ON FLAVOR ANOMALIES

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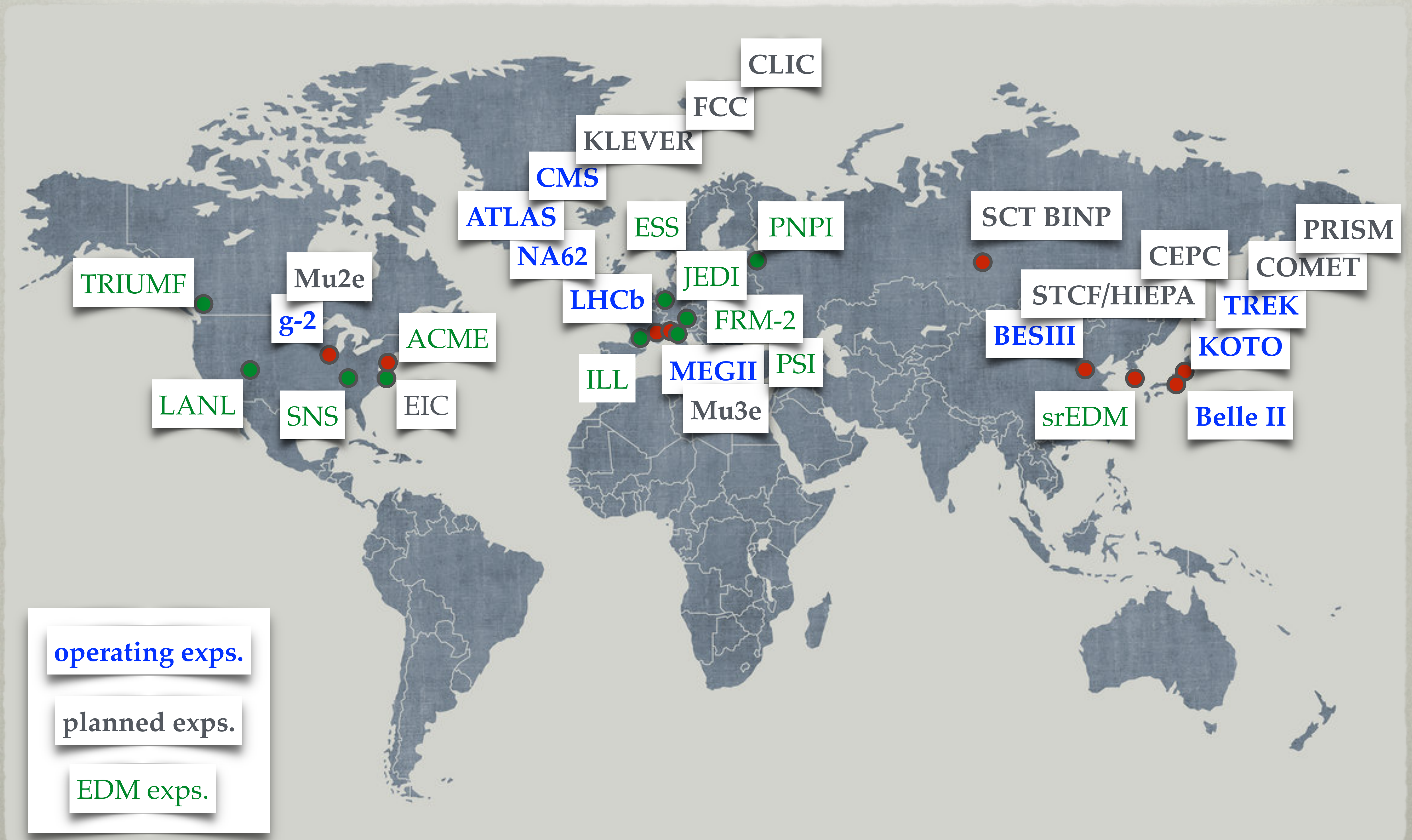
LFC21, ECT-Trento (virtual), Sept 10 2021

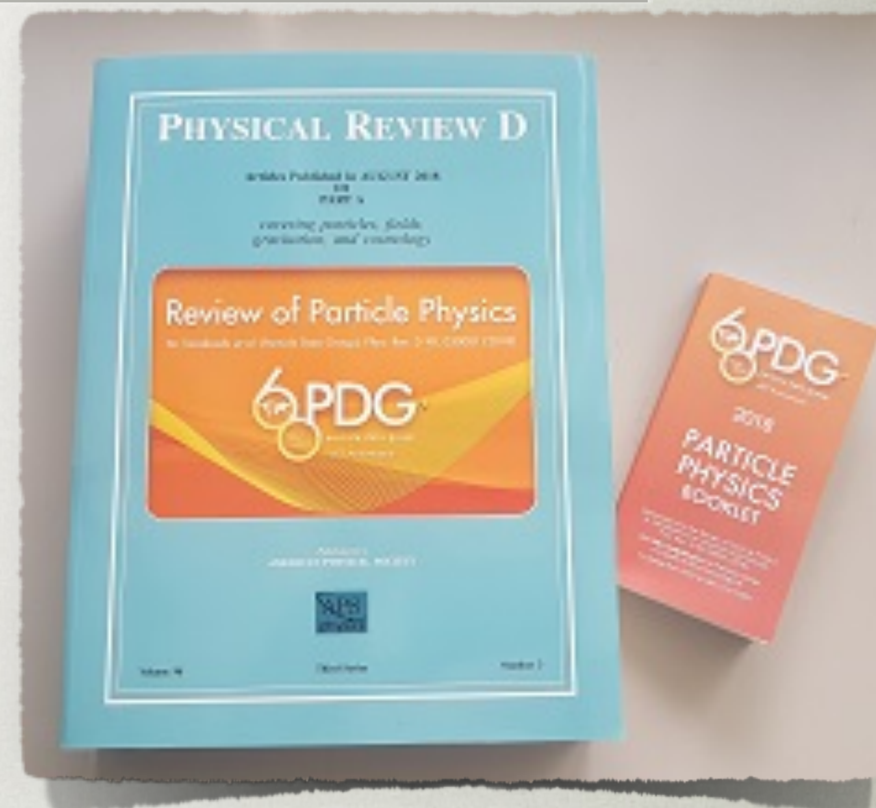
FLAVOR PHYSICS IN ONE SLIDE

- baryon asymmetry implies more CP violation than in the SM
- flavor measurements a way to probe such required new CPV sectors
    - high energy scales and/or small couplings
- probe also other puzzles: dark matter, strong CP problem,...

MANY EXPERIMENTS...



MANY MEASUREMENTS...



- PDG lists $\mathcal{O}(10^4)$ observables
  - branching ratios, angular distributions, CP violating asymmetries, ...
- focus of this talk:
  - hints of experimental deviations from the SM predictions
  - a sign of new physics?

OUTLINE

- flavor physics as a tool to search for new physics
  - heavy new physics → off shell modes
  - light new physics → rare decays to light NP states
- experimental anomalies
  - $(g-2)_\mu$, $b \to s\mu^+\mu^-$, $b \to c\tau\nu$
  - if NP, what are it's properties (heavy/light,...)?
- what next?
  - Belle II, LHCb upgrade, etc

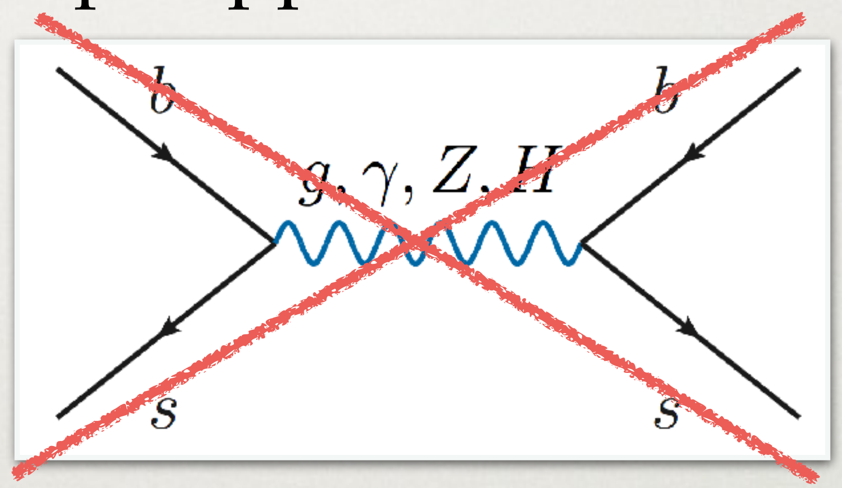
PROBING HEAVY NEW PHYSICS

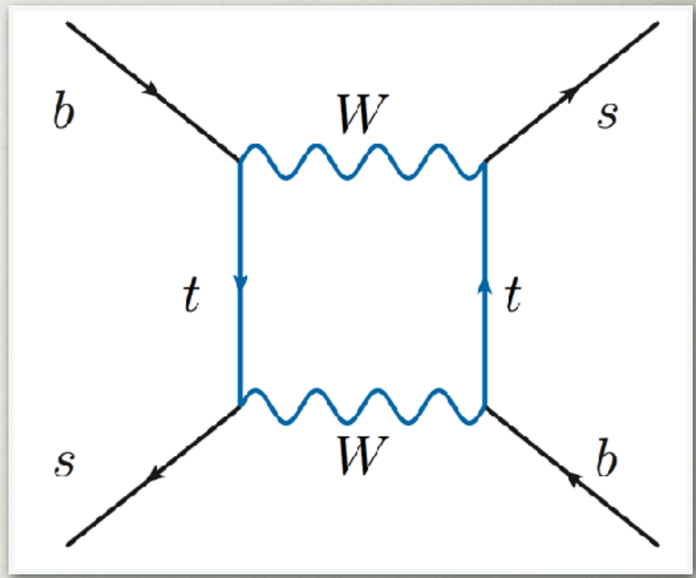
FROM FLAVOR PHYSICS TO HEAVY NEW PHYSICS

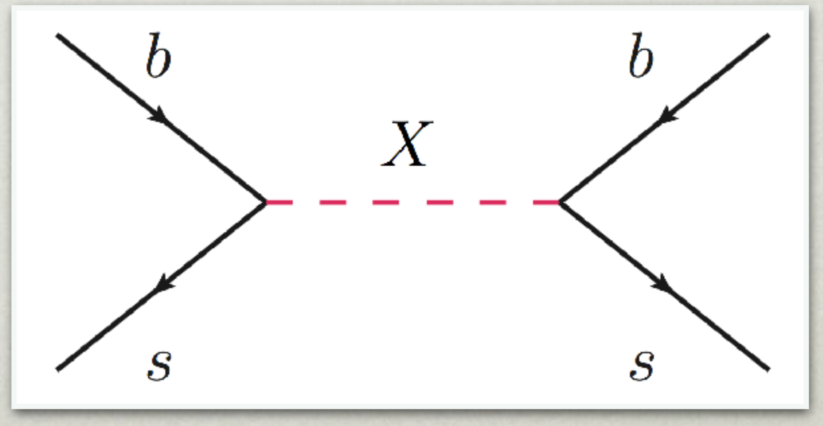
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

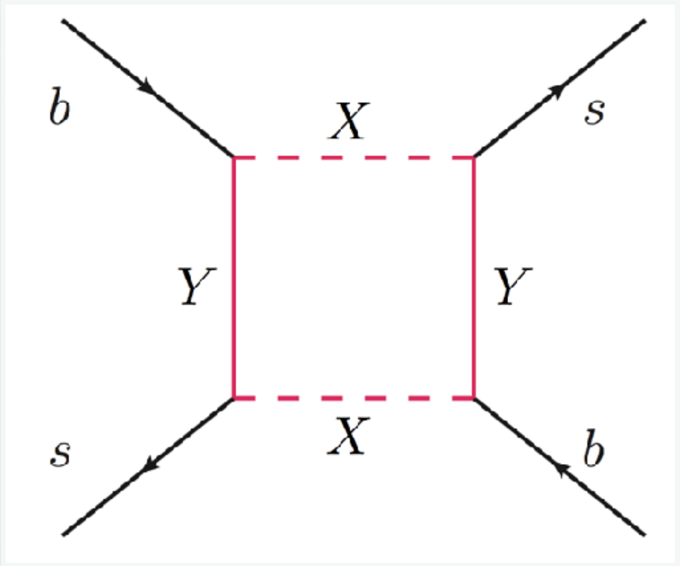
$$\delta C^{\rm NP} \propto \frac{g_{sb}^2}{M_{\rm NP}^2}$$

- depends on couplings and NP masses



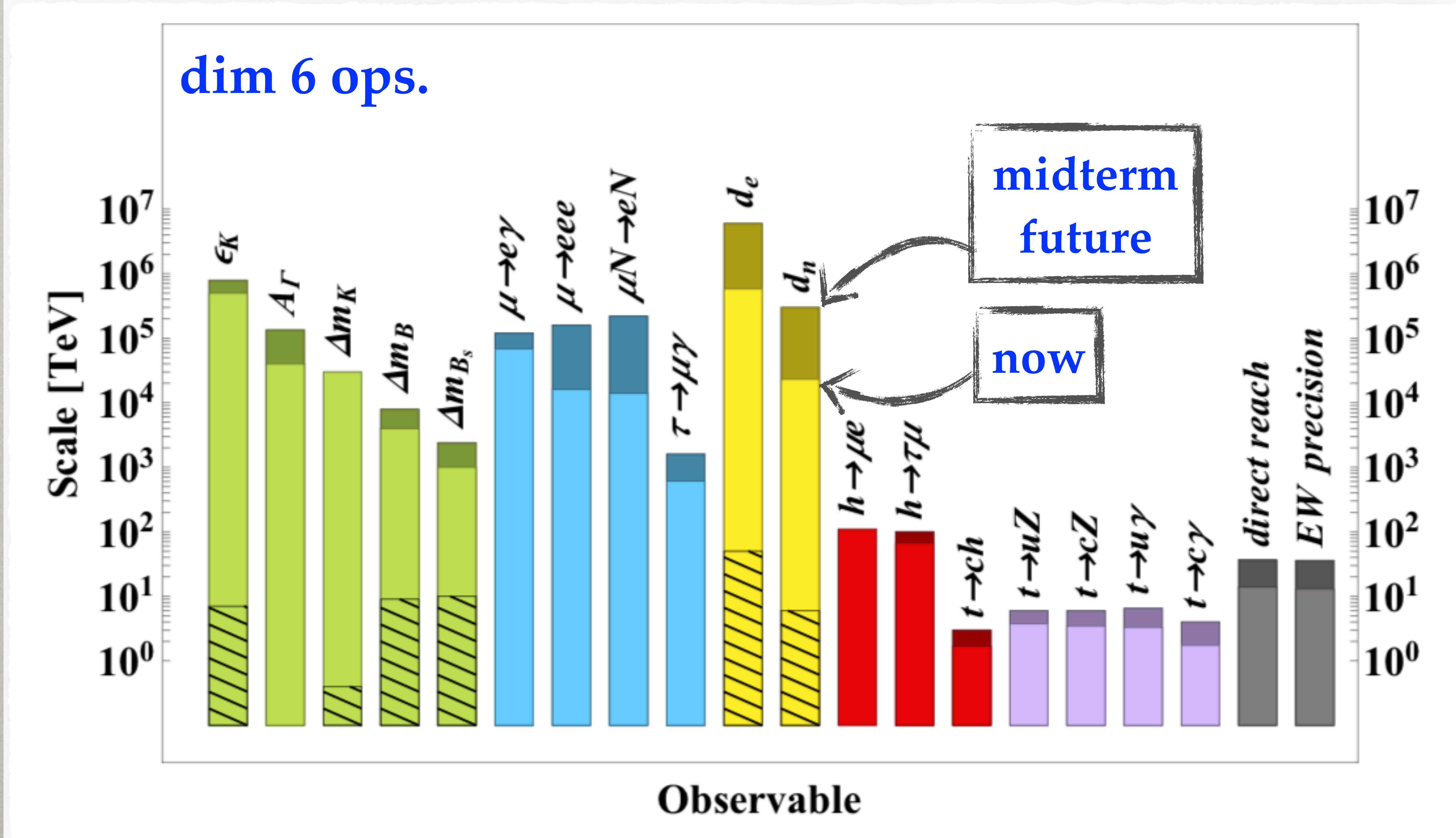






LARGE SCALES PROBED

Physics Briefing Book, 1910.11775

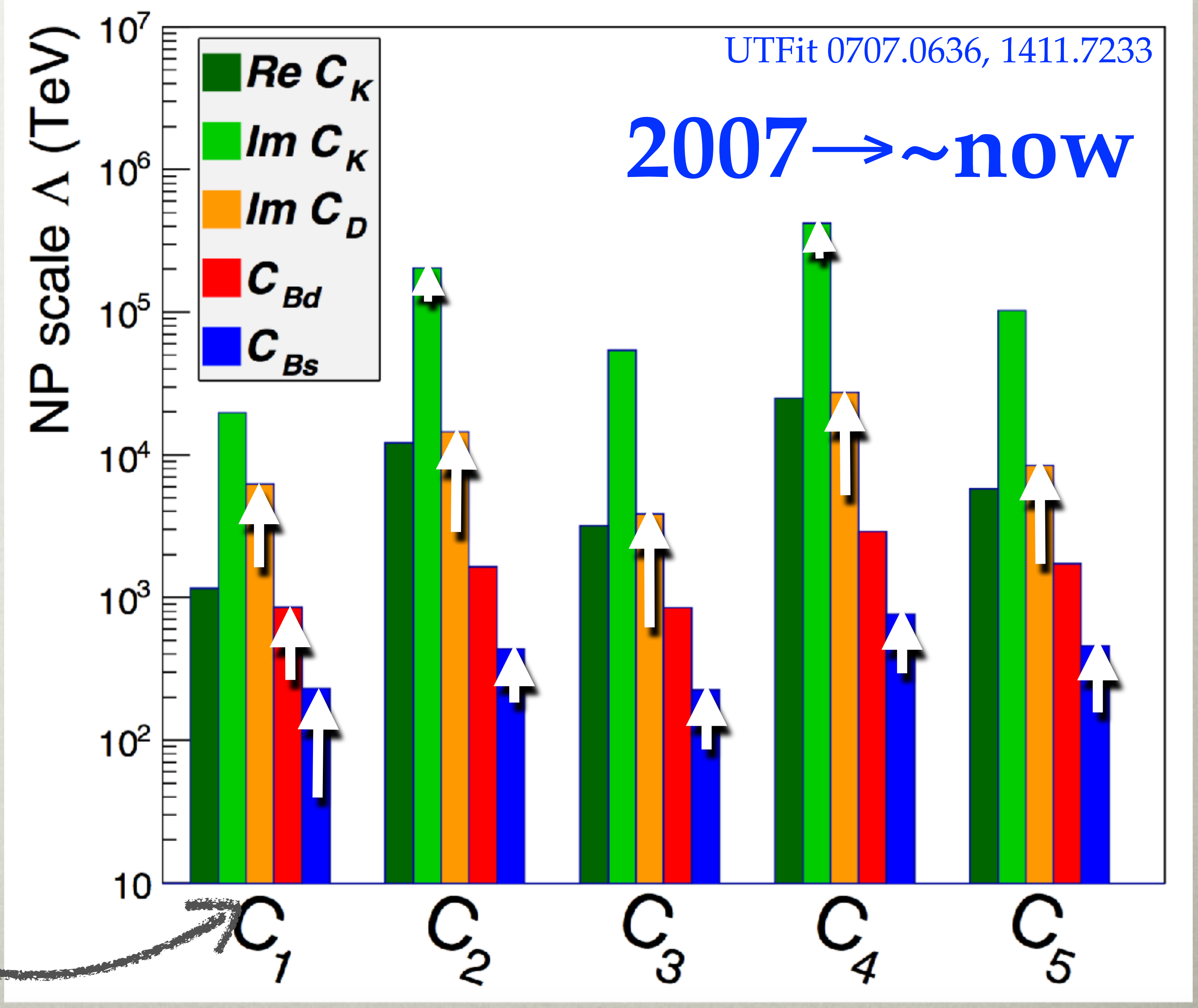


LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing ($c\bar{u}$, $\bar{b}s$)
- also from ε_K ($\bar{d}s$)

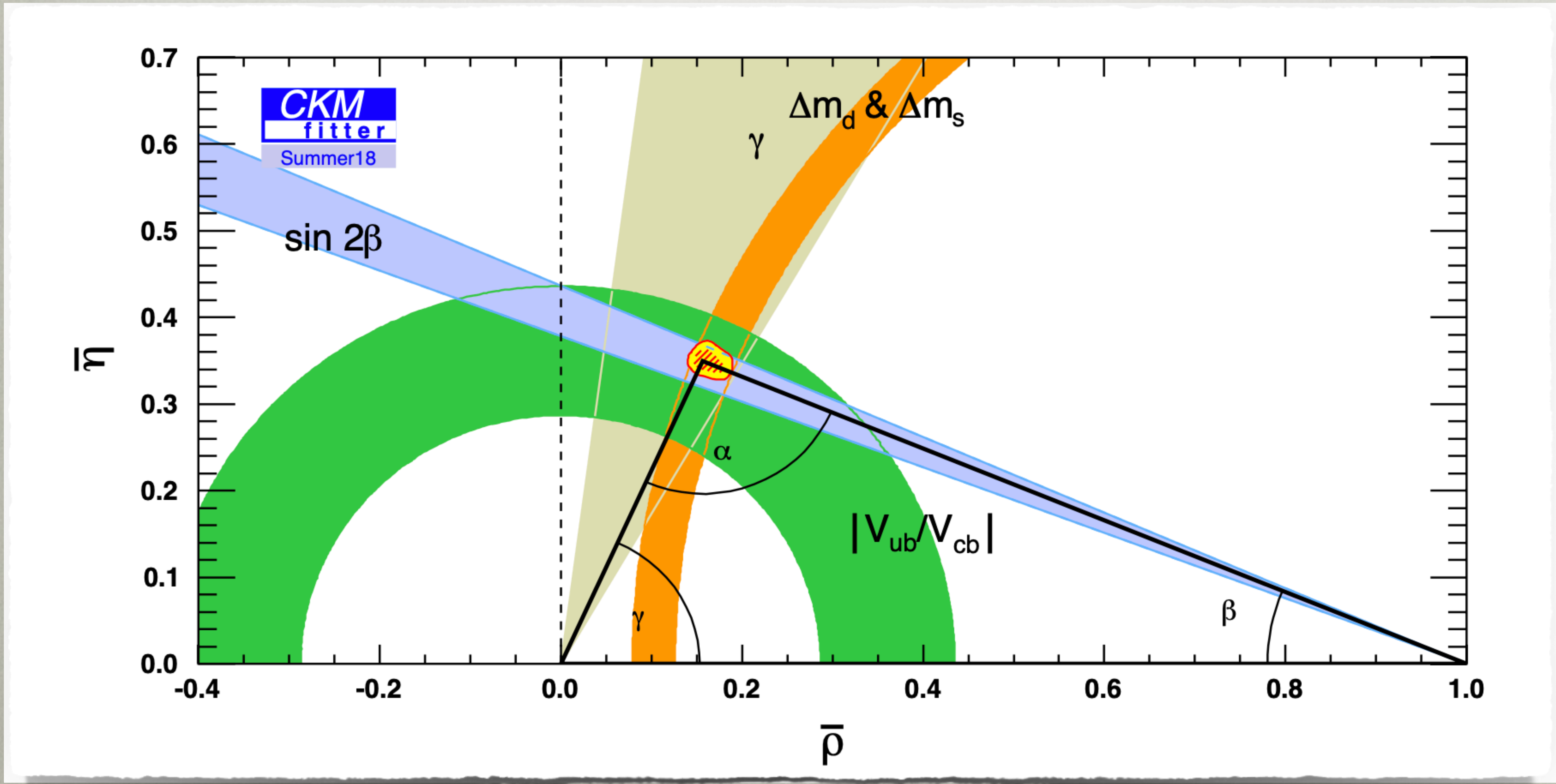
$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



THE (MID-TERM) FUTURE

Physics Briefing Book, 1910.11775

- just from LHCb:



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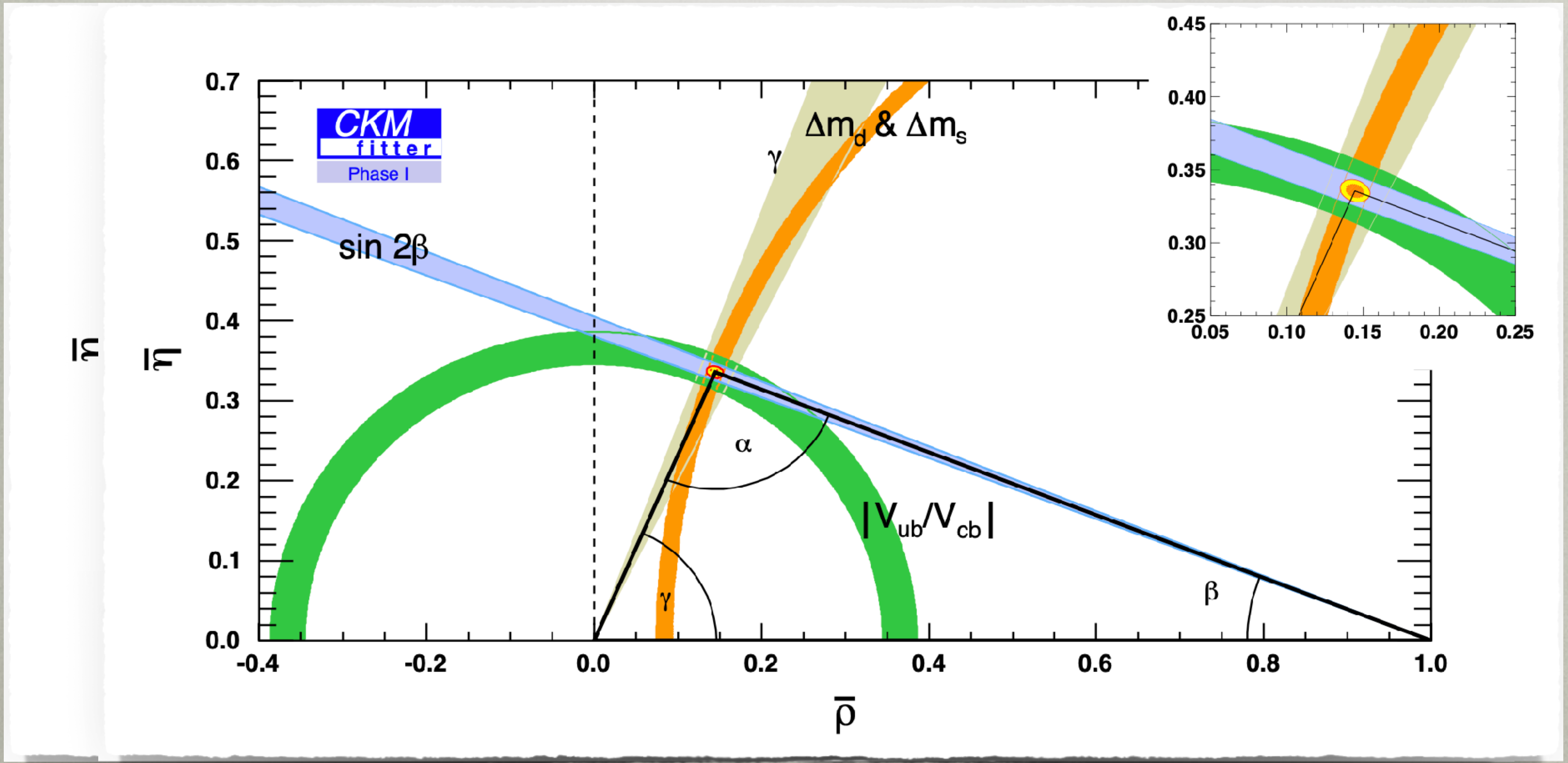

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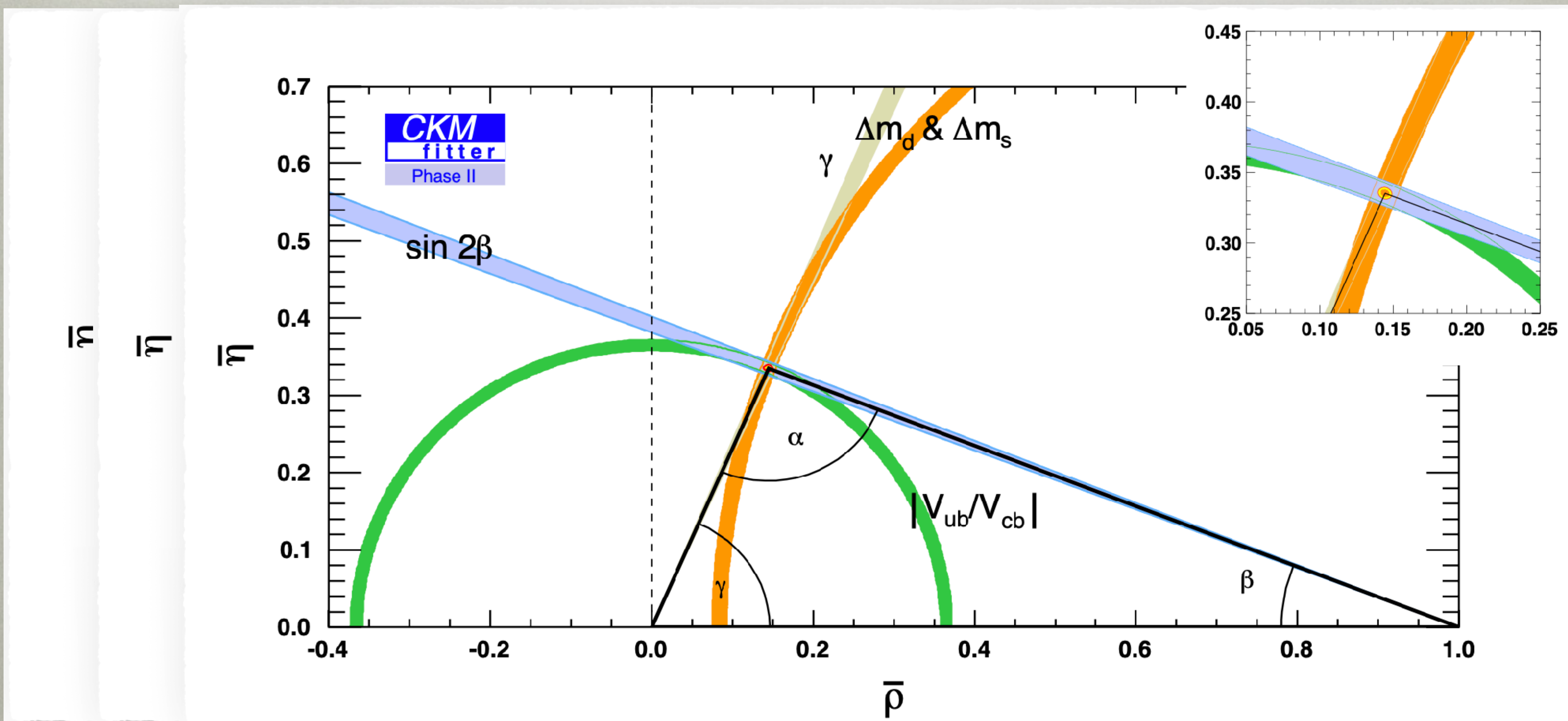
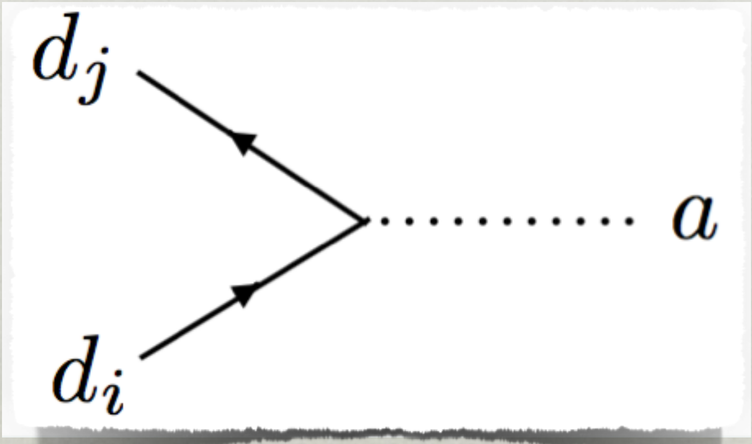


PROBING
LIGHT NEW PHYSICS

SEARCHING FOR LIGHT NEW PHYSICS

- if NP particle is light, can be produced on shell
- search for rare decays $q_j \to q_i + X_{\rm NP}$, $\ell_j \to \ell_i + X_{\rm NP}$



FLAVOR VIOLATING PNGBs

- if NP has a spontaneously broken global U(1) ⇒ light (pseudo)Nambu-Goldsone boson
  - interactions with the SM start at dim 5

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

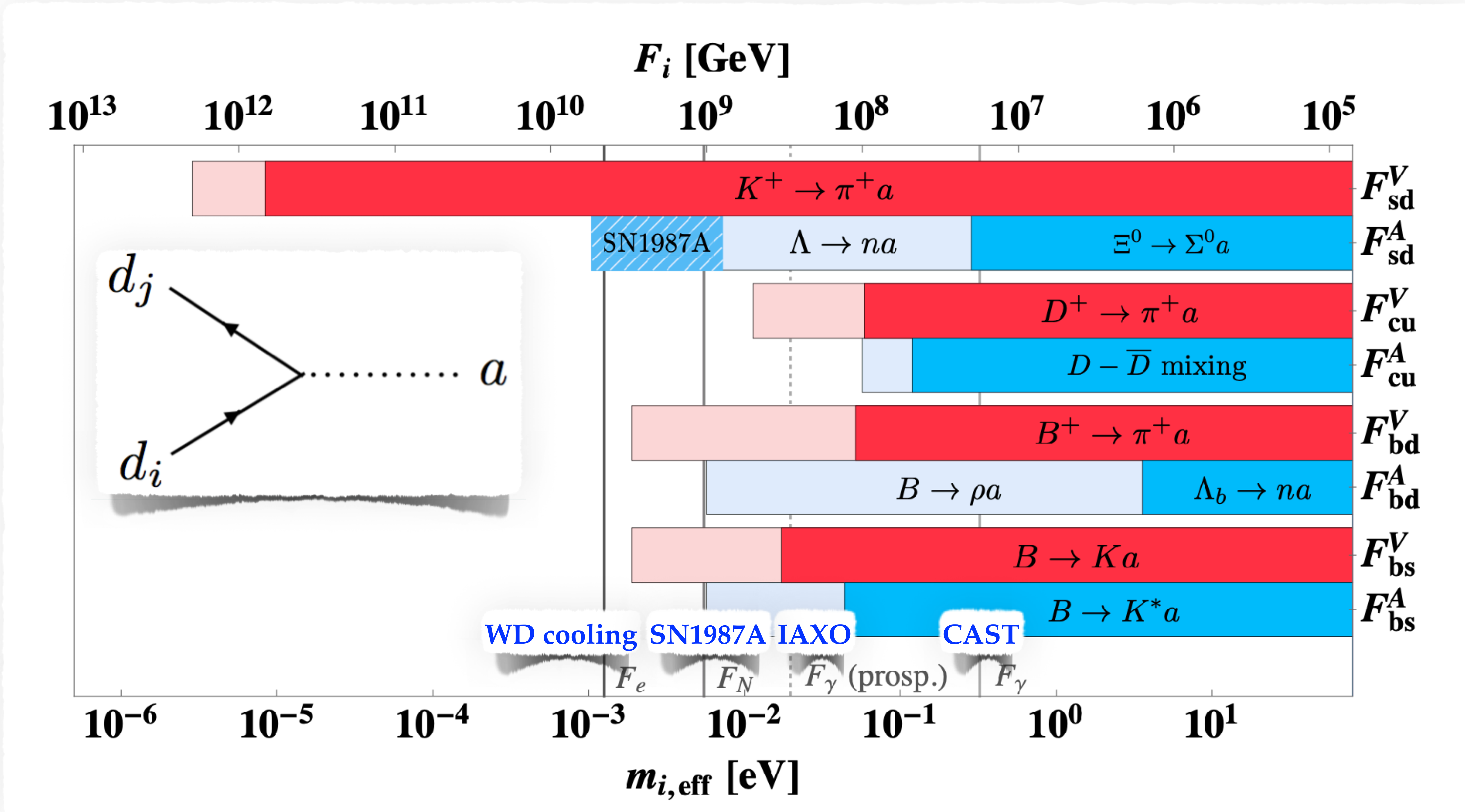
- in general the couplings can be flavor violating
  - since dim 5, FCNCs probe very high scales
  - even above astrophysics bounds

$$F^{V,A}_{f_if_j} \equiv \frac{2f_a}{c^{V,A}_{f_if_j}}$$

- concrete examples: FV QCD axion, axiflavon, majoron,...

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

Bounds on flavor violating QCD axion



EXPERIMENTAL ANOMALIES

EXPERIMENTAL ANOMALIES IN PROCESSES WITH MUONS&TAUS

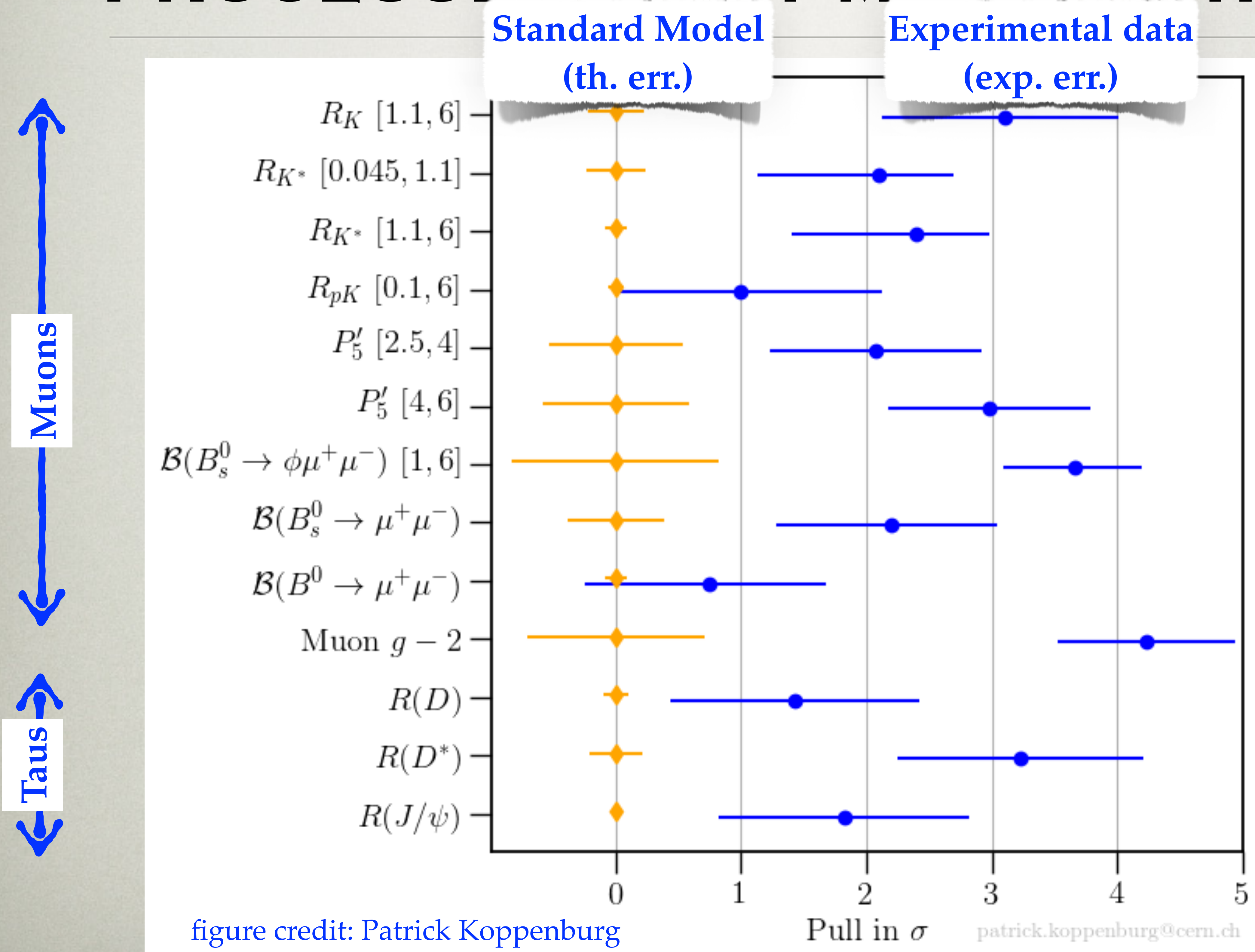


figure credit: Patrick Koppenburg

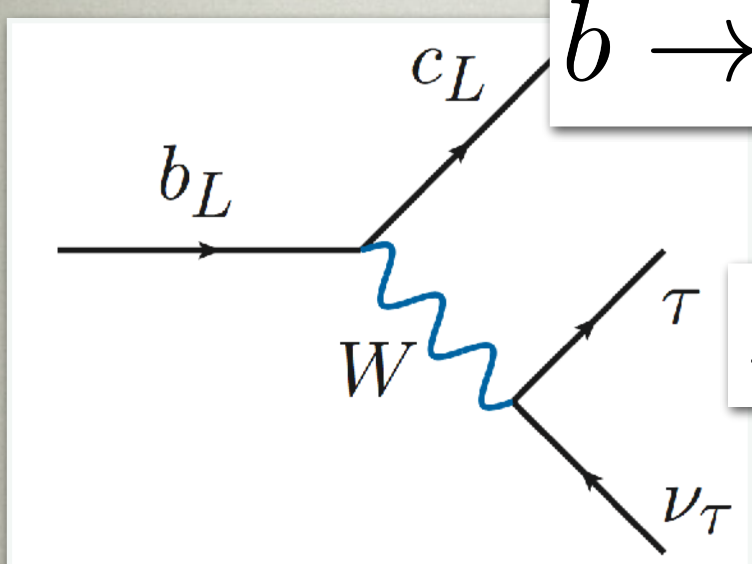
NEWS FROM EARLIER THIS YEAR

- theoretically "clean" observables
  - R_K went from 2.5σ to 3.1σ — LHCb 1903.09252, 2103.11769
    - the first single measurement in B anomalies to cross the "evidence" threshold
  - $\lesssim 2\sigma$ tension in $B_s \to \mu^+\mu^-$ — LHCb 2108.09284, 2108.09283
- theoretically "dirty" observables
  - $(g-2)_\mu$ went from 3.7σ to 4.2σ — The Muon g−2 Collaboration, 2104.03281
  - $Br(B_s \to \phi\mu\mu)$ 3.6σ below the nominal SM prediction — LHCb 2105.14007

IF NEW PHYSICS...

- the two quark level transitions that show ~4σ deviations from the SM
  - explanable with NP in $V - A$ quark currents

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

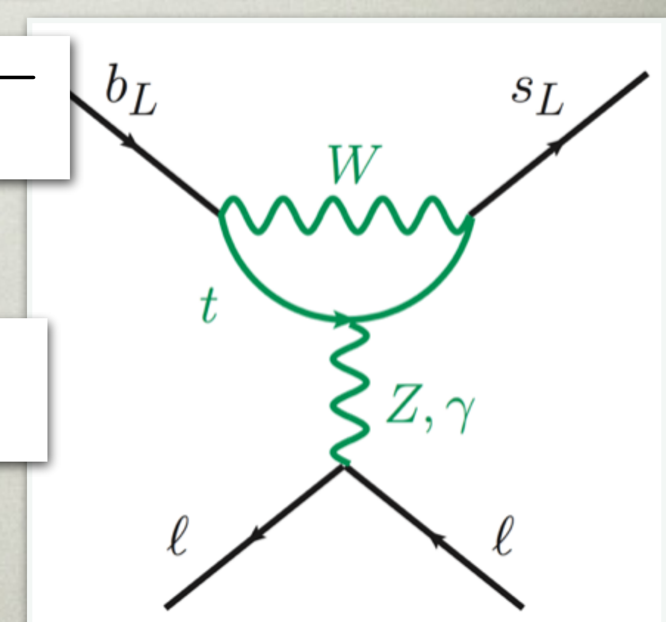


$$b \to c\tau\nu$$

$$\Lambda_{\rm NP} \sim 3 \text{ TeV}$$

$$b \to s\mu^+\mu^-$$

$$\Lambda_{\rm NP} \sim 40 \text{ TeV}$$



IF NEW PHYSICS...

- $(g-2)_\mu$ showing 4.2σ deviation from the SM
  - in SMEFT from dim6 operator

$$\mathcal{L} \supset -\frac{\sqrt{2} e\, v}{(4\pi\Lambda_{ij})^2} \bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu} + \text{h.c.} \,,$$

$$(g-2)_\mu \Rightarrow \Lambda_{22} \sim 15\,\text{TeV}$$

Greljo, Stangl, Thomsen, 2103.13991

- note: any flavor violation needs to be highly suppressed

$$\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$$

OUTLINE FOR THE REST OF THE TALK...

- overview of anomalies
  - exp+attempted explanations
    - $(g-2)_\mu$
    - $b \to s\mu\mu$
    - $b \to c\tau\nu$
- grand picture?

$(g-2)_\mu$

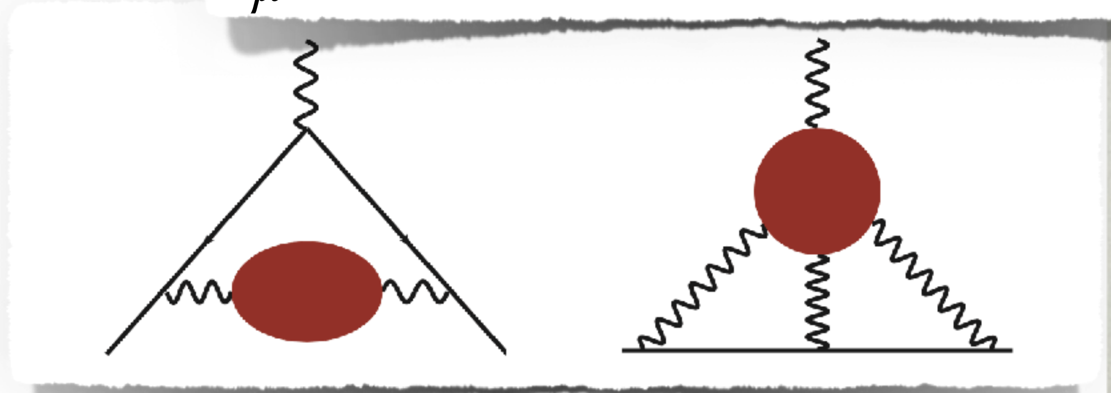
A DEVIATION?

- the value of $(g-2)_\mu$ from g-2 coll.

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

- the SM theory error dominated by hadronic uncert.

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

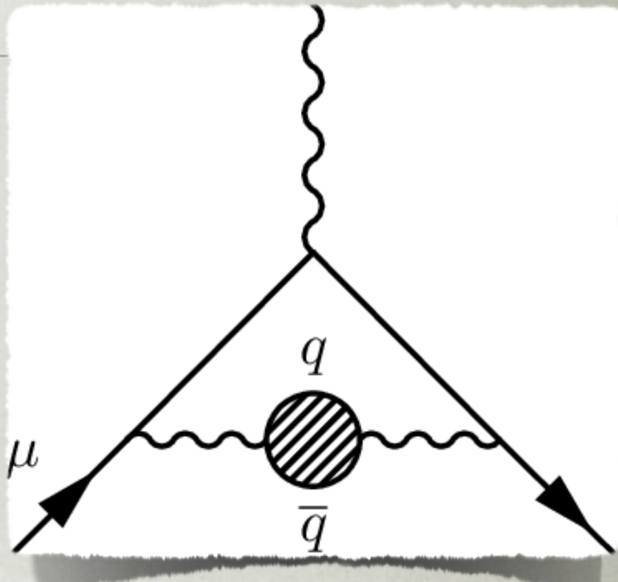


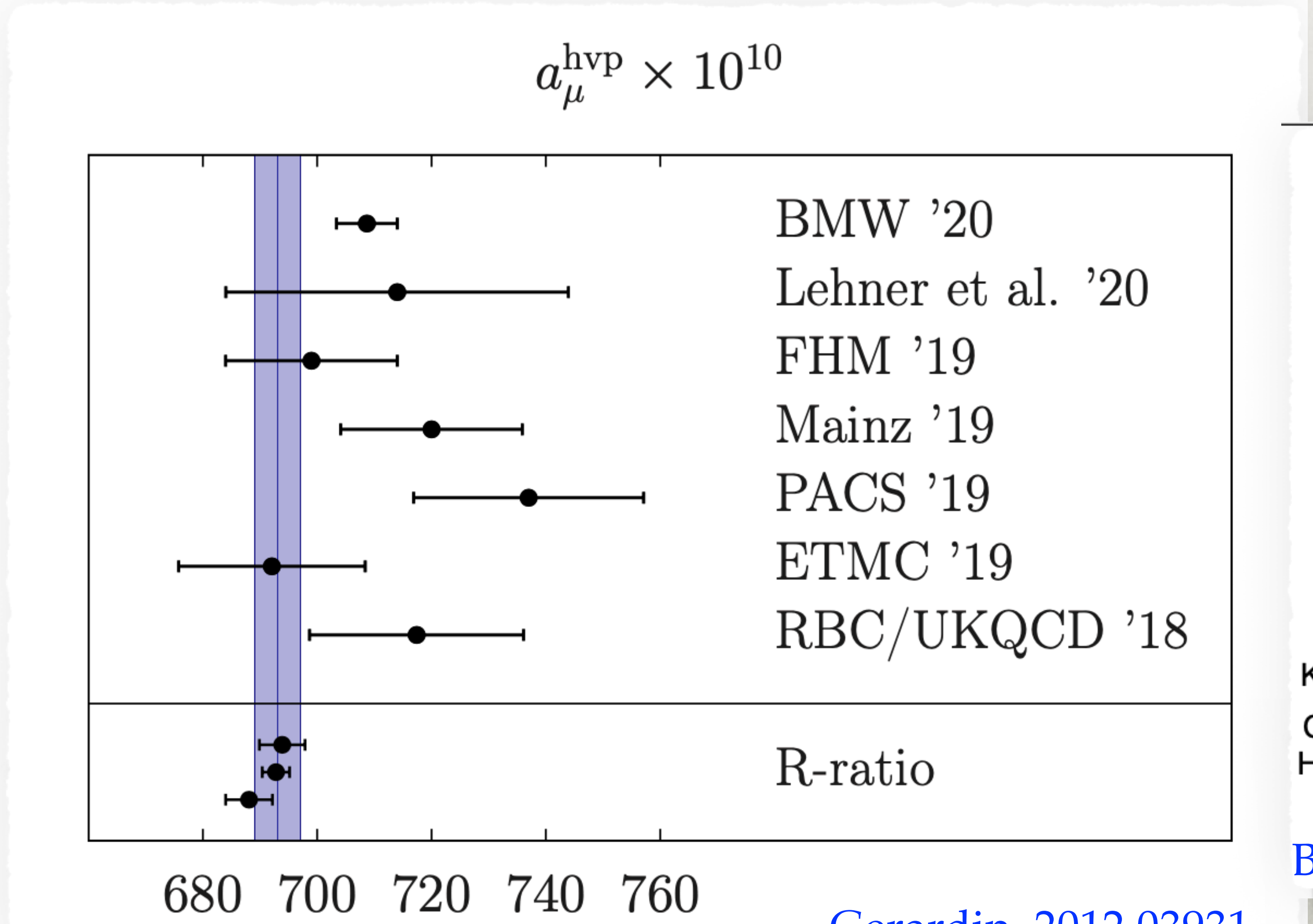
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)

The muon g-2 theory initiative, 2006.04822

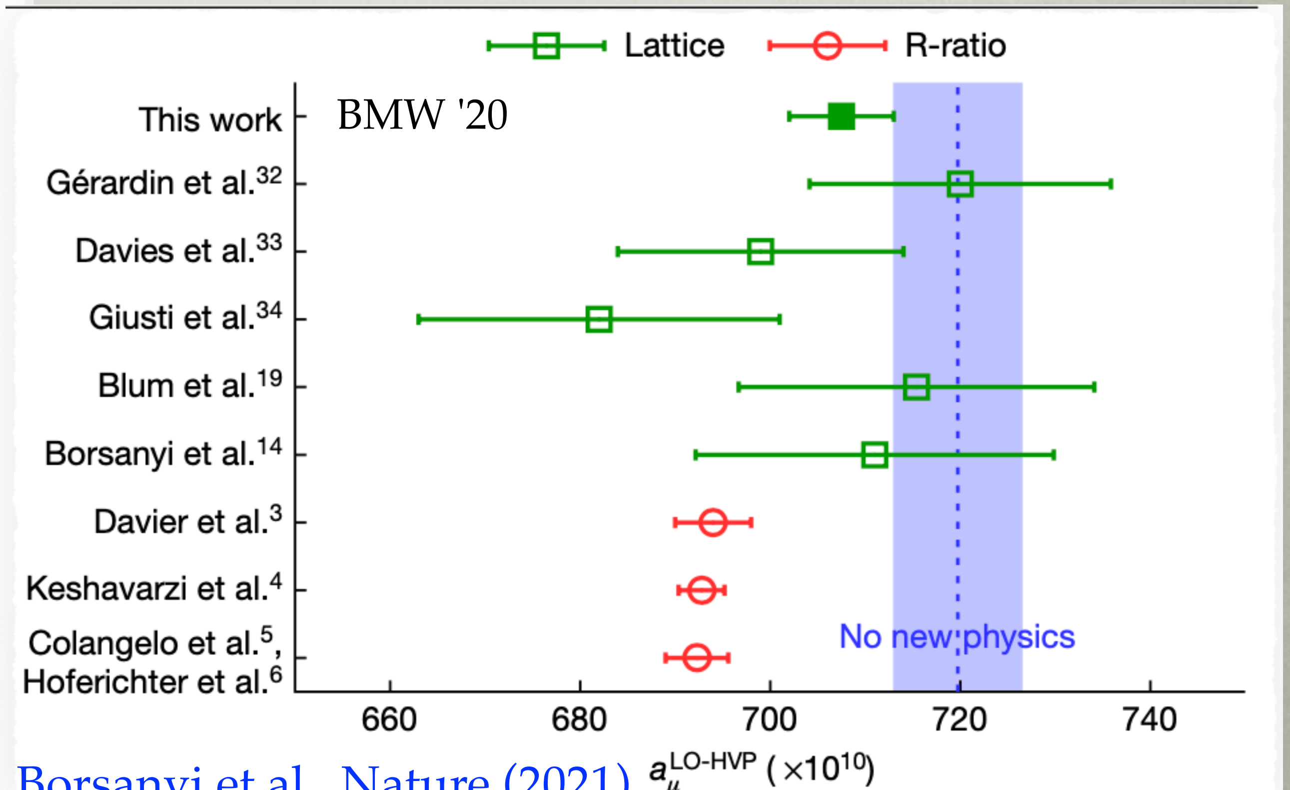
HADRONIC VACUUM POLARIZATION

- HVP the dominant uncertainty
  - a tension between determination using lattice QCD and from R-ratio



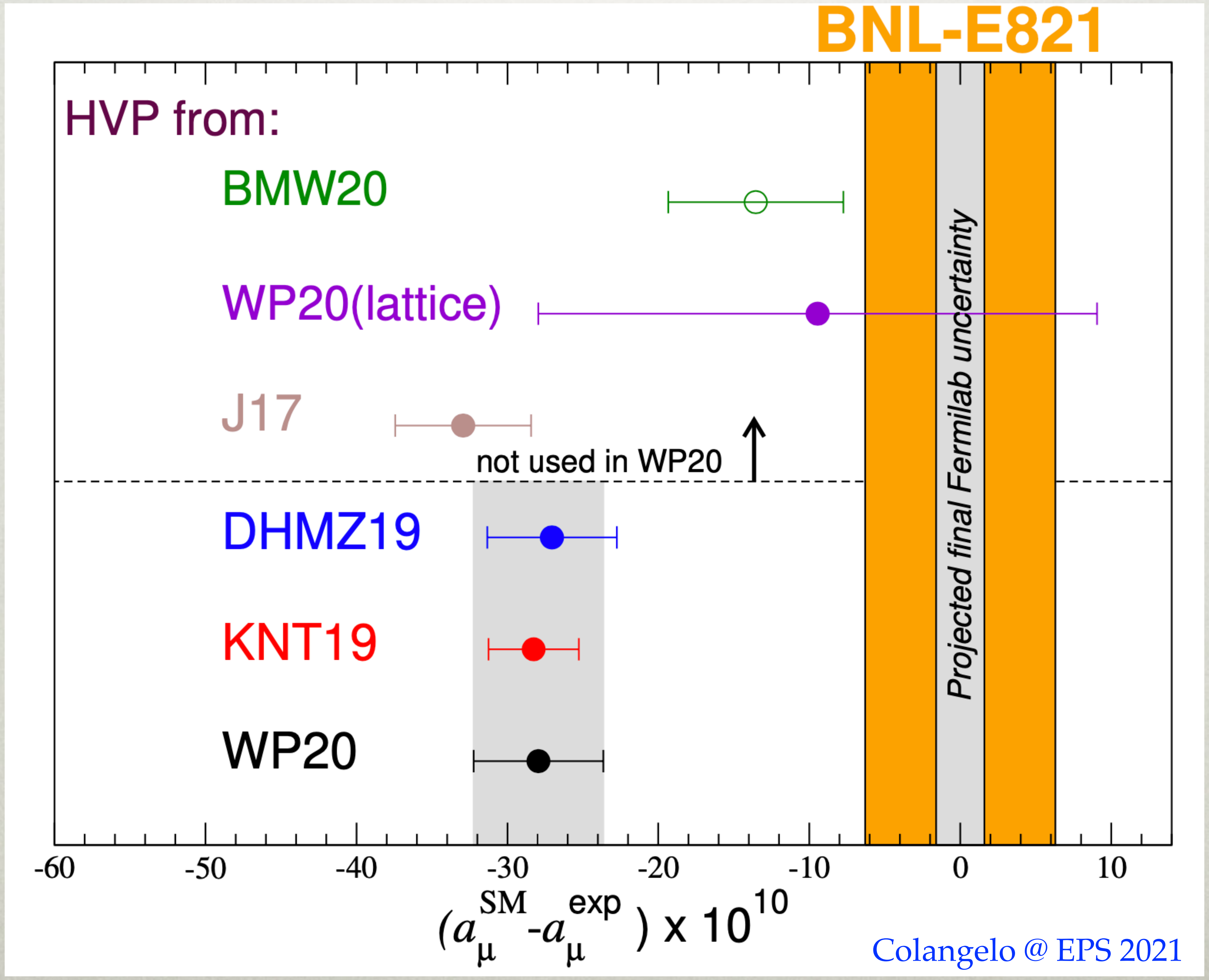


Gerardin, 2012.03931



Borsanyi et al, Nature (2021)

PRESENT STATUS BEFORE FERMILAB RESULT



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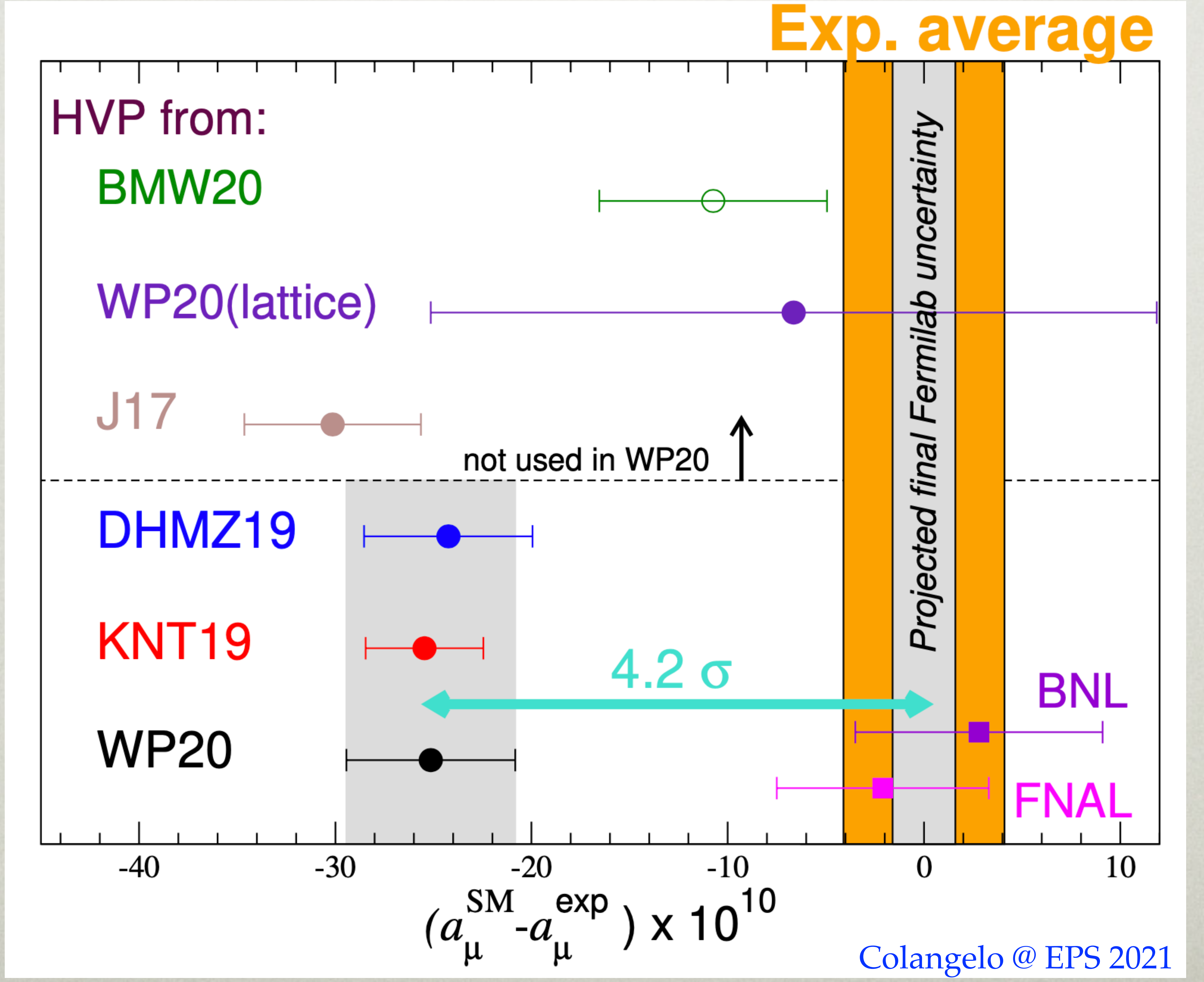
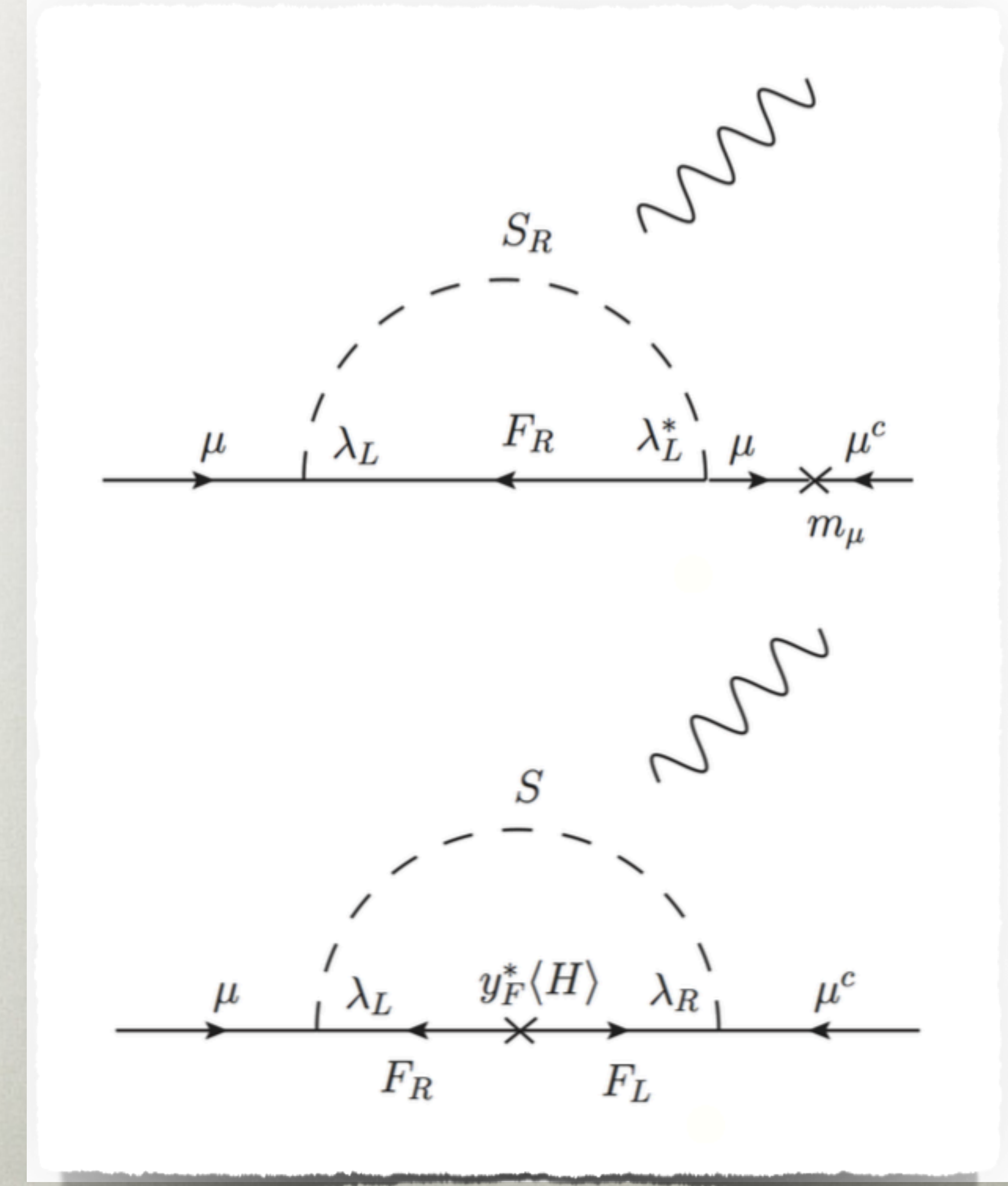


IF NEW PHYSICS...

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59)\times 10^{-10}$$

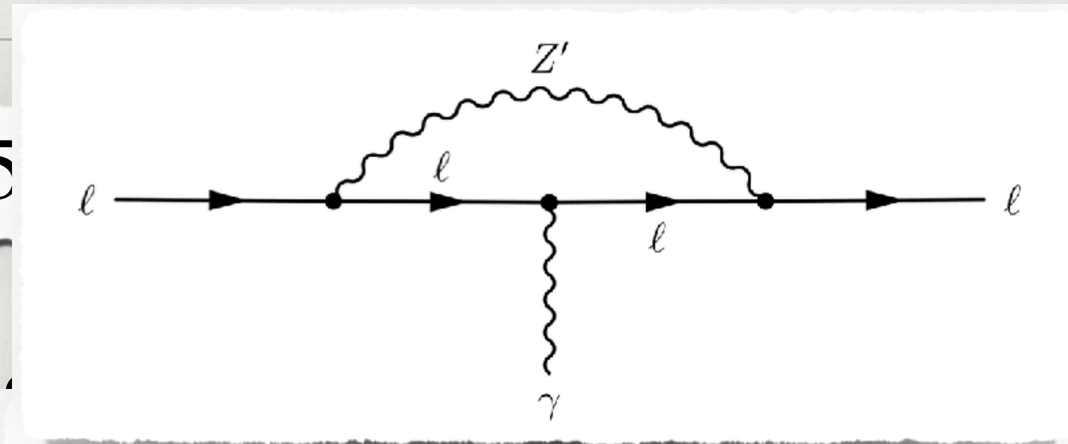
$$\frac{e}{8\pi^2}(\bar\mu_L\sigma^{\mu\nu}\mu_R)F_{\mu\nu}$$

- NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM



IF NEW PHYSICS...

