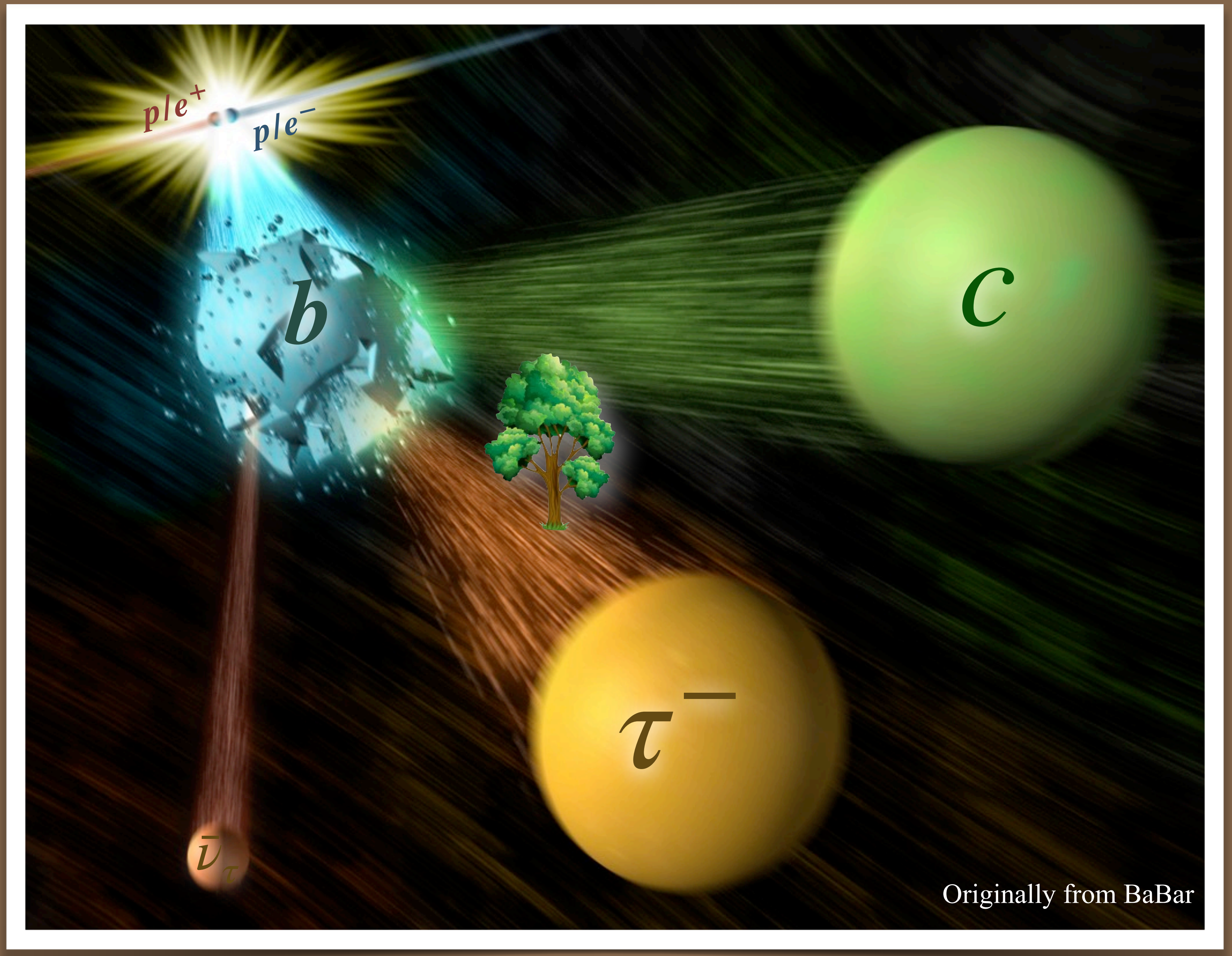
$\mathscr{R}\left(D^{(*)}\right)$, $\mathscr{R}_{K^{(*)}}$, and their cousins: update on the continued challenges to lepton flavor universality

Manuel Franco Sevilla

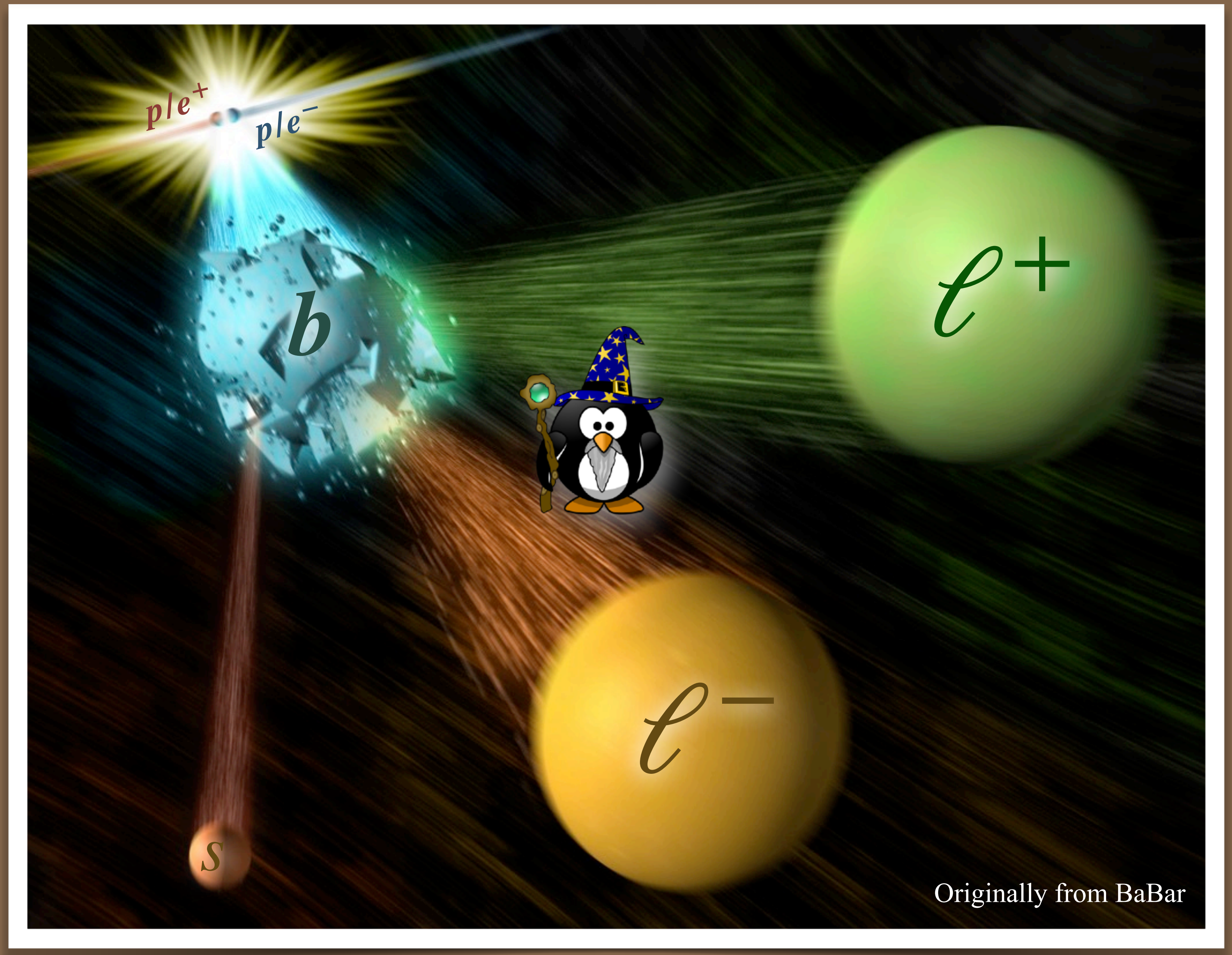
University of Maryland



5th May 2021

Virtual joint

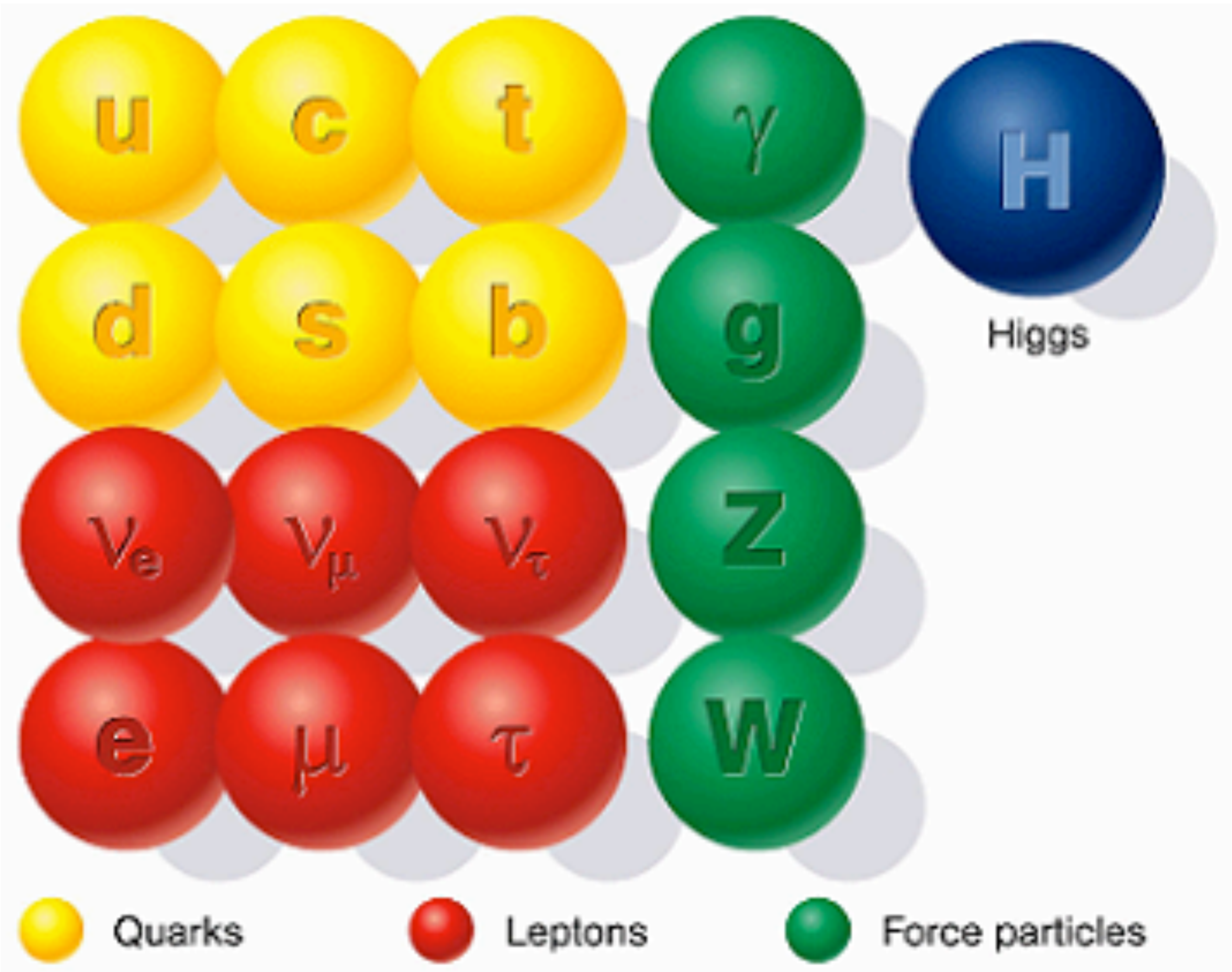
JHU/UMD seminar



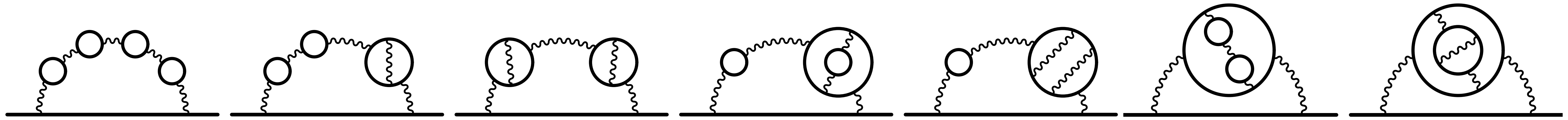
Penguin from Jeff Brassard

The SM is pretty good

- Assume **Universe** is $SU(3) \times SU(2)_L \times U(1)$ **symmetric**, put in a few particles, and bam!, **most precise** and **comprehensive theory** in the **history of mankind**



Anomalous magnetic dipole moment



12,672 diagrams of 10th order

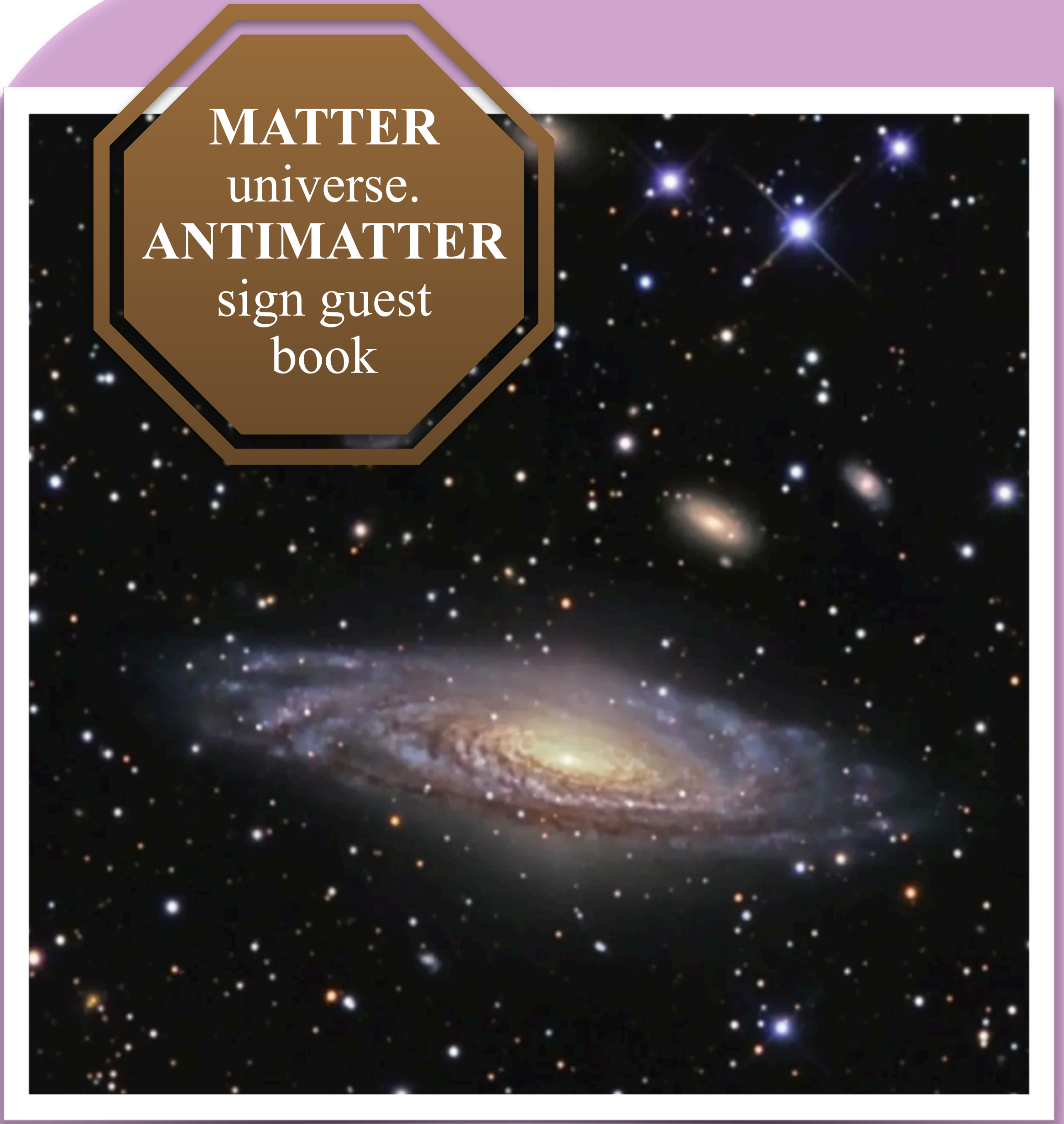
$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{SM}} = 0.001\ 159\ 652\ 181\ 606\,(230)$$

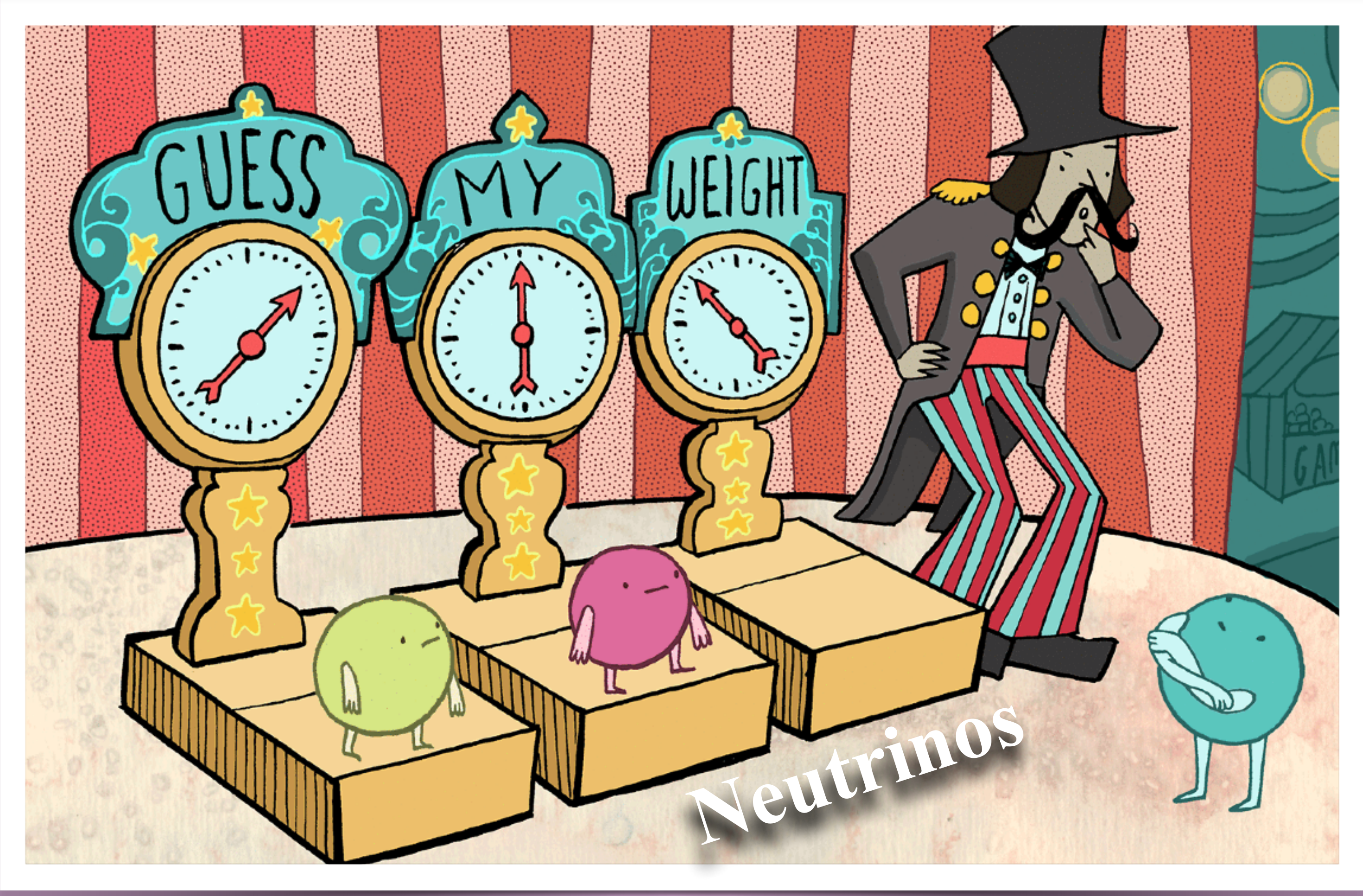
Atoms 7, 28 (2019)

$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{exp}} = 0.001\ 159\ 652\ 180\ 73\,(28)$$

Phys. Rev. Lett. 100, 120801 (2008)

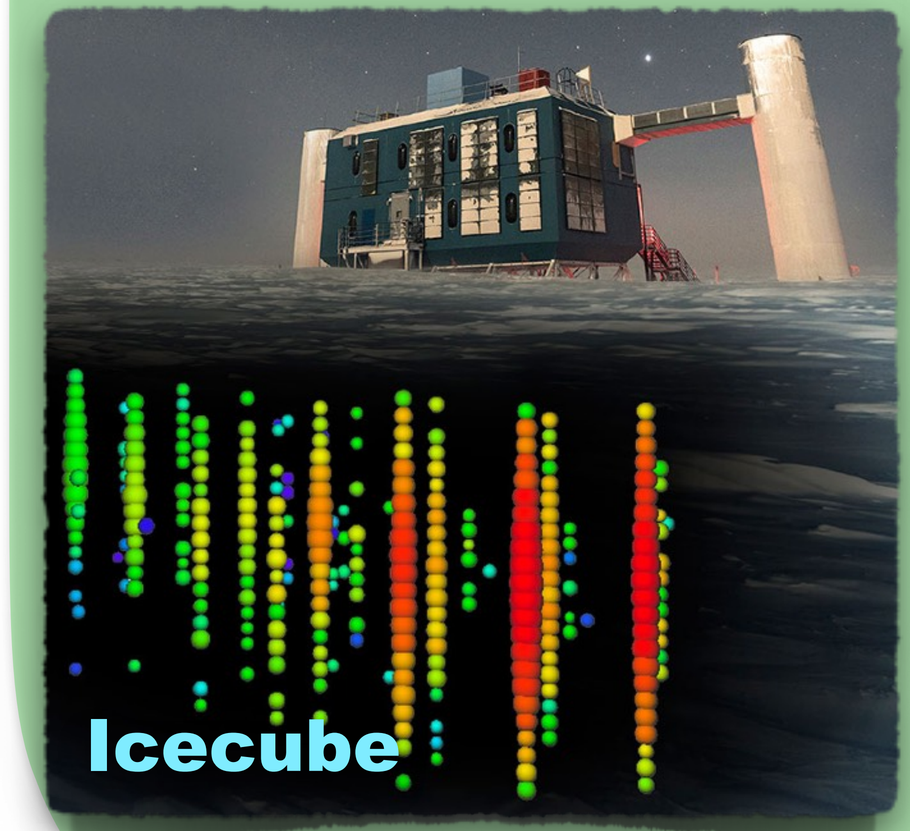
Beyond the SM

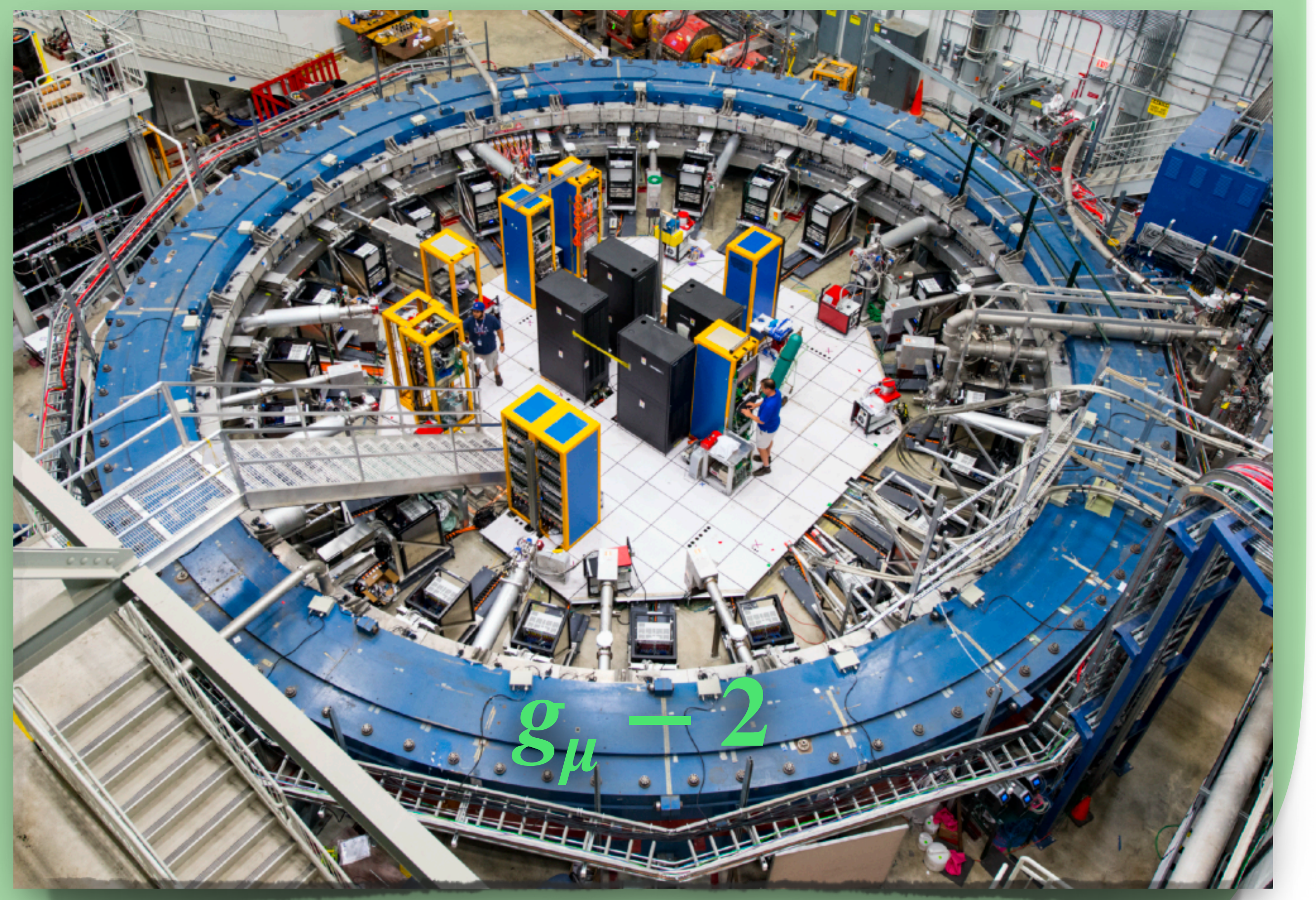




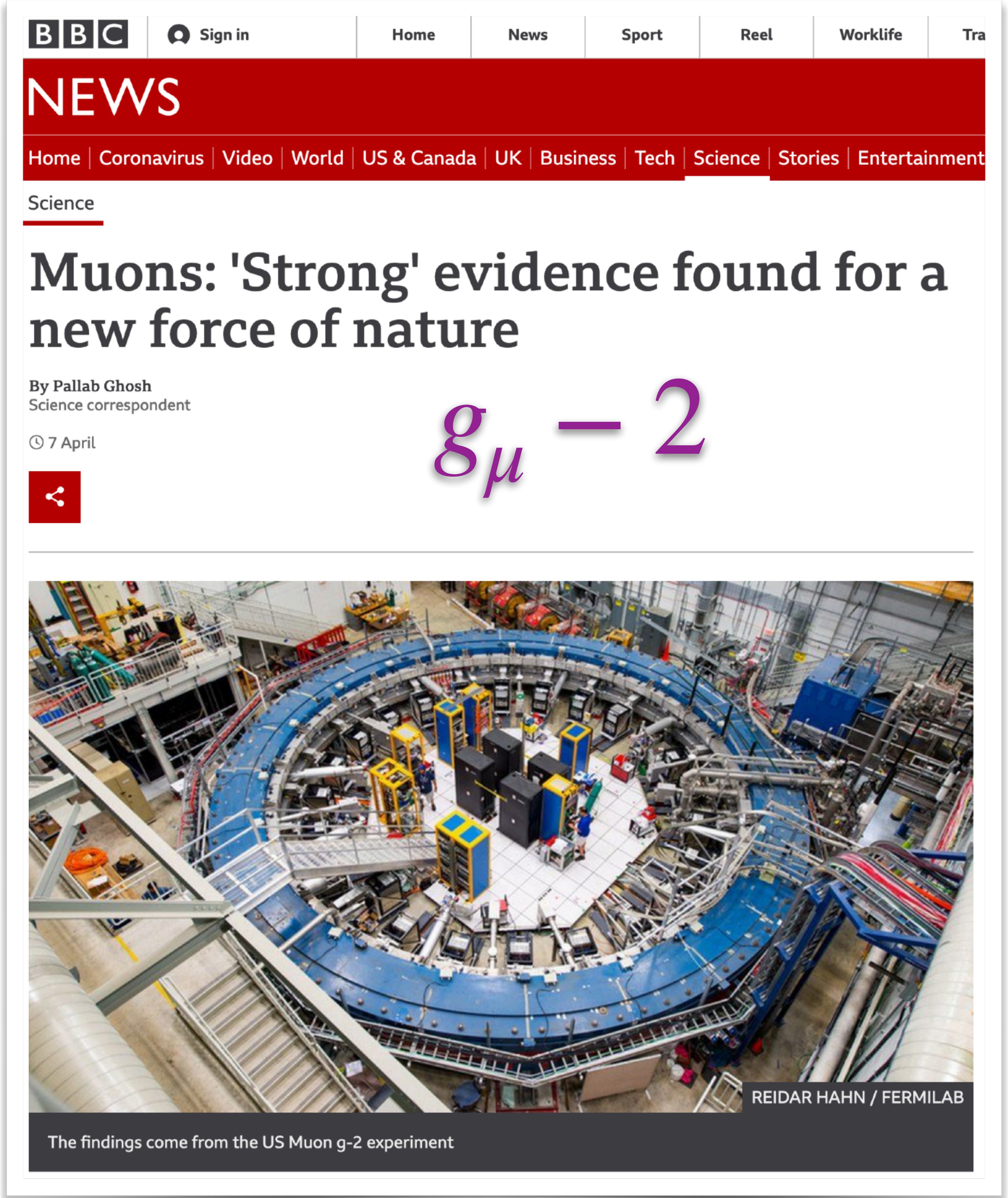
Sill, many questions left

Looking in many directions





Testing the SM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Science

Muons: 'Strong' evidence found for a new force of nature

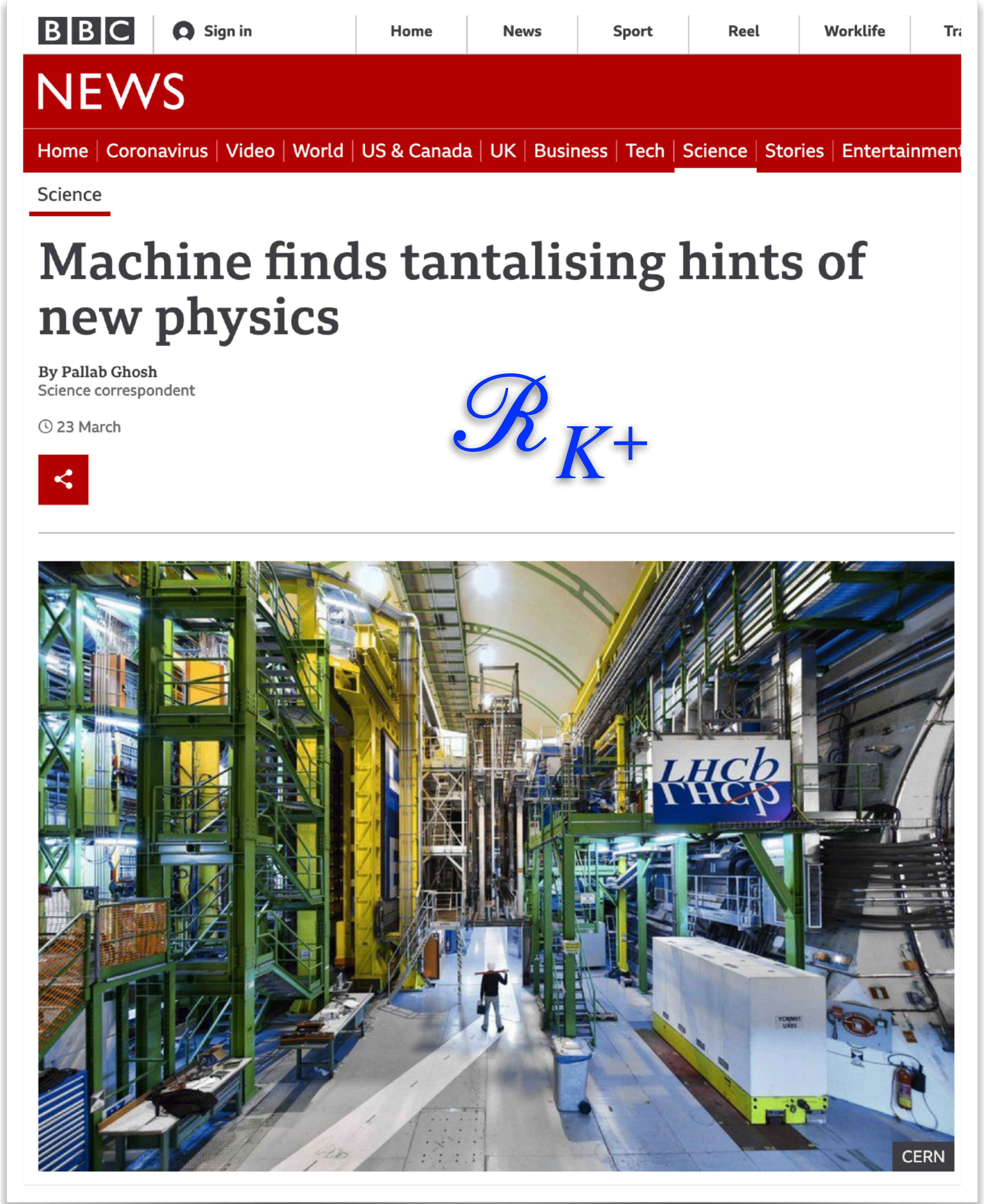
By Pallab Ghosh
Science correspondent

7 April

REIDAR HAHN / FERMILAB

The findings come from the US Muon g-2 experiment

$g_\mu - 2$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Science

Machine finds tantalising hints of new physics

By Pallab Ghosh
Science correspondent

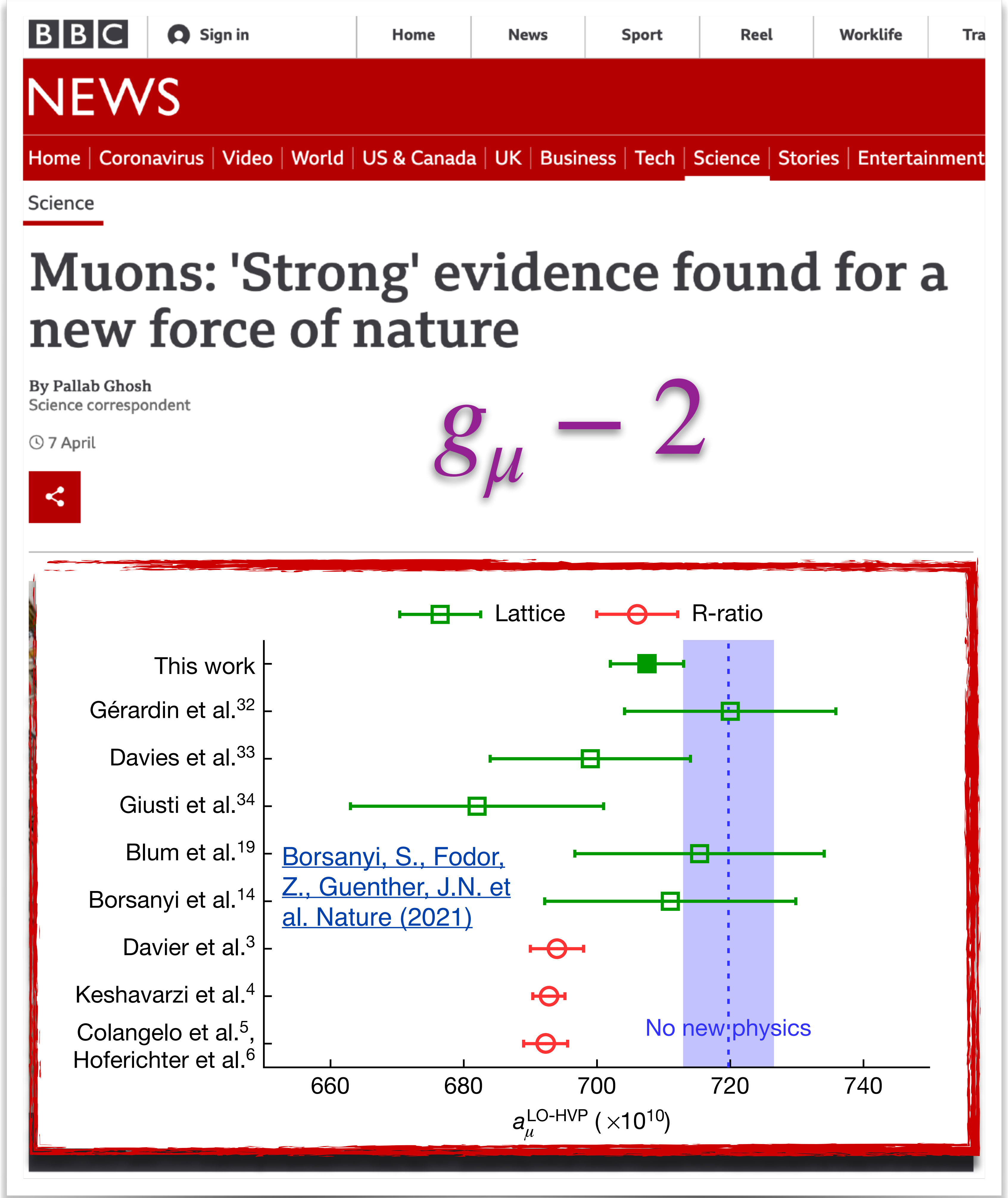
23 March

CERN

$\mathcal{R}_{K^+}$

- Alas, **no direct detection yet**
- Can access **mass scales beyond** the reach of **current particle accelerators** through **<u>precision tests</u>**
  - ➡ **Flavor physics** (study of quark and lepton species) is a key tool

Testing the SM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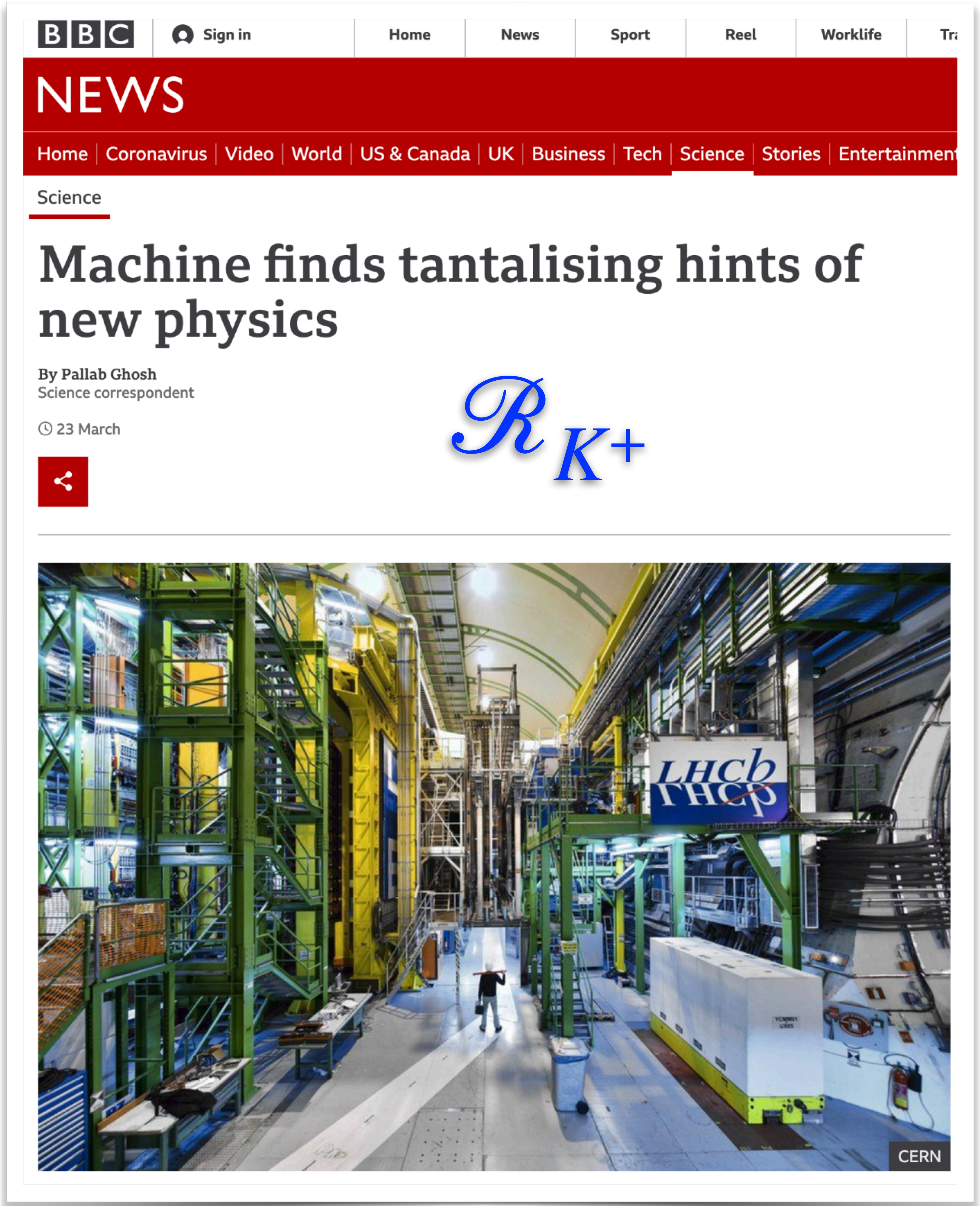
$g_\mu - 2$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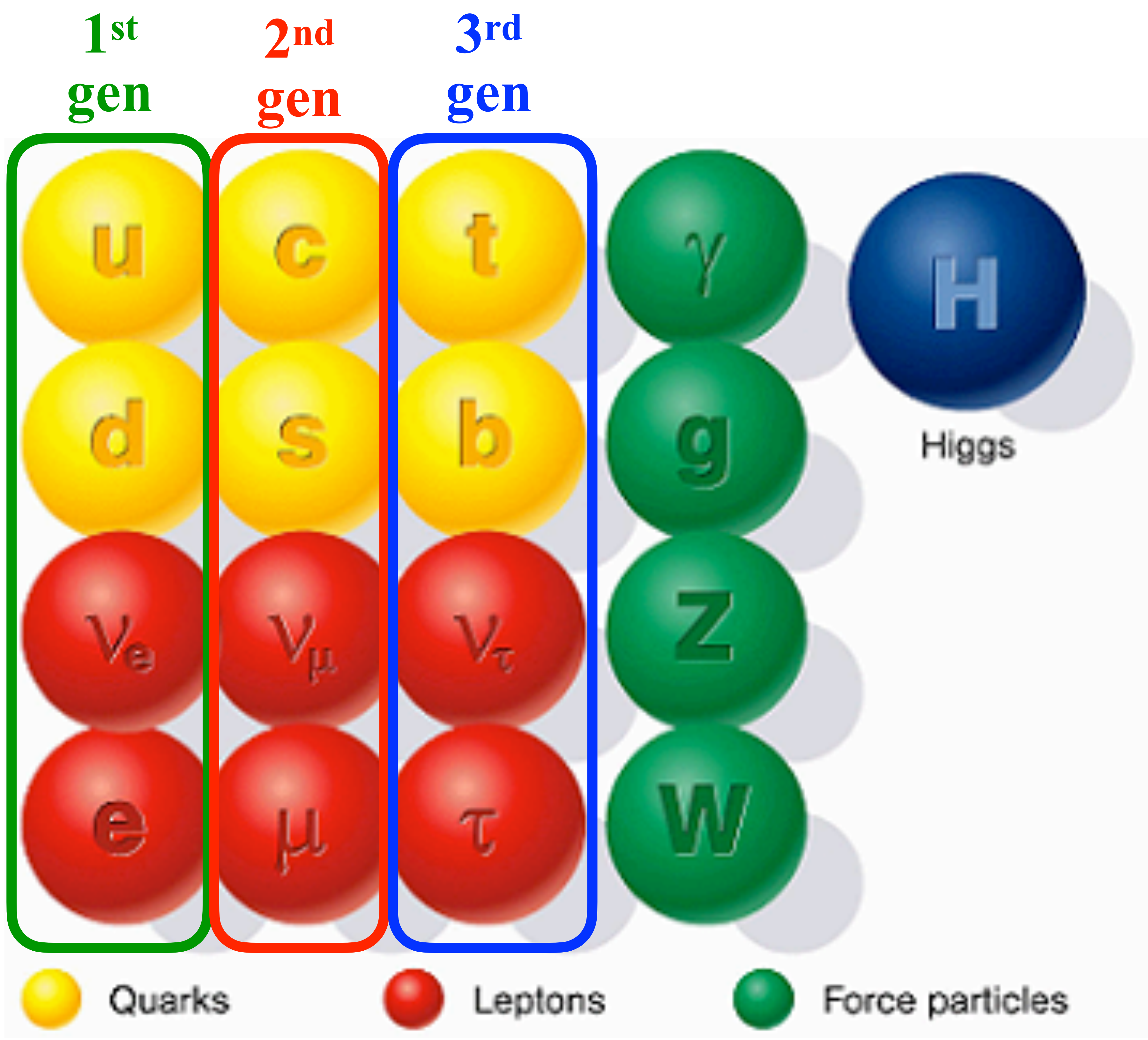
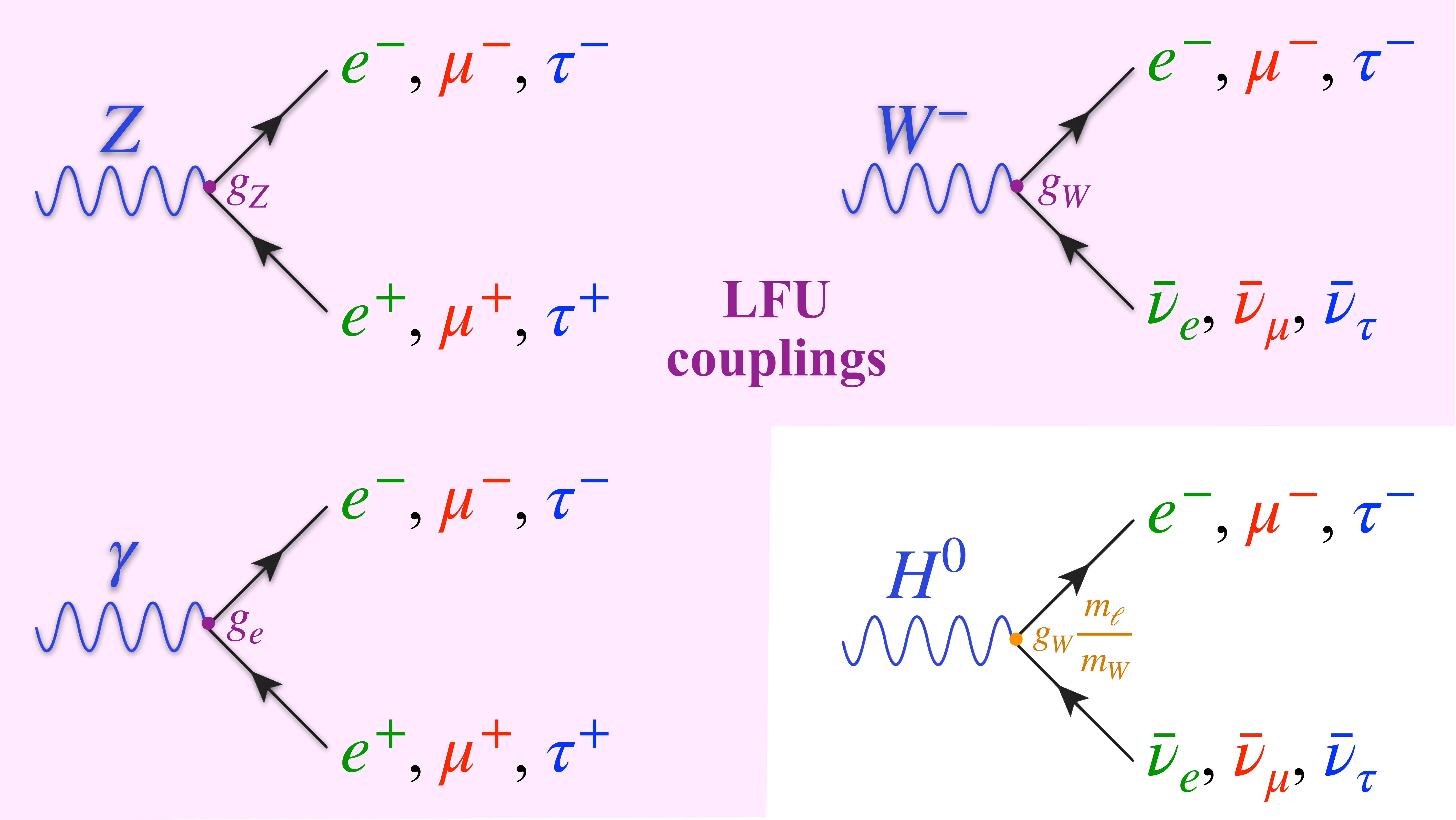
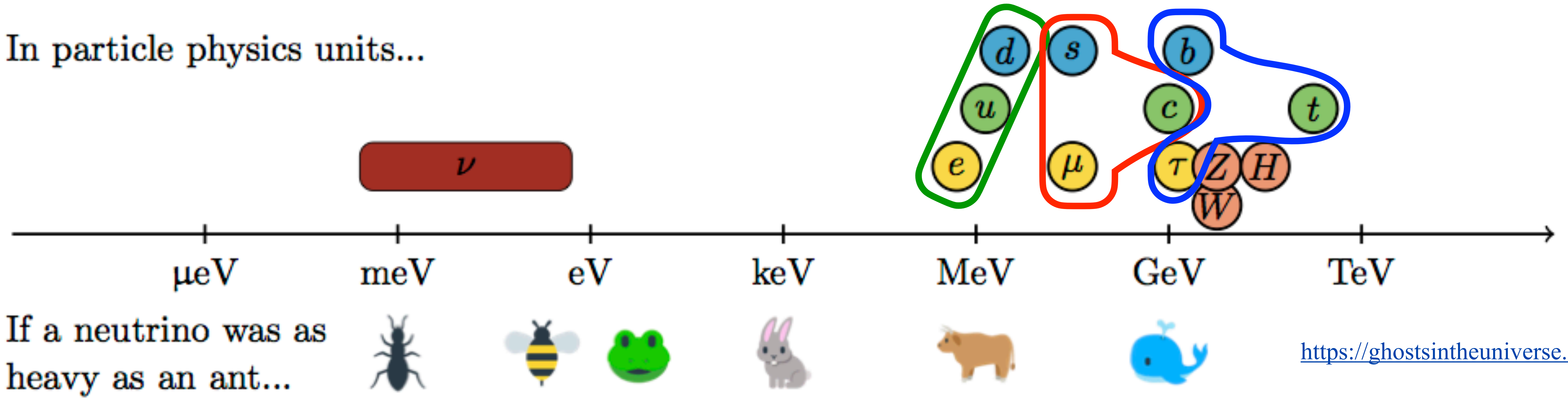
$\mathcal{R}_{K+}$

- Alas, **no direct detection yet**
- Can access **mass scales beyond** the reach of **current particle accelerators** through **precision tests**
  - **Flavor physics** (study of quark and lepton species) is a key tool

- It is assumed that electroweak gauge **couplings** to **3 fermion generations** are **identical**







https://ghostsintheuniverse.org/theory/

LFU tested to great precision

LFU tests with 1st/2nd gen.

To **0.28%** in Z decays

$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028$$

LEP, Phys. Rept. 427 (2006) 257

To **0.8%** in W decays

$$\frac{\mathcal{B}(W\to e\nu)}{\mathcal{B}(W\to\mu\nu)} = 1.004 \pm 0.008$$

CDF + LHC, JPG: NPP, 46, 2 (2019)

To **0.31%** in meson decays

$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$

PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{K\to e\nu}}{\Gamma_{K\to\mu\nu}} = (2.488 \pm 0.009) \times 10^{-5}$$

PDG (NA62), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.230 \pm 0.004) \times 10^{-4}$$

PiENu, Phys. Rev. Lett. 115, 071801 (2015)

To **0.14%** in $\tau \to \ell\nu\nu$

$$g_\mu/g_e = 1.0018 \pm 0.0014$$

PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

LFU tests with 3rd gen.

