Exotic hadron spectroscopy at LHCb

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Outline

- Exotic baryon resonances in $\Lambda_b^0 \to J/\psi\, pK^-$
  - Amplitude analysis and resonant caracter PRL 115 (2015) 072001
  - Model Independent confirmation arXiv:1604.05708
- NEW Search for exotic hadrons in $\Lambda_b^0 \to J/\psi\, p\pi^-$ LHCb-PAPER-2016-015
- NEW Search for exotic hadrons in $B^+ \to J/\psi\, \phi K^+$ LHCb-PAPER-2016-018 LHCb-PAPER-2016-019
- Search for $X(5568) \to B_s^0 \pi^+$ LHCb-CONF-2016-004

All results based on $3\,\mathrm{fb}^{-1}$ (Run 1)

The LHCb experiment

JINST 3 (2008) S08005

IJMP A30 (2015)1530022

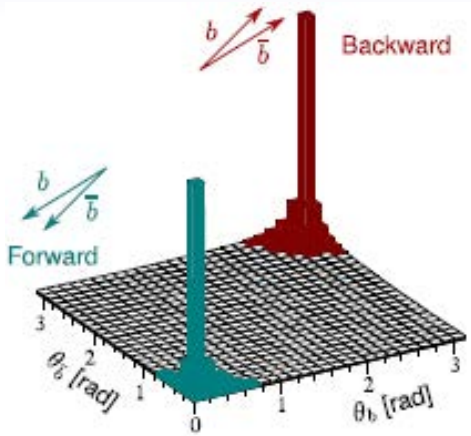
LHC has record numbers of b (and c) hadrons:

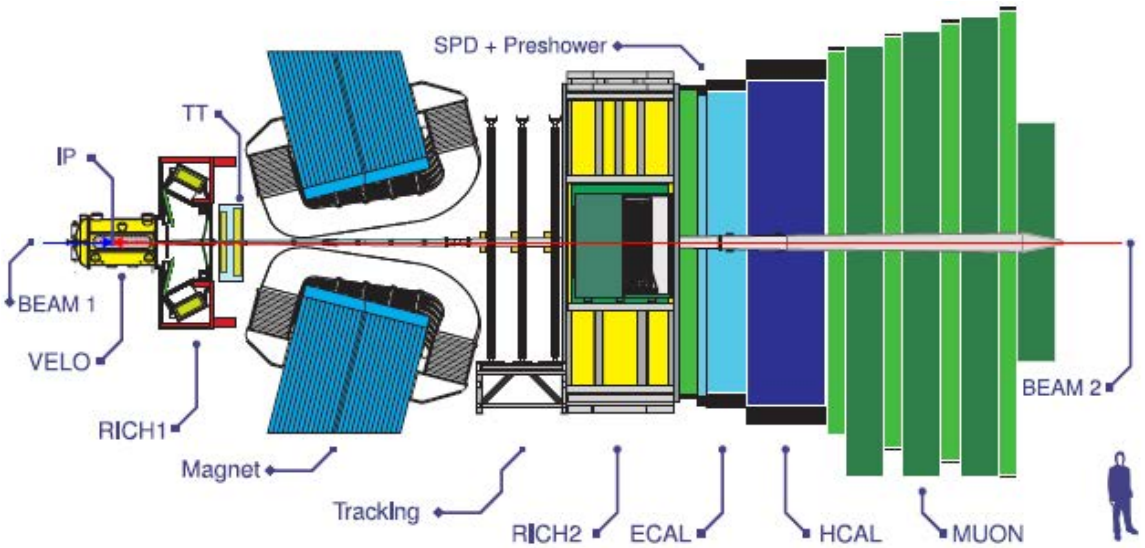
$\sigma_{b\bar{b}} \approx 250\ \mu\text{b}$ @ 7 TeV $\quad \sigma_{c\bar{c}} \approx 20 \times \sigma_{b\bar{b}}$

LHCb designed to study rare decays and CP violation in b-hadrons

ideal place also for spectroscopy

single-arm spectrometer covering the forward pseudorapidity region $2 < \eta < 5$





excellent performance:

- vertexing and tracking: good time of flight and invariant mass resolution
- PID for pions, kaons, protons and muons
- calorimeter

Trigger on high-p_t lepton or hadron from displaced vertexes

c and b-hadrons

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

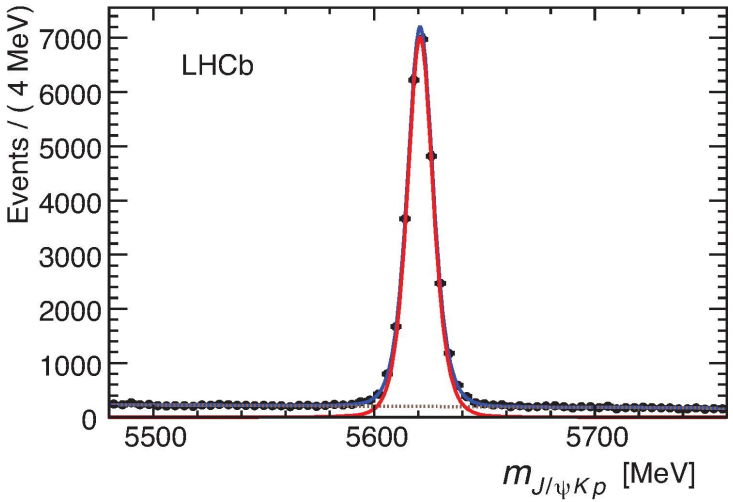
PRL 115 (2015) 072001

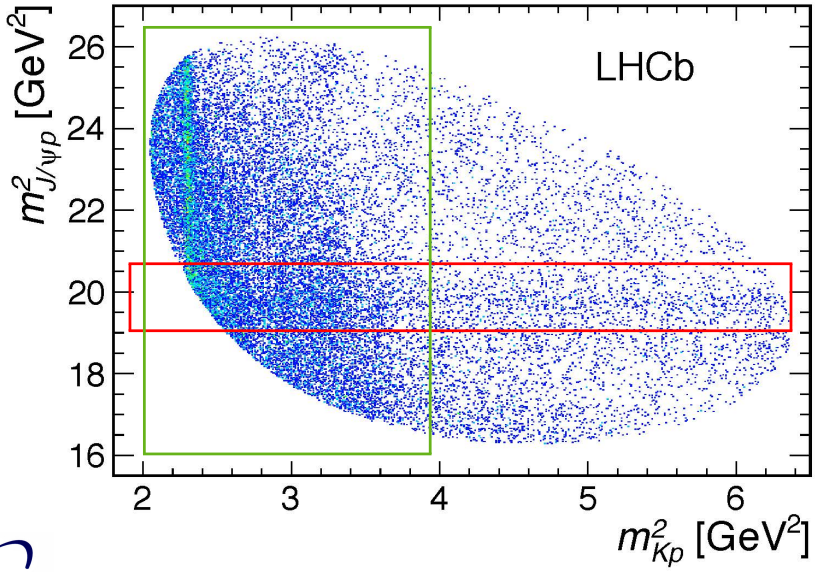
This decay mode, not observed before, found to have large rates and low background

Used to measure the Λ_b^0 lifetime with 1 fb^{-1} collected in 2011

PRL 111 (2013) 102003

Clean signal of 26,000 candidates with 5.4% background within $\pm 2\sigma$ in the whole Run 1 data sample (3 fb^{-1})





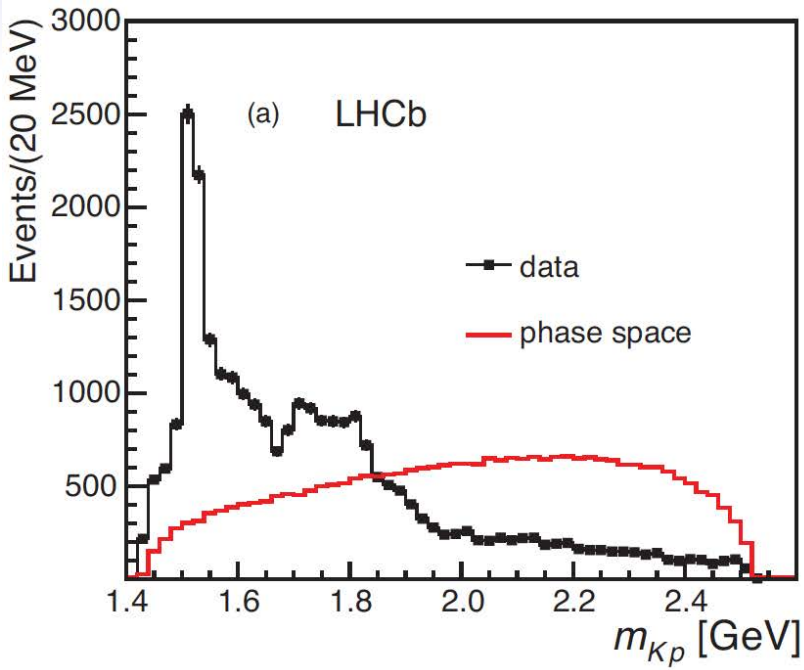
... but the Dalitz plot has unusual features:

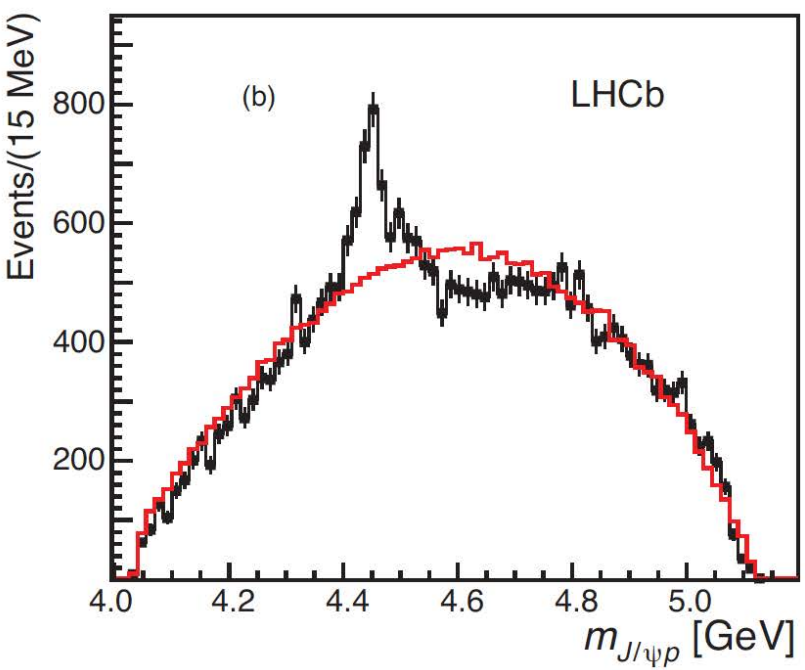
vertical bands for Λ^*'s

Horizontal band???

Dalitz plot projections

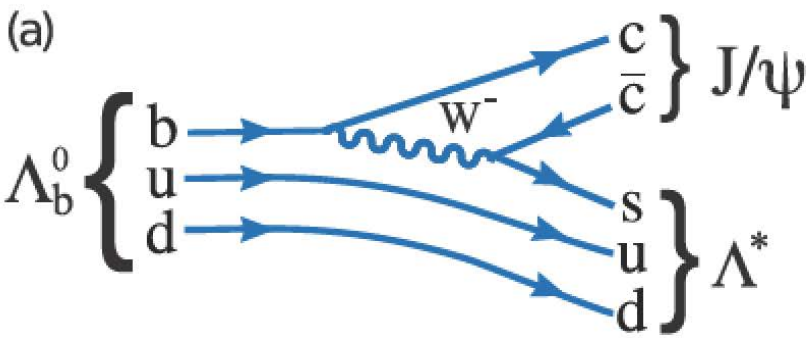
PRL 115 (2015) 072001

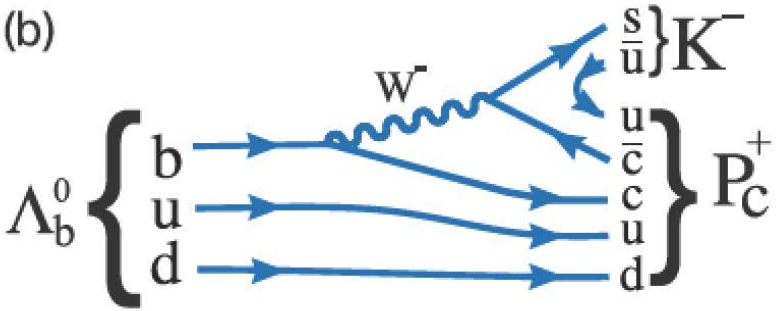




many Λ^* $\Longrightarrow$ Interference!

reflections from m(Kp)?
or exotic resonances???

