Heavy Flavor Spectroscopy and exotic states at LHCb

Ivan Polyakov

Syracuse University

on behalf of the LHCb collaboration

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Outlook

- The LHCb detector

- Near threshold DD spectroscopy

- Observation of $B_c^{(*)}(2S)$

- Pentaquarks in $\Lambda_b \to J/\psi pK$

all results are fresh
(this spring)

- Summary

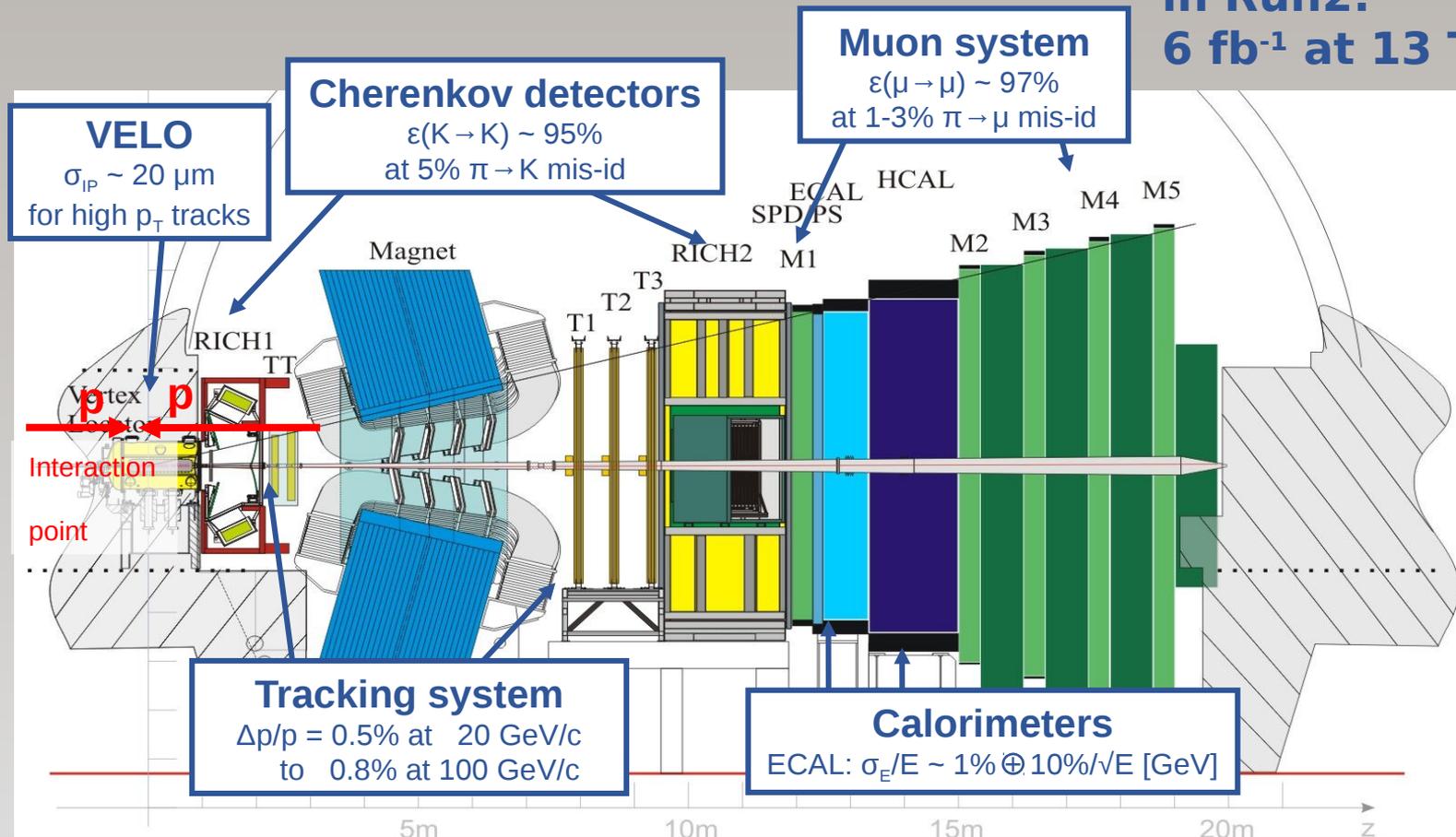see talks on
flavor anomalies by Nicola
and **hidden sectors** by Mike

