Recent results of exotic states at LHCb

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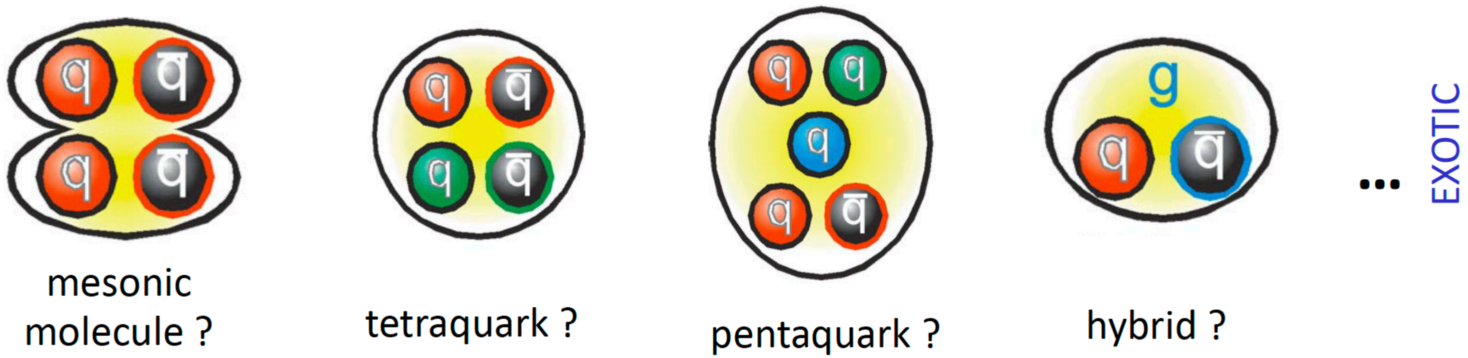
Introduction

- QCD at low energy scale is not well understood due to its non-perturbative nature
- Exotic hadrons provide unique probe to QCD

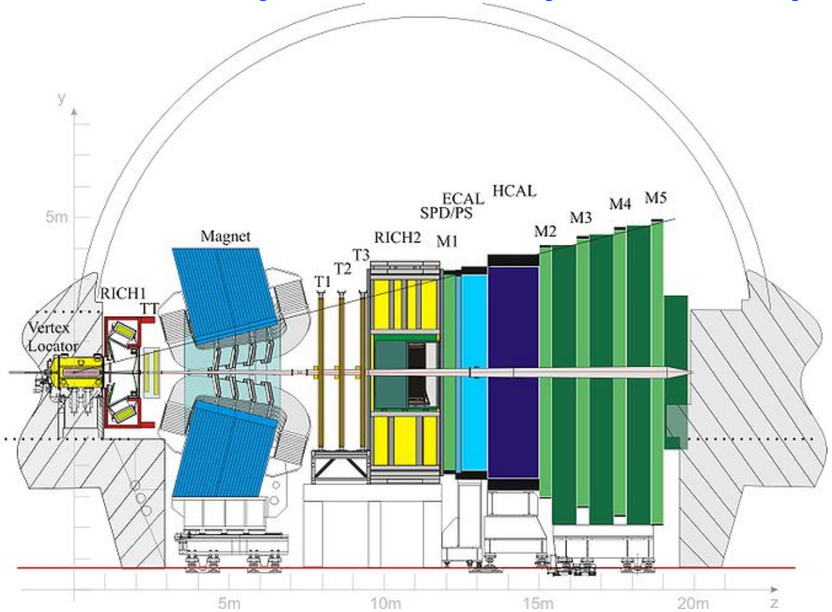


- Selected results from LHCb
  - New pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$
  - Evidence for an $\eta_c \pi^-$ resonance in $B^0 \to \eta_c K^+ \pi^-$

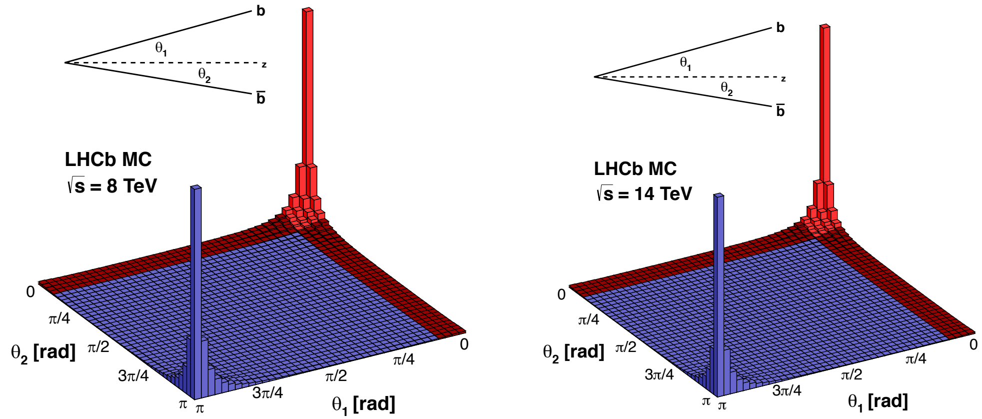
The LHCb detector

Int. J. Mod. Phys. A 30, 1530022 (2015) JINST 3 (2008) S08005

- Single-arm forward spectrometer, designed for the study of heavy flavor physics



$2 < \eta < 5$ range: $\sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance



Excellent vertex, IP and decay-time resolution:

- $\sigma(\text{IP}) \approx 20\ \mu\text{m}$ for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)\text{GeV}$
- $\sigma(m_B) \approx 24$ MeV for two-body decays

