Experiment LHCb
selected 2019-2020 results

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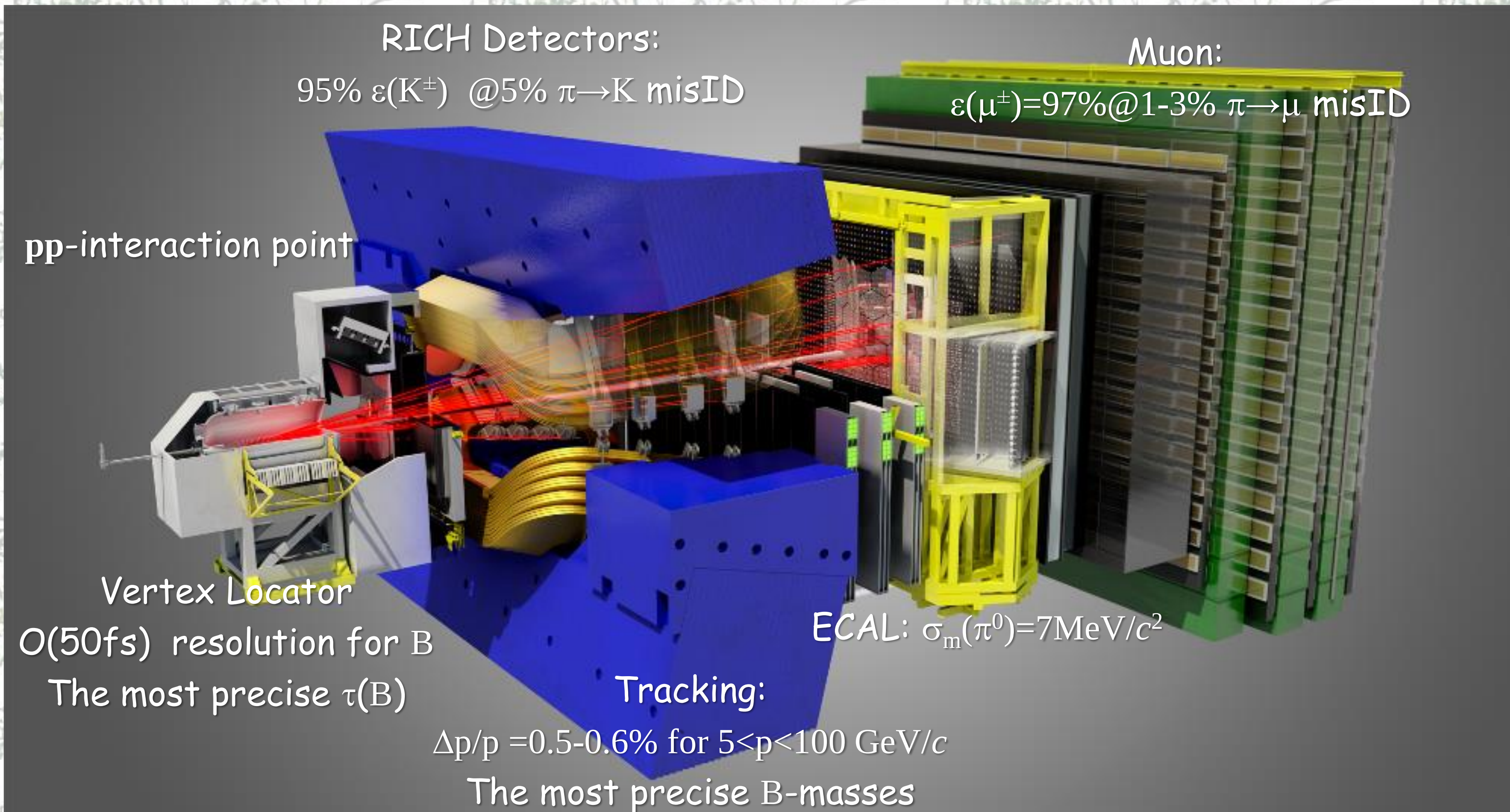
On behalf of LHCb collaboration

LHCb

- Detector
- Selected results 2019-2020
  - Rare decays
  - Lepton universality
  - Charm and beauty spectroscopy

$\sim$40% of heavy quarks in $<4\%$ of 4π

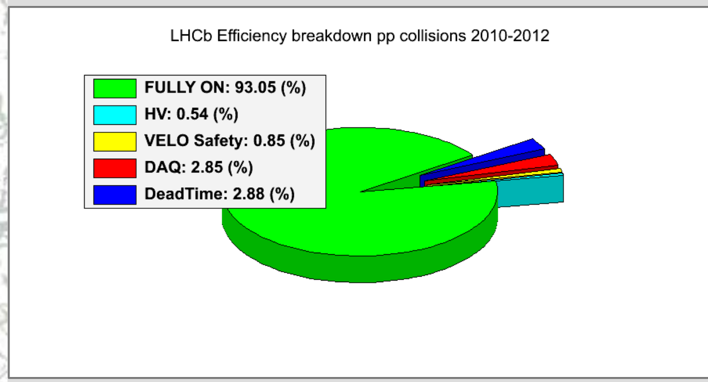


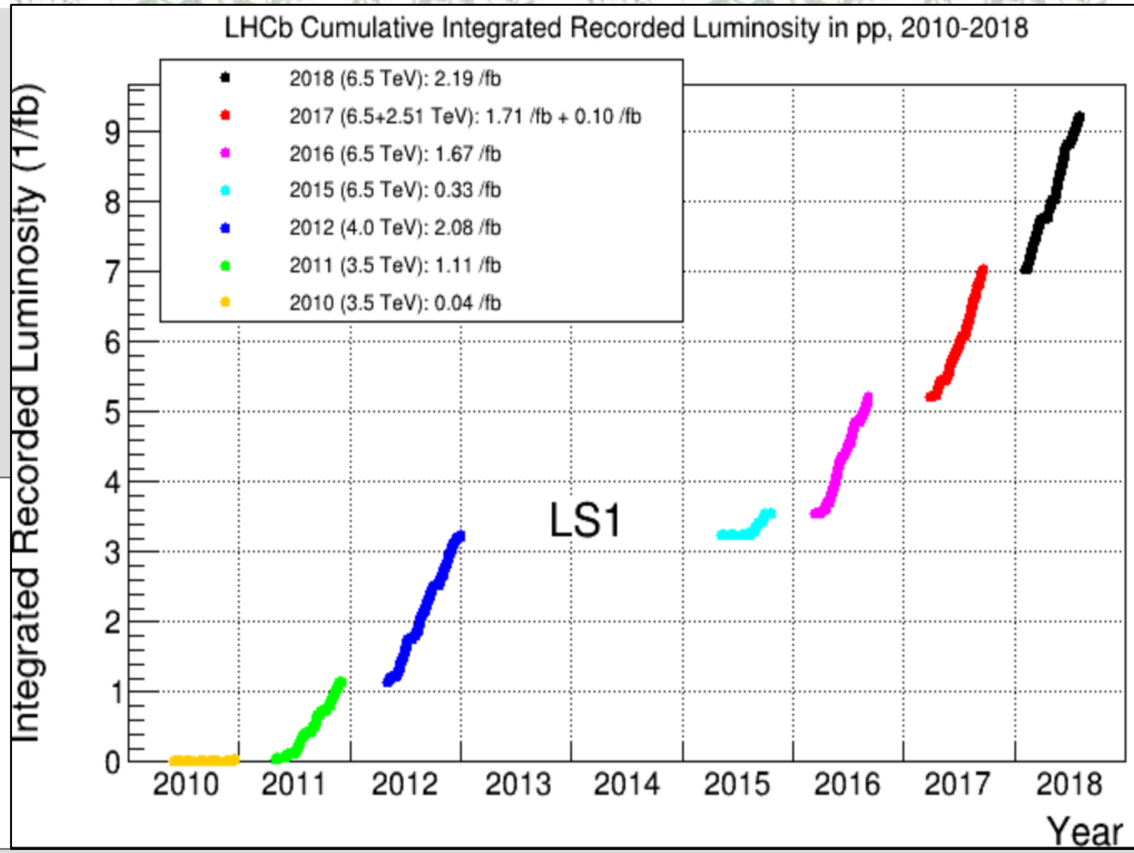
Run I+II

1fb^{-1}@7TeV

2fb^{-1}@8TeV

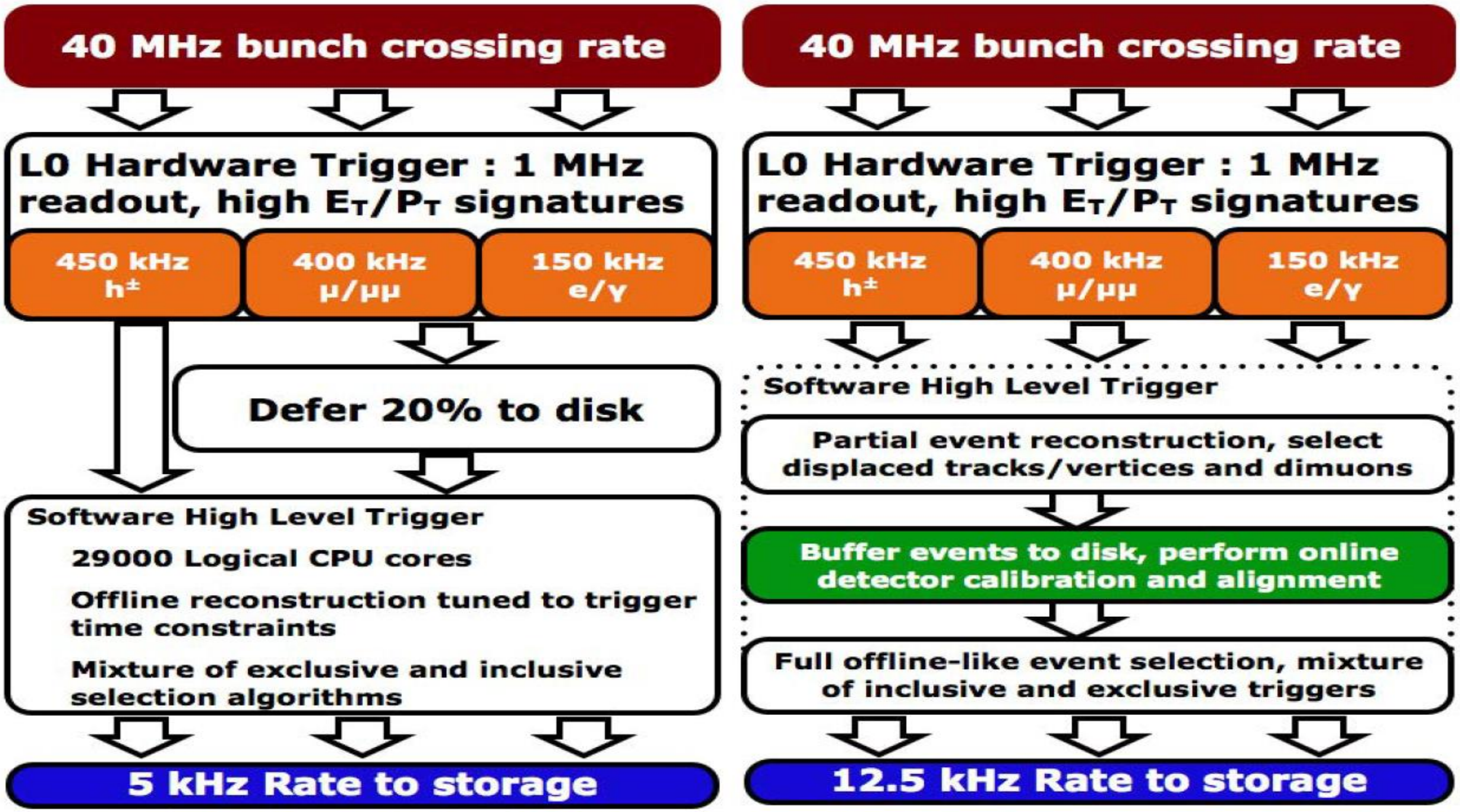
8fb^{-1} @13TeV





Thanks to LHC accelerator team for the excellent performance of machine

Trigger


40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Defer 20% to disk
Software High Level Trigger
29000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
5 kHz Rate to storage
40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
Partial event reconstruction, select displaced tracks/vertices and dimuons
Buffer events to disk, perform online detector calibration and alignment
Full offline-like event selection, mixture of inclusive and exclusive triggers
12.5 kHz Rate to storage

2019-2020

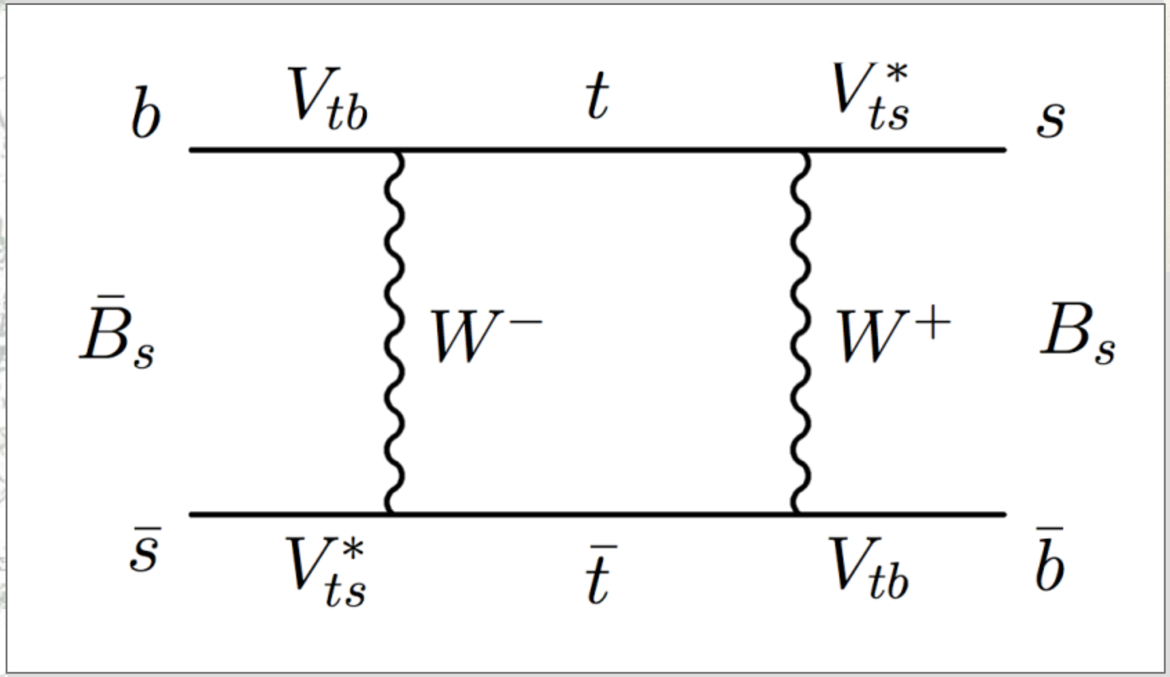
- Rare decays
  - $B_s \to \mu^+\mu^-$
  - Angular analysis $B \to K^*\mu^+\mu^-$
- CKM & CP violation
- CP violation in charm
- Spectroscopy
  - *O(30)* new states
  - Properties of X(3982)
  - Pentaquarks
  - Ξ_{cc}^{++}
  - tetraquarks

- $B_{(s)} \to e^+e^-$, $K_S \to \mu^+\mu^-$
- Lepton Universality
  - R_K, R_{K*} , …
  - $D_{(s)} \to h^+ l_1 l_2$
- $B \to K\pi\ \mu^+\mu^-$
- X(3872) mass and width
- New heavy baryon
- $J/\psi J/\psi$ structures

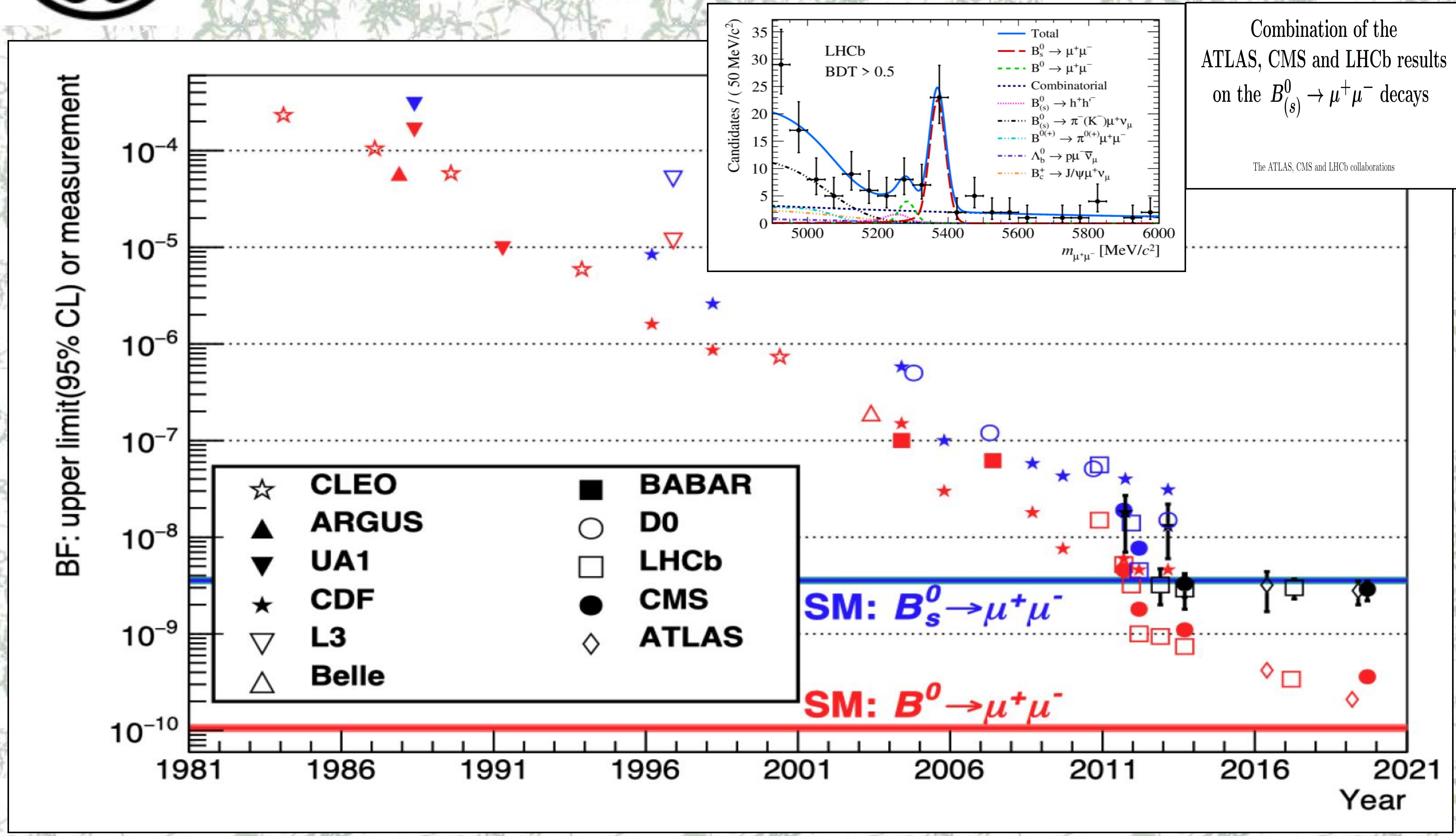
Rare decays: $B_{(s)} \to l^+l^-$

- FCNC, very rare, sensitive to NP contributions
- $Br(B \to l^+l^-) < Br(B_s \to l^+l^-)$ $|V_{td}| < |V_{ts}|$
- Helicity suppressed

	d	s	b
u	$1-\lambda^2/2$	λ	$A\lambda^3(\rho - i\eta)$
c	$-\lambda$	$1-\lambda^2/2$	$A\lambda^2$
t	$A\lambda^3(1-\rho-i\eta)$	$-A\lambda^2$	1



$B_s \to \mu^+\mu^-$ 40 years



Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \to \mu^+\mu^-$ decays

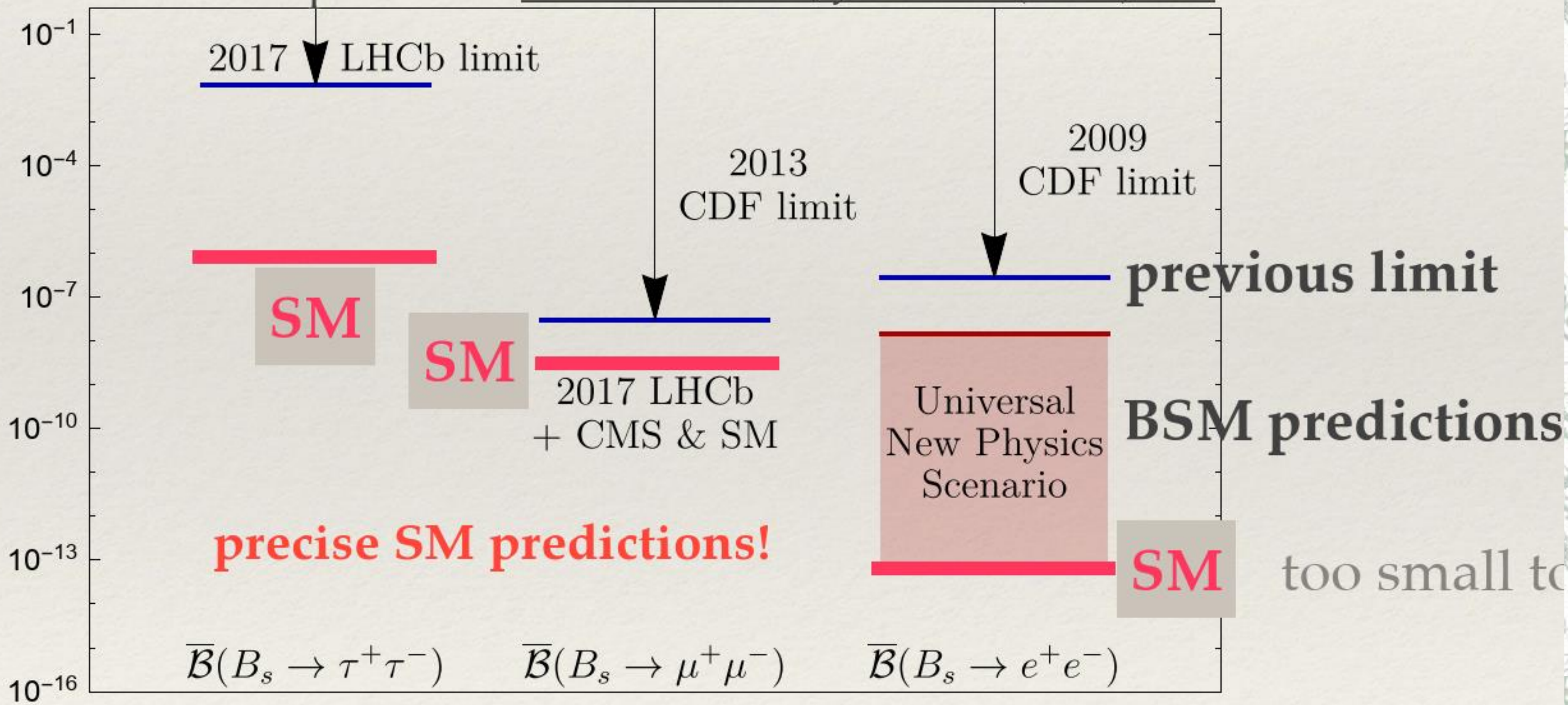
The ATLAS, CMS and LHCb collaborations

$B_s \to e^+e^-$

LHCb-PAPER-2020-001, PRL 124(2020) 211802

$$\mathcal{B}(B_s^0 \to e^+e^-) \sim \mathcal{B}(B_s^0 \to \mu^+\mu^-) \times (m_e/m_\mu)^2$$

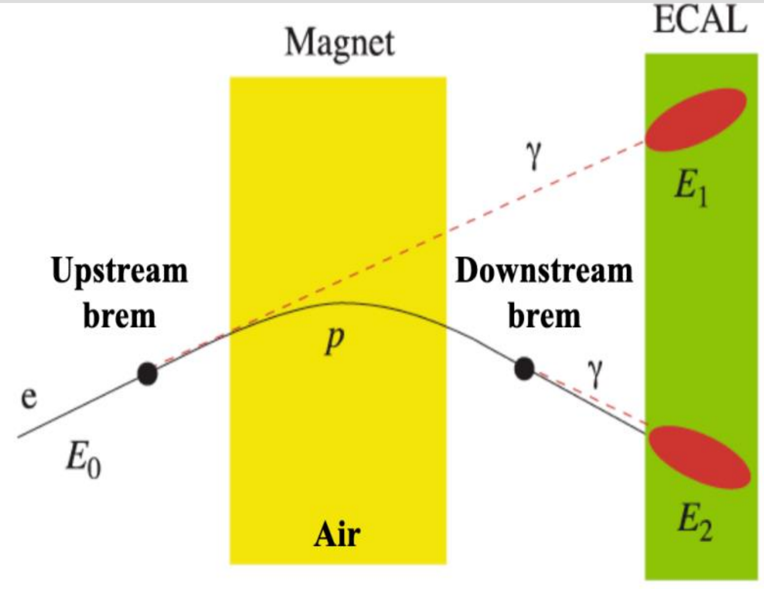
adapted from Fleischer et al., JHEP 05 (2017) 156

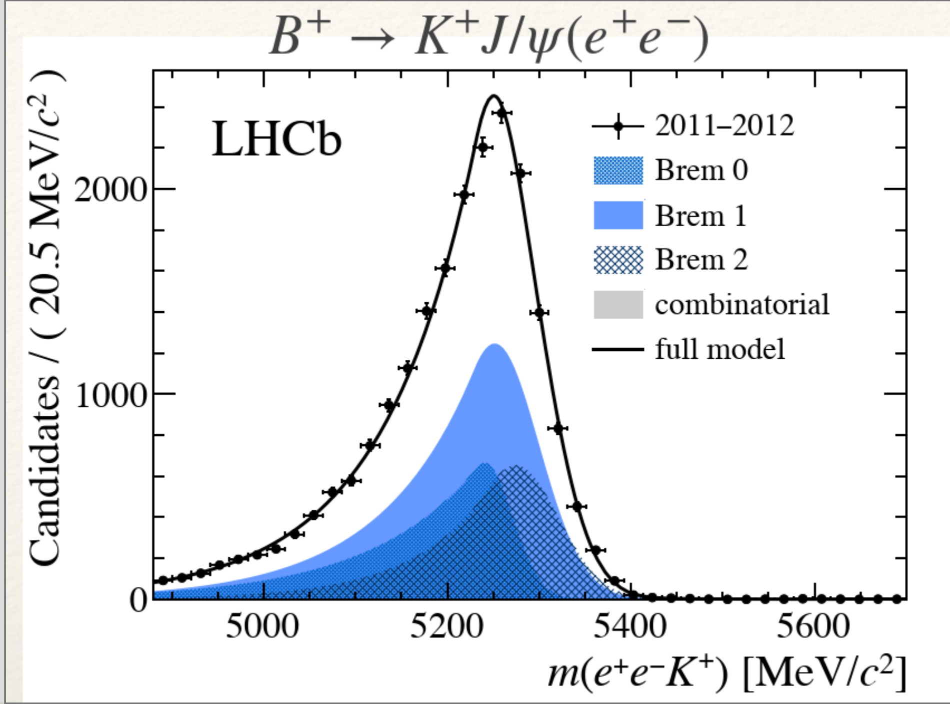


$B_s \to e^+e^-$ Bremsstrahlung

LHCb-PAPER-2020-001, PRL 124(2020) 211802

- Mass resolution is limited by bremsstrahlung
  - Number of emitted high-energy photons
  - Bremsstrahlung recovery is important but not perfect

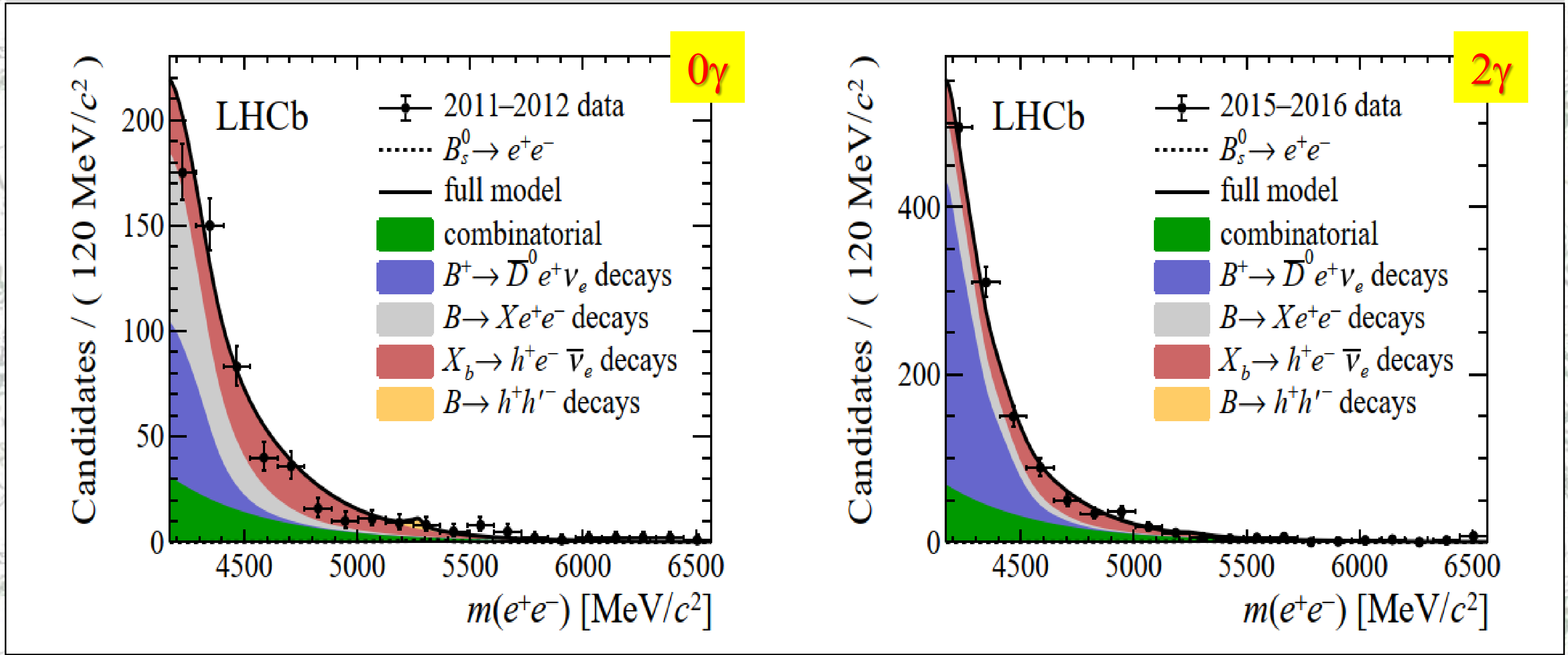




$B_s \to e^+e^-$

LHCb-PAPER-2020-001, PRL 124(2020) 211802

- Multivariate analysis, powerful particle ID
- Bremsstrahlung recovery is important



