

Some thoughts on muon g-2 and B-meson anomalies



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Hyun Min Lee
Chung-Ang University, Korea



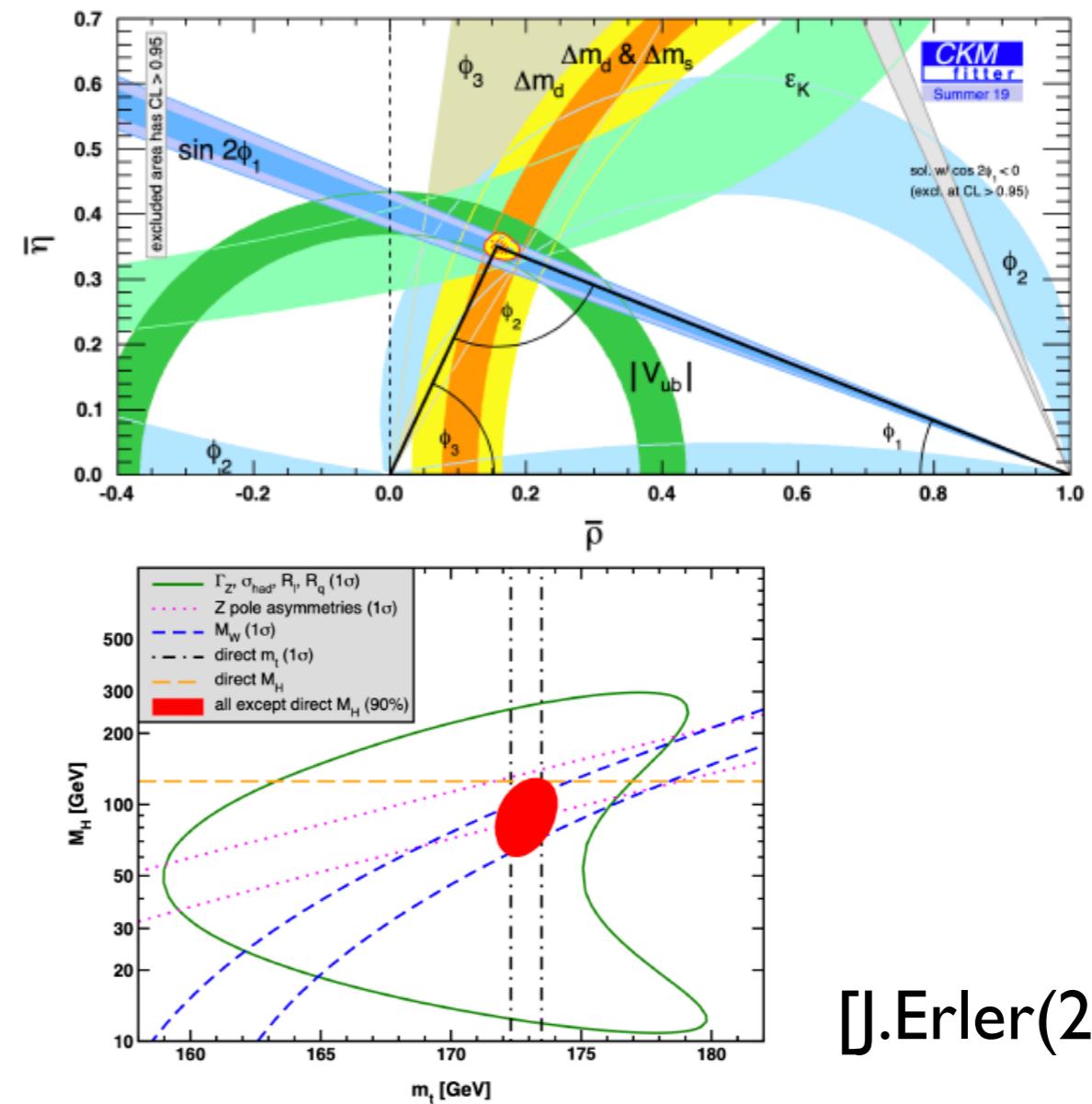
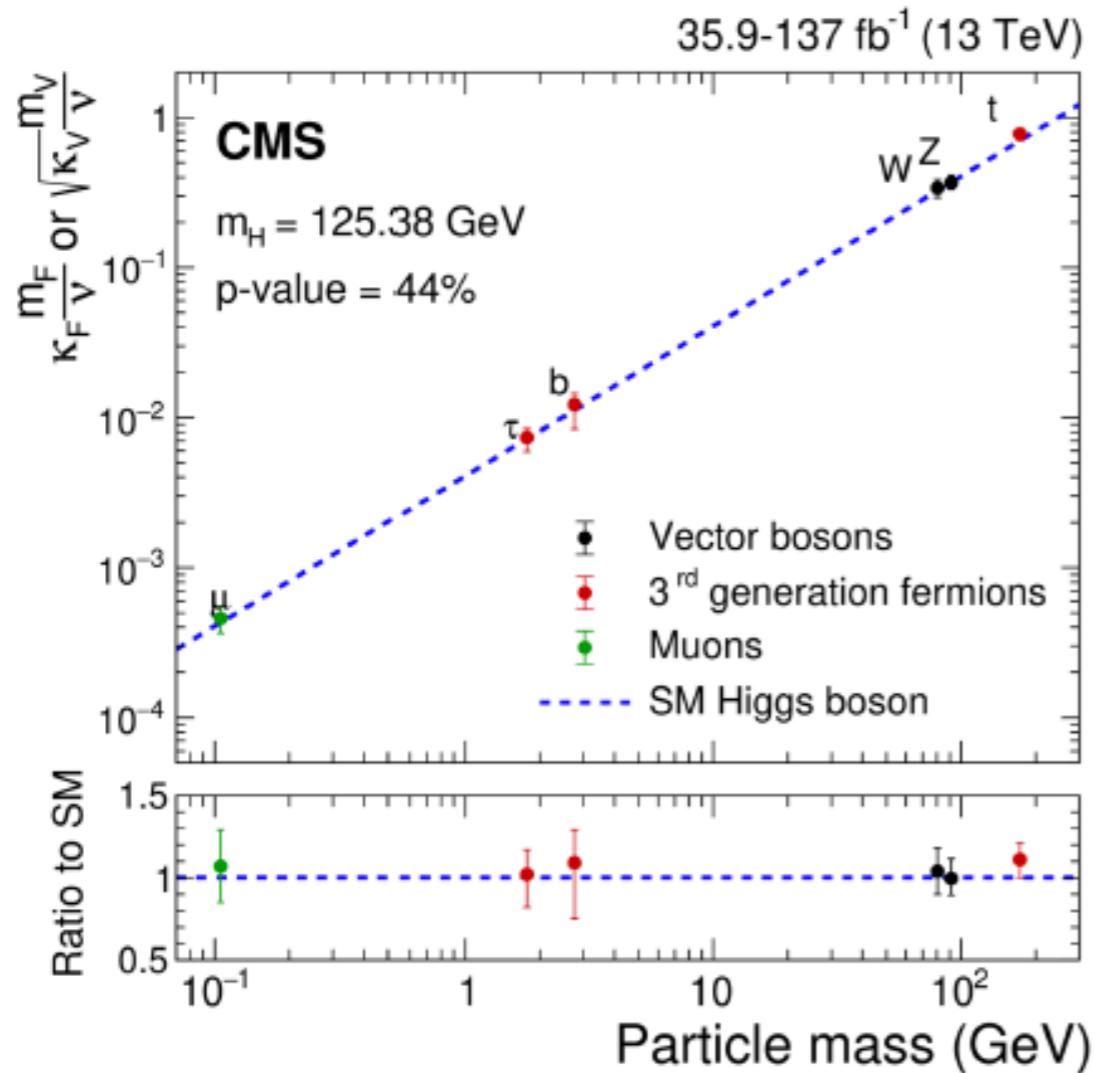
LIO international conference
Future colliders and the origin of mass
IP2I Lyon, France, June 23, 2021

Outline

- Muon g-2 anomalies
- B-mesons anomalies
- Models for muon g-2 and B-meson anomalies
- Conclusions

Muon g-2 anomalies

Standard Model in precision era



[J.Erler(2021)]

- SM gauge/flavor structures are well-tested.
- No clues for origins of Higgs mass, flavors, dark matter, etc.



Interplay of HL LHC, future colliders, precision and intensity experiments are much more important.

Testing flavors and new physics

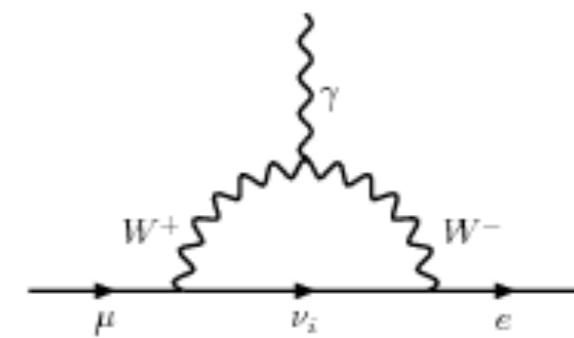
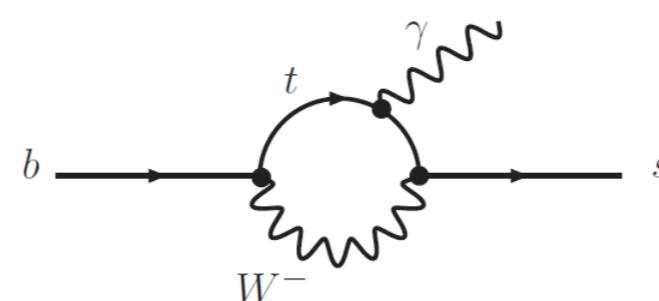
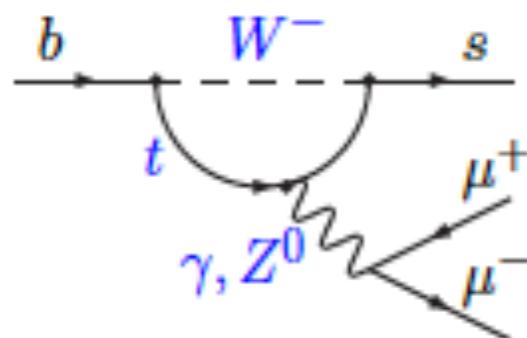
- “Charged currents” induce flavor violating processes at tree level, while FCNCs are induced at loop level. -2-

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

- Lepton universality is well tested within the SM.

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

- “FCNC processes”, g-2, EDM, and lepton universality, etc, are sensitive probes of new physics.



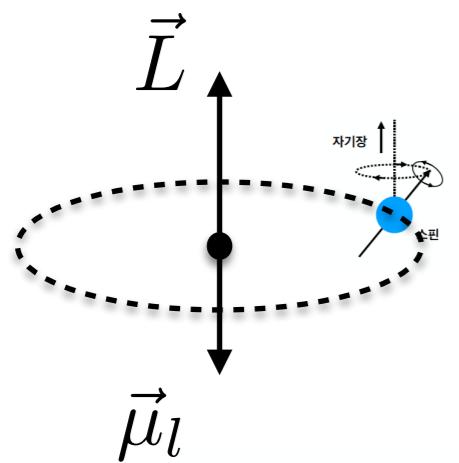
Lepton g-2

-3-

- Dirac predicted the gyromagnetic ratio of fermion spin to orbital magnetic dipole moments to unity.

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu(\partial_\mu + ieA_\mu) - m)\psi$$

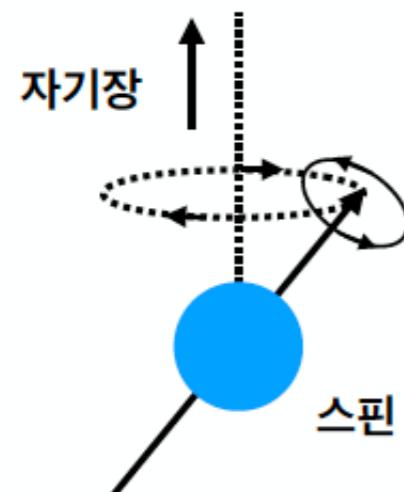
→ $H_{\text{int}} = -\vec{\mu} \cdot \vec{B}, \quad \vec{\mu} = g \cdot \frac{e}{2m_e} \vec{S}, \quad g = 2!$



$$\vec{\mu}_l = -\frac{e}{2m_e} \vec{L}$$

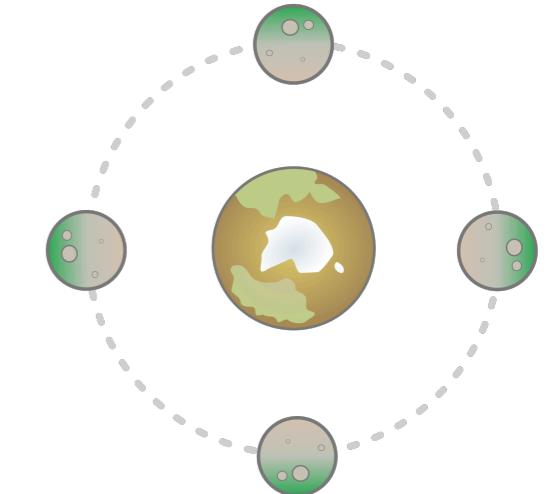
“Magnetic dipole moment”

$$\frac{|\vec{\mu}|}{|\vec{\mu}_l|} = \frac{g}{2} = 1$$



Spin precession frequency
= orbital frequency

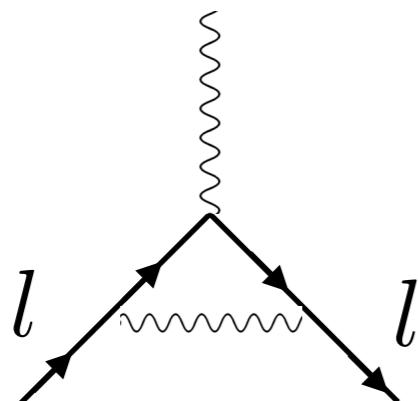
cf. Tidal locking for Moon



Electron g-2 at loops

-4-

- Loop corrections with virtual particles modify charge/mass as well as g-2, so called anomalous mdm.
- Julian Schwinger(1948): one-loop corrections in QED.



$$a_e = \frac{1}{2}(g - 2)_e = \frac{\alpha}{2\pi} = 0.00116$$

- Kusch & Foley(1948): first evidence for nonzero g-2.

$$a_e^{\text{exp}} = \frac{1}{2}(g - 2)_e = 0.00119 \pm 0.00005$$

- QED up to 5-loops agree at 12 digits:

$$a_e^{\text{th}} = 115965218160.6(11)(12)(229) \times 10^{-14} \quad [\text{Aoyama, Kinoshita, Nio}(2019)]$$

$$a_e^{\text{ex}} = 115965218073(28) \times 10^{-14} \quad [\text{Harvard}(2008)]$$

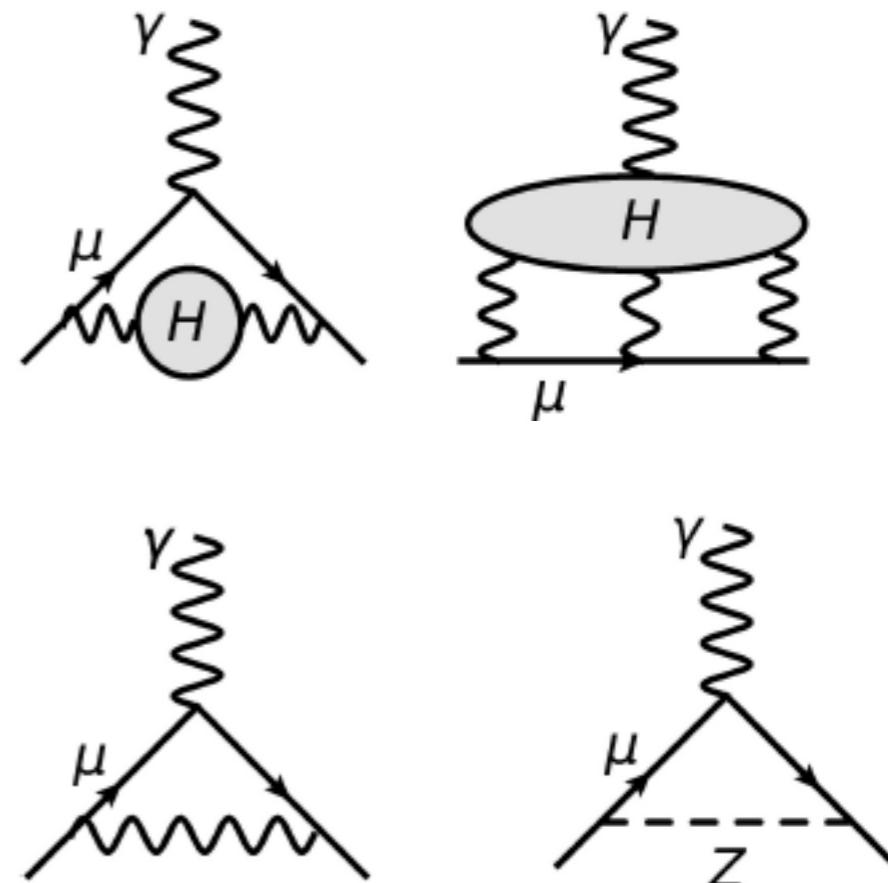
Muon g-2 anomalies

-5-

- Muon g-2 is composed of QED, hadronic and electroweak contributions.

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	-98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, $udsc$)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^- , LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{had}} + a_\mu^{\text{EW}}$$



BNL E821 (2000) + White Paper (2020)

3.7 σ from SM

Muon g-2 update

-6-

- g-2 measurement at Fermilab E989 reinforces the case.



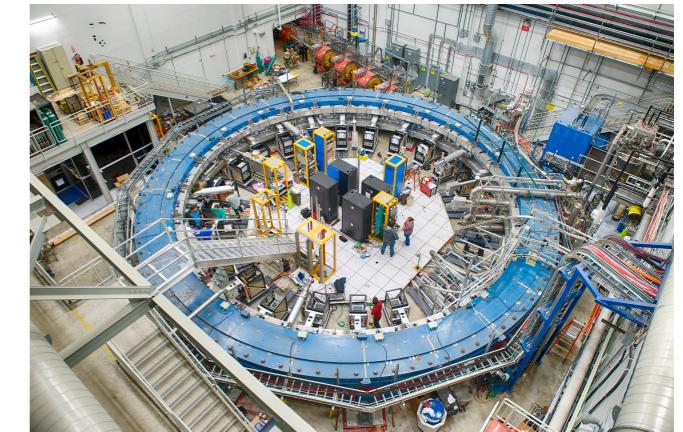
$$a_\mu^{\text{th}}(\text{MP}) = 116591810(43) \times 10^{-11}$$

$$a_\mu(\text{BNL}) = 116592080(63) \times 10^{-11}$$

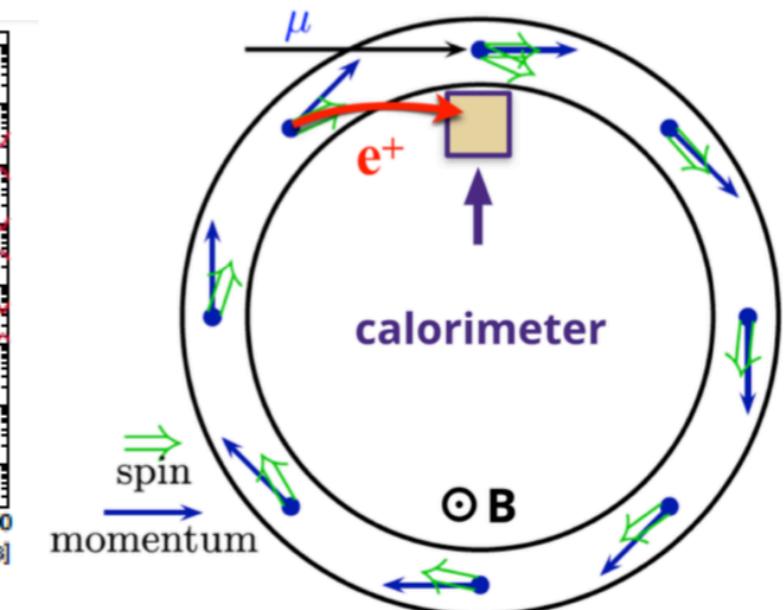
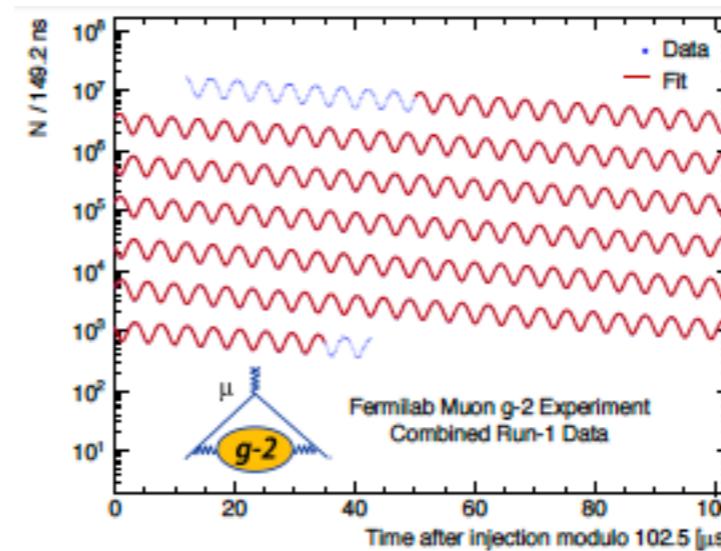
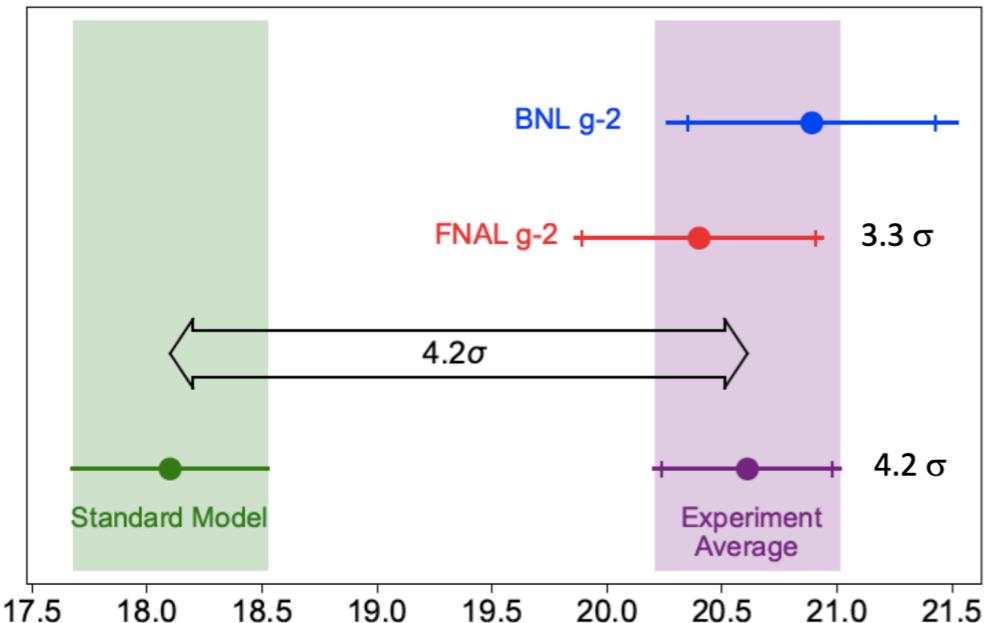
$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11}$$

