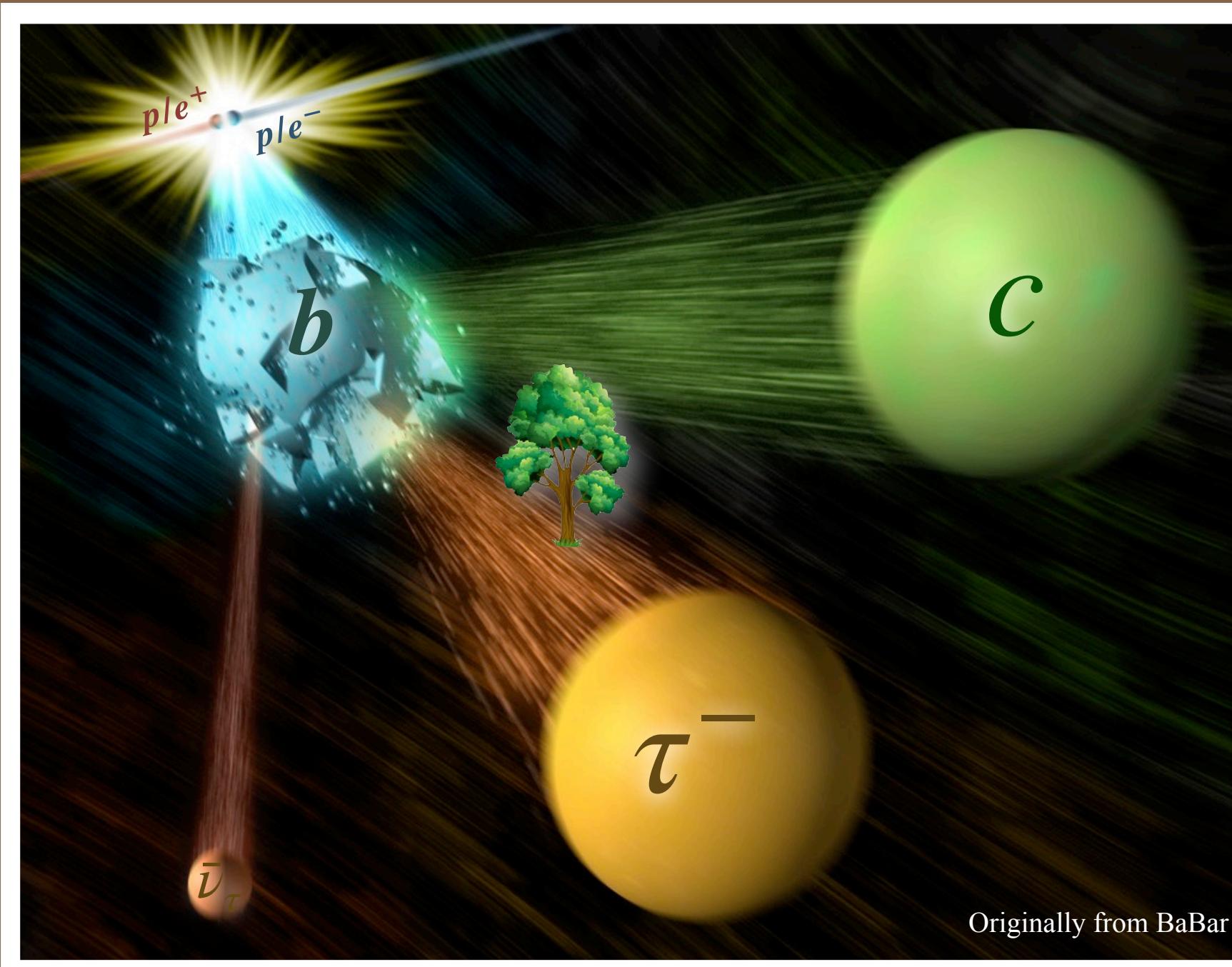


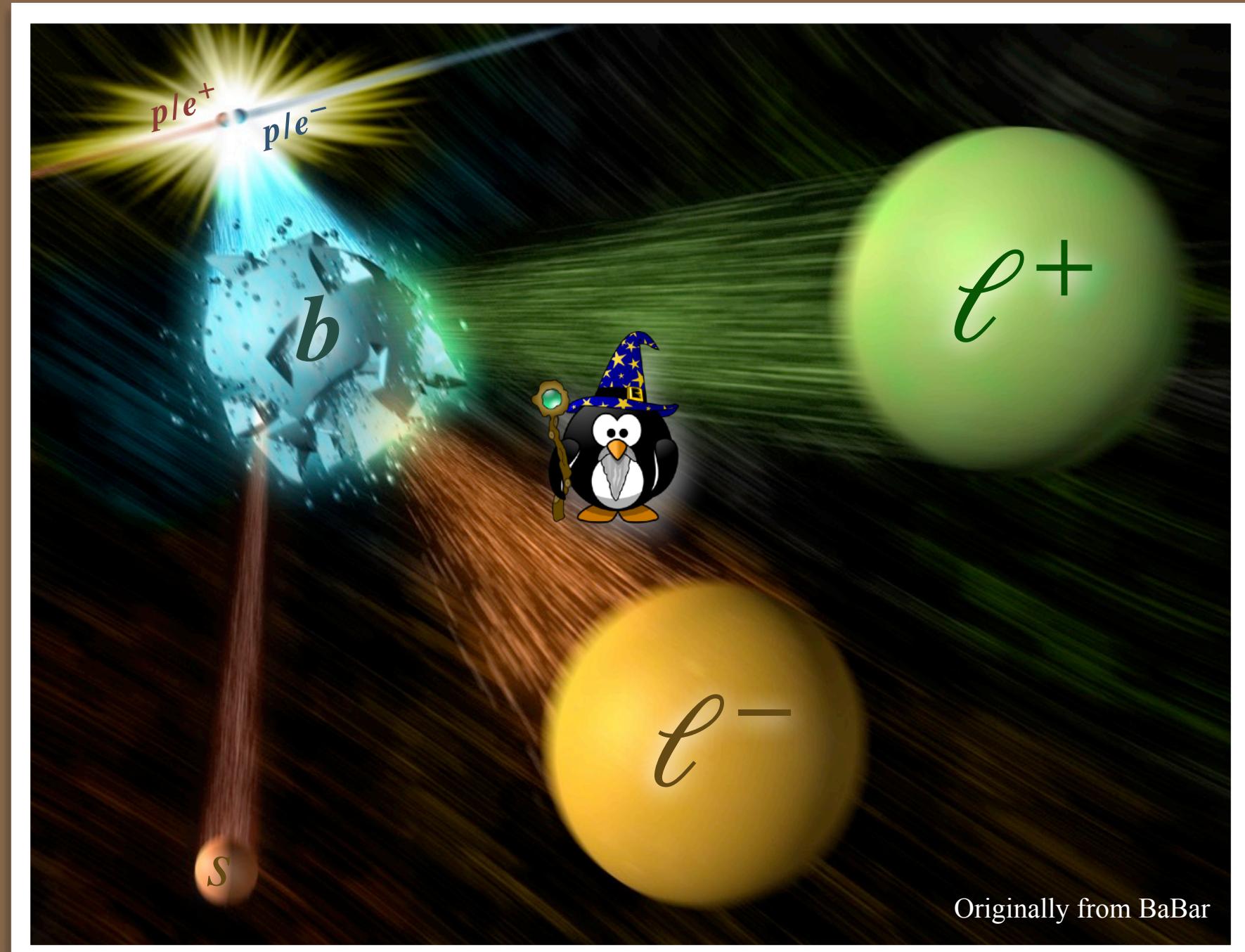
$\mathcal{R}(D^{(*)})$, $\mathcal{R}_{K^{(*)}}$, and their cousins: update on the continued challenges to lepton flavor universality

Manuel Franco Sevilla

University of Maryland



5th May 2021
Virtual joint
JHU/UMD seminar

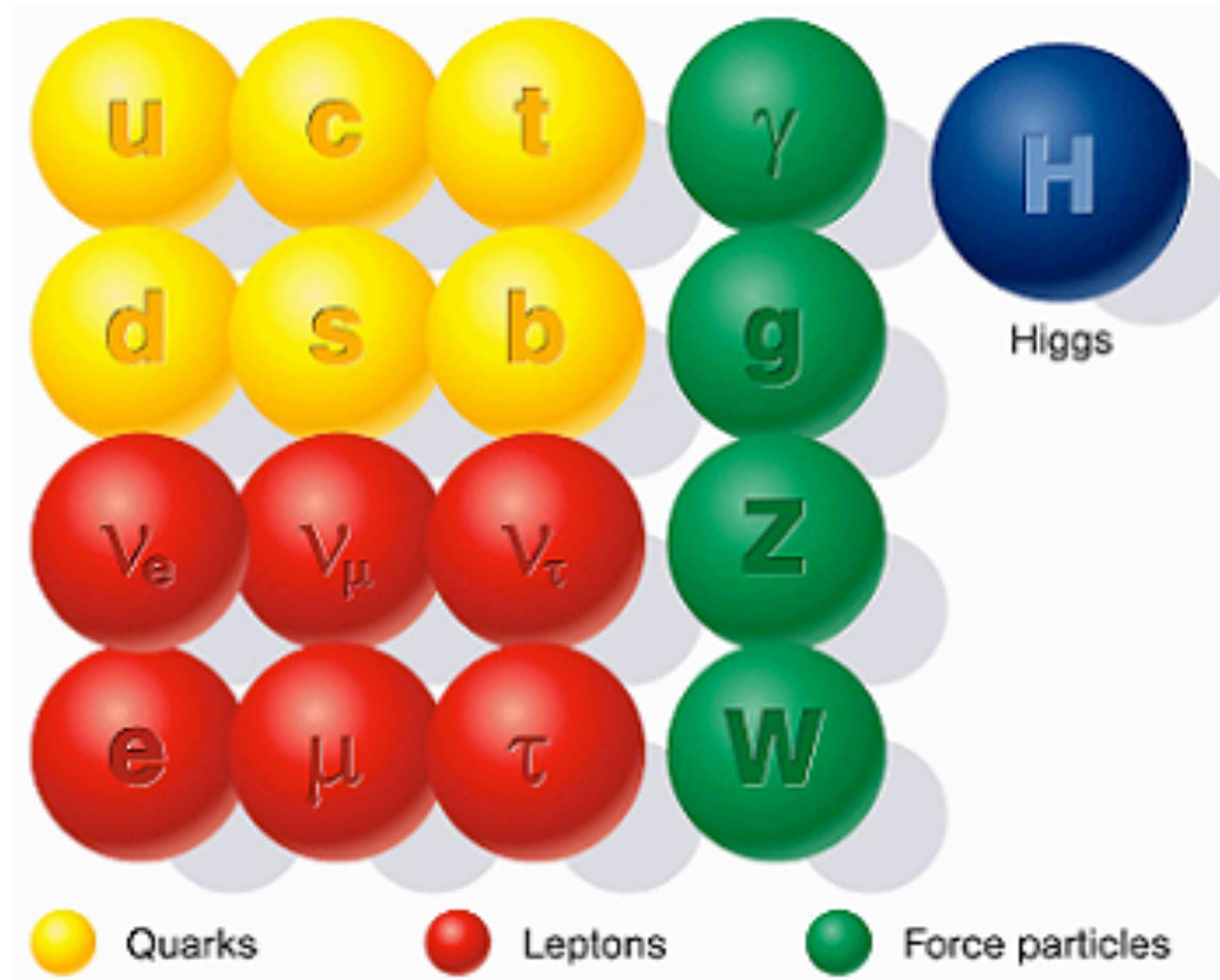


Penguin from Jeff Brassard

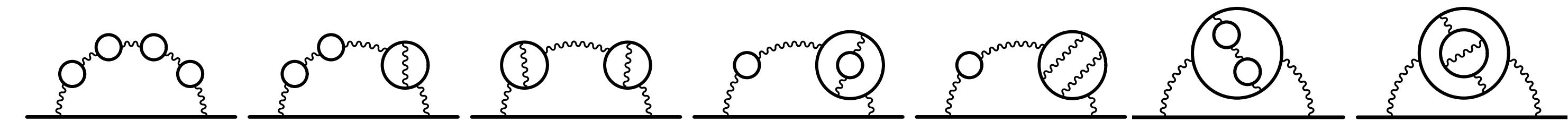
The SM is pretty good



~ 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

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

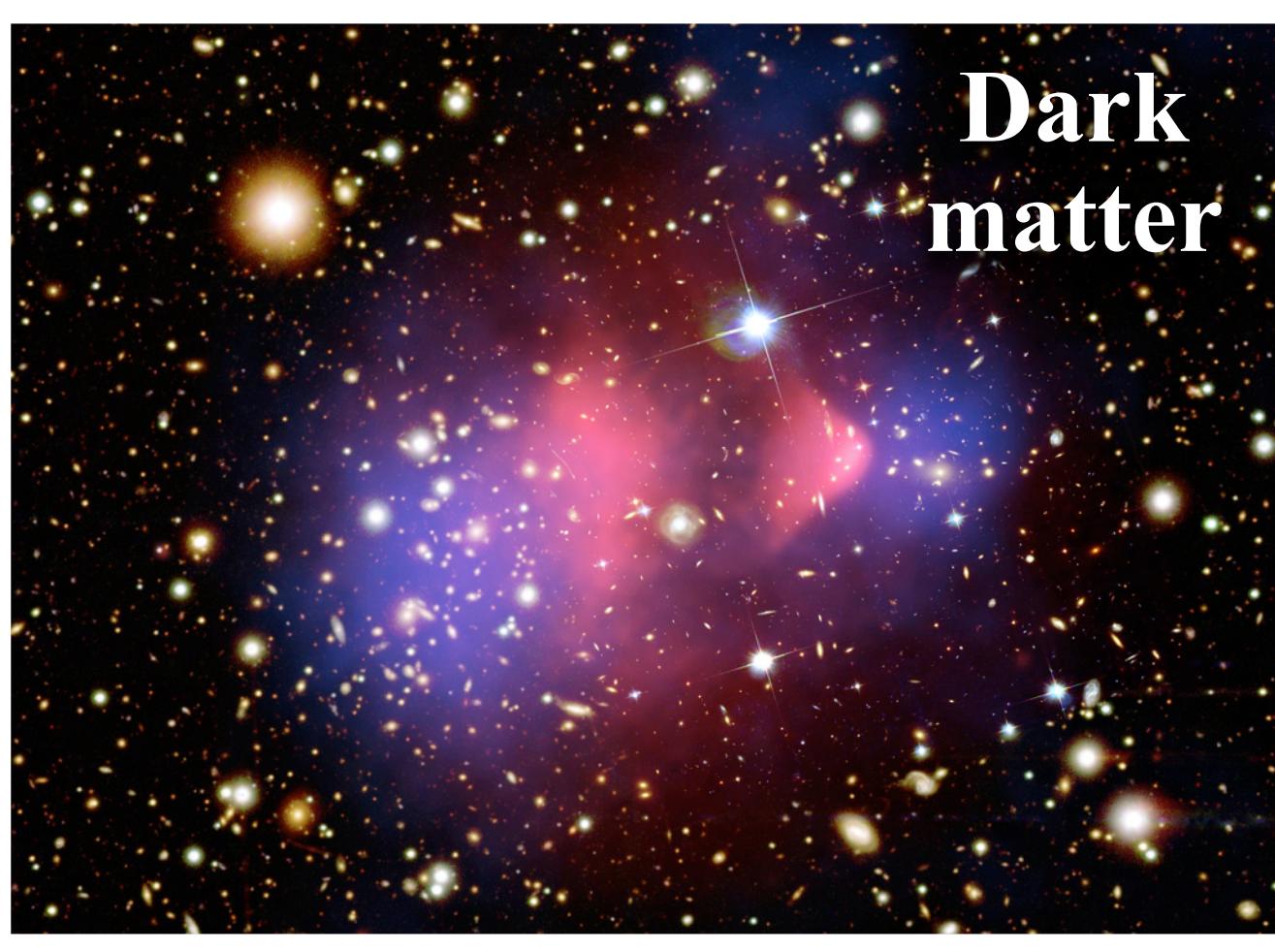
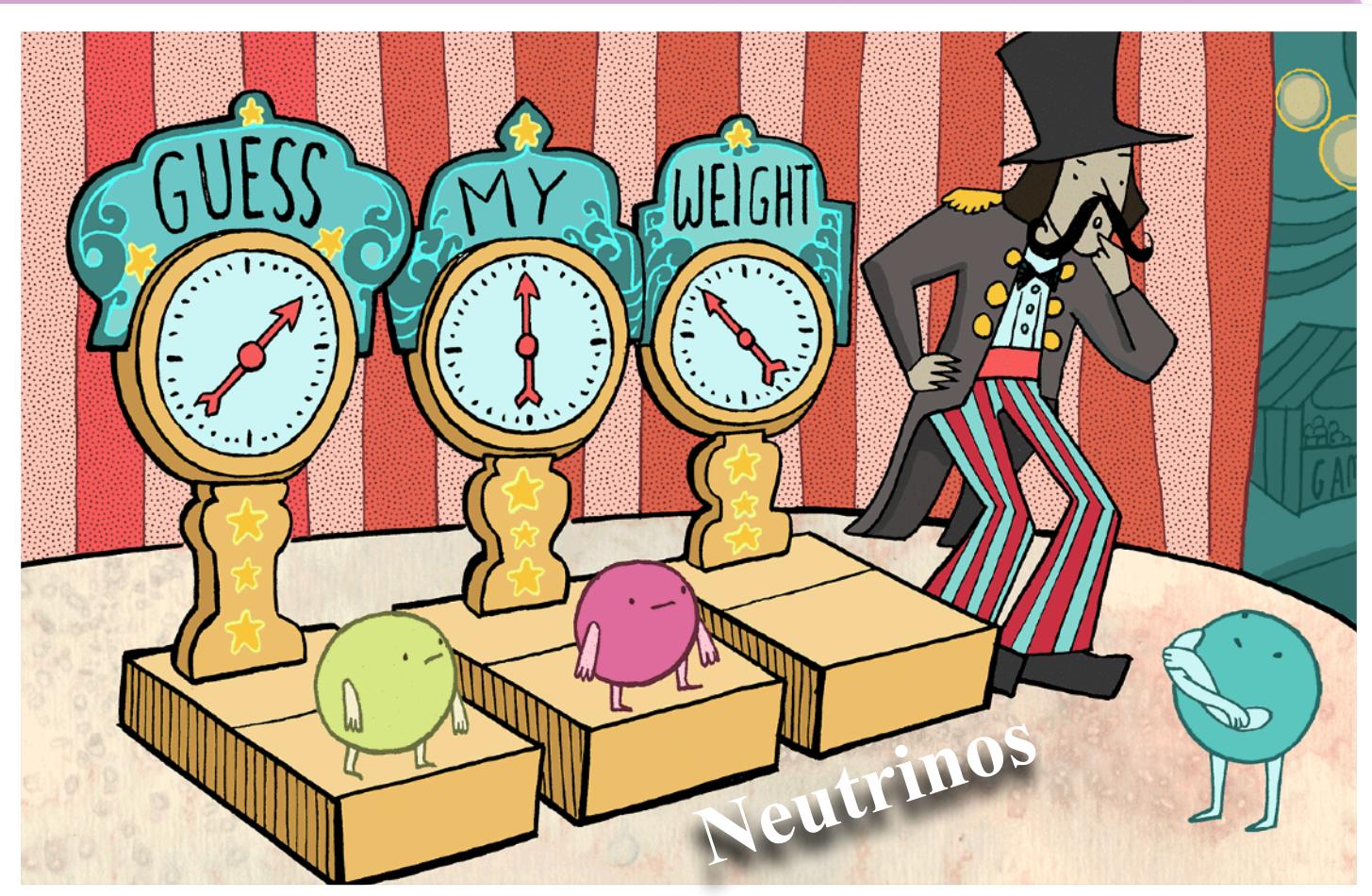
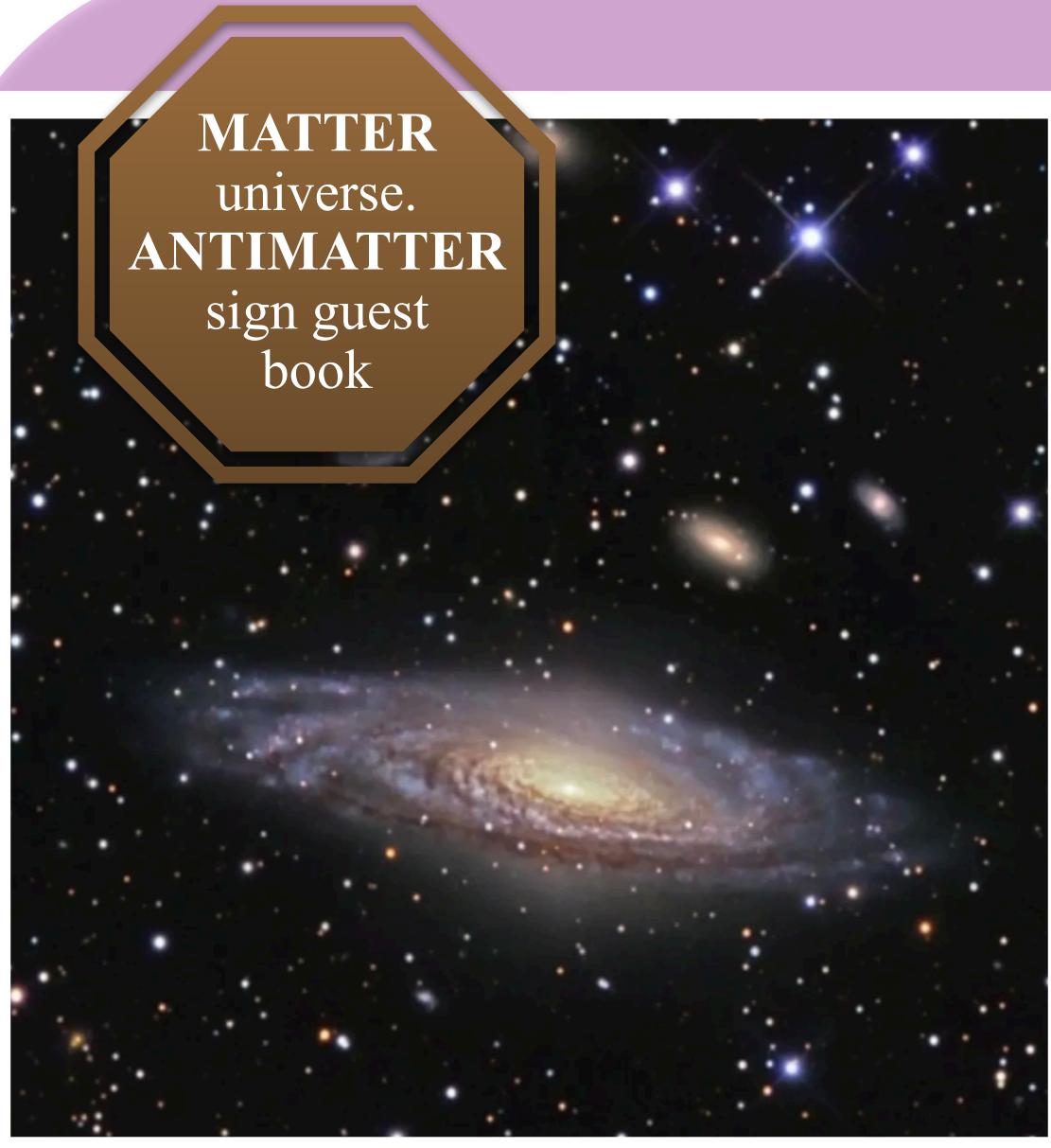
[Atoms 7, 28 \(2019\)](#)

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

[Phys. Rev. Lett. 100, 120801 \(2008\)](#)



Beyond the SM



Dark matter

Sill, many questions left



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

$g_\mu - 2$

REIDAR HAHN / FERMILAB

The findings come from the US Muon g-2 experiment

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Science

Machine finds tantalising hints of new physics

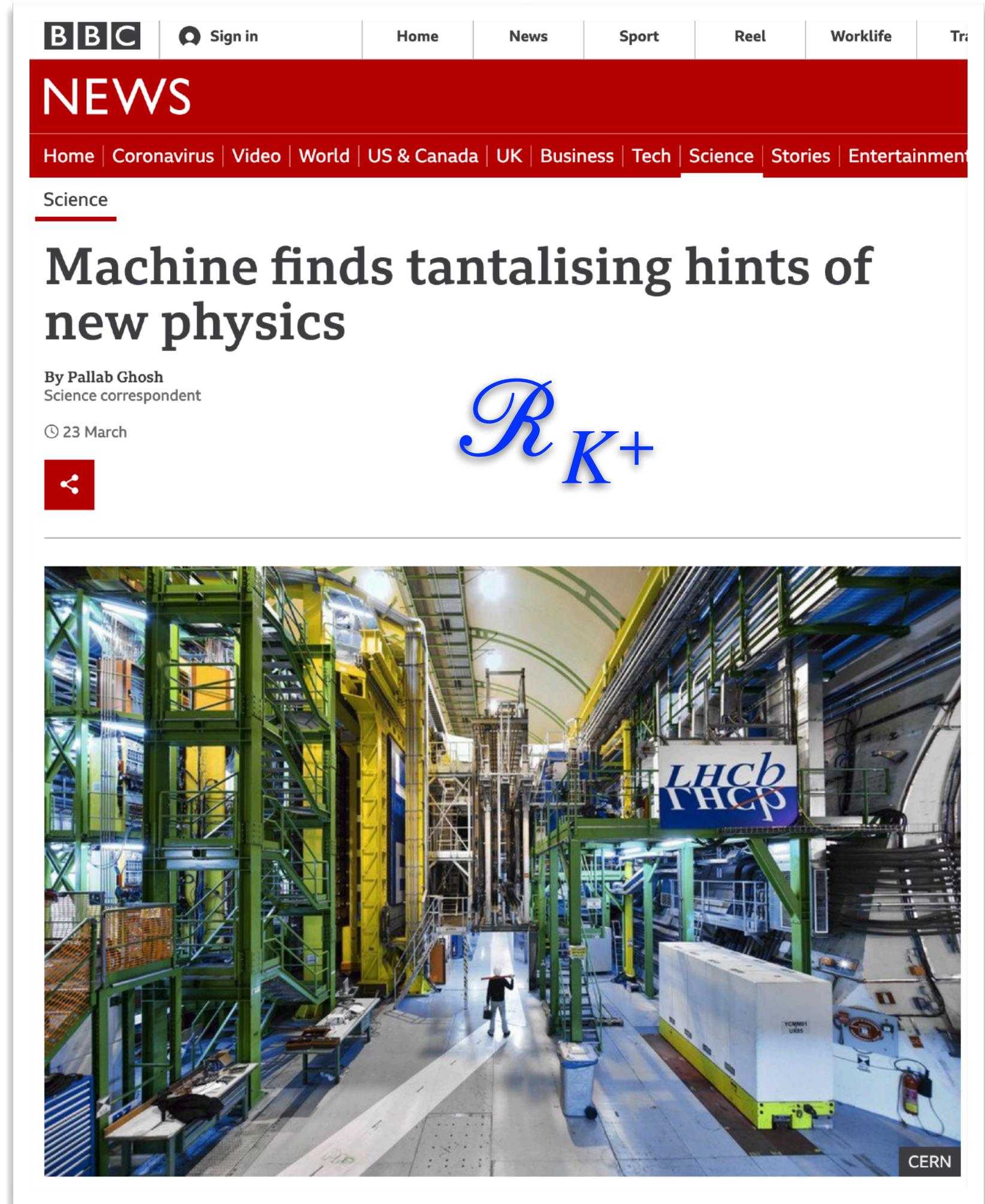
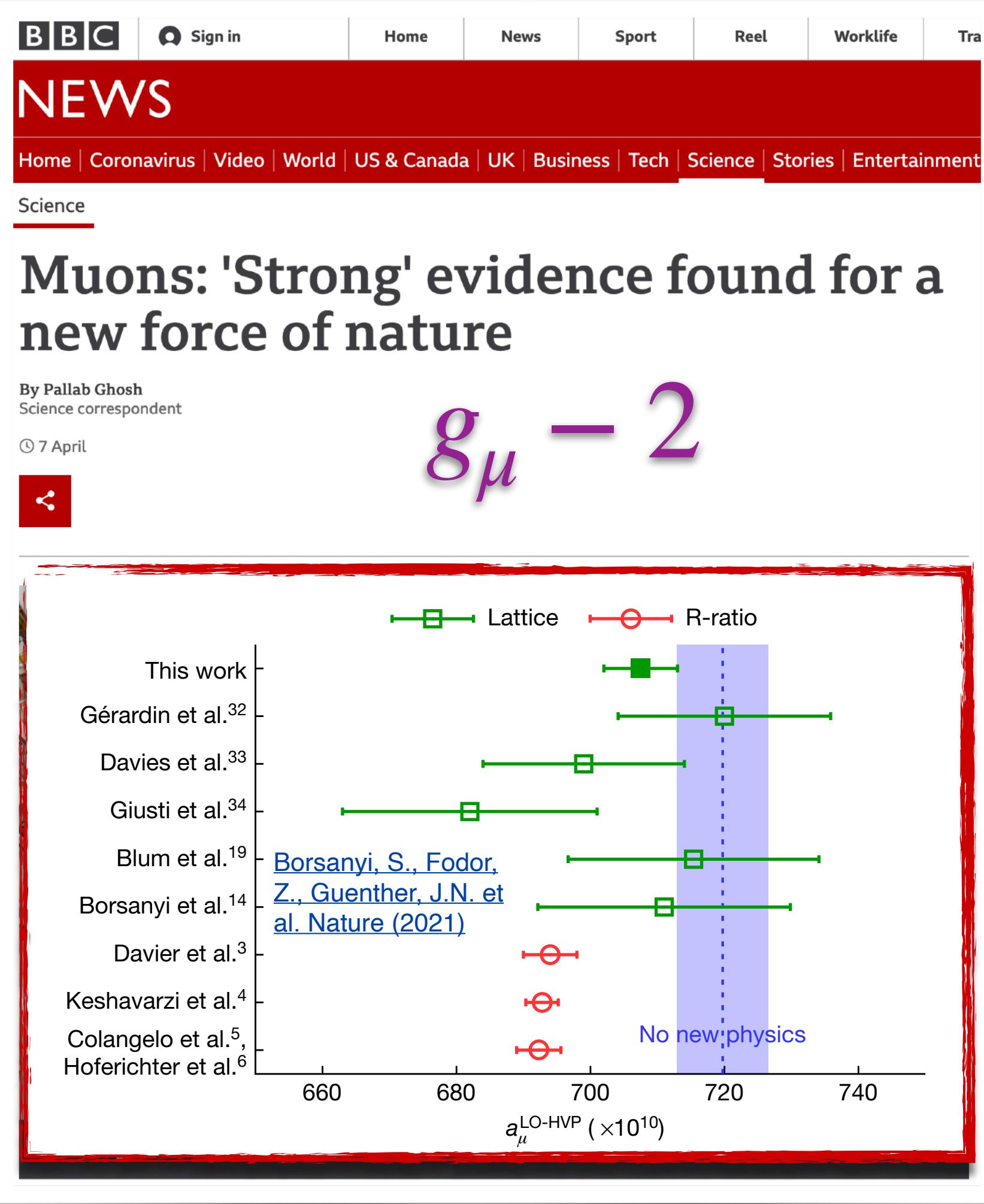
By Pallab Ghosh
Science correspondent
🕒 23 March

\mathcal{R}_{K^+}

LHCb
CERN

- ~ 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

Testing the SM



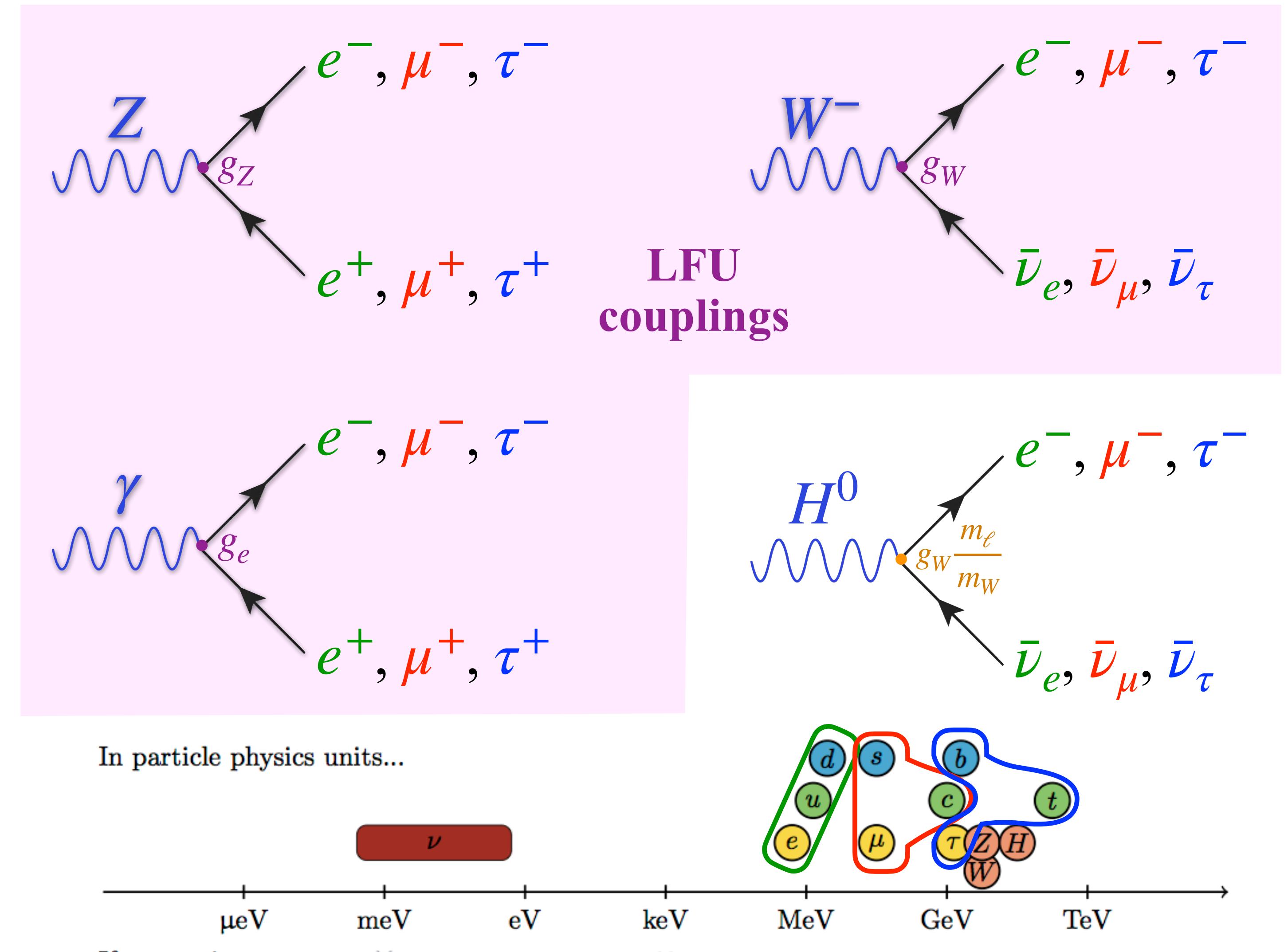
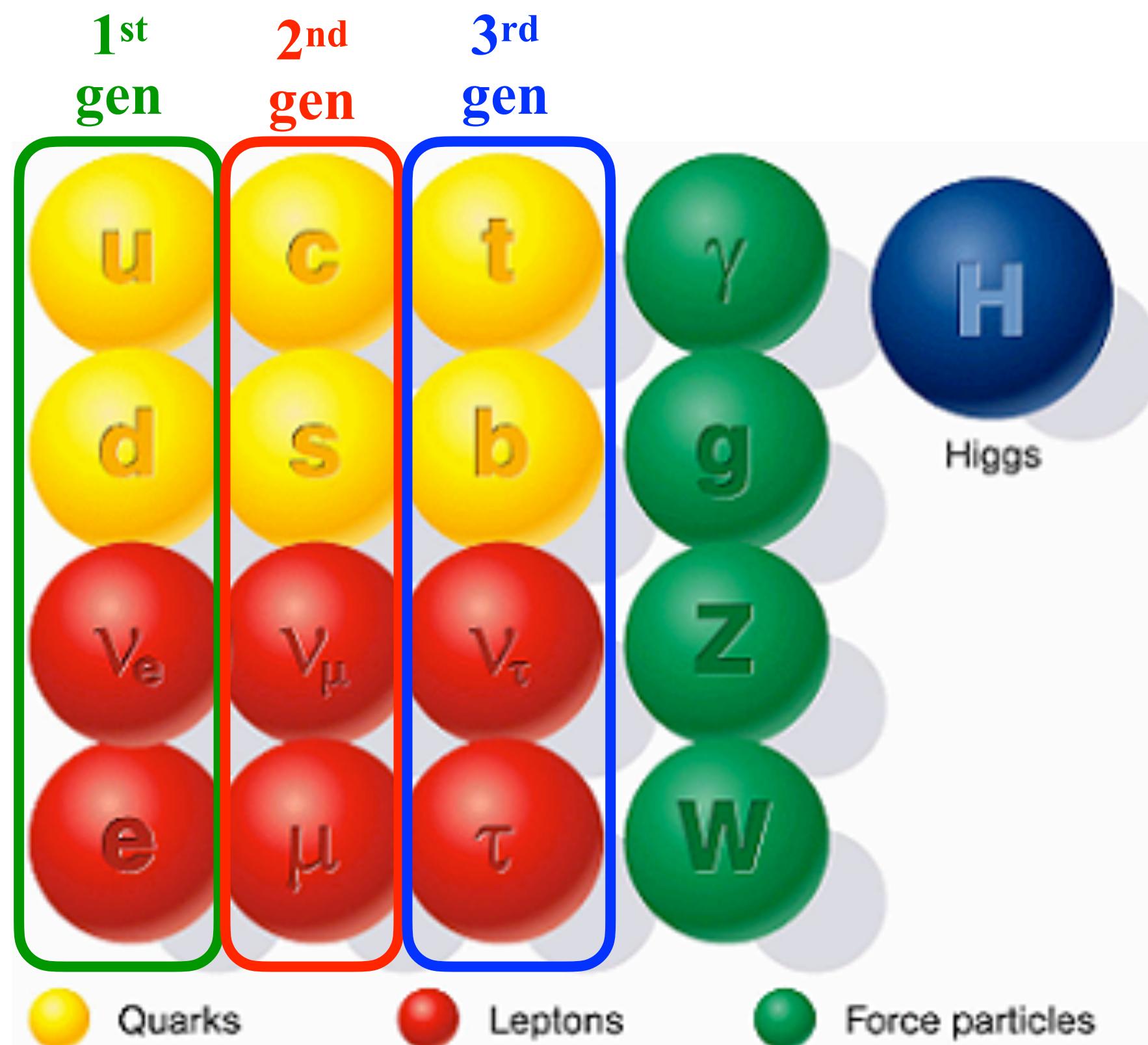
- ~ Alas, no direct detection yet
- ~ Can access mass scales beyond the reach of current particle accelerators through precision tests
- Flavor physics (study of quark and lepton species) is a key tool



Lepton Flavor Universality (LFU)



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



If a neutrino was as heavy as an ant...



<https://ghostsintheuniverse.org/theory/>

LFU tested to great precision



LFU tests with 1st/2nd gen.

To **0.28%** in
Z decays

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

LEP, [Phys. Rept. 427 \(2006\) 257](#)

To **0.8%** in
W decays

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

CDF + LHC, [JPG: NPP, 46, 2 \(2019\)](#)

To **0.31%** in
meson decays

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

PDG (BESIII), [RPP, Chin. Phys. C40 \(2016\) 100001](#)

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

PDG (NA62), [RPP, Chin. Phys. C40 \(2016\) 100001](#)

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

PiENu, [Phys. Rev. Lett. 115, 071801 \(2015\)](#)

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

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

PDG, A. Pich, [Prog. Part. Nucl. Phys. 75 \(2014\) 41](#)

LFU tests with 3rd gen.

To **0.32%** in
Z decays

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

LEP, [Phys. Rept. 427 \(2006\) 257](#)

2.6 σ tension in
W decays

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

LEP, [Phys. Rept. 532 \(2013\) 119,](#)

To **1.3%** in
W decays

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

ATLAS, [arXiv:2007.14040](#)

To **6.1%** in
 D_s decays

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

HFLAV, [Eur. Phys. J. C77 \(2017\) 895](#)

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

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

PDG, S. Pich, [Prog. Part. Nucl. Phys. 75 \(2014\) 41](#)

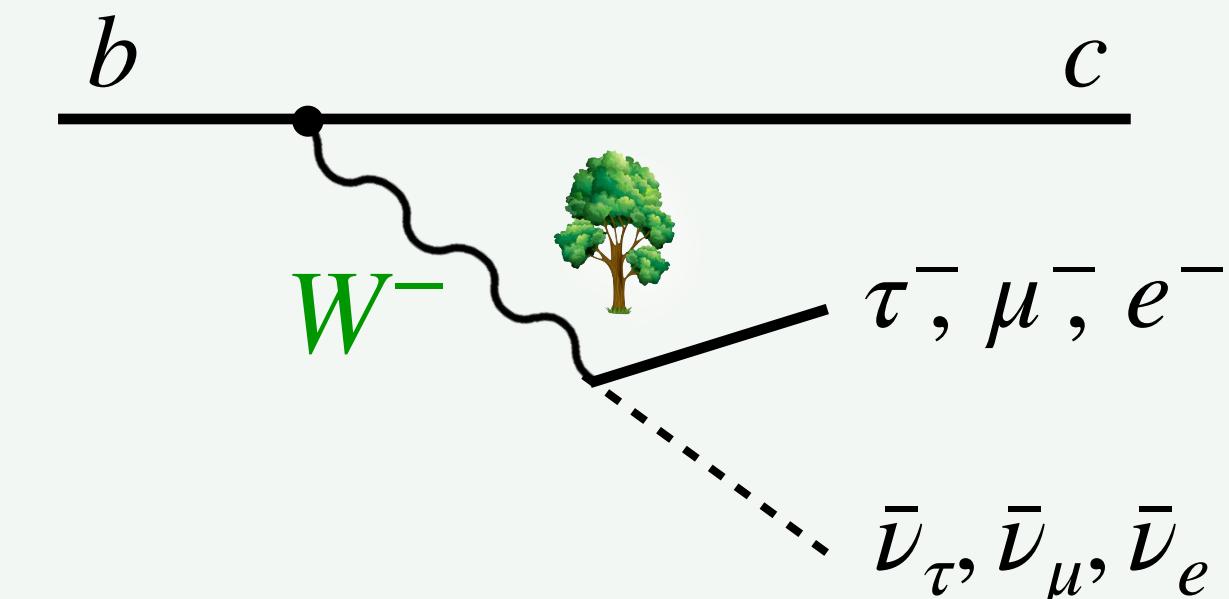


B anomalies

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

$b \rightarrow c\tau\nu$ transitions

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

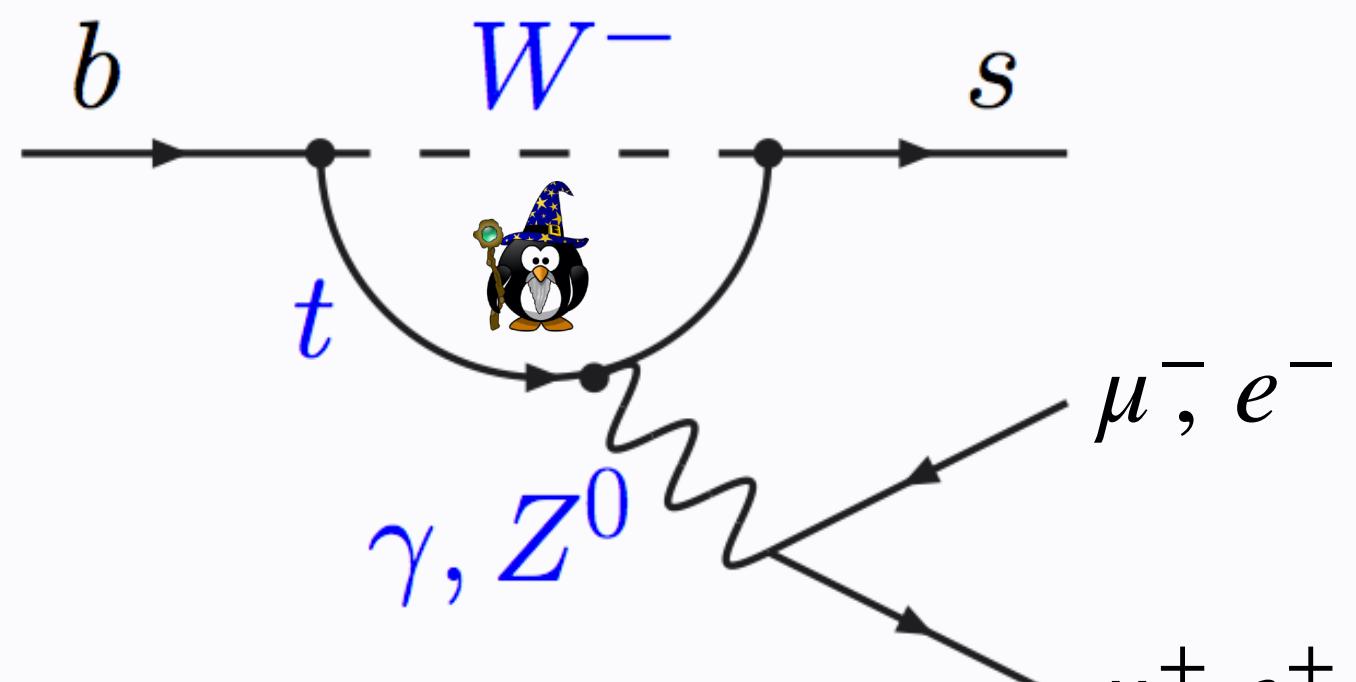


$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\ell\nu_\ell)} \quad \text{with } \ell = \mu, e$$

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

$b \rightarrow s\ell\ell$ transitions

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



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

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

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



Outline

Overview of experiments

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

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

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

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

One elegant interpretation

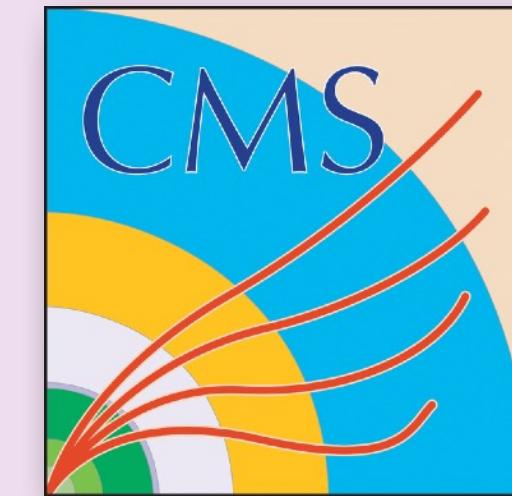
Contributions from several experiments

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

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

B-factoriesWith $\mathcal{O}(10^8)$ $B^{0/+}$ mesons
already competitive search
for $B \rightarrow K\nu\bar{\nu}$ (backup)! $\mathcal{O}(10^{11})$ $B_{(s)}^{0/+}$ mesons

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

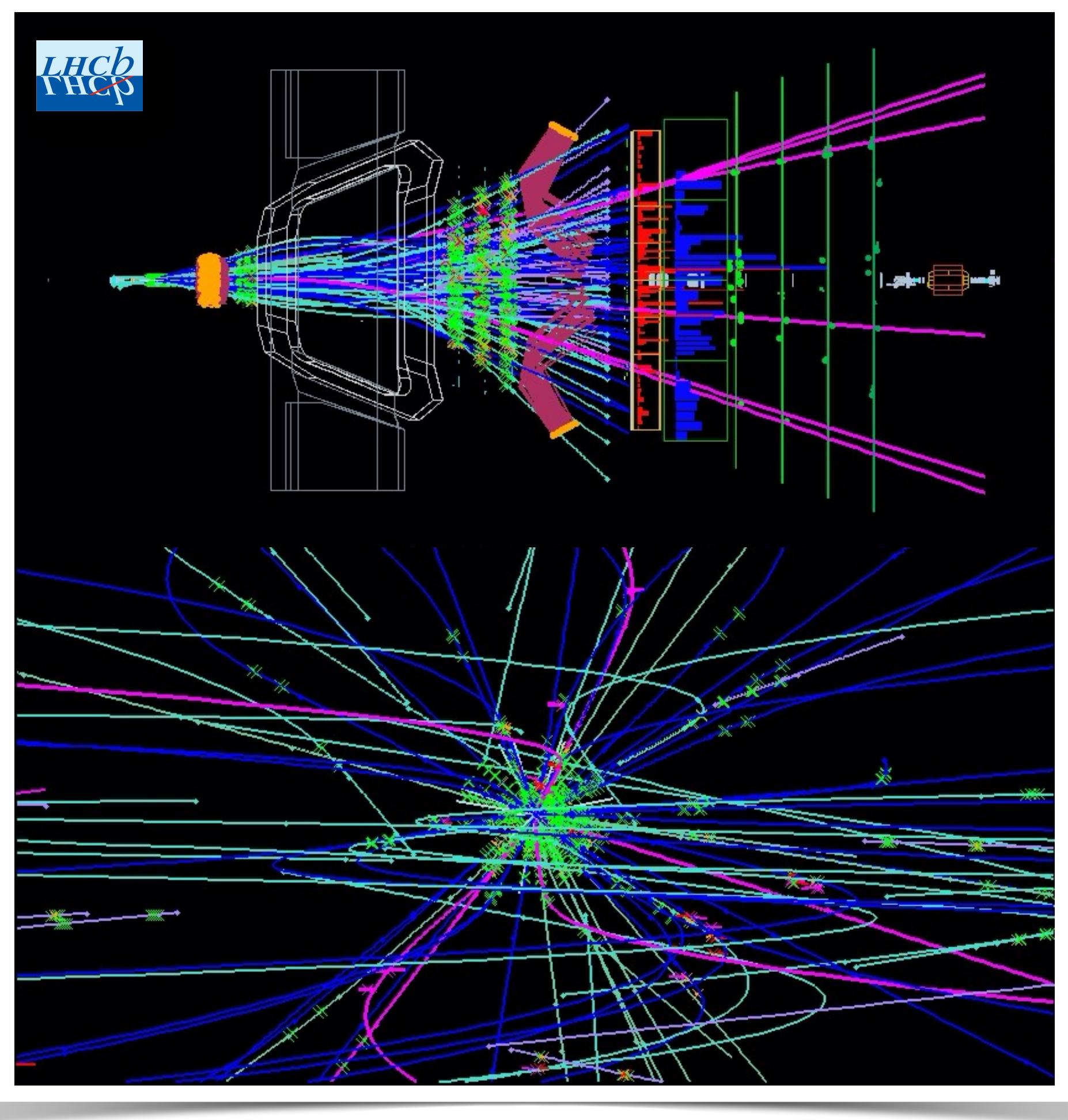
LHC $\mathcal{O}(10^{12})$ $B_{(s)}^{0/+}$ mesons**All b-hadron species**