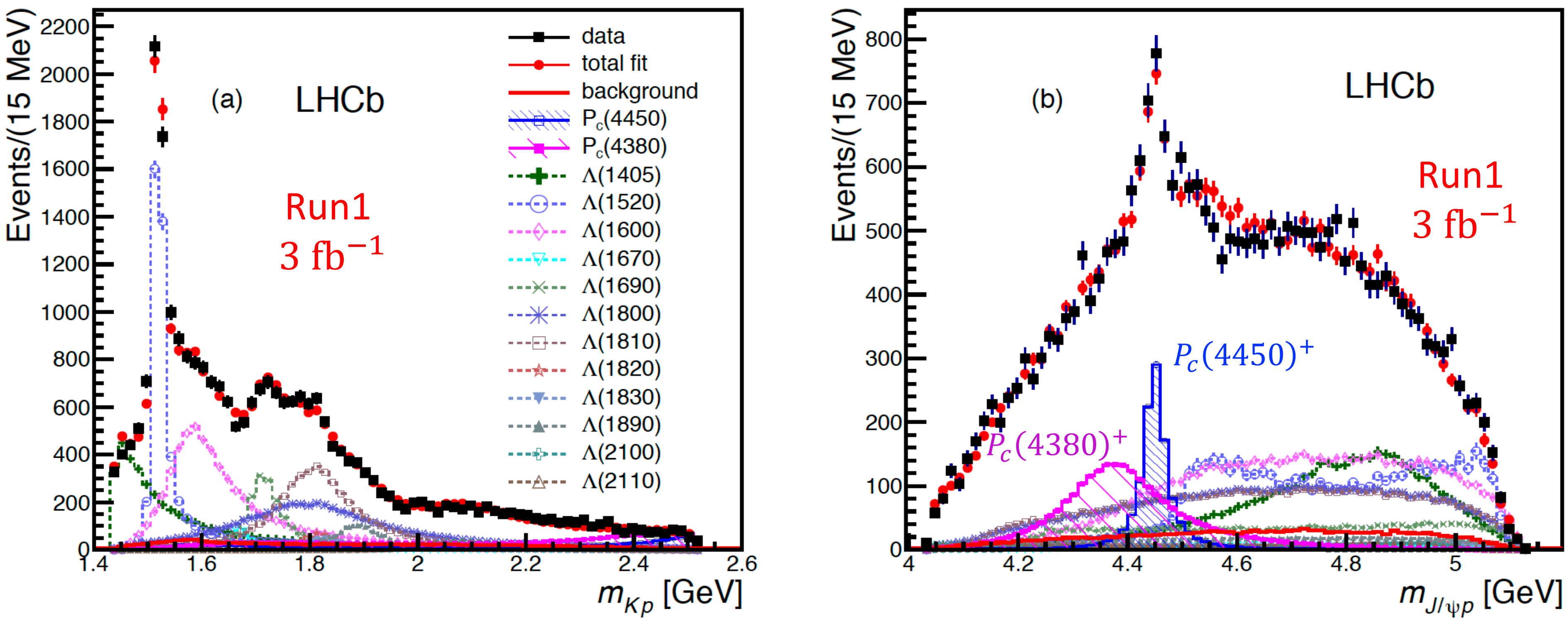
Hadron and Muon identification

- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1 - 3\%$

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

Pentaquark in LHCb

- Two pentaquark candidates in 2015 PRL115(2015)072001
  - Observe $P_c(4450)^+$, $P_c(4380)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decay
  - A full amplitude analysis based on Run1 data



PRL122(2019)222001

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

- An order of magnitude increases in signal yield
  - Inclusion of Run1+Run2 data
  - Improvement of event selections

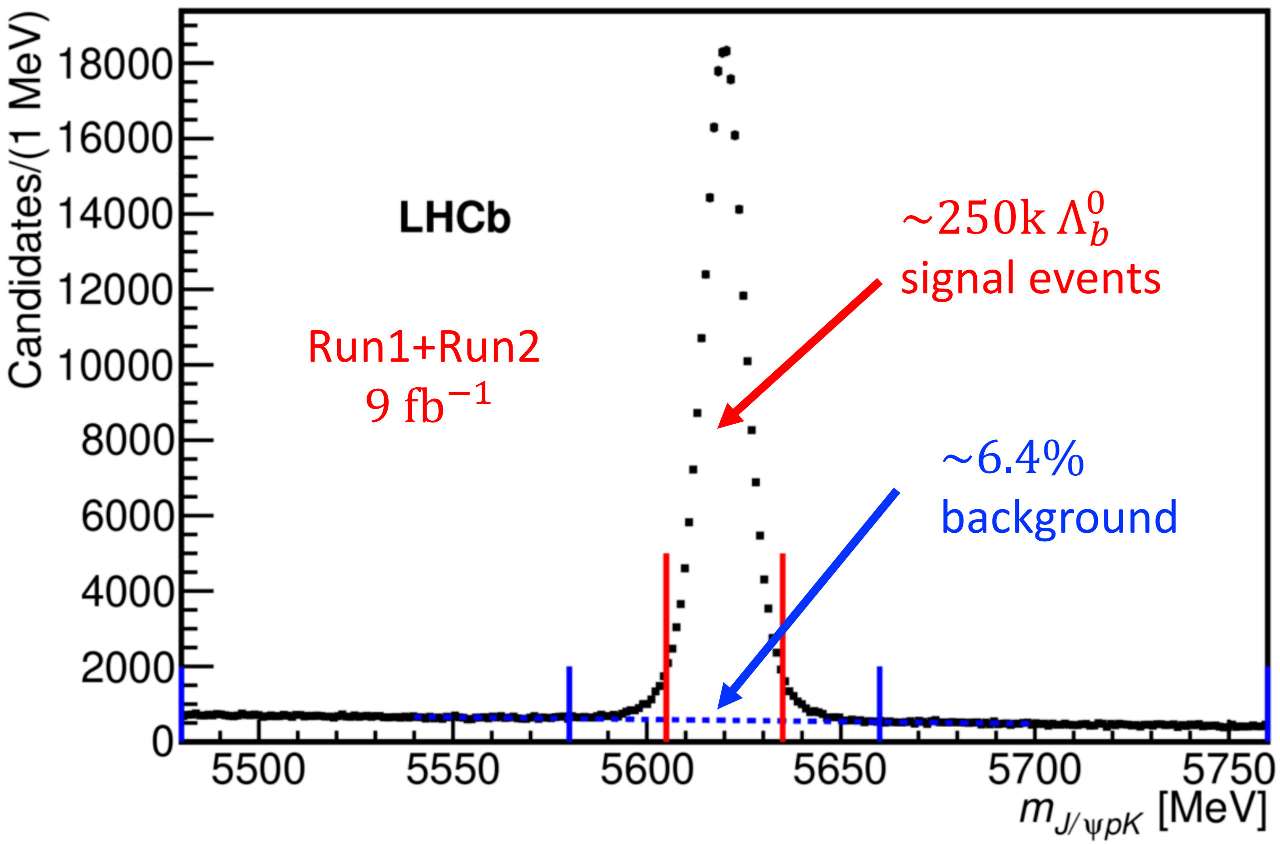


Figure in PRL supplemental material

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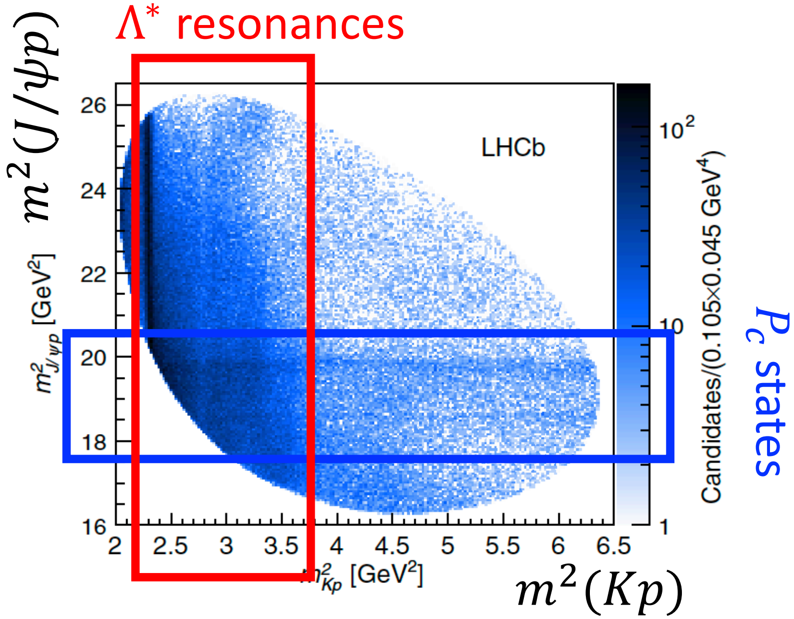
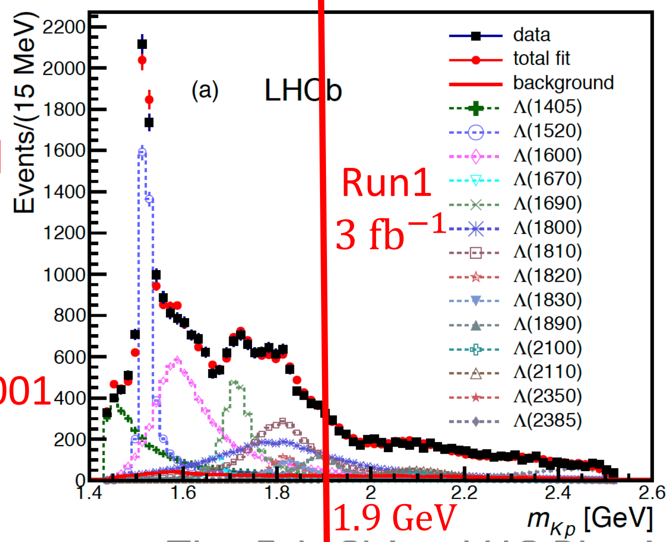
Subtract $\Lambda^* \to Kp$ background

