Les Rencontres de Physique de la Vallée d'Aoste, 2022

Rare decays and LFNU at LHCb

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See other talks by the LHCb speakers:
- Classical and exotic spectroscopy by Daniele Marangotto; this morning
- CKM & CPV in charm & beauty by Peilian Li; after my talk
- W mass and Z production by Menglin Xu; later today

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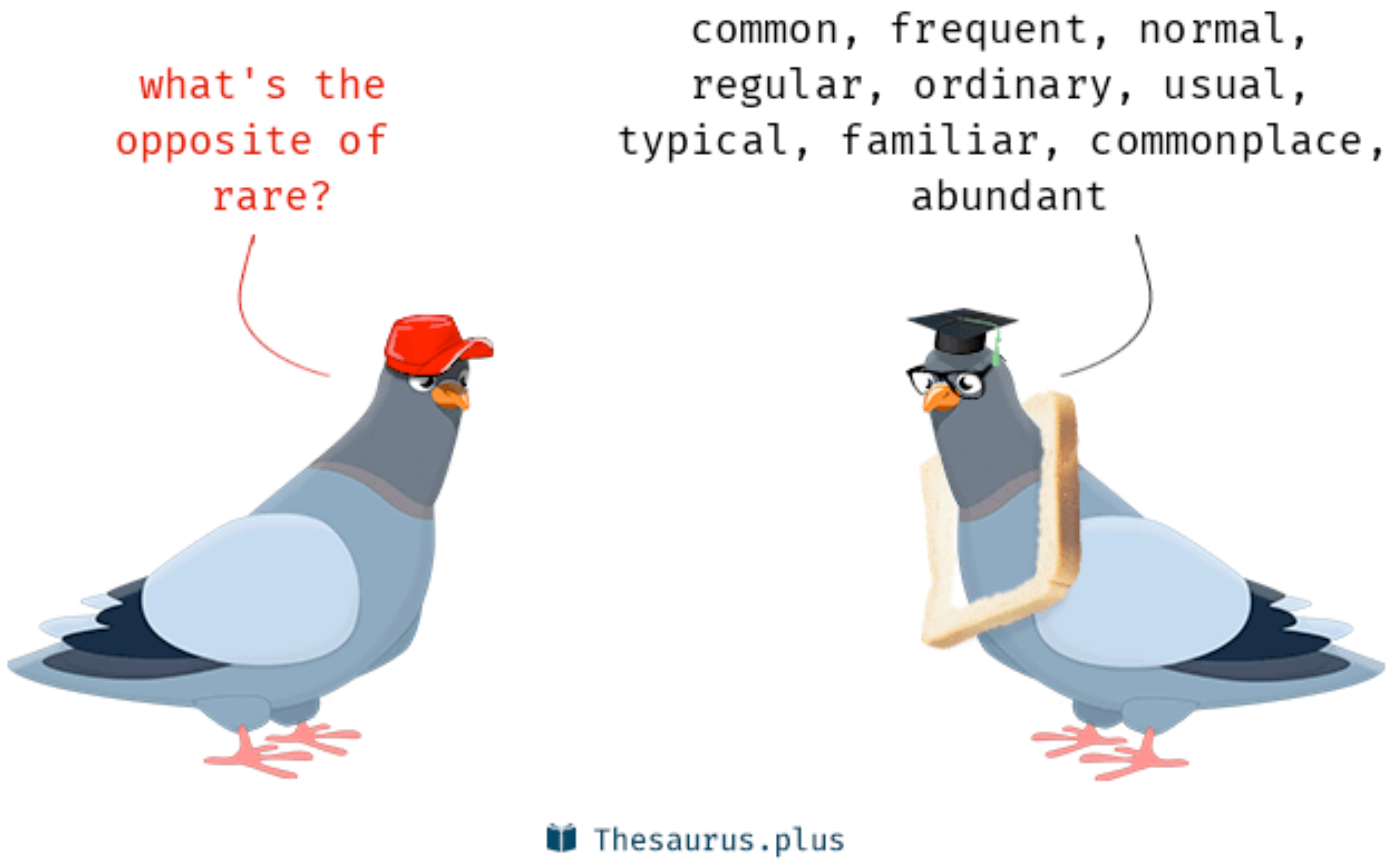
Dedicated to my family
trying to survive under bombs
in Kharkiv, Ukraine

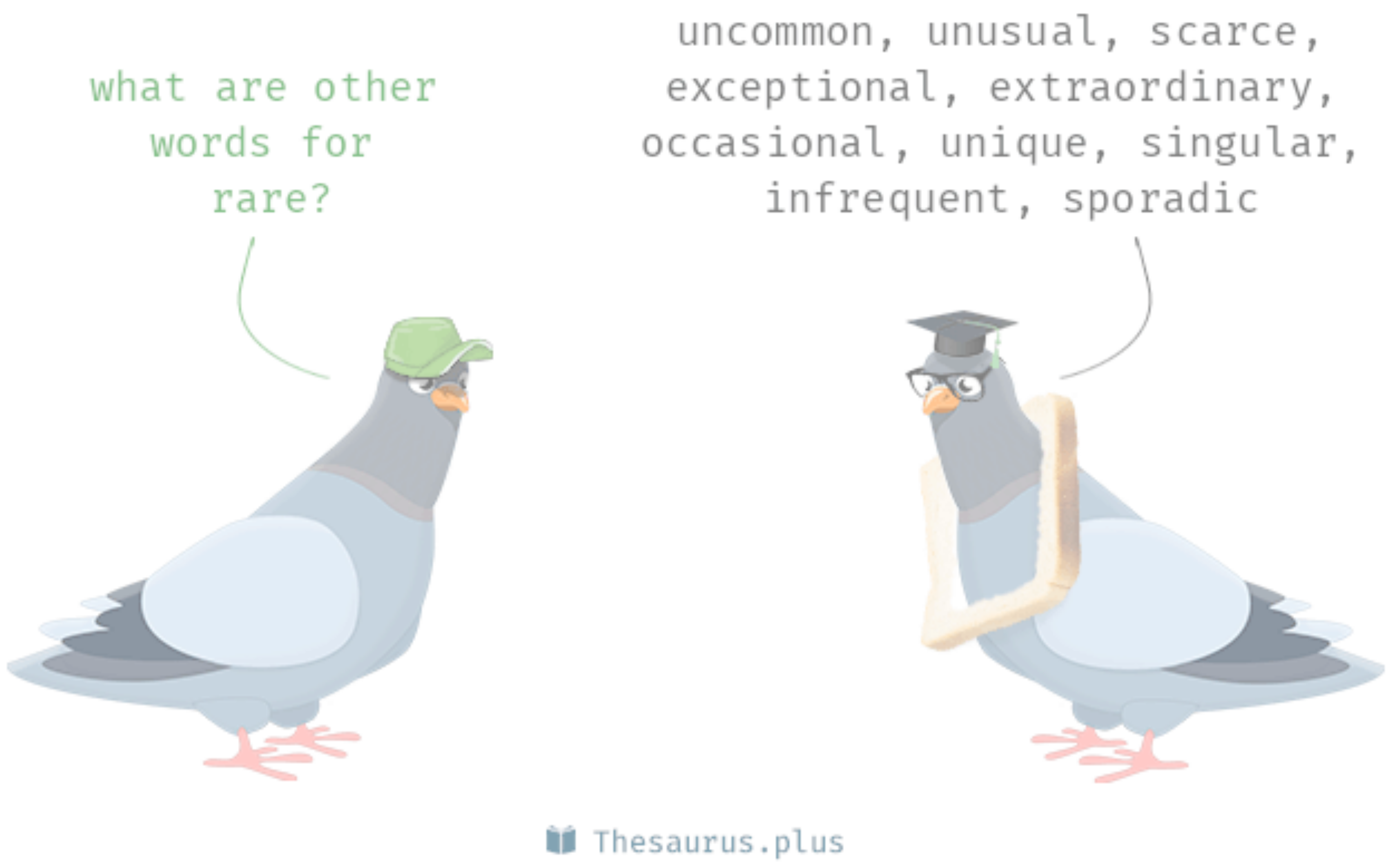
- What is ‘rare’?

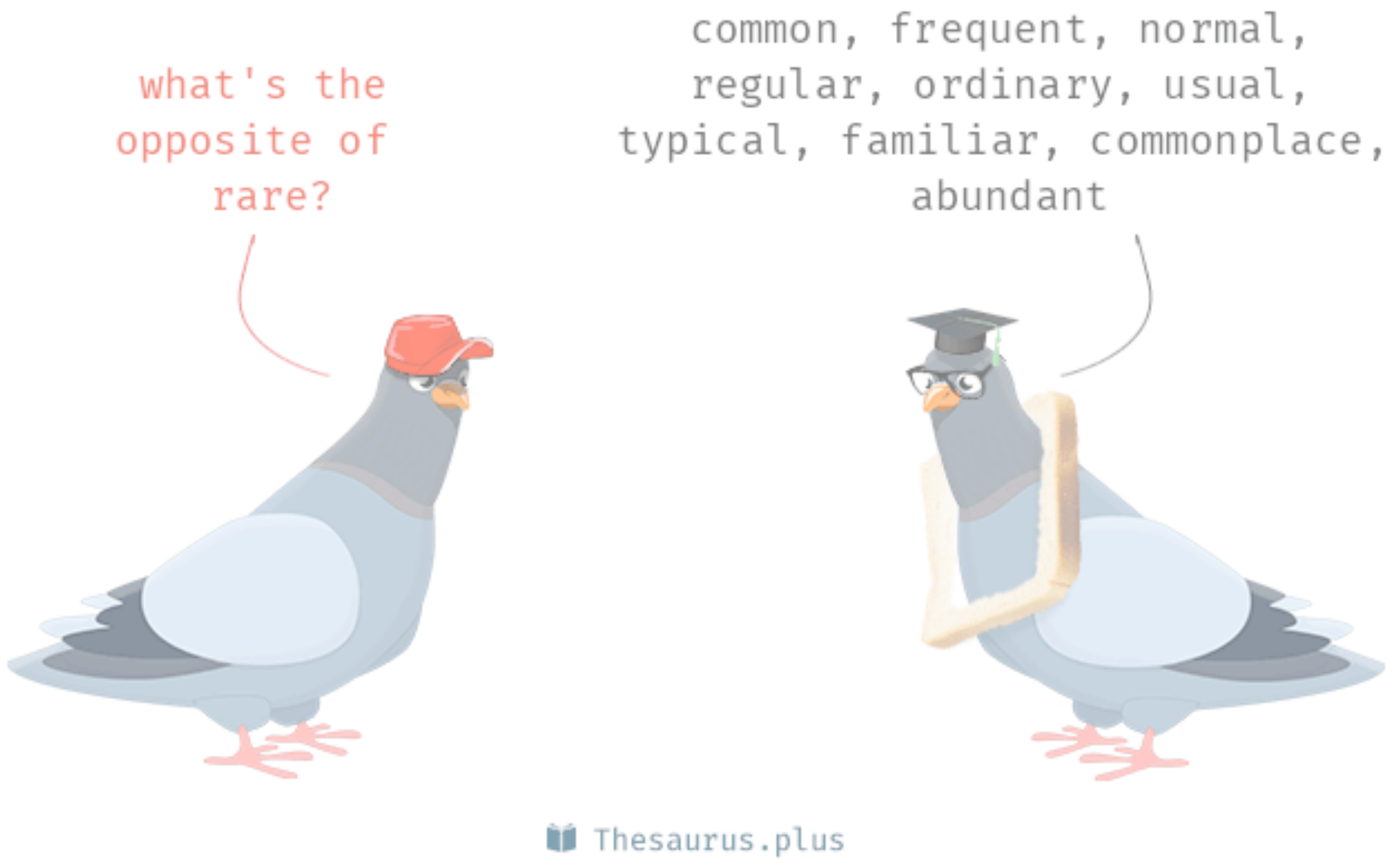

what are other words for rare?
uncommon, unusual, scarce, exceptional, extraordinary, occasional, unique, singular, infrequent, sporadic
Thesaurus.plus


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

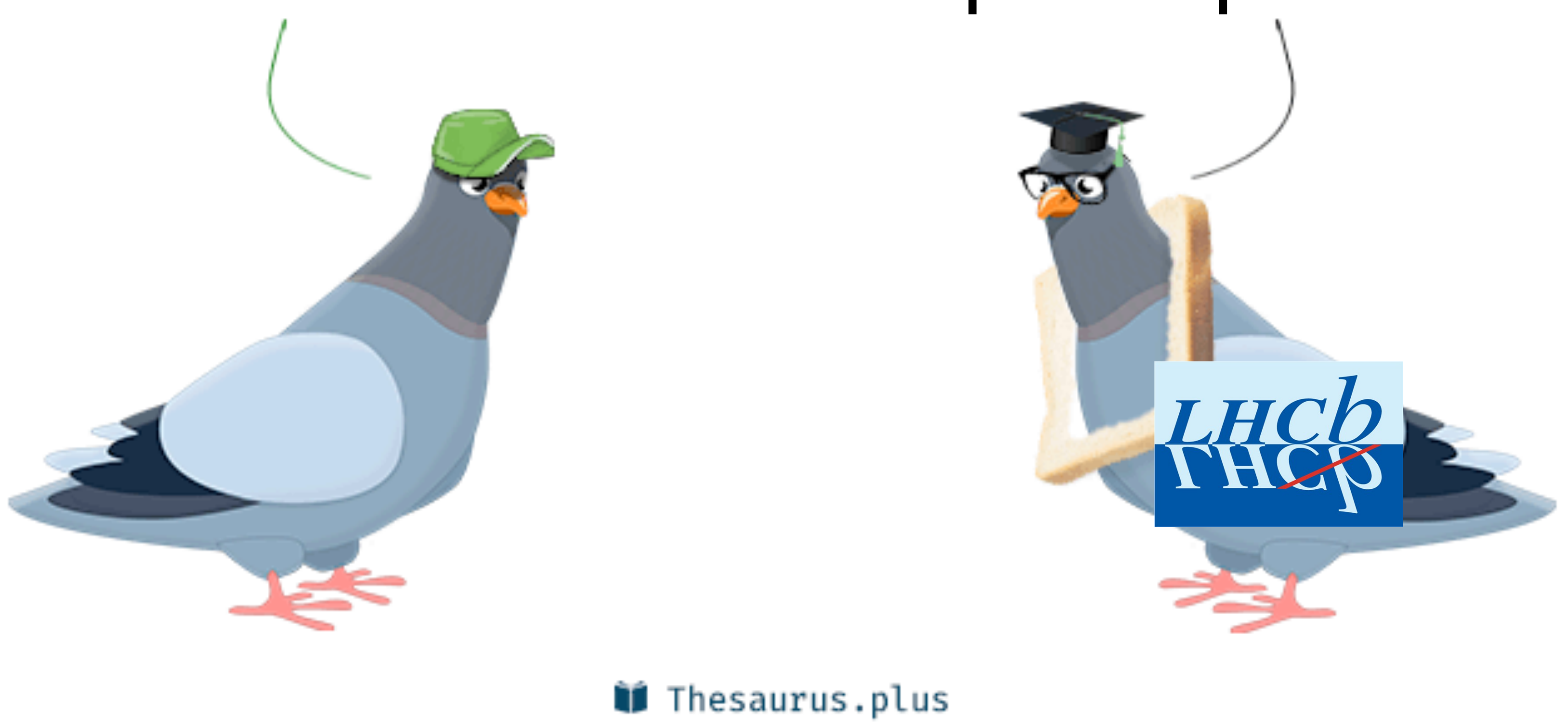
RARE DECAYS

- What is ‘rare’?

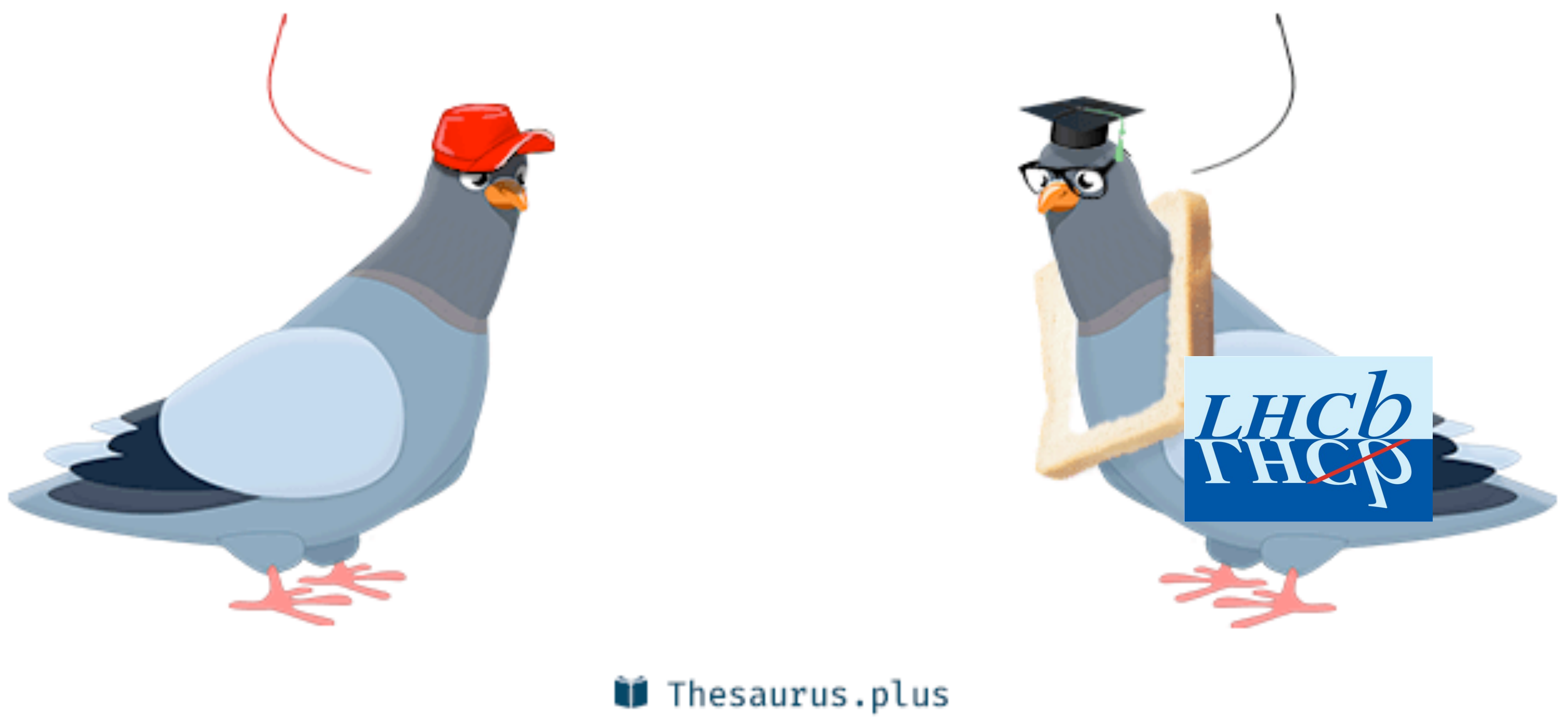


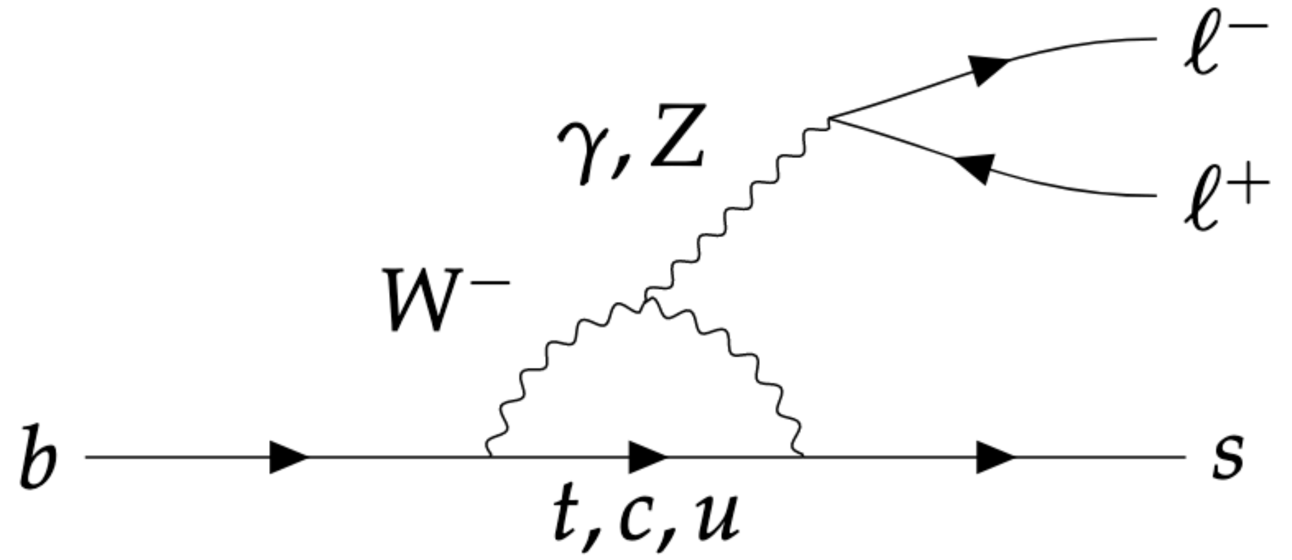


- electroweak decay with small BF ($\lesssim 10^{-4}$)
- (usually) penguin or box SM diagram
  - or: forbidden in SM (LFV, etc)
- dilepton or photon in the final state



- tree-level
- …

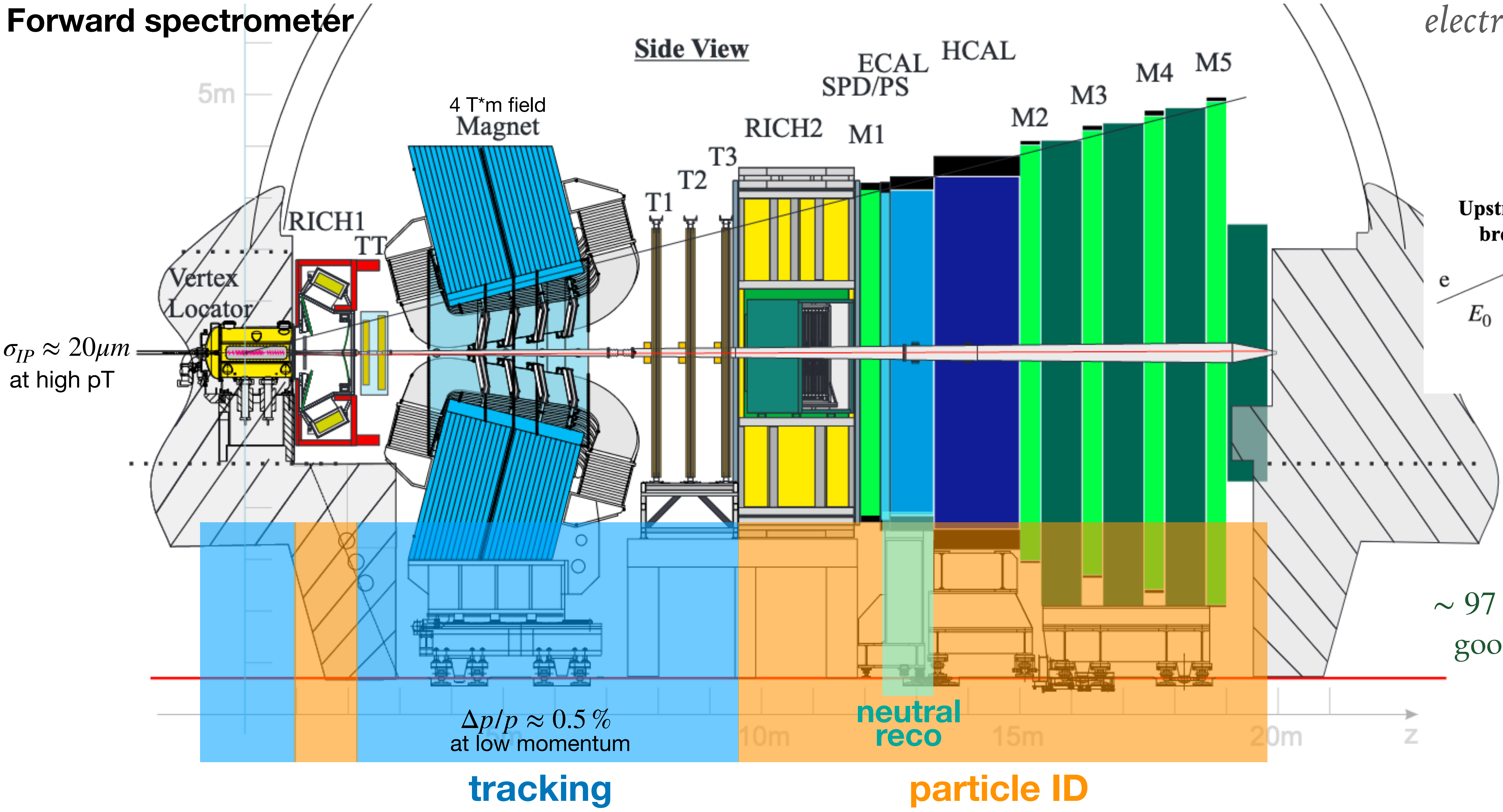




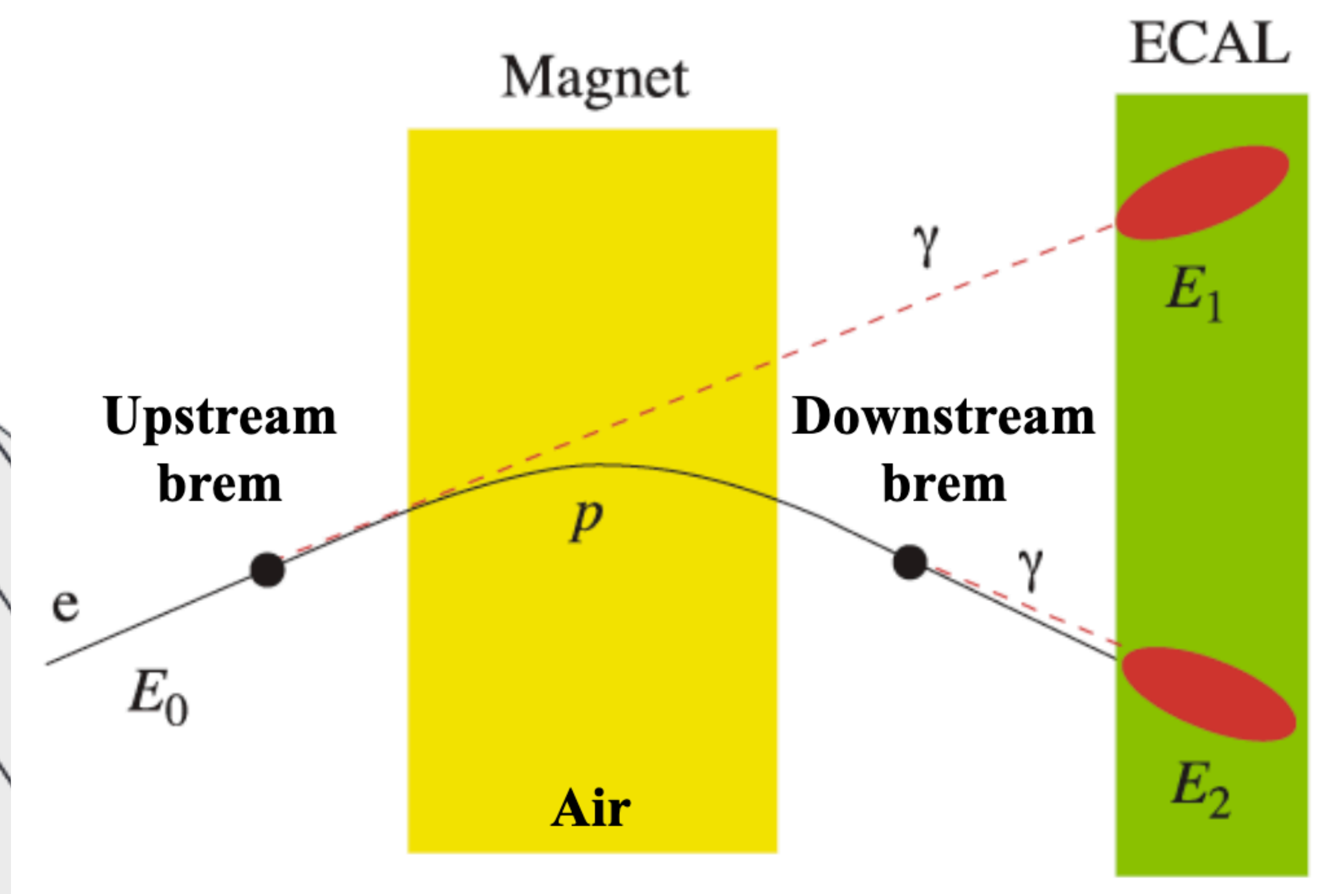
- In **beauty** sector, we study $\boldsymbol{b \to s\ell^+\ell^-}$ **or** $\boldsymbol{b \to s\gamma}$ **processes:**
    - $\ell^\pm$ is muon or electron. Or the tau.
- Flavour-changing neutral current, rare in the SM
    - Sensitive to non-SM contributions
    - Theoretically clean: can construct observables where QCD uncertainties cancel
    - Can be studied in meson or baryon decays: $B \to K\ell^+\ell^-$, $B_s^0 \to \phi\ell^+\ell^-$, $\Lambda_b^0 \to \Lambda\ell^+\ell^-$...
- Crossing: $\boldsymbol{b\bar{s} \to \ell^+\ell^-}$ **decay**
    - very rare due to helicity suppression
- In **charm** sector, $\boldsymbol{c \to u\ell^+\ell^-}$ is the analog with up-type quarks
- **Other processes with dilepton emission: weak annihilation (W exchange), initial-state radiation, etc**