LHC environment is slightly busier



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

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

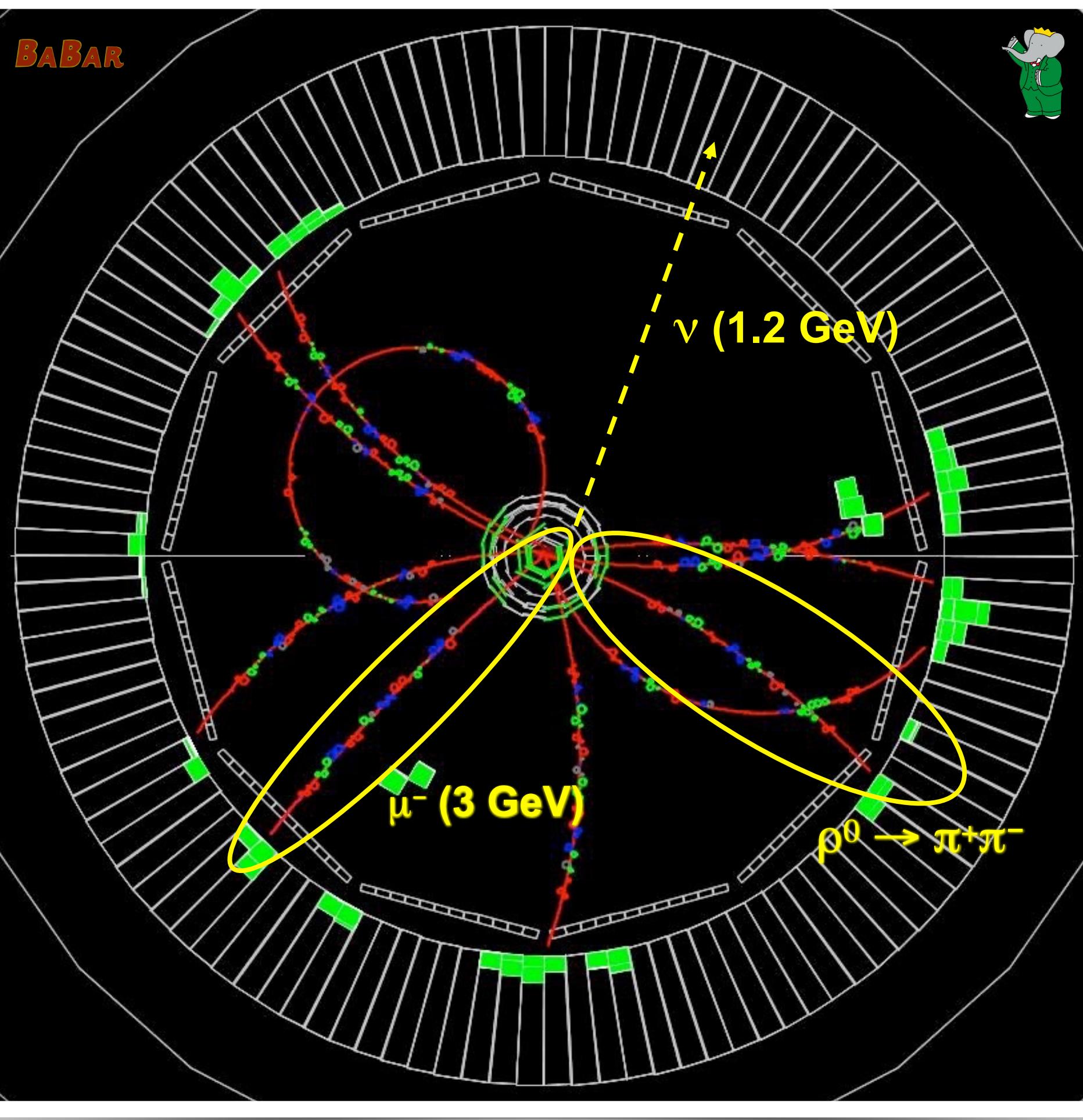


LHC

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

$$e^+ e^- \rightarrow B_{\text{tag}}^+ B_{\text{sig}}^-$$

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



B-factories

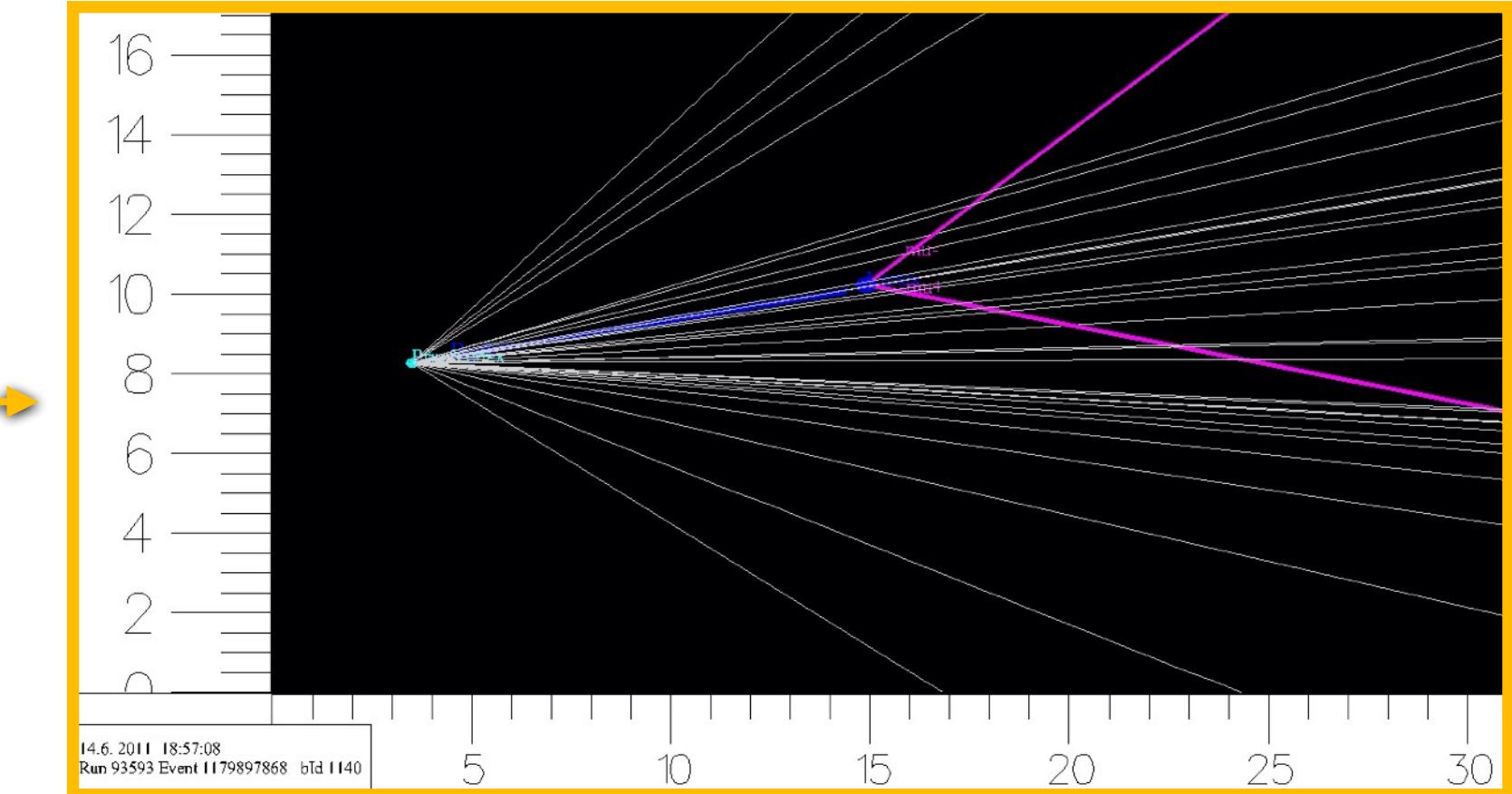
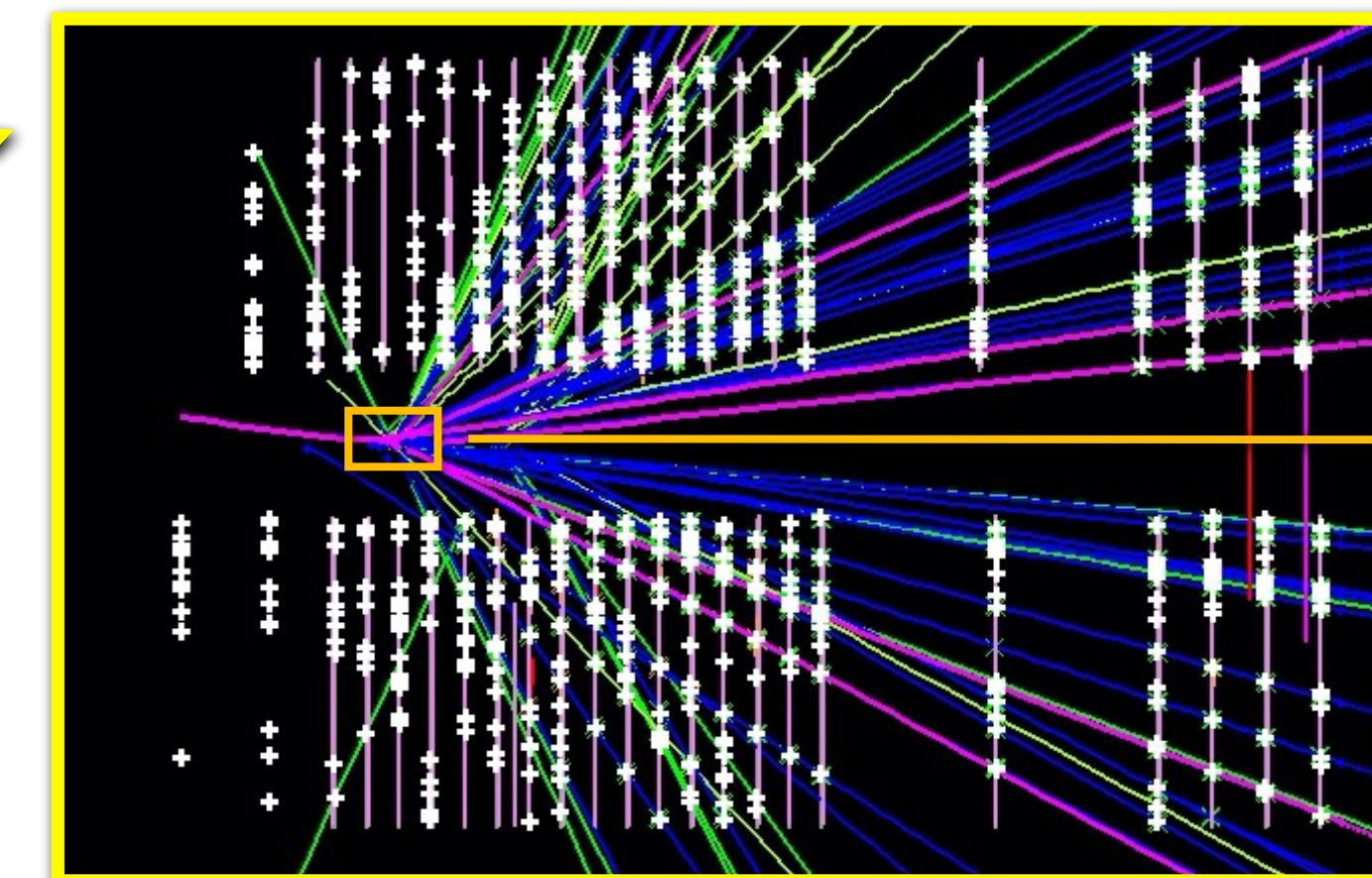
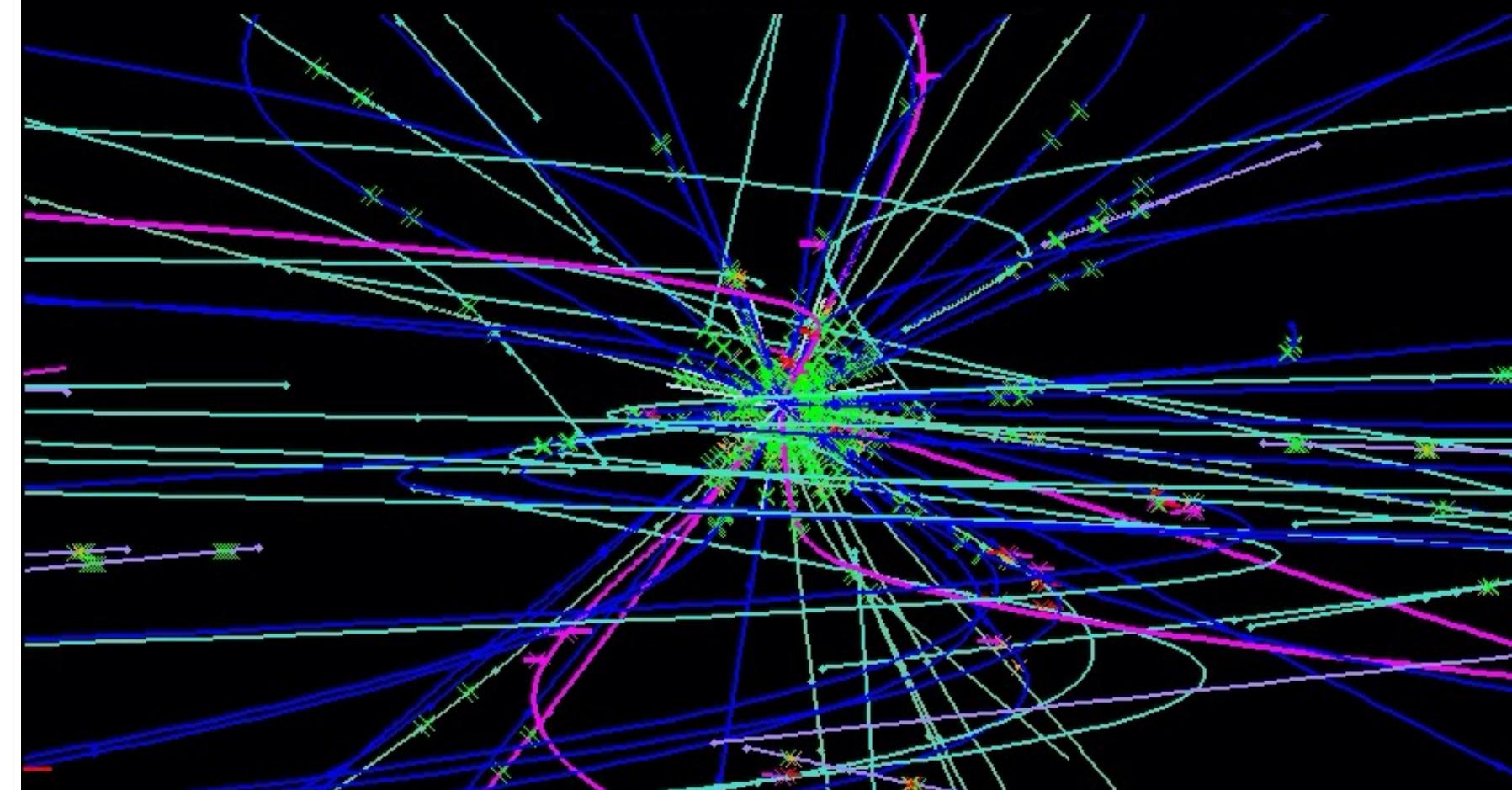
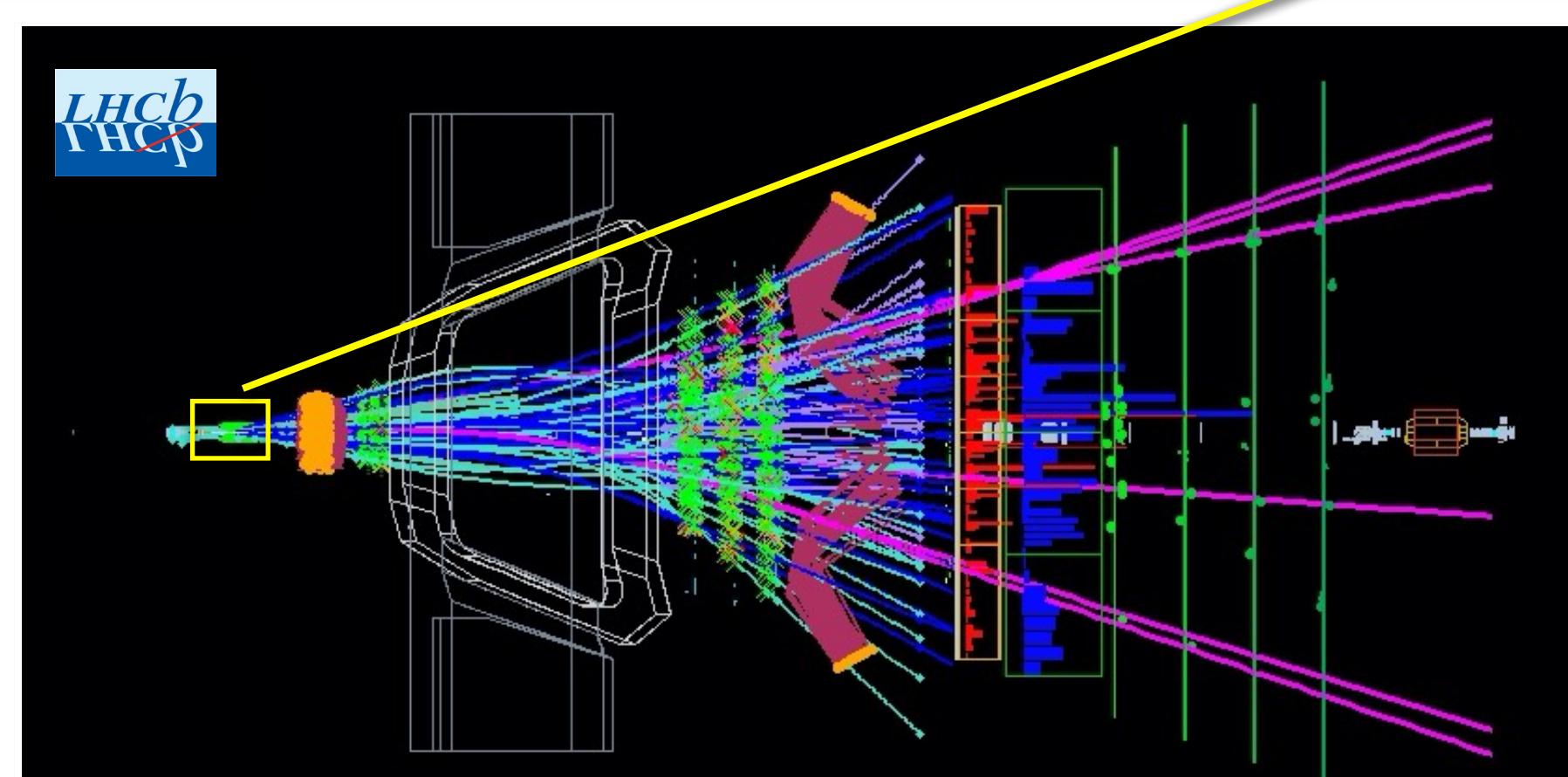
Clean $e^+ e^-$ collisions only produce two B mesons (for the most part)

Vertexing and isolation key to LHC

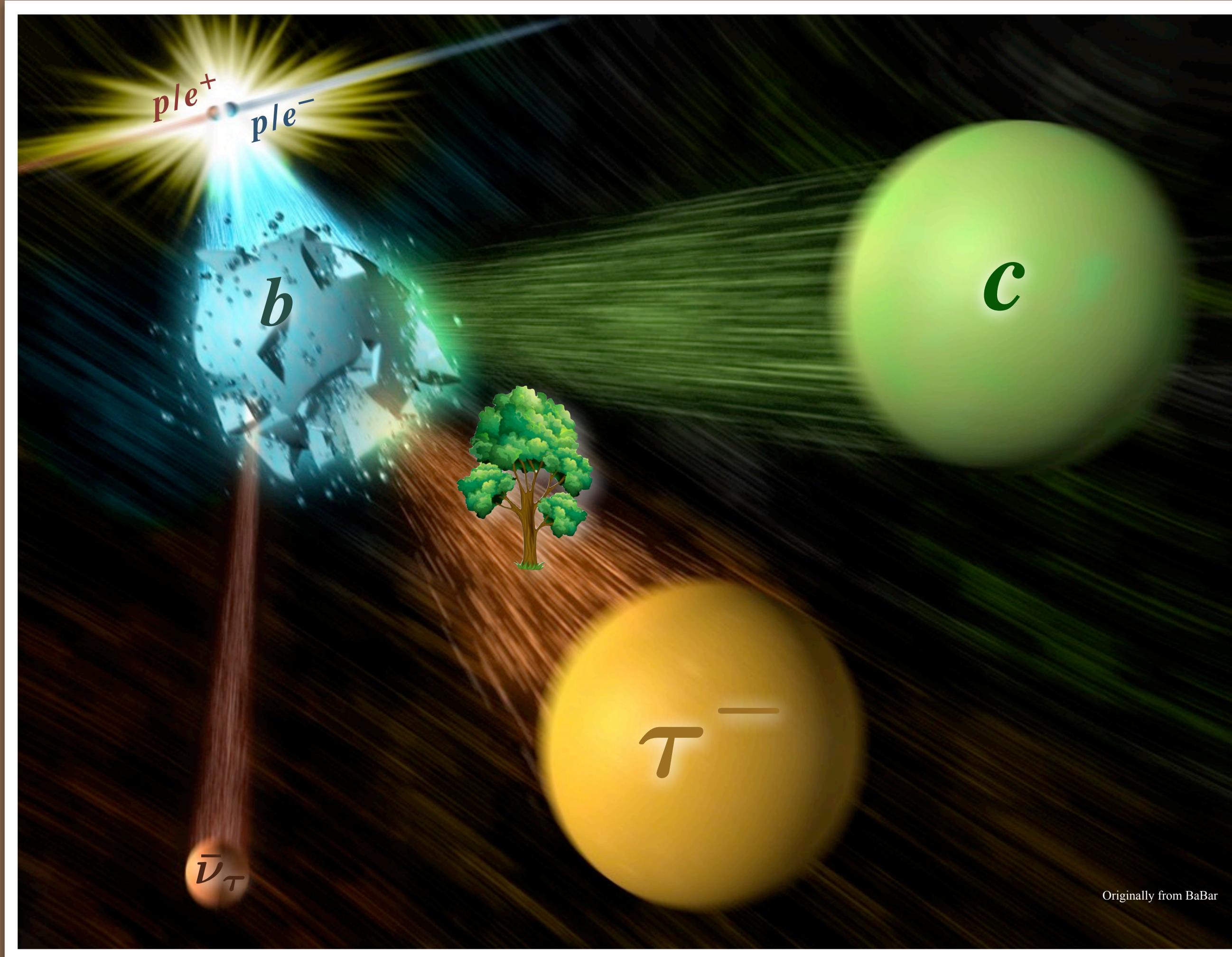


$$pp \rightarrow X_b B_s^0 X$$

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



- ~ **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 $b \rightarrow c\tau\nu$
transitions

τ^- reconstruction

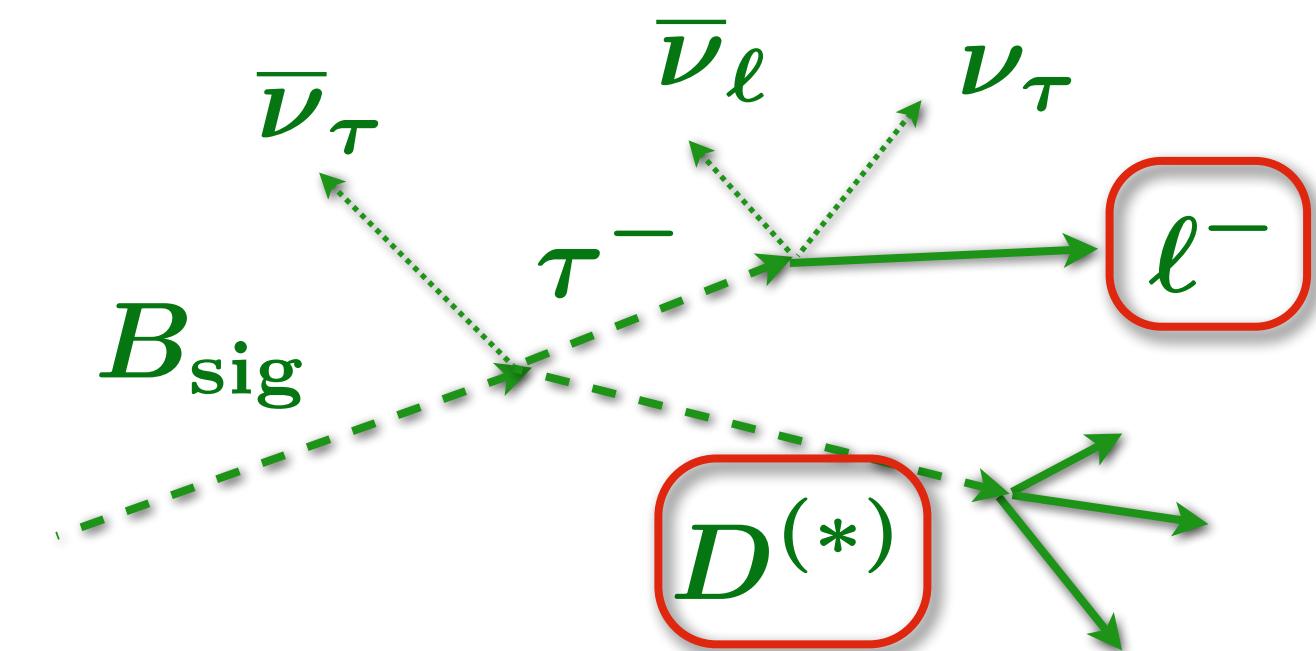


Leptonic τ

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

Same reco particles as normalization

$B \rightarrow D^{(*)} \ell \nu$, many uncertainties
cancel on $\mathcal{R}(D^{(*)})$



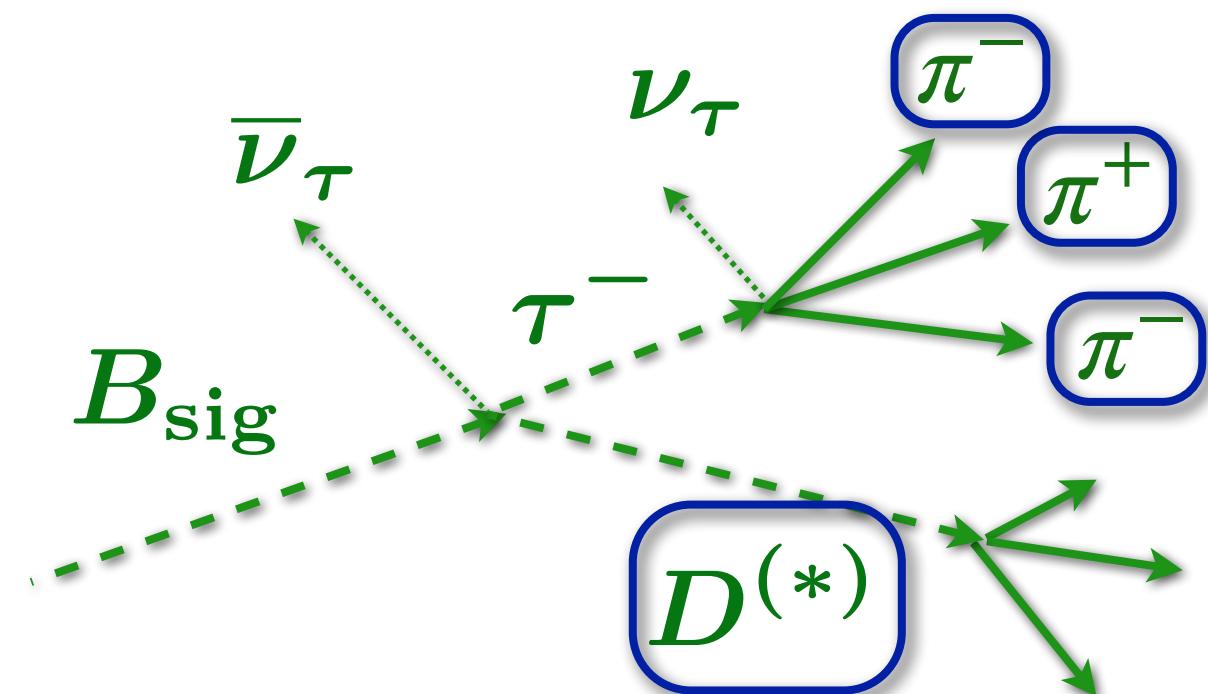
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell \nu_\ell)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$$

ϵ ratio easy, yields are key

Hadronic τ

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

Better measurement of τ kinematics



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

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B} \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^* \pi \pi \pi)} \times \frac{\mathcal{B}(\bar{B} \rightarrow D^* \pi \pi \pi)}{\mathcal{B}(\bar{B} \rightarrow D^* \mu \nu_\mu)}$$

Measure this ratio

p_B reconstruction at the B-factories

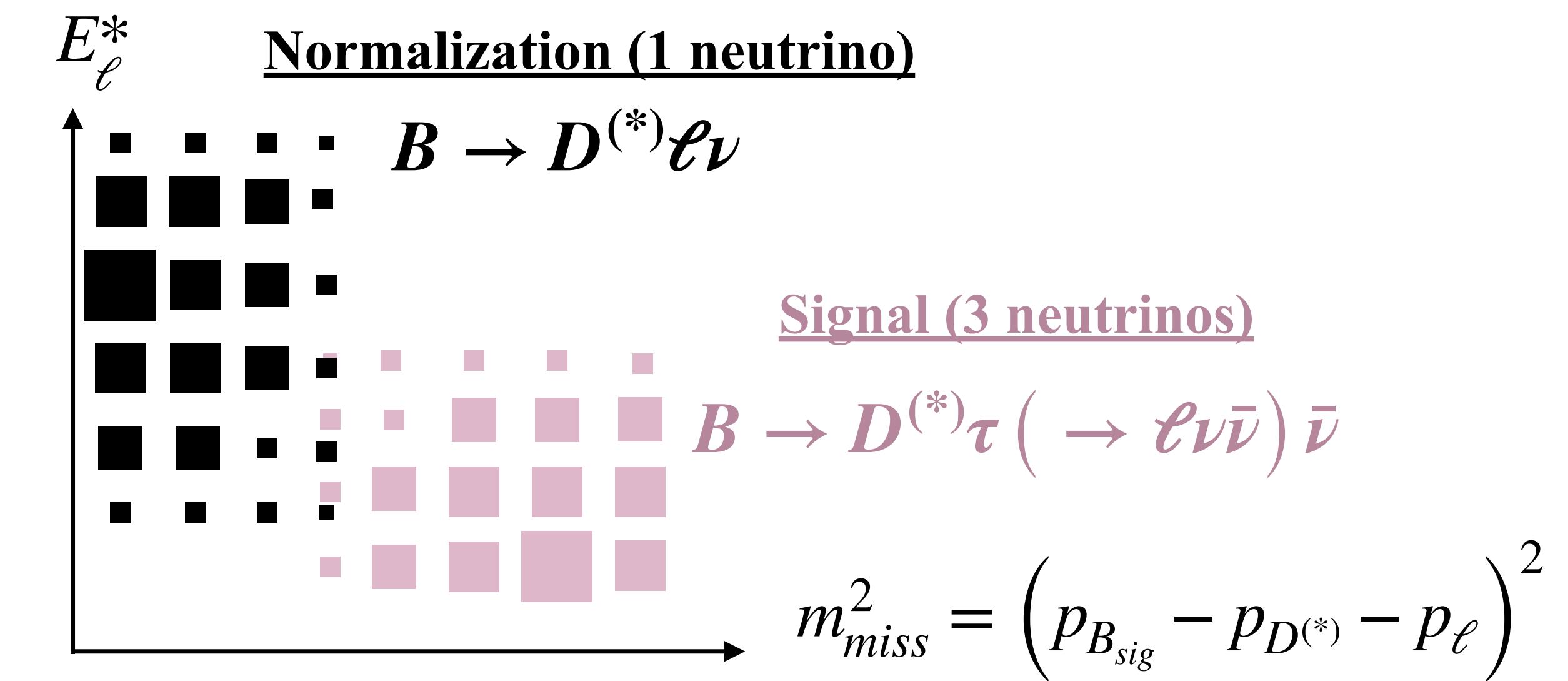
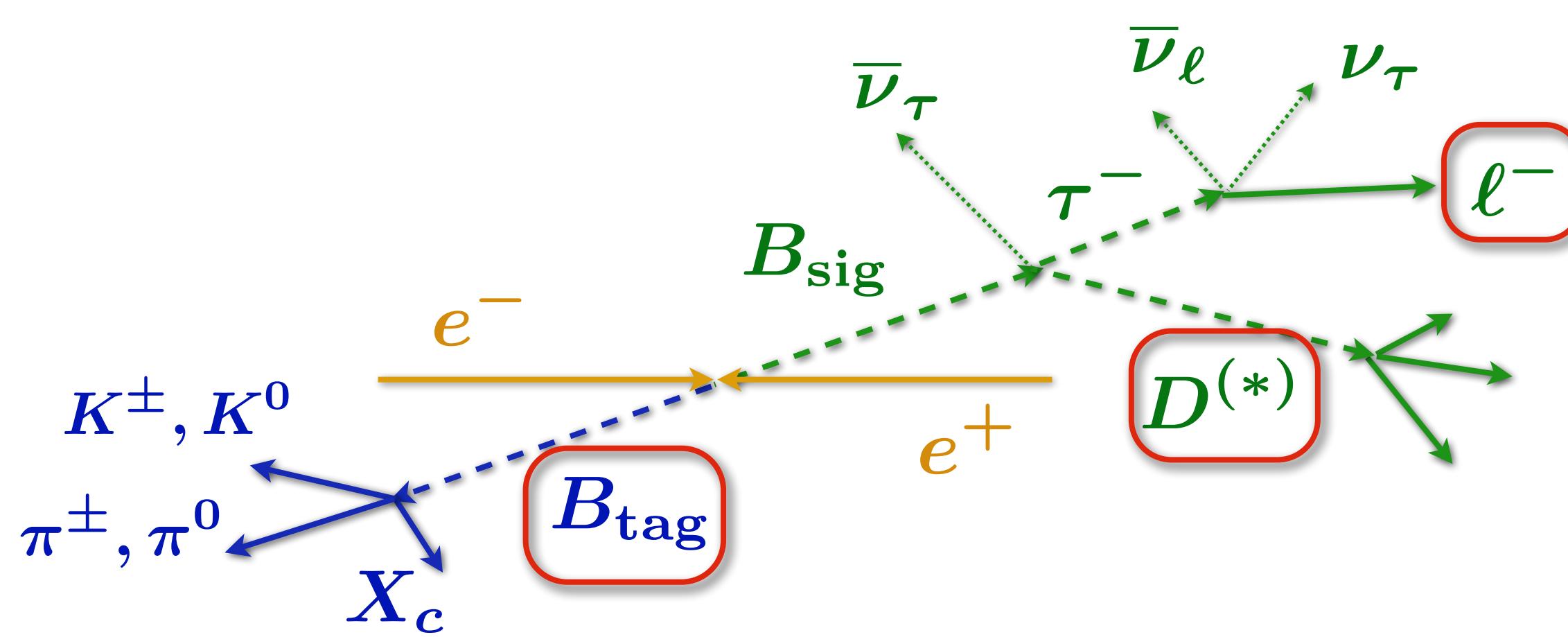
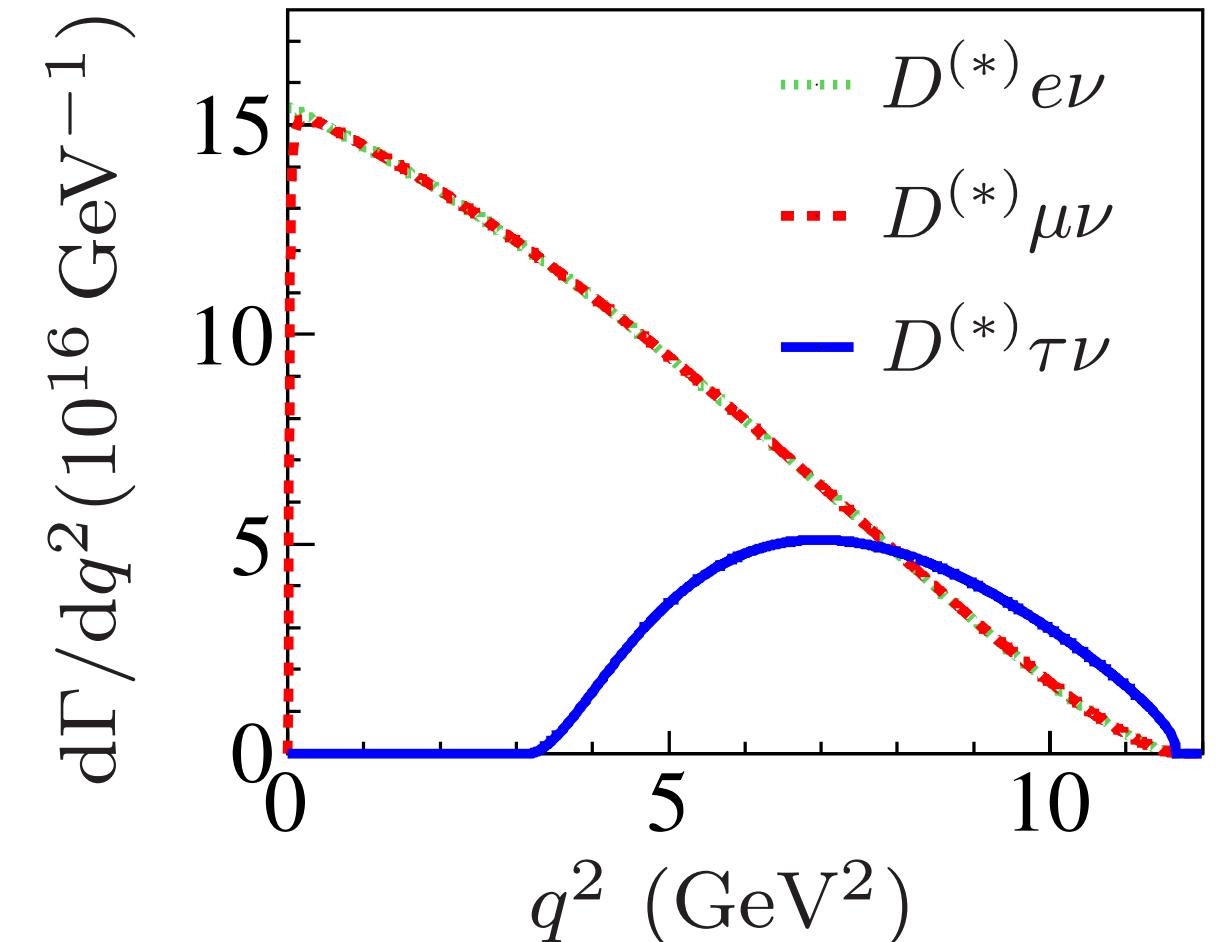
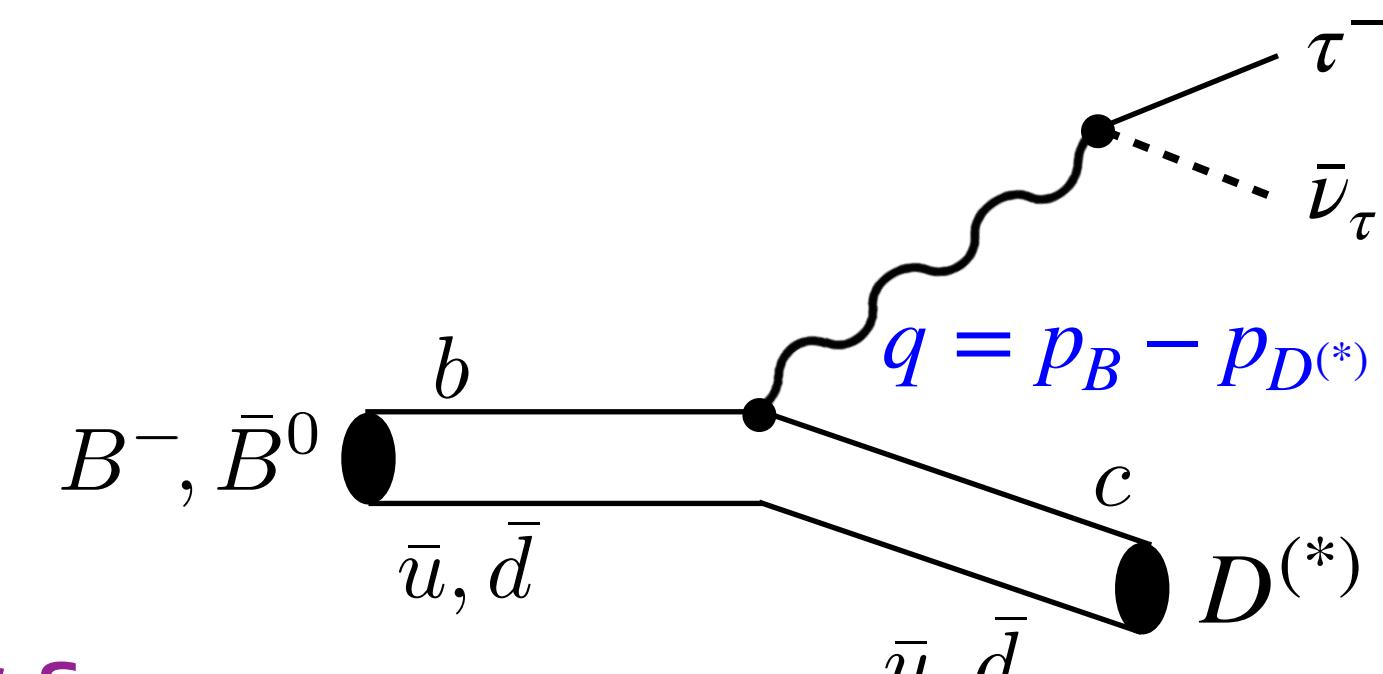


B tagging: $p_{B_{sig}} = p_{e^+e^-} - p_{B_{tag}}$

Hadronic: best $\sigma(p_B)$, $\epsilon_{had} \sim 0.2\text{-}0.4\%$

Semileptonic: worse $\sigma(p_B)$, $\epsilon_{sl} \sim 0.3\text{-}0.6\%$

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

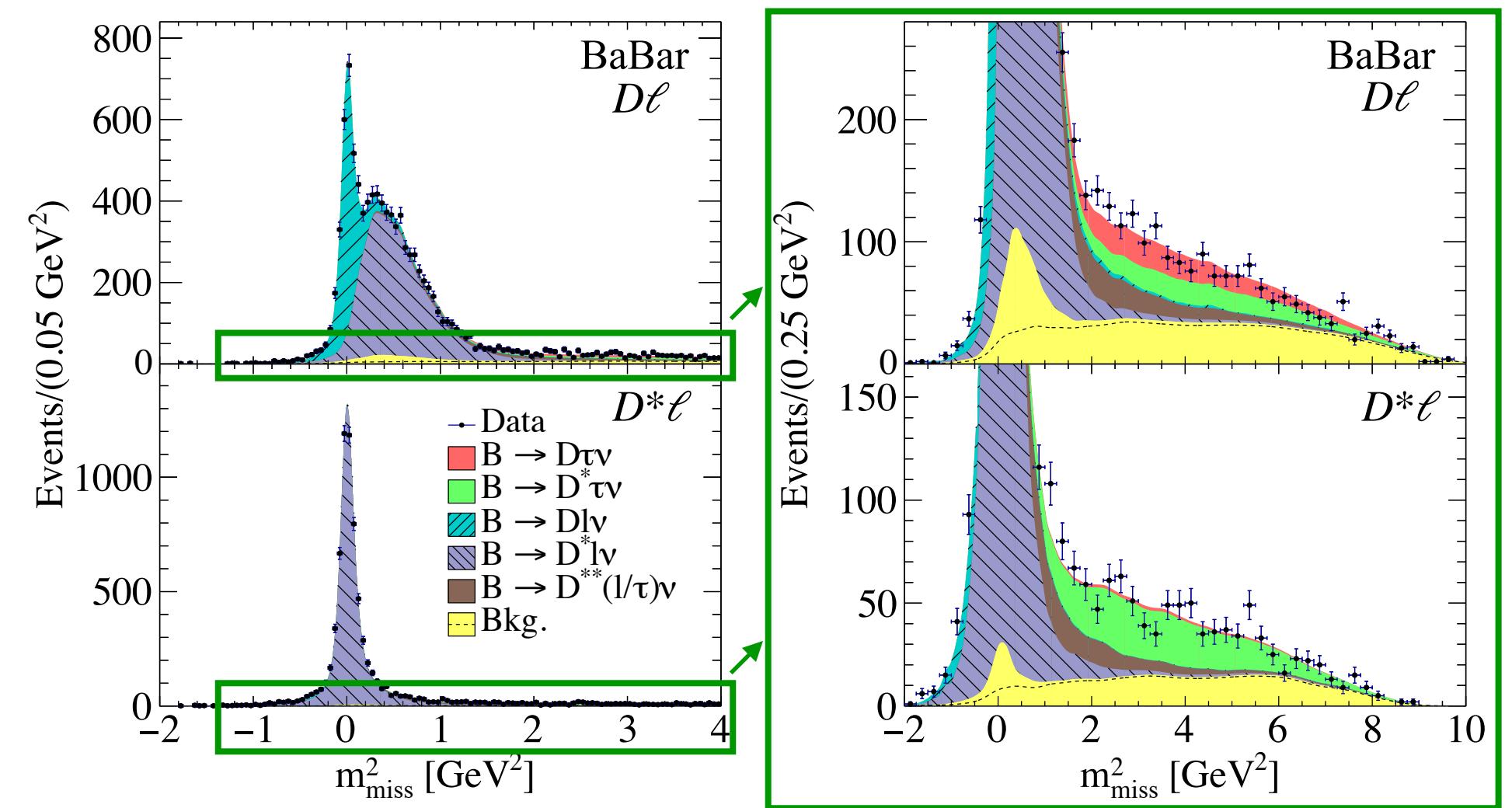


BaBar 2012 $\mathcal{R}(D^{(*)})$



~ Hadronic B_{tag} ,
leptonic τ

Phys. Rev. Lett. **109**, 101802 (2012)
Phys. Rev. D **88**, 072012 (2013)



