FLAVOR PHYSICS: STATUS AND PROSPECTS

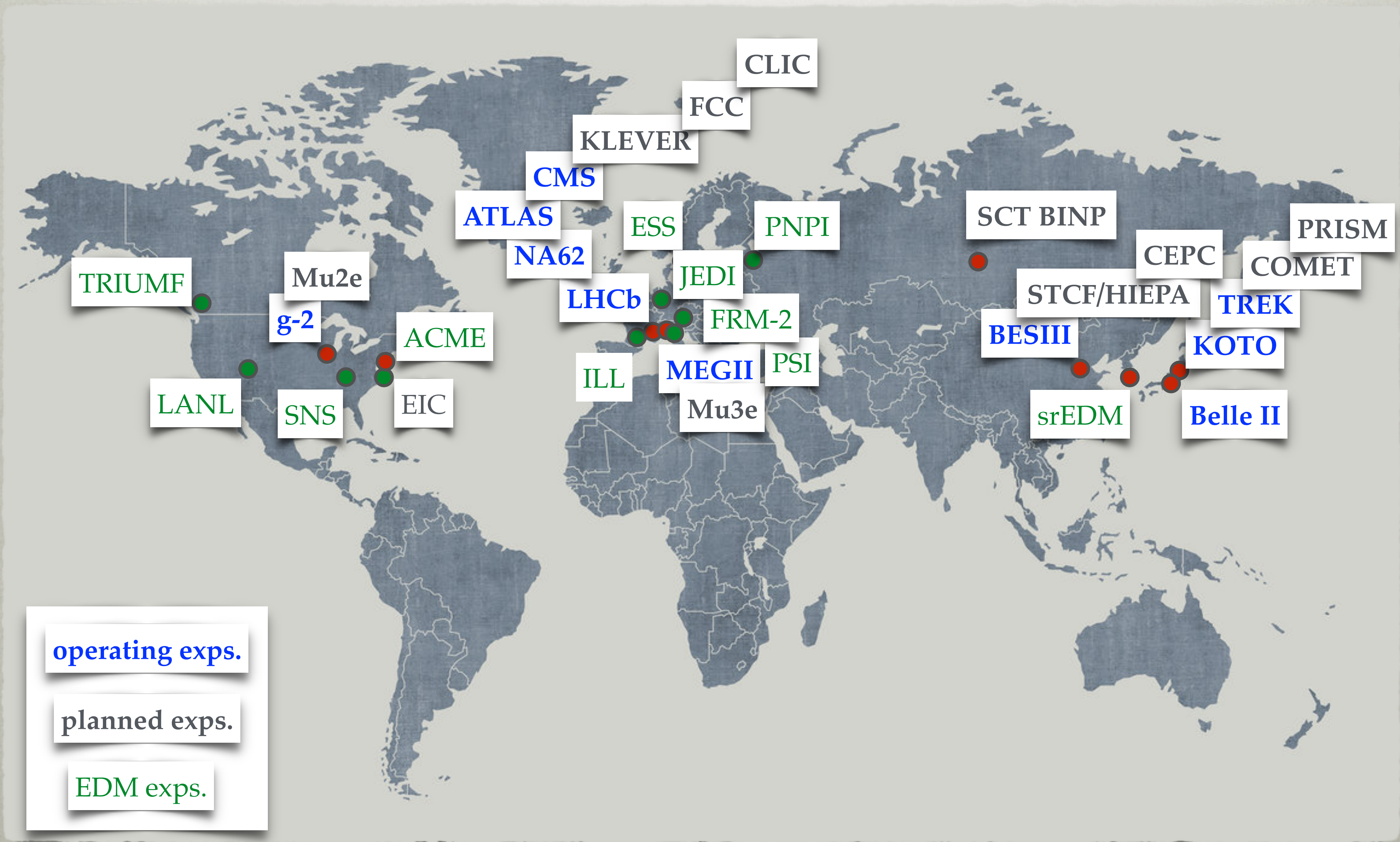
Jure Zupan
u. of cincinnati

GGI TH Colloquium ("GGI Tea Breaks") May 5 2021

FLAVOR PHYSICS IN ONE SLIDE

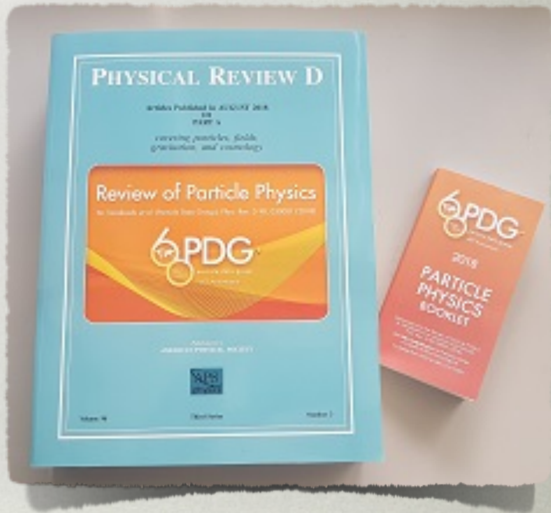
- baryon asymmetry implies more CP violation than in the SM
- flavor measurements a way to probe such required new CPV sectors
    - high energy scales and/or small couplings
- probe also other puzzles: dark matter, strong CP problem,...

MANY EXPERIMENTS...



MANY MEASUREMENTS...

