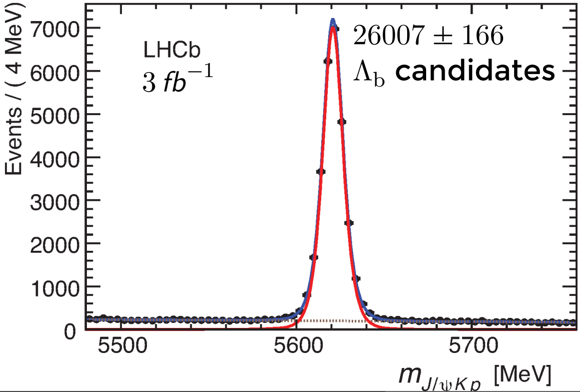
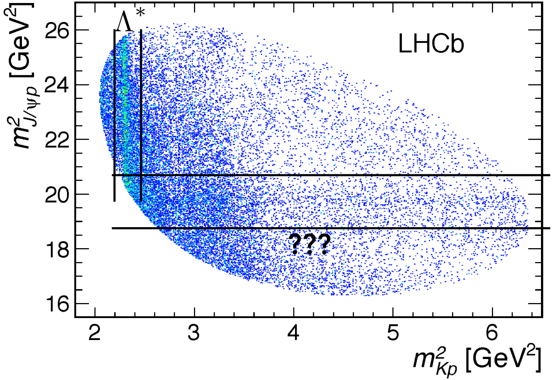
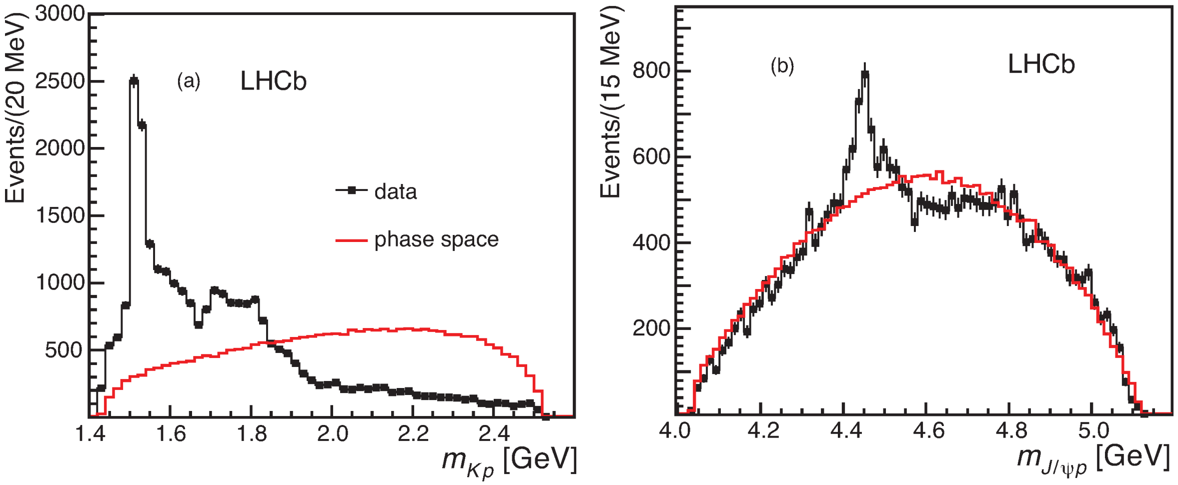
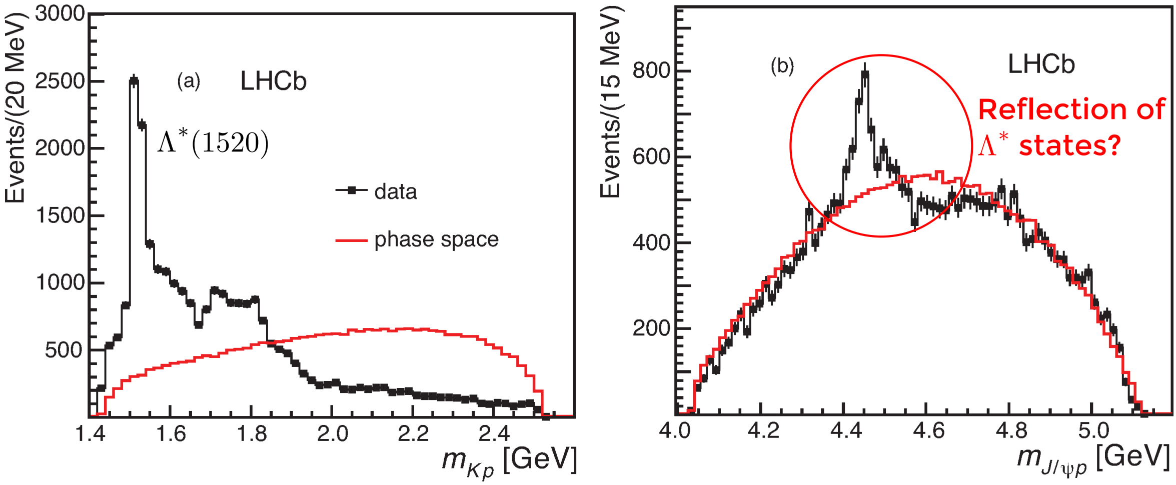





Events/(20 MeV)
3000
2500
2000
1500
1000
500
(a)
LHCb
data
phase space
1.4
1.6
1.8
2.0
2.2
2.4
m_{Kp} [GeV]
Events/(15 MeV)
800
600
400
200
(b)
LHCb
4.0
4.2
4.4
4.6
4.8
5.0
$m_{J/\psi p}$ [GeV]

Dalitz Plot Projections

↪ PRL115(2015)072001



Reflection of Λ^* states?