To **0.32%** in Z decays

$$\frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032$$

LEP, Phys. Rept. 427 (2006) 257

2.6σ tension in W decays

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 1.070 \pm 0.026$$

LEP, Phys. Rept. 532 (2013) 119,

To **1.3%** in W decays

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 0.992 \pm 0.013$$

ATLAS, arXiv:2007.14040

To **6.1%** in D_s decays

$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$

HFLAV, Eur. Phys. J. C77 (2017) 895

To **0.15%** in $\tau \to \ell\nu\nu$ (with τ_τ)

$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$

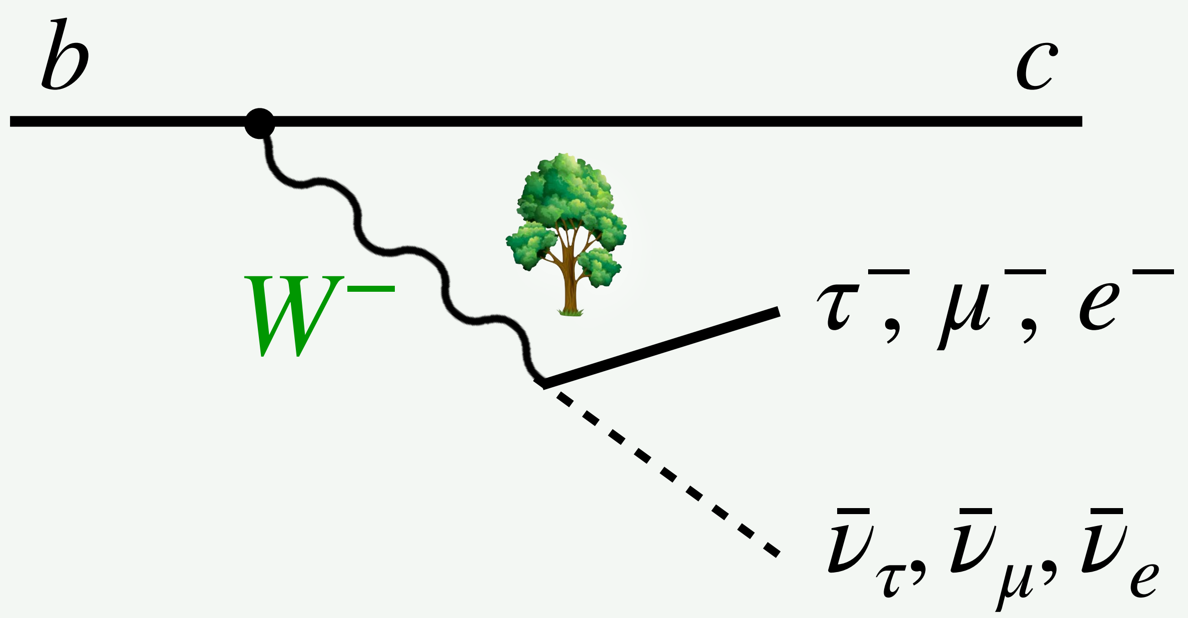
PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

B anomalies

~ Since 2012, **hints of LFU** in **transitions** involving **3rd gen. b quark**

$b \to c\tau\nu$ transitions

Charged currents (FCCC), tree diagram in SM → frequent

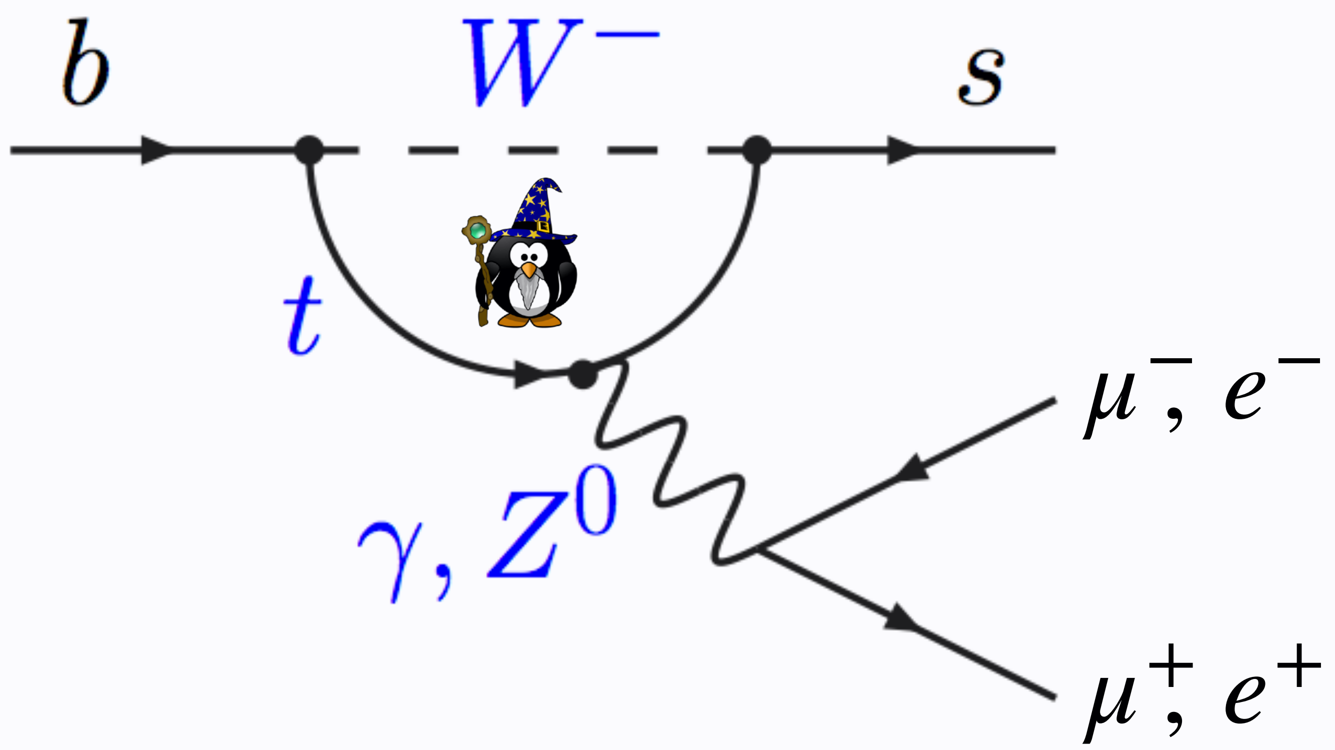


$$\mathcal{R}\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\bar{B} \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^{(*)}\ell\nu_\ell\right)}$$ with $\ell = \mu, e$

$\mathcal{R}(D)^{SM} = 0.299 \pm 0.003$ $\quad$ $\mathcal{R}(D^*)^{SM} = 0.258 \pm 0.005$

$b \to s\ell\ell$ transitions

Neutral currents (FCNC), loop (penguin, box...) diagrams in SM → rare



$$\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}\left(\bar{B} \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(\bar{B} \to K^{(*)}e^+e^-\right)}$$

$\mathcal{R}_K^{SM} \approx \mathcal{R}_{K^*}^{SM} \approx 1.00 \pm 0.01$ *(at low-ish q^2)*

Very solid SM predictions with **1-2% uncertainty,** established **deviations** would be clear indications of **BSM physics**

Overview of experiments

LFU results with $b \to c\tau\nu$

- p_B reconstruction
- B-factory and LHCb measurements of $\mathcal{R}\left(D^{(*)}\right)$
- Beyond $\mathcal{R}\left(D^{(*)}\right)$
- Future prospects

LFU results with $b \to s\ell\ell$

- $B^0_{(s)} \to \mu^+\mu^-$ Fresh!
- Differential BF rates Fresh!
- $B \to K^*\ell\ell$ angular observables
- LFU ratios $\mathcal{R}_{K^{(*)}}$ Fresh!
- Future prospects

One elegant interpretation

Contributions from several experiments

B-factories

BaBar, Belle

$\mathcal{O}\left(10^9\right)$ $B^{0/+}$ **mesons**

Low uncertainty on **absolute rates**, 100% ε(trigger), PID, **low e-brem**, **knowledge of collision momentum**

Belle II

With $\mathcal{O}\left(10^8\right)$ $B^{0/+}$ mesons already competitive search for $B \to K\nu\bar{\nu}$ (backup)!

LHC

LHCb

$\mathcal{O}\left(10^{11}\right)$ $B^{0/+}_{(s)}$ **mesons**

Triggers primarily for flavor, PID, VELO, **all b-hadron species**

ATLAS EXPERIMENT, CMS

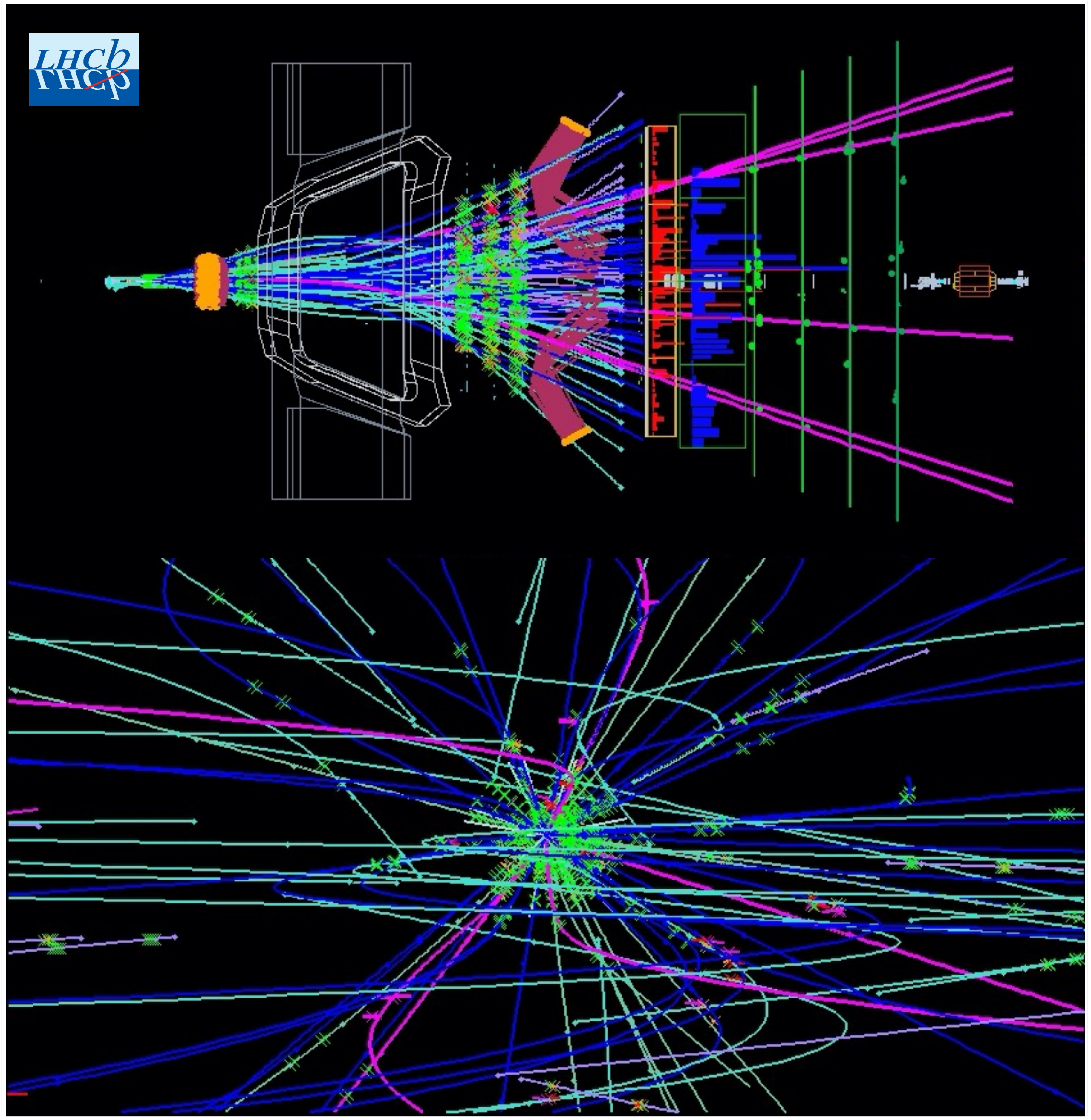
$\mathcal{O}\left(10^{12}\right)$ $B^{0/+}_{(s)}$ **mesons**

All b-hadron species

LHC environment is slightly busier

$pp \to X_b B_s^0 X$

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



LHC

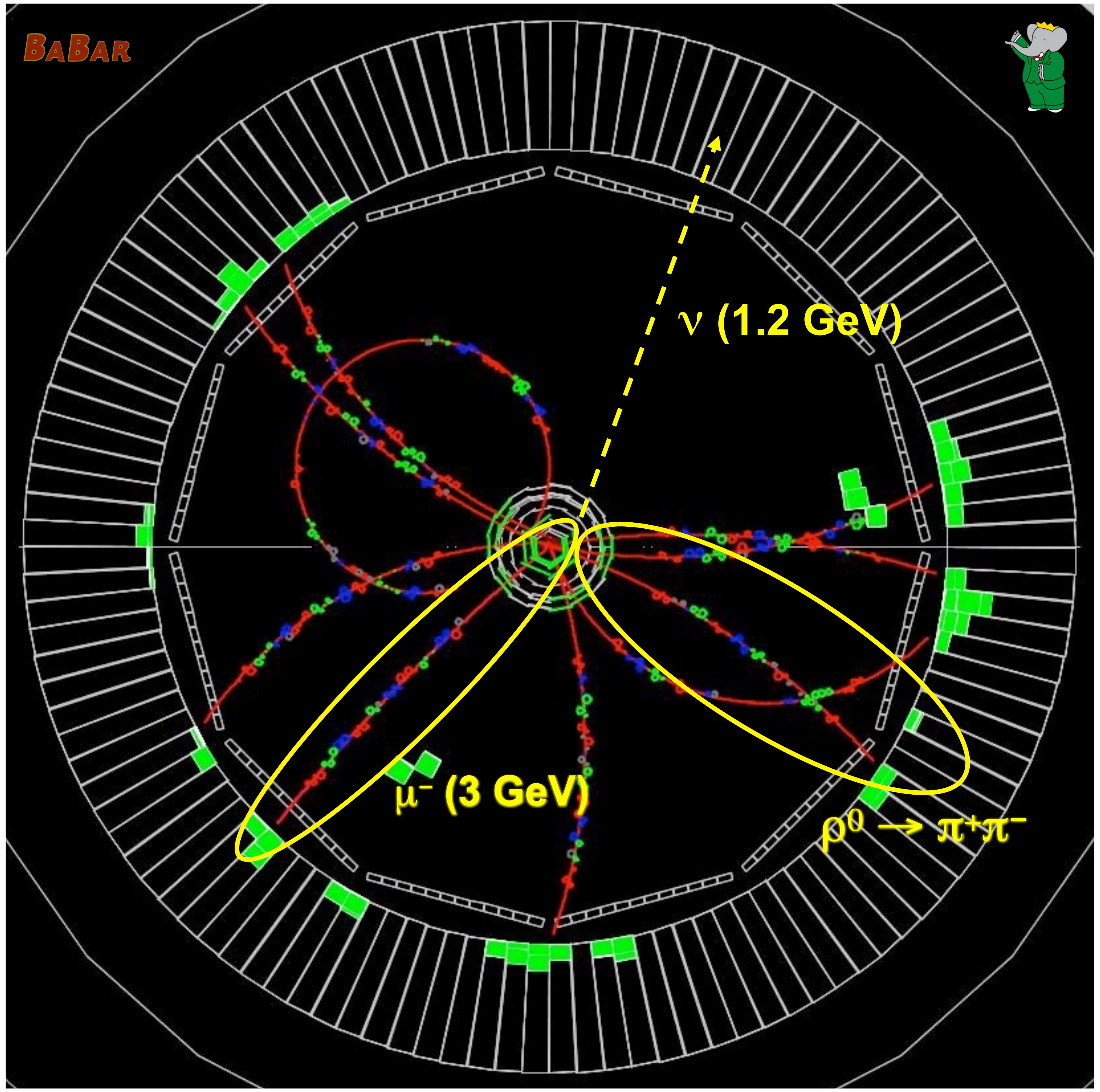
pp collisions have background from $b\bar{b}$ hadronization, underlying event, and pileup

B-factories

Clean e^+e^- collisions only produce two B mesons (for the most part)

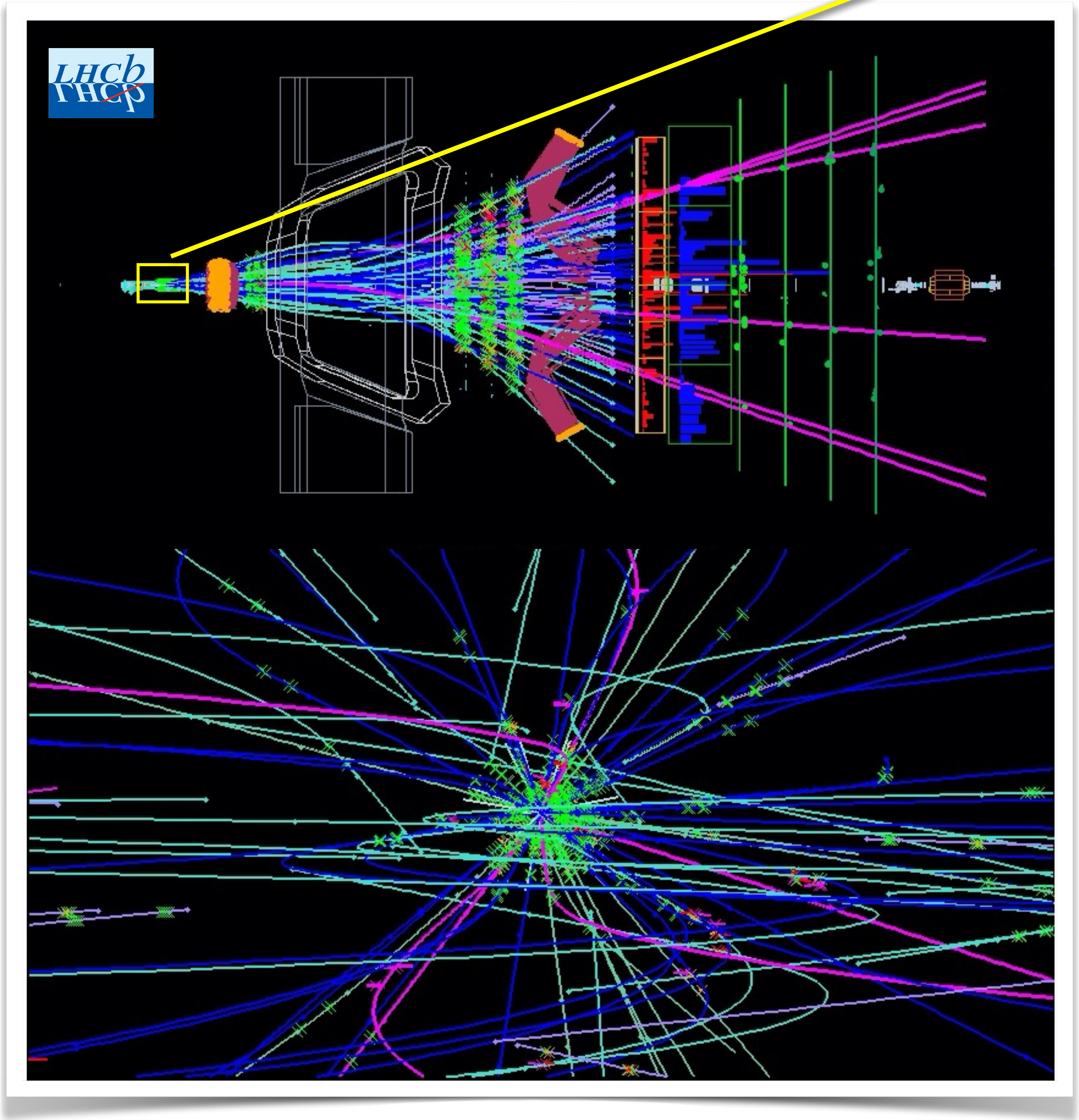
$e^+e^- \to B^+_{\text{tag}} B^-_{\text{sig}}$

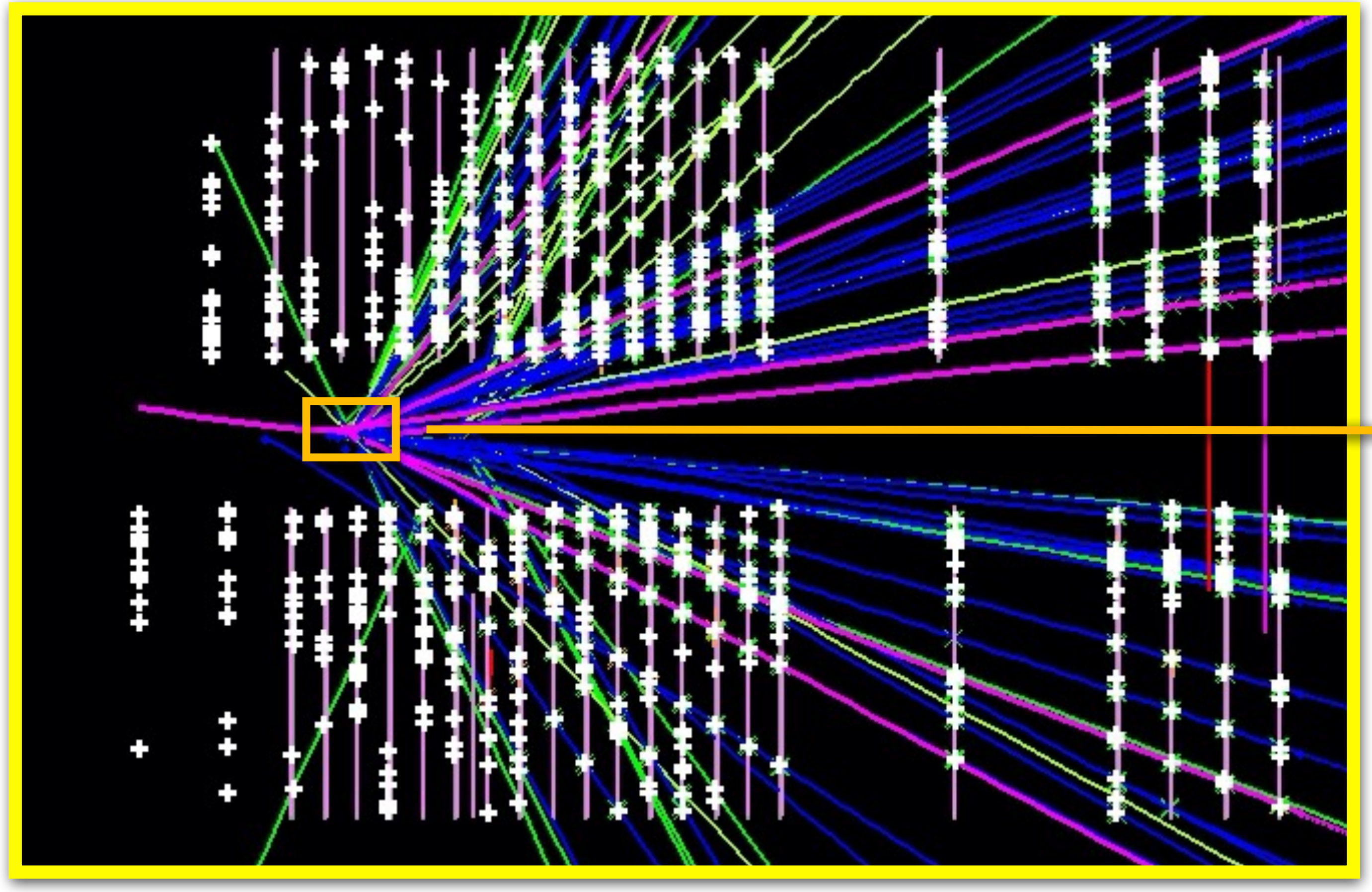
$B^- \to \rho^0 \mu^- \nu_\mu$

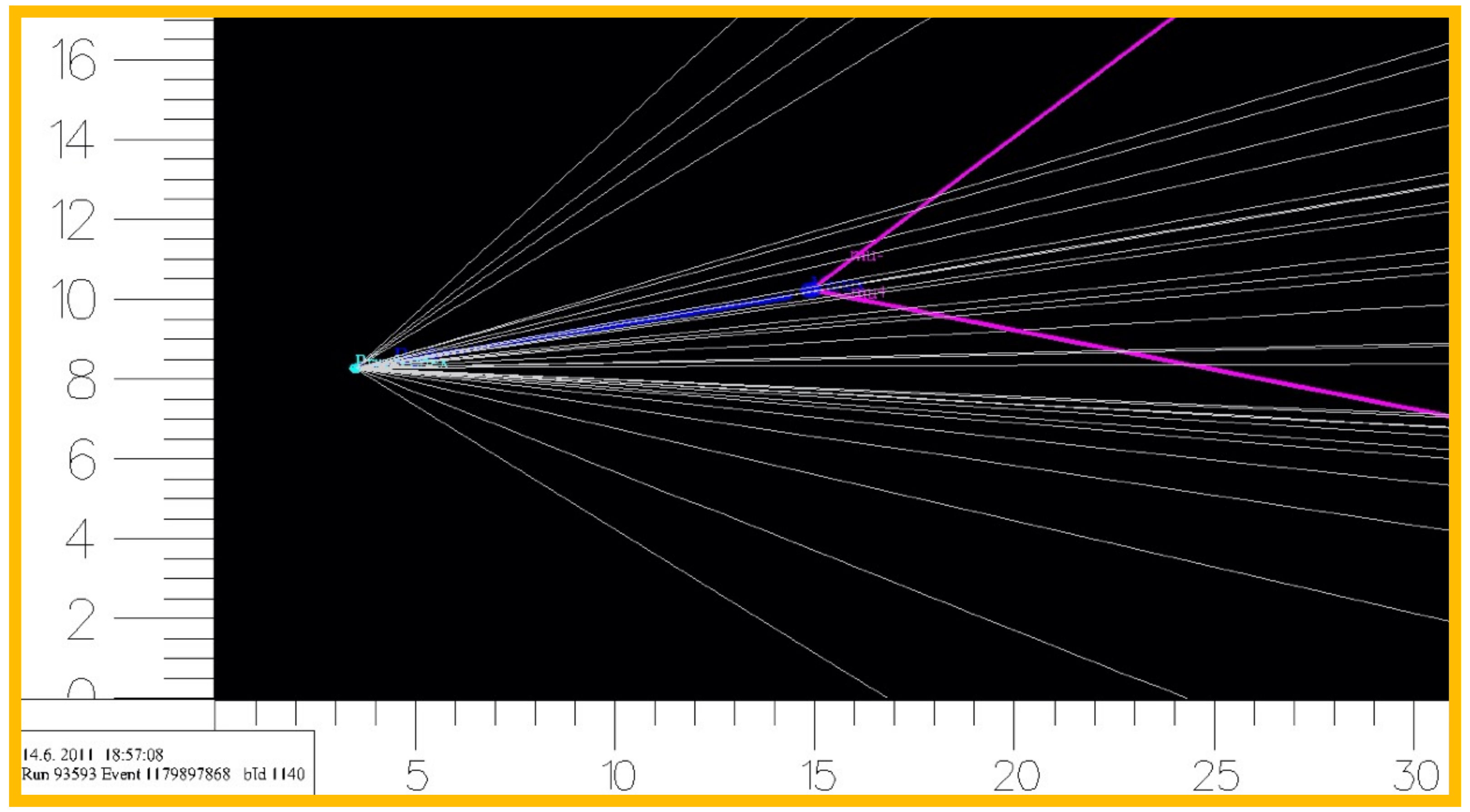


$$pp \to X_b B_s^0 X$$

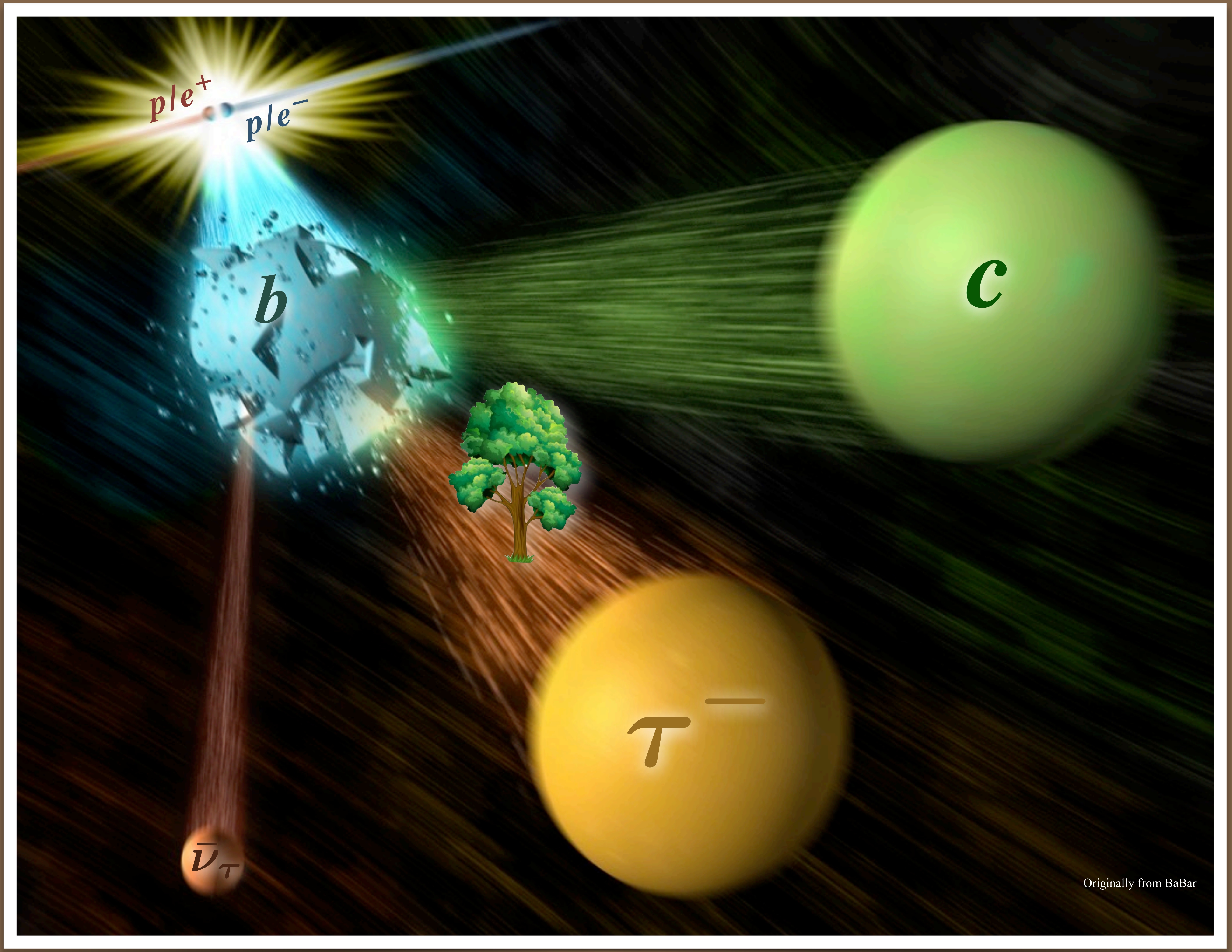
$$B_s^0 \to \mu^+\mu^-$$







- **B mesons can fly ~cm** thanks to large boost
- **Excellent trackers** in **CMS** and **ATLAS**
- **Superb vertexing** by VELO in **LHCb**
  - Only 8.2 mm from IP, reduced to 5.1 in upgrade
- Multivariate algorithms ensure **tracks isolated**
  - Based on track impact parameter, other variables



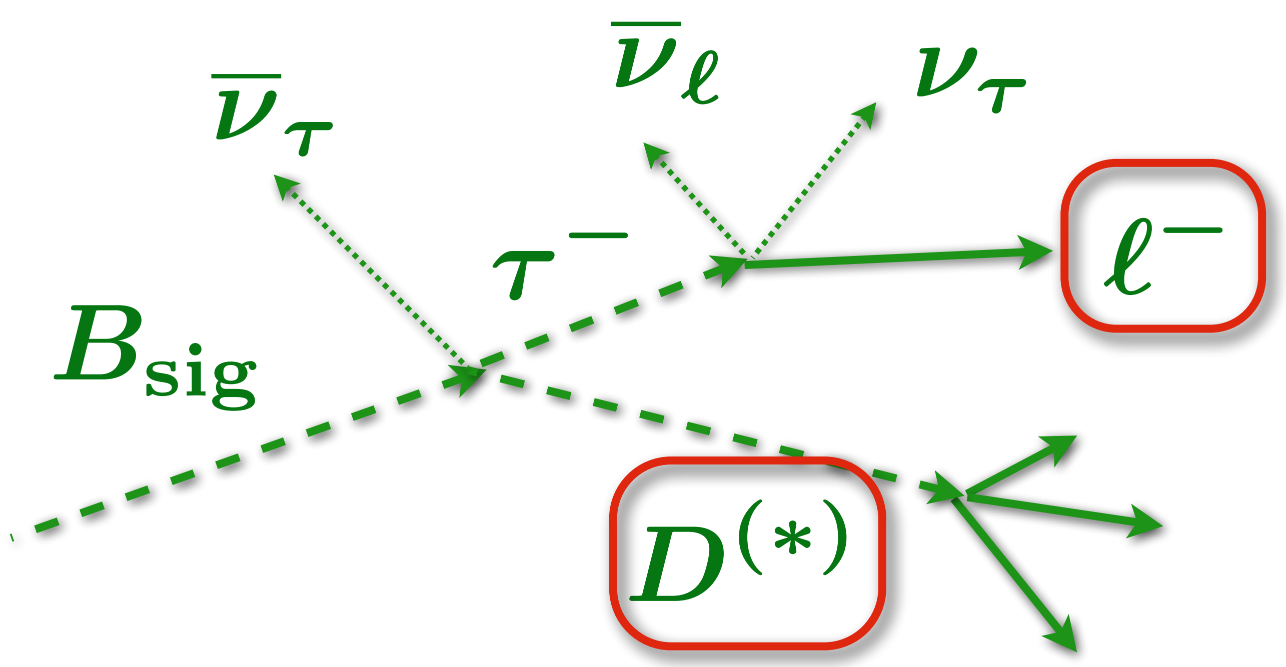
LFU results with $b \to c\tau\nu$ transitions

τ reconstruction

Leptonic τ

$$\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell$$

Same reco particles as normalization $B \to D^{(*)}\ell\nu$, many uncertainties cancel on $\mathscr{R}\left(D^{(*)}\right)$



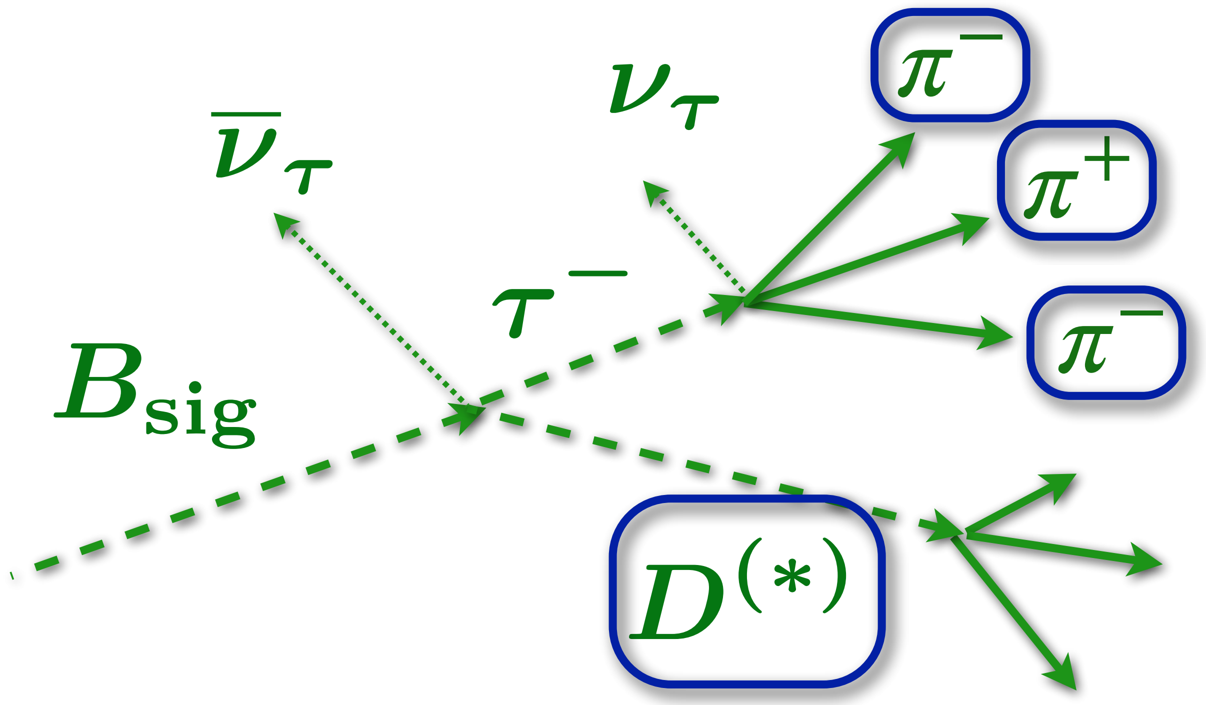
$$\mathscr{R}\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau\nu_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)}\ell\nu_\ell\right)} = \boxed{\frac{N_{sig}}{N_{norm}}}\,\frac{\epsilon_{norm}}{\epsilon_{sig}}$$

ε ratio easy, yields are key

Hadronic τ

$$\tau^- \to \pi^-\nu_\tau,\ \rho^-\nu_\tau,\ \pi^-\pi^+\pi^-\nu_\tau$$

Better measurement of τ kinematics



$\mathscr{R}(D^{*+})$ depends on external branching fractions

$$\mathscr{R}(D^*) = \boxed{\frac{\mathscr{B}\left(\bar{B} \to D^*\tau\nu_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^*\pi\pi\pi\right)}} \times \boxed{\frac{\mathscr{B}\left(\bar{B} \to D^*\pi\pi\pi\right)}{\mathscr{B}\left(\bar{B} \to D^*\mu\nu_\mu\right)}}$$

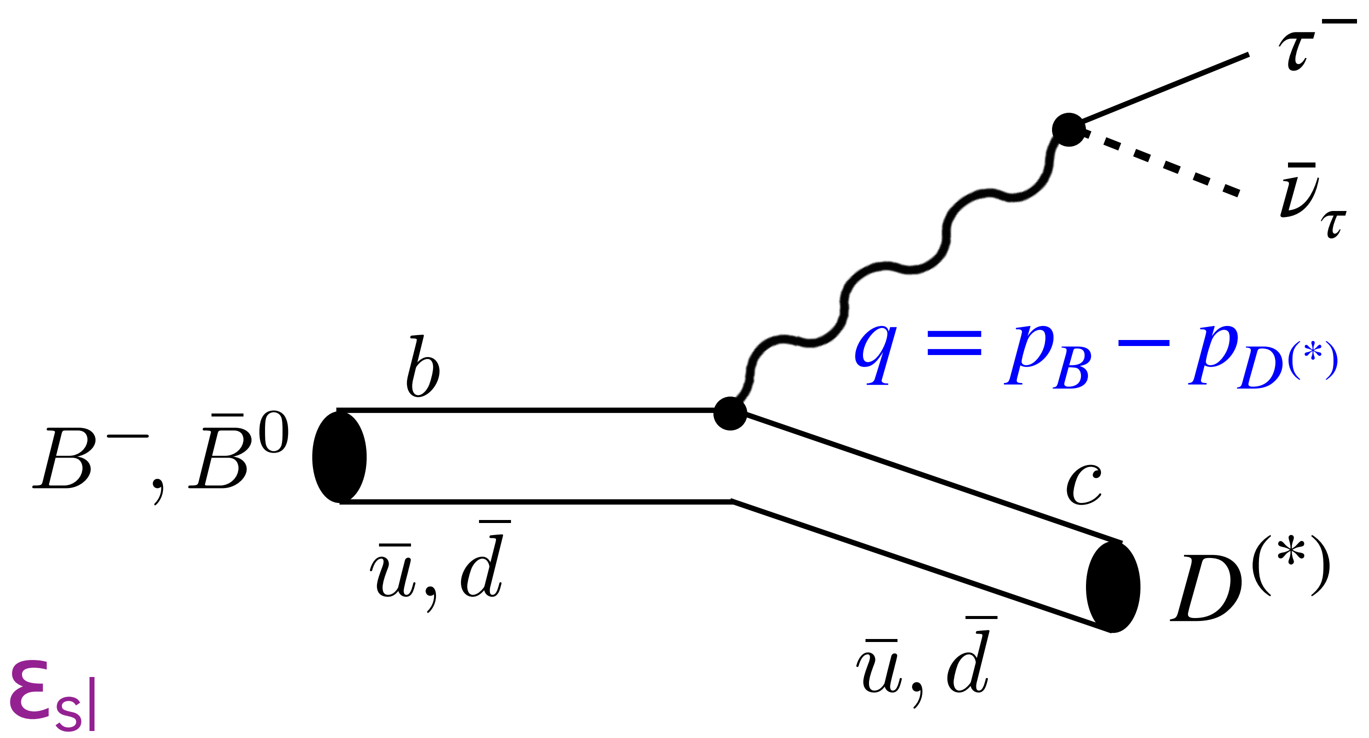
Measure this ratio

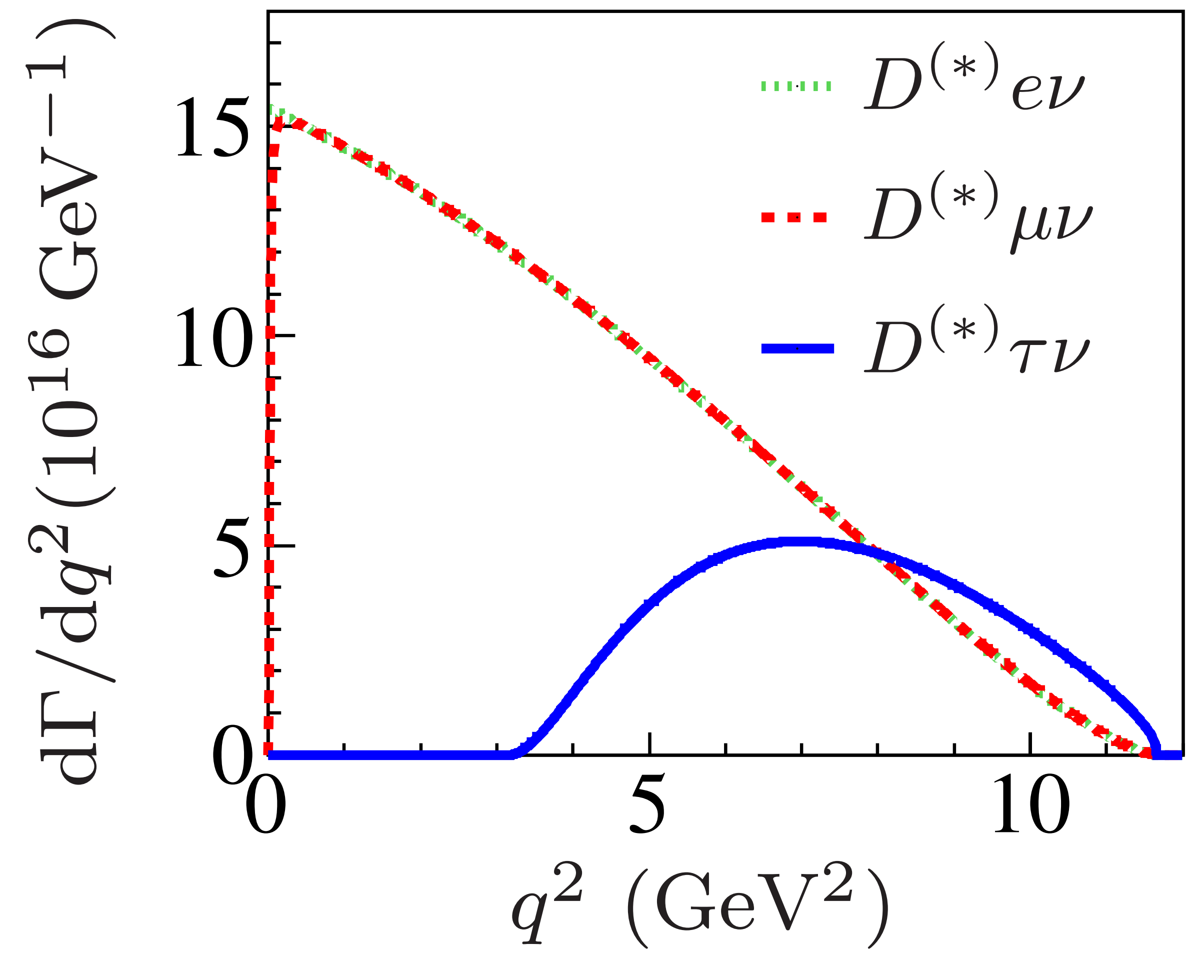
B tagging: $p_{B_{sig}} = p_{e^+e^-} - p_{B_{tag}}$

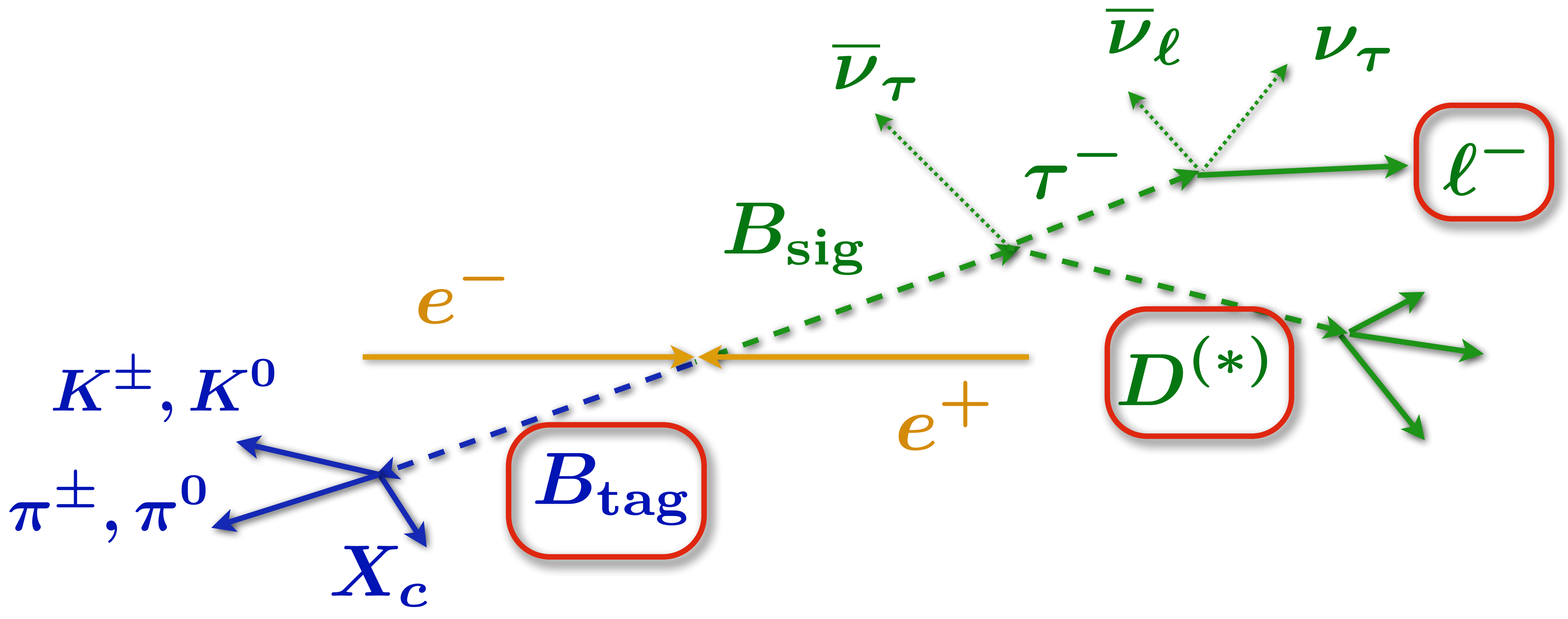
Hadronic: best $\sigma(p_B)$, ε_{had} ~ 0.2-0.4%

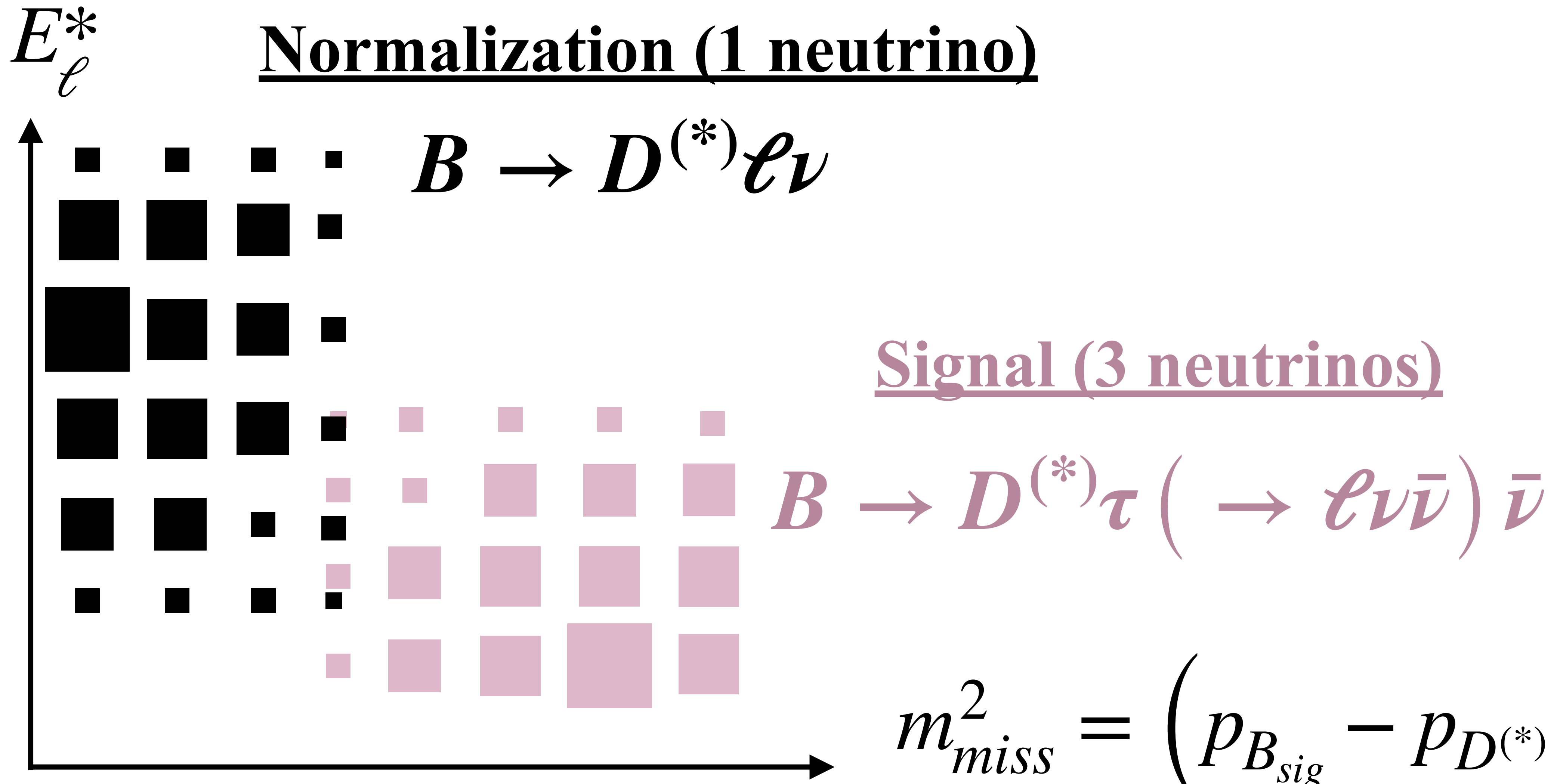
Semileptonic: worse $\sigma(p_B)$, ε_{sl} ~ 0.3-0.6%

FEI: bottom-up approach based on BDTs with ε_{FEI} up to 3x the corresponding ε_{had} or ε_{sl}







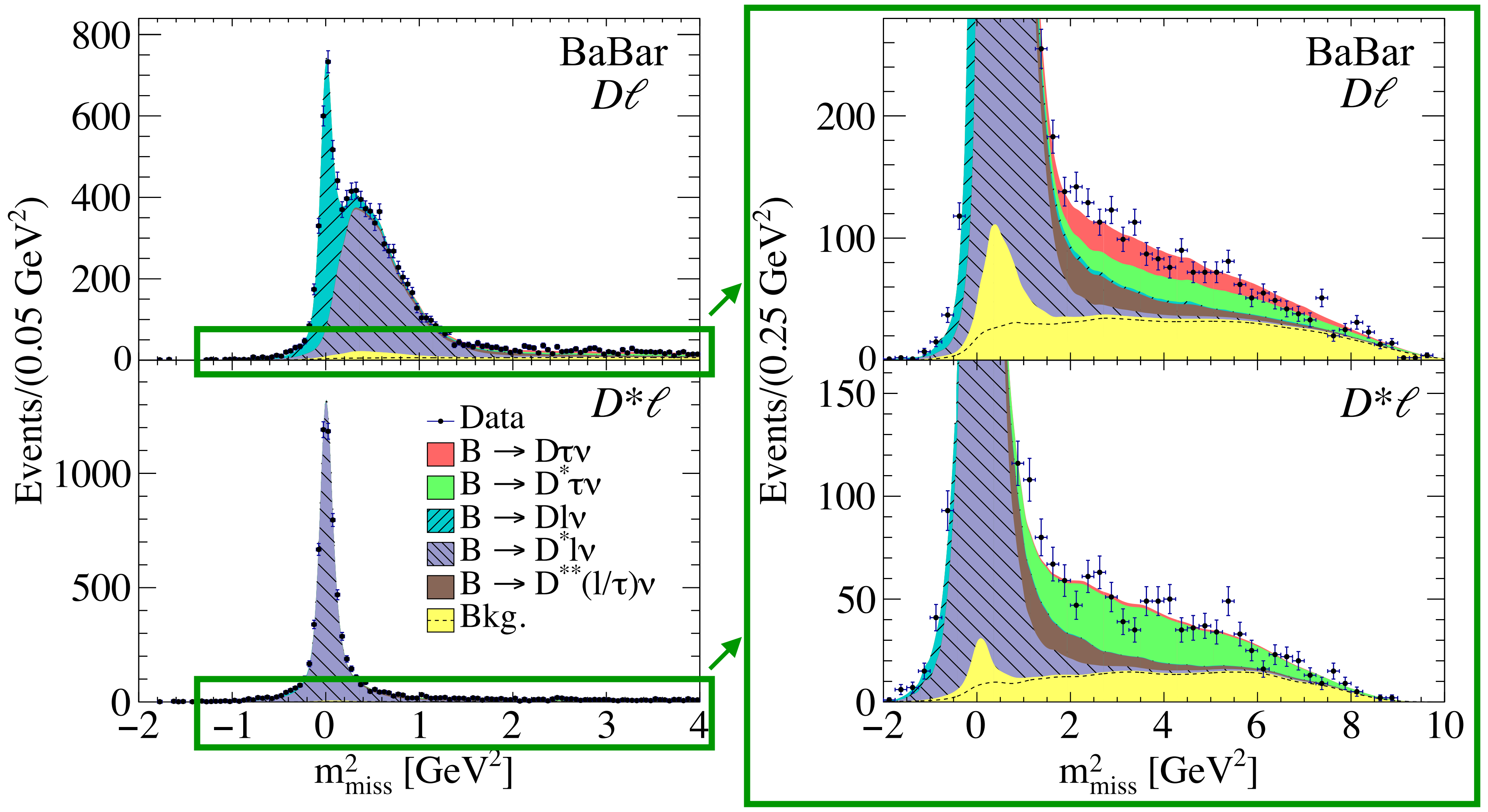


$$m^2_{miss} = \left(p_{B_{sig}} - p_{D^{(*)}} - p_\ell\right)^2$$

- Hadronic B_{tag}, leptonic τ

Phys. Rev. Lett. **109**, 101802 (2012)

Phys. Rev. D **88**, 072012 (2013)



BABAR

$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BABAR} \\ 0.300 \pm 0.008 & \text{SM} \end{cases} \quad \mathbf{2.0\sigma}$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BABAR} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \quad \mathbf{2.7\sigma}$$

BaBar 2012 $\mathscr{R}(D^{(*)})$

- Hadronic B_{tag}, leptonic τ

Phys. Rev. Lett. **109**, 101802 (2012)