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

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



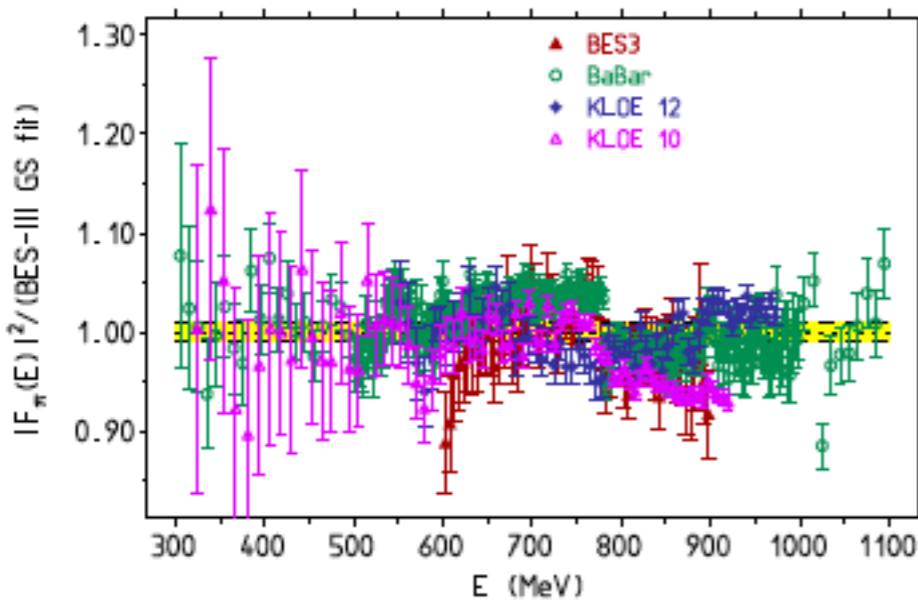
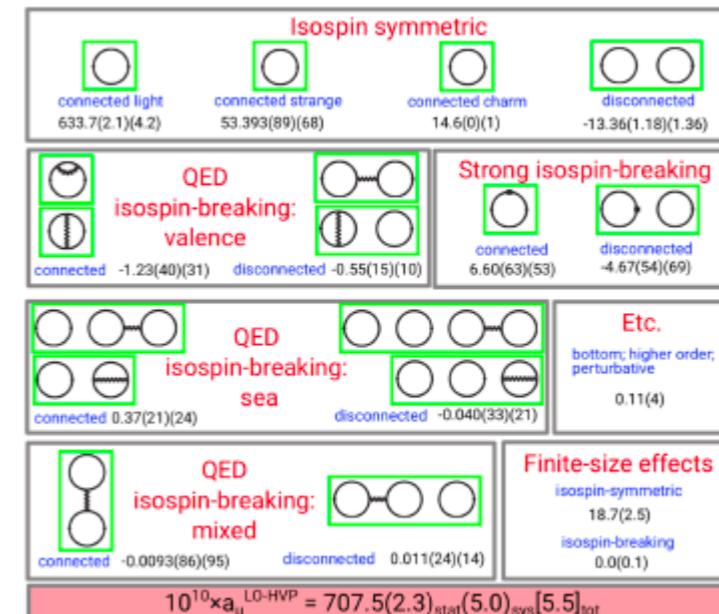
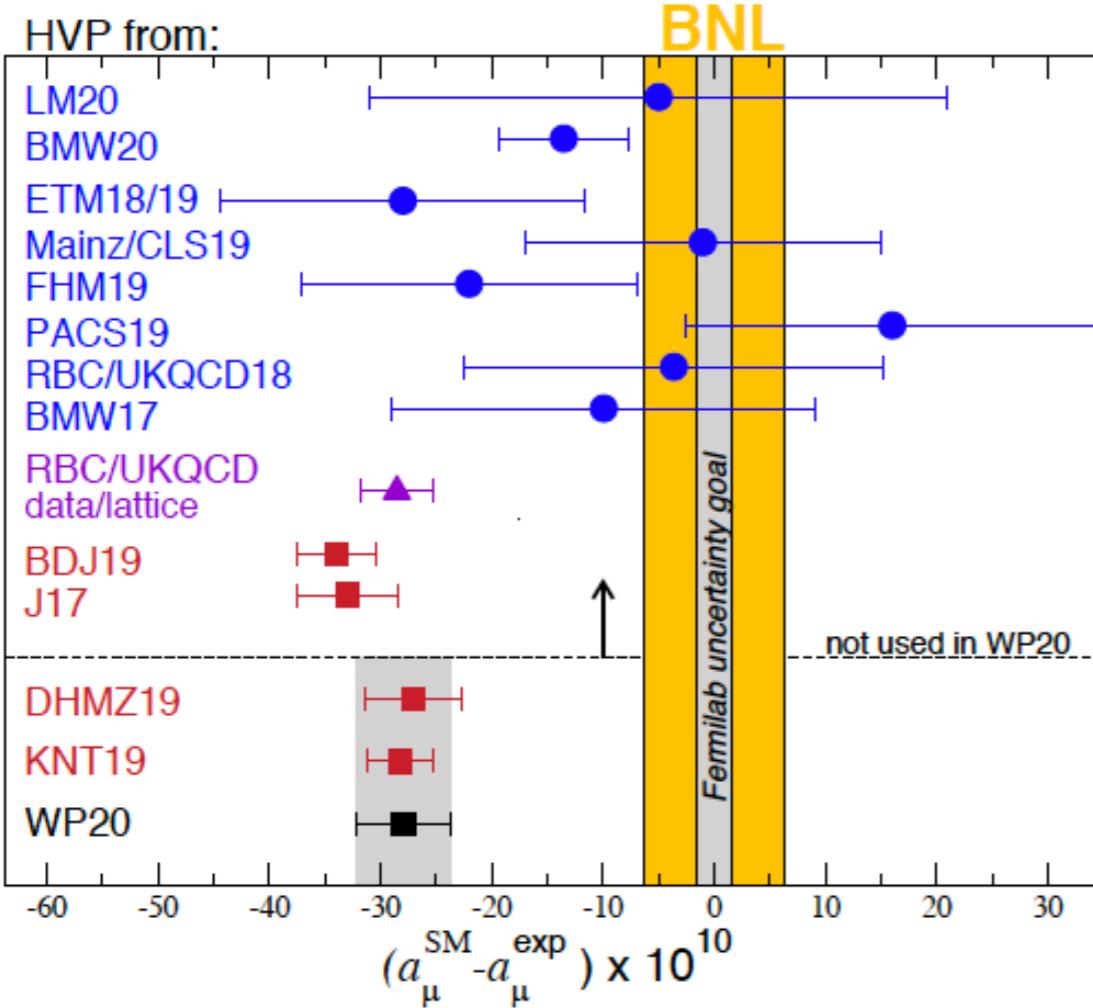
4.2 σ from SM



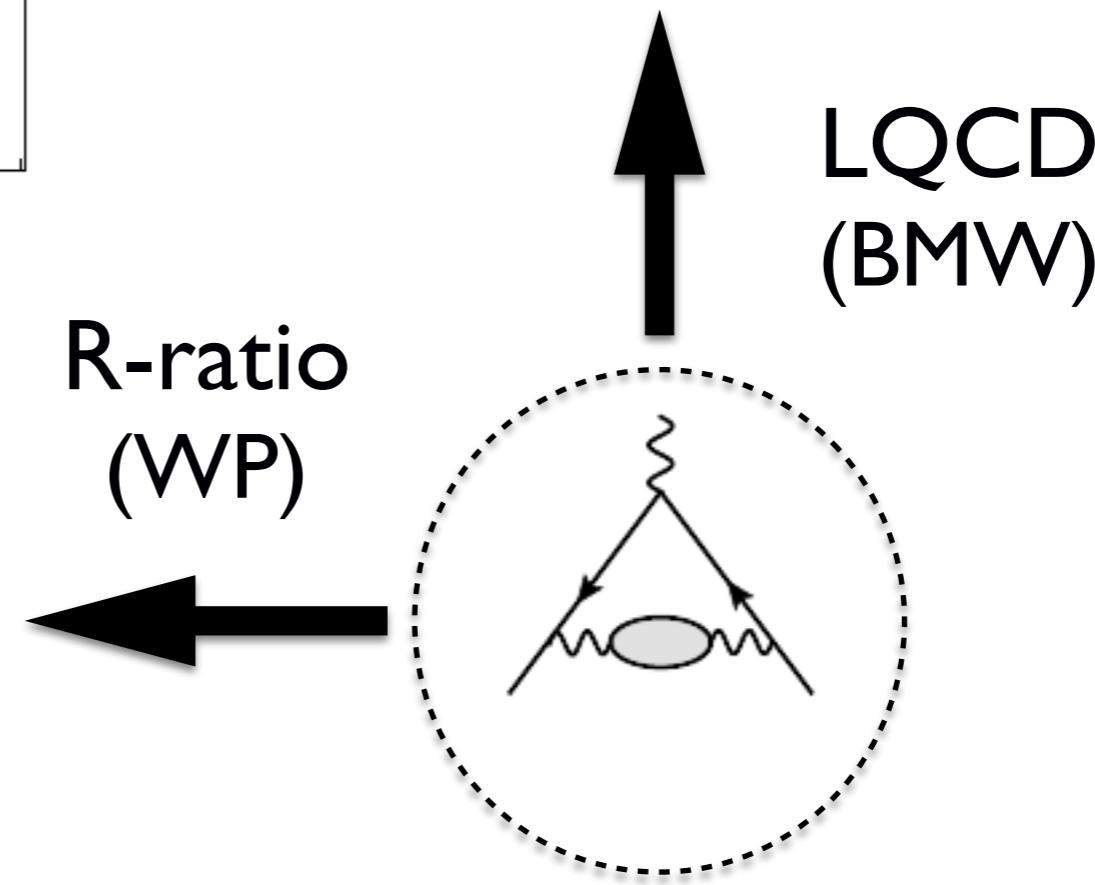
$$\vec{\omega}_a = -\frac{q}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \quad \gamma = 29.3.$$

Hadronic corrections

-7-



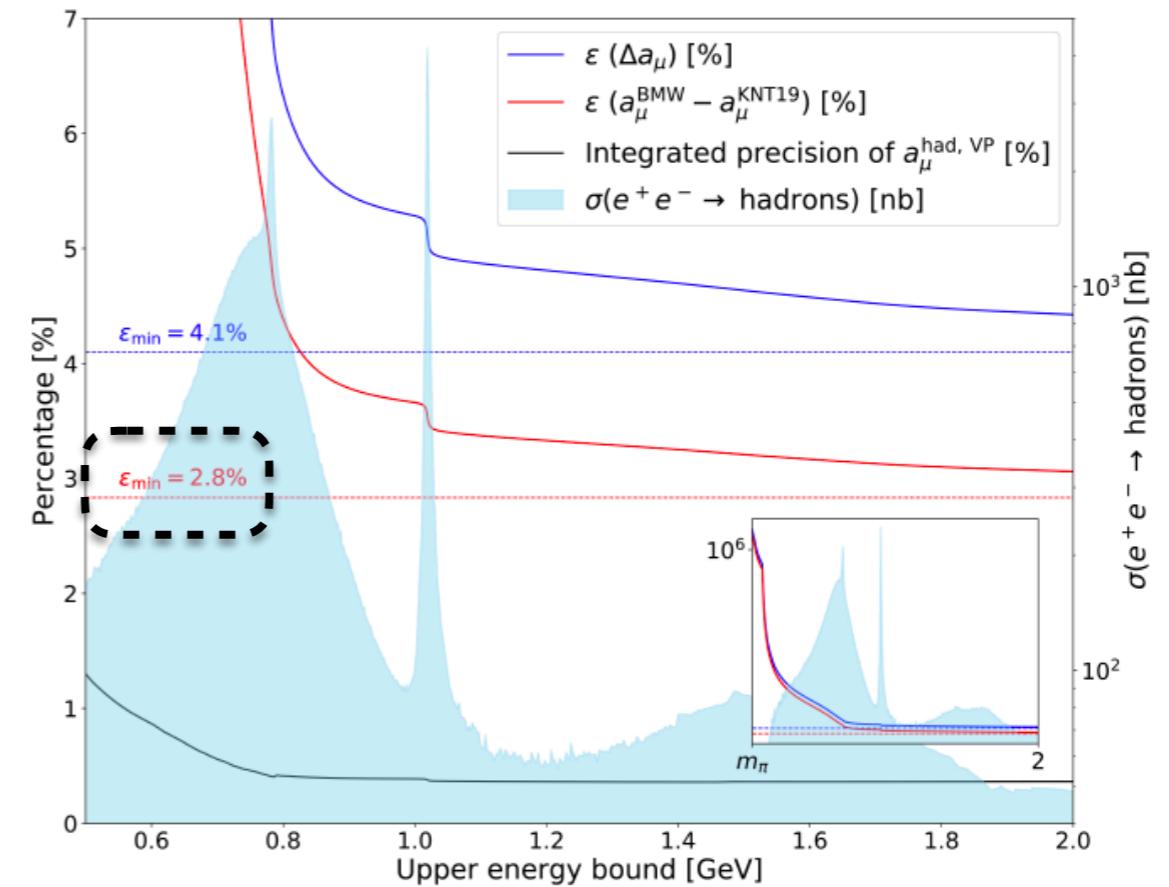
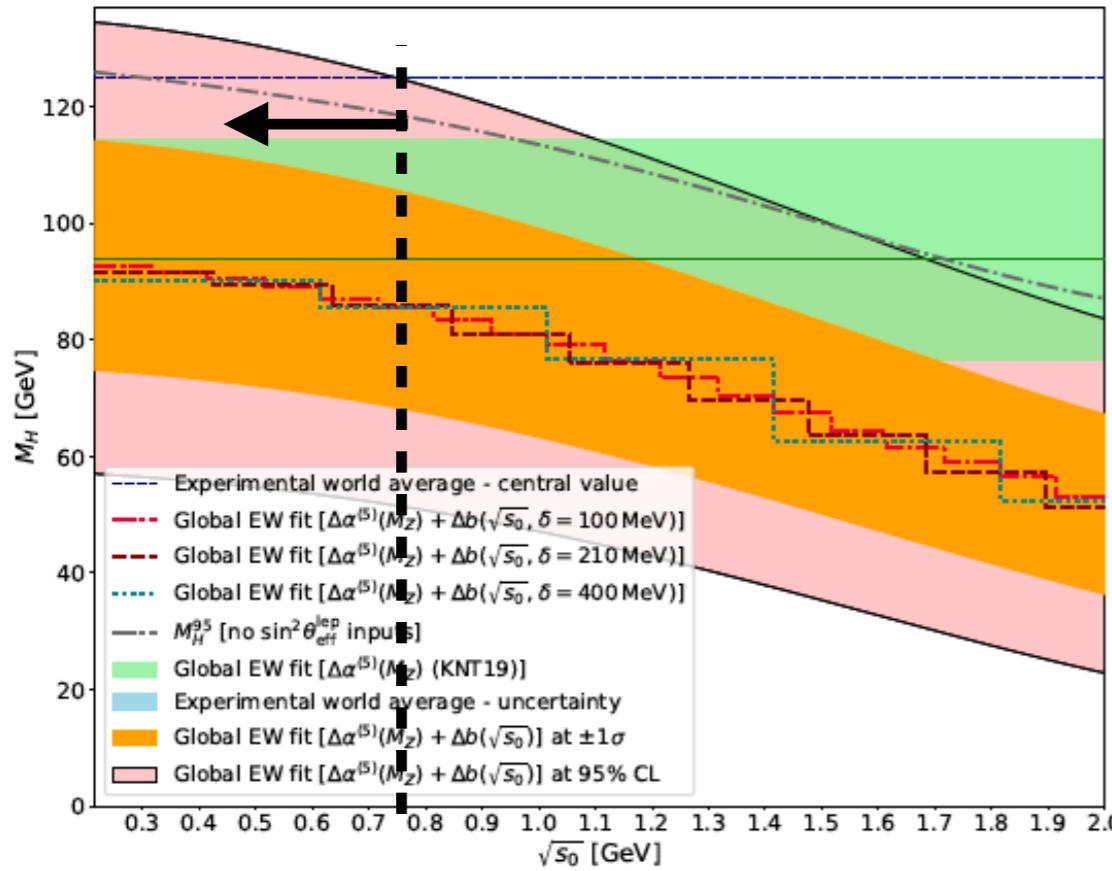
R-ratio
(WP)



[F.Jegerlehner, 2021]

Hadronic corrections

-8-



[Keshavarzi, Marciano, Passera, Sirlin, 2020/2021]

$$\Delta\sigma(s) = \epsilon\sigma(s)$$

BMW HVP results would imply just 1.5σ from SM.
 But, there are issues such as electroweak data at high E
 (through α running) or R-ratio data at low E.
 => independent LQCD needed. (See talks on Friday)

EFT for muon g-2

-9-

Effective operator for magnetic dipole moment:

$$\mathcal{L} = \frac{1}{\Lambda_{\text{UV}}} \bar{\psi}_L \sigma^{\mu\nu} \psi_R F^{\mu\nu} + \text{h.c.}$$

→ $\Delta a_\mu = \frac{4m_\mu}{e\Lambda_{\text{UV}}} \simeq 2.5 \times 10^{-9}$ [E821+E989]

→ $\Lambda_{\text{UV}} \simeq 5.6 \times 10^8 \text{ GeV}$

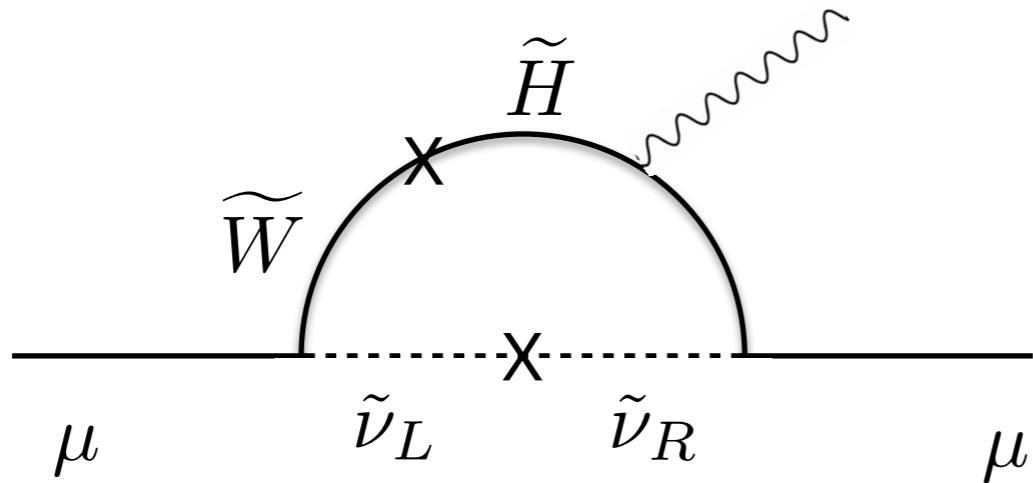
Sensitive probe of new physics beyond SM.