BABAR

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

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

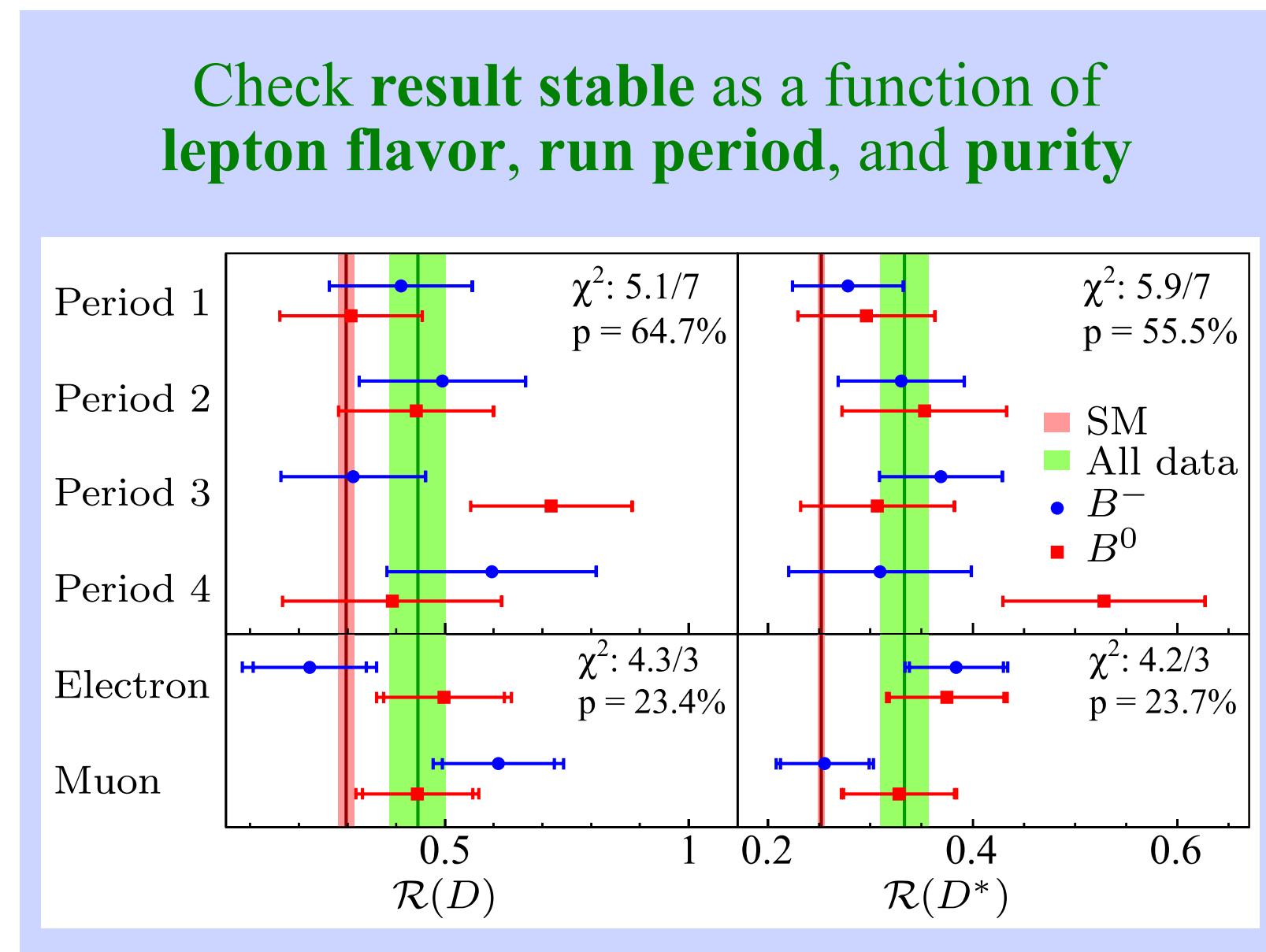
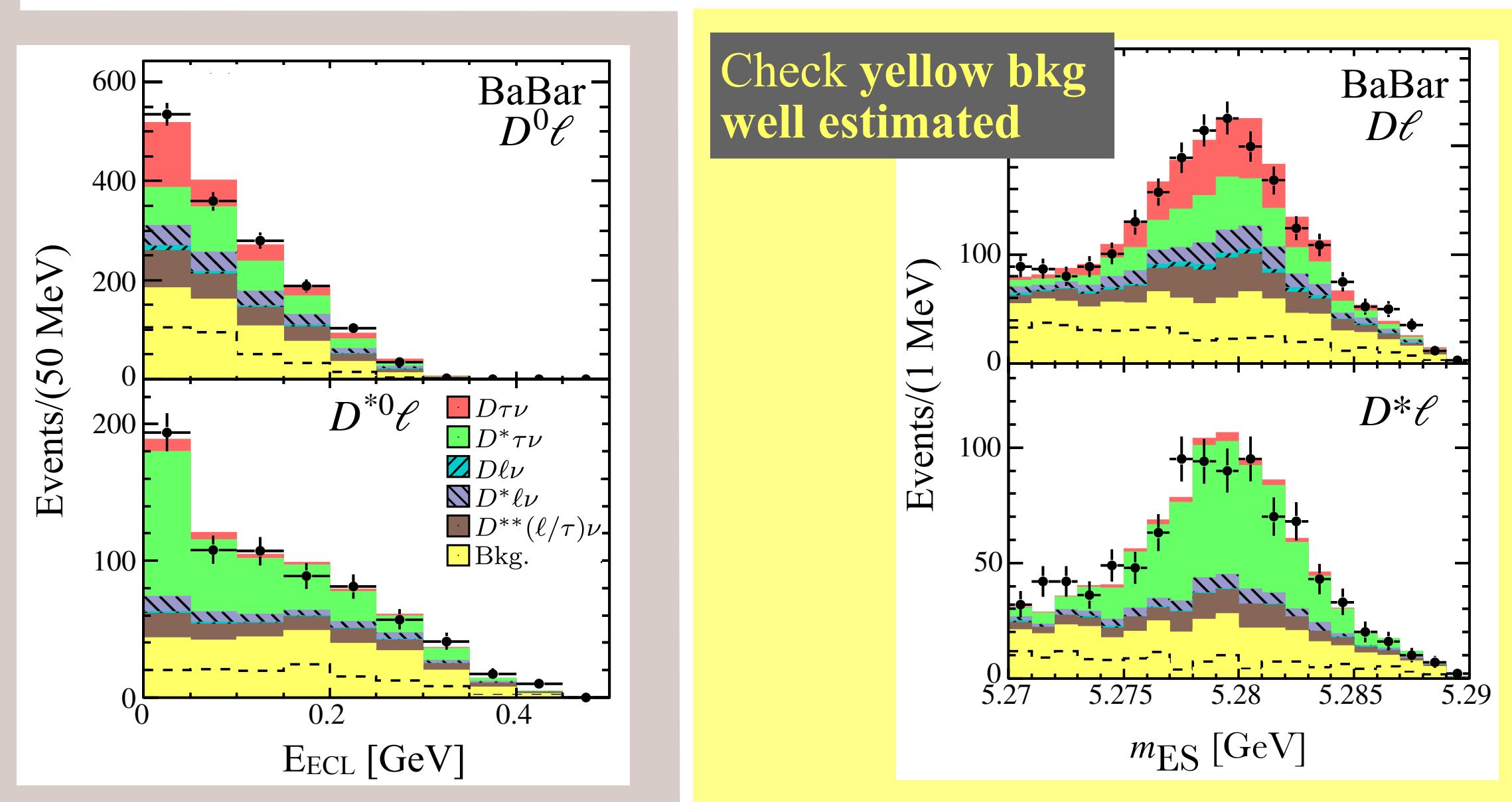
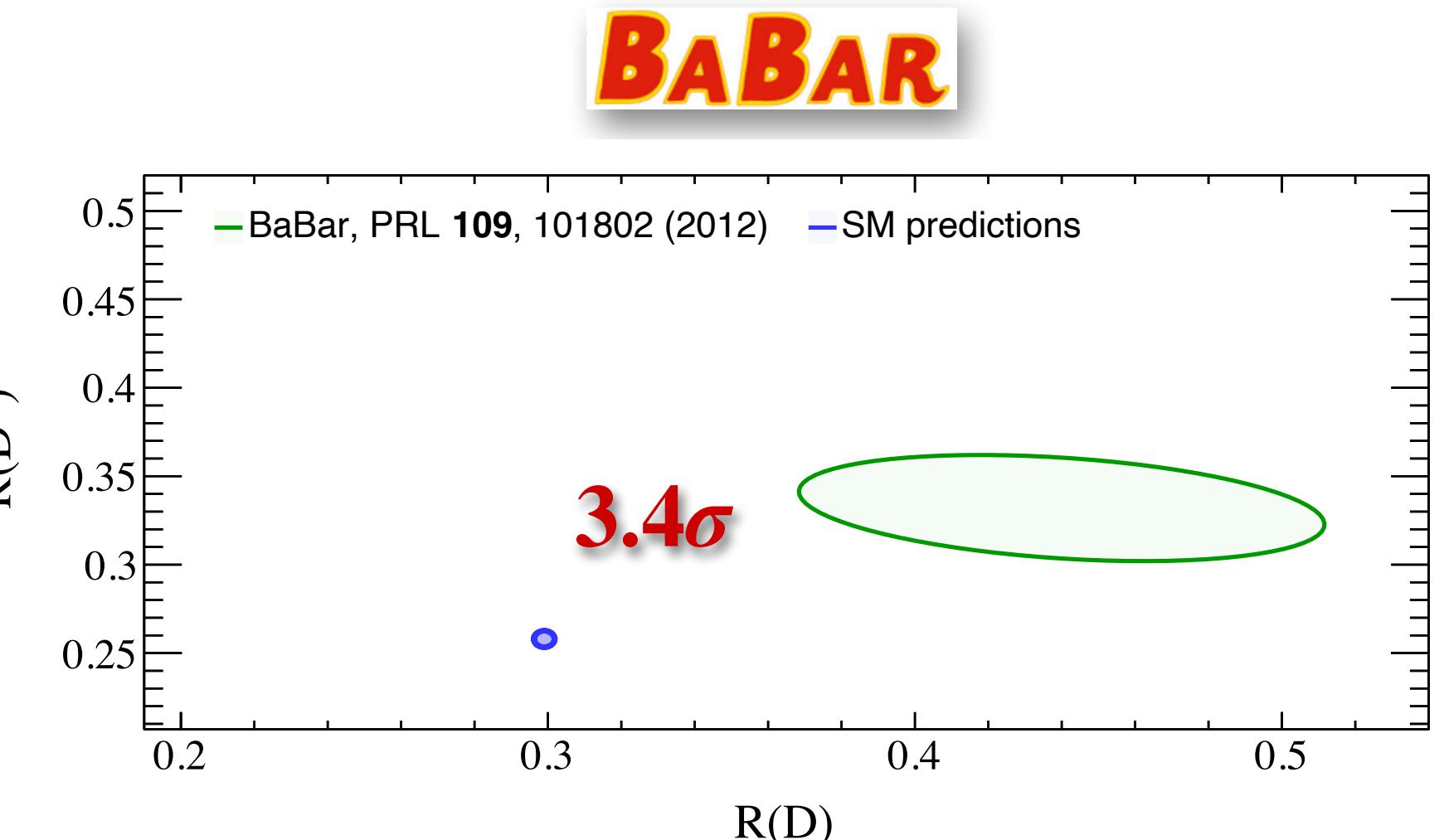
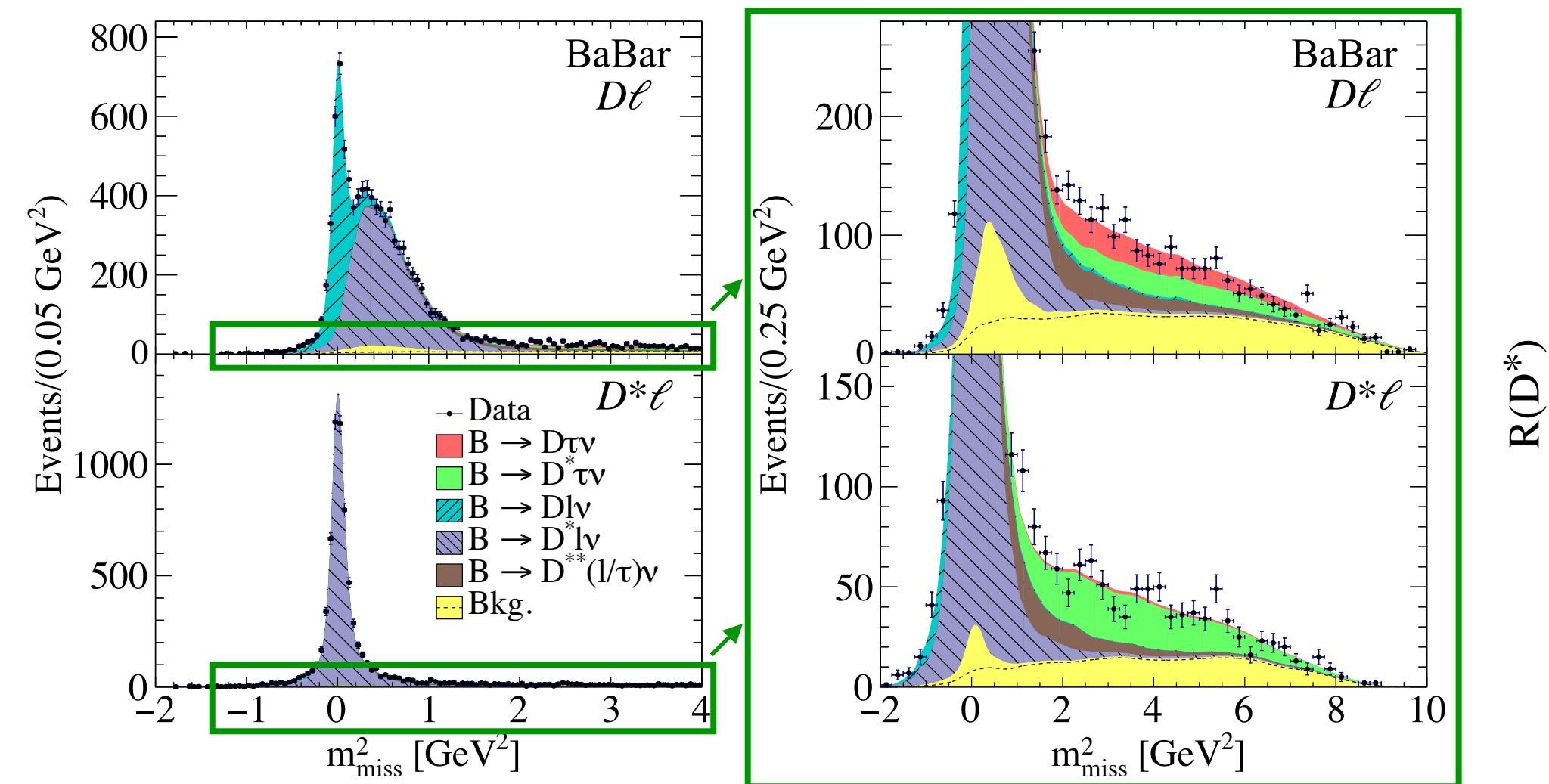
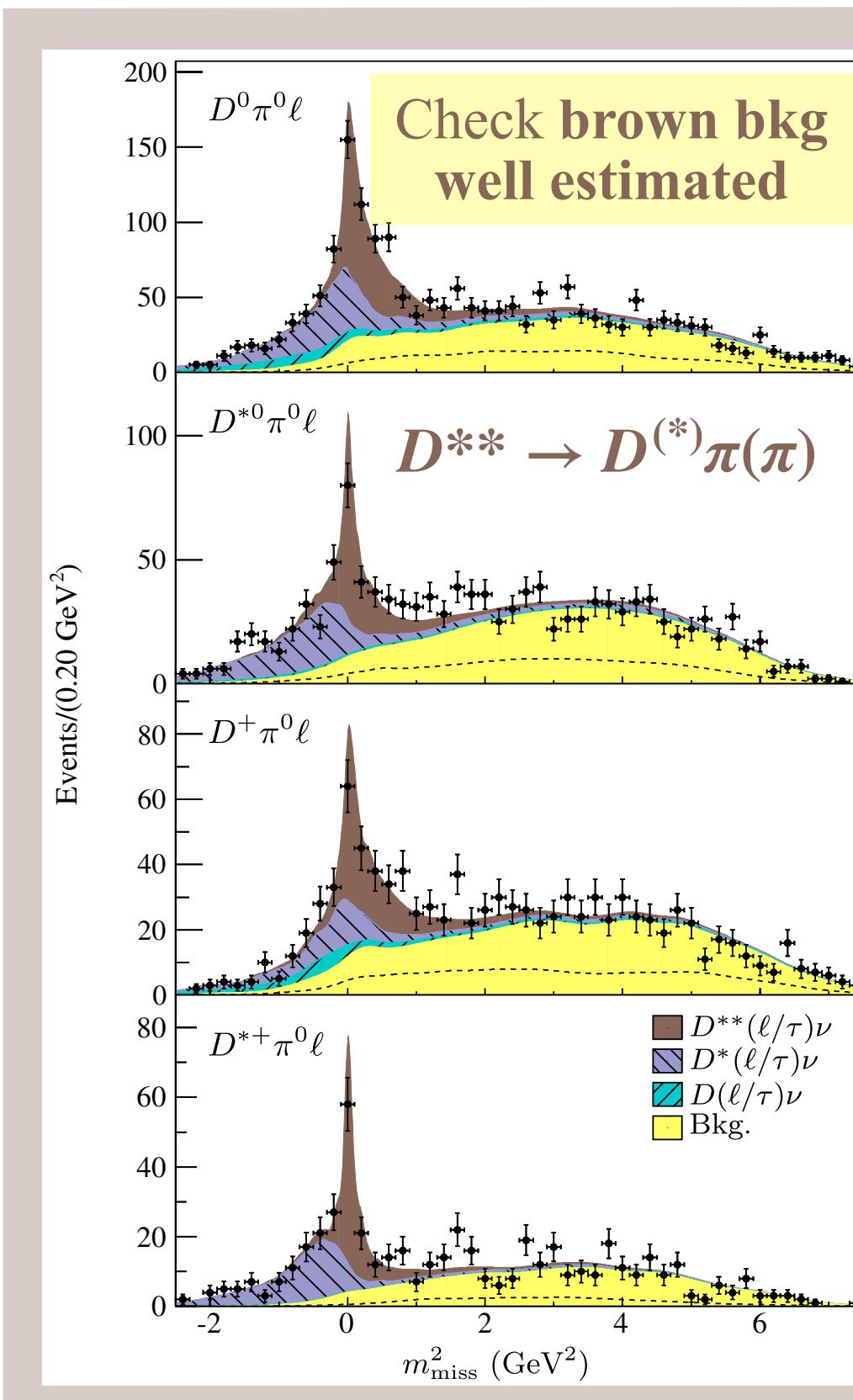
BaBar 2012 $\mathcal{R}(D^{(*)})$



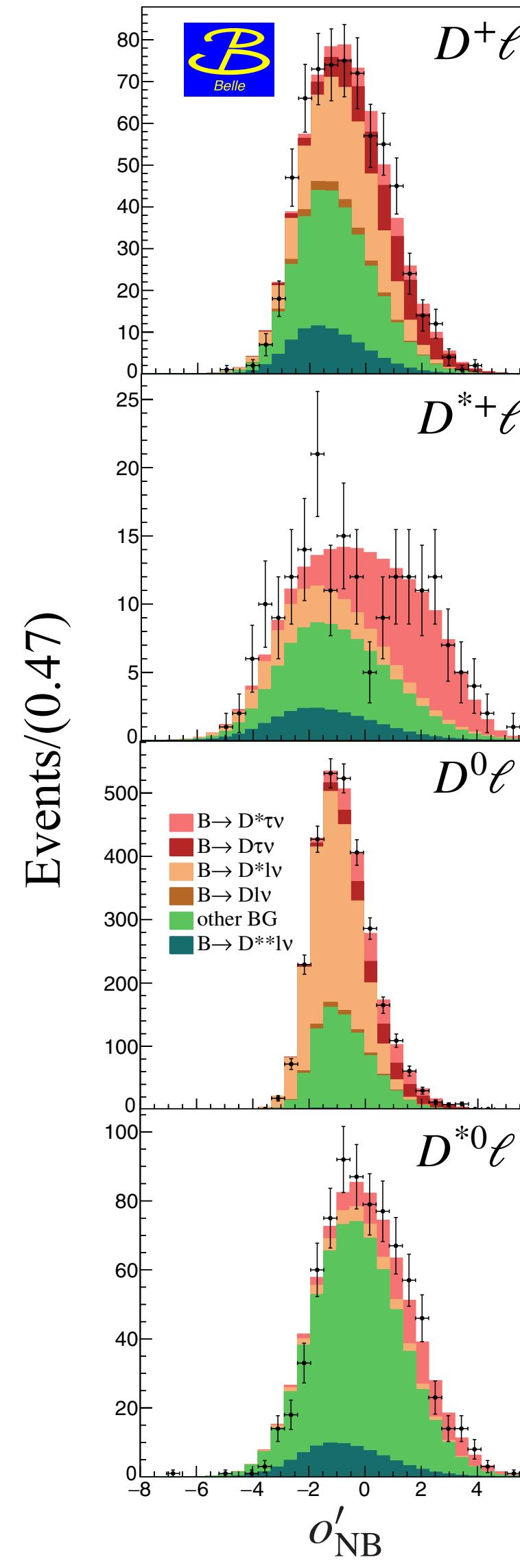
~ Hadronic B_{tag} ,
leptonic τ

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

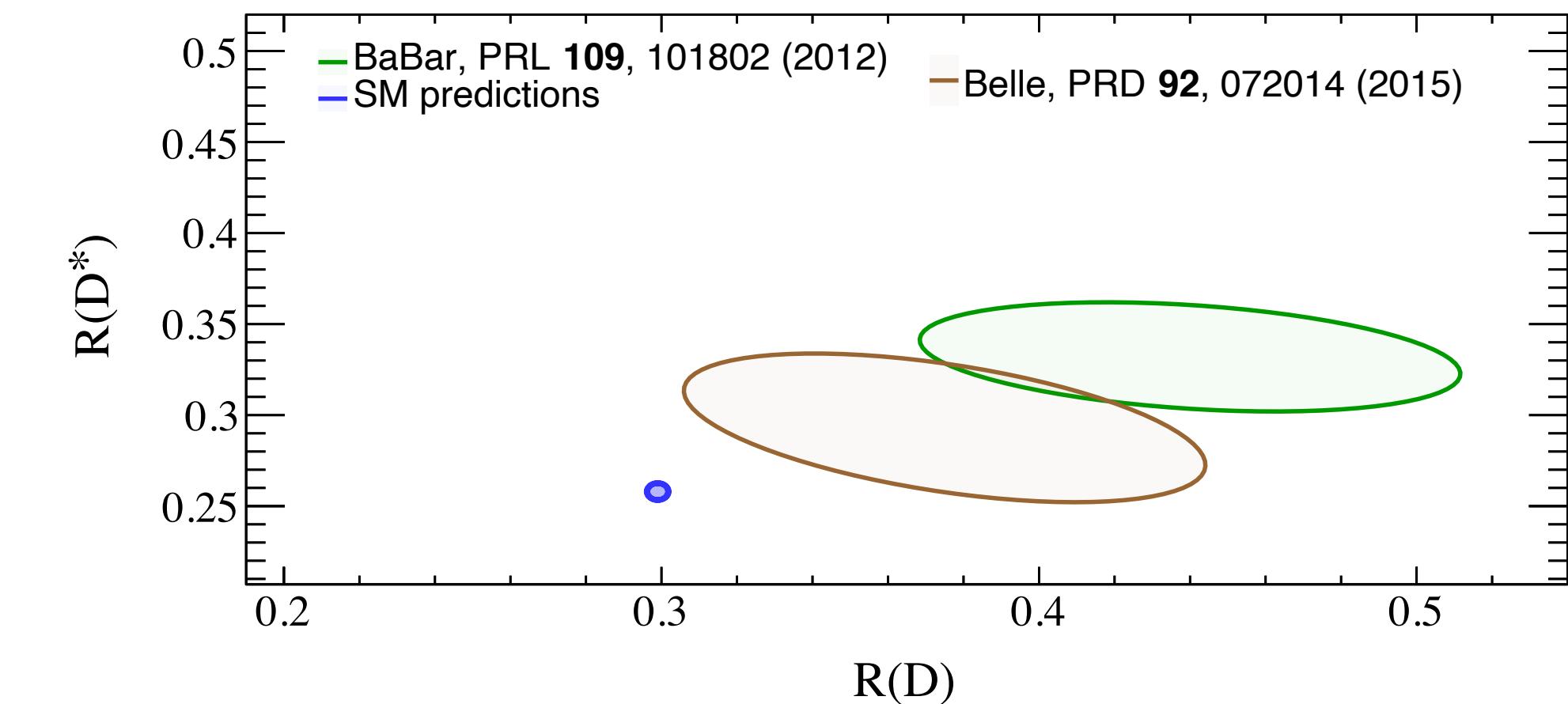
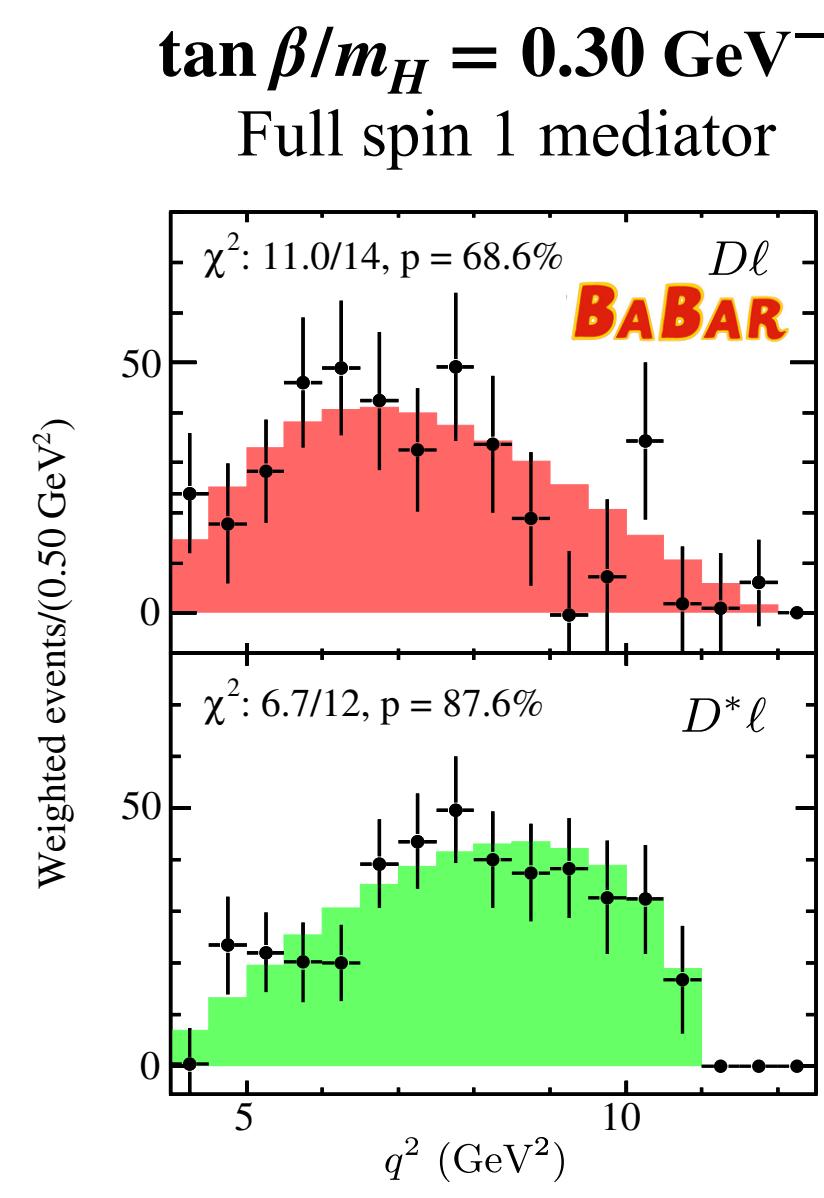
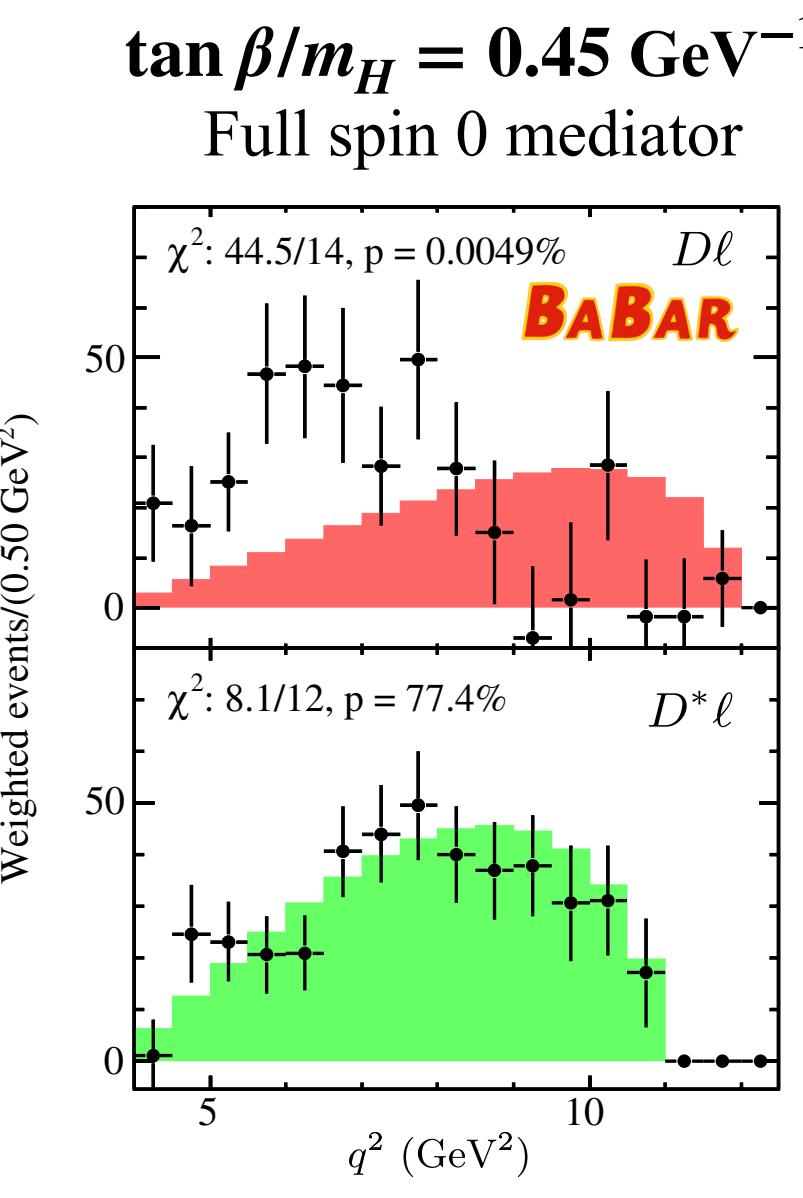
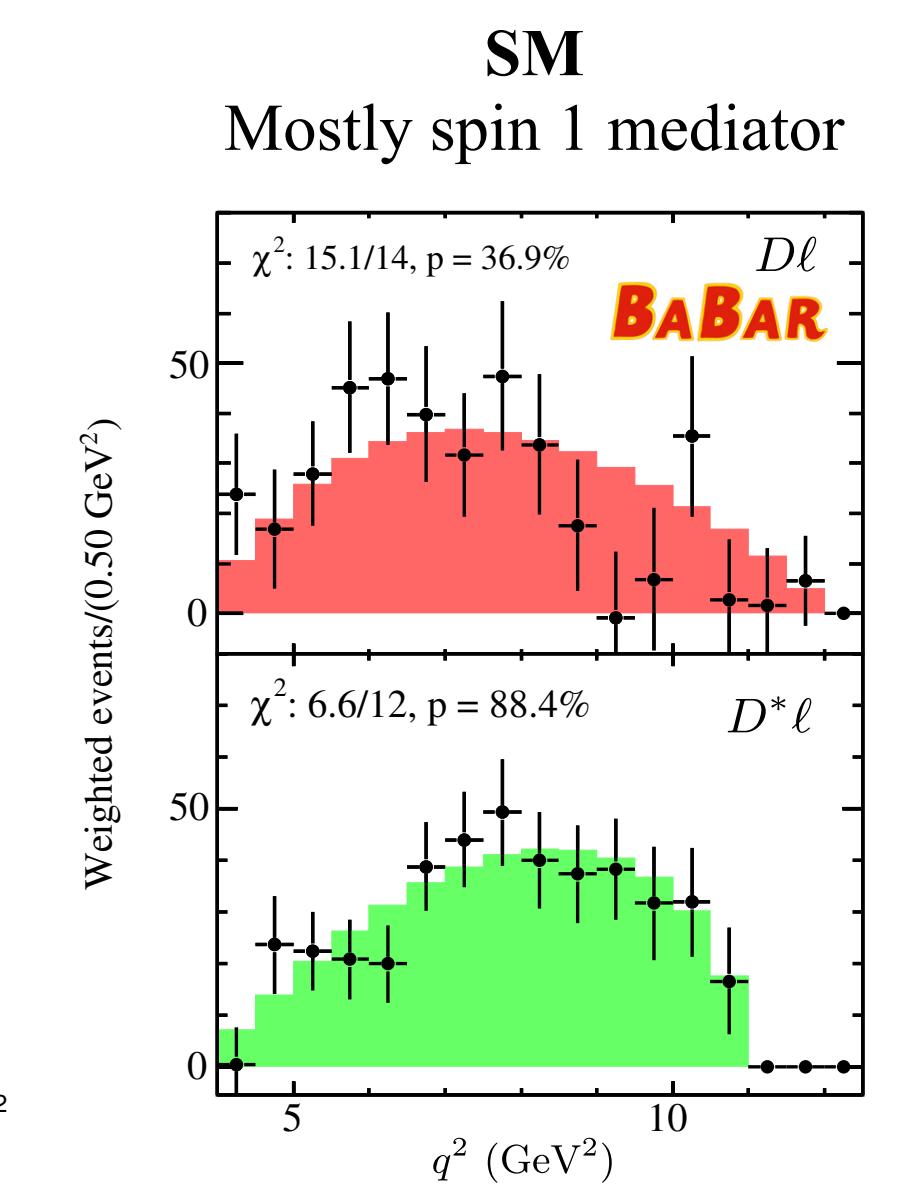
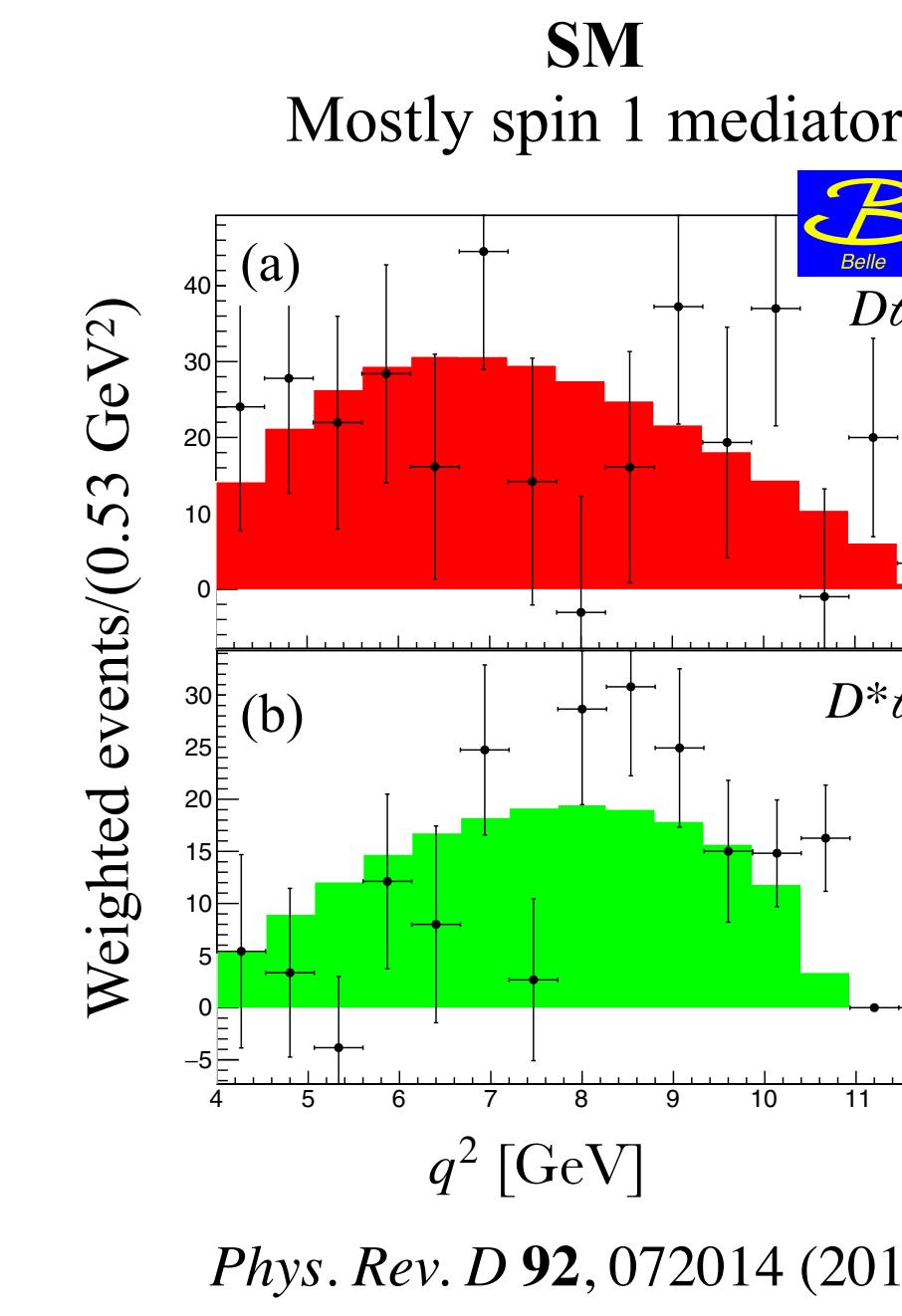
Phys. Rev. D **88**, 072012 (2013)



Belle 2015 $\mathcal{R}(D^{(*)})$, q^2 distributions



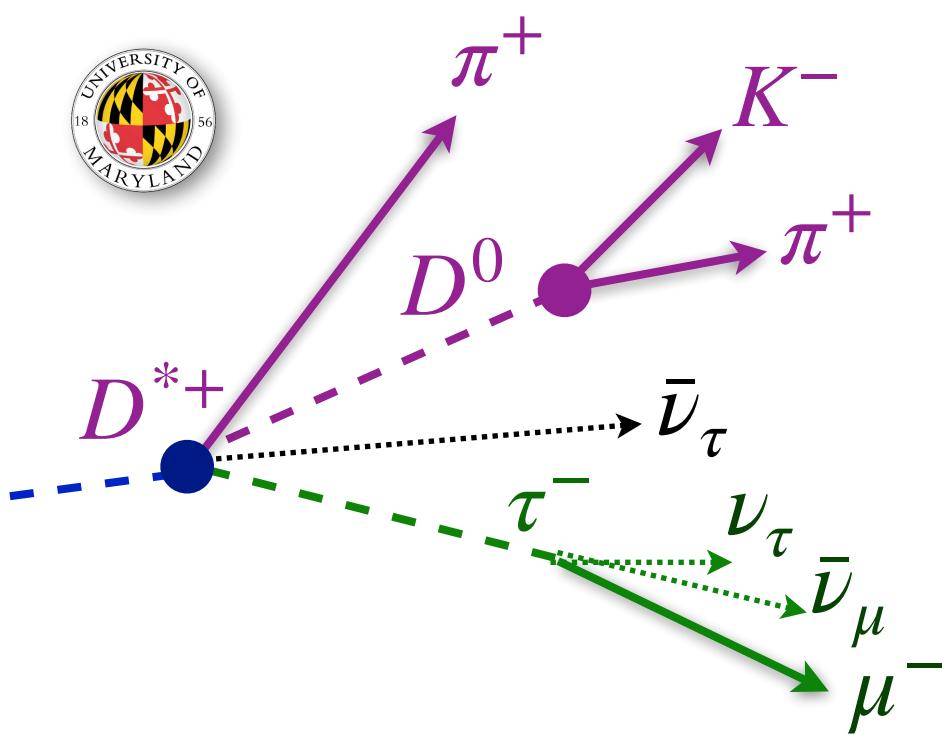
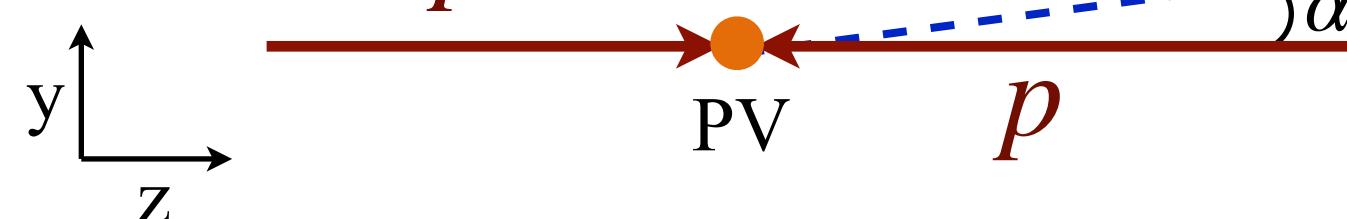
- ~ Similar strategy to BaBar
 - Hadronic B_{tag} , leptonic τ
- ~ Also excess, consistent with BaBar
- ~ q^2 distributions rule out 2HDM



p_B reconstruction at LHCb



Leptonic- τ : Rest Frame Approximation (RFA)



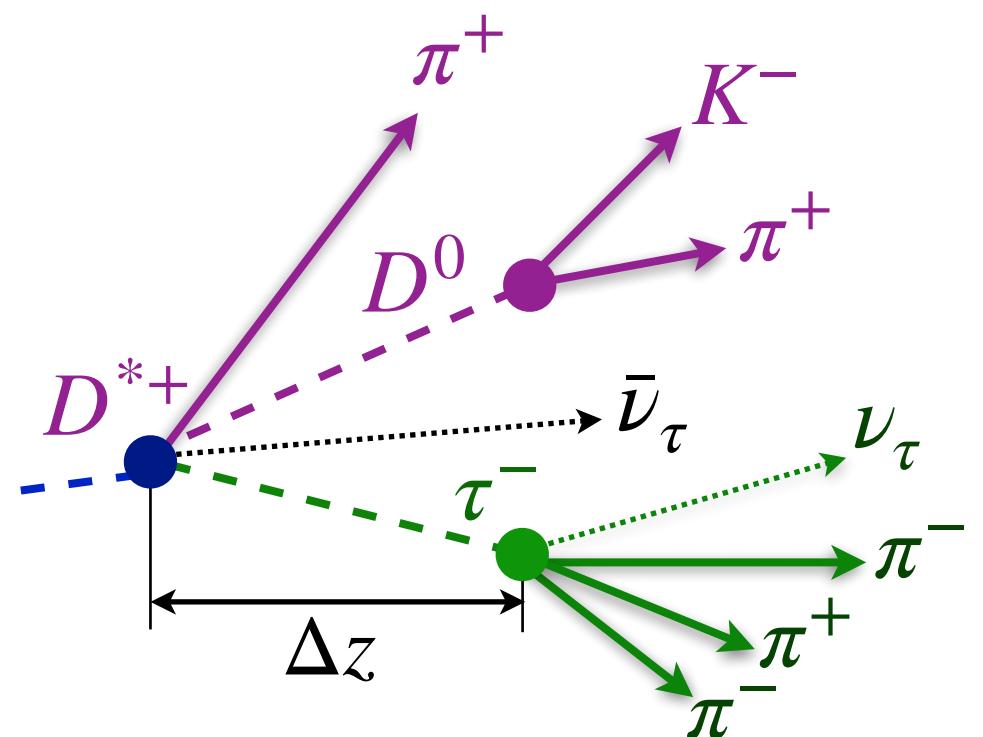
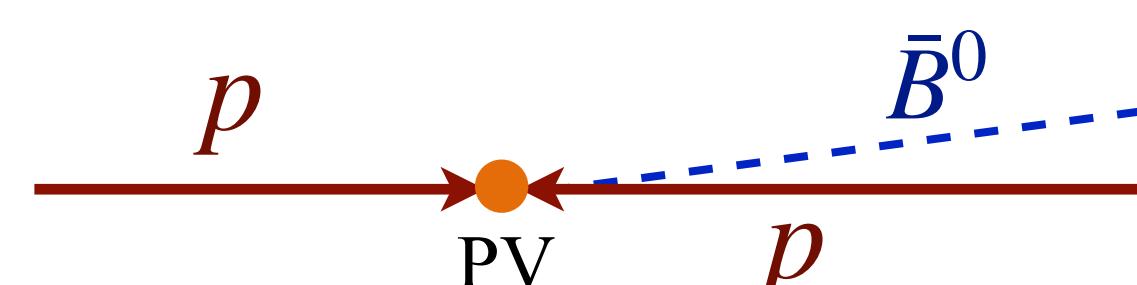
Assume proper **velocity** of **B** and **reco particles** (μD^*) **along z** is the **same** to find $p_z(B)$

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

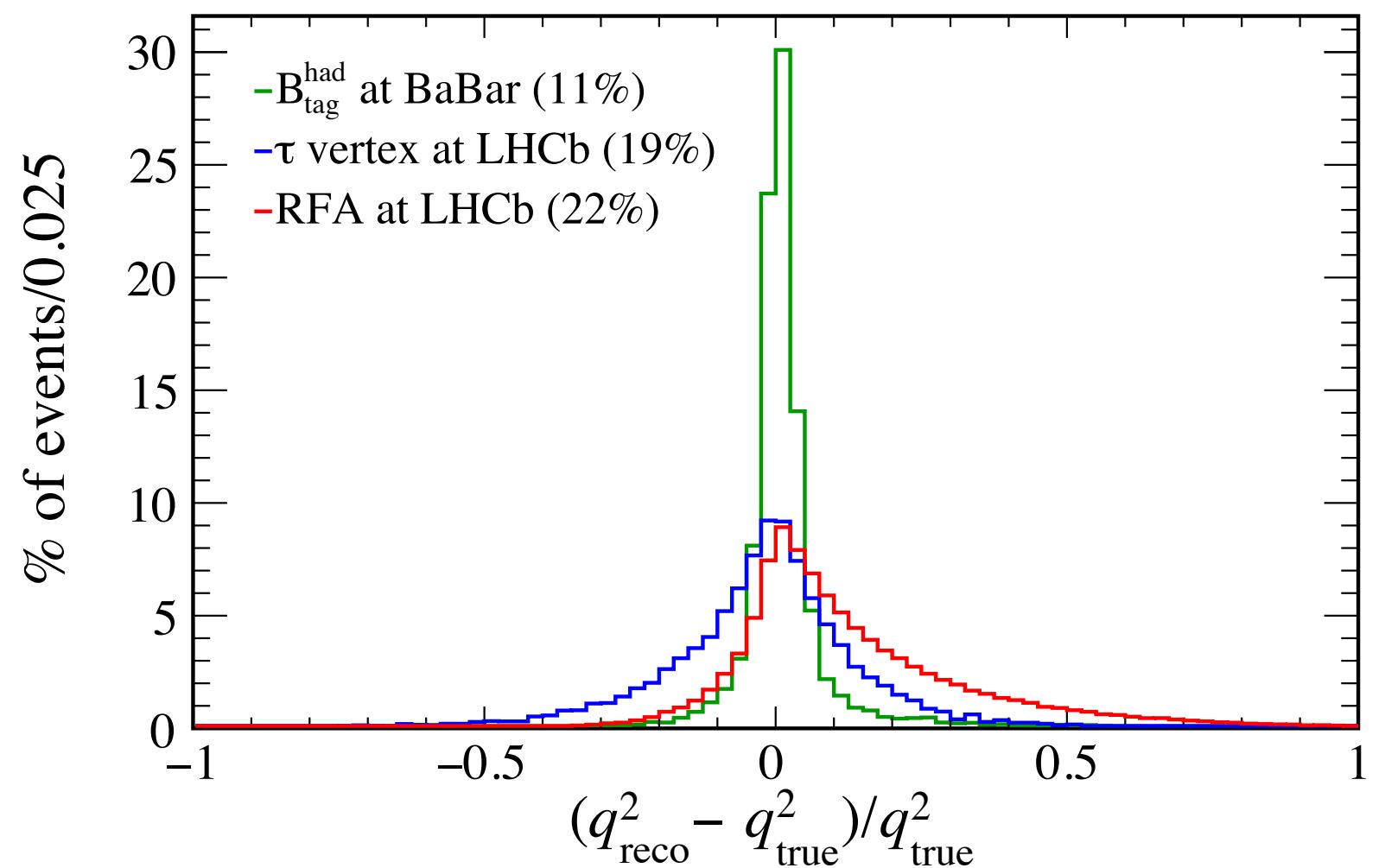
Find **B vertex** assuming muon comes from it,
scale $p_z(B)$ with angle α

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

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

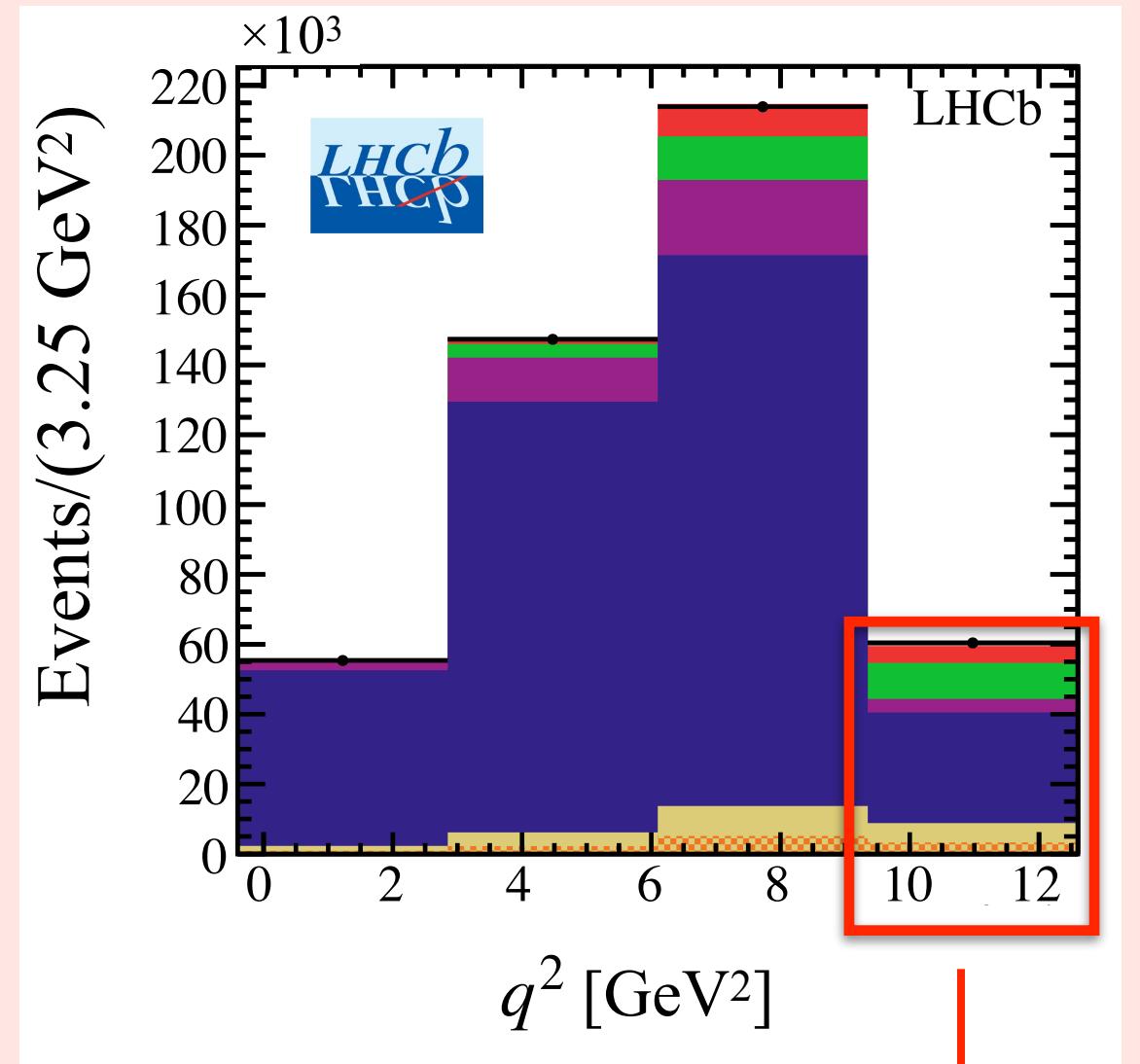


Use τ direction between B and τ vertices,
solve $(p_\tau - p_{\pi\pi\pi})^2 = 0$, then solve
 $(p_B - p_\tau - p_{D^*})^2 = 2$