- PDG lists $O(10^4)$ observables
  - branching ratios, angular distributions, CP violating asymmetries, ...
- focus of this talk:
  - sensitivity to new physics



OUTLINE

- why flavor physics?
  - heavy new physics
  - light new physics
- experimental anomalies
- what next?
  - Belle II, LHCb upgrade, etc

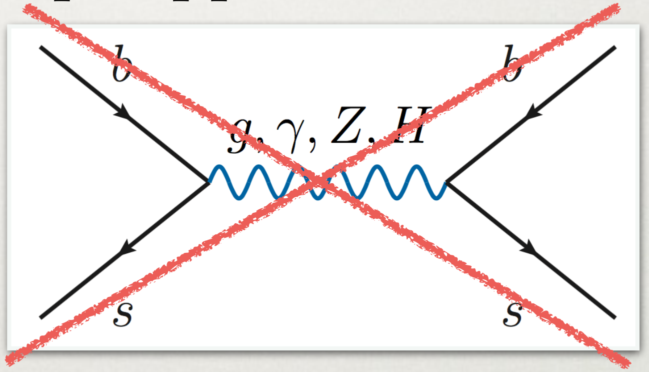
PROBING
HEAVY NEW PHYSICS

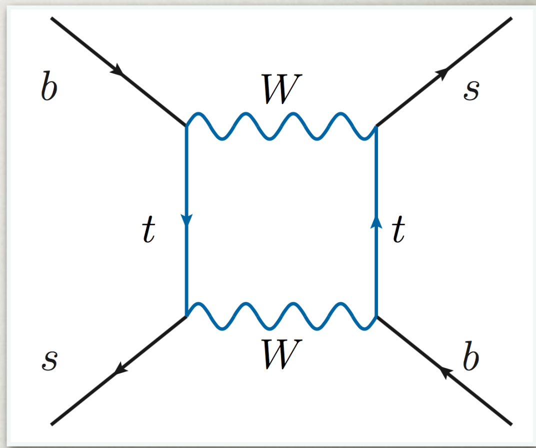
FROM FLAVOR PHYSICS TO HEAVY NEW PHYSICS

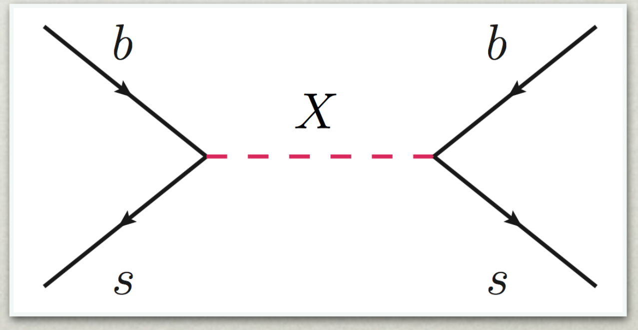
- SM@tree level: no Flavor Changing Neutral Currents
    - all FCNC processes loop suppressed
    - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

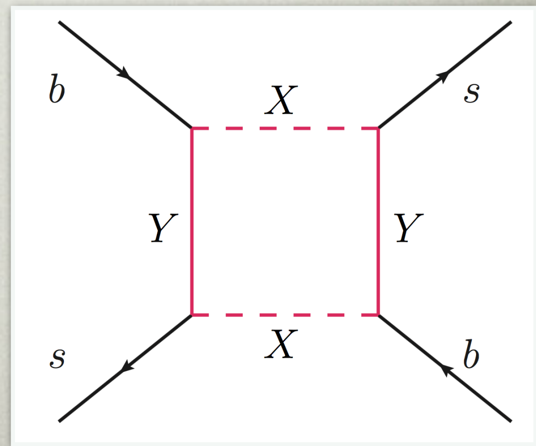
$$\delta C^{\text{NP}} \propto \frac{g_{sb}^2}{M_{\text{NP}}^2}$$