$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 25$ ... $\frac{e}{8\pi^2}(\bar{\mu}_L \sigma^{\mu\nu} \mu_R) F_{\mu\nu}$



- NP models
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    example:
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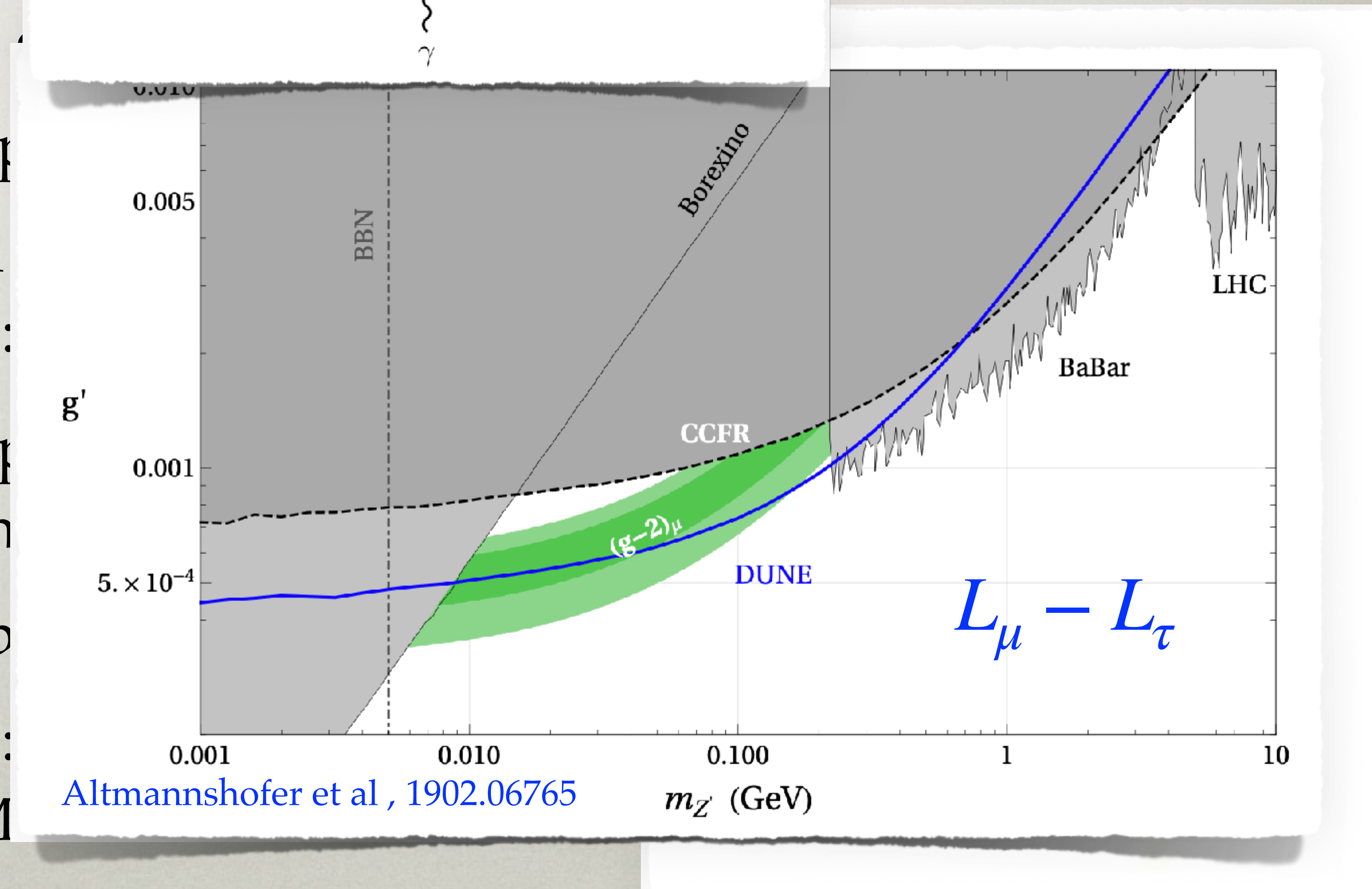

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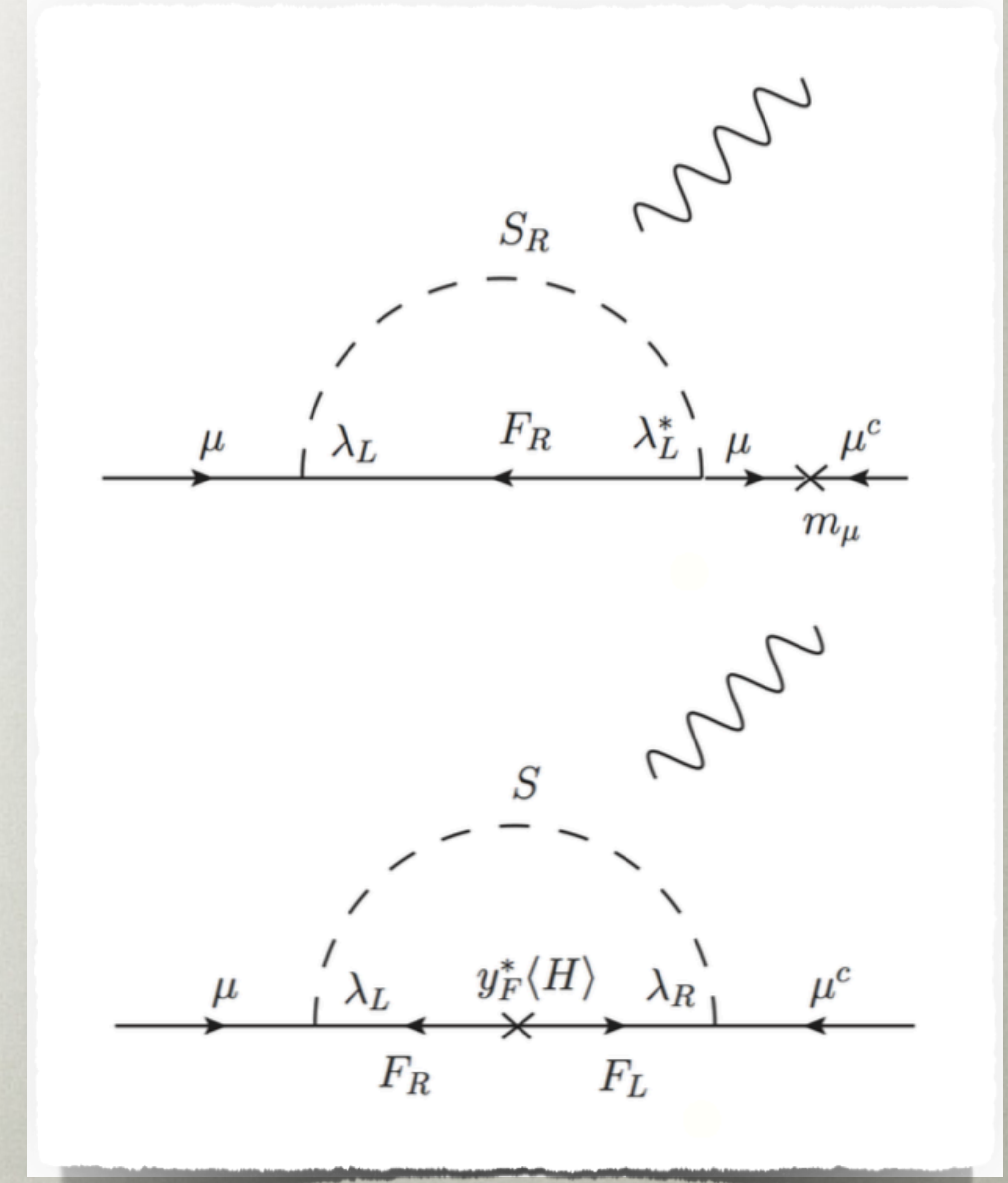

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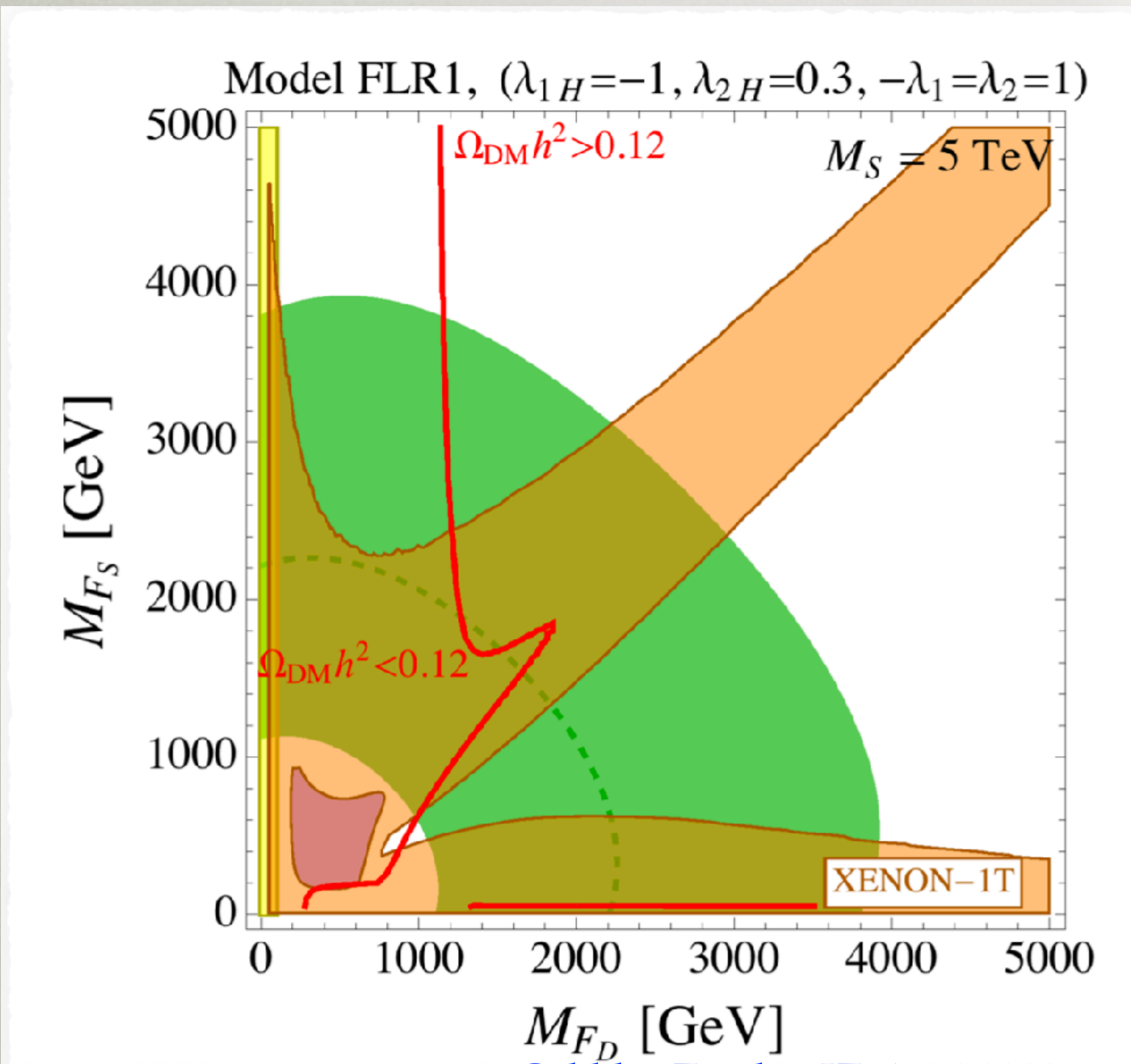
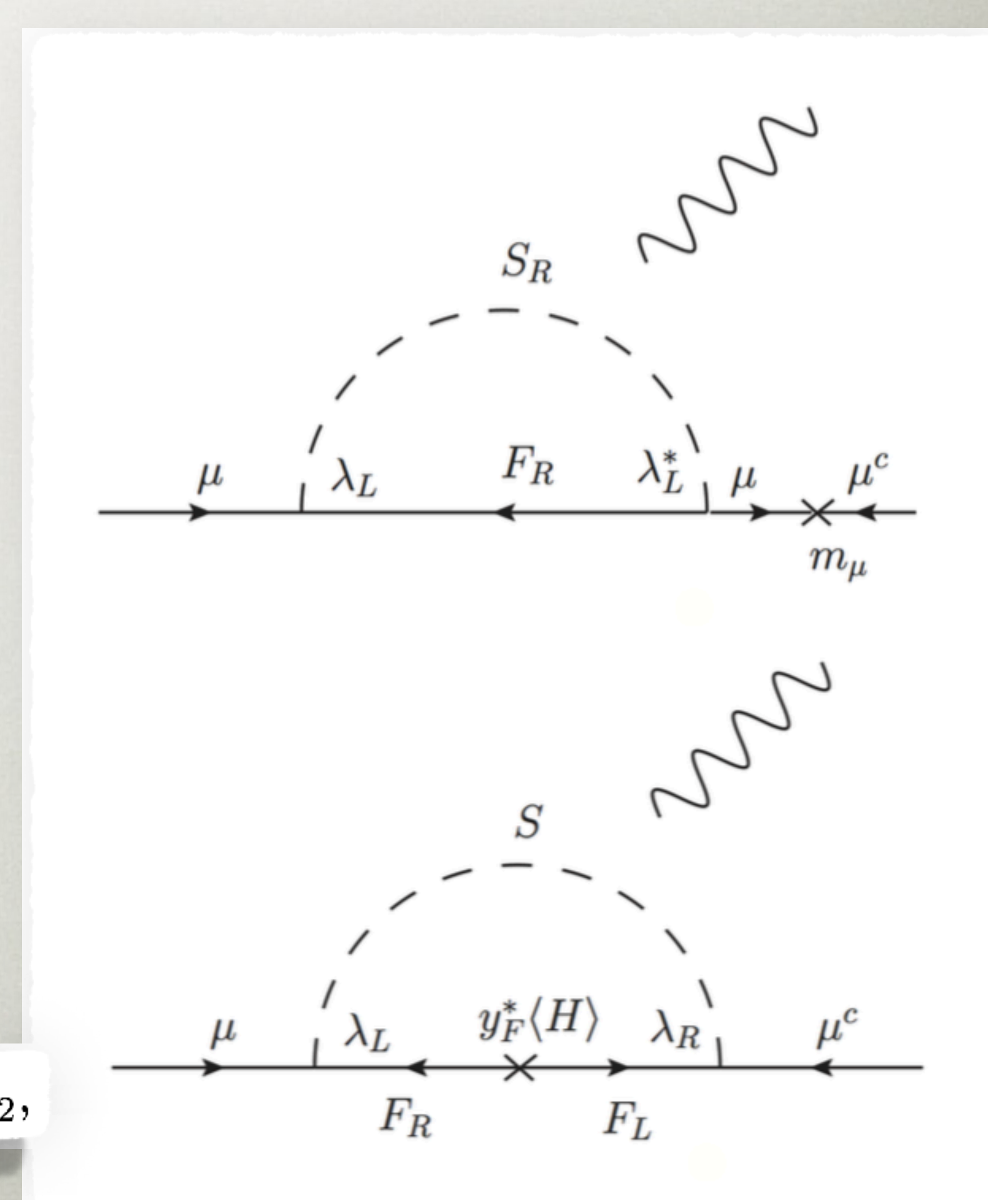


Calibbi, Ziegler, JZ, 1804.00009

leg

s



$$F_S \equiv F_R \sim 1_0, \qquad F_D \equiv F_L \sim 2_{-1/2}, \qquad F_D^c \equiv F_L^c \sim 2^*_{1/2}, \qquad S \equiv S_R \sim 2_{1/2},$$

$b \longrightarrow s\mu\mu$

UPSHOT

- $b \to sll$ flavor anomaly
  - theoretically clean, ~5σ excess
  - consistent with many additional obs. that require hadronic inputs
  - relatively high NP scale ⇒ less constrained by other probes

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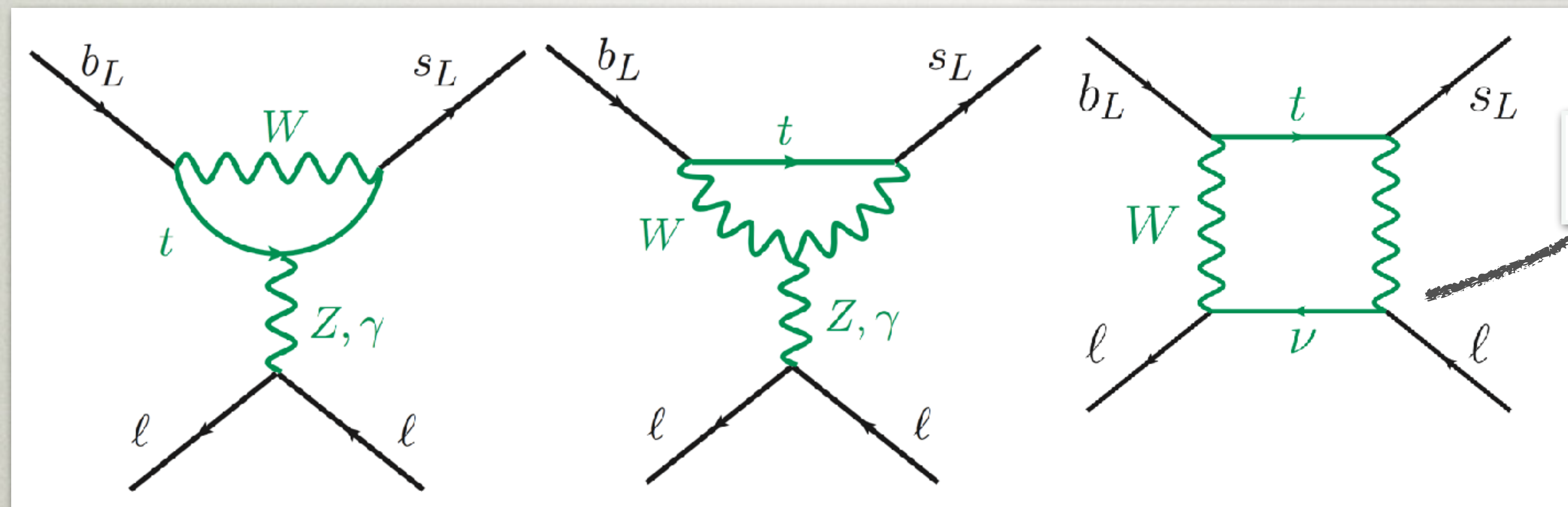
EXPERIMENTAL SITUATION

- *b→sll* : generated at 1-loop in the SM

$$G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma^\mu b_L \; \bar{\ell}\gamma_\mu(\gamma_5)\ell$$



$$C_9^{\rm SM} \approx -C_{10}^{\rm SM}$$

- in the SM *b→see* the same as *b→sμμ*
  - Lepton Flavor Universality in the SM

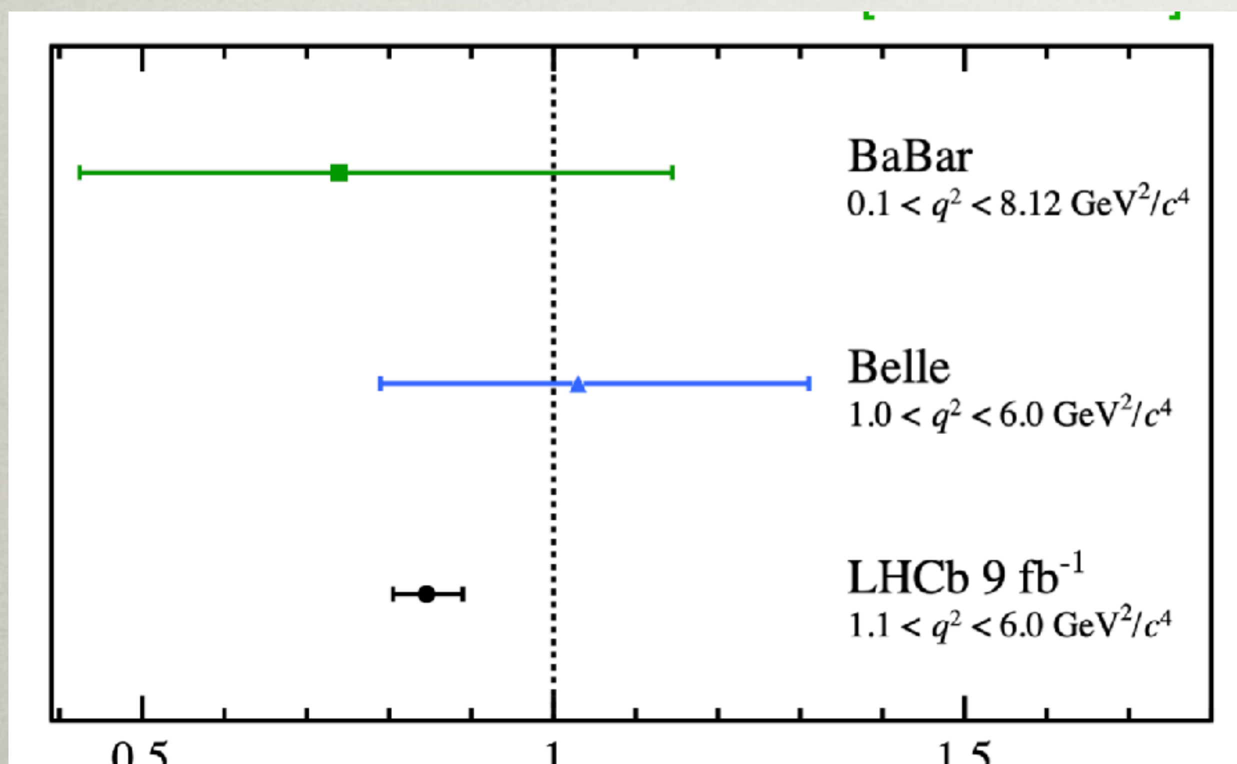
$b \to sll$: EXPERIMENT

- clean observables: R_K, R_{K^*}, $BR(B_s \to \mu^+\mu^-)$ **two bins**

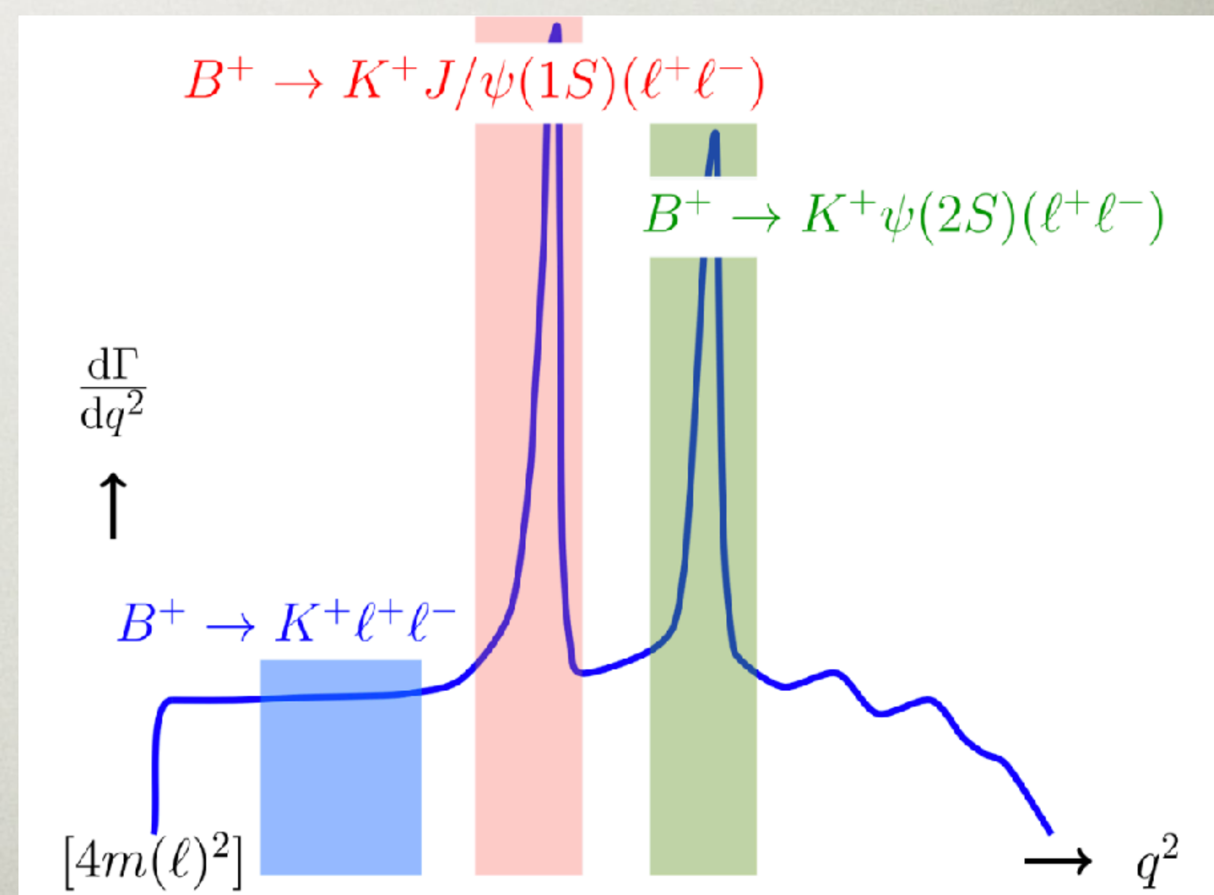
$$R_K = \left.\frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}\right|_{[1,6]\mathrm{GeV}^2}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$$

- 3.1σ anomaly in R_K



LHCb, 2103.11769

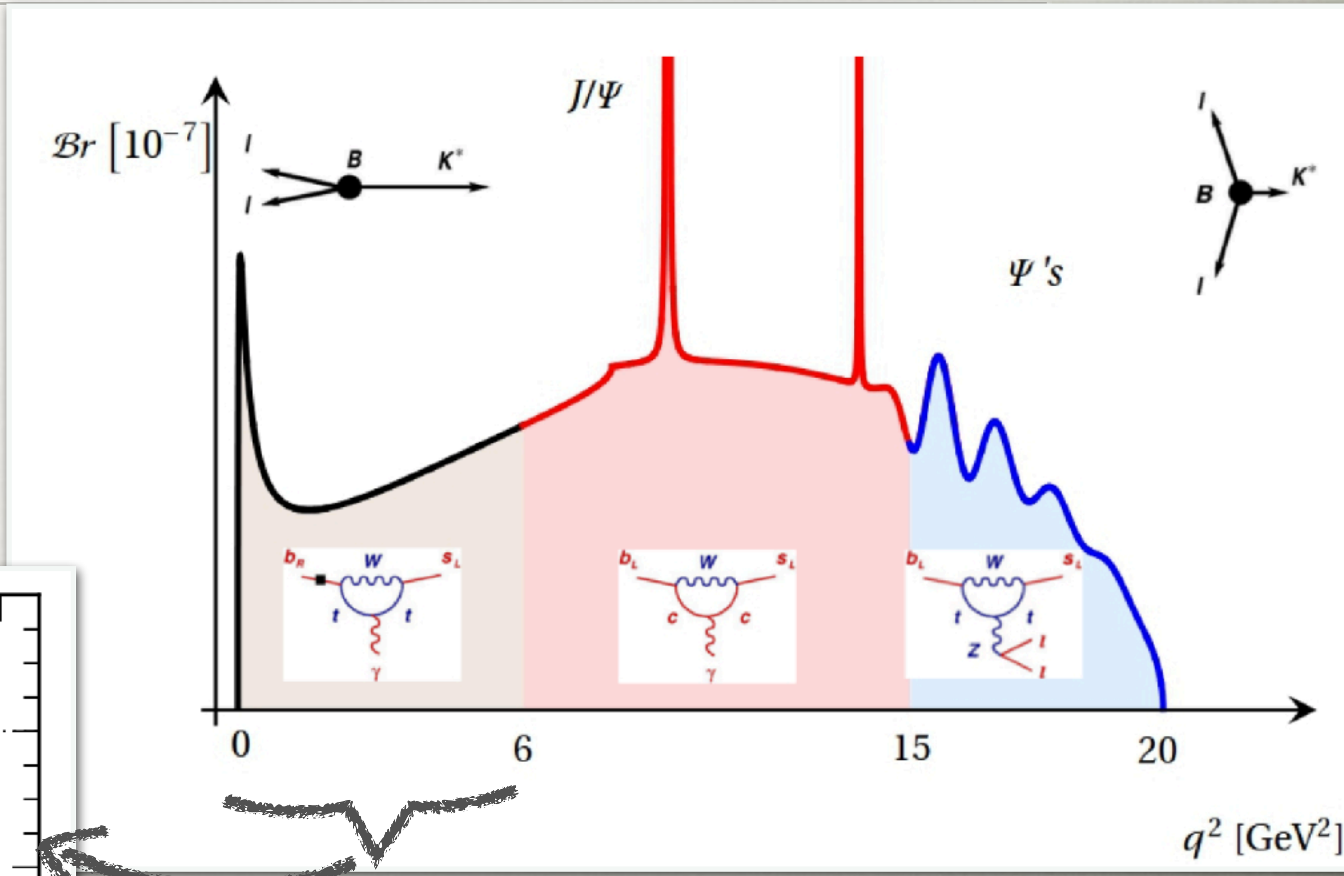


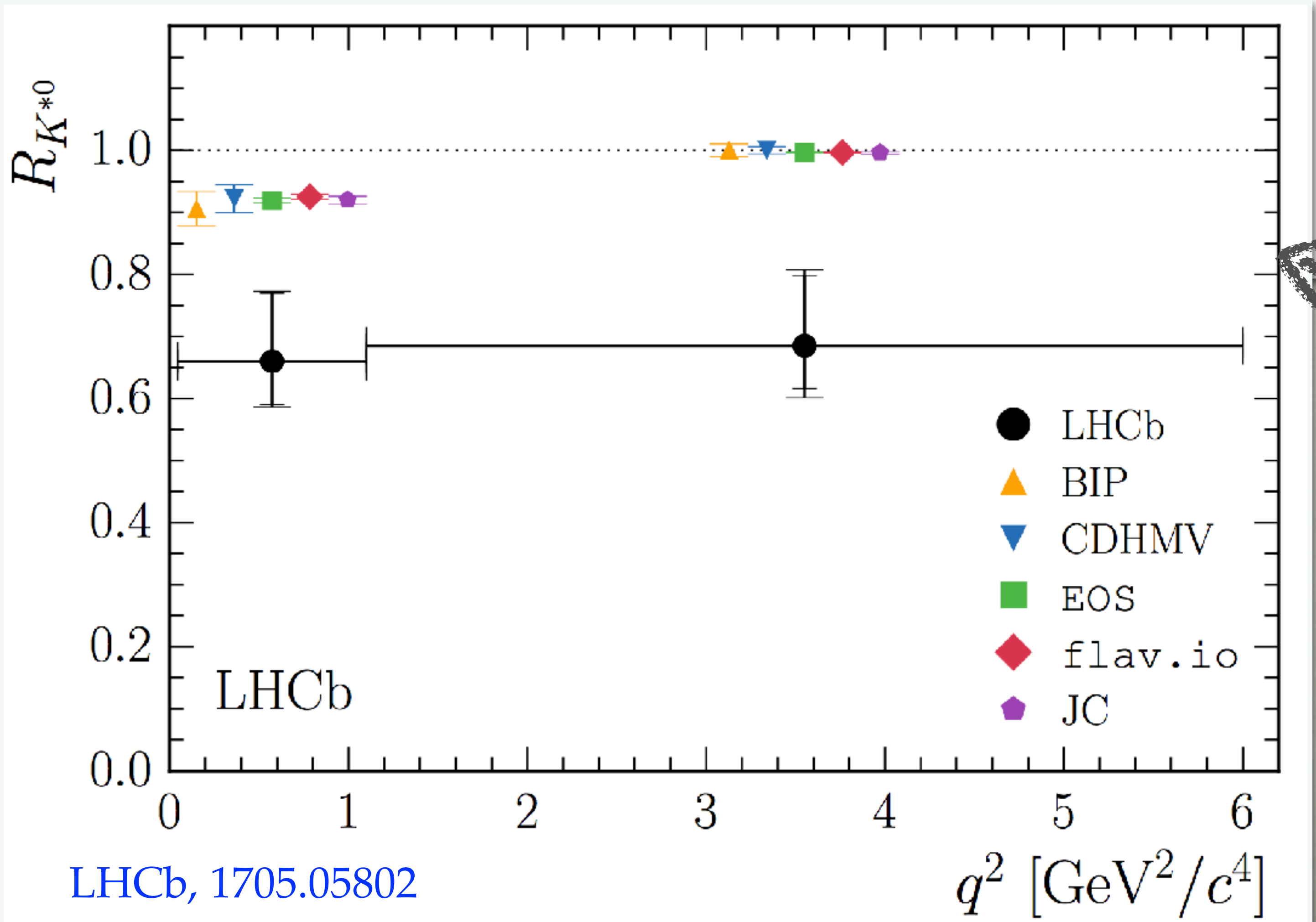
$b \to sll$: EXPERIMENT

- 2 bins in R_{K^*}

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu^+ \mu^-)}{\mathrm{BR}(B \to K^* e^+ e^-)}$$

- 2.2-2.5σ deviation in each





LHCb, 1705.05802

experiment: LHCb, 1705.05802 (3.0 fb^{-1} @7+8TeV)

$$R_{K^*[0.045,\ 1.1]\ \mathrm{GeV^2}} = 0.660^{+0.110}_{-0.070} \pm 0.024,$$

$$R_{K^*[1.1,\ 6]\ \mathrm{GeV^2}} = 0.685^{+0.113}_{-0.069} \pm 0.047,$$

INFORMATION JUST FROM THE LFUV RATIOS

see, e.g., Alonso, Grinstein, Martin Camalich, 1407.7044

- $R_{K^{(*)}}$ can only be explained by NP in

$$\mathcal{O}_9^{(\prime)\ell} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)} b)\,(\bar{\ell}\gamma_\mu \ell),$$

$$\mathcal{O}_{10}^{(\prime)\ell} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)} b)\,(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

  - scalar currents constrained by $B_S \to ll$

- R_K and R_{K^*} different parity, complementary info, e.g. for central bin

$$R_K \simeq 1 + 2\frac{{\rm Re}\, C^{\rm BSM}_{b_{L+R}(\mu-e)_L}}{C^{\rm SM}_{b_L \mu_L}}$$

$$R_{K^*} \simeq R_K - 4p\frac{{\rm Re}\, C^{\rm BSM}_{b_R(\mu-e)_L}}{C^{\rm SM}_{b_L \mu_L}}$$

see, e.g., D'Amico et al., 1704.05438

- from ratios: NP can be either in muons or electrons
  - in both cases $(\bar{s}b)_L$ ok
  - for electrons also $(\bar{s}b)_R(\bar{e}e)_R$ possible (from quadratic dep.)

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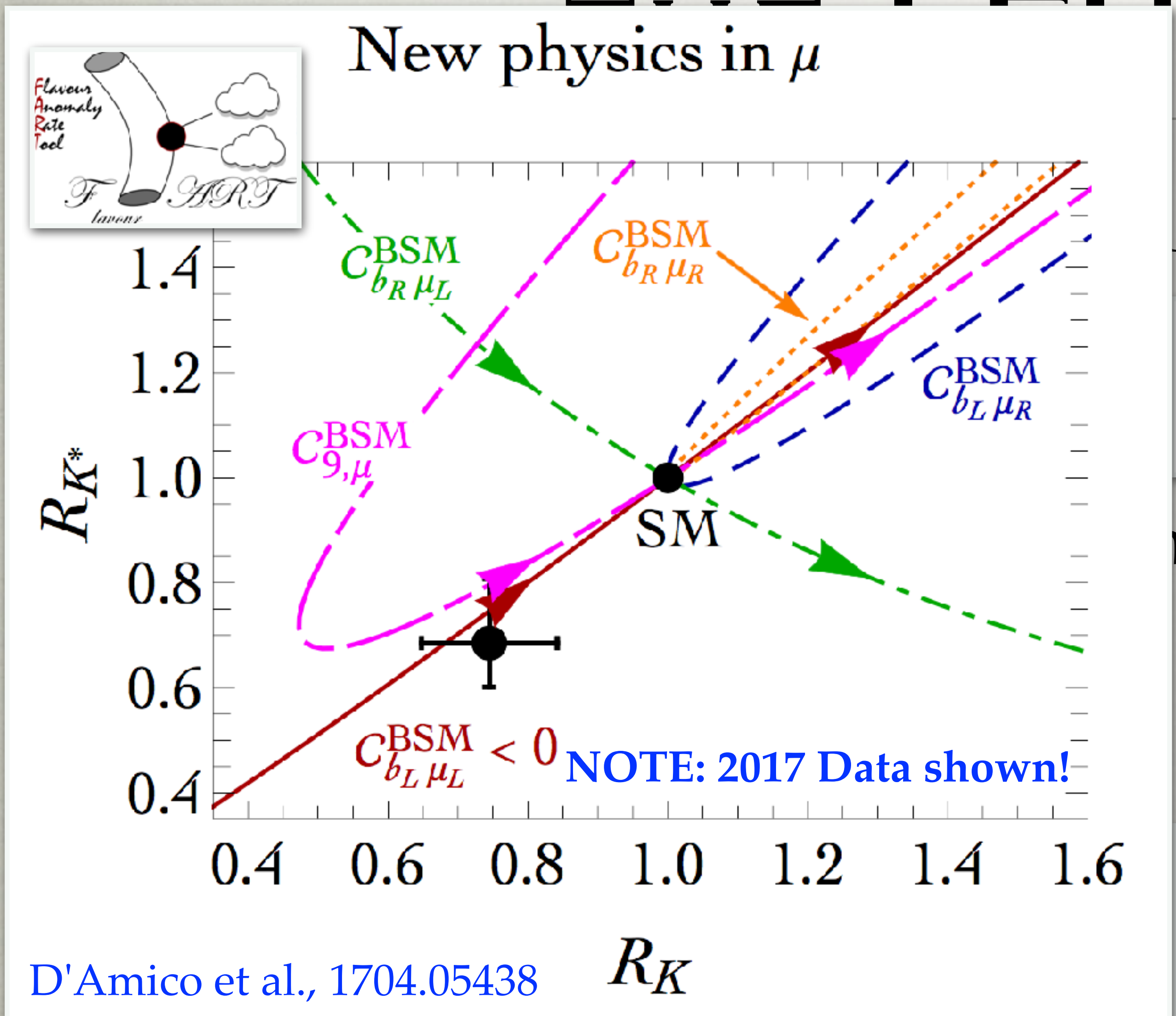

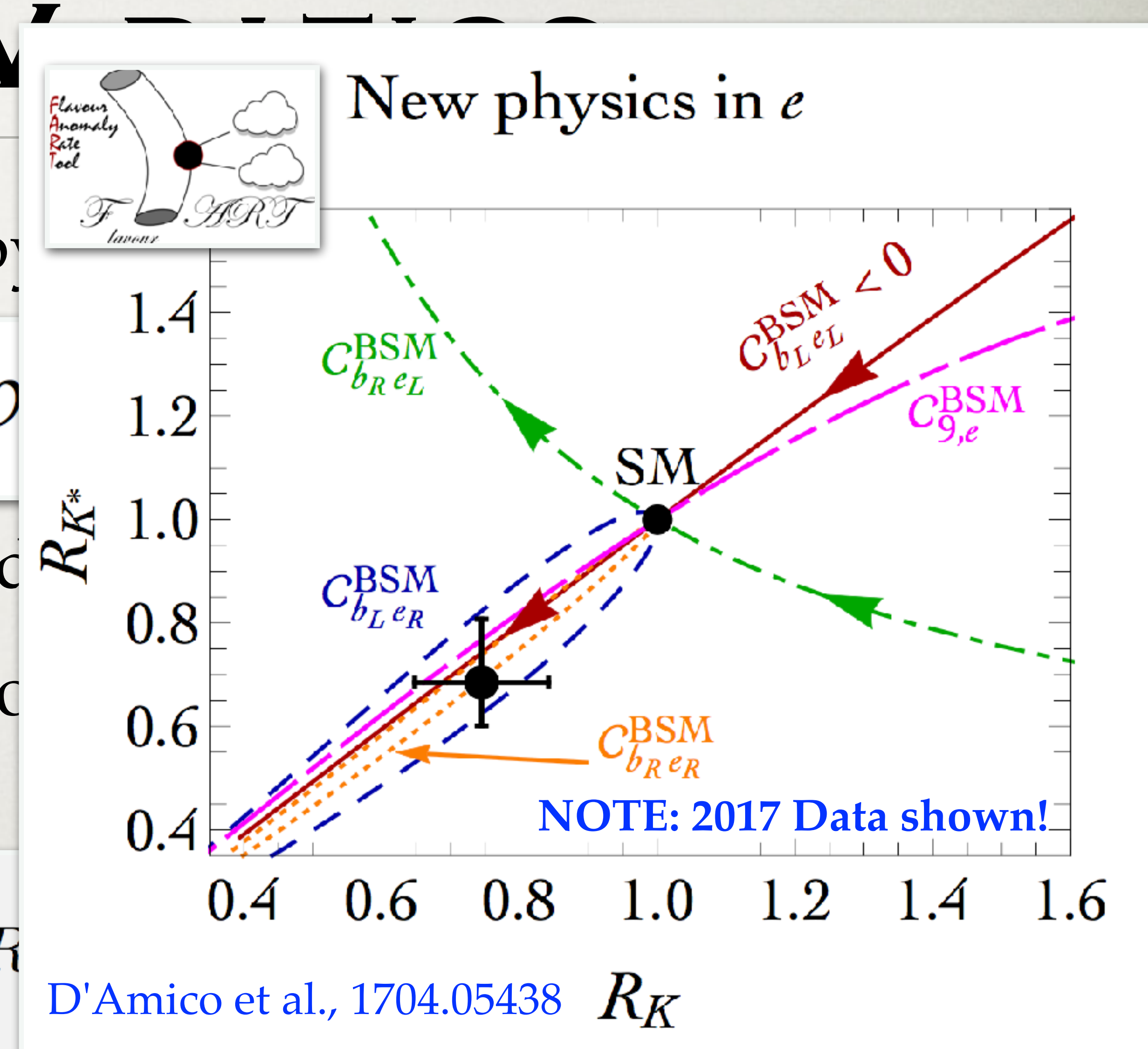

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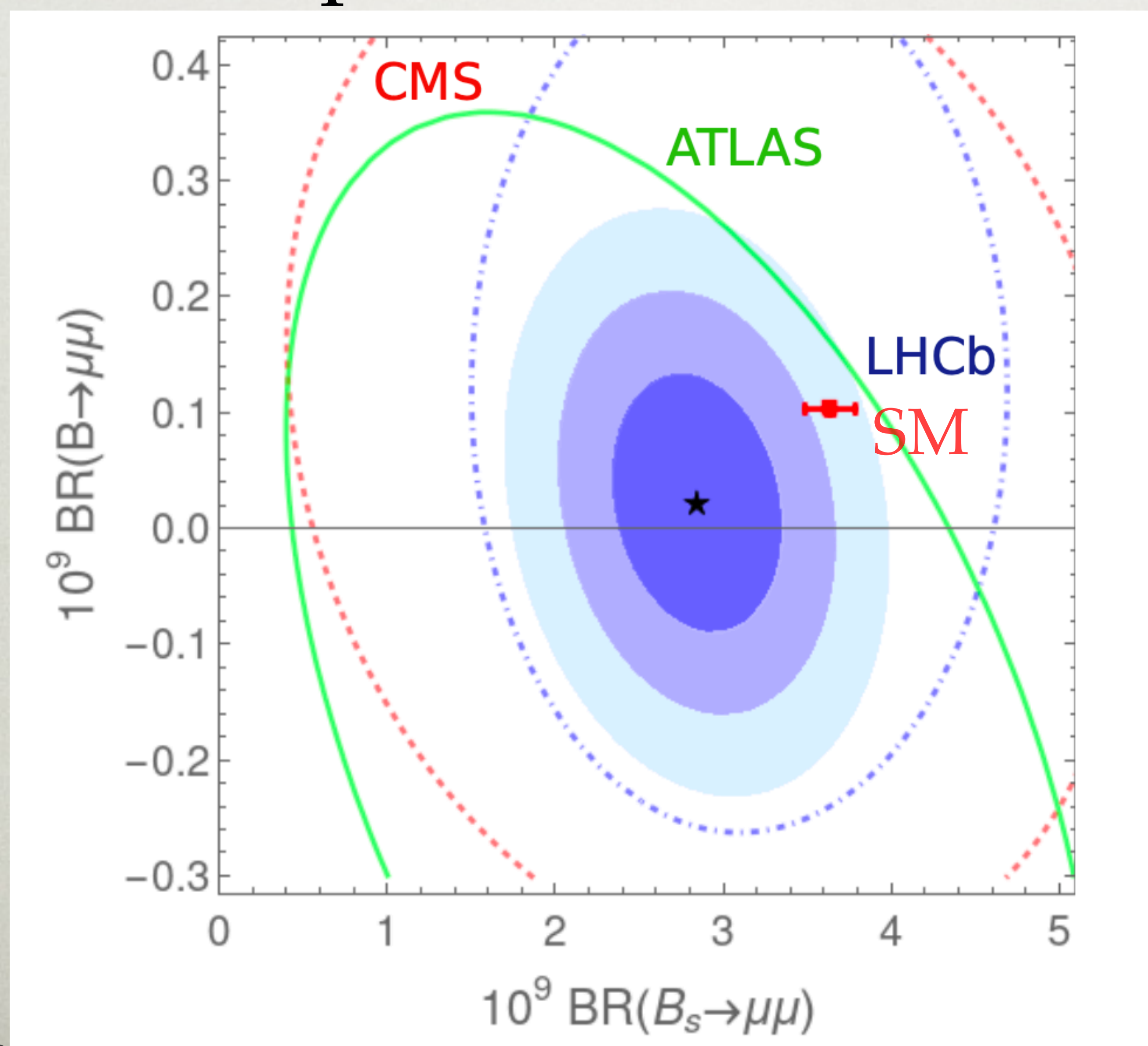
PREFERENCE FOR NP IN MUONS?

- $Br(B_s \to \mu^+\mu^-)$ precise SM theory prediction
  - $\lesssim 2\sigma$ exp. deficit

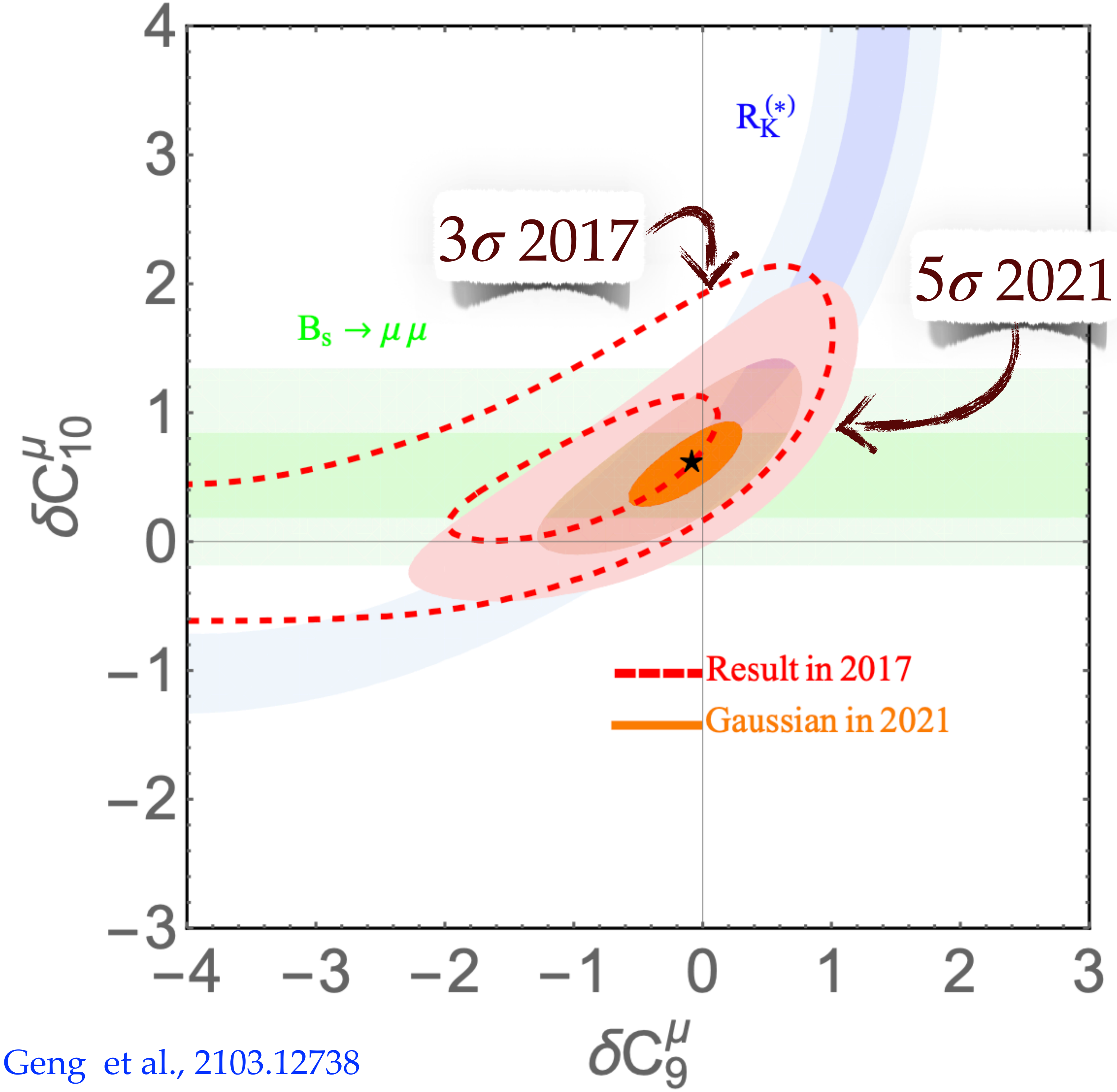


Geng et al., 2103.12738

see also Alguero et al, 2104.08921;
Hurth et al, 2104.10058;
Altmannshofer, Stangl, 2103.13370

FIT TO CLEAN OBSERVABLES

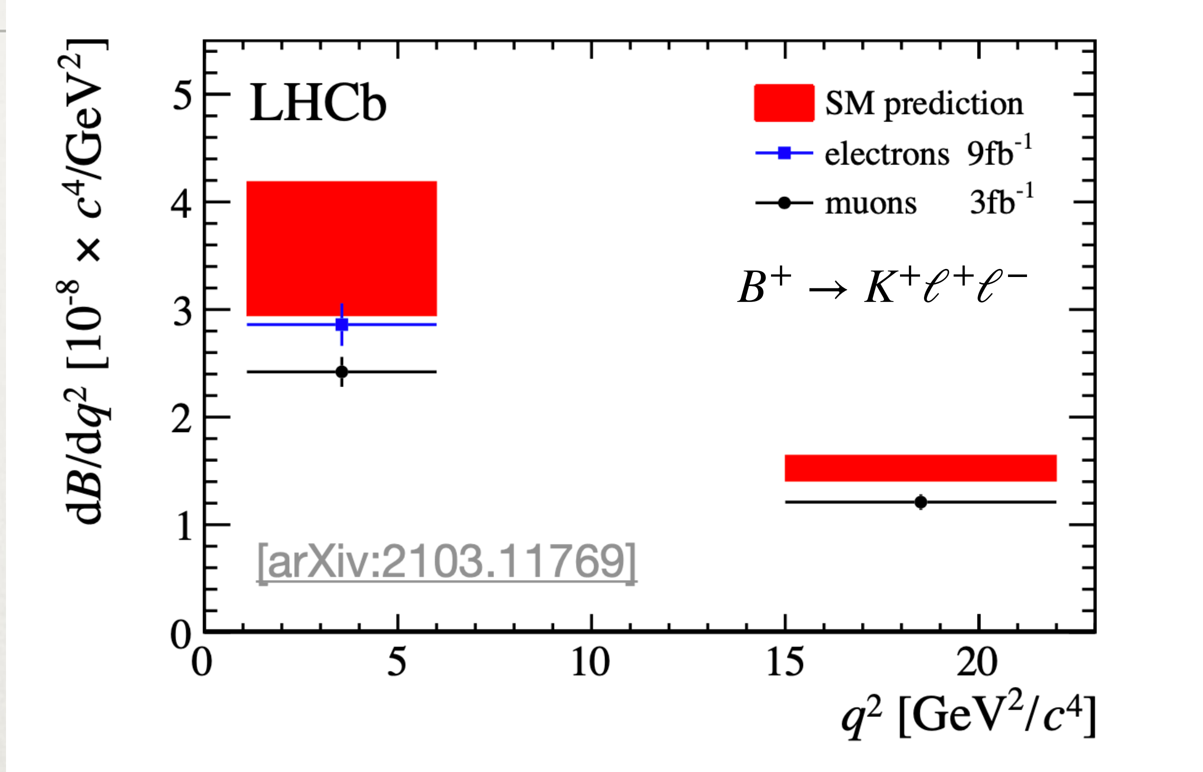
- a fit to only the clean observables
  - R_K
  - R_{K^*}
  - $Br(B_s \to \mu\mu)$

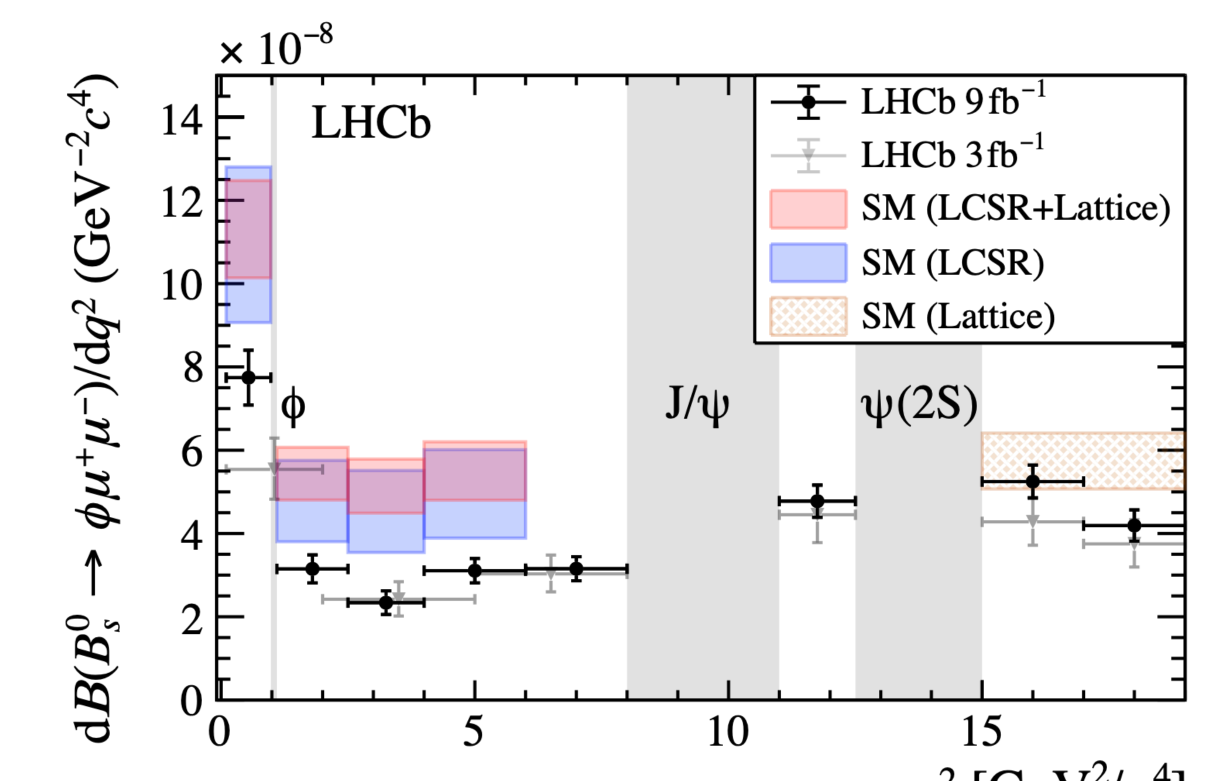


Geng et al., 2103.12738

GLOBAL FITS

- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
  - angular obs. in $B^0 \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$
- sensitive to hadronic inputs
  - require form factors predict. (QCD sum rules), charm loops, nonfactor. contribs.
- prefer NP in muons





LHCb 2105.14007

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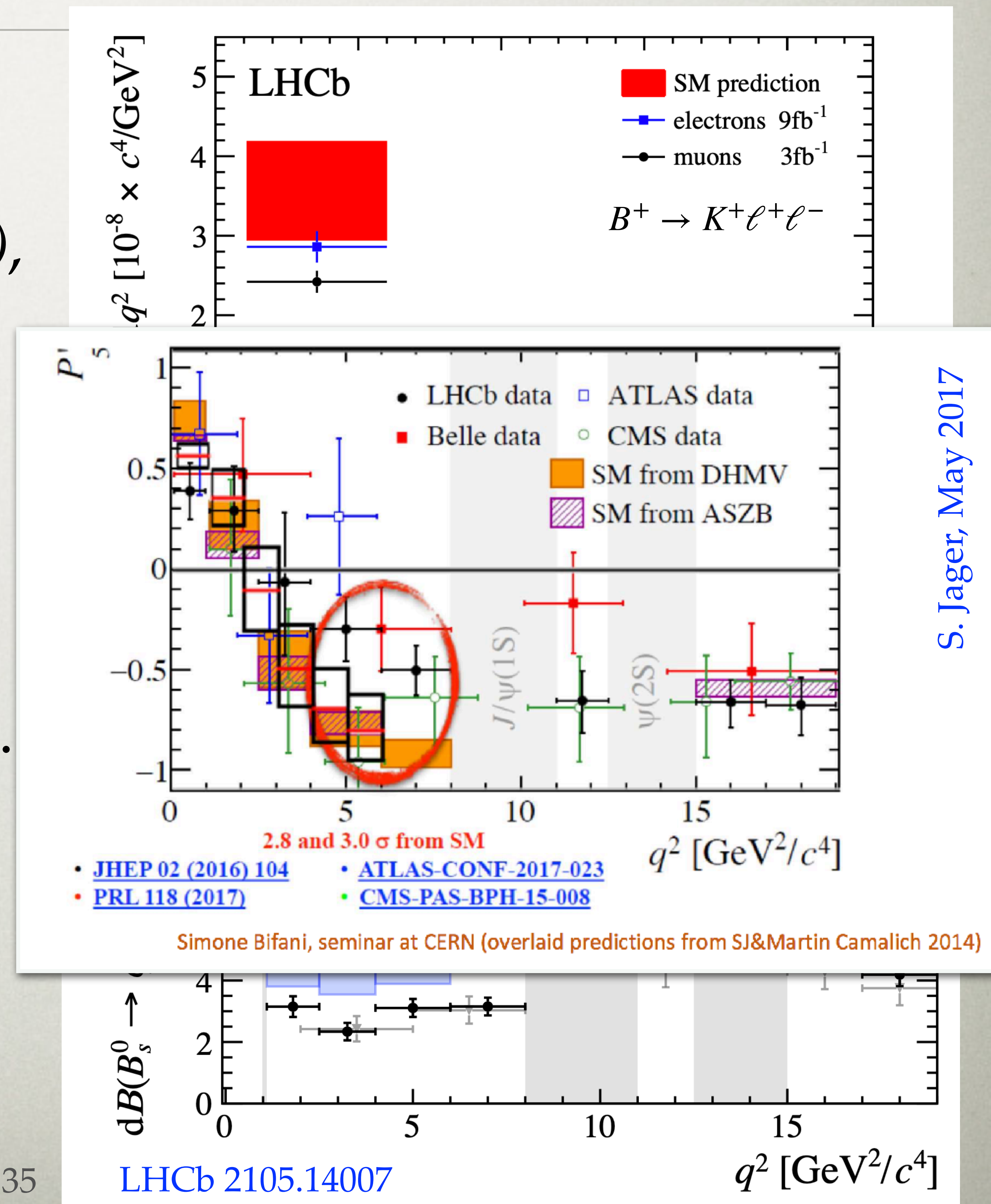
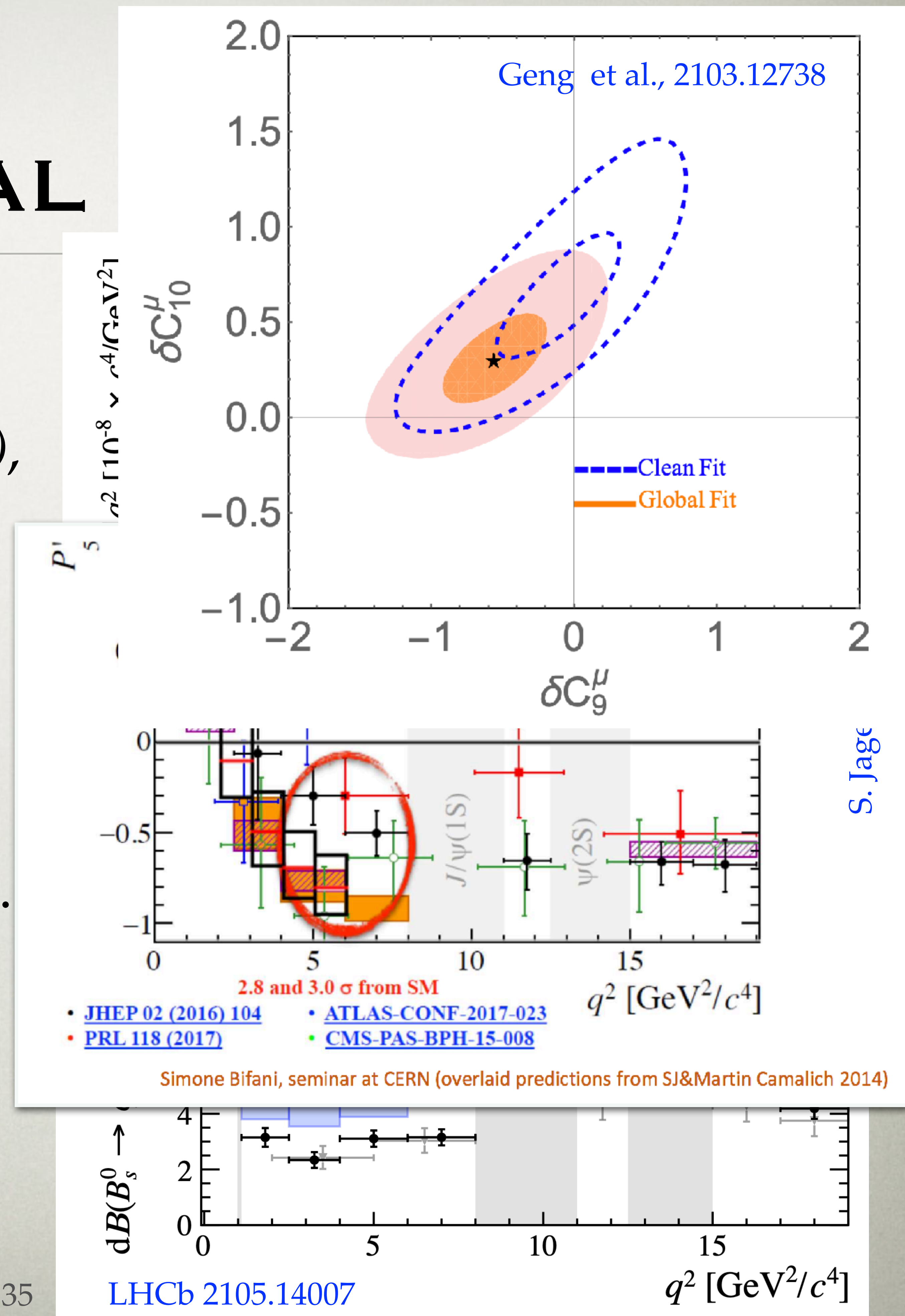


GLOBAL

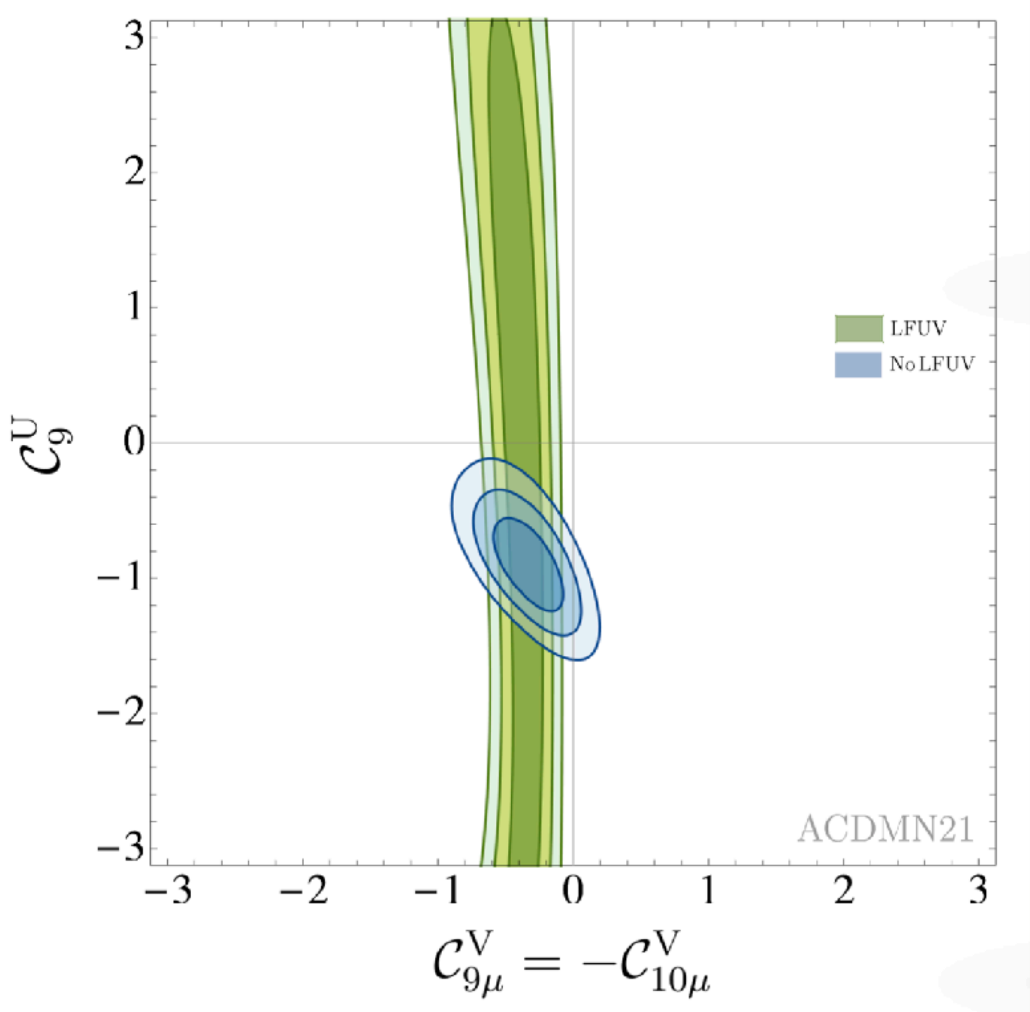
- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
  - angular obs. in $B^0 \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$
- sensitive to hadronic inputs
  - require form factors predict. (QCD sum rules), charm loops, nonfactor. contribs.
- prefer NP in muons



NP just in muons?

- from global fits preference for also a nonzero universal coupling to both e and μ

What's in the fits? ⇨ **246 obs (Global) + 22 obs (LFUV) from LHCb, Belle, ATLAS, CMS**



Alguero talk at Moriond QCD 2021

see also Alguero et al, 2104.08921

$$C_{ie}^{\mathrm{NP}} = C_i^{\mathrm{U}}$$

$$C_{i\mu}^{\mathrm{NP}} = C_{i\mu}^{\mathrm{V}} + C_i^{\mathrm{U}}$$

WHAT KIND OF NP?

- from now on will assume that NP in $b \to s\mu\mu$
- what is the NP scale?
  - the Wilson coeffs. in previous slides

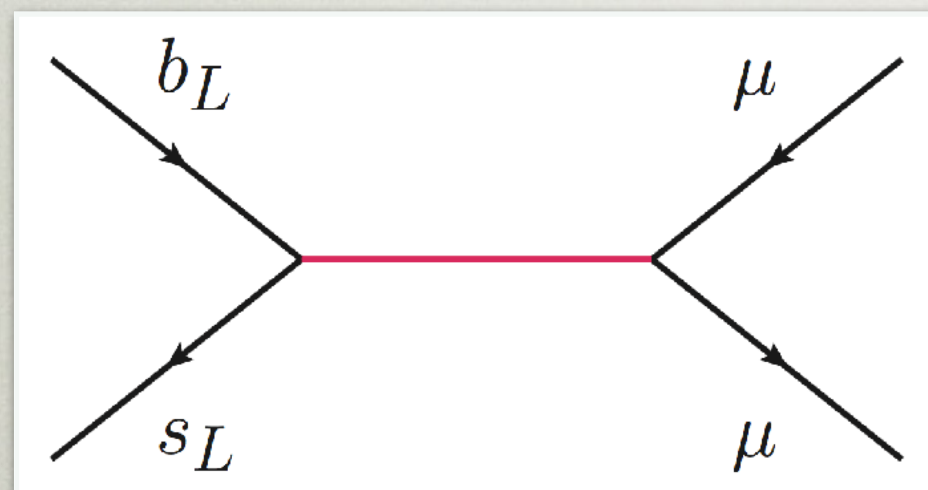
$$V_{tb}V_{ts}^{*}\frac{\alpha_{\rm em}}{4\pi v^2}C_I = \frac{C_I}{(36\,{\rm TeV})^2}$$

$C_I^{NP} \sim O(1)$

- types of NP
  - tree level (heavy or light)
  - loop level

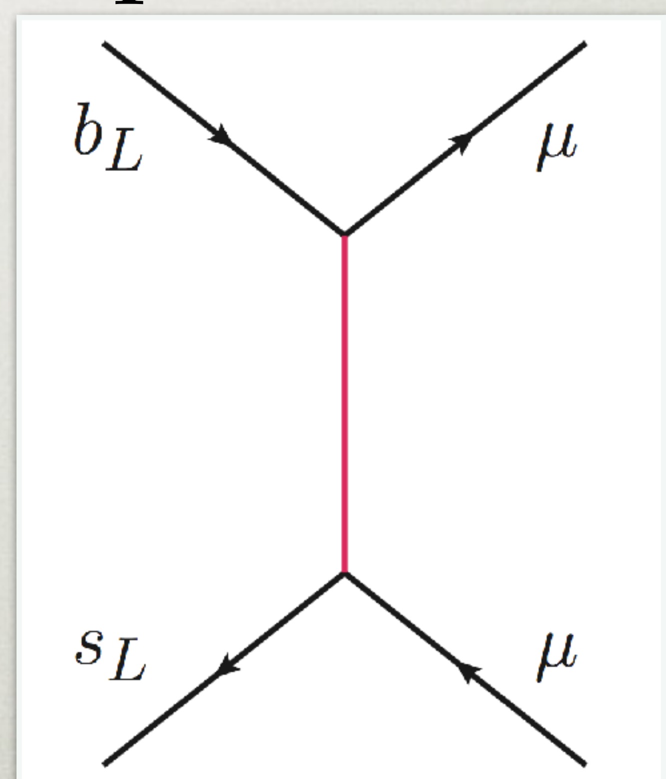
TREE LEVEL

- two distinct types:
- mediated by a Z'
  - $SU(2)_L$ singlet or triplet



Altmannshofer, Straub, 1308.1501;
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269;
Greljo, Isidori, Marzocca, 1506.01705;
+many refs.

