Resonant Structures in $J/\psi\ p$

The LHCb Pentaquark Candidates

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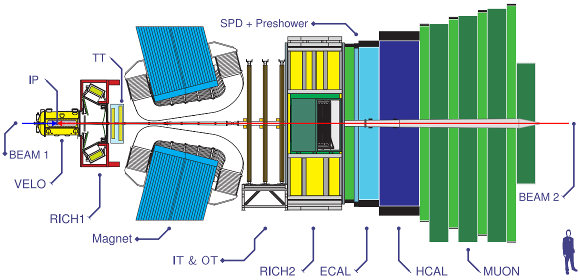
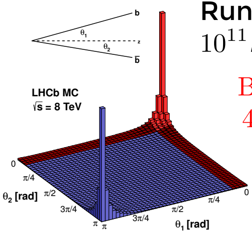
The LHCb Experiment

- 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

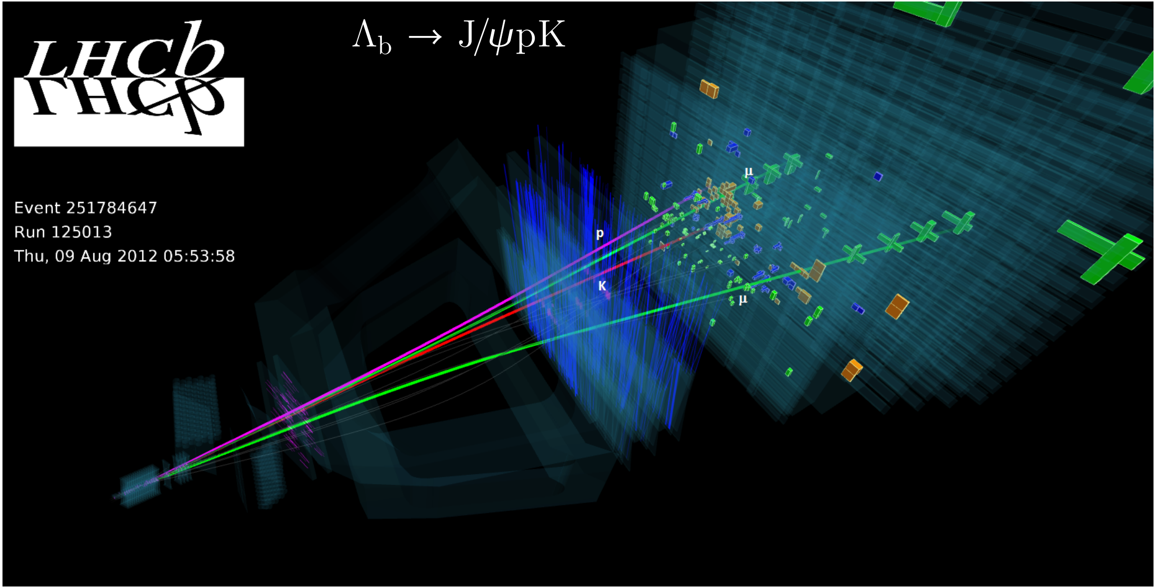




Run I: $3\ fb^{-1}$
$10^{11}\ b\bar{b}$ pairs

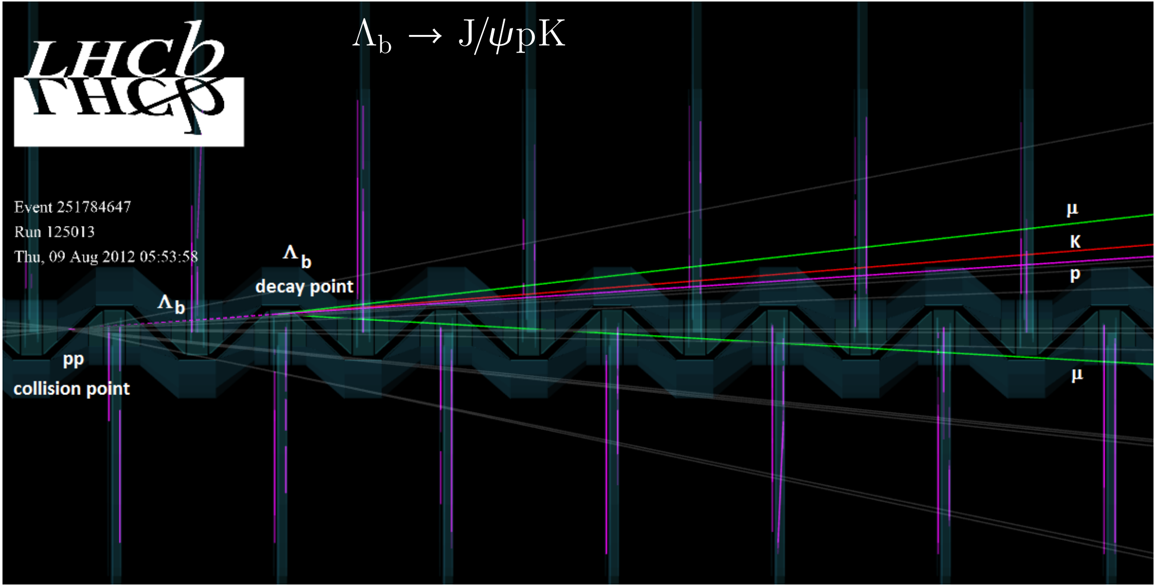
$\mathrm{B} : \Lambda_\mathrm{b} : \mathrm{B}_\mathrm{s}^0$
$4 : 2 : 1$

- Time-dependent analyses require good time resolution: ~ 40 *fs* (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Highly efficient trigger: di-muons, displaced vertices (topological B-hadron), ..