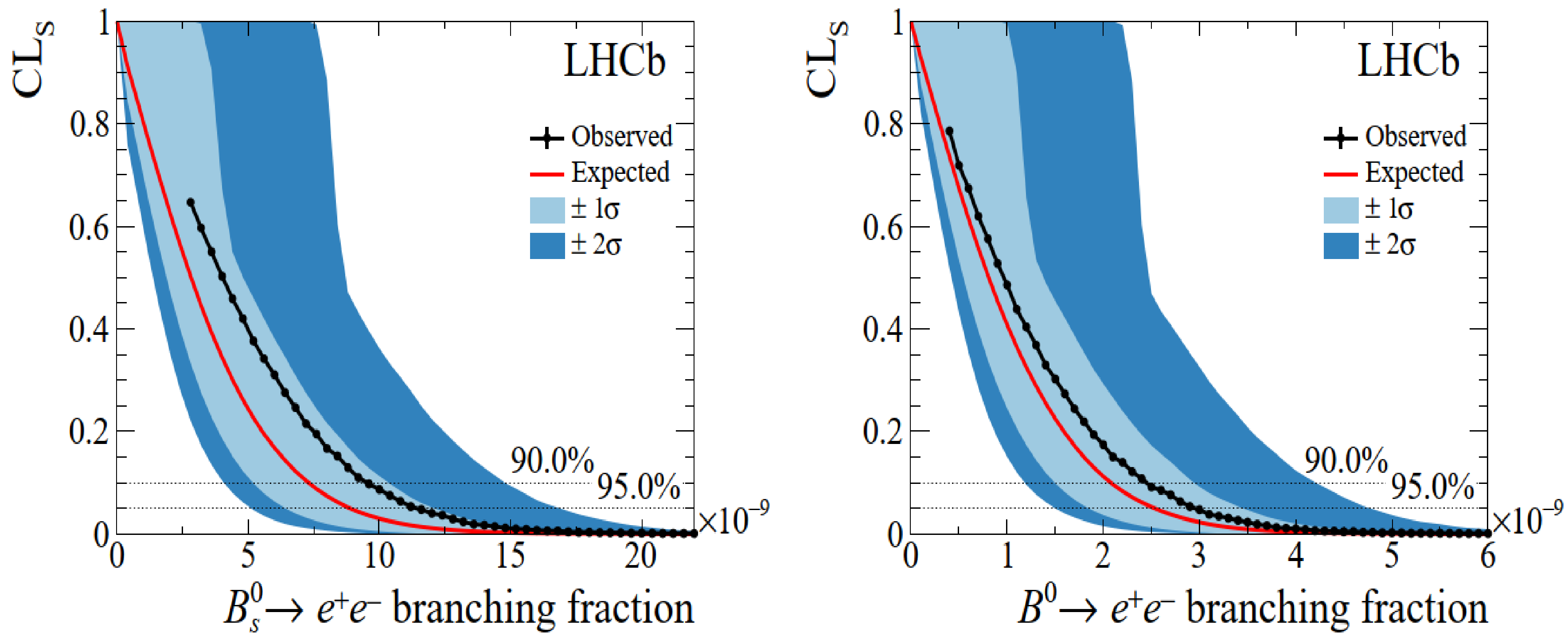
$B_s \to e^+e^-$

LHCb-PAPER-2020-001, PRL 124(2020) 211802

$$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4\,(11.2) \times 10^{-9}$$

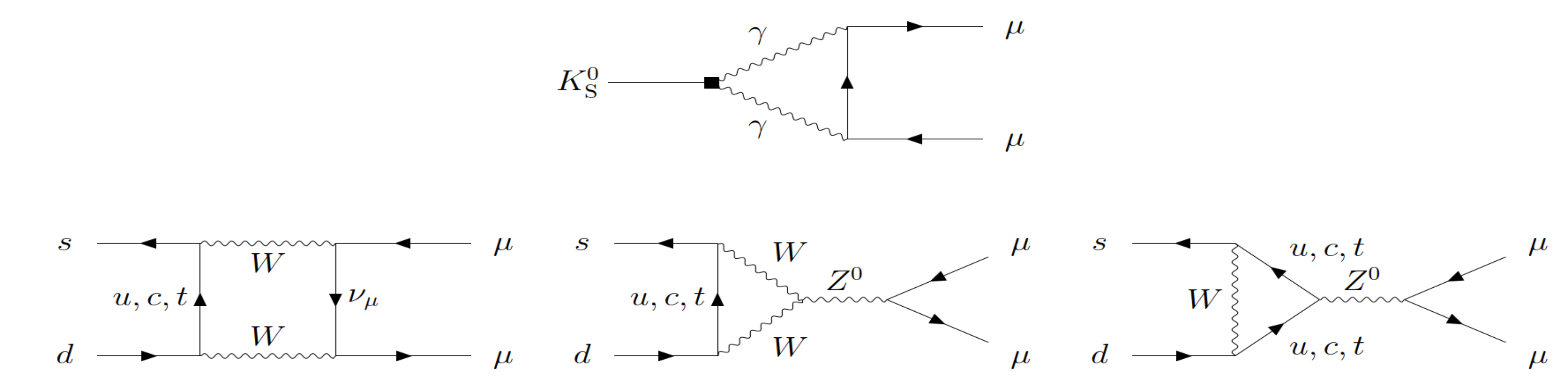
$$\mathcal{B}(B^0 \to e^+e^-) < 2.5\,(3.0) \times 10^{-9}$$

O(30) improvement

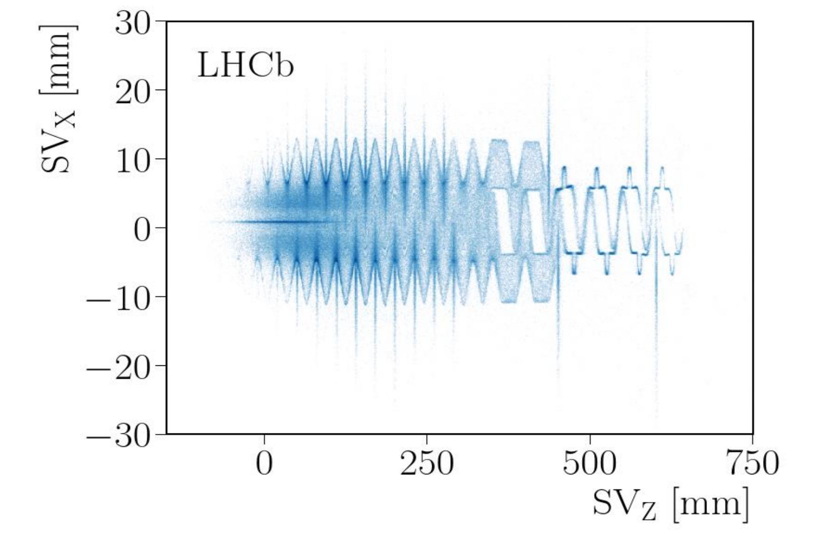


Search for $K_S \to \mu^+\mu^-$

LHCb-PAPER-2019-038, arXiv:2001.10354



- Soft kinematics:
  - dedicated trigger & reco
  - in place since 2016
  - Limited by hardware trigger
- Only decays of K_S within VELO
  - (22%)
  - Remove secondary interactions



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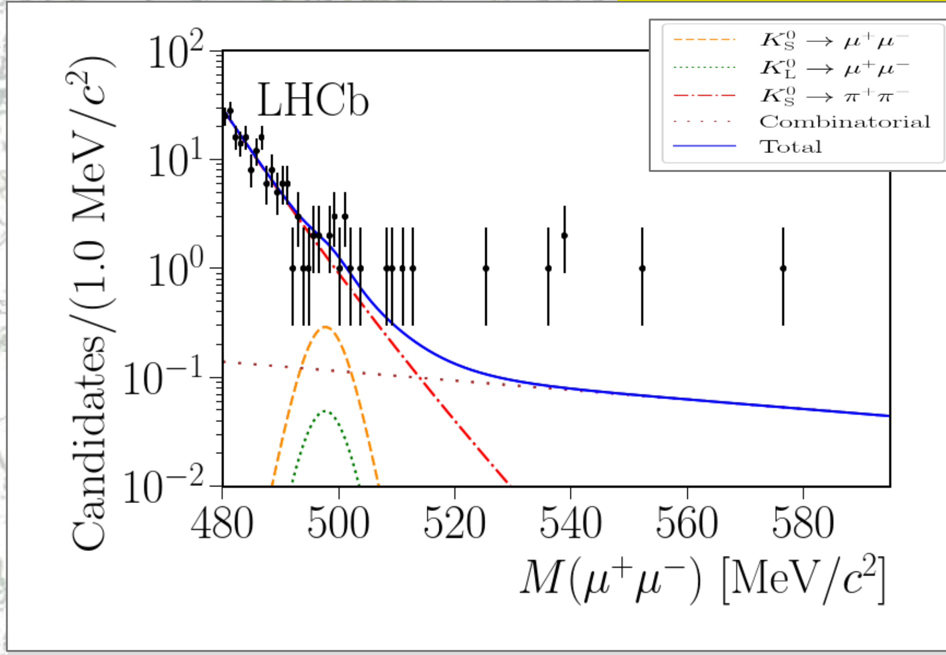
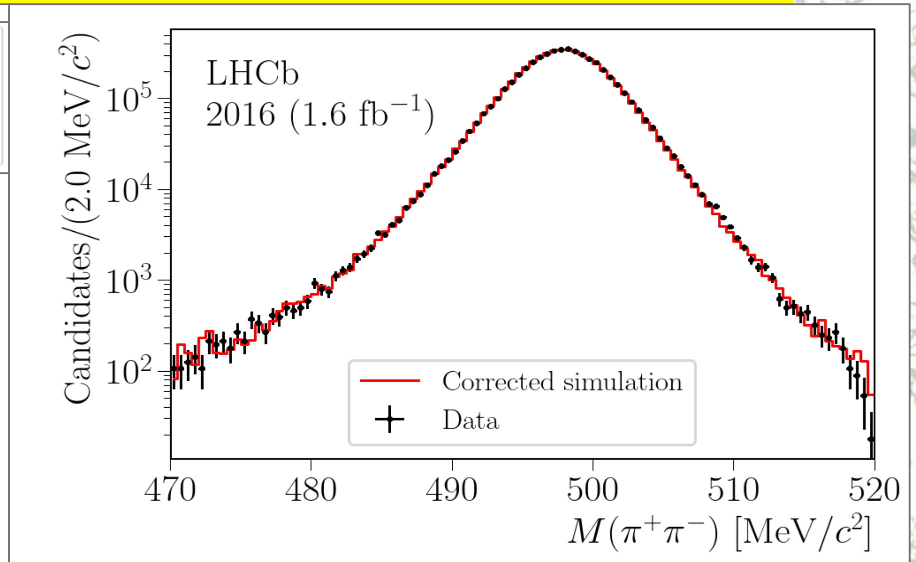
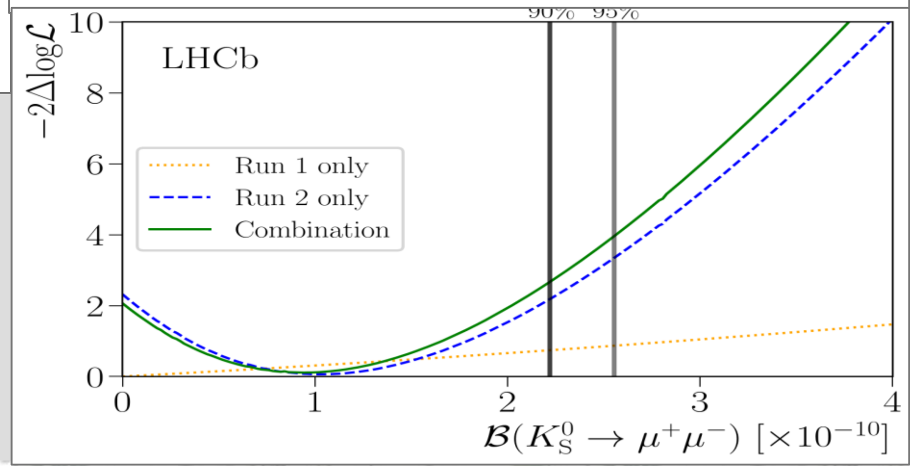




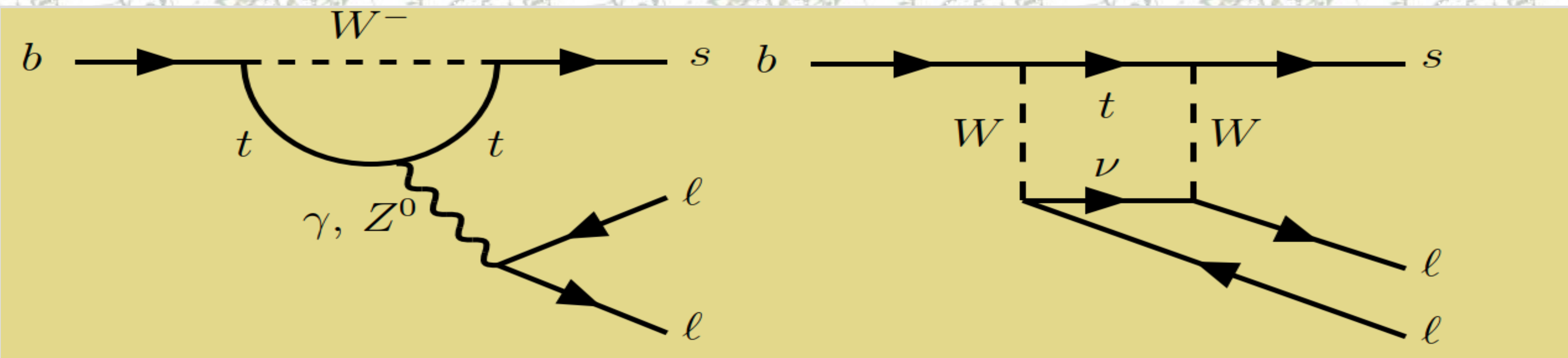


Upper limit $<2.2(2.6)\times10^{-10}$

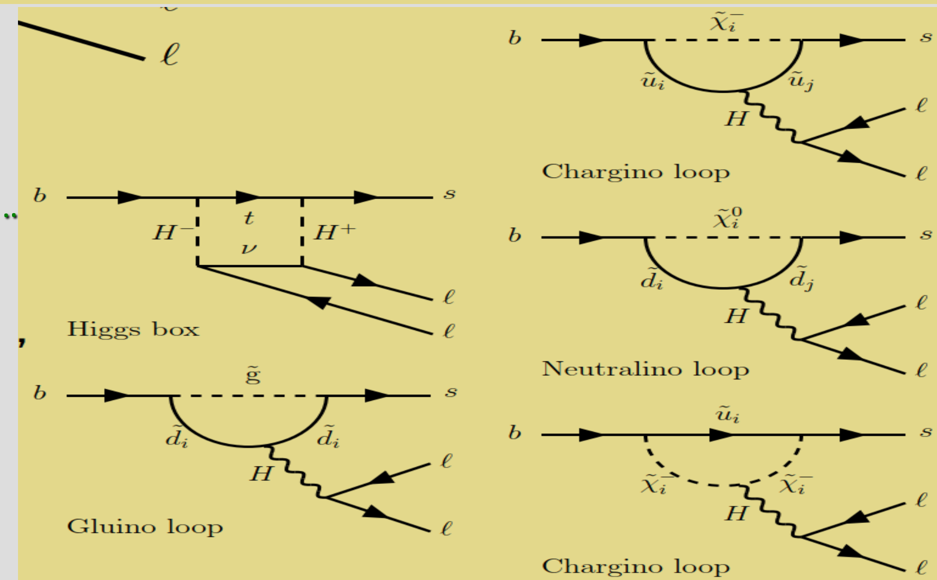
Combined with Run-I

$<2.1(2.4)\times10^{-10}$

$b\to sl^+l^-$



- "Rare" in SM
- Sensitive to NP :
  - Supersymmetry, 2HDM,
    4 generation, extra dimensions, leptoquarks, ..
- Many sensitive observables
  - For some of them the theory
    uncertainties claimed to be under the control



Lepton universality in $b\to sl^+l^-$

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{d\Gamma\left(B\to X\mu^+\mu^-\right)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{d\Gamma\left(B\to Xe^+e^-\right)}{\mathrm{d}q^2}} \stackrel{\mathrm{SM}}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

- "Accidental symmetry" of gauge Lagrangian
- May be violated at some level

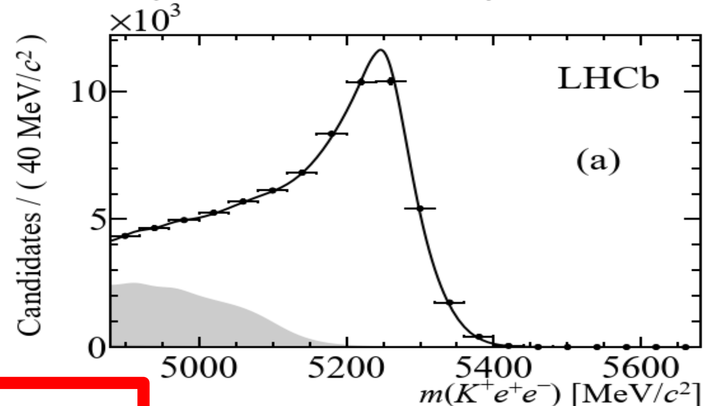
R_K strategy

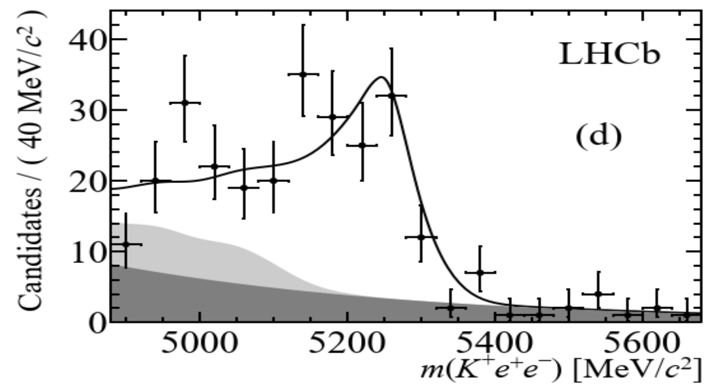
PRL 113 (2014) 151601, arXiv: 1406.6482

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to K\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} dq^2 \frac{d\Gamma(B\to Ke^+e^-)}{dq^2}} \overset{\text{measure}}{=} \frac{\frac{N(B^+\to K^+\mu^+\mu^-)}{\epsilon_{tot}(B^+\to K^+\mu^+\mu^-)}}{\frac{N(B^+\to K^+e^+e^-)}{\epsilon_{tot}(B^+\to K^+e^+e^-)}}$$

Double ratio
→ Reduce systematic

$$\overset{\text{measure}}{=} \frac{\frac{\epsilon_{tot}(B^+\to J/\psi(\mu^+\mu^-)K^+)}{\epsilon_{tot}(B^+\to K^+\mu^+\mu^-)} \times \frac{N(B^+\to K^+\mu^+\mu^-)}{N(B^+\to J/\psi(\mu^+\mu^-)K^+)}}{\frac{\epsilon_{tot}(B^+\to J/\psi(e^+e^-)K^+)}{\epsilon_{tot}(B^+\to K^+e^+e^-)} \times \frac{N(B^+\to K^+e^+e^-)}{N(B^+\to J/\psi(e^+e^-)K^+)}}$$





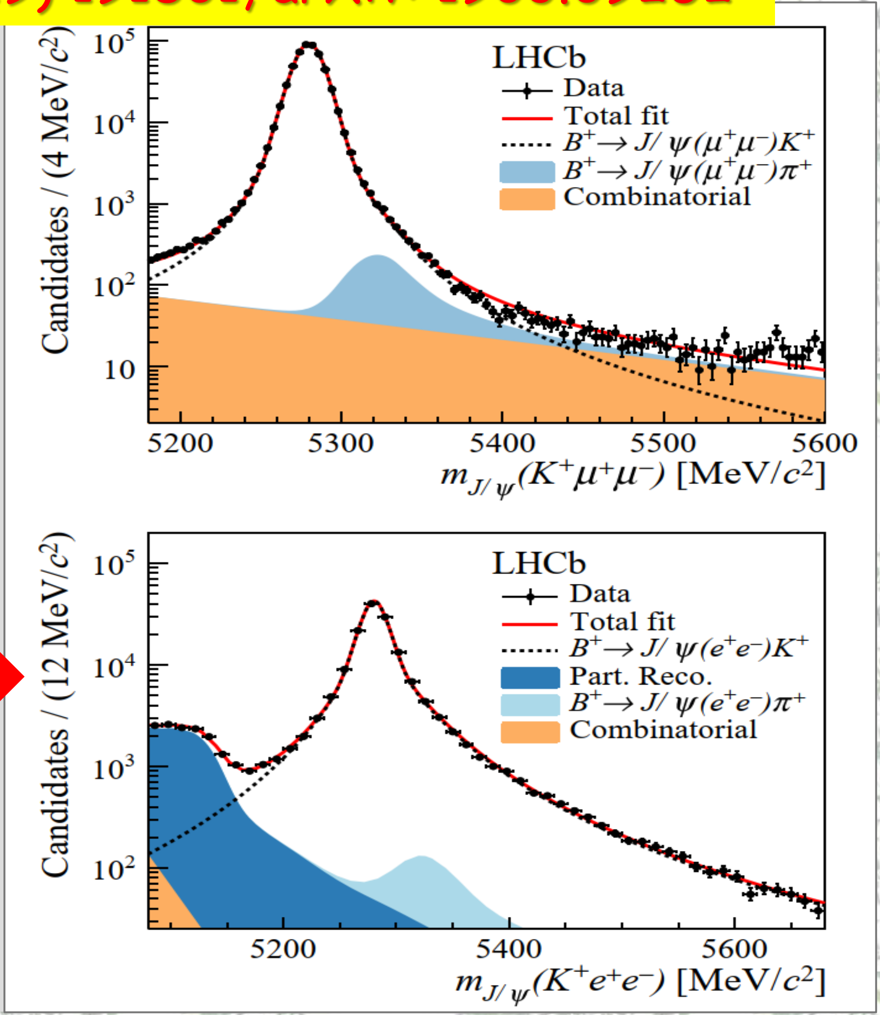
$0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst}).$

2.6σ

Lepton universality R_K

PRL 122 (2019) 191801, arXiv: 1903.09252

- $5 fb^{-1}$
  - 2011, 2012 and 2016
- Trigger categories:
  $e^{\pm}$, K, rest of event
- 1.2×10^6 $B^+ \to J/\psi(\mu^+\mu^-)K^+$
- 3.4×10^5 $B^+ \to J/\psi(e^+e^-)K+$
- The ratio for J/ψ modes
  - 1.014 ± 0.035
  - Stable in kinematics!
- Double ratio for ψ'
  - 0.986 ± 0.013 OK!



Lepton universality R_K

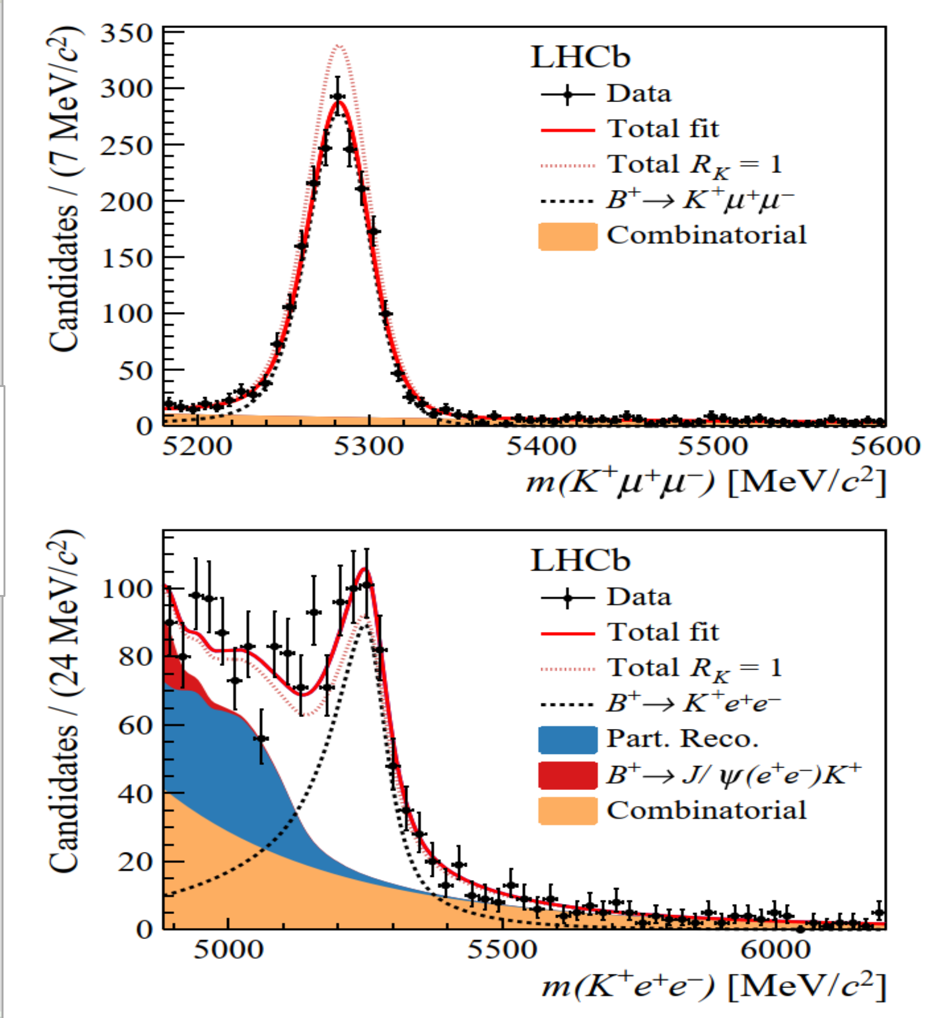
PRL 122 (2019) 191801, arXiv: 1903.09252

- $1 < q^2 < 6\ \mathrm{GeV}^2$
- 1940 ±50 $B^+ \to K^+\mu^+\mu^-$
- 770 ±50 $B^+ \to K^+e^+e^-$

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

$0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$.