In reality, the effective operator is suppressed by loop factor, chirality-flip and extra small couplings:

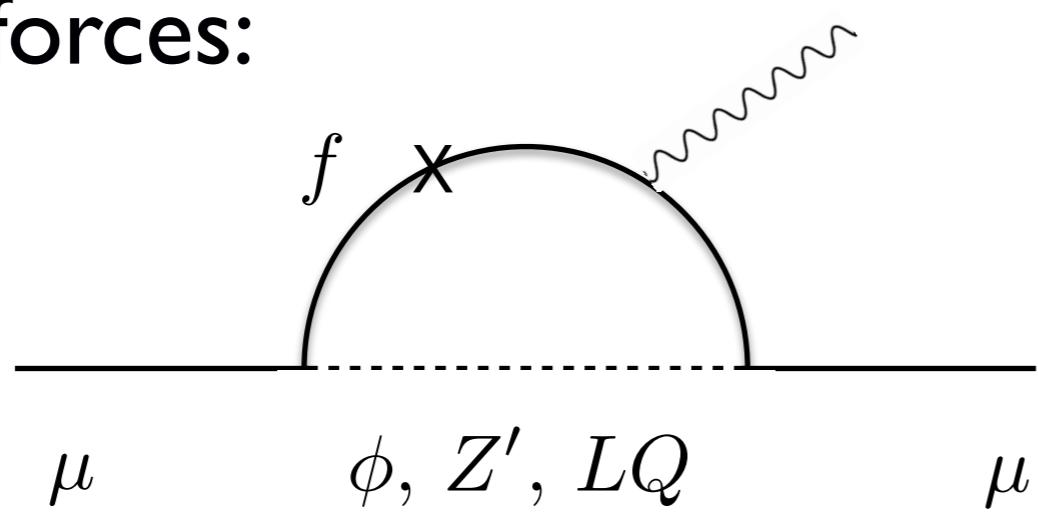
$$\frac{1}{\Lambda_{\text{UV}}} \rightarrow \frac{e\lambda^2 v}{16\pi^2 \Lambda_{\text{UV}}^2}, \quad \lambda \lesssim 0.1 \quad \rightarrow \quad \Lambda_{\text{UV}} \lesssim 2 \text{ TeV}$$

Muon g-2 from new physics

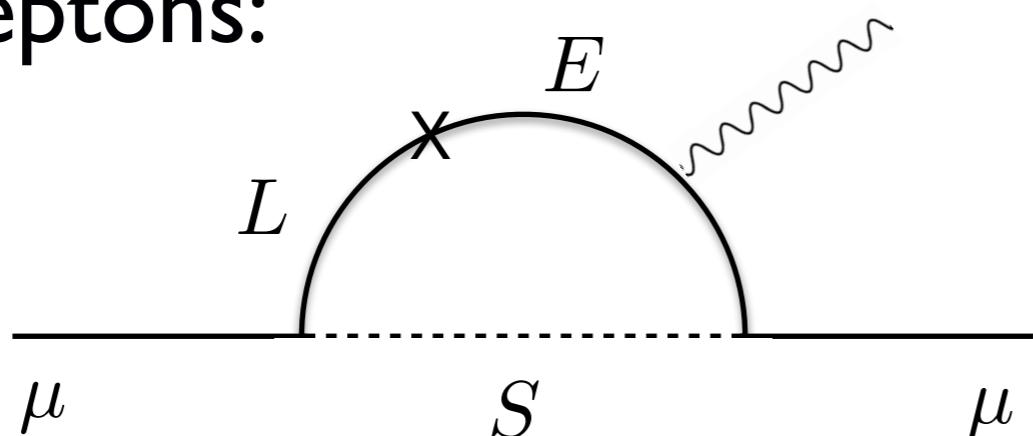
SUSY:



New forces:



New leptons:



-10-

$$\Delta a_\mu \sim \frac{g^2}{16\pi^2} \frac{m_\mu^2}{\mu M_2} \tan \beta$$

$\rightarrow m_{\text{SUSY}} \sim 100 \text{ GeV}$

$$\Delta a_\mu \sim \frac{g'^2}{16\pi^2} \frac{m_\mu^2}{m_{\phi, Z'}^2} (\phi, Z')$$

$\rightarrow m_{\phi, Z'} \sim 100 \text{ MeV}$

$$\Delta a_\mu \sim \frac{\lambda_L \lambda_R}{16\pi^2} \frac{m_\mu m_f}{m_{LQ}^2} (LQ)$$

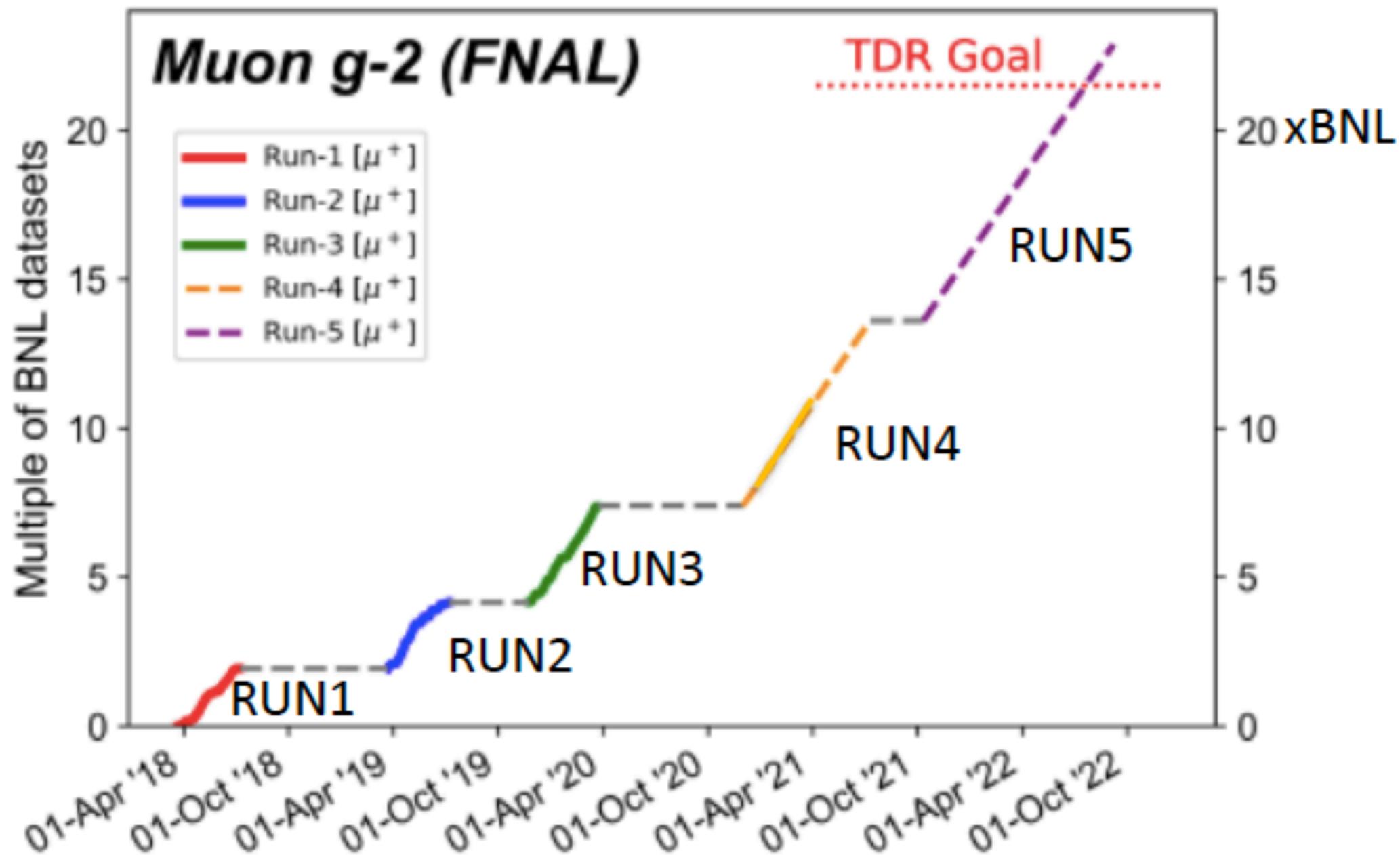
$\rightarrow m_{LQ} \sim 1 \text{ TeV}$

$$\Delta a_\mu \sim \frac{y_L y_R}{16\pi^2} \frac{m_\mu M_L}{m_S^2}$$

$\rightarrow m_S \sim M_L \sim 1 \text{ TeV}$

Prospects for g-2

-11-



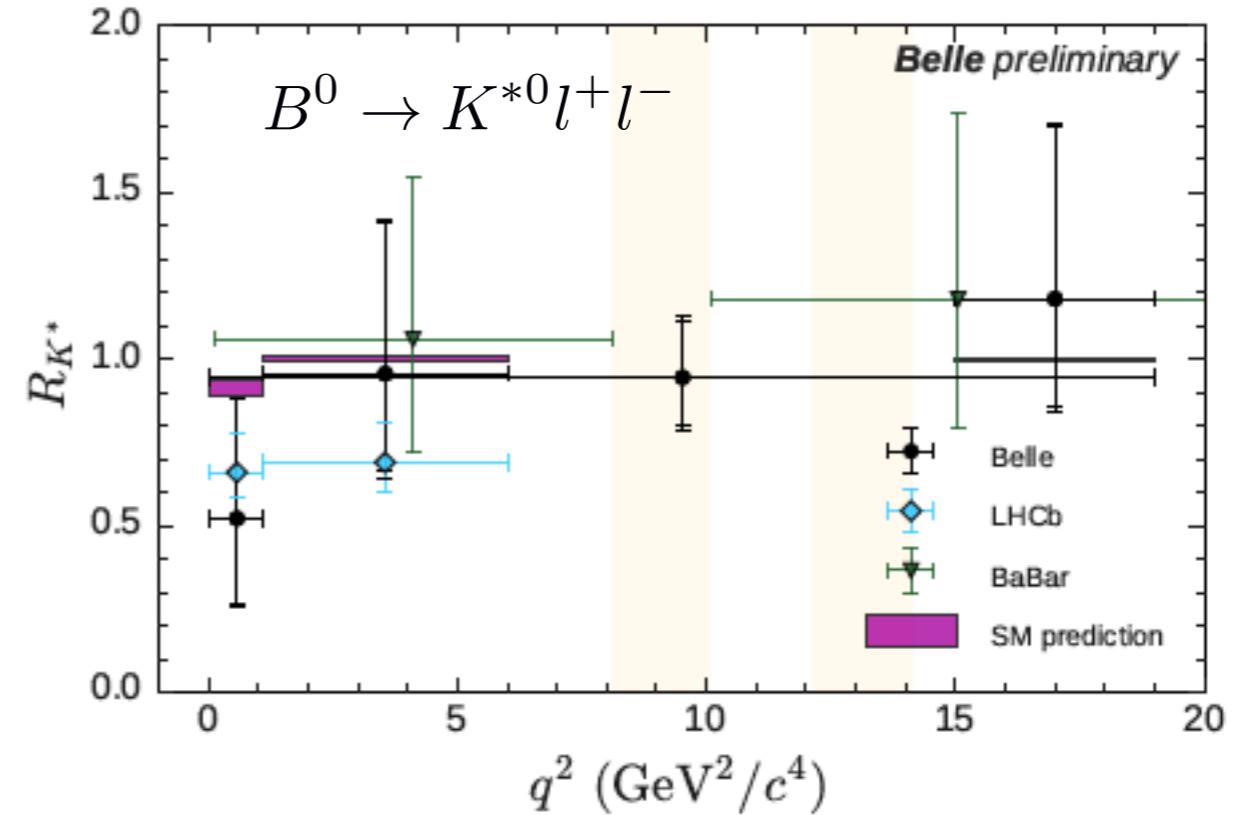
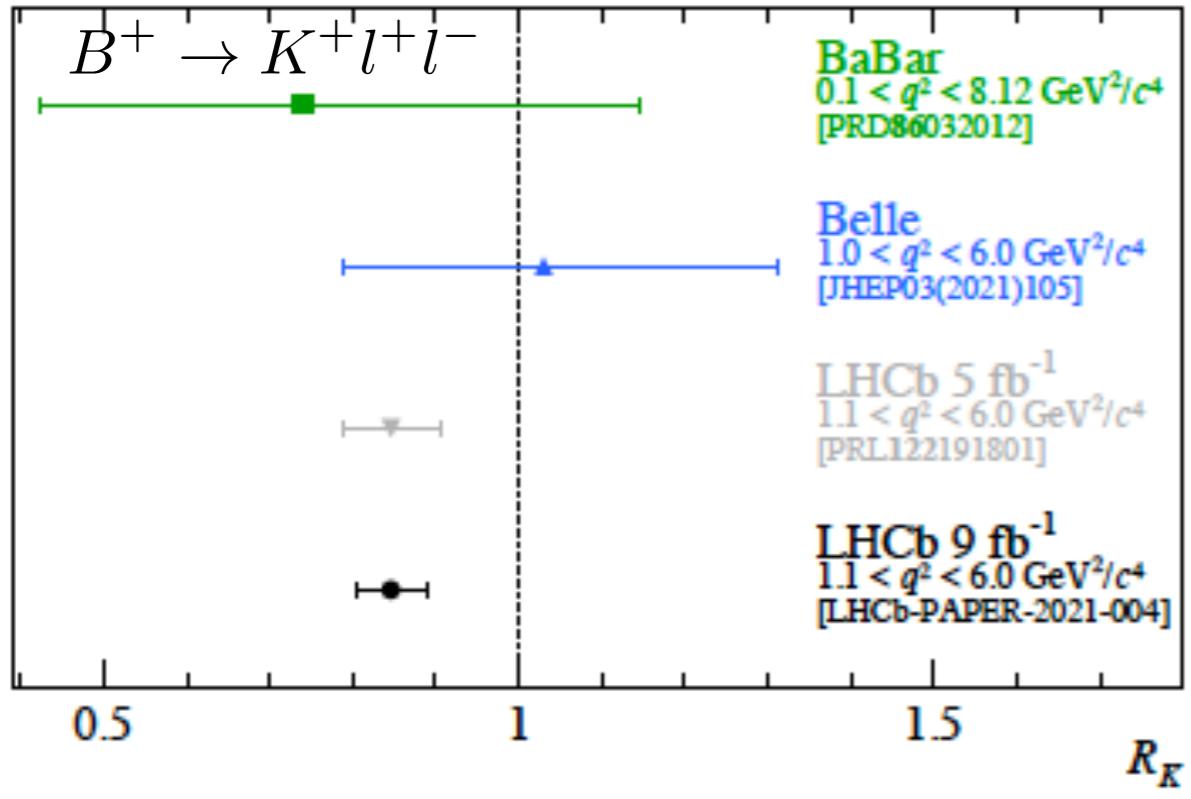
[Graziano Venanzoni, CERN Seminar, April 8, 2021]

- Run 1 data is just 6%. Final goal in 2022 is 20 x BNL data.

B-meson anomalies

B-anomalies at LHCb

-12-



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

$$R_{K^{(*)}} \simeq 1 \text{ (SM)}$$

$$R_K = 0.846^{+0.042}_{-0.039} \text{ (stat)}^{+0.013}_{-0.012} \text{ (syst)}$$

$\sim 3.1\sigma$

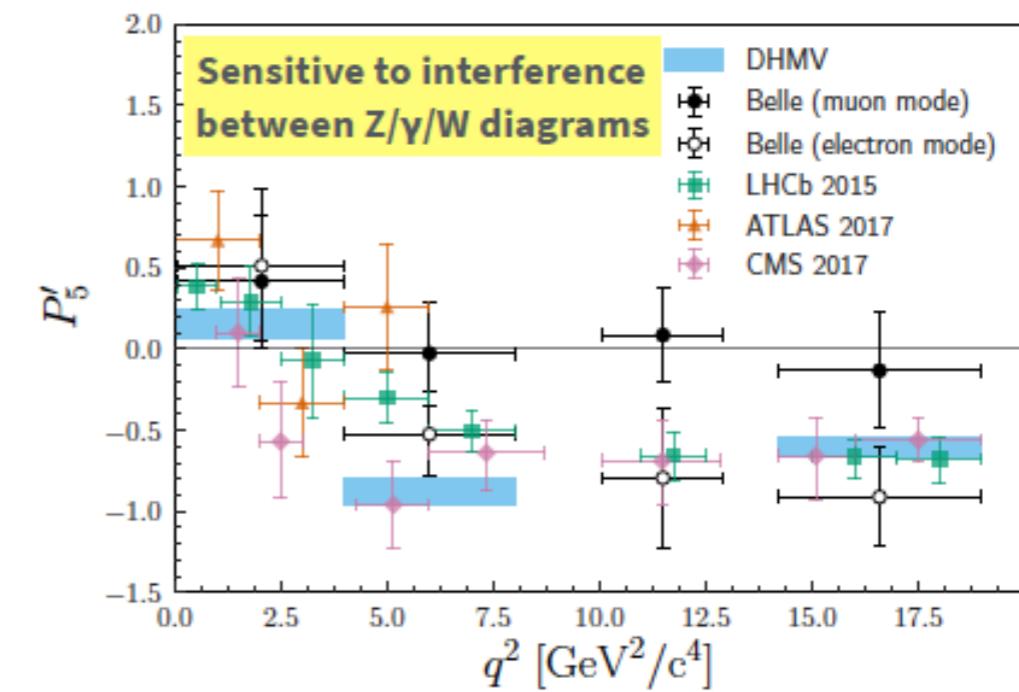
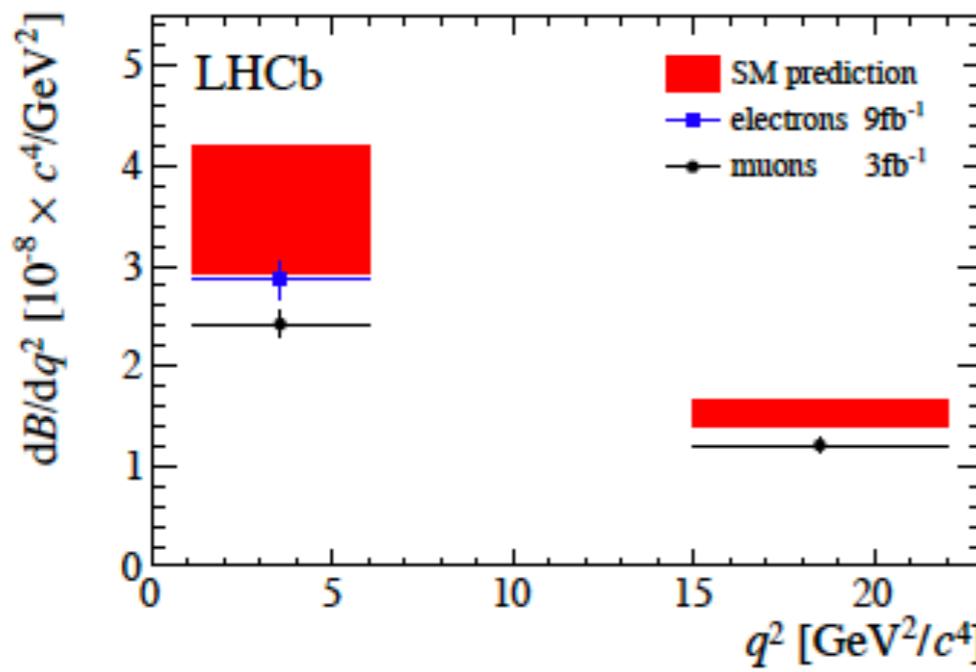
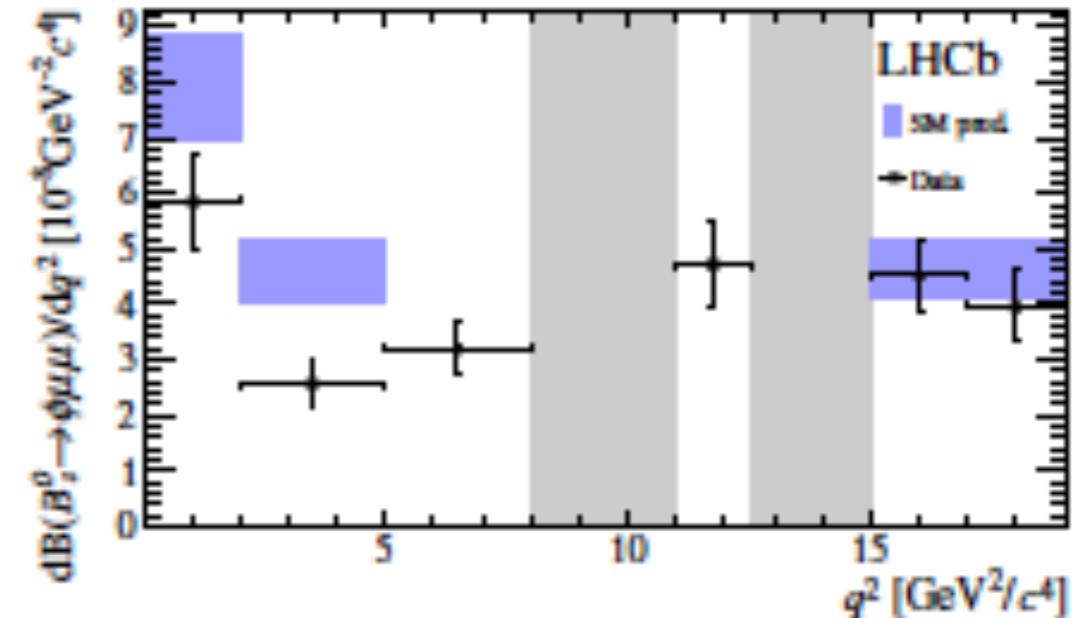
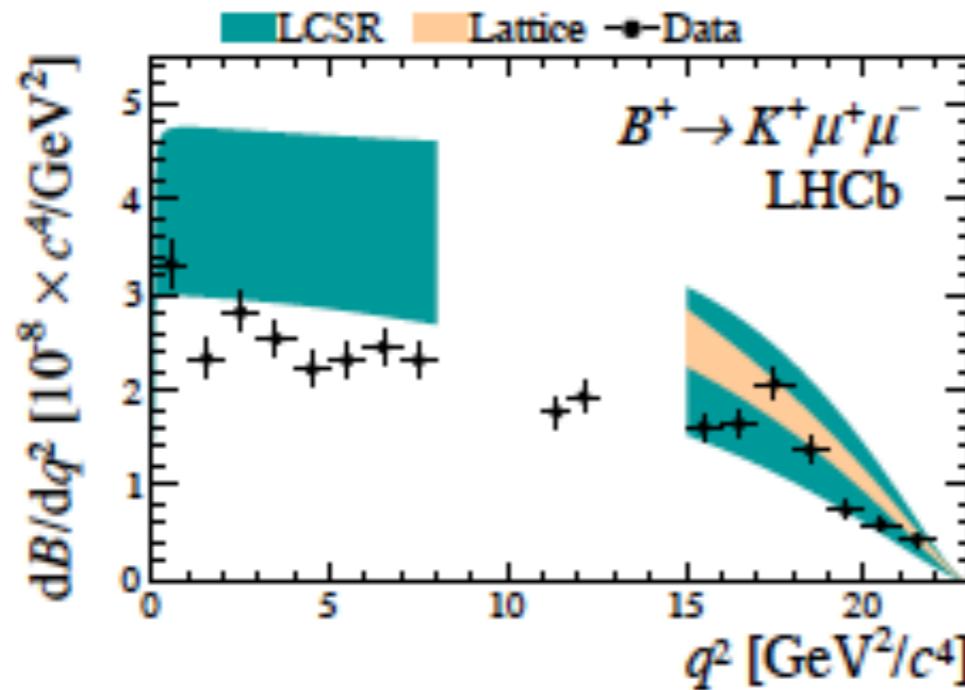
Hadronic uncertainties cancelled
 → Clean test of Lepton Flavor Universality

LHCb Preliminary	low- q^2	central- q^2
$\mathcal{R}_{K^{*0}}$	$0.660^{+0.110}_{-0.070} \pm 0.024$	$0.685^{+0.113}_{-0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

$\sim 2.2\text{--}2.5\sigma$

New physics from muon

-13-

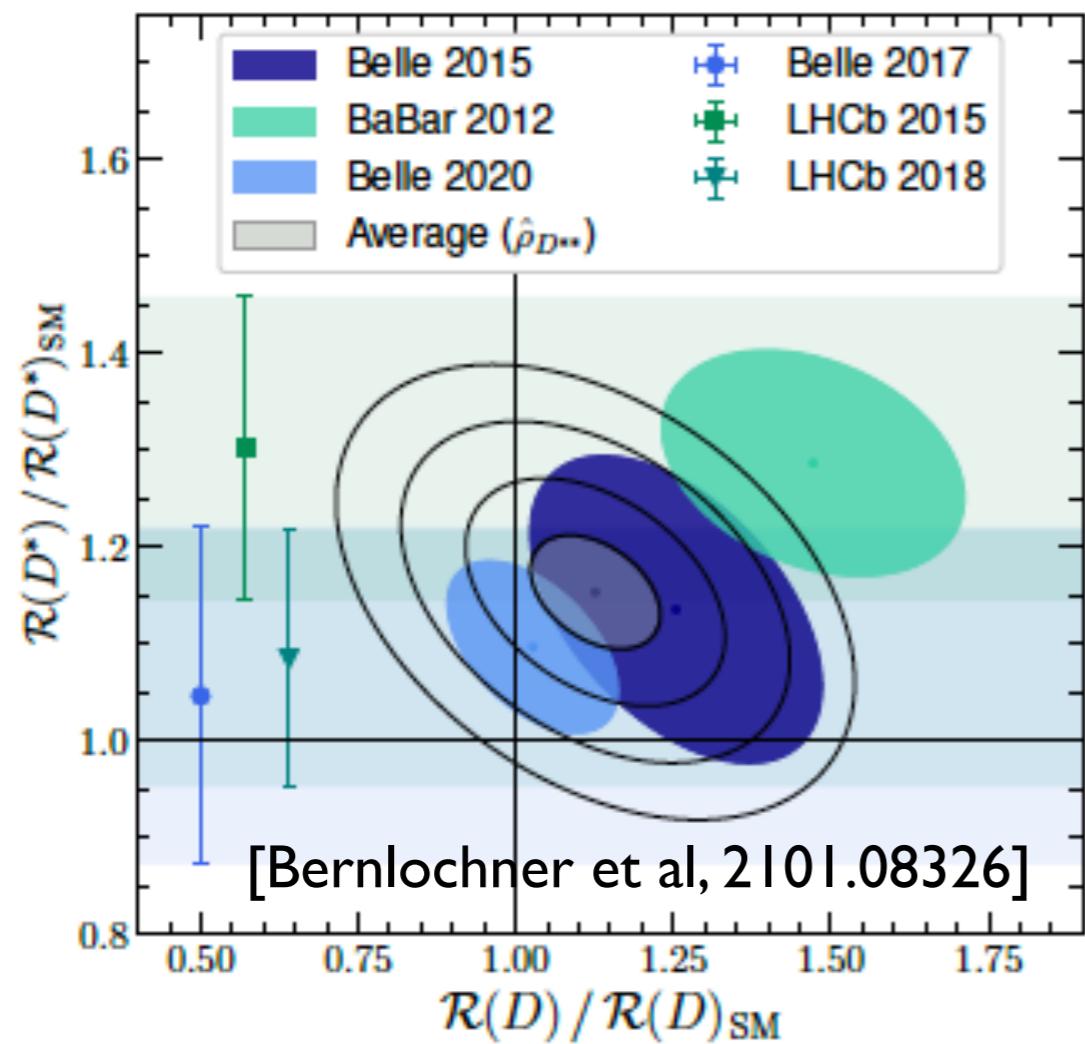


- Differential branching fractions & angular distribution in muon channels are consistently lower than the SM values.

