LHCb

technische universität dortmund

European Research Council
Established by the European Commission

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

What's new at LHCb?

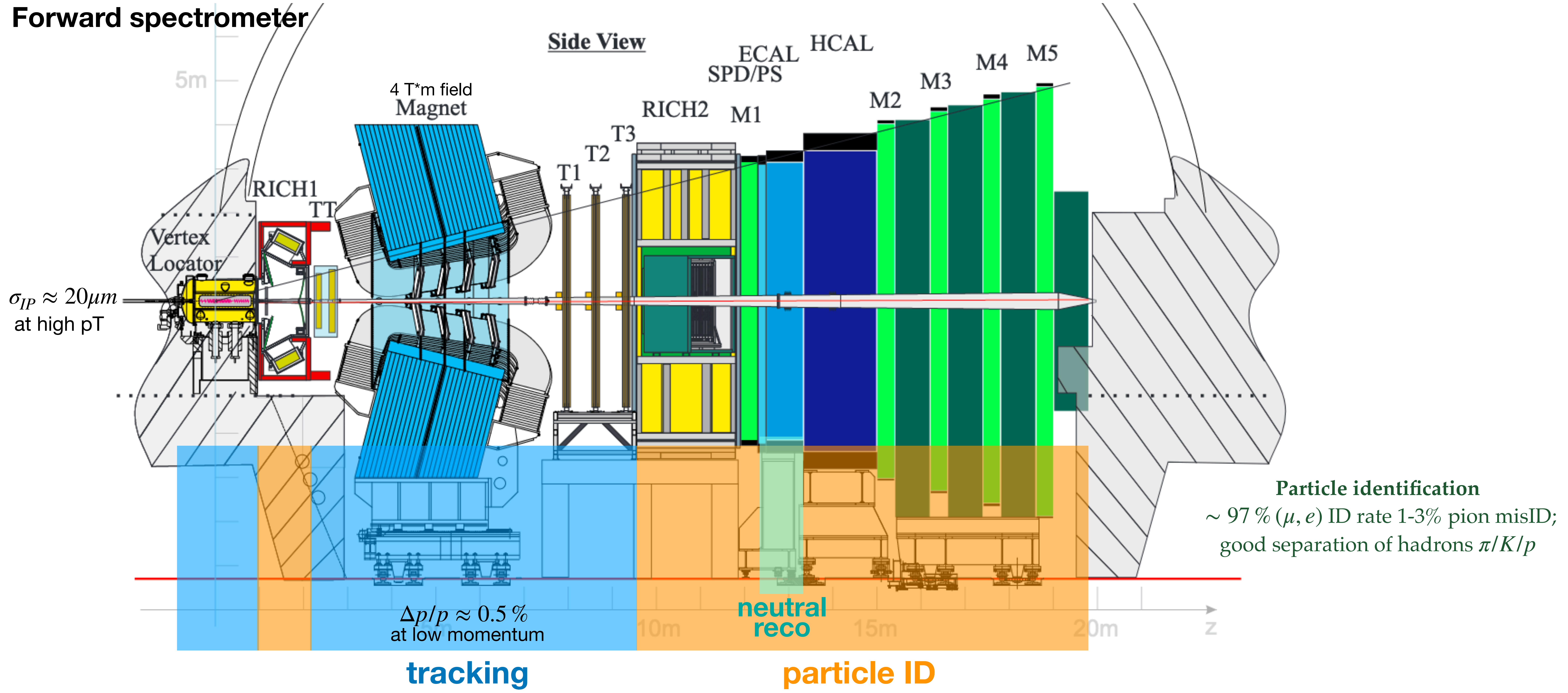
Vitalii Lisovskyi (TU Dortmund)
for the LHCb Collaboration

Belle II Germany Meeting
20/Sep/2021

photo: Janina Nicolini

2010–2018 (RUNS 1–2)

Forward spectrometer



- Collected about 9 fb^{-1} integrated luminosity at 7-8-13 TeV pp collisions with >90% data-taking efficiency
  - instantaneous luminosity $\sim 3 \times 10^{32}\, cm^{-2}s^{-1}$
  - shorter runs in other conditions (pPb, PbPb, p-gas fixed-target, etc)

Produce all types of b hadrons:

- Weakly-decaying
  - B^+, B^0: 35% each
  - B_s^0: 8.5%
  - Λ_b^0 (udb): 18%
  - Ξ_b^0, Ξ_b^- (usb, dsb): ~1.5% each
  - B_c^+, Ω_b^- (ssb): ~0.3% each
- Bottomonia

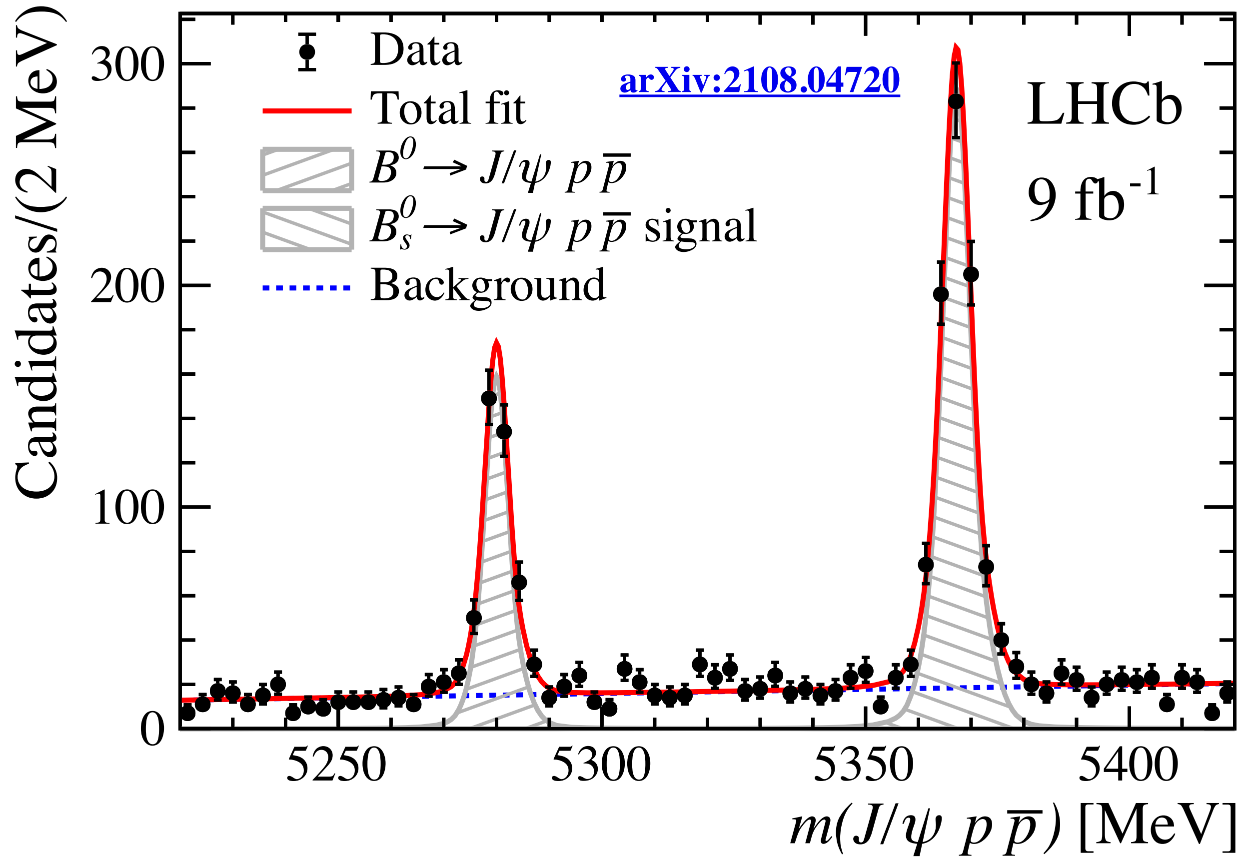
Cross-section of $b\bar{b}$ production ~150 μb

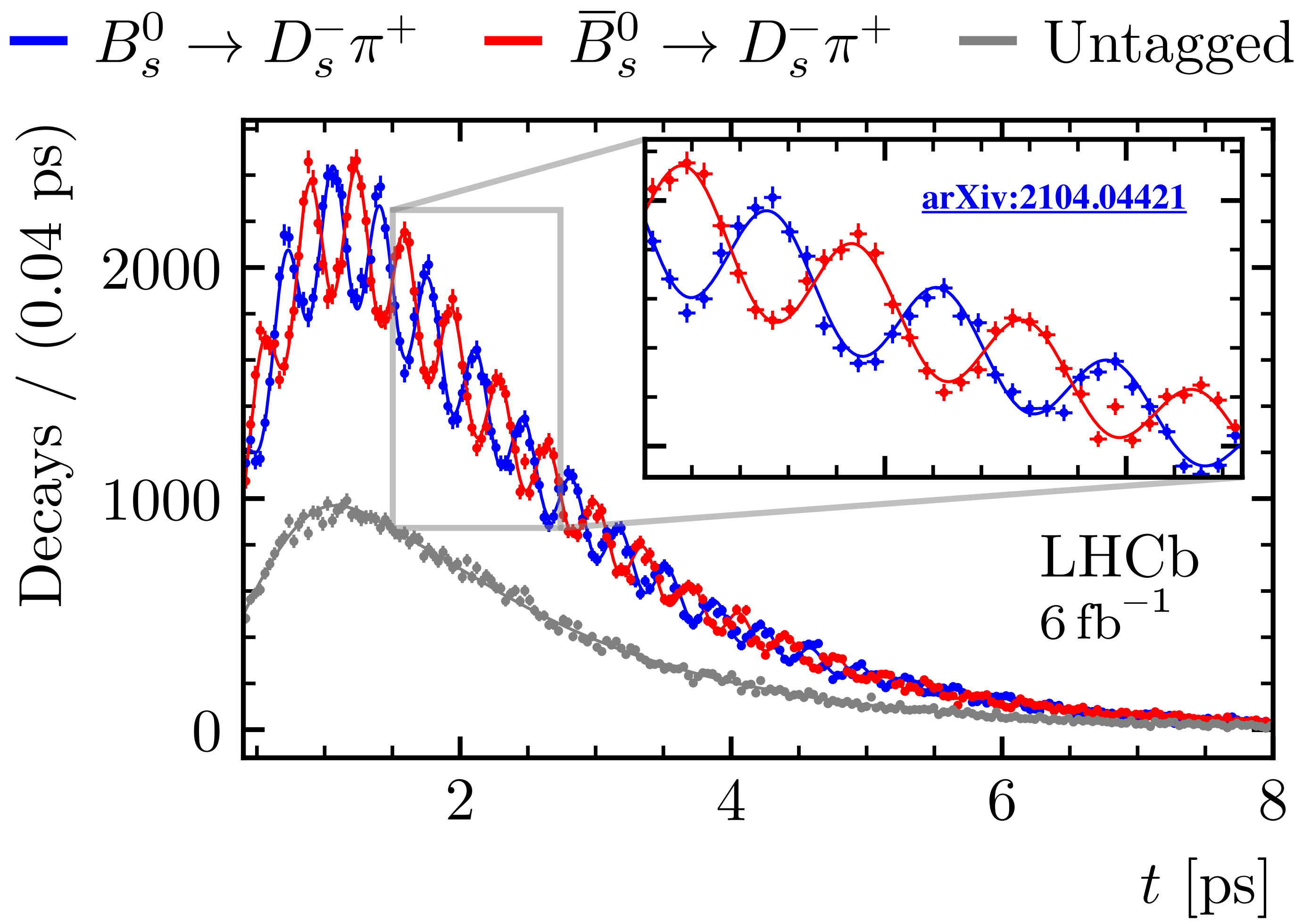
Huge cross-section of charm and strange hadrons

Large b-hadron flight distance (~mm-cm)

good time resolution → resolve B_s^0 oscillations

good mass resolution → resolve B_s^0 and B^0



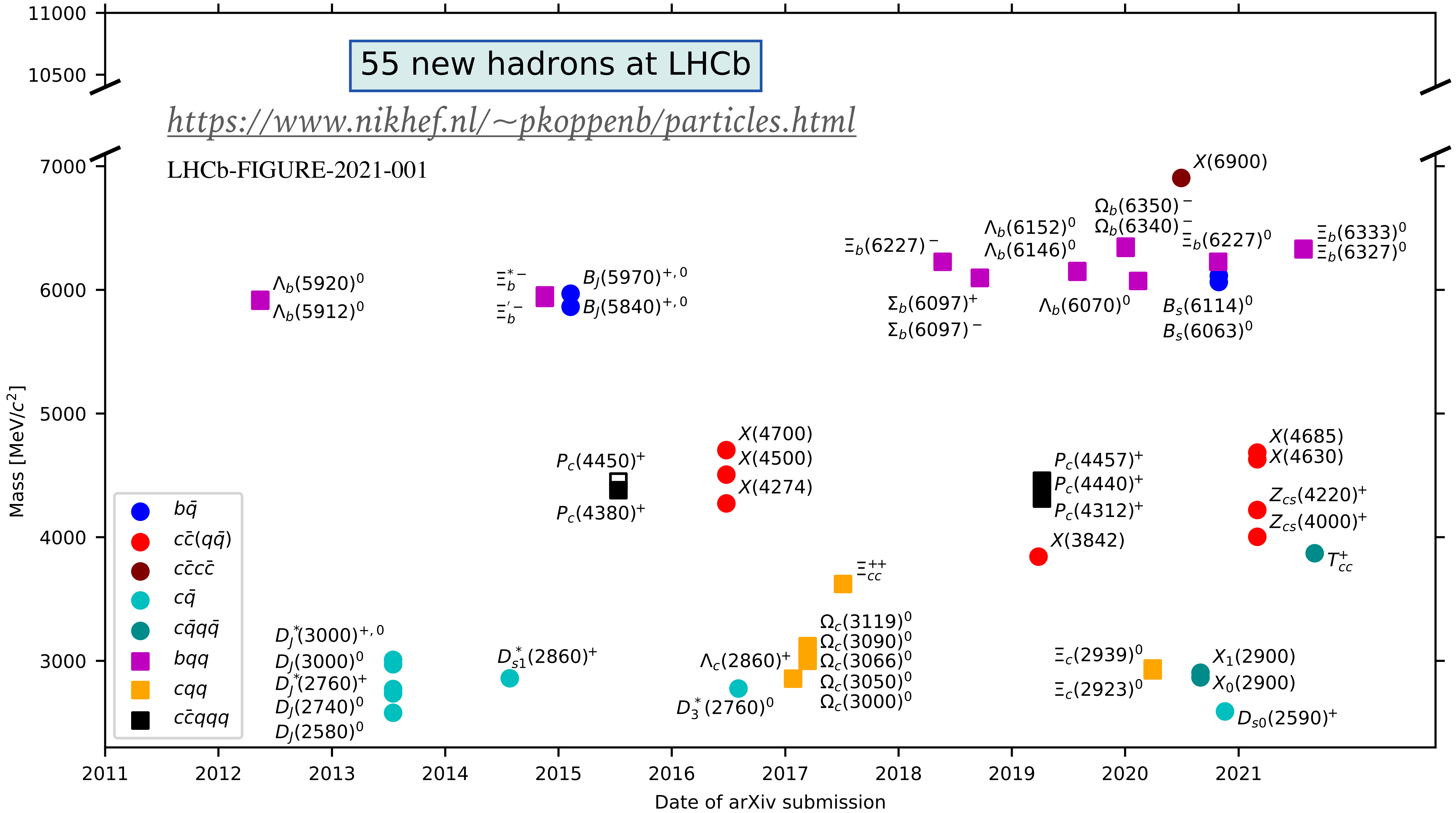


- **Compared to ATLAS/CMS:** forward acceptance; dedicated soft triggers; but lower luminosity
- **Compared to Belle II:**
  - no $B\bar{B}$ entanglement (a $b\bar{b}$ can hadronise to e.g. $B_s^0\bar{\Lambda}_b^0$); no beam-energy-constraint
  - less efficient flavour tagging
  - we prefer relative measurements (BF, lifetimes) to absolute ones
- See the excellent talk on Belle II vs LHCb detailed comparison by Diego Tonelli

We are happy to see so many complementary players in flavour physics!

Conventional spectroscopy:
charm/beauty baryons & mesons in ground or excited states

Exotic spectroscopy:
tetra- and pentaquark candidates

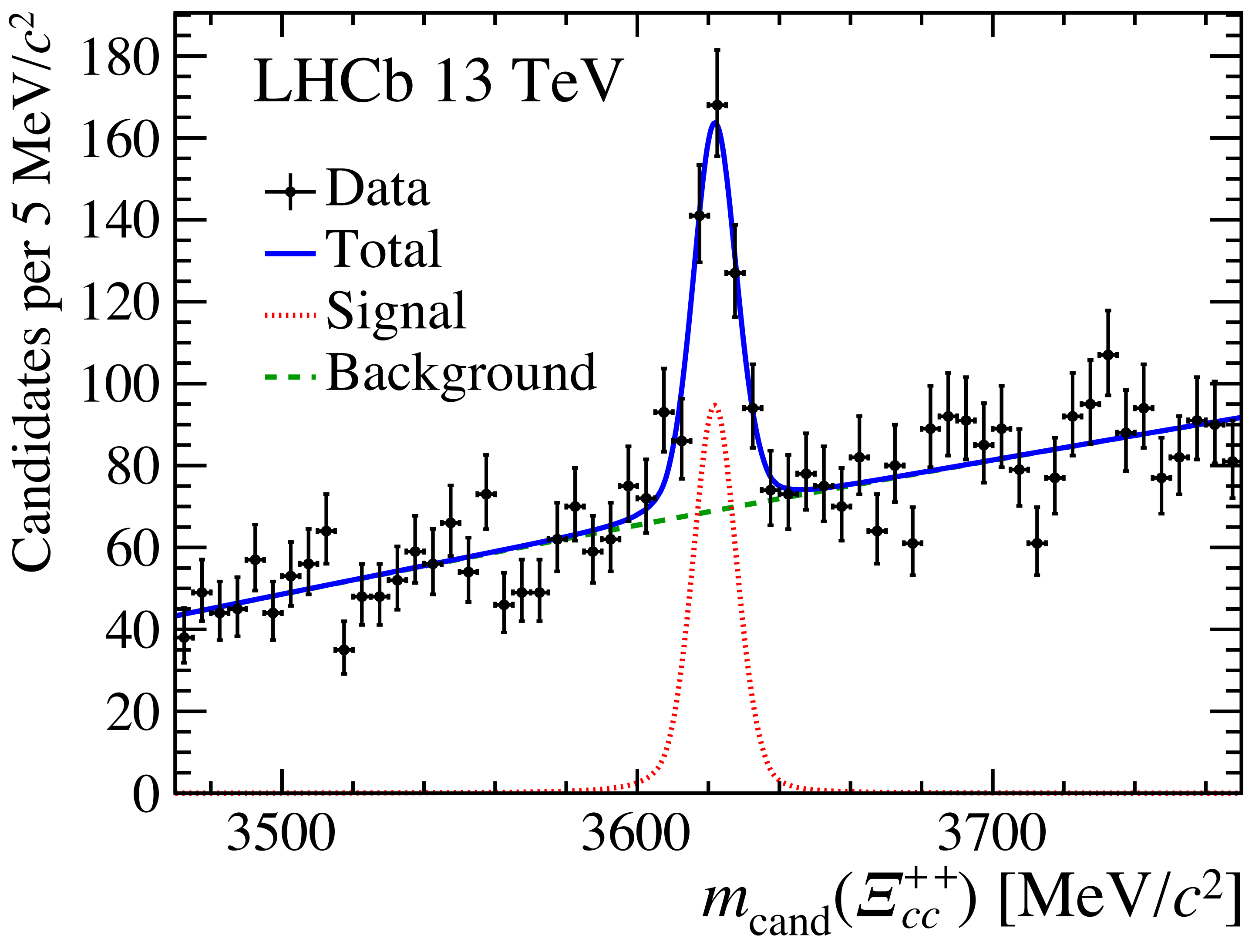


arXiv: 2109.01038 , 2109.01056

Full Run1+Run2 dataset

- States with two charm quarks (rather than a $c\bar{c}$ pair):

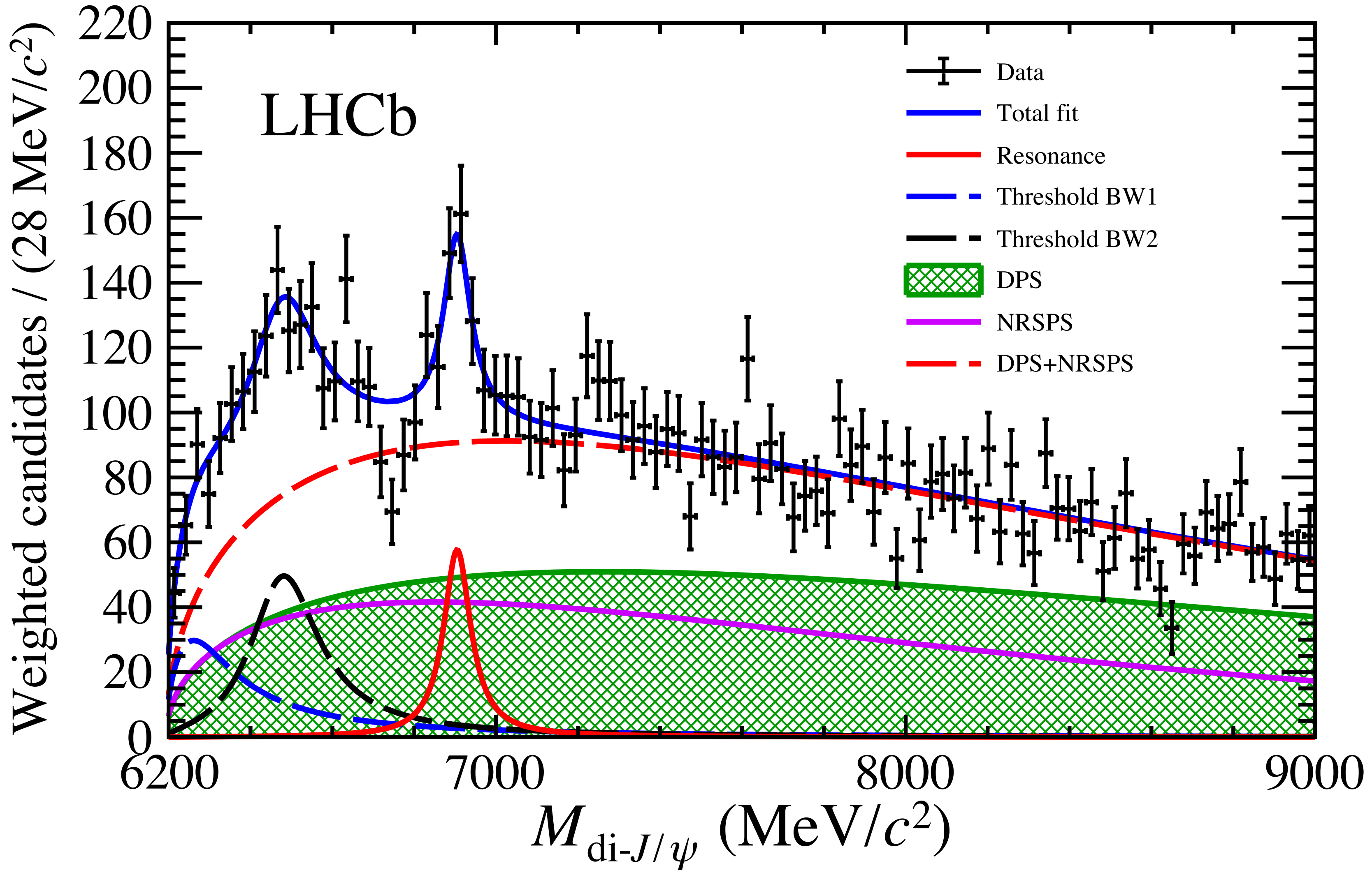
2017



$\Xi_{cc}^{++}\,(ccu)$

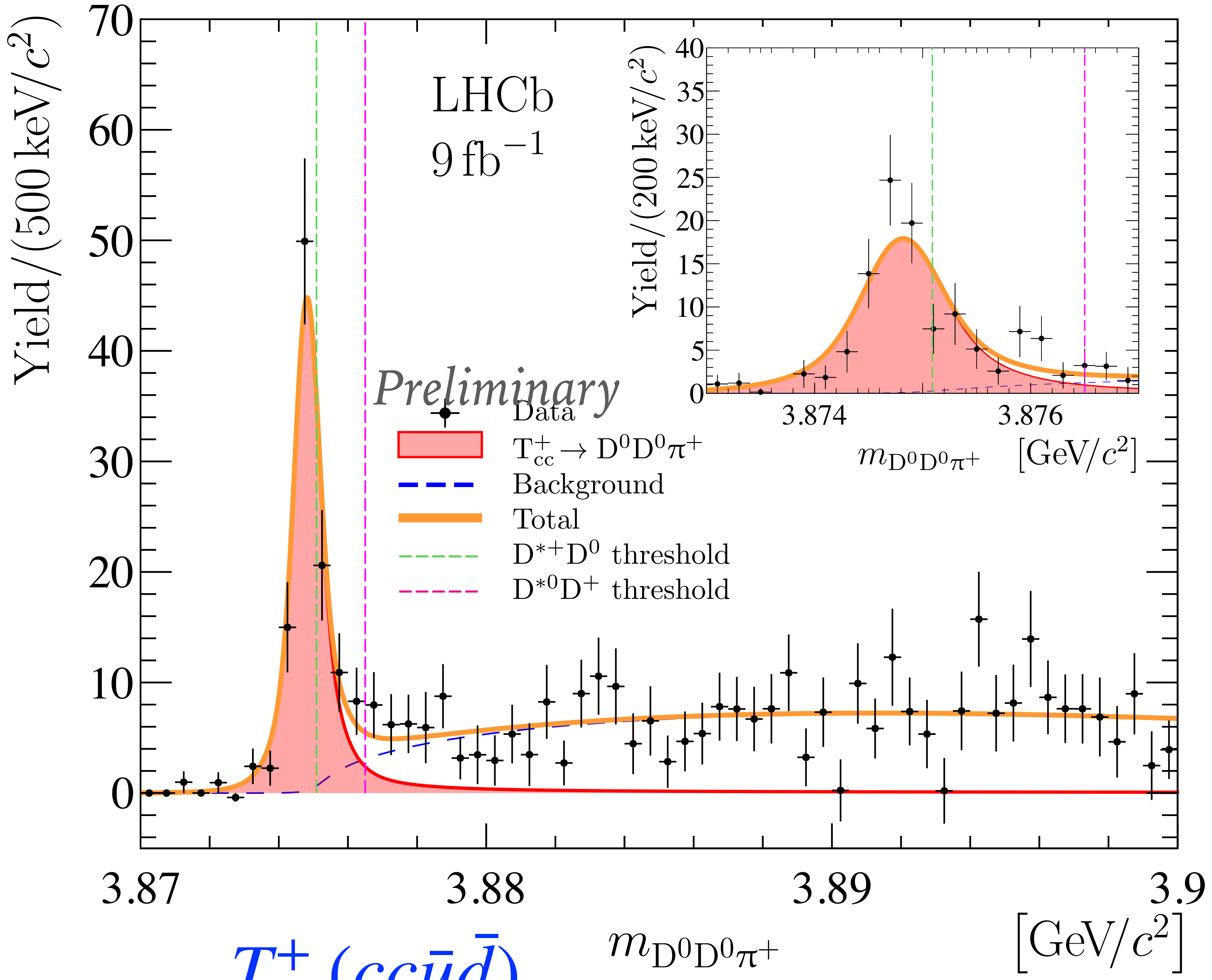
also: searches for Ξ_{cc}^{+} (ccd)

