Exotic Hadrons

News, Status at LHCb, Some Ideas

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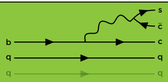
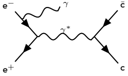
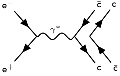
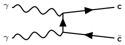
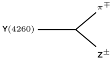
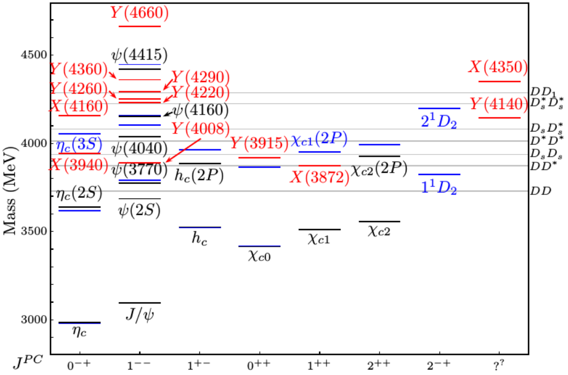
Workshop on Heavy Hadron Spectroscopy CERN, 18.07.2017

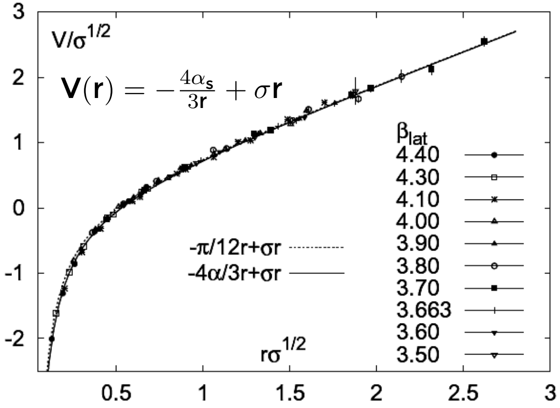
						$p\bar{p}$ incl.	pp incl.
$J/\psi\,\pi^+\pi^-$	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
$\psi(2S)\,\pi^+\pi^-$		Y(4360) Y(4660)					
$\Lambda_c\bar{\Lambda}_c$		Y(4630)					
$\psi\,\gamma$	X(3872)						
$\chi_{c1}(1P)\,\gamma$	X(3832)						
$\chi_{c1}(1P)\,\omega$				Y(4220)			
$J/\psi\,\omega$	X(3872) Y(3940)			X(3915)			
$J/\psi\,\phi$	X(4140) X(4274) X(4500) X(4700)			X(4350)			
$J/\psi\,\pi$	Z(4430) Z(4200) Z(4240)				Z(3900)		
$\psi(2S)\,\pi$	Z(4430)						
$\chi_{c1}(1P)\,\pi$	Z(4051) Z(4248)						
$h_c(1P)\,\pi$					Z(4020)		
$D\bar{D}$				Z(3930)			
$D\bar{D}^*$	X(3872)		X(3940)		Z(3885)		
$D^*\bar{D}^*$			X(4160)		Z(4025)		
$J/\psi\,p$	$P_c(4380)$ $P_c(4430)$						

↪ arXiv:1411.5997



Cornell potential vs lattice QCD

[PRD71(2005)114510]



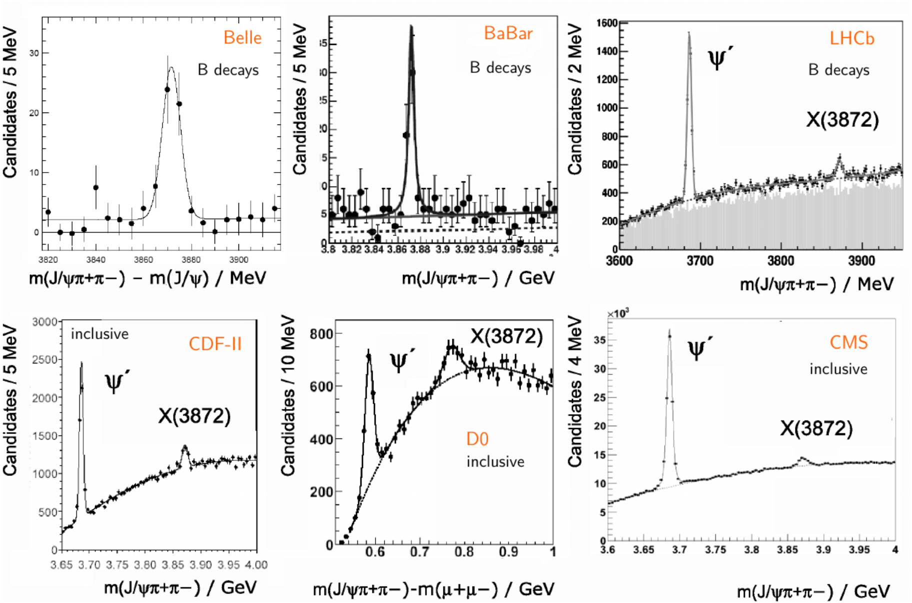
Observed charmonium

Potential model

↪ arXiv:hep-ph/0701117

Exotic states

The $\mathrm{X}(3872)$



$X(3872)$ decays

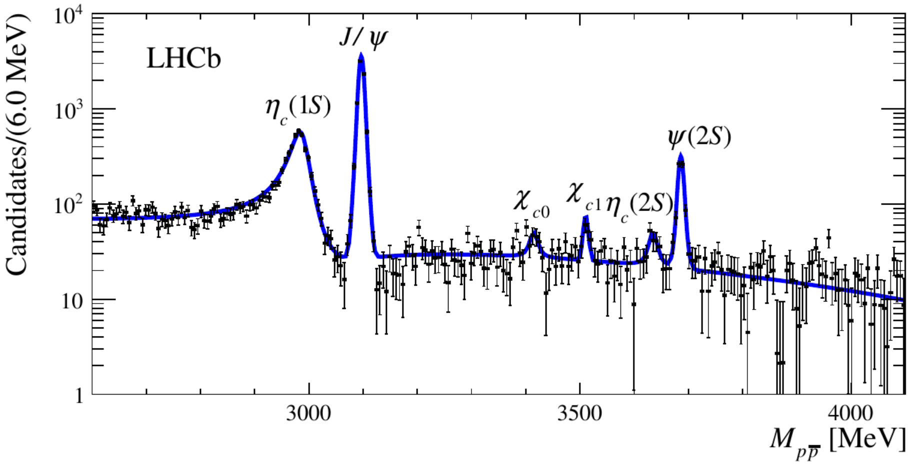
Approx. product branching fractions		
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to D^{*0}\overline{D}^0)$	$\sim 1 \times 10^{-4}$	
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi \underbrace{\pi\pi}_{\rho})$	$\sim 1 \times 10^{-5}$	
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi\omega)$	0.6×10^{-5}	Allowed in molecule picture [PLB742(2015)394] [EPJ C75(2015)26]
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi\gamma)$	$\sim 2 \times 10^{-6}$	
$\frac{\mathcal{B}(\mathbf{X}\to\psi(2S)\gamma)}{\mathcal{B}(\mathbf{X}\to J/\psi\gamma)}$	$\sim 2-3$	
$\frac{\mathcal{B}(B^+\to\mathbf{X}K^+)\times\mathcal{B}(\mathbf{X}\to p\overline{p})}{\mathcal{B}(B^+\to J/\psi K^+)\times\mathcal{B}(J/\psi\to p\overline{p})}$	$< 0.25 \times 10^{-2}$ @95%C.L.	[PLB 769(2017)10]
$\mathcal{B}(B^+ \to \mathbf{X}K^+) \times \mathcal{B}(\mathbf{X} \to p\overline{p})$	$< 6 \times 10^{-9}$	

for a more details and precise values see the review $\hookrightarrow$ arXiv:1601.02092

Search for $X(3872)$ in $B^+ \to p\bar{p}K^+$

[PLB769(2017)10]

Background subtracted spectrum:



Search for narrow charmonia: $p\bar{p}$ fit model [PLB769(2017)10]

State	Parametrisation	Signal Yield	
$\eta_c(1S)$+non res.	rel. BW+gaussian + interference	11246 ± 119	
J/ψ	double gaussian	6721 ± 93	
$\chi_{c0}(1P)$	rel. BW+gaussian	84 ± 22	
$\chi_{c1}(1P)$	gaussian	95 ± 16	
η_c (2S)	rel. BW+gaussian	106 ± 22	first obs. 6.0σ
ψ (2S)	double gaussian	588 ± 30	
ψ (3770)	rel. BW+gaussian	-6 ± 9	
X(3872)	gaussian	-14 ± 8	

- $\eta_c(1S)$ allowed to interfere with $\ell = 0$ $p\bar{p}$ non-resonant component (phase-space distribution)
- $\chi_{c0}(1P)$,$\chi_{c1}(1P)$,X(3872) and ψ (3770) masses fixed to PDG values

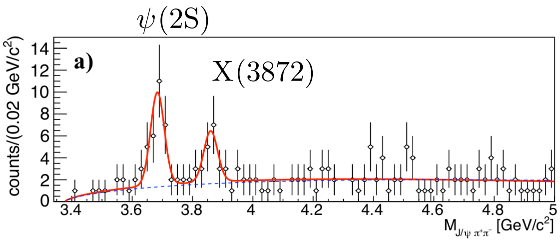
$$\Delta M_{J/\psi,\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\ \text{MeV}$$

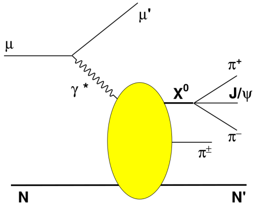
$$\Delta M_{\psi(2S),\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6\ \text{MeV}$$

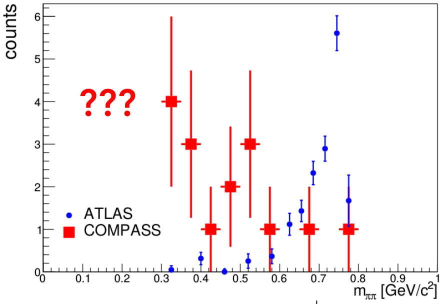
$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\ \text{MeV}$$

NEWS: $X(3872)$ in muo-production ↪ arXiv:1707.01796

- COMPASS @ CERN
- Muon beam 160 or 200 GeV/c on ^{6}LiD or NH_3 targets
- Data corresponds to 14 pb^{-1} (2003-2011)







$\psi(2S) \to J/\psi\gamma(\to e^-e^+)$?

$$\sigma_{\gamma N\to X\pi N'} \times \mathcal{BR}_{X\to J/\psi\pi\pi} = 71 \pm 28 \pm 39\ \text{pb}$$

Status of the $X(3872)$

- $J^{PC} = 1^{++}$ established
  LHCb [PRL110(2013)222001][PRD92(2015)011102]

- Mass $m = 3871.69 \pm 0.17$ MeV (in $X(3872) \rightarrow J/\psi$ X decays)
- $D\bar{D}^*$ threshold: 3871.81 ± 0.09 MeV
- Mass difference $m_X - m_{J/\psi} = 775 \pm 4$ MeV
- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

- Mass and decay mode disfavor pure $c\bar{c}$ state.
- $J^{PC} = 1^{++}$: $D^0 D^*$ molecule or tetra-quark admixture

- No charged partner, no $C = -1$ partner found
  - $X \rightarrow J/\psi \pi^+ \pi^0$ Belle[PRL111(2013)032001],BaBar[PRD71(2005)031501]
  - $X \rightarrow J/\psi \eta$ Belle[PTEP(2014)043C01],Belle[PRL111(2013)032001]

Upcoming LHCb measurement: $X(3872)$ mass

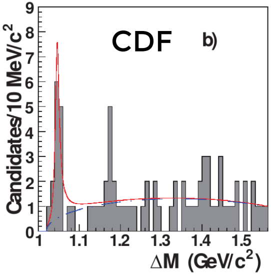
- Measure $\Delta m = m(X(3872)) - m(\psi(2S))$
- Expect an improvement in mass-resolution by factor of ~ 2
- Analysis in internal review

Resonances decaying to $J/\psi\phi$

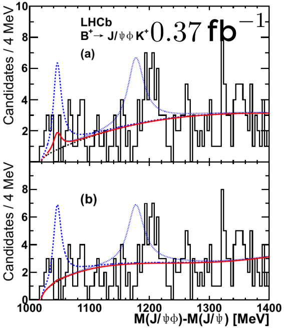
$c\bar{c}s\bar{s}$ Tetraquarks?

Narrow resonances in $J/\psi\phi$ (from B-decays)

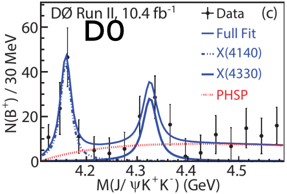
[PRL102(2009)242002]

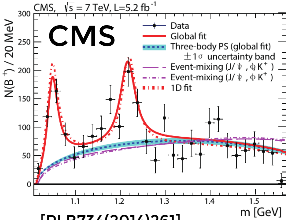


LHCb [PRD85(2012)091103]



[PRD89(1)(2014)012004]





[PLB734(2014)261]

- Narrow structures in $J/\psi\phi$ discovered by CDF in 2008
- Subsequent observations by D0 and CMS
- BaBar, Belle and LHCb $(0.37\,\text{fb}^{-1})$: no significant signal

[PRL104(2010)112004][PRD91(2015)012003][PRD85(2012)091103]

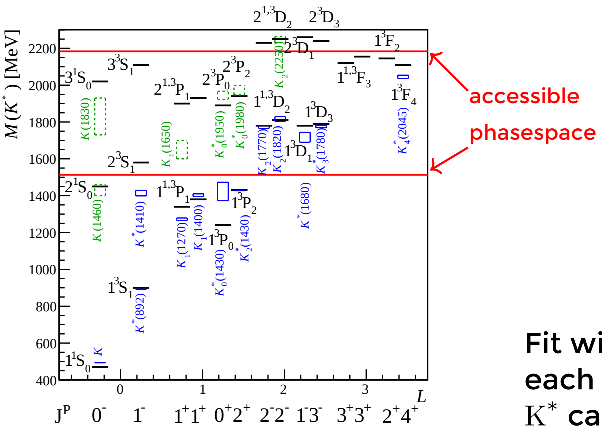
Averages	M [MeV]	Γ [MeV]
X(4140)	4143.4 ± 1.9	15.7 ± 6.3
X(4274)	4293 ± 20	35 ± 16

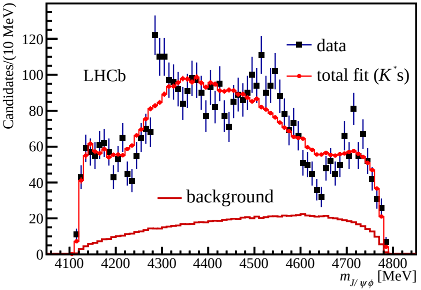
- No amplitude analysis so far
- CDF/CMS X(4274) mass measurements disagree at 3.16σ

Fit with K^* resonances only

[PRL118(2017)022003]
[PRD95(2017)012002]

Kaon excitations





- Black: Godfrey-Isgur quark model
- Blue: well established states
- Green: unconfirmed states

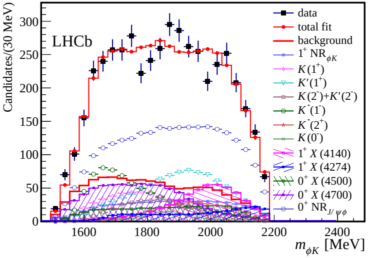
Fit with two $2\mathrm{P}_1$, two $1\mathrm{D}_2$ and one of each $1^3\mathrm{F}_3, 1^3\mathrm{D}_1, 3^3\mathrm{S}_1, 3^1\mathrm{S}_0, 2^3\mathrm{P}_2, 1^3\mathrm{D}_3, 1^3\mathrm{F}_4$ K^* candidates + non-resonant S-wave
11 resonances
all parameters floating in the fit.