- 2.5σ away from SM



Lepton universality in $B \to K^{*} l^{+} l^{-}$

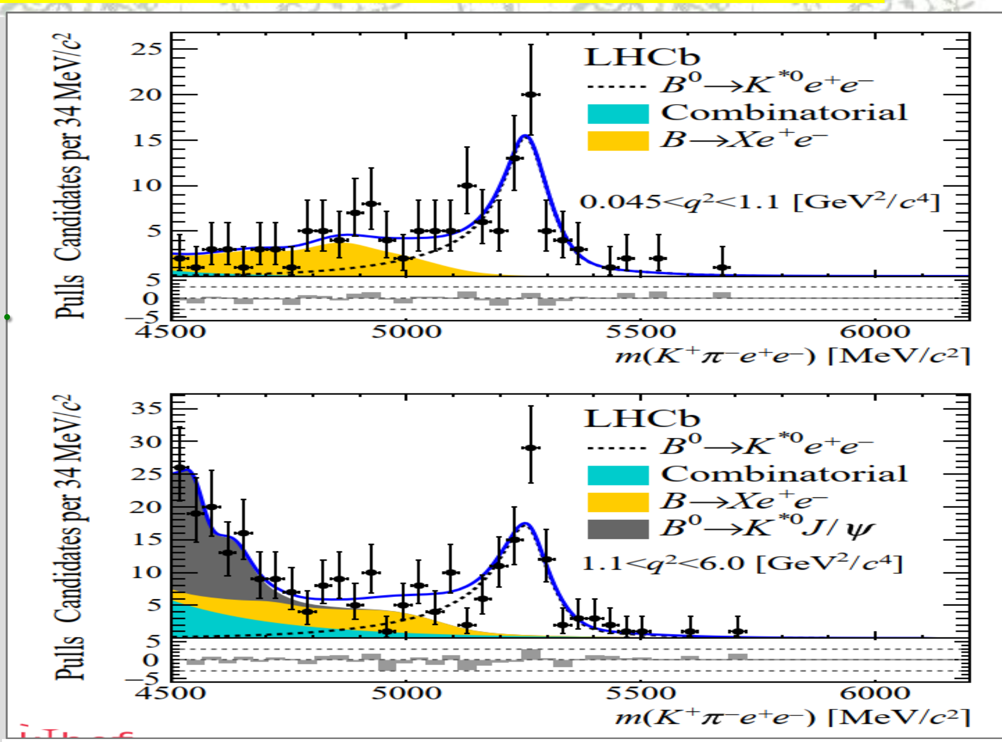
JHEP 08 (2017) 055, arXiv: 1705.05802

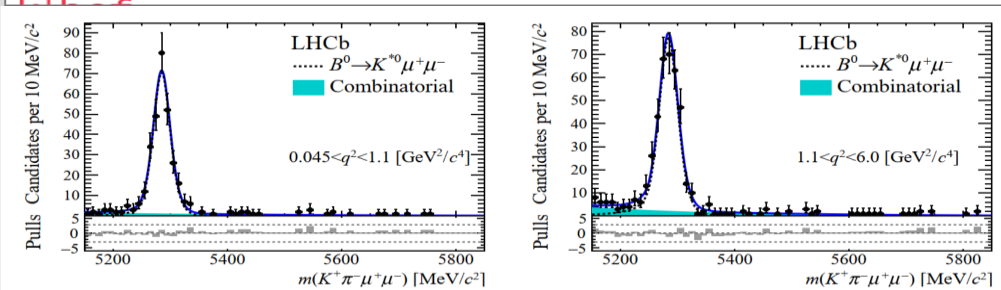
- Two bins
- $0.045 < q^2 < 1.1\ \mathrm{GeV}^2$ γ
- $1.1 < q^2 < 6\ \mathrm{GeV}^2$ $Z, \gamma, ..$

Double ratio
→ Reduce systematic

$$\left(\frac{\mathcal{N}_{K^{*0}\mu^+\mu^-}}{\mathcal{N}_{K^{*0}e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^{*0}}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^{*0}}}\right) = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03 & 0.045 < q^2 < 1.1 \\ 0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05 & 1.1 < q^2 < 6.0 \end{cases}$$

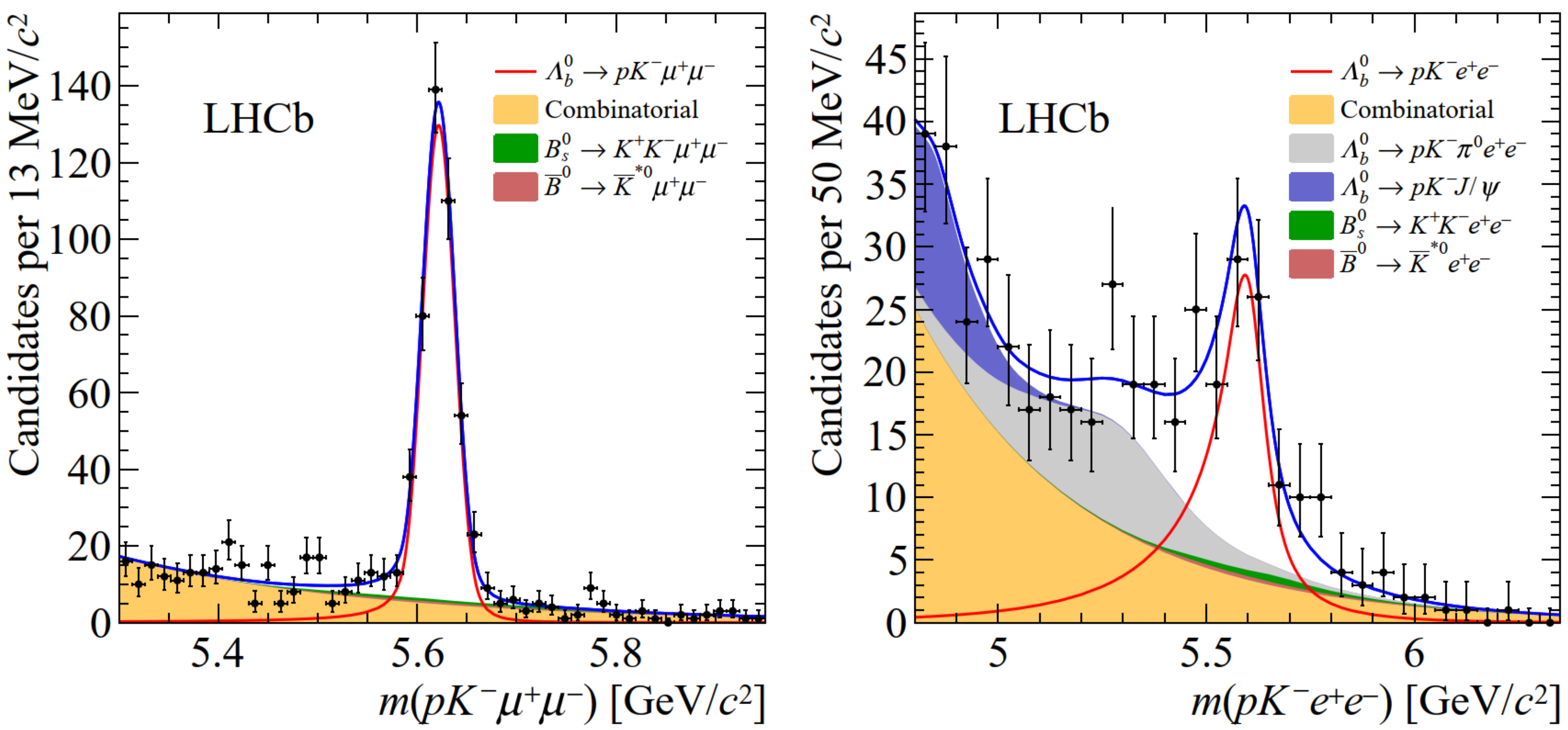
- 2-2.5σ away from SM





Lepton universality in $\Lambda_b \to pK^- l^+ l^-$

JHEP 05 (2020) 040, arXiv: 1912.08139



$$R_{pK} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)} = 0.86\,^{+0.14}_{-0.11} \pm 0.05$$

The same direction…

Lepton Flavor Violation in B Decays?

Sheldon L. Glashow, Diego Guadagnoli, and Kenneth Lane
Phys. Rev. Lett. **114**, 091801 – Published 3 March 2015

, any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. *No known symmetry principle can protect the one in the absence of the other.* Thus, LHCb's reported value of R_K implies, e.g., that $B \to K^{(*)}\mu^\pm e^\mp$ and $B \to K^{(*)}\mu^\pm \tau^\mp$ must occur at rates much larger than would occur in the SM due to tiny neutrino masses. We urge that these and other lepton flavor violations (LFV) be sought with renewed vigor in LHC Run II and elsewhere.

-> Lepton flavor violation

$B^+ \to K^+ \mu e$

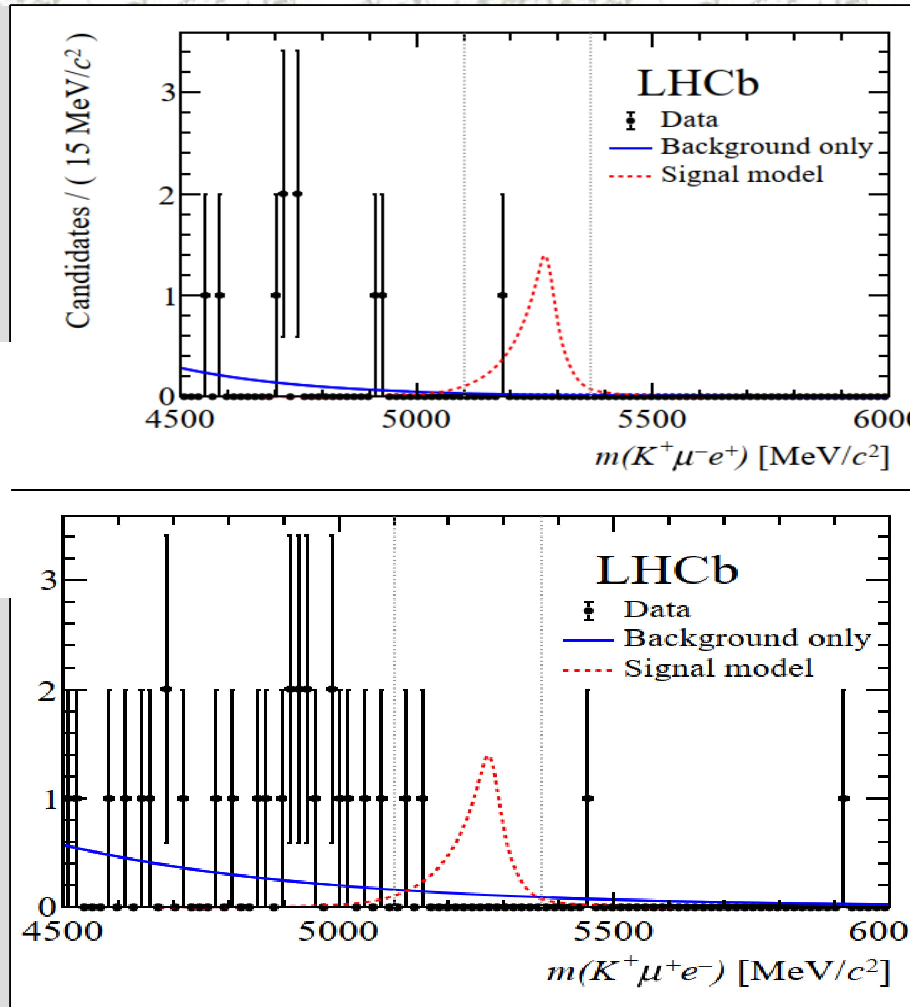
PRL 123 (2019) 231802, arXiv: 1909.01010

- Use Run-I data, $3 fb^{-1}$
- multivariate selection
- No signals are found

$$\mathcal{B}(B^+ \to K^+ \mu^+ e^-) < 7.0 \times 10^{-9}$$

$$\mathcal{B}(B^+ \to K^+ \mu^- e^+) < 6.4 \times 10^{-9}$$

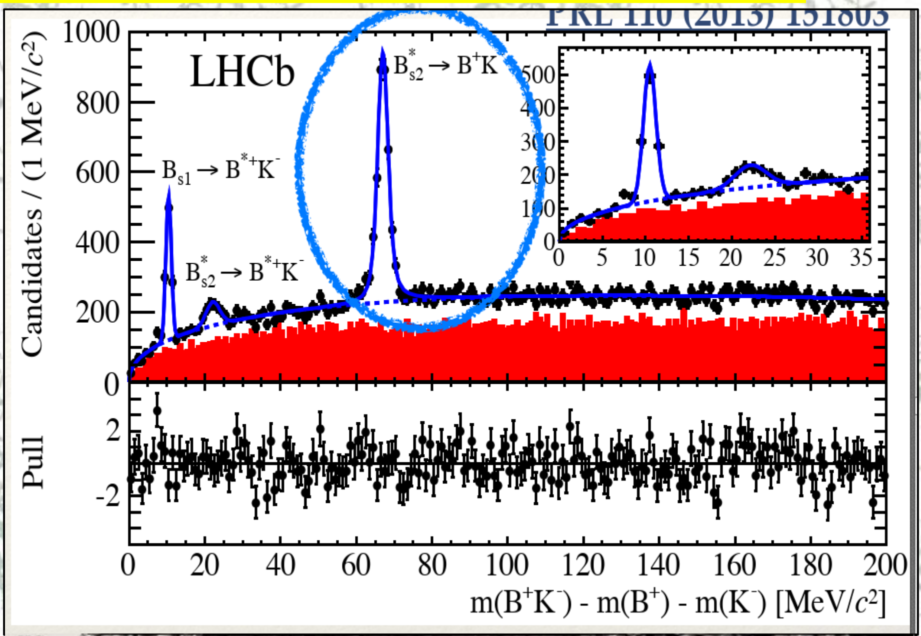
- Also no signals for
  - $B \to e\mu$
  - $B \to \tau\mu$
  - $D \to e\mu$

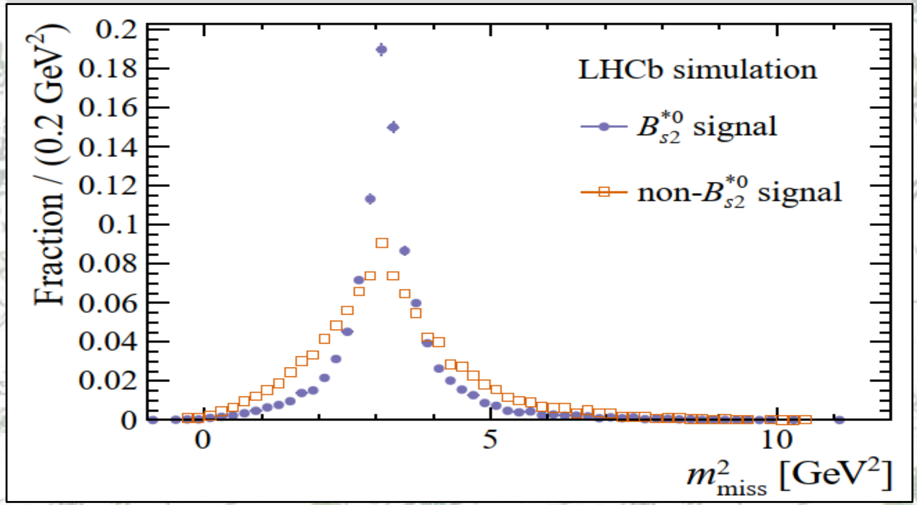


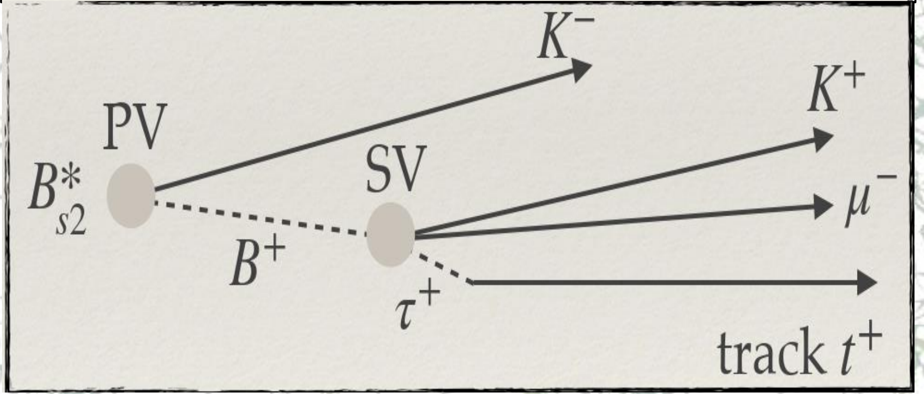
$B^+ \to K^+ \mu^- \tau^+$

JHEP 06 (2020) 129 , arXiv: 2003.04352

- Recontruction is difficult
  - two missing neutrinos
- Idea: use B_{s2}^* to tag B^+ mesons with K^-
  - Use momentum of K^-
  - Constraint B_{s2}^* and B^+ masses
  - known vertices
- Can reconstruct missing mass!



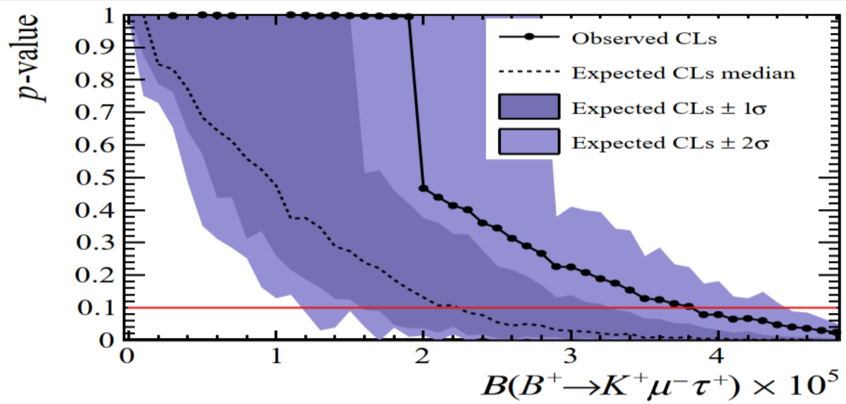




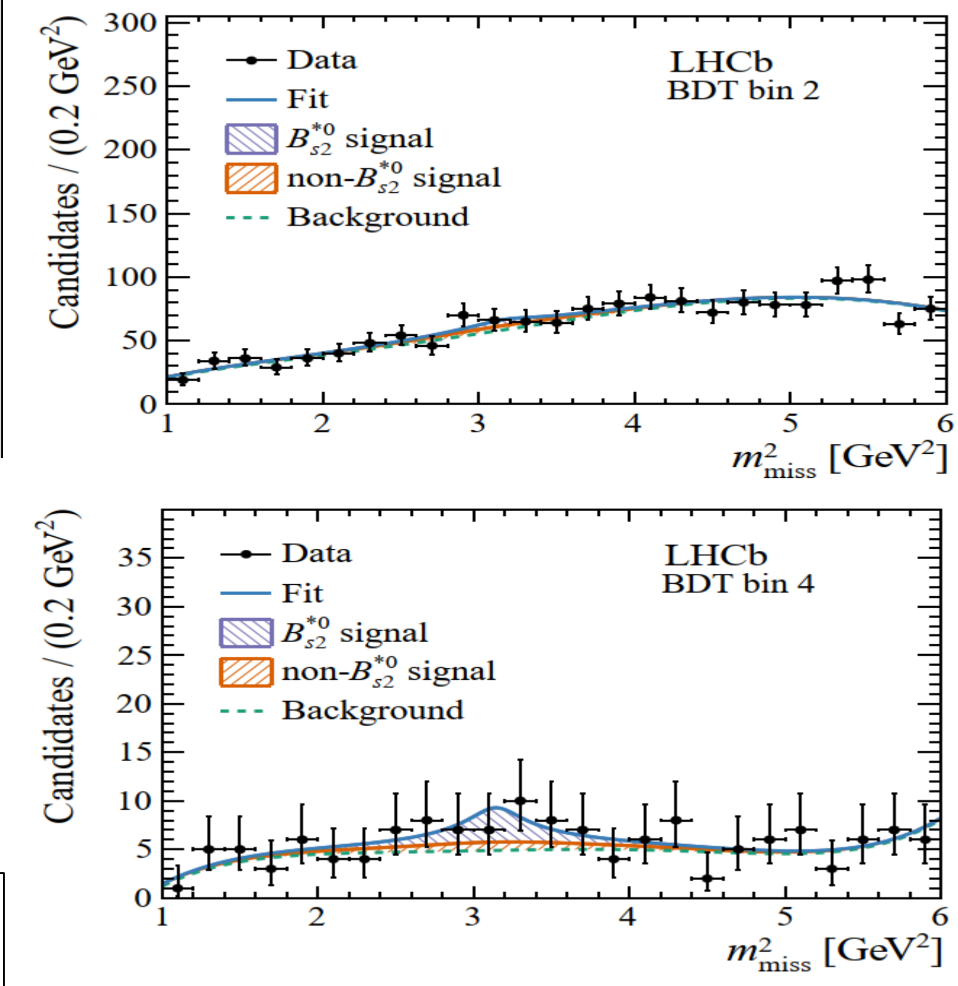
$B^+ \to K^+ \mu^- \tau^+$

JHEP 06 (2020) 129 , arXiv: 2003.04352

- MVA, 4 bins
- Suppress background
- Normalization:
  - use $B^+ \to K^+ J/\psi(\mu\mu)$
- No signal is found



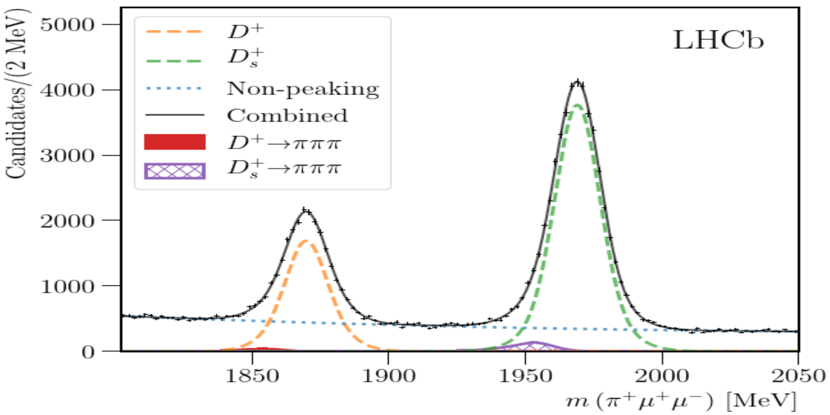
$$\mathcal{B}(B^+ \to K^+ \mu^- \tau^+) < 3.9 \times 10^{-5} \text{ at } 90\% \text{ CL,}$$
$$< 4.5 \times 10^{-5} \text{ at } 95\% \text{ CL.}$$

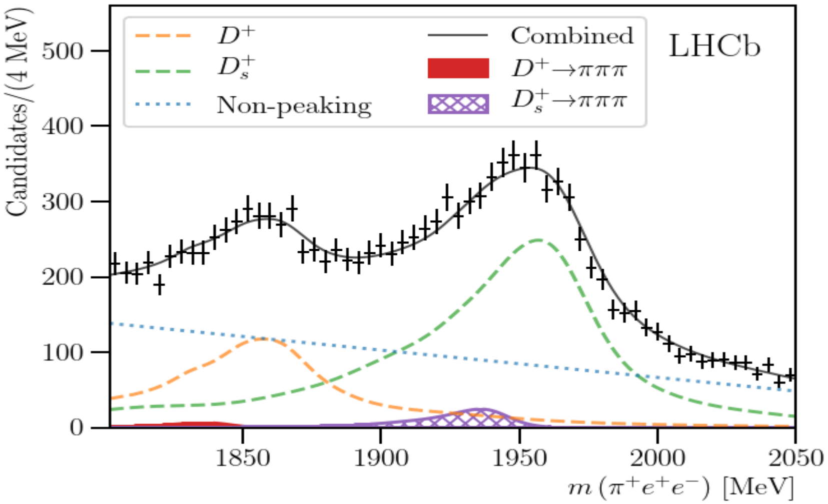


$D_{(s)}^{+} \to h l_1 l_2$ modes

LHCb-PAPER-2020-007

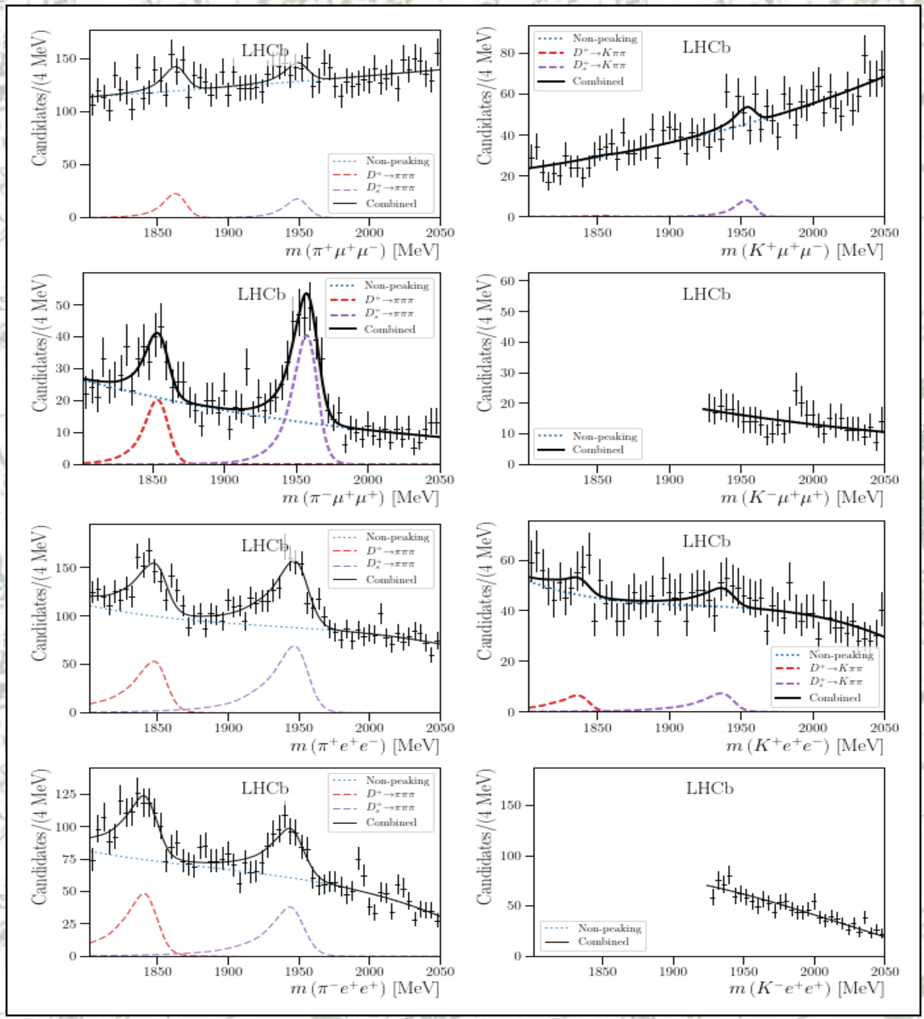
- 2016 data, $1.7 fb^{-1}$
- 25 modes:
  - 4 $c \to u l^+ l^-$
  - 2 WA
  - 8 LFV
  - 9 LNV
- Exclude $\eta, \rho, \omega, \phi \to l^+ l^-$
- Normalization:
  - $D_{(s)}^{+} \to \pi\phi(l^+ l^-)$