2020



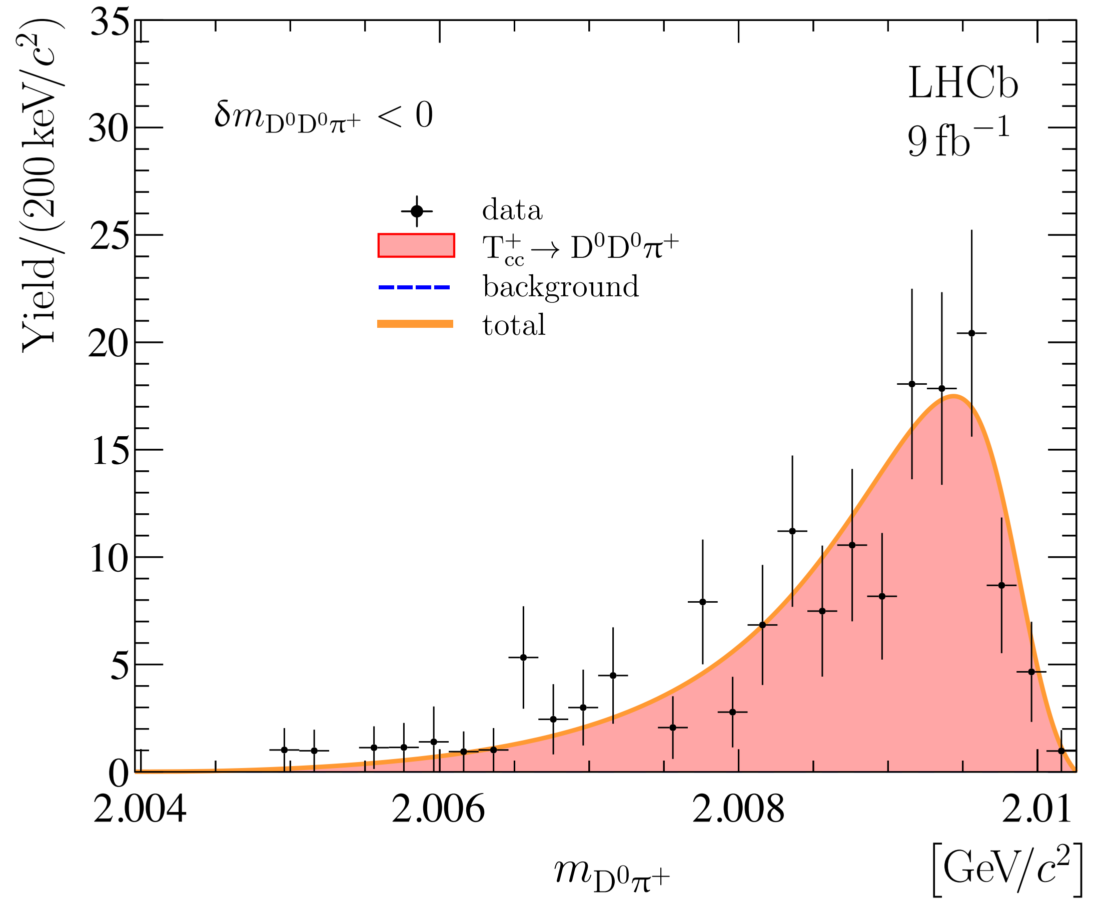
structure in $m(J/\psi J/\psi)$: $(cc\bar{c}\bar{c})$

2021: NEW



$T_{cc}^{+}\,(cc\bar{u}\bar{d})$

- Observation of a narrow peak in $m(D^0D^0\pi^+)$ at the threshold
  - manifestly exotic state: $cc\bar{u}\bar{d}$; expected isospin 0 and $J^P = 1^+$
  - decays via off-shell D^{*+}



- Mass measurement: relativistic Breit-Wigner lineshape gives $\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0}) = -273 \pm 61(\text{stat}) \pm 5(\text{syst})^{+11}_{-14}(J^P)\ \text{keV}/c^2$;

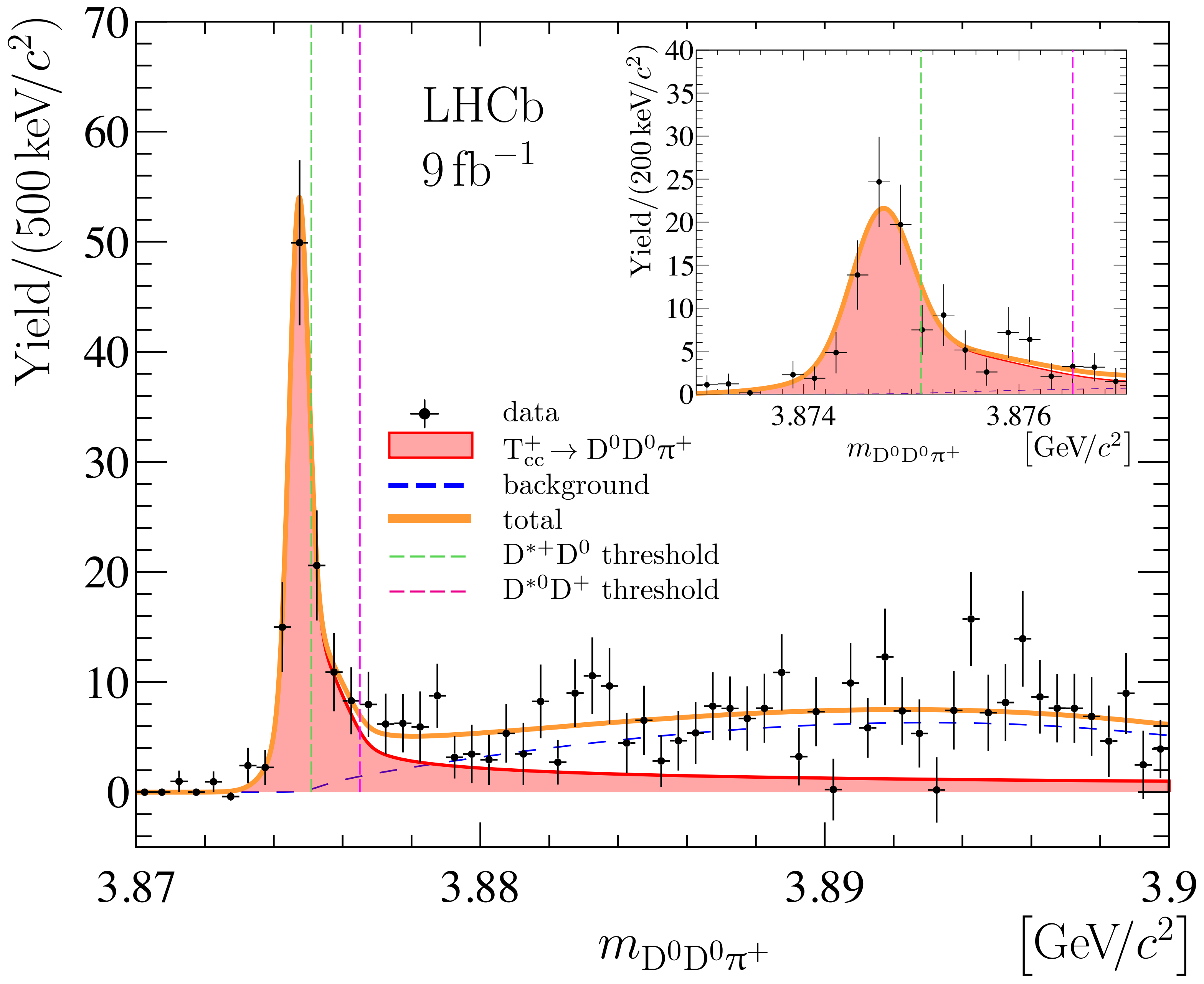
mass ~3874.8 MeV/c²

  - consistent with some of theoretical predictions

- **width** $\Gamma_{\text{BW}} = 410 \pm 165(\text{stat}) \pm 43(\text{syst})^{+18}_{-38}(J^P)$ keV

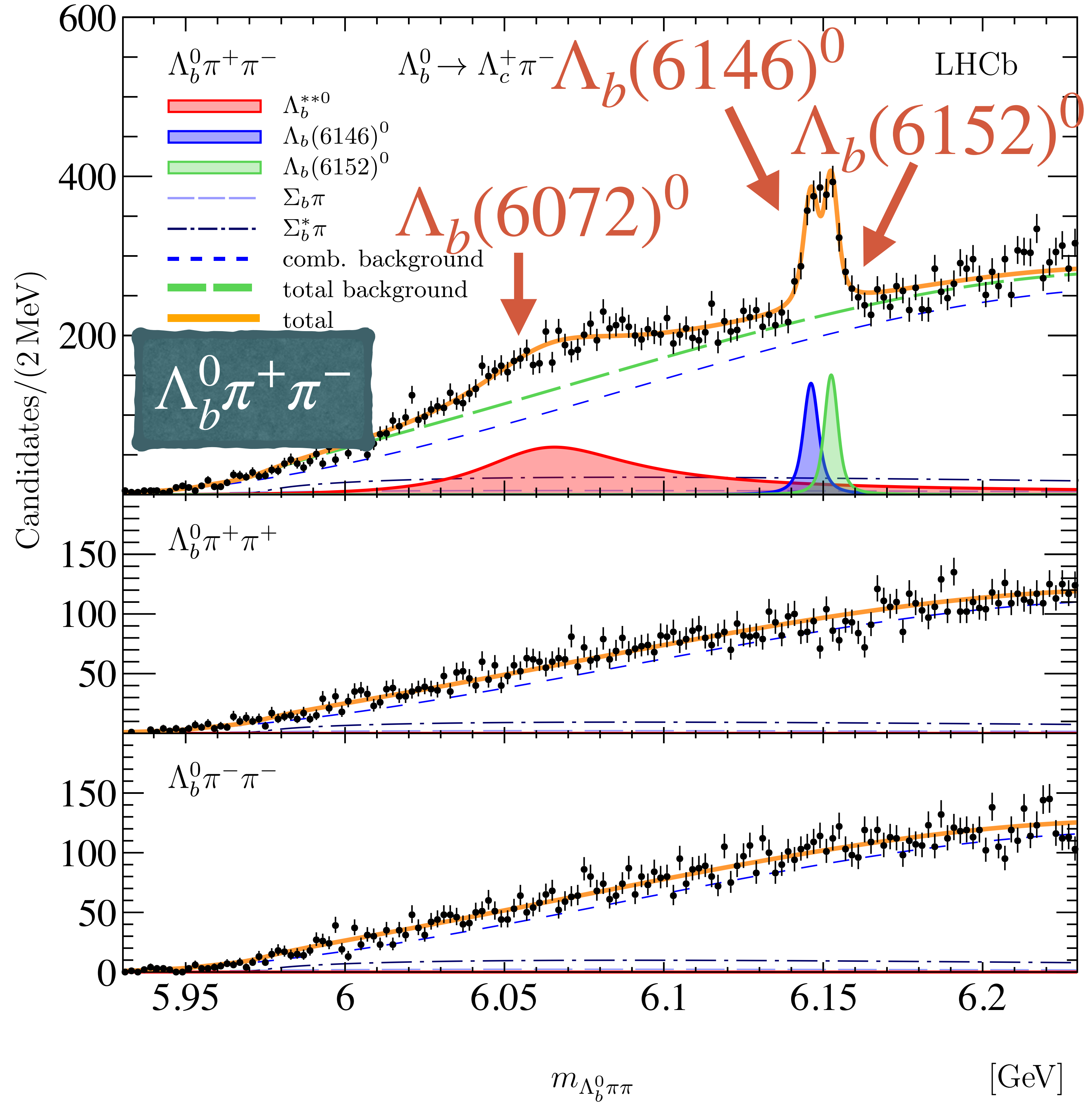
the smallest BW width of any known exotic state

- A more physical lineshape model explored as well: take into account thresholds openings & unitarity
  - A plethora of other studies: pole position, multiplicity dependence, characteristic size, etc

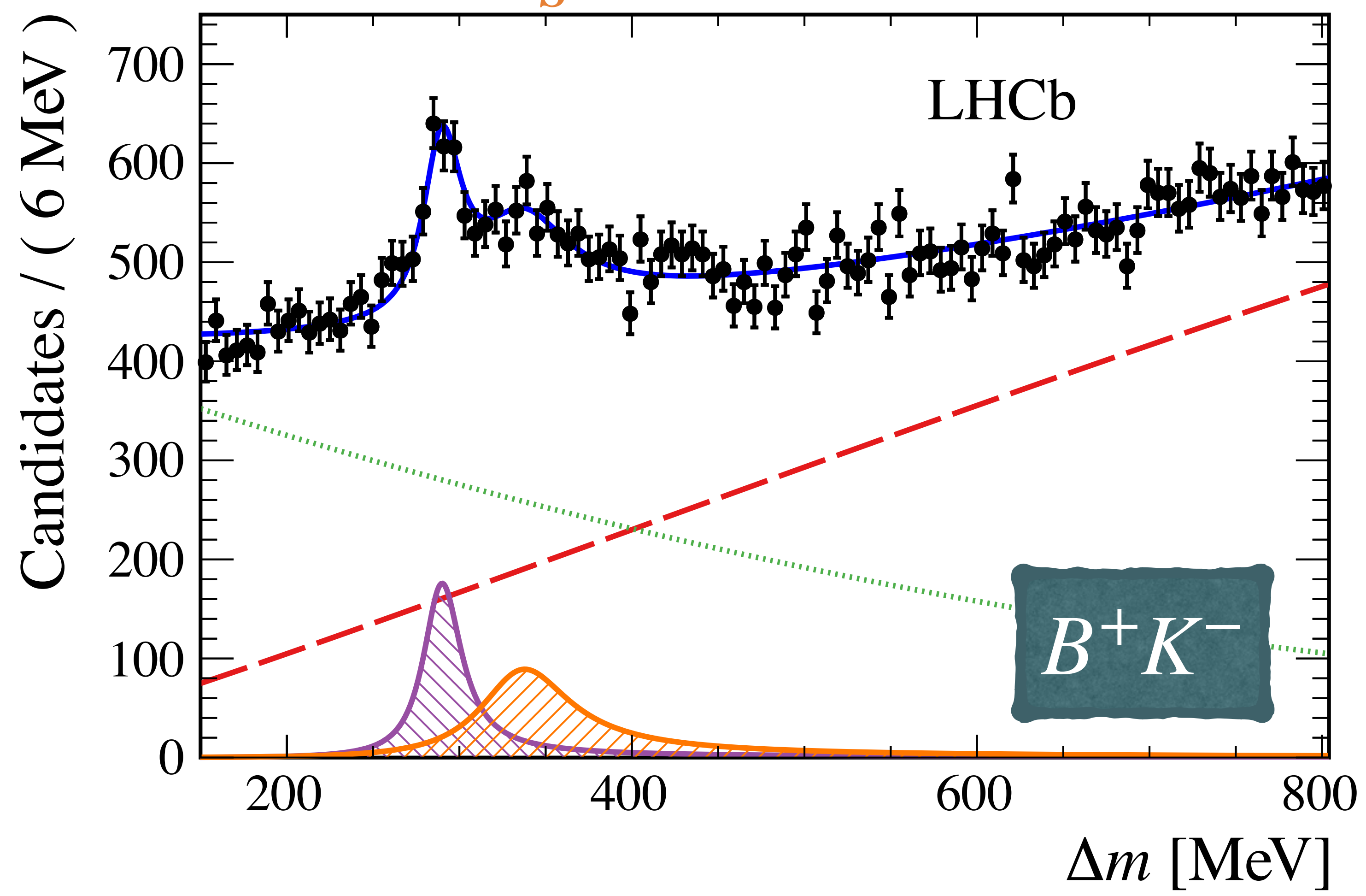


- This result likely implies existence of a **weakly**-decaying $bb\bar{u}\bar{d}$ state (a tetraquark flying some mm before decay?)