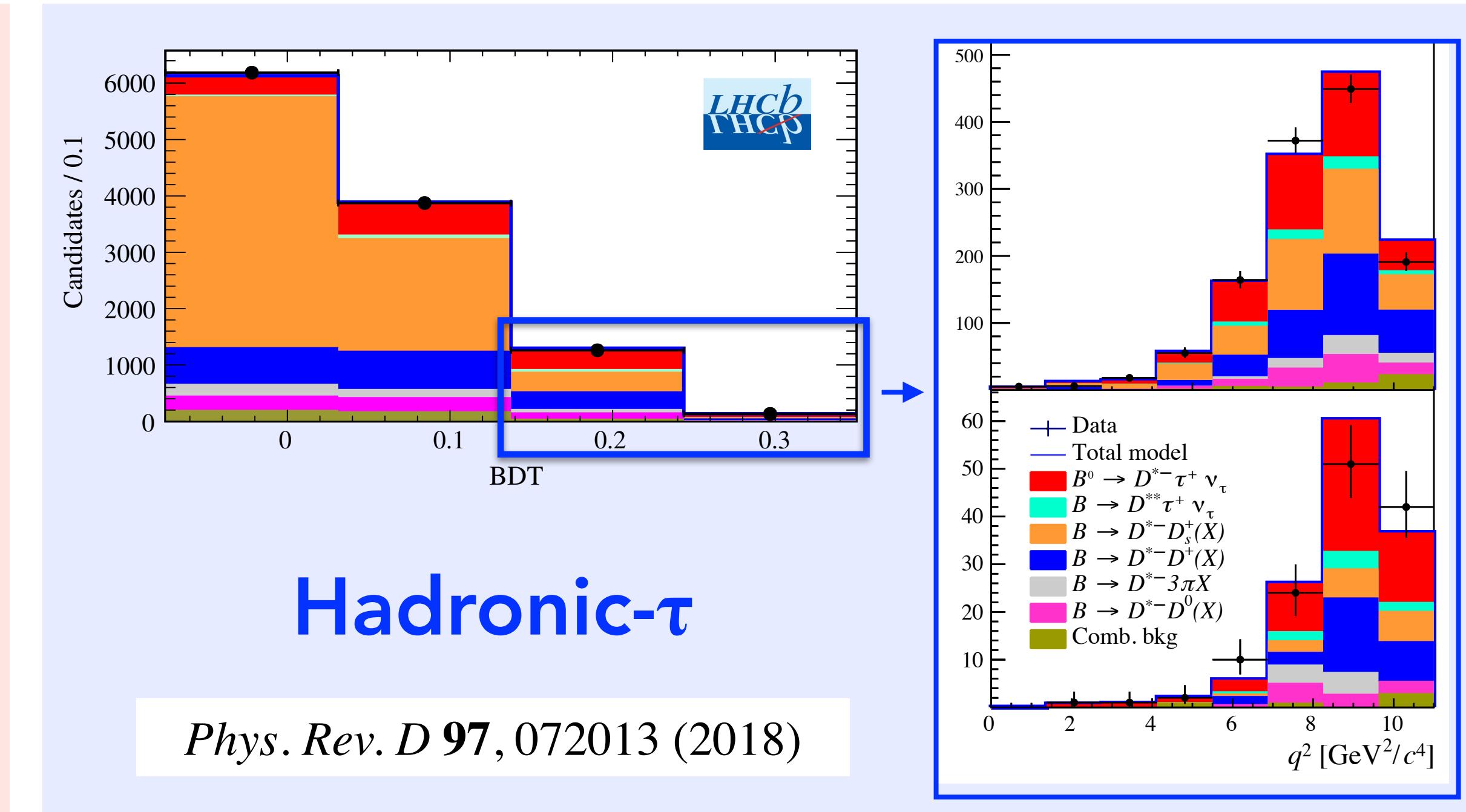
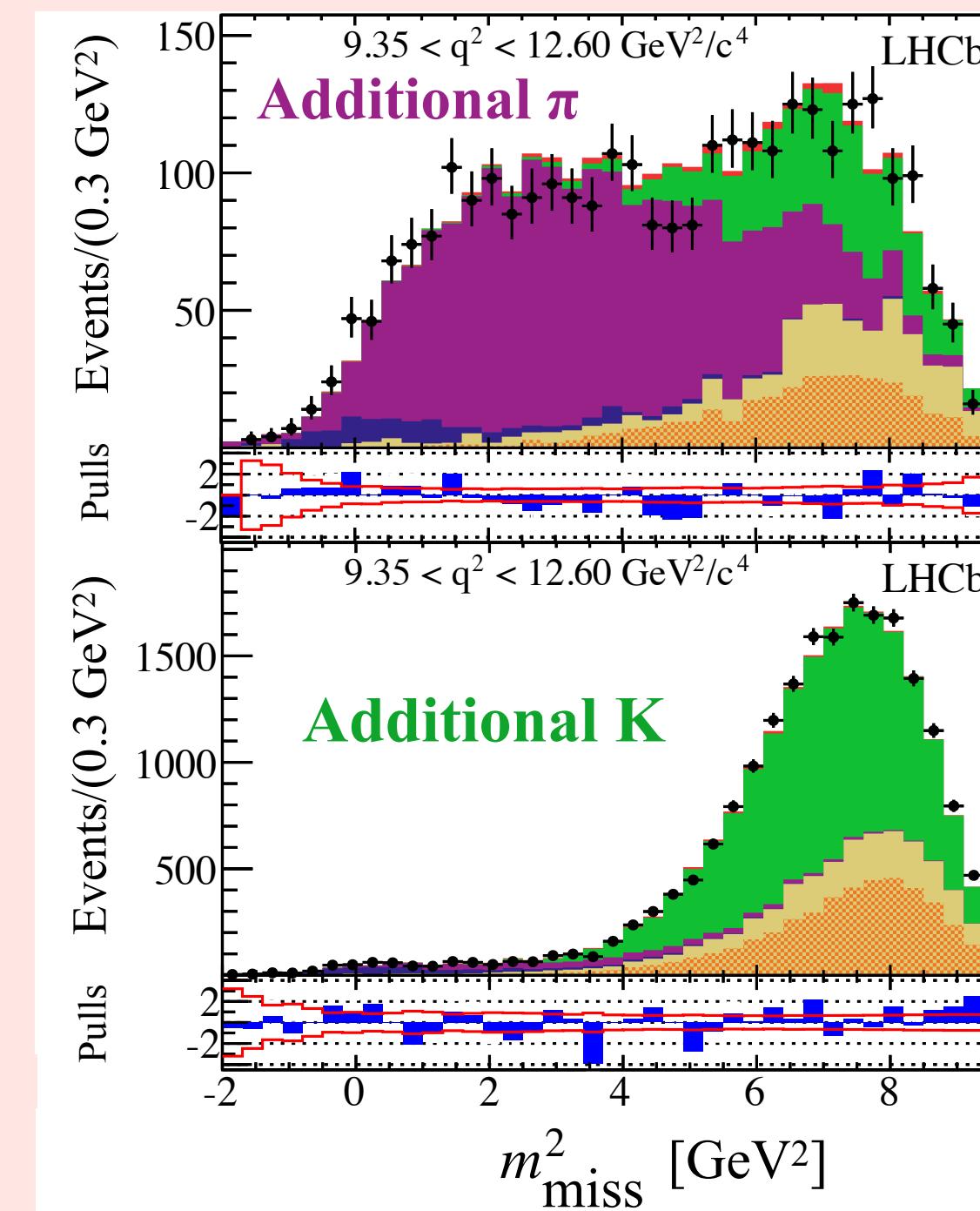
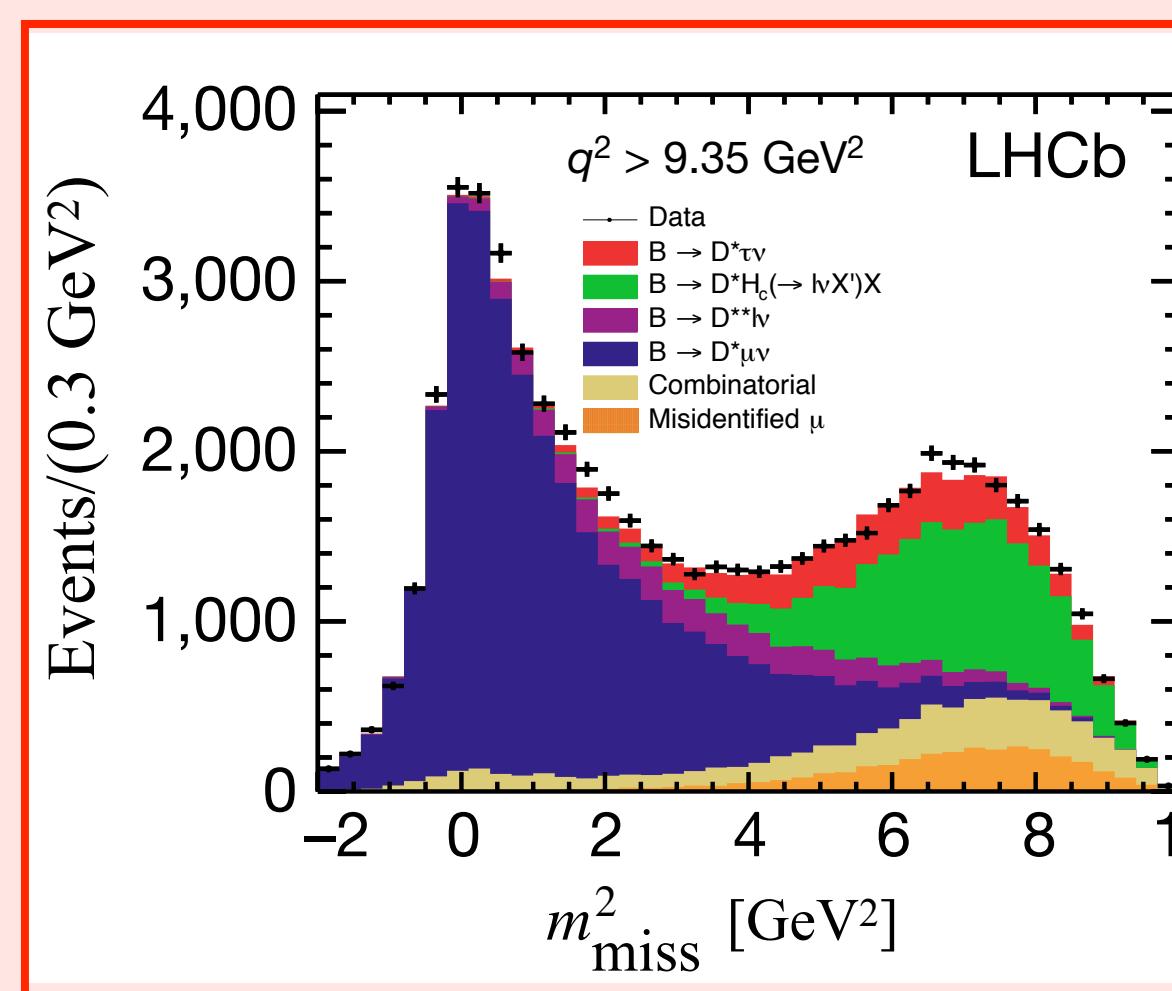
Bernlochner, MFS, Robinson
Wormser, arXiv:2101.08326

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



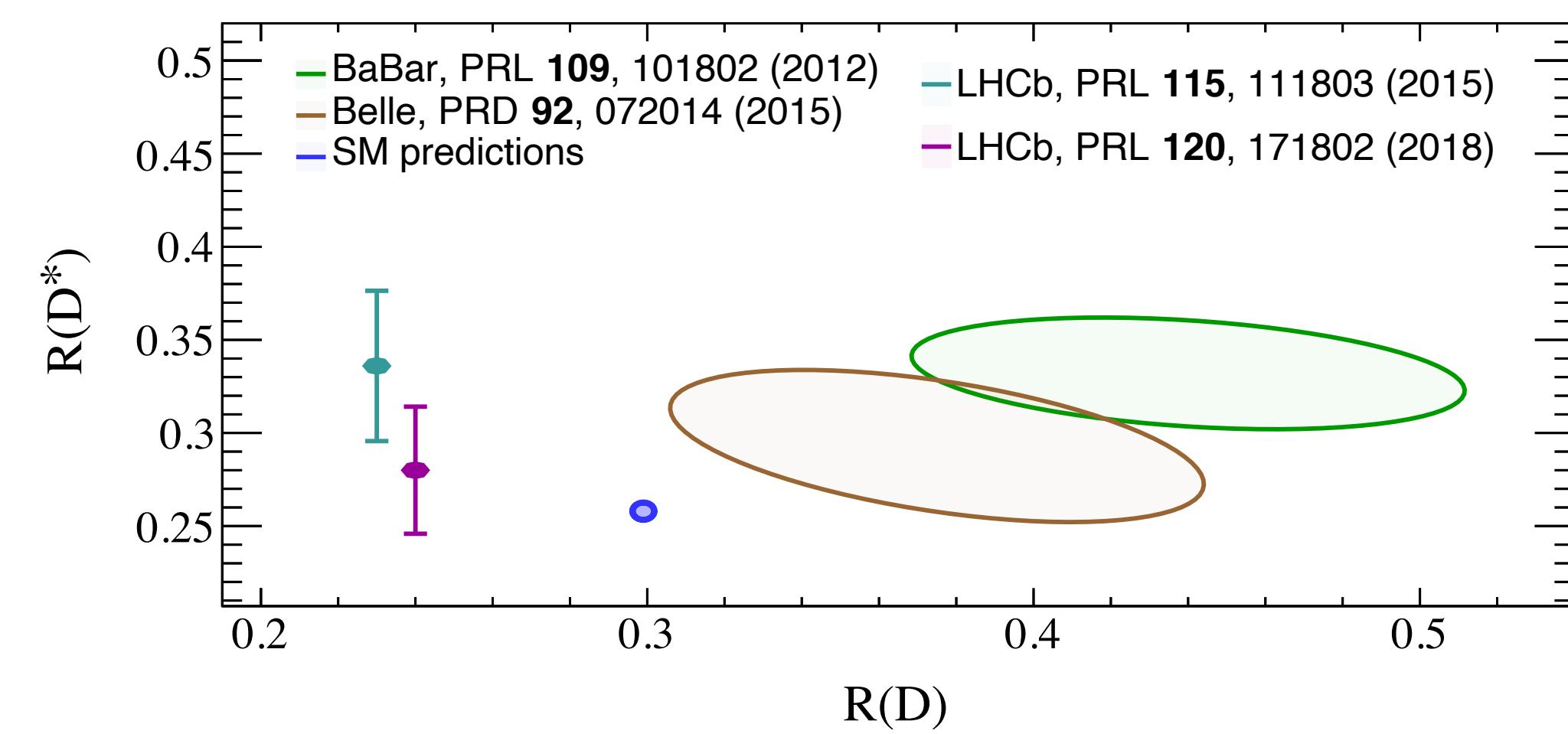
Leptonic- τ

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



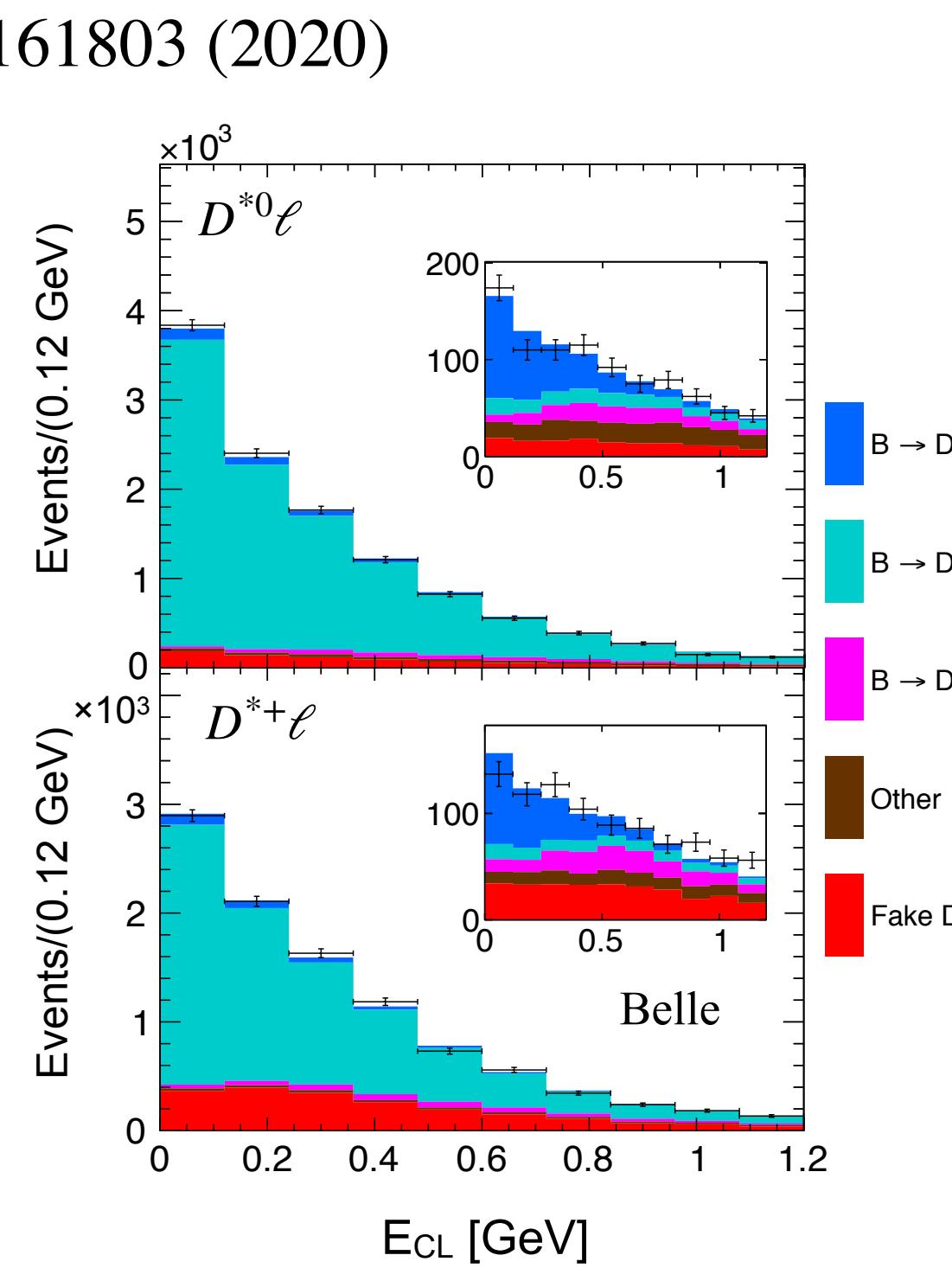
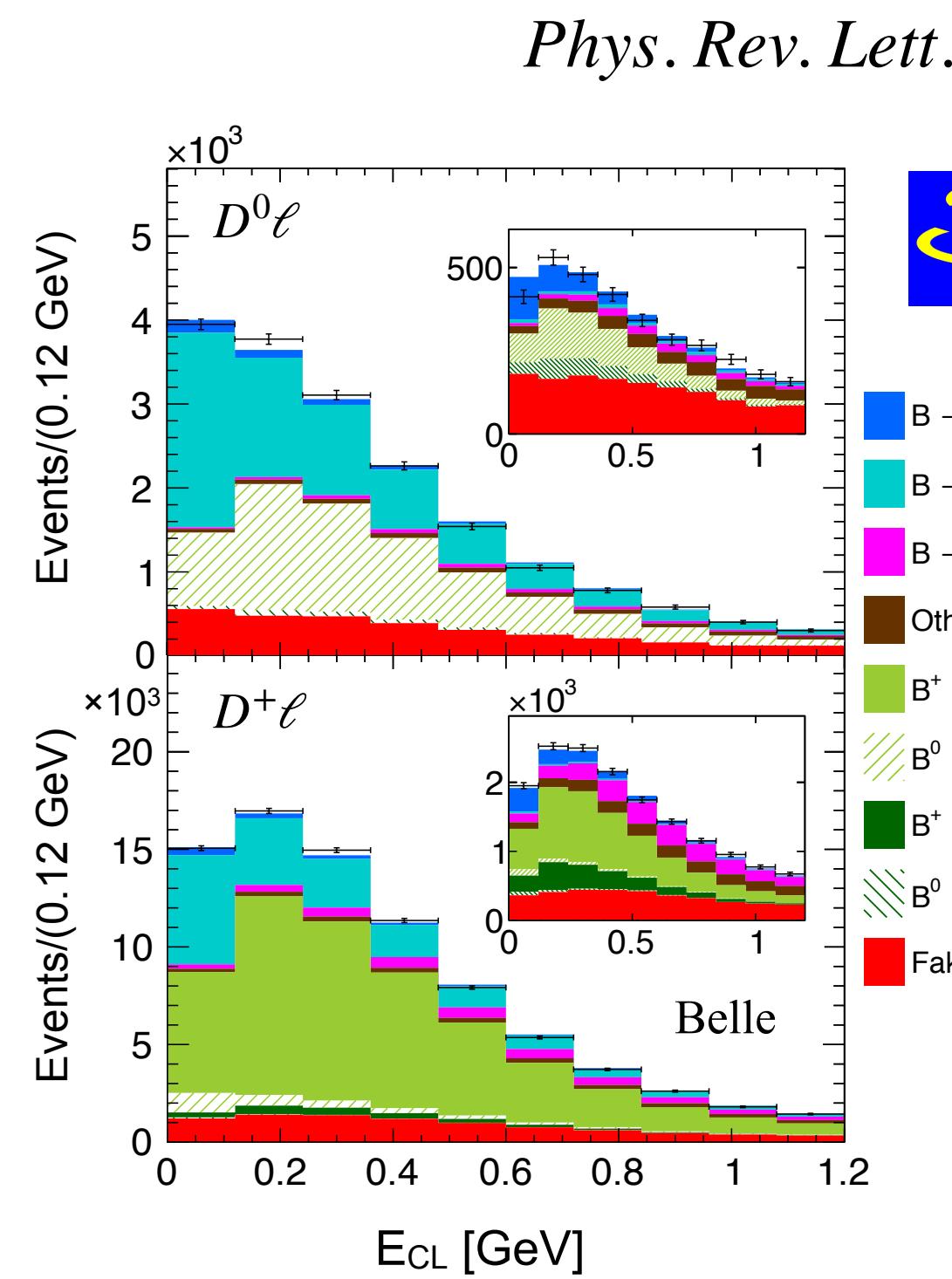
Hadronic- τ

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

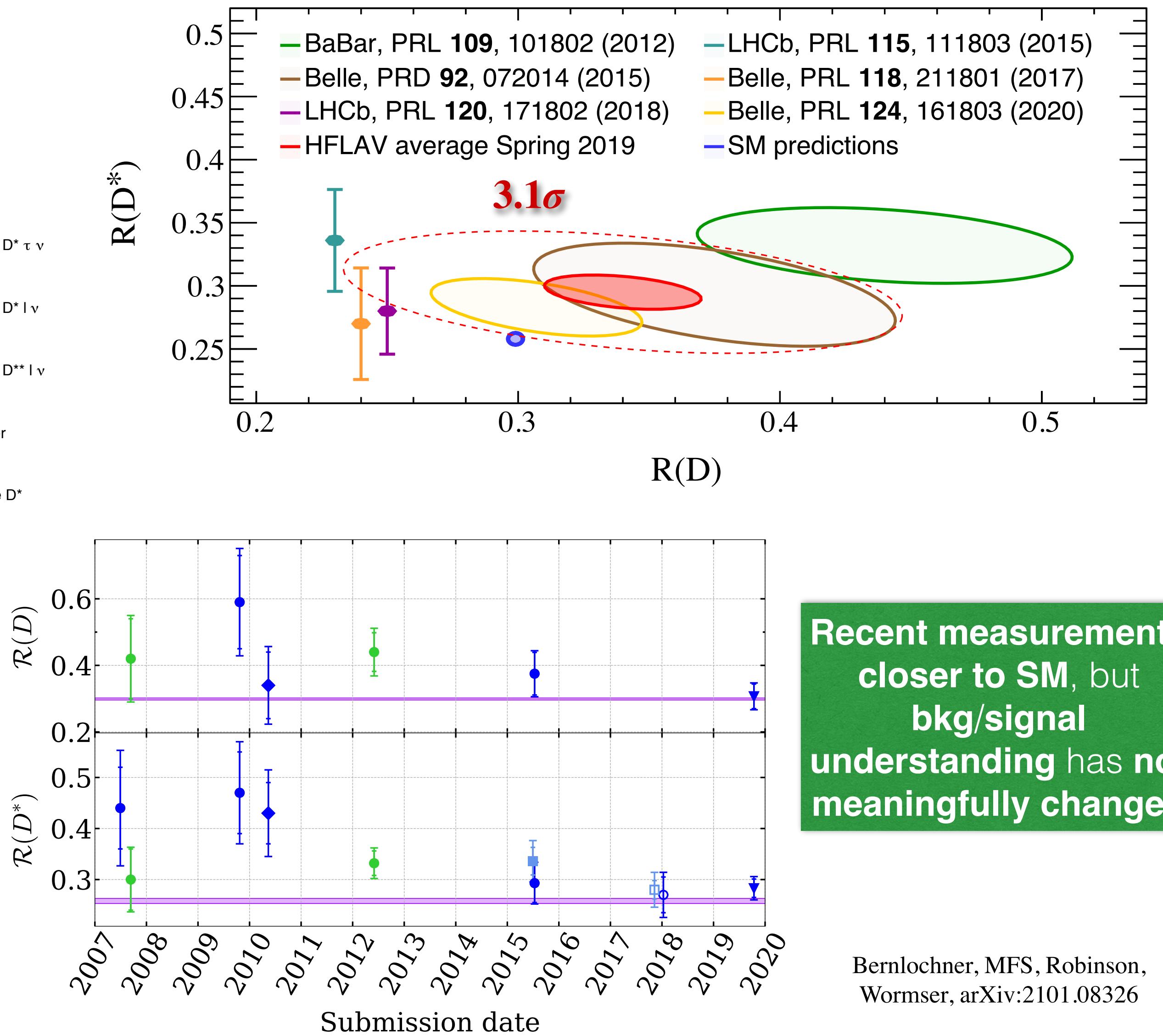




Belle 2019 $\mathcal{R}(D^{(*)})$, current status



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



Bernlochner, MFS, Robinson,
Wormser, arXiv:2101.08326

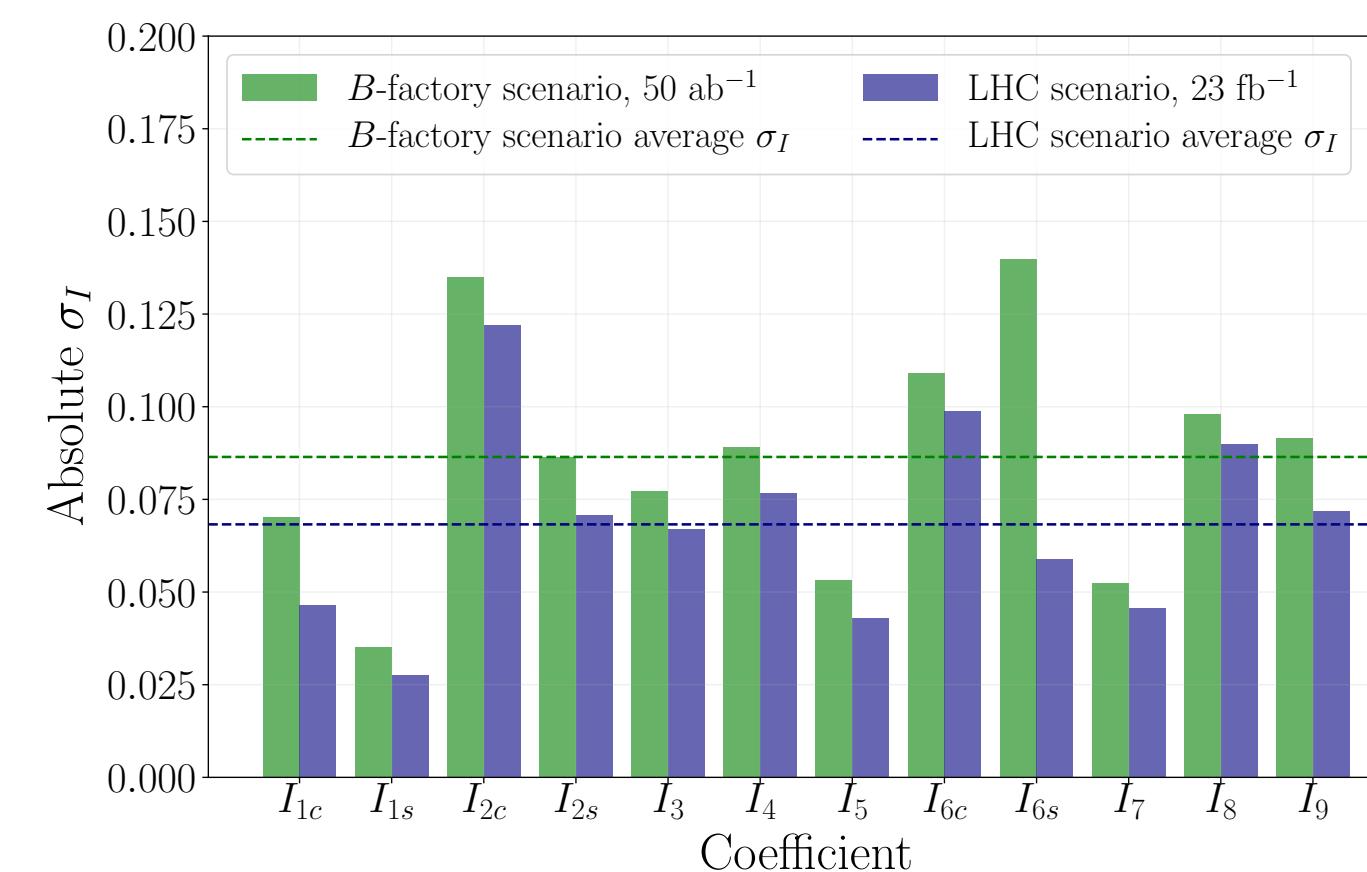
Beyond $\mathcal{R}(D^{(*)})$



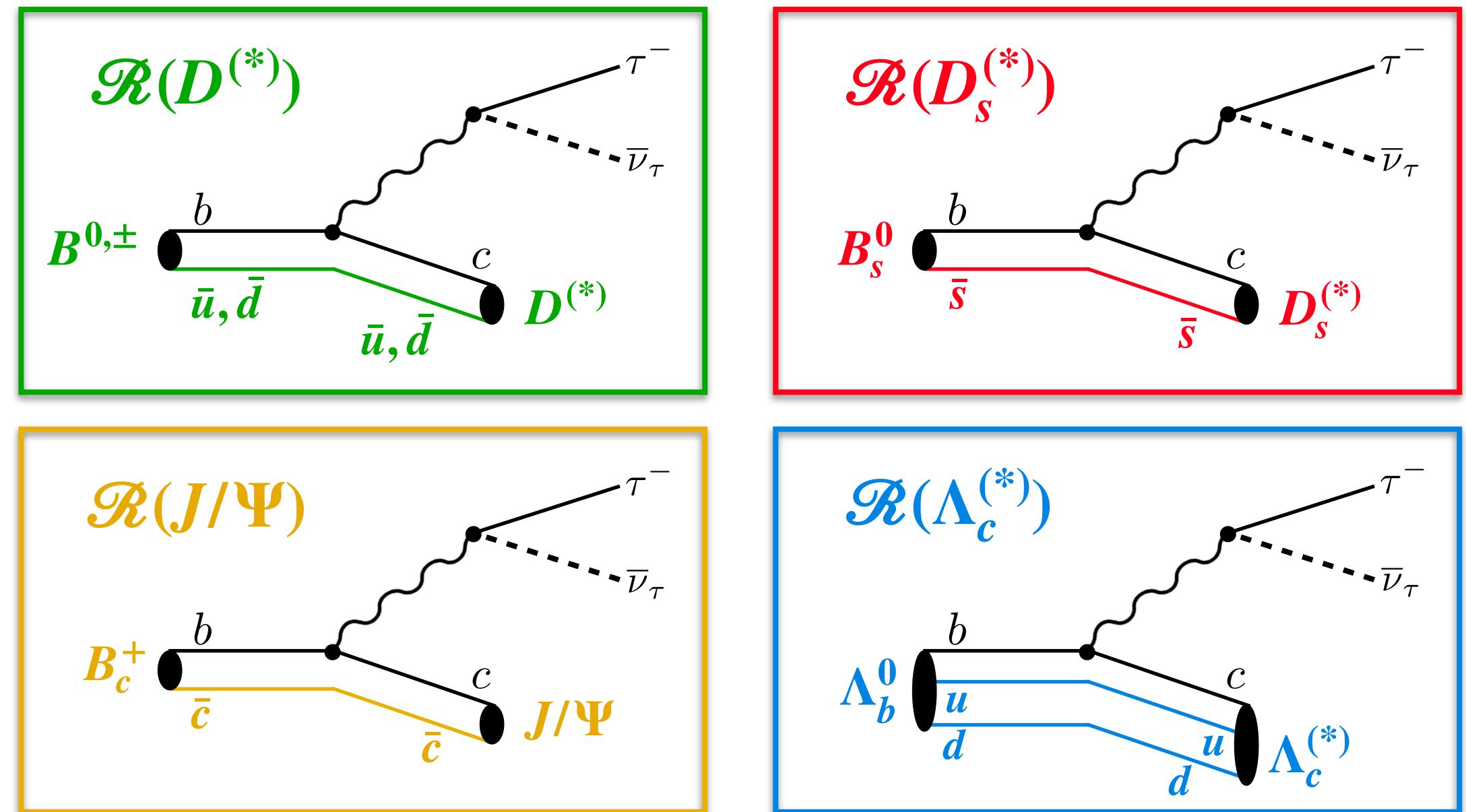
- ~ Even a 5σ on $\mathcal{R}(D^{(*)})$ would not be sufficient to convince ourselves of NP
 - Indirect measurement with broad signal distributions due to multiple ν in final state
- ~ It will be important to have
 - Confirmation by independent experiments
 - Confirmation in different decays
 - Characterization 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 $b \rightarrow c\tau\nu$ transitions because $b\bar{b}$ production at the LHC hadronizes into all species of b-hadrons



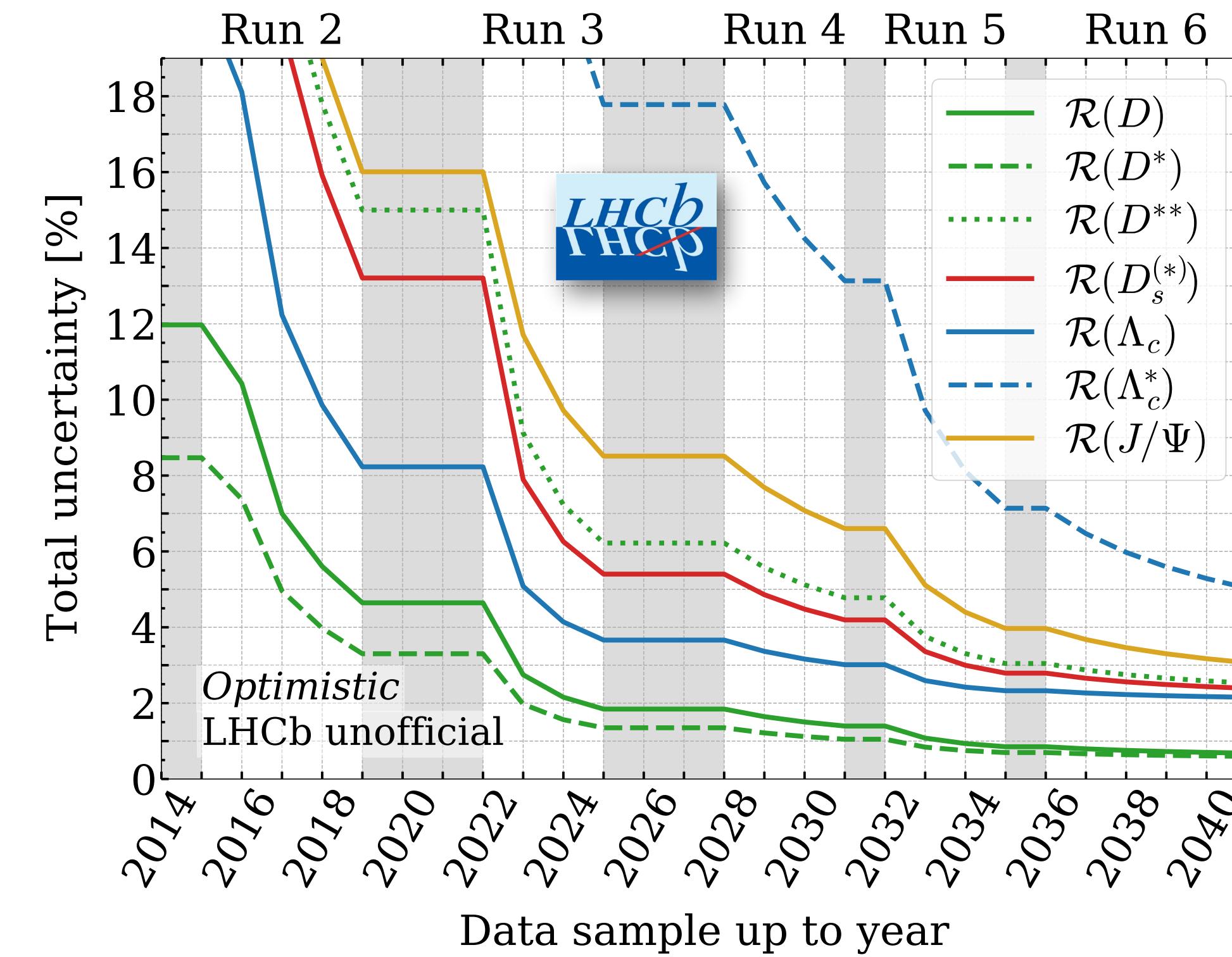
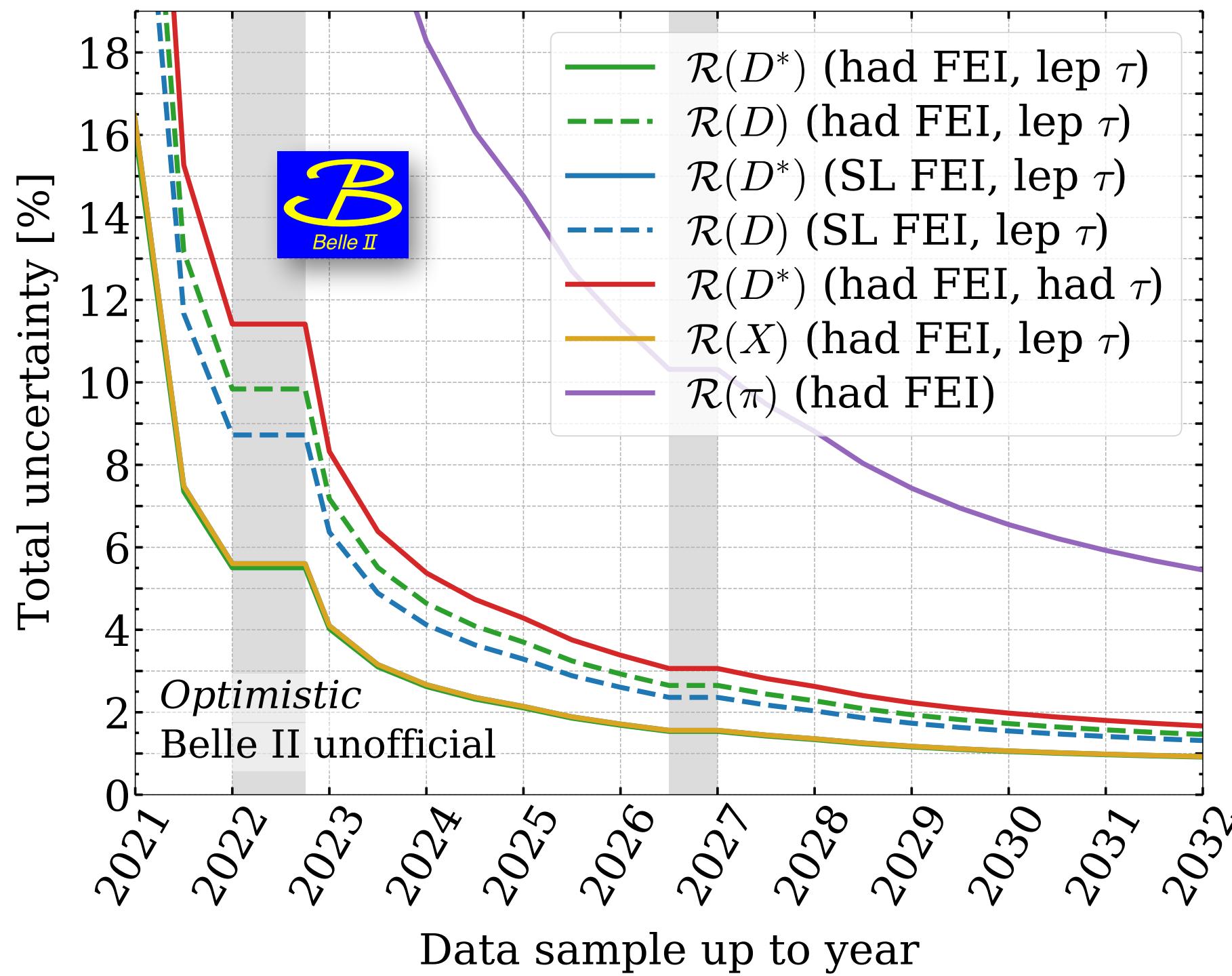
LHCb already published first non-
 $\mathcal{R}(D^{(*)})$ measurement
 $\mathcal{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$,
1.8 σ above SM

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

Future prospects for LFU in $b \rightarrow c\tau\nu$

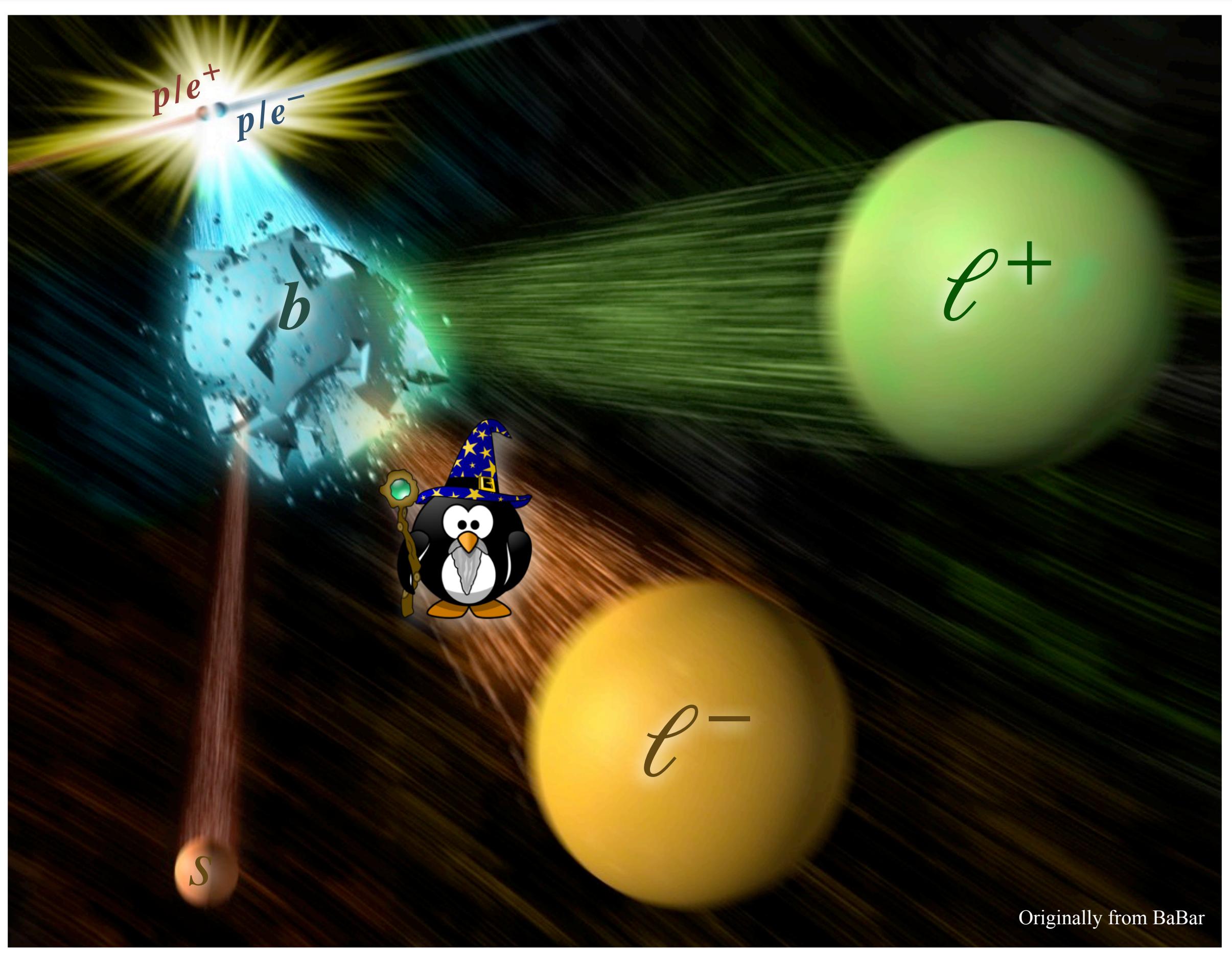


- ~ Currently, world-averaged $\mathcal{R}(D^{(*)})$ **exceeds SM by ~14%**
- ~ With **Belle II** and **upgraded LHCb**, could get uncertainties below 3% in a few years
 - In addition to $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(J/\Psi)$, LHCb has $\mathcal{R}(D^{**})$, $\mathcal{R}(p\bar{p})$, $\mathcal{R}(D_s)$,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



Wherever this ends up, very exciting times ahead!

Bernlochner, MFS, Robinson,
Wormser, arXiv:2101.08326



Penguin from Jeff Brassard

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

Leptonic $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ (very rare)



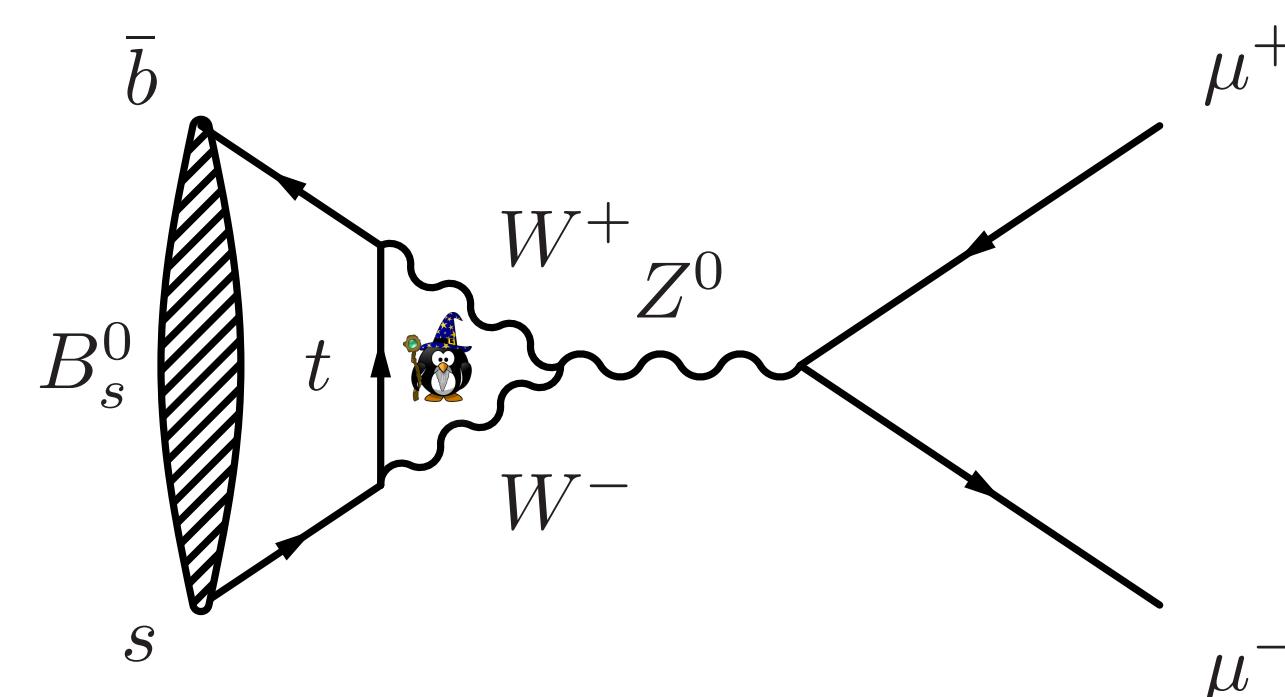
~ FCNC and helicity/Cabibbo suppressed → **very rare** $\mathcal{B} \sim 10^{-9}$

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

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

Clipped from
Marco Santimaria

[PRD 98 (2019) 074512]



SM Predictions

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &= (3.66 \pm 0.14) \times 10^{-9} \rightarrow 4\% \text{ uncertainty} \\ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &= (1.03 \pm 0.05) \times 10^{-9} \rightarrow 5\% \text{ uncertainty} \end{aligned}$$

[JHEP 10 \(2019\) 232](#)

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

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

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \frac{N_S}{N_{\text{obs}}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\text{tot}}^{B^+}}{\varepsilon_{\text{tot}}} \boxed{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} \boxed{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}$$

2.4% uncert. **BaBar** 0.6% uncert. **BES III**

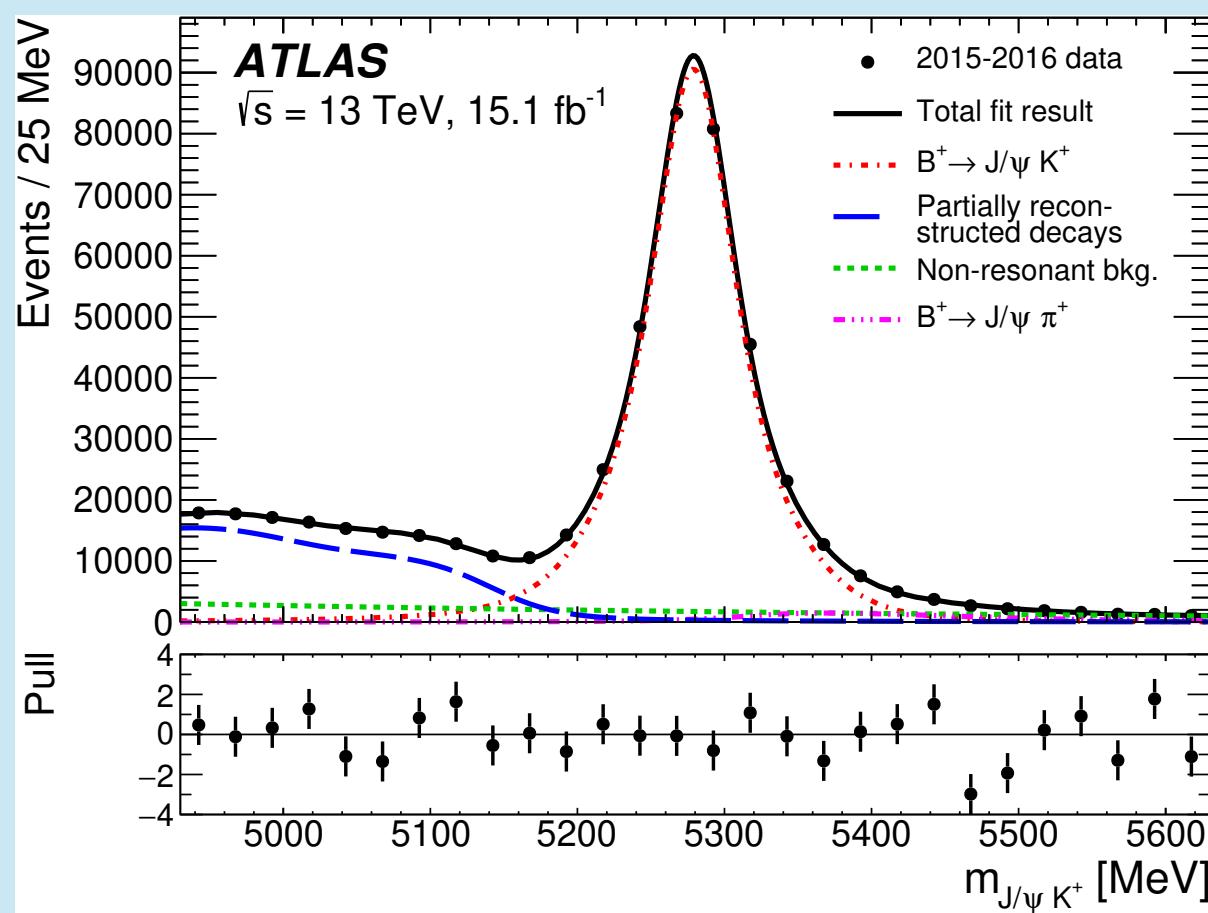
3.2% uncert. from [2103.06810](#) (7% until this March)



