The State of Rare B Decay Anomalies

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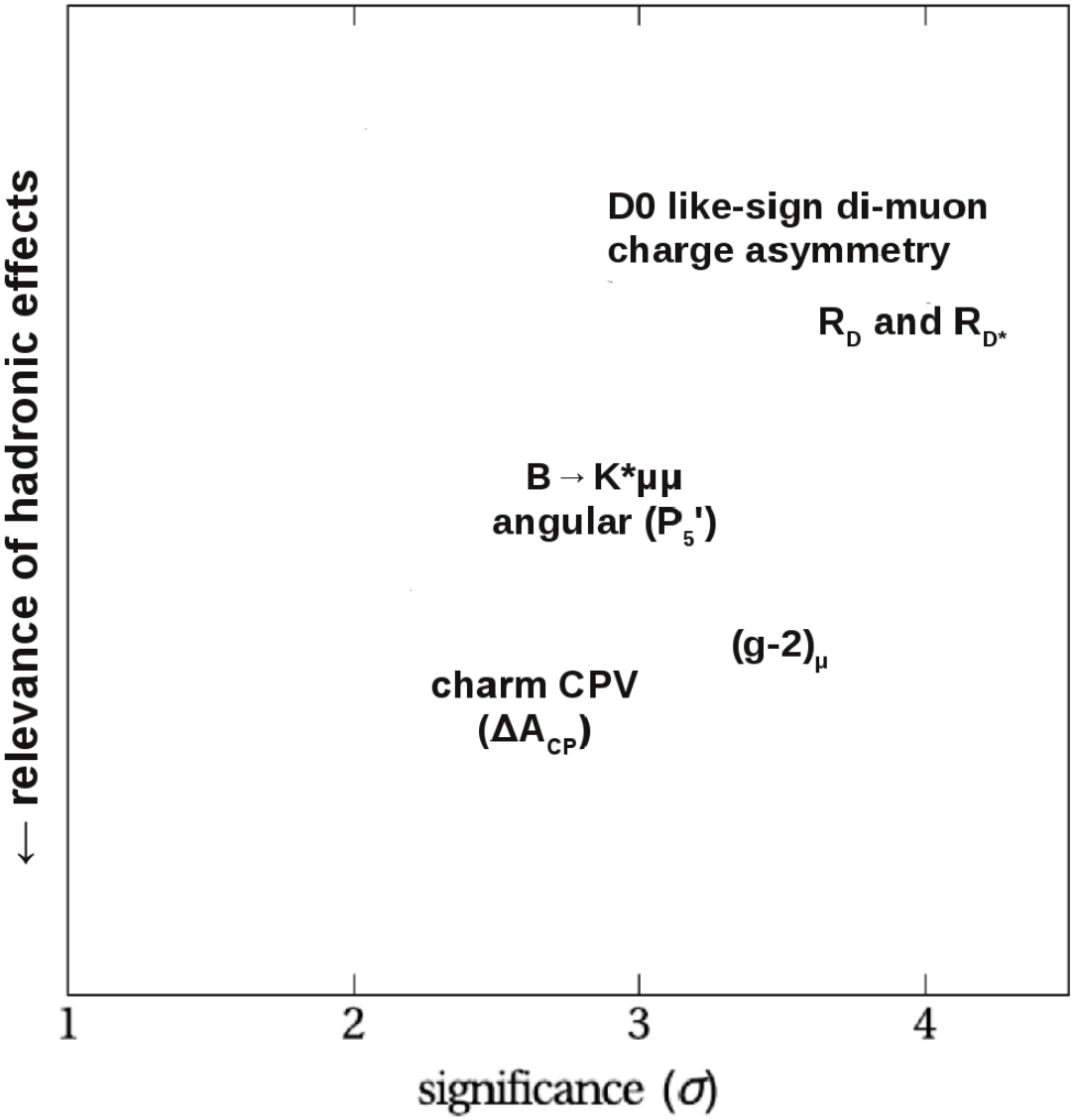
Beyond the BSM
The 4th Kavli IPMU-Durham IPPP-KEK-KIAS workshop

Ikaho, Japan, October 1-4, 2018

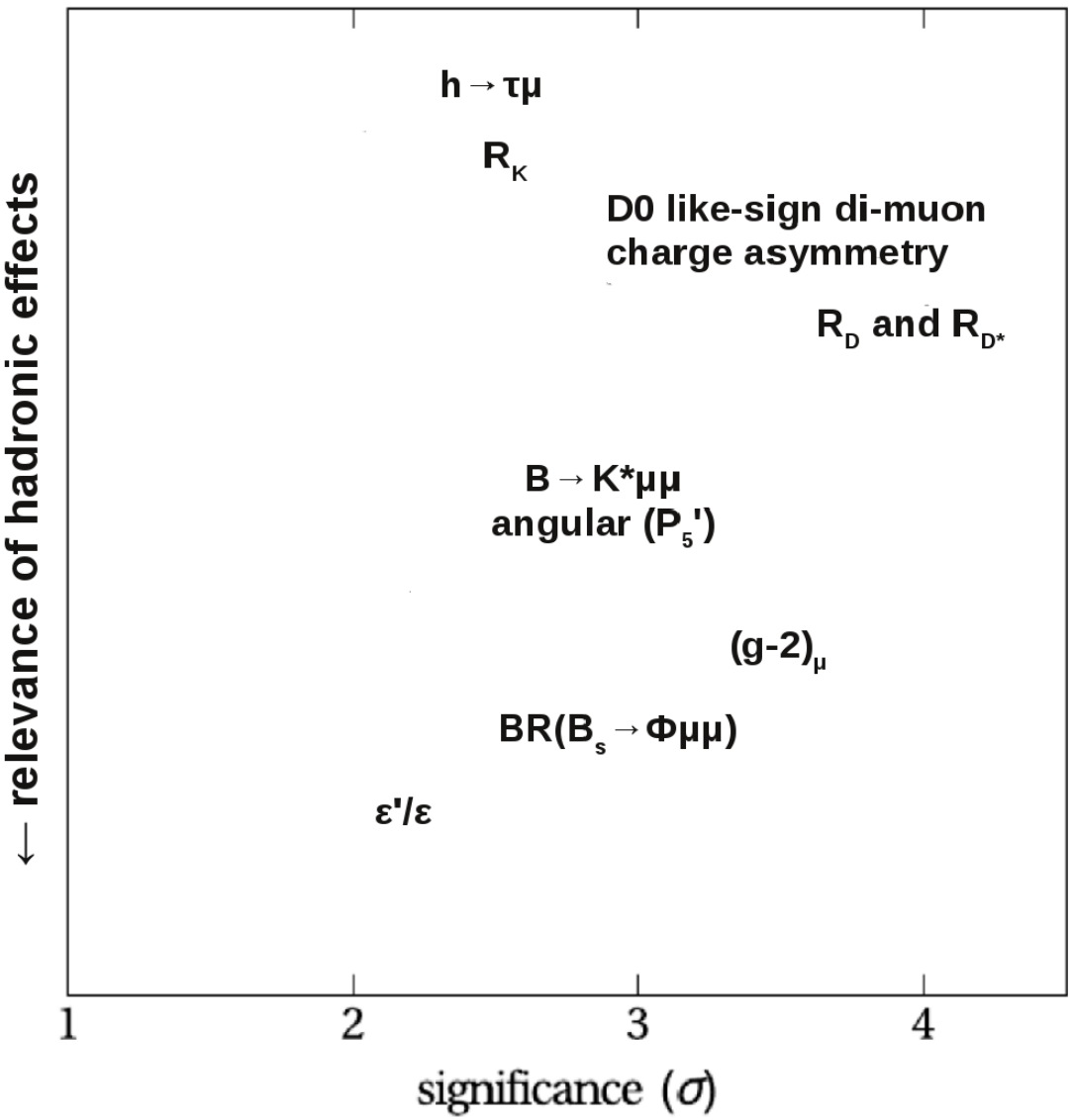
The State of Flavor Anomalies 2014



adapted from

Zoltan Ligeti

The State of Flavor Anomalies 2016



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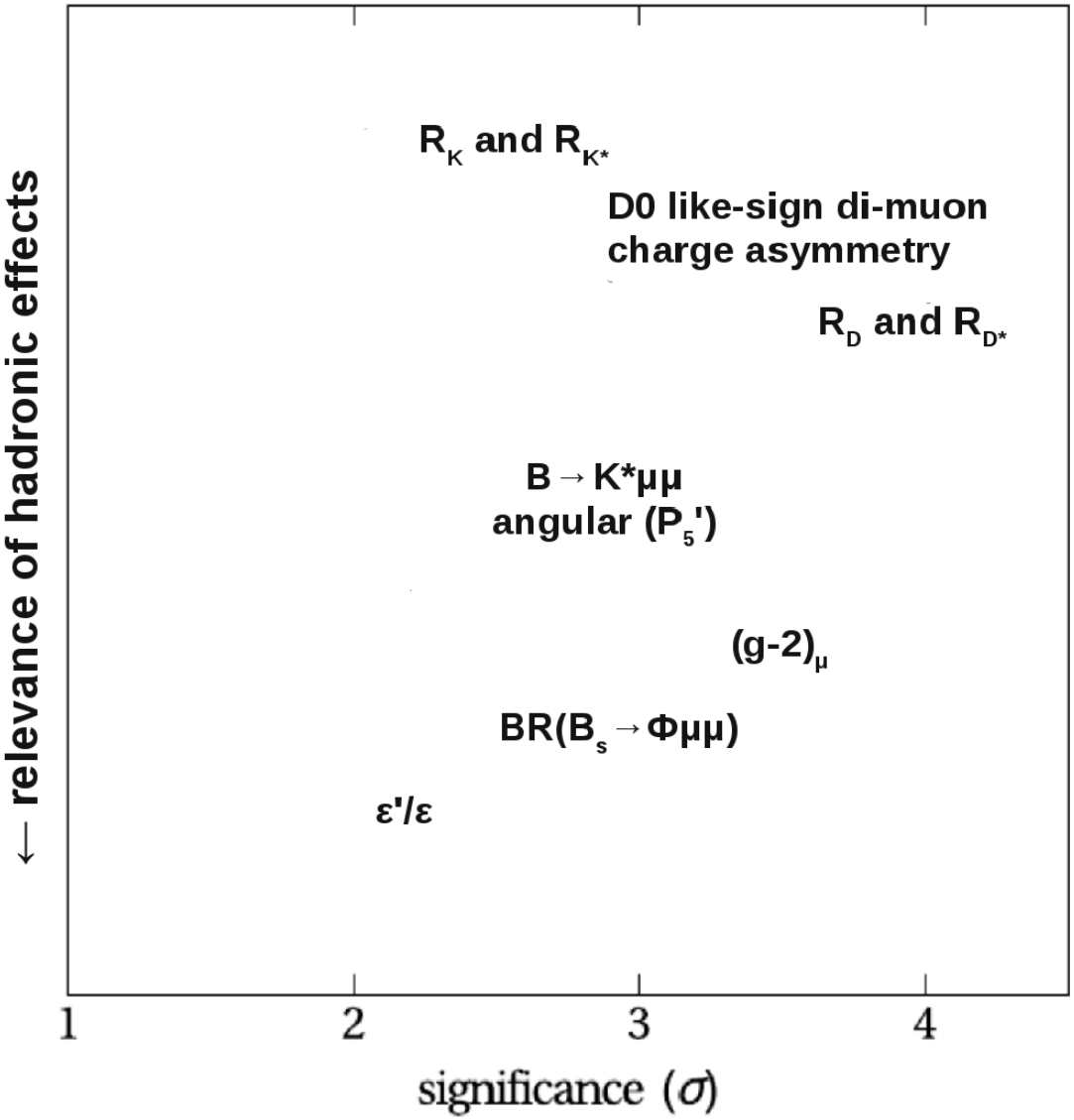
The State of Flavor Anomalies 2018