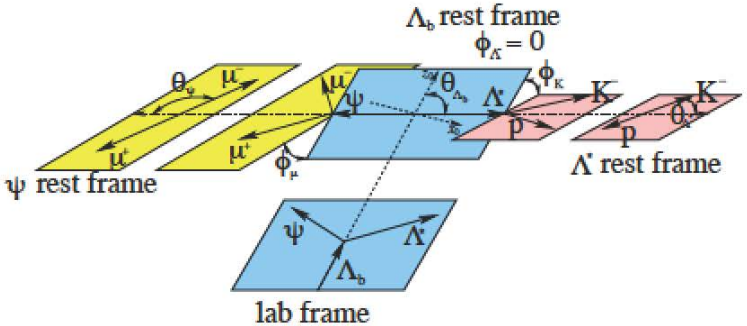




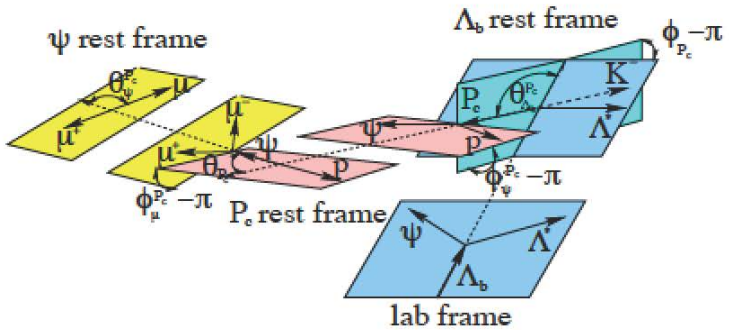
Amplitude Model

Six-dimensional amplitude fit: invariant mass, three helicity angles and two differences between decay planes. Allow for two interfering channels:

$\Lambda_b^0 \to J/\psi \Lambda^*$



$\Lambda_b^0 \to P_c^+ K^-$



all known Λ^* resonances (Extended)
or
just well motivated (Reduced)

All allowed L values

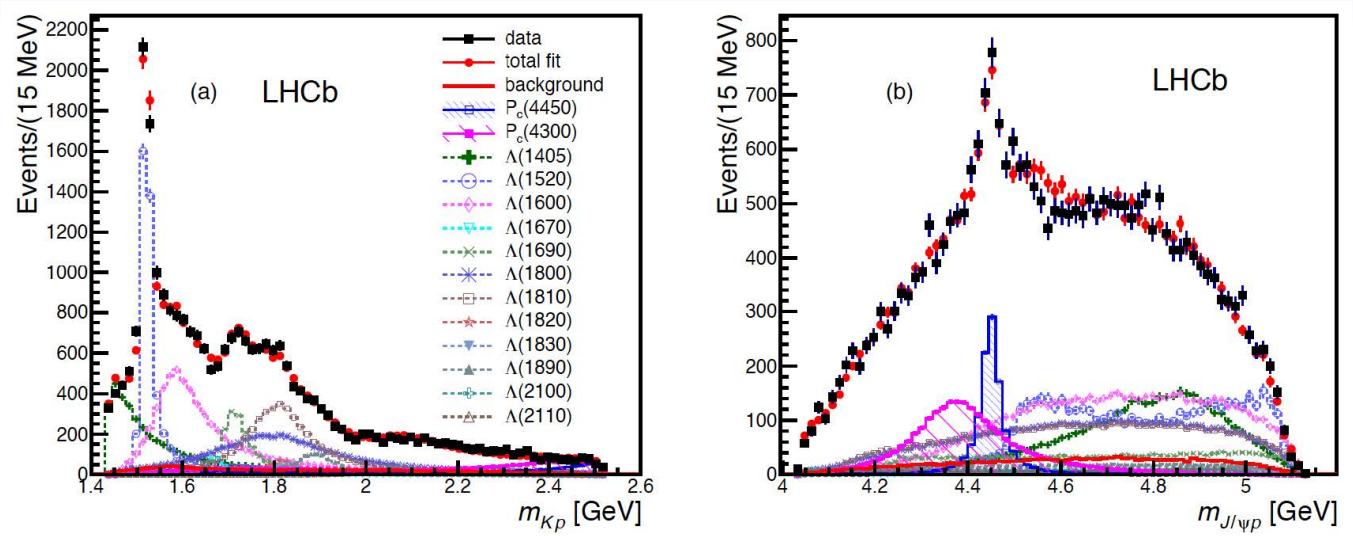
Resonance mass shape: Flatté or Breit-Wigner

Angular distribution in helicity formalism

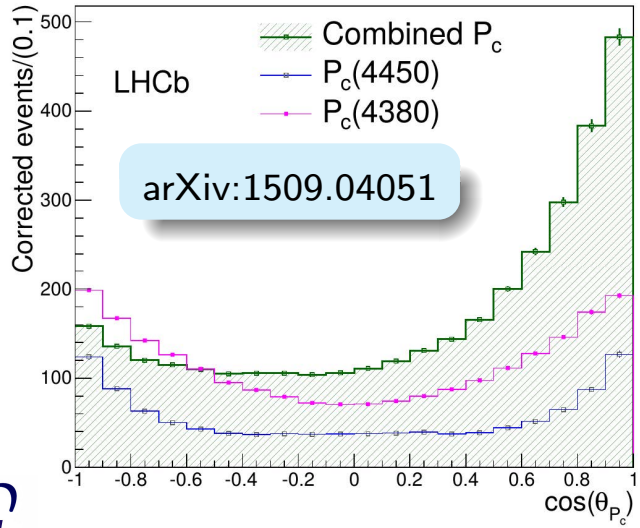
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	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
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6

Amplitude Model: results

Two exotic states are required to obtain an adequate fit



Interference between two P_c of opposite parity required to explain the P_c decay angular distribution



The P_c parameters from the "reduced" fit are

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

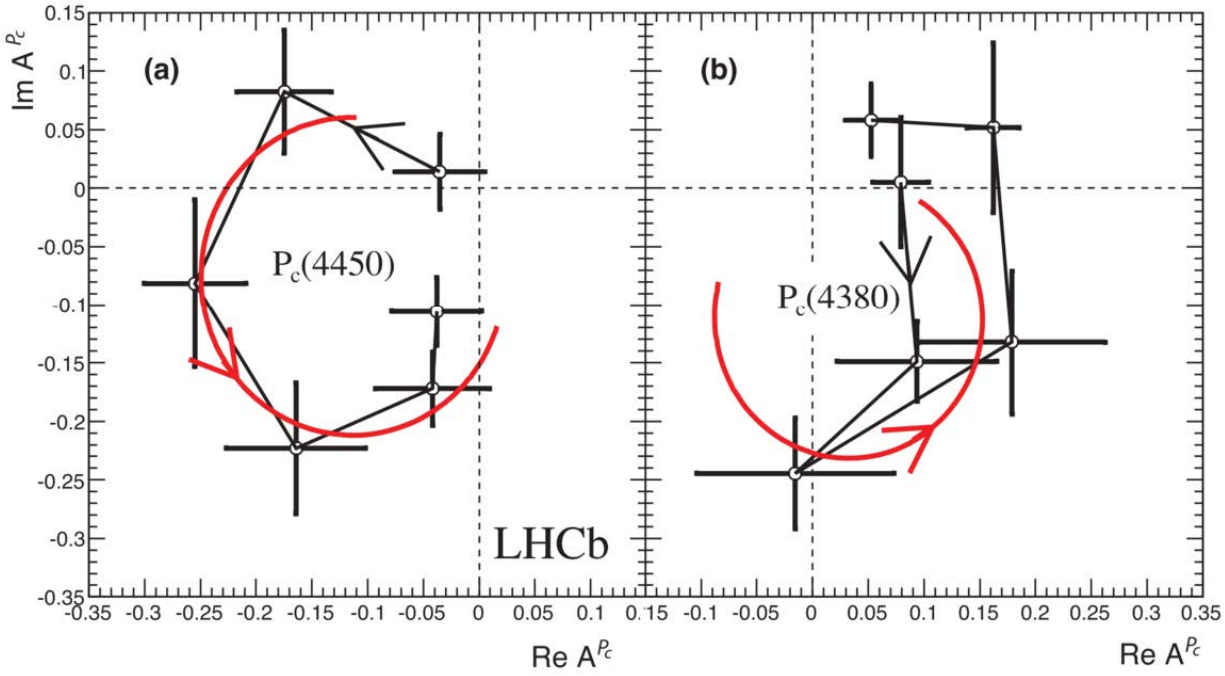
significance from pseudo-experiments (includes systematic)

The combined significance $> 15\sigma$

Resonance?

PRL 115 (2015) 072001

Real and immaginary part of the amplitude determined independently in 6 bins between $M - \Gamma$ and $M + \Gamma$



The $P_c(4450)$ amplitude shows a phase variation consistent with what expected for a Breit-Wigner resonance

Not conclusive for $P_c(4380)$

Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

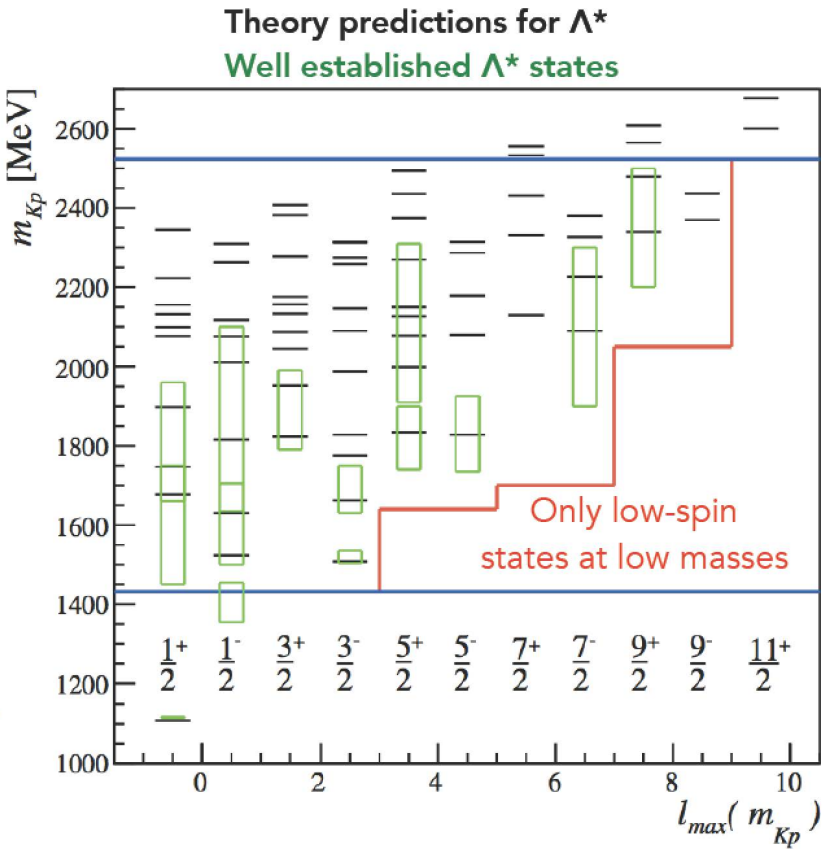
arXiv:1604.05708

The $\Lambda*$ spectrum is the largest systematic uncertainty in the P_c observation

The NR $K^- p$ component could have non trivial mass-dependence

Model independent approach: no assumption on Λ^*, Σ or NR structure

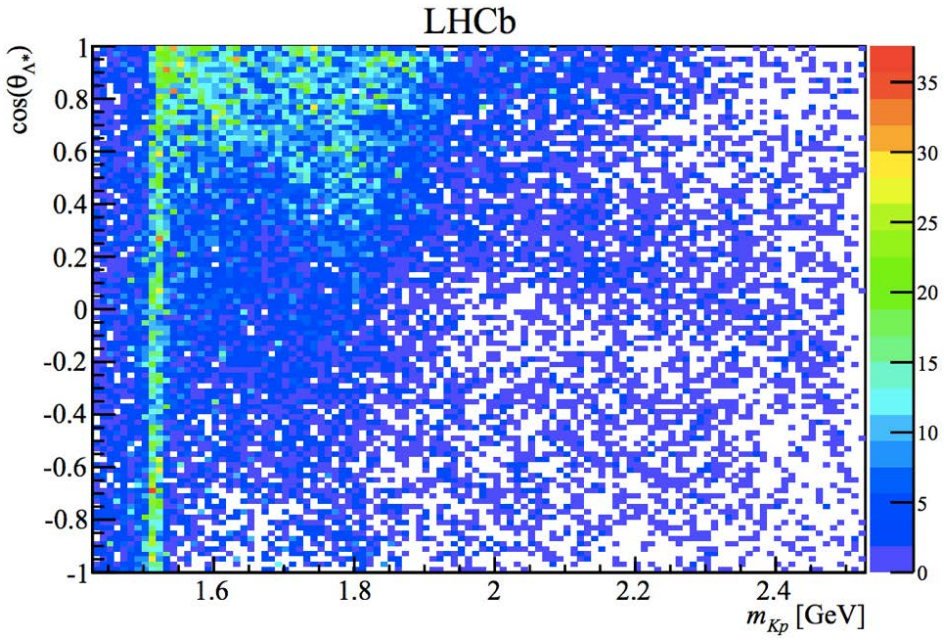
Only restrict maximum spin of Λ^* component in each interval of Kpi invariant mass



Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

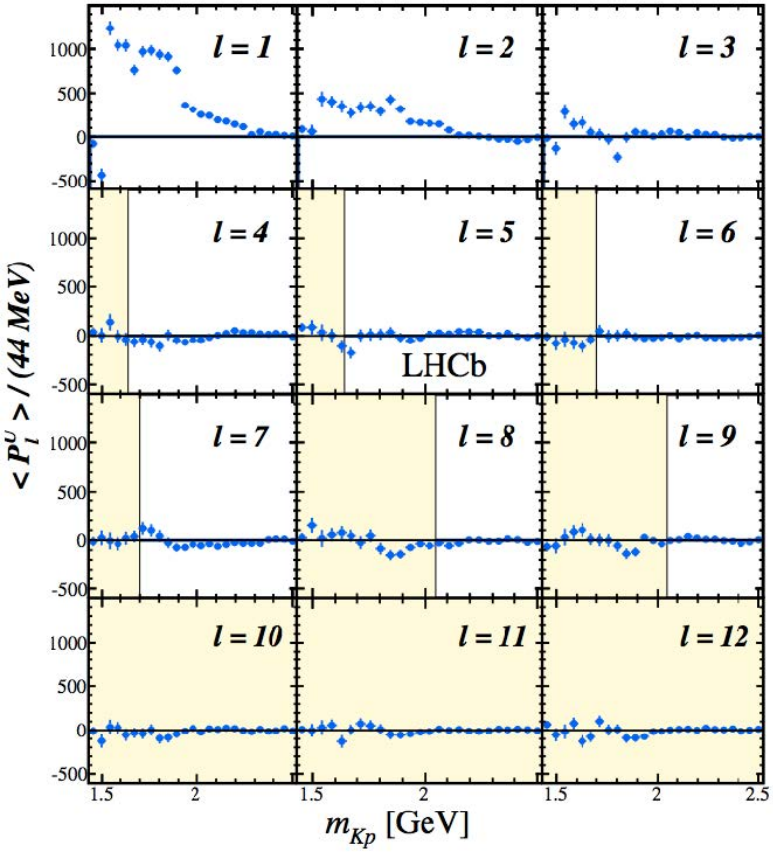
arXiv:1604.05708

Hypothesis: data can be described by Kp mass and angular structures



Moments from data in bins of $m(Kp)$

$$\langle P_l^U \rangle^k = \sum_{i=1}^{n_{\rm cand}{}^k} (w_i/\epsilon_i) P_l(\cos\theta^i_{\Lambda^*})$$



In each bin of $m(Kp)$, the $\cos\theta_{\Lambda*}$ distribution in terms of Legendre polynomial

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\rm max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

