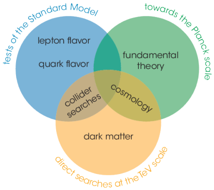
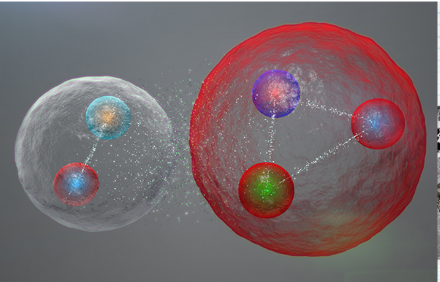
RTG students lecture
II - Pentaquark candidates at LHCb

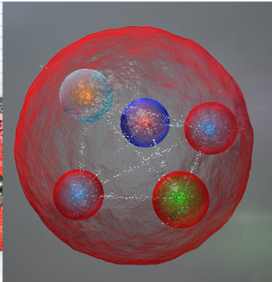


Marian Stahl

December 05th, 2016

[PRL 115 072001], [PRL 117 082002], [PRL 117 082003]

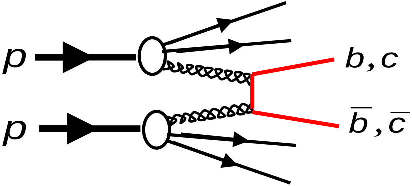




Lessons

1. Pentaquark is a loaded word with a long history
2. Bumps can come and go (also at 750 GeV/c^2)
3. Pentaquarks have done so twice already

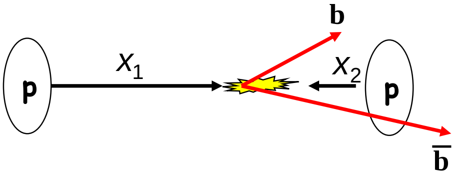
[U. Uwer, Erice 2015]

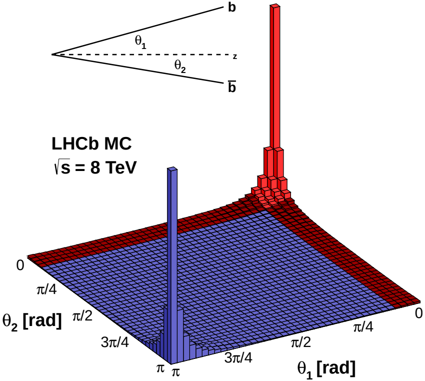


Run 2011-2012: 3 fb^{-1} (LHCb)

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

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





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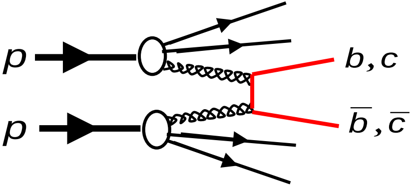

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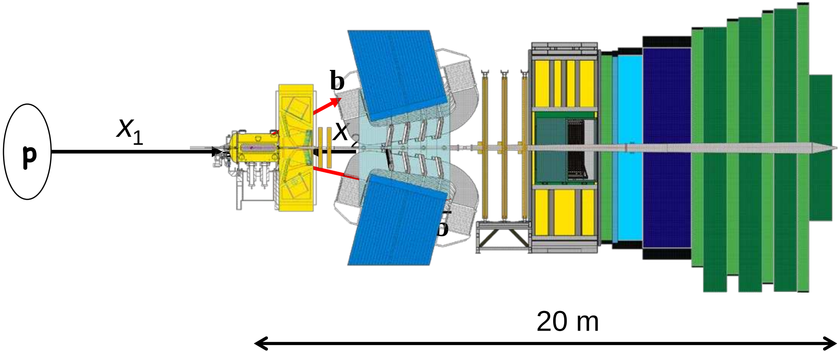
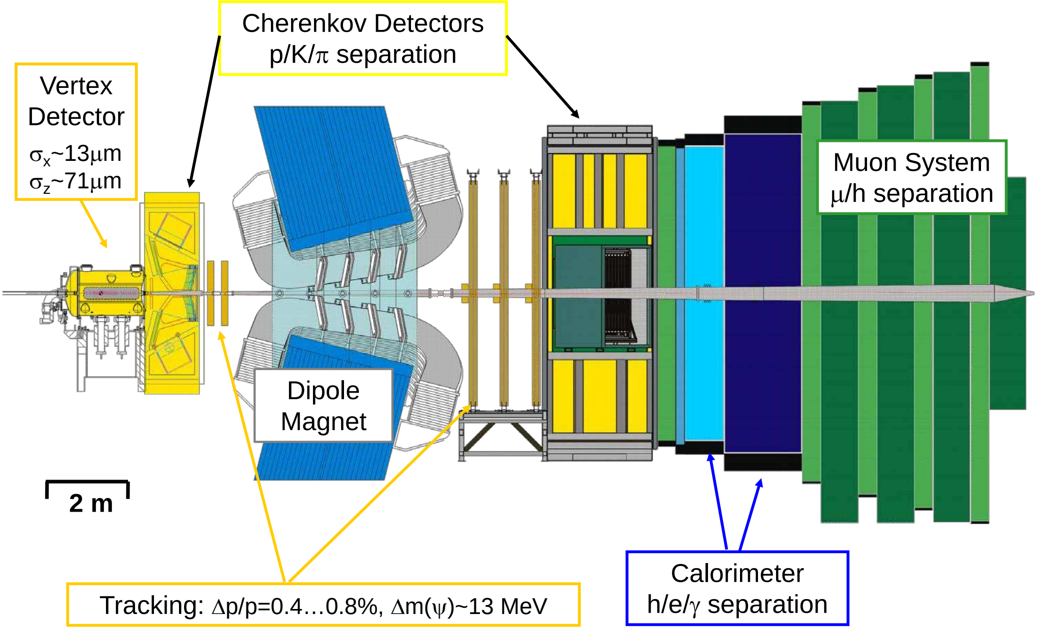
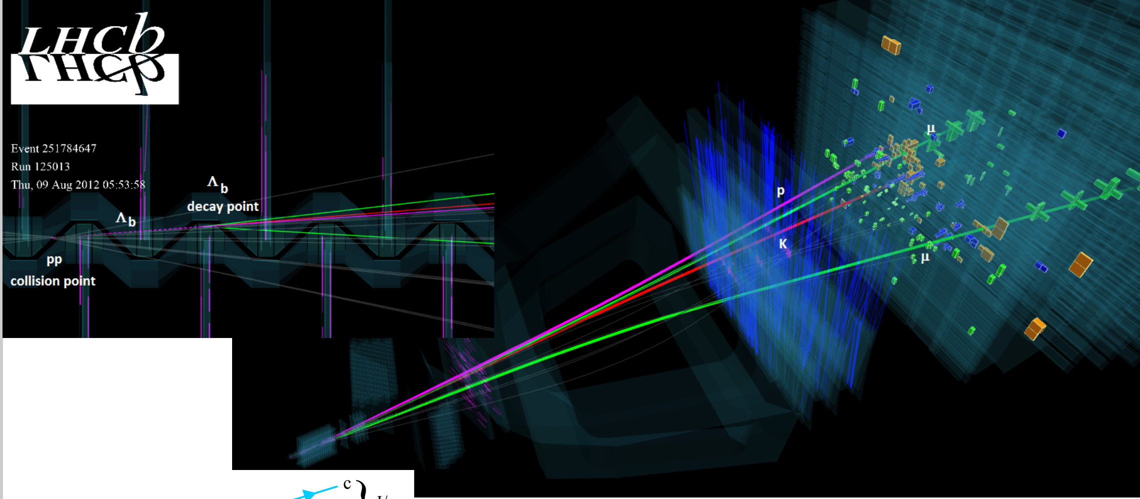
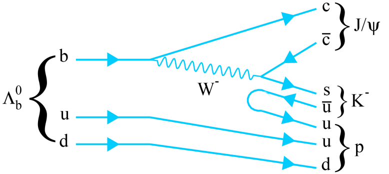