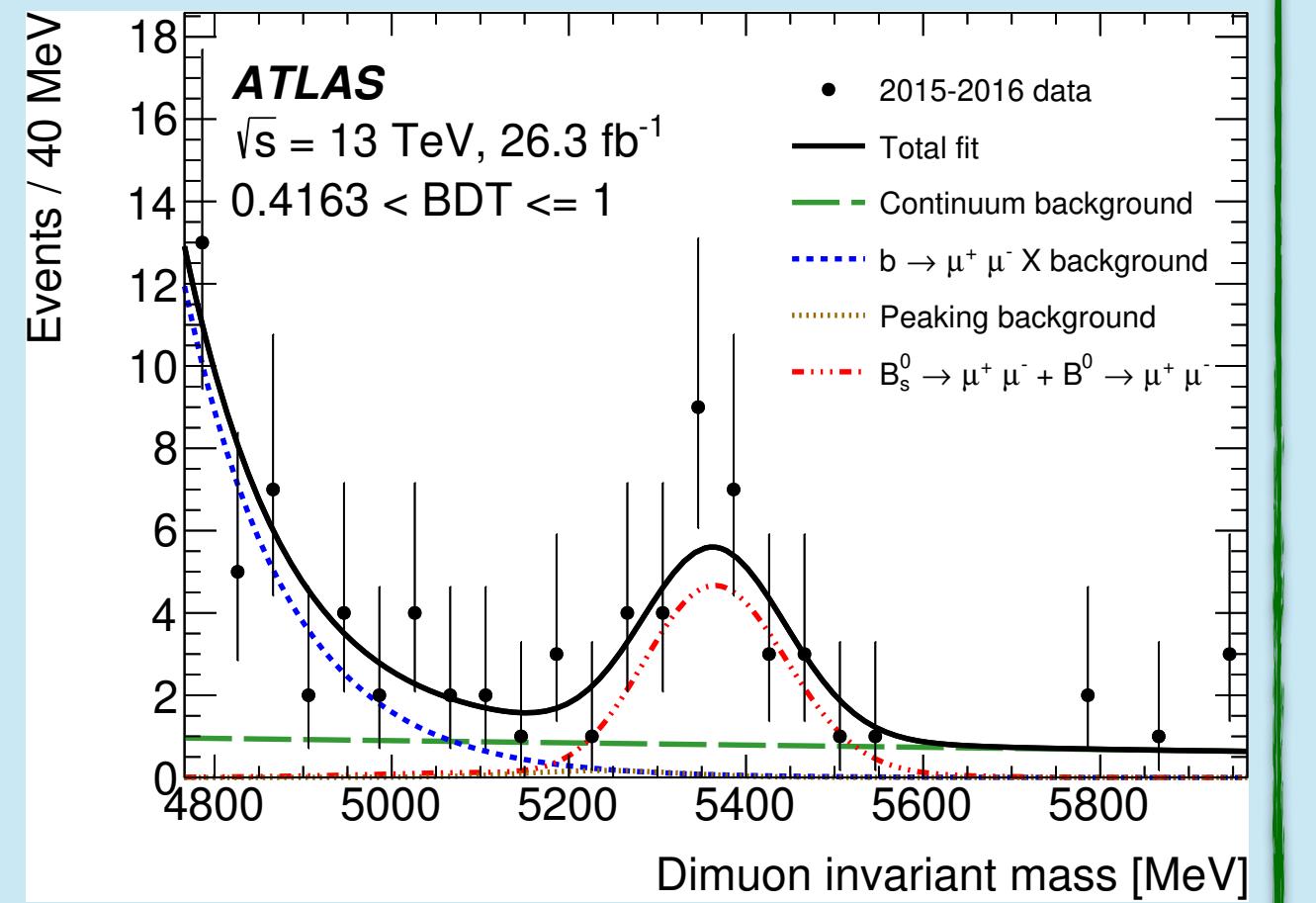
$B^0_{(s)} \rightarrow \mu^+ \mu^-$: ATLAS and CMS



Normalization



Signal

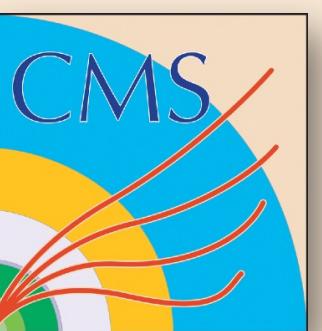
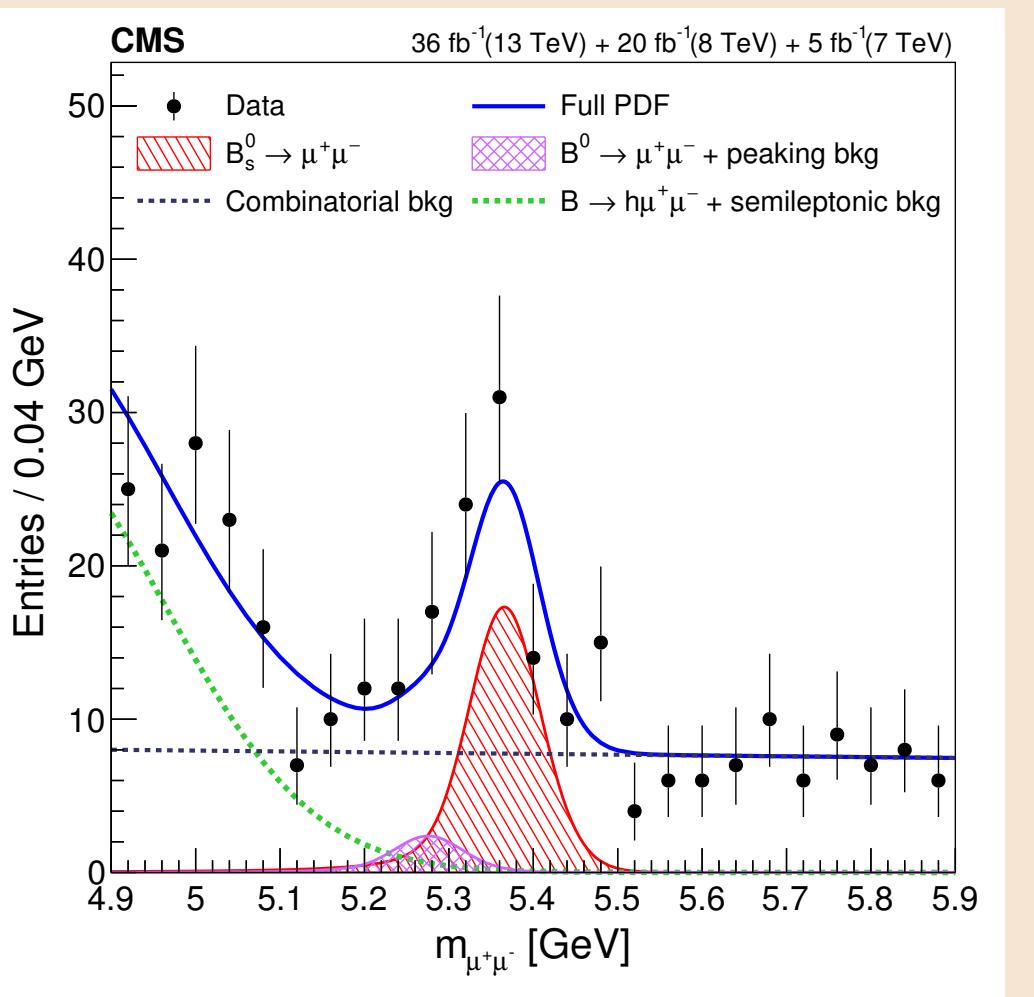
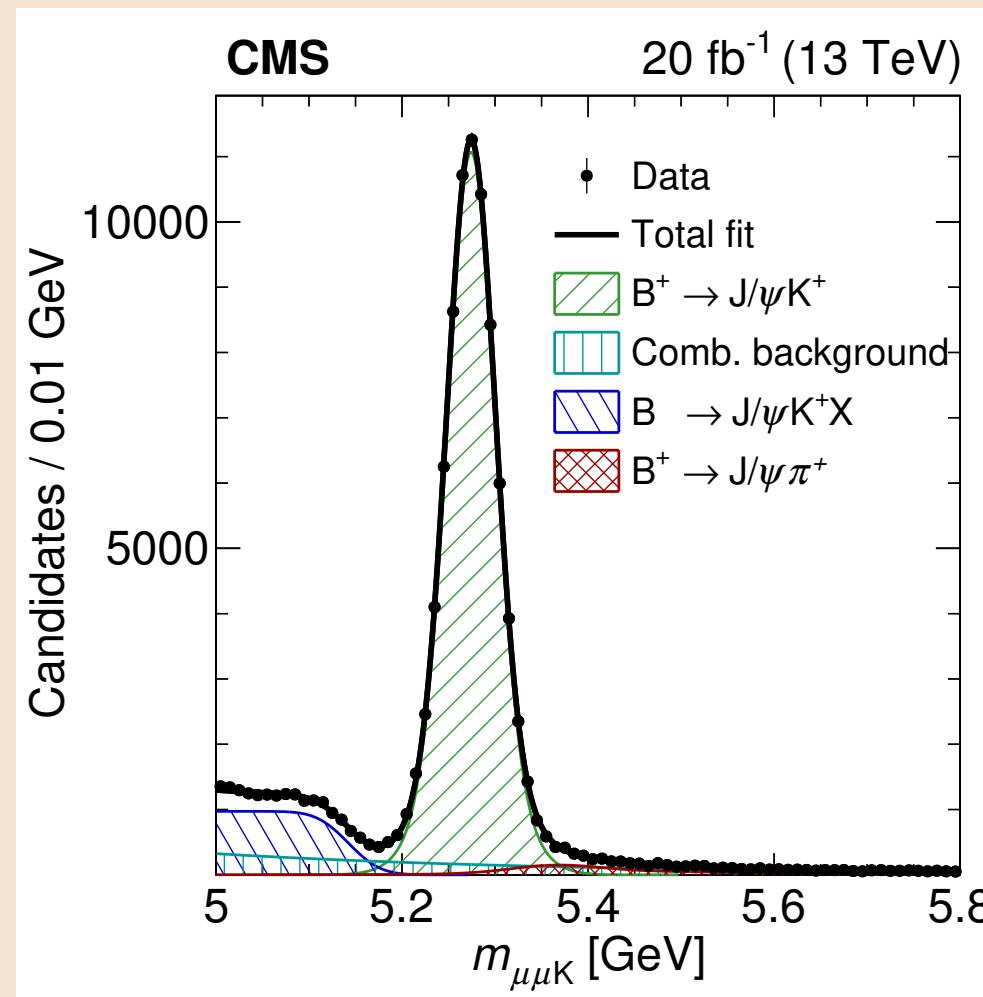


25% of B_s in Run 1+2 dataset

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \rightarrow 4.6\sigma$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \text{ (95 \% CL)}$$

[JHEP 04 \(2019\) 098](#)



32% of B_s in Run 1+2 dataset

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+0.7}_{-0.8}) \times 10^{-9} \rightarrow 5.6\sigma$$

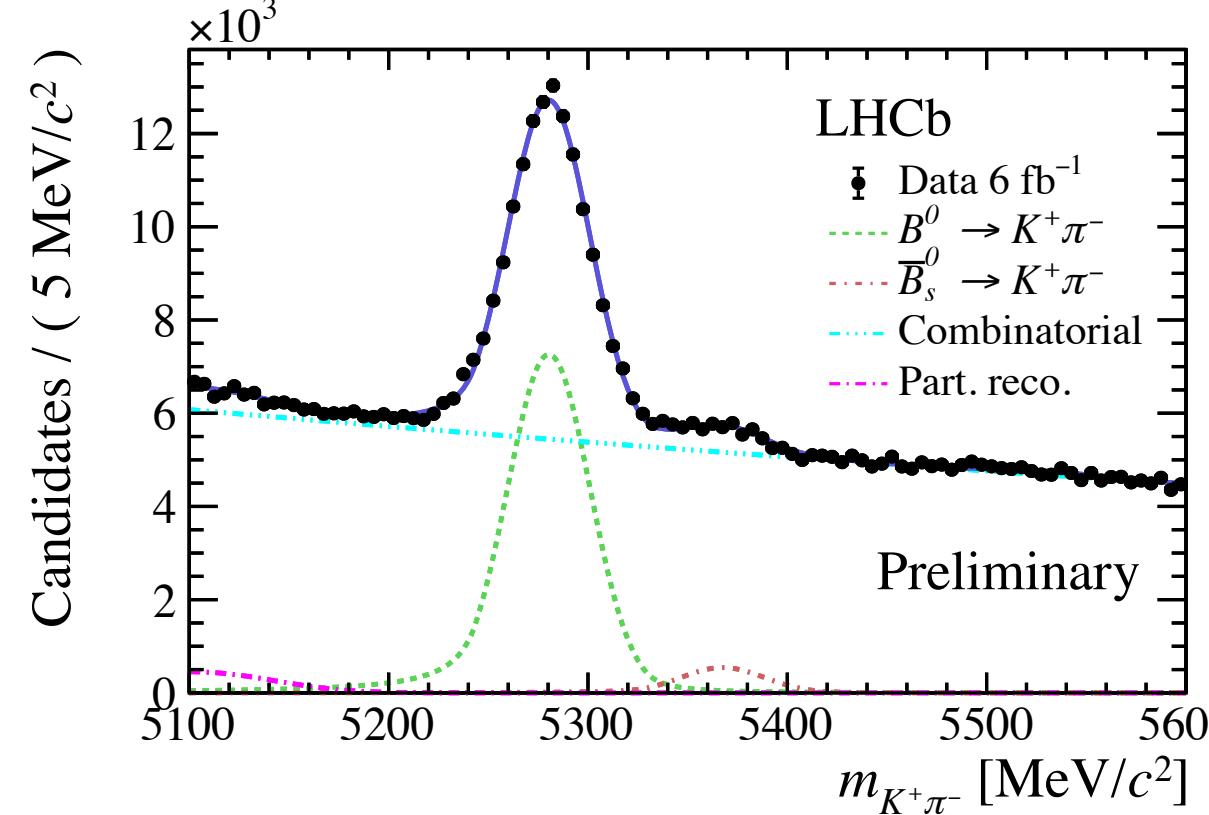
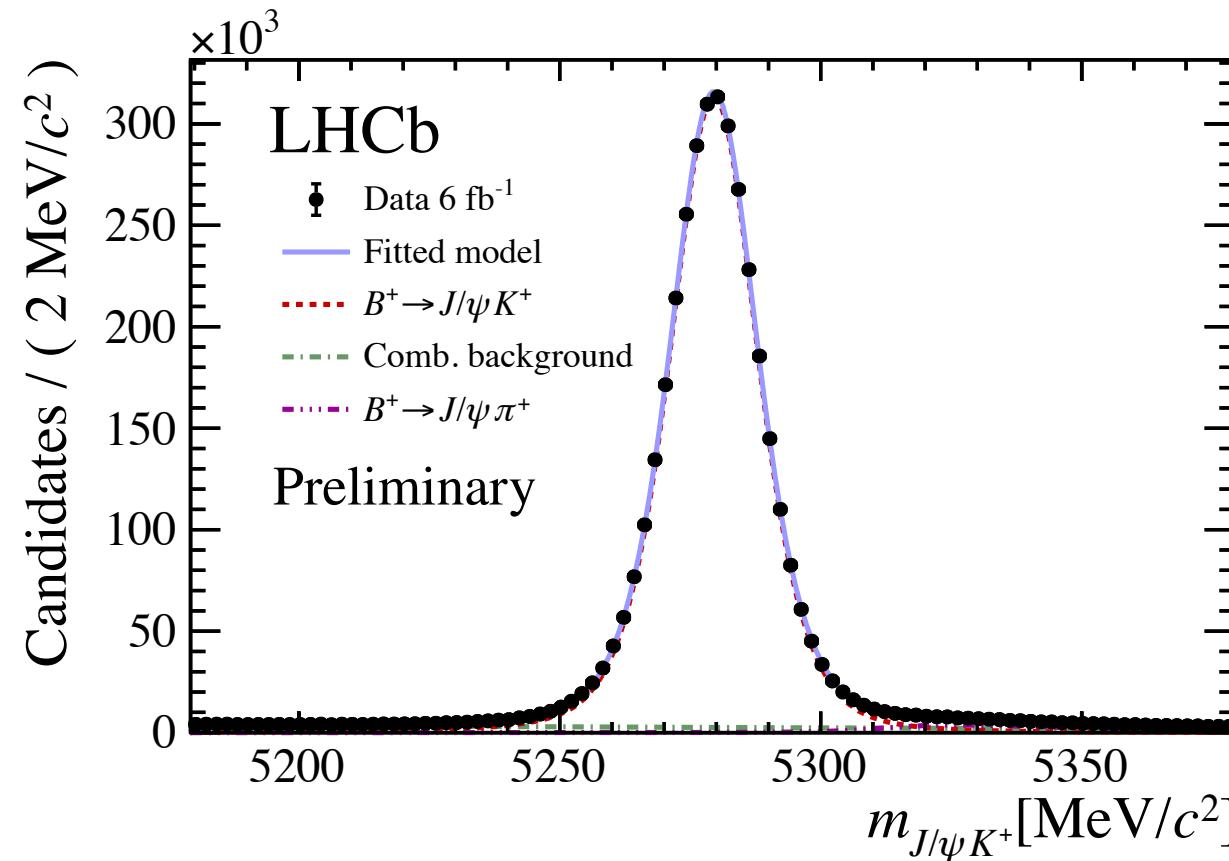
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.6 \times 10^{-10} \text{ (95 \% CL)}$$

[JHEP 04 \(2020\) 188](#)

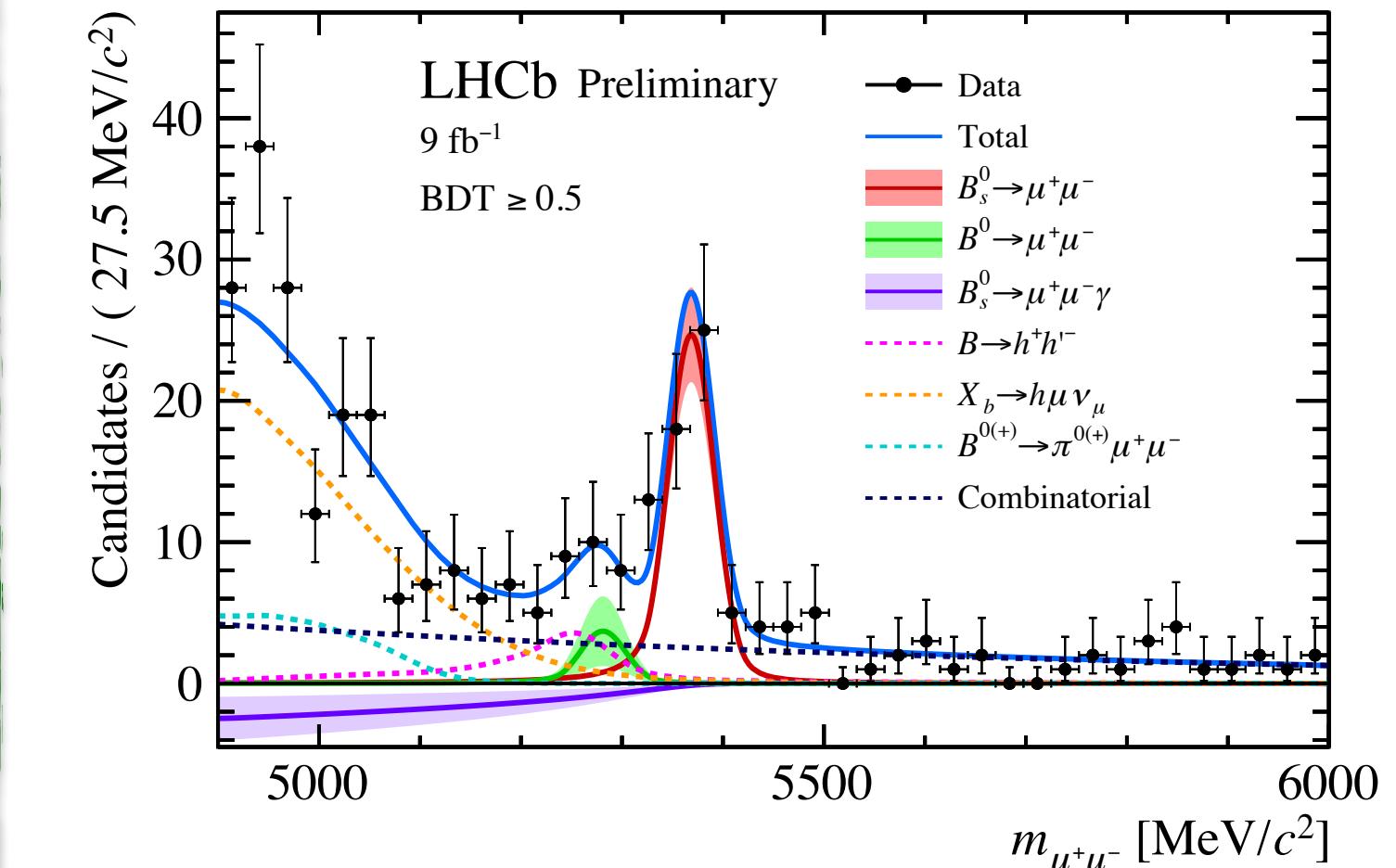
$B_{(s)}^0 \rightarrow \mu^+ \mu^-$: LHCb



Normalization



Signal



100% of B_s in Run 1+2 dataset

[PAPER-2021-007 forthcoming](#)

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

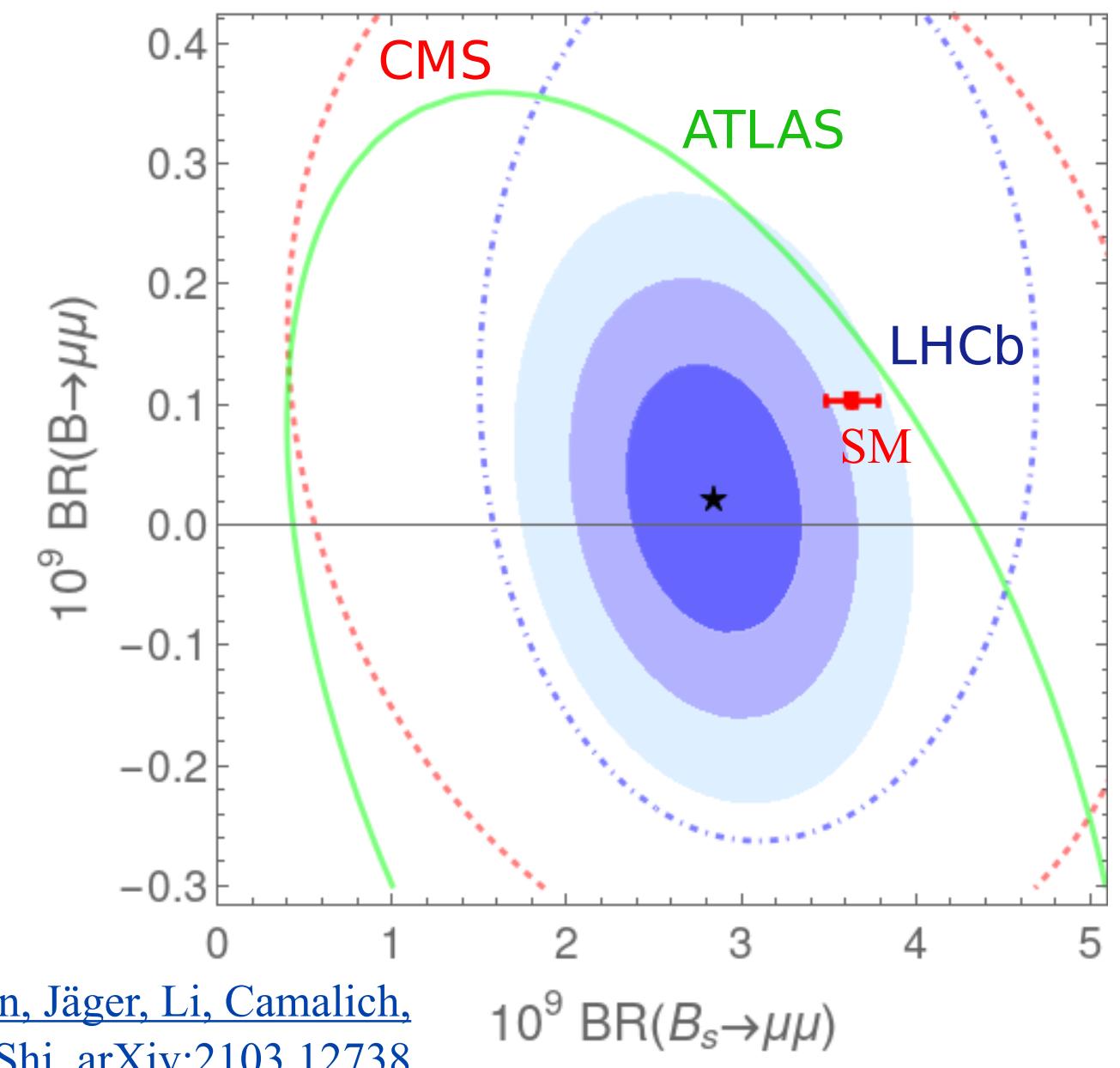
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-10} \text{ (95 \% CL)}$$

~ Combination with ATLAS/CMS

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{WA} = (2.84 \pm 0.33) \times 10^{-9}$$

→ 22% below SM prediction

~ 2.3σ tension with SM

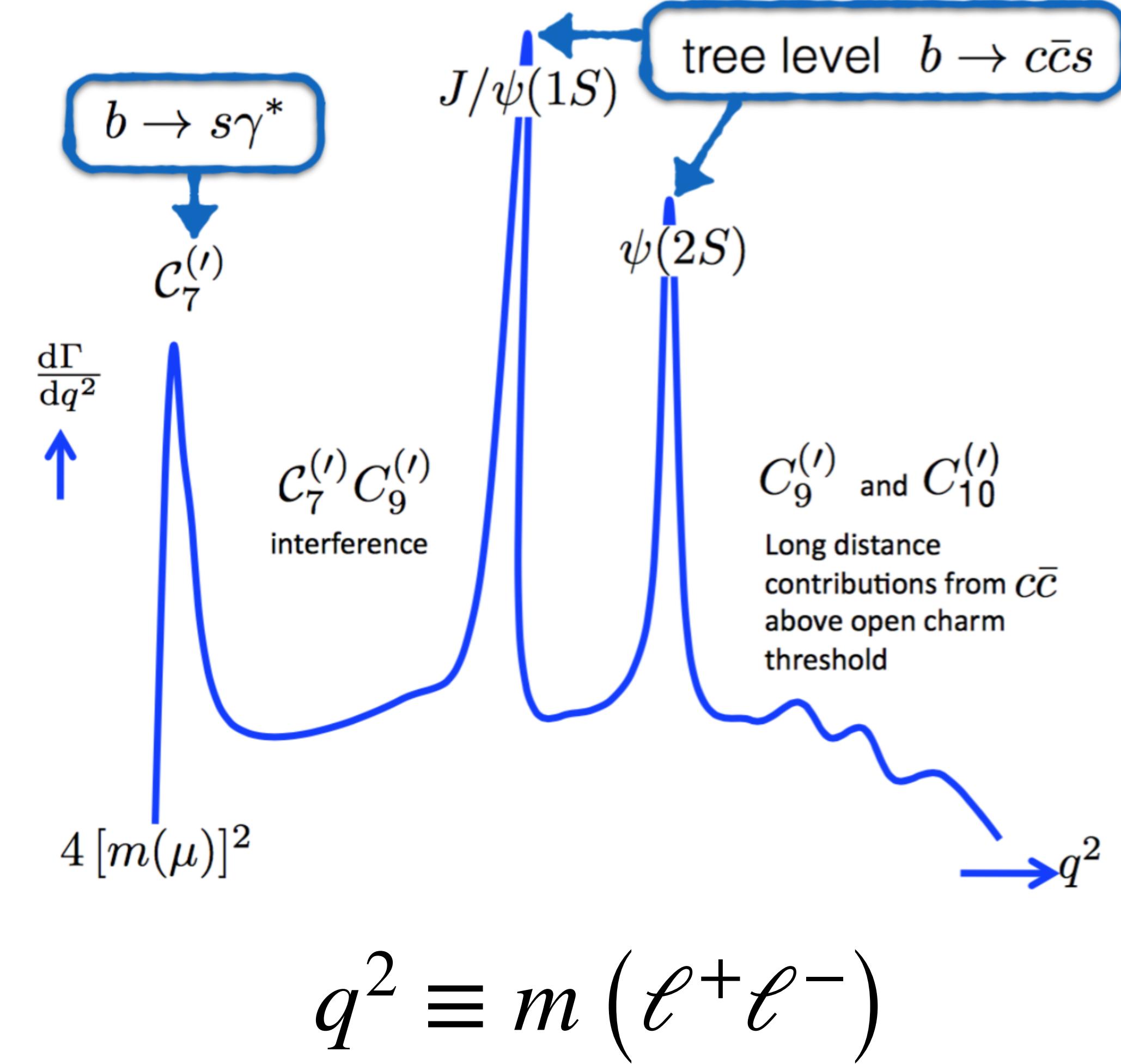
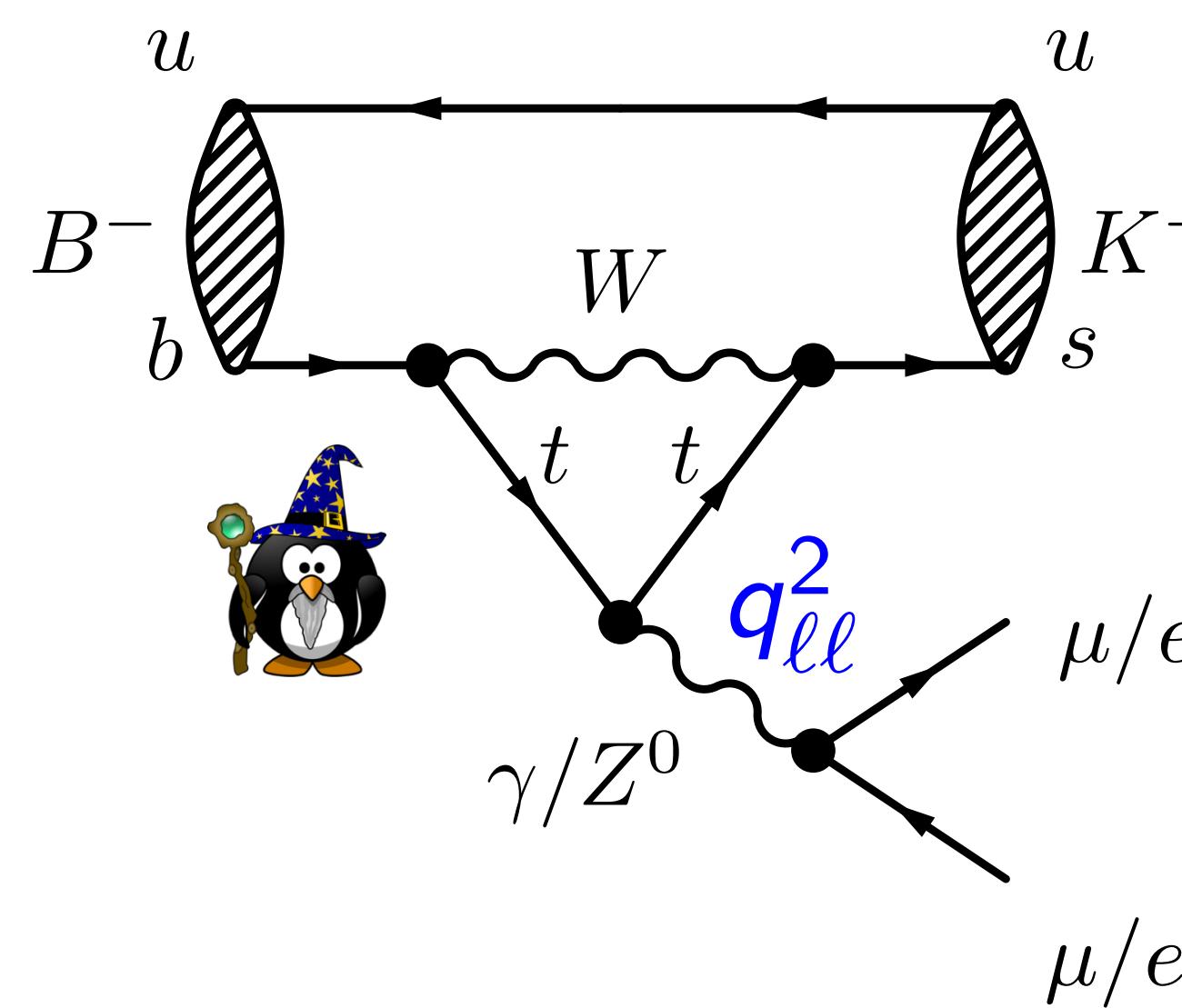


[Geng, Grinstein, Jäger, Li, Camalich, Shi, arXiv:2103.12738](#)

Semileptonic $B_{(s)} \rightarrow H\ell^+\ell^-$ (medium rare)



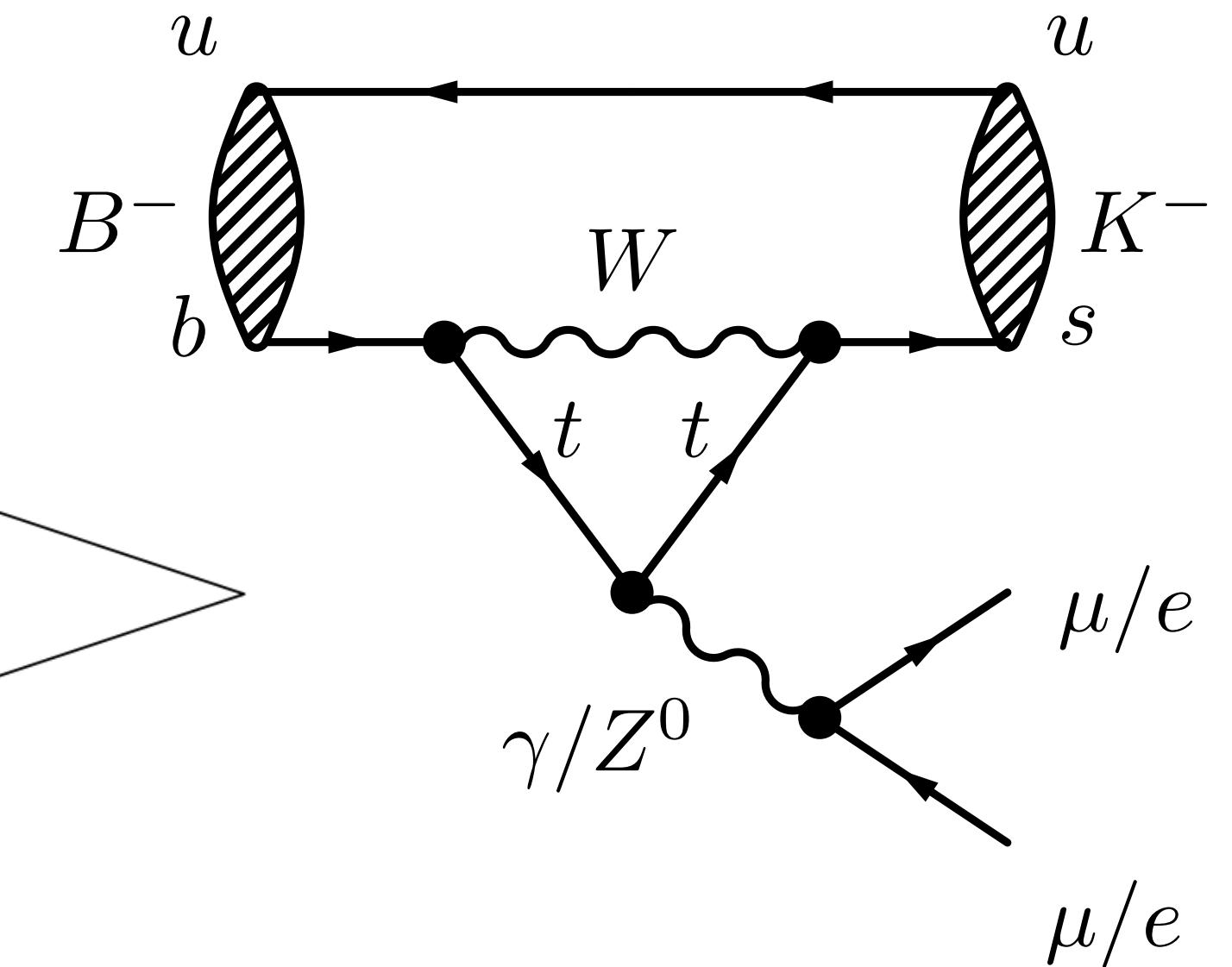
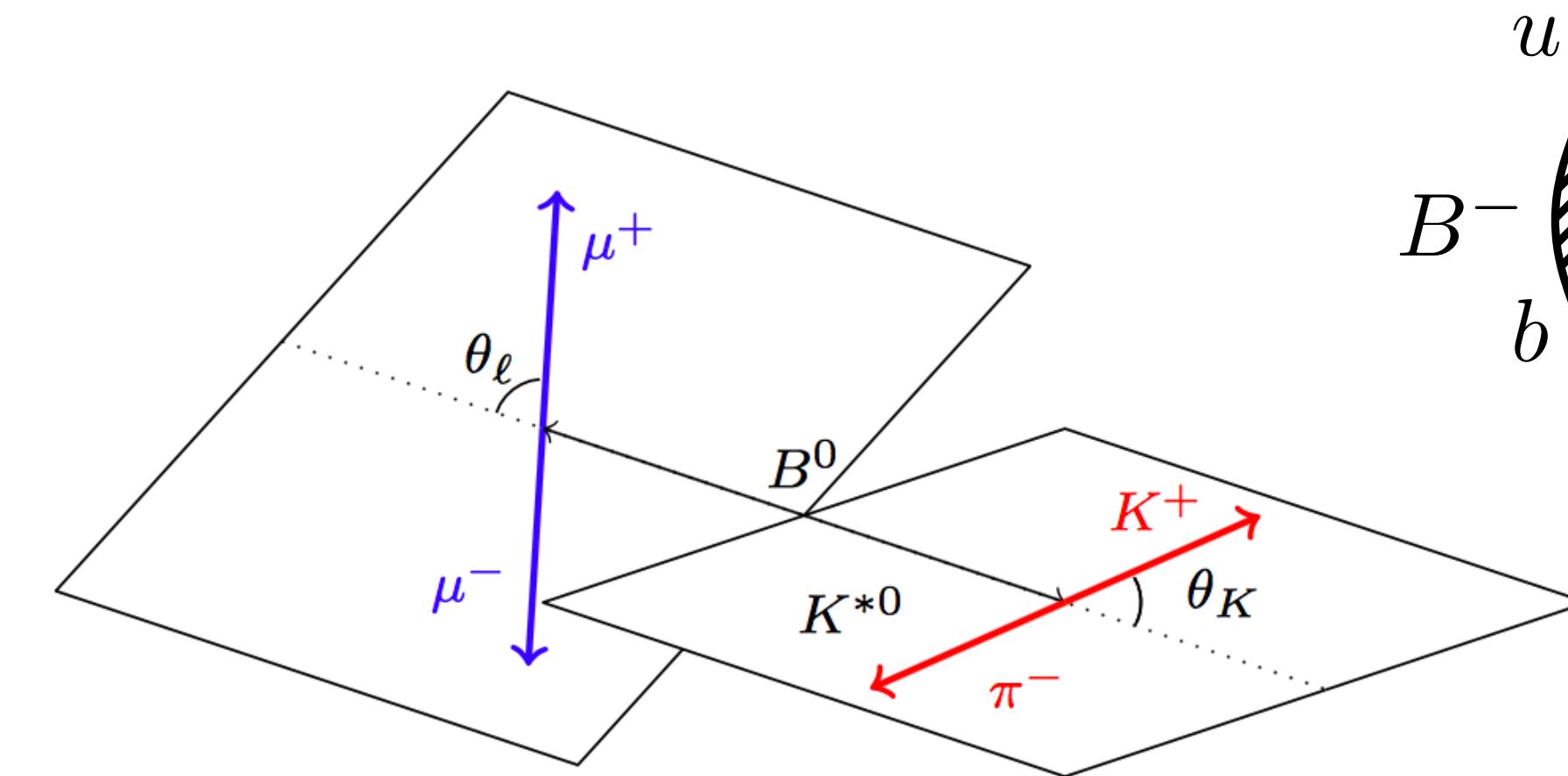
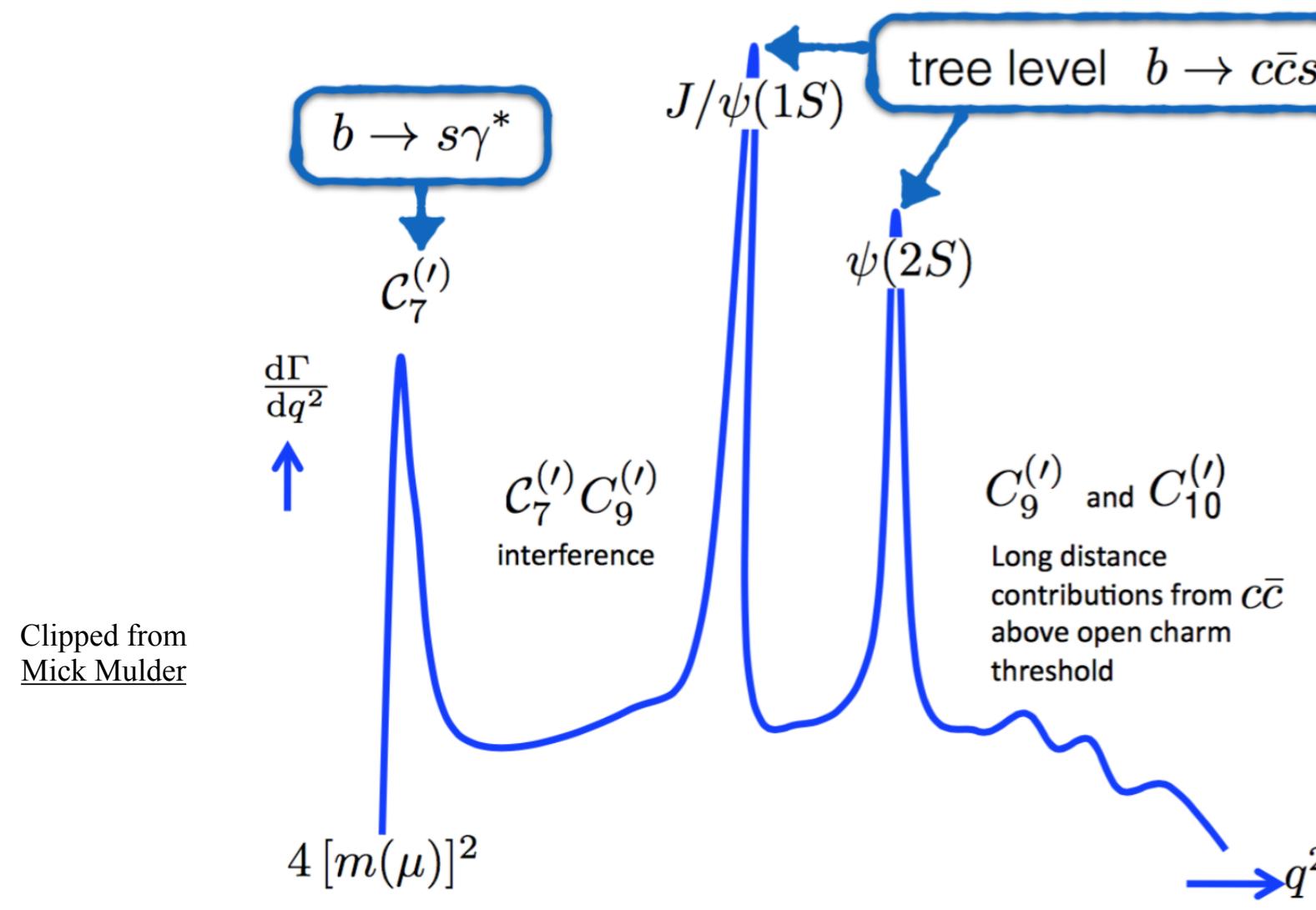
Not as suppressed as leptonic decays, but still **rare** with $\mathcal{B} \sim 10^{-7}$



Precision test strategies



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



Branching fractions

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

Angular observables

Minimal FF uncertainties,
though sensitive to charm loops

$$\text{LFU ratios } \mathcal{R}_{H_s} = \frac{\mathcal{B}(H_b \rightarrow H_s \mu\mu)}{\mathcal{B}(H_b \rightarrow H_s ee)}$$

Theory uncertainty of $\sim 1\%$, but
electrons harder at the LHC

Differential BF rates



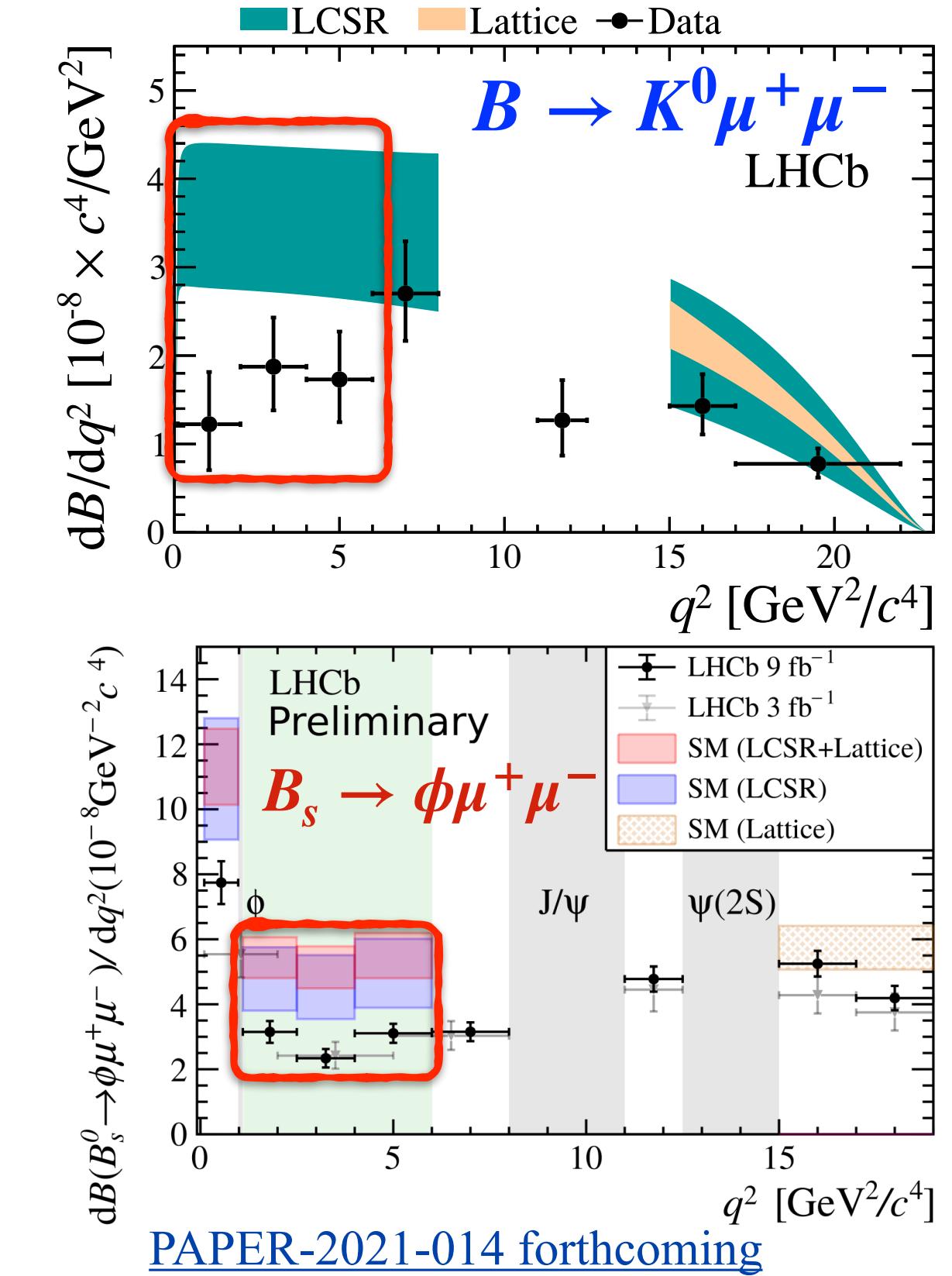
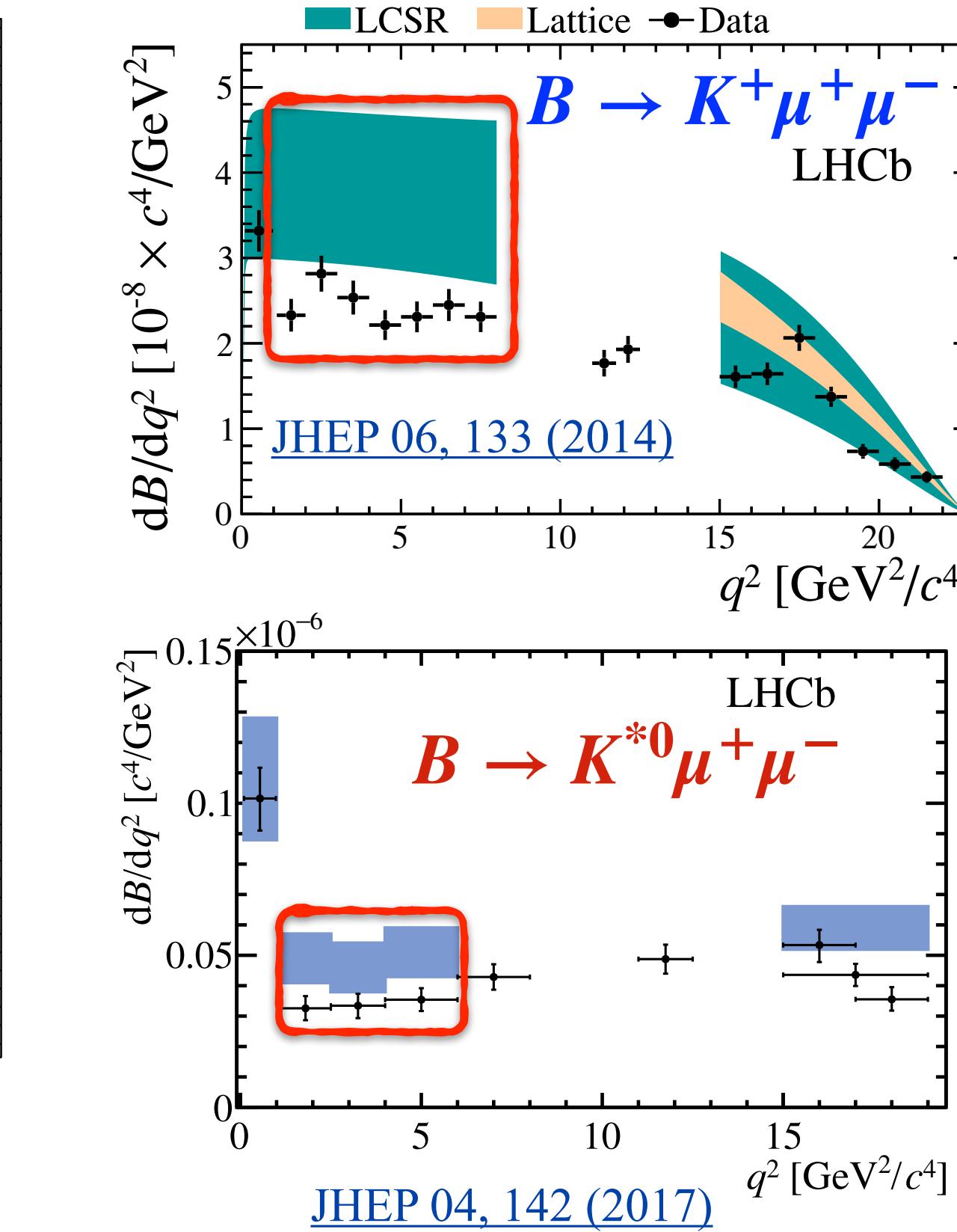
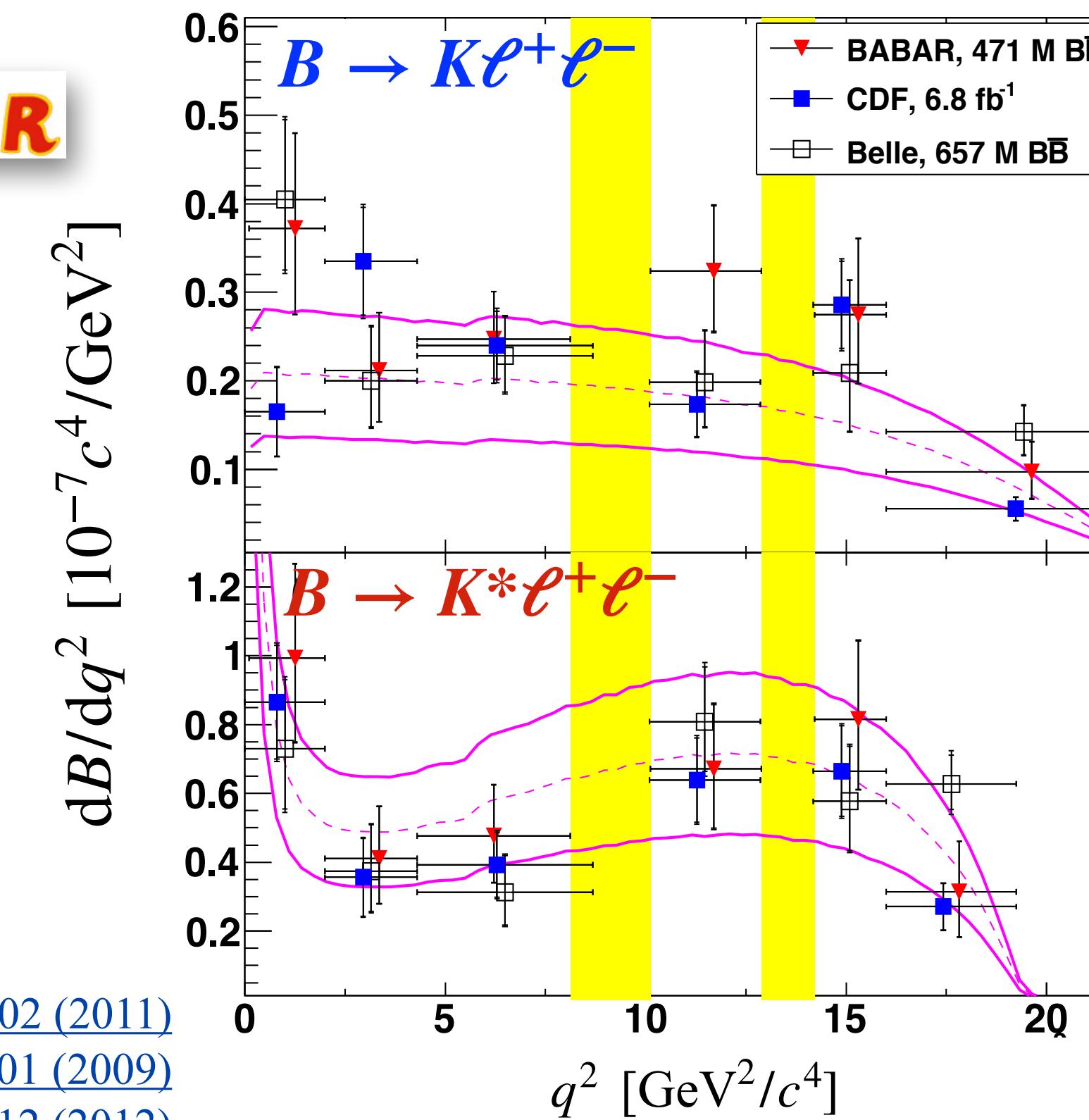
- ~ First measurements of $B \rightarrow K^{(*)}\ell\ell$ at Tevatron and the B-factories
 - Consistent with expectations though large uncertainties

