Hadron Spectroscopy at LHCb

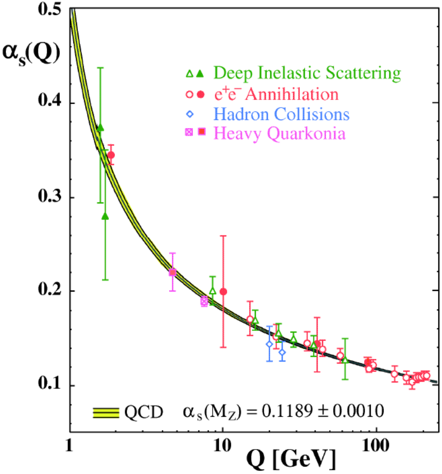
Hidden Charm Exotic Mesons & Baryons

Sebastian Neubert
for the LHCb Collaboration

54th International Winter Meeting on Nuclear Physics
25-29 January 2016 Bormio

From QCD to Hadron Physics

$$\mathcal{L}_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$



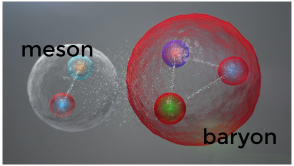
S. Bethke [arXiv:hep-ex/0606035v2]

- $SU(3)_{color}$ symmetry
- Quarks&Gluons relevant DOF
- Perturbative QCD
- However: Hadronization

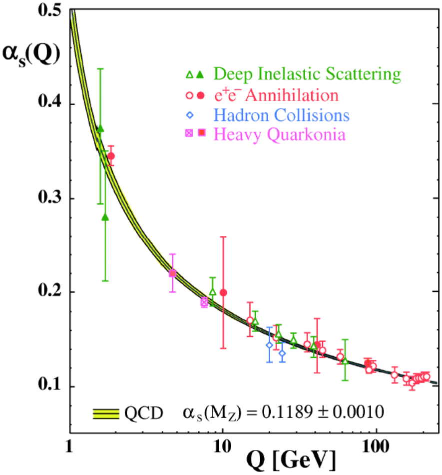
From QCD to Hadron Physics

$$\mathcal{L}_{QCD} = \bar{\psi}_i(i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- Confinement
- Hadrons relevant DOF



- Structure of excited hadrons?
- Hadronic renaissance: B-factories find charmonium-like exotics



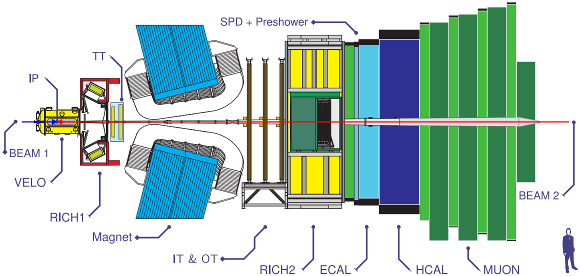
S. Bethke [arXiv:hep-ex/0606035v2]

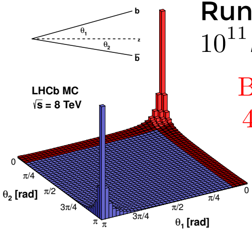
- $SU(3)_{color}$ symmetry
- Quarks&Gluons relevant DOF
- Perturbative QCD
- However: Hadronization

The LHCb Experiment

[IJMP A30(2015)1530022]

- LHCb is a single-arm $(2 < \eta < 5)$ spectrometer at the LHC
  - *CP* violation measurements, rare decays,
    heavy flavor decays as source for exotic hadrons
  - Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment





Run I: $3\ fb^{-1}$
$10^{11}\ b\bar{b}$ pairs
$\mathrm{B} : \Lambda_\mathrm{b} : \mathrm{B}_\mathrm{s}^0$
$4 : 2 : 1$

- Clean B-hadron samples through excellent vertex resolution: $\mathcal{O}(15)\ \mu m$ (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Highly efficient trigger: di-muons, displaced vertices (topological B-hadron), ..

Exotic Mesons with Hidden Charm

The $\mathrm{X}(3872)$

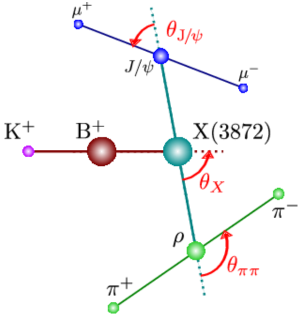
The $\mathrm{X}(3872)$

- Since its discovery a decade ago by Belle ↪ [PRL 91 262001] in $\mathrm{B}^{\pm} \to \mathrm{J}/\psi\pi\pi\mathrm{K}^{\pm}$ the $\mathrm{X}(3872)$ has been studied at a number of experiments
- The existence of the $\mathrm{X}(3872)$ is now beyond doubt, but structure is still unclear:
  - Mass and decay mode disfavor $\mathrm{c\bar{c}}$ state.
  - $C = +1 \quad \Leftarrow \quad \mathrm{X}(3872) \to \mathrm{J}/\psi\gamma$
  - CDF, Babar and Belle analyses left 2 options for J^{PC} assignment
  - $J^{PC} = 2^{-+}$: Nearest in mass to $\eta_{\mathrm{c}}(1^1\mathrm{D}_2)$
  - $J^{PC} = 1^{++}$: $\mathrm{D}^0\,\mathrm{D}^*$ molecule, Tetra-quark

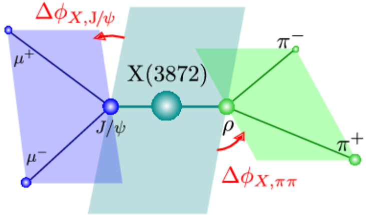
Measurement of the $\mathrm{X}(3872)$ Quantum Numbers @ LHCb

Analysis of the decay $\mathrm{B}^+ \to \mathrm{X}(3872)\mathrm{K}^+ \to \mathrm{J}/\psi\pi\pi\mathrm{K}^+$ uses full angular correlations in 5D

- Amplitude analysis on $1\,fb^{-1}$ [PRL110(2013)222001]
  - 313 ± 26 $\mathrm{B}^+ \to \mathrm{X}(3872)\mathrm{K}^+$ candidates
  - $\pi\ \pi$ in P-wave
  - Only S/P-wave decays of X taken into account
  - Established $J^{PC} = 1^{++}$

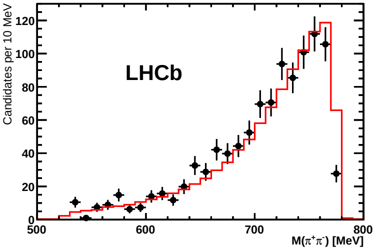


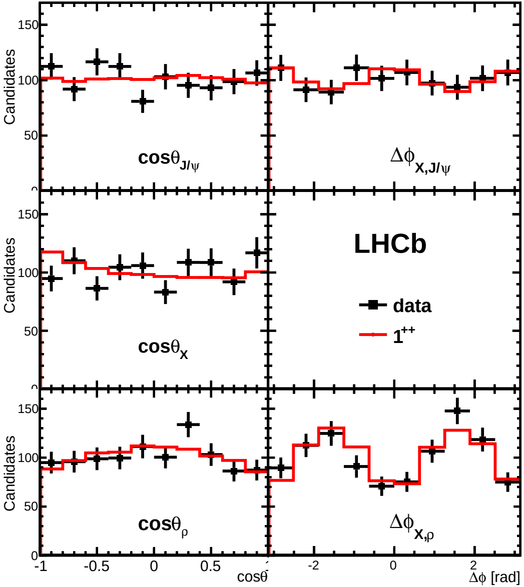
- Reanalysis on $3\,fb^{-1}$ [PRD92(2015)011102]
  - 1011 ± 38 $\mathrm{B}^+ \to \mathrm{X}(3872)\mathrm{K}^+$ candidates
  - Full amplitude model
  - Including D-wave decays



Amplitude Analysis $X(3872) \to J/\psi\rho$ on $3\,fb^{-1}$ [PRD92(2015)011102]

- Tripled size of data set
  1011 ± 38 candidates
- Allows a full amplitude model, including D-wave contributions

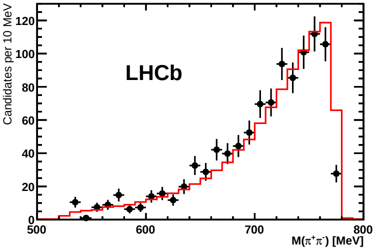


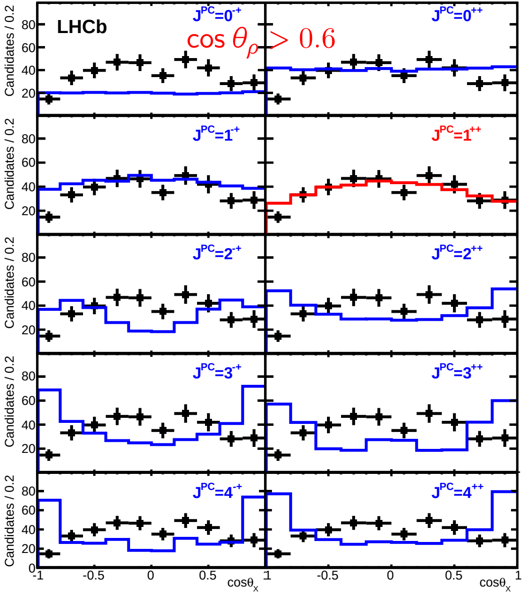


- $J^{PC} = 1^{++}$ confirmed
- D-wave negligible $< 4\%@95\%CL$

Amplitude Analysis $X(3872) \to J/\psi\rho$ on $3\ fb^{-1}$ [PRD92(2015)011102]

- **Tripled size of data set**
  1011 ± 38 **candidates**
- **Allows a full amplitude model, including D-wave contributions**





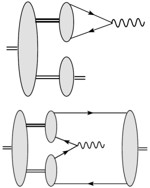
- $J^{PC} = 1^{++}$ **confirmed**
- **D-wave negligible** $< 4\%@95\%CL$

Radiative Decays of the $\mathrm{X}(3872)$

- The $\mathrm{X}(3872)$ lies right at the $D\bar{D}^*$ threshold ($3871.81 \pm 0.09\ MeV$)
- Popular model: Molecular state, characterised by tiny binding energy

Radiative decays as a test for molecular models

[PLB598(2004)197]



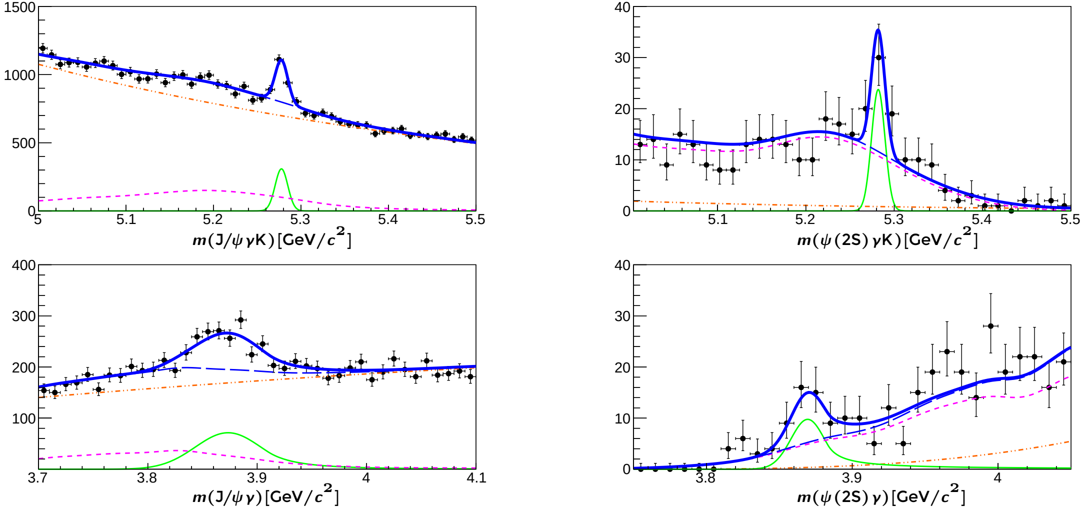
$$R_{\psi\gamma} = \frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2S)\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to J/\psi\gamma)}$$

