Probing new horizons with flavour at the LHCb experiment

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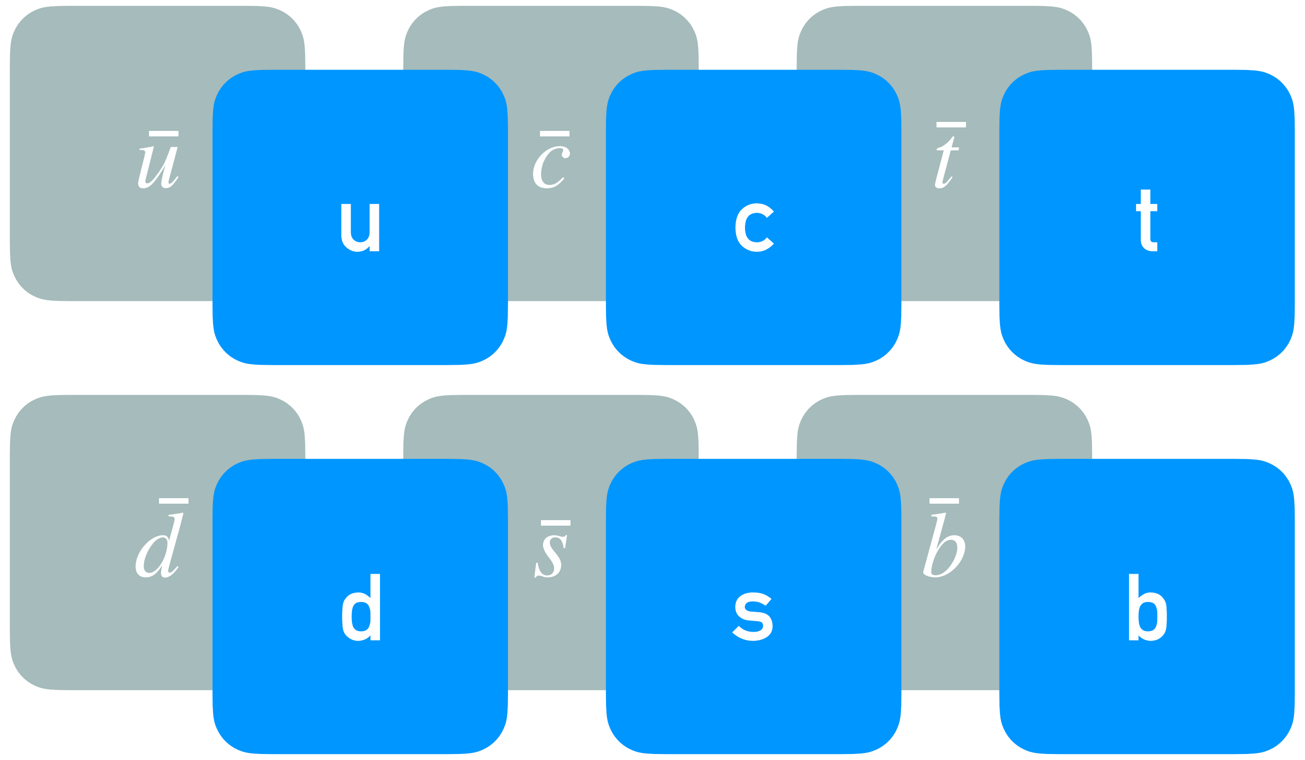
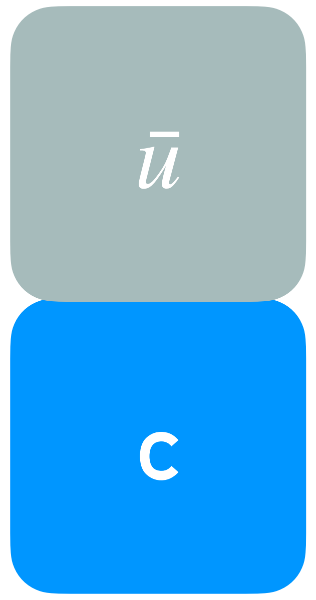
photo: Janina Nicolini

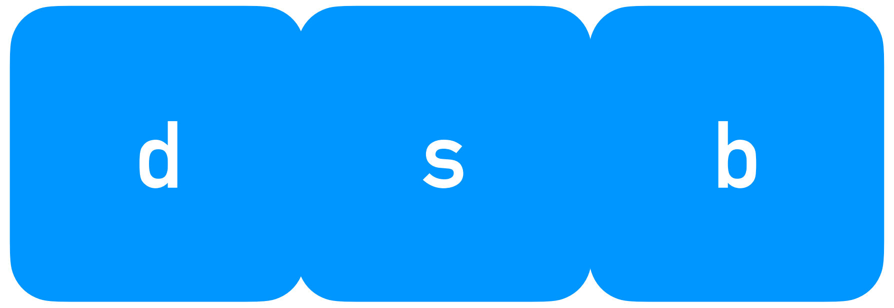
- Take the Standard Model's building blocks:



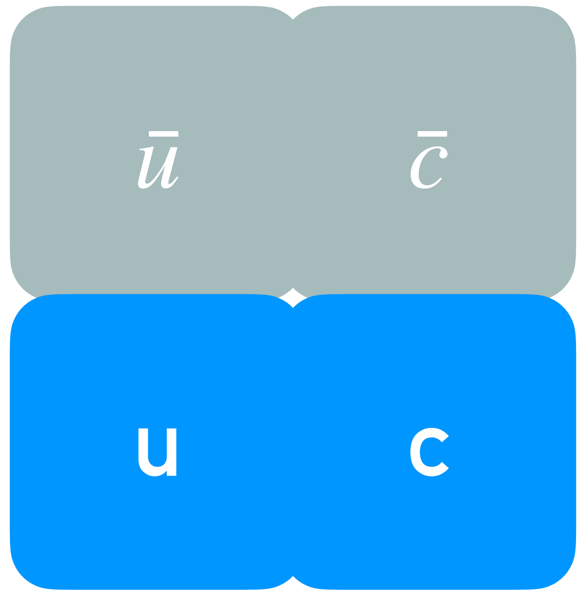
- Build all possible creatures:



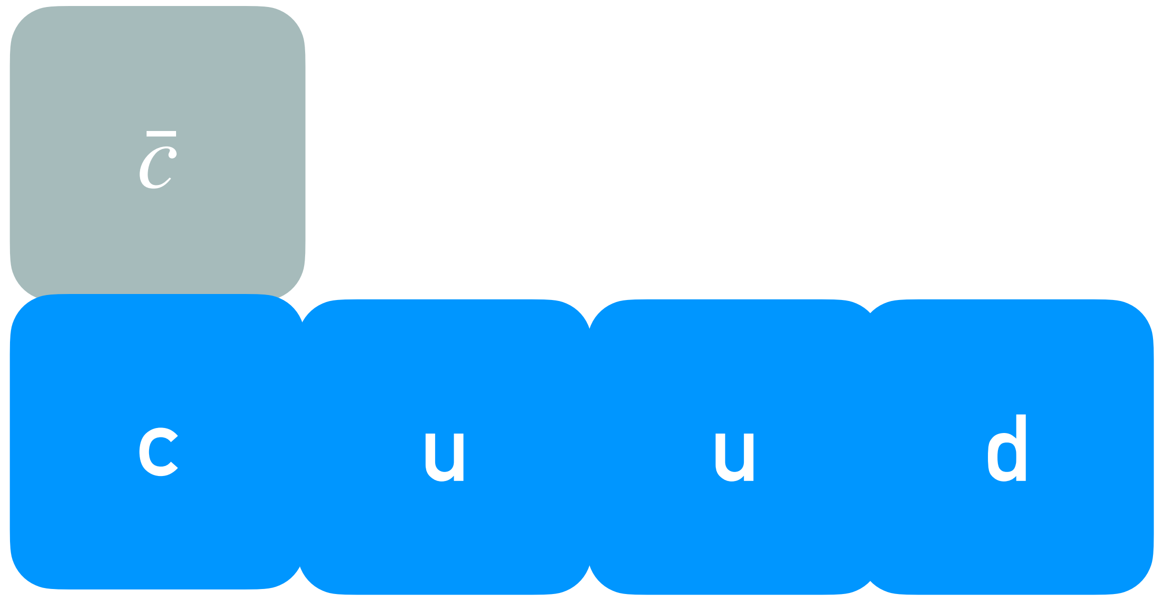
D^0 meson



Ξ_b^- baryon



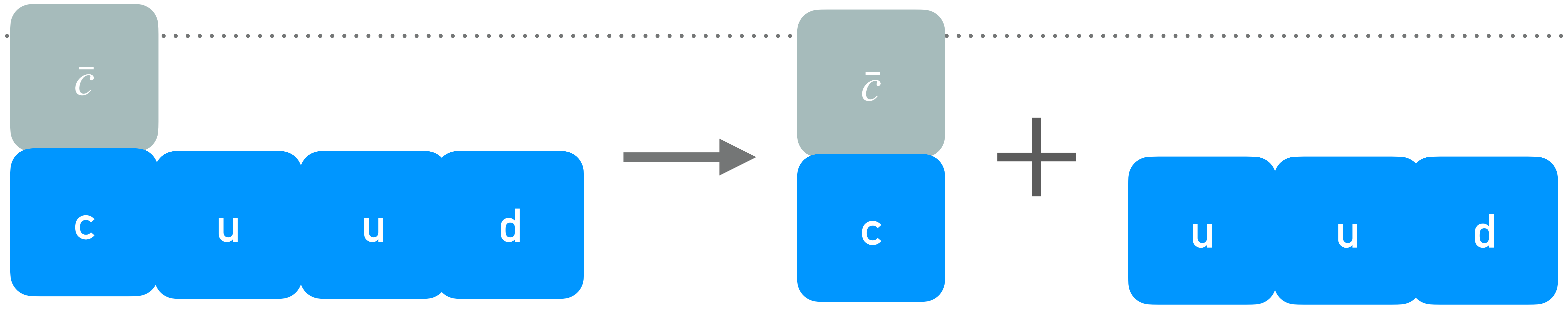
tetraquark?



pentaquark?

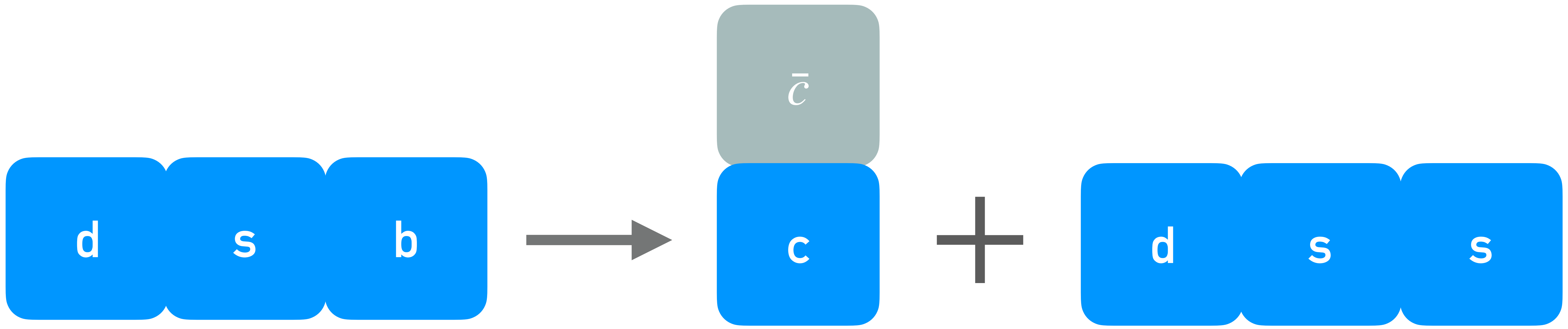
- Let them decay:

$P_c^+ \to J/\psi p$



Strong interaction: flavour unchanged

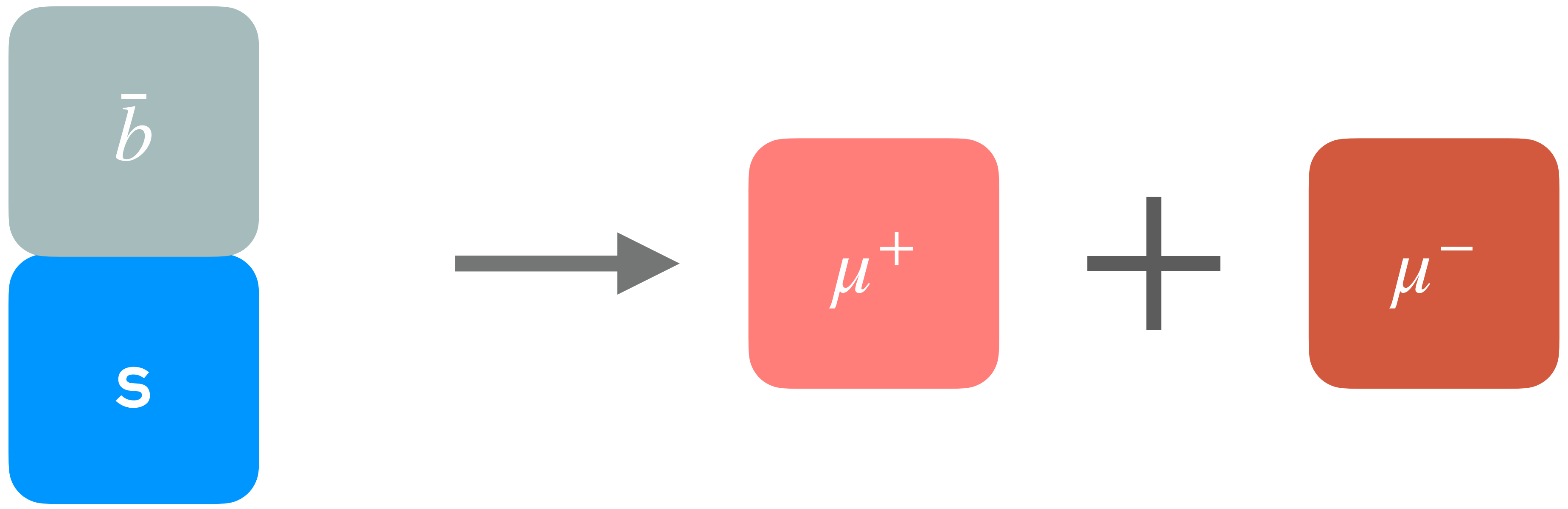
$\Xi_b^- \to J/\psi \Xi^-$



Electroweak interaction: flavour changes

- Search for very rare (in SM) decays: are there other, unknown, interactions at play?

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



Are properties of such decays consistent with the SM?

- Can we find decays forbidden in the Standard Model?

THE KEY PLAYERS

- We are most interested in states containing b or c quarks.

- **Beauty** is the popular one:
  - Picosecond lifetime – measureable displacement
  - Large variety of allowed decay modes; CP violation; …
  - 'Easy' theoretical description: heavy-quark effective limit

- **Charm** is for those who need no easy ways:
  - Somewhat shorter lifetime
  - Small CP violation
  - Theoretically challenging: charm quark mass ~ QCD scale
  - But easier to produce (higher cross-section)

The two complementary approaches to study heavy flavour in 2021:

Electron-positron colliders:

B-factories: run at the $e^+e^- \rightarrow B\bar{B}$ threshold energy

- *clean environment, only B and $\bar{B}$ in the event*
- *efficient tagging: knowing the B tags the $\bar{B}$*

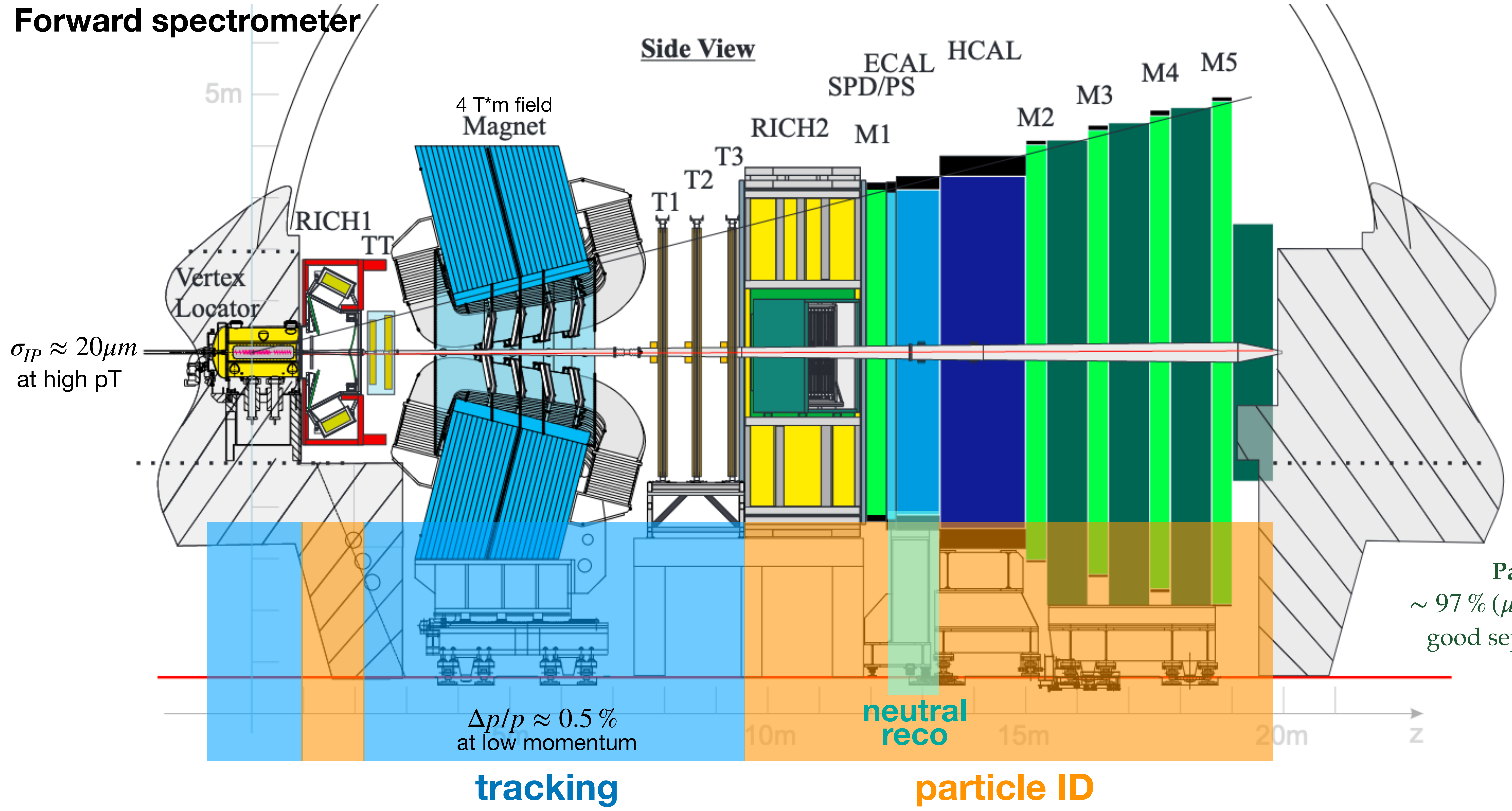
Charm factories: similar ideas at lower energy

Hadron colliders:

LHC: collides protons at 13TeV energy, produces a lot of everything

- *huge (!) cross-sections but large background*
- *produce heavier states: b-baryons, B_c^+*

Forward spectrometer



Particle identification
$\sim 97\,\%\,(\mu, e)$ ID rate 1-3% pion misID;
good separation of hadrons $\pi/K/p$

- 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)

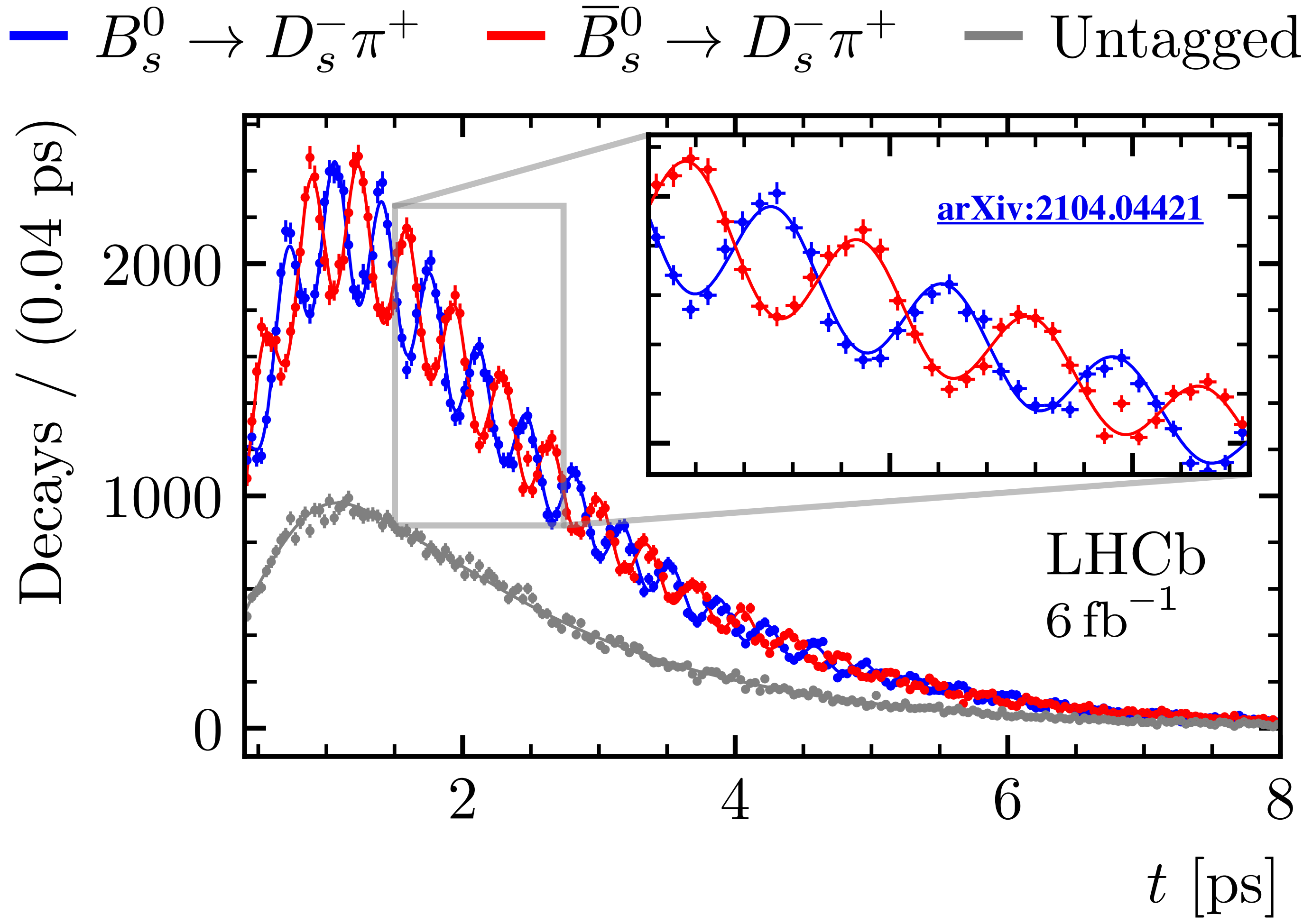
QUICK FACTS

Produce all types of b hadrons:

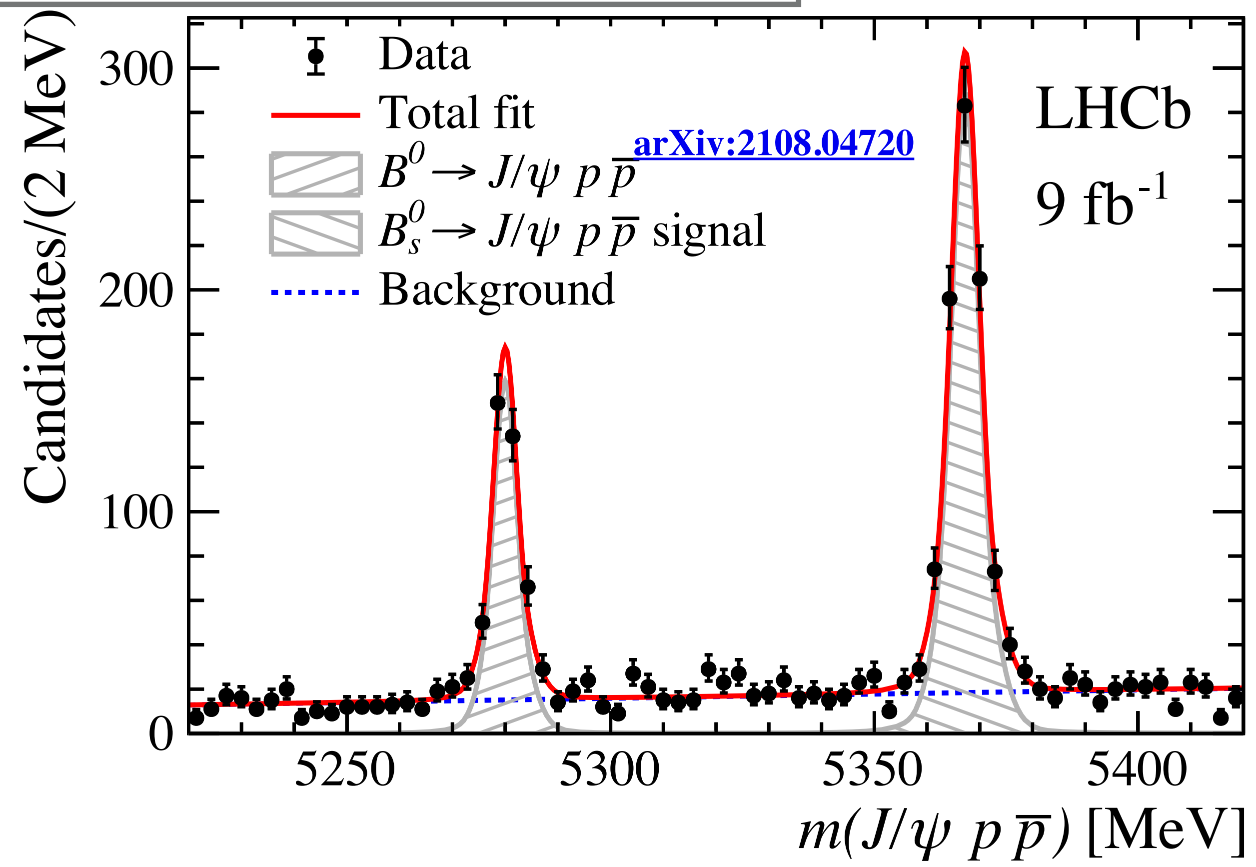
- ➤ Weakly-decaying
  - B^+, B^0: 35% each
  - B_s^0: 8.5%
  - Λ_b^0 (udb): 18%
  - Ξ_b^0, Ξ_b^- (usb, dsb): ~1.5% each
  - B_c^+, Ω_b^- (ssb): ~0.3% each
- ➤ Bottomonia