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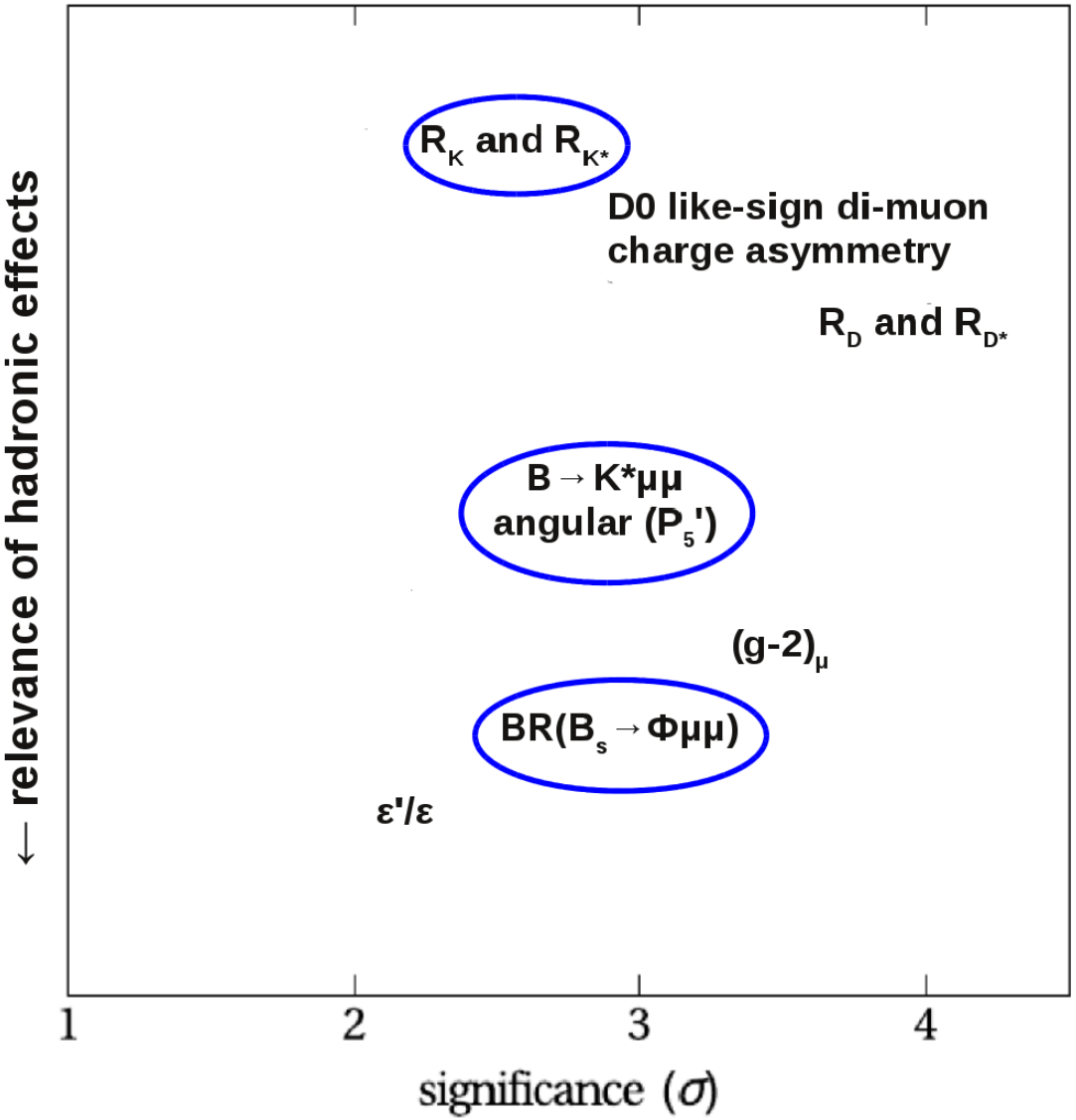
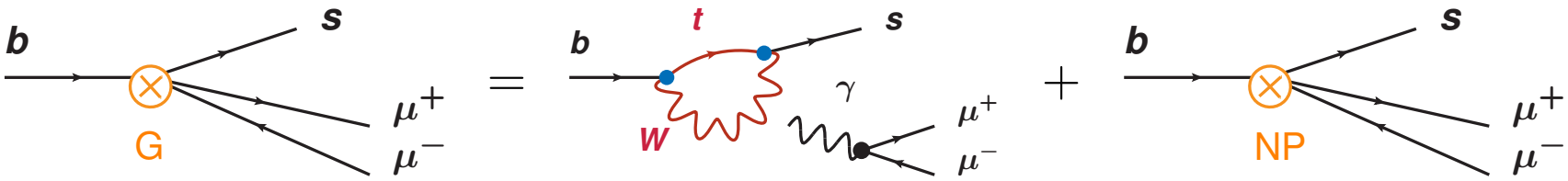
The State of Flavor Anomalies 2018



adapted from

Zoltan Ligeti

New Physics in Rare B Decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

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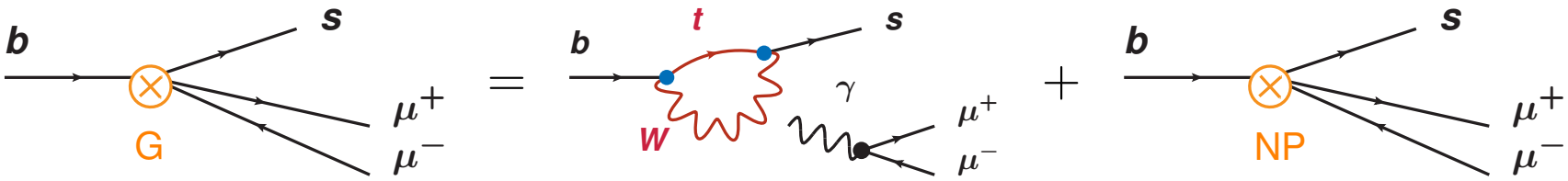

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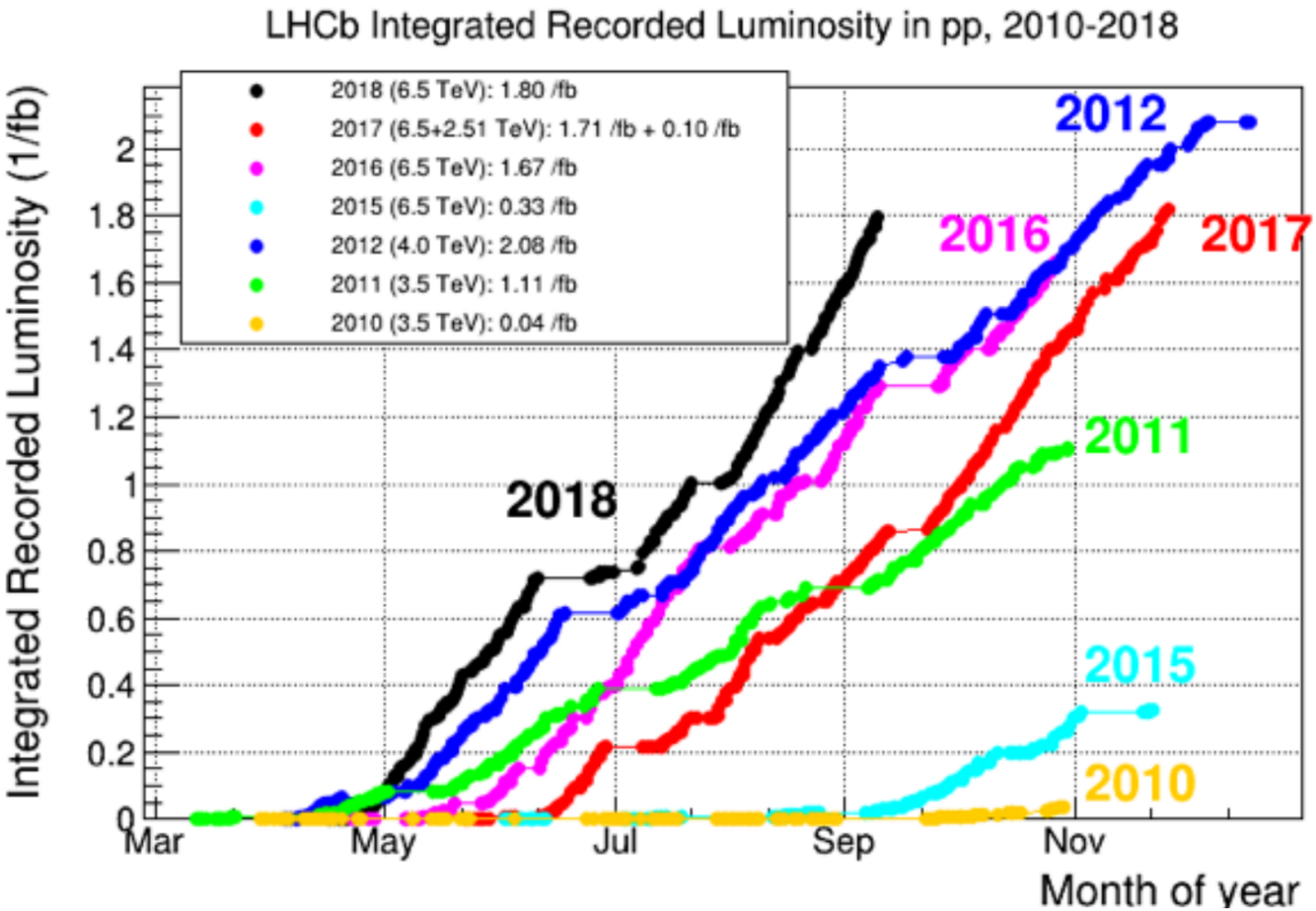
measure precisely	calculate precisely the SM contribution	get information on NP coupling and scale

Anomalies in rare B decays would establish a scale of new physics

$$\Lambda_{NP} \sim \frac{4\pi v}{\sqrt{|V_{tb}V_{ts}^*|}} \sim O(10\text{TeV})$$