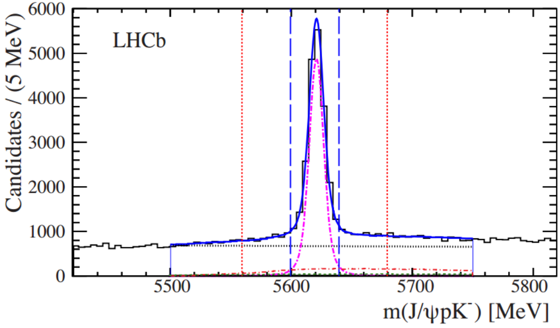
$\Lambda_b \to J/\psi pK$
LHCb
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
μ
p
K
μ

$\Lambda_b \to J/\psi pK$



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



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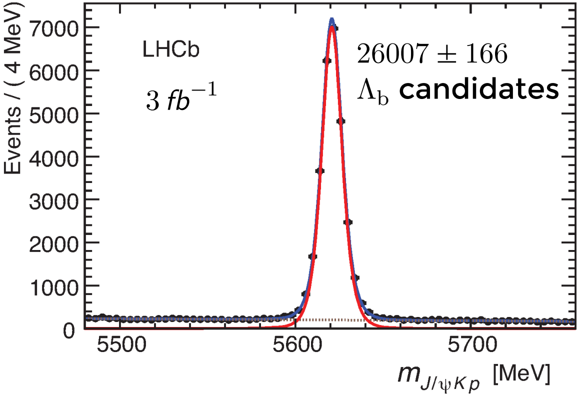

$\hookrightarrow$ arXiv:1509.00292

(to appear in Chin. Phys. C)

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

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

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

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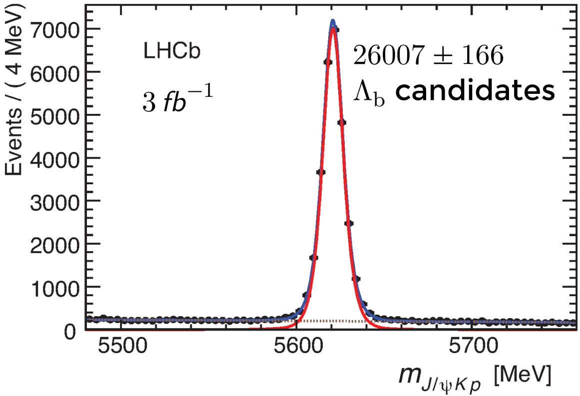

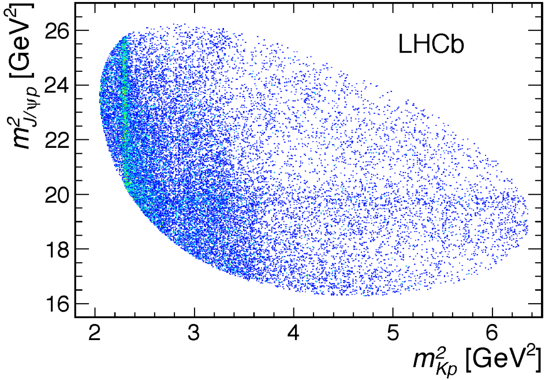

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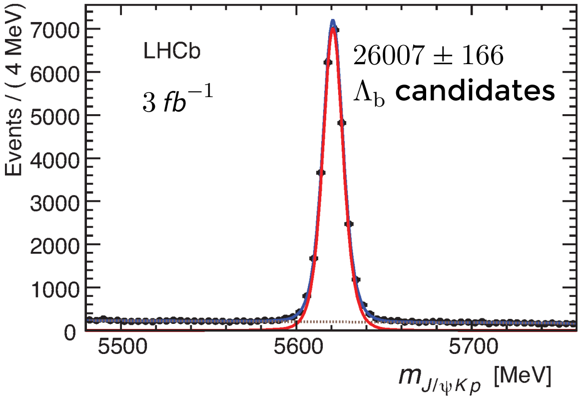

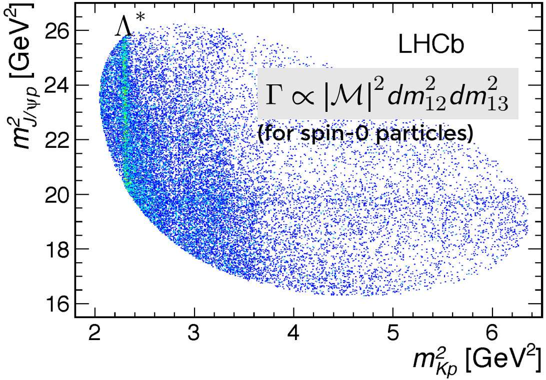

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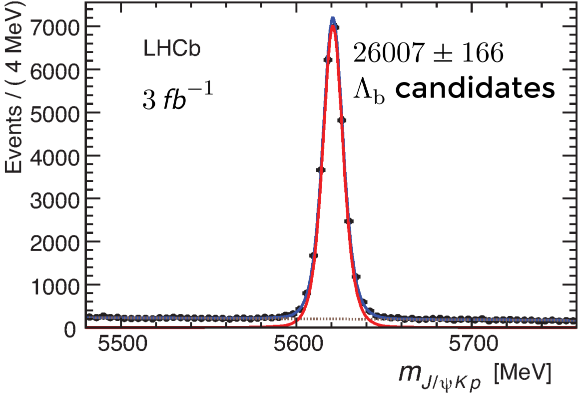
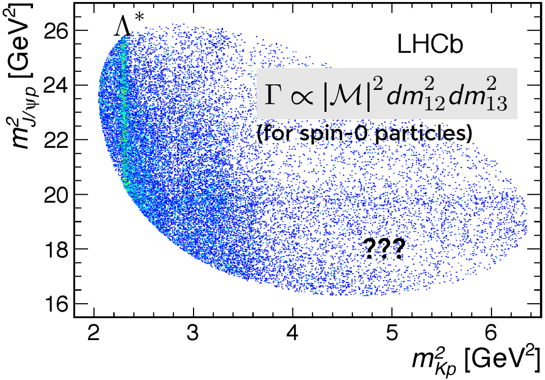
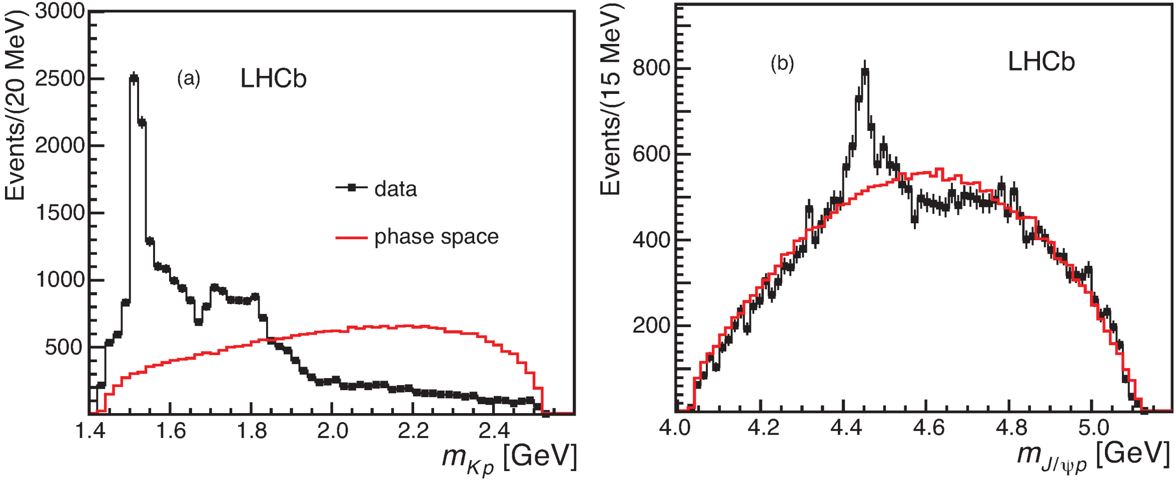