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



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

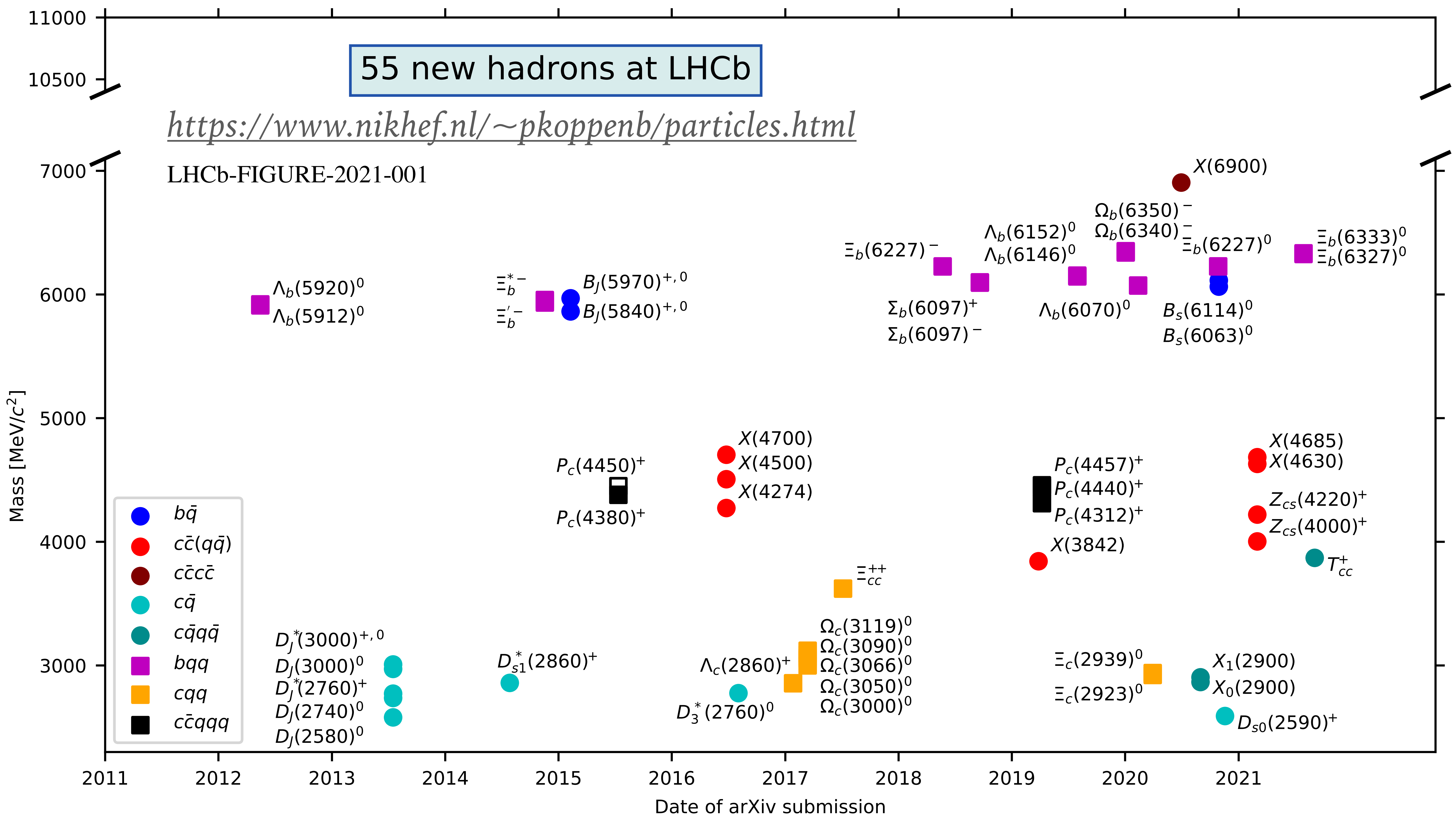
Huge cross-section of charm and strange hadrons

- ➤ **Compared to ATLAS/CMS:** forward acceptance; dedicated soft triggers; but lower luminosity
  - ➤ importantly, LHCb has triggers for fully hadronic decays, and hadron PID
- ➤ **Compared to B-factories (e.g. 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
  - ➤ we are less efficient flavour tagging; less efficient for final states with neutrals
  - ➤ we prefer relative measurements (BF, lifetimes) to absolute ones

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

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

Exotic spectroscopy:
tetra- and pentaquark candidates



DOUBLY-CHARM SPECTROSCOPY

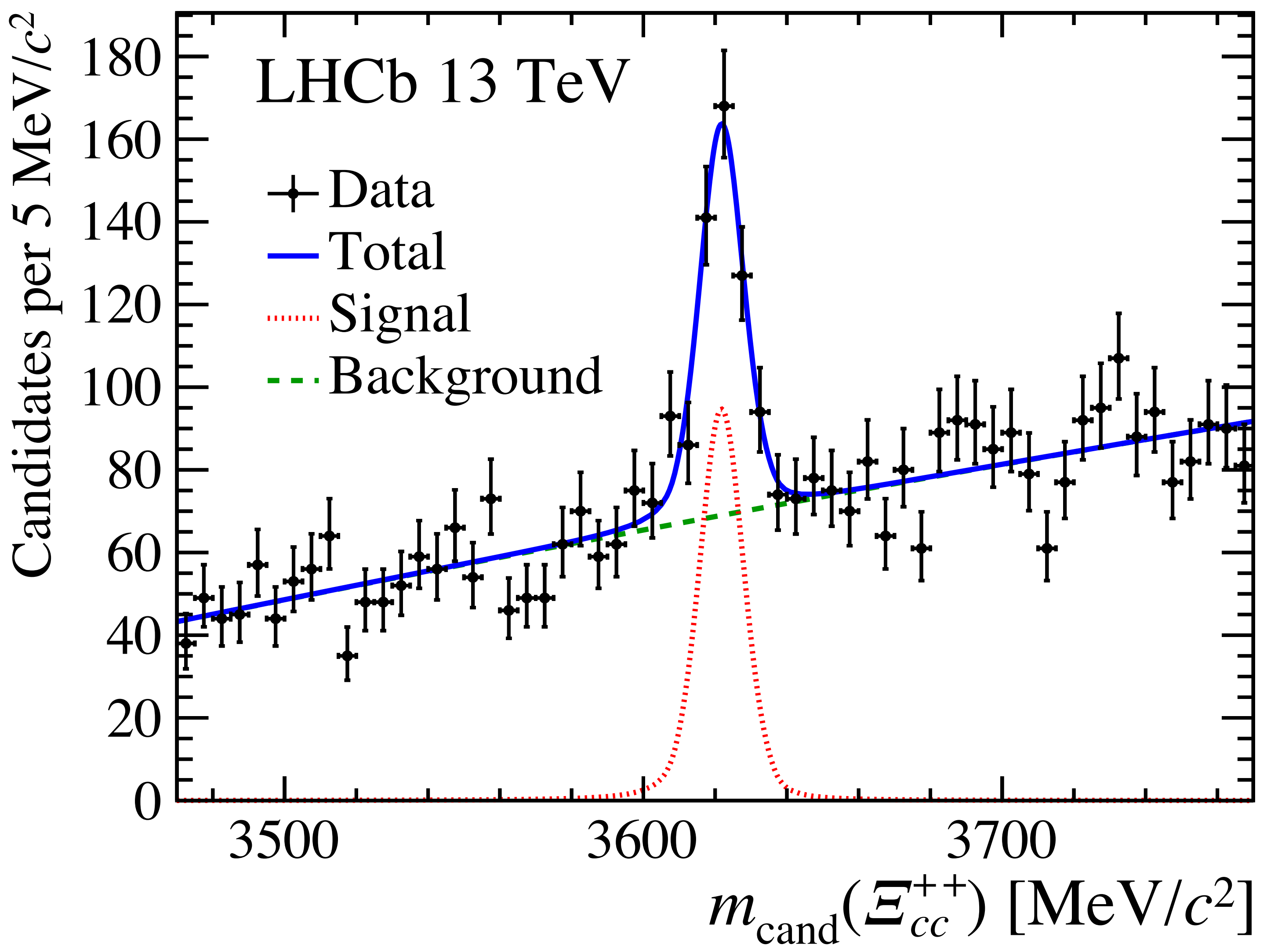
arXiv: 2109.01038 , 2109.01056

Full Run1+Run2 dataset

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

2021: NEW

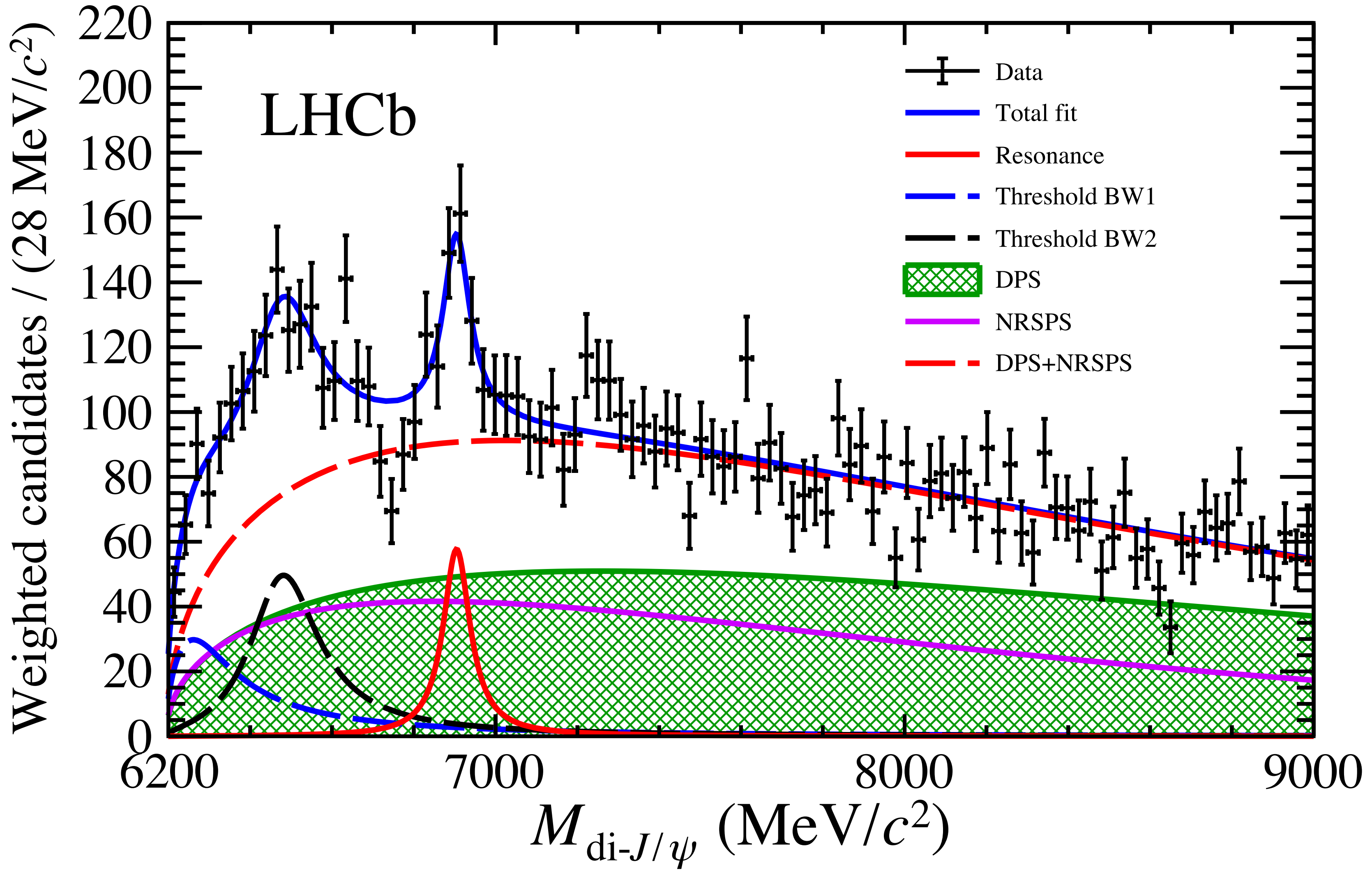
2017



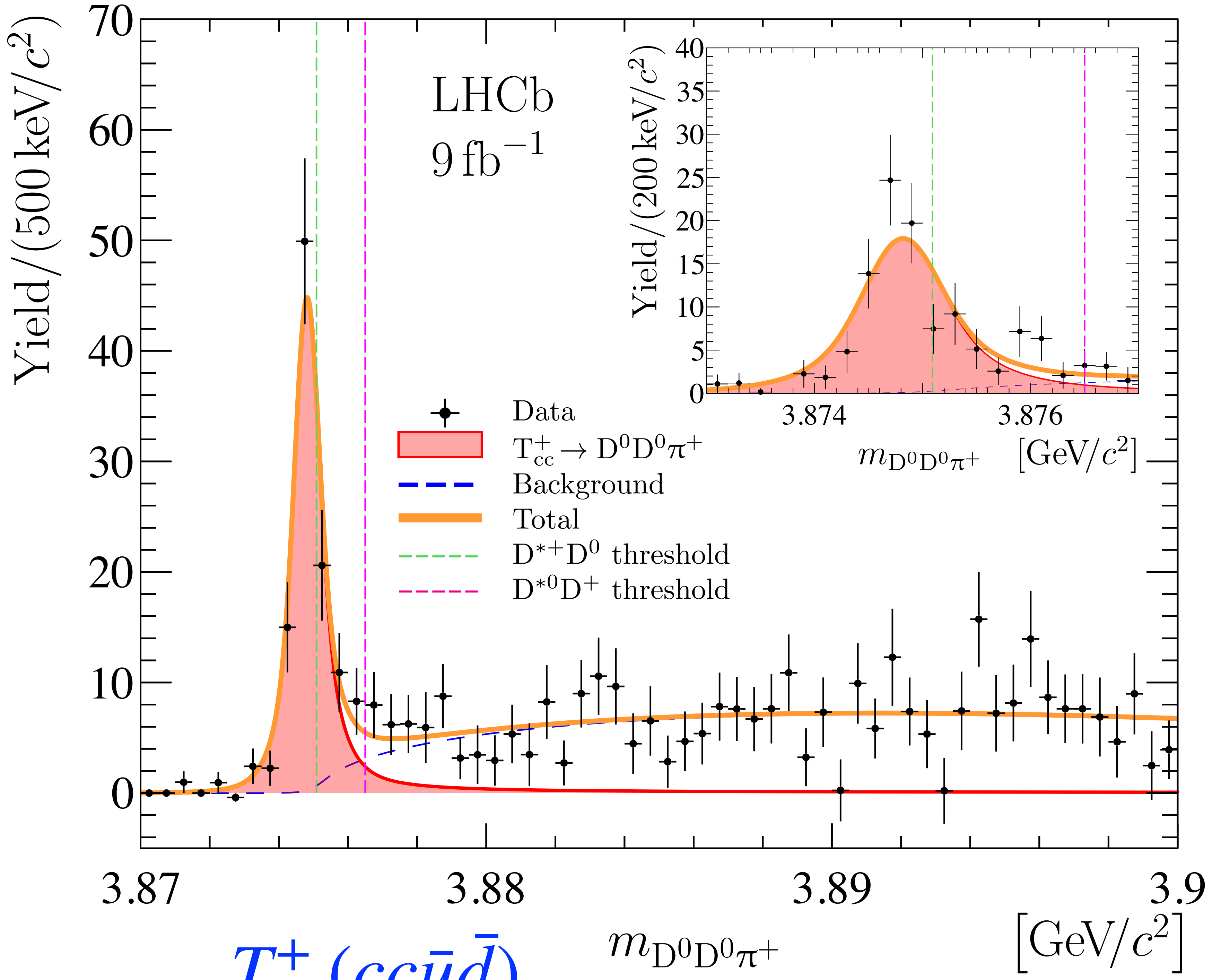
Ξ_{cc}^{++} (ccu)

also: searches for Ξ_{cc}^{+} (ccd)

2020

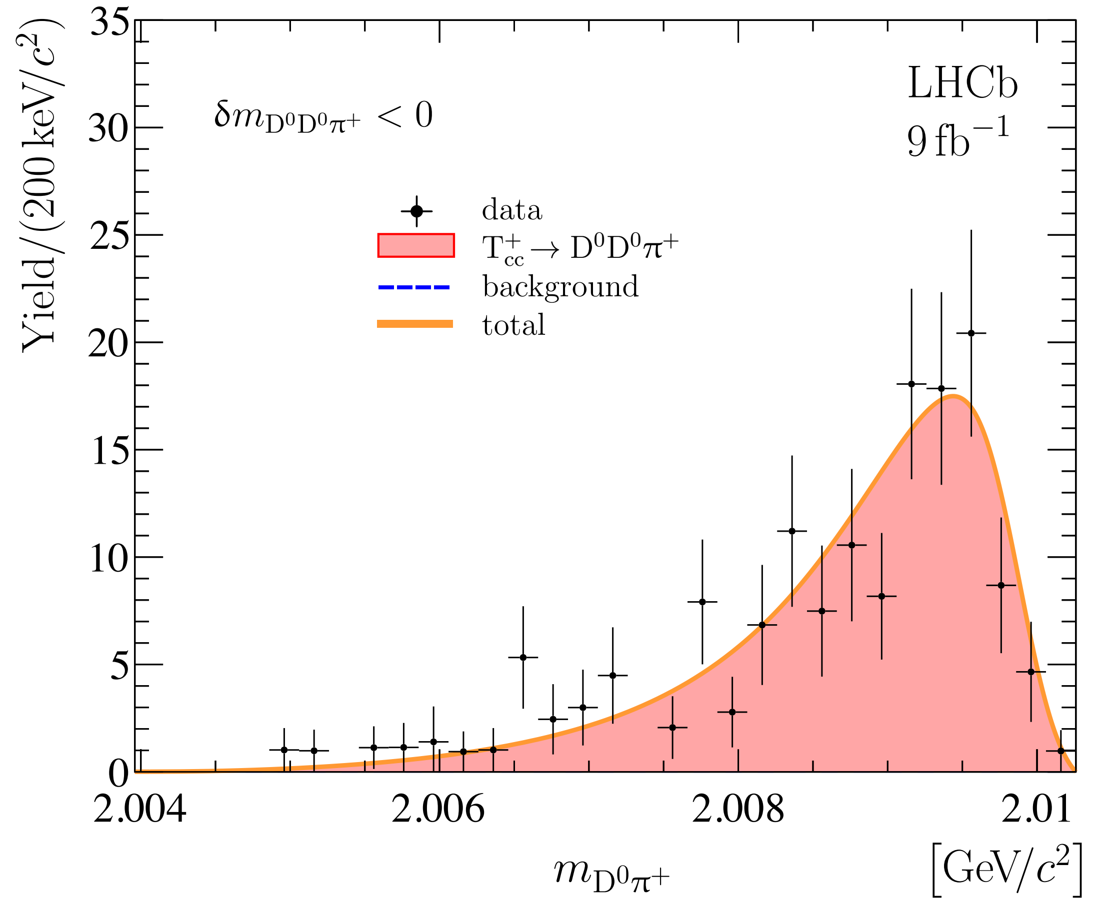


structure in $m(J/\psi J/\psi)$: $(cc\bar{c}\bar{c})$

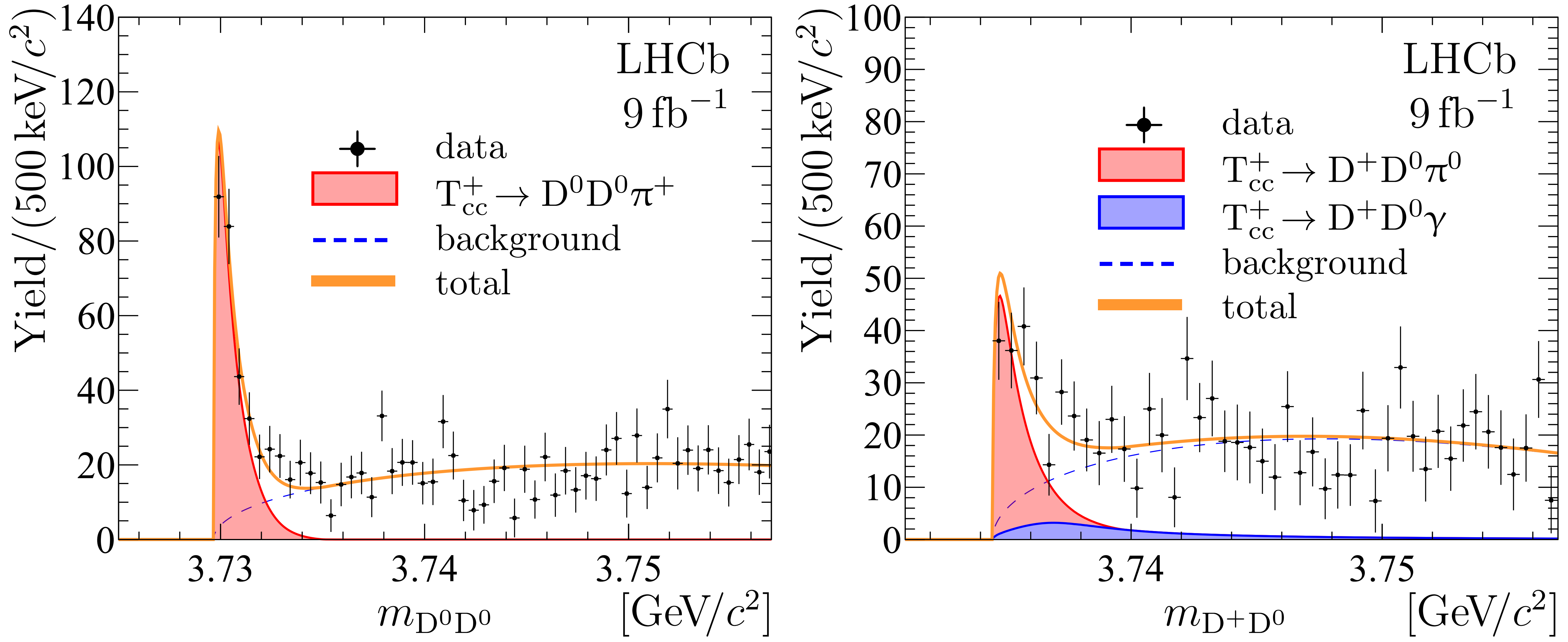


T_{cc}^{+} $(cc\bar{u}\bar{d})$

- 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 $J^P = 1^+$
    - no signal in $D^0D^+\pi^+$ final state
  - decays via off-shell D^{*+}



- Study partially reconstructed signal in D^0D^0 and D^0D^+



relative yields of the partially-reconstructed signal in agreement with isospin-0 prediction

- Mass measurement: relativistic Breit-Wigner lineshape, smeared by resolution, 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 3874.75±0.11 MeV/c²

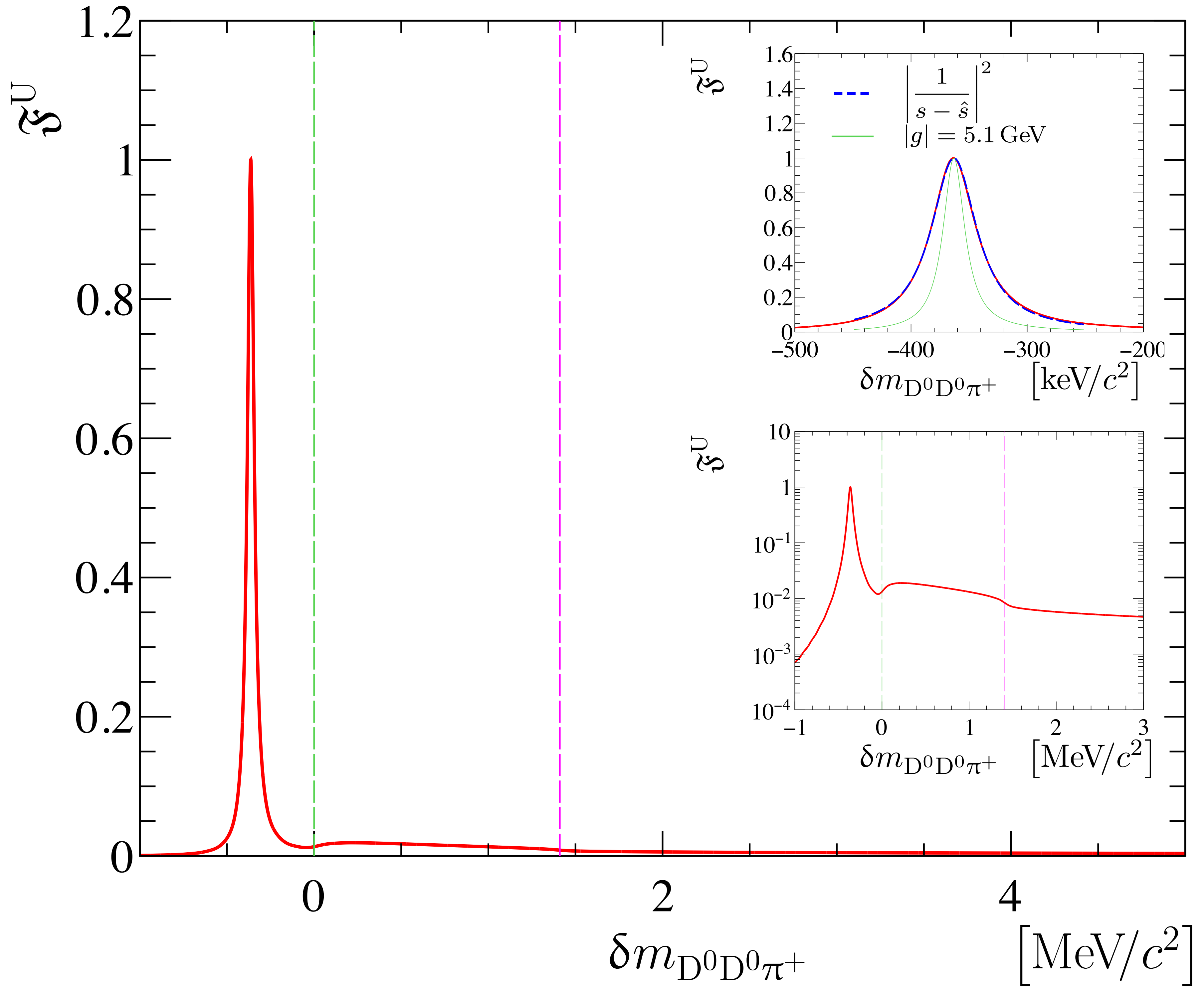
curious similarity to the X(3872) state (which has a $c\bar{c}$ rather than cc)

  - consistent with some of theoretical predictions (large spread)

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

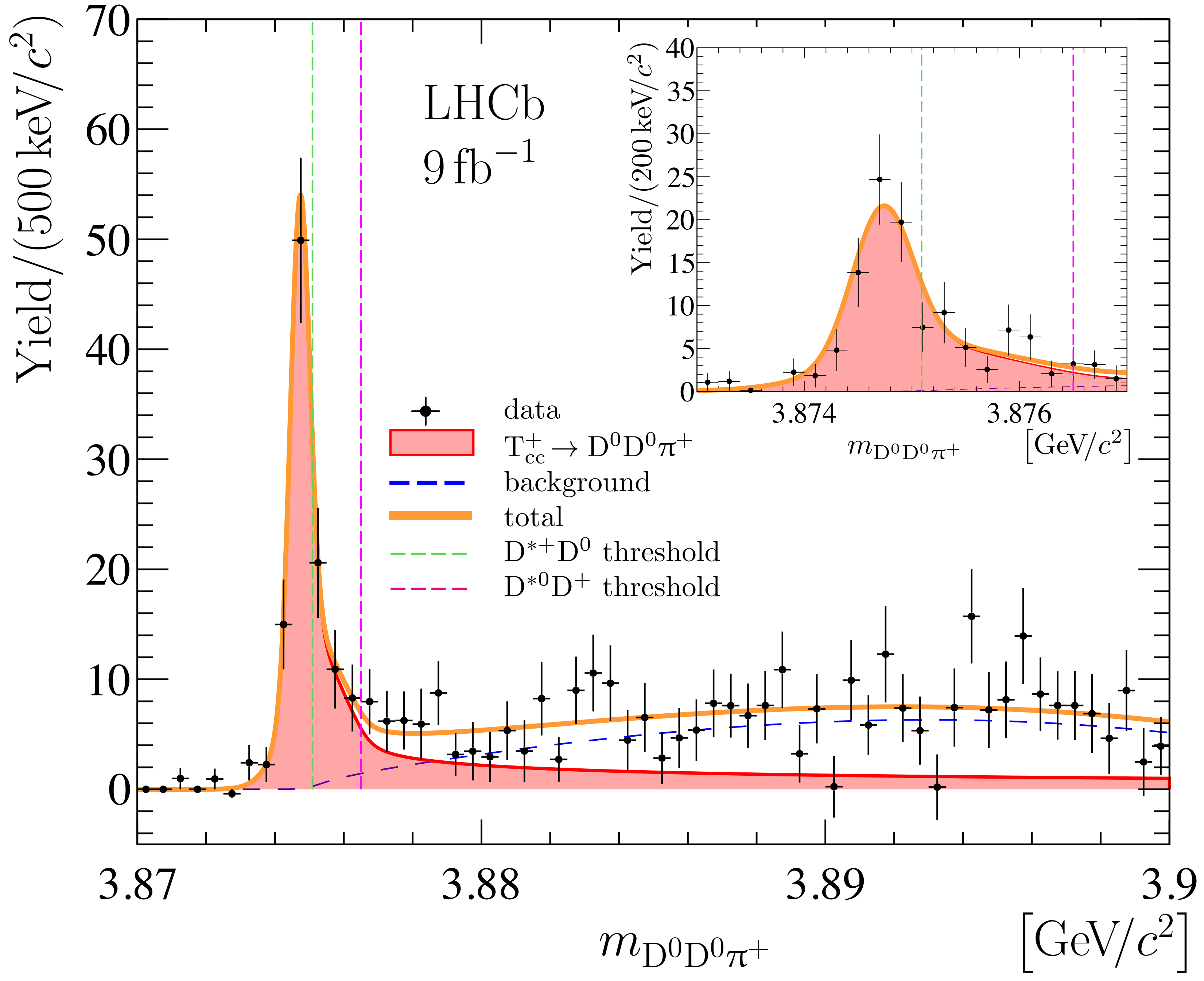
the smallest BW width of any known exotic state