Rank $\mathrm{l_{max}} < 2\mathrm{J_{max}}$

J_{max} : highest spin in $m(Kp)$ bin

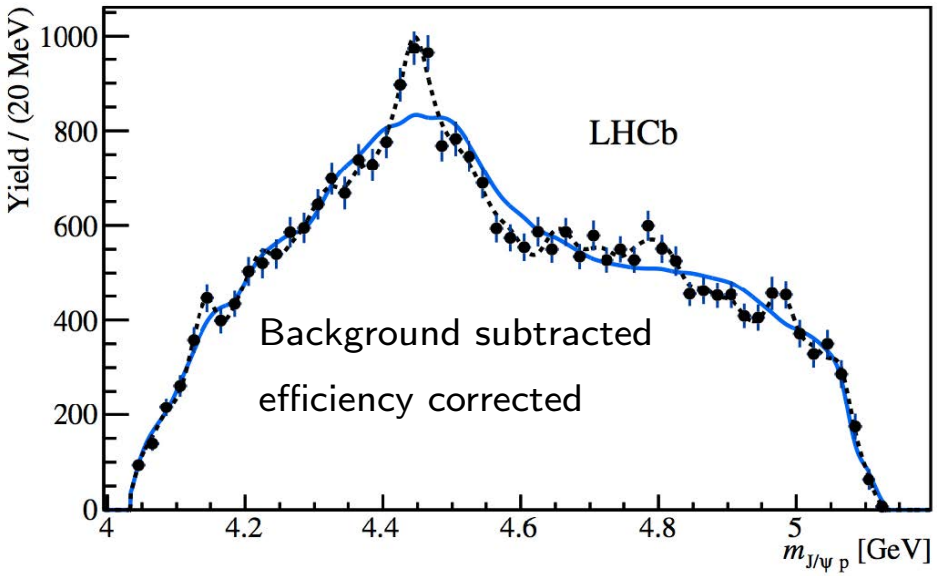
Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

arXiv:1604.05708

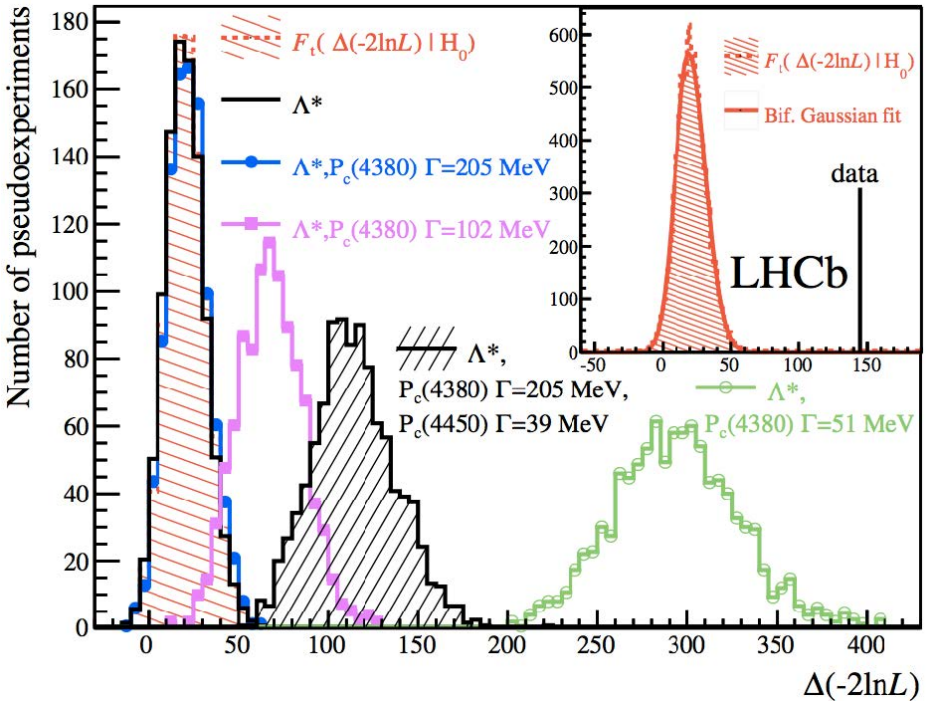
Phase-space $\Lambda_b^0 \to J/\psi p K^-$ MC weighted by $m(Kp)$ and moments

$m(J/\psi p)$ in data vs weighted MC

(Λ^* reflections based on moments)



Likelihood ratio (pseudoexperiments) for various hypotheses



The hypothesis that data can be described by reflections of Kp structures is excluded at 9σ

Search for exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

NEW

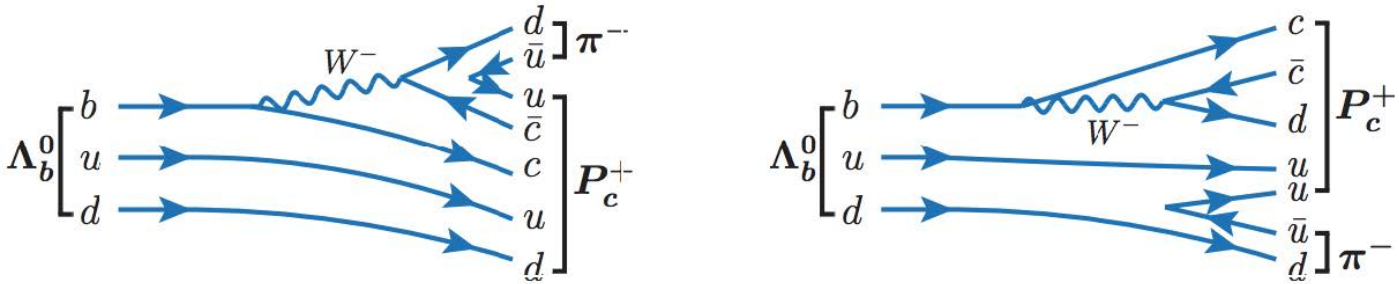
Cabibbo-suppressed – observed by LHCb JHEP 1407 (2014) 103

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst})$$

Observing the same P_c^+ states in a different decay mode could indicate they are really resonances and not some kinematical effects

Wang et al; arXiv:1512.01959

Cabibbo-suppressed Λ_b^0 decays to baryonic exotic resonances



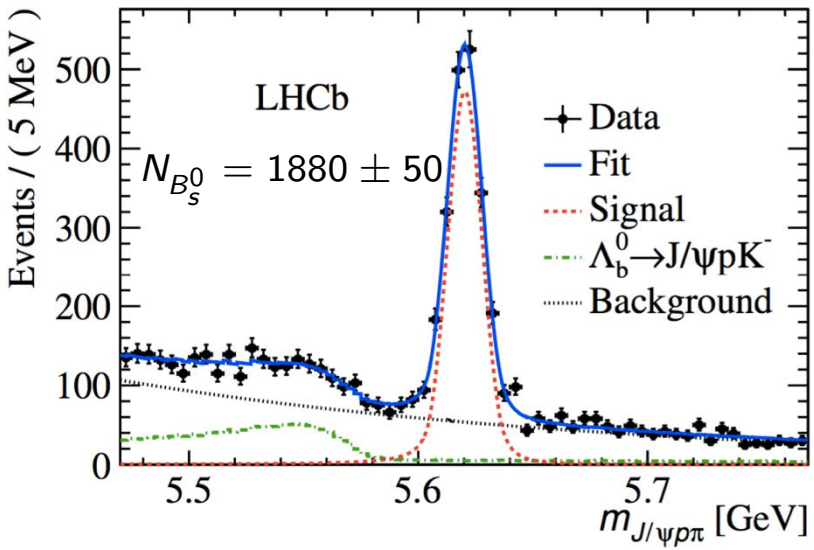
are predicted to have Cheng, Chua arXiv:1509.03708

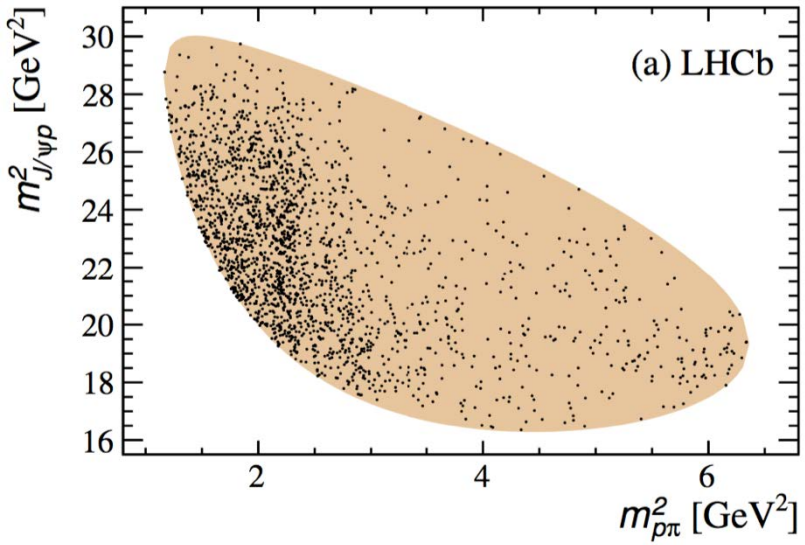
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

NEW

$\Lambda_b^0 \to J/\psi p \pi^-$

Similar candidates selection as for $\Lambda_b^0 \to J/\psi p K^-$, with additional vetos for specific background sources ($\bar{B}^0 \to J/\psi K^+\pi^-$, $\bar{B}_s^0 \to J/\psi K^+K^-$, $\Lambda \to K^+\pi^-$)





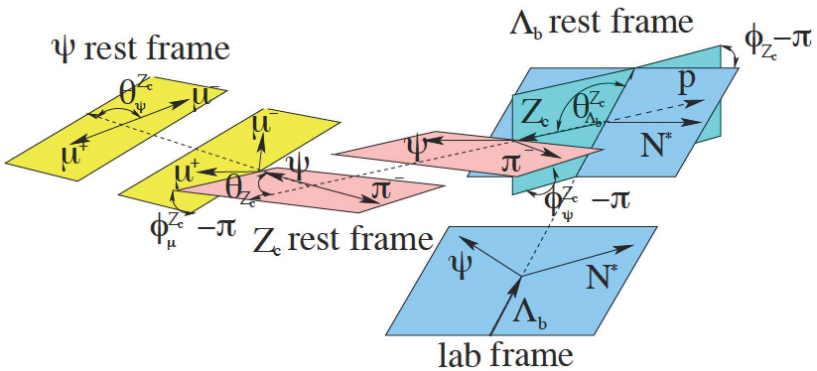
No striking features in the Dalitz plot, perform amplitude analysis

$\Lambda_b^0 \to Z_c^+ p$

As in the CF mode, six-dimensional fit to interfering amplitudes. In this case:

- $\Lambda_b^0 \to J/\psi N^*$
- $\Lambda_b^0 \to P_c^+ \pi^-$
- $\Lambda_b^0 \to Z_c^- p$

$Z_c(4200)^- \to J/\psi \pi^-$ reported by Belle in $B^0 \to J\psi K\pi$ PRD 90 (2014) 112009



Amplitude model fits to $\Lambda_b^0 \to J/\psi p\pi^-$

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NEW

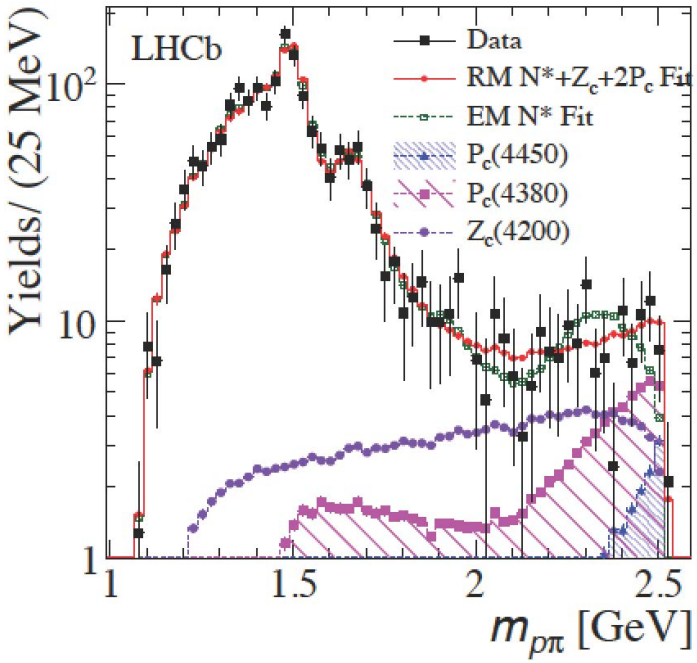
State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	0	3
$N(1700)$	$3/2^-$	1700	150	0	3
$N(1710)$	$1/2^+$	1710	100	0	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	0	3
$N(1900)$	$3/2^+$	1900	200	0	3
$N(2190)$	$7/2^-$	2190	500	0	3
$N(2220)$	$9/2^+$	2250	400	0	0
$N(2250)$	$9/2^-$	2275	500	0	0
$N(2600)$	$11/2^-$	2600	650	0	0
$N(2300)$	$1/2^+$	2300	340	0	3
$N(2570)$	$5/2^-$	2570	250	0	3
Free parameters				40	106

Include in the fit

- all known N^* (Extended)
- only well motivated (Reduced)

All L allowed

Limited sample size: fix P_c and Z_c parameters when testing if their amplitudes are required



