RECENT RESULTS FROM LHCB

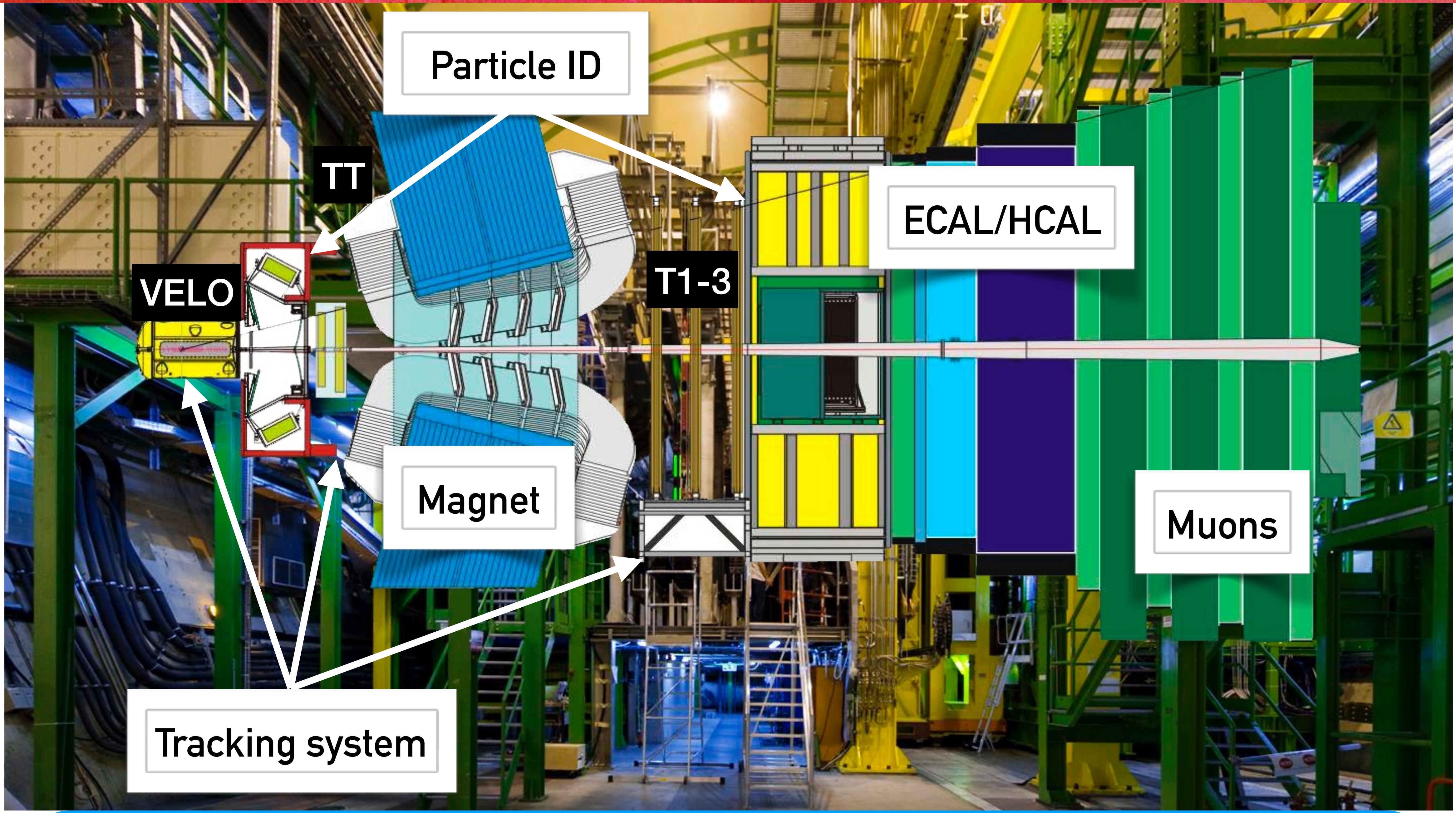
Daniel Johnson

on behalf of the LHCb collaboration

Outline

1. CP violation in beauty — Last Thursday
2. CP violation in charm — Last Thursday
3. Exotic hadron spectroscopy — This morning
4. Lepton universality — Last Friday

The LHCb experiment



Efficient trigger & reconstruction; effective identification
Magnet polarity routinely reversed

1. CP violation in beauty
2. CP violation in charm

Outline

3. Exotic hadron spectroscopy

4. Lepton universality

1903.05530
LHCb-PAPER-2019-013

1. CP violation in beauty

Indirect CPV in B_s^0 decays to non-flavour-specific f.s.

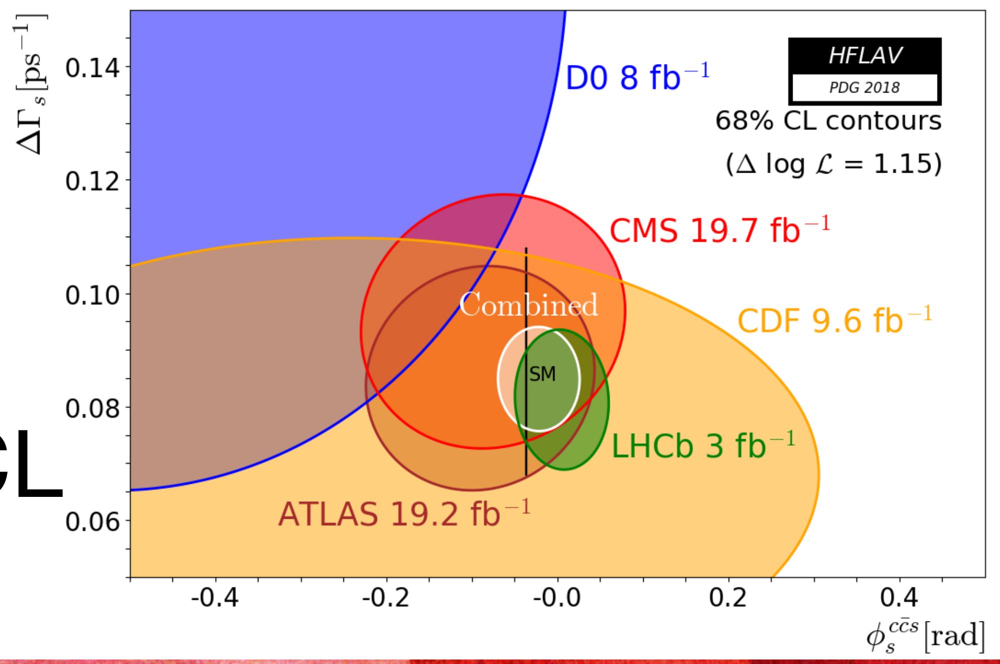
- in absence of penguin contamination $\phi_s \approx -2\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$

Expected to be very small: CKM $-2\beta_s = -37.04 \pm 0.64\,\text{mrad}$ 1106.4041

Classic mode for ϕ_s : $B_s^0 \to J/\psi\phi$

- admixture of CP-even and CP-odd t-dep. angular analysis
- most precise measurement uses $B_s^0 \to J/\psi K^+K^-$ from LHCb: $3\,\text{fb}^{-1}$

$\phi_s = 60 \pm 49 \pm 6\,\text{mrad}$ 1411.3104



Significant K^+K^- S-wave present

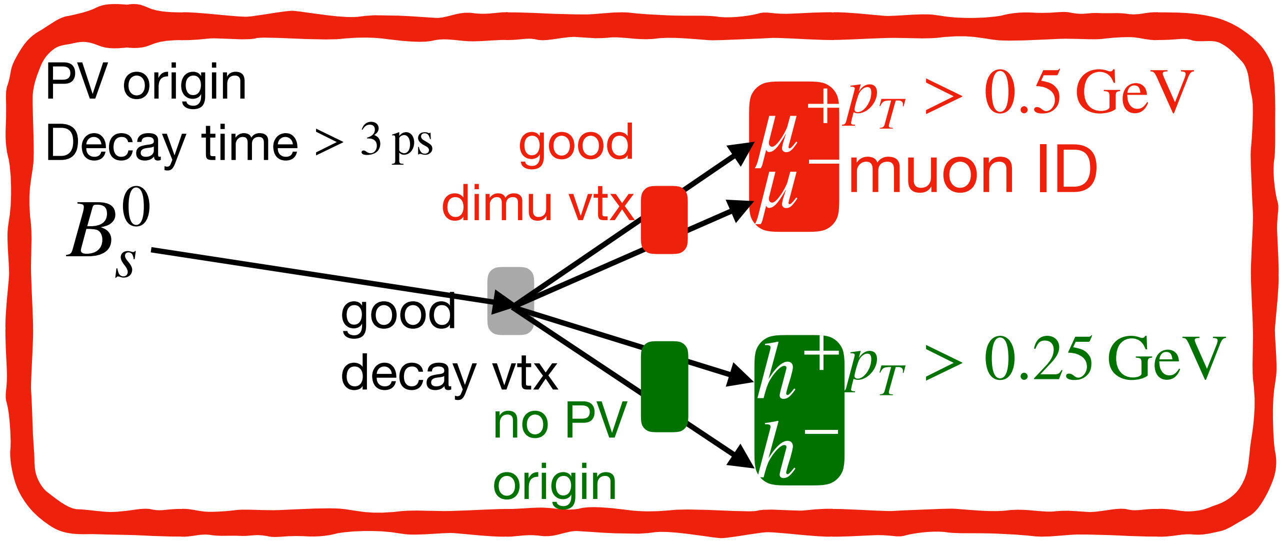
- $s\bar{s}$ can manifest in $f_0(980)\,[\to \pi^+\pi^-]$ 0812.2832
- $B_s^0 \to J/\psi\pi^+\pi^-$ is $> 97.7\,\%$ CP-odd at 95% CL 1402.6248

1. CP violation in beauty

Data 2015 - 2016: $2\,\mathrm{fb}^{-1}$ @ 13 TeV

Trigger:

- **Hardware:** high p_T muon or high E_T calorimeter deposit
- **Software 1:** High p_T & χ^2_{IP} muon or muon-pair with $m(\mu^+\mu^-) > 2.7\,\mathrm{GeV}/c^2$
- **Software 2:** Full reco; good dimuon vertex, well-separated from PVs, near $m_{J/\psi}$