The LHCb Detector

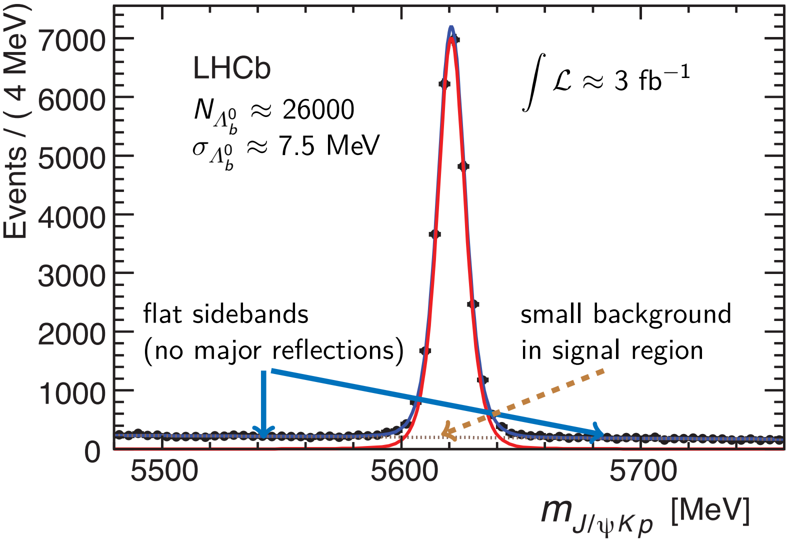


$\Lambda_b^0 \to J/\psi p K^-$ Selection



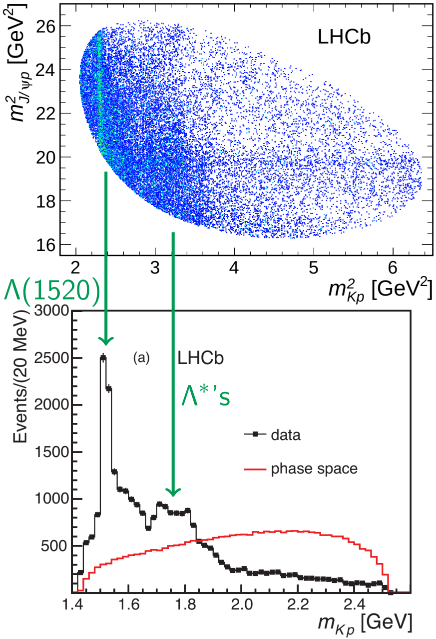


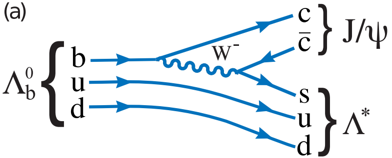
- "Standard" selection using decay chain fitting [NIM A 552 566] and Multi-Variate-Analysis [arXiv:0703039]



- Initial goal: measurement of Λ_b^0 lifetime [PRL 111 102003]
- $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.04^{+0.55}_{-0.43}) \times 10^{-4}$ [Chin. Phys. C40, 011001]

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





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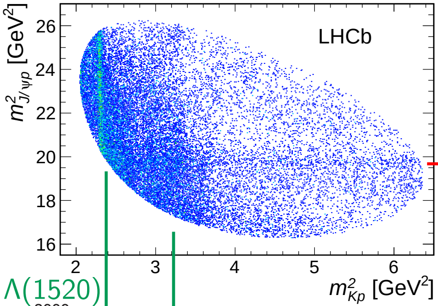
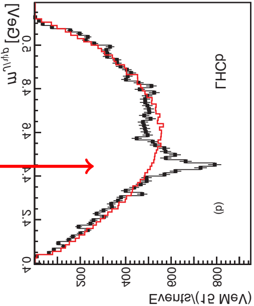
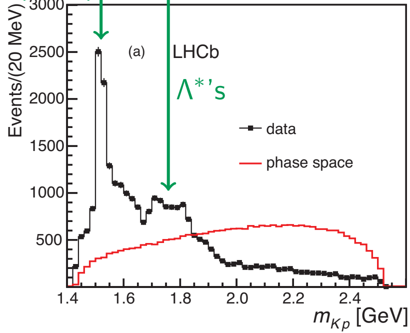
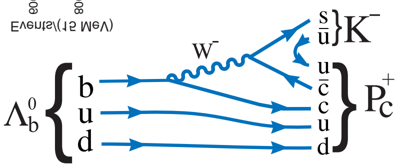
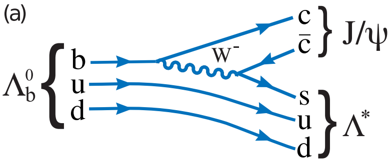




