Rare and LFNU B decays at LHCb

The 2022 Conference on Flavour Physics and CP Violation

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on behalf of the LHCb Collaboration

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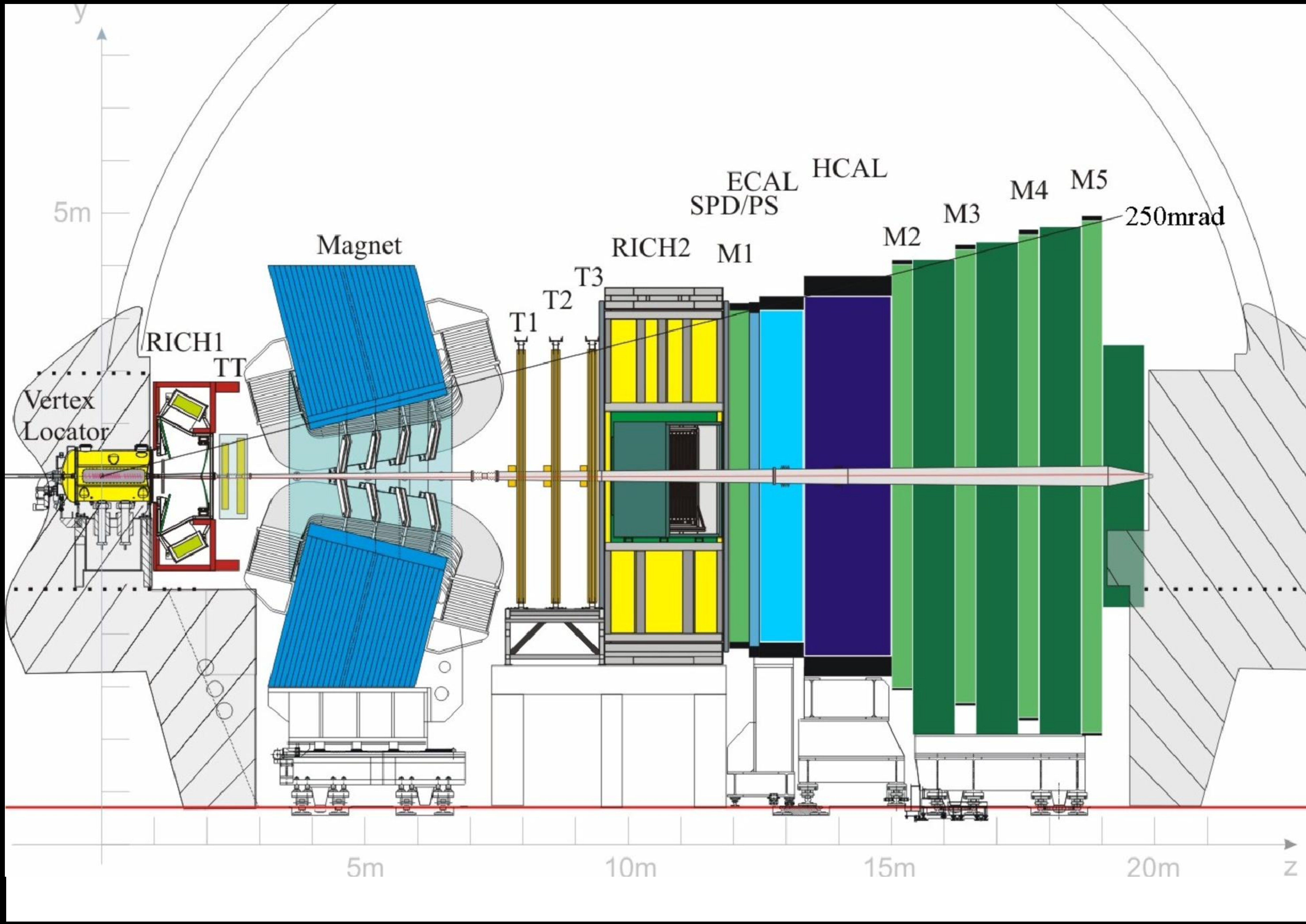
LHCb detector

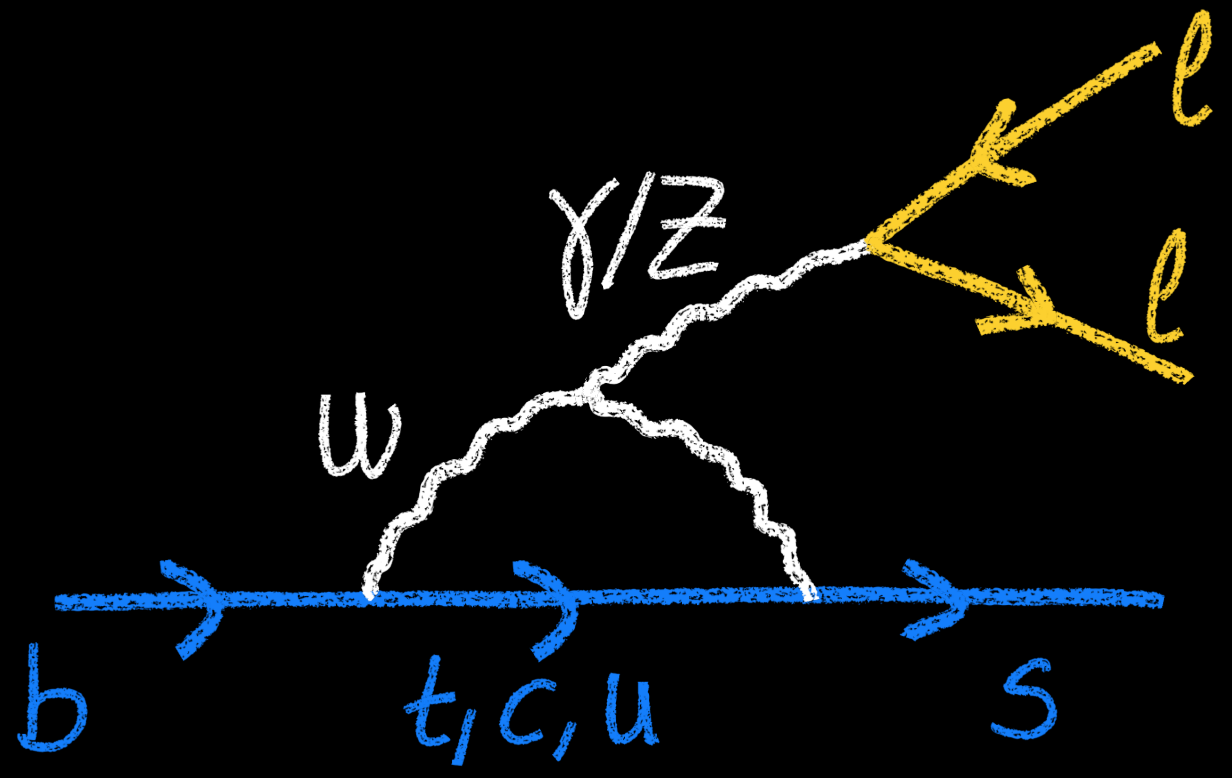
- Forward spectrometer
- Production of B-hadrons in pp collisions
- Run 1 and Run 2 → 9 fb^{-1} of integrated luminosity

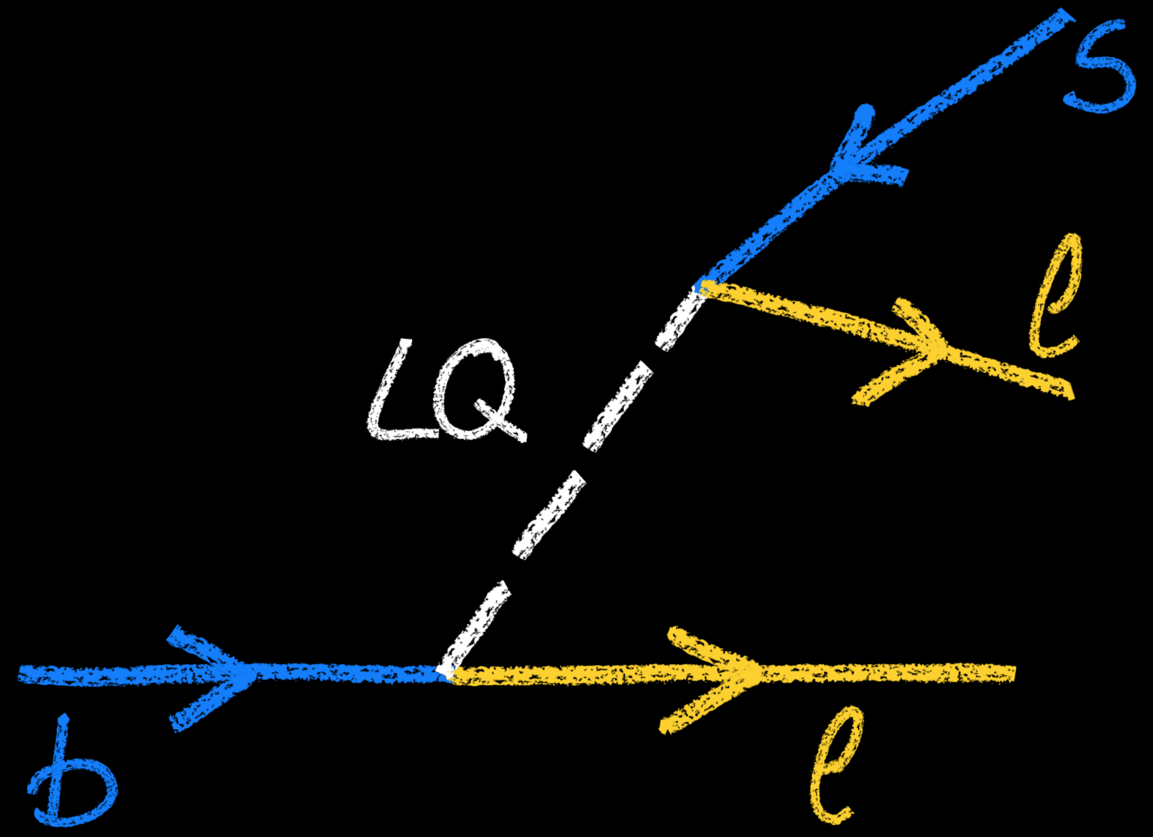


Rare decays

Rare decays: Electroweak decays with low BF or forbidden in SM

Study of the $b \to s\ell\ell$ transition





Very suppressed in the SM

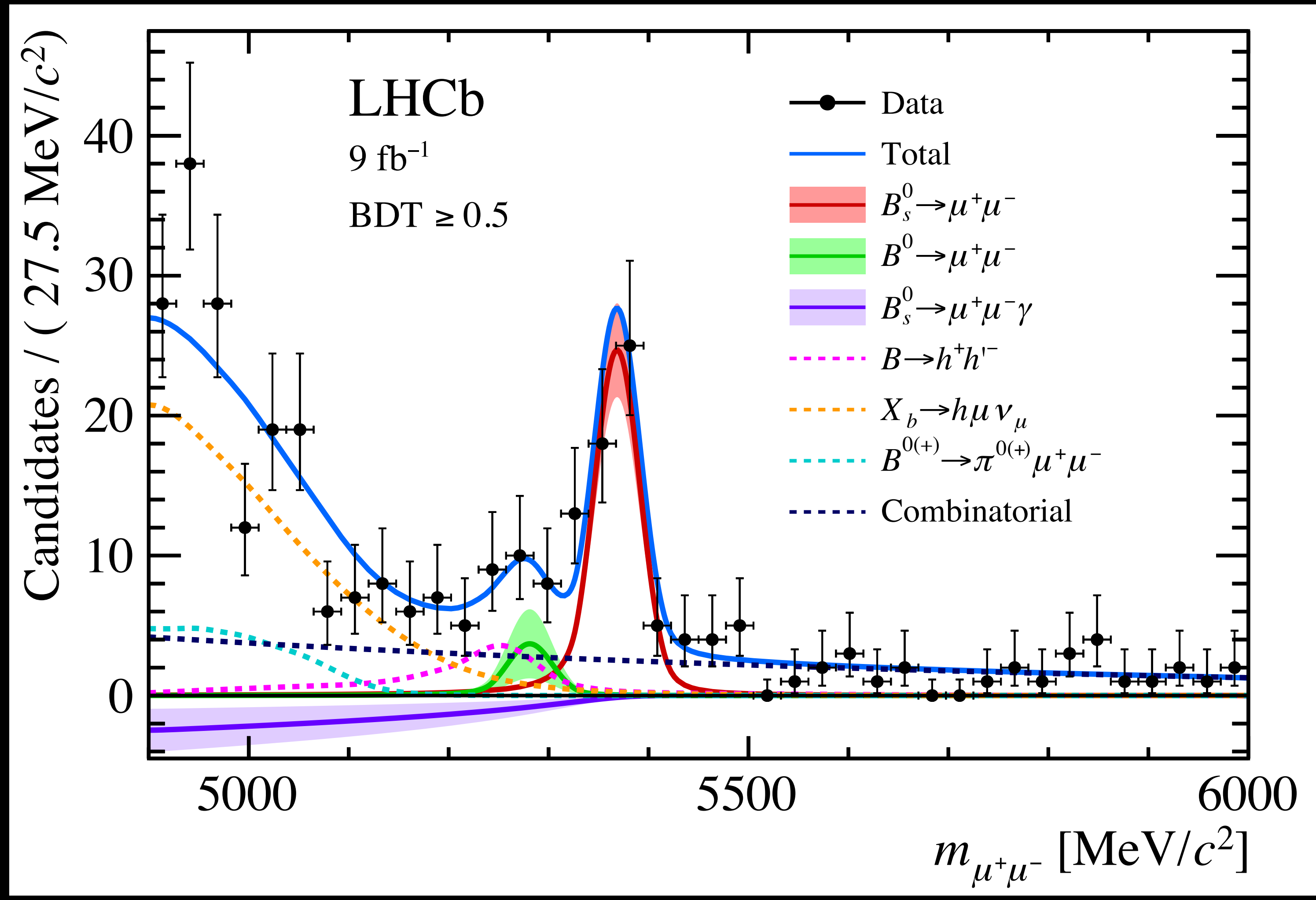
Theoretically clean in ratios or lepton species

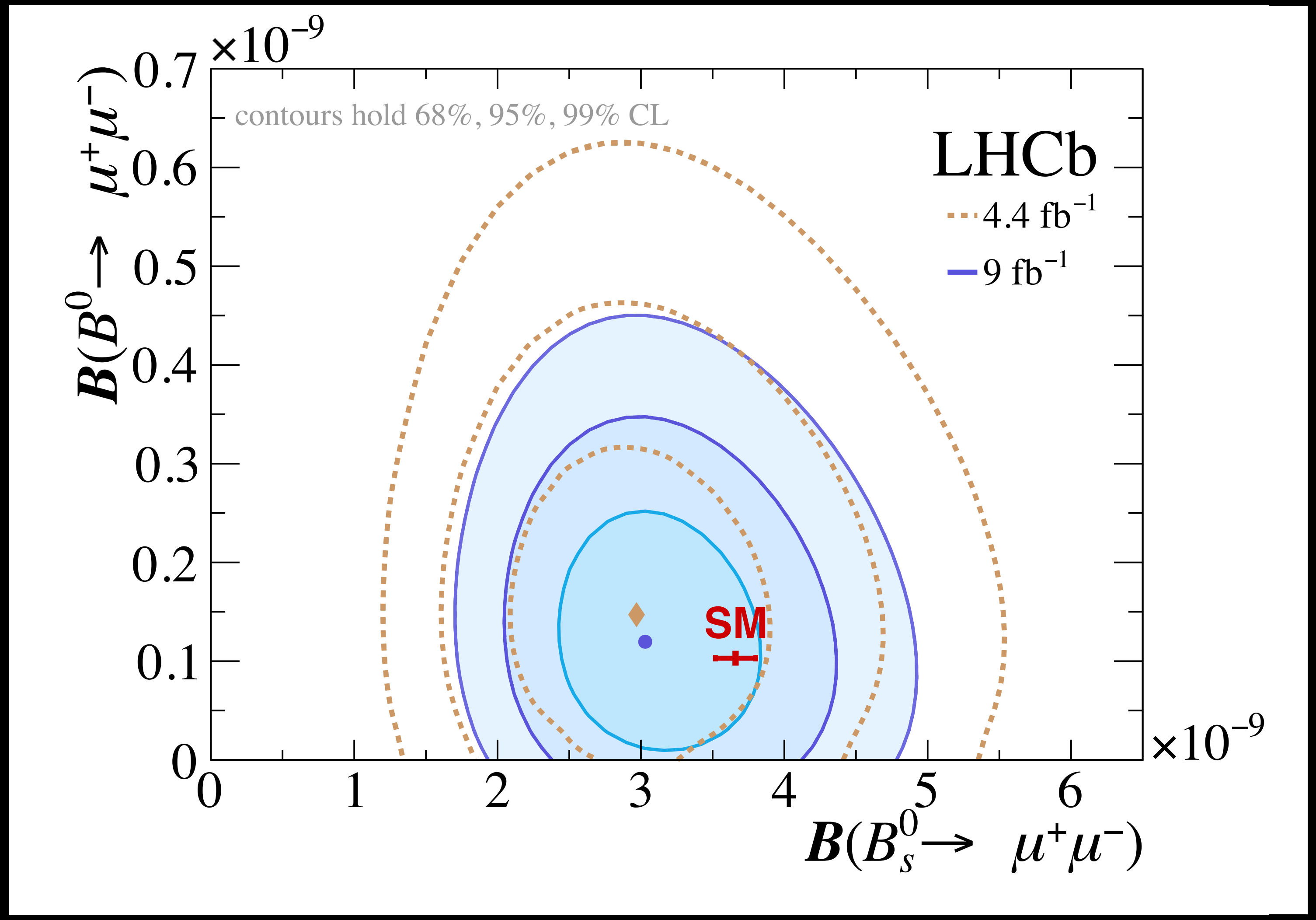
Very sensitive to New Physics

Phys. Rev. D105 (2022) 012010
Phys. Rev. Lett. 128 (2022) 041801

$B^0_{(s)} \to \mu^+\mu^-(\gamma)$

Run1+Run2 datasets





- $\mu^+\mu^-$ candidates forming a good, displaced vertex
- Signal from fit to $m_{\mu^+\mu^-}$ in bins of a BDT classifier