... and a BDT

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1. CP violation in beauty

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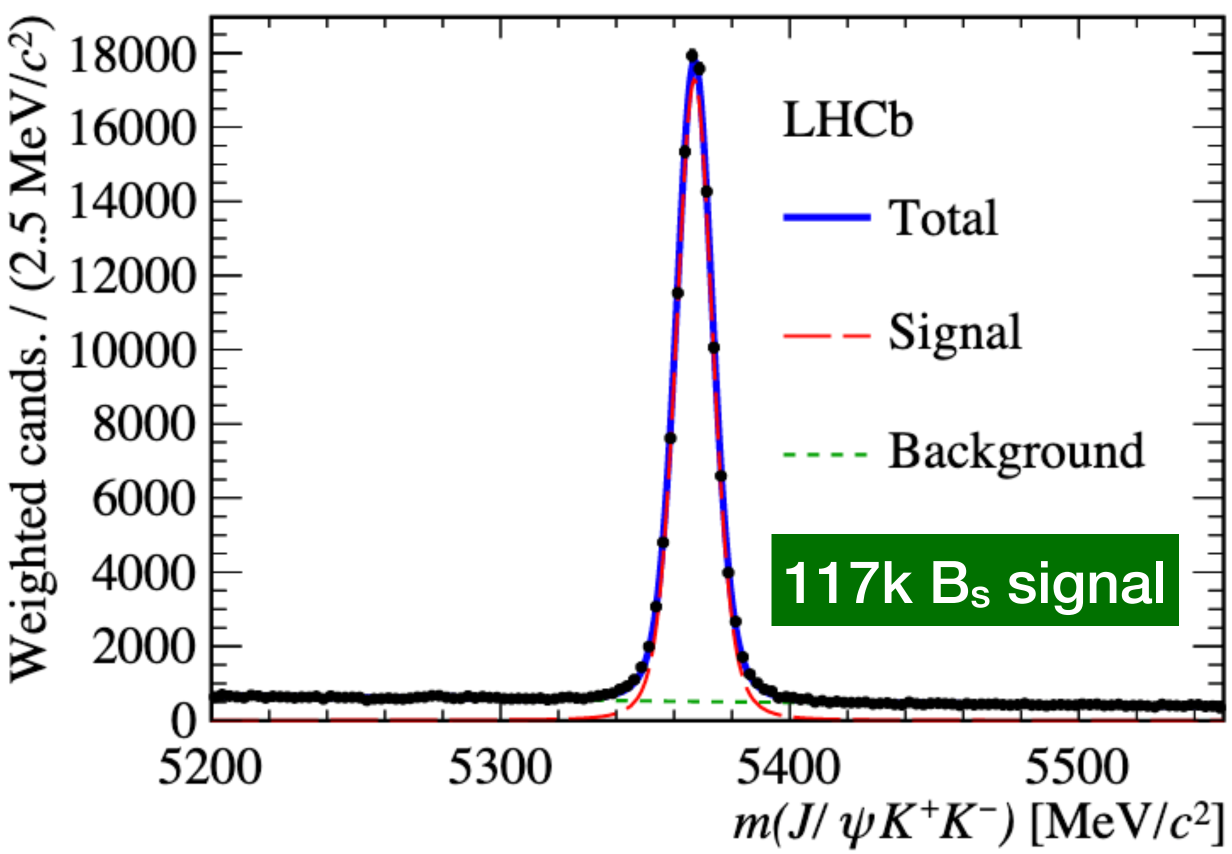
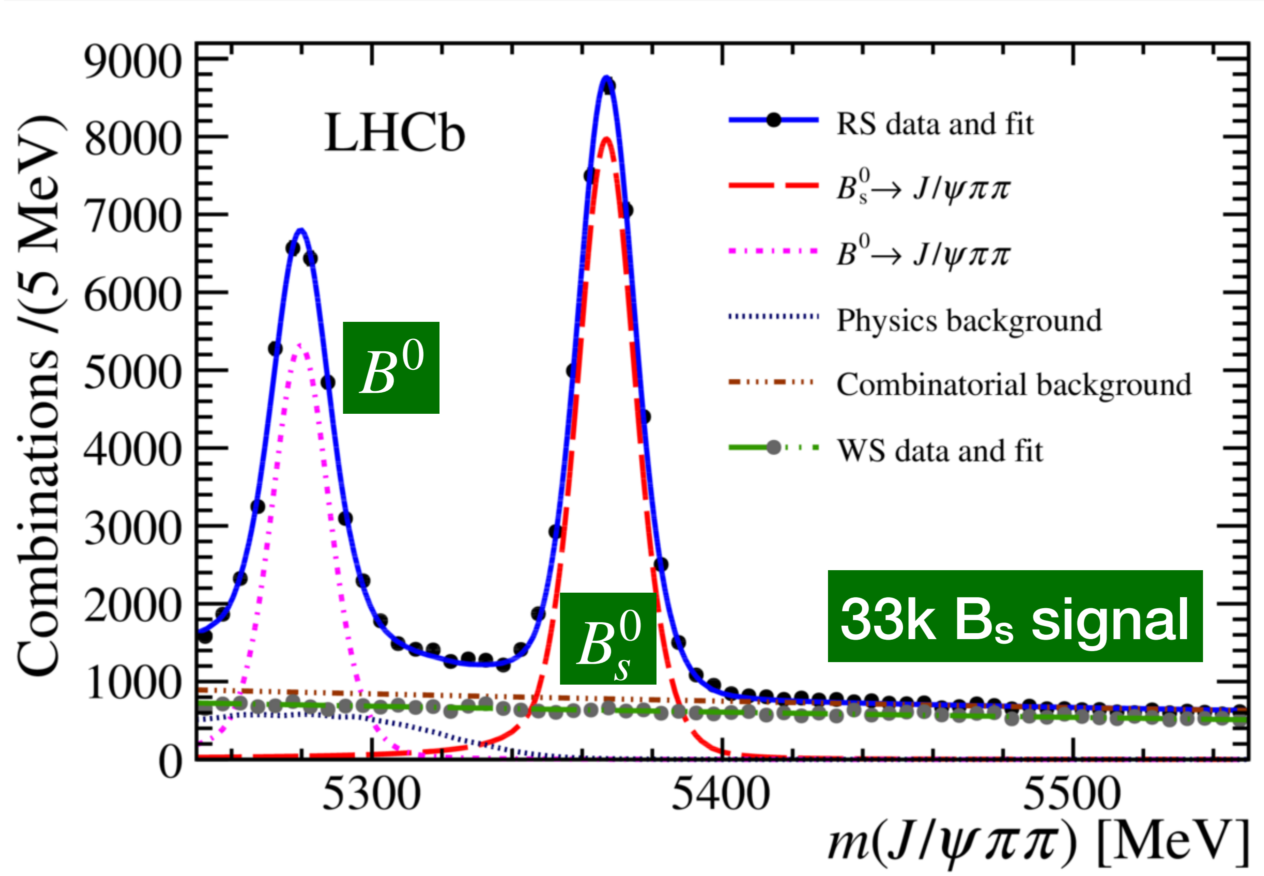


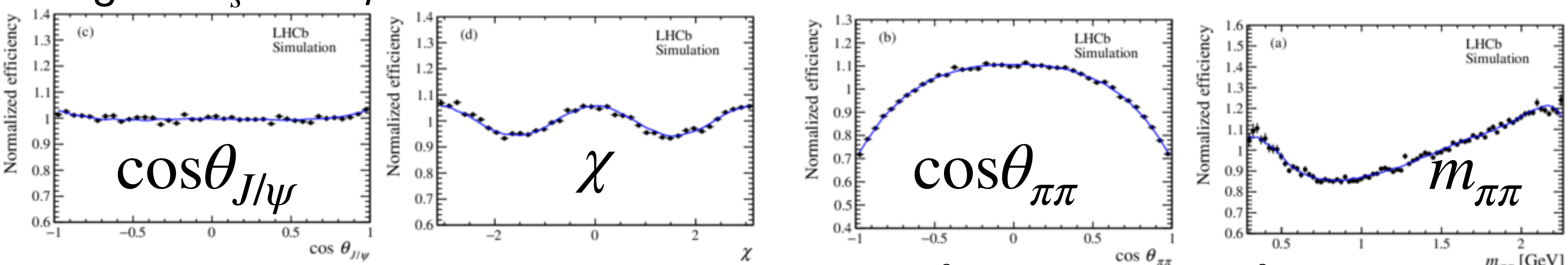


1. CP violation in beauty

Fit: Unbinned max-L fit to: decay time, flavour tag, $(m_{\pi\pi}/m_{KK}\,\mathrm{bin})$, B_s^0 helicity angles

- **Efficiencies in angular variables (and $m_{\pi\pi}$) taken from simulation**

e.g. for $B_s^0 \to J/\psi\pi^+\pi^-$



- **Decay time acceptance determined using $B^0 \to J/\psi K^*(892)^0$ and known τ_{B^0}**
- **Decay time uncertainty calibrated with prompt $J/\psi + h^+h^-$**
  - effective resolution: $40 - 45\,\mathrm{fs}$
- **Flavour tag**

  calibrate with $B^+ \to J/\psi K^+$

  a) decays of 'opposite side' b-hadron

  b) jet fragments on 'same side' containing a kaon

  calibrate with $B_s^0 \to D_s^-\pi^+$

Total:
$\epsilon_{\mathrm{tag}} = (78.5 \pm 0.7)\,\%$
$\epsilon_{\mathrm{tag}}D^2 = (5.06 \pm 0.38)\,\%$

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1. CP violation in beauty

Results

$B_s^0 \to J/\psi K^+ K^-$

$\phi_s = -80 \pm 41 \pm 6\,\text{mrad}$

main syst: factorisation of mass and helicity angle

$B_s^0 \to J/\psi \pi^+ \pi^-$

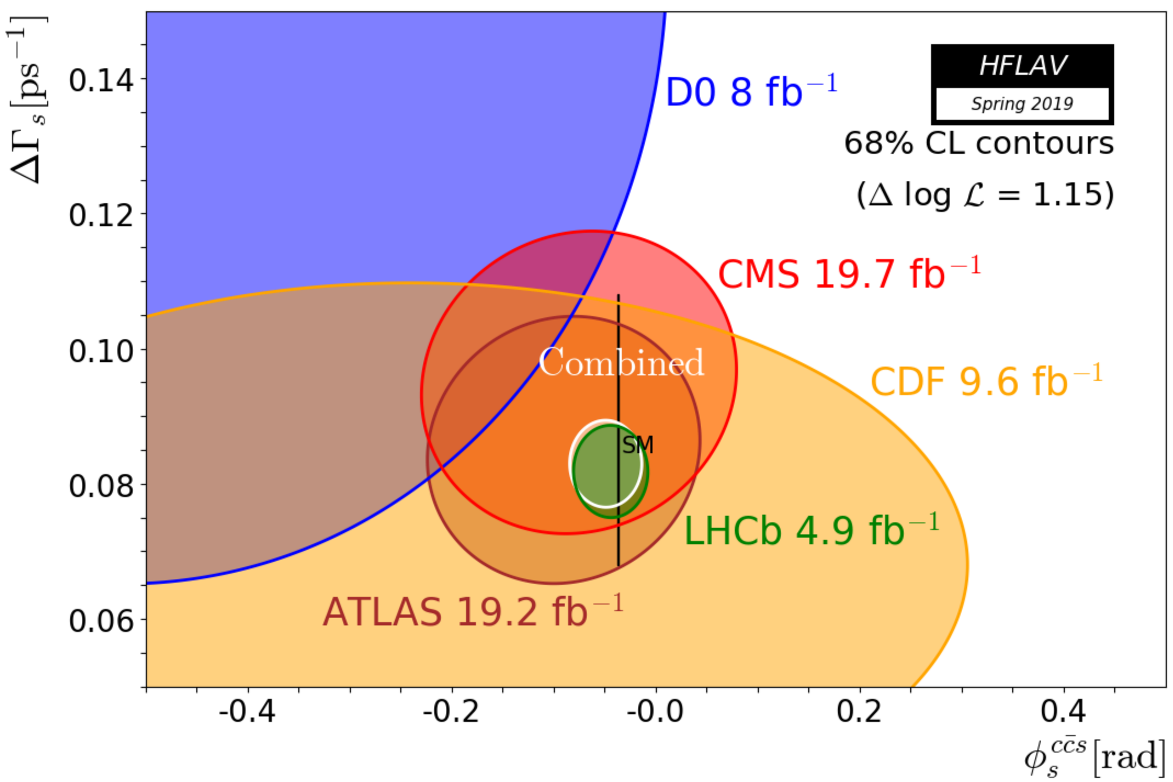
$\phi_s = -57 \pm 60 \pm 11\,\text{mrad}$

main syst: ππ amp. model

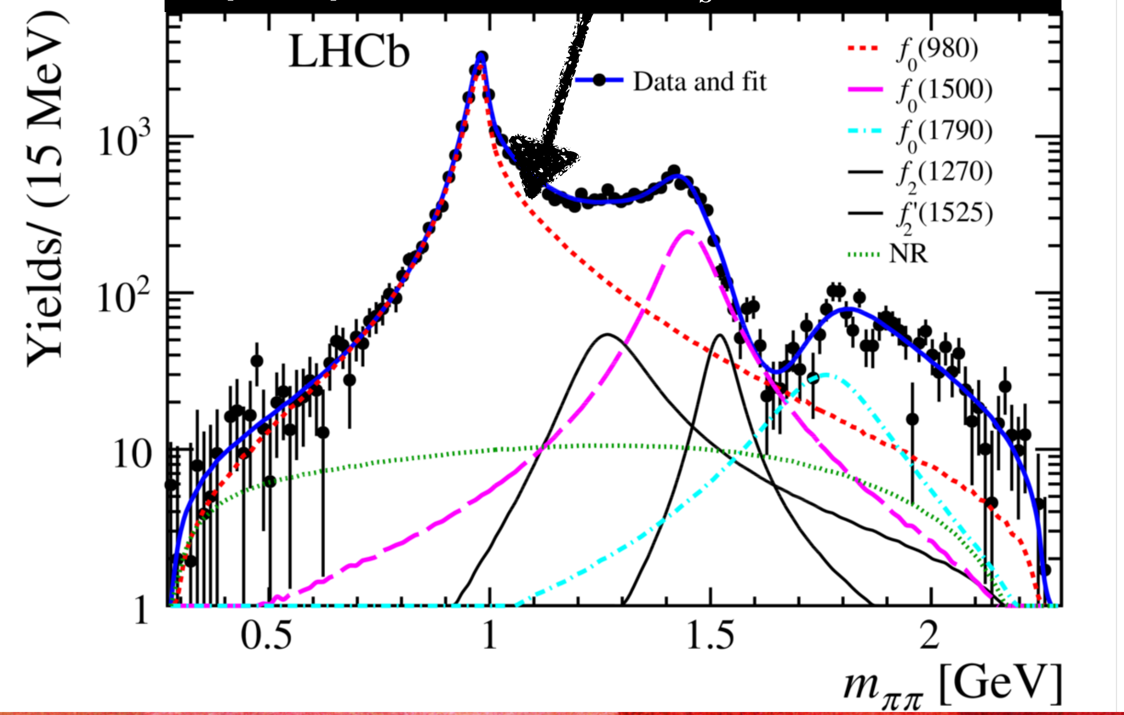
Combined, including Run 1 results: $\phi_s = -53 \pm 26\,\text{mrad}$

Most precise determination of ϕ_s to date!