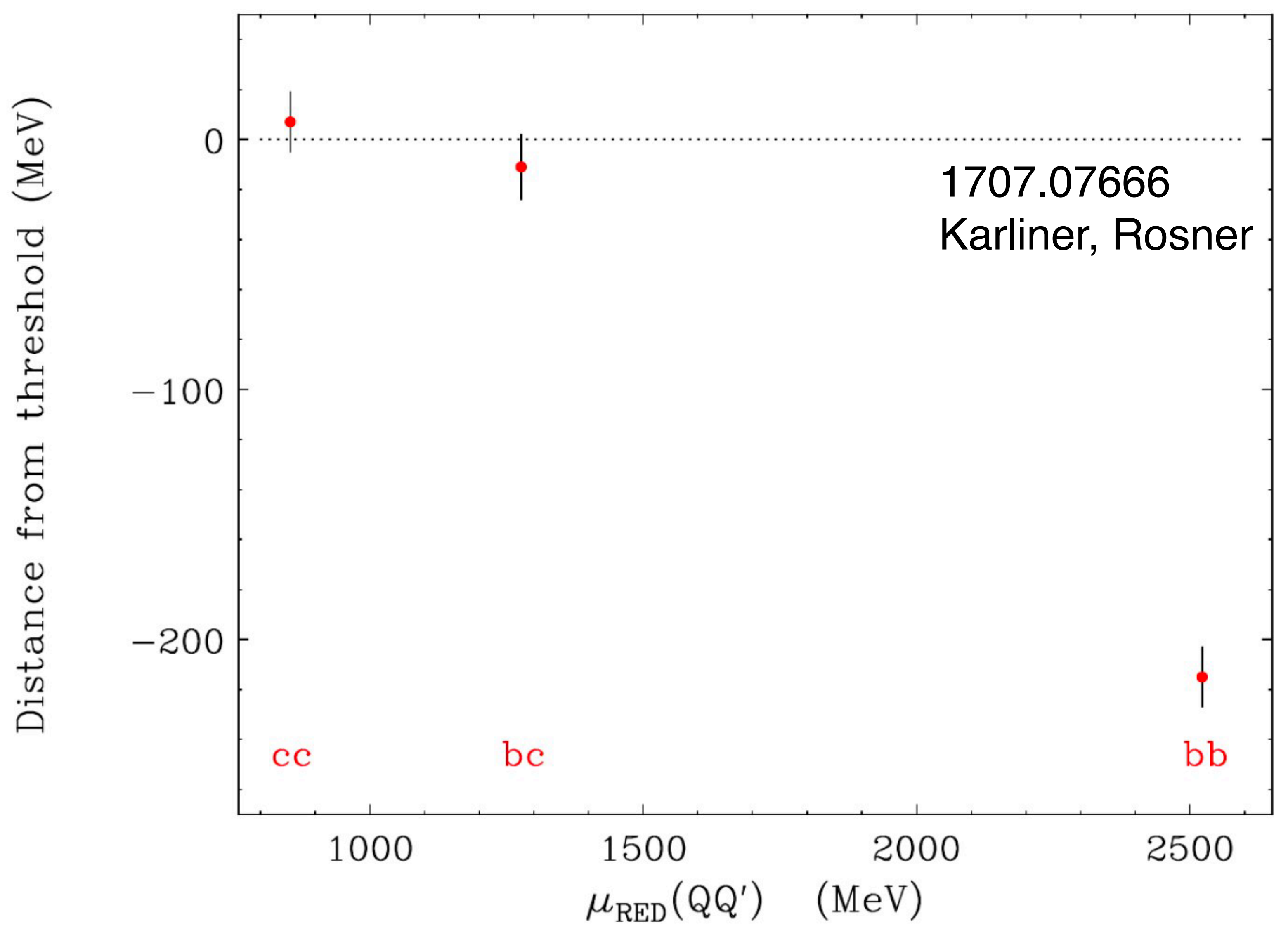
- **A more physical lineshape model explored as well:** take into account thresholds openings
  - Unitarised Breit-Wigner for $T_{cc}^{+} \to D^{0/+}D^{*+/0}$ decay, with $D^* \to D\pi^{0/+}$ and $D^* \to D\gamma$ linked by unitarity



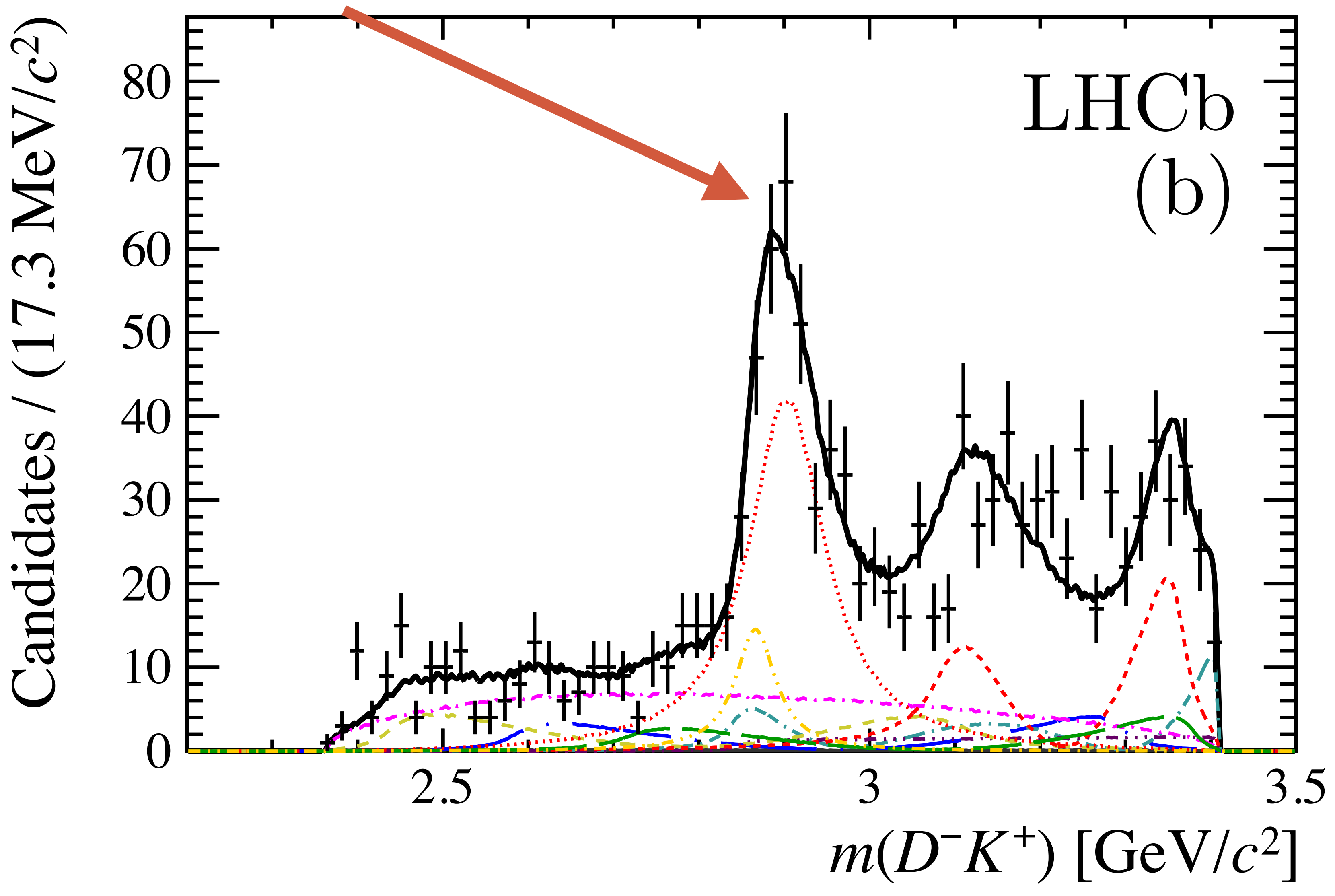
- **A more physical lineshape model explored as well:** take into account thresholds openings
  - Unitarised Breit-Wigner for $T_{cc}^{+} \to D^{0/+}D^{*+/0}$ decay, with $D^{*} \to D\pi^{0/+}$ and $D^{*} \to D\gamma$ linked by unitarity
  - Smeared with the detector resolution function
- $\delta m_{U} = -359 \pm 40^{+9}_{-6}\,\mathrm{keV/c^2}$: clearly below the $D^{*+}D^{0}$ threshold
- Measured also the pole position and characteristic size.

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

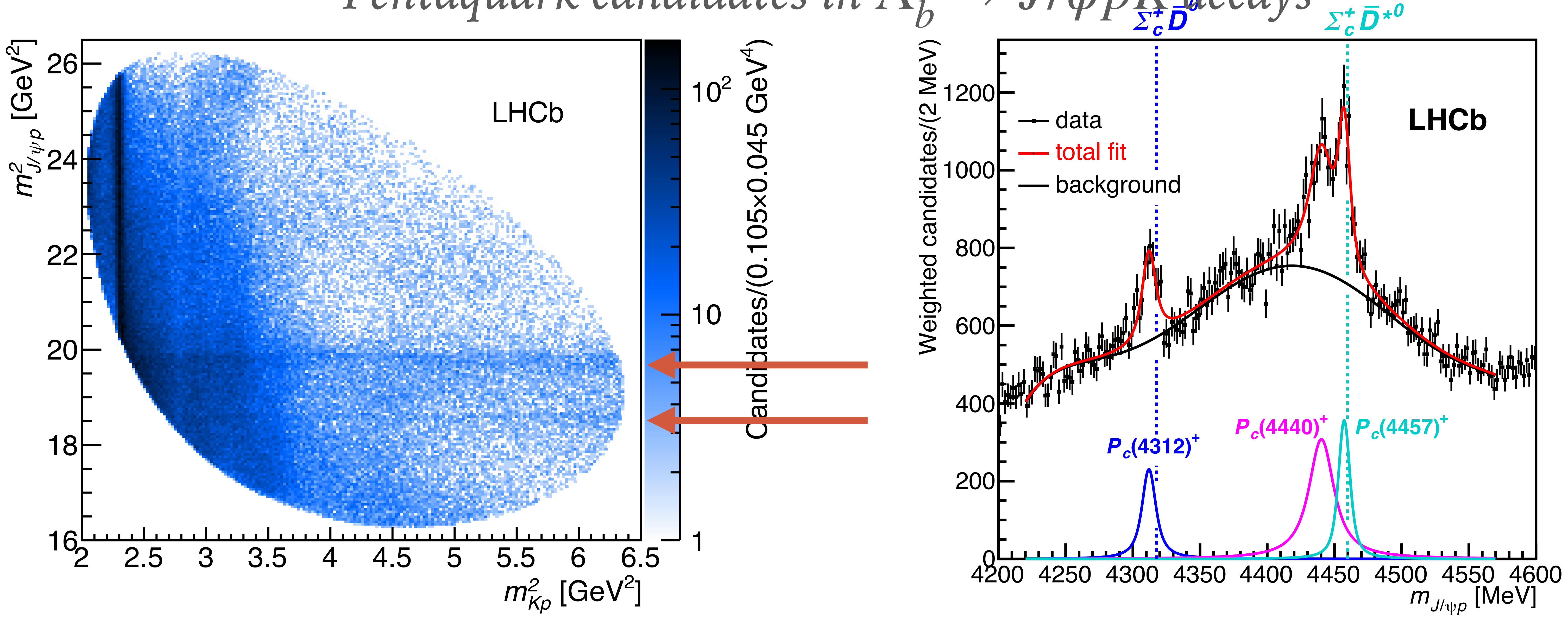




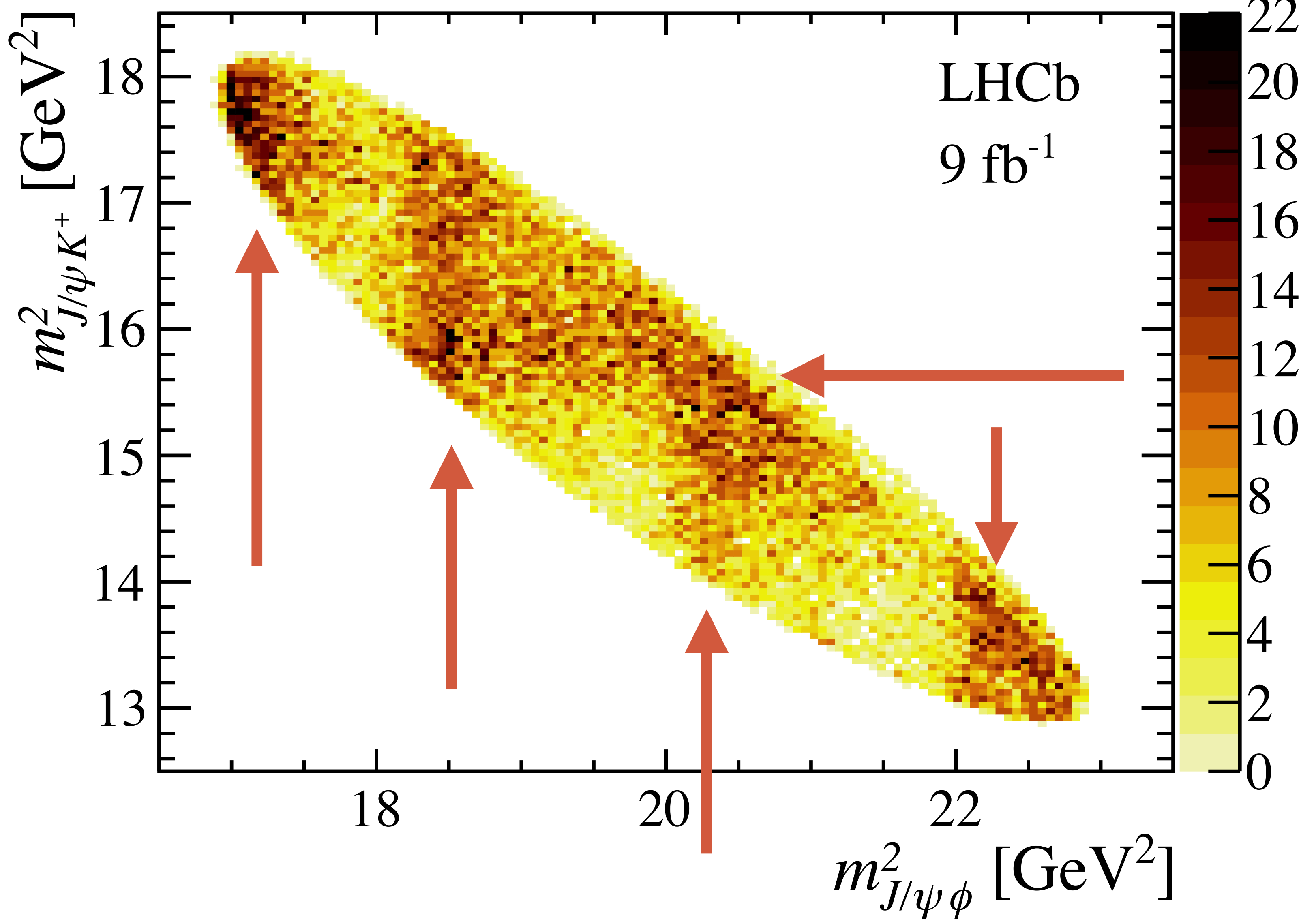
$X(2900) \to D^- K^+$ in $B \to DDK$ decays



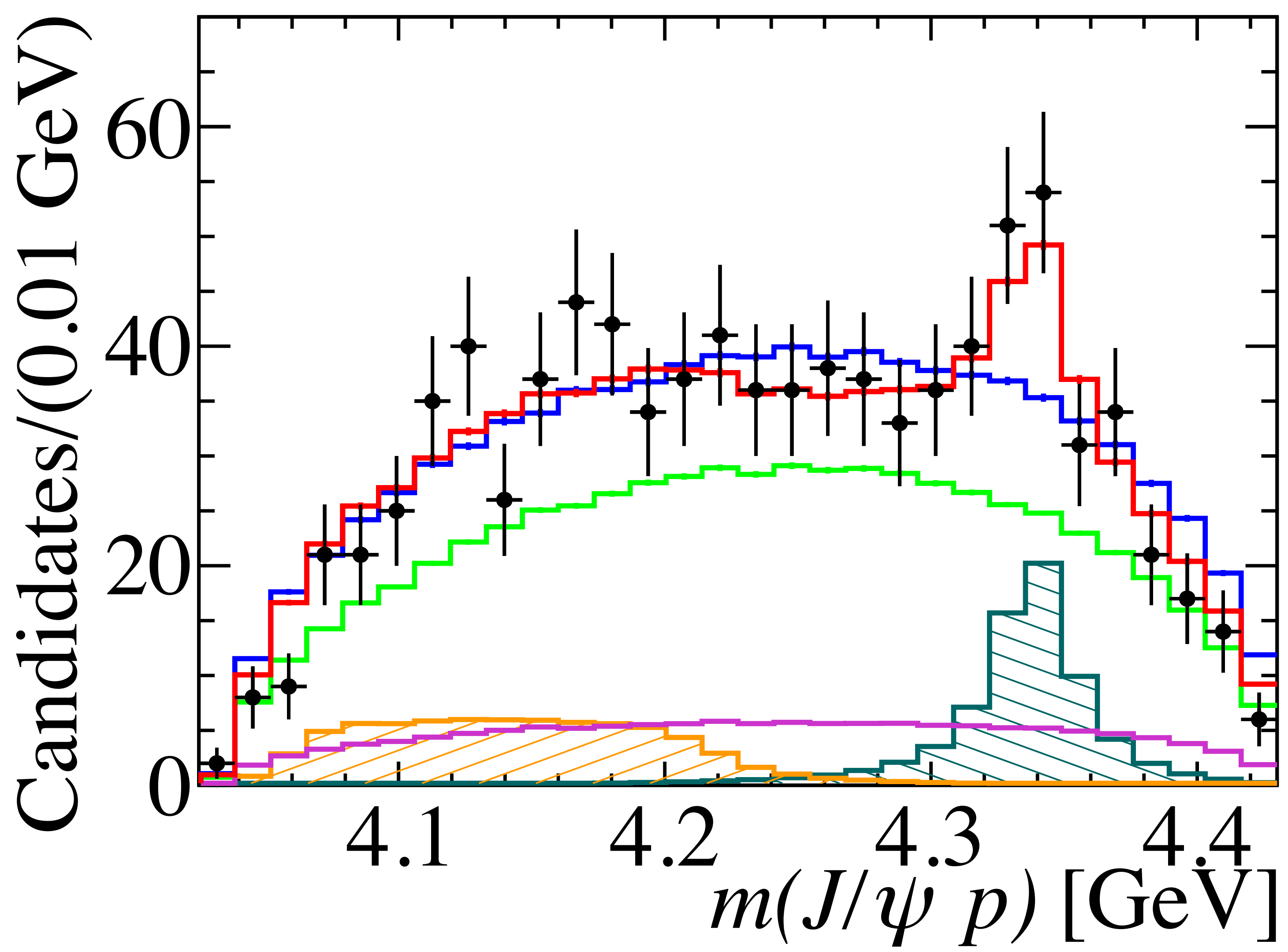
Pentaquark candidates in $\Lambda_b^0 \to J/\psi p K$ decays



Structures in $B^+ \to J/\psi \phi K$ decays

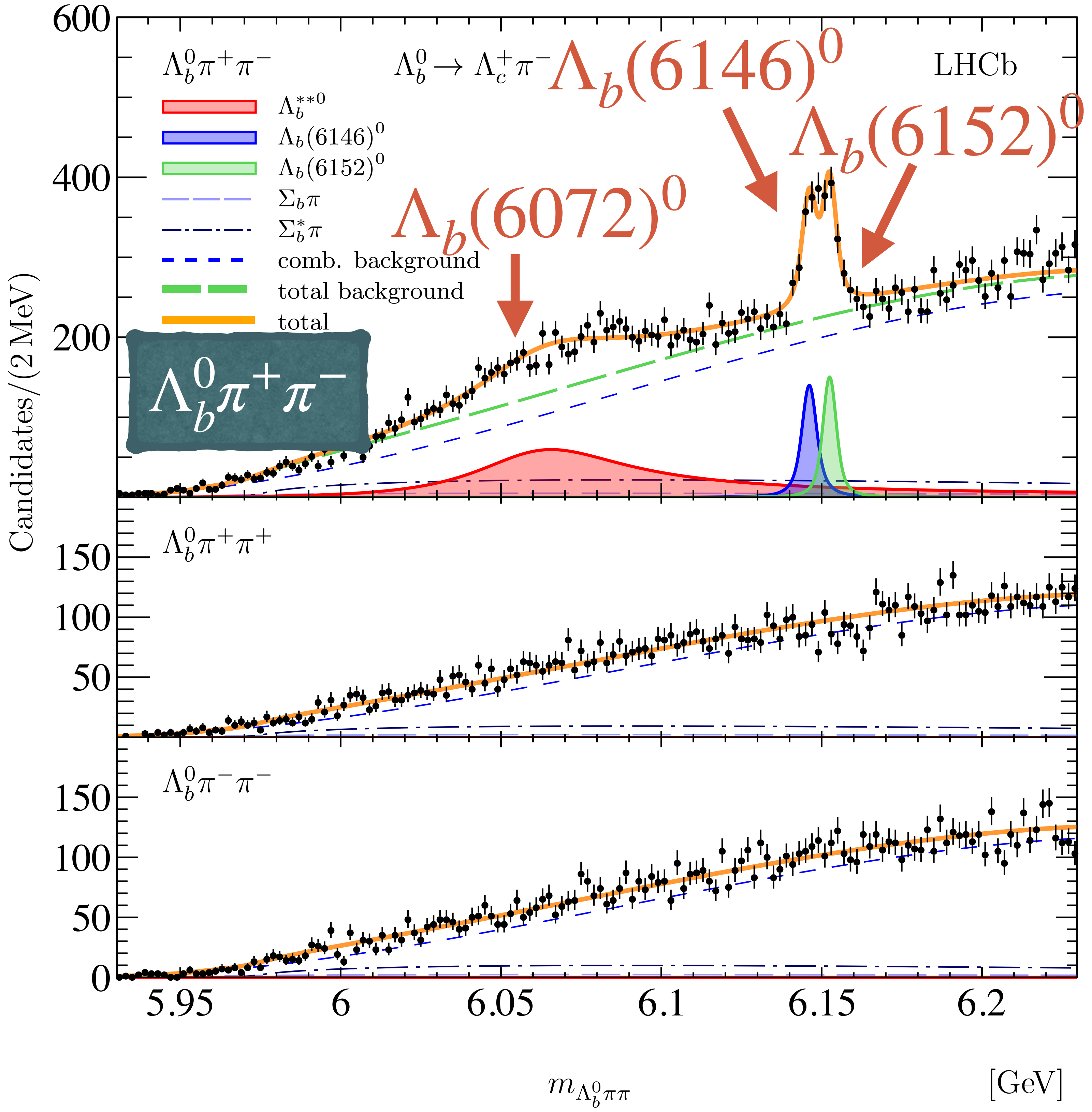


A different (?) pentaquark candidate in $B_s^0 \to J/\psi p \bar{p}$ decays

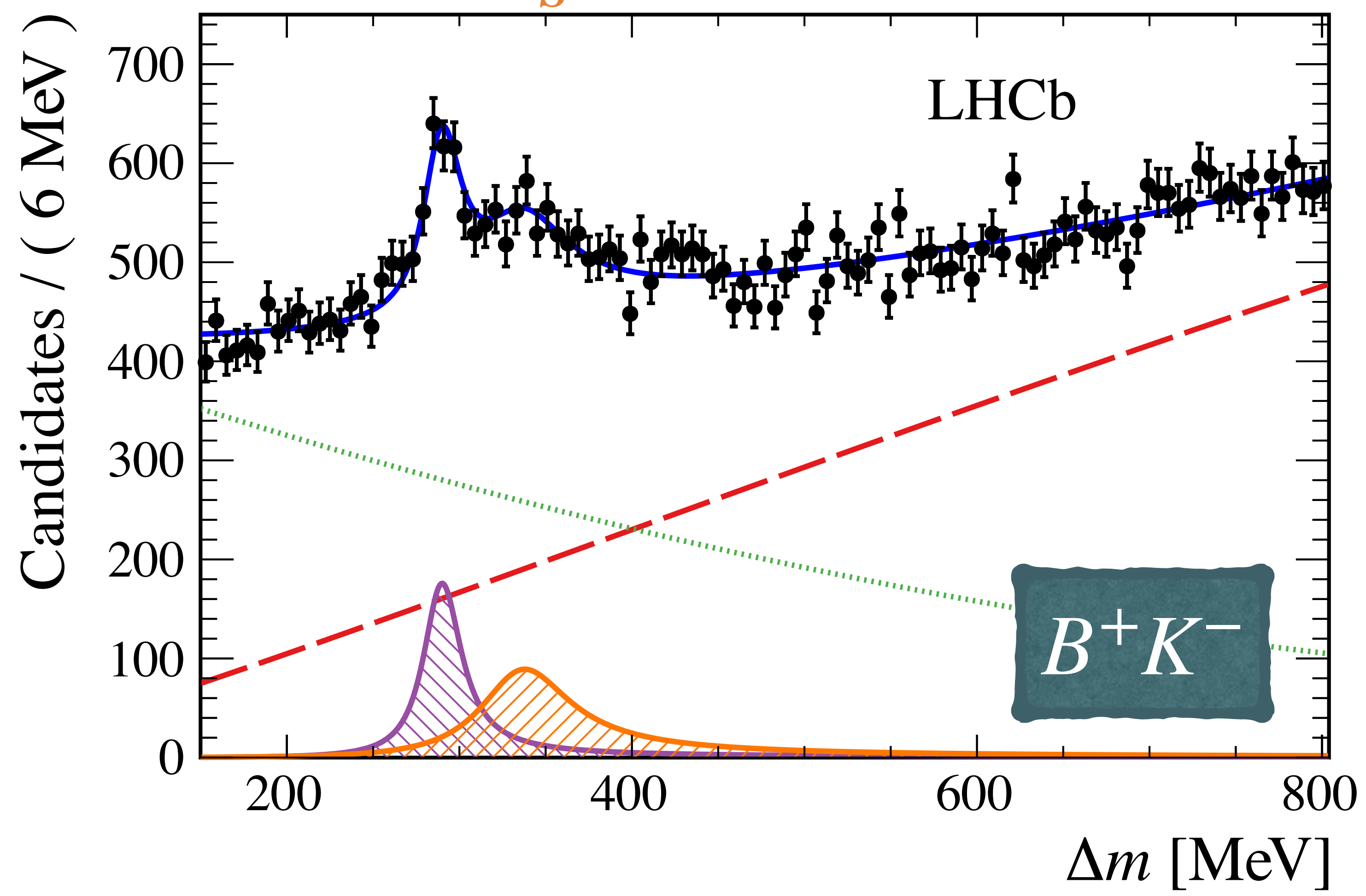


Understanding and systematising the exotic states is a major task for the coming years.