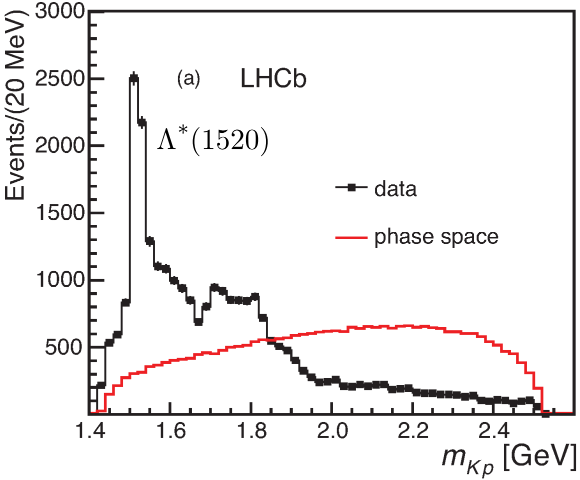


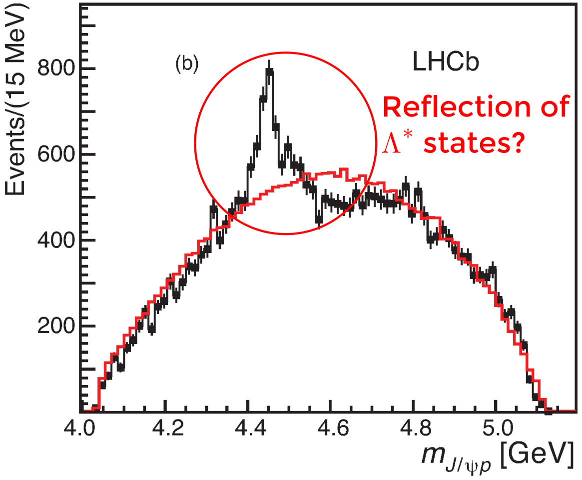
2-Body Mass Spectra $\hookrightarrow$ PRL115(2015)072001



2-Body Mass Spectra

↪ PRL115(2015)072001





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

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$\Lambda^*(1405)$	$1/2^-$				ouplings	4
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$\Lambda^*(1670)$	$1/2^-$					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
$\Lambda^*(2585)$	?					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?

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$\Lambda^*(1710)$	$1/2^+$	*	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			
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$\Lambda^*(2050)$	$3/2^-$	*	2056 ± 22	[illegible]	[illegible]	[illegible]
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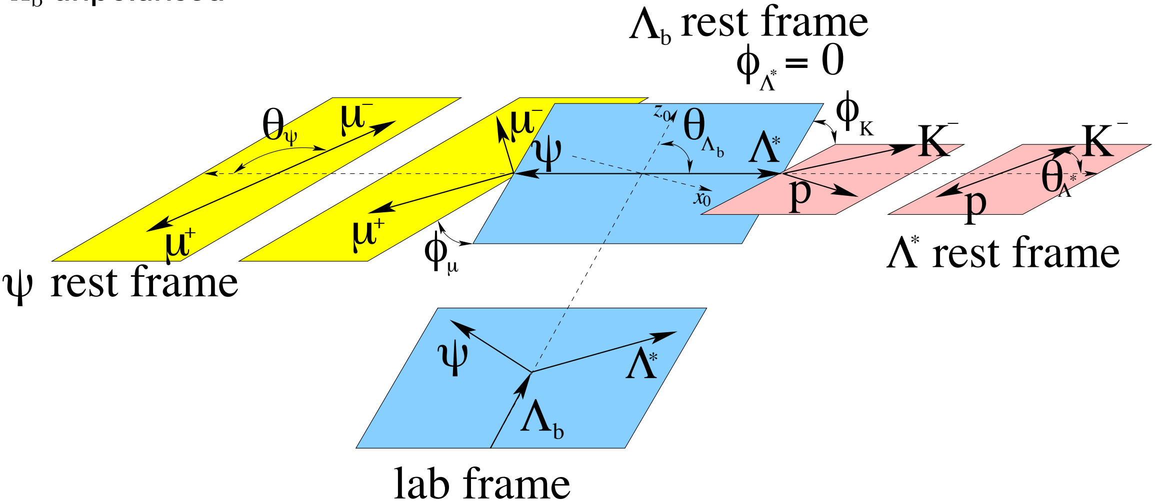
$\Lambda^*(2325)$	$3/2^-$	*	≈ 2325	?	0	0
$\Lambda^*(2350)$	$9/2^+$	***	2350	150	0	6
$\Lambda^*(2585)$	?	**	≈ 2585	200	0	6

Two Λ^* models

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

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 $\leftarrow$ complex numbers, floating in fit
- Λ^* resonant amplitudes see next slide

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

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

Resonance parametrisation

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

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

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

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.

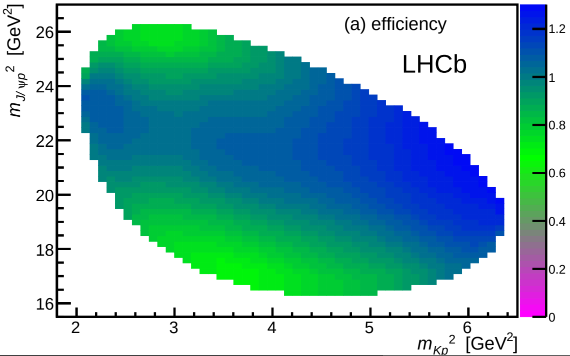
$p_0(q_0)$ calculated on the nominal resonance mass