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

-14-

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



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

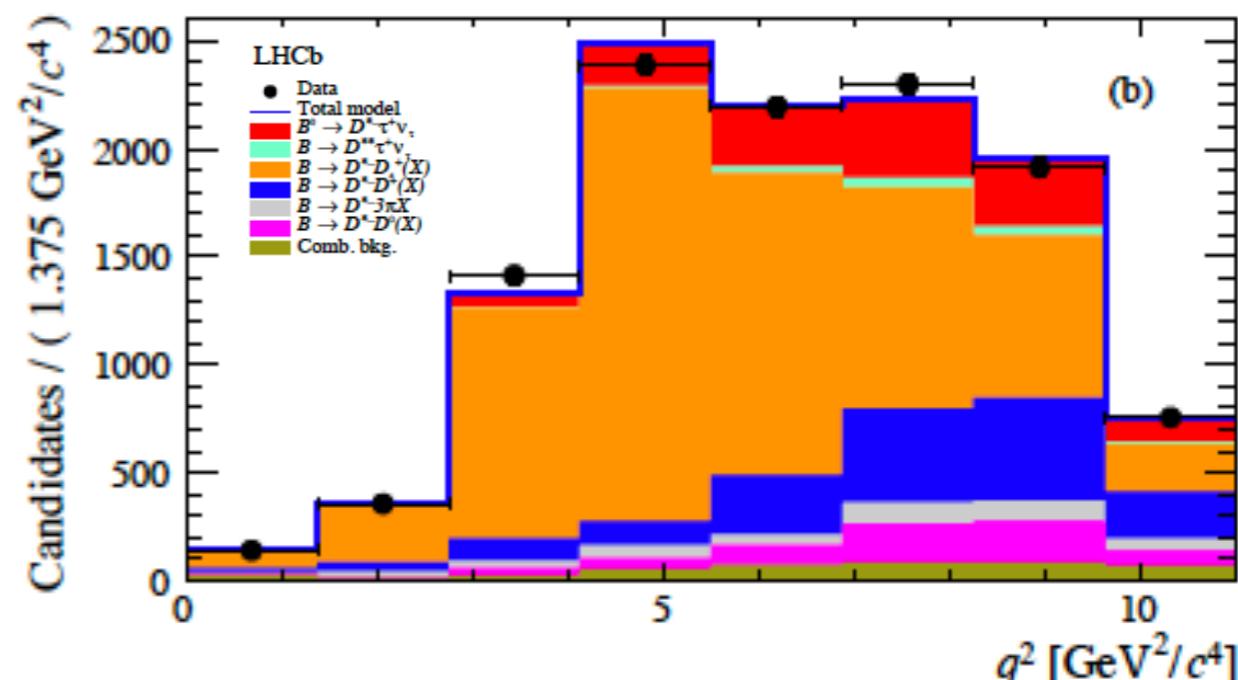
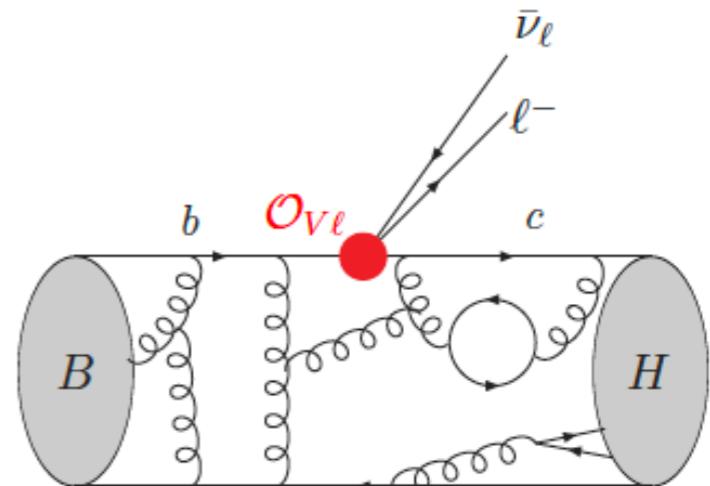
$$R_D^{\text{SM}} = 0.299 \pm 0.003,$$

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

$$R_D^{\text{exp}} = 0.403 \pm 0.040 \pm 0.024,$$

$$R_{D^*}^{\text{exp}} = 0.310 \pm 0.015 \pm 0.008.$$

~3.1 σ with Belle data (2019).



EFT for B-decays

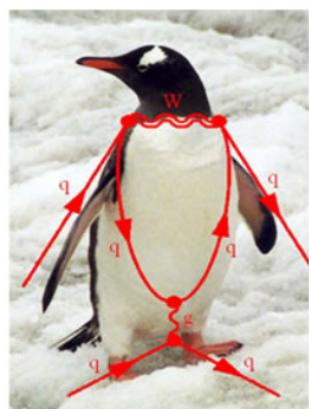
-15-

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

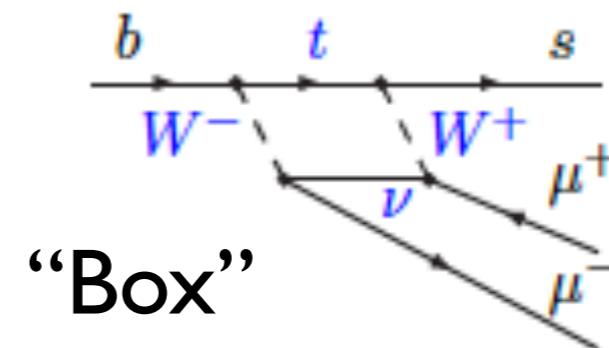
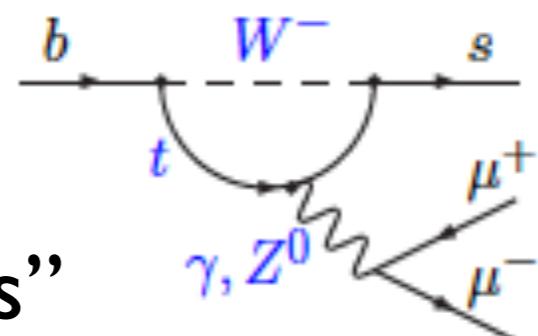
$$\mathcal{H}_{\text{eff}, \bar{b} \rightarrow \bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} (C_9^\mu \mathcal{O}_9^\mu + C_{10}^\mu \mathcal{O}_{10}^\mu + C_9'^\mu \mathcal{O}_9'^\mu + C_{10}'^\mu \mathcal{O}_{10}'^\mu) + \text{h.c.}$$

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

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



“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”



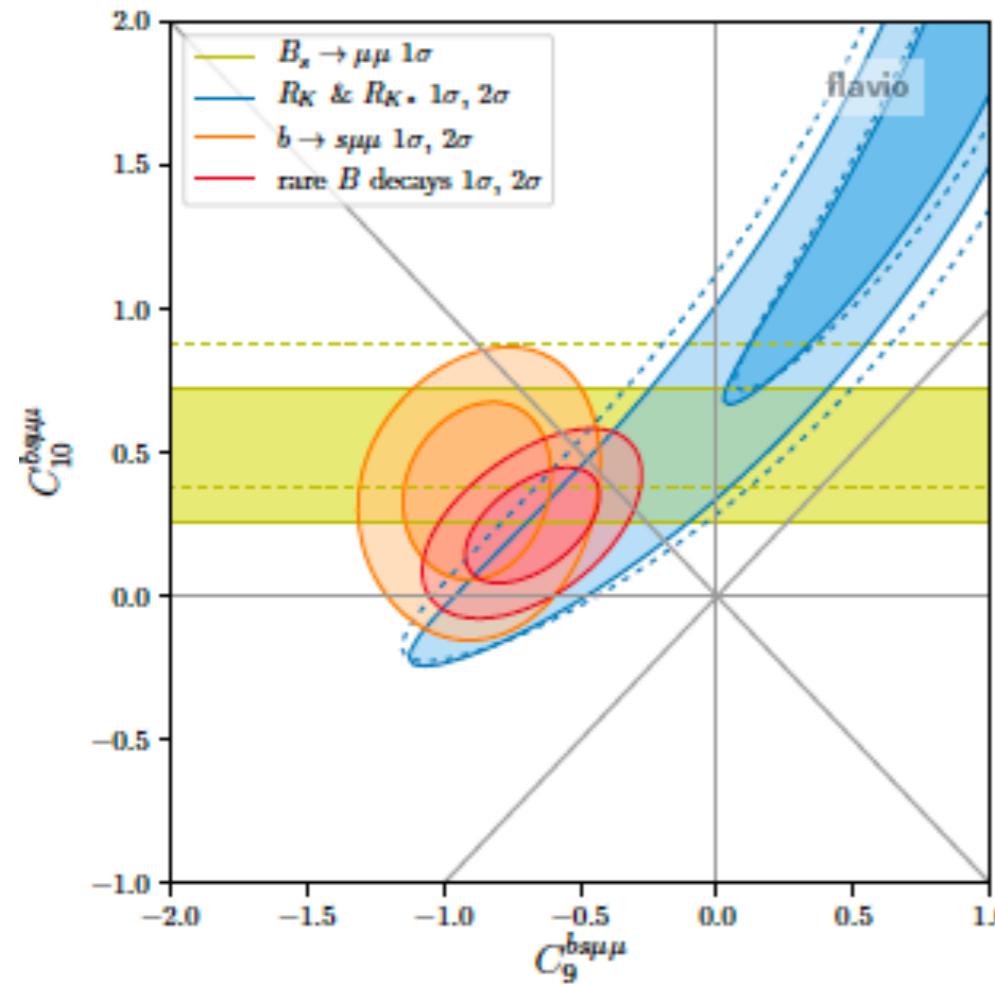
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_V (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_S (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau) + C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \right] + \text{h.c.}$$

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

Global fits

-16-

[Altmannshofer, Stangl, 2021]

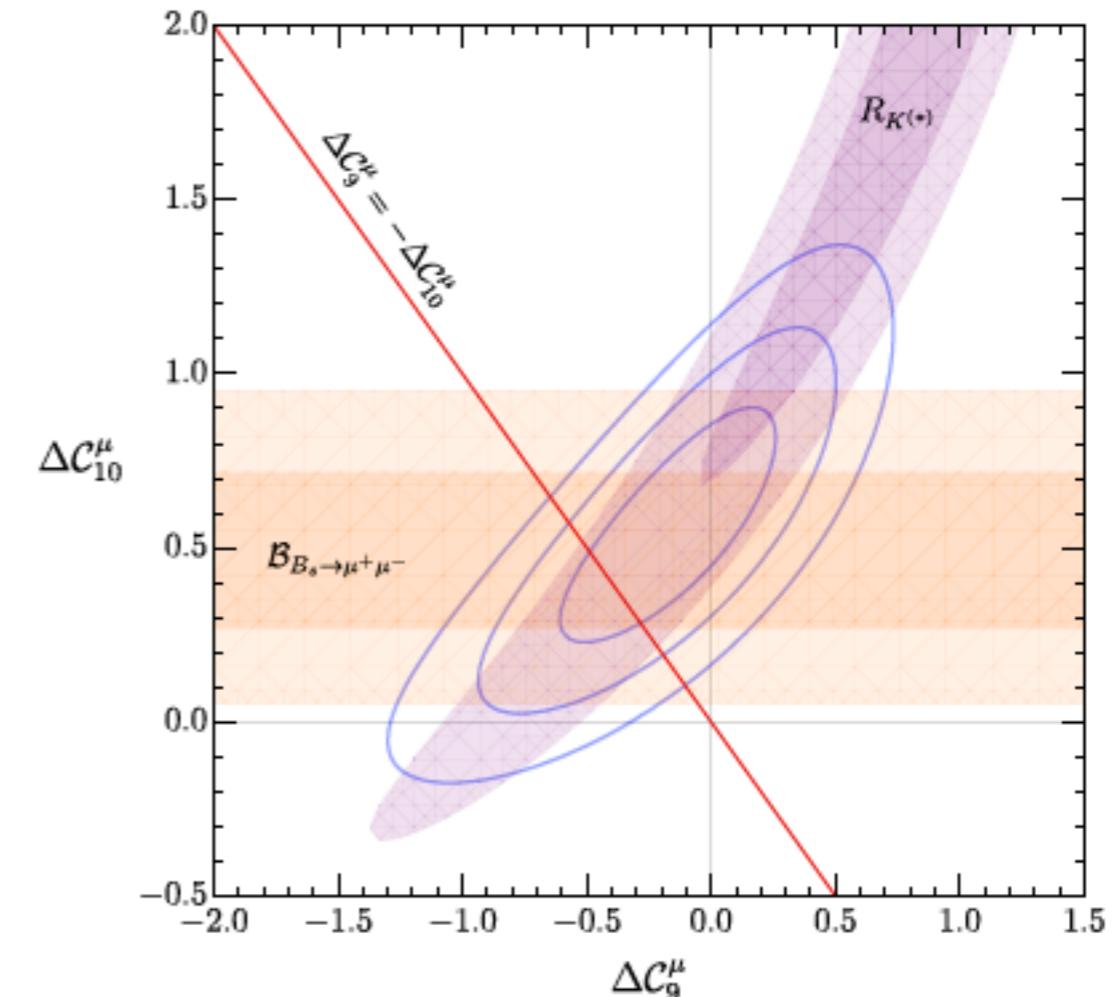


Combine best fit:

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

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

[Cornella et al, 2021]



$\sim 6.1\sigma$ from SM

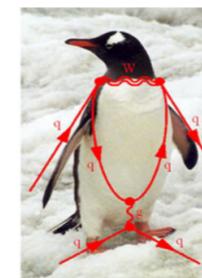
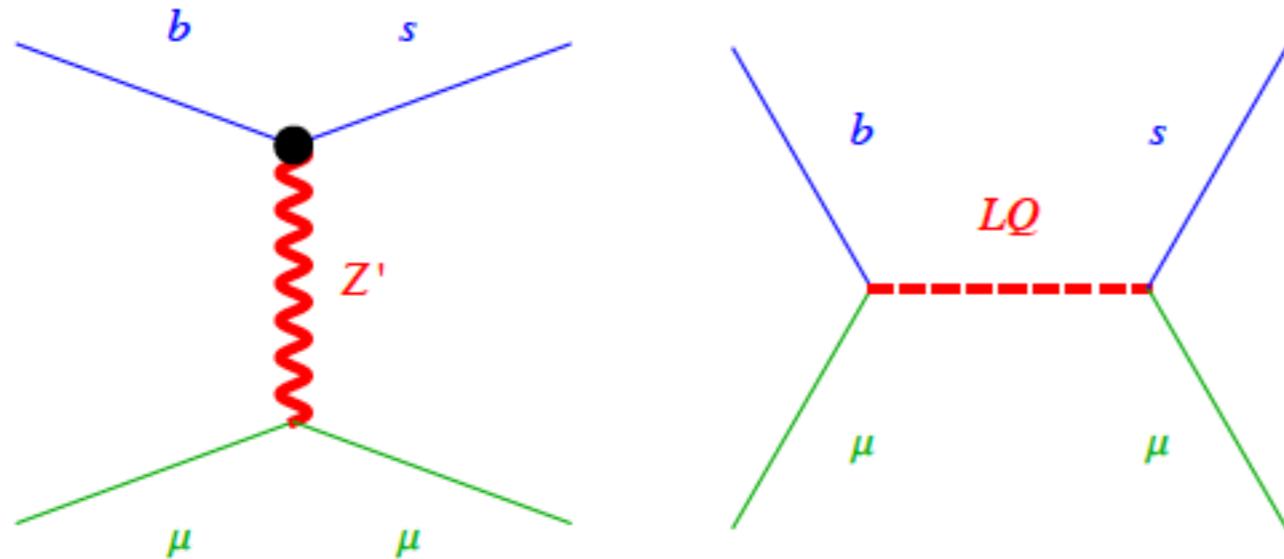
Z' models

Leptoquark models

New physics for B-anomalies

-17-

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

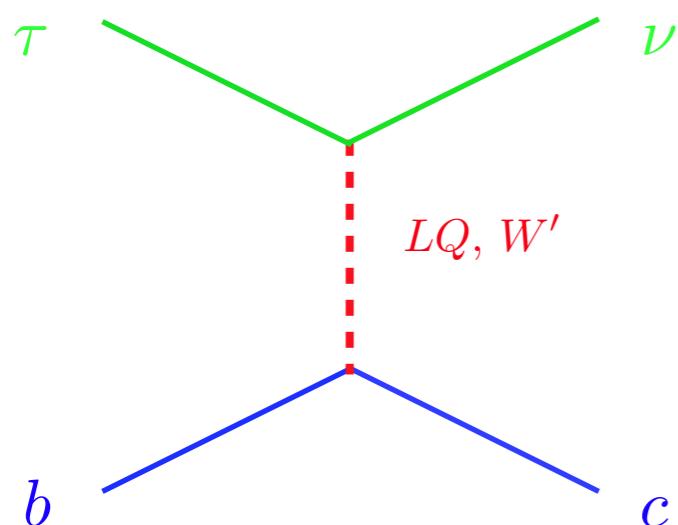


Z' , leptoquarks, loops, etc.

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

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

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



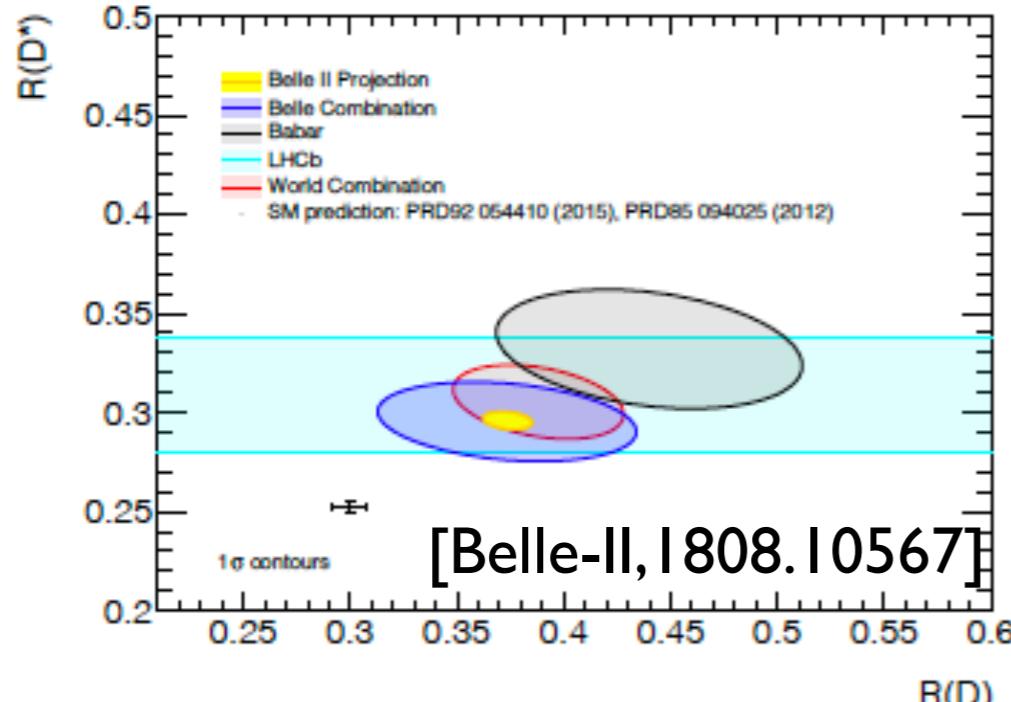
Leptoquarks, W' , charged Higgs, etc.