Model	$R_{\psi\gamma}$ prediction	
$D\bar{D}^*$ molecule	$(3-4)\cdot 10^{-3}$	see
pure $c\bar{c}$ state	$1.2-15$	[Nucl. Phys. B886(2014)665]
Mixture	$0.5-5$	and ref. therein

Radiative Decays of the $X(3872)$

[Nucl. Phys. B886(2014)665]

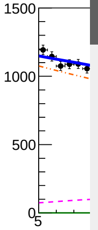
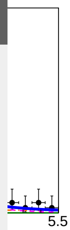
$B \to X(3872)K \to J/\psi\gamma K$ | $B \to X(3872)K \to \psi(2S)\gamma K$



Radiative Decays of the X(3872)

[Nucl. Phys. B886(2014)665]

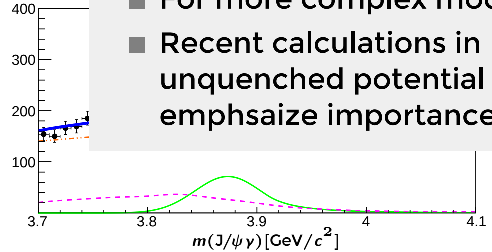
$B \to X(3872)K \to J/\psi\gamma K$ $\qquad$ $B \to X(3872)K \to \psi(2S)\gamma K$

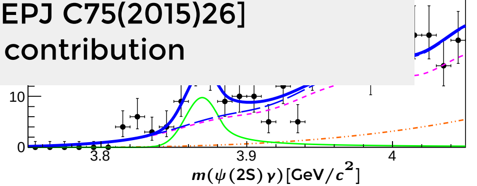



Branching fraction ratio

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

- Does not support the pure $D\bar{D}^*$ molecule interpretation
- For more complex models see e. g. [JPG38(2011)015001]
- Recent calculations in EFT [PLB742(2015)394] and unquenched potential model [EPJ C75(2015)26] emphsaize importance of $D\bar{D}^*$ contribution





Status of the $\mathrm{X}(3872)$

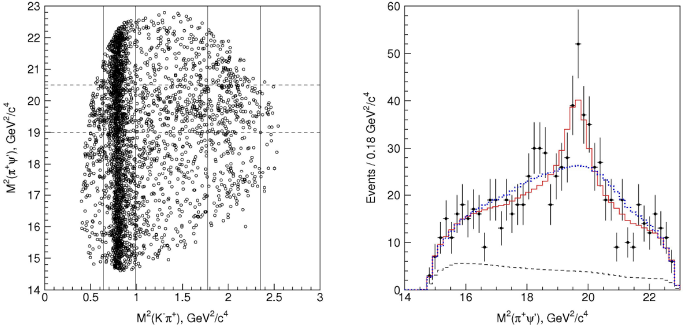
- $J^{PC} = 1^{++}$ is established
- Radiative decays indicate a complex substructure: Mixture between $D\bar{D}^*$-molecule and $c\bar{c}$?
- Significant isospin violation in its decays
- Mass $m = 3871.69 \pm 0.17\,MeV$ ($\mathrm{X}(3872) \rightarrow \mathrm{J}/\psi\ X$)
- $D\bar{D}^*$ threshold: $3871.81 \pm 0.09\,MeV$
- Mass difference $m_X - m_{\mathrm{J}/\psi} = 775 \pm 4\,MeV$
- Width $\Gamma < 1.2$ MeV
- Next steps at LHCb: Precision mass measurement $m_X - m_{\psi(2S)}$

The charged exotic meson $Z^+(4430)$

A Charged Charmonium-like Exotic

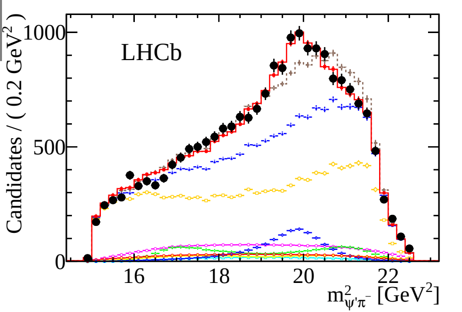
- $Z(4430)^-$ has first been claimed by Belle in $\mathrm{B} \to \mathrm{K}(\pi^- \psi(2\mathrm{S}))$
- Minimal quark content: $\mathrm{c\bar{c}d\bar{u}}$
- BaBar could explain this through reflections of the $\mathrm{K}\pi$ system (K^*)
- Amplitude analysis by Belle confirms new state (assuming a resonant shape)

Belle data



PRL 100(2008)142001

$\mathrm{B} \to \mathrm{K}\pi^-\psi(2\mathrm{S})$ at LHCb



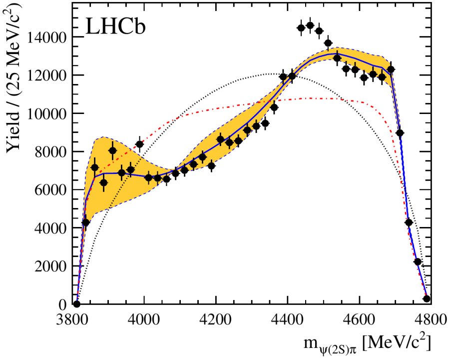
Data sample:

- $\sim 25\,000$ $\mathrm{B} \to \mathrm{K}\pi^-\psi(2\mathrm{S})$ candidates in $3\,fb^{-1}$ at LHCb with $\sim 3\%$ residual background

2 Analysis methods:

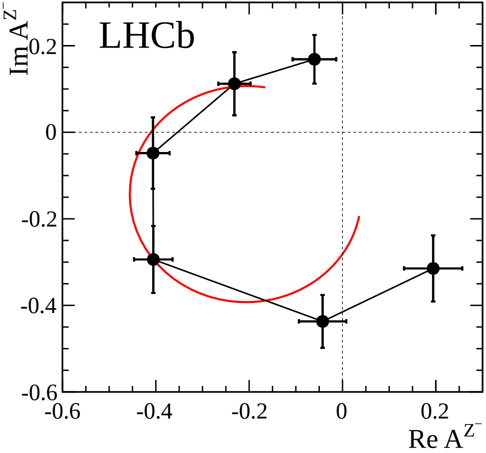
- 4D amplitude analysis a'la Belle model the decay matrix element extract resonant phase [PRL112(2014)222002]

- Moments analysis a'la BaBar model independent confirms existence of Z(4430) [PRD92(2015)112009]



Z(4430) Resonance from Amplitude Analysis [PRL112(2014)222002]

- Full 4-dimenisonal amplitude analysis of $\mathrm{B} \to \mathrm{K}\pi^- \psi(2\mathrm{S})$
- Model-independent extraction of resonant phase



- Argand plot: amplitude in complex plane
- Circular shape corresponds to resonant phase motion (anti-clockwise)
- $M = 4475 \pm 7^{+15}_{-25}$ MeV
- $\Gamma = 172 \pm 13^{+37}_{-34}$ MeV
- $J^P = 1^+$

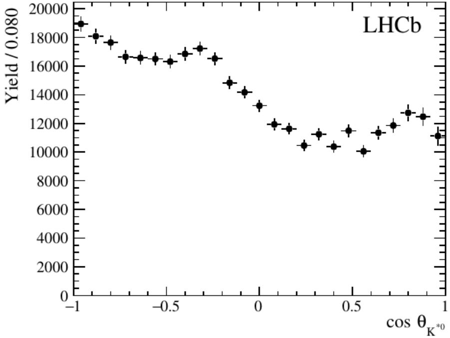
Model-independent Moments Analysis [PRD92(2015)112009]

- Extract the angular structure of the $\mathrm{K}\pi$ system by moments:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{k=0}^{l_{max}} \langle P_k^U \rangle P_k(\cos\theta_{K^*})$$

- with Legendre polynomials P_k
- highest moment l_{max} corresponds to twice the highest orbital angular momentum
- Moments are determined in bins of $m_{\mathrm{K}\pi}$:

$$\langle P_k^U \rangle = \sum_{i=0}^{N_{events}} \frac{W_i}{\epsilon_i} P_k(\cos\theta^i_{K^*})$$



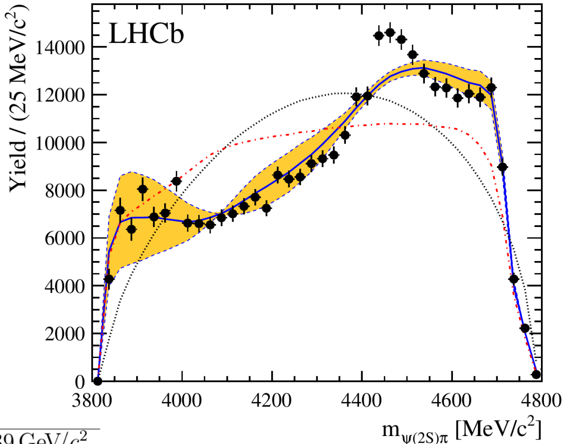
Resonance	Mass (MeV/c^2)	Γ (MeV/c^2)	J^P
$K^*(892)^0$	895.81±0.19	47.4±0.6	1^-
$K^*(1410)^0$	1414±15	232±21	1^-
$K_0^*(1430)^0$	1425±50	270±80	0^+
$K_2^*(1430)^0$	1432.4±1.3	109±5	2^+
$K^*(1680)^0$	1717±27	322±110	1^-
$K_3^*(1780)^0$	1776±7	159±21	3^-

Reflections from K^* Resonances not sufficient

- Higher spin K^* resonances are heavier

$$l_{\max} = \begin{cases} 2 & m_{K\pi} < 836\,\text{MeV}/c^2 \\ 3 & 836\,\text{MeV}/c^2 < m_{K\pi} < 1000\,\text{MeV}/c^2 \\ 4 & m_{K\pi} > 1000\,\text{MeV}/c^2. \end{cases}$$

- $K_3^*(1780)$ is outside the Dalitz plot
- Hypothesis that K^* reflections alone cause $\psi(2S)\ \pi$ shape rejected:



	S, whole $m_{K\pi}$ spectrum	S, $1.0 < m_{K\pi} < 1.39\,\text{GeV}/c^2$
$l_{\max} = 4$	13.3σ	18.2σ
$l_{\max} = 6$	8.0σ	14.1σ
$l_{\max}(m_{K\pi})$	15.2σ	17.3σ

Higher moments are reflections of Z(4430) into $\mathrm{K}\ \pi$!

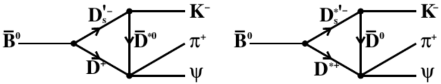
Status of the $Z^+(4430)$

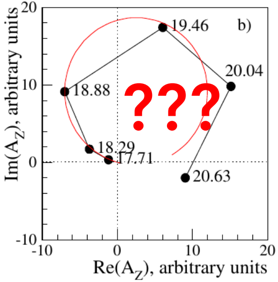
- Resonant nature established
- $M = 4475 \pm 7^{+15}_{-25}$ MeV
- $\Gamma = 172 \pm 13^{+37}_{-34}$ MeV
- $J^P = 1^+$
  - positive parity rules out S-wave molecules $\bar{D}^*(2007)D_1^+(2420)$ and $\bar{D}^*(2007)D_2^+(2460)$
- $\frac{\mathcal{B}(Z^+(4430) \to \psi'\pi)}{\mathcal{B}(Z^+(4430) \to J/\psi\pi)} \approx 10$

Belle: [PRD88(2013)074026]

[PRD90(2014)112009]

- Candidate for a tetraquark
- Rescattering effect?