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$

Most precise to date
In agreement with SM

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL

Tighter upper limit
Affected by $B \to h^+h'^-$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\ \mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ at 95% CL

Only ISR included
First limit ever set

PRD105 (2022) 012010
PRL128 (2022) 041801

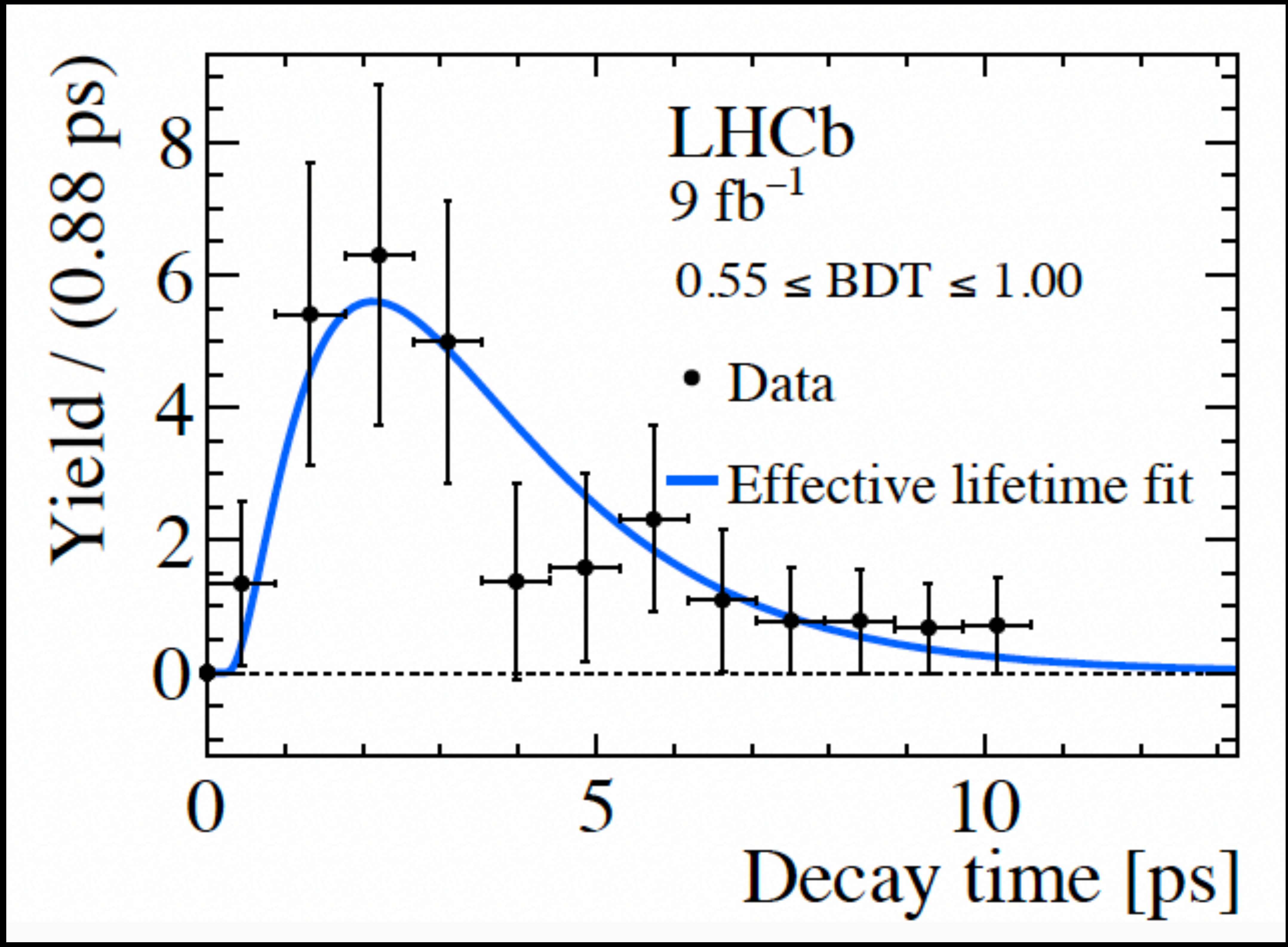
$B_s^0 \to \mu^+\mu^-$ effective lifetime

Run1+Run2 datasets

- Effective lifetime: Average decay time of decay candidates in experiment

$$\tau_{\mu\mu} = (2.07 \pm 0.29 \pm 0.03)\ \text{ps}$$

Consistent with heavy mass eigenstate (SM) → 1.5 σ



Lepton Flavour Universality

- IN SM ELECTROWEAK COUPLING IS UNIVERSAL FOR ALL LEPTONS
- ONLY DIFFERENCES FROM MASSES → PHASE SPACE
* TESTED IN MANY DIFFERENT DECAYS

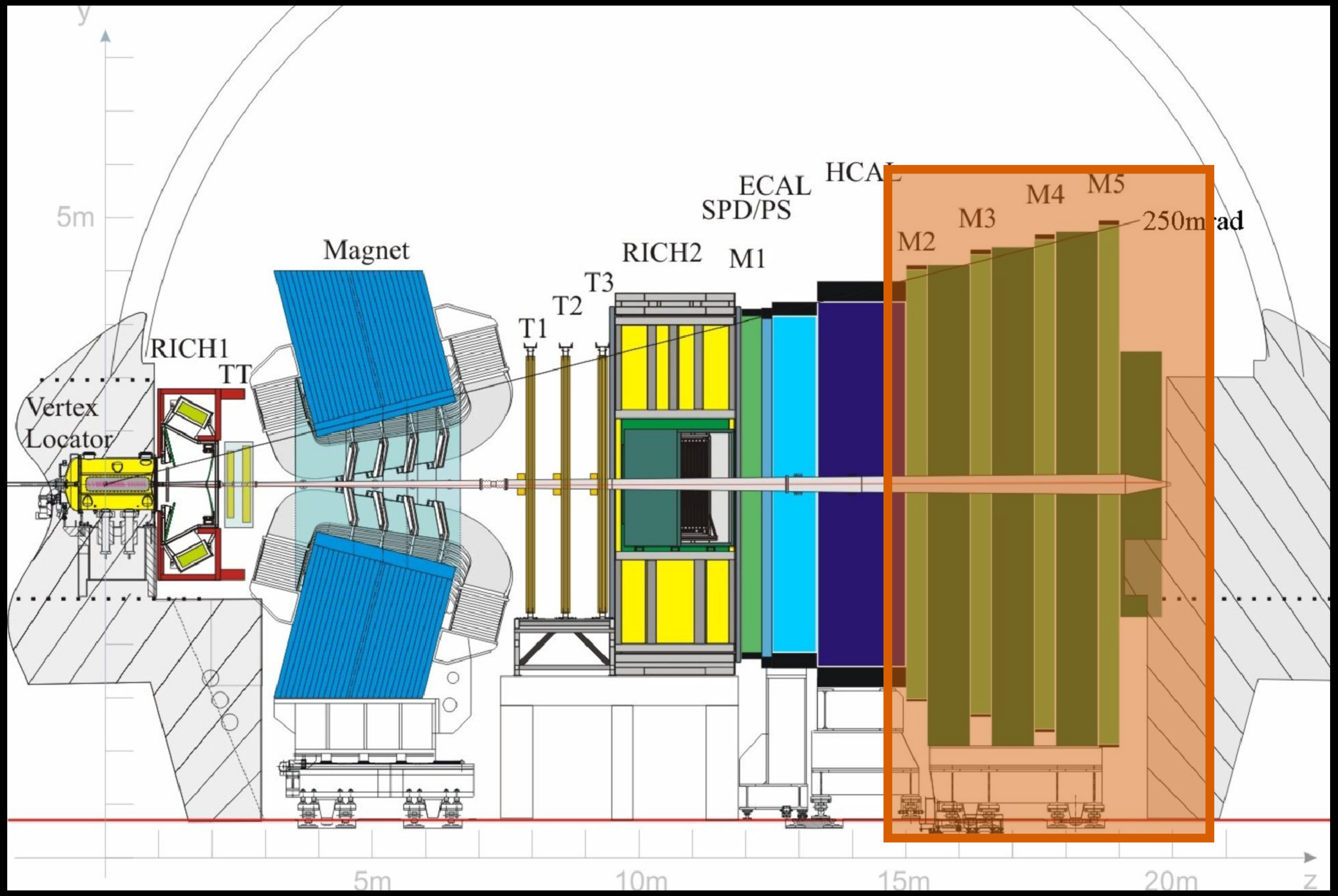
$$R_H = \frac{\mathcal{B}(X_b \to H\mu^+\mu^-)}{\mathcal{B}(X_b \to He^+e^-)} \text{ with } H = K^+, K_S^0, K^{*+}, \ldots$$

- GOOD WAY TO SEARCH FOR NEW PHYSICS:
  * SOME NP MODELS DO NOT HAVE LFU
  * WELL PREDICTED → QCD UNCERTAINTIES CANCEL

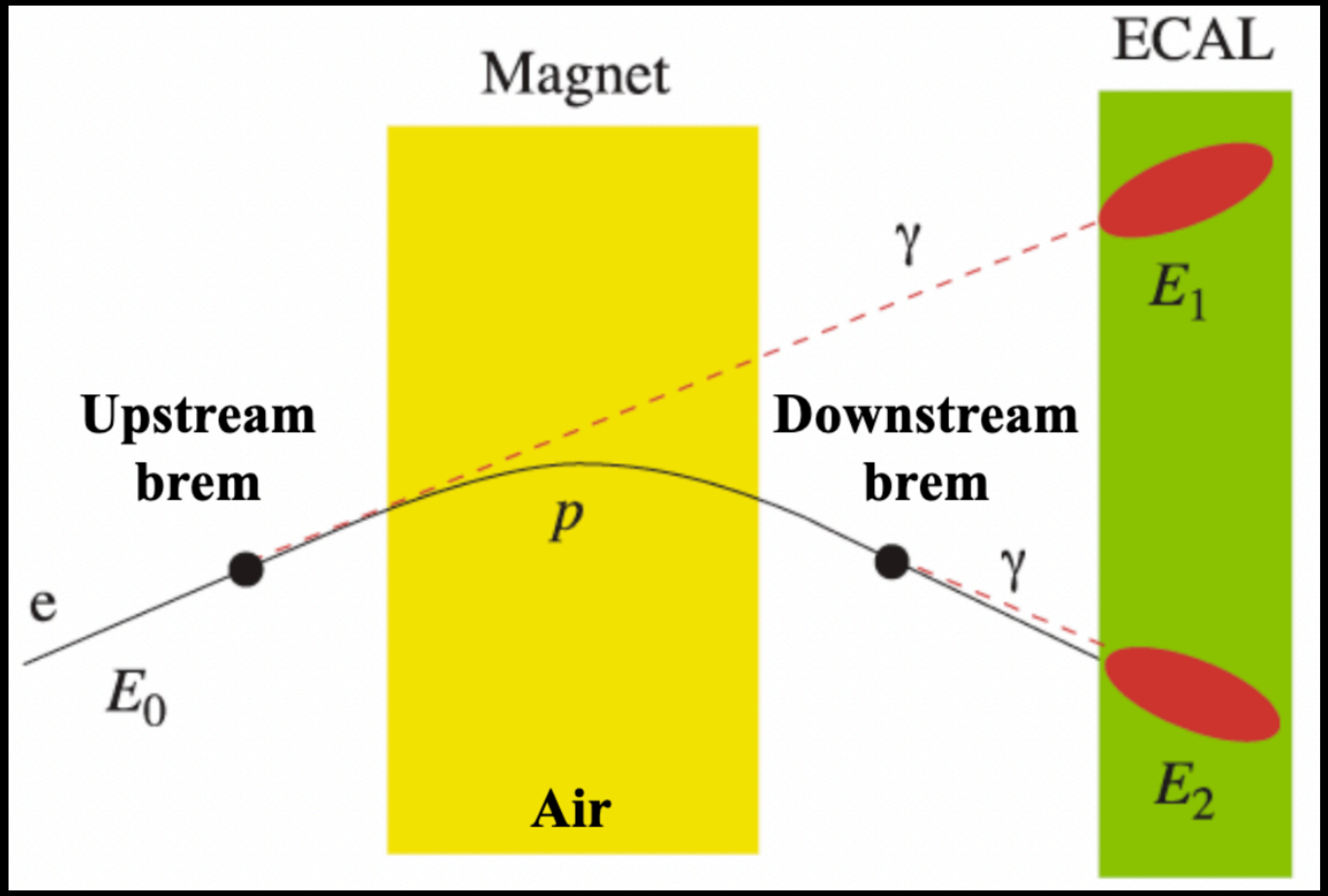
Muon vs electron detection

DETECTION ASYMMETRIES μ VS e → DIFFERENT IN TRIGGERING AND RECONSTRUCTION

- GOOD AND EASY FOR MUONS



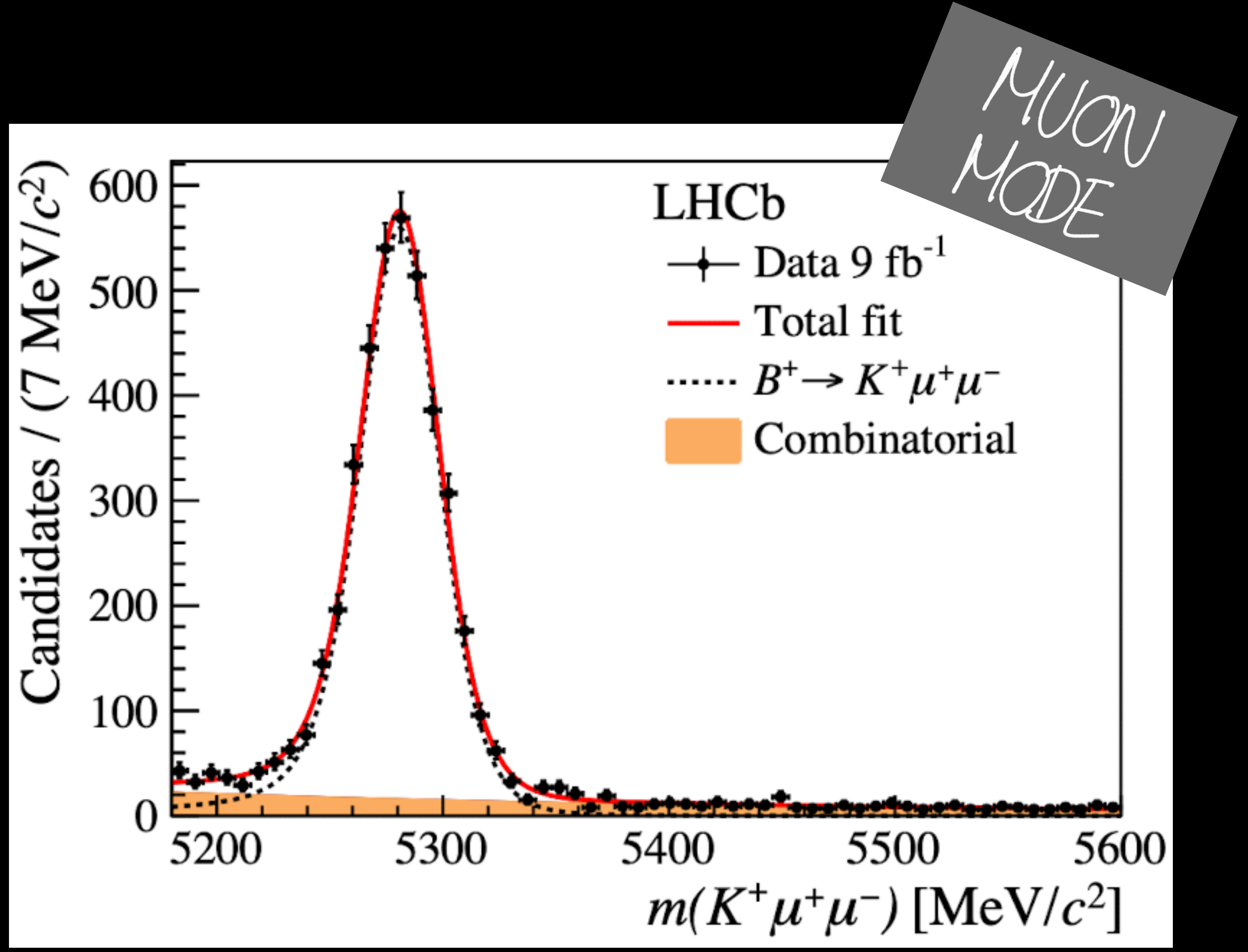
- DIFFICULT FOR ELECTRONS → BREMSSTRAHLUNG