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

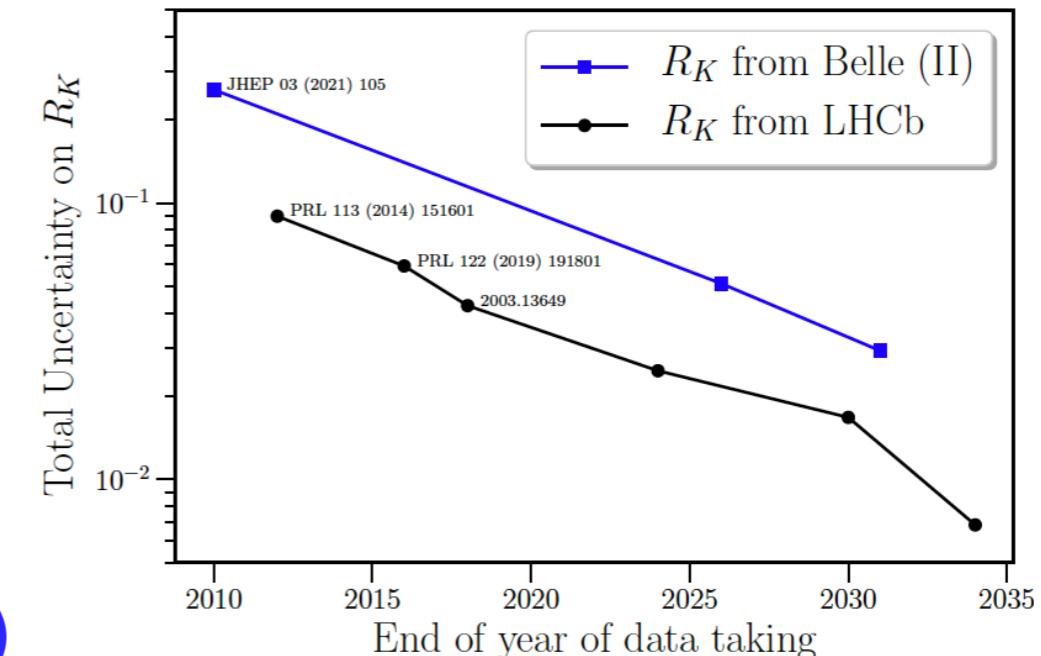
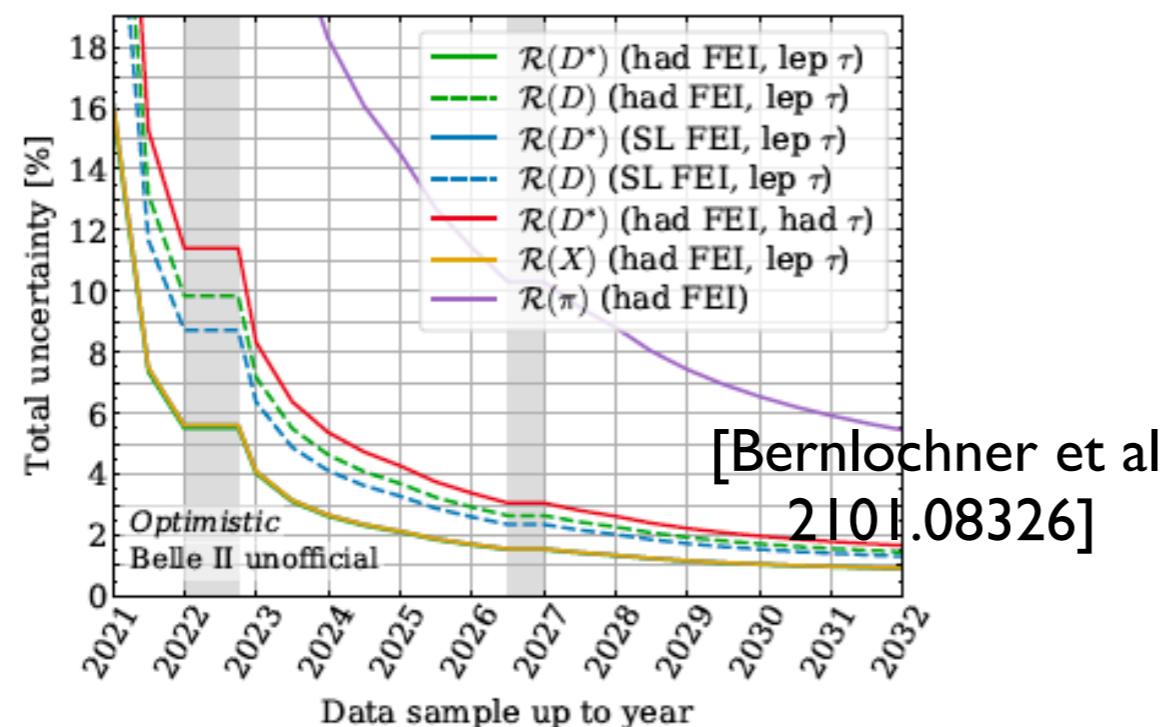
$$\rightarrow \Lambda_{\text{NP}} \simeq 3.5 \text{ TeV}.$$

Prospects for B-anomalies

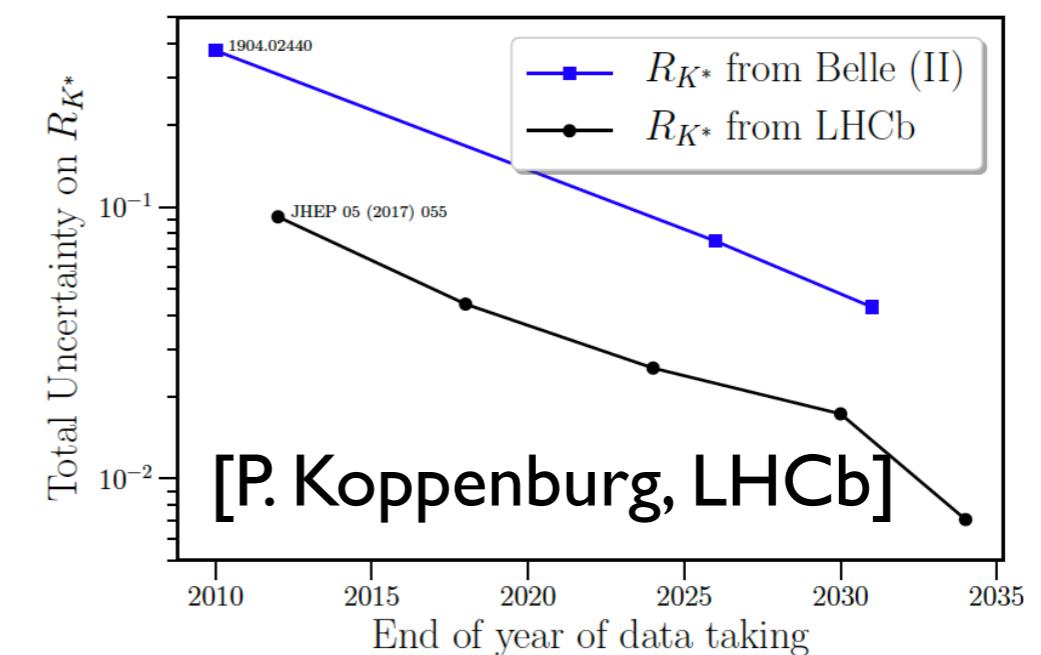
-18-



$R_D^{(*)}$



$R_K^{(*)}$



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

Models for muon g-2 & B-meson anomalies

Flavor-dependent Z'

-19-

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

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

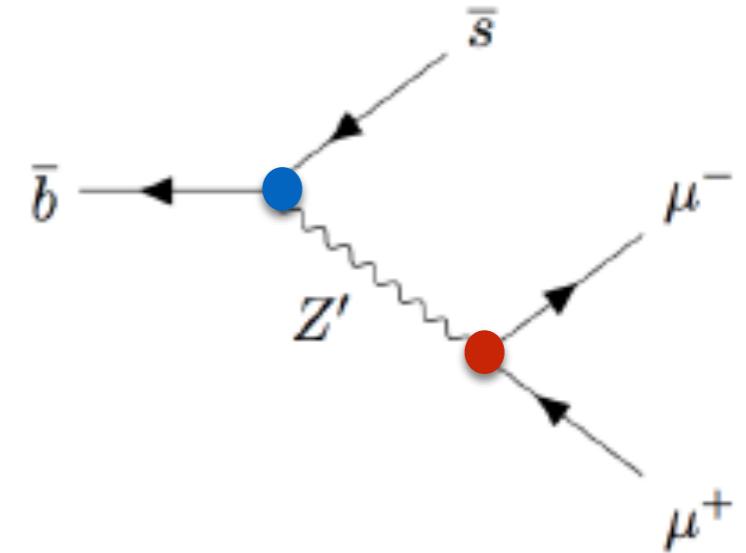
$$\mathcal{L}_{Z'} = g_{Z'} Z'_\mu \left(\frac{1}{3} x \bar{t} \gamma^\mu t + \boxed{\frac{1}{3} x \bar{b} \gamma^\mu b} + \boxed{y \bar{\mu} \gamma^\mu \mu} + y \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu - (x+y) \bar{\tau} \gamma^\mu \tau \right. \\ \left. - (x+y) \bar{\nu}_\tau \gamma^\mu P_L \nu_\tau +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

CKM is the only source for flavor violation.

[Bian, Choi, Kang, HML, 2017;
Bian, HML, Park, 2017,2020]

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

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

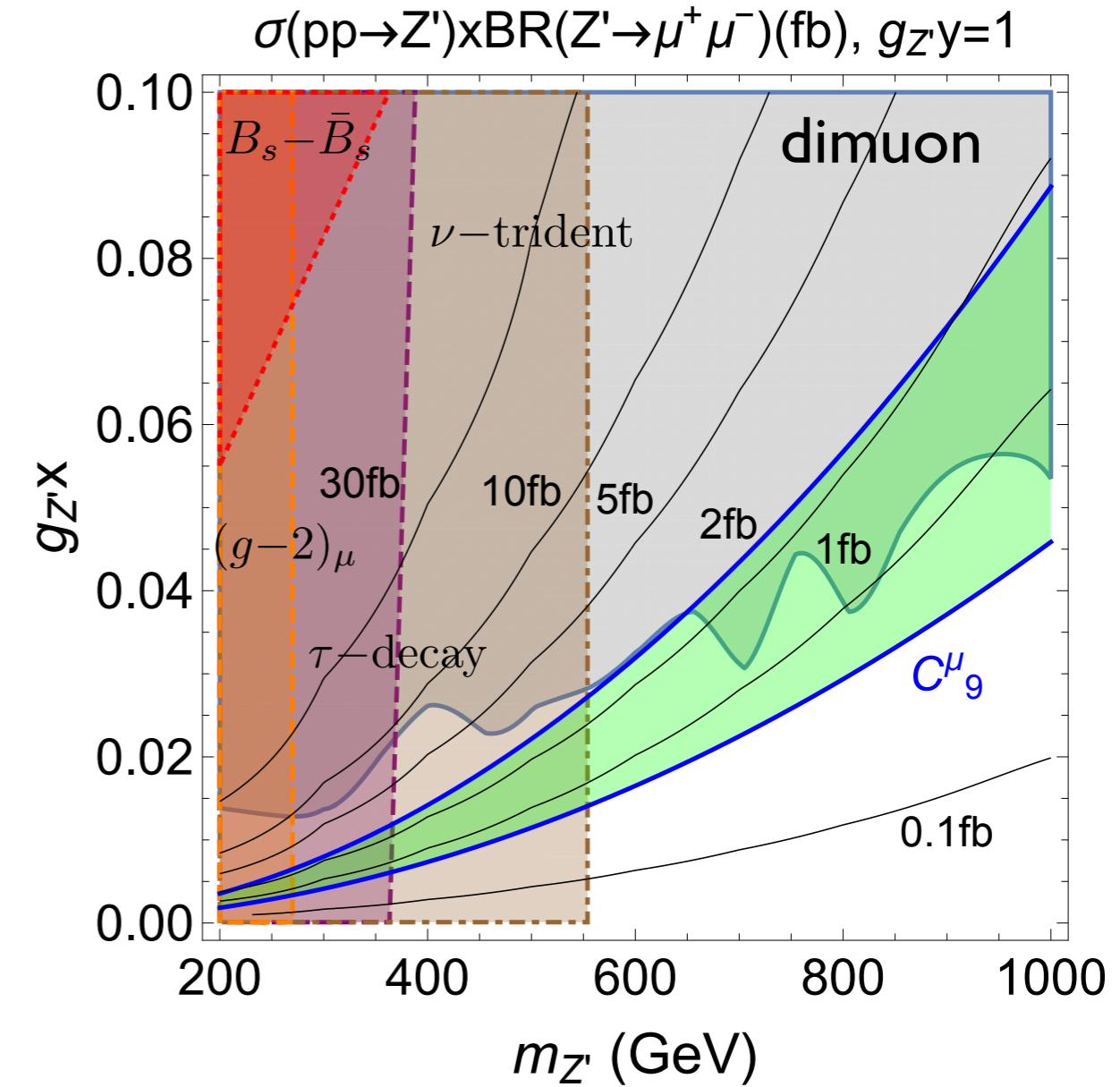
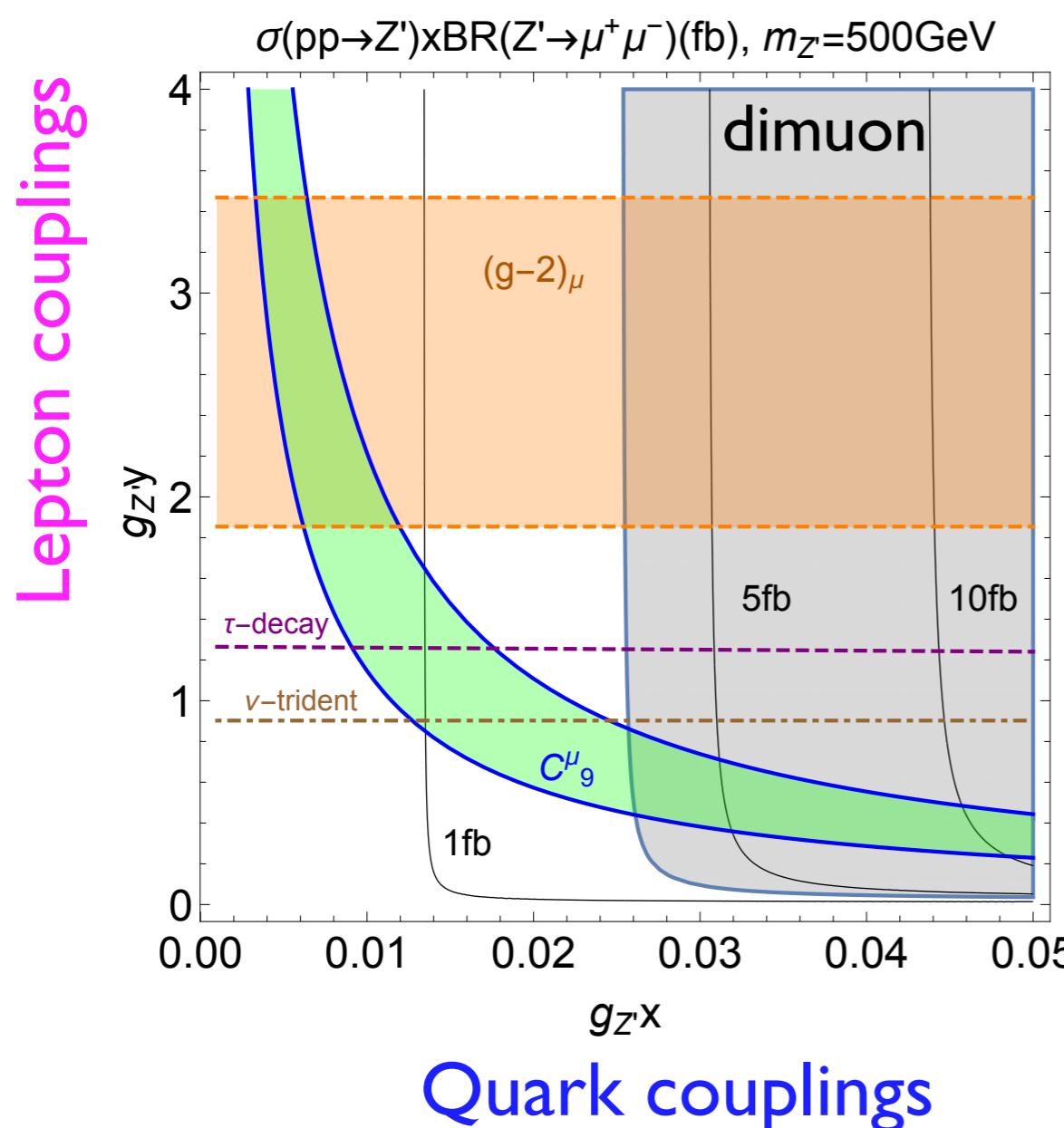


$$\Delta \mathcal{H}_{\text{eff}, \bar{b} \rightarrow \bar{s} \mu^+ \mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} C_9^{\mu, \text{NP}} \mathcal{O}_9^\mu ,$$

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

B-anomalies & Z' bounds

-20-



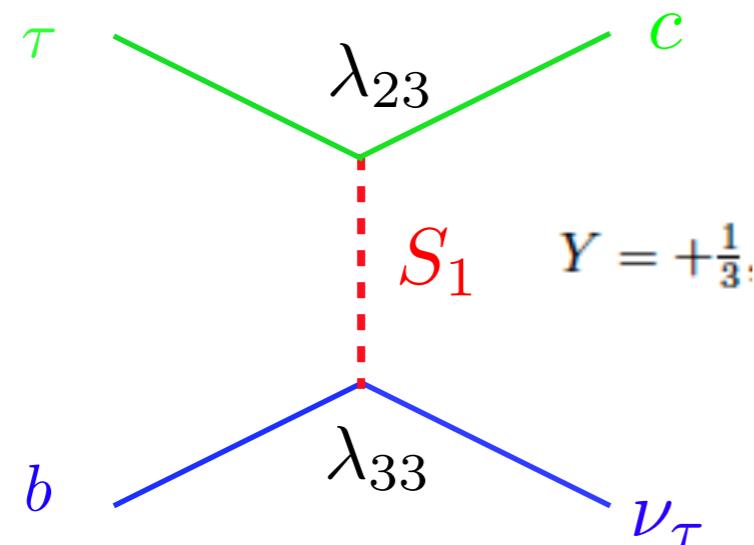
[Bian, Choi, Kang, HML, 2017]

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

Scalar leptoquarks

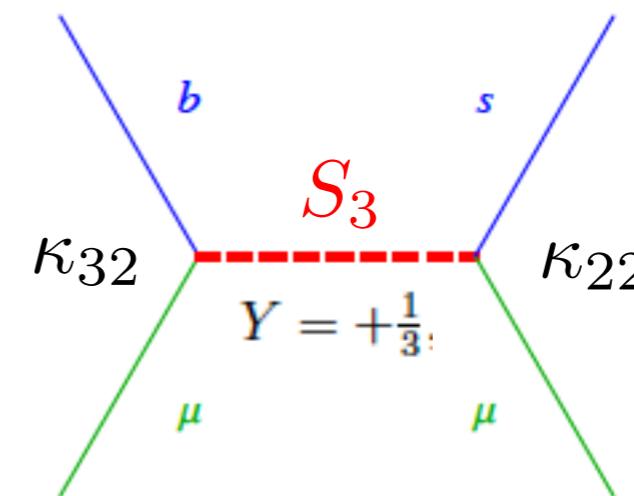
-21-

Singlet leptoquark for $R_{D^{(*)}}$



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

Triplet leptoquark for $R_{K^{(*)}}$



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

[Crivellin, Mueller, Ota, 2017; Choi, Kang, HML, Ro, 2018]

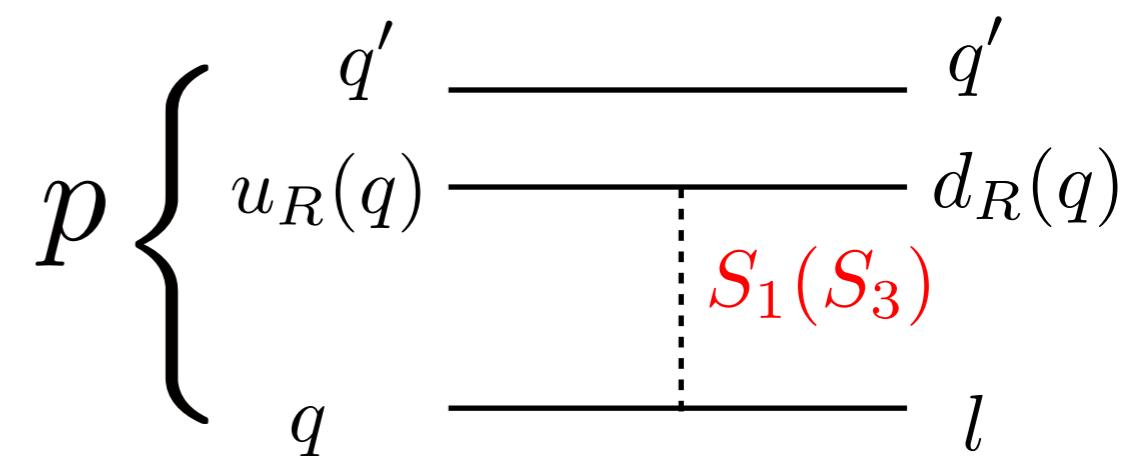
Scalar LQ couplings: renormalizable but constrained by proton decay.

Singlet LQ: either $q l$ or $u_R^c d_R^c$

Triplet LQ: either $q l$ or $q q$

B-meson anomalies: $q l$

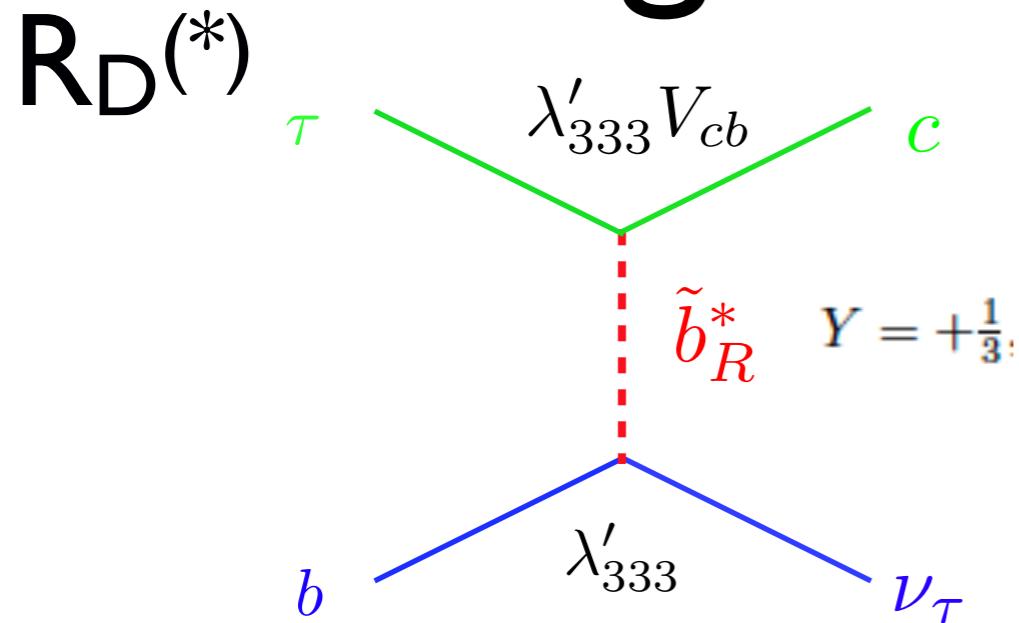
Extra symmetry?



cf. Vector LQ: not renormalizable

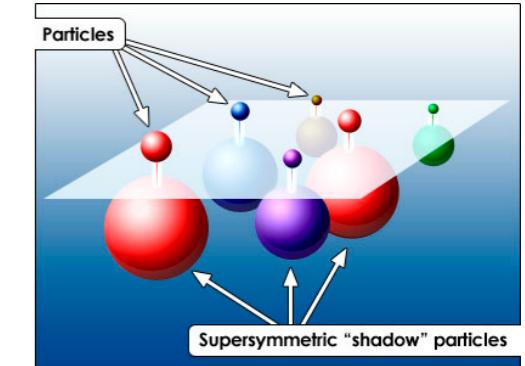
Origin of leptoquarks I

-22-



SUSY with RPV:
 S_I = bottom squark

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



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

RPV safe from proton decay:

sbottom- $u_R^c d_R^c$ is forbidden.