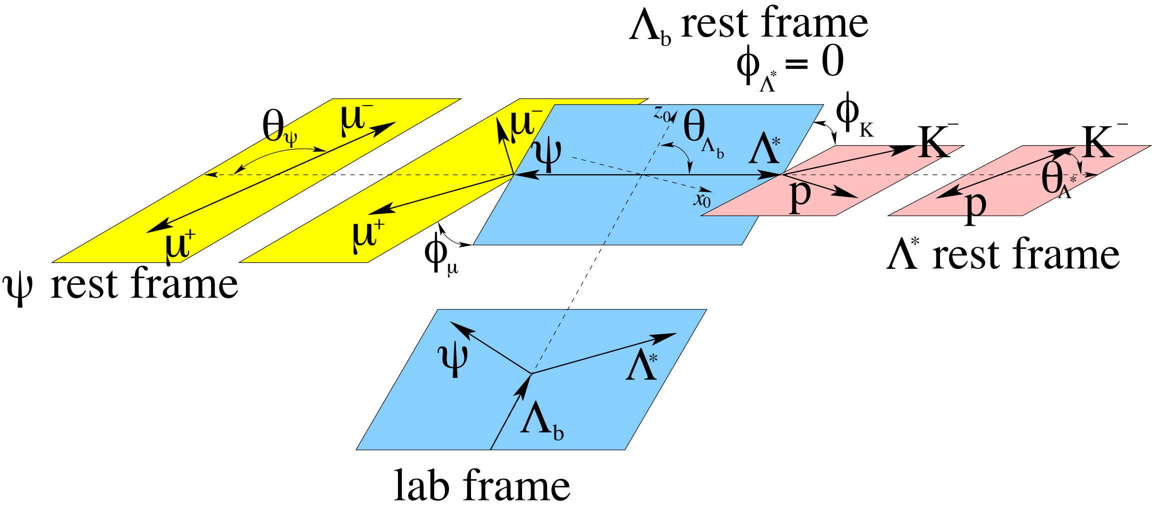
Known Λ^* States

2 Fit-Models used!

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 ℓs couplings	4
anchor → $\Lambda^*(1520)$	$3/2^-$	****	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
$\Lambda^*(2585)$	?	**	≈ 2585	200	0	6

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

Matrix Element $\mathcal{M}^{\Lambda^*}$ is a function of 5 angles and one mass m^2_{pK}



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

Wigner D-functions for $A \to BC$:

$$D^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\phi,\theta,0) = \langle J\,\Delta\lambda|\mathcal{R}(\phi,\theta,0)|J\lambda\rangle = e^{i\lambda_A\phi} d^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\theta)$$

$$D^{\ell}_{m0}(\alpha,\beta,0) = \sqrt{\frac{4\pi}{2\ell+1}}\, Y^{m*}_{\ell}(\alpha,\beta)$$

- Angular structure of J/ψ decay (no free parameters)
- Helicity coupling for Λ^* decay (complex fit parameters)
- Λ^* resonant amplitudes (masses/widths)

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n R_n(m_{Kp})\, \mathcal{H}^{\Lambda^*_n\to Kp}_{\lambda_p} \sum_{\lambda_\psi} e^{i\,\lambda_\psi\phi_\mu}\, d^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi) \times$$
$$\sum_{\lambda_{\Lambda^*}} \mathcal{H}^{\Lambda_b\to\Lambda^*_n\psi}_{\lambda_{\Lambda^*},\lambda_\psi}\, e^{i\,\lambda_{\Lambda^*}\phi_K}\, d^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{\Lambda^*}-\lambda_\psi}(\theta_{\Lambda_b})\, d^{J_{\Lambda^*_n}}_{\lambda_{\Lambda^*},\lambda_p}(\theta_{\Lambda^*})$$

- Helicity coupling for Λ_b decay (complex fit parameters)
- Angular structure of Λ_b decay (no free parameters)
- Angular structure of Λ^* decay (no free parameters)

Resonance parametrisation

Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda^*_n}, \Gamma_0^{\Lambda^*_n})$
- special case $\Lambda(1405)$ is subthreshold: Flatté ($\mathrm{K}\ \mathrm{p}$ and $\Sigma\ \pi$ channels)
- Blatt-Weiskopf barrier factors $B'_\ell(p, p_0, d)$

$$R_n(M_{Kp}) = B'_{\ell^{\Lambda^*_n}_{\Lambda_b}}(p, p_0, d) \left(\frac{p}{M_{\Lambda_b}}\right)^{\ell^{\Lambda^*_n}_{\Lambda_b}} \times BW(M_{Kp}|M_0^{\Lambda^*_n}, \Gamma_0^{\Lambda^*_n}) \times B'_{\ell_{\Lambda^*_n}}(q, q_0, d) \left(\frac{q}{M_0^{\Lambda^*_n}}\right)^{\ell_{\Lambda^*_n}} .$$

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

where

$$\Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2\,\ell_{\Lambda^*}+1} \frac{M_0}{M} B'_{\ell_{\Lambda^*}}(q, q_0, d)^2 .$$

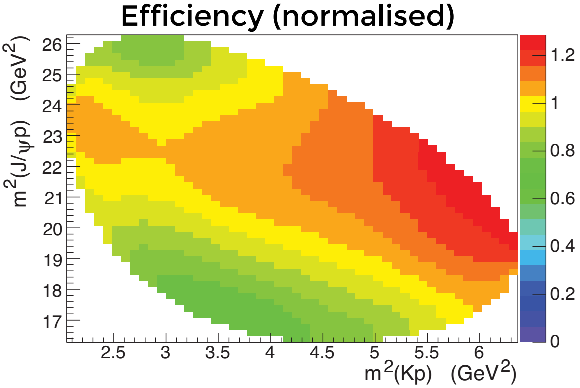
$p(q)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

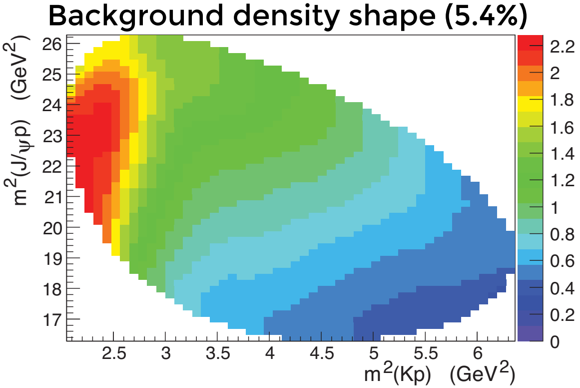
$p_0(q_0)$ calculated on the nominal resonance mass