2 Fitters - XCheck of Background Treatment

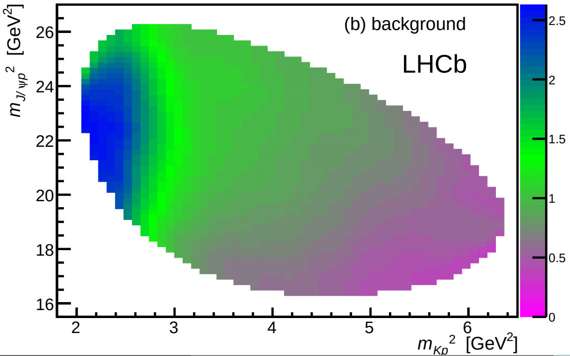
Log-likelihood fitters:

- 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

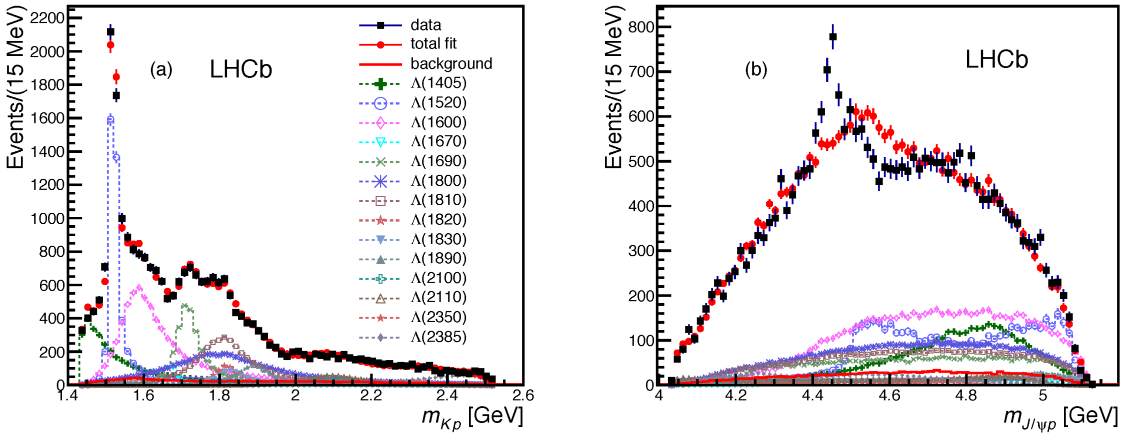


Background density shape (5.4%)



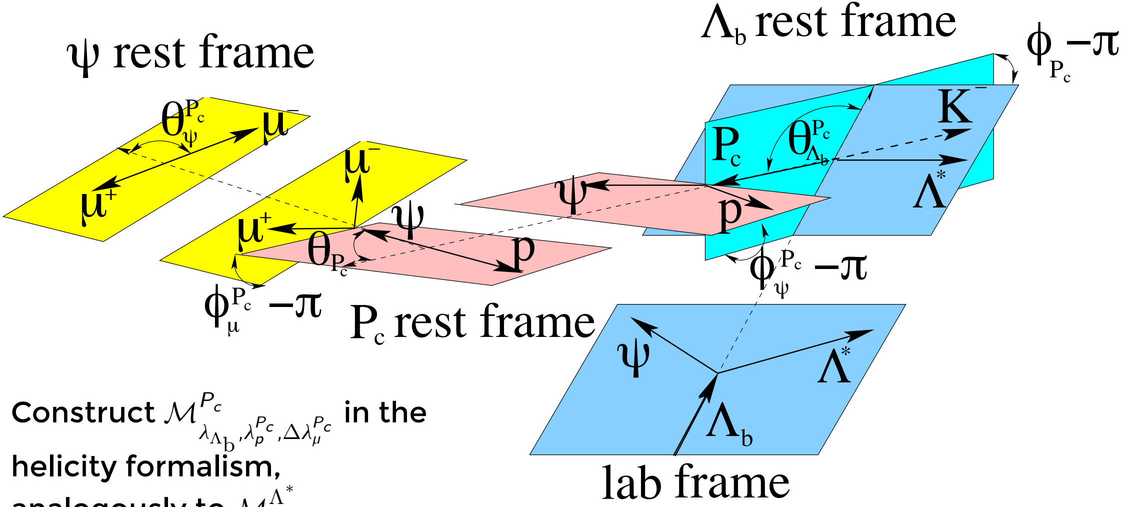
Results with only Λ^* States

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 $m_{J/\psi p}$

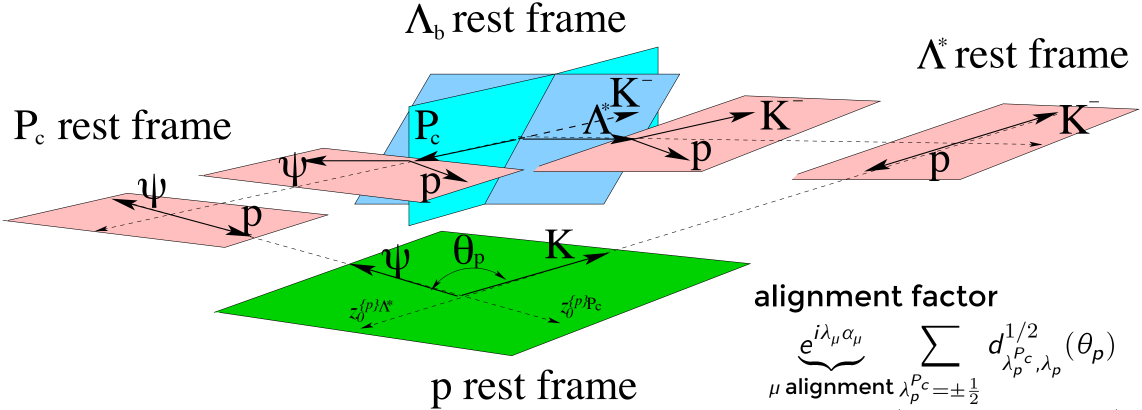
Adding Helicity Amplitudes for $\Lambda_b \to P_c K$



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

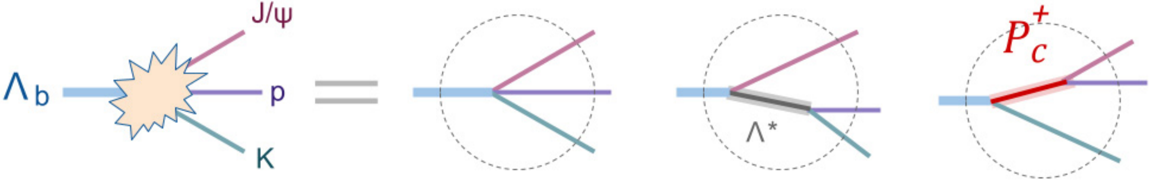
Helicities of final state particle have to be evaluated in the same reference system!