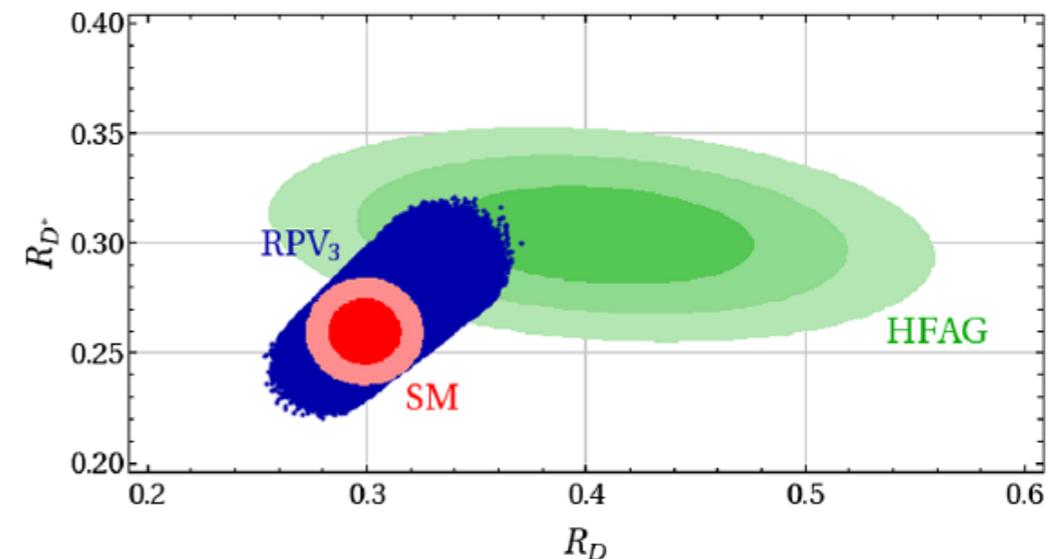
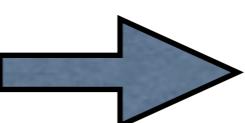
CKM mixing induces charm coupling:

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

LHC direct searches:

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

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



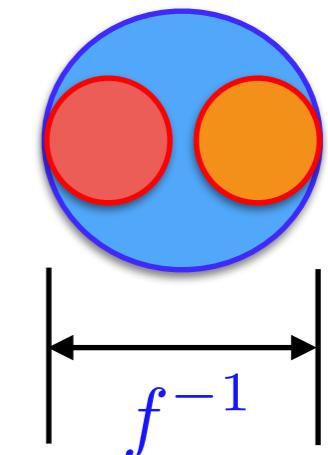
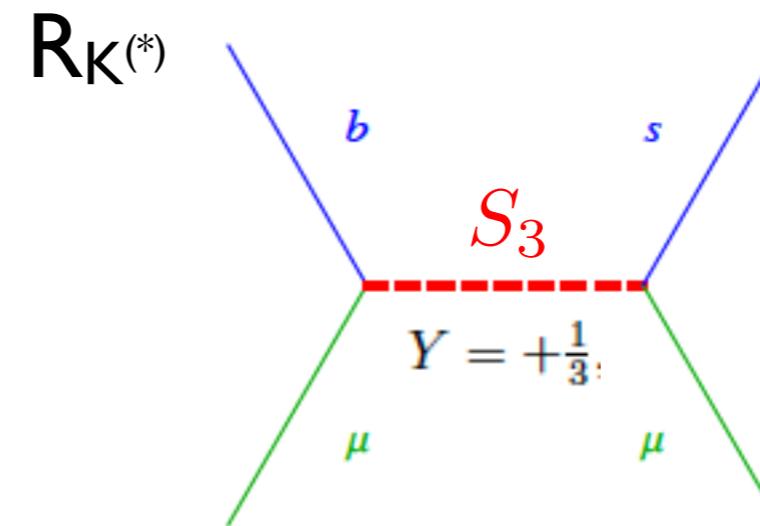
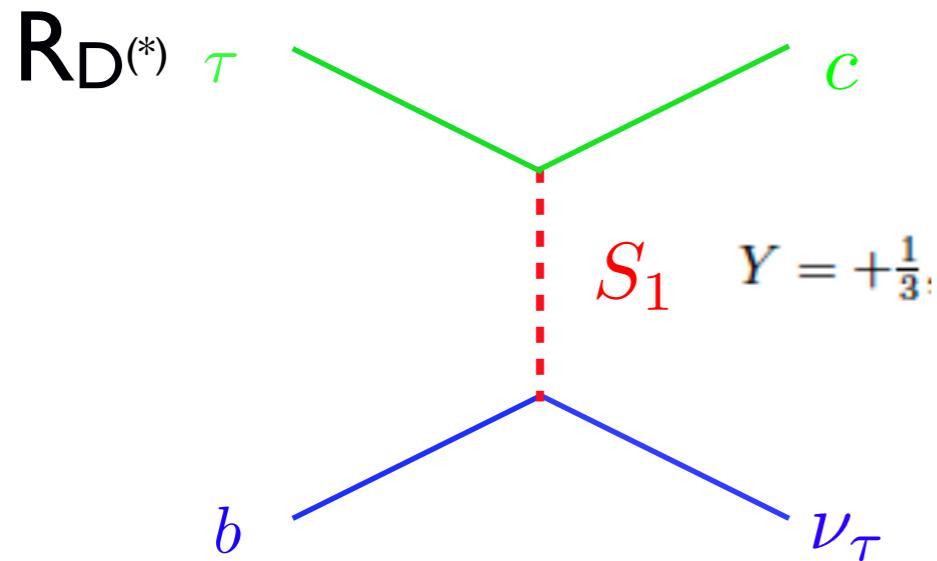
[Altmannshofer et al, 2017]

Large RPV couplings in tension
with perturbative unification.

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

Origin of leptoquarks II

-23-



Scalar leptoquarks = pseudo Nambu-Goldstone bosons

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

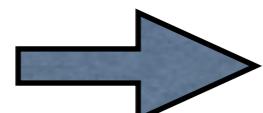
[B. Gripaios, 2010]

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]

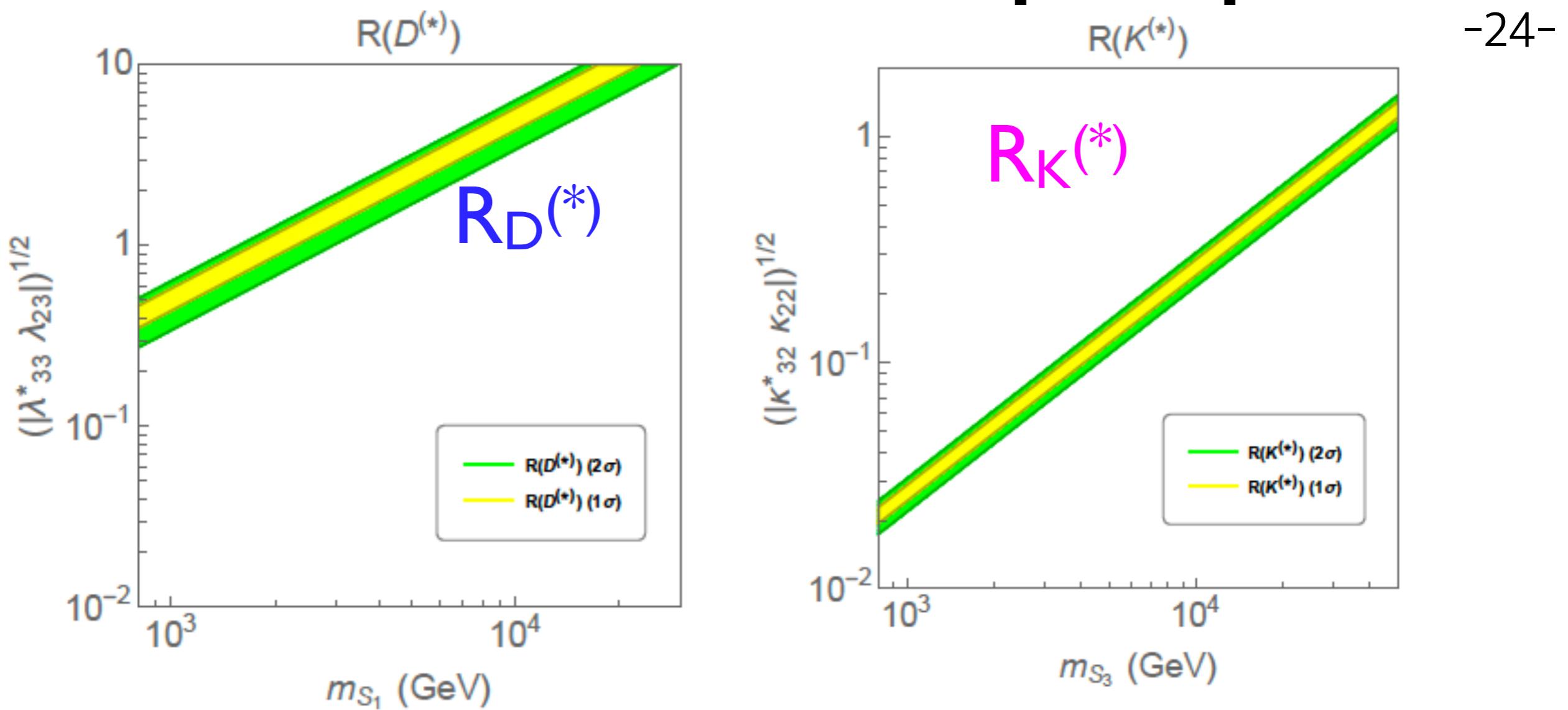
Coset space: $SO(9) \times SO(5)/[(SU(4)_{PS} \times SU(2)_{LQ}) \times (SU(2)_H \times SU(2)_R)]$



Naturally light SM Higgs + LQ scalars

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

Minimal flavor for leptoquarks



[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

$$\frac{|\kappa_{33}^* \kappa_{23}|}{|\lambda_{33}^* \lambda_{23}|} \approx \frac{|\kappa_{32}^* \kappa_{23}|}{|\lambda_{32}^* \lambda_{23}|} \approx \frac{m_{S_3}^2}{m_{S_1}^2}$$

for $B \rightarrow K^{(*)}\nu\bar{\nu}$

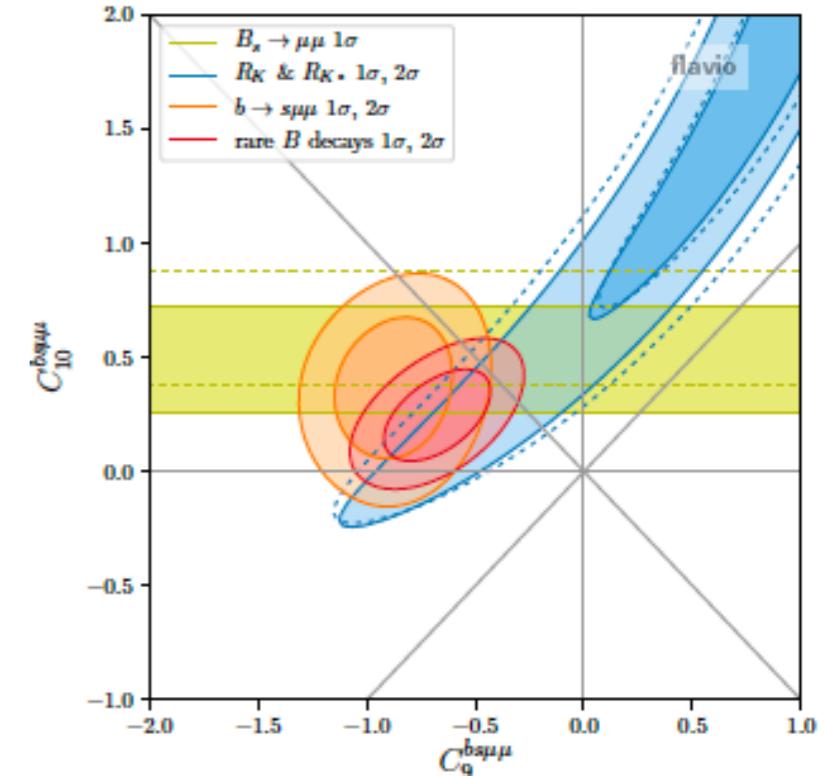
Hadronic constraints

-25-

$B - \bar{B}$ 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.



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

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

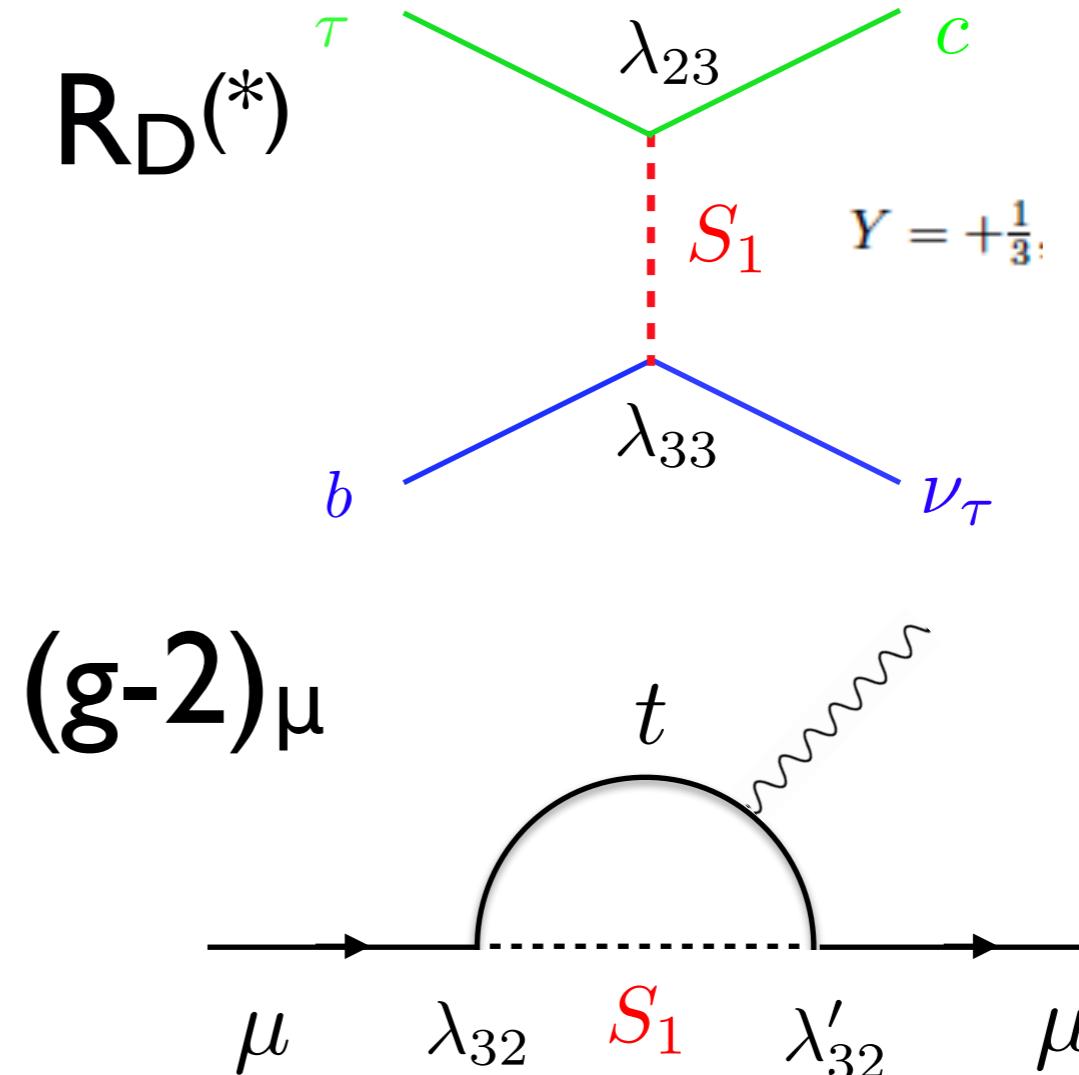
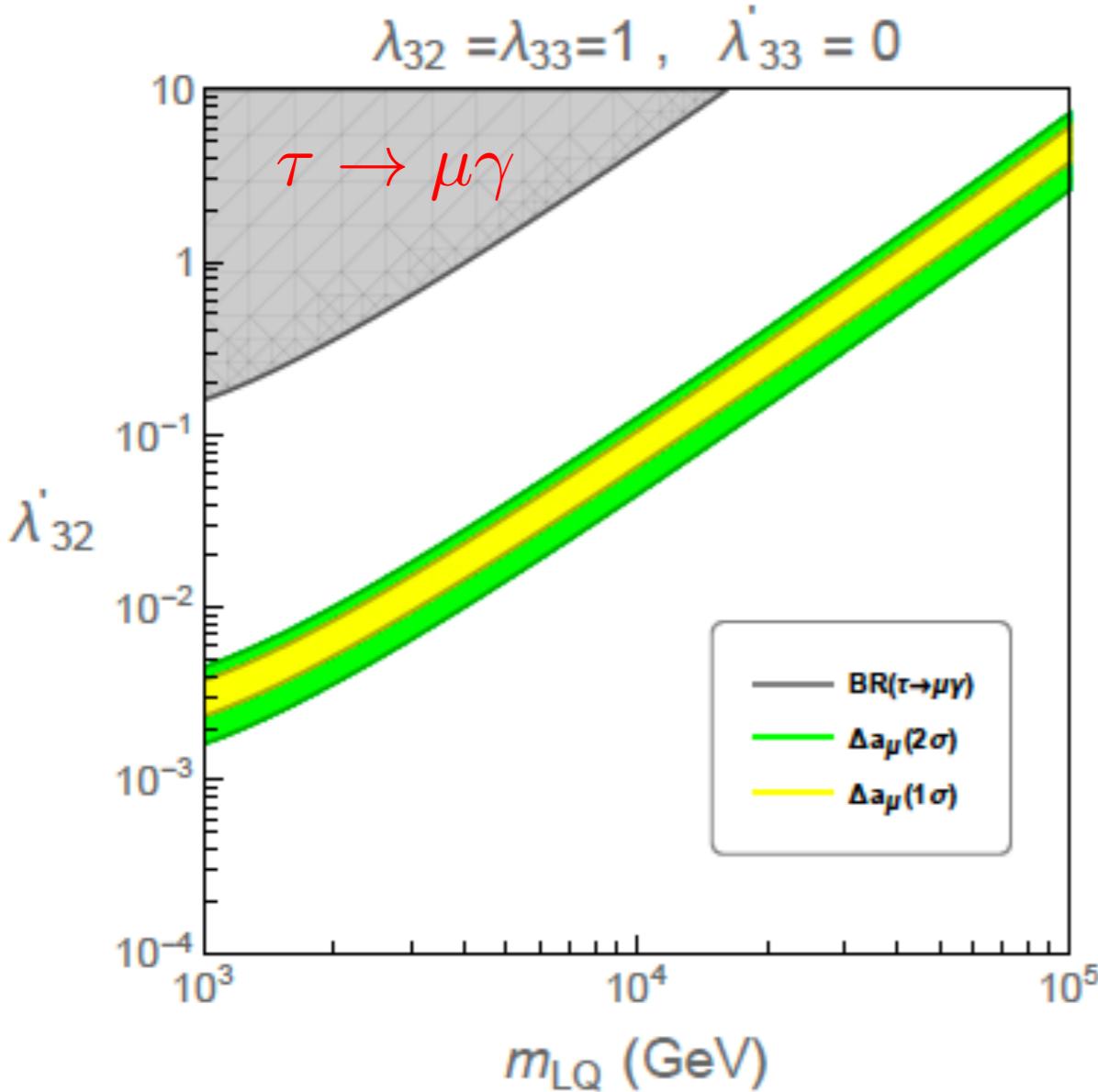
→ Cancellation between singlet and triplet leptoquarks.

Belle-2 at 10% level

→ strong constraints on leptoquark models.

Leptoquark for muon g-2

-26-



Minimal flavor: $\lambda' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \lambda'_{31} & \lambda'_{32} & 0 \end{pmatrix}$

[Choi, Kang, HML, Ro, 2018]

Top + Singlet leptoquark loops



$$\Delta a_\mu \sim \frac{1}{16\pi^2} \lambda_{32} \lambda'^*_{32} \frac{m_\mu m_t}{m_{S_1}^2}$$

Leptonic constraints

-27-

- Electron g-2, Lepton flavor violation and Electric dipole moment are also cross checks of the SM.

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

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

Fine structure constant differs by 5.4σ .

