Hadron spectroscopy and exotic states at LHCb

Tomasz Skwarnicki

on behalf of the LHCb collaboration

Present only the most recent measurements based on Run 1 + Run 2 data:

- Near threshold $D\overline{D}$ spectroscopy
- Excited B_c^+ states
- Update on $P_c^+ \to J/\psi p$ pentaquarks in $\Lambda_b \to J/\psi p K^-$ decays (**first presentation!**)

Moriond QCD
March 26, 2019

Near-threshold $D\bar{D}$ spectroscopy

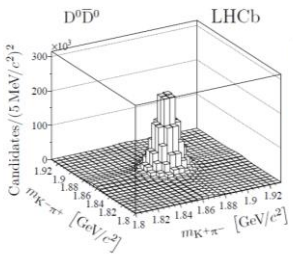
LHCb-PAPER-2019-005
in preparation

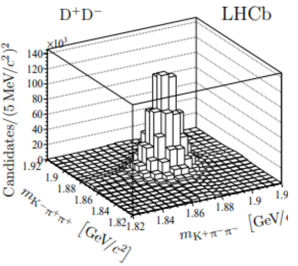
Run 1 + Run 2
9 fb^{-1}

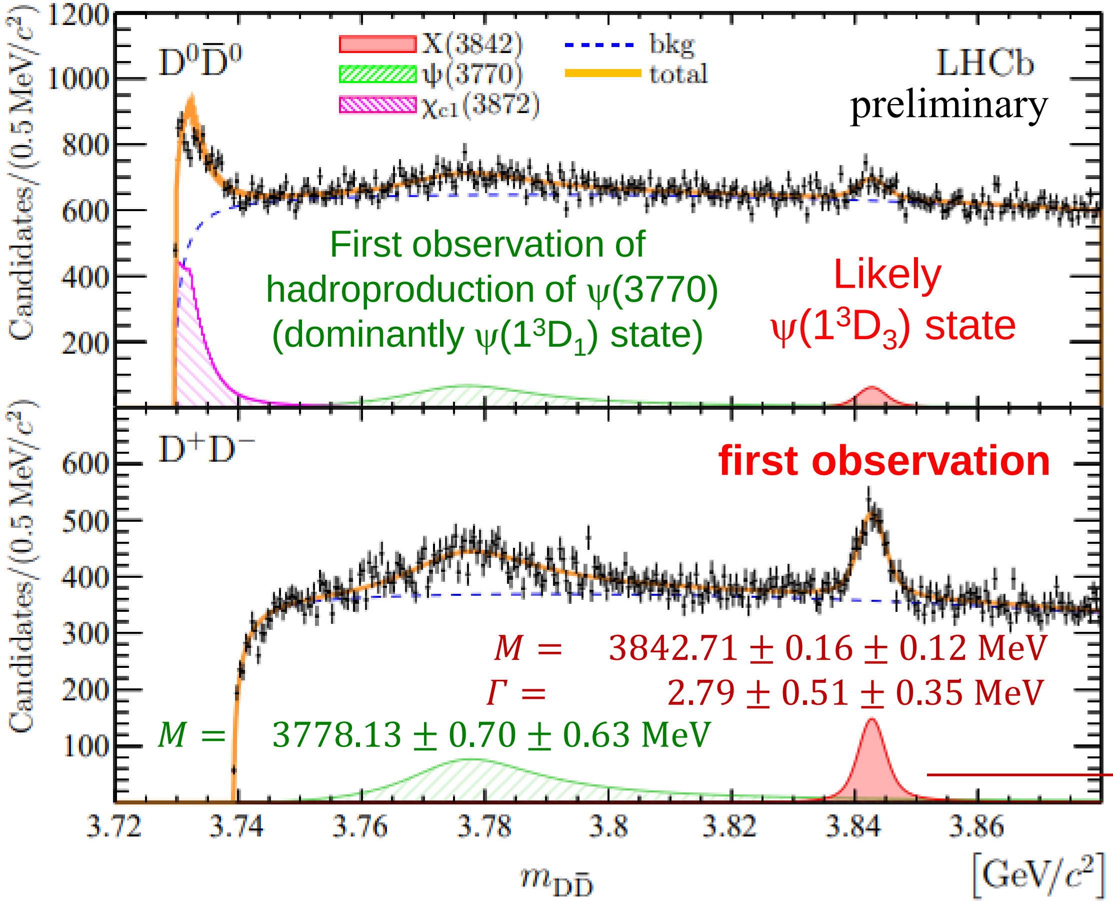
		$m_{\psi(3770)}$ [MeV/c^2]
PLB 769, 187 (2017)	Shamov and Todyshev	3779.8 ± 0.6
	PDG average	3778.1 ± 1.2
	PDG fit	3773.13 ± 0.35
	This analysis	3778.13 ± 0.70 ± 0.63

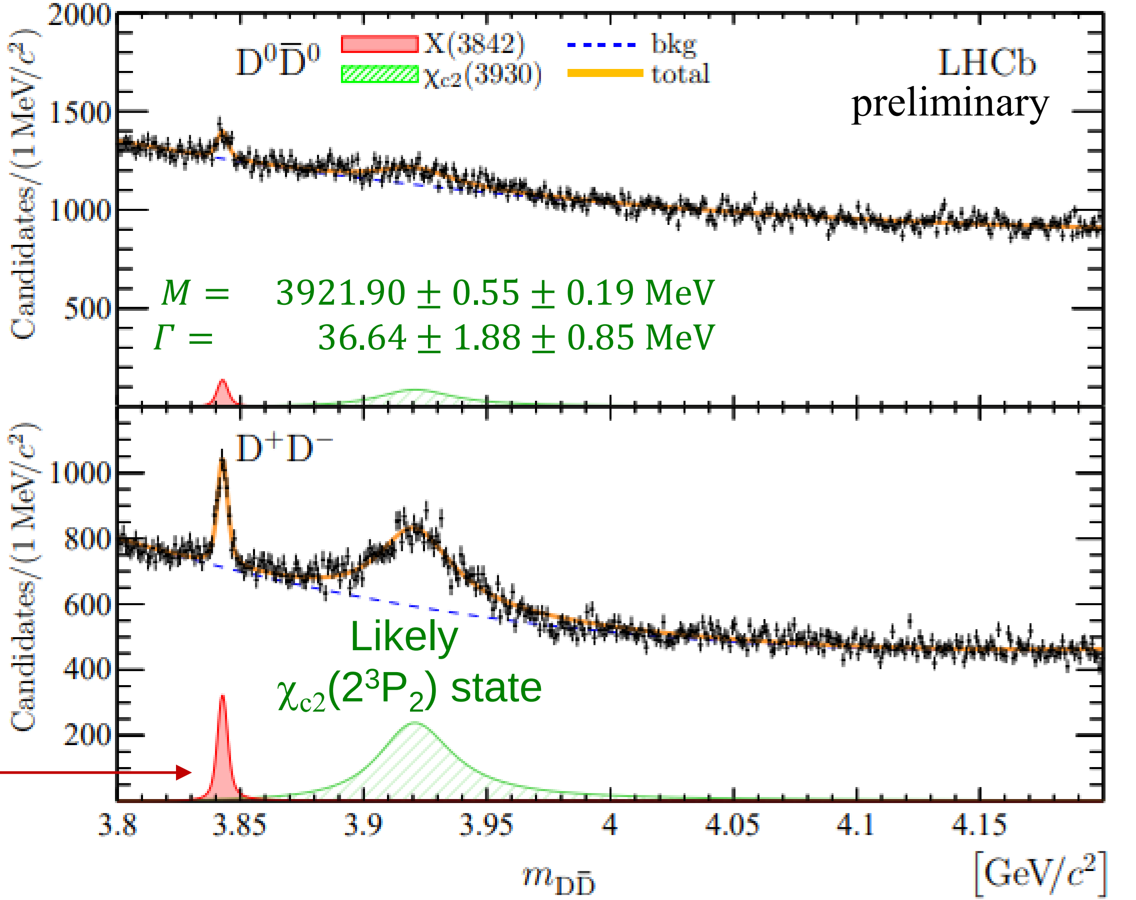
		$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
PRL 96, 082003 (2006)	Belle	3929 ± 5 ± 2	29 ± 10 ± 2
PRD 81, 092003 (2010)	BaBar	3926.7 ± 2.7 ± 1.1	21.3 ± 6.8 ± 3.6
	This analysis	3921.90 ± 0.55 ± 0.19	36.64 ± 1.88 ± 0.85

Purely hadronic final states!

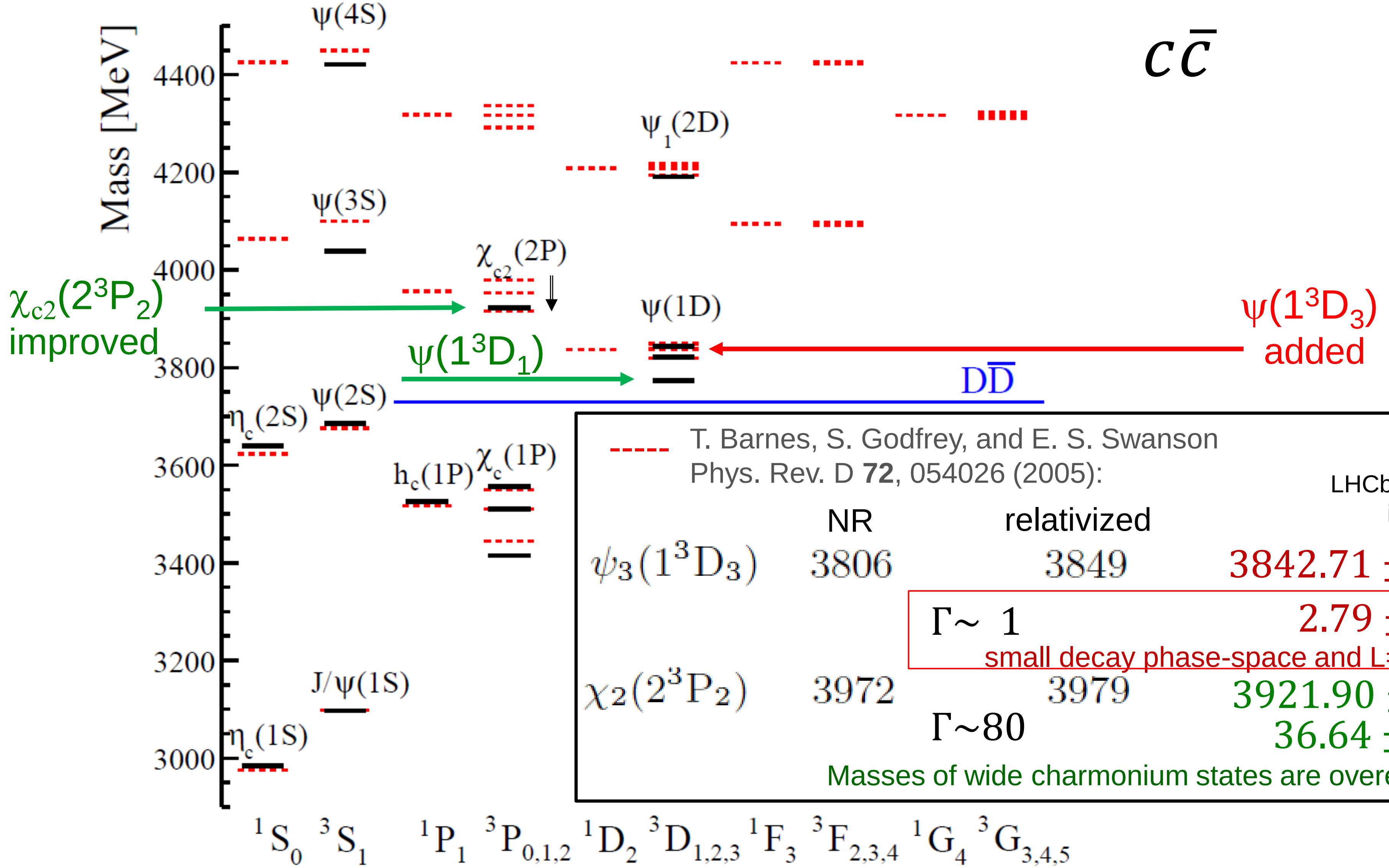








Status of charmonium spectroscopy



----- T. Barnes, S. Godfrey, and E. S. Swanson
Phys. Rev. D **72**, 054026 (2005):