The $m(p\pi^-)$ projection is adequately described by fits with N^* only

Exotic components seem not required

Fits with and without exotic hadrons

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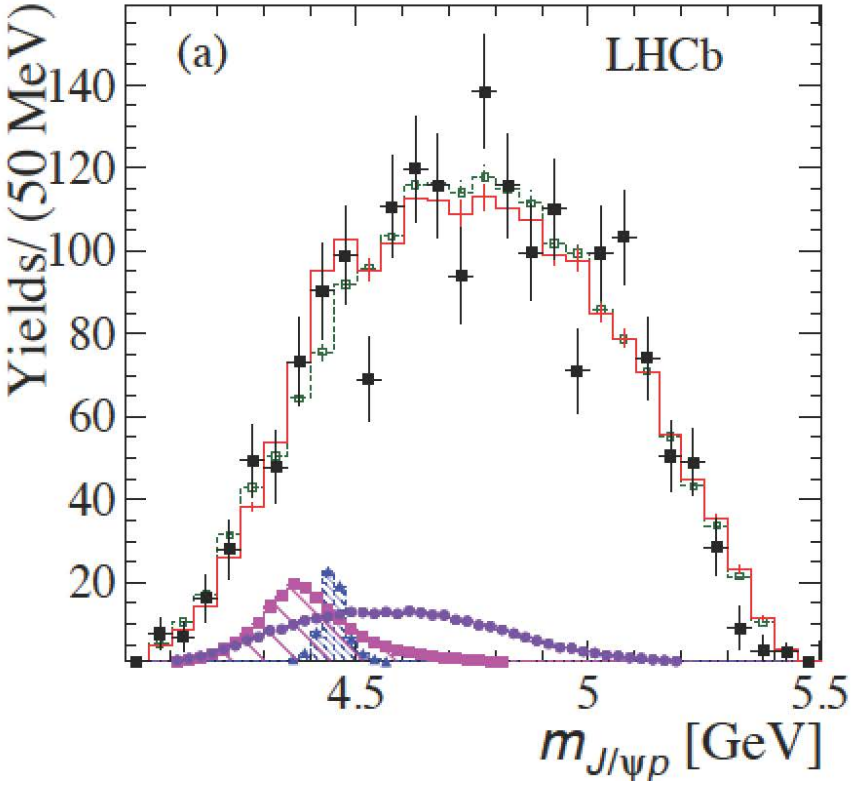
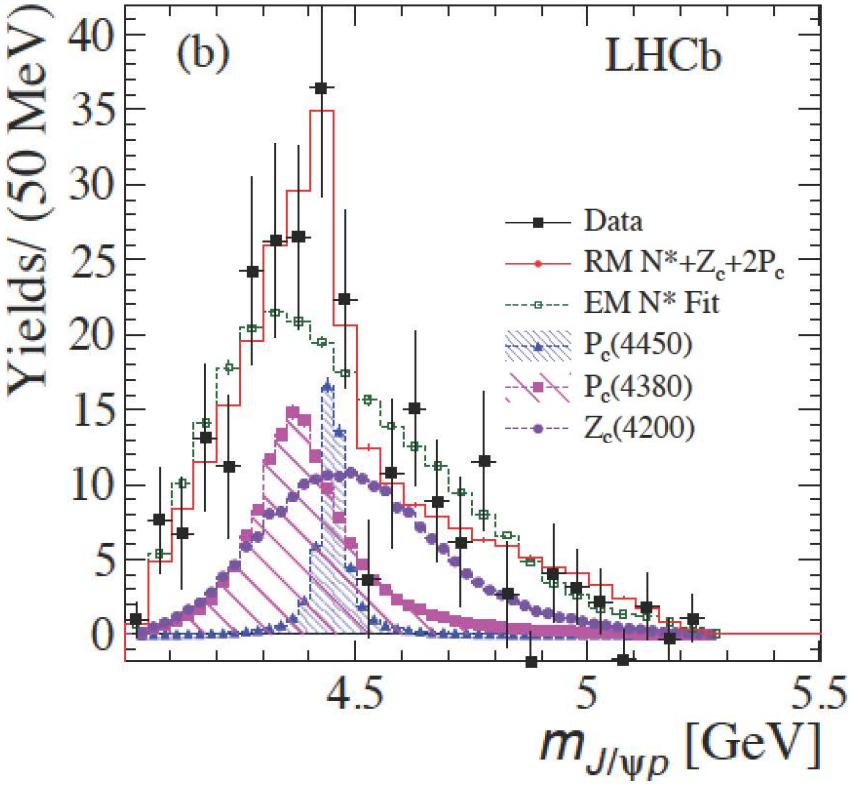
NEW

The amplitude model without P_c or Z_c amplitudes may appear adequate in the projections, but exotic components are required for an acceptable fit in all regions of variable space

All events



$m_{p\pi} > 1.8\,\mathrm{GeV}$



Differences in a six-dimensional fit often manifest only in restricted regions

NEW

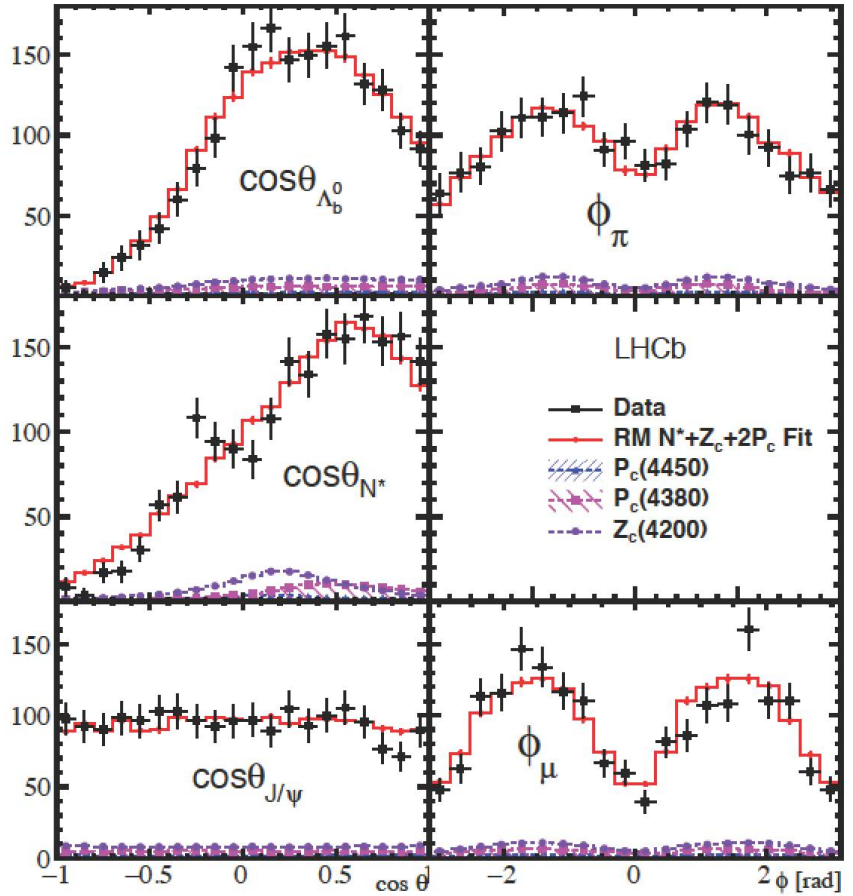
Evidence for exotic components in $\Lambda_b^0 \to J/\psi p \pi^-$

The N^*-only (extended) model does not describe data in all variable space

The reduced models with exotic (2 P_c or Z_c, or both) have acceptable fits in all variables

The significance (including syst) for $2P_c$ without Z_c is 3.3σ
The significance for $2P_c + Z_c$ is 3.1σ

States	Fit fraction (%)
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$



Ratios of CS/CF for exotic components compatible with $0.07 - 0.08$

Cheng, Chua arXiv:1509.03708

$$R_{\pi^-/K^-}(4380) = 0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$$
$$R_{\pi^-/K^-}(4450) = 0.033^{+0.016+0.011}_{-0.014-0.009} \pm 0.009$$

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)}$$

Exotic(?) states $X \to J/\psi\,\phi$?

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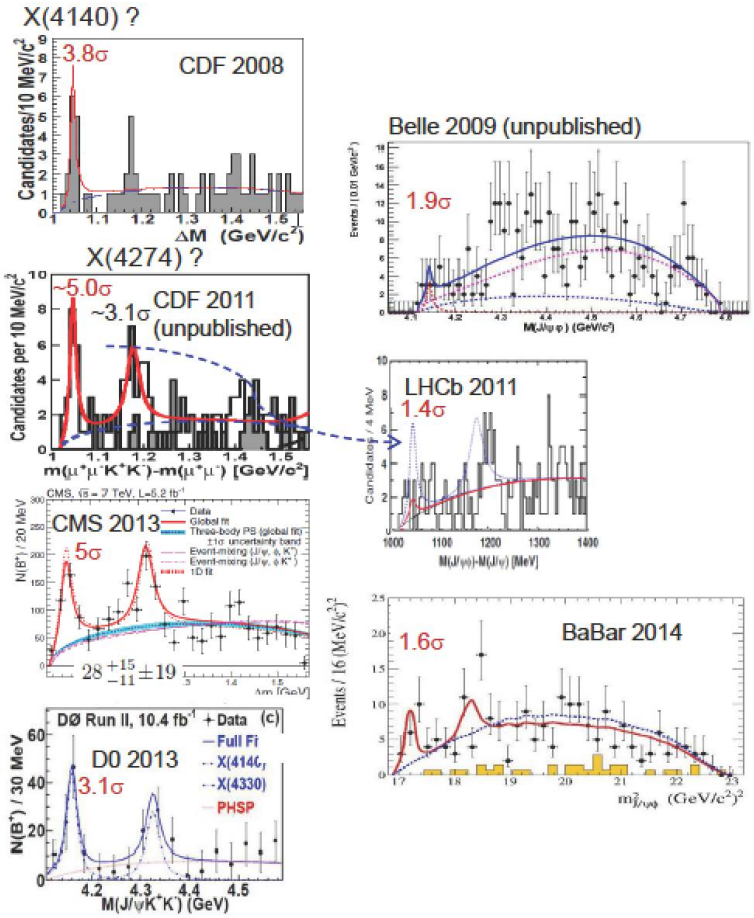
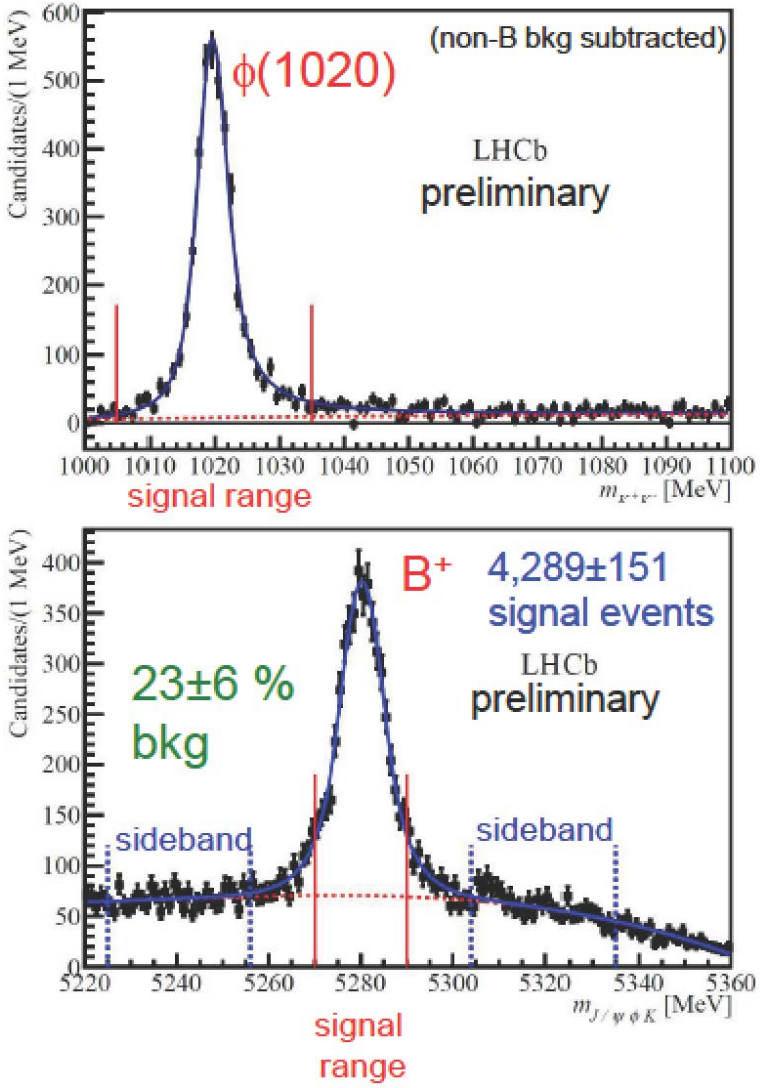
LHCb-PAPER-2016-019

Many experiments reported states decaying to $J/\psi\phi$:
$X(4140)$ and/or other higher mass states in B decays, but also $\gamma\gamma$, double $c\bar{c}$.





The LHCb sample of $B^+ \to J/\psi\,\phi K^+$ from Run1 is the largest analysed so far

$B^+ \to J/\psi\,\phi K^+$ Dalitz plot

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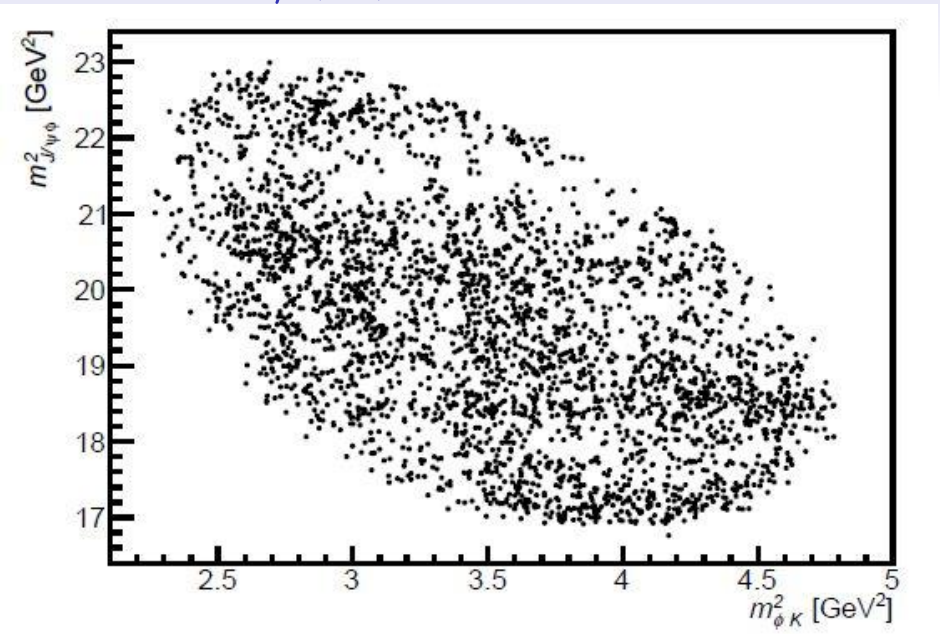
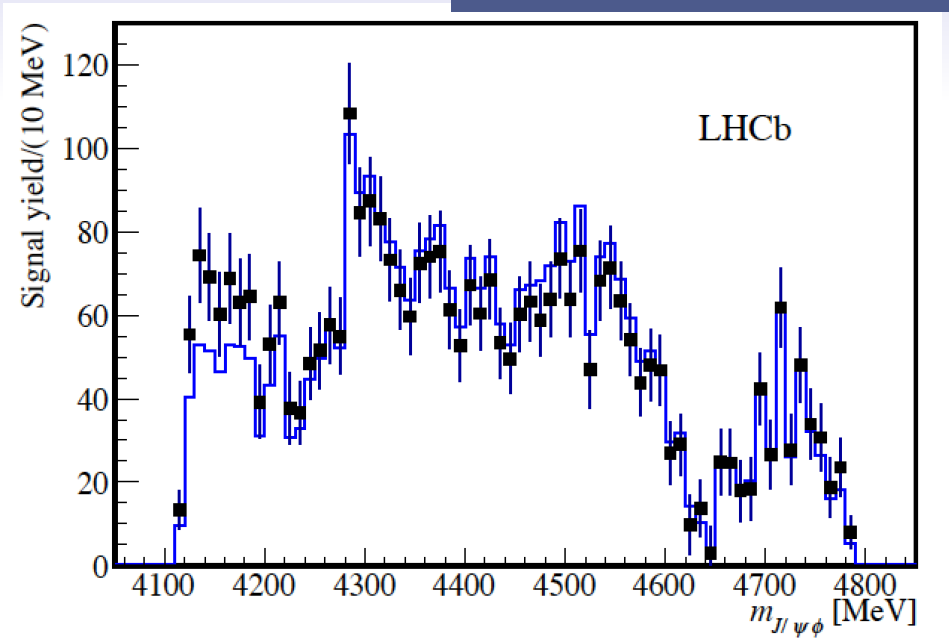
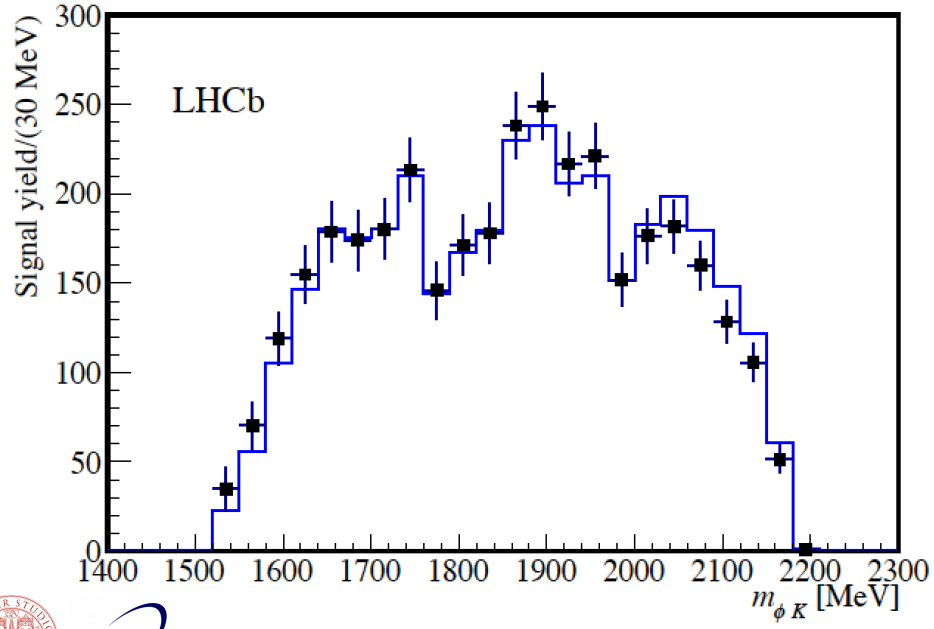
LHCb-PAPER-2016-019