2 Fitters - Background Treatment

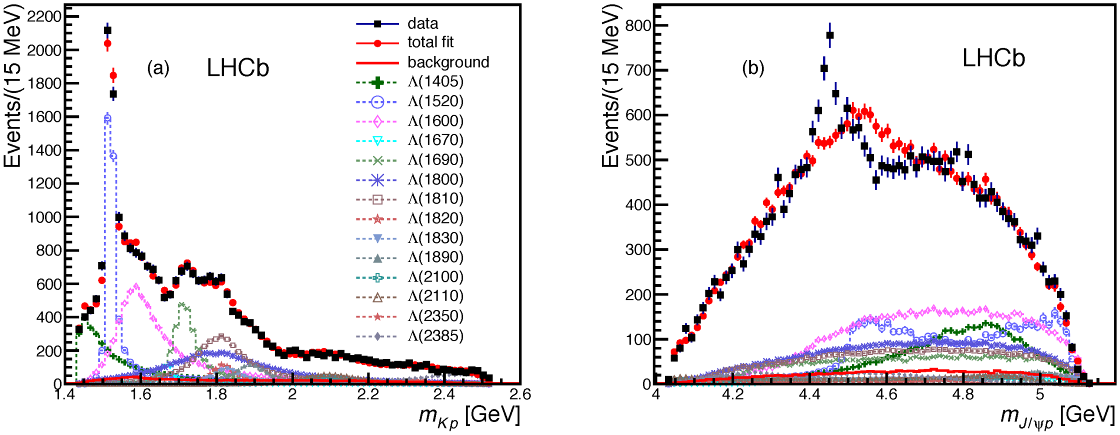
Log-likelihood fitters:

- sFit : subtract background with the sWeight method
- cFit : explicitly model background from sidebands (default)
- Both fitters give comparable results





cFit with extended Λ^* model (14 states allowed):

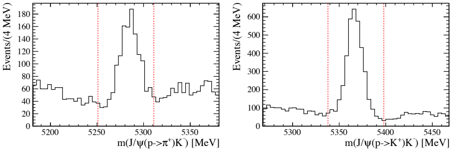


- Λ^* reflections don't explain the structure in $m_{\mathrm{J}/\psi \mathrm{p}}$

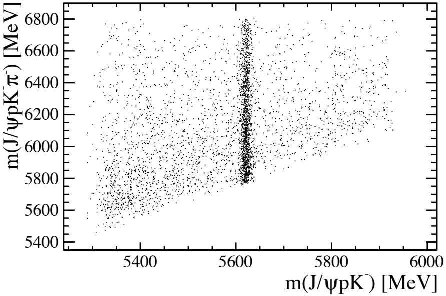
Could the Structure in J/ψ p be an Artifact?

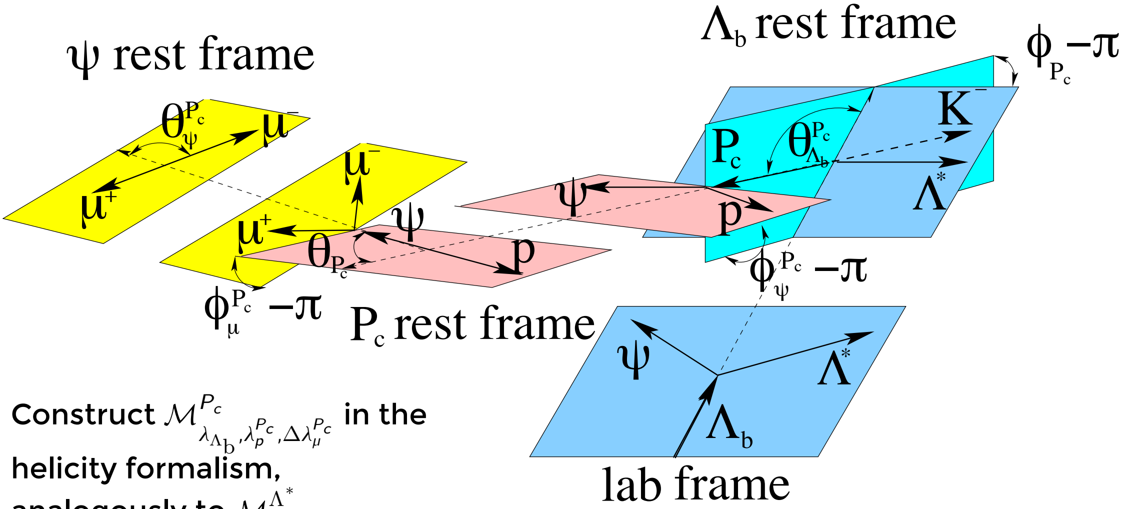
- Background modelled from sidebands and from sWeights (5.4% within signal region)
- Peaking backgrounds?
  - B reflections vetoed
  - Partially reconstructed higher B-Baryon resonances excluded
  - Could some protons be μ^+? (similar problems in past pentaquark analyses) Explicitely checked and found to be completely negligible

B $\rightarrow J/\psi$ K π and $B_s^0 \rightarrow J/\psi$ K K vetoes



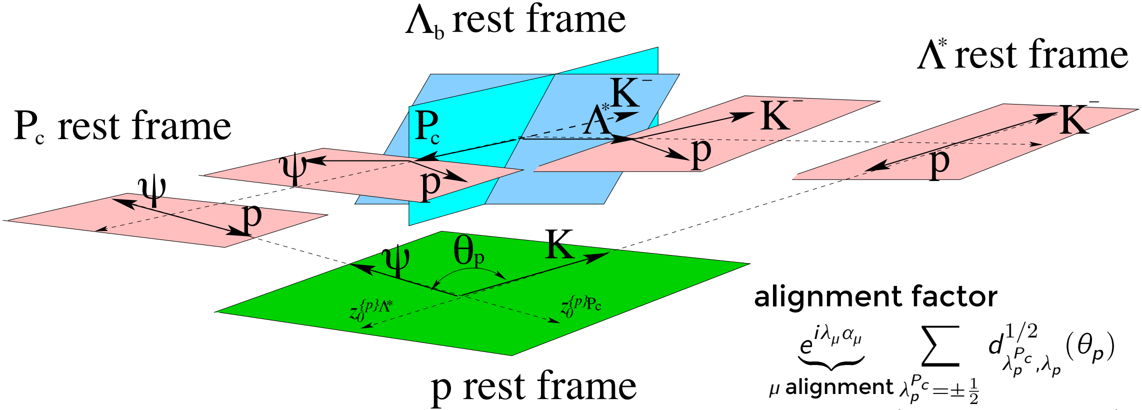
No hint for Ξ_b in J/ψ p K π





Construct $\mathcal{M}^{P_c}_{\lambda_{\Lambda_b}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}}$ in the helicity formalism, analogously to $\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}$