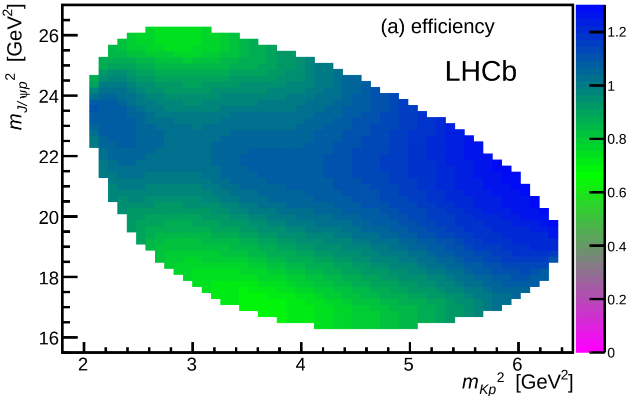
High rate, narrow structure
$\Rightarrow$ N^* excluded
(needs $V_{ub} \cdot V_{us}$ and
$c\bar{c}$ from vaccuum)





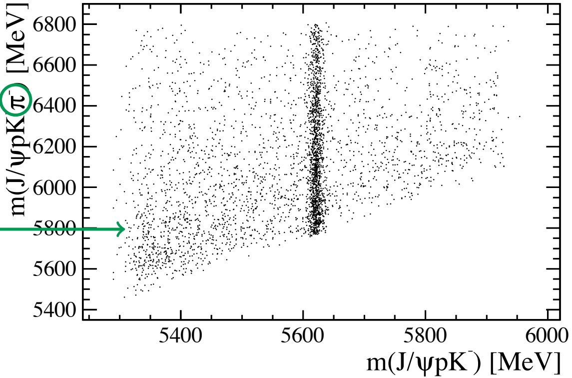


- Smooth efficiency cannot create a peak



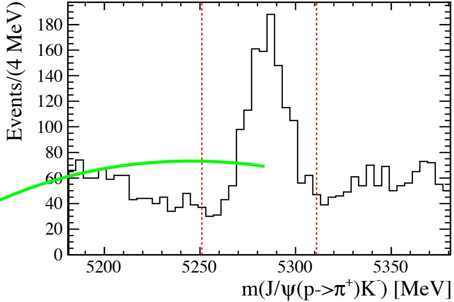
- ✓ Smooth efficiency cannot create a peak
- Feed-down from higher b-baryons ruled out

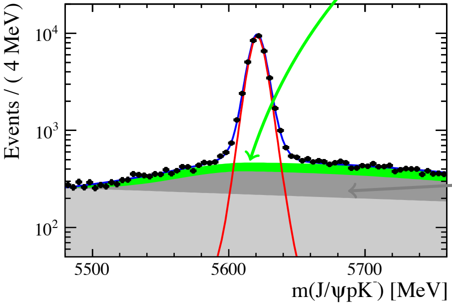
No Ξ_b^-

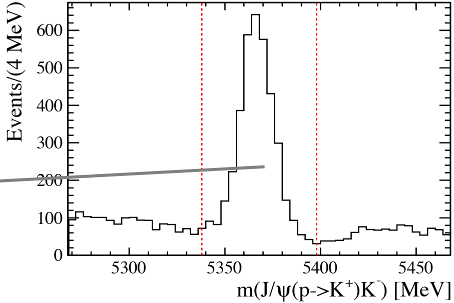


Is the Structure due to an Artefact?

- ✓ Smooth efficiency cannot create a peak
- ✓ Feed-down from higher b-baryons ruled out
- Veto against $\bar{B}_s^0 \to J/\psi K^- K^+$ and $\bar{B}^0 \to J/\psi K^- \pi^+$ from $p \to K^+/\pi^+$ misID







Is the Structure due to an Artefact?

- ✓ Smooth efficiency cannot create a peak
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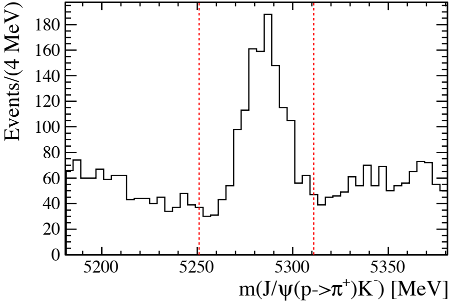
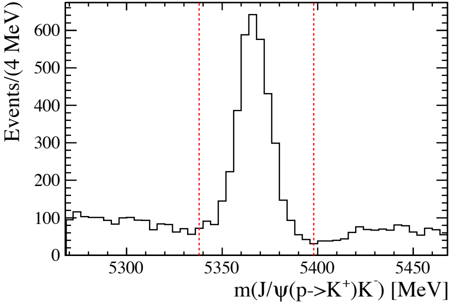
- ✓ Veto against $\bar{B}_s^0 \to J/\psi K^- K^+$ and $\bar{B}^0 \to J/\psi K^- \pi^+$ from $p \to K^+/\pi^+$ misID
- ✓ Cross-checked by different analysis-teams
- ✓ Tested against selection artefacts
- ✓ Checked against clones/ghost-tracks



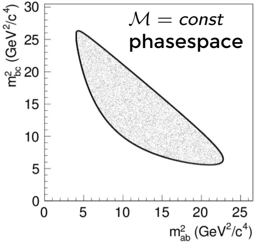


Three-body decays and Dalitz-Plots

all particles spin 0:

$$X \to ABC$$

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



plots by Antimo Palano

Three-body decays and Dalitz-Plots

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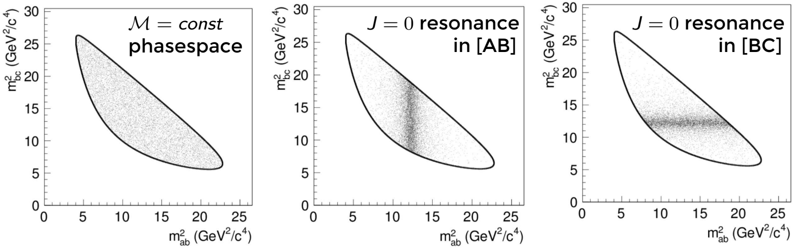

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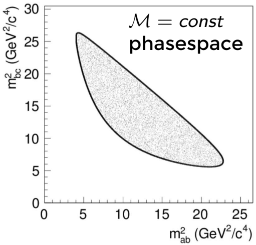