All previous results based on 1D projections

Need to understand reflections of interfering higher K^*

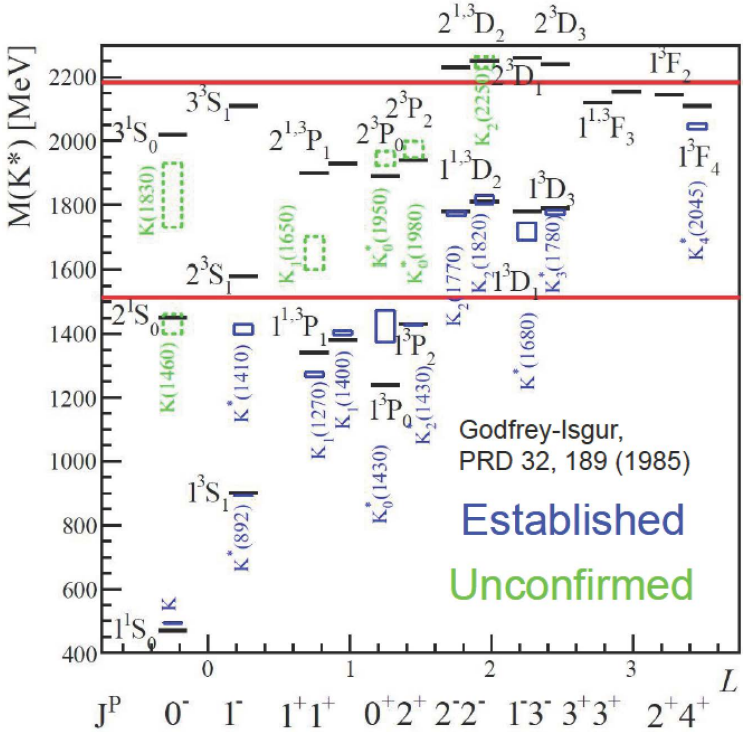
Amplitude fits

NEW

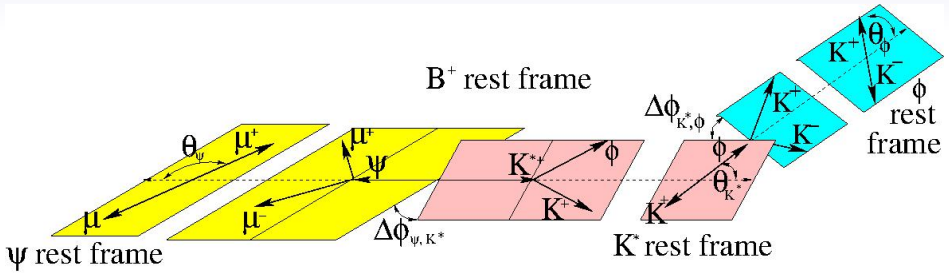
LHCb-PAPER-2016-018
LHCb-PAPER-2016-019

6D fit including K^* resonances + interfering NR background (0^{++} not allowed)

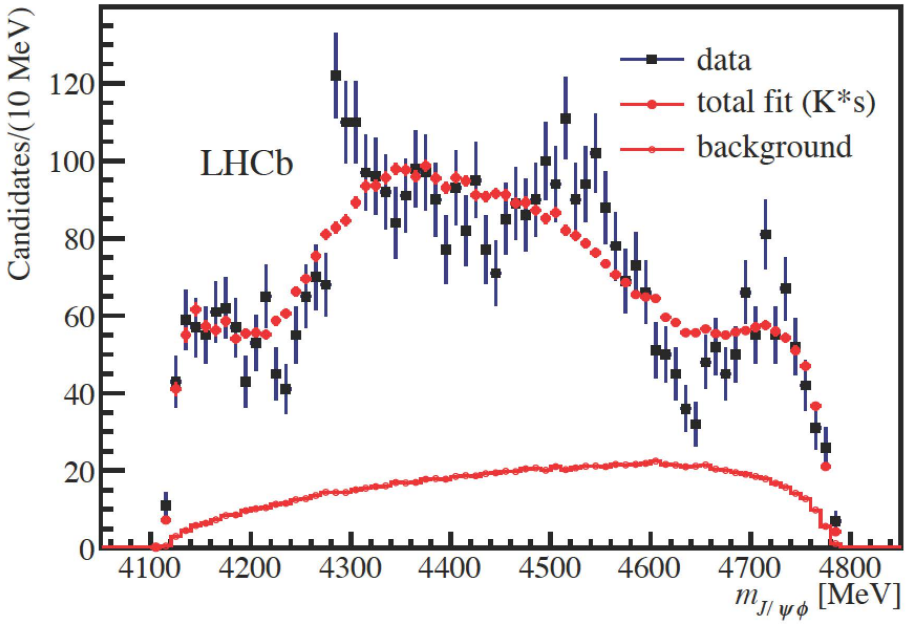
Experimental knowledge + predictions to choose the states to include in the model



masses and widths not constrained



1-4 complex helicity terms per K^*

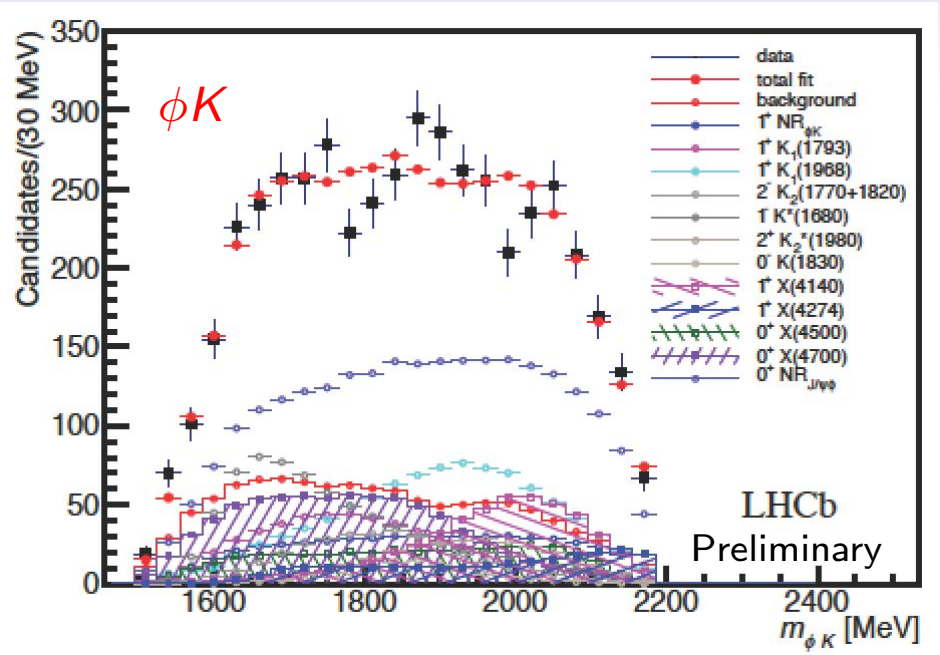


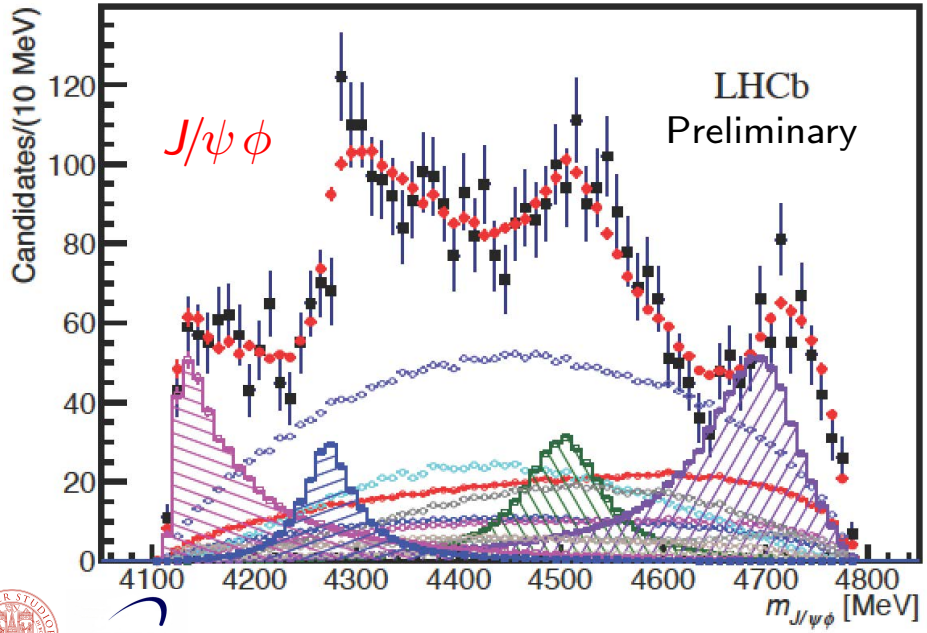
K^* resonances alone don't describe data

Fits allowing exotic components

LHCb-PAPER-2016-018
LHCb-PAPER-2016-019

NEW





Add X and Z^+ components with various quantum numbers

Z^+ components improve fit marginally

Two 1^{++} and two 0^{++} states with large significance

Contri-bution	sign. or Ref.	M_0 MeV	Γ_0 MeV	Fit results F.F. %
All $X(1^+)$				$16\pm3\ ^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
ave.		4146.9 ± 2.3	17.8 ± 6.8	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-3.6}$	$56\pm11\ ^{+8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF		$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	

Significance of $J^{PC}=1^{++}$:
$X(4140)$: 5.7σ $X(4274)$: 5.8σ

Contri-bution	sign.	M_0 MeV	Γ_0 MeV	Fit results F.F. %
All $X(0^+)$				$28\pm5\ ^{+7}_{-7}$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm5\ ^{+9}_{-5}$

Significance of $J^{PC}=0^{++}$:
$X(4500)$: 4.0σ $X(4700)$: 4.5σ

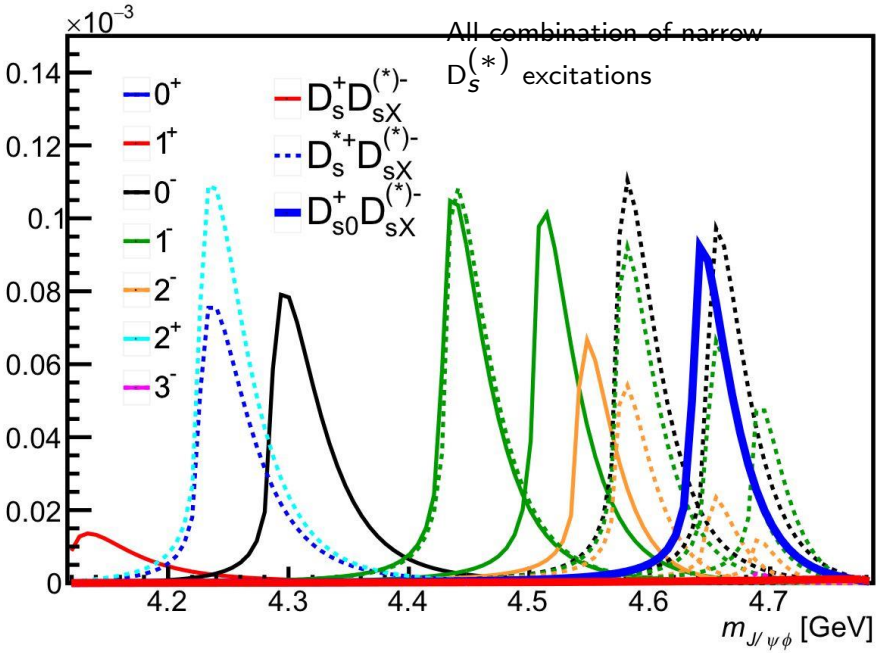
Resonances or cusps?