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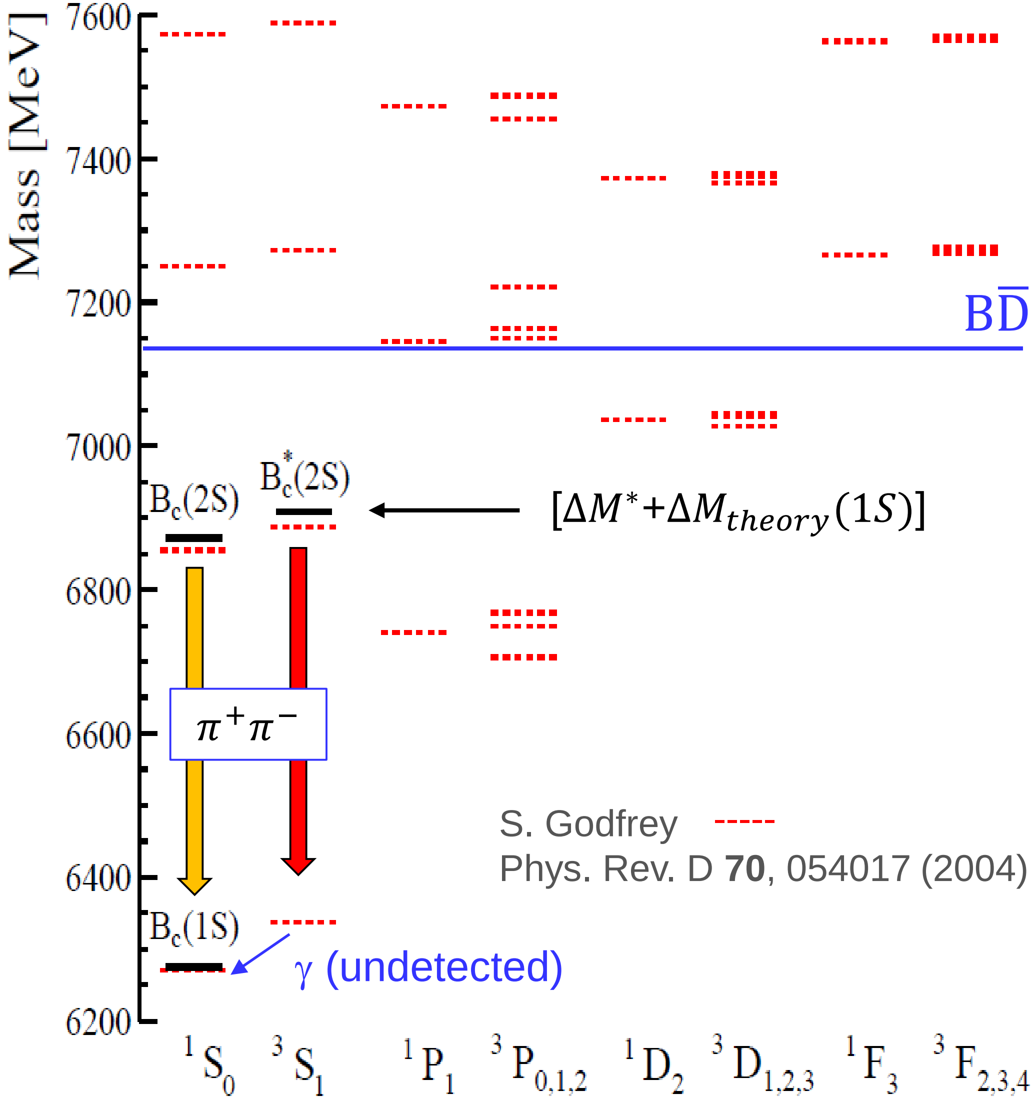
	NR	relativized	LHCb-PAPER-2019-005
$\psi_3(1^3D_3)$	3806	3849	$3842.71 \pm 0.16 \pm 0.12$ MeV
	$\Gamma\sim$ 1		$2.79 \pm 0.51 \pm 0.35$ MeV
$\chi_2(2^3P_2)$	3972	3979	$3921.90 \pm 0.55 \pm 0.19$ MeV
	$\Gamma\sim$80		$36.64 \pm 1.88 \pm 0.85$ MeV

small decay phase-space and L=3 centrifugal barrier!

Masses of wide charmonium states are overestimated in potential approaches.

Observation of an excited B_c^+ states



$b\bar{c}$

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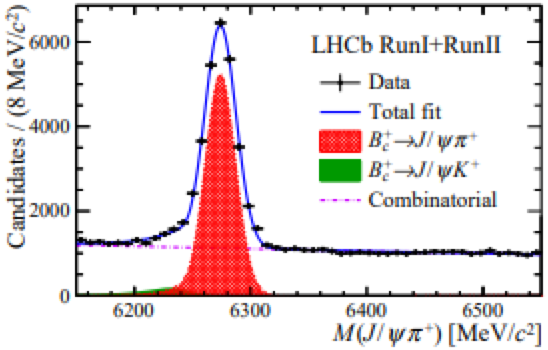
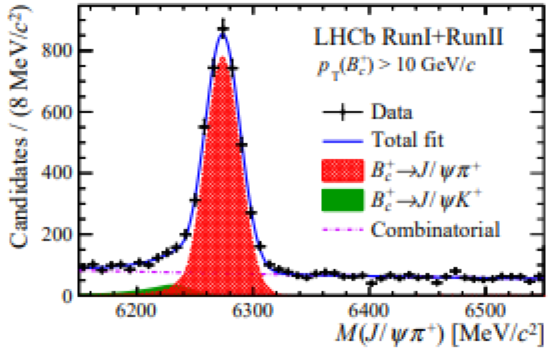
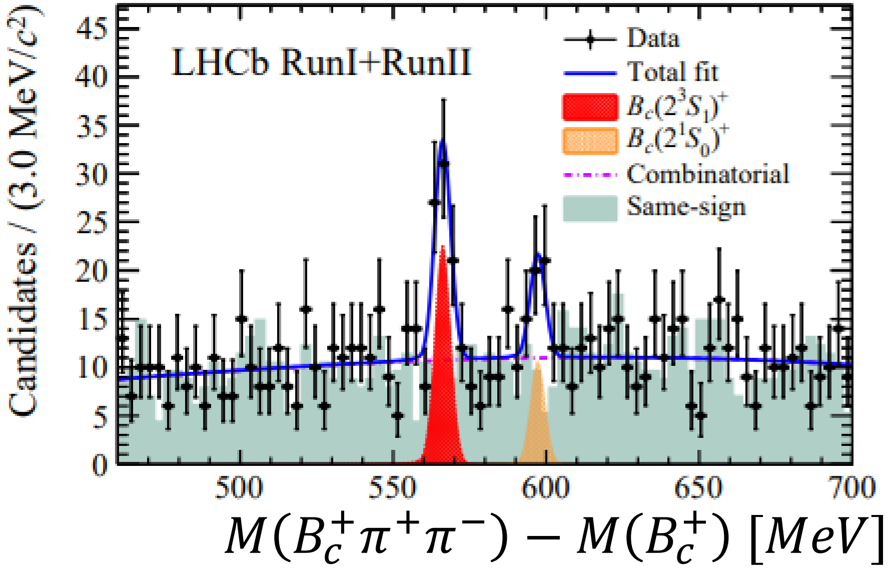
Run 1 + Run 2
8.5 fb^{-1}
$J/\psi \rightarrow \mu^+\mu^-$







$\Delta M^* = M(2^3S_1) - \Delta M(1S)$; $\Delta M(1S) = M(1^3S_1) - M(1^1S_0)$;

$6841.2 \pm 0.6\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.8\,(B_c^+)\ \text{MeV}/c^2$,

$M(2^1S_0)$

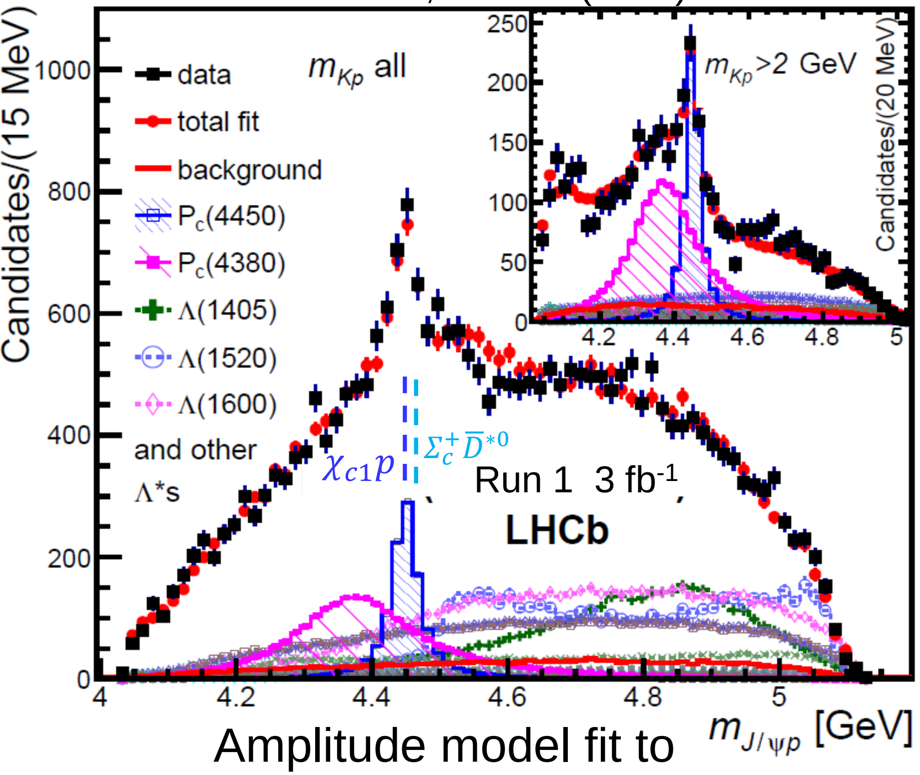
$6872.1 \pm 1.3\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.8\,(B_c^+)\ \text{MeV}/c^2$.