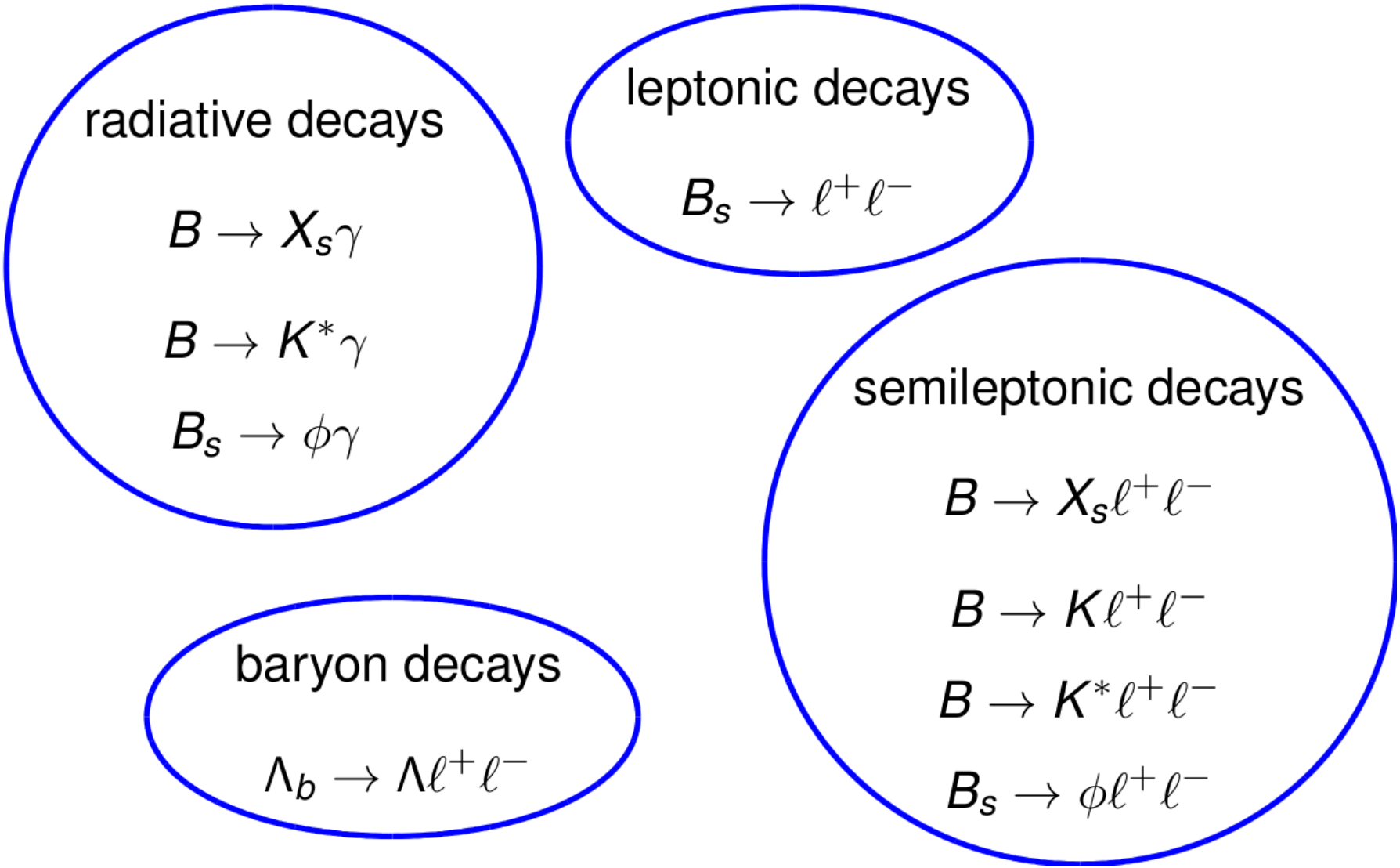
LHC is a “b-factory”



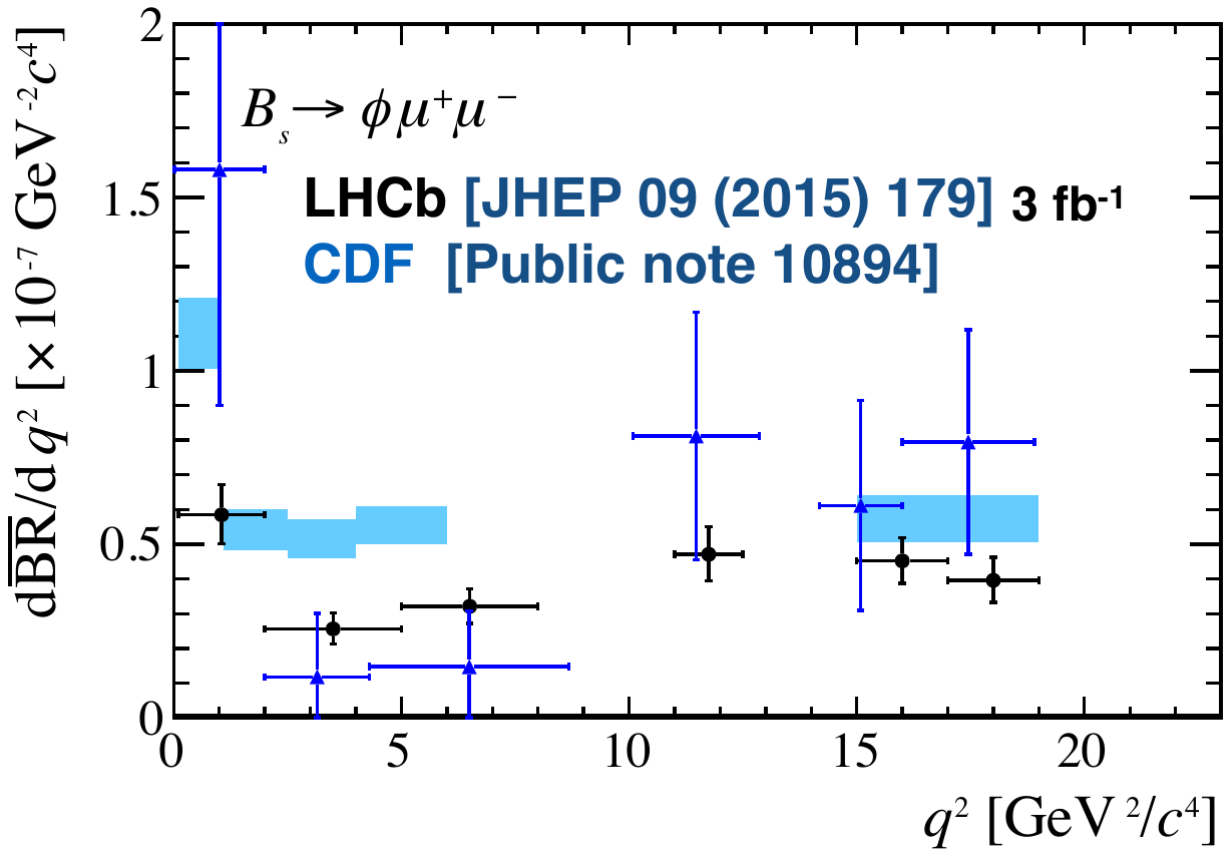
more than $\sim 10^{12}$ b quarks produced in the LHCb detector so far

$\Rightarrow$ unique sensitivity to many rare b decays

Many Accessible $b \to s$ Decay Modes

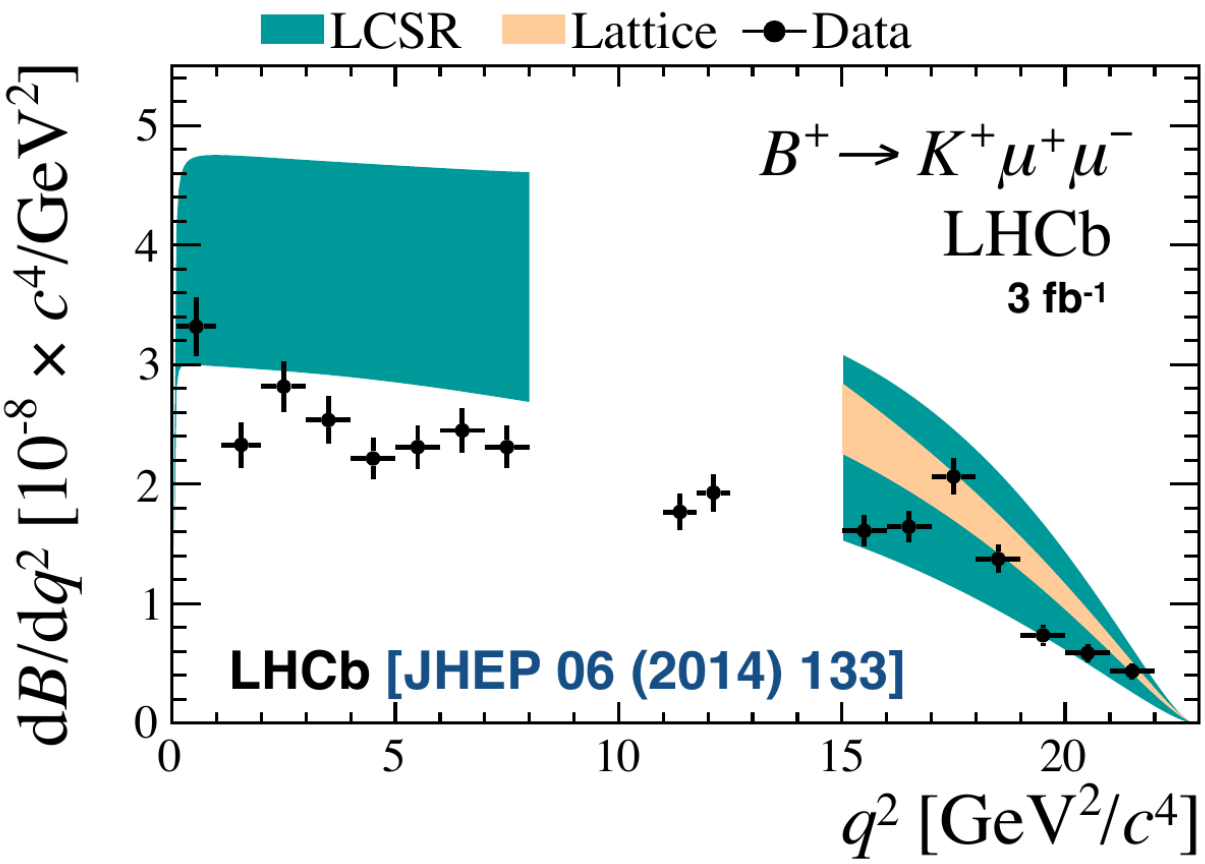


Branching Ratios I



several $b \to s\mu\mu$ branching ratios seem to be systematically smaller compared to SM predictions