LHCb detector

- High cross-section of heavy-quark production

- Excellent decay time resolution

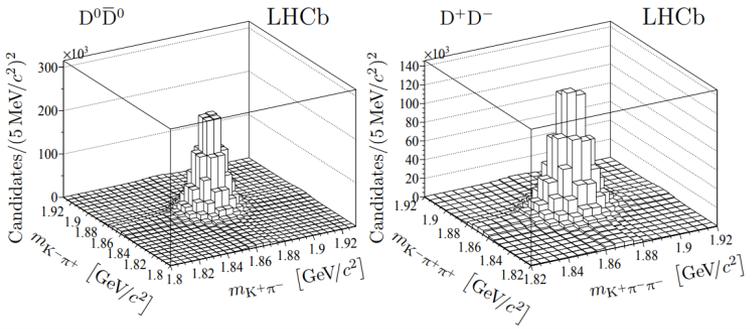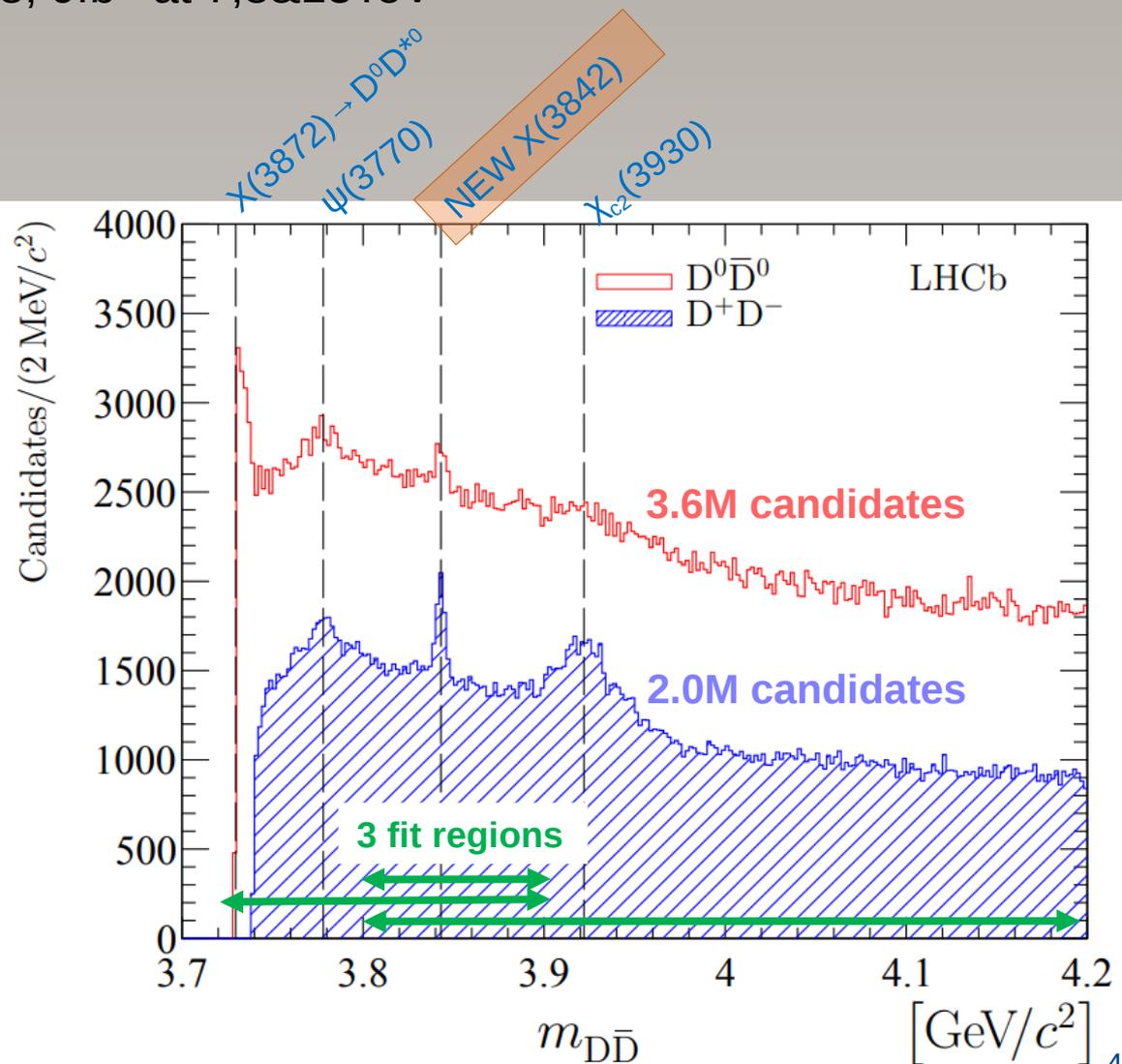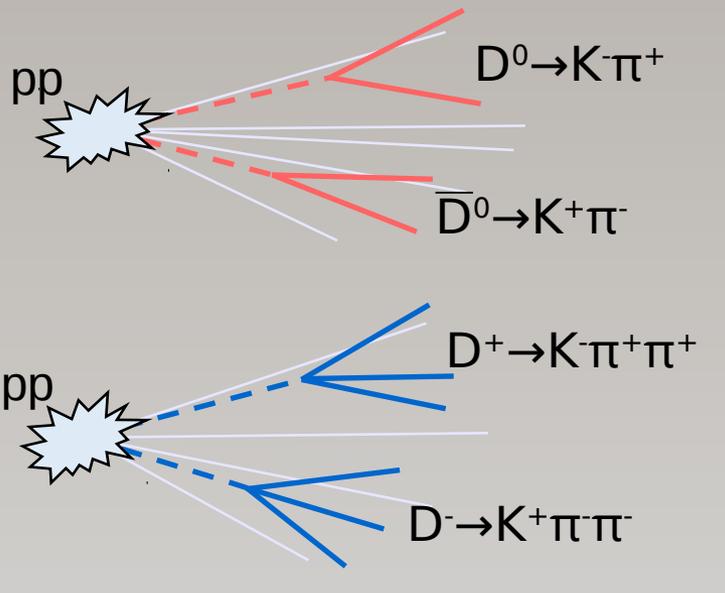- Excellent particle identification

- Excellent momentum resolution

Data collected in Run1:
1 fb⁻¹ at 7 TeV
2 fb⁻¹ at 8 TeV
in Run2:
6 fb⁻¹ at 13 TeV

Muon system
$\varepsilon(\mu \to \mu) \sim 97\%$
at 1-3% $\pi \to \mu$ mis-id

Cherenkov detectors
$\varepsilon(K \to K) \sim 95\%$
at 5% $\pi \to K$ mis-id

VELO
$\sigma_{IP} \sim 20\ \mu m$
for high p_T tracks

Tracking system
$\Delta p/p = 0.5\%$ at 20 GeV/c
to 0.8% at 100 GeV/c

Calorimeters
ECAL: $\sigma_E/E \sim 1\% \oplus 10\%/\sqrt{E}$ [GeV]