THE LHCb EXPERIMENT IN 2010–2018 (RUNS 1–2)

Forward spectrometer



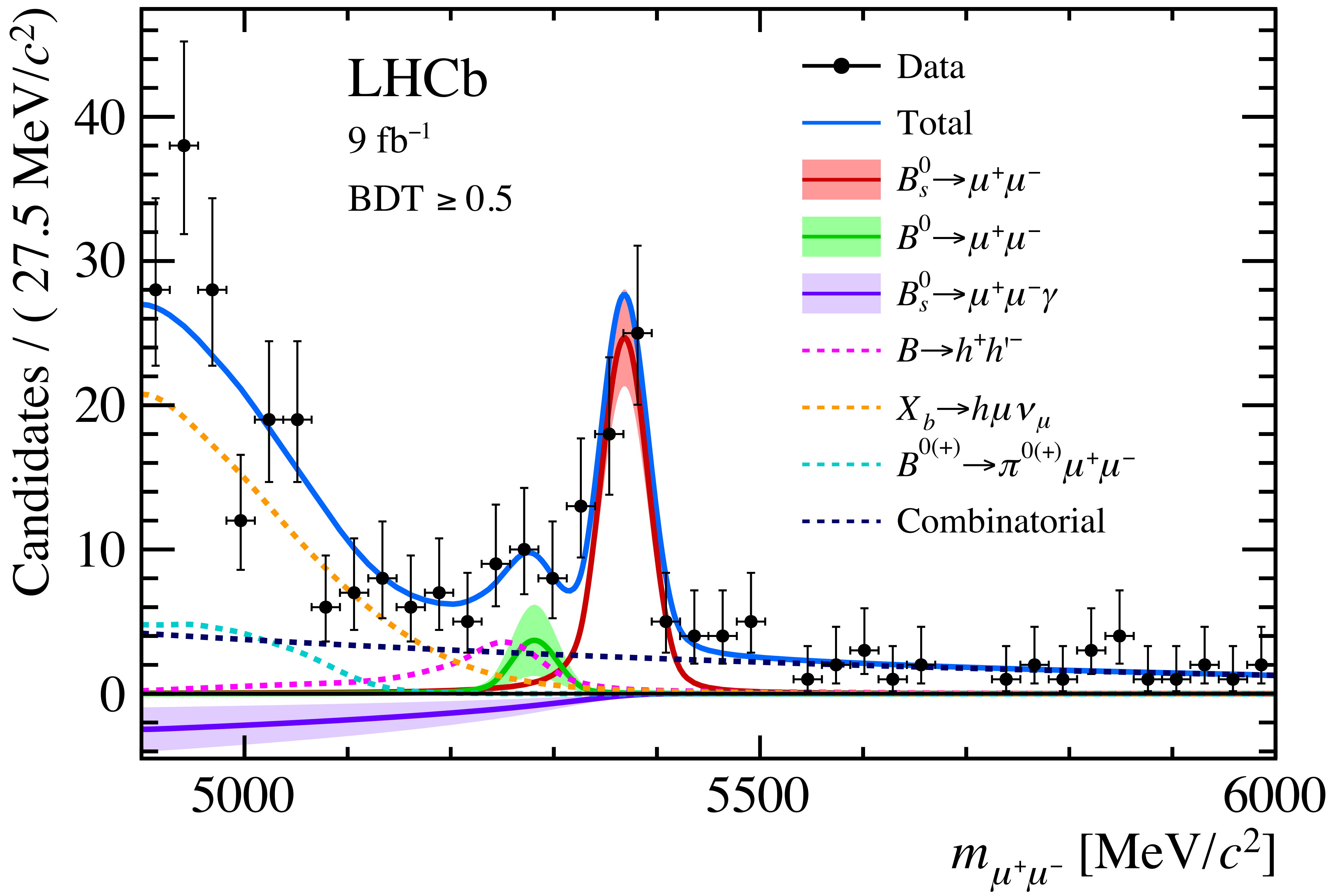
electrons: bremsstrahlung recovery



Particle identification

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

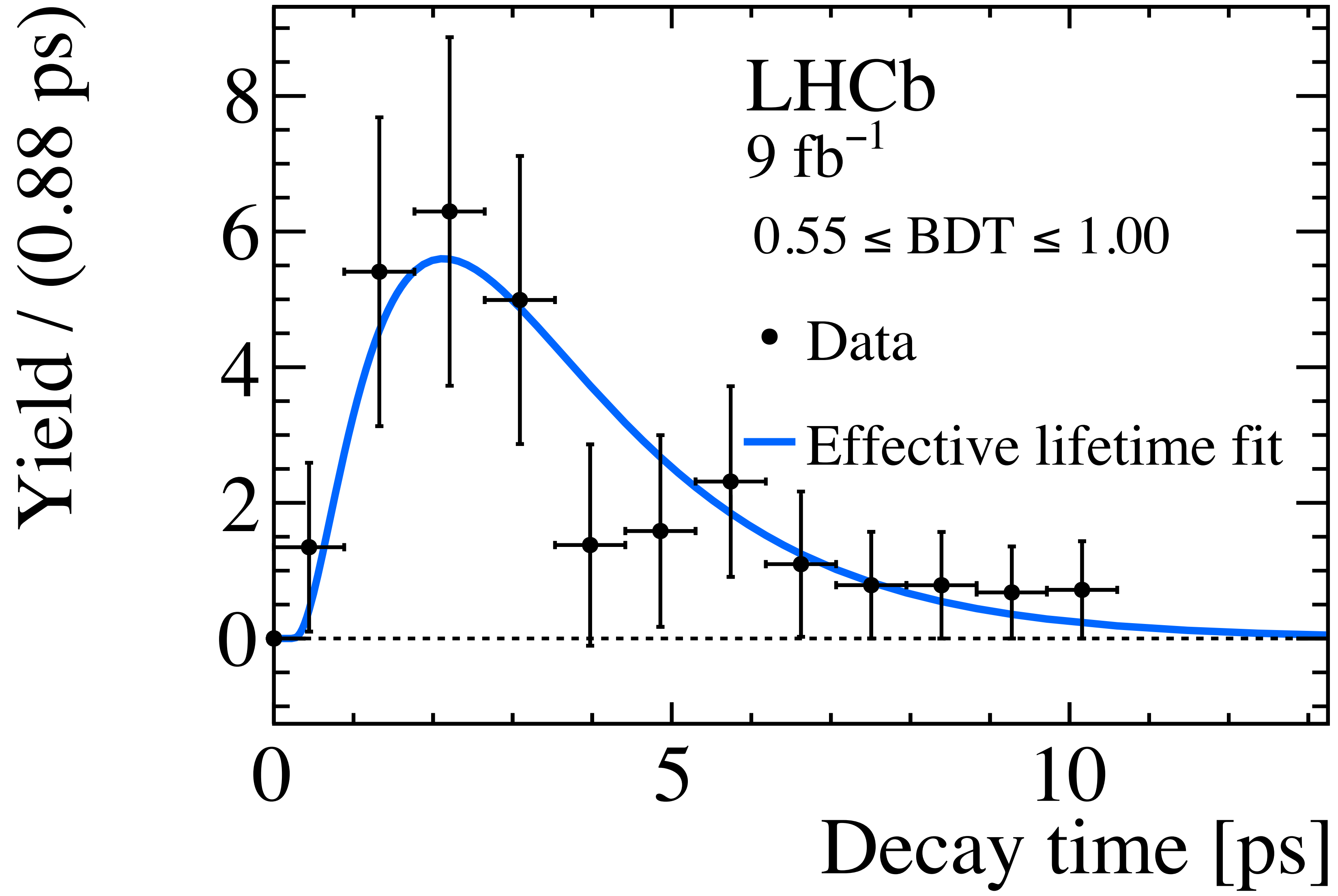
- Collected about 9 fb^{-1} integrated luminosity at 7-8-13 TeV pp collisions with >90% data-taking efficiency
  - instantaneous luminosity $\sim 3 \times 10^{32}\, cm^{-2}s^{-1}$



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

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

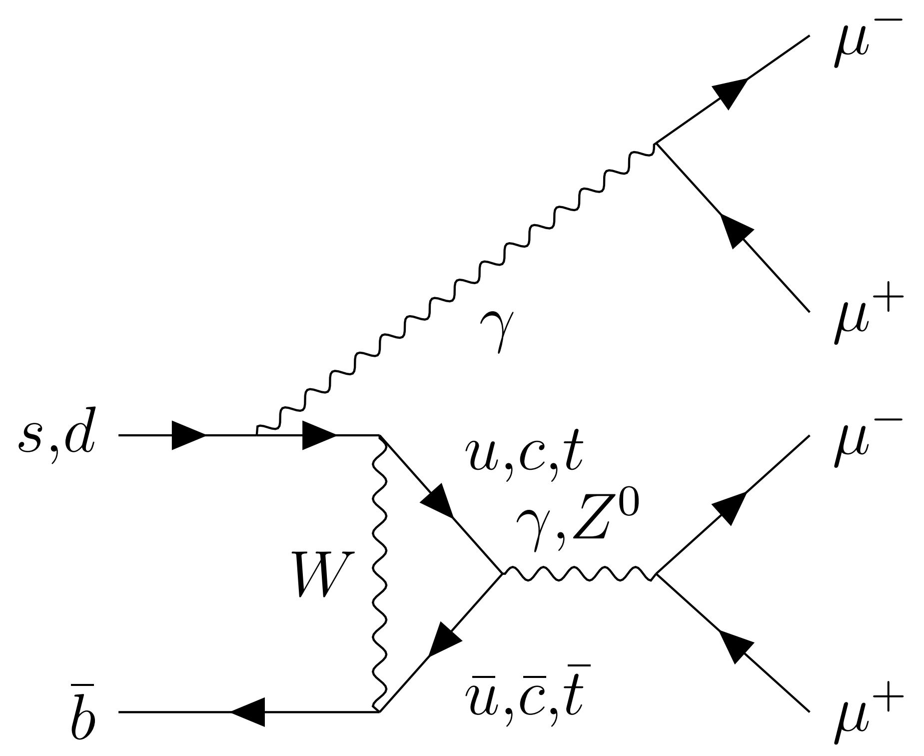
$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m(\mu\mu)<4.9\,\mathrm{GeV}} < 2.0 \times 10^{-9}$ *first limit*



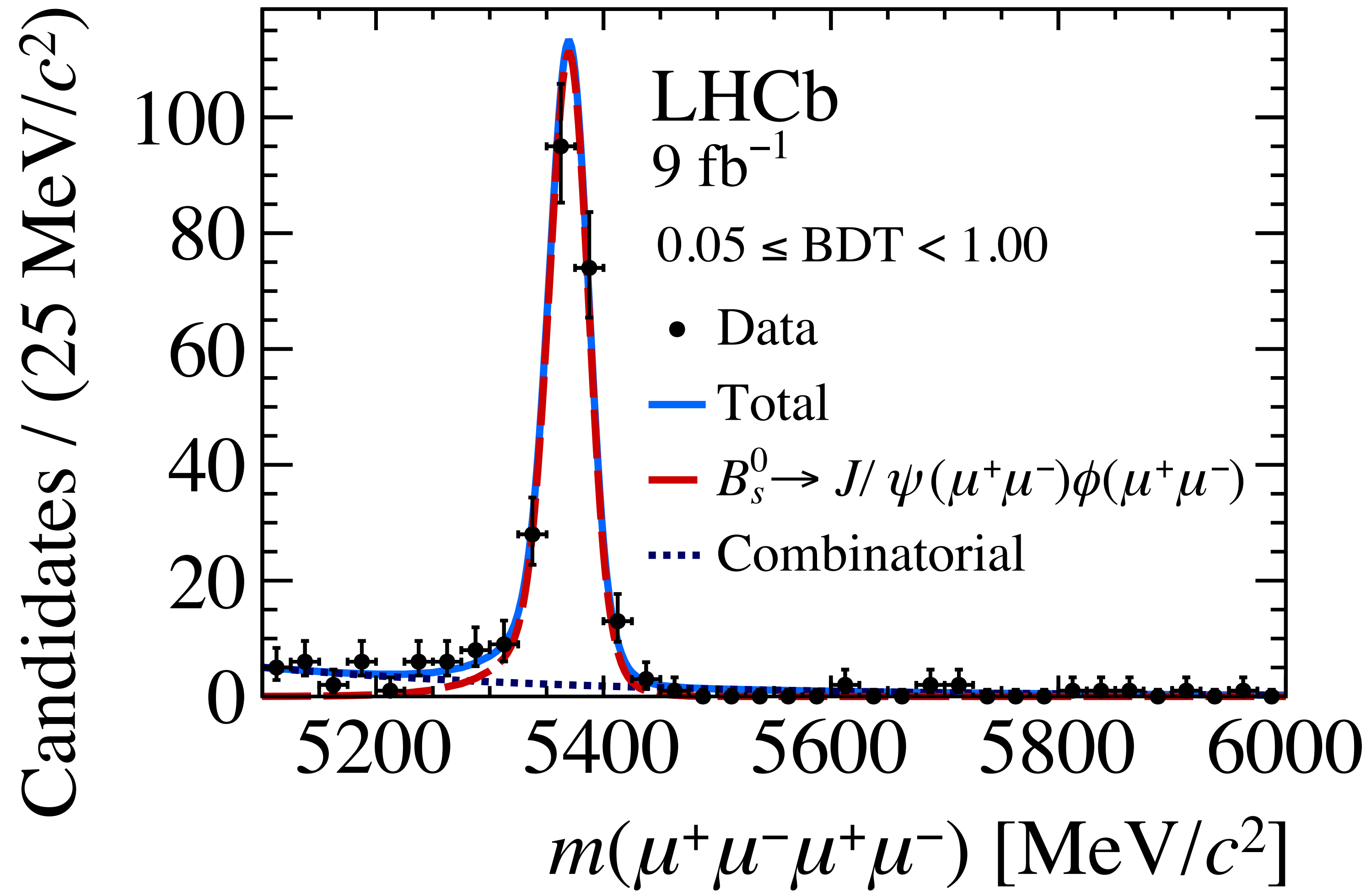
Effective lifetime $\tau(B^0_s \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)\,\mathrm{ps}$

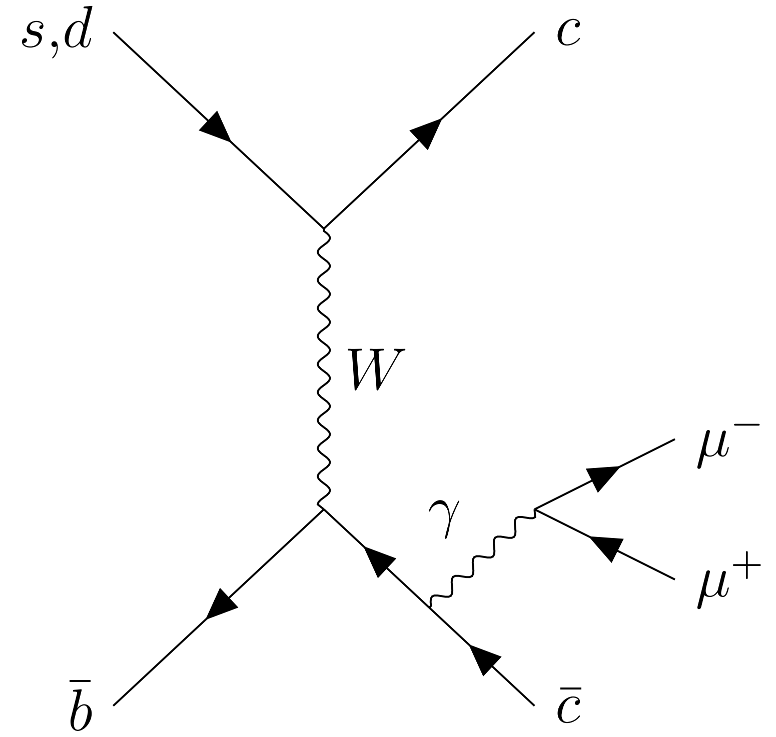
closer to the lifetime of the heavy mass eigenstate, ~1.62 ps (in SM, only the heavy eigenstate can decay to two muons)

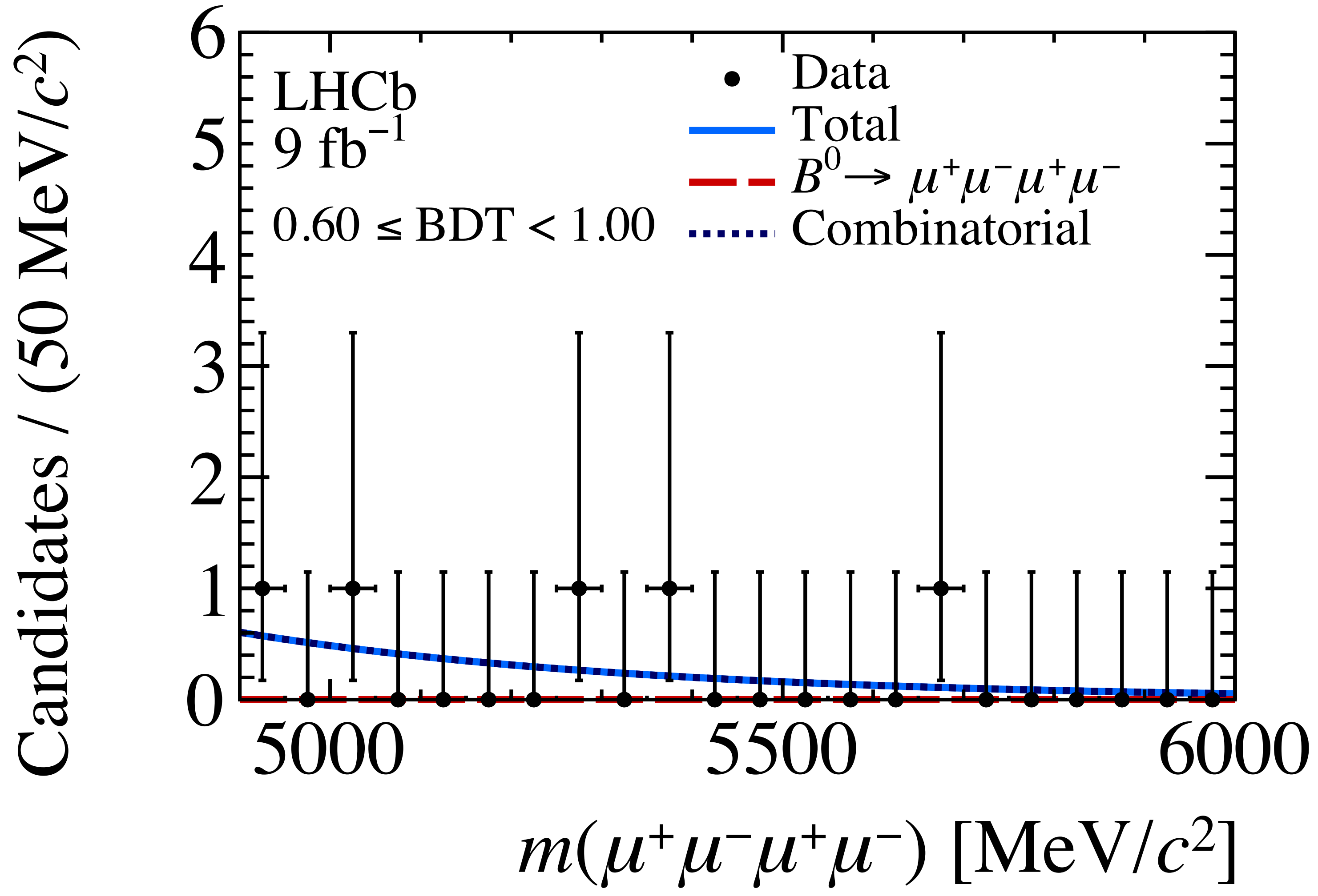
- **Even more suppressed in the SM:** $\sim 10^{-10}$ for the B^0_s mode and $\sim 10^{-12}$ for the B^0 mode

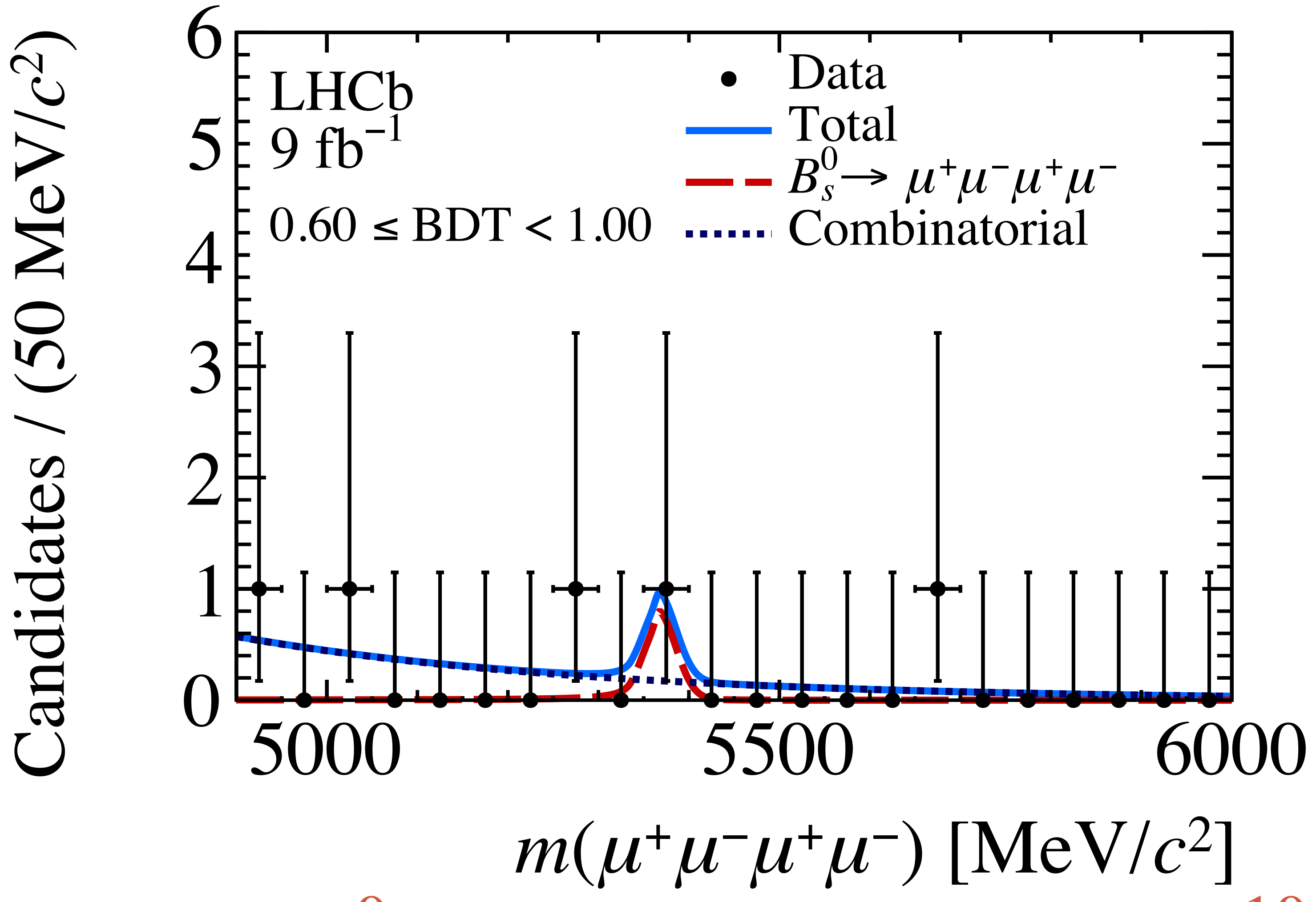


- Can be enhanced in models with BSM **light resonances**: $B^0_{(s)} \to a(\mu^+\mu^-)a(\mu^+\mu^-)$
- SM **resonant** contributions: veto around $\phi, J/\psi, \psi(2S) \to \mu\mu$
  - $B^0_s \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$: normalisation channel
  - $B^0_s \to \phi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ etc: negligible
  - $B^0_{(s)} \to J/\psi(\mu^+\mu^-)\mu^+\mu^-$: search for the first time
    - W-exchange process
    - $\mathscr{B}(B^0_s \to J/\psi\gamma) < 7.4 \times 10^{-6}$: LHCb, PRD92 (2015) 112002
- Muon ID rejects various hadronic backgrounds.