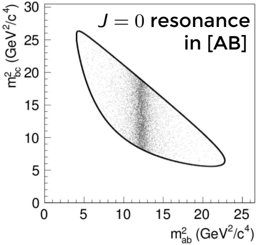

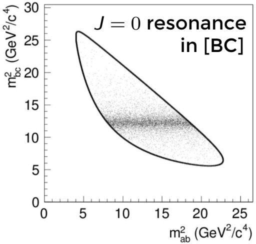

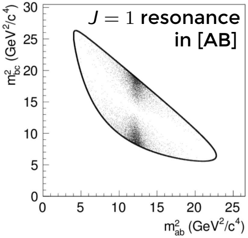

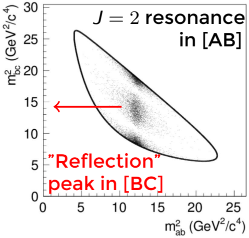

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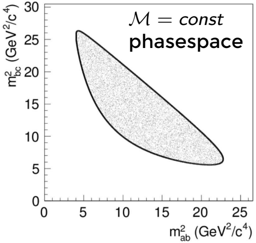
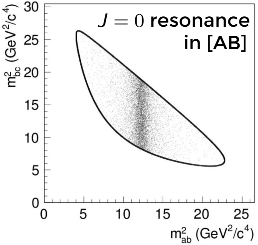
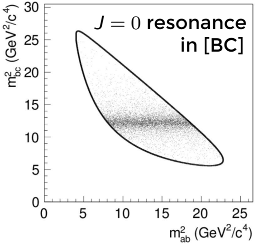
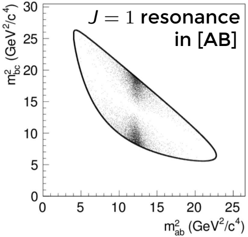
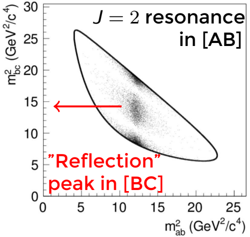
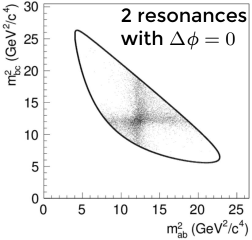


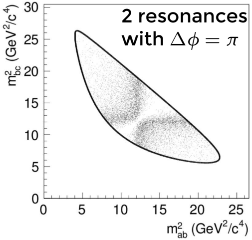












plots by Antimo Palano

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

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

Normalization integral

Matrix element for Λ_b^0 decay (on next slides)

Phase space factor

- Background handled by conventional sideband subtraction ***cFit*** or signal unfolding using *sPlot* [NIM A 555, 356] ***sFit***

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

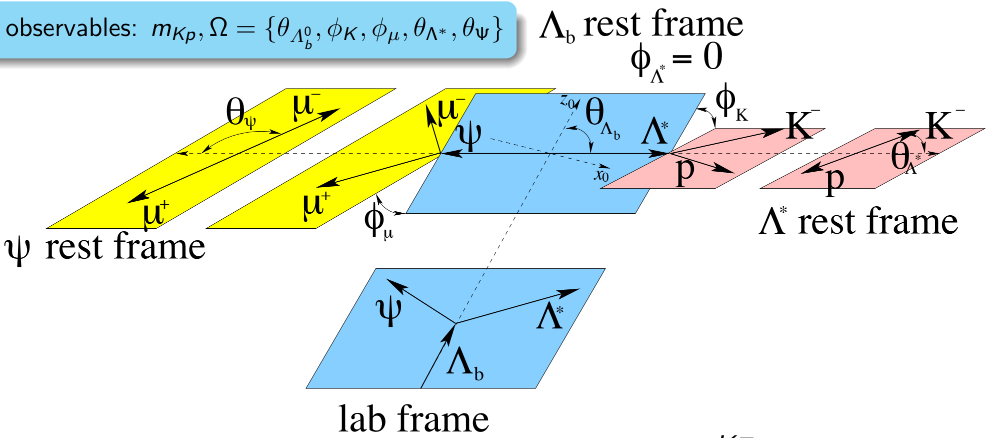
$$-2 \ln \mathcal{L}(\omega) = -2 \frac{\sum_i w_i}{\sum_i w_i^2} \sum_i w_i \ln \mathcal{P}(m_{Kp,i}, \Omega_i|\omega)$$

$$w_i = 1$$

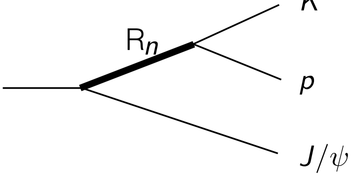
- Fits coded independently for cross-check

$\beta = 5.4\%$

Fit observables: $m_{Kp}, \Omega = \{\theta_{\Lambda_b^0}, \phi_K, \phi_\mu, \theta_{\Lambda^*}, \theta_\Psi\}$



$$\mathcal{M} \propto \sum_n c_R e^{i\theta_R} \times \mathrm{M}$$



The matrix element of the $\Lambda_b^0 \to J/\psi\Lambda^*$ decay chain is given by:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} = \sum_n R_n(m_{Kp}) \, \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p} \sum_{\lambda_\psi} e^{i\,\lambda_\psi\phi_\mu} \, d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi) \times$$

$$\sum_{\lambda_{\Lambda_n^*}} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\,\lambda_\psi} \, e^{i\,\lambda_{\Lambda^*}\phi_K} \, d^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\,\lambda_{\Lambda_n^*}-\lambda_\psi}(\theta_{\Lambda_b^0}) \, d^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\theta_{\Lambda_n^*})$$

- Λ^* resonances (masses/widths) modelled by Breit-Wigner amplitudes
- Helicity couplings for Λ^* and Λ_b decays (4-6 complex fit parameters per amplitude)
- Angular structure of Λ_b^0, J/ψ and Λ^* decays (no free parameters)