- leptoquark
  - spin 0 or 1

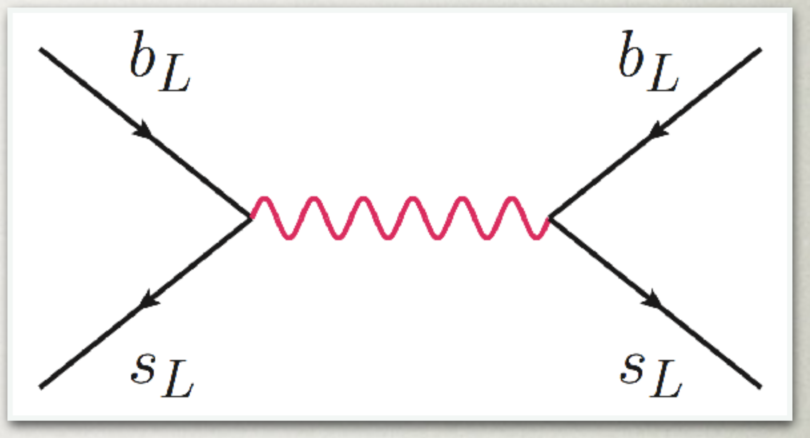


see, e.g., Hiller, Nisandzic, 1704.05444;
Hiller, Schmaltz, 1411.4773; +many refs

GENERAL CONSIDERATIONS ABOUT Z'

- nontrivial constraint from B_s mixing

Altmannshofer, Straub, 1308.1501; 1411.3161



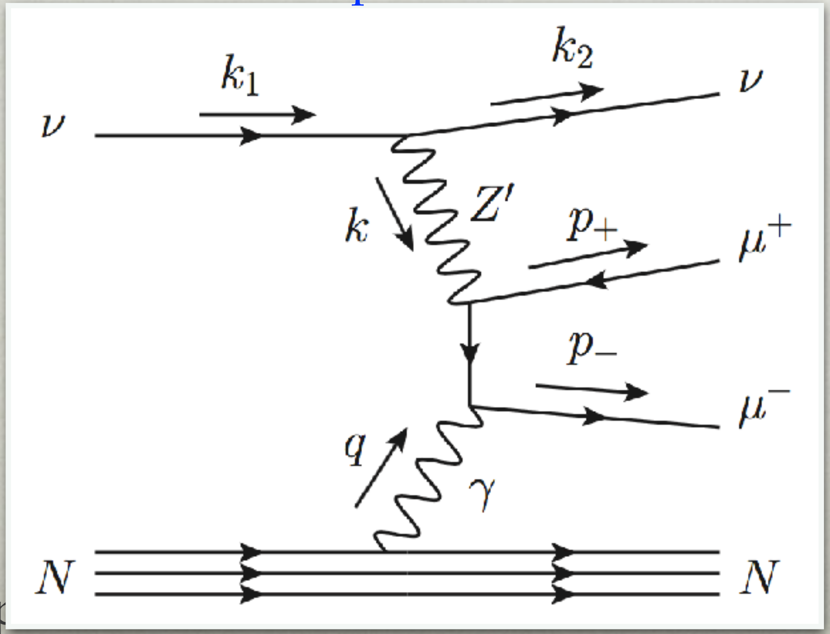
$$\frac{g_{bsZ'}}{m_{Z'}} \lesssim \frac{0.01}{2.5\ \mathrm{TeV}}$$

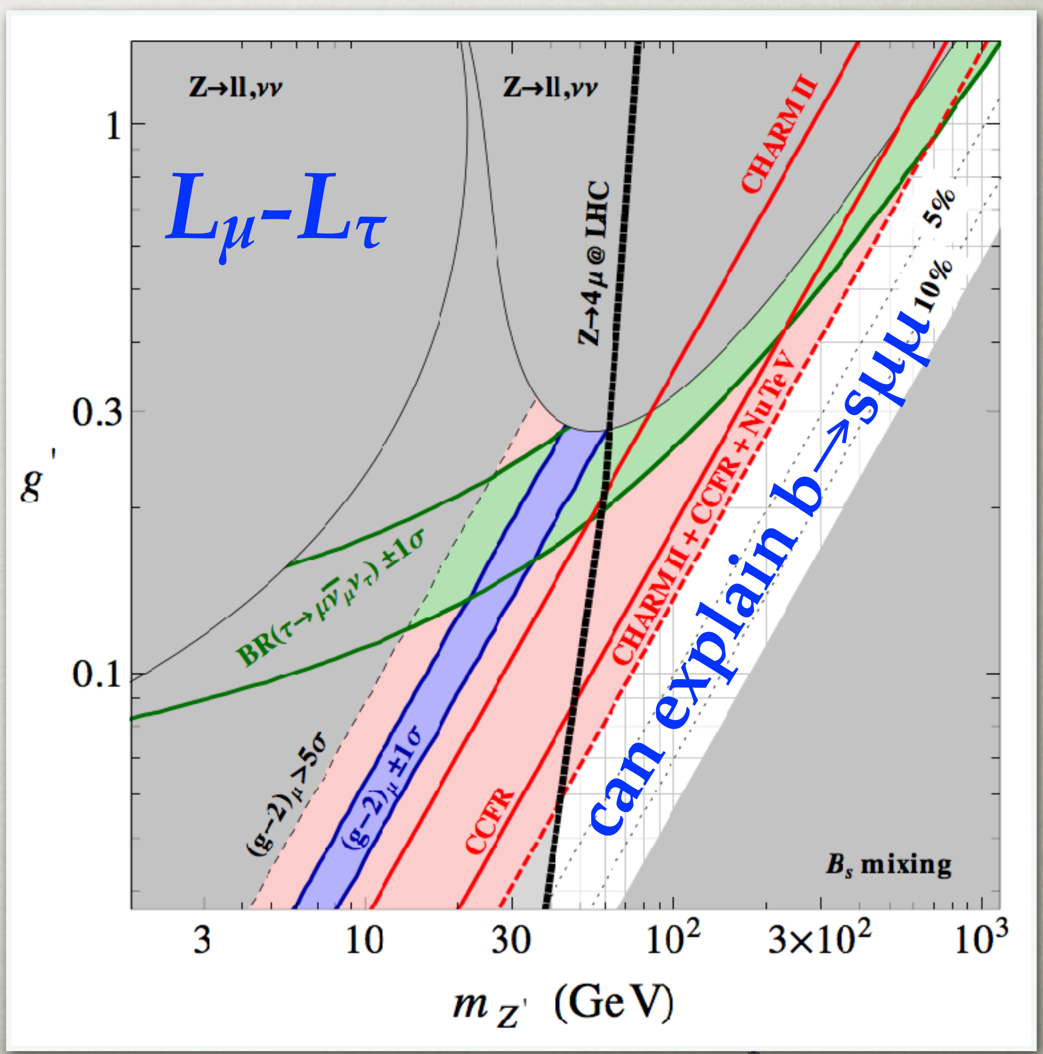
compare: $V_{ts} \simeq 0.04$

- if coupling to μ_L then a related signal in $b \to s\nu\nu$

- constraints from neutrino trident production

Altmannshofer, Gori, Pospelov, Yavin, 1406.2332; 1403.1269





LEPTOQUARKS

Hiller, Nisandzic, 1704.05444

- 3 options if a single LQ dominates

$SU(3)_C \times SU(2)_L \times U(1)_Y$

Scalar LQ

label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
$\tilde{S}_2$	$(3, 2, 1/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1,\ R_{K^*} > 1$
S_3	$(\bar{3}, 3, 1/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1.$
S_2	$(3, 2, 7/6)$	C_{LR}	$C_9 = C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	C_{RR}	$C_9' = C_{10}'$	$R_K \simeq R_{K^*} \simeq 1$

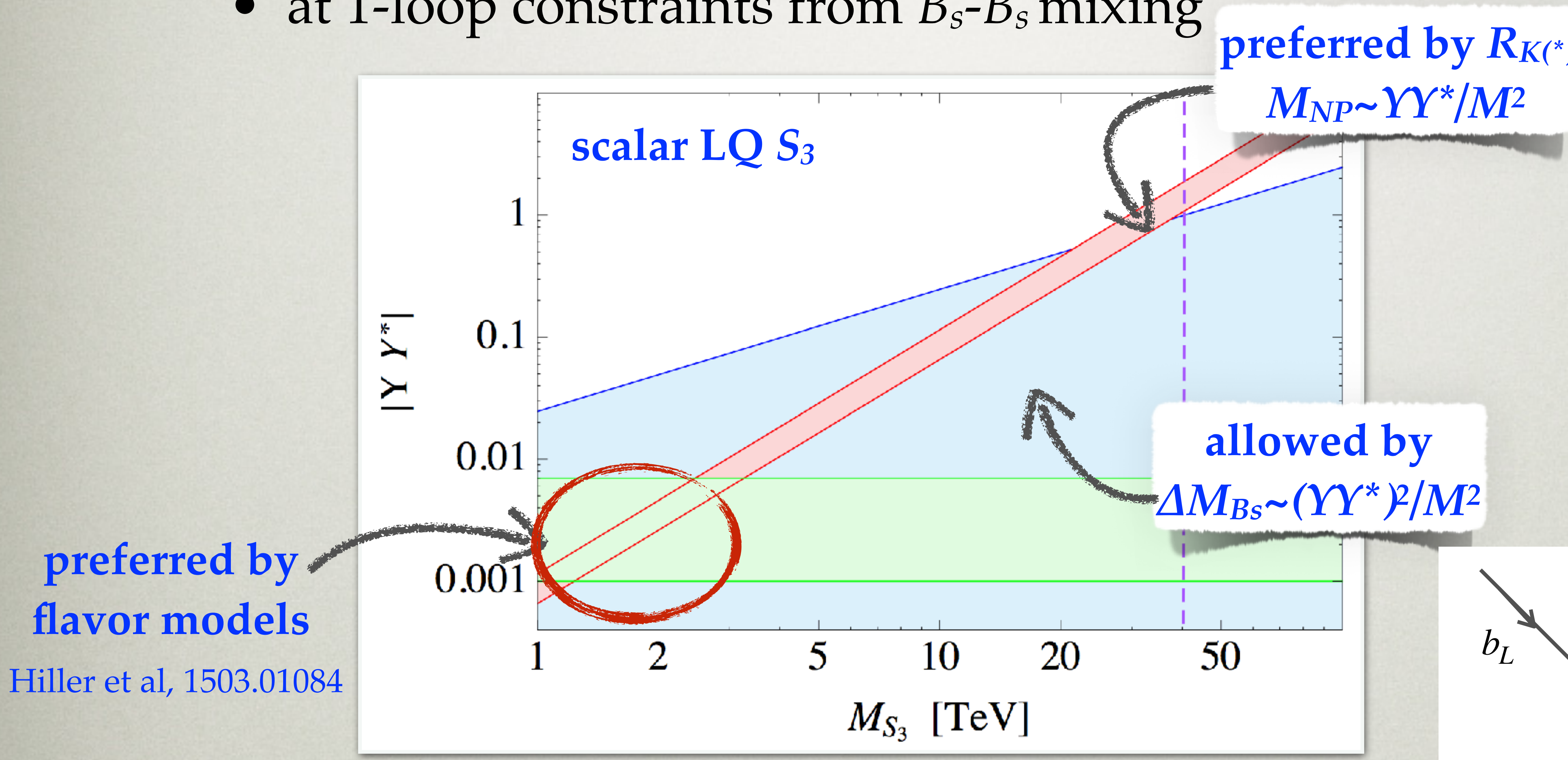
Vector LQ

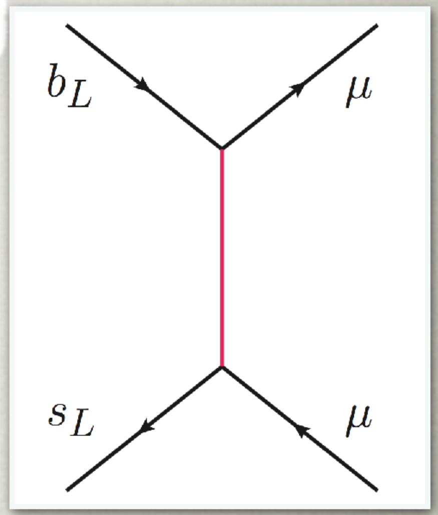
label	representation	Wilson coefficient	Relation	$R_{K^{(*)}}$
V_1	$(3, 1, 2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		C_{LR}	$C_9 = +C_{10}$	$R_K \simeq R_{K^*} \simeq 1$
V_2	$(3, 2, -5/6)$	C_{RL}	$C_9' = -C_{10}'$	$R_K < 1,\ R_{K^*} > 1$
		C_{RR}	$C_9' = +C_{10}'$	$R_K \simeq R_{K^*} \simeq 1$
V_3	$(3, 3, -2/3)$	C_{LL}^{NP}	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$

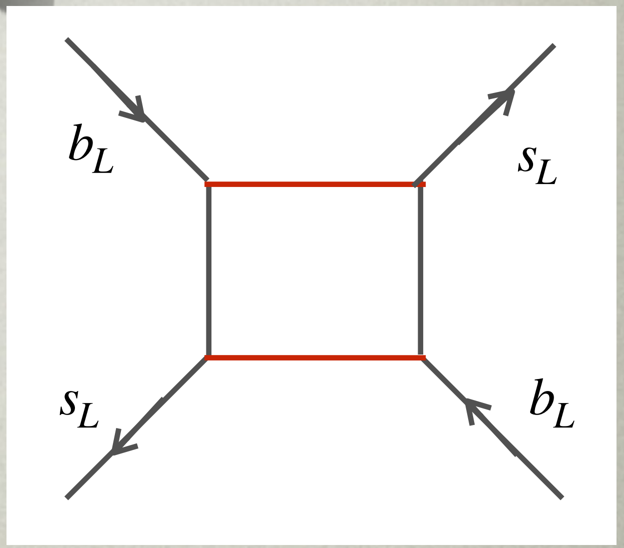
LEPTOQUARKS

Hiller, Nisandzic, 1704.05444

- at 1-loop constraints from B_s-$\bar{B}_s$ mixing







- implies upper bound on LQ mass

$$M \lesssim 40\,\text{TeV}\,, 45\,\text{TeV}\,, 20\,\text{TeV} \qquad \text{for } S_3, V_1, V_3$$

- UV model building often in terms of strong dynamics

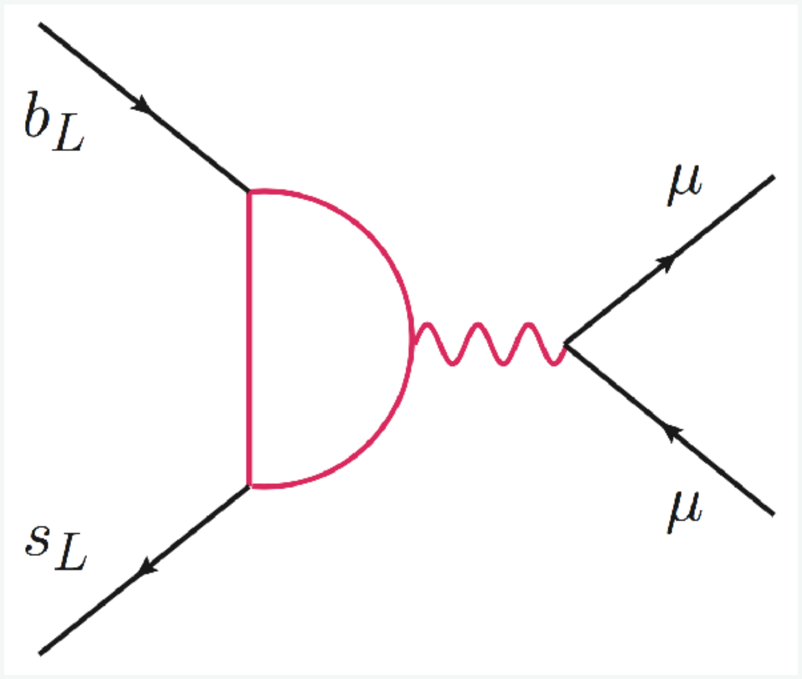
Gripaios, Nardecchia, Renner, 1412.1791; Gripaios, 0910.1789; Alonso et al, 1505.05164; Barbieri et al, 1512.01560, 1611.04930

LOOP LEVEL

in general in tension with direct searches

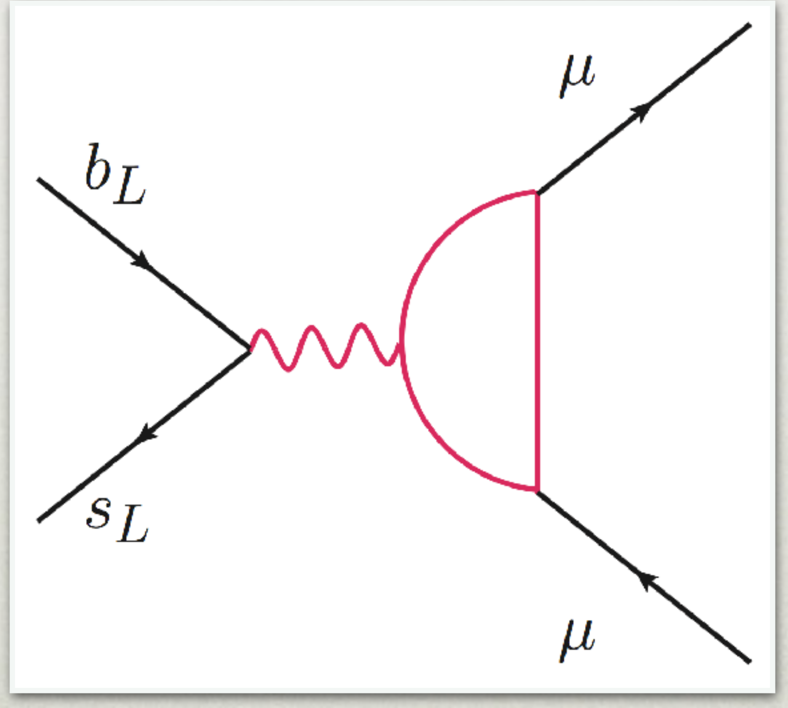
- three distinct options

- Z′ w/ loop to *bs*



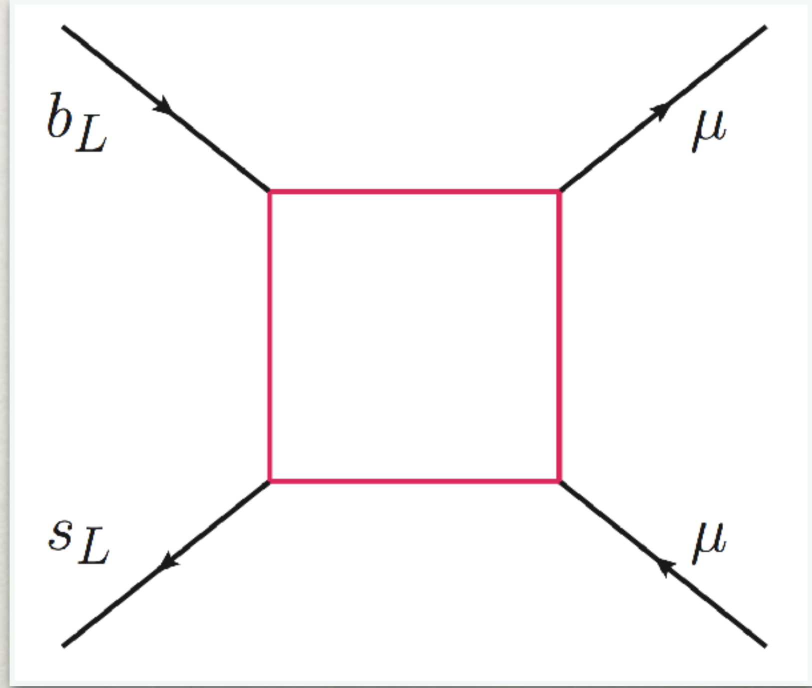
Kamenik, Soreq, JZ, 1704.06005

- Z′ w/ loop to $\mu\mu$



Bélanger, Delaunay, 1603.03333

- box w/ NP fields

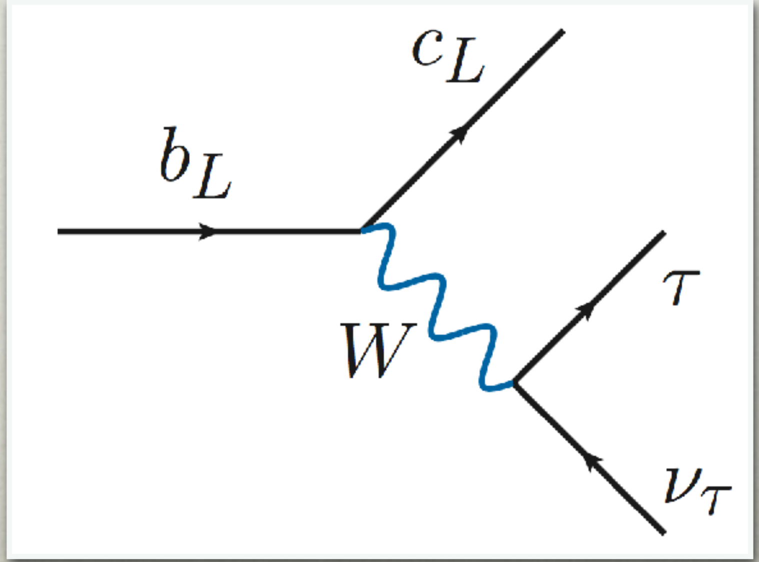


Gripaios, Nardecchia, Renner, 1509.05020;
Bauer, Neubert, 1511.01900;
Becirevic, Sumensari, 1704.05835

$b \to c \tau \nu$

UPSHOT

- $b \to c\tau\upsilon$ flavor anomaly
  - theoretically clean, ~4σ excess
  - NP effect large: *O(20%)* of SM tree level
    - NP interpr. often in conflict with other constraints

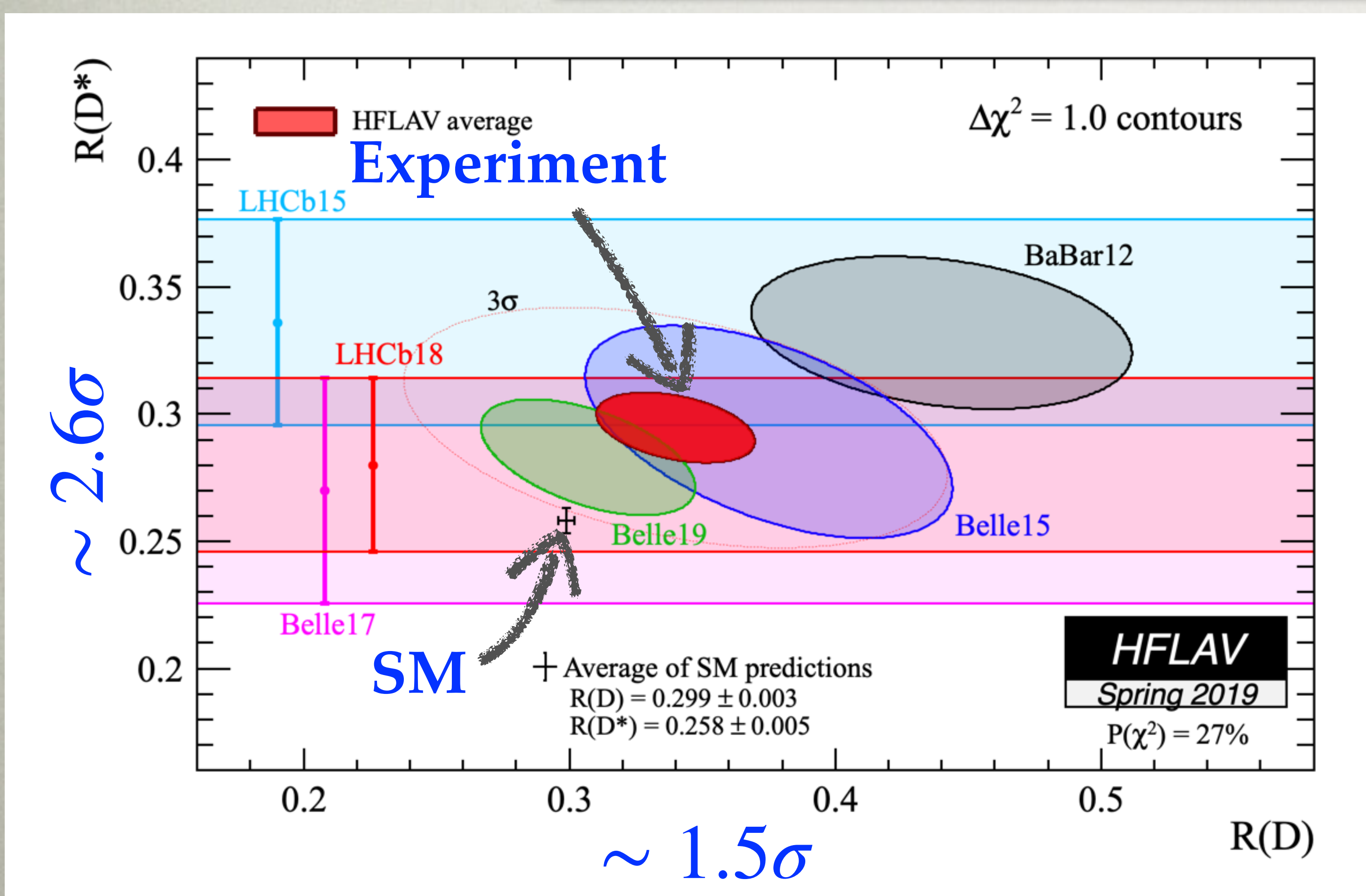


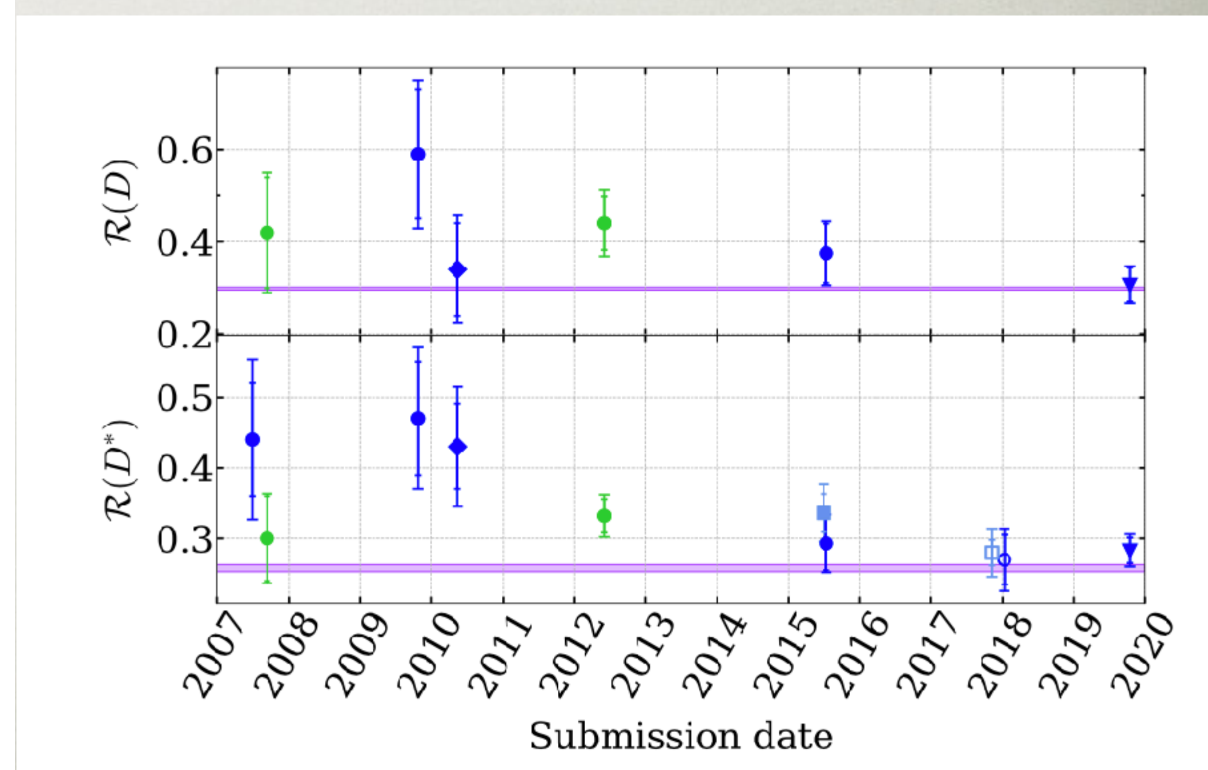
EXPERIMENTAL SITUATION

- seen in several experiments
- theory well under control

for theory predictions see, e.g.,
Fajfer, Kamenik, Nisandzic, 1203.2654
Bailey et al, 1206.4992
Becirevic, Kosnik, Tayduganov, 1206.4977
Bernlochner, Ligeti, Papucci, Robinson, 1703.05330
Bigi, Gambino, Schacht, 1707.09509

$$R(D^{(*)}) = \frac{\Gamma(\overline{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\overline{B} \to D^{(*)} l\bar{\nu})}, \qquad l = \mu, e$$

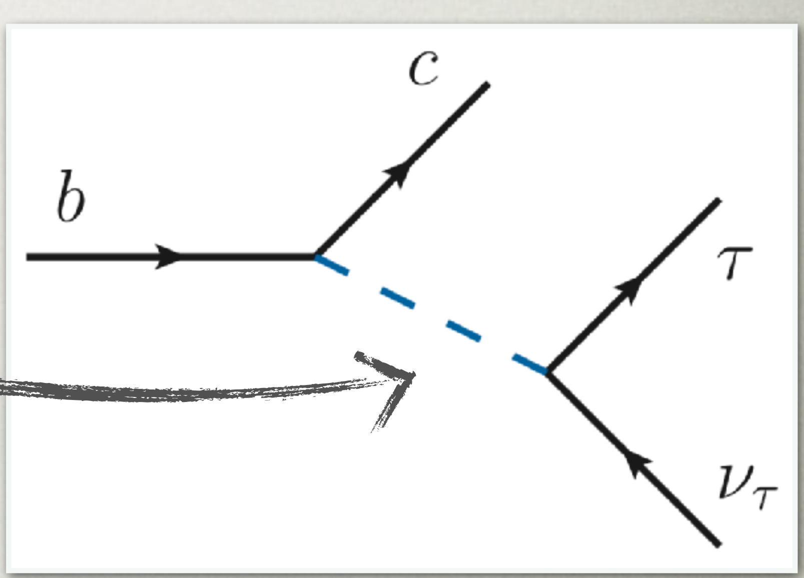


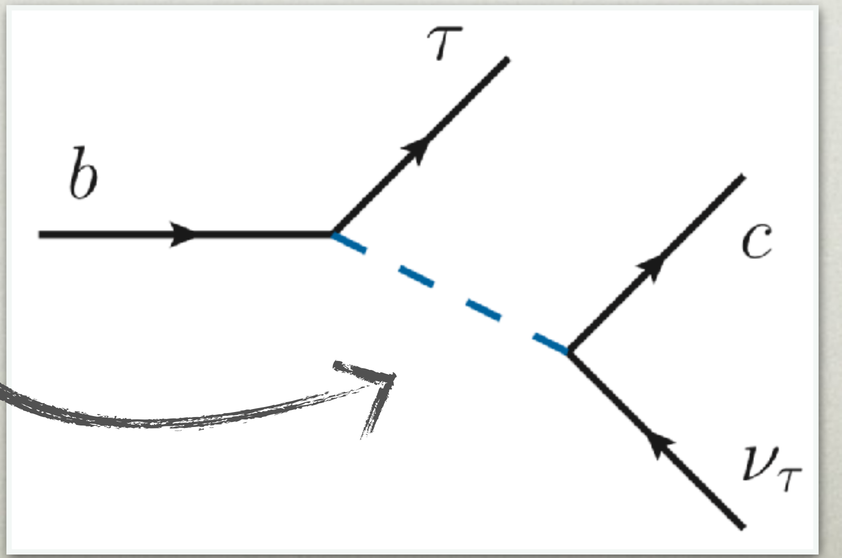


MODELS WITH SM NEUTRINO

Freytsis, Ligeti, Ruderman, 1506.08896
Faroughy, Greljo, Kamenik, 1609.07138

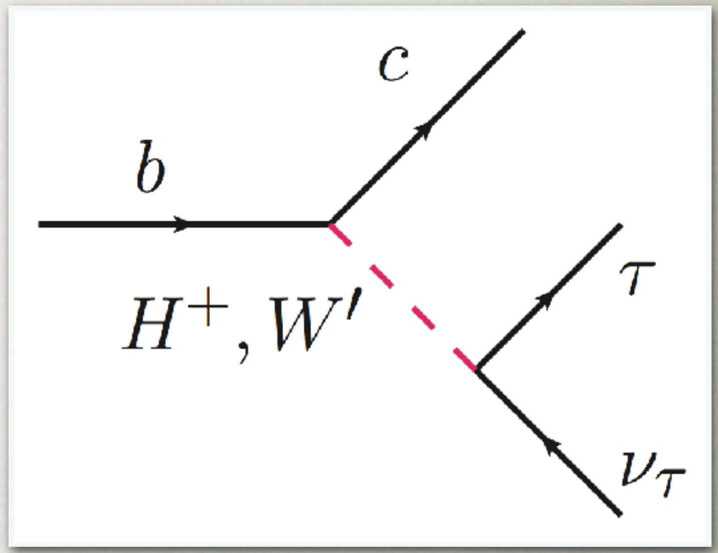
- big effect, needs to be tree level
- two types of exchanges
  - color singlet (W', H^+)
  - color octet (leptoquarks)

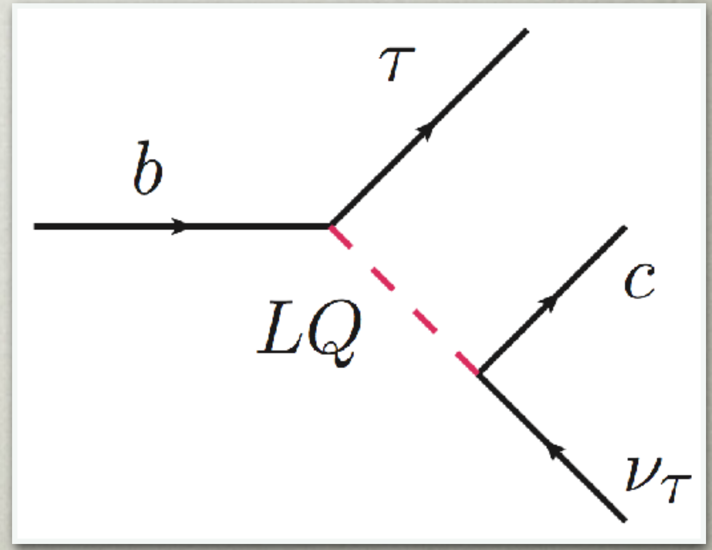




NEW PHYSICS INTERPRETATIONS

- the most obvious candidates ruled out
  - charged Higgs: total B_c lifetime, $b \to c\tau\upsilon$ q^2 distributions, searches in $pp \to \tau\tau$
  - W': related Z' ruled out from $pp \to \tau\tau$
- left with leptoquarks, some also ruled out

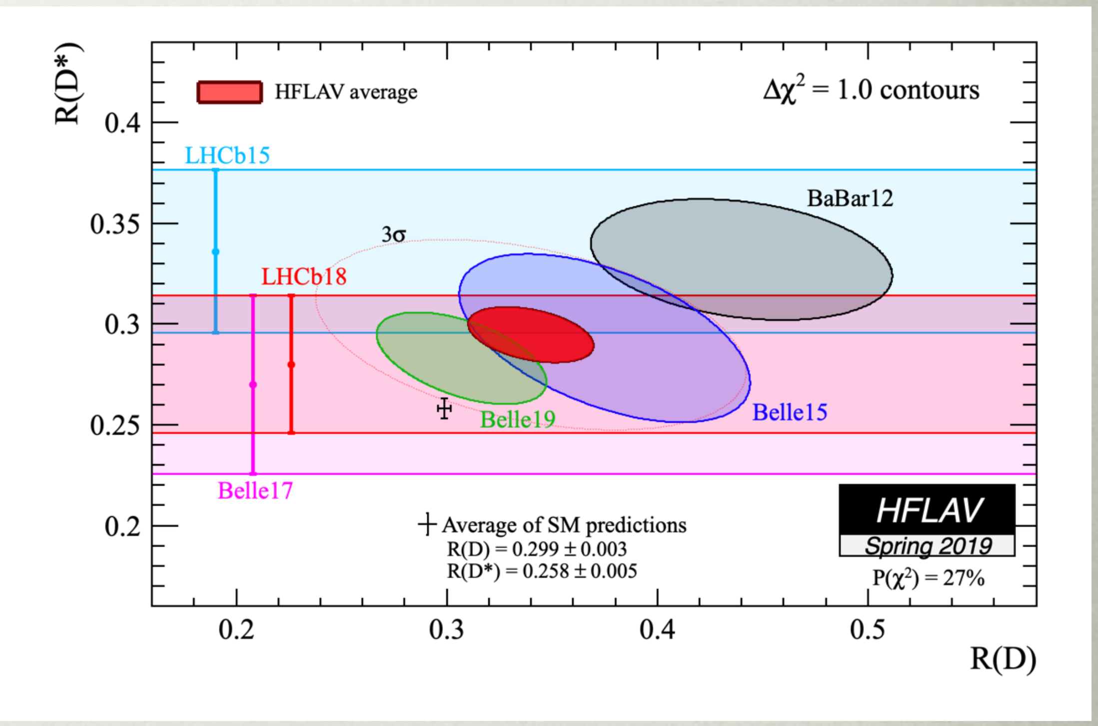


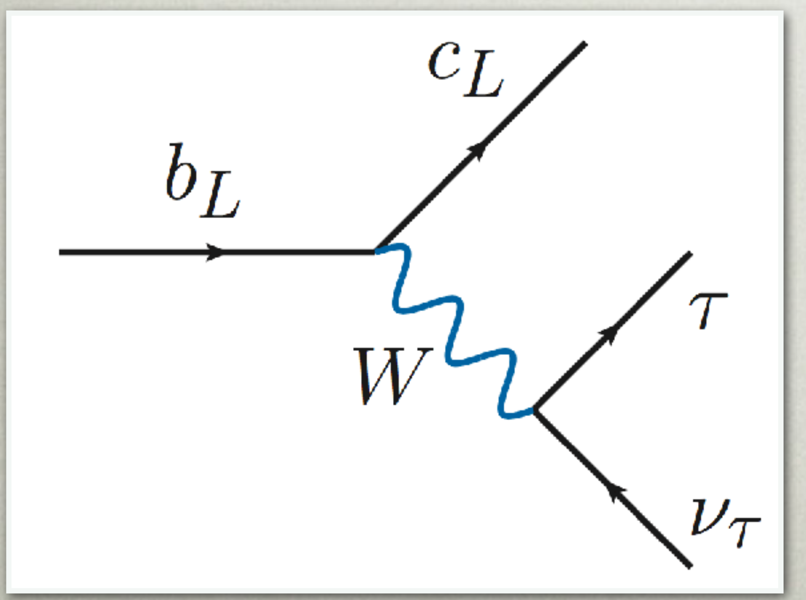


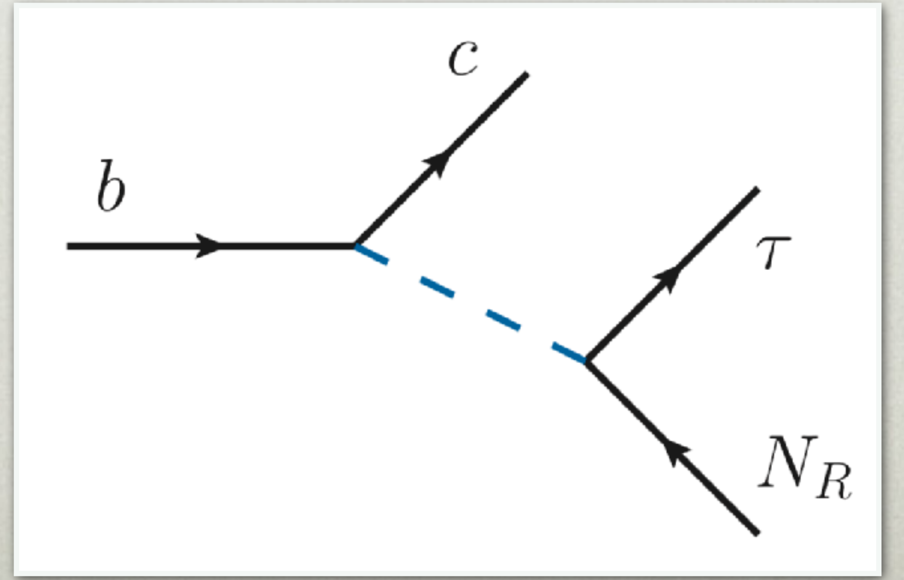
MODELS WITH RIGHT HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

- experimentally R_D, R_{D^*} above SM
- N_R not part of a doublet
  - no interf. between NP and SM
  - avoids some constraints from charged leptons
  - scale lower



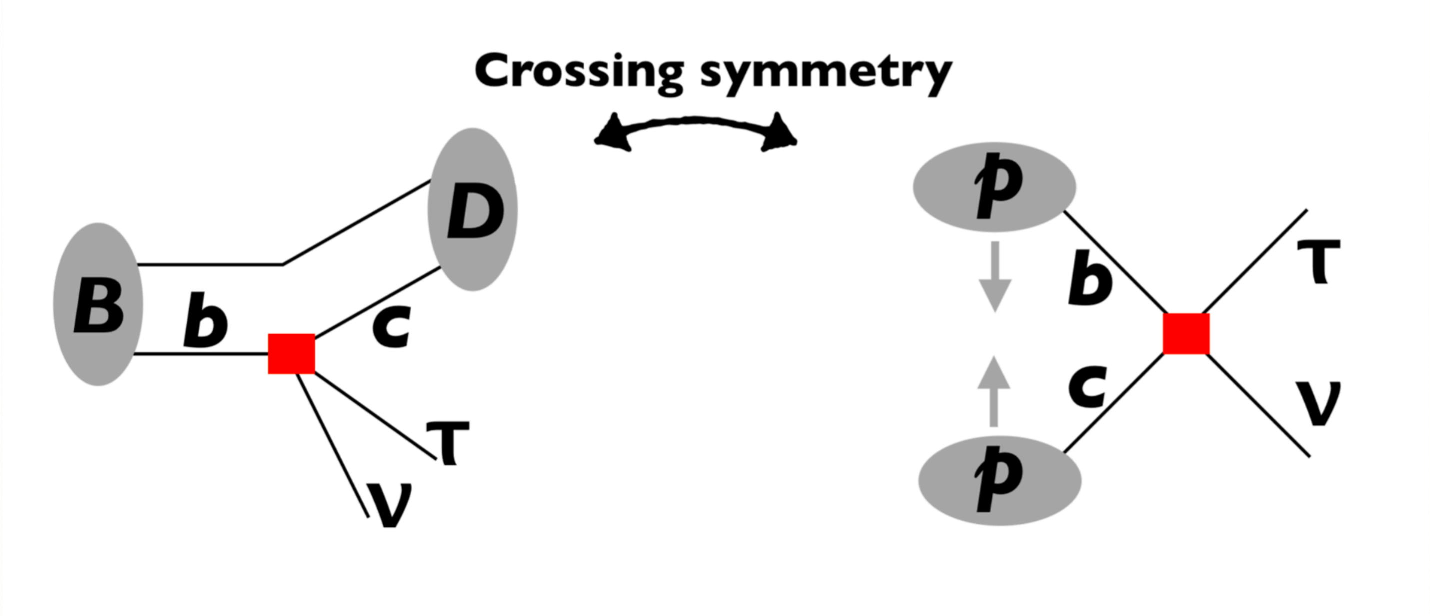




HIGH p_T CONSTRAINTS

- since mediator scale $\mathcal{O}$(TeV), can be searched for at the LHC
- model independent constraints from $pp \to \tau + \text{MET}$
  - rules out most of the solutions with RH neutrino

Greljo, Martin Camalich, Ruiz-Alvarez, 1811.07920



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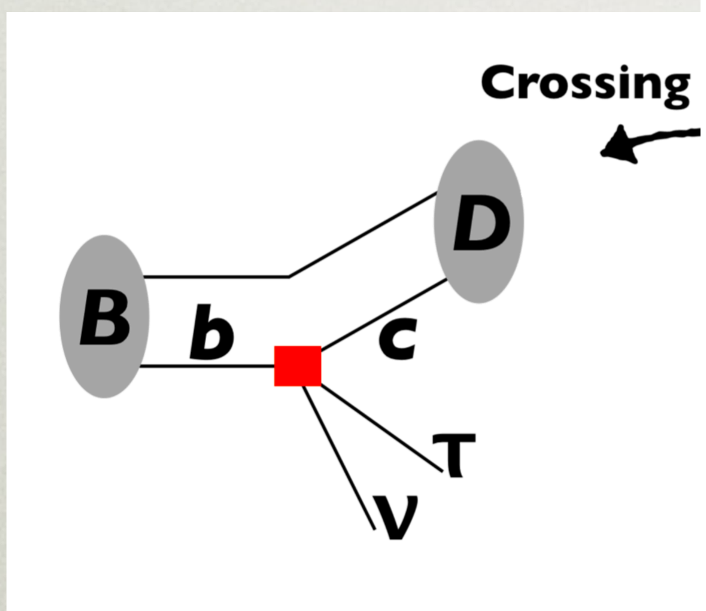
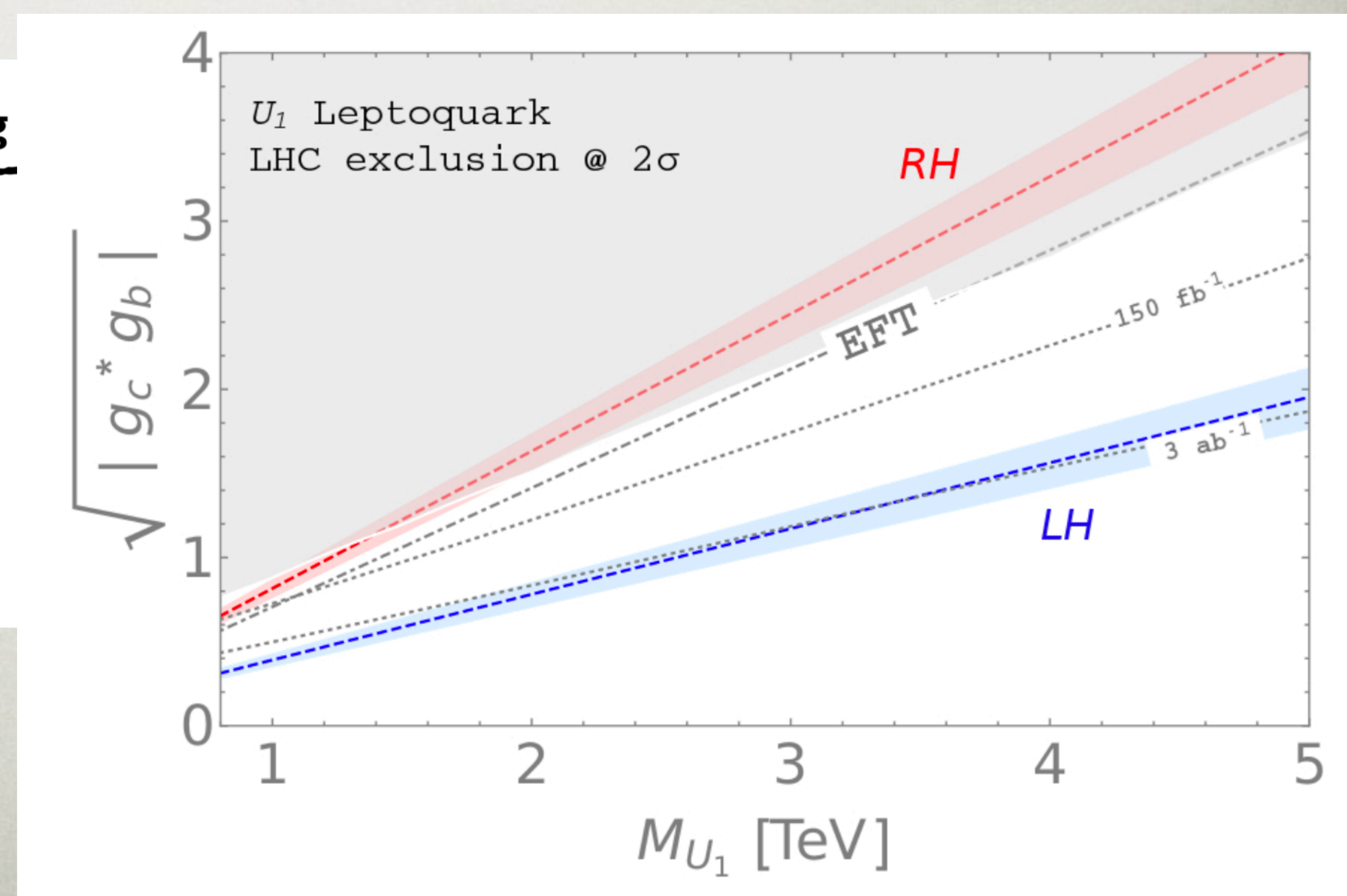




GRAND VIEW

COMBINED NP EXPLANATIONS

- all anomalies or a subset?
- $R_{K^{(*)}}$ and $R_{D^{(*)}}$
    - vector leptoquark $U_1 \sim (3,1,2/3)$ Cornella et al., 2103.16558 + many refs.
        - UV realization: 4321 model?
    - 2 scalar leptoquarks $S_3 \sim (\bar{3},3,1/3)$, $S_1 \sim (\bar{3},1,1/3)$
        - UV realization: composite Higgs? Crivellin, Muller, Ota, 1703.09226 +many refs.
- $R_{K^{(*)}}$ and $(g-2)_\mu$
    - 2 scalar leptoquarks $S_3 \sim (\bar{3},3,1/3)$, $S_1 \sim (\bar{3},1,1/3)$ Greljo et al, 2103.13991
    - from simplified DM models in the loop Arcadi, Calibbi, Fedele, Mescia, 2104.03228
- $R_{K^{(*)}}$ and $R_{D^{(*)}}$ and $(g-2)_\mu$

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

What LQ scenario?

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

from a talk by D. Becirevic at EW Moriond 2021

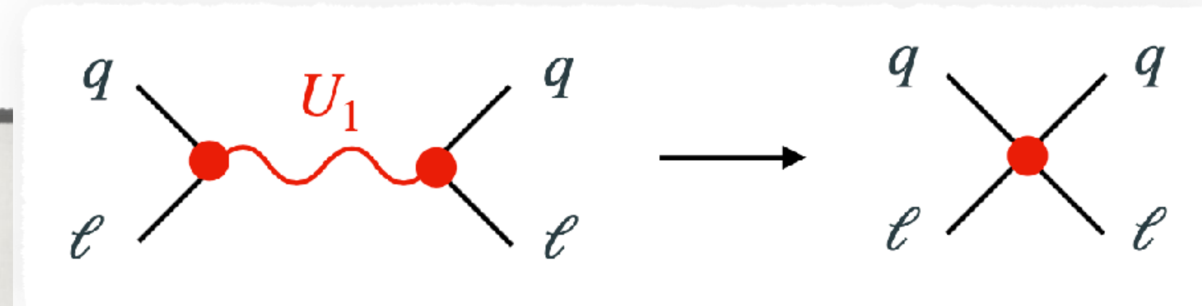
figure credits, talk by Fuentes Moriond 2021

VECTOR LEPTOQUARK U_1 FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$

- effective Lagrangian for $U_1 \sim (3,1,2/3)$ vector leptoquark

Cornella et al., 2103.16558+many refs

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



- $U(2)^3$ MFV flavor structure assumed
  - agrees well with data for U_1 as well

Barbieri et al., 1105.2296
Kagan, Perez, Volansky, JZ, 0903.1794

$$Y_{u(d)} = y_{t(b)} \begin{pmatrix} \Delta_{u(d)} & x_{t(b)} V_q \\ 0 & 1 \end{pmatrix}$$

$U(2)_q$, $U(2)_{u(d)}$

$$Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}$$

$U(2)_\ell$, $U(2)_e$

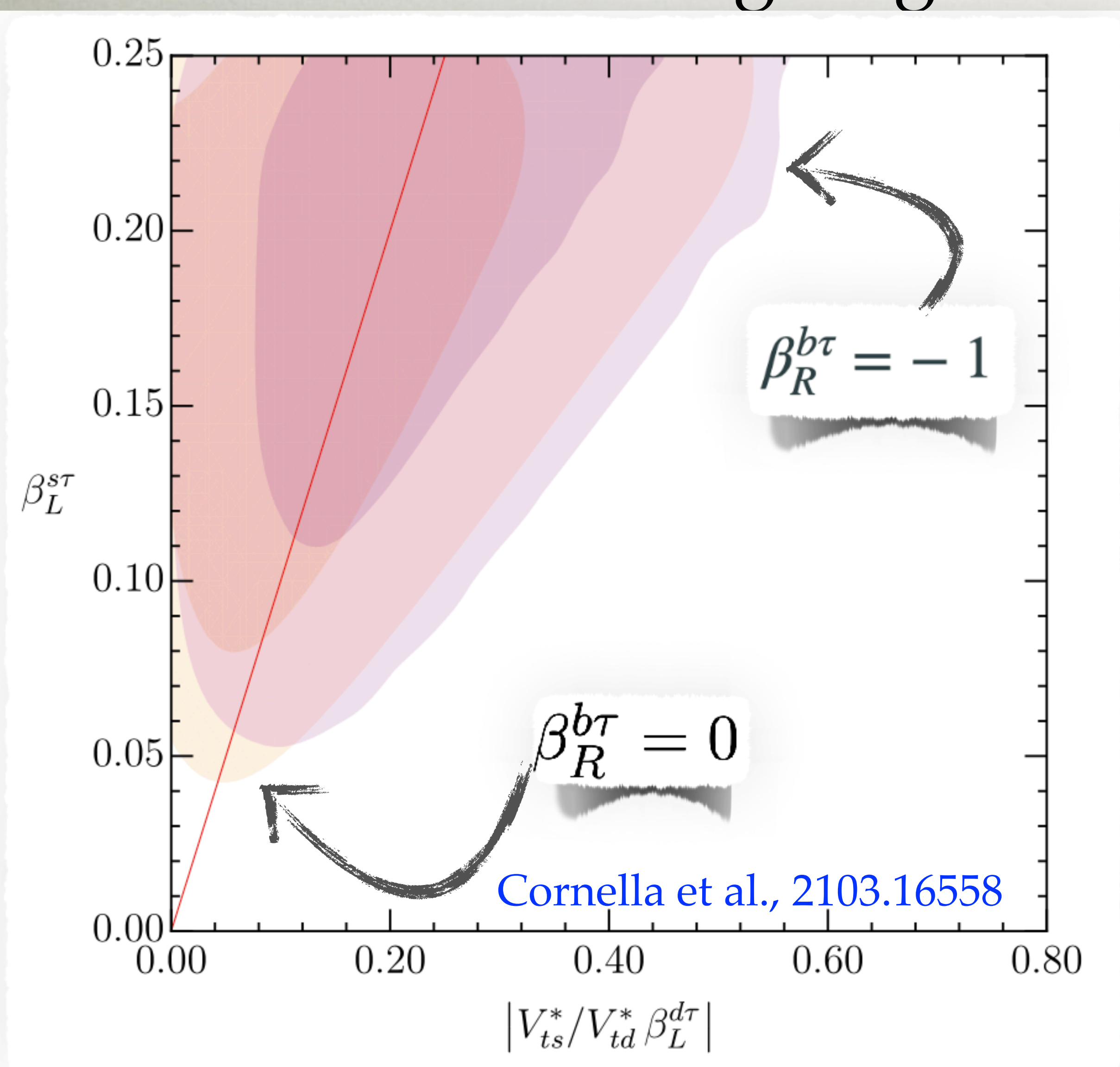
figure credits, talk by Fuentes Moriond 2021

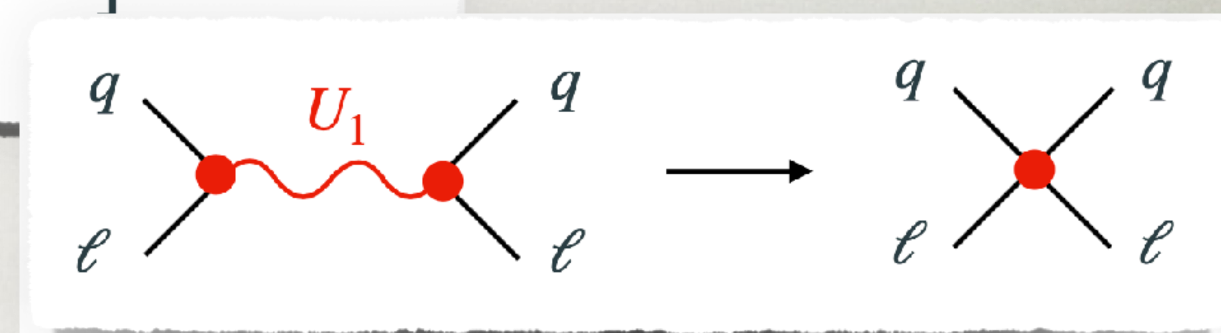
VECTOR LEPTOQUARK U_1 FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$

- effective Lagrangian for $U_1 \sim (3,1,2/3)$ vector leptoquark

Cornella et al., 2103.16558+many refs

$(\bar{d}^i_R \gamma_\mu e^\alpha_R)\Big] + \mathrm{h.c.}$





…cture assumed

Barbieri et al., 1105.2296

Kagan, Perez, Volansky, JZ, 0903.1794

…a for U_1 as well

$U(2)_{u(d)}$

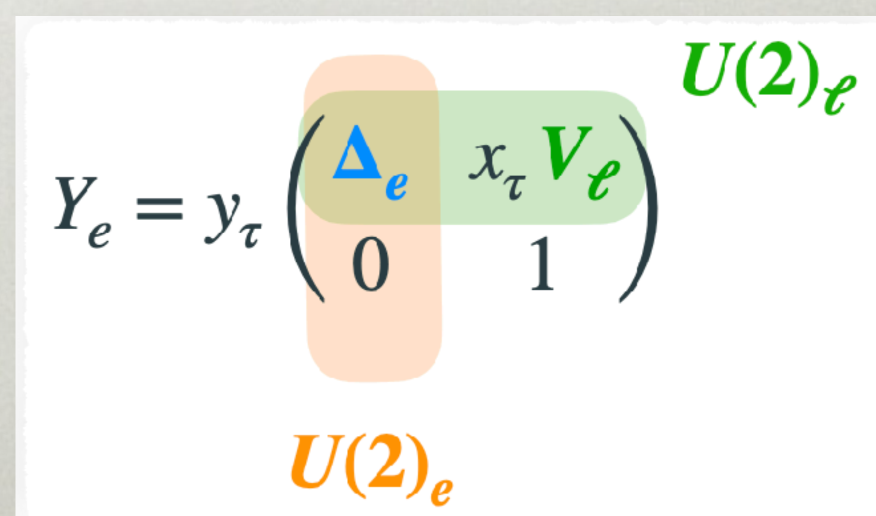
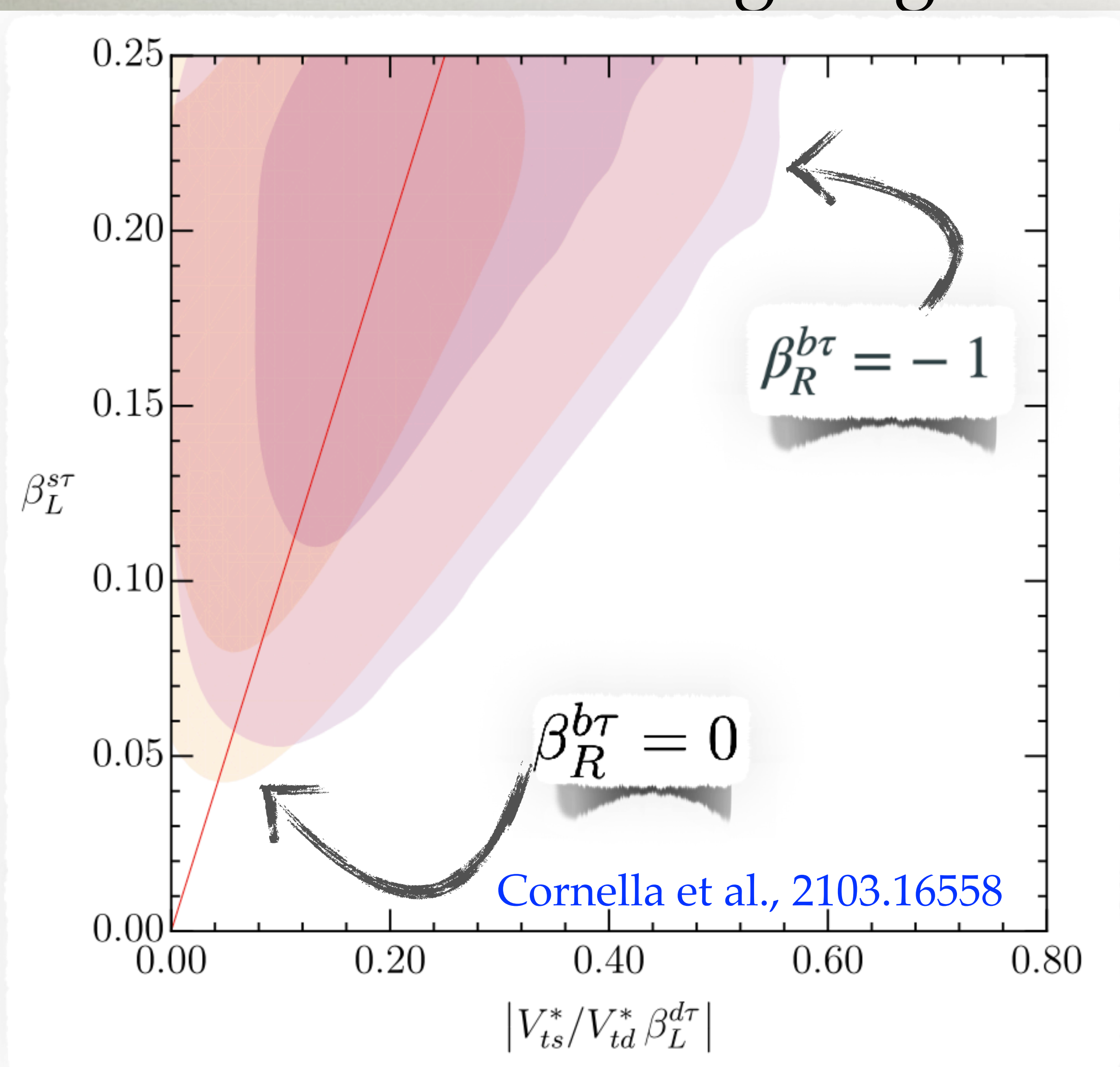
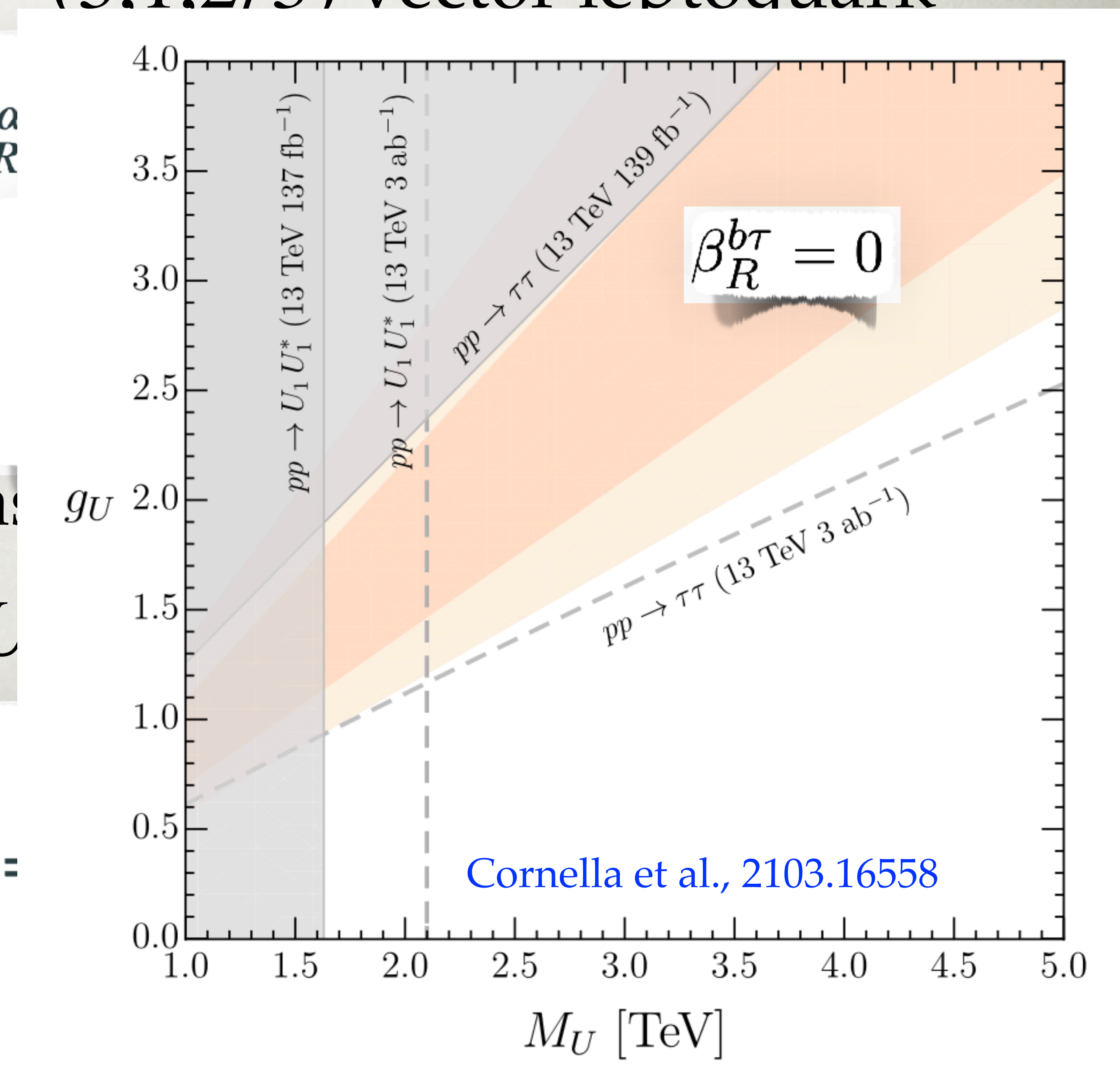


figure credits, talk by Fuentes Moriond 2021

VECTOR LEPTOQUARK U_1 FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$

- effective Lagrangian for $U_1 \sim (3,1,2/3)$ vector leptoquark

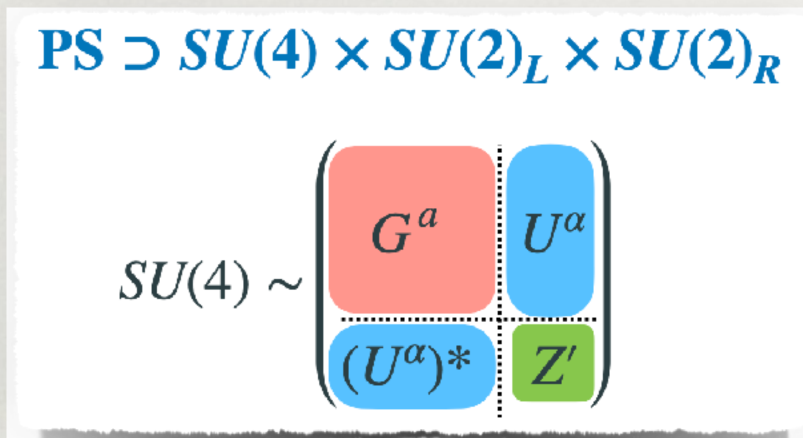


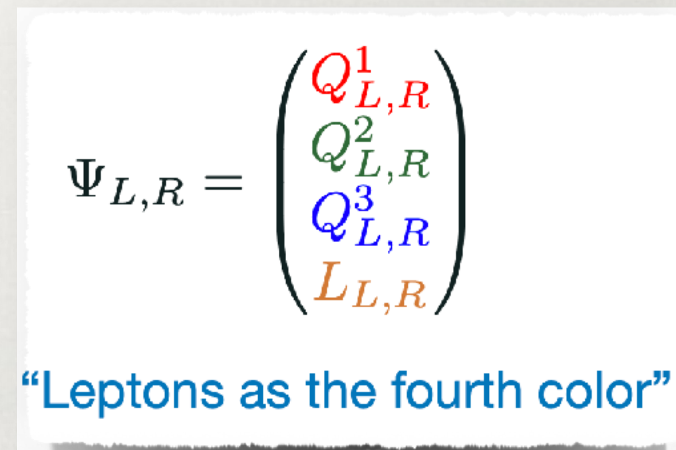


4321 MODEL

Pati, Salam, Phys. Rev. D10 (1974) 275

- U_1 gauge boson arises in Pati-Salam unification

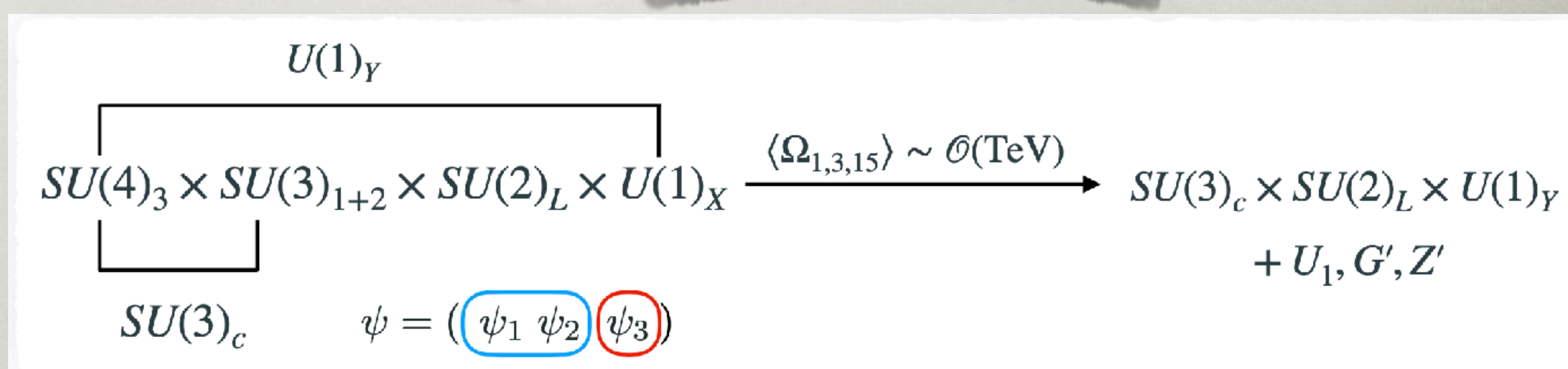




- 4321 model

Di Luzio et al, 1708.08450

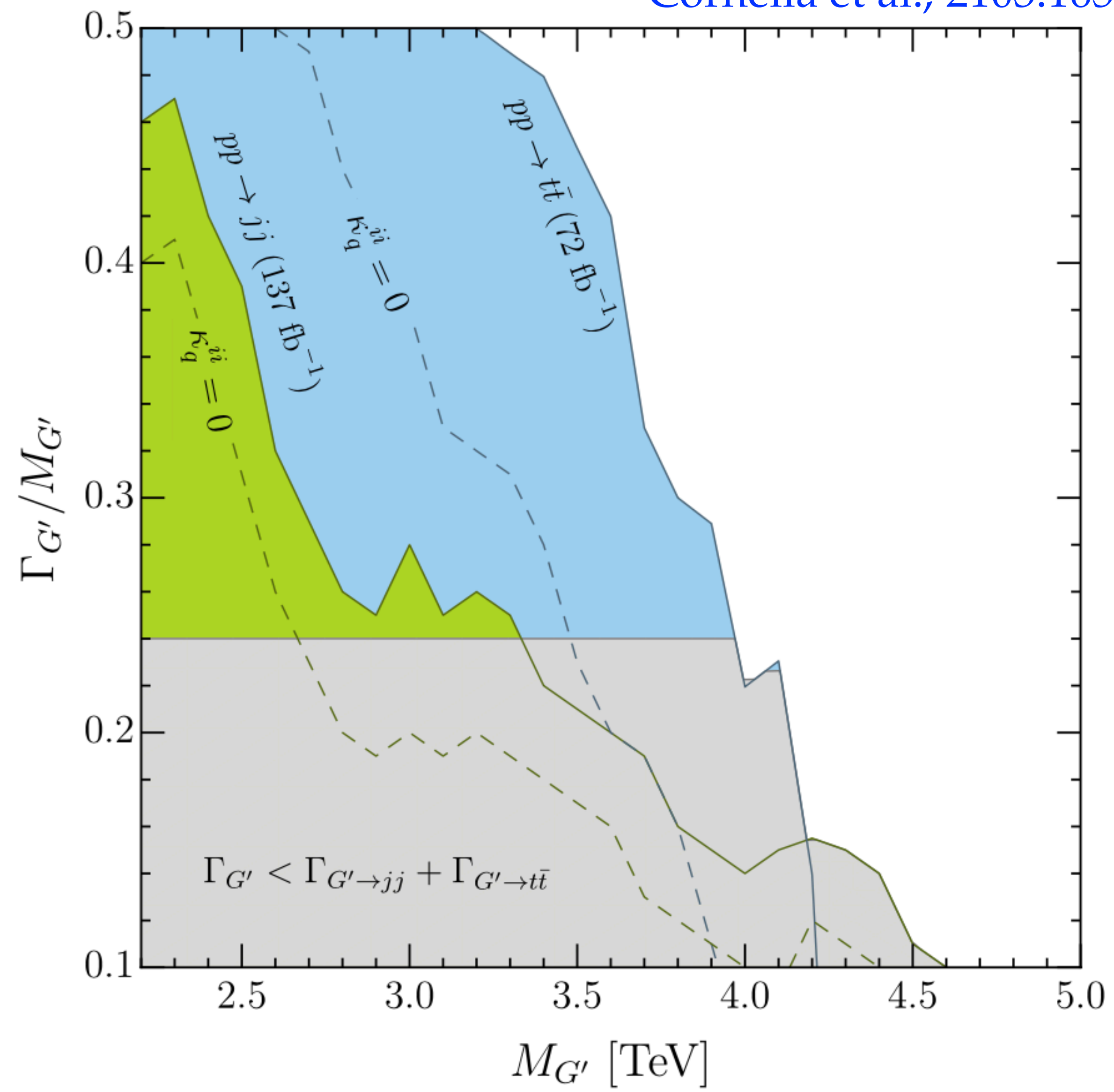
Bordone et al, 1712.01368, 1805.09328
Greljo, Stefanek, 1802.04274;
Cornella et al, 1903.11517



- cannot be flavor universal: $K_L \to \mu e$ would bound $M_U > 100\,\text{TeV}$
- 3rd generation gauged under SU(4)
- additional states: G', Z'

...s, talk by Fuentes Moriond 2021

Cornella et al., 2103.16558



Salam, Phys. Rev. D10 (1974) 275

- U_1 gauge b...

