

Leptoquark option for B-meson anomalies and leptonic signatures

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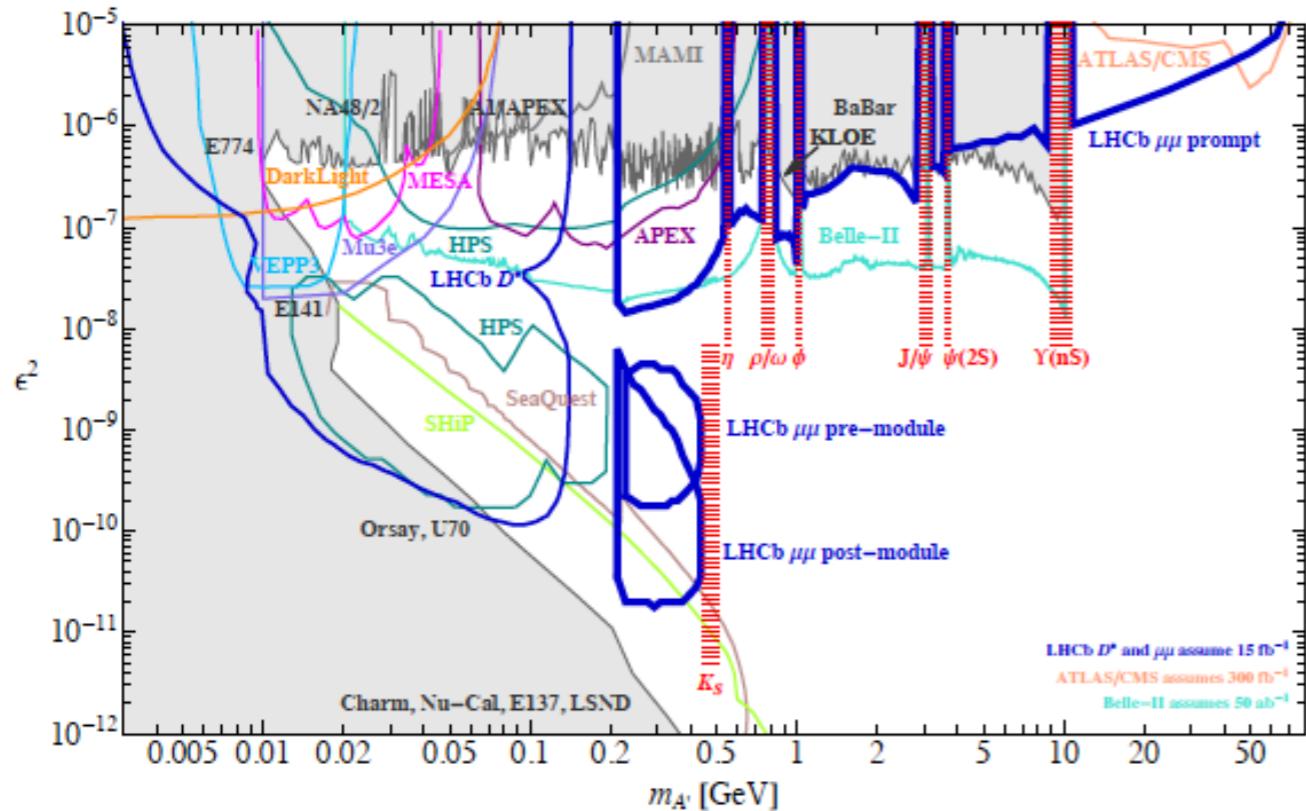
Muon Anomalies Workshop
Zoom, Korea, May 21, 2021

Outline

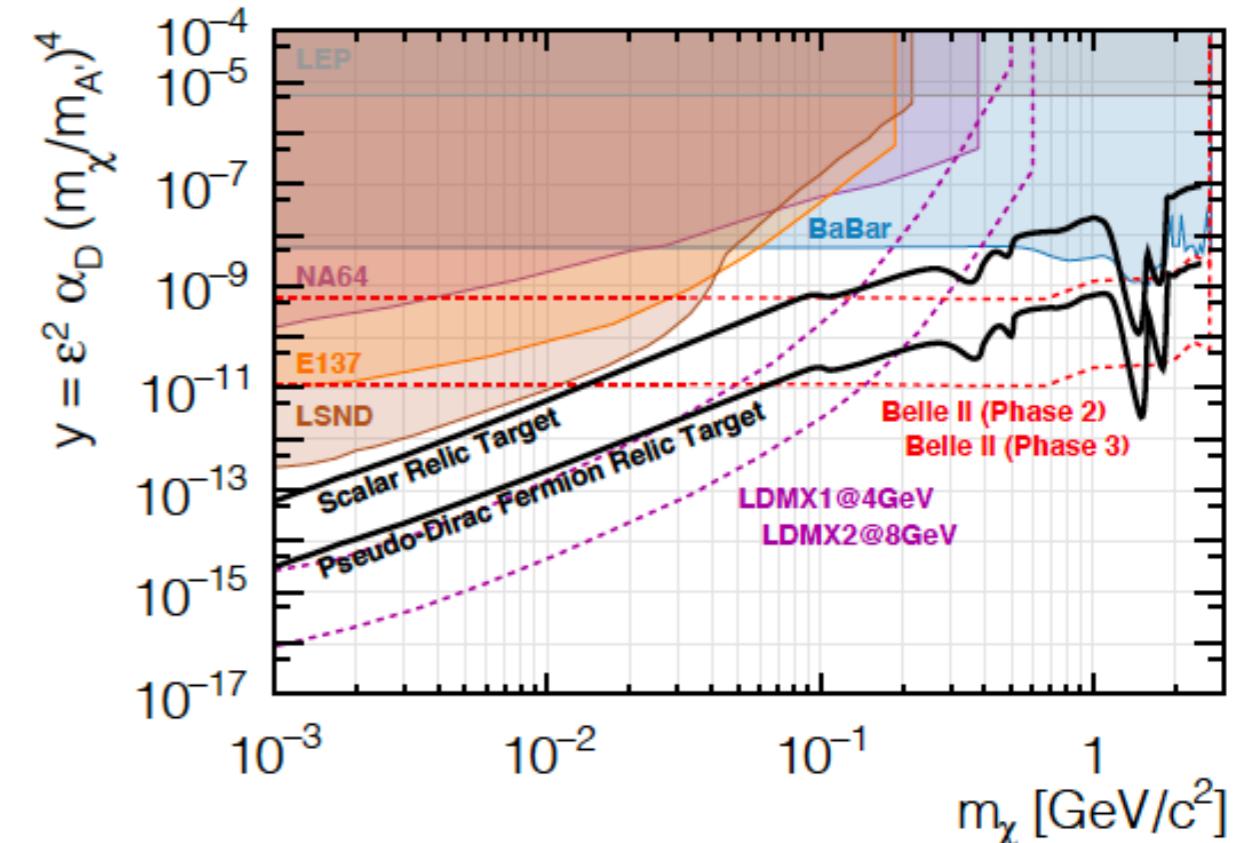
- B-meson anomalies and new physics
- Leptoquarks for B-mesons and g-2
- Conclusions

B-meson anomalies and new physics

Energy/Intensity interplay



[Ilten et al, 2016]



[Belle-II, 1808.10567]

- No direct evidence for new physics at LHC.
→ Little hierarchy between weak scale and new physics?
- New particles are very weakly coupled and/or light.
→ Testable with precision and intensity experiments?

Flavors and new physics

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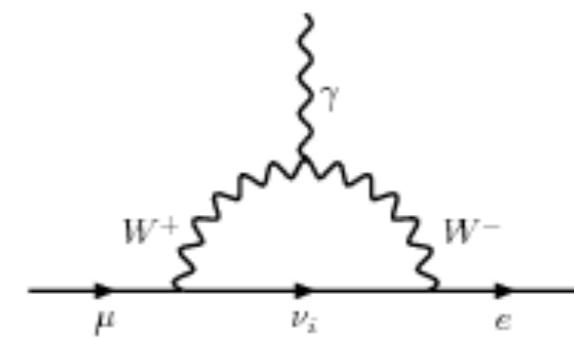
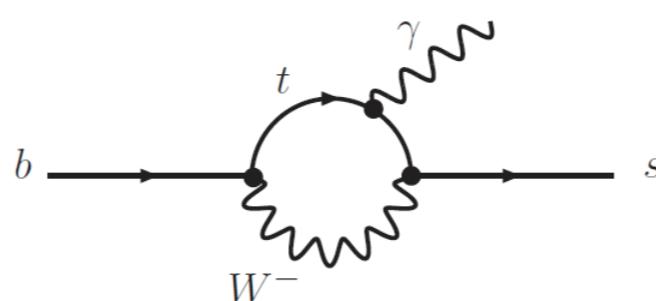
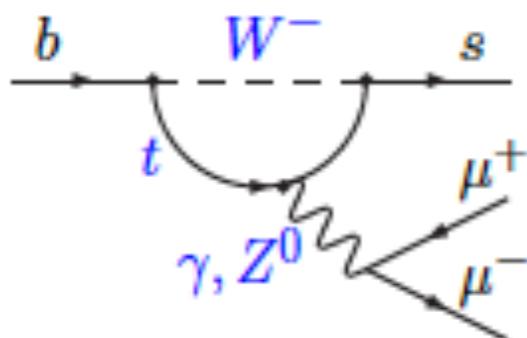
- “Charged currents” induce flavor violating processes at tree level, while FCNCs are induced at loop level.

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \quad V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

- Lepton universality is well tested within the SM.

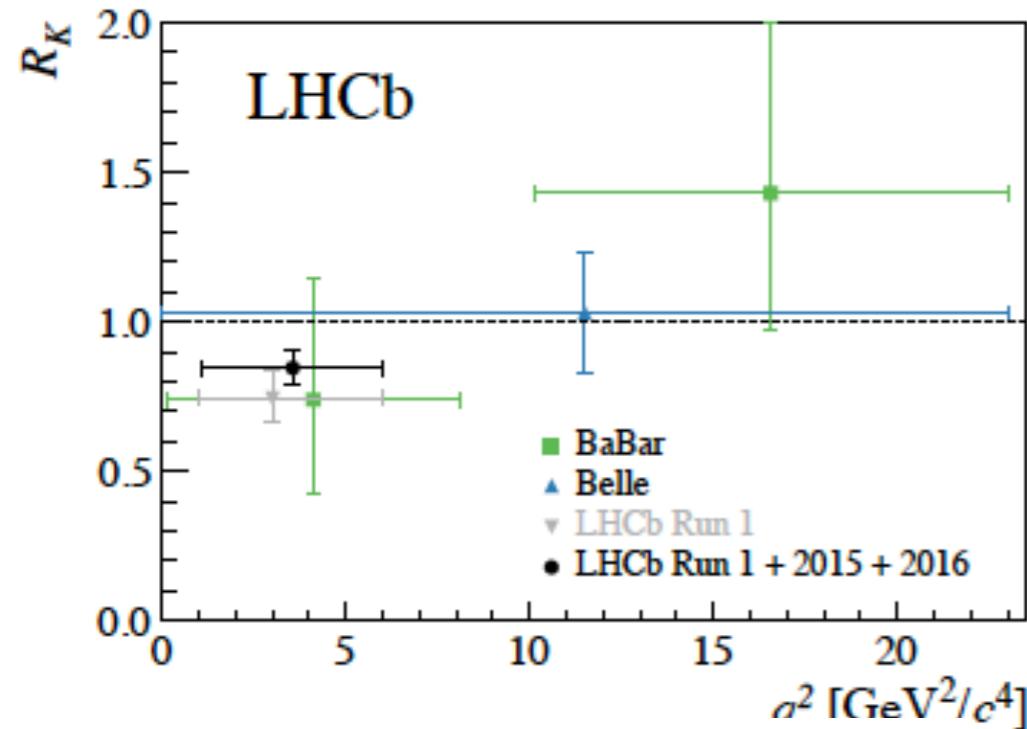
$$\frac{\Gamma_{Z \rightarrow \mu^+ \mu^-}}{\Gamma_{Z \rightarrow e^+ e^-}} = 1.0009 \pm 0.0028, \quad \frac{\mathcal{B}(W^- \rightarrow e^- \bar{\nu}_e)}{\mathcal{B}(W^- \rightarrow \mu^- \bar{\nu}_\mu)} = 1.004 \pm 0.008. \quad \frac{\Gamma_{K^- \rightarrow e^- \bar{\nu}_e}}{\Gamma_{K^- \rightarrow \mu^- \bar{\nu}_\mu}} = (2.488 \pm 0.009) \times 10^{-5}$$

- “FCNC processes” and lepton universality are sensitive probes of new physics.

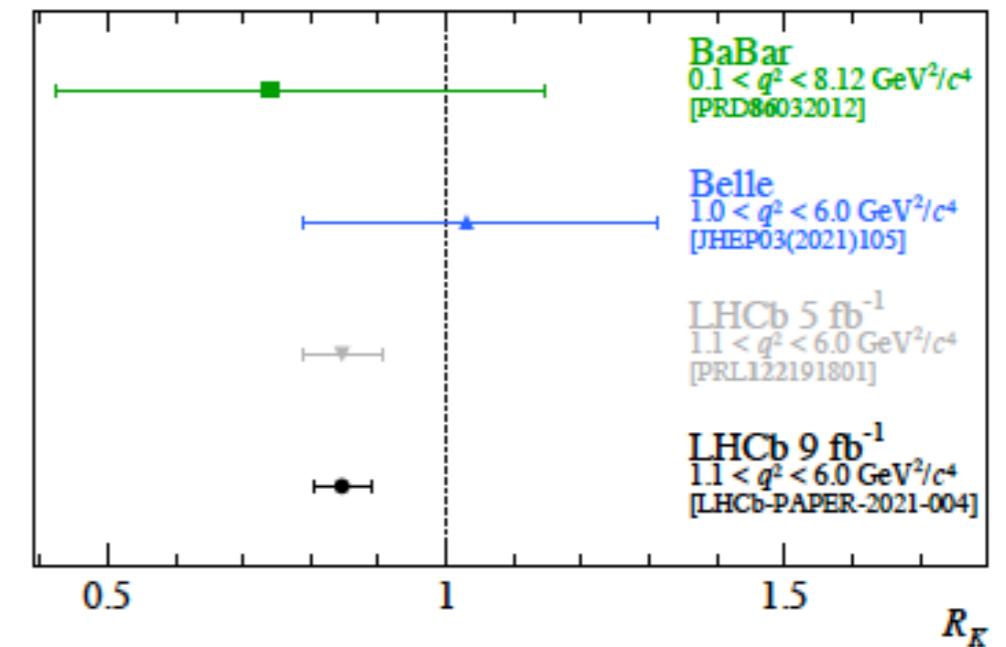


B-anomalies at LHCb

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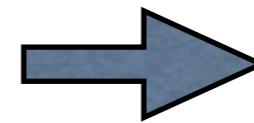


$$R_K = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B^+ \rightarrow K^+ e^+ e^-]}{dq^2} dq^2}$$



$$R_K^{[1.1,6.0]} = 1.00 \pm 0.01 \text{ (SM)}$$

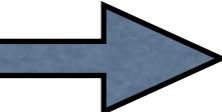
Hadronic uncertainties cancelled



Clean test of LFU

LHCb: 2011~2016 data

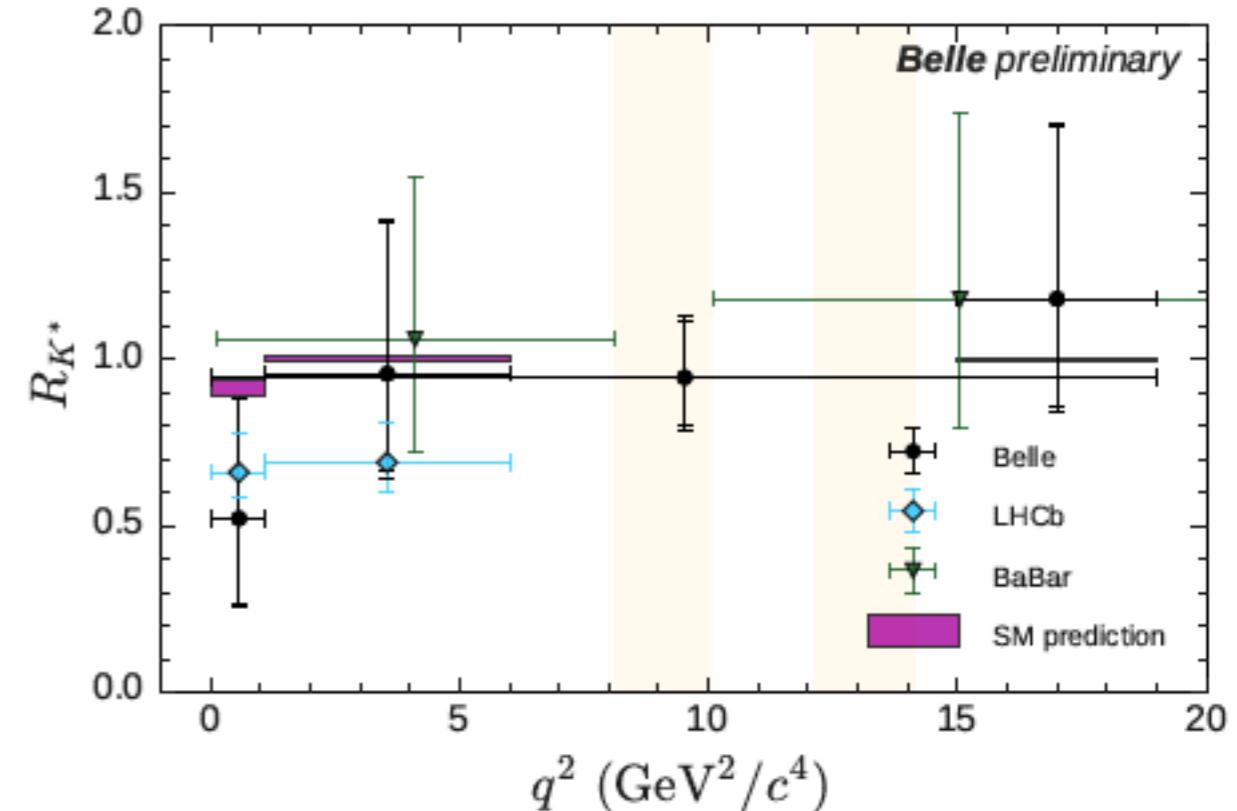
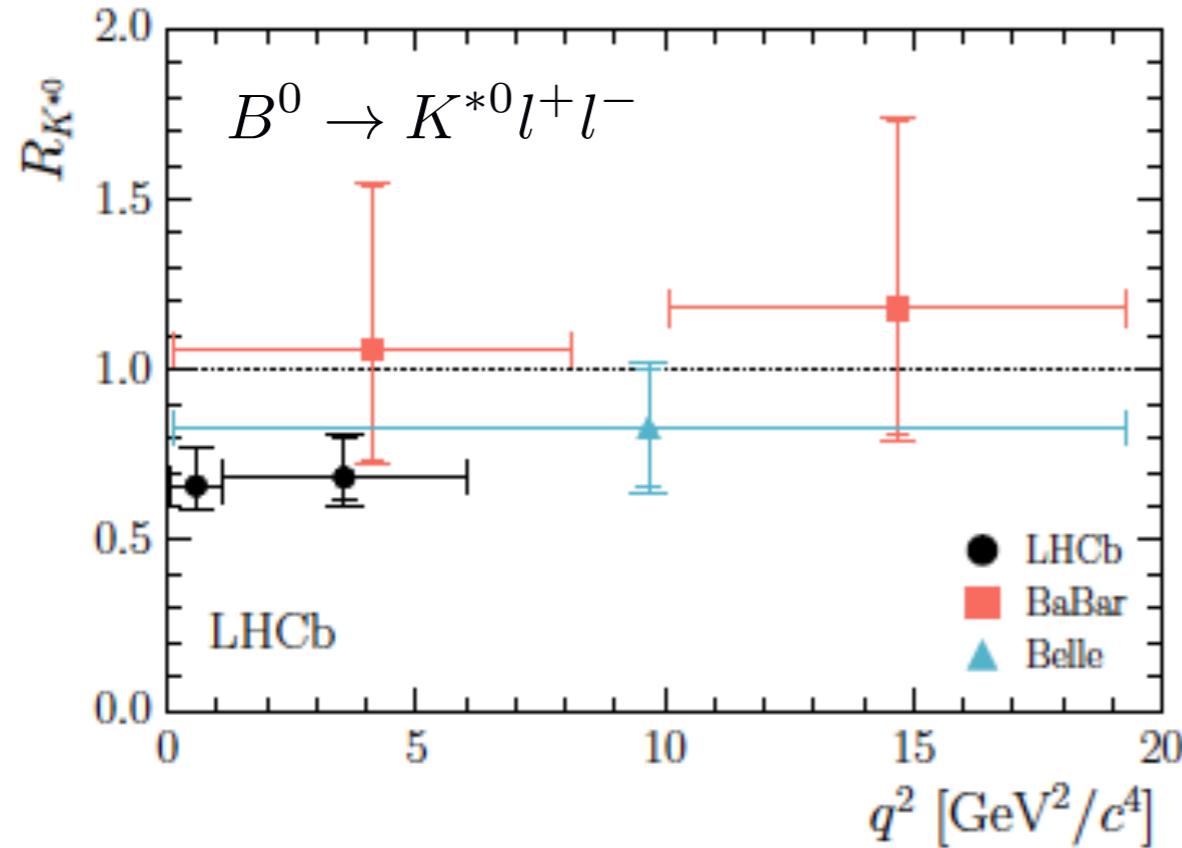
$$R_K = 0.846 \begin{array}{l} +0.060 \\ -0.054 \end{array} \text{ (stat.)} \begin{array}{l} +0.016 \\ -0.014 \end{array} \text{ (syst.)} \sim 2.5\sigma$$