D$\overline{\text{D}}$ near threshold

- Analyze D+D- and D⁰$\overline{\text{D}}$⁰ spectra

- Full LHCb dataset 2011-2018, 9fb⁻¹ at 7,8&13TeV

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

$\overline{D}^0 \to K^+ \pi^-$

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

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

3.6M candidates

2.0M candidates

3 fit regions

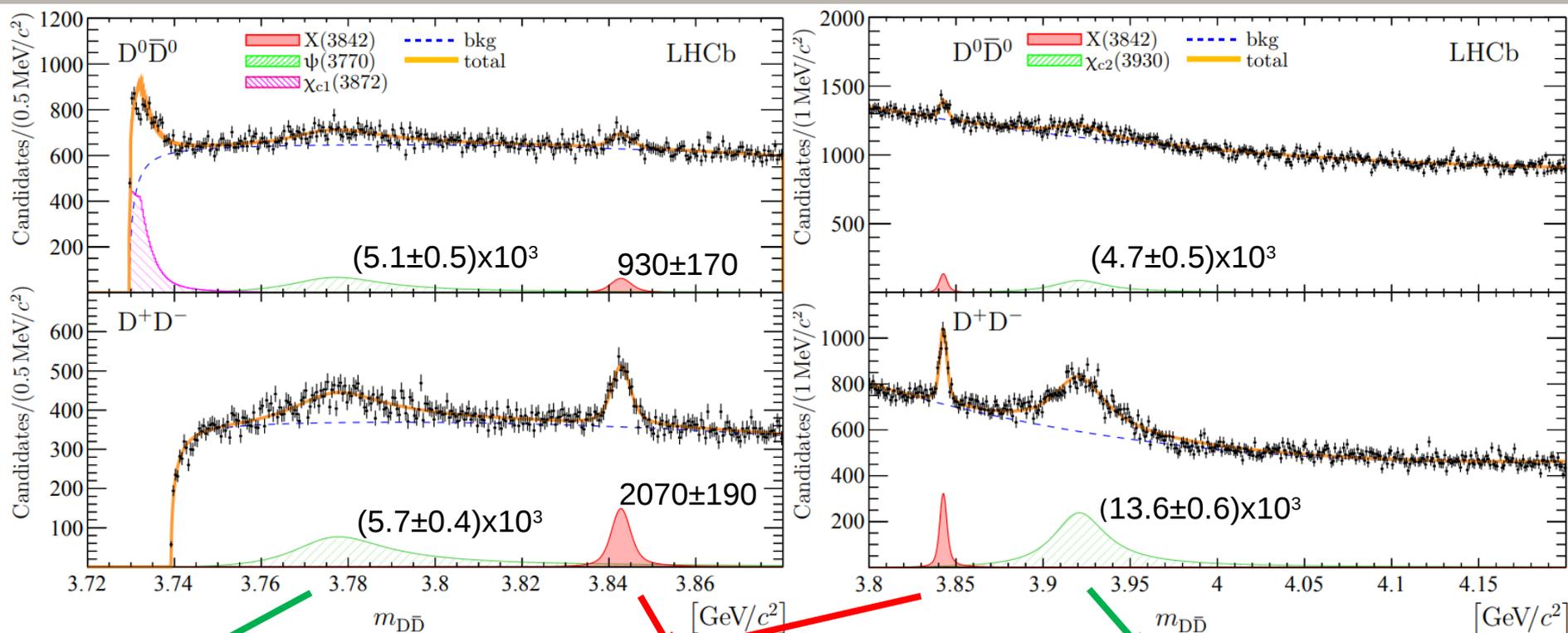# D$\bar{\text{D}}$ near threshold

- Simultaneous fit of D+D- and D0$\bar{\text{D}}$0
  - Signals: Relativistic Breit-Wigner convoluted with Resolution (from 0.9 to 1.9 MeV)
  - Background: pol*PhaseSpace / pol / pol*exponential
  - χ_{c1}(3872) → D0D*0 with missing π^0/γ contribution: constrained from MC

systematics dominated by Bkg/Signal models and D-meson masses

ψ(3770):
m = 3778.13±0.70±0.63 MeV
Γ constrained to 27.2±1.0 MeV [PDG]

X(3842):
m = 3842.71±0.16±0.12 MeV
Γ = 2.79±0.51±0.35 MeV

χ_{c2}(3930):
m = 3921.90±0.55±0.19 MeV
Γ = 36.64±1.88±0.85 MeV

$D\overline{D}$ near threshold

- Narrow state X(3842) observed

 **m = 3842.71±0.16±0.12 MeV**
  Γ = 2.79±0.51±0.35 MeV

  - Consistent with expected 1^3D_3 state $\psi_3(1D)$ with $J^{PC}=3-$

- Precise measurements for $\chi_{c2}(3930)$ and $\psi(3770)$ parameters
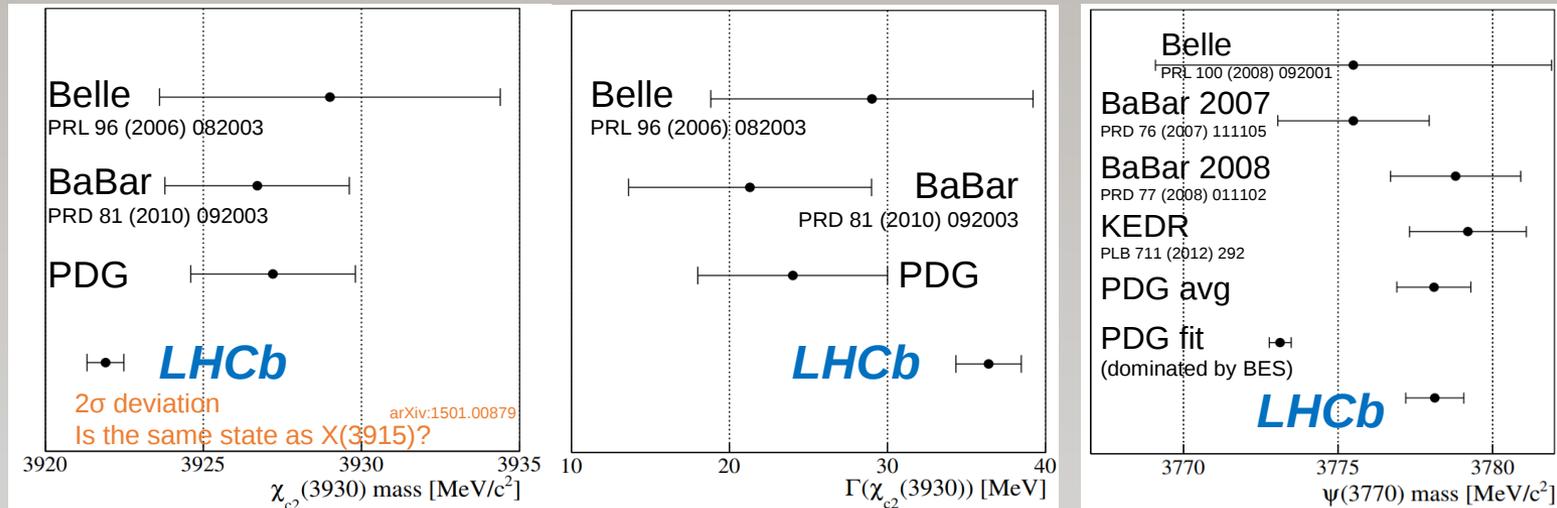
- First observation of $\chi_{c2}(3930)$ prompt hadroproduction