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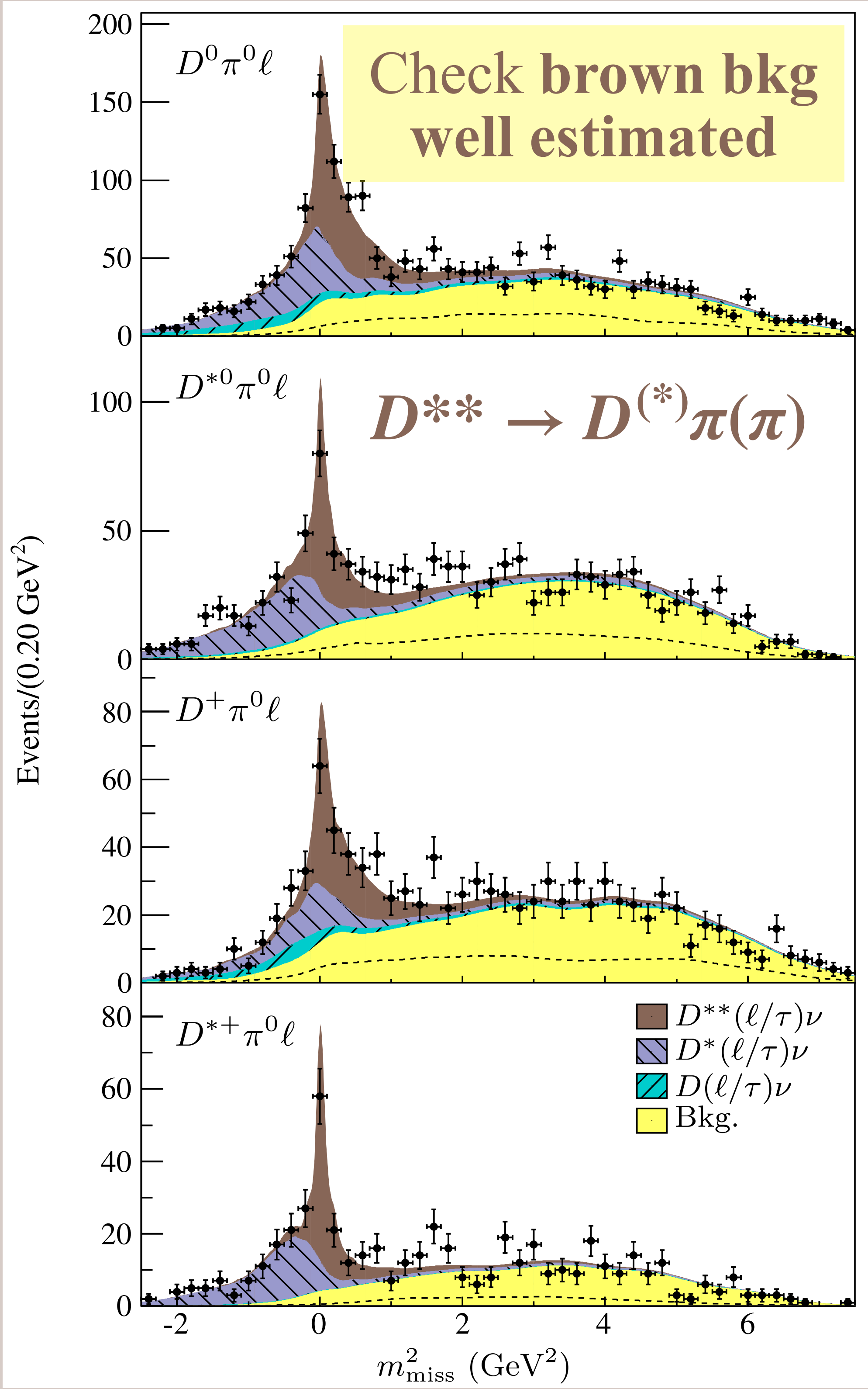
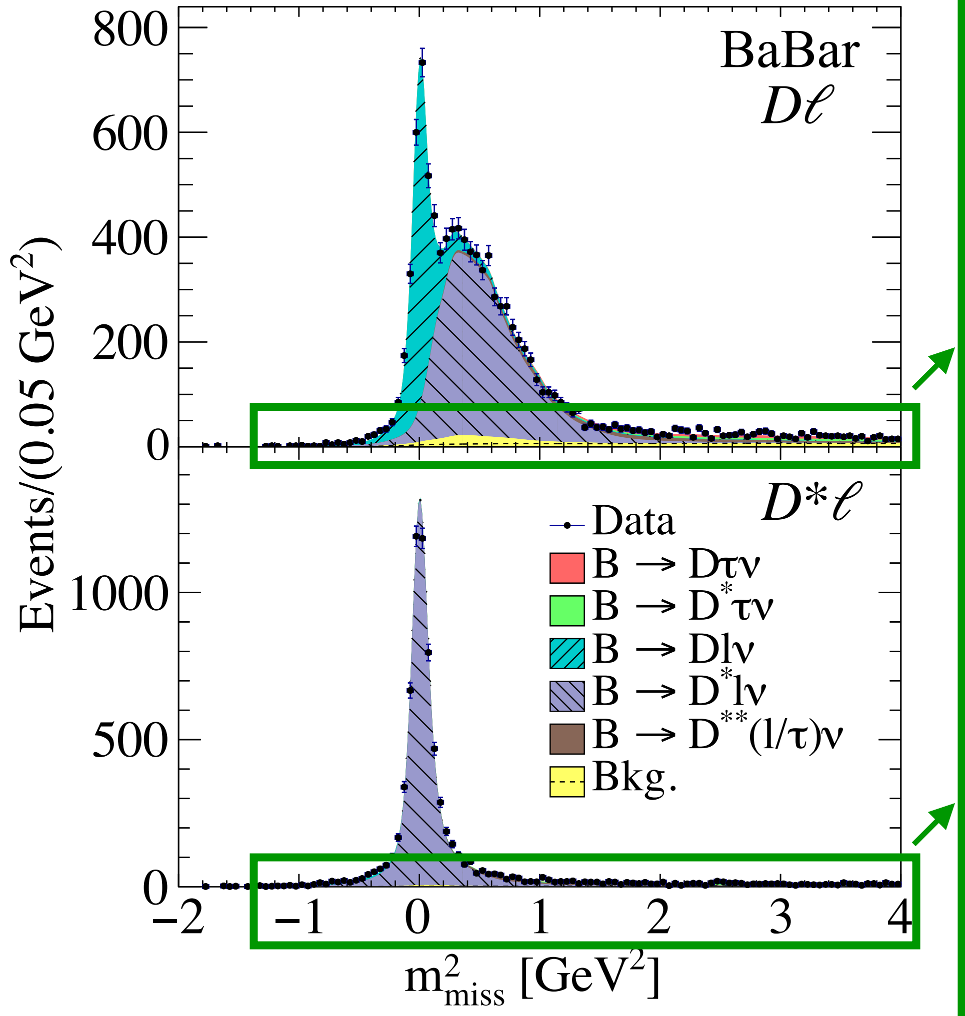
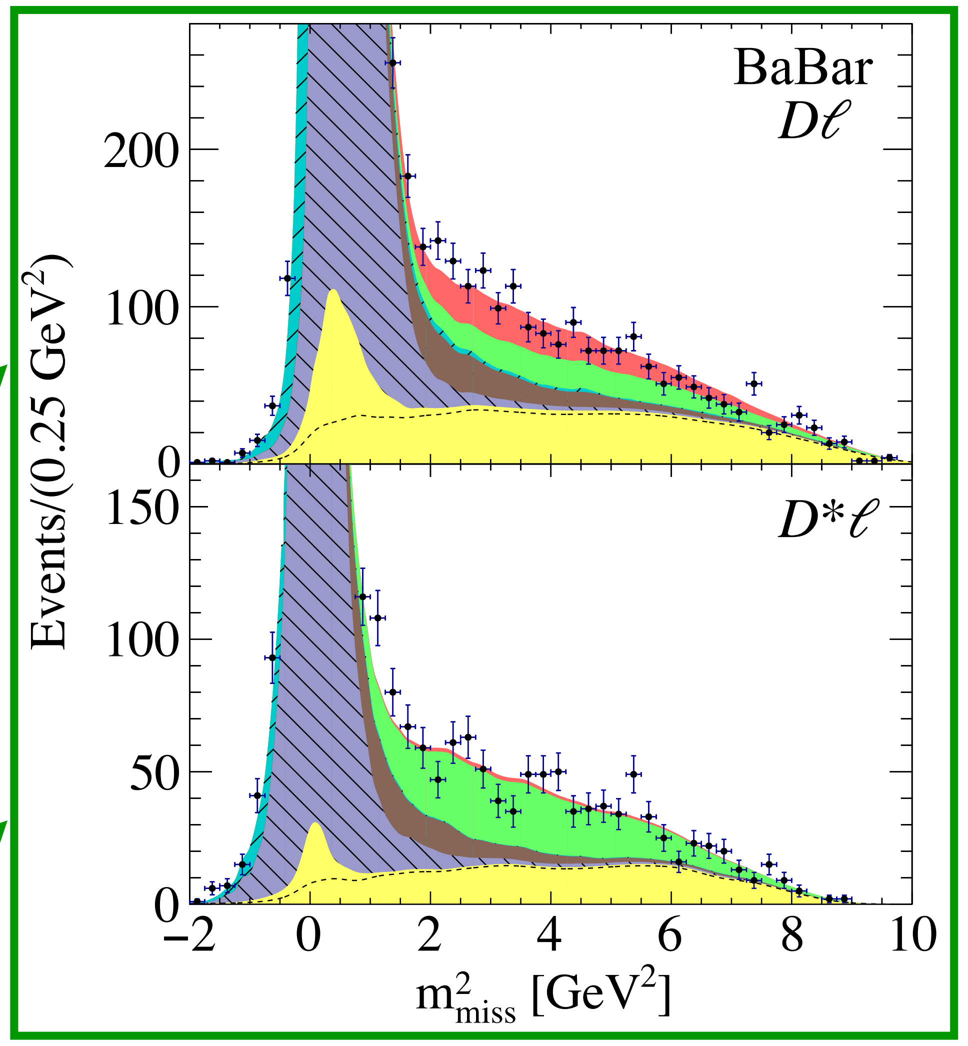
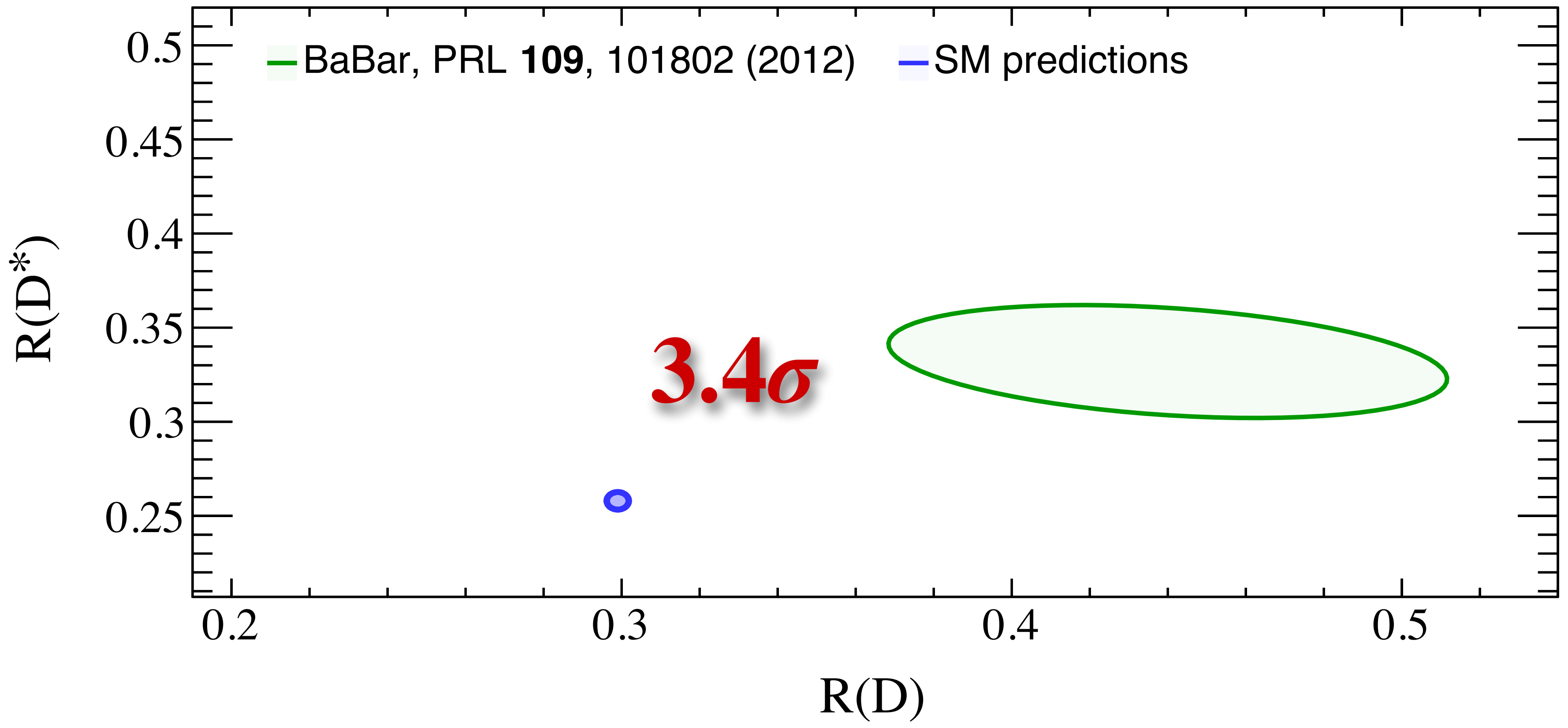
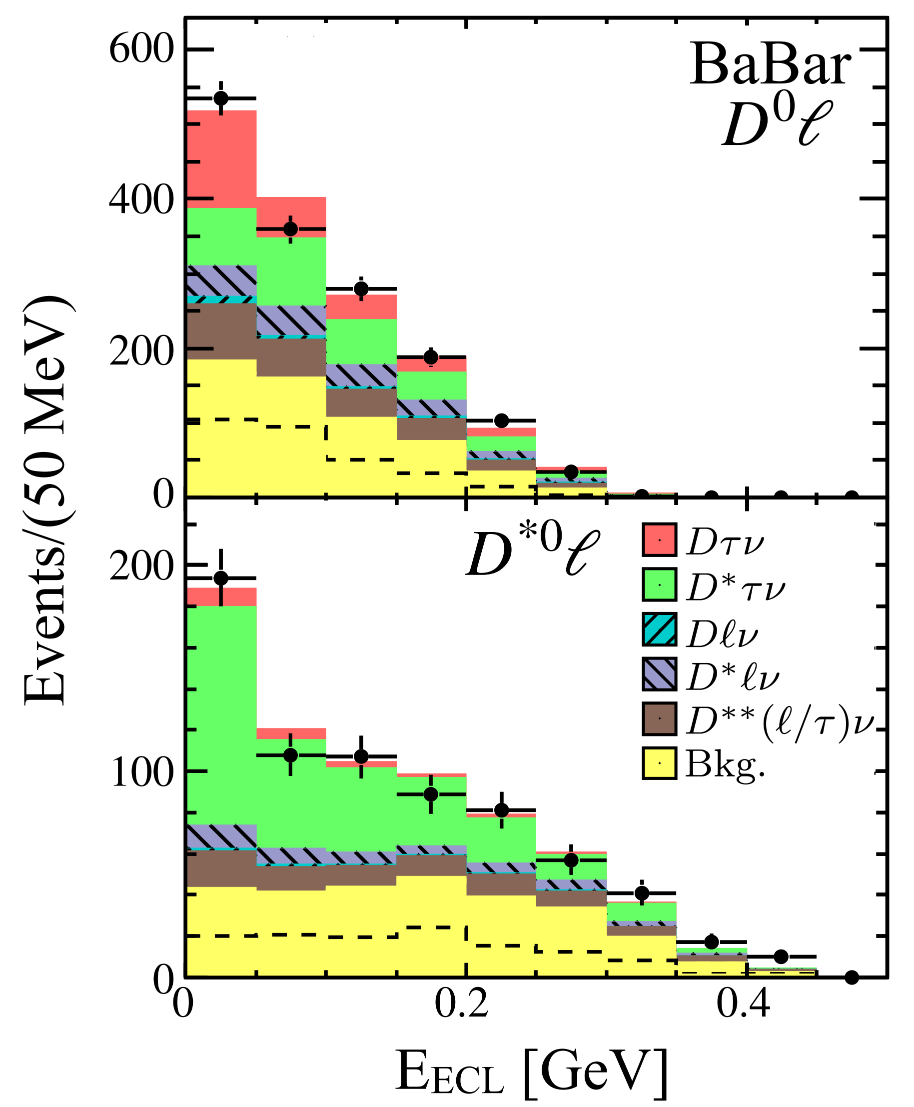
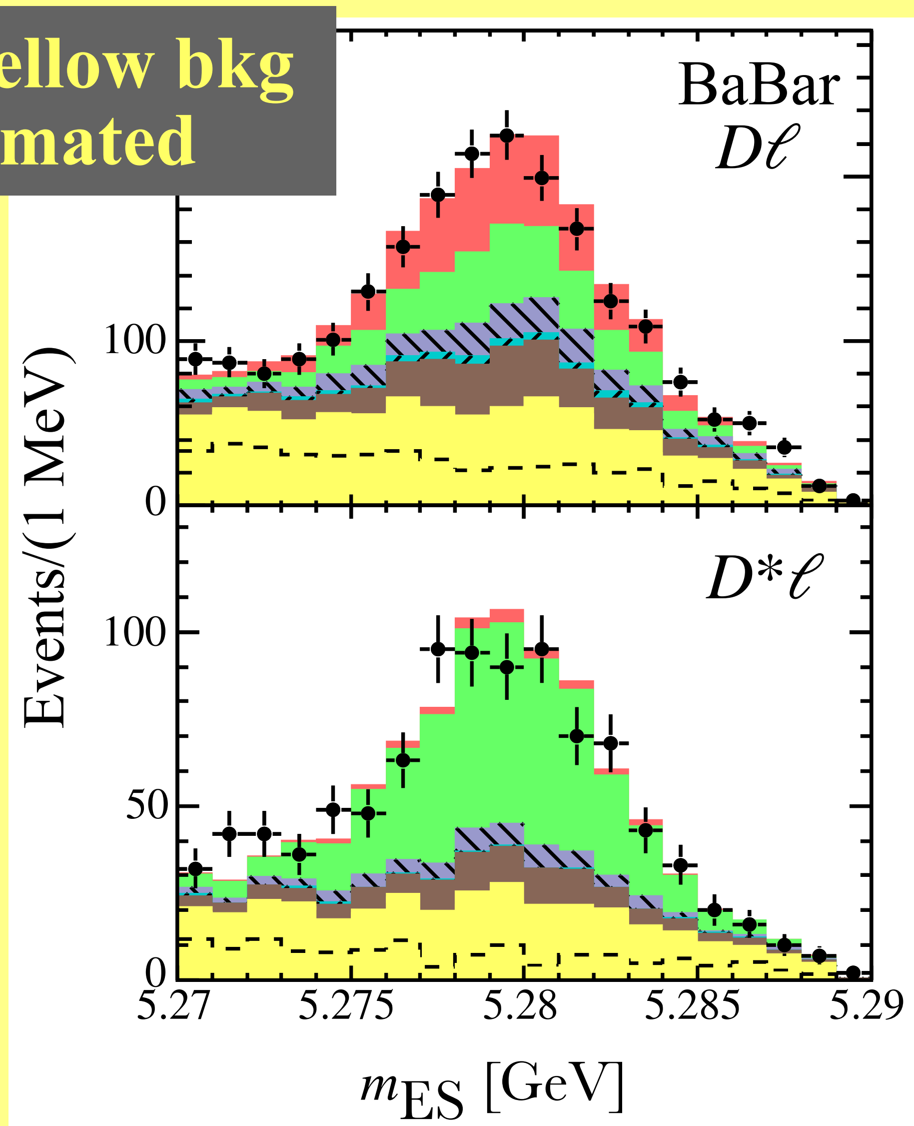




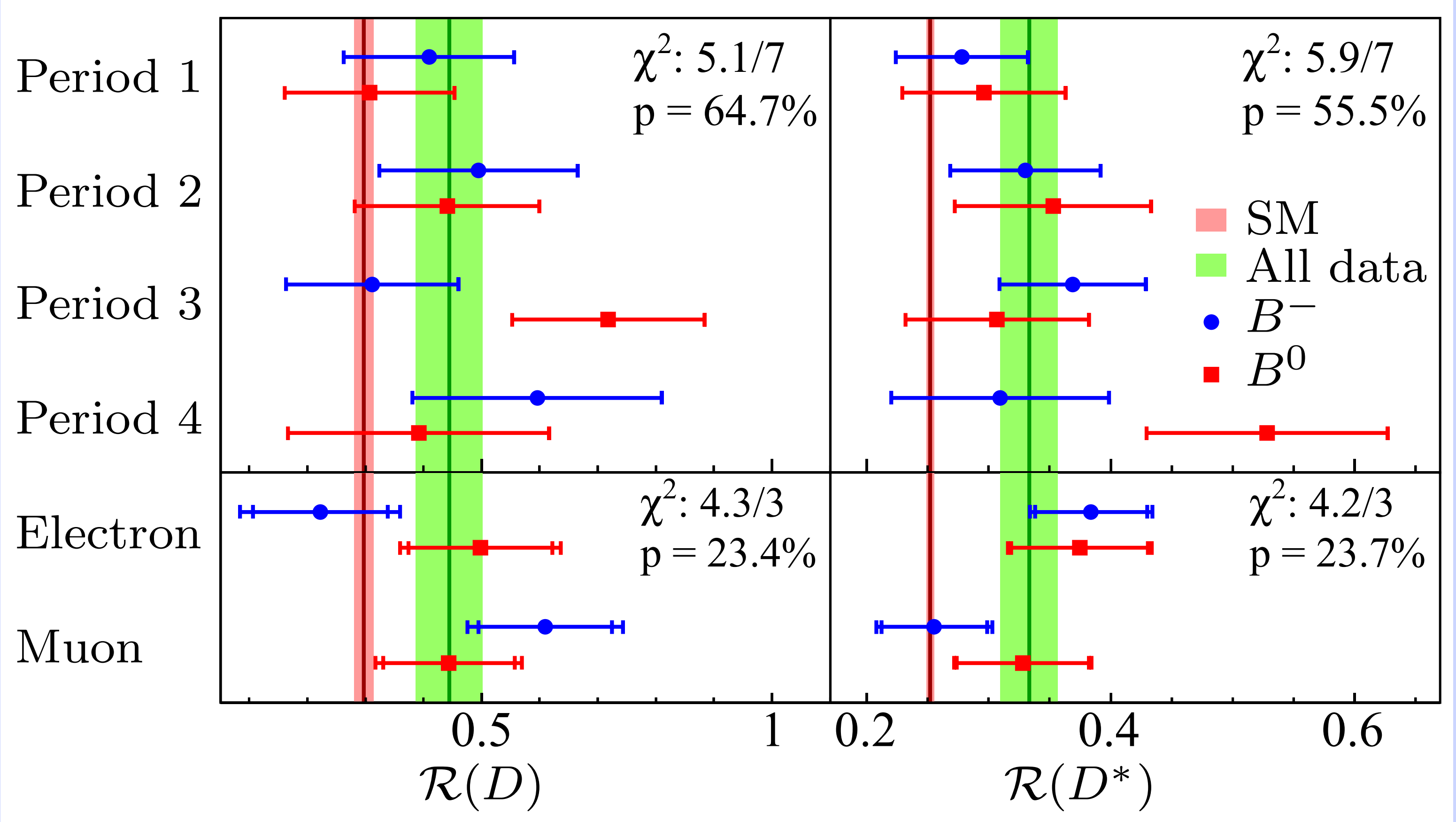




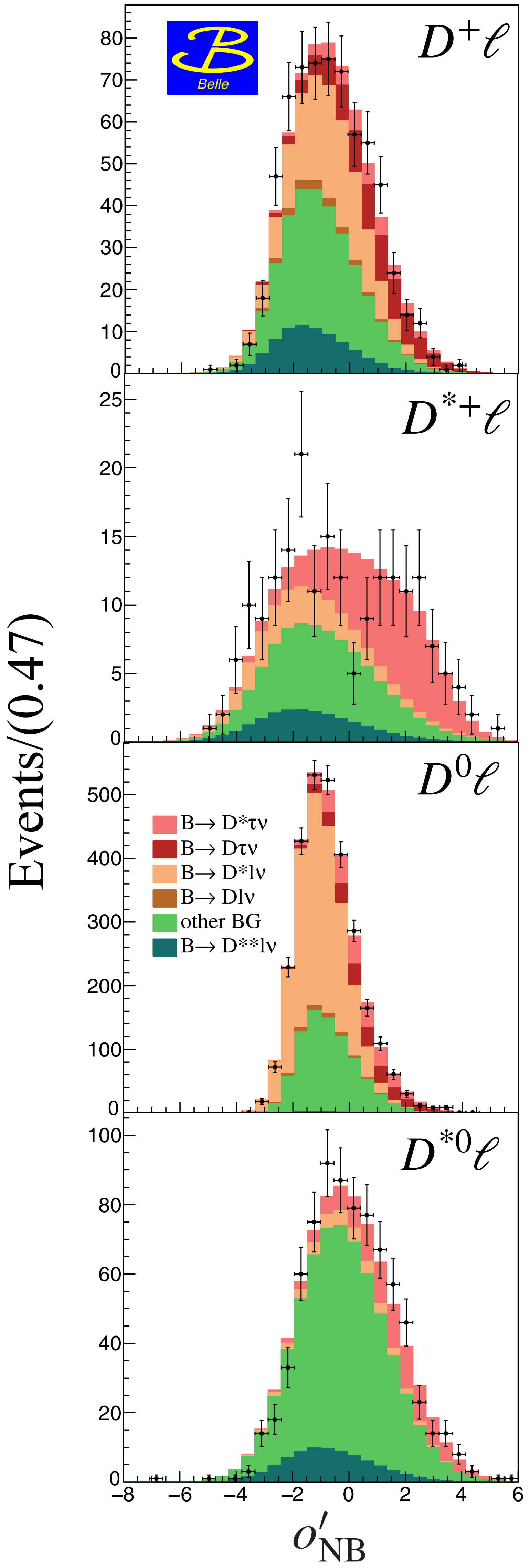




Check **result stable** as a function of **lepton flavor**, **run period**, and **purity**

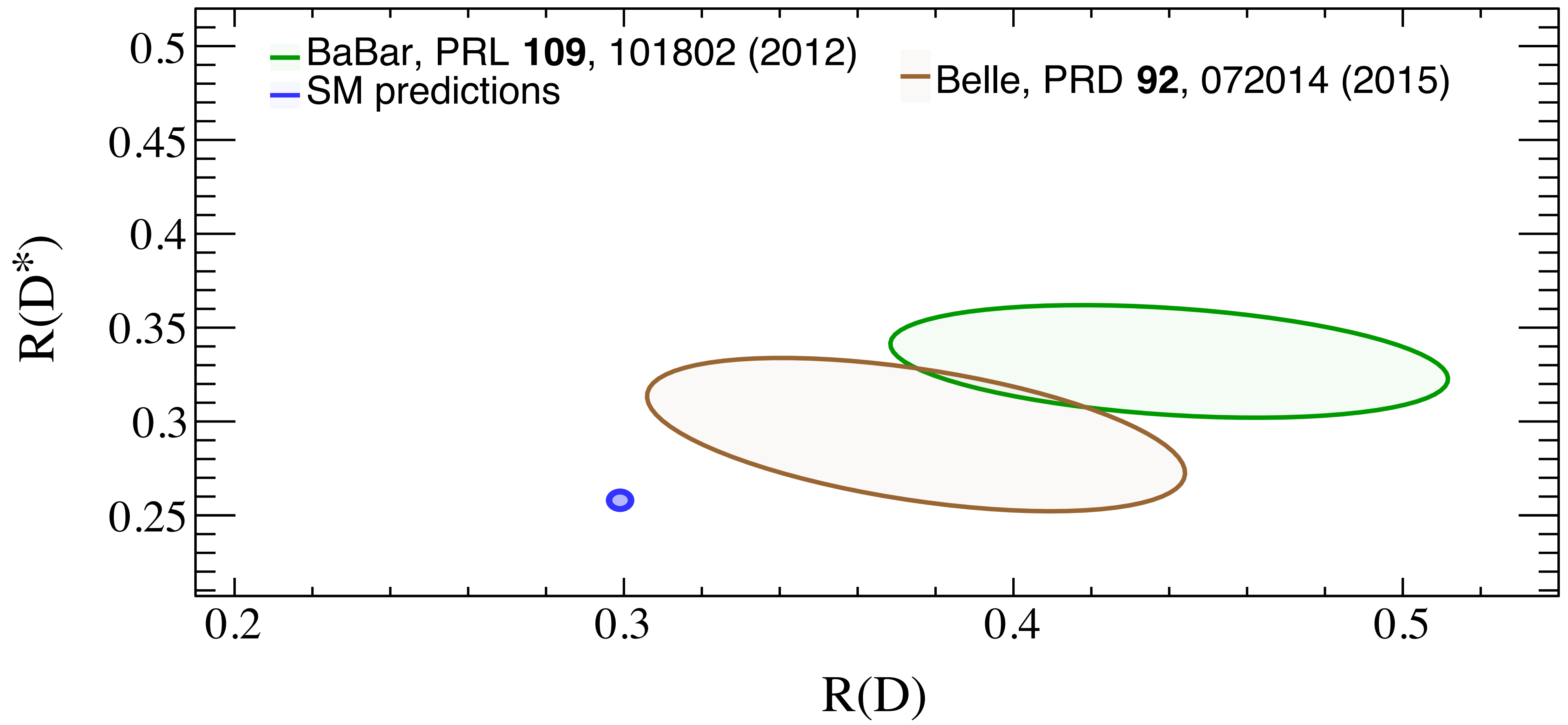


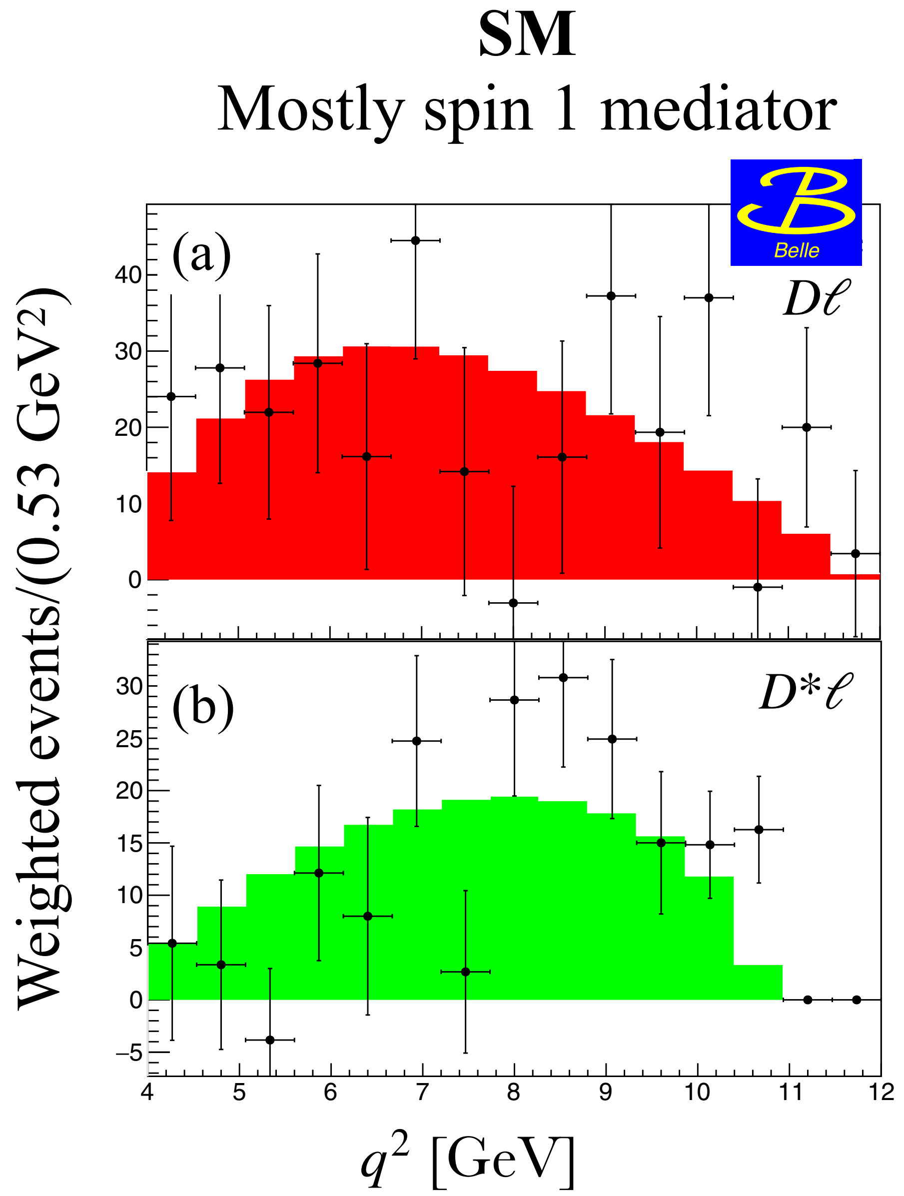
Belle 2015 $\mathcal{R}(D^{(*)})$, q² distributions



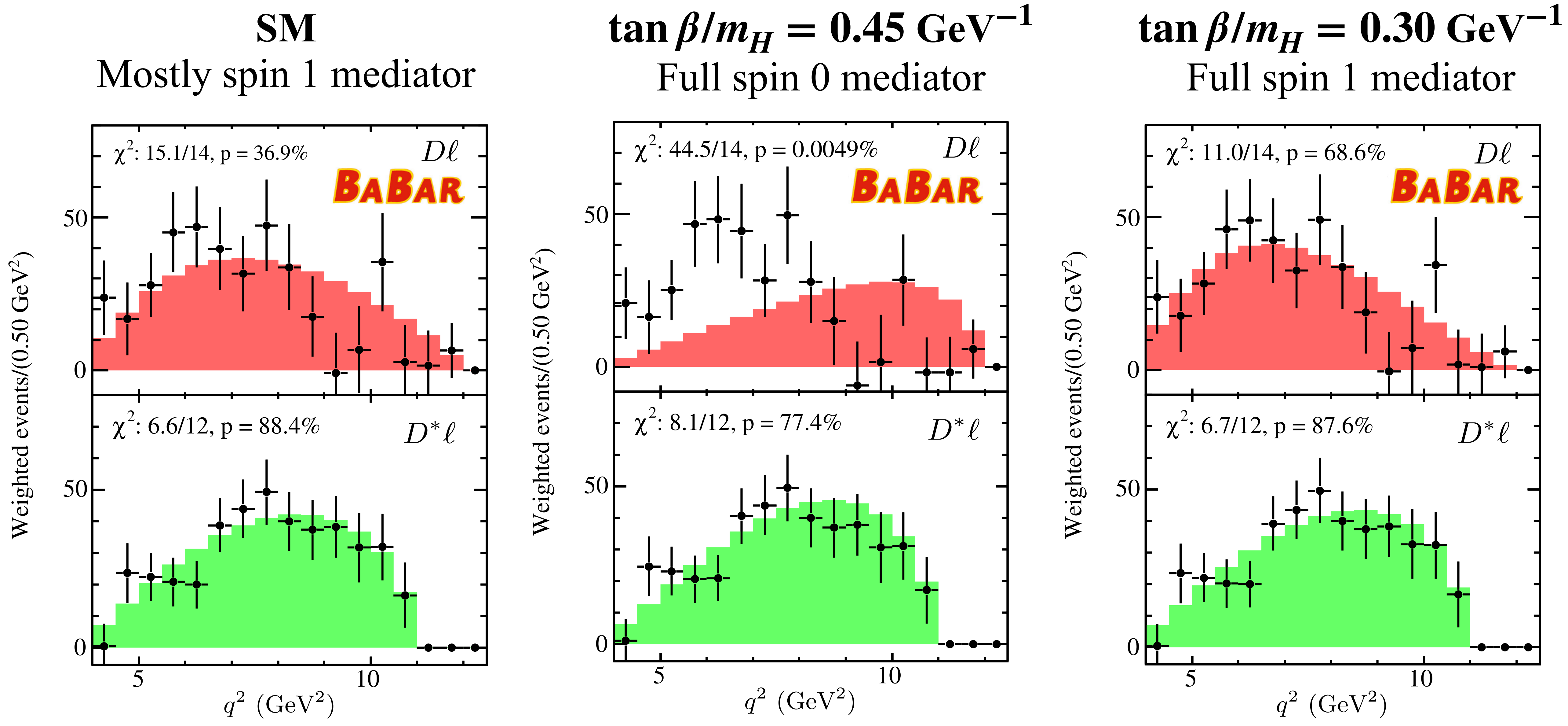
Phys. Rev. D **92**, 072014 (2015)

- Similar strategy to BaBar
  - Hadronic B_{tag}, leptonic τ
- Also excess, consistent with BaBar
- q² distributions rule out 2HDM



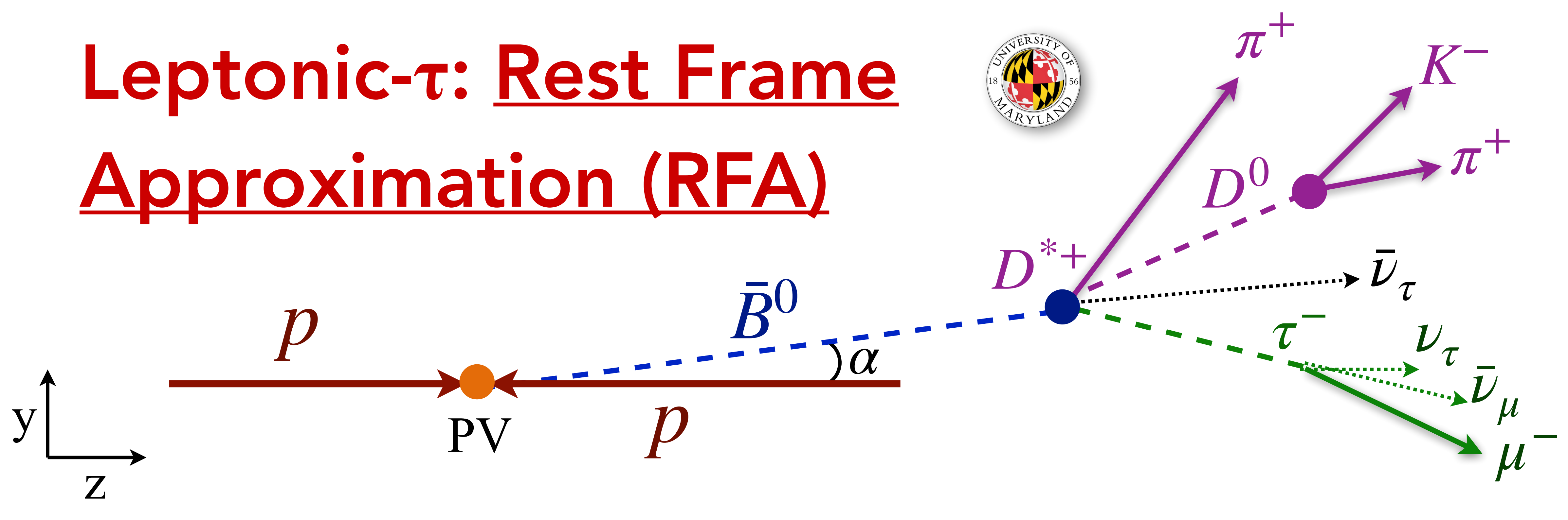


Phys. Rev. D **92**, 072014 (2015)

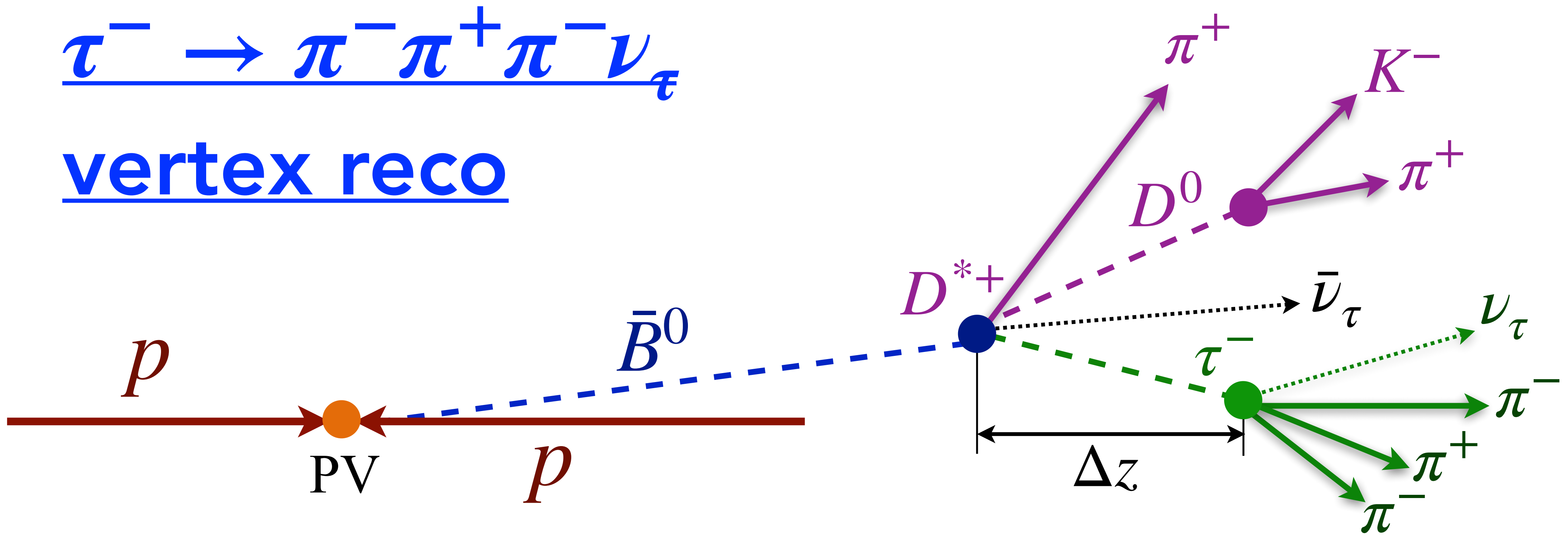


Phys. Rev. D **88**, 072012 (2013)

Leptonic-τ: Rest Frame Approximation (RFA)



$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ vertex reco



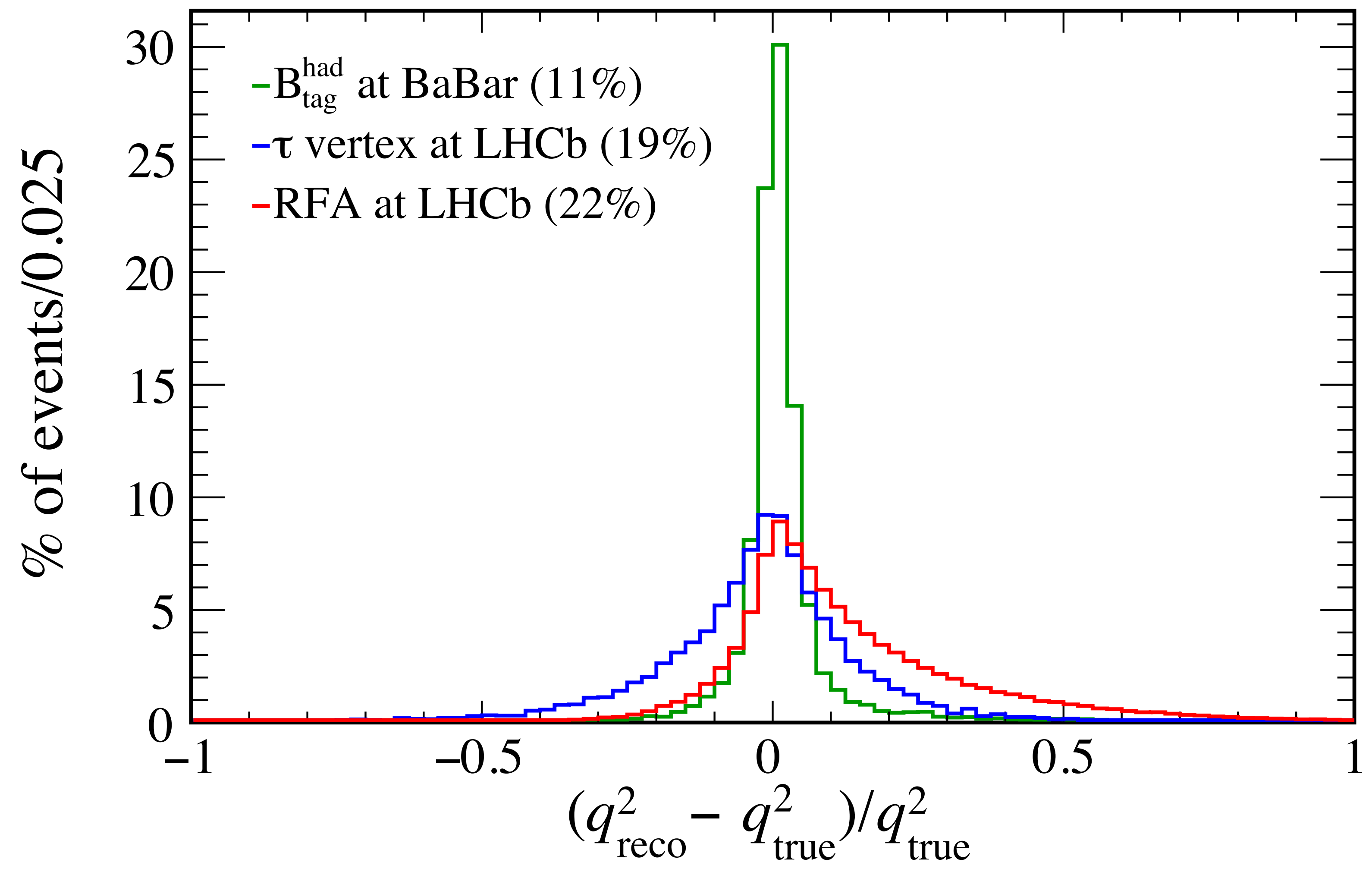
Assume proper **velocity** of **B** and **reco particles** ($\mu\, D^*$) **along z** is the **same** to find $p_z(B)$

$$p_z(B) = \frac{m_B}{m(\mu\, D^*)}\, p_z(\mu\, D^*)$$

Find **B vertex** assuming muon comes from it, **scale $p_z(B)$** with angle **α**

$$|\,p(B)\,| = p_z(B)\sqrt{1+\tan^2\alpha}$$

Use τ direction between B and τ vertices, solve $\left(p_\tau - p_{\pi\pi\pi}\right)^2 = 0$, then $p_B = p_\tau + p_{D^*}$

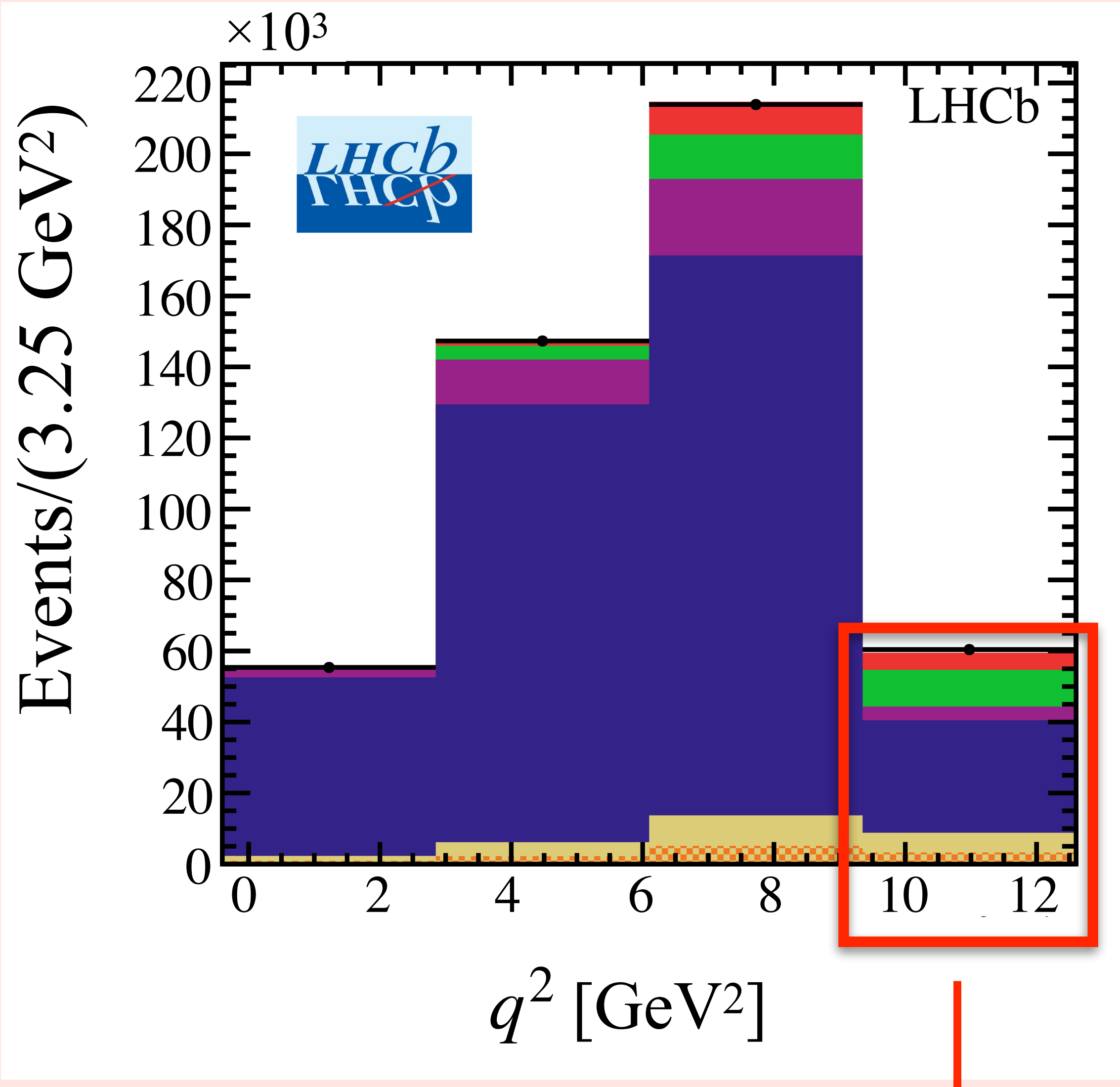


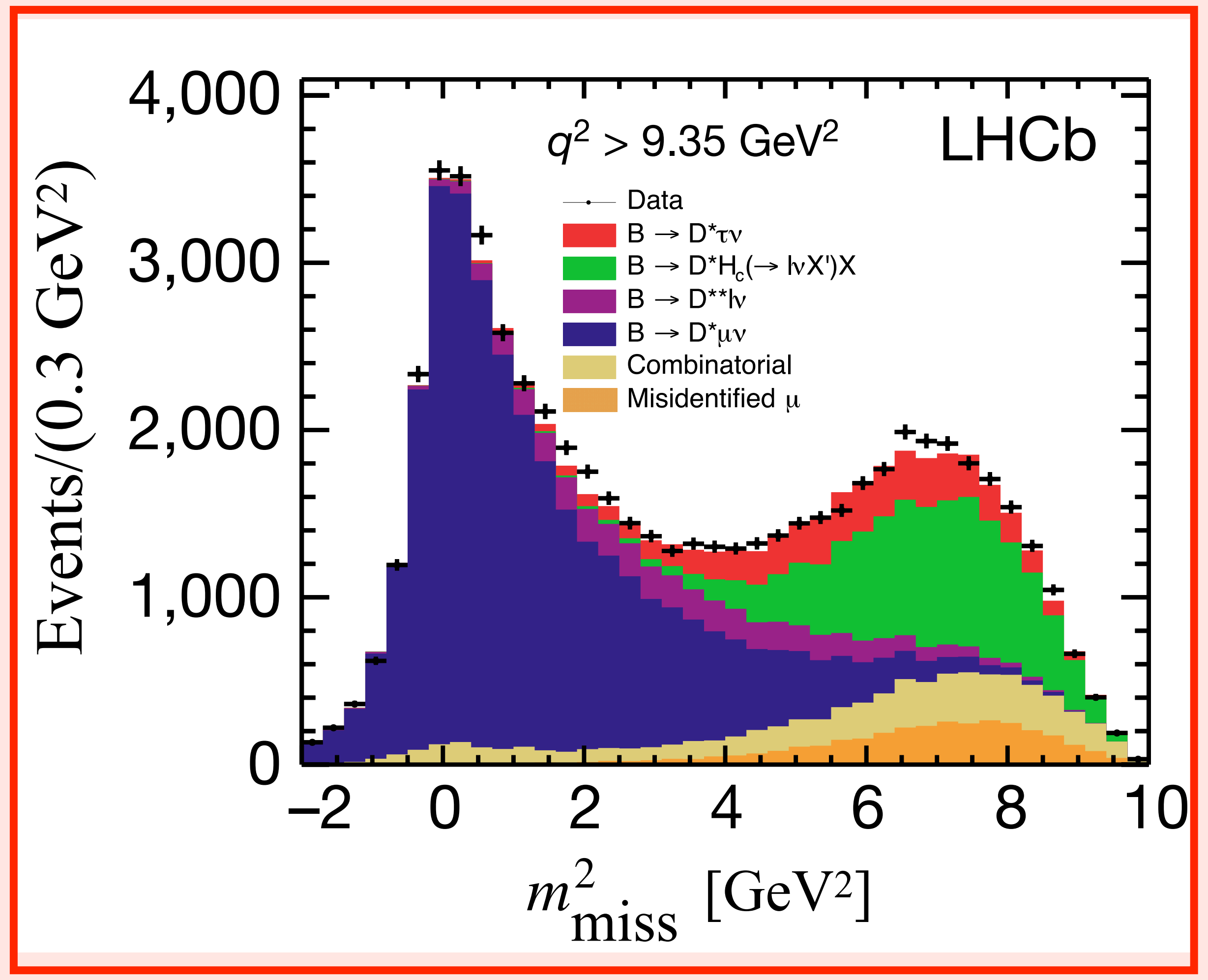
Bernlochner, MFS, Robinson, Wormser, arXiv:2101.08326

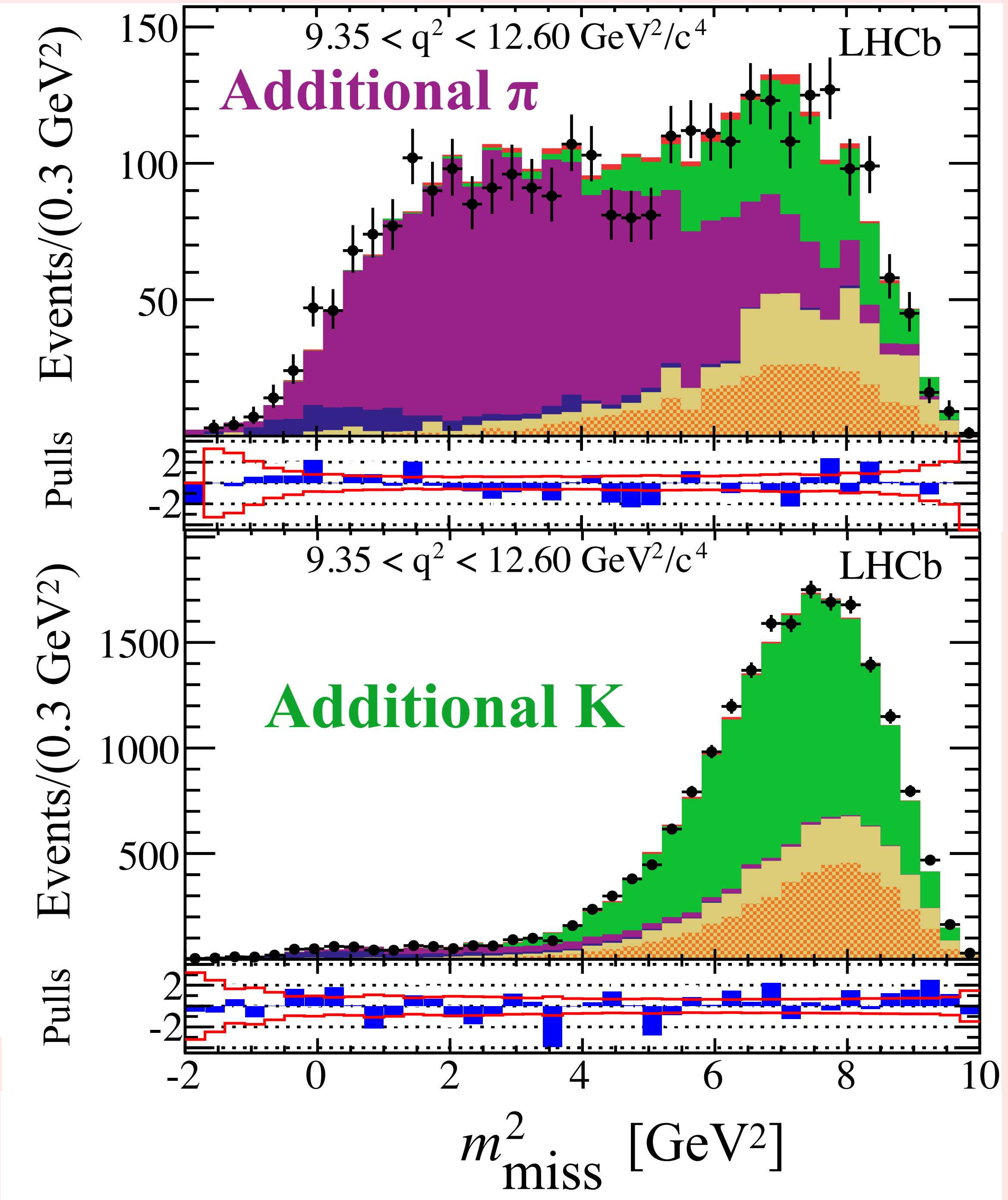
LHCb 2015 and 2018 $\mathscr{R}(D^*)$

Leptonic-τ

Phys. Rev. Lett. **115**, 111803 (2015)