2017~2018 data 

$$R_K = 0.846 \begin{array}{l} +0.042 \\ -0.039 \end{array} \text{ (stat)} \begin{array}{l} +0.013 \\ -0.012 \end{array} \text{ (syst)} \sim 3.1\sigma$$

B-anomalies at LHCb

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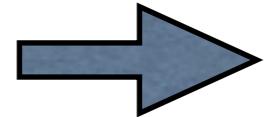


LHCb Preliminary	low- q^2	central- q^2
$\mathcal{R}_{K^{*0}}$	$0.660 \pm 0.110 \pm 0.024$	$0.685 \pm 0.113 \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

$$R_{K^*}^{[1.1, 6.0]} = 1.00 \pm 0.01 \text{ (SM)}$$

$$R_{K^*}^{[0.045, 1.1]} = 0.906 \pm 0.028 \text{ (SM)}$$

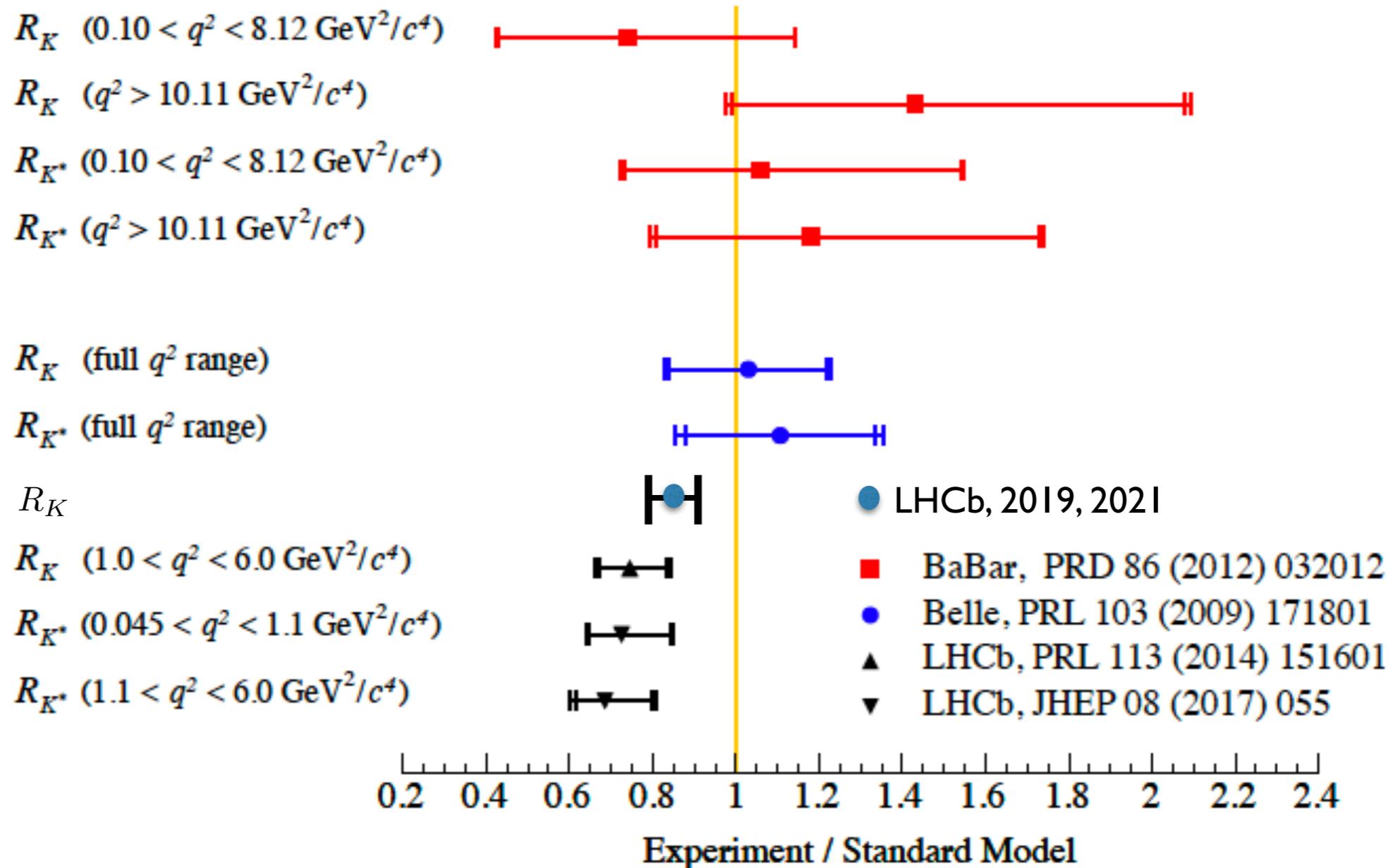
- R_{K^*} : $2.2\text{-}2.4\sigma$ deviation and $2.4\text{-}2.5\sigma$ deviation.



Hints for lepton flavor non-universality?

Summary of B-anomalies

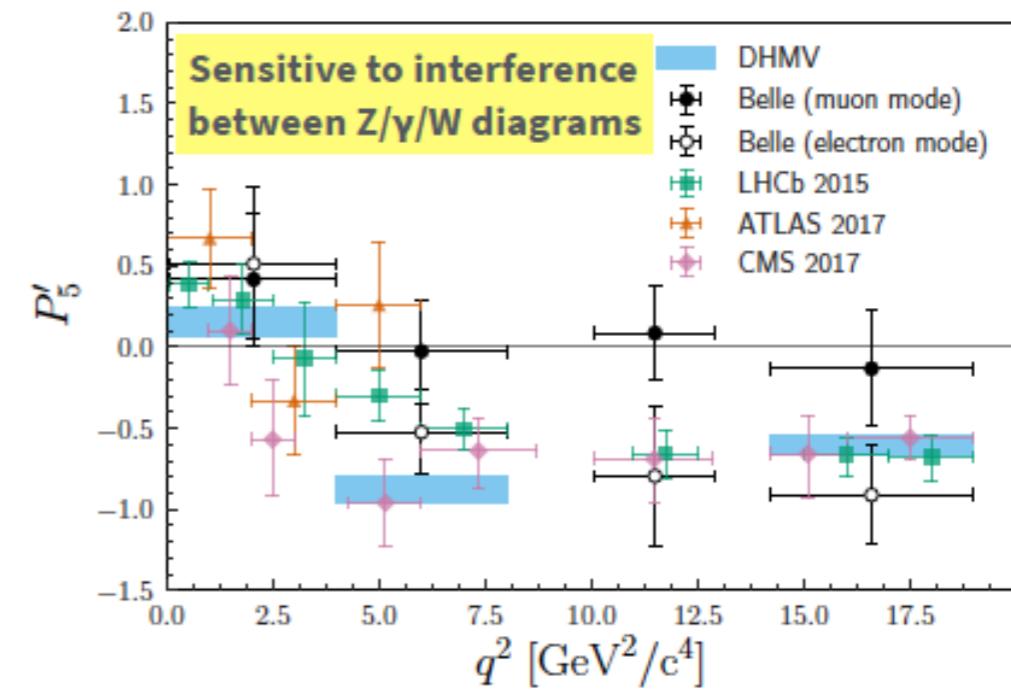
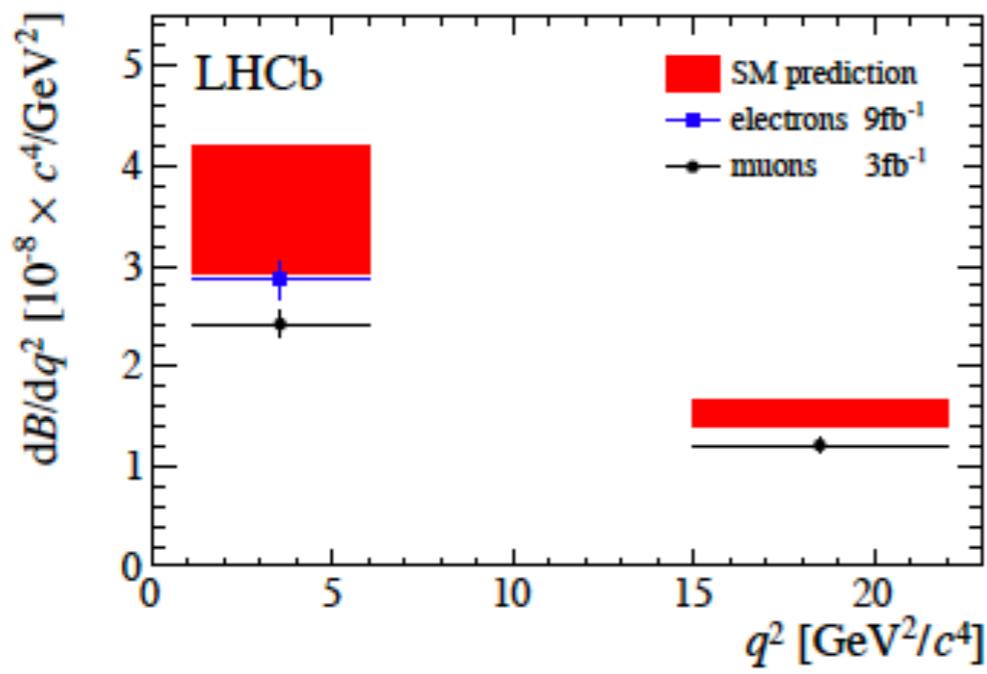
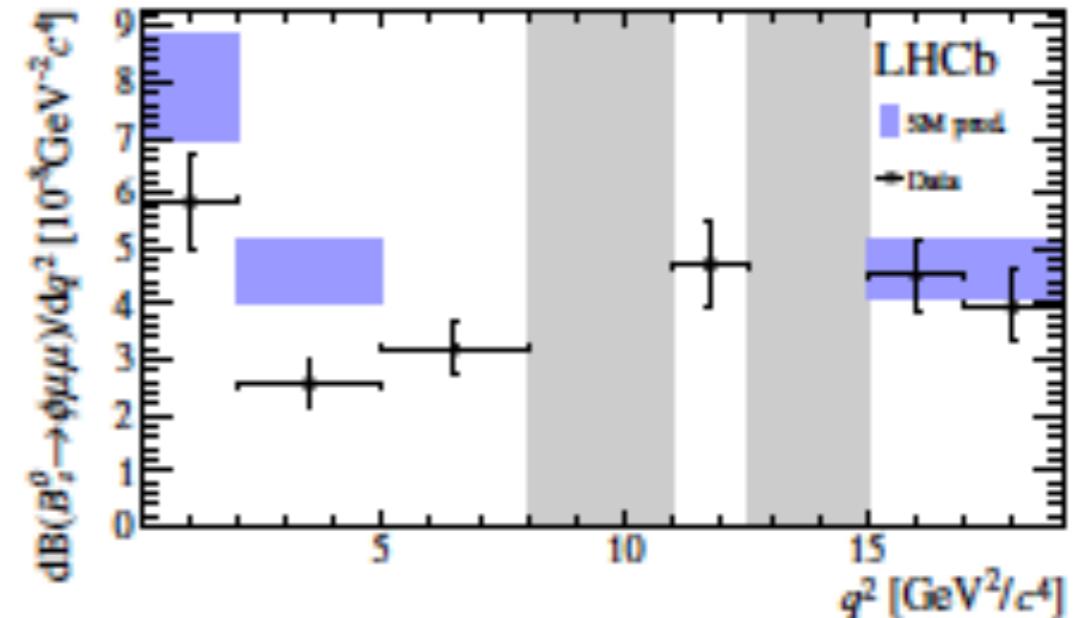
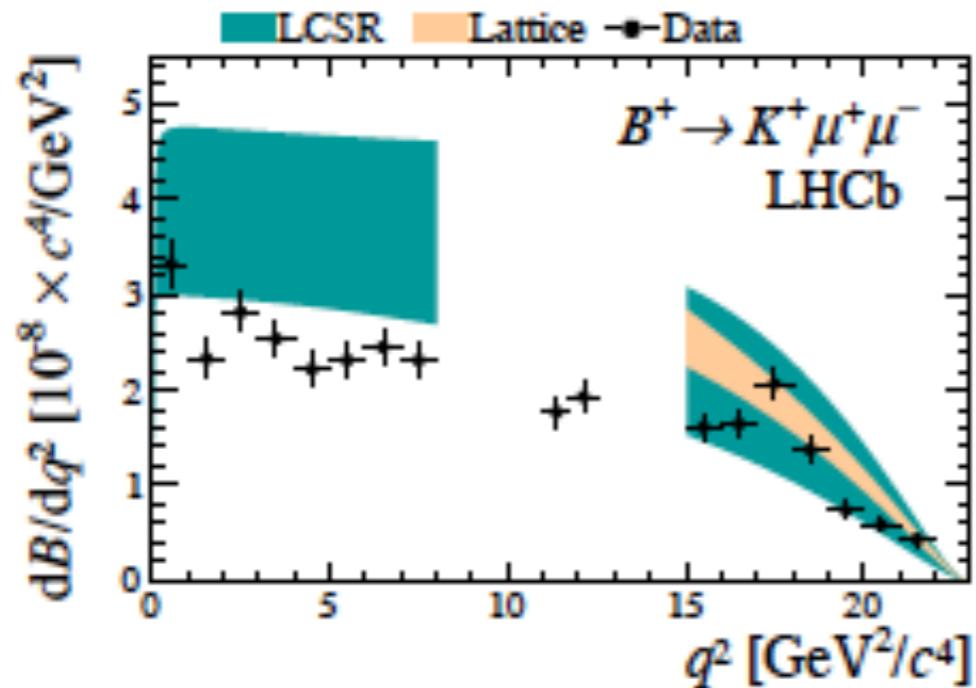
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[S. Bifani et al, 1809.06229 + updates]

Muon less SM than electron

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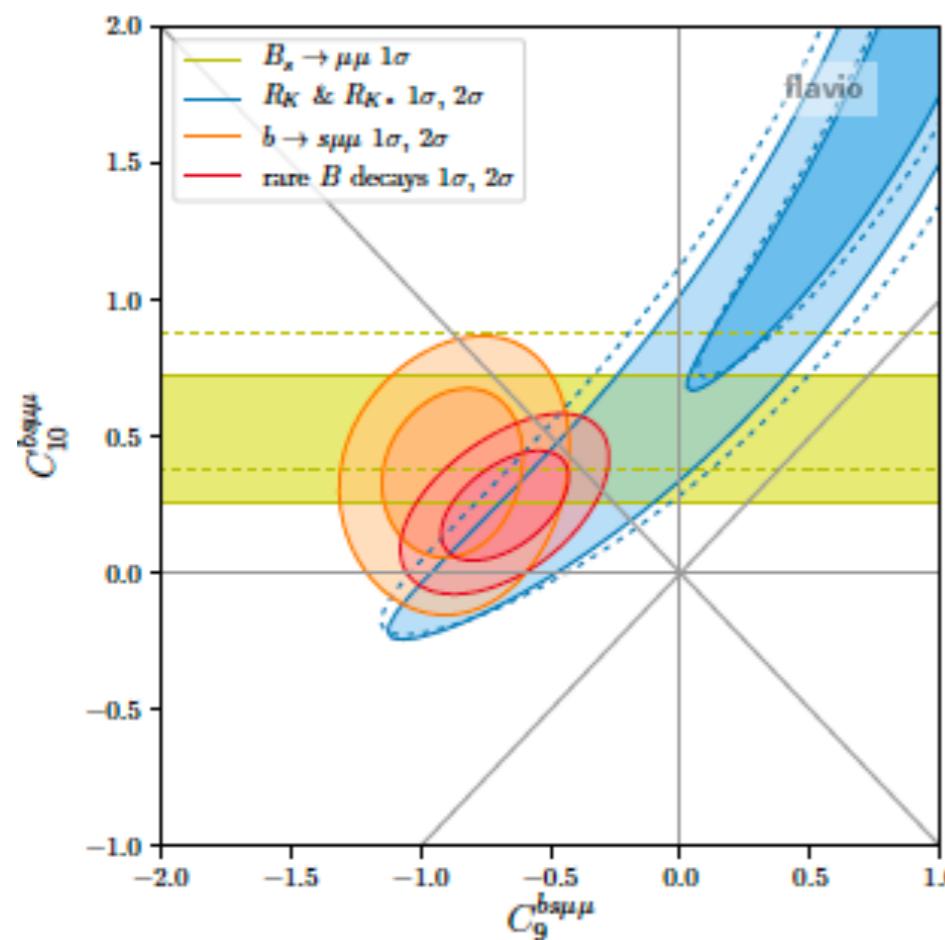


- Differential branching fractions & angular distribution are consistently lower than the SM values in muon channels.