Excited B$_c$ states

- **B$_c$ has a rich spectroscopy**
  - Allow to probe quarkonium-based QCD models
  - Less explored due limited statistics
  - Search for 2S excitations with pion transitions
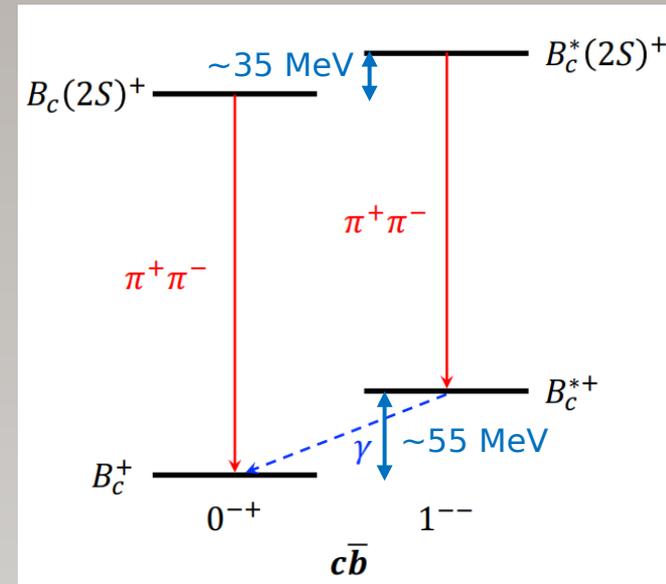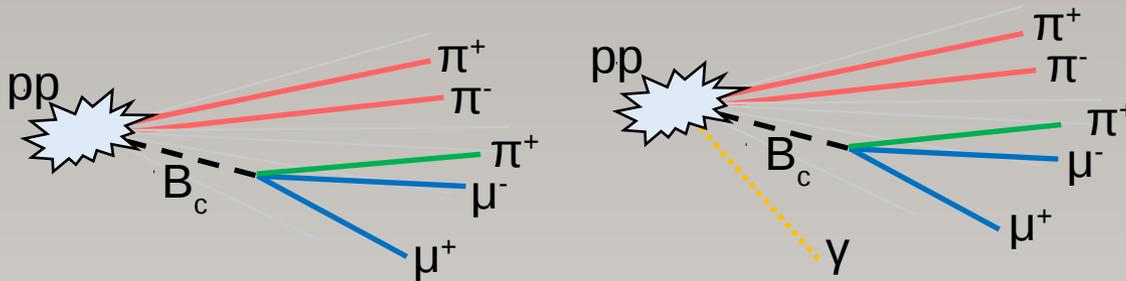
when considering $\Delta M = M(B_c\pi\pi) - M(B_c)$ or
$M(B_c\pi\pi)_{rec} = M(B_c\pi\pi) - M(B_c) + M(B_c)_{PDG}$
expect B$_c$*(2S) to give peak lower than B$_c$(2S) by 10-55 MeV

see refs. in
arXiv:1904.00081

$B_c(2S) \rightarrow B_c\pi\pi$ prehistory

- **Forward (LHCb) vs. Central (CMS/ATLAS) detectors**
  - LHCb is more efficient in selecting B-mesons (trigger, PID, …), higher bb~ cross-section
    (14 new B_c decay modes firstly observed)
    however suffers from huge background of prompt pions
  - ATLAS/CMS trigger is less efficient to select B-mesons, but those selected have high p_T
    + compensate lower cross-section rate by higher luminosity

- **2014: First observation of $B_c^{(*)}(2S)$ by ATLAS** can't distinguish $B_c(2S)$ and $B_c^*(2S)$
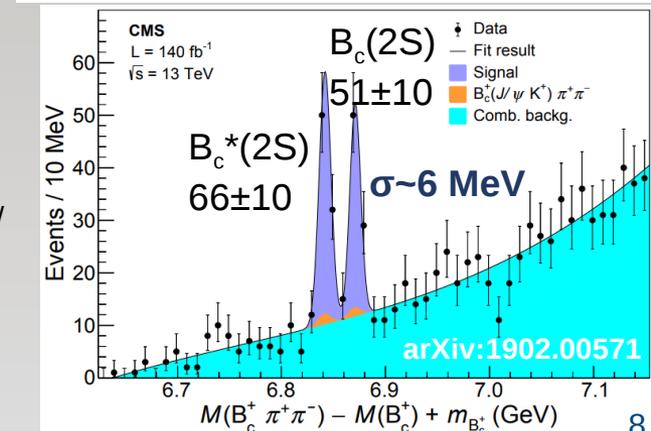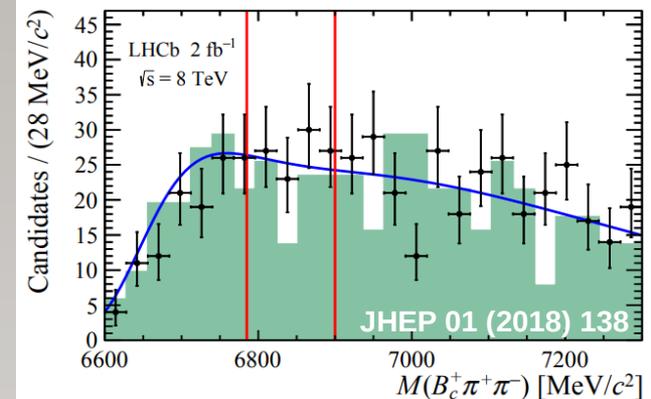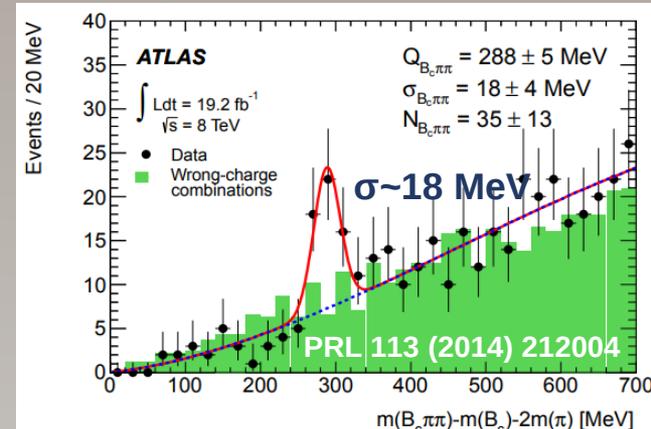
- **2018: Non-observation by LHCb**

- **Early 2019: CMS showed analysis of all 140fb^{-1} of Run2 data**
  - Require $p_T(B_c)>15$ GeV, $p_T(\pi_1)>0.6$ GeV, $p_T(\pi_2)>0.8$ GeV
  - Resolved $B_c(2S)$ and $B_c^*(2S)$ with $>5\sigma$ significance

    $M(B_c^*(2S))_{rec} = 6842.0 \pm 1.0(\text{stat}) \pm 0.8(B_c)$ MeV /my derivation/
    $M(B_c(2S)) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c)$ MeV
 $M(B_c(2S))-M(B_c^*(2S))_{rec} = 29.0 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV

ATLAS
$\int L dt = 19.2$ fb^{-1}
$\sqrt{s} = 8$ TeV
• Data
Wrong-charge combinations
$Q_{B_c\pi\pi} = 288 \pm 5$ MeV
$\sigma_{B_c\pi\pi} = 18 \pm 4$ MeV
$N_{B_c\pi\pi} = 35 \pm 13$
$\sigma \sim 18$ MeV
PRL 113 (2014) 212004
$m(B_c\pi\pi)-m(B_c)-2m(\pi)$ [MeV]