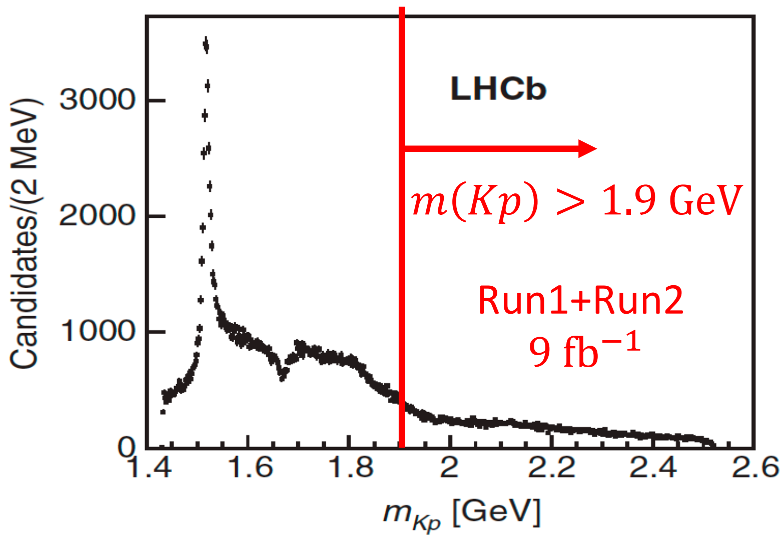
- Significant contribution from $\Lambda_b^0 \to \Lambda^* J/\psi, \Lambda^* \to Kp$ decays
- Two approaches for subtraction
- Approach 1:
  - Cut $m(Kp) > 1.9$ GeV
  - Eliminate 80% $\Lambda^* \to Kp$



Run1 amplitude fit result. Λ^* background mostly enrich low $m(Kp)$ regions.

PRL115(2015)072001





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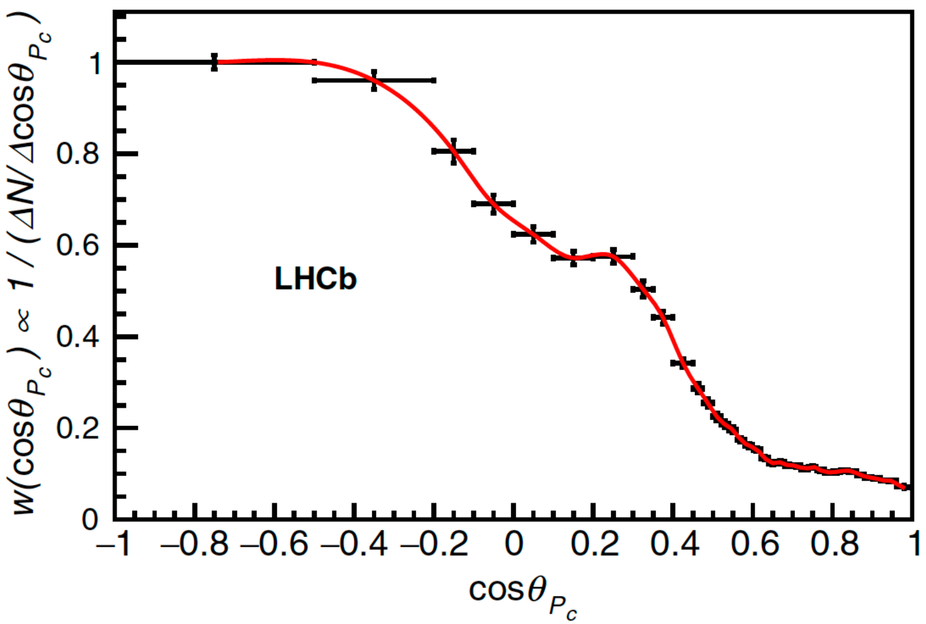
Subtract $\Lambda^* \to Kp$ background

- Approach 2:
  - Apply $\cos\theta_{P_c}$ − dependent weights for Λ^* subtraction
  - θ_{P_c}: angle between K and p in $J/\psi p$ rest frame
  - For any fixed $m(J/\psi p)$, large $\cos\theta_{P_c}$ => small $m(Kp)$
  - The $\Lambda^* \to Kp$ background mostly populate regions with high $\cos\theta_{P_c}$ value

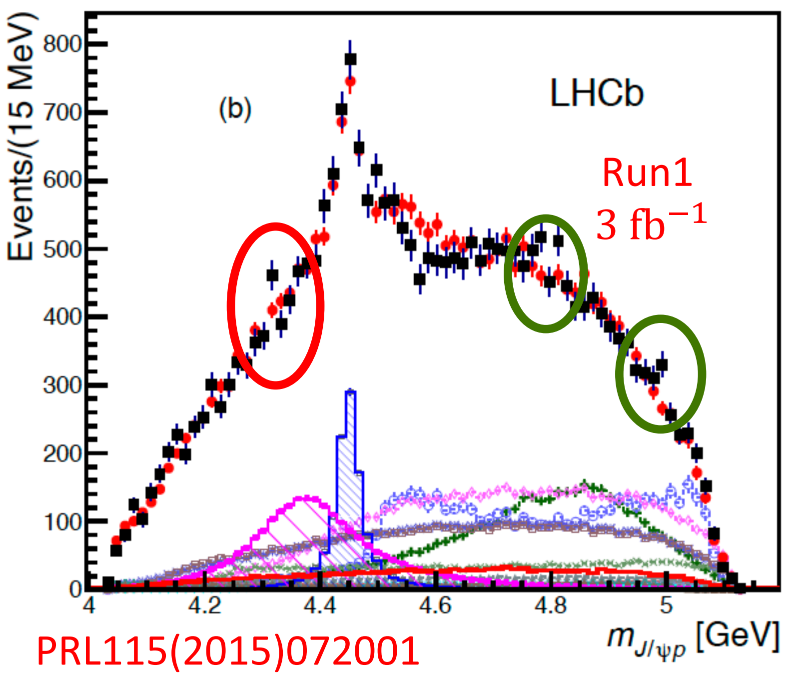
Apply single-event weights to subtract data with high $\cos\theta_{P_c}$ value



New observations

- a narrow $J/\psi p$ peaking structure $P_c(4312)^+$
  - An insignificant structure seen in Run1
  - Confirmed using the new sample (Run1+Run2)