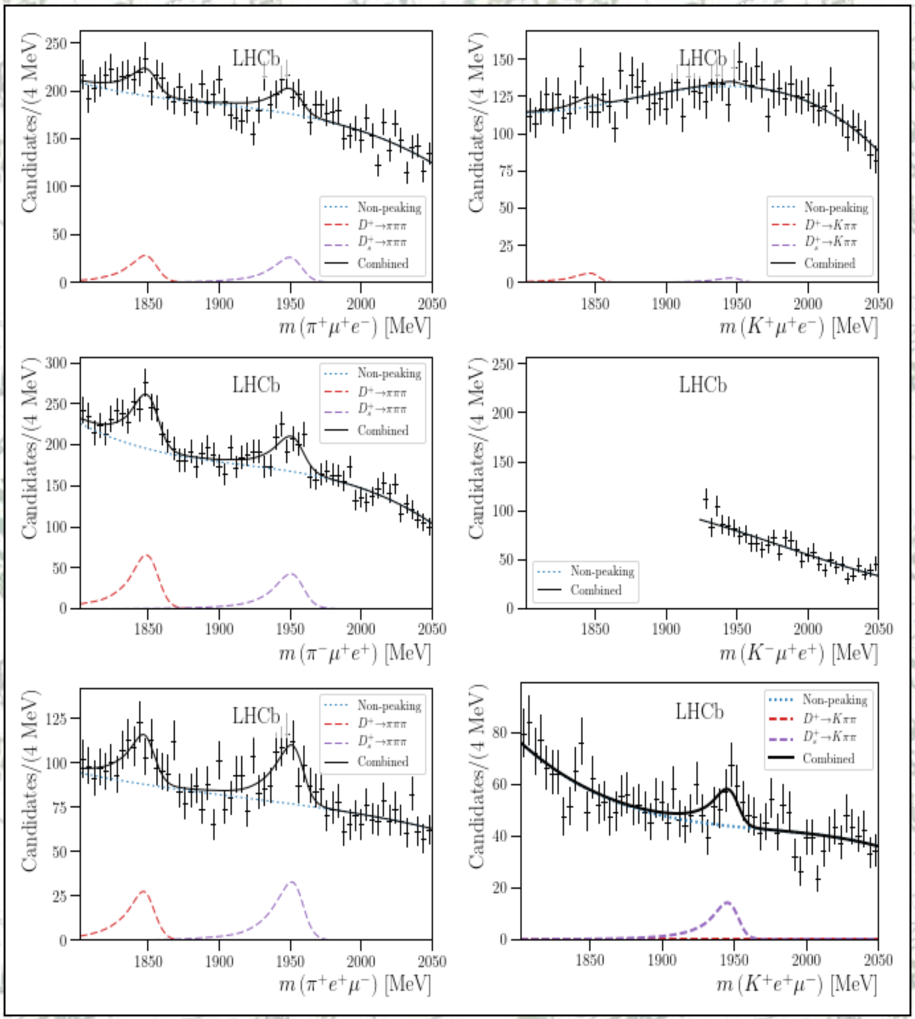




$D_{(s)}^{+} \to h l_1 l_2$ modes : no signals

LHCb-PAPER-2020-007, to appear soon



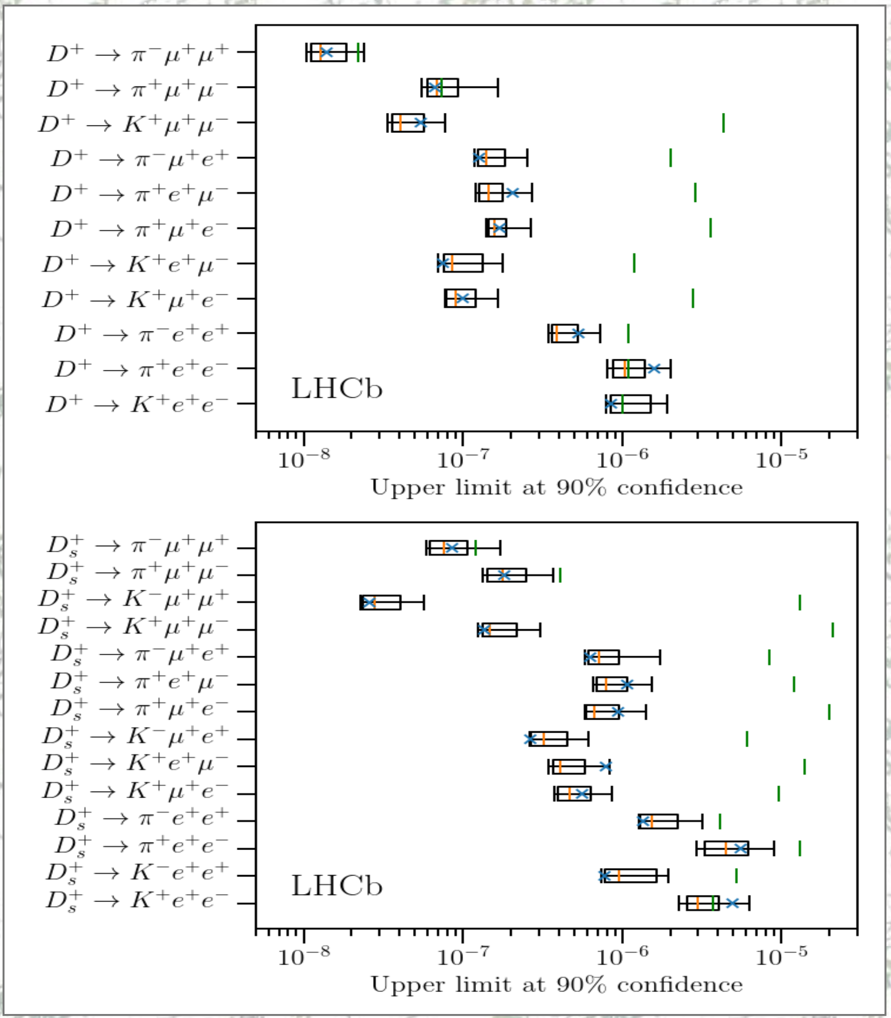


$D_{(s)}^{+} \to h l_1 l_2$ modes: 25 best limits

LHCb-PAPER-2020-007

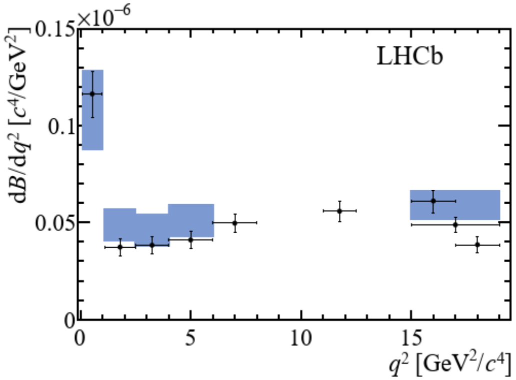
- 25 best upper limits

Decay	Branching fraction upper limit $[10^{-9}]$ D^+ 90% CL	D^+ 95% CL	D_s^+ 90% CL	D_s^+ 95% CL	Improvement factor D^+	Improvement factor D_s^+
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$	67	74	180	210	1.1	2.3
$D_{(s)}^+ \to \pi^-\mu^+\mu^+$	14	16	86	96	1.6	1.4
$D_{(s)}^+ \to K^+\mu^+\mu^-$	54	61	140	160	79.0	150.0
$D_{(s)}^+ \to K^-\mu^+\mu^+$	-	-	26	30	-	500.0
$D_{(s)}^+ \to \pi^+e^+\mu^-$	210	230	1100	1200	14.0	11.0
$D_{(s)}^+ \to \pi^+\mu^+e^-$	220	220	940	1100	16.0	21.0
$D_{(s)}^+ \to \pi^-\mu^+e^+$	130	150	630	710	16.0	13.0
$D_{(s)}^+ \to K^+e^+\mu^-$	75	83	790	880	16.0	18.0
$D_{(s)}^+ \to K^+\mu^+e^-$	100	110	560	640	28.0	17.0
$D_{(s)}^+ \to K^-\mu^+e^+$	-	-	260	320	-	23.0
$D_{(s)}^+ \to \pi^+e^+e^-$	1600	1800	5500	6400	0.7	2.3
$D_{(s)}^+ \to \pi^-e^+e^+$	530	600	1400	1600	2.1	3.0
$D_{(s)}^+ \to K^+e^+e^-$	850	1000	4900	5500	1.2	0.8
$D_{(s)}^+ \to K^-e^+e^+$	-	-	770	840	-	6.7



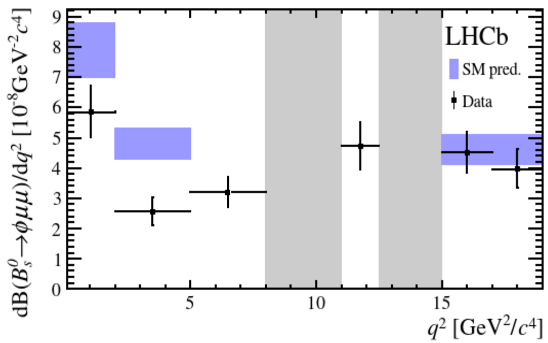
Other anomalies?

$\mathrm{Br}(b \to s\mu^+\mu^-)$: too small?



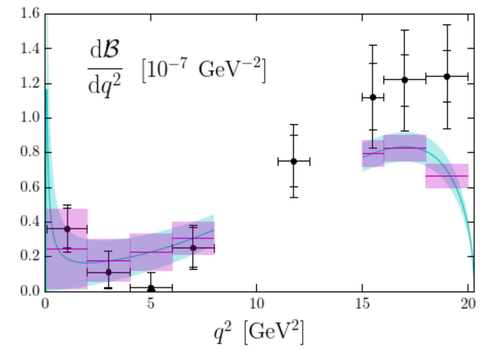
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 11 (2016) 047



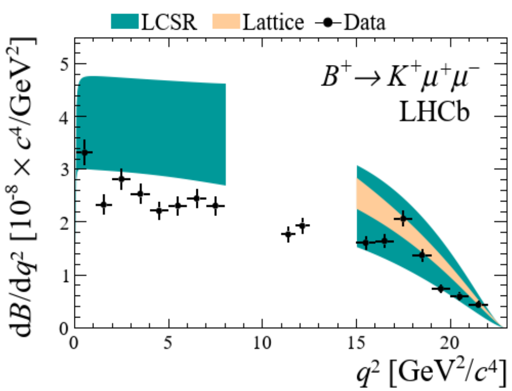
$B_s^0 \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179



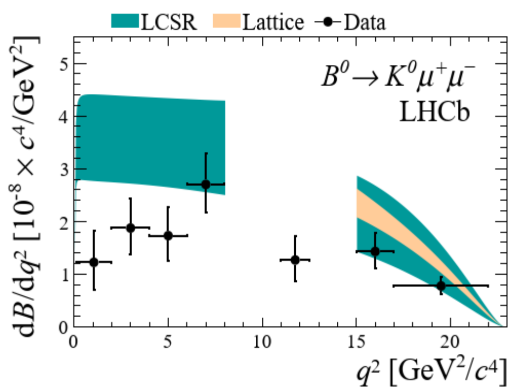
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

JHEP 06 (2015) 115



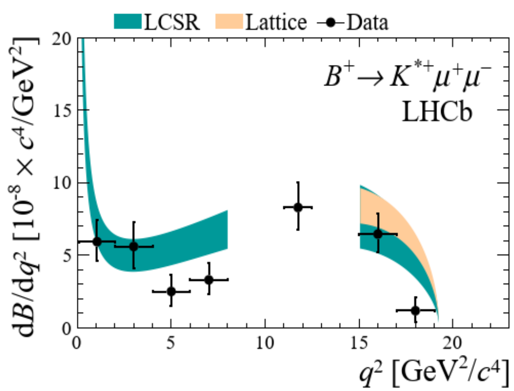
$B^+ \to K^+\mu^+\mu^-$

JHEP 06 (2014) 133



$B^0 \to K^0\mu^+\mu^-$

JHEP 06 (2014) 133



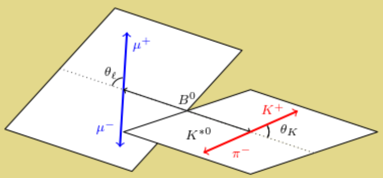
$B^+ \to K^{*+}\mu^+\mu^-$

JHEP 06 (2014) 133

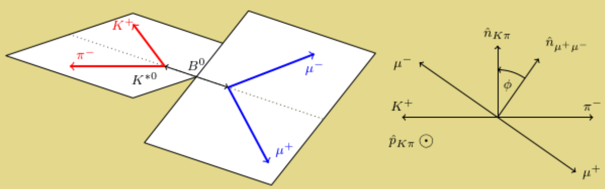
Angular analysis $B^0 \to K\pi\mu^+\mu^-$

A lot of information in the full θ_ℓ, θ_K and ϕ distributions

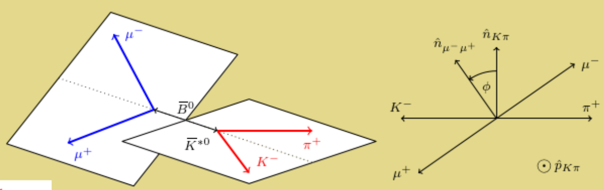
$$
\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[& \frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K \\
& + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell \\
& + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
& + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
& + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
& + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi \\
& + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \;\Big]
\end{aligned}
$$



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



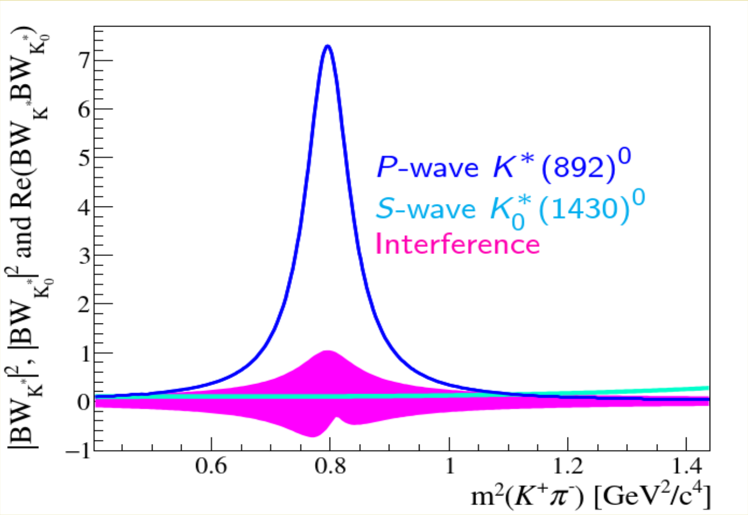
(c) ϕ definition for the $\overline{B}^0$ decay

➜ Many observables depending on $q^2 = m^2_{\ell\ell}c^4$

Kπ: not only K*

- **Account S-wave Kπ**

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = P\text{-wave term}(F_\mathrm{L}, S_{3-9})$$
$$+\frac{2}{3}F_\mathrm{S}\sin^2\theta_\ell$$
$$+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_\ell)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_\ell+S_{15}\sin\theta_\ell)\sin\theta_K\cos\phi$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_\ell+S_{17}\sin 2\theta_\ell)\sin\theta_K\sin\phi$$

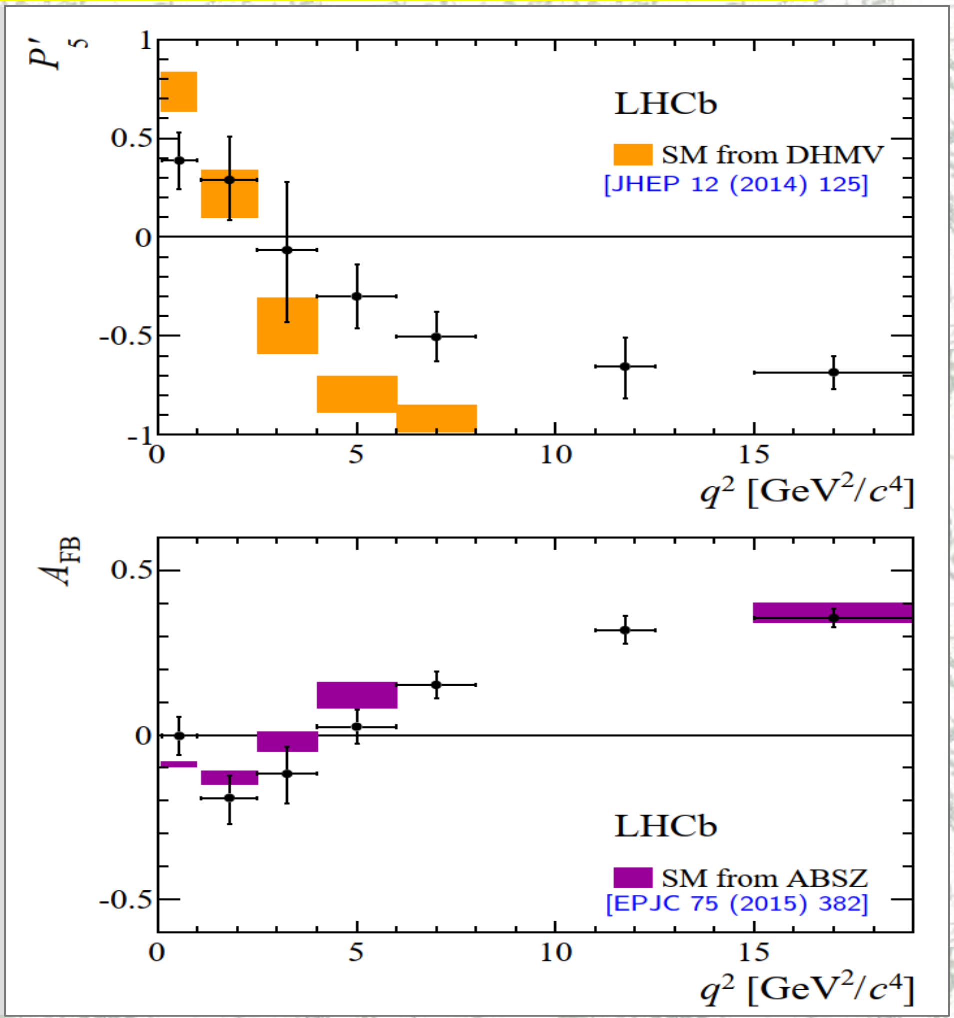


- **15 parameters in total**

$B \to K\pi \mu^+\mu^-$ Run-I

JHEP 02 (2016) 104, arXiv: 1512.04442

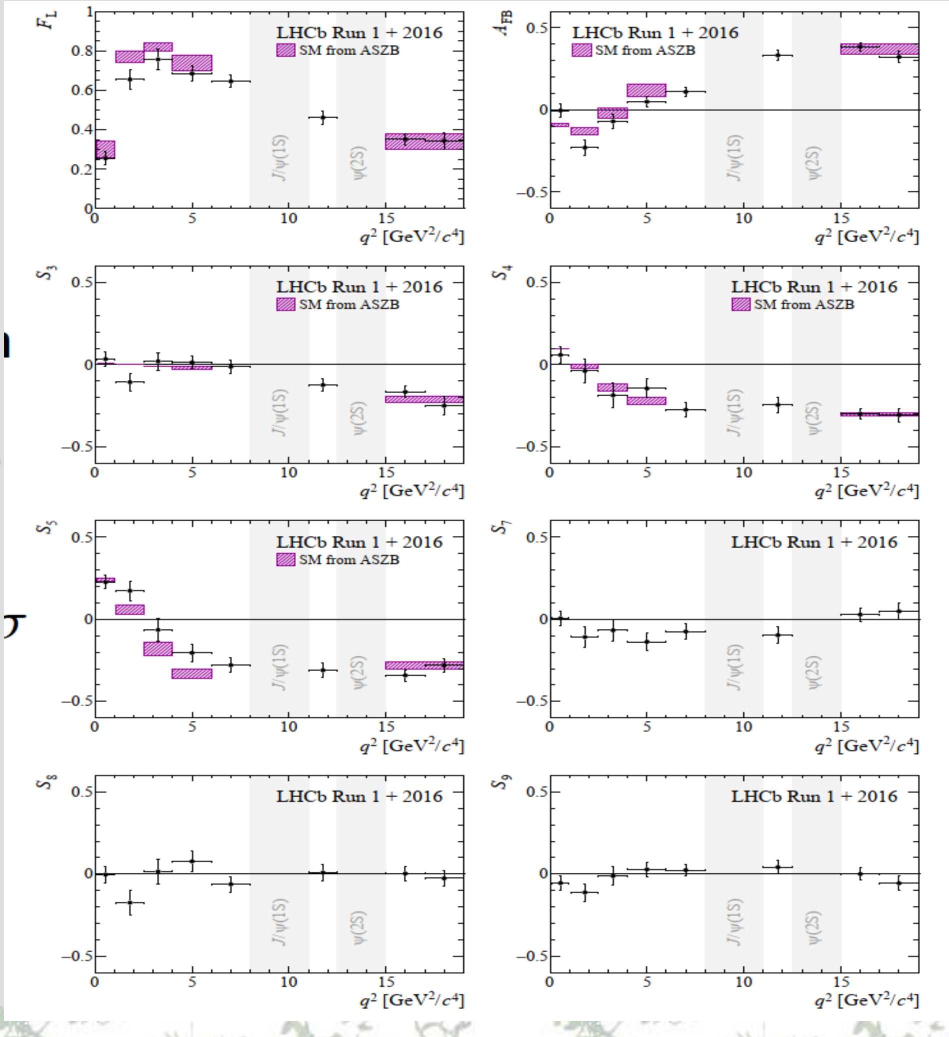
- Observables, but S_5 agree with SM
- $P'_5 = S_5/\sqrt{F_L(1-F_L)}$
  - local discrepancy
  - two bins
- A_{FB} is consistent



B→ Kπ μ⁺μ⁻ Run-I + 2016

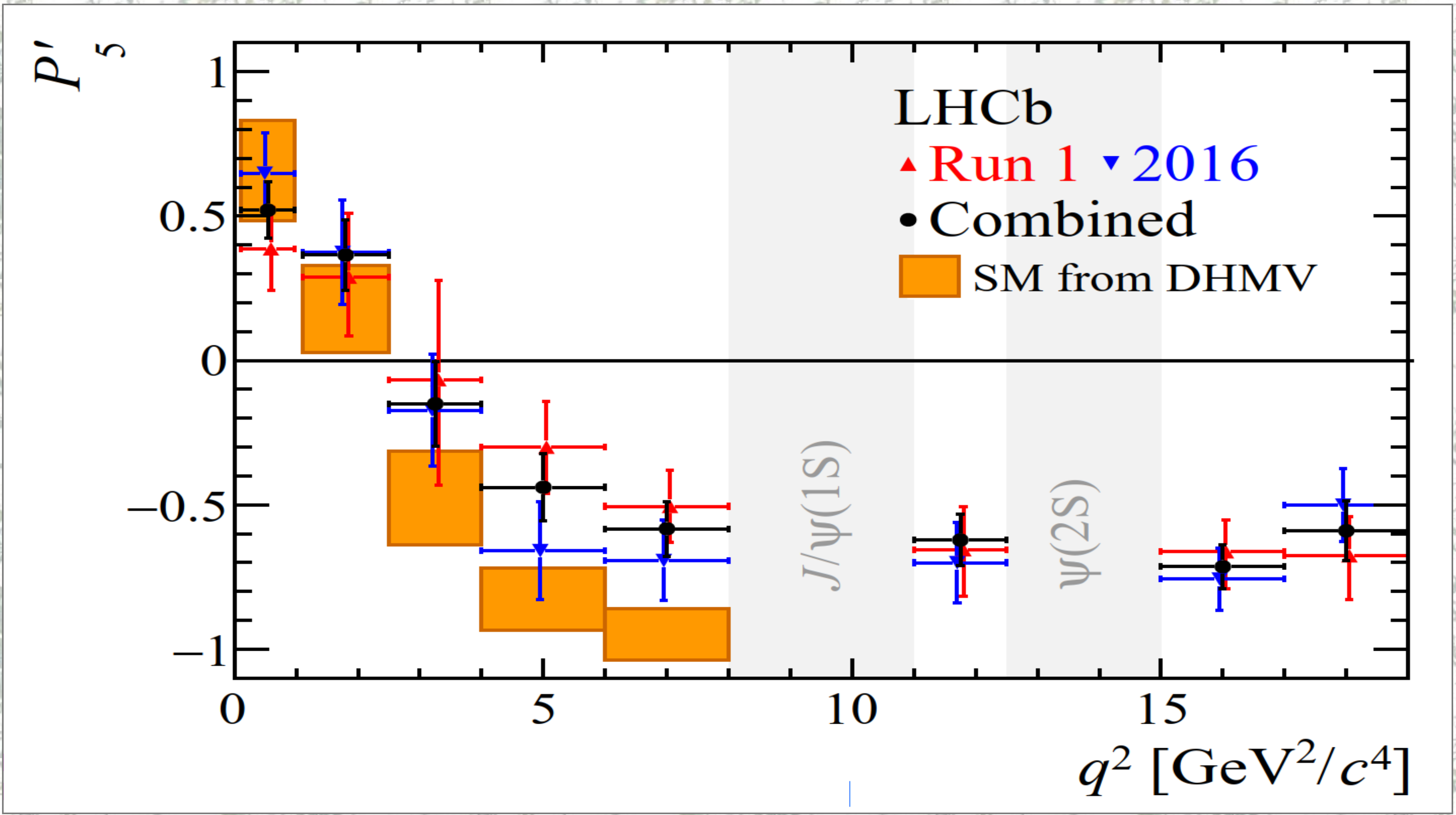
PRL 125 (2020) 011802 , arXiv: 2003.04831

- Almost double dataset
  2187± 53 $B \to K\pi\mu^+\mu^-$
  The same selection
- No large local tensions
- Overall (dis)agreement
  - 3σ

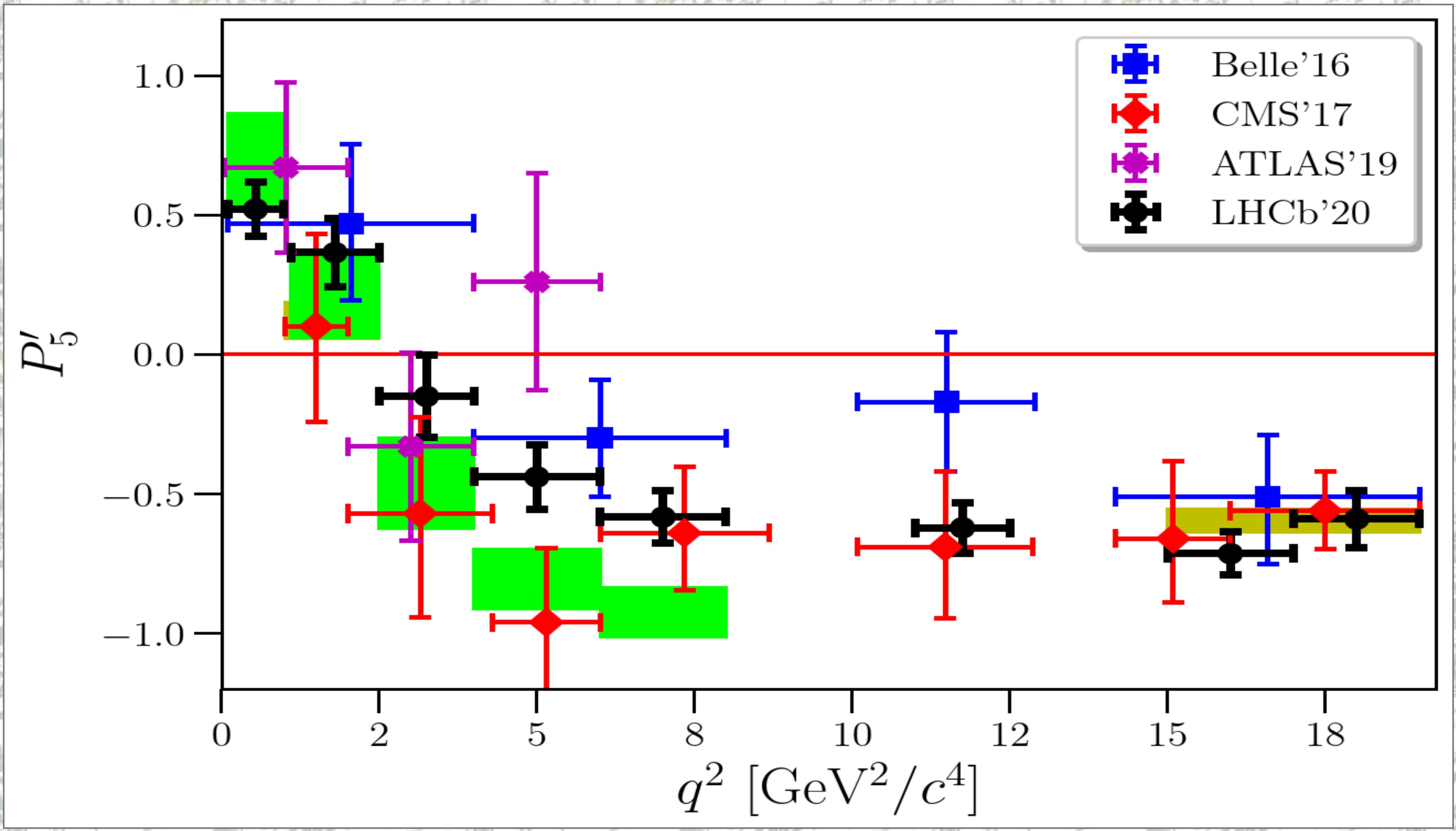


P_5' LHCb

PRL 125 (2020) 011802 , arXiv: 2003.04831



P_5' summary



Belle'16
CMS'17
ATLAS'19
LHCb'20
P_5'
1.0
0.5
0.0
−0.5
−1.0
0
2
5
8
10
12
15
18
q^2 [GeV^2/c^4]

Spectroscopy

- O(30) new charm(onium), beauty and exotic hadrons

  Ξ_{cc}^{++}

  Pentaquarks,

  Tetraquarks, …

  quantum numbers for some of them

- precise masses and widths/lifetimes
  - Almost always the most precise …

- Mass and width of X(3872)
- New beauty and charm baryons
- New puzzle : structures in $J/\psi J/\psi$ mass spectrum
  - 4c tetraquarks ?

$\chi_{c1}(3872)$ aka $X(3872)$

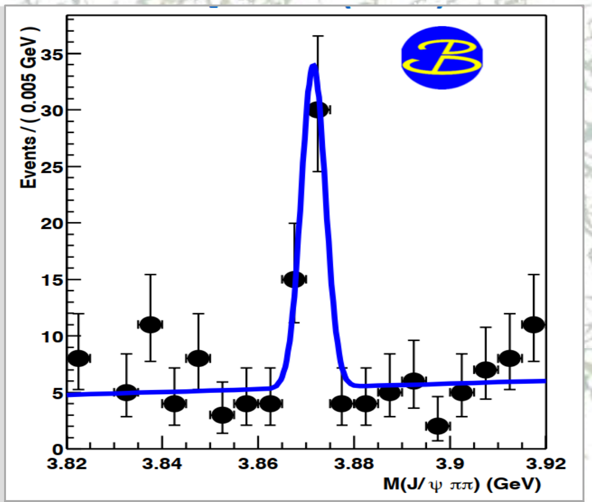
- Discovered 17 years ago by Belle
- Quantum numbers 1^{++} by LHCb
- Mass close to DD^* threshold
- Rather high production rate in environment

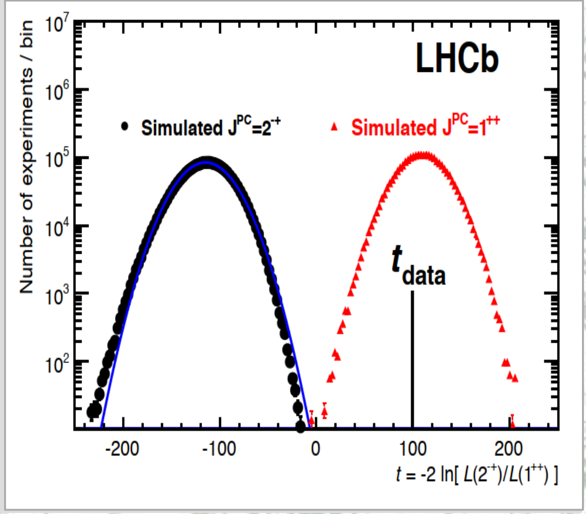
  Too large for "large" molecular?
- Interesting pattern of decays

  $J/\psi\rho^0$ vs $J/\psi\omega^0$, $\psi'\gamma$ vs $J/\psi\gamma$, …
- Nature is still unclear

  Molecule? Compact tetraquark?