Branching Ratios II



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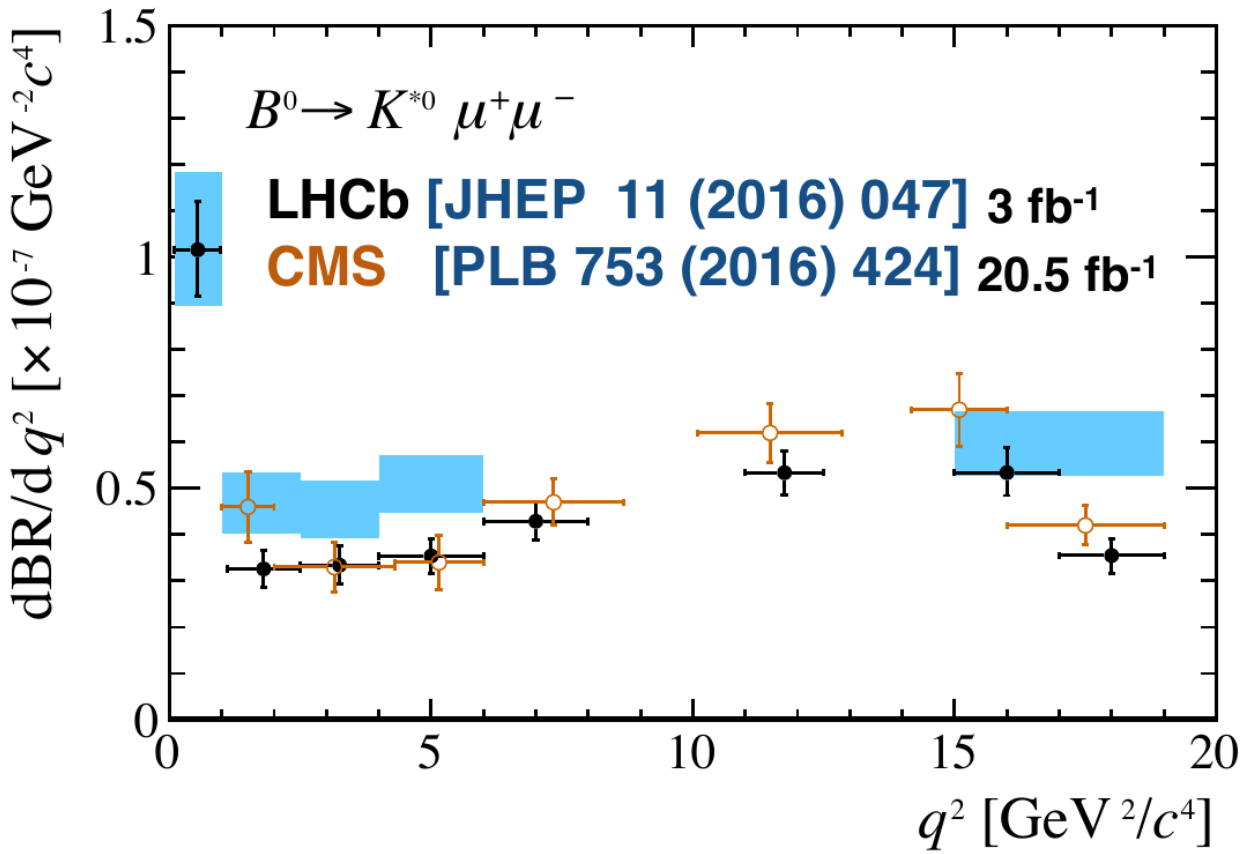
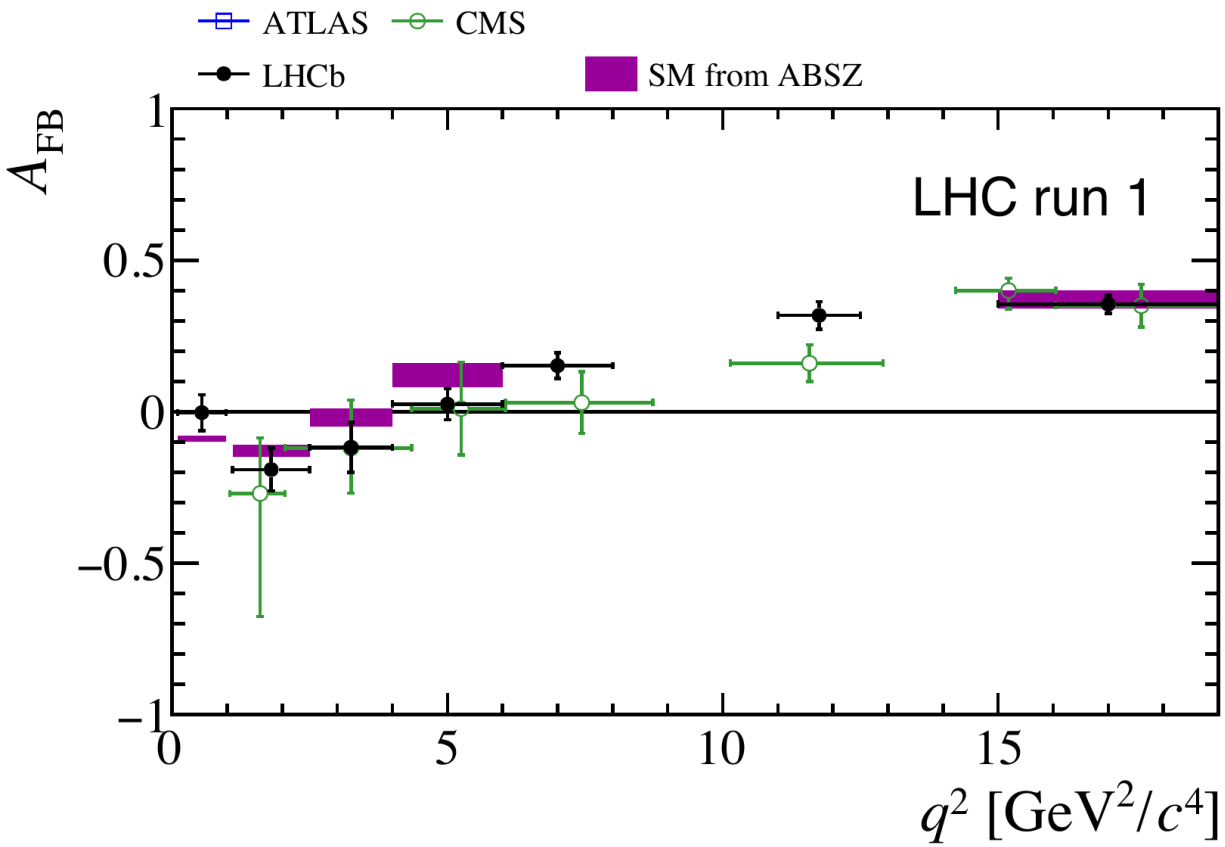
Branching Ratios III



several $b \to s\mu\mu$ branching ratios seem to be systematically smaller compared to SM predictions

Angular Distributions I

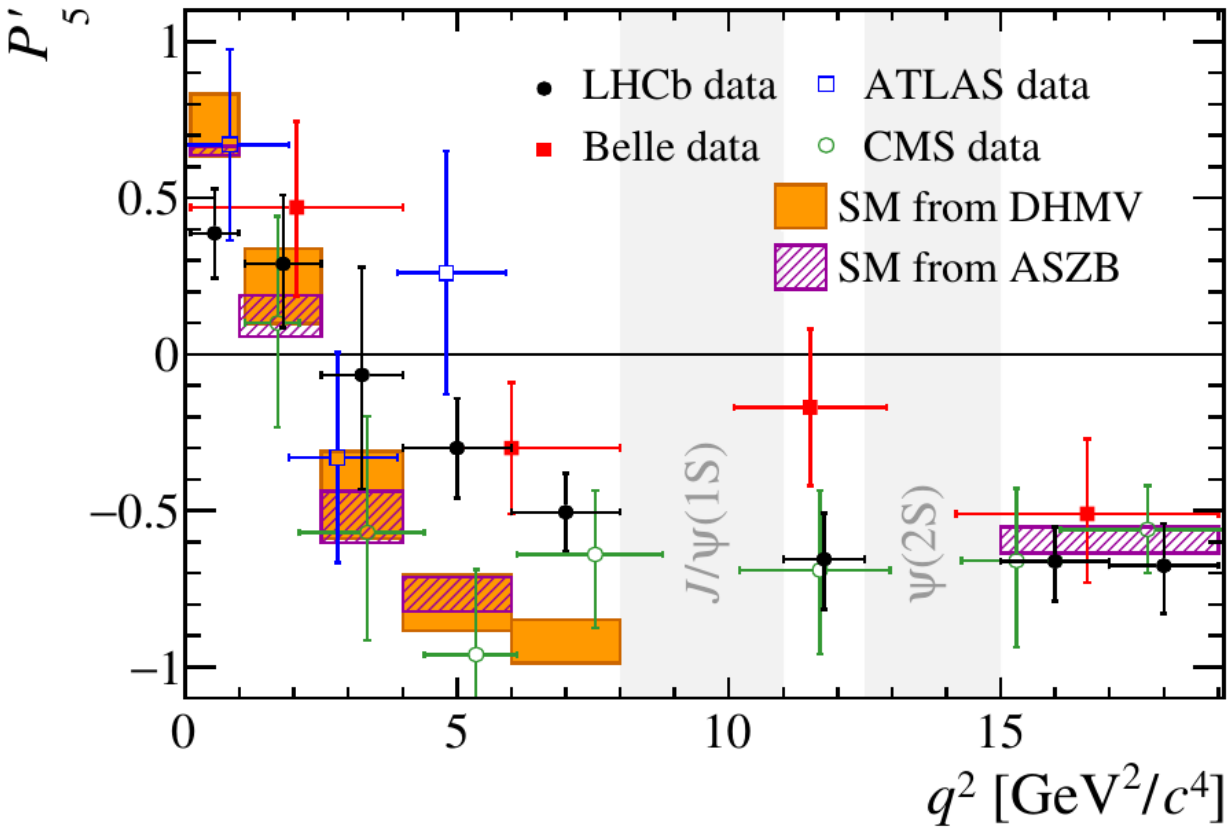
$A_{FB}(B \to K^* \mu\mu)$ agrees reasonably well with SM predictions



ABSZ = WA, Straub 1411.3161 + Bharucha, Straub, Zwicky 1503.05534

Angular Distributions II

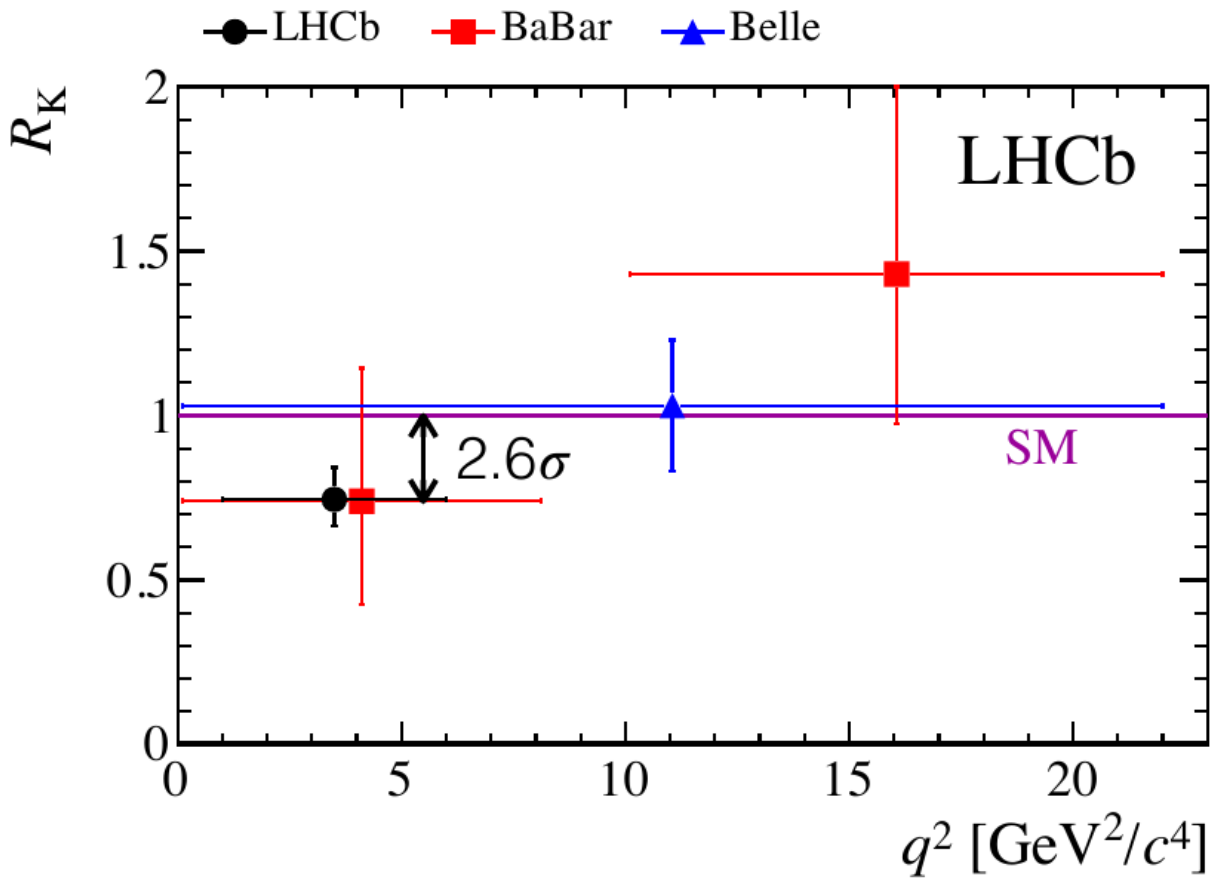
$P_5'(B \to K^* \mu\mu)$ is off by $\sim 2.5\sigma$ in a couple of bins