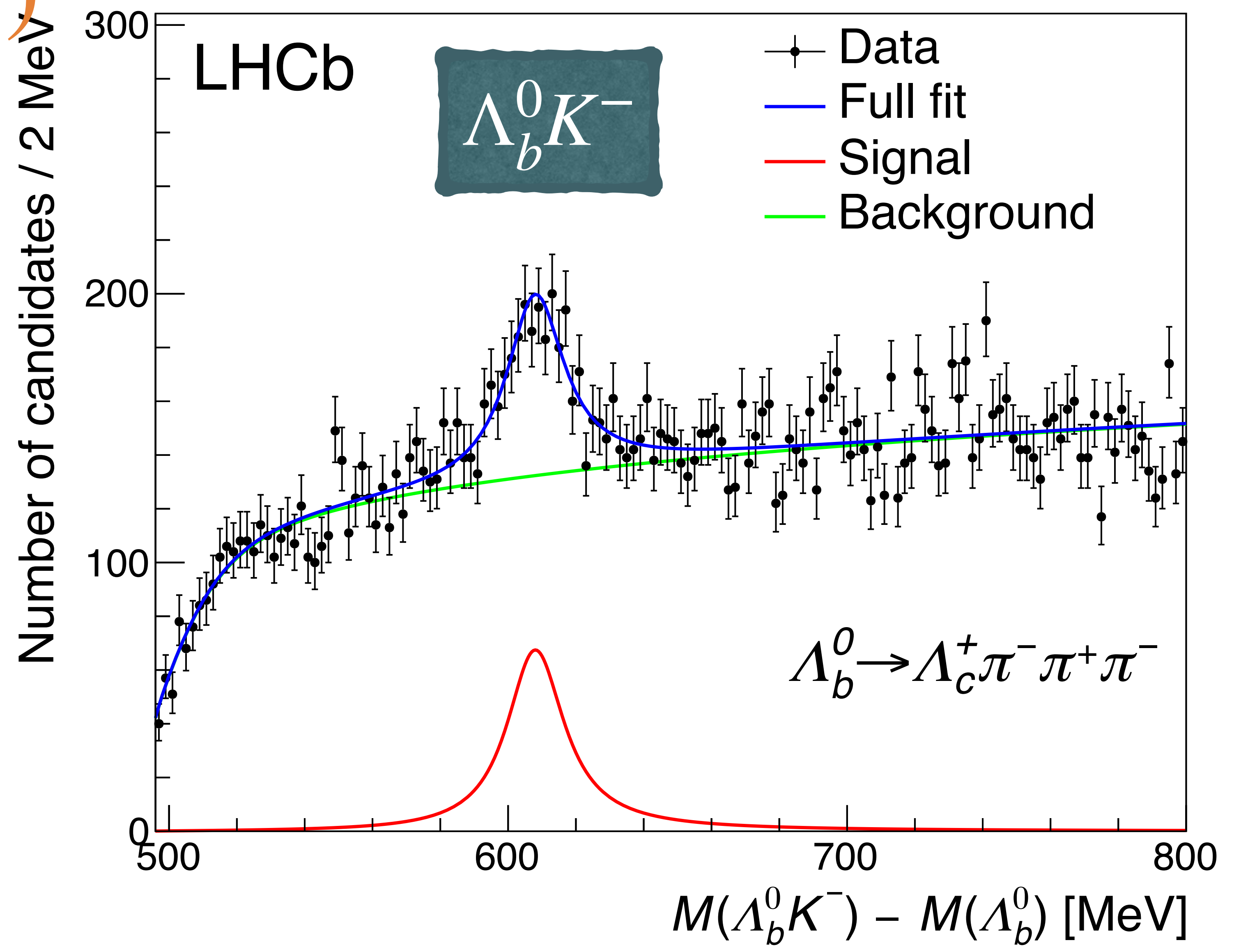
$\Lambda_b^0 = (udb)$



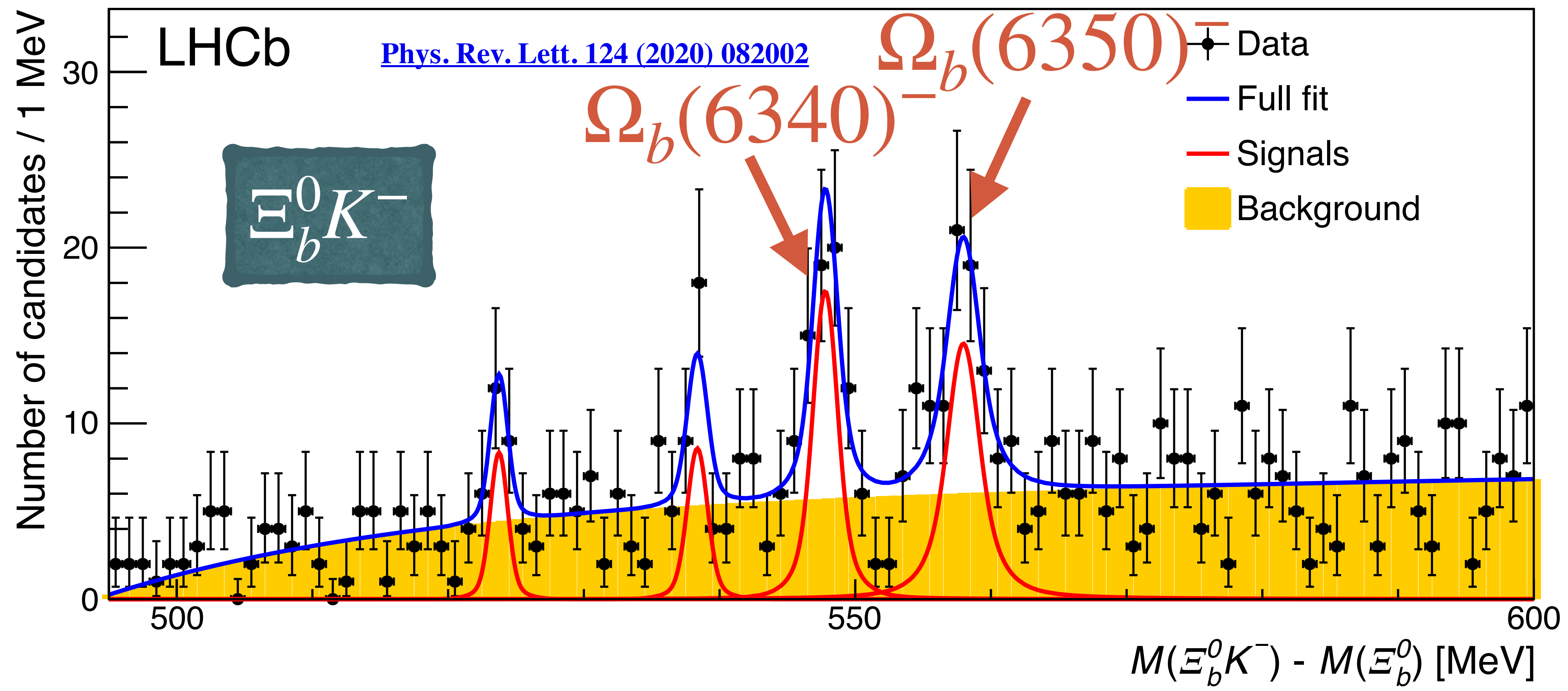
$B_s^0 = (\bar{b}s)$



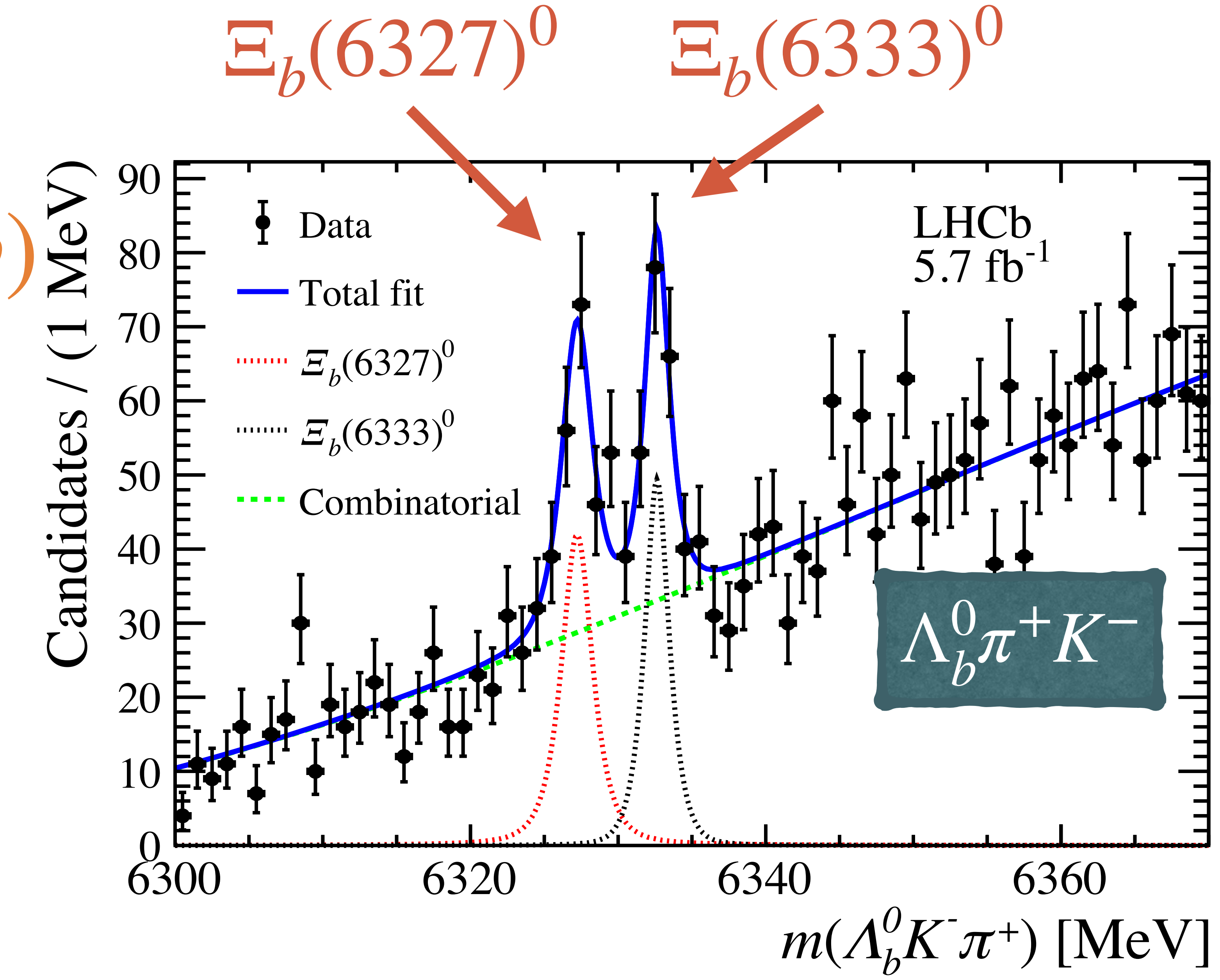
$\Xi_b^- = (dsb)$



$\Omega_b^- = (ssb)$



$\Xi_b^0 = (usb)$



some of these observations are currently only possible at LHCb: require good PID and hadronic triggers arXiv: 2109.01334

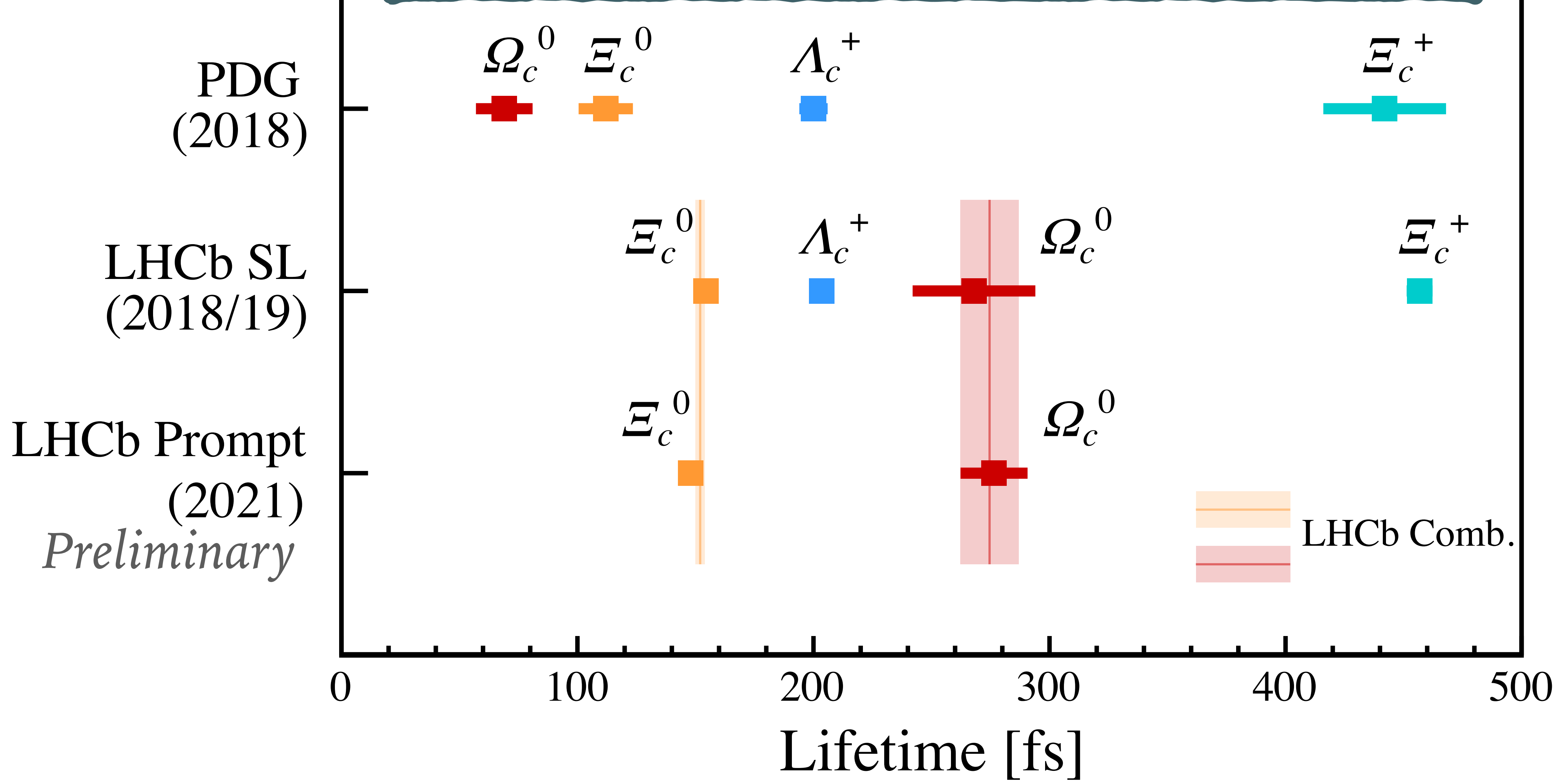
Run 2 dataset

- 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

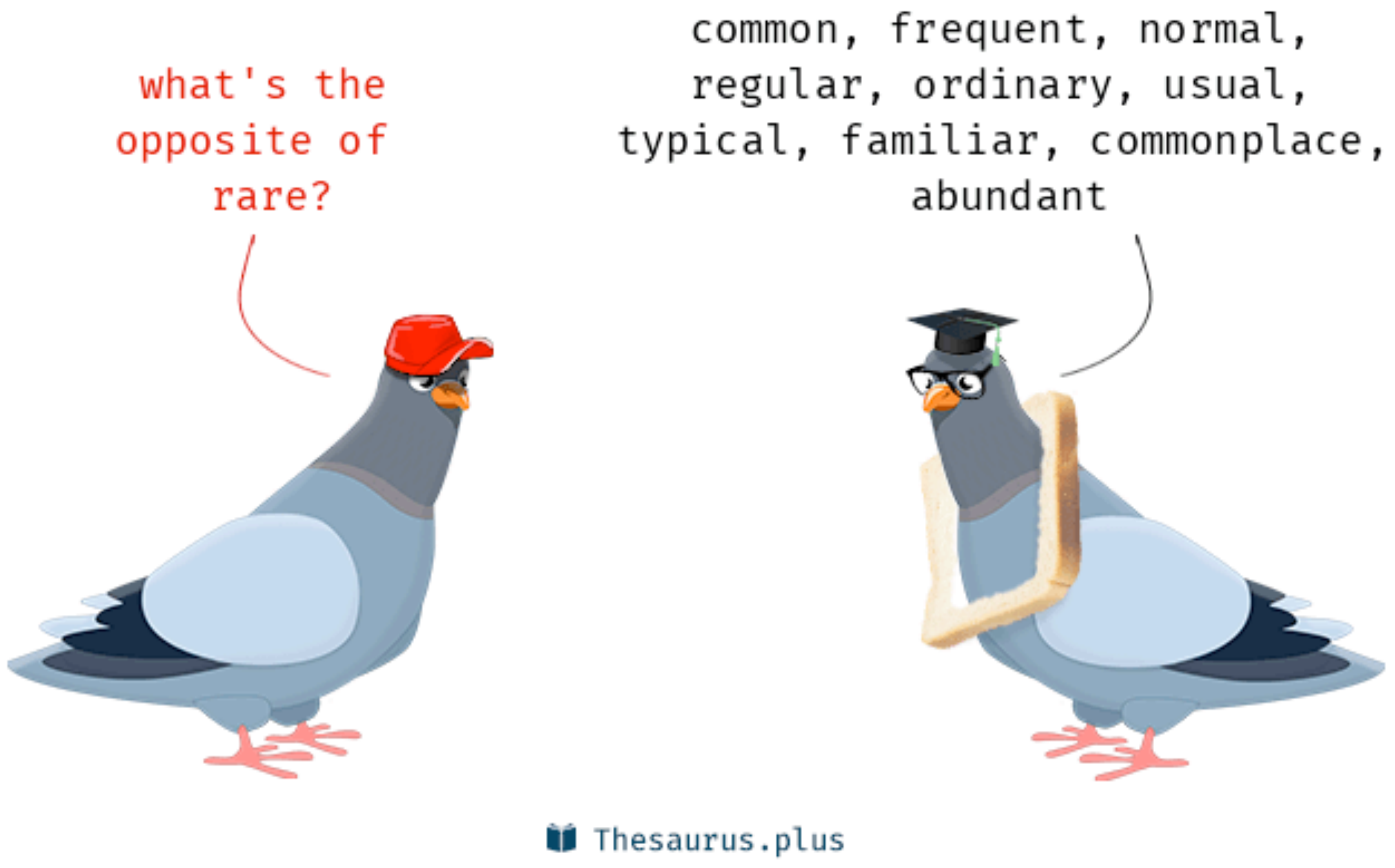
It would be great to have a confirmation from another experiment.

New hierarchy confirmed!

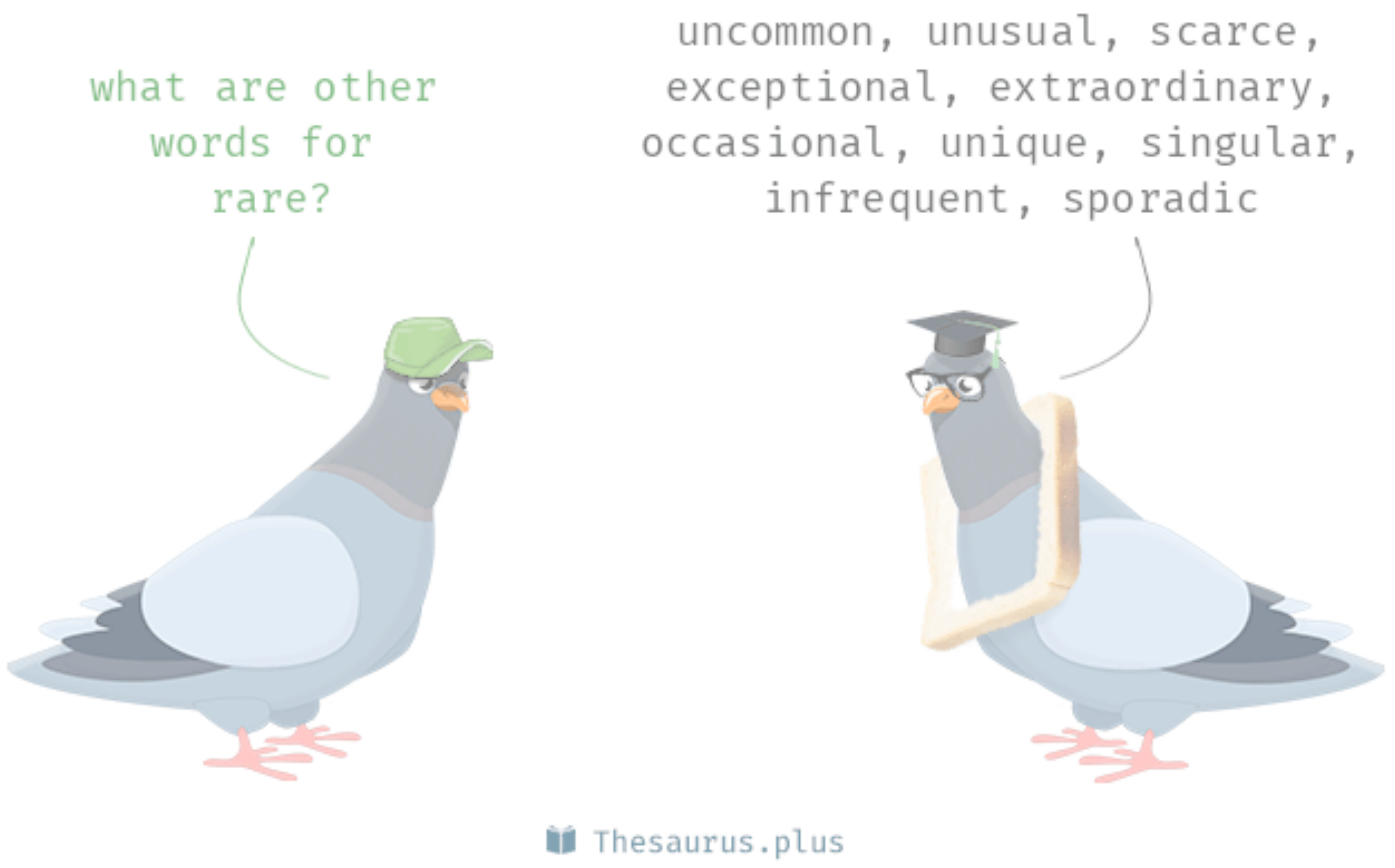


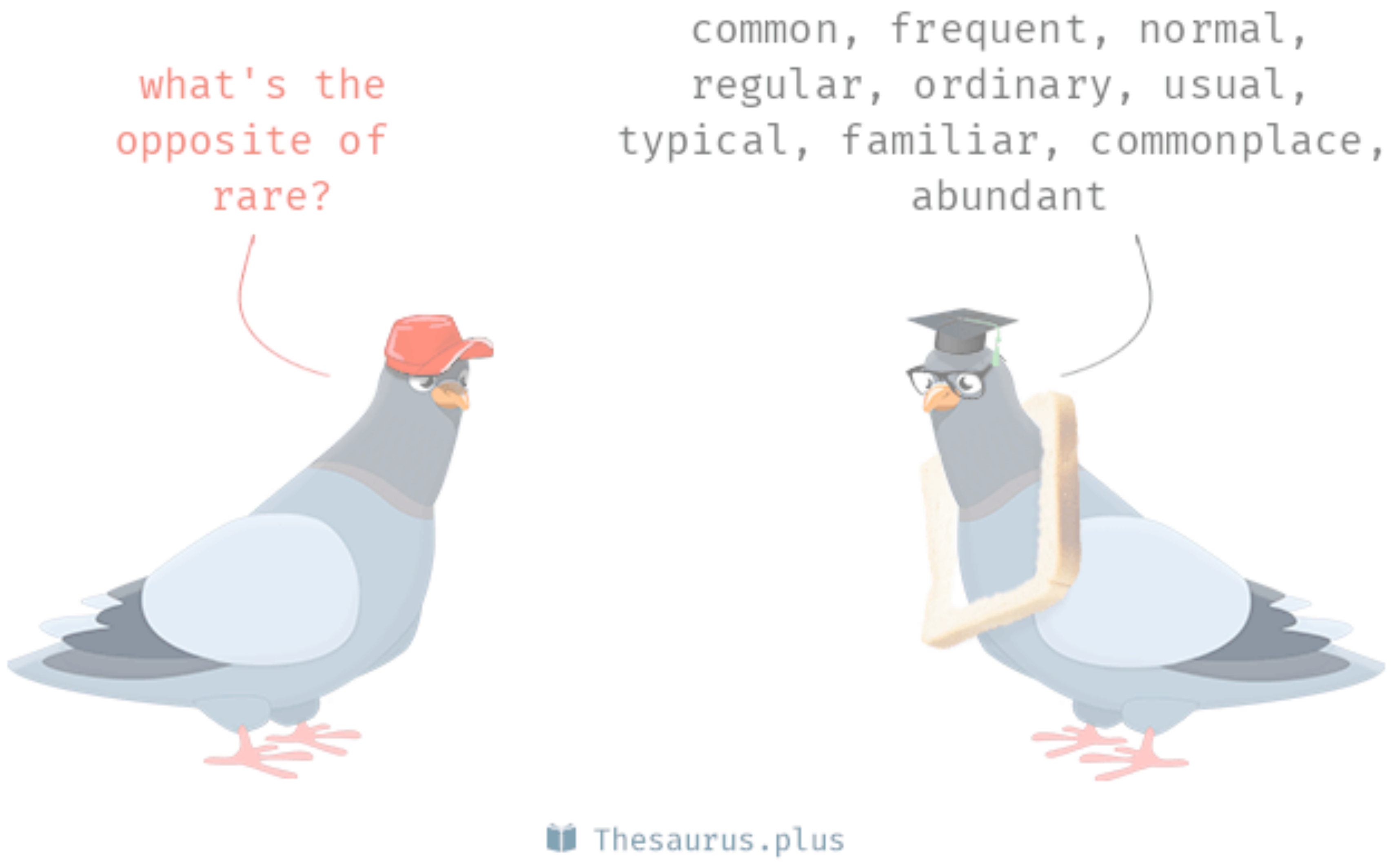
- What is 'rare'?