- depends on couplings and NP masses



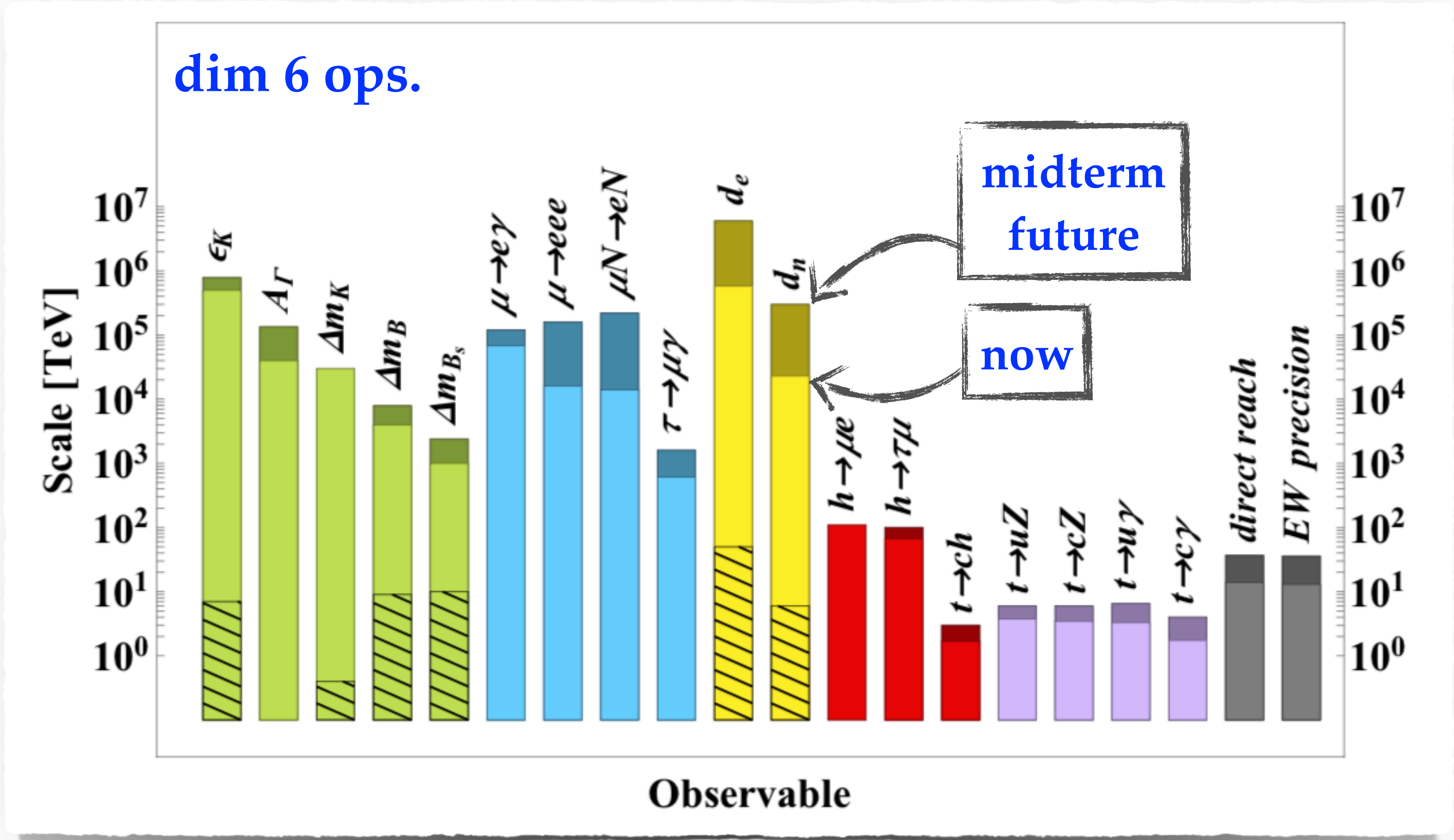






LARGE SCALES PROBED

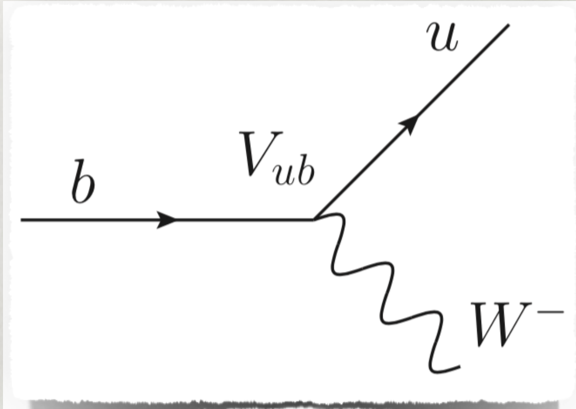
Physics Briefing Book, 1910.11775



CKM UNITARITY

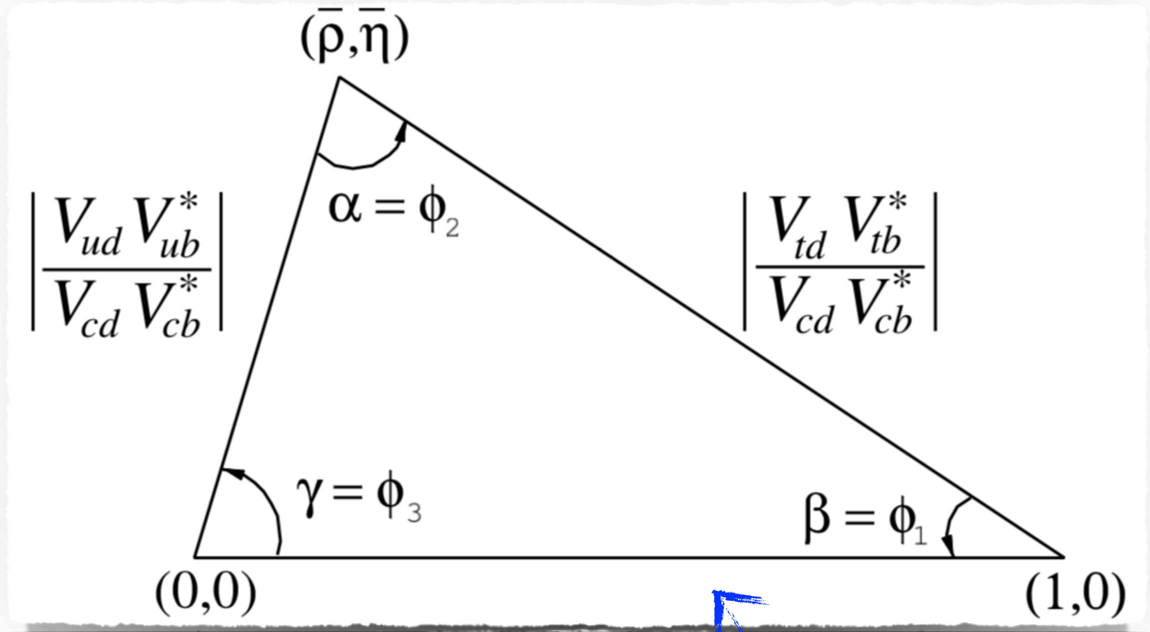
- a test: CKM matrix is unitary in the Standard Model

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

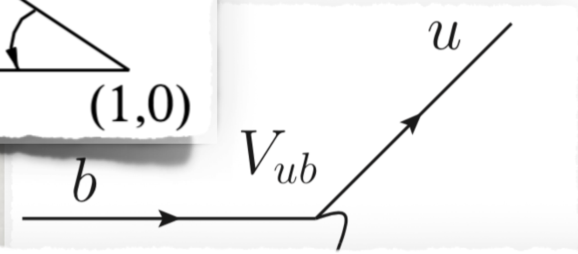


$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- 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