Nature Phys. 18 (2022) 3, 277-282

Run1+Run2 datasets

LFU: R_K

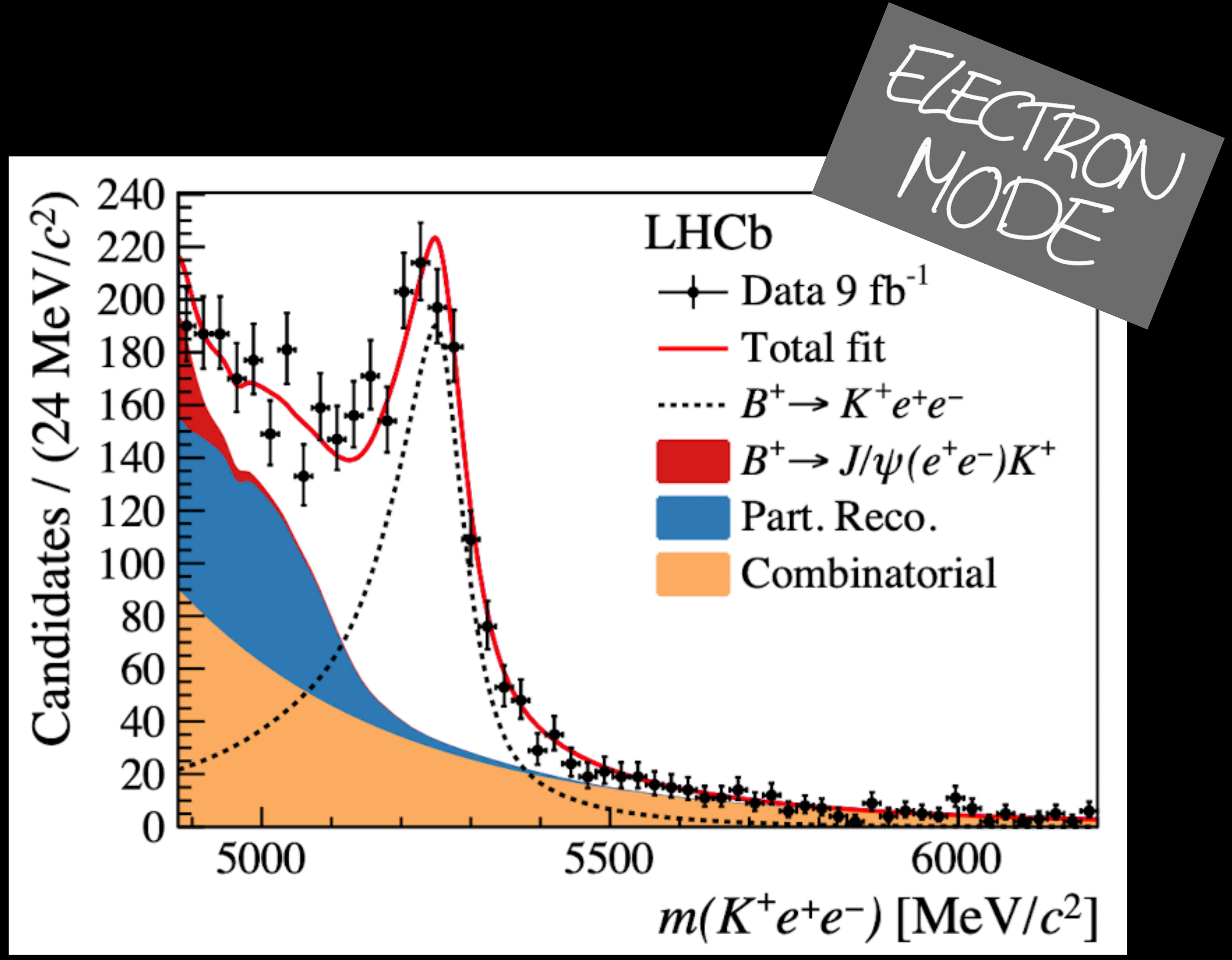


DOUBLE RATIO → REDUCE SYSTEMATICS FROM μ VS e RECONSTRUCTION

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

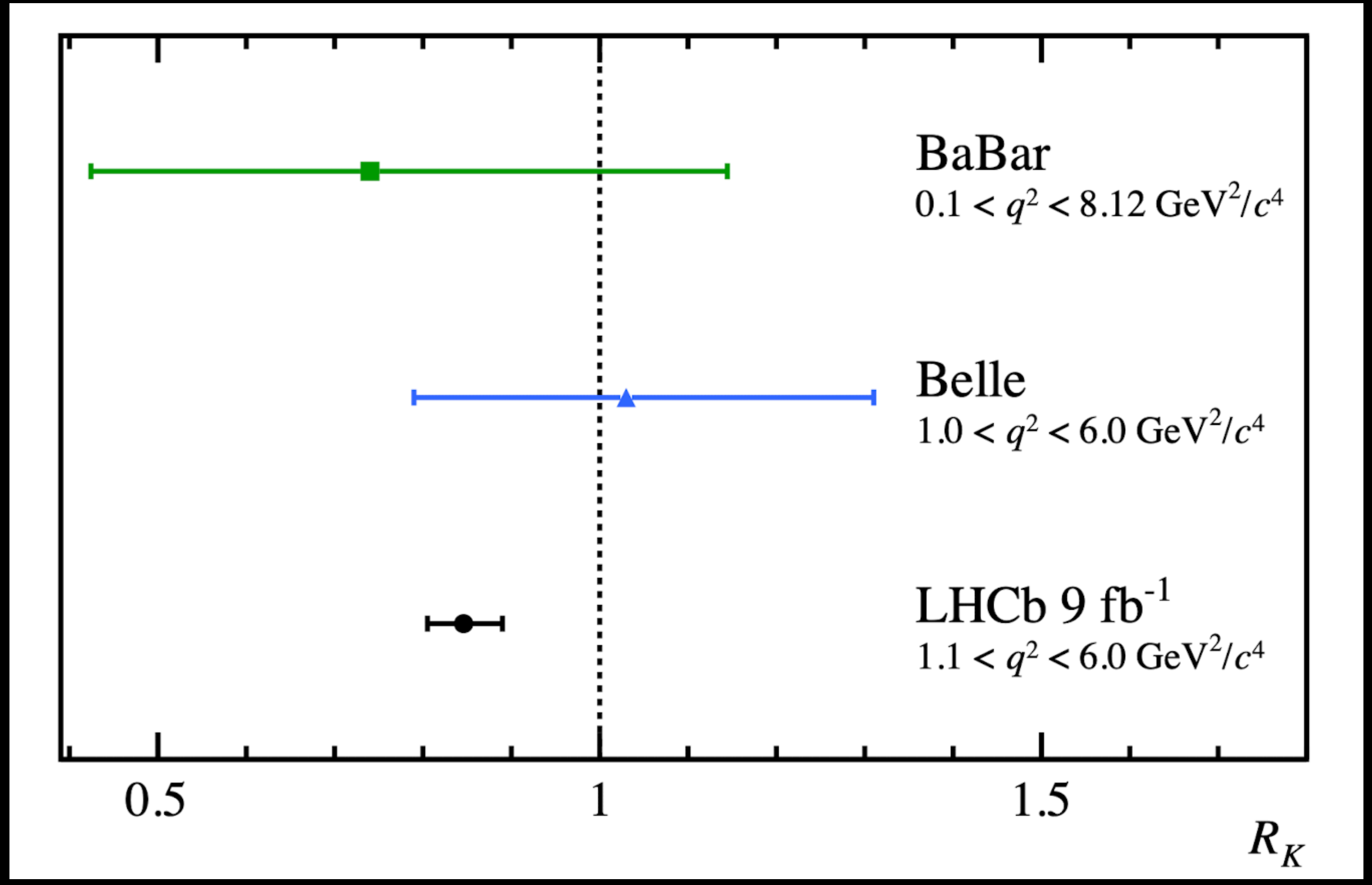
FOR RARE MODE ONLY $1.1 < q^2_{\ell\ell} < 6\ \mathrm{GeV}^2/c^4$