ASZB = WA, Straub 1411.3161 + Bharucha, Straub, Zwicky 1503.05534

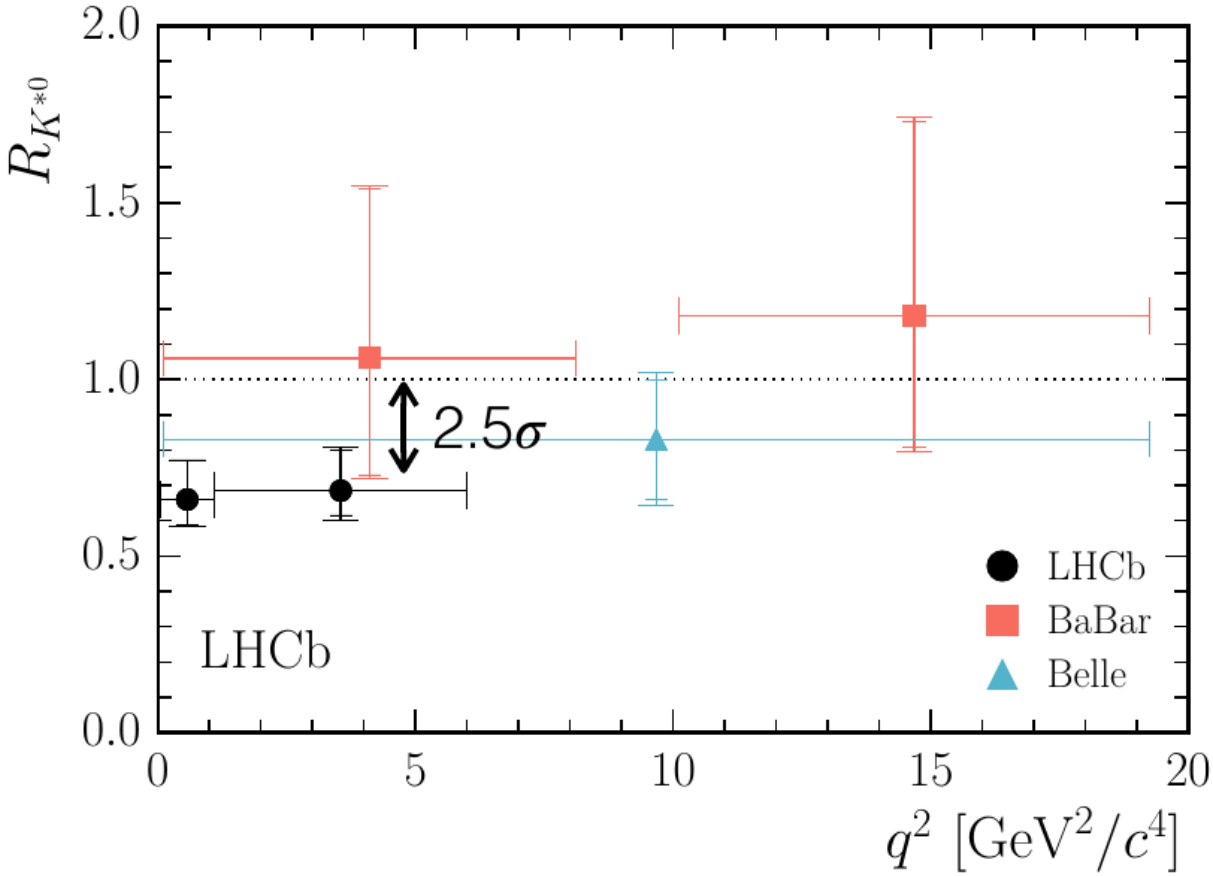
DHMV = Descotes-Genon, Hofer, Matias, Virto 1510.04239

Lepton Flavor Universality Tests I



$$R_K = \frac{BR(B \to K\mu\mu)}{BR(B \to Kee)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{for } 1 < q^2/\text{GeV}^2 < 6$$

Lepton Flavor Universality Tests II



$$R_{K^*} = \frac{BR(B \to K^* \mu\mu)}{BR(B \to K^* ee)} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045 < q^2/\text{GeV}^2 < 1.1 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1 < q^2/\text{GeV}^2 < 6 \end{cases}$$

What Could It Be?

	branching ratios	angular observables	LFU ratios

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	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
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New Physics?	✓	✓	✓

Standard Model Predictions for R_K and R_{K^*}

$$R_{K^{(*)}} = 1$$

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$$R_{K^{(*)}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) \times \left(1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right) + \mathcal{O}\left(\alpha_s\right)\right) + \mathcal{O}\left(\frac{\alpha_{\text{em}}}{\pi} \log^2\left(\frac{m_e^2}{m_\mu^2}\right)\right)$$

phase space
(tiny effect)

hadronic corrections
(tiny effect)

QED corrections
(soft and collinear
photon emission)

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phase space (tiny effect)

hadronic corrections (tiny effect)

QED corrections (soft and collinear photon emission)

Bordone, Isidori, Pattori 1605.07633

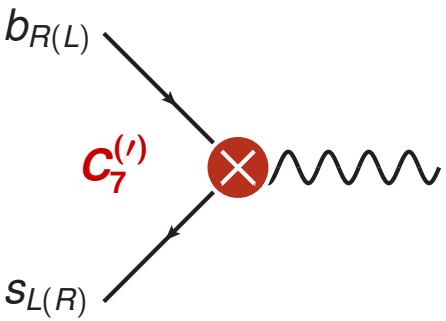
$$R_K^{[1,6]} = 1.00 \pm 0.01 \quad , \quad R_{K^*}^{[1.1,6]} = 1.00 \pm 0.01 \quad , \quad R_{K^*}^{[0.045,1.1]} = 0.91 \pm 0.03$$

- QED corrections seem well modeled by Monte Carlo (Photos)
- additional corrections at low q^2 from $B \to K^* \eta (\to ee\gamma)$

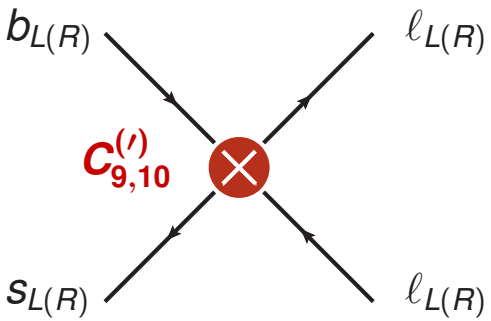
Model Independent New Physics Analysis

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

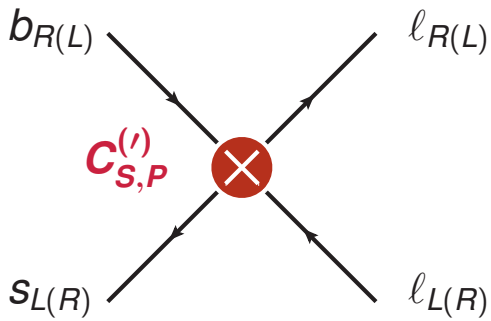
magnetic dipole operators



semileptonic operators



scalar operators



$$C_7^{(\prime)} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s} \gamma_\nu P_{L(R)} b)(\bar{\mu} \gamma^\nu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

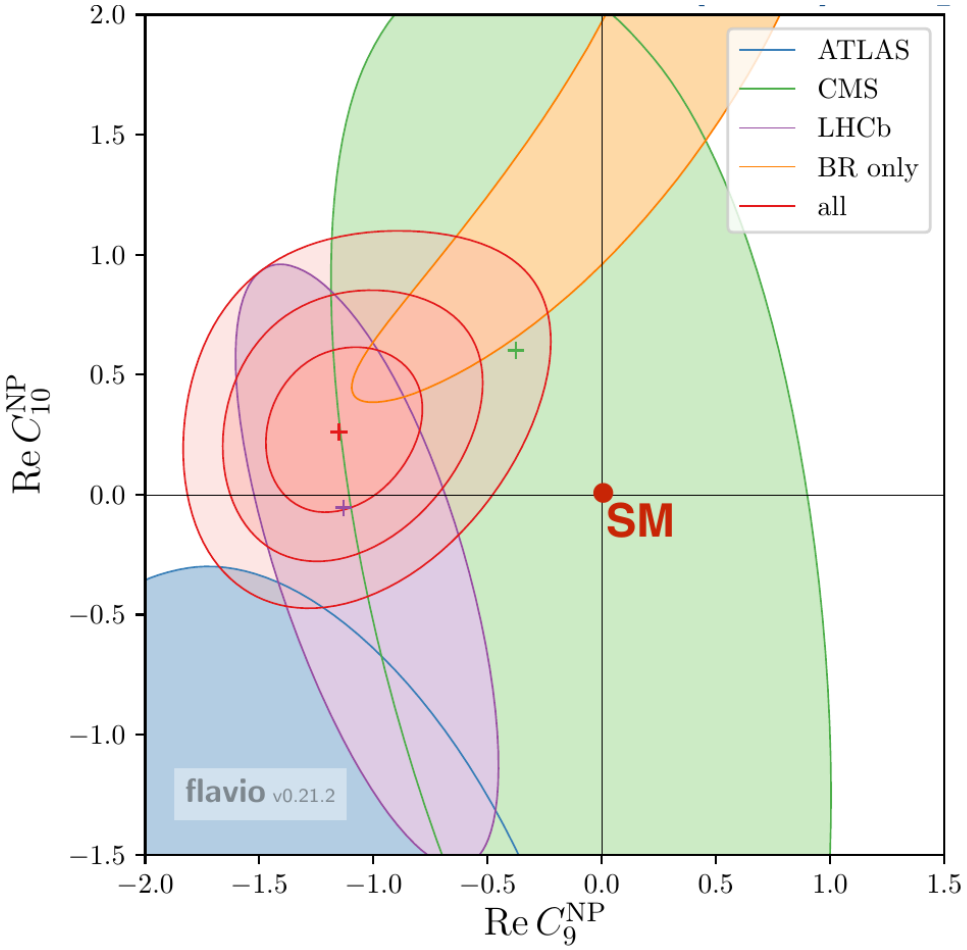
$$C_{10}^{(\prime)} (\bar{s} \gamma_\nu P_{L(R)} b)(\bar{\mu} \gamma^\nu \gamma_5 \mu)$$

neglecting tensor operators and additional scalar operators (secretly dimension 8)

Complementary Sensitivity

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'	C_S, C_S'
$B \to (X_s, K^*)\gamma$	★			
$B_s \to \phi\gamma$	★			
$B \to (X_s, K, K^*)\ \mu^+\mu^-$	★	★	★	⋆
$B_s \to \phi\ \mu^+\mu^-$	★	★	★	⋆
$\Lambda_b \to \Lambda\ \mu^+\mu^-$	★	★	★	⋆
$B_s \to \mu^+\mu^-$			★	★

Global Fit (*Without LFU Data*)



WA, Niehoff, Stangl, Straub 1703.09189

(+ many others ...)