…consistent (0.5σ) with expectation assuming SM, and 2σ from zero



f0(980) dominates $B_s^0 \to J/\psi \pi^+ \pi^-$



1. CP violation in beauty
2. CP violation in charm

Outline

3. Exotic hadron spectroscopy

4. Lepton universality

2. CP violation in charm

Expected to be very small $O(10^{-4} - 10^{-3})$

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)\left(1-\frac{1}{2}\lambda^2\right)\right] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} + O(\lambda^6)$$

Opportunity to probe NP effects in up-type-quark sector

Imprecise predictions:

small $m_c \Rightarrow$ long-distance effects are significant

Time integrated asymmetry difference

many systematic effects cancel $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

Much sought!

Experiment	ΔA_{CP}	Year
CDF	$(-62 \pm 21 \pm 10) \times 10^{-4}$	2012
BaBar	$(+24 \pm 62 \pm 26) \times 10^{-4}$	2008
Belle	$(-87 \pm 41 \pm 6) \times 10^{-4}$	2012
LHCb (3.0 fb^{-1}, muon-tagged)	$(+14 \pm 16 \pm 8) \times 10^{-4}$	2014
LHCb (3.0 fb^{-1}, pion-tagged)	$(-10 \pm 8 \pm 3) \times 10^{-4}$	2016

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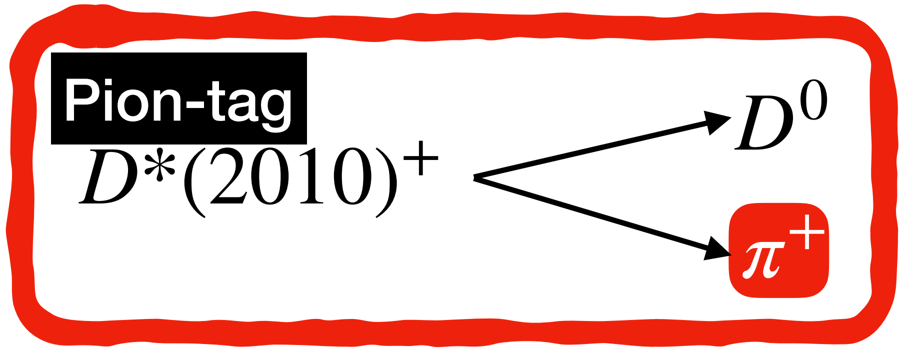
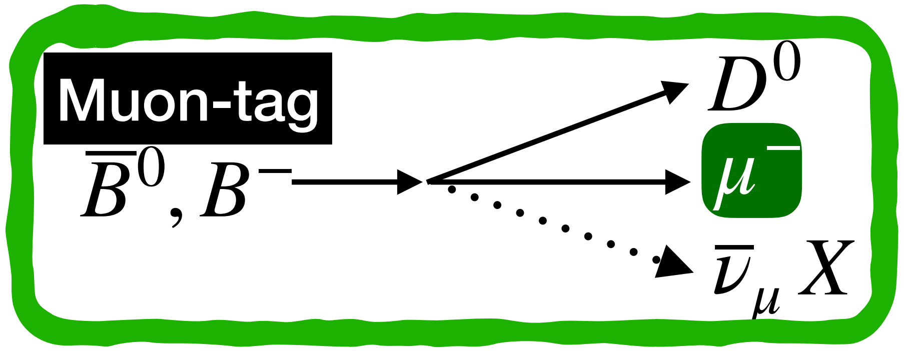
2. CP violation in charm

Data 2015 - 2018: $6\,\mathrm{fb}^{-1}$ @ 13 TeV





Systematic cancellation: $A_{\mathrm{raw}}(f) \approx A_{CP}(f) + A_D + A_P$

independent of final state

$$\Delta A_{CP} = A_{\mathrm{raw}}(D^0 \to K^+K^-) - A_{\mathrm{raw}}(D^0 \to \pi^+\pi^-)$$

Trigger:

- **Hardware:** significant calorimeter / muon system deposits
- **Software 1:** High p_{T} & χ^2_{IP} track or 2-track secondary vtx consistent with D^0

  (Nearly) real-time detector alignment and calibration

- **Software 2:** Full reconstruction; kinematic/topological/PID selection

1903.08726

2. CP violation in charm

Selection

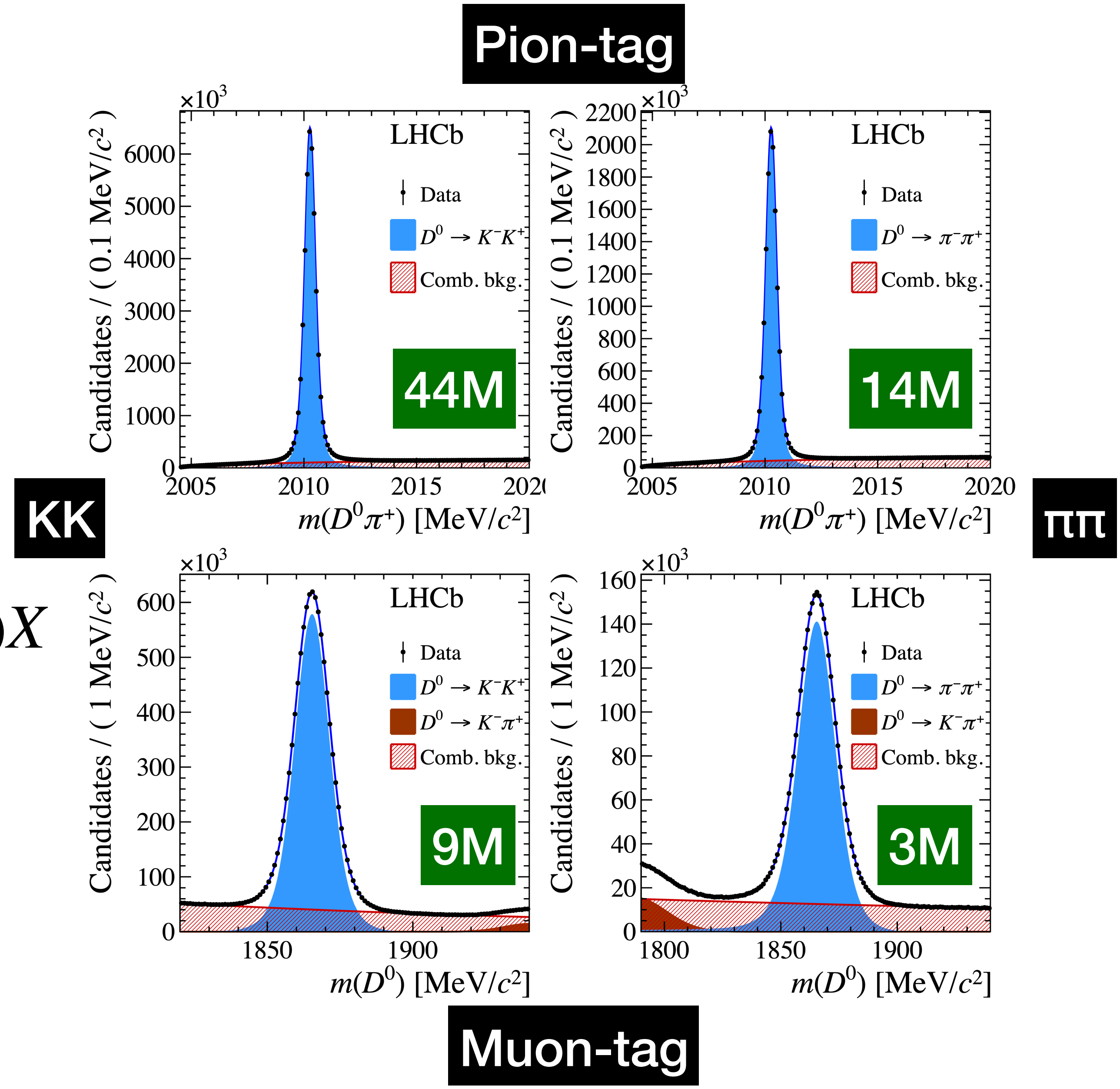
- **Exclude** regions with large $A_D(\pi^{tag},\mu^{tag})$
- **Mass window** for D^0
- Require **good D^{*+} vertex**, close to PV
- Correct different KK/ππ tag-kinematics

Muon-tag only:

- Dedicated BDT to suppress comb. bg.
- Explicit veto for $b \to [c\bar{c} \to \mu^+\mu^-]h(=\pi, K)X$