EFFICIENCIES VALIDATED WITH J/ψ RATIO → CONSISTENT WITH UNITY



$$R_K = 0.846\ {}^{+0.042}_{-0.039}\ {}^{+0.013}_{-0.012}$$

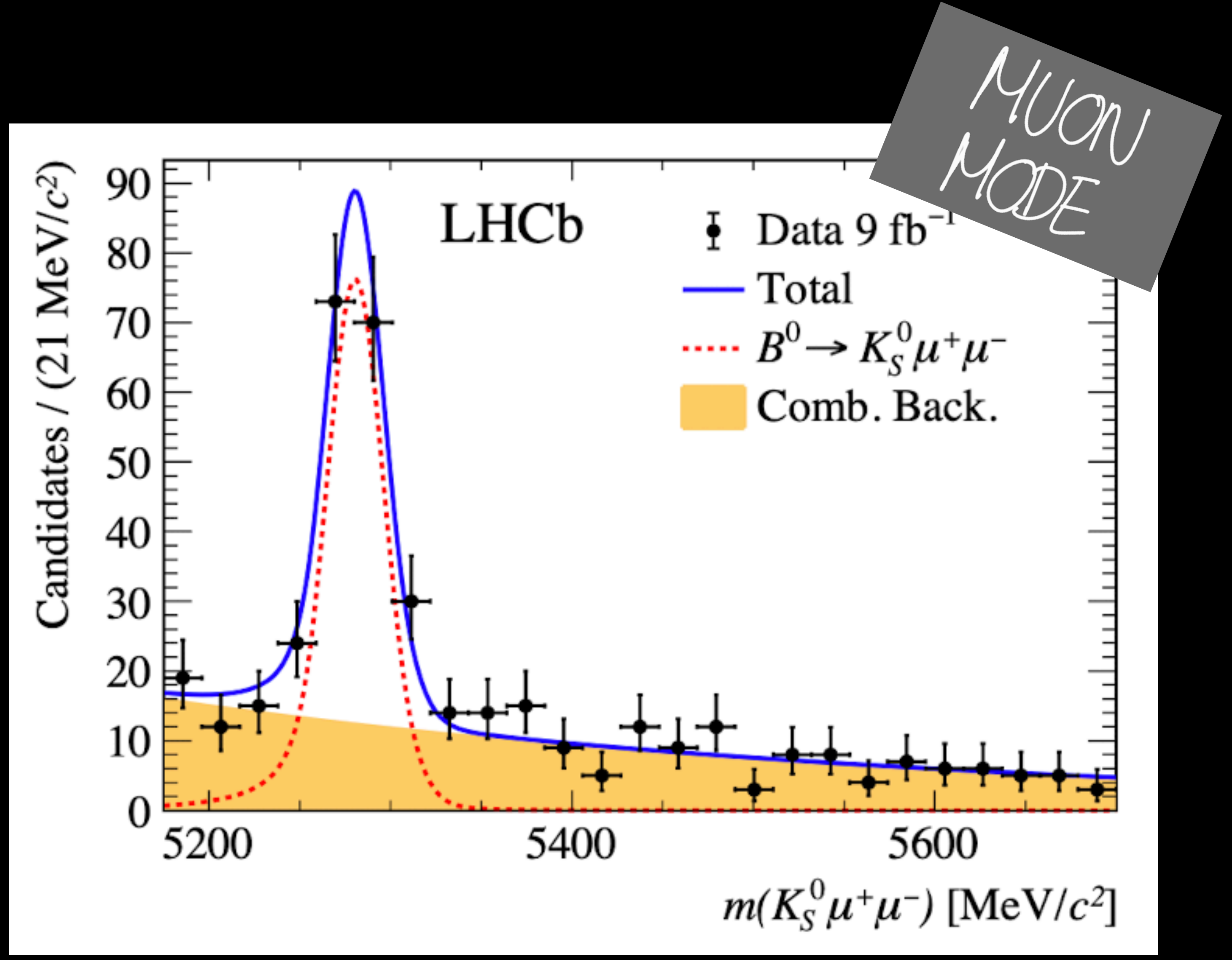
TENSIONS WITH SM → 3.1σ



Phys. Rev. Lett. 128 (2022) 191802

LFU: $R_{K^0_s}$

Run1+Run2 datasets

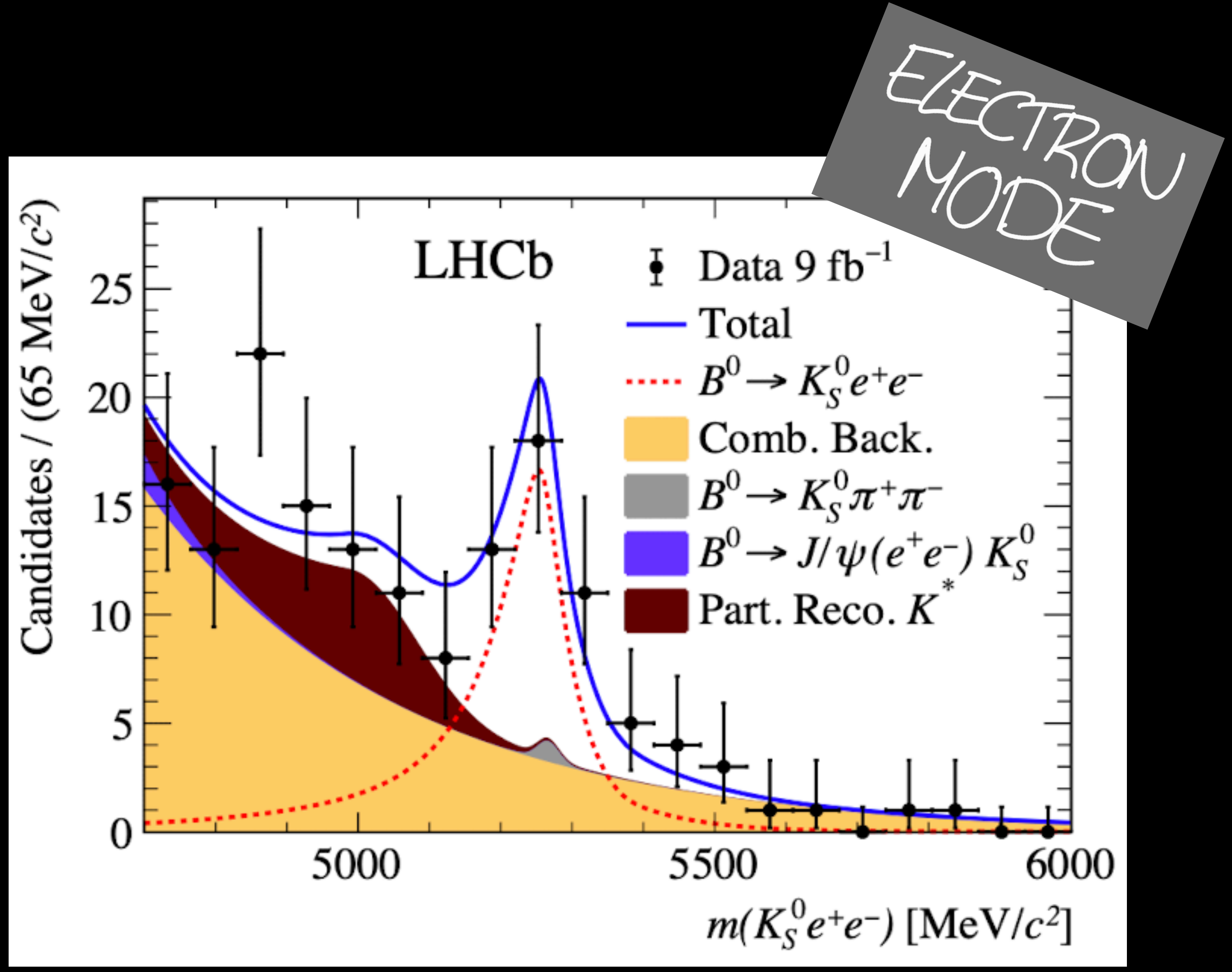


ISOSPIN PARTNER. INVERSE DOUBLE RATIO

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

FOR RARE MODE ONLY $1.1 < q^2_{\ell\ell} < 6\ GeV^2/c^4$

K^0_S RECONSTRUCTED AS $K^0_S \to \pi^+\pi^-$ → LESS PRECISE



$$R^{-1}_{K^0_s} = 1.51^{+0.40+0.09}_{-0.35-0.04}$$

$$R_{K^0_s} = 0.66^{+0.20+0.02}_{-0.14-0.04}$$

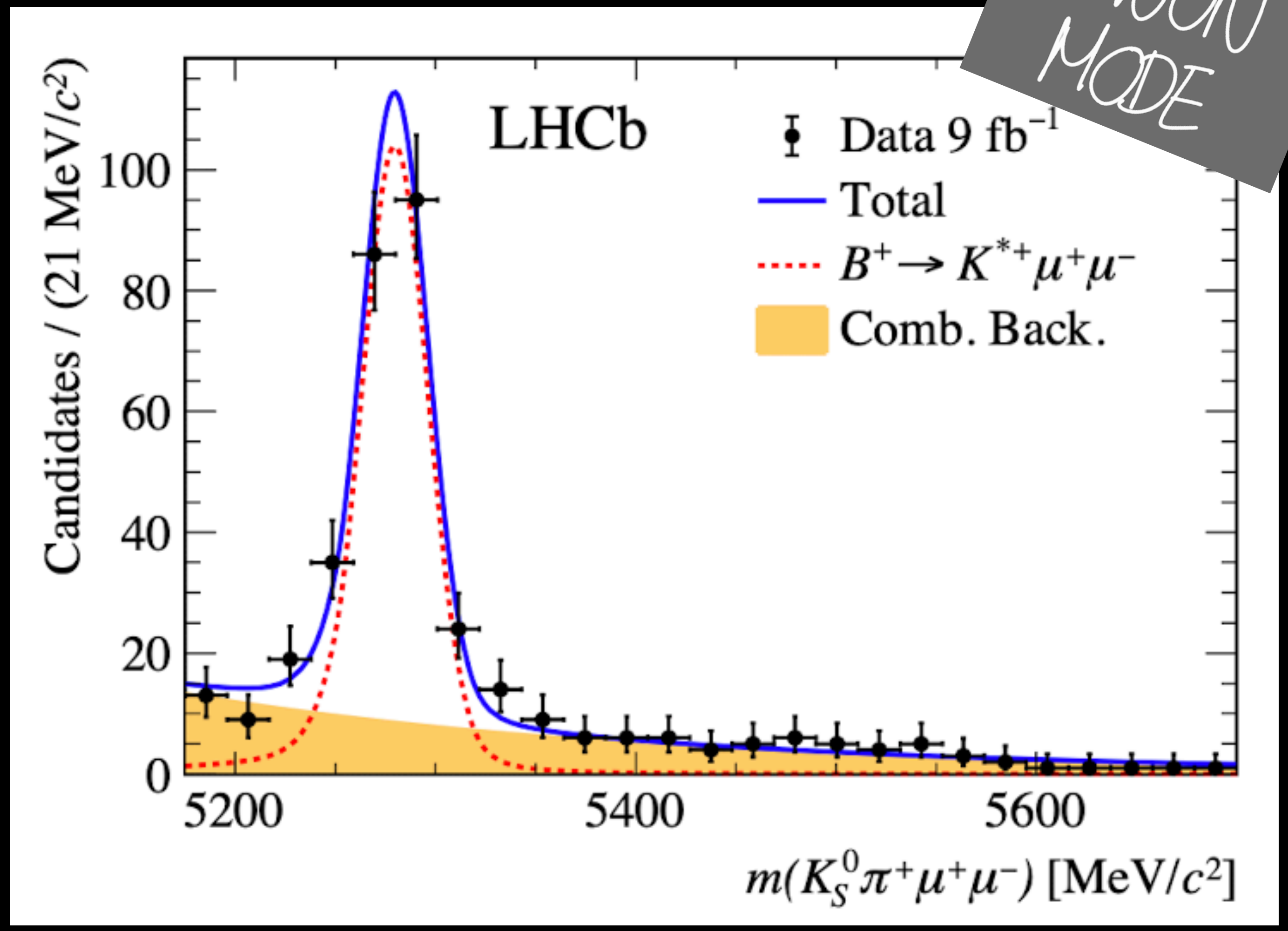
AGREES WITH SM → 1.5σ

Phys. Rev. Lett. 128 (2022) 191802

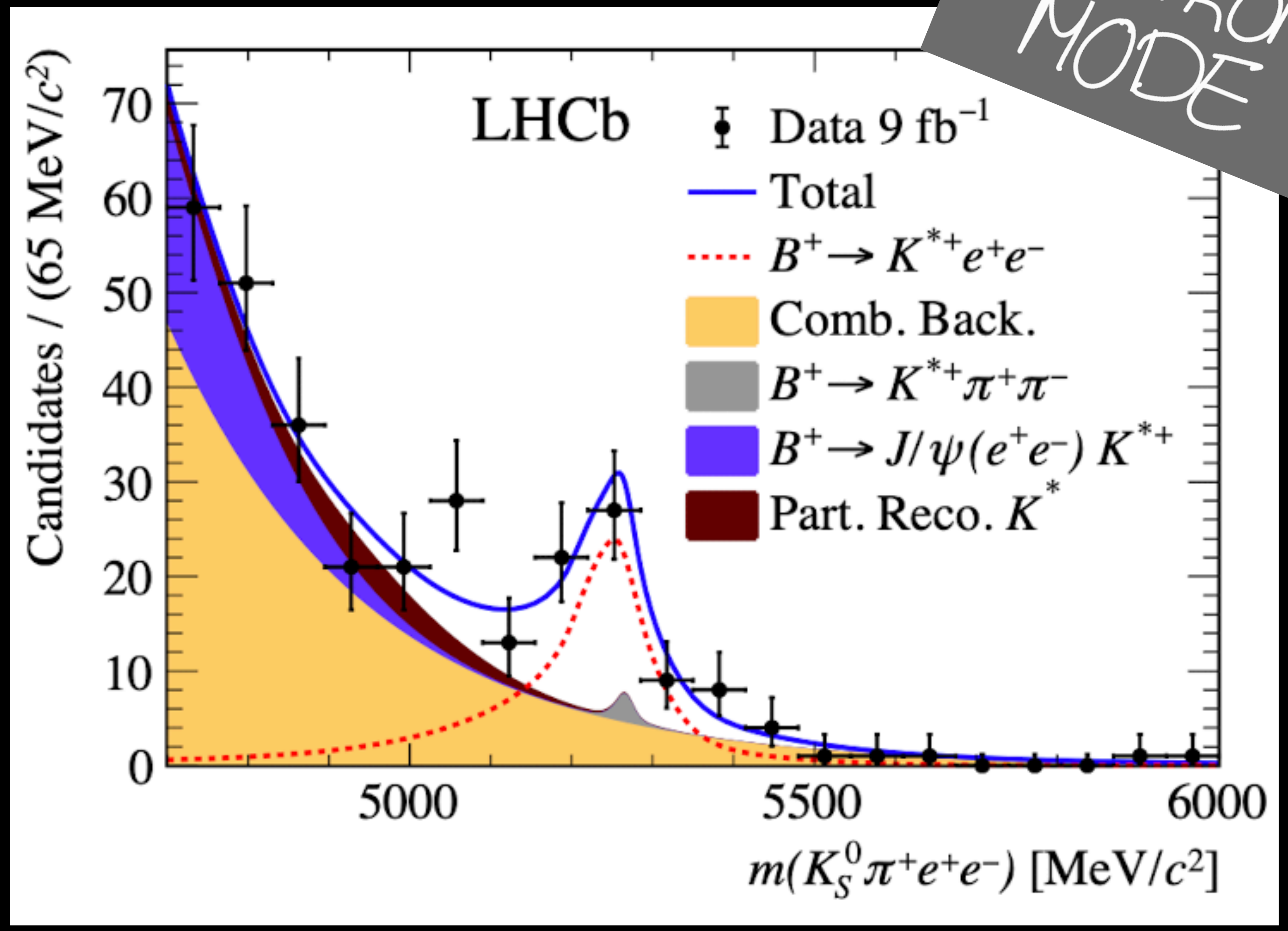
LFU: $R_{K^{*+}}$

Run1+Run2 datasets

MUON MODE



ELECTRON MODE



AND ALSO $B^+ \to K^{*+}\ell^+\ell^-$ WITH INVERSE DOUBLE RATIO

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

FOR RARE MODE ONLY $0.045 < q^2_{\ell\ell} < 6\ \mathrm{GeV}^2/c^4$

K^{*+} RECONSTRUCTED AS $K^{*+} \to K^0_S\pi^+$

$$R^{-1}_{K^{*+}} = 1.44^{+0.32+0.09}_{-0.29-0.06}$$

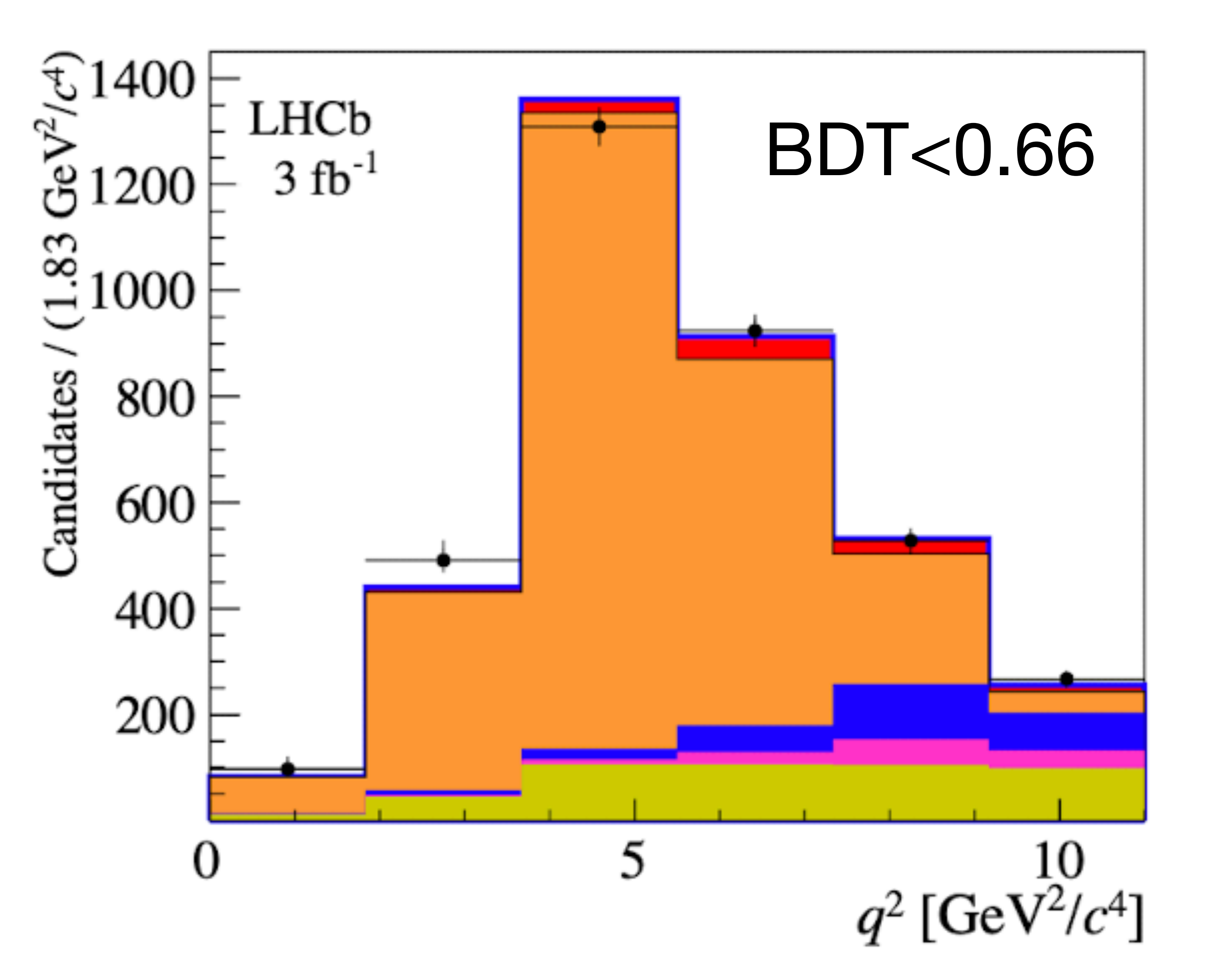
$$R_{K^{*+}} = 0.70^{+0.18+0.03}_{-0.13-0.04}$$

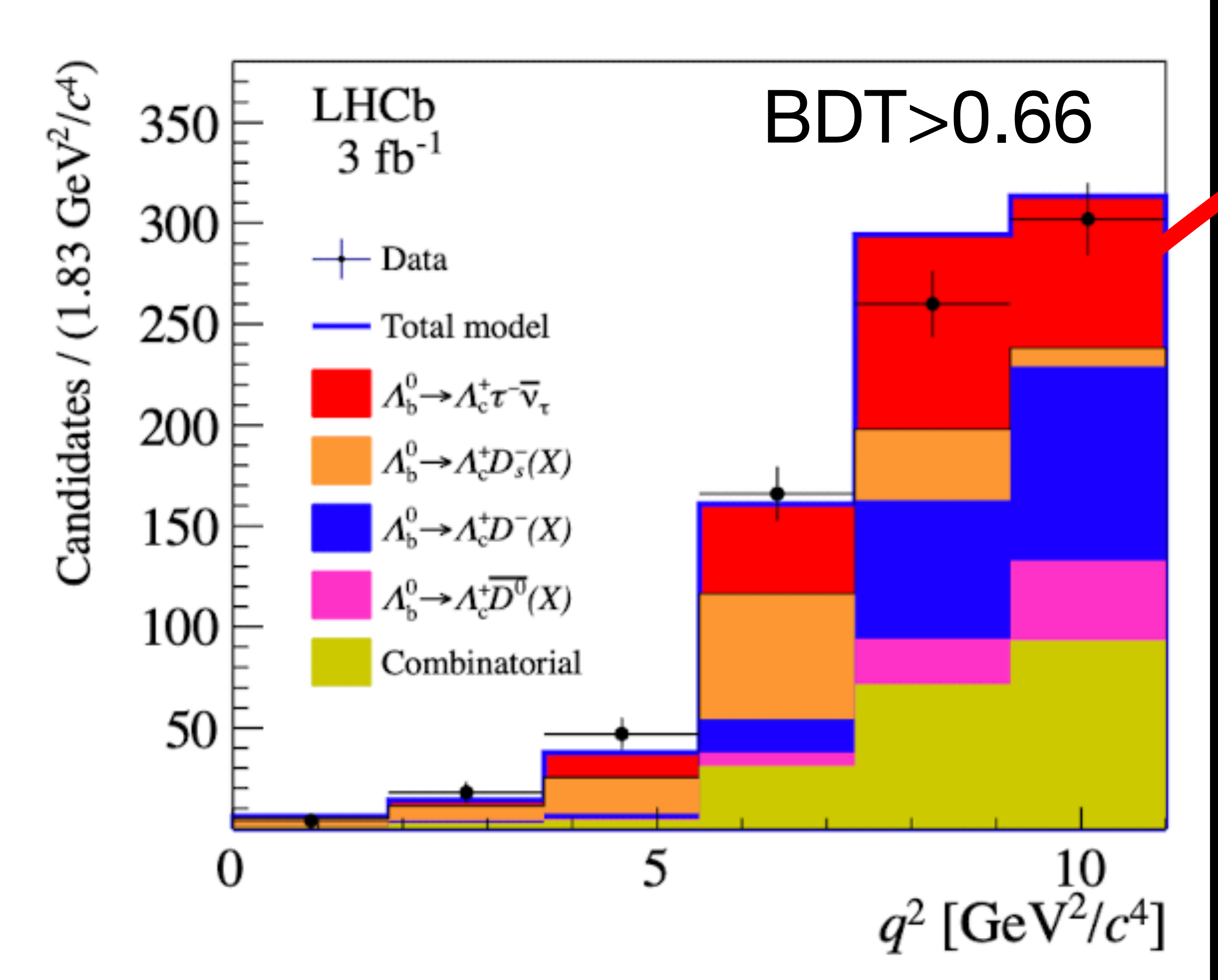
AGREES WITH SM → 1.4σ

arXiv: 2201.03497

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ and $R_{\Lambda_c^+}$

Run1 datasets





COMPLEMENTARY: SPIN 1/2 AND DIFFERENT FORM-FACTORS

DECAY $\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ WITH $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ AND $\Lambda_c^+ \to p K^- \pi^+$

3-D FIT TO BDT, PSEUDO DECAY-TIME OF τ AND q^2

$$R_{\Lambda_c^+} = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

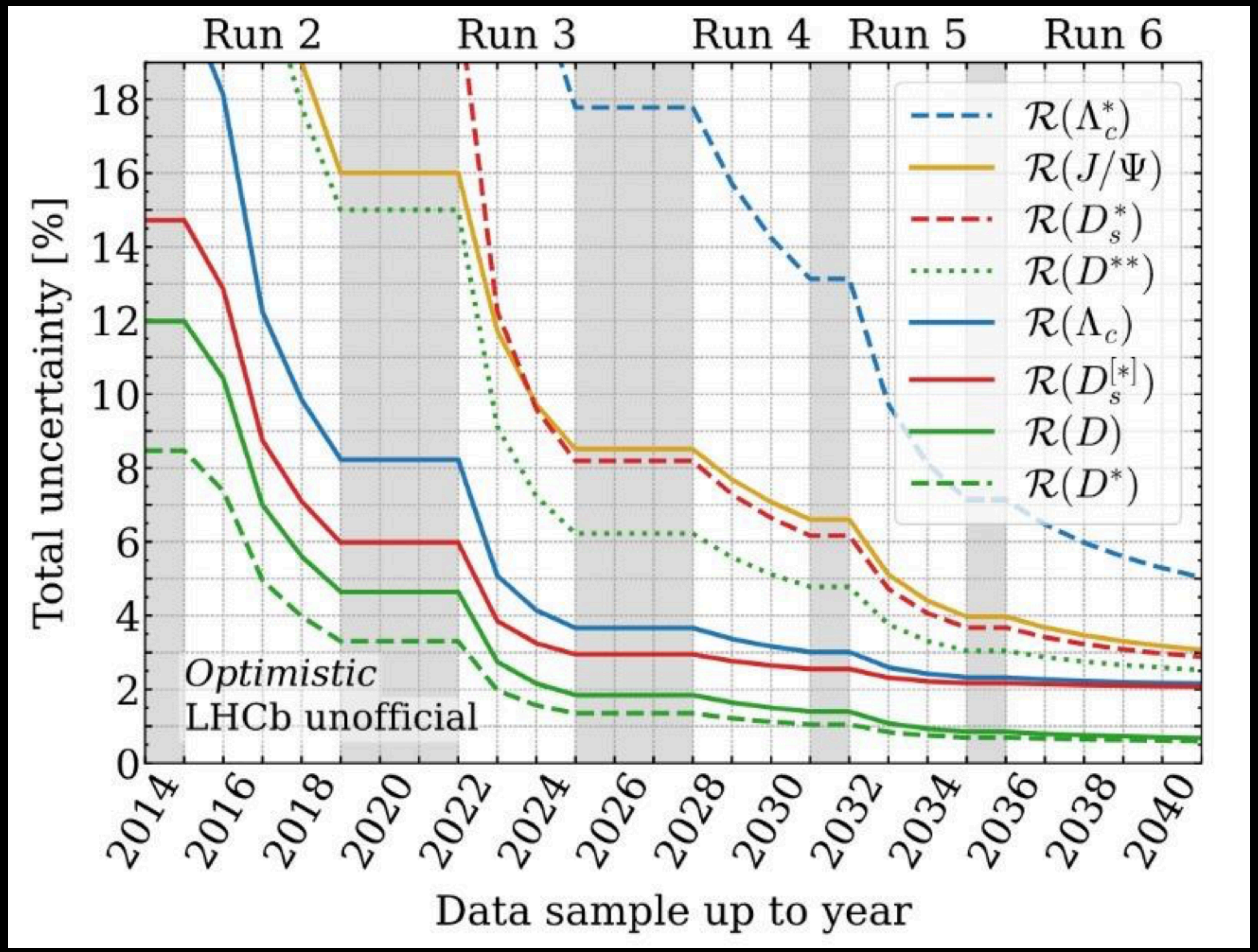
FROM DELPHI
Phys. Lett. B585 (2004)