Global fits

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[Altmannshofer, Stangl, 2021]

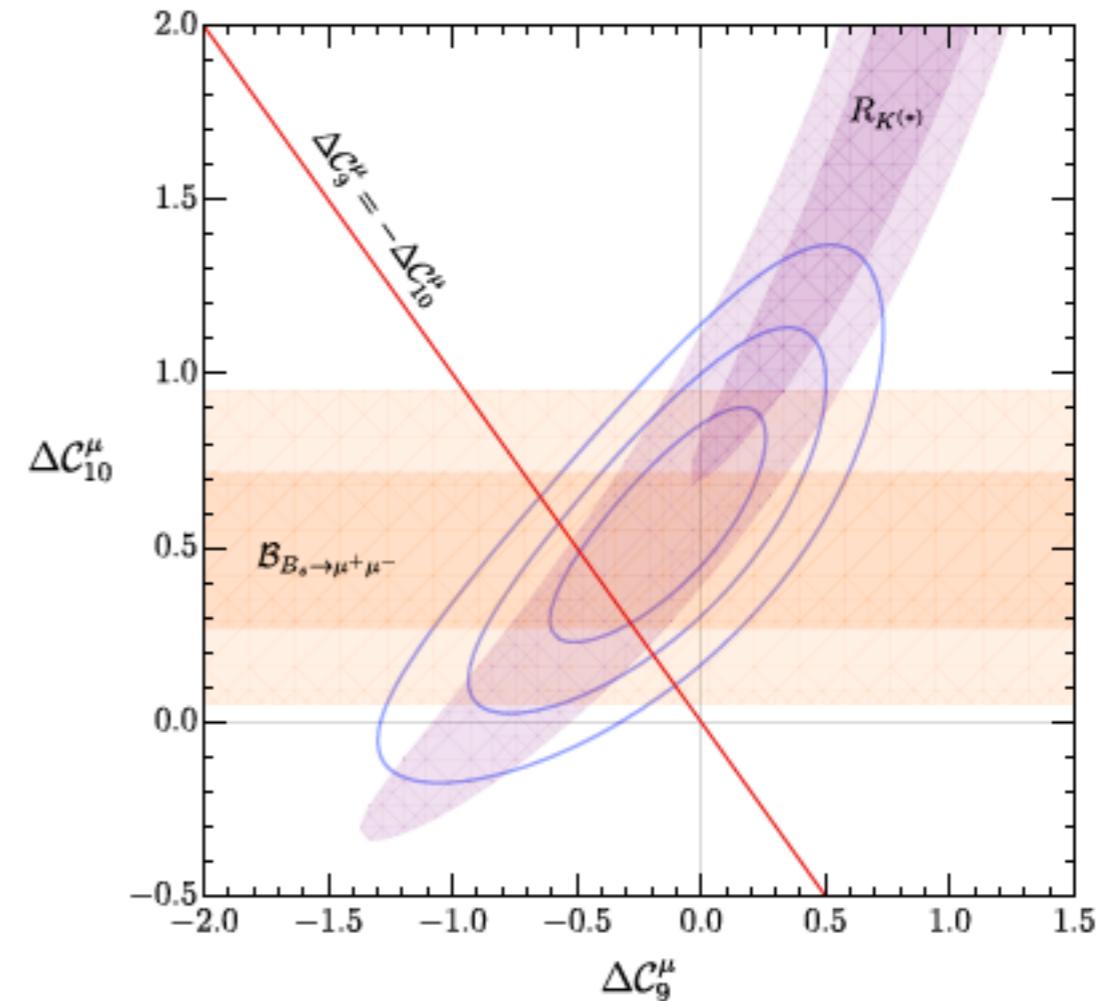


Best fit: $\sim 6.1\sigma$ from SM

$$C_9^{bs\mu\mu} \simeq -0.82$$

$$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \simeq -0.43$$

[Cornella et al, 2021]



(Consistent with $B_s \rightarrow \mu^+ \mu^-$)

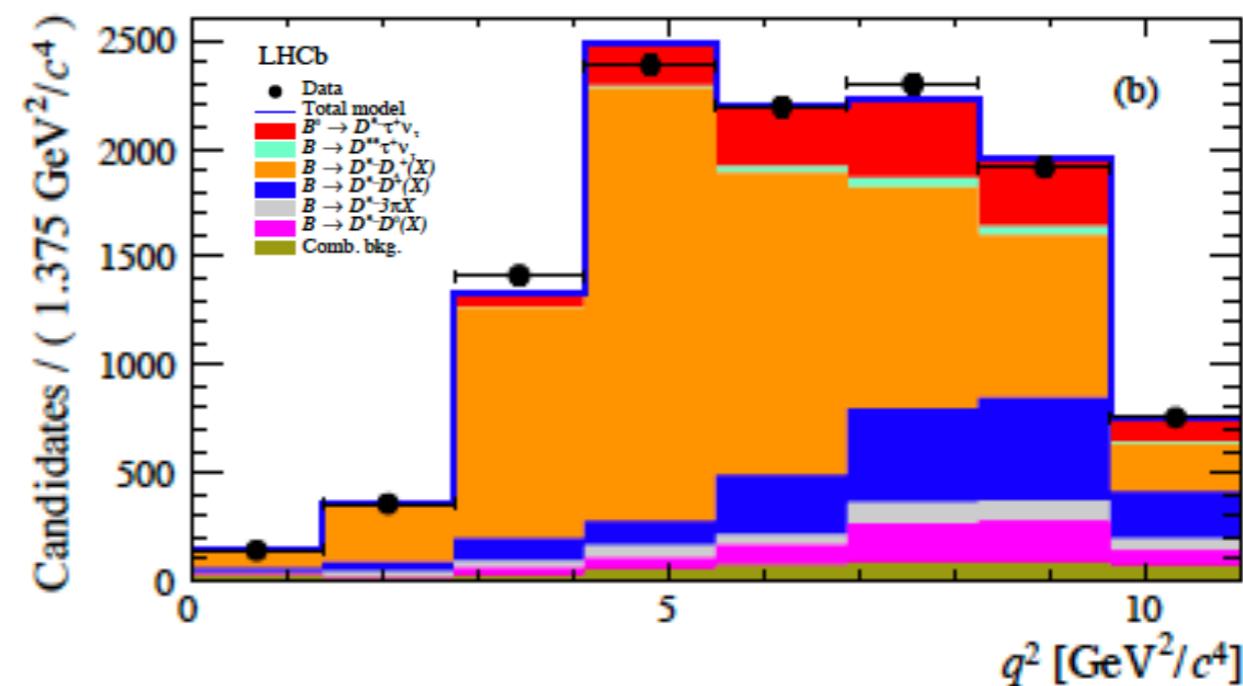
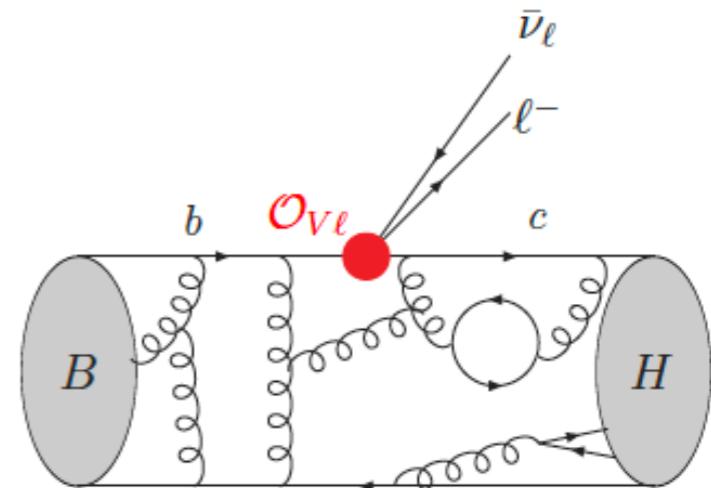
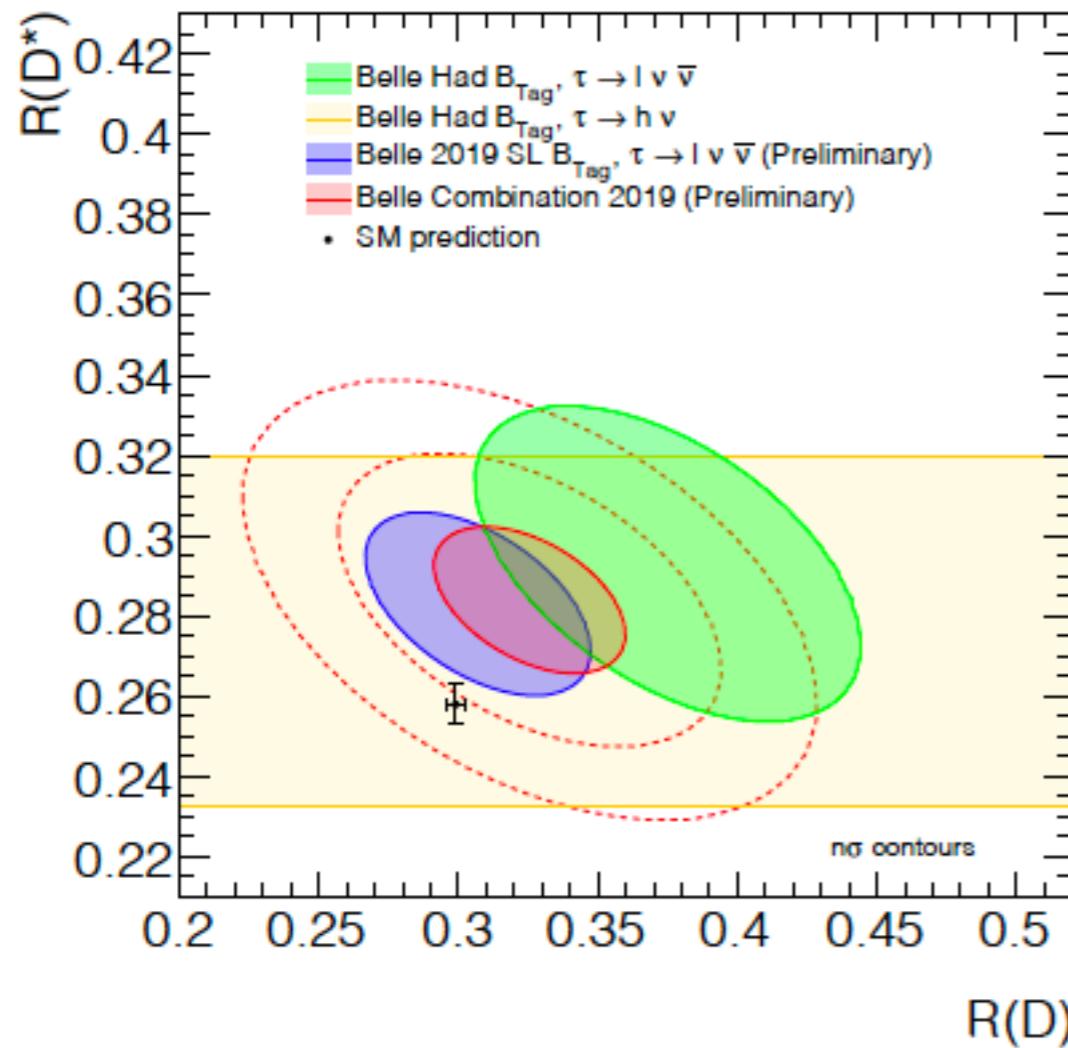
Z' models

Leptoquark models

$B \rightarrow D^{(*)}\tau\nu$

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$$R_{D^*} = \mathcal{B}(B \rightarrow D^*\tau\nu)/\mathcal{B}(B \rightarrow D^*l\nu)$$



[Belle-II, 1808.10567]

$$R_D = \mathcal{B}(B \rightarrow D\tau\nu)/\mathcal{B}(B \rightarrow Dl\nu)$$

$$R_D^{\text{SM}} = 0.299 \pm 0.003,$$

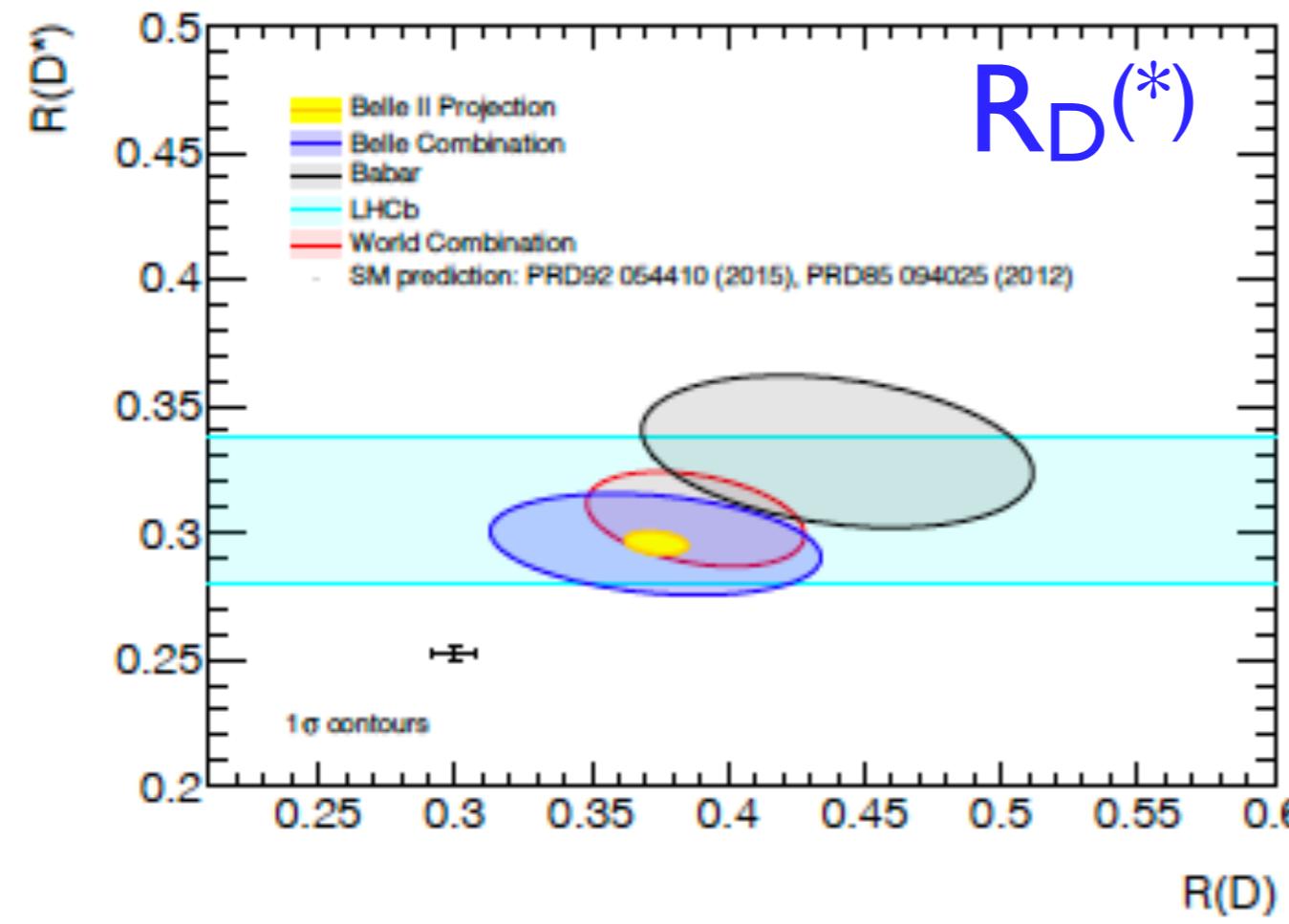
$$R_{D^*}^{\text{SM}} = 0.257 \pm 0.003.$$

$$\begin{aligned} R_D^{\text{exp}} &= 0.403 \pm 0.040 \pm 0.024, \\ R_{D^*}^{\text{exp}} &= 0.310 \pm 0.015 \pm 0.008. \end{aligned}$$

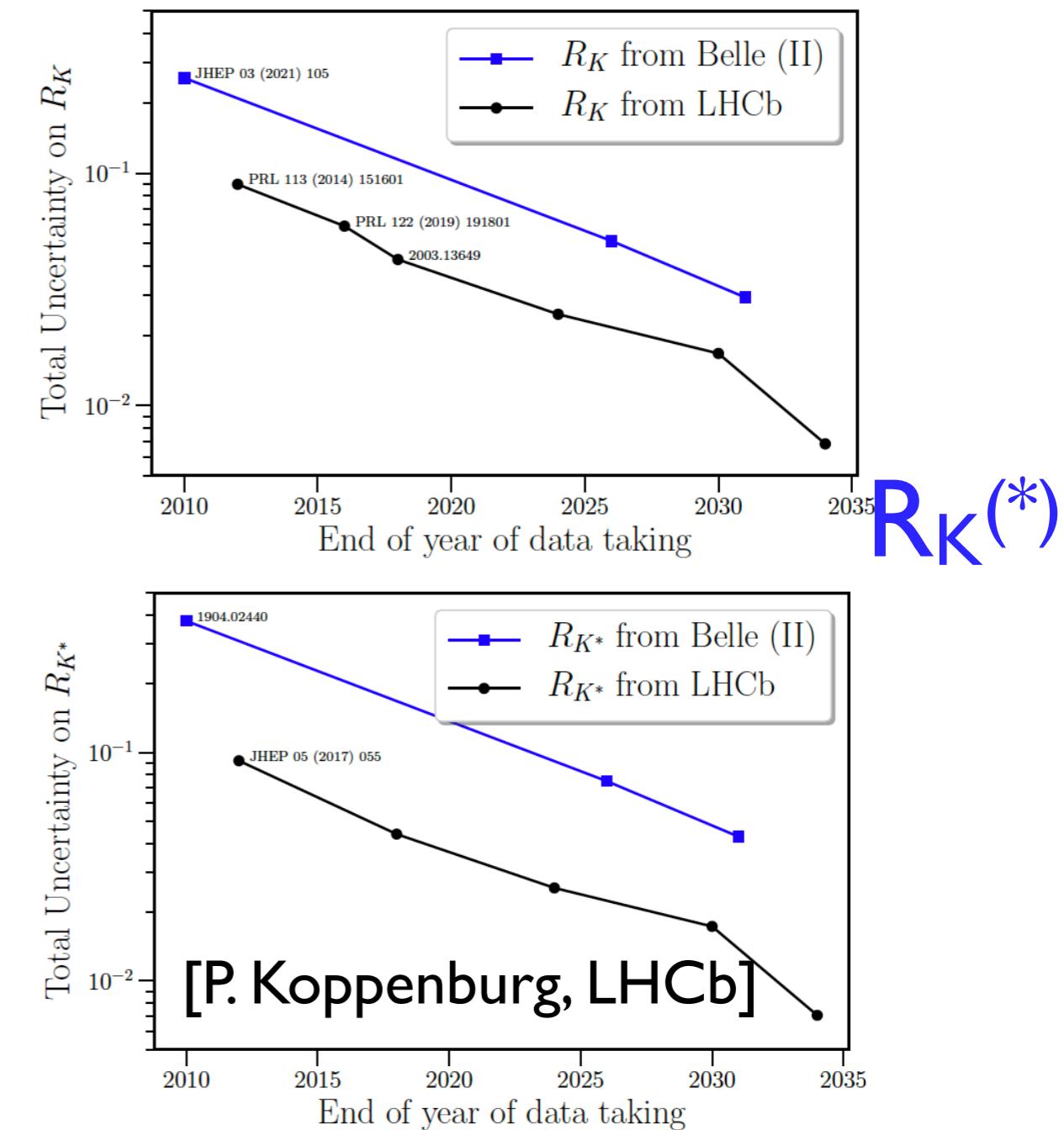
- 3.8 σ anomalies in $B \rightarrow D^{(*)}\tau\nu$.
- 3.1 σ after Belle (Moriond 2019).

Prospects for B-anomalies

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[Belle-II, 1808.10567]



- Starting in 2019, Belle II and LHCb can test LFUV in B-meson decays to few % accuracy with data of 5 ab⁻¹.

Lepton g-2, LFV, EDM

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- Lepton g-2 and lepton flavor violation are important precision tests of the SM.

Muon g-2:



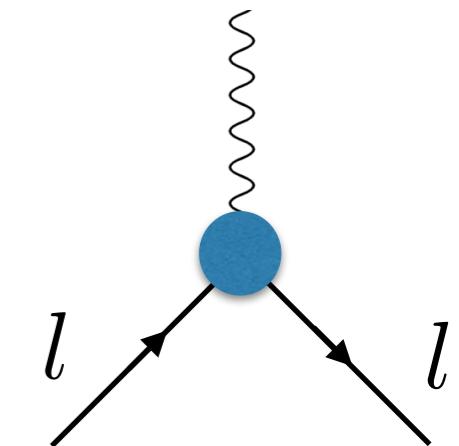
$$a_\mu(E821) = 116592089(63) \times 10^{-11}$$

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11}$$

$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11}$$

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

4.2 σ from SM



Electron g-2: $\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -89(36) \times 10^{-14}$ [Cs] -2.4 σ

$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = 48(30) \times 10^{-14}$$
 [Rb] 1.6 σ

Fine structure constant differs by 5.4 σ .