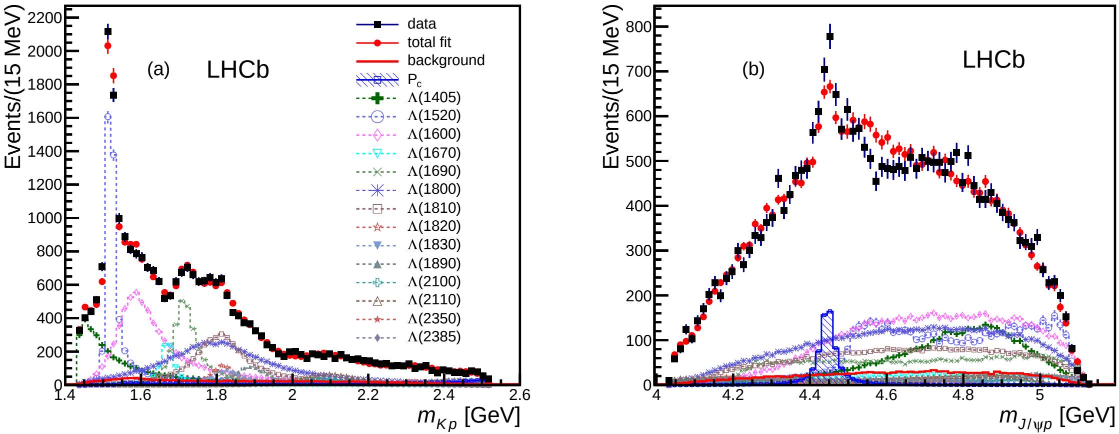
Helicities of final state particle have to be evaluated in the same reference system!



alignment factor

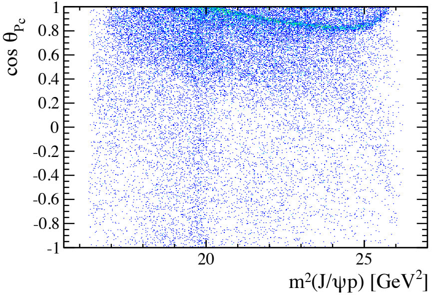
$$\underbrace{e^{i\lambda_\mu \alpha_\mu}}_{\mu\text{ alignment}} \underbrace{\sum_{\lambda_p^{P_c}=\pm\frac{1}{2}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)}_{\text{proton align.}}$$

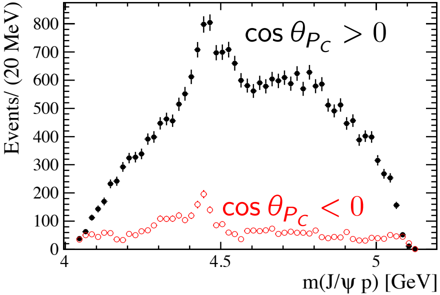
Extended Λ^* model + 1 J/ψ p resonance (floating mass and width) with $J^P = 5/2^+$



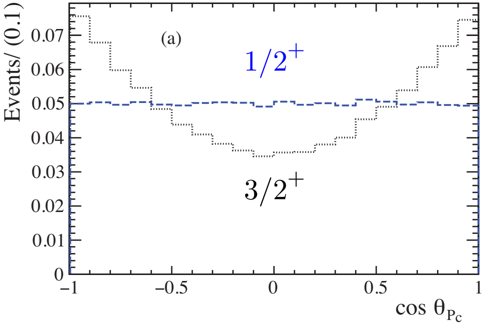
Improvement w.r.t to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$

Why a second state with opposing parity?





- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of $\cos\theta_{P_c}$
- This can be explained by interference of two states with opposing parity
- Toy simulation:



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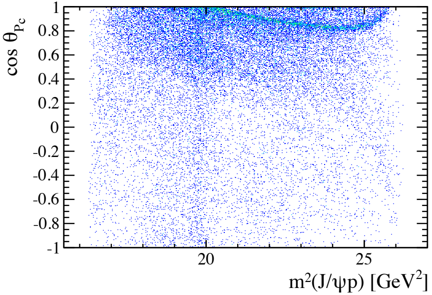

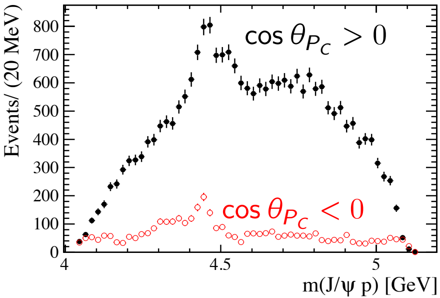

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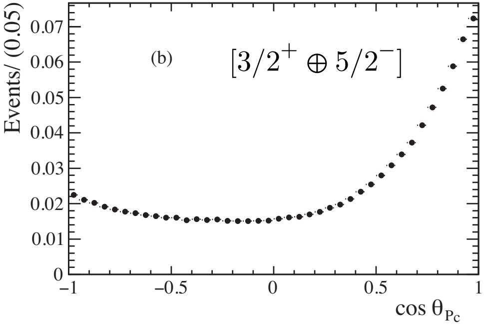
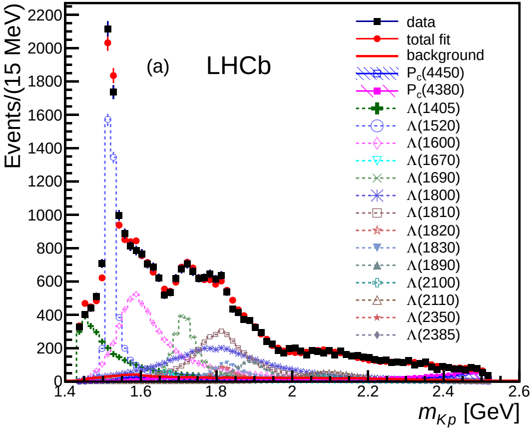
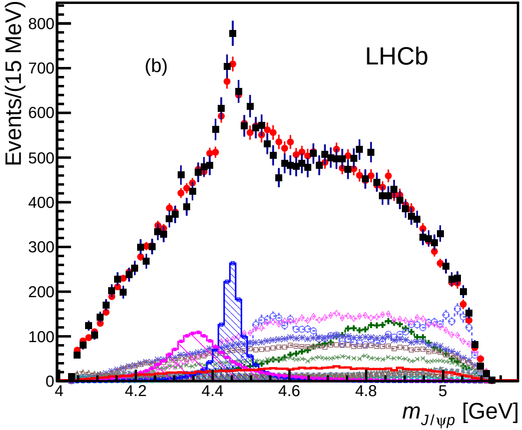