LHCb: $B^+ \to J/\psi \phi K^+$ amplitude analysis

[PRL118(2017)022003]
[PRD95(2017)012002]

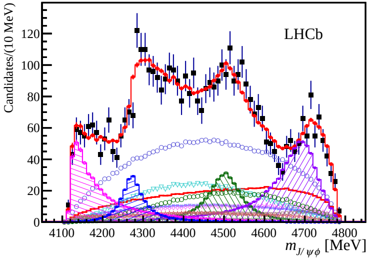
χ^2_{1D}/ndof $= 37.9/22$

ϕ K



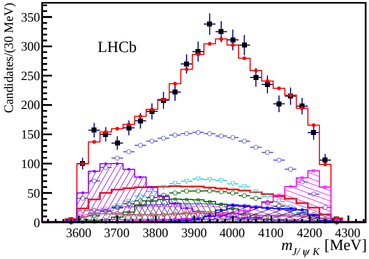
χ^2_{1D}/ndof $= 71.5/67$

$J/\psi\ \phi$



- 3 fb^{-1} yield 4289 ± 151
  $B^+ \to J/\psi \phi K^+$ candidates
- 7 K^* resonances
  + non-resonant ϕ K amplitude
- 4 exotic resonances in $J/\psi\ \phi$
- Fit quality on Dalitz-Plot: $p_{2D} = 17\%$
- No J/ψ K resonances needed

J/ψ K



χ^2_{1D}/ndof $= 21.1/23$

Results for X(4140), X(4274), X(4500) & X(4700)

[PRL118(2017)022003][PRD95(2017)012002]

State	M [MeV]	Γ [MeV]	signi	J^{PC}	J^{PC} signi
X(4140)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	1^{++}	5.7σ
X(4274)	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	6.0σ	1^{++}	5.8σ
X(4500)	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	6.1σ	0^{++}	4.0σ
X(4700)	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	5.6σ	0^{++}	4.5σ

- X(4140) & X(4274) confirmed but with larger width than previous analyses
- First evidence of two new states X(4500) and X(4700)

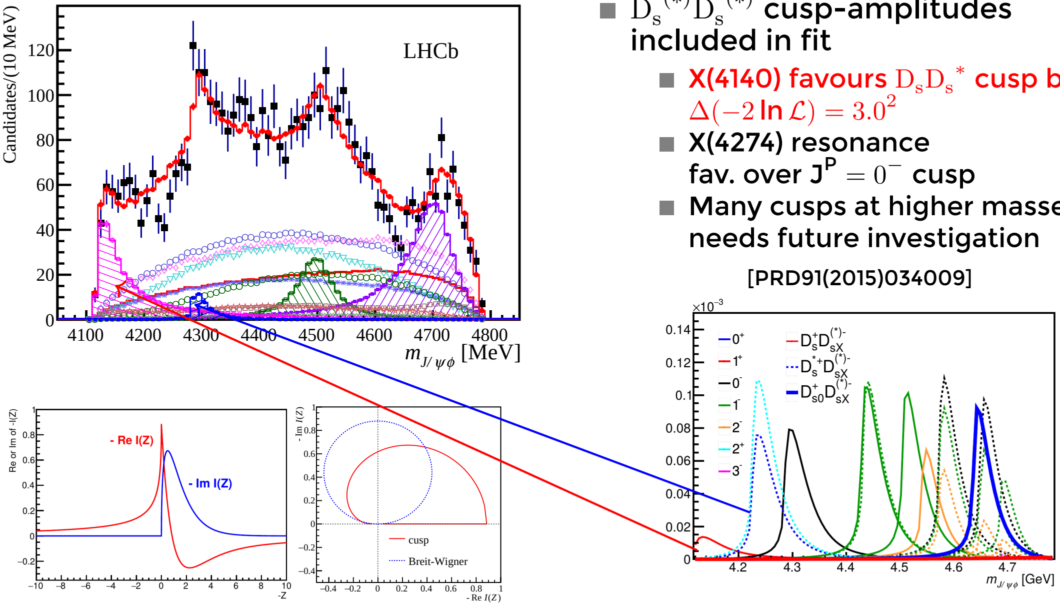
- Large contribution from K^* resonances, including first observation of $K^*(1680) \to K^+\phi$
- non-resonant contribution in 0^{++} amplitude.

$D_sD_s^*$ cusp amplitudes

[PRL118(2017)022003]
[PRD95(2017)012002]

- $D_s^{(*)}D_s^{(*)}$ cusp-amplitudes included in fit
  - X(4140) favours $D_sD_s^*$ cusp by $\Delta(-2\ln\mathcal{L}) = 3.0^2$
  - X(4274) resonance fav. over $J^P = 0^-$ cusp
  - Many cusps at higher masses, needs future investigation

[PRD91(2015)034009]



Status of $J/\psi\phi$ resonances

State	M [MeV]	Γ [MeV]	M^{LHCb} [MeV]	Γ^{LHCb} [MeV]	J^{PC}
X(4140)	4143.4 ± 1.9	15.5 ± 6.3	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
X(4274)	4293 ± 20	35 ± 16	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	1^{++}
X(4350)	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$			0^{+} or 2^{+}
X(4500)			$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
X(4700)			$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

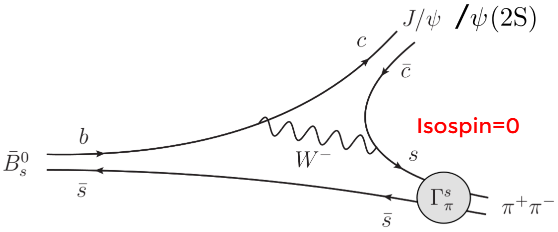
- $J^PC = 1^{++}$ assignment of X(4140) and X(4274) consistent with non-observation in $\gamma\gamma$ fusion
- Are X(4350) and X(4500) the same state? masses and widths don't match well
- X(4140) consistent with $D_sD_s^*$ cusp

Some Experimental Ideas

- Search for spin-exotic charmonia
  - A $\eta_c \pi$ P-wave resonance?
  - $B^0 \to p\bar{p}\pi K$
- Y(4260) in B-decays?
- Different production mechanisms for charged exotics
  - Z(4430) in B_s^0-decays

The B_s^0 as a source of Exotic Mesons??

Z(4430) in $B^0_{(s)} \to \psi(2S)\pi\pi$



(see also ↪ `arXiv:1508:06841`)

- B^0 decay Caibbo suppressed
- B_s^0 on equal footing
- Compare exotic contributions in both channels!

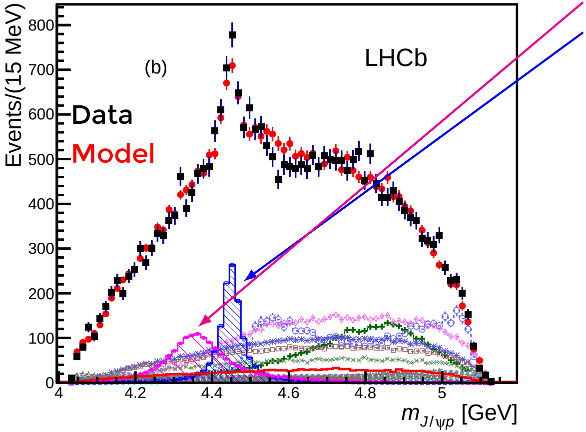
Y(4260) in B-decays?

- Limit from BaBar: $\mathcal{B}(B \to Y(4260)K \to J/\psi\pi\pi K) < 2.9 \times 10^{-5}$
  [PRD73(2006)011101]
- QCD sum rules: $3.0 \times 10^{-8} < 1.8 \times 10^{-6}$
  ↪ `arXiv:1502.00119`
- Could be produced in $B_s^0 \to Y(4260)\phi$
- Isolate strangeness in well defined state (ϕ)
- 3-body final state instead of 4-body in B^+ decay

Exotic Baryons

Two resonances decaying to $J/\psi p$ [PRL115(2015)072001]

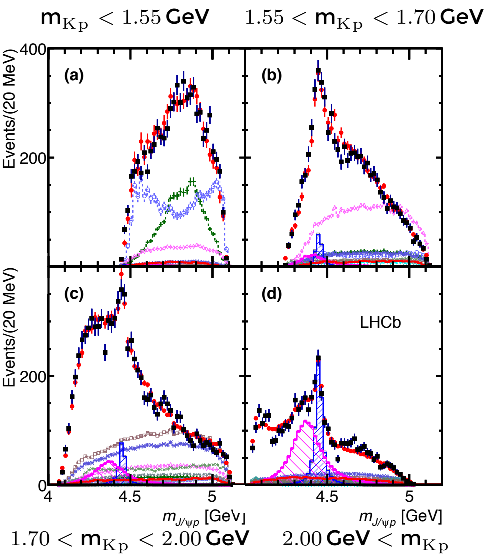
6D Amplitude analysis allows to measure resonance parameters



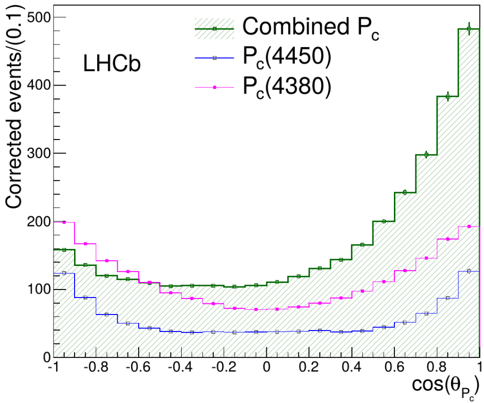
State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$

- Spin parity assignment not unique
- Excluded: same parity solution
- Results confirmed in two subsequent analyses
  - $\Lambda_b \to J/\psi p K$ moments analysis [PRL117(2016)082002]
  - $\Lambda_b \to J/\psi p \pi$ amplitude analysis [PRL117(2016)082003]

Why a second state with opposing parity?

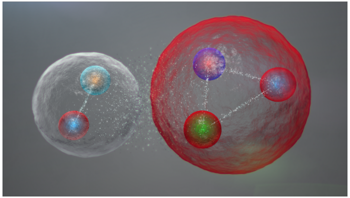


- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of $\cos\theta_{P_c}$)
- This can be explained by interference of two states with opposing parity



Models overview

- Proximity of thresholds suggests two-body contributions



Closeby thresholds

[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

[EPJ A51(2015)11,152]

Rescattering	Hadronic molecules	Tightly bound states
kinematic effect	loosely bound system of color-singlets	constituents carrying color (di-quarks)
above threshold	below threshold	no association
–	S-wave binding restricts J^P	large multiplets

Models overview

- Proximity of thresholds suggests two-body contributions

Closeby thresholds

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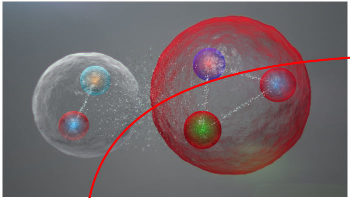
[EPJ A51(2015)11,152]



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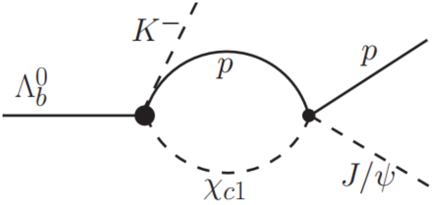
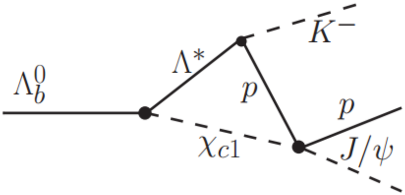
Rescattering	Hadronic molecules	Tightly bound states

Rescattering: hadronic loops

[PRD92(2015)071502]





Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

with a form factor $f_\Lambda(\vec{q}^2)$.

Triangle Singularity given by Landau-equation

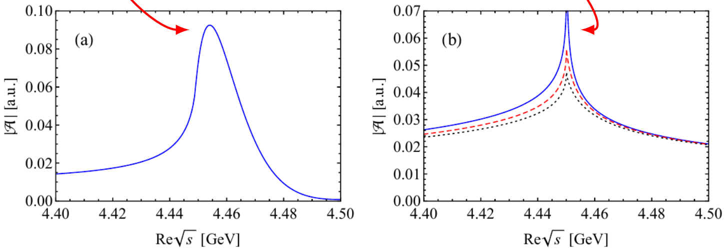
$$1 + 2y_{12}y_{23}y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2$$

$$y_{ij} = \left(m_i^2 + m_j^2 - (p_i + p_j)^2\right)/2m_i m_j$$

Rescattering: hadronic loops

[PRD92(2015)071502]

Cusps just above threshold



But: no cusp in elastic channel here: $p\chi_{c1}$

Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

with a form factor $f_\Lambda(\vec{q}^2)$.