LHCb 2 fb^{-1}
$\sqrt{s} = 8$ TeV
JHEP 01 (2018) 138
$M(B_c^+\pi^+\pi^-)$ [MeV/c^2]

CMS
L = 140 fb^{-1}
$\sqrt{s} = 13$ TeV
• Data
— Fit result
Signal
$B_c^+(J/\psi K^+)\pi^+\pi^-$
Comb. backg.
$B_c(2S)$
51 ± 10
$B_c^*(2S)$
66 ± 10
$\sigma \sim 6$ MeV
arXiv:1902.00571
$M(B_c^+\pi^+\pi^-)-M(B_c^+)+m_{B_c^+}$ (GeV)

$B_c(2S) \rightarrow B_c\pi\pi$ at LHCb

- Reanalysis of joint Run1&2 data sample (8.5fb^{-1})
  x5 more statistics in comparison to Run1 analysis

- Require $p_T(B_c)$>10 GeV, $p_T(\pi)$>0.3 GeV, $M(B_c\pi\pi)$-$M(B_c)$-$M(\pi\pi)$<0.2 GeV

- Observe $B_c^*(2S)$ with >5σ significance

- Hint for $B_c(2S)$ with global(local) significance of 2.2σ(3.2σ)

arXiv:1904.00081
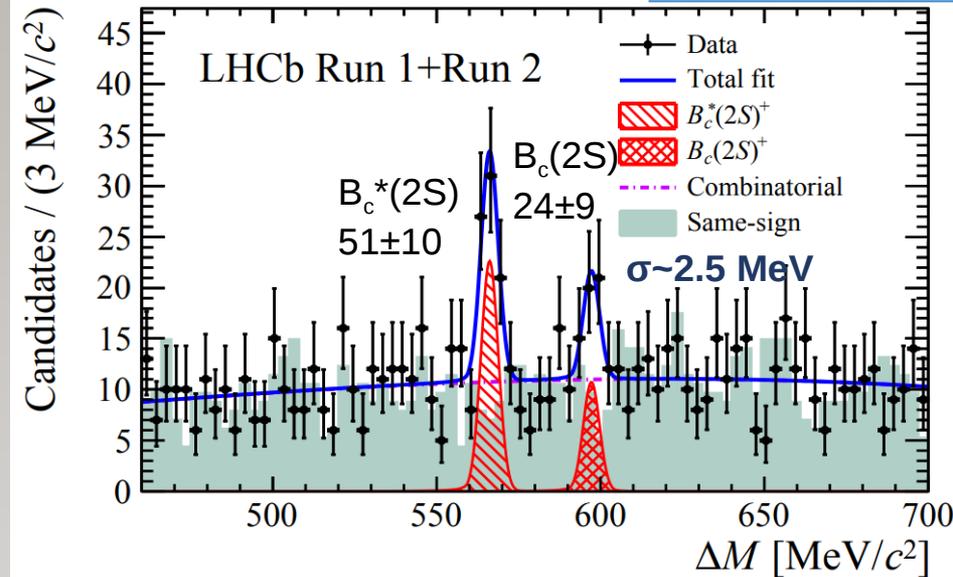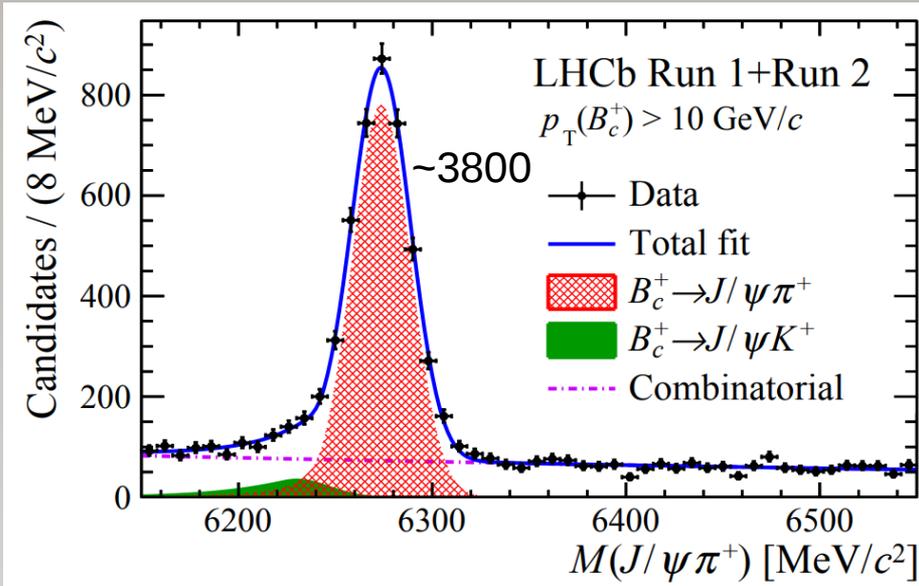
$$M(B_c^*(2S))_{rec} = 6841.2 \pm 0.6(stat) \pm 0.1(syst) \pm 0.8(B_c) \text{ MeV}$$
$$M(B_c(2S)) = 6872.1 \pm 1.3(stat) \pm 0.1(syst) \pm 0.8(B_c) \text{ MeV}$$
$$M(B_c(2S))\text{-}M(B_c^*(2S))_{rec} = 31.0 \pm 1.4 \text{ MeV}$$