BABAR

Belle

CDF

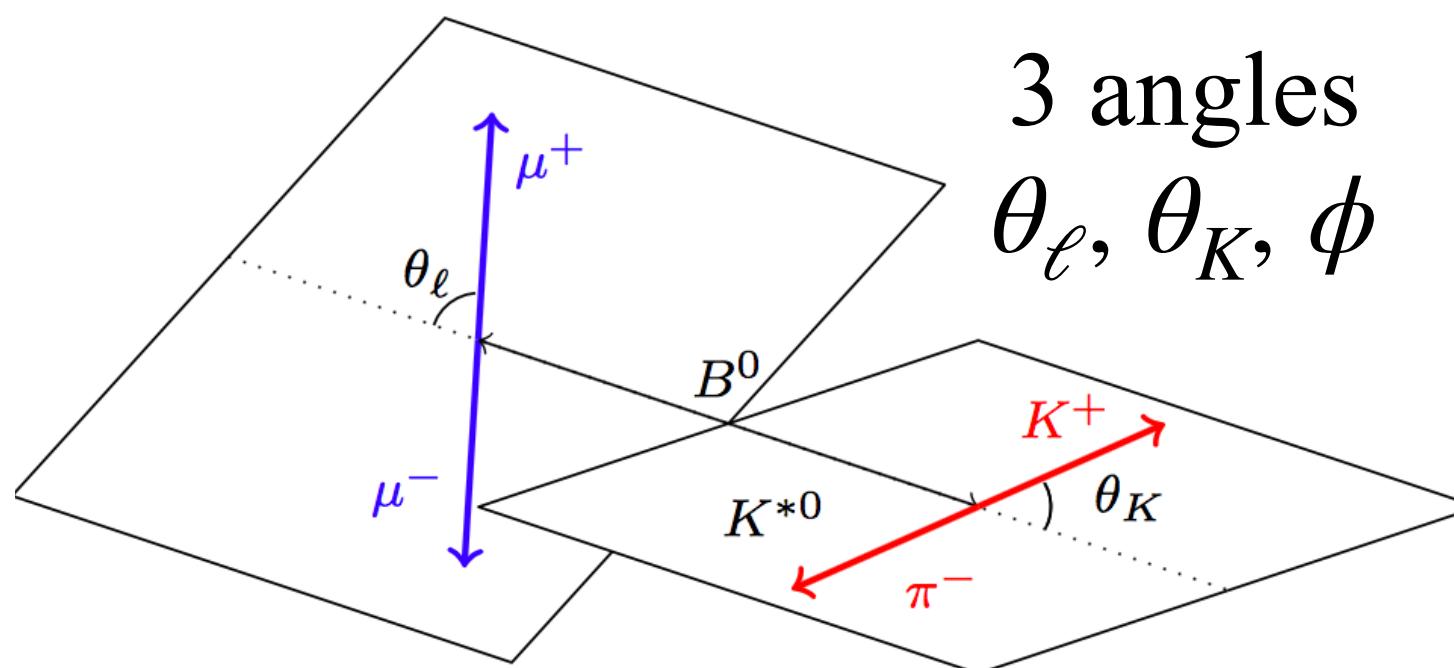
[PRL 107, 201802 \(2011\)](#)
[PRL 103, 171801 \(2009\)](#)
[PRD 86, 032012 \(2012\)](#)



LHCb

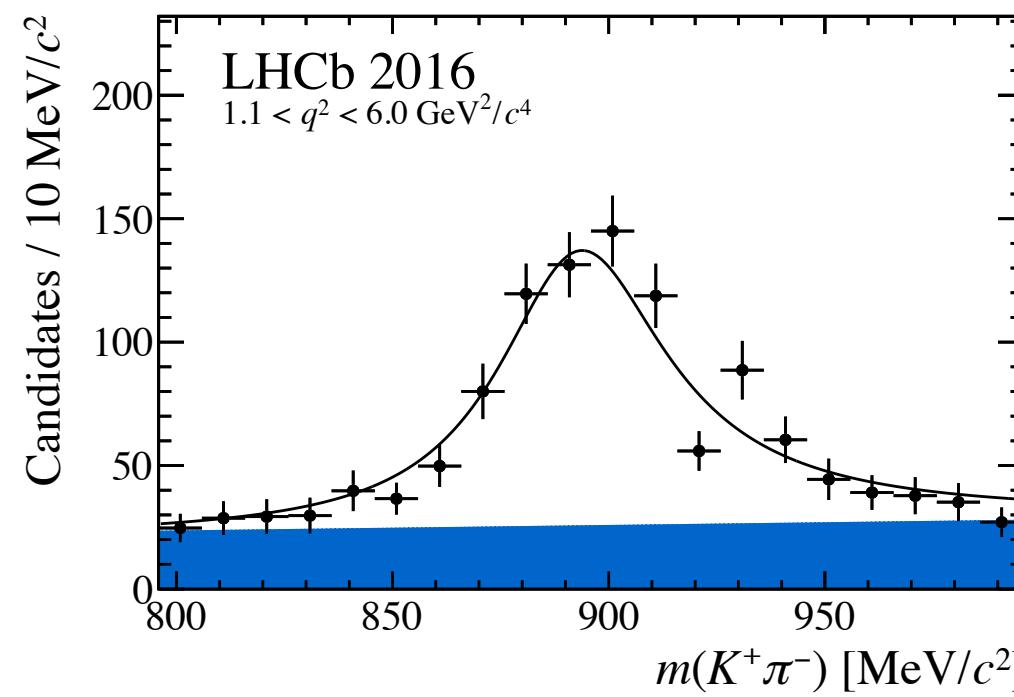
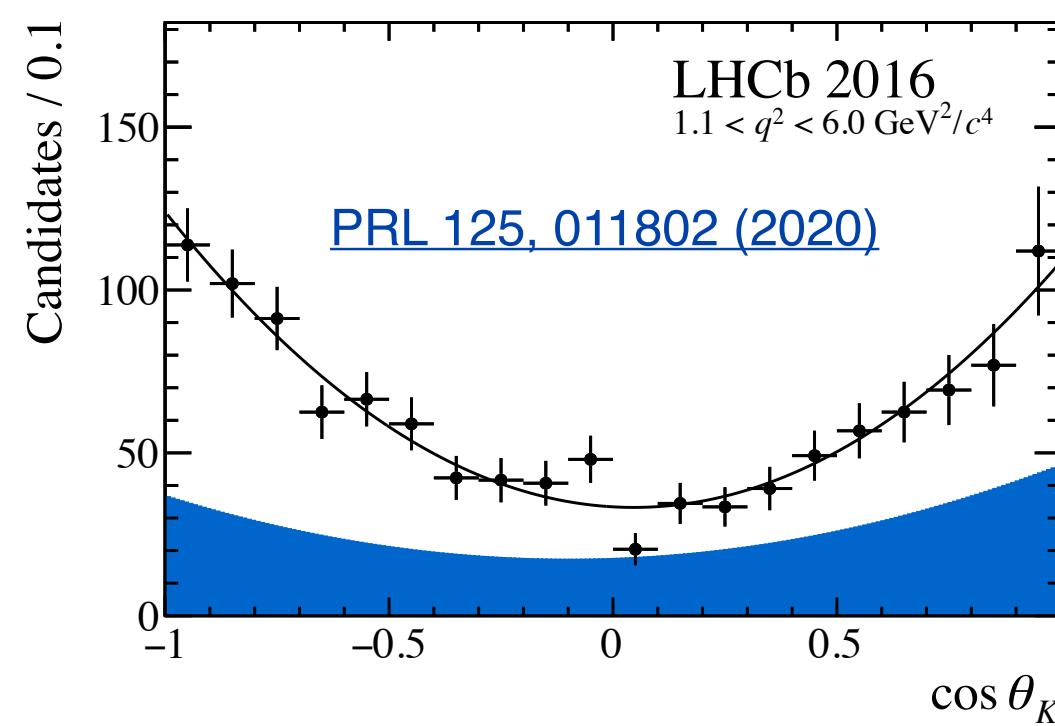
Fresh!

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



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

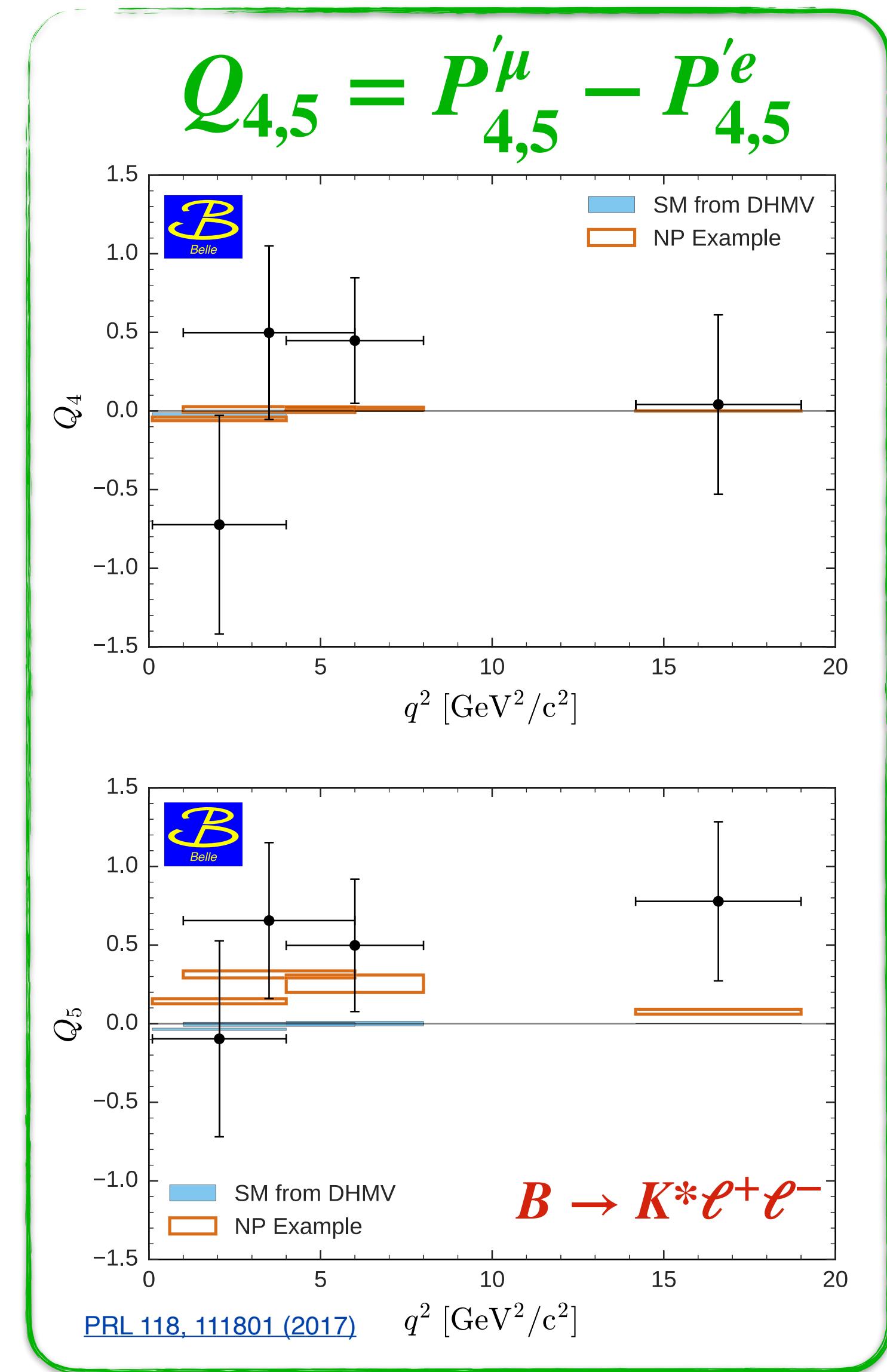
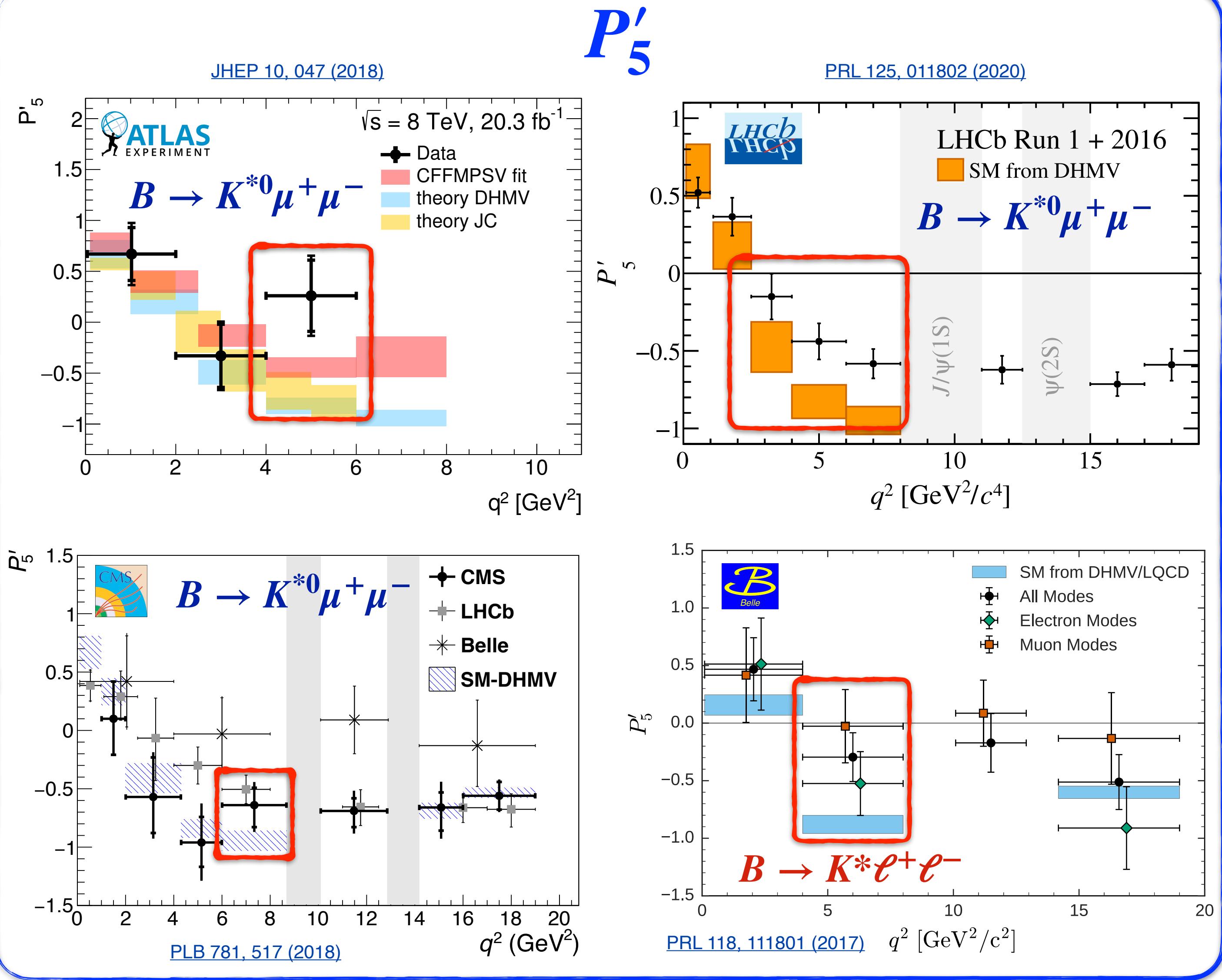
P-wave



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

[JHEP 10, 075 \(2016\)](#)

P'_5 and $Q_{4,5}$ in $B \rightarrow K^* \ell \ell$



Possible discrepancies at low q^2 , driven by muons

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



- ~ Measured all isospin variants for $\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu\mu)}{\mathcal{B}(B \rightarrow K^{(*)}ee)}$
- ~ Fit $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$
→ \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 $B \rightarrow J/\psi(\rightarrow \ell\ell) K^{(*)}$

$$r_{J/\psi}^K = \frac{\mathcal{B}[B \rightarrow K J/\psi(\rightarrow \mu\mu)]}{\mathcal{B}[B \rightarrow K J/\psi(\rightarrow ee)]} = 0.994 \pm 0.015$$

[JHEP 03, 105 \(2021\)](#)

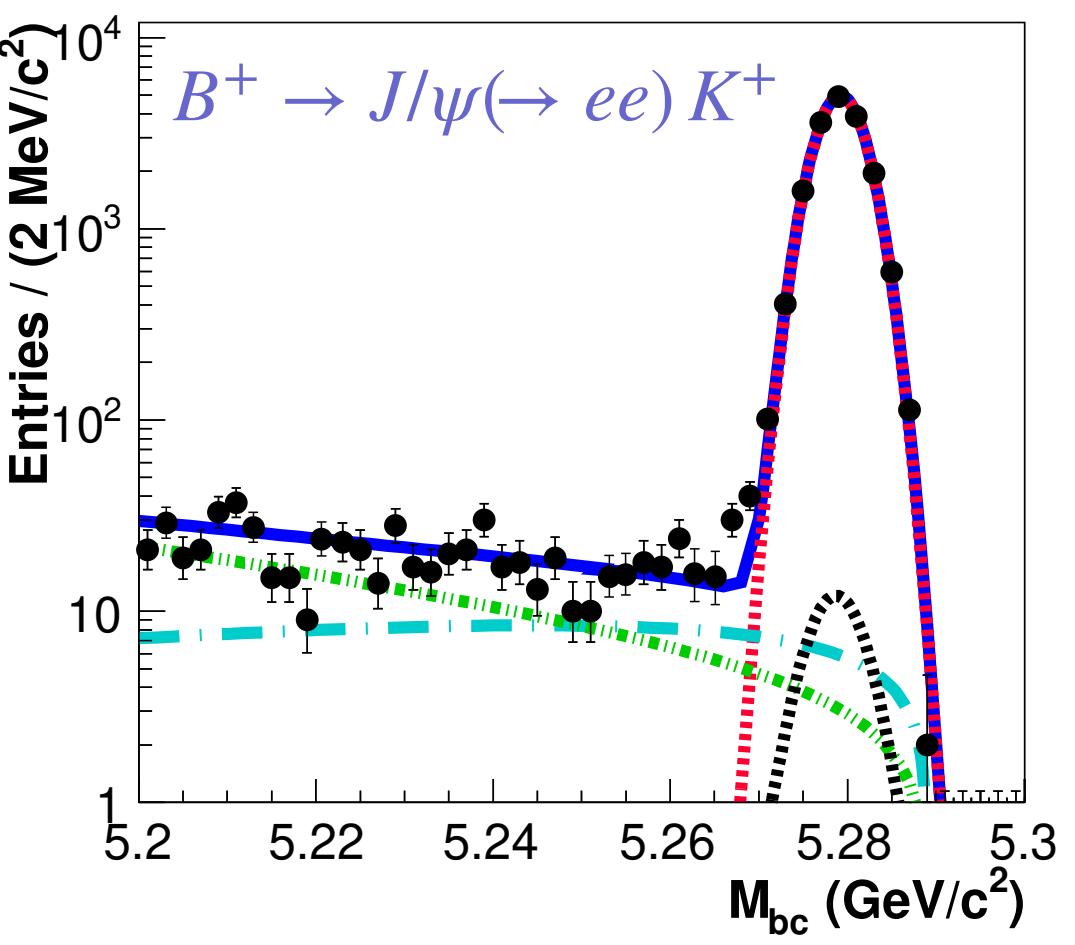
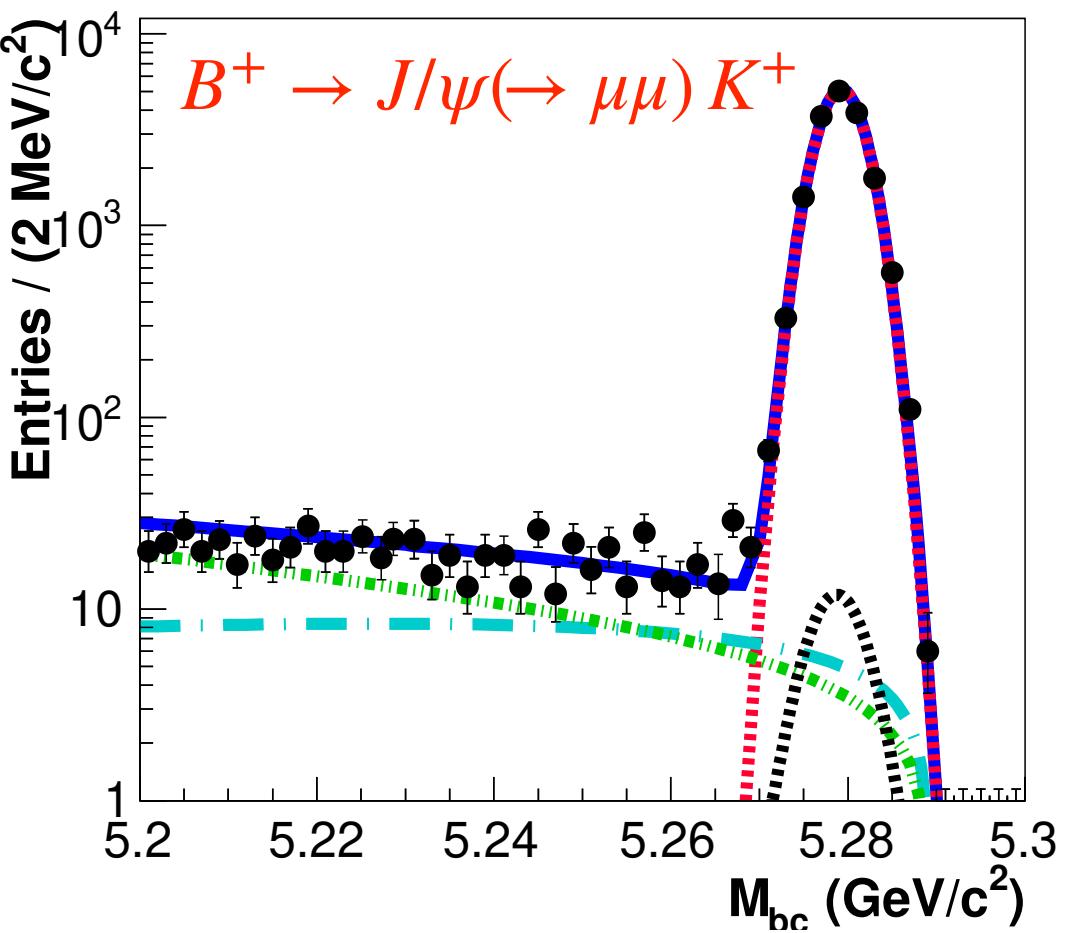
$$r_{J/\psi}^{K^*} = \frac{\mathcal{B}[B \rightarrow K^* J/\psi(\rightarrow \mu\mu)]}{\mathcal{B}[B \rightarrow K^* J/\psi(\rightarrow ee)]} = 1.015 \pm 0.045$$

[arXiv:1904.02440](#)

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

$$\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.032 \pm 0.025) \times 10^{-3}$$

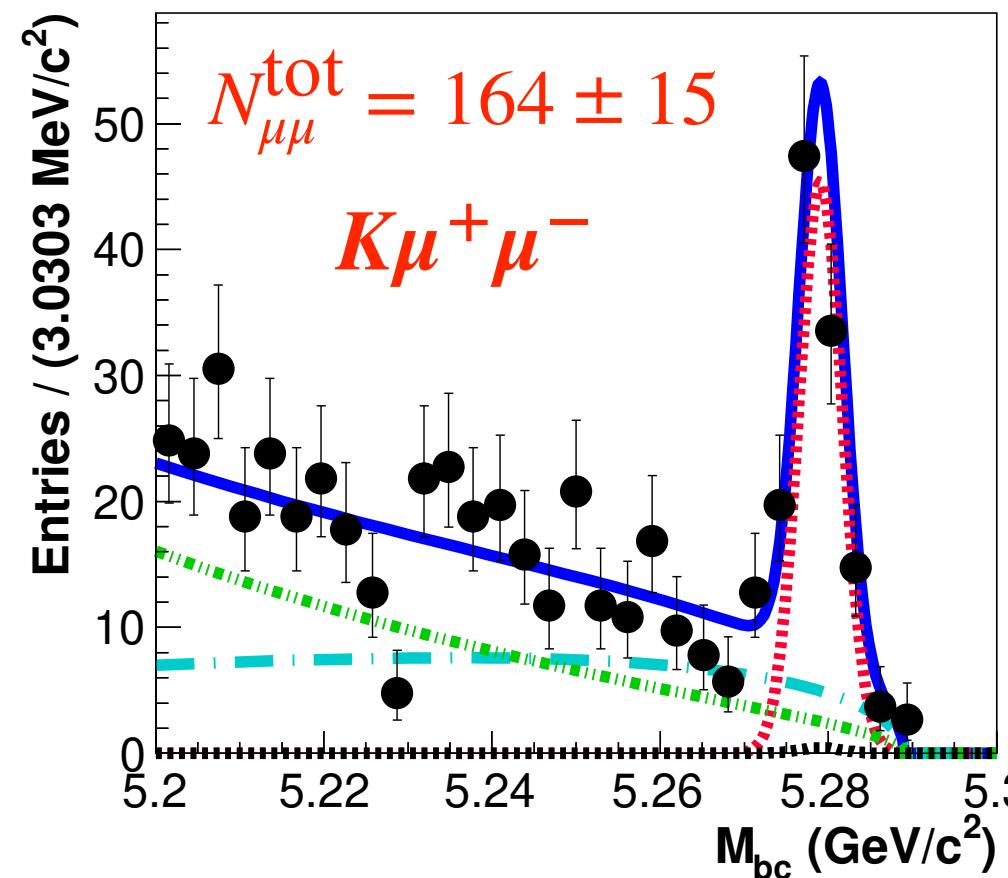
$$\mathcal{B}(B^0 \rightarrow J/\psi K^0) = (0.902 \pm 0.028) \times 10^{-3}$$



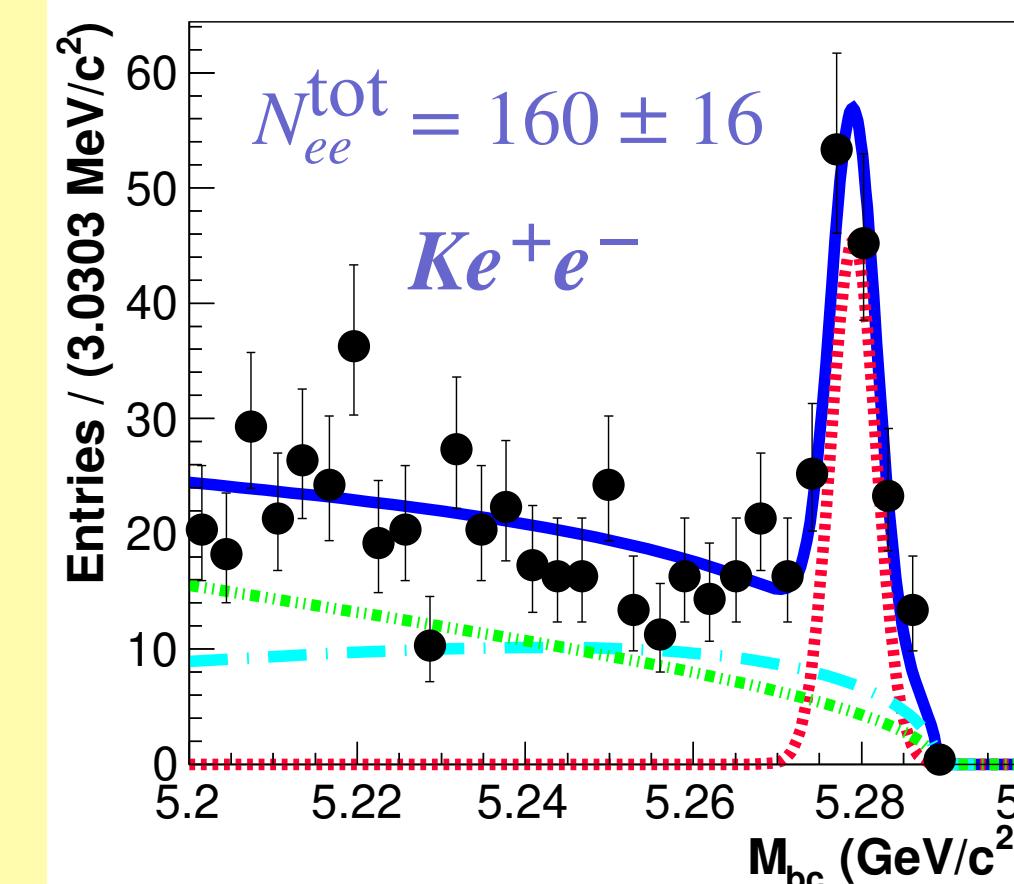
LFU $\mathcal{R}_{K^{(*)}}$ at Belle: results



Muons



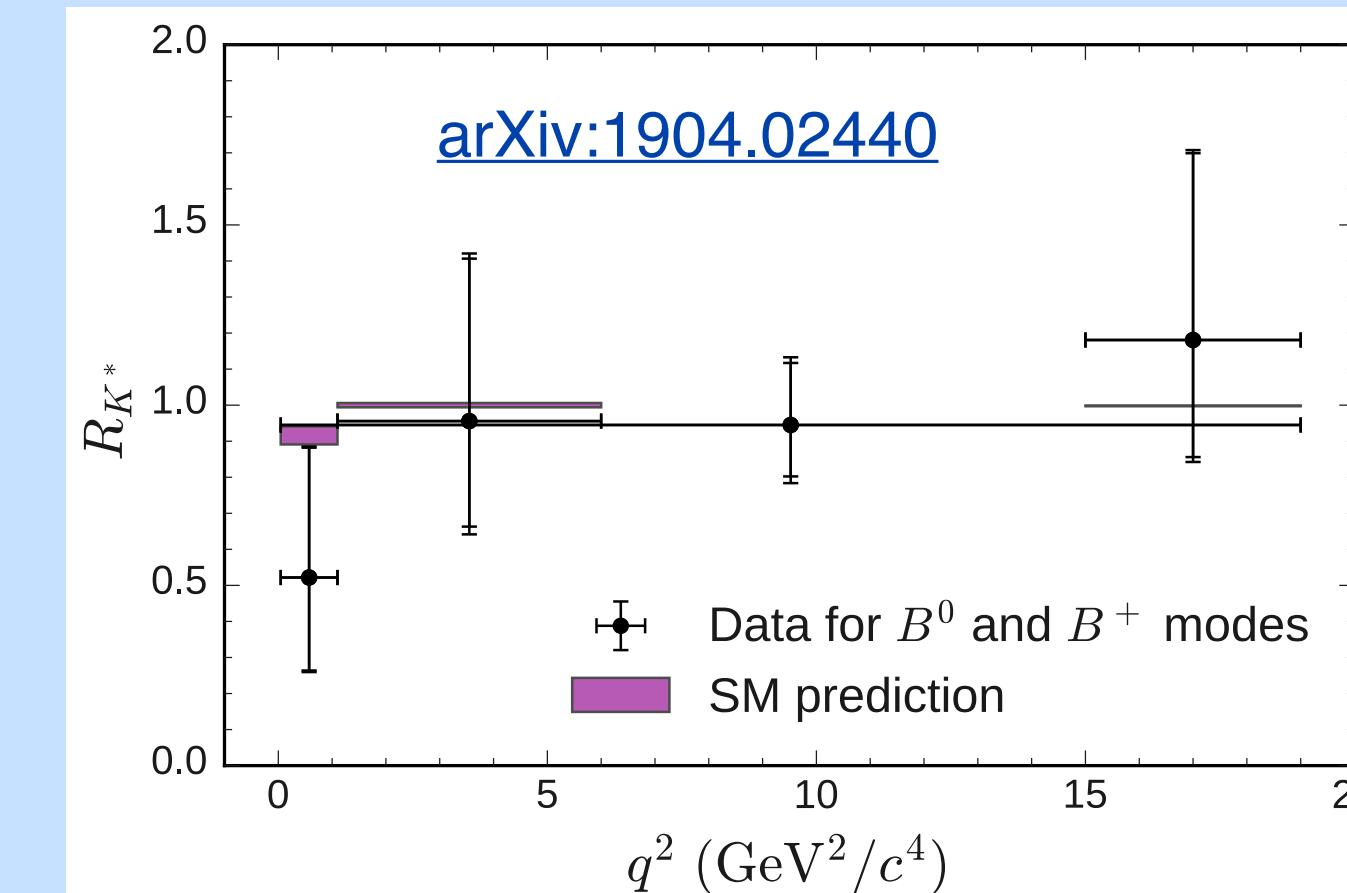
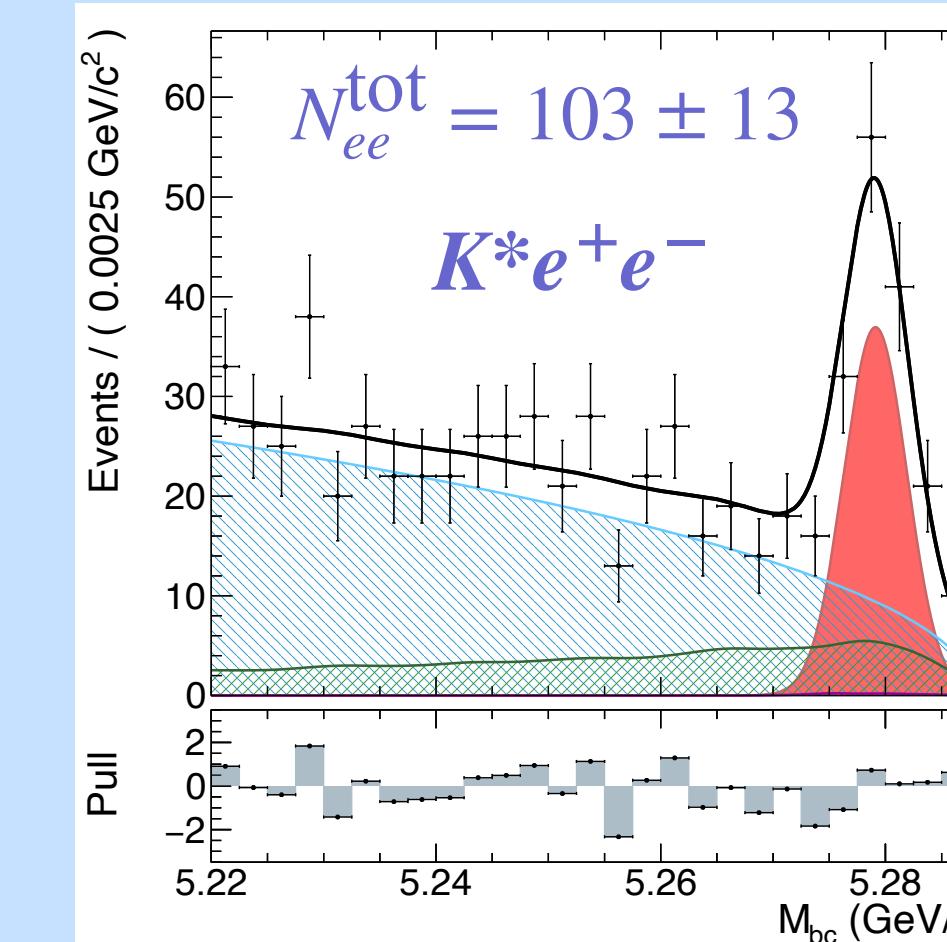
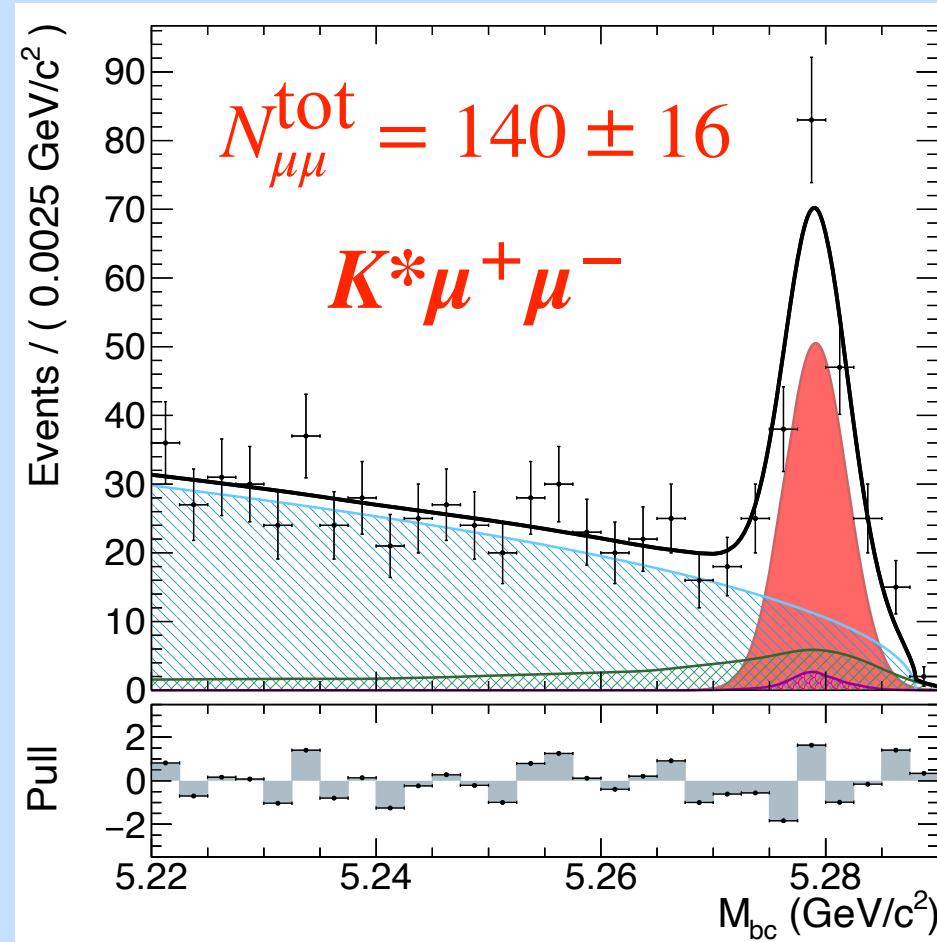
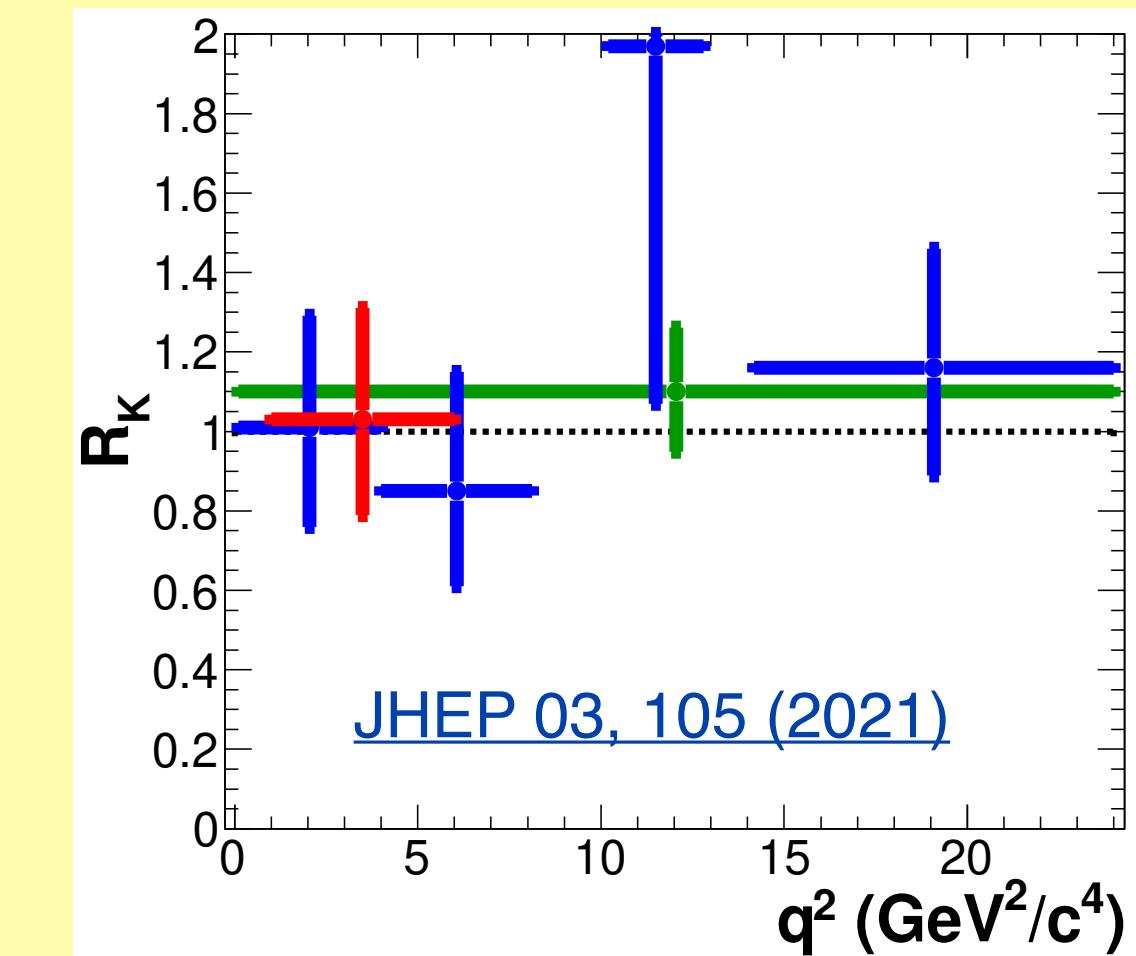
Electrons



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



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



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

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



[JHEP 08, 055 \(2017\)](#)

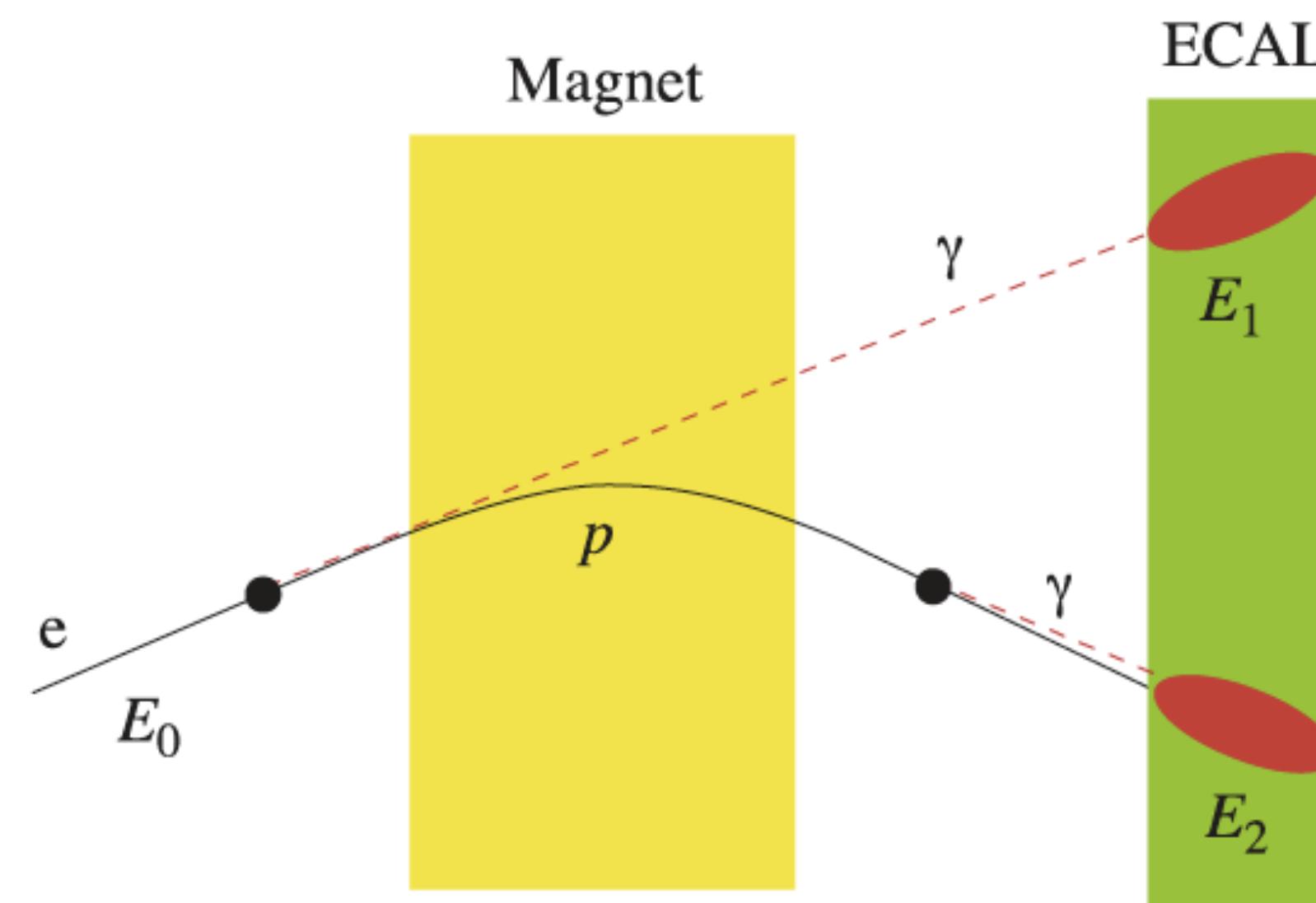
[arXiv 2103.11769](#)

Fresh!