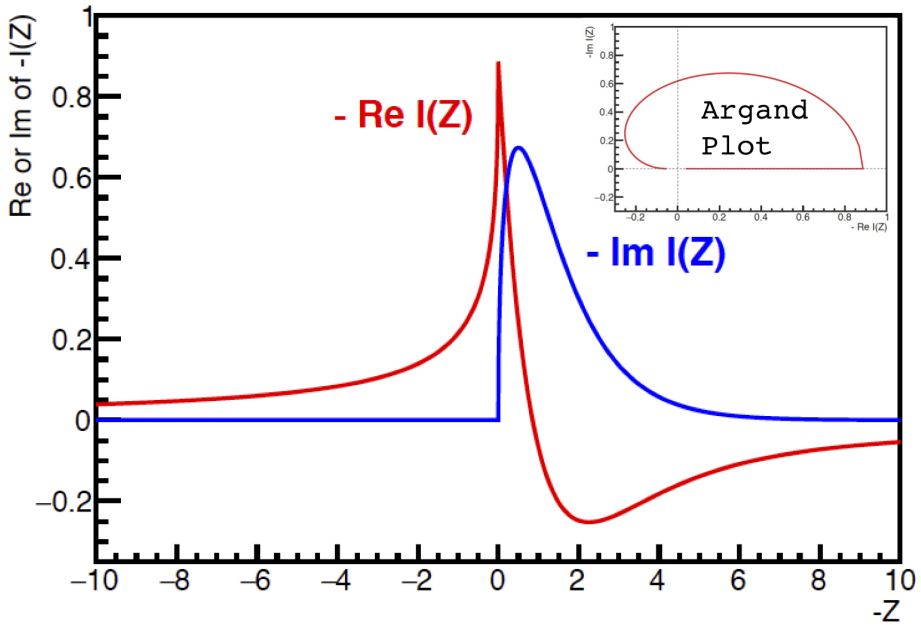
NEW

LHCb-PAPER-2016-018
LHCb-PAPER-2016-019

4 states...?? Kinematical effects?

Rescattering in S-wave. J^P is that of virtual $D_s^{(*)}$ pair. Cusp peaks at sum of $D_s^{(*)}$ masses





Test one of the cusp models which proposes to explain Z's just above $D^{(*)}\bar{D}^{(*)}$ thresholds (rescattering) Swanson arXiv:1504.07952

For the $X(4140)$ the cusp amplitude gives a better fit than BW (by 1.6σ)

For all other X's this cusp model has a worse fit

K^* spectroscopy in $B^+ \to J/\psi\,\phi K^+$

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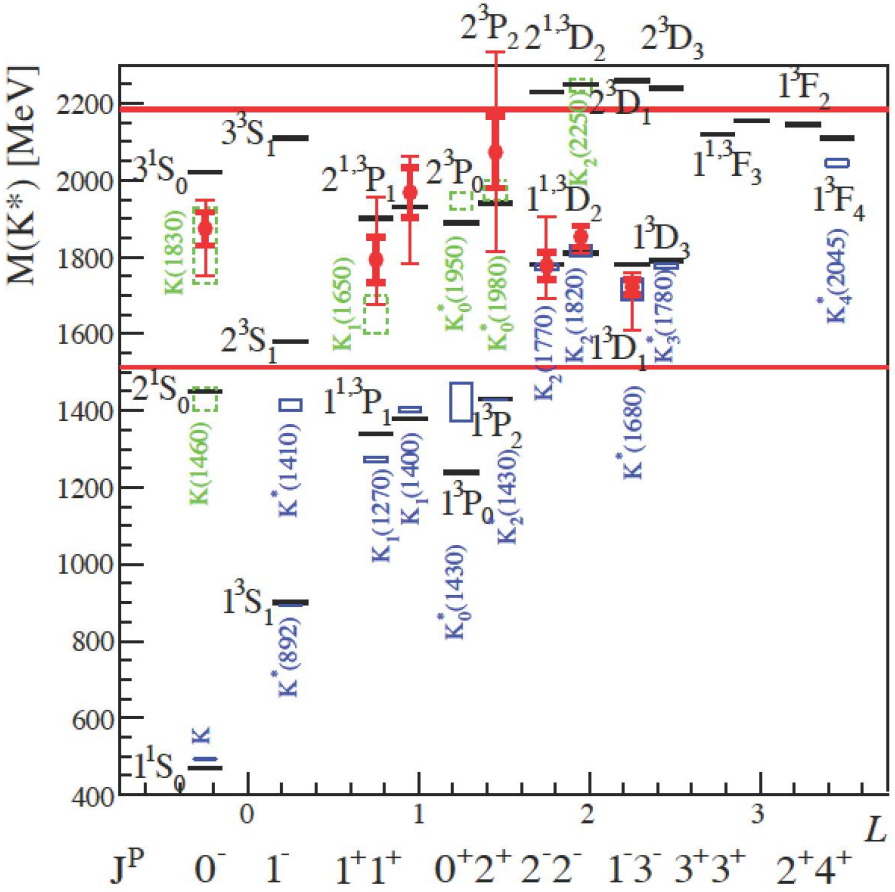
Our results for mass and widths of higher kaon excitations as red points

Excellent agreement with theory and previous experiments

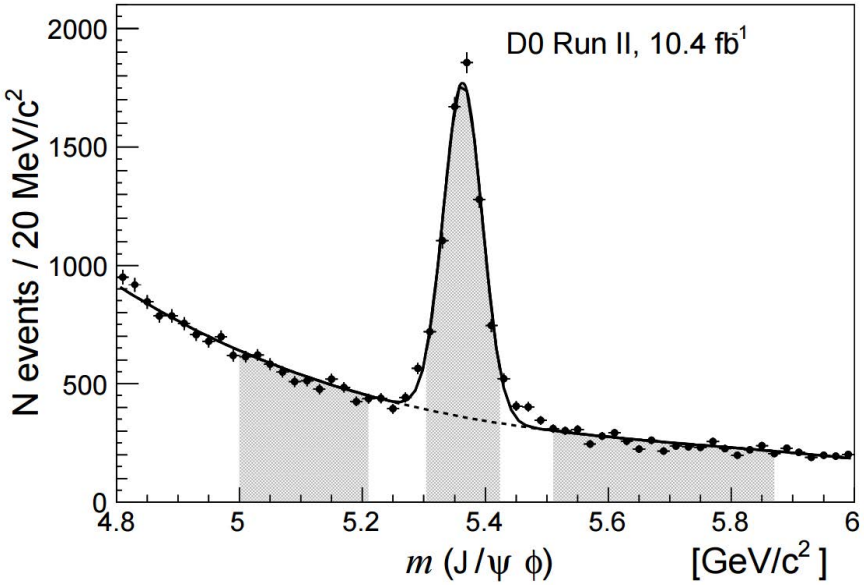
$J = 3 - 4$ states not observed expected to be suppressed in B decays
(angular momentum barrier)

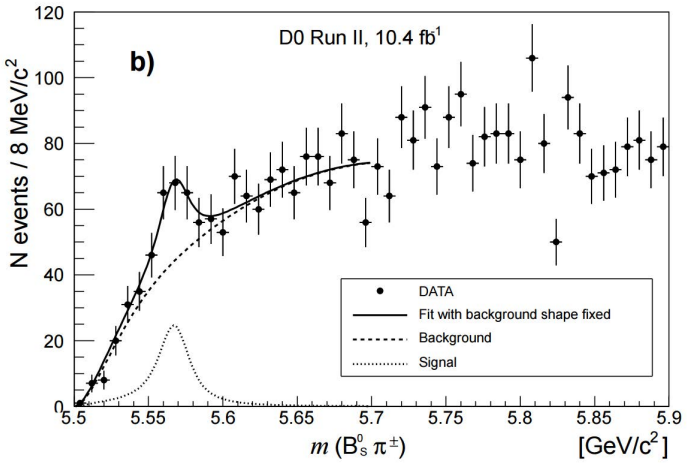


$B_s^0\pi^-$ spectroscopy

D0 reported observation (5.1σ) of a tetraquark candidate $X(5568)^+ \to B_s^0\pi^+$

with ≈ 5500 B_s^0 signal events reconstructed in $J/\psi\,\phi$ arXiv:1602.07588v2



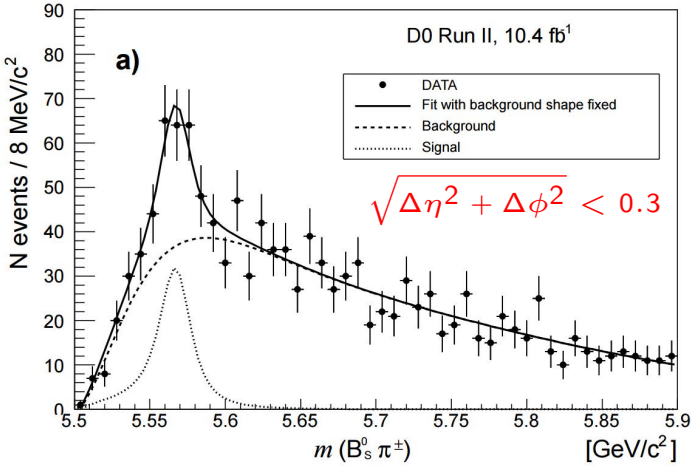


$N_X = 133 \pm 31$ with π^+ in a cone around B_s^0

$$m = 5567.8 \pm 2.9\,(\text{stat})\,^{+0.9}_{-1.9}\,(\text{syst})\,\text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\text{stat})\,^{+5.0}_{-2.5}\,(\text{syst})\,\text{MeV}/c^2$$

with a large fraction of B_s^0 from $X(5568)^+$ decays:

$$\rho_X^{D0} \equiv \left.\frac{\sigma(p\bar{p} \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})}\right|_{\text{D0Acc.}} = (8.6 \pm 1.9 \pm 1.4)\%$$

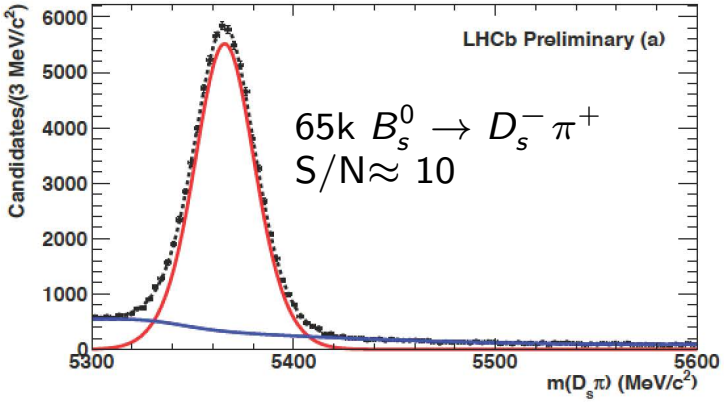


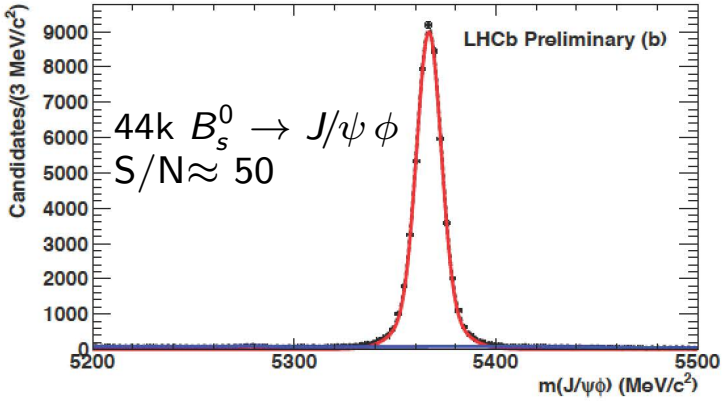
Unique state with four different quarks $\bar{b}su\bar{d}$

LHCb: $B_s^0\pi^-$ spectrum

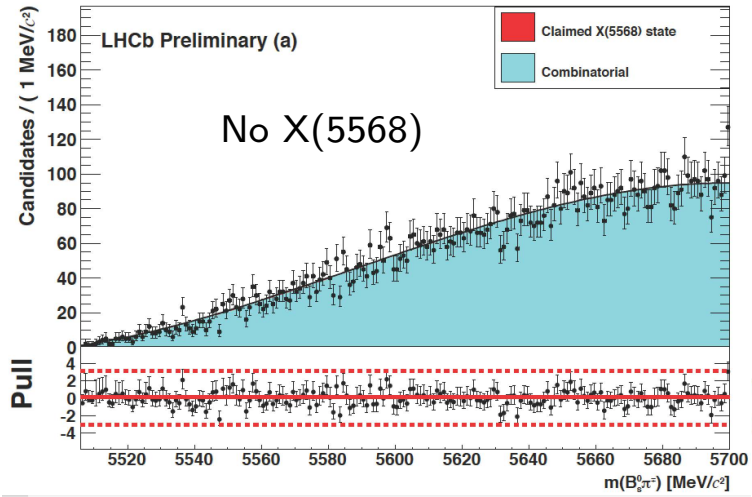
Large and clean B_s^0 samples reconstructed in $J/\psi\,\phi$ and $D_s^-\pi^+$

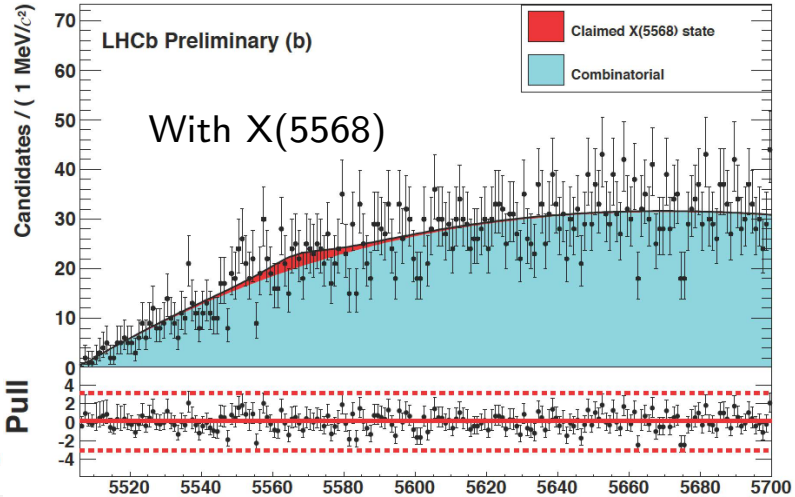
Constrain J/ψ and D_s mass to improve resolution





pair π^+ from primary vertex with a displaced B_s^0





Fit spectrum with and without a narrow resonant structure.