Simultaneous fit

- $m(D^*(2010)^+)$ for pion-tagged
- $m(D^0)$ for muon-tagged



2. CP violation in charm

Systematic uncertainties

- **Signal/background mass models**

  Pion-tag: $\sigma(\Delta A_{CP})$ = 0.6 x 10^{-4}

- **Muon mistag**

  Main syst. for muon-tag: $\sigma(\Delta A_{CP})$ = 4 x 10^{-4}

- **Tag KK/ππ kinematic reweighting**

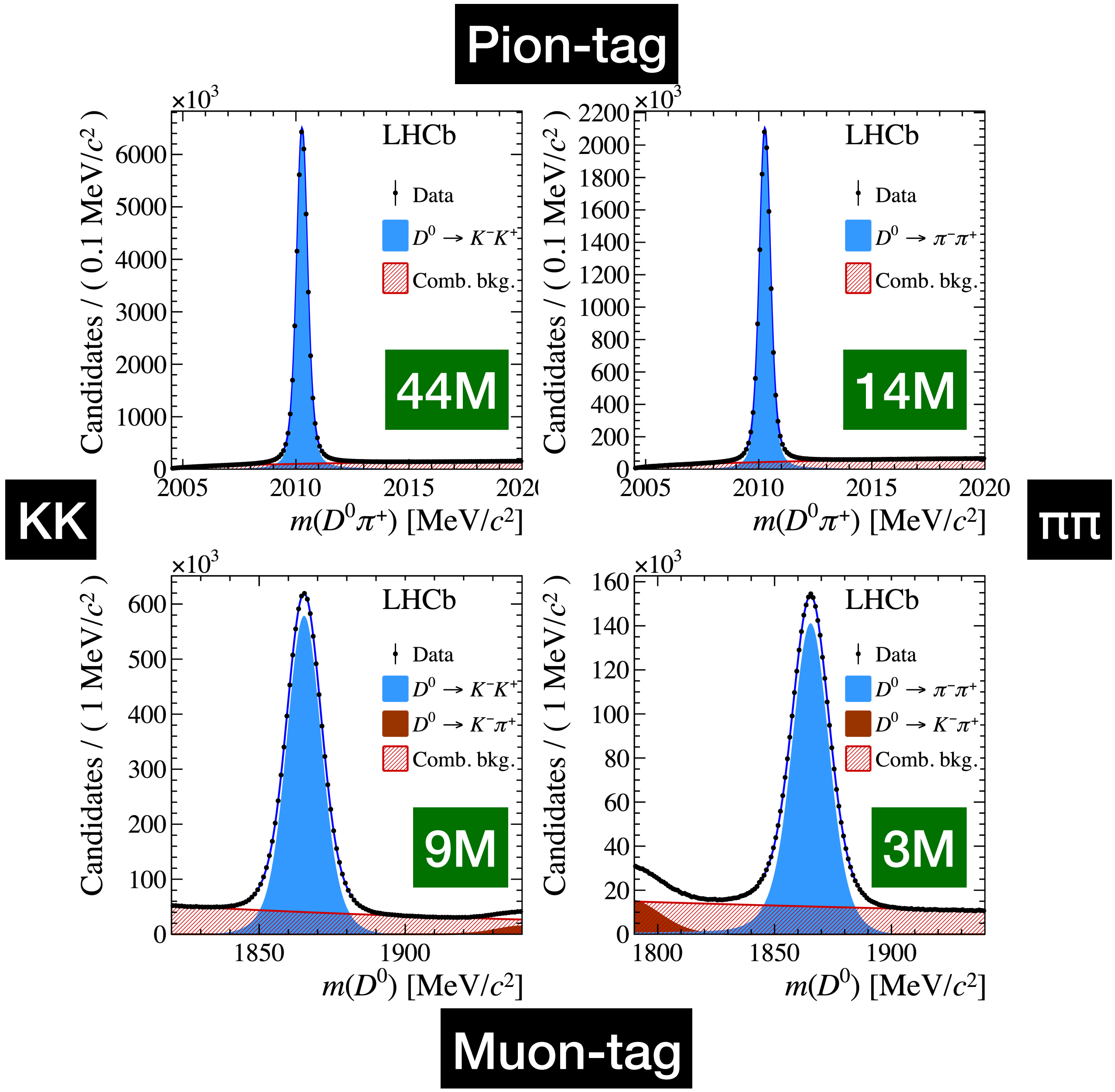
- **Bg peaking in $m(D^0\pi^+)$ but not $m(D^0)$**

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

  ππ $D^0 \to \pi^-\mu^+\nu_\mu$, $D^0 \to \pi^-e^+\nu_e$

  Pion-tag: $\sigma(\Delta A_{CP})$ = 0.5 x 10^{-4}

- **Fractions of B^0 and B^+ in KK or ππ**
  - different A_P and reco. effs.



2. CP violation in charm

Results

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- In good agreement with world averages and previous LHCb results
- Combining with previous LHCb measurements:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3 standard deviations

First observation of CPV in charm hadron decay

$$\Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

$\frac{\overline{\langle t \rangle}}{\tau(D^0)}$ ~1.71; y_{CP} ~0.006; $\frac{\Delta \langle t \rangle}{\tau(D^0)}$ ~0.115

- **Primarily sensitive to direct CPV**

previously… $\Delta a_{CP}^{\text{dir}} = (-13.4 \pm 7.0) \times 10^{-4}$

now… $(-15.6 \pm 2.9) \times 10^{-4}$

1. CP violation in beauty
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Outline

3. Exotic hadron spectroscopy

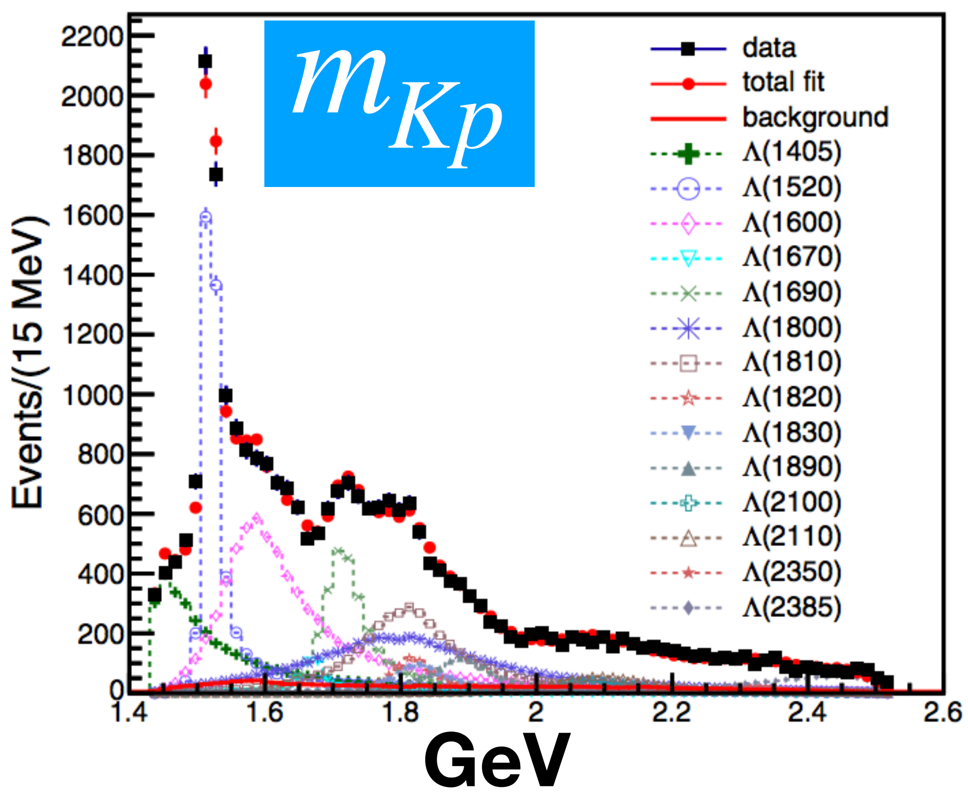
4. Lepton universality

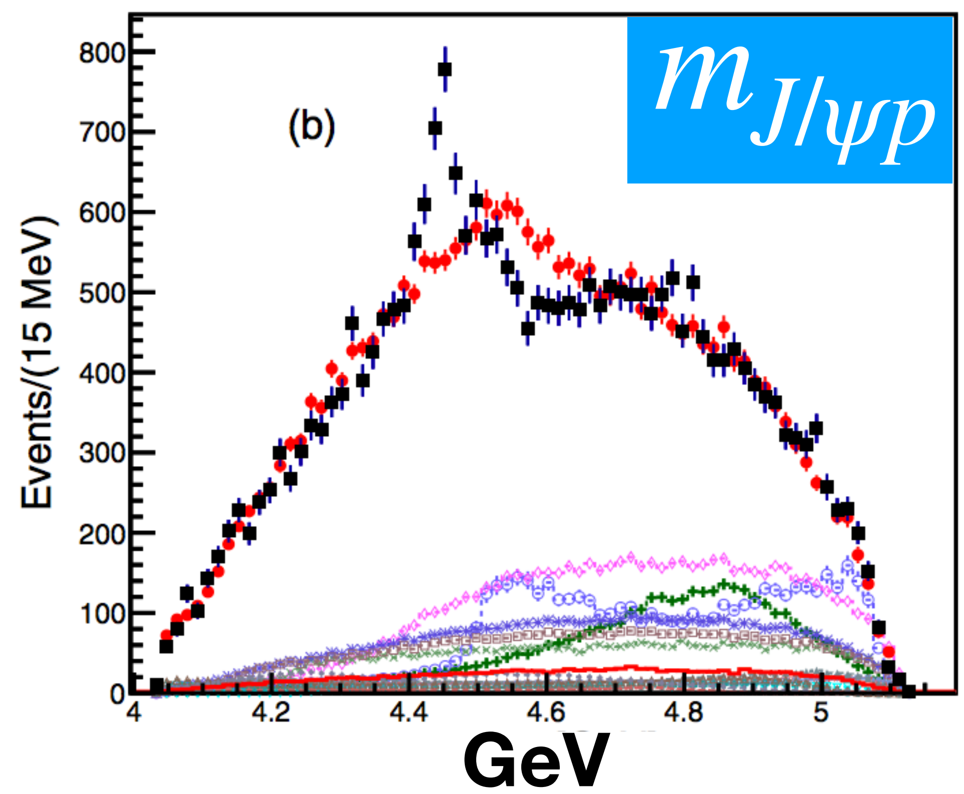
3. Pentaquarks

Back to 2015…

1507.03414

- 6-dimensional amplitude fit to $\Lambda_b^0 \to J/\psi p K$ with Run 1 ('11-'12) data





Data

Fit with known states

- All-known Λ^* states, and new ones tried
- Floated masses and widths
- Tested non-resonant terms/Σ^*
- Cannot be a reflection 1604.05708

… 2 new pentaquarks

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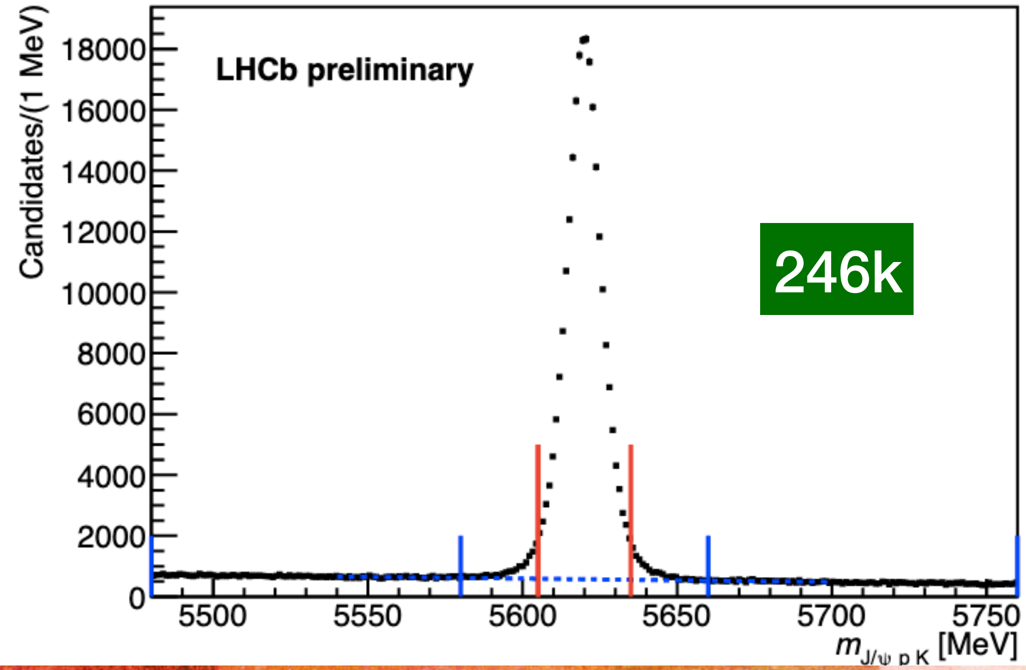
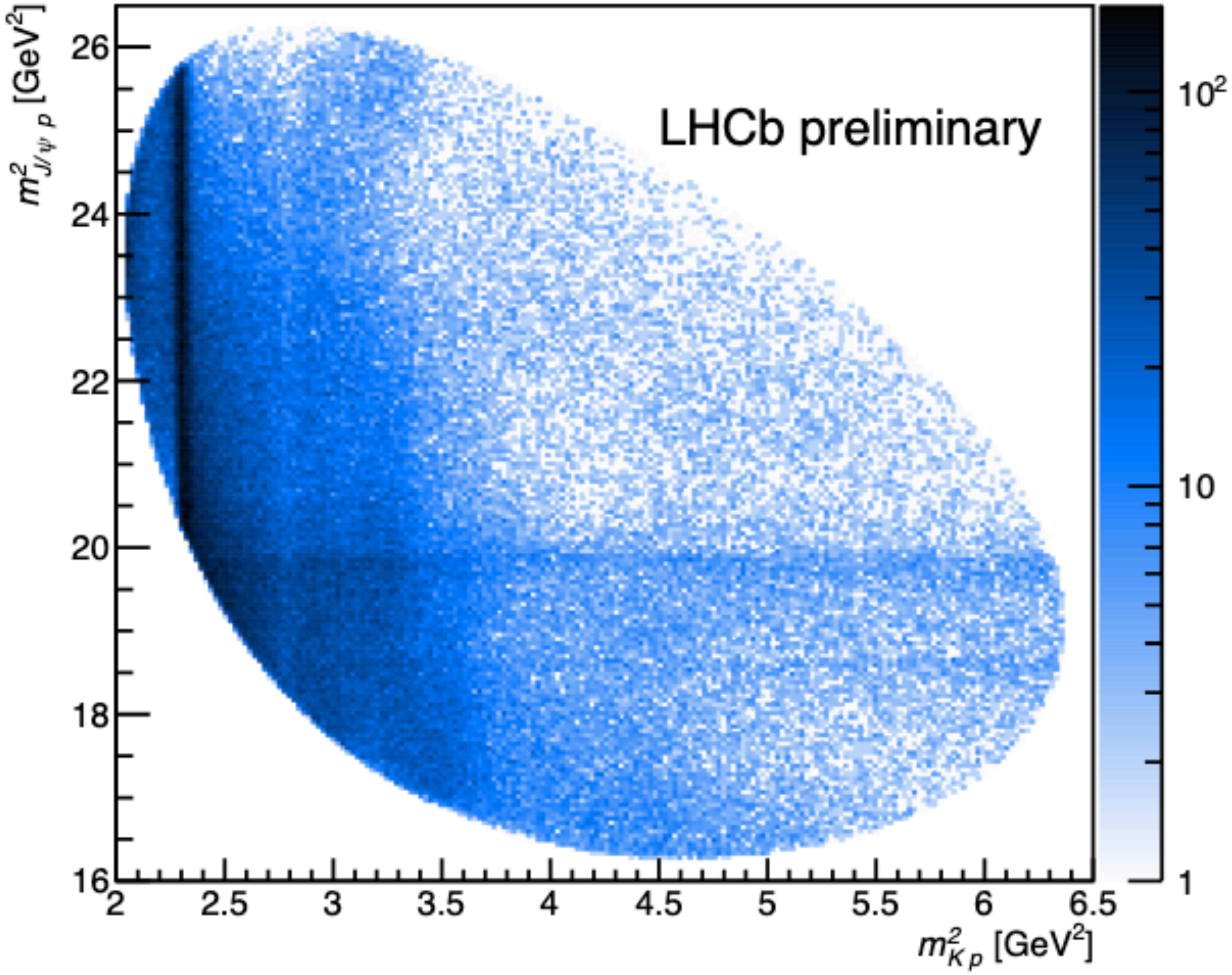
in preparation