...h color”

- 4321 mode...

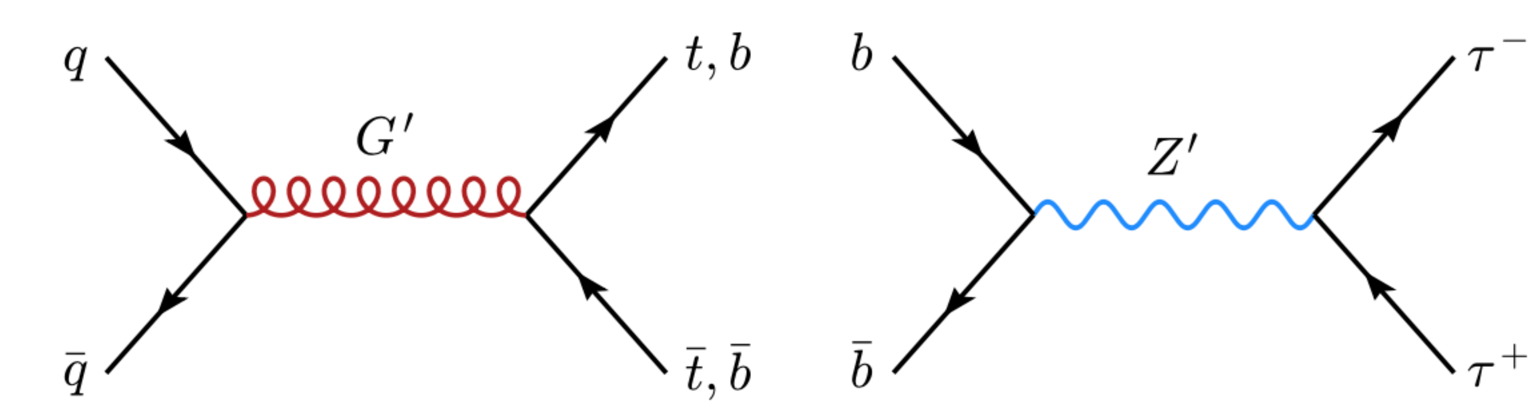
Di Luzio et al, 1708.08450

Bordone et al, 1712.01368, 1805.

Greljo, Stefanek, 1802.04274:

Cornella et al, 1903.1

...V) $\longrightarrow$ $SU(3)_c \times SU(2)_L \times U(1)_Y$
$+ U_1, G', Z'$



- ca... $M_U > 100\,\text{TeV}$
- 3r...
- additional states: G', Z'

$R_{K^{(*)}}$ AND $(g-2)_\mu$

SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- can a single mediator explain both $(g-2)_\mu$ and $b \to s\mu\mu$ anomalies?
  - each separately possible with neutral spin-1 boson X_μ
    - for $(g-2)_\mu$ required to be light, $m_X \lesssim \mathcal{O}(\text{few GeV})$
    - for $b \to s\mu\mu$ can be light ~GeV or very heavy ~10s TeV
- however, not possible to explain both at the same time
  - $\Rightarrow$ combined explanation requires at least two new states

SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- can a single mediator explain both $(g-2)_\mu$ and $b \to s\mu\mu$ anomalies?
- the relevant effective interactions

$$\mathcal{L}_{\rm eff} \supset + g_X\,(q_V + q_A)\,\overline{\nu_{\mu L}}\,\not{X}\,\nu_{\mu L} + g_X\,\bar{\mu}\,\not{X}\,(q_V - q_A\,\gamma_5)\,\mu + \Big[\bar{b}\,\not{X}\,(g_L^{bs}\,P_L + g_R^{bs}\,P_R)\,s \;+\; {\rm H.c.}\Big]\,,$$

- for $(g-2)_\mu$ need $g_V \gg g_A$

$$g_X = \left(\frac{\Delta a_\mu}{251\times 10^{-11}}\right)^{1/2} \begin{cases} 4.5\times 10^{-4}\big[q_V^2 - 2\,q_A^2\,r_\mu^2\big]^{-1/2}, & m_X \ll m_\mu, \\ 5.5\times 10^{-4} r_\mu^{-1/2}\big[q_V^2 - 5\,q_A^2\big]^{-1/2}, & m_X \gg m_\mu. \end{cases}$$

- $\Rightarrow X_\mu$ necessarily couples to neutrinos*

* as long as EFT applies, i.e. dim 6 ops not cancelled by dim 8

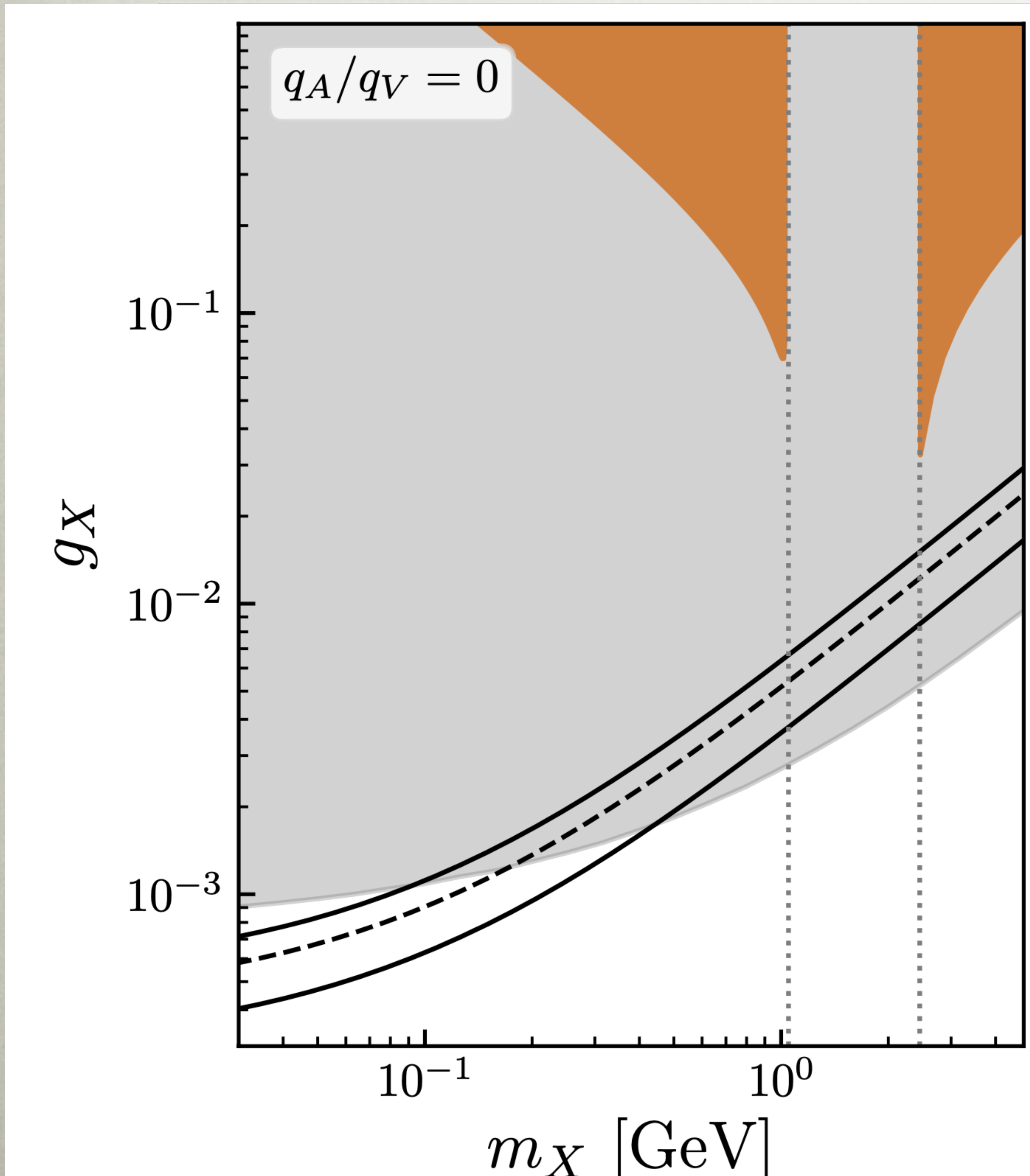
SINGLE MEDIATOR?

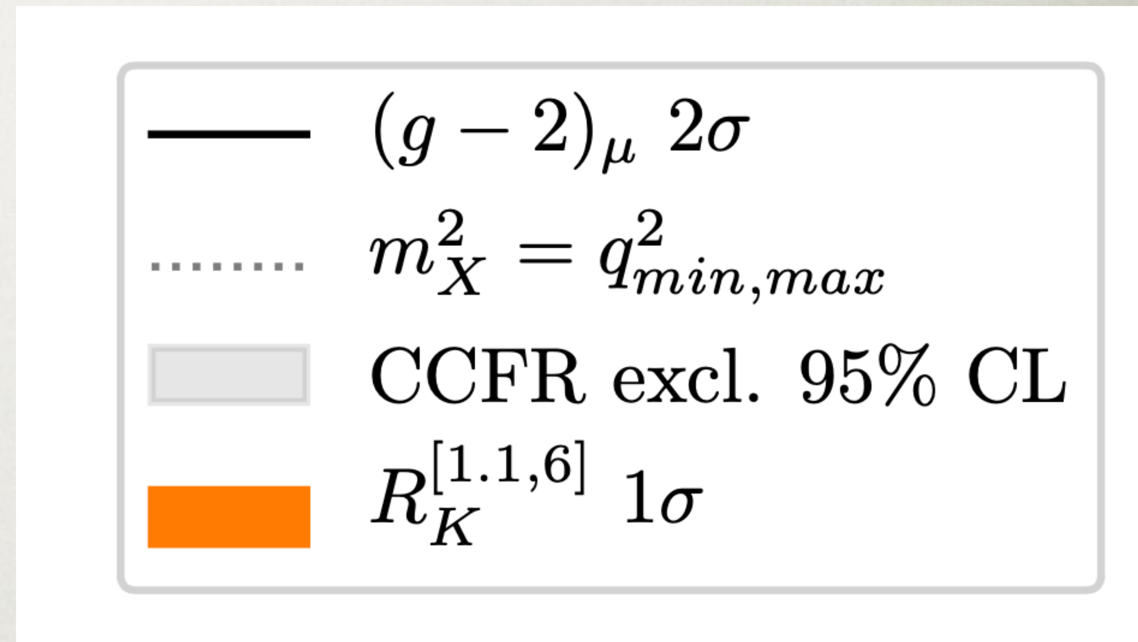
Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- because of X_μ couplings to neutrinos competing requirements
  - $B \to K\nu\nu$ bound implies small g_L^{bs}
  - neutrino trident bound implies small $g_X(q_V + q_A)$
  - $B \to K\mu\mu$ requires large enough $g_L^{bs} g_X q_{V,A}$
  - $(g-2)_\mu$ requires large enough $g_X q_V$

SINGLE MEDIATOR?

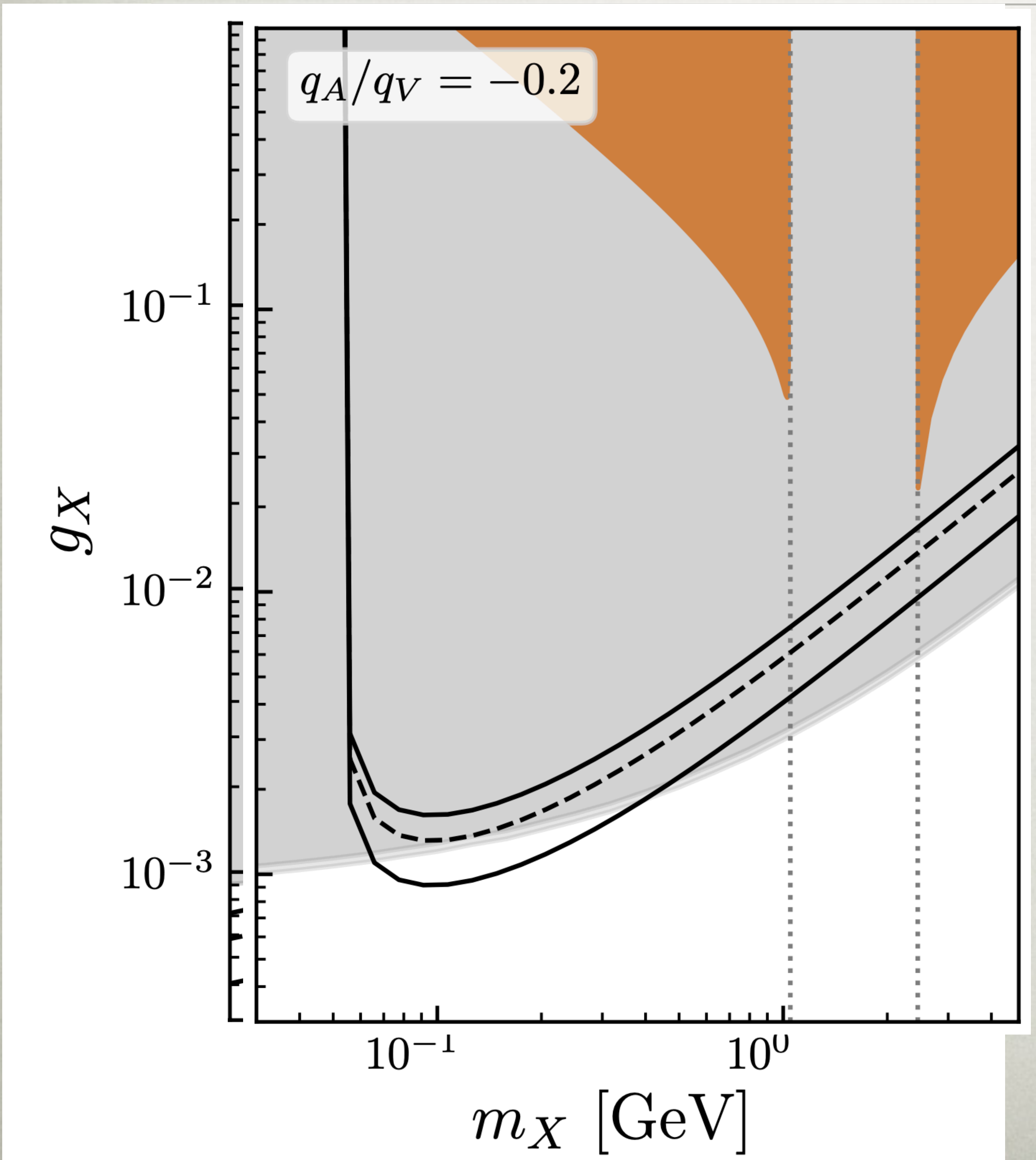
Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

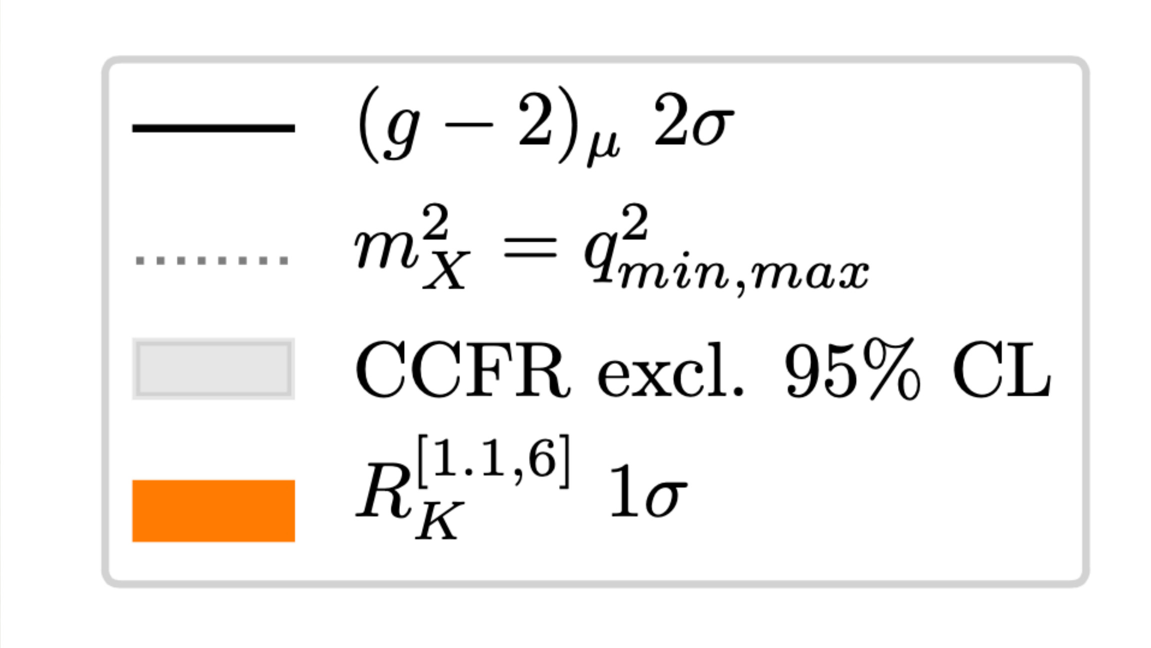




SINGLE MEDIATOR?

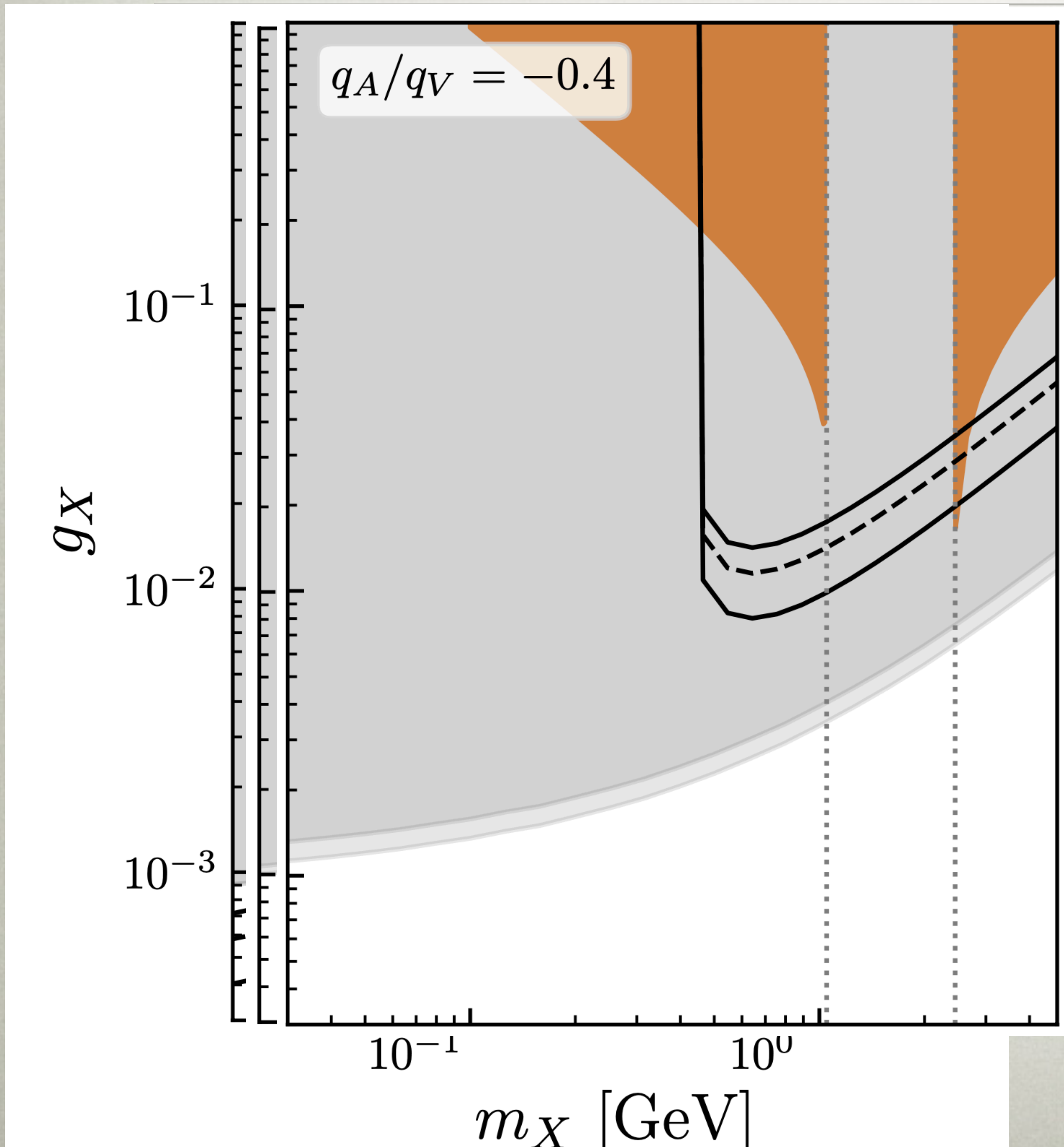
Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

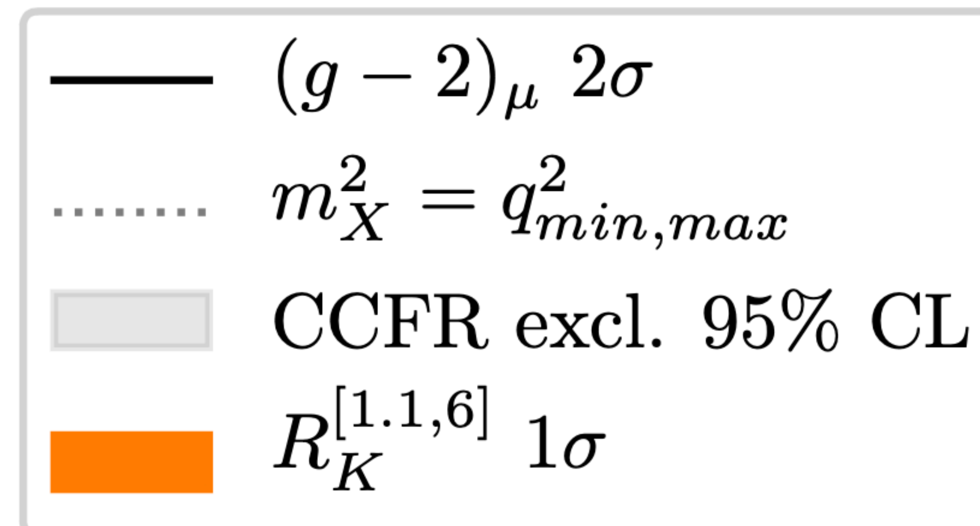




SINGLE MEDIATOR?

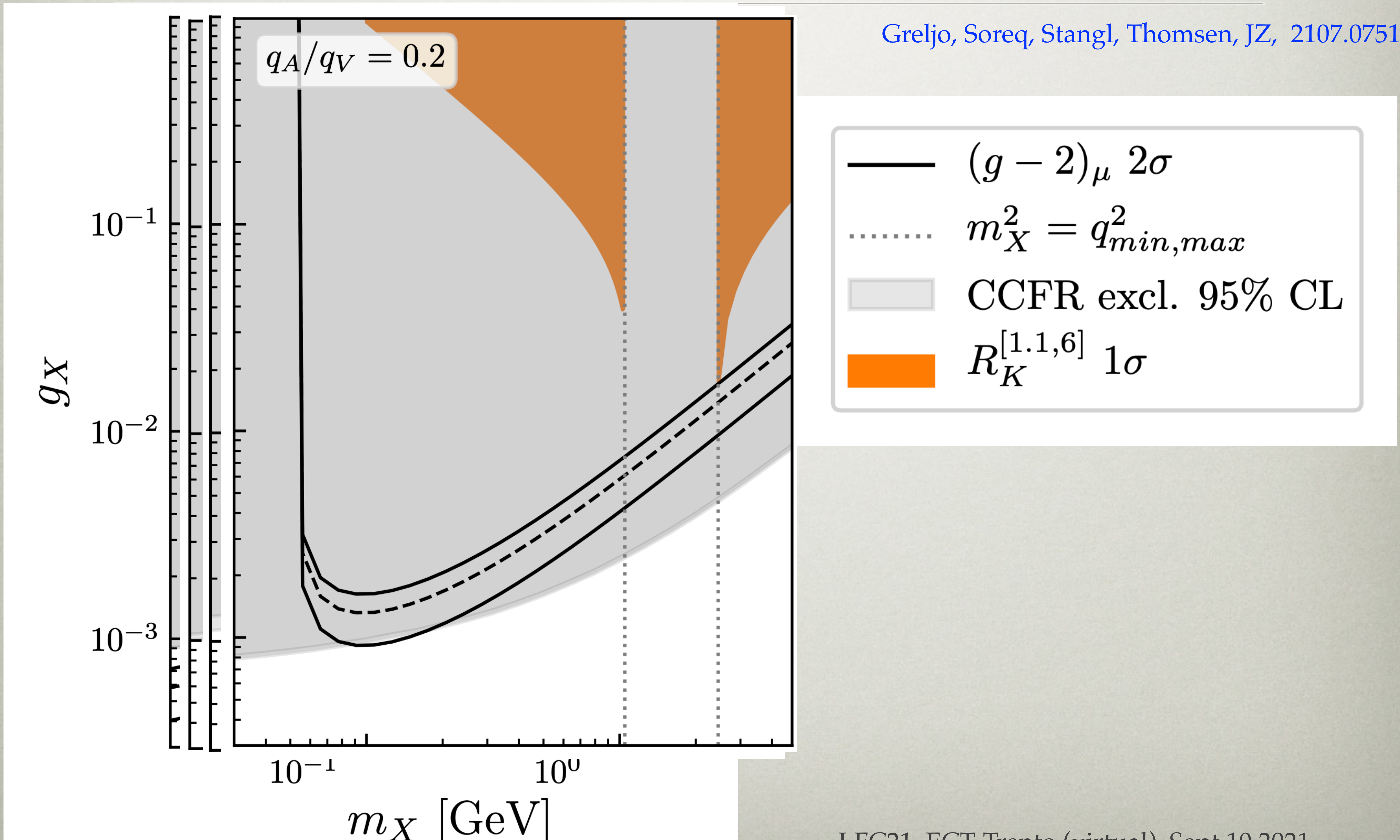
Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518





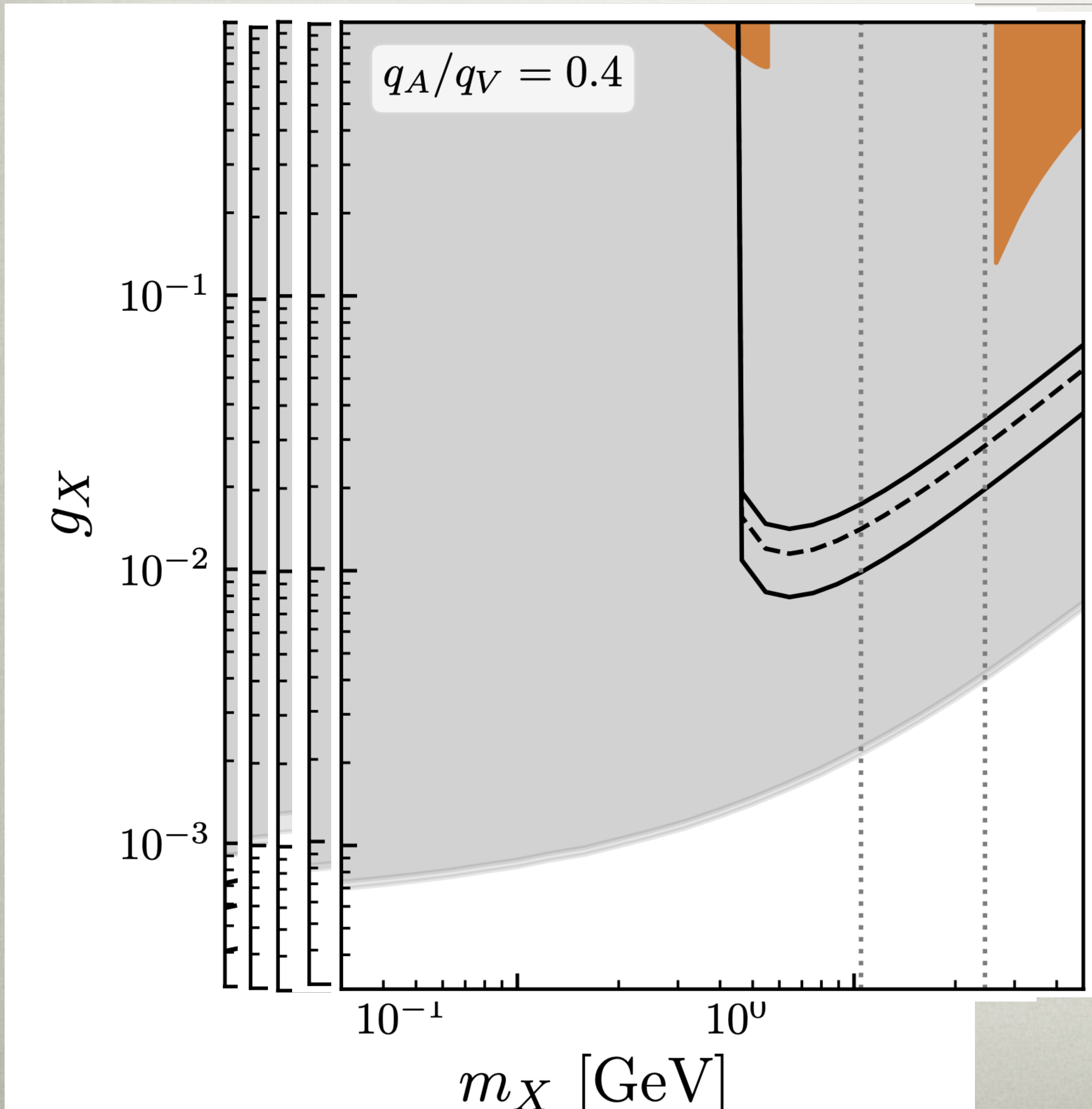
SINGLE MEDIATOR?

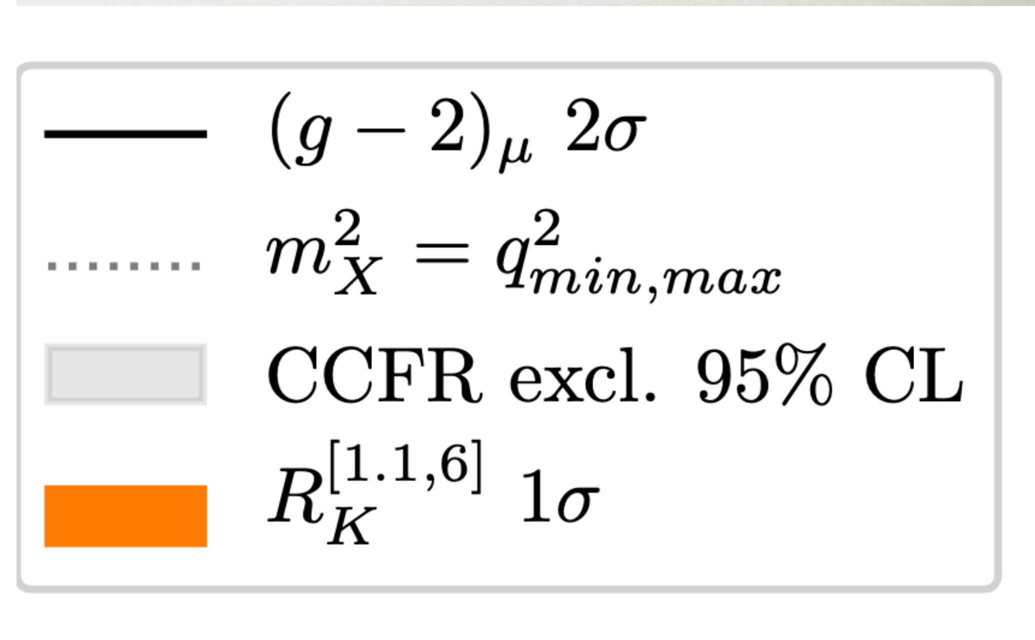
Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518



SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518





$(g-2)_\mu$, $b \to s\mu\mu$ FROM $U(1)_X$ AND LQ

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- $R_{K^{(*)}}$ from tree-level LQ exchange
  - for instance from $S_3 = (\bar{3}, 3, 1/3)_{8/3}$
- $(g-2)_\mu$ from $U(1)_X$ gauge boson
- the $U(1)_X$ solves the flavor problem
  - gauge charges such that S_3 only couples to muons, not τ, e $\Rightarrow$ LQ is a "*muoquark*"
    - $\Rightarrow$ no FCNC problems
  - universal charges for quarks
  - gauge charges such that forbid (too fast) proton decay
    - no dim5 ops. mediating proton decay

$(g-2)_\mu$, $b \to s\mu\mu$ from $U(1)_X$ and LQ

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- exploration of viable charge assignments for SM+$3\nu_R$ field content
- require anomaly free charge assignments
  - keeping max charge ratios $\leq 10 \Rightarrow$ 273 models (out of $\sim 2 \cdot 10^7$)
  - two categories of charge assignments

$$\textbf{vector category}: \quad X_{L_i} = X_{E_i} \quad \text{for all} \quad i = 1,2,3\,,$$
$$\textbf{chiral category}: \quad \text{the rest.}$$

  - in vector category 3 parameter families of solutions, with the lepton charges given by (up to flavor permutations)

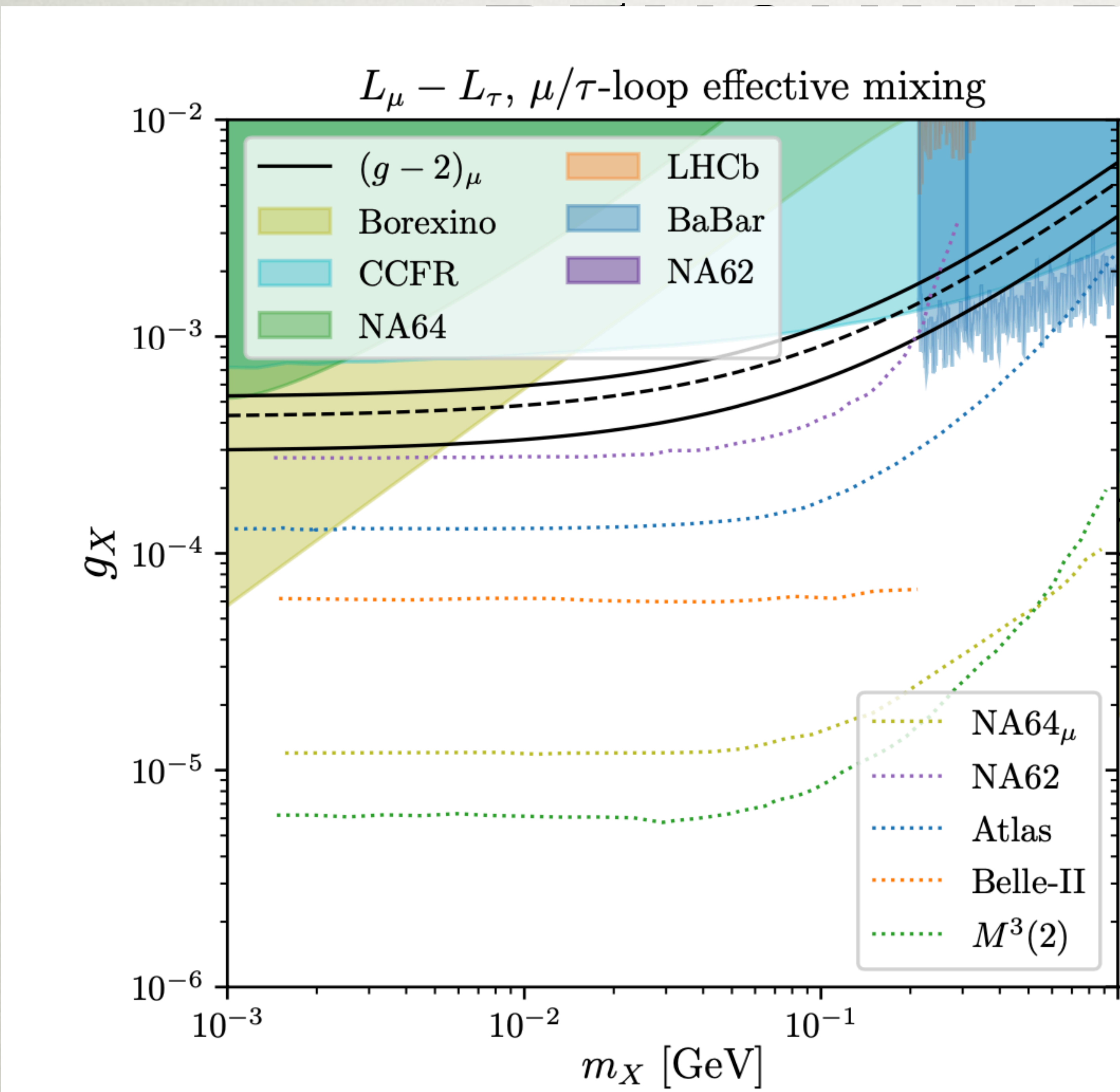
$$\text{Class 1}: \quad X_e = X_{N_1}, \quad X_\mu = X_{N_2}, \quad X_\tau = X_{N_3},$$
$$\text{Class 2}: \quad X_e = X_{N_1}, \quad X_\mu = -X_\tau, \quad X_{N_2} = -X_{N_3},$$
$$\text{Class 3}: \quad \text{the rest.}$$

  - note: the classes may overlap, e.g., $L_\mu - L_\tau$ is both Class 1 and 2

BENCHMARKS

- several relevant constraints
  - neutrino trident, light resonance searches, neutrino electron scattering (Borexino), nonstandard neutrino interactions
- benchmark models that can explain $b \to s\mu\mu$ through S_3 exchange and $(g-2)_\mu$ through $U(1)_X$ gauge boson
  - $L_\mu - L_\tau$: viable region near $m_X \sim 20\text{MeV}$
  - $L_\mu - L_e$: viable region if kinetic mixing recudes couplings to electrons $X_{\text{eff}} = X_e - \dfrac{e}{g_X}\varepsilon$
  - chiral $\tilde{L}_{\mu-\tau}$: possible viable region near $m_X \sim 20\text{MeV}$
  - other possible benchmarks, $B - 3L_\mu$, $\tilde{L} - 3B$,...

RKS



rches, neutrino electron

ieutrino interactions

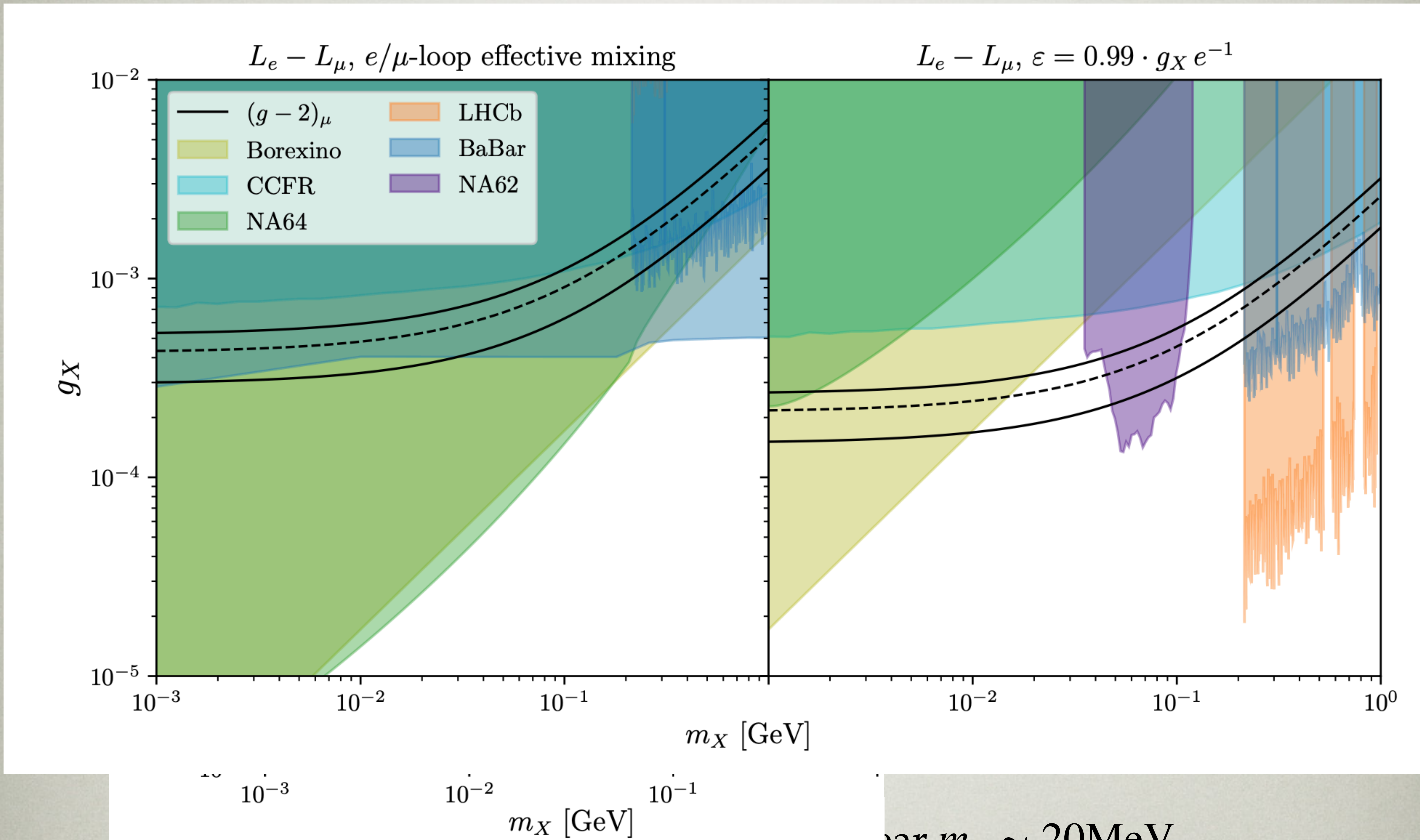
$\to s\mu\mu$ through S_3

auge boson

MeV

ng recudes couplings to

- ar $m_X \sim$ 20MeV
- other possible benchmarks, $B - 3L_\mu$, $\tilde{L} - 3B$,...

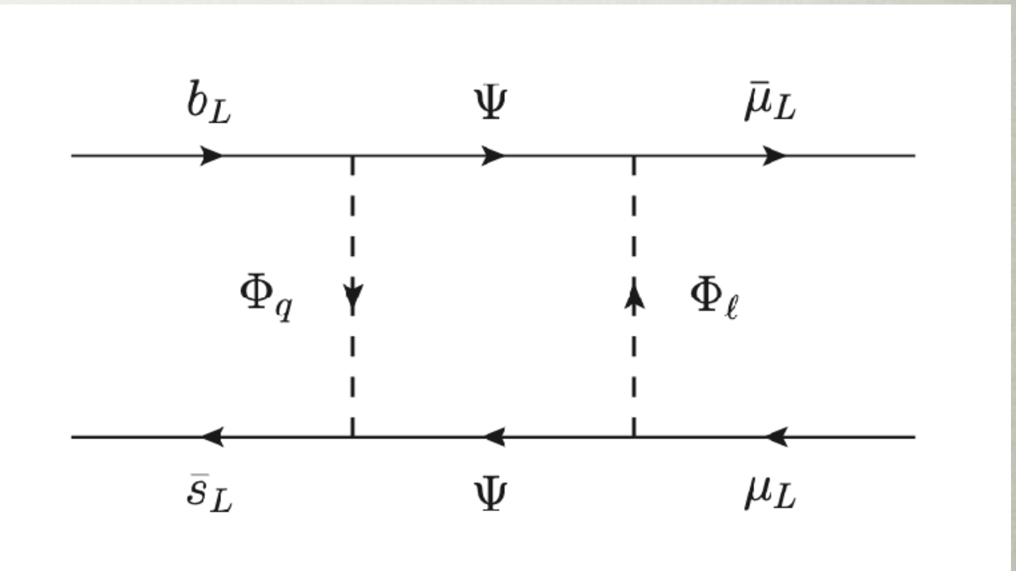


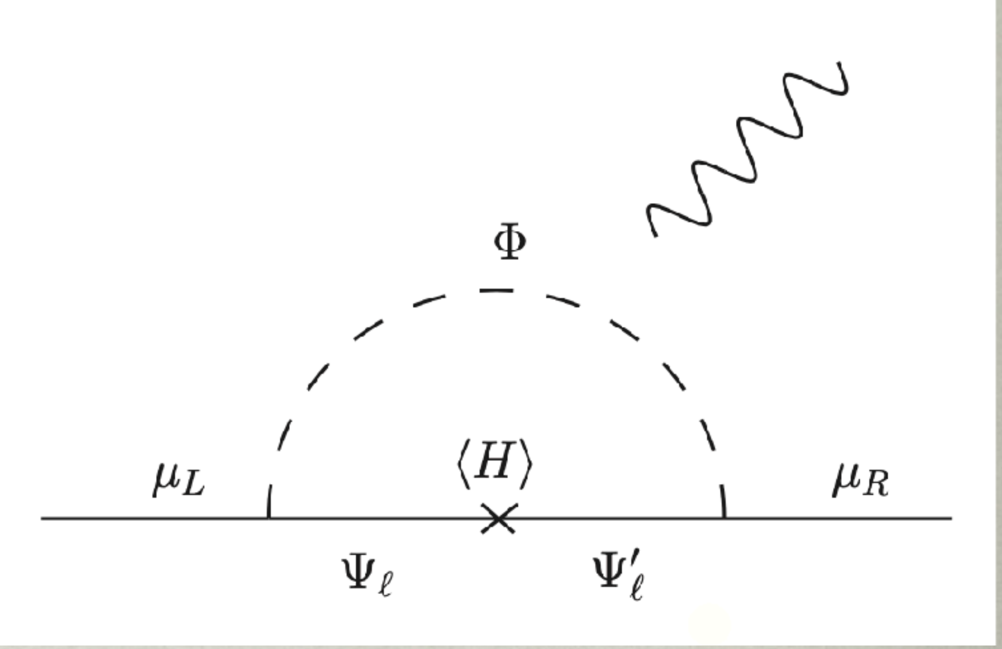
- chiral $L_{\mu-\tau}$: possible viable region near $m_X \sim 20$MeV
- other possible benchmarks, $B - 3L_\mu$, $\tilde{L} - 3B$,...

SIMPLIFIED DM MODELS FOR $R_{K^{(*)}}$ AND $(g-2)_\mu$

- $b \to s\mu\mu$ and $(g-2)_\mu$ both from loops
- finite number of simplified models, if DM candidate required

Arcadi, Calibbi, Fedele, Mescia, 2104.03228



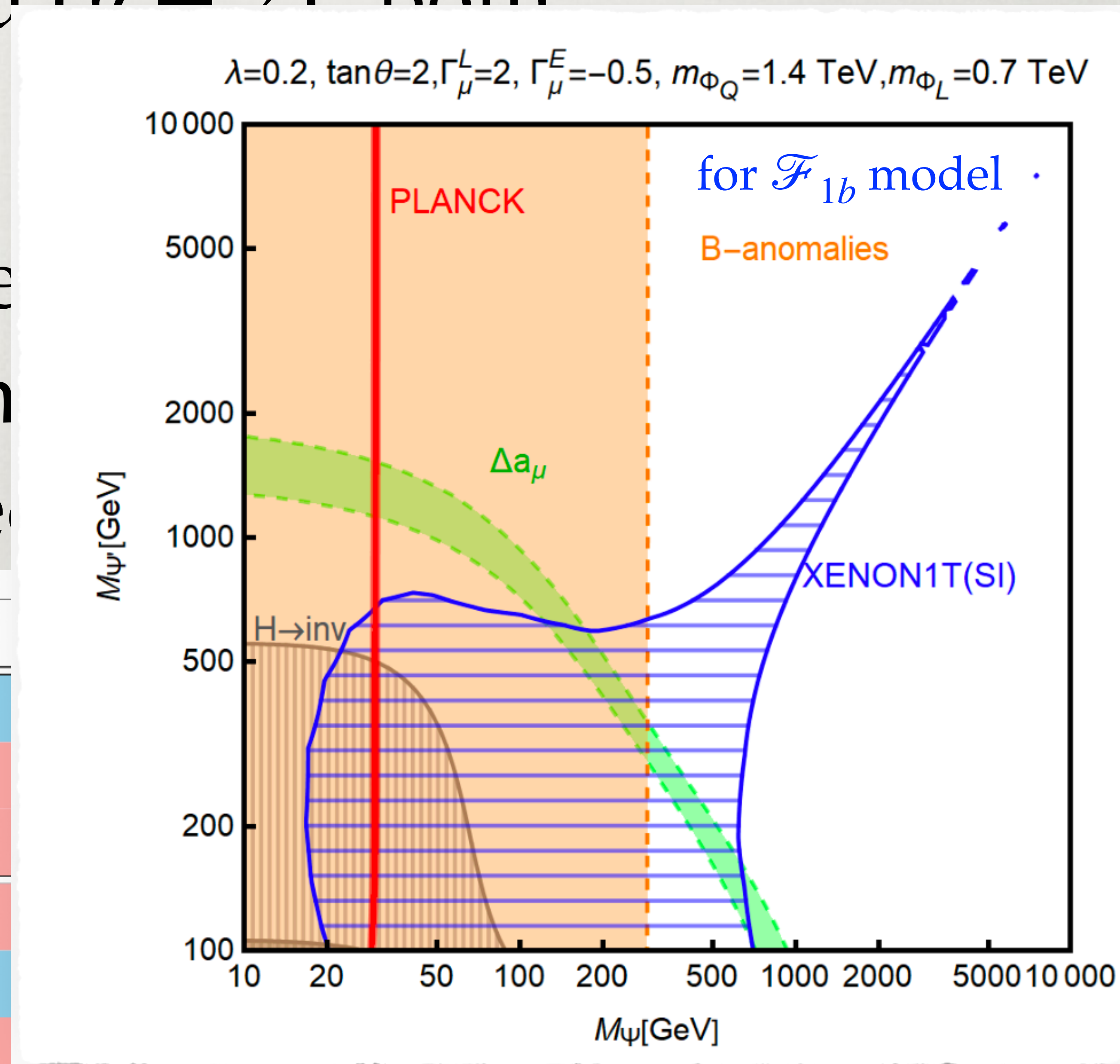


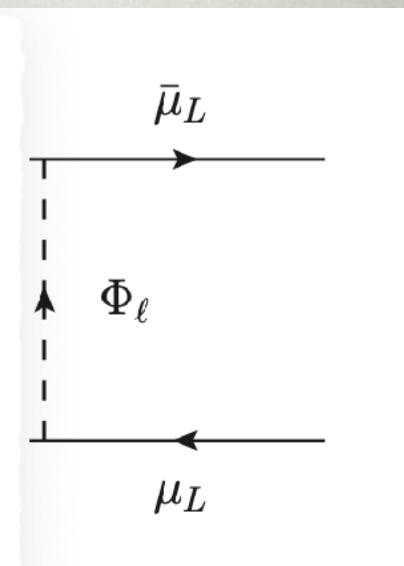
Label	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ'_ℓ/Ψ'_ℓ	Ψ'/Φ'
$\mathcal{F}_{\rm Ia}/\mathcal{S}_{\rm Ia}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{1},-1)$	–
$\mathcal{F}_{\rm Ib}/\mathcal{S}_{\rm Ib}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$	–	$(\mathbf{1},\mathbf{2},-1/2)$
$\mathcal{F}_{\rm Ic}/\mathcal{S}_{\rm Ic}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{1},0)$	–
$\mathcal{F}_{\rm IIa}/\mathcal{S}_{\rm IIa}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{2},-1/2)$	–
$\mathcal{F}_{\rm IIb}/\mathcal{S}_{\rm IIb}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	–	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{\rm IIc}/\mathcal{S}_{\rm IIc}$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$	–	$(\mathbf{1},\mathbf{1},0)$
$\mathcal{F}_{\rm Va}/\mathcal{S}_{\rm Va}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{2},-1/2)$	–
$\mathcal{F}_{\rm Vb}/\mathcal{S}_{\rm Vb}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	–	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{\rm Vc}/\mathcal{S}_{\rm Vc}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$	–	$(\mathbf{1},\mathbf{1},0)$

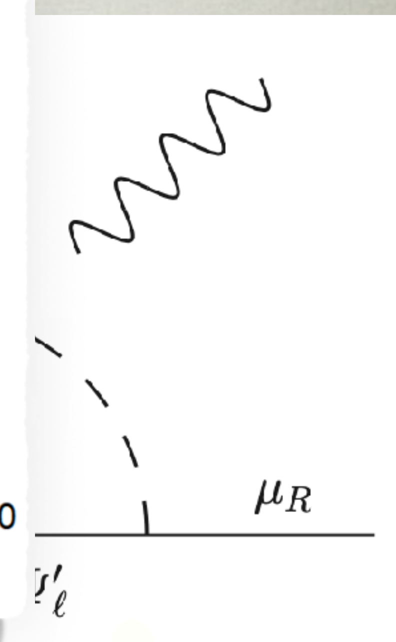
SIMPLIFIED DM MODELS FOR $R_{K^{(*)}}$ AND $(g-2)_\mu$

Arcadi, Calibbi, Fedele, Mescia, 2104.03228

- $b \to s\mu\mu$ and $(g-2)_\mu$ both from loops
- finite numbe… simplified m… candidate re…







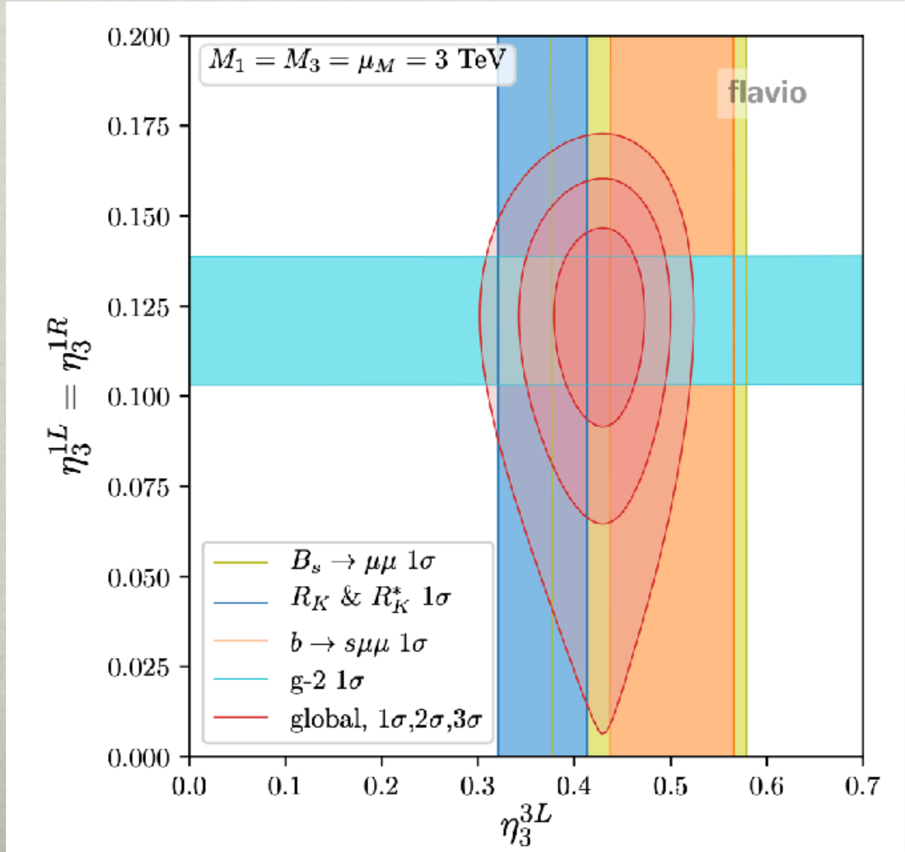
Label	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ		
$\mathcal{F}_{Ia}/\mathcal{S}_{Ia}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$		
$\mathcal{F}_{Ib}/\mathcal{S}_{Ib}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$		
$\mathcal{F}_{Ic}/\mathcal{S}_{Ic}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)$	$(\mathbf{1},\mathbf{1},-1)$		
$\mathcal{F}_{IIa}/\mathcal{S}_{IIa}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$		
$\mathcal{F}_{IIb}/\mathcal{S}_{IIb}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$		
$\mathcal{F}_{IIc}/\mathcal{S}_{IIc}$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$		
$\mathcal{F}_{Va}/\mathcal{S}_{Va}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{2},-1/2)$	–
$\mathcal{F}_{Vb}/\mathcal{S}_{Vb}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	–	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{Vc}/\mathcal{S}_{Vc}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$	–	$(\mathbf{1},\mathbf{1},0)$

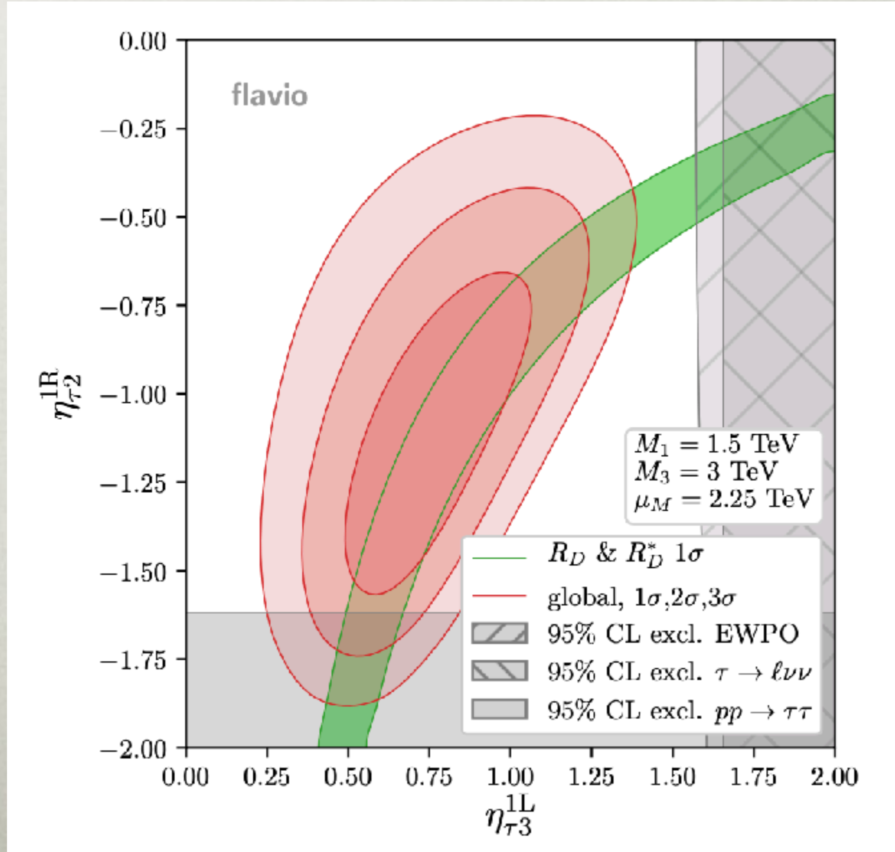
$R_{K^{(*)}}$ AND $R_{D^{(*)}}$ AND $(g-2)_\mu$

S_1 AND S_3 LEPTOQUARKS FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$ AND $(g-2)_\mu$

Greljo et al, 2103.13991

- $R_{K^{(*)}}$ from tree-level S_3 exchange
- $(g-2)_\mu$ from muon-philic S_1 at 1 loop
- $R_{D^{(*)}}$ from tau-philic S_1 at tree-level
  - symmetry structure realizable in gauged $L_\mu - L_\tau$ (± 1 charges for S_1's)
  - $U(2)^3$ MFV in quark sector





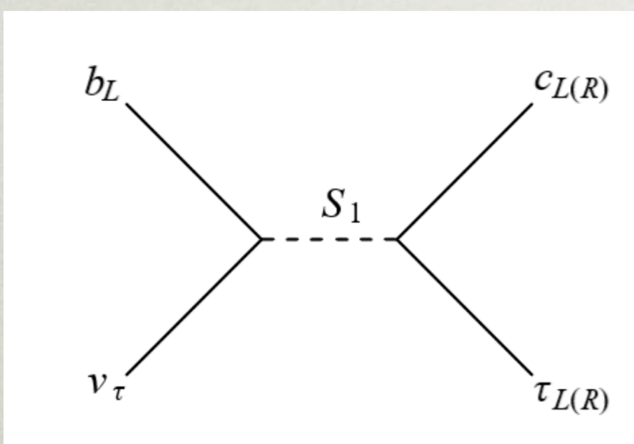
S_1 AND CHARGED SINGLET FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$ AND $(g-2)_\mu$

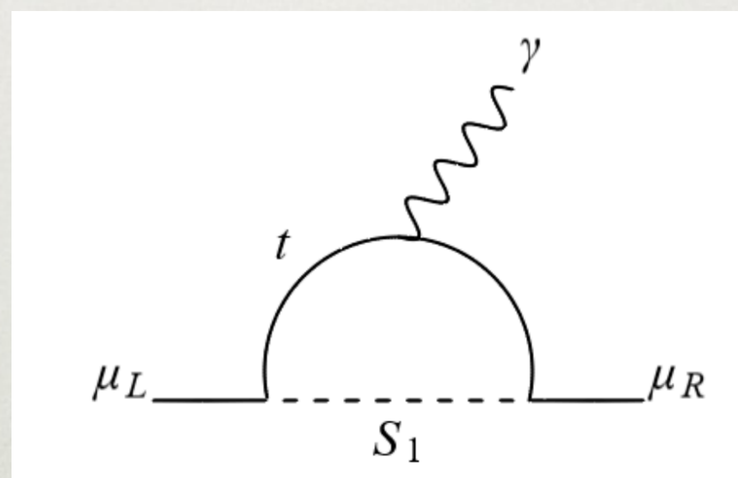
Marzocca, Trifinopoulos, 2104.05730

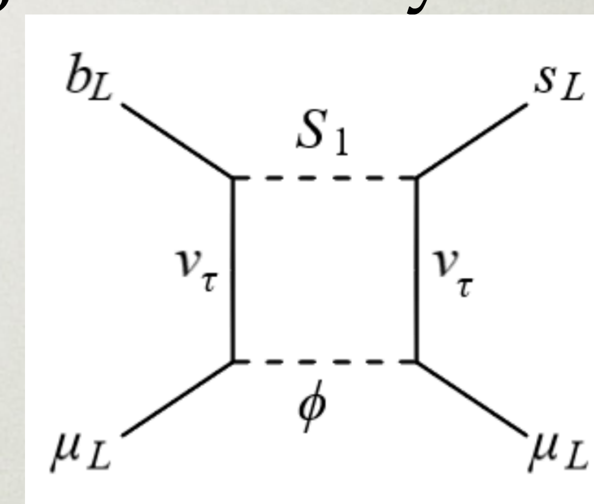
- two new fields

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3}\,, \qquad \phi^+ \sim (\mathbf{1}, \mathbf{1})_1$$

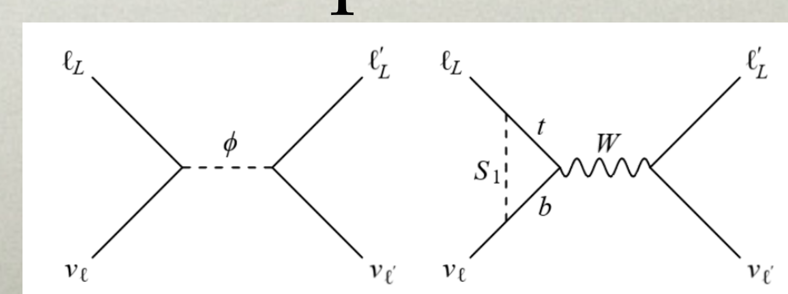
- in addition to resolving $R_{K^{(*)}}$, $(g-2)_\mu$ also possible to resolve the Cabibbo angle anomaly







- 3.6σ (or 5.1σ) discrepancy in V_{us} from $K \to \pi \ell \nu$ vs. V_{ud} (+CKM unitarity) from super- allowed nuclear β decays



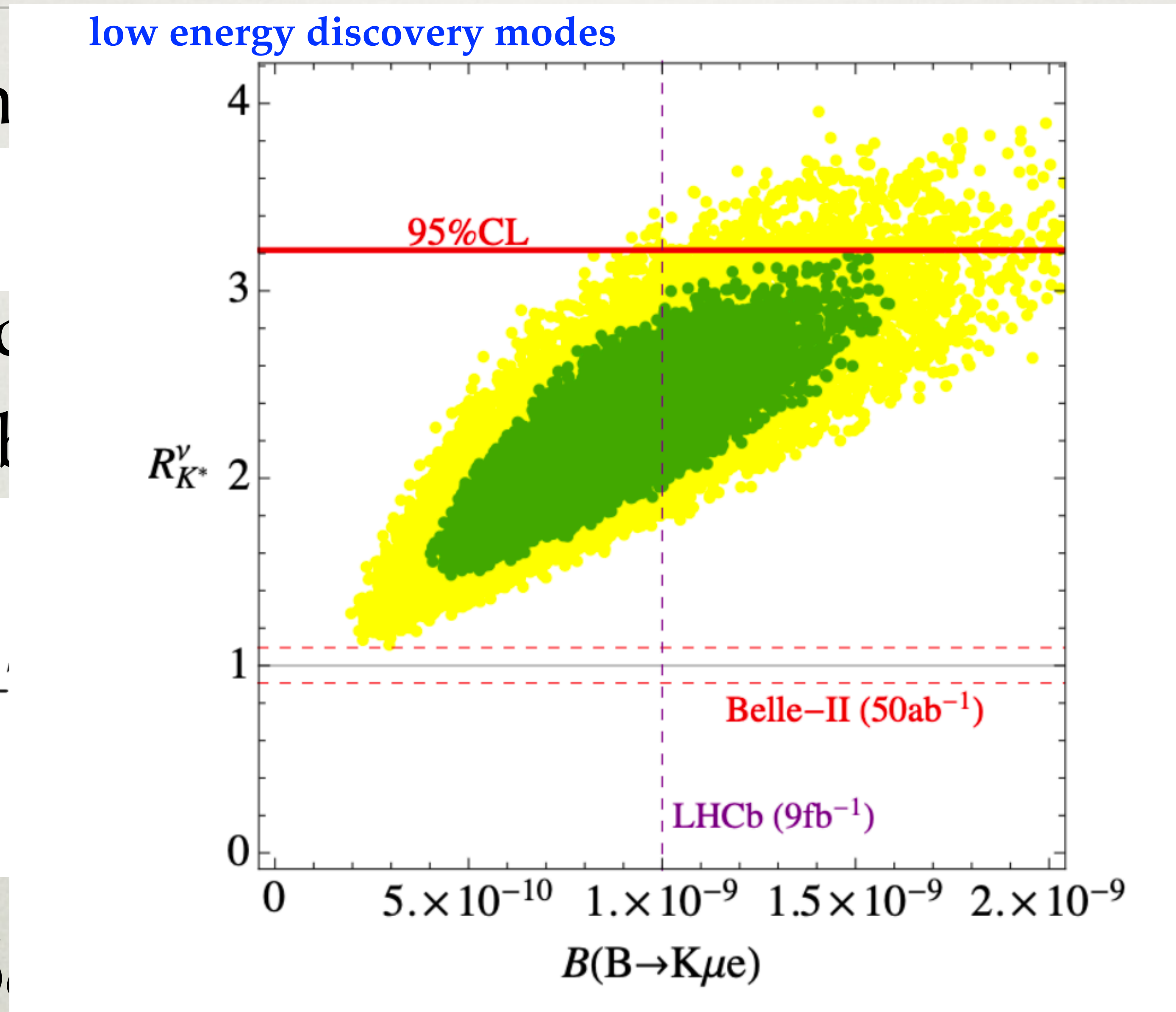
see also Crivellin et al, 2012.09845; Belfatto et al, 1906.02714

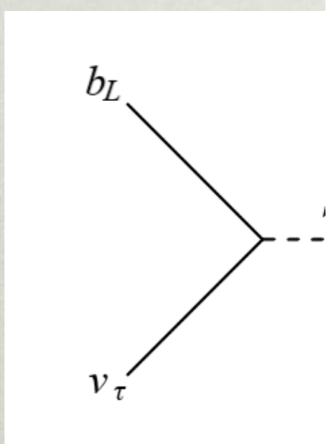
S_1 AND CHARGED SINGLET FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$ AND $(g-2)_\mu$