Results with 2 J/ψ p Resonances



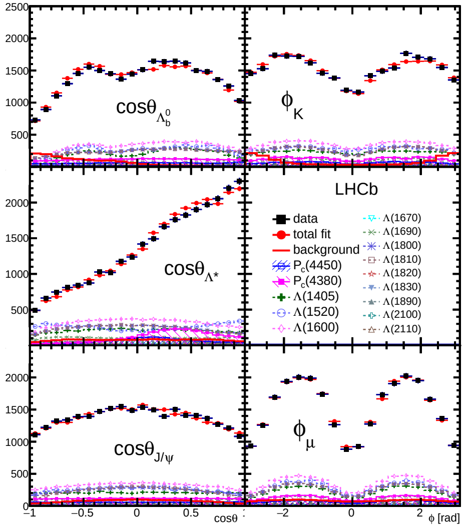


Improvement w.r.t to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 18.7\sigma$

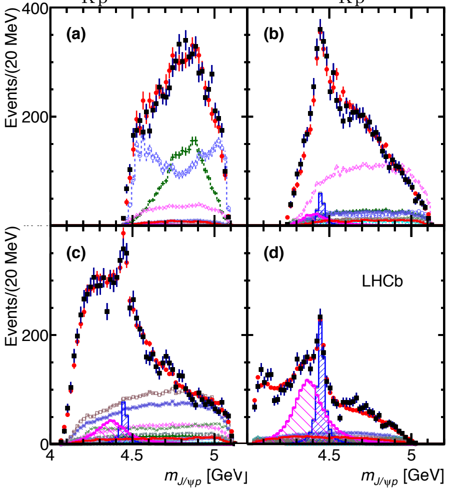
Adding further states (also in J/ψ K) did not improve the fit significantly

Fit Projections

Angular distributions



$m_{J/\psi p}$ in bins of m_{Kp}



Extracted Resonance Parameters

State	Mass [MeV]	Width [MeV]	fav. J^P	Fit fraction	Signi.
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	$(8.4 \pm 0.7 \pm 4.2)$%	9σ
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$	$(4.1 \pm 0.5 \pm 1.1)$%	12σ

- Reduced fit model used for central values
- Significances evaluated on Toy-MC samples: $-2\ln\mathcal{L}$ distributions consistent with χ^2 distribution $\rightarrow$ p-value
- Spin-parity assignment not conclusive:

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

⋮

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$\vdots$

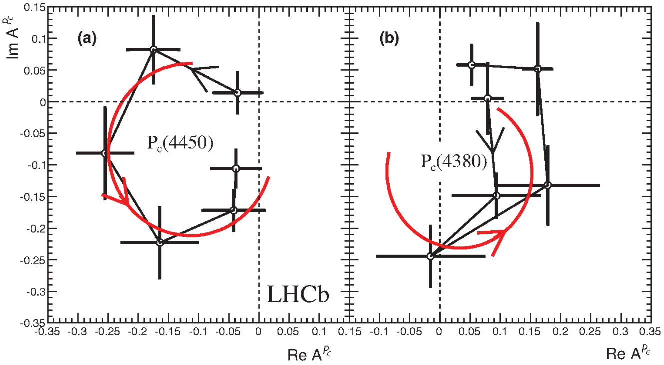
- Λ^* states fit-fractions:

$$\Lambda(1405) \rightarrow \mathrm{pK} \quad (15 \pm 1 \pm 6)\%$$
$$\Lambda(1520) \rightarrow \mathrm{pK} \quad (19 \pm 1 \pm 4)\%$$

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
Non-resonant	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
$\ell_{\Lambda_b}^{P_c}$ $\Lambda_b \to P_c^+$ (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		
$\ell_{\Lambda_b}^{\Lambda_n^*}$ $\Lambda_b^* \to J/\psi \Lambda^*$	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

- Replace the Breit-Wigner amplitude in the model with complex valued cubic spline A in 6 bins of $m^2(\mathrm{J}/\psi \mathrm{p})$, centered around the P_c peaks from nominal fit



- Amplitude in complex plane
- Circular shape corresponds to resonant phase motion (anti-clockwise)

- In red: BW amplitude from nominal fit
- Offset in phase from reference amplitude(s)

Where to go from here?

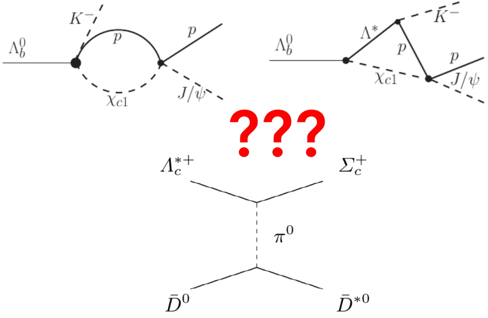
What causes these resonant structures in $J/\psi\ p$?

- Valence quark content of the $J/\psi\ p$ system is trivial
- Why a resonance? What are the relevant degrees of freedom?