Several "peak candidates" in Run1 $m(J/\psi p)$ spectrum



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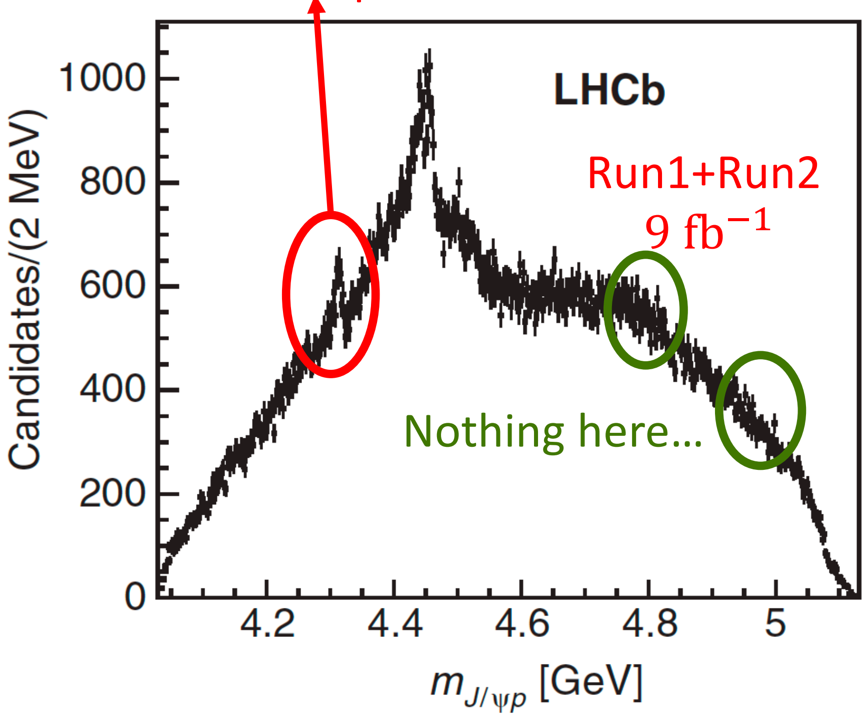
Confirmed in the new sample!



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New observations

- The two-peak structure of $P_c(4450)^+$

Now with more statistic...

And thanks to the good resolution!

Run1 result: broad resonance at 4.45 GeV

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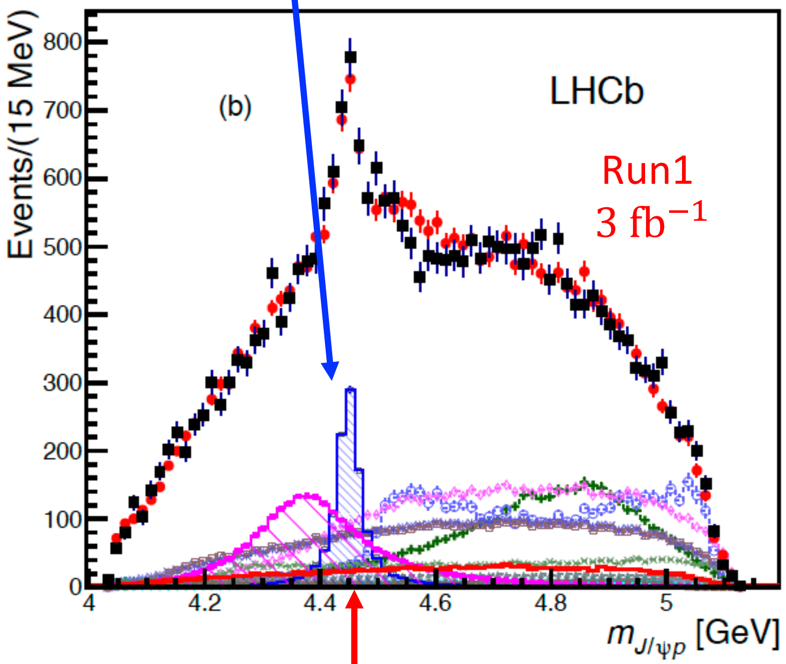