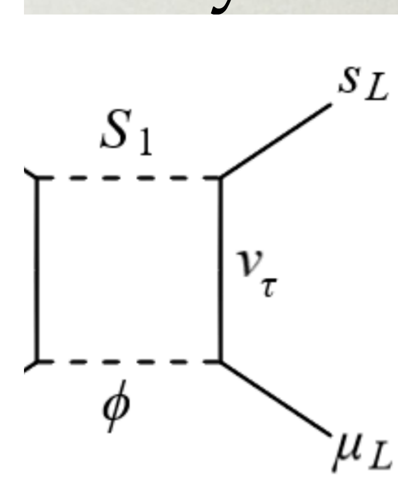
- two n

  ...cca, Trifinopoulos, 2104.05730

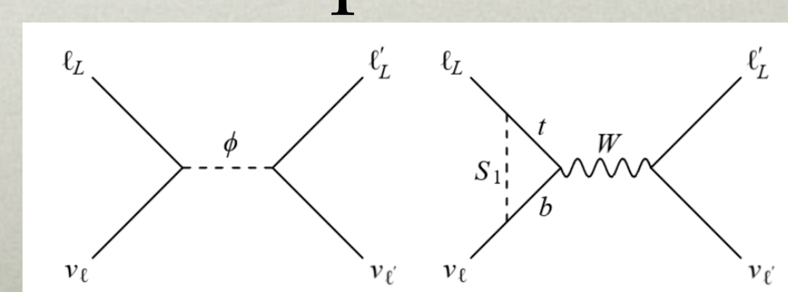
- in add ... o possi... omaly







- 3.6... $K \to \pi \ell \nu$ vs. V_{ud} (+CKM unitarity) from super- allowed nuclear β decays



see also Crivellin et al, 2012.09845; Belfatto et al, 1906.02714

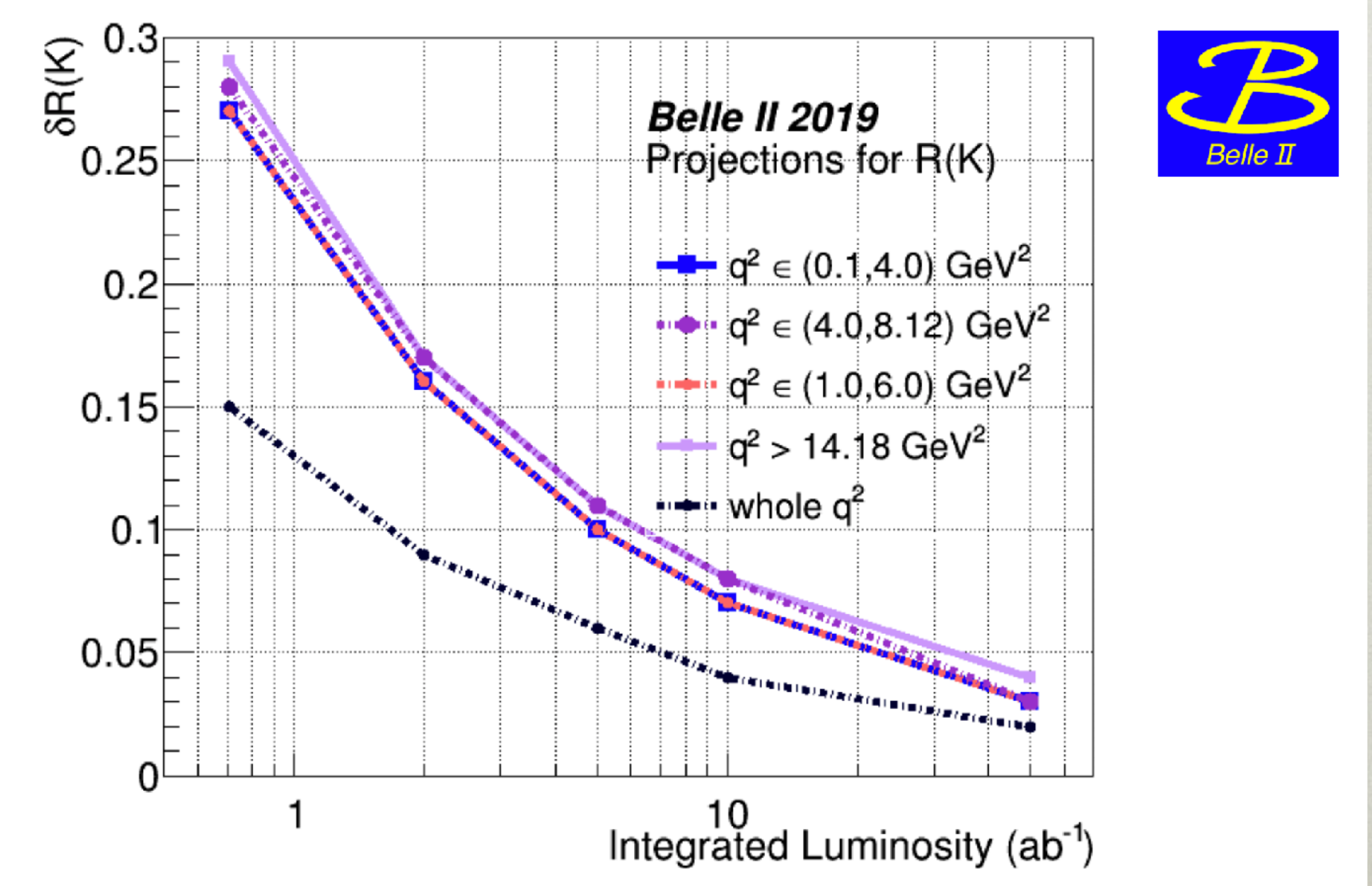
THE FUTURE

THE FUTURE

- many related modes/observables in $b \to c\tau\upsilon$ and $b \to s\mu\mu$
  - $\Lambda_b \to \Lambda_c \tau\upsilon$, $B_C \to J/\psi\tau\upsilon$, $B_S \to D_s^* \tau\upsilon$, $B_s \to \phi ll$, $b \to sll$ inclusive, LFU in angular obs., ...
- a rule of thumb: Belle 2 50x statistics of Belle
  - corresponds to ~reach in Λ_{NP} of $\sqrt[4]{50}=2.7x$
  - like going from 13TeV LHC to 35TeV LHC
- similar for LHCb (Phase 2 Upgrade 100x stat.)
- Muon g-2/EDM experiment at J-PARC
- many of the heavier states could be produced at high p_T
  - ATLAS, CMS, 100 TeV *pp*, muon collider,

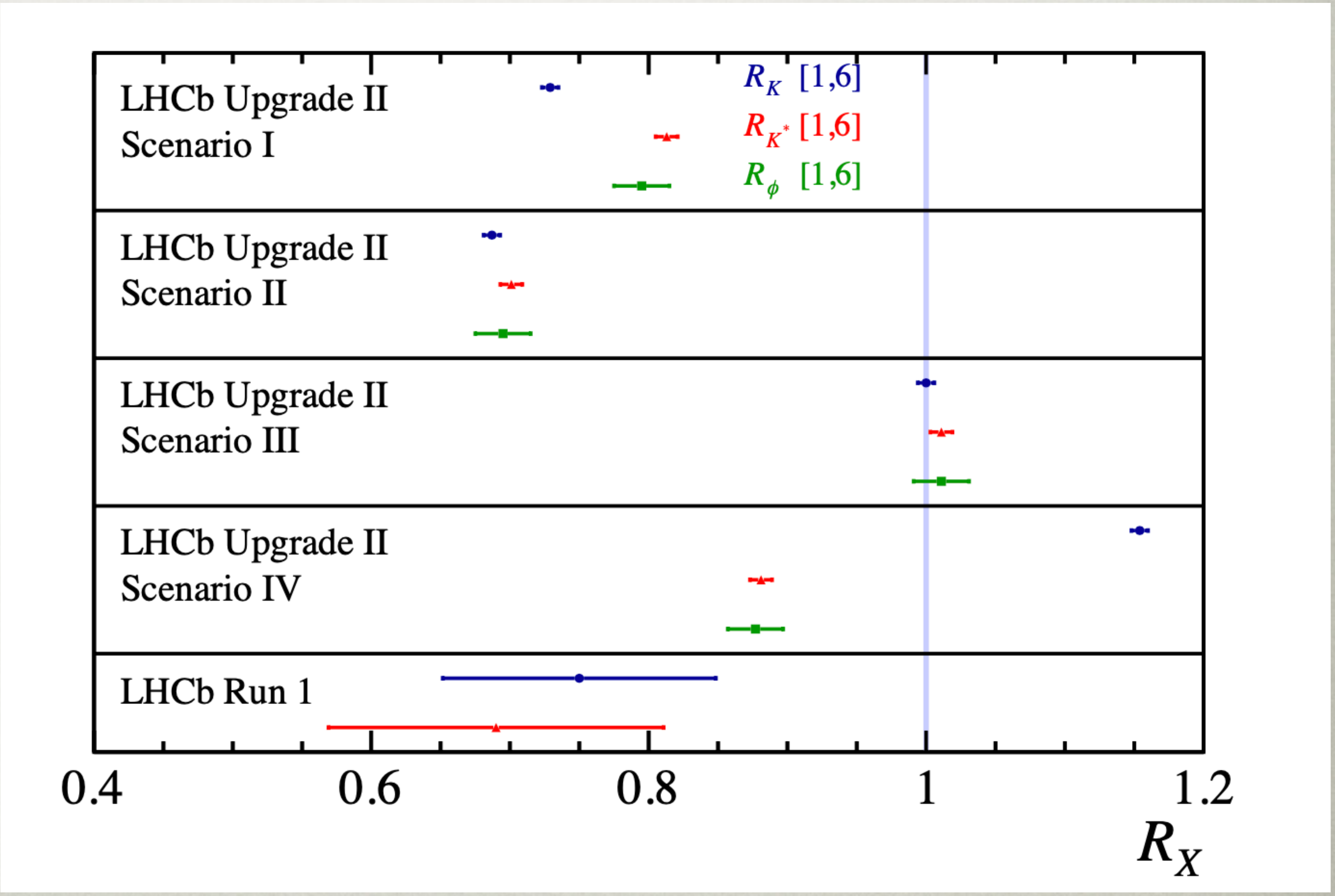
THE FUTURE - BELLE II

talk by Carsten Niebuhr at EPS-HEP 2021

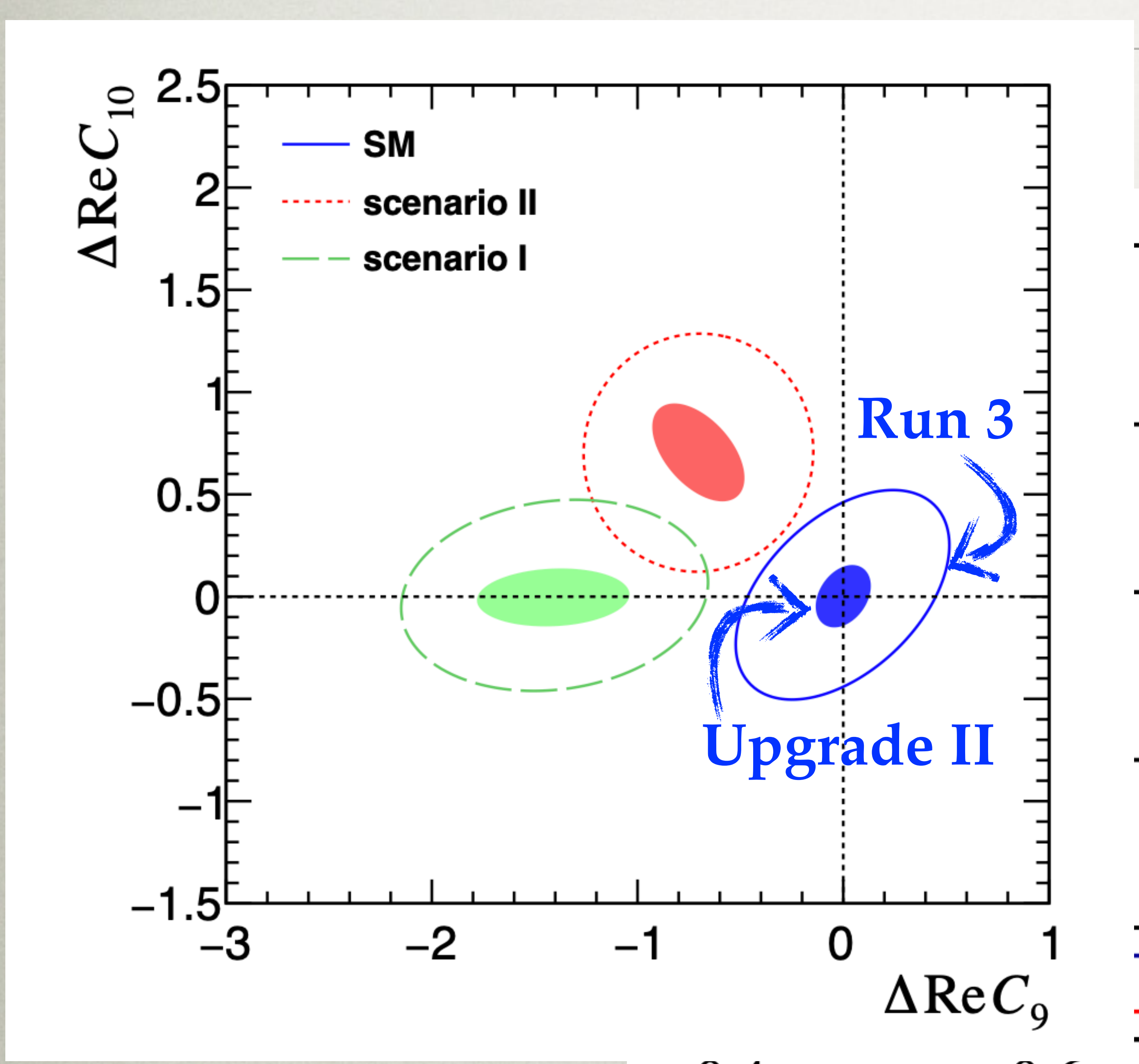


THE FUTURE - LHCB

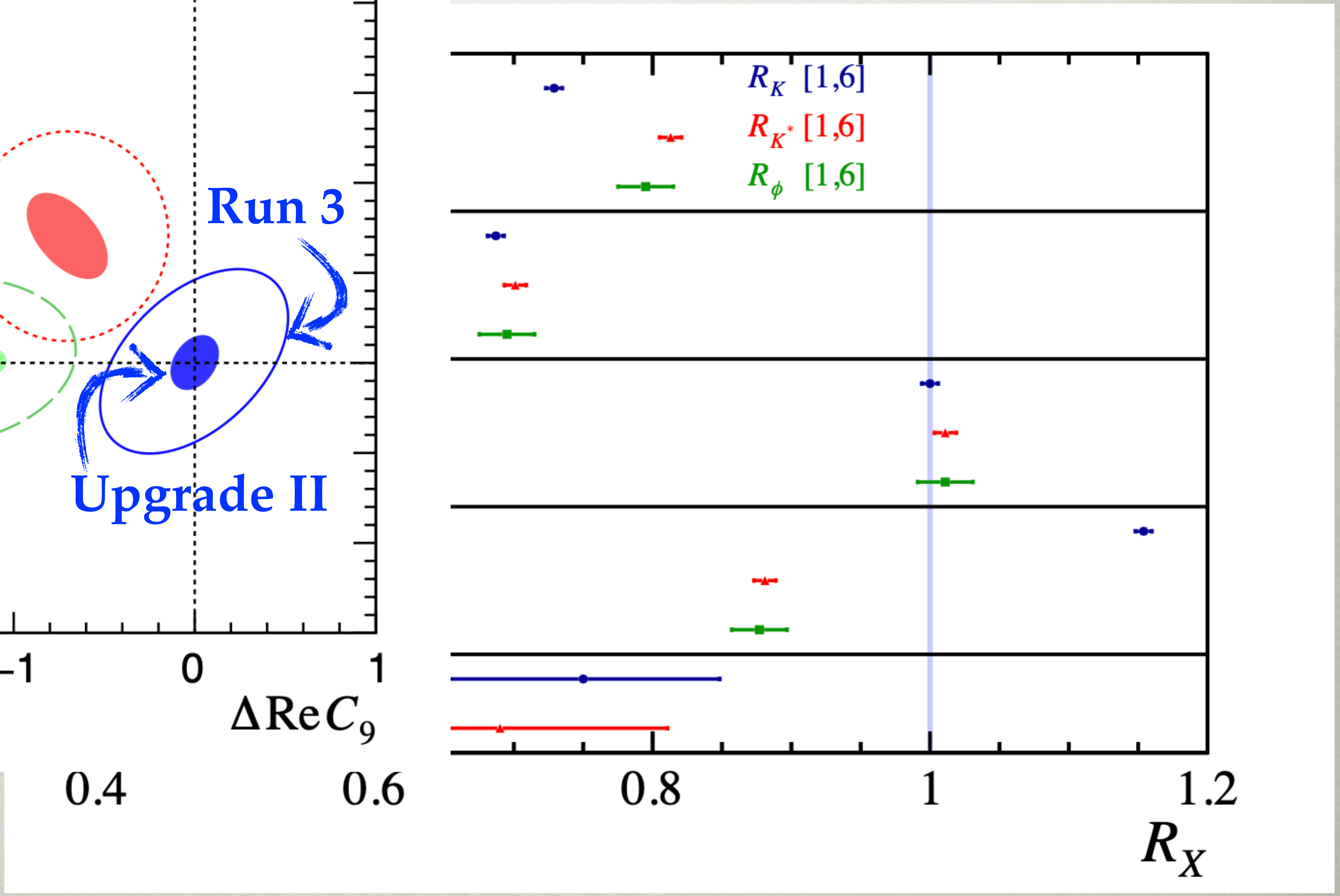
WG4 Yellow Report, 1812.07638



THE FUTURE - LHCB



WG4 Yellow Report, 1812.07638



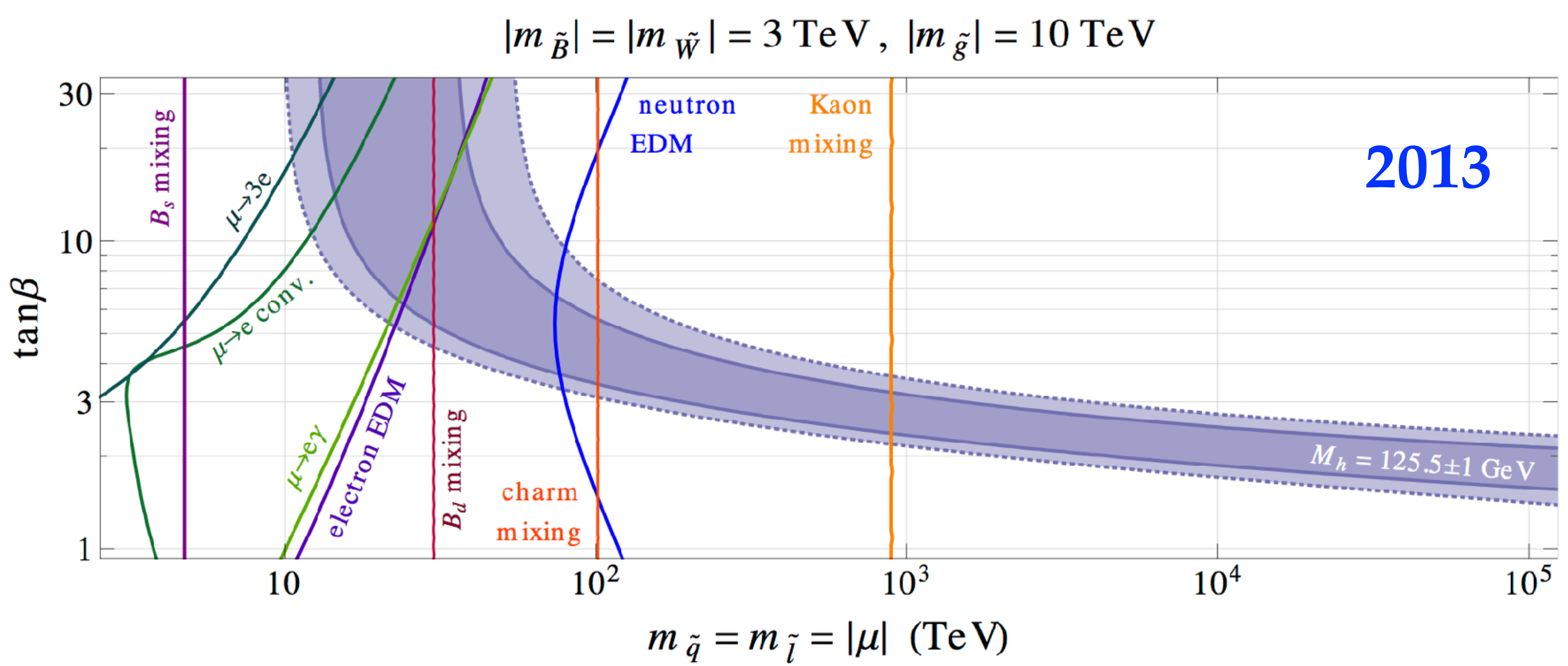
CONCLUSIONS

- FCNCs very sensitive probes of new physics
- growing tensions in $(g-2)_\mu$, $R_{K^{(*)}}$
  - evidence of new physics?

BACKUP SLIDES

EXPERIMENTAL PROGRESS

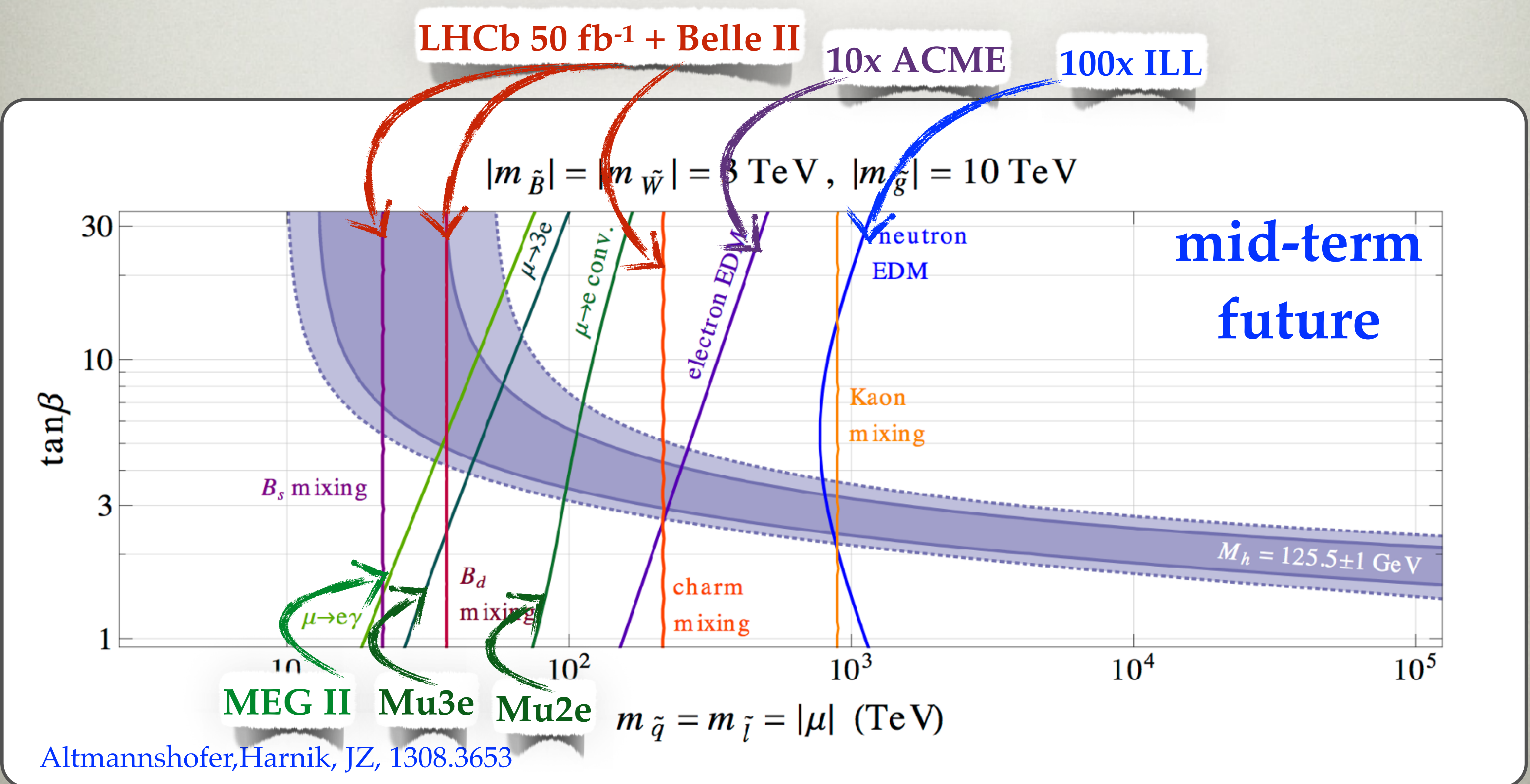
- example: mini-split SUSY
  - *O(1-10TeV)* gauginos at LHC or future collider; PeV sfermions from low energy precision probes



Altmannshofer,Harnik, JZ, 1308.3653

EXPERIMENTAL PROGRESS

- and will improve dramatically in the future

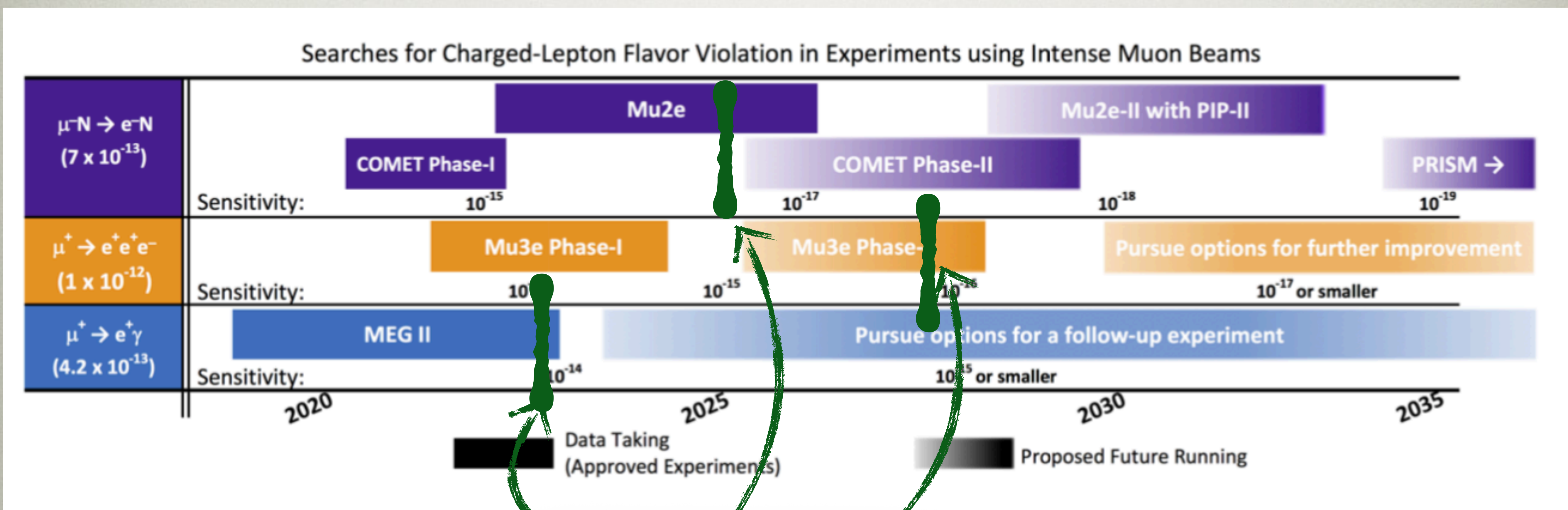


Altmannshofer,Harnik, JZ, 1308.3653

EXPERIMENTAL PROGRESS

Physics Briefing Book, 1910.11775

- further orders of magnitude experimental progress expected in CLFV transitions



assumed sensitivies in the previous slide

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

AXION

- if $\bar{\theta}(x)$ a dynamical field and couples only to $\bar{\theta}G\tilde{G} \Rightarrow$ potential min. at $\bar{\theta}(x) = 0$

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{c^{V,A}_{f_i f_j}}$$

  - new ultra-light particle - axion

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\text{em}}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2 f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5)f_j$$

  - obtains mass from QCD anomaly

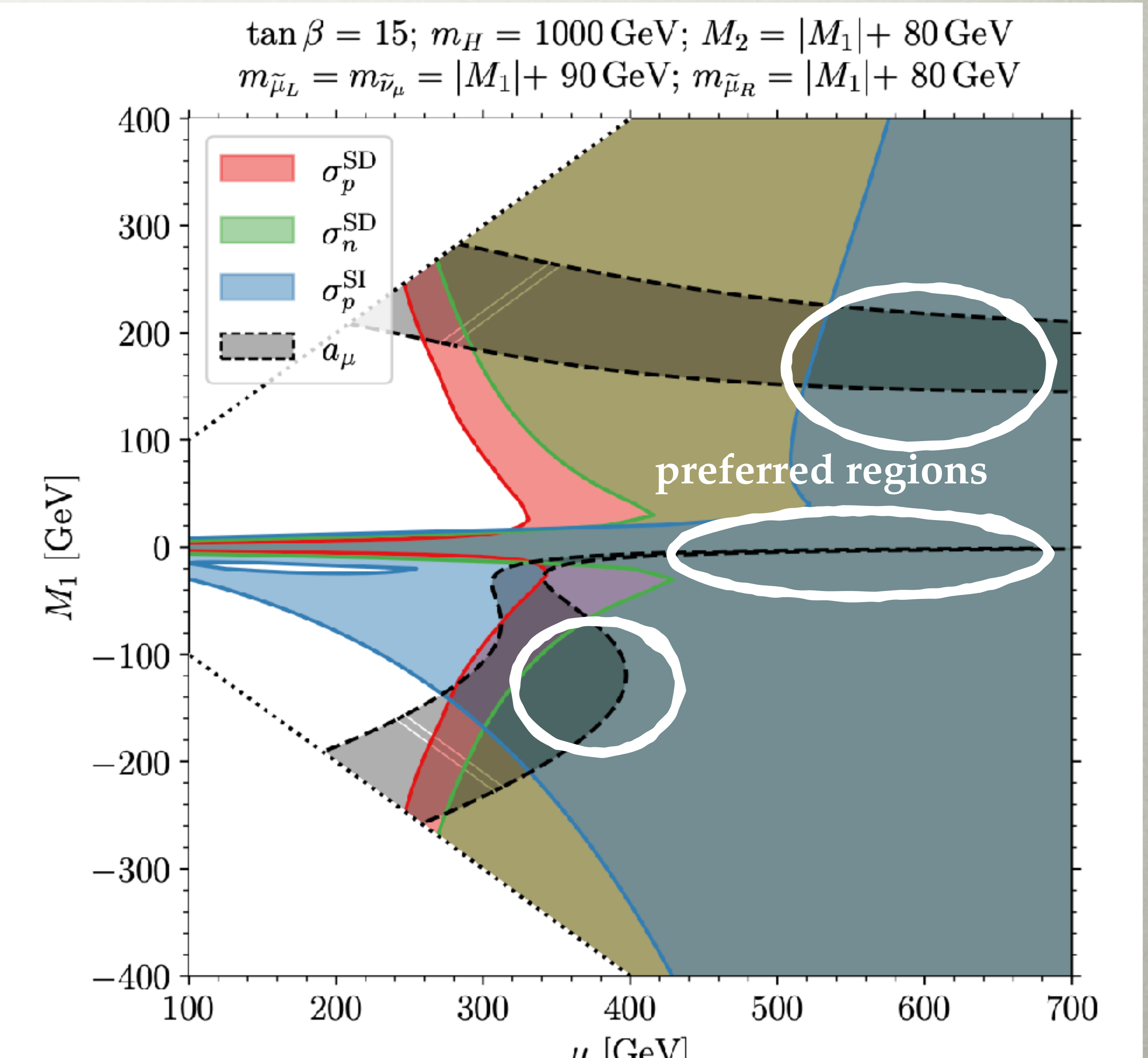
$$m_a = 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

  - viable cold dark matter candidate for

$$10^{-8}\,\text{eV} \lesssim m_a \lesssim 10^{-3}\,\text{eV}$$

SUSY?

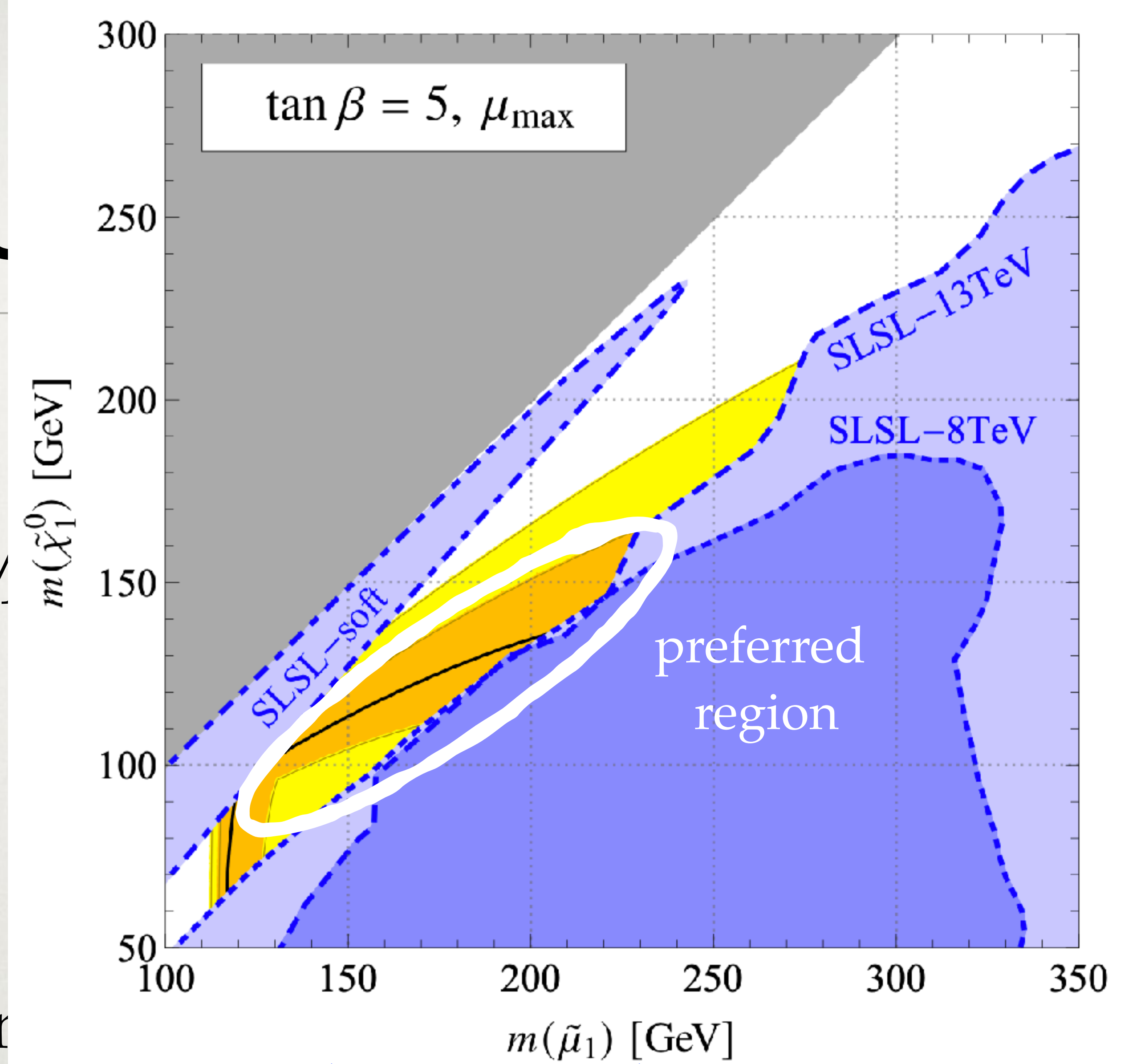
- a_μ via chargino-sneutrino and neutralino-smuon loops
- bino-like neutralino is DM
- requires cancellations in DM direct detection xsec
  - "blind spot": h and H exch. with opposite signs
- can evade LHC constraints in the soft region



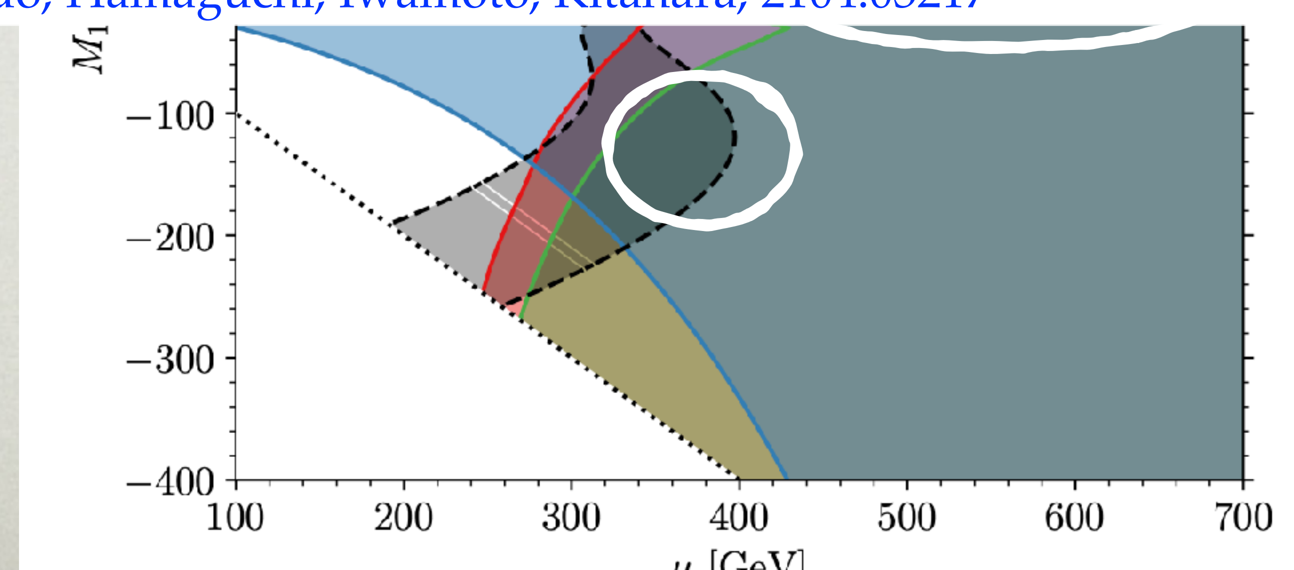
Baum, Carena, Shah, Wagner, 2104.03302

SU

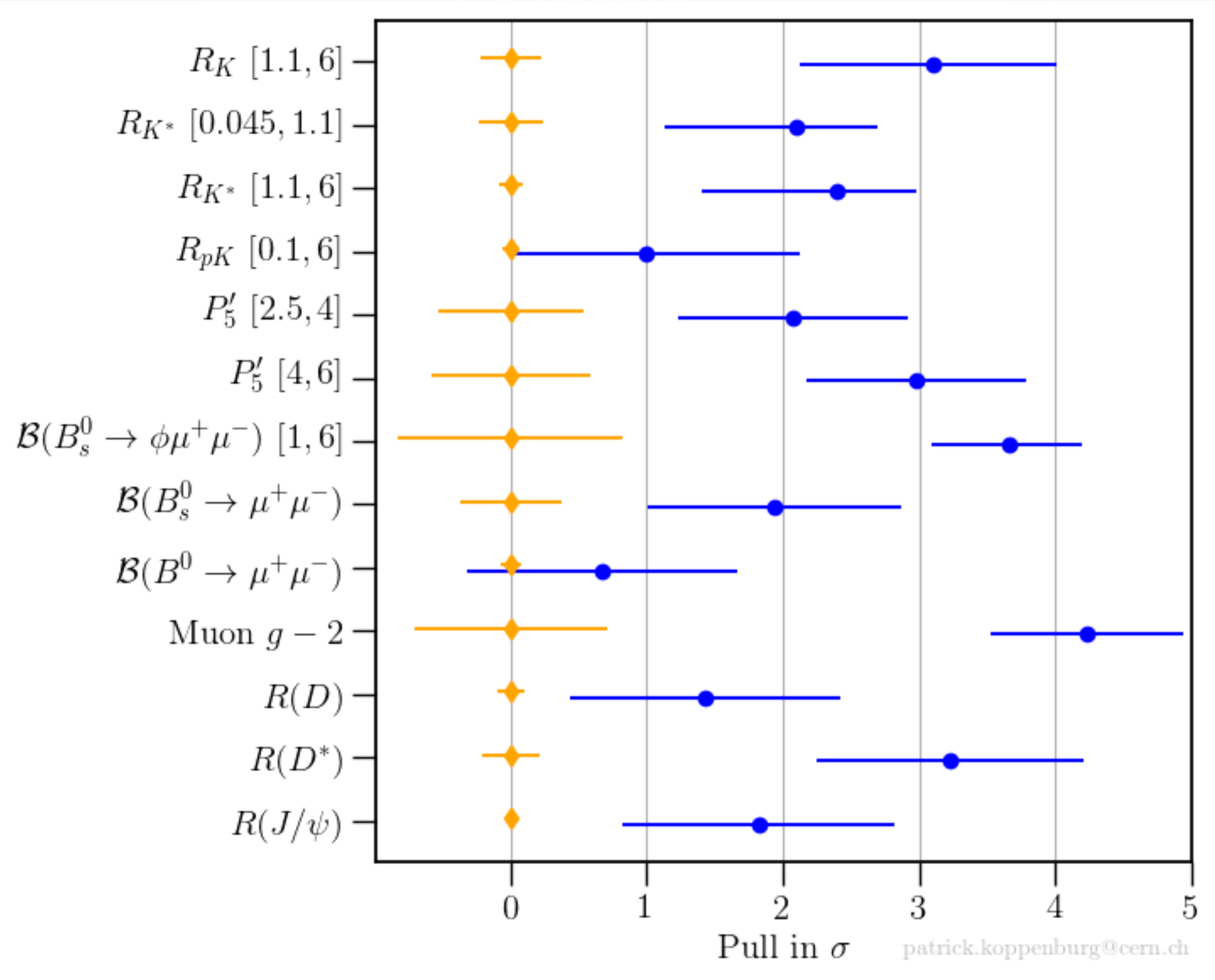
- a_μ via chargino-sneutrino
- bino-like neutralino is DM
- requires cancellations in DM direct detection xsec
    - "blind spot": h and H exch. with opposite sign
- can evade LHC constraints in the soft region



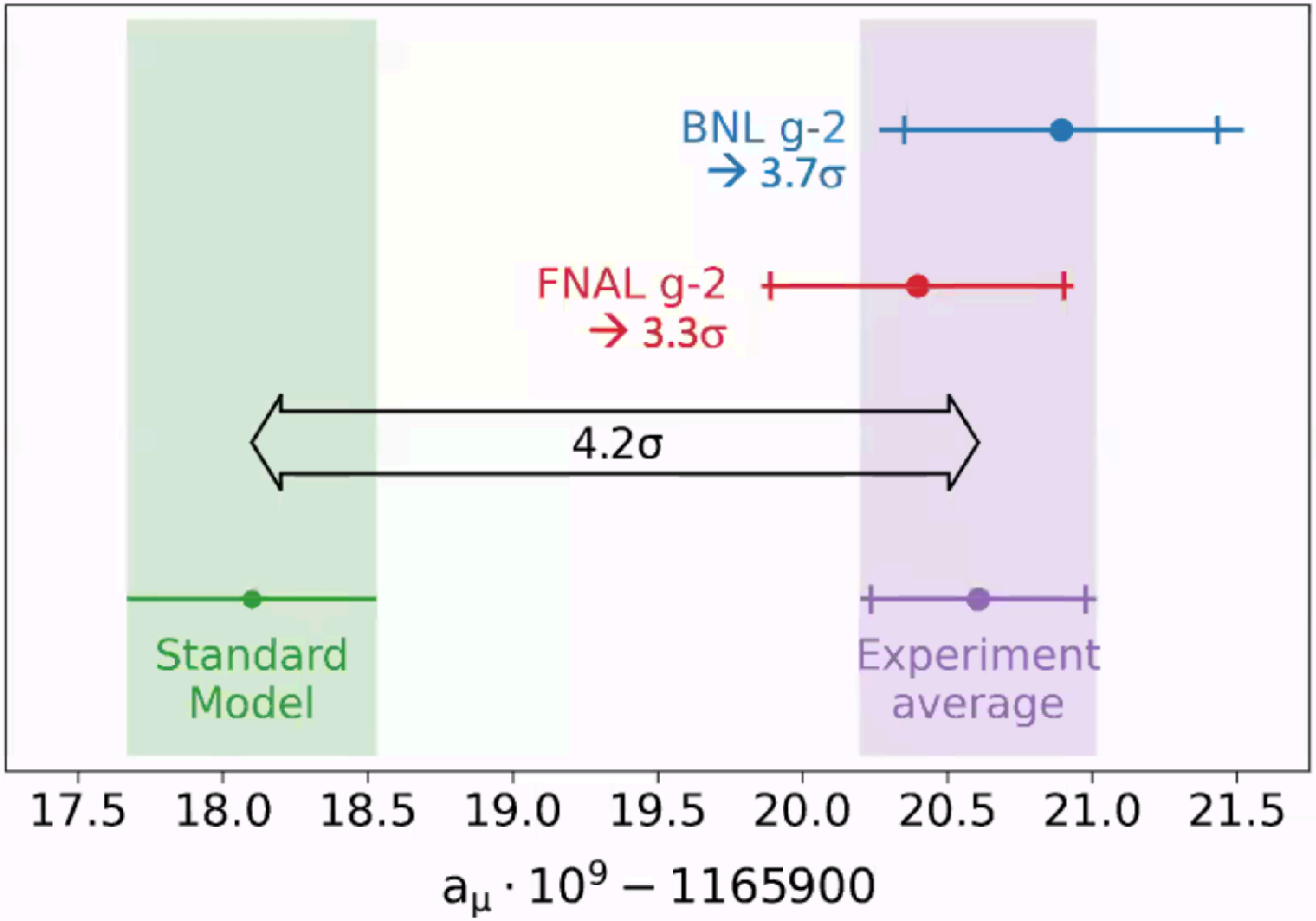
Endo, Hamaguchi, Iwamoto, Kitahara, 2104.03217



Baum, Carena, Shah, Wagner, 2104.03302


R_K [1.1, 6]
R_{K^*} [0.045, 1.1]
R_{K^*} [1.1, 6]
R_{pK} [0.1, 6]
P_5' [2.5, 4]
P_5' [4, 6]
$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ [1, 6]
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Muon $g-2$
$R(D)$
$R(D^*)$
$R(J/\psi)$
0
1
2
3
4
5
Pull in σ
patrick.koppenburg@cern.ch

$a_\mu(SM) = 0.00116591810(43) \rightarrow 368$ ppb



- Individual tension with SM
  - BNL: 3.7σ
  - FNAL: 3.3σ

$a_\mu(Exp) - a_\mu(SM) = 0.00000000251(59) \rightarrow 4.2\sigma$

THE Z' MODELS

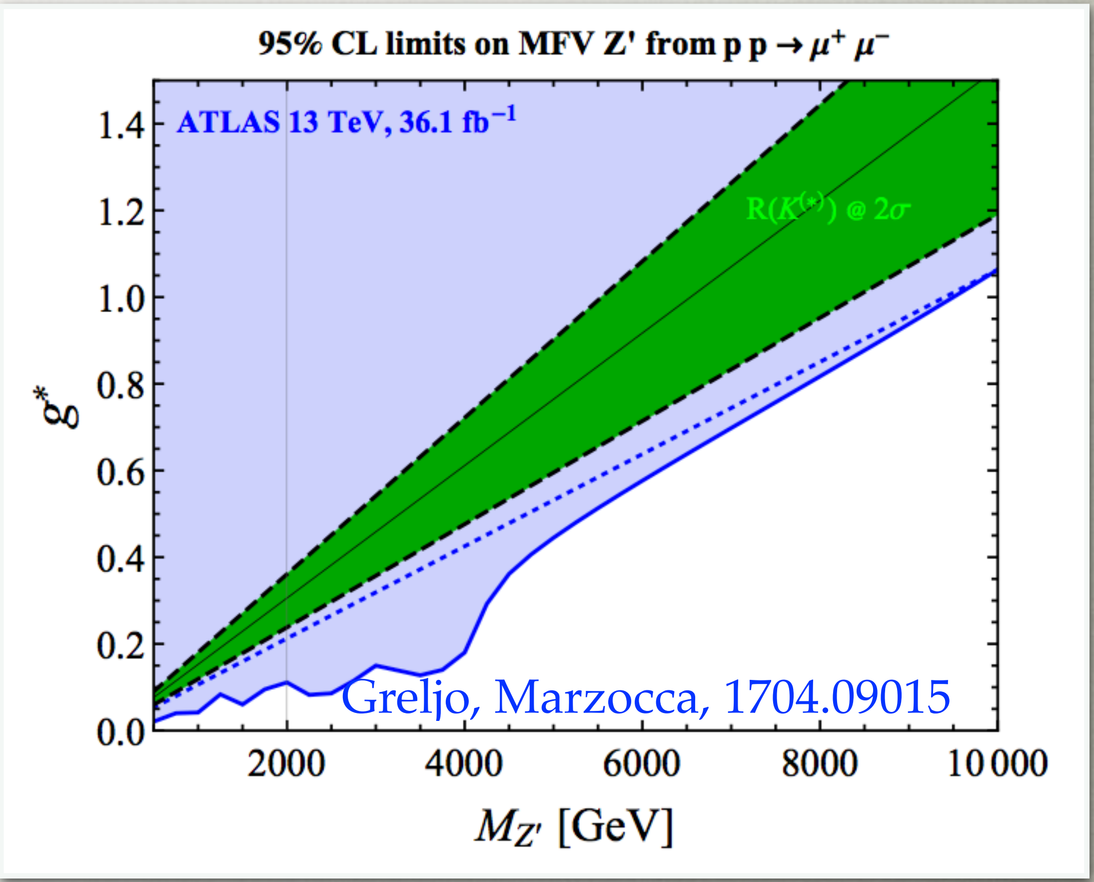
- bounds from ATLAS, CMS from $pp \to Z' \to \mu\mu$

  Greljo, Marzocca, 1704.09015

  - e.g., for MFV ansatz

$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(\mathbf{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

$$J_\mu = g_Q^{(1),ij}(\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl}(\bar{L}_k \gamma^\mu L_l)$$

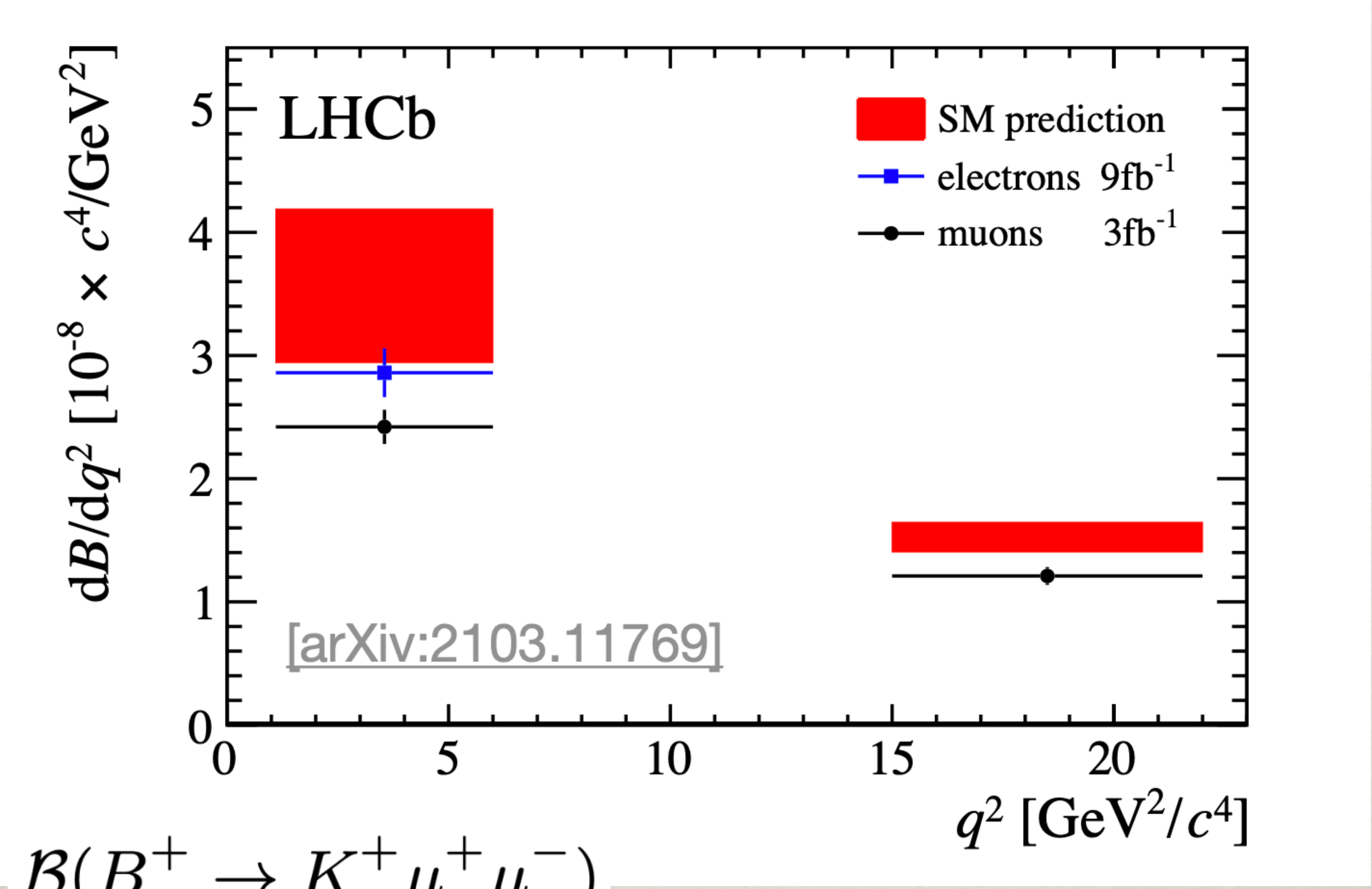


- "LHC safe" models

  Altmannshofer et al, 1403.1269

  - $U(1)_{\mu\text{-}\tau}$ models with vector-like quarks
  - models with more than one mediator (mixing suppression), e.g. $U(1)_q x U(1)_{\mu\text{-}\tau}$ Crivellin, Fuentes, Greljo, Isidori, 1611.02703
  - composite ρ exchanges Carmona, Goertz, 1510.07658; Megías et al, 1608.02362 , 1705.04822;
  - fully horizontal Z' models with third-family charges only, e.g., $U(1)_{B3\text{-}\tau}$,$U(1)_{B3\text{-}3\mu}$ Alonso, Cox, Han, Yanagida, 1705.03858; Bonilla, Modak, Srivastava, Valle, 1705.00915
    - interesting textures in the neutrino mass matrix

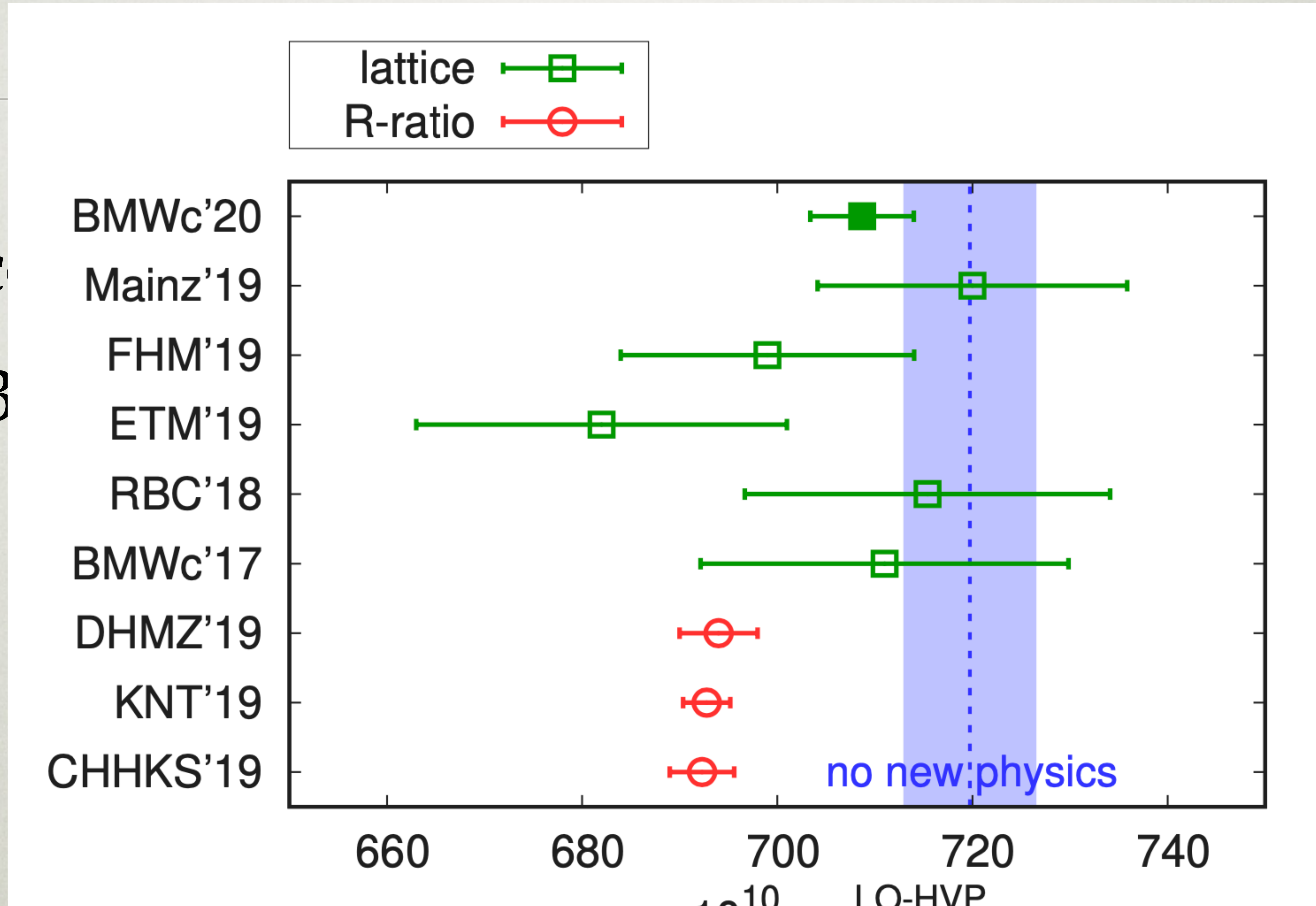
      Bhatia, Chakraborty, Dighe, 1701.05825



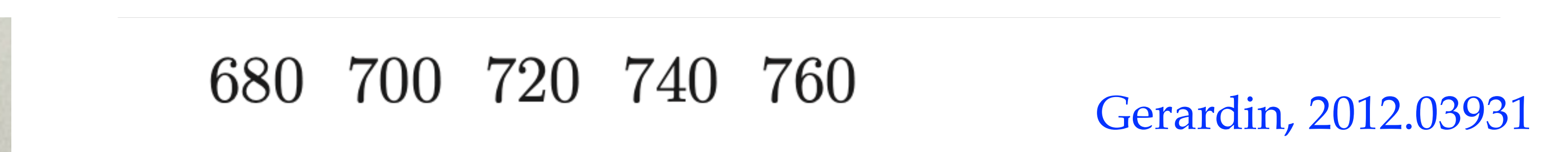
$\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$

HADRONIC VACUUM

- c
- B



BMW collaboration, 2002.12347



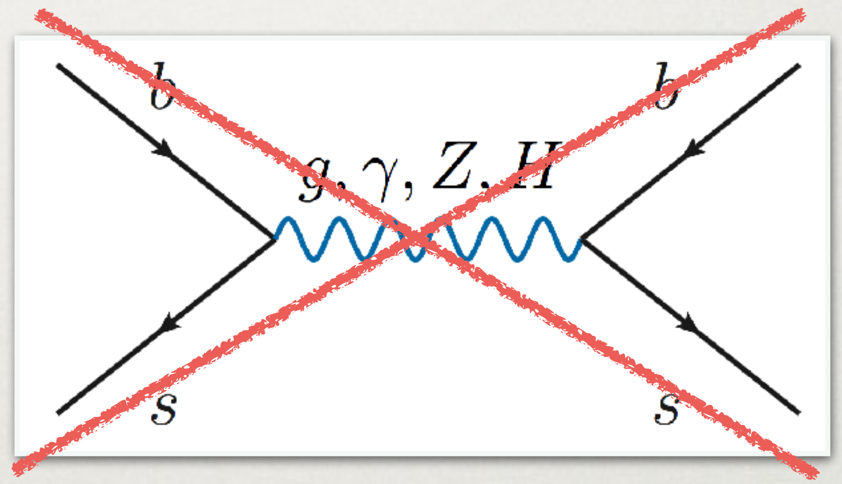
Gerardin, 2012.03931

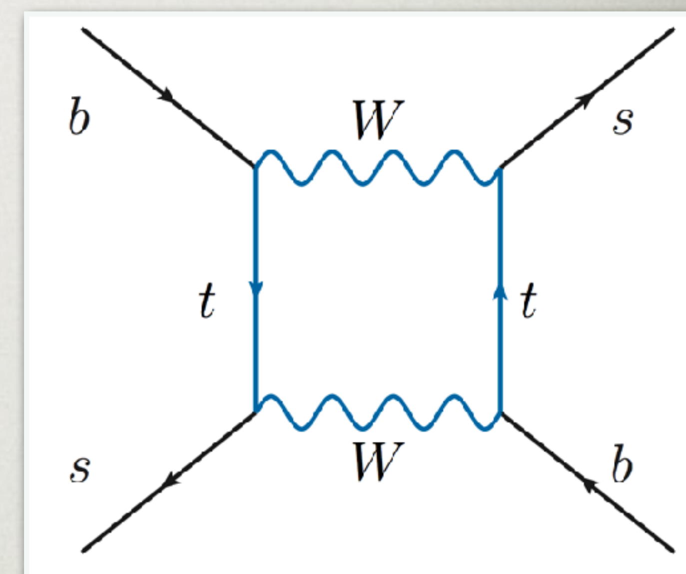
SENSITIVITY TO NEW PHYSICS

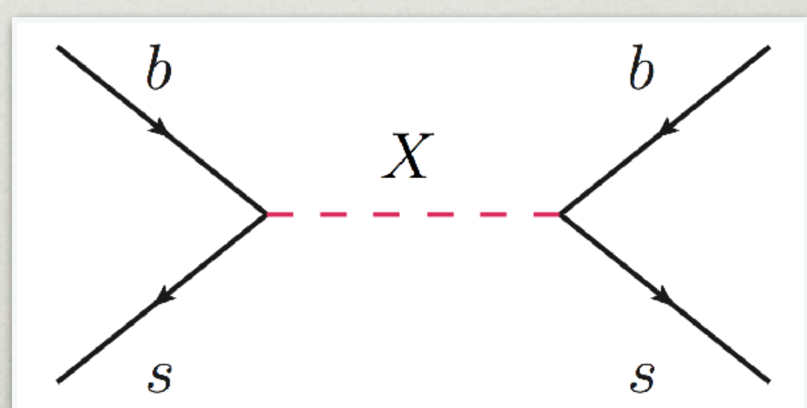
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

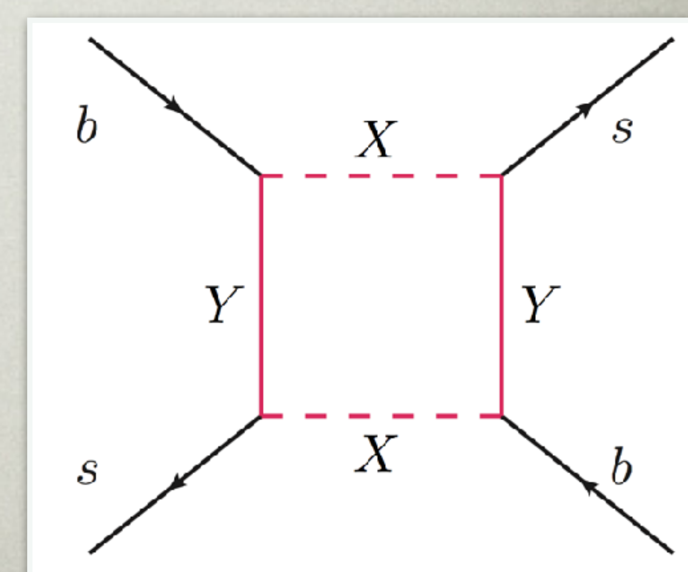
$$\delta C^{\mathrm{NP}} \propto \frac{\sin\theta_i \sin\theta_j}{M_{\mathrm{NP}}^2}$$

- depends on mix. angles and NP masses







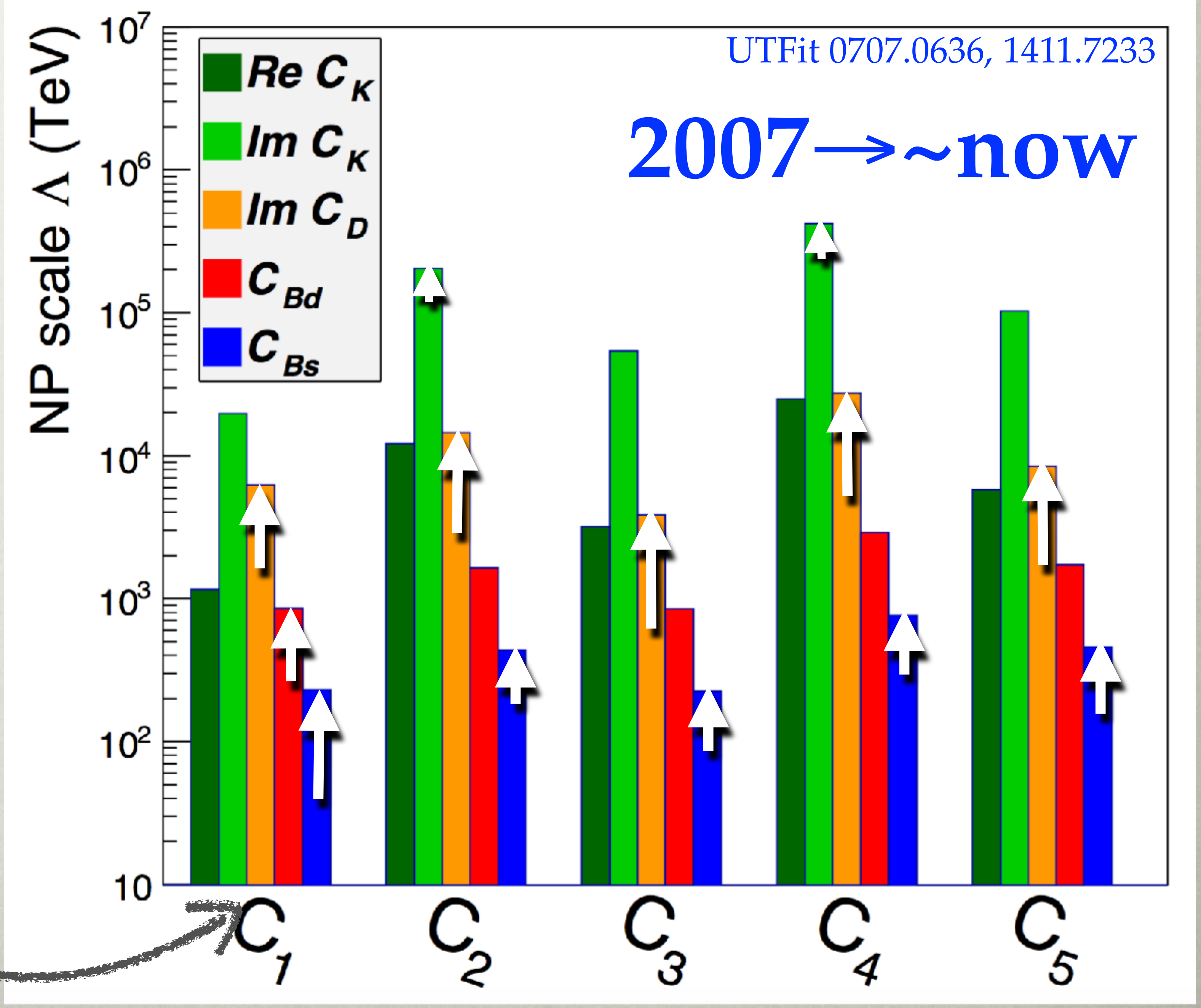


LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing
- also from ε_K

$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



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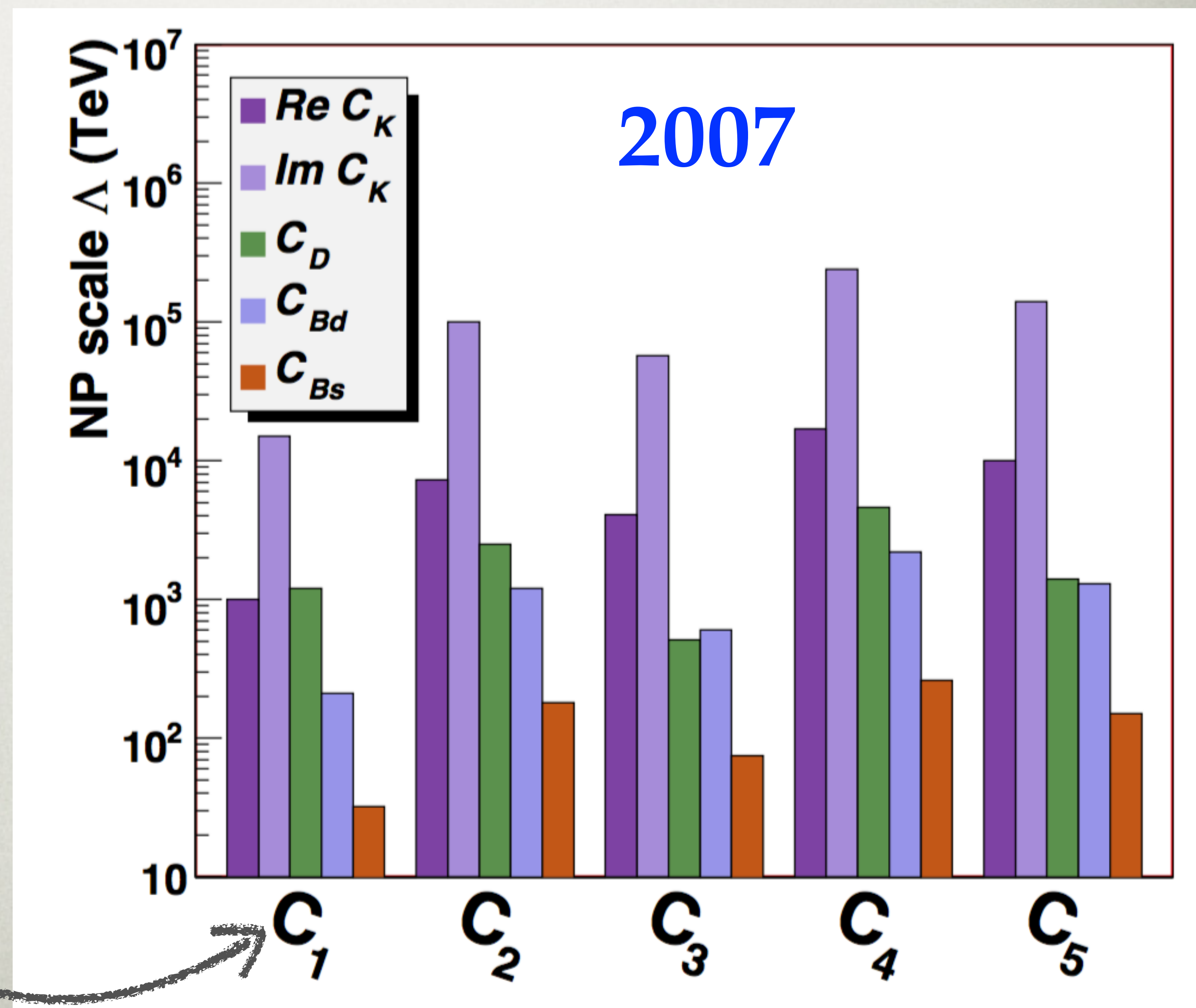