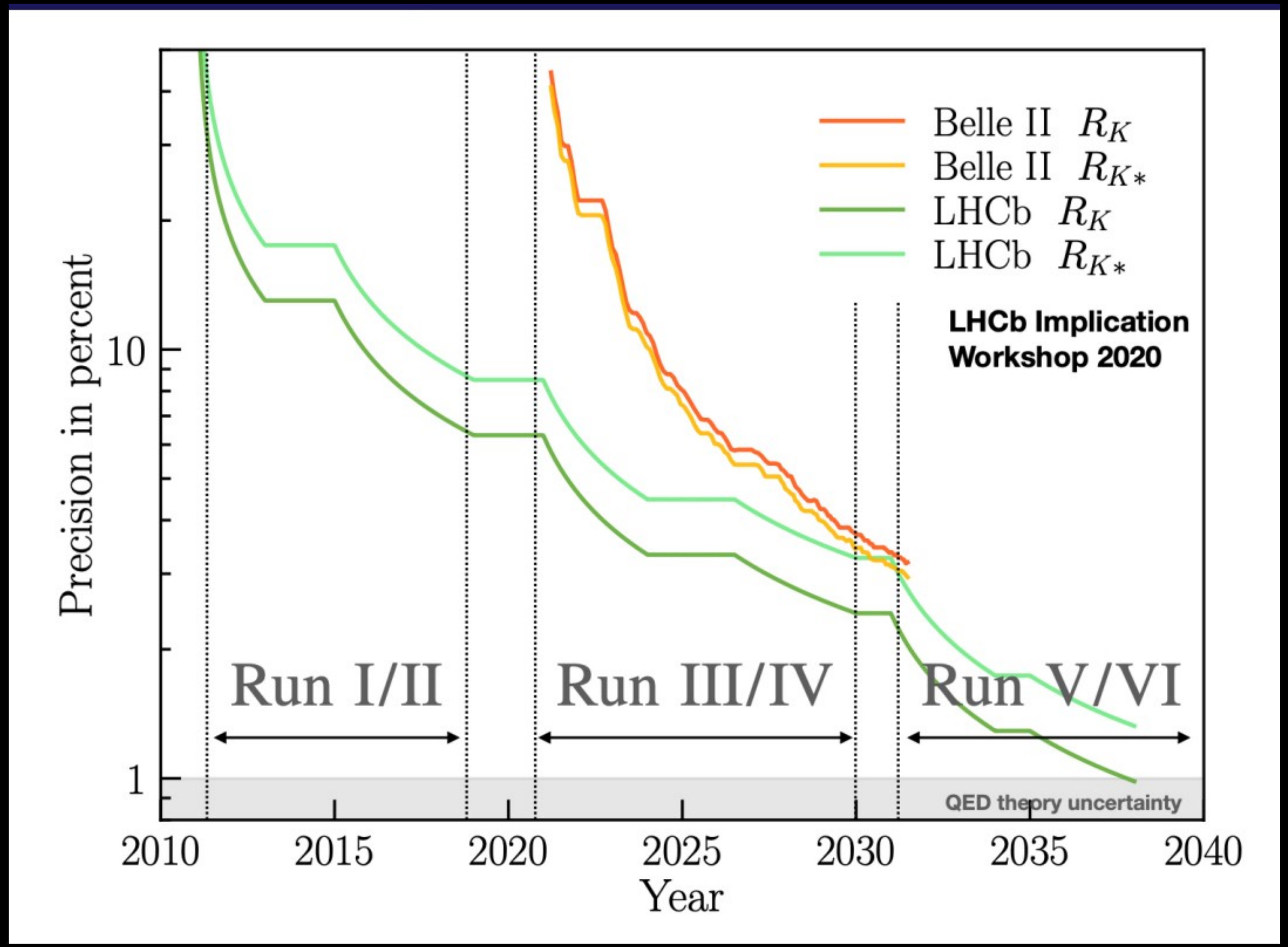
$R_{\Lambda_c^+} = 0.242 \pm 0.026$ (stat) ± 0.040 (syst) ± 0.059 (ext BF)

IN AGREEMENT WITH SM

Summary

- Branching fractions and LFU in $b \to s\ell\ell$ transitions
- R_K shows tensions with SM (3.1σ)
- $R_{K_S^0}$ and $R_{K^{*+}}$ also suggest deficit in muon mode
- Baryonic decays look promising





arXiv:2101.08326

Fig. by Martino Borsato

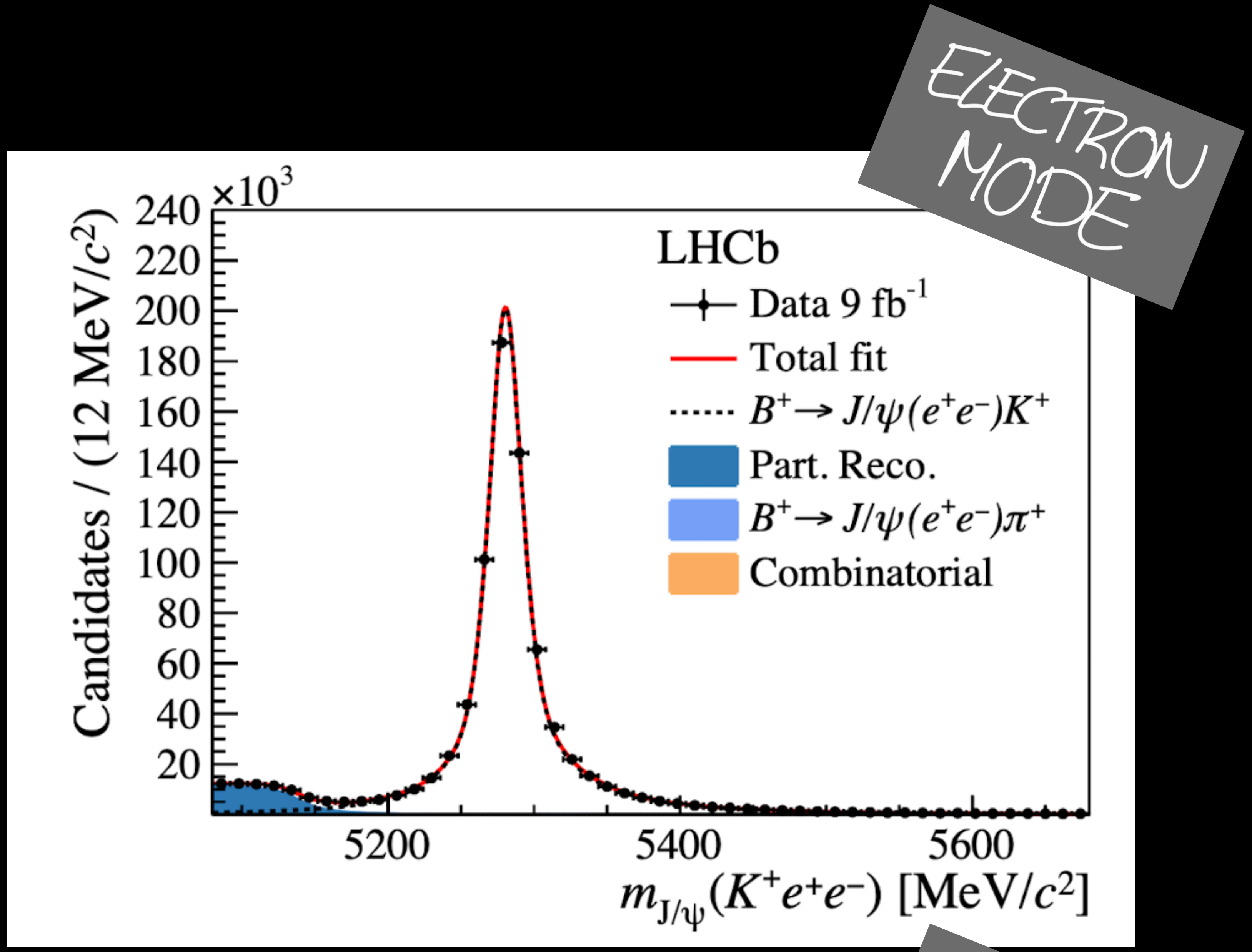
BACKUP

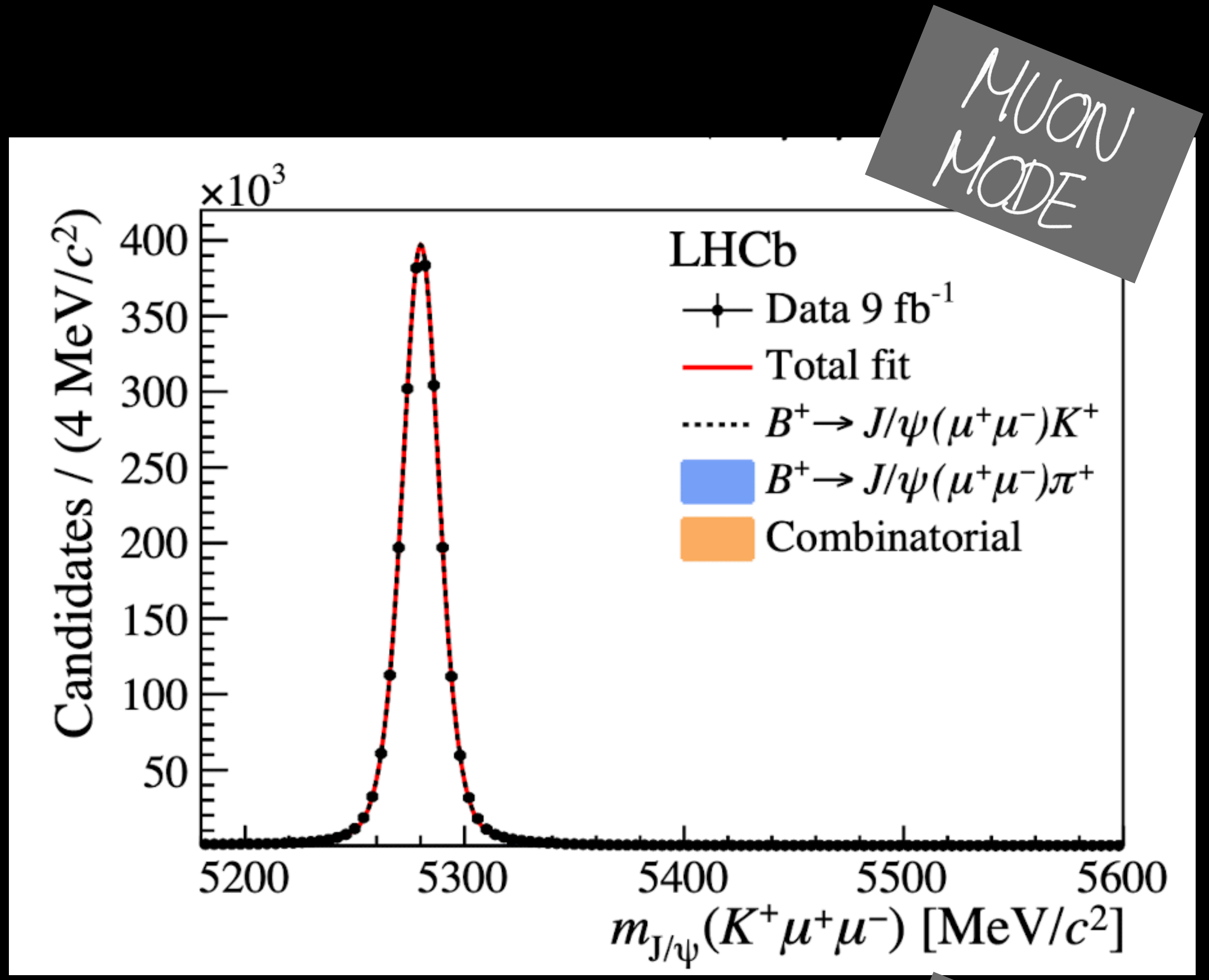
R_K fits to (non) resonant modes

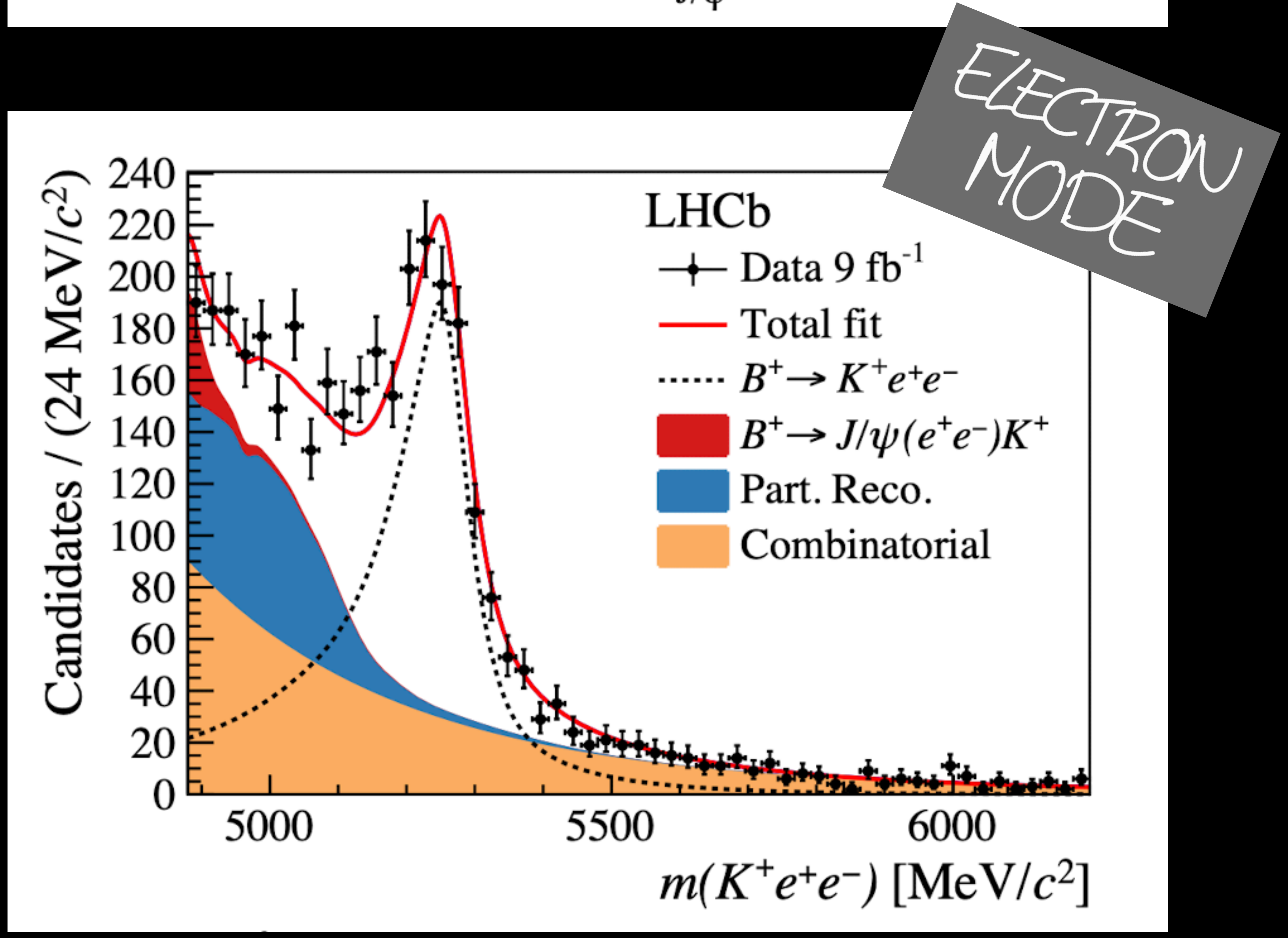
NON-RESONANT →

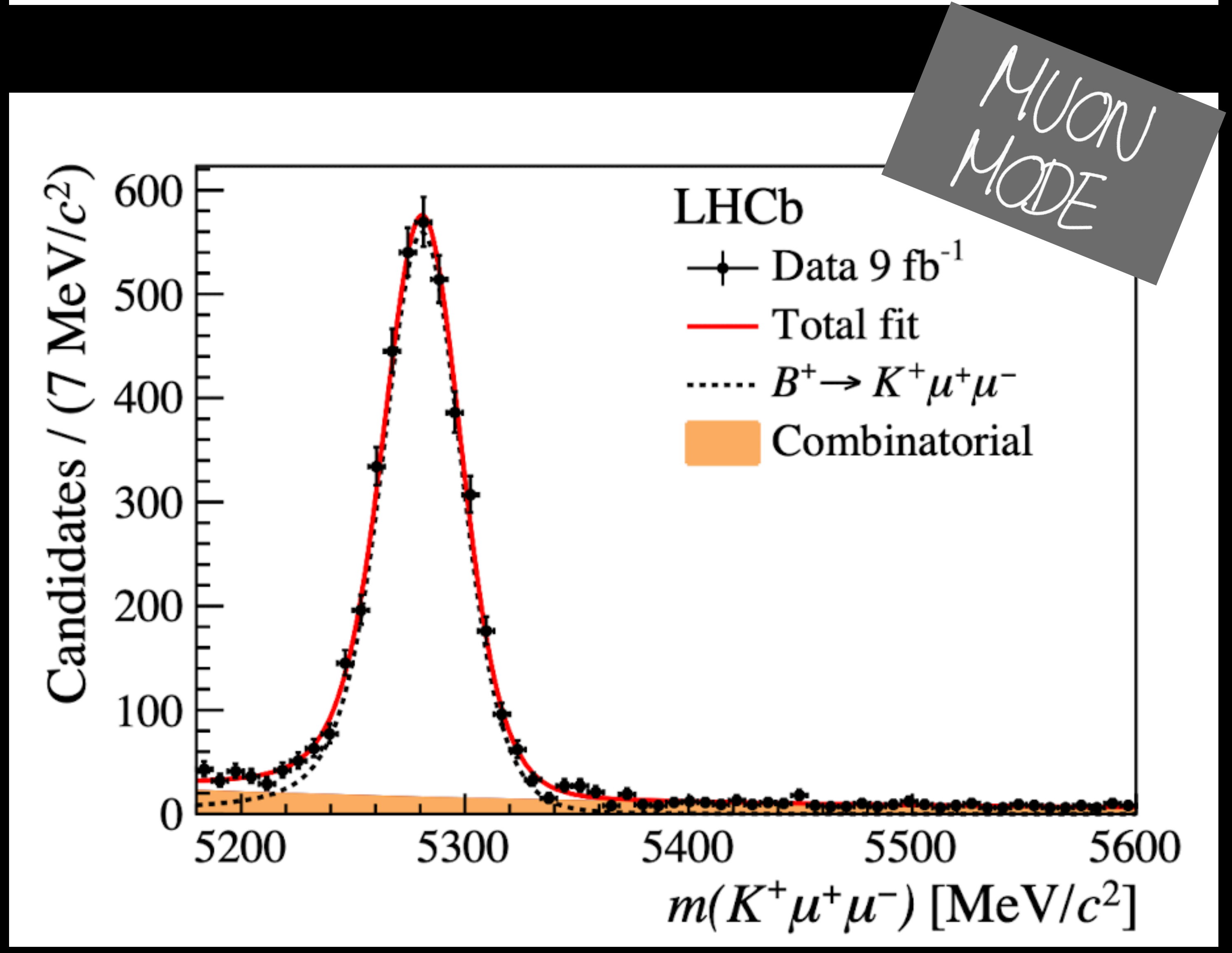
RESONANT →

Decay mode	q^2 [GeV^2/c^4]	$m_{(J/\psi)}(K^+\ell^+\ell^-)$ [GeV/c^2]
nonresonant e^+e^-	1.1 – 6.0	4.88 – 6.20
resonant e^+e^-	6.00 – 12.96	5.08 – 5.70
nonresonant $\mu^+\mu^-$	1.1 – 6.0	5.18 – 5.60
resonant $\mu^+\mu^-$	8.68 – 10.09	5.18 – 5.60