3. Pentaquarks

Data 2011 - 2018: $9\,\mathrm{fb}^{-1}$ @ 7,8,13 TeV

- new BDT, including hadron ID, doubles Λ_b^0 signal efficiency; still 94% pure
- resulting dataset is 9 times larger than that of the earlier analysis





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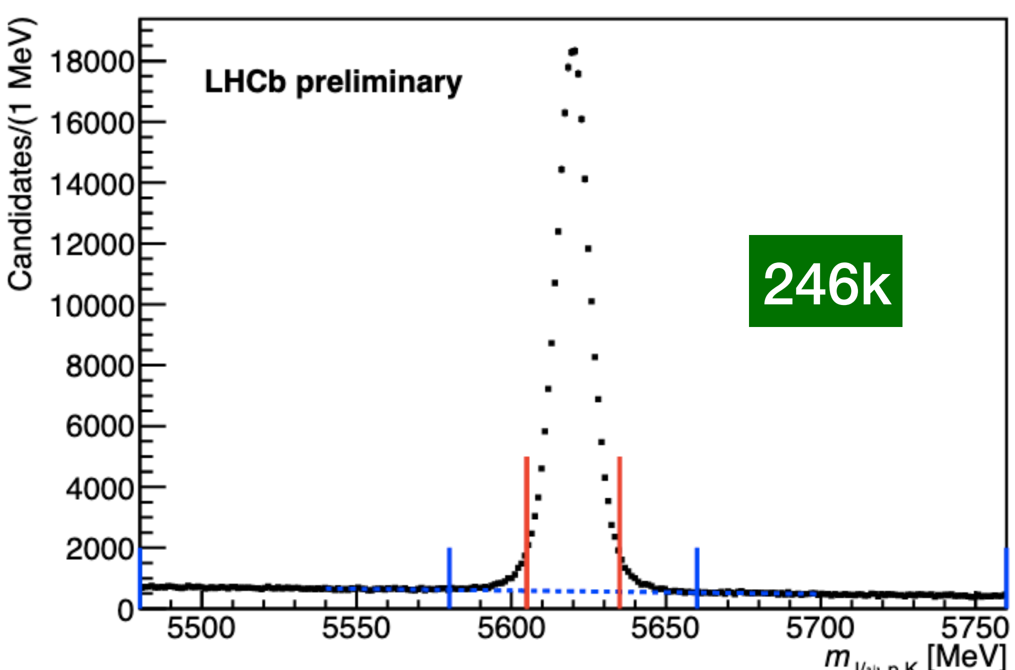
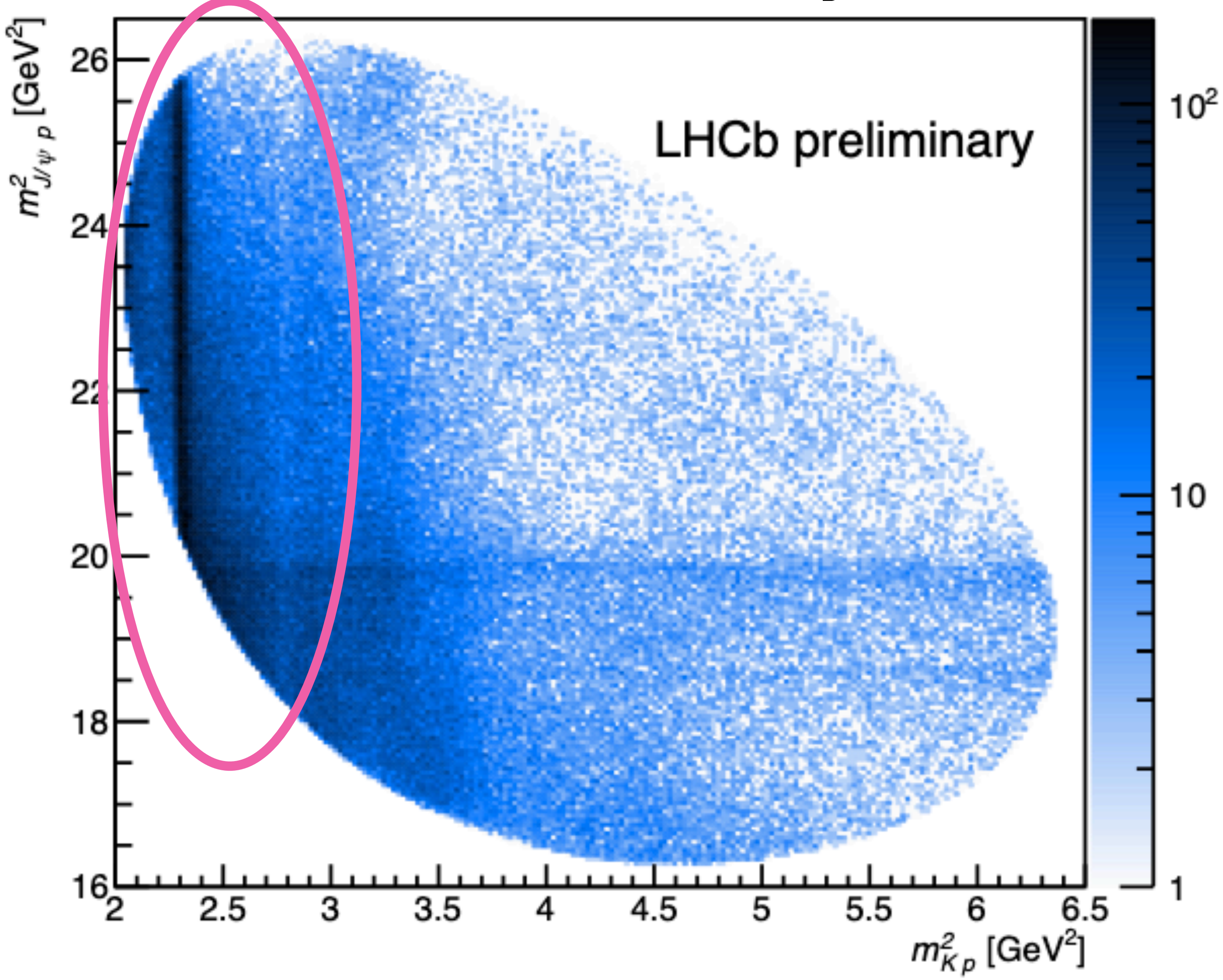
Complicated Λ^* structure