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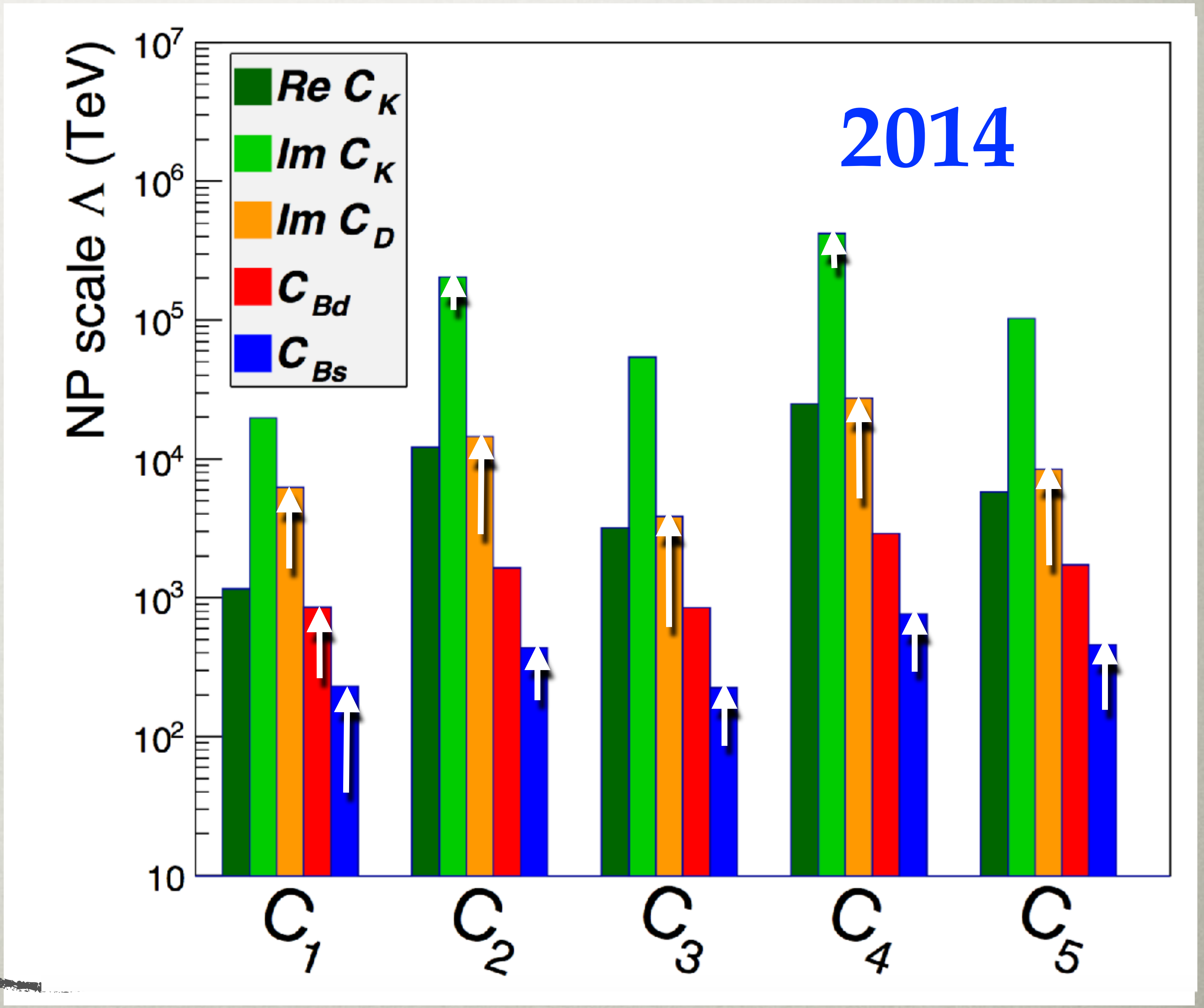


$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

LEPTOQUARKS UPSHOT

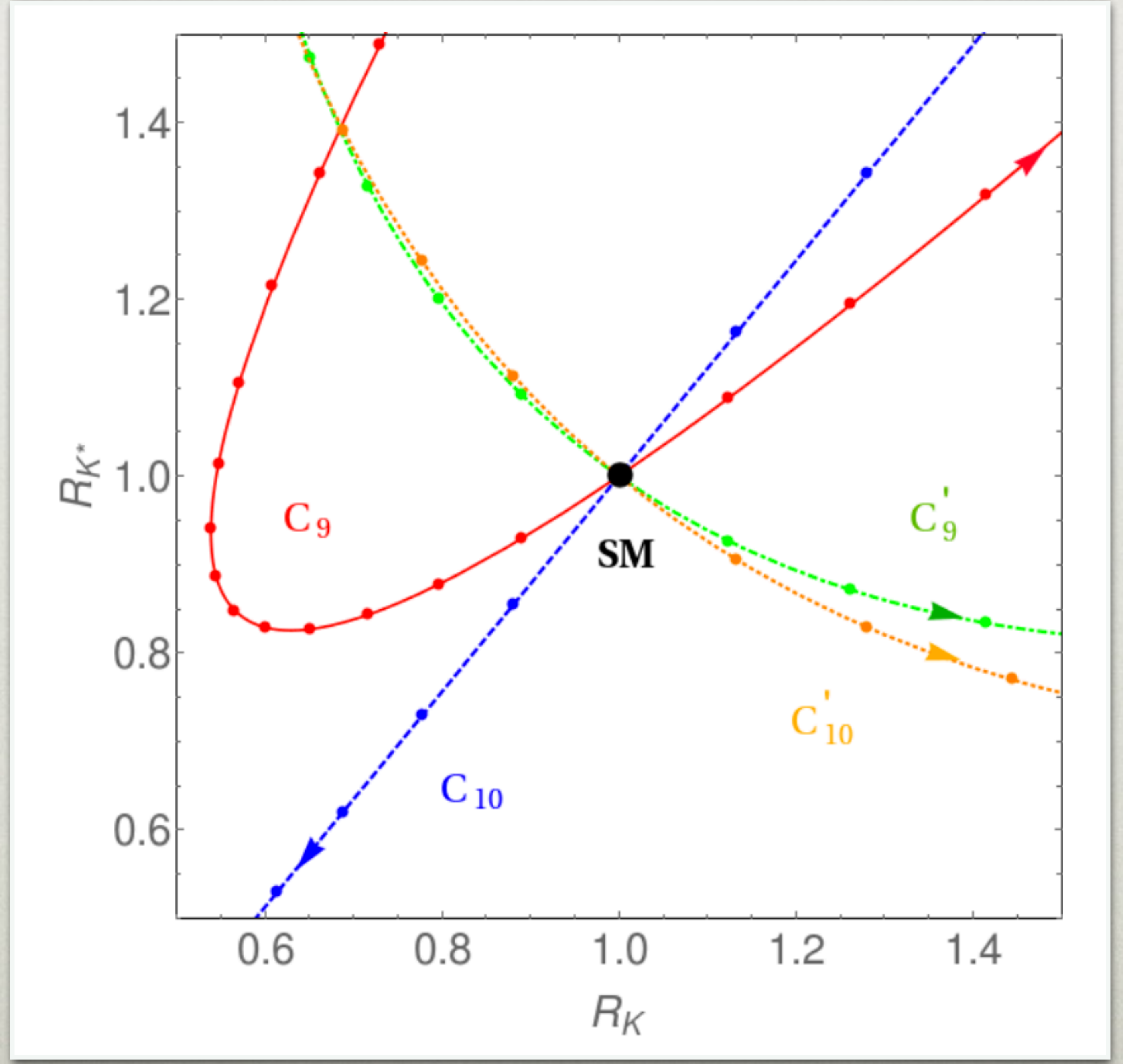
L. di Luzio, 1706.01868

Simplified Model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j \nu\bar{\nu}$
Z'	1	$(1,1,0)$	0	×	✓	×
V'	1	$(1,3,0)$	∞	✓	✓	×
S_1	0	$(\bar{3},1,1/3)$	-1	✓	×	×
S_3	0	$(\bar{3},3,1/3)$	3	✓	✓	×
U_1	1	$(3,1,2/3)$	1	✓	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓	×

Anomaly	$\mathcal{O}$	FS_Q	FS_L	Λ_A[TeV]	$\lvert\Lambda_{\mathcal{O}}\rvert$ [TeV]	Λ_U[TeV]	$M_\star$[TeV]
$b \to c\tau\bar{\nu}$	$Q_{23}L_{33}$	1	1	3.4	3.4	9.2	43
$b \to c\tau\bar{\nu}$	$Q_{33}L_{33}$	$\lvert V_{cb}\rvert$	1	3.4	0.7	1.9	8.7
$b \to s\mu\bar{\mu}$	$Q_{23}L_{22}$	1	1	31	31	84	390
$b \to s\mu\bar{\mu}$	$Q_{33}L_{22}$	$\lvert V_{ts}\rvert$	1	31	6.2	17	78
$b \to s\mu\bar{\mu}$	$Q_{33}L_{33}$	$\lvert V_{ts}\rvert$	$^{\ddagger}m_\mu/m_\tau$	31	1.5	4.1	19
$b \to s\mu\bar{\mu}$	$Q_{33}L_{33}$	$\lvert V_{ts}\rvert$	$^{*}(m_\mu/m_\tau)^2$	31	0.4	1.0	4.7

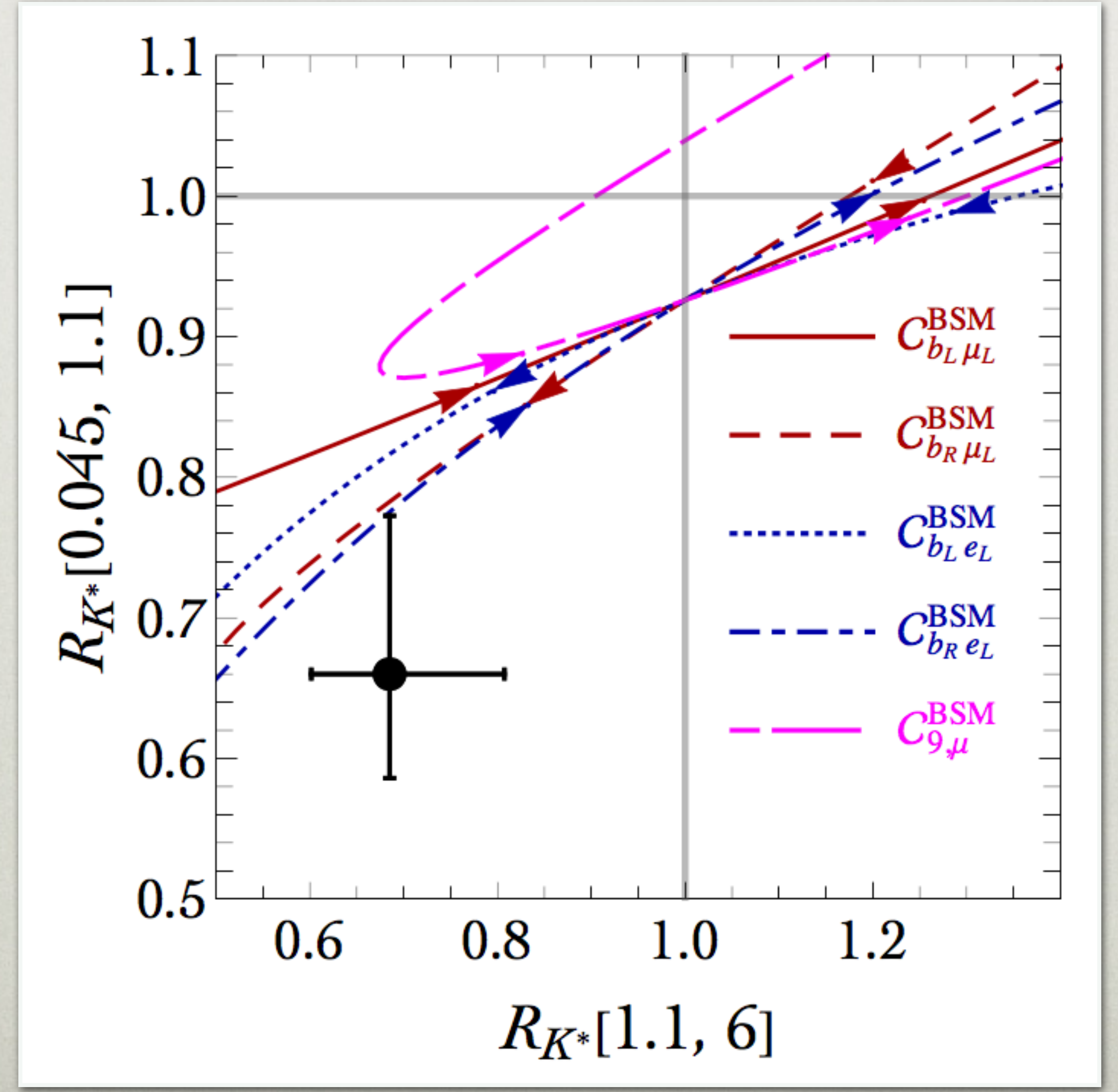
R_K vs. R_{K^*}

Geng et al, 1704.05446



LOW q^2 BIN

D'Amico et al., 1704.05438



SENSITIVITY TO NEW PHYSICS

- sensitivity to NP from virtual corrections
  - e.g. $b \to s l^+ l^-$
- NP contribs. scale as

$$\delta C^{\rm NP} \propto \frac{\sin\theta_i \sin\theta_j}{M_{\rm NP}^2}$$

- depends on mix. angles and NP masses

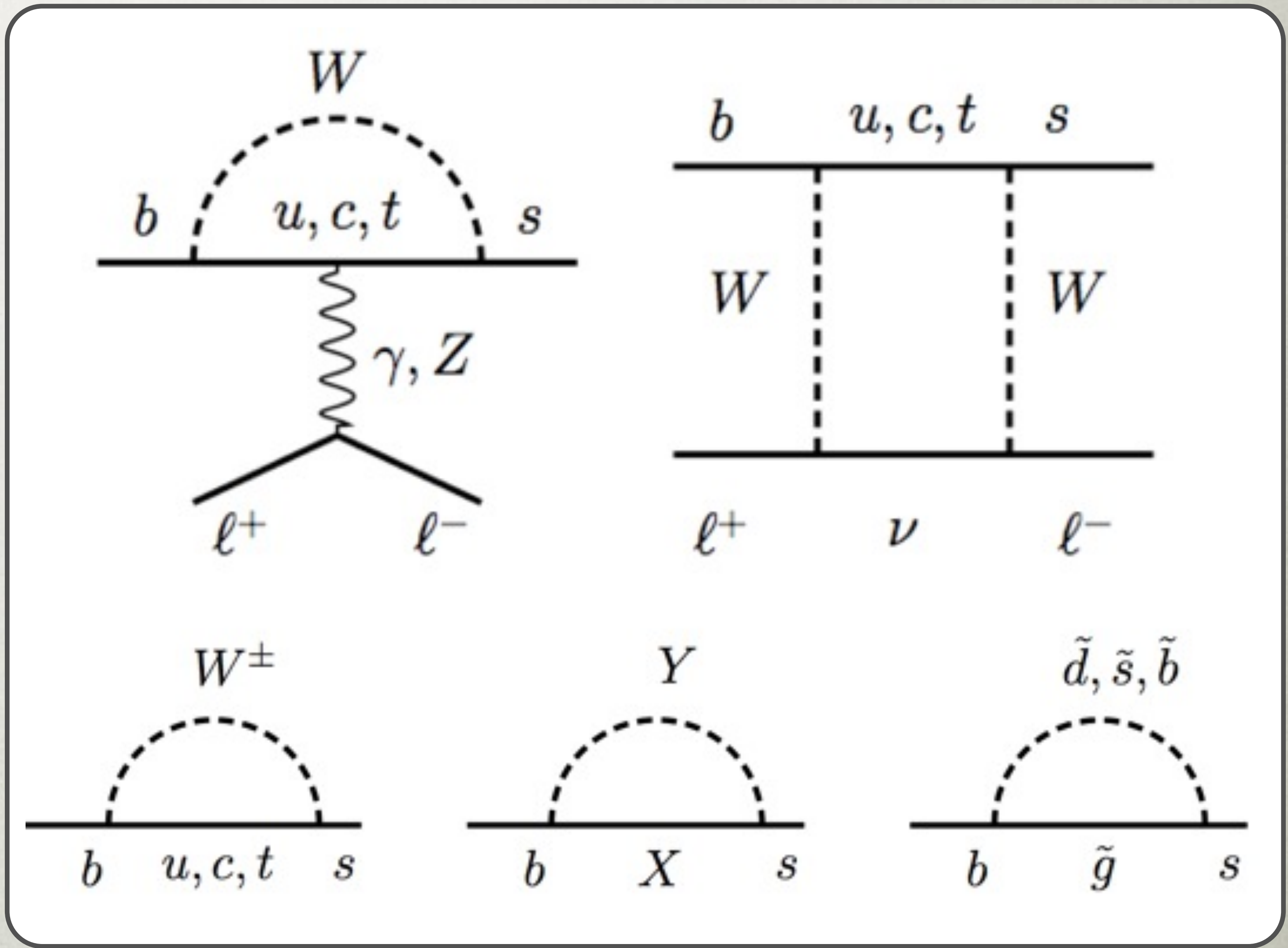
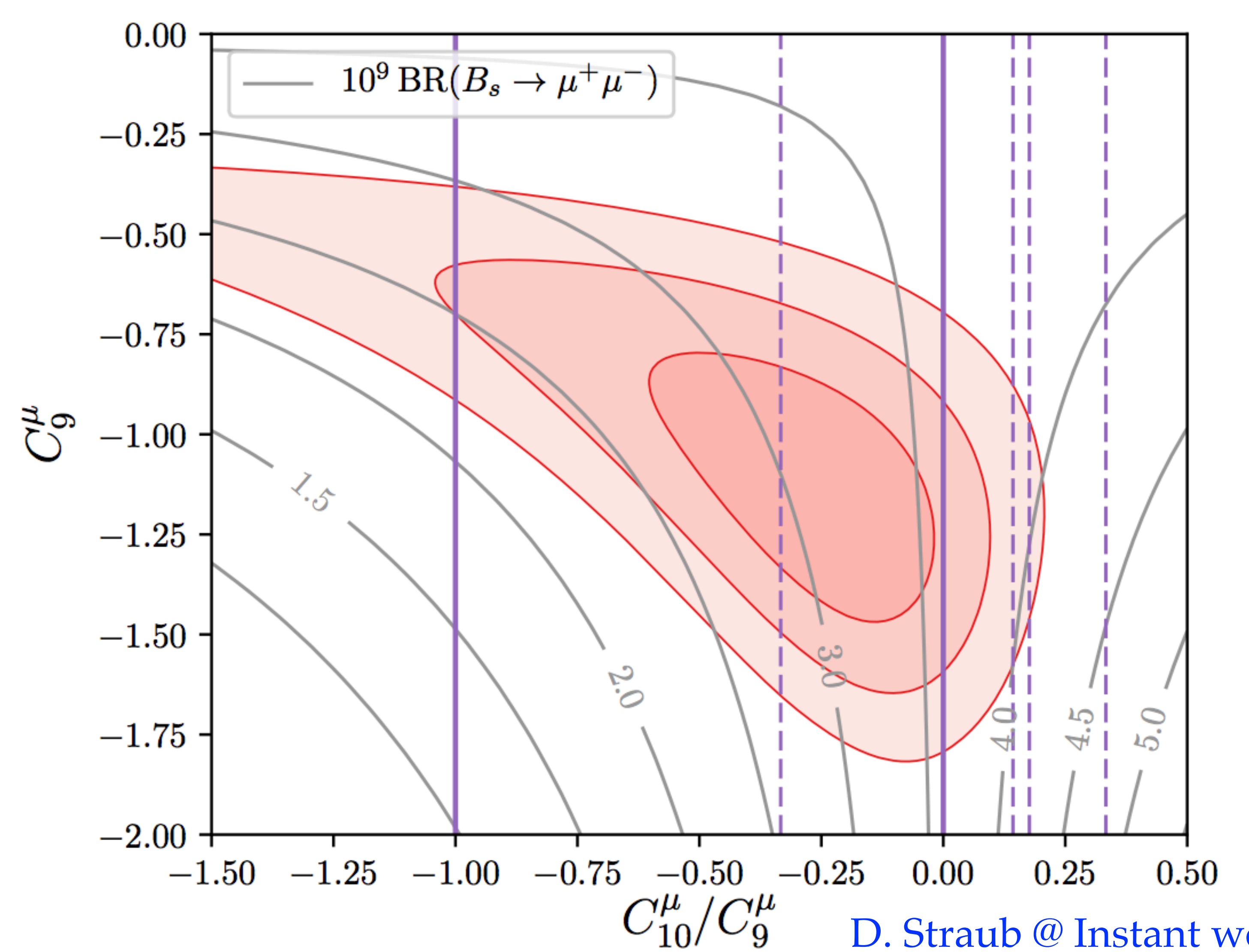


fig. from talk by G. Hiller at The First Three years of LHC, Mainz, Mar 2013

BOUNDS ON MODELS

- $B_s \to \mu\mu$ important discriminator of models



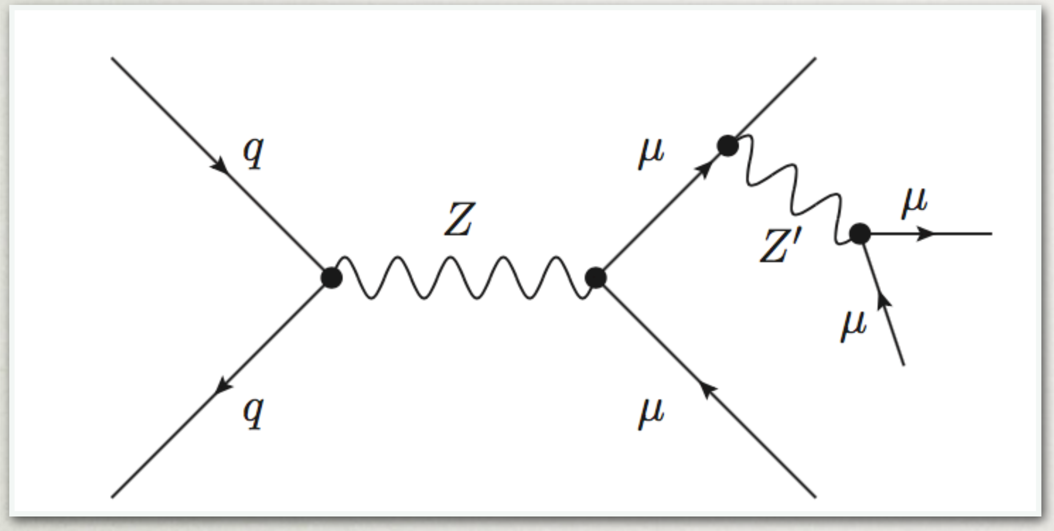
$\frac{C_{10}^\mu}{C_9^\mu}$ =: special cases

- 0: models involving L_μ
- 1: LQ models
- $\frac{3}{17}$ or $\frac{1}{3}$ Celis et al. 1505.03079
- $-\frac{1}{3}$ or $\frac{1}{7}$ Ellis et al. 1705.03447
- ...

D. Straub @ Instant workshop on B anomalies, 2017

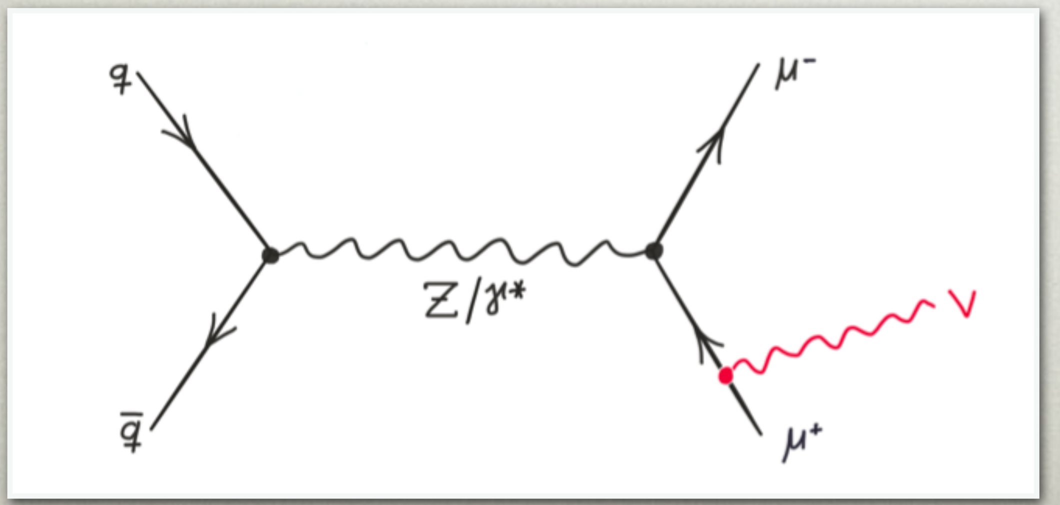
OTHER CONSTRAINTS

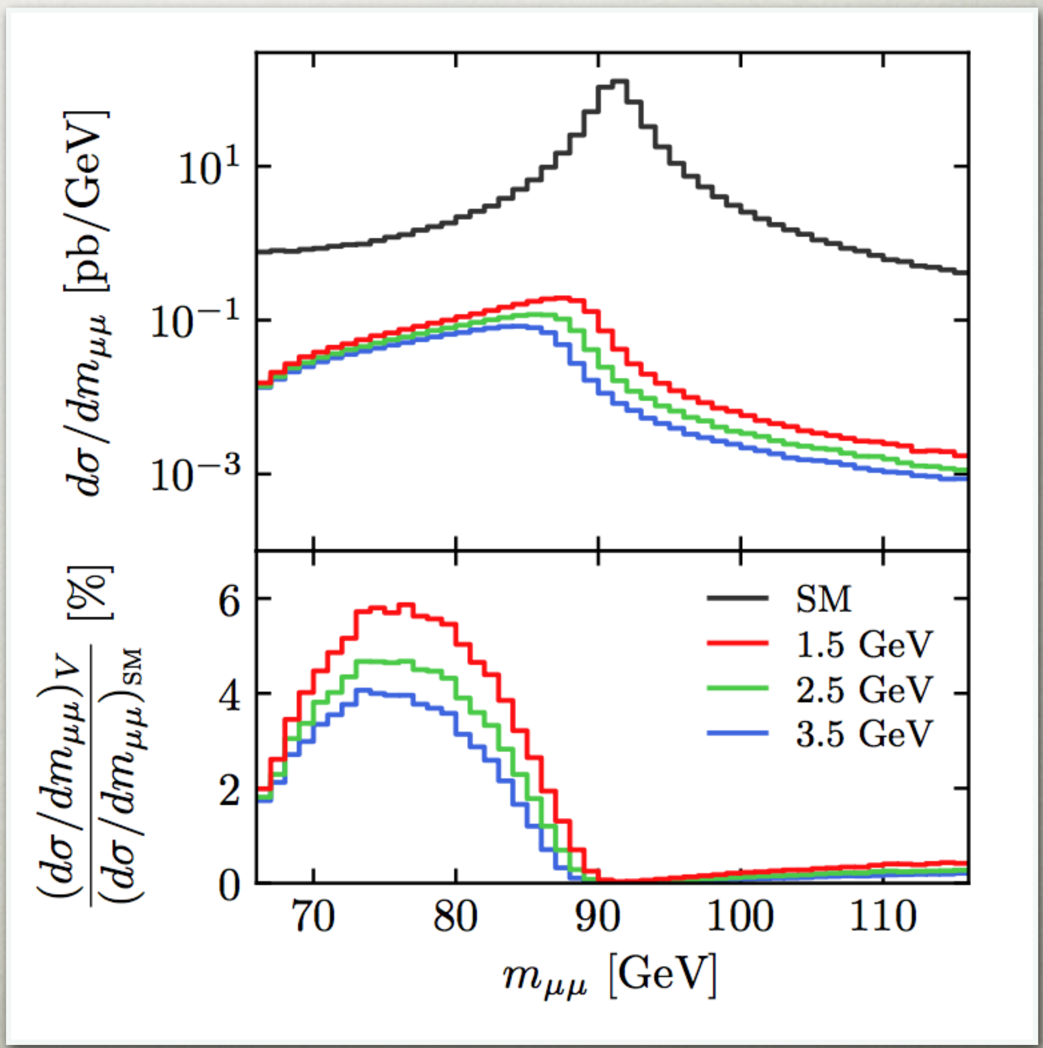
- nontrivial constraint from $Z \to 4l$



- especially for light Z' also important constraint from $\mu\mu$ p_T spectrum at the LHC

Bishara, Haisch, Monni, 1705.03465





$b \to c\tau\upsilon$

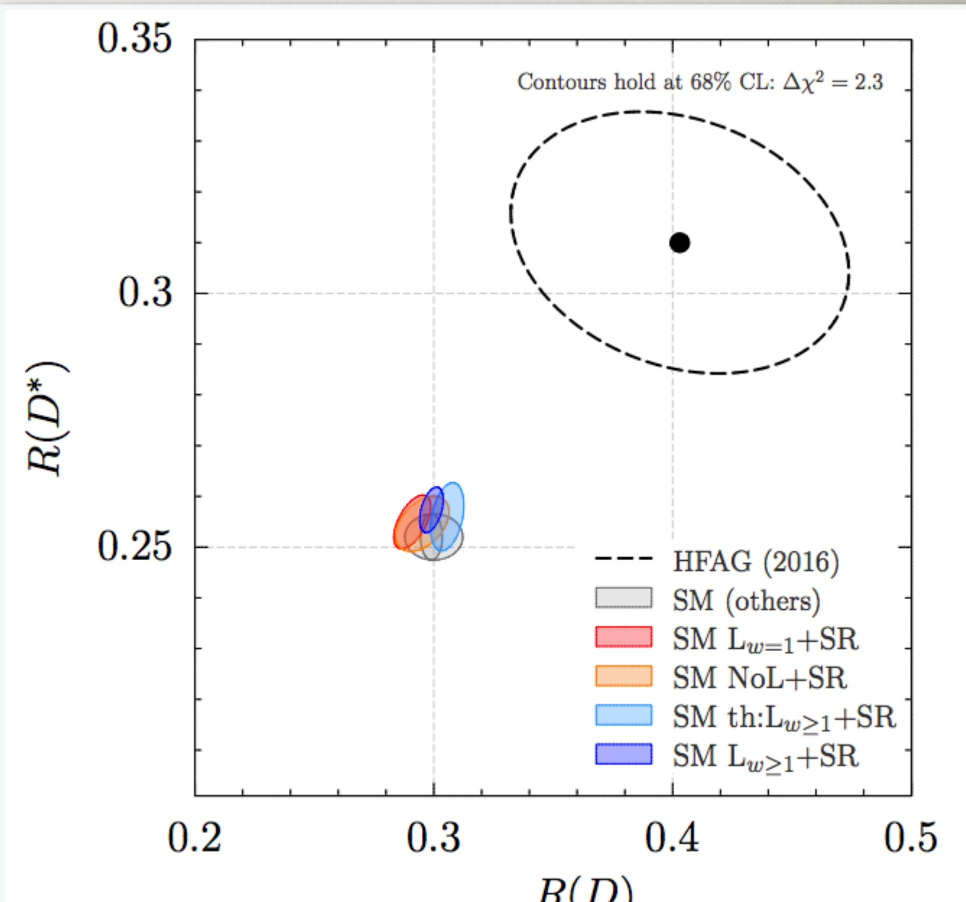
- numerical values

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50 ab^{-1}	± 0.010	± 0.005

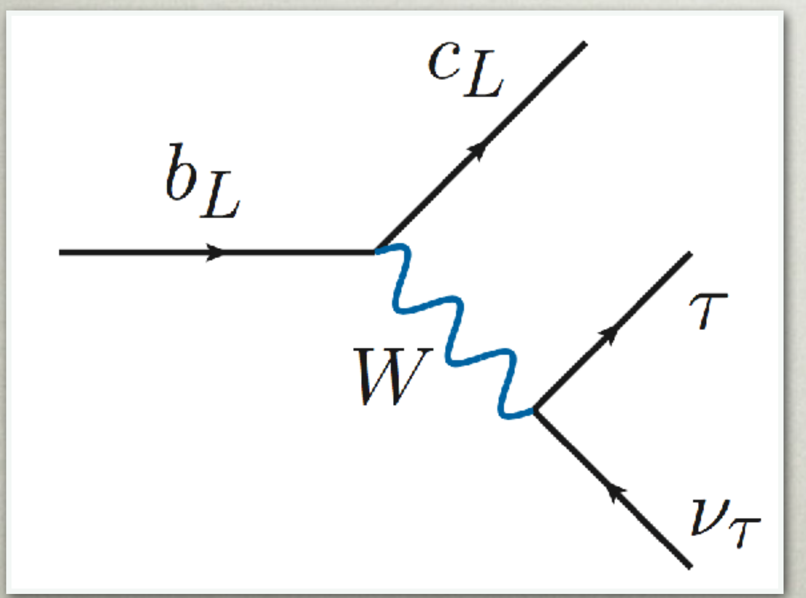
MODELS WITH RIGHT HANDED NEUTRINO

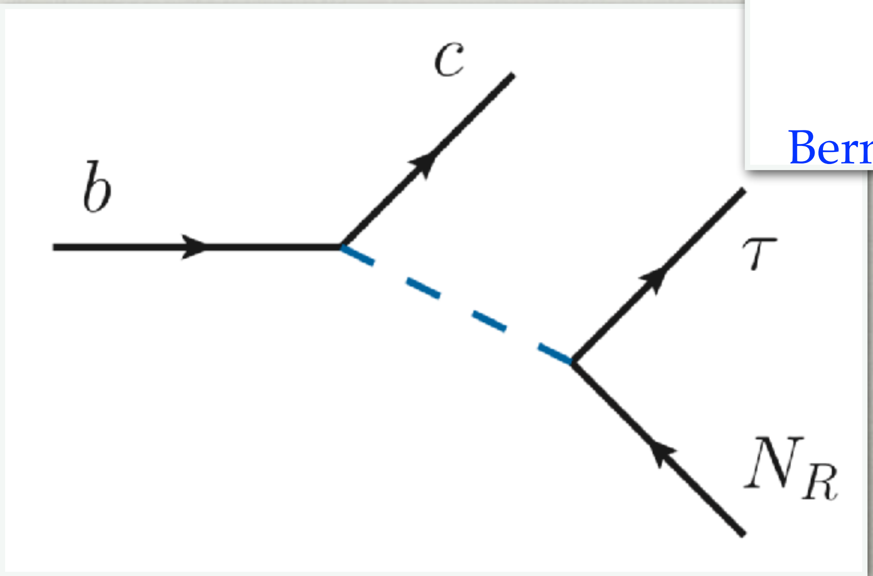
Robinson, Shakya, JZ, 1807.04753

- experimentally R_D, R_{D^*} above SM
  - no interf. between NP and SM
- N_R not part of a doublet
  - the constraints from charged leptons are absent



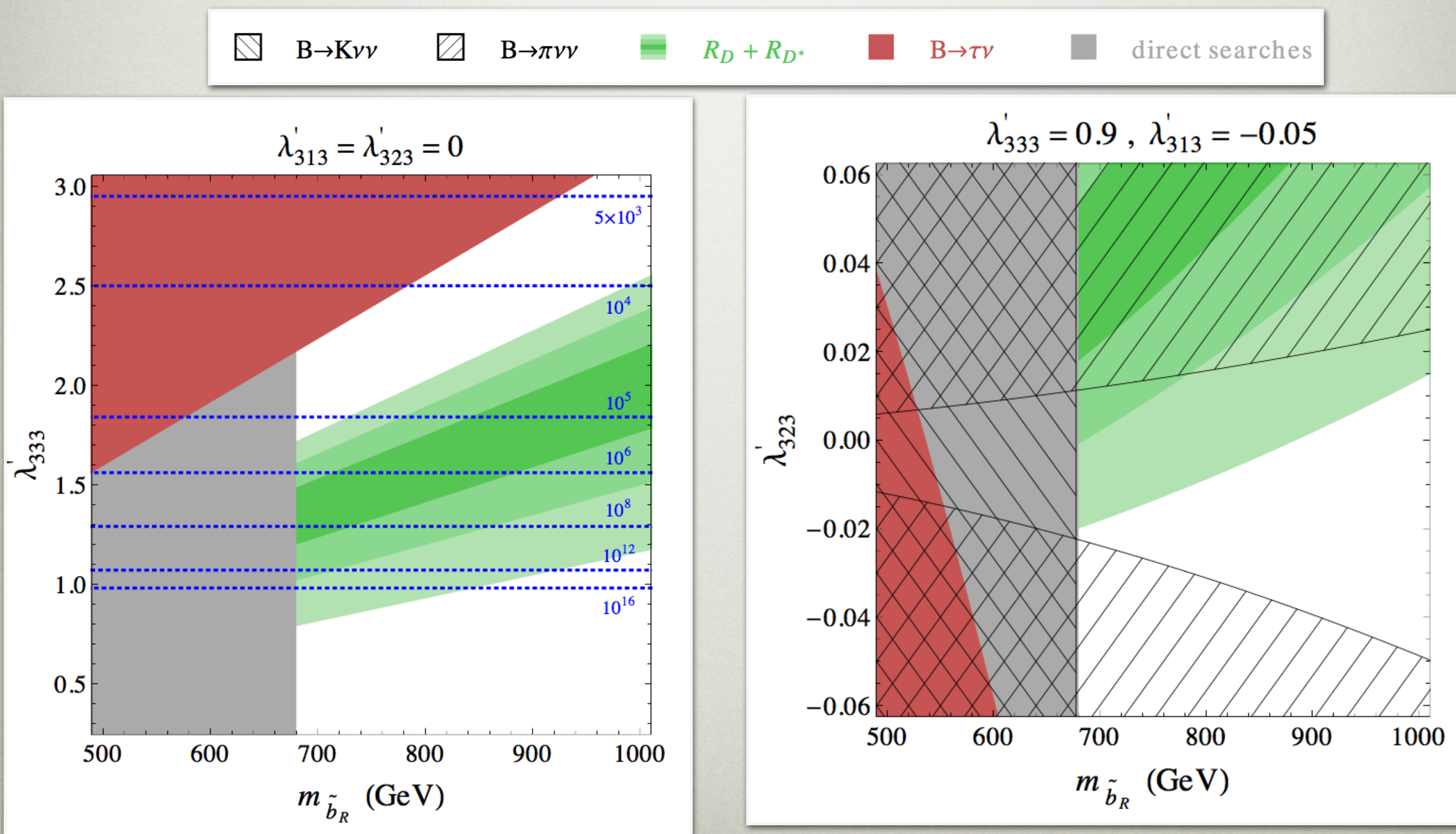
Bernlochner et al, 1703.05330





SBOTTOM SOLUTION

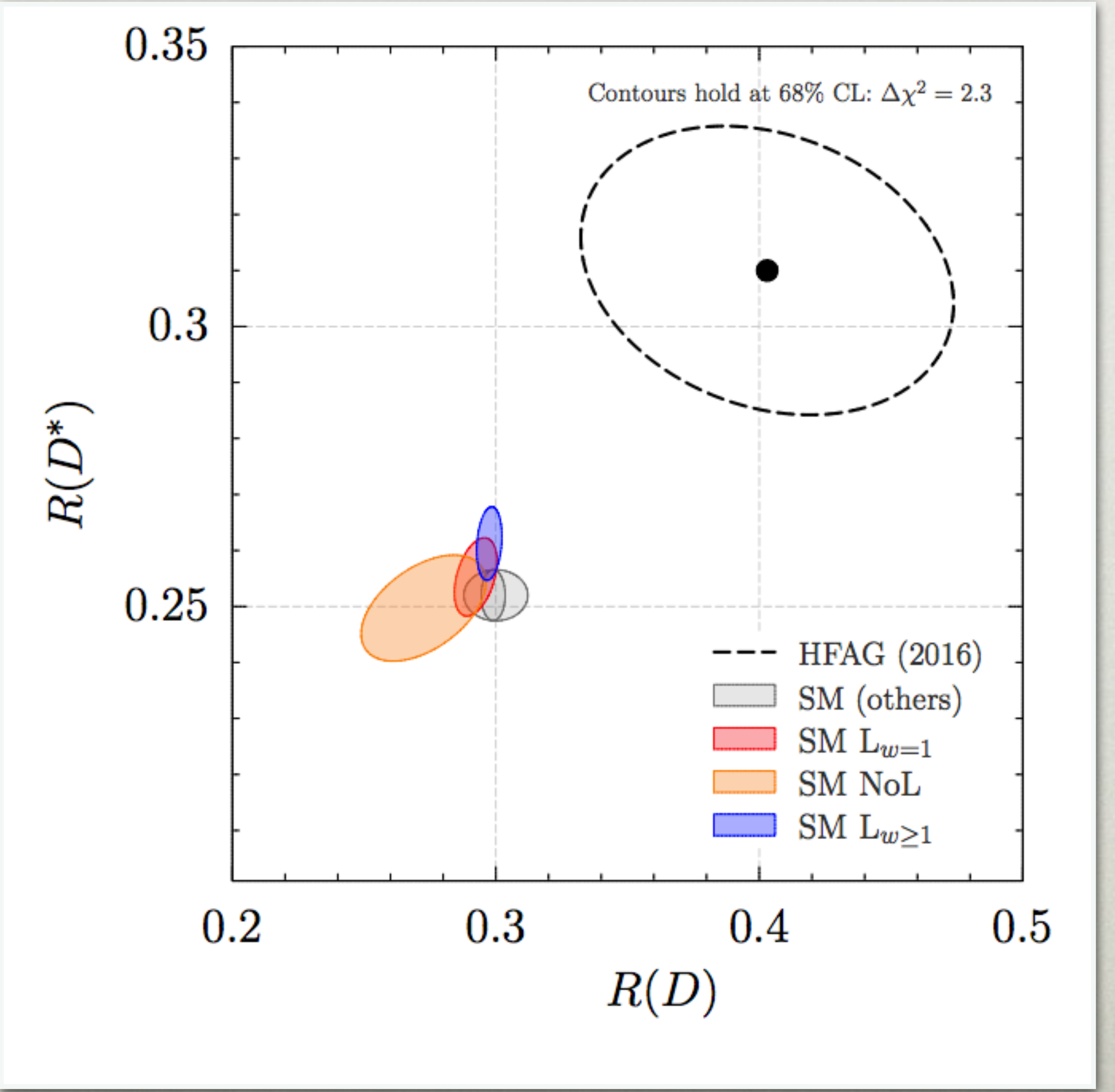
Altmannshofer, Dev, Soni, 1704.06659



R_D, R_{D^*} Predictions

Bernlochner, Ligeti, Papucci, Robinson, 1703.05330

- without light cone sum rule estimates

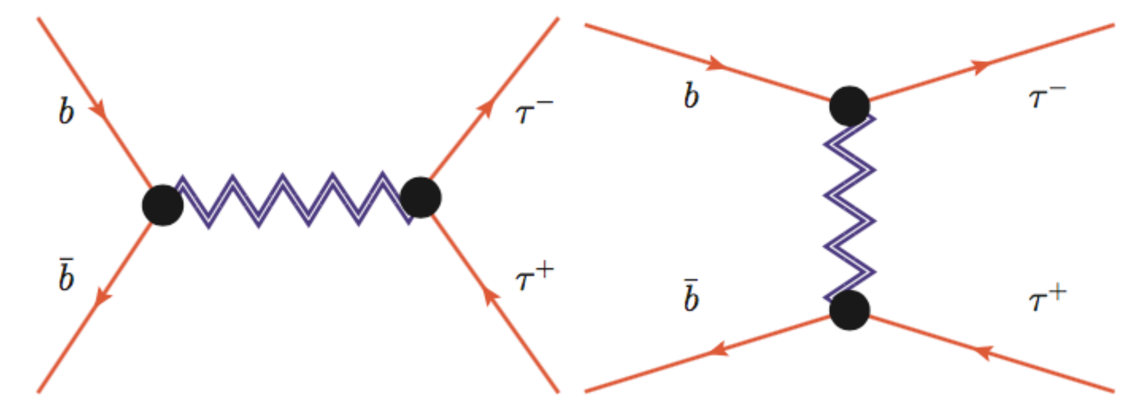


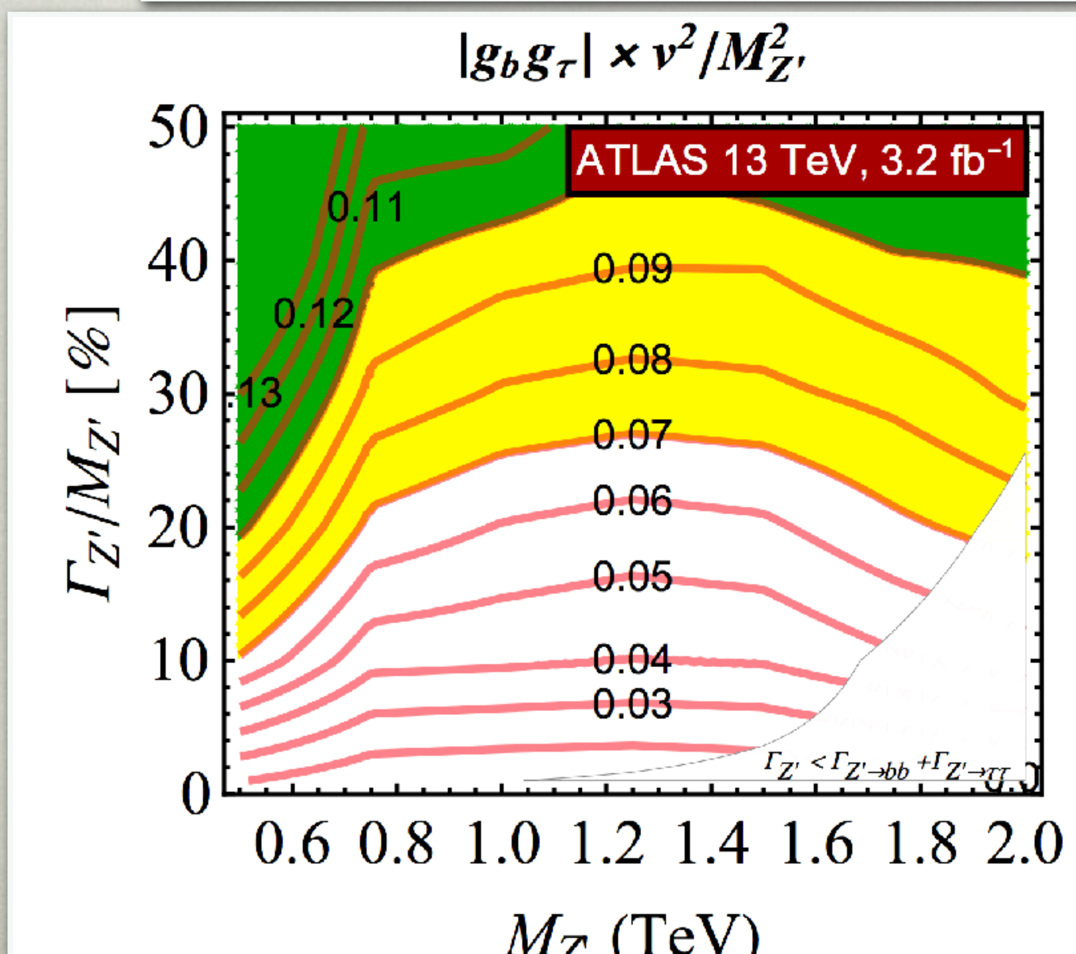
DIRECT SEARCHES IN $\tau\tau$

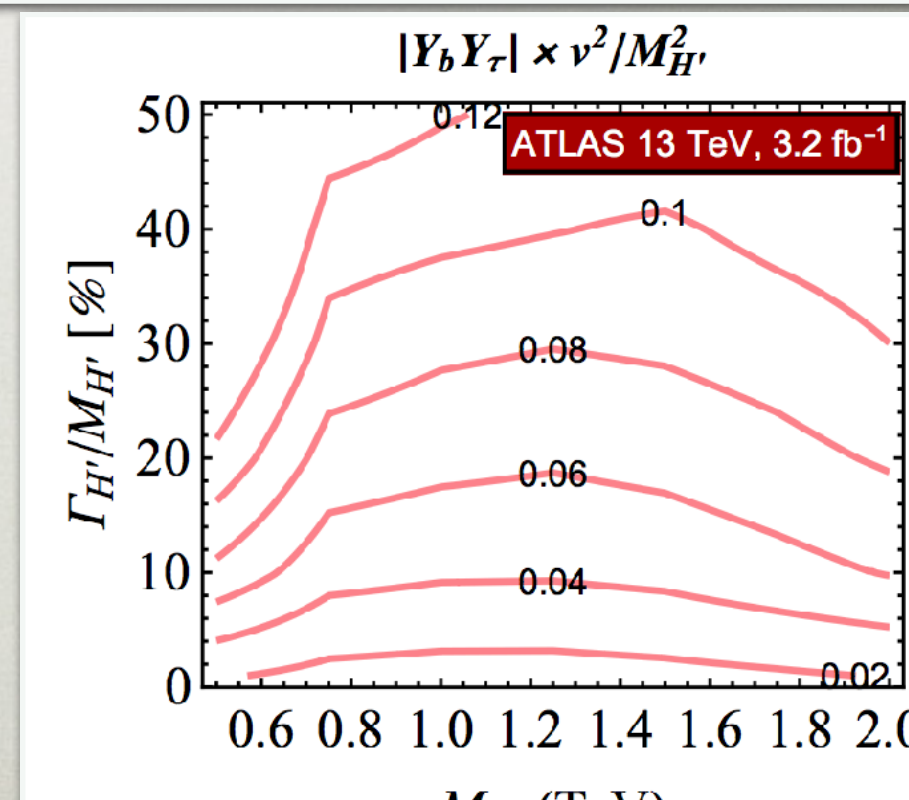
- $b\to c\tau\nu$ also implies a $1/V_{cb}$ enhanced $b\bar{b}\to\tau^+\tau^-$

	Color singlet	Color triplet
Scalar	2HDM	Scalar LQ
Vector	W'	Vector LQ

Faroughy, Greljo, Kamenik, 1609.07138







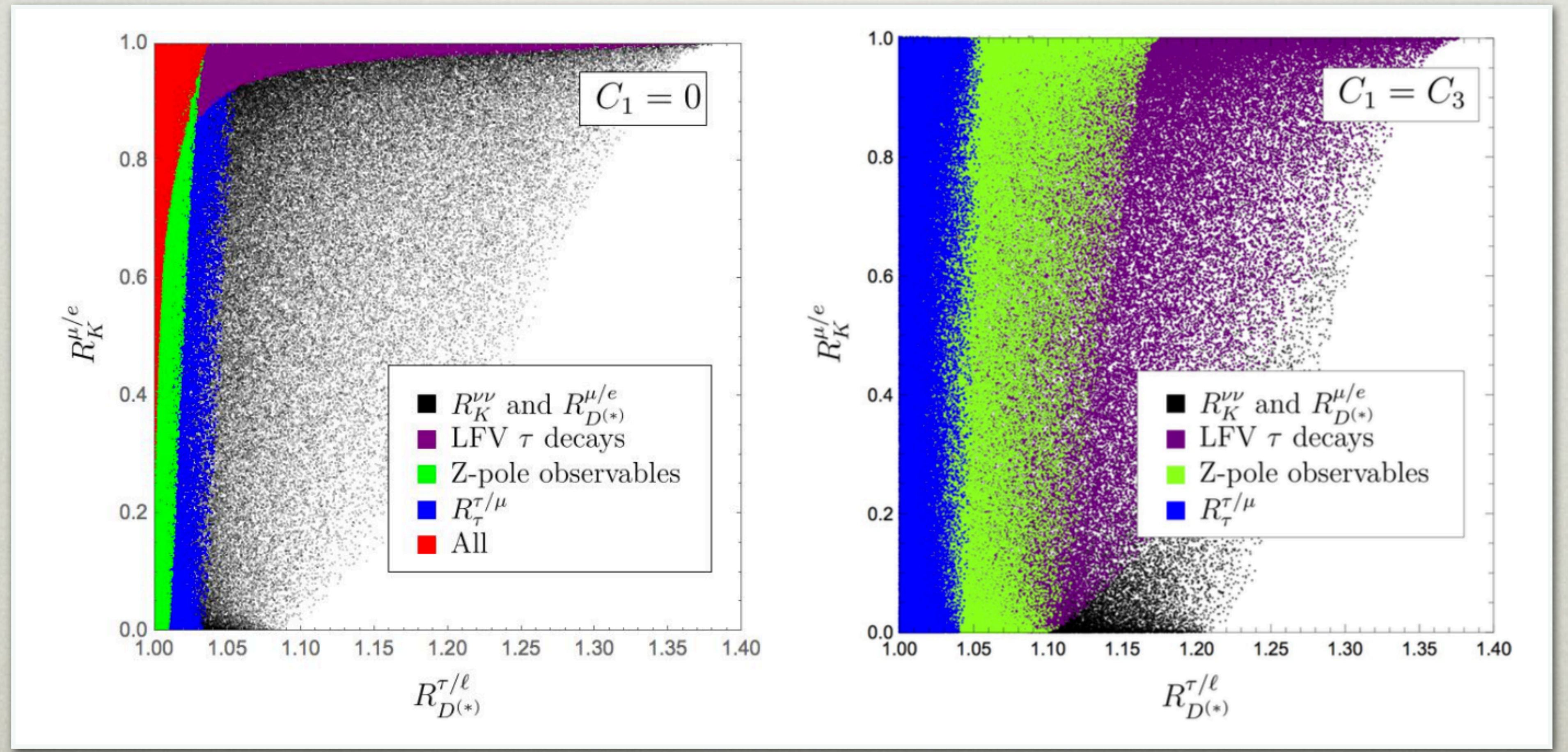
would need:

$$Y_b Y_\tau^* \times v^2/M_{H+}^2 = (2.9\pm0.8)$$

RADIATIVE CORRECTIONS

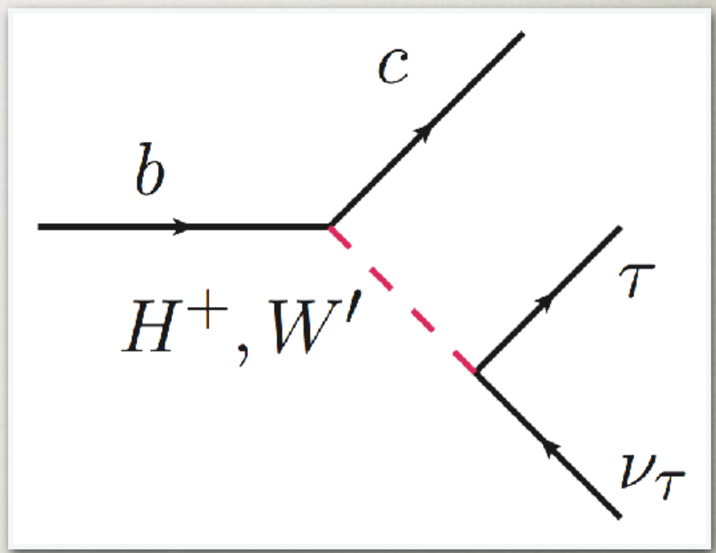
Feruglio, Paradisi, Pattori, 1705.00929, 1606.00524

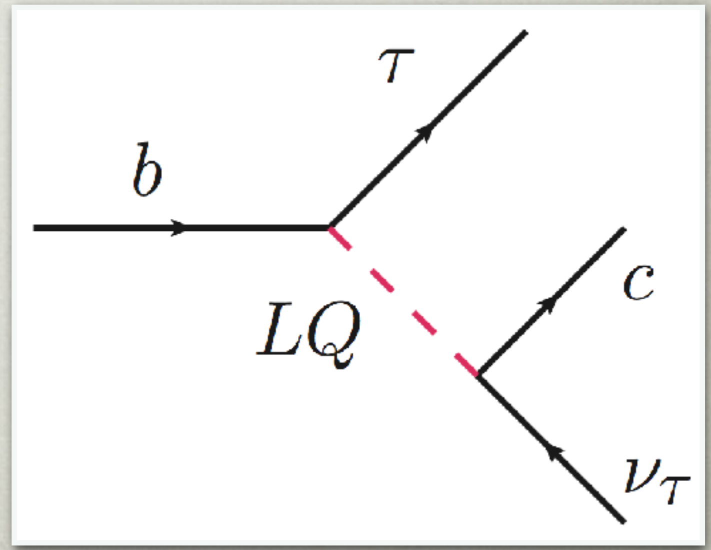
- loop corrections important
  - modifications of the W, Z couplings to leptons
  - induced τ decays



NEW PHYSICS INTERPRETATIONS

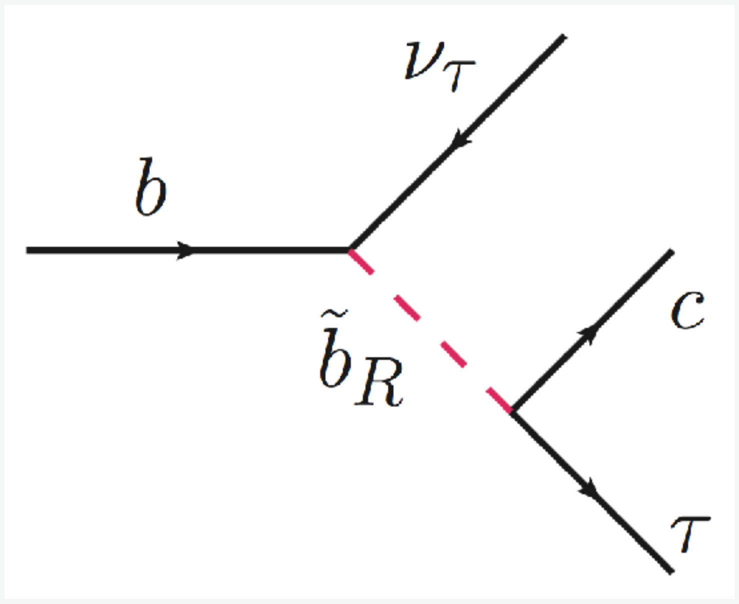
- the most obvious candidates ruled out
  - charged Higgs: total B_c lifetime, $b\to c\tau\upsilon$ q^2 distributions, searches in $pp\to\tau\tau$
  - W': related Z' ruled out from $pp\to\tau\tau$
- left with leptoquarks, will show two
  - RPV sbottom: explains $b\to c\tau\upsilon$, not ~~$b\to s\mu\mu$~~
  - vector leptoquark: explains $b\to c\tau\upsilon$ & $b\to s\mu\mu$
    - also possible if more than one scalar leptoquark   Crivellin, Muller, Ota, 1703.09226





RPV $\tilde{b}_{R,L}$

Altmannshofer, Dev, Soni, 1704.06659

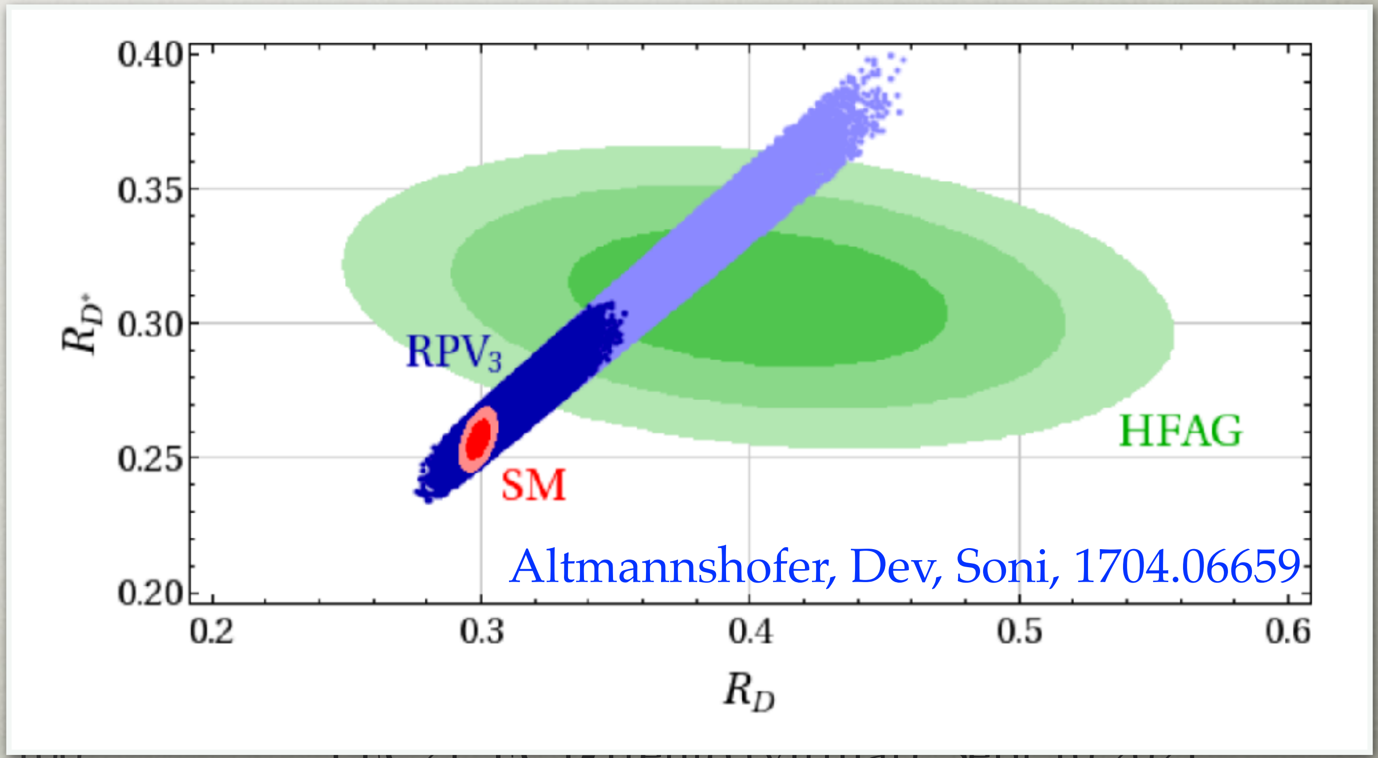


- leptoquarks: $\tilde{b}_{R,L}$ with RPV interactions

$$\lambda'_{ijk} L_i Q_j D^c_k$$

- to avoid proton decay constraints: 1st, 2nd gen. squarks taken heavy
- direct searches $pp \to tt\tau\tau$: $m(\tilde{b}_R) > 650\text{GeV}$
- unification still possible
- cannot explain $b \to s\mu\mu$

Deshpande, He, 1608.04817; Becirevic et al. 1608.07583



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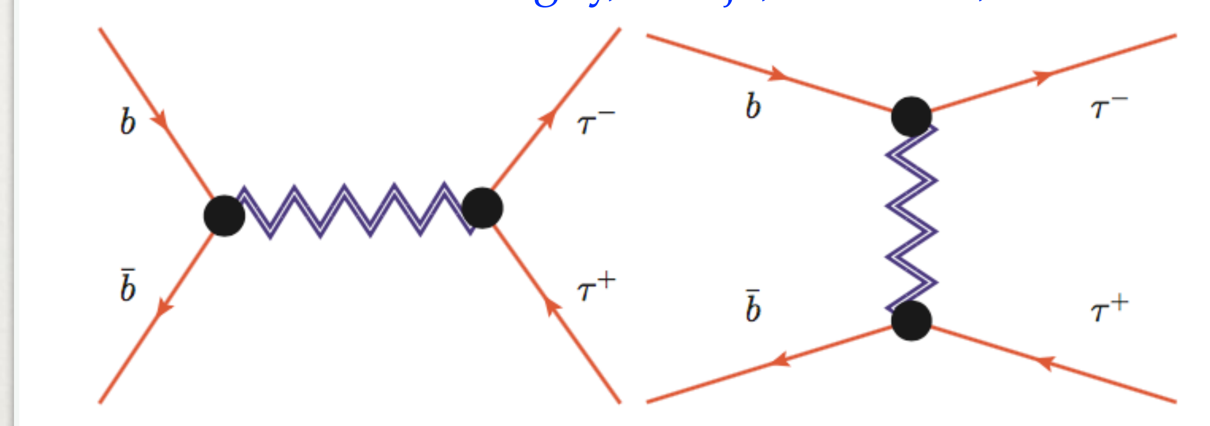
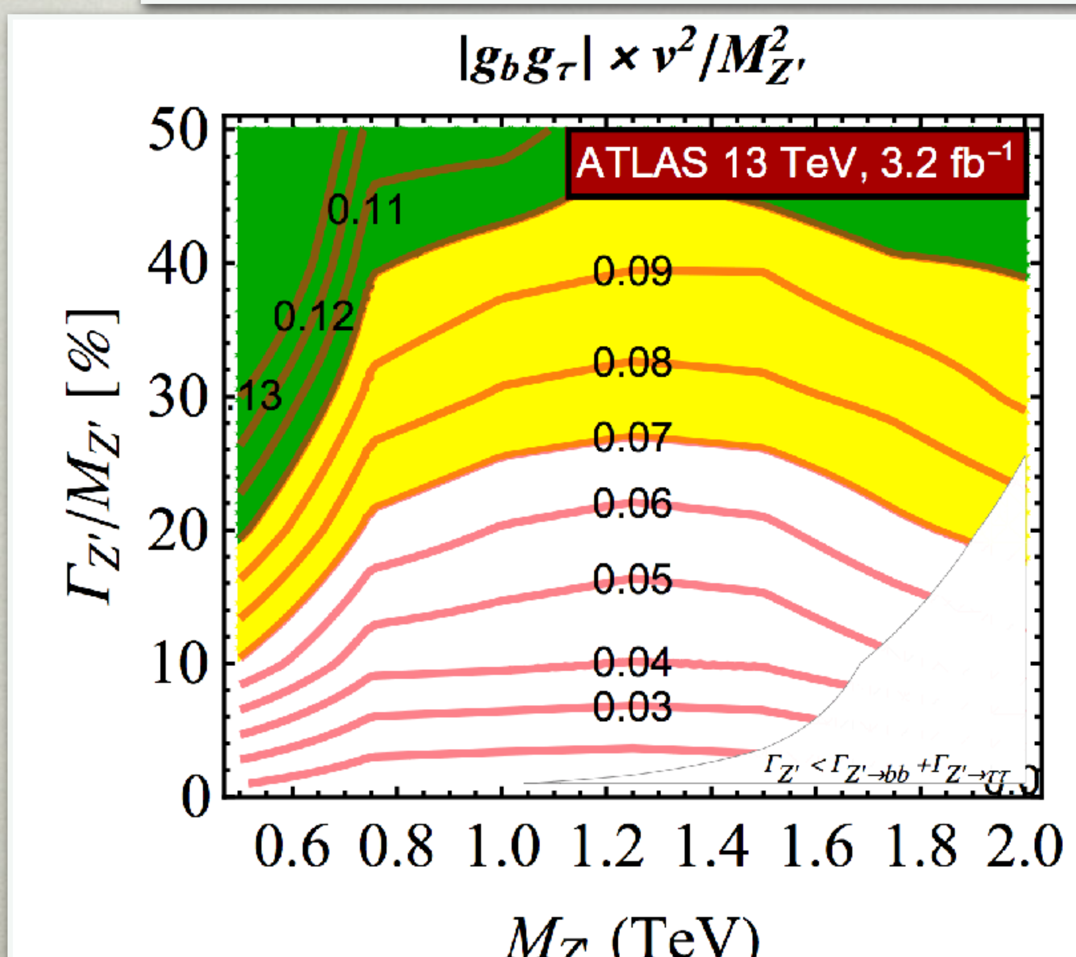
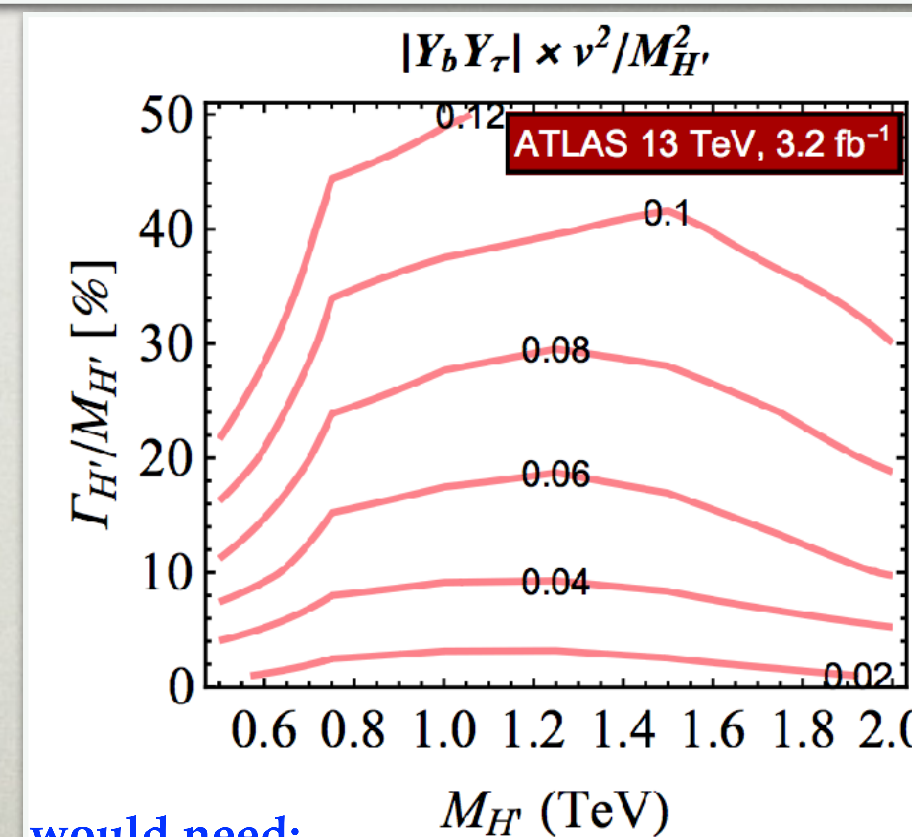
Faroughy, Greljo, Kamenik, 1609.07138







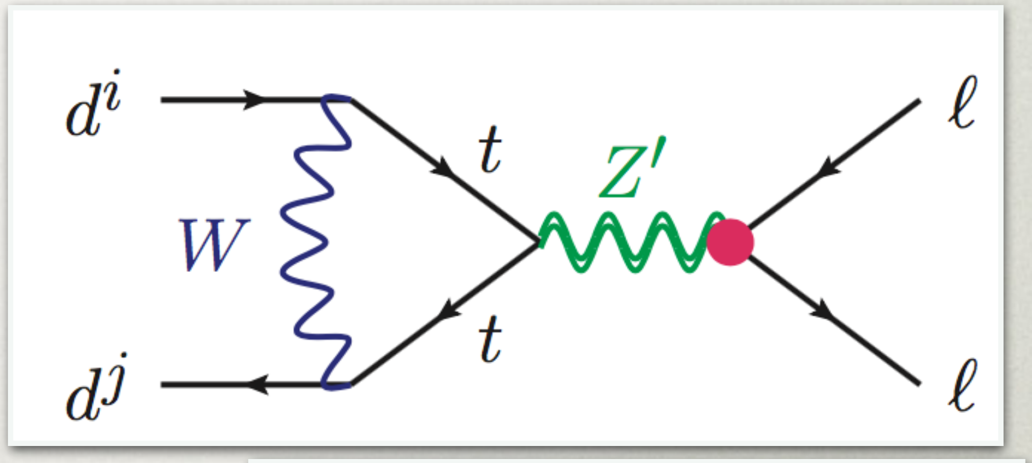
would need:

$$Y_b Y_\tau^* \times v^2/M^2_{H^+} = (2.9 \pm 0.8)$$

TOP-PHILIC Z'