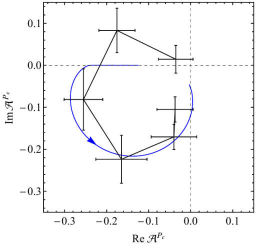
Triangle Singularity given by Landau-equation

$$1 + 2y_{12}y_{23}y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2$$

$$y_{ij} = \left(m_i^2 + m_j^2 - (p_i + p_j)^2\right) / 2m_i m_j$$

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

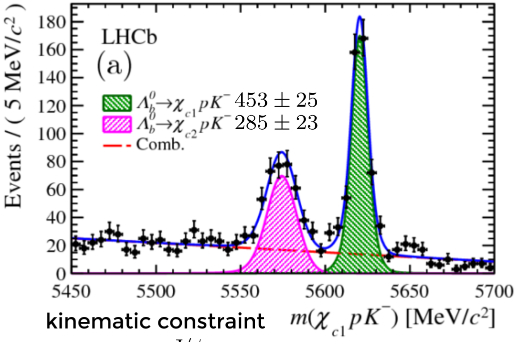
- Even in amplitude analyses cusps are difficult to distinguish from real resonances
- phase motion: resonance vs cusp



- Add complementary data: Rescattering can be ruled out if there is a narrow enhancement in the elastic channel $\chi_{c1}(1P)\ p$

arXiv:1704.07900

First observation of $\Lambda_b \to \chi_{c1(2)} pK$



kinematic constraint $\chi_c = \chi_{c1} \to J/\psi\gamma$

PRL accepted for publication

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

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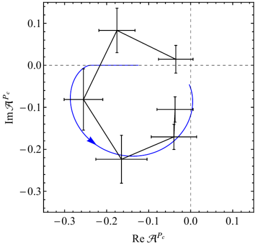

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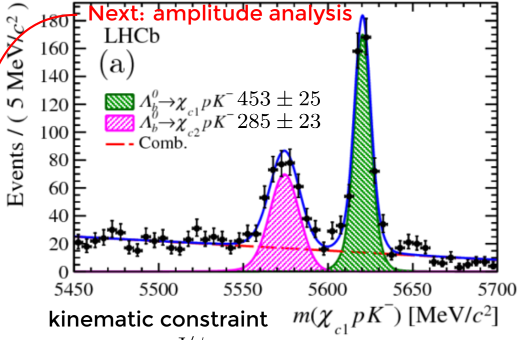


kinematic constraint $\chi_c = \chi_{c1} \to J/\psi\gamma$

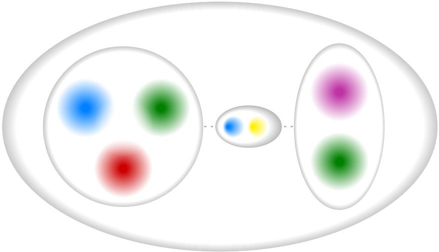
PRL accepted for publication

Rescattering	Hadronic molecules	Tightly bound states

Meson-Baryon Molecules

Building color-neutral objects from color-neutral constituents

- Small binding energy
  $\rightarrow$ state just below 2-body thresholds
- Different parametrisations of the binding force available
- Predictions from coupled channel dynamics
  [Nucl.Phys.A776(2006)17][PRC 85 (2012) 044002]
- Constituents in S-wave
  Opposite parity problematic to explain



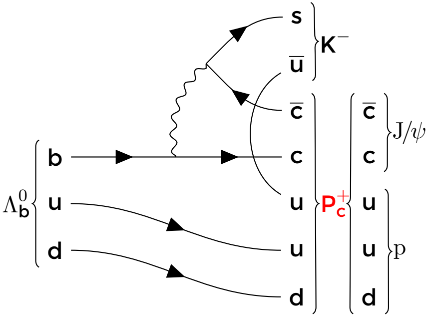
Channel	$\Sigma_c^*\overline{D}/\Sigma_c\overline{D}^*$	$J/\psi N(1440/1520)$
Features	Pion exchange	opposite parity with S-wave for both states
Exp.Sign.	Isospin $I = \frac{3}{2}$	150 MeV binding?

considered here: $J^P \in \left\{\frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}\right\}$

Decay of the P_c to Open Charm

In preparation

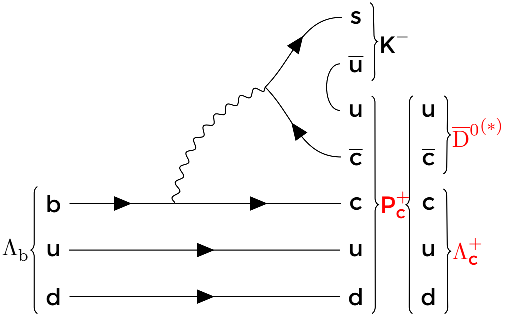
P_c discovery in $\Lambda_b \to J/\psi p K^-$



Molecular-Models:

$P_c^+ \to \Lambda_c^+ \overline{D}^{0(*)}$ favoured decay mode

[PRC85(2012)044002][↪ arXiv:1703.01045]



c and c̄ in meson/baryon pair

Combined Analysis $\Lambda_b \to \Lambda_c^+ \overline{D}^0 K$ and $\Lambda_b \to \Lambda_c^+ \overline{D}^{0*} K$

- Predictions on relative widths ↪ arXiv:1703.01045

Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	41.6	80.5	22.6
$J/\psi p$	3.8	8.4	8.3	2.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8

- Possible spin-party combinations for the $\Lambda_c^+ \overline{D}^{0(*)}$ system

ℓ	$\Lambda_c^+ \overline{D}^0$	$\Lambda_c^+ \overline{D}^*$	pJ/ψ
S	$\frac{1}{2}^-$	$\frac{1}{2}^-$, $\frac{3}{2}^-$	$\frac{1}{2}^-$, $\frac{3}{2}^-$
P	$\frac{1}{2}^+$, $\frac{3}{2}^+$	$\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$	$\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$
D	$\frac{3}{2}^-$, $\frac{5}{2}^-$	$\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$	$\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$

favoured quantum numbers highlighted

- Complementary information on quantum numbers

Rescattering	Hadronic molecules	Tightly bound states

Pentaquarks in the Di-Quark Picture

[PLB749(2015)289]

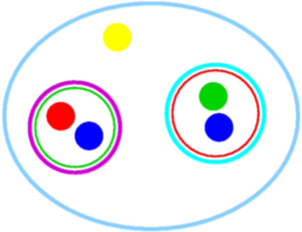
Diquark color configuration:

$3 \otimes 3 \to \bar{3}$

$$P = \{\bar{c}[cq]_s[qq]_s, \ell\}$$

- Opposite parity understood: additional orbital angular momentum ℓ
- One unit ℓ costs:
  $\delta m \approx m(\Lambda(1405)) - m(\Lambda(1116)) \approx 300$ MeV
- Coupling spins to $s = 1$ in the light-light di-quark:
  $\delta m \approx m(\Sigma_c(2455)) - m(\Lambda_c(2286)) \approx 200$ MeV

$P_c(4380)$	$\frac{3}{2}^-$	$\{\bar{c}[cq]_{s=1}[qq]_{s=1}, \ell = 0\}$
$P_c(4450)$	$\frac{5}{2}^+$	$\{\bar{c}[cq]_{s=1}[qq]_{s=0}, \ell = 1\}$

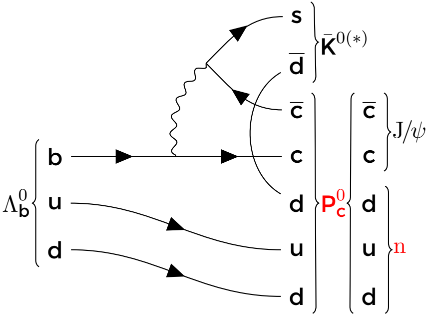


- Can explain the small mass gap!
- Predicts a large multiplet of states

Exploring the Pentaquark Multiplet

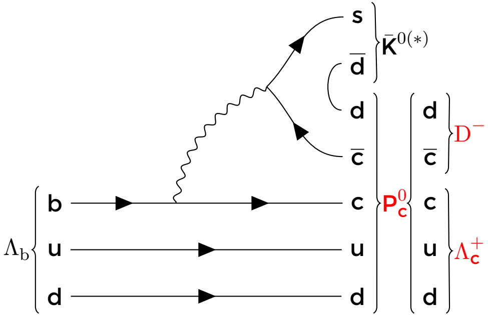
A neutral Pentaquark?

Are there isospin partners to the P_c^+? $uudc\bar{c} \leftrightarrow uddc\bar{c}$



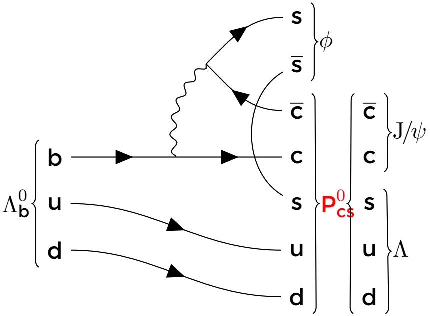
Neutron not detectable in LHCb

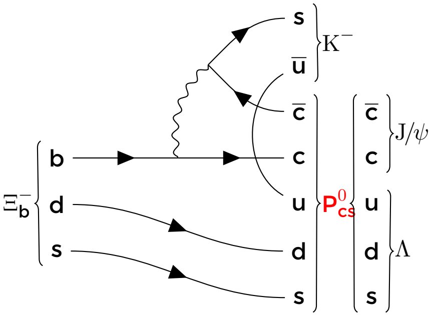
Decay into open charm hadrons accessible



Pentaquarks with Strangeness?

Both final states provide access to strange pentaquarks $usdc\bar{c}$





- $J/\psi\phi$ system $\rightarrow$ $c\bar{c}s\bar{s}$ Tetraquarks
- LHCb Analyse $B \rightarrow J/\psi\phi K$:
  [PRL118(2017)022003]
  [PRD95(2017)012002]

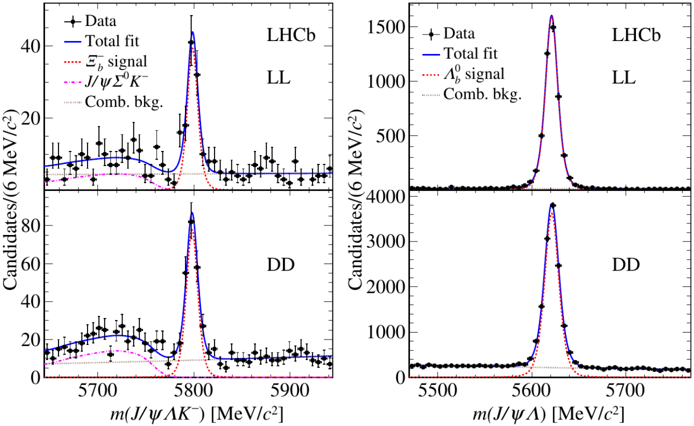
- Less tracks reconstruct
- Lower Ξ_b production cross section
- Expect comparable statistics

First Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ [PLB772(2017)265]

$$\frac{f_{\Xi_b} \mathcal{B}(\Xi_b \to J/\psi \Lambda K)}{f_{\Lambda_b} \mathcal{B}(\Lambda_b \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.14) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b) = 177.08 \pm 0.47 \pm 0.16\,\text{MeV}/c^2$$

- Need Run II data set to study $J/\psi \Lambda K^-$ amplitudes



Pentaquark program at LHCb

Amplitude analyses will leverage Run II data

What are they?

- Observe $P_c \to J/\psi p$ as subsystems in different final states
  - $\Lambda_b \to J/\psi\ p\ \pi$ — DONE
  - $\Upsilon \to J/\psi\ p\ \bar{p}$ — in progress
  - $\Lambda_b \to J/\psi\ p\ \pi\ K^0_S$ — in progress
- Search for new decay modes of P_c
  - $\Lambda_b \to \chi_{c1}(1P)\ p\ K$ — observed Λ_b-decay mode
  - $\Lambda_b \to \Lambda_c^+ \overline{D}^{0(*)} K$ — in progress

Are there more of their kind?

- Explore a possible multiplet of pentaquarks
  - $\Lambda_b \to J/\psi\ p\ \pi\ K^0_S$ — in progress
  - $\Lambda_b \to \Lambda_c^+ D^- K^*$ — in preparation
  - $\Xi_b \to J/\psi \Lambda K$ — observed Ξ_b decay-mode
  - $\Lambda_b \to J/\psi\ \Lambda\ \phi$ — in progress

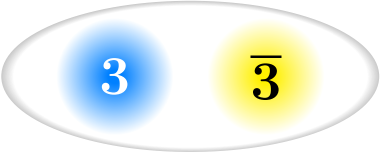
Outlook

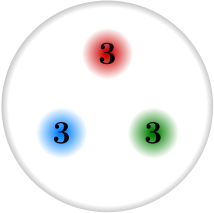
- LHCb not done yet with RUN I data
- RUN II set will enable amplitude analyses of more complicated final states
- Experimental approaches
  - Exploring different sources (B,B^0,B_s^0,Λ_b,Ξ_b,..., prompt)
  - Precision measurements of known exotics
  - Spin Exotics?
  - Open strangeness exotics?
  - Exotic Baryons
  - Radiative decays

Backup

The Di-Quark Model

Building color-neutral objects from coloured constituents



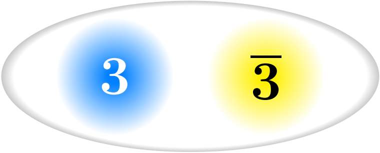


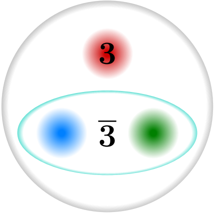
- $q\bar{q}$ mesons are bound through attractive $\mathbf{3}\bar{\mathbf{3}}$ color coupling

- qqq is also bound $\Rightarrow$ $\mathbf{3} \otimes \mathbf{3} \rightarrow \bar{\mathbf{3}}$
- At short distances the $\bar{3}$ qq binding is still half as strong as the color singlet binding
- $\Rightarrow$ qq di-quark correlations

The Di-Quark Model

Building color-neutral objects from coloured constituents





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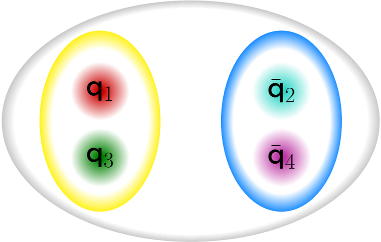
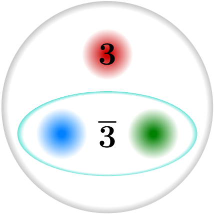




- Tetraquark in the di-quark model
- Qualitatively explains relations between X(3872), Z(3900), Z(4430) and Y(4260) exotic mesons

  e.g. ↪ arXiv:1405.1551

- qqq is also bound ⇒ $\mathbf{3} \otimes \mathbf{3} \rightarrow \bar{\mathbf{3}}$
- At short distances the $\bar{3}$ qq binding is still half as strong as the color singlet binding
- ⇒ qq di-quark correlations

Predictions from low-energy QCD?

Crypto-Exotic Baryons in Coupled-Channel Dynamics

Few predictions for states with hidden charm are available.