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 $\Lambda_b \to P_c K$

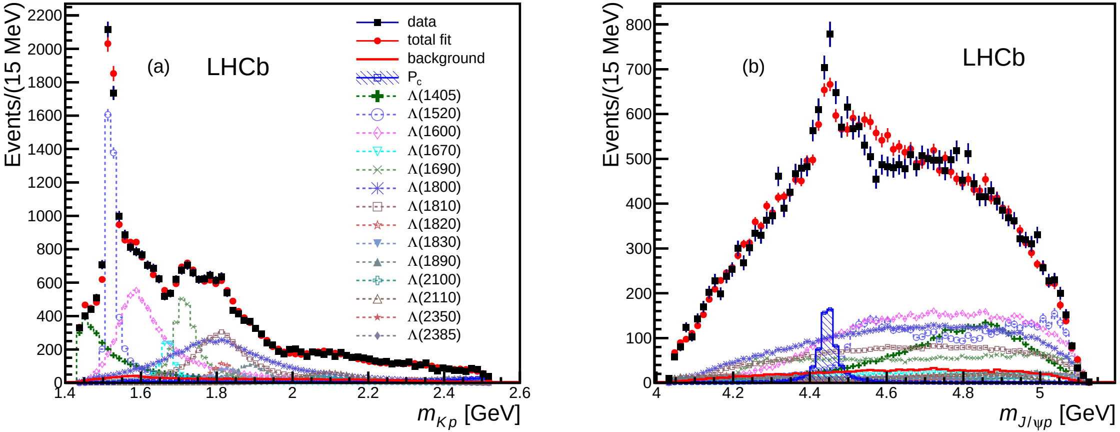


- Coherent sum over amplitudes, incoherent sum over external helicities

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

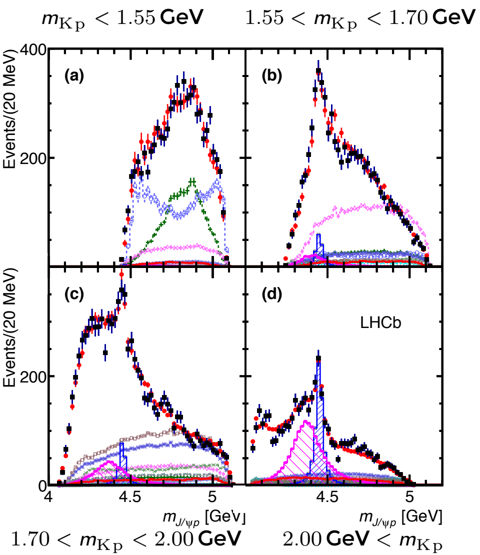
Results with One $\mathrm{J}/\psi\ \mathrm{p}$ Resonance

Extended Λ^* model + 1 $\mathrm{J}/\psi\ \mathrm{p}$ resonance (floating mass and width, $J^P = 5/2^+$)

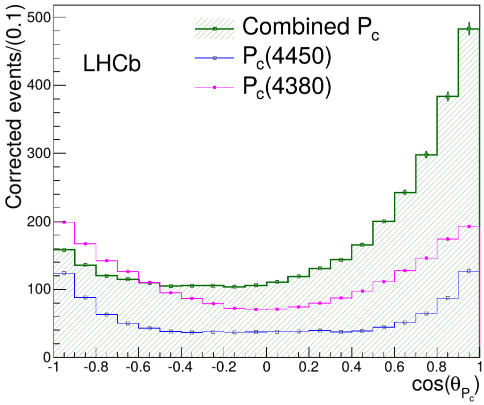


Improvement w.r.t to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$

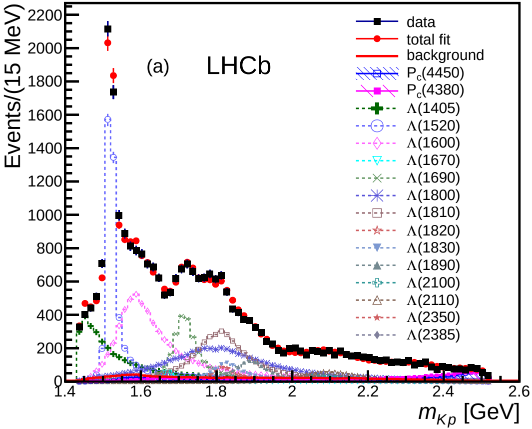
Why a second state with opposing parity?

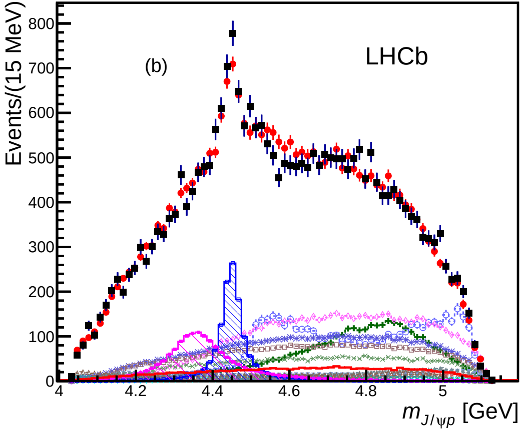


- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of m_{Kp} (or $\cos\theta_{P_c}$)
- This can be explained by interference of two states with opposing parity



Results with 2 J/ψ p Resonances



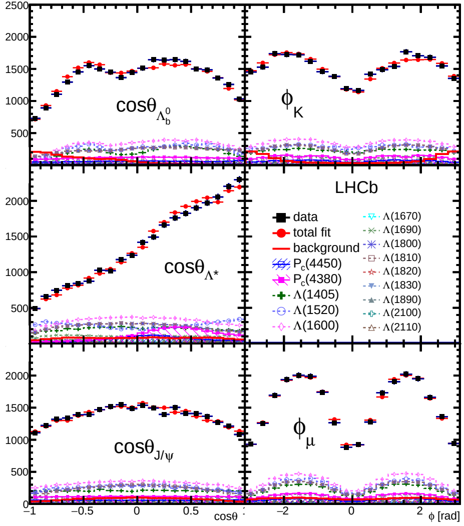


Improvement w.r.t to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 18.7\sigma$