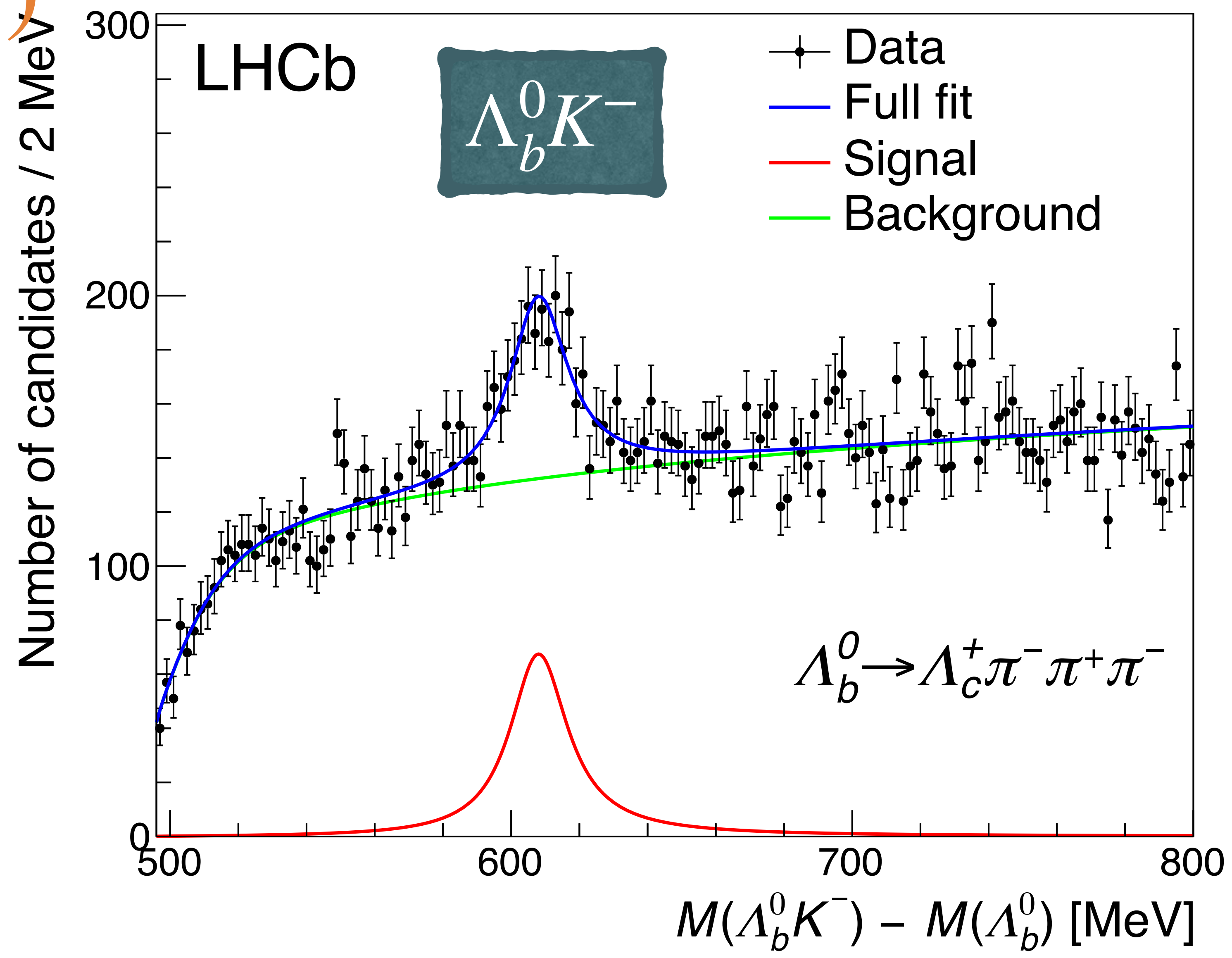
$\Lambda_b^0 = (udb)$



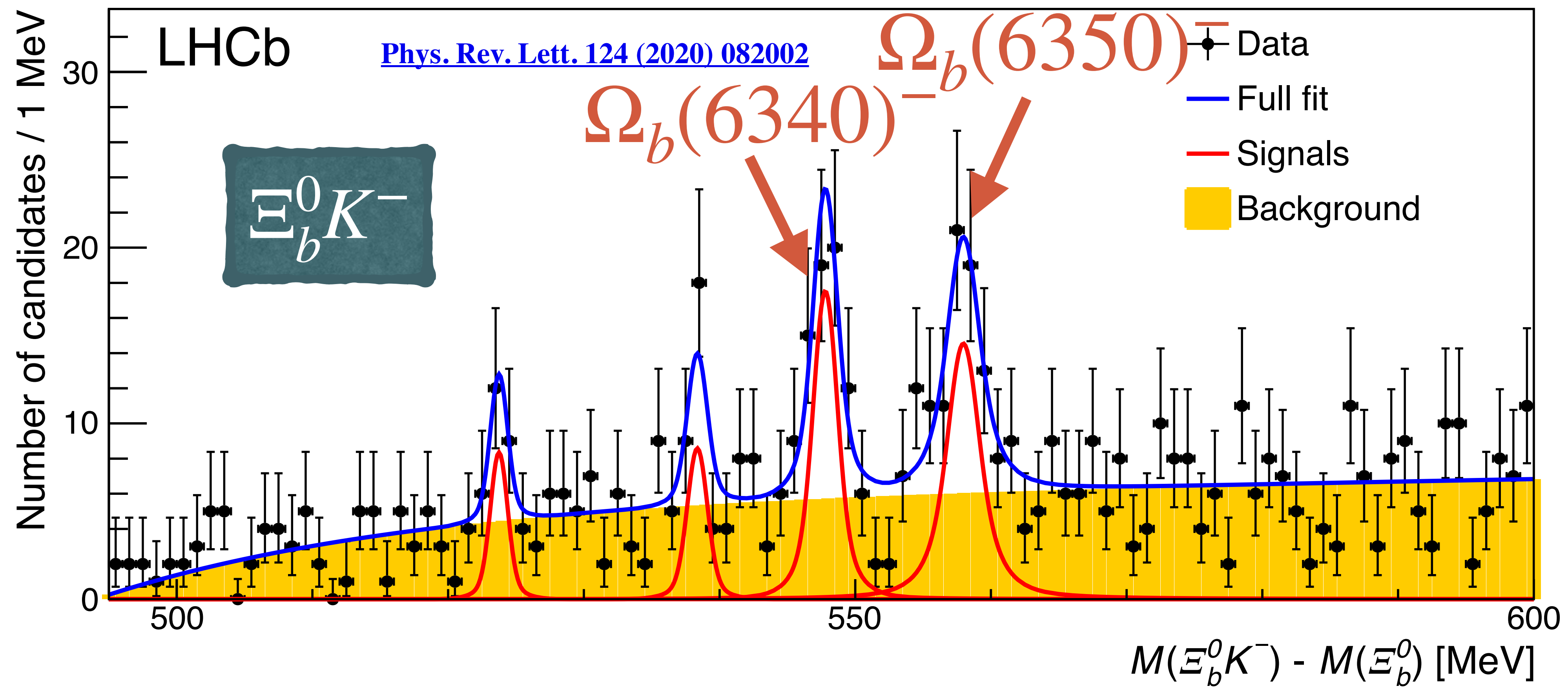
$B_s^0 = (\bar{b}s)$



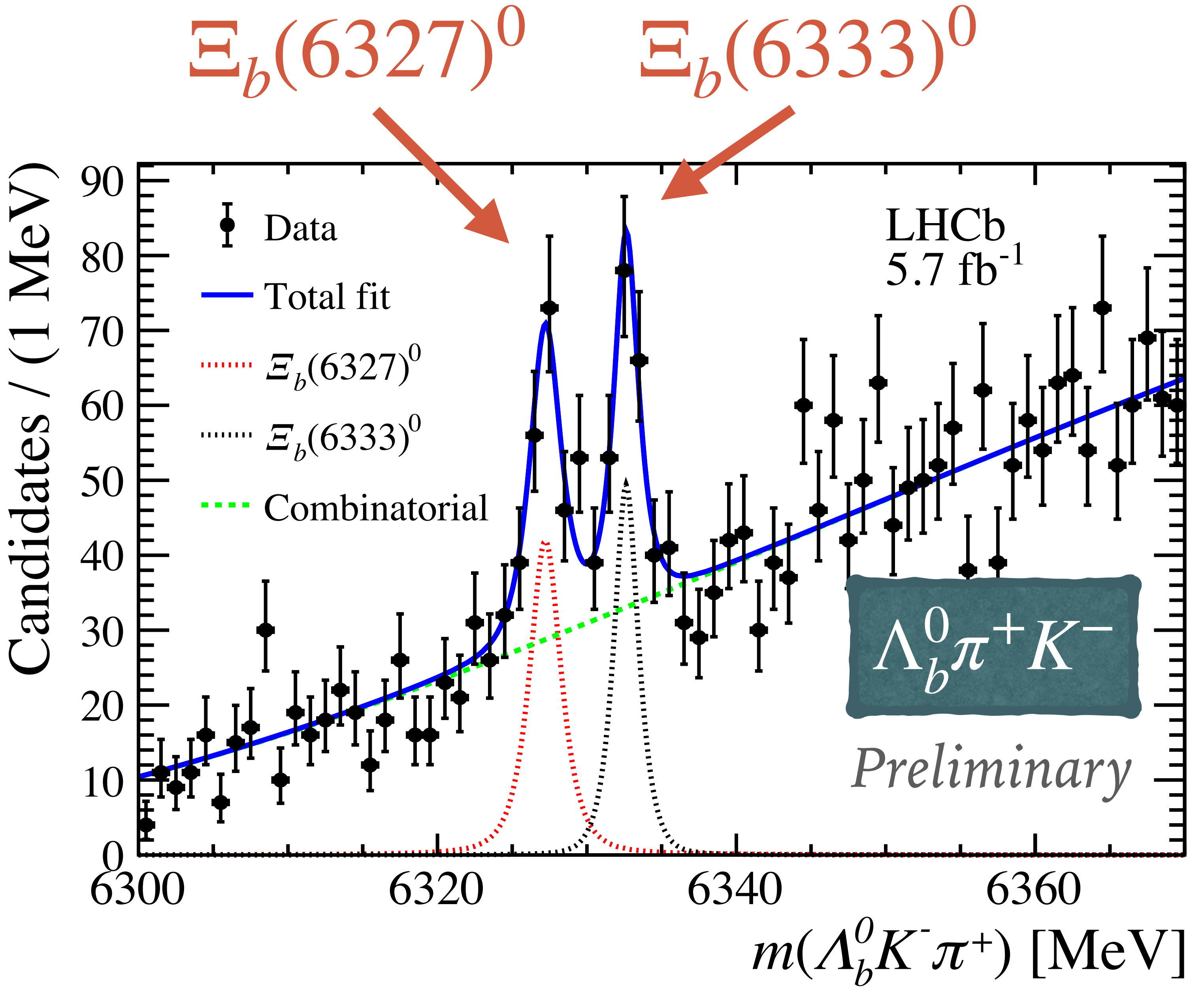
$\Xi_b^- = (dsb)$



$\Omega_b^- = (ssb)$



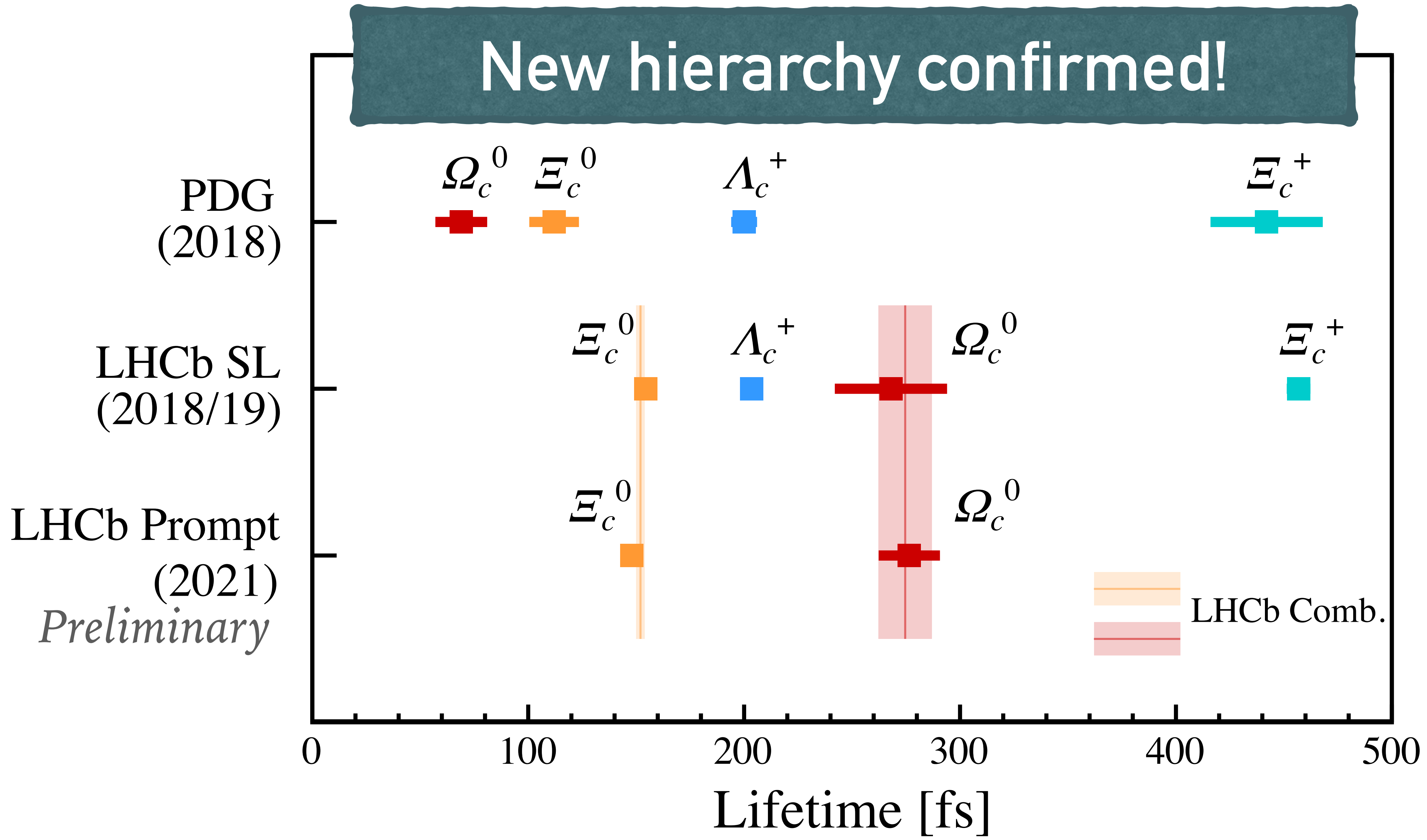
$\Xi_b^0 = (usb)$



 arXiv: 2109.01334 Run 2 dataset

- PDG'2018: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$; $\tau(\Omega_c^0) = 69 \pm 12$ fs (fixed-target data)
  (usc) (udc) (dsc) (ssc)
- LHCb, 2018-2019: measurement of lifetimes of charm baryons produced in **semileptonic** decays of beauty baryons PRL 121 (2018) 092003; PRD 100 (2019) 032001
  - Lifetimes of Ω_c^0 and Ξ_c^0 changed significantly, **new hierarchy**: $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$; $\tau(\Omega_c^0)$ **four times larger than the world average**
- **Now: we measure the lifetimes of Ω_c^0 and Ξ_c^0 with prompt production**
  - larger signal, but higher backgrounds
  - relative measurement: $\Xi_c^0, \Omega_c^0 \to pK^-K^-\pi^+$ vs $D^0 \to K^+K^-\pi^+\pi^-$

Average of LHCb results:
$\tau(\Omega_c^0) = 274.5 \pm 12.4$ fs
$\tau(\Xi_c^0) = 152.0 \pm 2.0$ fs



- PDG'2018: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$; $\tau(\Omega_c^0) = 69 \pm 12$ fs (fixed-target data)

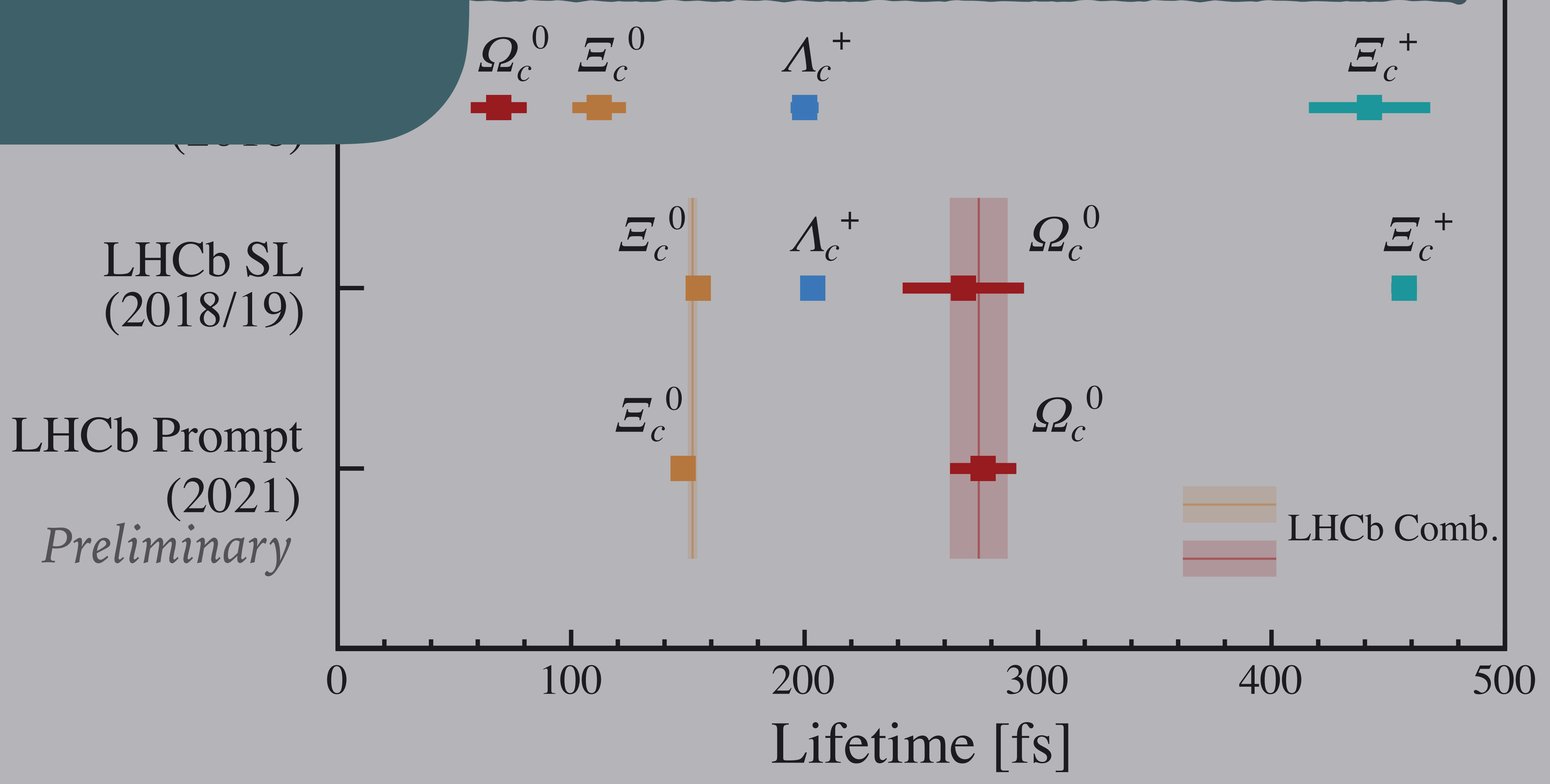
  (usc) (udc) (dsc) (ssc)

- LHCb, 2018-2019: measurement of lifetimes of charm baryons produced in **semileptonic** decays of beauty baryons PRL 121 (2018) 092003; PRD 100 (2019) 032001
  - Lifetimes of Ω_c^0 and Ξ_c^0 cha… …$) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$; $\tau(\Omega_c^0)$ **four times larger th…**

- **Now: we measure the lif… production**
  - larger signal, but higher ba…
  - relative measurement: Ξ_c^0, … vs $D^0 \to K^+K^-\pi^+\pi^-$

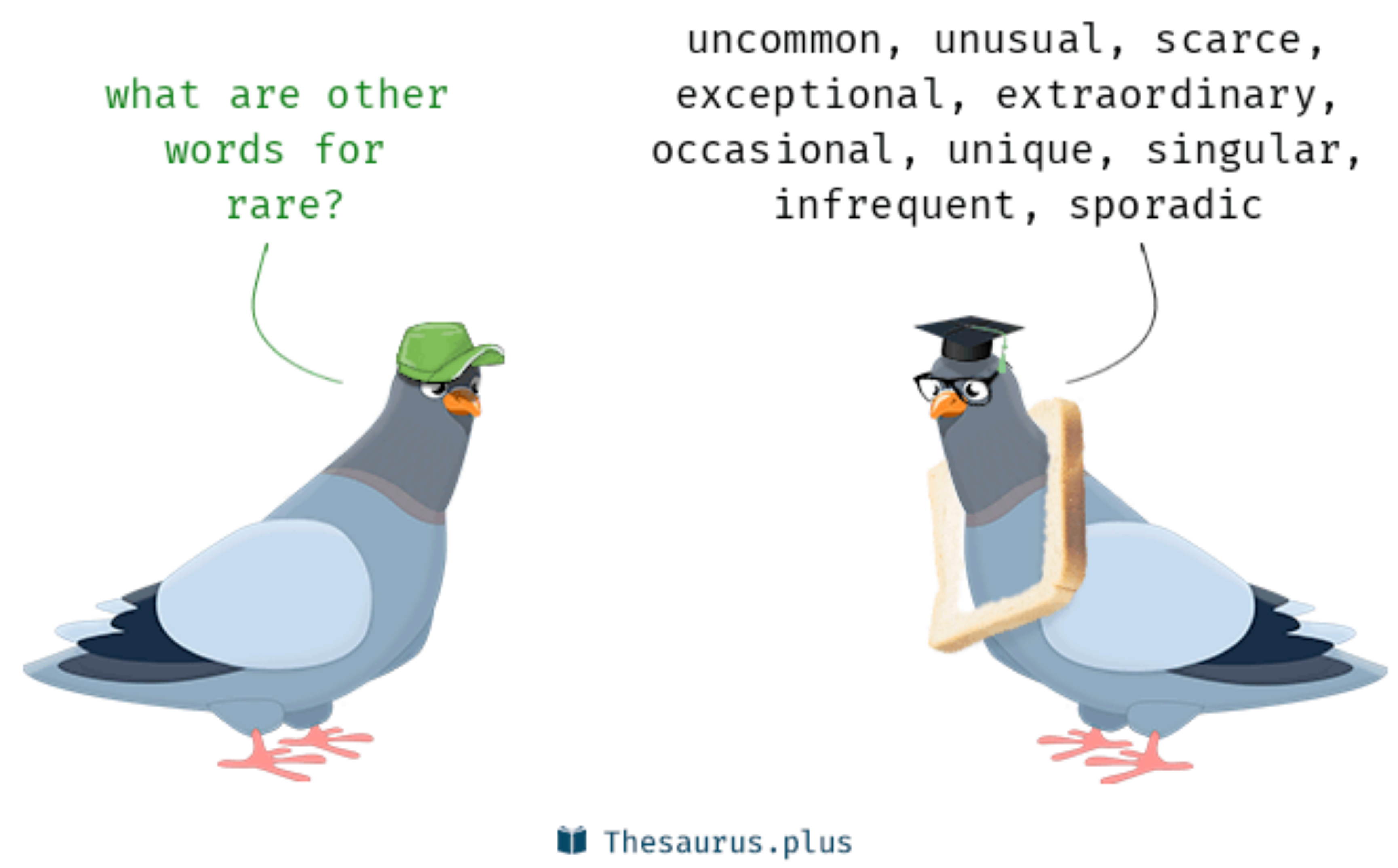
Question: can we hope for measurements from Belle II?

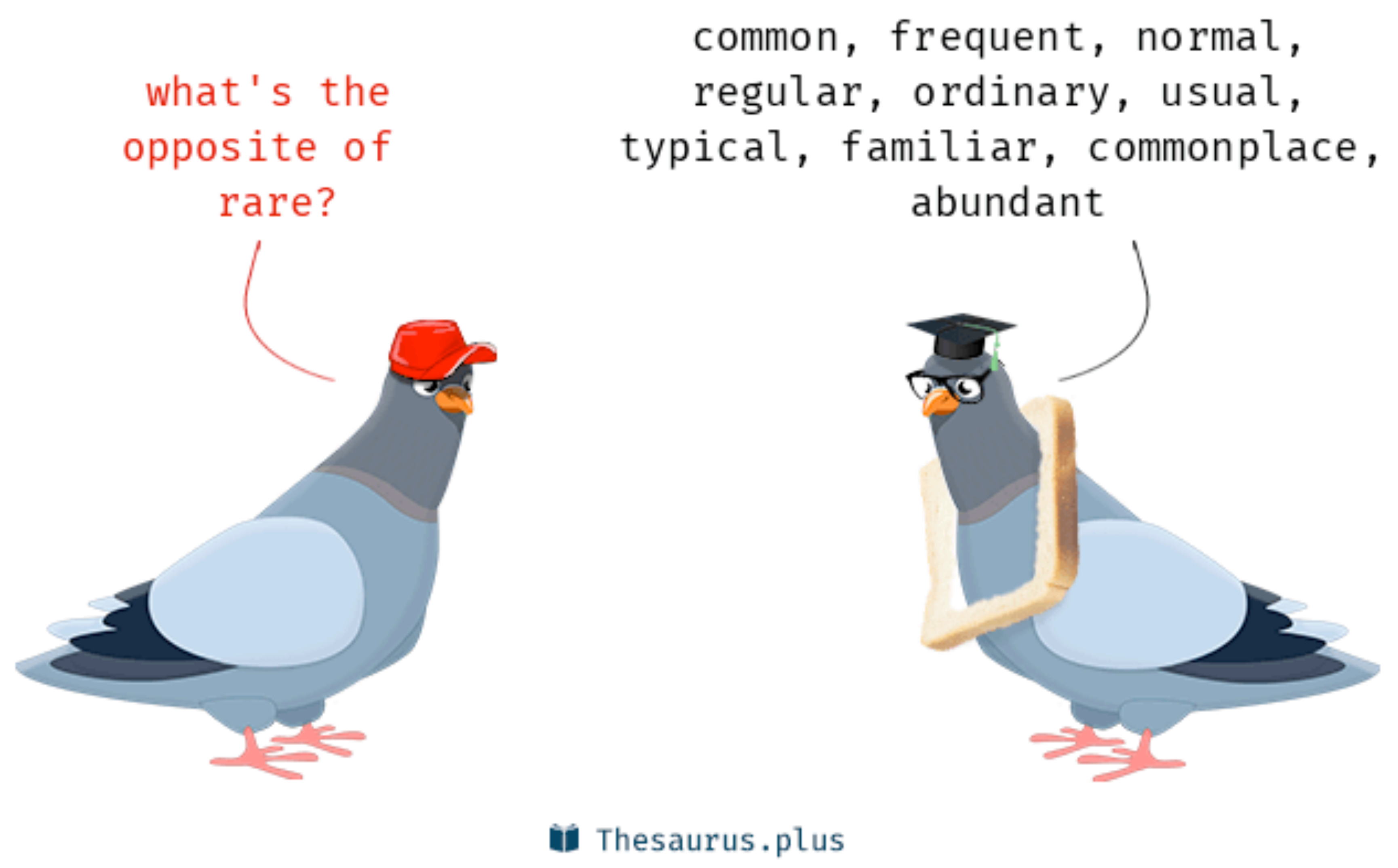
New hierarchy confirmed!



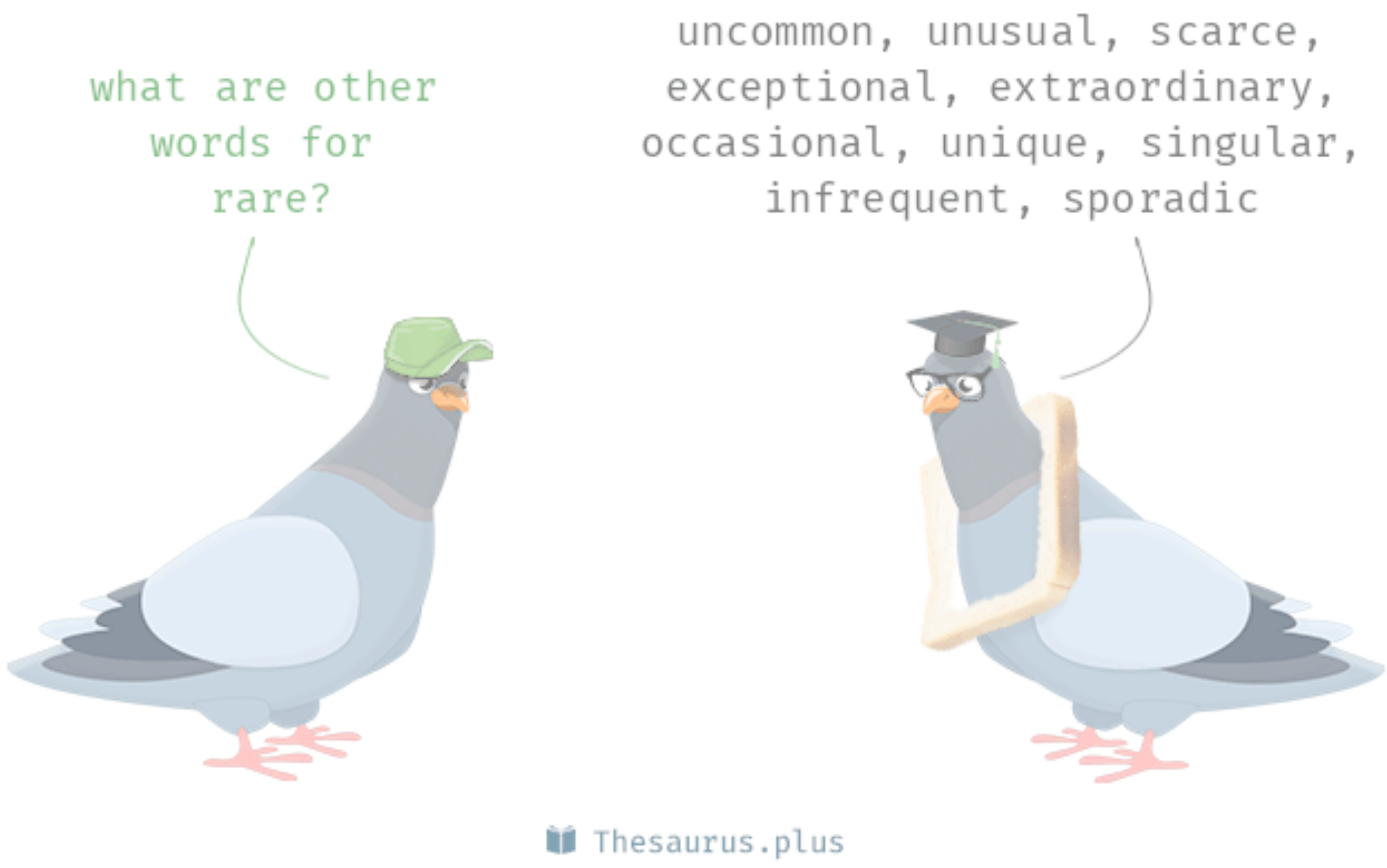
Average of LHCb results: $\tau(\Omega_c^0) = 274.5 \pm 12.4$ fs
$\tau(\Xi_c^0) = 152.0 \pm 2.0$ fs

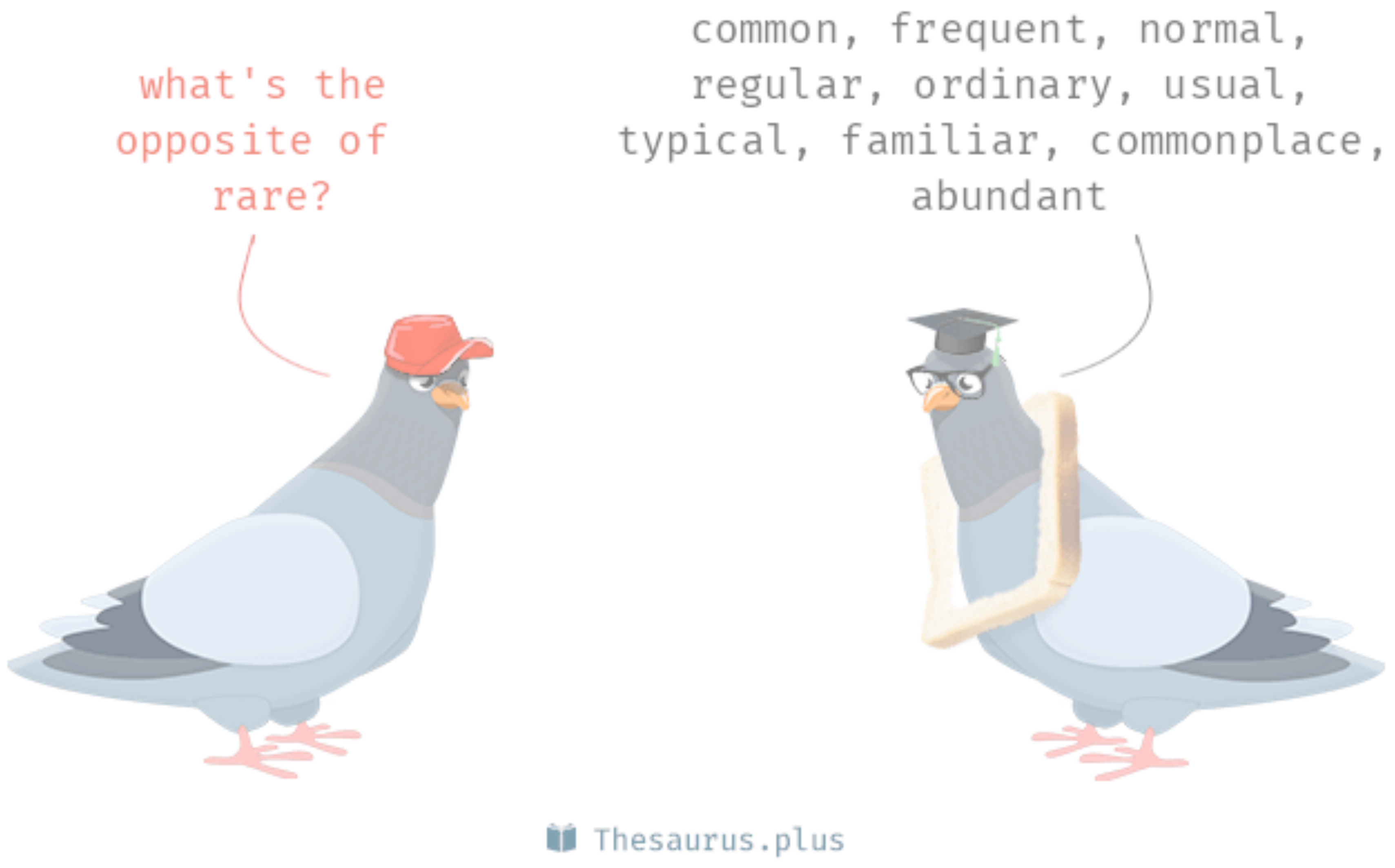
- What is ‘rare’?