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

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

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

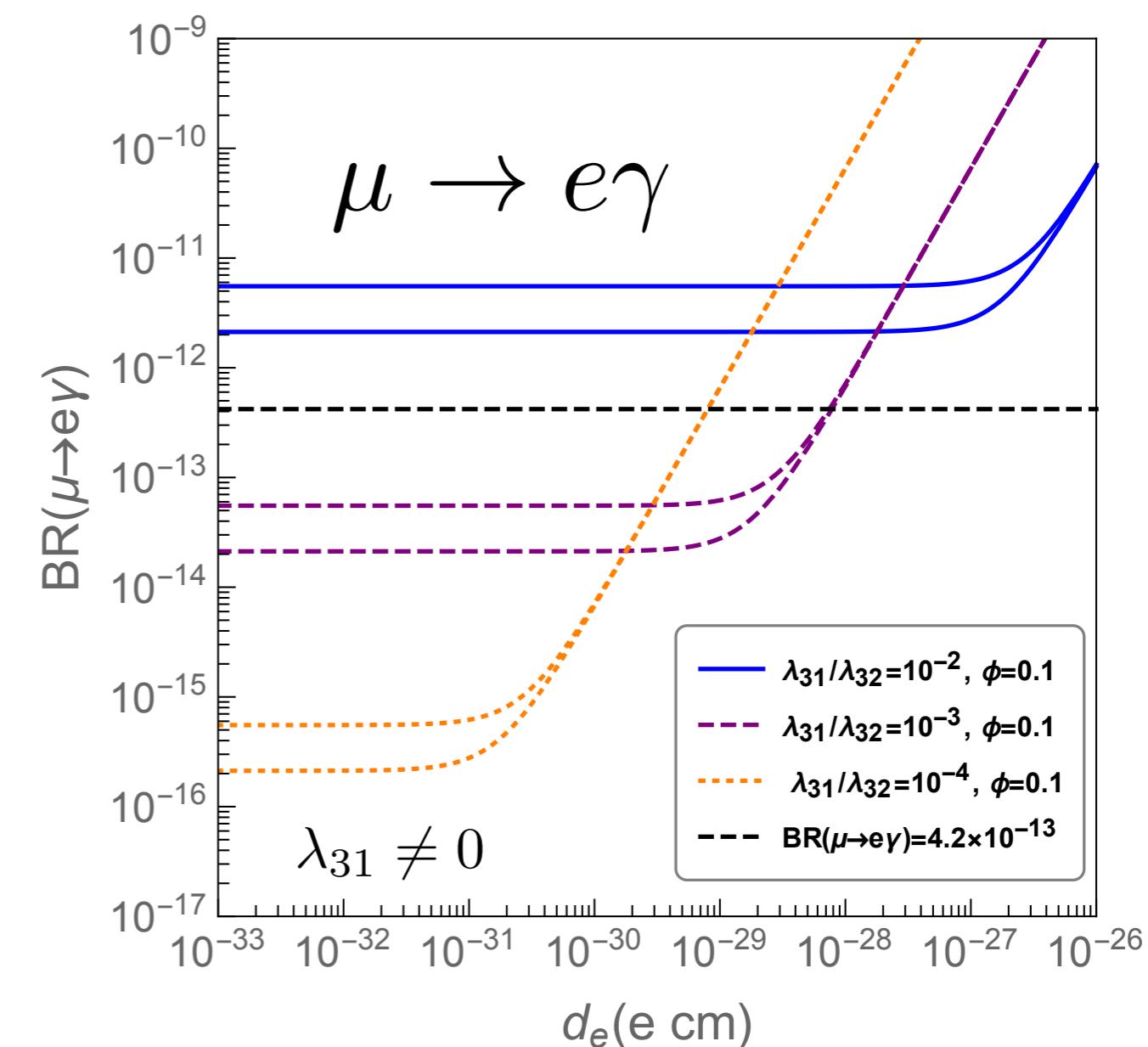
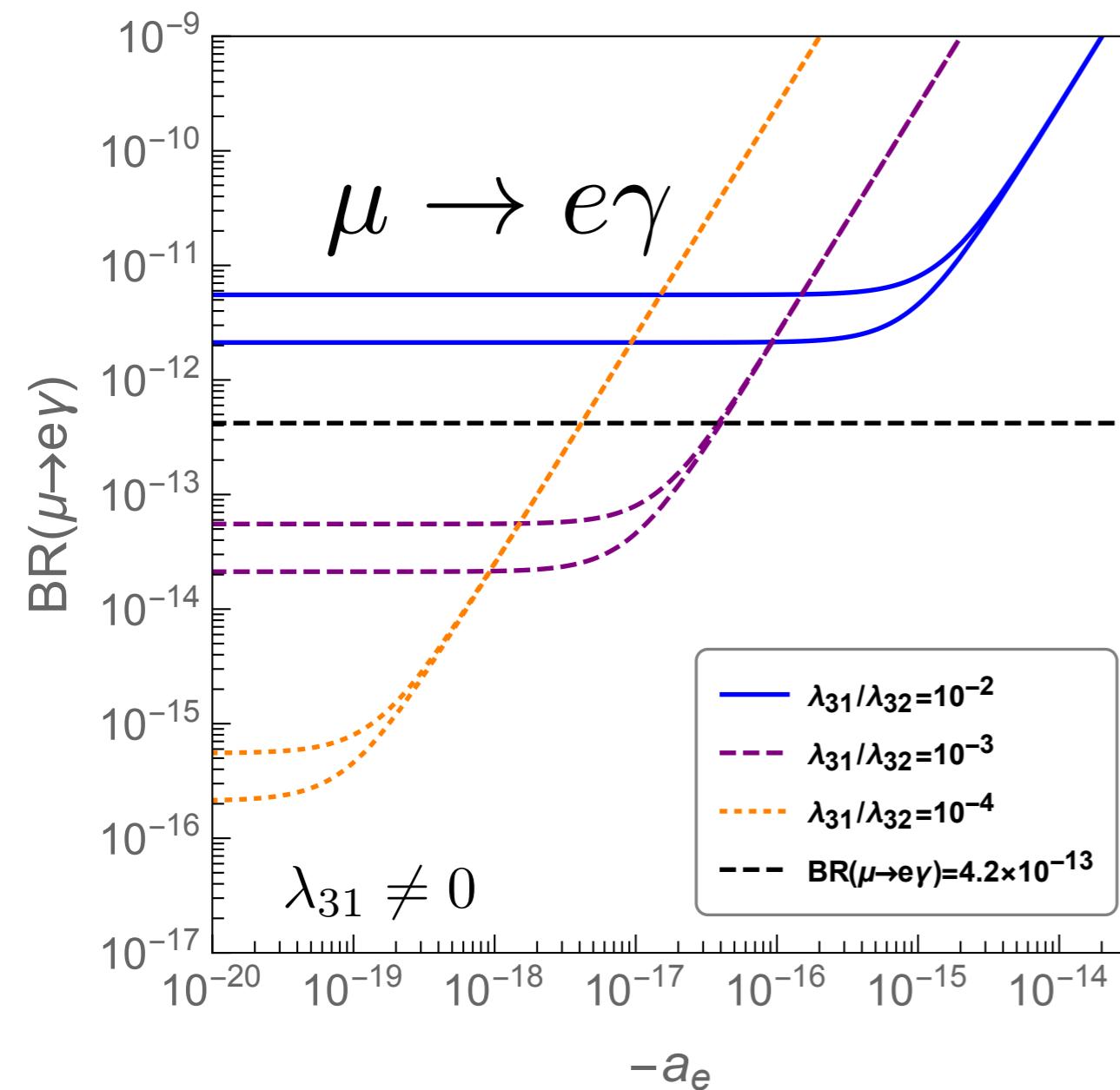
EDM: $d_e < 1.1 \times 10^{-29} \text{ e cm}$ [ACMEII]

$d_\mu < 1.5 \times 10^{-19} \text{ e cm}$

Leptonic signatures

-28-

[HML, 2021]



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

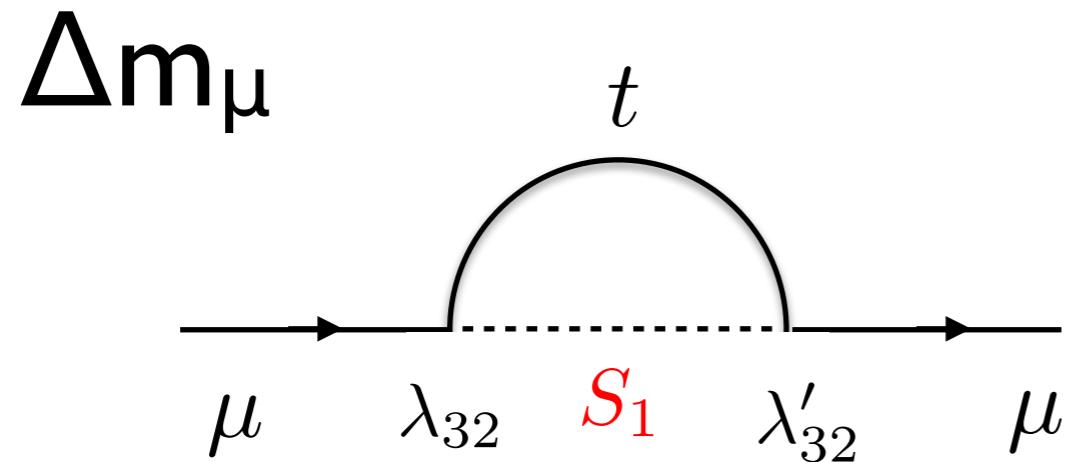


Small electron g-2

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

g-2 and muon mass

-29-

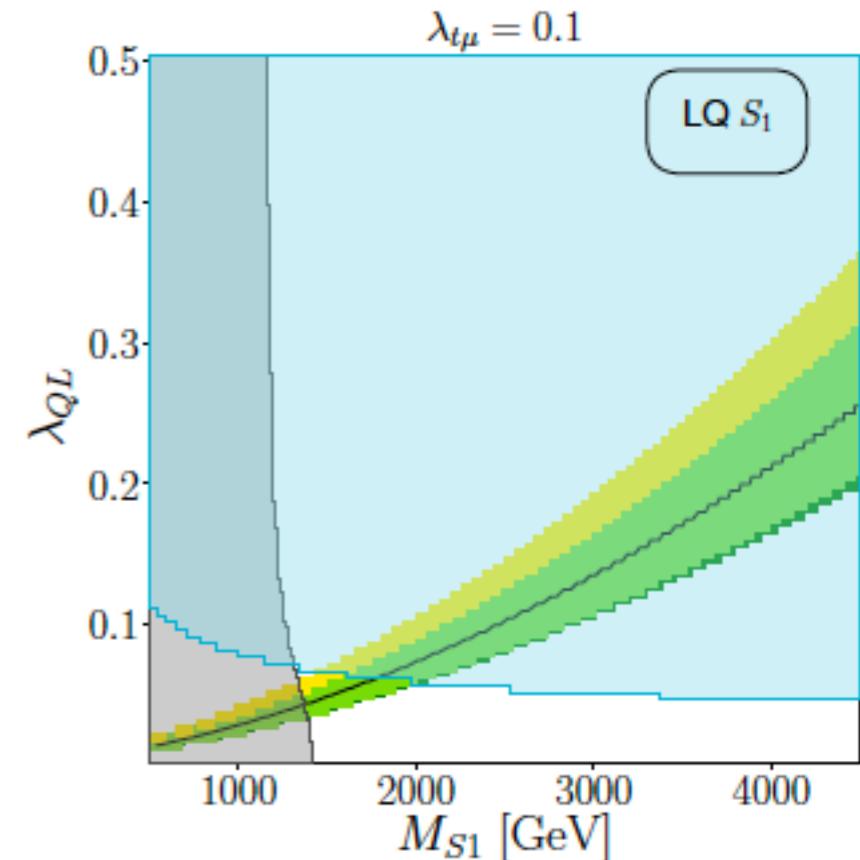


$$\begin{aligned}\Delta m_\mu &\sim \frac{1}{16\pi^2} m_t \lambda_{32} \lambda'^*_ {32} \\ &\sim m_\mu \left(\frac{\Delta a_\mu}{2.5 \times 10^{-9}} \right) \left(\frac{m_{S_1}}{1 \text{ TeV}} \right)^2\end{aligned}$$

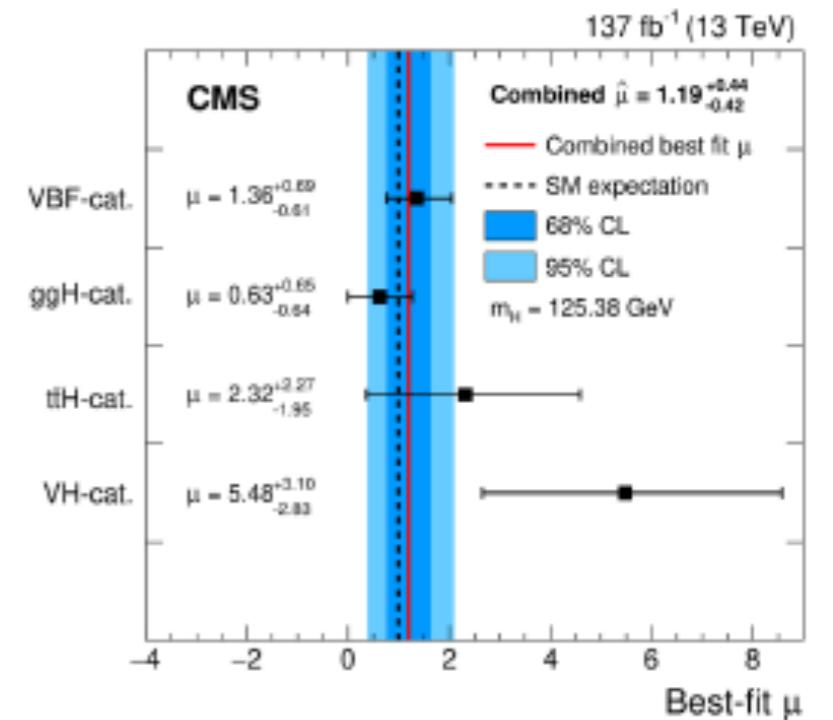
For $m_{S_1} \gtrsim 1 \text{ TeV}$,

tuning is required for muon mass;

Higgs decay into muon pair is modified.



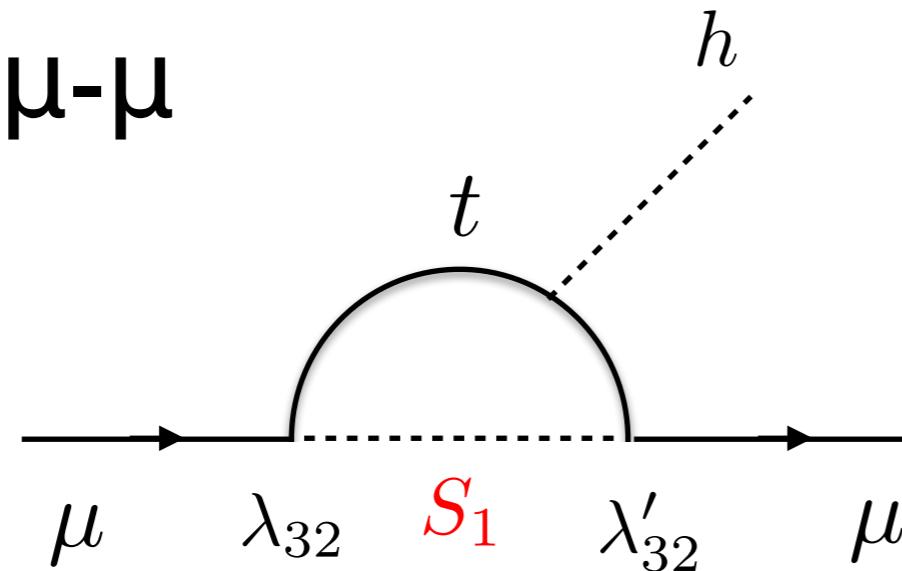
[Athron et al, 2014.03691]



g-2 and other couplings

-30-

$h\text{-}\mu\text{-}\mu$

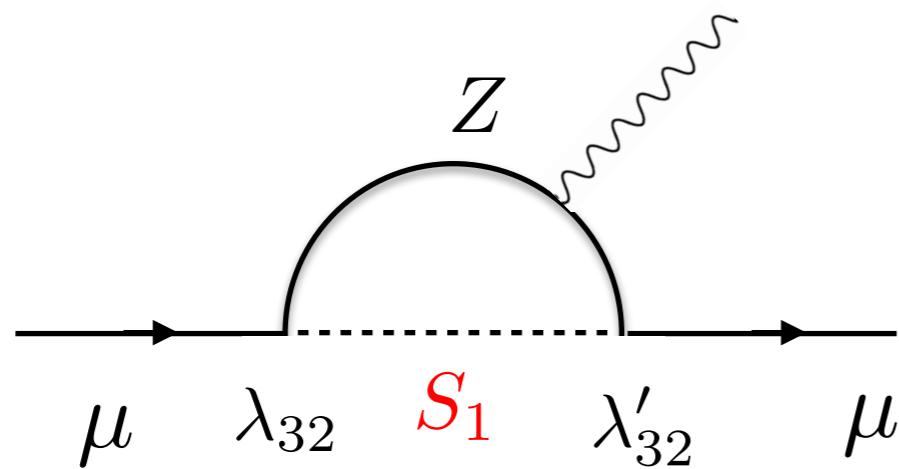


$$\Delta y_\mu \sim \frac{1}{16\pi^2} \frac{m_t^2}{m_{S_1}^2} \lambda_{32} \lambda'^*_{{32}}$$

$$\sim 4 \times 10^{-6} \left(\frac{\Delta a_\mu}{2.5 \times 10^{-9}} \right)$$

: corrections at 1% level.

$Z\text{-}\mu\text{-}\mu$



$$m_Z = (91.1876 \pm 0.0021) \text{ GeV}$$

$$\text{BR}_Z(\mu\bar{\mu}) = (3.3662 \pm 0.0066)\%$$

Dipole operator for Z :

$$\mathcal{L}_{\text{eff}} \supset \frac{g}{16\pi^2} \frac{m_t}{m_{S_1}^2} \bar{\mu} \sigma^{\mu\nu} \mu Z_{\mu\nu}$$

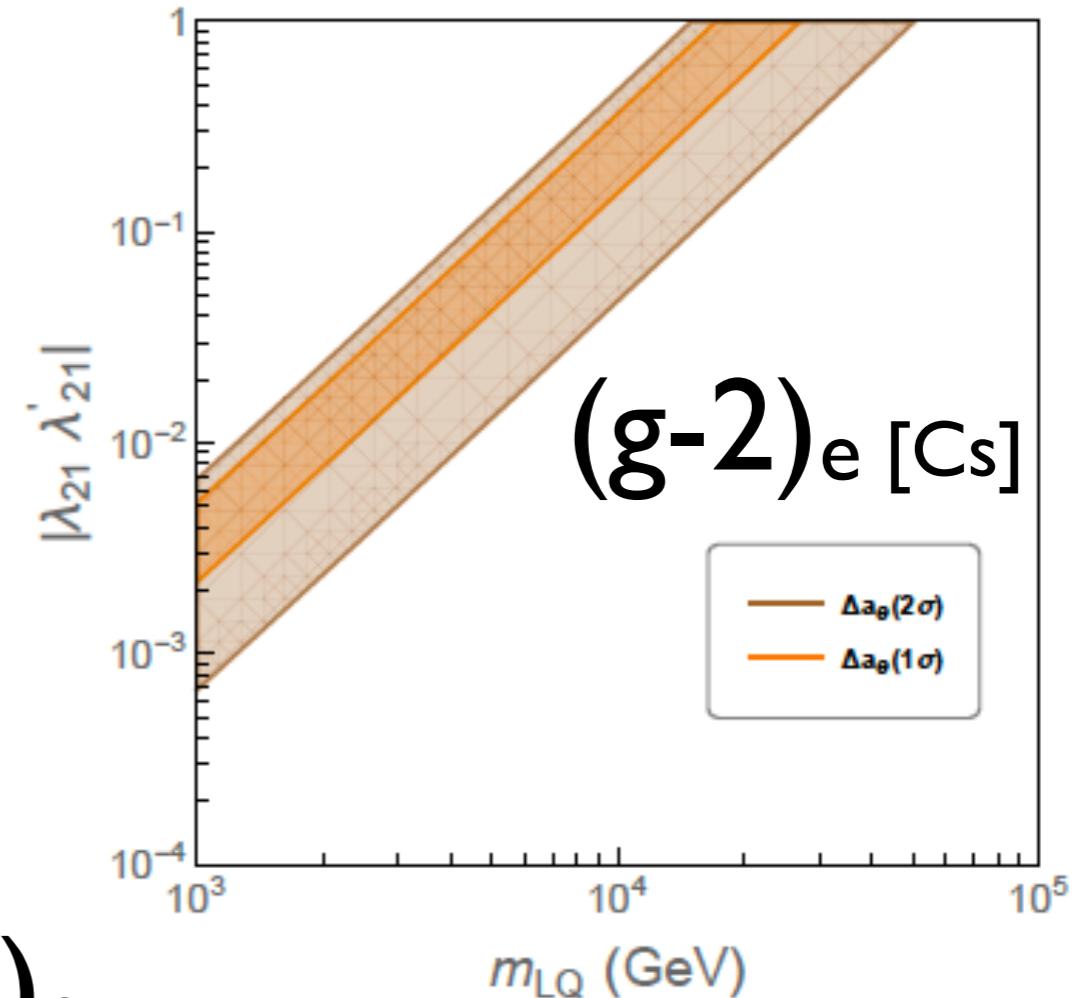
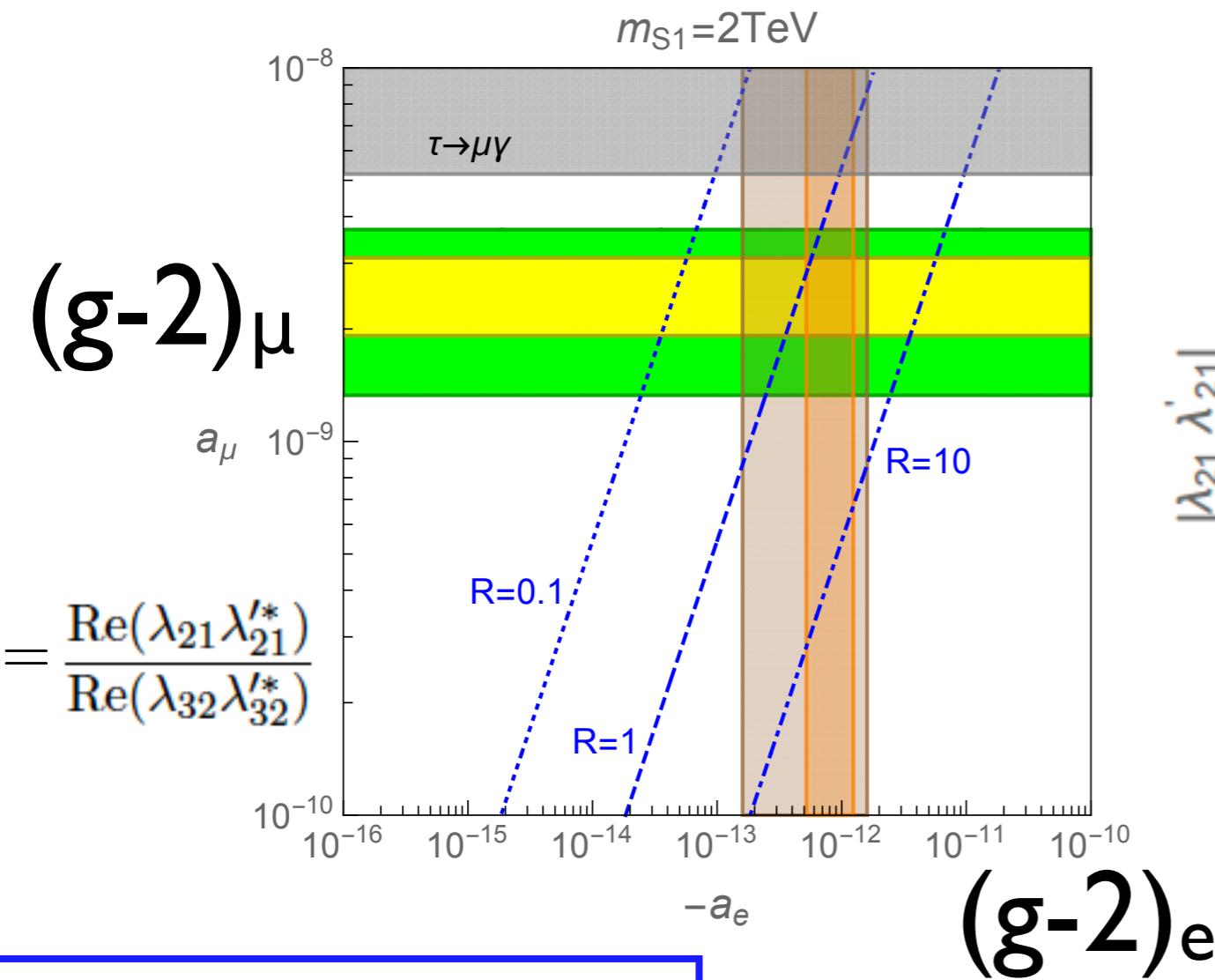
$$\Delta\Gamma_Z \sim \Gamma_Z(\mu\bar{\mu}) \cdot \left(\frac{m_Z}{m_\mu} \Delta a_\mu \right)$$

$$\sim 10^{-4} \text{ MeV}$$

: negligibly small for Z width.