M. Lutz and J. Hofmann [Nucl.Phys.A776(2006)17]

- Building baryon resonances from coupled-channel dynamics within ground state multiplets
- 16-plet 0^- mesons $\times$ 20-plet $\frac{3}{2}^+$ baryons
- $\Rightarrow$ narrow octet of $J^P = \frac{3}{2}^-$ crypto-exotics

(I, S)	M[MeV]	Γ[MeV]
$(\frac{1}{2}, 0)$	3430	0.50
$(0, -1)$	3538	0.63
$(1, -1)$	3720	0.83
$(\frac{1}{2}, -2)$	3752	1.1

- No tuning
- Resonant states predicted!
- Very narrow width

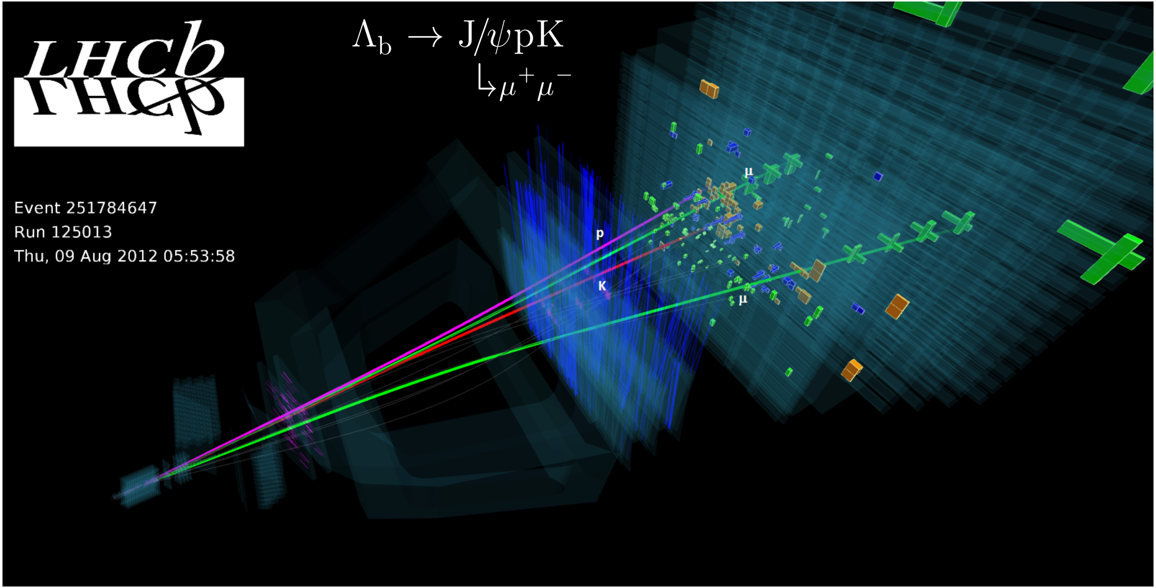
Dynamically Generated N^* with Hidden Charm

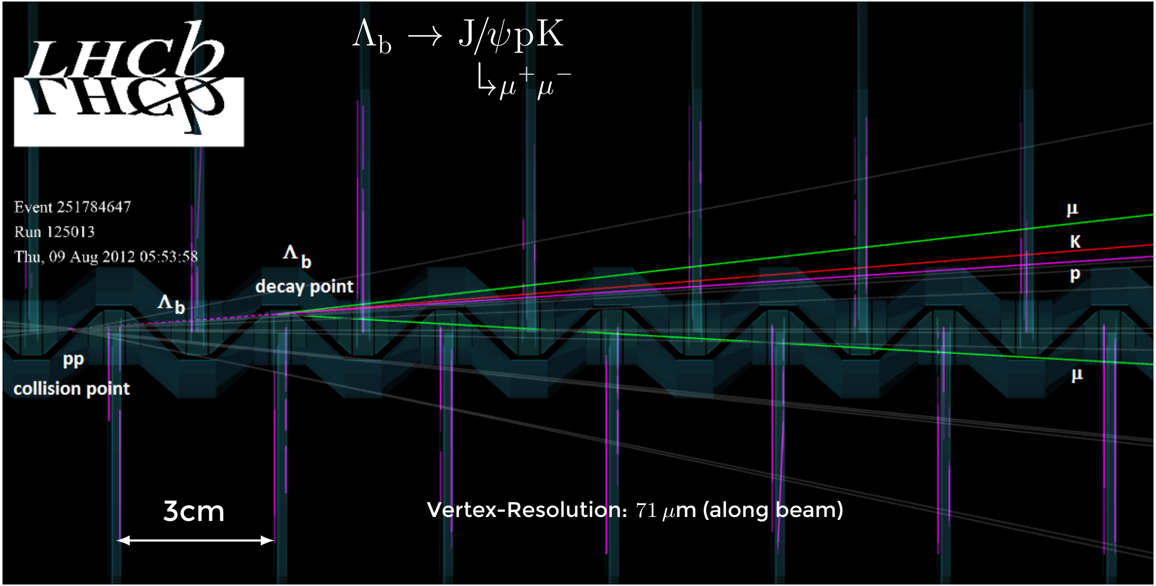
- Meson-Baryon interaction with vector exchange force
- Vector forces from local hidden gauge formalism
- Coupled channels $\overline{D}\,\Lambda_c^+$, $\overline{D}\,\Sigma_c$, $\overline{D}^*$,Λ_c^+,$\overline{D}^*\Sigma_c$,$\overline{D}\Sigma^*$, $\overline{D}^*\Sigma_c$ (η_c N,π N,η N,η'N,K Σ,K Λ)
- tuned to reproduce Λ_c^+ (2592) and Λ_c^+ (2625)
- $\Rightarrow$6 Nucleon resonances with hidden charm

Several similar models:
[PRC 84 (2011) 015202]
[PRC 85 (2012) 044002]
[EPJ A52 (2016) 43]

Main channel	J^P	M ± 20 MeV	Γ [MeV]	Main decay
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c + \overline{D}\Sigma_c)$	$1/2^-$	4228	21-51	$\overline{D}\ \Lambda_c^+$
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c - \overline{D}\Sigma_c)$	$1/2^-$	4295	11-41	$\overline{D}\ \Lambda_c^+$
$\overline{D}^*\Sigma_c$	$3/2^-$	4218	103	$\overline{D}\ \Lambda_c^+$
$\overline{D}^*\Sigma_c{}^*$	$1/2, 5/2^-$	4344	0	-
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c{}^* + \overline{D}\Sigma_c{}^*)$	$3/2^-$	4325	0	-
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c{}^* - \overline{D}\Sigma_c{}^*)$	$3/2^-$	4378	0	-

- Only negative parity

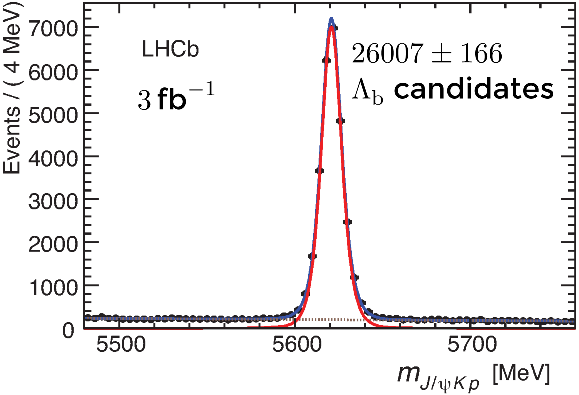

LHCb
$\Lambda_b \to J/\psi p K$
$\hookrightarrow \mu^+\mu^-$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
p
K
μ
μ

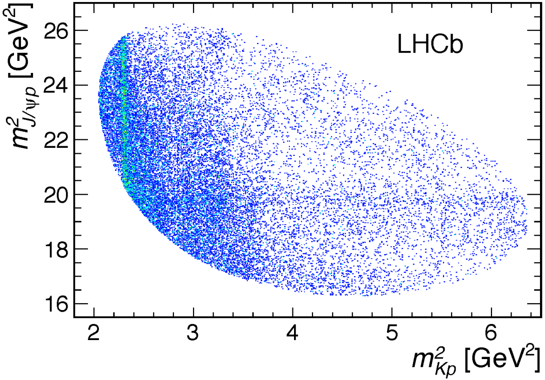


$\Lambda_b \to J/\psi p K$
$\hookrightarrow \mu^+\mu^-$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
μ
K
p
μ
Λ_b
decay point
Λ_b
pp
collision point
3cm
Vertex-Resolution: 71 μm (along beam)

A Surprise in Λ_b Decays

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





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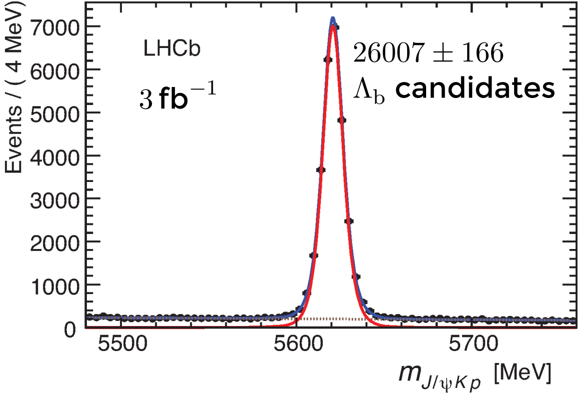

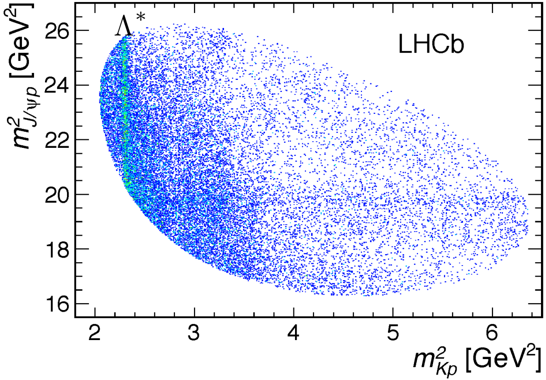

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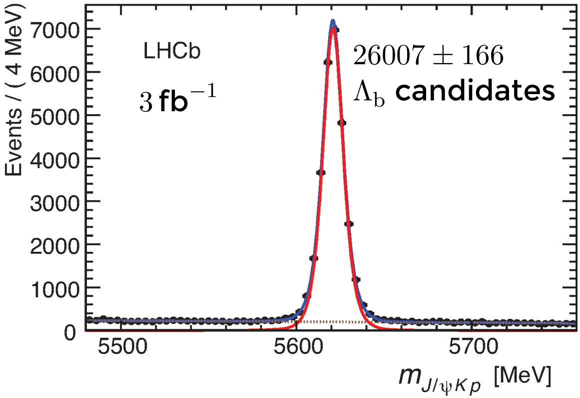
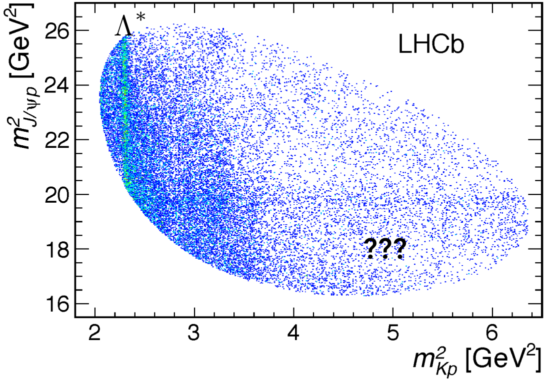


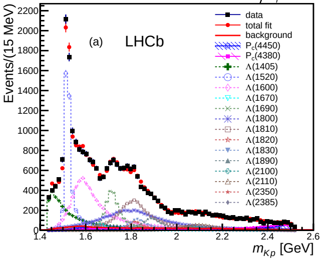


Discovery of $J/\psi p$ baryon resonances at LHCb

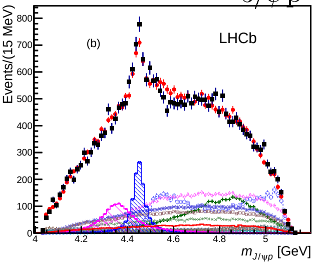
Three analyses performed:

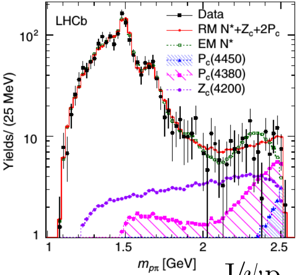
- $\Lambda_b \to J/\psi p K$
  - $26\,000\ \Lambda_b$ candidates
  - 6D amplitude analysis
    [PRL115(2015)072001]
  - moments analysis
    [PRL117(2016)082002]
- $\Lambda_b \to J/\psi p \pi$
  - $1\,900\ \Lambda_b$ candidates
  - 6D amplitude analysis
    [PRL117(2016)082003]

$J/\psi K$

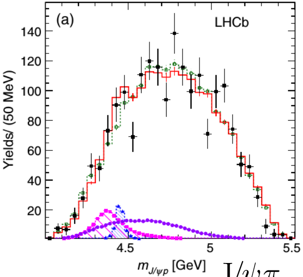


$J/\psi p$





$J/\psi p$



$J/\psi \pi$

Discovery of $J/\psi p$ baryon resonances at LHCb

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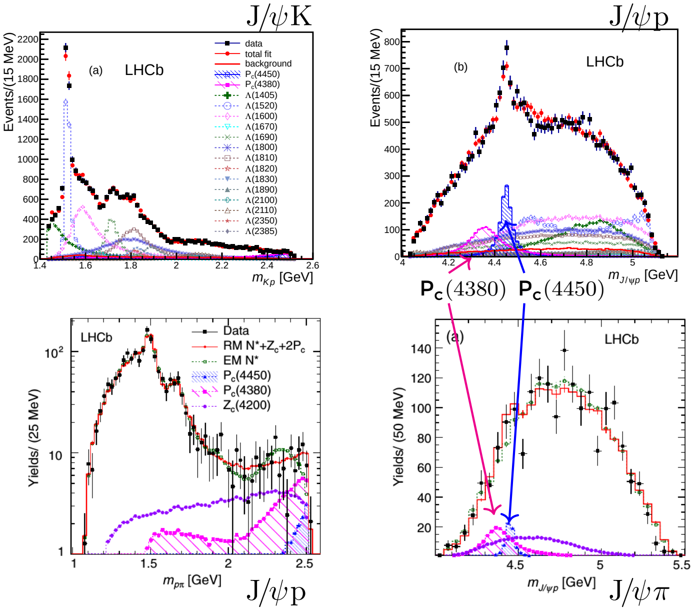