- In agreement with CMS

$Λ_b → J/ψpK$

- Run1 (3 fb^{-1}) evidence for two $P_c → J/ψp$ pentaquarks

  $P_c(4450)$: M = 4450 ±2 ±3 MeV

   Γ = 39 ±5 ±19 MeV

  $P_c(4380)$: M = 4380 ±8 ±29 MeV
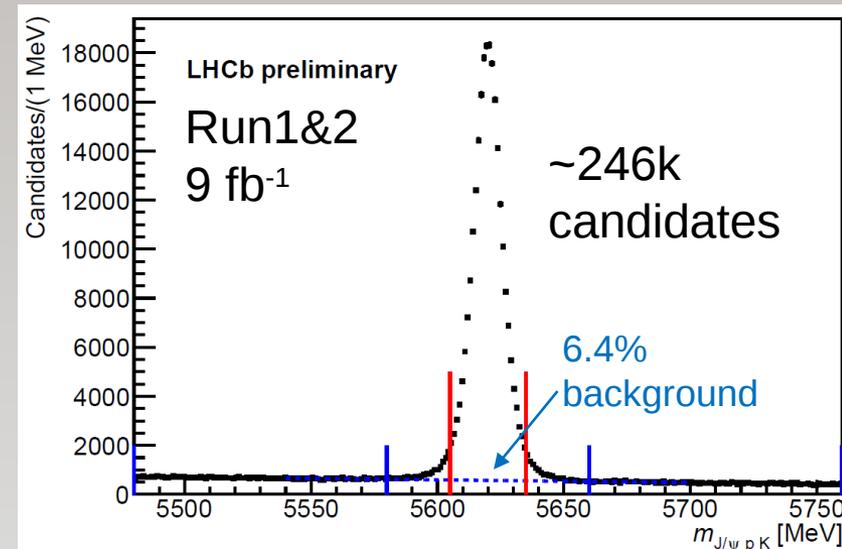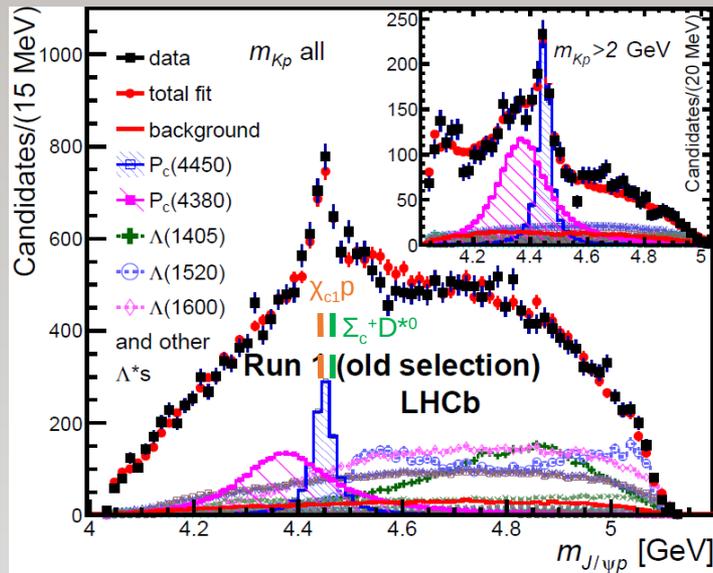
   Γ = 205 ±18 ±86 MeV

- Possible interpretations
  - Tightly-bound pentaquark
  - Loosely-bound molecula ($Σ_c^+ D^{(*)0}$)
  - Threshold triangle diagram ($χ_{c1}p$ rescattering)

- New analysis with Run1&2 (9 fb^{-1})

- x9 increase in statistic
  (27k → 246k candidates)

  thankfully to:
  data selection (x2), luminosity(x3),
  cross-section at 13TeV vs. 7(8)TeV (x2)

Λ$_b$→J/ψpK, data consistency

- Check data consistency by fitting Run1&2 data with same 6D amplitude used for Run1

- Gives consistent parameters for the two peaks

- However larger statistics reveals previously hidden features …

- Combination of good tracking, vertexing and J/ψ and Λ$_b$ mass constrains allow to bring resolution down to 2.3-2.7 MeV