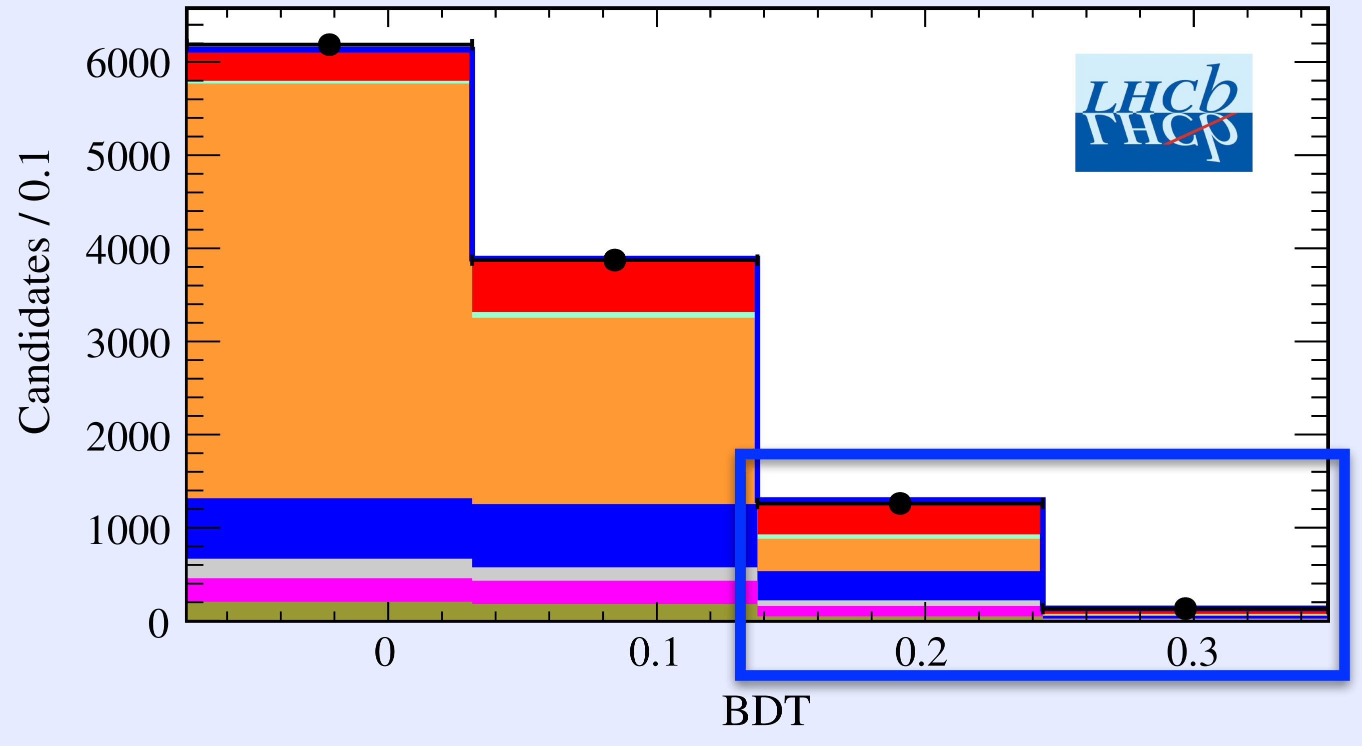


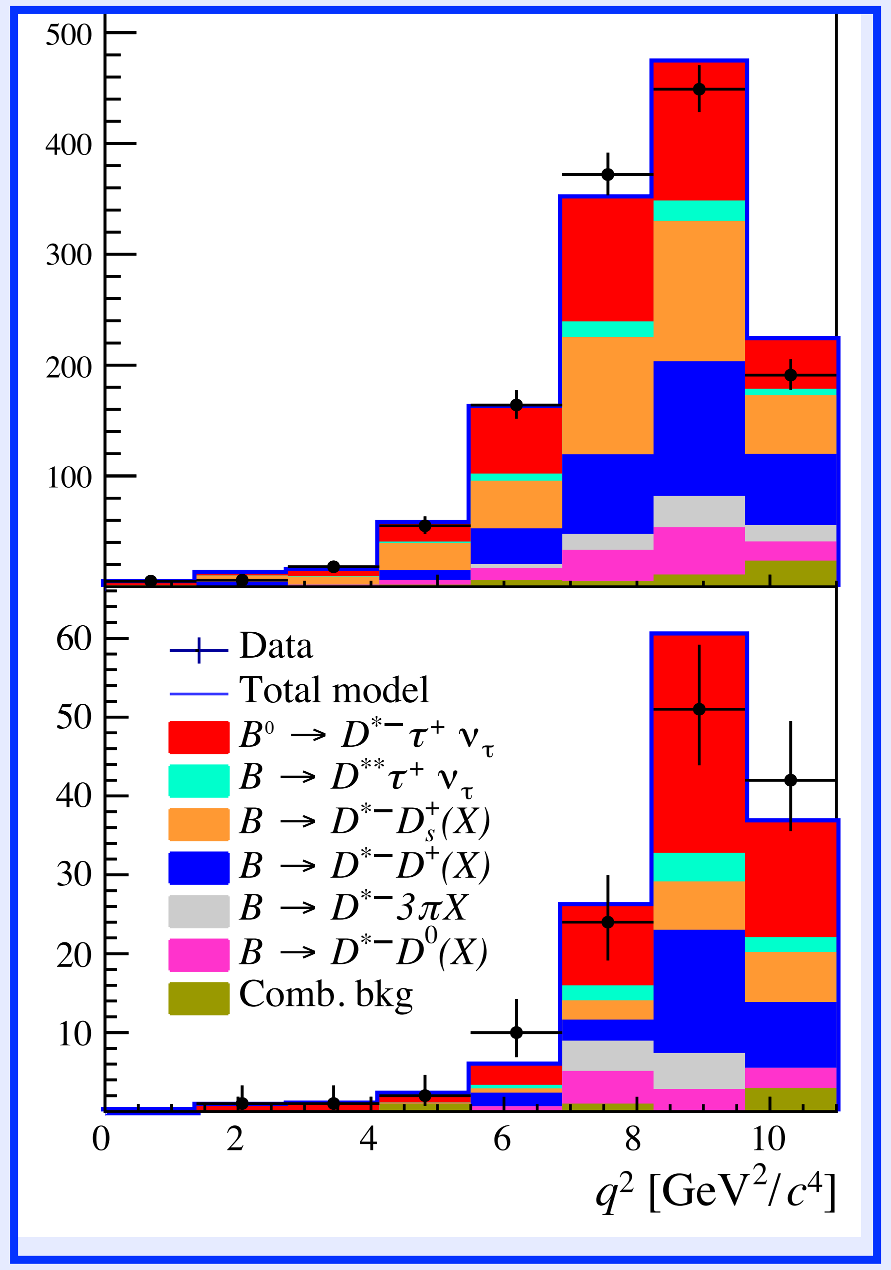


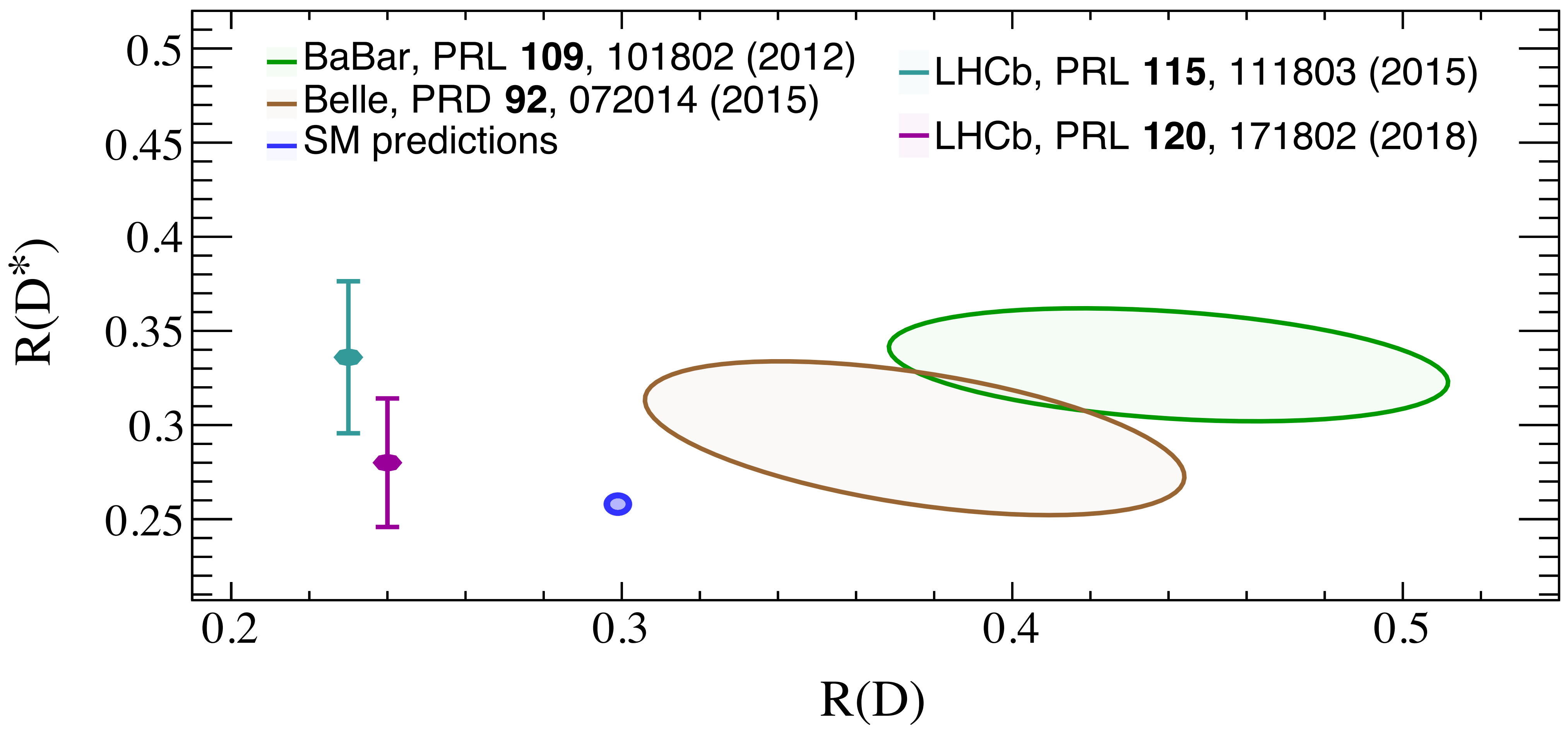


Hadronic-τ

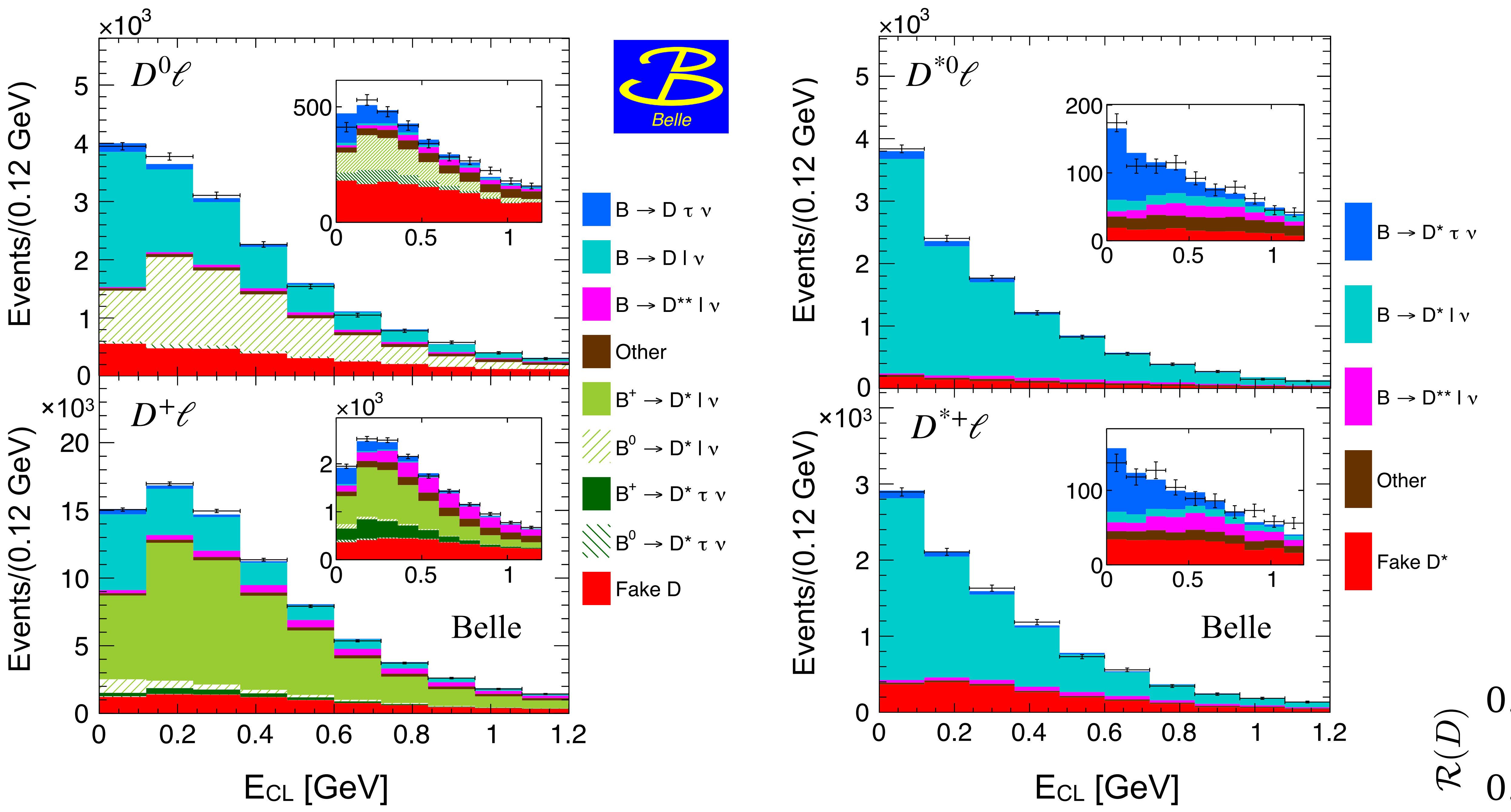
Phys. Rev. D **97**, 072013 (2018)

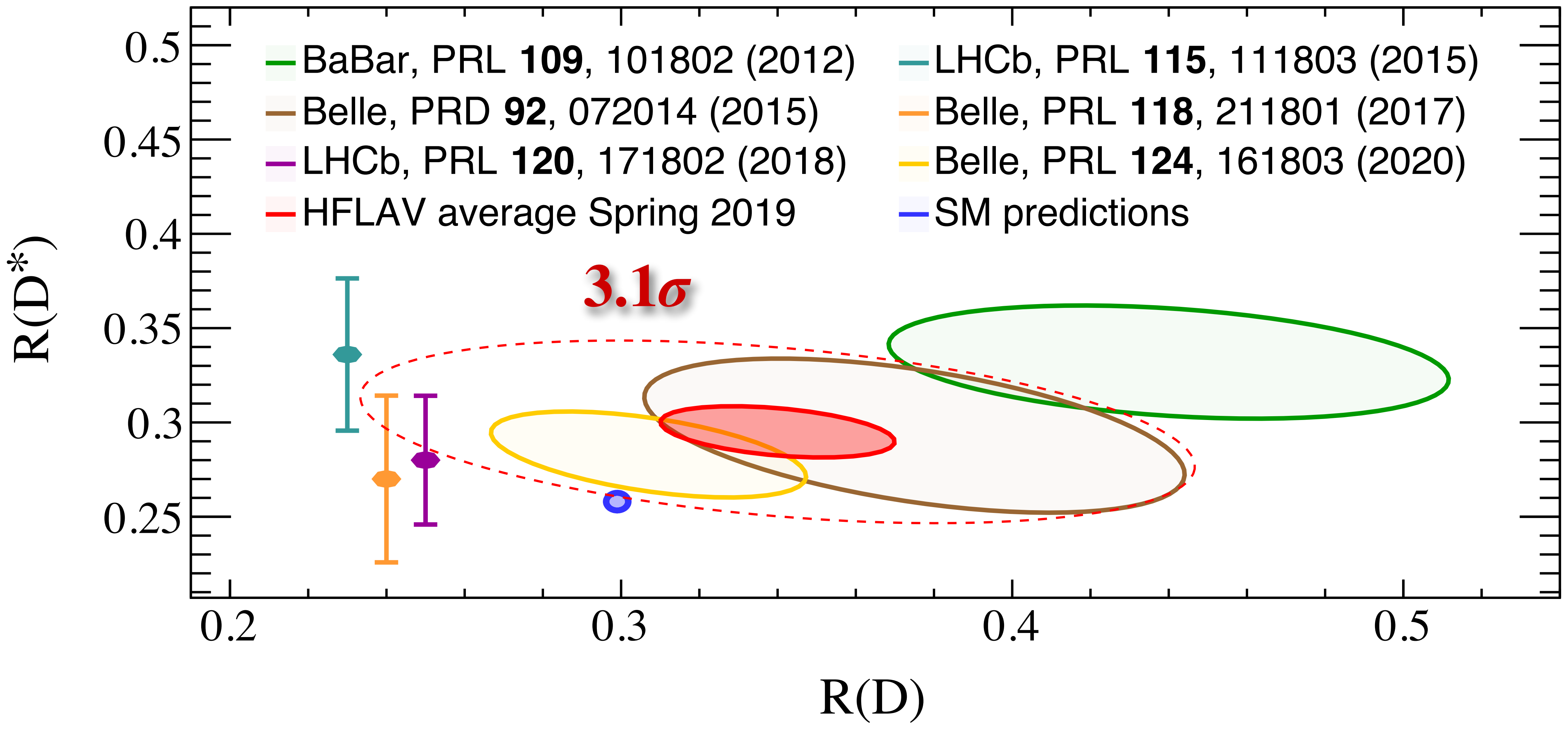


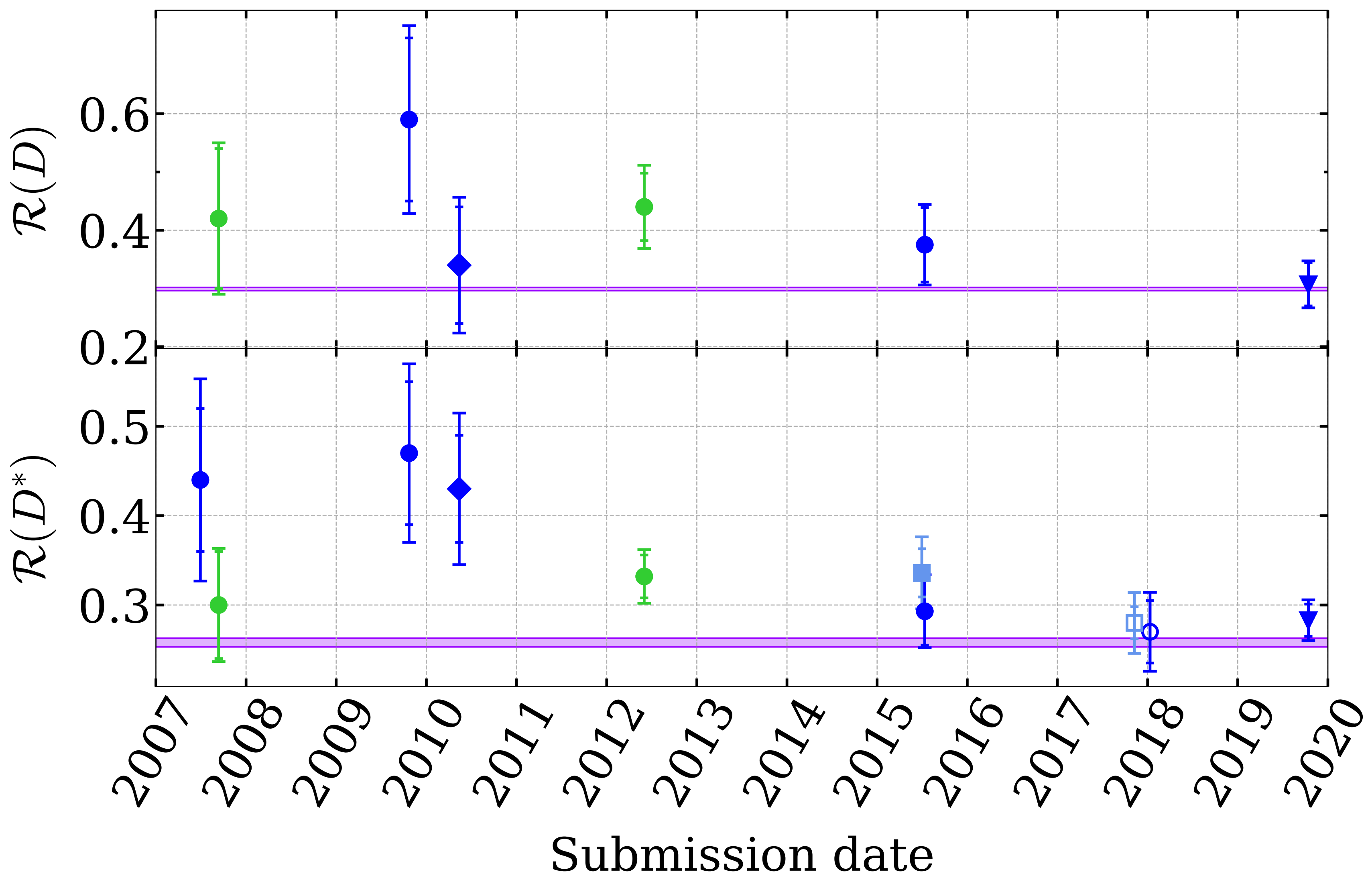




Phys. Rev. Lett. **124**, 161803 (2020)







Bernlochner, MFS, Robinson, Wormser, arXiv:2101.08326

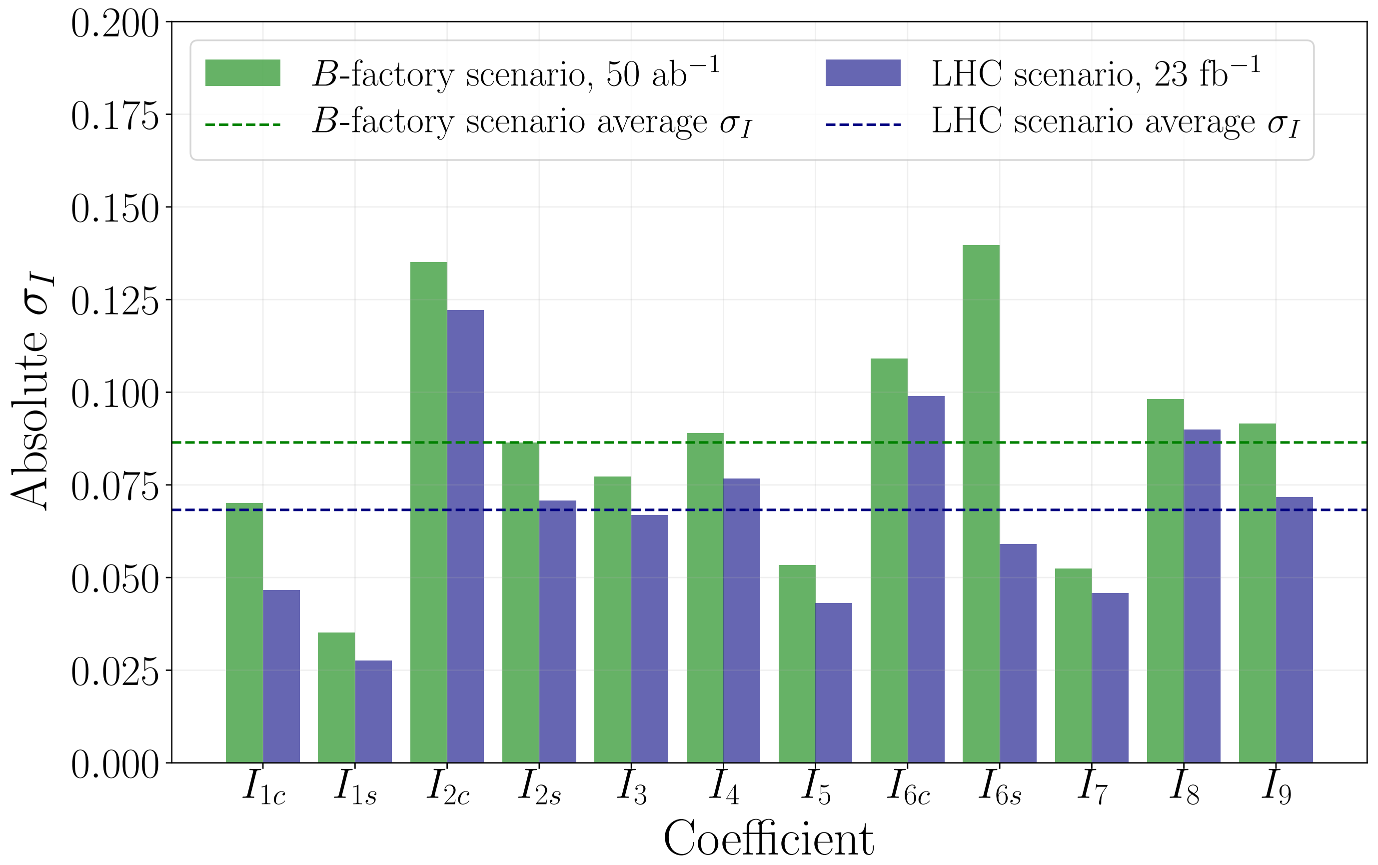
Recent measurements closer to SM, but **bkg/signal understanding** has **not meaningfully changed**

- **Leptonic-τ** and **semileptonic B_{tag}** with super-efficient **`FEI`**

Beyond $\mathscr{R}(D^{(*)})$

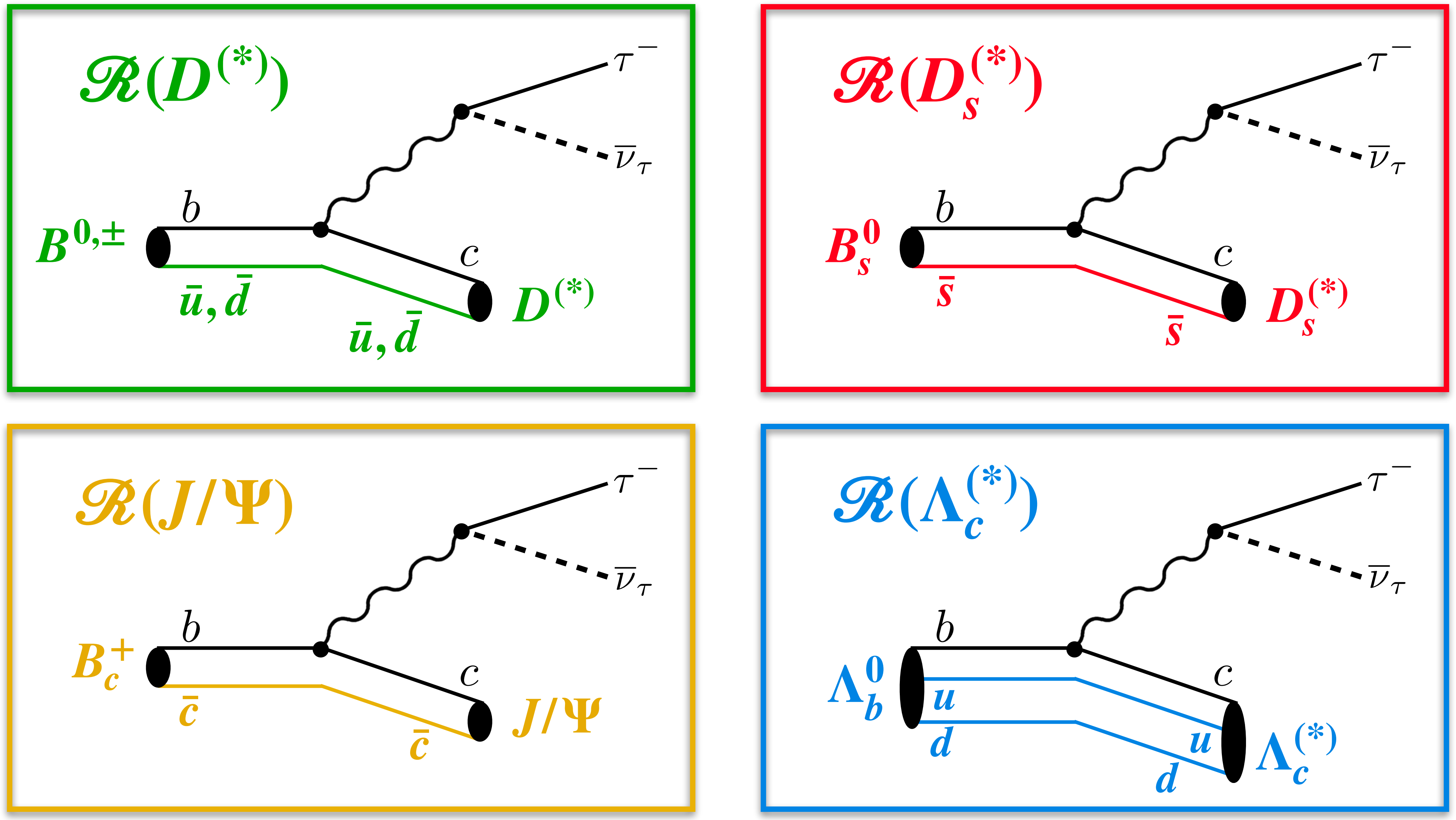
- Even a **5σ** on $\mathscr{R}(D^{(*)})$ **would not be sufficient** to **convince** ourselves of **NP**
  - **Indirect measurement** with **broad signal distributions** due to multiple ν in final state
- It will be important to have
  - Confirmation by **independent experiments**
  - Confirmation in **different decays**
  - Characterization in **kinematic distributions**

Belle II and **upgraded LHCb** both **sensitive** to **angular distributions**



Hill, John, Ke, Poluektov, *JHEP* 2019, 133 (2019)

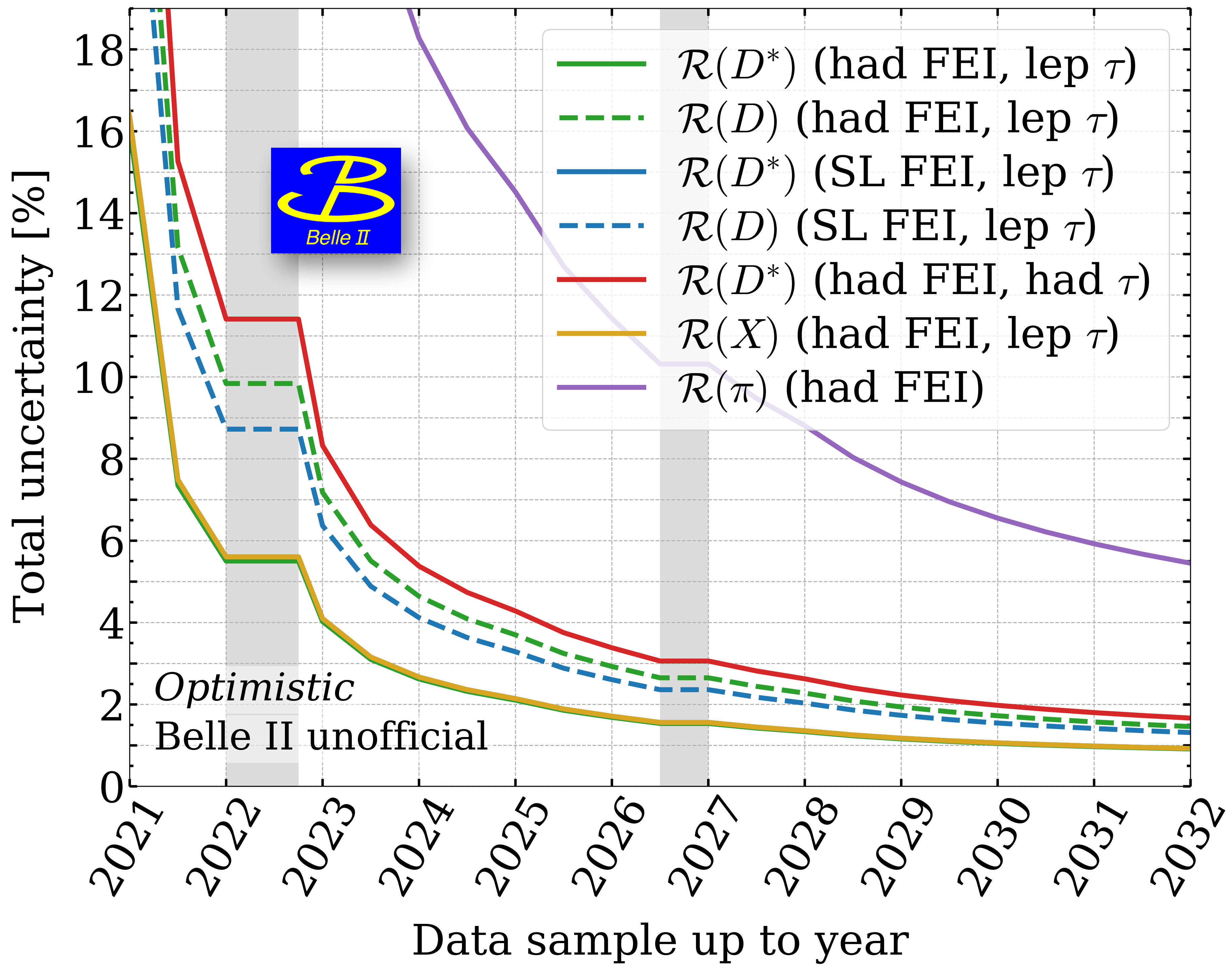
LHCb has a unique ability to study $b \to c\tau\nu$ transitions because $b\bar{b}$ production at the LHC hadronizes into all species of b-hadrons

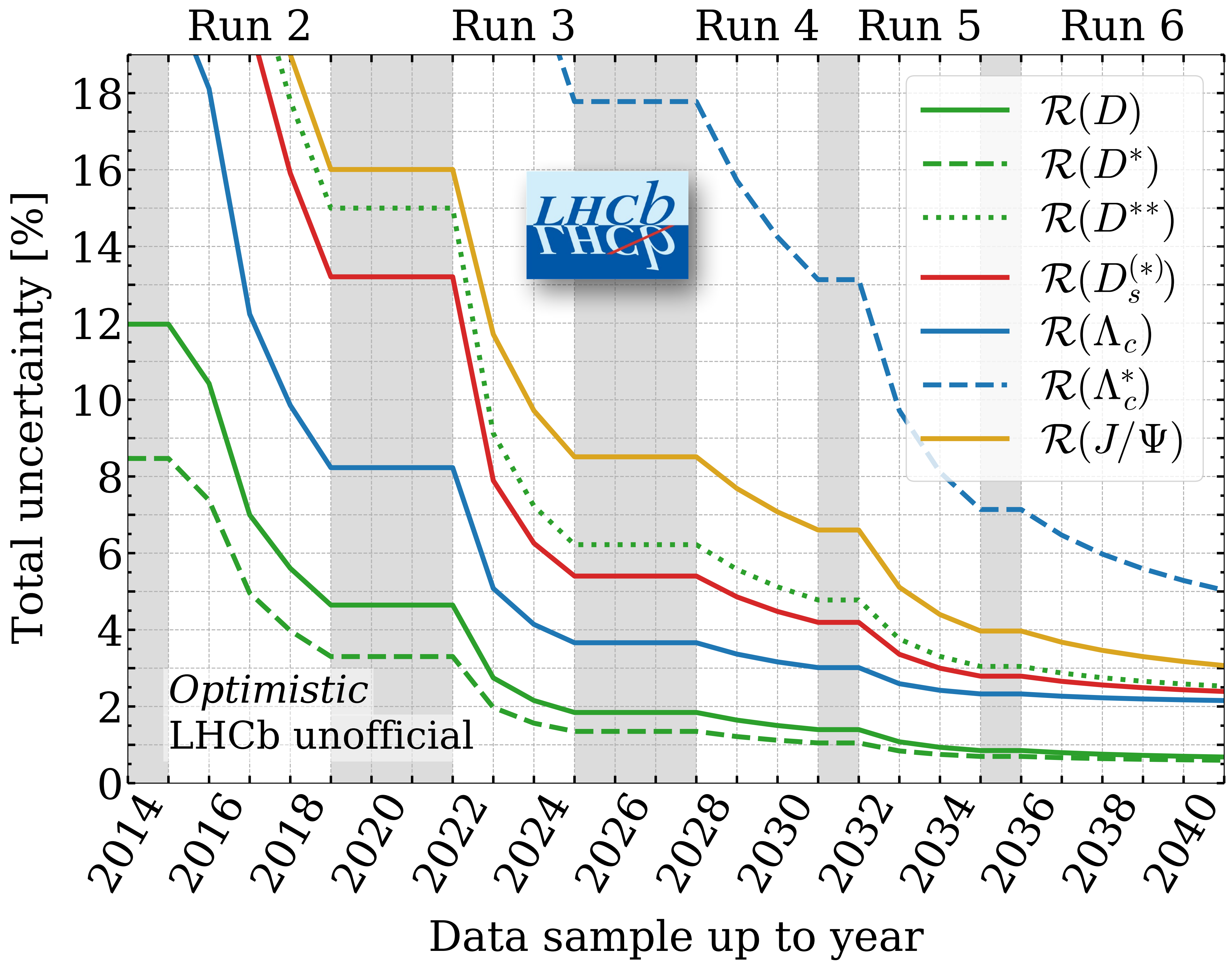


LHCb already published first non-$\mathscr{R}(D^{(*)})$ measurement
$\mathscr{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$,
1.8σ above SM

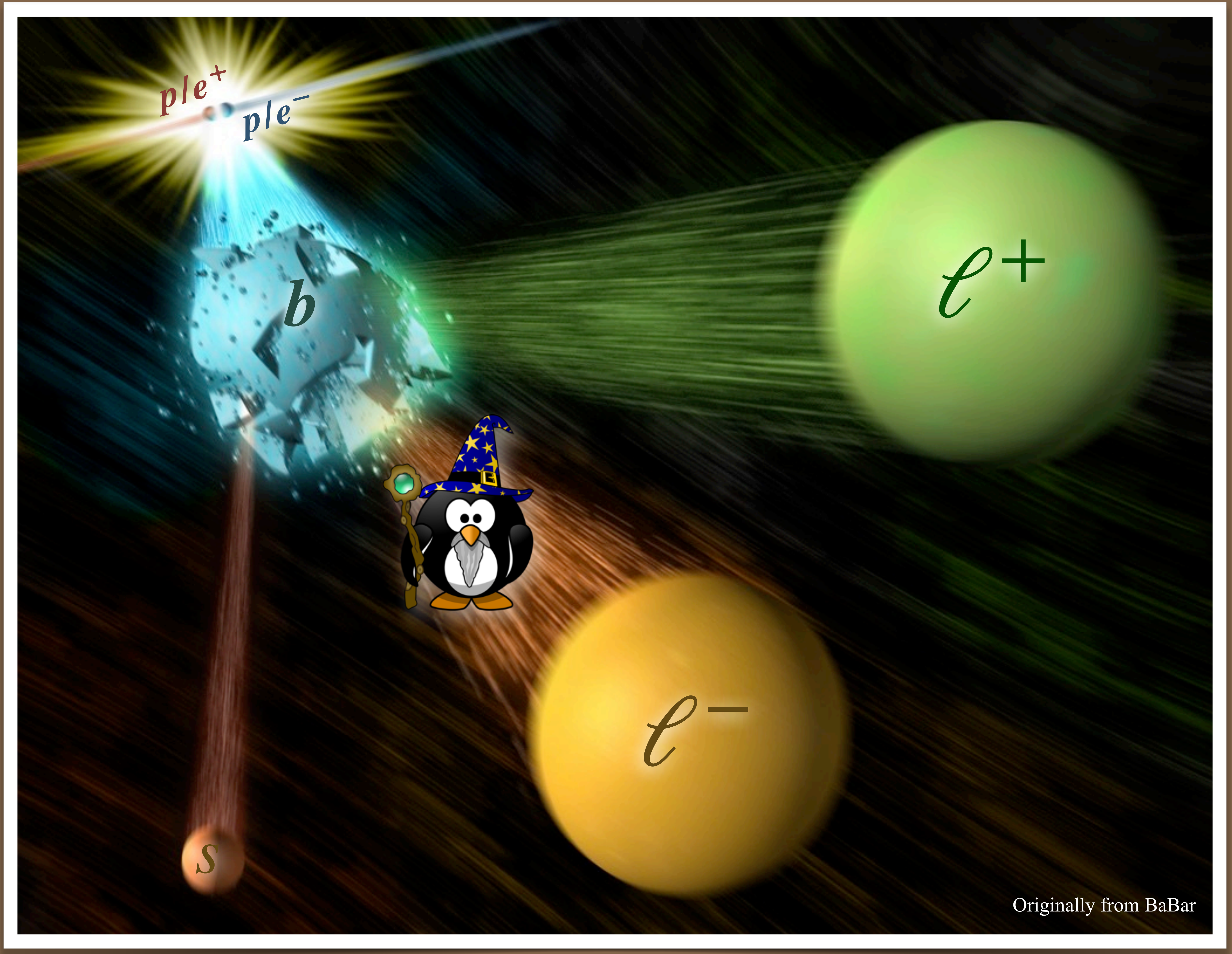
Phys. Rev. Lett. **120**, 121801 (2018)

- Currently, world-averaged $\mathscr{R}(D^{(*)})$ **exceeds SM by ~14%**
- With **Belle II** and **upgraded LHCb**, could get uncertainties below 3% in a few years
  - ➡ In addition to $\mathscr{R}(D^{(*)})$ and $\mathscr{R}(J/\Psi)$, LHCb has $\mathscr{R}(D^{**})$, $\mathscr{R}(p\bar{p})$, $\mathscr{R}(D_s)$, $\mathscr{R}(D_s^*)$, and $\mathscr{R}(\Lambda_c)$ **ongoing**!
  - ➡ Even **CMS** trying to get out a measurement with **ingenious trigger strategy**





Wherever this ends up, very exciting times ahead!



Penguin from Jeff Brassard

LFU results with $b \to s\ell\ell$ transitions

Leptonic $B^0_{(s)} \to \mu^+\mu^-$ (very rare)

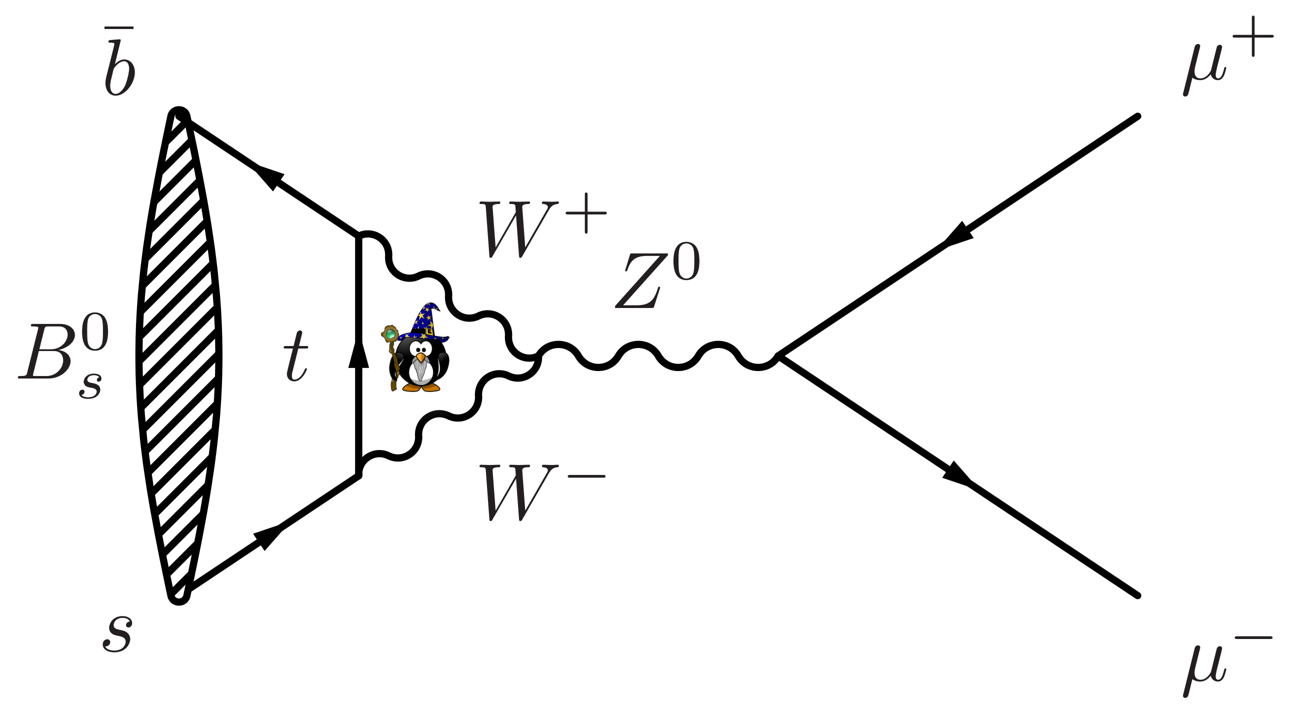
- FCNC and helicity/Cabibbo suppressed → **very rare** $\mathscr{B} \sim 10^{-9}$

$$\mathscr{B}(B^0_q \to \mu^+\mu^-)_{\rm SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{\rm SM} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1-y_q} \qquad q = d, s$$

Clipped from Marco Santimaria

single Wilson coefficient & single hadronic constant (known at $\simeq 0.5\,\%$!)

[PRD 98 (2019) 074512]



SM Predictions JHEP 10 (2019) 232

$$\mathscr{B}\left(B^0_s \to \mu^+\mu^-\right) = \left(3.66 \pm 0.14\right) \times 10^{-9} \quad \to \quad \textbf{4\% uncertainty}$$

$$\mathscr{B}\left(B^0 \to \mu^+\mu^-\right) = \left(1.03 \pm 0.05\right) \times 10^{-9} \quad \to \quad \textbf{5\% uncertainty}$$

- **BFs out of reach** from **B-factories**, but **their measurements are key**

Normalization from $B^+ \to J/\psi K^+$
(and $B^0 \to K^+\pi^-$ in LHCb)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_S}{N_{\rm obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\rm tot}^{B^+}}{\varepsilon_{\rm tot}} \mathcal{B}(B^+ \to J/\psi K^+) \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

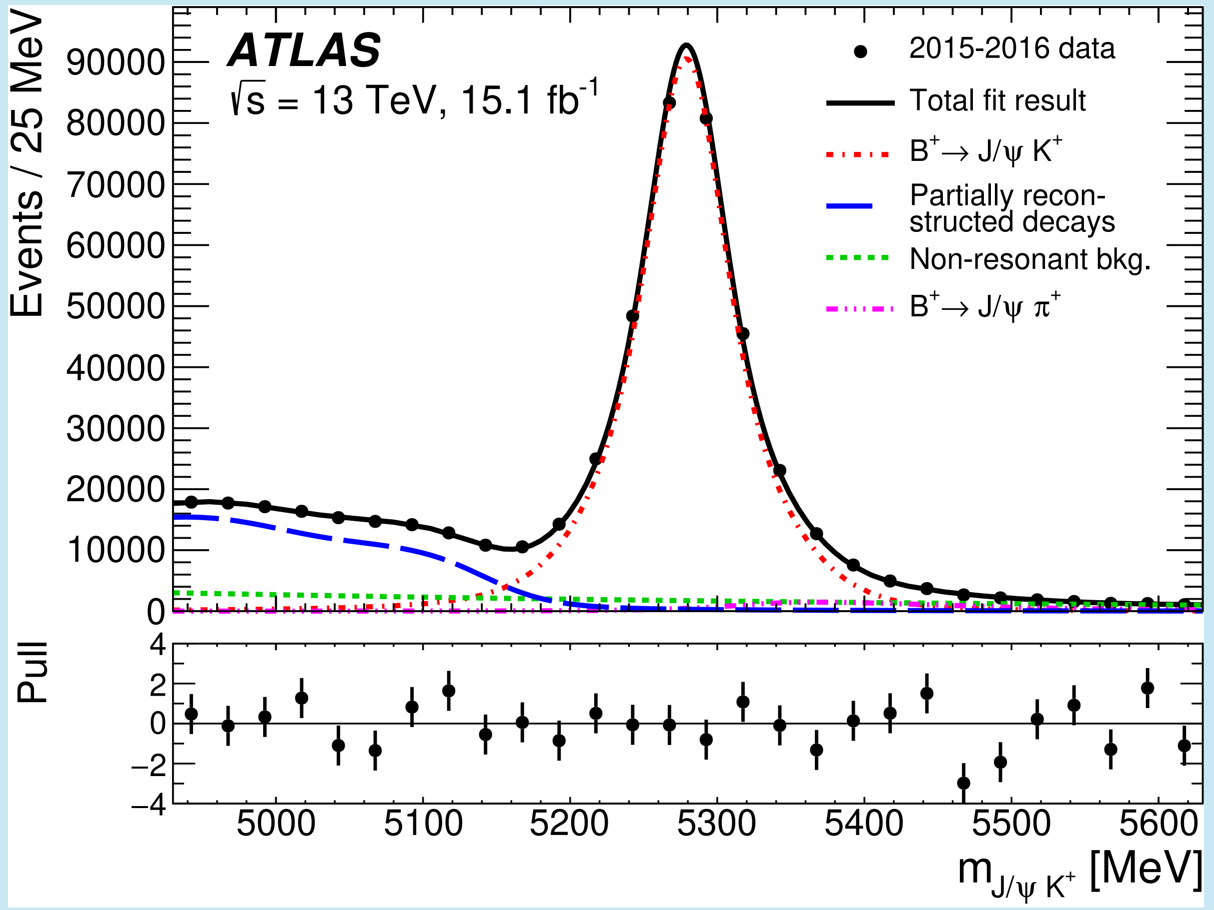
Belle **2.4% uncert.** BaBar **0.6% uncert.** BESIII

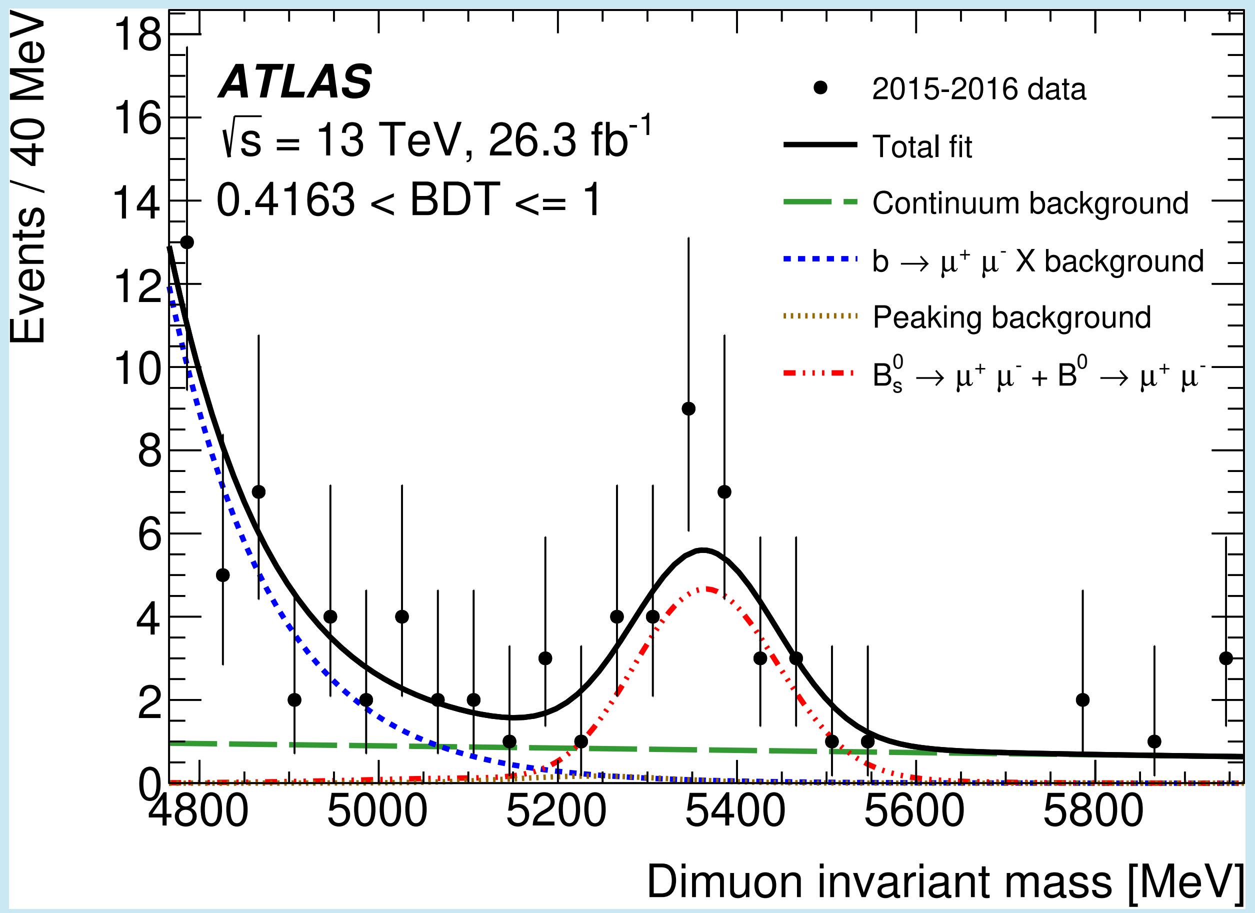
3.2% uncert. from 2103.06810 (7% until this March) Fresh! LHCb