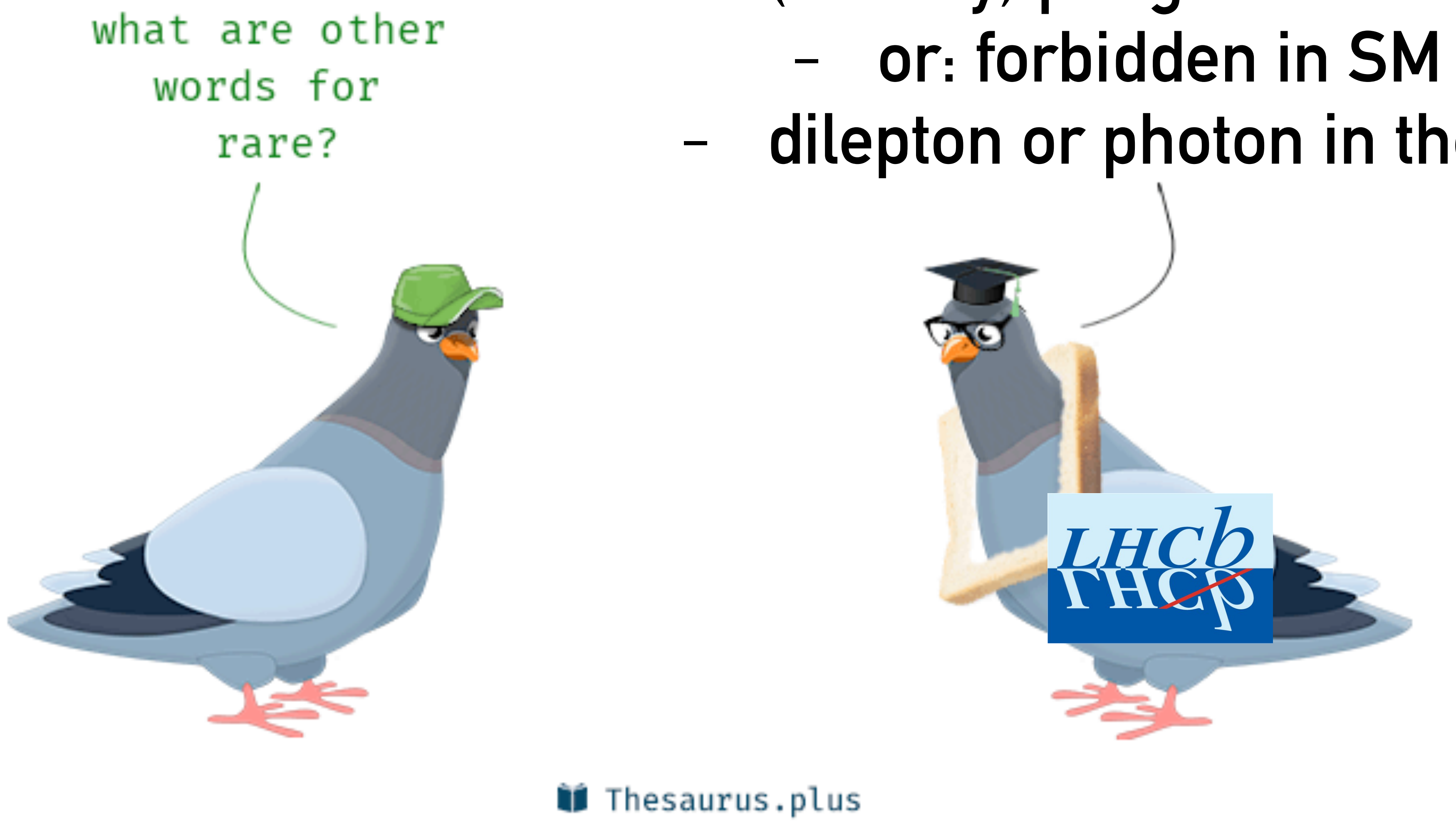

what are other words for rare?
uncommon, unusual, scarce, exceptional, extraordinary, occasional, unique, singular, infrequent, sporadic
Thesaurus.plus


what's the opposite of rare?
common, frequent, normal, regular, ordinary, usual, typical, familiar, commonplace, abundant
Thesaurus.plus

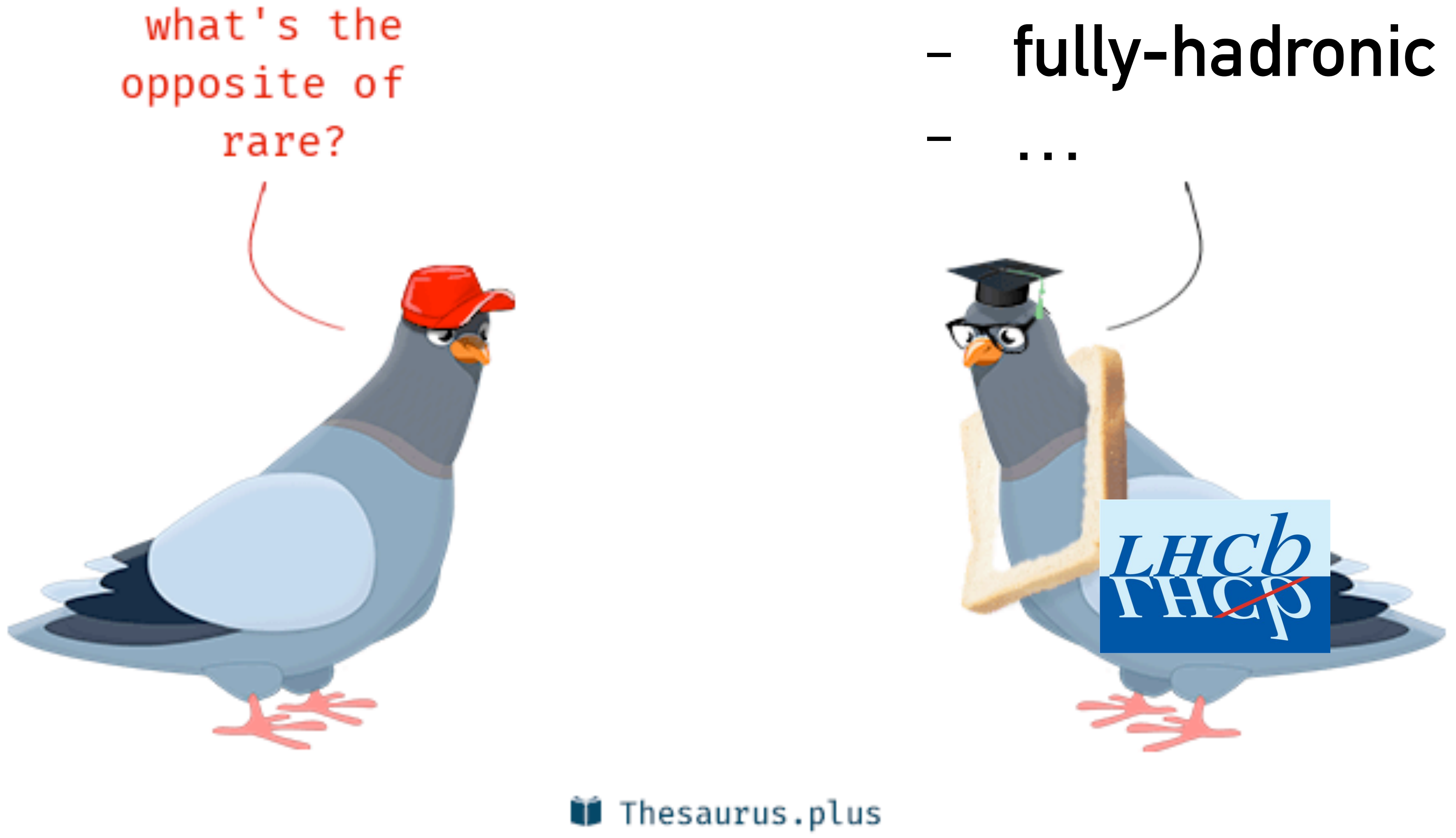
➤ What is 'rare'?



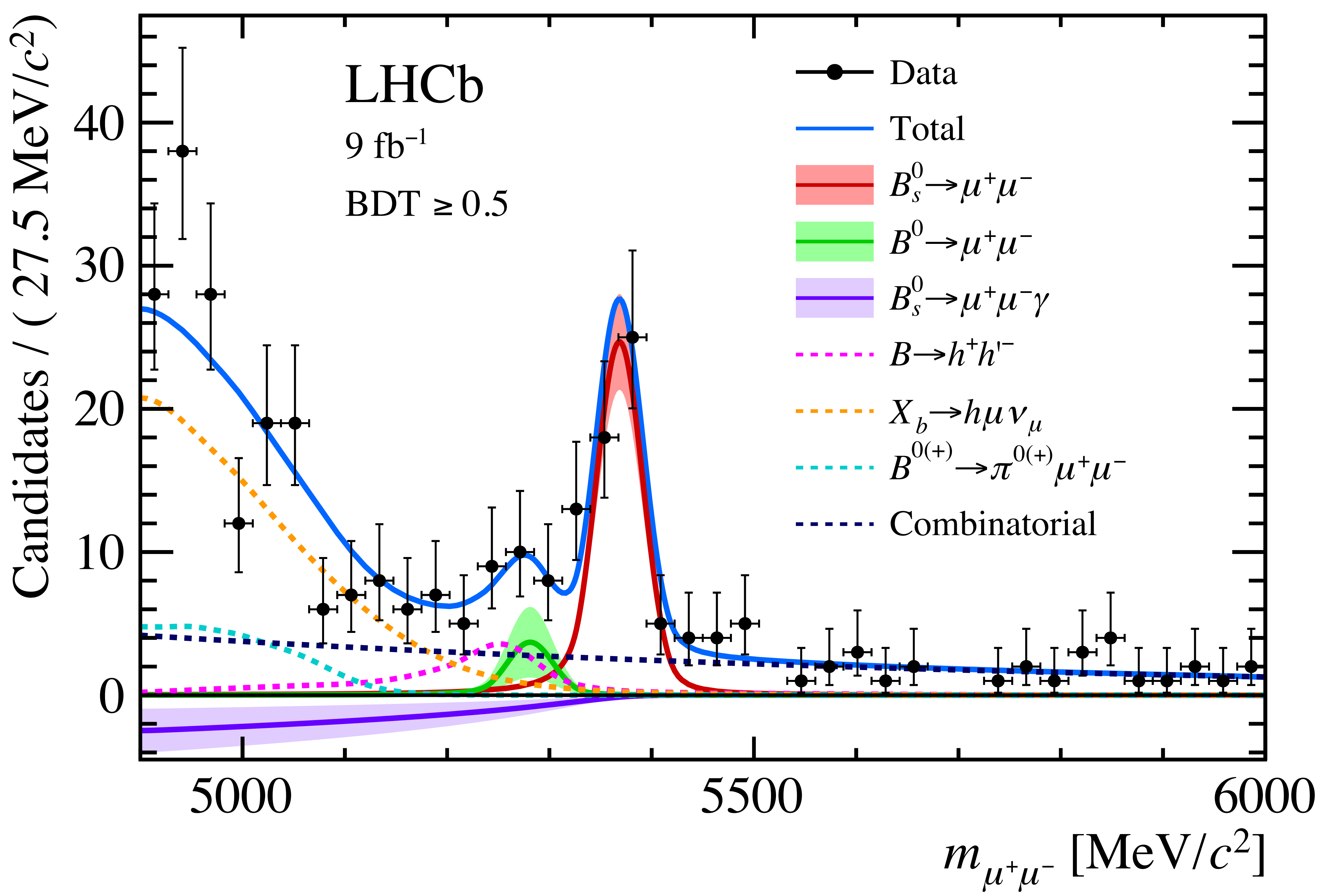




- electroweak decay with small BF ($\lesssim 10^{-4}$)
- (usually) penguin or box SM diagram
  - or: forbidden in SM (LFV, etc)
- dilepton or photon in the final state



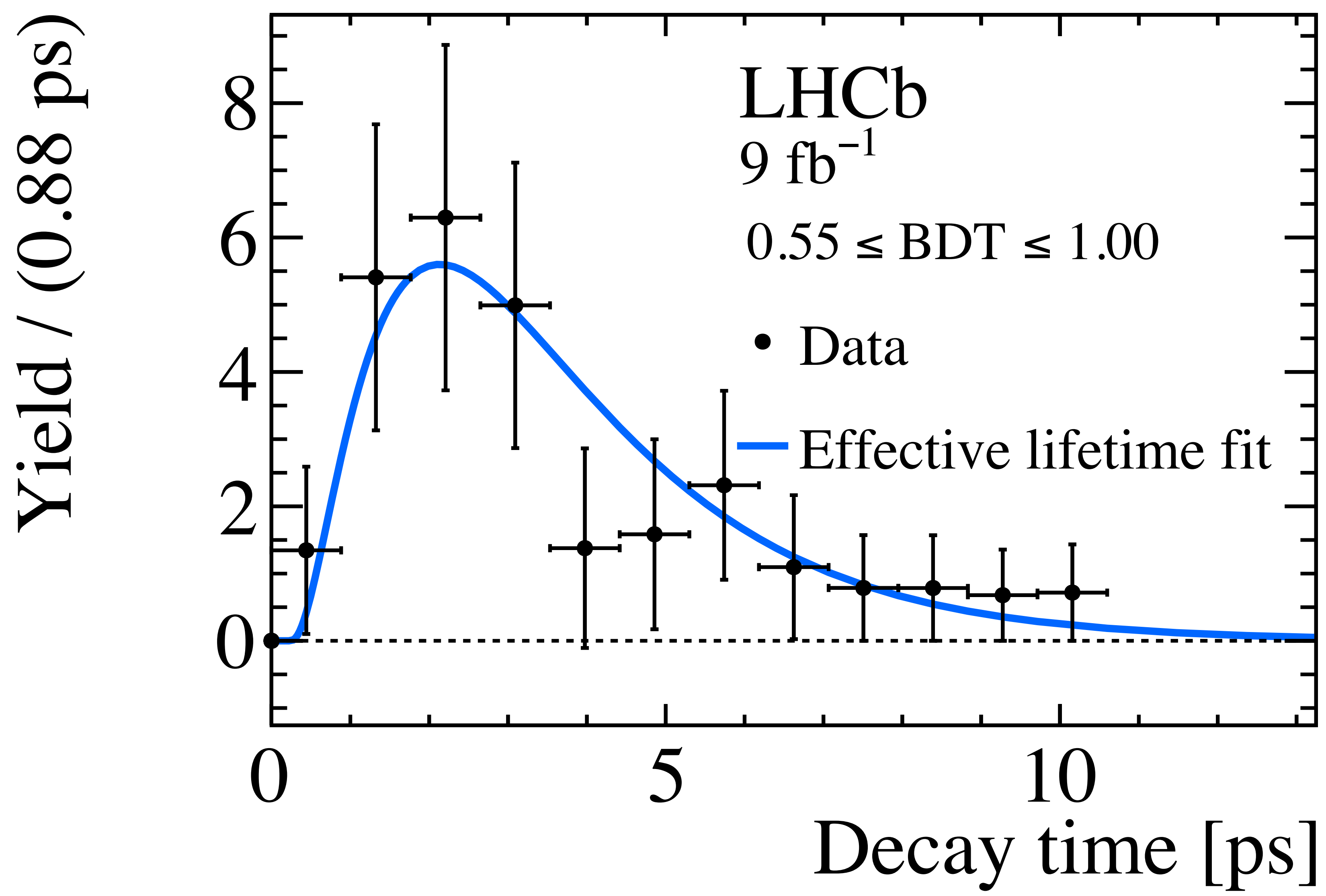
- tree-level
- fully-hadronic
- …



$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ *most precise to date, agrees with the SM*

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ *sensitivity affected by misID*

$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m(\mu\mu)<4.9\,\mathrm{GeV}} < 2.0 \times 10^{-9}$ *first limit*



Effective lifetime $\tau(B^0_s \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)$ ps

closer to the lifetime of the heavy mass eigenstate, ~1.62 ps
(in SM, only the heavy eigenstate can decay to two muons)

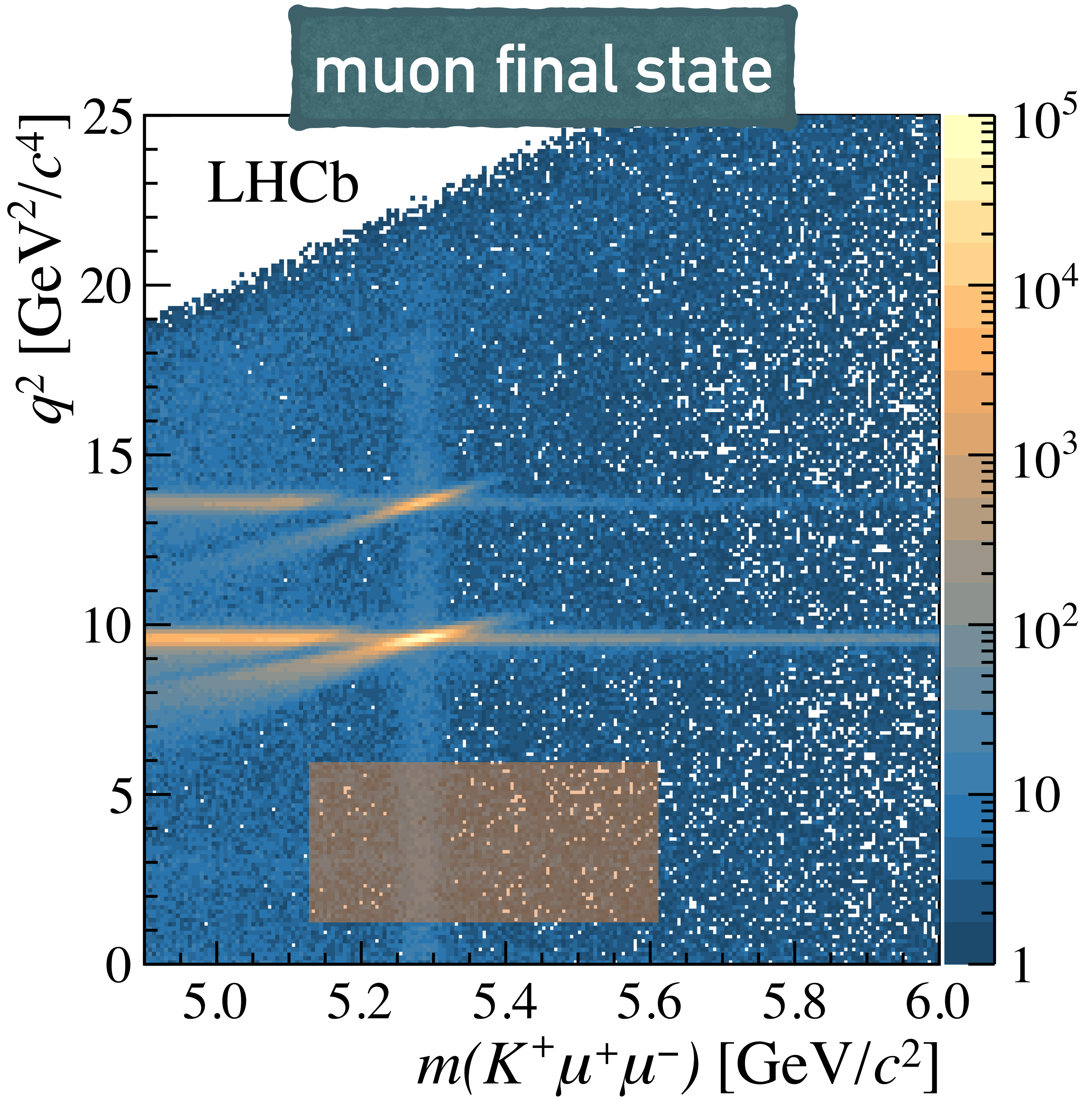
- Couplings to SM gauge bosons are identical for $e/\mu/\tau$, e.g.

$$\frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} = 1.0009 \pm 0.0028 \text{ or } \frac{\Gamma(W \to e\nu)}{\Gamma(W \to \mu\nu)} = 1.004 \pm 0.008$$

- Challenged in B decays: $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ transitions

- I will focus on $b \to s\ell^+\ell^-$.