Spectroscopy of $b\bar{c}$ is clean theoretically (no EM or gluon annihilations) but difficult experimentally: low production cross-sections, large backgrounds in detection of soft hadrons or γ originating from the primary pp interaction vertex

Confirm the recently presented CMS results
arxiv:1902.00571 (see the talk by Greg Landsberg)
(also ATLAS PRL 113 (2014) 12004; two peaks unresolved)

Run 1 evidence for $P_c^+ \to J/\psi p$ pentaquarks in $\Lambda_b \to J/\psi p K^-$

PRL 115, 072001 (2015)



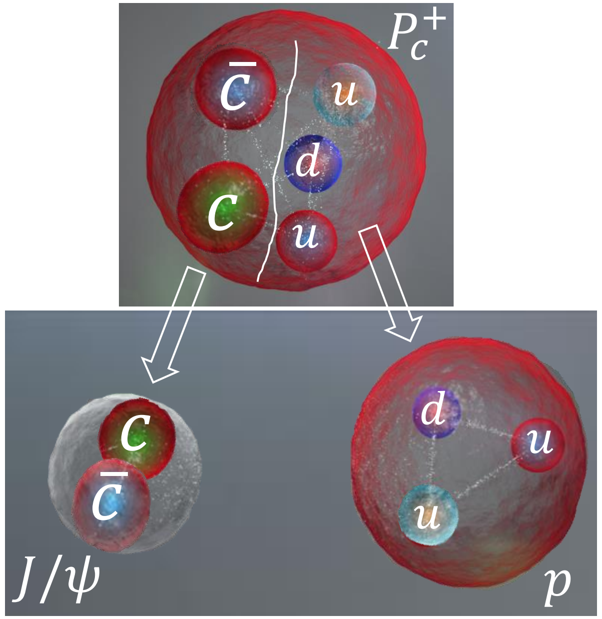
Amplitude model fit to masses and decay angles

$P_c(4450)^+$	$M =$	$4450 \pm 2 \pm 3$ MeV
	$\Gamma =$	$39 \pm 5 \pm 19$ MeV
	$F.F. =$	$4.1 \pm 0.5 \pm 1.1$ %
$P_c(4380)^+$	$M =$	$4380 \pm 8 \pm 29$ MeV
	$\Gamma =$	$205 \pm 18 \pm 86$ MeV
	$F.F. =$	$8.4 \pm 0.7 \pm 4.2$ %

27k $\Lambda_b \to J/\psi p K^-$ signal events
5.4% background

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400$MeV

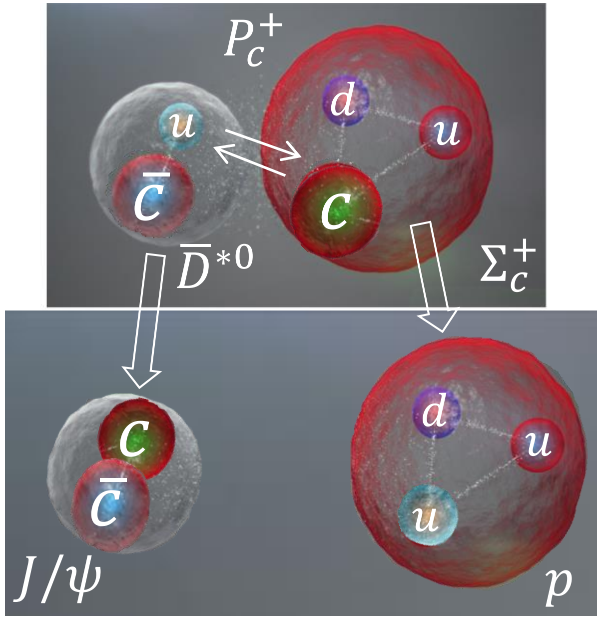
Tightly-bound pentaquark



- Decay by fall-apart:
  - **Wide states?**
  - What slows it down to make $P_c(4450)^+$ narrow? L between **diquarks**?
  - $P_c(4380)^+$ S=1,L=0 broad, $P_c(4450)^+$ S=0,L=1 narrow
- Spectrum (**confining potential**)
  - Many states expected (n,L,S)

L. Maiani, A. D. Polosa, V. Riquer, PL B749 (2015) 289
R. F. Lebed, PL, B749 (2015) 454
V.V. Anisovich, M.A. Matveev, J. Nyiri, A.V. Sarantsev PL,. B749 (2015) 454
and others

Loosely-bound pentaquark



$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim$few MeV

Fast fall-apart prevented

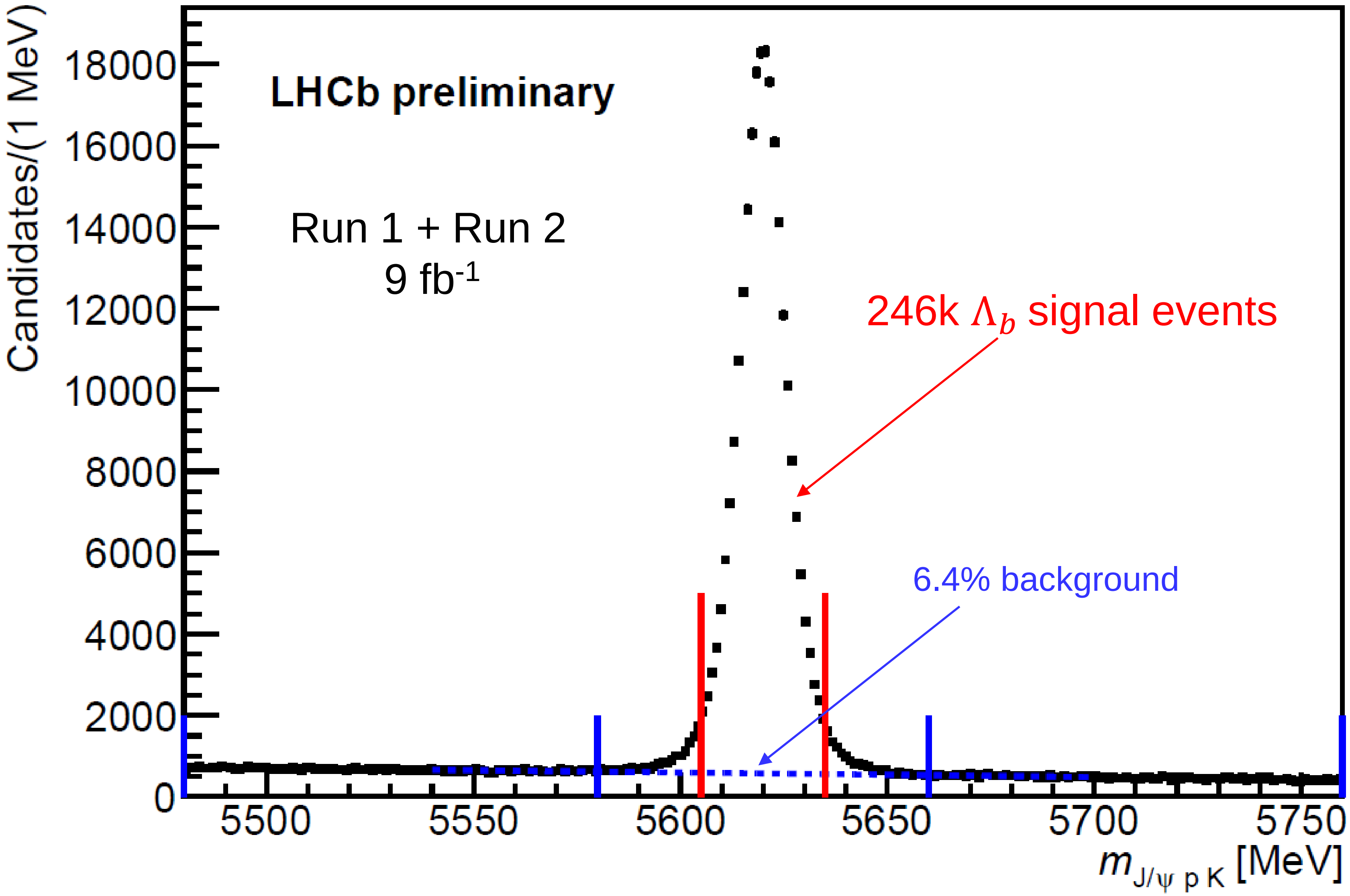
- Decay by heavy quarks changing confinement partners, then fall-apart:
  - **All states narrow**
- Spectrum (**shallow potential well**)
  - n=0,L=0 between hadron
  - Very few states expected (S)
  - Weak binding: masses a few MeV below the related baryon-meson thresholds
- Only $\Sigma_c^+ \bar{D}^{(*)0}$ expected to bind:
  - $P_c(4450)^+ = \Sigma_c^+ \bar{D}^{*0}$ molecule?
- Peaking at $\Lambda_c^+ \bar{D}^{(*)0}, \chi_{cJ} p$ thresholds possible from triangle diagram processes:
  - $P_c(4450)^+ = \chi_{c1} p$ threshold?

Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PR C84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

Guo,Meissner,Wang,Yang, PRD92 (2015) 071502

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

9x more than used in the Run 1 2015-2016 papers



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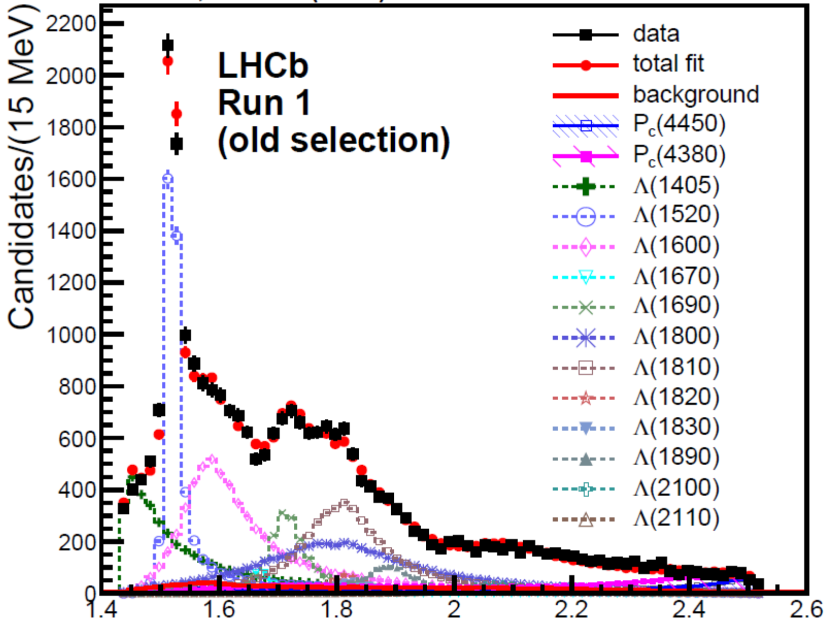
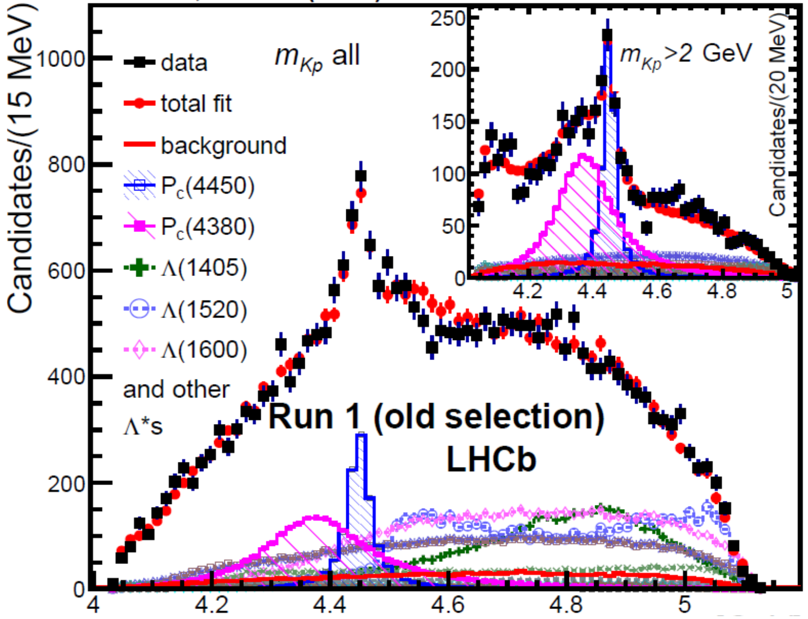
Improvements in the data selection (x 2), integrated luminosity (x 3) and cross-section ($\sqrt{s}$ =13 TeV vs 7-8 TeV)

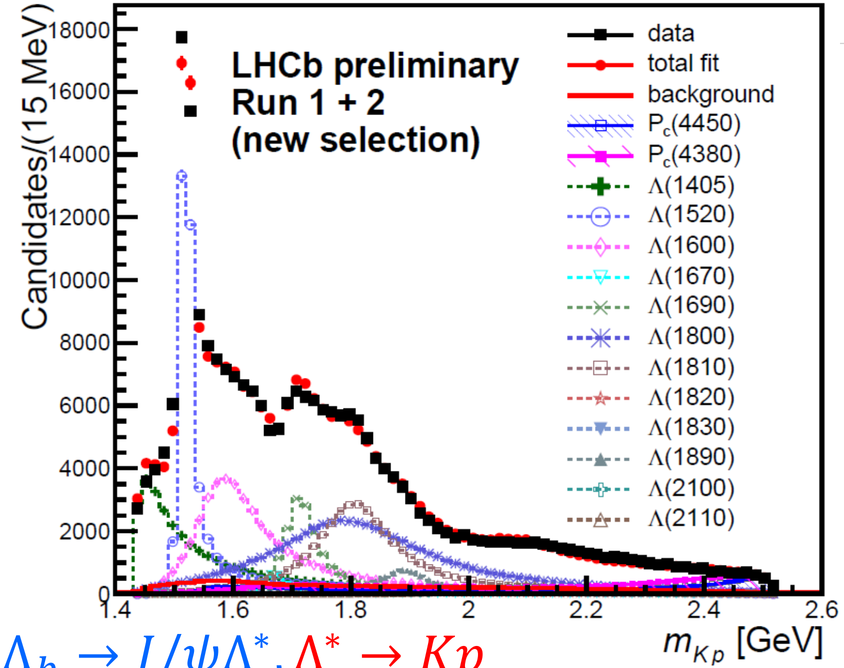
Data consistency check

PRL 115, 072001 (2015)

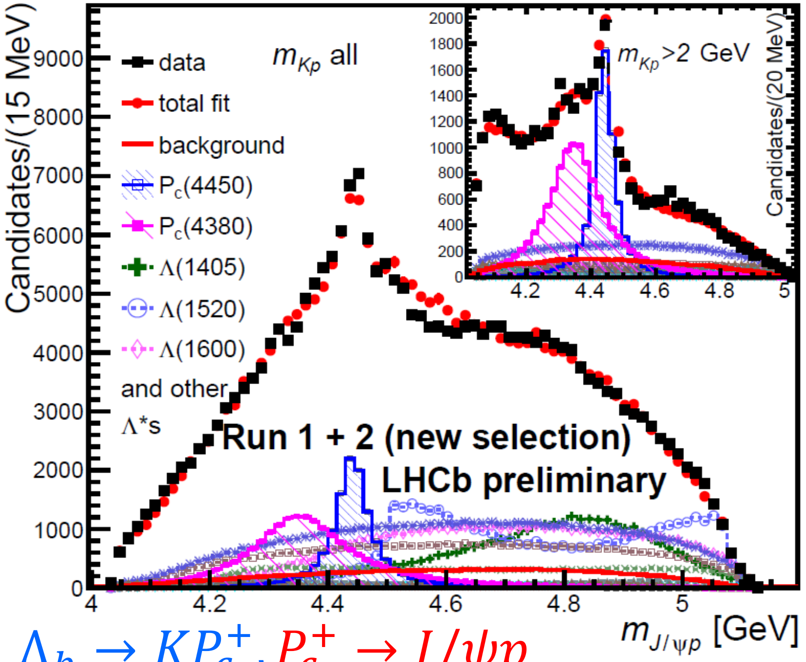


PRL 115, 072001 (2015)





$\Lambda_b \to J/\psi \Lambda^*, \Lambda^* \to Kp$

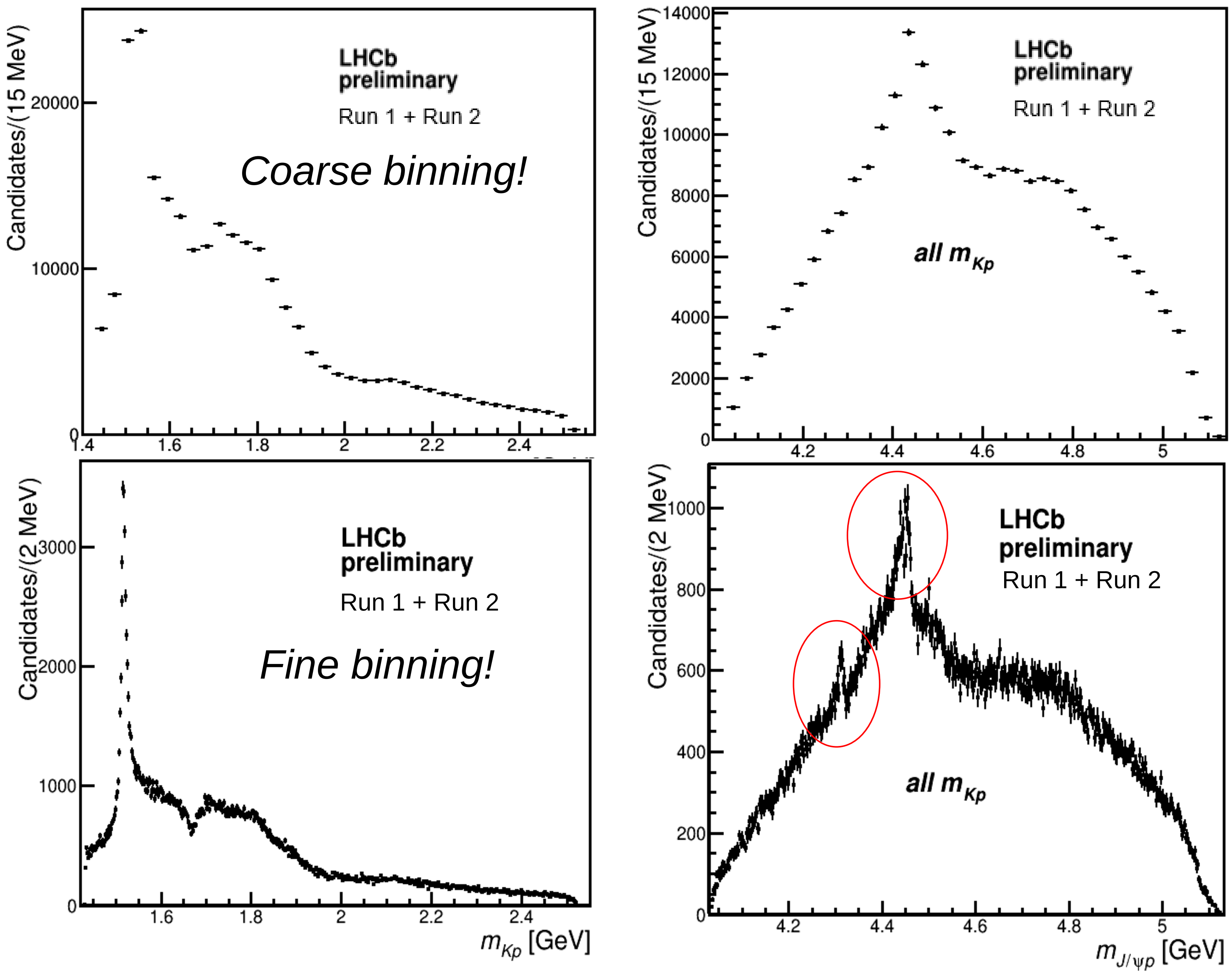


$\Lambda_b \to K P_c^+, P_c^+ \to J/\psi p$

6D amplitude model
fit to masses and decay angles

- When fit with the 2015 amplitude model, the full data sample gives the $P_c(4450)^+$ and $P_c(4380)^+$ parameters **consistent** with the 2015 results
- But…

New $\Lambda_b \to J/\psi p K^-$ data sample – narrow $P_c^+ \to J/\psi p$ peaks



The $J/\psi p$ mass resolution is 2.3-2.7 MeV (RMS) in 4.3-4.6 GeV region

(the excellent momentum resolution, vertexing and J/ψ and Λ_b mass constraints)