  $\chi_{c1}(2P)$? Hybrid? Mixture? …



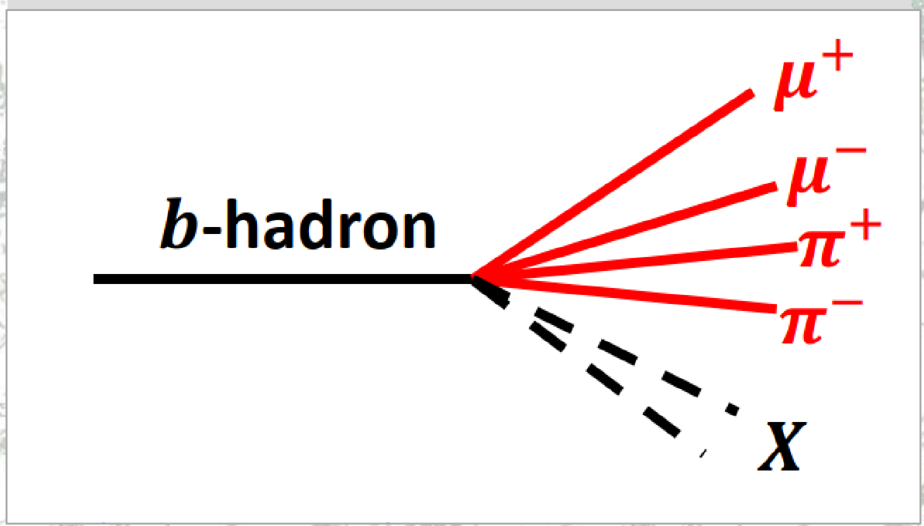


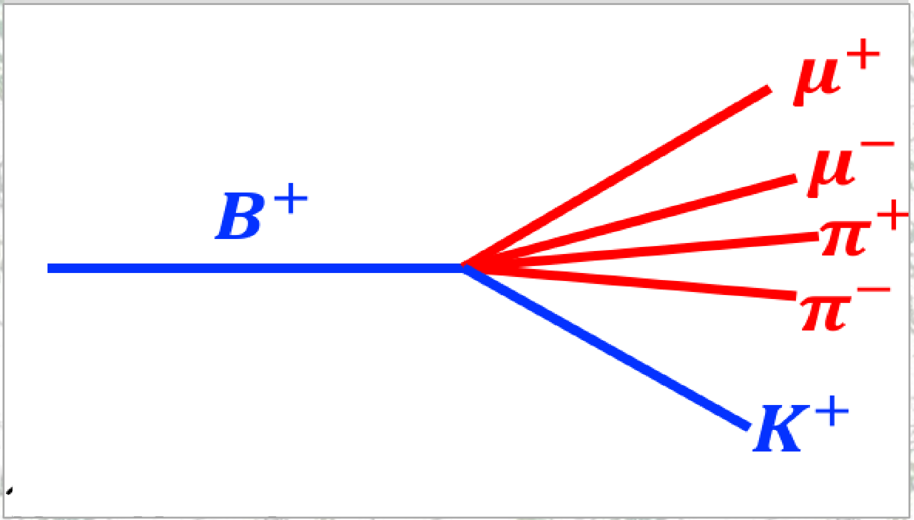
Two concurrent analyses

LHCb-PAPER-2020-008/009, arXiv: 2005.13419/2005.13422

- Inclusive $b \to X(3872)X$
- Run I, 3fb^{-1}
- Large statistics
- Large background

- $B^+ \to X(3872)K^+$
- RunI&II, 9fb^{-1}
- Smaller statistic
- Smaller background

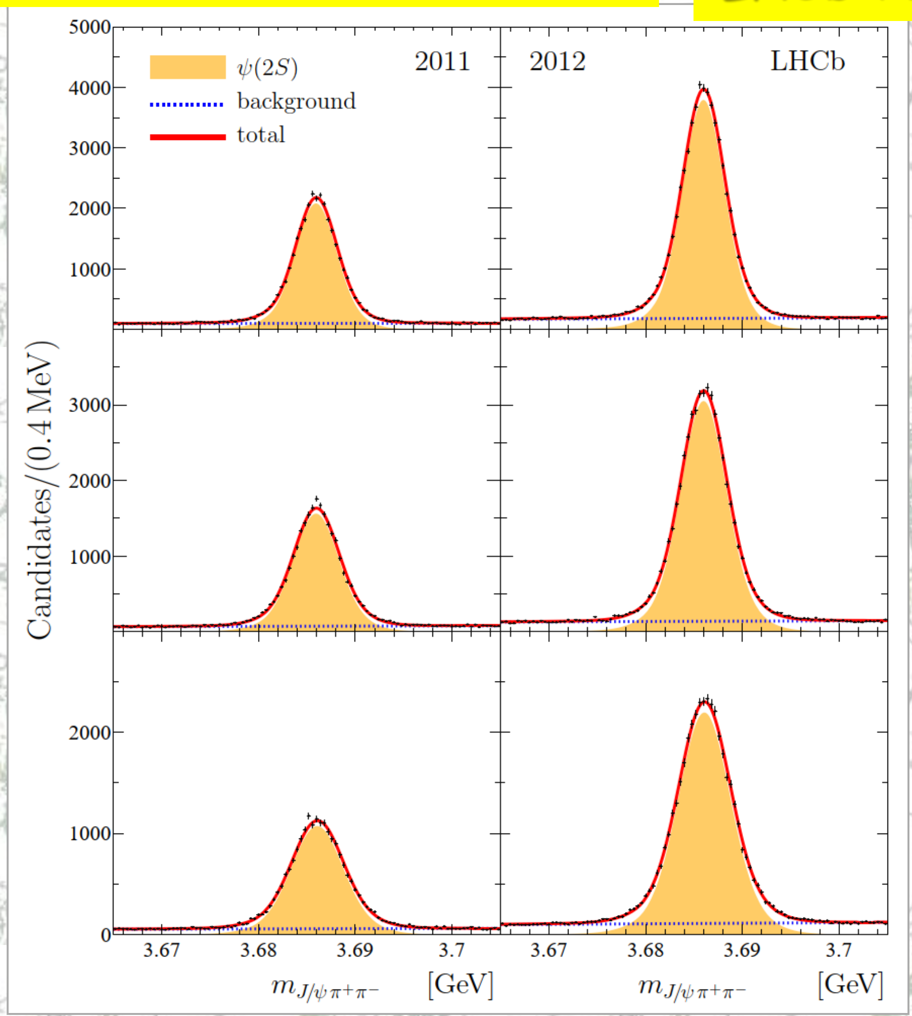




b→ (X(3872)→J/ ψ π⁺π⁻) X

Control mode: ψ'→J/ψπ⁺π⁻

LHCb-PAPER-2020-008, arXiv: 2005.13419



- Calibrate detector resolution using large sample of

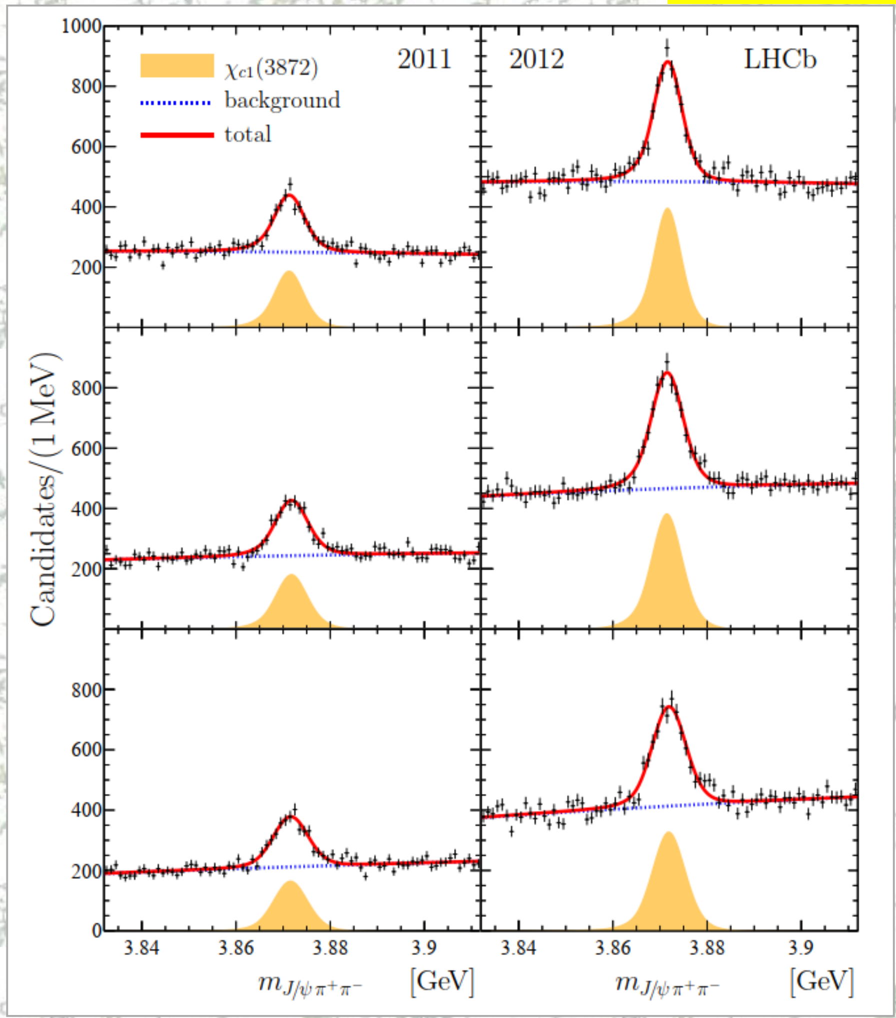
  b → (ψ'→J/ψ π⁺π⁻) X

  - account small data/MC difference

    s=1.03±0.01 (1%!)
- Analysis in $p_{\pi\pi}$ bins
- Separately for 2011& 2012

b→ (X(3872)→J/ ψ π⁺π⁻) X

LHCb-PAPER-2020-008, arXiv: 2005.13419



- Using S-wave Breit-Wigner

$$\Delta m = 185.598 \pm 0.067 \pm 0.068\,\text{MeV}\,,$$

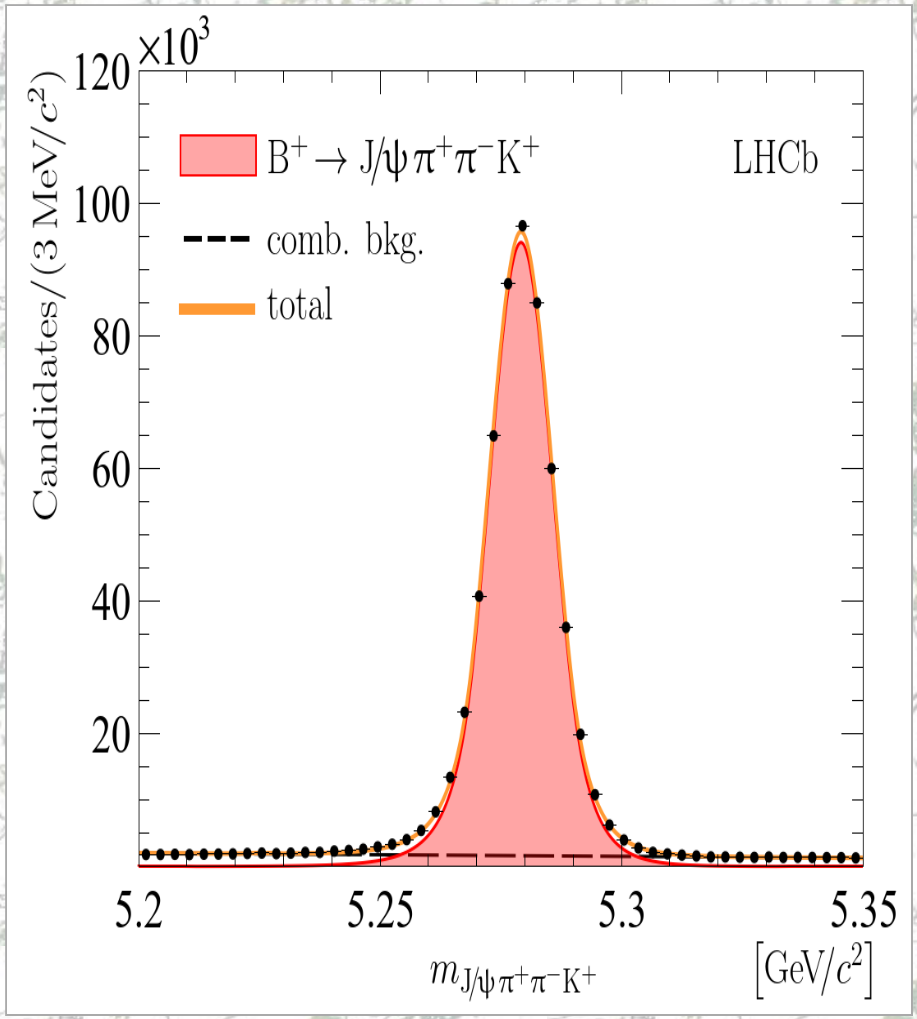
- Width is 5σ from zero!

$$\Gamma_{\text{BW}} = 1.39 \pm 0.24 \pm 0.10\,\text{MeV}\,,$$

- Cross-check: if $\Gamma=0$
  - $s = 1.20\text{-}1.25$
  - versus the measured value of $s=1.03\pm0.01$

$B^+ \to (X(3872) \to J/\psi\pi^+\pi^-)K^+$

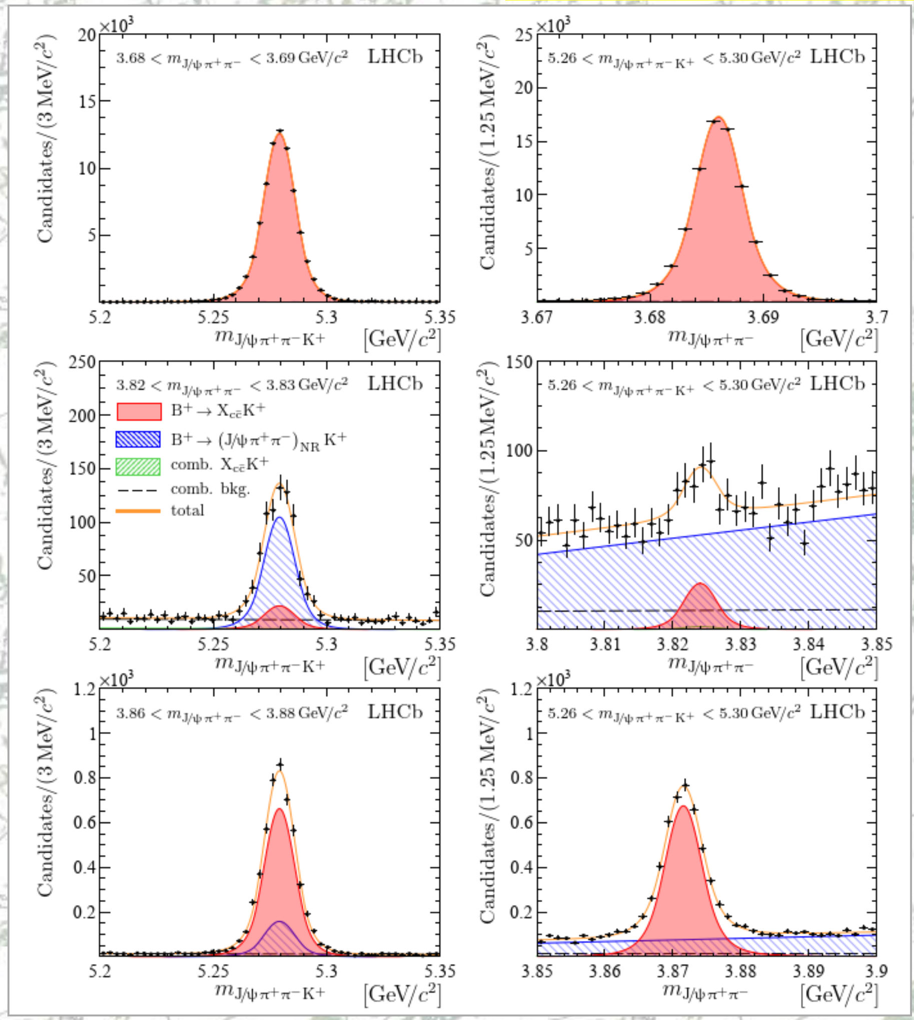
LHCb-PAPER-2020-009, arXiv: 2005.13422



- $(547.8 \pm 0.9) \times 10^3$
- Split into :
  - ψ' region,
  - $\psi_2(3823)$
  - X(3872)
- Simultaneous 2D fit in three regions
  - Measure masses relative to ψ' mass
  - Fix ψ' width :
    - allow to measure $\psi_2(3823)$ and X(3872) widths

$B^+ \to (X(3872) \to J/\psi\pi^+\pi^-)K^+$

LHCb-PAPER-2020-009, arXiv: 2005.13422



Parameter	$B^+ \to \psi(2S)K^+$	$B^+ \to \psi_2(3823)K^+$	$B^+ \to \chi_{c1}(3872)K^+$
$N_{B^+ \to X_{c\bar{c}}K^+}$	$(81.14 \pm 0.29) \times 10^3$	137 ± 26	4230 ± 70
$\delta m_{X_{c\bar{c}}}$ [MeV/c^2]	—	137.98 ± 0.53	185.49 ± 0.06
$\Gamma_{X_{c\bar{c}}}$ [MeV]	0.29 (fixed)	$0\,^{+0.68}_{-0.00}$	$0.96\,^{+0.19}_{-0.18}$
f_{B^+}	1.052 ± 0.003		
$f_{X_{c\bar{c}}}$	1.048 ± 0.004		

- MC/data: 1.048 ± 0.004
- Precise X(3872) mass

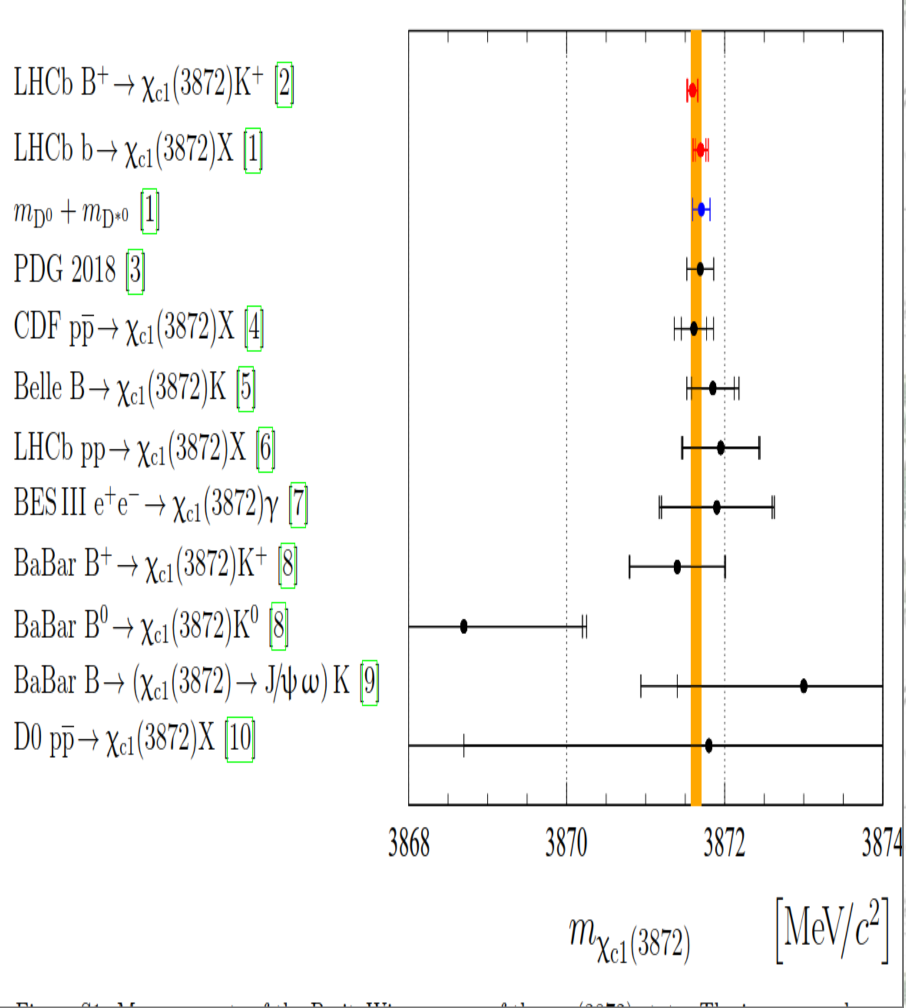
$$m_{\chi_{c1}(3872)} - m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03\,\mathrm{MeV}/c^2\,.$$

- Large width! $5\sigma > 0$

$$\Gamma_{\chi_{c1}(3872)} = 0.96\,^{+0.19}_{-0.18} \pm 0.21\,\mathrm{MeV}\,,$$

X(3872) mass and width

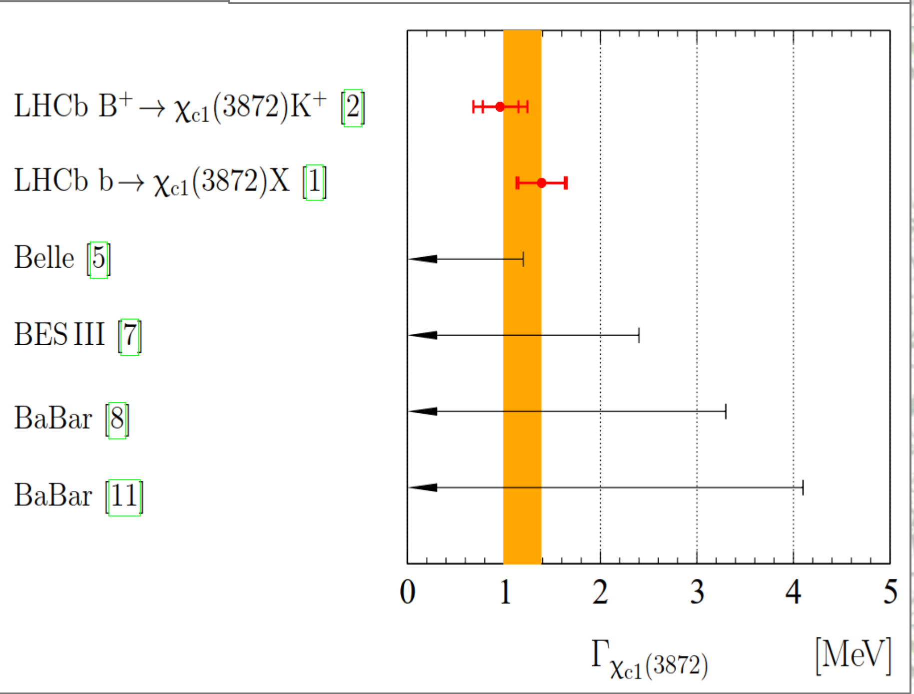
LHCb-PAPER-2020-008/009, arXiv: 2005.13419/2005.13422



$$\delta E|_{\mathrm{LHCb}} = 66 \pm 124\,\mathrm{keV}\,.$$

m(K)!!!

$$\delta E|_{\mathrm{ALL}} = 60 \pm 122\,\mathrm{keV}\,.$$



… but *Breit-Wigner* cannot be correct shape

LHCb-PAPER-2020-008, arXiv: 2005.13419

- Make a try using *Flatte-type* model (*C.Hanhart et et..*)

$$\frac{dR(J/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{\left|E - E_f + \frac{i}{2}\left[g\left(\sqrt{2\mu_1 E} + \sqrt{2\mu_2(E-\delta)}\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right]\right|^2}$$

✓ $E \equiv m_{J/\psi\pi^+\pi^-} - (m_{D^0} + m_{D^{*0}})$; $E_f \equiv m_0 - (m_{D^0} + m_{D^{*0}})$

✓ $\frac{\Gamma(\chi_{c1}(3872)\to J/\psi\pi^+\pi^-)}{\Gamma(\chi_{c1}(3872)\to D^0\overline{D}^{*0})} = 0.11 \pm 0.03$ constraint enforces a large coupling to $D^0\overline{D}^{*0}$

✓ Free parameters: m_0, Γ_0, effective couplings g and f_ρ

g	$f_\rho \times 10^3$	Γ_0 [MeV]	m_0 [MeV]
0.108 ± 0.003	1.8 ± 0.56	1.4 ± 0.4	3864.5 (fixed)

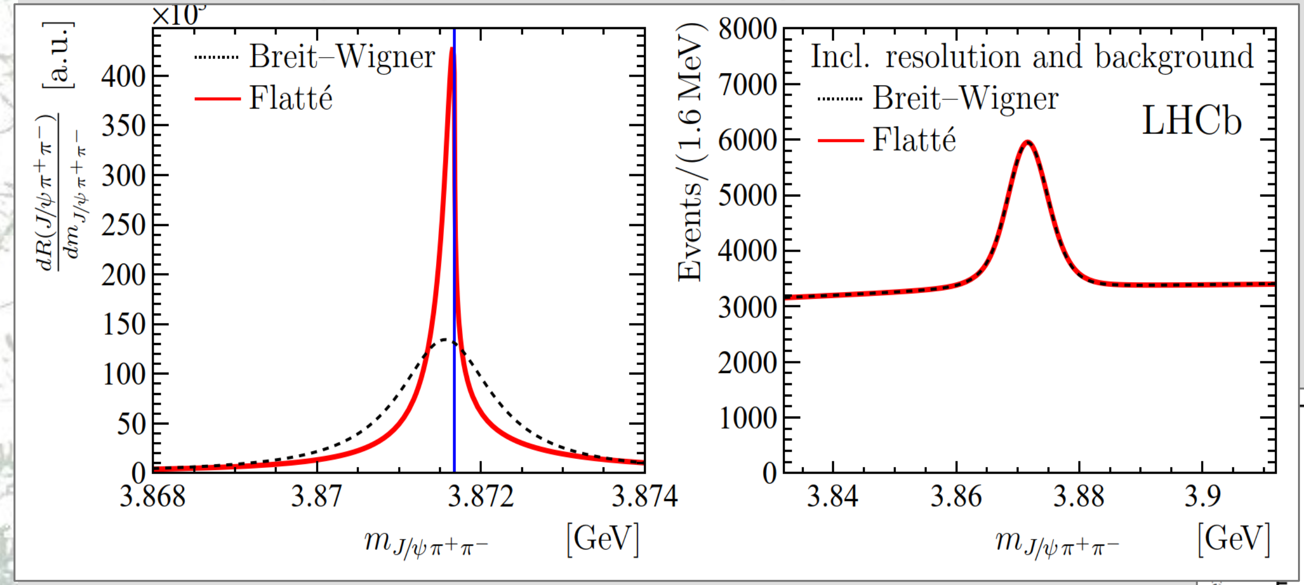
- Parameter interpretation is not easy:
  - *Flatte scaling*

Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

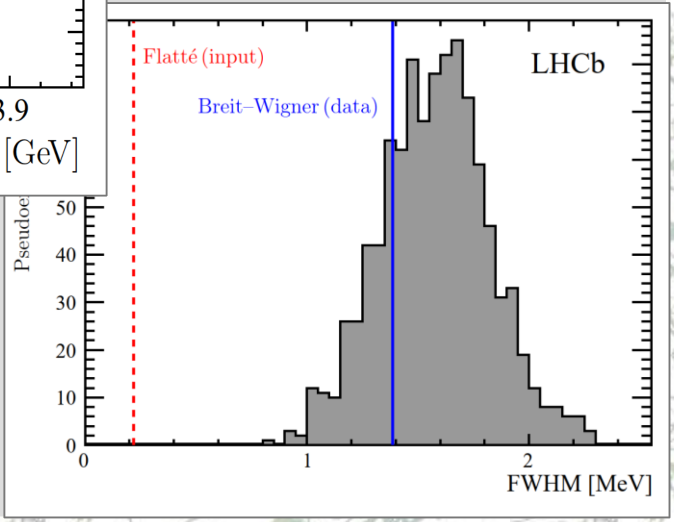
Flatte vs Breit-Wigner

LHCb-PAPER-2020-008, arXiv: 2005.13419

- Equally good description: resolution is important!