State	J^P	PDG class	Mass (MeV)	Γ (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	****	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	****	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	***	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	****	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	****	1690	60	5	6
$\Lambda(1710)$	$1/2^+$	*	1713 ± 13	180 ± 40	0	0
$\Lambda(1800)$	$1/2^-$	***	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	***	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	****	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	****	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	****	1890	100	3	6
$\Lambda(2000)$	?	*	≈2000	?	0	0
$\Lambda(2020)$	$7/2^+$	*	≈2020	?	0	0
$\Lambda(2050)$	$3/2^-$	*	2056 ± 22	493 ± 60	0	0
$\Lambda(2100)$	$7/2^-$	****	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	***	2110	200	1	6
$\Lambda(2325)$	$3/2^-$	*	≈2325	?	0	0
$\Lambda(2350)$	$9/2^+$	***	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	**	≈2585	200	0	6

- All established Λ^* resonances included in fit

State	J^P	PDG class	Mass (MeV)	Γ (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	****	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	****	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	***	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	****	1670	35	[illegible]	[illegible]
$\Lambda(1690)$	$3/2^-$	****	1690	60	[illegible]	6
$\Lambda(1710)$	$1/2^+$	*	$1713\pm$ 13	[illegible]	[illegible]	0
$\Lambda(1800)$	$1/2^-$	***	1800	[illegible]	[illegible]	4
$\Lambda(1810)$	$1/2^+$	***	[illegible]	[illegible]	3	4
$\Lambda(1820)$	$5/2^+$	****	[illegible]	[illegible]	1	6
$\Lambda(1830)$	$5/2^-$	****	[illegible]	95	1	6
$\Lambda(1890)$	$3/2^+$	[illegible]	[illegible]	100	3	6
$\Lambda(2000)$	?	[illegible]	[illegible]	?	0	0
$\Lambda(2020)$	[illegible]	[illegible]	$\approx$2020	?	0	0
[illegible]	[illegible]	[illegible]	2056 ± 22	493 ± 60	0	0
[illegible]	[illegible]	****	2100	200	1	6
[illegible]	[illegible]	***	2110	200	1	6
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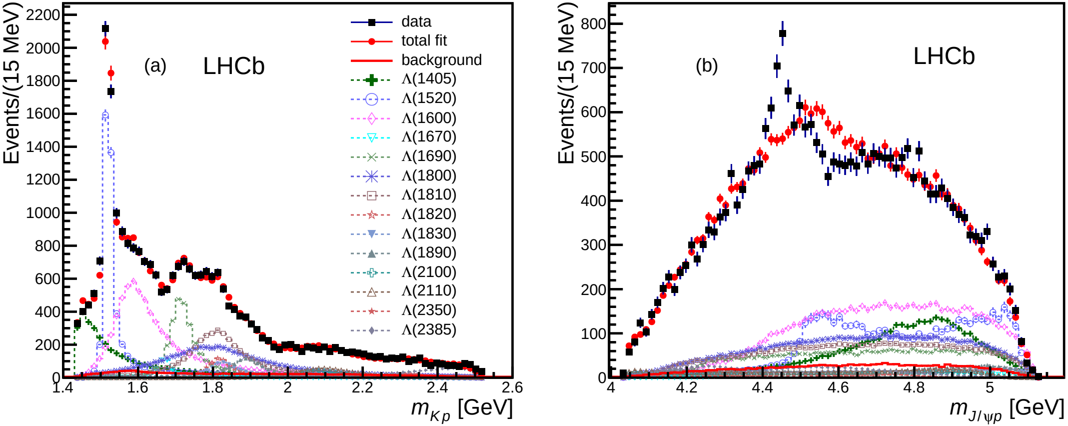
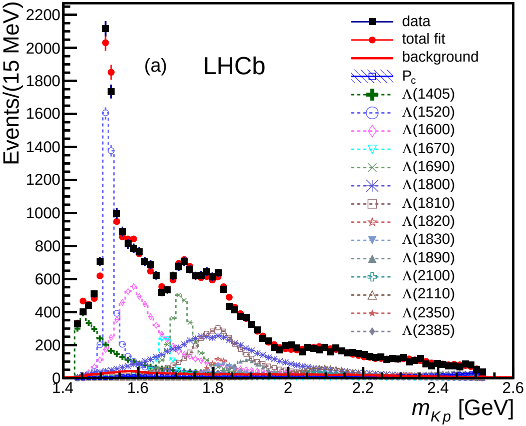
[illegible]	$9/2^+$	***	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	**	$\approx$2585	200	0	6

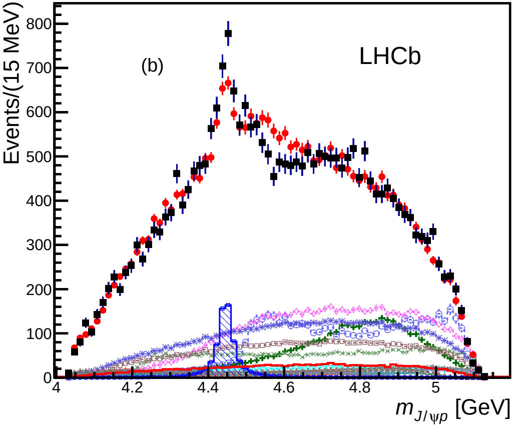
Large number of free parameters (in 6D)
$\rightsquigarrow$ computationally expensive and challenging fit

- All established Λ^* resonances included in fit



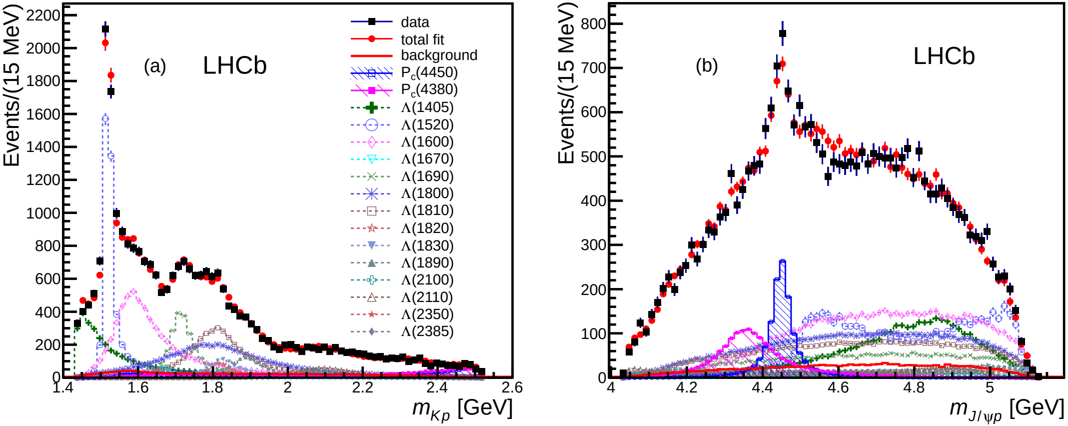
- Including non resonant components up to $J^P = 3/2^\pm$, Σ^*'s and floating masses and widths of Λ^*'s can also not describe $m_{J/\psi p}$
- Next: attempt to obtain better fit by including $m_{J/\psi p}$ resonances