3. Pentaquarks

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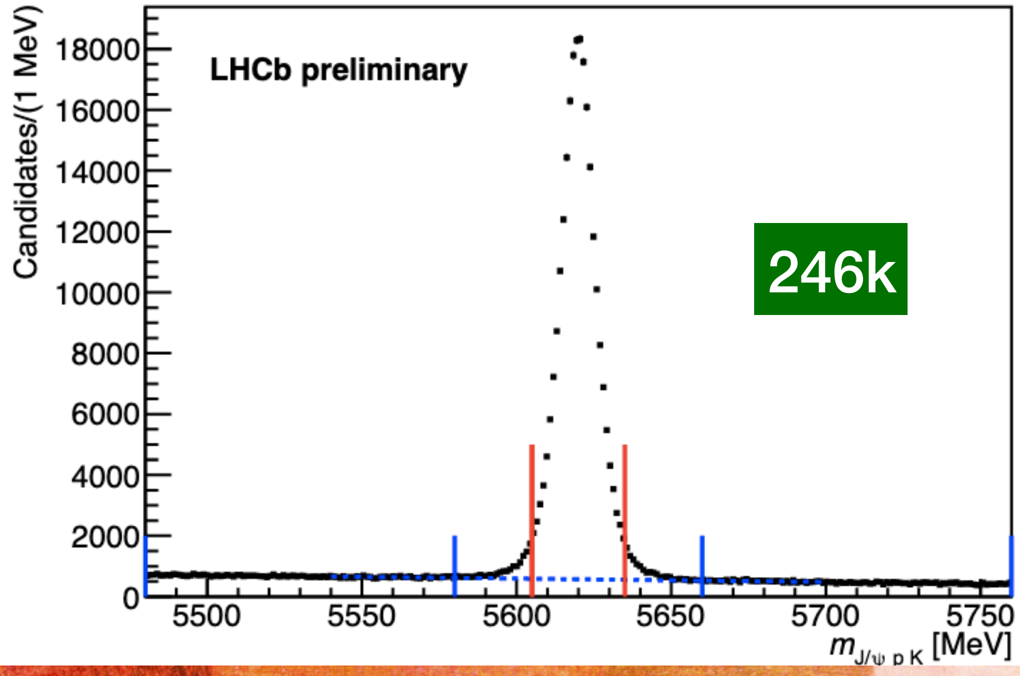
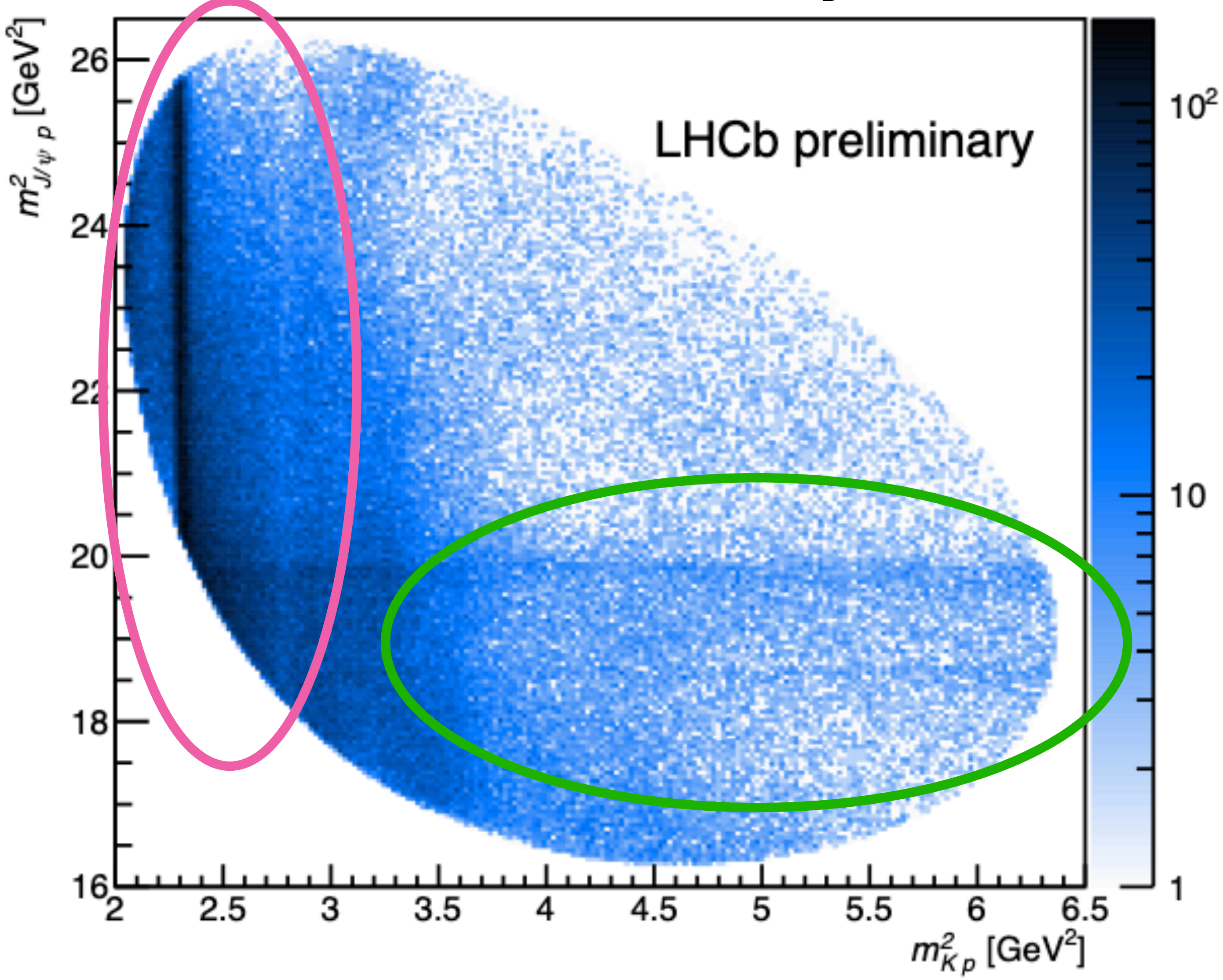
Complicated Λ^* structure

Clearly visible P_c states





3. Pentaquarks

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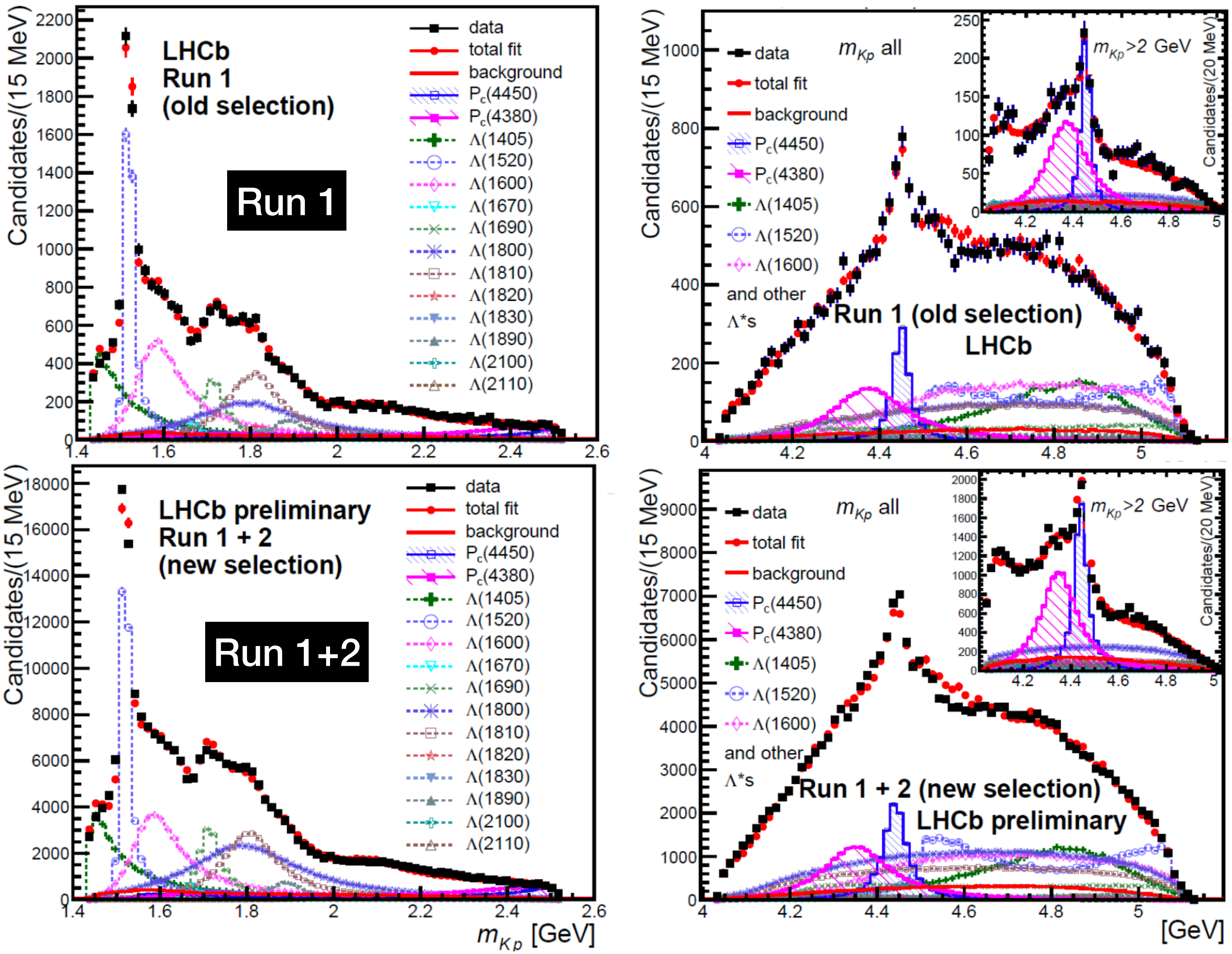
Run 1 vs Run 2

- **Consistent structure when apply 2015 model to new data**



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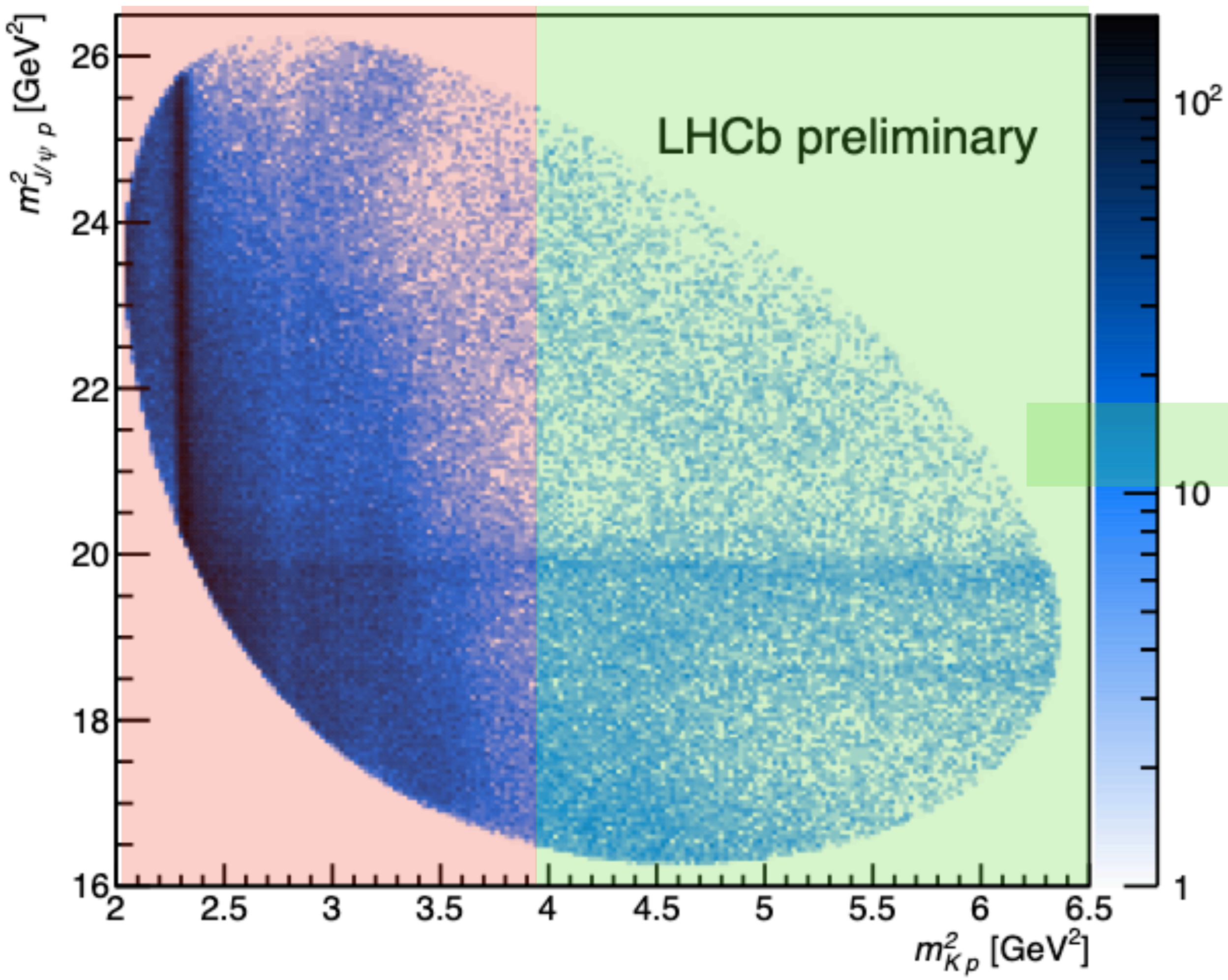
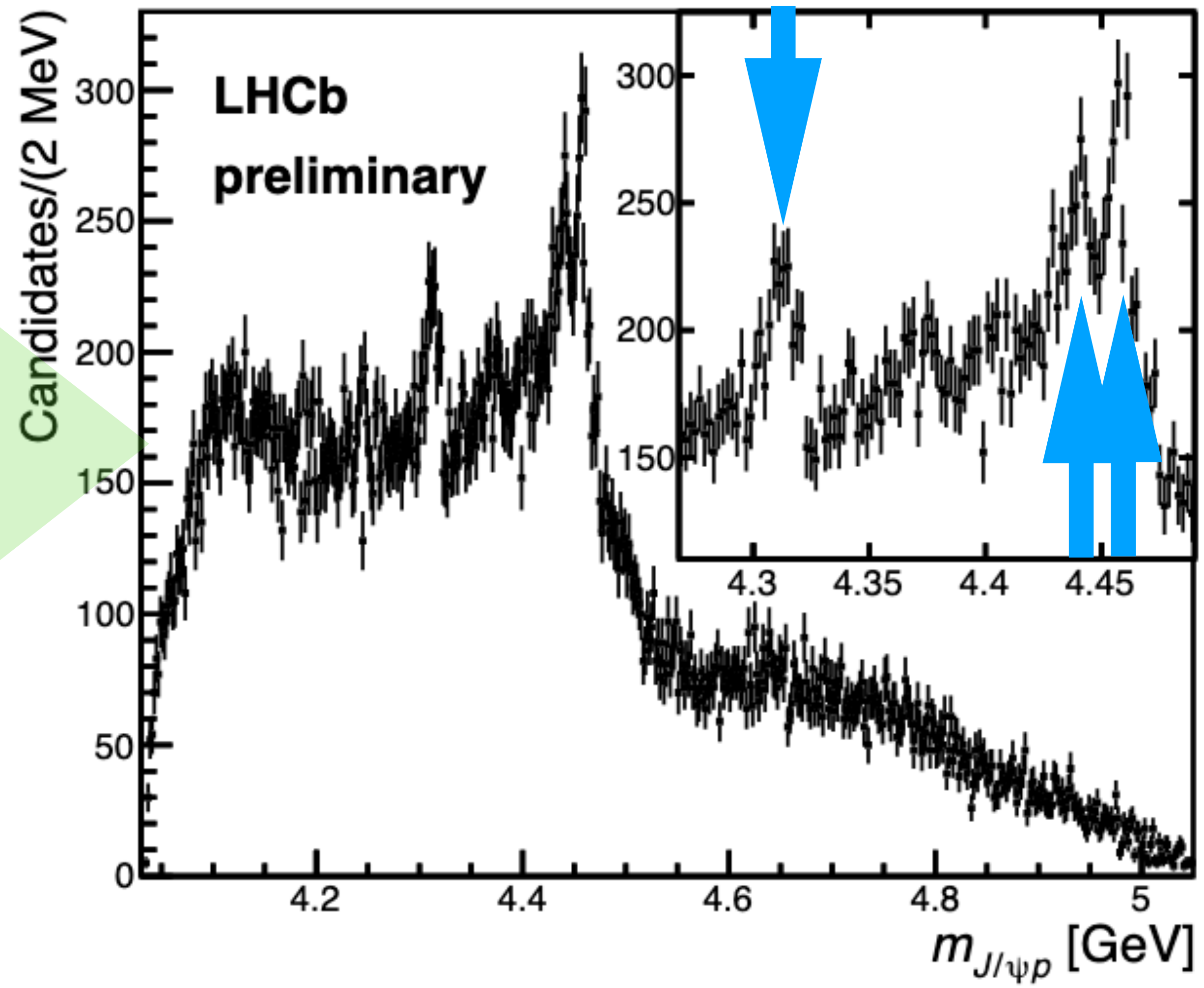
3. Pentaquarks