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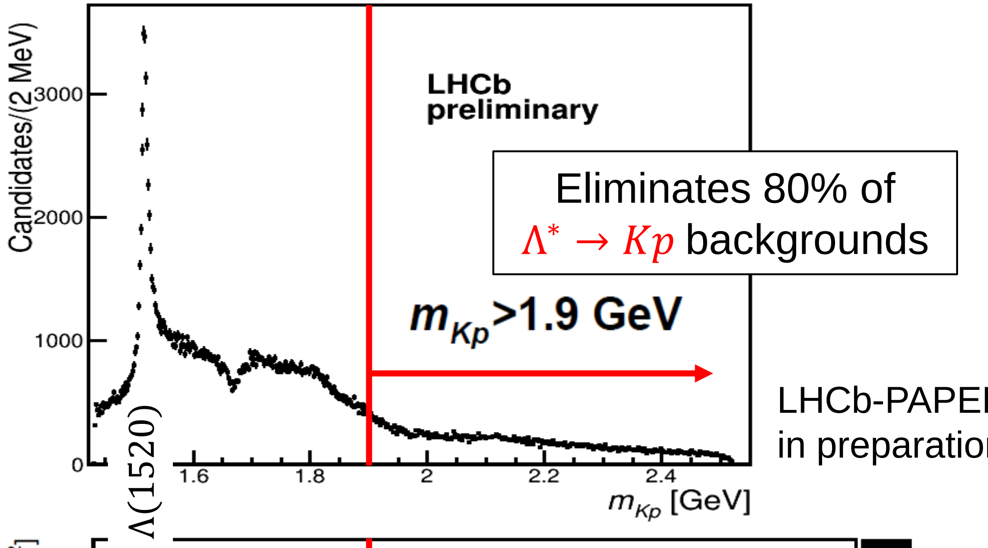
Observe narrow $J/\psi p$ structures which were insignificant with 1/9th of the present $\Lambda_b \to J/\psi p K^-$sample

Narrow $P_c^+ \to J/\psi p$ peaks with Λ^* suppression



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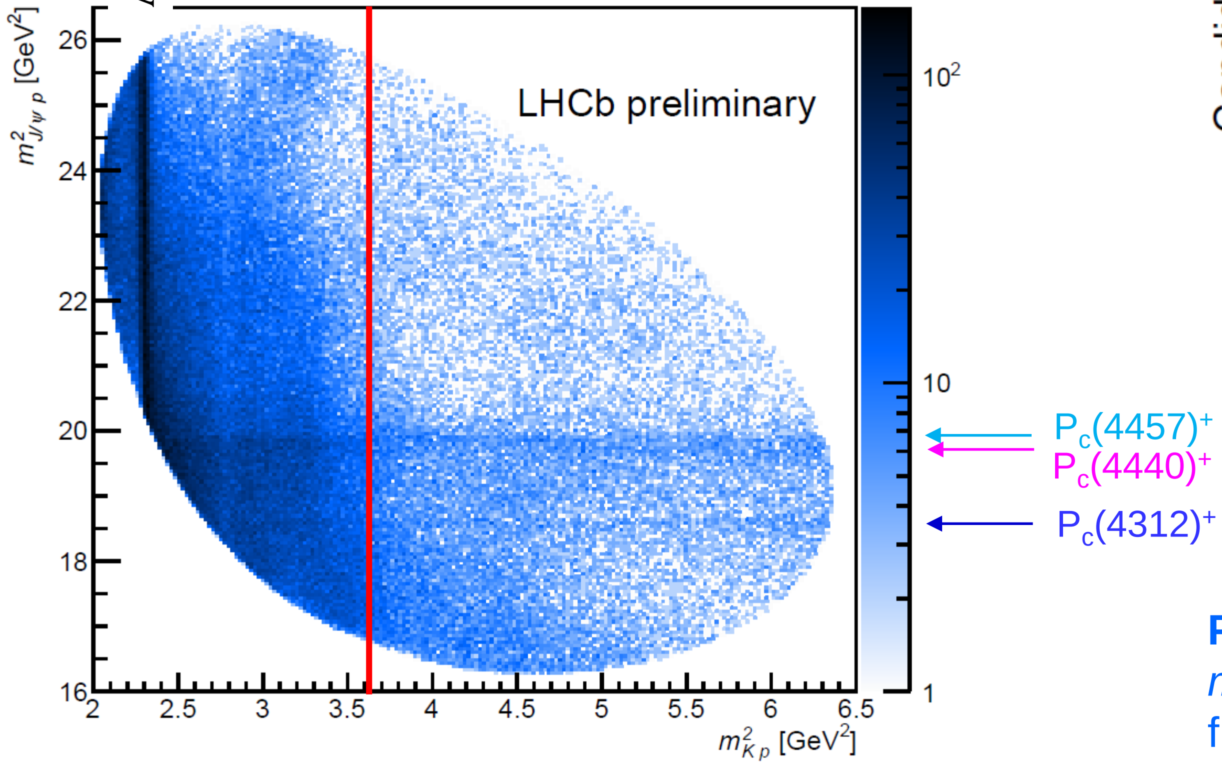
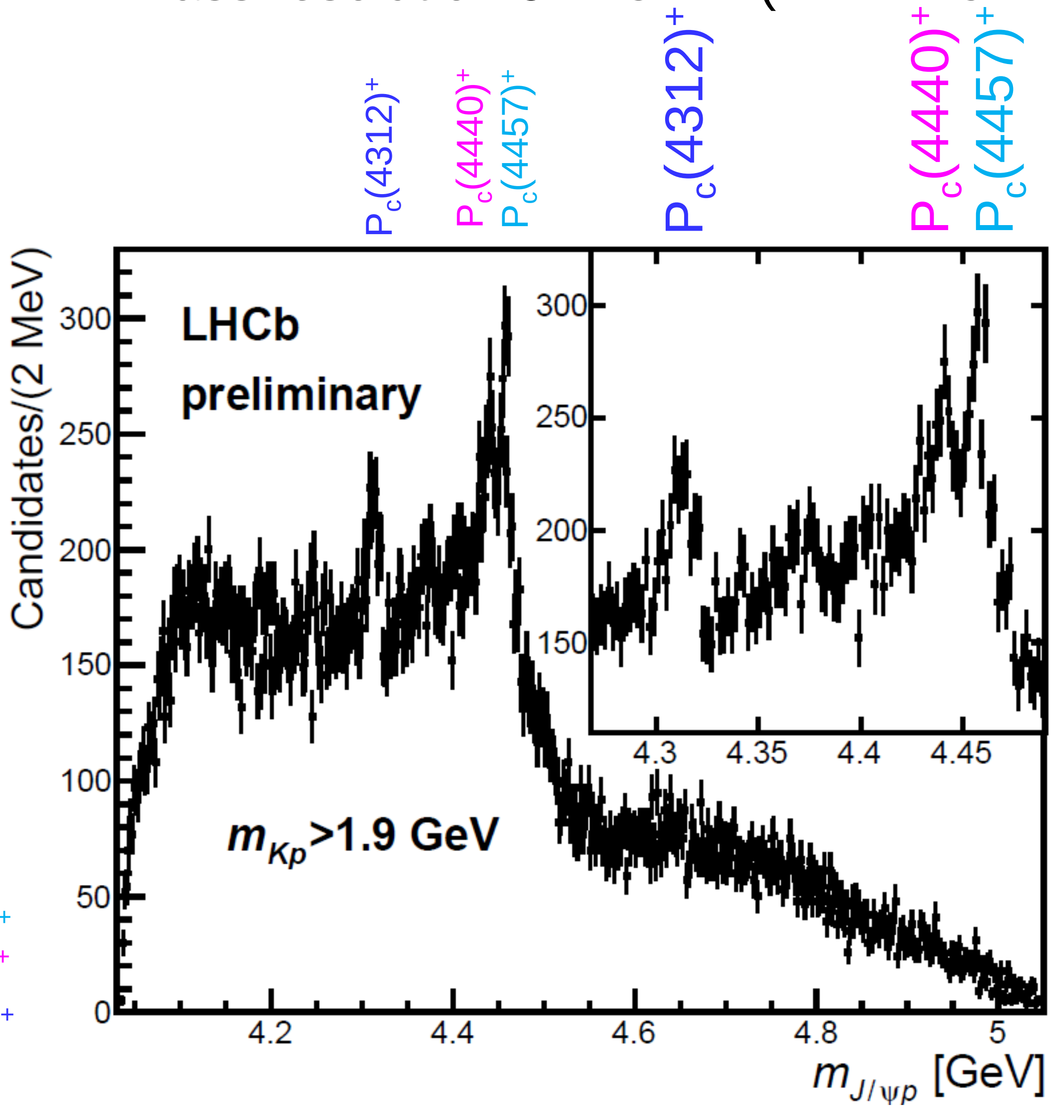


Mass resolution σ=2.3-2.7 (FWHM 5.4-6.4) MeV



Proper amplitude analysis faces new challenges: must consider $m_{J/\psi p}$ resolution effects, large statistics and sub-percent precision in fit fractions required in the amplitude model – work in progress

Fits to $J/\psi p$ mass distributions

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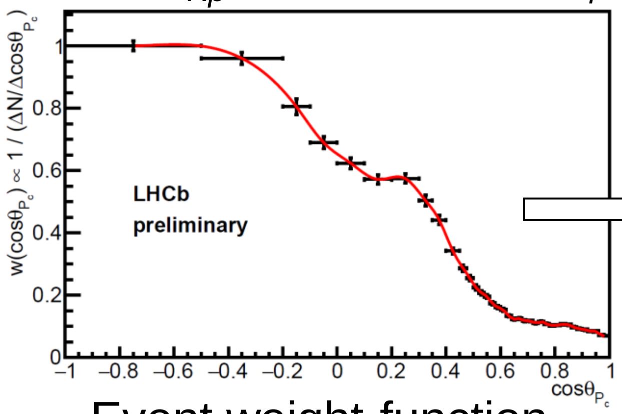
No need for amplitude analysis to prove that the **narrow** $J/\psi p$ peaks are not Λ^* reflections [see LHCb PRL **117**, 082002 (2016)].

Perform one-dimensional fits to $m_{J/\psi p}$ to characterize the narrow peaks.

The analysis is **not sensitive** to broad $J/\psi p$ contributions like $P_c(4380)^+$.