Strong preference for new physics in form of

$$C_9^{\mathrm{NP}} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\ell \ell)$$

$$\mathrm{Re}\, C_9^{\mathrm{NP}} \sim -25\% C_9^{\mathrm{SM}}$$

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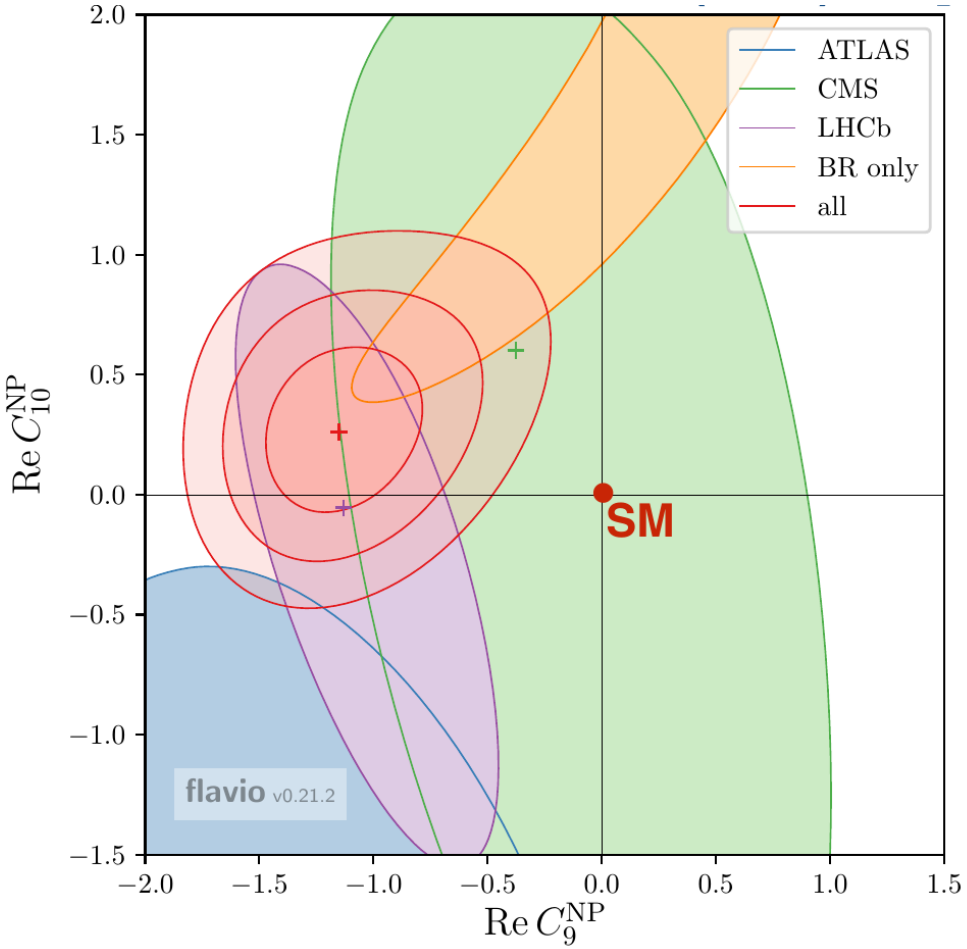

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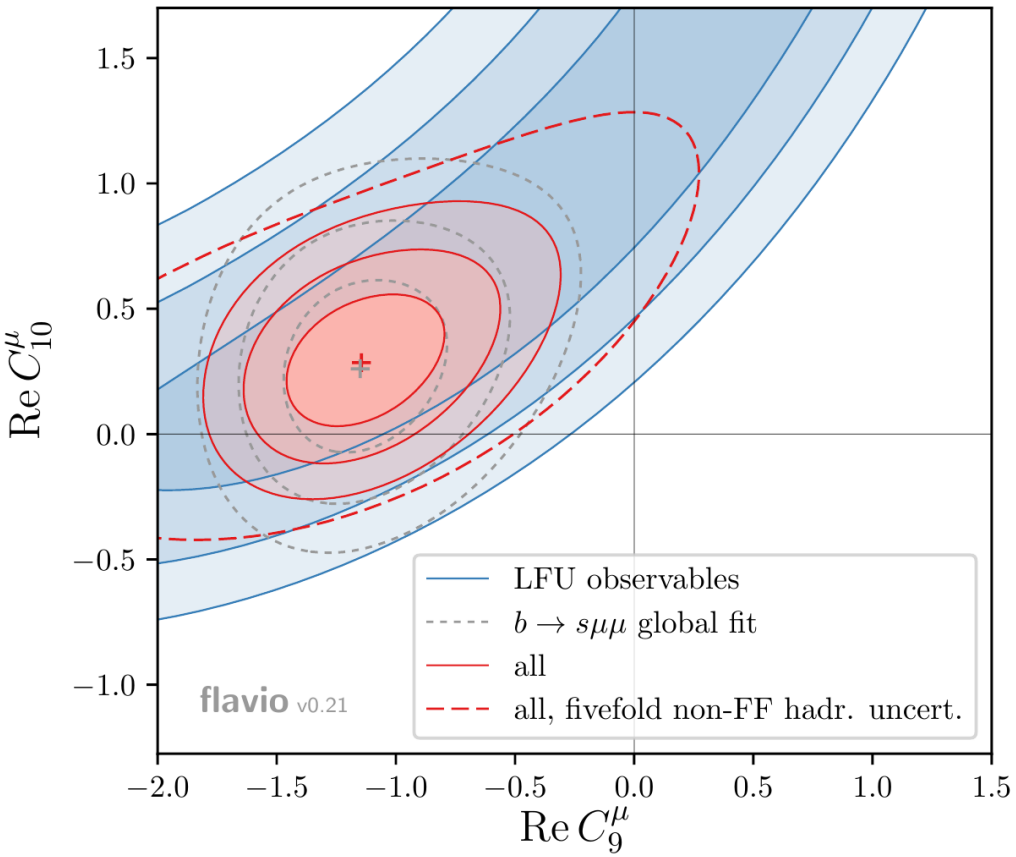
$$C_L^{\mathrm{NP}}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \ell)$$

$$\mathrm{Re}\, C_L^{\mathrm{NP}} \sim -15\%\, C_9^{\mathrm{SM}}$$

works almost equally well

Fits of LFU Data



WA, Stangl, Straub 1704.05435

(+ many others ...)

the LFU observables are fully compatible with the other anomalies

Best description of all anomalies by:

new physics in final states with muons

$C_9^{\mu}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

($R_{K^{(*)}}$ by themselves could also be explained by C_{10}^{μ}, C_9^{e}, or C_{10}^{e})

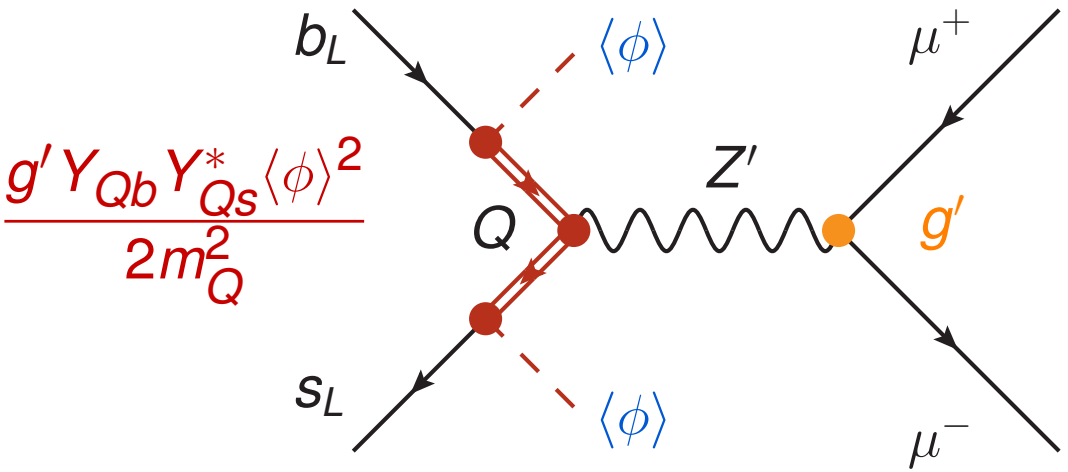
Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2} V_{tb}V_{ts}^* (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ {\rm TeV} \times (C_9^{\rm NP})^{-1/2}$

My Favorite Model

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

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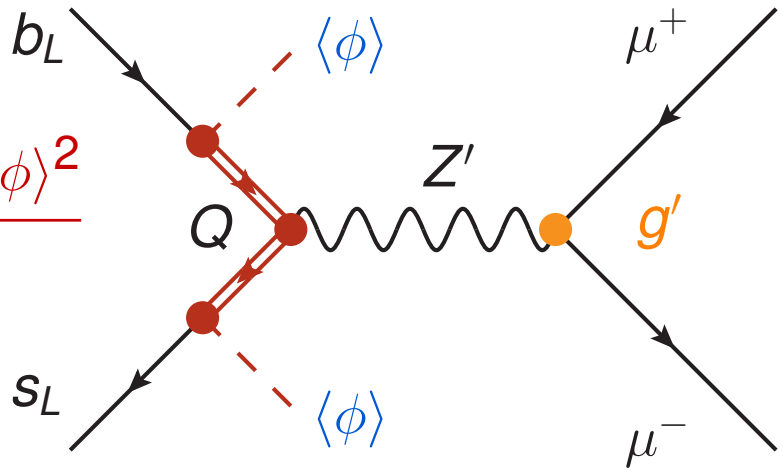
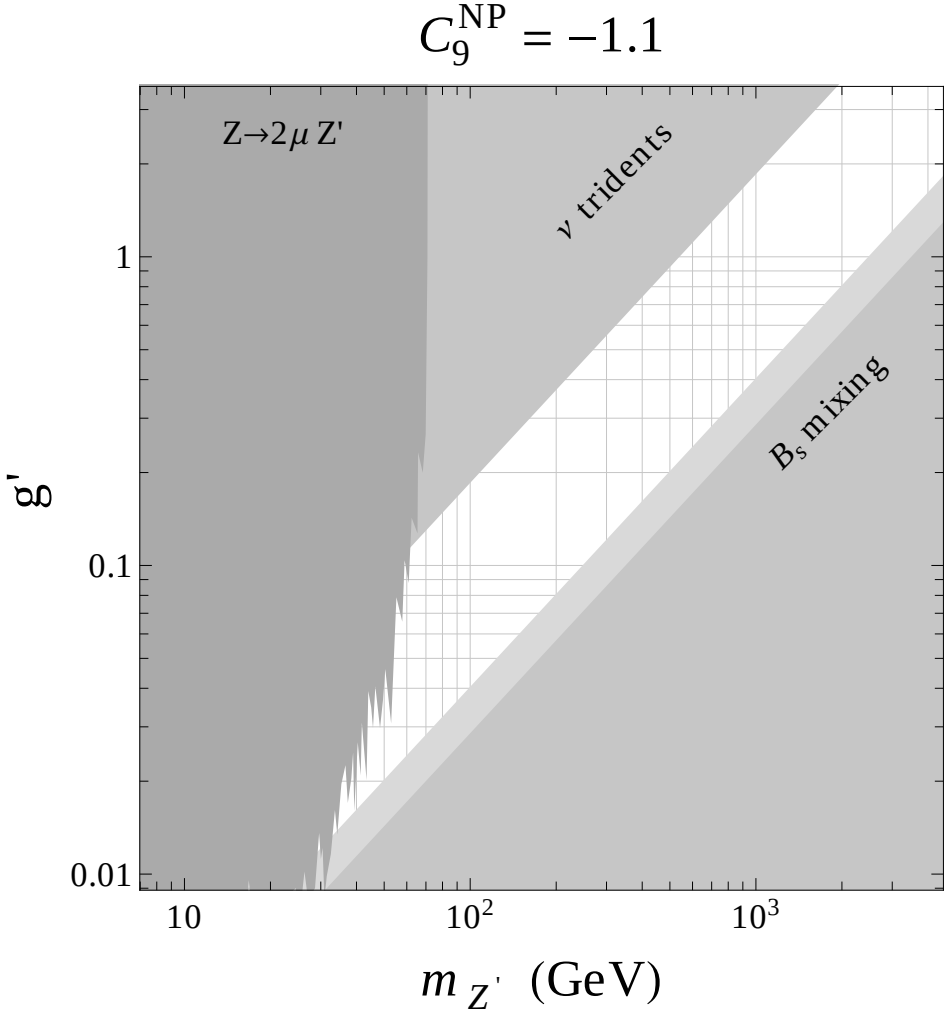