$B^0_{(s)} \to \mu^+\mu^-$: ATLAS and CMS

Normalization

Signal



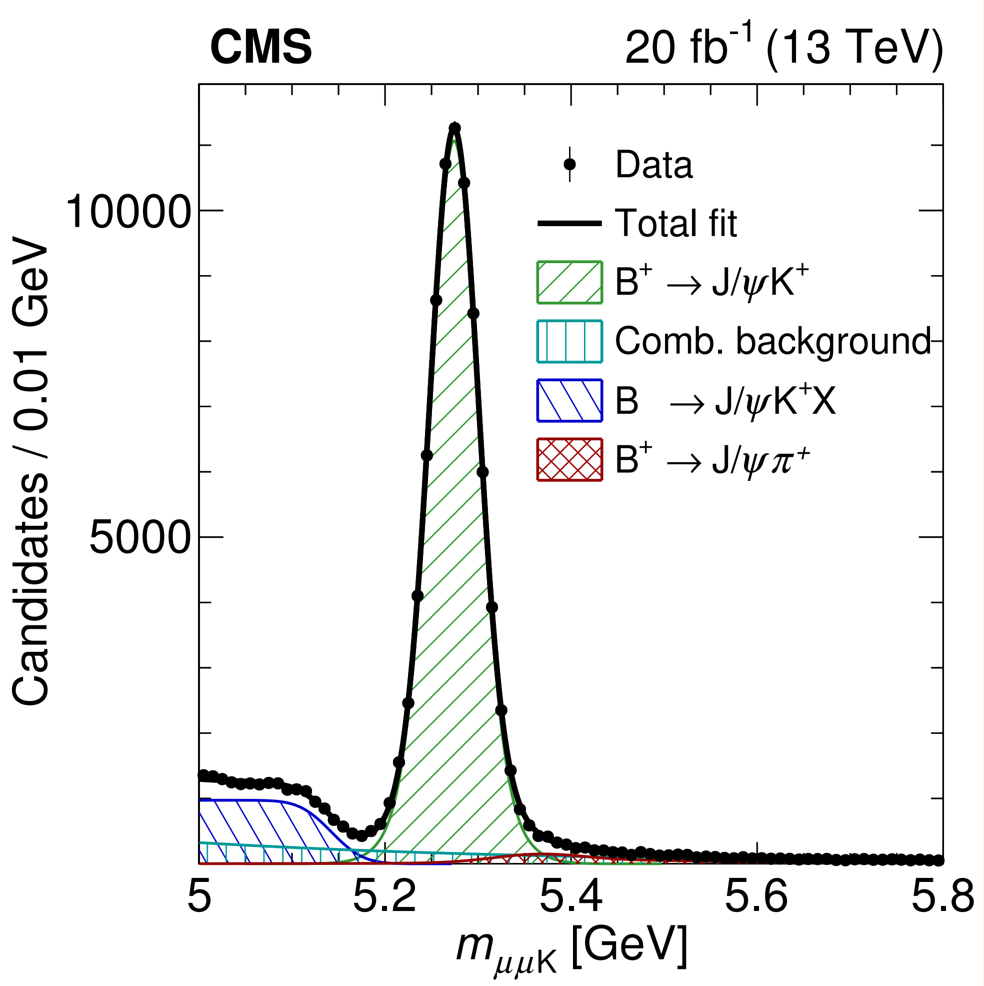


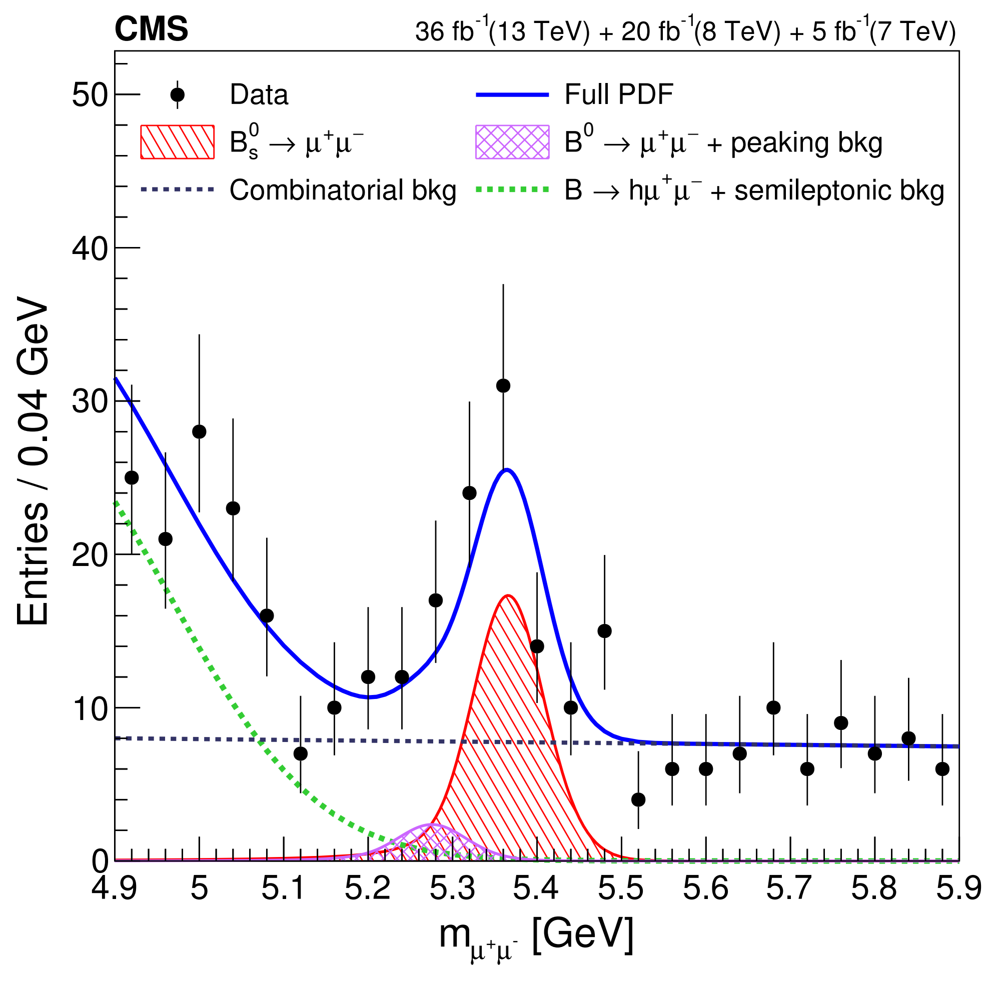
25% of B_s in Run 1+2 dataset

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \quad \to \quad 4.6\sigma$$

$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 2.1 \times 10^{-10} \quad (95\,\%\ \mathrm{CL})$$

JHEP 04 (2019) 098





32% of B_s in Run 1+2 dataset

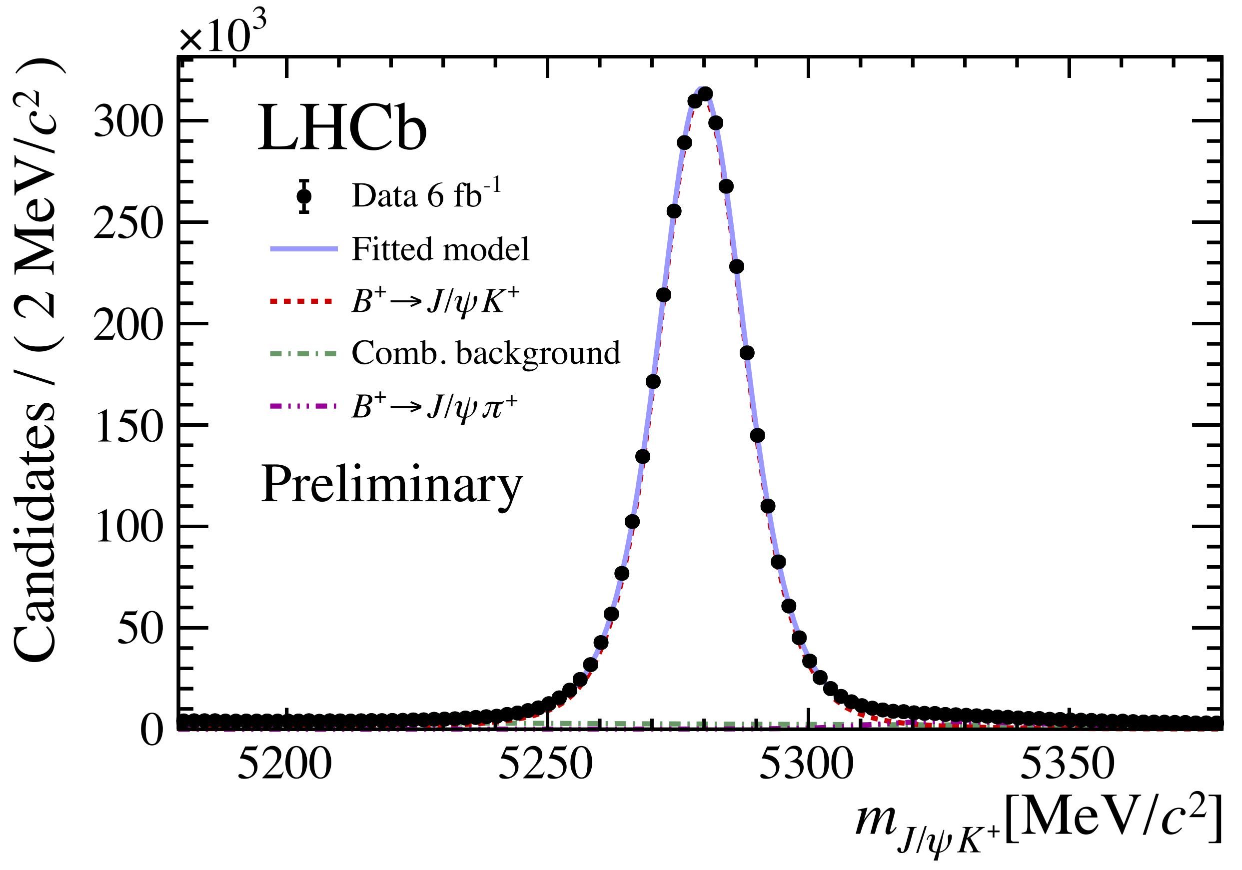
$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = \left(2.9^{+0.7}_{-0.8}\right) \times 10^{-9} \quad \to \quad 5.6\sigma$$

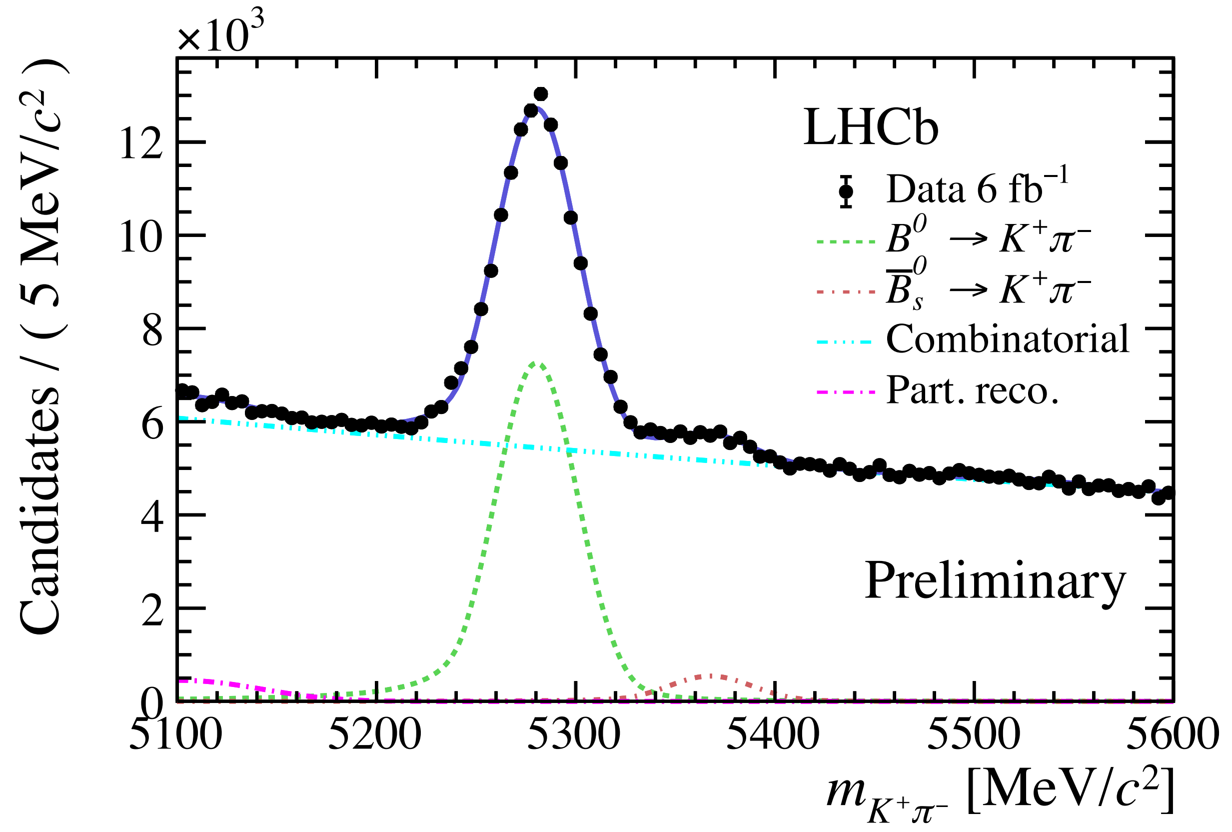
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 3.6 \times 10^{-10} \quad (95\,\%\ \mathrm{CL})$$

JHEP 04 (2020) 188

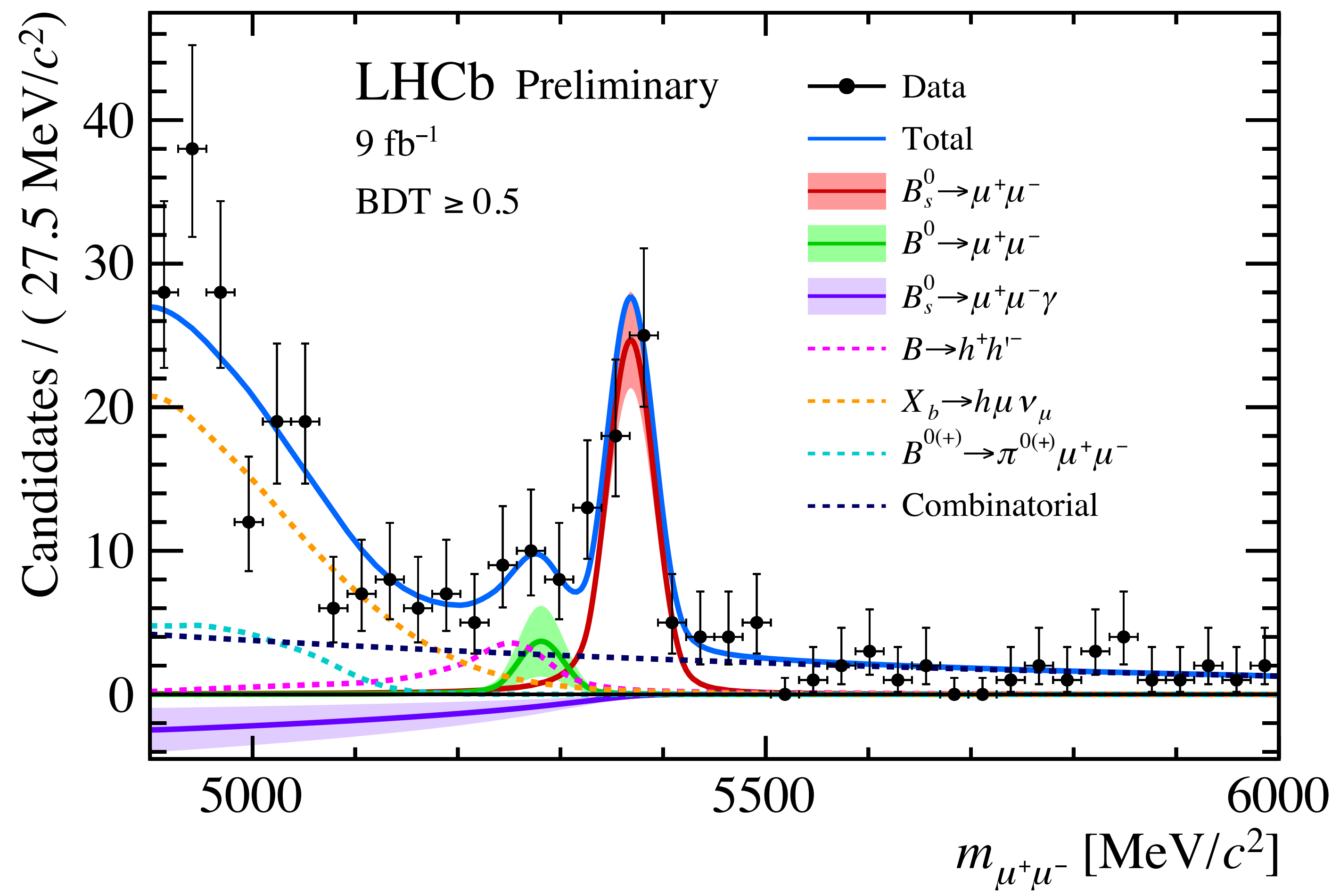
$B^0_{(s)} \to \mu^+\mu^-$: LHCb

Normalization





Signal



Fresh!

100% of B_s in Run 1+2 dataset

PAPER-2021-007 forthcoming

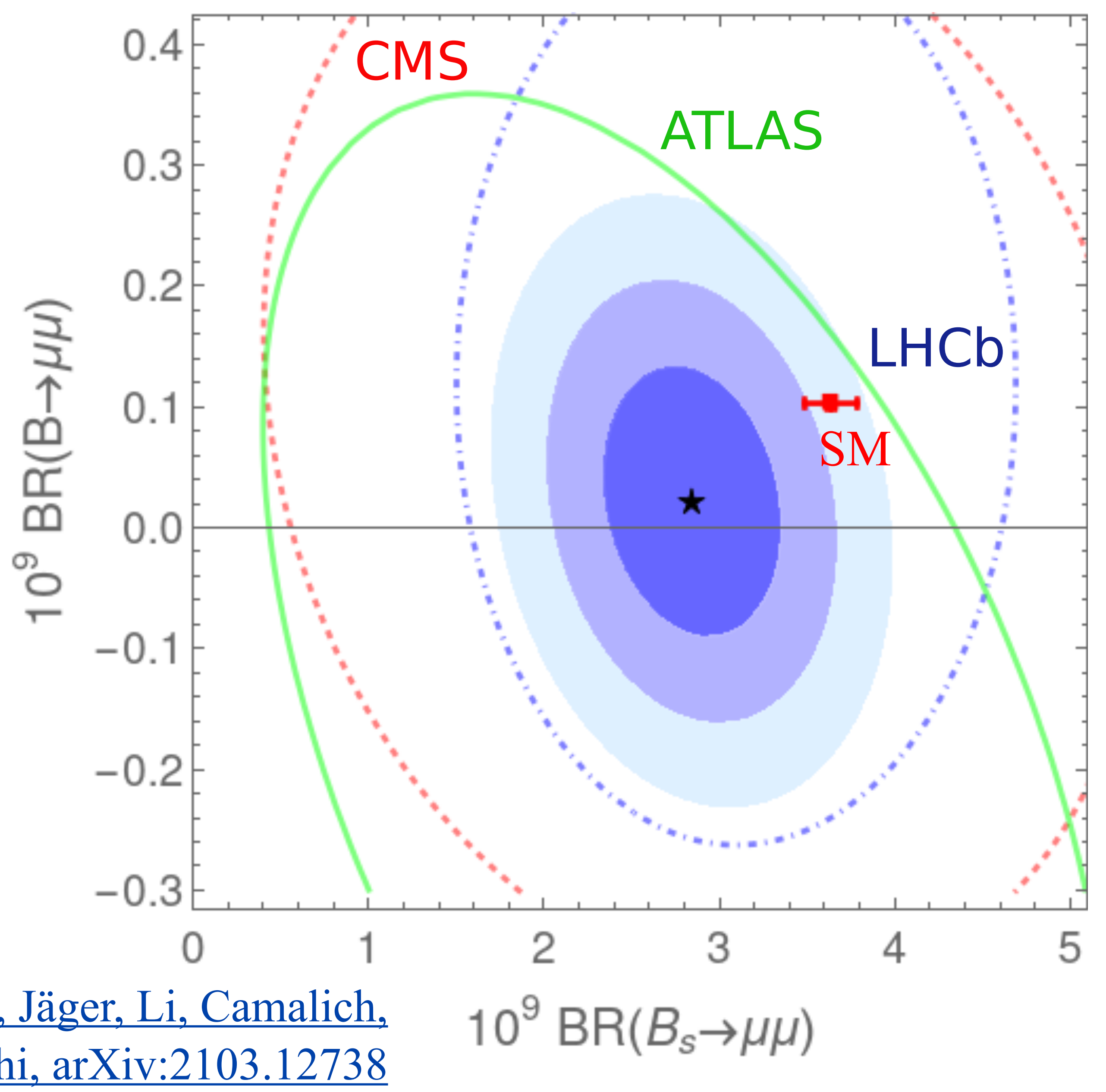
$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right) \times 10^{-9} \to 10.8\sigma$$

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

- Combination with ATLAS/CMS

$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right)_{WA} = (2.84 \pm 0.33) \times 10^{-9}$$

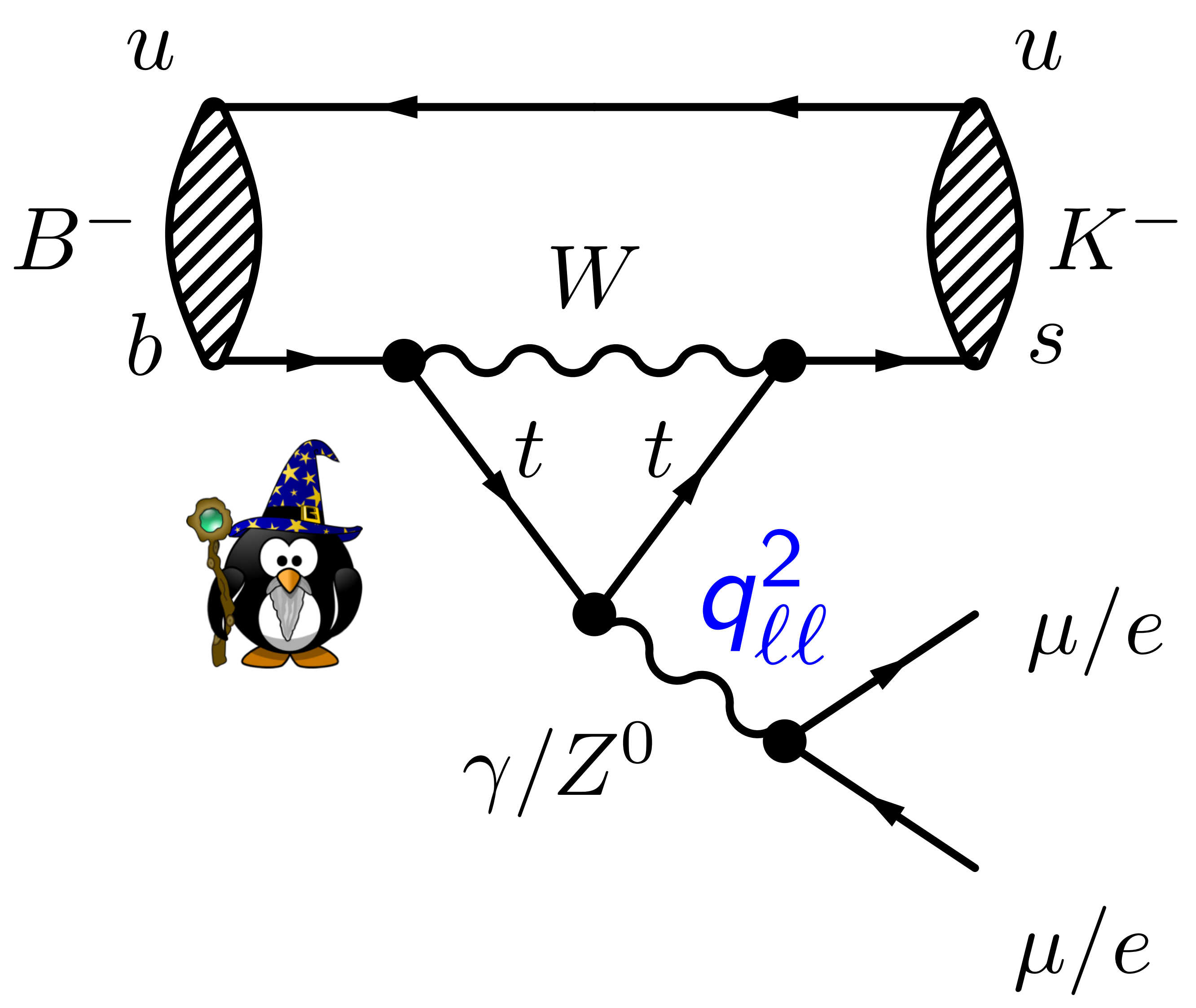
➡ 22% below SM prediction

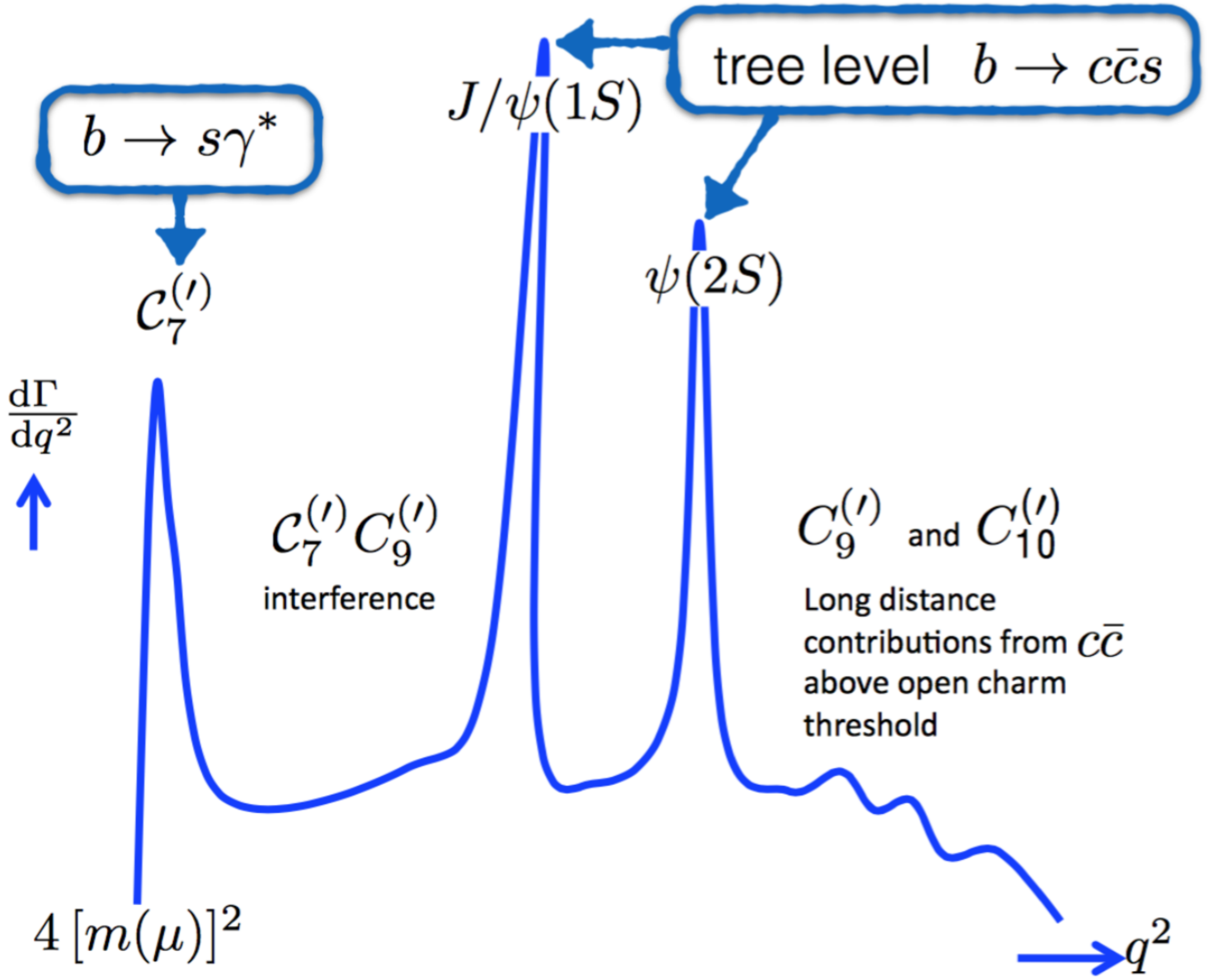


Geng, Grinstein, Jäger, Li, Camalich, Shi, arXiv:2103.12738

~ 2.3σ tension with SM

Not as suppressed as leptonic decays, but still **rare** with $\mathscr{B} \sim 10^{-7}$

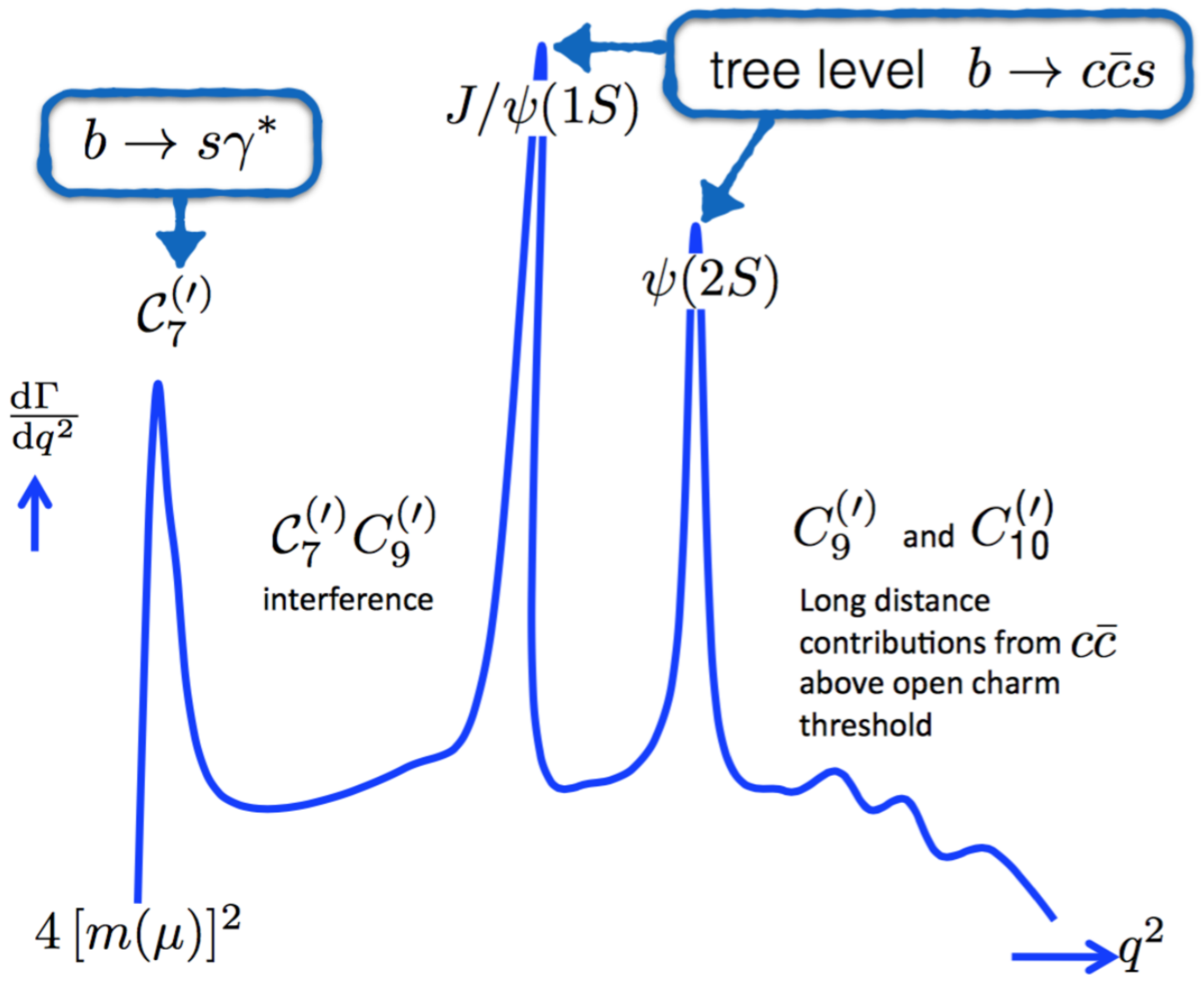




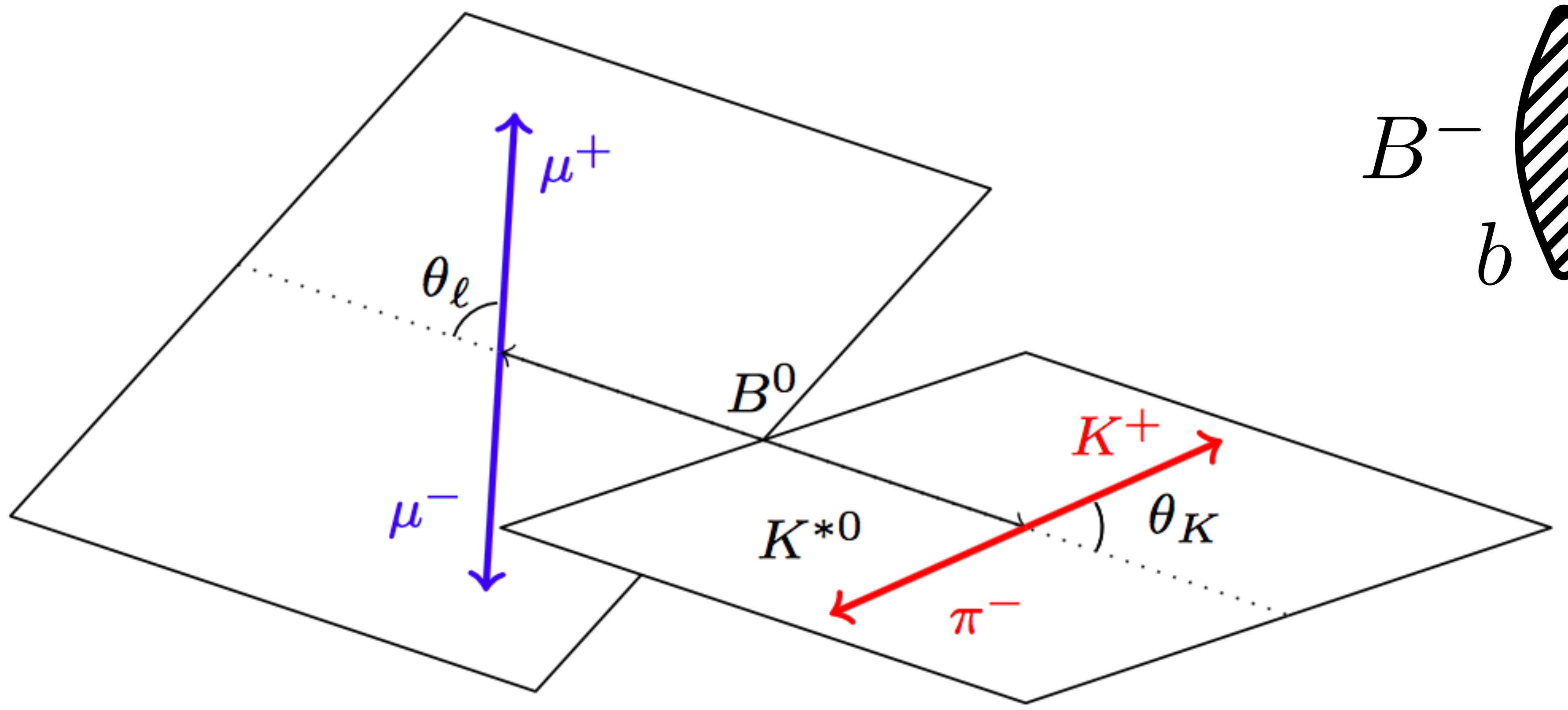
$$q^2 \equiv m\left(\ell^+\ell^-\right)$$

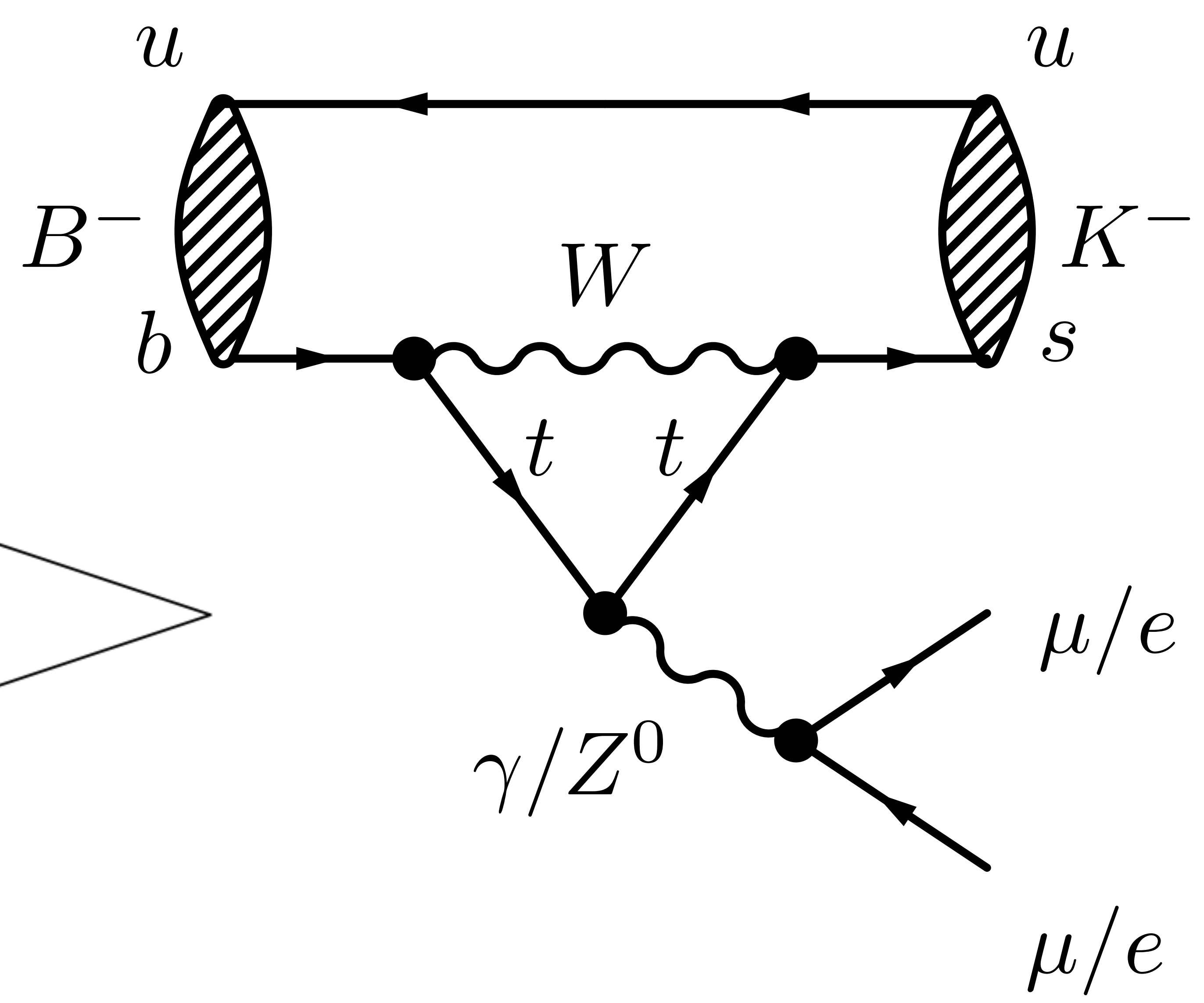
Precision test strategies

- **Experimental** and **theoretical uncertainties** depend on strategy



Clipped from Mick Mulder





Branching fractions

Simpler for LHC (focus on μ), but large theory uncertainties

Angular observables

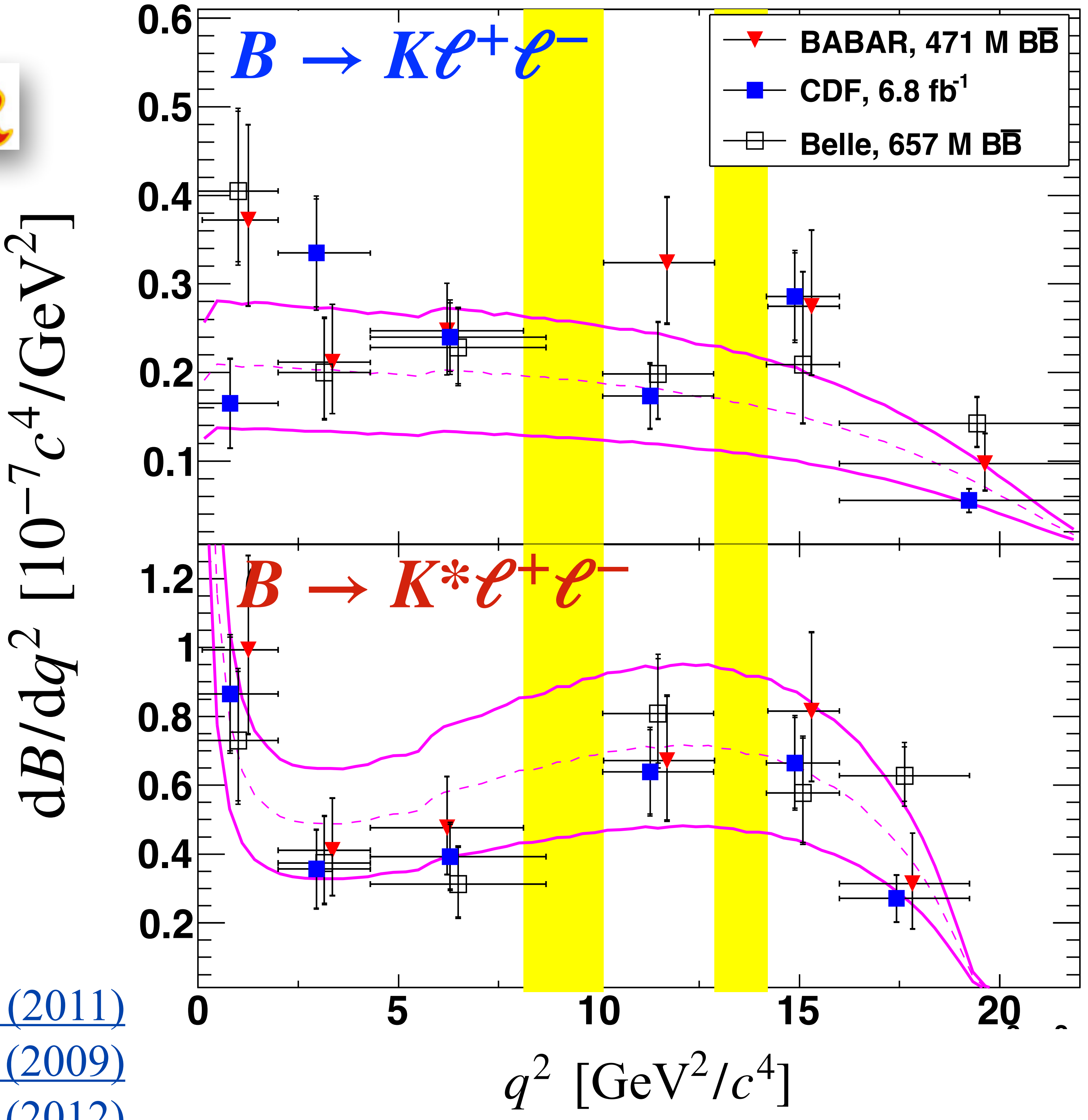
Minimal FF uncertainties, though sensitive to charm loops

LFU ratios $\mathcal{R}_{H_s} = \dfrac{\mathcal{B}(H_b \to H_s \mu\mu)}{\mathcal{B}(H_b \to H_s ee)}$

Theory uncertainty of ~1%, but electrons harder at the LHC

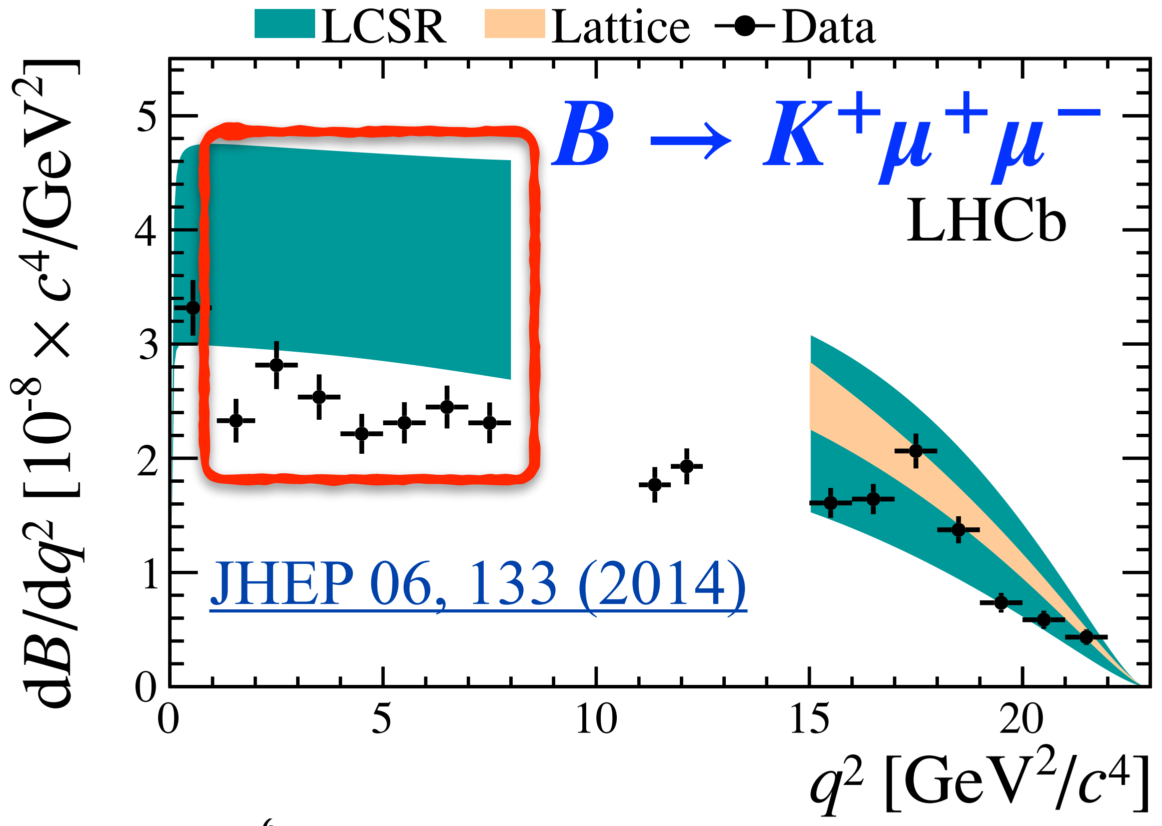
Differential BF rates

- **First measurements** of $B \to K^{(*)}\ell\ell$ at **Tevatron** and the **B-factories**
  - ➡ Consistent with expectations though **large uncertainties**

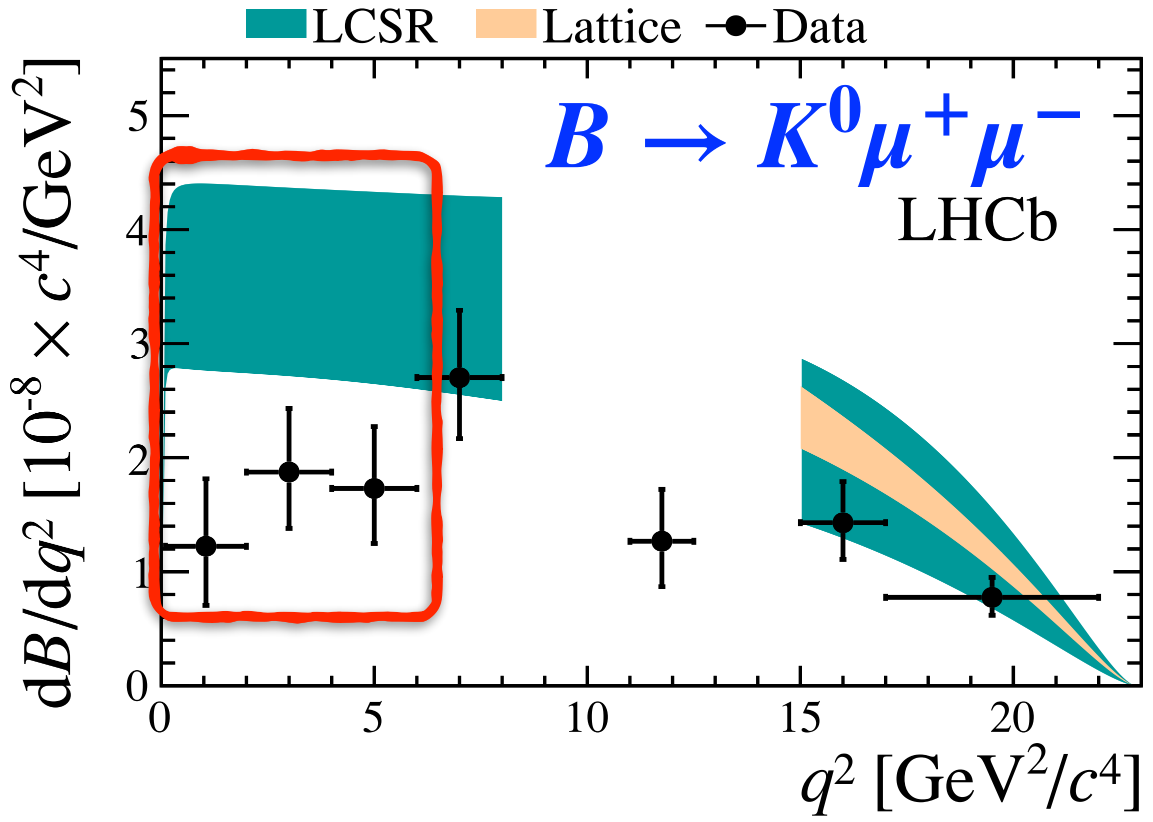


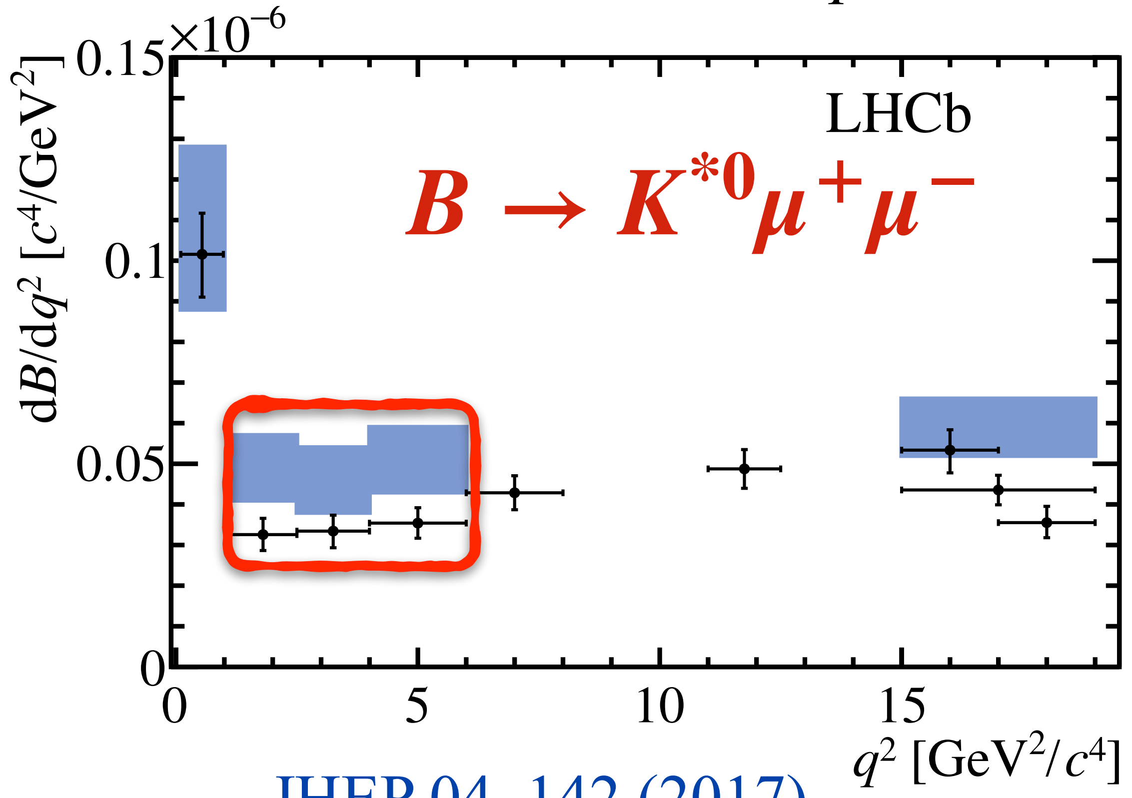
PRL 107, 201802 (2011)
PRL 103, 171801 (2009)
PRD 86, 032012 (2012)

Deficit in LHCb measurements **with muons** at **low q^2**

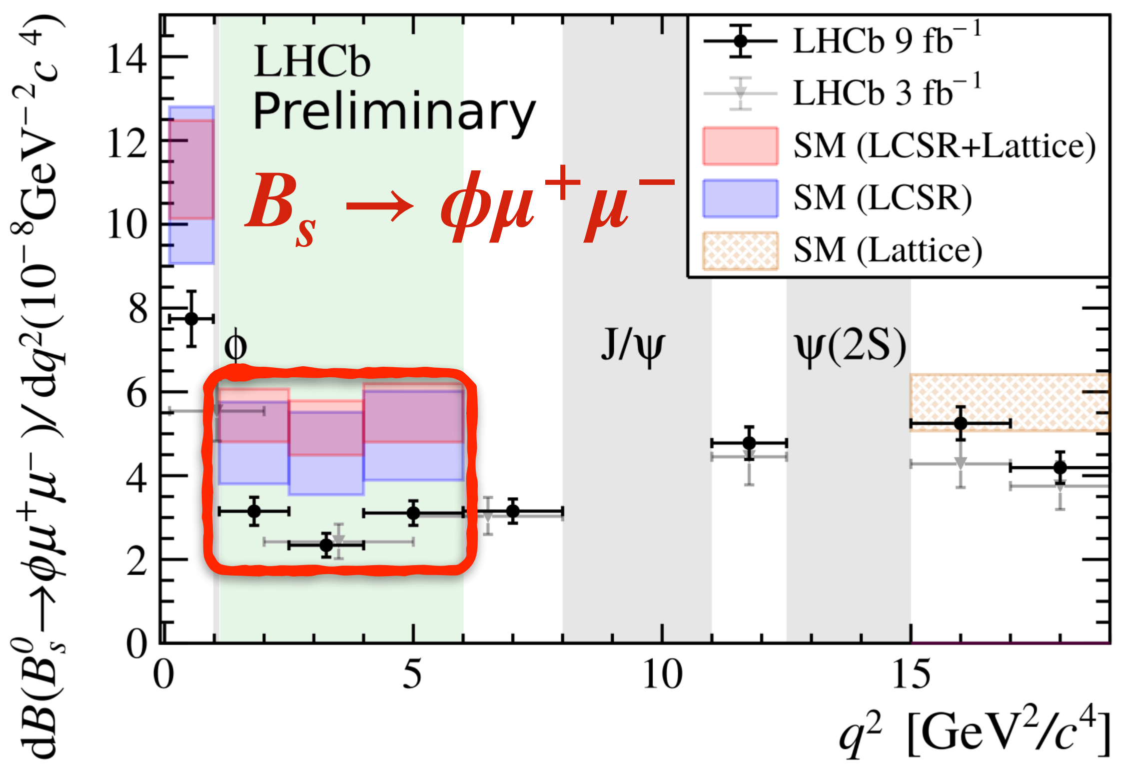


JHEP 06, 133 (2014)





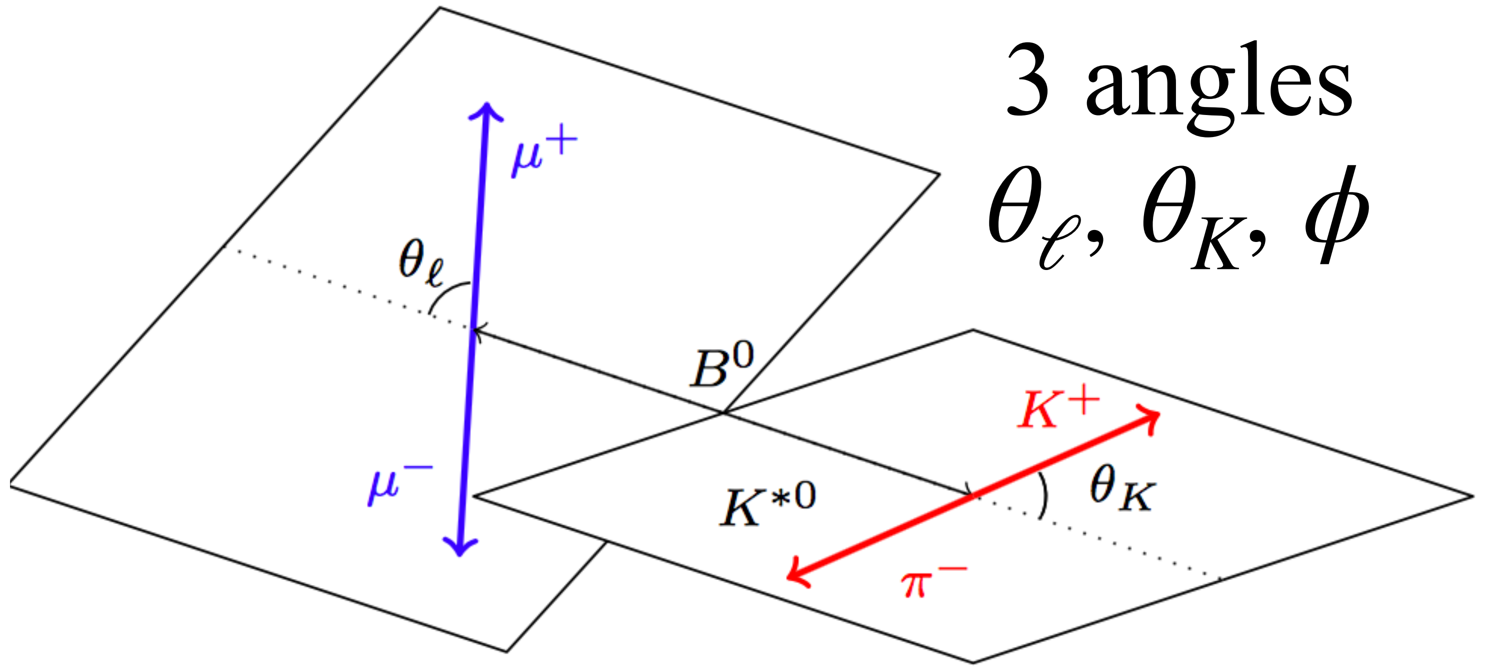
JHEP 04, 142 (2017)



PAPER-2021-014 forthcoming

Fresh!