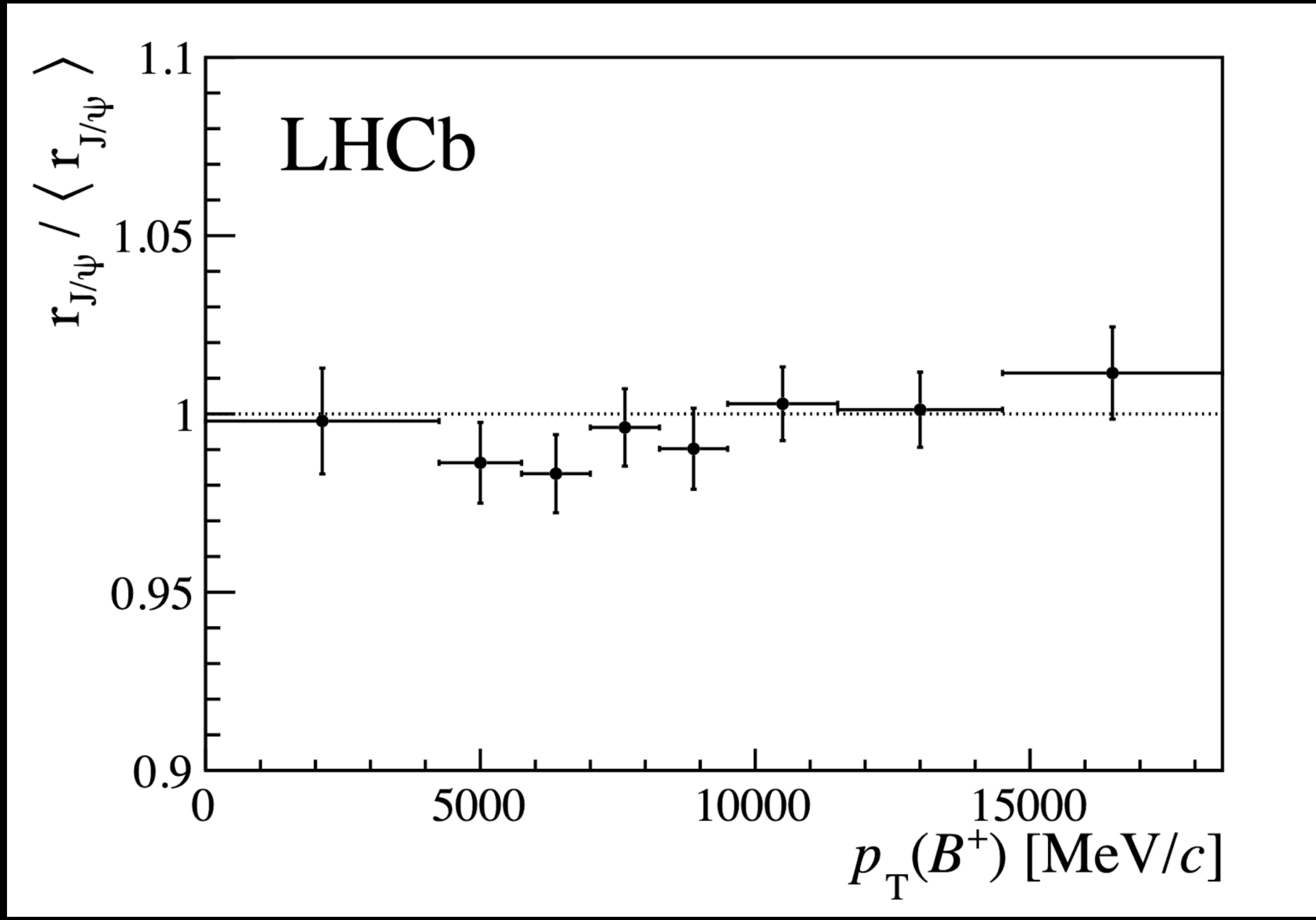
R_K cross-checks: $r_{J/\psi}$ and $R_{\psi(2S)}$