$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$

predicted Lepton Universality Violation!

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Viable Z' Parameter Space



Most important constraints from

- $B_s - \bar{B}_s$ oscillation frequency
- neutrino tridents

$$\nu_\mu N \to \nu_\mu N \mu\mu$$

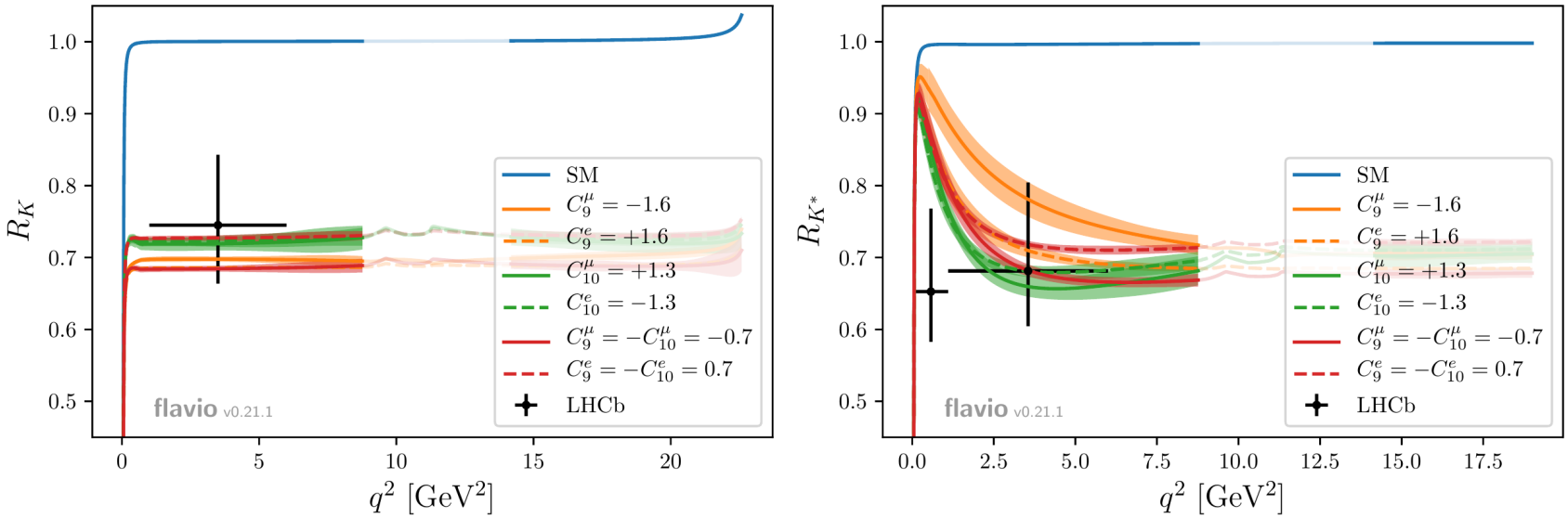
- direct searches

  CMS 1808.03684

$$Z \to 2\mu Z' \to 4\mu$$

The low q^2 Bin in R_{K^*}

WA, Stangl, Straub 1704.05435



$B \to K^* \ell^+ \ell^-$ decays at low q^2 are dominated by the (lepton flavor universal) photon pole $B \to K^* \gamma$

$\to$ Effect of (heavy) new physics in R_{K^*} gets diluted at low q^2.

This behavior is not seen in the data.
Hint for new light degrees of freedom?

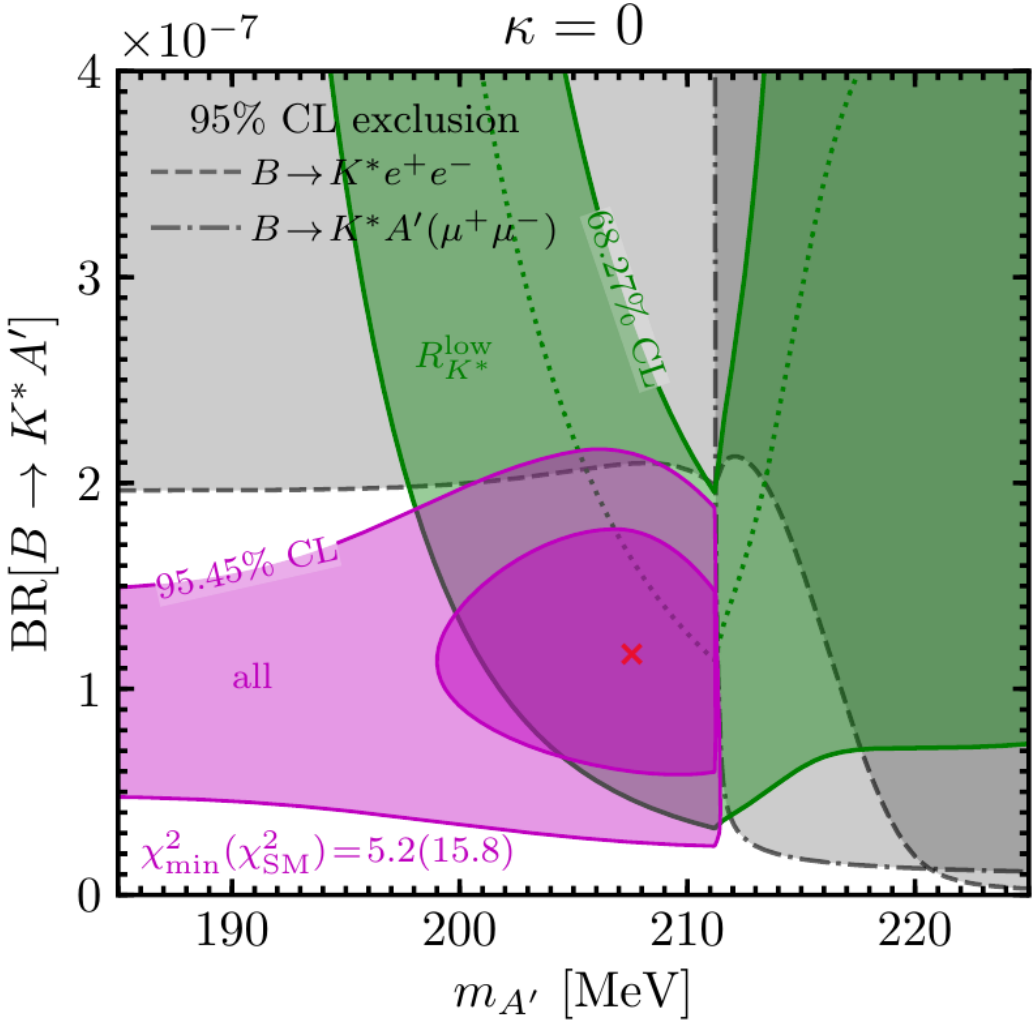
A Light Resonance at the Di-Muon Threshold?

Example: Dark photon* with $m_{A'} \sim 2m_\mu$

$$B \to K^* A'$$

$$A' \to e^+ e^-$$

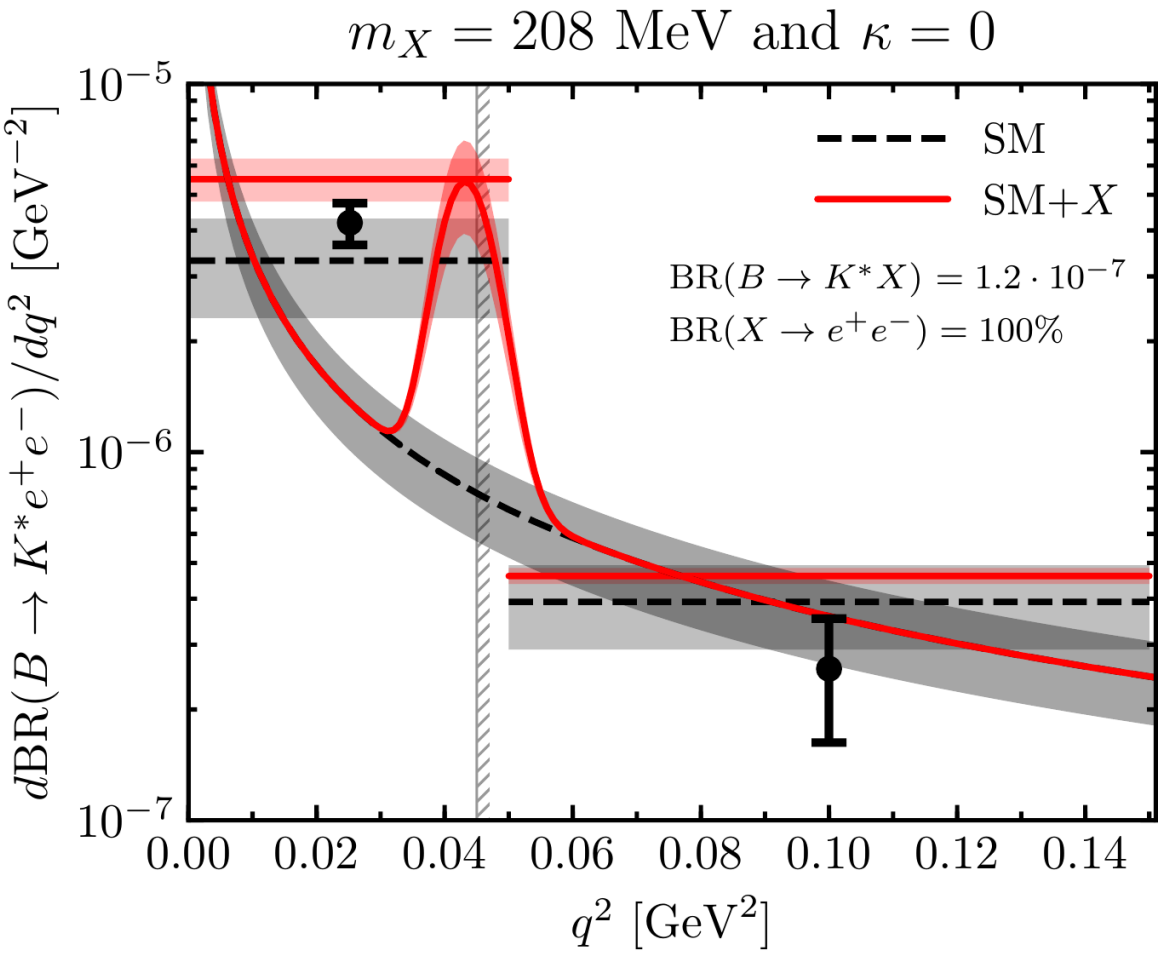
(* a dark photon that for some reason has a large flavor violating $b \to s$ coupling)