Bounds on LFV: $\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [MEG]

$$\text{BR}(\tau \rightarrow e\gamma) < 3.3 \times 10^{-8}$$

$$\text{BR}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$$

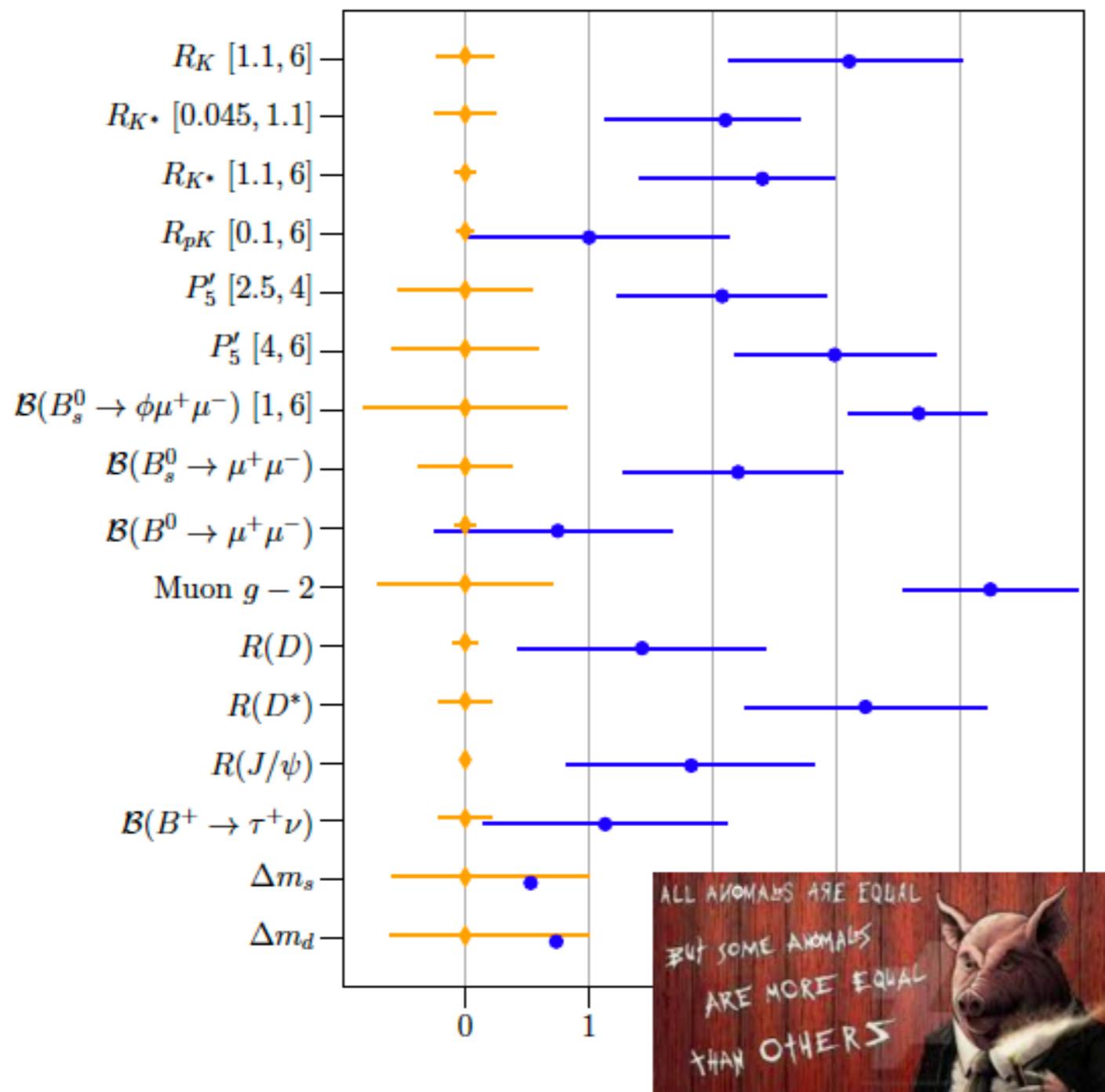
EDM: $d_e < 1.1 \times 10^{-29} \text{ e cm}$ [ACMEII] $d_\mu < 1.5 \times 10^{-19} \text{ e cm}$

Summary for All

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PULLS OF FLAVOUR ANOMALIES

[P. Koppenburg, LHCb]



R_K, R_{K^*} : LHCb [[arXiv:2103.11769](#)] [[JHEP 08 \(2017\) 055](#)] vs [Bordone, Isidori, Pottori EPJC 76 (2016) 440].

R_{pK} LHCb [[JHEP 05 \(2020\) 040](#)].

P'_5 my average of LHCb [[PRL 125 \(2020\) 011802](#)], CMS [[PLB 781 \(2018\) 517](#)], ATLAS [[JHEP 10 \(2018\) 047](#)] vs [Bharucha, Straub, Zwicky, JHEP 08 (2016) 098].

$B_s^0 \rightarrow \phi \mu^+ \mu^-$ [[JHEP 09 \(2015\) 179](#)] vs FLAVIO [Straub, [arXiv:1810.08132](#)].

$B \rightarrow \mu^+ \mu^-$ Combination [Altmannshofer, Stangl] of LHCb [[LHCb-PAPER-2021-007](#)], CMS [[JHEP 04 \(2020\) 188](#)], ATLAS [[JHEP 04 \(2019\) 098](#)] vs [Beneke, Bobeth, Szafron, JHEP 10 (2019) 232].

Muon $g - 2$ [Muon $g - 2$, [PRL 126 \(2021\) 141801](#)] vs [Aoyama et al., [Phys. Rept. 887 \(2020\) 1](#)].

$R(D^{(*)})$ [[HFlav, arXiv:1909.12524](#)].

$\mathcal{B}(B^+ \rightarrow \tau \mu)$ [[UTFit](#)].

Δm_q [[arXiv:2104.04421](#)] and [[PDG](#)] vs [Di Luzio, Kirk, Lenz, Rauh, [JHEP 12 \(2019\) 009](#)].

EFT for B-decays

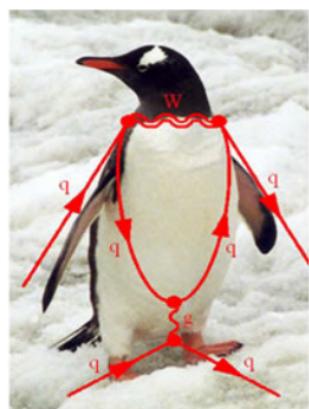
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Effective Hamiltonian for $b \rightarrow s\mu\mu$:

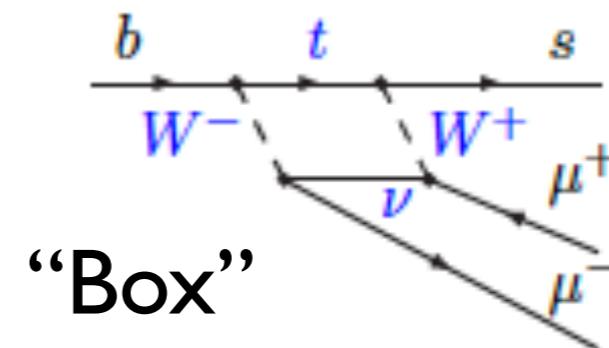
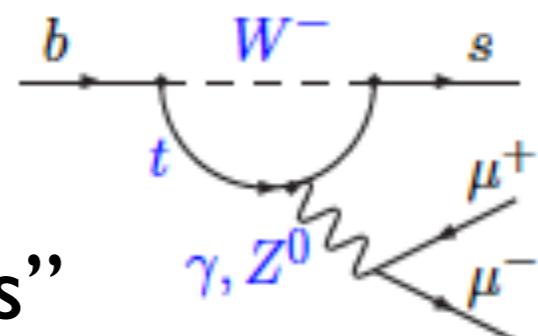
$$\mathcal{H}_{\text{eff}, \bar{b} \rightarrow \bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} (C_9^\mu \mathcal{O}_9^\mu + C_{10}^\mu \mathcal{O}_{10}^\mu + C_9'^\mu \mathcal{O}_9'^\mu + C_{10}'^\mu \mathcal{O}_{10}'^\mu) + \text{h.c.}$$

$$\mathcal{O}_9^\mu \equiv (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu\mu), \quad \mathcal{O}_{10}^\mu \equiv (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu\gamma^5\mu), \quad C_9^{\mu, \text{SM}}(m_b) = -C_{10}^{\mu, \text{SM}}(m_b) = 4.27$$

$$\mathcal{O}_9'^\mu \equiv (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu\mu), \quad \mathcal{O}_{10}'^\mu \equiv (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu\gamma^5\mu) \quad C_9'^{\mu, \text{SM}}(m_b) \approx -C_{10}'^{\mu, \text{SM}}(m_b) \approx 0.$$



“Penguins”

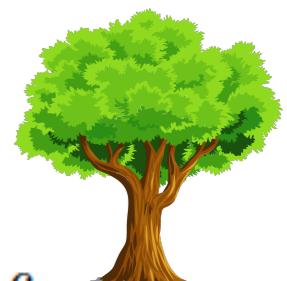


$$R_K[1,6] \simeq 1 + 0.24 \left(C_{LL}^{\text{NP}\mu} + C_{RL}^\mu \right), \quad R_{K^*}[1,6] \simeq 1 + 0.24 \left(C_{LL}^{\text{NP}\mu} - C_{RL}^\mu \right) + 0.07 C_{RL}^\mu,$$

$$C_{LL}^{\text{NP}\ell} = C_9^{\text{NP}\ell} - C_{10}^{\text{NP}\ell}, \quad C_{RL}^\ell = C_9'^\ell - C_{10}'^\ell$$

Effective Hamiltonian for $b \rightarrow c\tau\nu$:

“Tree”



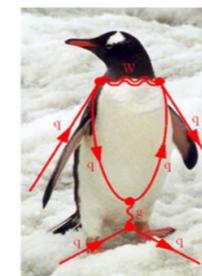
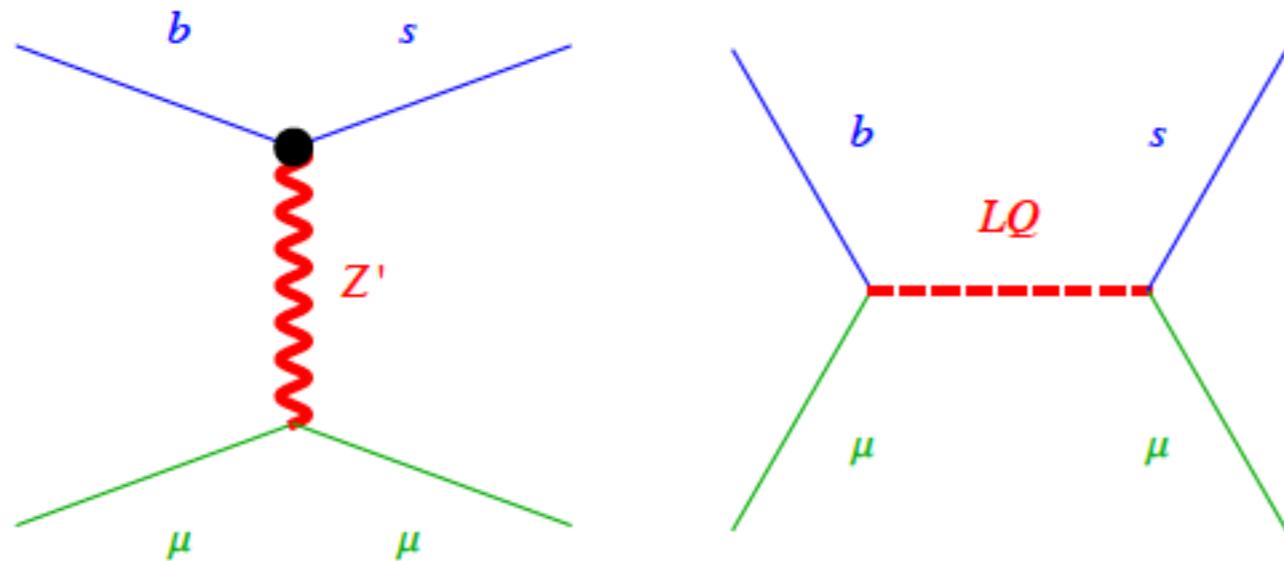
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_V (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_S (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau) + C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \right] + \text{h.c.}$$

$C_V = 1$ and $C_S = C_T = 0$ in the SM

New physics for B-anomalies

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New physics for $R_{K^{(*)}}$ anomalies:

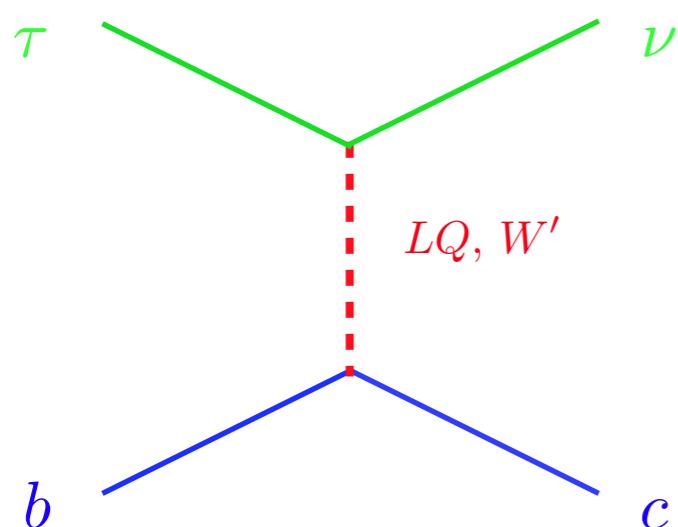


Z' , leptoquarks, loops, etc.

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_{\text{NP}}^2} (\bar{s} \gamma^\mu P_L b)(\bar{\mu} \gamma_\mu \mu),$$

$$\rightarrow \Lambda_{\text{NP}} \simeq 30 \text{ TeV}.$$

New physics for $R_{D^{(*)}}$ anomalies:



Leptoquarks, W' , charged Higgs, etc.

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_{\text{NP}}^2} (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma_\mu P_L \nu_\tau),$$

$$\rightarrow \Lambda_{\text{NP}} \simeq 3.5 \text{ TeV}.$$

Minimal flavored Z'

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[Bian, Choi, Kang, HML, 2017]

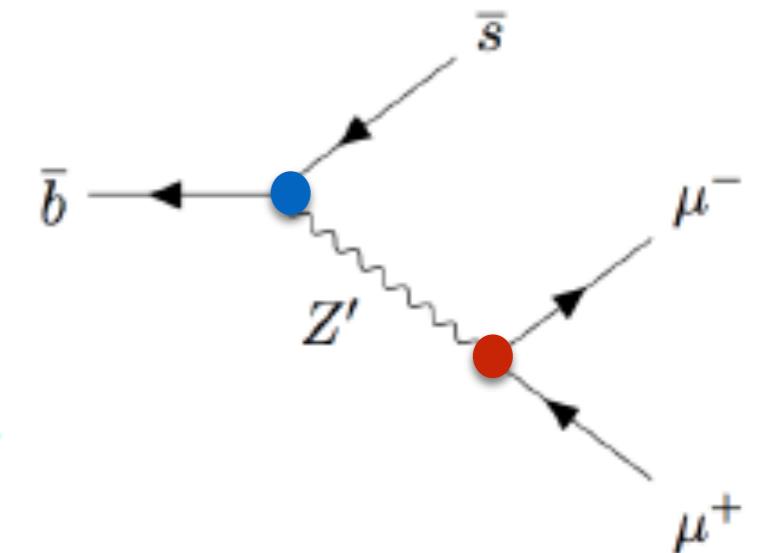
Anomaly-free U(1)' for R_{K^*} anomalies: $U(1)_{x(B_3 - L_3) + y(L_\mu - L_\tau)}$

$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \left(\frac{1}{3} x \bar{t} \gamma^\mu t + \frac{1}{3} x \bar{b} \gamma^\mu b + y \bar{\mu} \gamma^\mu \mu + y \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu - (x+y) \bar{\tau} \gamma^\mu \tau - (x+y) \bar{\nu}_\tau \gamma^\mu P_L \nu_\tau + y \bar{\nu}_{2R} \gamma^\mu P_R \nu_{2R} - (x+y) \bar{\nu}_{3R} \gamma^\mu P_R \nu_{3R} \right).$$

CKM is the only source for flavor violation.

$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \left(\frac{1}{3} x \bar{t}' \gamma^\mu t' + \frac{1}{3} x \bar{d}'_i \gamma^\mu \Gamma_{ij}^{dL} P_L d'_j + \frac{1}{3} x \bar{b}' \gamma^\mu P_R b' \right).$$

$$\Gamma^{dL} \equiv V_{\text{CKM}}^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} V_{\text{CKM}} = \begin{pmatrix} |V_{td}|^2 & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{ts}^* V_{td} & |V_{ts}|^2 & V_{ts}^* V_{tb} \\ V_{tb}^* V_{td} & V_{tb}^* V_{ts} & |V_{tb}|^2 \end{pmatrix}.$$

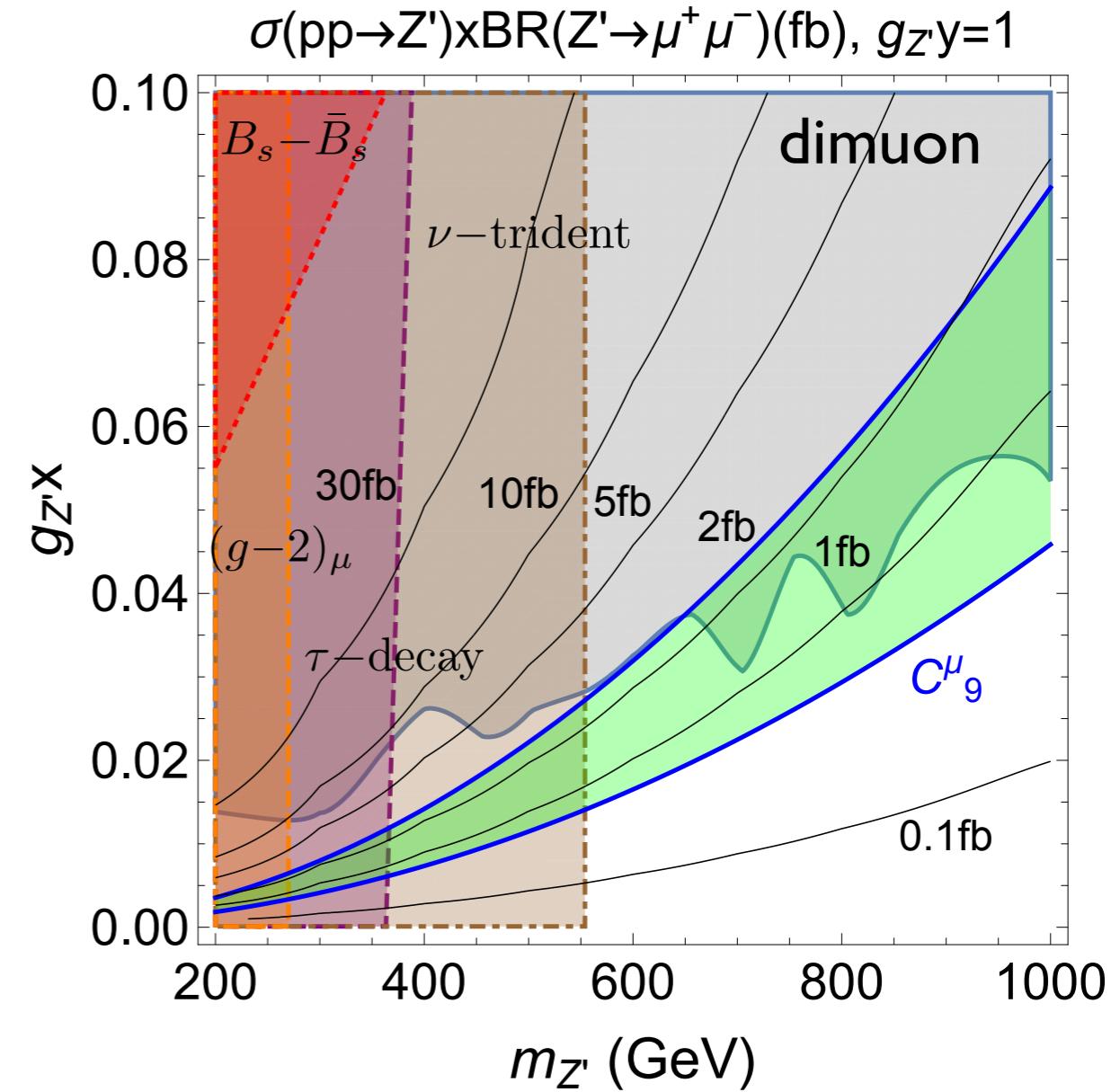
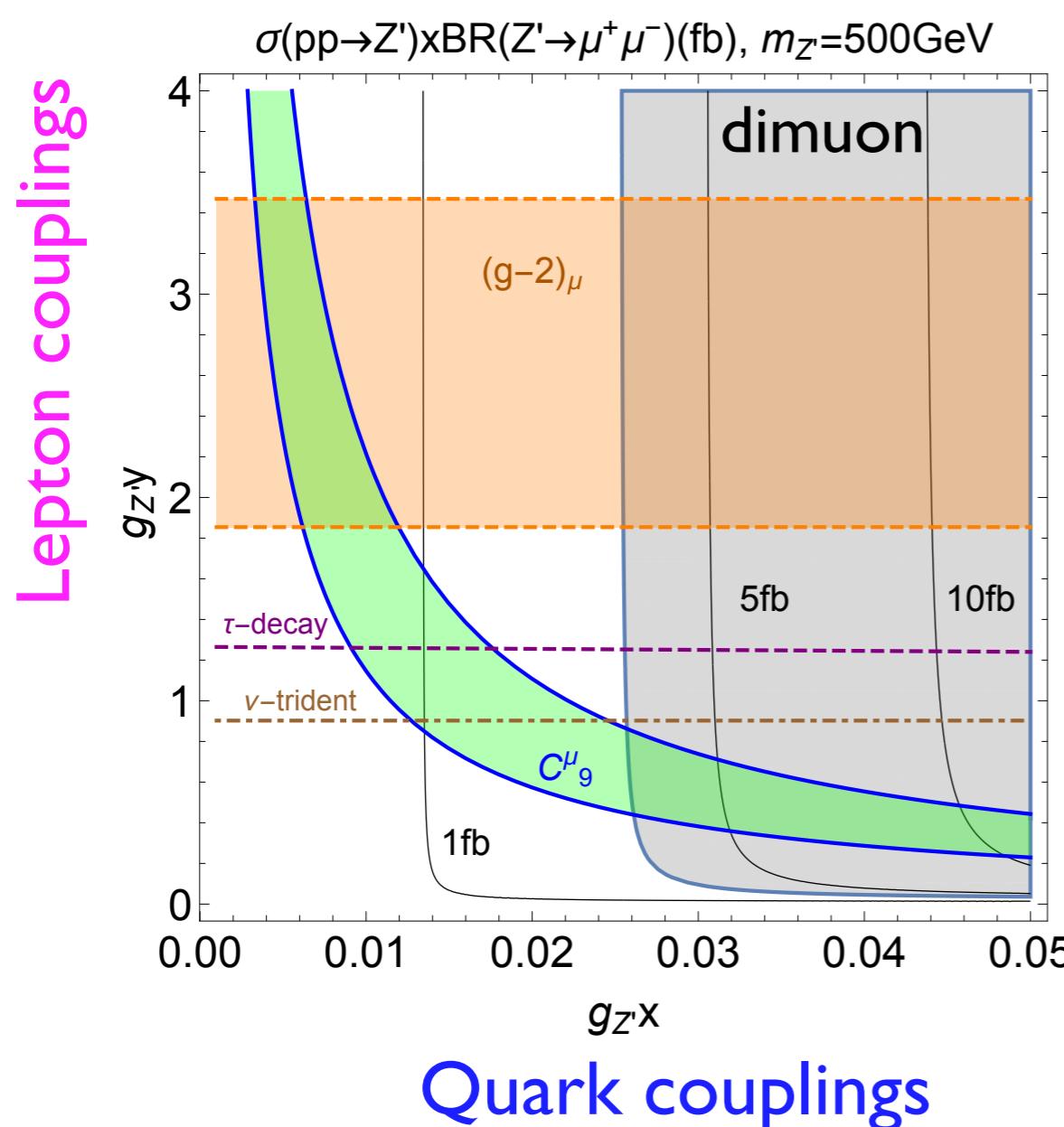