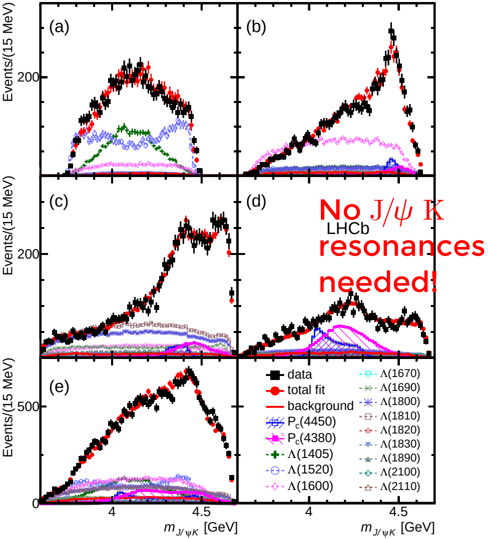
Adding further P_c states did not improve the fit significantly

Fit describes data well in all variables

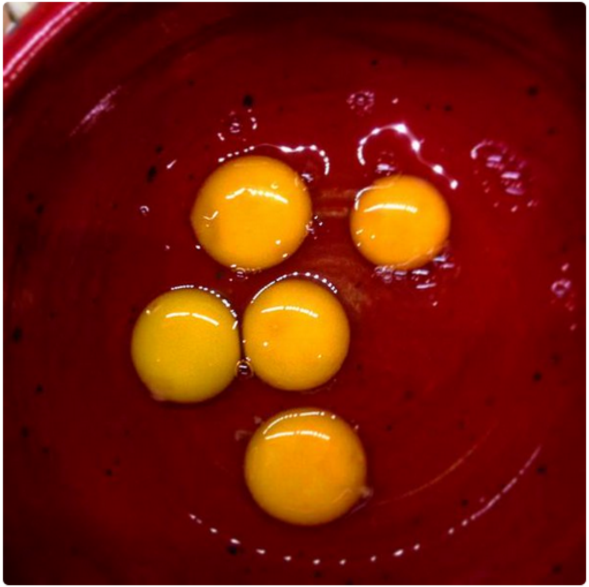
Angular distributions



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



amarsollier @amarsollier · Jul 13



Extracted Resonance Parameters

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

- Reduced fit model used for central values
- Significances evaluated on Toy-MC samples: $-2\ln\mathcal{L}$ distributions consistent with χ^2 distribution → 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

$\vdots$

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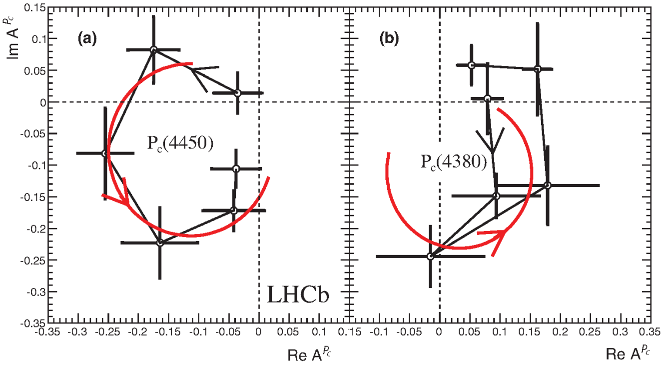
$\vdots$

- Λ^* states fit-fractions:

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

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)

Interpretations

Inspirations

Pentaquarks are not a new idea

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q q q)$, $(q q q q \bar{q})$, etc., while mesons are made out of $(q \bar{q})$, $(q q \bar{q} \bar{q})$, etc. It is assuming that the lowest baryon configuration $(q q q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q \bar{q})$ similarly gives just **1** and **8**.

Pentaquarks are not a new idea

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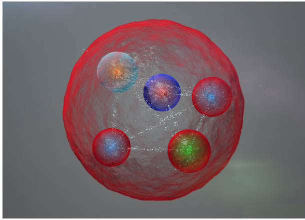
All previous searches have failed

Historical account:
"On the conundrum of the pentaquark"
EPJ H37(2012)1

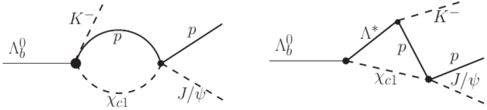
What causes these resonant structures in $J/\psi\ p$?

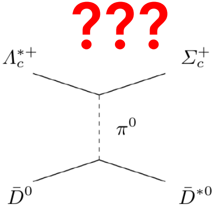


- Valence quark content: $uudc\bar{c}$
- What are the relevant degrees of freedom?

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

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

Rescattering effects:

- $\chi_{c1}(1P)p$ rescattering ↪ arXiv:1507.04950
- $D^*, D_s{}^*, \Sigma_c$ 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
- Hadrocharmonium ↪ arXiv:1508.00888

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:

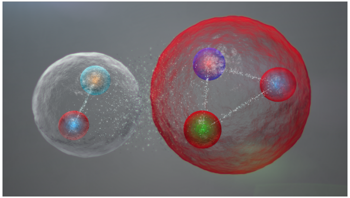
- Bottom baryon decays ↪ arXiv:1509.03708

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

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

Meson-Baryon degrees of freedom following ↪ arXiv:1509.02460

- Proximity of thresholds makes two-body contributions unavoidable



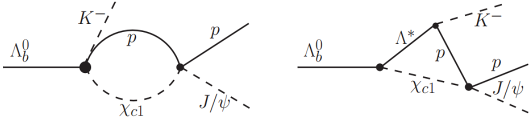
Closeby thresholds

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

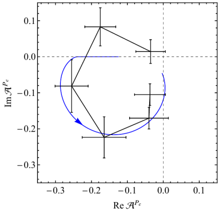
Channel	$\chi_{c1}(1\mathrm{P})$ p $\quad \Lambda_c^{+*}\overline{\mathrm{D}}$	$\Sigma_c^*\overline{\mathrm{D}}/\Sigma_c\overline{\mathrm{D}}^*$	$\mathrm{J}/\psi N(1440/1520)$
Features	phase-motion of $P_c(4450)$	Pion exchange	opposite parity with S-wave for both states
Exp.Sign.	Decays to direct channels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

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

- **Guo et al** ↪ `arXiv:1507.04950`

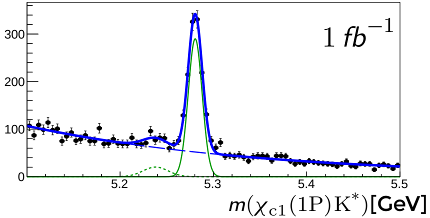


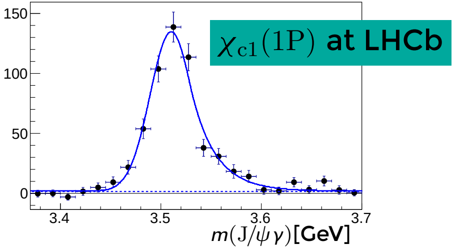
- can explain $P_c(4450)$ phase motion



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

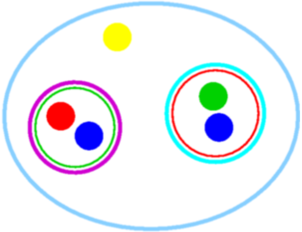
$B \to \chi_{c1}(1P) K^*$
↪ `arXiv:1305.6511`