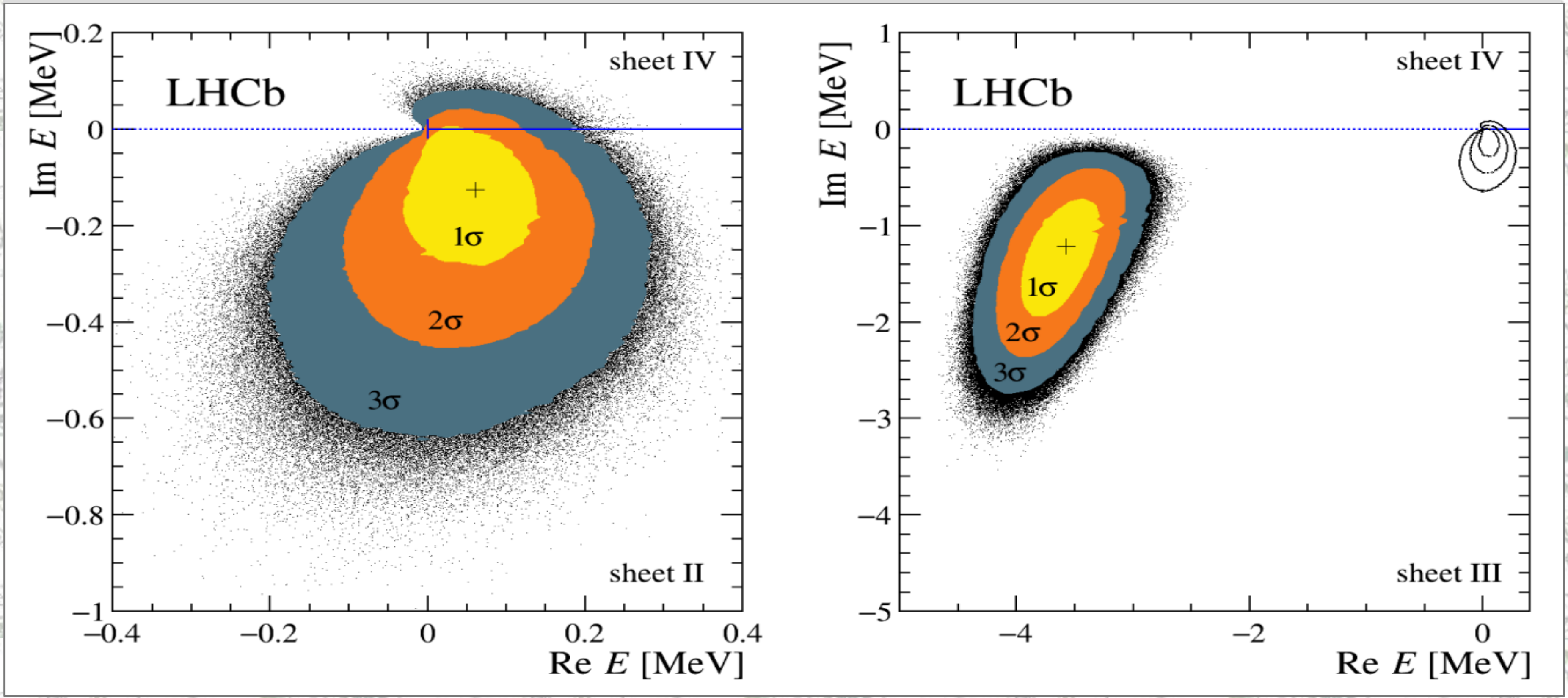


- Results are compatible



Flatte poles

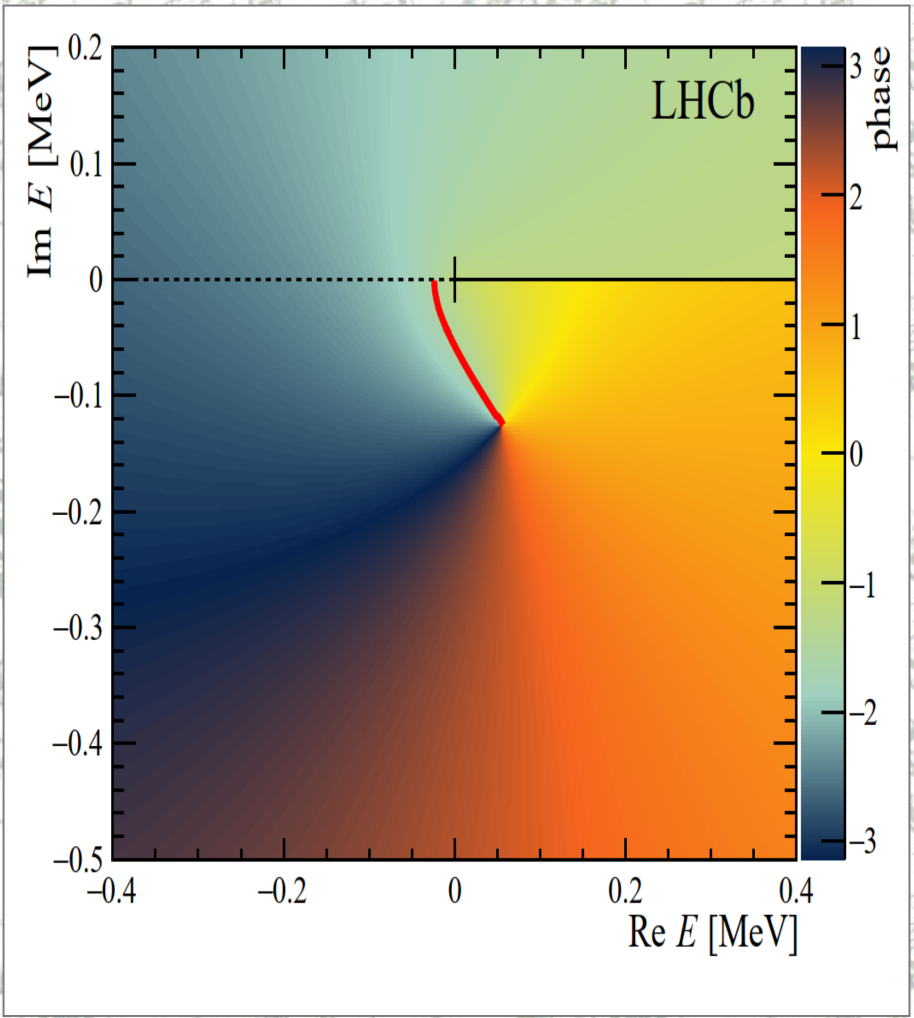
- E_{II} = (60-i130)keV: forms a peaking line shape
- E_{III}= (-3.58-i1.22)MeV



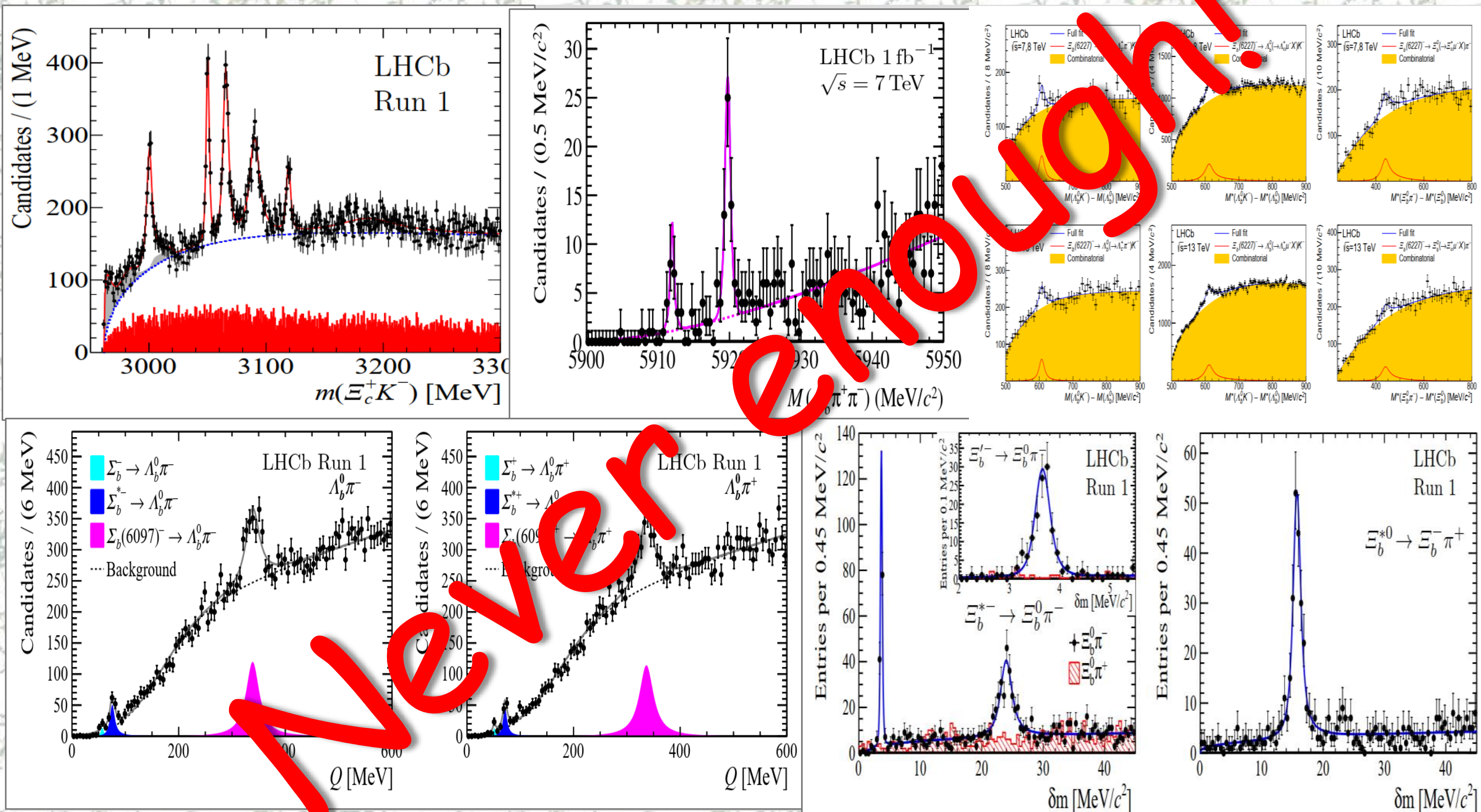
Binding energy

- Switching off other channels except D^0D^{*0}, pole II moves and gives E_b=24keV
- *Quasi-bound* D^0D^{*0} state is preferred

  E_b < 100keV 90%CL
- *Quasi-virtual* is still allowed at 2sigma



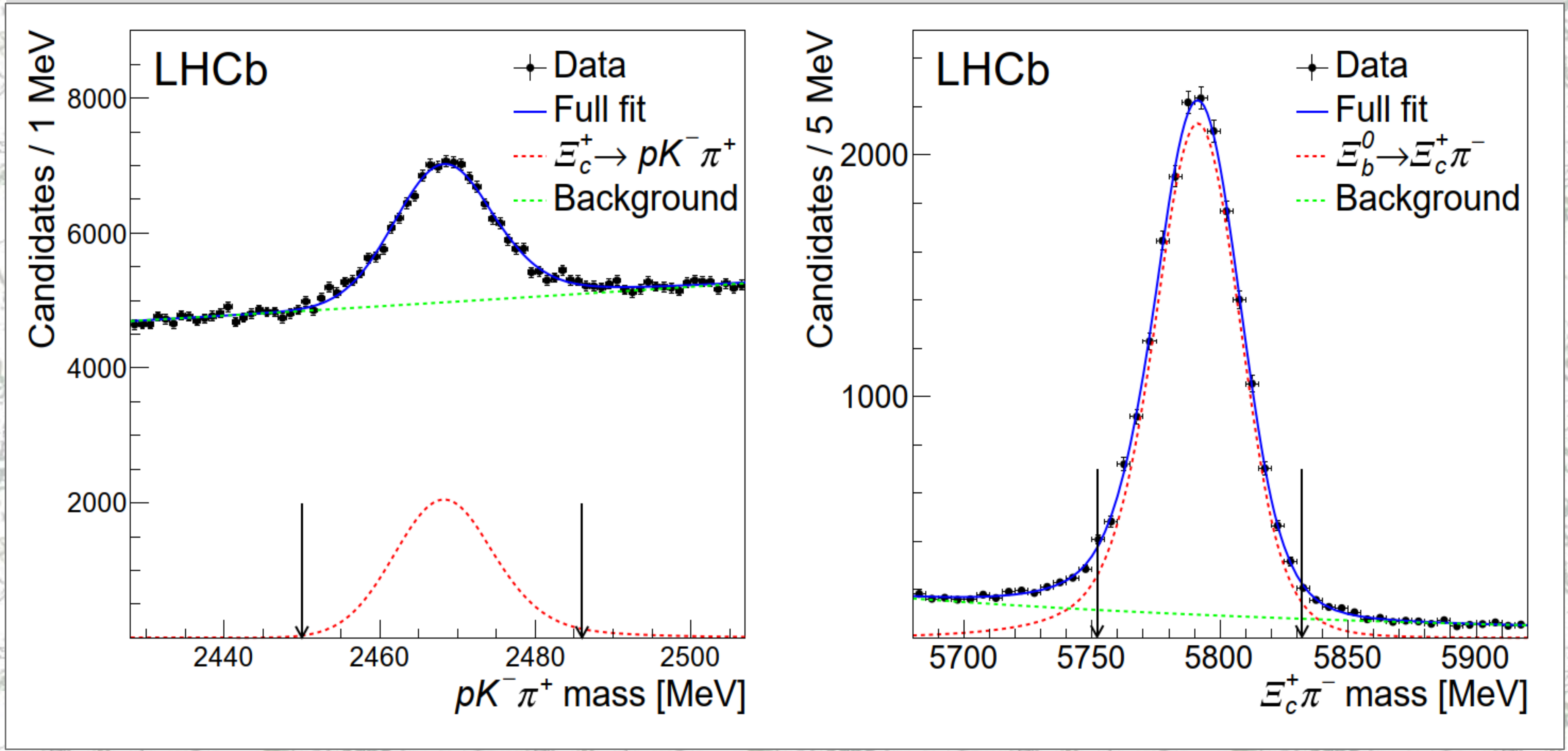
New heavy baryons



Excited Ω_b states in $\Xi_b^0 K^-$

PRL 124 (2020) 082002

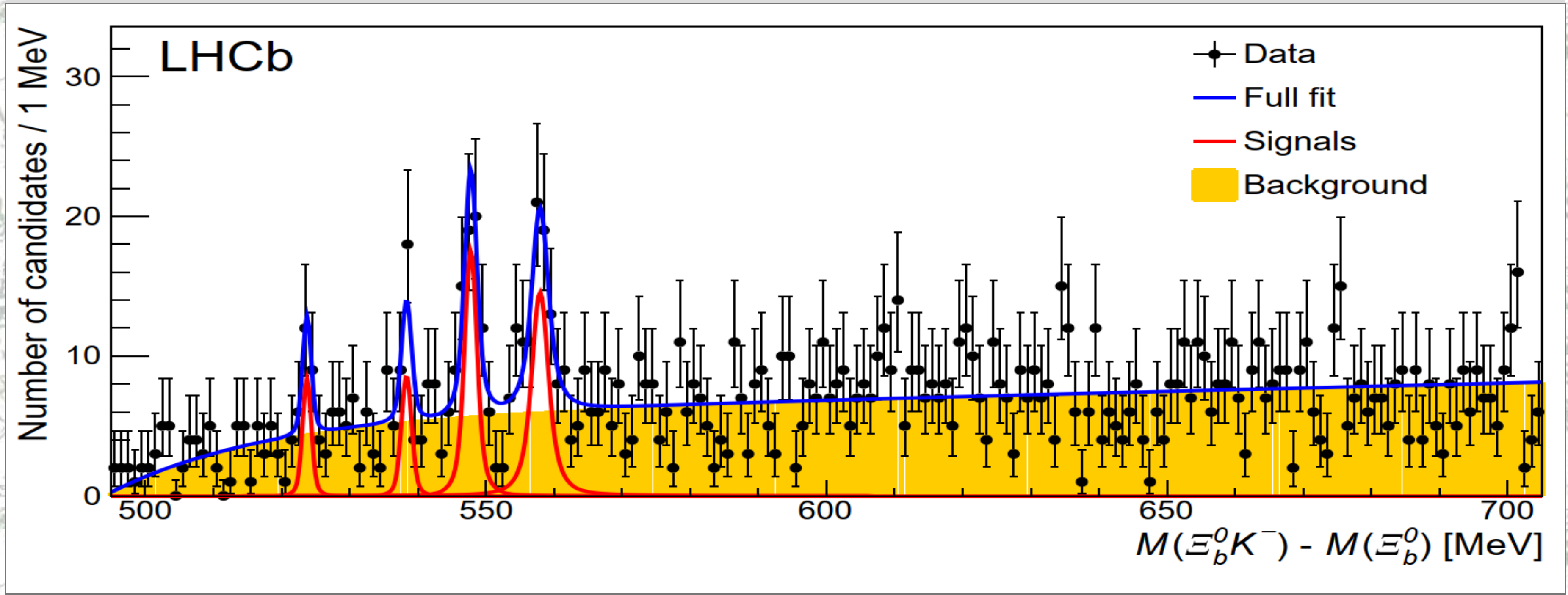
- Full data set with $\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$



Excited Ω_b states in $\Xi_b^0 K^-$

PRL 124 (2020) 082002

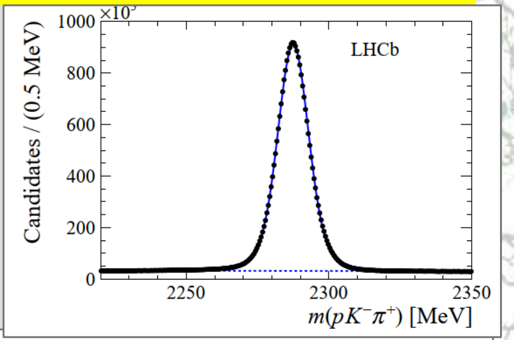
- Four narrow peaks
- local significances from 3.6 to 7.2σ
  - Global significance : 2 peaks $>6\sigma$, 2 peaks $<3\sigma$

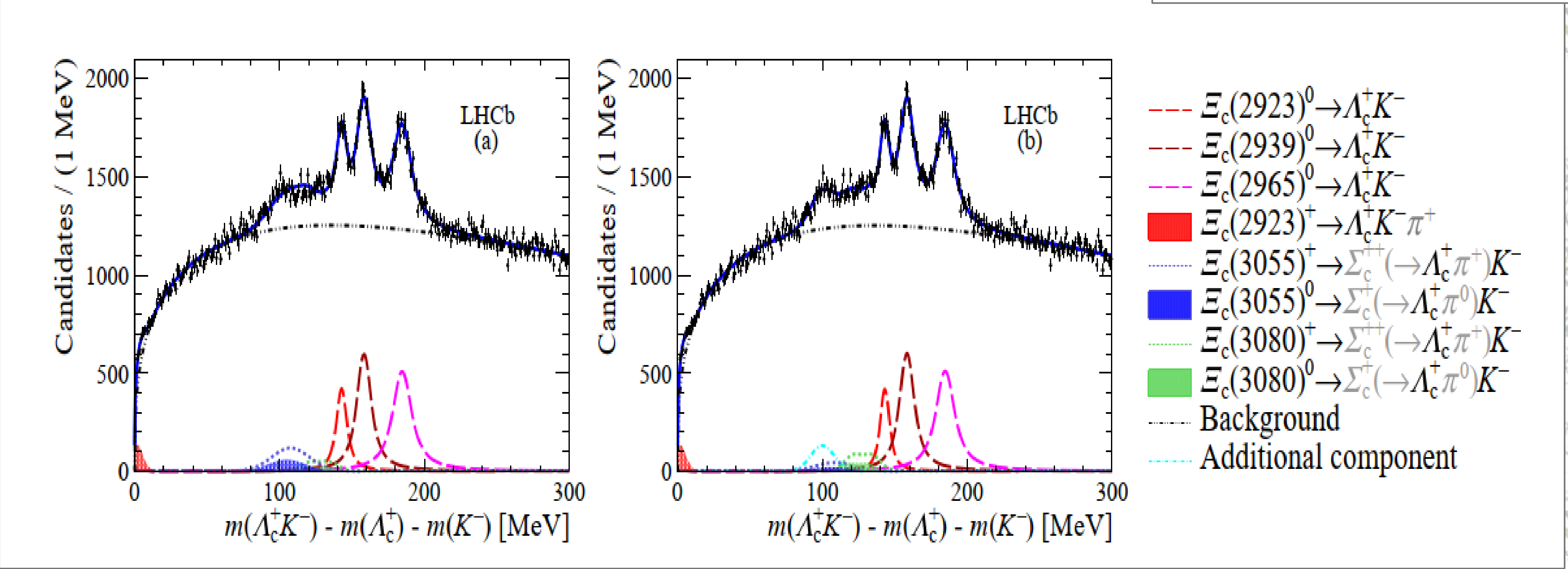


Excited Ξ_c^0 in $\Lambda_c K^-$

PRL 124 (2020) 082002

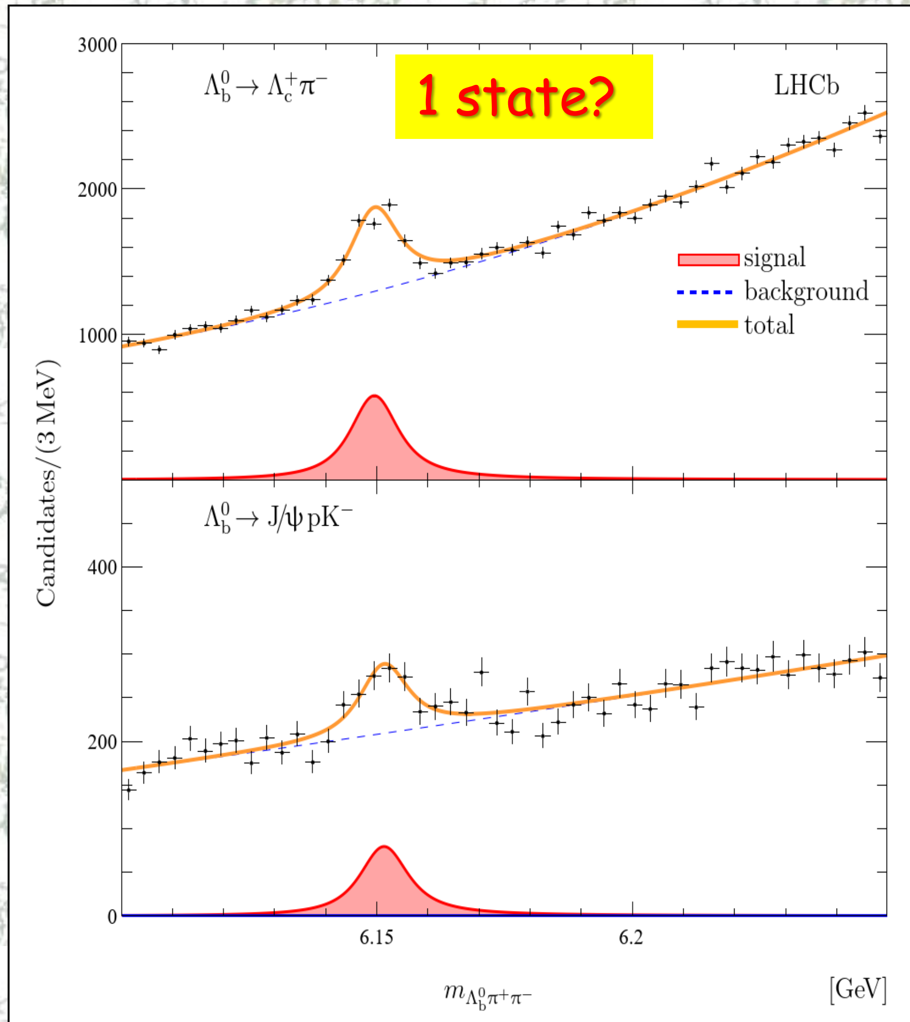
- 5.6fb^{-1}, “background-free” $\Lambda_c \to pK^- \pi^+$
- Three peaks with yields 4-12k
  - Two are definitely new