no signal $\Longrightarrow$ upper limit

No evidence for $X(5568) \to B_s^0\pi^+$

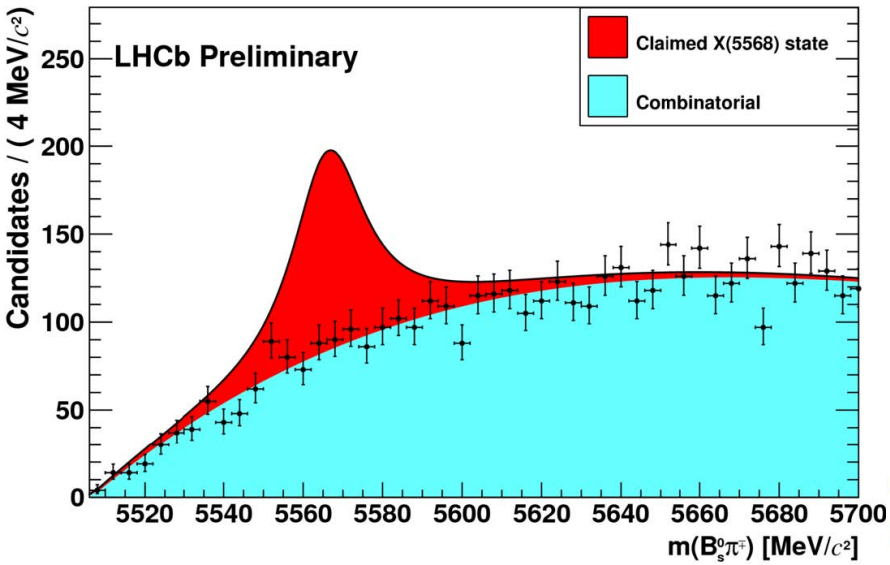
Set upper limit on the B_s^0 production ratio (including systematic)

$$\rho_X^{\mathrm{LHCb}} \equiv \frac{\sigma(pp \to X(5568) + \mathrm{anything}) \times \mathcal{B}\left(X(5568) \to B_s^0\pi^\pm\right)}{\sigma(pp \to B_s^0 + \mathrm{anything})}$$

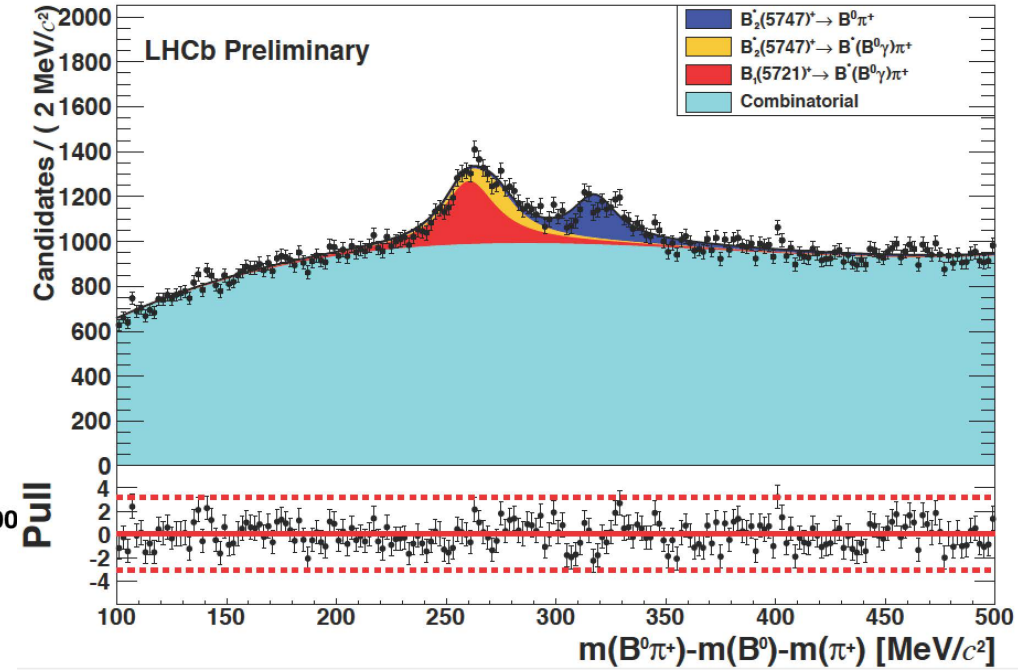
for two different cuts on the transverse B_s^0 momentum

$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > \ 5\,\mathrm{GeV}/c) \ < \ 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) \ < \ 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$

Expected X(5568) signal for $\varrho = 8.6\%$



Cross check: $B^* \to B^0\pi$ mode



Conclusions

- Observation of $P_c(4450)^{\pm}$ and $P_c(4380)^{\pm} \to J/\psi\, p$ in $\Lambda_b^0 \to J/\psi\, pK^-$ from both amplitude analysis and model independent approach
  PRL 115 (2015) 072001 arXiv:1604.05708
  - $c\bar{c}uud \Longrightarrow$ pentaquark!
  - resonant behaviour of $P_c(4450)^{\pm}$ amplitude
  - resonant behaviour inconclusive for $P_c(4380)^{\pm}$

    more data needed $\Longrightarrow$ Run 2!

NEW
- Evidence for exotic hadrons in $\Lambda_b^0 \to J/\psi\, p\pi^-$ LHCb-PAPER-2016-015
  - compatible with P_c states in different decay mode
  - amplitude analysis limited by sample size

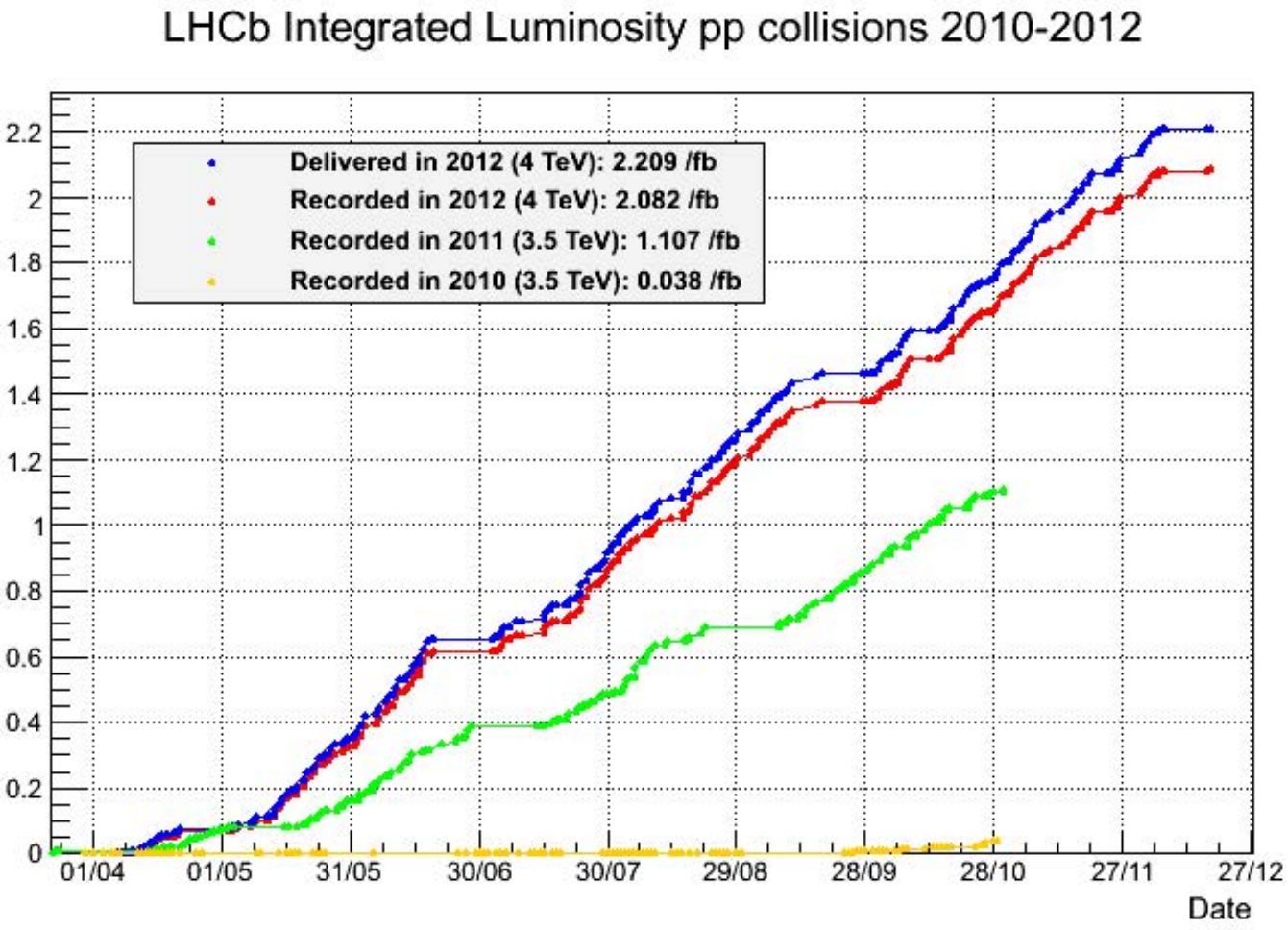
    more data needed $\Longrightarrow$ Run 2!

NEW
- First 6D amplitude analysis of $B^+ \to J/\psi\, \phi K^+$
  LHCb-PAPER-2016-018 LHCb-PAPER-2016-019
  - 4 $J/\psi\, \phi$ structures required to describe the data each with $> 5\sigma$
    quantum numbers assigment $> 4\sigma$
  - Kaon spectroscopy of higher mass excitations
- No evidence for $X(5568) \to B_s^0\pi^+$ LHCb-CONF-2016-004
  - $\times 20$ more data than D0.

    ... different process (pp vs $\bar{p}p$), different energy, different kinematical region.... yet ...

Extra Slides

Run I data samples



Lower instantaneous luminosity with respect to other LHC experiments

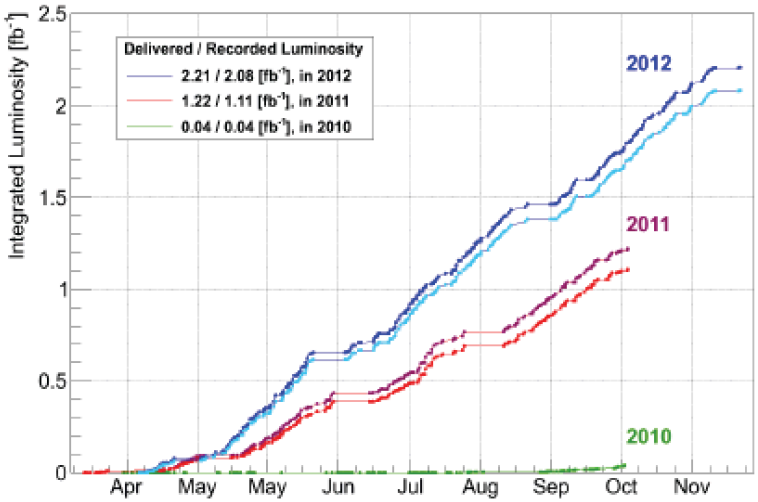
optimized for b and c physics

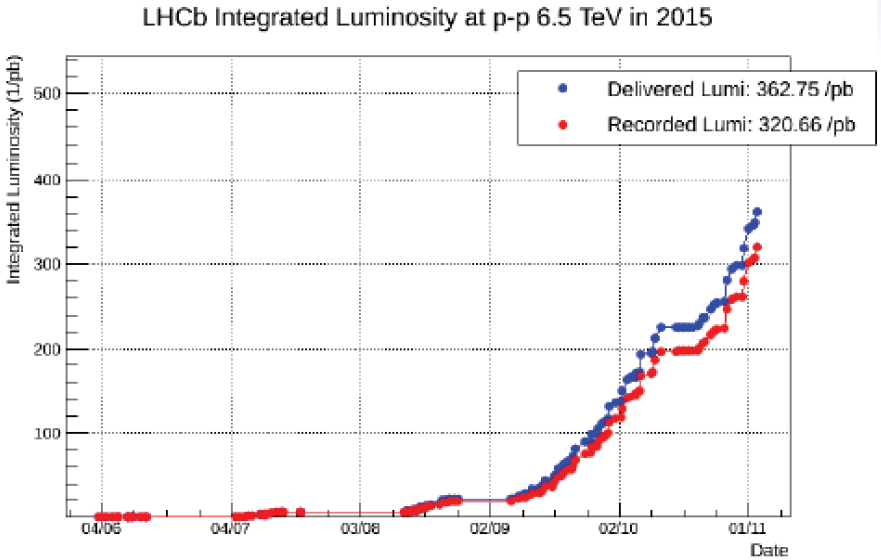
in 2011:
$\mathcal{L} \approx 2 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

in 2012:
$\mathcal{L} \approx 4 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

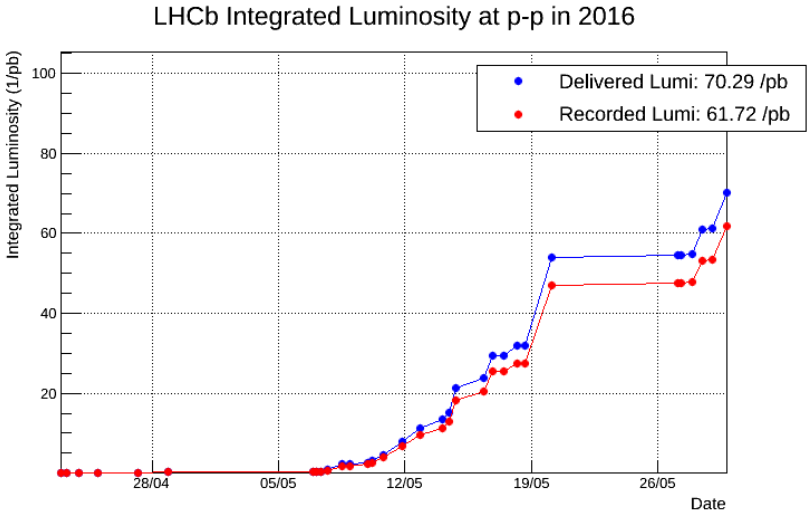
$\times 2$ design luminosity

Run 2





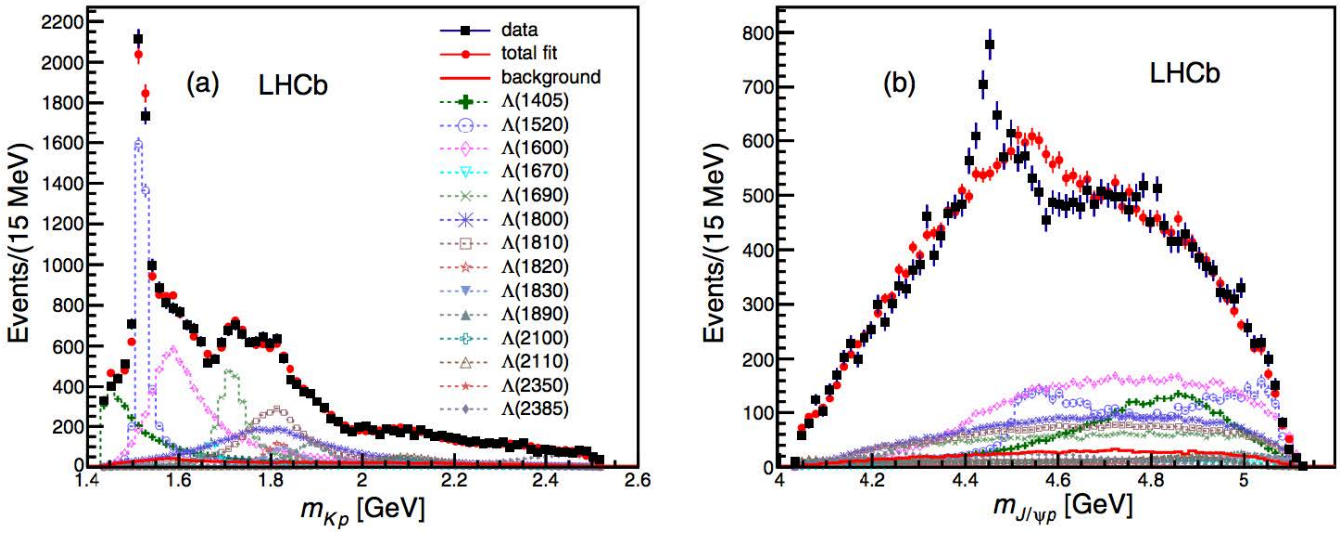
	Run 1 2011-2012	Run 2 2015-2018
$\sqrt{s}$ (TeV)	7 – 8	13
Bunch spacing (ns)	50	25
$\int \mathcal{L} dt$ (fb^{-1})	1+2	> 5