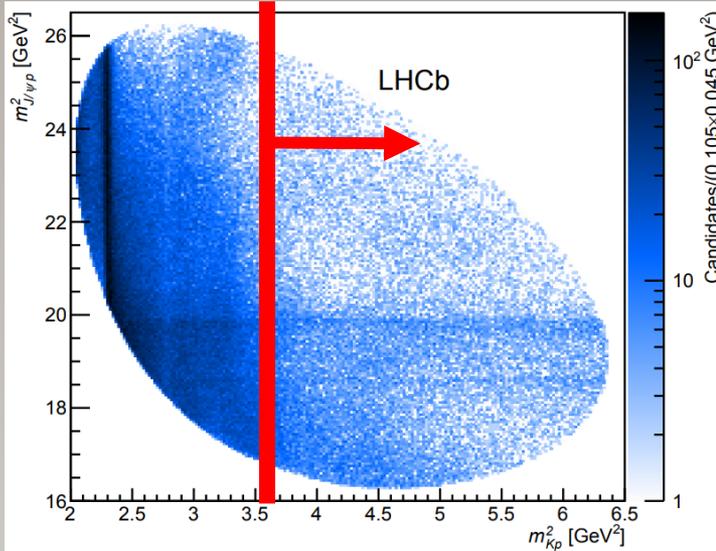- Note how finer binning reveals narrow structures insignificant before
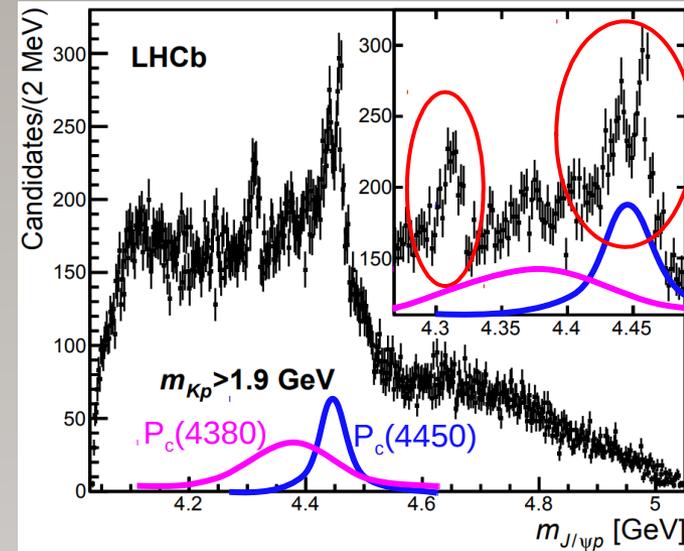
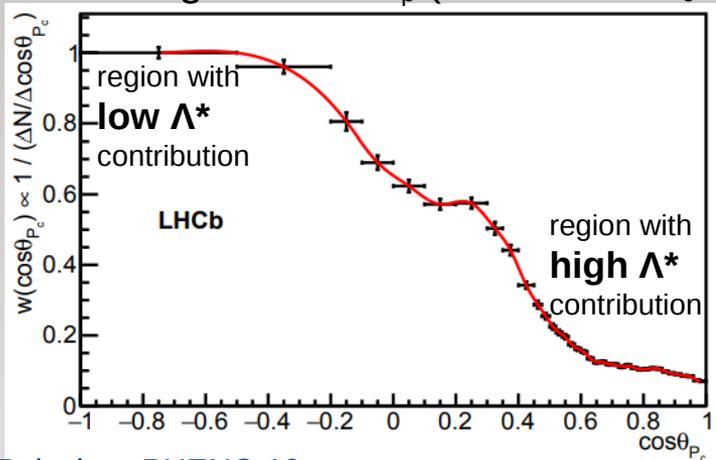# $\Lambda_b \rightarrow$ J/ψpK, Λ* suppression
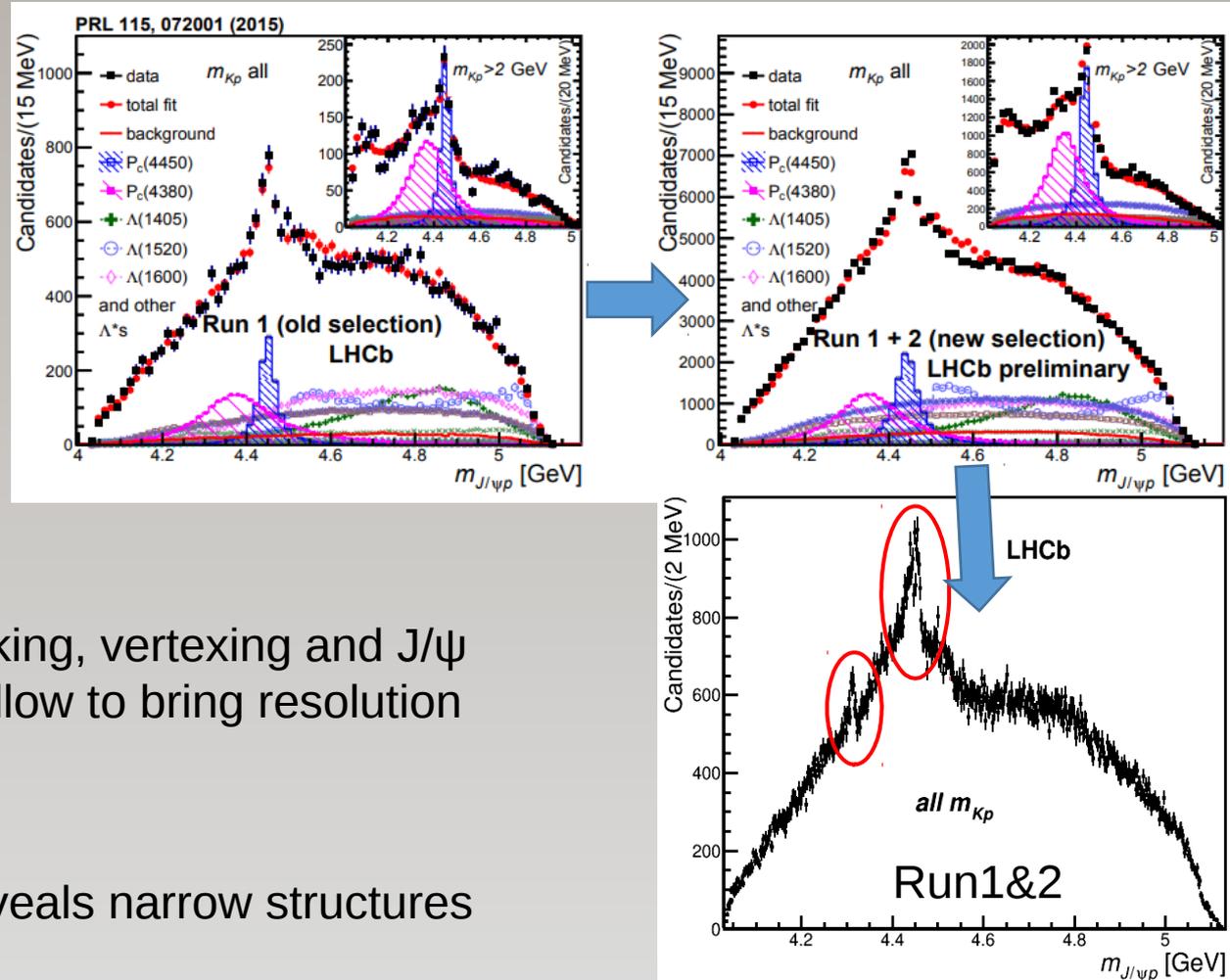
Two ways to suppress Λ* → pK background:

- Cut on M(pK)>1.9 GeV (suppress Λ* contribution by ~80%)

Cut on
M(pK)>1.9 GeV

(suppress Λ*
contribution by ~80%)

- or reweight on cosθ$_p$ (save more P$_c$ signal)

- Significant narrow peak near 4.3 GeV

- Previously reported P$_c$(4450) appears to have a split structure

- With such a narrow peaks (~10 MeV) no need in full amplitude analysis, 1D is enough

$\Lambda_b \rightarrow J/\psi pK$, fits

- Fit M(J/ψp) with both variants of Λ* suppression and without it

- Signal: Breit-Wigner convoluted with resolution Background: polynomials of different order

- Not sensitive to broad $P_c(4380)$ contribution

- Tried both incoherent and coherent sum of individual resonances → no evidence for interference (though dominant systematics)