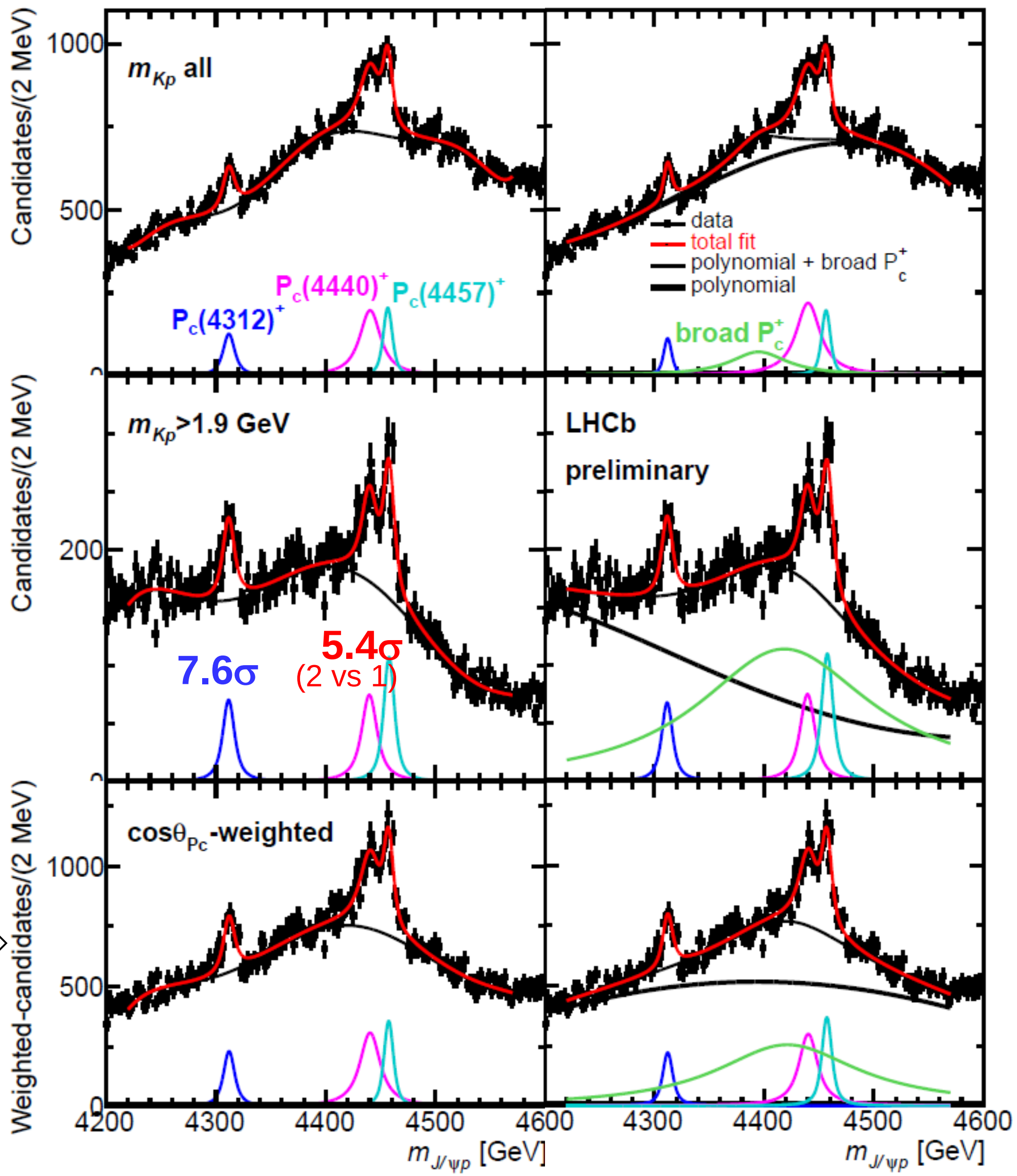
high m_{Kp} low m_{Kp}



Event weight-function

Three narrow Breit-Wigner resonances +

high-order polynomial low-order polynomial + broad P_c^+ as bkg.



Vary order of polynomial for systematic uncertainty.

In addition, do local fits to $P_c(4312)^+$ alone.

Also fit $m_{J/\psi p}$ obtained with alternative data selection. No multivariate discriminant – similar Λ_b yield, larger bkg.

Different composition of Λ^* reflections. Tests systematic uncertainties.

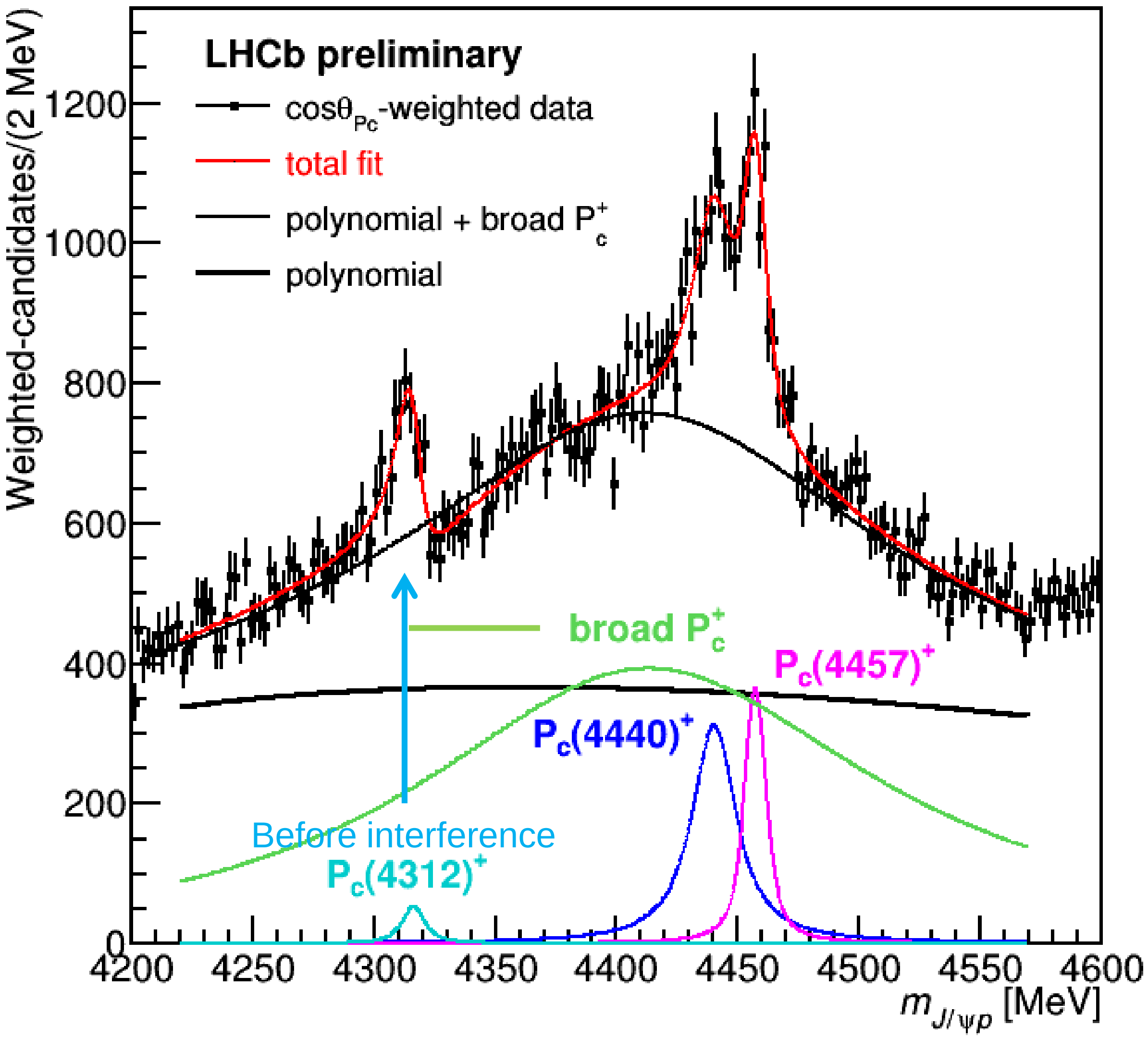
Best statistical sensitivity

The fitting approaches verified with large statistics 6D-amplitude-model simulations approximating the data, and ensemble of pseudo-experiments with the statistics matching the real data.

Fits with interferences

- Nominal fits preformed with incoherent sum of Breit-Wigner amplitudes.
- Also perform fits with coherent sum between various Breit-Wigner amplitudes, including the broad P_c^+ state (implies the same spin and parity).
- No significant evidence for interferences, but the source of the largest systematic uncertainty on the mass and width determinations.

Example of the fit with interference:
$P_c(4312)^+$ interfering with the broad P_c^+



Results

To determine the relative P_c^+ production rates, fit inclusive $m_{J/\psi p}$ obtained with $1/\varepsilon$ event-weights, where ε is the efficiency parameterization in six-dimensional Λ_b^0 decay phase-space (masses and angles). Makes the results J^P independent.

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)}$$

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

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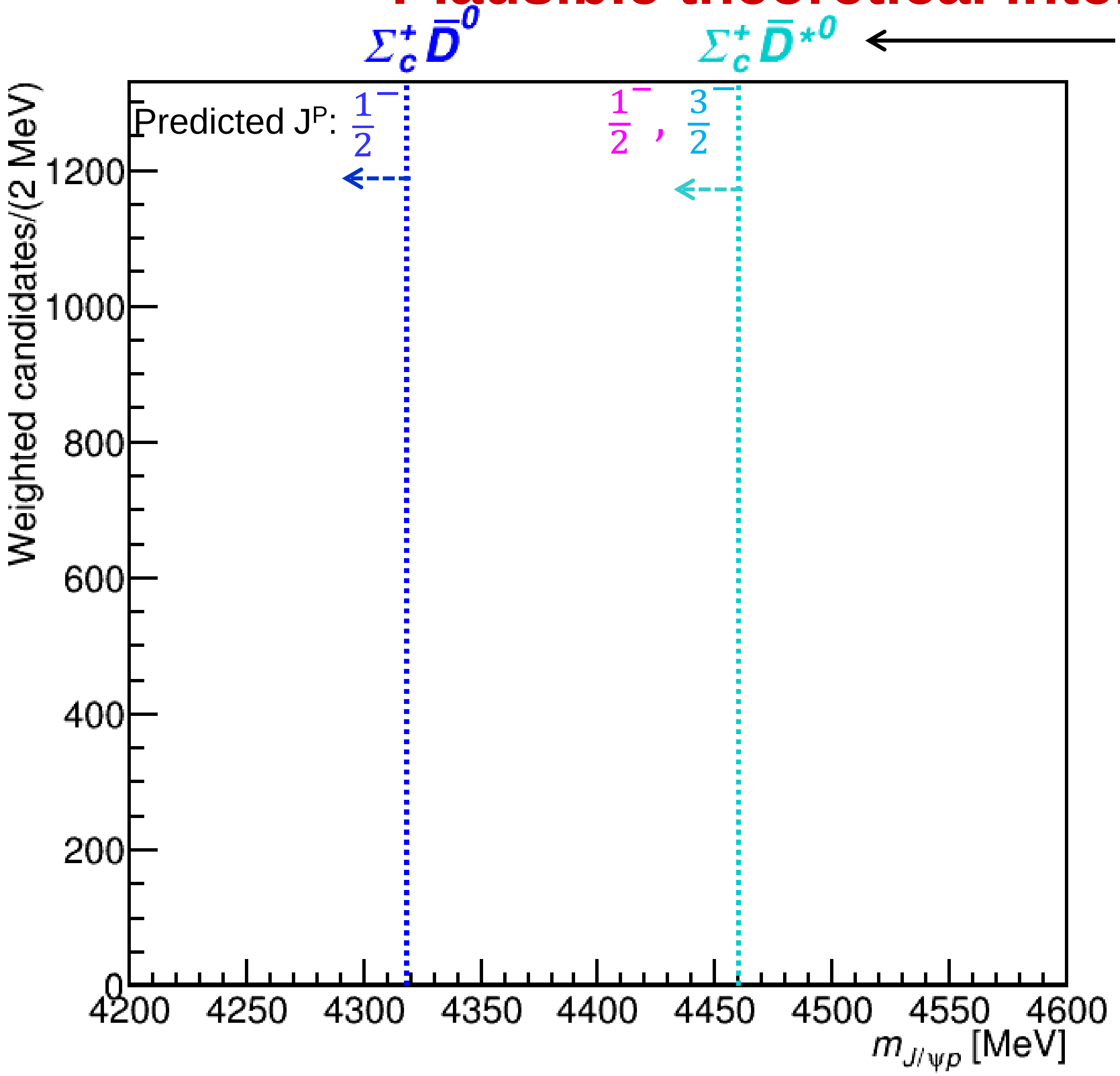
Plausible theoretical interpretation