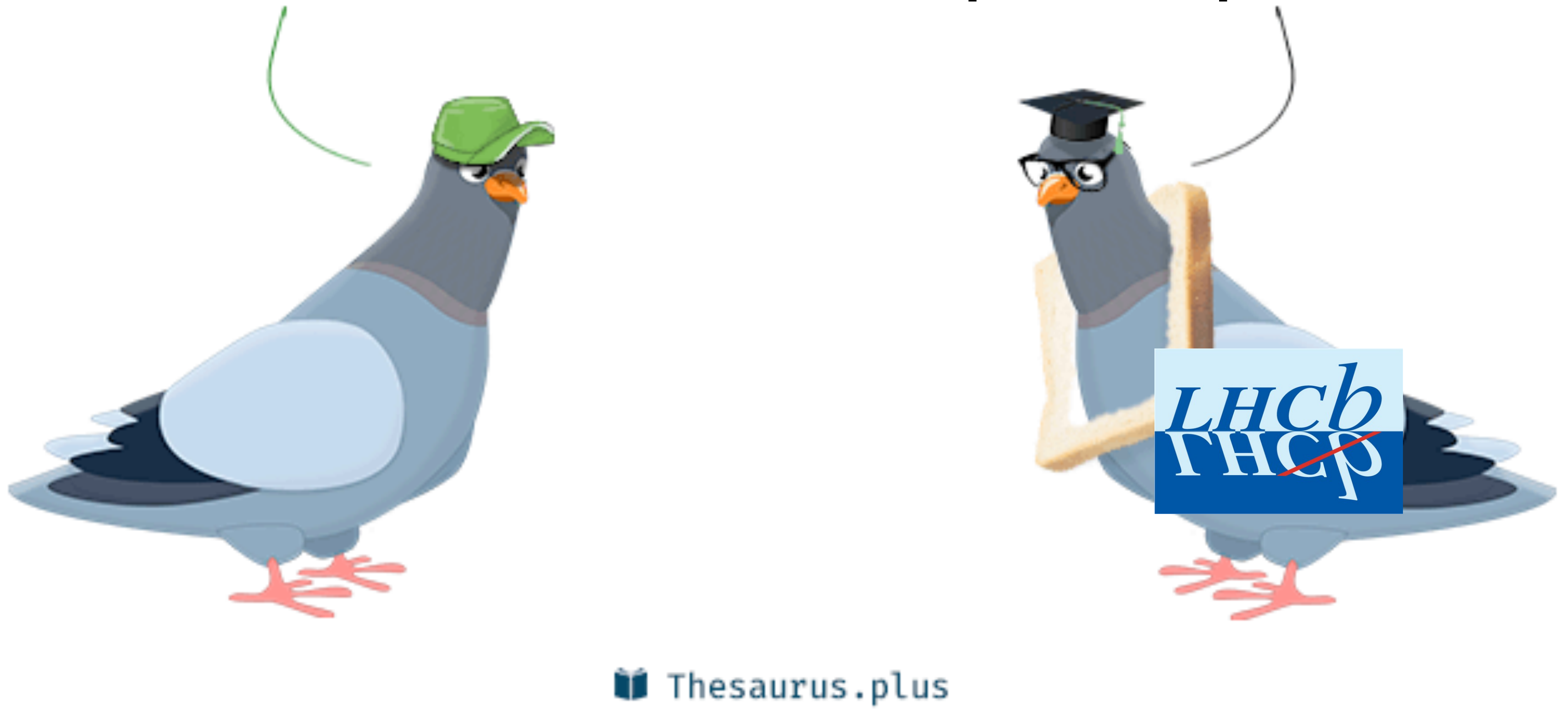

what are other words for rare?
uncommon, unusual, scarce, exceptional, extraordinary, occasional, unique, singular, infrequent, sporadic
Thesaurus.plus


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

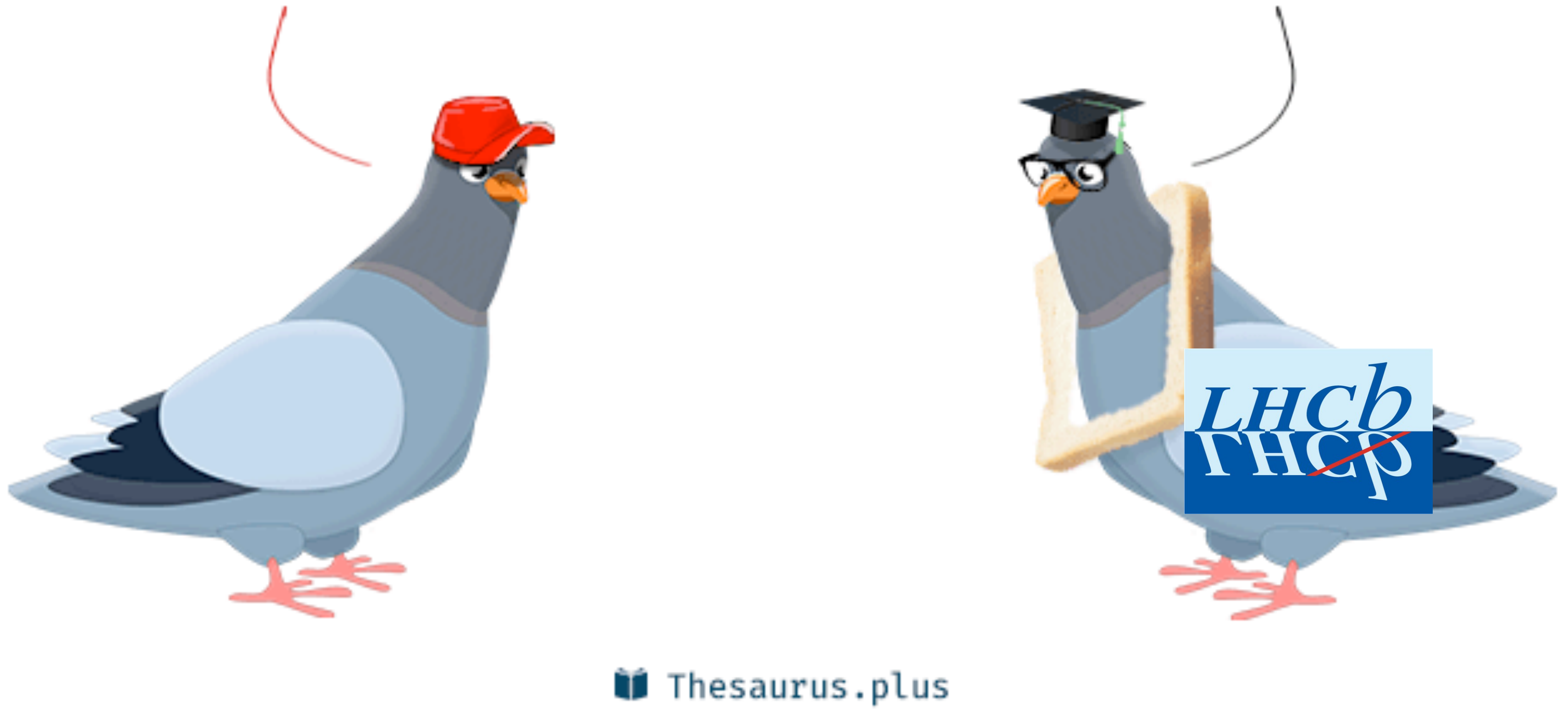
- What is ‘rare’?





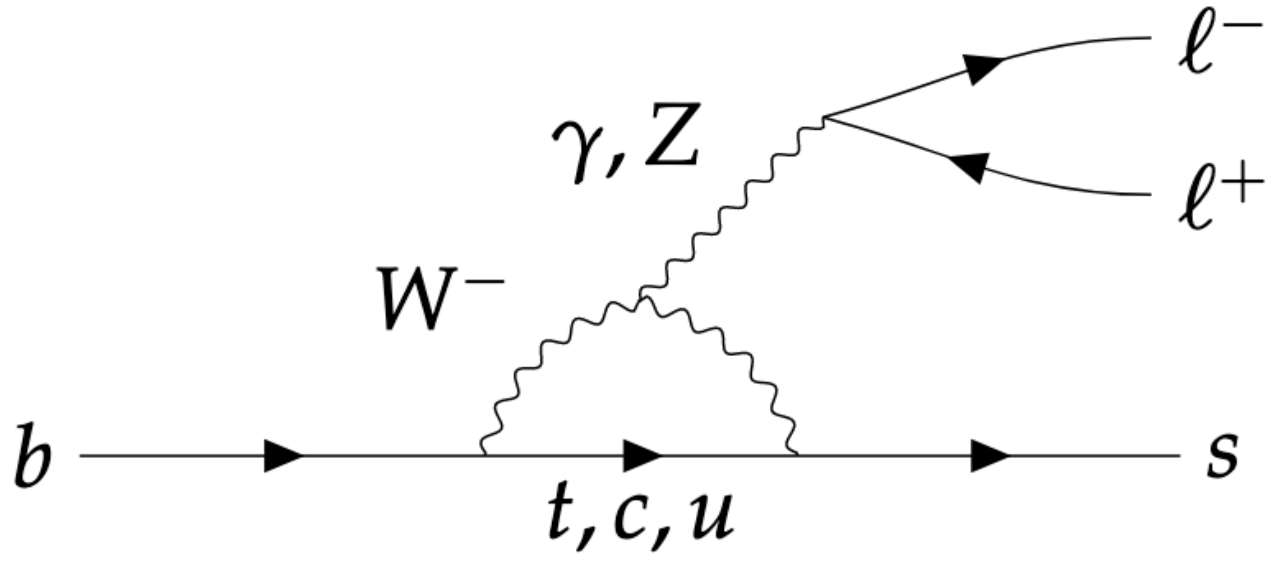


- electroweak decay with small BF ($\lesssim 10^{-4}$)
- (usually) penguin or box SM diagram
  - or: forbidden in SM (LFV, etc)
- dilepton or photon in the final state

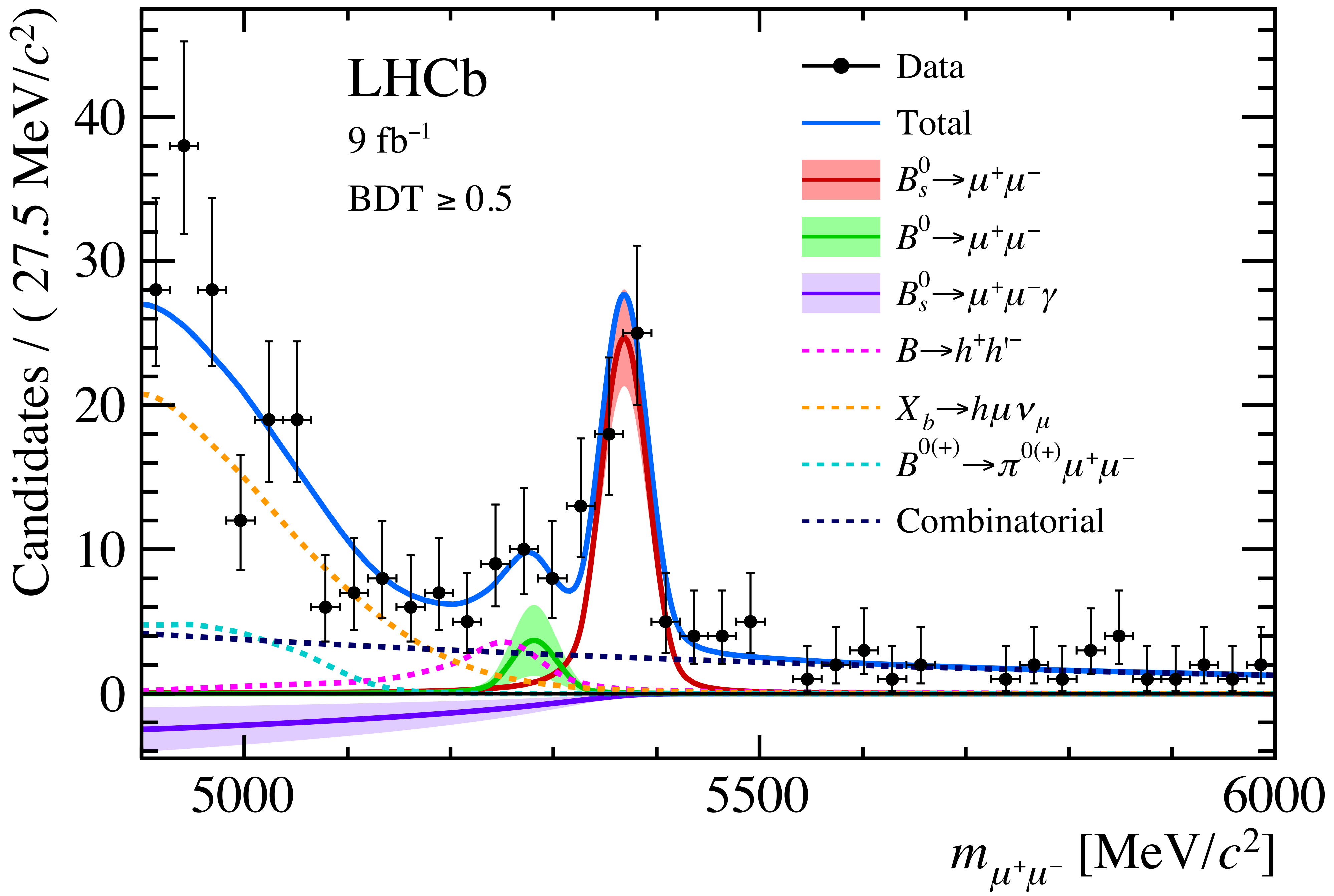


- tree-level
- fully-hadronic
- …

- We are mostly interested in $b \to s\ell^+\ell^-$ processes:
  - ℓ is muon or electron. Or the tau.



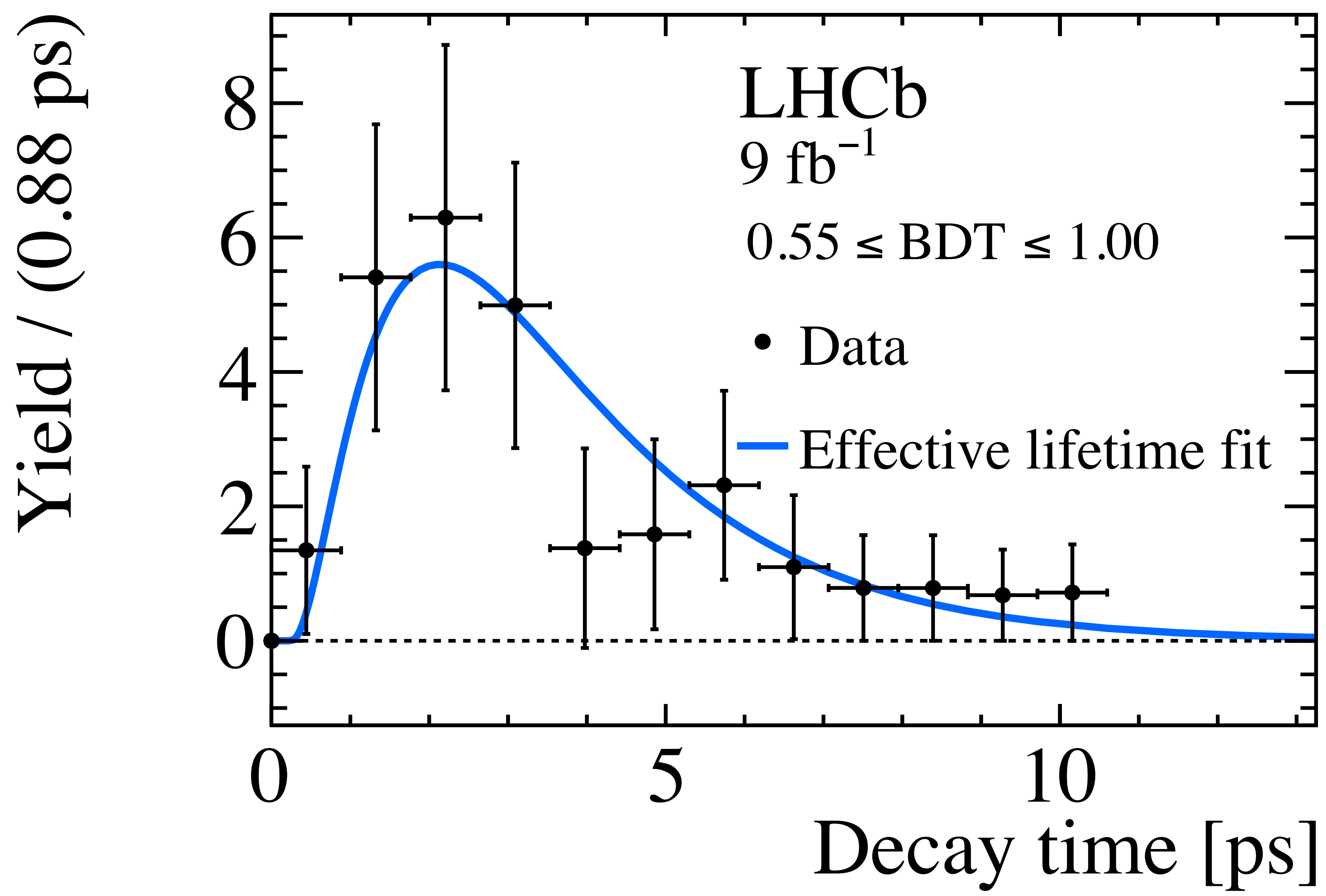
- Flavour-changing neutral current, rare in the SM (decay rate 10^{-6} or smaller)
  - Sensitive to non-SM contributions
  - Theoretically clean: can construct observables where QCD uncertainties cancel
  - Can be studied in meson or baryon decays: $B \to K\ell^+\ell^-$, $B_s^0 \to \phi\ell^+\ell^-$, $\Lambda_b^0 \to \Lambda\ell^+\ell^-$ and so on
- Crossing: $b\bar{s} \to \ell^+\ell^-$ decay
  - even more rare due to helicity suppression



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

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

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



Effective lifetime $\tau(B_s^0 \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)\,\mathrm{ps}$

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

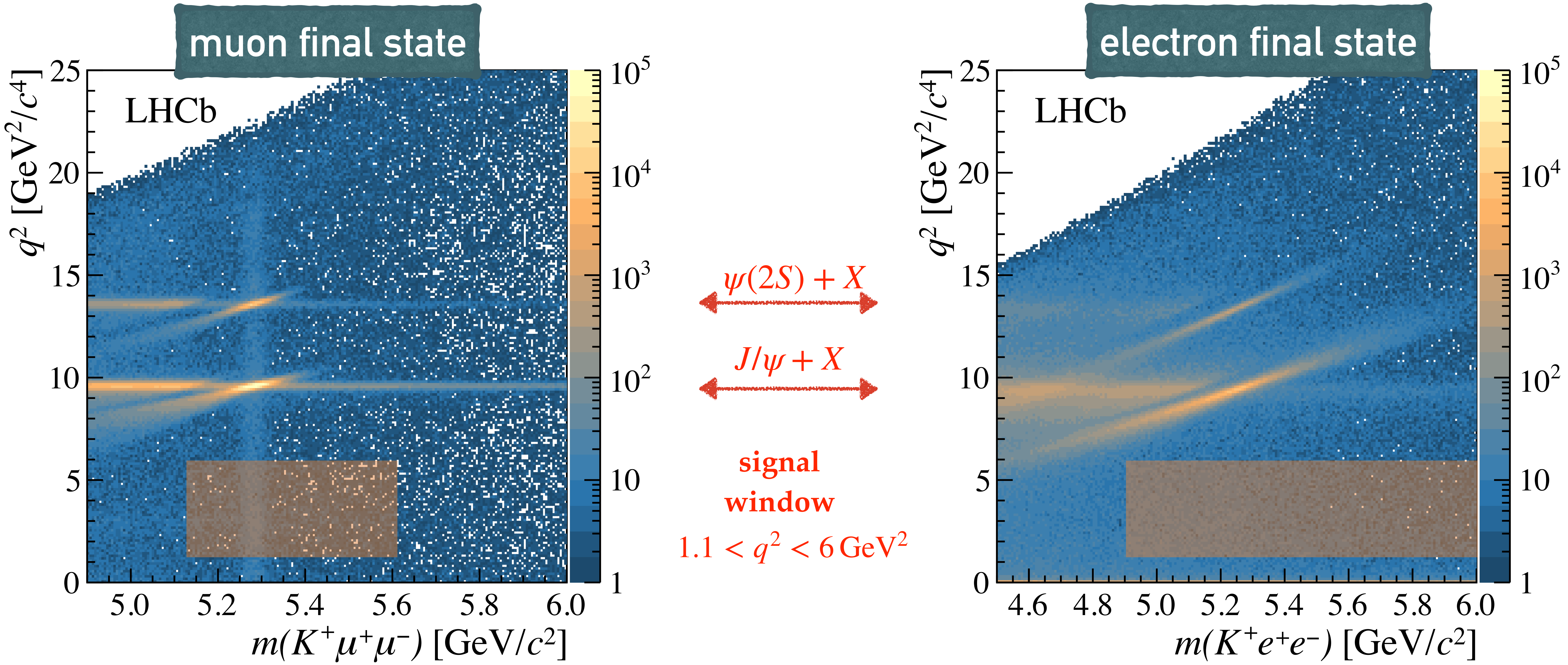
- Couplings to SM gauge bosons are identical for $e/\mu/\tau$, e.g.

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

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

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

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



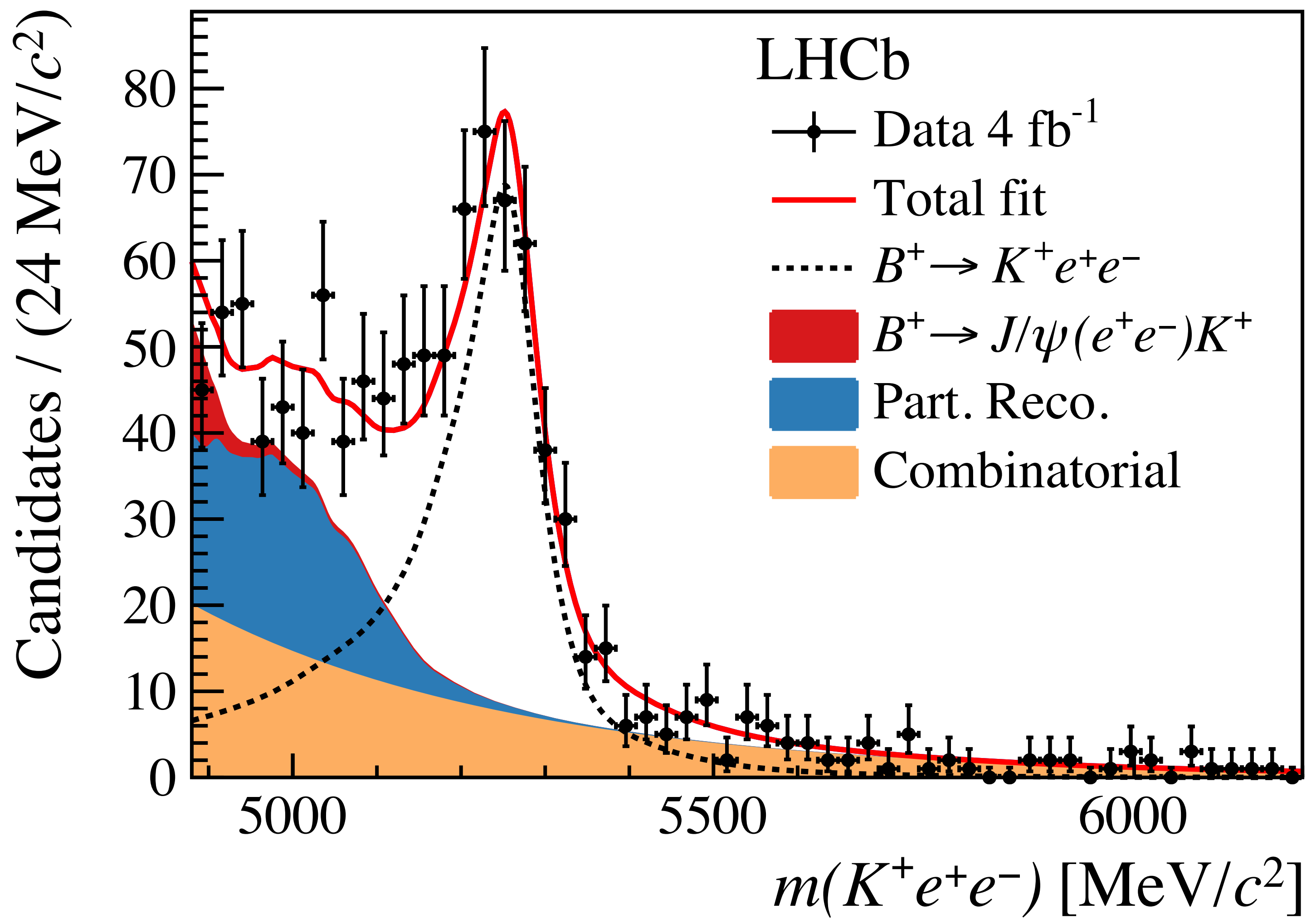
worse resolution due to bremsstrahlung

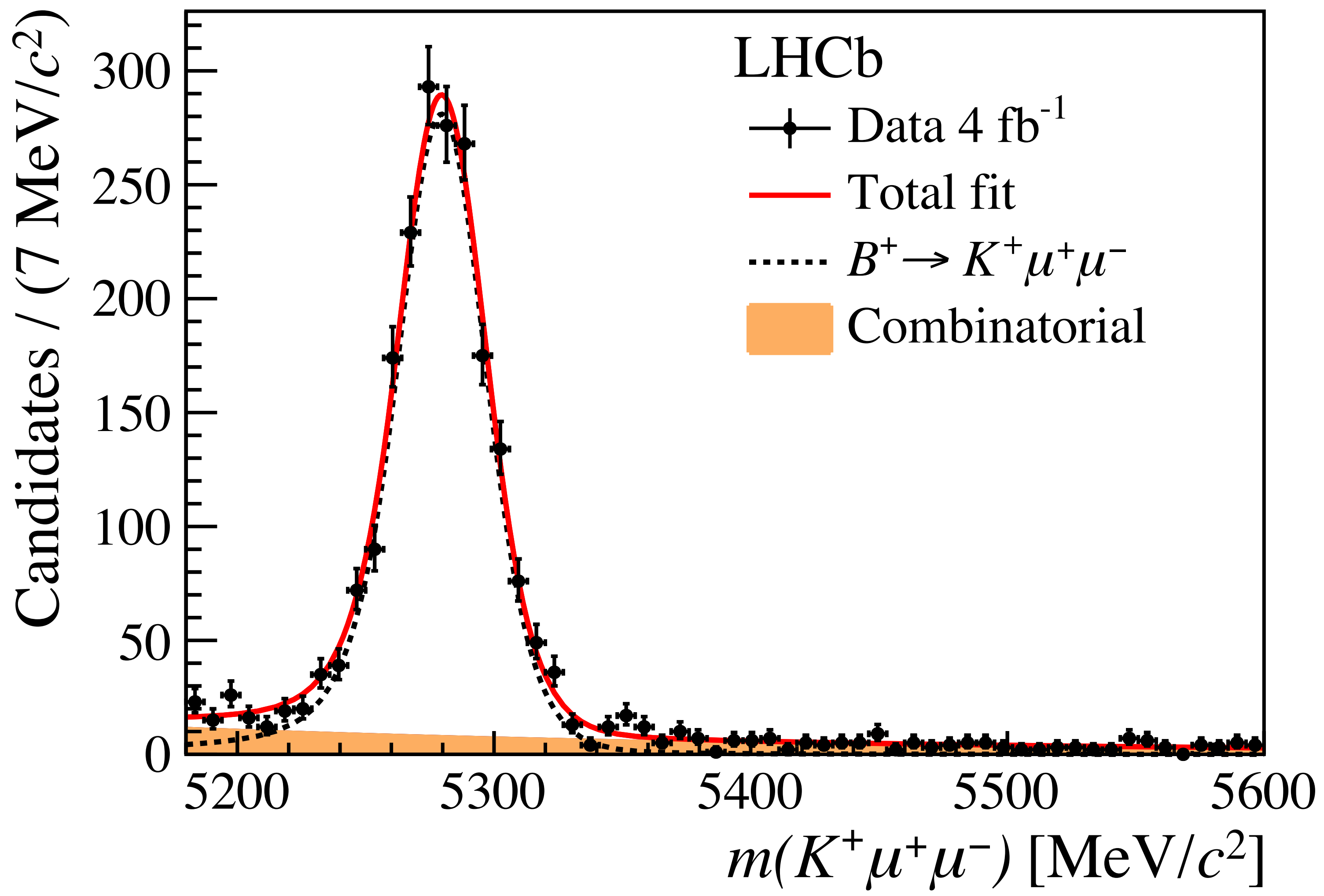
- What we measure: (to cancel detection asymmetries)

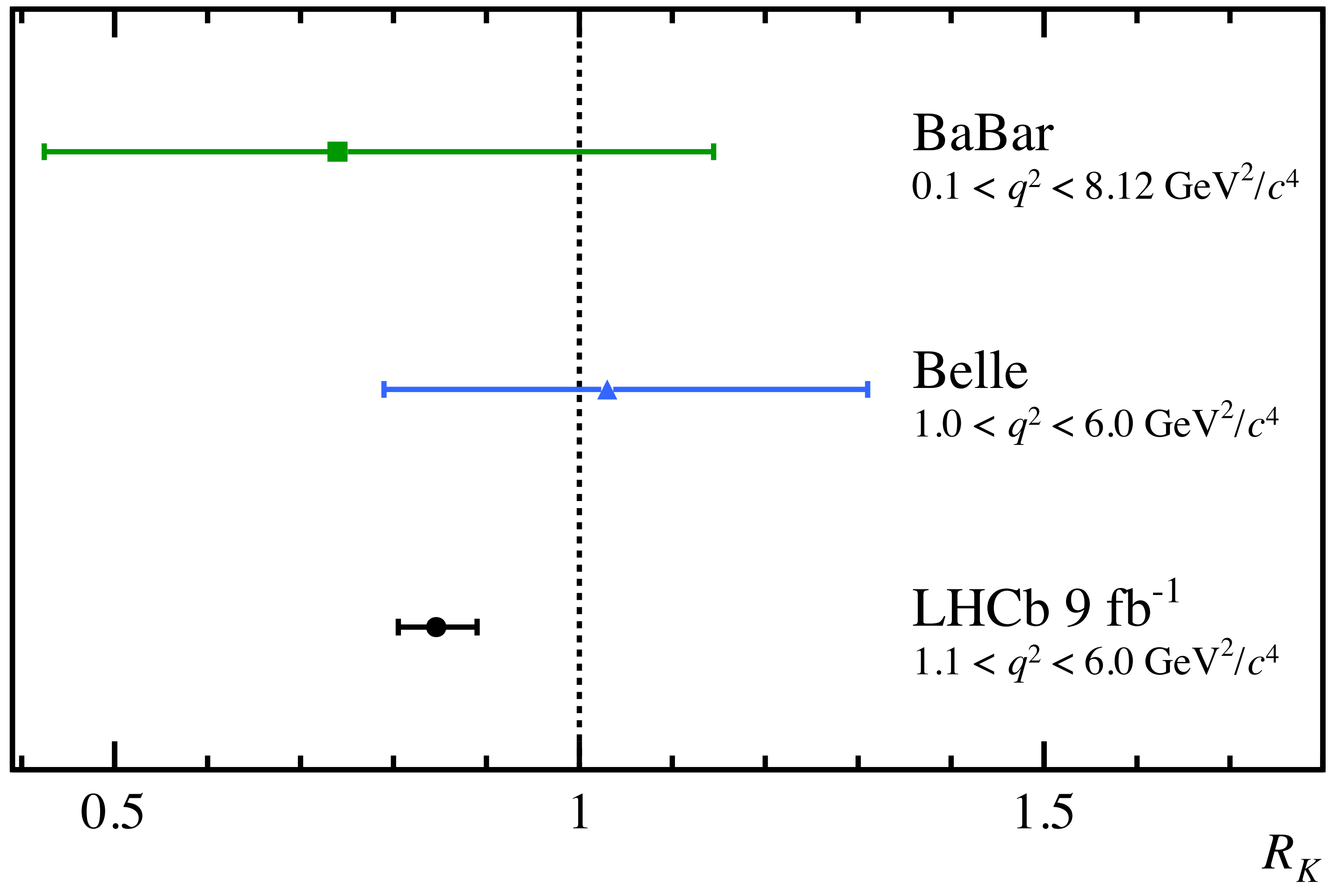
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

where only $1.1 < q^2 < 6\,\mathrm{GeV}^2$ 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 ($R_{K^*}, R_{K_S}, R_\Lambda$ etc).