$q^2 \equiv m^2_{\ell^+\ell^-}$

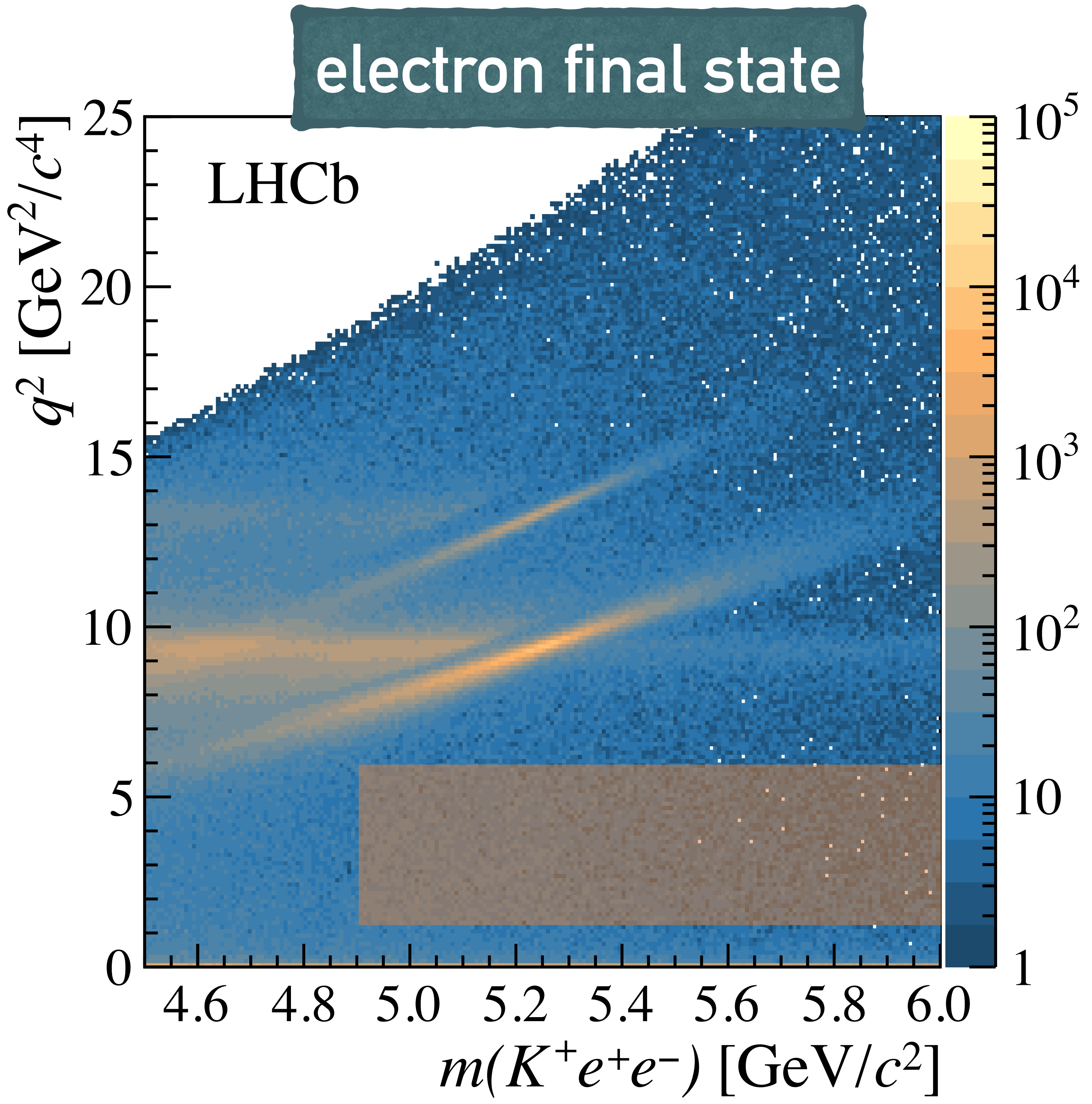


$\psi(2S) + X$

$J/\psi + X$

signal window

$1.1 < q^2 < 6\,\text{GeV}^2$



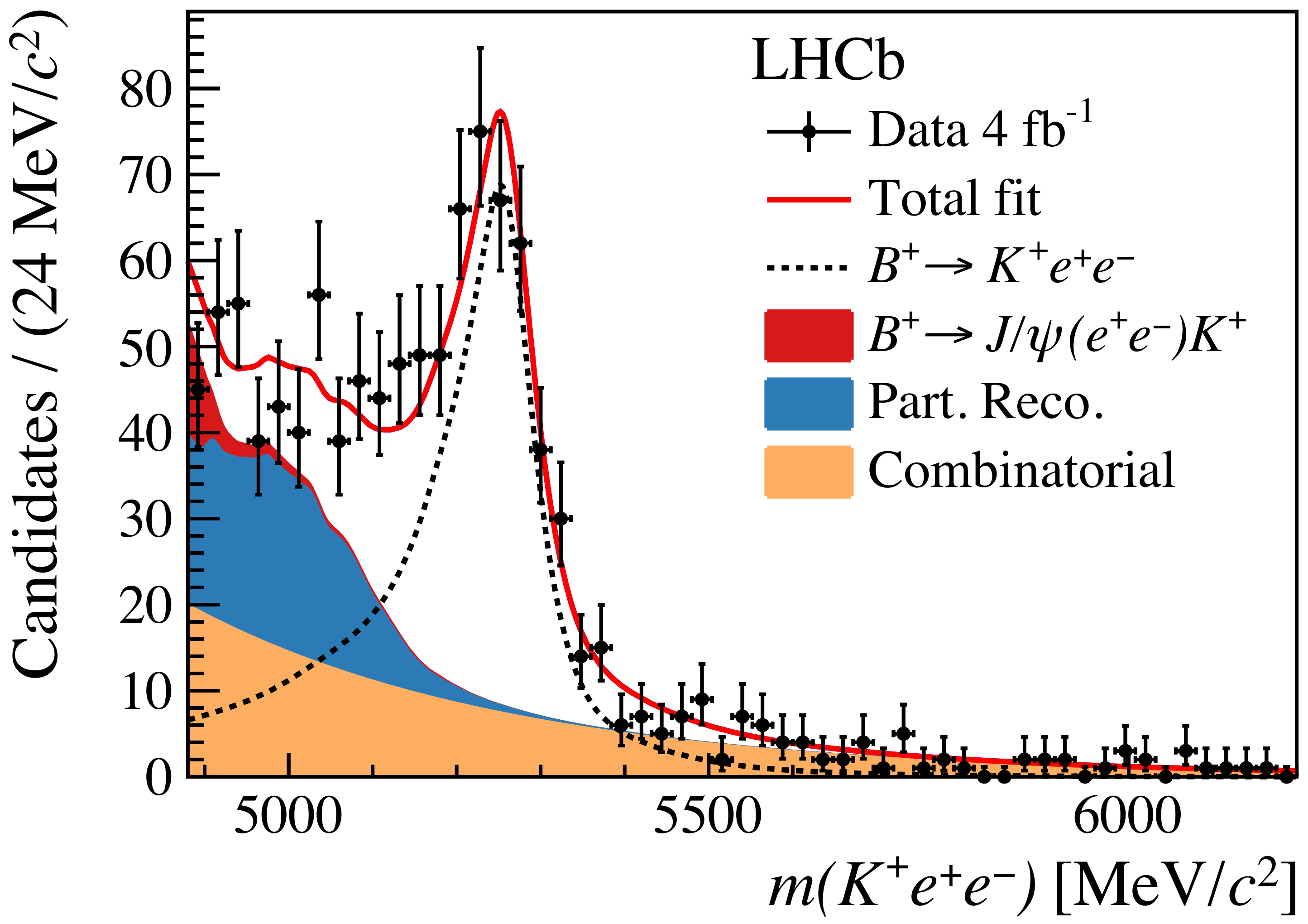
worse resolution due to bremsstrahlung

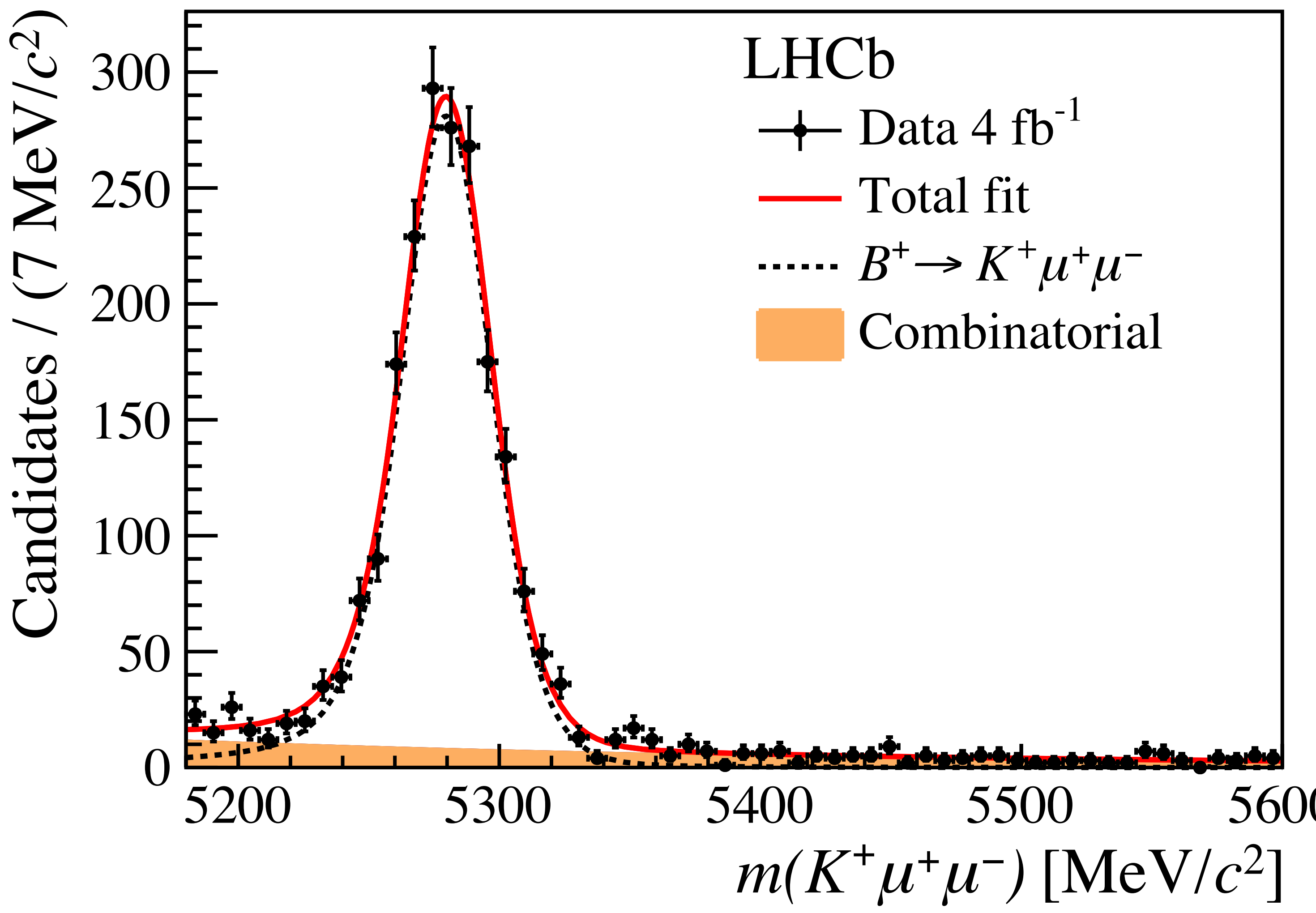
- What we measure: (to cancel detection asymmetries)

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

where only $1.1 < q^2 < 6\,\text{GeV}^2$ is considered for the rare mode

- The J/ψ single ratio consistent with unity in any considered region of phase-space

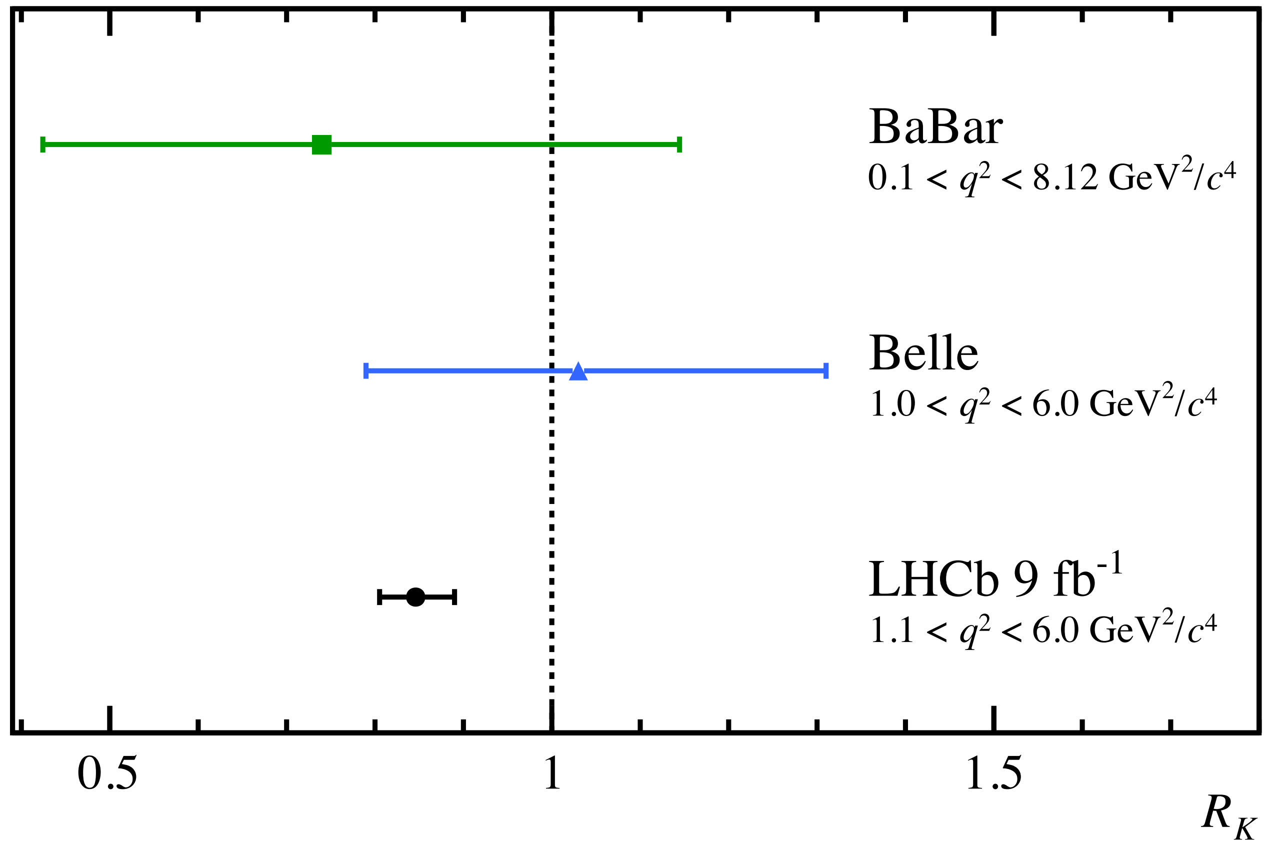




- We measure: $R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$

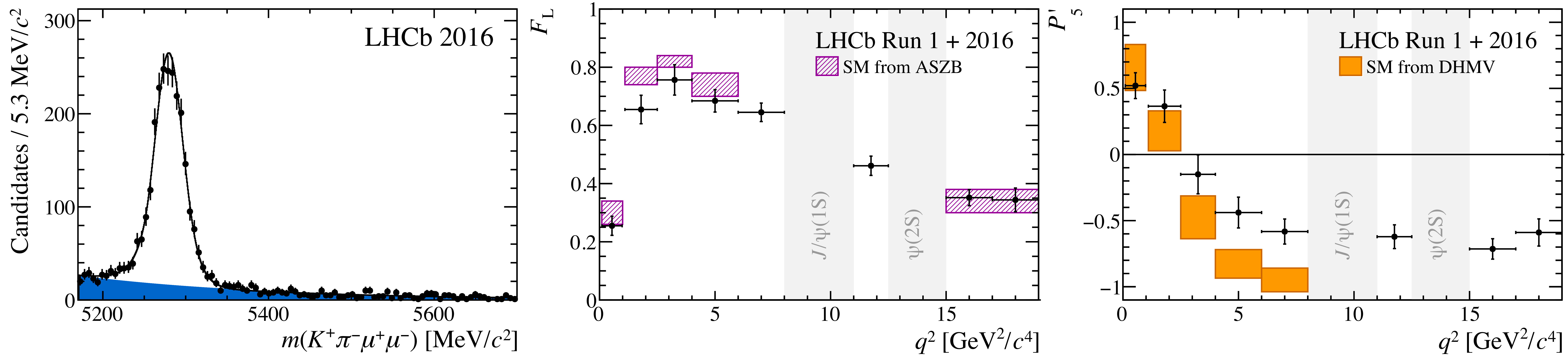
3.1σ from unity

- Similar measurement in Λ_b^0 decays: $R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$
- Other final states in the pipeline (R_{K^*}, R_{K_S}, R_Λ etc).

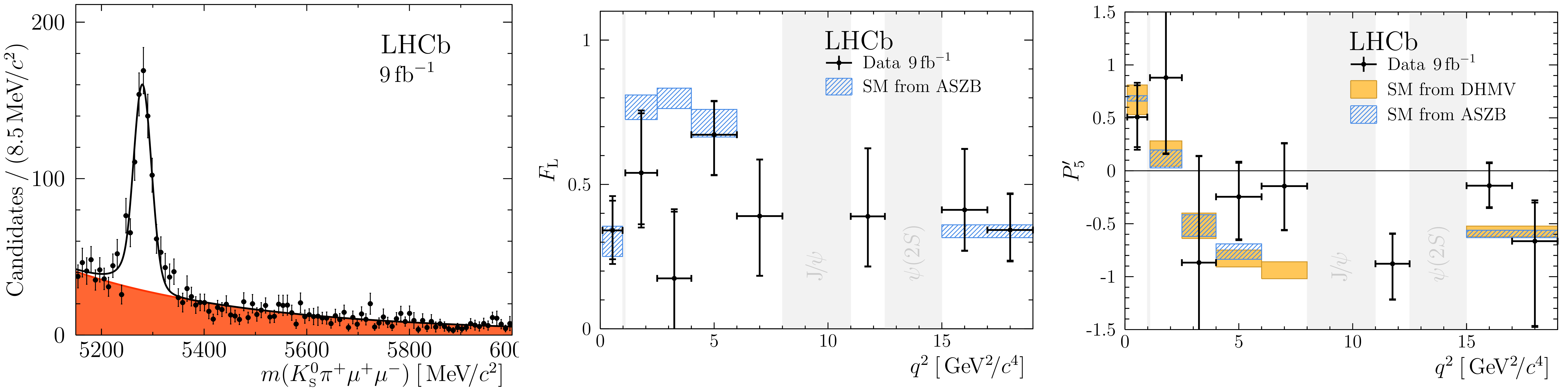


- Neutral and charged modes analysed, CP-averaged angular observables measured:

F_L P'_5 +*many others…*

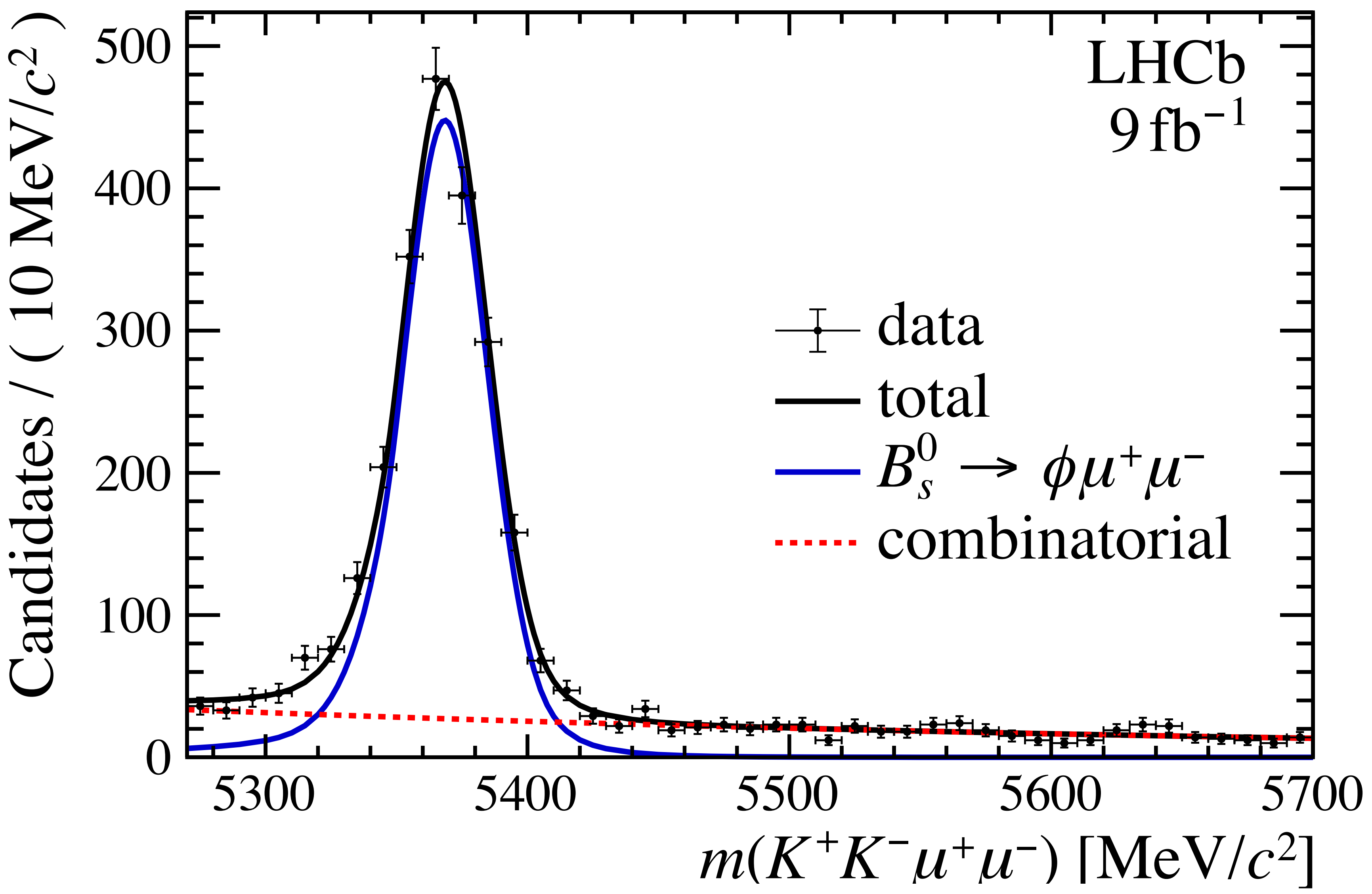


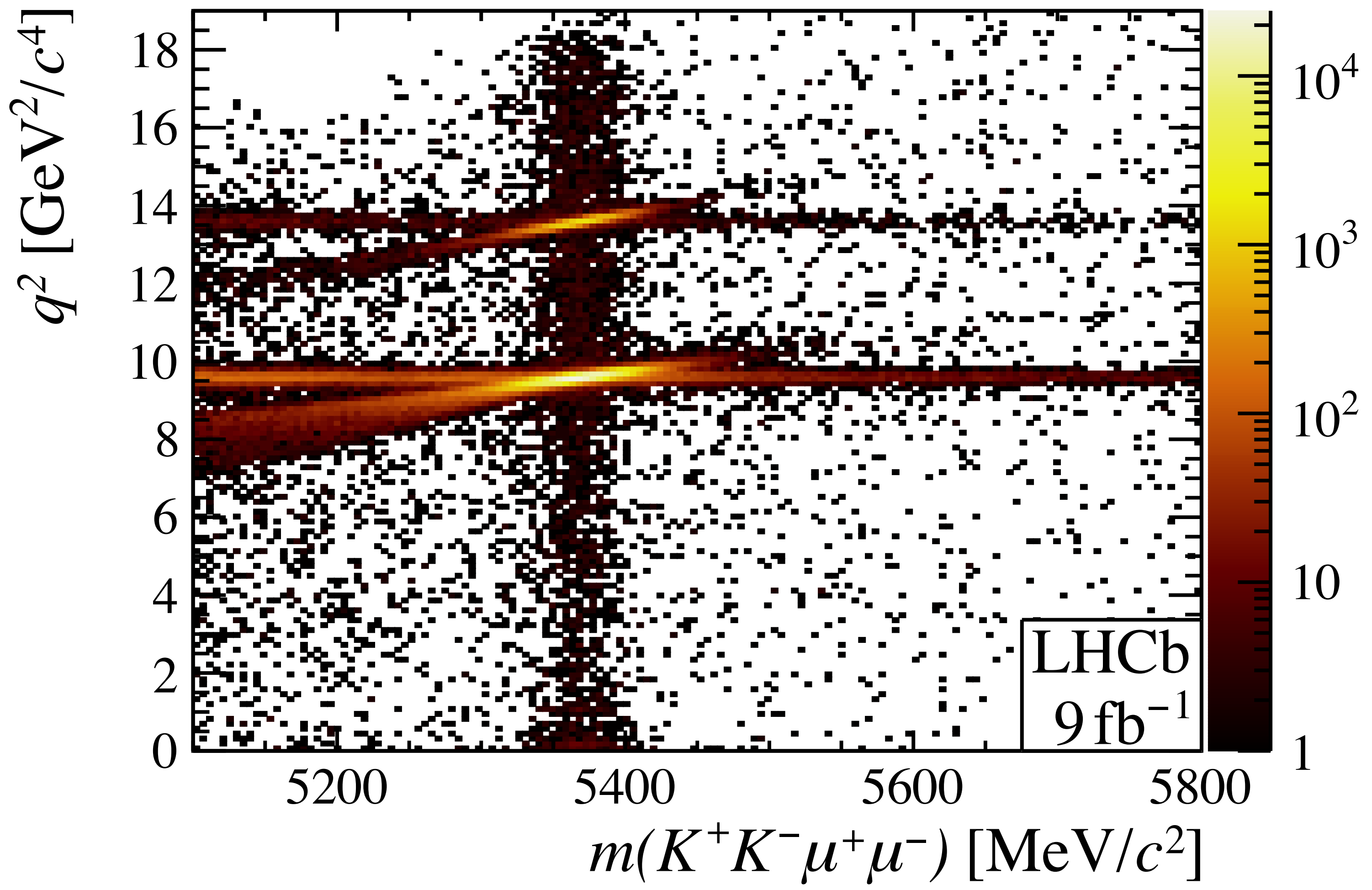
the tension persists

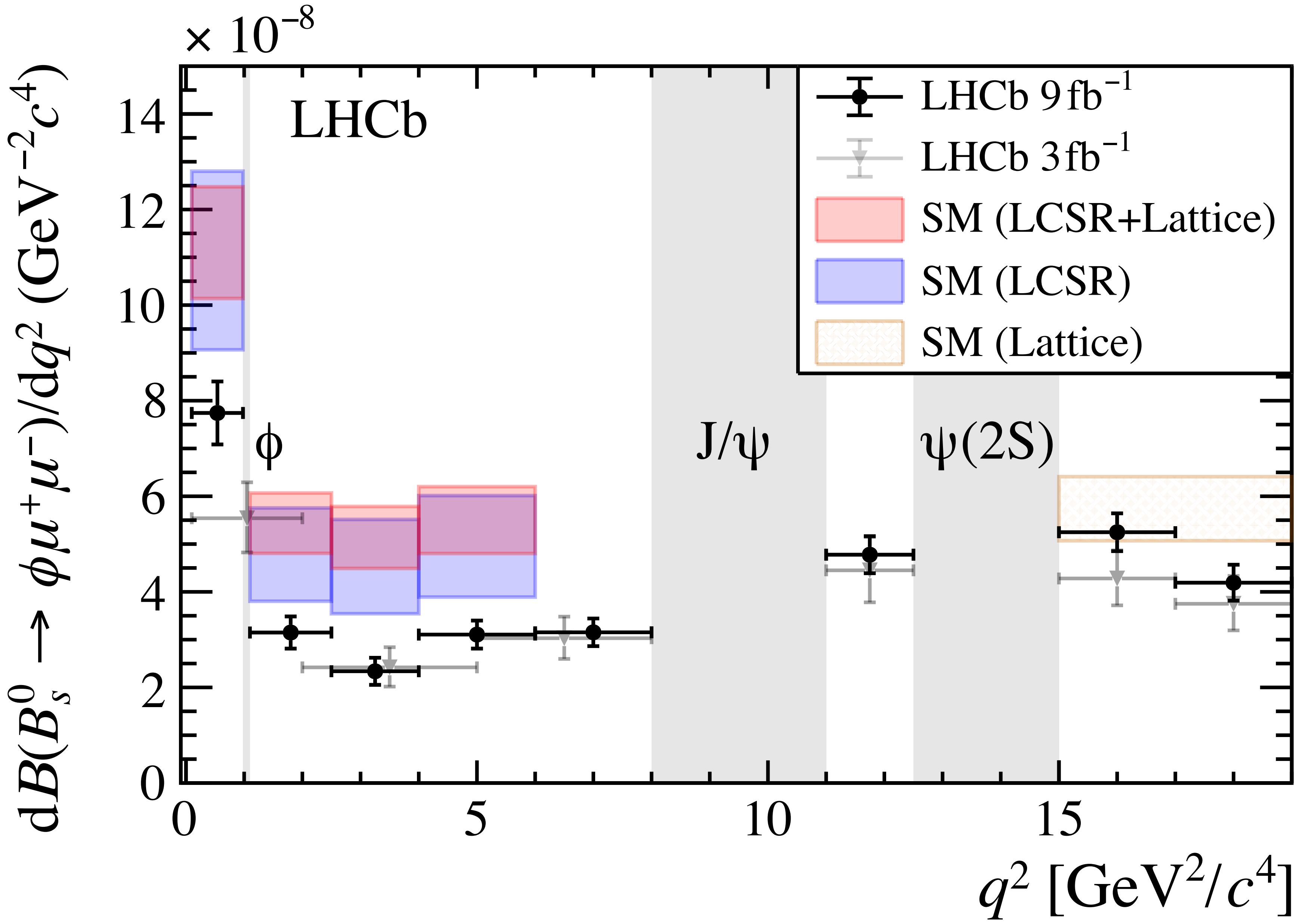


need more data

➤ Differential BF measurement:





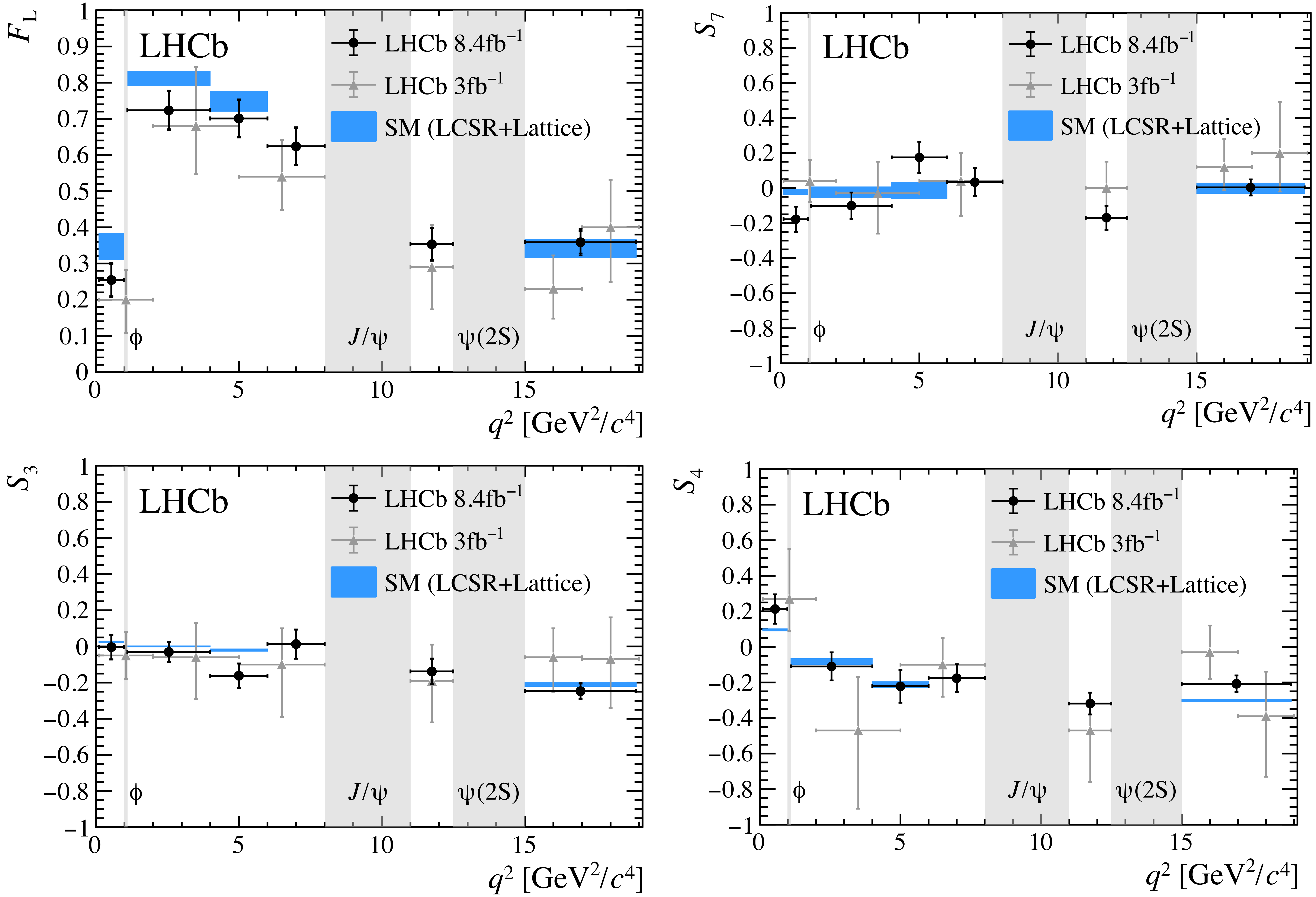


in q^2 region 1.1 … 6:
3.6σ below SM (lattice+LCSR)
1.8σ below SM (LCSR)

➤ This is clearly not a stat. fluctuation, but (???) could be some bias in theory estimate.

- ***Angular analysis** performed with **untagged** B_s^0*

Untagged analysis – no separation of $B_s^0/\overline{B_s^0}$ – no observables like P_5' here (which show anomalies in $B^0 \to K^{*0}\mu^+\mu^-$)

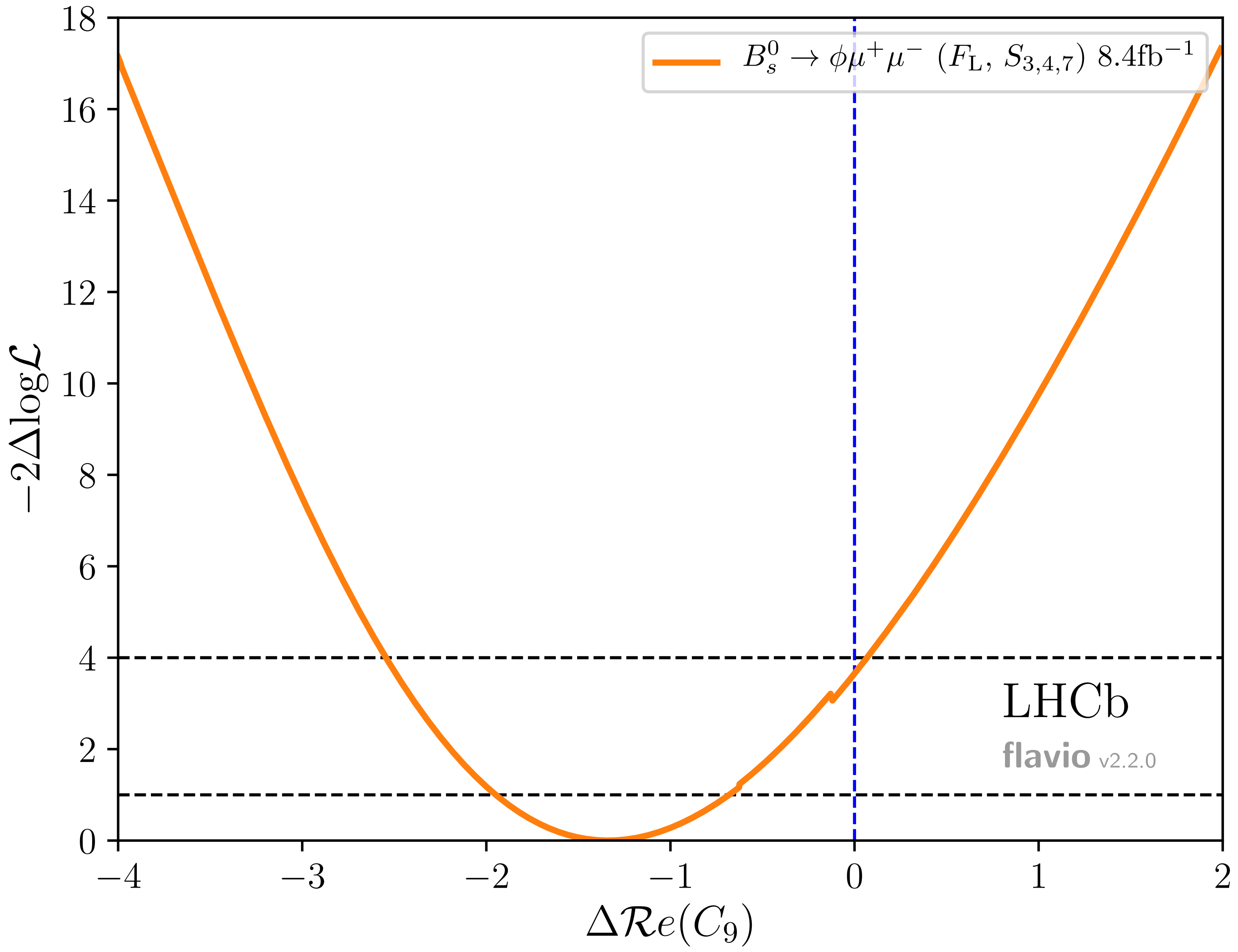


Results compatible with SM, but some deviation in F_L: same as in $B \to K^*\mu^+\mu^-$?

- Interpretation of recent LHCb results in terms of the Wilson coefficient C_9 (vector coupling in the EFT)
- The three recent LHCb angular analyses **consistently** favour a negative shift in $\Delta Re(C_9) \equiv Re(C_9) - Re(C_9^{SM})$:

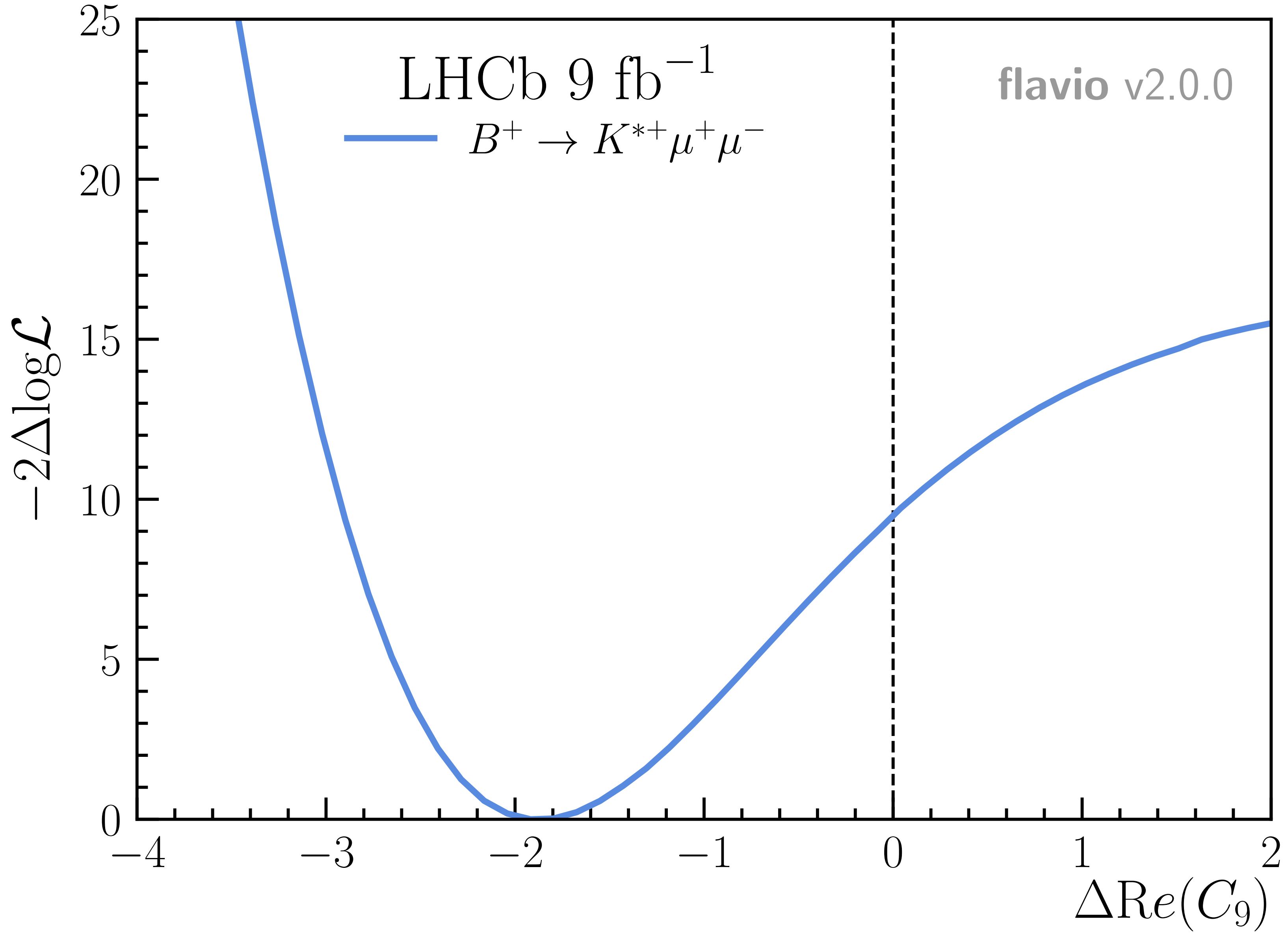
$B_s^0 \to \phi\mu^+\mu^-$

[PAPER-2021-014]



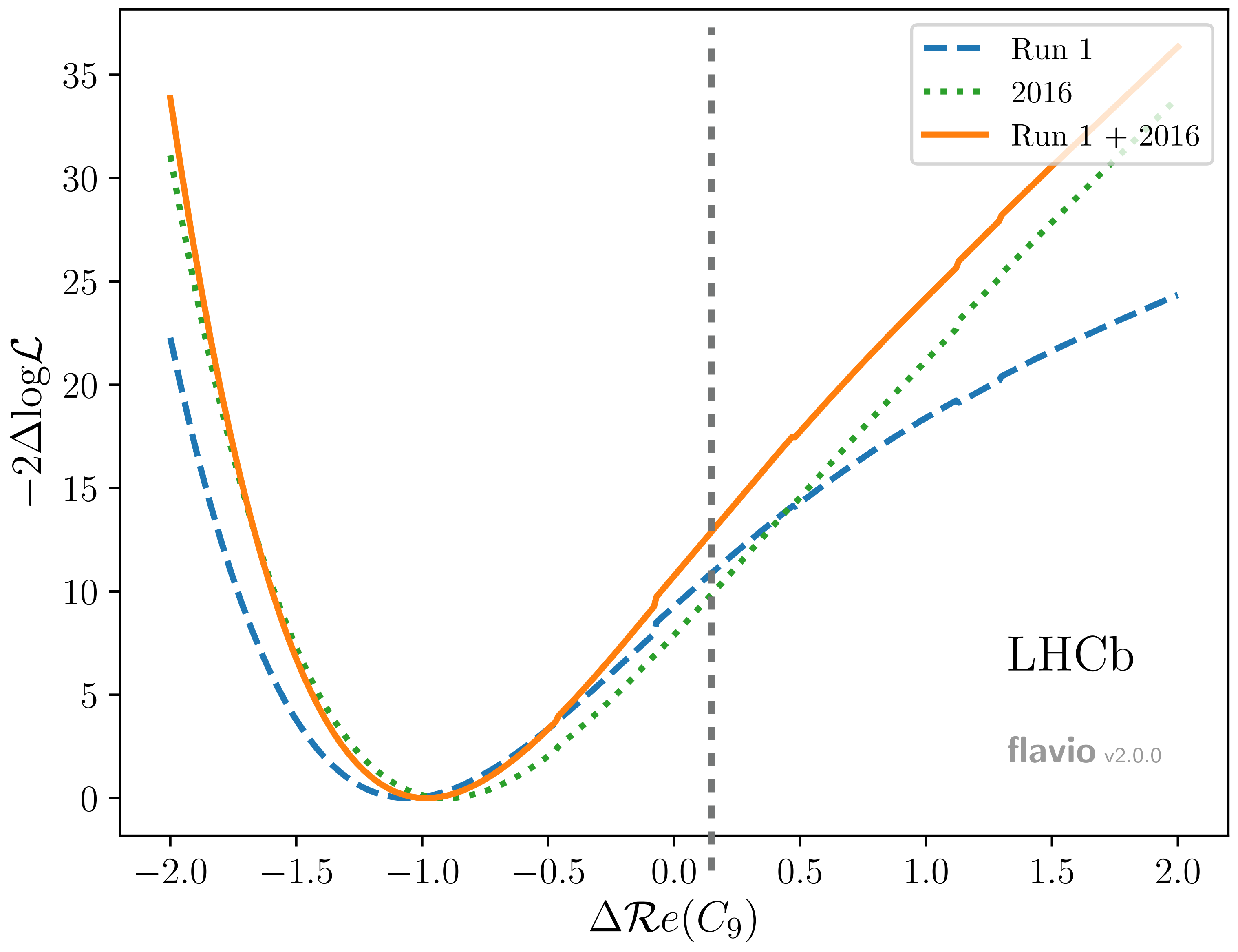
$B^+ \to K^{*+}\mu^+\mu^-$

[PAPER-2020-041] / PRL 126 (2021) 161802



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

[PAPER-2020-002] / PRL 125 (2020) 011802

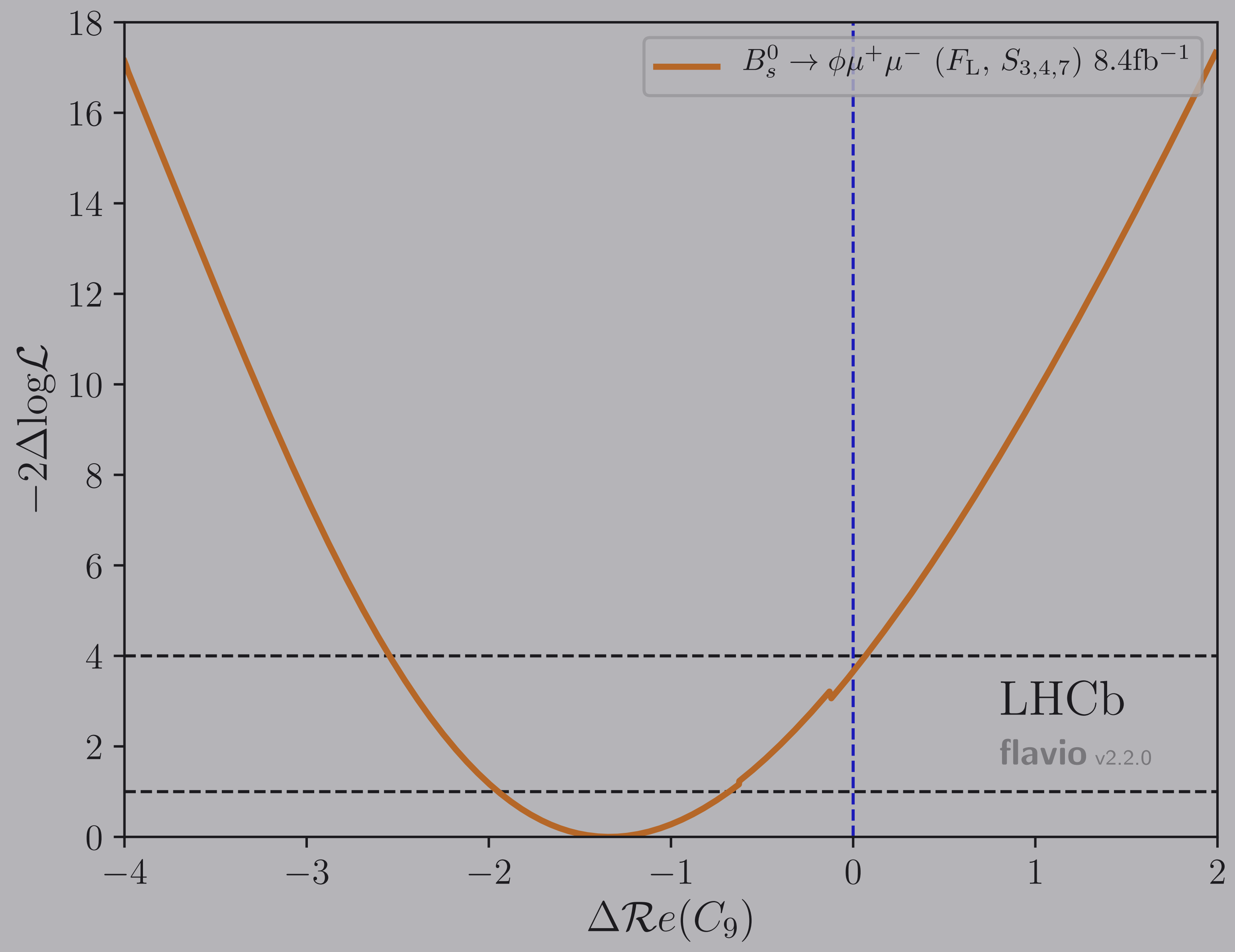


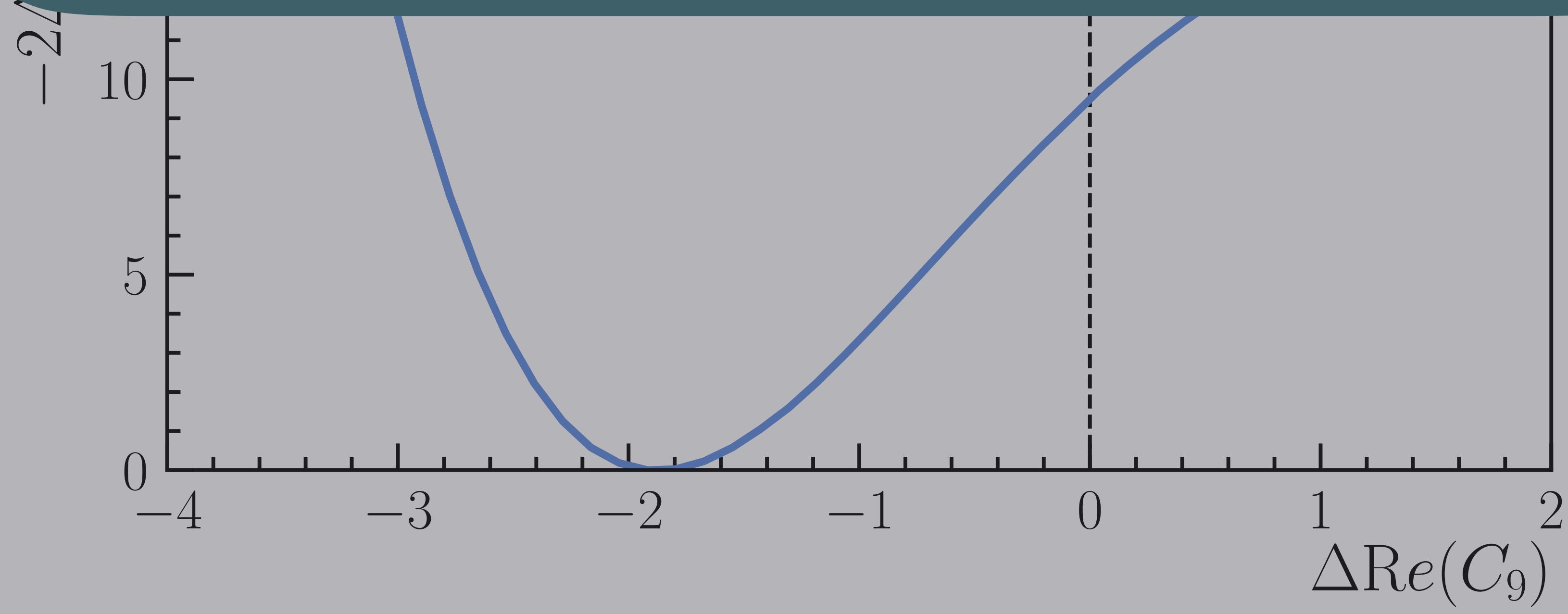
- Interpretation of recent LHCb results in terms of the Wilson coefficient C_9 (vector coupling in the EFT)
- The three recent LHCb angular analyses **consistently** favour a negative shift in $\Delta Re(C_9) \equiv Re(C_9) - Re(C$

Looking forward to complementary measurements from Belle II!