The **only** thresholds below which molecular bound states are expected in this mass range

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Plausible theoretical interpretation

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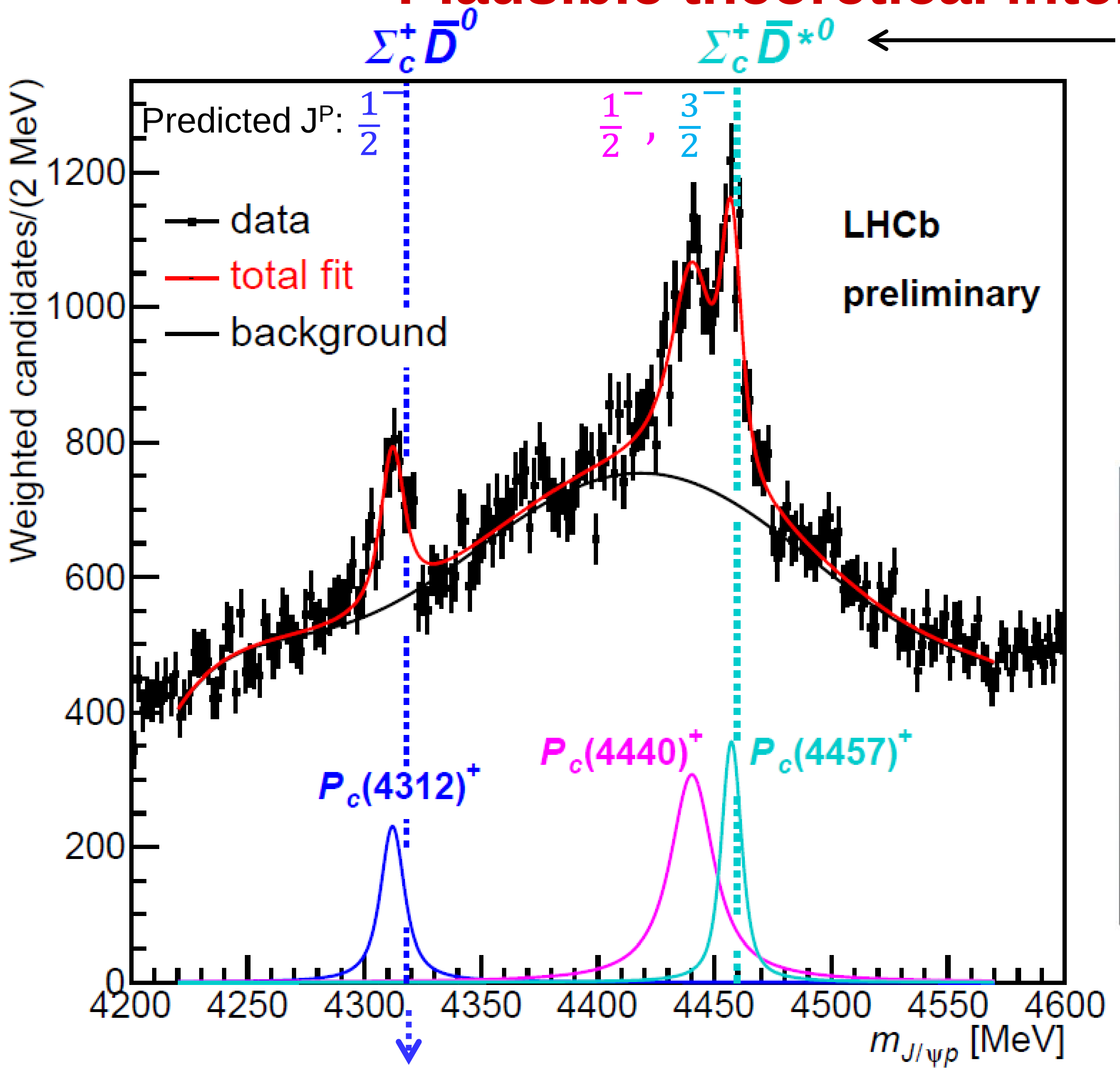
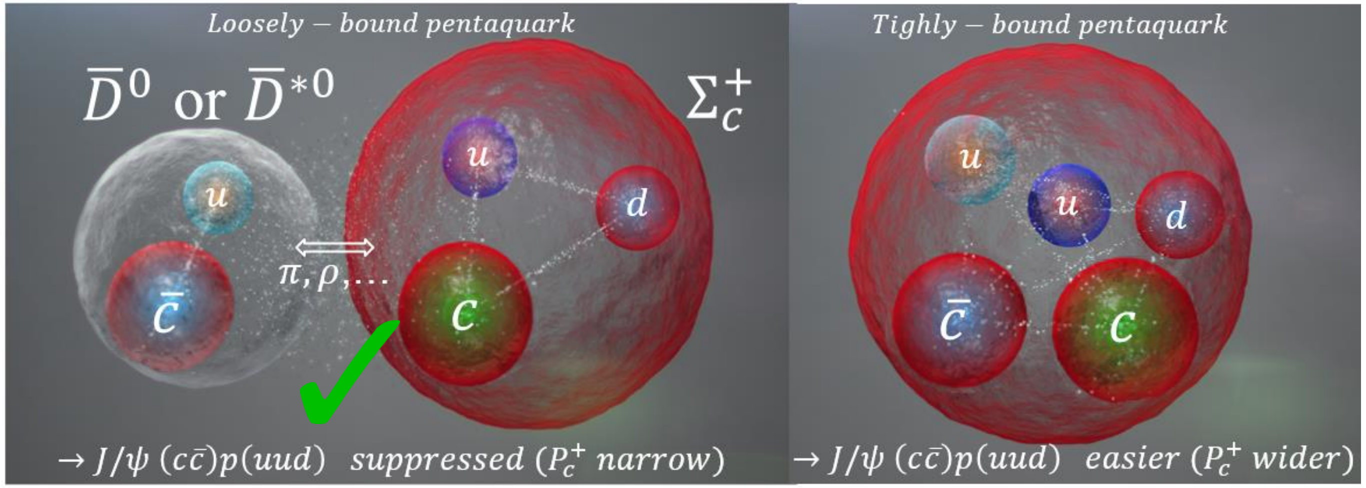


← The **only** thresholds below which molecular bound states are expected in this mass range

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!



Existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of ρ-exchange

However, we need to measure J^Ps to confirm molecular hypothesis, find isospin partners, …

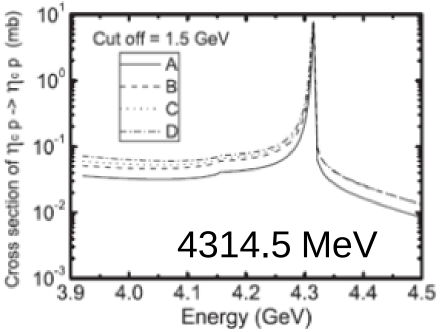
Can diquark substructure separated by a potential barrier [Maiani, Polosa, Riquer, PL,B778, 247 (2018)] produce width suppression?
Are masses near thresholds just by coincidence?
This hypothesis is not ruled out

$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is (see backup slides).

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012)**,
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position $(M - i\Gamma/2)$ and "binding energy" $(\Delta E = E_{thr} - M)$ for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $\bar{D}^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-		
	800		-	4462.178 − 0.002i	0.002
	1200	4318.964 − 0.362i	1.826	4459.513 − 0.417i	2.667
	1500	4314.531 − 1.448i	6.259	4454.088 − 1.662i	8.092
	2000	4301.115 − 5.835i	19.68	4438.277 − 7.115i	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	-	-	4459.507 − 0.420i	2.673
	1500	-	-	4454.057 − 1.681i	8.123
	2000	-	-	4438.039 − 7.268i	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Λ - cut off on exchanged meson mass.

Summary

- Astonishing first results from Run 1 + Run 2 LHCb data!
  - Observation of prompt production a very narrow $X(3842) \to D\bar{D}$ state, consistent with spin-3 1^3D_3 $c\bar{c}$ state (in addition to less surprising the first observation of prompt hadroproduction of $\psi(3770)$, $\chi_{c2}(3930)$, and observation of excited B_c^+ states)
  - Observation of three narrow pentaquark states $P_c^+ \to J/\psi p$, shedding more light into the nature of the $J/\psi p$ pentaquark structures in $\Lambda_b \to J/\psi p K^-$
    - The previously reported $P_c(4450)^+$ structure is now resolved at 5.4σ significance into two narrow states: the $P_c(4440)^+$ and $P_c(4457)^+$ exotic baryons:
      - The new results supersede the previously reported 4450 results.
      - The new analysis not sensitive to broad $J/\psi p$ states. Confirmation of $P_c(4380)^+$ awaits construction of new amplitude model.
    - A narrow companion state, $P_c(4312)^+$, is discovered with 7.3σ significance.
    - Since all three states are narrow and below the $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds within plausible hadron-hadron binding energies, they provide the strongest experimental evidence to date for the existence of molecular states of a baryon and a meson.
    - However, alternative explanations, like tightly-bound pentaquarks, cannot be ruled out.
    - Proper identification of the internal structure of the observed states will require more experimental (J^P?, isospin partners?) and theoretical scrutiny.

BACKUP SLIDES

Could the narrow P_c^+ peaks be due to hadron rescattering via triangle diagrams?