THE PLAYERS

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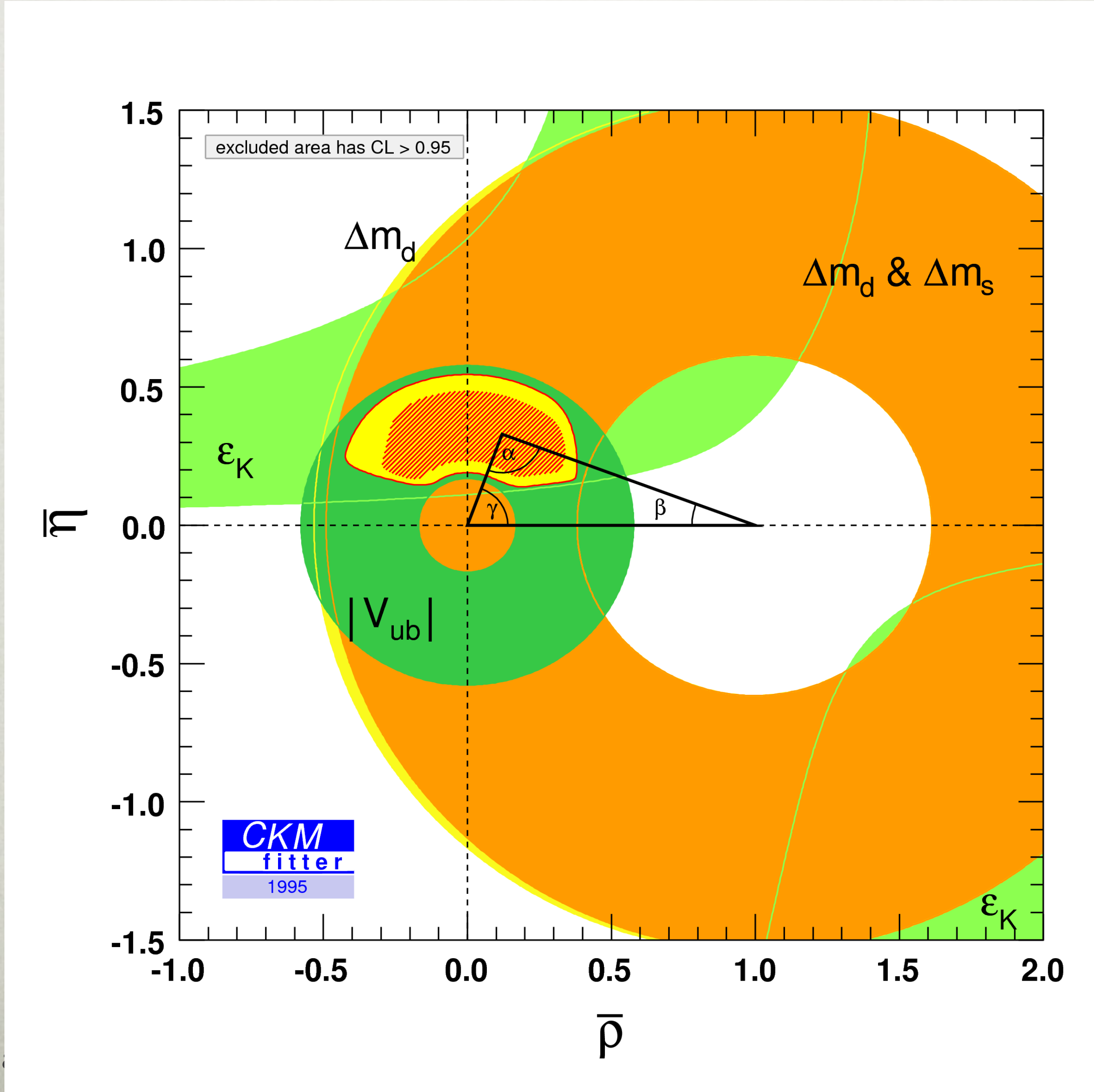
- (super)B-factories
  - LHCb(2010-2030?): up to 10^{13} (useful) B's
  - Belle II (2018-2024?): ~ 8 x 10^{10} B mesons

B physics experiencing deflation:

in 2000s: ~50¢/B meson

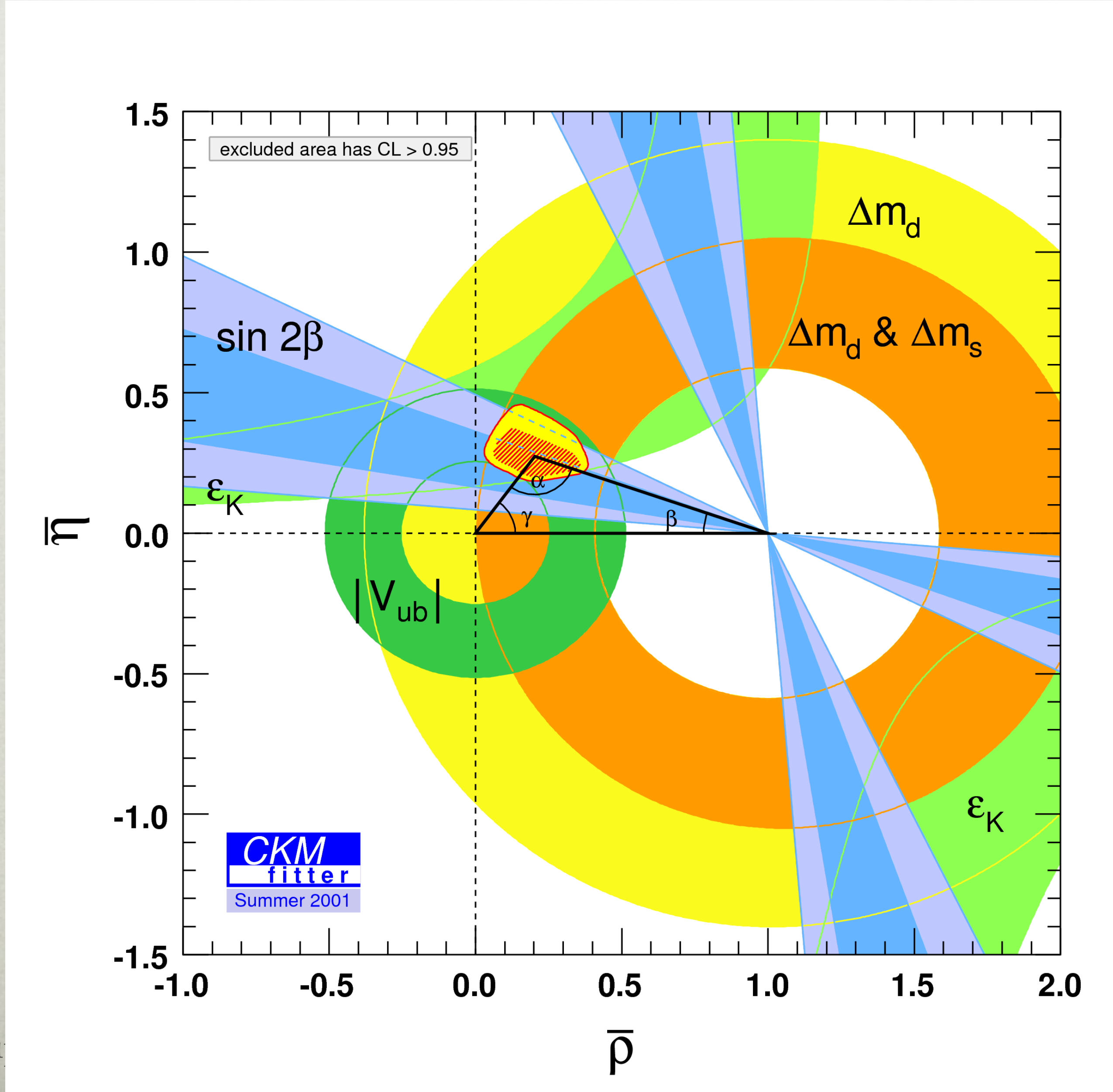
in 2020s: <1¢/B meson

1995



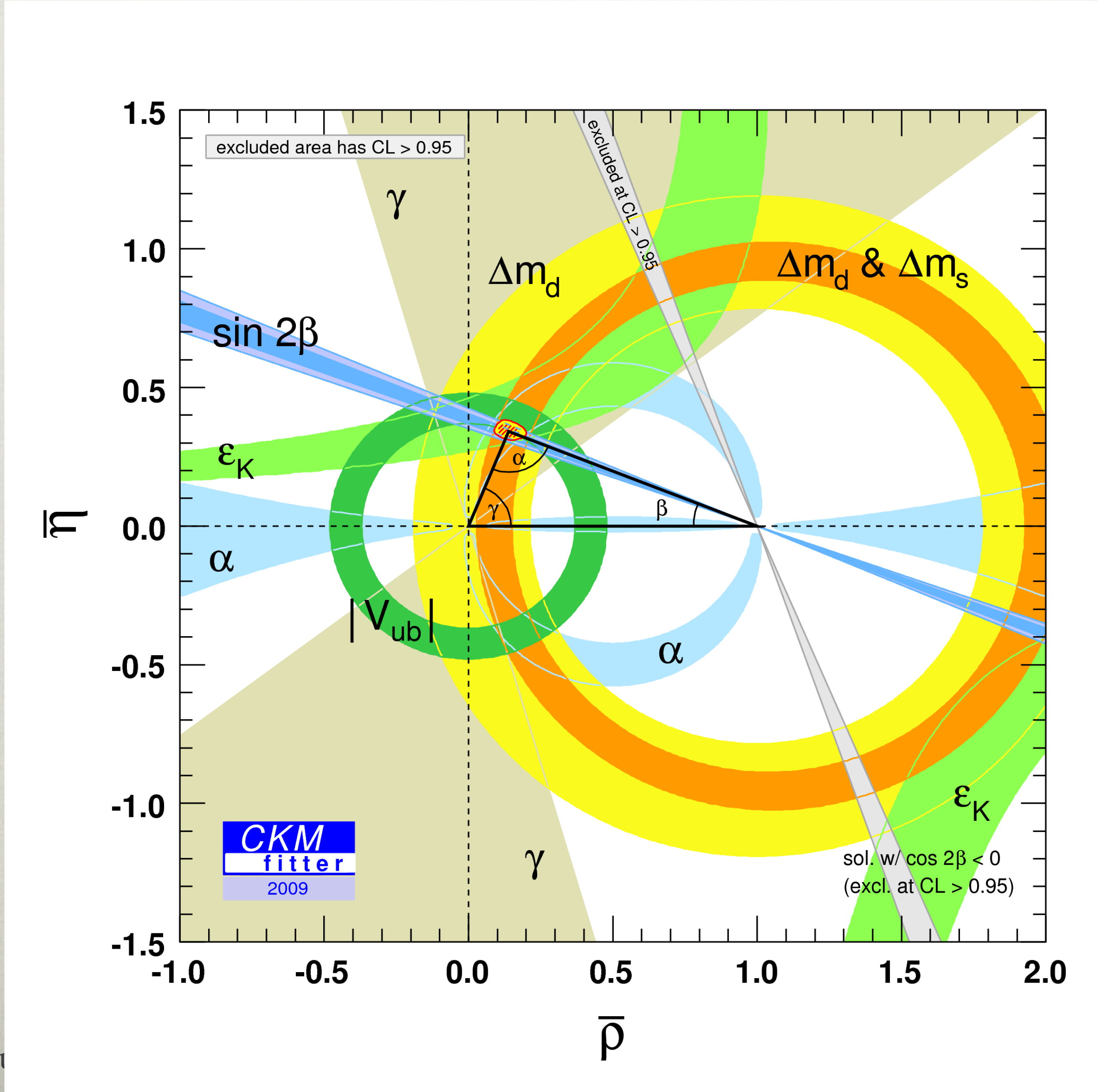
excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
$|V_{ub}|$
α
β
γ
ε_K
CKM fitter
1995
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