Two Analysis Techniques

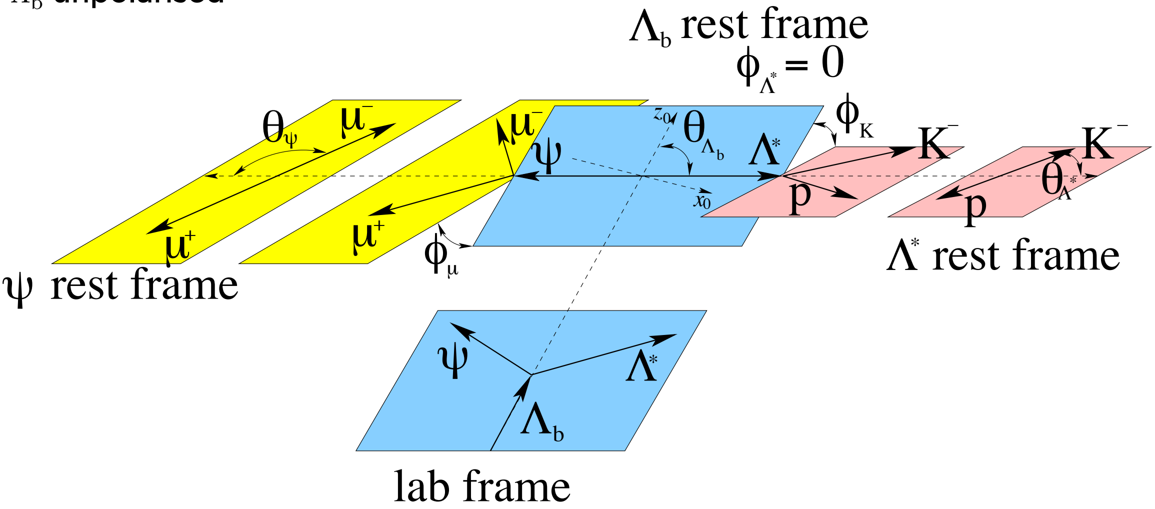
1. Isobar-model amplitude analysis
   - Use known Λ^* spectrum as input
   - Parameterize the decay matrix element (model dependent)
   - Search for $\mathrm{J}/\psi\ \mathrm{p}$ resonances
   - Extract their masses/widths and quantum numbers

2. Model independent moments analysis
   - Minimal assumptions, no modelling of decay amplitude
   - Hypothesis test:
     Can the structures in $\mathrm{J}/\psi\ \mathrm{p}$ be explained by reflections of Λ^* resonances?
   - Cannot extract properties of potential $\mathrm{J}/\psi\ \mathrm{p}$ resonances

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

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

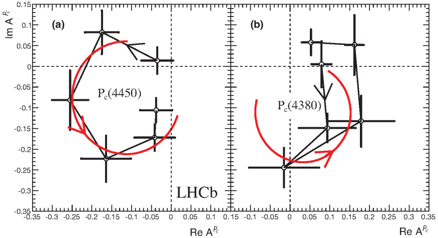
Λ_b unpolarised



Parameters from $\Lambda_b \to J/\psi pK$ amplitude analysis

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

- Interference of two states of opposite parity required by forward-backward asymmetry in P_c helicity angle

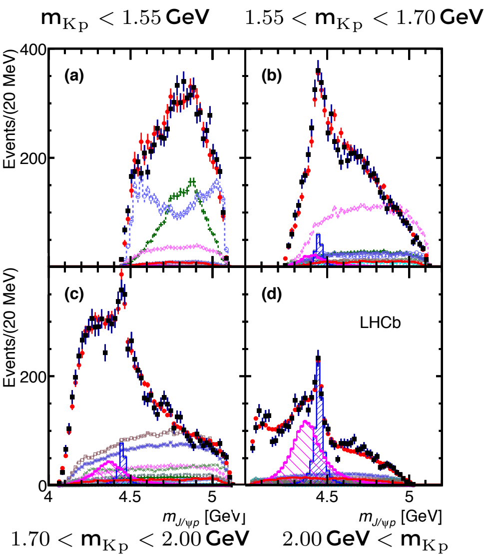


- Spin-parity assignment not conclusive:

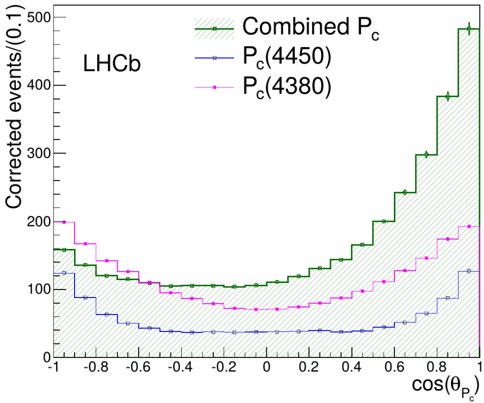
Fit	$\Delta(-2\ln\mathcal{L})$	P_c (Low) Mass	P_c (Low) Γ	P_c (High) Mass	P_c (High) Γ
$3/2^-, 5/2^+$	0	4.3799 ± 0.0064	0.205 ± 0.011	4.4498 ± 0.0017	0.0387 ± 0.0037
$3/2^+, 5/2^-$	0.9^2	4.3696 ± 0.0063	0.211 ± 0.012	4.4504 ± 0.0017	0.0492 ± 0.0040
$5/2^+, 3/2^-$	2.3^2	4.3770 ± 0.0098	0.239 ± 0.024	4.4486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

⋮

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



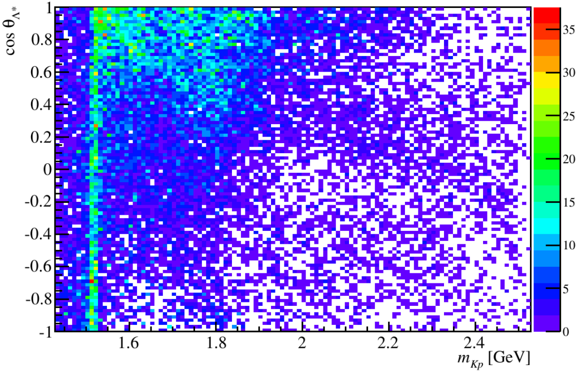
Model independent analysis of $\Lambda_b \to J/\psi pK$

- Observation of the $P_c(4380)$ and $P_c(4450)$ used a model for the decay matrix element
- Λ^* spectrum biggest uncertainty

- In bins of $m(pK)$: decompose decay-angle distribution into Legendre-moments

$$\langle P_\ell \rangle = \sum_{i=0}^{N_{events}} \frac{w_i}{\epsilon_i} P_\ell(\cos\theta^i_{pK})$$

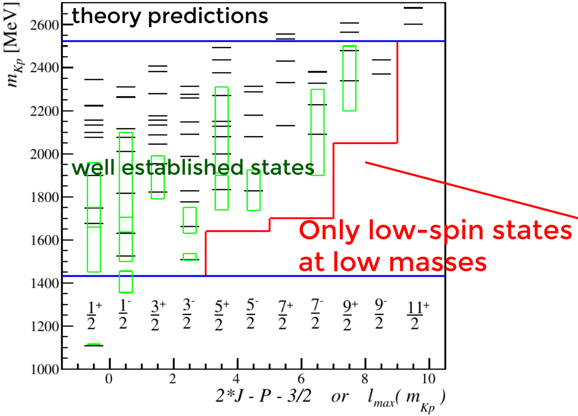
Helicity angle $\cos\theta_{pK}$ vs. m_{pK}



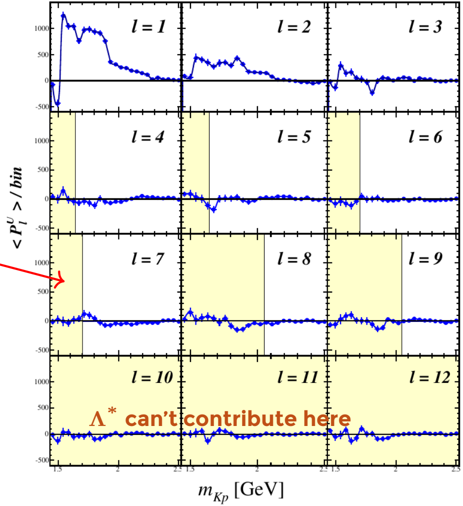
efficiency corrected (ϵ_i), bkg subtracted (w_i)

Extracted pK moments

Minimal assumption on Λ^* spectrum



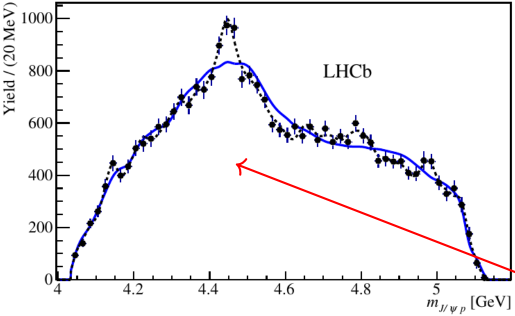
Moments extracted from data

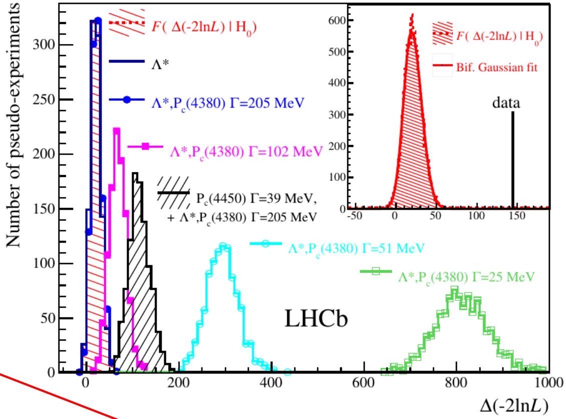


Model-independent analysis of $\Lambda_b \to J/\psi p K$

Testing sensitivity on MC for various models

Construct ℓ_{max}-filtered toy MC:
Reflections of $p\,K$-system in $J/\psi\,p$

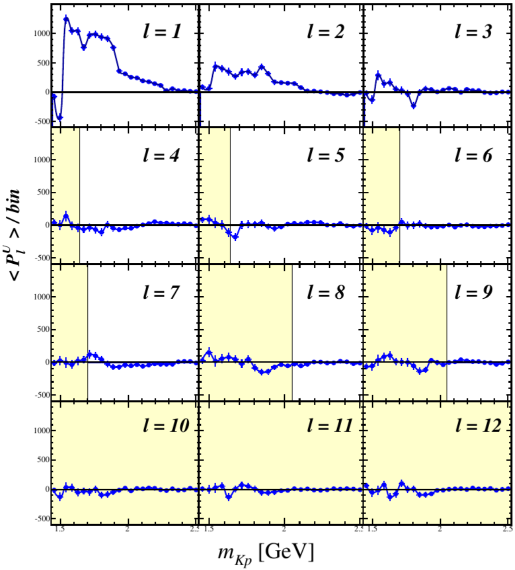




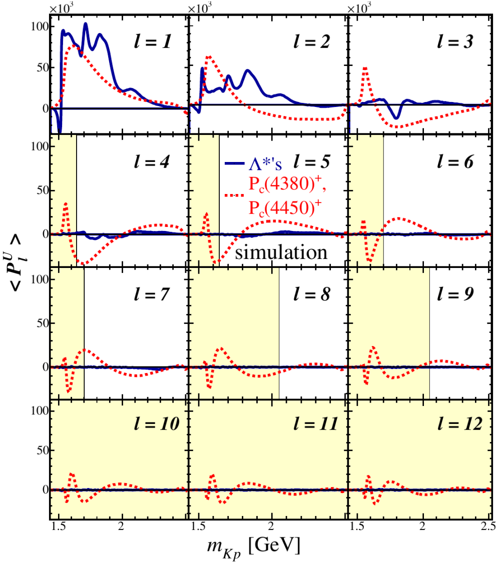
- $p\,K$-reflections cannot explain the narrow structure in $J/\psi\,p$
- Hypothesis "only Λ^*" rejected with $> 9\sigma$
- Confirms findings of amplitude analysis

Compare to the model dependent analysis

Data



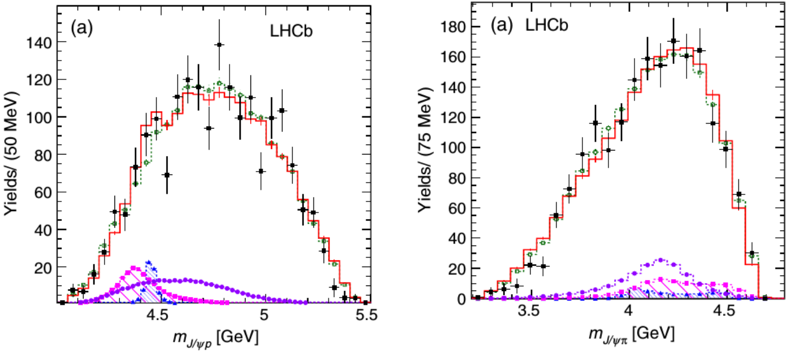
Simulation, driven by amplitude model



Amplitude Analysis of $\Lambda_b \to J/\psi\ p\ \pi^-$

Challenges:

- Cabibbo suppr. $\frac{\mathcal{B}(\Lambda_b \to J/\psi p \pi)}{\mathcal{B}(\Lambda_b \to J/\psi p K)} \approx 8\%$ [JHEP 07(2014)103]
- Need to deal with N^* resonances
- 6 N^* states needed
- Up to 14 used for systematic studies
- Bonn-Gatchina model for systematics [EPJ A48(2012)15]
- Possibility in $J/\psi\pi$: Z(4200)



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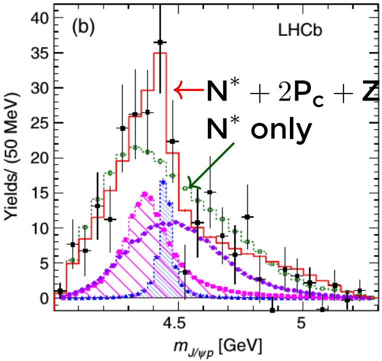
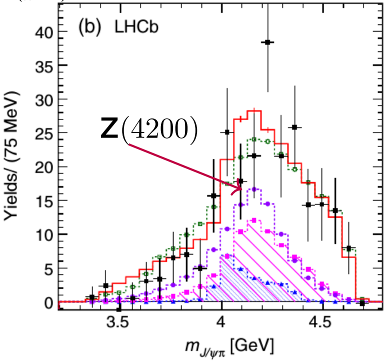
plot fit results for m$(p\pi) > 1.8$ GeV





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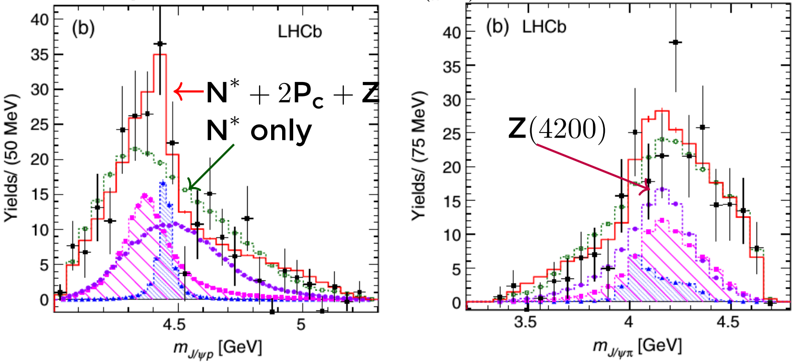


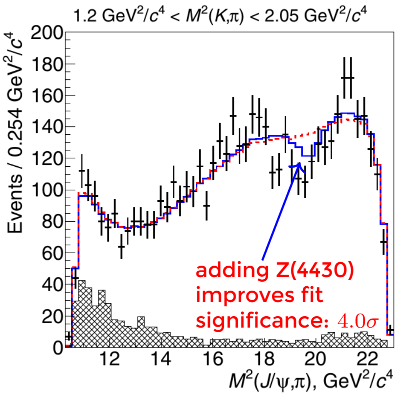
- Both types of exotics: significance 3.1σ
- Two P$_c$ have a significance of 3.3σ
  Assuming Z(4200) negligible
- Exotic contributions needed, can't distinguish scenarios

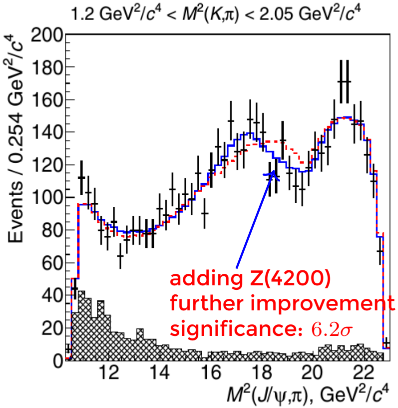
What about these charged exotics in $J/\psi\pi$??