$\mathscr{B}(B^0 \to \mu\mu\mu\mu) < 1.8 \times 10^{-10}$ $\mathscr{B}(B^0_s \to \mu\mu\mu\mu) < 8.6 \times 10^{-10}$ @ 95% CL

Special case (inspired by 1902.10156):

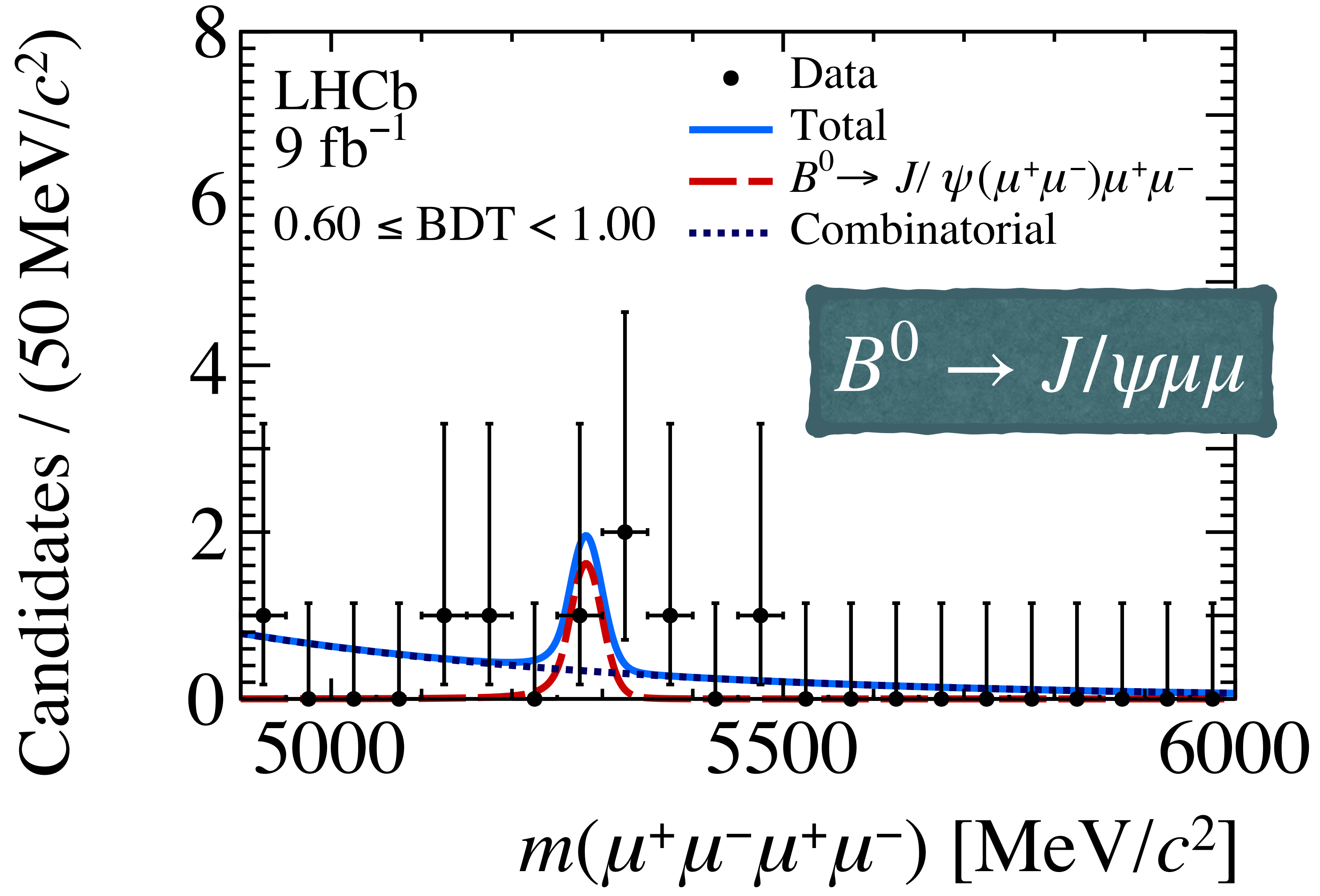
$B^0_{(s)} \to a(\mu^+\mu^-)a(\mu^+\mu^-)$ where a is the light scalar of a mass ~1 GeV (remove the ϕ veto)

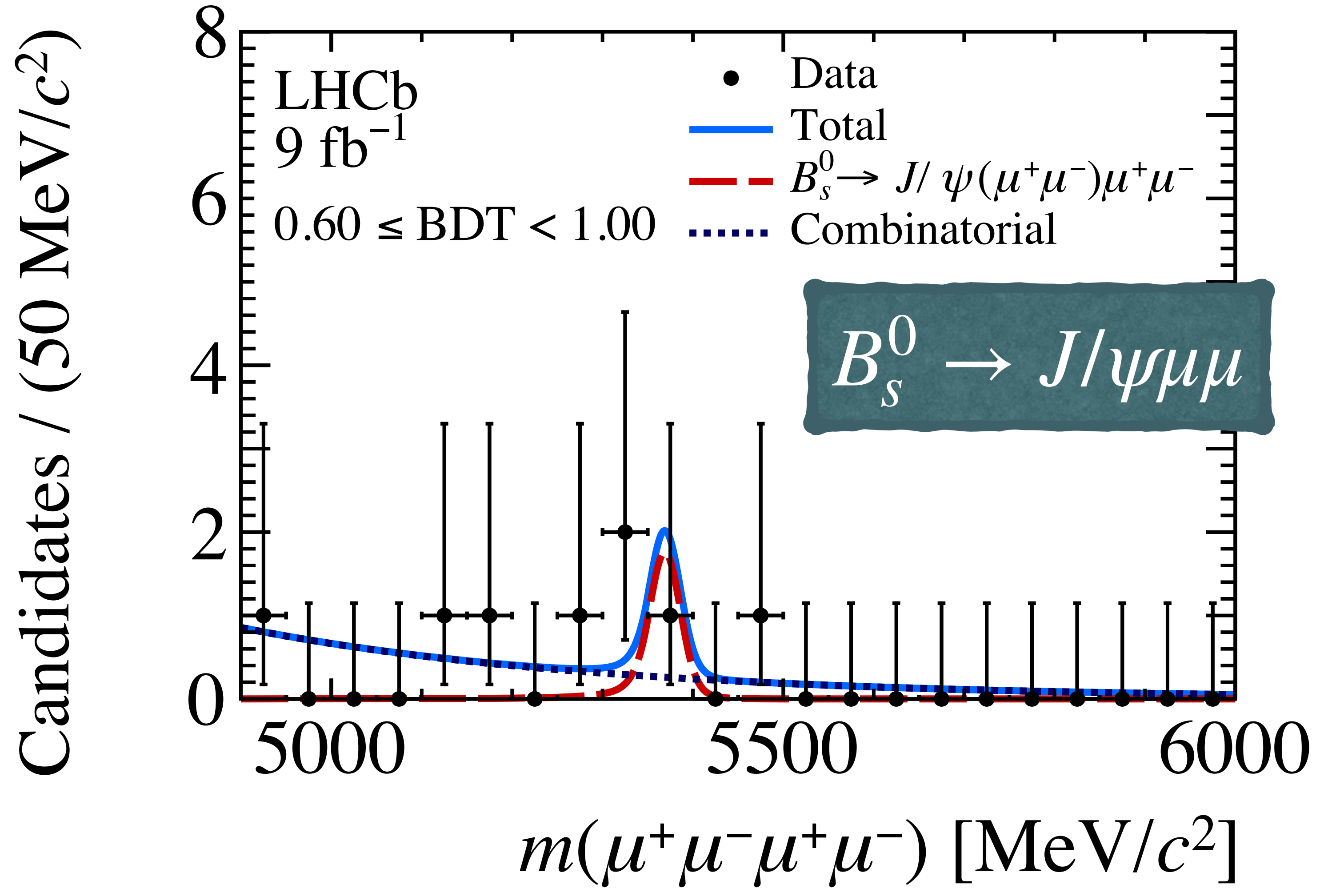
$\mathscr{B}(B^0_s \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 5.8 \times 10^{-10}$

$\mathscr{B}(B^0 \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 2.3 \times 10^{-10}$

@ 95% CL

Largest systematic uncertainty from the decay model assumptions.





- No significant signal observed in any decay mode.

$\mathscr{B}(B^0 \to J/\psi(\mu\mu)\mu\mu) < 1.0 \times 10^{-9}$ $\mathscr{B}(B^0_s \to J/\psi(\mu\mu)\mu\mu) < 2.6 \times 10^{-9}$ @ 95% CL

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

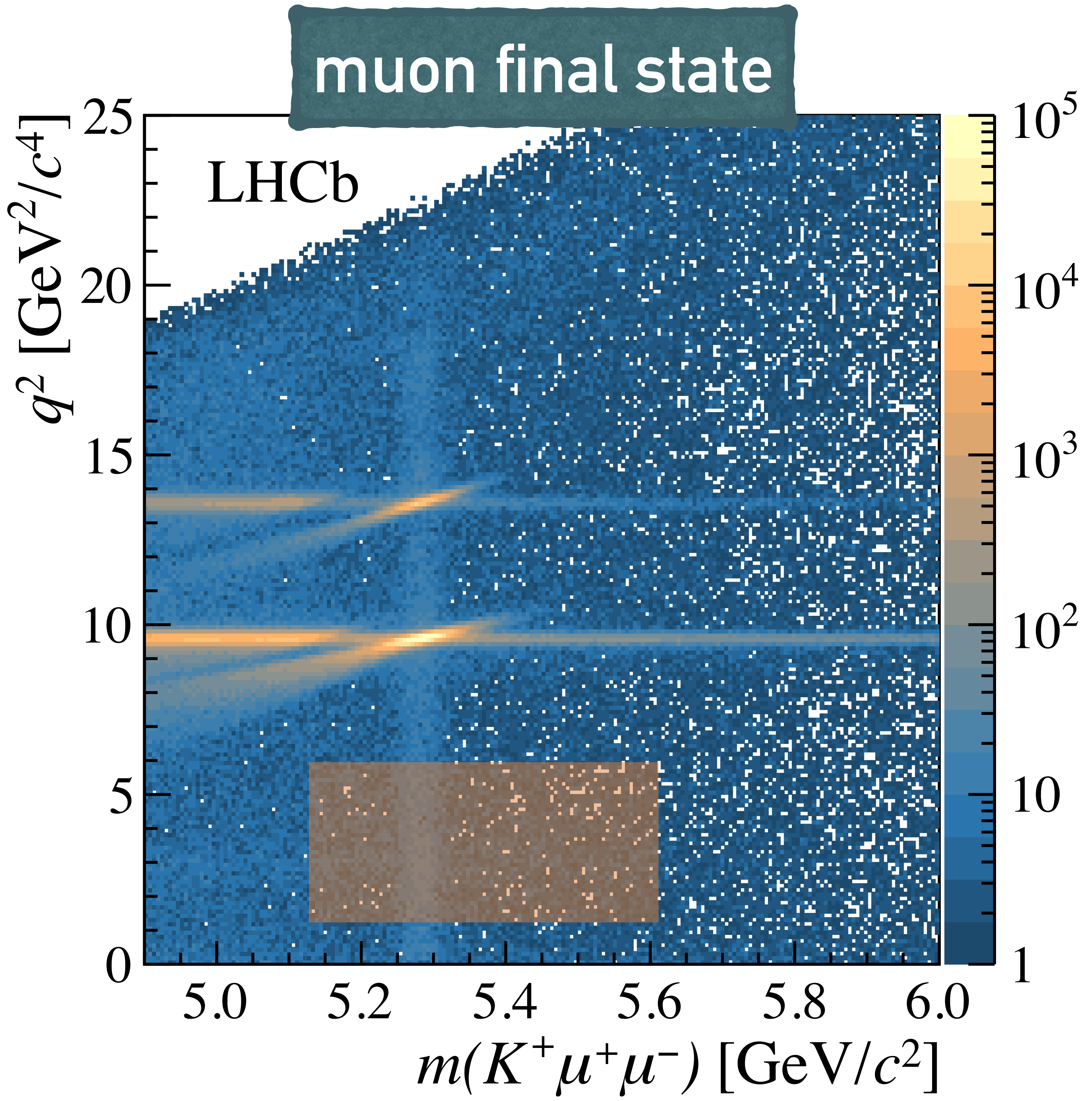
$$\frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)} = 1.0001 \pm 0.0024 \text{ or } \frac{\Gamma(W \to \mu\nu)}{\Gamma(W \to e\nu)} = 0.996 \pm 0.008$$

PDG'2021

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

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

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

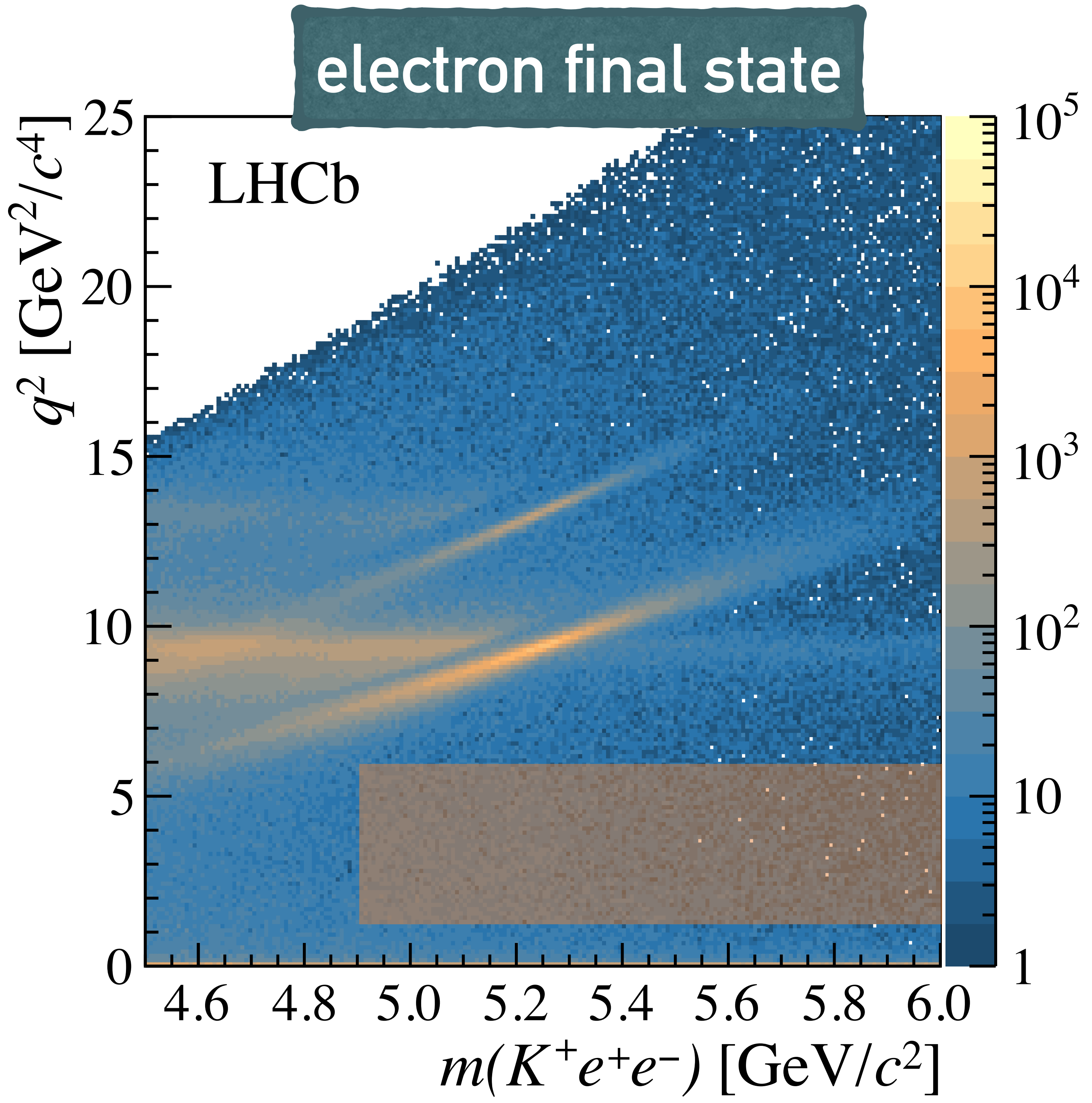


$\psi(2S) + X$

$J/\psi + X$

signal window

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



worse resolution due to bremsstrahlung

LEPTON UNIVERSALITY

arXiv 2103.11769

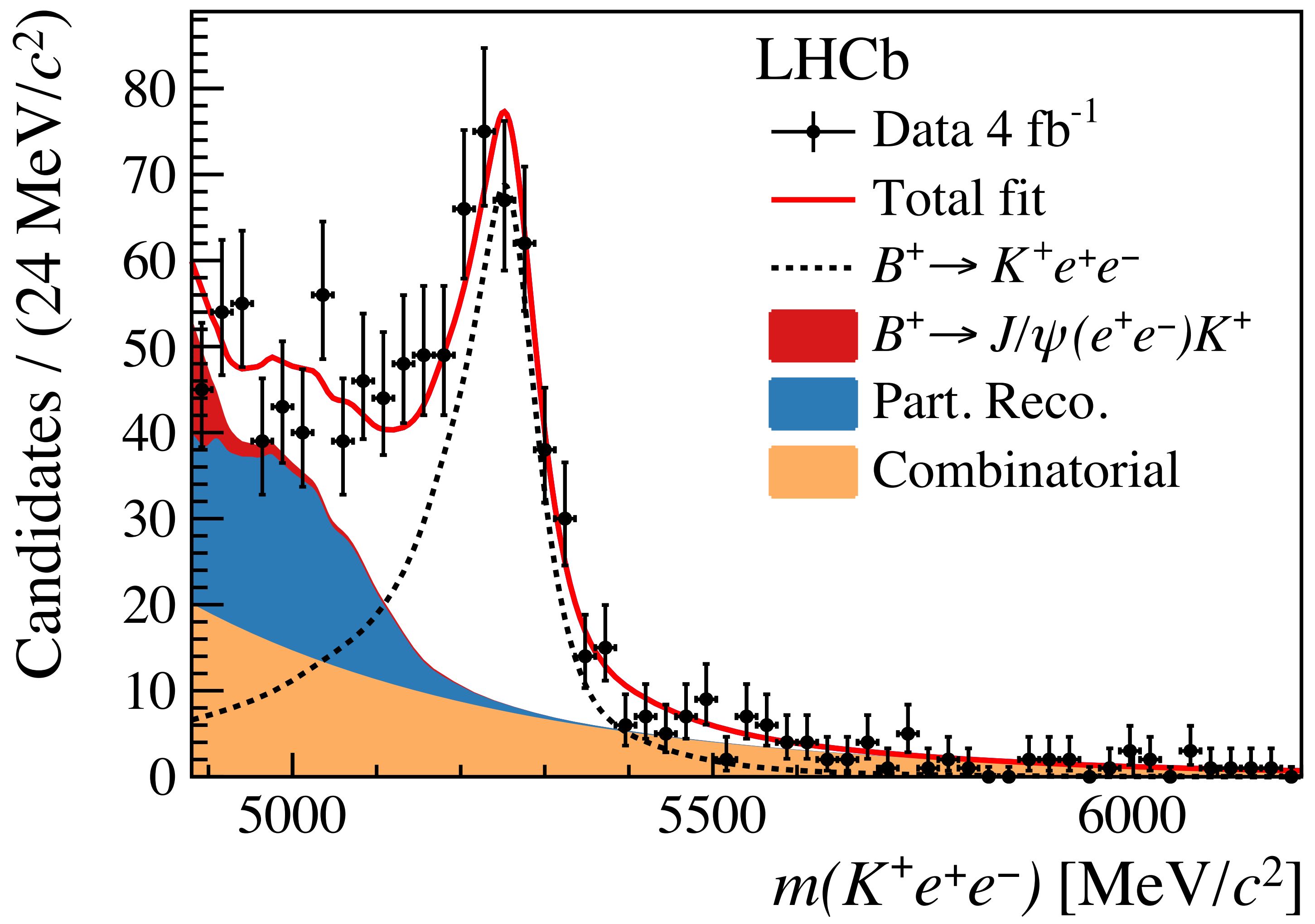
Run1+Run2 dataset

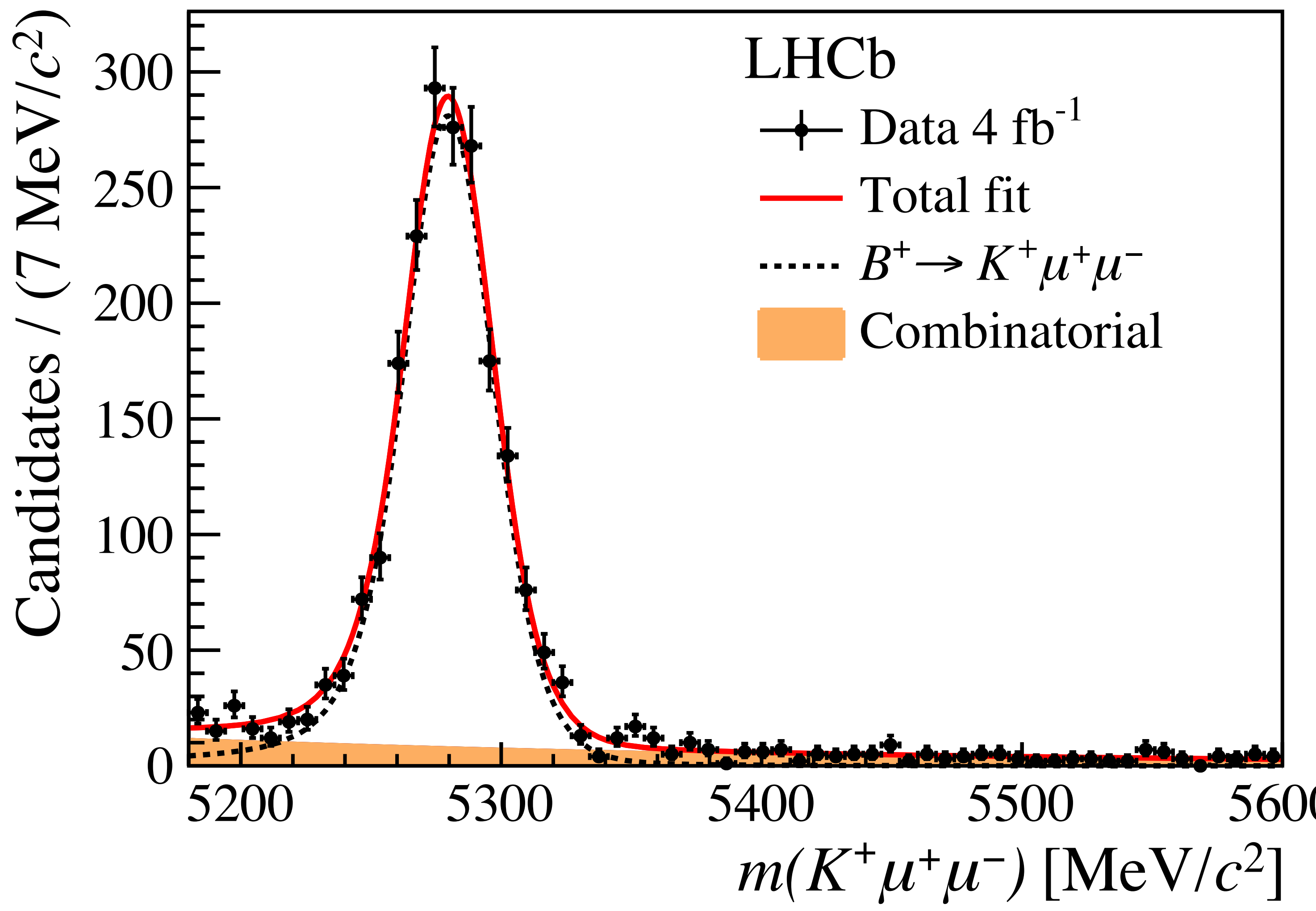
- What we measure: (to cancel detection asymmetries)

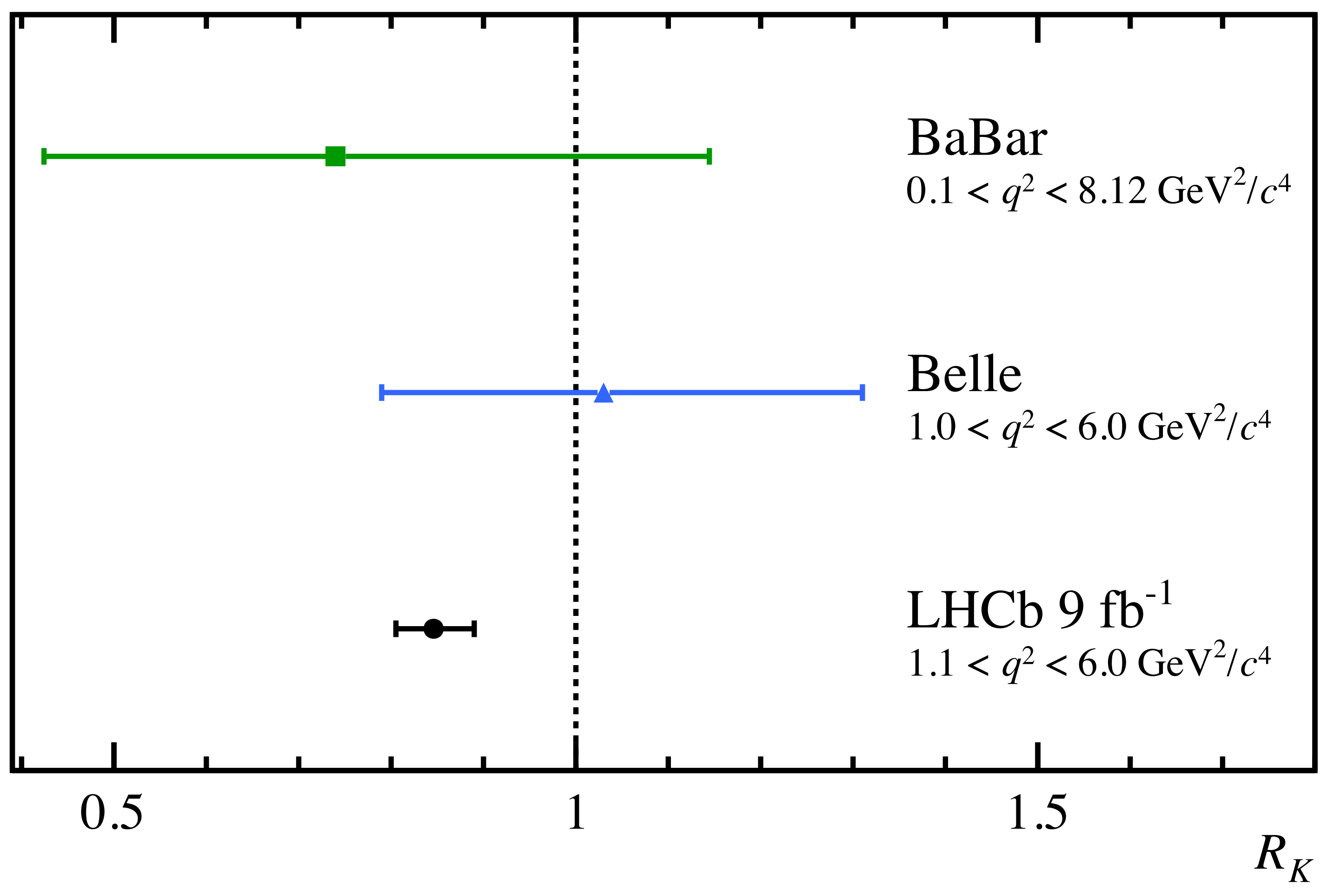
$$R_K = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \times \frac{\mathscr{B}(B^+ \to K^+ J/\psi(e^+e^-))}{\mathscr{B}(B^+ \to K^+e^+e^-)}$$

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: $R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$
- Similar deviations (less precise) in $\Lambda_b^0 \to pK\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays

JHEP 05 (2020) 040

JHEP 08 (2017) 055

- **What about other initial/final states?**

- Study the isospin partner process:

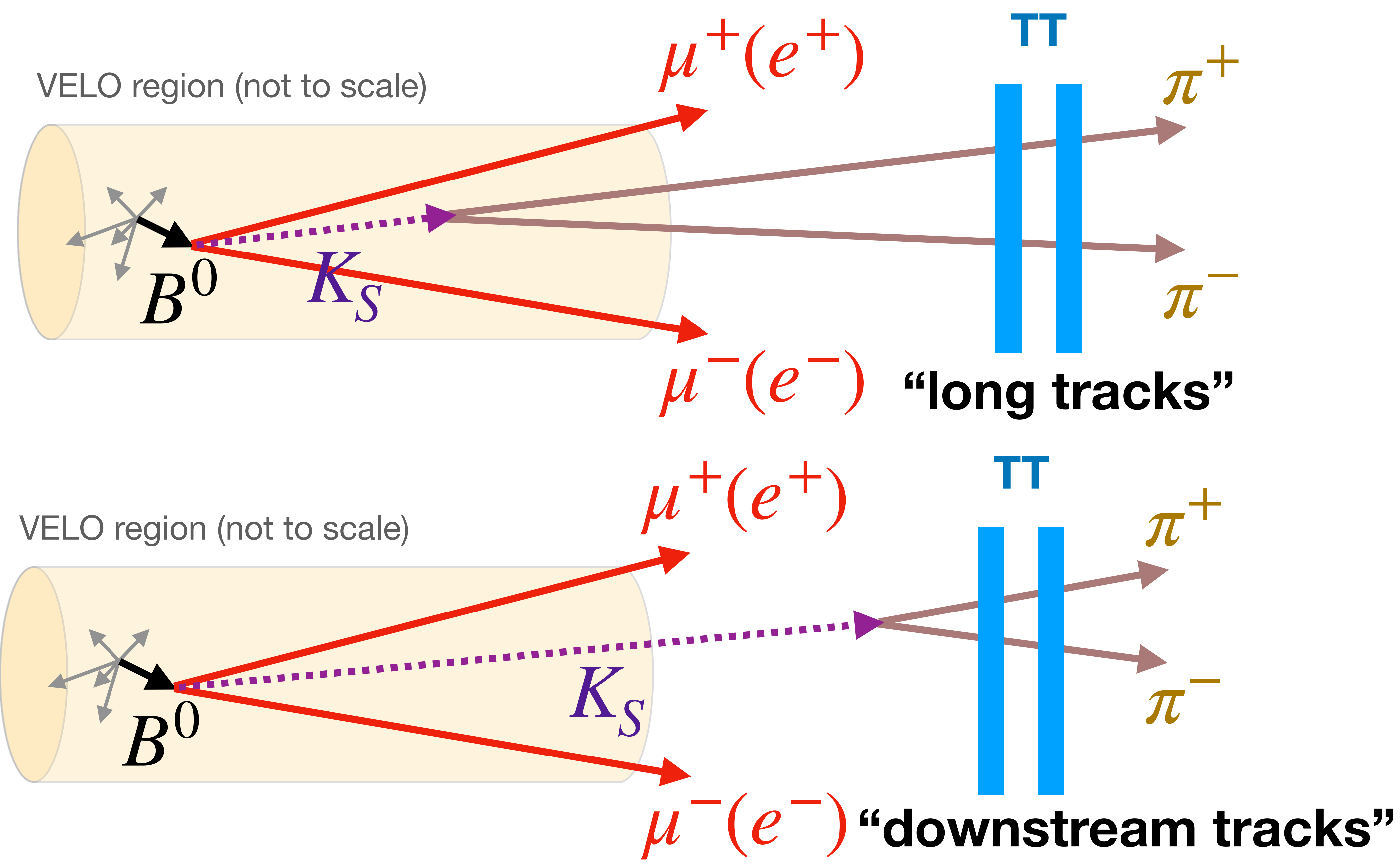
$$R_{K_S^0}^{-1} = \left(\frac{\mathcal{B}(B^0 \to K_S^0 \mu^+\mu^-)}{\mathcal{B}(B^0 \to K_S^0 J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B^0 \to K_S^0 J/\psi(e^+e^-))}{\mathcal{B}(B^0 \to K_S^0 e^+e^-)} \right)^{-1}$$

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

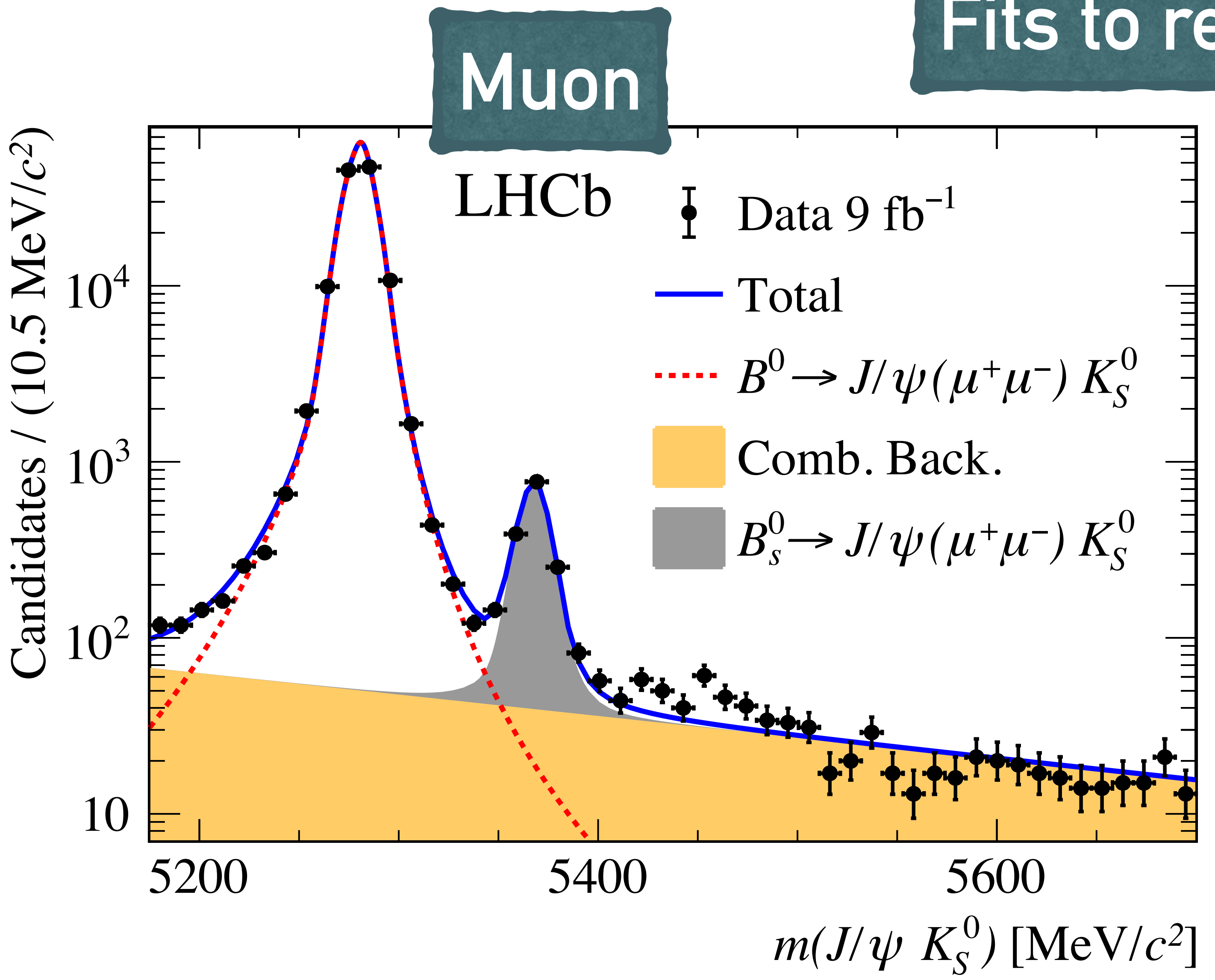
- Less precise than the charged mode: $K^0 \to K_S^0$; $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$; K_S^0 reconstruction

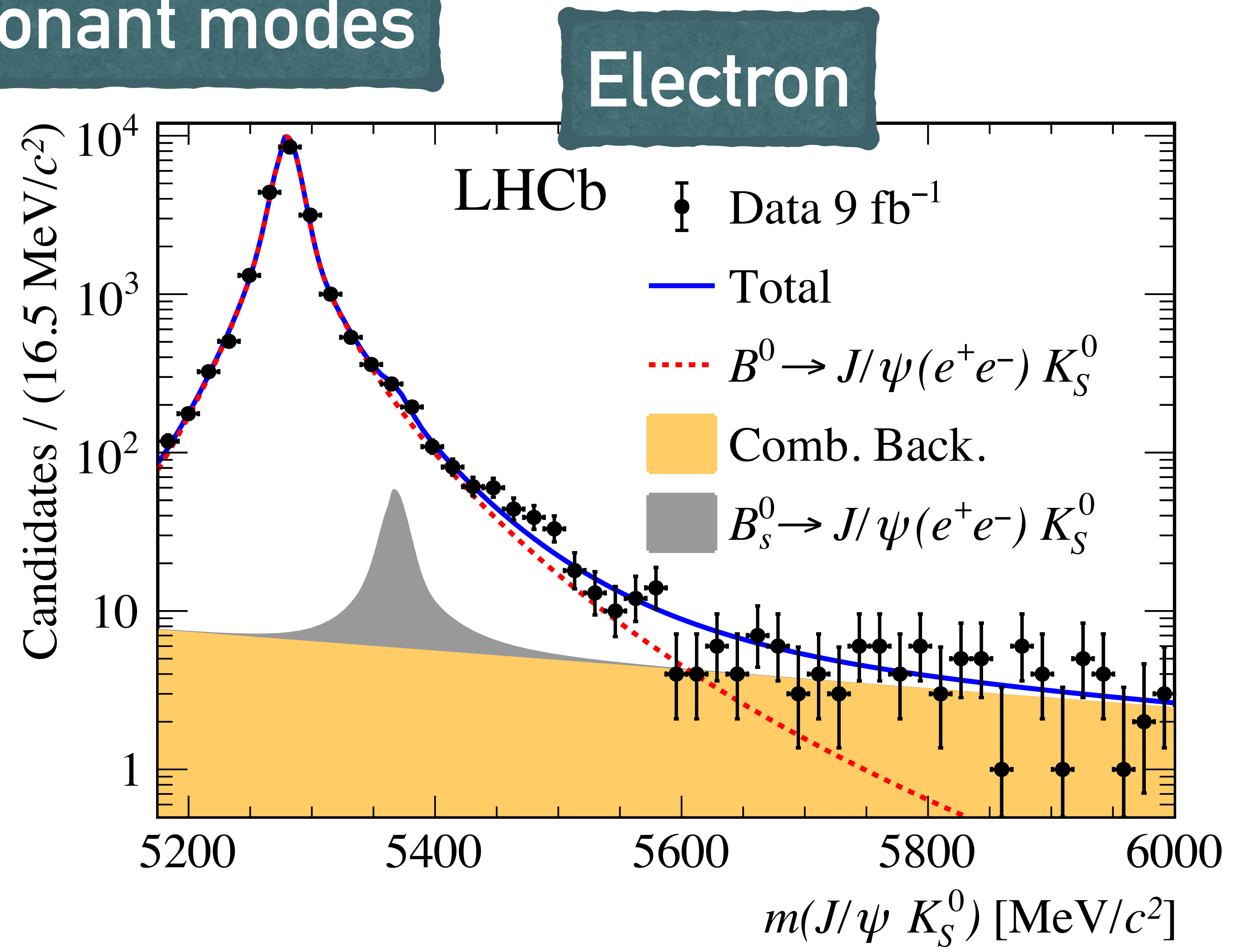
K_S^0 reconstruction types

Both merged, similar resolution on the B mass



Fits to resonant modes





$$r_{J/\psi}^{-1}(K_S^0) = 0.977 \pm 0.008(\mathrm{stat}) \pm 0.027(\mathrm{syst})$$

- Study the isospin partner process:

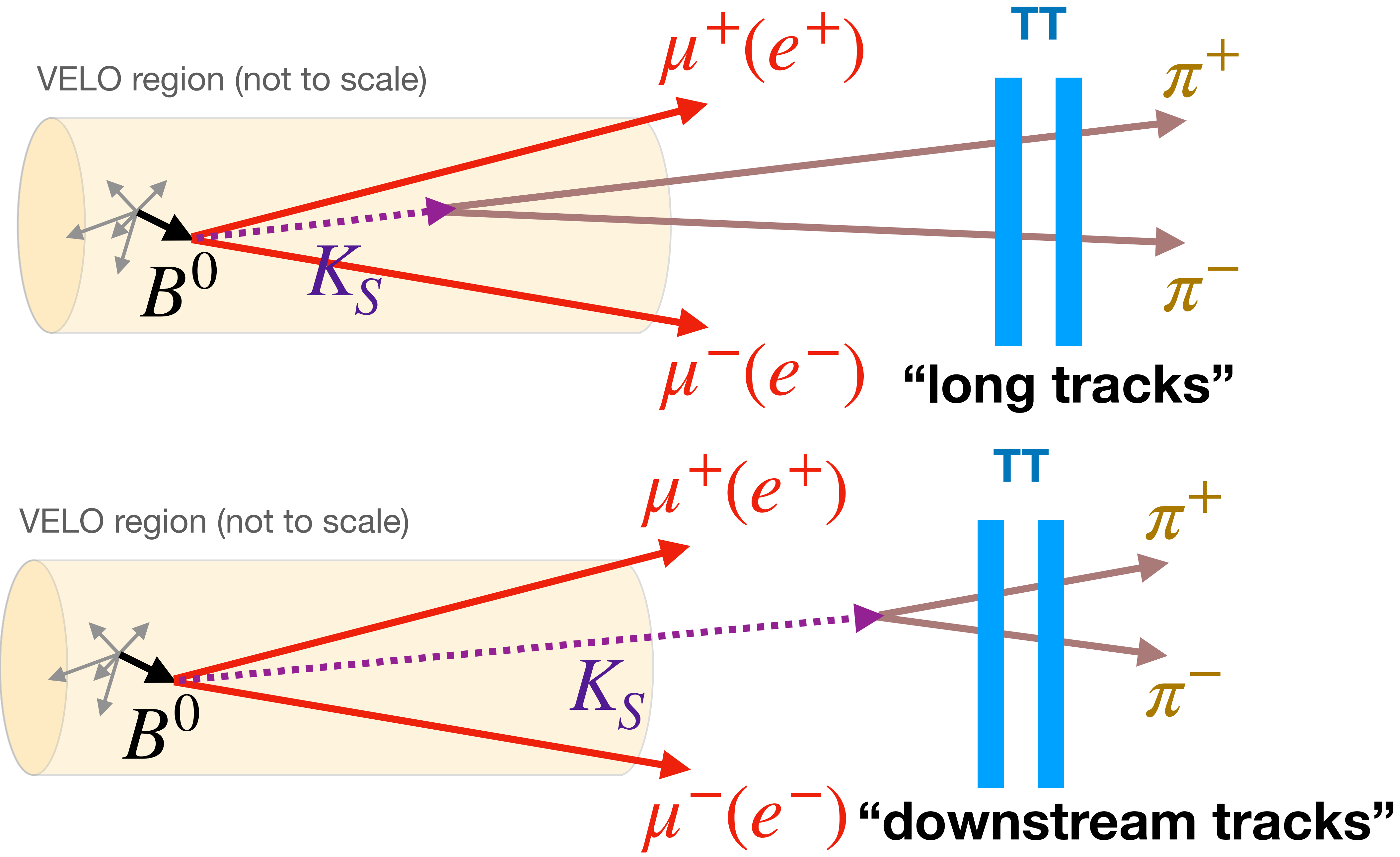
$$R_{K_S^0}^{-1} = \left(\frac{\mathcal{B}(B^0 \to K_S^0 \mu^+\mu^-)}{\mathcal{B}(B^0 \to K_S^0 J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B^0 \to K_S^0 J/\psi(e^+e^-))}{\mathcal{B}(B^0 \to K_S^0 e^+e^-)} \right)^{-1}$$

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

- Less precise than the charged mode: $K^0 \to K_S^0$; $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$; K_S^0 reconstruction

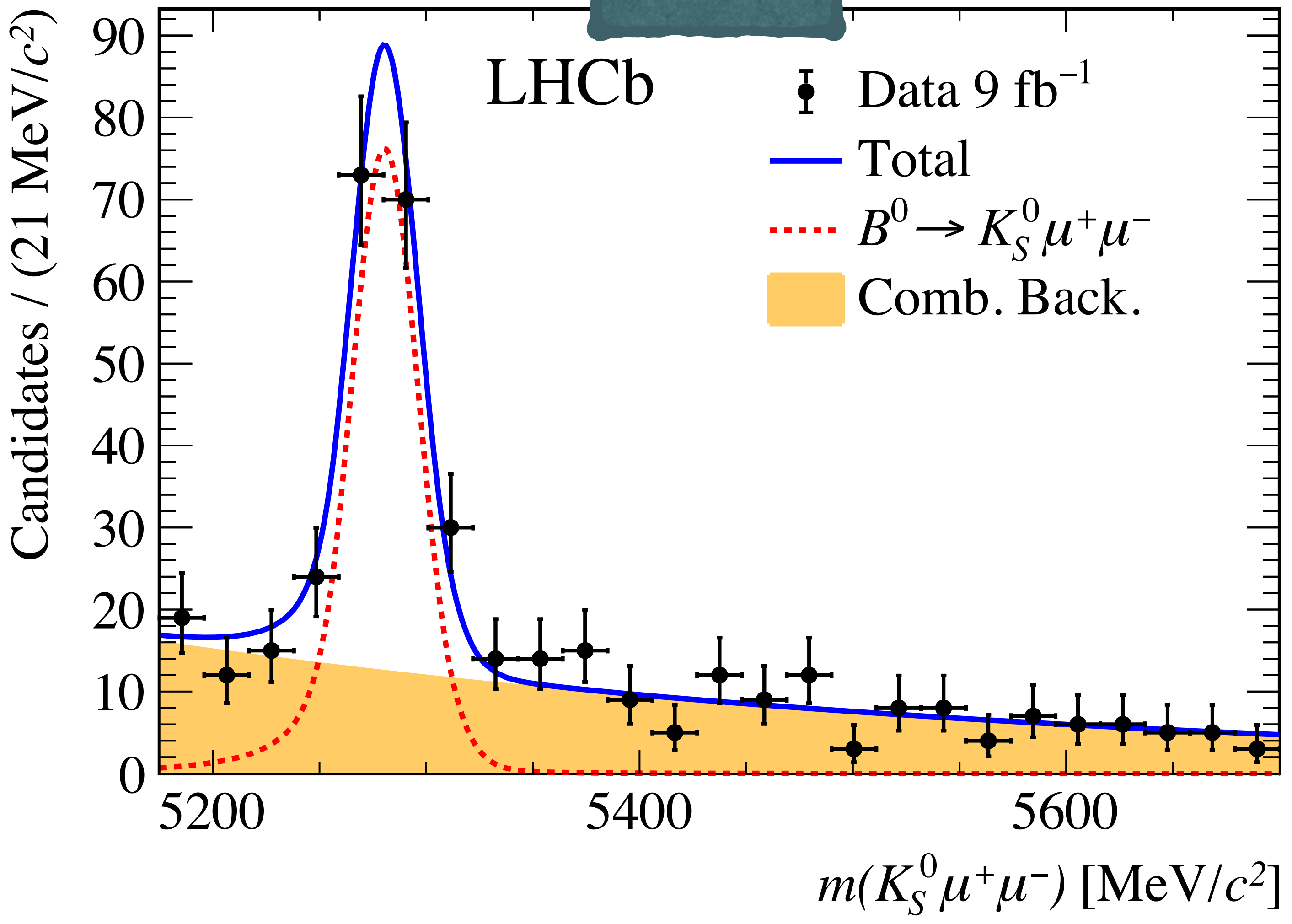
K_S^0 reconstruction types

Both merged, similar resolution on the B mass

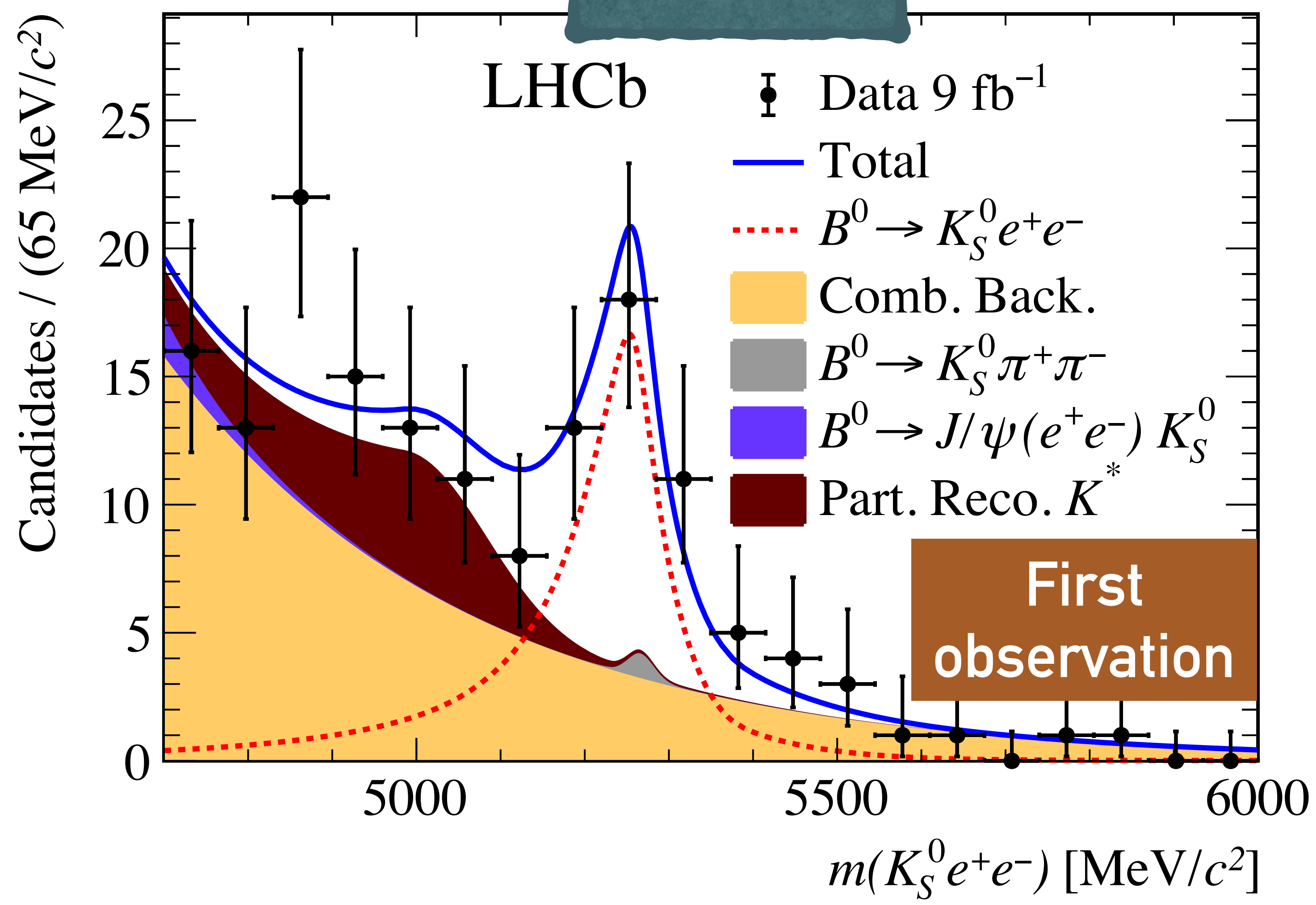


Fits to rare modes

Muon



Electron



First observation

$$R_{K_S^0}^{-1} = 1.51^{+0.40}_{-0.35}(\text{stat.})^{+0.09}_{-0.04}(\text{syst.})$$

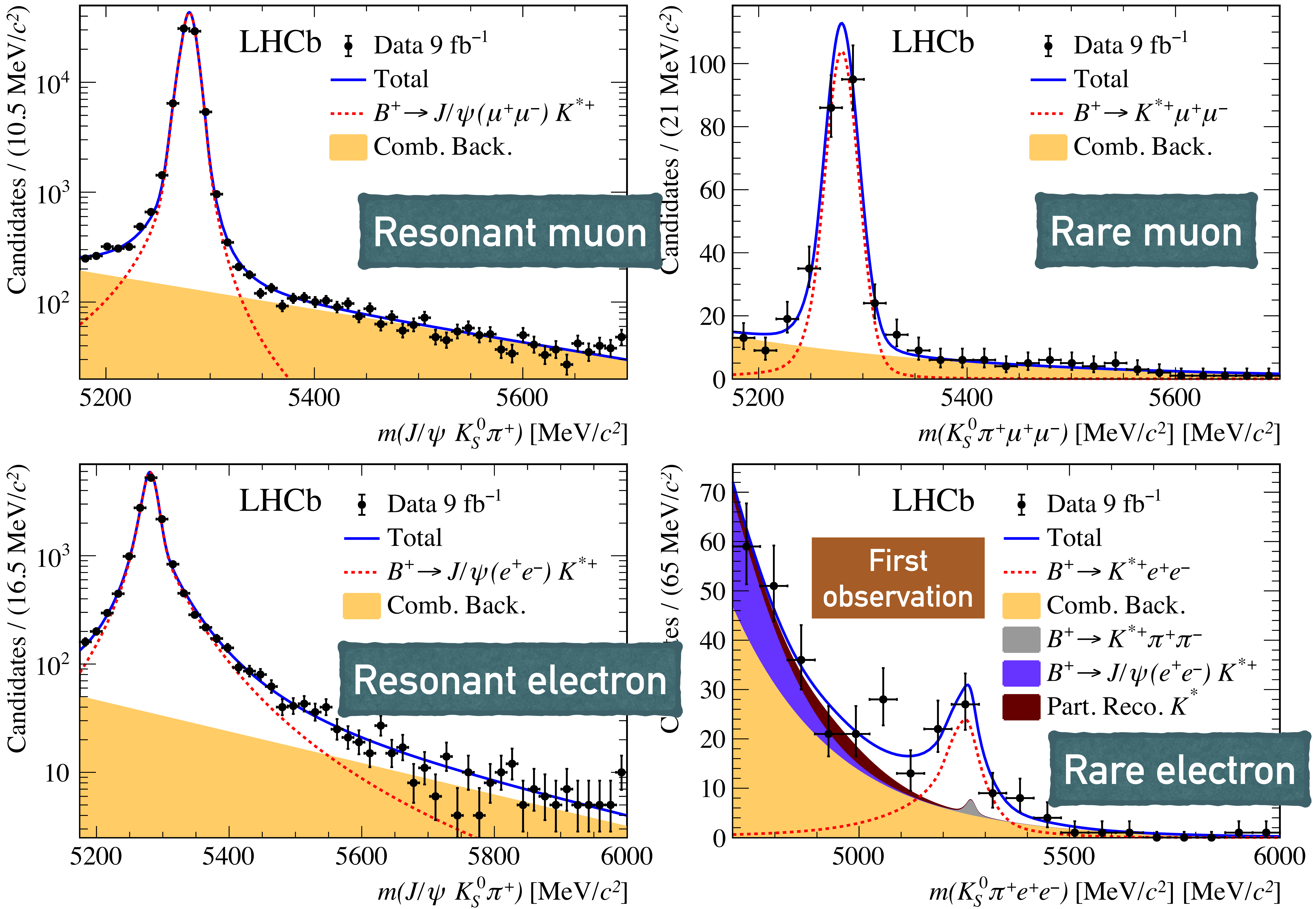
$$R_{K_S^0} = 0.66^{+0.20}_{-0.14}(\text{stat.})^{+0.02}_{-0.04}(\text{syst.})$$

$\sim 1.5\sigma$ from unity

- And one more process: reconstructed via $K^{*+} \to K_S \pi^+$

$$R_{K^{*+}}^{-1} = \left(\frac{\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^{*+}J/\psi(\mu^+\mu^-))} \times \frac{\mathcal{B}(B^+ \to K^{*+}J/\psi(e^+e^-))}{\mathcal{B}(B^+ \to K^{*+}e^+e^-)} \right)^{-1}$$

where only $0.045 < q^2 < 6\,\mathrm{GeV}^2$ is considered for the rare mode



$$r_{J/\psi}^{-1}(K^{*+}) = 0.965 \pm 0.011(\mathrm{stat}) \pm 0.034(\mathrm{syst})$$