Strategy

- new, narrow, $J/\psi p$ structures can be investigated without full model
- binned χ^2 fits performed to $m(J/\psi p)$ in range $4.22 < m(J/\psi p) < 4.57\,\text{GeV}$
- previous, broad, $P_c(4380)^+$ state too broad to be studied for now





3. Pentaquarks

Results

- **Fit with full dataset, Λ^*-veto, and $\cos(\theta_{P_c})$-weighting**
- **1-D fit strategy validated on toys sampled from 6-D amp. models**
  dominant systematic from possible P_c^+ interference, not probed in $m(J/\psi p)$
- **In all fits, 3 narrow BW P_c^+ terms + smooth bg description**
  - **results insensitive to background models**
  - $m(J/\psi p)$ **negligibly impacted by detector efficiency**

- **Systematic uncertainties account for:**
  - background model
  - P_c^+ interference
  - mass resolution
  - S-/P-wave production/decay
  - alternative (non-BDT) selection

LHCb-PAPER-2019-014
in preparation

3. Pentaquarks

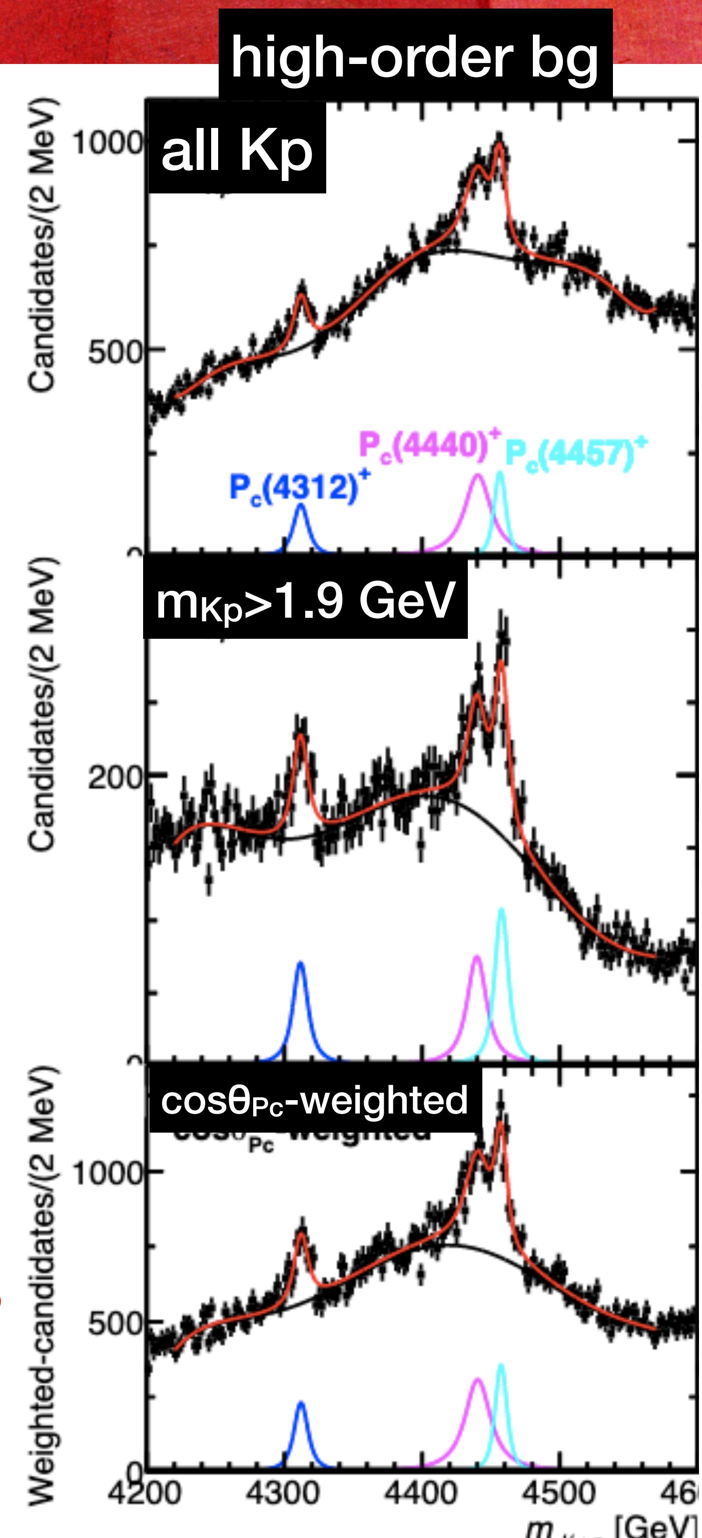
Results

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

Significance of $P_c(4312)$: 8.2σ
including L.E. effect

Significance of two-peak: 6.2σ
resolve $P_c(4440)$ & $P_c(4457)$

Broad $P_c(4380)$ awaits amp. analysis



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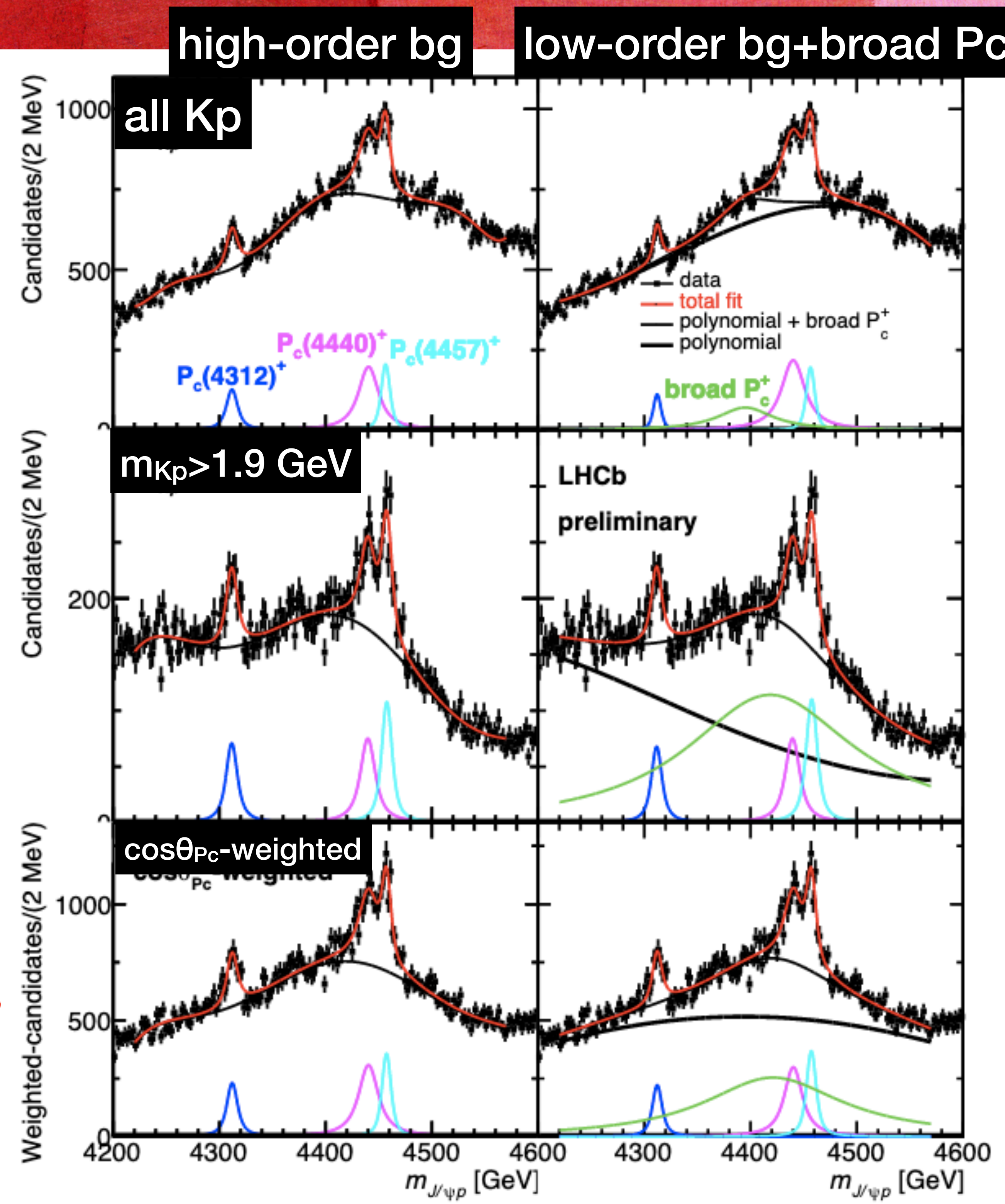

1. CP violation in beauty
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1903.09252

4. Lepton flav. universality

> **"Electroweak couplings of charged leptons are universal"**
>
> *Standard Model, 1970s*

FCNC $b \to s\ell^+\ell^-$ decays proceed via electroweak loop diagrams
sensitive to virtual contributions from BSM particles

Predictions rely on calculation of hadronic effects
focus on BF ratios below $q^2(\ell^+\ell^-)$ where charmonium plays a role