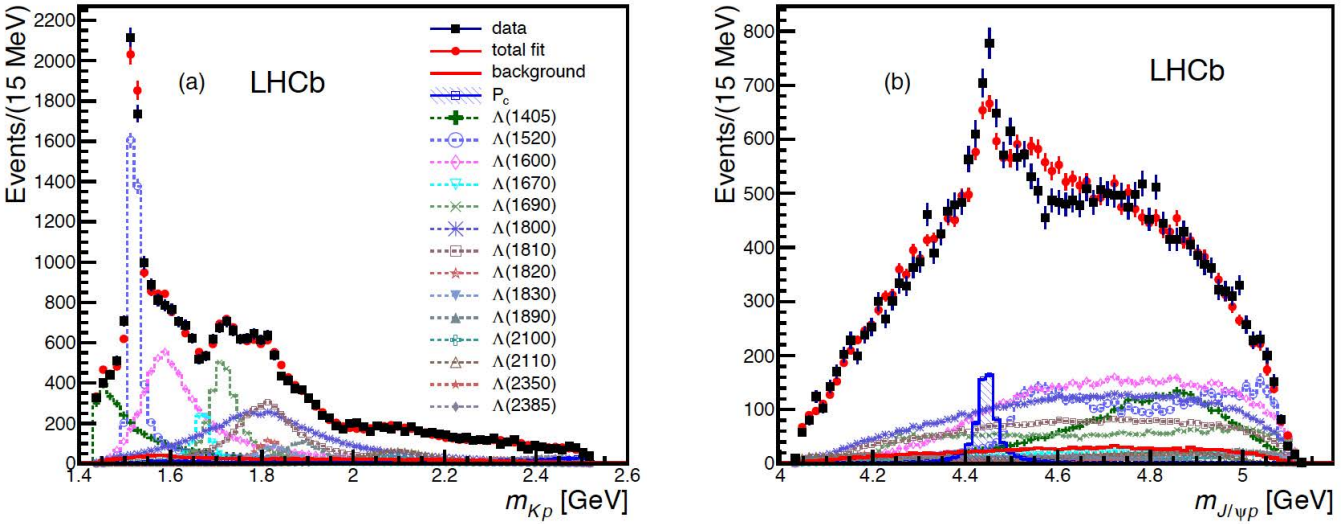
Already 0.36 fb^{-1} collected for Run 2
b-hadron cross section $\approx$ 50% larger than in Run 1
with higher energy short-lived particles are further displaced from primary vertex

Extended Model fits to $\Lambda_b^0 \to J/\psi p K^-$

The extended fit without additional exotic resonances describes well the $K^- p$ projection, fails to describe the $J/\psi p$ projection

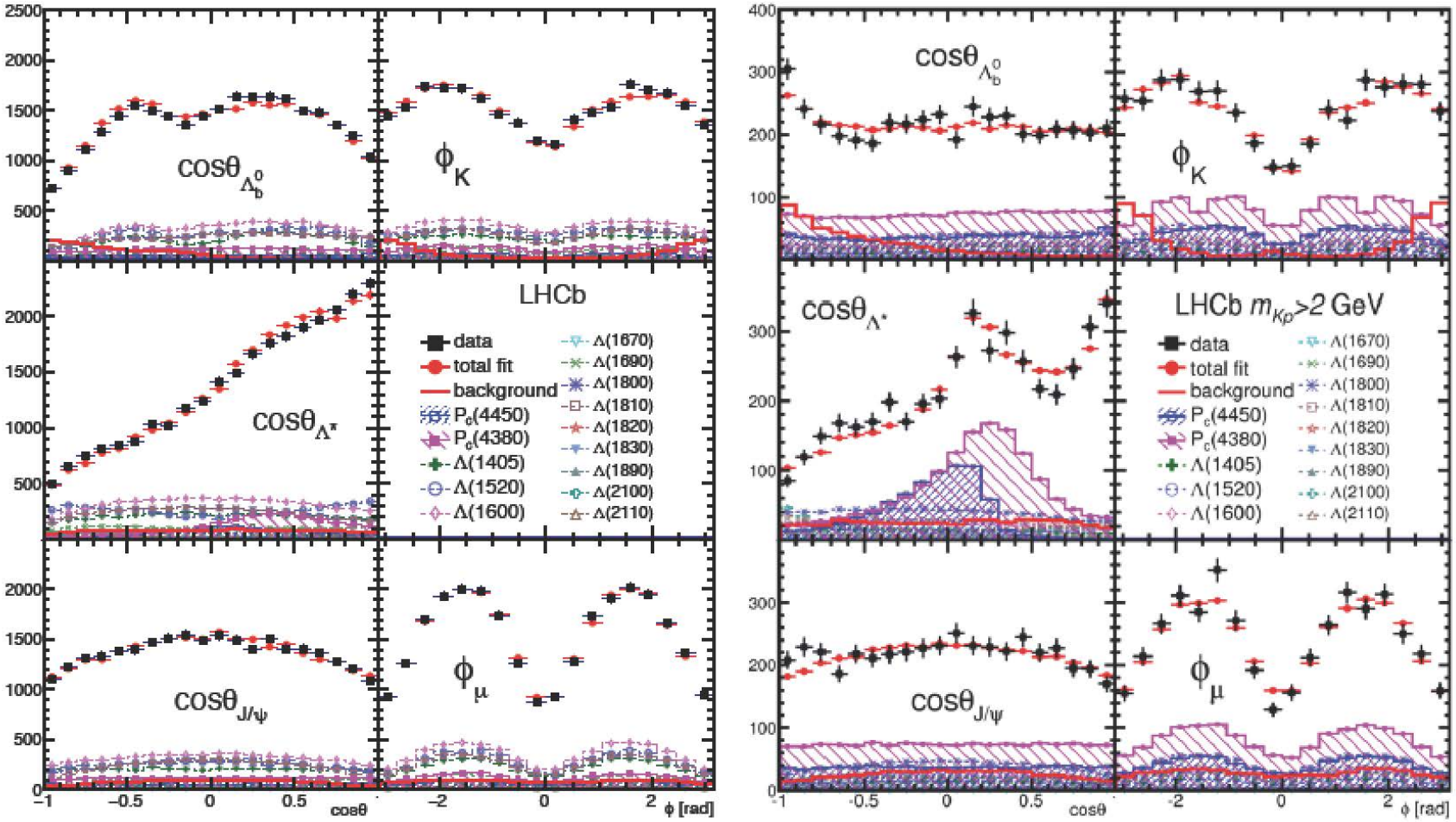


adding one exotic resonance is not enough:



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

Reduced fit $+2$ P_c describes data well in all fit variables, also in restricted variable ranges



Efficiency and backround $\Lambda_b^0 \to J/\psi p \pi^-$

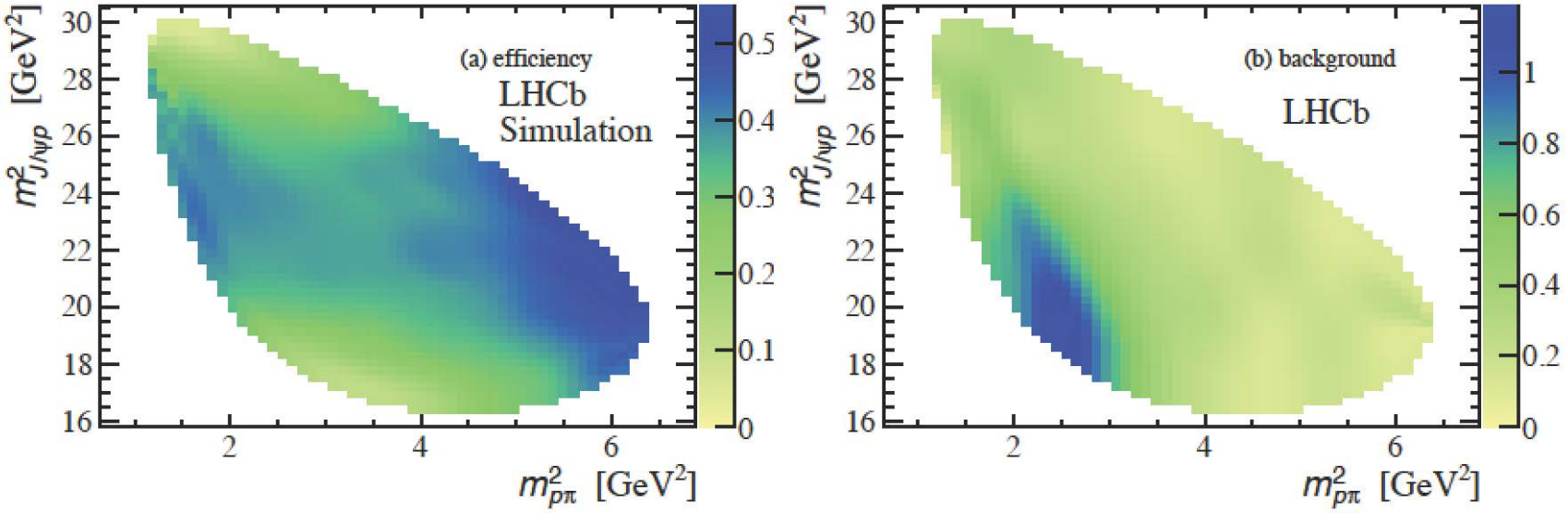
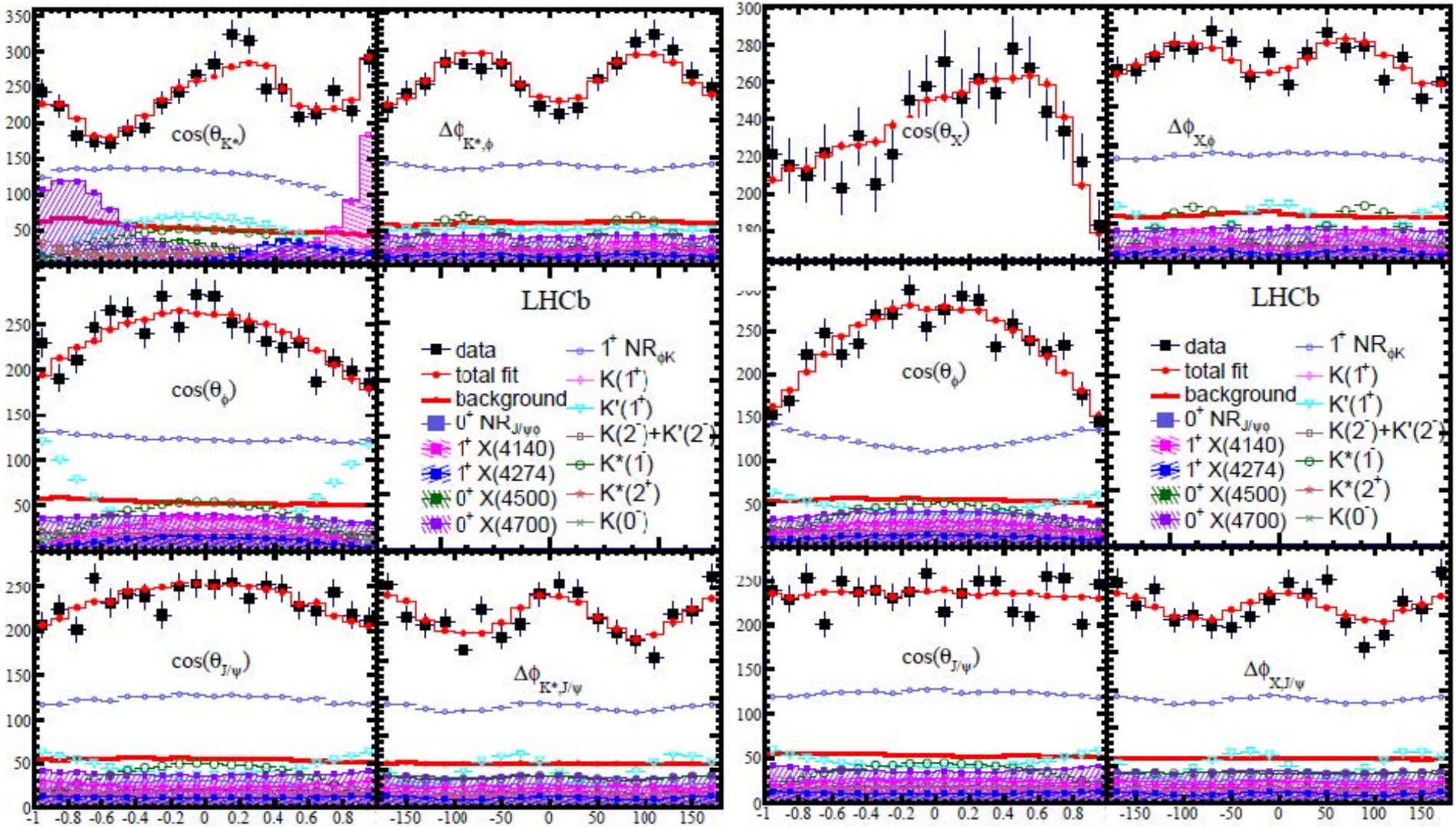


Figure 7: (a) Signal efficiency and (b) background distribution on the Dalitz plane.

Fit projections $B^+ \to J/\psi\,\phi K^+$

The fit with 4 X states describes well data in all angles