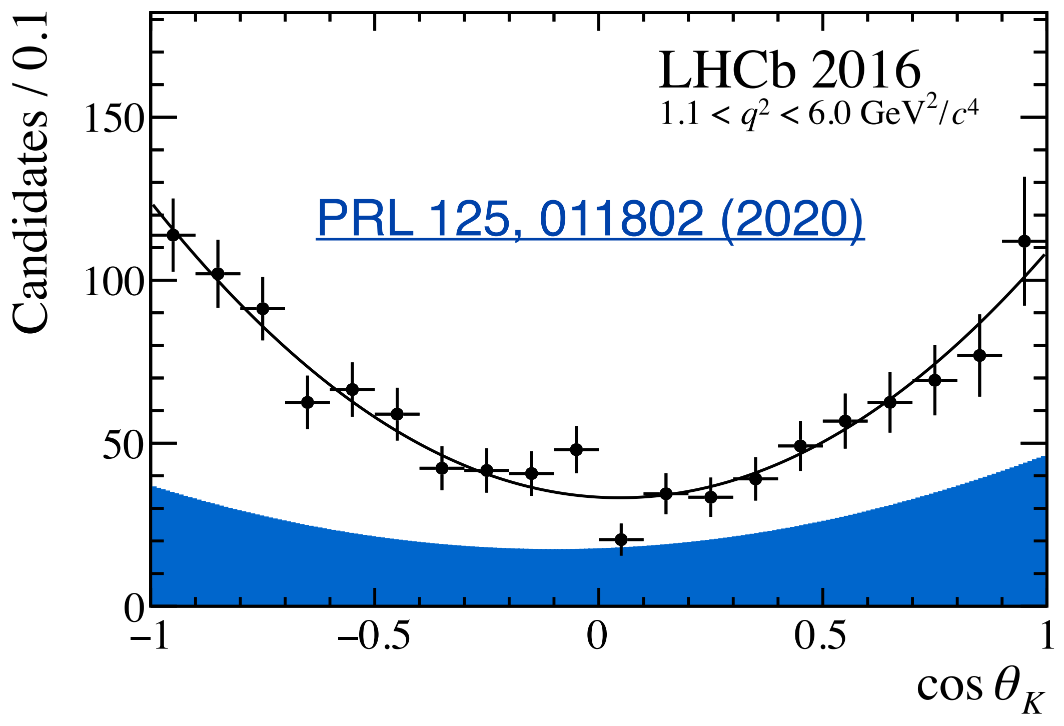
Angular observables in $B \to K^* \ell\ell$

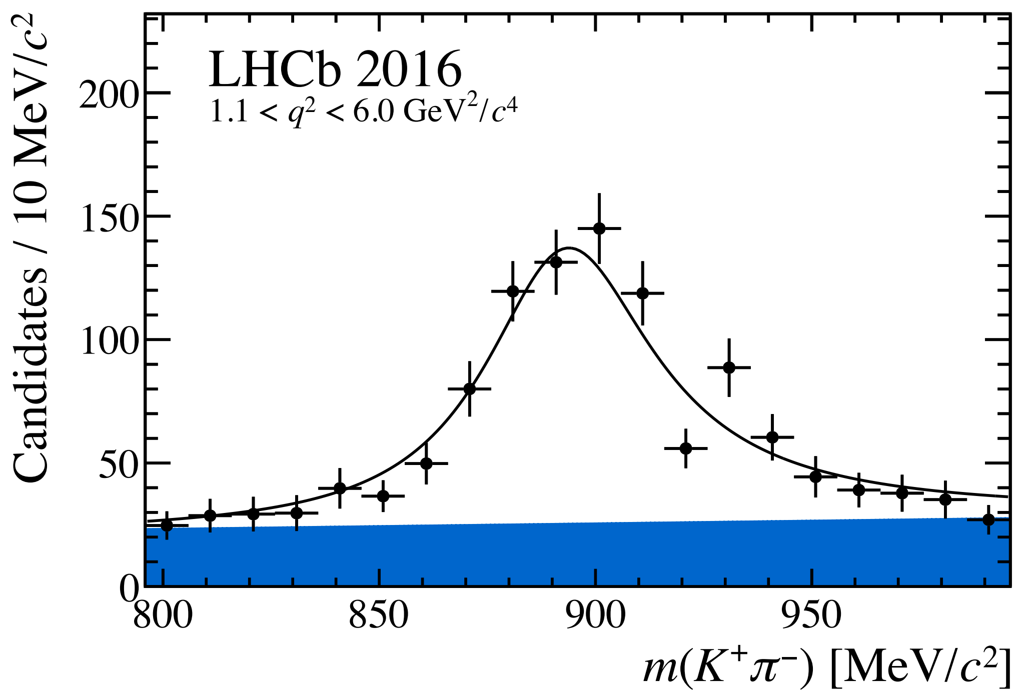


3 angles
θ_ℓ, θ_K, ϕ

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar\Gamma)}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

P-wave

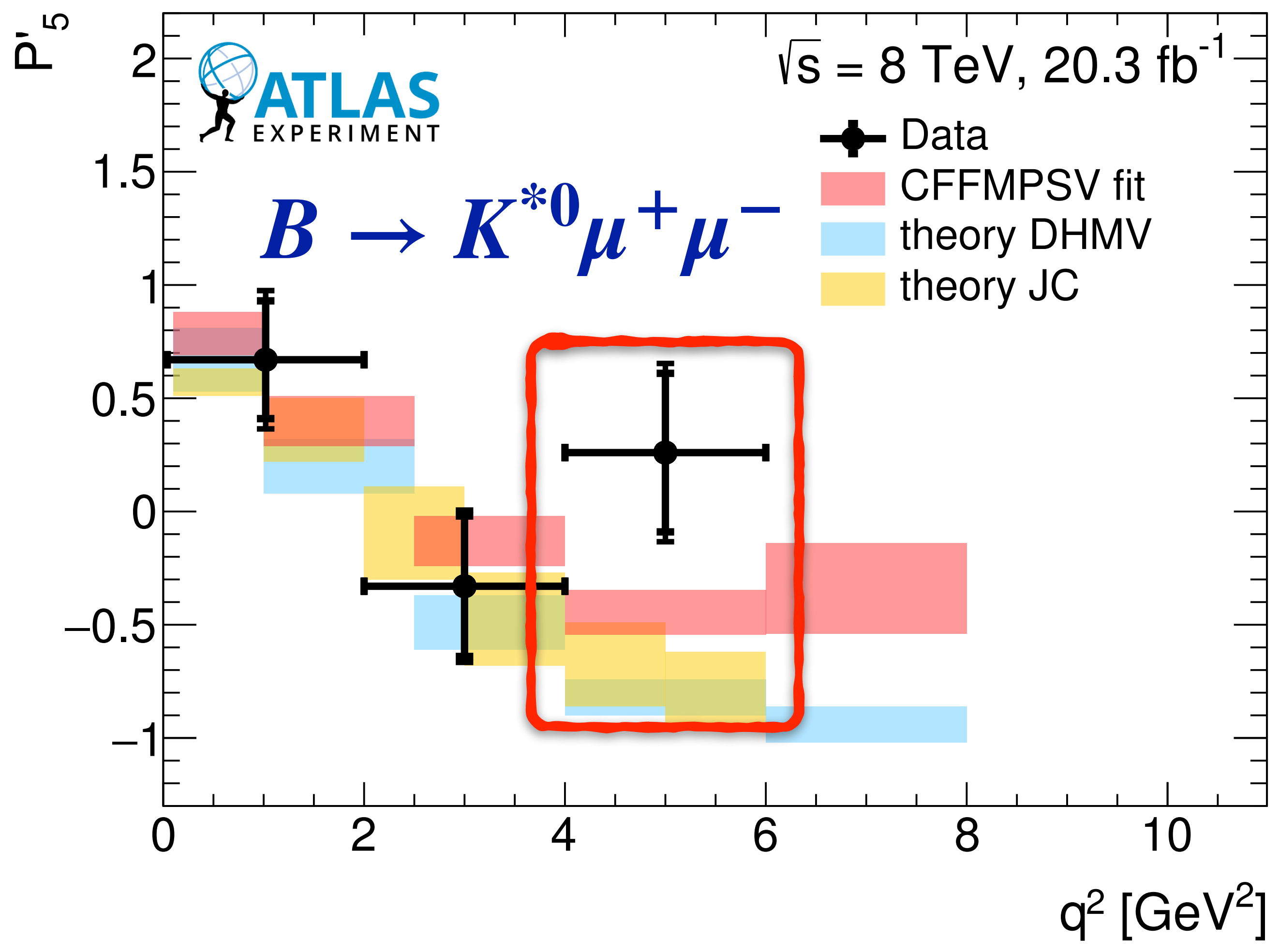




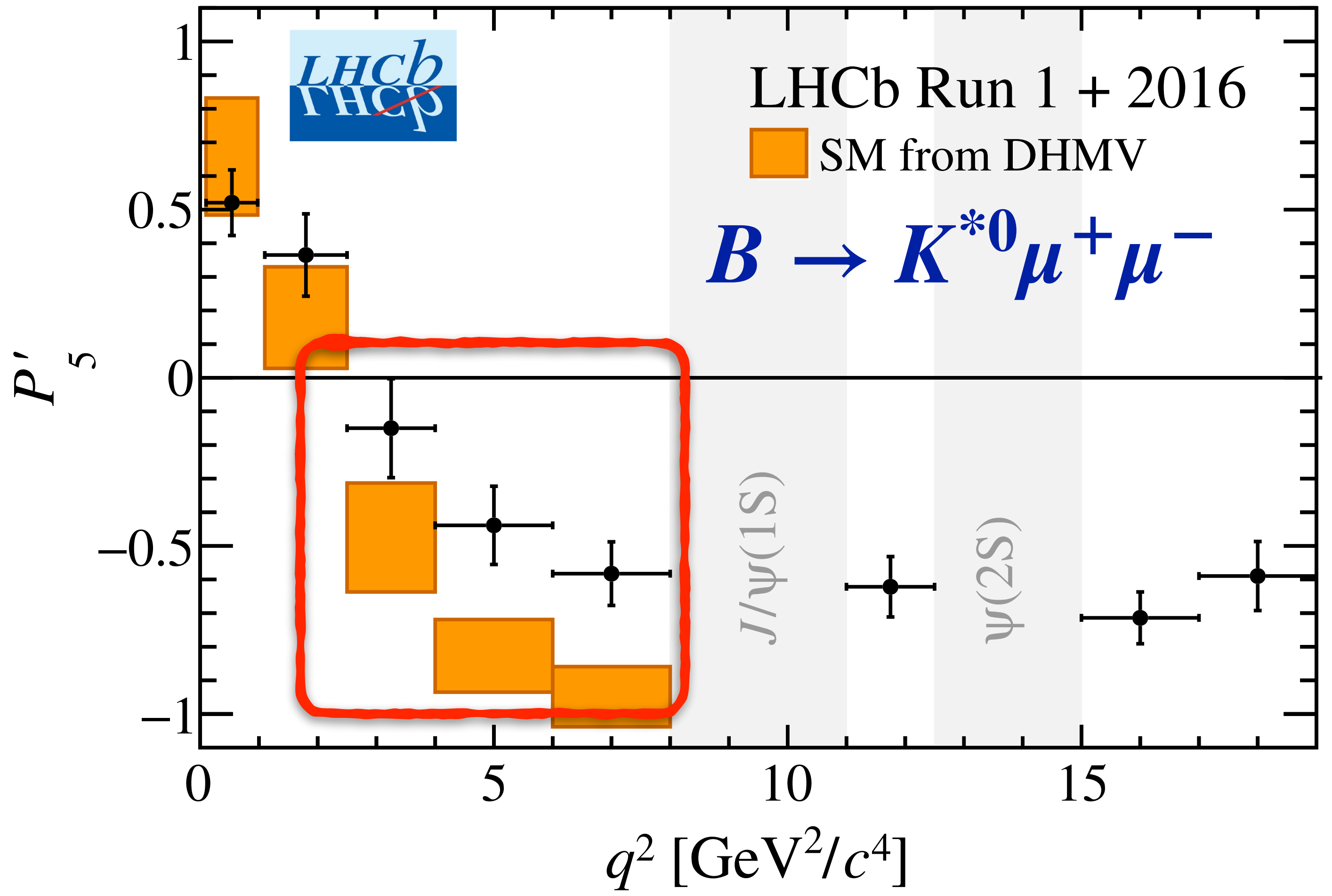
- **Optimized** $P'_{4,5,8} = \dfrac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$ **observables** make a clever use of the symmetries to cancel soft FF at LO
  JHEP 1301, 048 (2013)
- Also, **LFU** $Q_i = P_i^\mu - P_i^e$ **observables** independent of long distance charm contributions JHEP 10, 075 (2016)

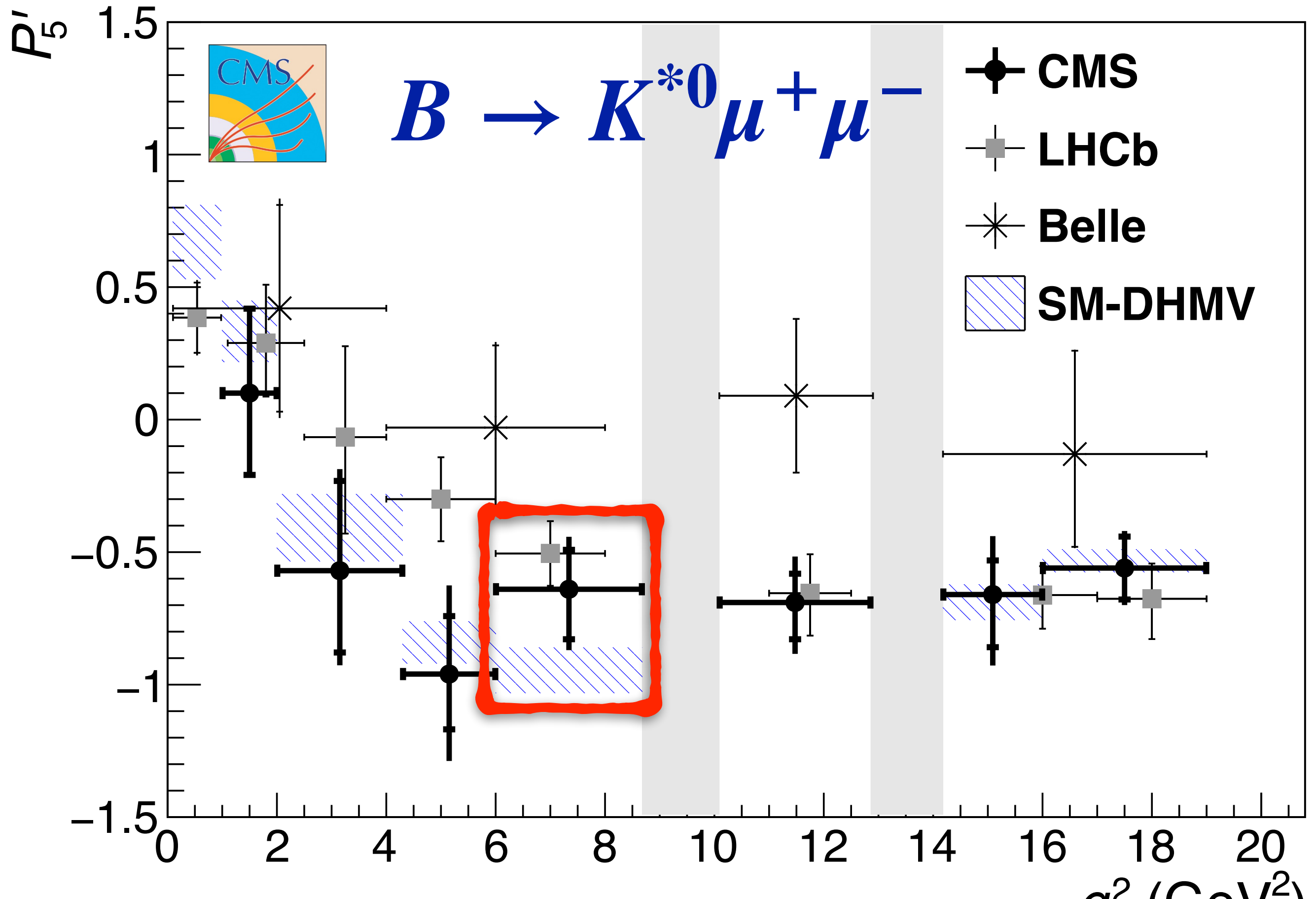
P_5'

JHEP 10, 047 (2018)

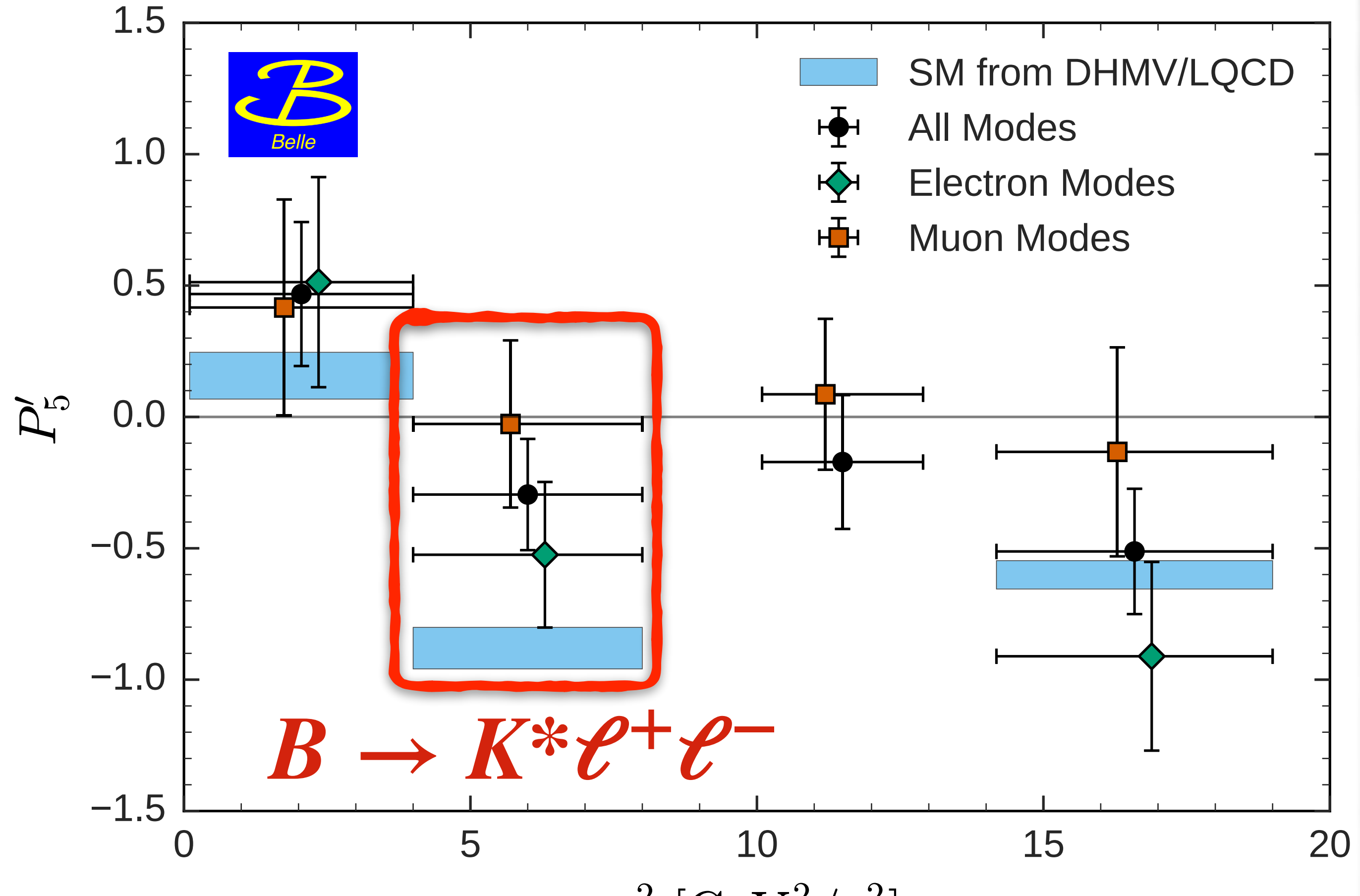


PRL 125, 011802 (2020)



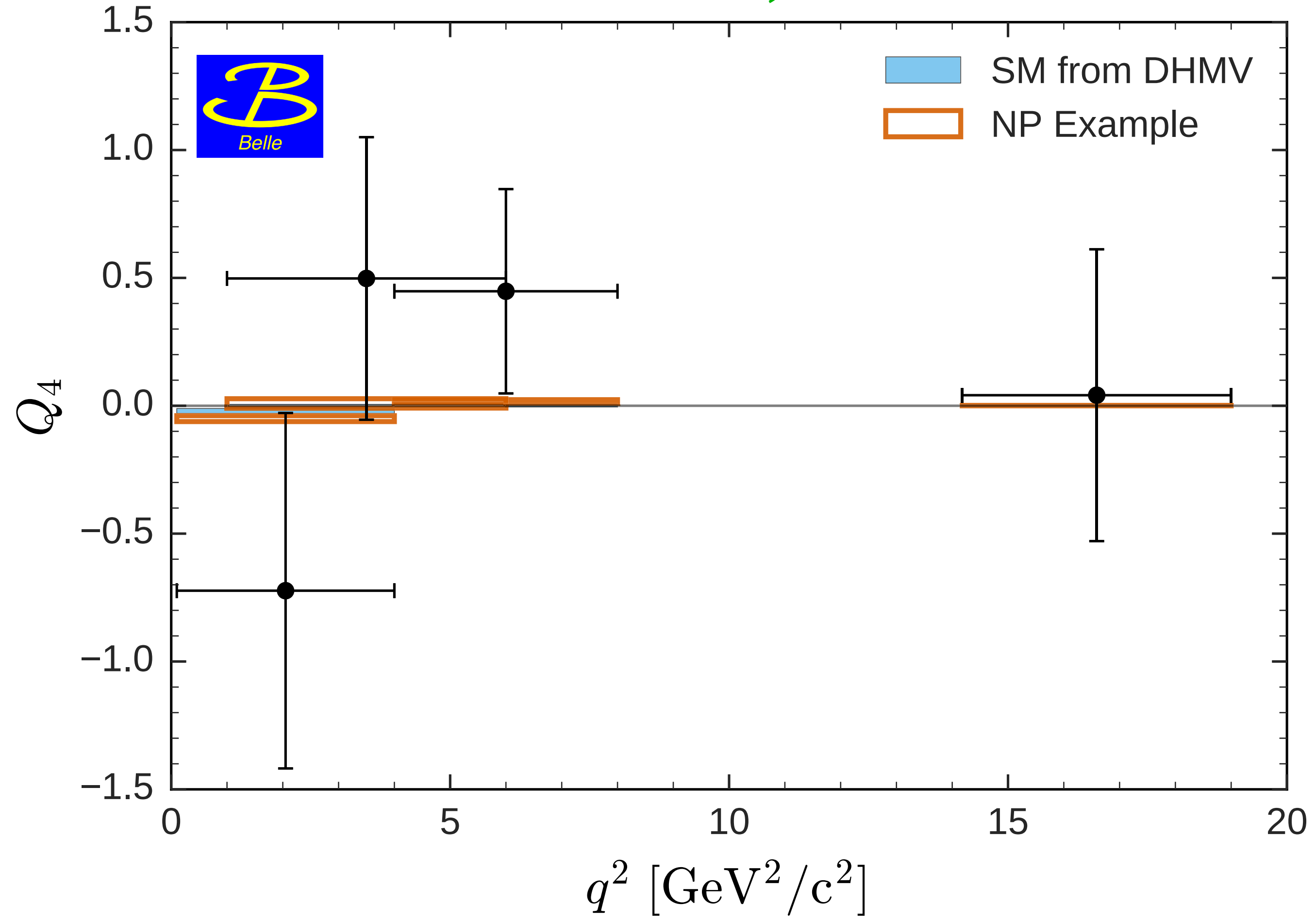


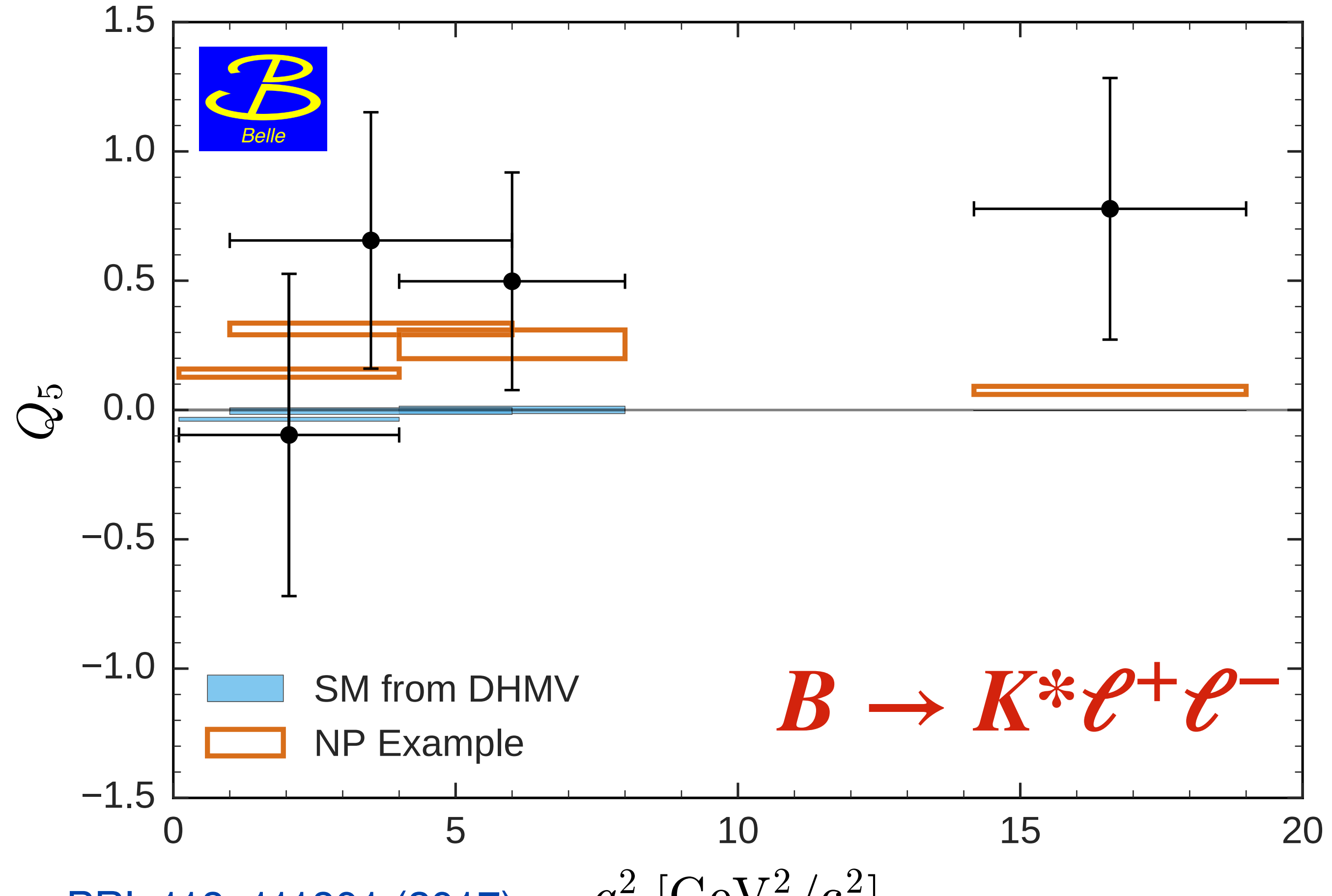
PLB 781, 517 (2018)



PRL 118, 111801 (2017)

$Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$





PRL 118, 111801 (2017)

Possible discrepancies at **low q²**, driven by **muons**

LFU $\mathcal{R}_{K^{(*)}}$ at Belle

- Measured all isospin variants for $\mathcal{R}_{K^{(*)}} = \dfrac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$
- Fit $M_{bc} = \sqrt{E^2_{\text{beam}} - p^2_B}$
  - ➡ $\mathcal{R}_K$ also fits NN and $\Delta E = E_B - E_{\text{beam}}$, $\mathcal{R}_{K^*}$ cuts on them
- **Similar mass resolution for μ and e**
- **Powerful check** with $B \to J/\psi(\to \ell\ell)\, K^{(*)}$

$$r^K_{J/\psi} = \frac{\mathcal{B}\left[B \to K\, J/\psi(\to \mu\mu)\right]}{\mathcal{B}\left[B \to K\, J/\psi(\to ee)\right]} = 0.994 \pm 0.015$$

JHEP 03, 105 (2021)

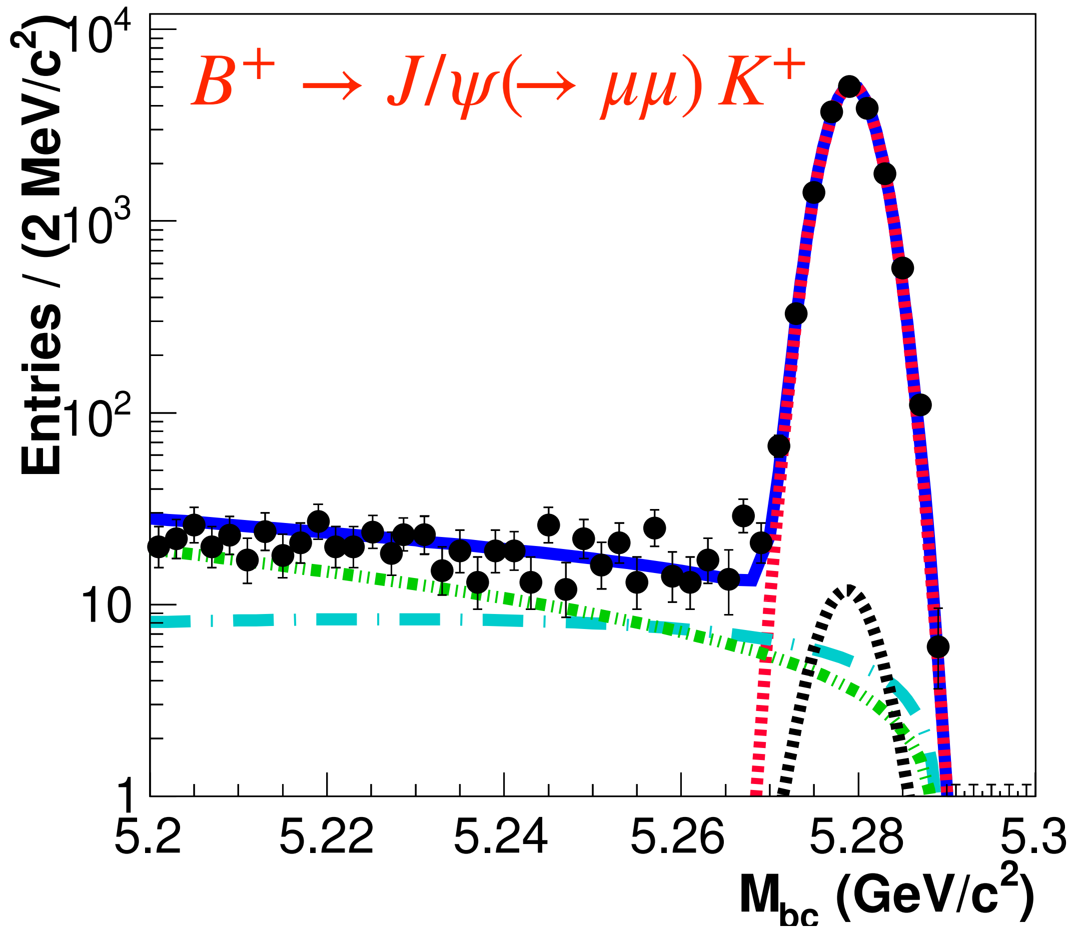
$$r^{K^*}_{J/\psi} = \frac{\mathcal{B}\left[B \to K^*\, J/\psi(\to \mu\mu)\right]}{\mathcal{B}\left[B \to K^*\, J/\psi(\to ee)\right]} = 1.015 \pm 0.045$$

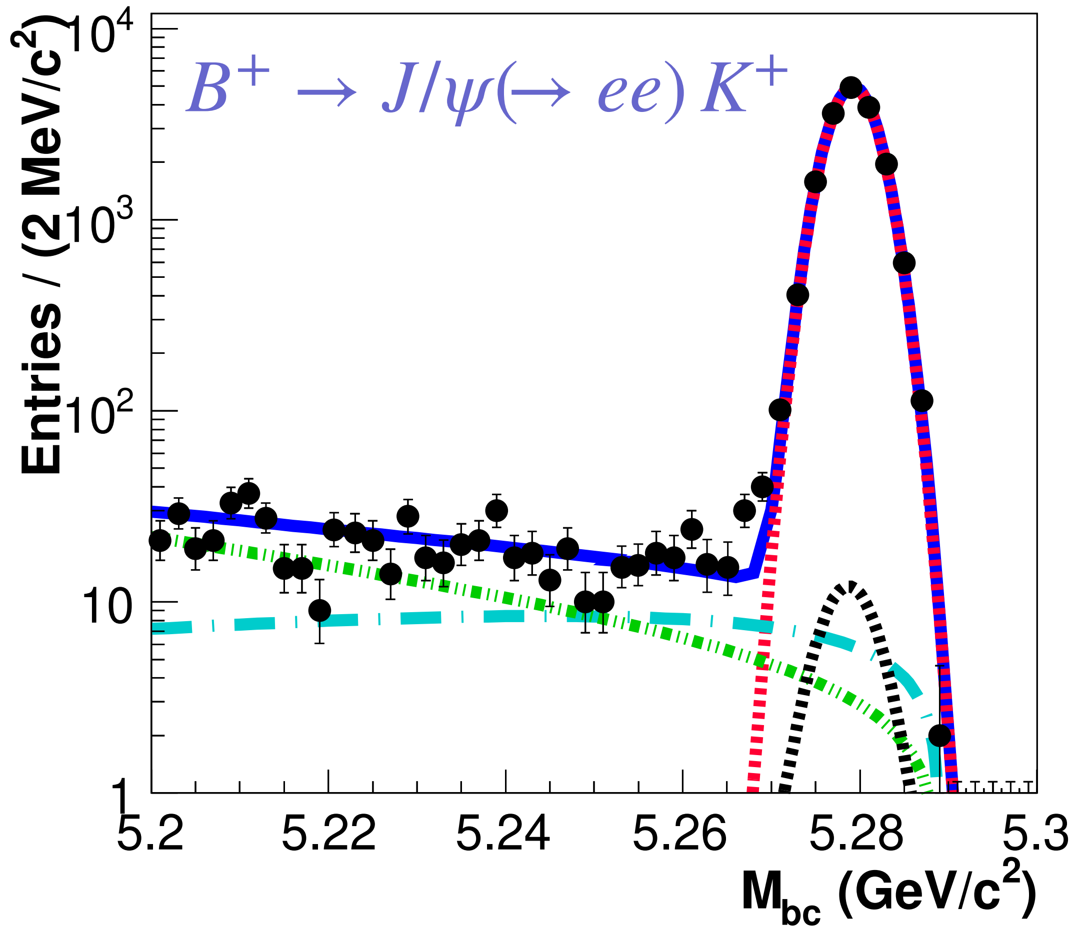
arXiv:1904.02440

Aside: most precise $\mathcal{B}\left(B \to J/\psi K\right)$ in the world, just added to PDG

$$\mathcal{B}\left(B^+ \to J/\psi K^+\right) = \left(1.032 \pm 0.025\right) \times 10^{-3}$$
$$\mathcal{B}\left(B^0 \to J/\psi K^0\right) = \left(0.902 \pm 0.028\right) \times 10^{-3}$$

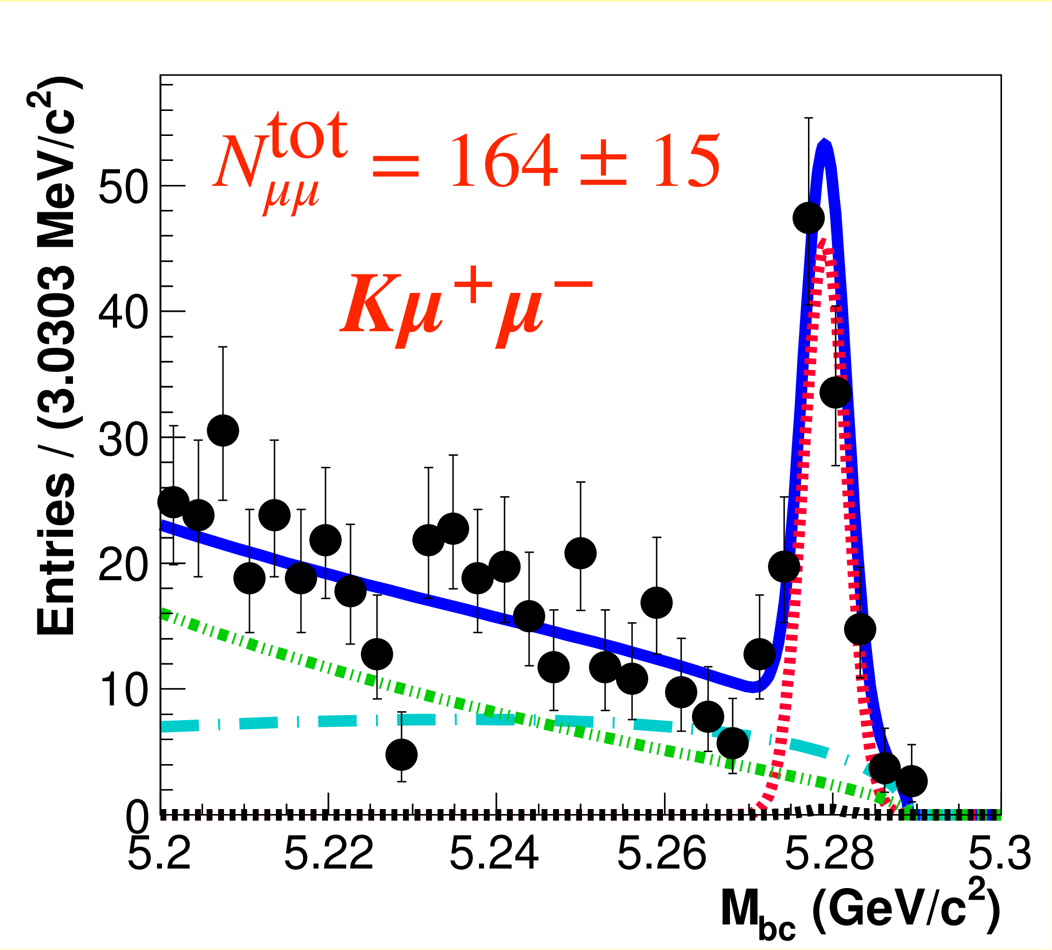
Belle

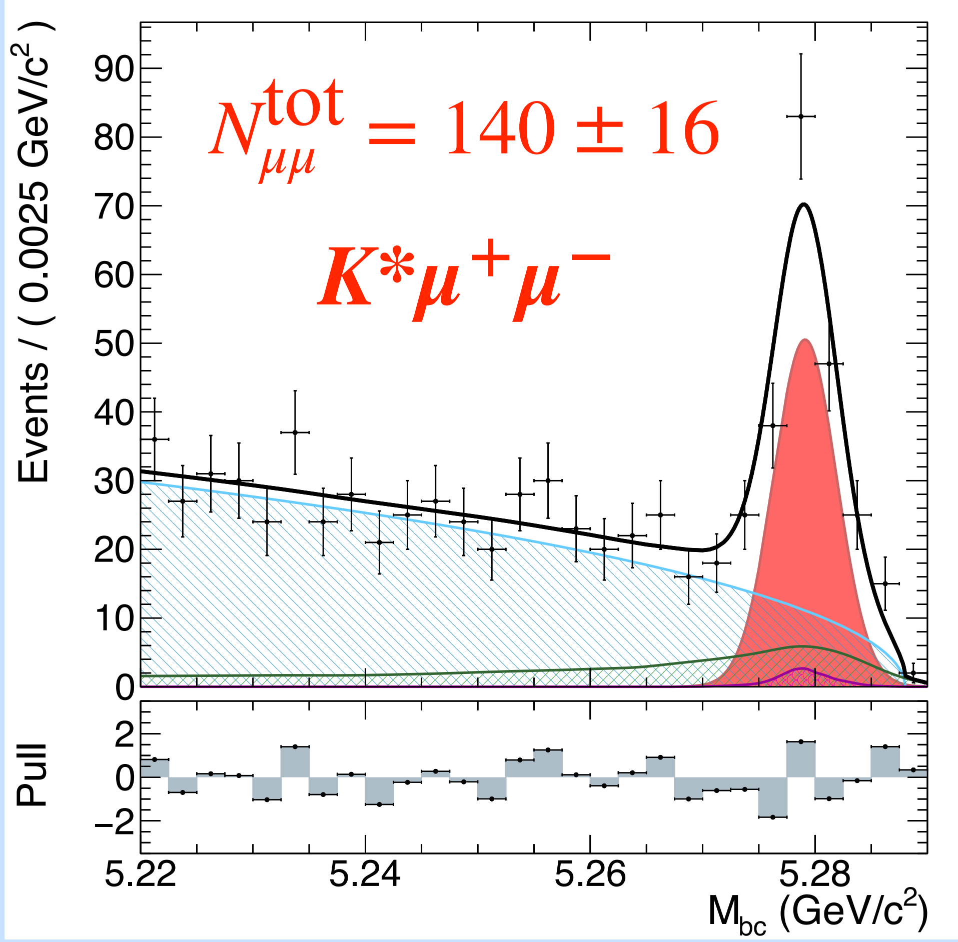




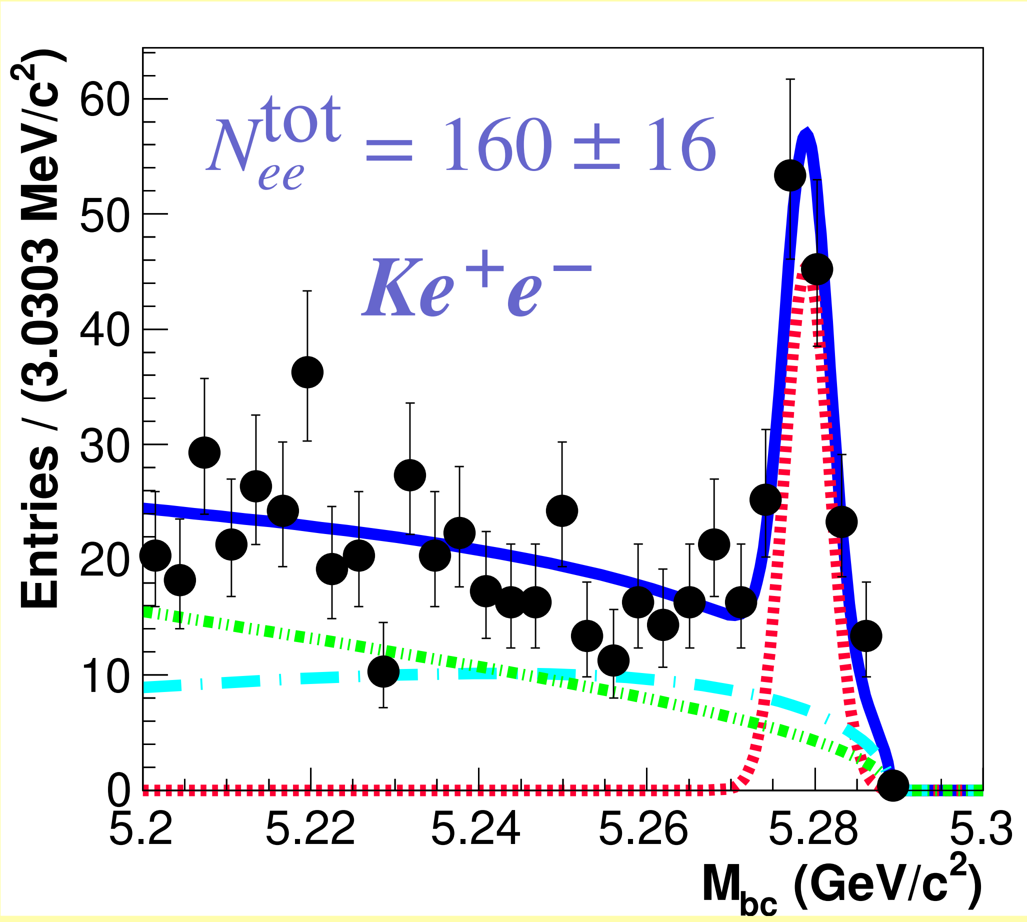
$\mathscr{R}_{K^{(*)}}$ with 100% of Belle's dataset: 711 fb^{-1}

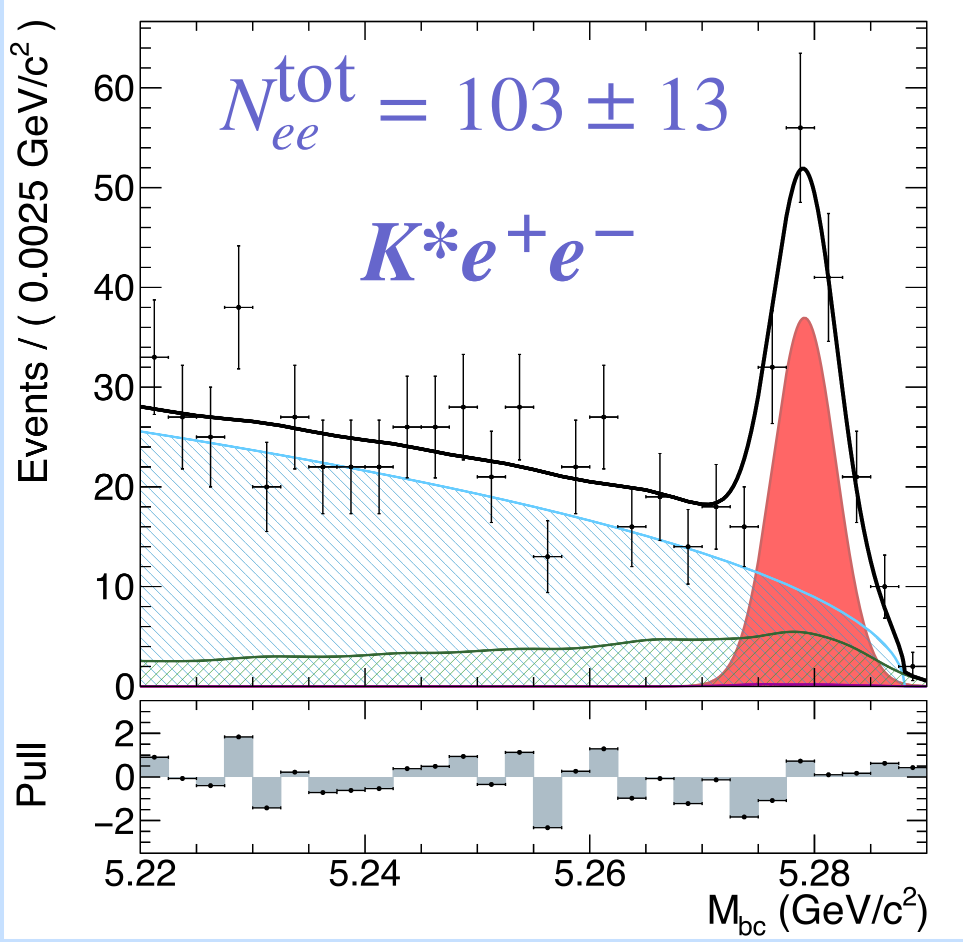
Muons

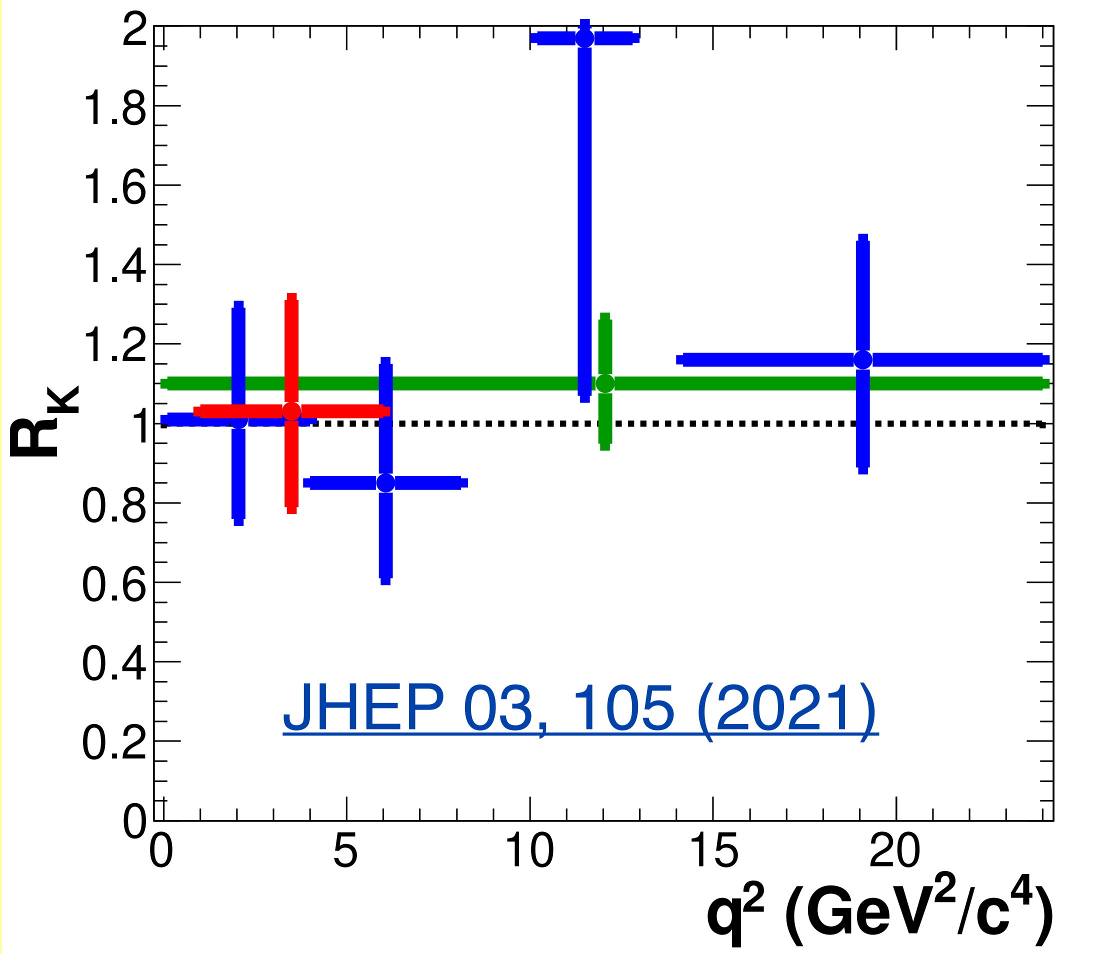




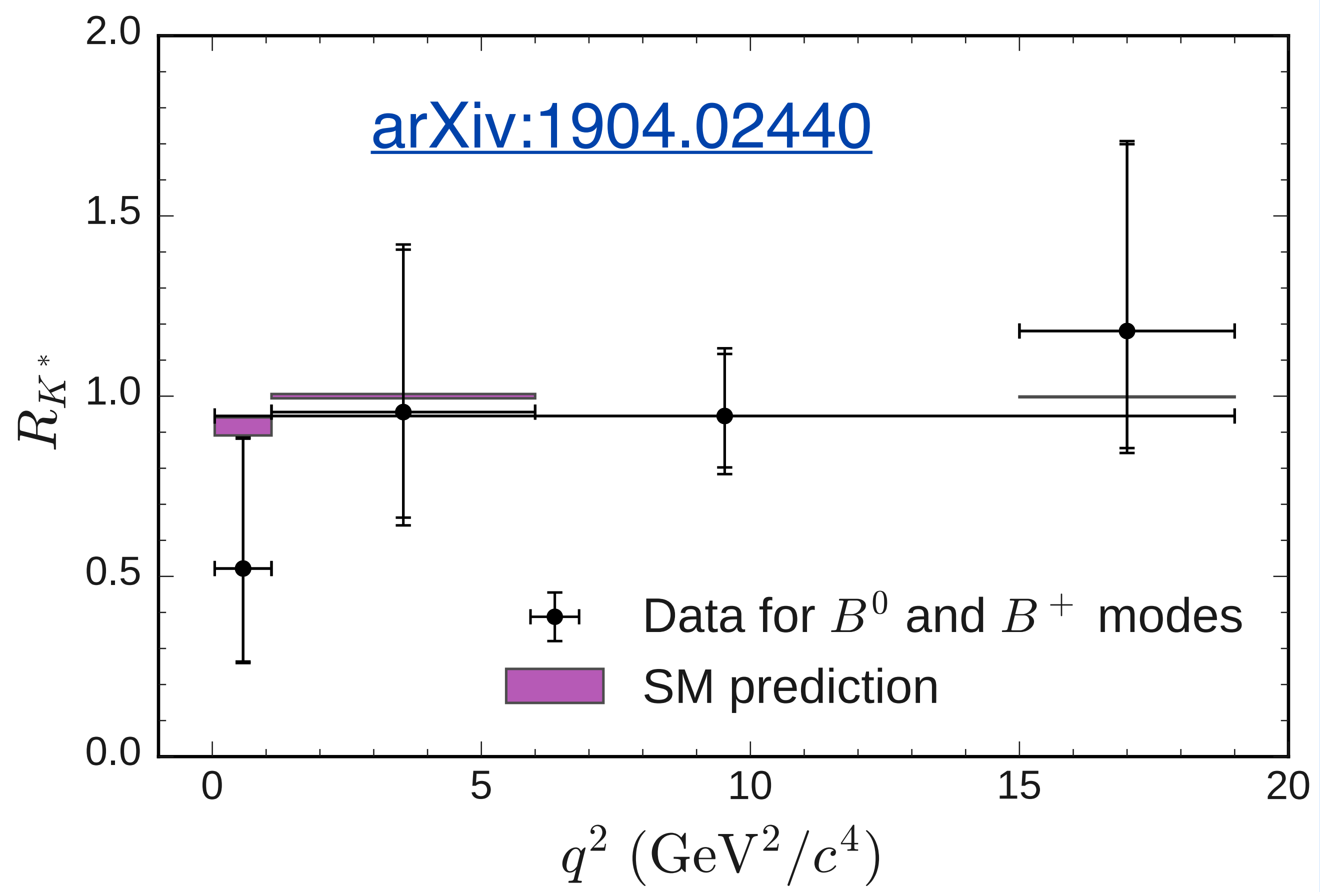
Electrons







Compatible with $\mathscr{R}_K^{SM} \approx 1$

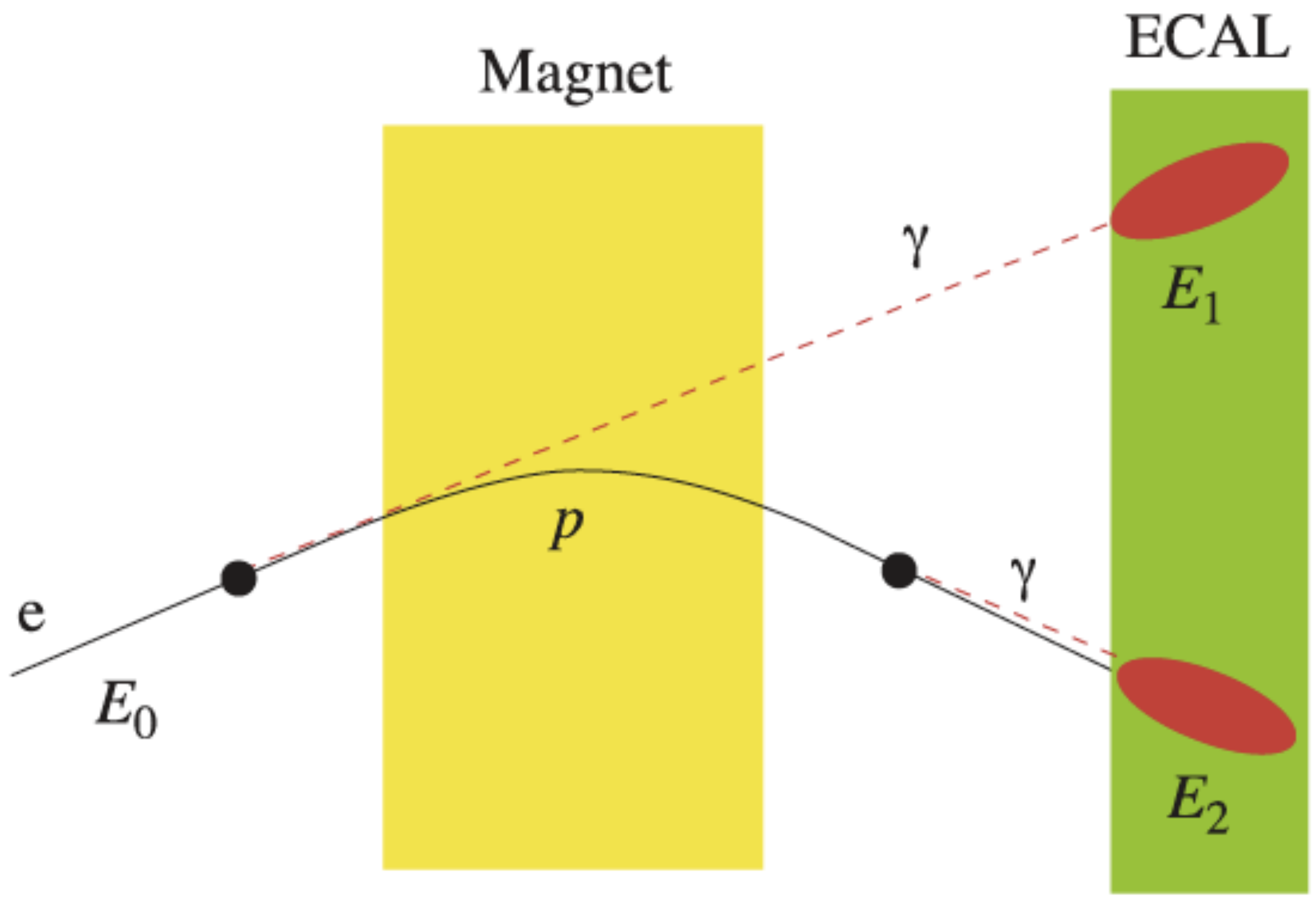


Compatible with $\mathscr{R}_{K^*}^{SM} \approx 1$

LFU $\mathscr{R}_{K^{(*)}}$ at LHCb

JHEP 08, 055 (2017) arXiv 2103.11769 Fresh!