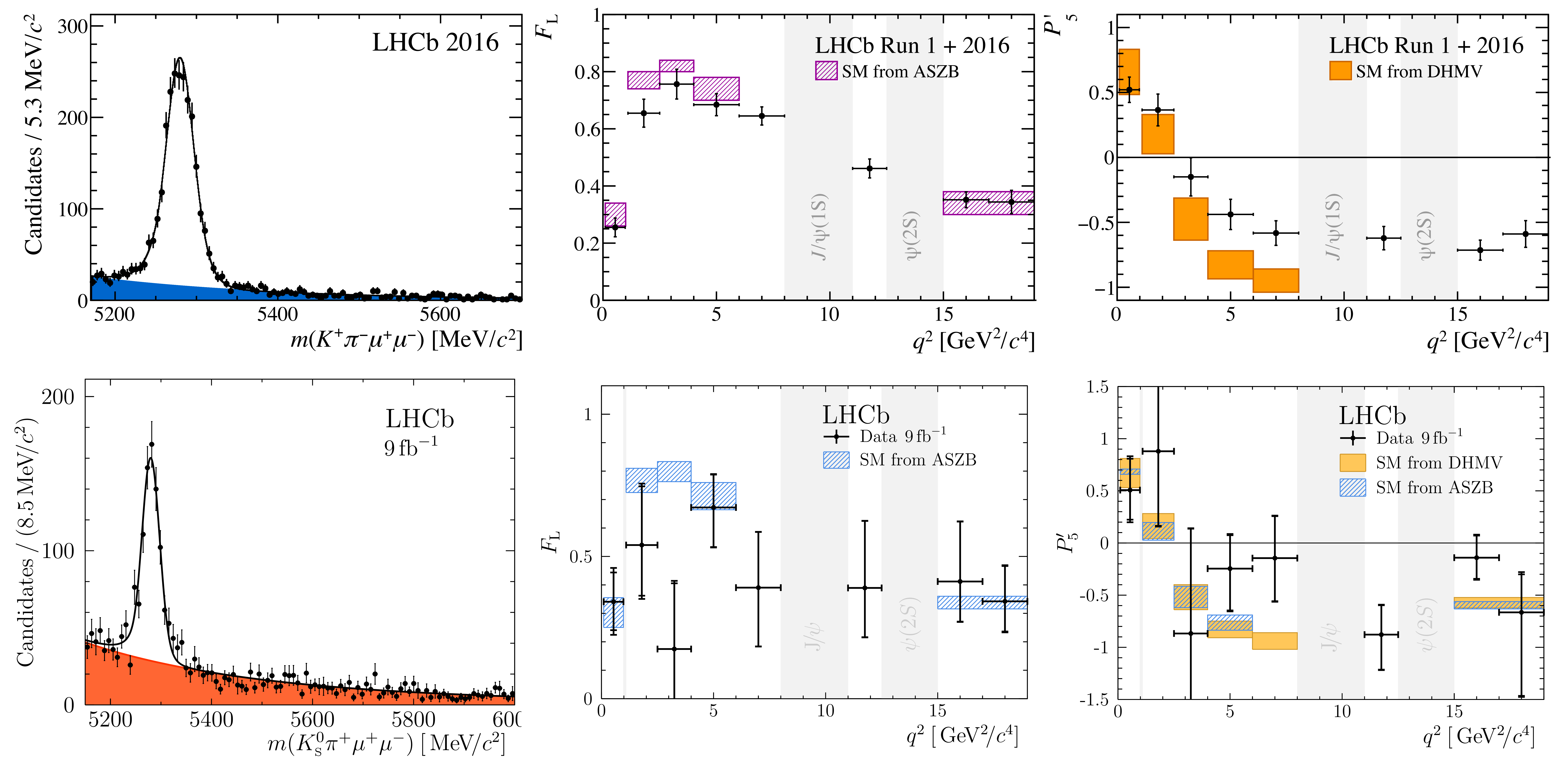
more results coming soon.

$B^0 \to K^*\mu^+\mu^-$ ANGULAR ANALYSIS

PRL 125 (2020) 011802; PRL 126 (2021) 161802

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

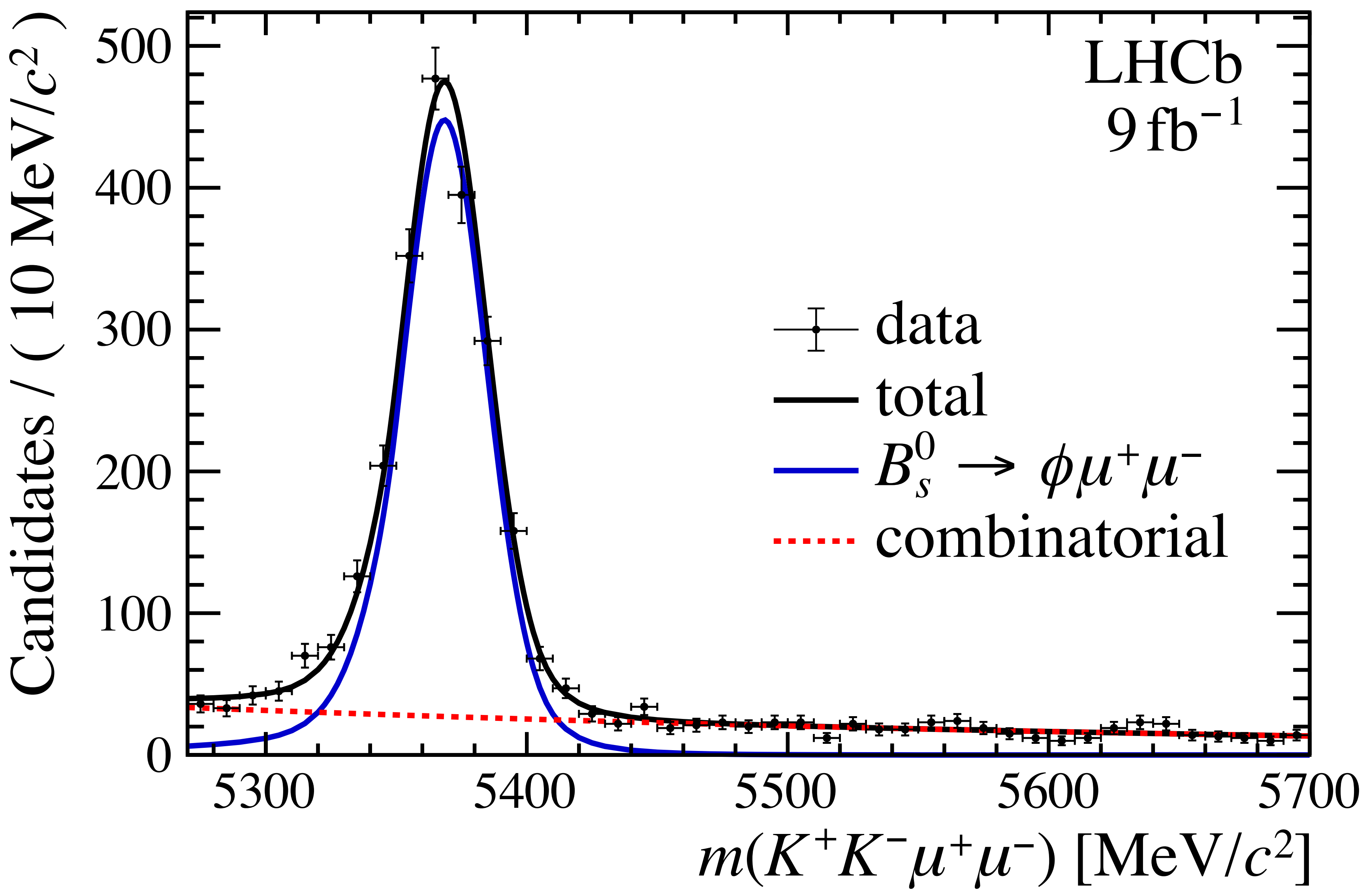
F_L P'_5 +*many others…*

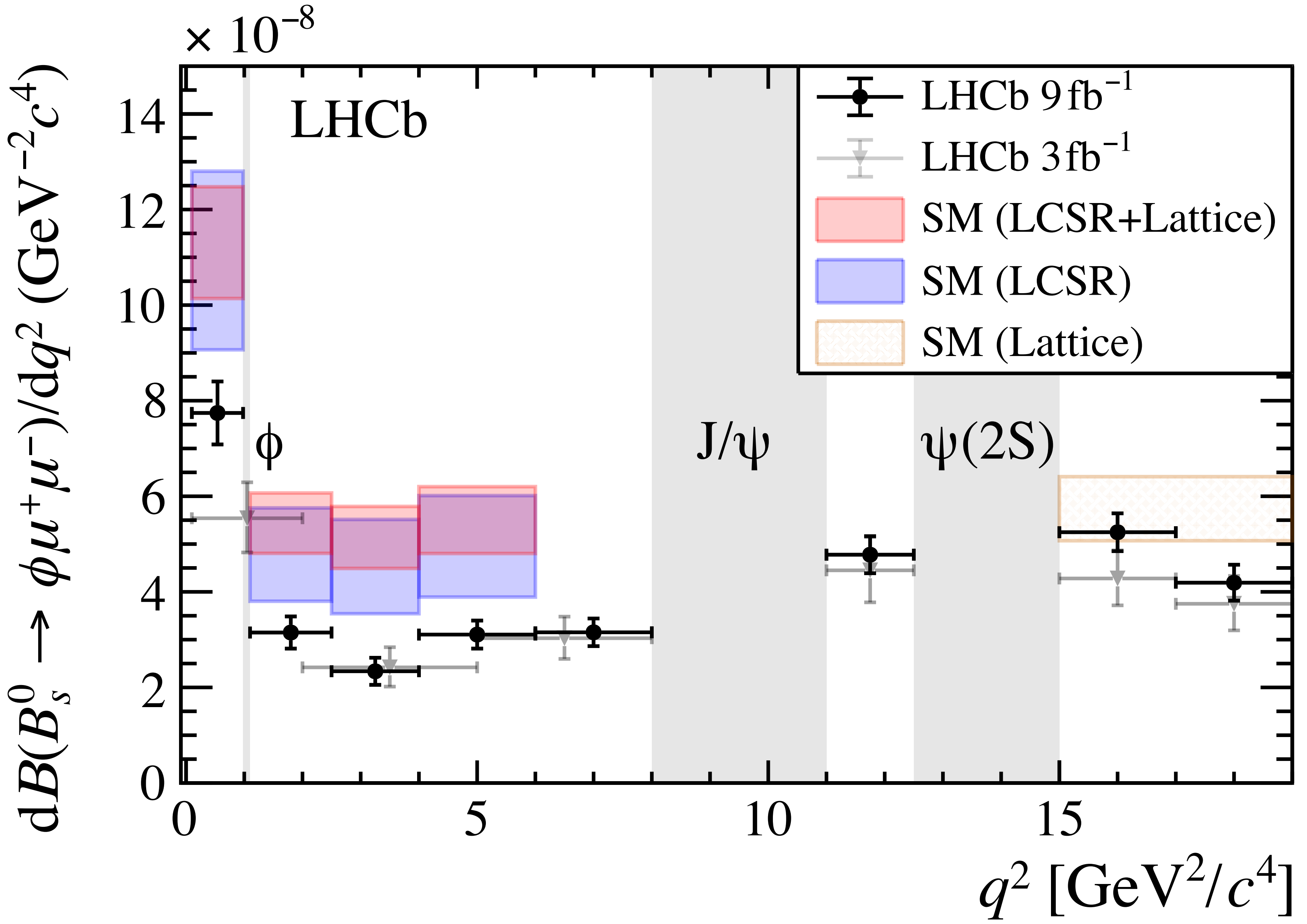


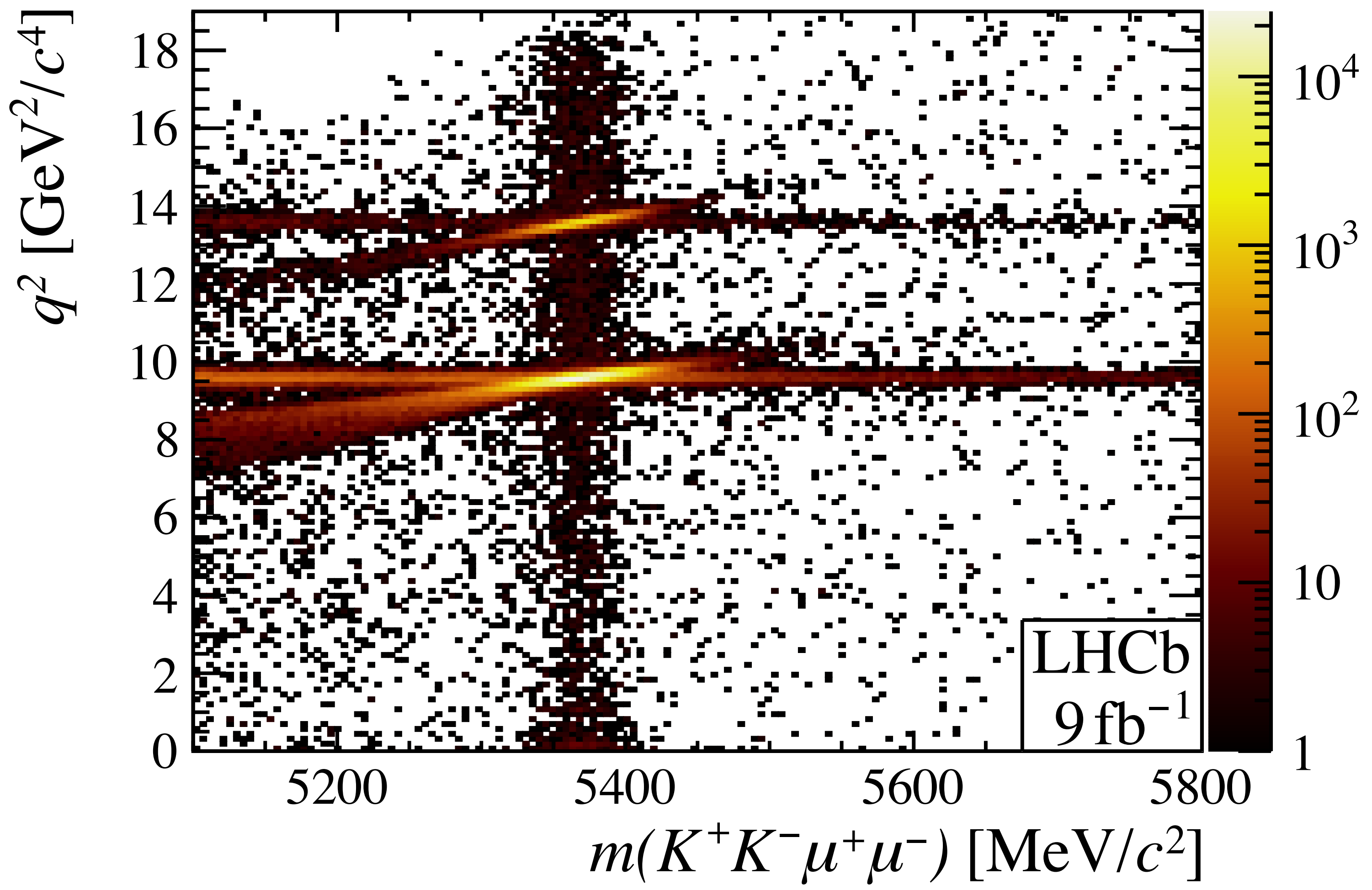
the tension persists

need more data

- Differential BF measurement:

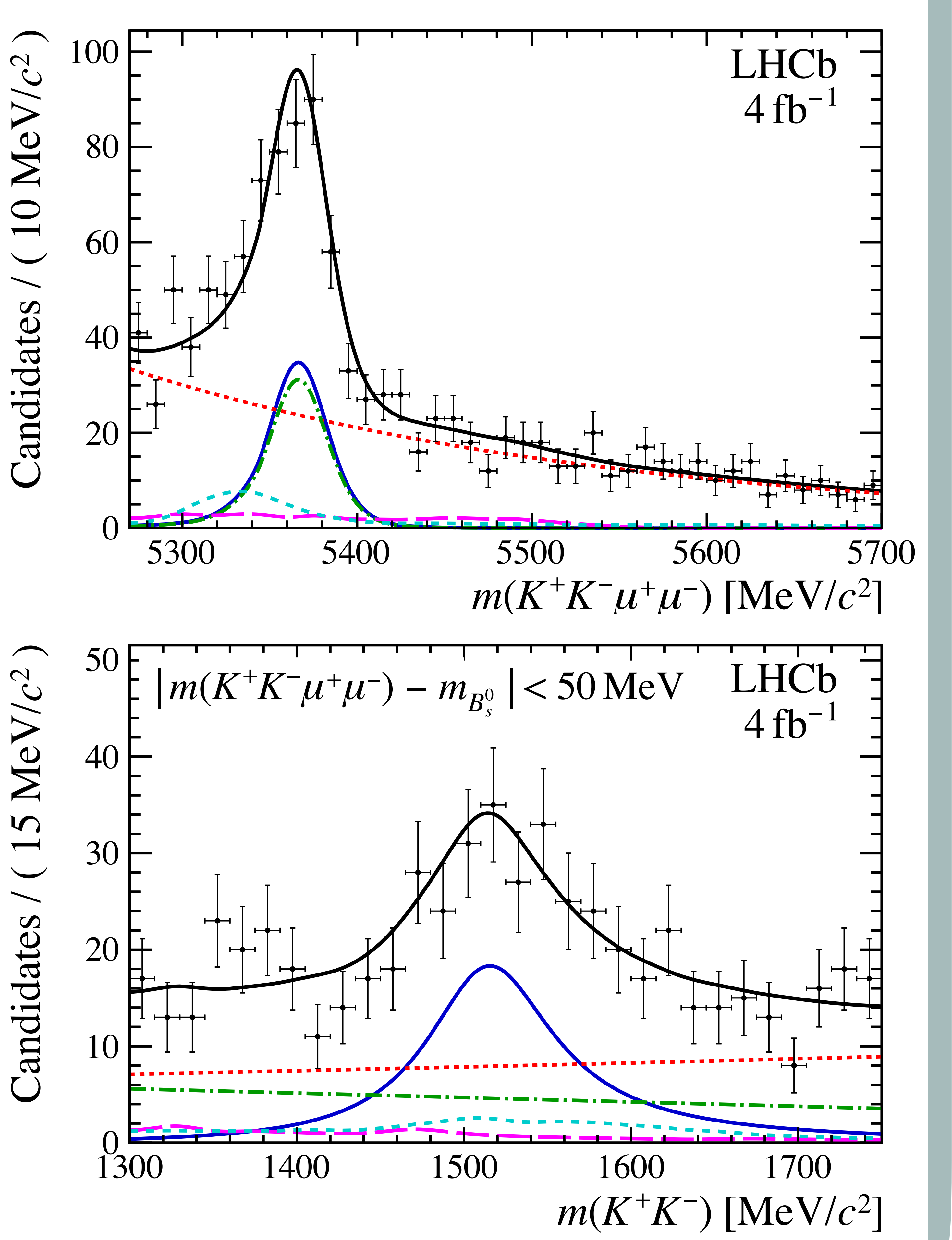






in q^2 region 1.1 … 6:
3.6σ below SM (lattice+LCSR)
1.8σ below SM (LCSR)

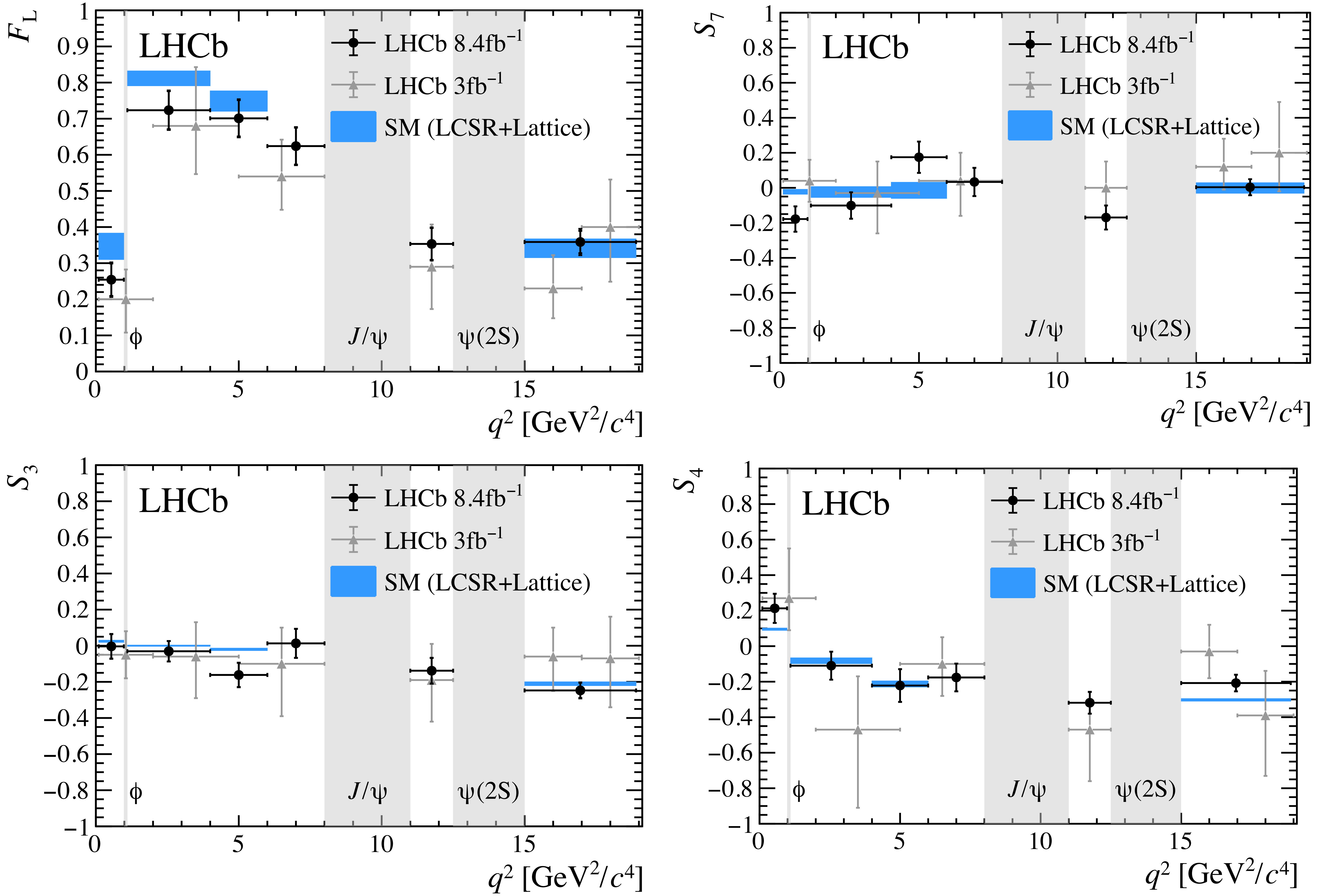
A side study: observation of $B_s^0 \to f_2'(1525)\mu^+\mu^-$ (spin-2 meson!)



- This is clearly not a stat. fluctuation, but could be some bias in theory estimate.