Proposed paradigms and a "thresholds deja-vu":

- Rescattering effects
- Meson-Baryon Molecules
- Pentaquarks in the Di-Quark model

[MeV]	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
$\Sigma_c^{*+}\overline{D}^0$	4382.3 ± 2.4	
$\chi_{c1}(1P)p$		4448.93 ± 0.07
$\Lambda_c^{+*}\overline{D}^0$		4457.09 ± 0.35
$\Sigma_c\overline{D}^{0*}$		4459.9 ± 0.5
$\Sigma_c\overline{D}^0\pi^0$		4452.7 ± 0.5



Past literature suggesting generating mechanisms

Tight binding	Phys. Rev. D 15, 267 (1977)
	Nucl. Phys.B123, 507 (1977).
	Nucl. Phys. B145, 119 (1978)
	Phys. Rev. D 20, 748 (1979)
Di-quark models	Phys. Lett. B 575, 249 (2003)
	Phys. Rev. Lett. 91, 232003 (2003)
	Phys. Rev. D 71, 014028 (2005)
	Mod. Phys. Lett. A 27, 1250006(2012)
Coupled Channels	Nuclear Physics A 763 (2005) 90–139
	Phys. Rev. Lett. 105, 232001 (2010)
Baryon-Meson Molecules	Phys. Rev. Lett. 38, 317 (1977)
	Phys. Rev. Lett. 67, 556 (1991)
	Z. Phys. C 61, 525 (1994)
	Phys. Rev. C 84, 015203 (2011)
	Chin. Phys. C 36, 6 (2012)
	arXiv:1506.06386

Theory community reacting to $J/\psi pK$ (selection)

Rescattering effects:

- $\chi_{c1}(1P)p$ rescattering ↪ arXiv:1507.04950
- D^*, D_s^*, Σ_c triangle singularity ↪ arXiv:1507.06552
- $P_c(4380)$ rescat, $P_c(4450)$ di-quark model ↪ arXiv:1507.07652
- Anomalous triangle singularity ↪ arXiv:1507.05359

Molecules:

- Chiral constituent quark model ↪ arXiv:1507.08046
- Isospin exchange model ↪ arXiv:1506.06386
- $D^*\ \Sigma_c$ molecule ↪ arXiv:1507.04249

Di-Quark Models:

- Dynamical di-quark tri-quark picture ↪ arXiv:1507.05867
- Strange and Nonstrange pentaquarks ↪ arXiv:1509.04898
- QCD sum rules for $(qq)(qq)(\bar{q})$ ↪ arXiv:1509.06436
- Flavour SU(3) in di-quark model ↪ arXiv:1507.04980
- P_c masses in di-quark model ↪ arXiv:1508.00356
- Coloured constituents ↪ arXiv:1507.04694

Production:

- Bottom baryon decays ↪ arXiv:1509.03708

Mini Review on Meson-Baryon composite models: ↪ arXiv:1509.02460

	P_c^*				P_c	
	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
$J/\psi N$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi\Delta$	×	✓	×	×	✓	×
$\eta_c\Delta$	×	✓	×	×	✓	×
$\Lambda_c\bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c\bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c\bar{D}$	✓	[×]	✓	×	[×]	×
$\Sigma_c^*\bar{D}$	✓	✓	[×]	✓		
$J/\psi N\pi$	×	✓	×	✓	✓	✓
$\Lambda_c D\pi$	×	×	×	×	✓	×
$\Lambda_c\bar{D}^*\pi$	×	✓	×	×		
$\Sigma_c^+\bar{D}^0\pi^0$	×	✓	✓	×		

$P_c(4380)$ & $P_c(4450)$: a New Sector in Baryon Spectroscopy?

What are they?

Are there more of their kind?

$P_c(4380)$&$P_c(4450)$: a New Sector in Baryon Spectroscopy?

What are they?

- Observe $P_c \to \mathrm{J}/\psi \mathrm{p}$ as subsystems in different final states
  - $\Lambda_\mathrm{b} \to \mathrm{J}/\psi\ \mathrm{p}\ \pi$
  - $\Upsilon \to \mathrm{J}/\psi\ \mathrm{p}\ \overline{\mathrm{p}}$
  - $\Lambda_\mathrm{b} \to \mathrm{J}/\psi\ \mathrm{p}\ \pi\ \mathrm{K}^0_\mathrm{S}$
- Confirmation by other experiments urgently needed!

- Search for new decay modes of P_c
  - $\Lambda_\mathrm{b} \to \chi_{\mathrm{c1}}(1\mathrm{P})\ \mathrm{p}\ \mathrm{K}$
  - $\Lambda_\mathrm{b} \to \Lambda_\mathrm{c}^+\ \overline{\mathrm{D}}^0\ \mathrm{K}$

Are there more of their kind?

- Explore a possible multiplet of pentaquarks
  - $\Lambda_\mathrm{b} \to \mathrm{J}/\psi\ \mathrm{p}\ \pi\ \mathrm{K}^0_\mathrm{S}$
  - $\Lambda_\mathrm{b} \to \mathrm{J}/\psi\ \Lambda\ \phi$
  - Triply charged baryons?

$P_c(4380)$&$P_c(4450)$: a New Sector in Baryon Spectroscopy?

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  - $\Lambda_b \to J/\psi\ \Lambda\ \phi$
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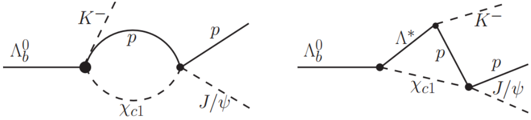
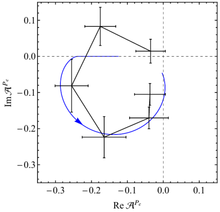
All modes unobserved so far!

Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)\, p\, K$

- **Guo et al** ↪ `arXiv:1507.04950`

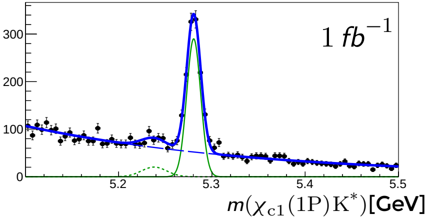


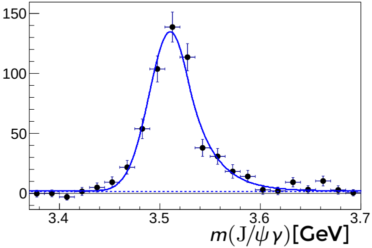
- can explain $P_c(4450)$ phase motion



- Rescattering would not explain a narrow enhancement right above $\chi_{c1}(1P)\, p$ threshold

LHCb $B \to \chi_{c1}(1P) K^*$
↪ `arXiv:1305.6511`

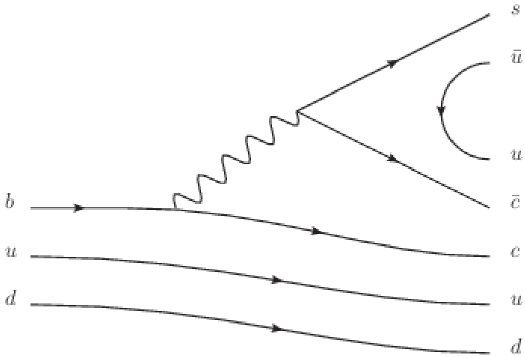




Pentaquark Isospin Multiplet?

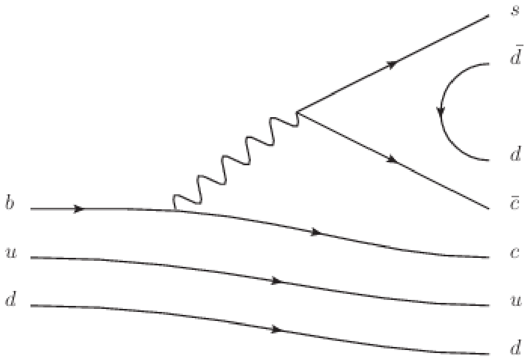
The observed pentaquark

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



Isospin partner: replacing $u\bar{u}$ with $d\bar{d}$

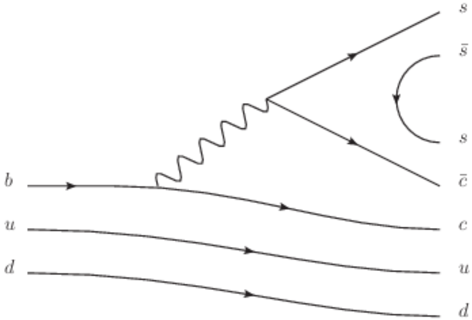
$$\Lambda_b \to P_c^0 K^0 \to J/\psi n K^0 \quad \textit{or} \quad J/\psi p \pi^- K^0$$



Neutron in the final state or 4-body $J/\psi\, p\, \pi^-\, K^0_S$

SU(3) Flavour Multiplet!?
Strange partner: replacing $u\bar{u}$ with $s\bar{s}$

$$\Lambda_b \rightarrow P^0_{cs}\phi \rightarrow J/\psi\Lambda\phi$$



- Each subsystem exotic
  - $J/\psi\ \Lambda$: Strange Pentaquark
  - $J/\psi\ \phi$: X(4140) ?
  - $\Lambda\ \phi$: Spectrum unexplored

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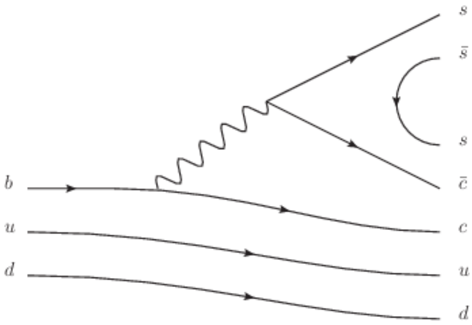


- Each subsystem exotic
  - $J/\psi\ \Lambda$: Strange Pentaquark
  - $J/\psi\ \phi$: X(4140) ?
  - $\Lambda\ \phi$: Spectrum unexplored

Di-quark model suggestions

Maiani et al ↪ arXiv:1507.04980

Process	$\mathbb{P} \in 10 \oplus 8$
$\Lambda_b \to K\ J/\psi p$	$\mathbb{P}_8(\bar{c}[cq]_{s=1}[q'q'']_{s=0,1}, \ell = 0,1)$
$\Lambda_b \to \pi\ J/\psi\Sigma(1385)$ $\Xi_b \to K\ J/\psi\Sigma(1385)$	$\mathbb{P}_{10}(\bar{c}[cq]_{s=0,1}[q's]_{s=0,1})$
$\Omega_b^- \to \phi\ J/\psi\Omega^-(1672)$	$\mathbb{P}_{10}(\bar{c}[cs]_{s=0,1}[ss]_{s=1})$
$\Omega_b^- \to K\ J/\psi\Xi(1387)$	$\mathbb{P}_{10}(\bar{c}[cq]_{s=0,1}[ss]_{s=1})$

Search for Triply Charged Baryons P^{+++}

- If pentaquarks exist we should be able to find huge multiplets
- A striking signature would be a triply charged baryon

Quark content	final state
$uuuc\bar{d}$	$\Lambda_b \to (\Sigma_c{}^{++}\pi^+)\pi^-\pi^-\pi^-$
$uuuc\bar{s}$	$\Lambda_b \to (\Sigma_c{}^{++}K^+)\pi^-\pi^-K^-$
$uuuc\bar{b}$	$P^{+++} \to \Sigma_c{}^{++}B^+$
	with $\Sigma_c{}^{++} \to \Lambda_c^+\pi^+$

- $\Lambda_b \to \Lambda_c^+\pi^+\pi^+\pi^-\pi^-\pi^-$ available in preselection for Run I data set
- Huge inclusive $B^+ \to D^0\pi^+$ sample preselected

Charm Pentaquarks at PANDA?