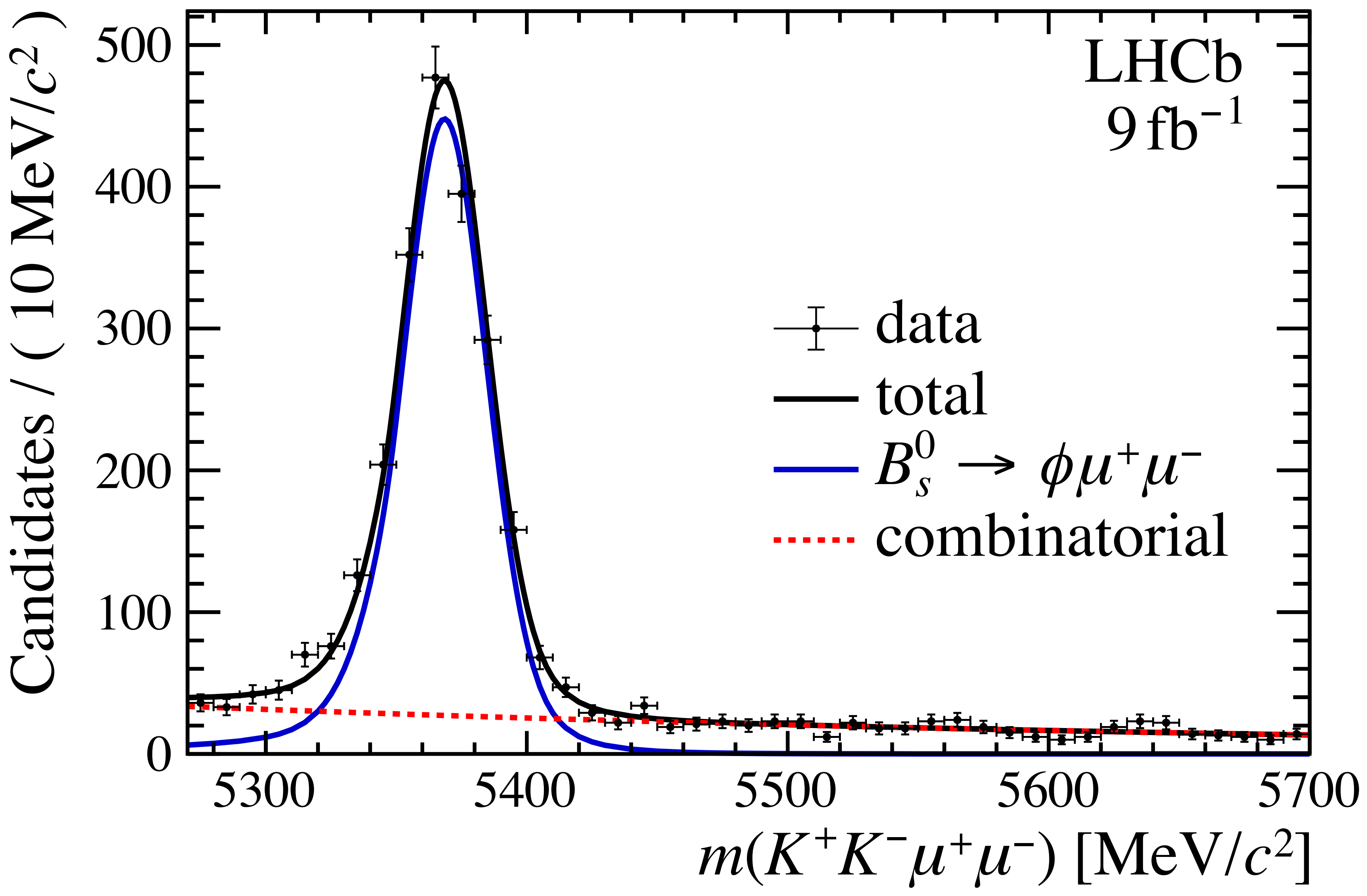
$$R_{K^{*+}}^{-1} = 1.44^{+0.32}_{-0.29}\,(\mathrm{stat.})^{+0.09}_{-0.06}\,(\mathrm{syst.})$$

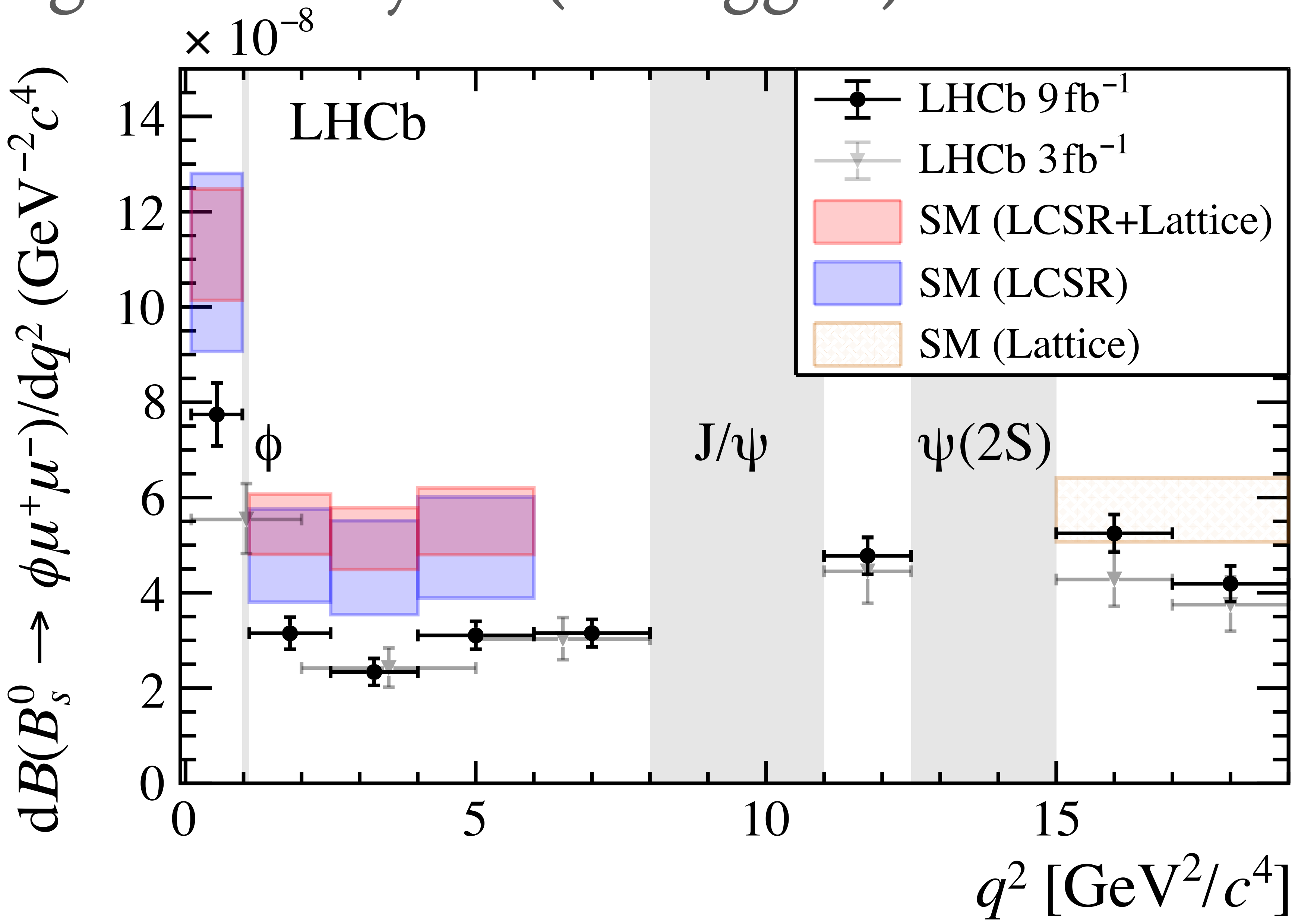
$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}\,(\mathrm{stat.})^{+0.03}_{-0.04}\,(\mathrm{syst.})$$

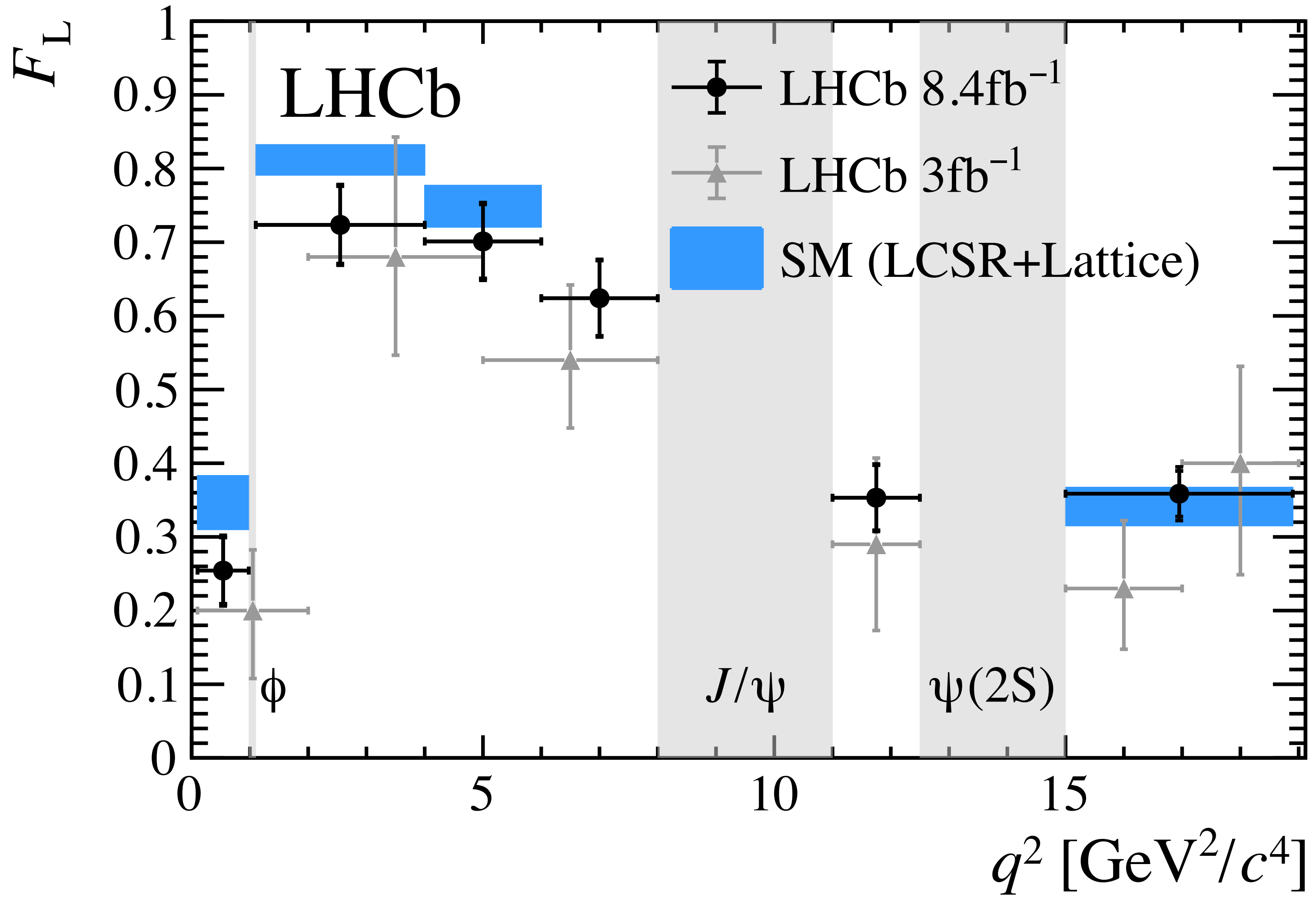
$\sim 1.4\sigma$ from unity

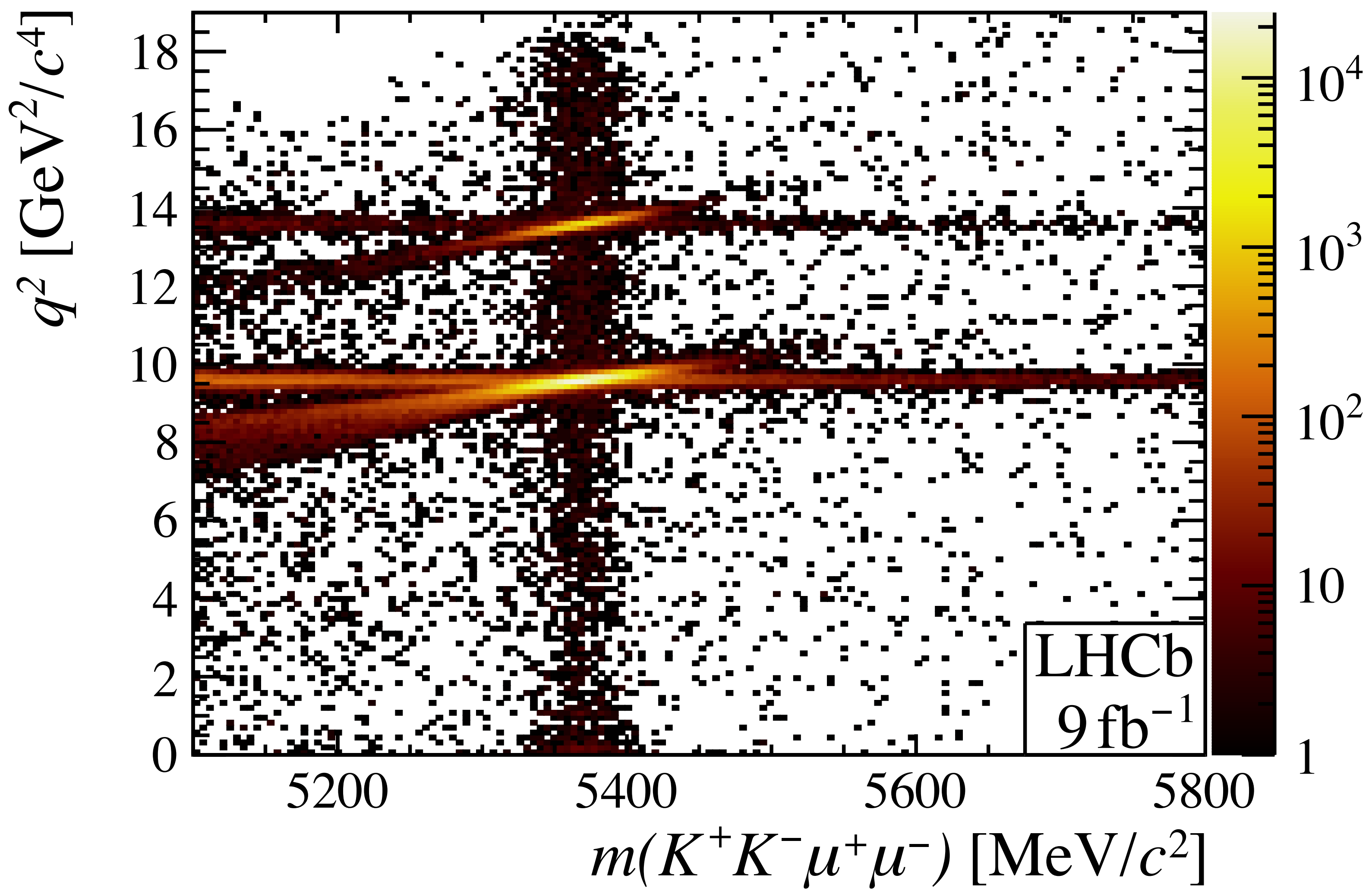
Both $R_{K_S^0}$ and $R_{K^{*+}}$ point to the same direction as the previous LHCb LFU results.

- Differential BF measurement and angular analysis (untagged)

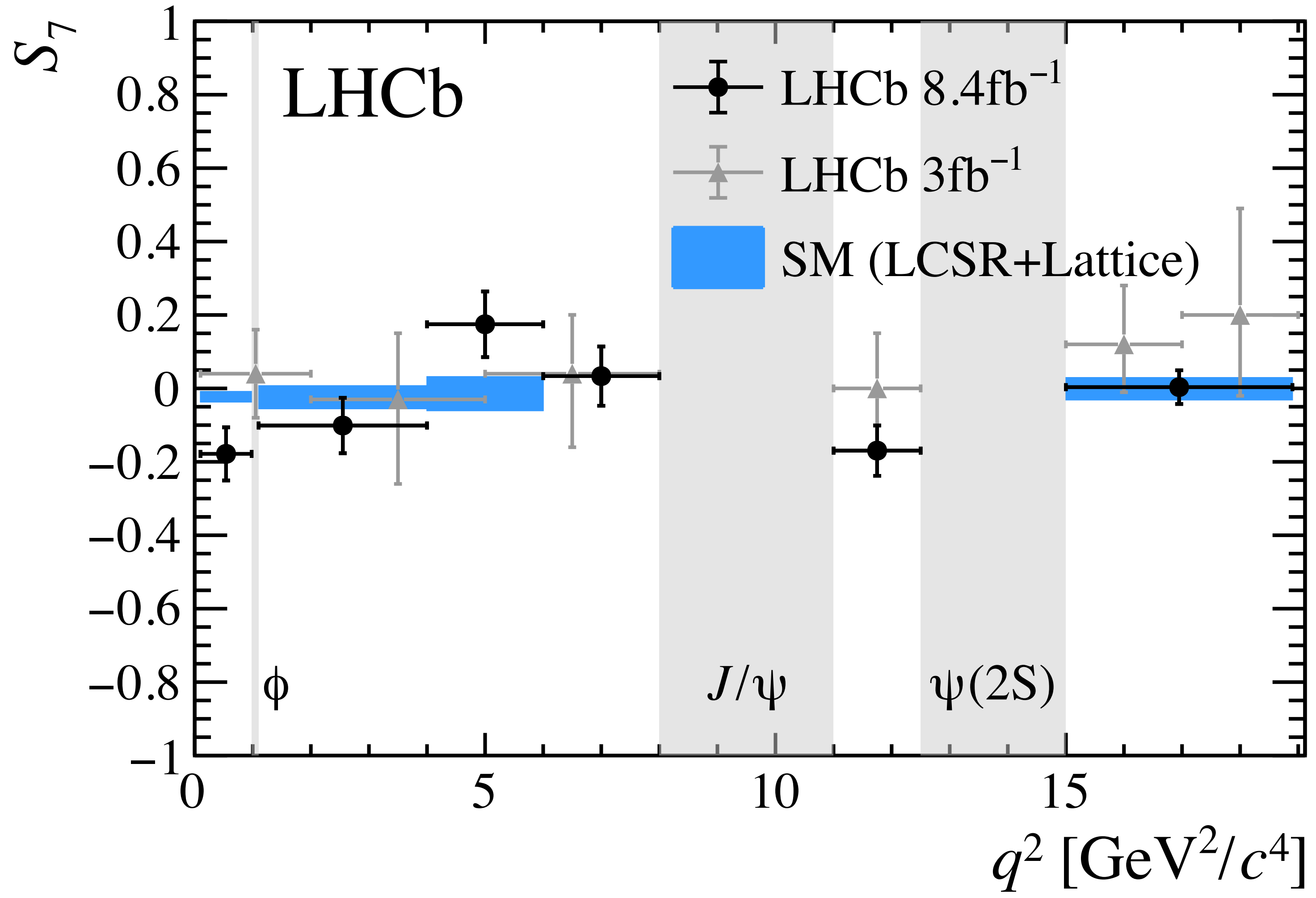








in q^2 region 1.1 … 6:
3.6σ below SM (lattice+LCSR)
1.8σ below SM (LCSR)

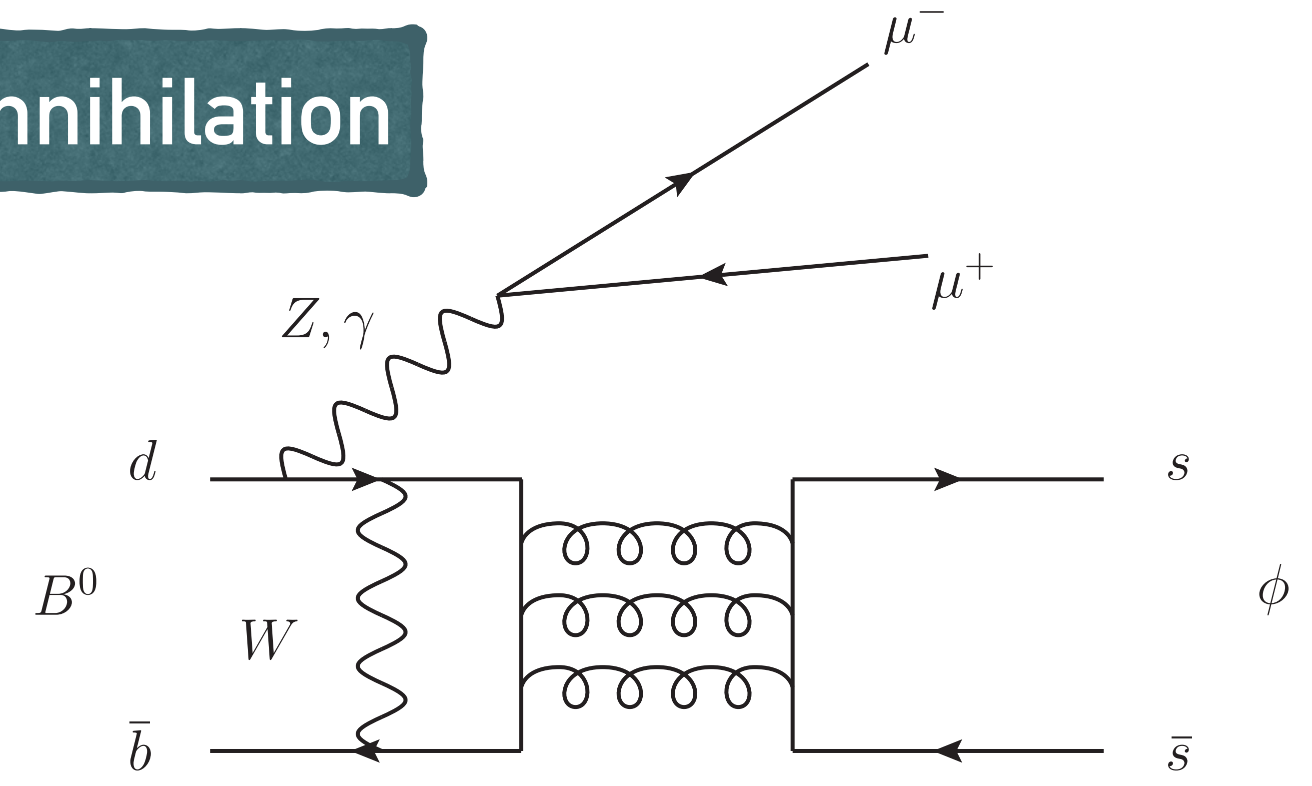


Angular observables compatible with SM, but some deviation in F_L: similar to $B \to K^*\mu^+\mu^-$?

- Could there be a bias in the theoretical BF estimate?

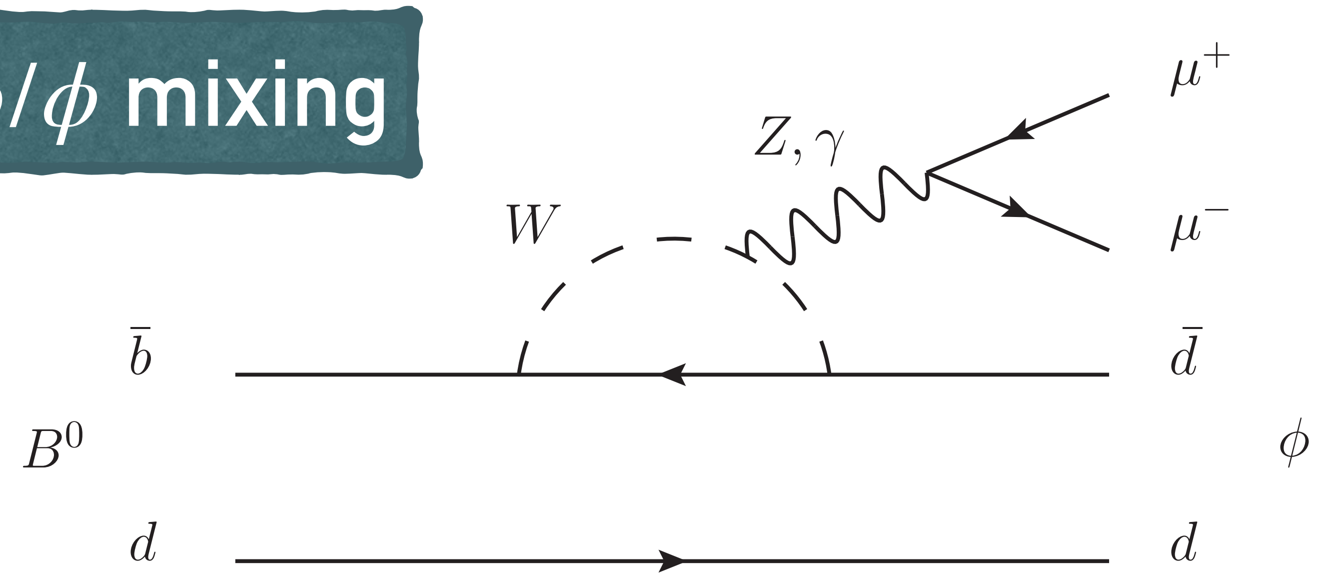
- Colour-suppressed annihilation diagram, very small SM rate
  - Contribution from ω/ϕ mixing can be larger ($d\bar{d}$ component in ϕ), up to 10^{-10} level

annihilation



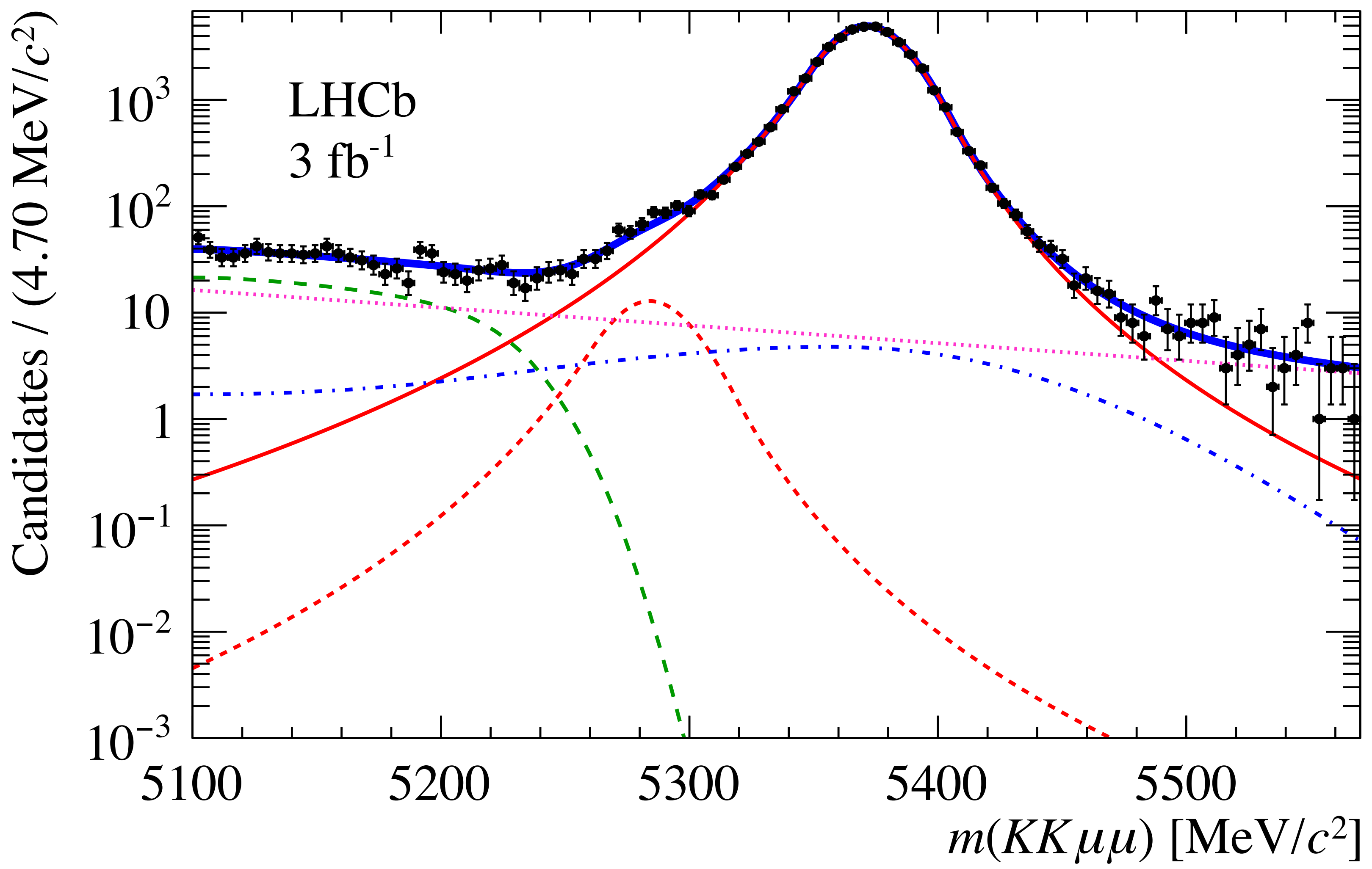
- Search for a B^0 peak in the left sideband of the B_s^0; profit from suppression of partially reconstructed B_s^0 decays (isospin 0)
- Exclude dimuon mass regions corresponding to $\phi, J/\psi, \psi(2S) \to \mu\mu$
- Dominant backgrounds: misidentification, combinatorial, semileptonic