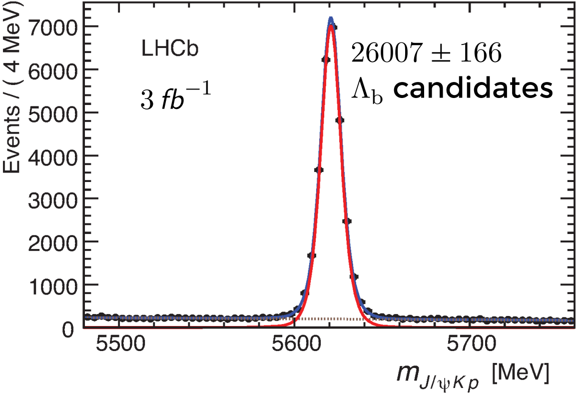
[PLB748(2015)183]

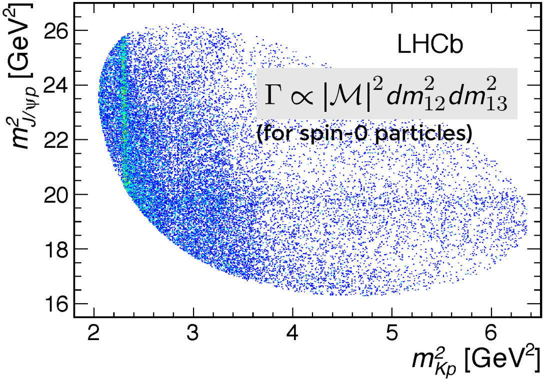
but: wrong sense of phasemotion

Baryon Resonances in $\Lambda_b \to J/\psi p K$

A Surprise in Λ_b Decays

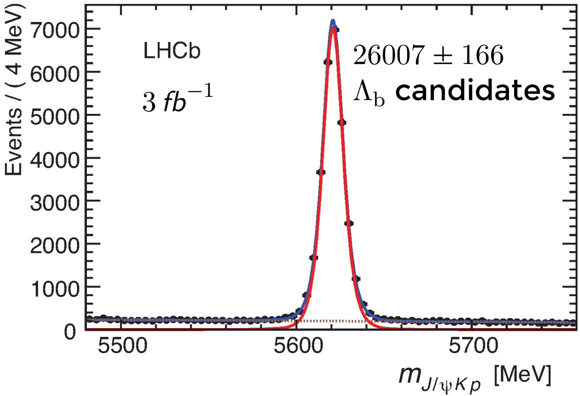
- Initial goal: a precise measurement of the Λ_b lifetime
- $1\,fb^{-1}$ of $\Lambda_b \to J/\psi pK$ + previous measurements: $\tau = 1.482 \pm 0.018 \pm 0.012\,ps$
  $\hookrightarrow$ PRL111(2013)102003
- But looking closer at the J/ψ p K Dalitz-Plot with a dataset of $3\,fb^{-1}$ (Run I)

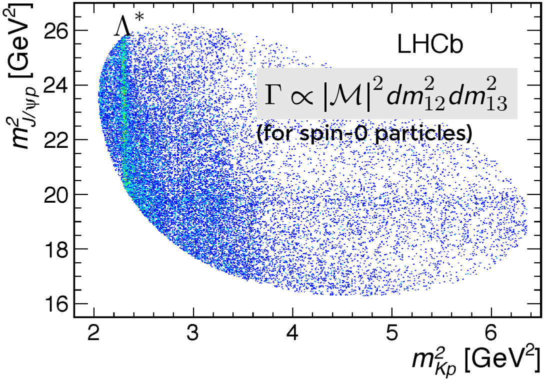




A Surprise in Λ_b Decays

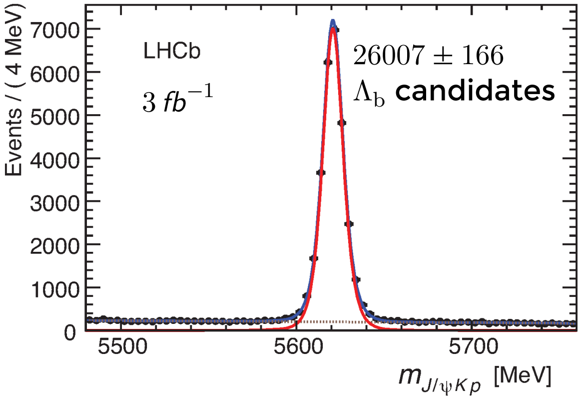
- Initial goal: a precise measurement of the Λ_b lifetime
- $1\ fb^{-1}$ of $\Lambda_b \to J/\psi pK$ + previous measurements: $\tau = 1.482 \pm 0.018 \pm 0.012\ ps$
  ↪ PRL111(2013)102003
- But looking closer at the J/ψ p K Dalitz-Plot with a dataset of $3\ fb^{-1}$ (Run I)

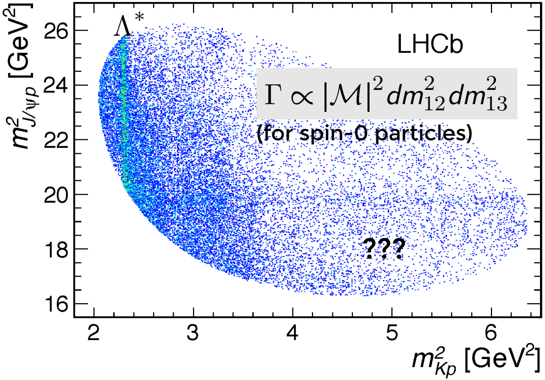




A Surprise in Λ_b Decays

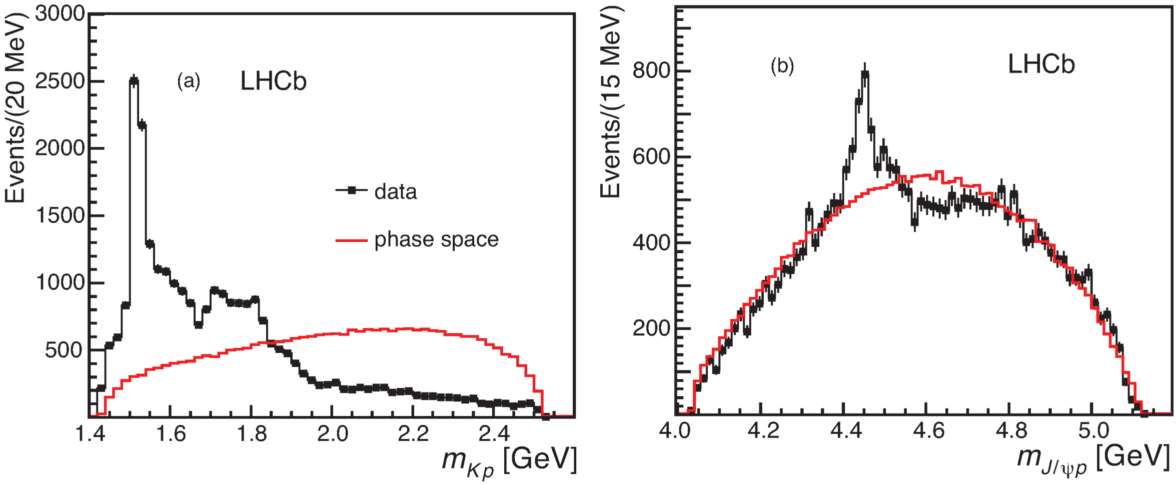
- Initial goal: a precise measurement of the Λ_b lifetime
- $1\,fb^{-1}$ of $\Lambda_b \to J/\psi pK$ + previous measurements: $\tau = 1.482 \pm 0.018 \pm 0.012\,ps$
  $\hookrightarrow$ PRL111(2013)102003
- But looking closer at the J/ψ p K Dalitz-Plot with a dataset of $3\,fb^{-1}$ (Run I)





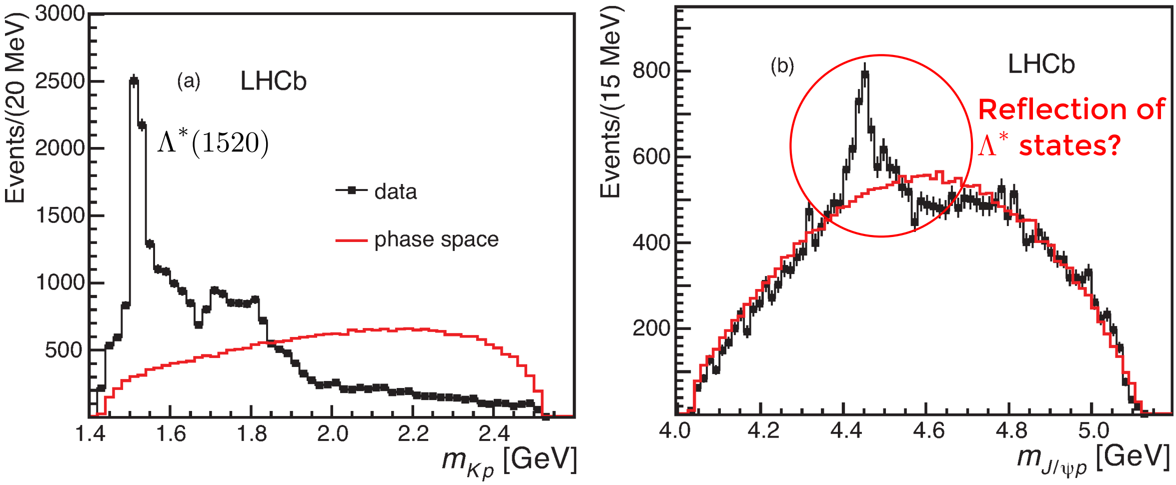
2-Body Mass Spectra

[PRL115(2015)072001]



2-Body Mass Spectra

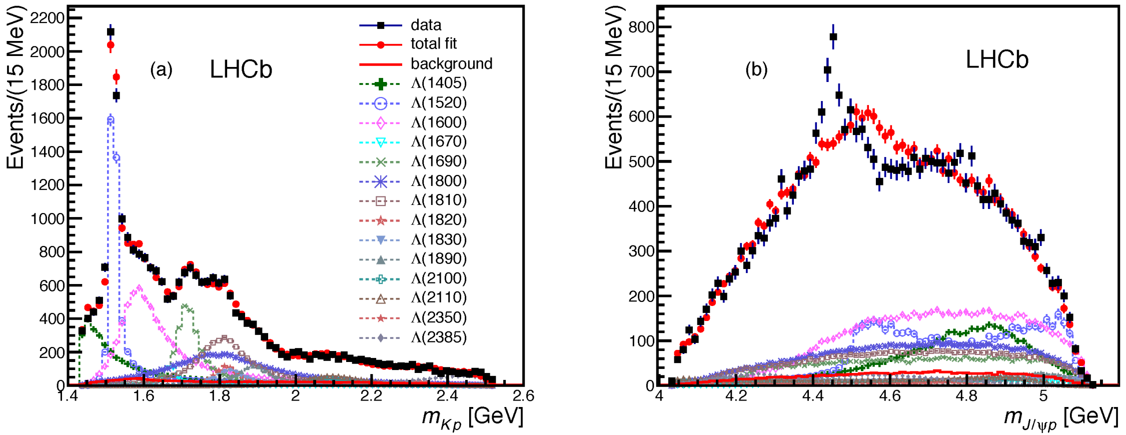
[PRL115(2015)072001]



Results with only Λ^* States

[PRL115(2015)072001]