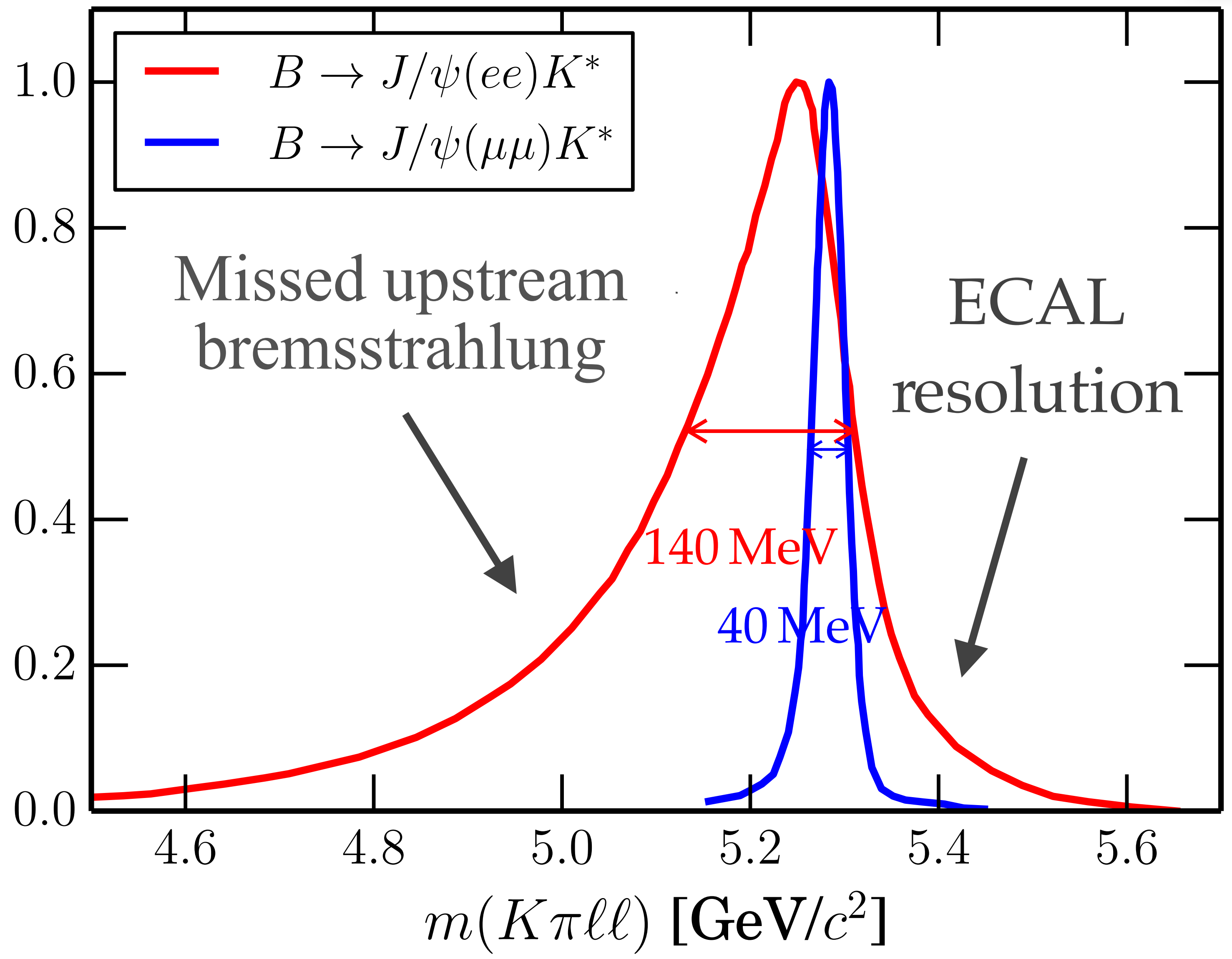
- Measurements of $\mathscr{R}_{K^{*0}}$ (3 fb^{-1}) and $\mathscr{R}_{K^+}$ (9 fb^{-1})
- At LHCb, **electrons** are **major challenge**



Algorithm to recover **upstream bremsstrahlung** when $E_\gamma > 75$ MeV

Downstream bremsstrahlung follows the track: easy to find

Unofficial from M. Borsato

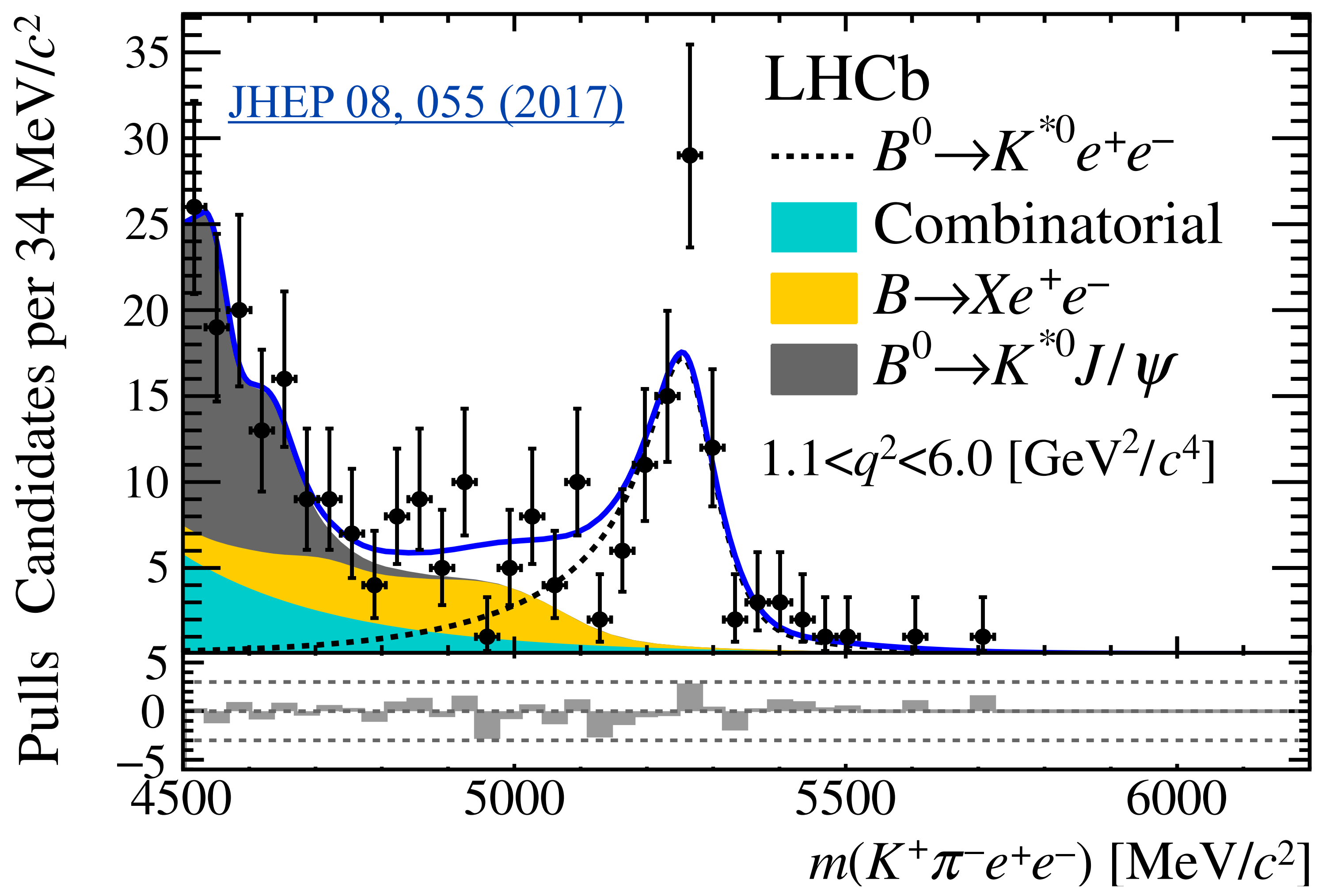


Electrons have **worse mass resolution** and are **more difficult to trigger on**

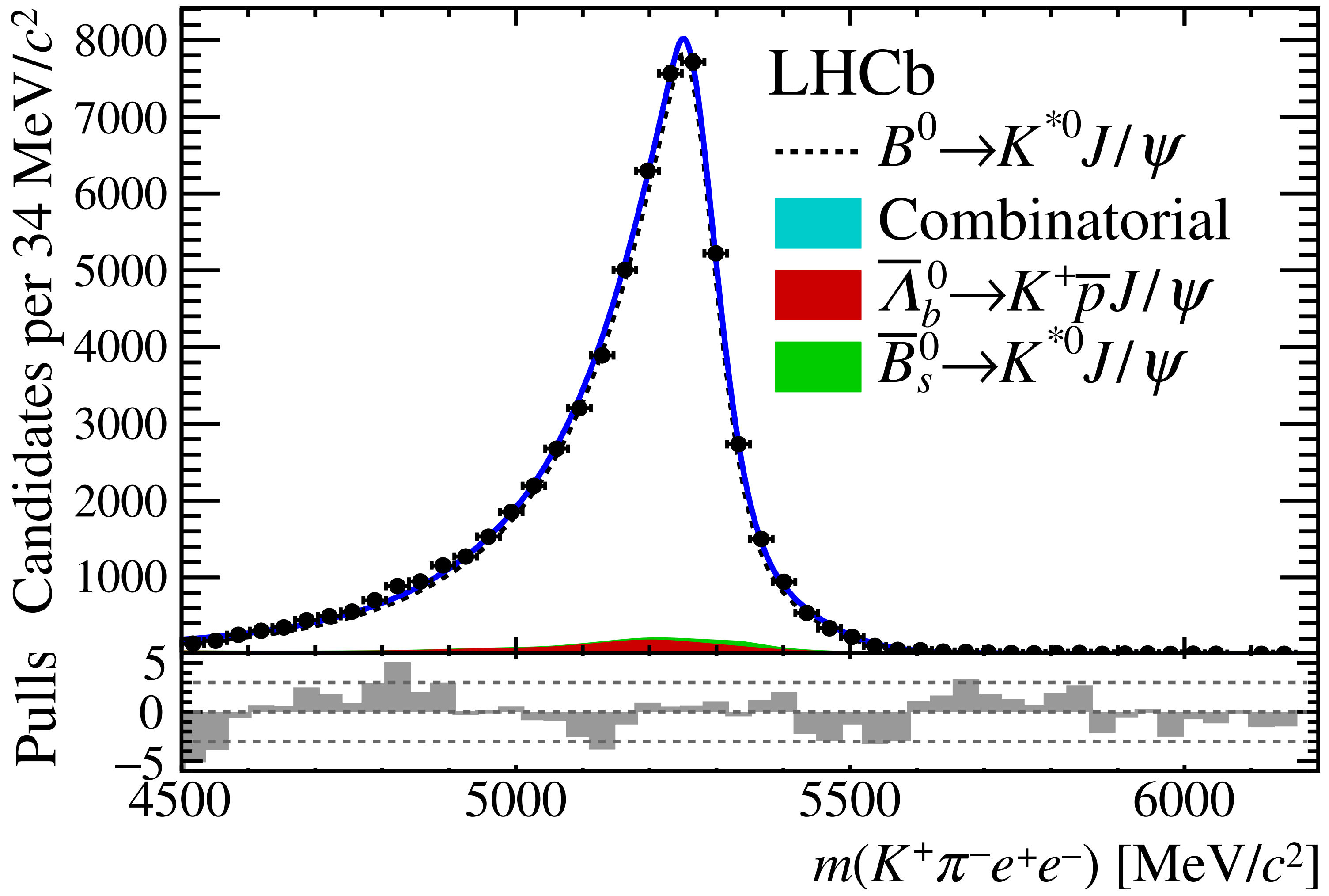
- Use **double ratio** with $B \to K^{(*)} J/\psi(\to \ell\ell)$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = \frac{N^{\rm rare}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}} \boxed{\frac{\varepsilon^{J/\psi}_{\mu^+\mu^-}}{\varepsilon^{\rm rare}_{\mu^+\mu^-}}} \times \frac{N^{J/\psi}_{e^+e^-}}{\boxed{N^{\rm rare}_{e^+e^-}}} \boxed{\frac{\varepsilon^{\rm rare}_{e^+e^-}}{\varepsilon^{J/\psi}_{e^+e^-}}}$$

$B^0 \to K^{*0}ee$

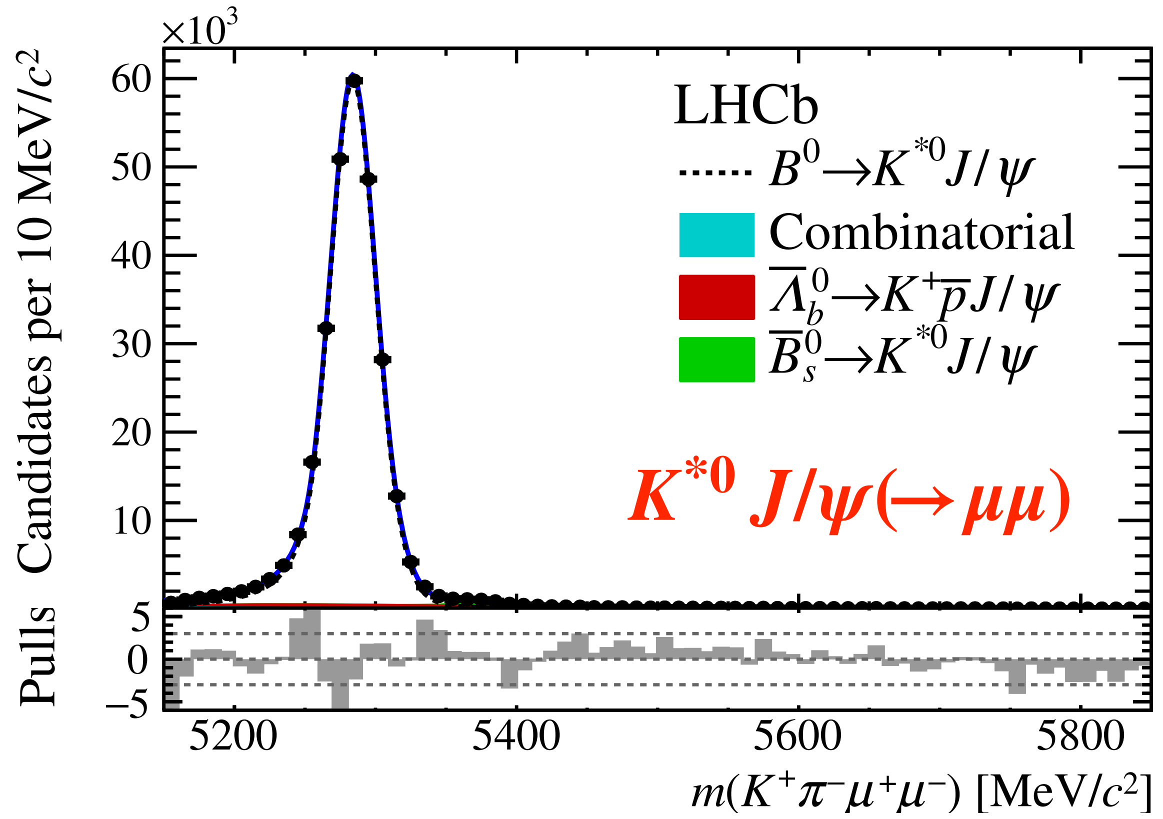


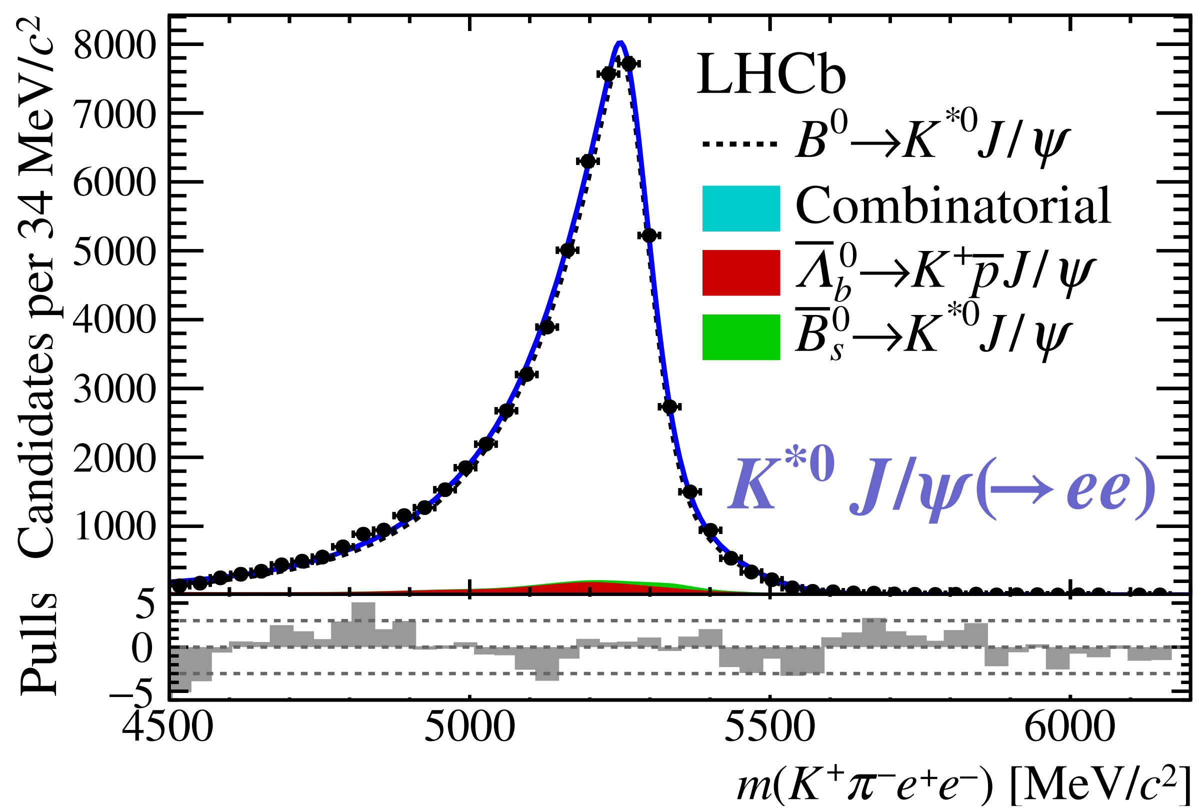
$B^0 \to K^{*0} J/\psi(\to ee)$



- **Backgrounds reduced** with
  - Tight PID
  - Vetoes on invariant masses, eg $m(K^+e) > m(D^0)$
  - Multivariate classifiers
- **Combinatorial** and **partially-reco** **bkgs** free in fit
- **$B \to K^{(*)} J/\psi(\to \ell\ell)$ contamination** from resonant fit
- **Signal shapes** taken from **simulation**
  - Small corrections obtained from clean $B \to K^{(*)} J/\psi(\to \ell\ell)$

- Rare and J/Ψ events have **identical final states, difference** only **q²**
  - ➡ Check **if we understand ε** with $r_{J/\psi}^{K^{(*)}} = \dfrac{\mathscr{B}\left[B \to K^{(*)} J/\psi(\to \mu\mu)\right]}{\mathscr{B}\left[B \to K^{(*)} J/\psi(\to ee)\right]} = 1$



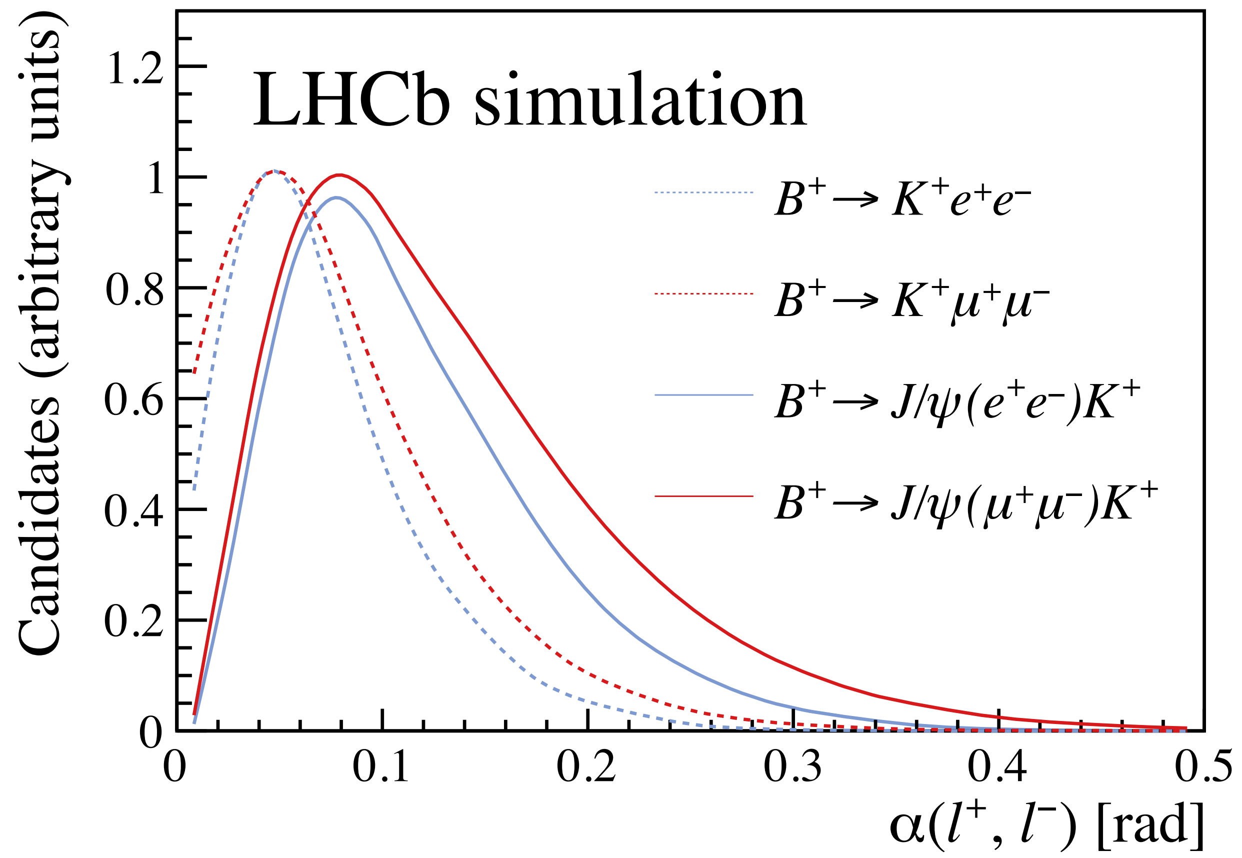


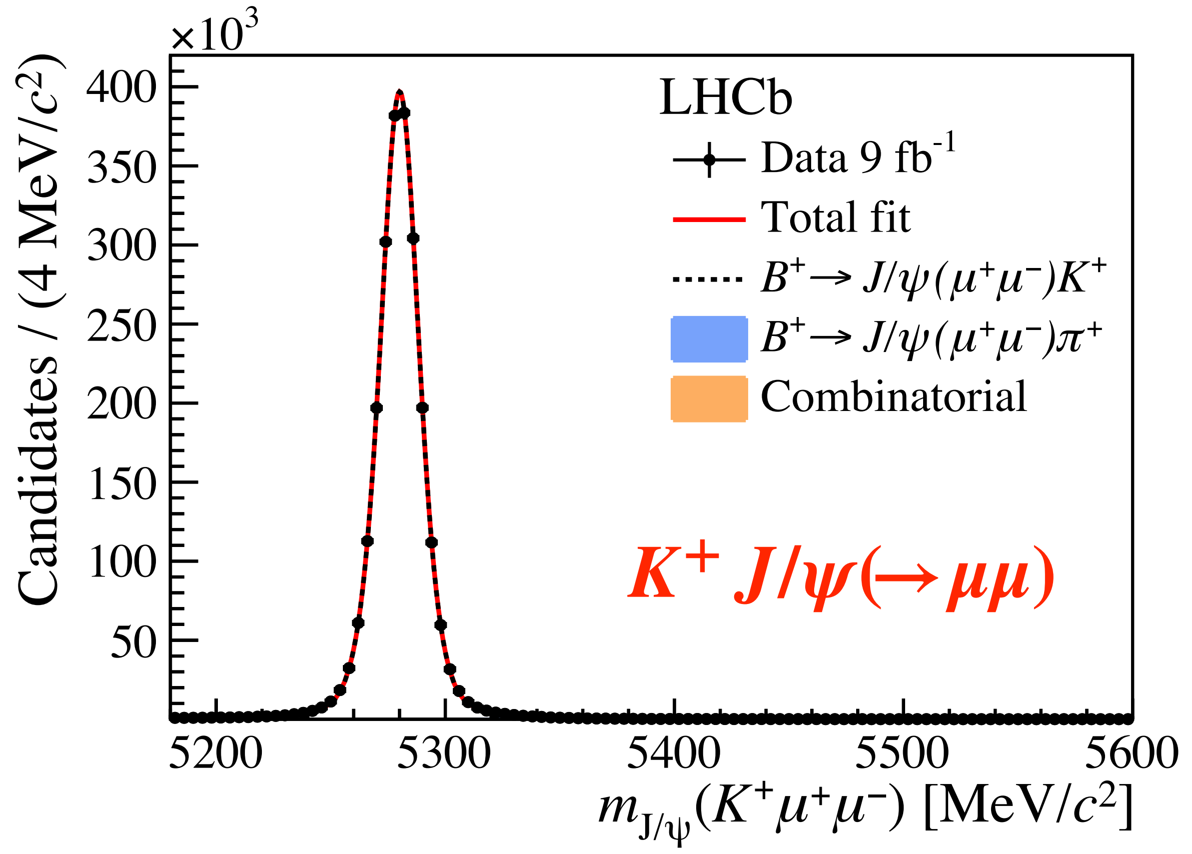
JHEP 08, 055 (2017)

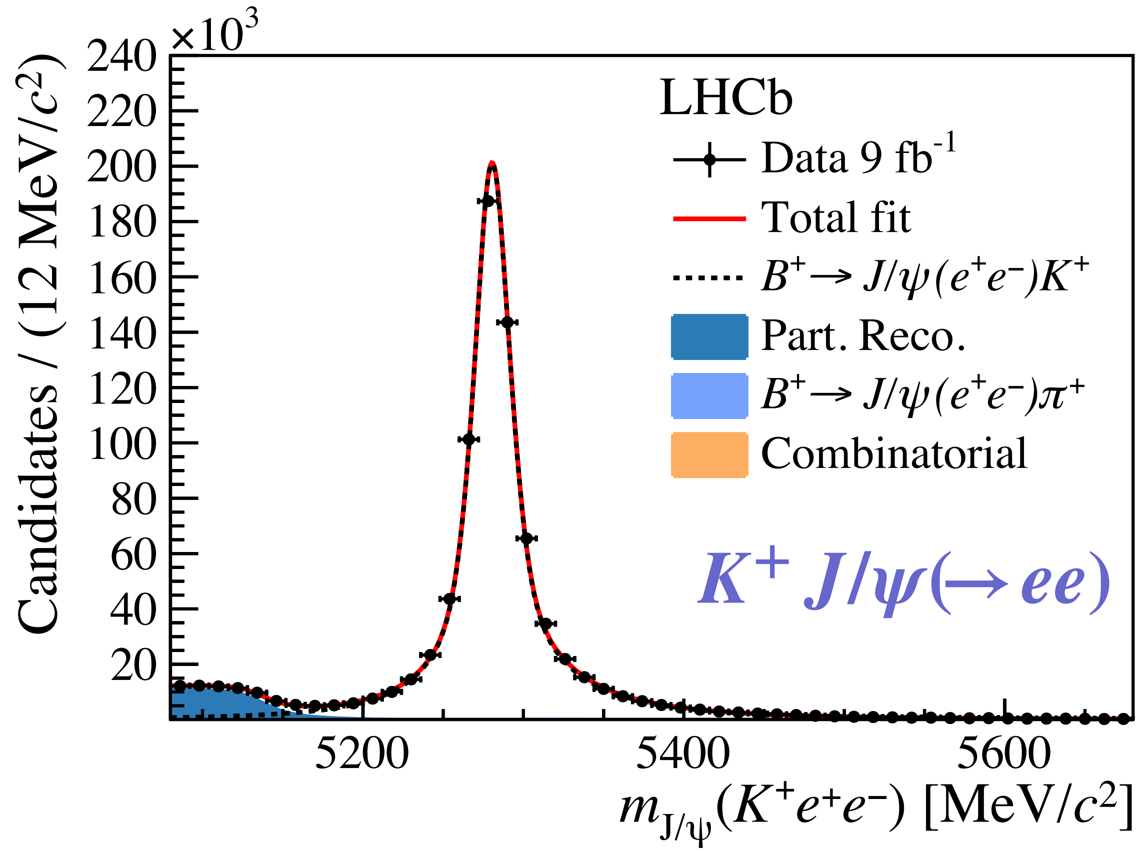
$r_{J/\psi}^{K^*} = 1.043 \pm 0.045$

$r_{\psi(2S)}^{K^*}/r_{J/\psi}^{K^*} = 0.980 \pm 0.040$

Also in bins of lab angle, p_T





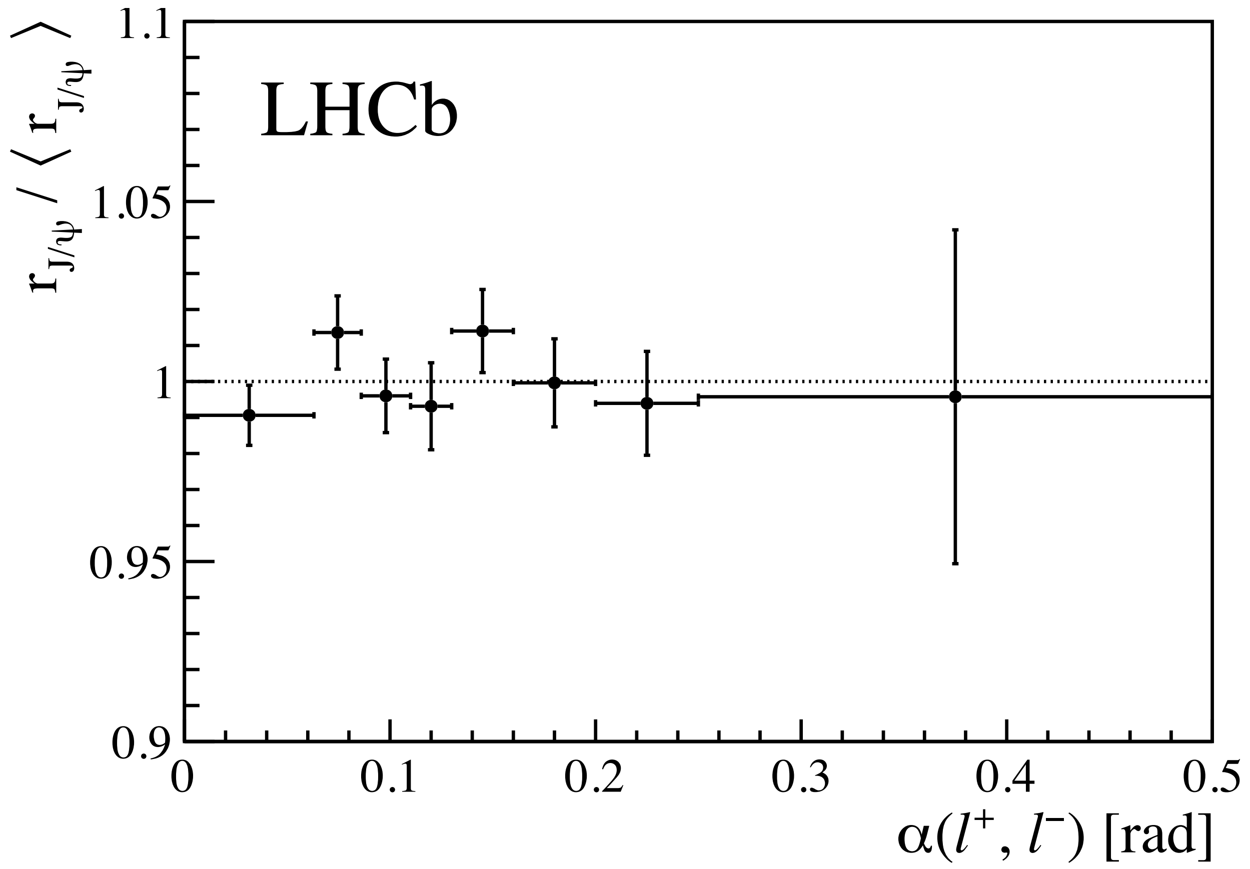


arXiv 2103.11769

$r_{J/\psi}^{K} = 0.981 \pm 0.020$

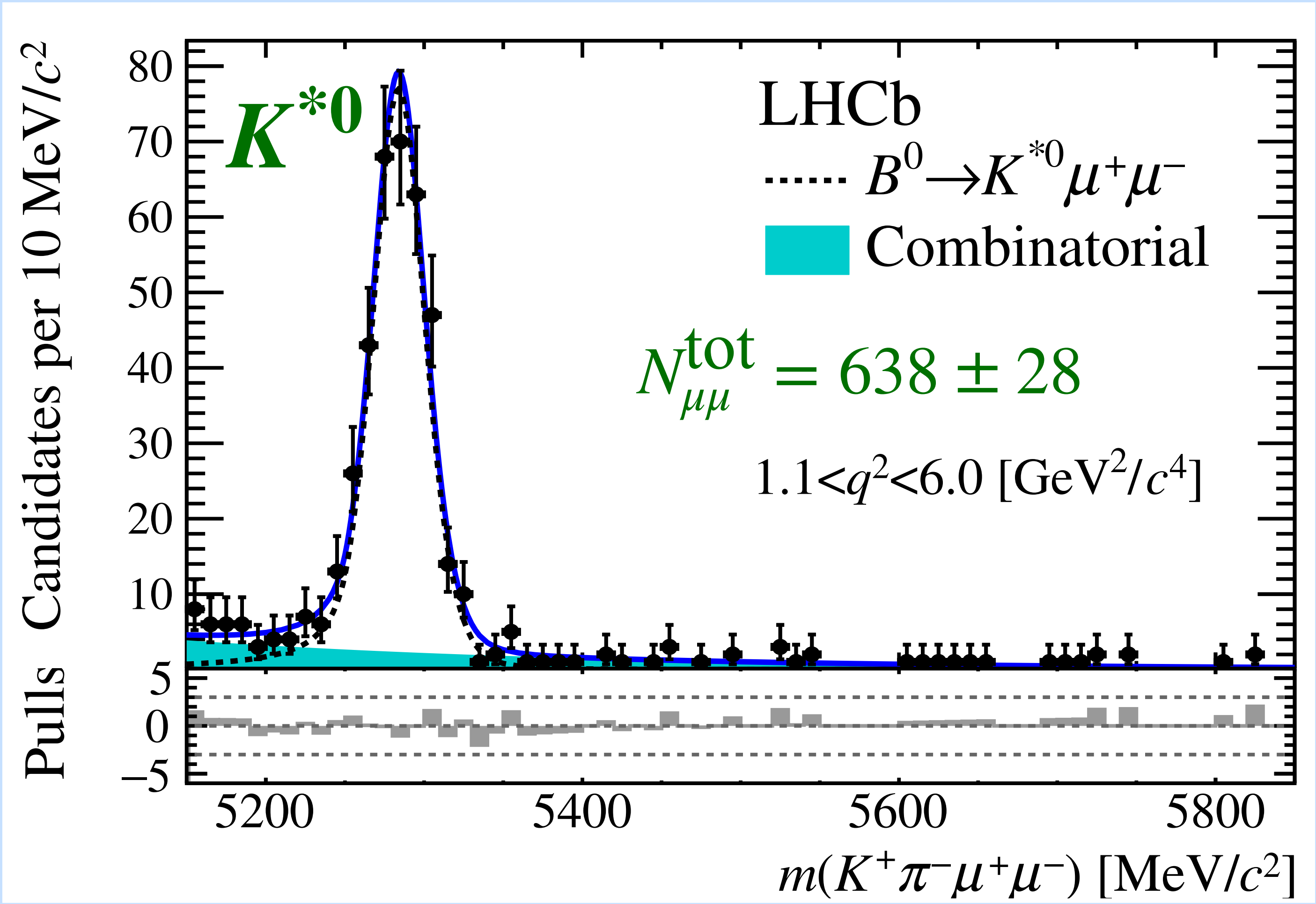
$r_{\psi(2S)}^{K}/r_{J/\psi}^{K} = 0.997 \pm 0.011$

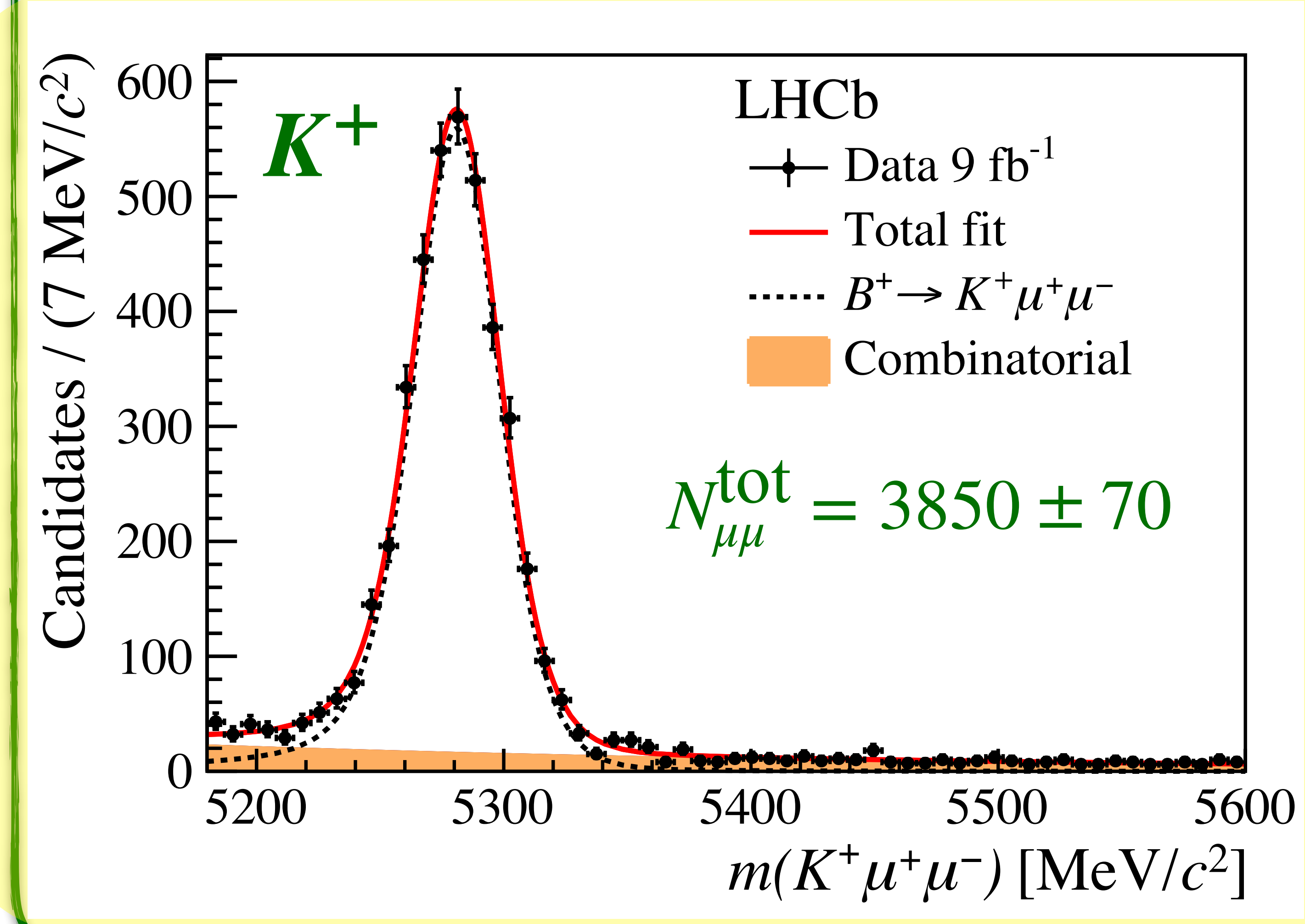
Apply **J/Ψ mass constraint**, but **check without** as well



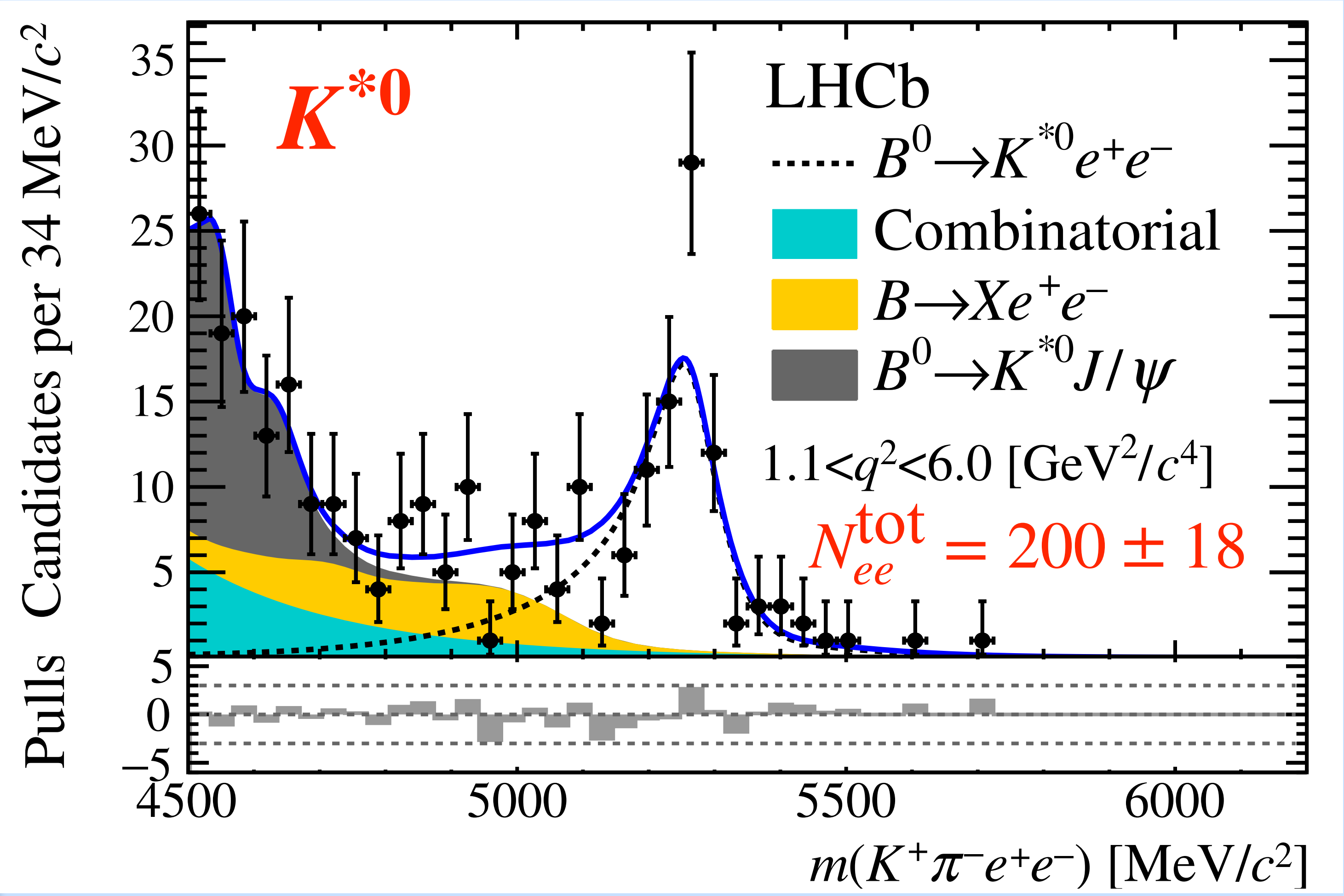
LFU $\mathcal{R}_{K^{(*)}}$ at LHCb: results

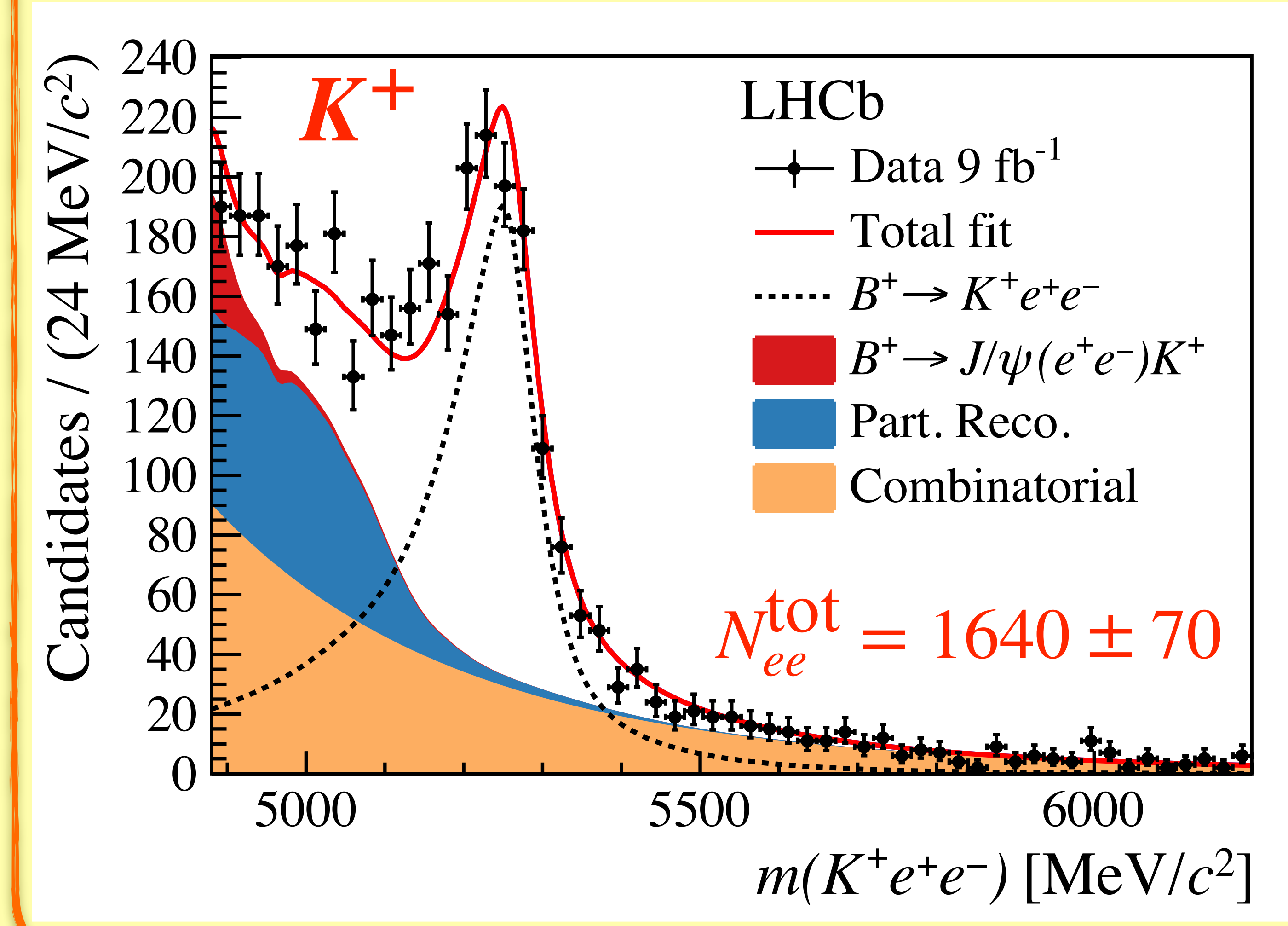
$B \to K^{(*)}\mu^+\mu^-$





$B \to K^{(*)}e^+e^-$





$\mathcal{R}_{K^{*0}}$ with 25% of Run 1+2

$$\mathcal{R}_{K^{*0}}^{[0.045,\,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

2.1σ below SM

JHEP 08, 055 (2017)

$$\mathcal{R}_{K^{*0}}^{[1.1,\,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

2.4σ below SM

$\mathcal{R}_{K^+}$ with 100% of Run 1+2

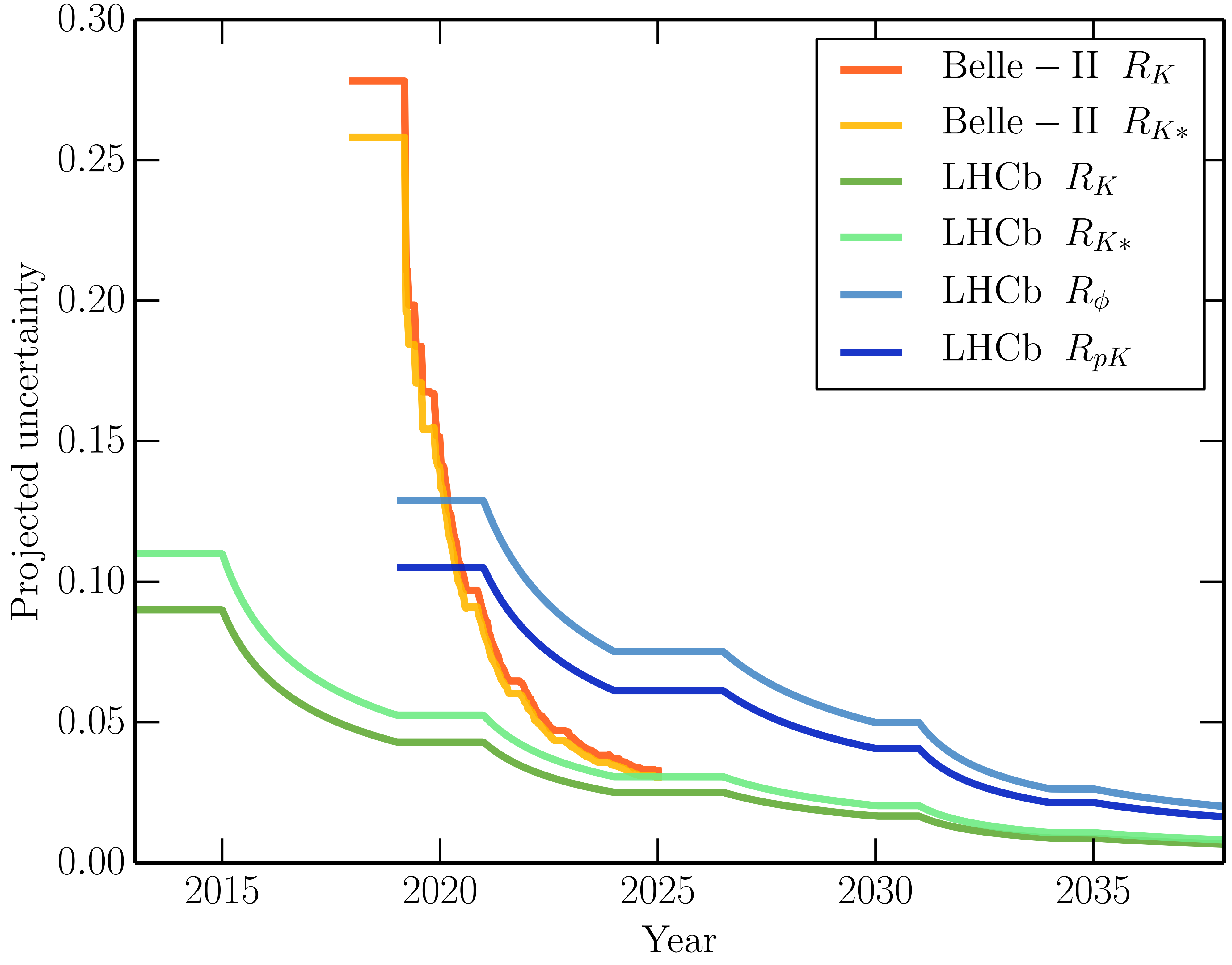
Fresh!

$$\mathcal{R}_{K^+}^{[1.1,\,6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