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

- 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**



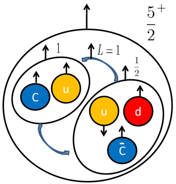
$P_c(4380)$	$\frac{3}{2}^-$	$\{\bar{c}[cq]_{s=1}[qq]_{s=1}, \ell = 0\}$
$P_c(4450)$	$\frac{5}{2}^+$	$\{\bar{c}[cq]_{s=1}[qq]_{s=0}, \ell = 1\}$

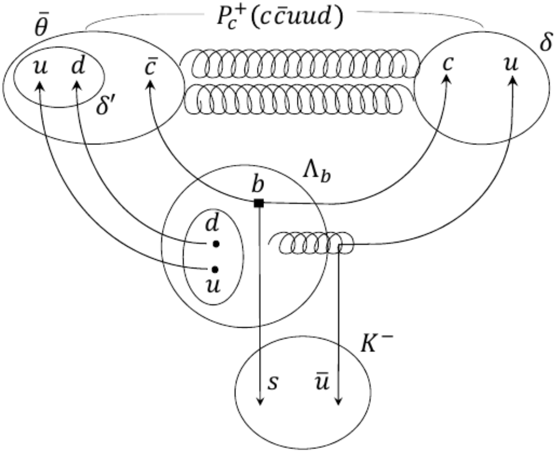
- Can explain the small mass gap!

Dynamical Di-Quark Picture

↪ arXiv:1507:05867

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





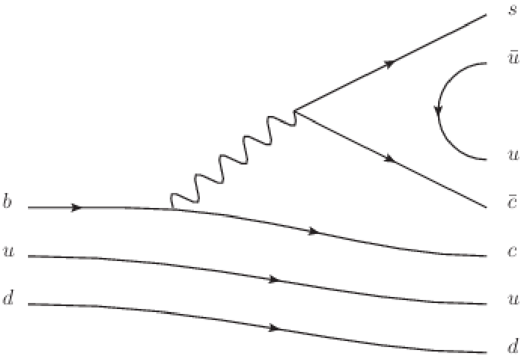
- Rapidly expanding system
- Can't hadronise by fluxtube breaking
- Decay through wavefunction overlap with daughters
- J/ψ as well as Λ_c^+ are compact
- Explains narrow width!

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

Pentaquark Isospin Multiplet?

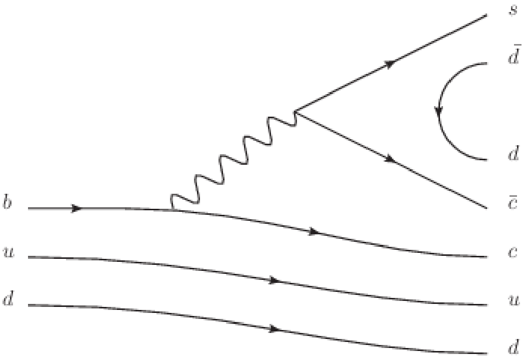
The observed pentaquark

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



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

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



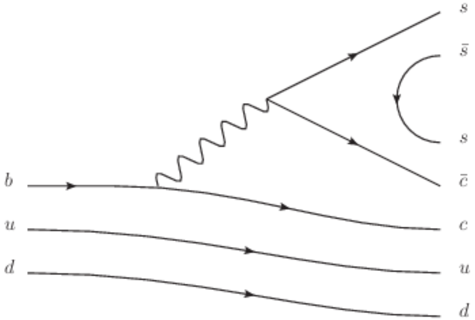
Neutron in the final state or 4-body $J/\psi\ p\ \pi^-\ K_S^0$

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

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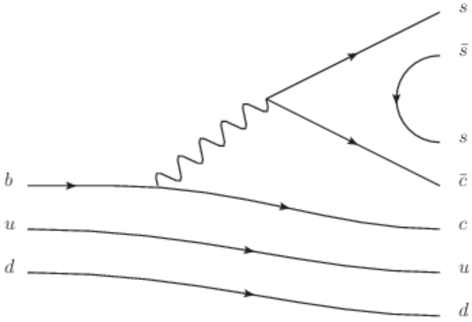
$$\Lambda_b \to P_{cs}^0 \phi \to J/\psi \Lambda \phi$$



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

Di-quark model suggestions

Maiani et al ↪ arXiv:1507.04980

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

A Program for Baryon Spectroscopy

$P_c(4380)$ & $P_c(4450)$: 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 $P_c \to J/\psi p$ as subsystems in different final states
  - $\Lambda_b \to J/\psi\ p\ \pi$
  - $\Upsilon \to J/\psi\ p\ \overline{p}$
  - $\Lambda_b \to J/\psi\ p\ \pi\ K^0_S$
- Confirmation by other experiments urgently needed!
- Search for new decay modes of P_c
  - $\Lambda_b \to \chi_{c1}(1P)\ p\ K$
  - $\Lambda_b \to \Lambda_c^+\ \overline{D}^0\ K$

Are there more of their kind?

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

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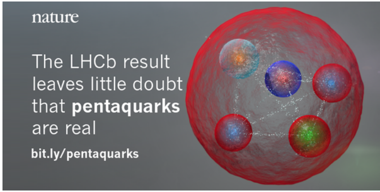
Are there more of their kind?

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

All modes unobserved so far!

Summary: First observation of $J/\psi\, p$ resonances

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



Backup

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`.