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

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

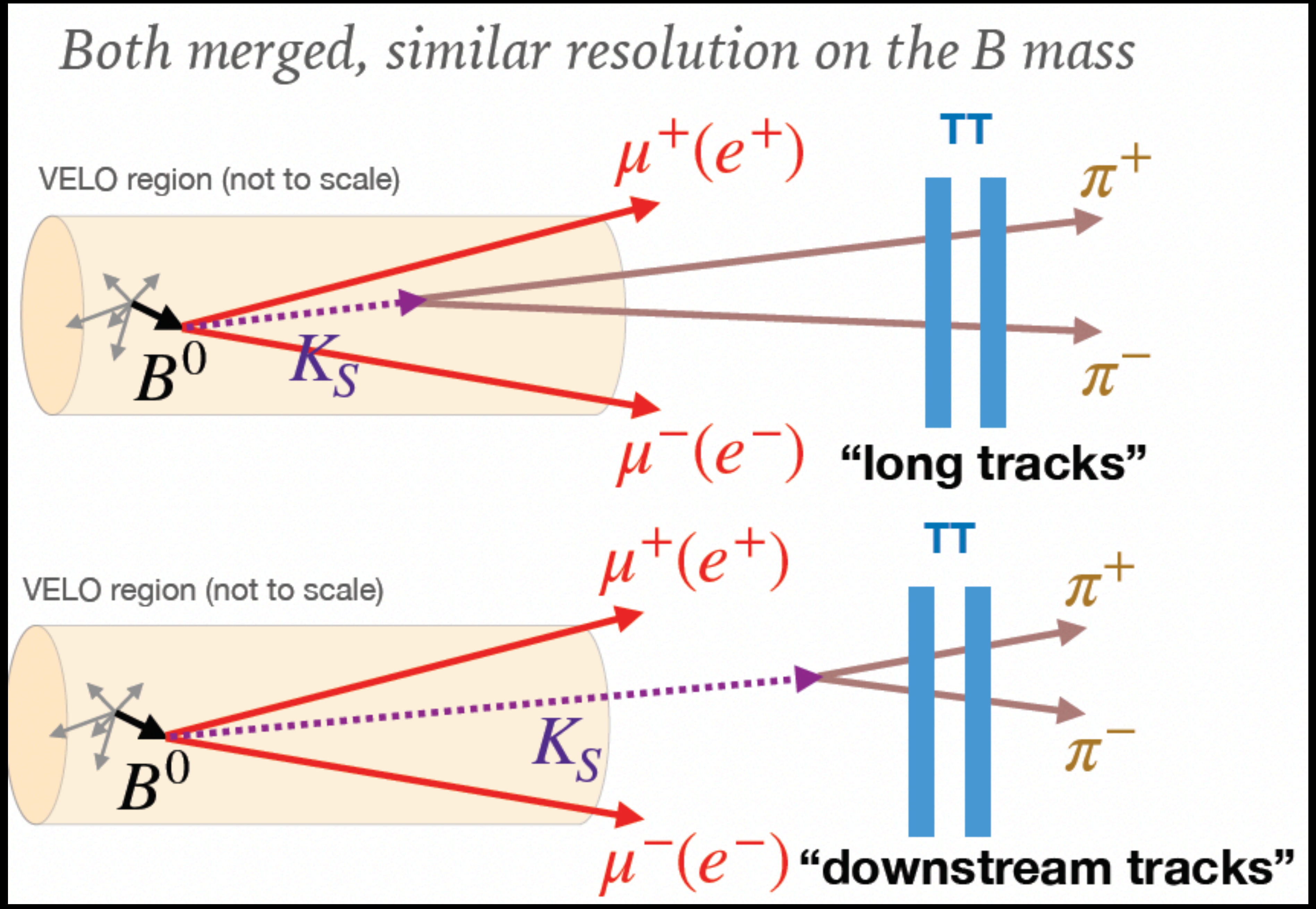
$$R_{\psi(2S)} = 0.997 \pm 0.011$$

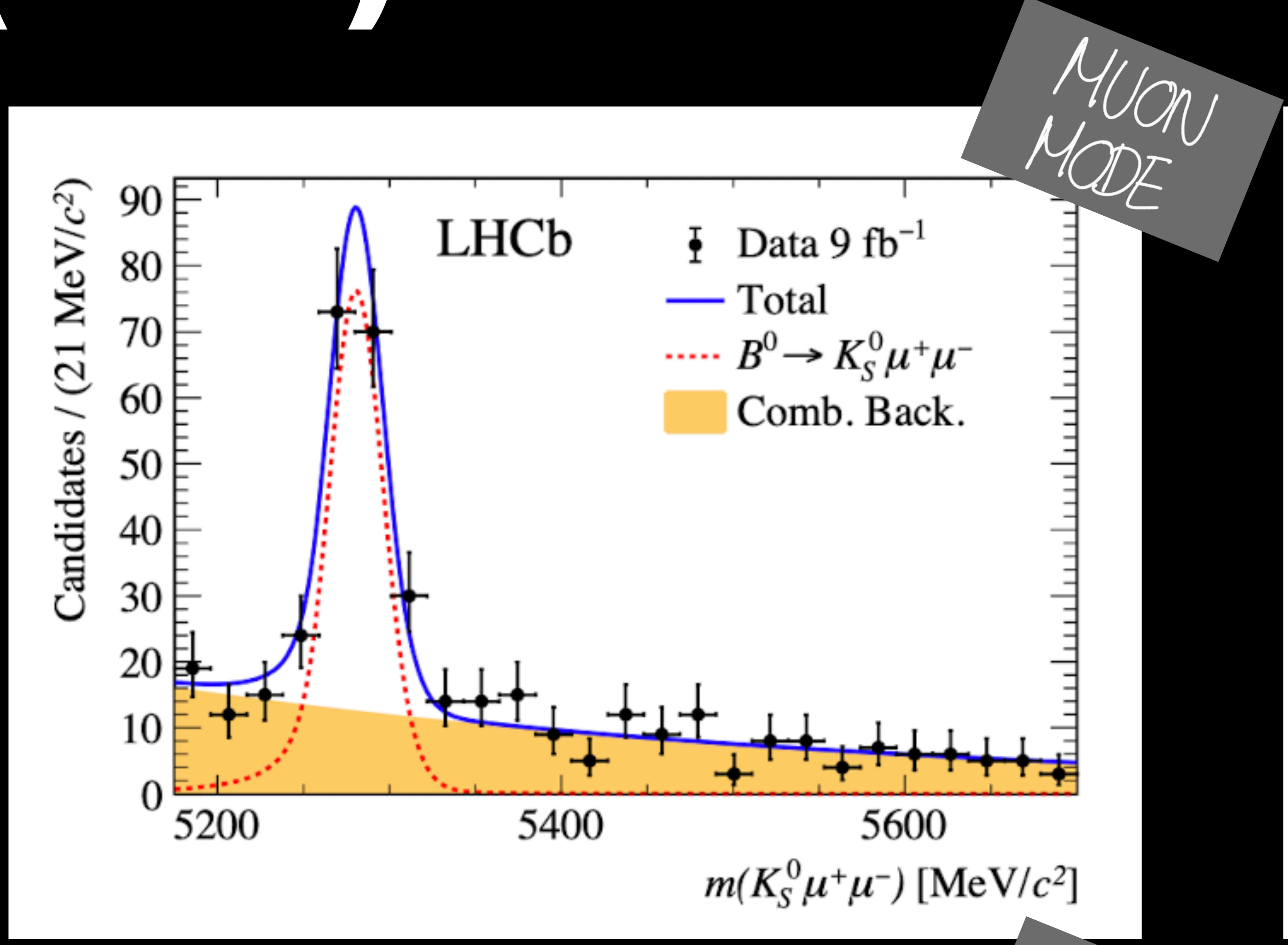
$$r_{J/\psi} = 0.987 \pm 0.020$$

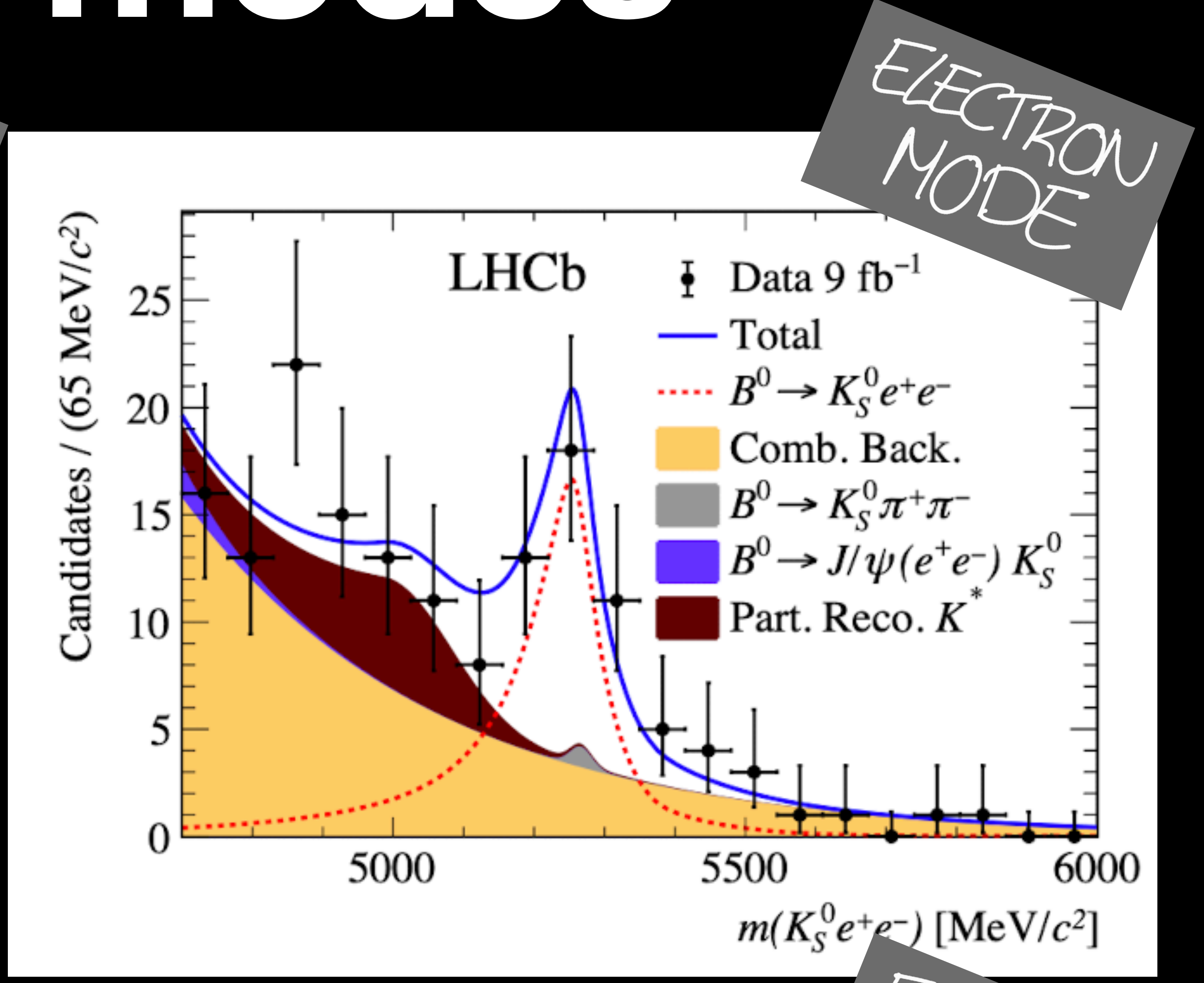


$R_{K_S^0}$ fits to (non) resonant modes

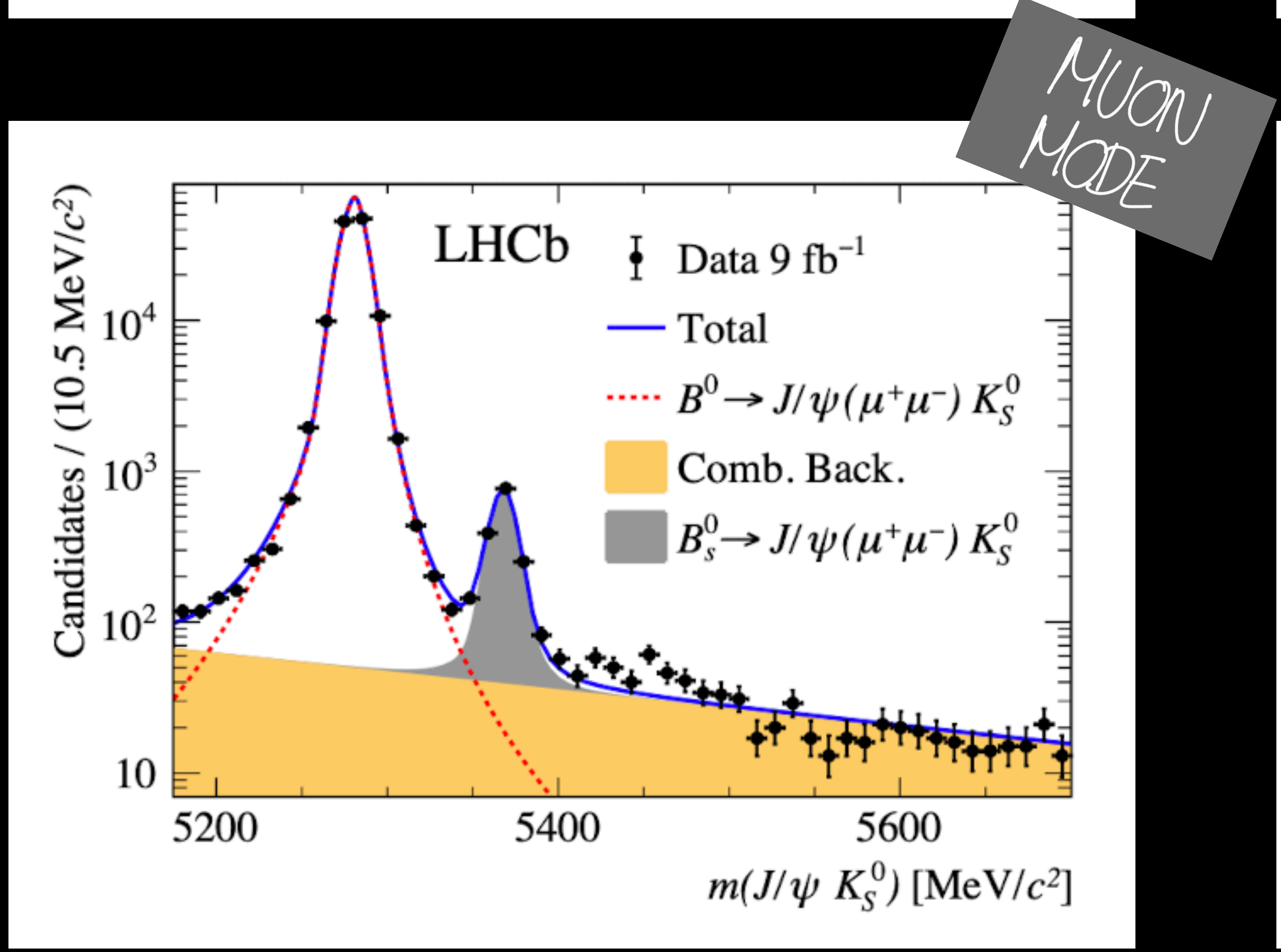
NON-RESONANT →

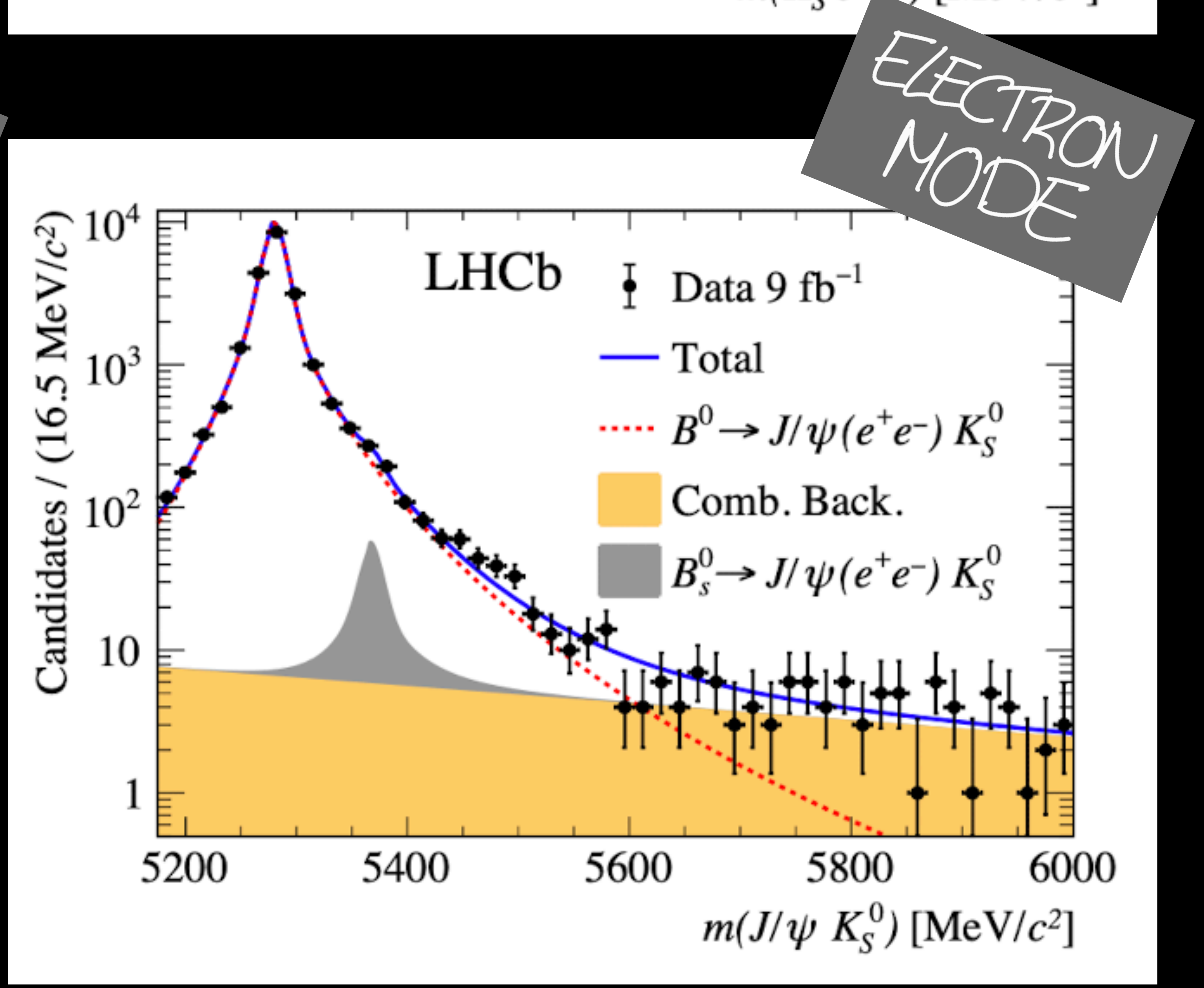






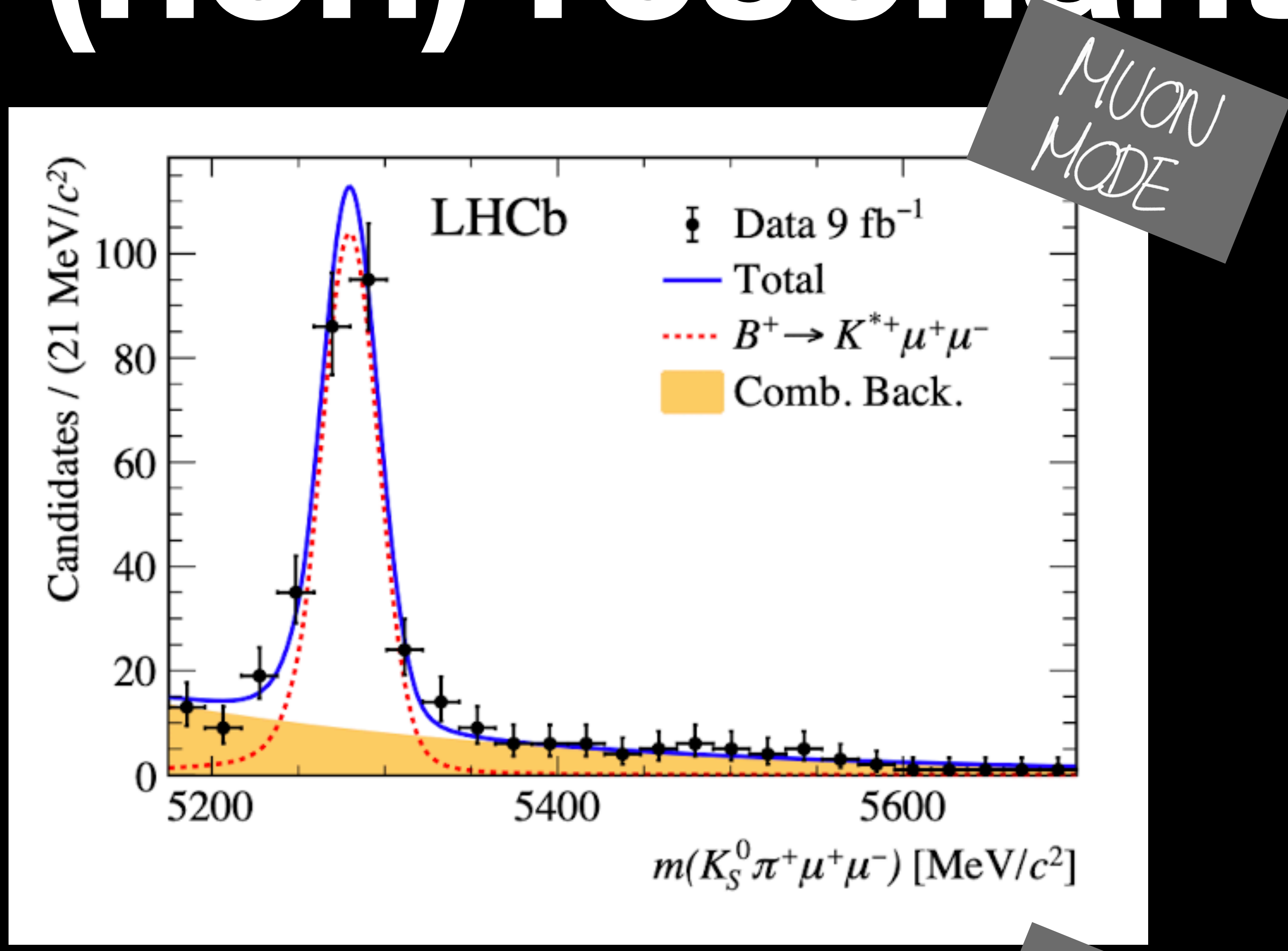
RESONANT →

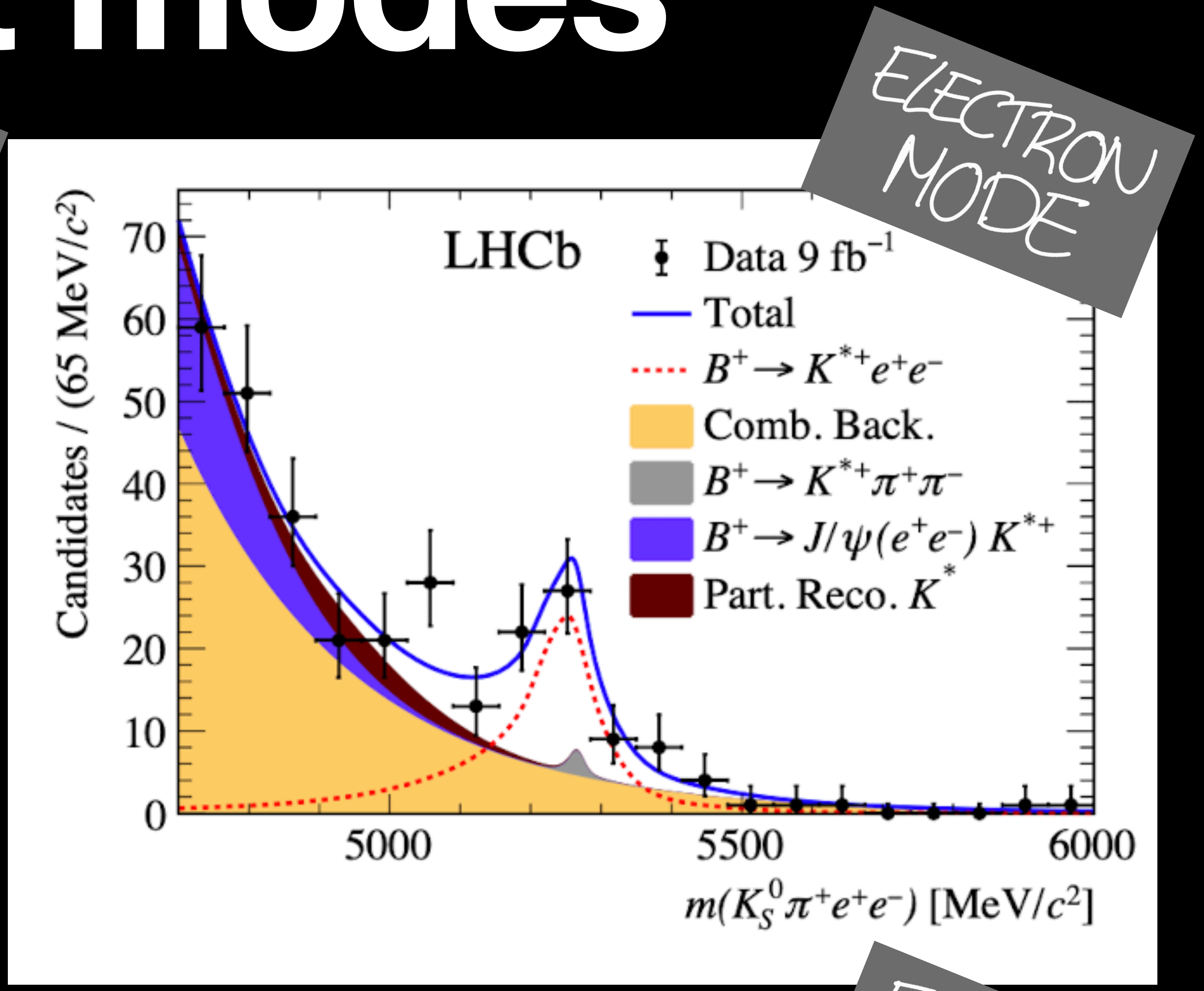




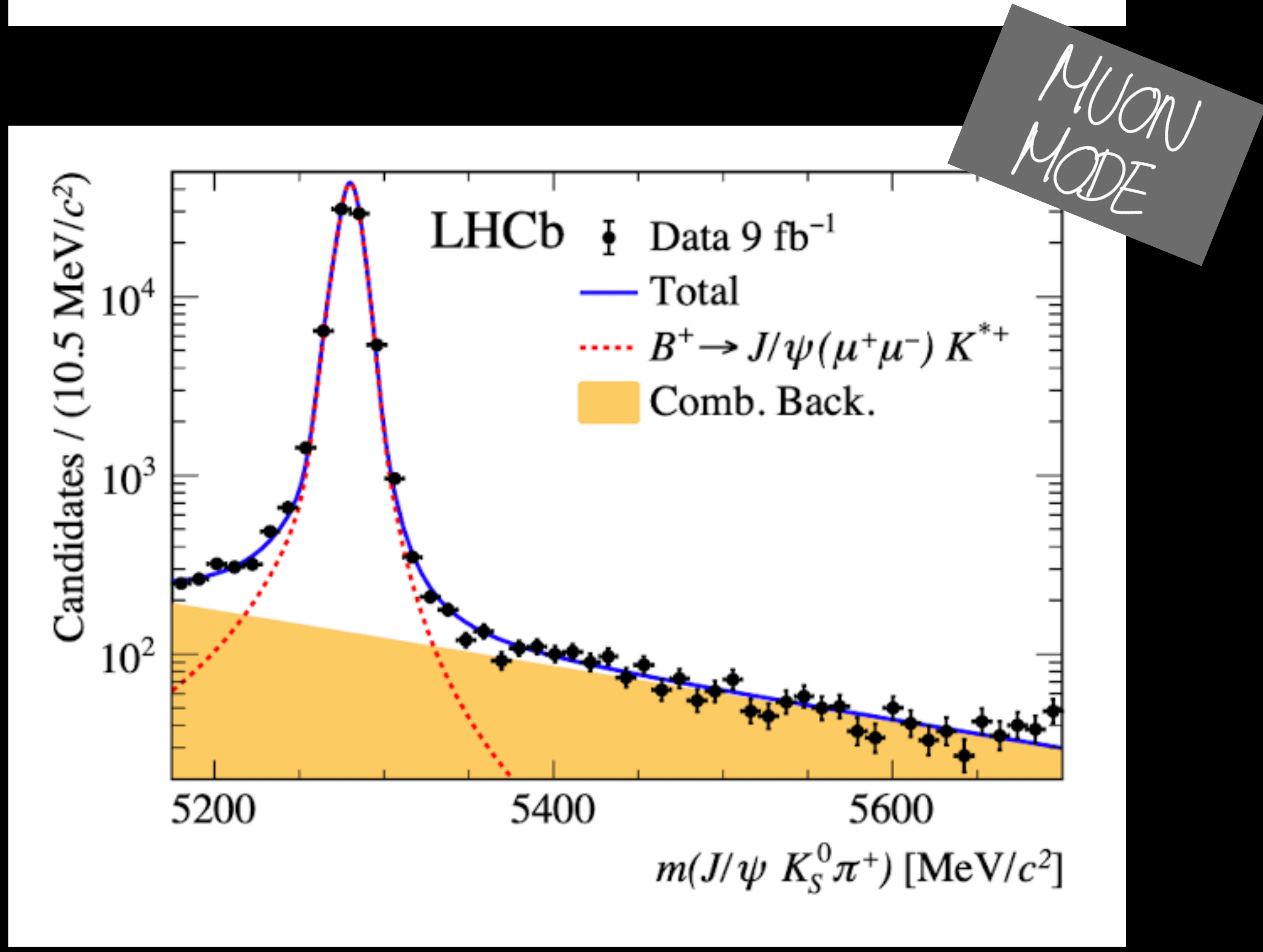
$R_{K^{*+}}$ fits to (non) resonant modes