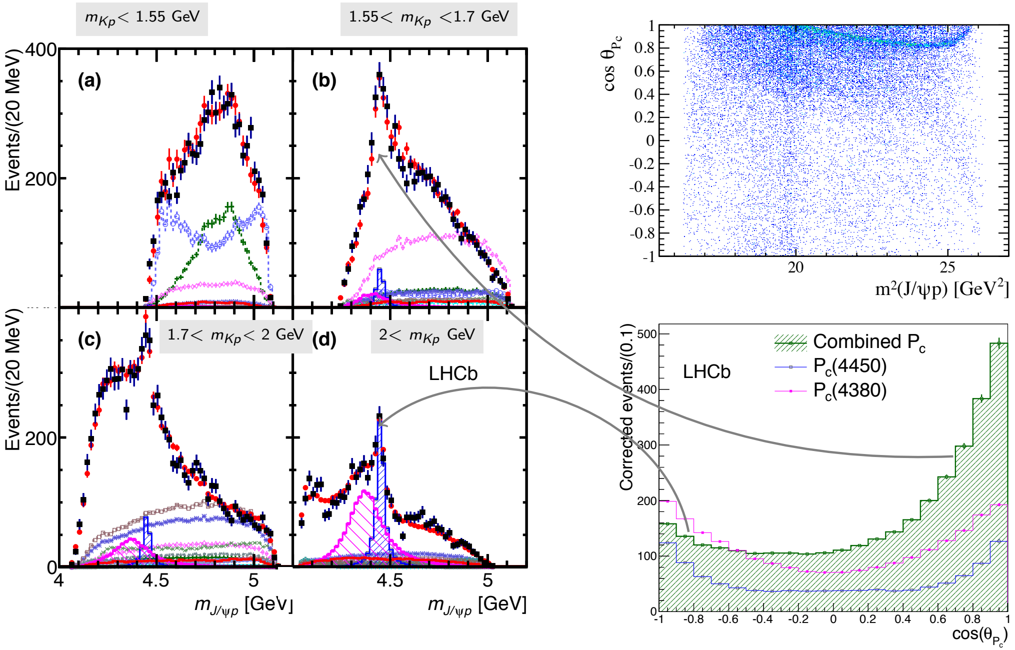
- P_c of best fit has $J^P\!=\!5/2^+$ (tried up to $J^P\!=\!7/2^\pm$)
- $\Delta(2\ln\mathcal{L}) = 14.7^2$ when adding single P_c vs. Λ^* only
- Likelihood significantly improved, but still discrepancies in $m_{J\psi p}$

Best Fit with Two P_c States



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

Preference of Opposite Parity P_c States



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

- Significances calculated by fitting test-statistic $\Delta(-2\ln\mathcal{L})$ of toyMC experiments in the extended model (the reduced model yielded higher significances)

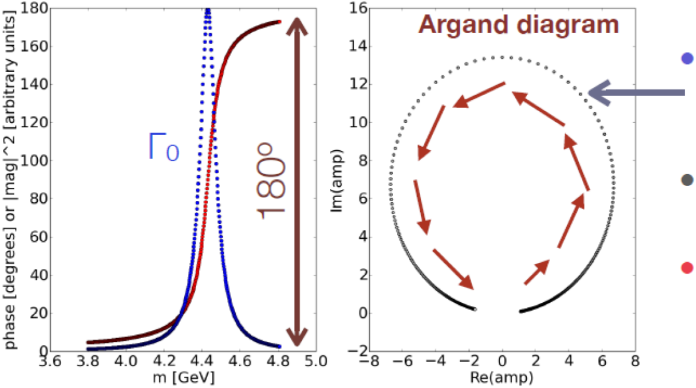
Null $\rightarrow$ Alternative Hypothesis	$\Delta(2\ln\mathcal{L})$	Significance
$0\ P_c \rightarrow 1\ P_c$	14.7^2	$12\,\sigma$
$1\ P_c \rightarrow 2\ P_c$'s	11.6^2	$9\,\sigma$
$0\ P_c \rightarrow 2\ P_c$'s	18.7^2	$15\,\sigma$

- In a separate paper, LHCb measured [Chin. Phys. C40, 011001]

$$\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-)\mathcal{B}(P_c^+ \rightarrow J/\psi p) = \begin{cases} (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} \text{ for } P_c(4380)^+ \\ (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} \text{ for } P_c(4450)^+ \end{cases}$$

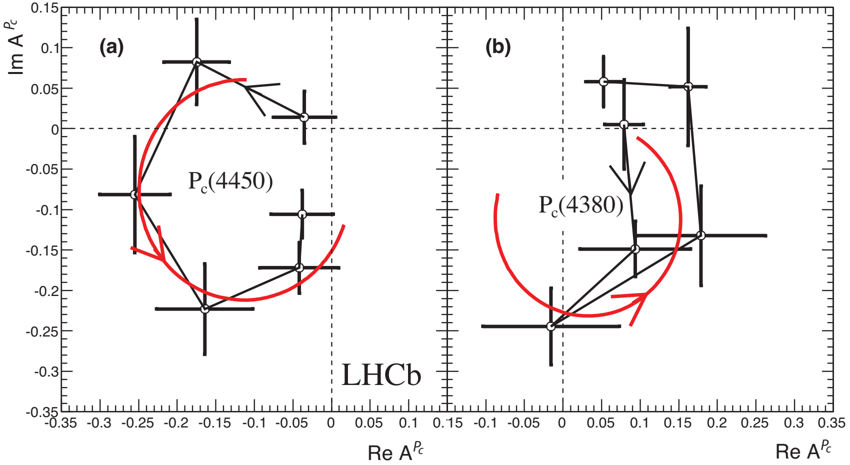
- P_c states parametrized by a relativistic Breit-Wigner amplitude.