$$\Delta \mathcal{H}_{\text{eff}, \bar{b} \rightarrow \bar{s} \mu^+ \mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} C_9^{\mu, \text{NP}} \mathcal{O}_9^\mu,$$

$$C_9^{\mu, \text{NP}} = -\frac{8xy\pi^2\alpha_{Z'}}{3\alpha_{em}} \left(\frac{v}{m_{Z'}}\right)^2$$

B-anomalies & Z' mass

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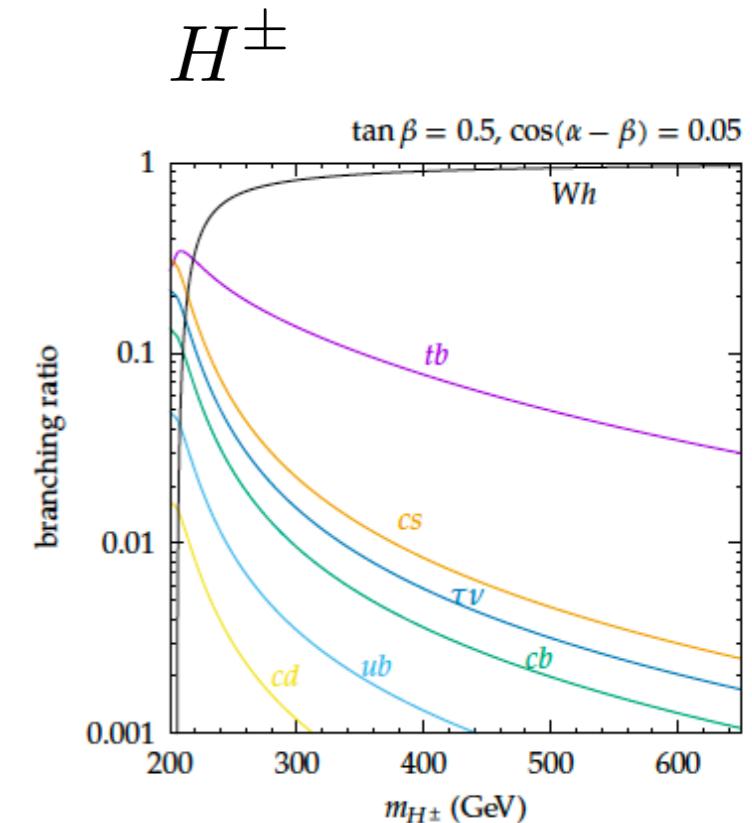
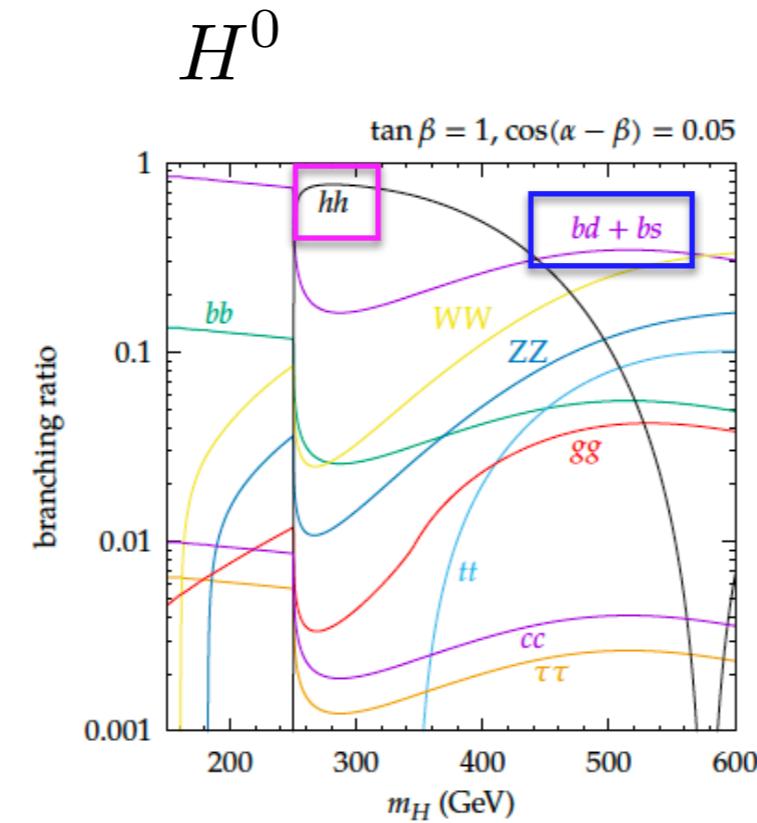
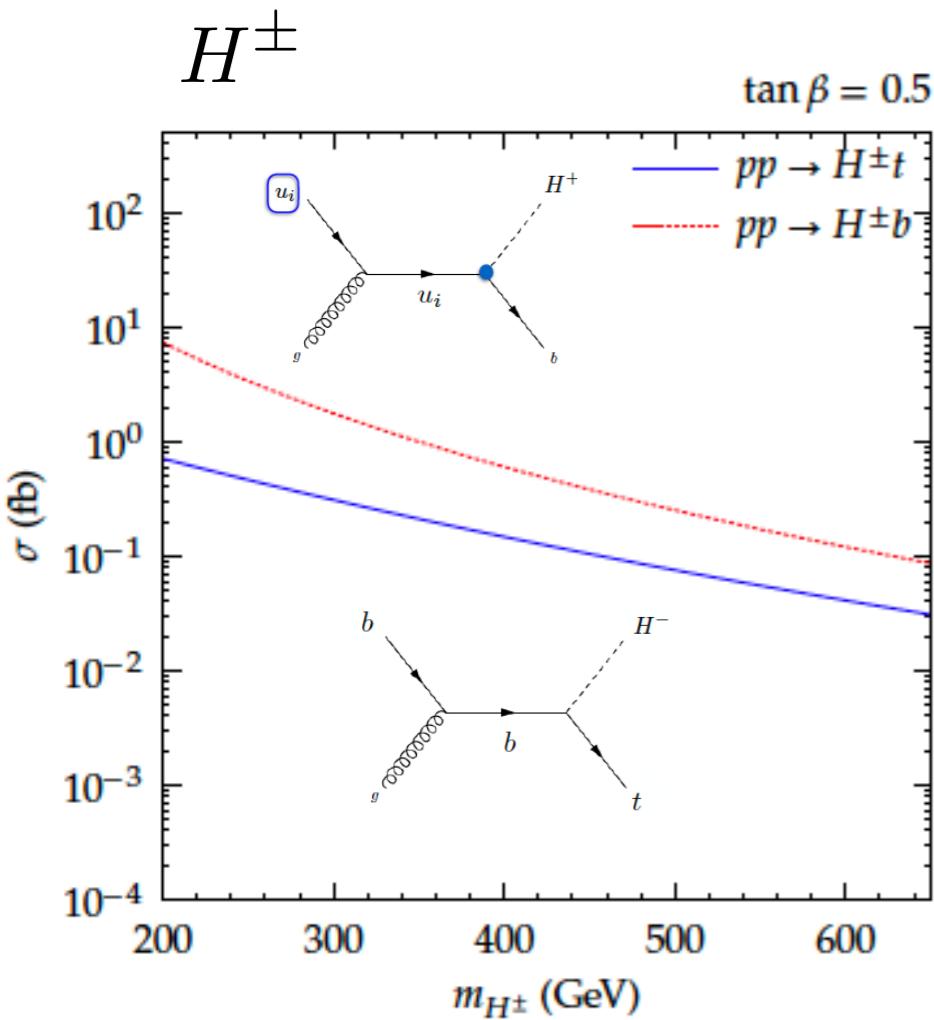


[Bian, Choi, Kang, HML, 2017]

- LHC dimuon and tau decay/neutrino trident searches are complementary to probe $R_{K^{(*)}}$ region.

Flavored Z'-2HDM

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Extra Higgs VEV is needed for CKM mixing for 3rd generation quarks.

New production (H^\pm) : Flavor-violation for bottom quark

New decays: H^0 dijet (b-jet) or di-Higgs

H^\pm $pp \rightarrow H^\pm b \rightarrow W^\pm h + b$

“3b’s: smoking gun signal”

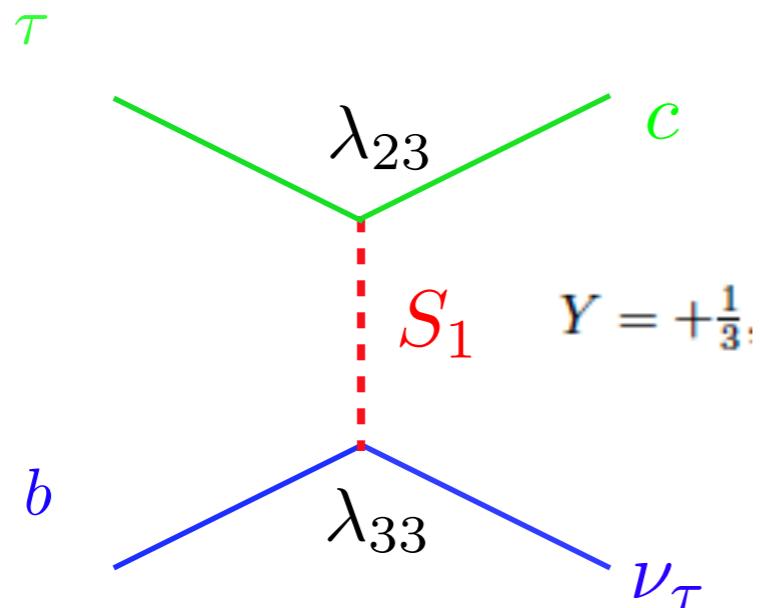
[L. Bian, HML, C.B. Park, 2017, 2020]

Leptoquarks for B-mesons and g-2

Scalar leptoquarks

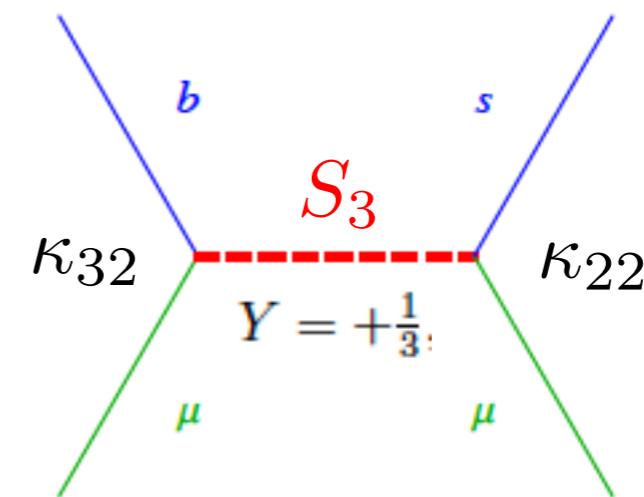
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Singlet leptoquark for $R_D^{(*)}$



$$\mathcal{L}_{S_1} = -\lambda_{ij} \overline{(Q^C)^a_{Ri}} (i\sigma^2)_{ab} S_1 L^b_{Lj} - \lambda'_{ij} \overline{(u^C)_Li} S_1 e_{jR} + \text{h.c.}$$

Triplet leptoquark for $R_K^{(*)}$

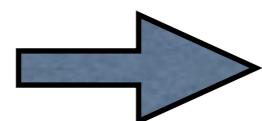


$$\mathcal{L}_{S_3} = -\kappa_{ij} Q^a_{Li} \Phi_{ab} L^b_{Lj} + \text{h.c.}$$

Leptoquark couplings are constrained by proton decay:

Singlet LQ: $q l$ or $u_R^c d_R^c$ must be forbidden.

Triplet LQ: $q l$ or $q q$ must be forbidden.



Extra symmetry?

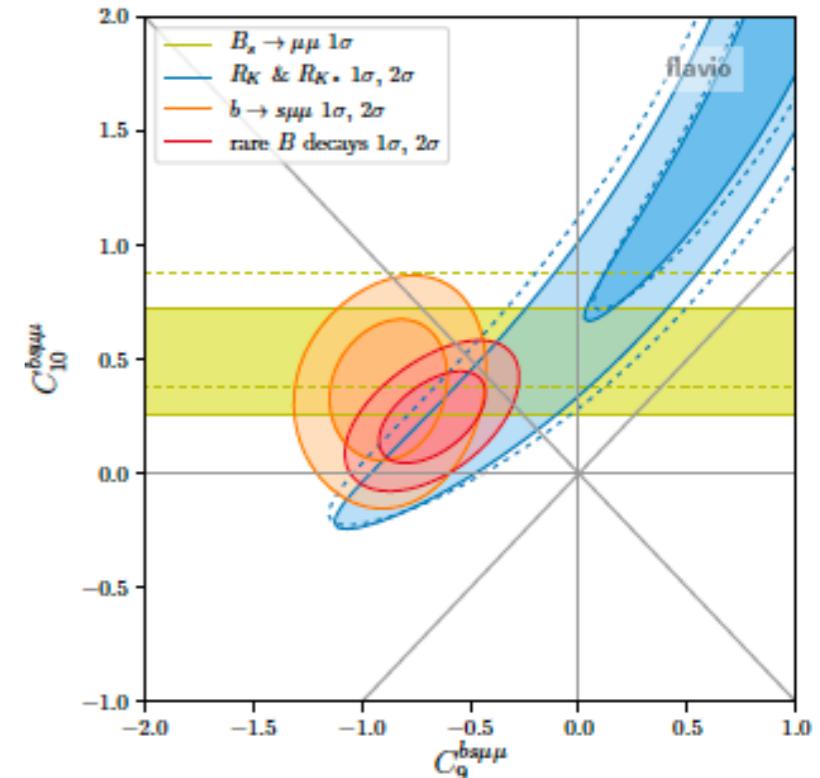
Other constraints

-17-

$B - \bar{B}$ mixing : loop-suppressed,
unlike Z' case.

$B_s \rightarrow \mu^+ \mu^-$: constrains only triplet
leptoquark couplings.

$B \rightarrow K^{(*)} \nu \bar{\nu}$: exists by SU(2) symmetry.



$$B(B \rightarrow K \nu \bar{\nu}) \Big|_{\text{SM}} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6}, \quad B(B \rightarrow K^* \nu \bar{\nu}) \Big|_{\text{SM}} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6}$$

$$B(B \rightarrow K \nu \bar{\nu}) < 1.6 \times 10^{-5}, \quad [\text{Belle}] \qquad B(B \rightarrow K^* \nu \bar{\nu}) < 2.7 \times 10^{-5}$$

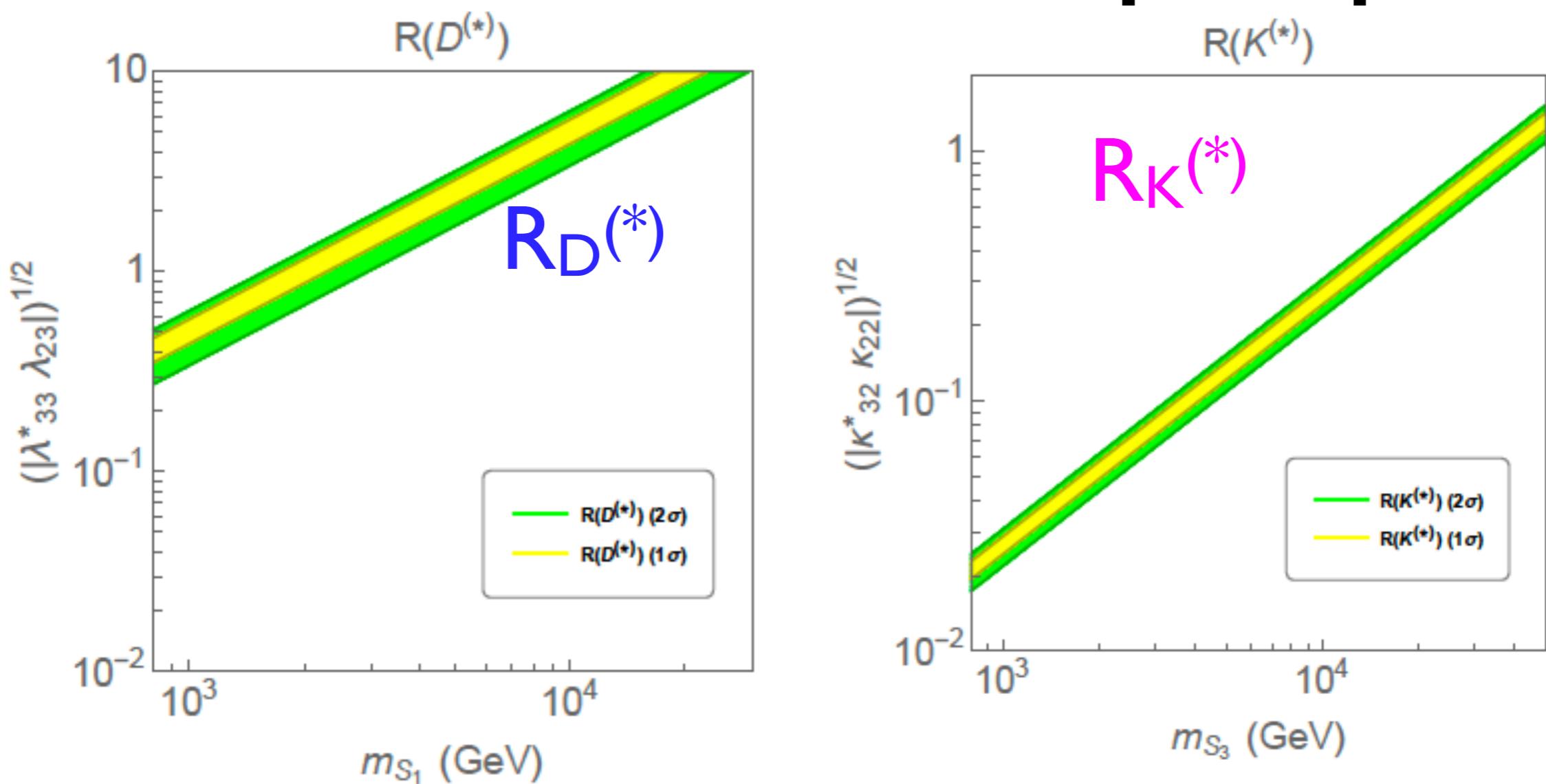
→ Cancellation between singlet and triplet leptoquarks.