LHCb
FNAL

~ Measurements of $\mathcal{R}_{K^{*0}}$ (3 fb $^{-1}$) and \mathcal{R}_{K^+} (9 fb $^{-1}$)

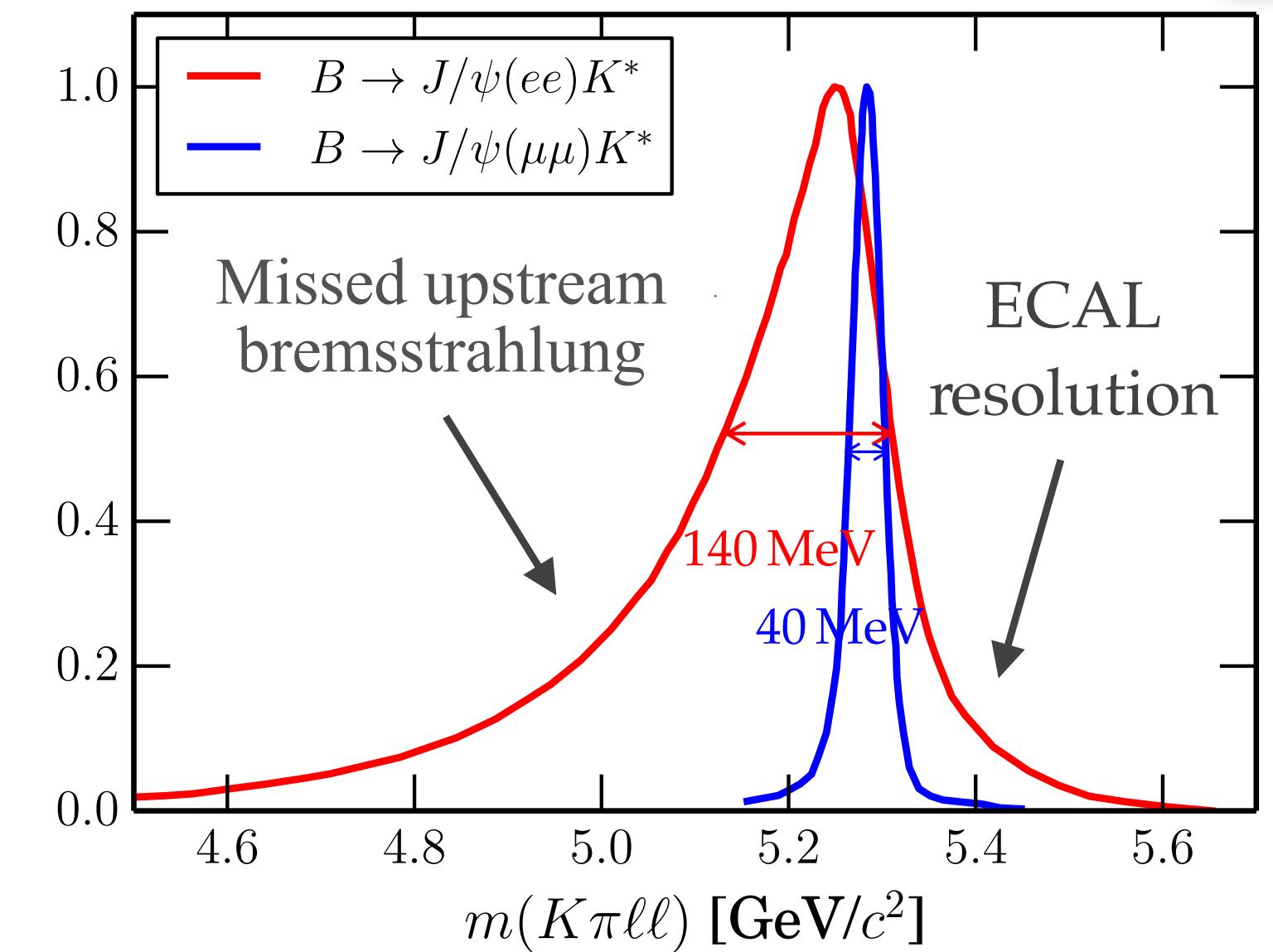
~ At LHCb, **electrons** are **major challenge**



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 $B \rightarrow K^{(*)} J/\psi(\rightarrow \ell\ell)$

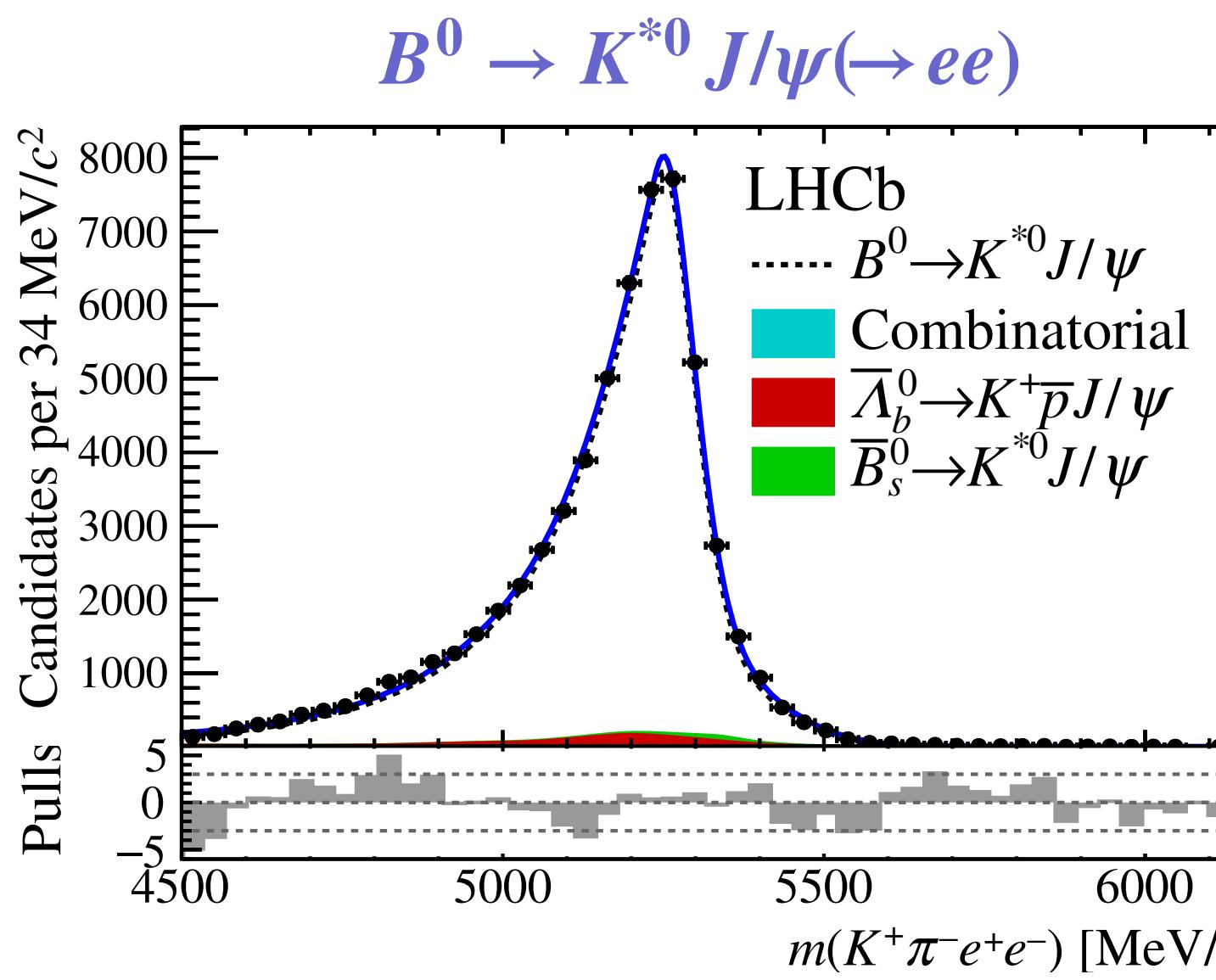
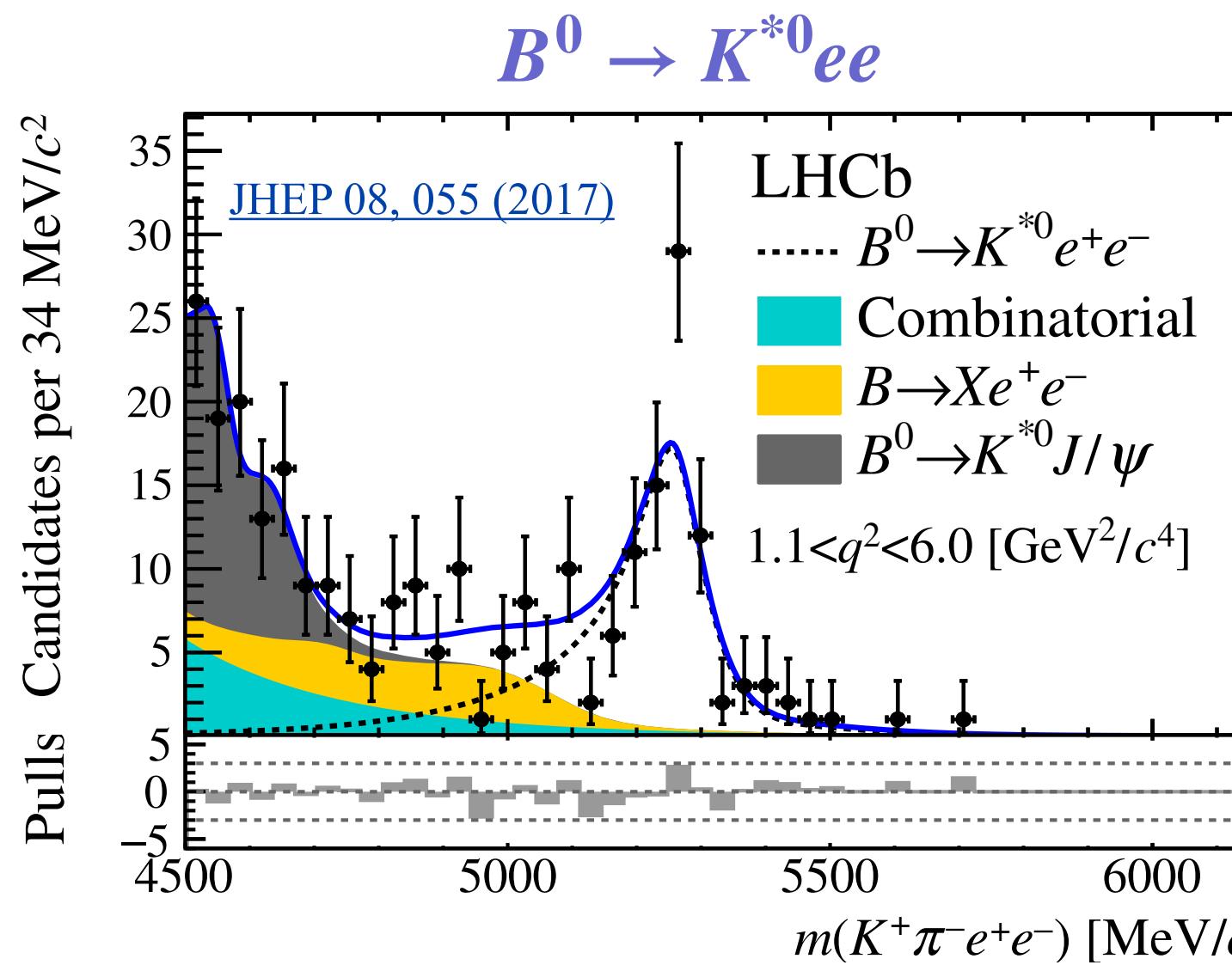
$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))} / \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))}$$

$$= \frac{N_{\mu^+ \mu^-}^{\text{rare}} \varepsilon_{\mu^+ \mu^-}^{J/\psi}}{N_{\mu^+ \mu^-}^{J/\psi} \varepsilon_{\mu^+ \mu^-}^{\text{rare}}} \times \frac{N_{e^+ e^-}^{J/\psi} \varepsilon_{e^+ e^-}^{\text{rare}}}{N_{e^+ e^-}^{\text{rare}} \varepsilon_{e^+ e^-}^{J/\psi}}$$

LFU $\mathcal{R}_{K^{(*)}}$ at LHCb: bkgs & signal shape



LHCb
FRACP



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

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



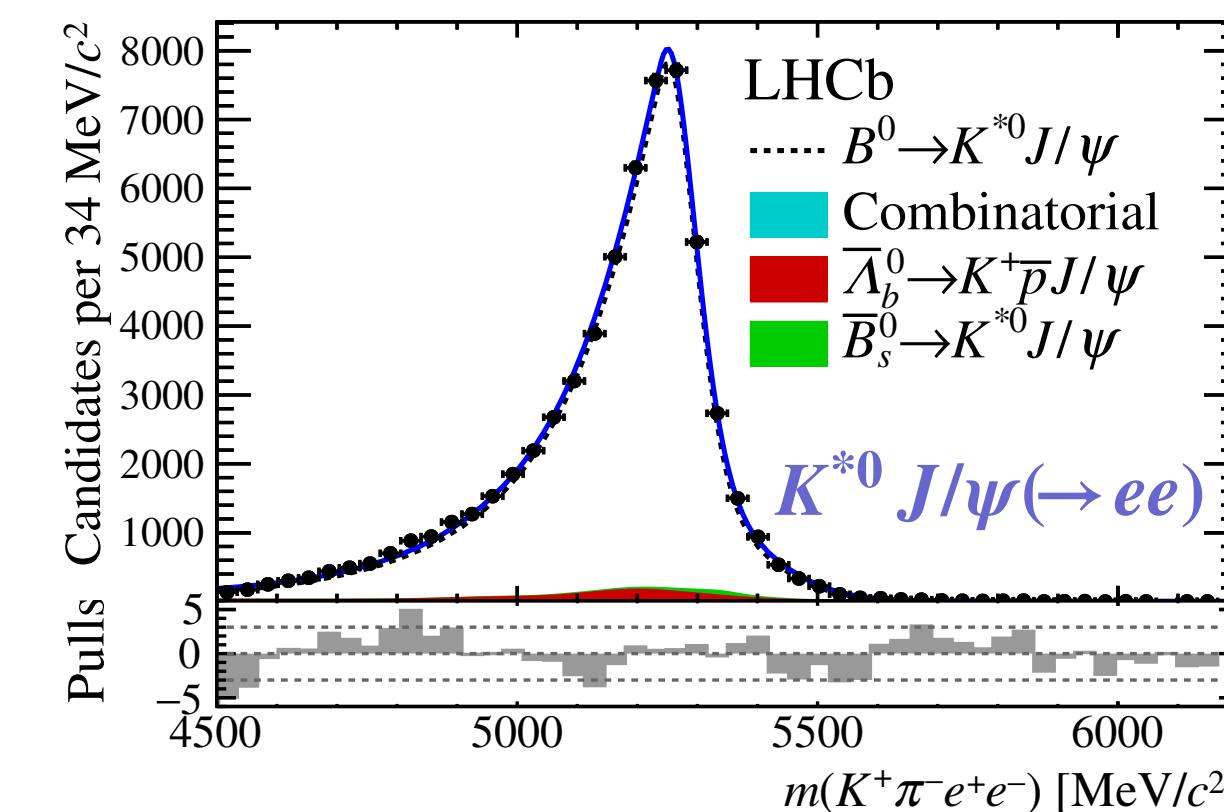
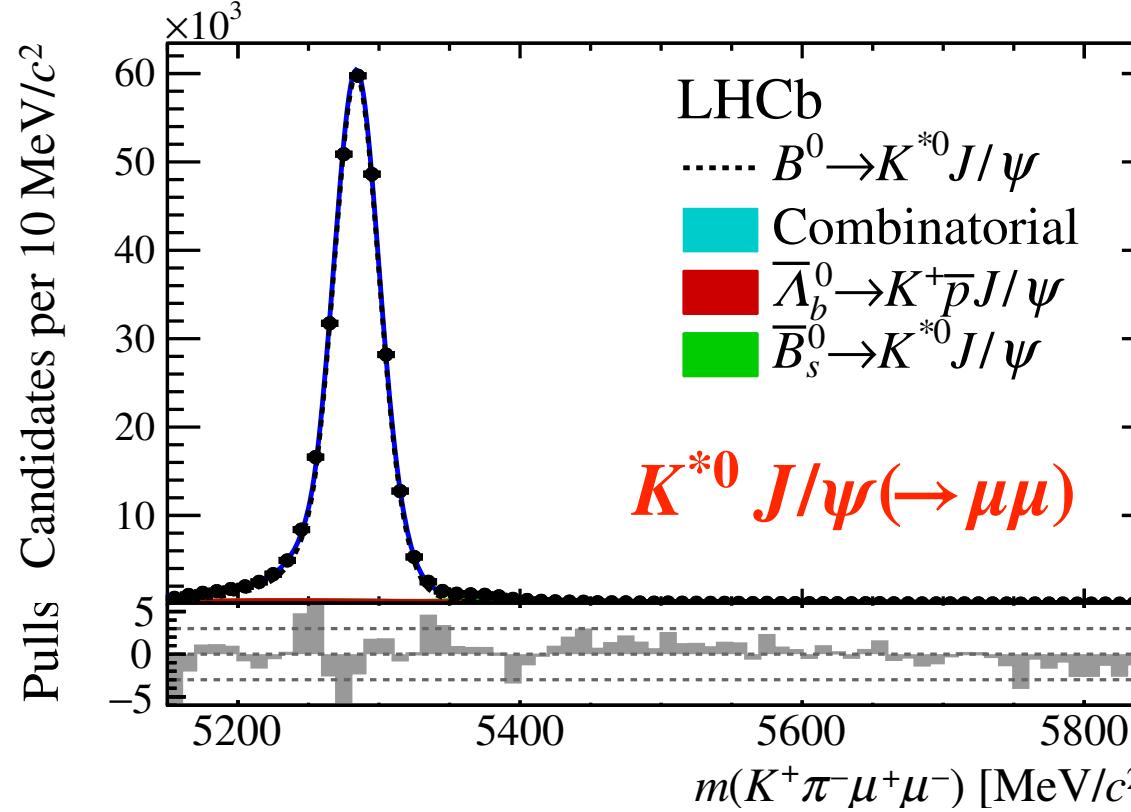
- ~ Rare and J/ Ψ events have **identical final states, difference only q^2**

LHCb
FACP

→ Check if we understand ϵ with

$$r_{J/\psi}^{K^{(*)}} = \frac{\mathcal{B}[B \rightarrow K^{(*)} J/\psi(\rightarrow \mu\mu)]}{\mathcal{B}[B \rightarrow K^{(*)} J/\psi(\rightarrow ee)]} = 1$$

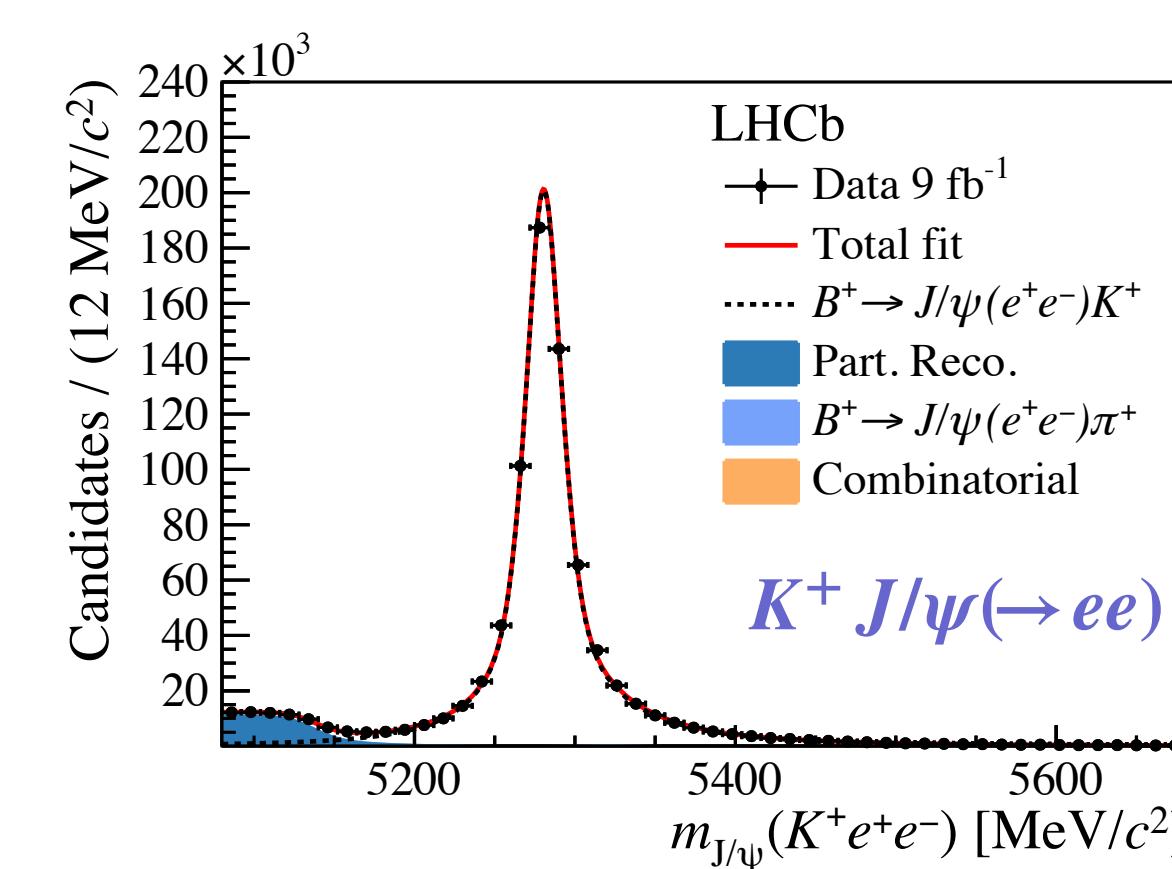
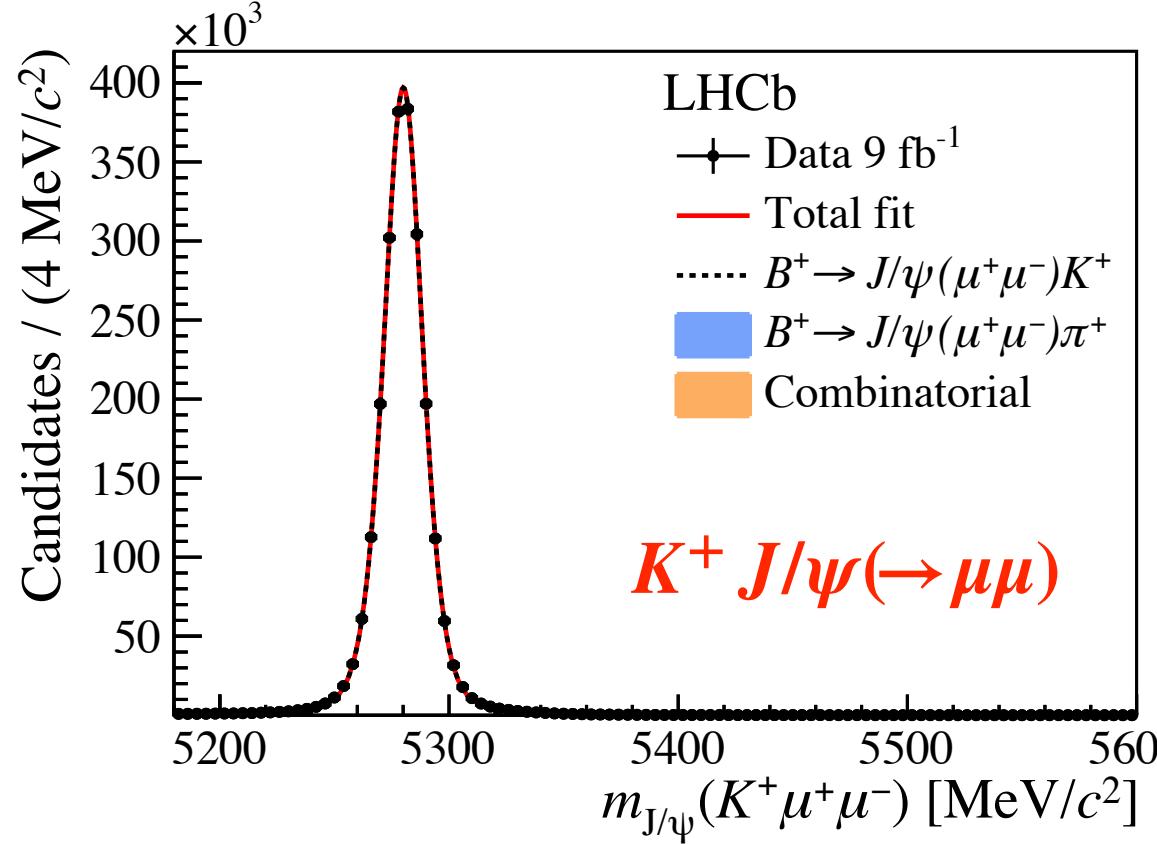
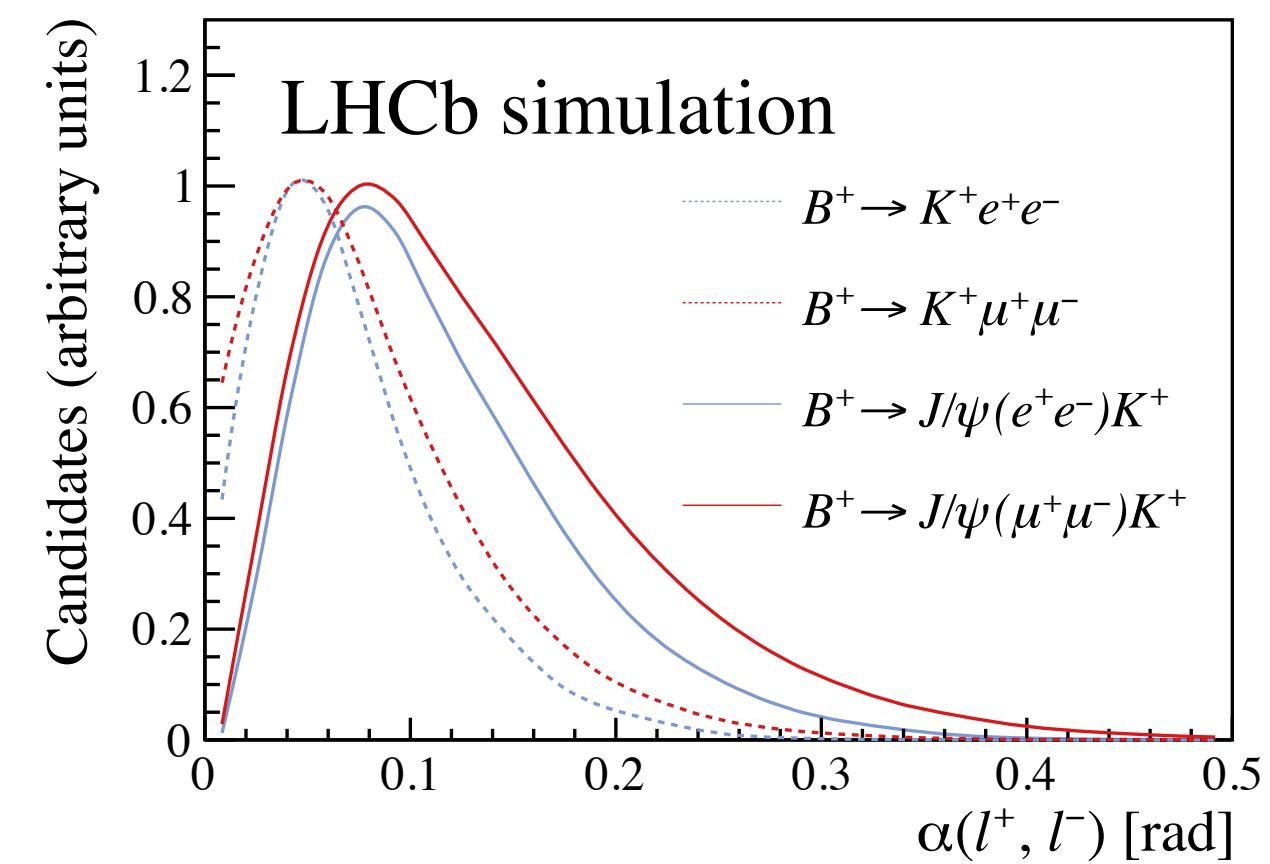
Also in bins of lab angle, p_T



[JHEP 08, 055 \(2017\)](#)

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

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

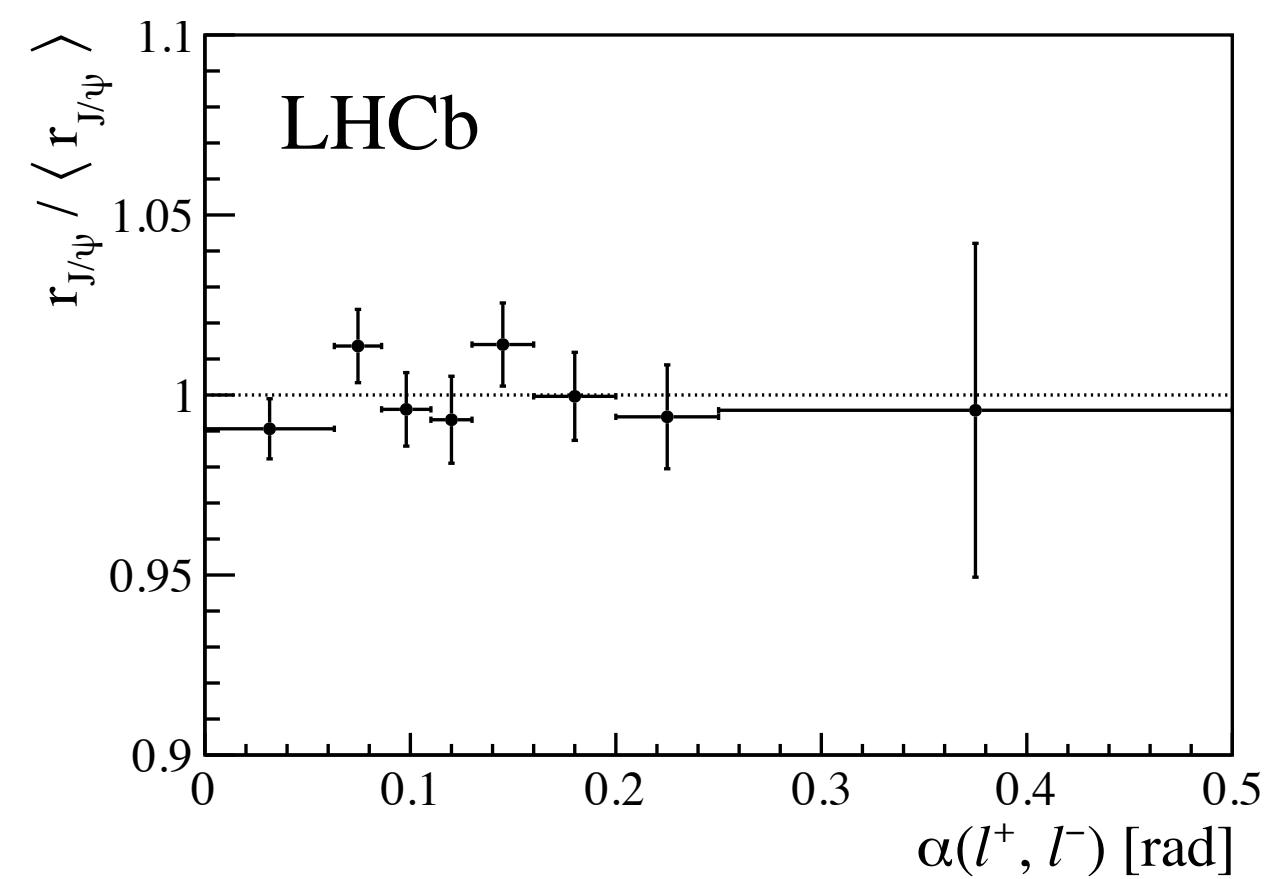


[arXiv 2103.11769](#)

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

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

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

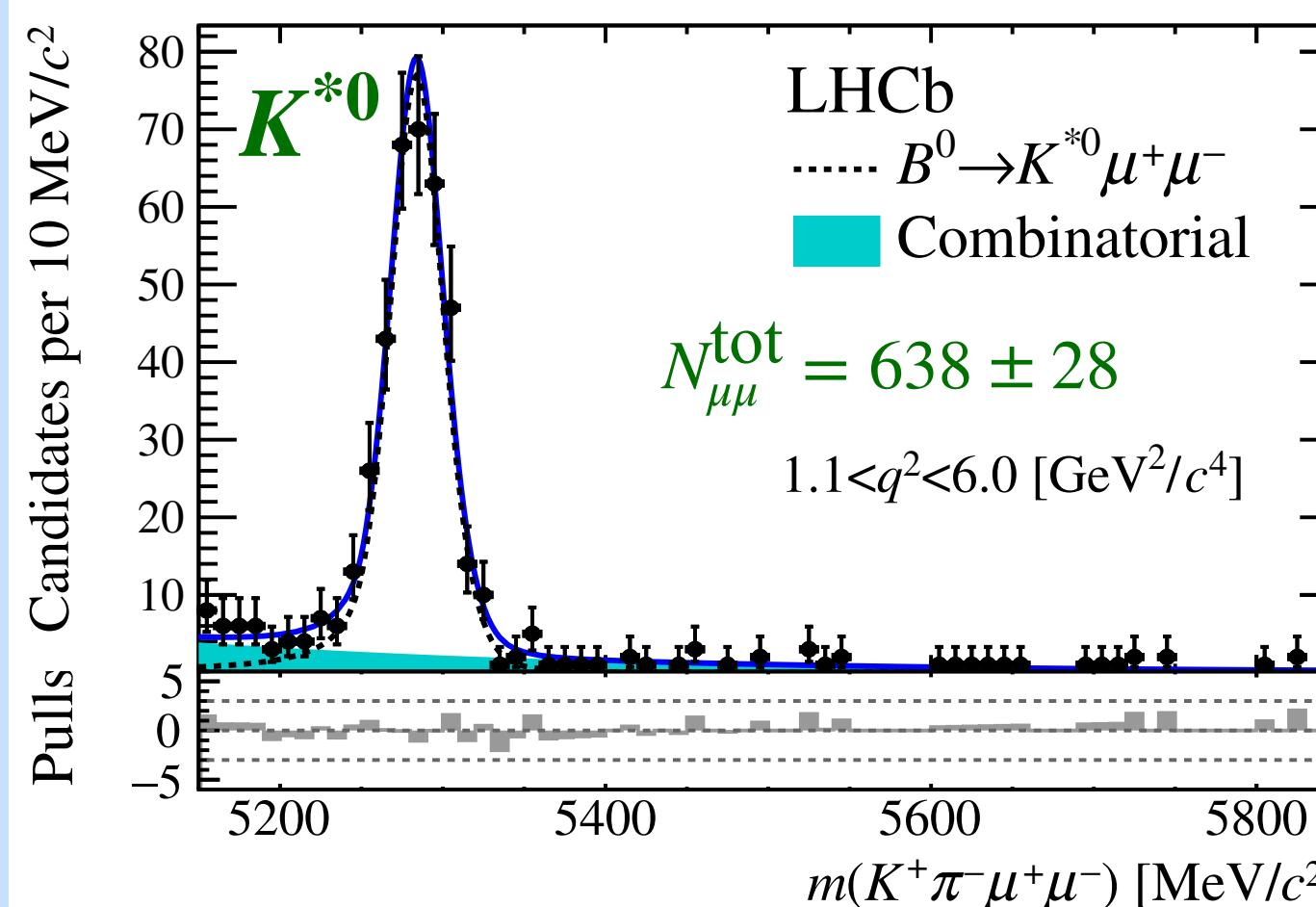


LFU $\mathcal{R}_{K^{(*)}}$ at LHCb: results

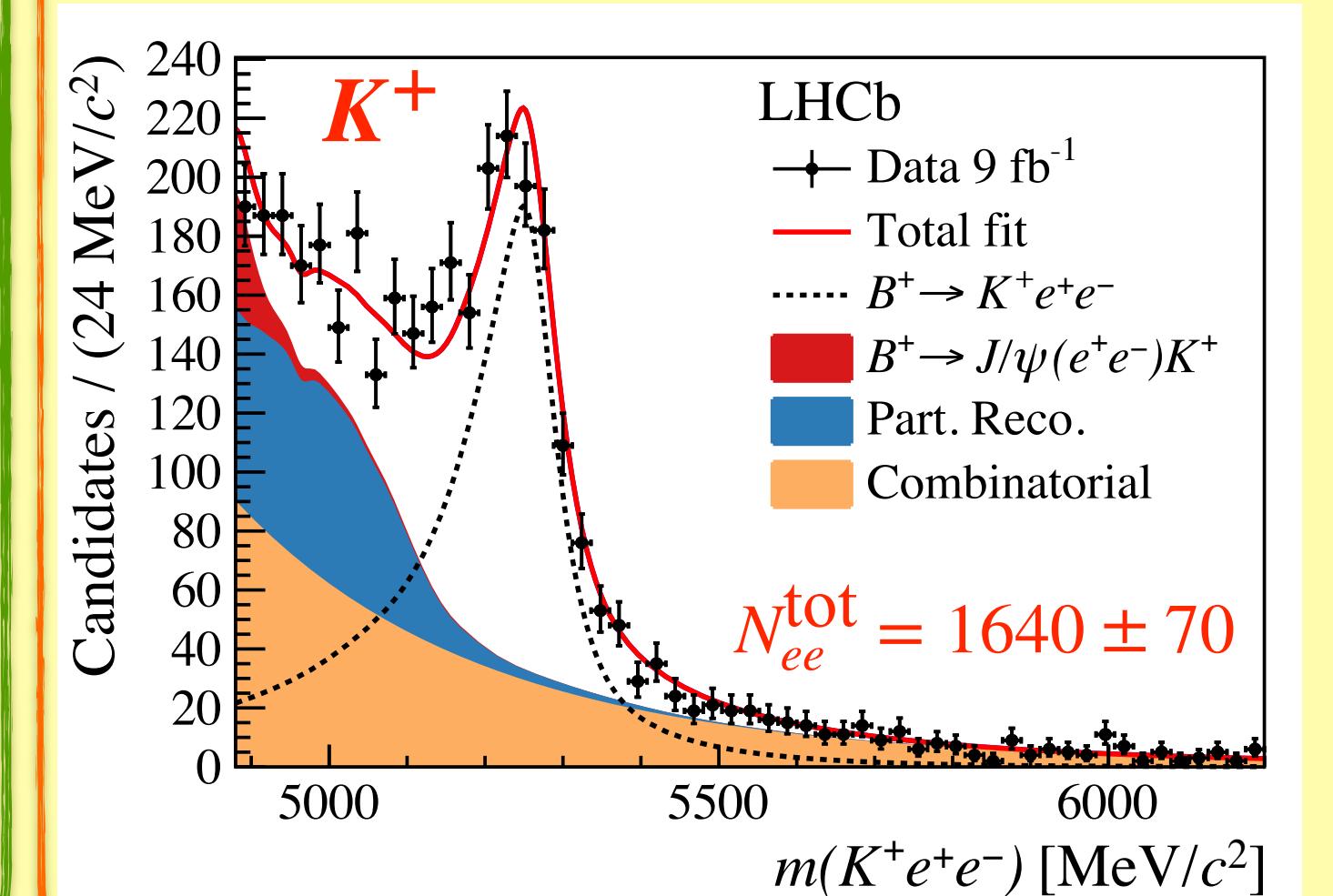
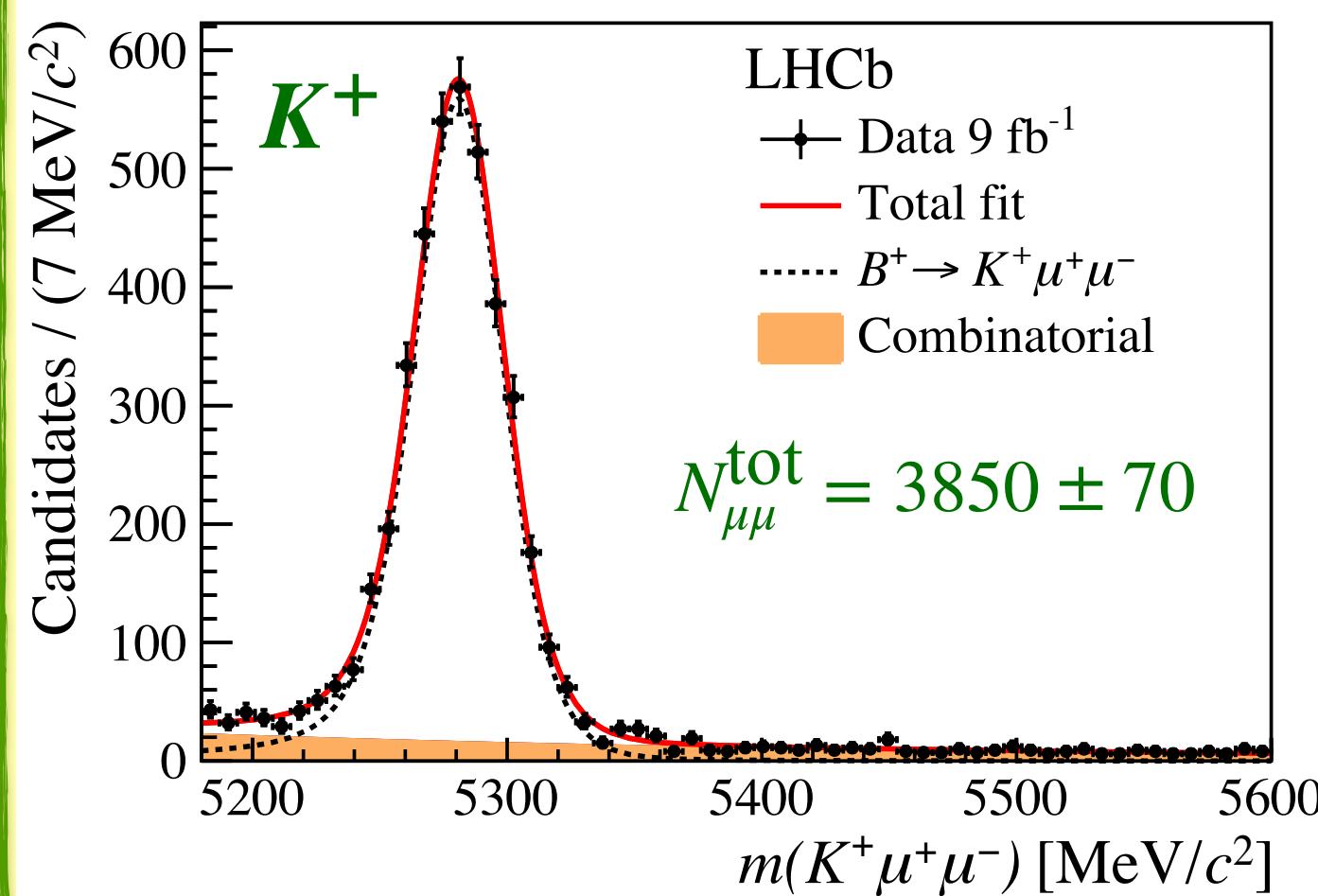
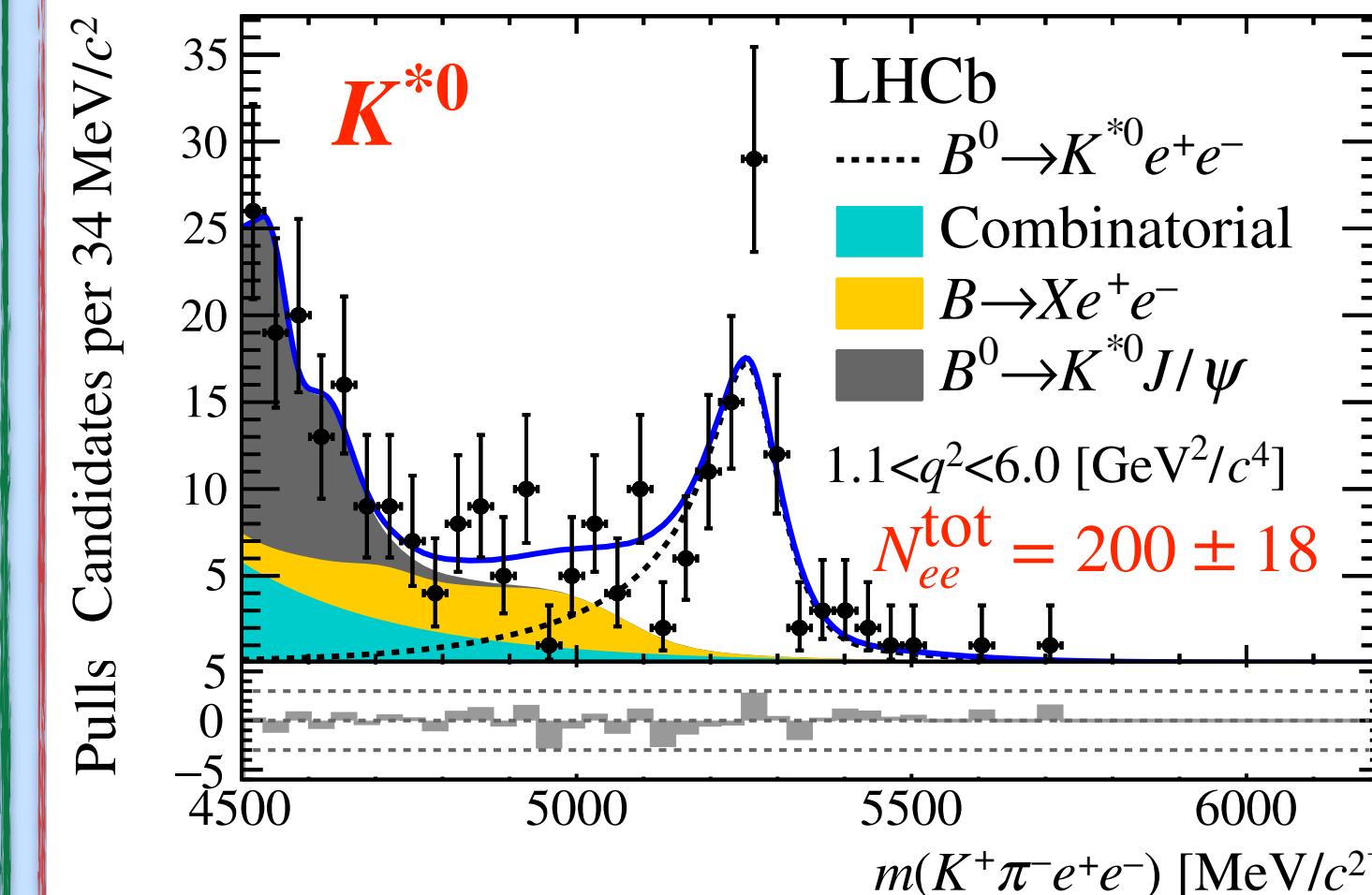


LHCb
FCC-SP

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



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



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

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

2.1 σ below SM [JHEP 08, 055 \(2017\)](https://arxiv.org/abs/1708.055)

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

2.4 σ below SM

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

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

3.1 σ below SM

Fresh!