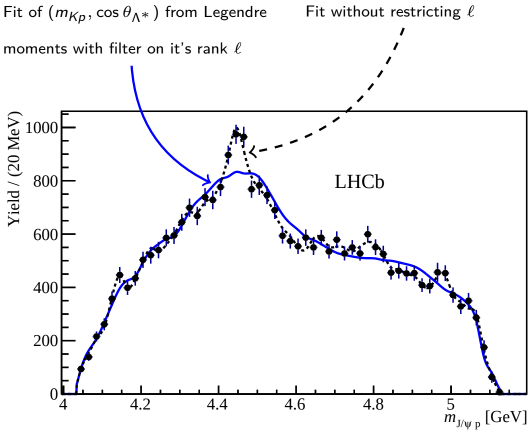
$$BW(m|m_0\Gamma_0) = \frac{1}{m_0^2 - m^2 - im_0\Gamma(m)} \text{ and } \Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L_{\Lambda^*}+1} \frac{m_0}{m} B'_{L_{\Lambda_n^*}}(q, q_0, d)^2$$

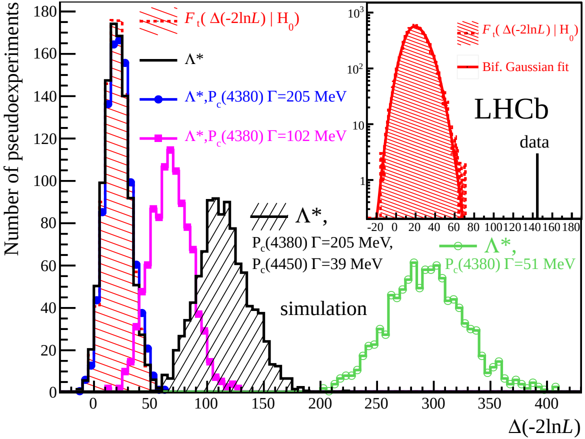


- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

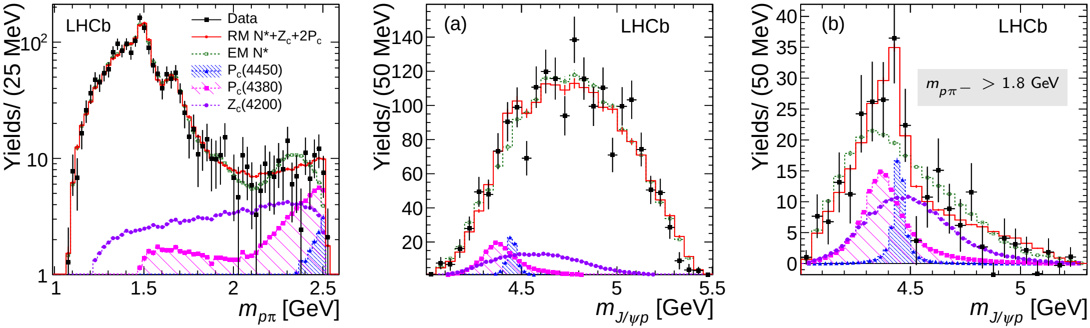
- Test resonant character by plotting Argand diagram of interpolated amplitude
  - Scan $m_{J/\psi p}$ in 6 bins around $m_0 \pm \Gamma_0$ of P_c's
  - Fit data with full model but replace Breit-Wigner parametrization of P_c with cubic spline interpolating from 4 closest neighbouring points





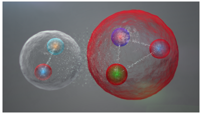


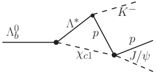
- Reject hypothesis that $m_{J/\psi p}$ can be described by model-independent fit to $(m_{K^-p}, \cos\theta_{\Lambda^*})$ subsystem by more than $9\,\sigma$
- Test not sensitive to large width of $P_c(4380)$

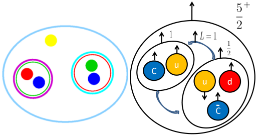


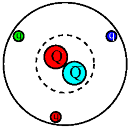
- Exotic components are needed to describe the data
- Fit is not able to disentangle P_c and $Z_c(4200)$ components
- Measurement consistent with P_c's reported in $\Lambda_b^0 \to J/\psi p K^-$

Echo from Theory Community









(List may be incomplete, not listing implications)

Molecular models:	
$P_c(4450)$ as $\Sigma_c\bar{D}^*$ molecule	PRL 115 122001
$P_c(4380)$ as $\Sigma_c\bar{D}^*$ and $P_c(4450)$ as $\Sigma_c^*\bar{D}^*$	PRL 115 132002
$P_c(4380)$ as $\Sigma_c\bar{D}^*$ and $P_c(4450)$ as $\Sigma_c^*\bar{D}$	PRL 115 172001
$P_c(4450)$ as $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ molecule	arXiv:1507.04249
P_c's not (colored) molecules	arXiv:1507.04694
$P_c(4380)$ as $\Sigma_c^*\bar{D}$ and $P_c(4450)$ as $\Sigma_c\bar{D}^*$	arXiv:1507.05200
$P_c(4450)$ as $\chi_{c1}p$ molecule (compositeness)	arXiv:1511.00870
Rescattering effects:	
$\chi_{c1}p$ rescattering, $\Lambda(1890)\chi_{c1}p$ triangle singularity	PRD 92 071502(R),PLB 751 59
ATS, cusp effect	arXiv:1507.05359
$D^*D_s^*\Sigma_c$ triangle singularity	arXiv:1507.06552
$P_c(4380)$ rescattering, $P_c(4450)$ diquark model	arXiv:1507.07652
Diquarks/Triquarks:	
Diquark-Diquark-Antiquark ($[qq][qq]\bar{q}$)	PLB 749 289
Dynamical Diquark-Triquark	PLB 749 454
Diquark-Diquark-Antiquark multiplets	arXiv:1507.08252
Quasi particle diquarks	arXiv:1508.00356
$[qq][qq]\bar{q}$ with QCD sum rules	arXiv:1508.01468
$P_c(4380)$ as $J/\psi K$ reflection, $P_c(4450)$ as $[qq][qq]\bar{q}$	arXiv:1509.04898
Dynamical Diquark-Triquark multiplets	arXiv:1510.08693
Other:	
Bound $\bar{D}$-soliton	PRD 92 051501(R)
Intrinsic charm in Λ_b^0 decays	arXiv:1508.03910
Baryocharmonium	PRD 92 031502(R)
Phenomenology review	arXiv:1509.02460
$J/\psi K$ reflection	arXiv:1509.03028
$Z_{2,3}$ geometrical symmetries	arXiv:1509.06013

- List from November 15, now at 285 citations

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

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

Incorporate coupled channel effects in amplitude analyses

Search for other types of pentaquarks

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

At distant horizons

- Dibaryons?
- Hexaquarks?
- ...