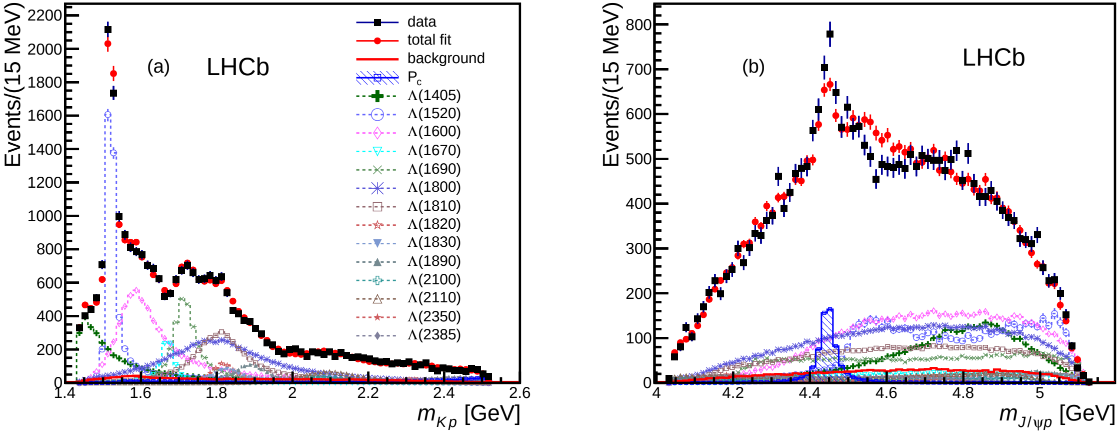
6D amplitude analysis with 14 Λ^* states included:



- Adding two new Λ^* states with floating mass/width does not improve fit
- Λ^* reflections don't explain the structure in $m_{J/\psi p}$

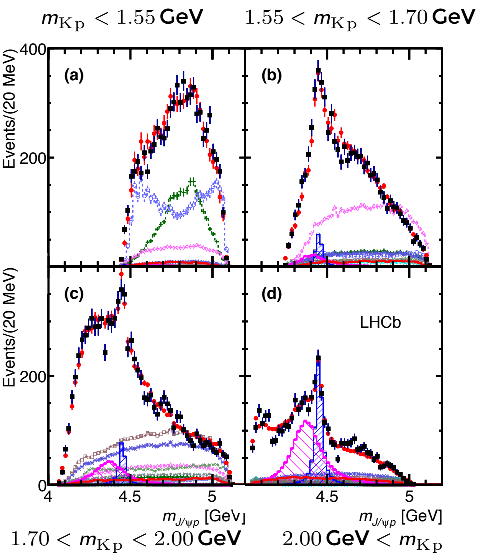
Results with One J/ψ p Resonance [PRL115(2015)072001]

Extended Λ^* model + 1 J/ψ p resonance (floating m, Γ) with $J^P = 5/2^+$

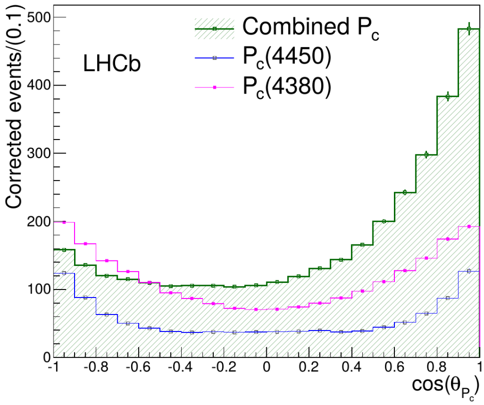


Improvement w.r.t to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$

Why a second state with opposing parity? [PRL115(2015)072001]

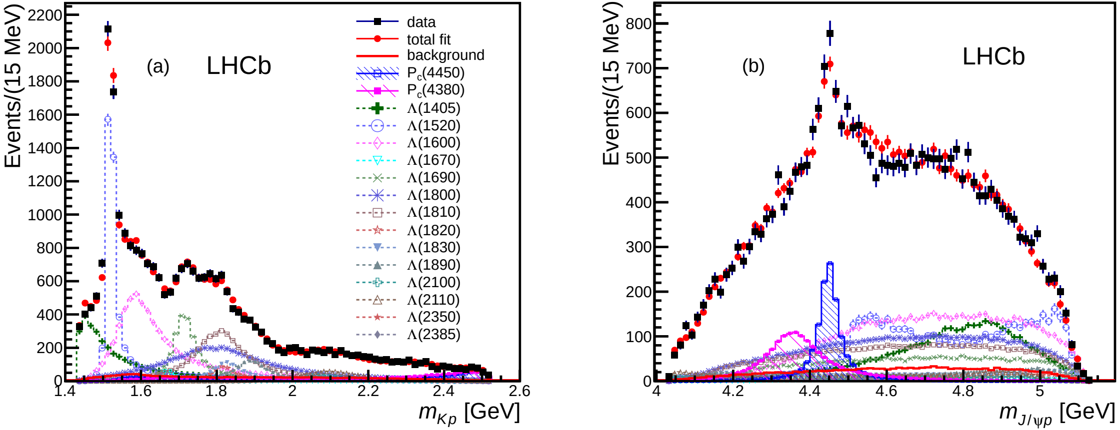


- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of m_{Kp} (or $\cos\theta_{P_c}$)
- This can be explained by interference of two states with opposing parity



Results with 2 J/ψ p Resonances

[PRL115(2015)072001]



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

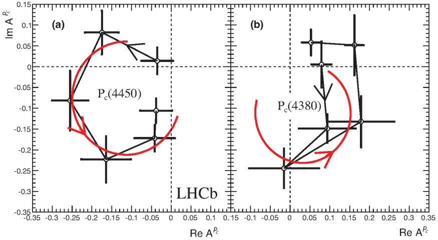
Adding further states (also in J/ψ K) did not improve the fit significantly

Extracted Resonance Parameters

[PRL115(2015)072001]

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

- Significances evaluated on Toy-MC samples: $-2\ln\mathcal{L}$ distributions consistent with χ^2 distribution → p-value



- Spin-parity assignment not conclusive:

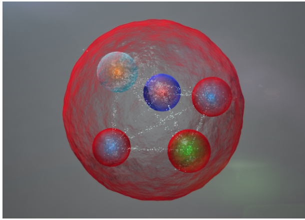
Fit	$\Delta(-2\ln\mathcal{L})$	P_c (Low) Mass	P_c (Low) Γ	P_c (High) Mass	P_c (High) Γ
$\frac{3}{2}^-, \frac{5}{2}^+$	0	4.3799 ± 0.0064	0.205 ± 0.011	4.4498 ± 0.0017	0.0387 ± 0.0037
$\frac{3}{2}^+, \frac{5}{2}^-$	0.9^2	4.3696 ± 0.0063	0.211 ± 0.012	4.4504 ± 0.0017	0.0492 ± 0.0040
$\frac{5}{2}^+, \frac{3}{2}^-$	2.3^2	4.3770 ± 0.0098	0.239 ± 0.024	4.4486 ± 0.0018	0.0444 ± 0.0053

⋮

Interpretations

Inspirations

What causes these resonant structures in J/ψ p?



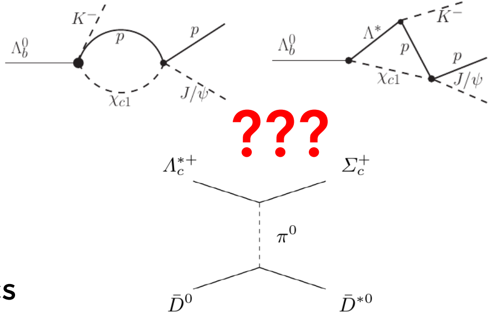
- Valence quark content: $uudc\bar{c}$
- What are the relevant degrees of freedom?

Challenges:

- Why two states with opposite parity?
- Small mass gap ≈ 100 MeV
- Narrow width of $P_c(4450)$

Proposed paradigms:

- Rescattering effects
- Meson-Baryon Molecules
- Pentaquarks in the Di-Quark model
- Crypto-exotics in chiral-unitary dynamics



Deja-vu: Threshold Effects?

Exotic states with hidden charm appear close to 2-body thresholds

[MeV]	$X(3872)$
Mass	3871.69 ± 0.17
DD^*	3871.81

Pure molecule disfavoured

by radiative decays

[MeV]	$Z^+(4430)$
Mass	$4475 \pm 7^{+15}_{-25}$
$D^*(2007)D_1^+(2420)$	4430.16
$D^*(2007)D_2^+(2460)$	4471.26

S-wave molecules excluded by parity

[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

Studies of further decay modes needed

Are thresholds the unifying pattern across the meson and baryon sectors?

Deja-vu: Threshold Effects?

Exotic states with hidden charm appear close to 2-body thresholds

[MeV]	$X(3872)$
Mass	3871.69 ± 0.17
$D\bar{D}^*$	3871.81

Pure molecule disfavoured

by radiative decays

[MeV]	$Z^+(4430)$
Mass	$4475 \pm 7^{+15}_{-25}$
$D^*(2007)D_1^+(2420)$	4430.16
$D^*(2007)D_2^+(2460)$	4471.26

S-wave molecules excluded by parity

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

Studies of further decay modes needed

Are thresholds the unifying pattern across the meson and baryon sectors?

Or are these just coincidences, because the density of thresholds is so high?

Deja-vu: Threshold Effects?

Exotic states with hidden charm appear close to 2-body thresholds

[MeV]	$X(3872)$
Mass	3871.69 ± 0.17
DD^*	3871.81

Pure molecule disfavoured

by radiative decays

[MeV]	$Z^+(4430)$
Mass	$4475 \pm 7^{+15}_{-25}$
$D^*(2007)D_1^+(2420)$	4430.16
$D^*(2007)D_2^+(2460)$	4471.26

S-wave molecules excluded by parity

[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

Studies of further decay modes needed

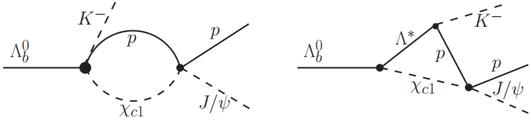
Are thresholds the unifying pattern across the meson and baryon sectors?

Or are these just coincidences, because the density of thresholds is so high?