- $R_K(1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4)$ — 2.6σ below unity — 1406.6482
- $R_{K^{*0}}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4)$ — 2.1-2.3σ below unity — 1705.05802
- $R_{K^{*0}}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4)$ — 2.4-2.5σ below unity — 1705.05802

At such low q^2, predictions have $\mathcal{O}(1\%)$ precision

4. Lepton flav. universality

Data 2011 - 2016: $5\,\mathrm{fb}^{-1}$ @ 7,8,13 TeV

Very different reconstruction strategy for muons and electrons

electron bremsstrahlung; different triggers; so:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

(J/ψ decays lepton-universal at 0.4% level)

Improved reconstruction wrt earlier measurement and higher q^2_{min}

Identical selections for resonant/non-resonant: exploit topology & PID

J/ψ constraint reduces mass resolution (MeV) 140→24.5 (e) & 30→17.5 (μ)

Efficiency ratios from simulation, calibrated using the resonant mode

Simultaneous, unbinned fit, constraining resonant yields, fitting R_K

4. Lepton flav. universality

Systematic uncertainties

$\sigma(R_K) =$ 0.01

- **Mass shape models: fit pseudo experiments with alternative models**

- **Efficiency uncertainties inserted via constraints in the fit**
  non-e-triggered events: data-derived trigger efficiency calibration
  e-triggered events: calib sample statistics and data/MC differences

- q^2 **migration studied in MC; negligible impact of data/MC differences**

- **Negligible uncertainty due to simulation decay model**
  (Wilson coefficients, form factors, other hadronic uncertainties)

- **Consistent cross-checks:**

$$r_{J/\psi} = \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)/\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+) = 1.014 \pm 0.035$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.986 \pm 0.013$$

1903.09252

4. Lepton flav. universality

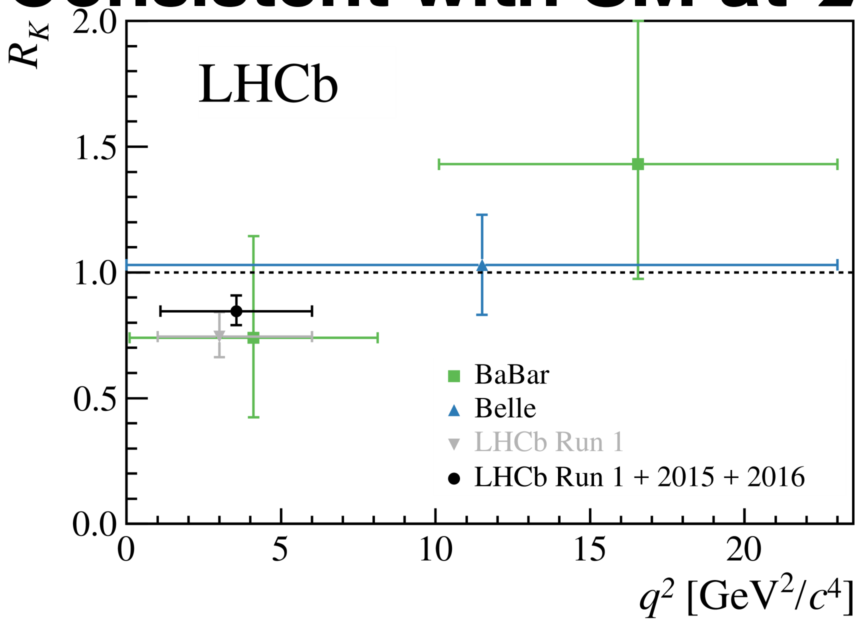
Results

Fit to selected candidates

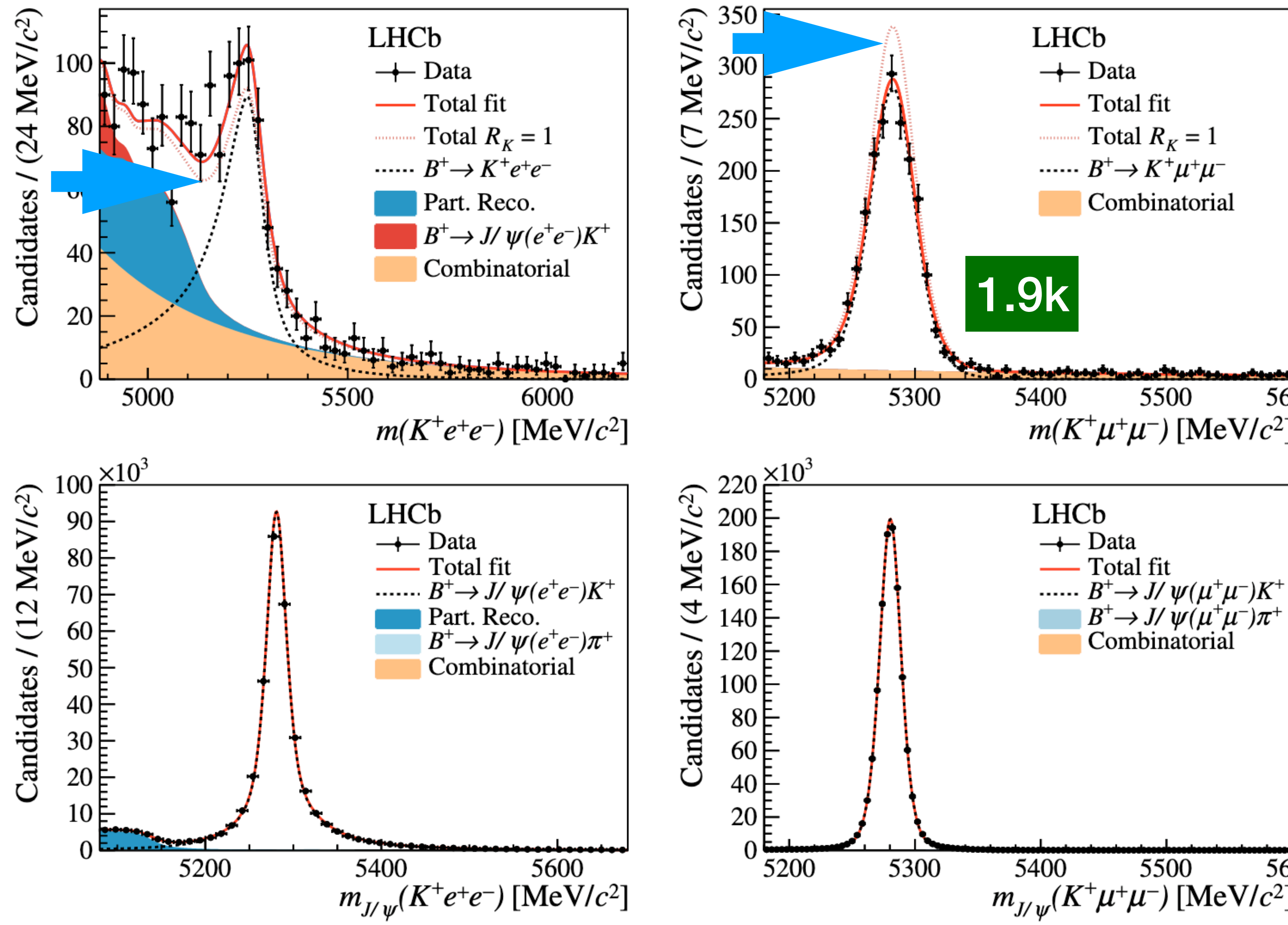
red-dashed line shows R_K=1

$$R_K = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$

Consistent with SM at 2.5σ



$$R_K^{7\,\text{and}\,8\,\text{TeV}} = 0.717\,^{+0.083}_{-0.071}\,^{+0.017}_{-0.016}$$
$$R_K^{13\,\text{TeV}} = 0.928\,^{+0.089}_{-0.076}\,^{+0.020}_{-0.017}$$



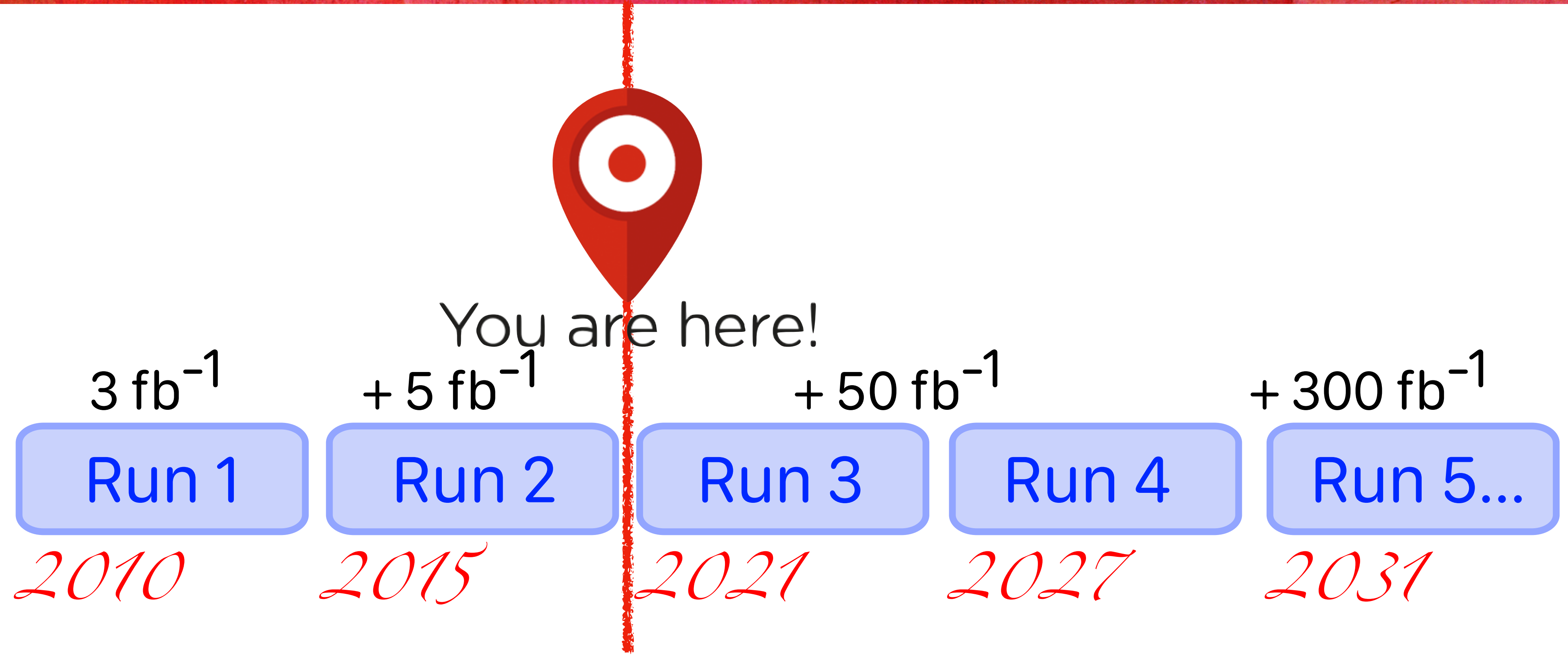
Consistent across trigger samples

7,8 TeV consistent with 13 TeV at 1.9σ

Reproduce earlier result at $< 1\sigma$

2017/2018 analysis still to come!

Prospects



Sample	$\mathcal{L}$ (fb^{-1})	Units of Run-1	
Run 1	3	1	
Run 2	6	3	$\sigma(b\bar{b}) \to 2\sigma(b\bar{b})$; $\uparrow \epsilon$(trig/offline)
Upgrade	$\sim$50	$\sim$60	$\epsilon_{trig}^{hadrons} \to 2\epsilon_{trig}^{hadrons}$
Phase-2 Upgrade	$\sim$300	$\sim$360	

- **Many Run 1/2 legacy results in preparation**
- **Installing and commissioning of the new detector well-underway**
- **Watch this space!**

Summary

- **World's best measurement of ϕ_s**
- **Discovery of CP violation in the charm sector**
- **New pentaquark discoveries** Released today!
- **Search for lepton non-universality**

journal details, hi-res plots and more at cern.ch/go/X7sX