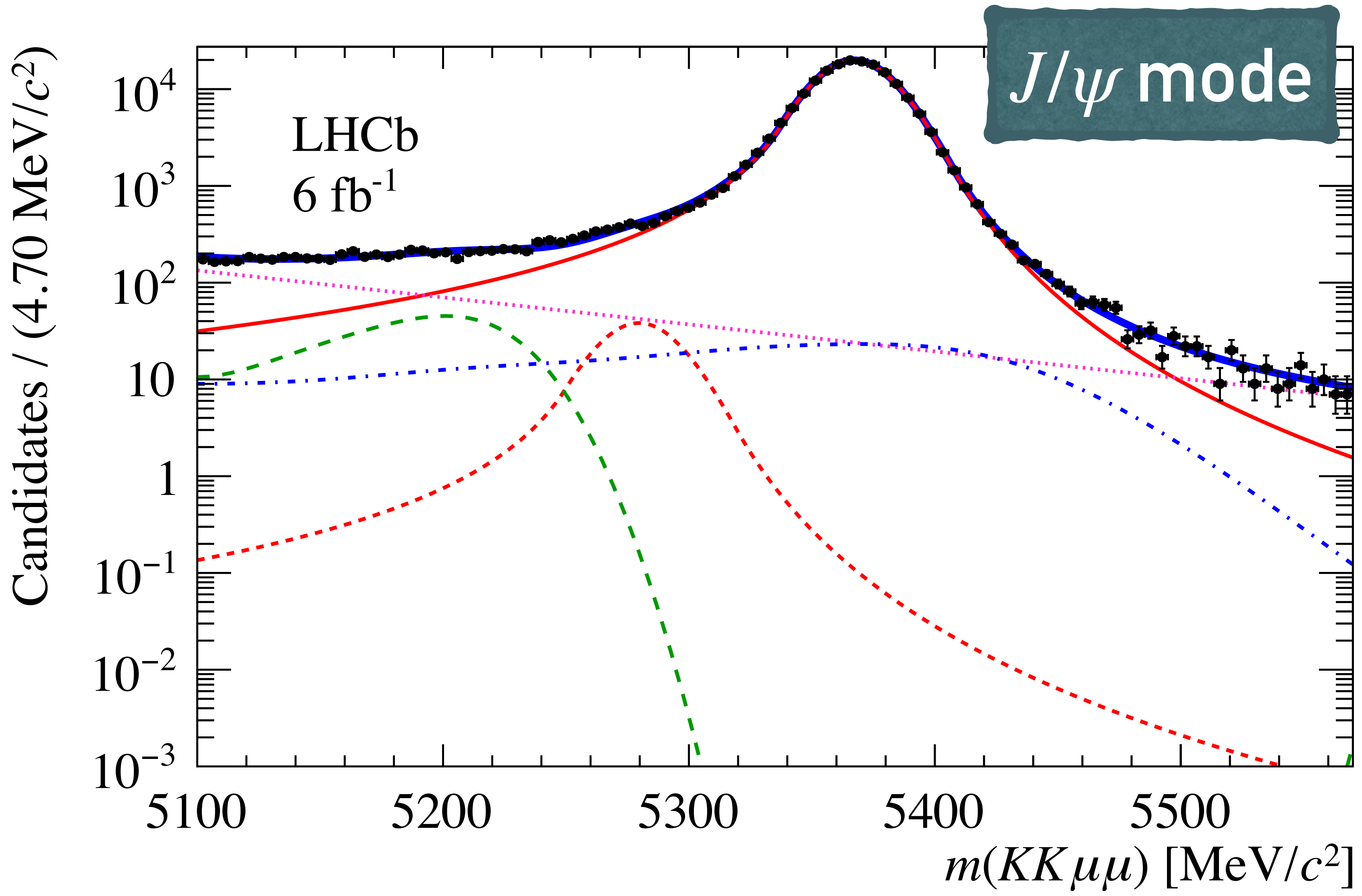
ω/ϕ mixing

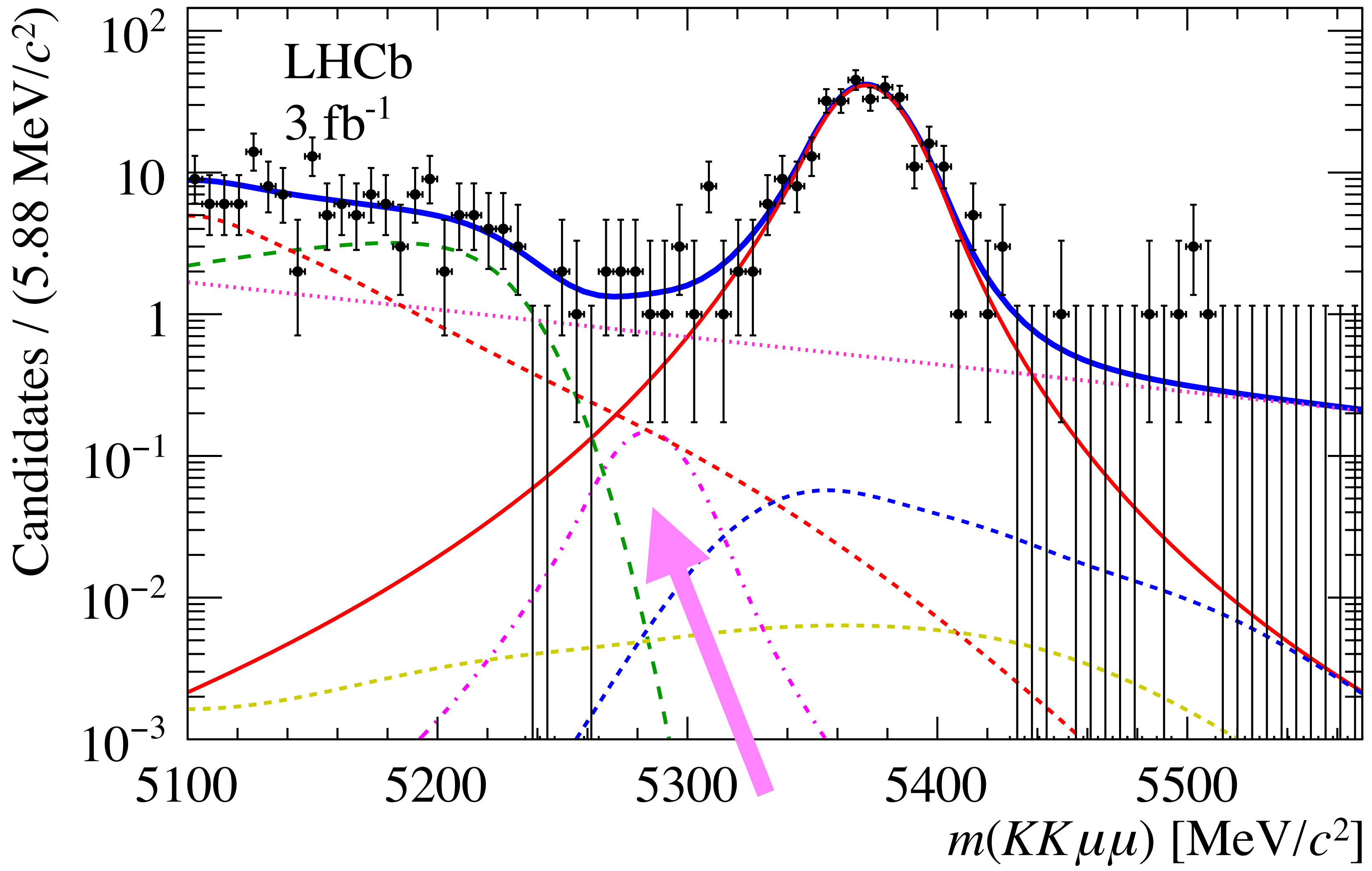


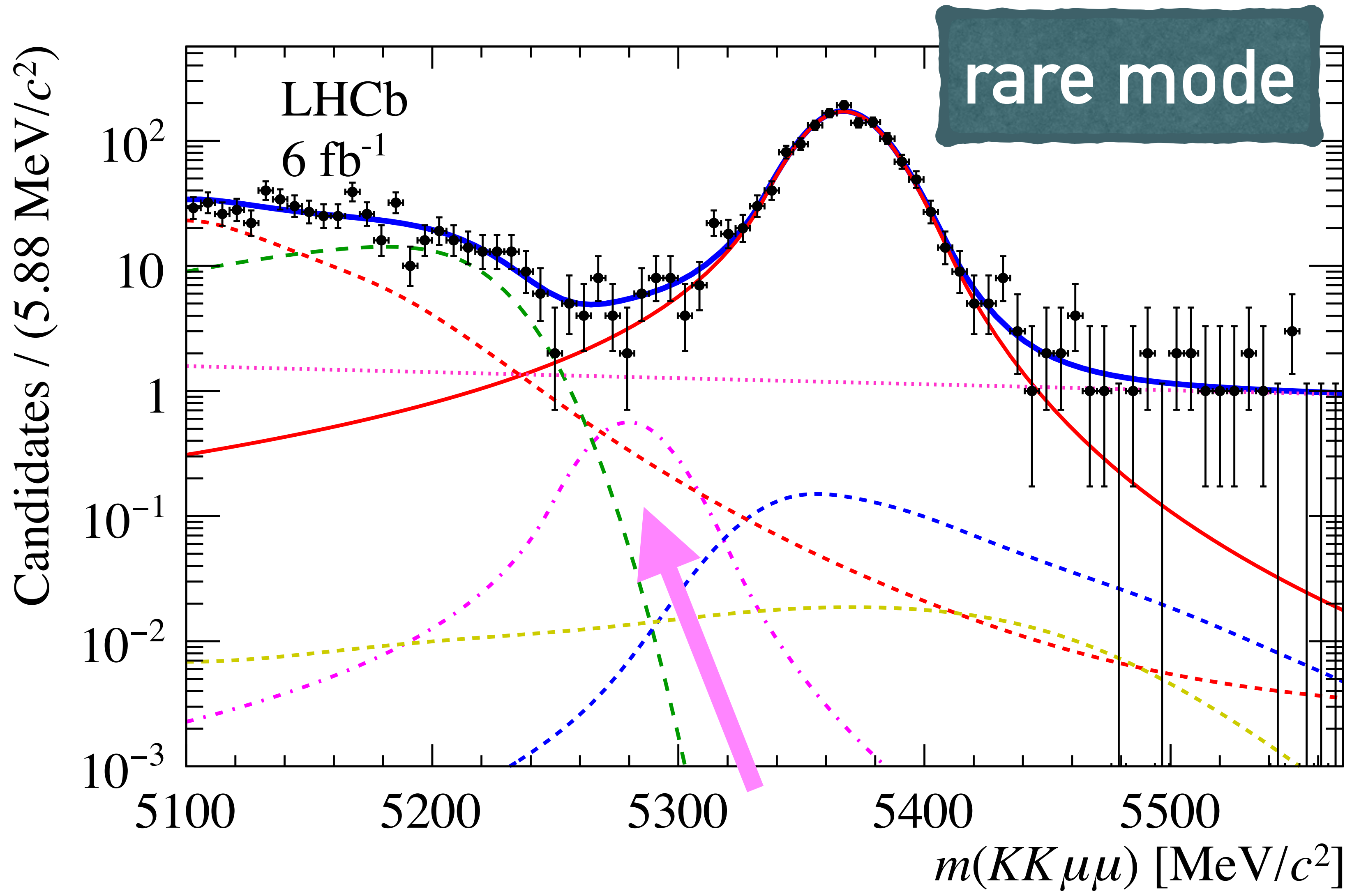
- Measure $\mathscr{R} = \dfrac{\mathscr{B}(B^0 \to \phi\mu\mu)}{\mathscr{B}(B_s^0 \to \phi\mu\mu)}$
- Use $B_s^0 \to J/\psi\phi$ as a control mode

- No significant signal observed.









Run 1 *Run 2*

Assuming the phase-space decay model:

$\mathcal{R} < 4.4 \times 10^{-3}$ *at 90 % CL*

Absolute BF extrapolated to the full dimuon range

$\mathcal{B} < 3.2 \times 10^{-9}$ *at 90 % CL*

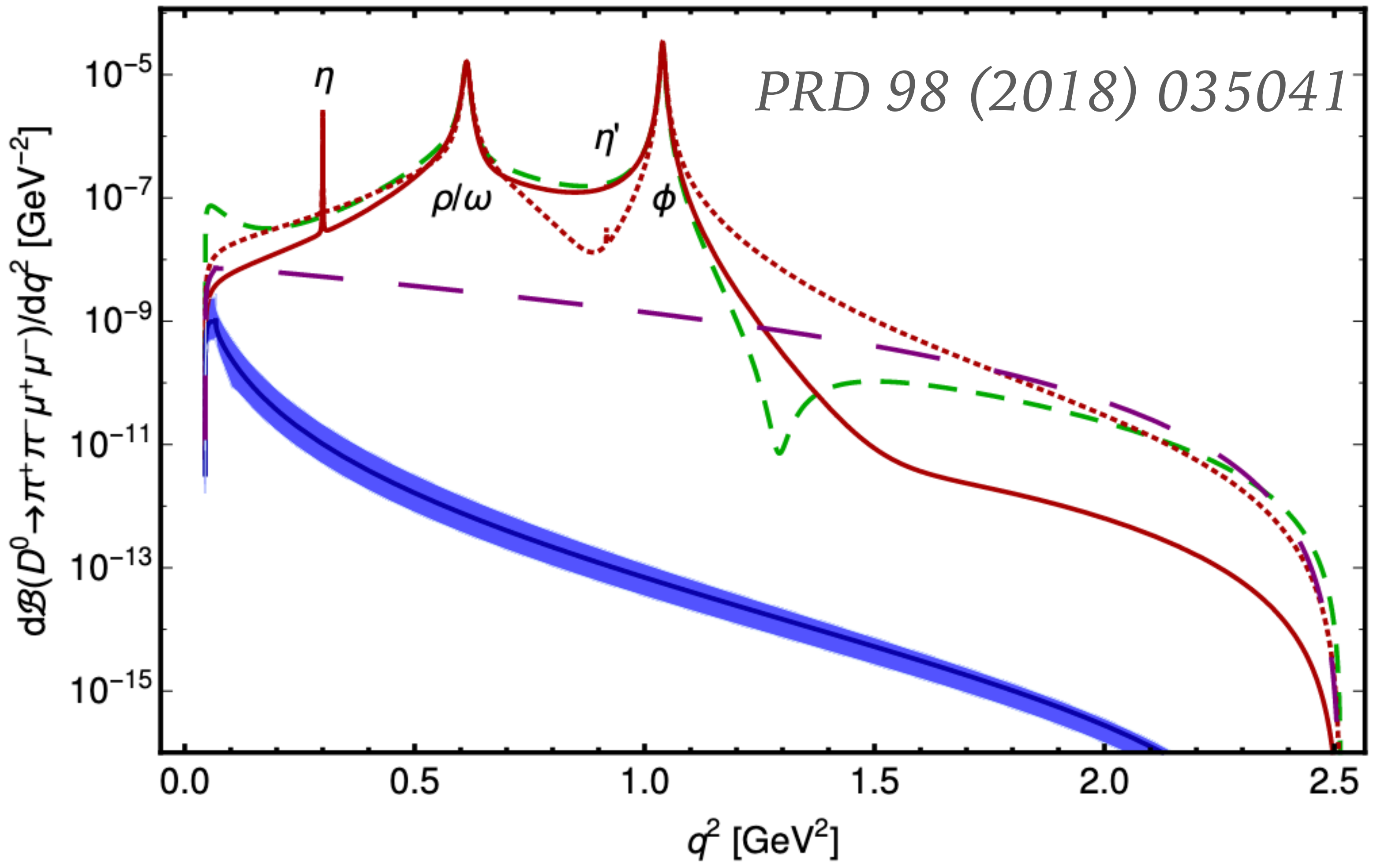
compatible with the SM

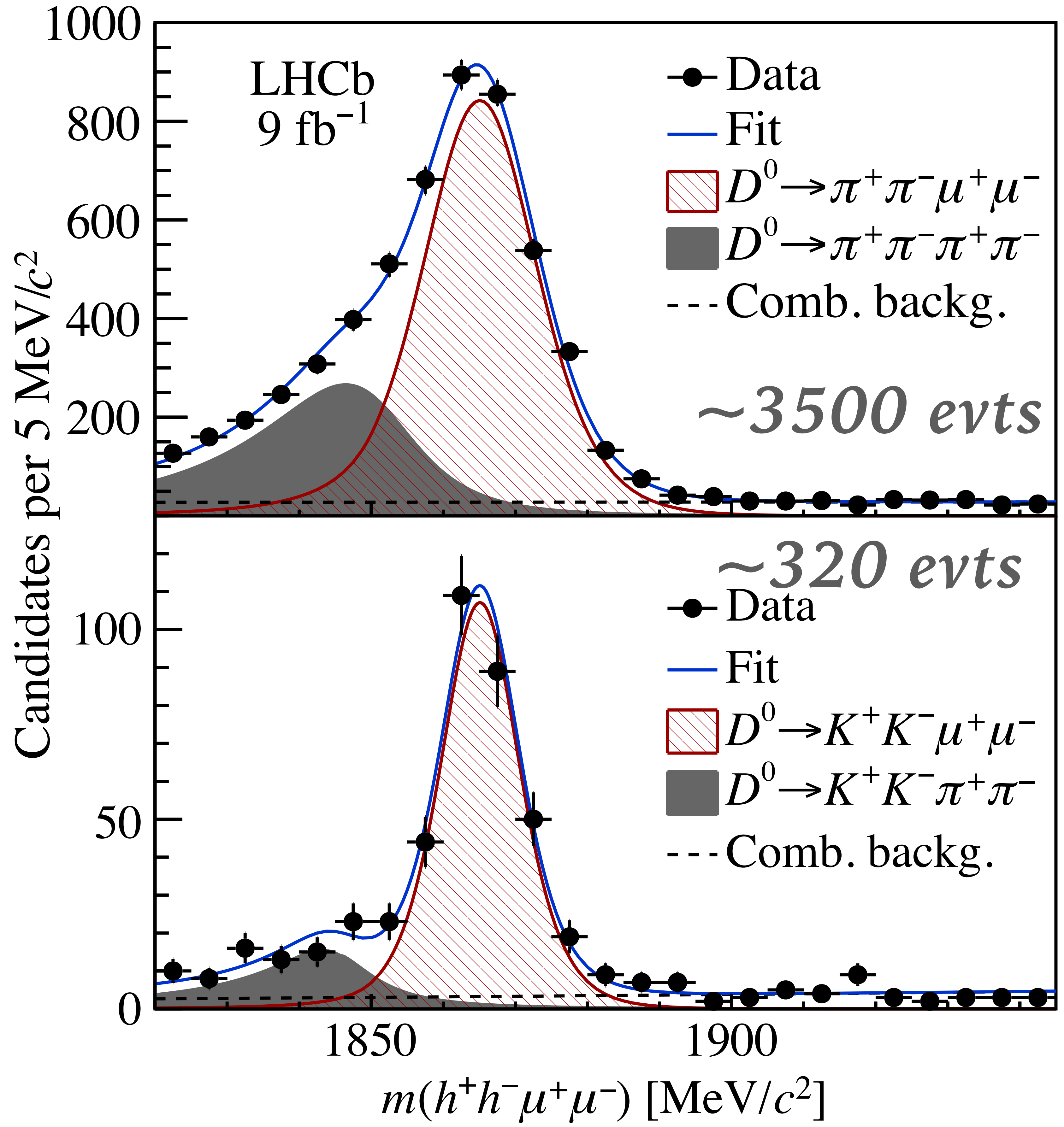
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ AND $D^0 \to K^+K^-\mu^+\mu^-$

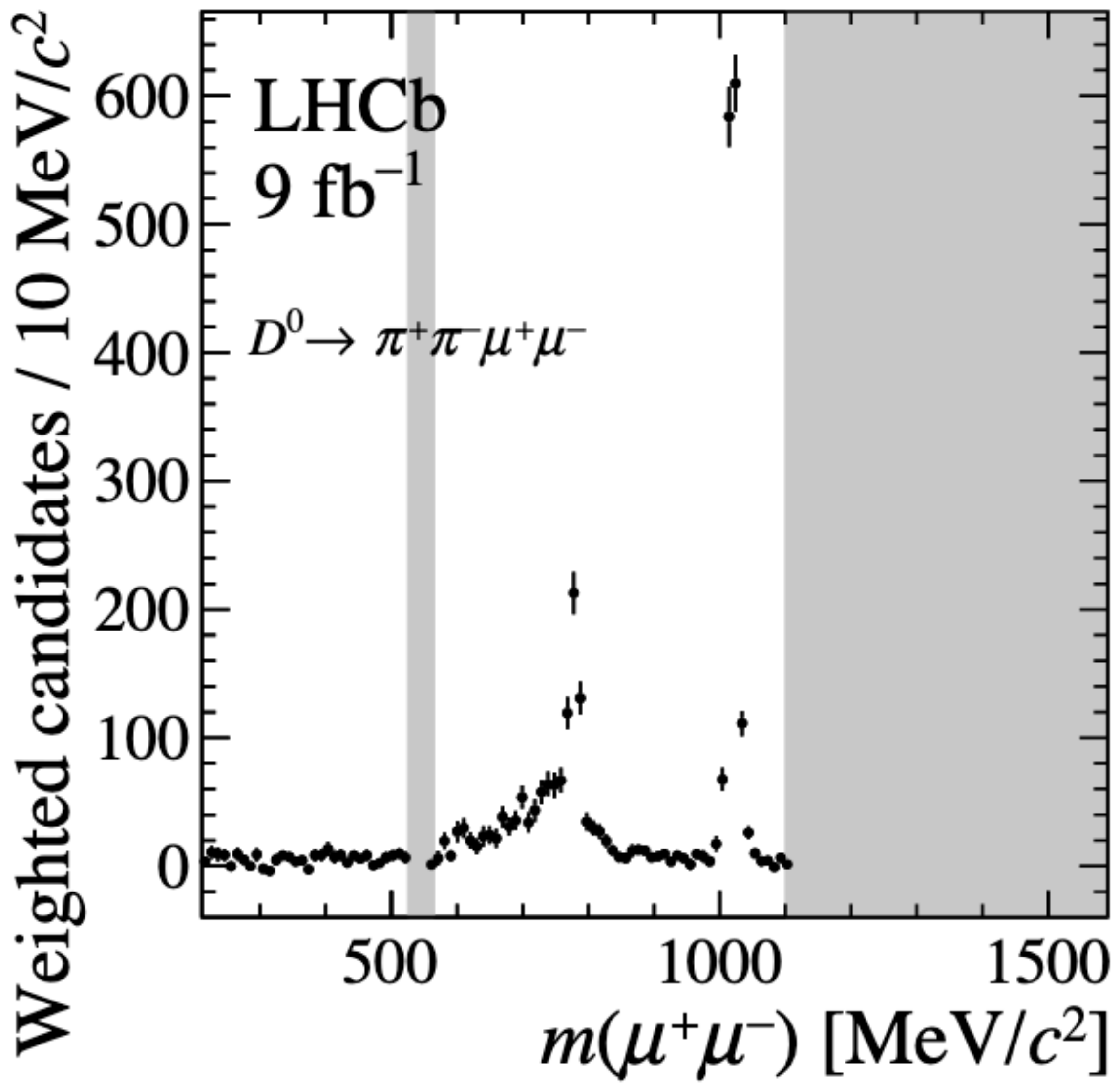
arXiv: 2111.03327

Run1+Run2 dataset

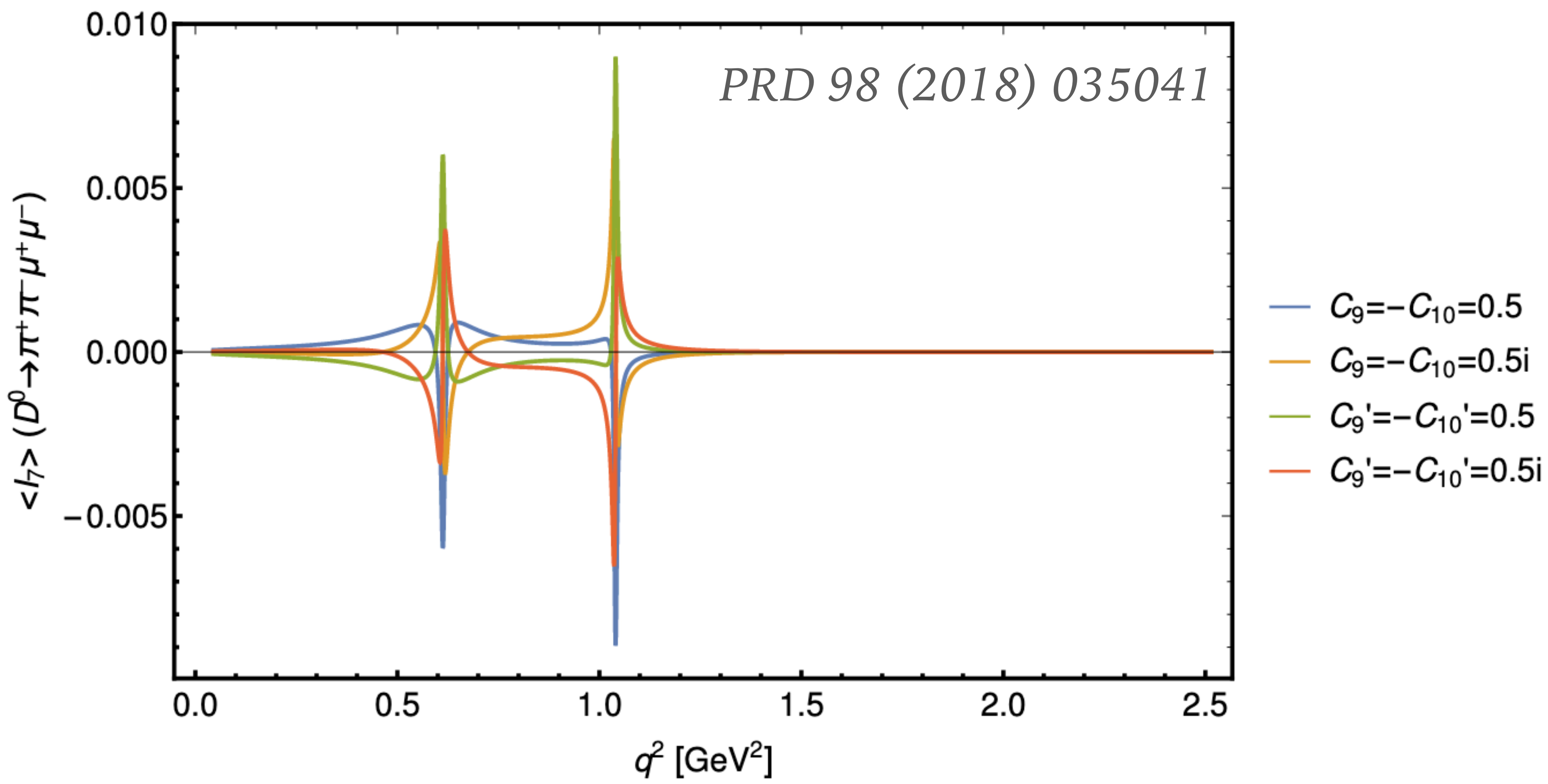
- Rare $c \to u\ell^+\ell^-$ transition; dominated by intermediate resonances $(\rho, \omega, \phi\ldots)$
  - Angular observables sensitive to BSM via interference of FCNC and resonances
- Tag by the $D^{*+} \to D^0\pi^+$; validate with $D^0 \to K^-\pi^+\mu^+\mu^-$ and $D^0 \to K^-K^+$
- **Complete angular analysis & CP asymmetry** measurement: "null test" of the SM