$\overline{\mathrm{B}} \to \mathrm{K}^-\pi^+\mathrm{J}/\psi$ at Belle

[PRD90(2014)112009]

- $30\,000\ \overline{\mathrm{B}} \to \mathrm{K}^-\pi^+\mathrm{J}/\psi$ decays (711 fb^{-1})
- 4D amplitude analysis





- Z(4430) with J$^{\mathrm{P}} = 1^+$ confirmed
- Z(4200) with J$^{\mathrm{P}} = 1^+$ observed

Ongoing analyses on $\overline{B} \to K^- \pi^+ J/\psi$ at LHCb

- LHCb Run I: $\sim 20\times$ Belle statistics
- 3 analysis techniques:
  - Amplitude analysis
  - Moments analysis
  - Novel 3D moments analysis

COMING SOON!

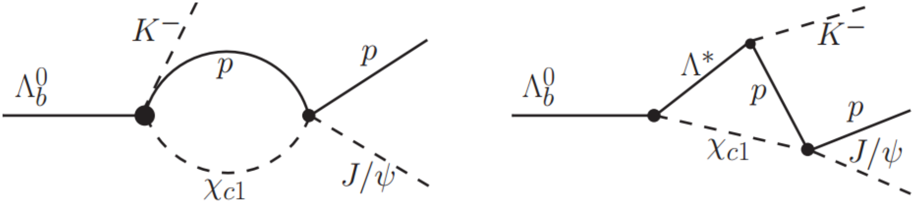
Results for K^* resonances

[PRD95(2017)012002]

	Contri-bution	sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %	f_L	$f_\perp$
1^+	All $K(1^+)$	8.0σ			$42\pm 8^{+5}_{-9}$		
	$\mathrm{NR}_{\phi K}$				$16\pm13^{+35}_{-6}$	0.52 ± 0.29	0.21 ± 0.16
	$K(1^+)$	7.6σ	$1793\pm59^{+153}_{-101}$	$365\pm157^{+138}_{-215}$	$12\pm10^{+17}_{-6}$	0.24 ± 0.21	0.37 ± 0.17
	$2^1\mathrm{P}_1$	[52]	1900				
	$K_1(1650)$	[36]	1650 ± 50	150 ± 50			
	$K'(1^+)$	1.9σ	$1968\pm65^{+70}_{-172}$	$396\pm170^{+174}_{-178}$	$23\pm20^{+31}_{-29}$	0.04 ± 0.08	0.49 ± 0.10
	$2^3\mathrm{P}_1$	[52]	1930				
2^-	All $K(2^-)$	5.6σ			$11\pm 3^{+2}_{-5}$		
	$K(2^-)$	5.0σ	$1777\pm35^{+122}_{-77}$	$217\pm116^{+221}_{-154}$		0.64 ± 0.11	0.13 ± 0.13
	$1^1\mathrm{D}_2$	[52]	1780				
	$K_2(1770)$	[36]	1773 ± 8	188 ± 14			
	$K'(2^-)$	3.0σ	$1853\pm27^{+18}_{-35}$	$167\pm 58^{+83}_{-72}$		0.53 ± 0.14	0.04 ± 0.08
	$1^3\mathrm{D}_2$	[52]	1810				
	$K_2(1820)$	[36]	1816 ± 13	276 ± 35			
1^-	$K^*(1^-)$	8.5σ	$1722\pm20^{+33}_{-109}$	$354\pm 75^{+140}_{-181}$	$6.7\pm1.9^{+3.2}_{-3.9}$	0.82 ± 0.04	0.03 ± 0.03
	$1^3\mathrm{D}_1$	[52]	1780				
first observation →	$K^*(1680)$	[36]	1717 ± 27	322 ± 110			
2^+	$K^*(2^+)$	5.4σ	$2073\pm94^{+245}_{-240}$	$678\pm311^{+1153}_{-559}$	$2.9\pm0.8^{+1.7}_{-0.7}$	0.15 ± 0.06	0.79 ± 0.08
	$2^3\mathrm{P}_2$	[52]	1940				
	$K_2^*(1980)$	[36]	1973 ± 26	373 ± 69			
0^-	$K(0^-)$	3.5σ	$1874\pm43^{+59}_{-115}$	$168\pm 90^{+280}_{-104}$	$2.6\pm1.1^{+2.3}_{-1.8}$	1.0	
	$3^1\mathrm{S}_0$	[52]	2020				
	$K(1830)$	[36]	~ 1830	~ 250			

Rescattering: Loop integrals

[PRD92(2015)071502]



Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

with a form factor $f_\Lambda(\vec{q}^2)$.

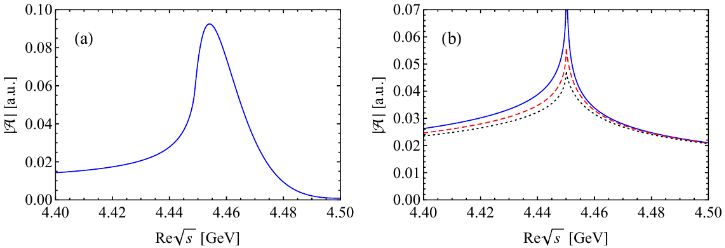
Triangle Singularity given by Landau-equation

$$1 + 2y_{12}y_{23}y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2$$

$$y_{ij} = \left(m_i^2 + m_j^2 - (p_i + p_j)^2\right)/2m_im_j$$

Rescattering: Loop integrals

[PRD92(2015)071502]



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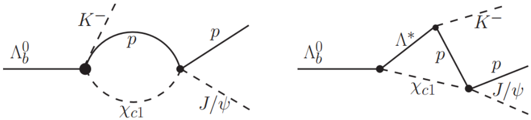
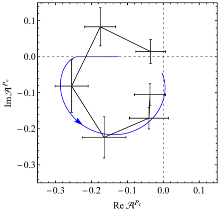
Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)\ p\ K$

- Guo et al [PRD92(2015)071502]



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



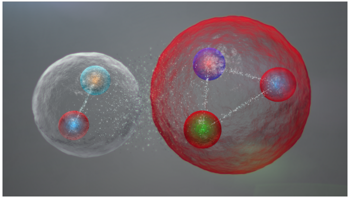
work in progress
$\Lambda_b \to \chi_{c1}(1P) pK$

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

COMING SOON!

Meson-Baryon degrees of freedom following ↪ arXiv:1509.02460

- Proximity of thresholds suggests two-body contributions



Closeby thresholds

[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

Channel	$\chi_{c1}(1P)\ p \quad \Lambda_c^{+*}\overline{D}$	$\Sigma_c^*\overline{D}/\Sigma_c\overline{D}^*$	$J/\psi N(1440/1520)$
Features	phase-motion of $P_c(4450)$	Pion exchange	opposite parity with S-wave for both states
Exp.Sign.	Decays to direct channels	Isospin $I = \frac{3}{2}$	150 MeV binding?

considered here: $J^P \in \left\{\frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}\right\}$

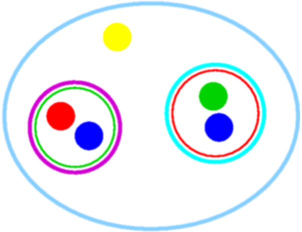
Pentaquarks in the Di-Quark Picture ↪ arXiv:1507.04980

$$\mathsf{P} = \{\bar{c}[cq]_s[qq]_s, \ell\}$$

Diquark color configuration:
$3 \otimes 3 \rightarrow \bar{3}$

- Opposite parity understood: additional orbital angular momentum ℓ
- One unit ℓ costs:
  $\delta m \approx m(\Lambda(1405)) - m(\Lambda(1116)) \approx 300\,\text{MeV}$
- Coupling spins to $s = 1$ in the light-light di-quark:
  $\delta m \approx m(\Sigma_c(2455)) - m(\Lambda_c(2286)) \approx 200\,\text{MeV}$

$P_c(4380)$	$\frac{3}{2}^-$	$\{\bar{c}[cq]_{s=1}[qq]_{s=1}, \ell = 0\}$
$P_c(4450)$	$\frac{5}{2}^+$	$\{\bar{c}[cq]_{s=1}[qq]_{s=0}, \ell = 1\}$

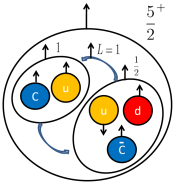


- Can explain the small mass gap!
- Predicts a large multiplet of states

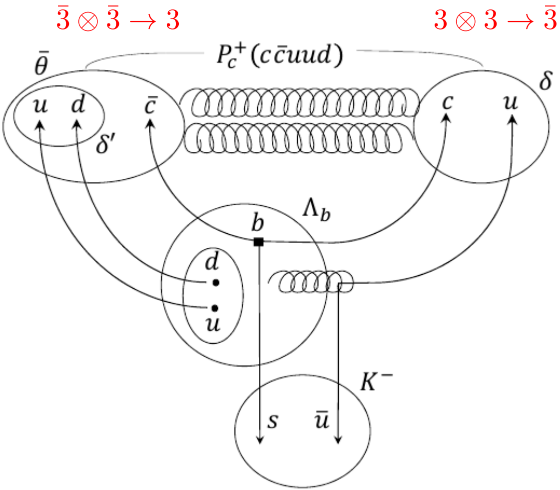
Dynamical Di-Quark Picture

↪ arXiv:1507:05867

- $P_c(4450)$ as Di-quark + Antitri-quark



- Rapidly expanding system prevents reorganisation into J/ψ p
- Decay through wavefunction overlap with daughters
- J/ψ as well as Λ_c^+ are compact
- Explains narrow width!



- Similar to model for X(3872) ↪ arXiv:1406.7281

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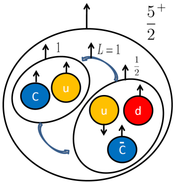

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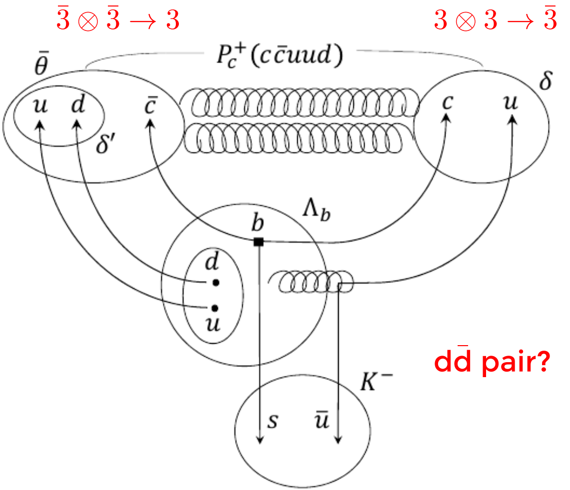

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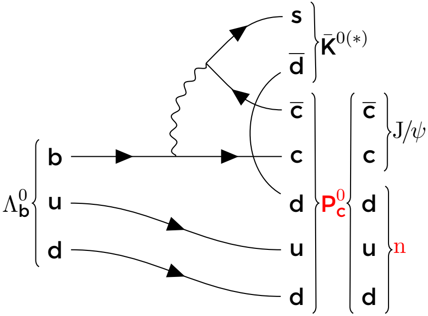
Exploring the Pentaquark Multiplet

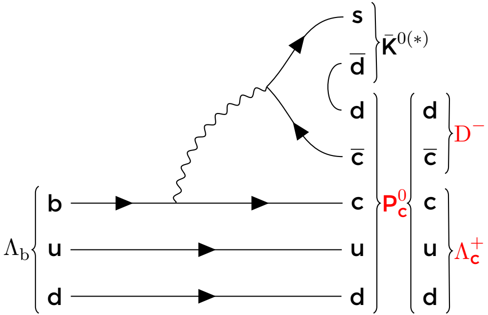
A neutral Pentaquark?

Are there isospin partners to the P_c^+? uudc$\bar{c}$ $\leftrightarrow$ uddc$\bar{c}$



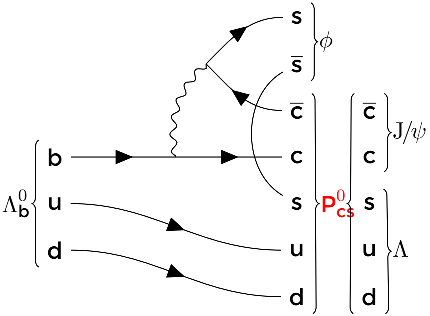
Neutron not detectable in LHCb

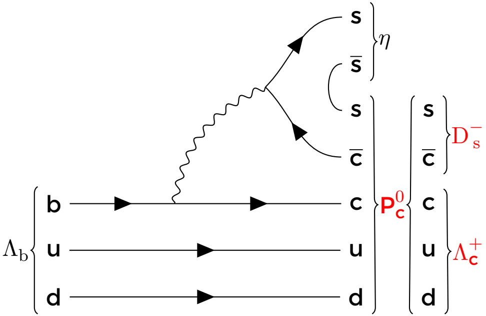
Decay into open charm hadrons accessible



Pentaquarks with Strangeness?