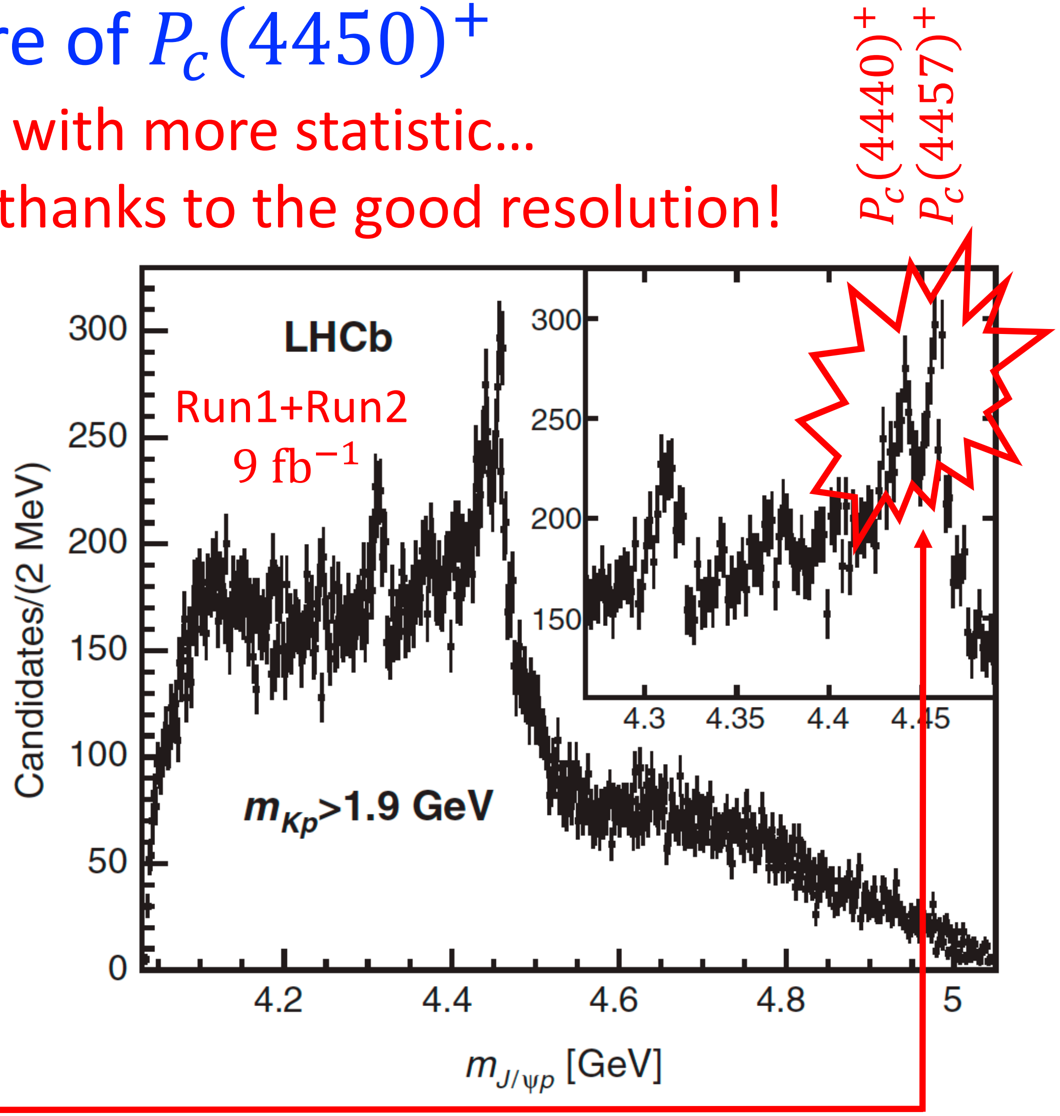

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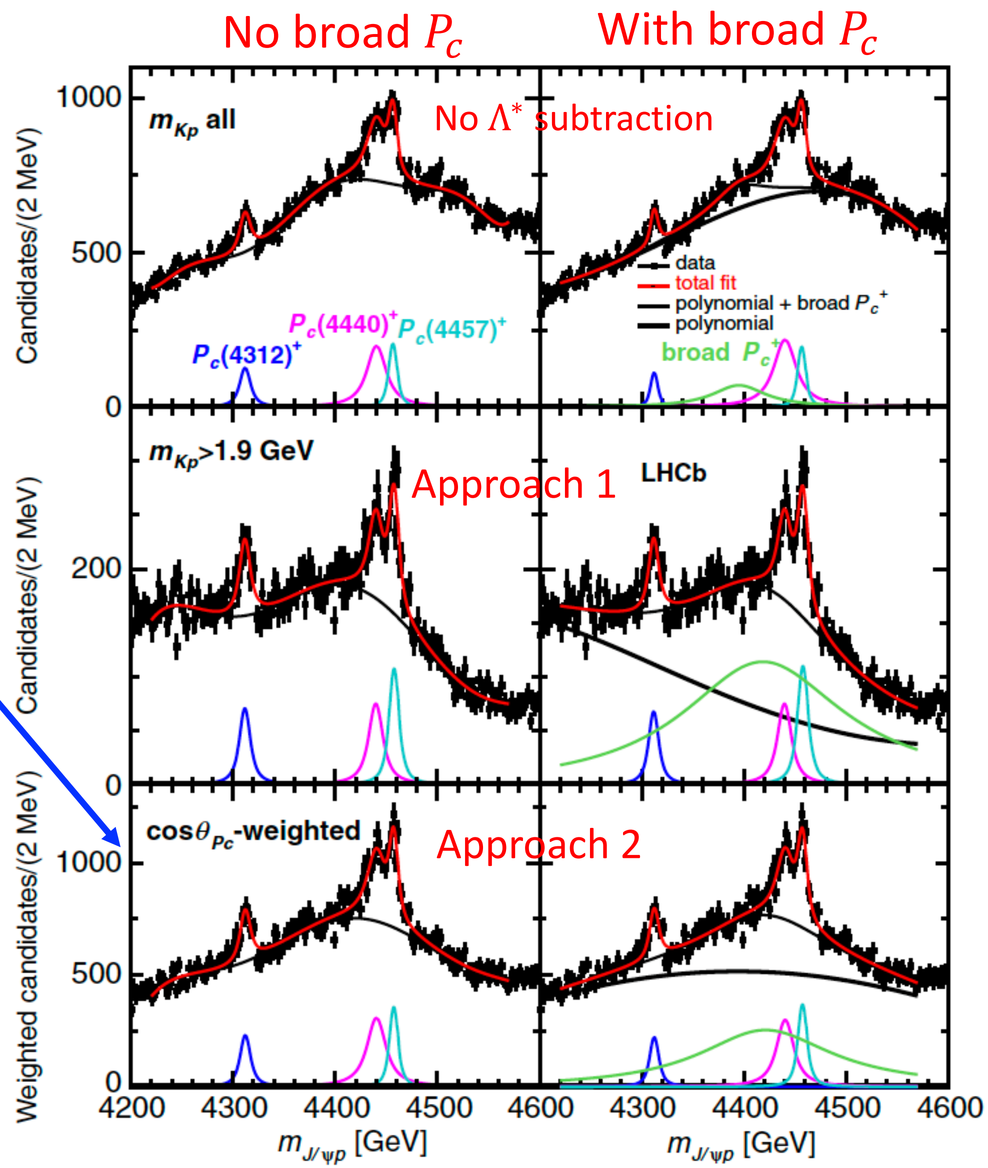
Fit $J/\psi p$ mass spectrum

PRL117(2016)082002

- For narrow $J/\psi p$ peaks, no need for amplitude analysis
- 1D fits to $\mathrm{m}(J/\psi p)$ to characterize narrow peaks
  - 1D fit not sensitive to broad structure $P_c(4380)^+$
- $\cos\theta_{P_c}$ – dependent weights lead to best statistical significance
  - 8.2σ for $P_c(4312)^+$
  - 6.2σ for two-peak structure of $P_c(4450)^+$ (w.r.t. the one-peak hypothesis)



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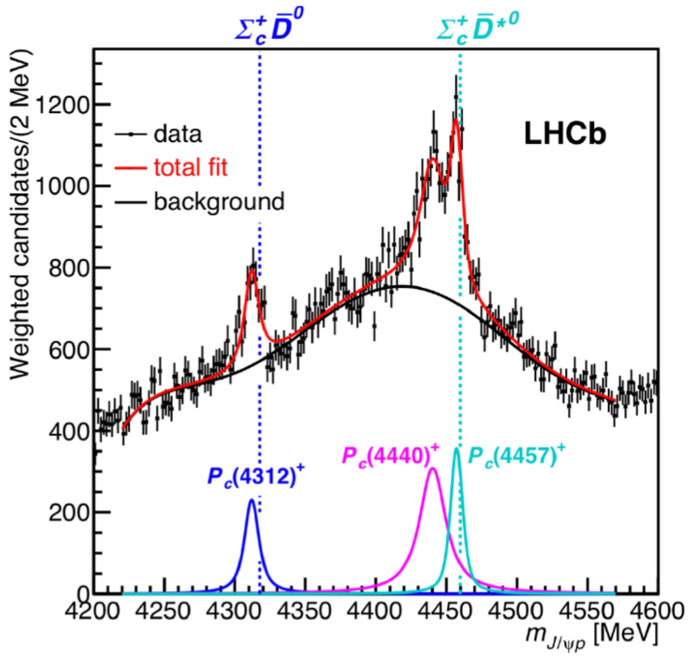
Properties of the new P_c states

- $P_c(4312)^+, P_c(4440)^+$ and $P_c(4457)^+$ just below the $\Sigma_c^+\bar{D}^{(*)0}$ threshold
- Full amplitude analysis needed:
  - For J^P determination
  - $P_c(4380)^+$ related studies (1D fit not enough for broad structures)



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

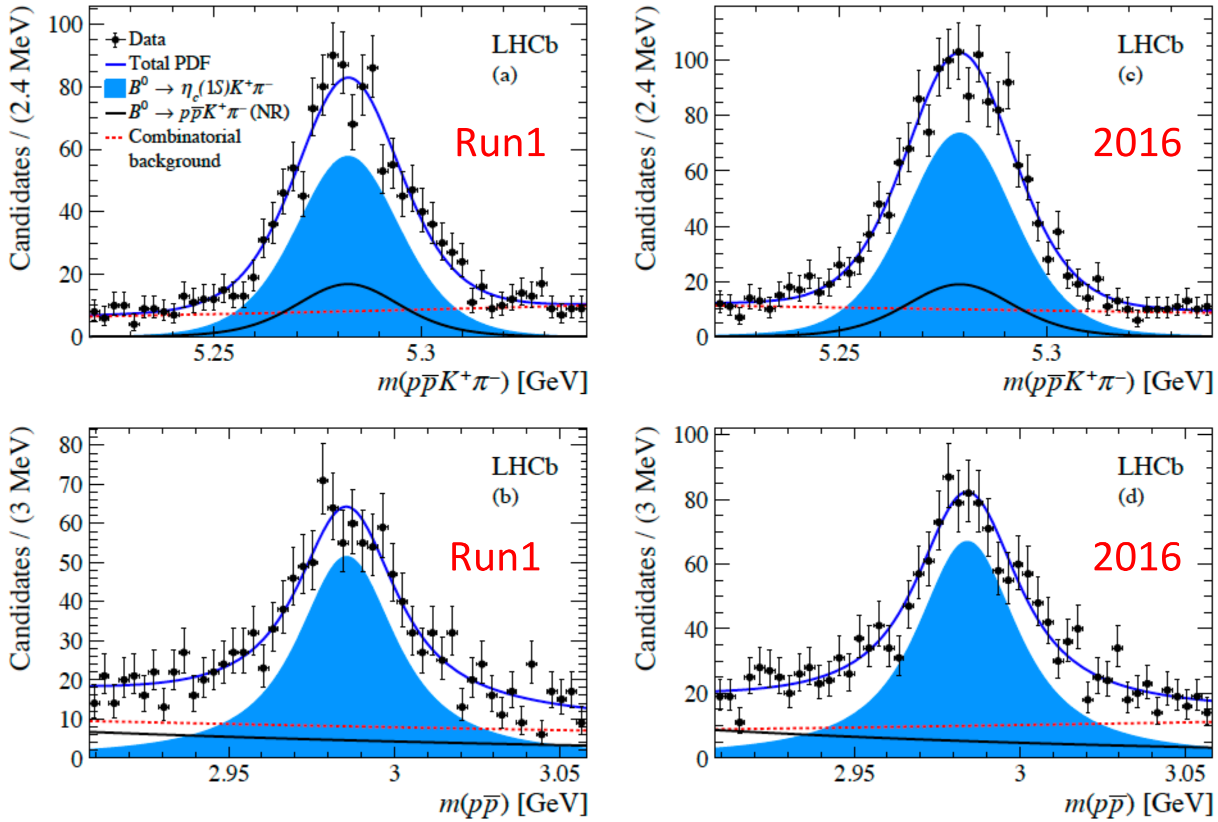
Evidence of $Z_c(4100)^-$ in $B^0 \to \eta_c \pi^- K^+$