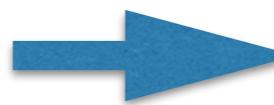
Leptoquark for electron g-2

-31-



Electron g-2 specific:

Charm loops

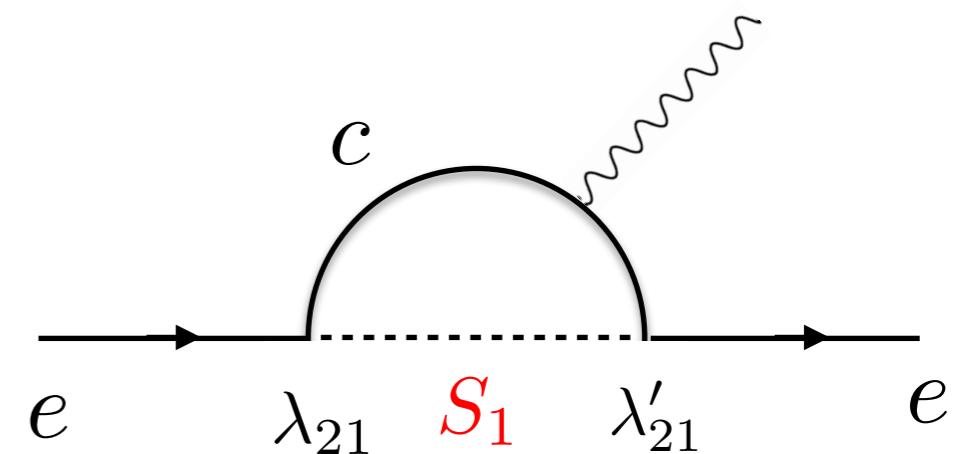


$$\Delta a_e \sim \frac{1}{16\pi^2} \lambda_{21} \lambda'_{21}^* \frac{m_e m_c}{m_{S1}^2}$$

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ \lambda_{21} & 0 & \lambda_{23} \\ 0 & \lambda_{32} & \lambda_{33} \end{pmatrix}, \quad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ \kappa_{21} & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}, \quad \lambda' = \begin{pmatrix} 0 & 0 & 0 \\ \lambda'_{21} & 0 & \lambda'_{23} \\ 0 & \lambda'_{32} & 0 \end{pmatrix}$$

[HML, 2021]

Safe from $\mu \rightarrow e\gamma$



Neutrino masses

-32-

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.

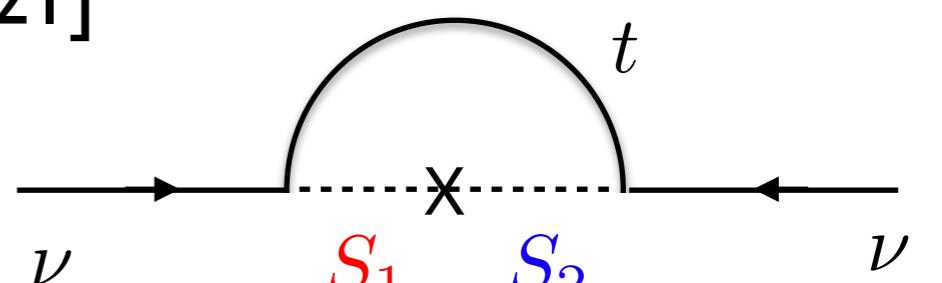
$$\mathcal{L}_{S_2} = -\tilde{\lambda}_{ij} \bar{d}_{Ri} l_{Lj} S_2 - \mu \tilde{H} S_2 S_1 + \text{h.c.} \quad [\text{HML, 2021}]$$

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

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



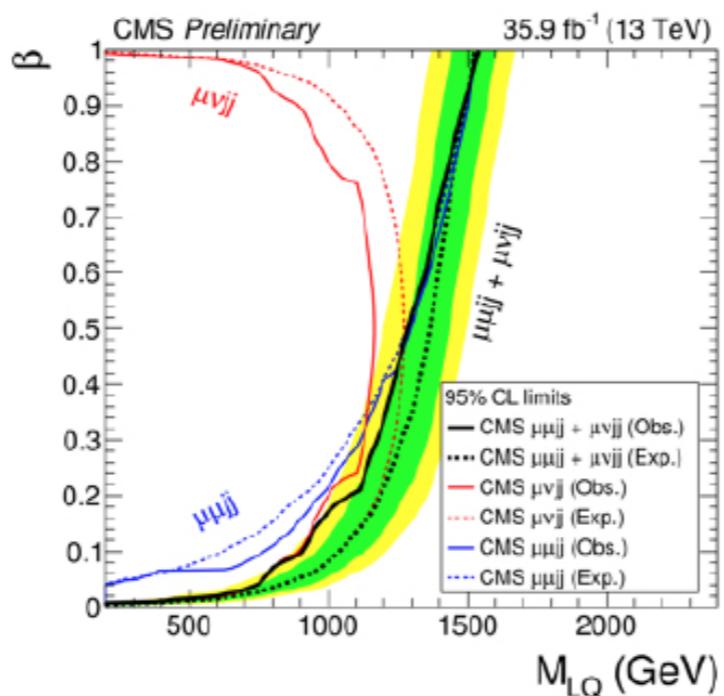
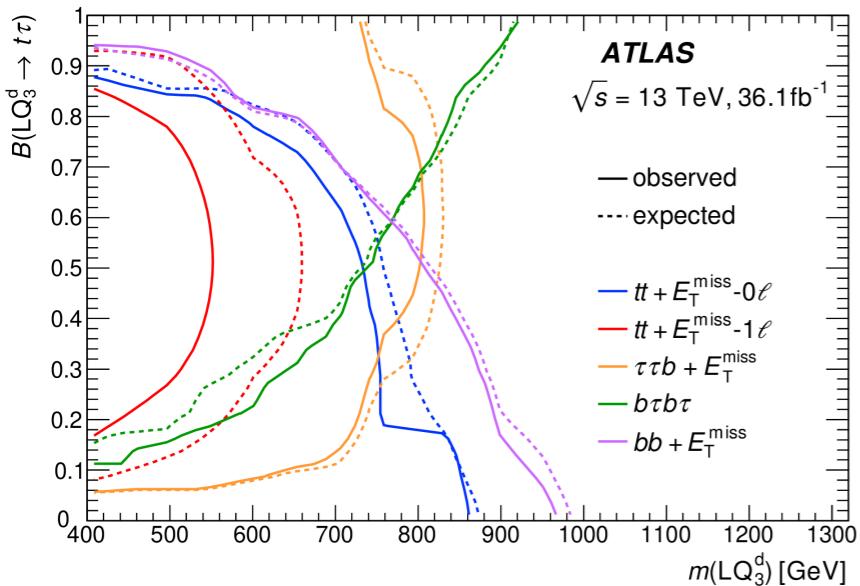
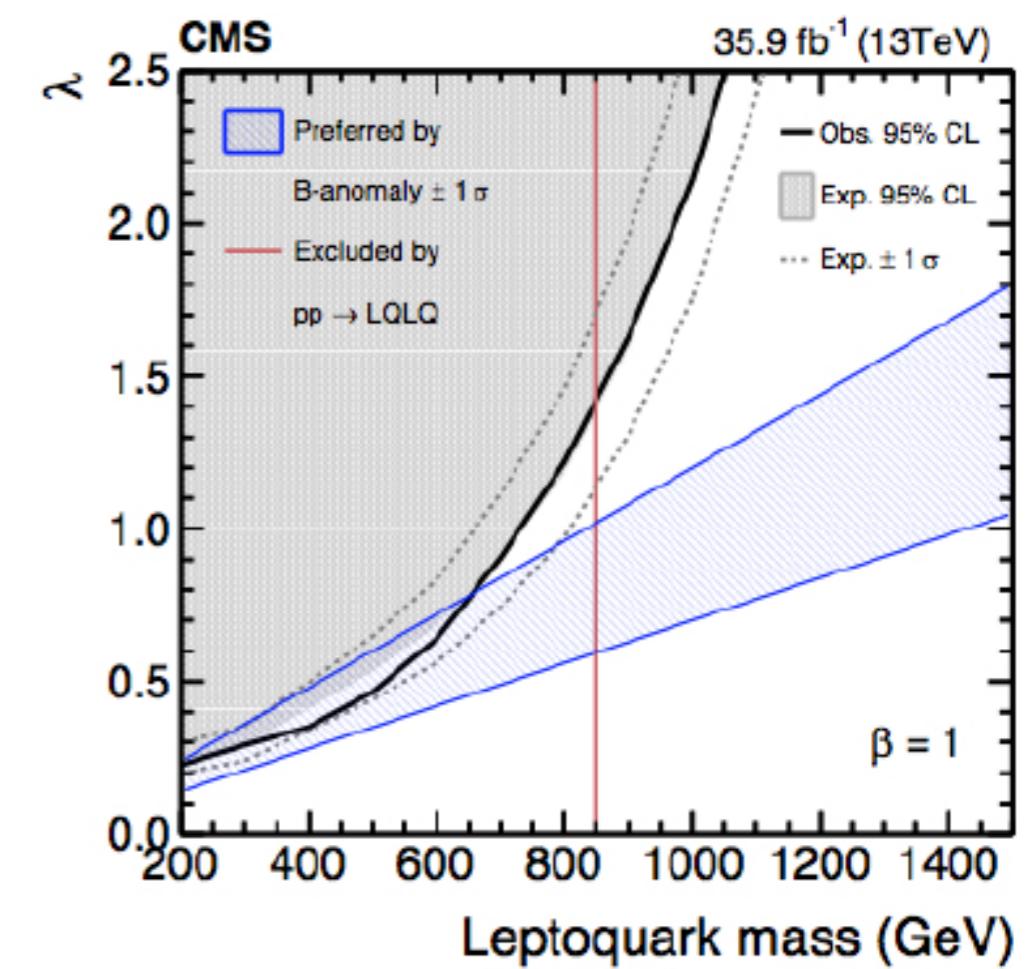
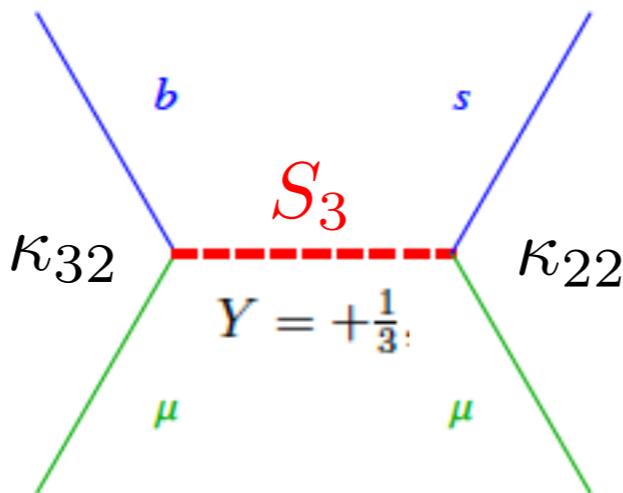
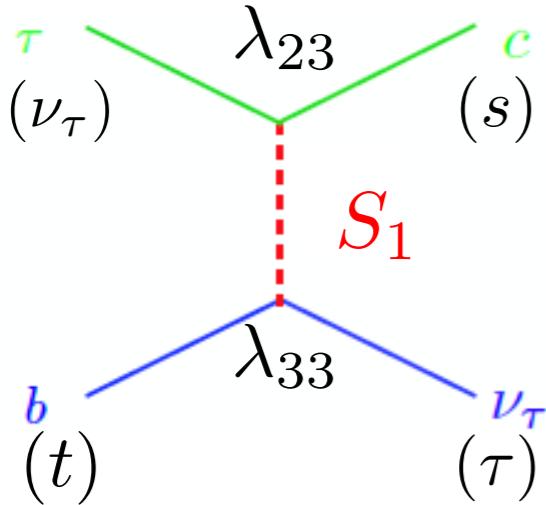
$$\max(|\lambda_{3i} \tilde{\lambda}_{3i}^*|) < 10^{-9} \left(\frac{v}{\mu}\right) \left(\frac{m_{S_1}}{1 \text{ TeV}}\right)^2$$



cf. RPV SUSY

Hunting leptoquarks

-33-



[Choi, Kang, HML, Ro, 2018]

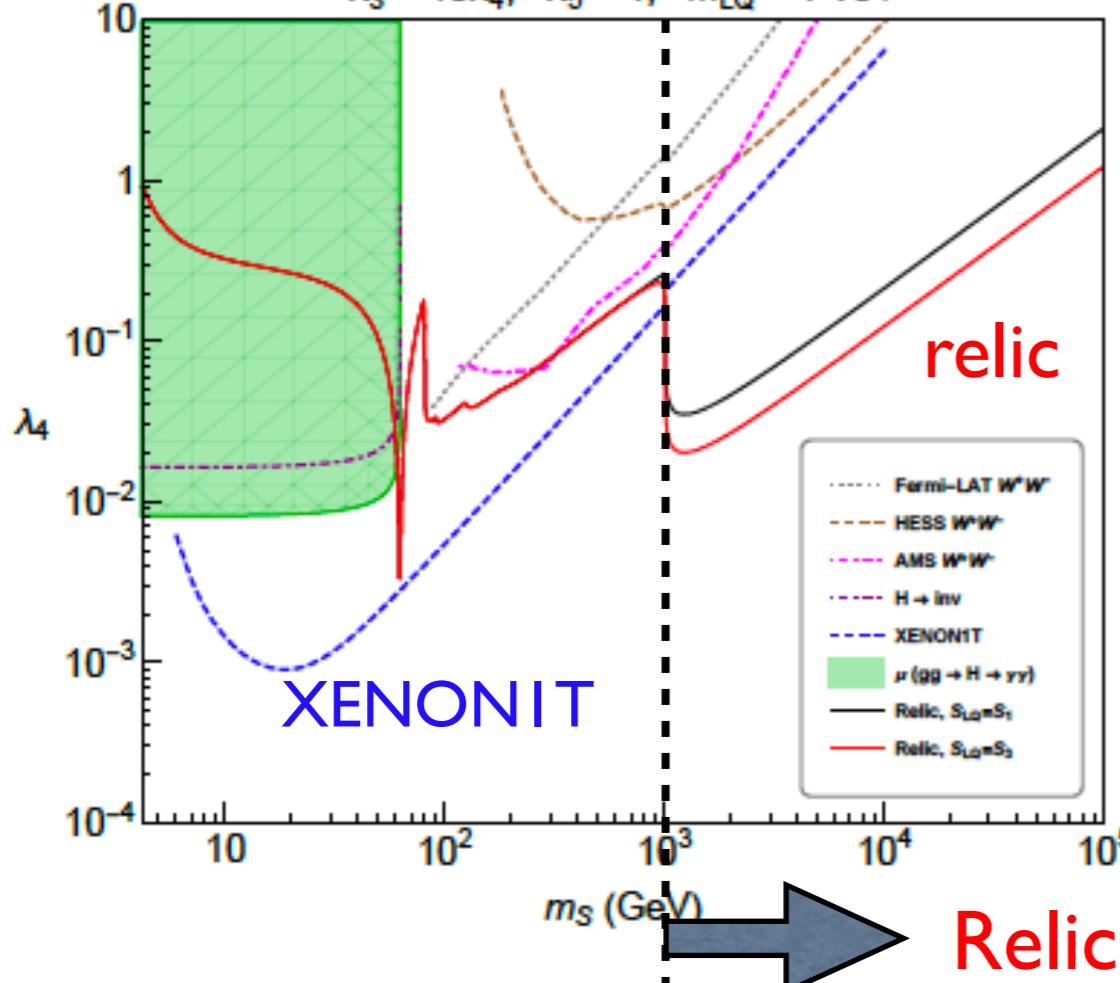
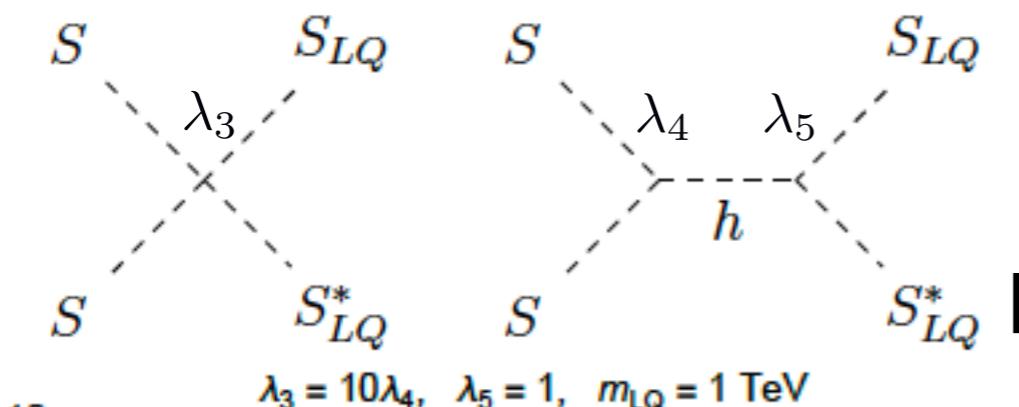
LQs	BRs	$m_{LQ,\text{min}}$	BRs	$m_{LQ,\text{min}}$
S_1	$B(\bar{t}\bar{\tau}/b\nu_\tau) = \frac{1}{2}\beta$	1.22 TeV($b\nu_\tau$) [32]	$B(\bar{c}\bar{\tau}/s\nu_\tau) = \frac{1}{2}(1 - \beta)$	950 GeV($\nu_\tau j$) [33]
$S_3(\phi_1)$	$B(\bar{b}\bar{\mu}) = \gamma$	1.4 TeV [34]	$B(\bar{s}\bar{\mu}) = 1 - \gamma$	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”

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

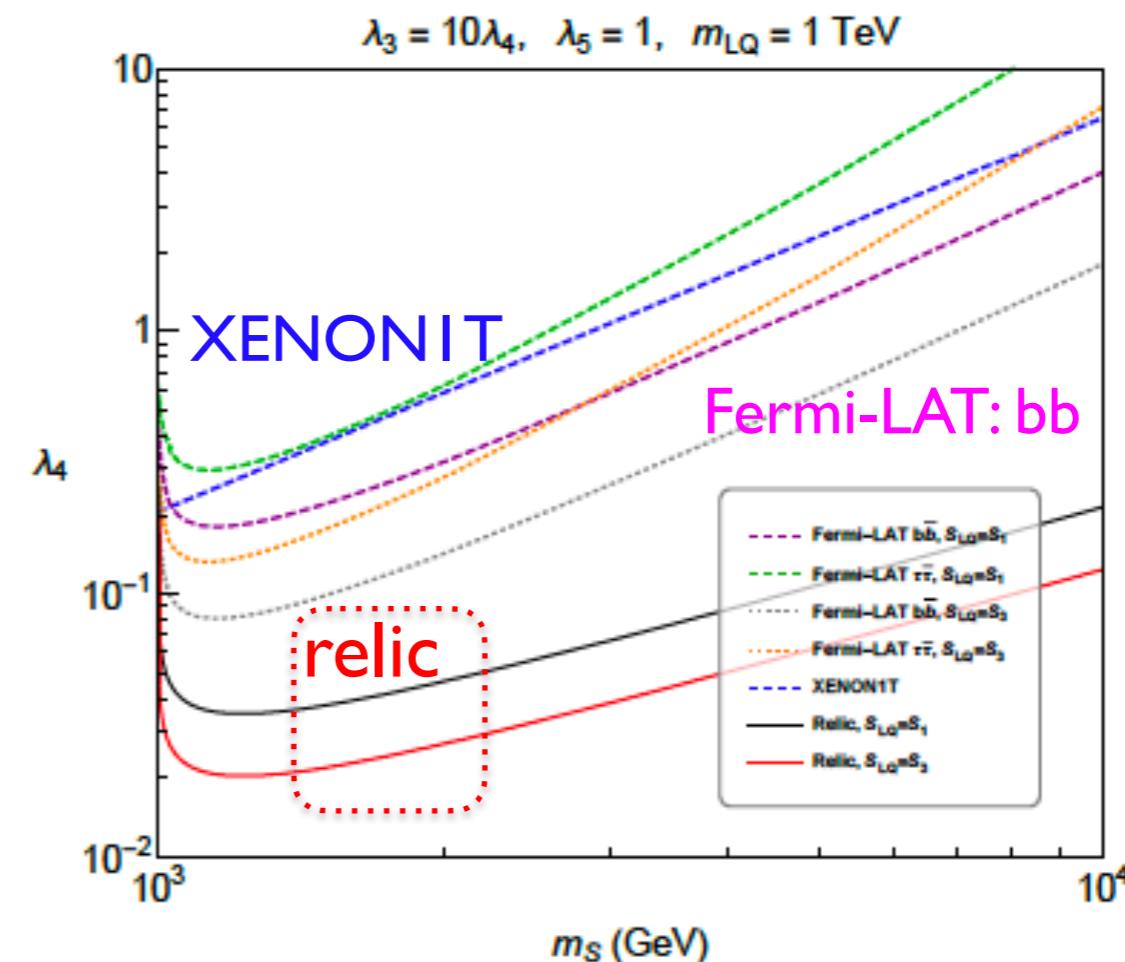
$$\gamma \equiv \kappa_{32}^2 / (\kappa_{32}^2 + \kappa_{22}^2)$$

Leptoquark portals



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

- Existing anomalies in muon g-2 and leptonic signatures such as LFV decays/EDM might be related to B-meson anomalies.
- 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.
- 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.