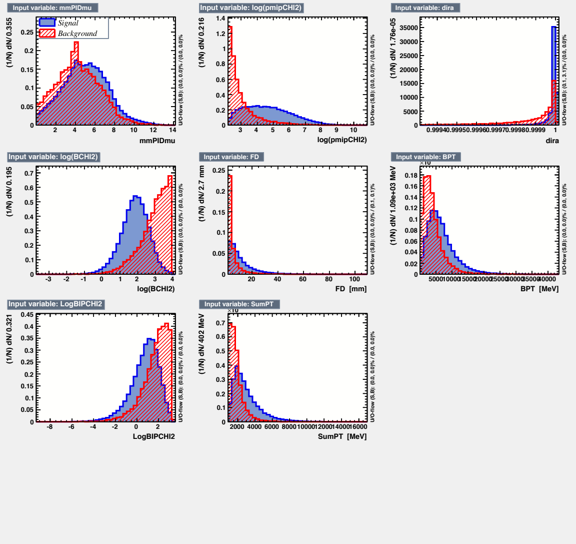
#	Selection variables	Requirements
1	All tracks χ^2/ndof	< 4
2	Muon PID	DLL$(\mu - \pi) > 0$
3	PT of muon	> 550 MeV
4	PT of hadron	> 250 MeV
5	J/ψ vertex χ^2	< 16
6	J/ψ mass window	$-48 < m(\mu^+\mu^-) - m(\mathrm{J}/\psi) < 43$ MeV
7	Hadron χ^2_{IP}	> 9
8	K^- ID	DLL$(K - \pi) > 0$ and DLL$(p - K) <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

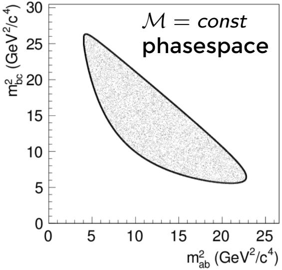
- Coherent sum over amplitudes, incoherent sum over external helicities
- Set Λ_b polarisation to 0

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

all particles spin 0:

$$X \rightarrow ABC$$

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

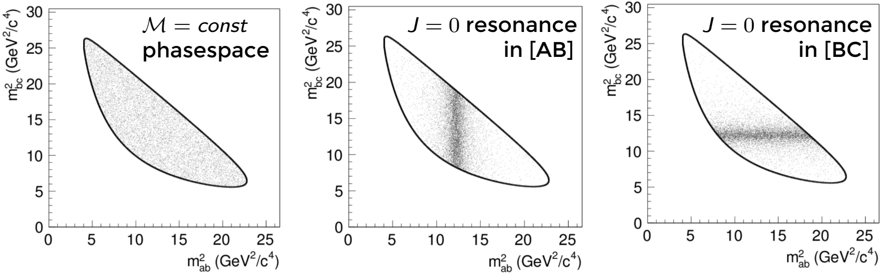


plots by Antimo Palano

all particles spin 0:

$$X \to ABC$$

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



plots by Antimo Palano

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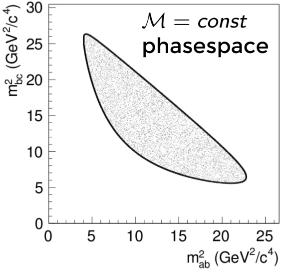

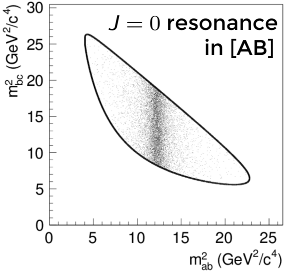

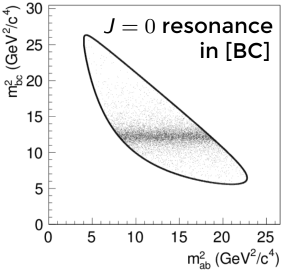

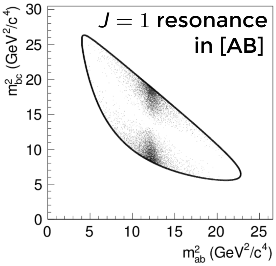

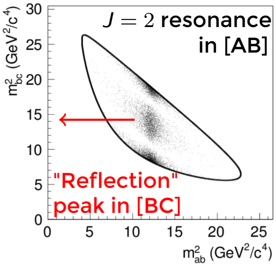

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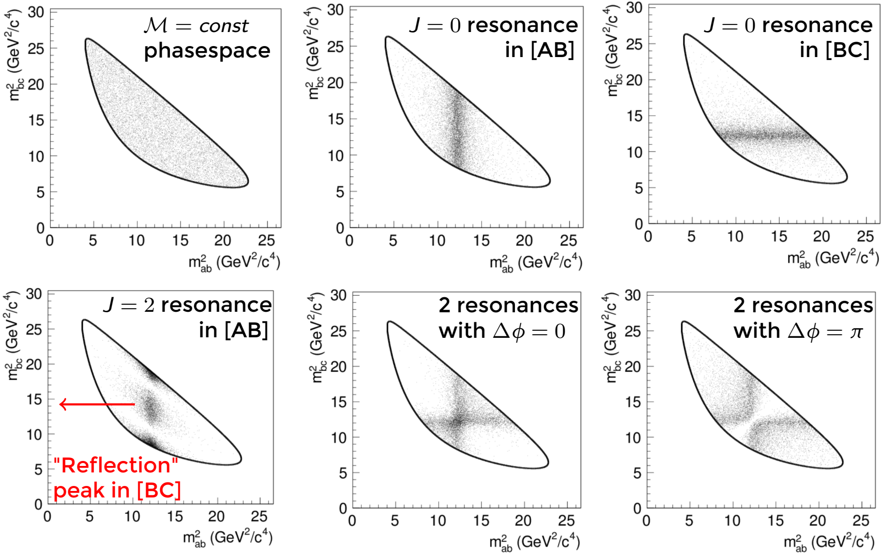
Reminder: 3-body decays and Dalitz-Plots

all particles spin 0:

$$X \to ABC$$

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



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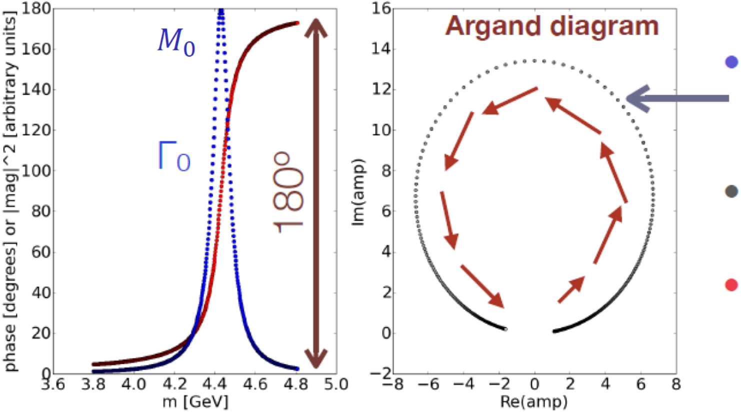
Phasemotion of Breit-Wigner Resonances



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