WA, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 1711.07494

Smoking Gun Signature

Resonance in the di-electron spectrum in $B \to K^* e^+ e^-$ right around $q^2 \sim 4m_\mu^2$



WA, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 1711.07494

b

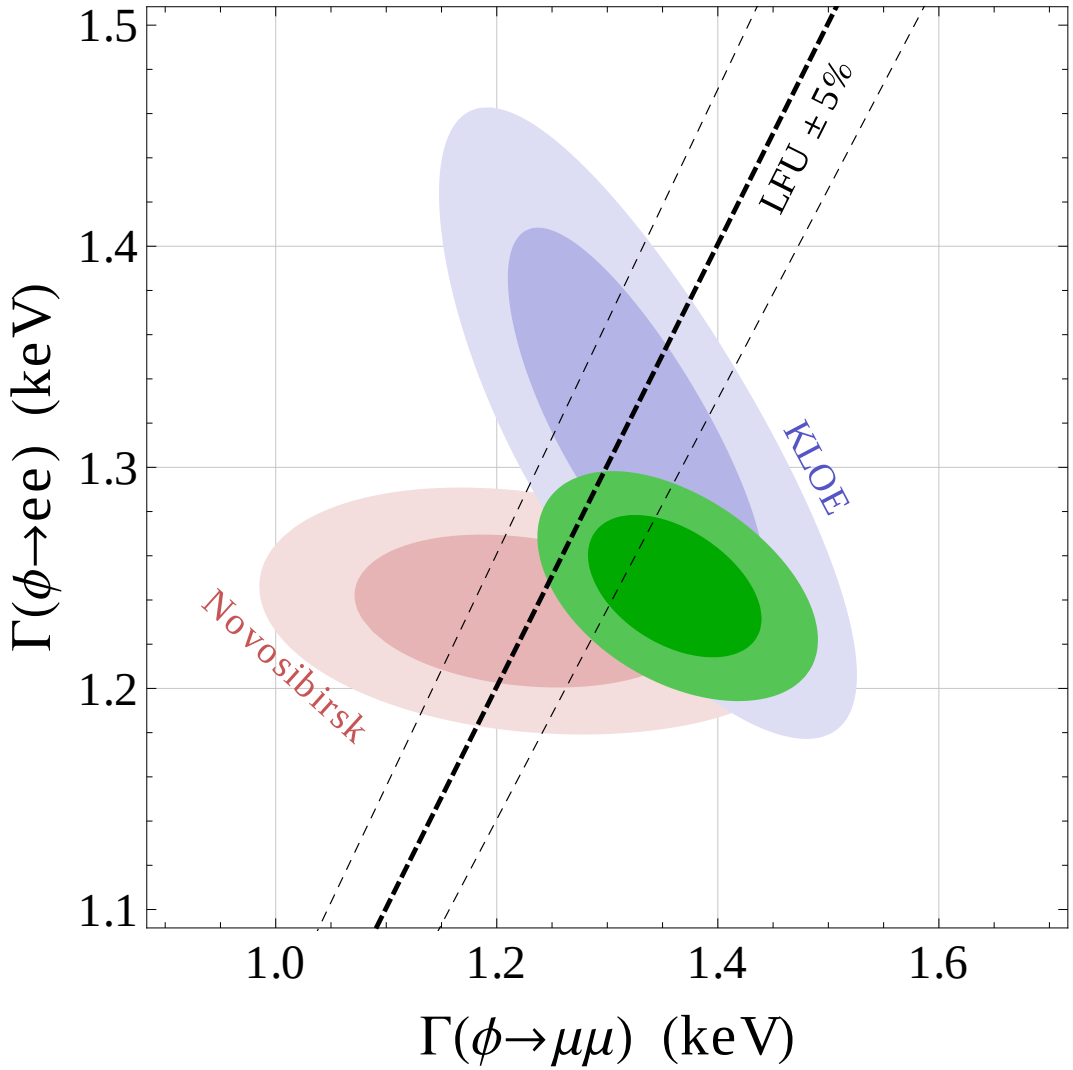
Future Prospects

Cross Check of Electron Efficiencies

LHCb should accumulate enough statistics to measure LFU in $\phi \to \ell\ell$ decays ($q^2 \sim 1$ GeV^2).

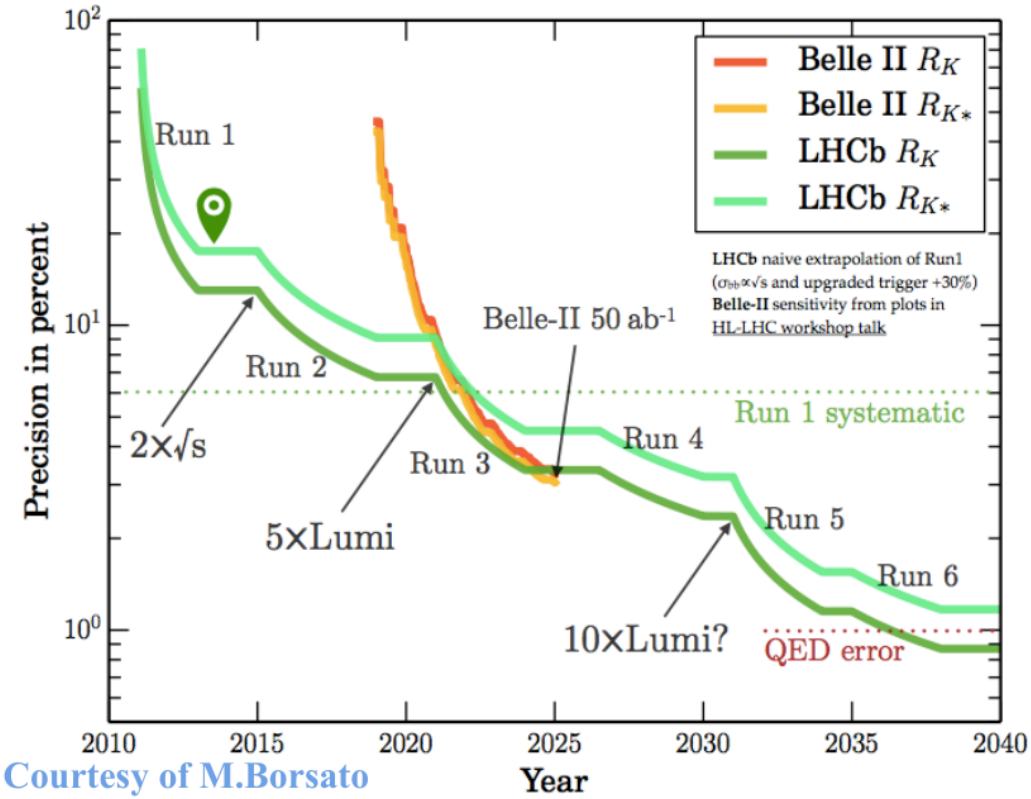
With run 2 data several 10,000 $\phi \to \ell\ell$ decays from $D^\pm \to \pi^\pm \phi$, $D^0 \to \pi^+\pi^-\phi$, $D_s^\pm \to \pi^\pm \phi$, ...

WA, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 1711.07494



R_K and R_{K^*}

- LHCb and Belle II can push uncertainties down to few percent
- (also ATLAS and CMS might be able to say something)
- with sufficient statistics, LFU of angular distrib. can be tested



- LHCb can cross check in many other modes:

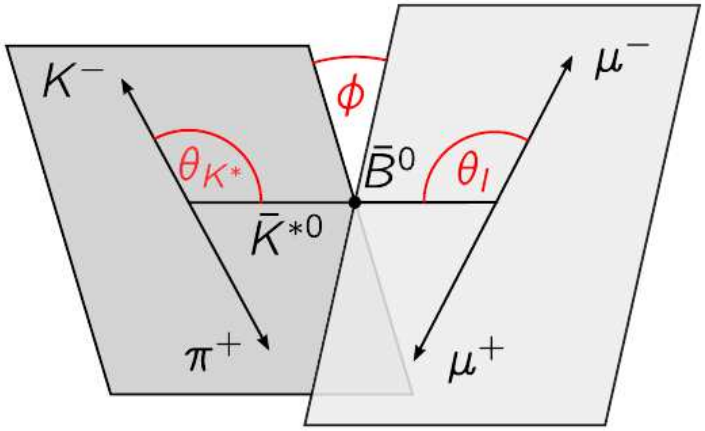
$$R_\phi \ , \quad R_\Lambda \ , \quad R_{\Lambda^*} \ , \quad R_{K\pi\pi} \ , \quad \ldots$$

Summary

- Over the last few years, several anomalies appeared in rare B decay data.
- The LFU ratios $R_{K^{(*)}}$ are theoretically clean probes of new sources of flavor violation.
- With more data from LHCb and Belle II (+ATLAS and CMS) it should be possible to understand if current discrepancies are signs of new physics.

Back Up

The $B \to K^* \mu^+ \mu^-$ Angular Decay Distribution



$$\frac{1}{\frac{d}{dq^2}(\Gamma + \bar{\Gamma})} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2\, d\vec{\Omega}} =$$

$$\begin{aligned}
= \; & \frac{3}{4}(1 - F_L)\sin^2\theta_{K^*} + F_L \cos^2\theta_{K^*} \\
& + \frac{1}{4}(1 - F_L)\sin^2\theta_{K^*}\cos 2\theta_\ell - F_L \cos^2\theta_{K^*}\cos 2\theta_\ell \\
& + S_3 \sin^2\theta_{K^*}\sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_{K^*}\sin 2\theta_\ell \cos\phi \\
& + S_5 \sin 2\theta_{K^*}\sin\theta_\ell \cos\phi \\
& + \frac{4}{3} A_{FB}\sin^2\theta_{K^*}\cos\theta_\ell + S_7 \sin 2\theta_{K^*}\sin\theta_\ell \sin\phi \\
& + S_8 \sin 2\theta_{K^*}\sin 2\theta_\ell \sin\phi + S_9 \sin^2\theta_{K^*}\sin^2\theta_\ell \sin 2\phi
\end{aligned}$$

$$P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$