Belle-2 at 10% level

→ strong constraints on leptoquark models.

Minimal flavor for leptoquarks

-18-



[Choi, Kang, HML, Ro, 2018]

Minimal flavor: $\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23} \\ 0 & \lambda_{32} & \lambda_{33} \end{pmatrix}, \quad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$.

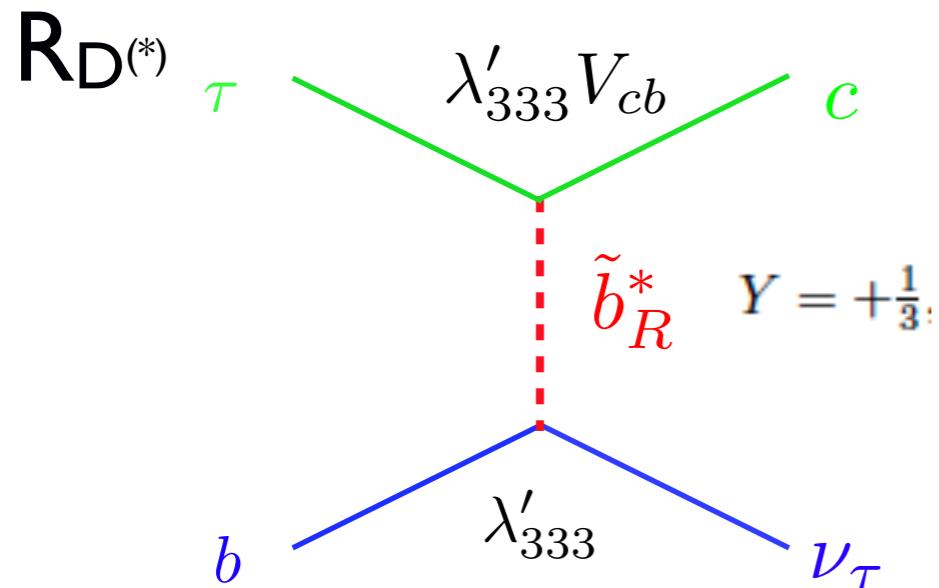
leptons \longrightarrow

quarks \downarrow

$$\frac{|\kappa_{33}^* \kappa_{23}|}{|\lambda_{33}^* \lambda_{23}|} \approx \frac{|\kappa_{32}^* \kappa_{23}|}{|\lambda_{32}^* \lambda_{23}|} \approx \frac{m_{S_3}^2}{m_{S_1}^2} \quad \text{for } B \rightarrow K^{(*)} \nu \bar{\nu}$$

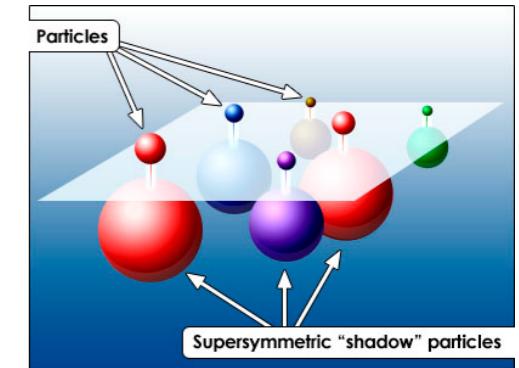
Leptoquark from SUSY

-19-



Singlet leptoquark
= Sbottom with RPV

$$W_{\text{RPV}} = \lambda'_{333} L_3 Q_3 D_3^c$$



$$\mathcal{L}_{\text{RPV}} = -\lambda'_{333} \nu_{\tau L} b_L \tilde{b}_R^* - \lambda'_{333} \tau_{L} t_L \tilde{b}_R^* + \text{h.c.},$$

RPV safe from proton decay:

sbottom- $u_R^c d_R^c$ forbidden

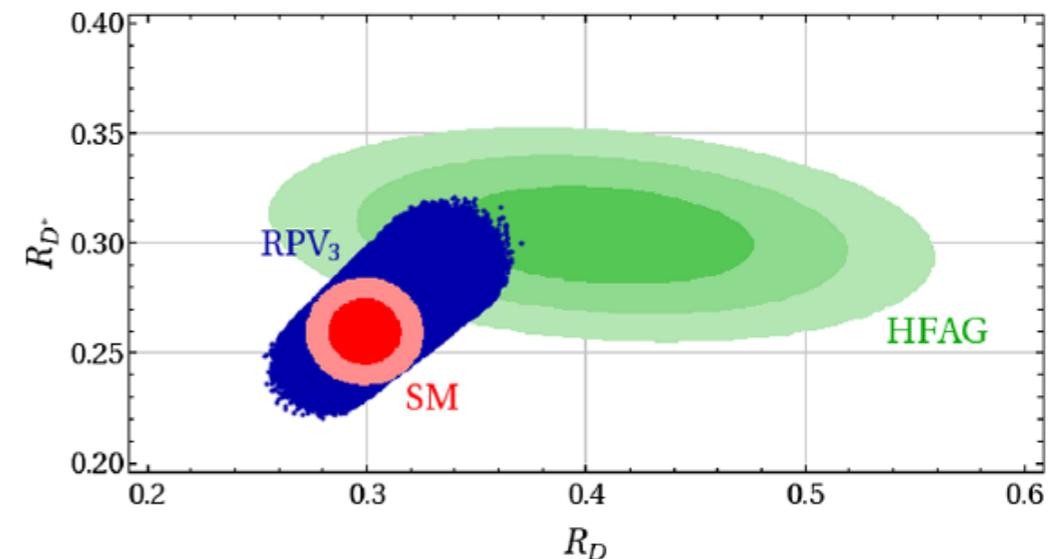
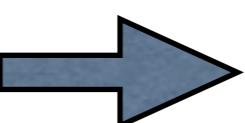
CKM mixing induces charm coupling:

$$t_L \rightarrow V_{tb} t_L + V_{cb} c_L + V_{ub} u_L.$$

LHC direct searches:

$$\tilde{b} \rightarrow t\tau, \quad m_{\tilde{b}_R} \gtrsim 680 \text{ GeV.}$$

$$\tilde{b} \rightarrow b\nu_\tau, \quad m_{\tilde{b}_R} \gtrsim 1.22 \text{ TeV.}$$



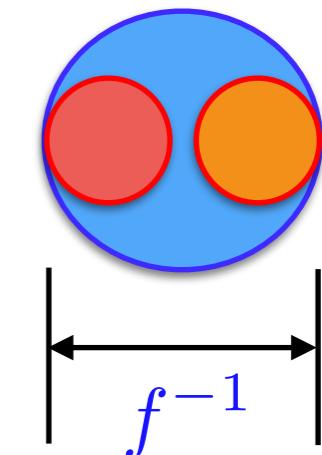
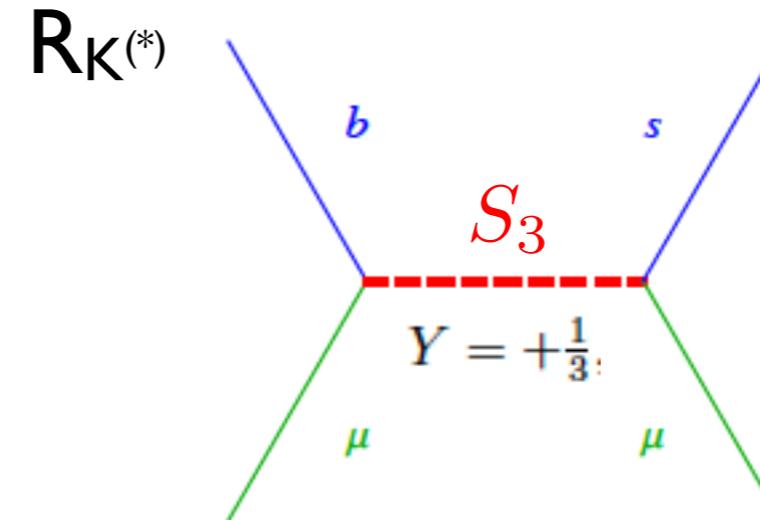
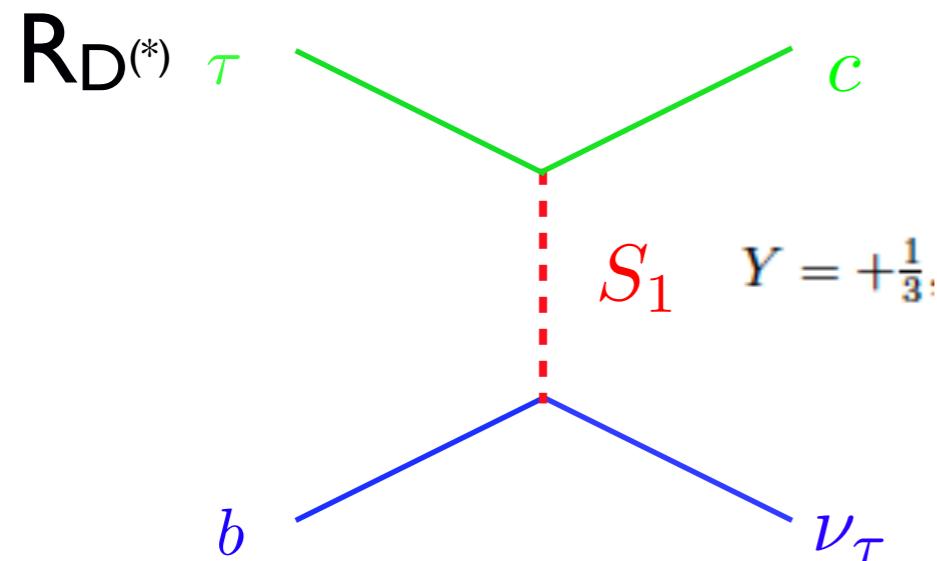
[Altmannshofer et al, 2017]

Large RPV couplings in tension
with perturbative unification.

$R_K^{(*)}$: one-loop suppressed, so small. cf. SU(5) GUT, Becirevic et al, 2018

Composite leptoquarks

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Scalar leptoquarks = pseudo Nambu-Goldstone bosons

$R_{D^{(*)}} \longrightarrow$ Singlet leptoquark

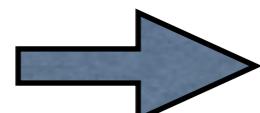
[B. Gripaios, 2010]

Coset space: $SU(4)_{PS} \times SO(5)/[(SU(3)_C \times U(1)_{B-L}) \times (SU(2)_L \times SU(2)_R)]$

$R_{K^{(*)}} \longrightarrow$ Triplet leptoquark

[B. Gripaios et al, 2014]

Coset space: $SO(9) \times SO(5)/[(SU(4)_{PS} \times SU(2)_{LQ}) \times (SU(2)_H \times SU(2)_R)]$

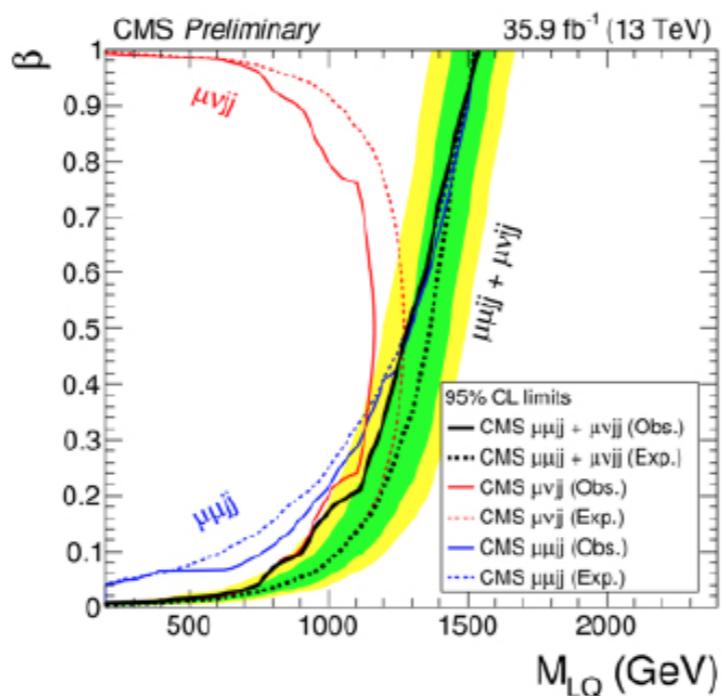
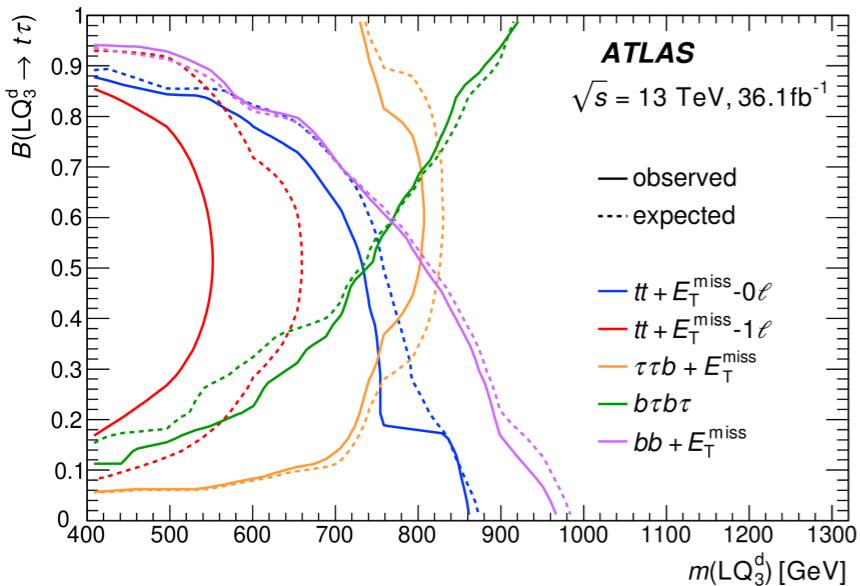
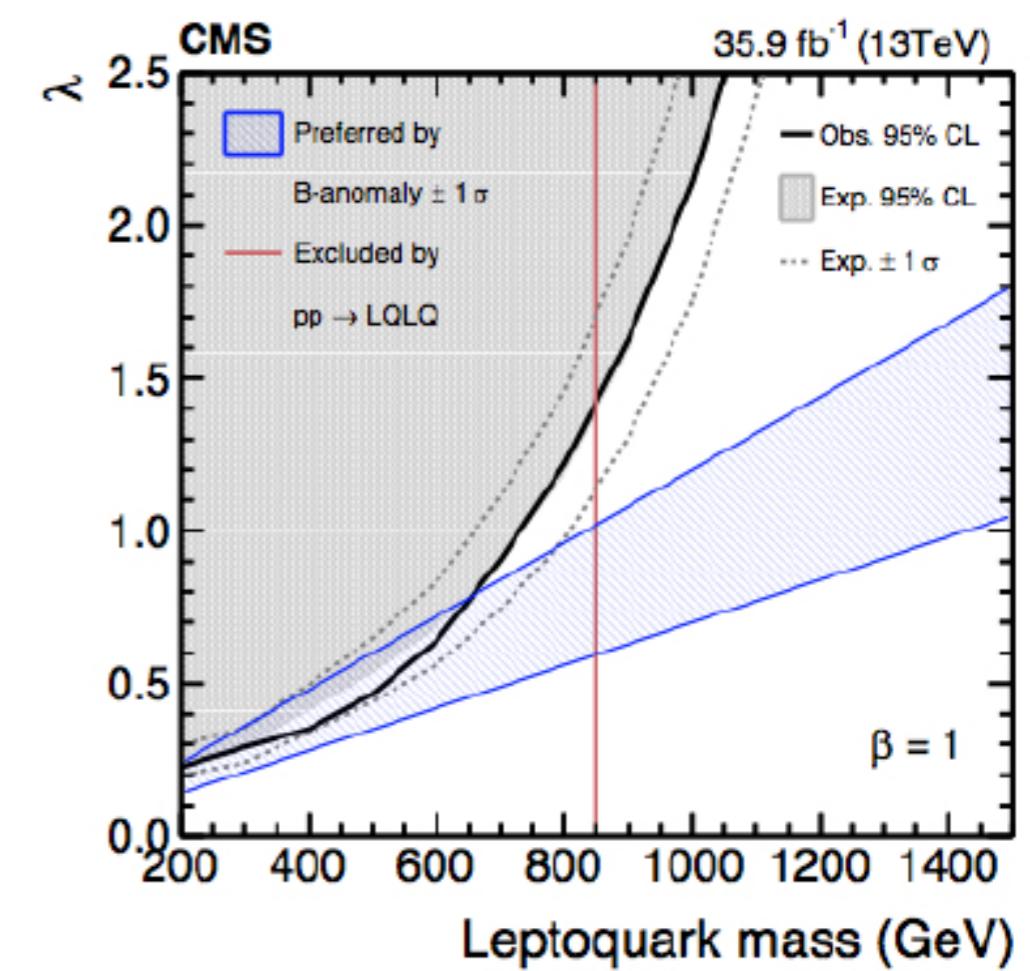
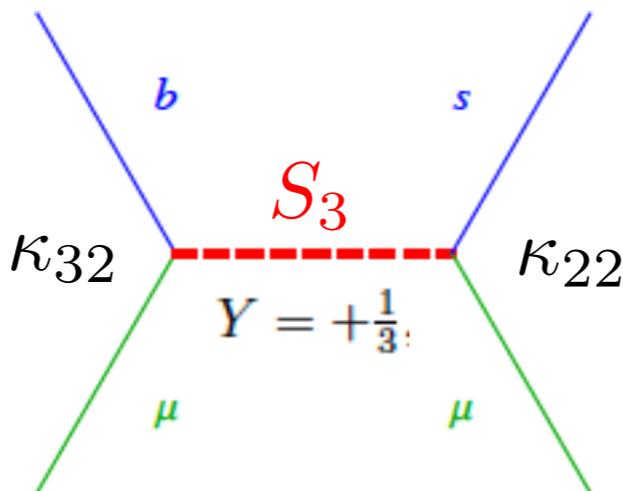
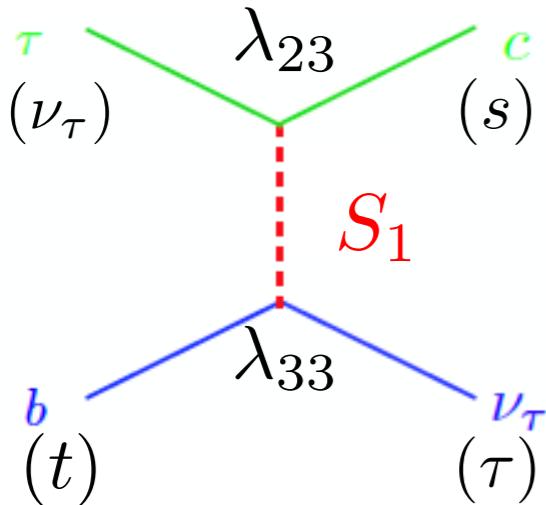