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

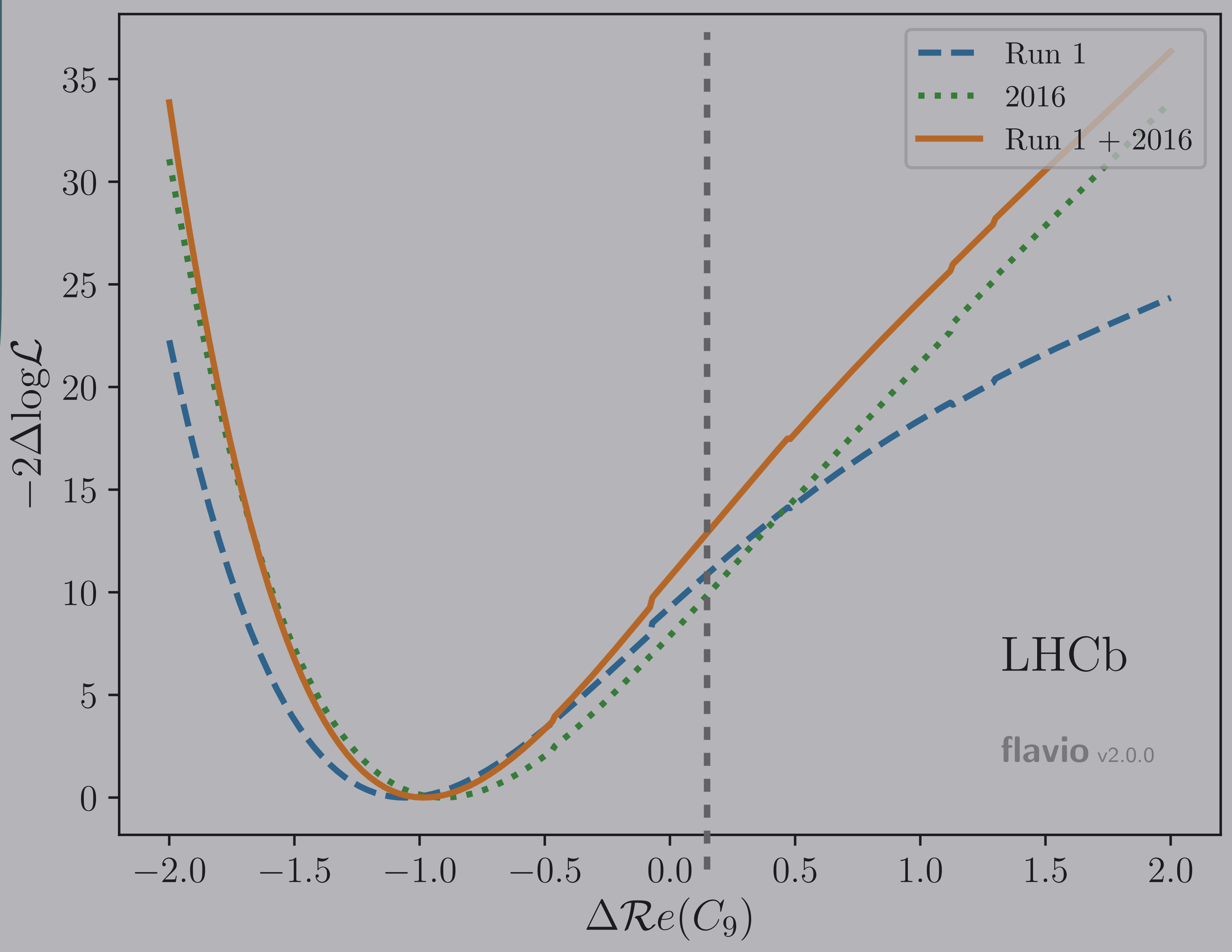
[PAPER-2021-014]



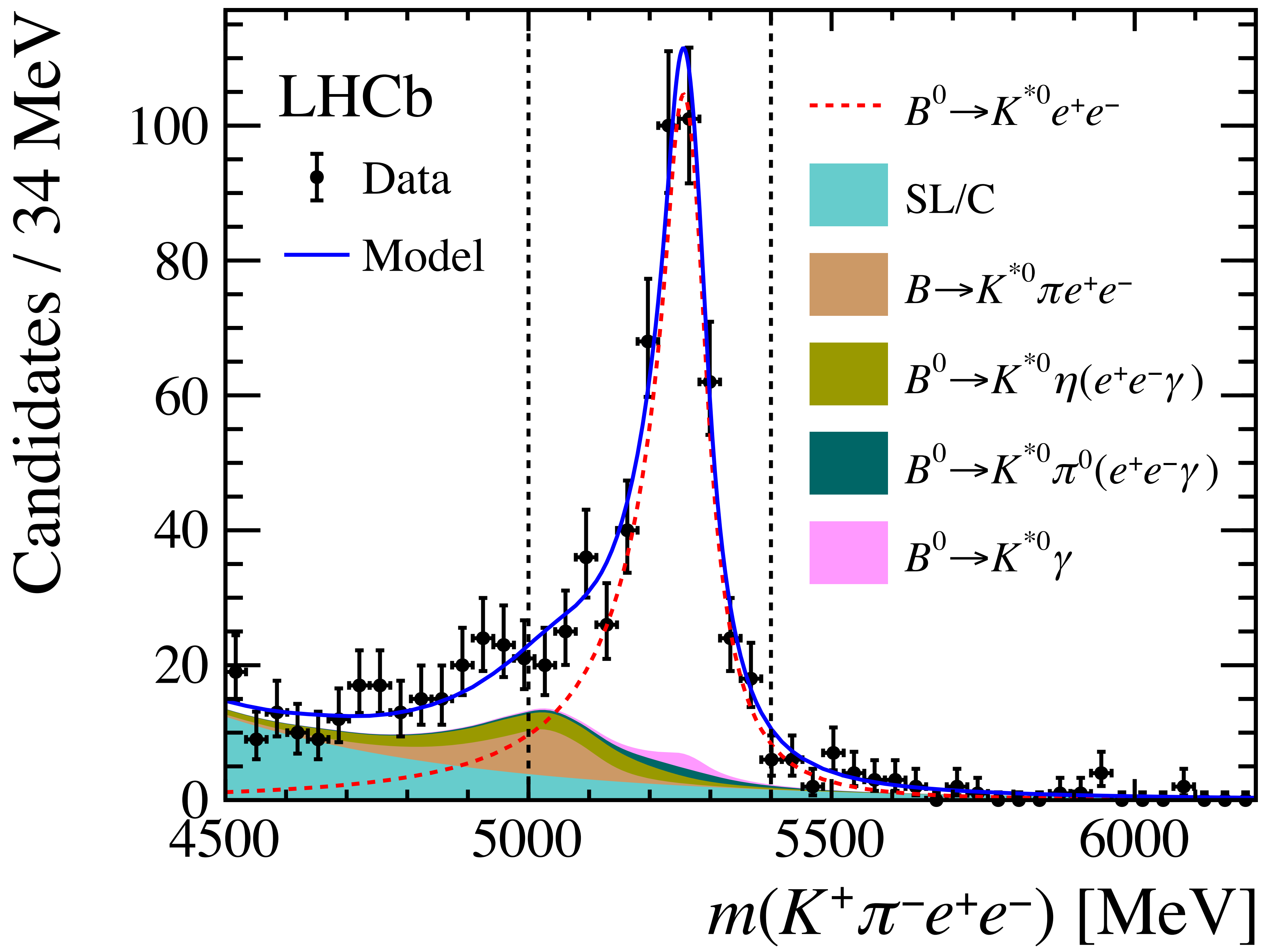


$B^0 \to K^{*0}\mu^+\mu^-$

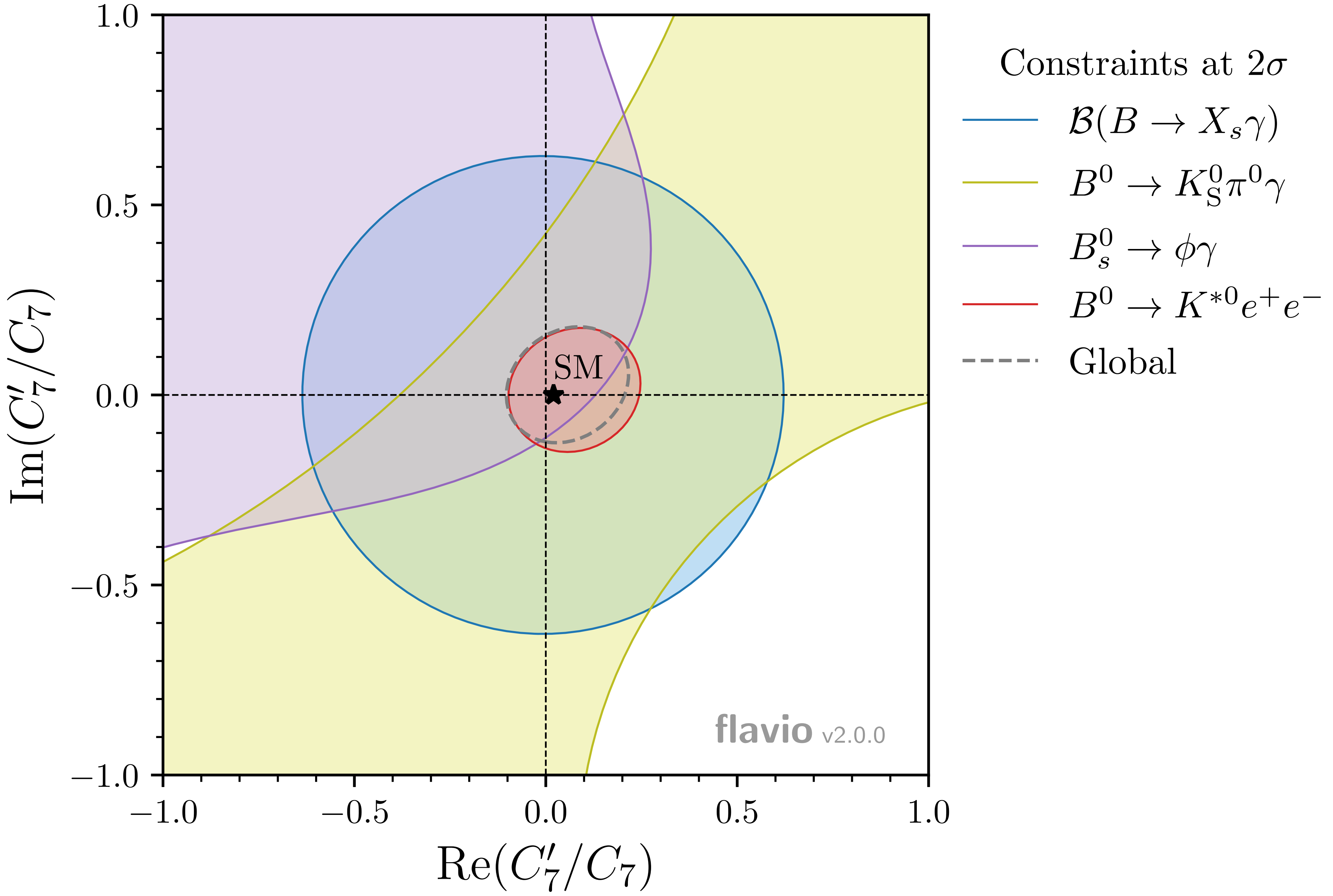
[PAPER-2020-002] / PRL 125 (2020) 011802



- SM: $b \to s\gamma$ transition produces almost always a left-handed photon
- Angular analysis of $B^0 \to K^{*0}e^+e^-$ in $0.0008 < q^2 < 0.257\,\mathrm{GeV}^2$
  - region dominated by the virtual photon
  - good resolution on the angle ϕ between the dielectron and $K\pi$ planes
- World's best constraint on right-handed photon polarisation in $b \to s\gamma$