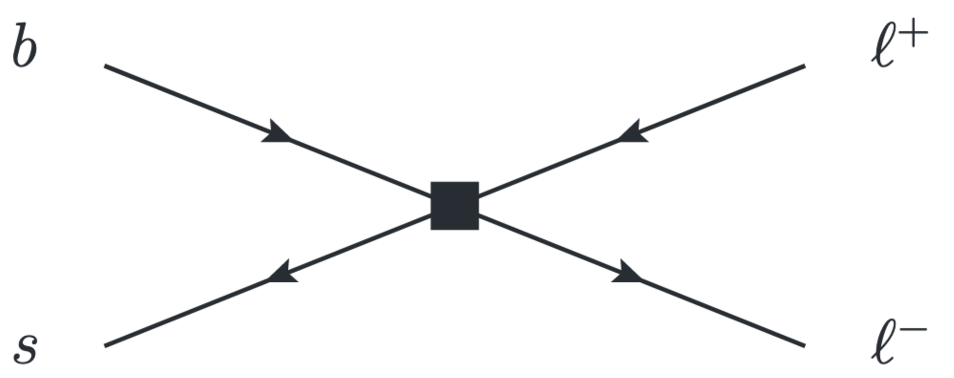
- ***Angular analysis** performed with **untagged** B_s^0*

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

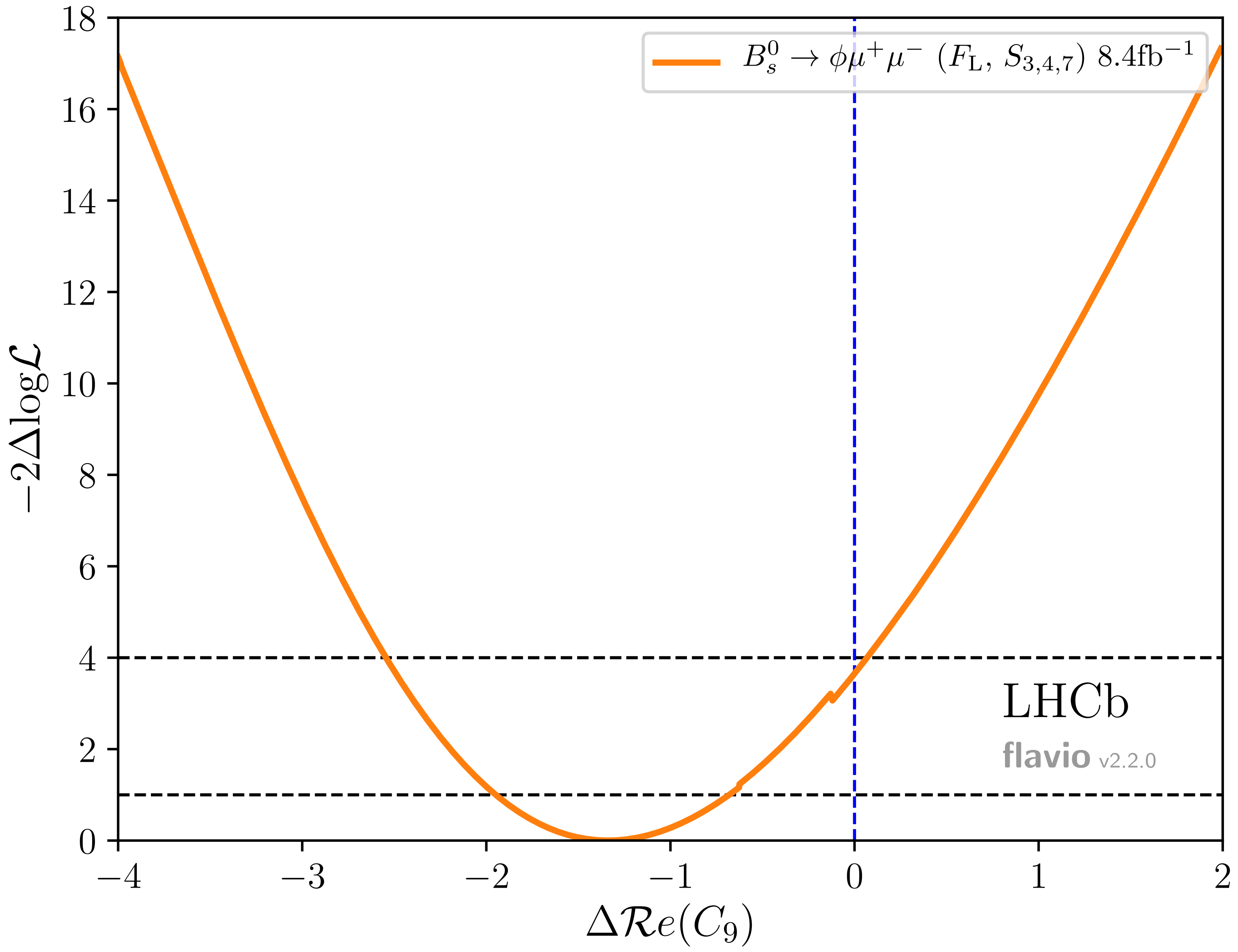
- Interpretation of recent LHCb results in terms of the Wilson coefficient C_9 (vector coupling in the EFT)



- The three recent LHCb angular analyses **consistently** favour a negative shift in $\Delta Re(C_9) \equiv Re(C_9) - Re(C_9^{SM})$:

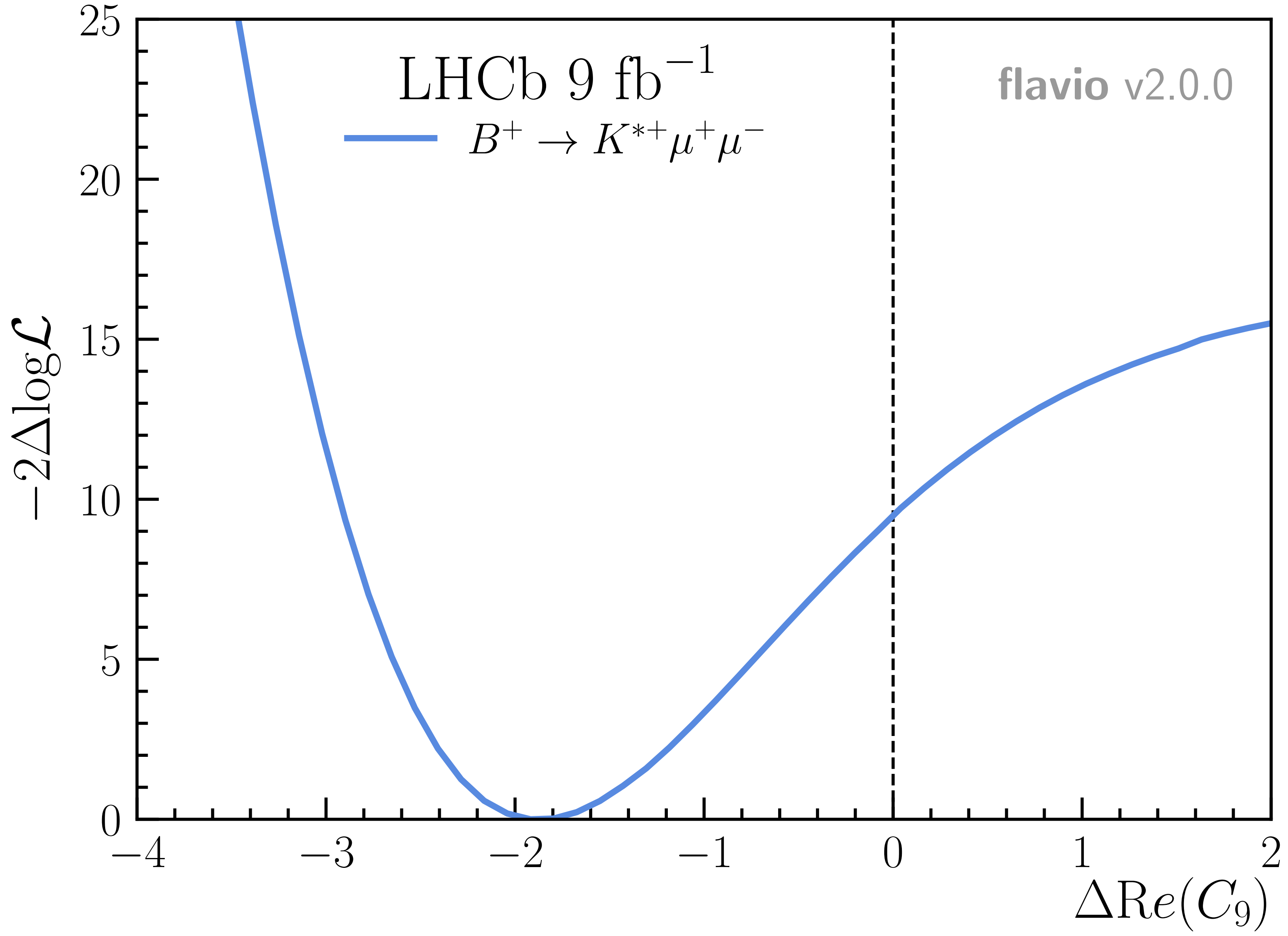
$B_s^0 \to \phi\mu^+\mu^-$

[PAPER-2021-014]



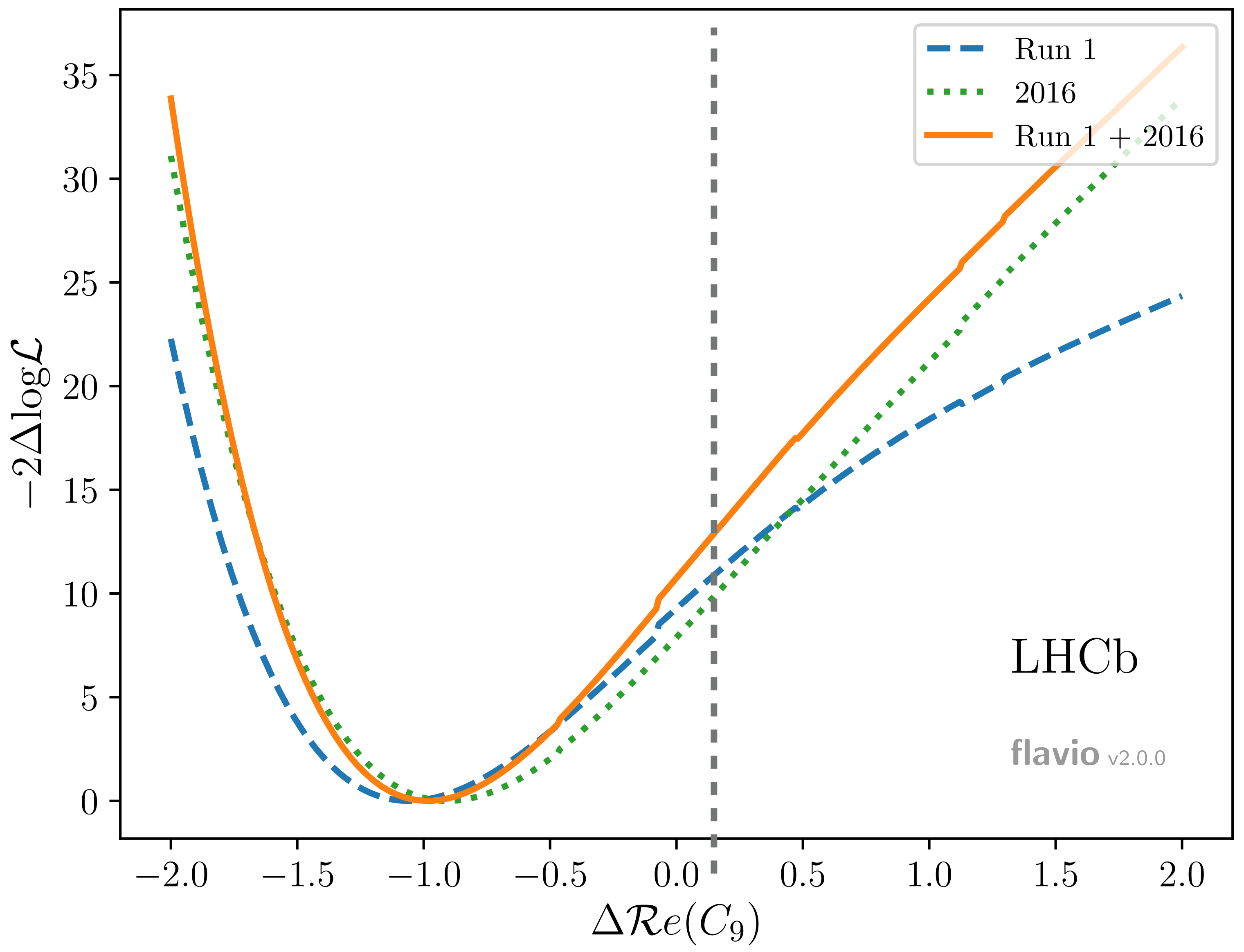
$B^+ \to K^{*+}\mu^+\mu^-$

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



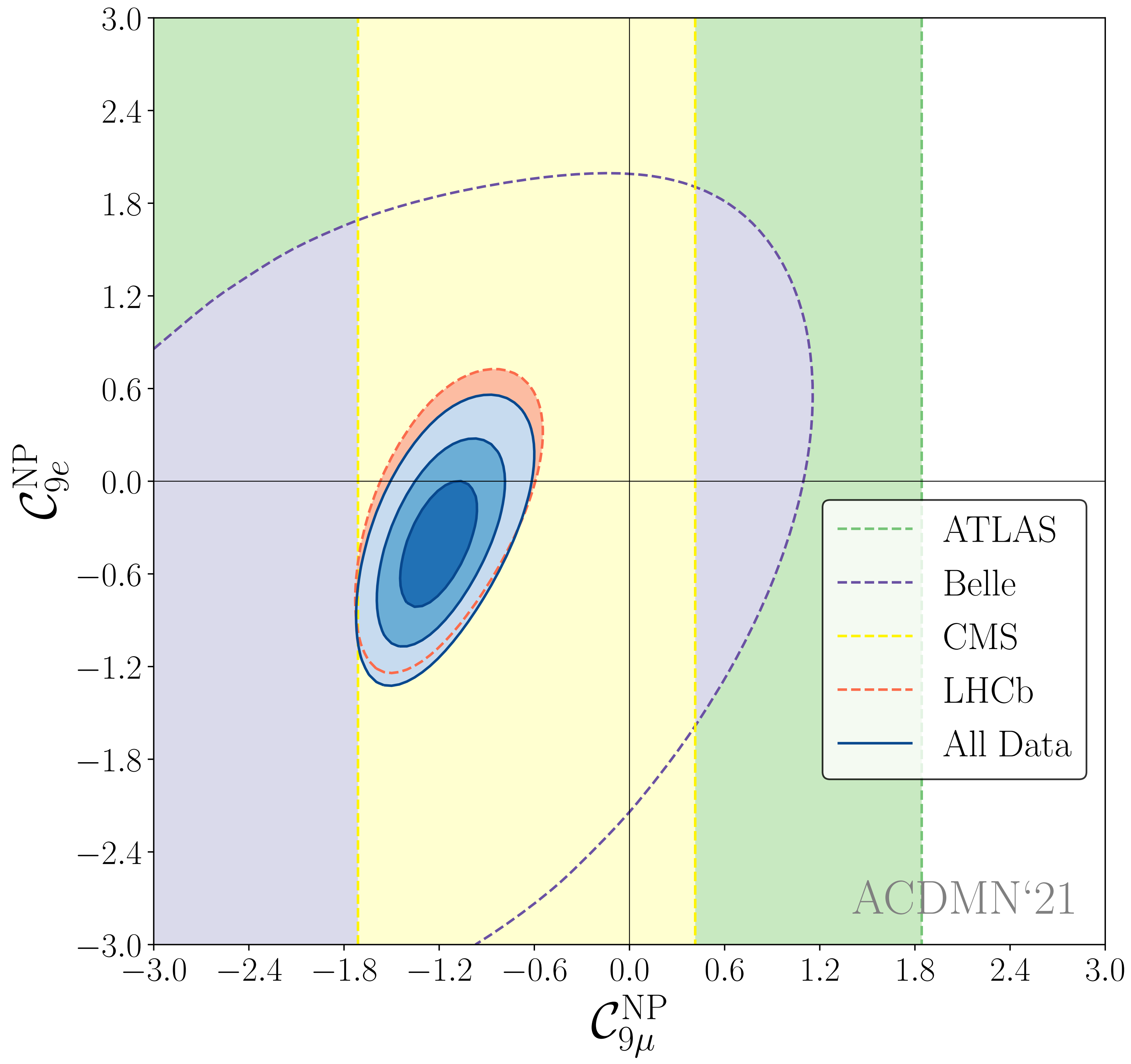
$B^0 \to K^{*0}\mu^+\mu^-$

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



INTERPRETATION: GOING GLOBAL

- The theory community regularly updates the "global fits" to hundreds of $b \to s\ell^+\ell^-$ observables in EFT framework:
- One example from [2104.08921] (Alguero et al):
  - **something funny is going on with muons**
  - electrons are closer to the SM (for now?)



- **Possible explanations:** vector leptoquark [1808.08179] or colourless bosons
- Search for LFV decays ($B_s^0 \to \mu\tau$...) is important to close down the window
- Precise inputs from other experiments are hoped for.

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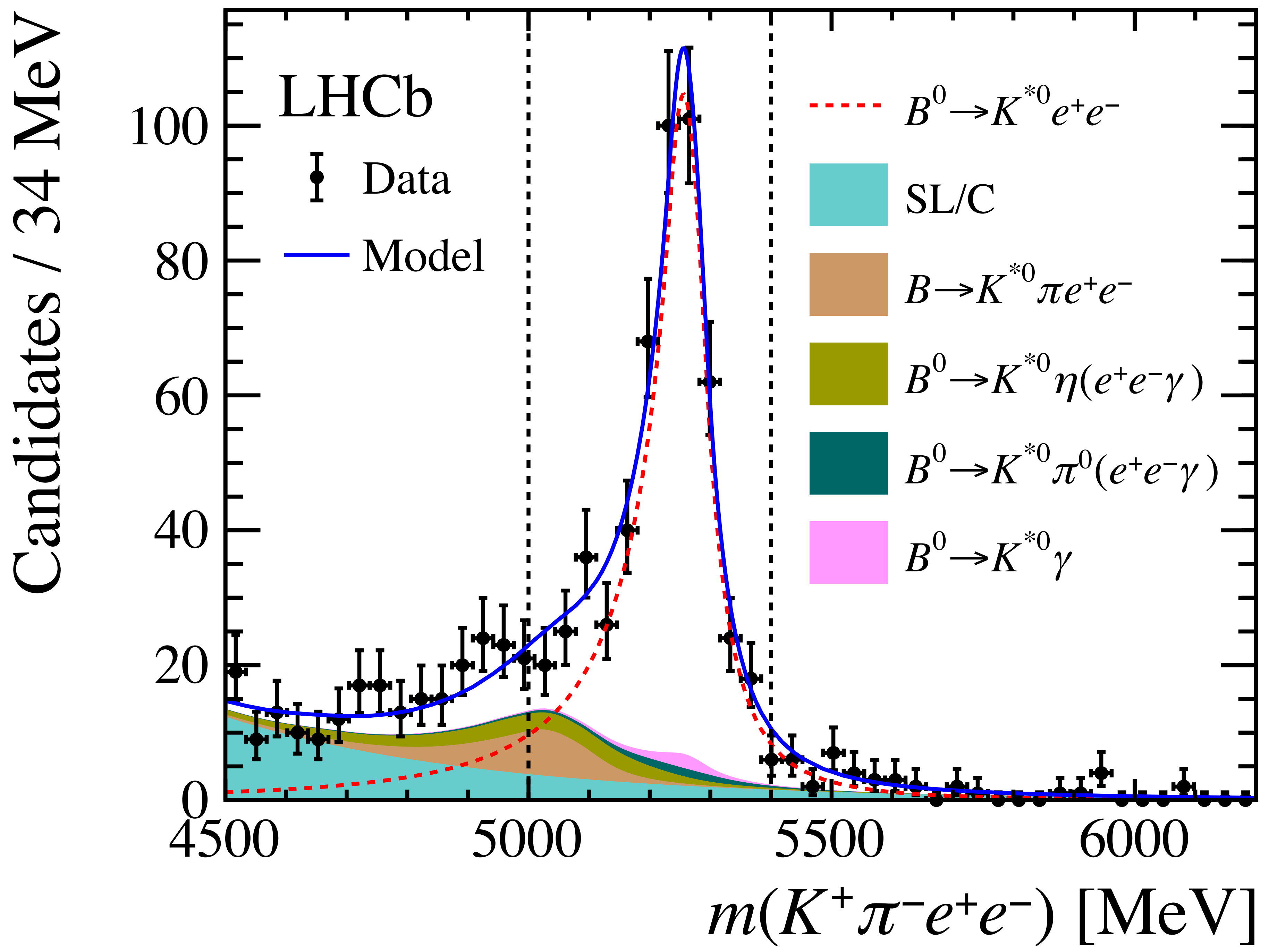
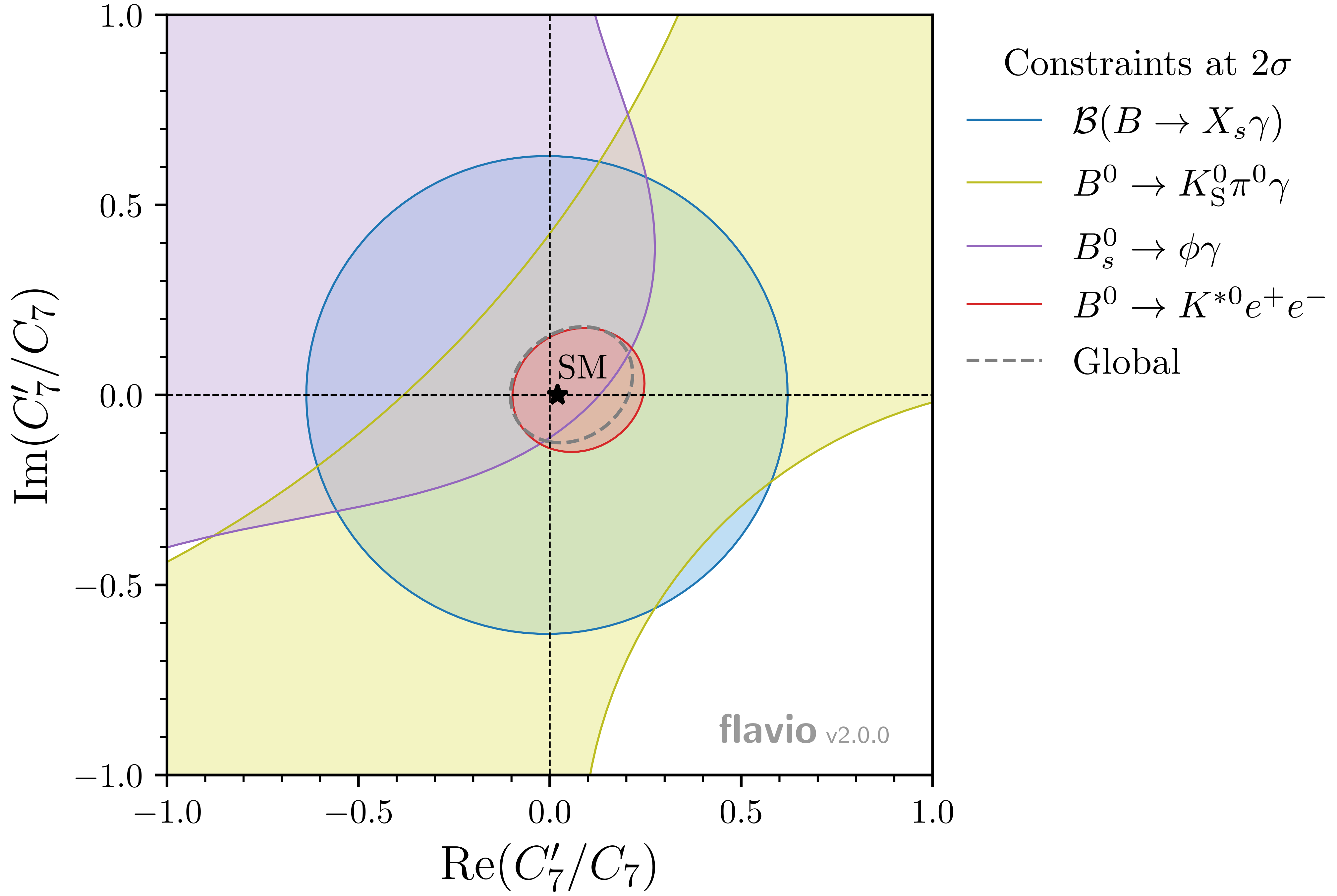
Run1+Run2 dataset