$B^0 \to \eta_c \pi^- K^+$ data sample

EPJC78(2018)1019

- LHCb Run1+2016 data, $\mathcal{L} = 4.7\ \mathrm{fb}^{-1}$
- Cut-based preselections followed by an MVA selection
- 2D fit to $m(p\bar{p}K^+\pi^-)$ VS $m(p\bar{p})$ for background subtraction

Obtain ~800 signals for Run1, and ~1000 signals for 2016



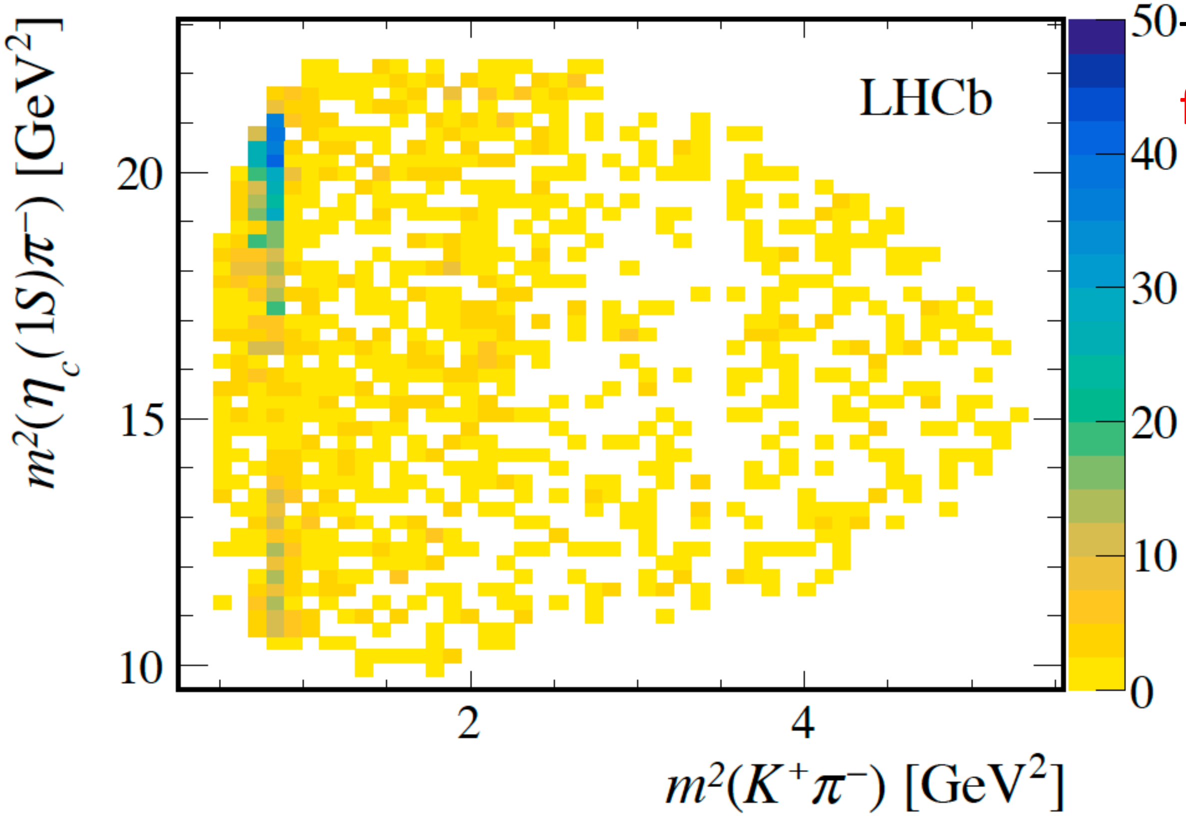
Amplitude analysis

EPJC78(2018)1019

- 2D Dalitz fit for amplitude analysis

$$\mathcal{A}[m^2(K^+\pi^-), m^2(\eta_c\pi^-)] = \sum_{j=1}^{N} c_j \mathcal{F}_j[m^2(K^+\pi^-), m^2(\eta_c\pi^-)],$$

Background-subtracted Dalitz plot



All $K^* \to K\pi$ with $m(K^*) < m(B^0) - m(\eta_c)$ are tested;

The ones significantly improving the fit are kept in baseline fit model:

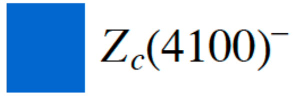
Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

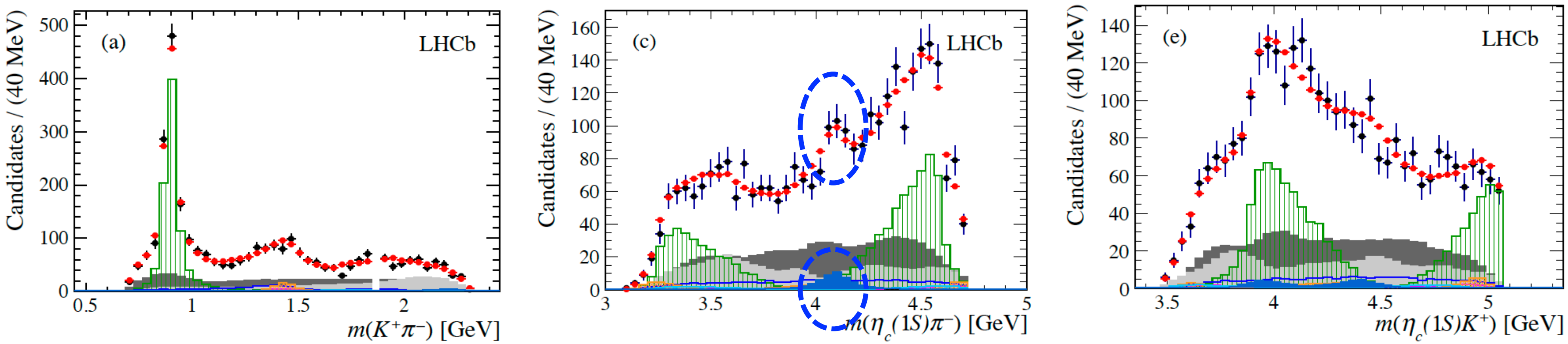
Add an additional $\eta_c\pi$ resonance with $J^P = 0^+, 1^-$ or 2^+

Amplitude analysis

EPJC78(2018)1019

- $J^P = 1^-$ fit data best





  - $m_Z = 4096 \pm 20^{+18}_{-22}$ MeV;
  - $\Gamma_Z = 152 \pm 58^{+60}_{-35}$ MeV
  - Statistical significance: 4.8σ
- $J^P = 0^+$ also allowed

Systematic effects on significance

Source	$\Delta(-2\ln\mathcal{L})$	Significance
Nominal fit	41.4	4.8σ
Fixed yields	45.8	5.2σ
Phase-space border veto	44.6	5.1σ
η_c width	36.6	4.3σ
$K^+\pi^-$ S-wave	31.8	3.9σ
Background	27.4	3.4σ

All above 3σ !