Kamenik, Soreq, JZ, 1704.06005

- where is the flavor structure coming from?
- why the $(\bar{s}b)_{V\text{-}A}$ chiral structure?
- automatic for top-philic Z'
  - $b \to s$ due to SM
    W in the loop
  - avoids contraints from dimuon resonance searches
  - MFV structure: all FV due to CKM
    - there is a correlated signal in $K \to \pi\nu\nu$



$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(\cancel{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

cf. NA62 reach: 10% of the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq (8.4 \pm 1.0) \times 10^{-11} \times \frac{1}{3} \sum_{\ell} \left| 1 + 0.11 (C_9^{\ell,\mathrm{NP}} - C_{10}^{\ell,\mathrm{NP}}) \right|^2$$

SM value

see also Bordone, Buttazzo, Isidori, Monnard, 1705.10729

MINIMAL U(1)' MODEL

Kamenik, Soreq, JZ, 1704.06005

- new U(1)' gauge symmetry
  - scalar Φ~$(1,1,0,q')$ $\quad \Phi = (\phi + \tilde{v})/\sqrt{2}$
  - vectorlike fermion T'~$(3, 1, 2/3, q')$ ← $SU(3)\times SU(2)\times U(1)\times U(1)'$
  - all the SM fields singlets under U(1)'
- interactions with the SM through only three terms

$$\mathcal{L}_{\rm mix} = -\lambda' |\Phi|^2 |H|^2 - \epsilon B^{\mu\nu} F'_{\mu\nu} - (y_T^i \bar{T}' \Phi u_R^i + {\rm h.c.})$$

  - assume alignment with the SM up Yukawa

$$y_u^{ij} \sim {\rm diag}(0,0,y_t) \qquad y_T^i \sim (0,0,y_T^t)$$

  - for us the interesting limit $|y_T{}^t| \gg \lambda', \varepsilon$

SIZE OF $b\to s\mu\mu$

- t–T mass matrix

$$\mathcal{M}_u^{t-T'} = \begin{pmatrix} y_t v/\sqrt{2} & 0 \\ y_T^t \tilde{v}/\sqrt{2} & M_T \end{pmatrix}$$

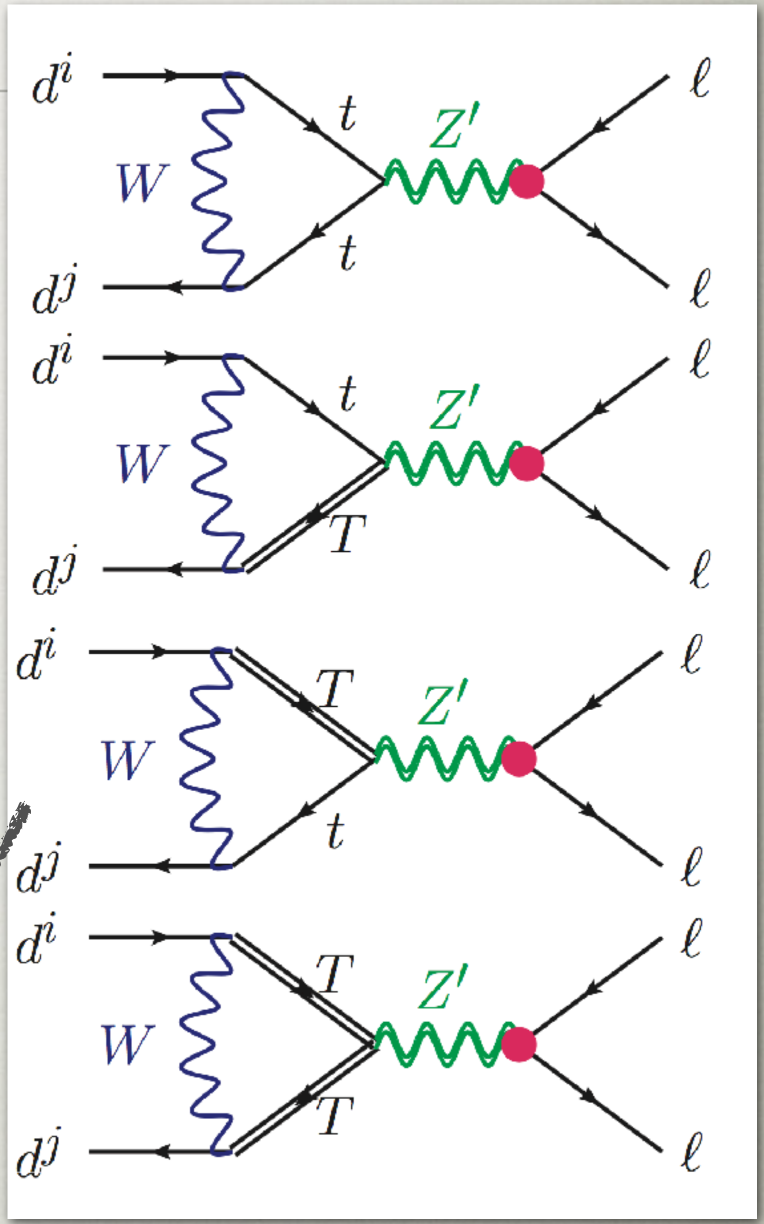
- the mixing angles for the two chiralities

$$\theta_R \sim y_T^t \tilde{v}/M_T \qquad \theta_L \sim \theta_R v/M_T$$

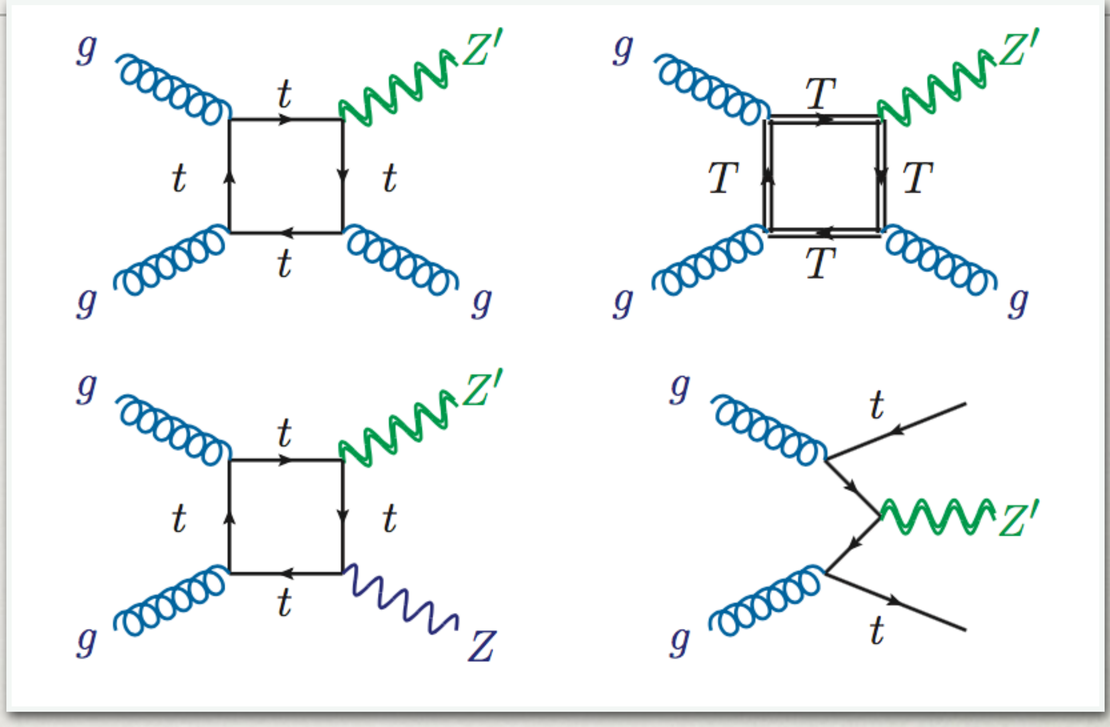
  - main effects due to mixing with t_R
- the induced $b\to sll$

$$C_{9,10}^{\mu,\mathrm{NP}} = \frac{1}{2} q' q'_{\mu,V,A} \frac{m_t^2}{m_{Z'}^2} \frac{\tilde{g}^2}{e^2} s_R^2 \log\left(\frac{m_T^2}{m_W^2}\right) + \ldots,$$

  - fits the anomaly for $m_{Z'}\sim O(500\ \mathrm{GeV})$, $\tilde{g}q'\sim O(1)$
- couplings to muons due to mixing with vectorlike leptons
  - depending on the details could explain $(g\text{-}2)_\mu$



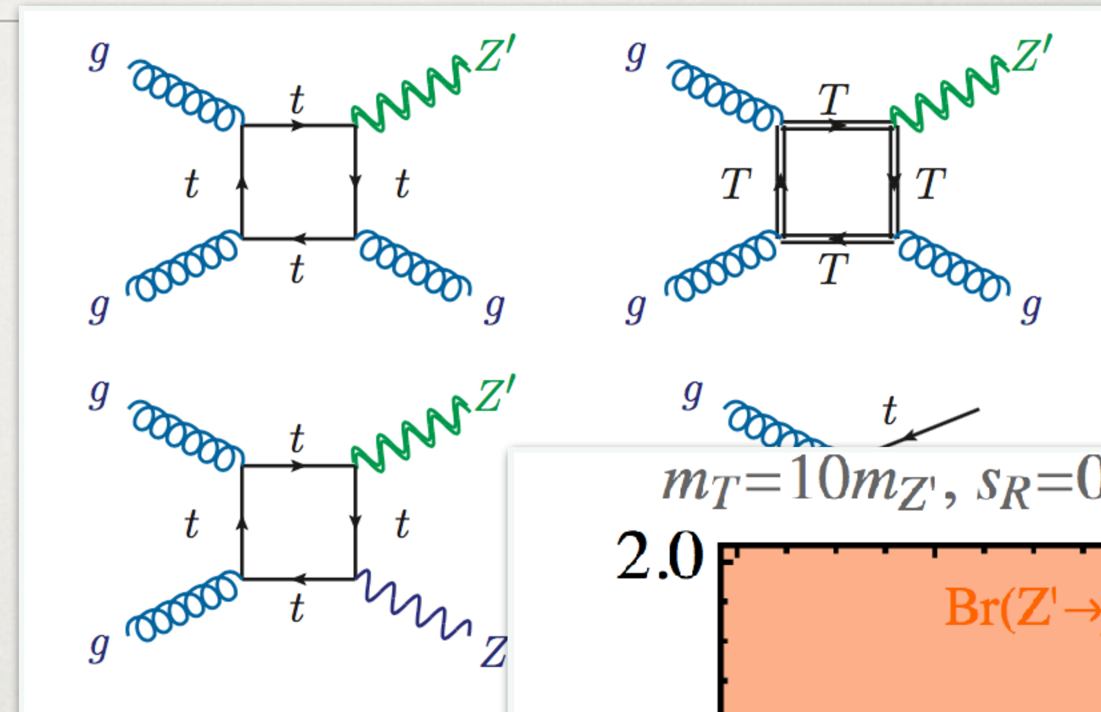
DIRECT SEARCHES

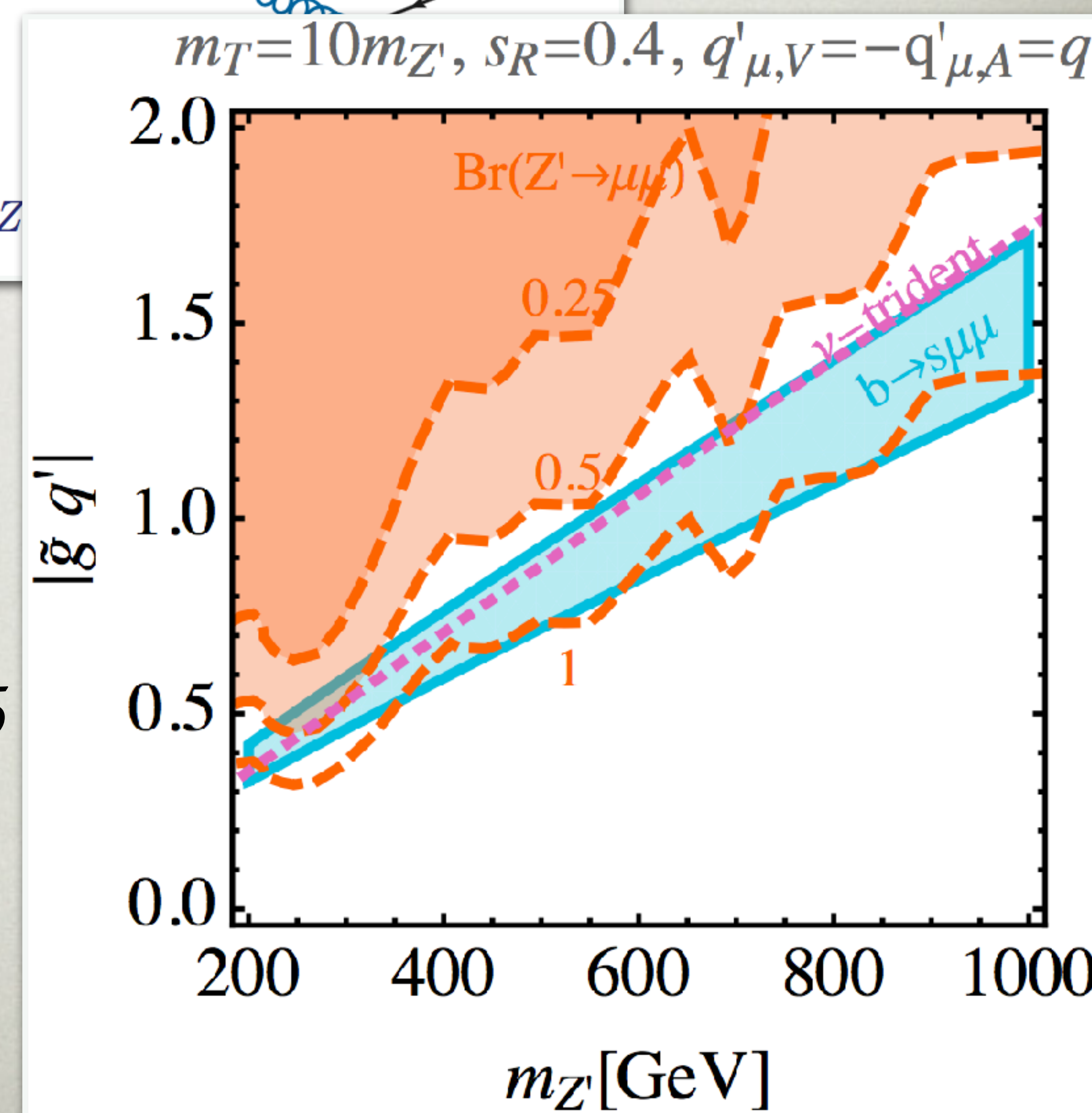


- contraints from dimuon searches:
- production channels:
  - tree level $pp \to \bar{t}tZ'$,
  - 1-loop: $pp \to ZZ', jZ'$
- depends on $Br(Z' \to \mu\mu)$
  - e.g. below $\bar{t}t$ threshold:
    - coupling to $\mu_L \Rightarrow Br(Z' \to \mu\mu)=0.5$
    - coupling to $\mu_L, \tau_L \Rightarrow Br(Z' \to \mu\mu)=0.25$
- interesting possible searches at LHC
  - $pp \to \bar{t}t(Z' \to \mu\mu)$, $\bar{t}t(Z' \to \tau\tau)$, $\bar{t}t(Z' \to \bar{t}t)$

DIRECT SEARCHES

- contraints from dimuon searches:
- production channels:
  - tree level $pp\to\bar{t}tZ'$,
  - 1-loop: $pp\to ZZ', jZ'$
- depends on $Br(Z'\to\mu\mu)$
  - e.g. below $\bar{t}t$ threshold:
    - coupling to μ_L $\Rightarrow Br(Z'\to\mu\mu)$=0.5
    - coupling to $\mu_L,\tau_L \Rightarrow Br(Z'\to\mu\mu)$=0.25
- interesting possible searches at LHC
  - $pp\to\bar{t}t(Z'\to\mu\mu)$, $\bar{t}t(Z'\to\tau\tau)$, $\bar{t}t(Z'\to\bar{t}t)$

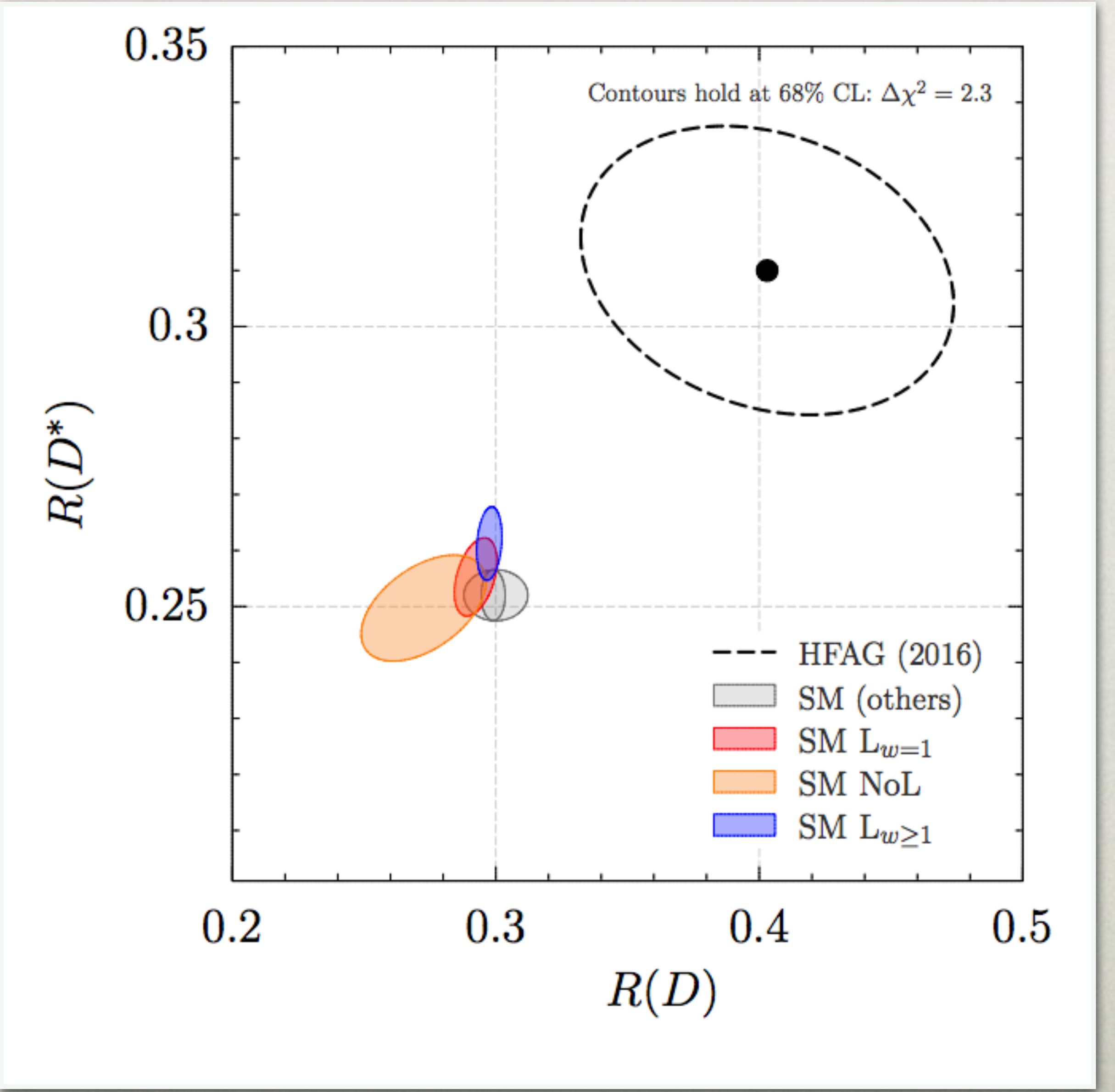




R_D, R_{D^*} Predictions

Bernlochner, Ligeti, Papucci, Robinson, 1703.05330

- without light cone sum rule estimates



MODELS WITH SM NEUTRINO

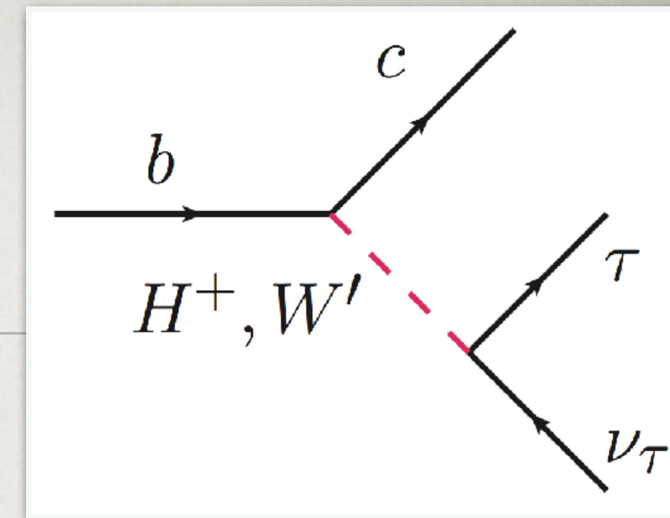
Freytsis, Ligeti, Ruderman, 1506.08896

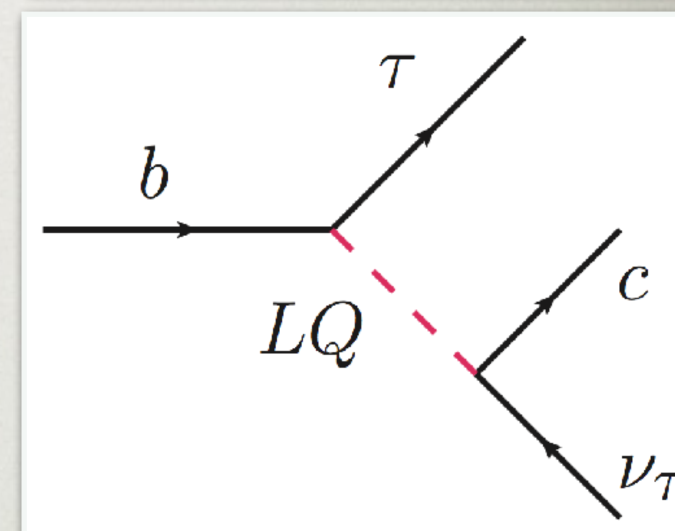
	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
$\mathcal{O}_{V_L}$	$(\bar c\gamma_\mu P_L b)\,(\bar\tau\gamma^\mu P_L\nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q\bar q_L\boldsymbol{\tau}\gamma^\mu q_L + g_\ell\bar\ell_L\boldsymbol{\tau}\gamma^\mu\ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar c\gamma_\mu P_R b)\,(\bar\tau\gamma^\mu P_L\nu)$			
$\mathcal{O}_{S_R}$	$(\bar c P_R b)\,(\bar\tau P_L\nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d\bar q_L d_R\phi + \lambda_u\bar q_L u_R i\tau_2\phi^\dagger + \lambda_\ell\bar\ell_L e_R\phi)$
$\mathcal{O}_{S_L}$	$(\bar c P_L b)\,(\bar\tau P_L\nu)$			
$\mathcal{O}_T$	$(\bar c\sigma^{\mu\nu}P_L b)\,(\bar\tau\sigma_{\mu\nu}P_L\nu)$			
$\mathcal{O}'_{V_L}$	$(\bar\tau\gamma_\mu P_L b)\,(\bar c\gamma^\mu P_L\nu)$	$\longleftrightarrow$ $\mathcal{O}_{V_L}$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\,\bar q_L\boldsymbol{\tau}\gamma_\mu\ell_L\boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar\tau\gamma_\mu P_R b)\,(\bar c\gamma^\mu P_L\nu)$	$\longleftrightarrow$ $-2\mathcal{O}_{S_R}$	$\rangle(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\,\bar q_L\gamma_\mu\ell_L + \tilde\lambda\,\bar d_R\gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar\tau P_R b)\,(\bar c P_L\nu)$	$\longleftrightarrow$ $-\frac12\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar\tau P_L b)\,(\bar c P_L\nu)$	$\longleftrightarrow$ $-\frac12\mathcal{O}_{S_L} - \frac18\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\,\bar u_R\ell_L + \tilde\lambda\,\bar q_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar\tau\sigma^{\mu\nu}P_L b)\,(\bar c\sigma_{\mu\nu}P_L\nu)$	$\longleftrightarrow$ $-6\mathcal{O}_{S_L} + \frac12\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar\tau\gamma_\mu P_L c^c)\,(\bar b^c\gamma^\mu P_L\nu)$	$\longleftrightarrow$ $-\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar\tau\gamma_\mu P_R c^c)\,(\bar b^c\gamma^\mu P_L\nu)$	$\longleftrightarrow$ $-2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda\,\bar d^c_R\gamma_\mu\ell_L + \tilde\lambda\,\bar q^c_L\gamma_\mu e_R)V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar\tau P_R c^c)\,(\bar b^c P_L\nu)$	$\longleftrightarrow$ $\frac12\mathcal{O}_{V_L}$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\,\bar q^c_L i\tau_2\boldsymbol{\tau}\ell_L\boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar\tau P_L c^c)\,(\bar b^c P_L\nu)$	$\longleftrightarrow$ $-\frac12\mathcal{O}_{S_L} + \frac18\mathcal{O}_T$	$\rangle(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\,\bar q^c_L i\tau_2\ell_L + \tilde\lambda\,\bar u^c_R e_R)S$
$\mathcal{O}''_T$	$(\bar\tau\sigma^{\mu\nu}P_L c^c)\,(\bar b^c\sigma_{\mu\nu}P_L\nu)$	$\longleftrightarrow$ $-6\mathcal{O}_{S_L} - \frac12\mathcal{O}_T$		

2 color singlet mediators

6 leptoquark mediators

THE MASS SCALE





- NP models with SM neutrino
  - color singlets: W', scalar doublet
  - color triplets: leptoquarks
  - typical mass ~*500*GeV for *O(1)* coupl.

Coefficient(s)	Best fit value(s) ($\Lambda = 1$ TeV)	
C_{V_L}	0.18 ± 0.04,	-2.88 ± 0.04
C_T	0.52 ± 0.02,	-0.07 ± 0.02
C''_{S_L}	-0.46 ± 0.09	
(C_R, C_L)	$(1.25, -1.02)$,	$(-2.84, 3.08)$
(C'_{V_R}, C'_{V_L})	$(-0.01, 0.18)$,	$(0.01, -2.88)$
(C''_{S_R}, C''_{S_L})	$(0.35, -0.03)$,	$(0.96, 2.41)$,
	$(-5.74, 0.03)$,	$(-6.34, -2.39)$

$W'_\mu \sim (1,3)_0$

Freytsis, Ligeti, Ruderman, 1506.08896

$\phi \sim (1,2)_{1/2}$

$U^\mu \sim (3,1)_{2/3}$

$S \sim (1,3)_{1/3}$

BOUNDS ON SIMPLIFIED MODELS

- all the four tree level mediators couple to LH quarks

Freytsis, Ligeti, Ruderman, 1506.08896

$$(g_q \bar{q}_L \boldsymbol{\tau} \gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau} \gamma^\mu \ell_L) W'_\mu$$

$$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$$

$$(\lambda \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R) U^\mu$$

$$(\lambda \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda} \bar{u}^c_R e_R) S$$

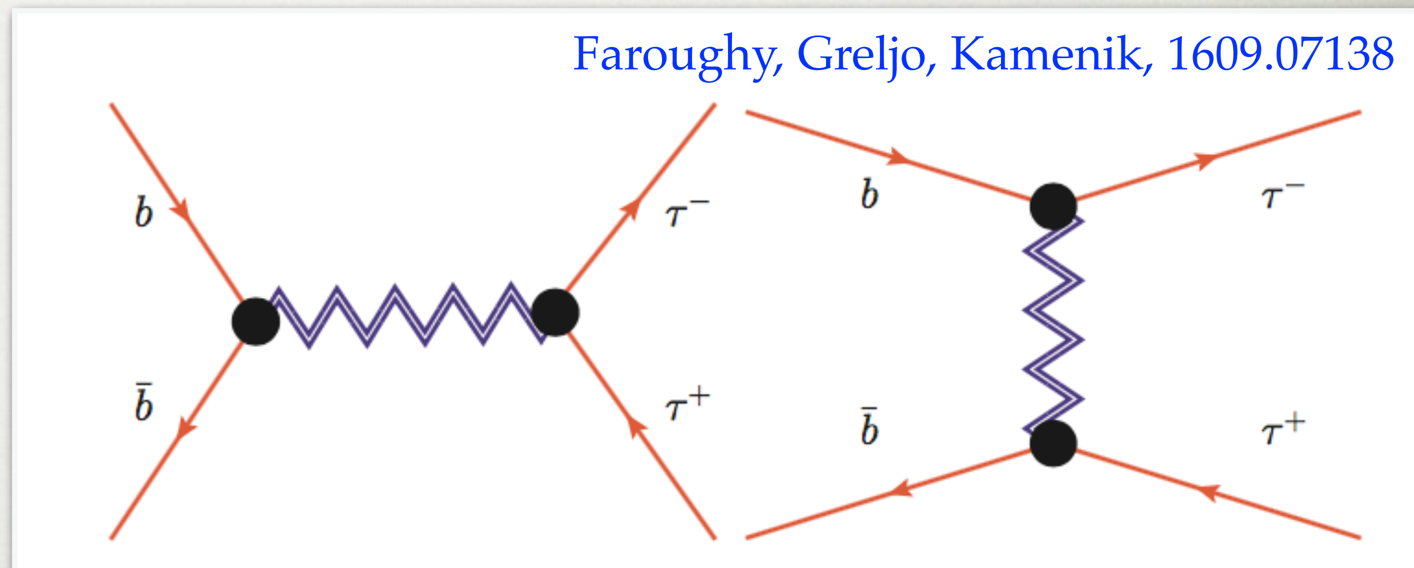
Faroughy, Greljo, Kamenik, 1609.07138

- the q_L flavor struct. that roughly minimizes constraints
  - only coupling to
  - then $b \to c\tau\upsilon$ is V_{cb} suppressed

$$Q_3 = \begin{pmatrix} V_{ub} u_L + V_{cb} c_L + V_{tb} t_L \\ b_L \end{pmatrix}$$

DIRECT SEARCHES IN $\tau\tau$

- $b \to c\tau\nu$ implies a $1/V_{cb}$ enhanced $b\bar{b} \to \tau^+\tau^-$
- severe bounds from LHC

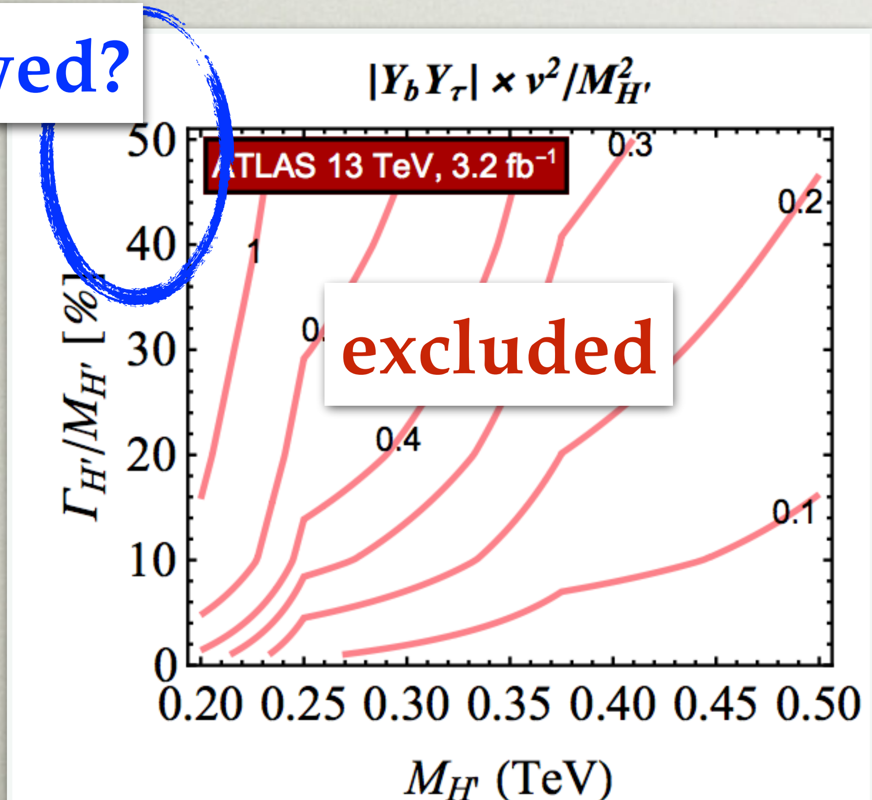


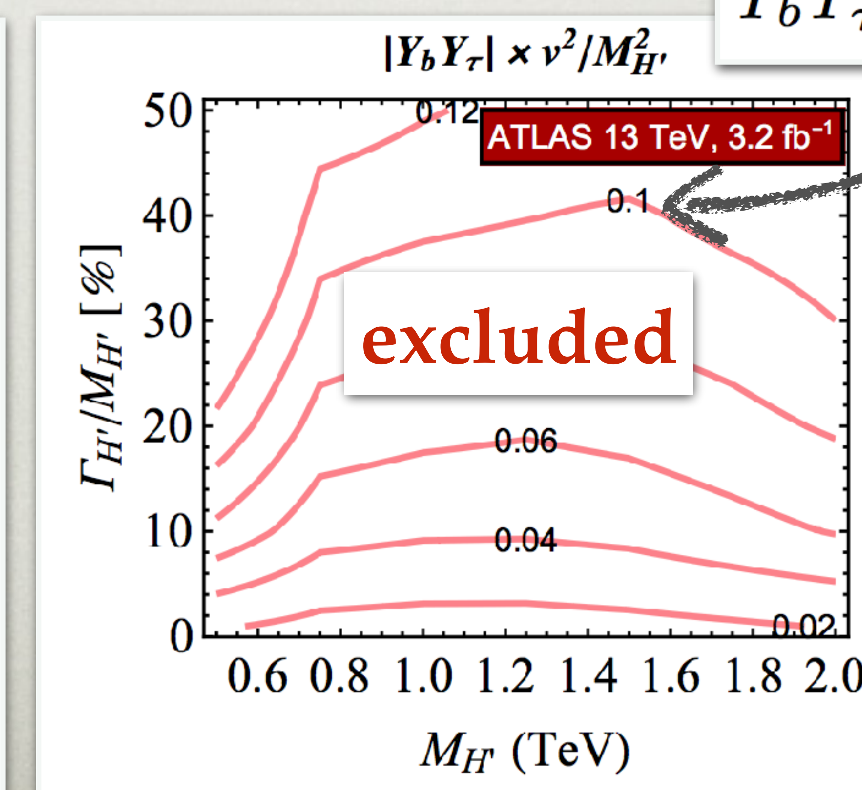
- for instance for scalar doublet

for $b \to c\tau\nu$ need:

$$Y_b Y_\tau^* \times v^2/M_{H^+}^2 = (2.9 \pm 0.8)$$

allowed?





perturbativity bound

$$Y_b Y_\tau < (4\pi)^2$$
$$\Downarrow$$
$$m_H < 2 \text{ TeV}$$

DIRECT SEARCHES IN $\tau\tau$

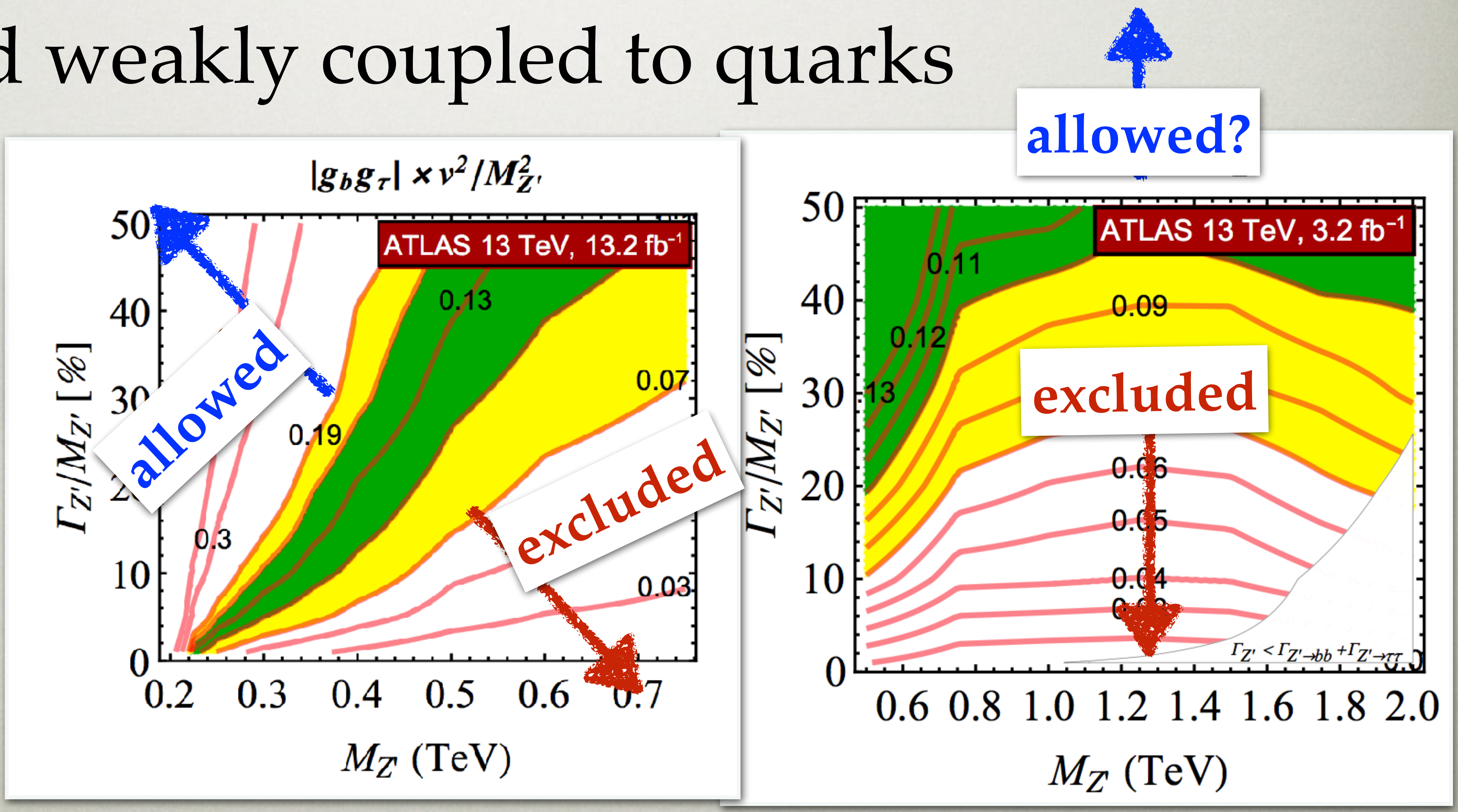
Faroughy, Greljo, Kamenik, 1609.07138

- vector triplet: W', Z'
  - either nonperturbative or very light and weakly coupled to quarks

unitarity bound

$m_{W'} < 6.5\text{TeV}$

di Luzio, Nardecchia, 1706.01868

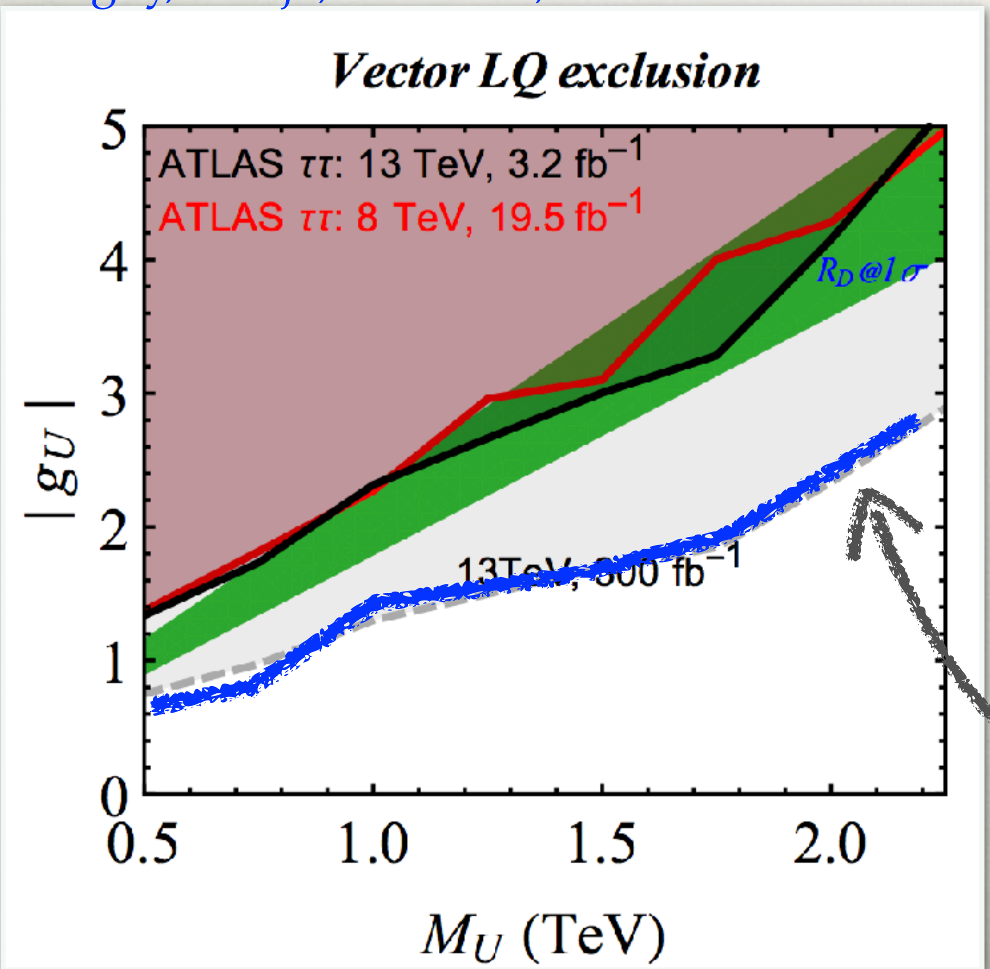


DIRECT SEARCHES IN $\tau\tau$

- vector leptoquark: U_μ
  - bounds depend somewhat on flavor structure assumed

$$\overset{g_U}{(\lambda}\bar{q}_L^3\gamma_\mu\ell_L + \tilde{\lambda}\bar{d}_R\gamma_\mu e_R)U^\mu$$

Faroughy, Greljo, Kamenik, 1609.07138



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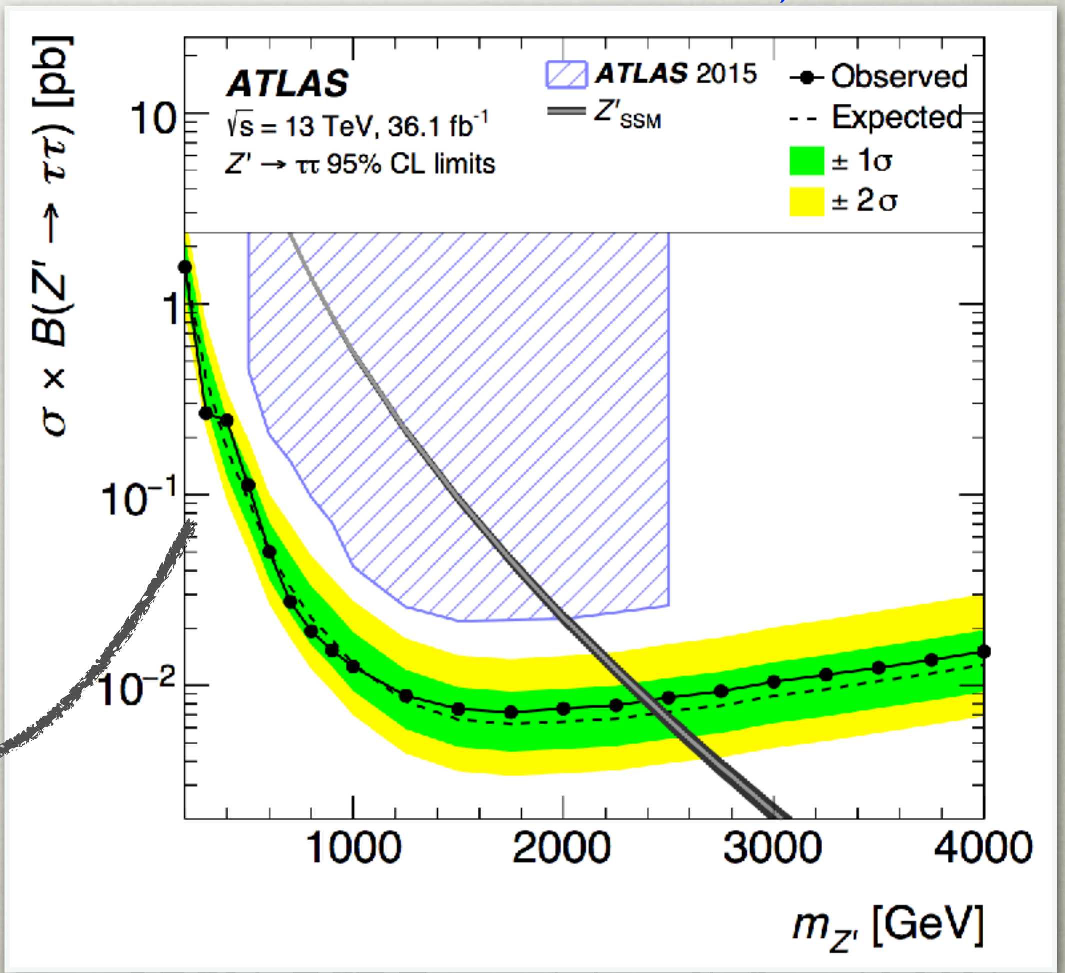
ATLAS, 1709.07242

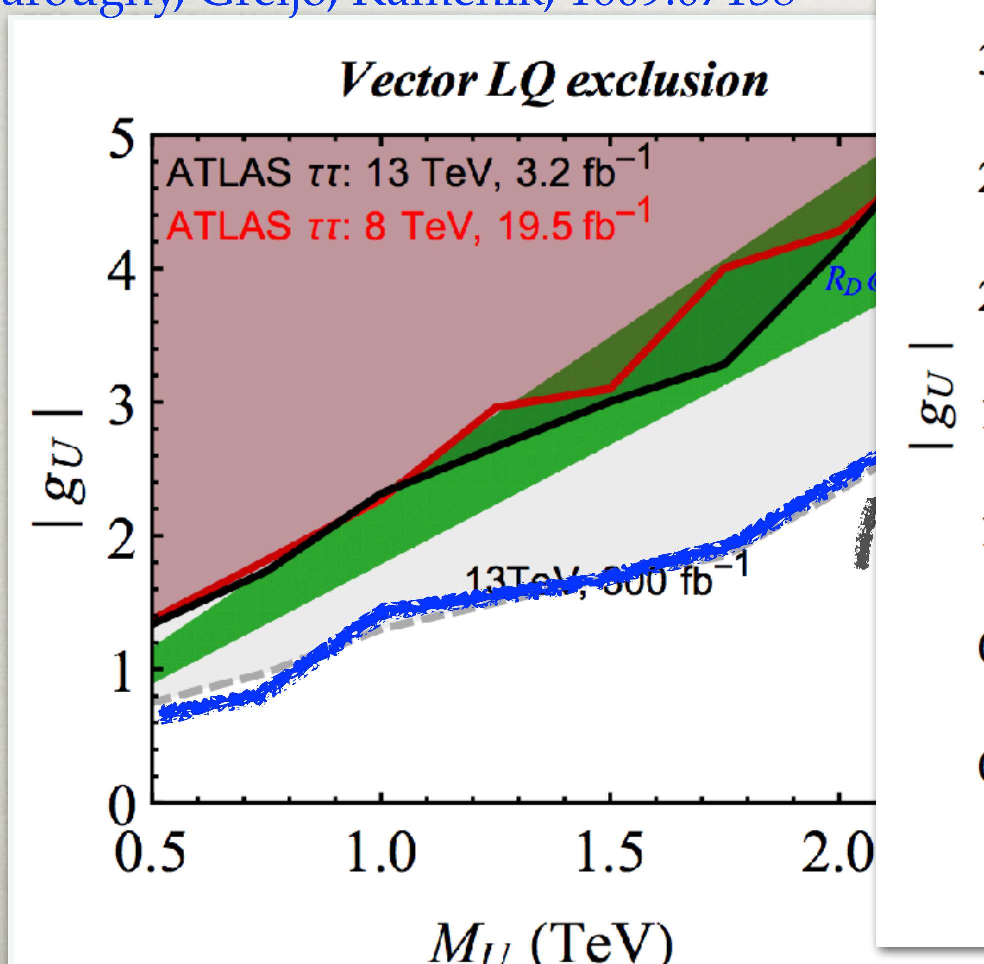


DIRECT SEARCHES IN $\tau\tau$

- vector leptoquark: U_μ
  - bounds depend somewhat on flavor structure assumed

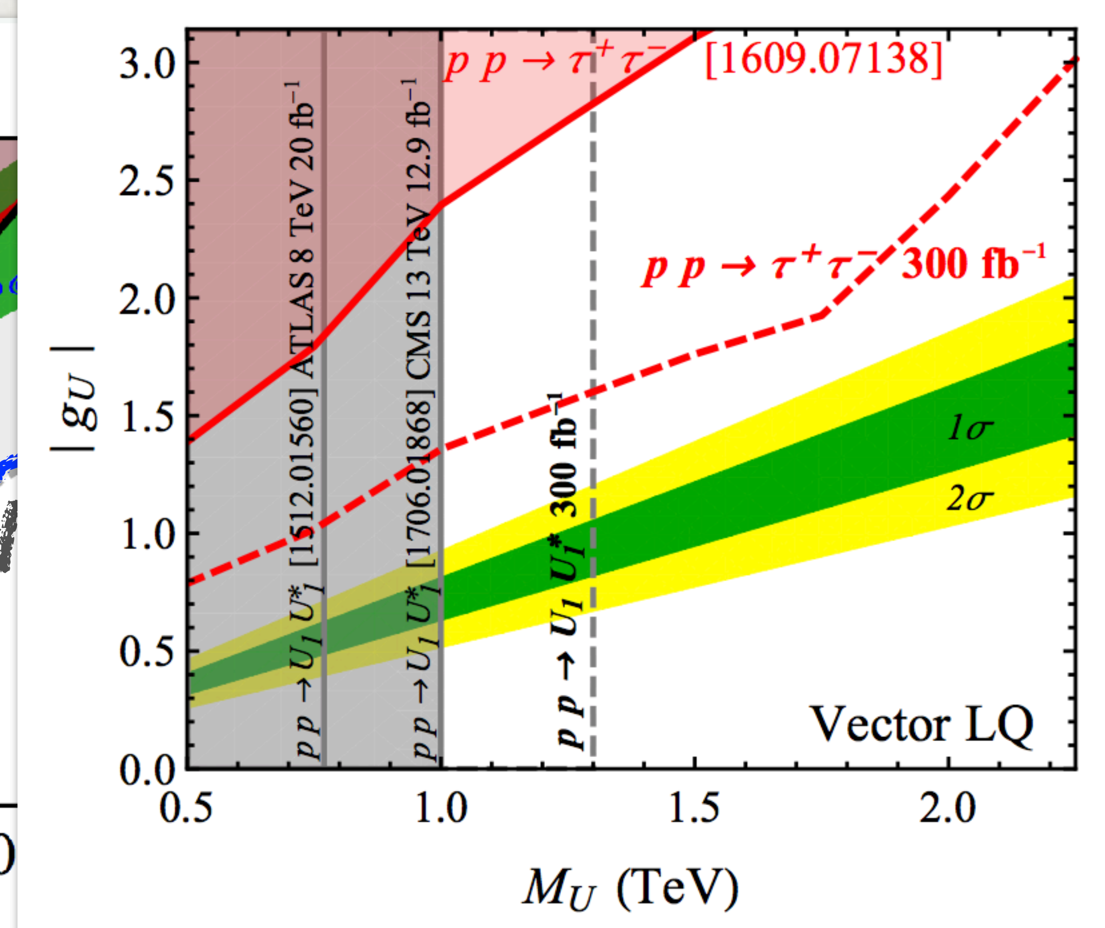
g_U $(\lambda \bar{q}_L^3 \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R) U^\mu$

Faroughy, Greljo, Kamenik, 1609.07138

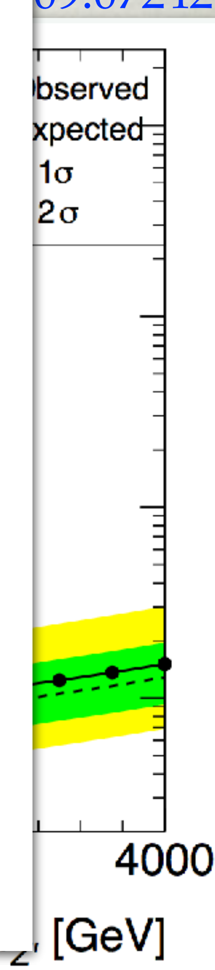


Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

allowing $\mathcal{O}(V_{cb}) \bar{q}_L^2 \gamma \tau_L U_\mu$



09.07242



MODELS WITH RIGHT-HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

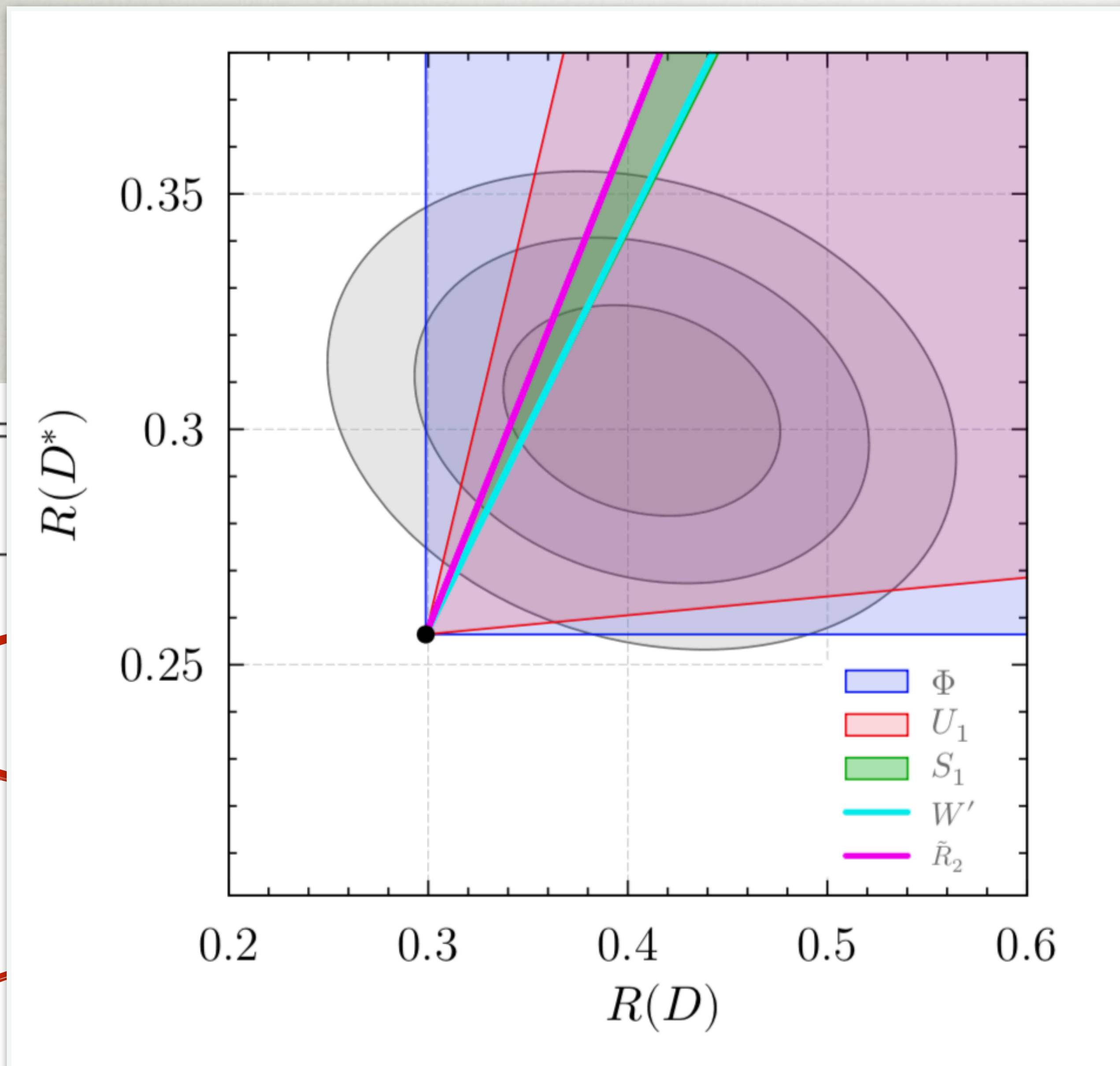
mediator	irrep	$\delta\mathcal{L}_{\rm int}$	WCs
W'_μ	$(1,1)_1$	$g'\big(c_q \bar{u}_R \gamma_\mu d_R + c_N \bar{\ell}_R \gamma_\mu N_R\big) W'^\mu$	$c_{\rm VR}$
Φ	$(1,2)_{1/2}$	$y_u \bar{u}_R Q_L \epsilon \Phi + y_d \bar{d}_R Q_L \Phi^\dagger + y_N \bar{N}_R L_L \epsilon \Phi$	$c_{\rm SL}$, $c_{\rm SR}$
U_1^μ	$(3,1)_{2/3}$	$\big(\alpha_{LQ} \bar{L}_L \gamma_\mu Q_L + \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R\big) U_1^{\mu\dagger} + \alpha_{uN} \big(\bar{u}_R \gamma_\mu N_R\big) U_1^\mu$	$c_{\rm SL}$, $c_{\rm VR}$
$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld} \big(\bar{L}_L d_R\big) \epsilon \tilde{R}_2^\dagger + \alpha_{QN} \big(\bar{Q}_L N_R\big) \tilde{R}_2$	$c_{\rm SR} = 4c_{\rm T}$
S_1	$(\bar{3},1)_{1/3}$	$z_u (\bar{U}^c_R \ell_R) S_1 + z_d (\bar{d}^c_R N_R) S_1 + z_Q (\bar{Q}^c_L \epsilon L_L) S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4c_{\rm T}$

2 color singlet mediators

3 leptoquark mediators

MODELS WITH RIGHT- ... UTRINO

Robinson, Shakya, JZ, 1807.04753



		$\delta\mathcal{L}_{\rm int}$	WCs
[illegible]	[illegible]	$\ldots + c_N \bar{\ell}_R \gamma_\mu N_R) W'^\mu$	$c_{\rm VR}$
[illegible]	[illegible]	$\ldots + y_d \bar{d}_R Q_L \Phi^\dagger + \ldots N_R L_L \epsilon \Phi$	$c_{\rm SL}$, $c_{\rm SR}$
[illegible]	[illegible]	$\ldots \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R) U_1^{\mu\dagger} + \ldots {}_R \gamma_\mu N_R) U_1^\mu$	$c_{\rm SL}$, $c_{\rm VR}$
$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}(\bar{L}_L d_R)\epsilon \tilde{R}_2^\dagger + \alpha_{QN}(\bar{Q}_L N_R)\tilde{R}_2$	$c_{\rm SR} = 4c_{\rm T}$
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}^c_R \ell_R)S_1 + z_d(\bar{d}^c_R N_R)S_1 + z_Q(\bar{Q}^c_L \epsilon L_L)S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4c_{\rm T}$

2 color singlet mediators

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MODELS WITH RIGHT-HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

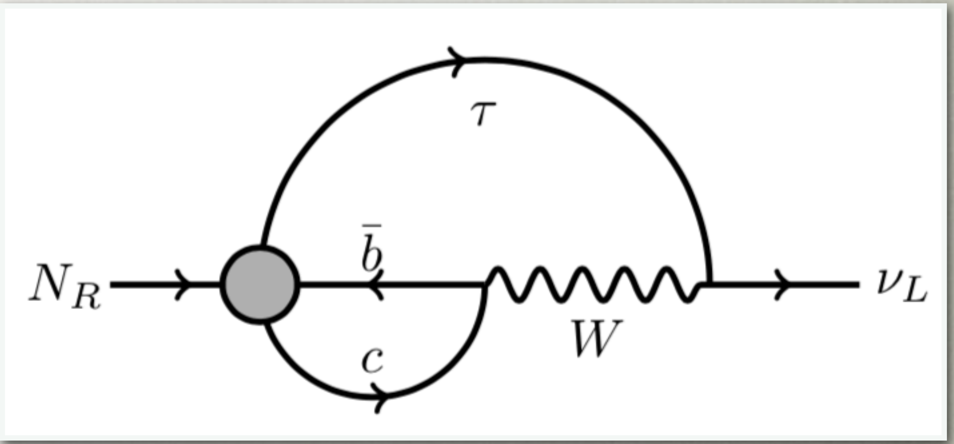
mediator	irrep	$\delta\mathcal{L}_{\rm int}$	WCs
W'_μ	$(1,1)_1$	$g'\big(c_q \bar{u}_R\gamma_\mu d_R + c_N \bar{\ell}_R\gamma_\mu N_R\big)W'^\mu$	$c_{\rm VR}$
~~Φ~~	~~$(1,2)_{1/2}$~~	~~$y_u \bar{u}_R Q_L \epsilon\Phi + y_d \bar{d}_R Q_L \Phi^\dagger +$ $y_N \bar{N}_R L_L \epsilon\Phi$~~	[illegible]
U_1^μ	$(3,1)_{2/3}$	$\big(\alpha_{LQ}\bar{L}_L\gamma_\mu Q_L + \alpha_{\ell d}\bar{\ell}_R\gamma_\mu d_R\big)U_1^{\mu\dagger} +$ $\alpha_{uN}\big(\bar{u}_R\gamma_\mu N_R\big)U_1^\mu$	$c_{\rm SL}$, $c_{\rm VR}$
~~R_2~~	~~$(3,2)_{1/6}$~~	~~$\alpha_{Ld}(\bar{L}_L d_R)\epsilon\tilde{R}_2^\dagger + \alpha_{QN}(\bar{Q}_L N_R)$~~ [illegible]	[illegible]
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}^c_R \ell_R)S_1 + z_d(\bar{d}^c_R N_R)S_1 +$ $z_Q(\bar{Q}^c_L \epsilon L_L)S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4c_{\rm T}$

excluded from $B_c \to \tau\nu$

excluded from $B \to K\nu\nu$

MODELS WITH RIGHT-HANDED NEUTRINO

- left with three simplified models: W', U_1, S_1
- couplings of U_1, S_1 further constrained
  - potentially too large contribs. to neutrino masses at 2 loops



- net result: all three match predominantly onto EFT operator

$$\mathcal{O}_{\rm VR} = \left(\bar{c}_R \gamma^\mu b_R\right)\left(\bar{\tau}_R \gamma_\mu N_R\right),$$

'3221' gauge model

- straightforward to UV complete W' model
- '3221' gauge model: $SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$
  - $SU(2)_V \times U(1)' \rightarrow U(1)_Y$ breaking, e.g., via $SU(2)_V$ doublet, H_V
  - extra vector-like fermions

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	$U(1)'$
Extra vector-like fermions				
$Q'^i_{L,R}$	**3**	**1**	**2**	1/6
$L'^i_{L,R}$	**1**	**1**	**2**	-1/2

  - large mixing with b_R, c_R, τ_R, ν_R ($\lambda v_V/M \gg 1$)

RIGHT-HANDED NEUTRINO

- the N_R in $b \to c\tau N_R$ is Majorana, mostly from L_R'
- for single generation neutrino mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & 0 & 0 \\ \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & \mu & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 \\ 0 & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 & M_L \\ 0 & 0 & M_L & 0 \end{pmatrix}$$

$$(\nu_L', \nu_R'^c, N_L', N_R'^c)$$

- for $v_{EW} = 0$, SM neutrino ν_L' decouples
- for $\mu = 0$ a massless Majorana neutrino is the state

$$N_R^c = \cos\theta_N \nu_R'^c - \sin\theta_N N_R'^c$$

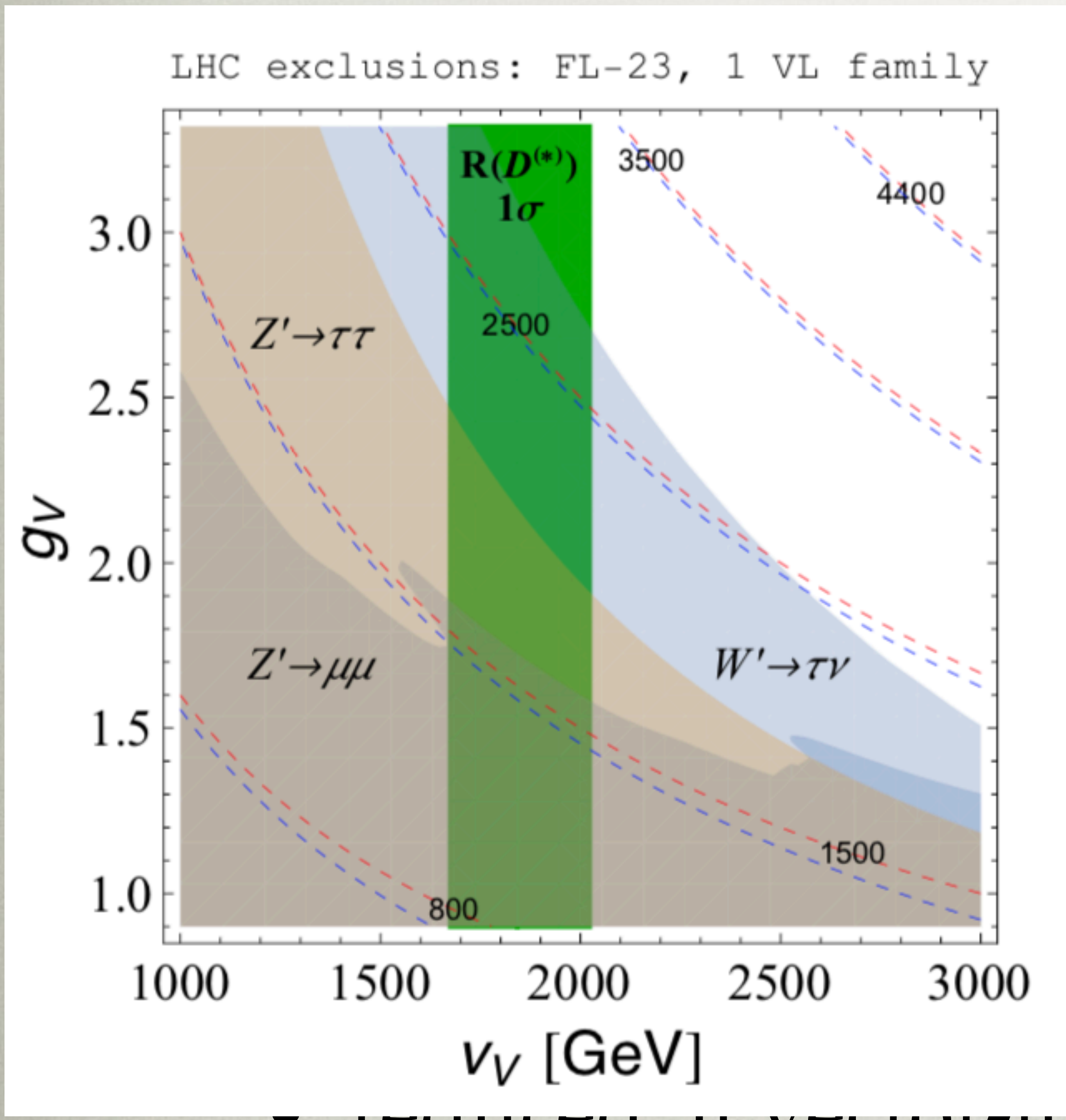
$$\tan\theta_N = (\lambda_\nu v_V)/(\sqrt{2} M_L)$$

- for $\lambda_\nu v_V \gg M_L$ the massless RH neutrino has a large admixture of N_R'

LHC constraints

- assume minimal flavor structure needed for the anomaly
  - large couplings to b,c,τ
- LHC constraints from $pp \to W' \to \tau N_R$, $pp \to Z' \to \tau\tau$ searches
- if only the SM channels open $Br(W' \to \tau N_R) : Br(W' \to cb) \simeq 1:3$
- reduced, if vector-like fermions light enough