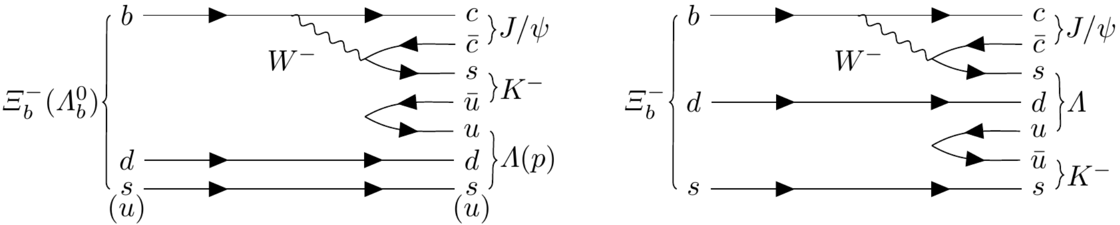
Both final states provide access to strange pentaquarks $usdc\bar{c}$





- $J/\psi\phi$ system $\rightarrow$ $c\bar{c}s\bar{s}$ Tetraquarks
- LHCb Analyse $B \rightarrow J/\psi\phi K$:
  [PRL118(2017)022003]
  [PRD95(2017)012002]

The decay $\Xi_b^- \to J/\psi \Lambda K^-$



NEWS: First Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ [↪ arXiv:1701.05274]

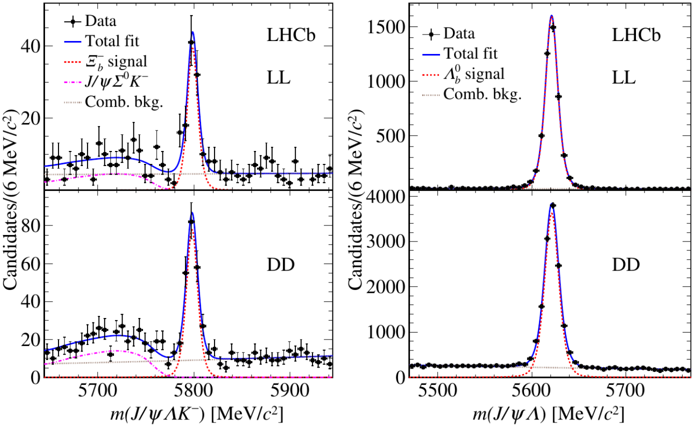
$$\frac{f_{\Xi_b}\mathcal{B}(\Xi_b \to J/\psi\Lambda K)}{f_{\Lambda_b}\mathcal{B}(\Lambda_b \to J/\psi\Lambda)}$$

$$= (4.19 \pm 0.29 \pm 0.14) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b)$$

$$= 177.08 \pm 0.47 \pm 0.16\,\mathrm{MeV}/c^2$$

- Add Run II data set to study $J/\psi\Lambda K^-$ amplitudes

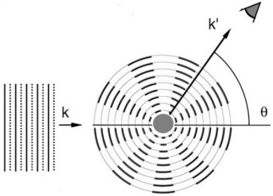


Reminder: $p\,n$ scattering

- Yukawa theory for low-energy nucleon-nucleon interactions:

$$\mathcal{L} = g\phi\bar{\psi}\psi \quad \Leftrightarrow \quad V(r) = -\frac{g^2}{4\pi}\frac{e^{-mr}}{r}$$

- $\Rightarrow$ strong force (mediated by pion exchange) is short range
- In the region outside of the nuclear interaction: S-wave scattering states



$$\psi \sim A(e^{2i\delta}e^{ikr} - e^{-ikr})$$

- with S-wave phase shift δ, at low energies (< 10 MeV) = close to threshold

$$k \cot\delta = -\frac{1}{a} + \frac{1}{2}r_0 k^2 + \ldots$$

- a is the scattering length, total forward cross section: $\sigma = 4\pi a^2$
- r_o is the effective range of the potential, $r_0 < 0$

The Deuteron, a Hadronic Molecule

From $\mathrm{p\,n}$ and $\mathrm{p\,p}$ scattering (Isospin 0):

$$a_{S=0} = -23.7\,\mathrm{fm}$$
$$a_{S=1} = 5.38\,\mathrm{fm}$$

The scattering amplitude f is given by

$$f^{-1} = k\cot\delta - ik$$

$$f \approx \frac{1}{-\frac{1}{a} + \frac{1}{2}r_0k^2 - ik}$$

For $a > 0$ and $r < 0$ there is a pole below threshold:

$$\boxed{f \approx \frac{-2/r_0}{k_R^2 - k^2 - i\gamma}} \qquad k_R^2 = \frac{2}{r_0 a} < 0, \gamma = -\frac{2k}{r_0}$$

Indeed the deuteron is a bound state of 2 nucleons with $J^P = 1^+$ and a binding energy of $E_B = 2.225\,\mathrm{MeV}$

Meson-Baryon Channels

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

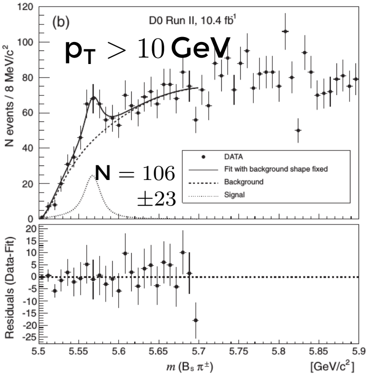
	P_c^*				P_c	
	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
$J/\psi N$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi\Delta$	×	✓	×	×	✓	×
$\eta_c\Delta$	×	✓	×	×	✓	×
$\Lambda_c\bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c\bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c\bar{D}$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

The $B_s^0\pi^+$ System

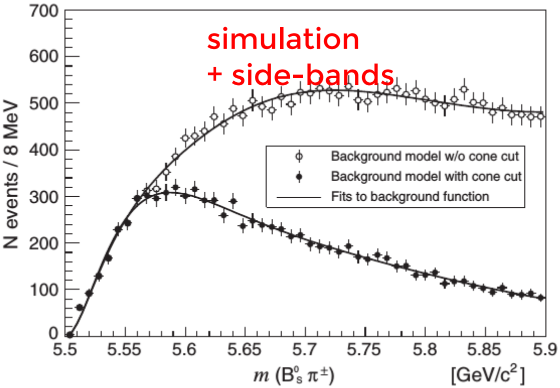
A resonance in $B_s^0\pi^+$ at DØ

[PRL117(2016)022003]

Peaking structure found by DØ



Applying a cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$

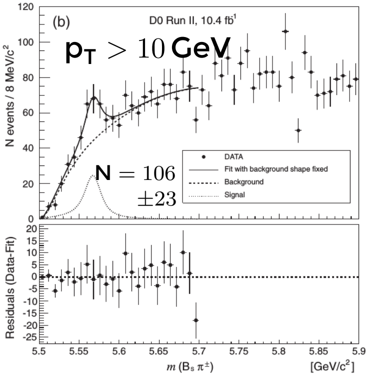


- 5582 ± 100 $B_s^0 \to J/\psi\phi$ candidates
- significance: 3.9σ (incl. LEE)

A resonance in $B_s^0\pi^+$ at D∅

[PRL117(2016)022003]

Peaking structure found by D∅



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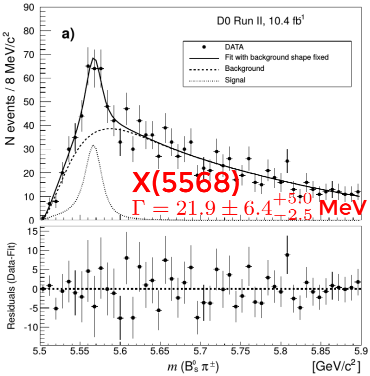


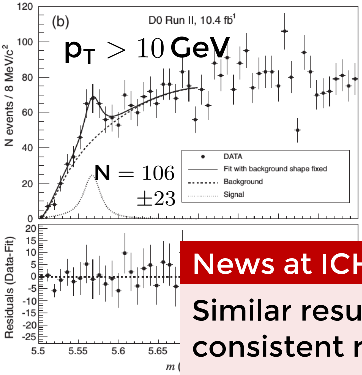
- 5582 ± 100 $B_s^0 \rightarrow J/\psi\phi$ candidates
- significance: 3.9σ (incl. LEE)

- 5.1σ significance after "cone"-cut
- $(8.6 \pm 1.9 \pm 1.4)\%$ of B_s^0 from X(5568)

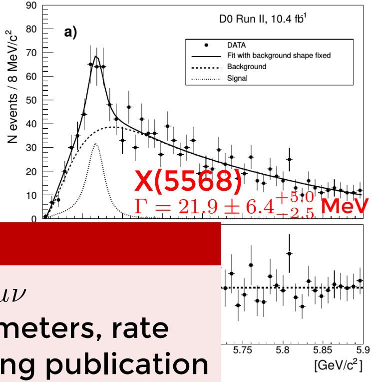
A resonance in $\mathrm{B_s^0}\pi^+$ at DØ

[PRL117(2016)022003]

Peaking structure found by DØ



Applying a cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$



News at ICHEP

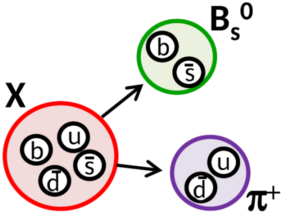
Similar result with $\mathrm{B_s^0} \to \mathrm{D_s}\mu\nu$
consistent resonance parameters, rate
awaiting publication

- 5582 ± 100 $\mathrm{B_s^0} \to J/\psi\phi$ candidates
- significance: 3.9σ (incl. LEE)

- 5.1σ significance after "cone"-cut
- $(8.6 \pm 1.9 \pm 1.4)\%$ of $\mathrm{B_s^0}$ from X(5568)

A four-flavour Tetraquark?

- Valence quark content $b\bar{s}u\bar{d}$
- How would such a state be generated/composed?
  - Tetraquark
  - $B_s^0\pi$, BK molecule
  - $B_s^*\pi$ cusp,
  - Nearest 2-body threshold: $B_s^*\pi$ @ 5555 MeV
  - All models have troubles explaining the X(5568)
    [CTP65(2016)593][PLB760(2016)627]

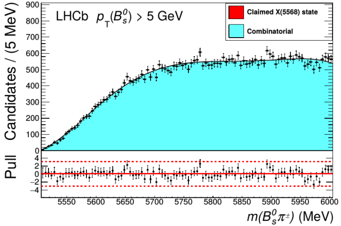


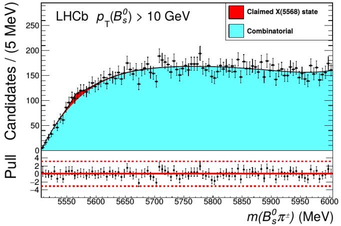
- Can it be confirmed by other experiments?

Search for X(5568) at the LHC

[PRL117(2016)152003]

LHCb: 50k $B_s^0 \to J/\psi\ \phi$ combined with
70k $B_s^0 \to D_s\ \pi$ candidates





Limit on cross-section times branching fraction ratio at 90(95)% C.L.

$$\rho_X = \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

$$\rho_X^{LHCb}(p_T > 10\,\text{GeV}) < 0.021(0.024)$$

Search for X(5568) at the LHC

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LHCb: 50k $B_s^0 \to J/\psi\ \phi$ combined with
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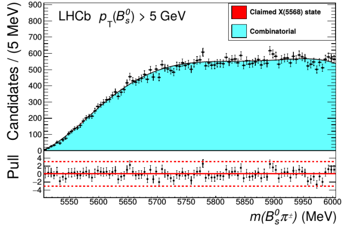

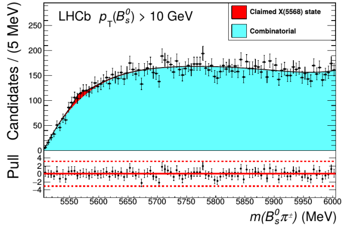

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$$\rho_X^{LHCb}(p_T > 10\,\text{GeV}) < 0.021(0.024)$$

News from CMS at ICHEP

$$\rho_X^{CMS} < 0.039 \quad @95\%\text{C.L.}$$

X(5568) Experimental Status

- Seen by D0 in $p\bar{p} \to (B_s^0\pi) +$ anything
  - with $B_s^0 \to J/\psi\phi$ [PRL 117(2016)022003]
  - with $B_s^0 \to D_s\mu\nu$ (presented at ICHEP)
  - $\rho_X^{p\bar{p}} = (8.6 \pm 1.9 \pm 1.4)\%$

- Not seen at the LHC $pp \to (B_s^0\pi) +$ anything
  - LHCb in $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s\pi$ [PRL117(2016)152003]
  - CMS in $B_s^0 \to J/\psi\phi$
  - $\rho_X^{pp} < 2.4\%$ @95%C.L. (LHCb)

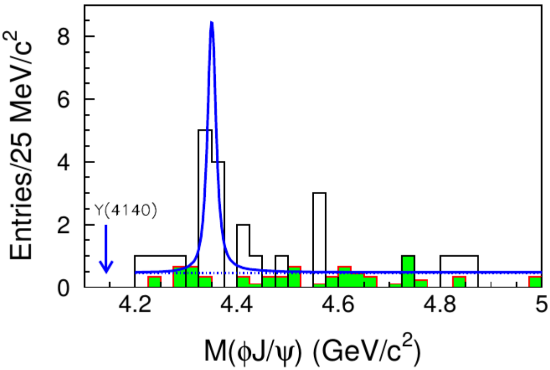
- A word from CDF?