Conclusion

- LHCb has made fruitful results about exotic studies
- Recent results (selected) :
  - Observation of a new pentaquark $P_c(4312)^+$ in the $\Lambda_b^0 \to J/\psi p K^-$ decay, and discovery of the two-peak structure of $P_c(4450)^+$
  - Evidence for $Z_c(4100)^-$ found in $\eta_c \pi^-$ system of the $B^0 \to \eta_c K^+ \pi^-$ decay
- Stay tuned for more results

Thank you for your attention

Any questions or comments!

Back up

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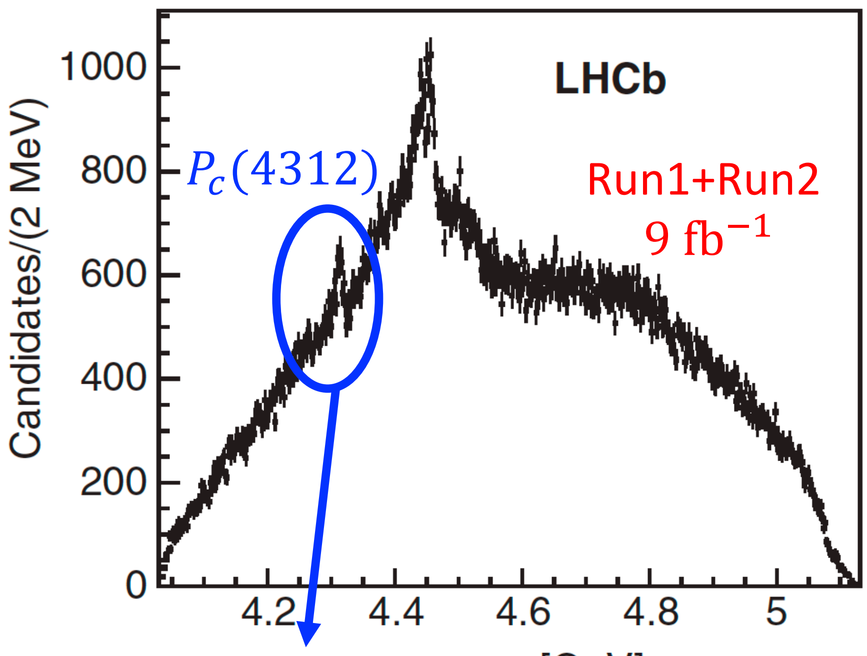
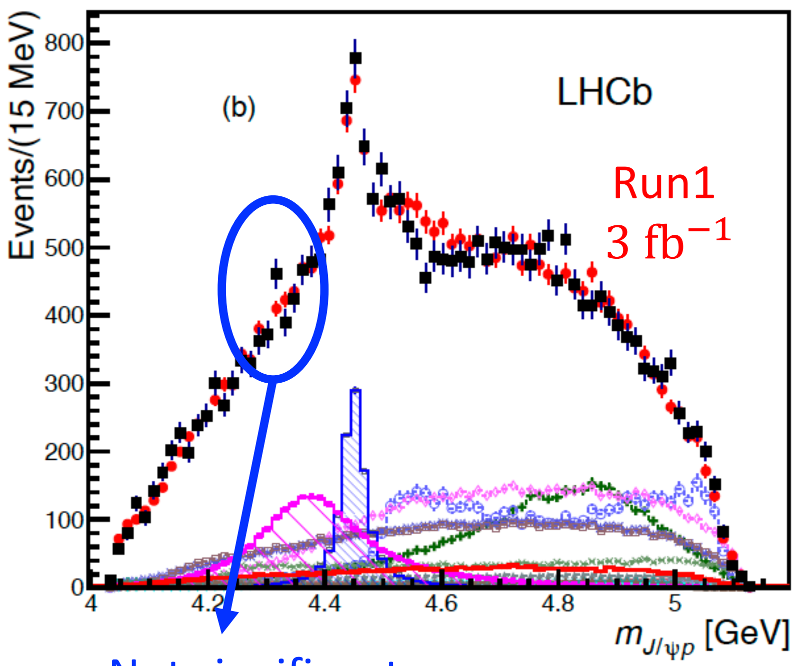
$J/\psi p$ resonance in new sample

- Fit new sample with the run1 amplitude model; obtain consistent $P_c(4450)^+$ and $P_c(4380)^+$ parameters
- New observation: a narrow $J/\psi p$ peaking structure