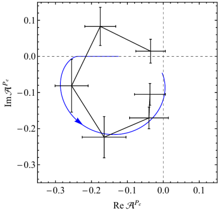
Most ambitious theory attempts use QCD symmetries and try to explain exotic states together with 'known' spectrum

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

- Guo et al ↪ `arXiv:1507.04950`

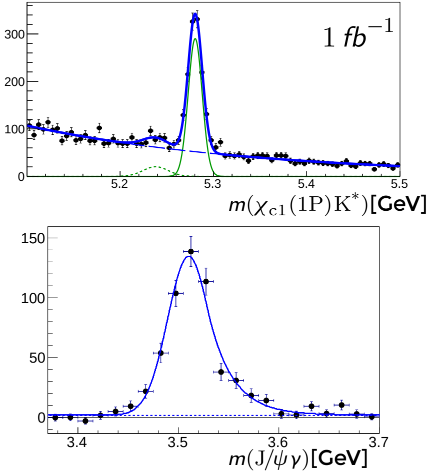


- can explain $P_c(4450)$ phase motion **but $P_c(4380)$?**



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

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



Summary

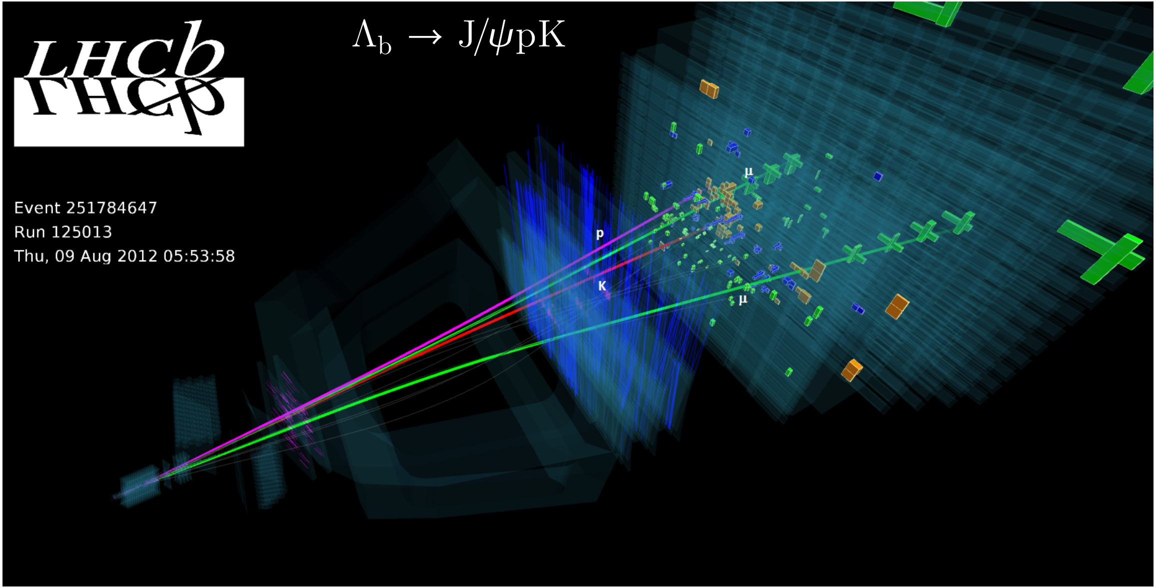
- B and Λ_b decays provide a valuable source of exotic mesons
- LHCb has collected $3\,fb^{-1}$ in Run I and is well situated to study spectroscopy

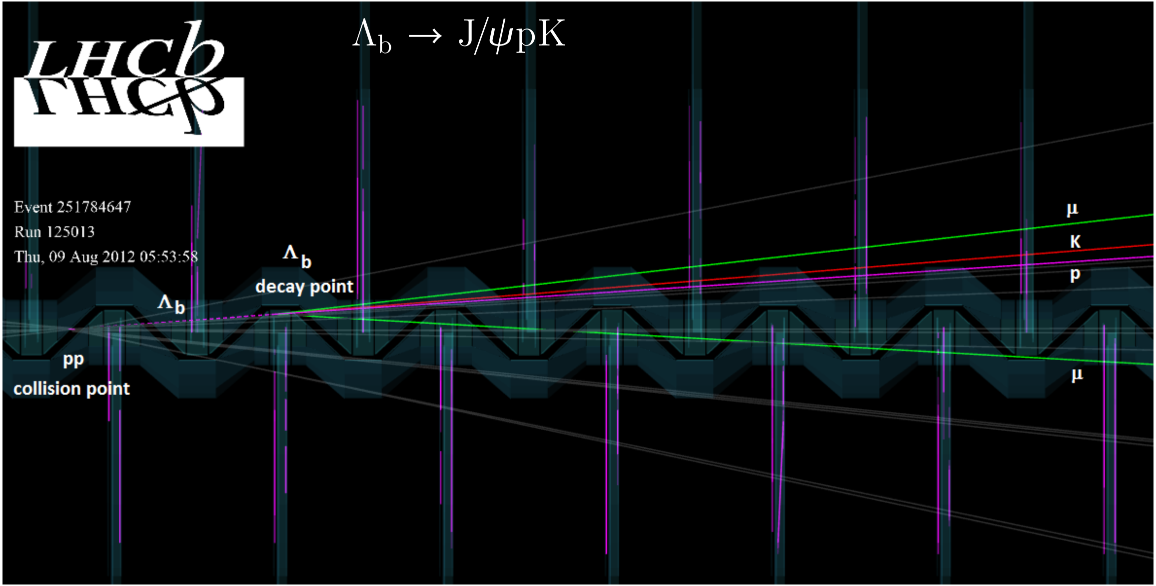
- In the meson sector:
  - Established quantum numbers $J^{PC} = 1^{++}$ of $X(3872)$
  - Radiative decays of $X(3872)$ disfavour pure molecular state
  - Established resonant nature of tetraquark candidate $Z^+(4430)$

- In the baryon sector:
  - First observation of exotic baryon resonances in a full amplitude analysis of $\Lambda_\mathrm{b} \to \mathrm{J}/\psi\mathrm{pK}$
  - Two states found, valence quark content: $uudc\bar{c}$
  - Starting big program to investigate

- Will triple data sample in Run II of the LHC: Stay tuned!

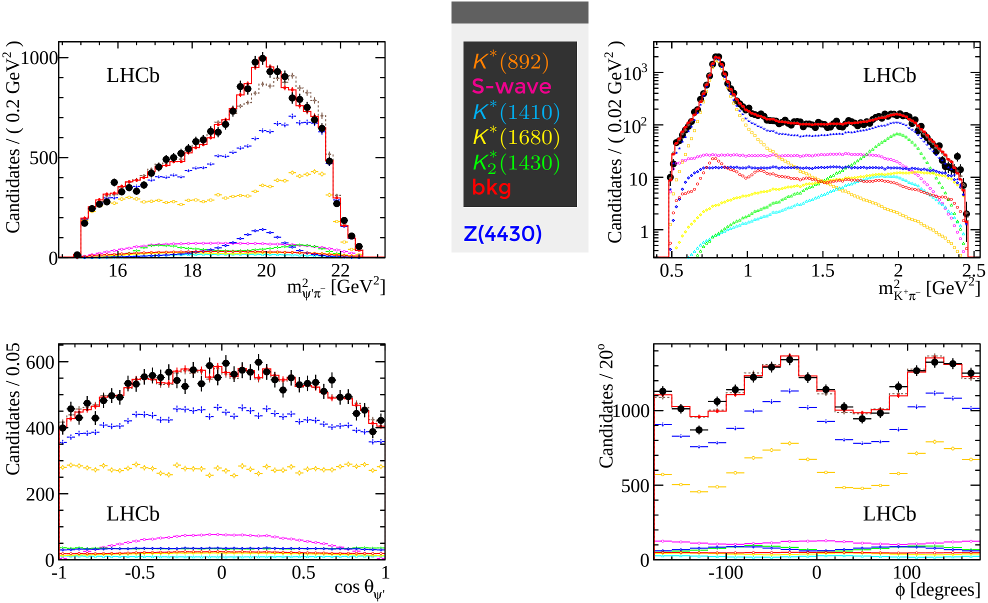
Backup


$\Lambda_b \rightarrow J/\psi pK$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
p
K
μ
μ

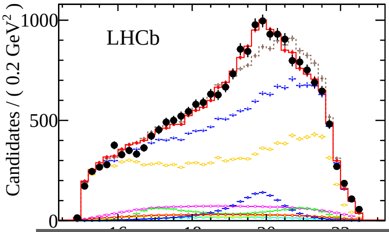


$\Lambda_b \to J/\psi p K$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λ_b
decay point
Λ_b
pp
collision point
μ
K
p
μ

Amplitude Analysis of $B \to K(\pi^- \psi(2S))$ [PRL112(2014)222002]

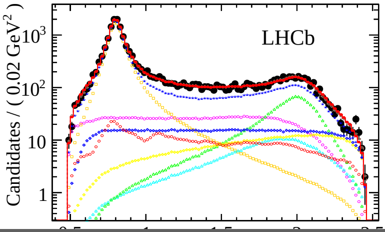


Amplitude Analysis of $B \to K(\pi^- \psi(2S))$ [PRL112(2014)222002]



$K^*(892)$
S-wave
$K^*(1410)$
$K^*(1680)$
$K_2^*(1430)$
bkg

Z(4430)



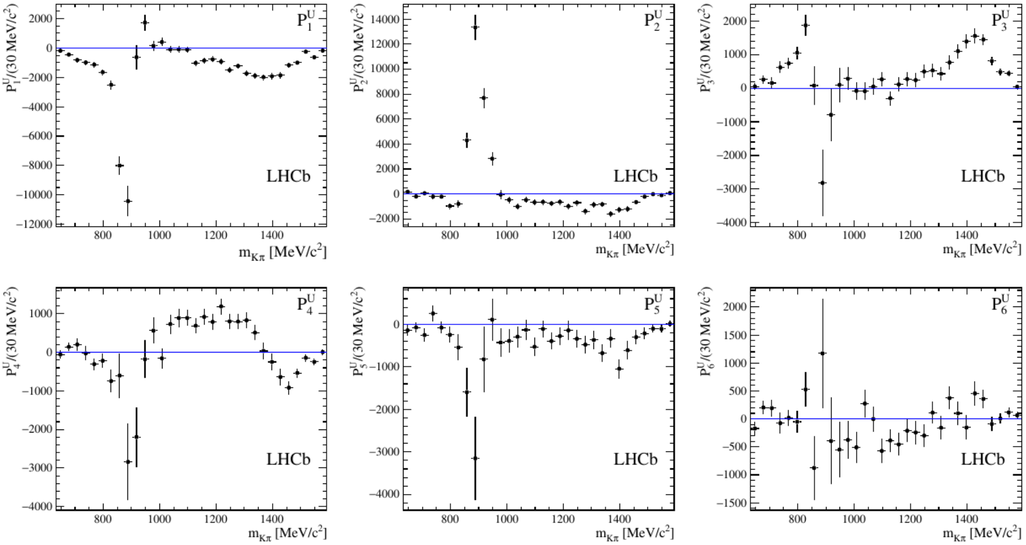
Results

Mass $[MeV]$	Width $[MeV]$	J^P	Significance
4475 ± 7	172 ± 13	1^+	$18.9\sigma (> 13.9)$

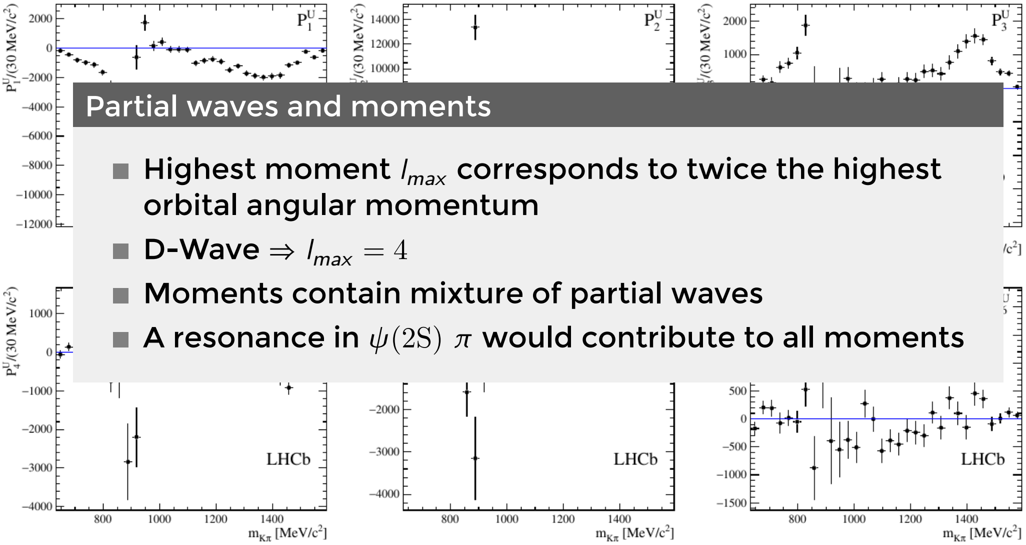
- D-wave contribution negligible (1.3σ using Wilks' theorem)
- Biggest systematic: inclusion of $K_3^*(1780)$ resonance