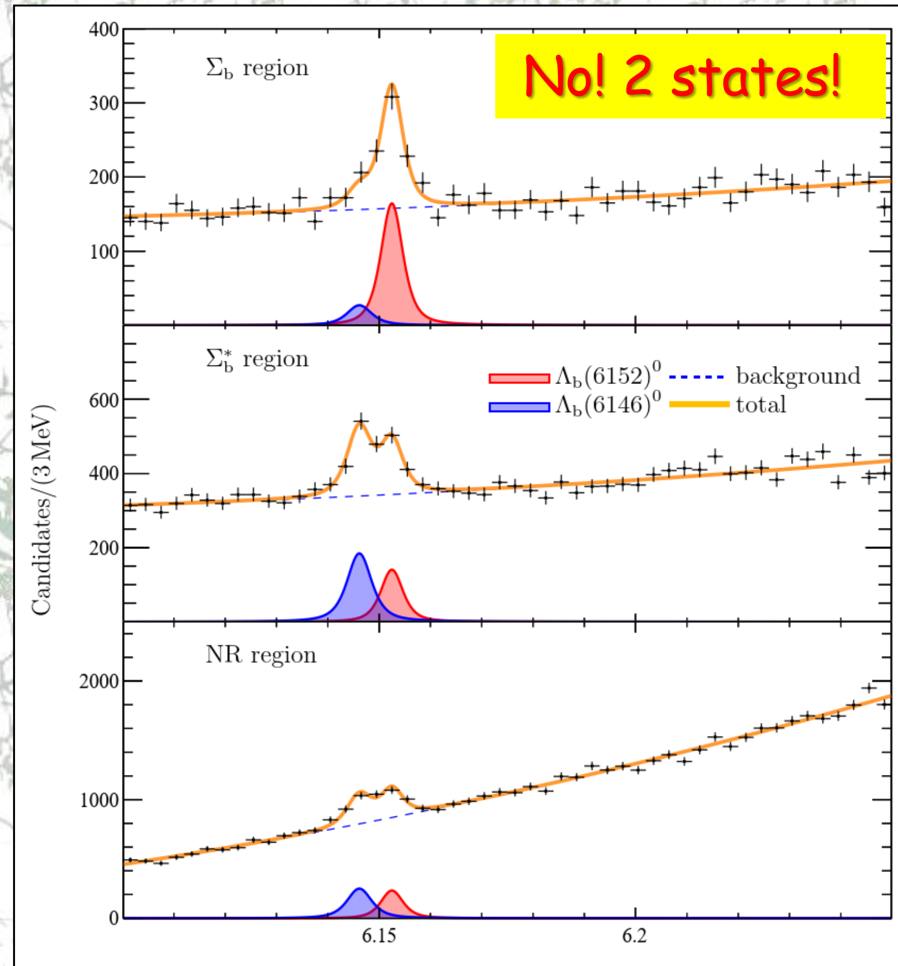




Excited Λ_b in $\Lambda_b\pi^+\pi^-$

PRL 123 (2019) 152001



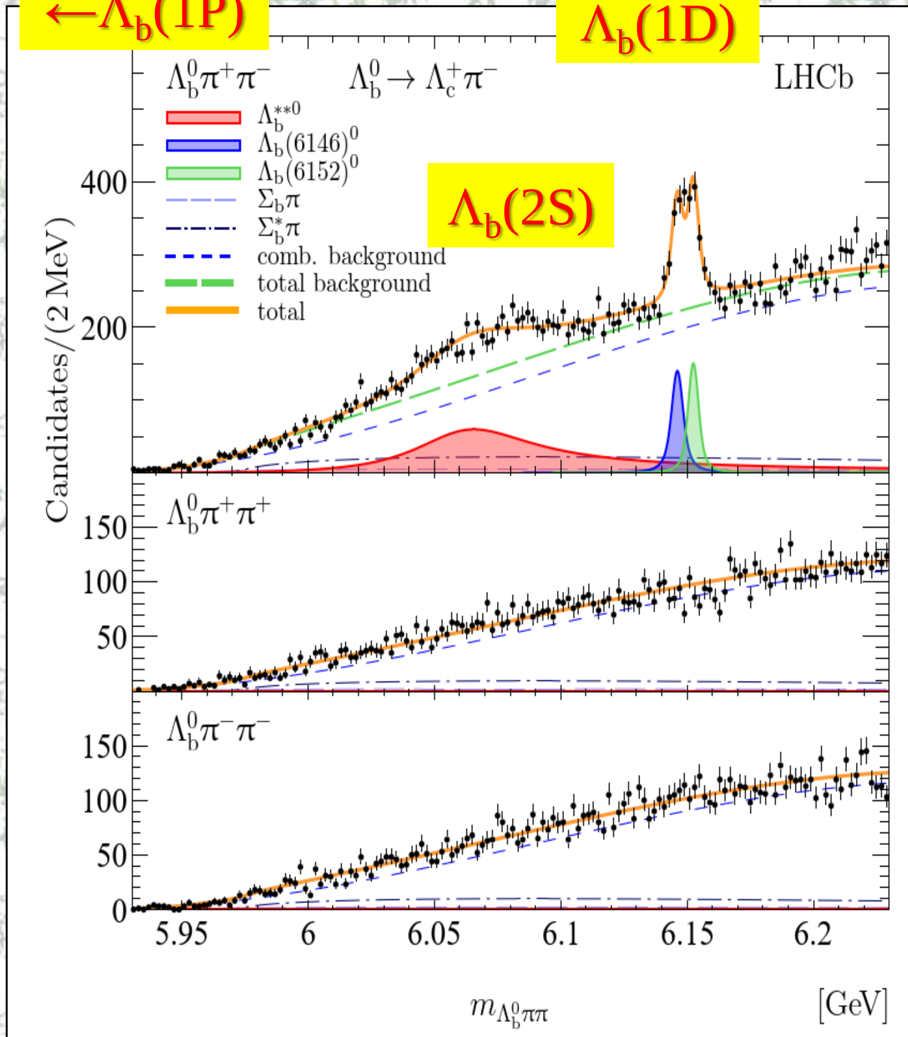


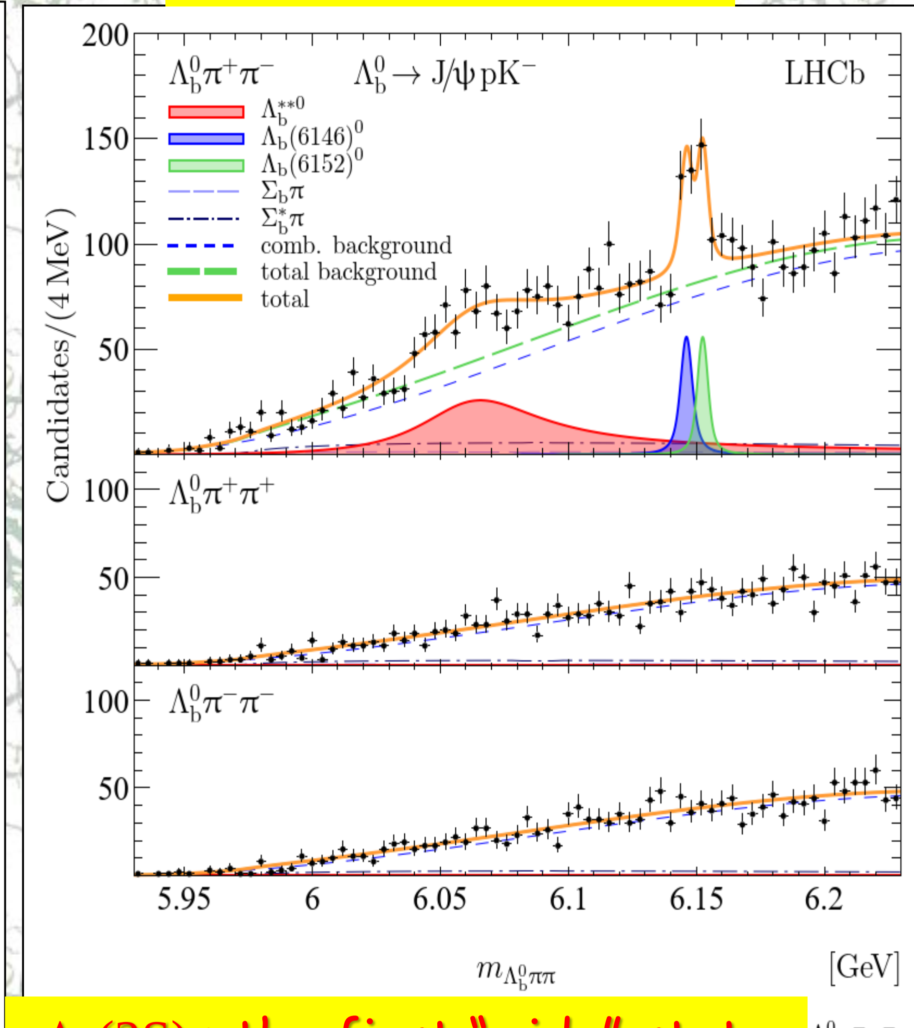
$\Lambda_b(1D)$ doublet

Excited Λ_b in $\Lambda_b\pi^+\pi^-$

JHEP 06 (2020) 136

←$\Lambda_b(1P)$ $\Lambda_b(1D)$ $\Lambda_b(2S)$



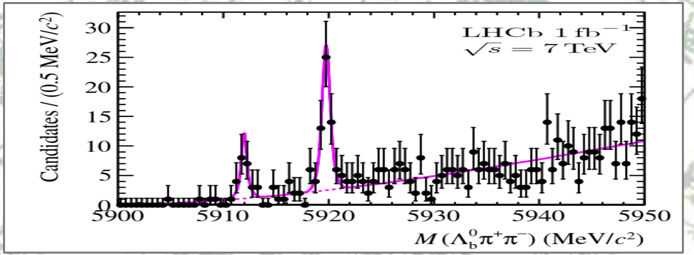


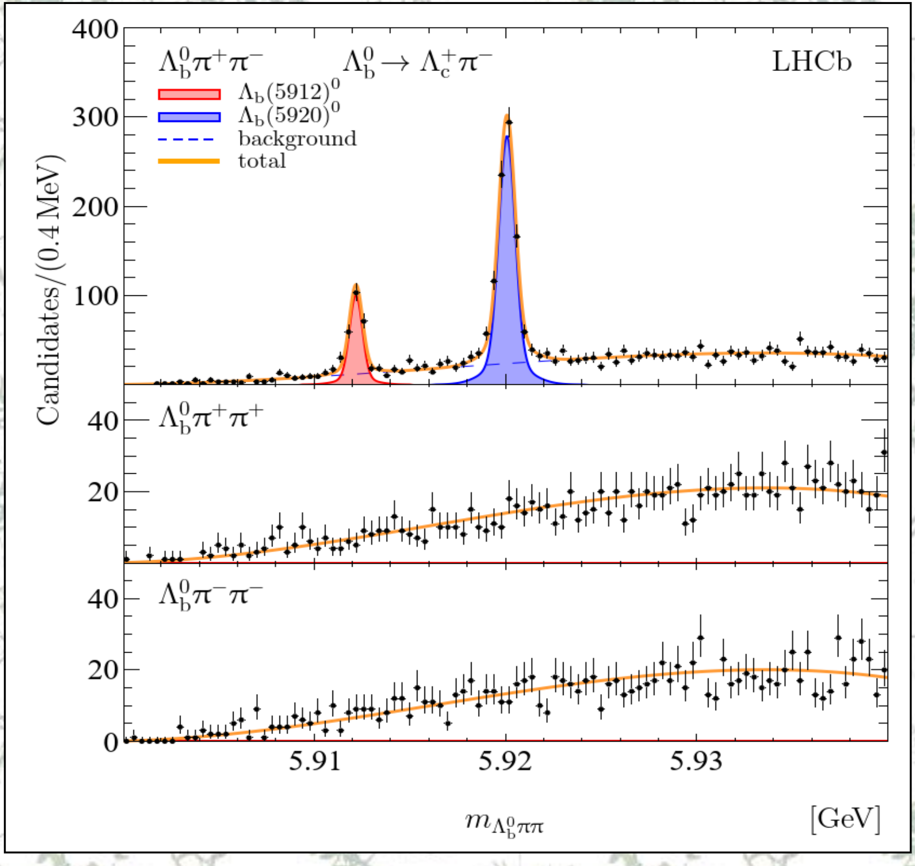
$\Lambda_b(2S)$: the first "wide" state

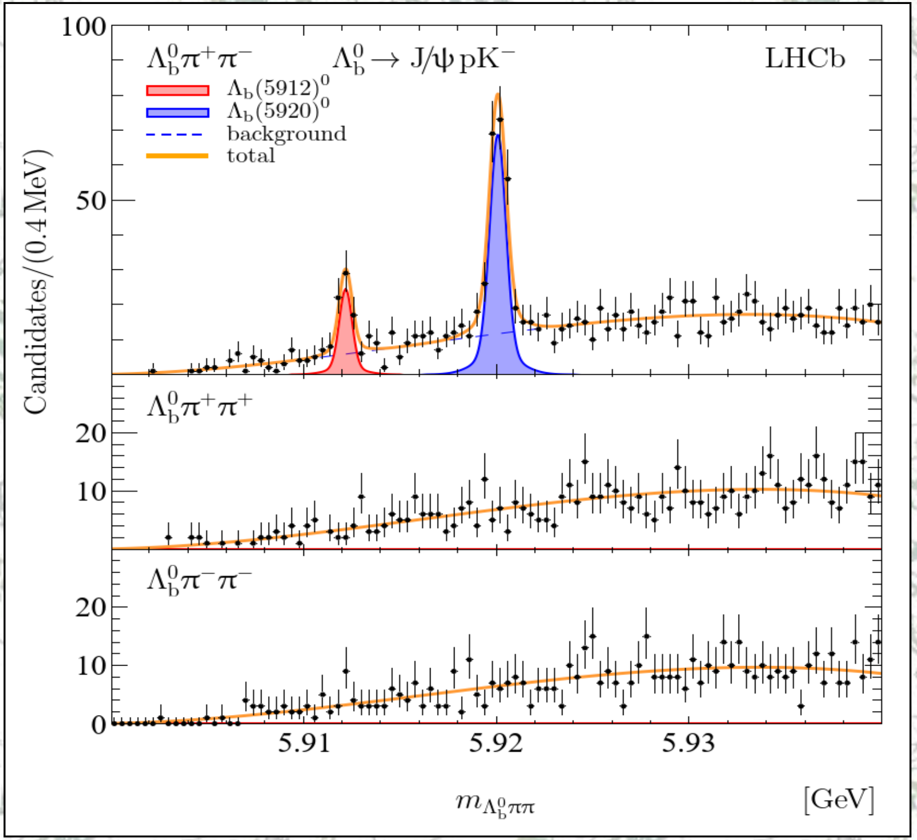
Λ_b in $\Lambda_b\pi^+\pi^-$

$\Lambda_b(1P)$ doublet

JHEP 06 (2020) 136

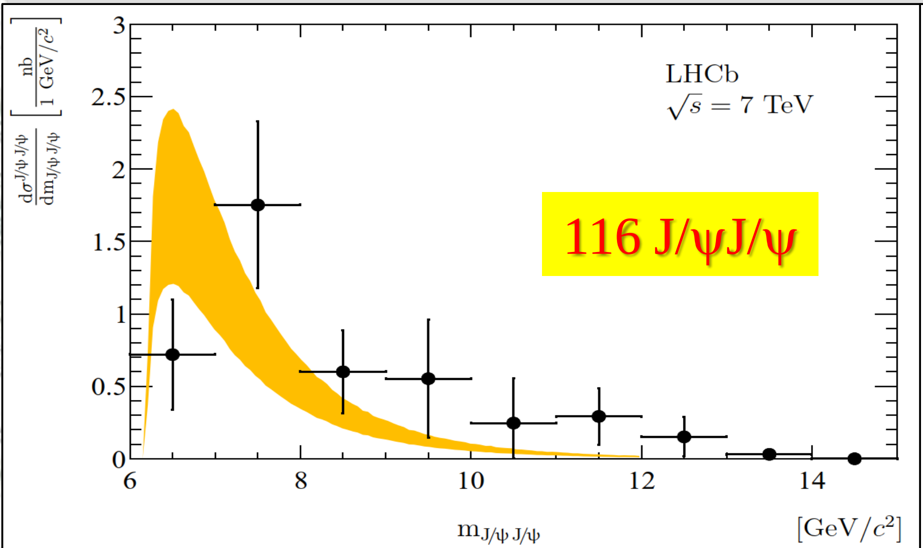


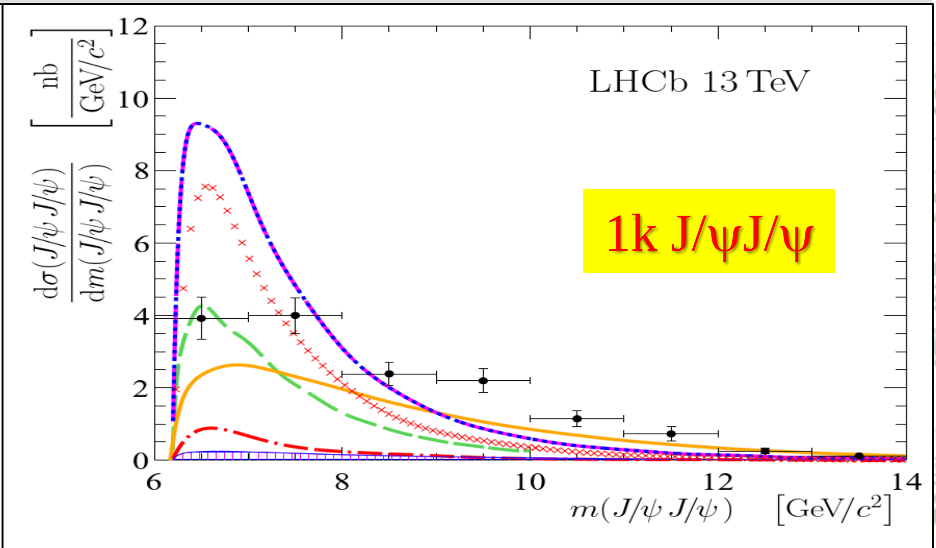




Structures in J/ψJ/ψ: charm tetraquark ?

- 4c tetraquarks are predicted in several models
  - Wide range of masses
  - J/ψJ/y is possible decay mode
- Was looked in LHCb in 2010 and 2015 data:



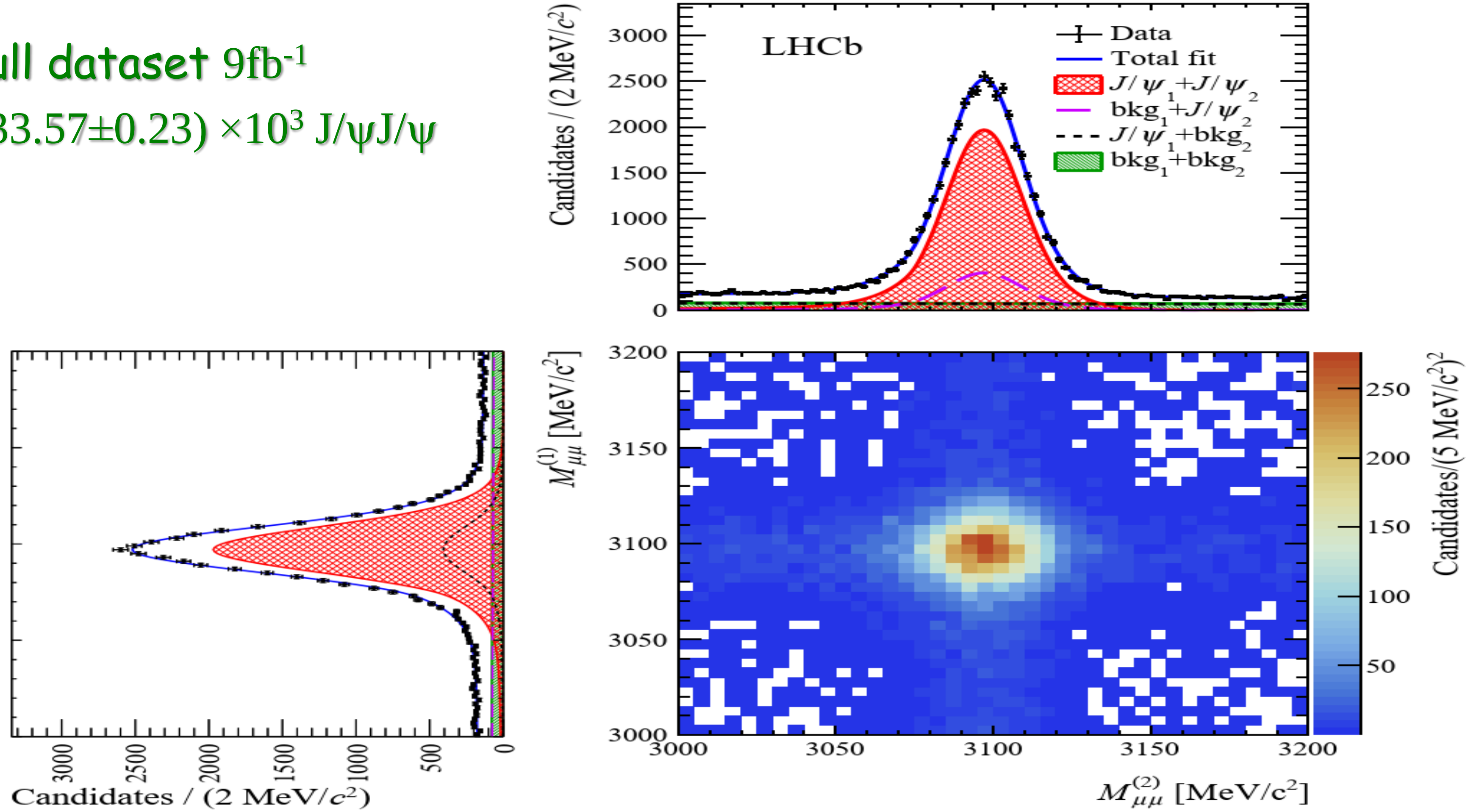


J/ψJ/ψ with full dataset

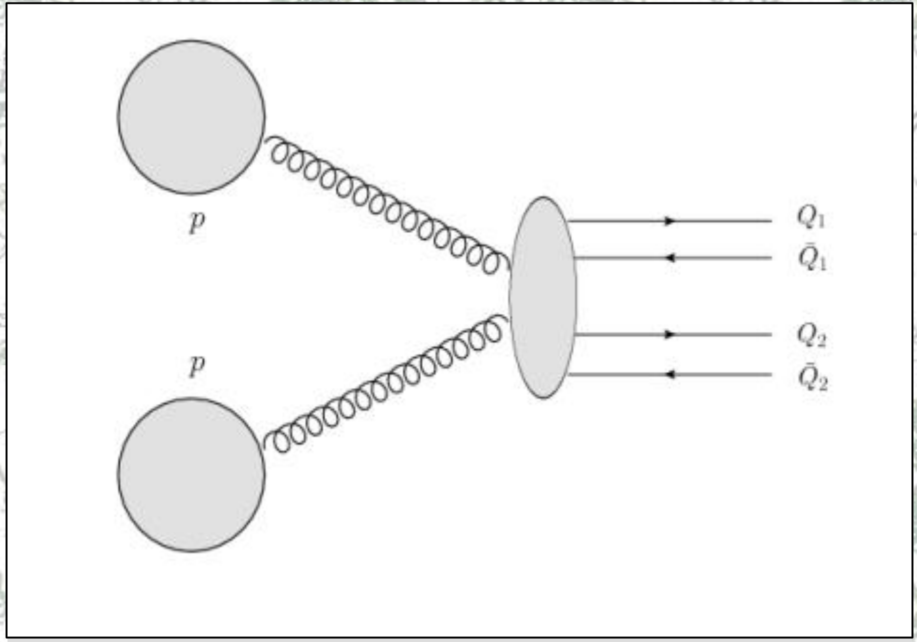
LHCb-PAPER-2020-011, arXiv: 2006.16957

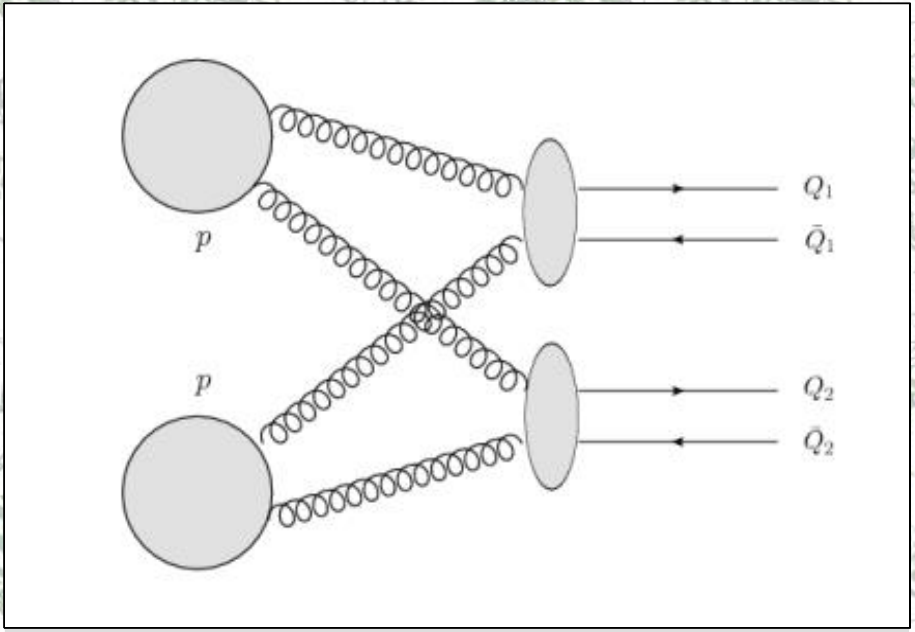
Full dataset 9fb^{-1}

(33.57±0.23) ×10^3 J/ψJ/ψ



Two contributions: SPS & DPS





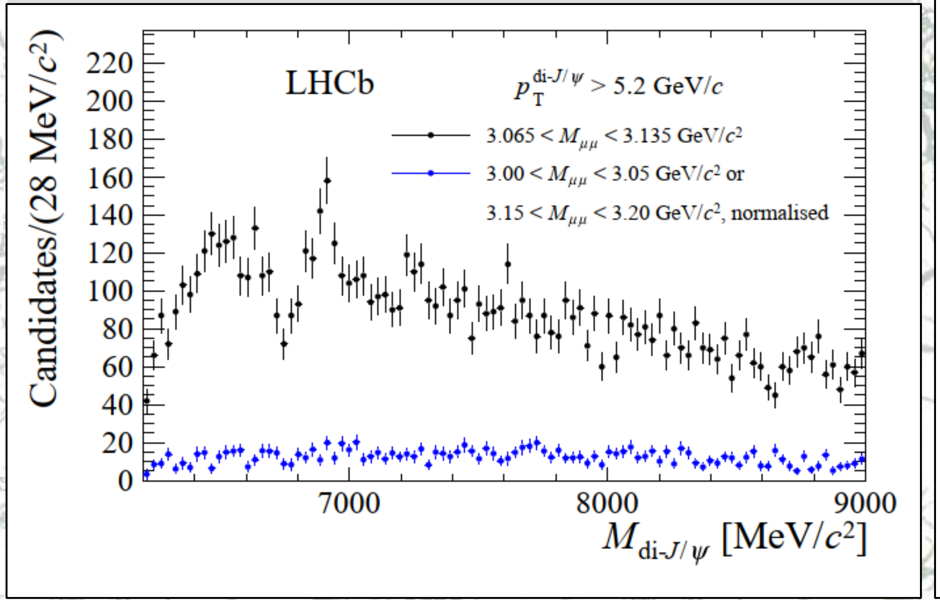
- Tetraquark is special case
- Interference is possible

- Play important role for large masses
- Shape can be fixed from data

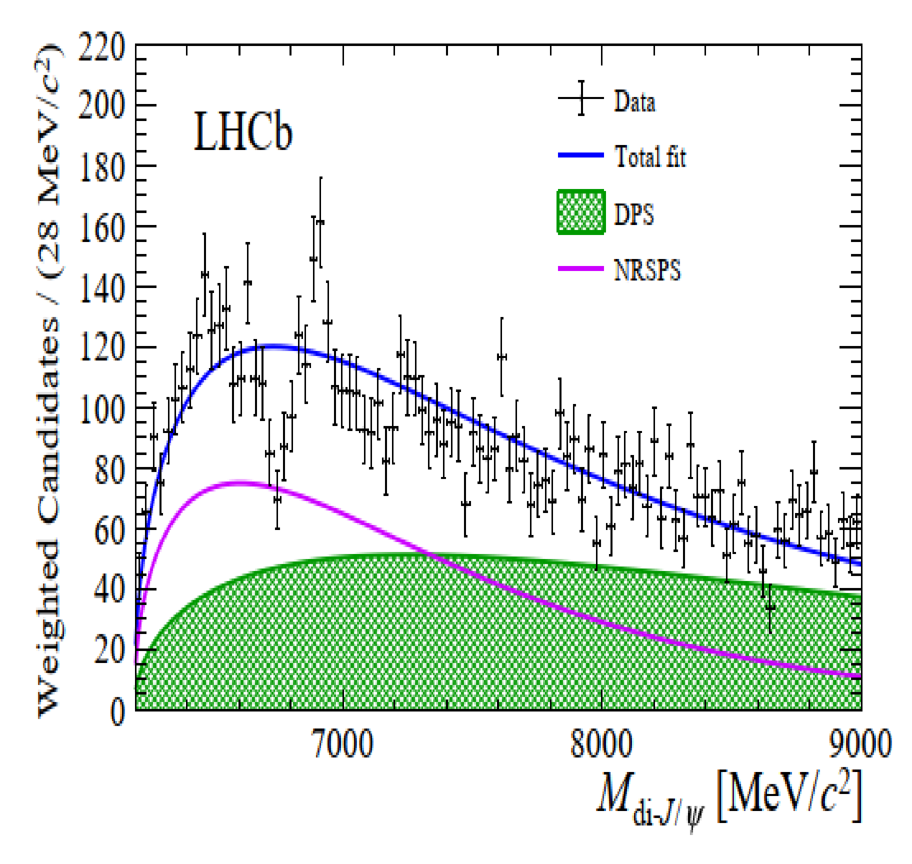
m(J/ψJ/ψ)

LHCb-PAPER-2020-011, arXiv: 2006.16957

- Spectrum is no smooth!
  - Broad structure
  - Dip
  - Narrow structure
  - ....

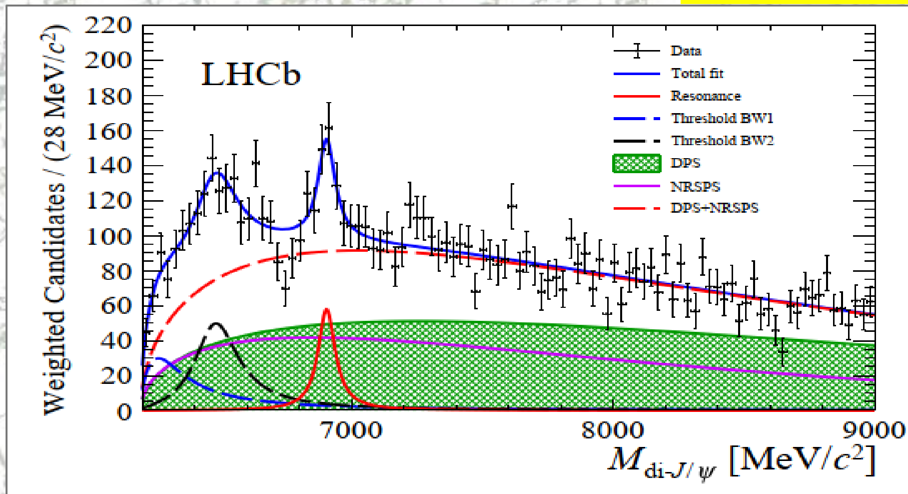


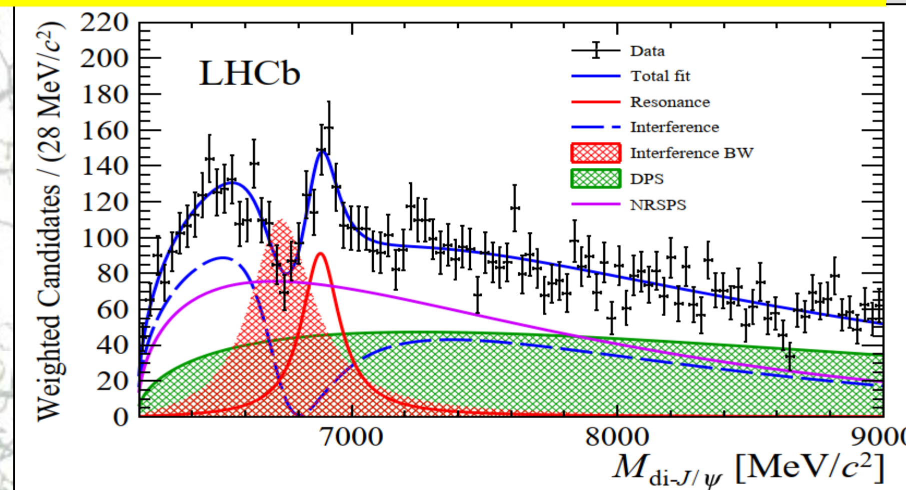
- Peaks are needed!



Fits: *without/with* interference

LHCb-PAPER-2020-011, arXiv: 2006.16957





$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV},$$

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$

$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

Structure	Significance	
	$p_{\mathrm{T}}^{\text{di-}J/\psi}$-threshold	$p_{\mathrm{T}}^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS plus DPS	$3.4\,\sigma$	$6.0\,\sigma$
Threshold enhancement plus $X(6900)$	$6.4\,\sigma$	$6.9\,\sigma$
Threshold enhancement	$6.0\,\sigma$	$6.5\,\sigma$
$X(6900)$	$5.1\,\sigma$	$5.4\,\sigma$

… instead of summary

- Analysis of Run-I&II data set continues
- Many important measurements to be updated for the full statistics
- Many interesting "*a-few-sigma*" puzzles and SM tensions
    - More data is needed..
- We are preparing for LHC Run-III and beyond
    - LHCb Upgrade progresses well

Stay tuned!

Thank you!

Heavy baryons in PDG on-line

PDG Live

Home | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

pdgLive Home > BOTTOM BARYONS ($B = -1$)

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

LHCb: almost for all cases)
The most precise mass
The most precise lifetime

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
Ω_b^-	$1/2^+$	***

?