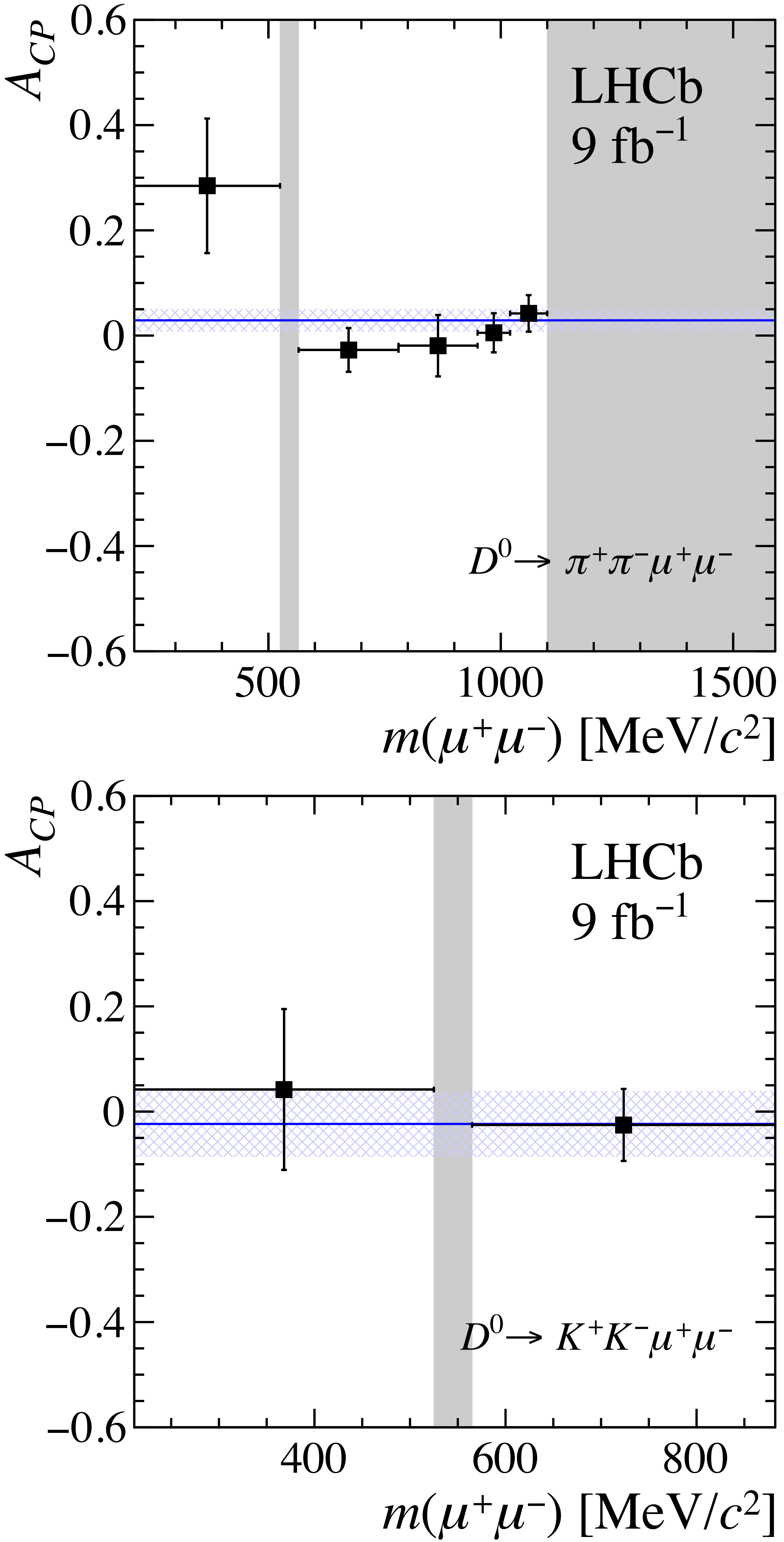




CP-averaged angular obs. in BSM scenarios



CP asymmetries

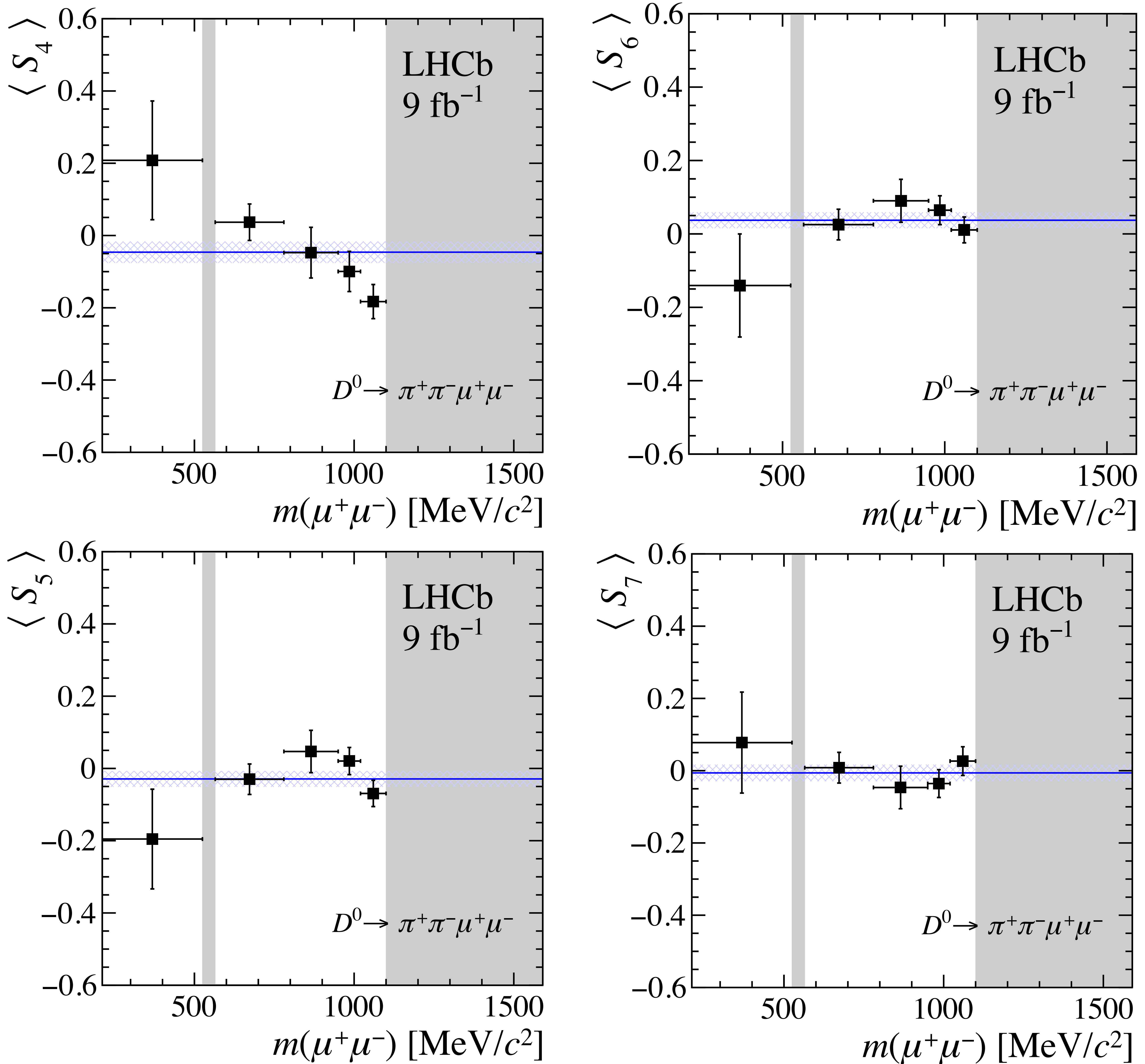


overall consistent with the SM null hypothesis:

p-value 79% (0.8%) for $\pi\pi\mu\mu(KK\mu\mu)$

will be curious with a larger dataset

CP-averaged angular observables



COMING BACK TO LFU

- Anomalies in $b \to c\tau\nu$ transitions: $R_D, R_{D^*}, R_{J/\psi}$ above SM predictions

tree-level: BF ~1%

- Baryonic decays offer complementary insight on a possible BSM mechanism: spin 1/2, different form-factors
- Search for $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$
- **Backgrounds:**
  - $\Lambda_b^0 \to \Lambda_c^+ \pi\pi\pi X$ with pions from the Λ_b^0 vertex: suppressed requiring τ displacement:

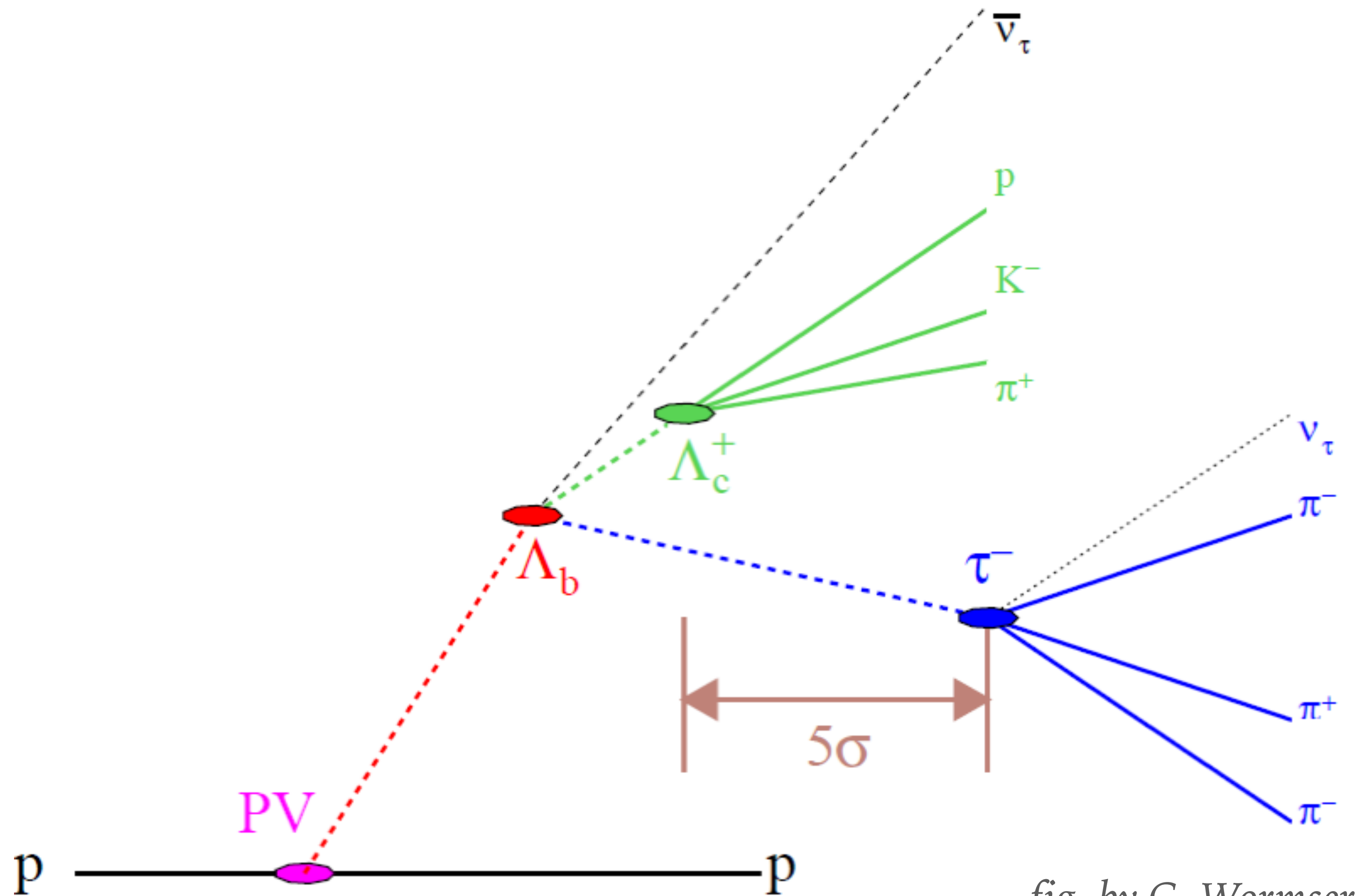


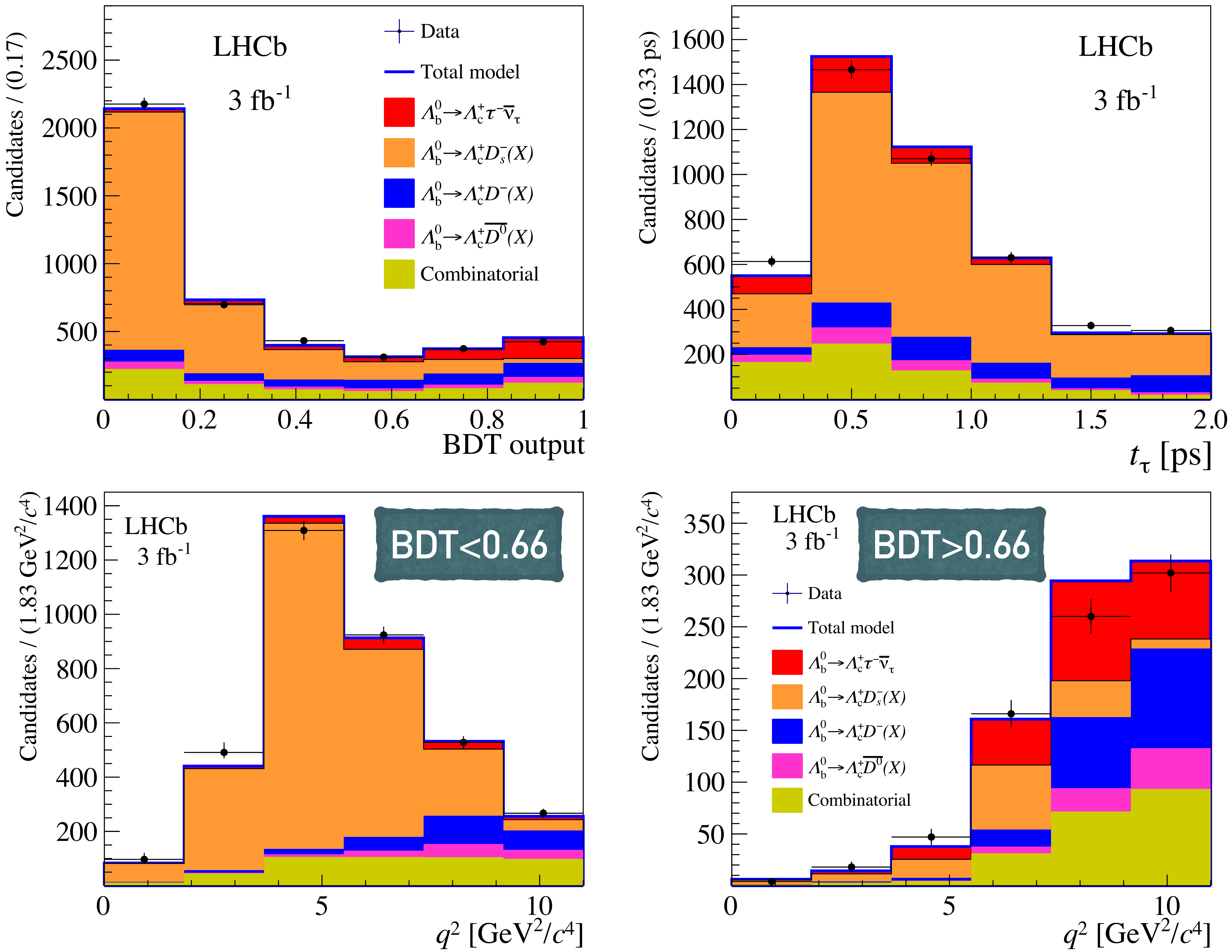
fig. by G. Wormser

  - Charm $\Lambda_b^0 \to \Lambda_c^+ (D_s \to 3\pi X)$: use the dynamics of the 3-pion system: $a_1 \to \rho\pi$ for τ, vs other resonances for charm → BDT selection
  - Combinatorial: parametrise using Λ_c sidebands and wrong-charge data
- Reconstruct kinematics knowing the positions of the **vertices**: measure pseudo-decay-time of the τ and q^2

- Fit to the BDT output, pseudo-decay-time of the τ, and the q^2
- 349 ± 40 $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ events, $\sim 6\sigma$ stat. significance
- Normalised to $\Lambda_b^0 \to \Lambda_c^+ \pi\pi\pi$: same final state, but poorly known BF: $0.614 \pm 0.094\,\%$

$$K(\Lambda_c^+) = \frac{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = 2.46 \pm 0.27 \pm 0.40$$

- Using the DELPHI value of $\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \mu\nu) = 6.2 \pm 1.4\,\%$ we get



$$R(\Lambda_c^+) = 0.242 \pm 0.026\,(\text{stat}) \pm 0.040\,(\text{syst}) \pm 0.059\,(\text{ext . BF})$$

- vs SM prediction: 0.324 ± 0.004

Phys. Rev. D99 (2019) 055008

Poor knowledge of baryonic BFs is the main limitation!

OUTLOOK

- **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.
    - Charm becomes a strong player in the game!
    - Baryons are another promising player, but more knowledge is needed on control channels.
  - More results from LHCb are in the pipeline.

- **LHCb Upgrade I is in its crucial phase.**
  - The detector is being assembled and commissioned as we speak now.

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

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

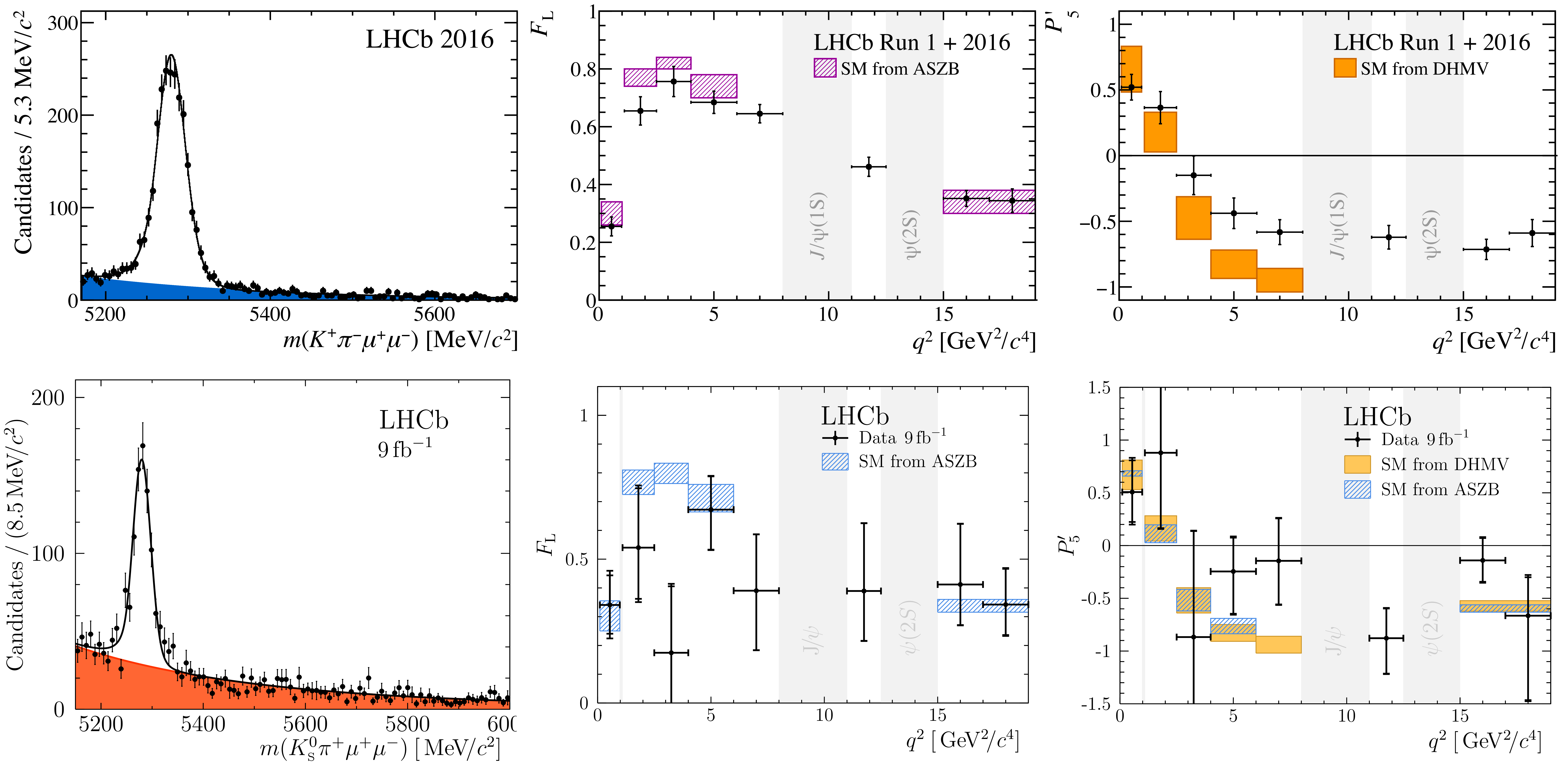
PRL 125 (2020) 011802; PRL 126 (2021) 161802