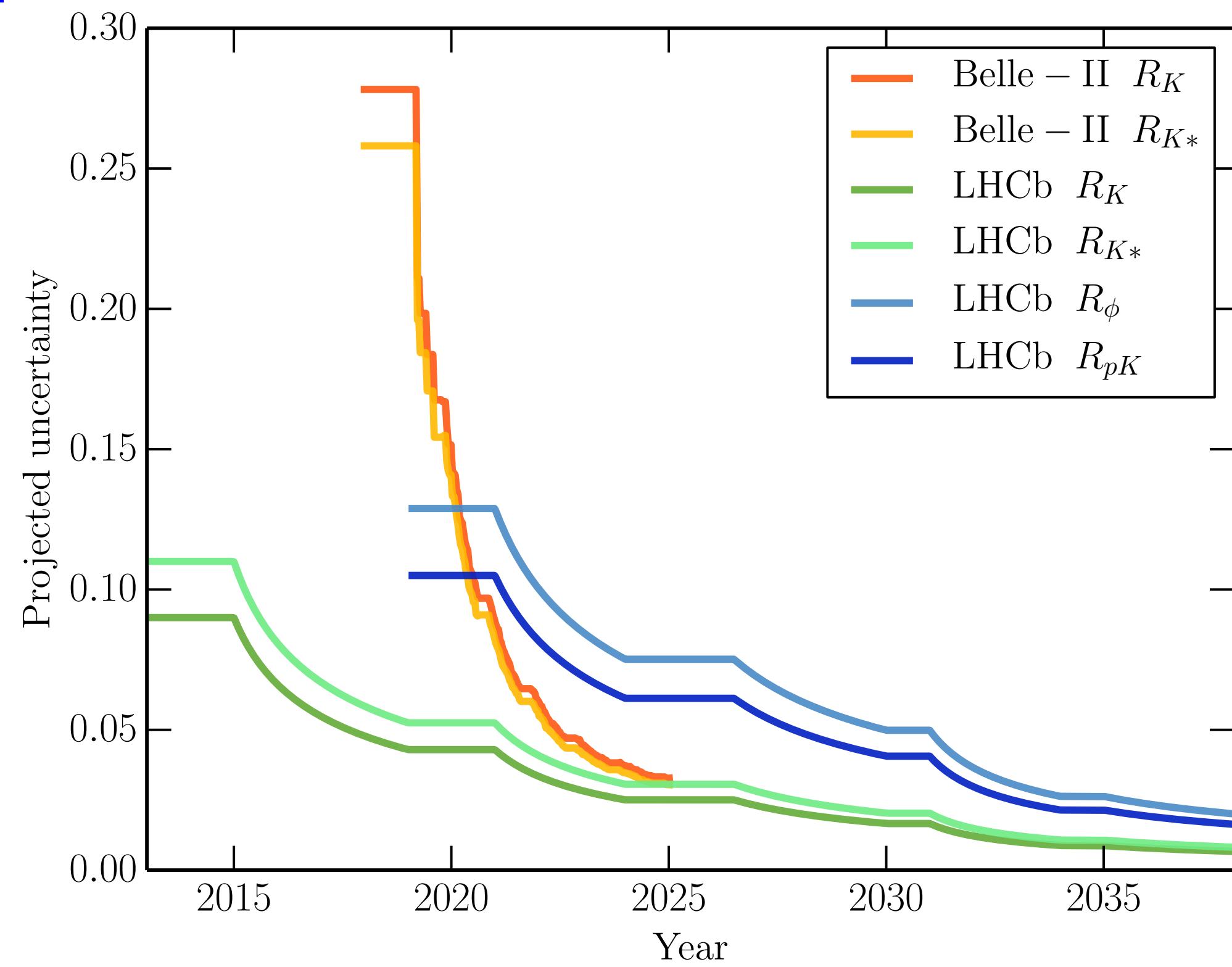
arXiv 2103.11769

Future prospects for LFU in $b \rightarrow s\ell\ell$

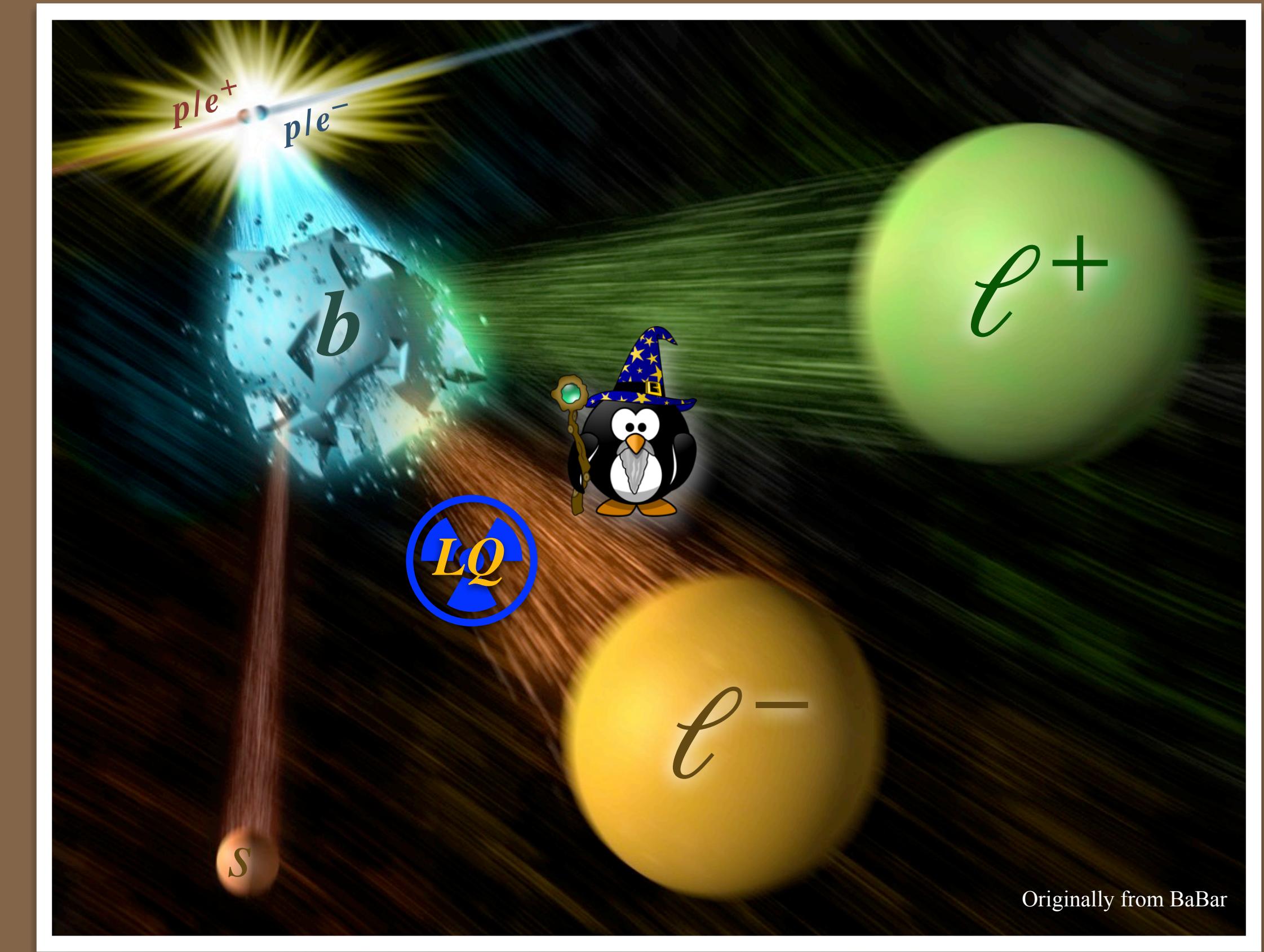
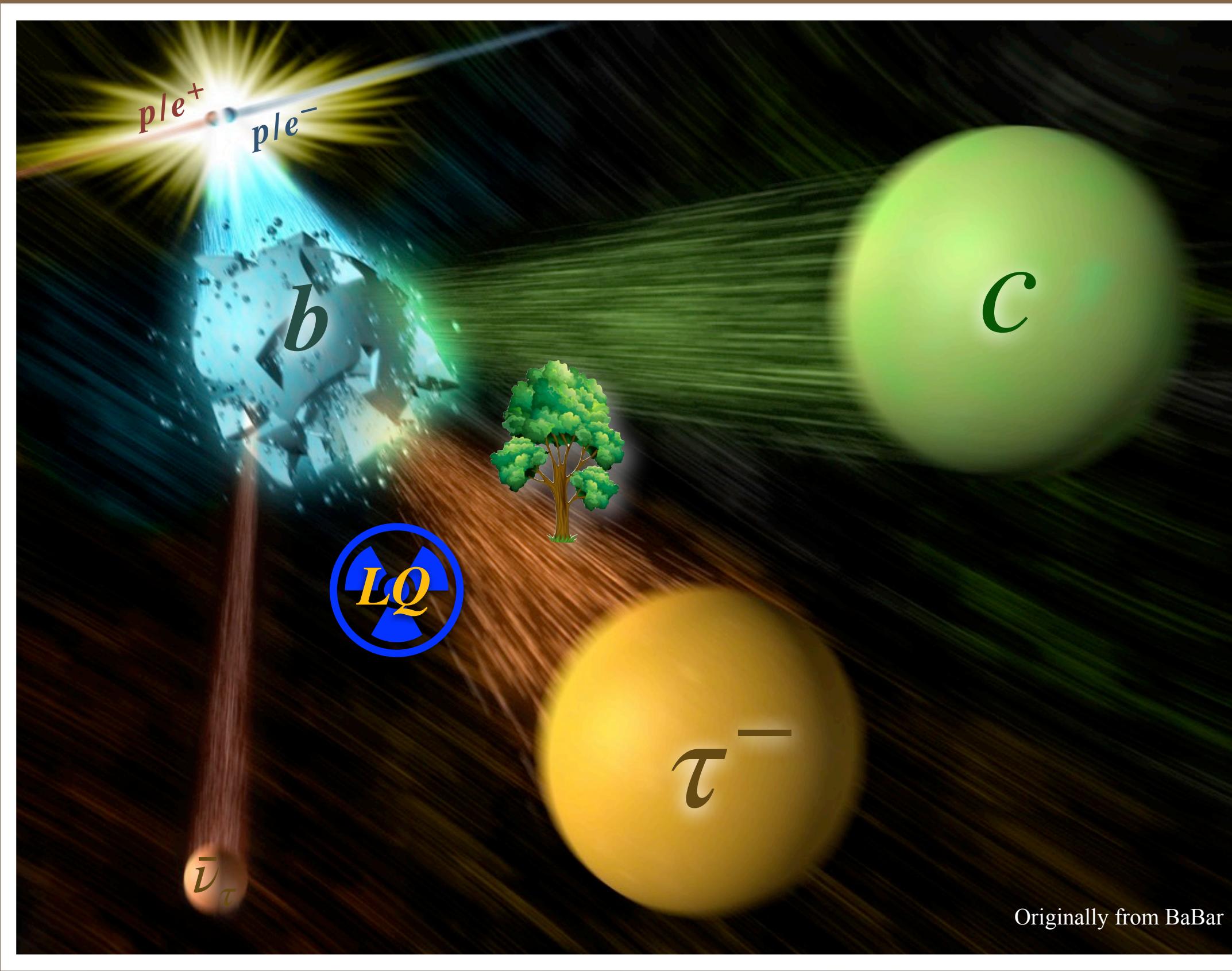


- ~ Currently, $\mathcal{R}_{K^{(*)}} \sim 15\text{-}30\% \text{ below SM}$
- ~ Uncertainties on LFU ratios expected to reach about 2-3% with 2025 LHCb dataset
- Belle II expected to take longer than in plot

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



One elegant interpretation



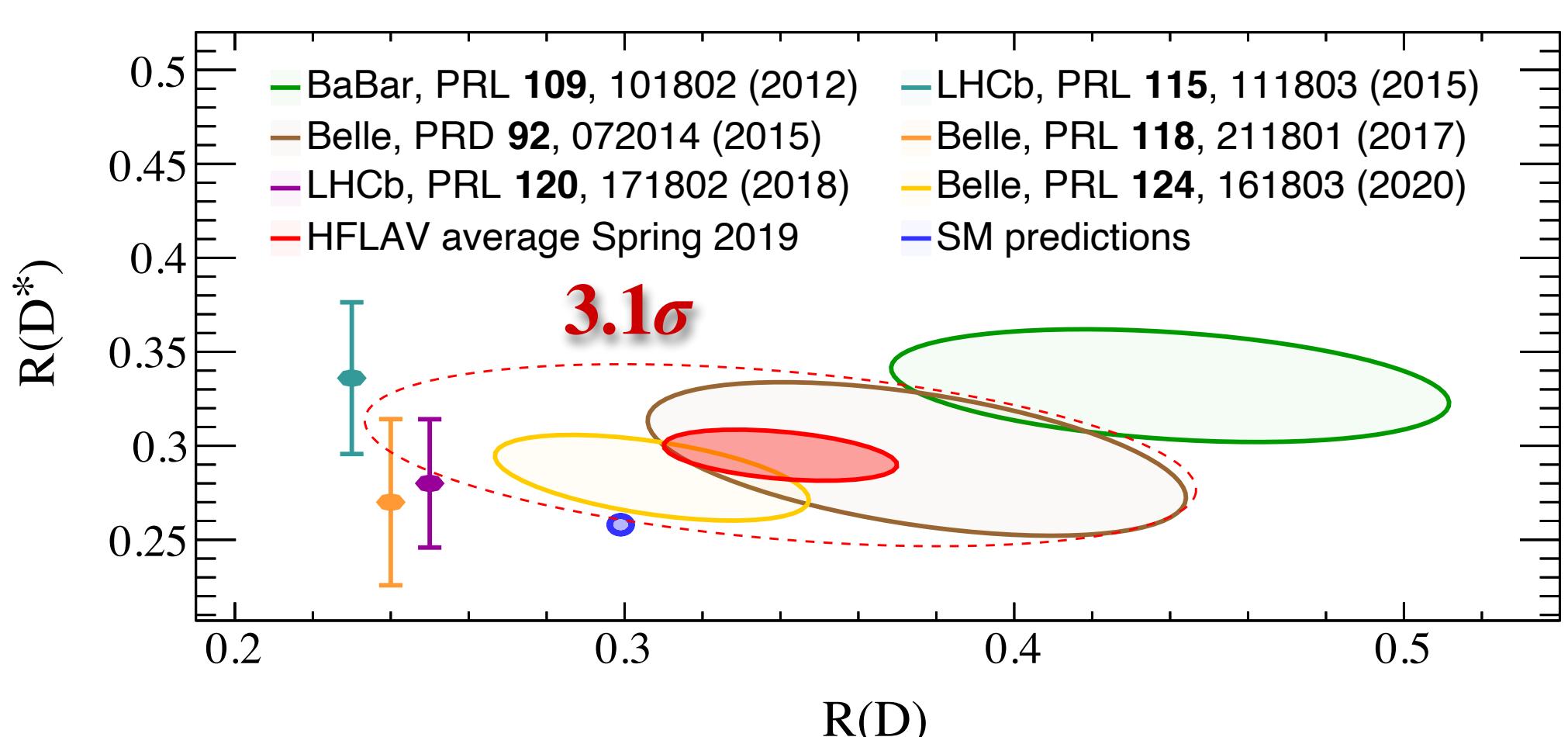
Based on *Isidori at APS April 2021* and *Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert - arXiv:2103.16558*

Anomalies recap



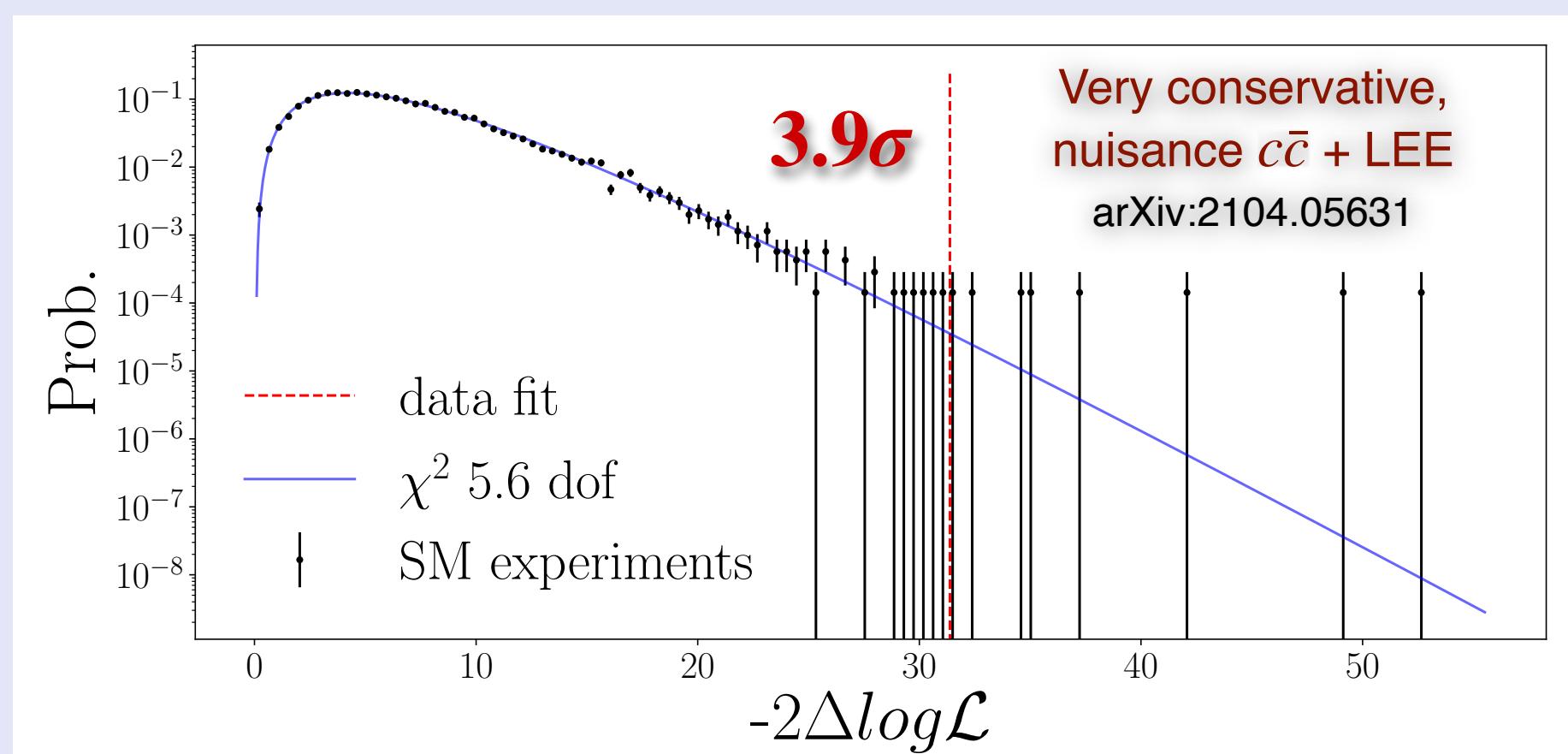
LFU results with $b \rightarrow c\tau\nu$

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



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

- **Deficit** in differential BF rates with μ
- 22% **deficit** in $B_{(s)}^0 \rightarrow \mu^+\mu^-$
- 15% **deficit** in \mathcal{R}_K
- $\sim 30\%$ **deficit** in \mathcal{R}_{K^*}
- Disagreement in $B \rightarrow K^*\ell\ell$ angular P'_5



EFT for $b \rightarrow s\ell\ell$



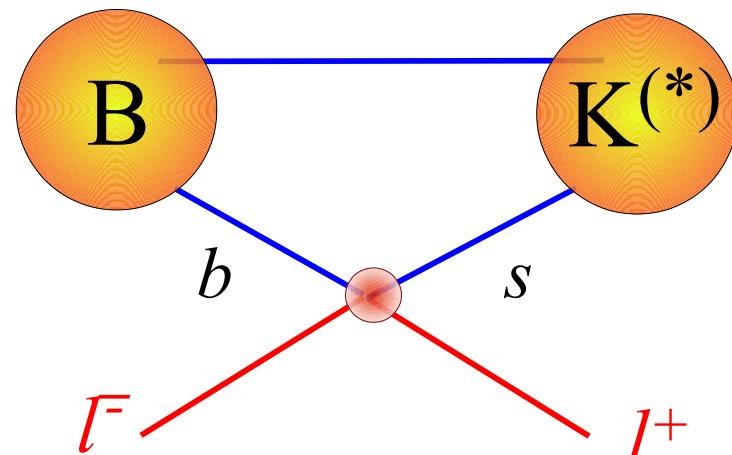
- ~ **Dimension-6 operators** identified as relevant set for combined **explanation of both anomalies**

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

FCNC operators:

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

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

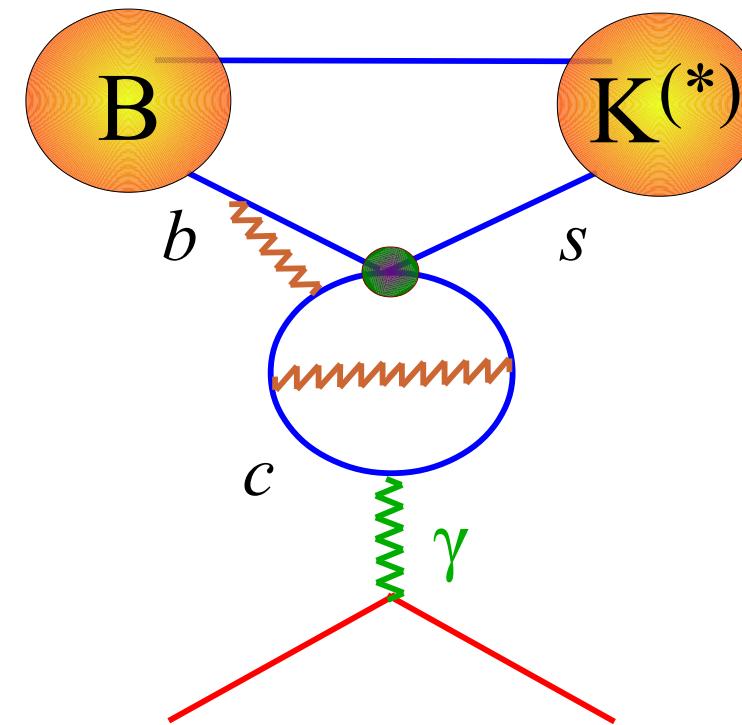


Easy and "clean"

Four-quark operators:

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

⋮



Difficult and "dirty"

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

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

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

Separate NP contributions between Lepton Flavor Universal

$$\Delta C_{9,10}^U \equiv C_{9,10}^e - C_{9,10}^{SM}$$

and **LFU-breaking**

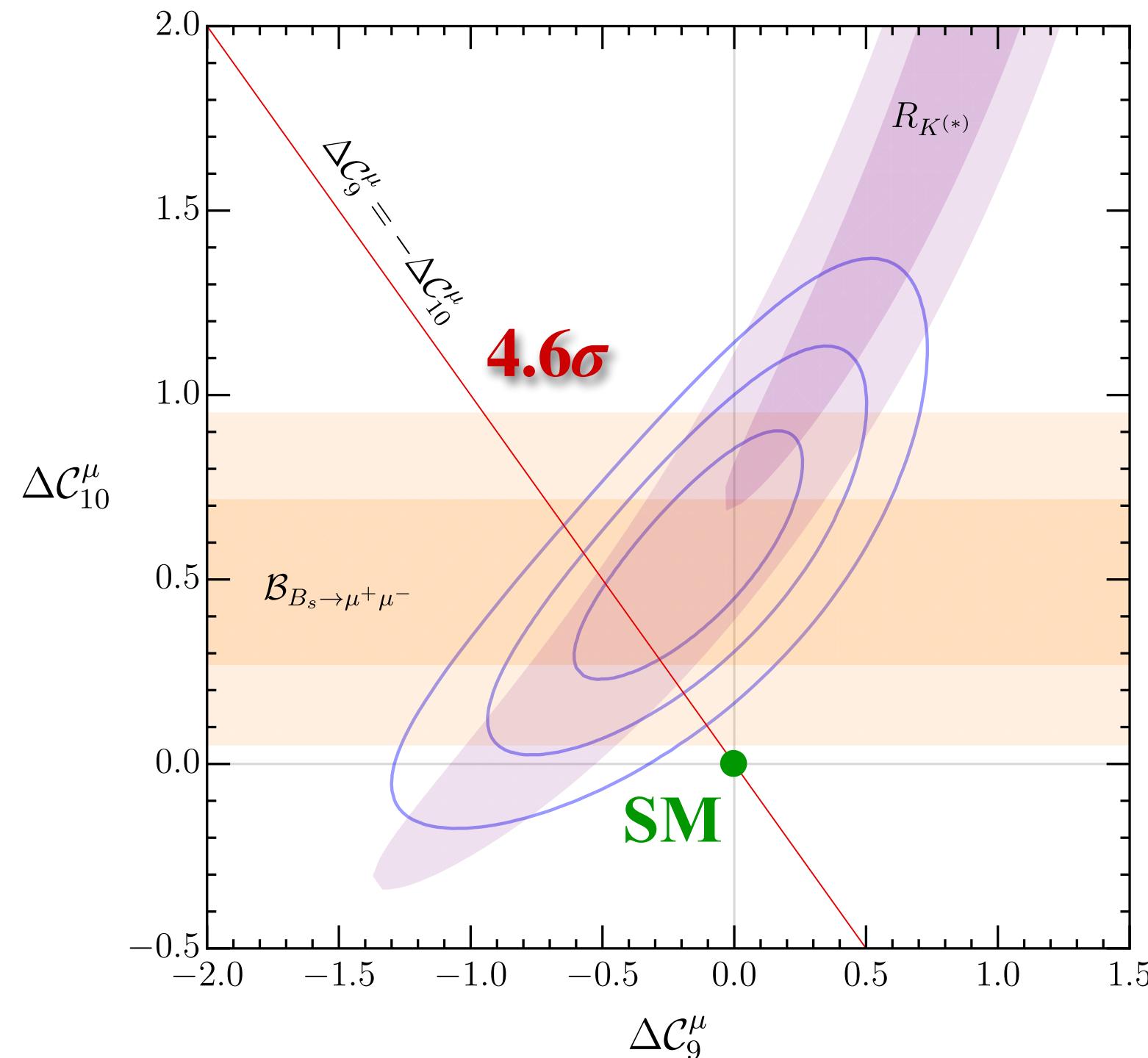
$$\Delta C_{9,10}^\mu \equiv C_{9,10}^\mu - C_{9,10}^e = C_{9,10}^\mu - (C_{9,10}^{SM} + \Delta C_{9,10}^U)$$

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

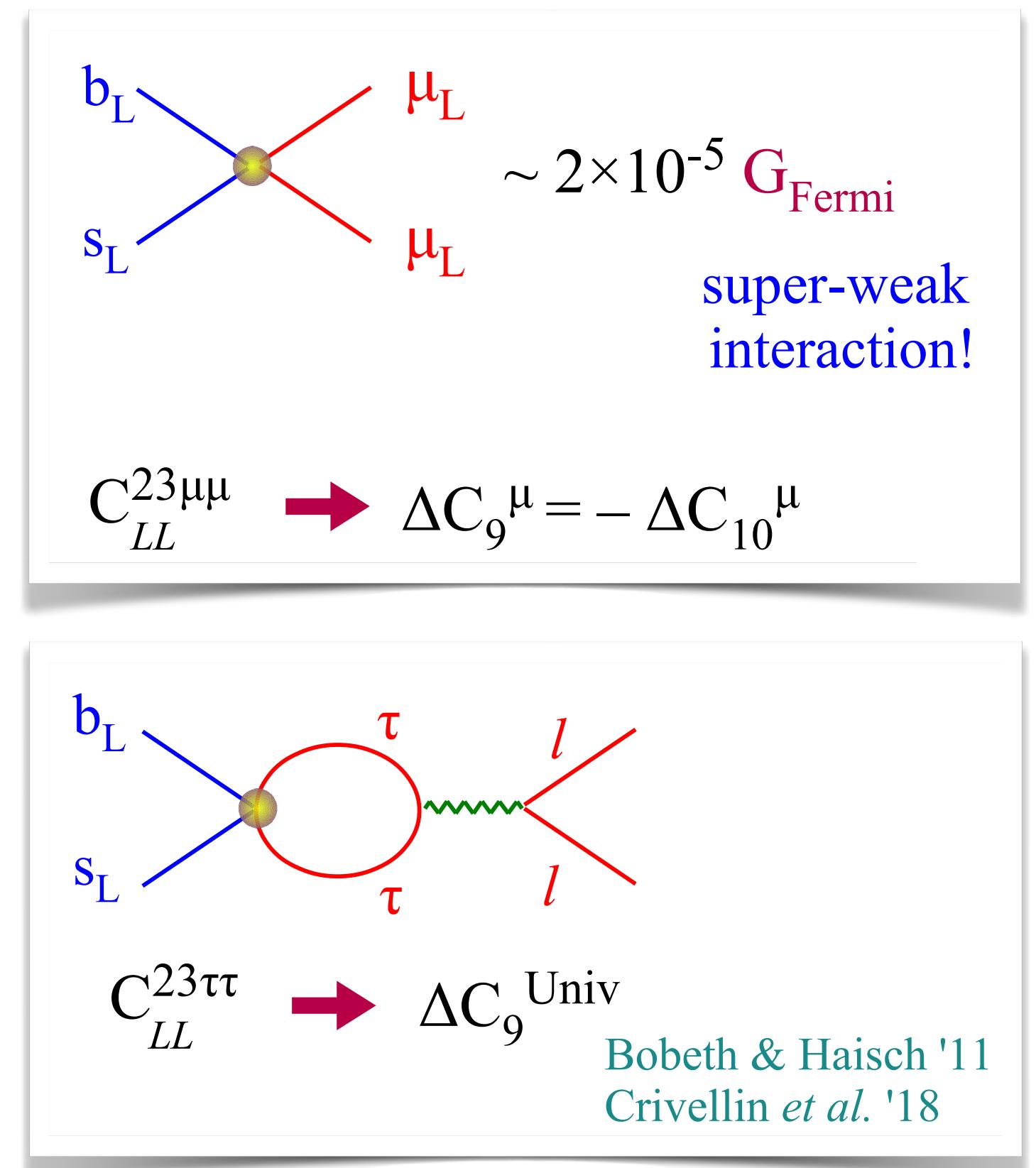
EFT fits for $b \rightarrow s\ell\ell$



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

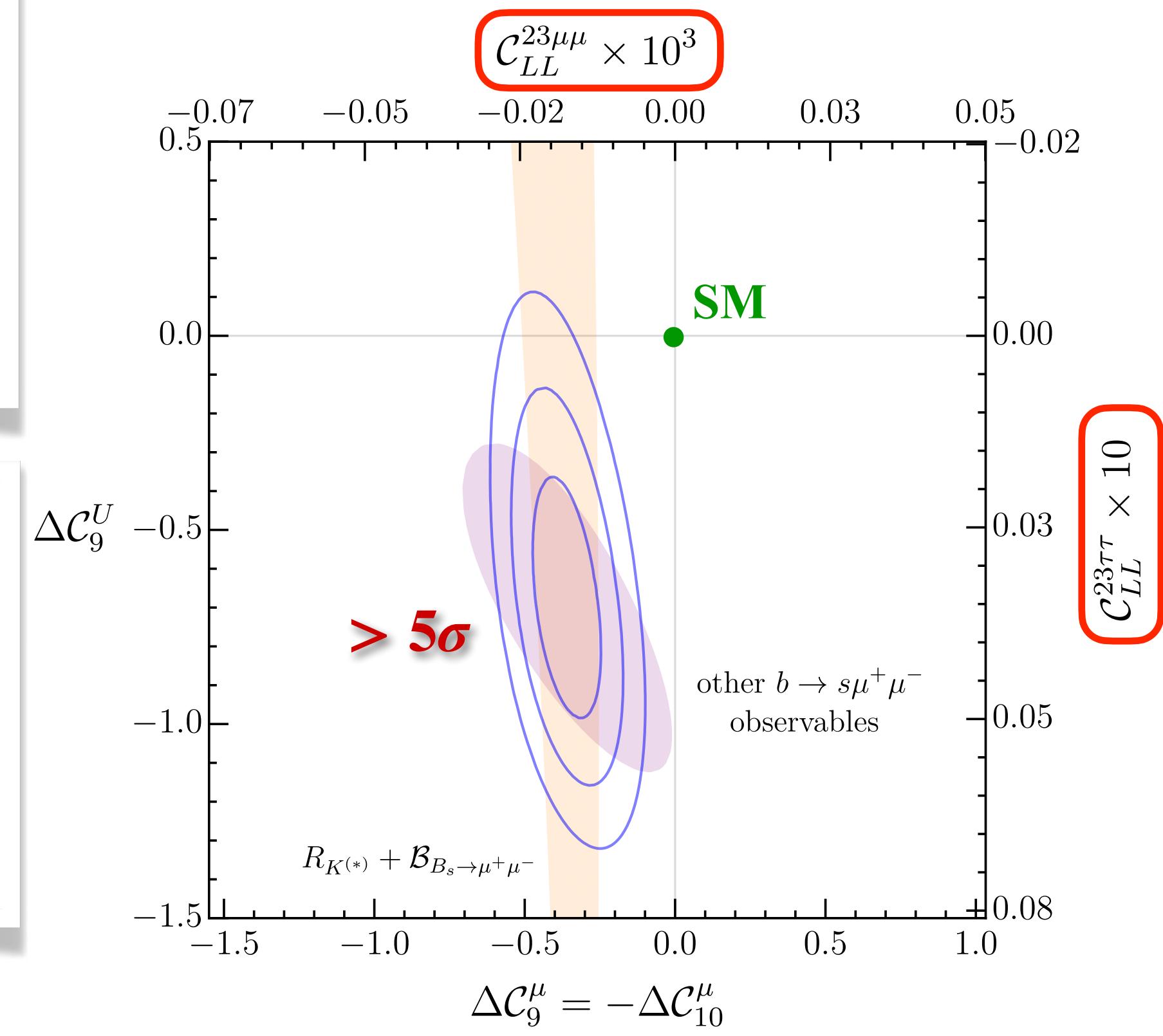


$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu q_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j) = \frac{1}{2} [Q_{lq}^{(1)} + Q_{lq}^{(3)}]^{\beta\alpha ij}$$



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

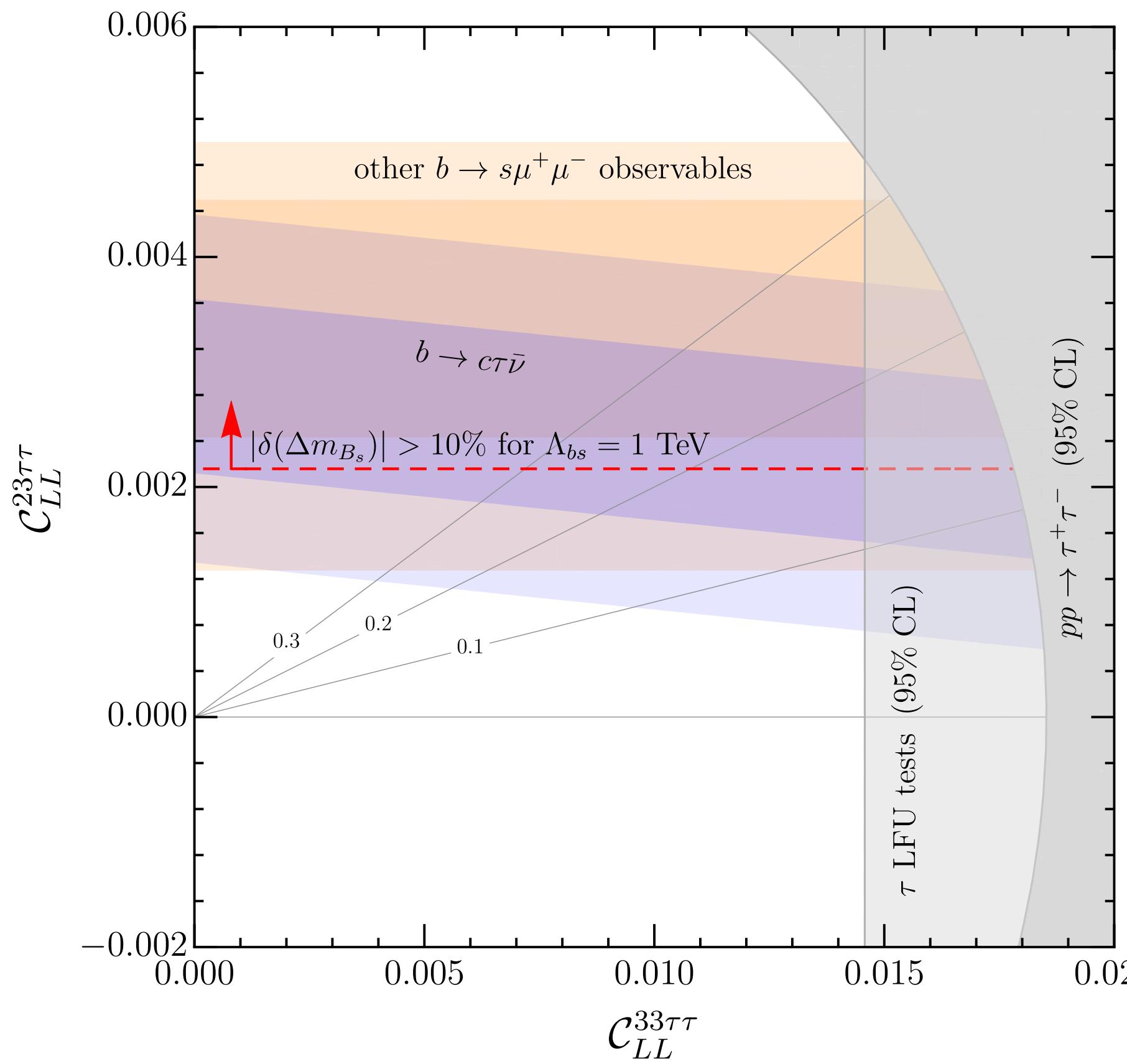
Fits to **clean** and **other observables** also consistent, away from SM



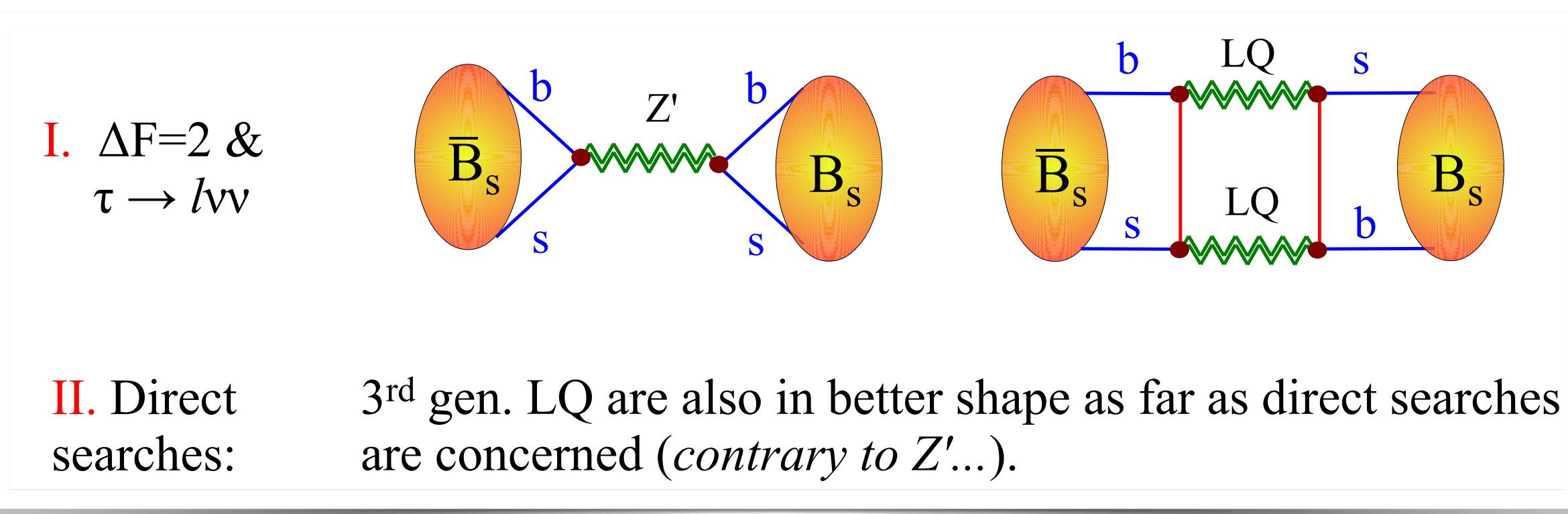
$b \rightarrow s\ell\ell$ and $b \rightarrow c\tau\nu$



$\sim b \rightarrow s\ell\ell$ and $b \rightarrow c\tau\nu$ give remarkably **consistent results**



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



- Additional $\sim 10^{-2}$ (~loop) suppression for
 - ✗ Four-quarks ($\Delta F=2$)
 - ✗ Four-leptons ($\tau \rightarrow \mu\nu\nu$)
 - ✗ Semi-leptonic $O^{(1-3)}$ ($b \rightarrow svv$)

U_1 leptoquark fits all low-energy data



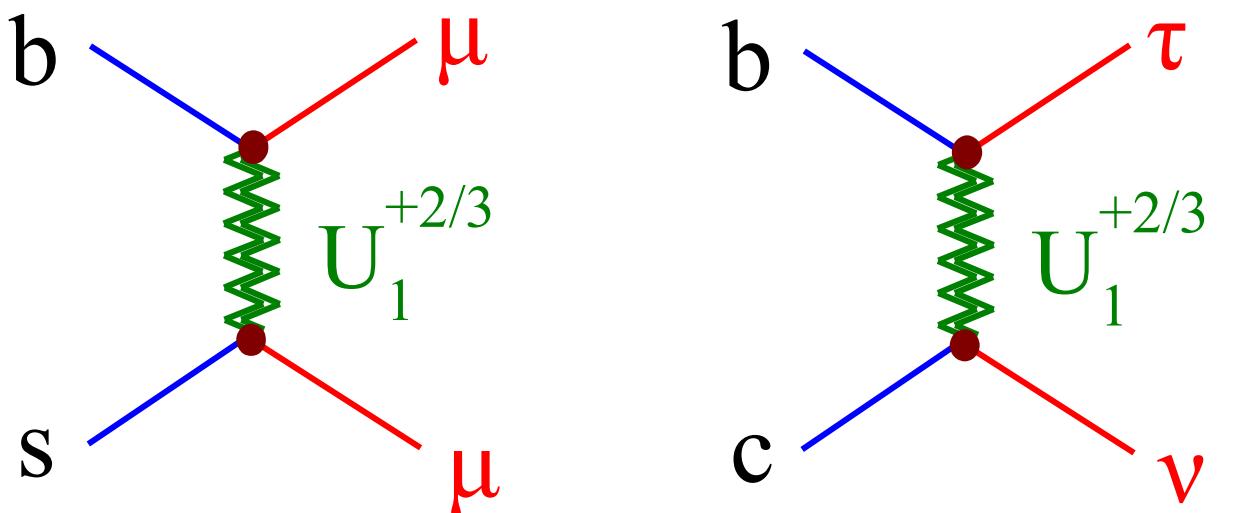
“Renaissance” of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
 - 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 as techni-fermion resonances
 - Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17
- Scalar LQ from GUTs & SUSY
 - Megias, Quiros, Salas '17 Megias, Panico, Pujolas, Quiros '17 Blanke, Crivellin, '18
- LQ as Kaluza-Klein excit.
 - Assad *et al.* '17 Di Luzio *et al.* '17 Bordone *et al.* '17 Heeck & Teresi '18 + ...

Which LQ explains which anomaly?

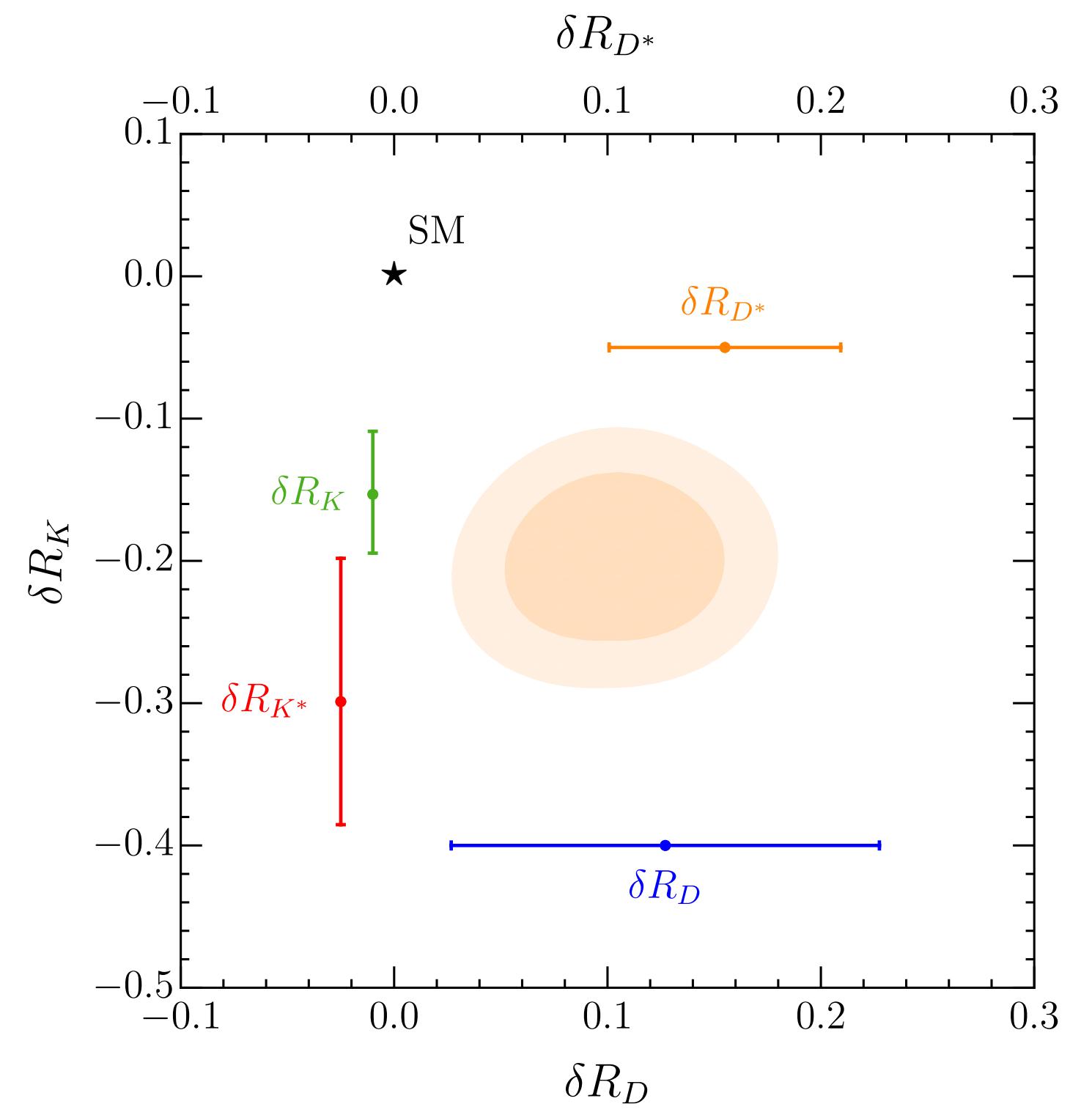
| Model | $R_{K(*)}$ | $R_{D(*)}$ | $R_{K(*)} \& R_{D(*)}$ |
|------------------------------|------------|------------|------------------------|
| $S_1 = (3, 1)_{-1/3}$ | ✗ | ✓ | ✗ |
| $R_2 = (3, 2)_{7/6}$ | ✗ | ✓ | ✗ |
| $\tilde{R}_2 = (3, 2)_{1/6}$ | ✗ | ✗ | ✗ |
| $S_3 = (3, 3)_{-1/3}$ | ✓ | ✗ | ✗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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



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

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

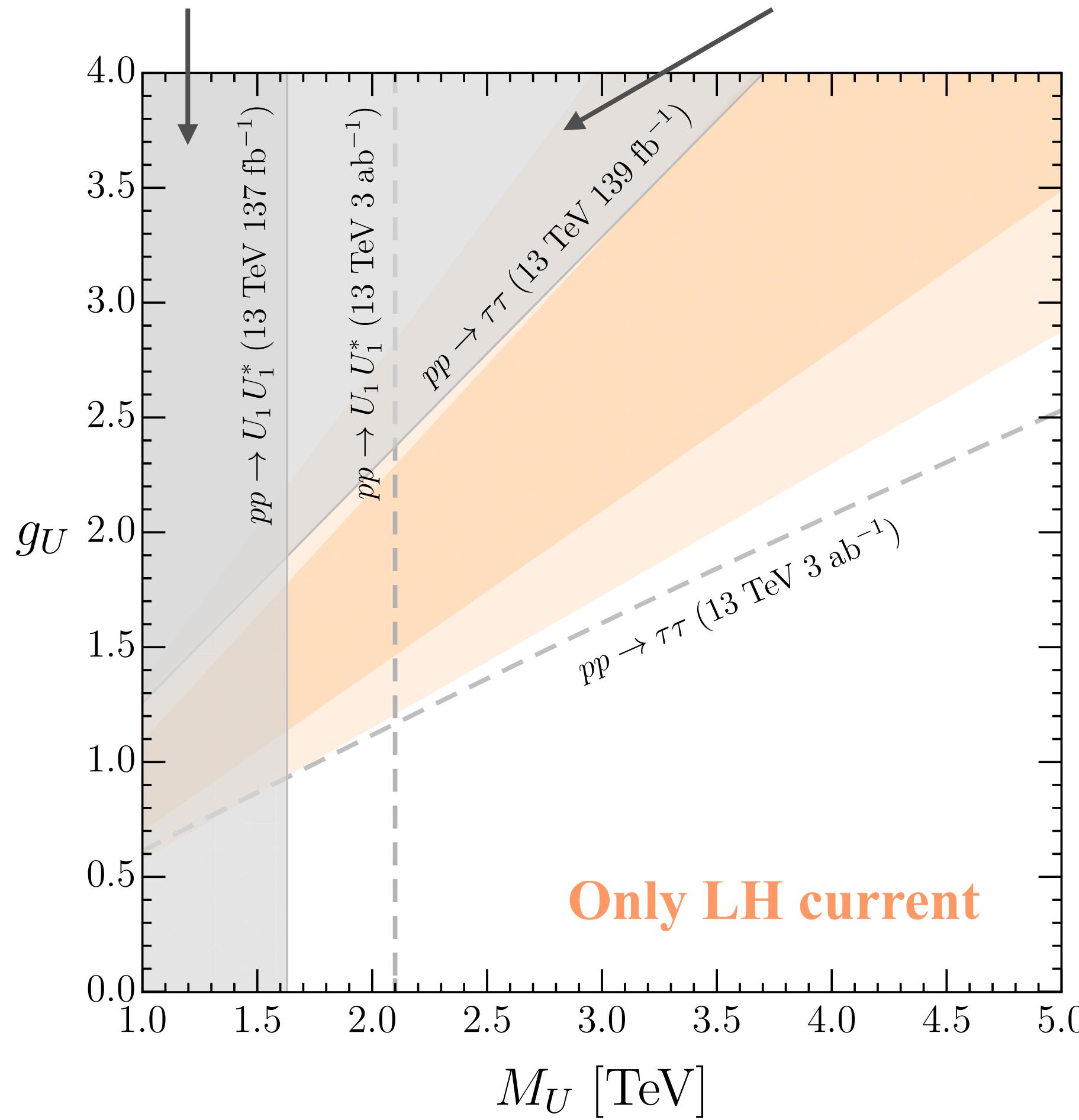


Isidori at APS April 2021,
arXiv:2103.16558

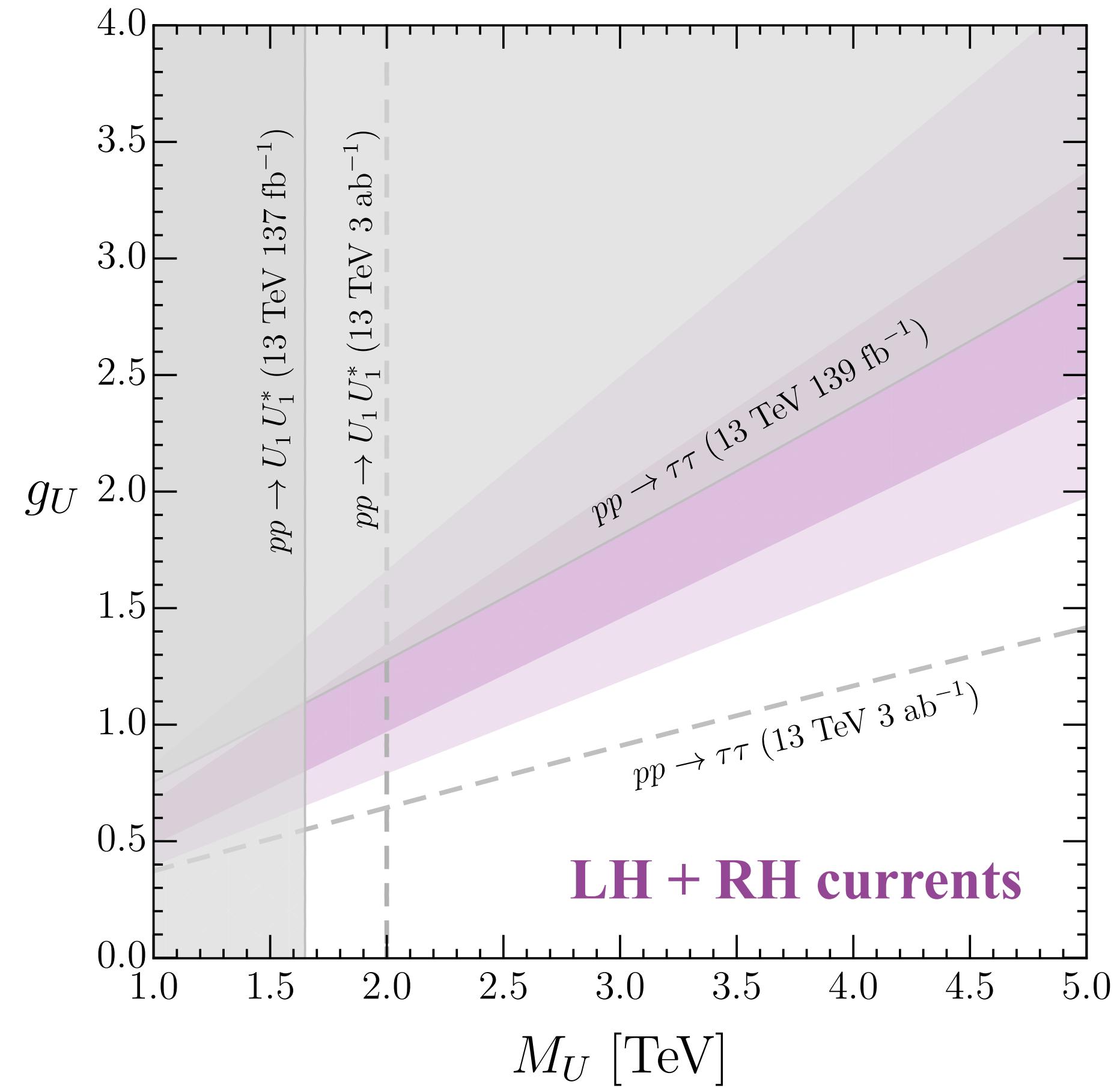
U_1 leptoquark within reach



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, $b \rightarrow d\mu\mu$, $b \rightarrow s\tau\tau$,
 $b \rightarrow s\tau\mu$, B_s mixing,
 $b \rightarrow s\nu\nu$, $\tau \rightarrow \mu\mu\mu$

Conclusions



- ~ **Excesses** in decays involving $b \rightarrow c\tau\nu$ transitions
 - 3.1σ significance
- ~ **Deficits** in decays involving $b \rightarrow s\mu\mu$ 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