Candidates / 0.05
6
4
2
cos $\theta_{\psi'}$
ϕ [degrees]

K π Angular Moments



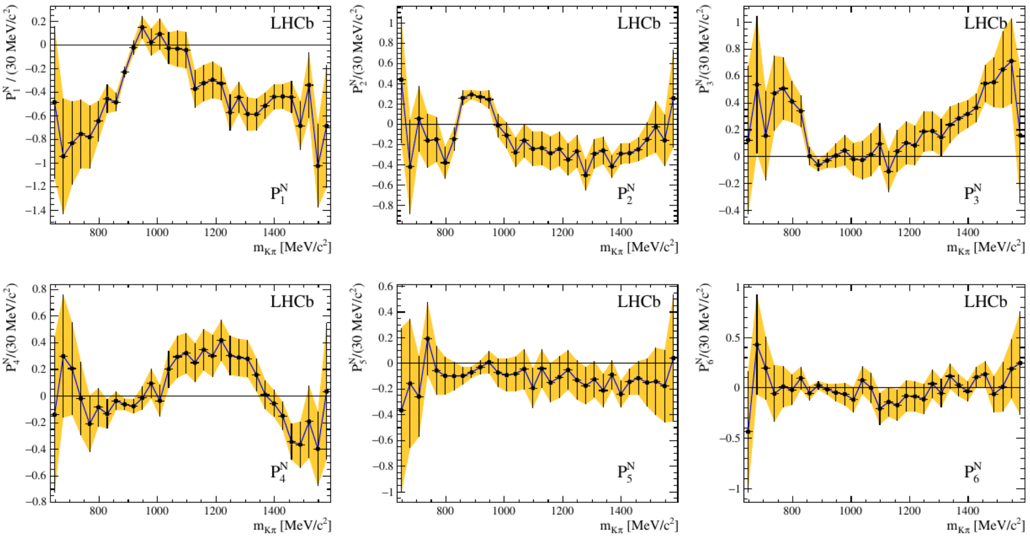
$K\ \pi$ Angular Moments



Partial waves and moments

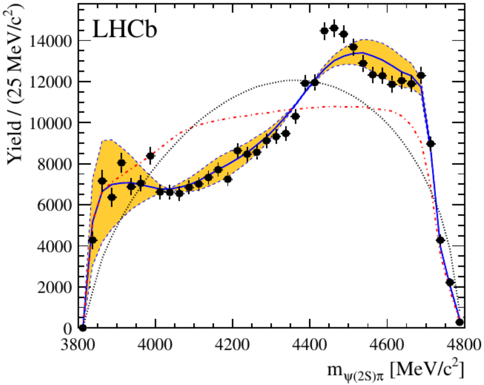
- Highest moment l_{max} corresponds to twice the highest orbital angular momentum
- D-Wave $\Rightarrow l_{max} = 4$
- Moments contain mixture of partial waves
- A resonance in $\psi(2S)\ \pi$ would contribute to all moments

K π Angular Moments - Normalised to Intensity

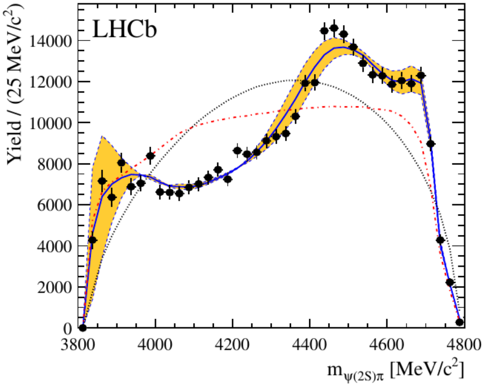


Reconstructing Reflections into $\psi(2S)\ \pi$

- Moments-weighted Monte Carlo
- Reflections with $l_{max} = 4$ do not explain $\psi(2S)\ \pi$ spectrum



- $l_{max} = 6$
- However: where should spin 3 (F-wave) come from?

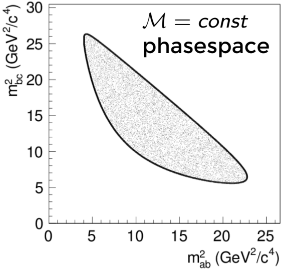


Reminder: 3-body decays and Dalitz-Plots

all particles spin 0:

$$X \to ABC$$

$$\Gamma \propto |\mathcal{M}|^2 dm_{AB}^2 dm_{BC}^2$$



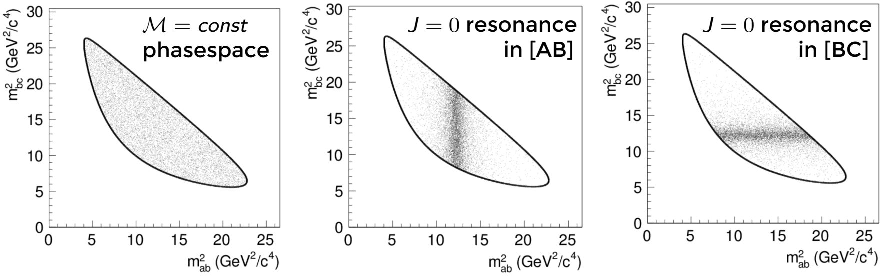
plots by Antimo Palano

Reminder: 3-body decays and Dalitz-Plots

all particles spin 0:

$$X \to ABC$$

$$\Gamma \propto |\mathcal{M}|^2 dm_{AB}^2 dm_{BC}^2$$



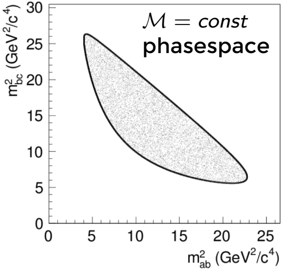
plots by Antimo Palano

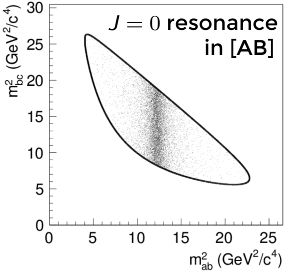
Reminder: 3-body decays and Dalitz-Plots

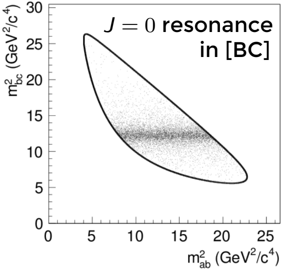
all particles spin 0:

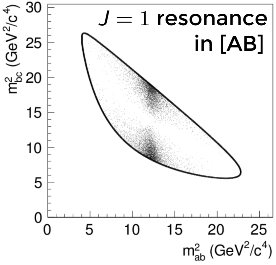
$$X \to ABC$$

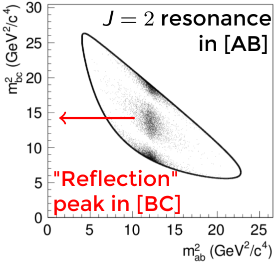
$$\Gamma \propto |\mathcal{M}|^2 dm^2_{AB} dm^2_{BC}$$











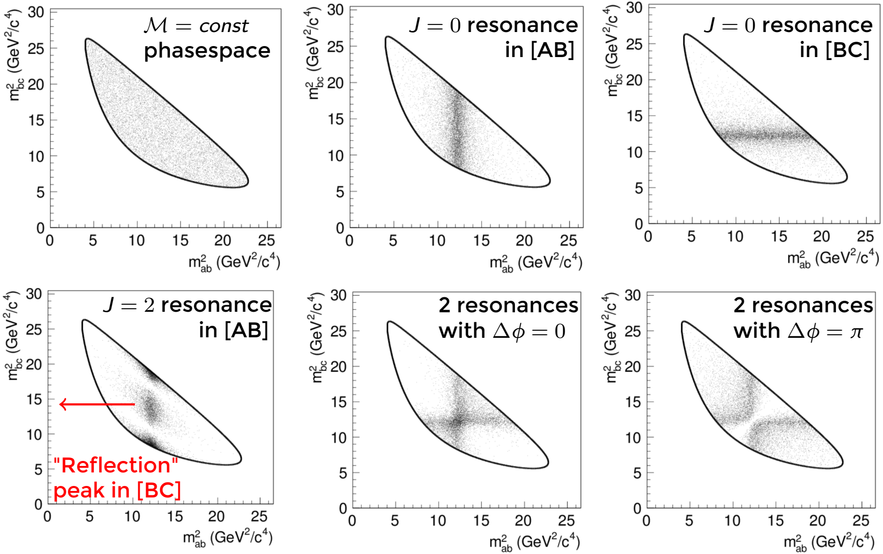
plots by Antimo Palano

Reminder: 3-body decays and Dalitz-Plots

all particles spin 0:

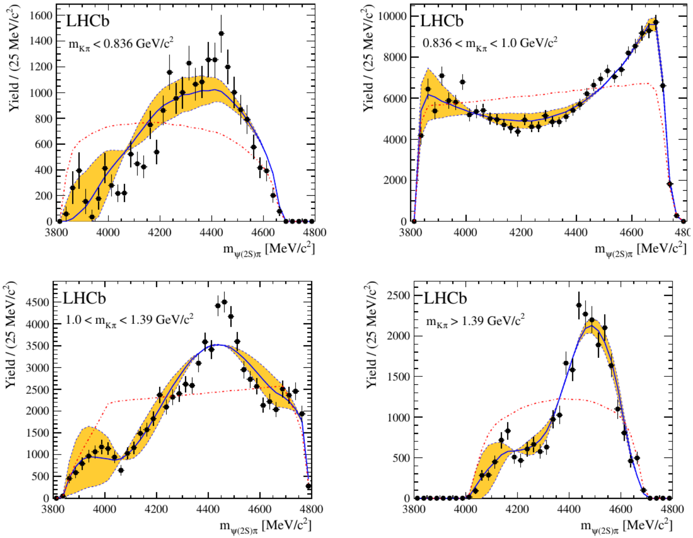
$$X \to ABC$$

$$\Gamma \propto |\mathcal{M}|^2 dm^2_{AB} dm^2_{BC}$$



plots by Antimo Palano

K^* Reflections in bins of $K\pi$ mass



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

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	[illegible]		
$\Lambda^*(1800)$	1/2$^-$	***	1800			
$\Lambda^*(1810)$	1/2$^+$	***	1810			
$\Lambda^*(1820)$	5/2$^+$	****	1820			
$\Lambda^*(1830)$	5/2$^-$	****	1830			
$\Lambda^*(1890)$	3/2$^+$	****	1890			
$\Lambda^*(2000)$	?	*	≈ 2000			
$\Lambda^*(2020)$	7/2$^+$	*	≈ 2020			
$\Lambda^*(2050)$	3/2$^-$	*	2056 ± 22	[illegible]	[illegible]	[illegible]
$\Lambda^*(2100)$	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

Two Λ^* models

- Extended: Explore model space
- Reduced: only keep non-vanishing components for final result
- Agreement checked by moments analysis

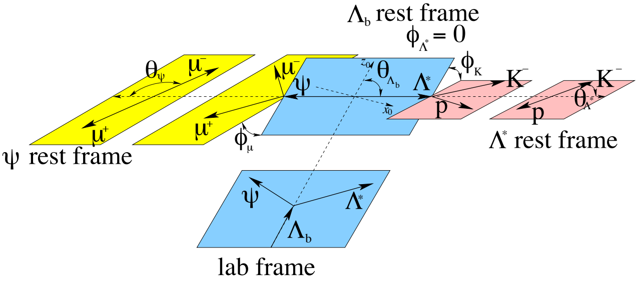
Amplitude Analysis of $\Lambda_b \to J/\psi pK$

Matrix Element $\mathcal{M}$ parametrised as function of 5 angles and one mass m^2_{pK}

Two coherent contributions:

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

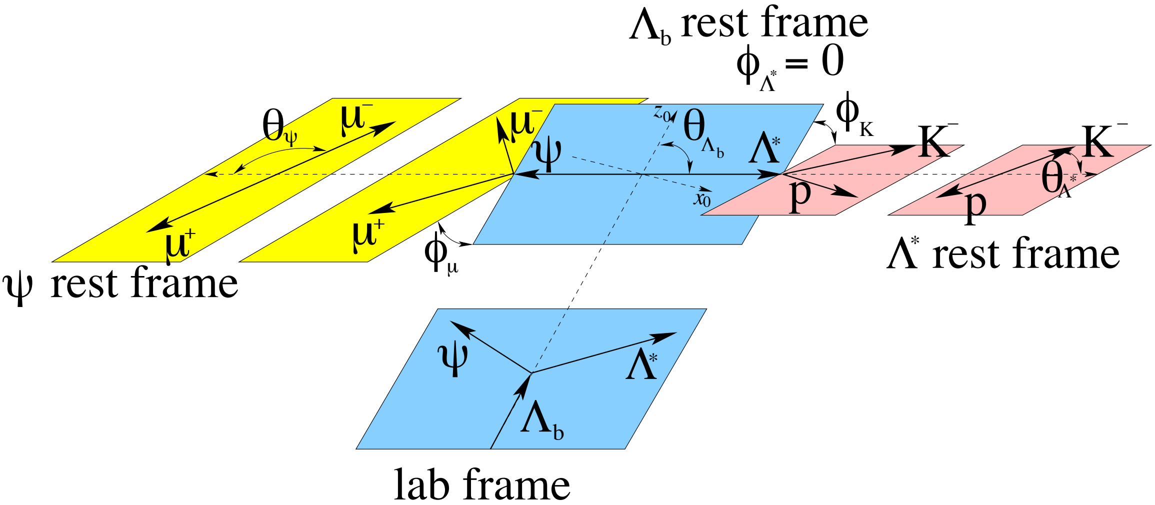
Full angular structure



- Helicity formalism
- 14 Λ^* resonances used
- XCheck with 2 Fitters (different background handling)
- Efficiency corrections from Monte Carlo

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}

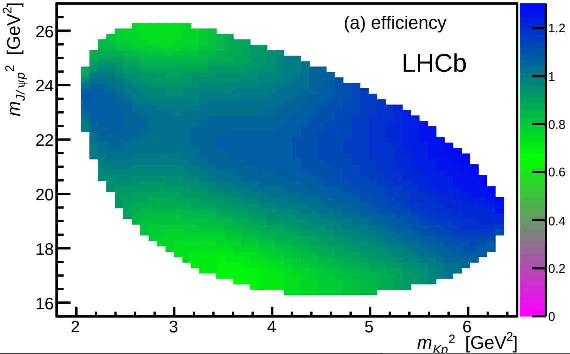


2 Fitters - XCheck of Background Treatment

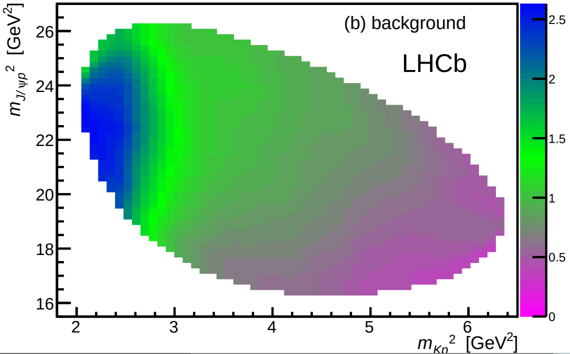
Log-likelihood fitters:

- sFit : subtract background with the sWeight method
- cFit : explicitly model background from sidebands (default)
- Missidentified B-meson decays vetoed $B \rightarrow J/\psi\ K\ \pi$ and $B_s^0 \rightarrow J/\psi\ K\ K$

Efficiency from MC



Background density shape (5.4%)



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

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

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

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

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

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

- 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 $B'_\ell(p, p_0, d)$

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

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

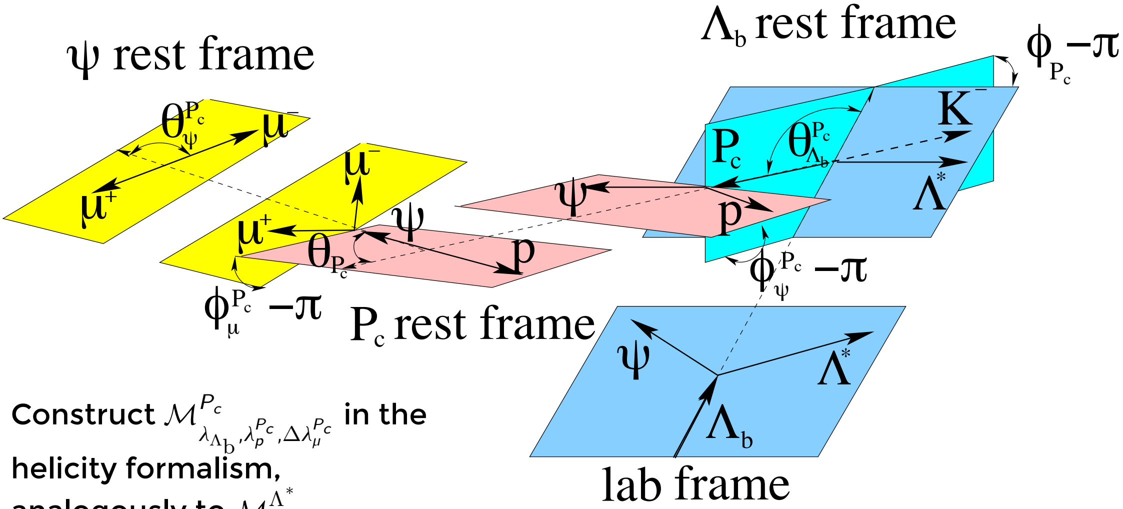
where

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

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

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

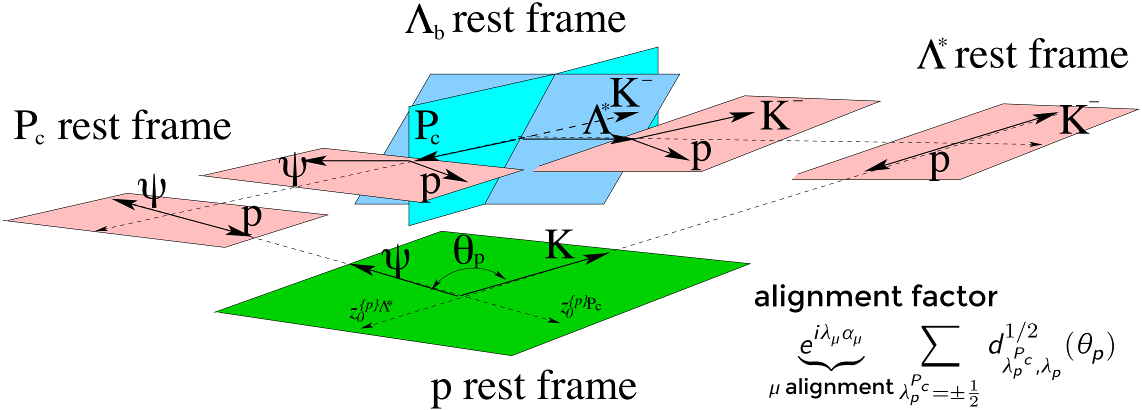
Adding Helicity Amplitudes for $\Lambda_b \to P_c K$



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

Aligning reference frames

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

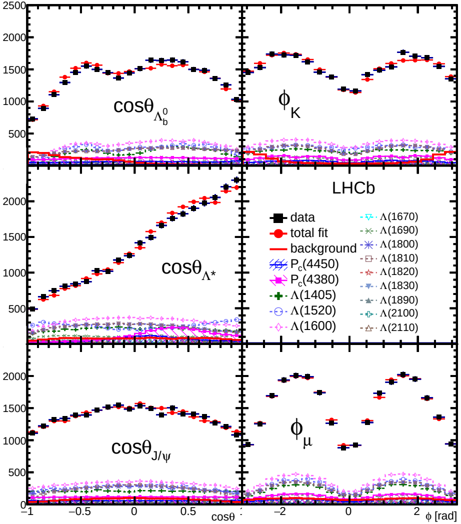


alignment factor

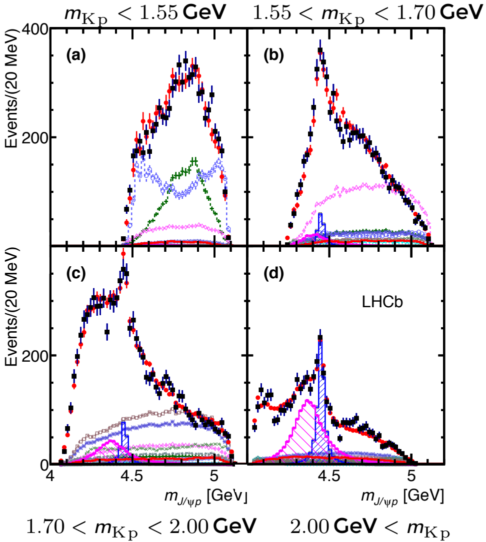
$$\underbrace{e^{i\lambda_\mu \alpha_\mu}}_{\mu\text{ alignment}} \underbrace{\sum_{\lambda_p^{P_c}=\pm\frac{1}{2}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)}_{\text{proton align.}}$$

Fit Projections

Angular distributions



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



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
$\ell^{P_c}_{\Lambda_b}$ $\Lambda_b \to P_c^+$ (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		
$\ell^{\Lambda^*_n}_{\Lambda_b}$ $\Lambda_b{}^* \to J/\psi\Lambda^*$	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

Pre Selection

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

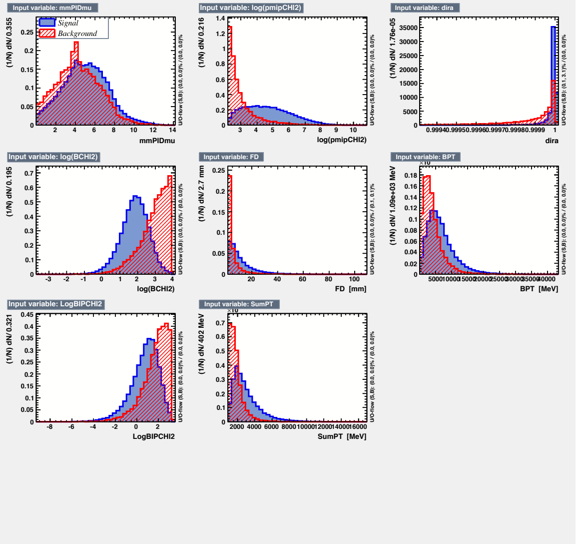
#	Selection variables	Requirements
1	All tracks χ^2/ndof	< 4
2	Muon PID	DLL$(\mu - \pi) > 0$
3	PT of muon	> 550 MeV
4	PT of hadron	> 250 MeV
5	J/ψ vertex χ^2	< 16
6	J/ψ mass window	$-48 < m(\mu^+\mu^-) - m(\mathrm{J}/\psi) < 43$ MeV
7	Hadron χ^2_{IP}	> 9
8	K^- ID	DLL$(K - \pi) > 0$ and DLL$(p - K) < 3$
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 χ^2_{IP} of the K^- and the p [log(pmipCHI2)];
- Λ_b (DIRA);
- Λ_b χ^2_{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