$\Lambda_b(6146)^0$
$\Lambda_b(6252)^0$

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

See related review:
Charmed Baryons

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$ was $\Xi_c(2980)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		
$\Omega_c(3050)^0$		
$\Omega_c(3065)^0$		
$\Omega_c(3090)^0$		
$\Omega_c(3120)^0$		

DOUBLY CHARMED BARYONS ($C = +2$)

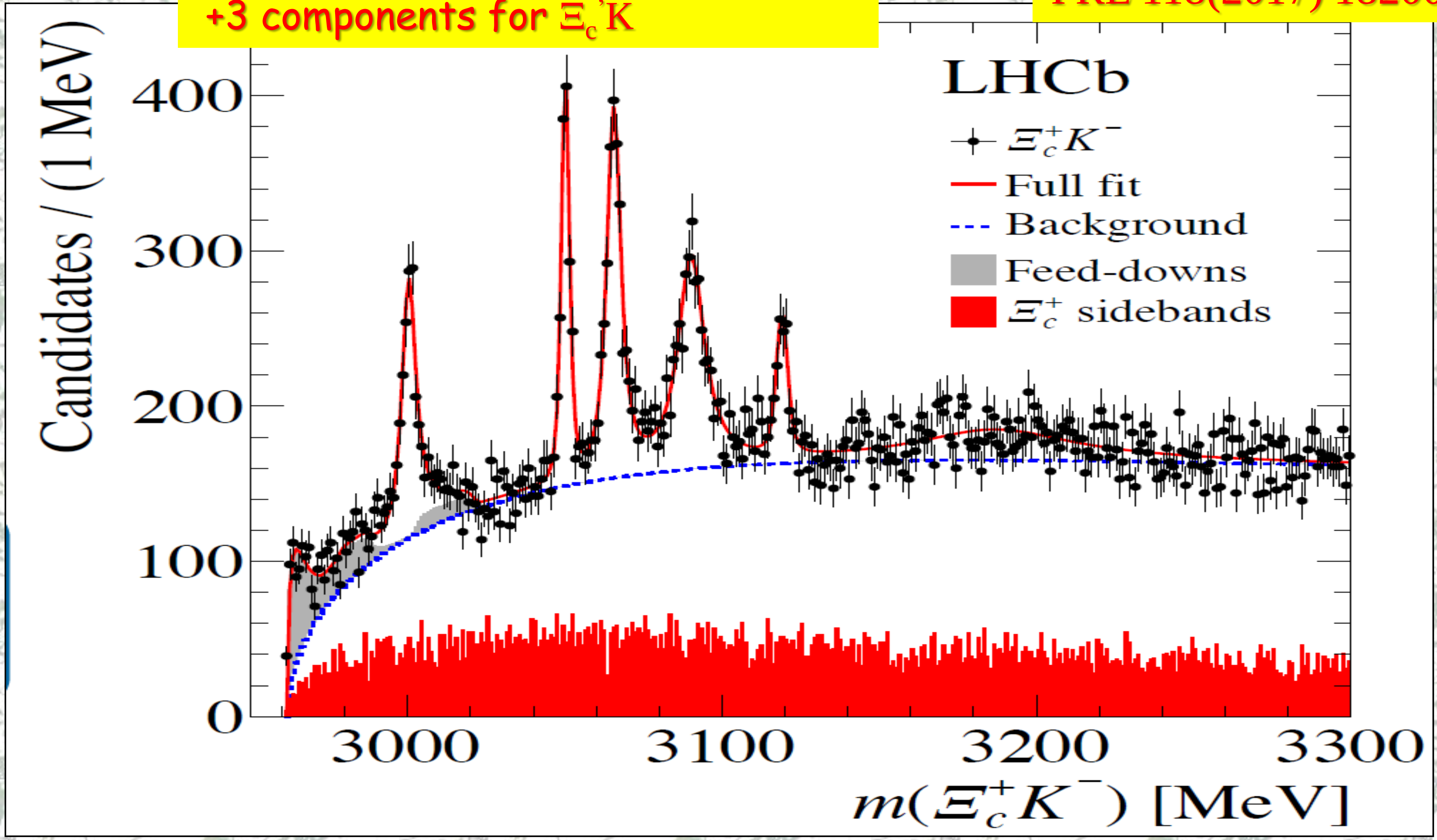
$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^+ = dcc$, $\Omega_{cc}^+ = scc$

Ξ_{cc}^{++}

Fit model

6 RBW*G, resolution: 0.7-1.7MeV/c^2
+3 components for $\Xi_c'K$

PRL 118(2017) 182001



Ξ_{cc}^{++} at LHCb

PRL 119(2017) 112001

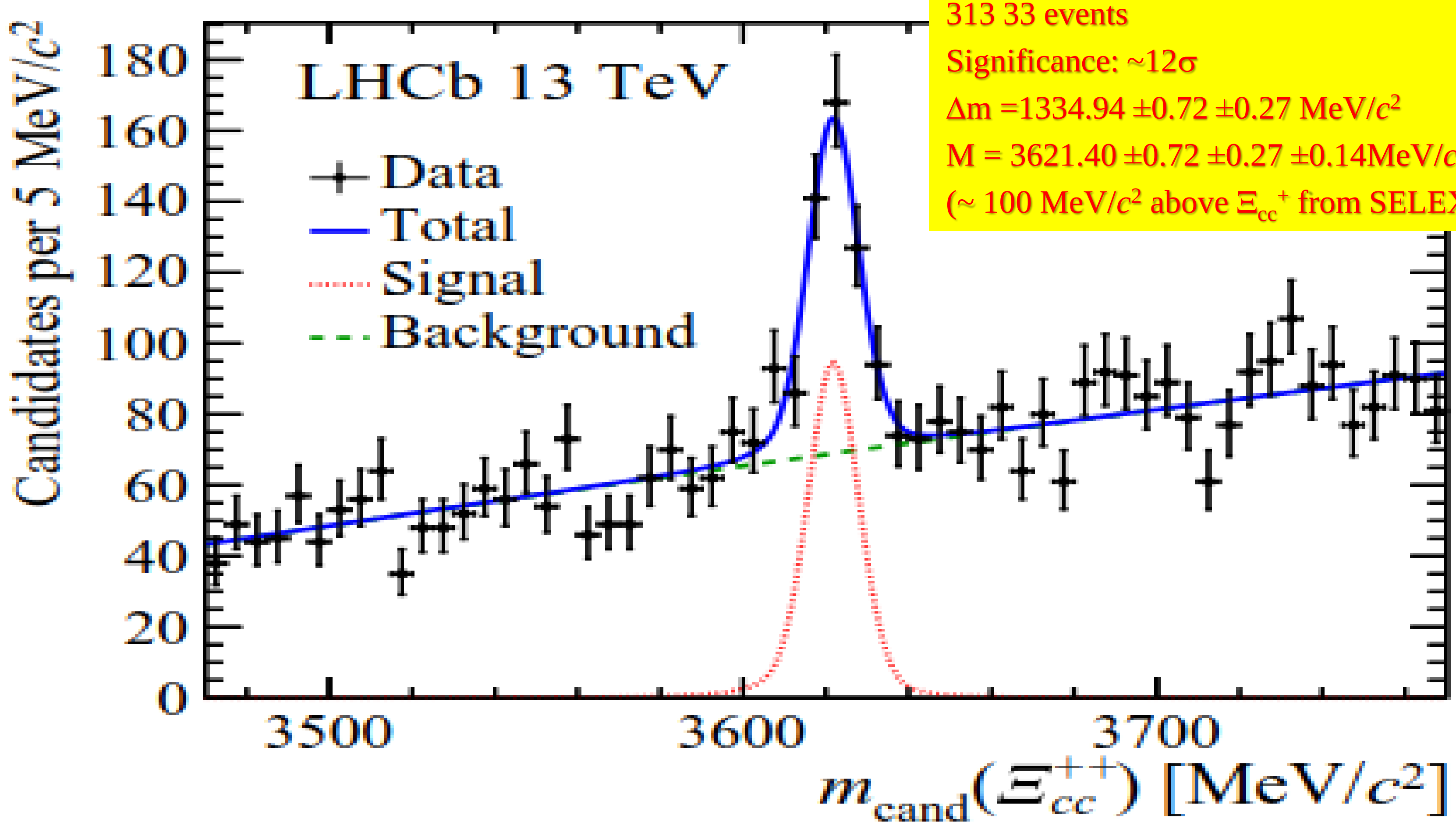
313 33 events

Significance: ~12σ

Δm =1334.94 ±0.72 ±0.27 MeV/c^2

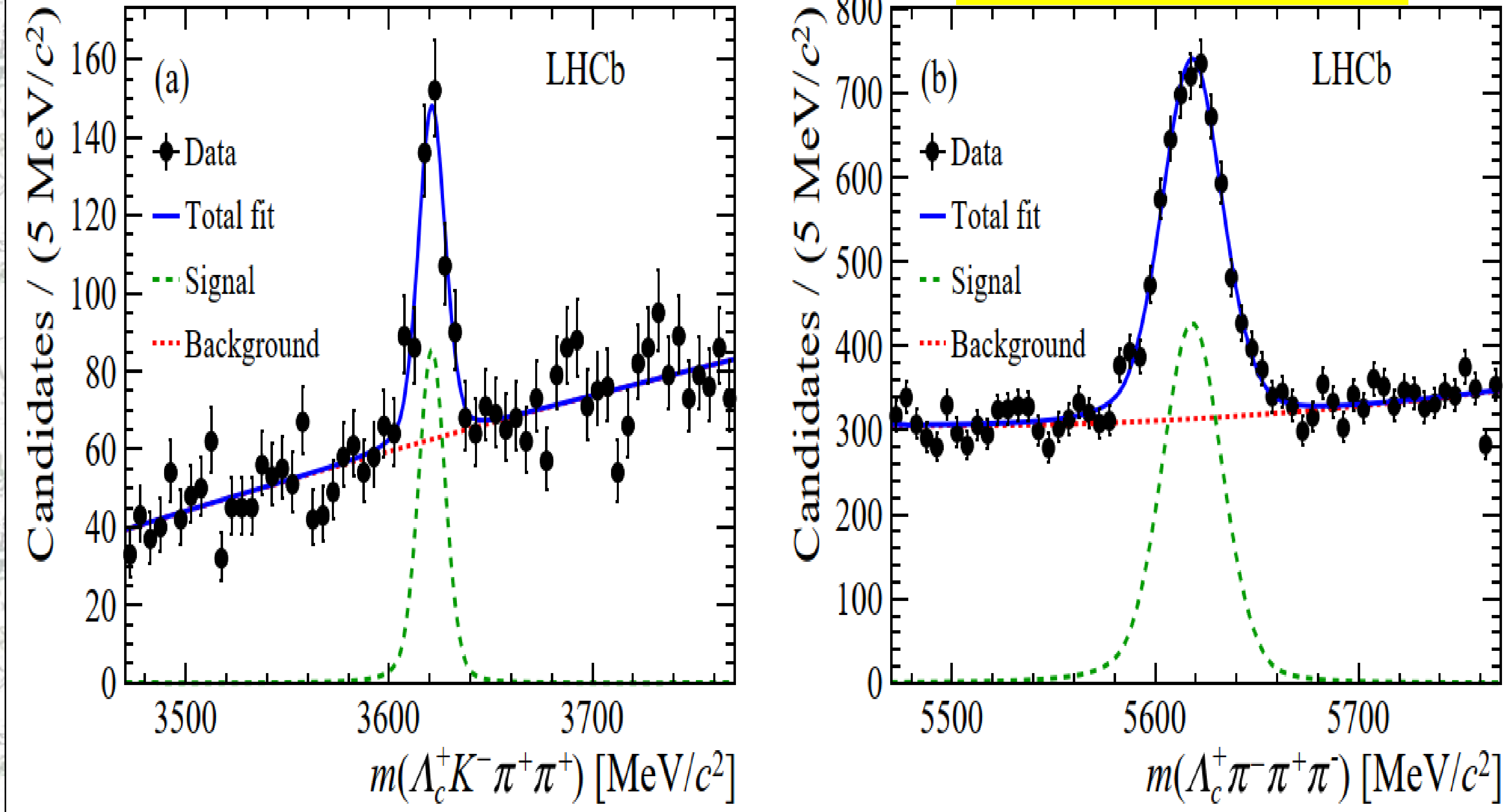
M = 3621.40 ±0.72 ±0.27 ±0.14MeV/c^2

(~ 100 MeV/c^2 above Ξ_{cc}^{+} from SELEX)



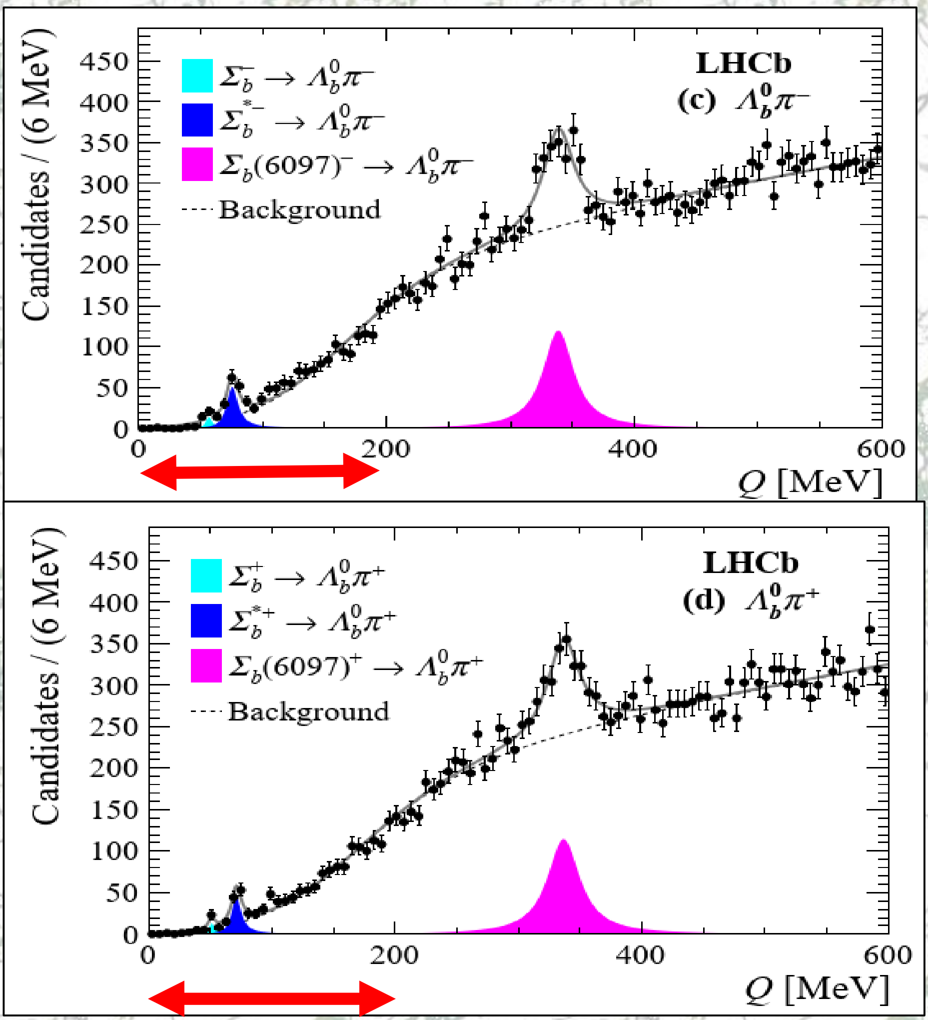
Ξ_{cc}^{++} and Λ_b^0

PRL 121(2018) 052002



Extend mass region 200→600 MeV/c^2

PRL 122(2019) 012001



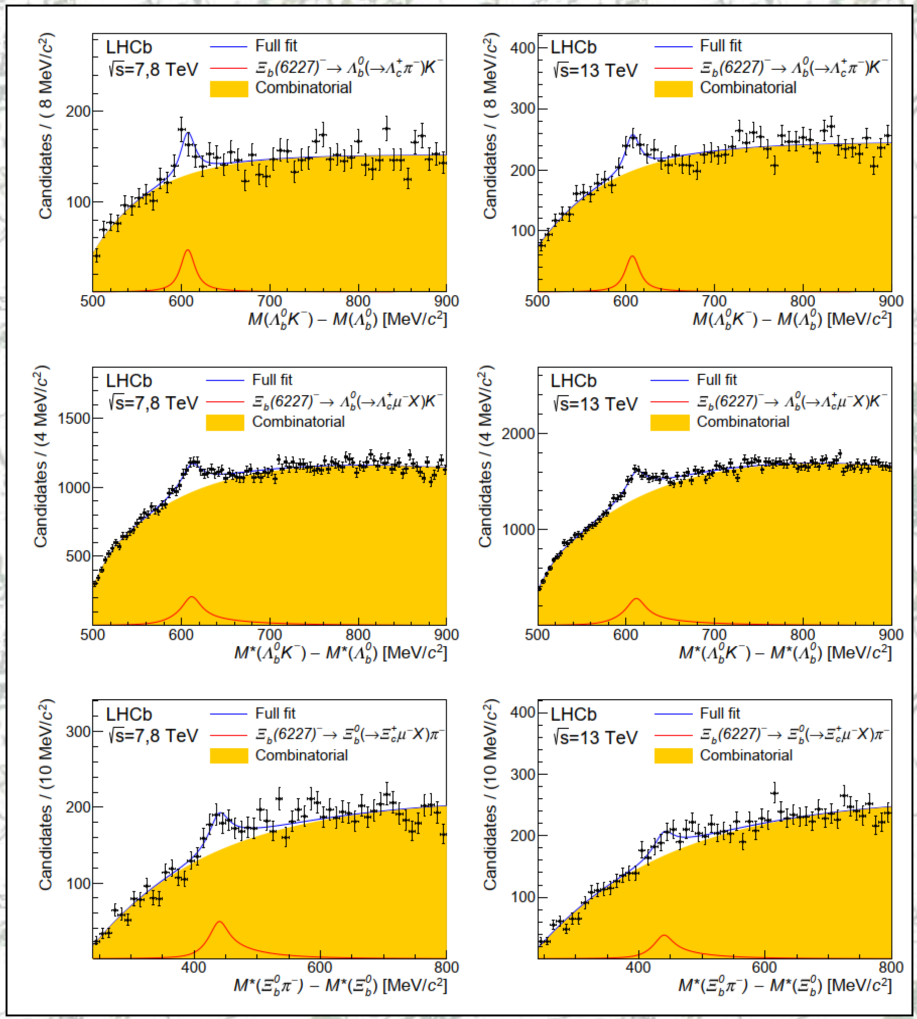
- Two new peaks!
  - $\Sigma_b(6097)^+$ & $\Sigma_b(6097)^-$
    - Significance ~13σ for each

	Quantity	Value [MeV]
	$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
	$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
	$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
	$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
Precise measurements included	$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
	$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
	$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
	$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
	$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
	$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
	$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
	$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$

(compatible with being $\Sigma_b(1P)$)

$\Xi_b(6227)^-$

PRL 121(2018) 072002



- New peak $\Xi_b(6227)^-$
  - Significance ~8σ
  - In perfect agreement for all three modes!

$$
\begin{aligned}
m_{\Xi_b(6227)^-} - m_{\Lambda_b^0} &= 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,\\
\Gamma_{\Xi_b(6227)^-} &= 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,\\
m_{\Xi_b(6227)^-} &= 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,
\end{aligned}
$$

Production ratios

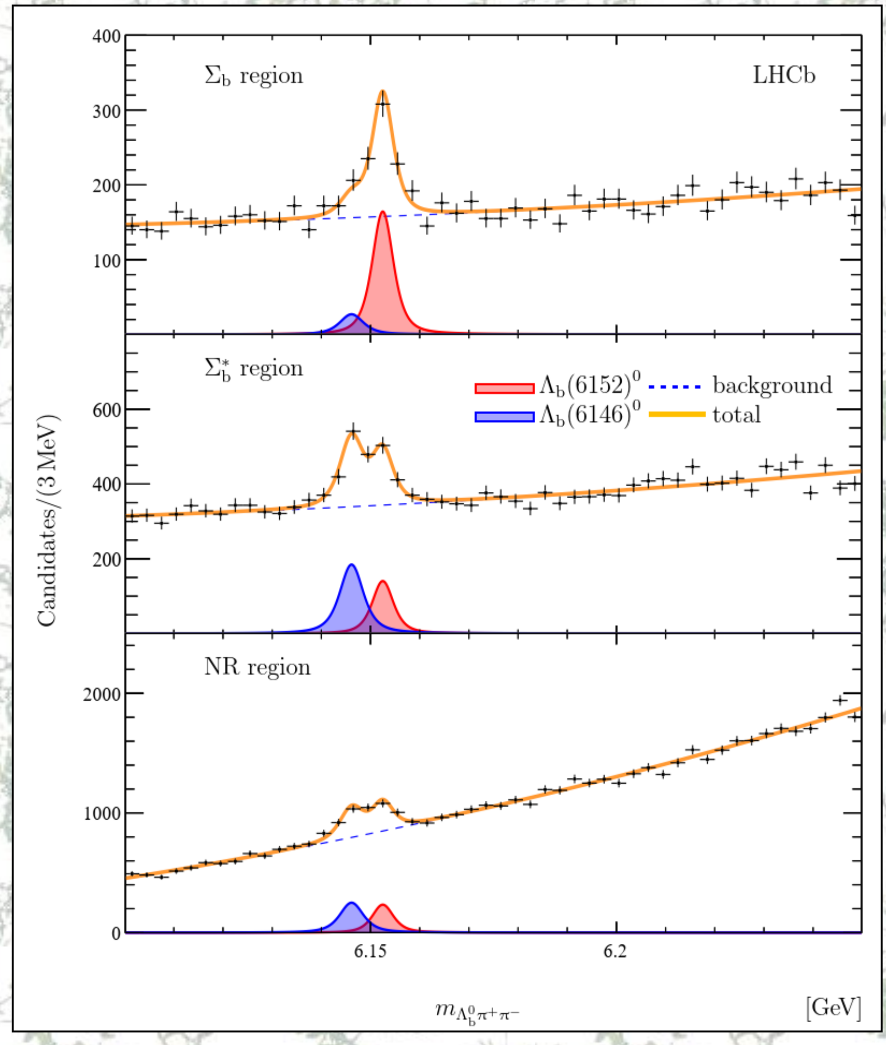
$$
R(\Lambda_b^0 K^-) \equiv \frac{f_{\Xi_b(6227)^-}}{f_{\Lambda_b^0}} \mathcal{B}(\Xi_b(6227)^- \to \Lambda_b^0 K^-),
$$

$$
R(\Xi_b^0 \pi^-) \equiv \frac{f_{\Xi_b(6227)^-}}{f_{\Xi_b^0}} \mathcal{B}(\Xi_b(6227)^- \to \Xi_b^0 \pi^-),
$$

Quantity $[10^{-3}]$	7 , 8 TeV	13 TeV
$R(\Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$R(\Xi_b \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

Intermediate Σ_b/Σ_b^* ?

PRL 123(2019) 152001



Select Σ_b/Σ_b^*/NR "regions"

- 2 almost degenerate peaks!
- >7σ with respect to 1-peak
- very similar widths

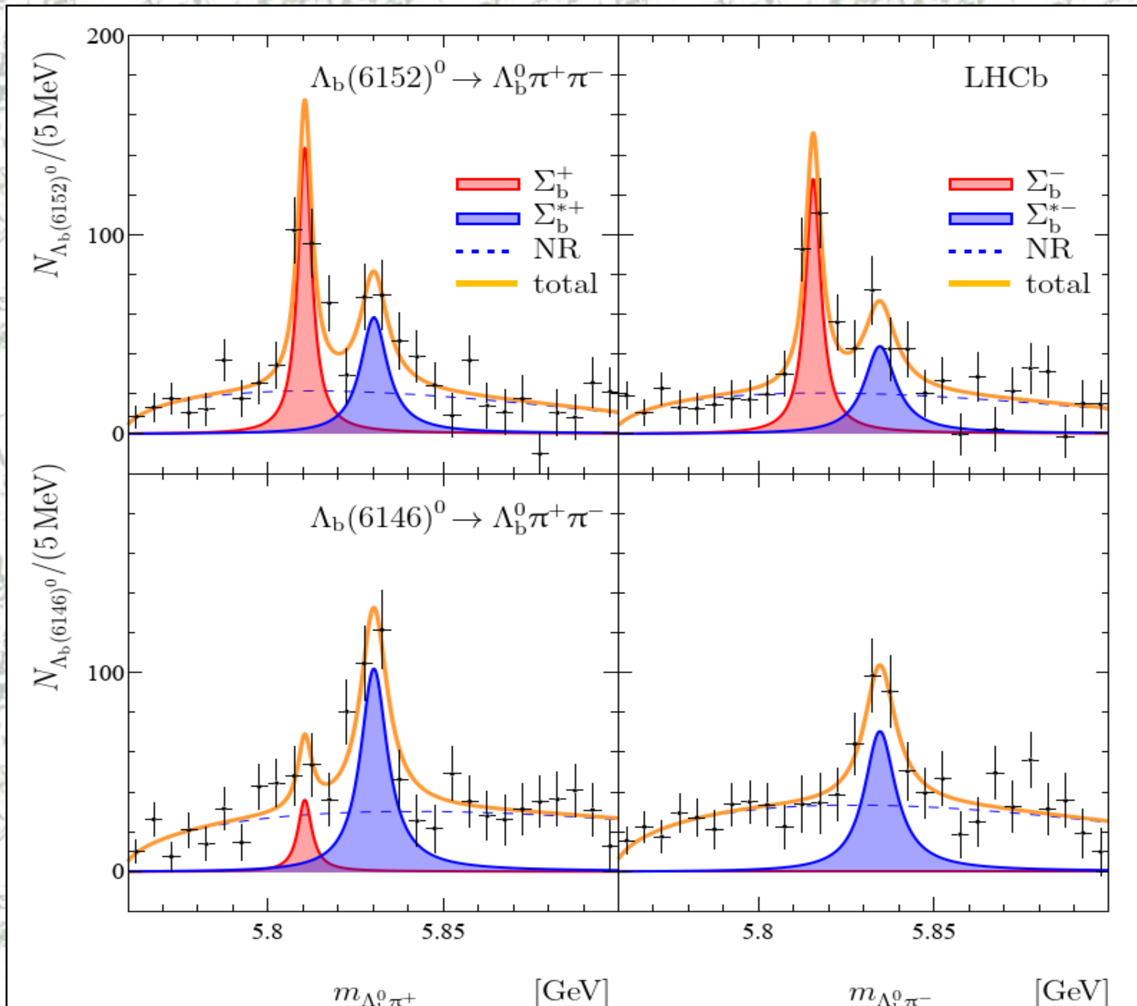
$$
\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\mathrm{MeV}\,,\\
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\mathrm{MeV}\,,\\
\Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3\,\mathrm{MeV}\,,\\
\Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3\,\mathrm{MeV}\,,
\end{aligned}
$$

- Mass difference:
  - $6.34 \pm 0.32 \pm 0.02\ \mathrm{MeV}/c^2$

$$
\begin{aligned}
m_{\Lambda_b(6146)^0} - m_{\Lambda_b^0} &= 526.55 \pm 0.33 \pm 0.10\,\mathrm{MeV}\,,\\
m_{\Lambda_b(6152)^0} - m_{\Lambda_b^0} &= 532.89 \pm 0.26 \pm 0.10\,\mathrm{MeV}\,,
\end{aligned}
$$

Intermediate Σ_b/Σ_b^* ?

PRL 123(2019) 152001



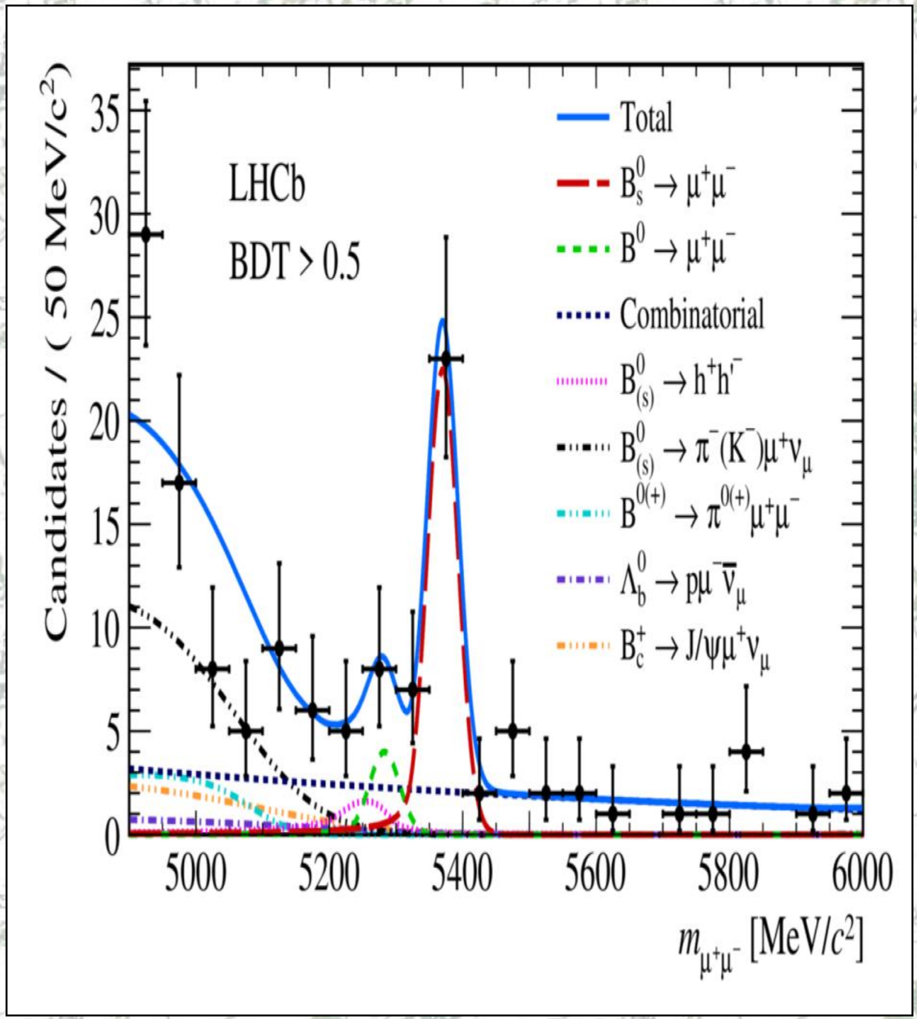
	N	$\mathcal{S}_W$
$\Lambda_b(6152)^0 \to \Sigma_b^+\pi^-$	213 ± 44	7.8σ
$\Lambda_b(6152)^0 \to \Sigma_b^-\pi^+$	208 ± 43	7.6σ
$\Lambda_b(6152)^0 \to \Sigma_b^{*+}\pi^-$	163 ± 45	5.3σ
$\Lambda_b(6152)^0 \to \Sigma_b^{*-}\pi^+$	141 ± 45	4.5σ
$\Lambda_b(6146)^0 \to \Sigma_b^+\pi^-$	53 ± 30	2.3σ
$\Lambda_b(6146)^0 \to \Sigma_b^-\pi^+$	0 ± 20	—
$\Lambda_b(6146)^0 \to \Sigma_b^{*+}\pi^-$	285 ± 51	8.4σ
$\Lambda_b(6146)^0 \to \Sigma_b^{*-}\pi^+$	227 ± 52	6.3σ

Puzzle ?

- High mass state
  decays into $\Sigma_b\pi$ and $\Sigma_b^*\pi$
- Low mass state
  decays only to $\Sigma_b^*\pi$

1D dublet with inverse mass hierarchy?

$B_s \to \mu^+\mu^-$



- (Di)muon trigger
- Excellent mass resolution
- Efficient muon ID
- Multivariate analysis
- 31 signal Bs events

- Confirmed by CMS and ATLAS
- Combined LHC result for Run-I&II in progress

$B_s \to \mu^+\mu^-$ 2020

Next Wednesday, August 5 at ICHEP-2020

Combination of the ATLAS, CMS and LHCb results on the $B^0_{(s)} \to \mu^+\mu^-$ decays

The ATLAS, CMS and LHCb collaborations

Abstract

A combination of results on the rare $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays from the ATLAS, CMS, and LHCb experiments using data collected between 2011 and 2016, is presented.