3.1σ below SM

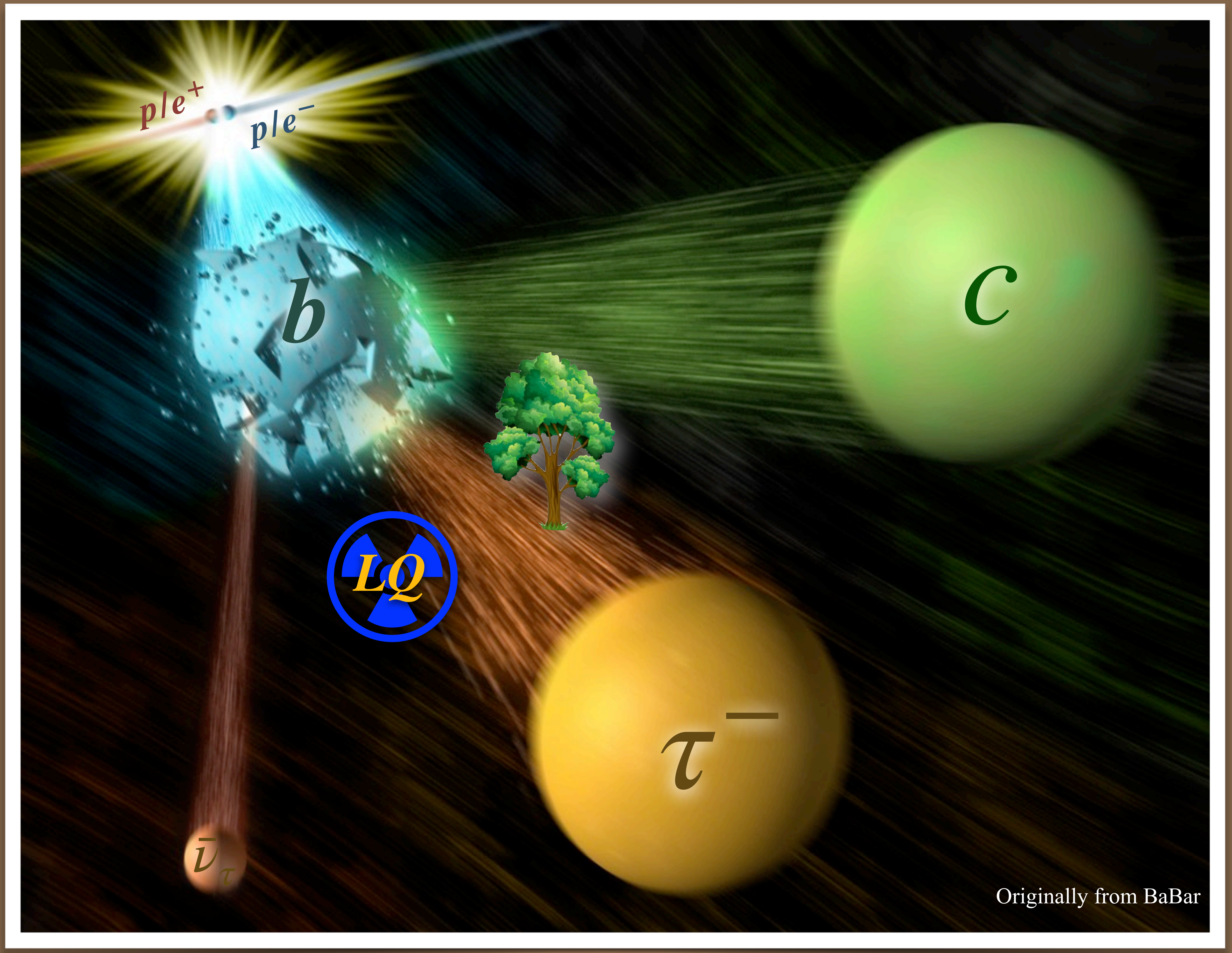
arXiv 2103.11769

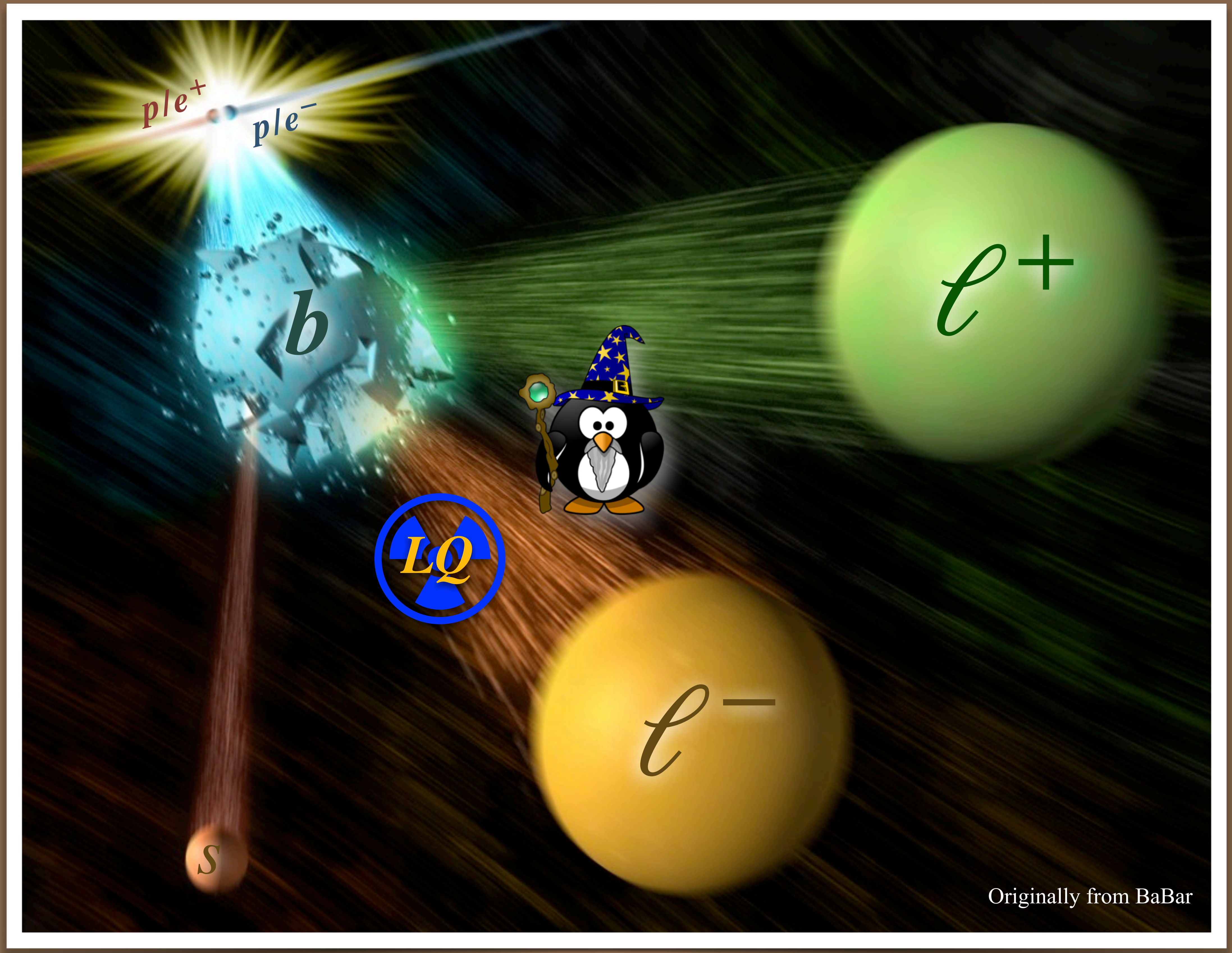
- Currently, $\mathscr{R}_{K^{(*)}}$ ~ **15-30% below SM**
- **Uncertainties** on **LFU ratios** expected to reach about **2-3% with 2025 LHCb dataset**
  - ➡ Belle II expected to take longer than in plot



Bifani, Descotes-Genon, Romero Vidal, Schune
[Journal of Physics G: Nuclear and Particle Physics, 46, 2 (2018)]

One elegant interpretation





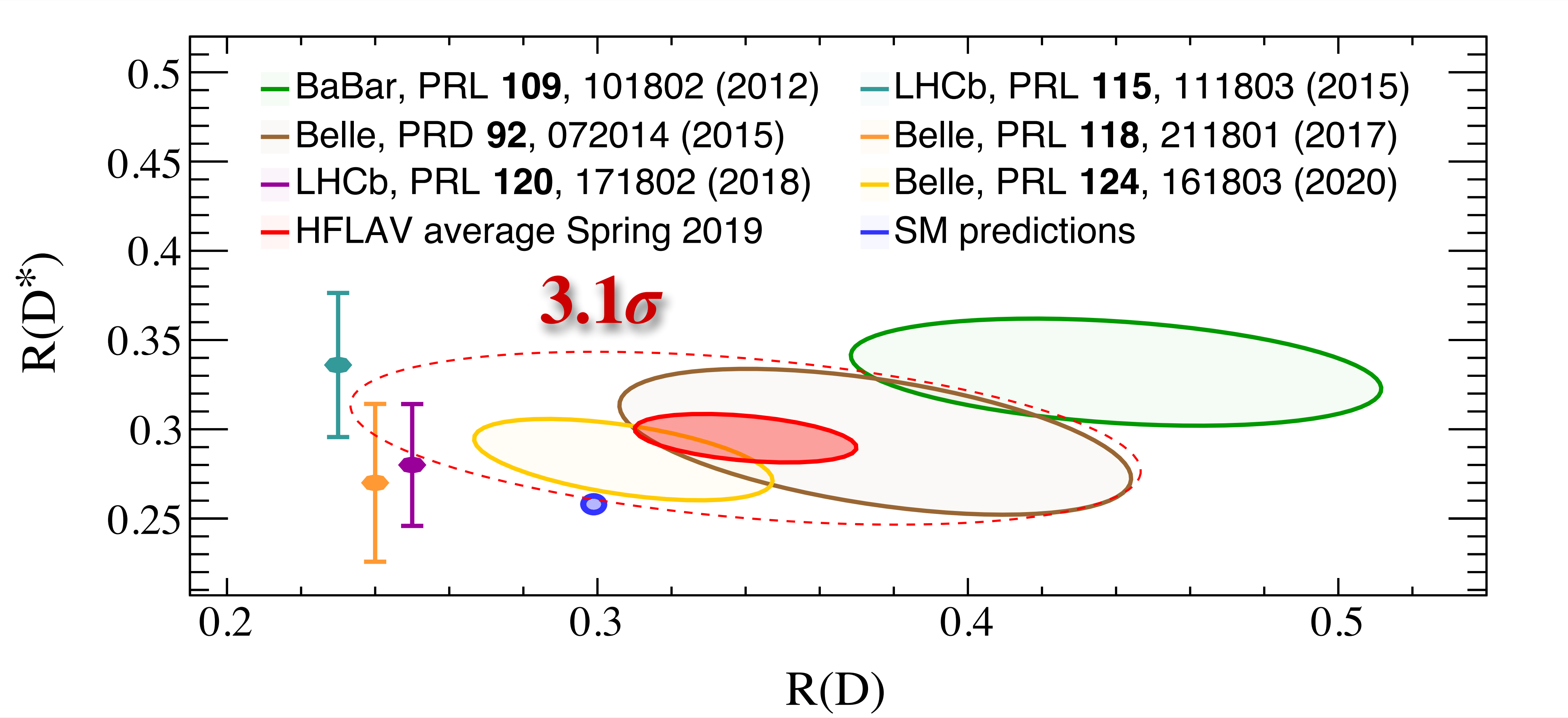
Penguin from Jeff Brassard

Based on *Isidori at APS April 2021* and *Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert - arXiv:2103.16558*

Anomalies recap

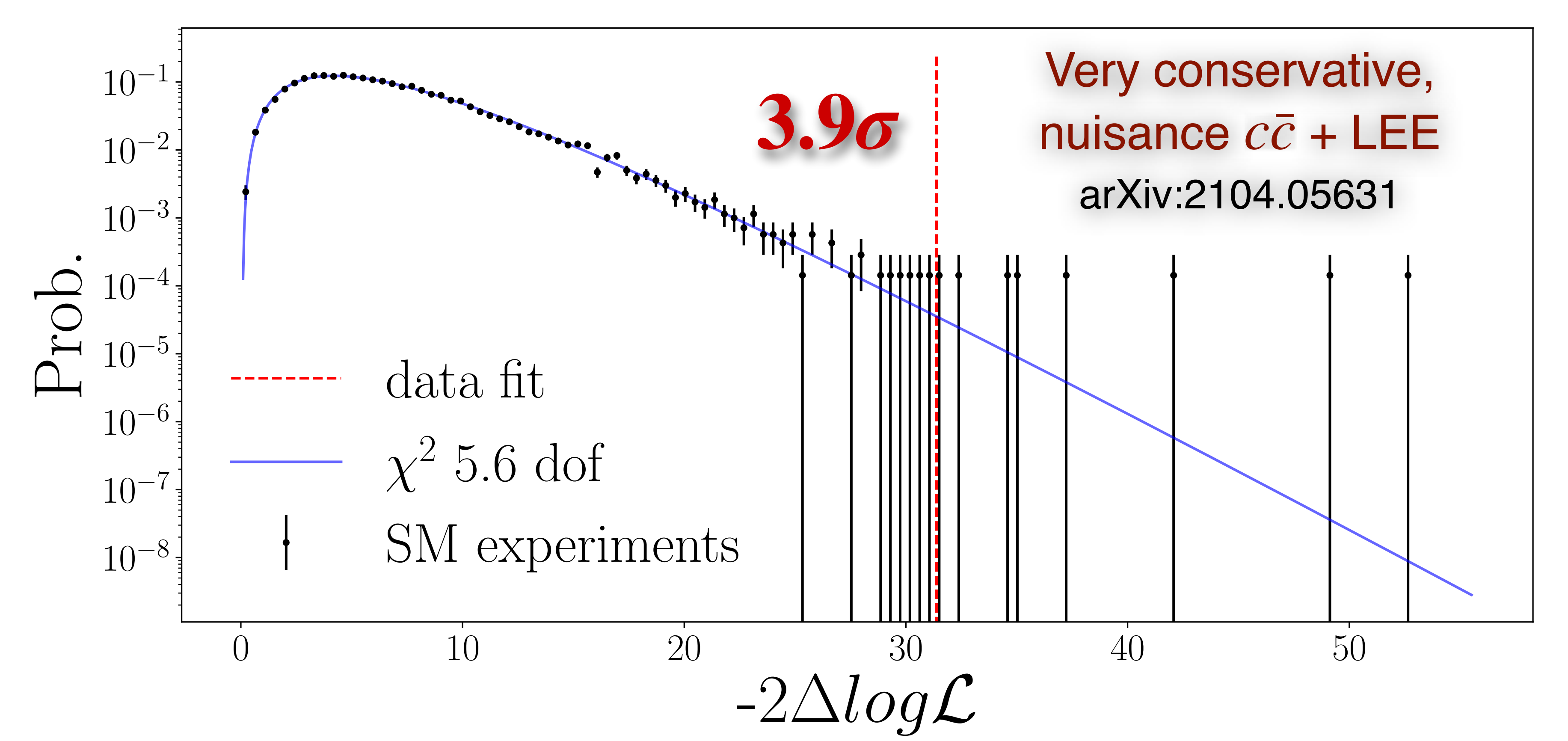
LFU results with $b \to c\tau\nu$

- 1.8σ **excess** in $\mathscr{R}(J/\Psi)$
- 14% **excess** in $\mathscr{R}(D)$
- 14% **excess** in $\mathscr{R}(D^*)$



LFU results with $b \to s\ell\ell$

- **Deficit** in differential BF rates with μ
- 22% **deficit** in $B^0_{(s)} \to \mu^+\mu^-$
- 15% **deficit** in $\mathscr{R}_K$
- ~30% **deficit** in $\mathscr{R}_{K^*}$
- Disagreement in $B \to K^*\ell\ell$ angular P_5'



EFT for $b \to s\ell\ell$

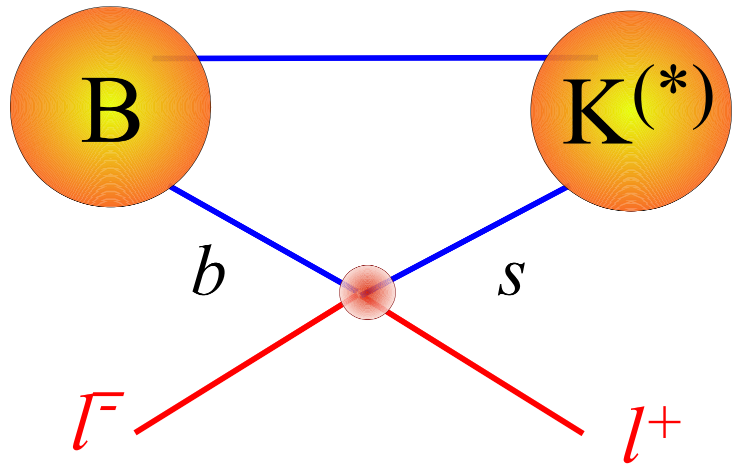
~ **Dimension-6 operators** identified as **relevant** set for combined **explanation of both anomalies**

$$\mathcal{L}_{b\to s\ell^+\ell^-} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i^\ell \, \mathcal{O}_i^\ell$$

FCNC operators:

$$\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

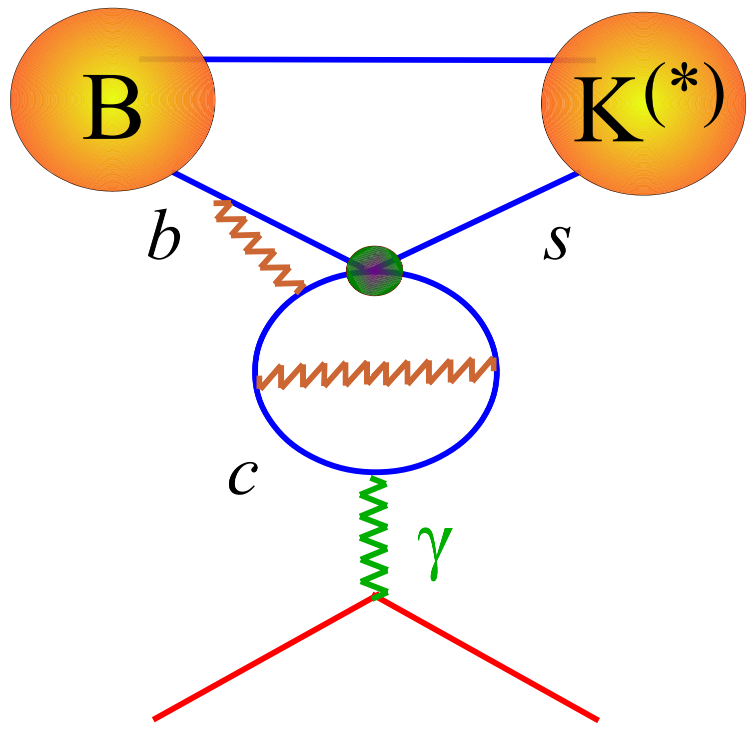


Easy and "clean"

Four-quark operators:

$$\mathcal{O}_2 = (\bar{s}_L \gamma_\mu b_L)(\bar{c}_L \gamma_\mu c_L)$$

$$\vdots$$



Difficult and "dirty"

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j)$$

$$\mathcal{O}_{LR}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{e}_R^\beta \gamma^\mu d_R^j)$$

$$\mathcal{O}_{RR}^{ij\alpha\beta} = (\bar{d}_R^i \gamma_\mu e_R^\alpha)(\bar{e}_R^\beta \gamma^\mu d_R^j)$$

Isidori at APS April 2021, arXiv:2103.16558

Separate **NP contributions** between **Lepton Flavor Universal**

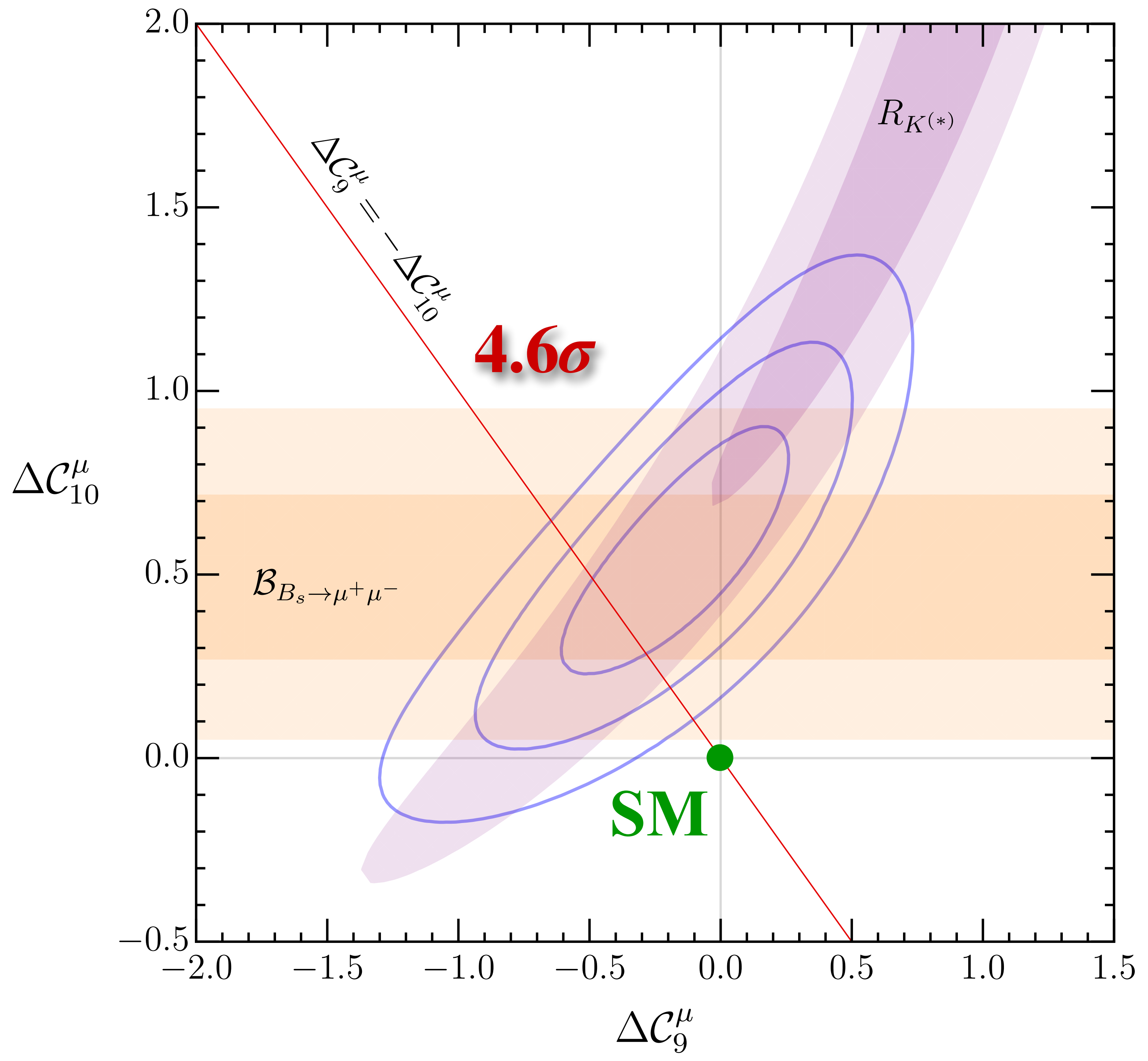
$$\Delta C^U_{9,10} \equiv C^e_{9,10} - C^{SM}_{9,10}$$

and **LFU-breaking**

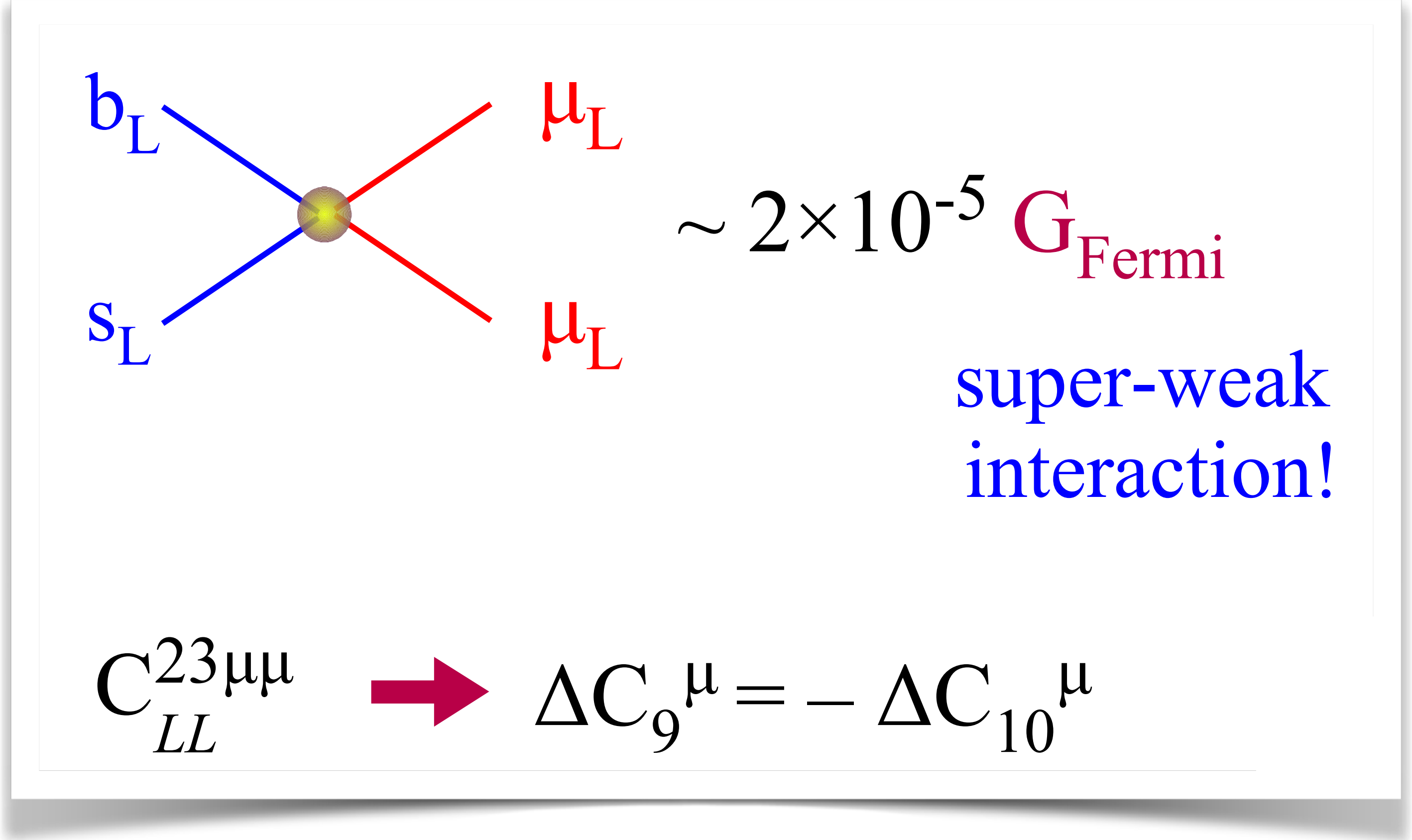
$$\Delta C^\mu_{9,10} \equiv C^\mu_{9,10} - C^e_{9,10} = C^\mu_{9,10} - (C^{SM}_{9,10} + \Delta C^U_{9,10})$$

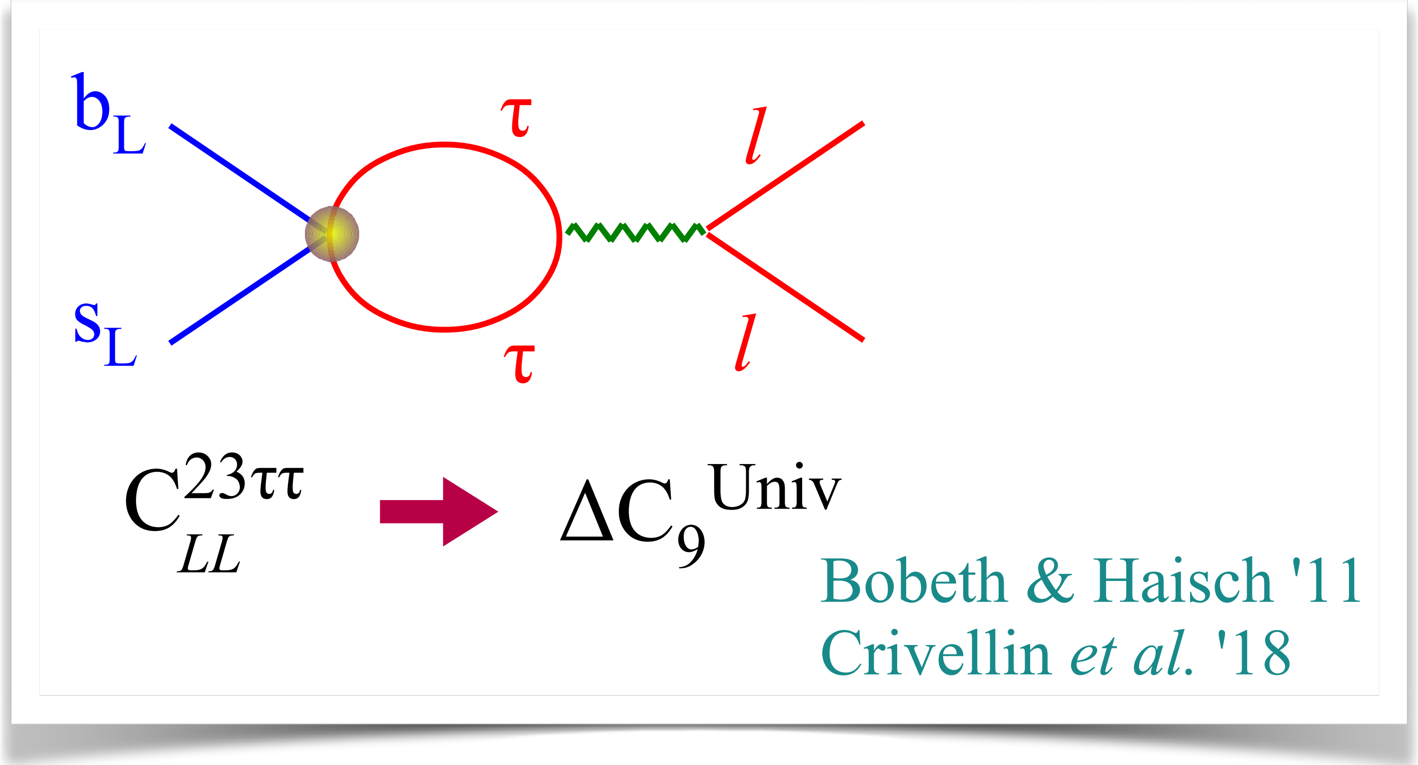
Induce ΔC_9^U but no LFU breaking terms ($\mathcal{R}_{K^{(*)}}$) or axial-current contributions ($B_s^0 \to \mu^+\mu^-$)

Fit to **clean observables** ($\mathscr{R}_{K^{(*)}}$ and $B_s^0 \to \mu^+\mu^-$) consistent with **single NP parameter** $\Delta C_9^\mu = -\Delta C_{10}^\mu$, discrepancy **very significant**



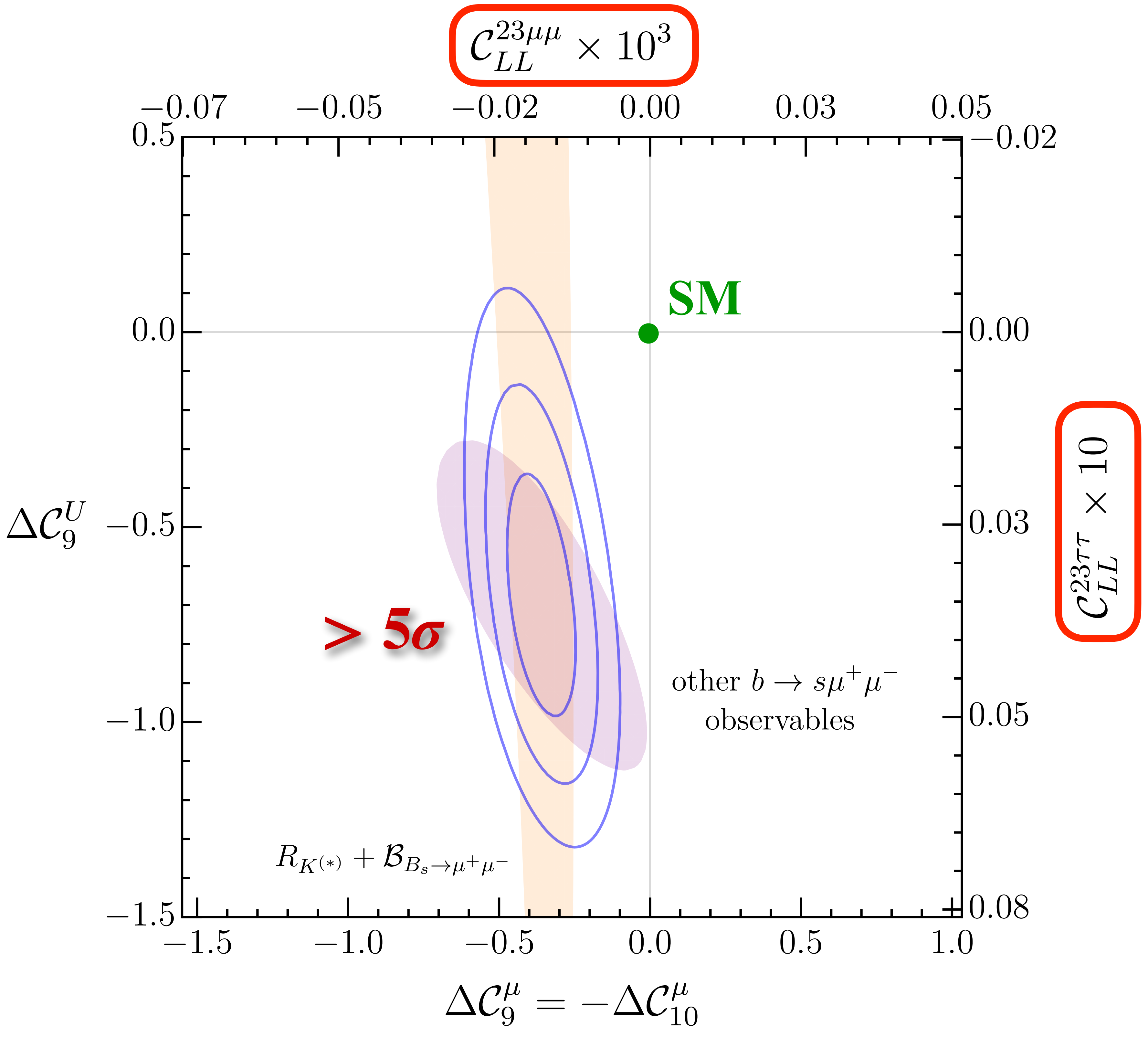
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j) = \frac{1}{2}\left[Q_{lq}^{(1)} + Q_{lq}^{(3)}\right]^{\beta\alpha ij}$$





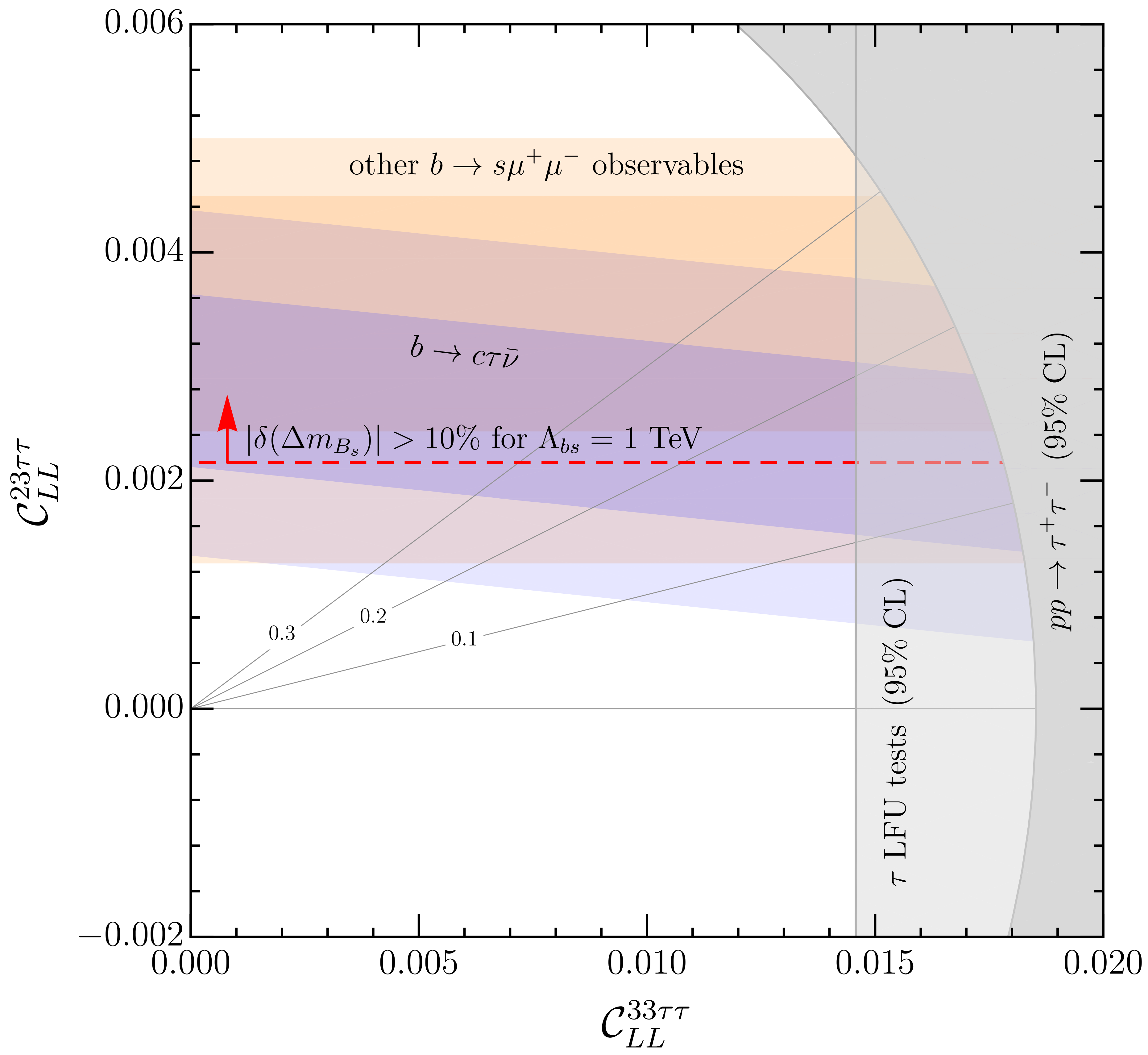
$C_{LL}^{23\tau\tau} \approx 10^2 \times C_{LL}^{23\mu\mu}$ points to scaling with fermion generation

Fits to clean and other **observables** also consistent, away from SM



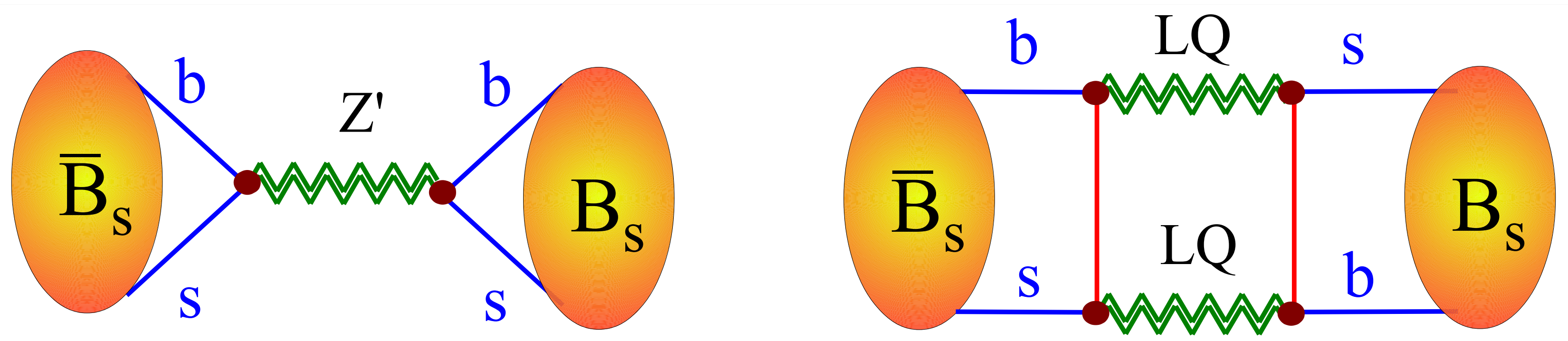
Isidori at APS April 2021, arXiv:2103.16558

~ $b \to s\ell\ell$ **and** $b \to c\tau\nu$ give remarkably **consistent results**



- ~ 10^{-1} for each 2nd gen. q_L or l_L
  - → $|C^{23\mu\mu}| \sim 10^{-3}\, |C^{33\tau\tau}|$
  - → $|V_{ts}| \sim 0.4\times10^{-1}$
- Nice consistency among the two sets of anomalies

I. $\Delta F=2$ & $\tau \to l\nu\nu$



II. Direct searches: 3rd gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

Additional ~10^{-2} (~loop) suppression for

- Four-quarks ($\Delta F=2$)
- Four-leptons ($\tau\to\mu\nu\nu$)
- Semi-leptonic $O^{(1-3)}$ ($b\to s\nu\nu$)

Isidori at APS April 2021, arXiv:2103.16558

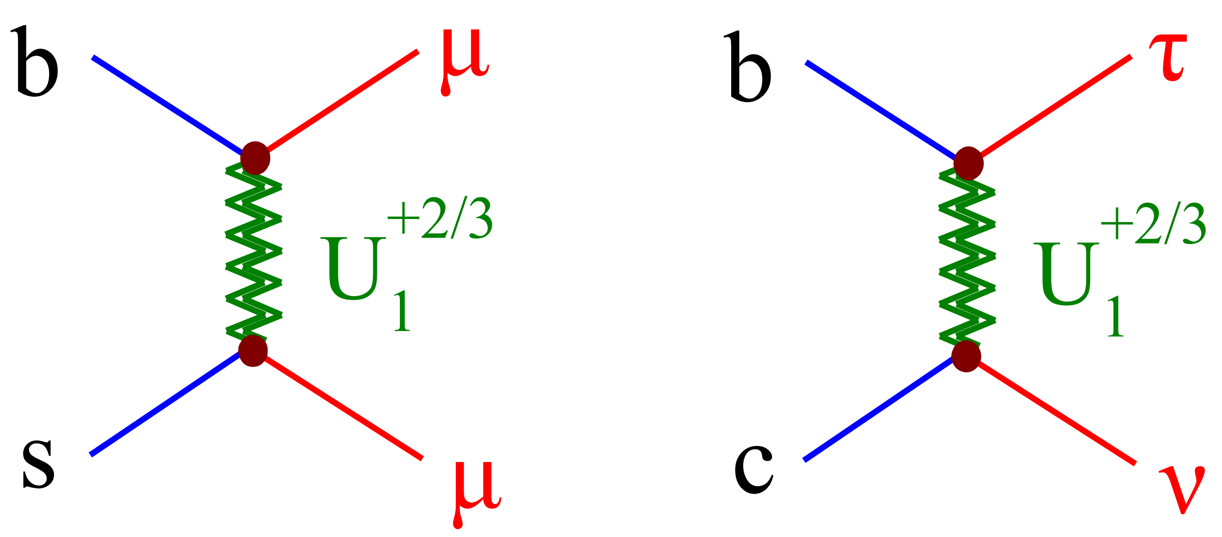
"Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & ~~R~~ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16,
  Fajfer *et al.* '15-'17; Dorsner *et al.* '17;
  Crivellin *et al.* '17; Altmannshofer *et al.* '17
  Trifinopoulos '18, Becirevic *et al.* '18 + ...
- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  Heeck & Teresi '18
  + ...
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16,
  Barbieri, Murphy, Senia, '17
- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18

Which LQ explains which anomaly?

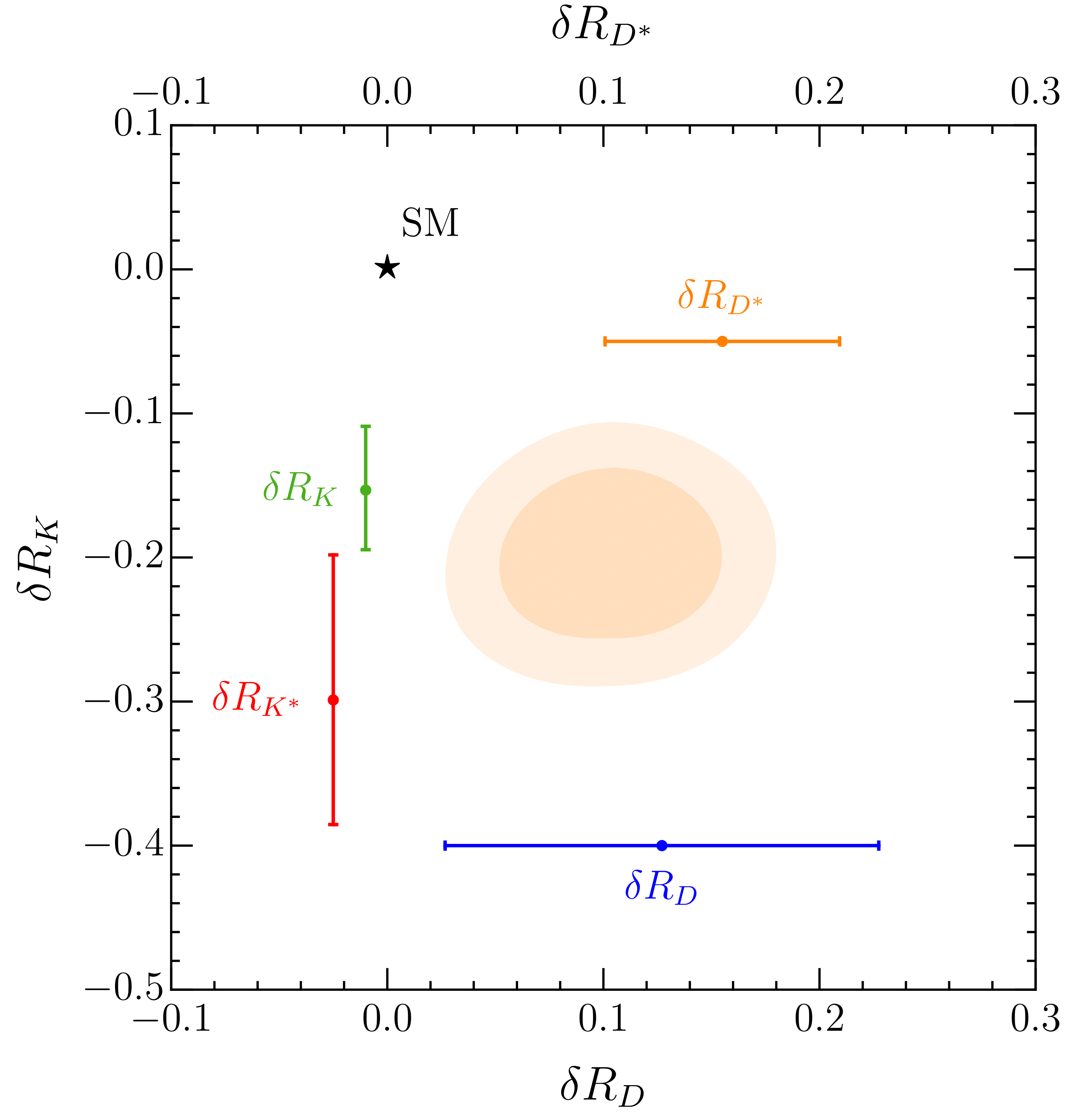
	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
Vectors	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



LQ of the Pati-Salam gauge group:
$SU(4)\times SU(2)_L\times SU(2)_R$

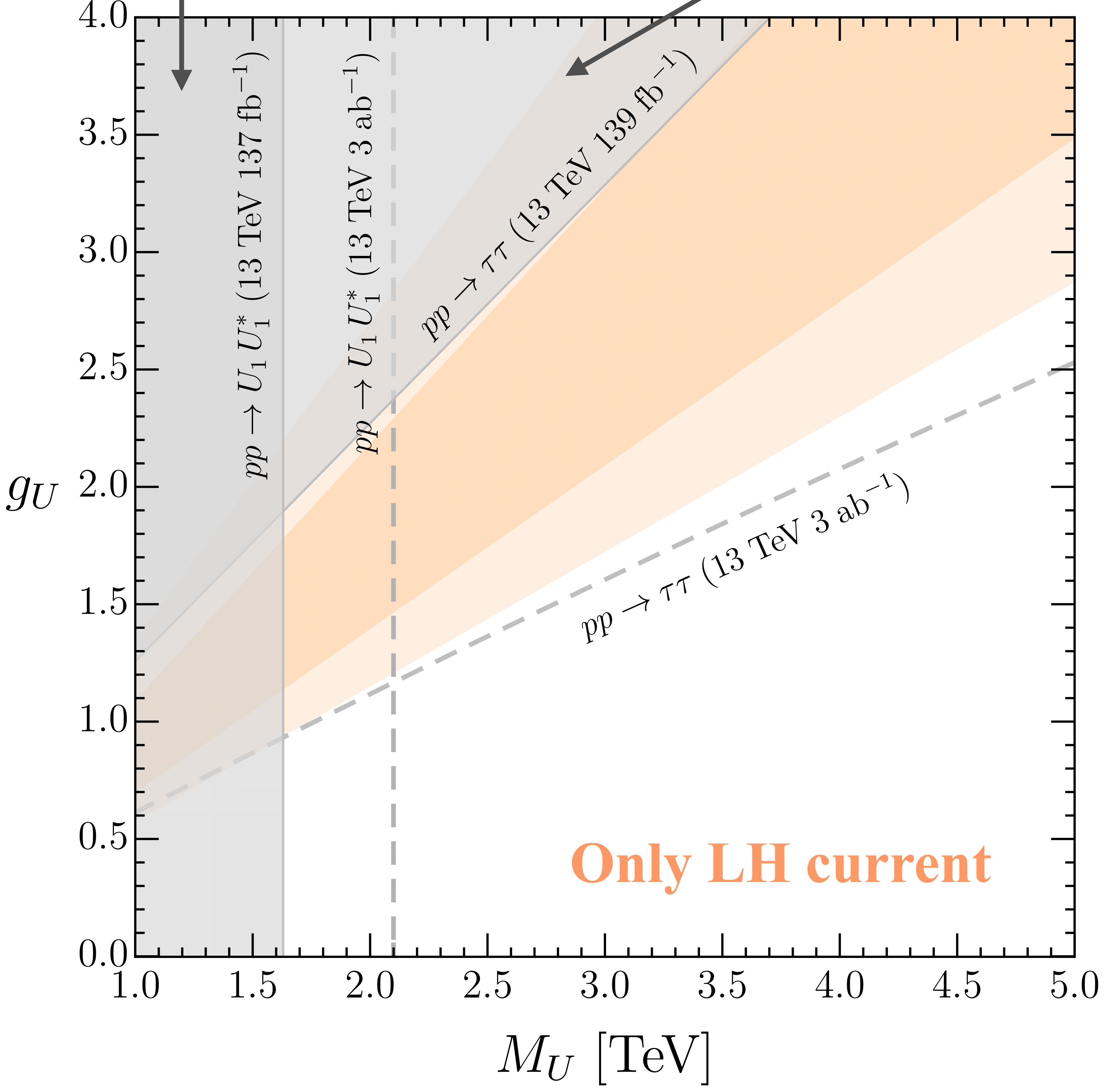
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.}$$

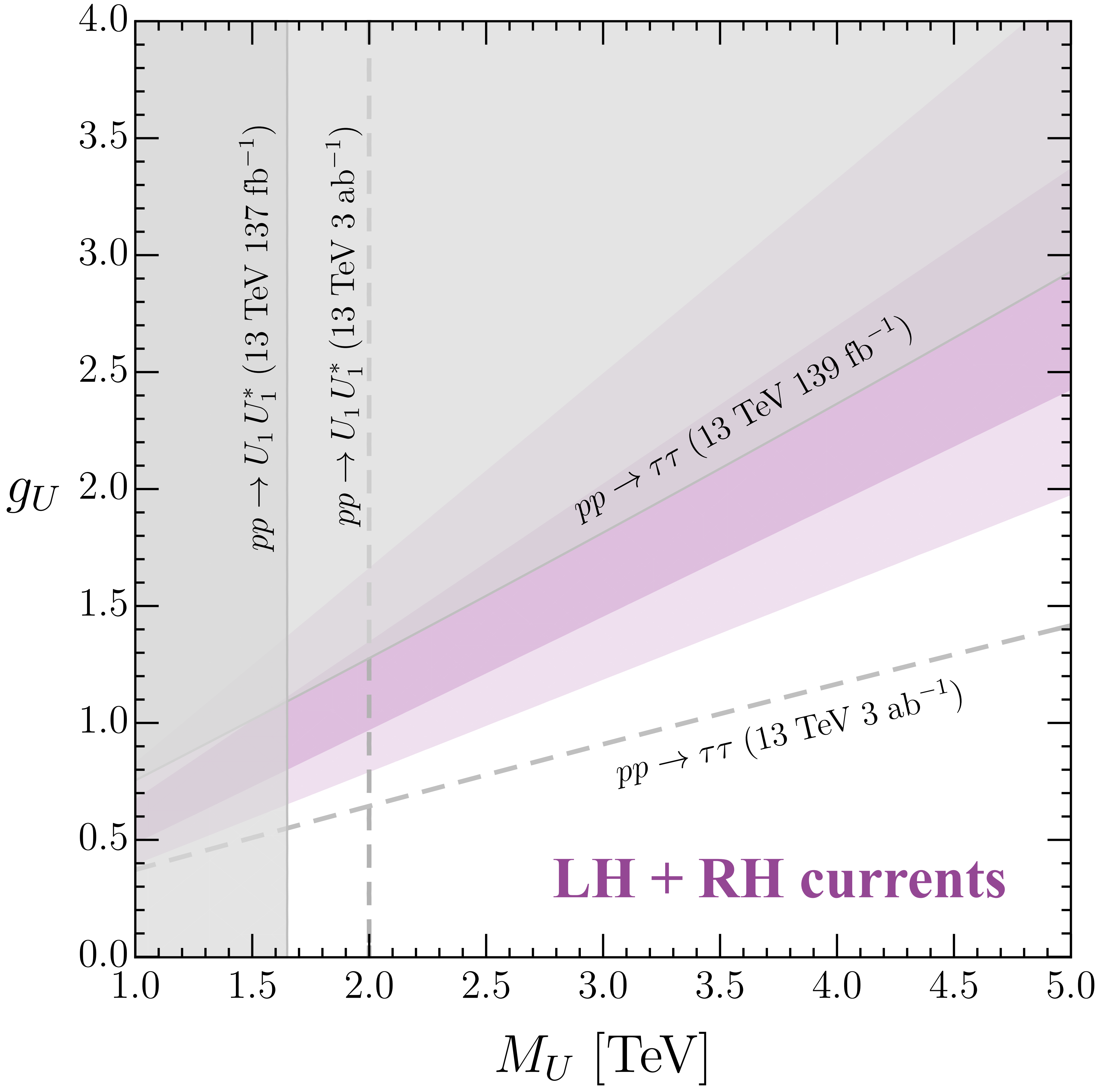


Isidori at APS April 2021, arXiv:2103.16558

Direct LQ search from CMS, arXiv:2012.04178

Study of high p_t tails in $\tau\tau$ events from ATLAS, PRL 125, 051801 (2020)





Direct LQ searches at LHC have limited mass reach, but **high p_T tails** in $\tau\tau$ events would have **sensitivity at HL-LHC**

Also, $b \to d\mu\mu$, $b \to s\tau\tau$, $b \to s\tau\mu$, B_s mixing, $b \to s\nu\nu$, $\tau \to \mu\mu\mu$

Isidori at APS April 2021, arXiv:2103.16558

Conclusions

- **Excesses** in decays involving $b \to c\tau\nu$ transitions
  - 3.1σ significance
- **Deficits** in decays involving $b \to s\mu\mu$ transitions
  - At least 3.9σ significant
- **U_1 leptoquark** could explain both
  - Within reach at HL-LHC
- Exciting times ahead
  - **LHC** still **analyzing Runs 1+2 data**
  - **Run 3** to start next year with **5x inst. lumi at LHCb**
  - **Belle II** will increase **B-factories dataset** by **50x**
  - **HL-LHC** will increase **current dataset** by **100x**