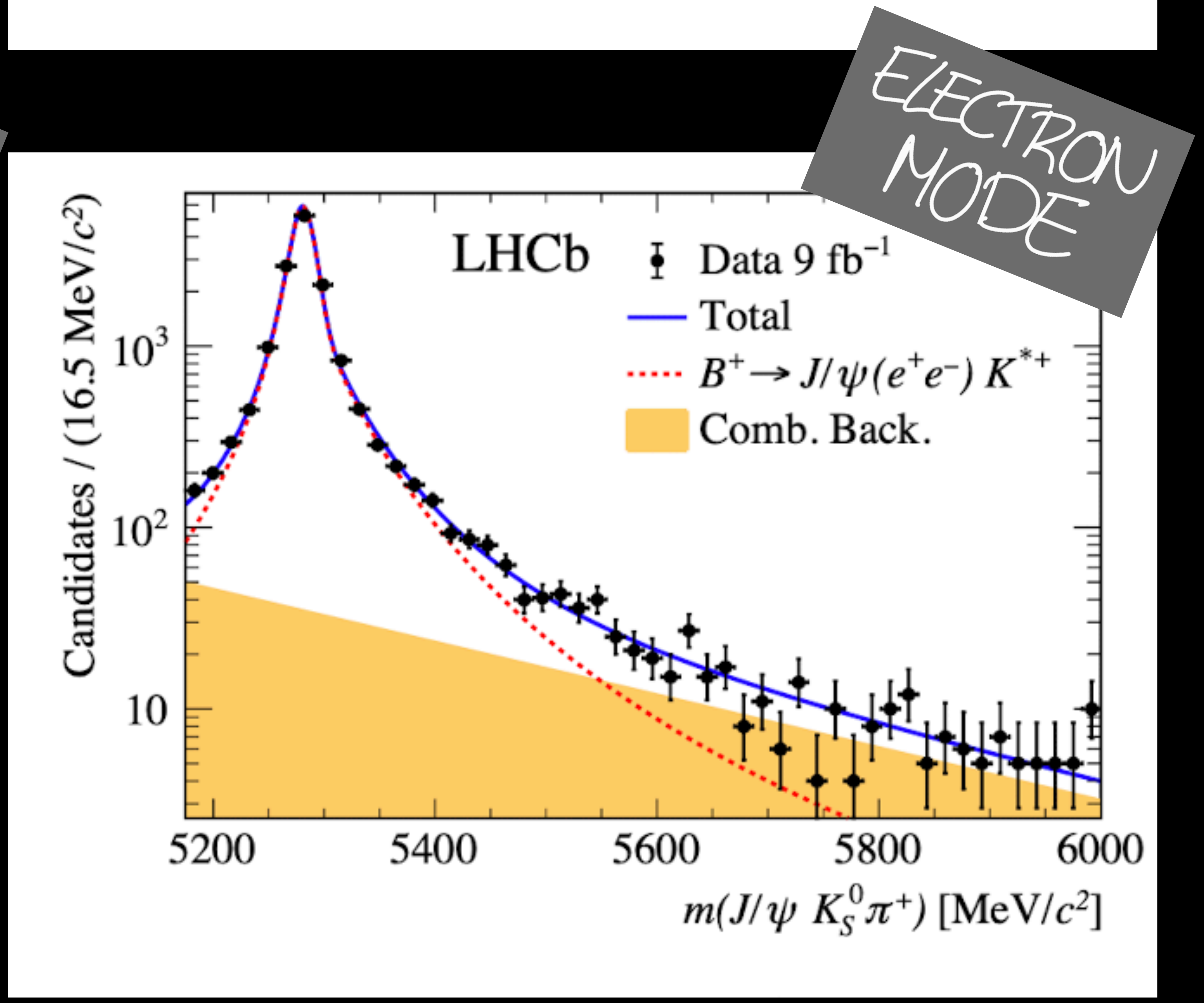
NON-RESONANT →





RESONANT →





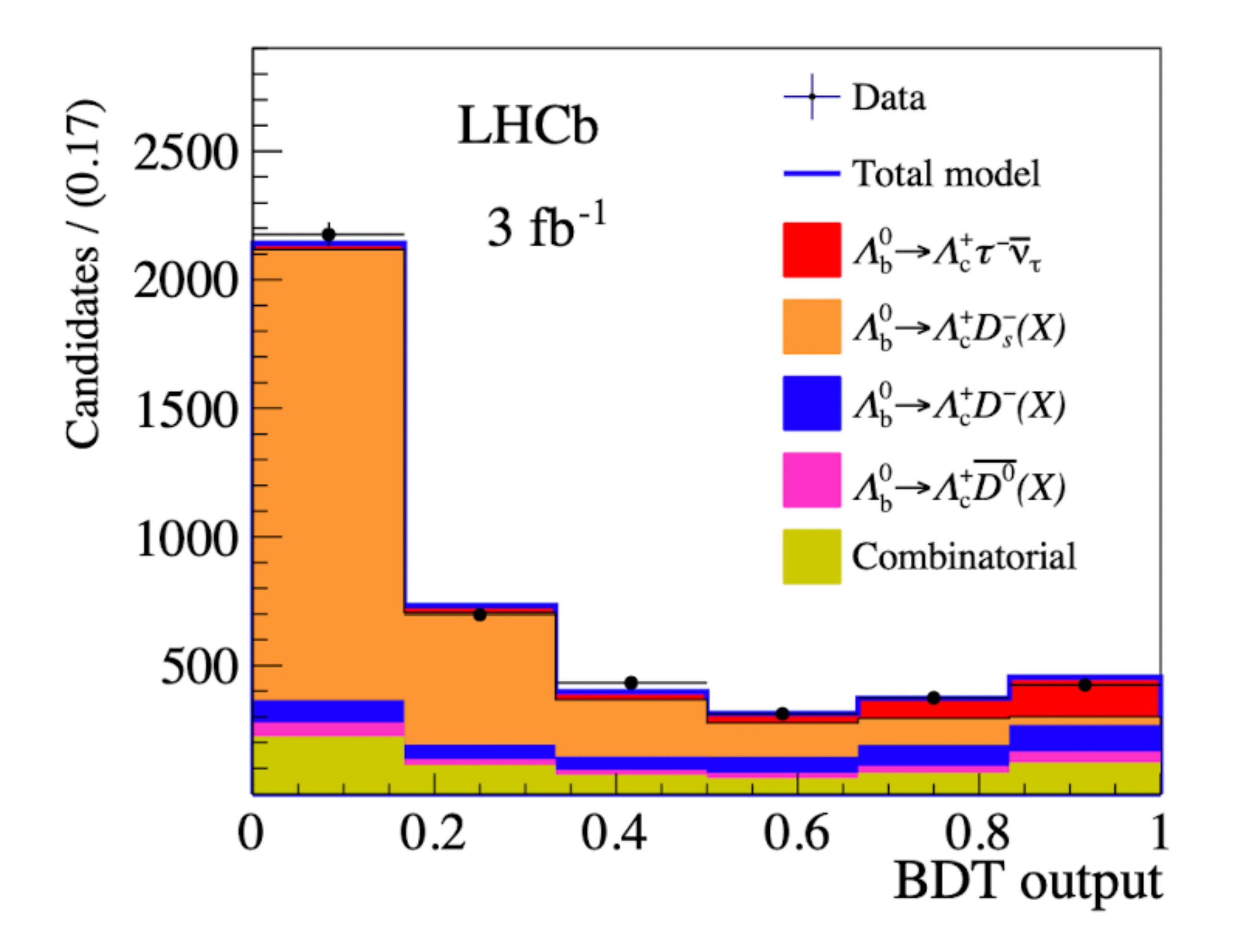
$R_{\Lambda_c^+}$ fit projections

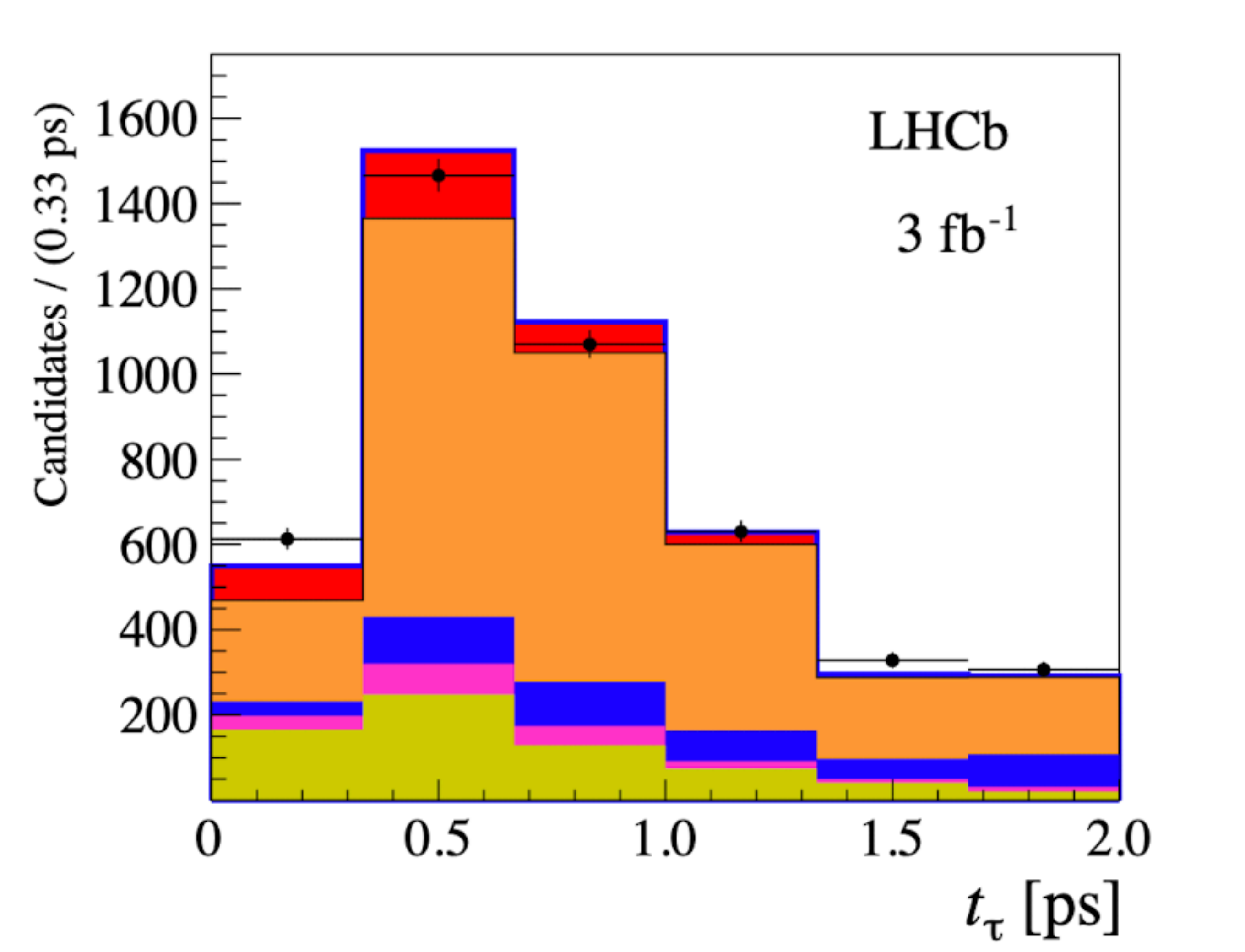
- $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ NORMALIZED TO $\Lambda_b^0 \to \Lambda_c^+ \pi\pi\pi$

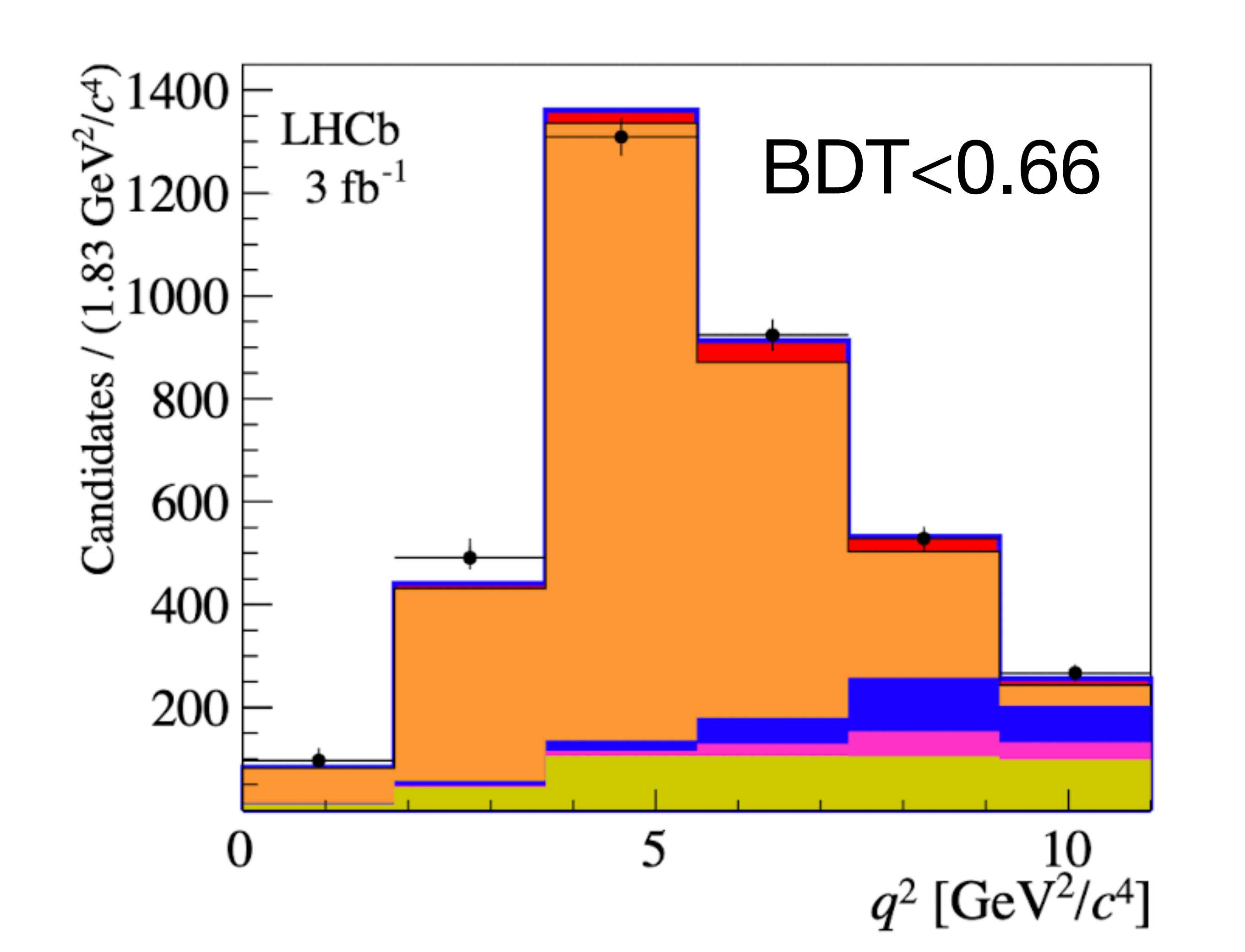
$$\mathcal{K}(\Lambda_c^+) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}$$

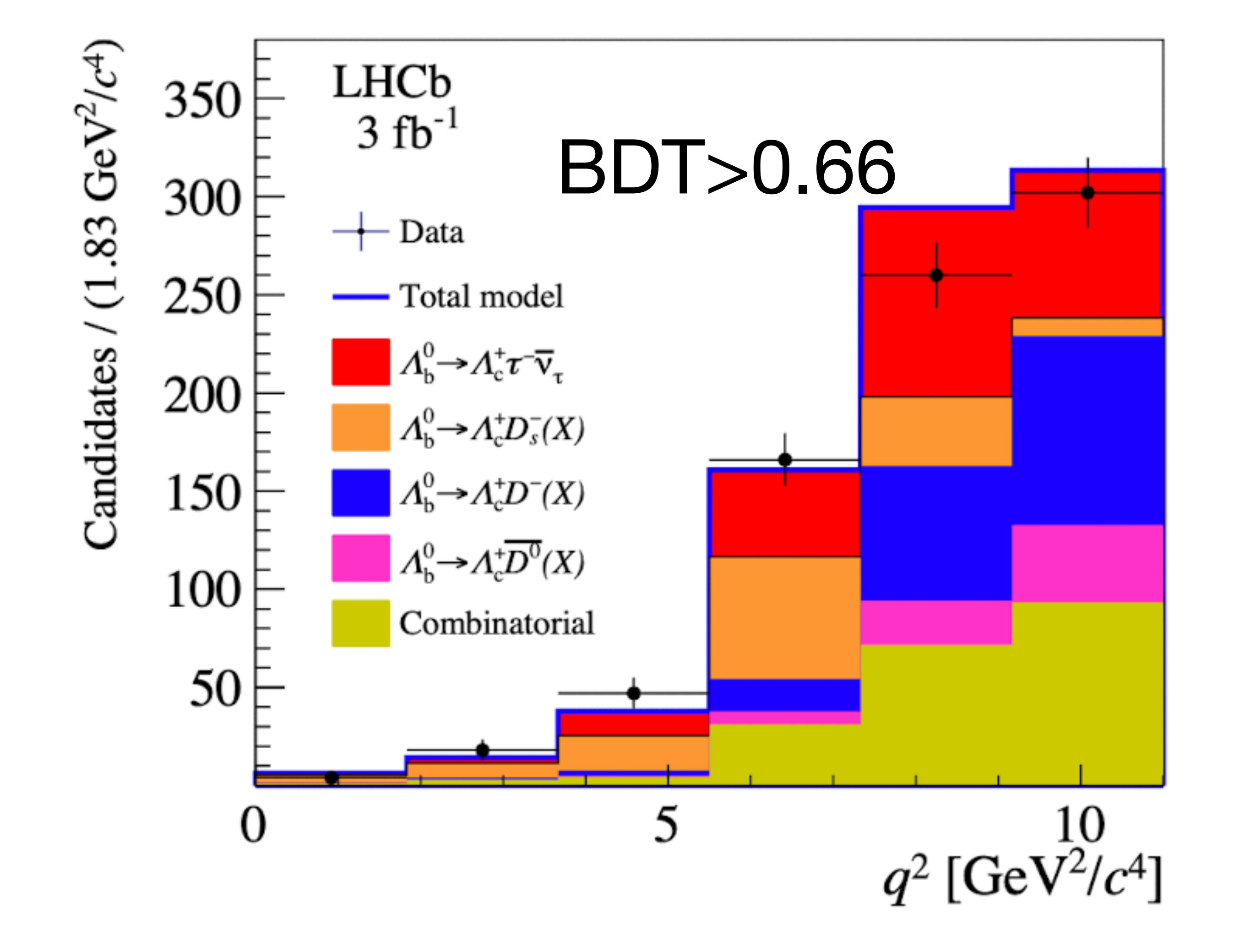
- USE EXTERNAL INPUT TO OBTAIN $R_{\Lambda_c^+}$:

$$\mathcal{R}(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \times \left(\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \right)_{\text{external}}$$









$R_{\Lambda_c^+}$ backgrounds

BACKGROUNDS:

* $\Lambda_b^0 \to \Lambda_c^+ \pi\pi\pi X$: SUPPRESSED REQUIRING τ DISPLACEMENT
* $\Lambda_b^0 \to \Lambda_c^+ D_s (\to \pi\pi\pi X)$: SUPPRESED WITH τ DECAY DYNAMICS
* COMBINATORIAL PARAMETRISED ON Λ_c^+ SIDEBANDS AND WRONG-CHARGE DATA