HESR: $\mathrm{p}\ \overline{\mathrm{p}}$ max $\sqrt{s} \approx 5.6$ GeV

Process	Threshold [MeV]
$\mathrm{p}\overline{\mathrm{p}} \rightarrow \mathrm{p}\mathrm{J}/\psi\overline{\mathrm{p}}$	4966
$\mathrm{p}\overline{\mathrm{p}} \rightarrow \mathrm{p}\eta_{\mathrm{c}}\overline{\mathrm{p}}$	4854
$\mathrm{p}\overline{\mathrm{p}} \rightarrow \Lambda_{\mathrm{c}}^{+}\overline{\mathrm{D}}^{0}\overline{\mathrm{p}}$	5086
$\overline{\mathrm{p}}P_c(4450)$	5385
$\overline{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{p}\phi\overline{\mathrm{p}}$	2890
$\overline{\mathrm{p}}d \rightarrow ??$	

Summary

- First observation of $\mathrm{J}/\psi\ \mathrm{p}$ resonances in a full amplitude analysis of $3\ fb^{-1}$ $\Lambda_\mathrm{b} \to \mathrm{J}/\psi \mathrm{pK}$ at LHCb ↪ PRL115(2015)072001
- Two states of opposite parity required
  - $P_c(4380)^+$: $m = 4380 \pm 8 \pm 29$, $\Gamma = 205 \pm 18 \pm 86$, $J^P = 3/2^-$ or $5/2^+$
  - $P_c(4450)^+$: $m = 4449.8 \pm 1.7 \pm 2.5$, $\Gamma = 39 \pm 5 \pm 19$, $J^P = 5/2^+$ or $3/2^-$
- Resonant phase motion extracted
  - Consistent with Breit-Wigner for $P_c(4450)$
  - $P_c(4380)$: More complicated (but counter-clockwise phase motion)
- No $\mathrm{J}/\psi \mathrm{K}$ resonances needed
- Starting program to confirm and search for new states
- Confirmation from other experiments needed!

Backup

Pre Selection

Table : **Pre-selection requirements used. The stripping line is** `FullDSTDiMuonJpsi2MuMuDetachedLine`.

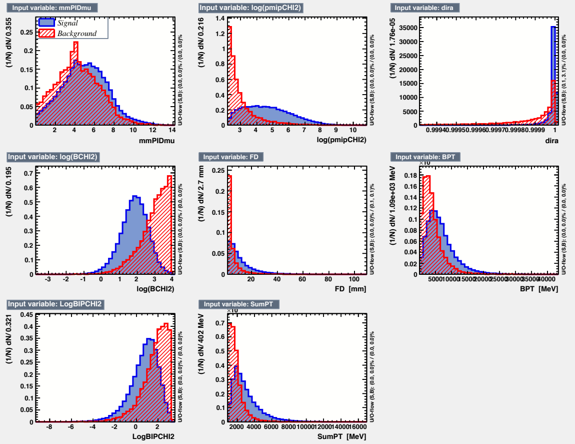
#	Selection variables	Requirements
1	All tracks χ^2/ndof	< 4
2	Muon PID	DLL$(\mu - \pi) > 0$
3	PT of muon	> 550 MeV
4	PT of hadron	> 250 MeV
5	J/ψ vertex χ^2	< 16
6	J/ψ mass window	$-48 < m(\mu^+\mu^-) - m(\mathrm{J}/\psi) < 43$ MeV
7	Hadron χ^2_{IP}	> 9
8	K^- ID	DLL$(K - \pi) > 0$ and DLL$(p - K) < 3$
9	p ID	DLL$(p - \pi) > 10$ and DLL$(p - K) > 3$
10	pK^- vertex χ^2	DOCA $\chi^2 < 16$
11	Λ_b χ^2_{IP}	< 25
12	Λ_b vertex χ^2/ndof	< 10
13	Λ_b flight distance	> 1.5 mm
14	Λ_b pointing, $\cos\theta_p$	> 0.999
15	Trigger	HLT1 and HLT2 TOS on J/ψ (see text)
16	Clone track rejection on hadron	Ghost probability < 0.2

BDT Classifier

BDT variables:

- minimum DLL($\mu - \pi$) of the μ^+ and μ^- (mmPIDmu);
- minimum of the $\chi^2_{\rm IP}$ of the K^- and the p [log(pmipCHI2)];
- Λ_b (DIRA);
- Λ_b $\chi^2_{\rm IP}$ log(BCHI2);
- Λ_b FD;
- PT of the Λ_b (BPT);
- Λ_b vertex χ^2 (LogBIPCHI2);
- PT sum of the K^- and p (SumPT).

- Trained on signal MC and sideband data for bkg
- Cut optimzed by maximising $S/\sqrt{S+B}$ in data, subsequently tightened to reduce background across DP



ℓS Couplings

- The angular momentum barrier should suppress decays with high orbital angular momentum.
- Express helicity couplings through ℓS-couplings $B_{\ell S}$ using Clebsch-Gordan coefficients

$$\mathcal{H}^{A\to B\,C}_{\lambda_B,\lambda_c} = \sum_{\ell}\sum_{S}\sqrt{\frac{2\ell+1}{2J_A+1}} \times B_{\ell,S} \times \underbrace{\left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B-\lambda_C \end{array}\right)}_{\text{Spin}-\text{Spin coupling}} \times \underbrace{\left(\begin{array}{cc|c} \ell & S & J_A \\ 0 & \lambda_B-\lambda_C & \lambda_B-\lambda_C \end{array}\right)}_{\text{Spin}-\text{Orbit coupling}}$$

- Limit the allowed range of ℓ in the fit model
- Automatically implements parity conservation in strong decays by choice of ℓ

Efficiency corrected Signal PDF

- Ω = 6 kinematical variables (m_{Kp} + 5 angles)
- $\vec{\omega}$ = fit parameters (couplings, masses, widths)

$$\frac{d\mathcal{P}}{d\Omega} \equiv \mathcal{P}_{\mathrm{sig}}(\Omega|\vec{\omega}) = \frac{1}{CI(\vec{\omega})} \left|\mathcal{M}(\Omega|\vec{\omega})\right|^2 \; \Phi(\Omega) \; \epsilon(\Omega)$$

- Phase space volume element
- efficiency
- With the normalisation calculated by MC-integration over accepted MC events

$$I(\vec{\omega}) \equiv \int \mathcal{P}_{\mathrm{sig}}(\Omega)\, d\Omega \propto \frac{\Sigma_j w_j^{\mathrm{MC}} \left|\mathcal{M}(\Omega_j|\vec{\omega})\right|^2}{\Sigma_j w_j^{\mathrm{MC}}},$$

- weights w_j^{C} account for differences in Λ_{b} production kinematics and PID between simulation and data

- Coherent sum over amplitudes, incoherent sum over external helicities
- Set Λ_b polarisation to 0

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

J/ψ K Dalitz Plot Projections in bins of m_{pK}