Naturally light SM Higgs + LQ scalars

$U(1)_{3B+L} \longrightarrow$ Keep only $q l$: Safe from rapid proton decay

Hunting leptoquarks

-21-



[Choi, Kang, HML, Ro, 2018]

LQs	BRs	$m_{LQ,\text{min}}$	BRs	$m_{LQ,\text{min}}$
S_1	$B(\bar{t}\bar{\tau}/b\nu_\tau) = \frac{1}{2}\beta$	1.22 TeV($b\nu_\tau$) [32]	$B(\bar{c}\bar{\tau}/s\nu_\tau) = \frac{1}{2}(1 - \beta)$	950 GeV($\nu_\tau j$) [33]
$S_3(\phi_1)$	$B(\bar{b}\bar{\mu}) = \gamma$	1.4 TeV [34]	$B(\bar{s}\bar{\mu}) = 1 - \gamma$	1.08 TeV ($\bar{\mu}j$) [35]
$S_3(\phi_2)$	$B(\bar{t}\bar{\mu}/\bar{b}\bar{\nu}_\mu) = \frac{1}{2}\gamma$	1.45 TeV ($\bar{t}\bar{\mu}$) [36]	$B(\bar{c}\bar{\mu}/\bar{s}\bar{\nu}_\mu) = \frac{1}{2}(1 - \gamma)$	850 GeV ($\bar{\mu}\bar{\nu}_\mu jj$) [37]
$S_3(\phi_3)$	$B(\bar{t}\bar{\nu}_\mu) = \gamma$	1.12 TeV [38]	$B(\bar{c}\bar{\nu}_\mu) = 1 - \gamma$	950 GeV ($\bar{\nu}_\mu j$) [33]

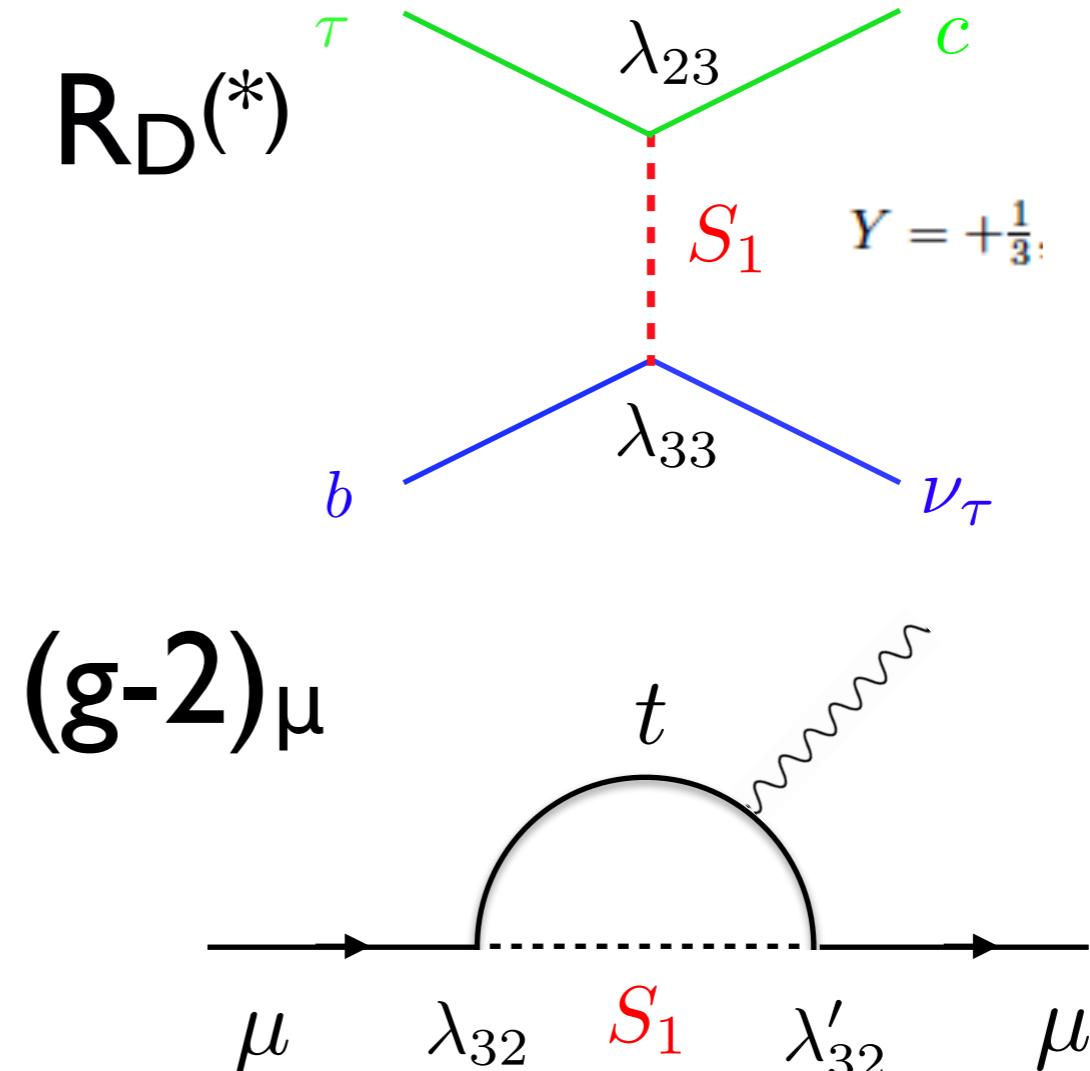
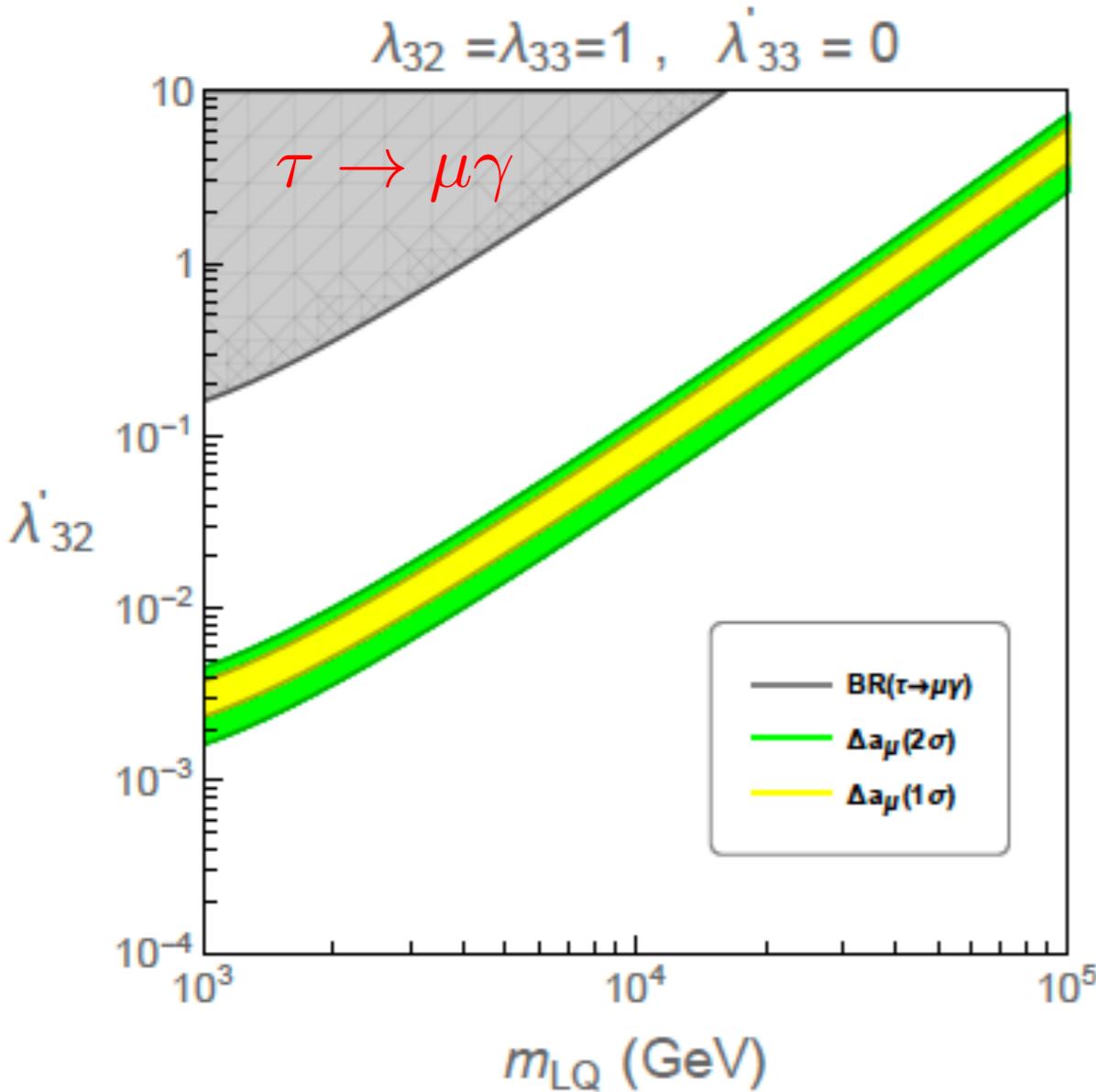
“Decay BRs”

$$\beta \equiv \lambda_{33}^2 / (\lambda_{33}^2 + \lambda_{23}^2)$$

$$\gamma \equiv \kappa_{32}^2 / (\kappa_{32}^2 + \kappa_{22}^2)$$

Lepton g-2 from top loops

-22-



Non-holomorphic RPV \rightarrow

$$\frac{1}{M_*^2} \int d^2\theta d^2\bar{\theta} c_{ij} X(U^c)_i^\dagger S_1(E^c)_j^\dagger: \quad \lambda'_{ij} = c_{ij} \frac{F_X}{M_*^2}$$

Minimal flavor: Top + Singlet leptoquark loops

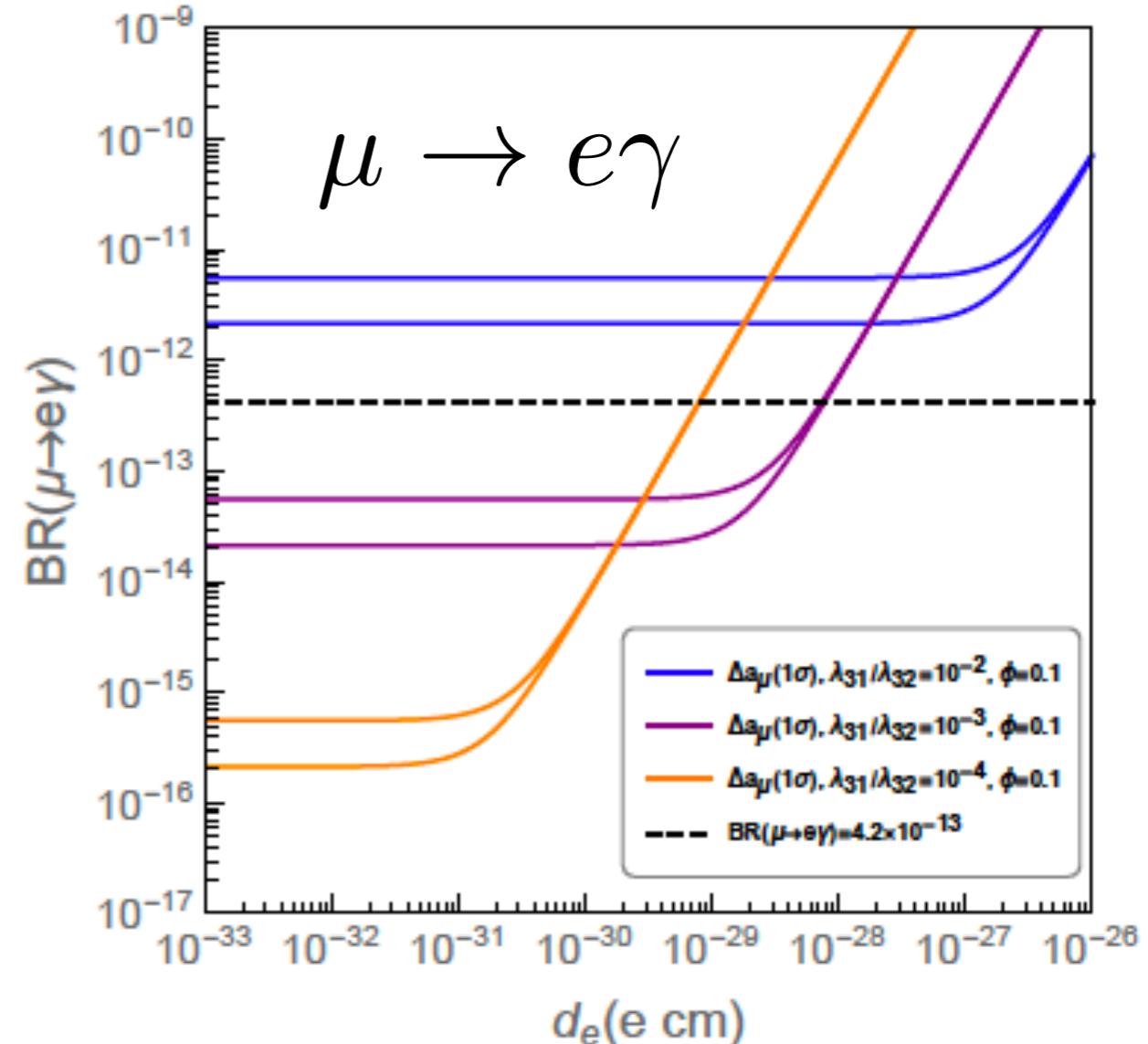
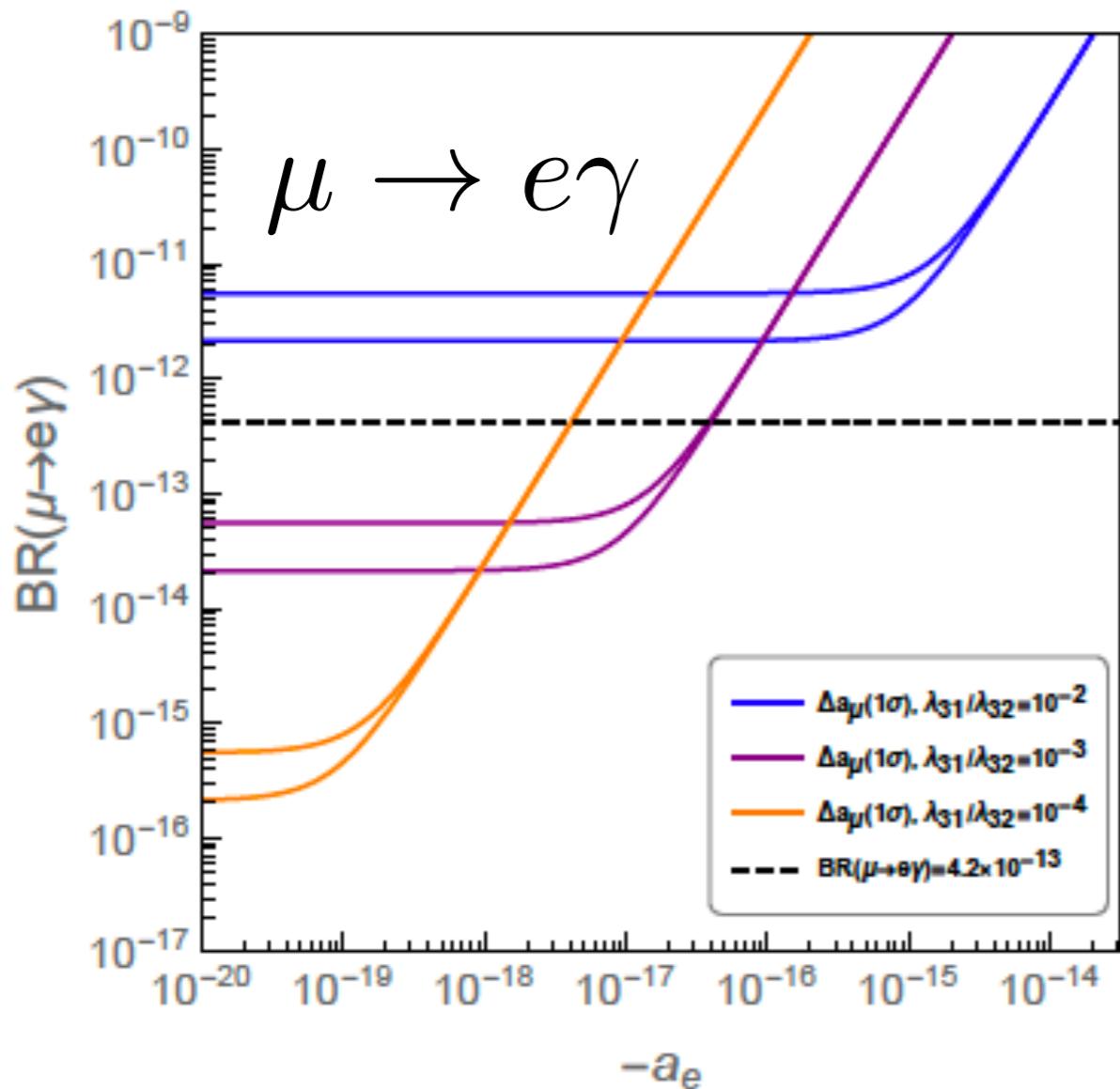
[Choi, Kang, HML, Ro, 2018]

a_μ, a_e

Leptonic signatures

-23-

[HML, 2021]