A $J/\psi\phi$ resonance in $\gamma\gamma$ fusion

[PRL104(2010)112004]

- Belle searched for the X(4140) in $\gamma\gamma \to J/\psi\phi$
- No events were found close to threshold
- Instead a peak with 3.2σ significance at
- m $= 4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV and $\Gamma = 13^{+18}_{-9} \pm 4$ MeV

J^P	$\Gamma_{\gamma\gamma}(X) \times \mathcal{B}(X \to J/\psi\phi)$[eV]
0^+	$6.7^{+3.2}_{-2.4} \pm 1.1$
2^+	$1.5^{+0.7}_{-0.6} \pm 0.3$



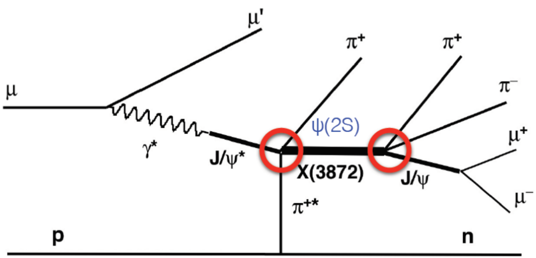
$X(3872)$ production

See talks by F. Navarra, F. Carvalho and L. Cristello in Sec. C, Thur. afternoon

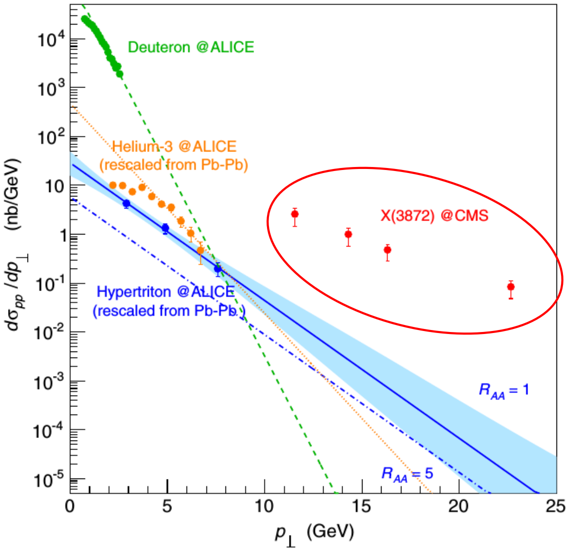
- Expectation: Production of loosely bound hadronic molecules in high energy hadronic collisions suppressed [PRL103(2009)162001]

- COMPASS showed preliminary results for virtual photo production

  J. Bernhard, @ Baryon2016



[PRD92(2015)034028]



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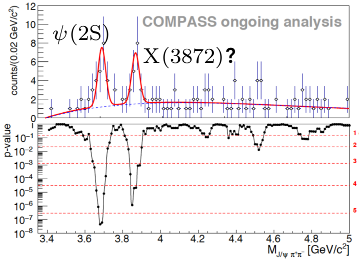
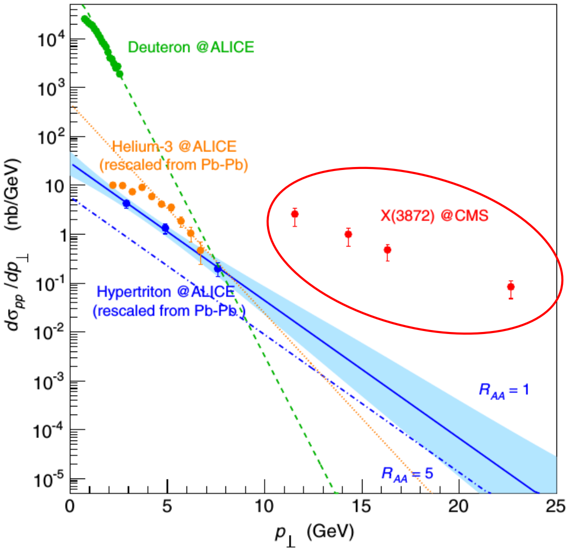


[PRD92(2015)034028]



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 $\rightarrow$	$\Lambda^*(1520)$	$3/2^-$	****	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 couplings	# Extended
$\Lambda^*(1405)$	$1/2^-$					4
anchor → $\Lambda^*(1520)$	$3/2^-$					6
$\Lambda^*(1600)$	$1/2^+$					4
$\Lambda^*(1670)$	$1/2^-$					4
$\Lambda^*(1690)$	$3/2^-$					6
$\Lambda^*(1710)$	$1/2^+$					0
$\Lambda^*(1800)$	$1/2^-$					4
$\Lambda^*(1810)$	$1/2^+$					4
$\Lambda^*(1820)$	$5/2^+$					6
$\Lambda^*(1830)$	$5/2^-$					6
$\Lambda^*(1890)$	$3/2^+$					6
$\Lambda^*(2000)$	?					0
$\Lambda^*(2020)$	$7/2^+$					0
$\Lambda^*(2050)$	$3/2^-$					0
$\Lambda^*(2100)$	$7/2^-$					6
$\Lambda^*(2110)$	$5/2^+$					6
$\Lambda^*(2325)$	$3/2^-$					0
$\Lambda^*(2350)$	$9/2^+$					6
$\Lambda^*(2585)$	?	**	≈ 2585	200	0	6

2-body systems

$$\Lambda^* \to pK$$

spin-spin and spin-orbit coupling

$$J = 1/2 \otimes 0 \otimes \ell$$

$$P = (+1) \times (-1) \times (-1)^\ell$$

ℓ	0	1	2	3
J^P	$\frac{1}{2}^-$	$\frac{1}{2}^+, \frac{3}{2}^+$	$\frac{3}{2}^-, \frac{5}{2}^-$	$\frac{5}{2}^+, \frac{7}{2}^+$

can you guess how this

looks like for J/ψ p?

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
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$\Lambda^*(1670)$	$1/2^-$	****	1670	35	3	4
$\Lambda^*(1690)$	$3/2^-$	****	1690	60	5	6
$\Lambda^*(1710)$	$1/2^+$	*	1713 ± 13	1		
$\Lambda^*(1800)$	$1/2^-$	***	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	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

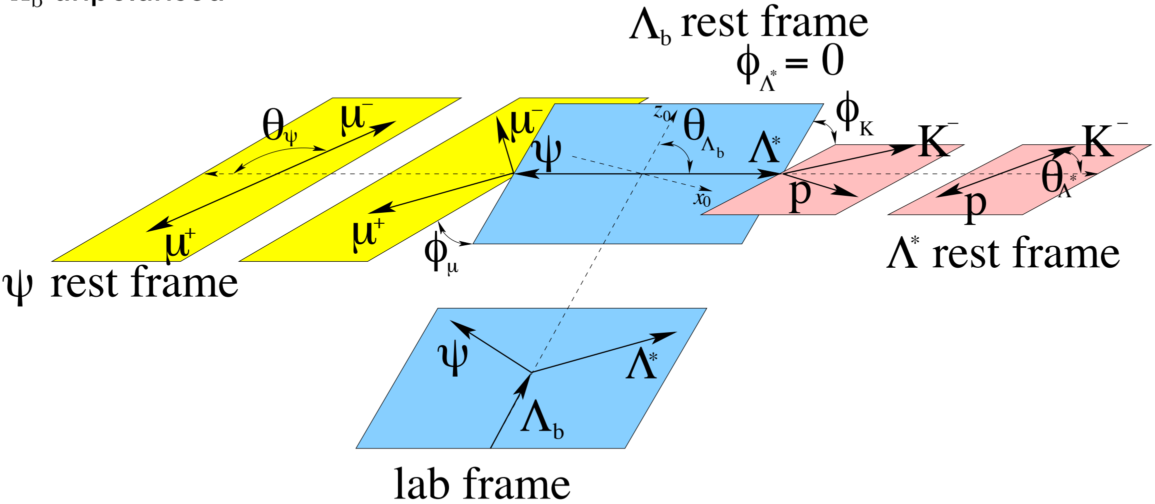
Two Λ^* models

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

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

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

Λ_b unpolarised



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

- Angular structures (no free parameters)
- Helicity couplings ← complex numbers, floating in fit
- Λ^* resonant amplitudes see next slide

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

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

Resonance parametrisation

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

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*})$

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

where

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

- Angular-momentum barrier factors $B'_\ell(p, p_0, d)$

$$R_n(m_{Kp}) = B'_{\ell_{\Lambda_b}}\left(\frac{p}{M_{\Lambda_b}}\right)^{\ell_{\Lambda_b}} \times BW(M_{Kp}) \times B'_{\ell_{\Lambda_n^*}}\left(\frac{q}{M_{\Lambda_n^*}}\right)^{\ell_{\Lambda_n^*}}\,.$$

- special case $\Lambda(1405)$ is subthreshold: Flatté ($\mathrm{K\ p}$ and $\Sigma\ \pi$ channels)

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

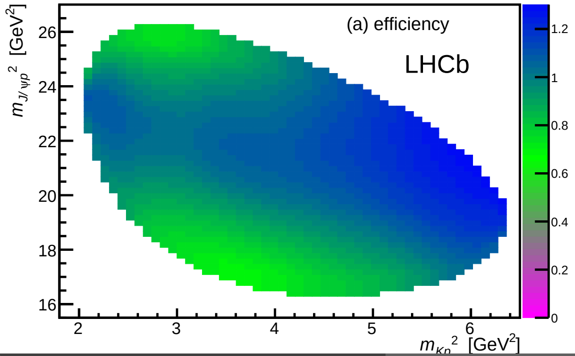
$p_0(q_0)$ calculated on the nominal resonance mass

2 Fitters - XCheck of Background Treatment

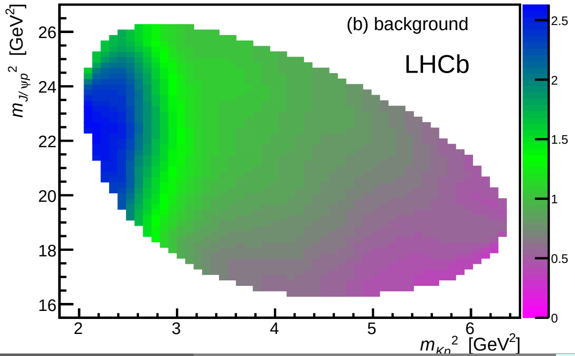
Log-likelihood fitters:

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

Efficiency from MC

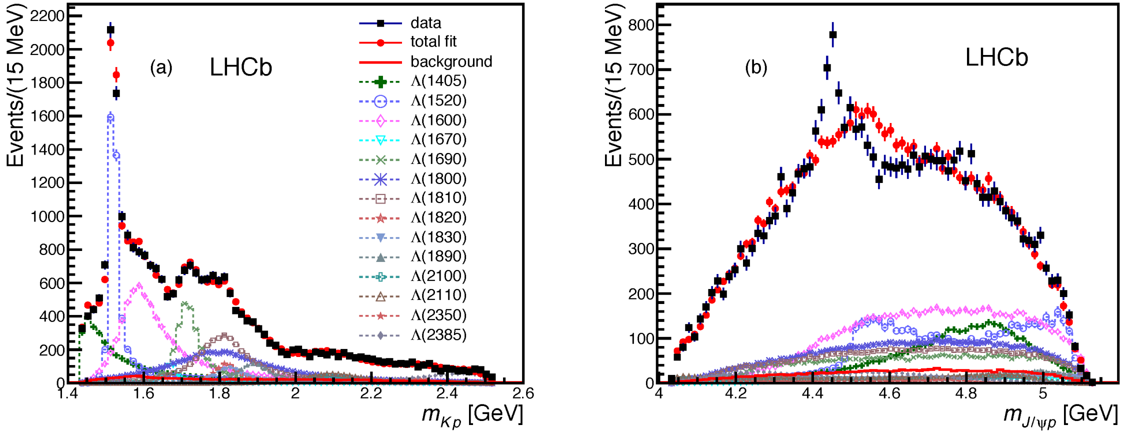


Background density shape (5.4%)



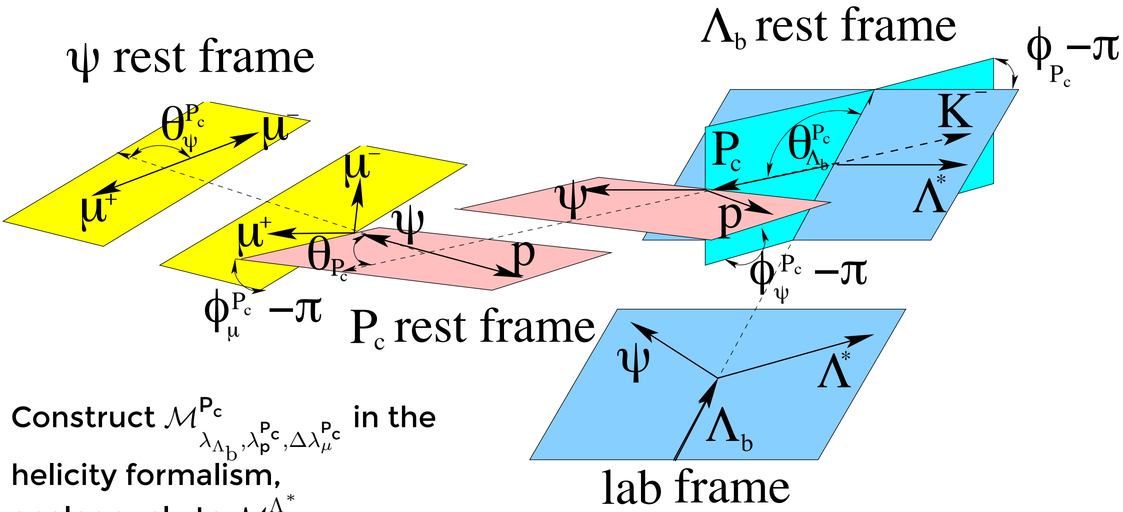
Results with only Λ^* States

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



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

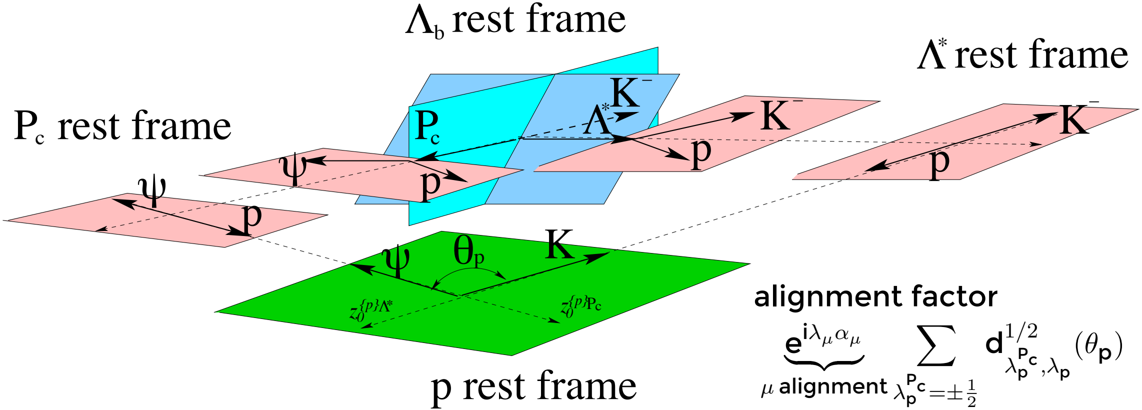
Adding Helicity Amplitudes for $\Lambda_b \to P_c K$



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

An important detail: Aligning reference frames

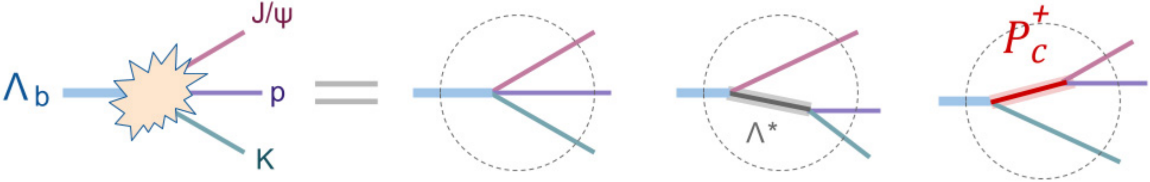
Helicities of final state particle have to be evaluated in the same reference system!



alignment factor

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

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



- Coherent sum over amplitudes, incoherent sum over external helicities

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