LHC constraints



vor structure needed for

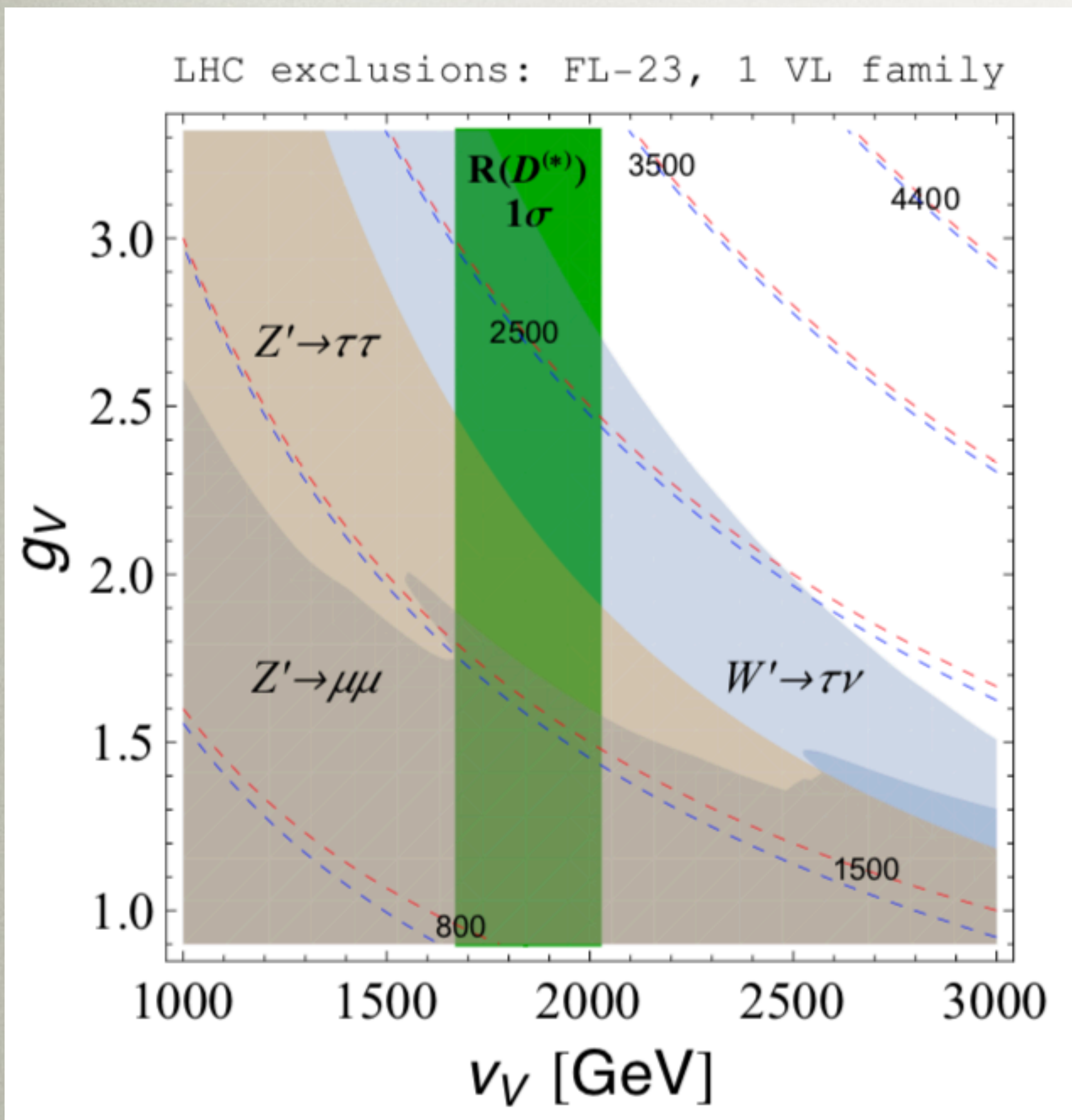
b,c,τ

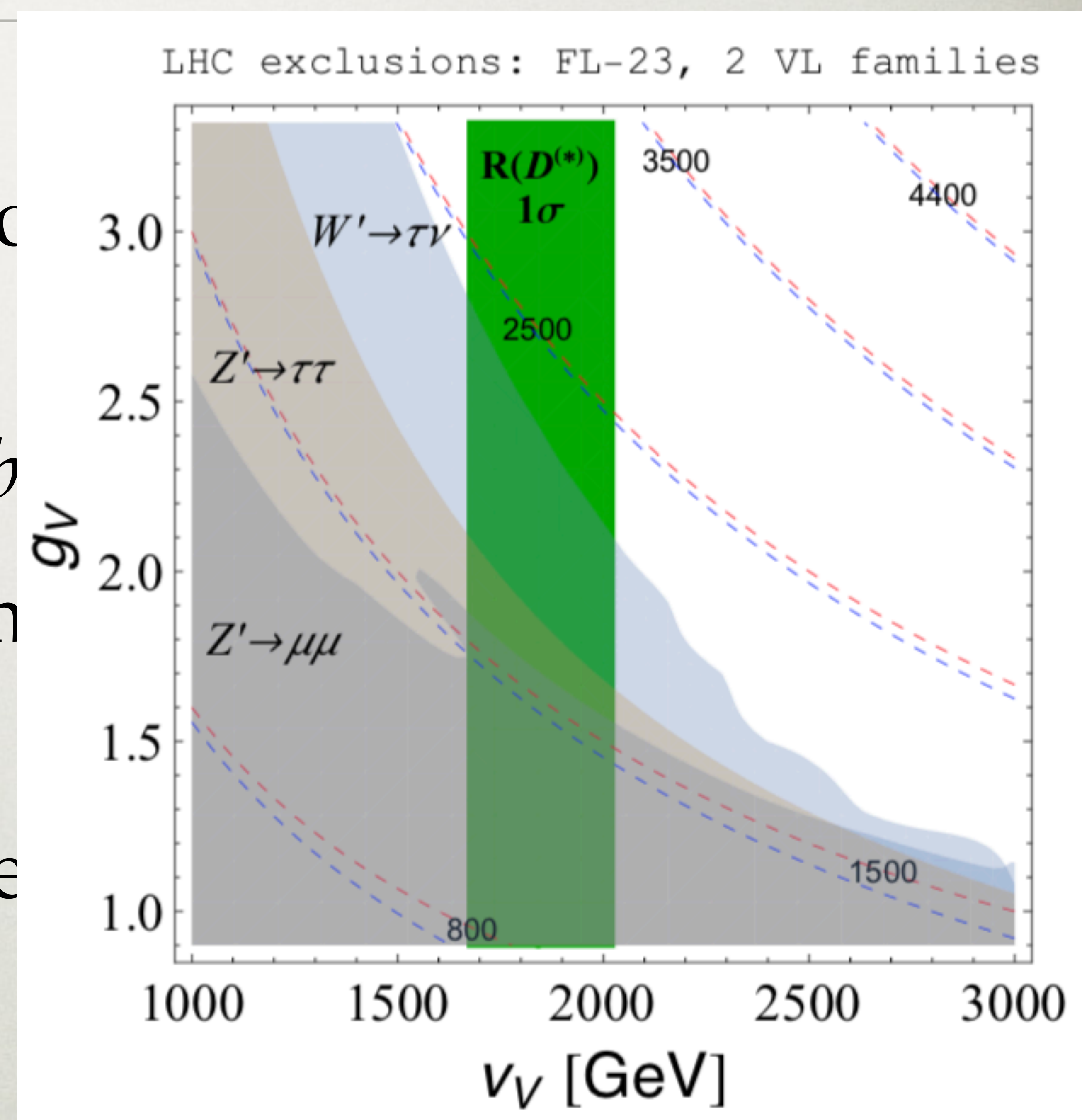
m $pp \to W' \to \tau N_R$, $pp \to$

nels open $Br(W' \to \tau N_R)$:

- reduced, if vector-like fermions light enough

LHC constraints





- reduced, if vector-like fermions light enough

LEPTOQUARK FOR BOTH $b \to c\tau\nu$ AND $b \to s\mu\mu$

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

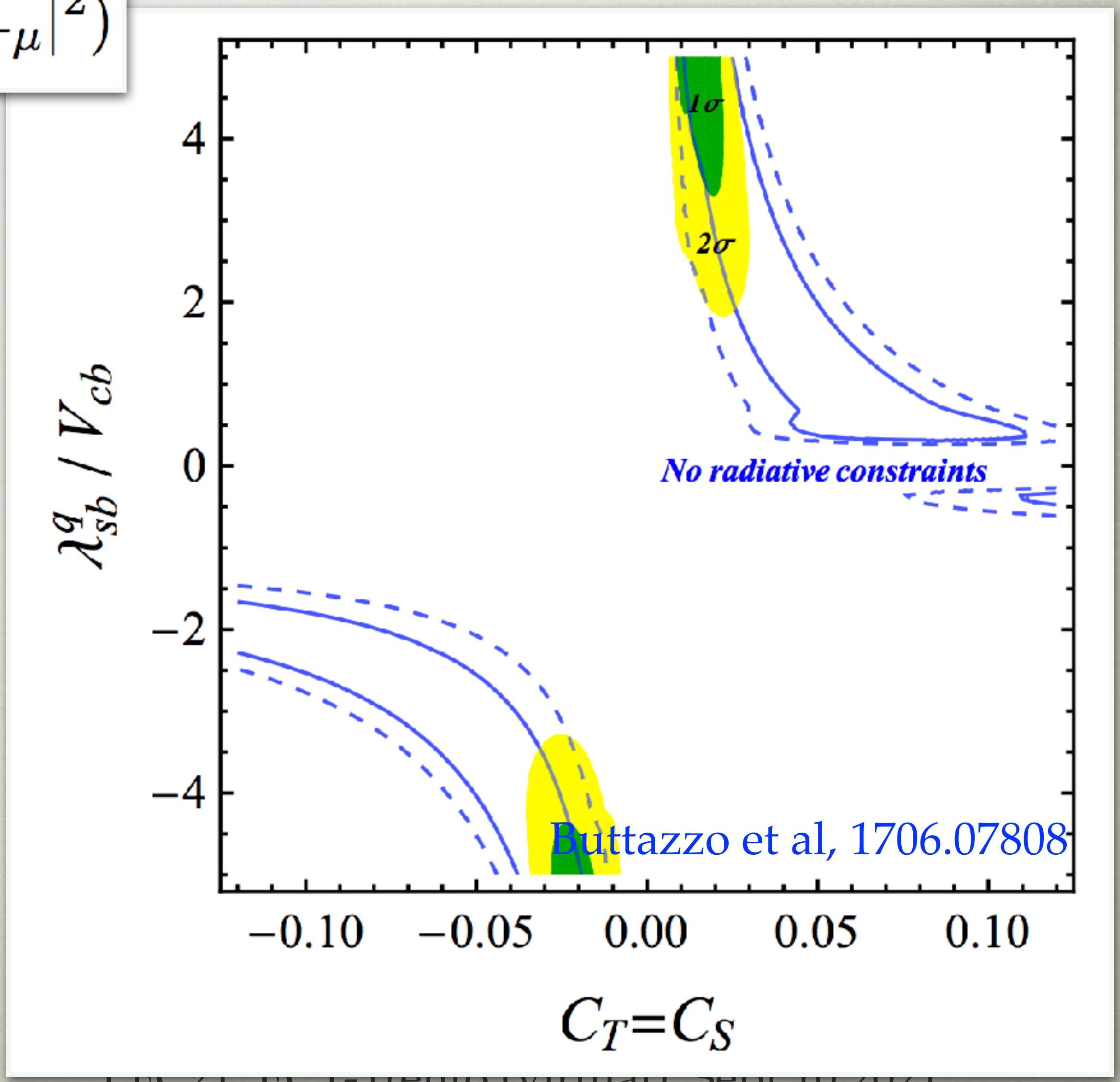
- in EFT possible to explain all anomalies

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\;(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\;(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

$$\lambda^q_{sb}=\mathcal{O}(|V_{cb}|)\;,\quad \lambda^\ell_{\tau\mu}=\mathcal{O}(|V_{\tau\mu}|)\;,\quad \lambda^\ell_{\mu\mu}=\mathcal{O}(|V_{\tau\mu}|^2)$$

  - with MFV-like flavor structure
  - predicts *Br(b→sττ)~O(100)x SM*
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu \equiv (\mathbf{3},\mathbf{1},2/3)$$



LEPTOQUARK FOR BOTH $b \to c\tau\nu$ AND $b \to s\mu\mu$

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

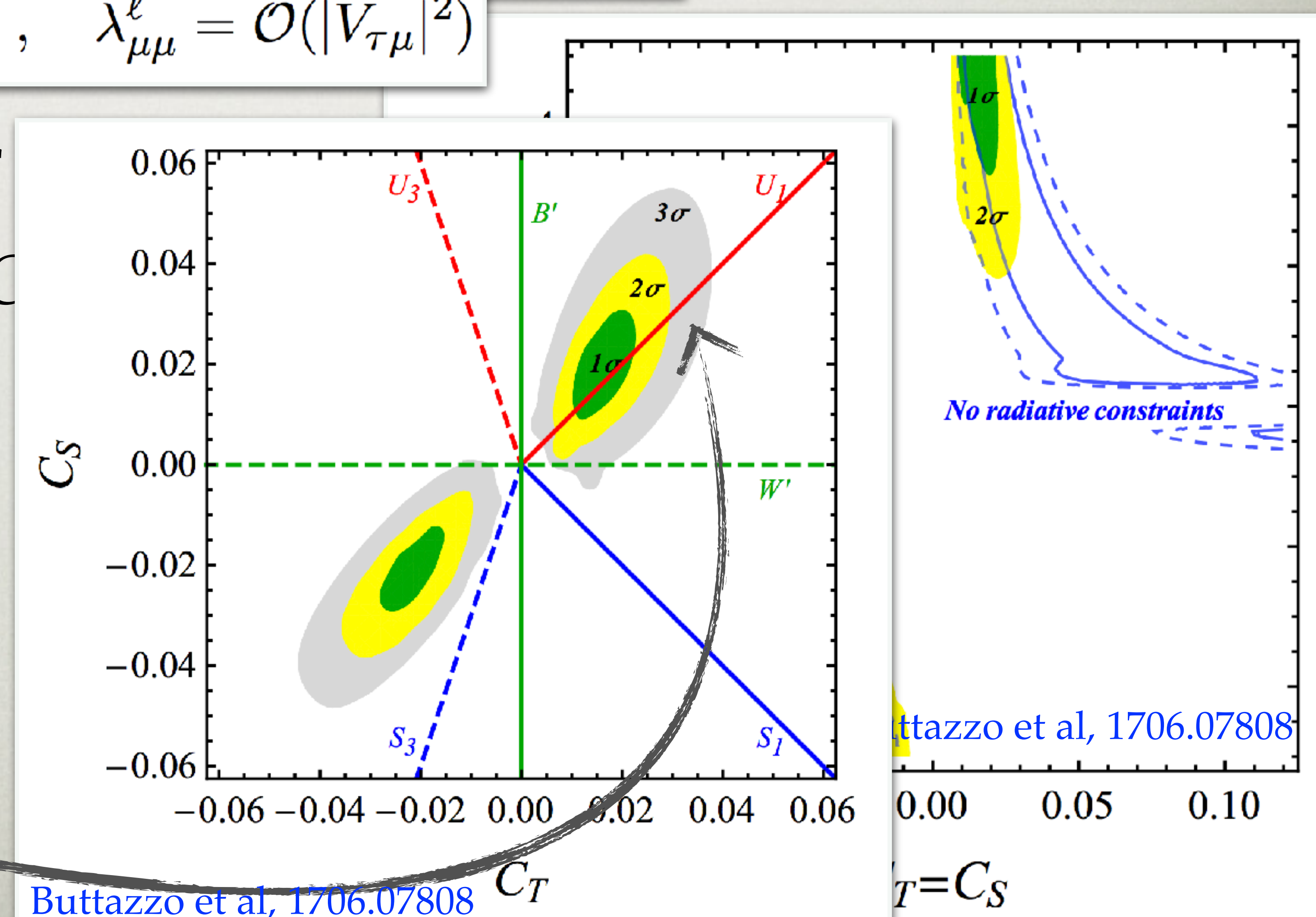
- in EFT possible to explain all anomalies

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

$$\lambda^q_{sb} = \mathcal{O}(|V_{cb}|)\ , \quad \lambda^\ell_{\tau\mu} = \mathcal{O}(|V_{\tau\mu}|)\ , \quad \lambda^\ell_{\mu\mu} = \mathcal{O}(|V_{\tau\mu}|^2)$$

  - with MFV-like flavor
  - predicts $Br(b \to s\tau\tau) \sim C$
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$$



LEPTOQUARK FOR BOTH

$b \to c\tau\nu$ AN

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

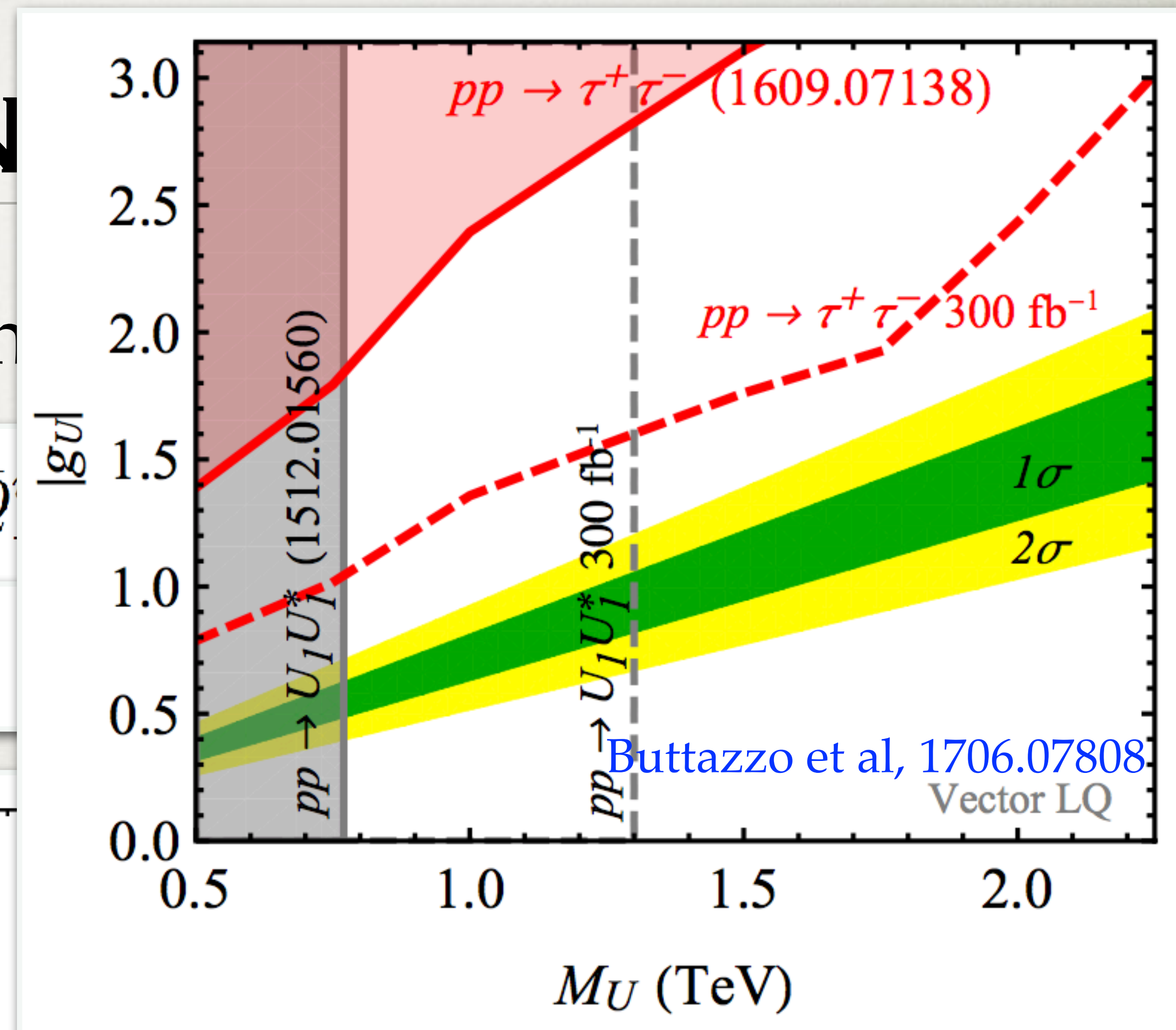
- in EFT possible to explain all an

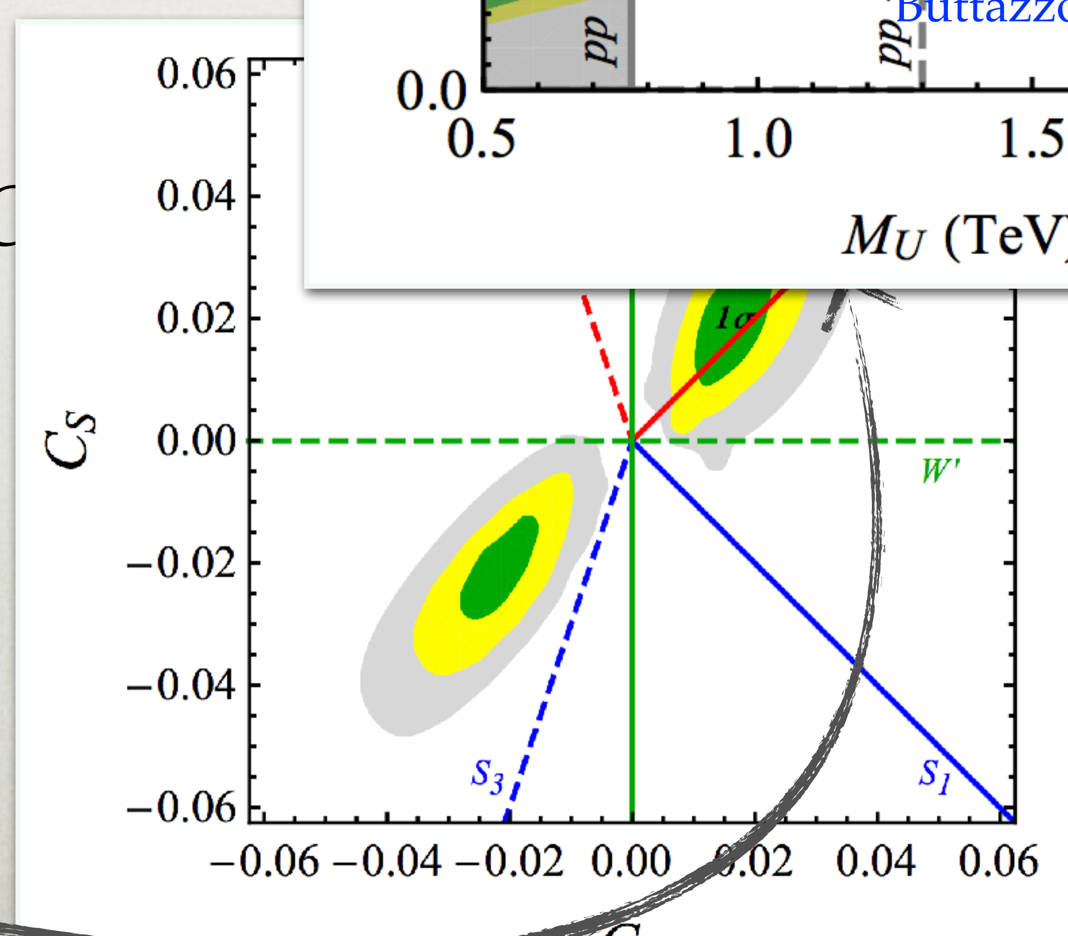
$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}\right.$$

$$\lambda^q_{sb} = \mathcal{O}(|V_{cb}|)\,, \quad \lambda^\ell_{\tau\mu} = \mathcal{O}(|V_{\tau\mu}|)\,, \quad \lambda^\ell_{\mu\mu} =$$

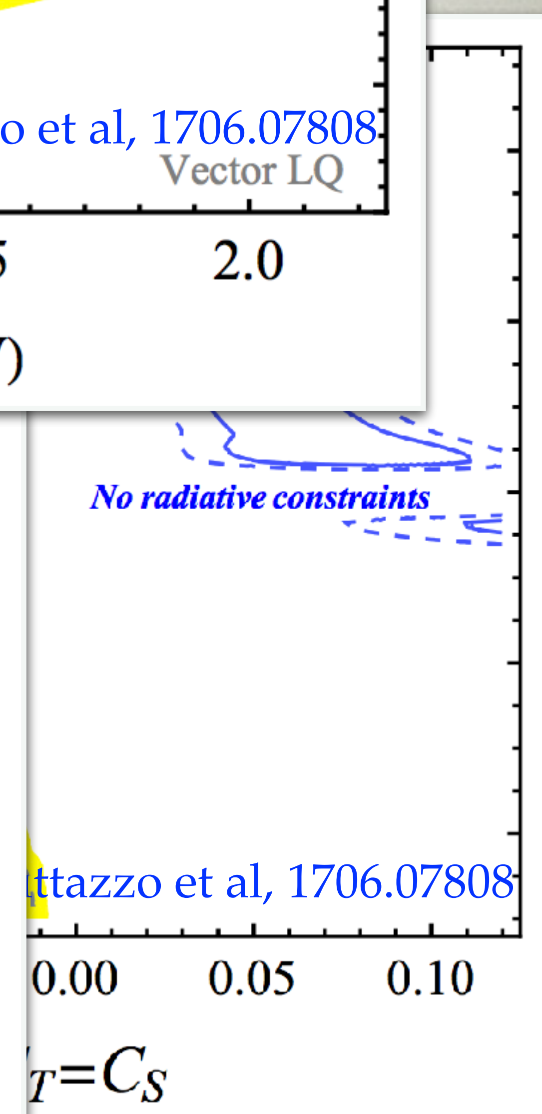
  - with MFV-like flavor
  - predicts *Br(b→sττ)~C*
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$$





Buttazzo et al, 1706.07808



Scenarios

V. Gherardi, E. Venturini, D.M. [2008.09548]

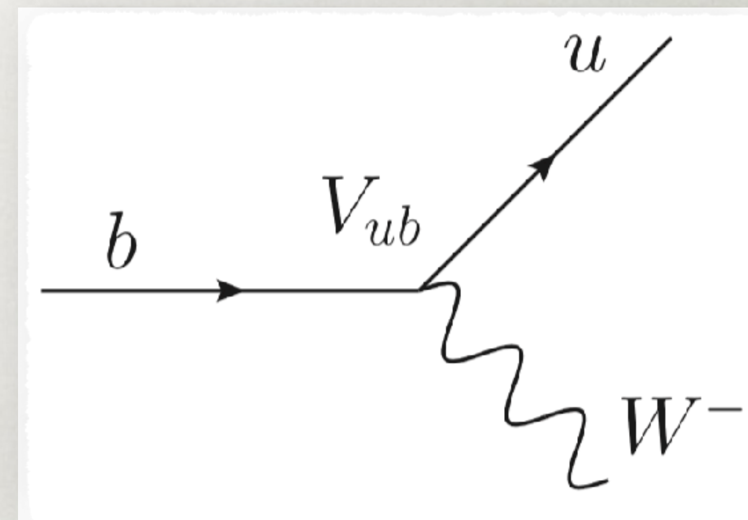
In each scenario we allow only a subset of all couplings to be non-vanishing*.
No other assumptions are imposed.

Model	Couplings	CC	NC	$(g-2)_\mu$
$S_1{}^{(CC)}$	$\lambda^{1R}_{c\tau}, \lambda^{1L}_{b\tau}$	✓	✗	✗
$S_1{}^{(NC)}$	$\lambda^{1L}_{b\mu}, \lambda^{1L}_{s\mu}$	✗	⊗	✗
$S_1{}^{(a_\mu)}$	$\lambda^{1R}_{t\mu}, \lambda^{1L}_{b\mu}$	✗	✗	✓
$S_1{}^{(CC+a_\mu)}$	$\lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{1L}_{b\tau}, \lambda^{1L}_{b\mu}$	✓	✗	✓
$S_3{}^{(CC+NC)}$	$\lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✗	✓	✗
$S_1 + S_3{}^{(\mathrm{LH})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✗
$S_1 + S_3{}^{(\mathrm{all})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{1L}_{b\mu}, \lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✓

CKM UNITARITY

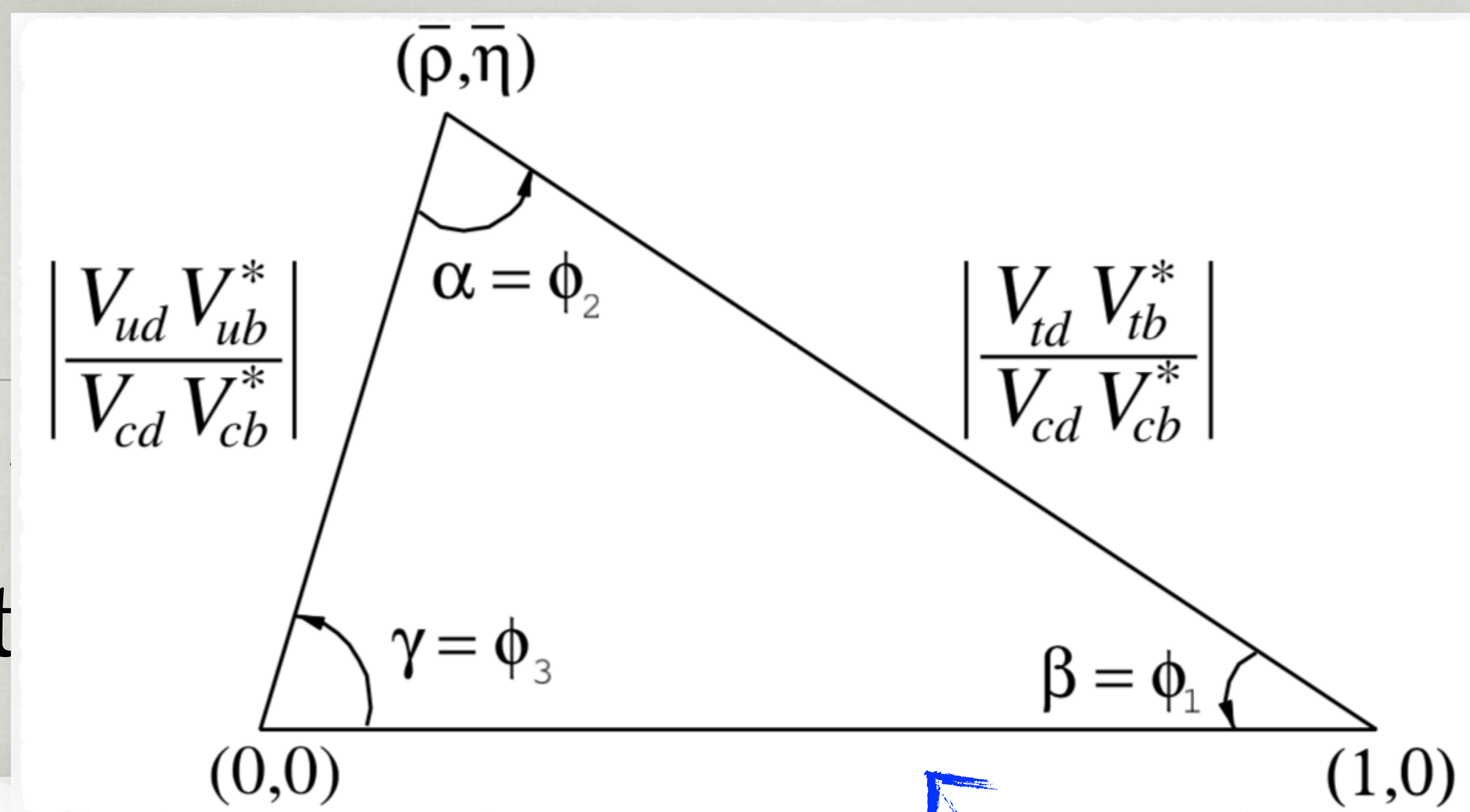
- a test: CKM matrix is unitary in the Standard Model

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.},$$

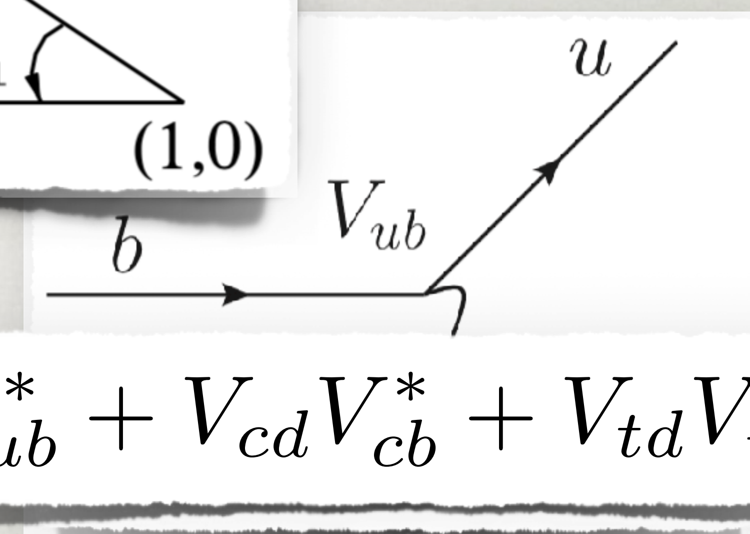


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- a the St



$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.},$$



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

THE PLAYERS

- B-factories
  - Belle (1999-2010): ~ 1.5 x 10^9 B mesons
  - Babar (1999-2008): ~ 0.9 x 10^9 B mesons
- (super)B-factories
  - LHCb(2010-2030?): ~ up to 10^{11} (useful) $B's$
  - Belle-II (2018- 2024?): ~ 8 x 10^{10} B mesons

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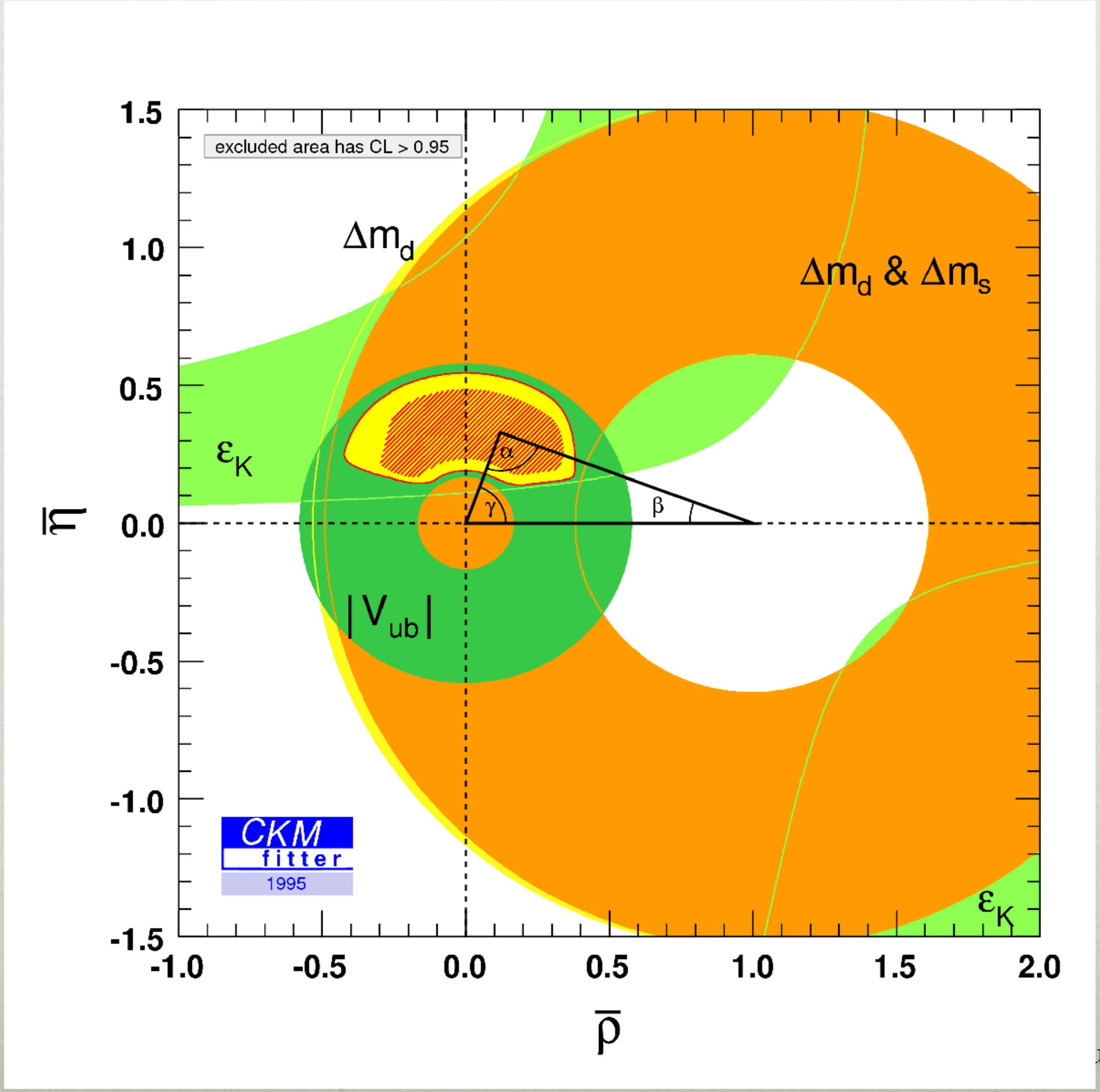
B physics experiencing deflation:

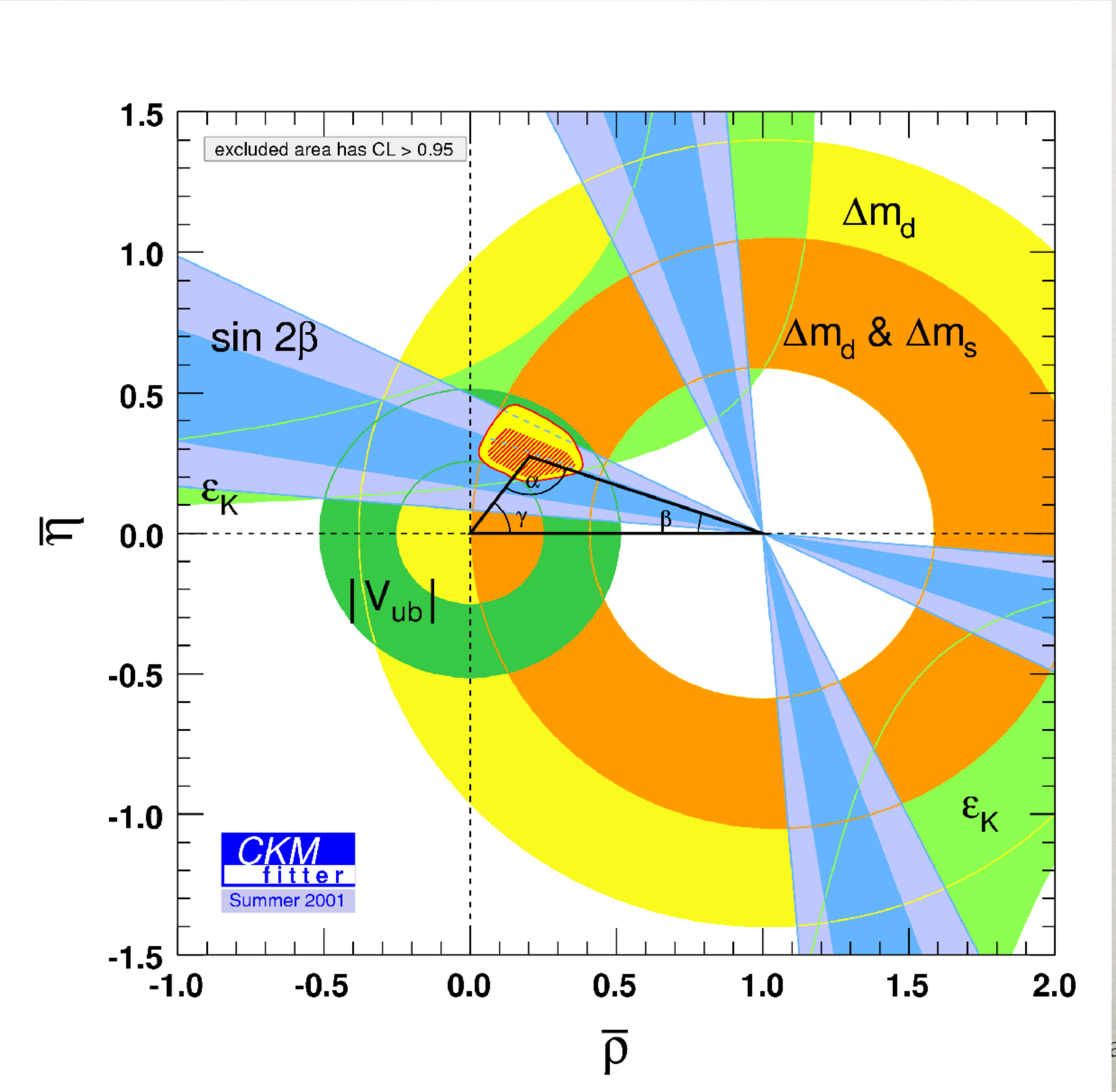
in 2000s: ~50¢/B meson

in 2020s: <1¢/B meson

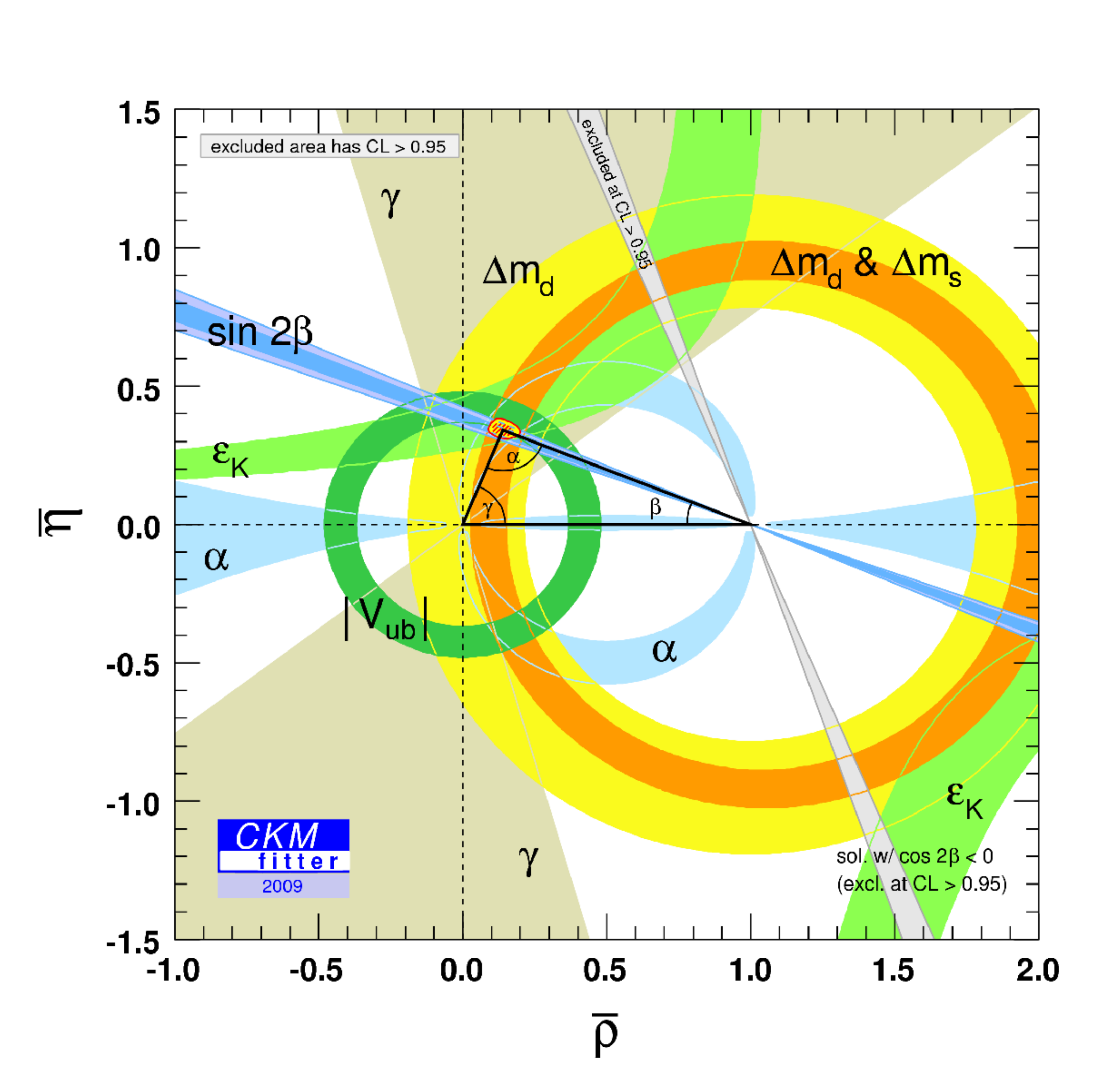
1995


excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
|V_ub|
α
β
γ
CKM
fitter
1995
ε_K
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

2001

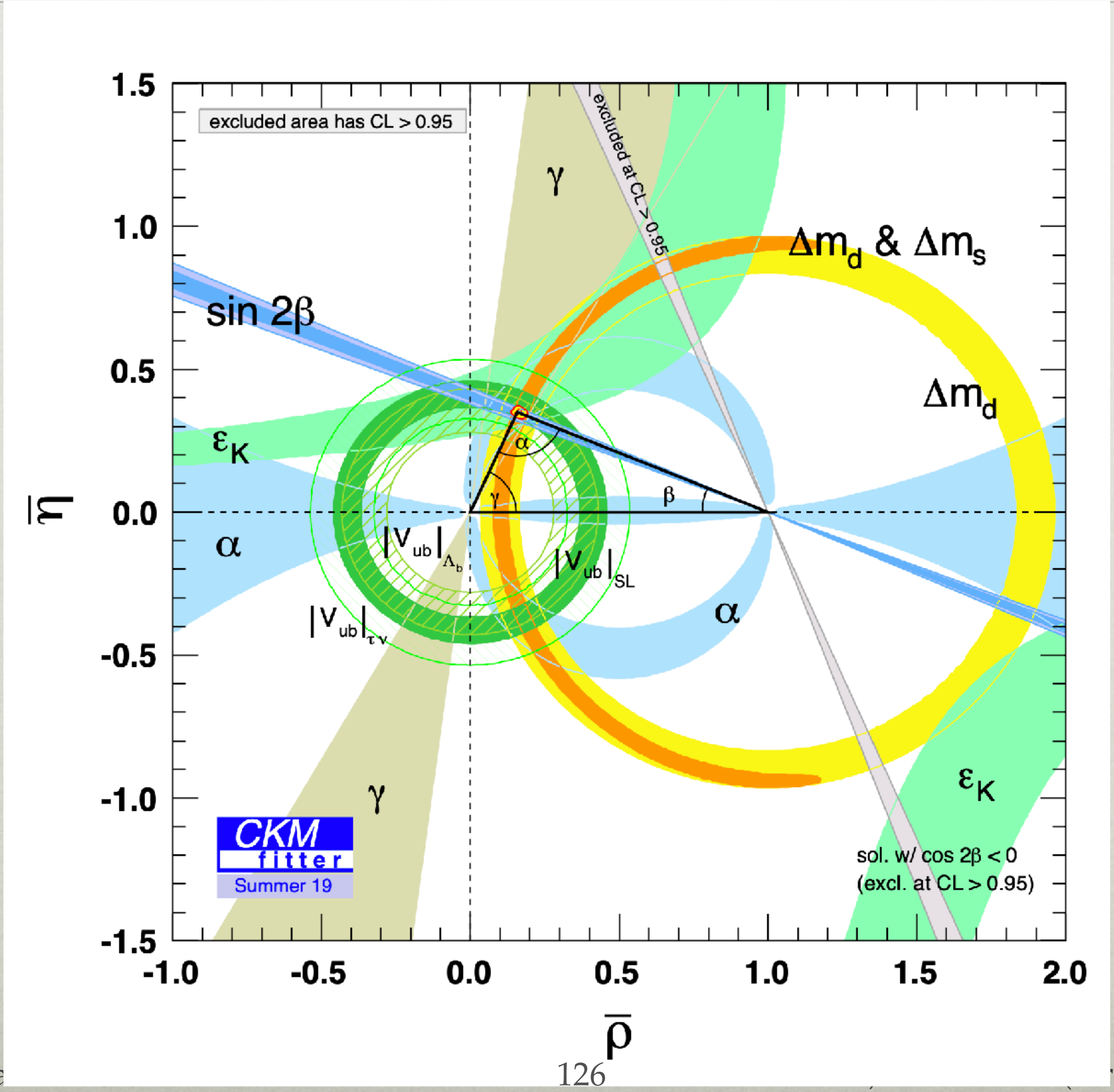

excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
|V_ub|
α
β
γ
ε_K
CKM fitter
Summer 2001
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

2009



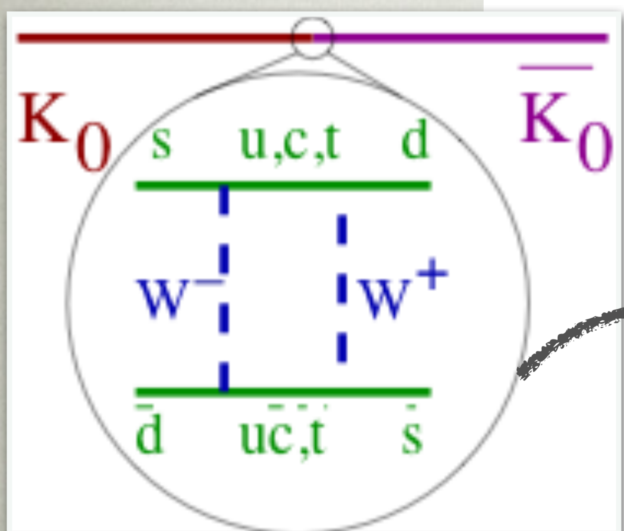
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
α
β
|V_ub|
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
2009
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
ρ̄
η̄

2019

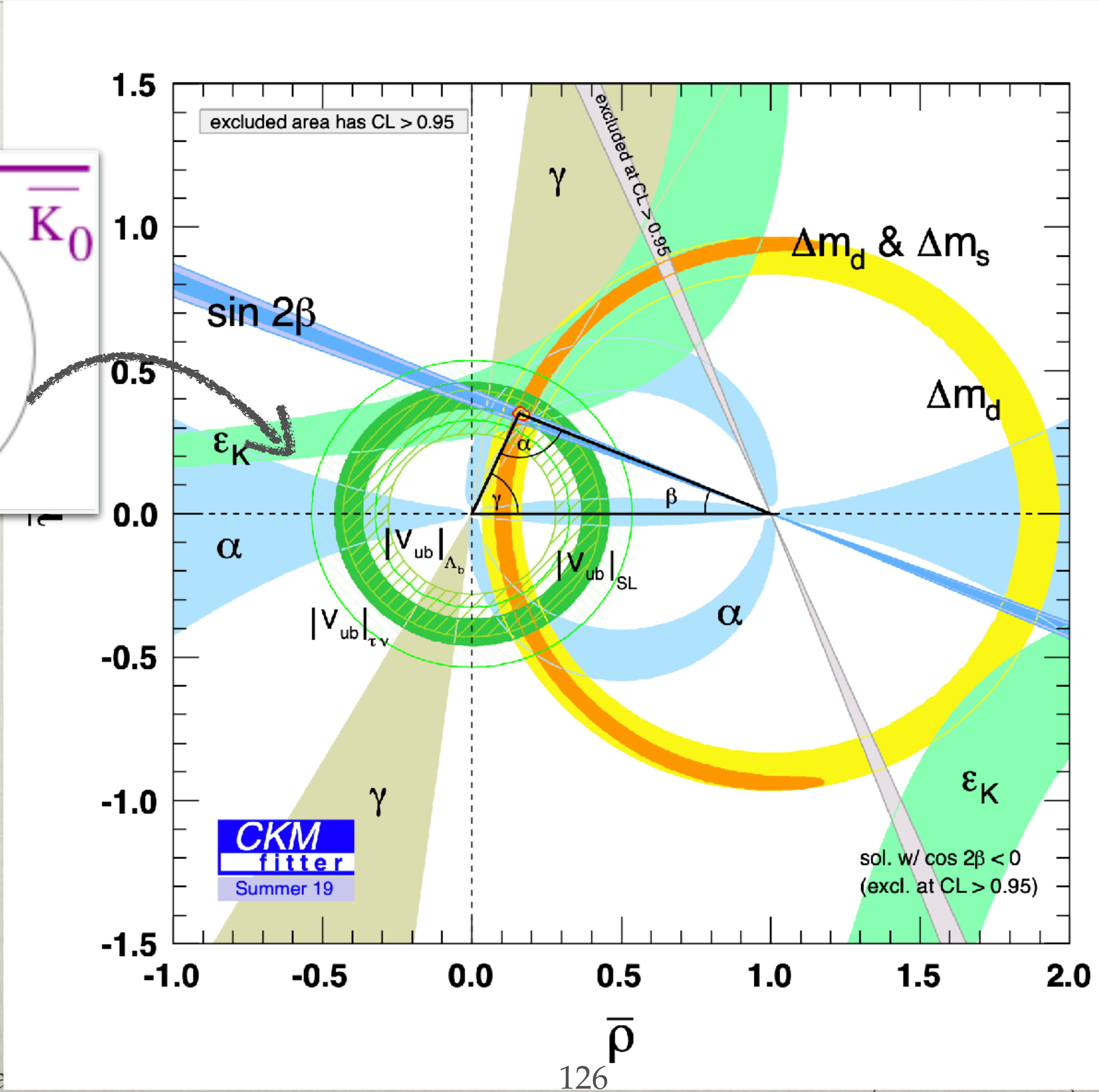


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|_{Λ_b}
|V_ub|_SL
|V_ub|_{τν}
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0
η̄
ρ̄

2019

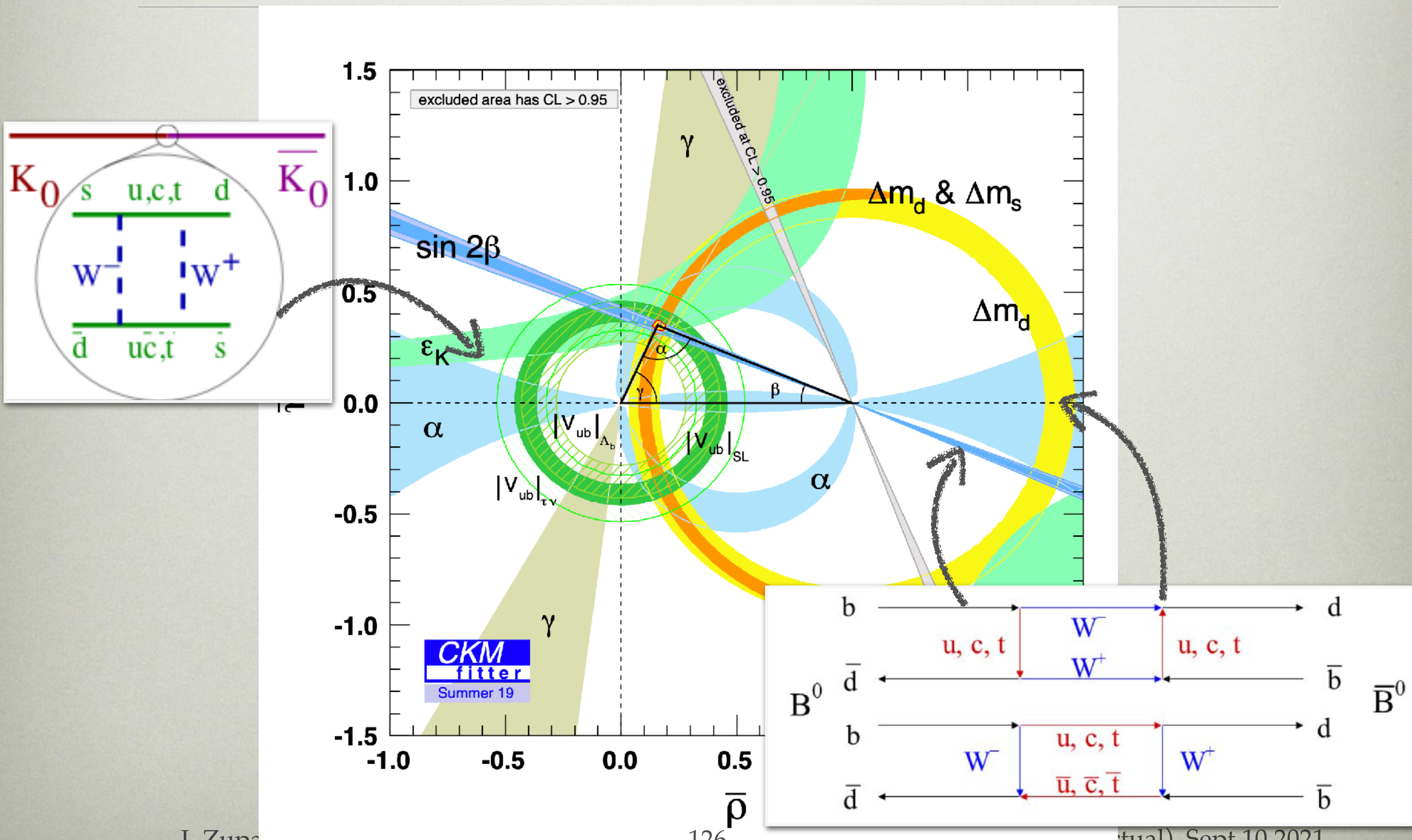


K0
s
u,c,t
d
W−
W+
d̄
ūc̄,t̄
s̄



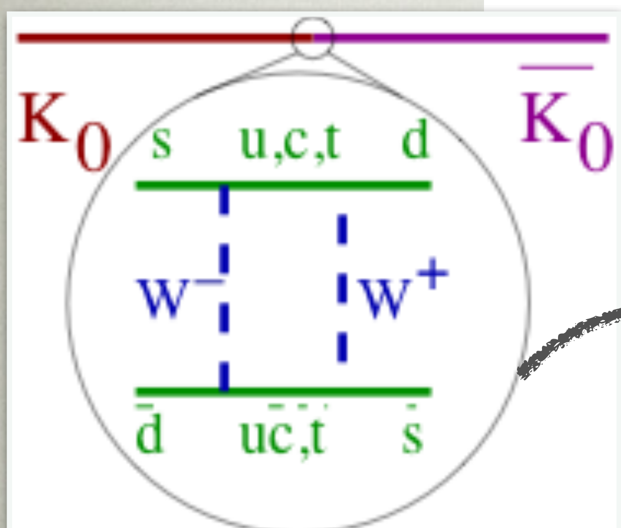
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δmd & Δms
sin 2β
Δmd
εK
α
β
|Vub|Λb
|Vub|SL
|Vub|τν
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
ρ̄

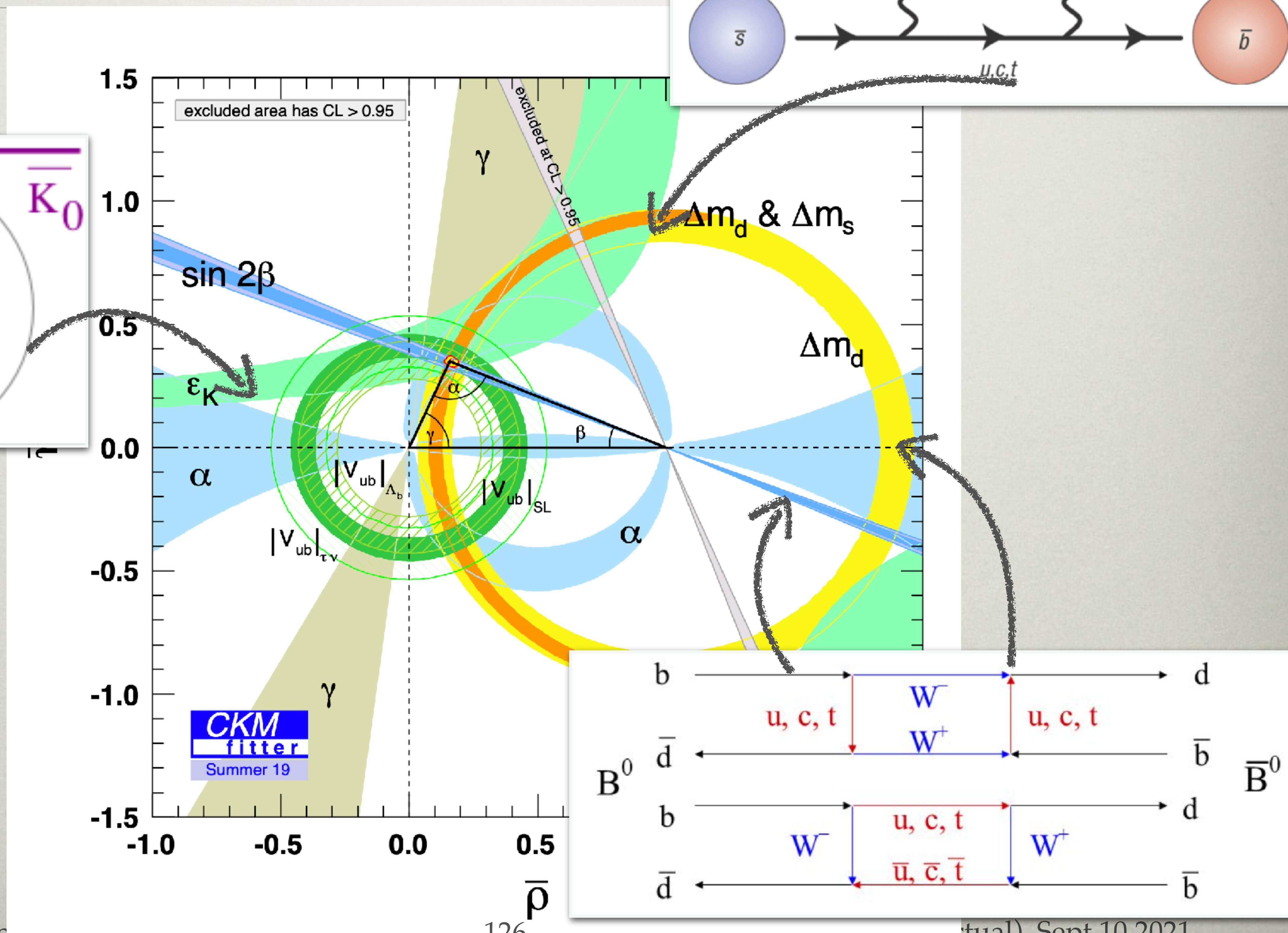
2019

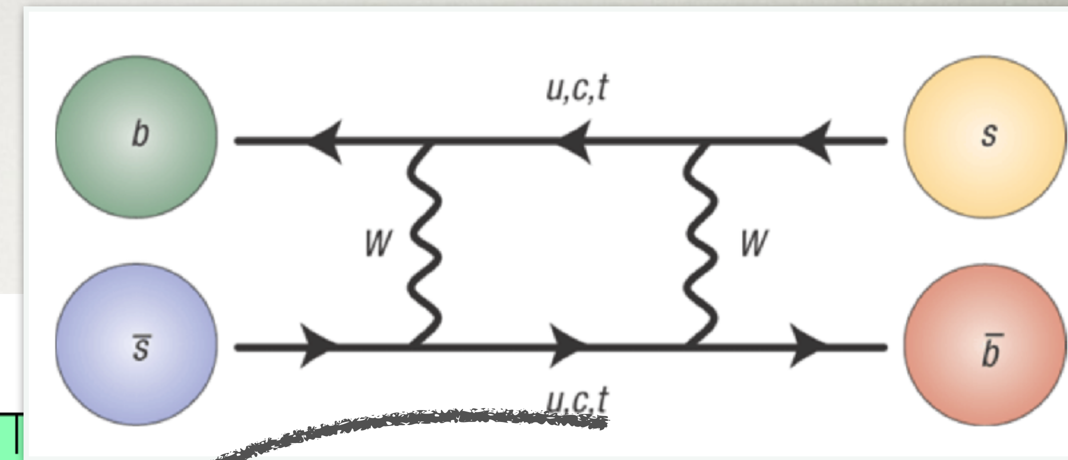


K0
s u,c,t d
W−
W+
d uc,t s
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|_Λb
|V_ub|_SL
|V_ub|_τν
CKM fitter
Summer 19
ρ
b
d
u, c, t
B0
u, c, t
ū, c̄, t̄
b̄

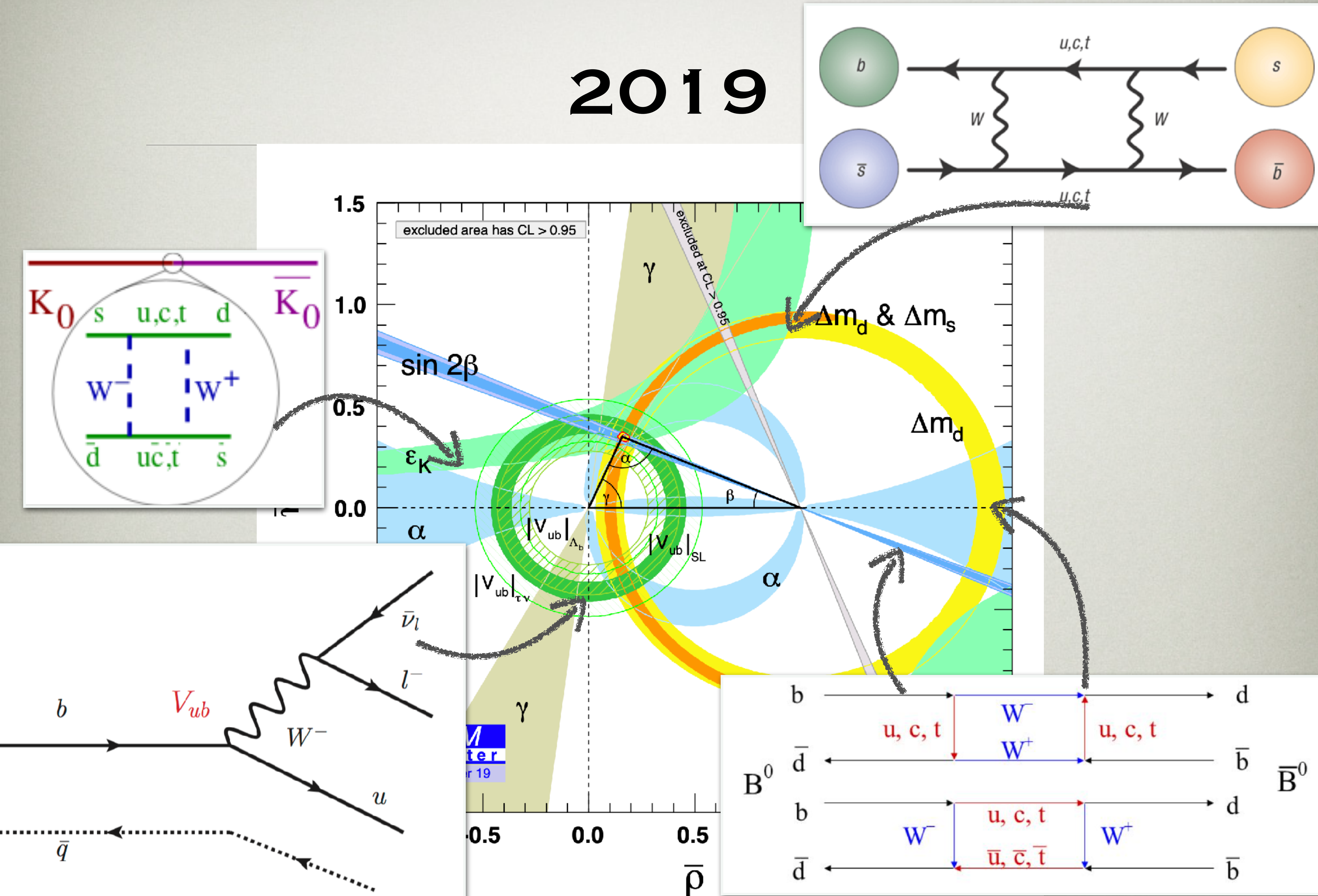
2019


K0
s
u,c,t
d
W−
W+
d̄
ūc̄,t̄
s̄
K̄0

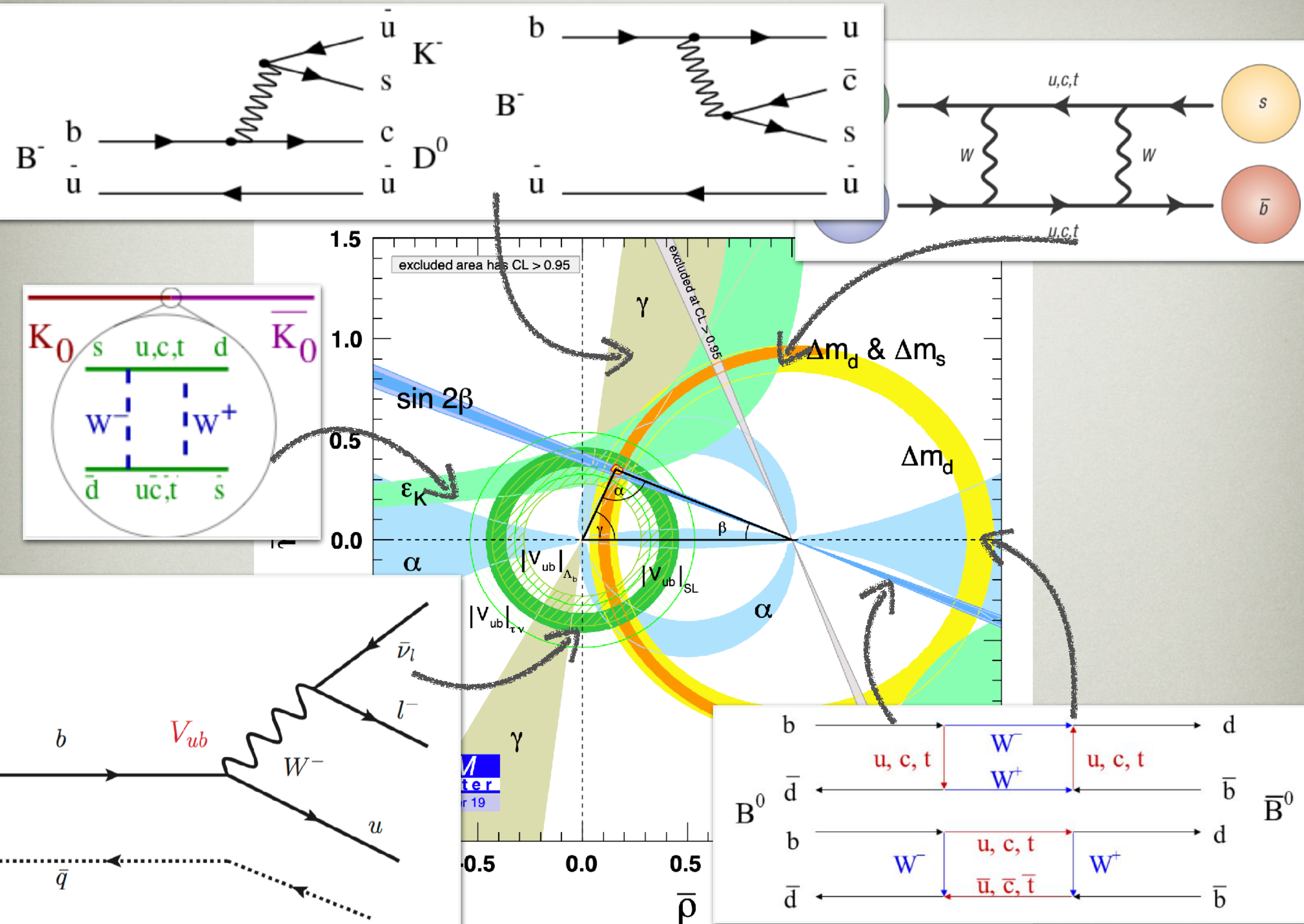

excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δmd & Δms
Δmd
εK
α
β
γ
|Vub|Λb
|Vub|SL
|Vub|τν
α
γ
CKM fitter
Summer 19
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
ρ̄


b
s̄
u,c,t
W
W
u,c,t
s
b̄
b
d̄
u, c, t
W−
W+
u, c, t
d
b̄
B0
B̄0
b
d̄
W−
u, c, t
ū, c̄, t̄
W+
d
b̄

2019



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|_SL
|V_ub|_τν
γ
b
u,c,t
s
W
W
s̄
b̄
u,c,t
K0
K̄0
s u,c,t d
W⁻ W⁺
d̄ ūc̄,t̄ s̄
b
V_ub
W⁻
ν̄_l
l⁻
u
q̄
b u, c, t W⁻ W⁺ u, c, t d
d̄ b̄
B0 B̄0
b u, c, t d
W⁻ W⁺
d̄ ū, c̄, t̄ b̄
ρ̄


B⁻
b
ū
u
s
c
K⁻
D⁰
ū
b
u
c̄
s
ū
u
u,c,t
W
W
s
b̄
u,c,t
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|_SL
|V_ub|_τν
α
γ
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
K0
K̄0
s
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄
b
V_ub
W⁻
ν̄_l
l⁻
u
q̄
b
d
u, c, t
W⁻
W⁺
u, c, t
B⁰
d̄
b̄
B̄⁰
b
d
u, c, t
W⁻
W⁺
ū, c̄, t̄
d̄
b̄