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

- 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

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

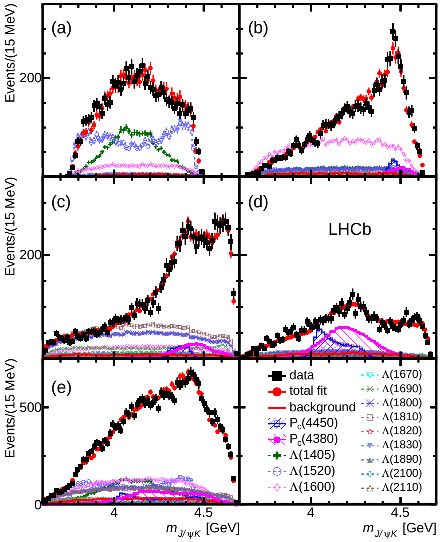
- weights w_j^{C} account for differences in Λ_{b} production kinematics and PID between simulation and data

Interference between $\Lambda_b \to J/\psi\Lambda^*$ and $\Lambda_b \to P_c K$

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

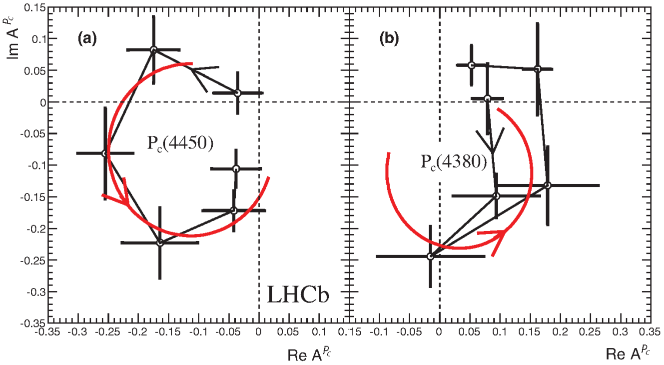
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm 1} \left| \mathcal{M}^{\Lambda^*} + \underbrace{e^{i\lambda_\mu \alpha_\mu}}_{\mu\text{ alignment}} \underbrace{\sum_{\lambda_p^{P_c}=\pm\frac{1}{2}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)}_{\text{proton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

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



Extracting the Phase

- 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)

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

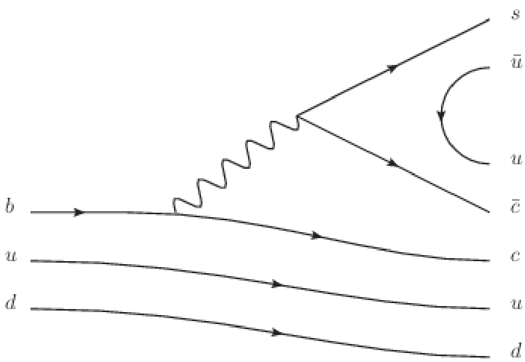
Mini Review on Meson-Baryon composite models: ↪ arXiv:1509.02460

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

Pentaquark Isospin Multiplet?

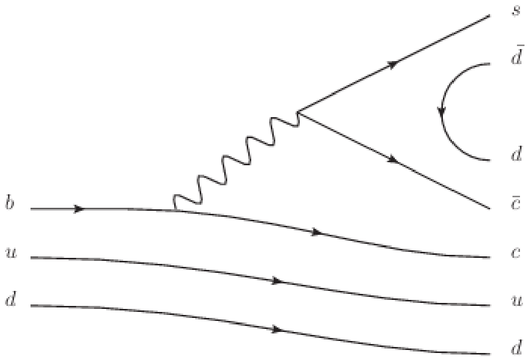
The observed pentaquark

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



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

$\Lambda_b \rightarrow P_c^0 K^0 \rightarrow J/\psi n K^0$ *or* $J/\psi p \pi^- K^0$

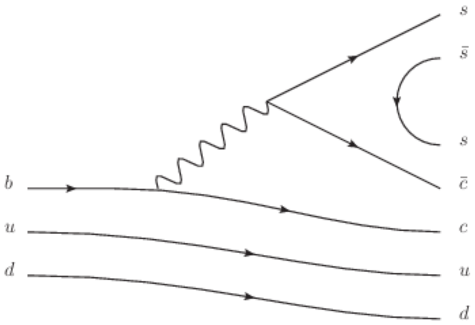


Neutron in the final state or 4-body J/ψ $p\ \pi^-\ K_S^0$

$\Lambda_b \rightarrow J/\psi\ \Lambda\ \phi$ and Friends

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

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

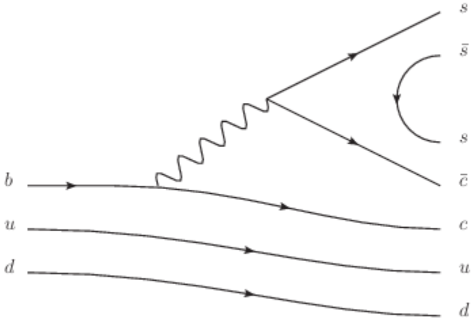


- Each subsystem exotic
  - $J/\psi\ \Lambda$: Strange Pentaquark
  - $J/\psi\ \phi$: X(4140) ?
  - $\Lambda\ \phi$: Spectrum unexplored

$\Lambda_b \to J/\psi\ \Lambda\ \phi$ and Friends

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

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



- 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

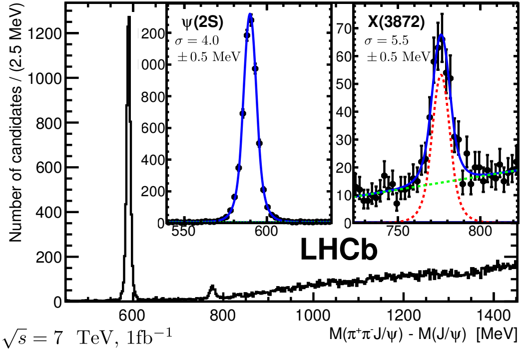
Process	$\mathbb{P} \in 10 \oplus 8$
$\Lambda_b \to K\ J/\psi p$	$\mathbb{P}_8(\bar{c}[cq]_{s=1}[q'q'']_{s=0,1}, \ell = 0, 1)$
$\Lambda_b \to \pi\ J/\psi\Sigma(1385)$ $\Xi_b \to K\ J/\psi\Sigma(1385)$	$\mathbb{P}_{10}(\bar{c}[cq]_{s=0,1}[q's]_{s=0,1})$
$\Omega_b^- \to \phi\ J/\psi\Omega^-(1672)$	$\mathbb{P}_{10}(\bar{c}[cs]_{s=0,1}[ss]_{s=1})$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

Charm Pentaquarks at PANDA?

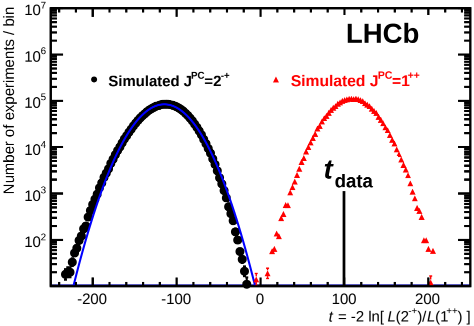
HESR: $\mathrm{p}\ \overline{\mathrm{p}}$ max $\sqrt{s} \approx 5.6$ GeV	
Process	**Threshold [MeV]**
$\mathrm{p\overline{p}} \to \mathrm{pJ}/\psi\mathrm{\overline{p}}$	4966
$\mathrm{p\overline{p}} \to \mathrm{p}\eta_{\mathrm{c}}\mathrm{\overline{p}}$	4854
$\mathrm{p\overline{p}} \to \Lambda_{\mathrm{c}}^{+}\overline{\mathrm{D}}^{0}\mathrm{\overline{p}}$	5086
$\mathrm{\overline{p}}P_c(4450)$	5385
$\mathrm{\overline{p}p} \to \mathrm{p}\phi\mathrm{\overline{p}}$	2890
$\mathrm{\overline{p}}d \to ??$	

Determination of $X(3872)$ Spin-Parity [PRL110(2013)222001]

- $B^{\pm} \to X(3872)(\to J/\psi\pi\pi)K^{\pm}$ selection calibrated on $B^{+} \to \psi(2S)K^{+}$ control channel



$\sqrt{s} = 7$ TeV, $1fb^{-1}$



Yields:

- 5642 ± 76 $B^{+} \to \psi(2S)K^{+}$
- 313 ± 26 $B^{+} \to X(3872)K^{+}$

- $J^{PC} = 1^{++}$ compatible
- $J^{PC} = 2^{-+}$ rejected at $> 8\sigma$

$P_c(4380)$ & $P_c(4450)$: 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
  - $\Lambda_b \to \mathrm{J}/\psi\ \mathrm{p}\ \pi$
  - $\Upsilon \to \mathrm{J}/\psi\ \mathrm{p}\ \overline{\mathrm{p}}$
  - $\Lambda_b \to \mathrm{J}/\psi\ \mathrm{p}\ \pi\ \mathrm{K}^0_\mathrm{S}$
- Confirmation by other experiments urgently needed!

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

Are there more of their kind?

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

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

What are they?

- Observe $P_c \to \mathrm{J}/\psi\mathrm{p}$ as subsystems in different final states
  - $\Lambda_b \to \mathrm{J}/\psi\ \mathrm{p}\ \pi$
  - $\Upsilon \to \mathrm{J}/\psi\ \mathrm{p}\ \overline{\mathrm{p}}$
  - $\Lambda_b \to \mathrm{J}/\psi\ \mathrm{p}\ \pi\ \mathrm{K}^0_S$
- Confirmation by other experiments urgently needed!
- Search for new decay modes of P_c
  - $\Lambda_b \to \chi_{c1}(1P)\ \mathrm{p}\ \mathrm{K}$
  - $\Lambda_b \to \Lambda_c^+\ \overline{\mathrm{D}}^0\ \mathrm{K}$

Are there more of their kind?

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

All modes unobserved so far!

A Hadronic Renaissance - Charmonium-like Exotics

New, narrow states found by Belle, BaBar and BES in a region where conventional mesons tend to have widths of $\mathcal{O}(100\text{MeV})$

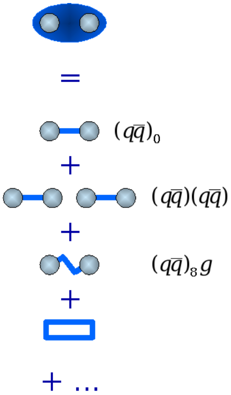
Among them charged states containing $c\bar{c}$.

State	M[MeV]	Γ[MeV]	J^{PC}	Process	Status
X(3872)	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)$	ok
				$pp \to (\pi^+\pi^- J/\psi)$	ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	ok
				$B \to K(\gamma J/\psi)$	ok
				$B \to K(\gamma\psi(2S))$	NC
				$B \to K(D\bar{D}^*)$	ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	NC
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ h_c(1P))$	NC
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	NC

Charmonium-like exotic mesons at open-charm thresholds ↪ arXiv:1404.3723

A Hadronic Renaissance - Charmonium-like Exotics

Narrow States above Open-Charm Thresholds ↪ arXiv:1404.3723



State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1050] (8), BaBar [1000, 1051] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1052] (7.7), BaBar [1053] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1054] (5.3), BaBar [1055] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1048, 1049] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1008, 1056] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (5.0), Belle [1061] (1.9), LHCb [1062] (1.4), CMS [1063] (>5) D0 [1064] (3.1)	2009	NC!
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1049] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1066, 1067] (8), CLEO [1068, 1069] (11) Belle [1008, 1056] (15), BES III [1007] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1067] (np), Belle [1008] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1007] (8), Belle [1008] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1070] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (3.1), LHCb [1062] (1.0), CMS [1063] (>3), D0 [1064] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1071] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (8), BaBar [1073] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1074, 1075] (6.4), BaBar [1076] (2.4) LHCb [1077] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\Lambda_c^-)$	Belle [1078] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (5.8), BaBar [1073] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}(\pi))$	PDG [1]	1985	Ok