Backup slides start here

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

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

$$R_n(m_{Kp}) = \tilde{B}^{\Lambda_b^0}_{L_{\psi\Lambda^*}} \times BW(m_{Kp}|m_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*}) \times \tilde{B}^{\Lambda^*}_{L_{pK}}$$

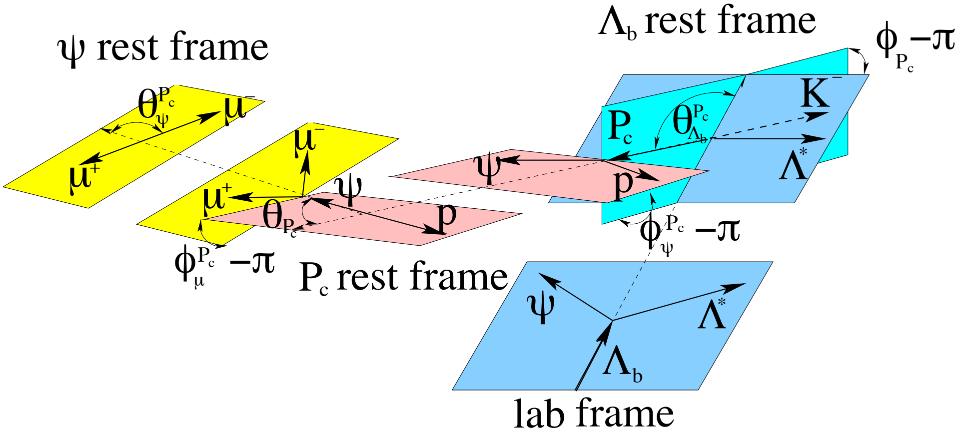
with $BW(m|m_0\Gamma_0) = \dfrac{1}{m_0^2 - m^2 - im_0\Gamma(m)}$

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

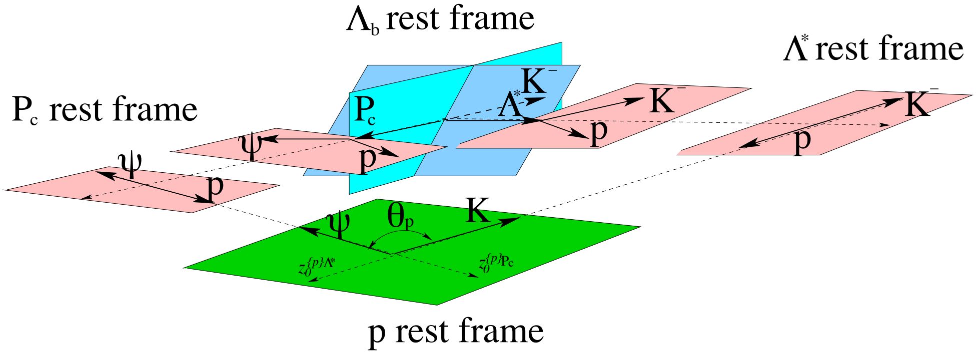
where $p(q)$ are momenta of daughters in CM frame of mother

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

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



construct $\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}}$ analogous to $\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0}, \lambda_p, \Delta\lambda_\mu}$



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

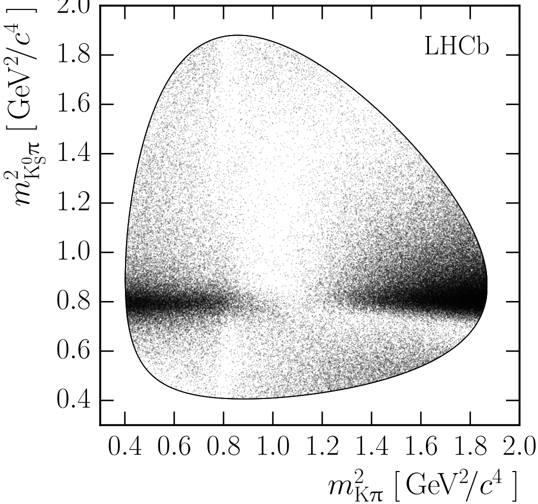
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\,\lambda_p,\,\Delta\lambda_\mu} + \underbrace{e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\,\lambda_p}(\theta_p)}_{\Lambda^* \text{ and } P_c \text{ decay chain alignment}} \; \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\,\lambda_p^{P_c},\,\Delta\lambda_\mu} \right|^2$$

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
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5$–4.5 GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+(\text{low/high})K^-$	6	0.7	4	8	0.37	0.16		
L_{P_c} $P_c^+(\text{low/high}) \to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi\Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

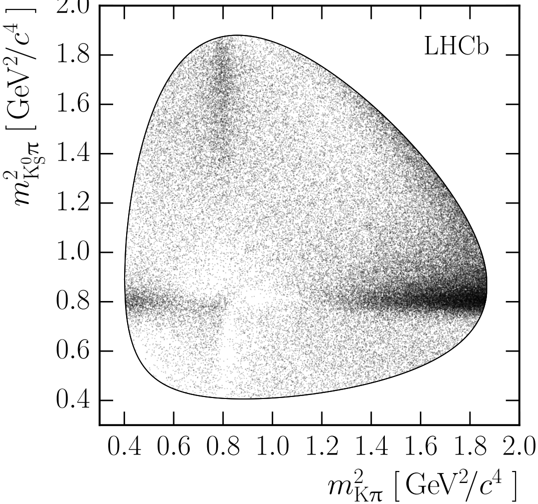
Uncertainties in Λ^* model dominate

Sizeable uncertainties from J^P assignment and resonance parametrization

[PRD 93 052018]



$D^0 \to K^0_S K^- \pi^+$



$D^0 \to K^0_S K^+ \pi^-$