2001



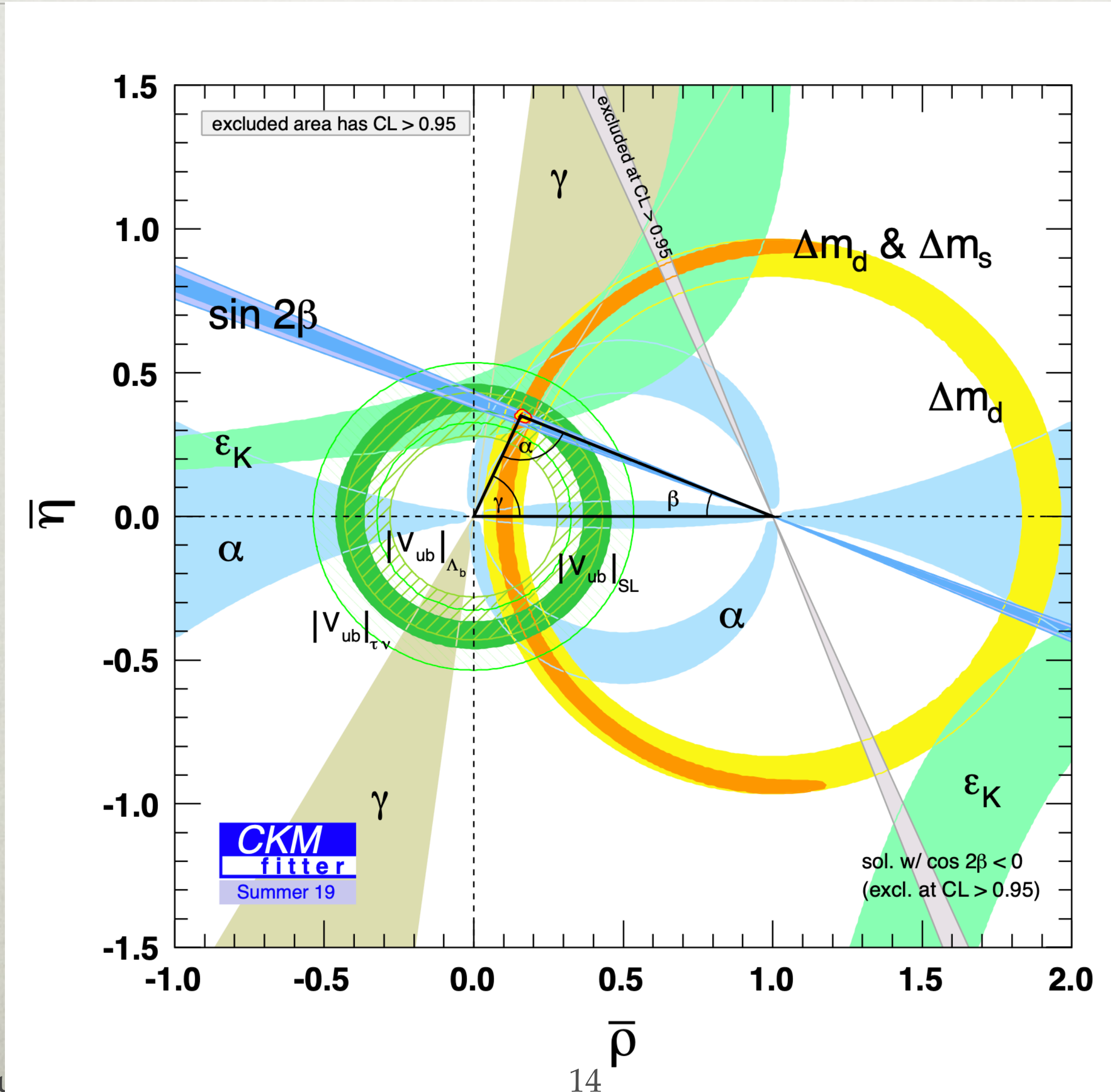
excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
$|V_{ub}|$
α
β
γ
ε_K
CKM fitter
Summer 2001
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

2009



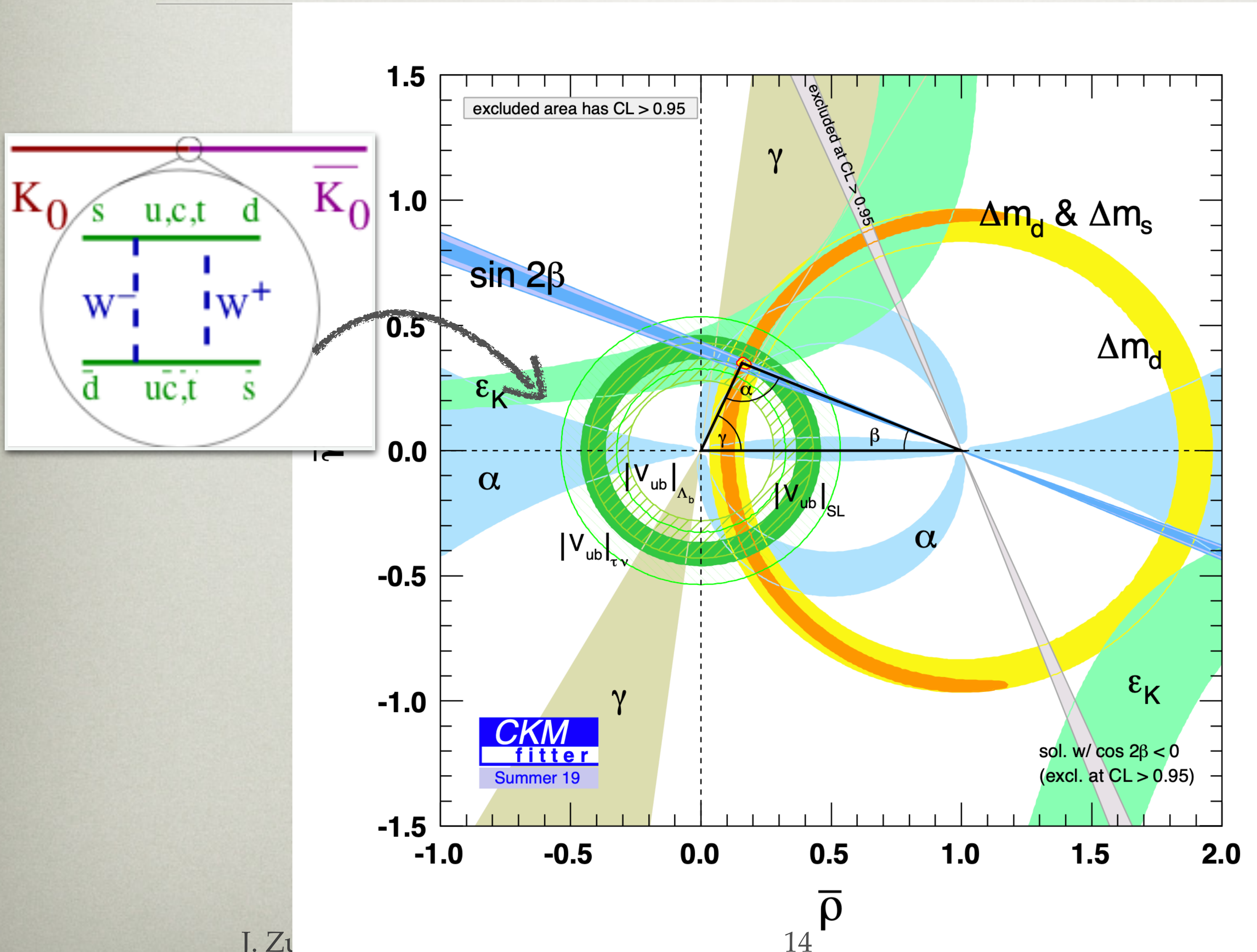
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm$_d$
Δm$_d$ & Δm$_s$
sin 2β
ε$_K$
α
β
|V$_{ub}$|
CKM fitter 2009
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