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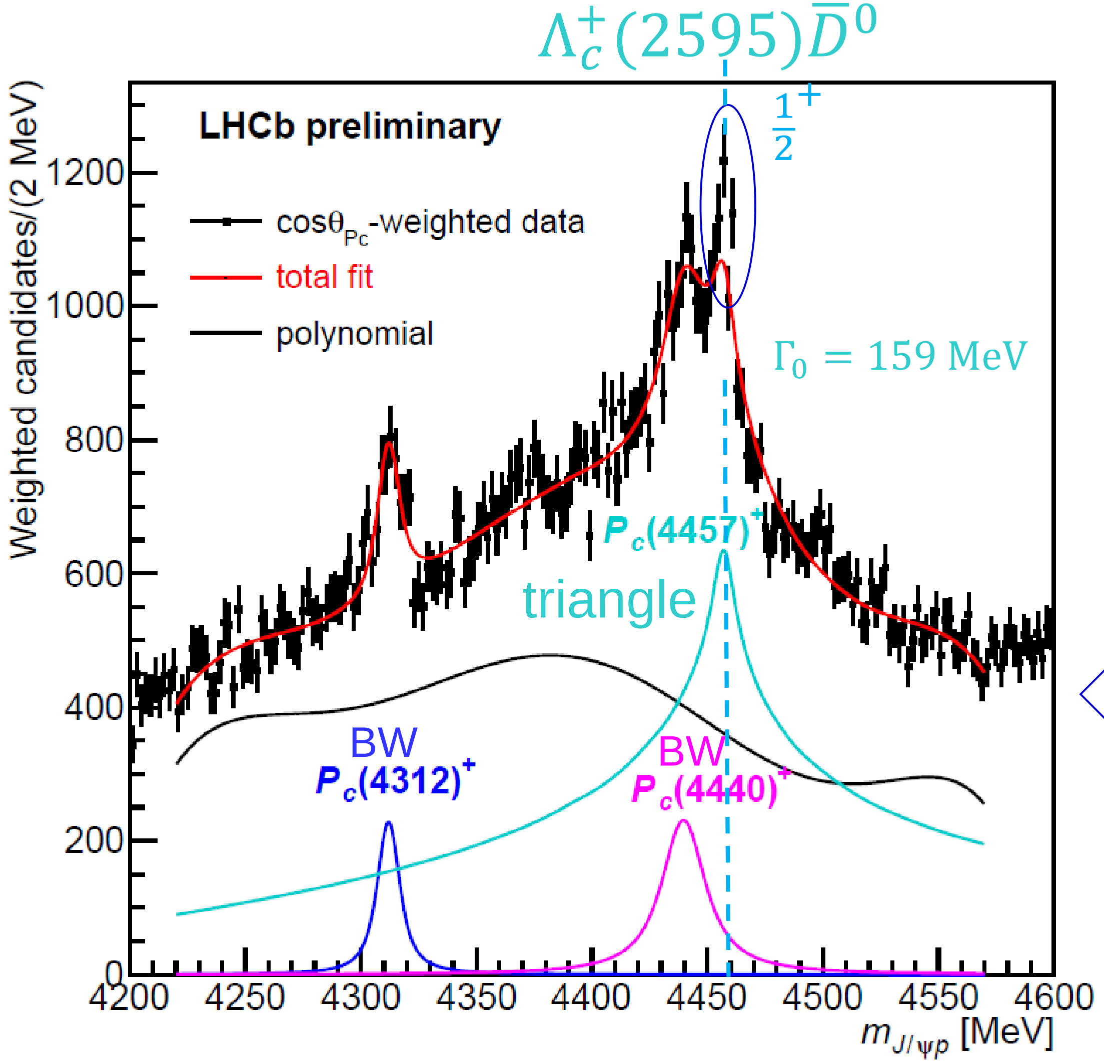
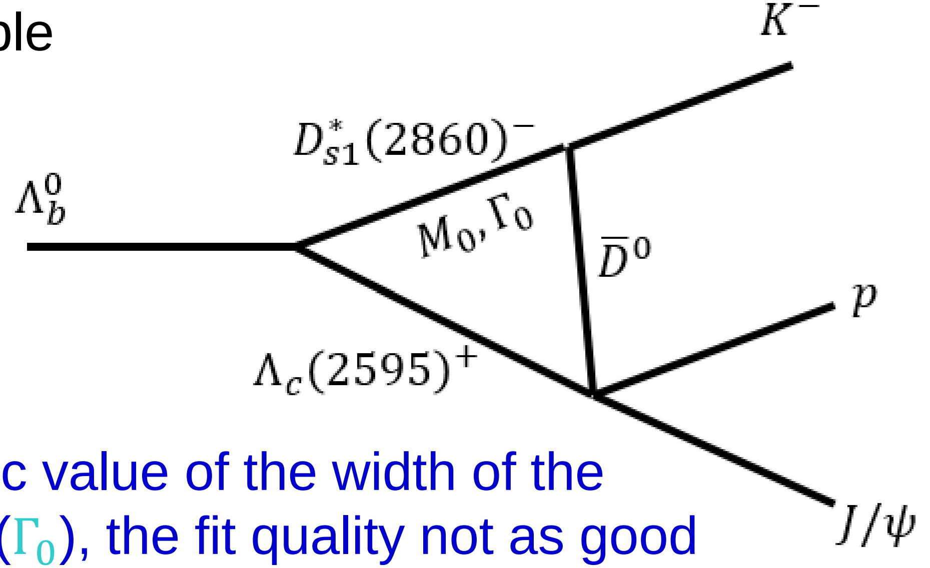


$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds to be triangle diagram peaks (see the next slide)

$P_c(4457)^+$ is right at the $\Lambda_c^+(2595)\bar{D}^0$ threshold, thus the peaking due to the triangle-diagram process is more plausible



For a realistic value of the width of the $D_{s1}^*(2860)^-$ (Γ_0), the fit quality not as good as with BW amplitude for $P_c(4457)^+$.

Amplitude analysis will have more handles on distinguishing triangle-diagram and BW amplitudes

PDG: $\Gamma_{D_{s1}^*(2860)^-} = 159 \pm 80$ MeV [LHCb PRL 113, 162001 (2014)]
QM prediction: $\Gamma_{\bar{c}s(1^3D_1)} = 197$ MeV S.Godfrey,K.Moats, PR D93, 034035 (2016)

Could the narrow P_c^+ peaks be due to hadron rescattering via triangle diagrams?

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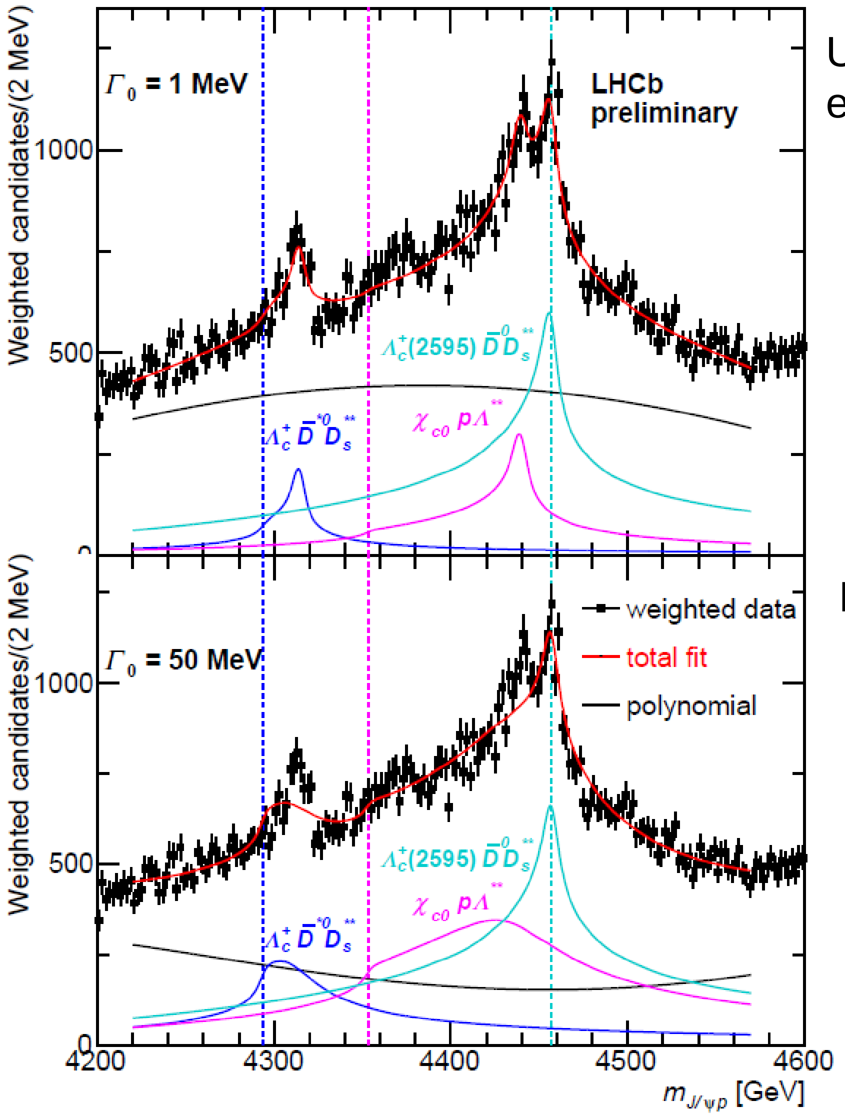
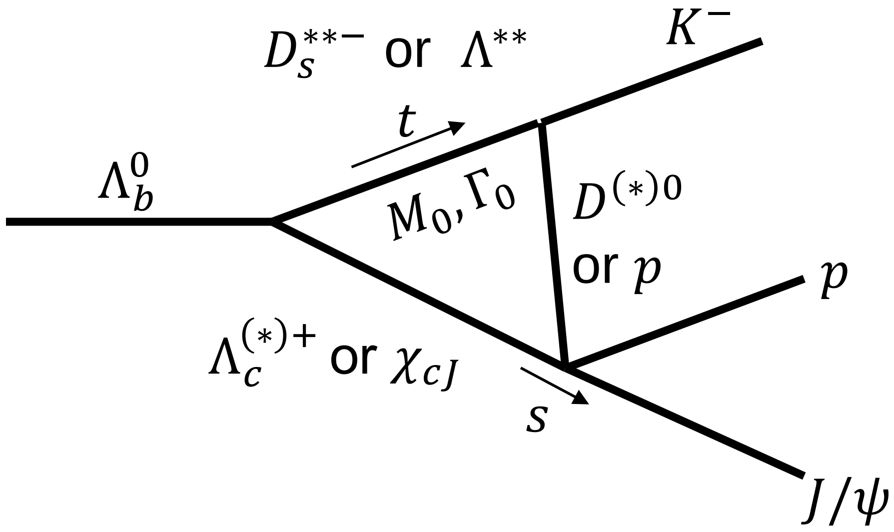
3 triangle-diagram amplitudes + polynomial



Unrealistic Γ_0 for excited D_s or Λ

More realistic Γ_0



$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds to be triangle diagram peaks