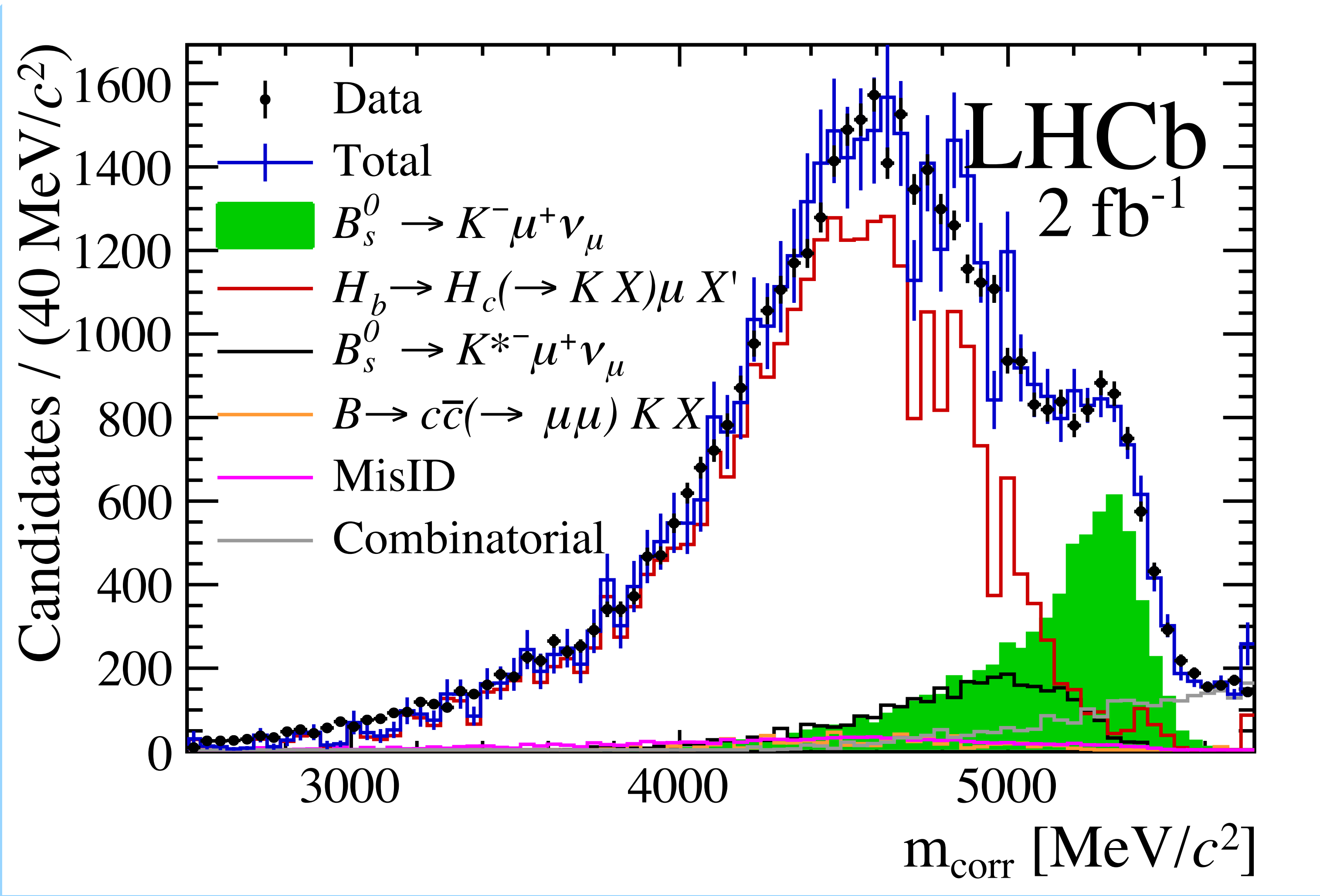


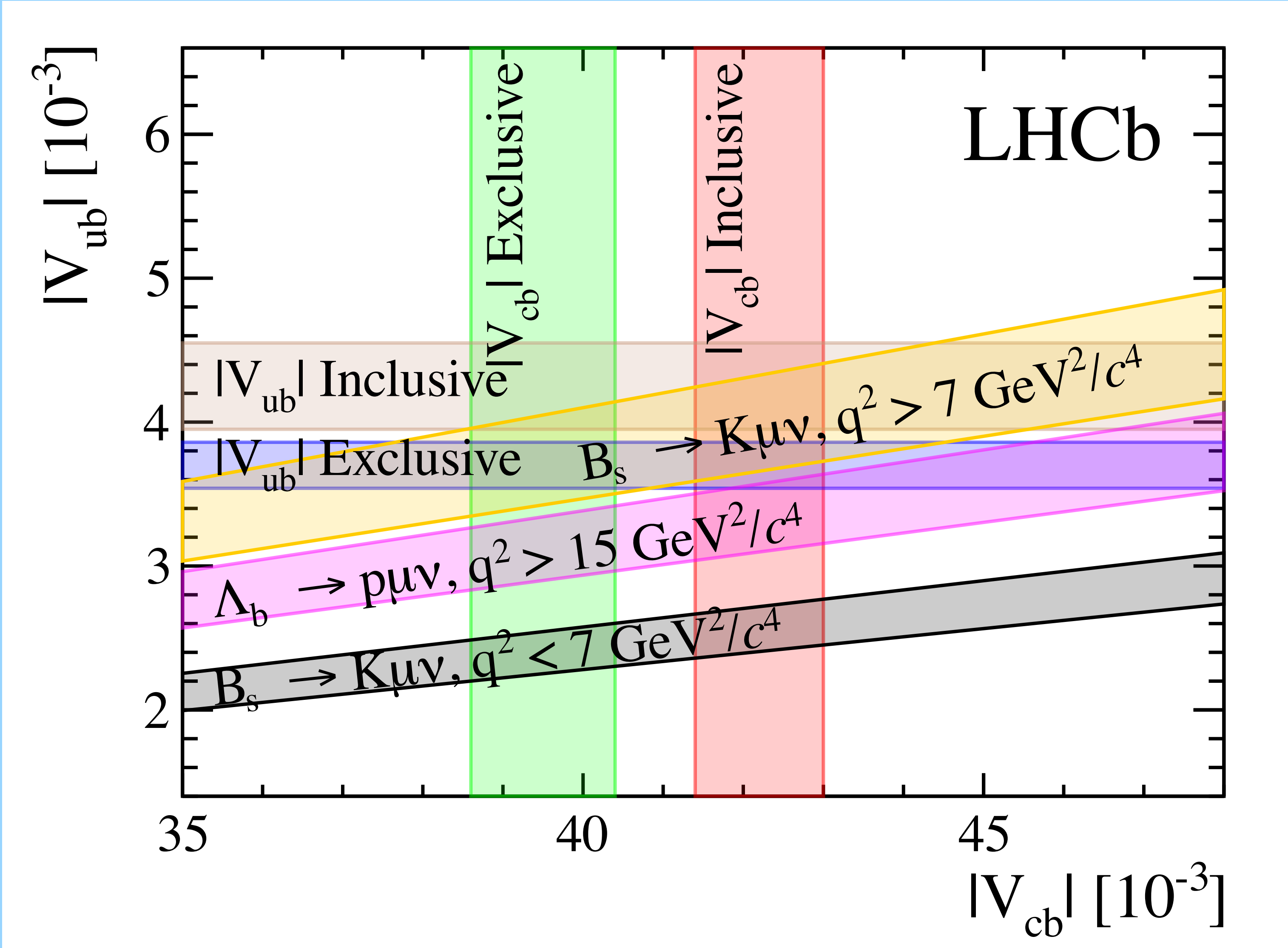
Ratio of RH and LH Wilson coefficients



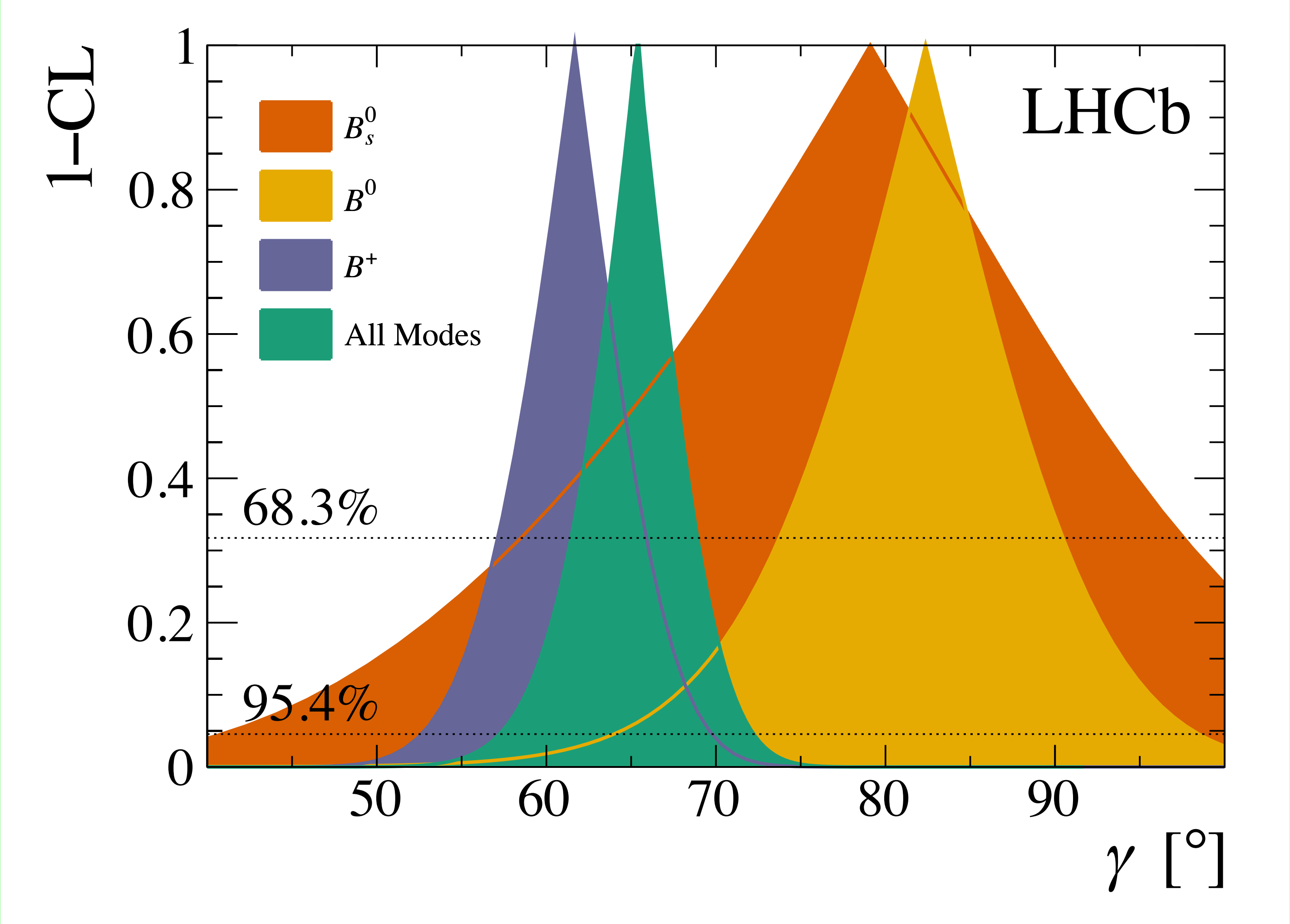
SELECTED OTHER RESULTS

all references here



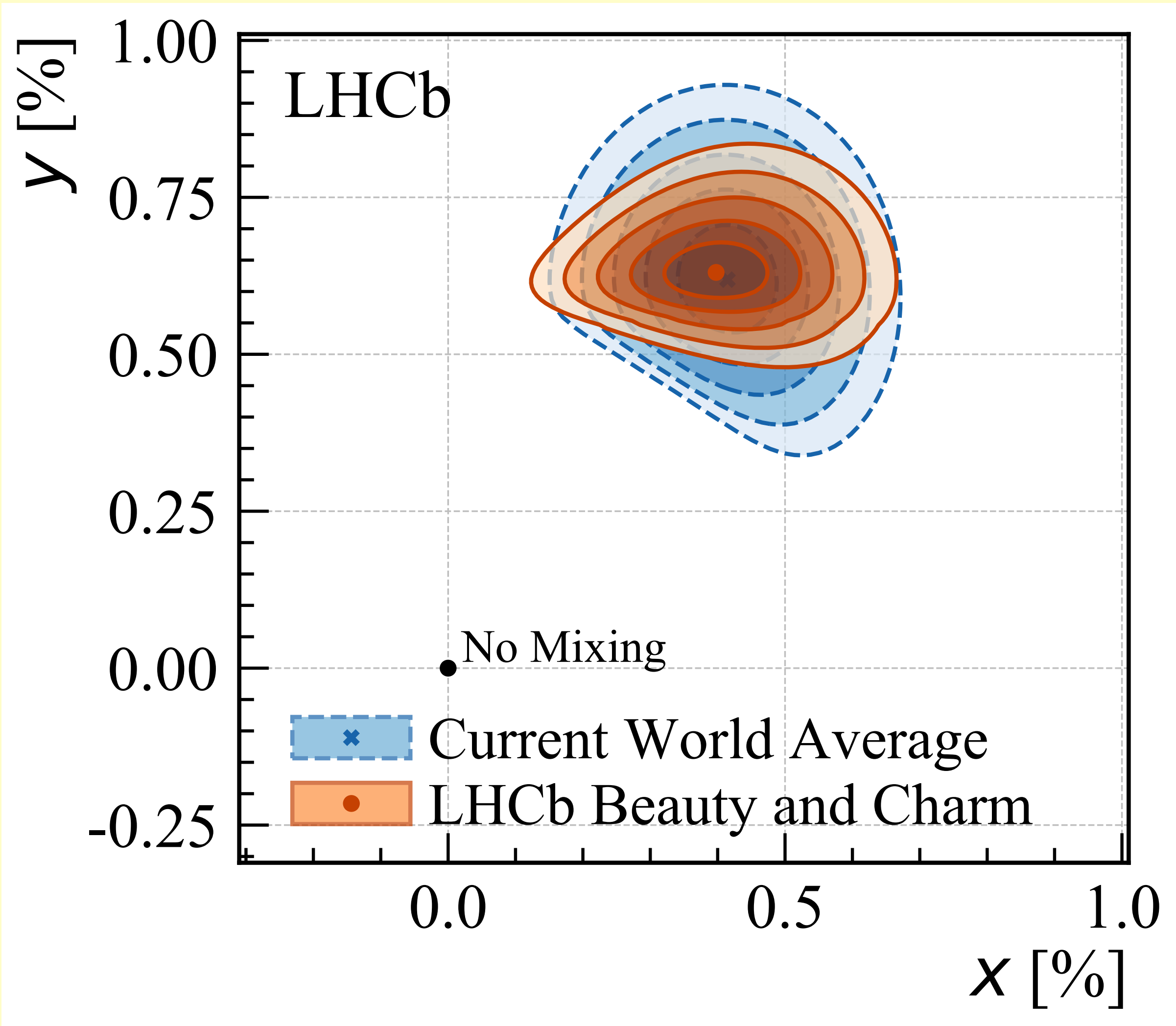


$B_s^0 \to K\mu\nu$: input to V_{ub} puzzle



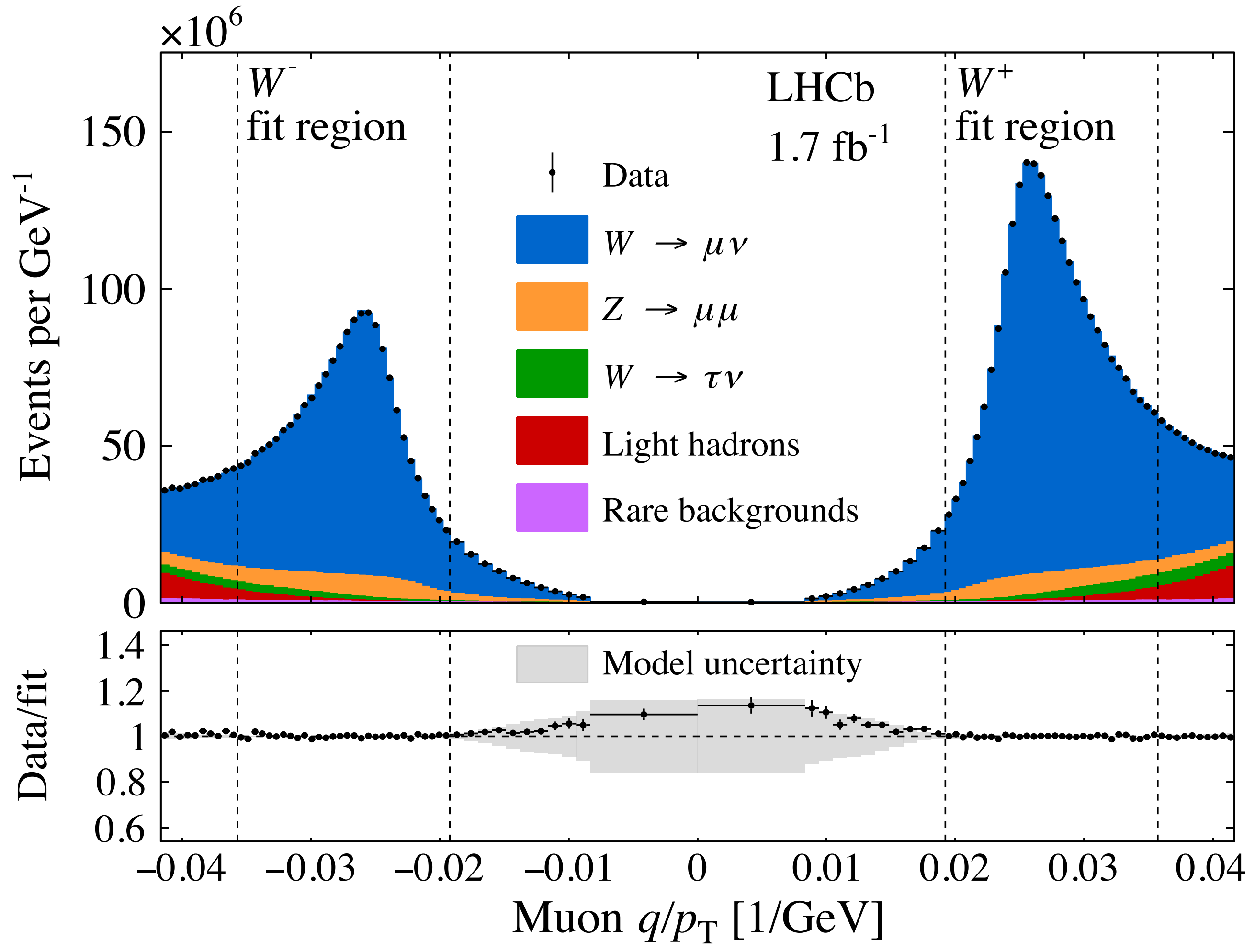
$$\gamma \equiv \phi_3 = \left(65.4^{+3.8}_{-4.2}\right)^\circ$$

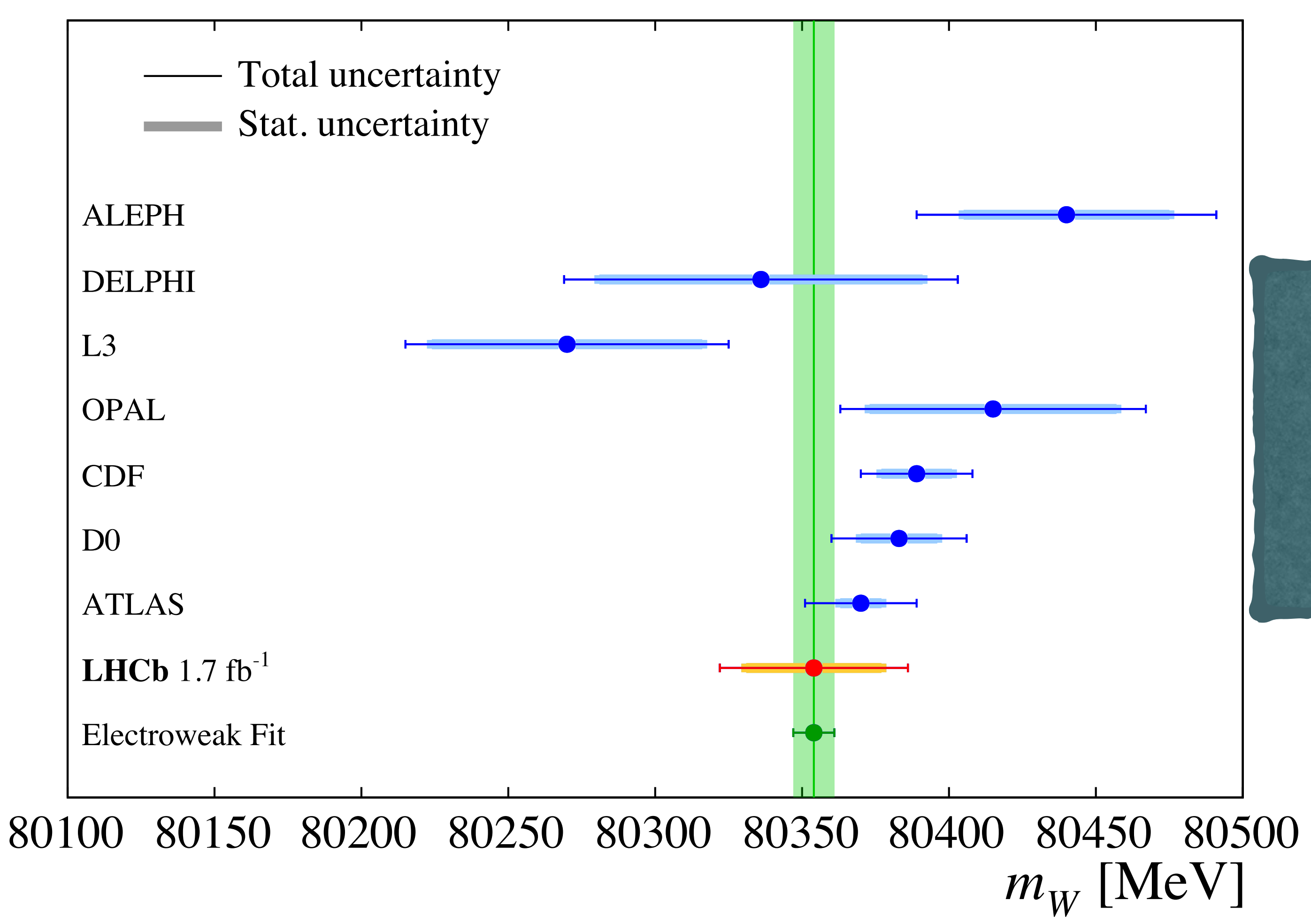
average of LHCb results consistent with global CKM fits



$$x = \left(0.400^{+0.052}_{-0.053}\right)\,\%$$

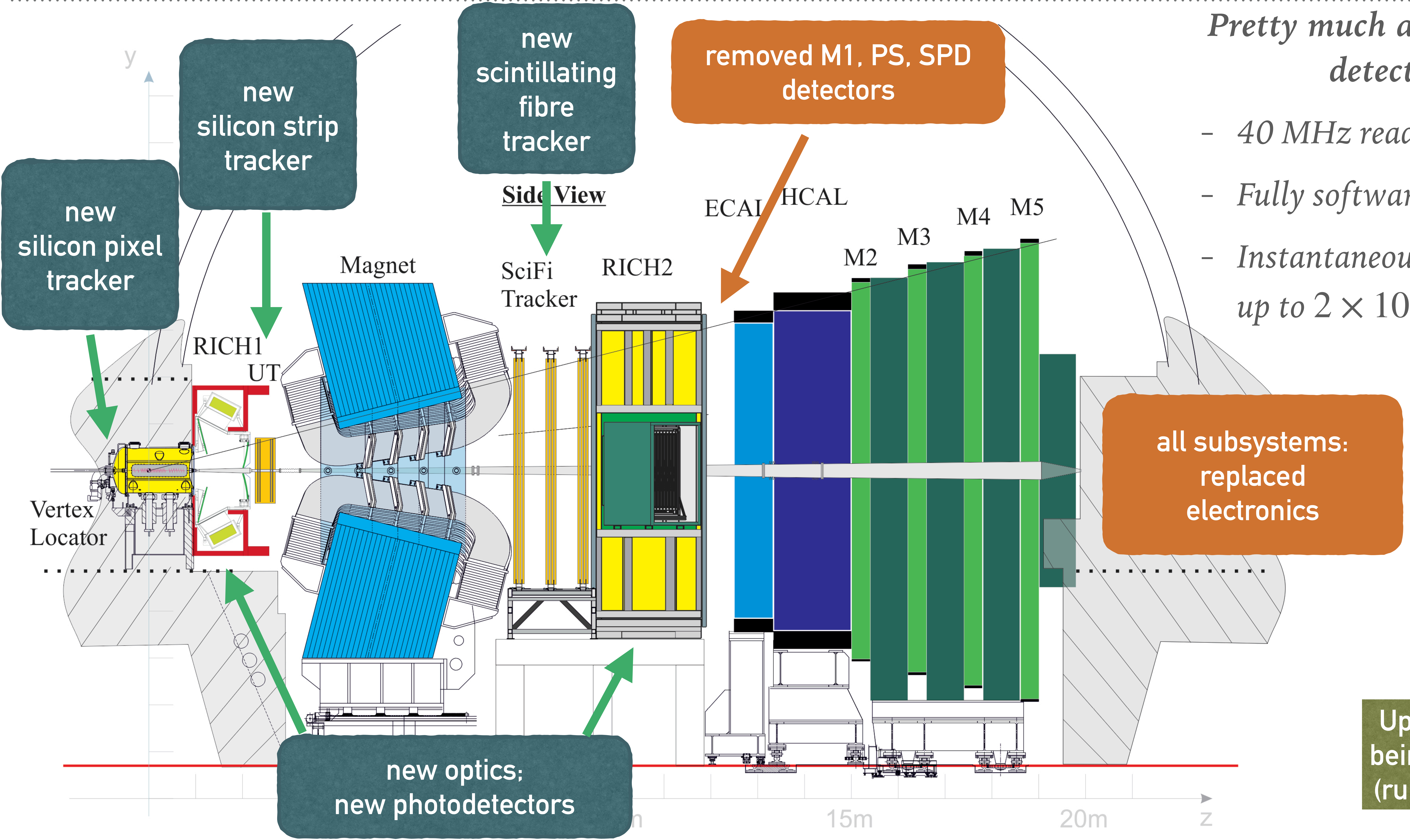
first observation of non-zero mass difference of D^0 mass eigenstates





W boson mass measurement

COMING SOON: UPGRADE I (2022-…)



Pretty much a brand new detector!

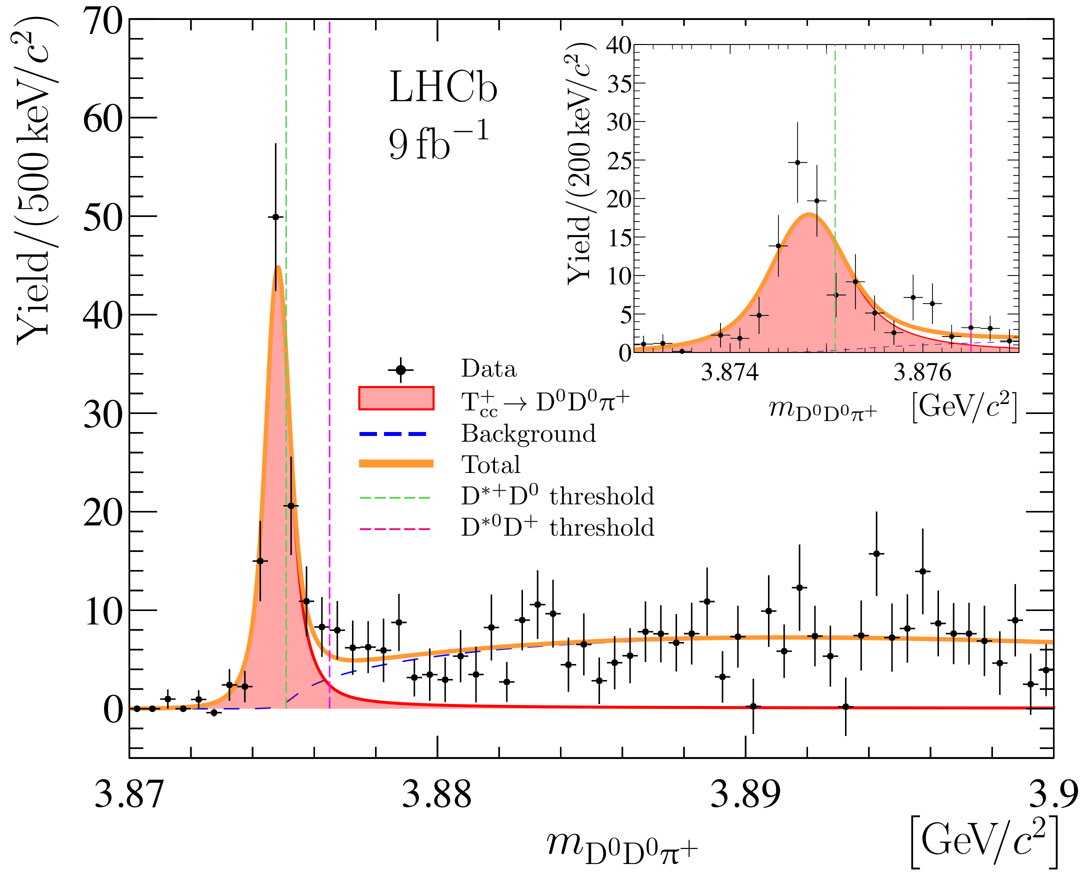
- *40 MHz readout*
- *Fully software trigger*
- *Instantaneous luminosity up to $2 \times 10^{33}\ cm^{-2}s^{-1}$*

Upgrade II is being planned (run in 2030s)

COMING SOON: UPGRADE I (2022-…)

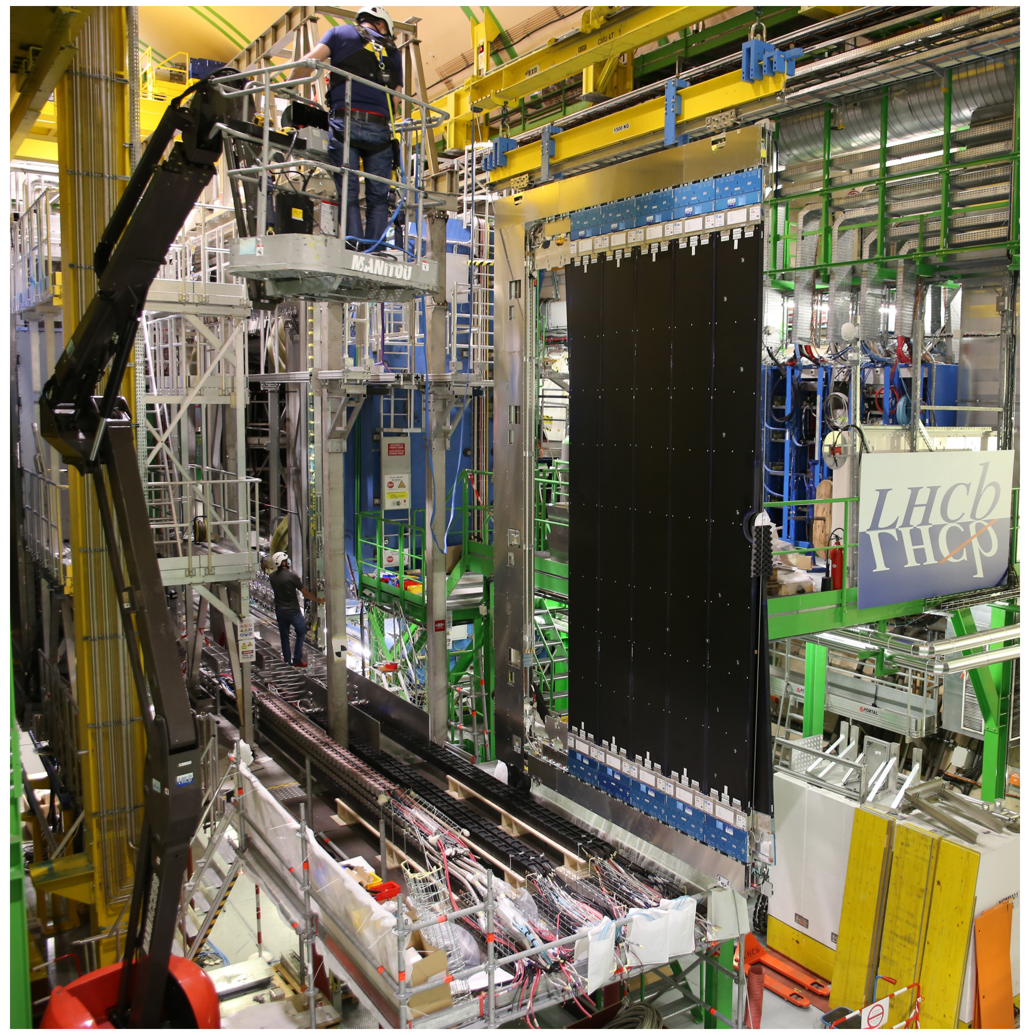
- With removal of the hardware trigger, we hope to get rid of the main bottleneck for final states without muons
  - The software trigger is much more flexible
  - We still need to make sure our new software trigger is not introducing any similar bottleneck :)
  - Even for final states with a dimuon, we can achieve better efficiency at low q^2.
- Complete rewrite of the reconstruction software (incl. electrons)
- Keeping the PID performance at a similar level
  - dedicated work on improvements of muon ID
- The hope is to collect up to ~50 fb^{-1} until the end of Run 4 -> ~5x current dataset
  - The yields should hopefully scale better than 5x
  - But the backgrounds scale too – incl. pile-up
- For official projections on physics channels, check our Physics case for Upgrade II.

- **Collecting harvest from our flavourful Run 1 + Run 2 datasets**
  - Flavour anomalies keep intriguing us
    - LFU and angular observables in $b \to s\ell^+\ell^-$ processes
  - Precision on the UT angle γ improved from $\sim 20°$ to $\sim 4°$ during the years of LHCb operation
  - Important contributions to hadron spectroscopy



Charming tetraquark

- **LHCb Upgrade I is in its crucial phase**
  - the detector is being assembled as we speak now

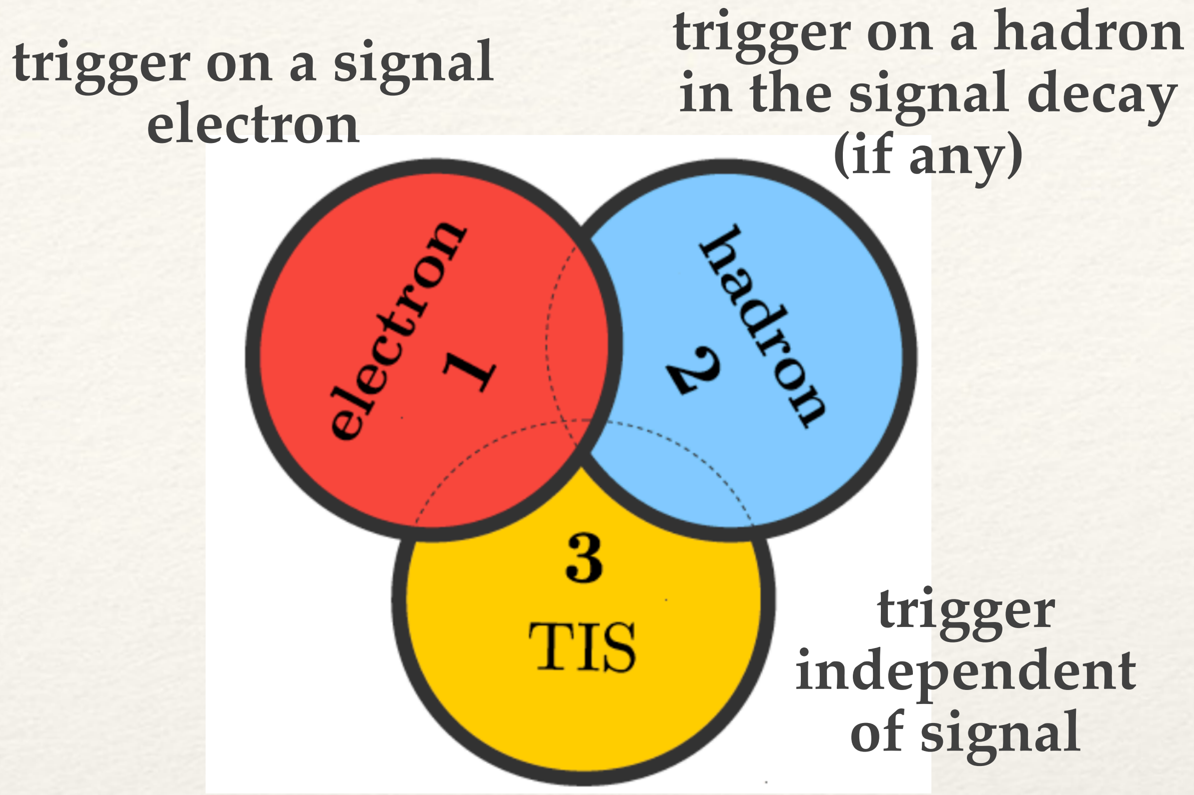


SciFi installation

- **Mapping the future of flavour physics with our planned Upgrade II**

Challenges with electrons

- **Hardware** trigger:
  - efficient for final states **with muons** (~90 %)
  - a bottleneck for final states *without* muons
    - calorimeter has a high occupancy, tight thresholds
  - final states **with electrons** can be triggered in several ways:



- **Electrons** emit a large amount of **bremsstrahlung** in interactions with the detector material
  - If a photon is emitted *before the magnet*:
    - electron momentum measured *after* bremsstrahlung;
    - photon ends up in a *different* ECAL cell
  - dedicated procedure to search for these photons and correct the electron momenta
  - not a perfect correction, **affects the resolution**