2019

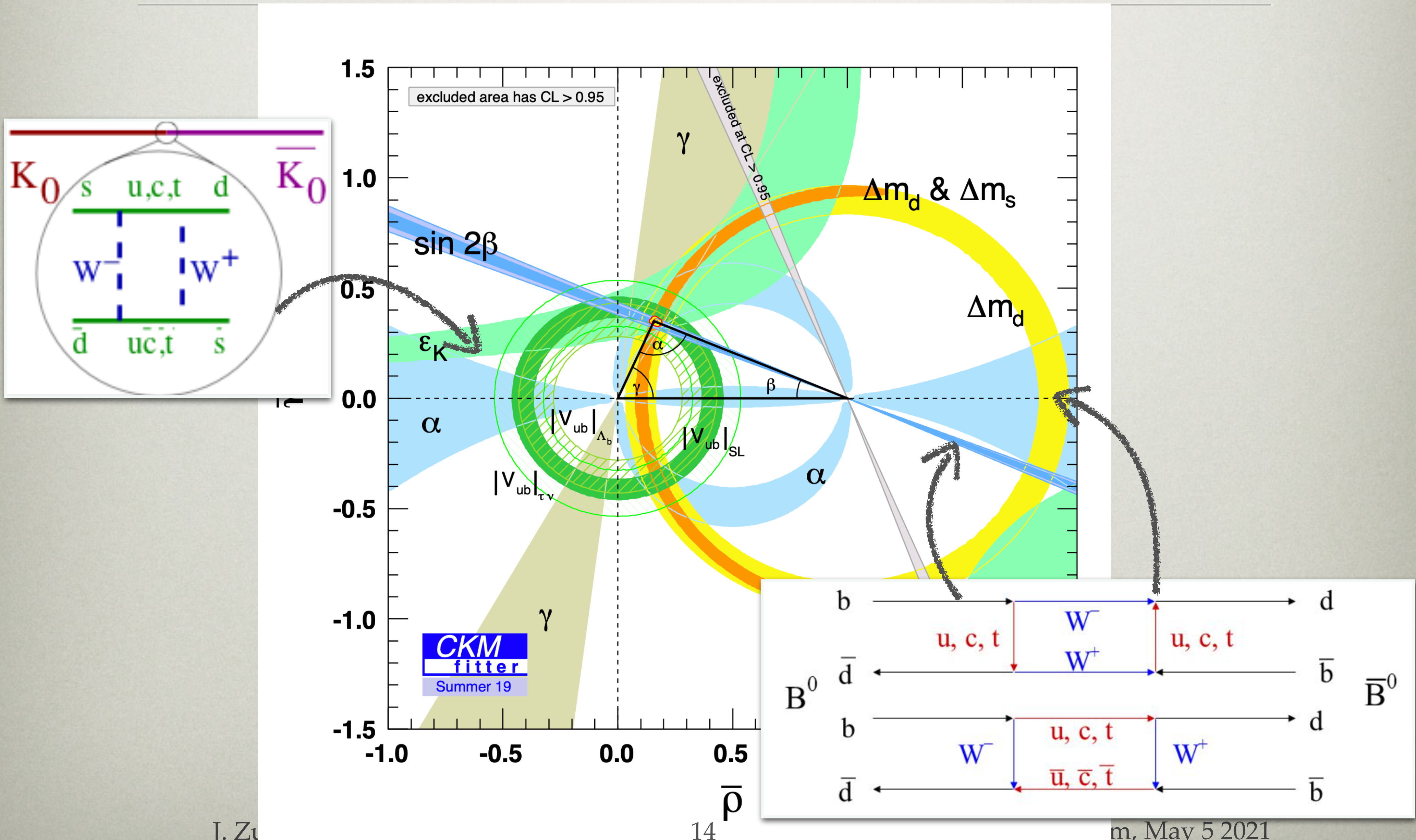


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
$|V_{ub}|_{\Lambda_b}$
$|V_{ub}|_{SL}$
$|V_{ub}|_{\tau\nu}$
α
α
γ
ε_K
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