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

F_L

P'_5

+*many others…*



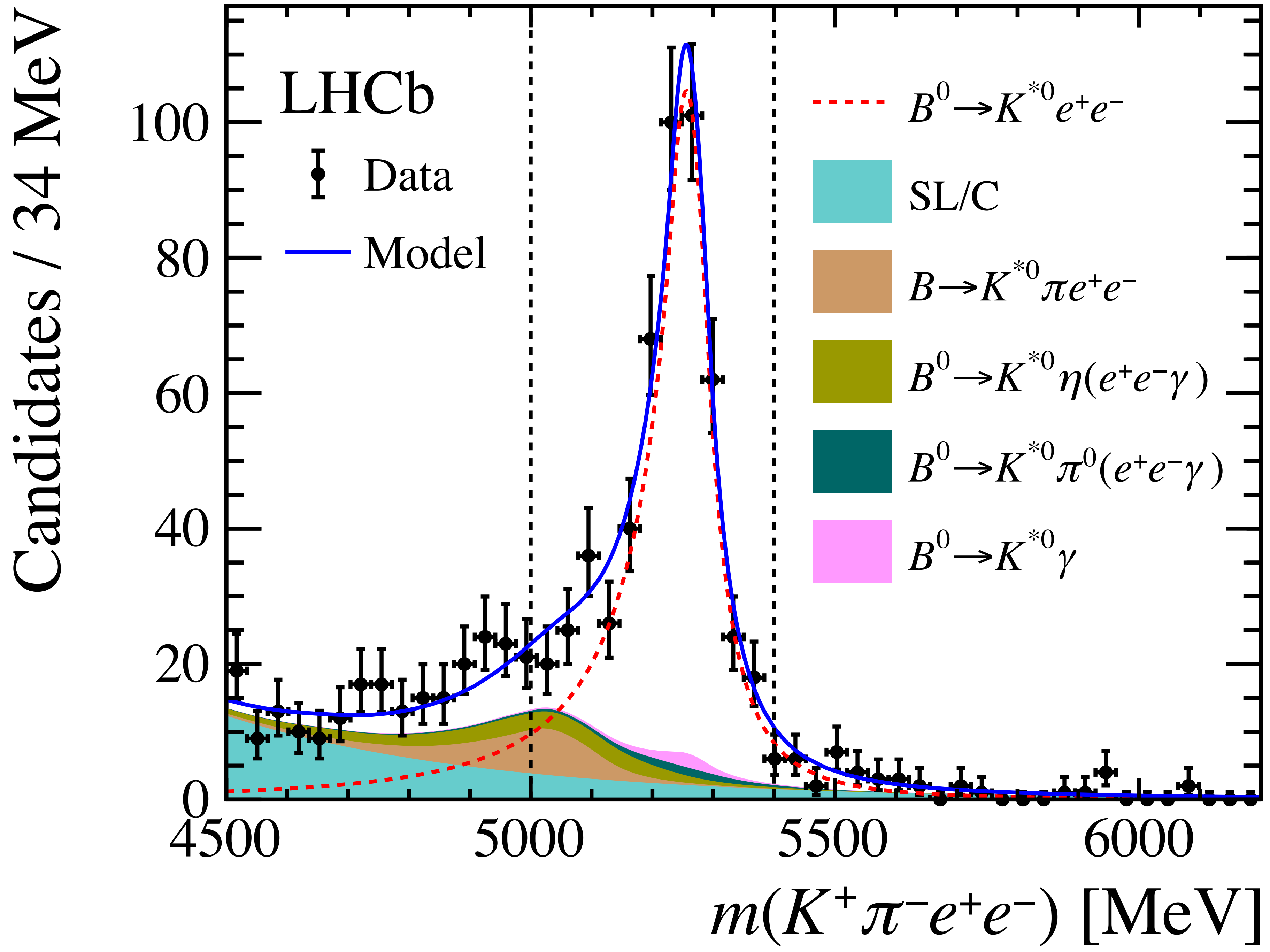
the tension persists

need more data

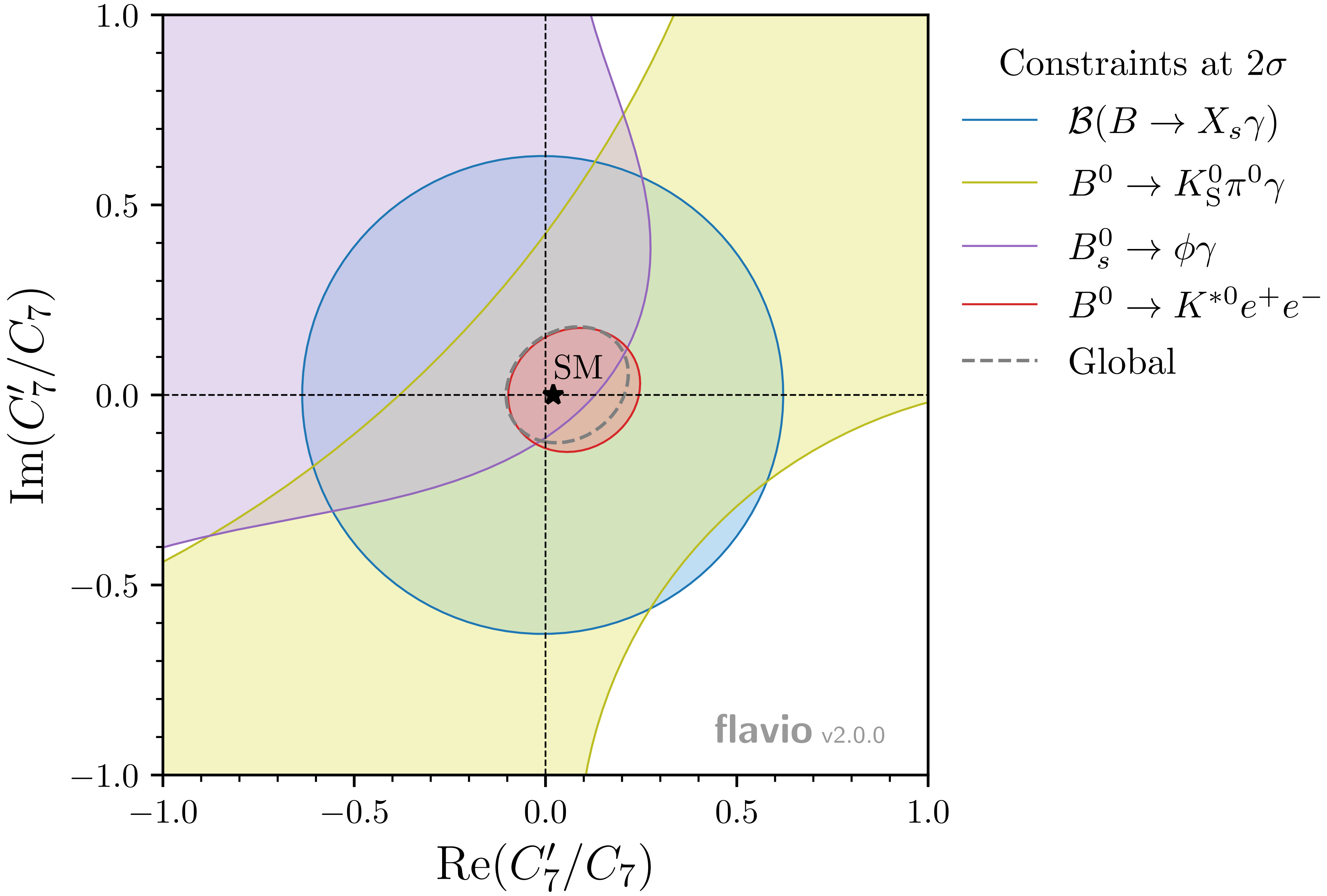
JHEP 12 (2020) 081

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



arXiv: 2111.10194

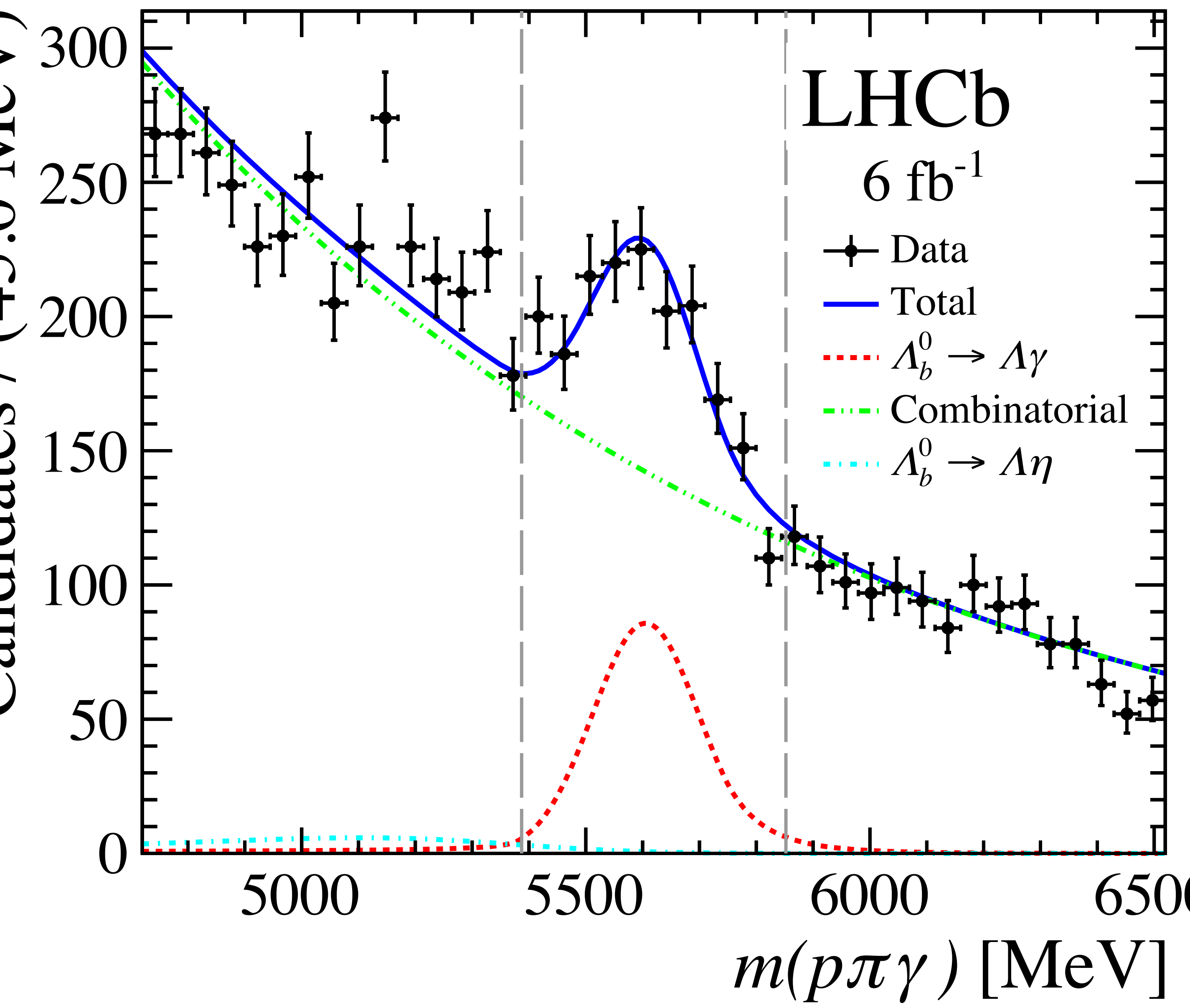
Run2 dataset

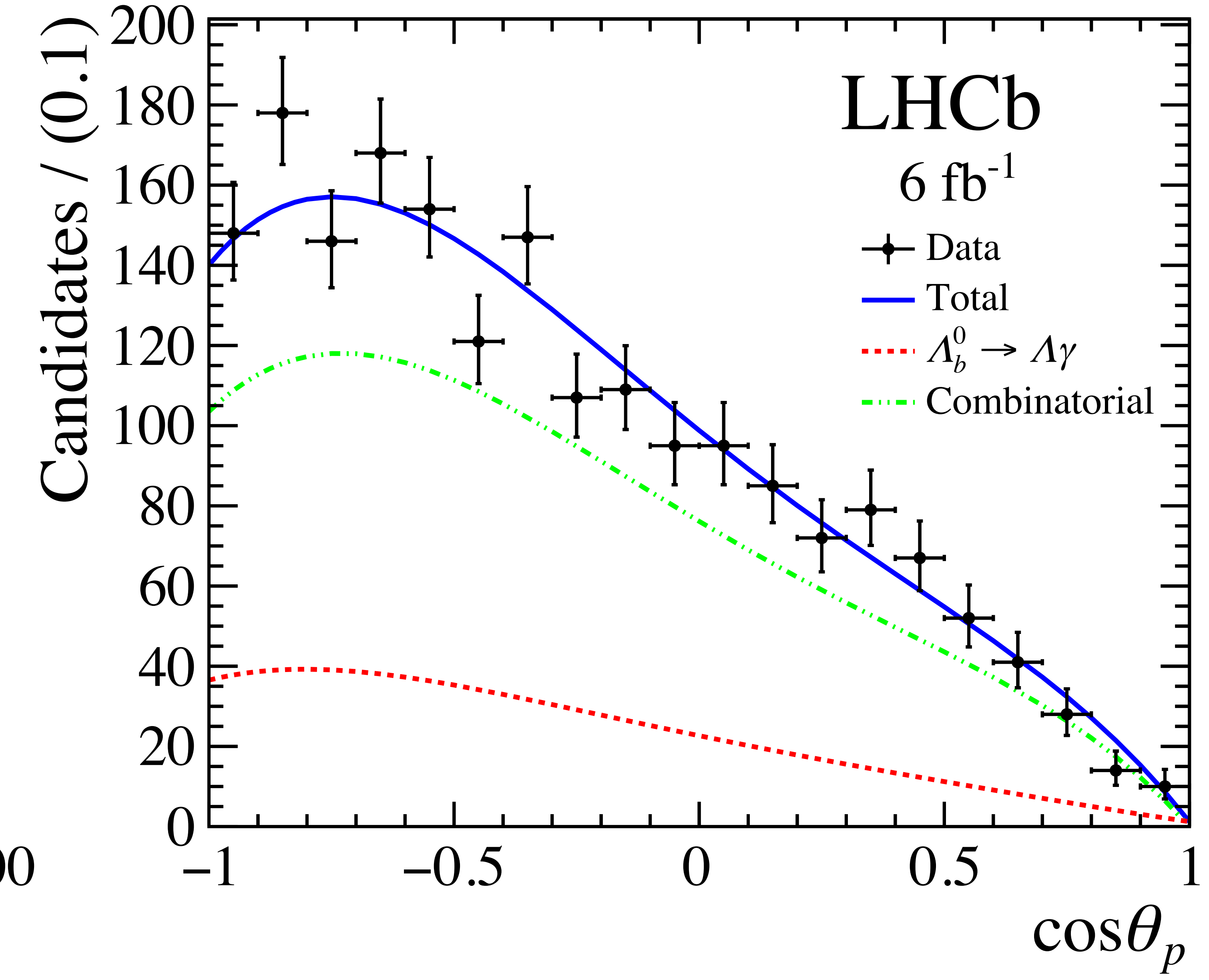
- Now also with b-baryons: use $\Lambda_b^0 \to \Lambda\gamma$ decay
- Spin 1/2 of initial and final baryon; weakly-decaying Λ; ~unpolarised Lb
- Angular distribution $\dfrac{d\Gamma}{d\cos\theta_p} \sim 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p$

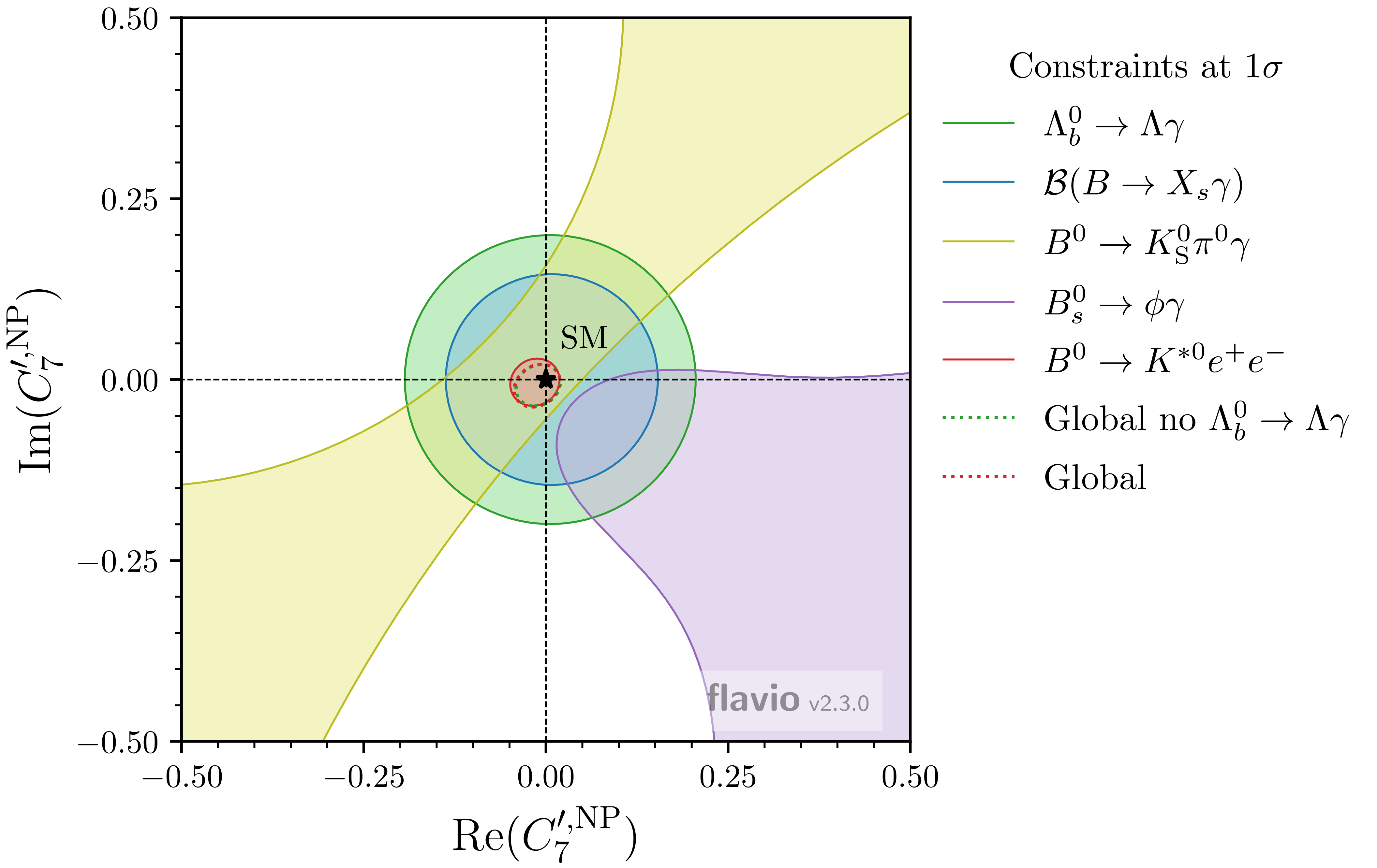
angle between the proton momentum in the Λ rest frame and the Λ momentum in the Λ_b rest frame

- Fit to data: $\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$: compatible with SM

less precise than $B^0 \to K^{*0} e^+ e^-$



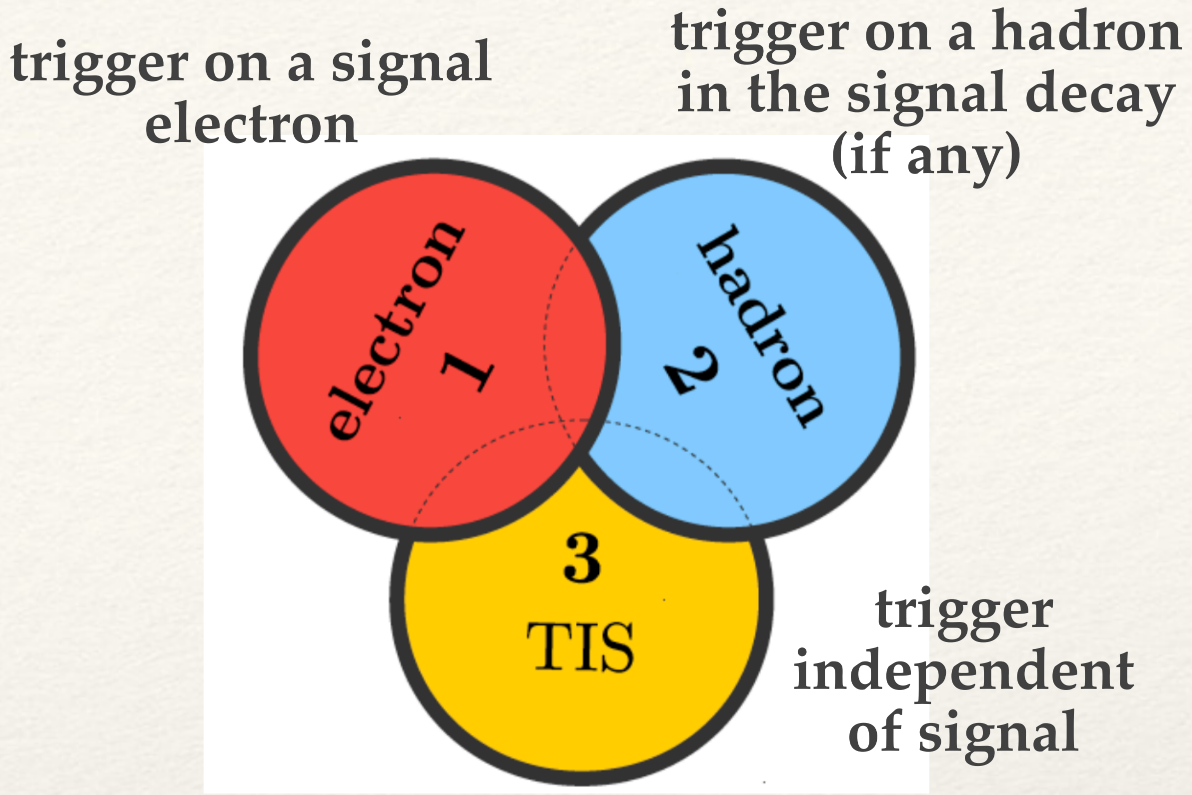




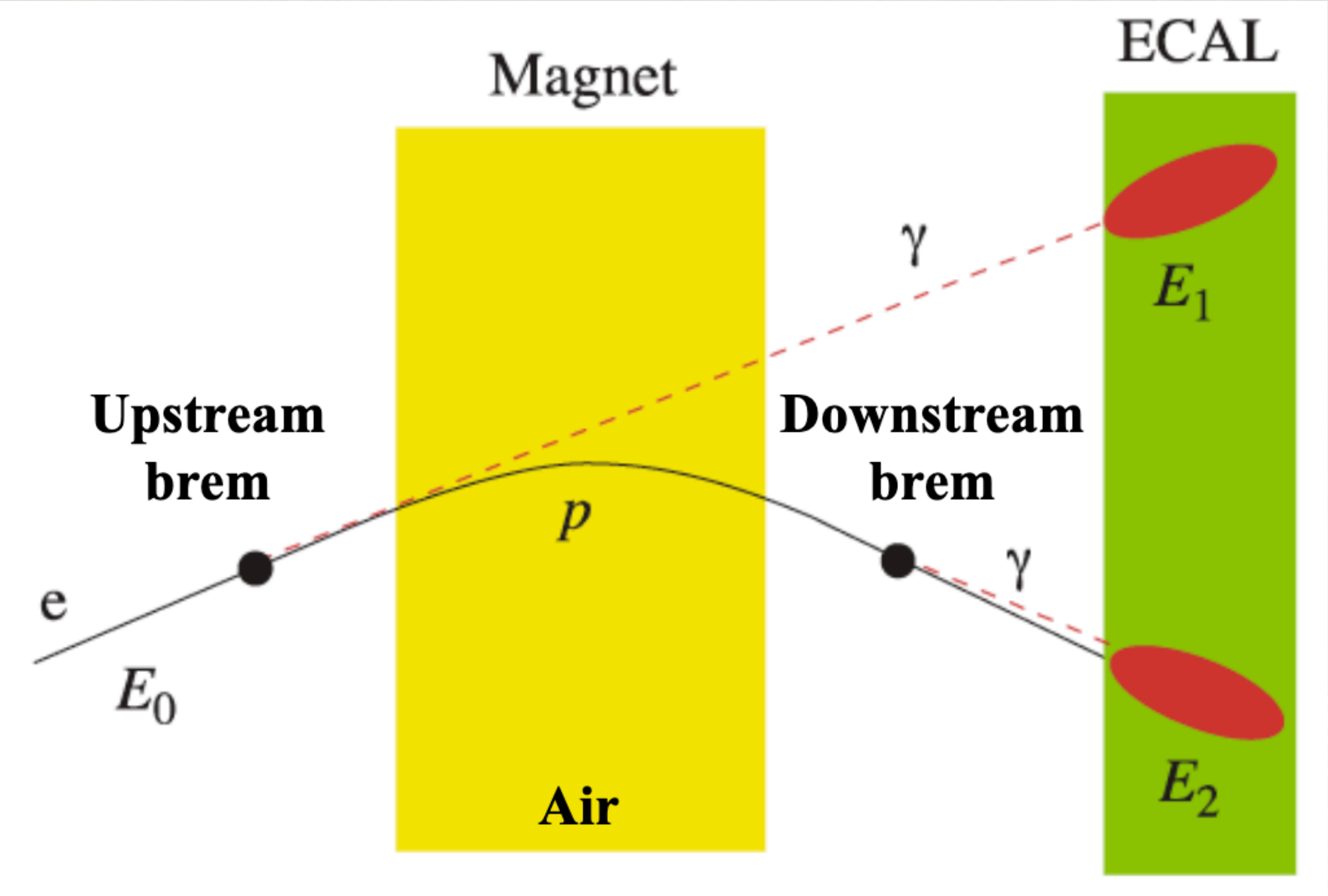
Challenges with electrons

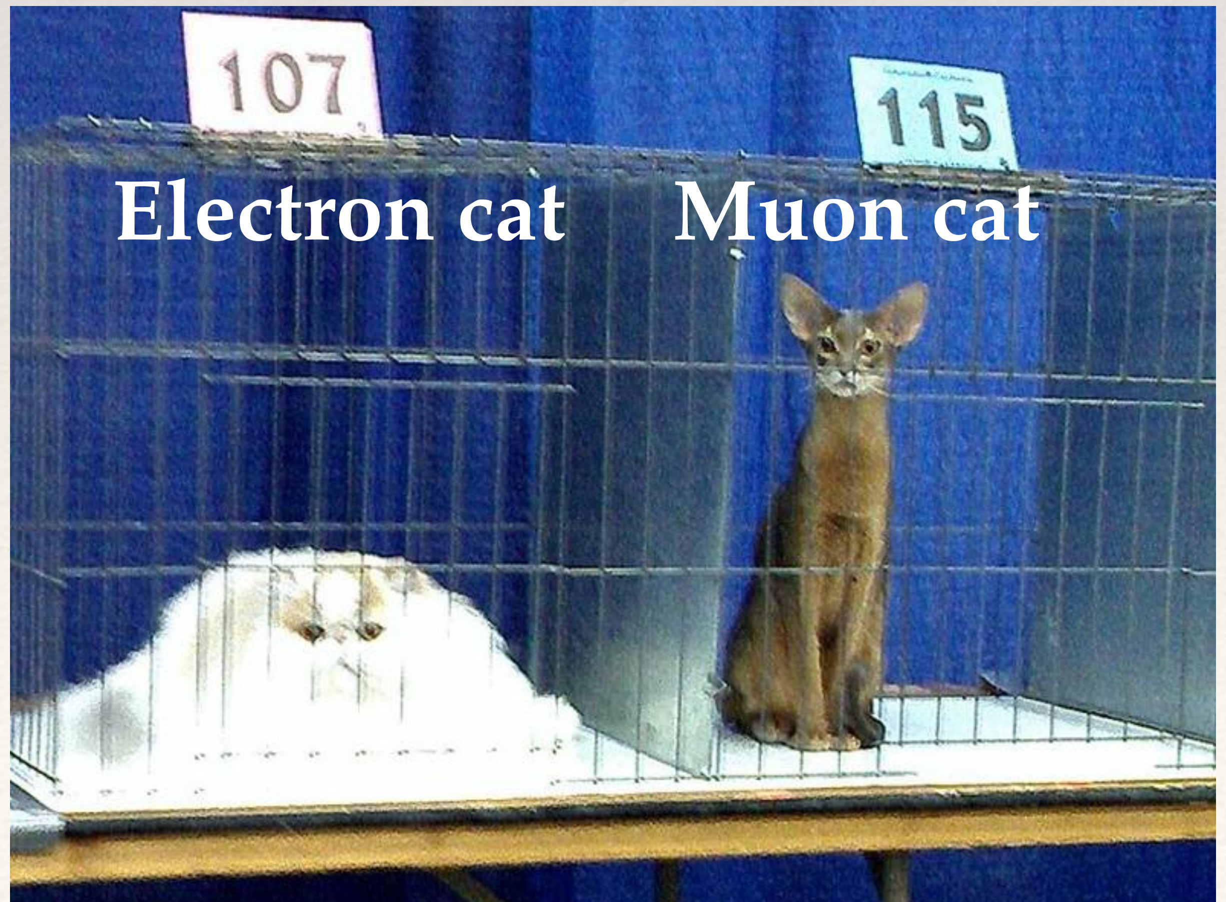
JINST 14 (2019) P04013

- **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:

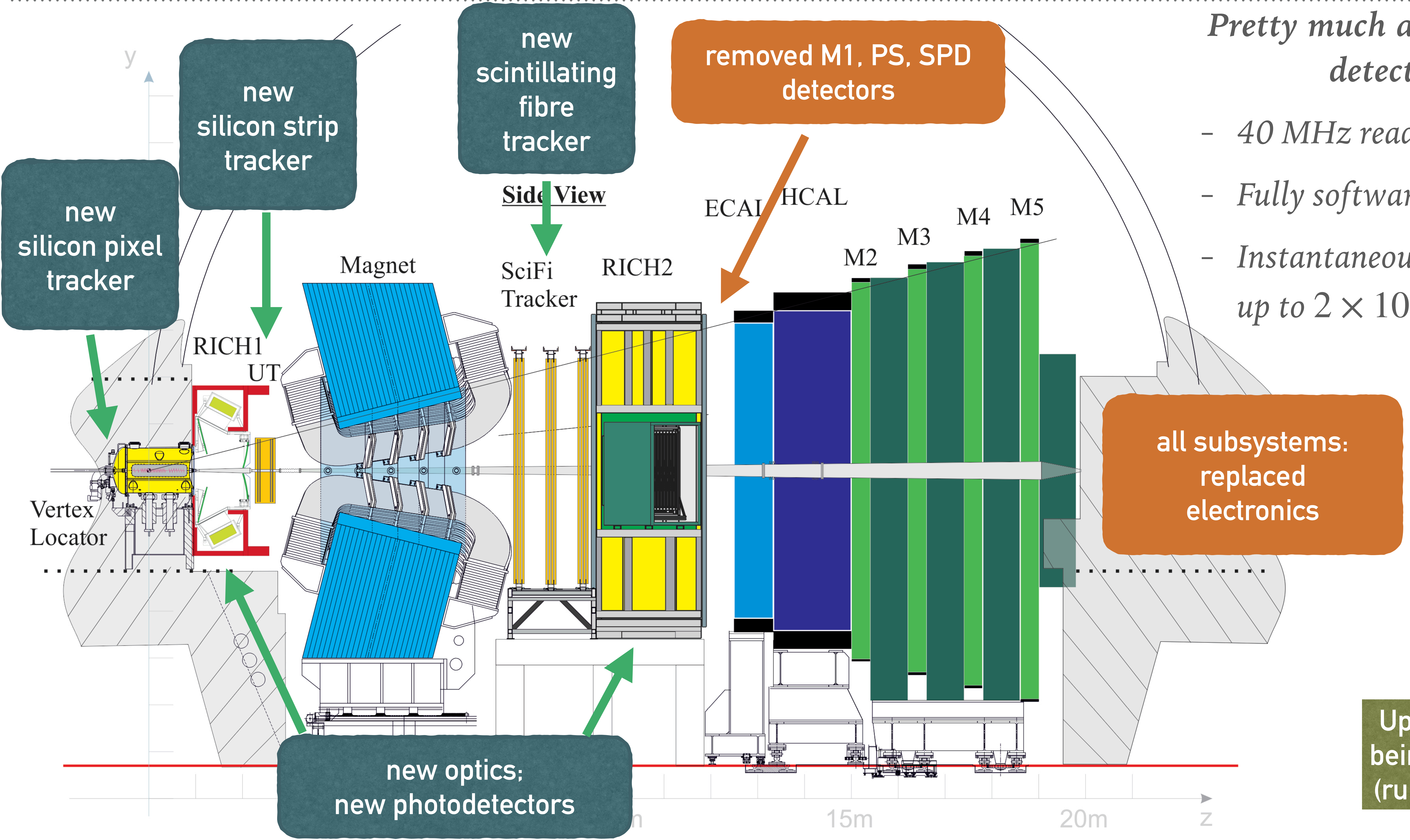


- **Electrons** emit a large amount of **bremsstrahlung** in interactions with the detector material
  - If a photon is emitted *before the magnet*:
    - electron momentum measured *after* bremsstrahlung;
    - photon ends up in a *different* ECAL cell
  - dedicated procedure to search for these photons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





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.