Significant peak in new (Run1+Run2) data sample



Not significant in run1 analysis

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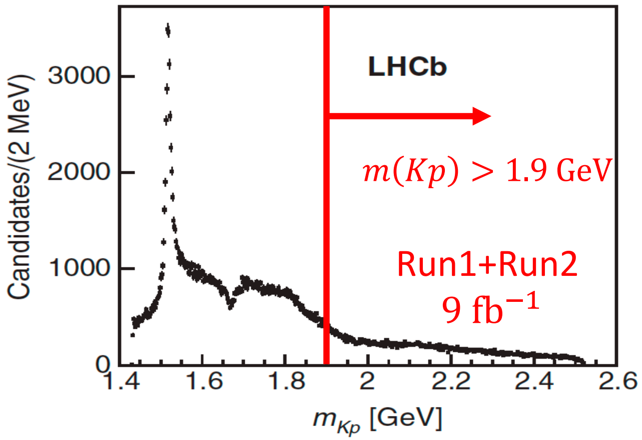
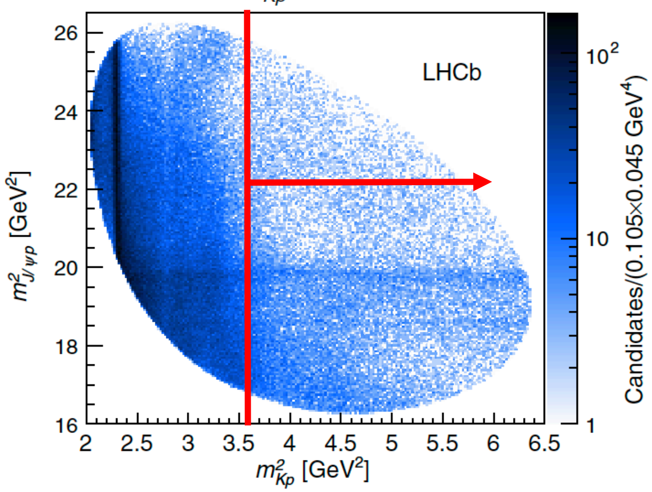
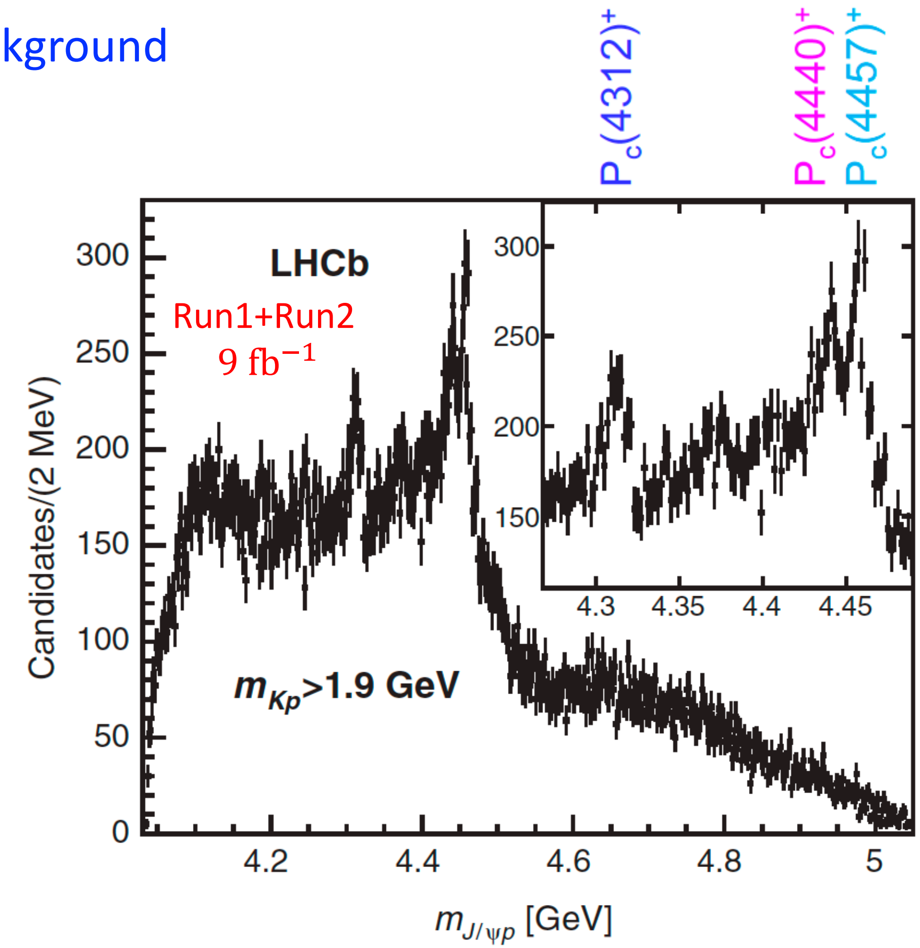
$J/\psi p$ resonance in new sample

- New observation: the two-peak structure of $P_c(4450)$

$m(Kp) > 1.9$ GeV: Eliminate 80% $\Lambda^* \to Kp$ background







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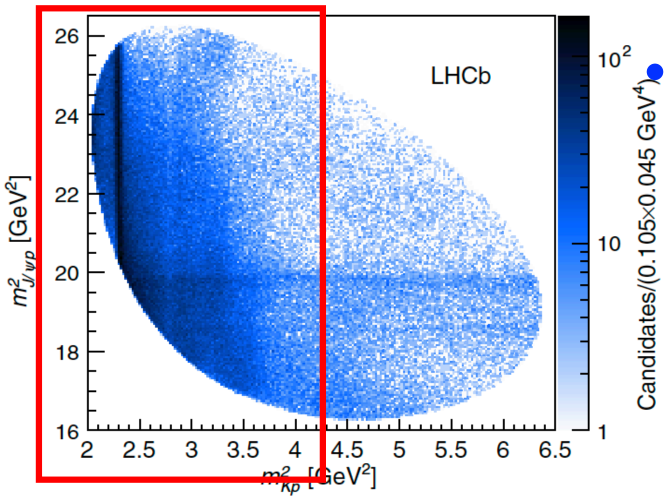
Subtract $\Lambda^* \to Kp$ background

Significant contribution from $\Lambda_b^0 \to \Lambda^* J/\psi$, $\Lambda^* \to Kp$ decays



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  - θ_{P_c}: angle between K and J/ψ in $J/\psi p$ rest frame
  - $\Lambda^* \to Kp$ background mostly populate $cos\theta_{P_c} > 0$ region

- Approach 1:
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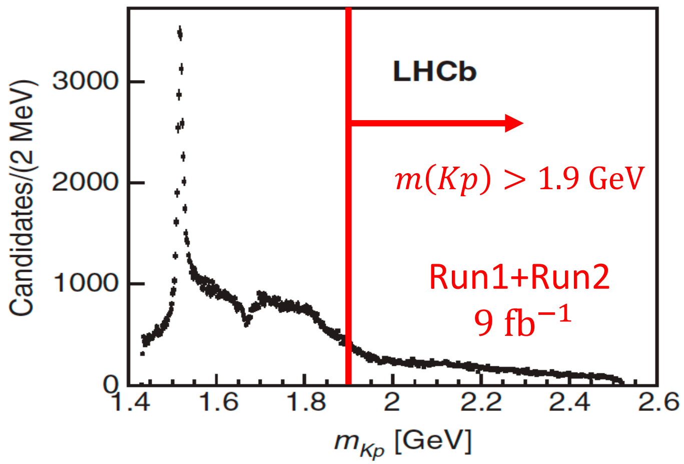

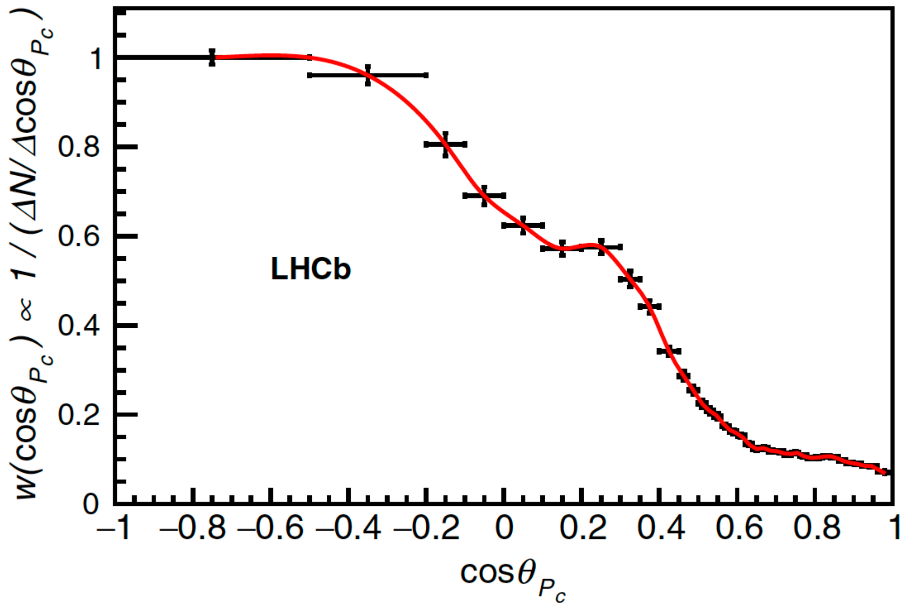

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$J/\psi p$ resonance in new sample

- New observations:
  - a narrow $J/\psi p$ peaking structure $P_c(4312)^+$
  - two-peak structure of $P_c(4450)^+$

Peak near 4.3GeV is not significant in run1 analysis