- 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 $b \to s\gamma$

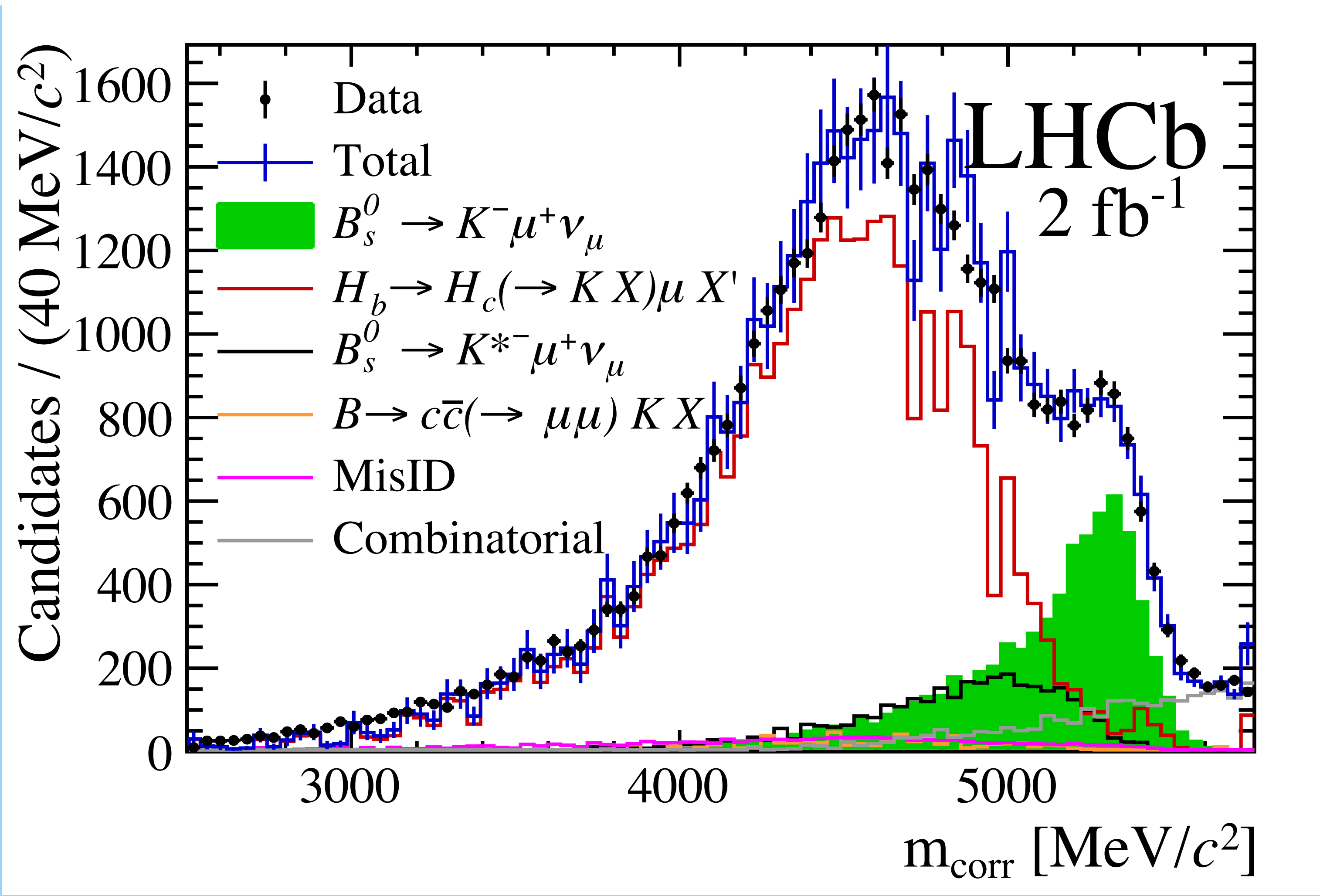


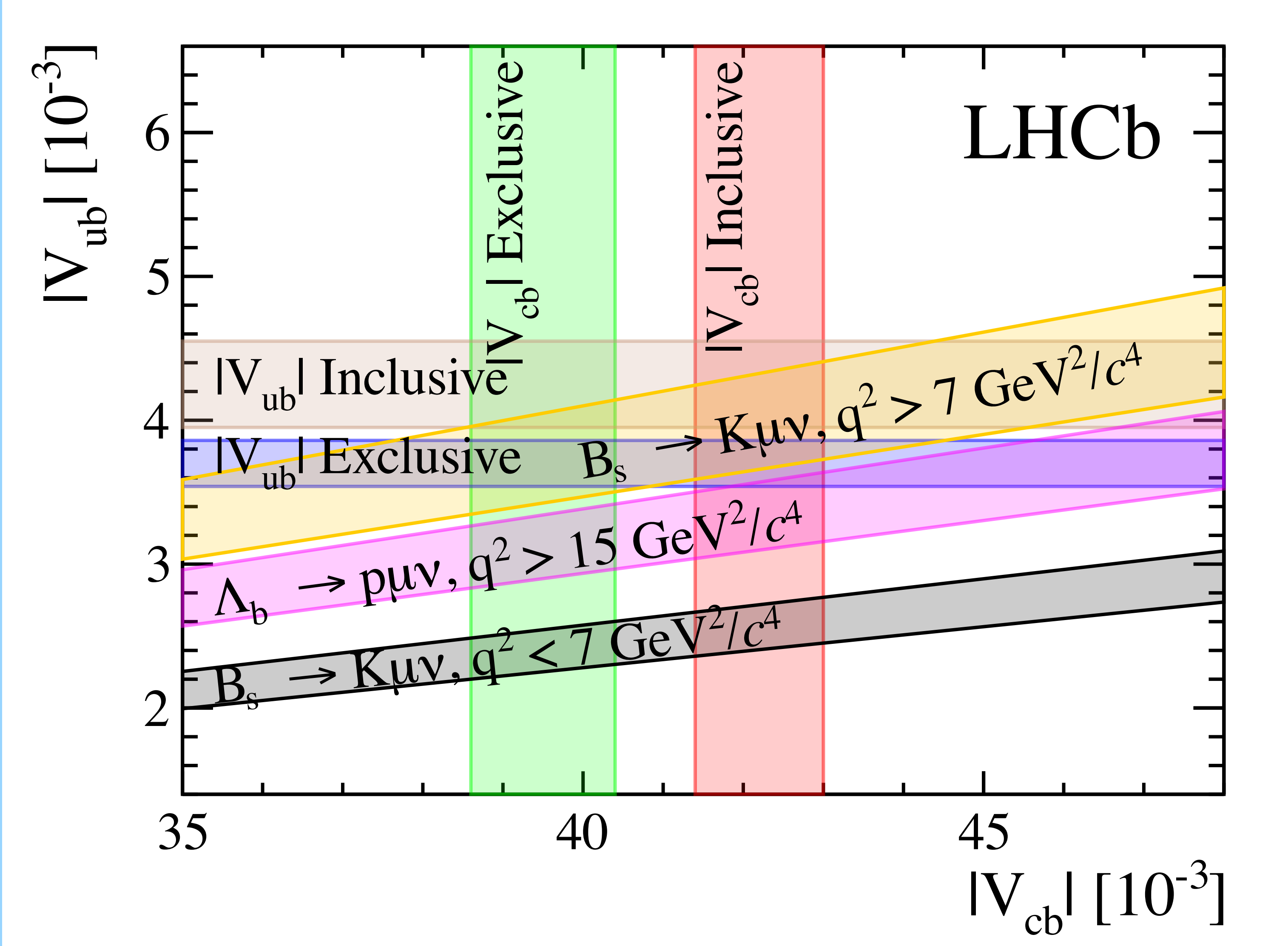
Ratio of RH and LH Wilson coefficients



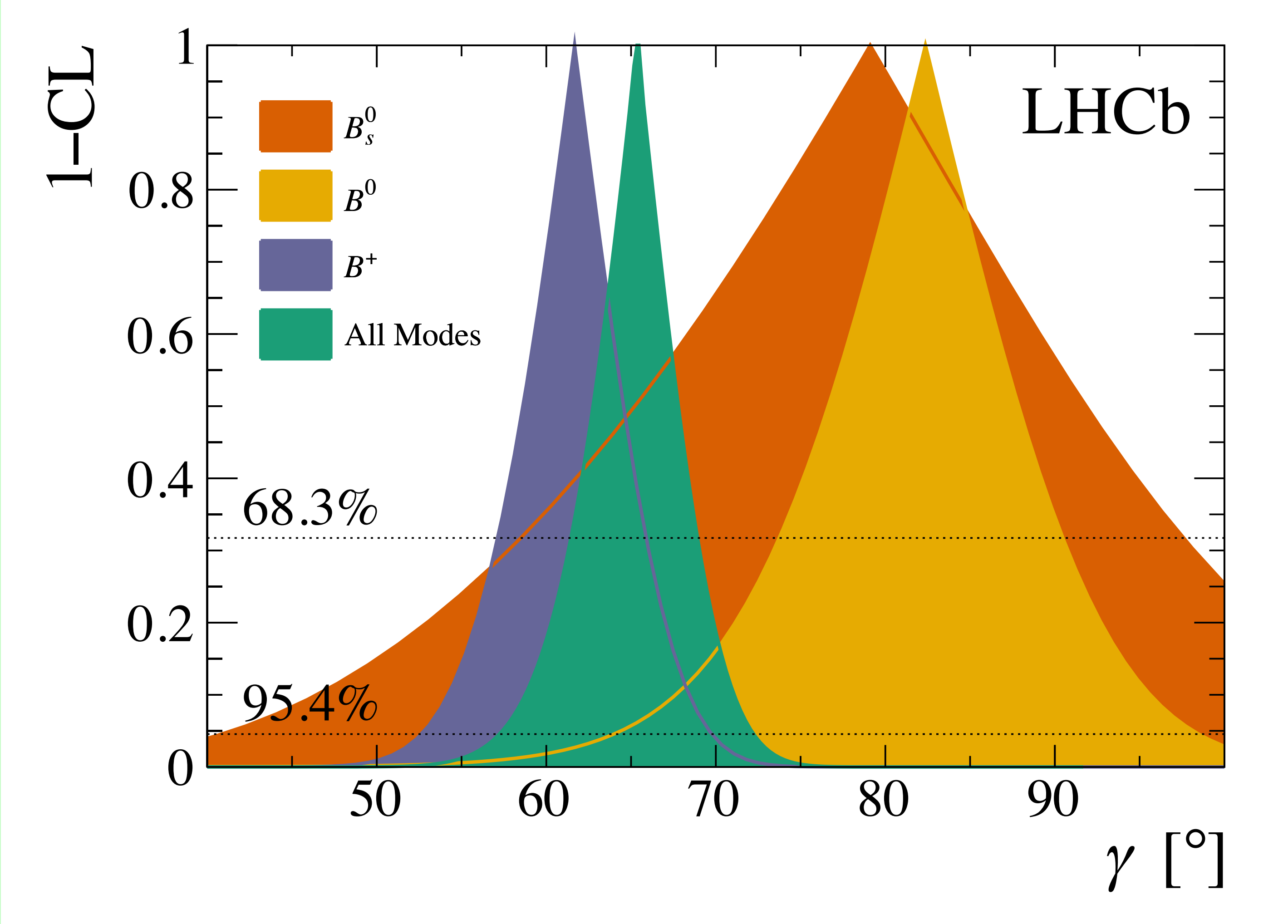
SELECTED OTHER RESULTS

all references here



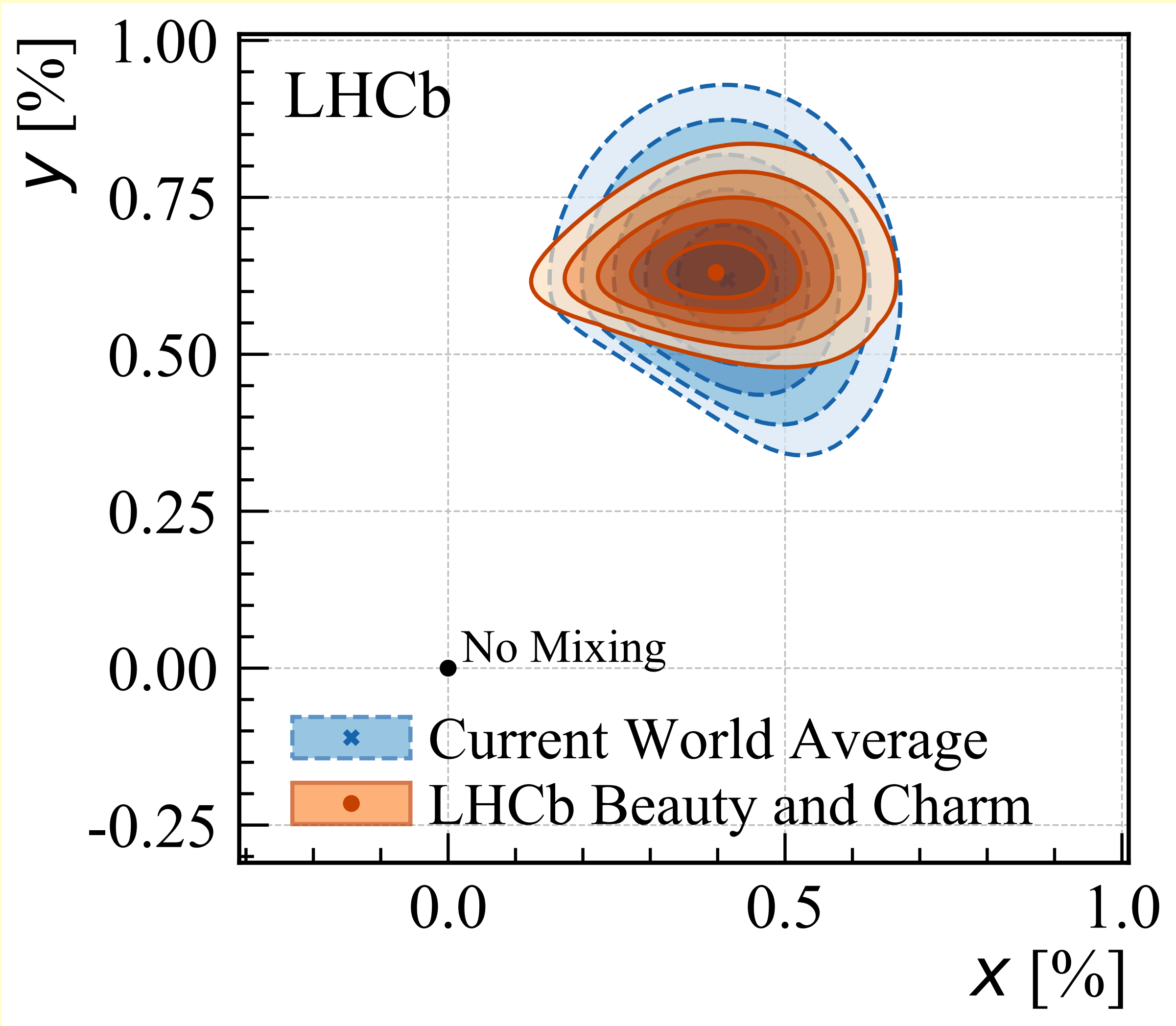


$B_s^0 \to K\mu\nu$: input to V_{ub} puzzle



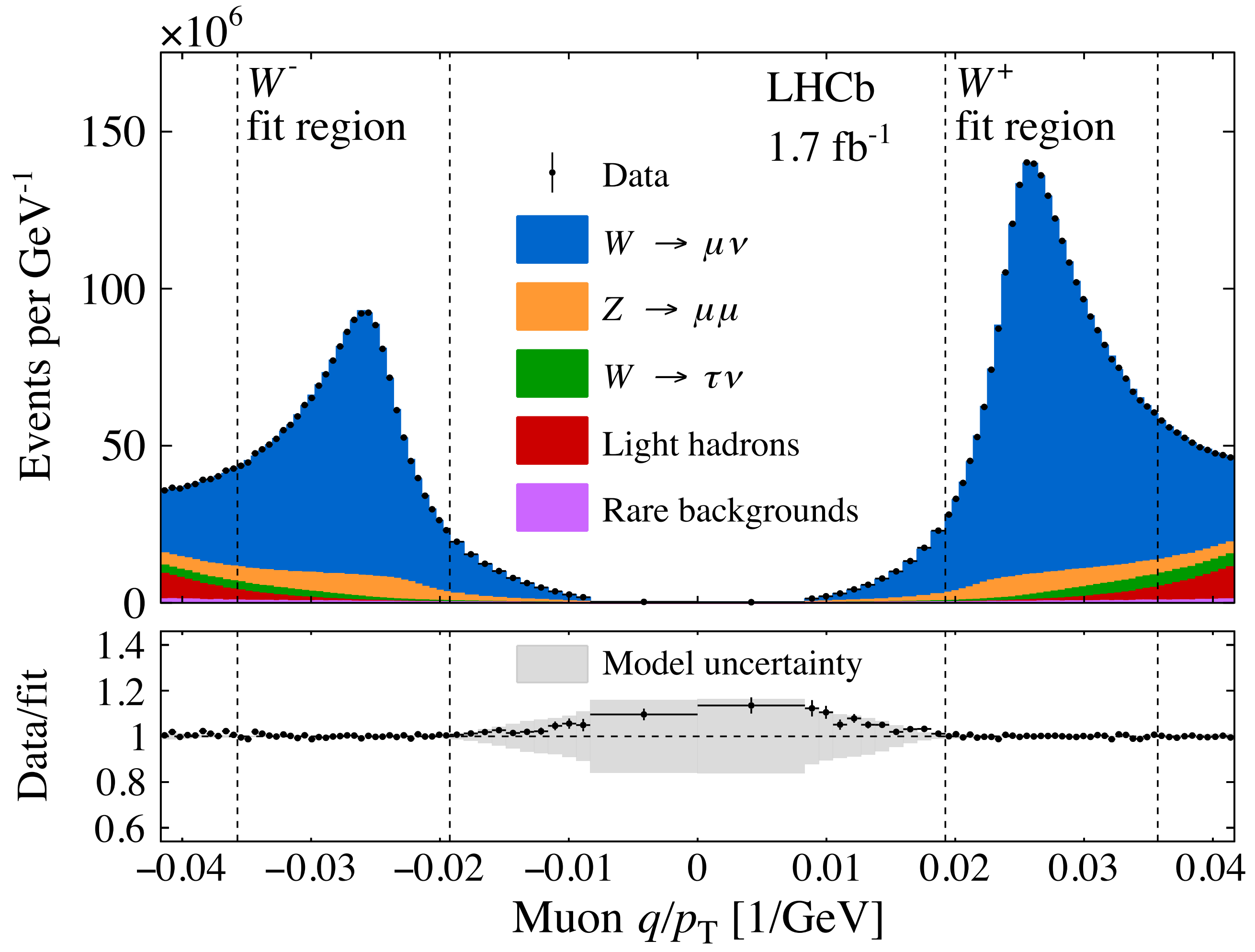
$$\gamma \equiv \phi_3 = \left(65.4^{+3.8}_{-4.2}\right)^\circ$$

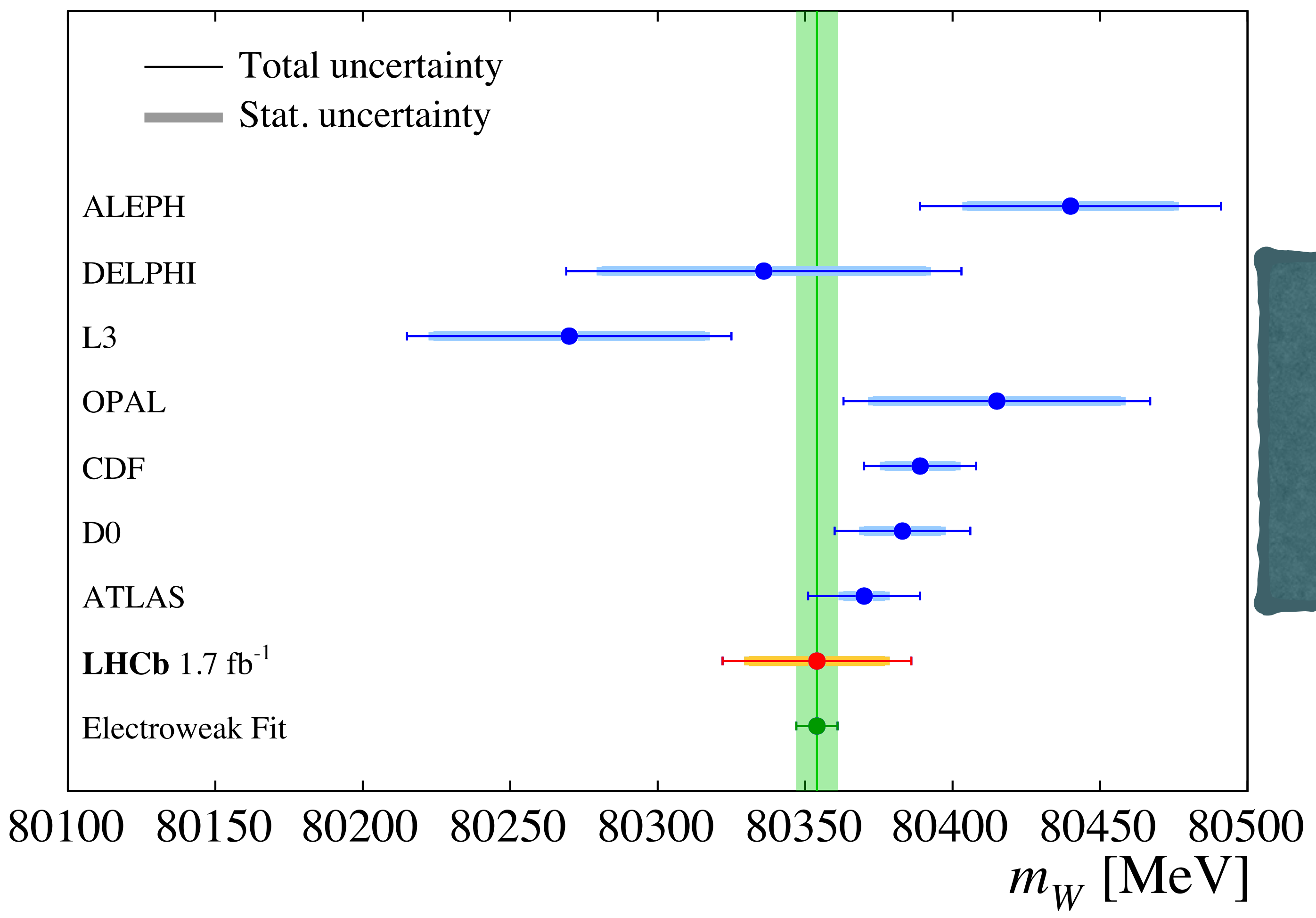
average of LHCb results consistent with global CKM fits



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

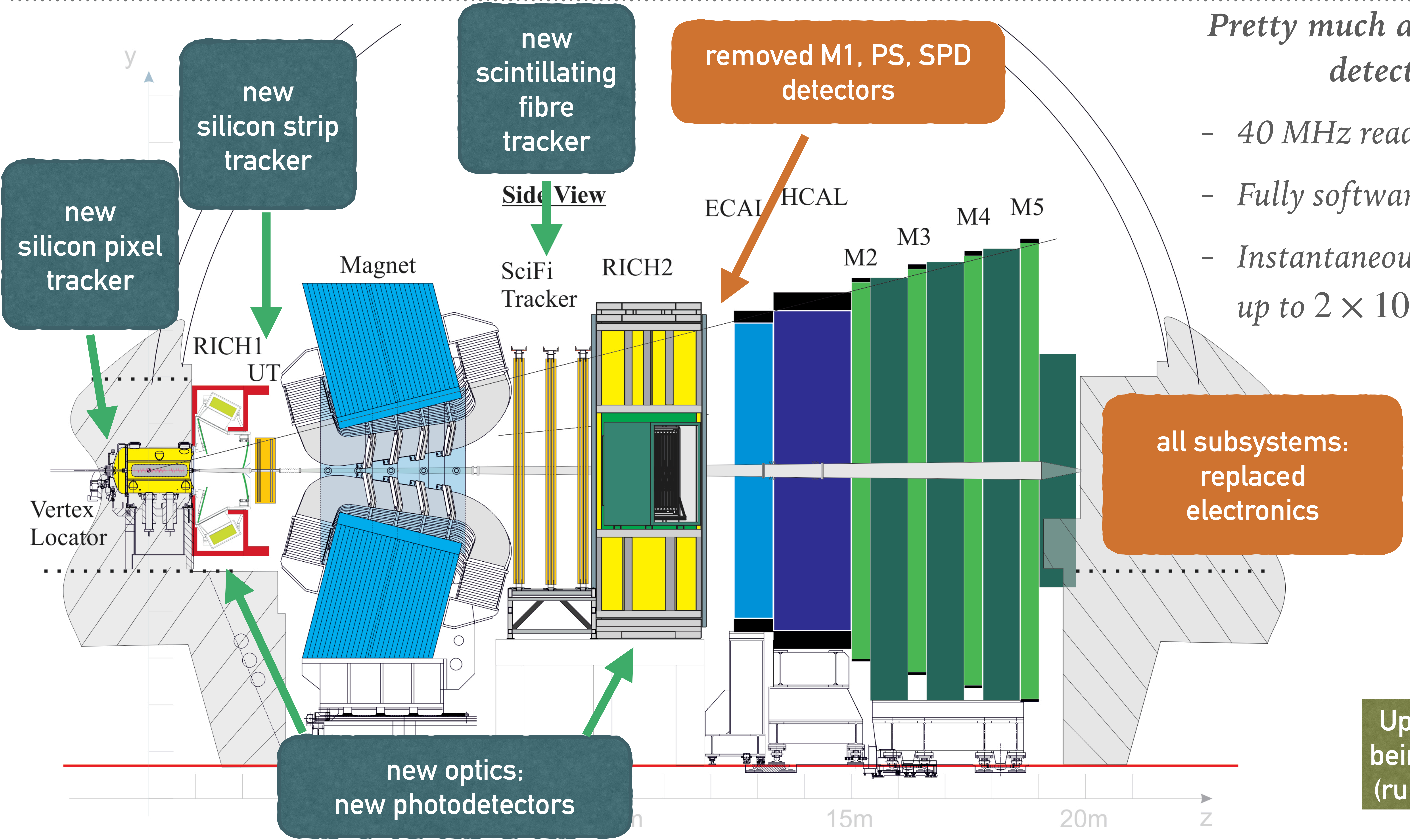
first observation of non-zero mass difference of D^0 mass eigenstates





W boson mass measurement

COMING SOON: UPGRADE I (2022-…)



Pretty much a brand new detector!

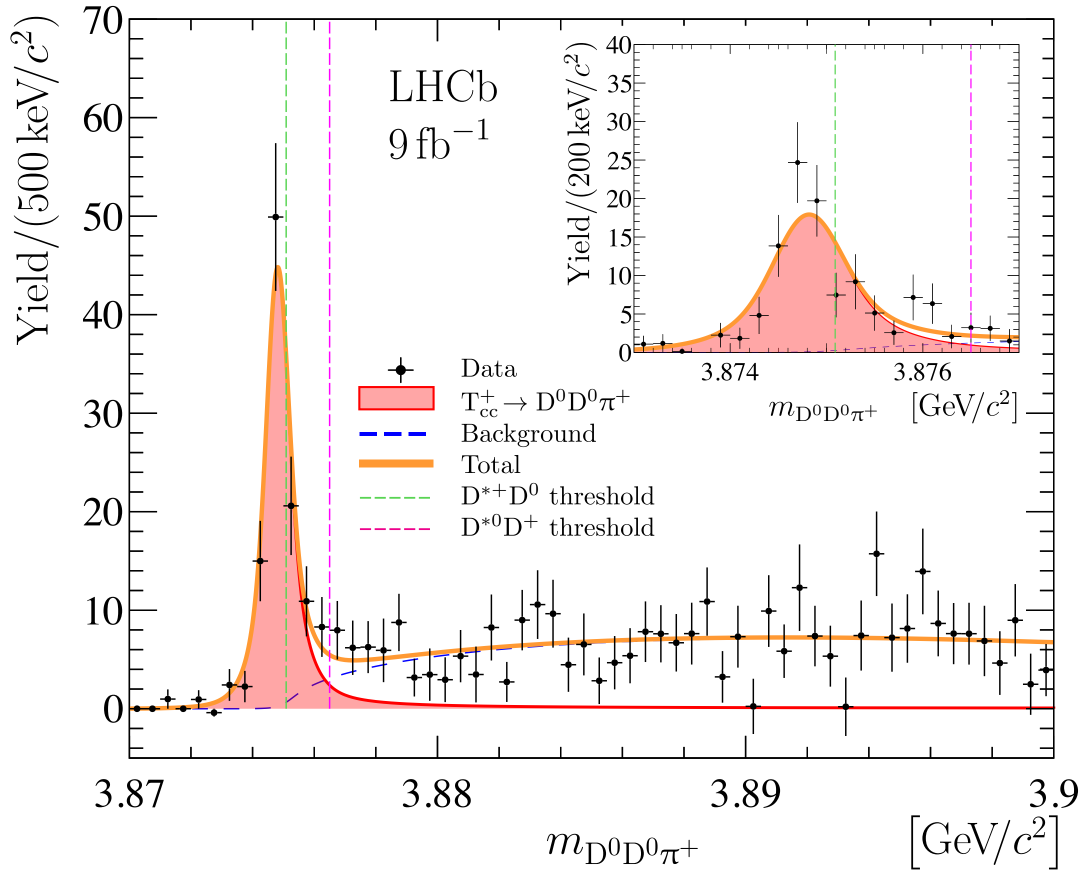
- *40 MHz readout*
- *Fully software trigger*
- *Instantaneous luminosity up to* $2 \times 10^{33}\ cm^{-2}s^{-1}$

Upgrade II is being planned (run in 2030s)

COMING SOON: UPGRADE I (2022-. . .)

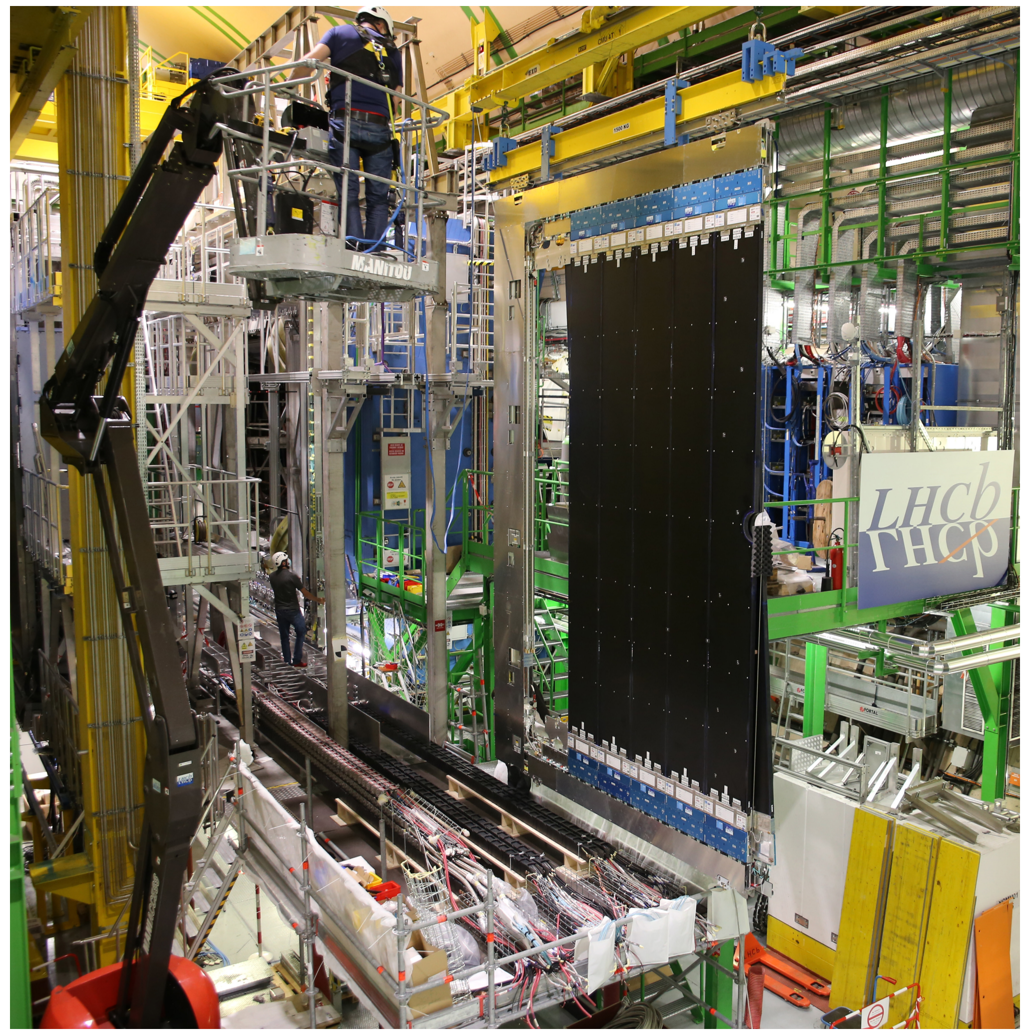
- With **removal of the hardware trigger**, we hope to get rid of the main bottleneck for final states without muons
  - The software trigger is much more flexible
  - We still need to make sure our new software trigger is not introducing any similar bottleneck :)
  - Even for final states with a dimuon, 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 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

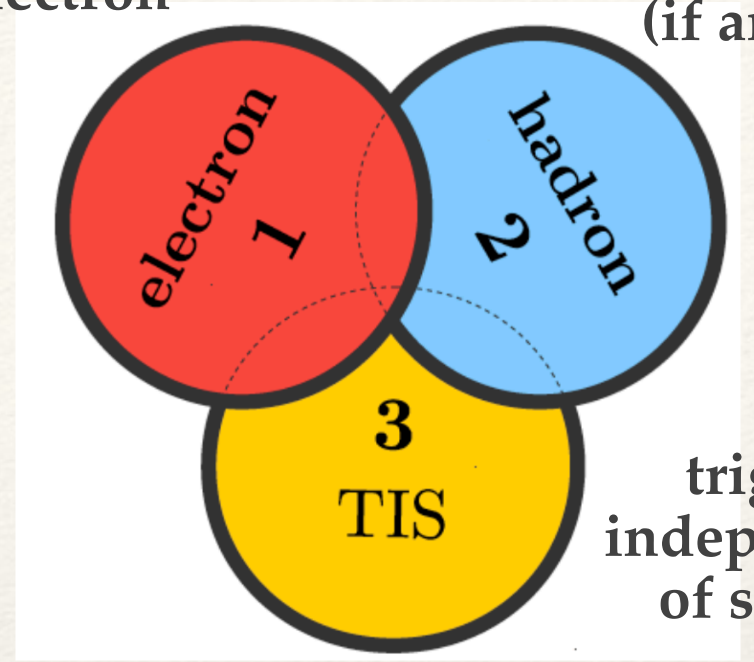
- **Mapping the future of flavour physics with our planned Upgrade II**

BACKUP

Challenges with electrons

JINST 14 (2019) P04013

- **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**