- $P_c(4312)$ significance is 7.3σ

- $P_c(4440)$ - $P_c(4457)$ separation 5.4σ

- Tested the 1D fit approach with large 6D-model simulations

bkg+3 peaks   + 4th broad peak
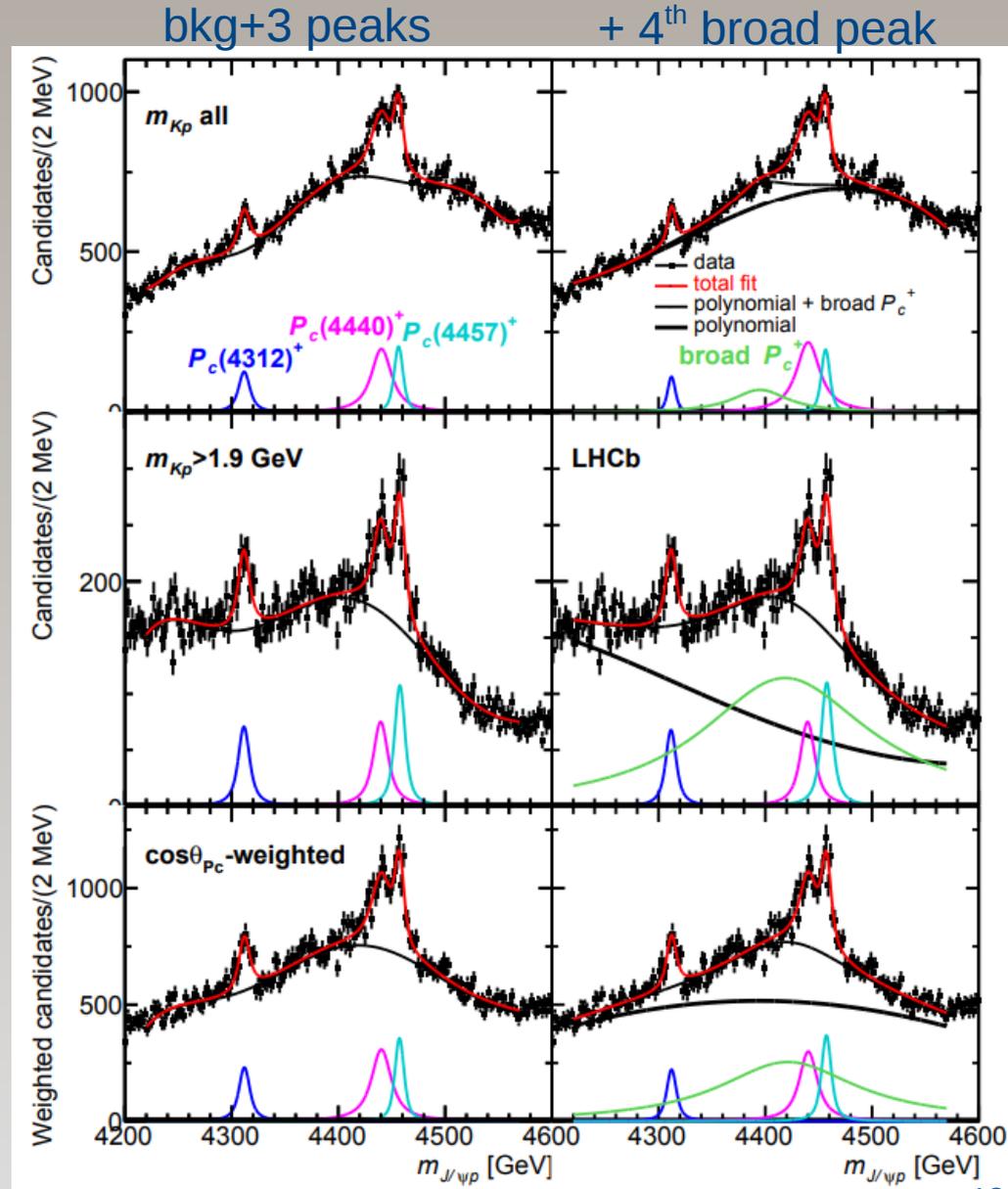
$\Lambda_b \rightarrow$ J/ψpK, results

arXiv:1904.03947

- ## Results

Relative decay rates are obtained after 6D efficiency correction (independent on J^P)

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$
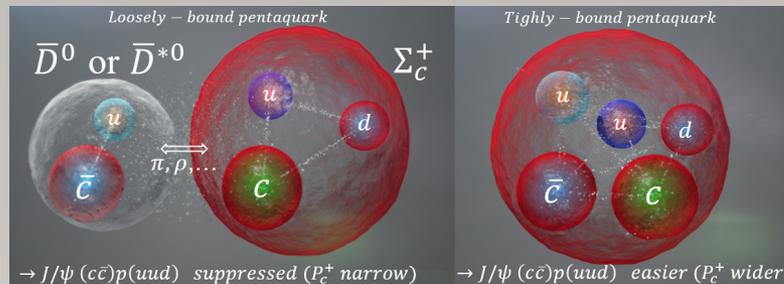
- Near threshold masses consistent with baryon-meson molecule structure

- Can't rule out tightly-bound pentaquarks

- Triangle diagram mechanism disfavored by narrow widths

- Measurement of quantum numbers is needed → full amplitude analysis is planned
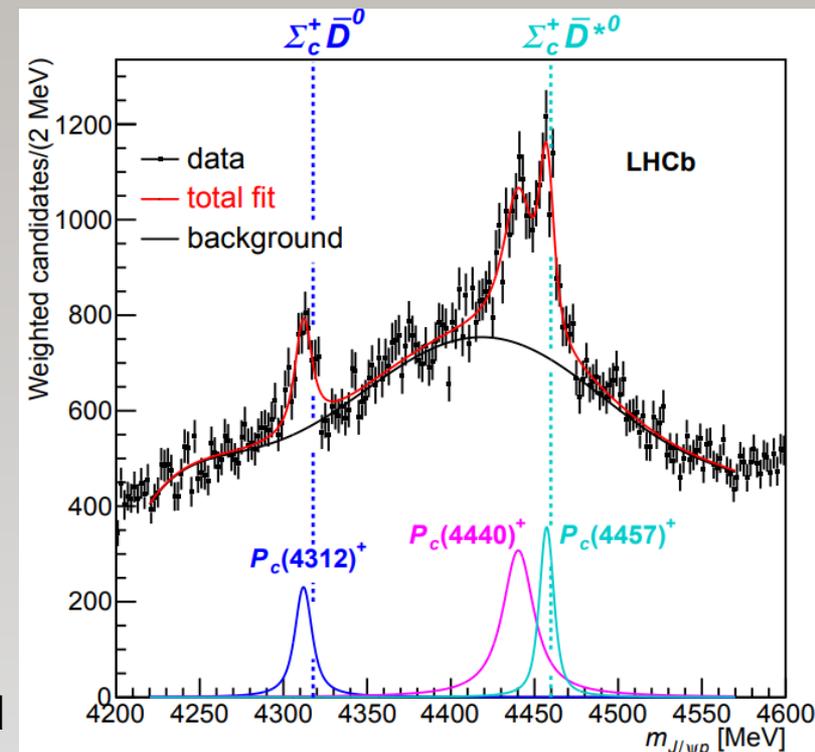
Summary

- Observation of X(3842) in $D\overline{D}$ arXiv:1903.12240

- Observation of $B_c^{(*)}$(2S)   arXiv:1904.00081

- New pentaquarks in $\Lambda_b \rightarrow J/\psi p K$ arXiv:1904.03947

    Other (earlier) results:

- Observation of $B_s \rightarrow J/\psi p\overline{p}$ arXiv:1902.05588

- Model-independent confirmation of exotics in $B^0 \rightarrow J/\psi K\pi$ PRL 122 (2019) 152002

- Ξ_b^- production and mass measurement   PRD 99 (2019) 052006

- Evidence for Z_c in $B^0 \rightarrow \eta_c K\pi$ EPJC 78 (2018) 1019

- Observation of Σ_b(6097) $\rightarrow \Lambda_b \pi$ and $\Sigma_b^{(*)}$ properties   PRL 122 (2019) 012001

- $\Lambda_b \rightarrow \psi(2S)/J/\psi\ \Lambda$ branching fraction measurement   JHEP 03 (2019) 126

- … check full list of relevant LHCb publications *here* and *here*