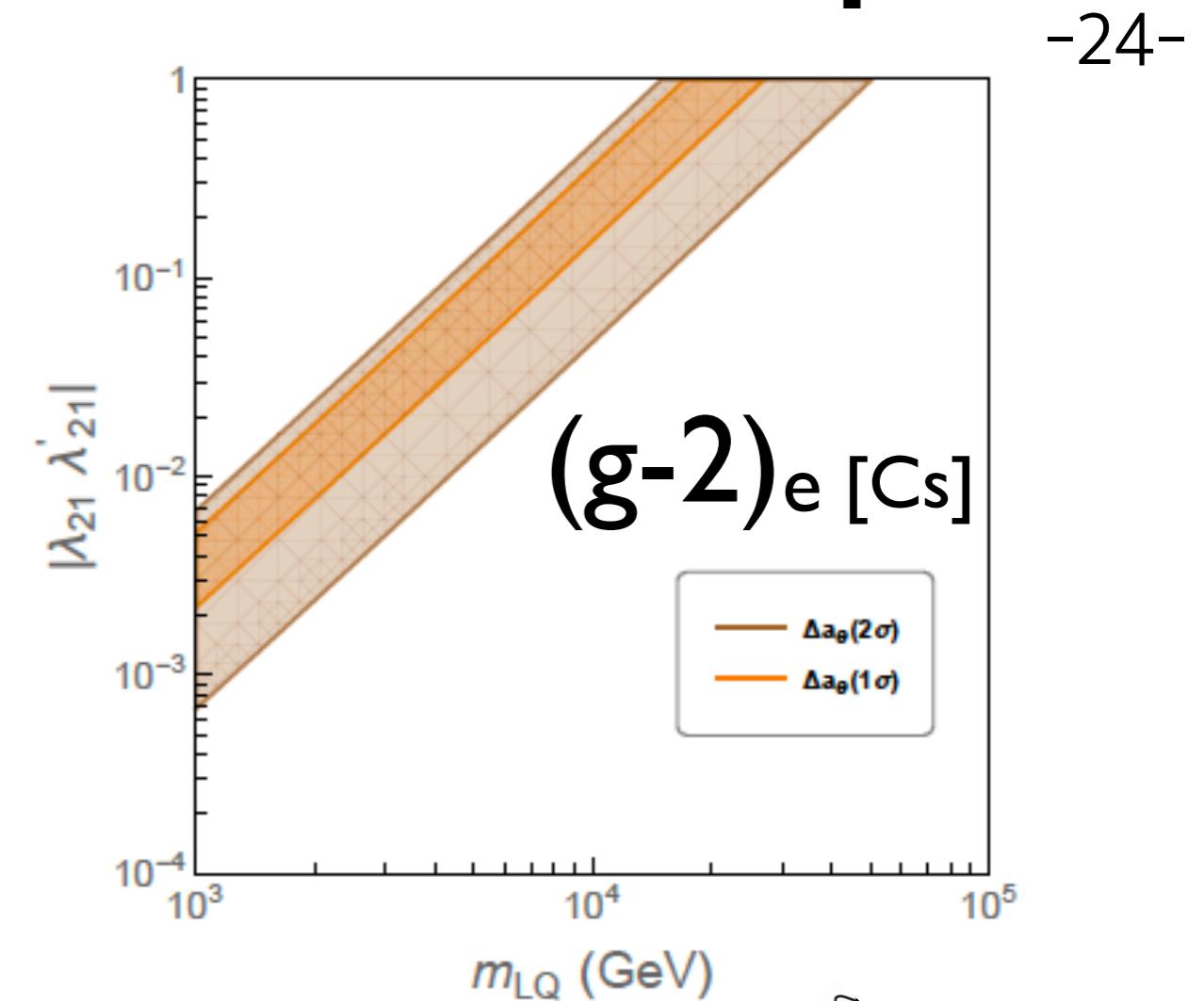
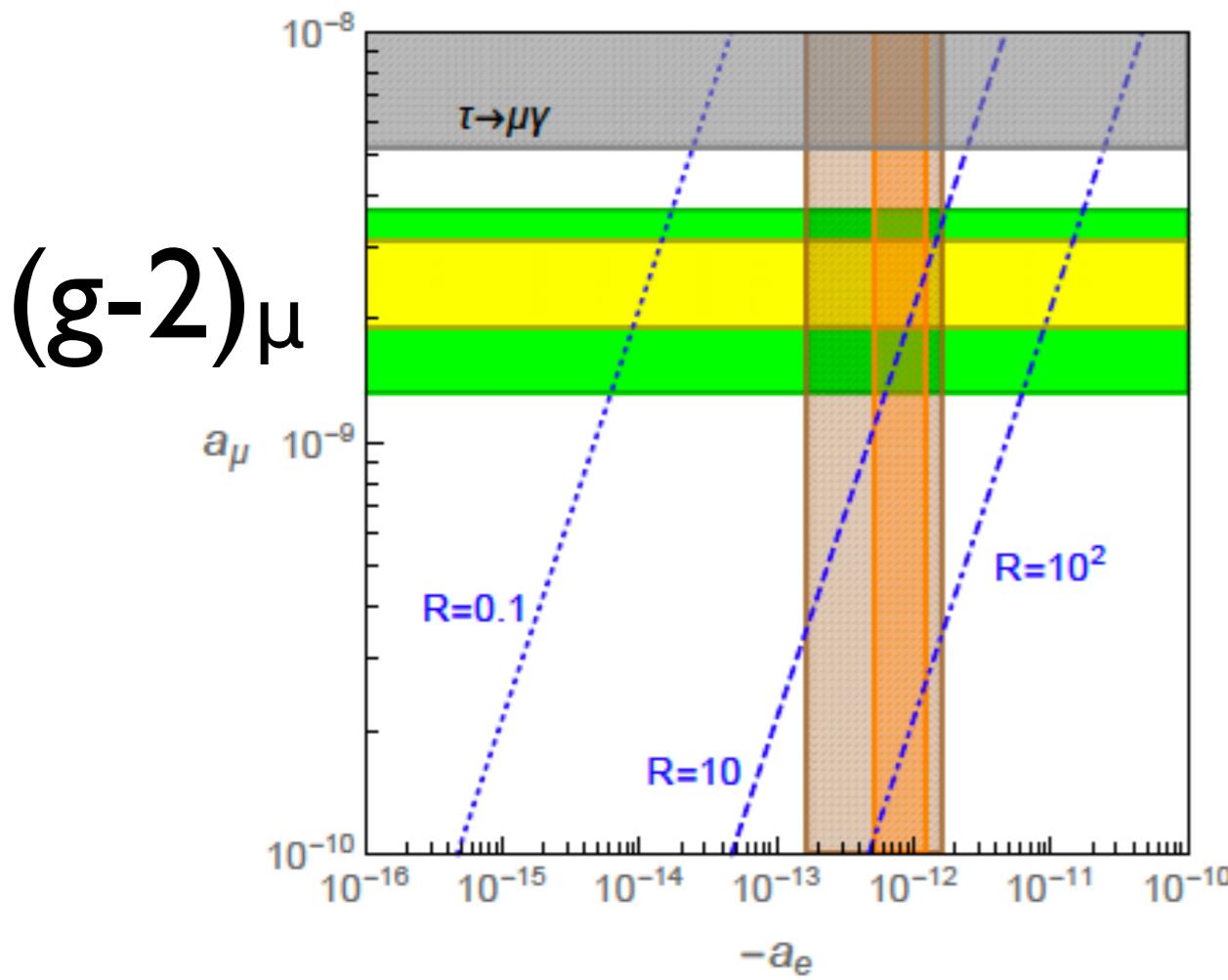
Strong constraint from $\mu \rightarrow e\gamma$



Small electron g-2

But, electron EDM is detectable for a sizable CP phase.

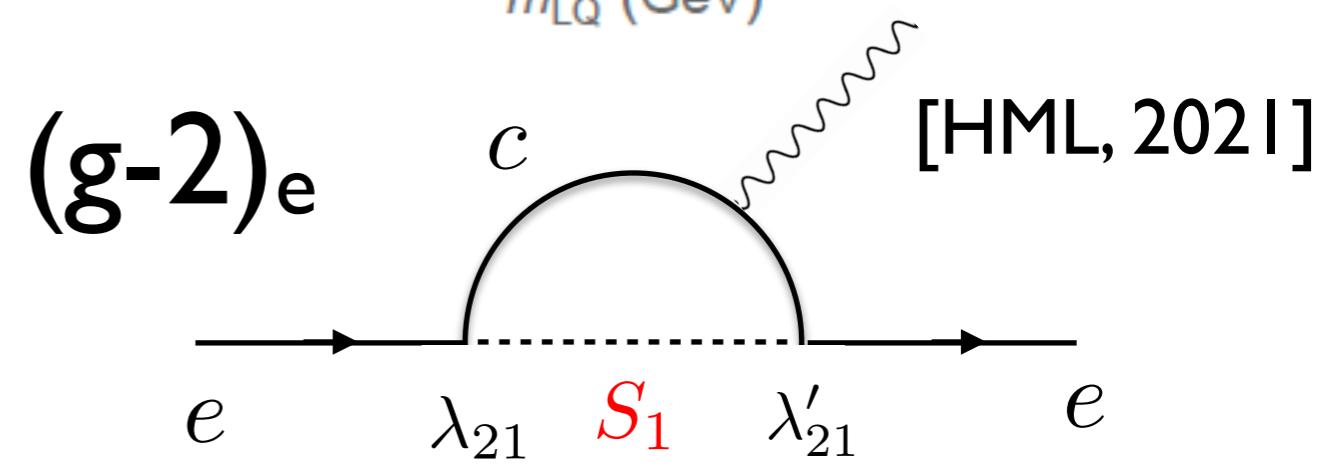
g-2 from top/charm loops



Electron g-2 specific flavor:

Top loops $\rightarrow a_\mu$
 Charm loops $\rightarrow a_e$

Safe from $\mu \rightarrow e\gamma$



$$\frac{a_e^{S_1}}{a_\mu^{S_1}} = \frac{m_e m_c}{m_\mu m_t} \cdot R, \quad R = \frac{\text{Re}(\lambda_{21} \lambda'_{21})}{\text{Re}(\lambda_{32} \lambda'_{32})}$$

Neutrino masses

-25-

Majorana neutrino masses violate lepton number by two units.

$$\mathcal{L}_{\text{dim-5}} = -\frac{c_{ij}}{M} (\bar{l}_i^c i \tau^2 H) (l_j i \tau^2 H) + \text{h.c.}$$

$$L = \begin{matrix} & +1 & +1 \end{matrix}$$

Scalar leptoquark couplings respect lepton number.

$$\mathcal{L}_{S_1} = -\lambda_{ij} \overline{(Q^C)^a_{Ri}} (i\sigma^2)_{ab} S_1 L_{Lj}^b - \lambda'_{ij} \overline{(u^C)_{Li}} S_1 e_{jR} + \text{h.c.}$$

$$L = \begin{matrix} -1 & +1 & & -1 & +1 \end{matrix}$$

$$\mathcal{L}_{S_3} = -\kappa_{ij} Q_{Li}^a \Phi_{ab} L_{Lj}^b + \text{h.c.}$$

$$\begin{matrix} -1 & +1 \end{matrix}$$

$$\mathcal{L}_{\text{mix}} = -\lambda_m H^\dagger \Phi H S_1^* + \text{h.c.}$$

leptoquark mixing

$$L = \begin{matrix} -1 & +1 \end{matrix}$$

Extra doublet leptoquarks >2 generate realistic neutrino masses.

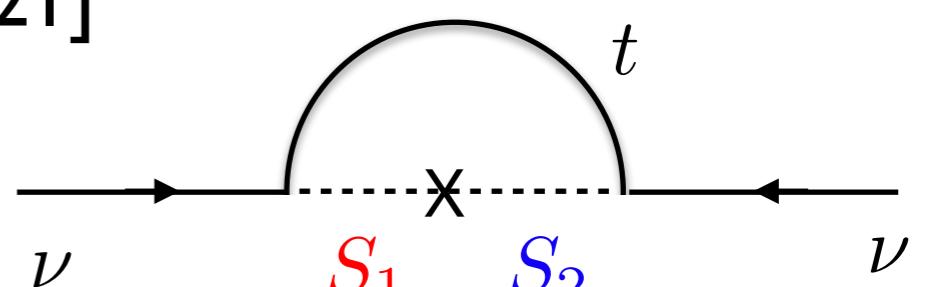
$$\mathcal{L}_{S_2} = -\tilde{\lambda}_{ij} \bar{d}_{Ri} l_{Lj} S_2 - \mu \tilde{H} S_2 S_1 + \text{h.c.} \quad [\text{HML, 2021}]$$

$$(m_\nu)_{ij} = A (\lambda_{31}, \lambda_{32}, \lambda_{33}) \begin{pmatrix} \tilde{\lambda}_{31}^* \\ \tilde{\lambda}_{32}^* \\ \tilde{\lambda}_{33}^* \end{pmatrix}, \quad A \simeq \frac{v m_t \mu}{8\sqrt{2}\pi^2 m_{S_1}^2}$$

$$m_\nu < 0.1 \text{ eV}$$



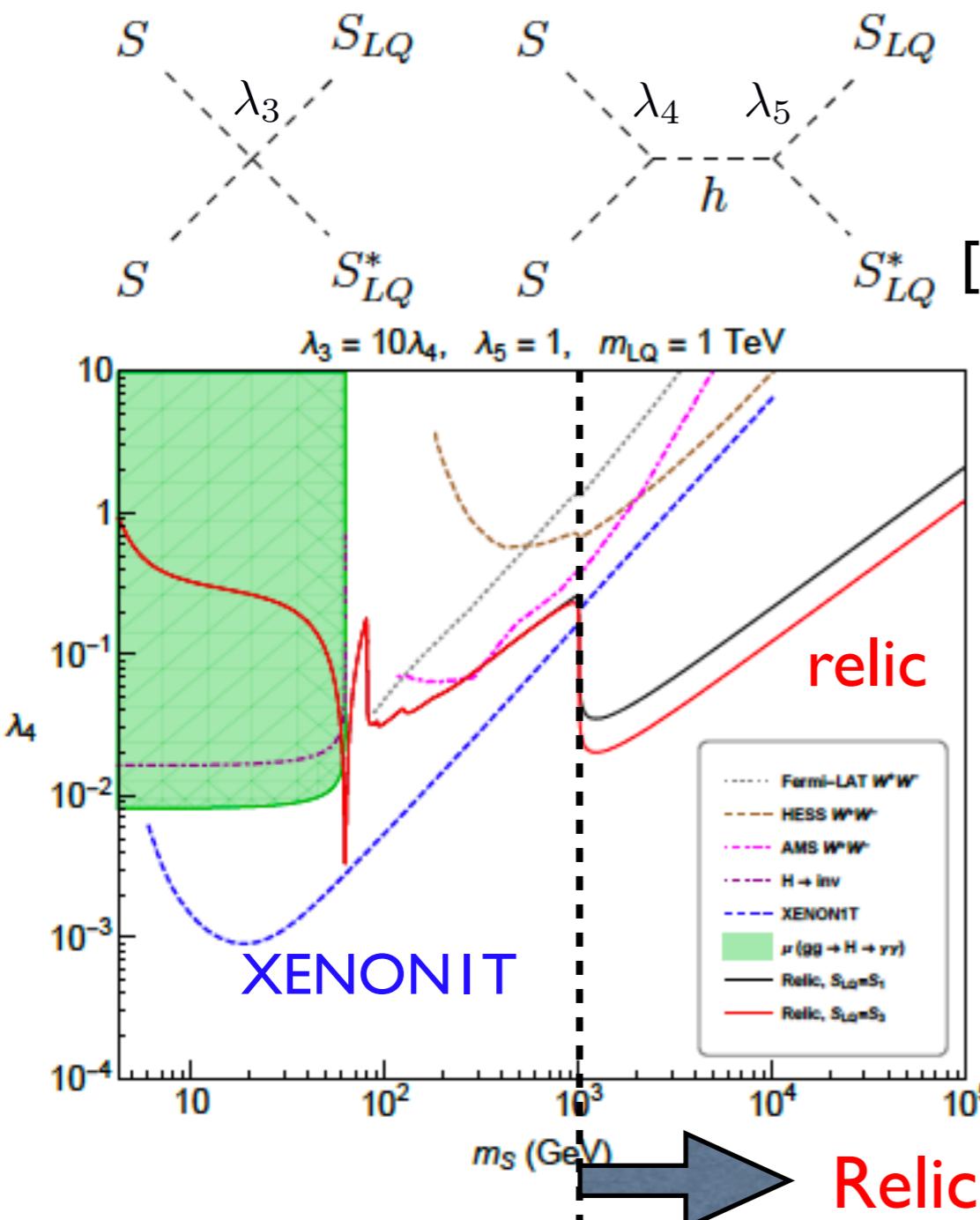
$$\max(|\lambda_{3i} \tilde{\lambda}_{3i}^*|) < 10^{-9} \left(\frac{v}{\mu}\right) \left(\frac{m_{S_1}}{1 \text{ TeV}}\right)^2$$



cf. RPV SUSY

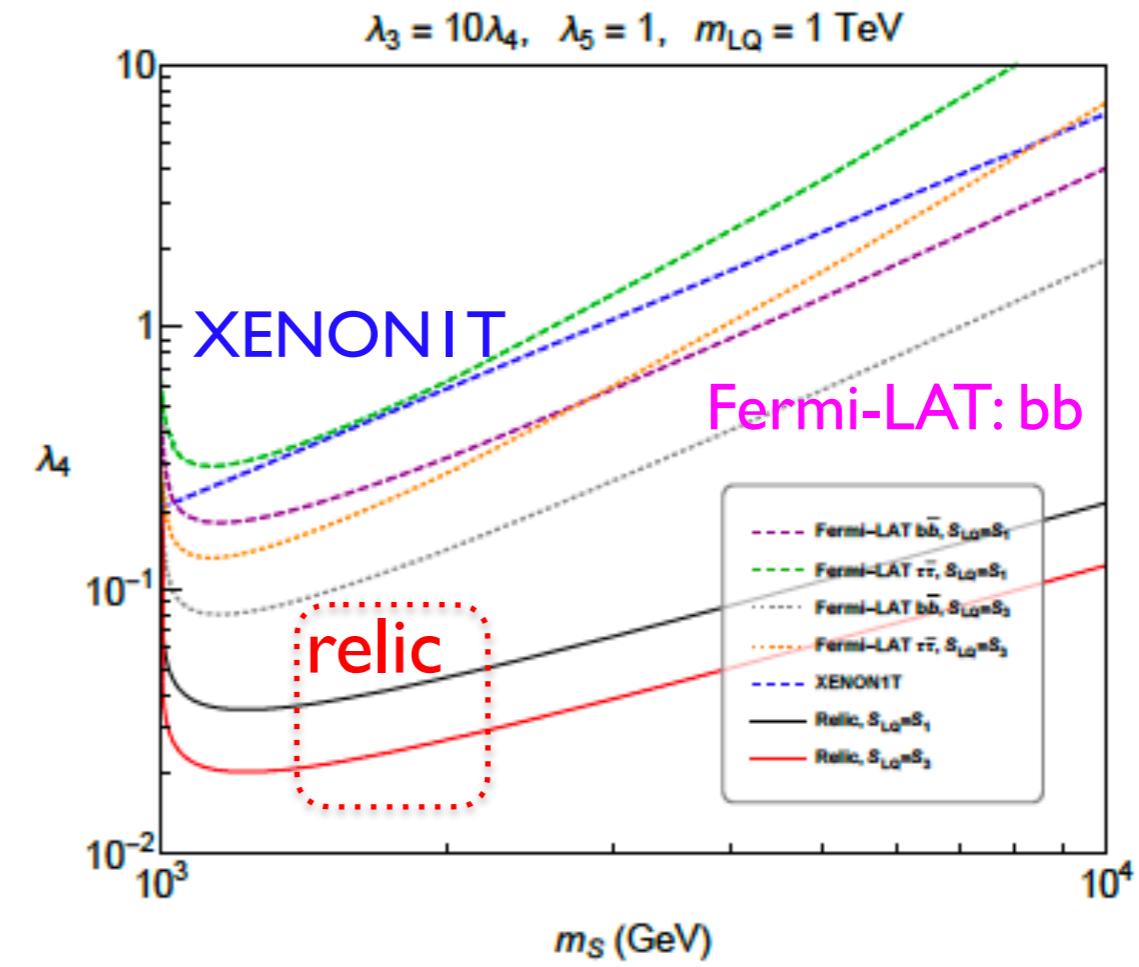
LQ-portal dark matter

-26-



Dark matter annihilation into a LQ pair makes Higgs-portal consistent.

[Choi, Kang, HML, Ro, 2018; Zhu, HML, Song, Kim, 2021]



Relic density is ok; Cascade DM annihilations!

$$R_D^{(*)}: \lambda_{33} \gg \lambda_{23} \quad B(\bar{t}t \bar{\tau}\tau) : B(\bar{b}b \bar{\nu}_\tau \nu_\tau) : B(\bar{t}b \bar{\tau}\nu_\tau + \text{h.c.}) = \frac{1}{2} : \frac{1}{2} : 1$$

$$R_K^{(*)}: \kappa_{32} \gg \kappa_{22} \quad B(\bar{b}b \bar{\mu}\mu) : B(\bar{t}t \bar{\mu}\mu) : B(\bar{b}b \bar{\nu}_\mu \nu_\mu) : B(\bar{t}b \bar{\mu}\nu_\mu + \text{h.c.}) : B(\bar{t}t \bar{\nu}_\mu \nu_\mu) = 1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{2} : 1. \quad \text{Predictive BRs from LQ decays}$$

Conclusions

- Flavor puzzles in B-meson decays may call for new forces or extra colored particles, opening a window for complementary tests between energy and intensity frontiers.
- Existing anomalies in muon g-2 and leptonic signatures such as LFV decays/EDM might be related to B-meson anomalies.
- Leptoquark option is well motivated in SUSY or composite Higgs models, testable by B-meson decays, muon g-2 and direct searches at Belle-II, LHC, etc.