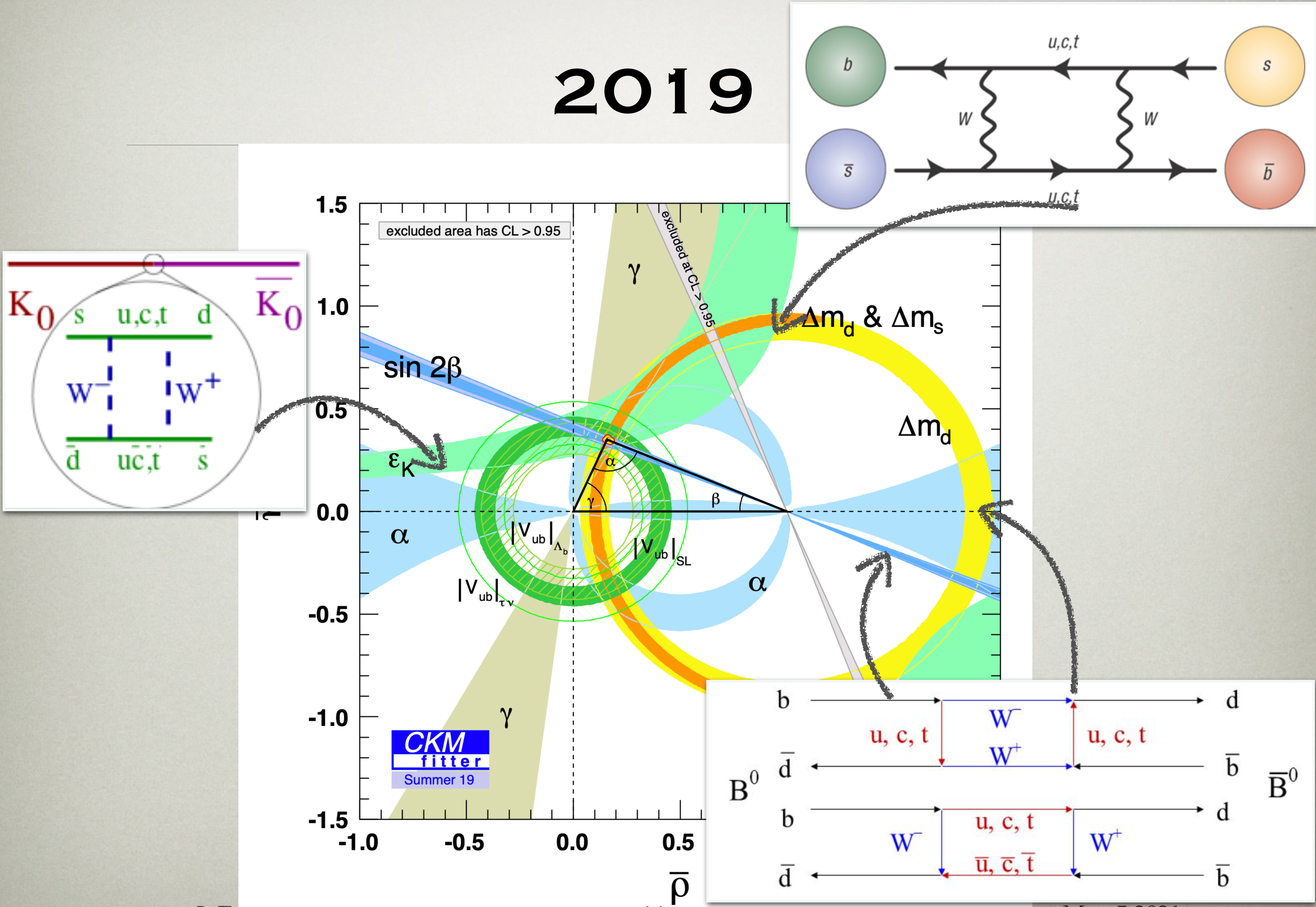
2019


K0
K0
s
u,c,t
d
W−
W+
d
uc,t
s
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
2.0
ρ̄

2019

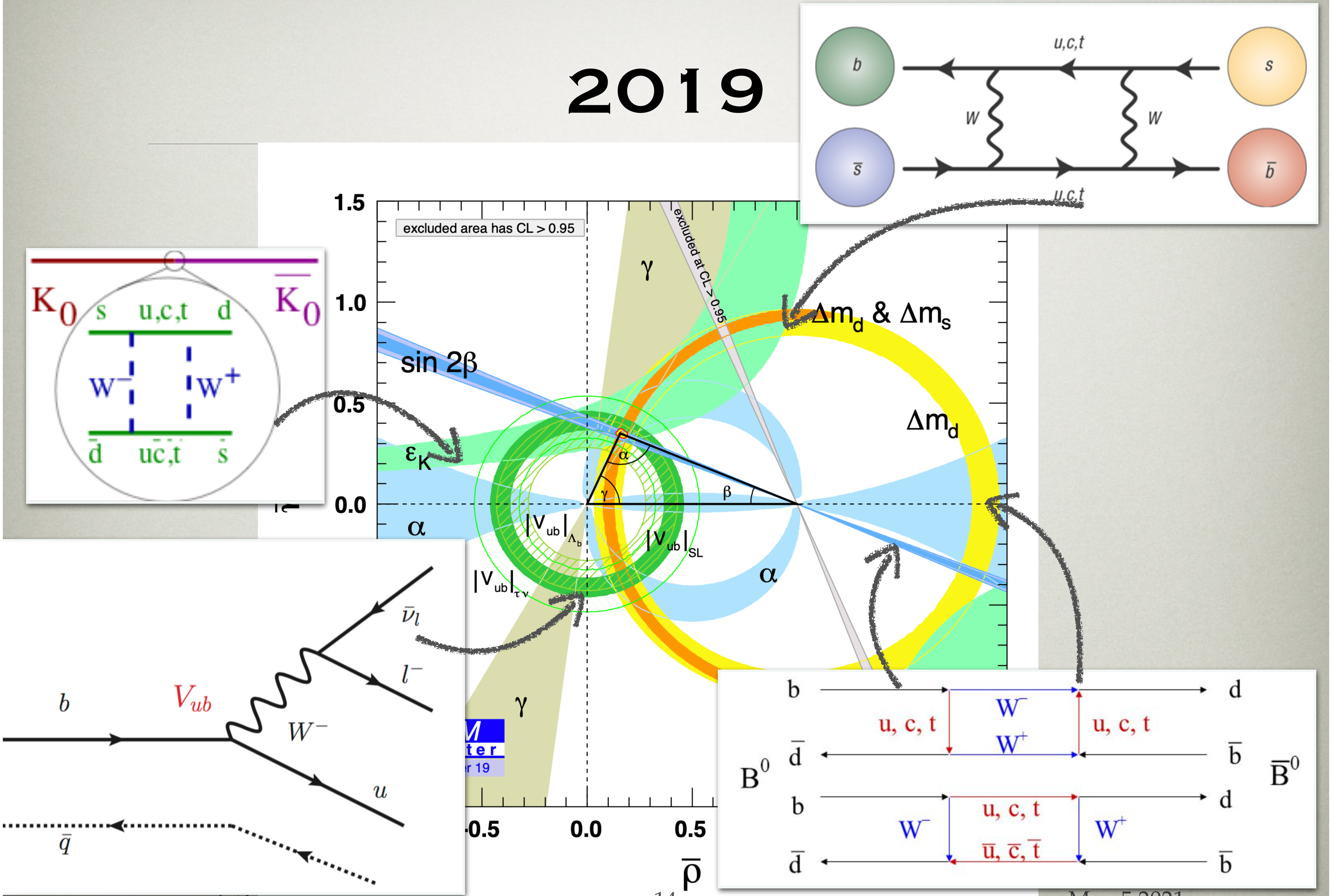

excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|_Λb
|V_ub|_SL
|V_ub|_τν
CKM fitter
Summer 19
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
ρ̄
K0
K̄0
s
u,c,t
d
W−
W+
d̄
ū c̄,t̄
s̄
b
d̄
u, c, t
W−
W+
b̄
B0
B̄0
u, c, t
ū, c̄, t̄

2019



excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
β
|V_ub|_SL
|V_ub|_τν
|V_ub|_Λb
CKM fitter
Summer 19
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.5
ρ̄
K_0
K̄_0
s u,c,t d
W⁻ W⁺
d̄ ūc̄,t̄ s̄
b
s
s̄
b̄
u,c,t
W
B^0
B̄^0
d
d̄
W⁻
W⁺
u, c, t
ū, c̄, t̄

2019



excluded area has CL > 0.95
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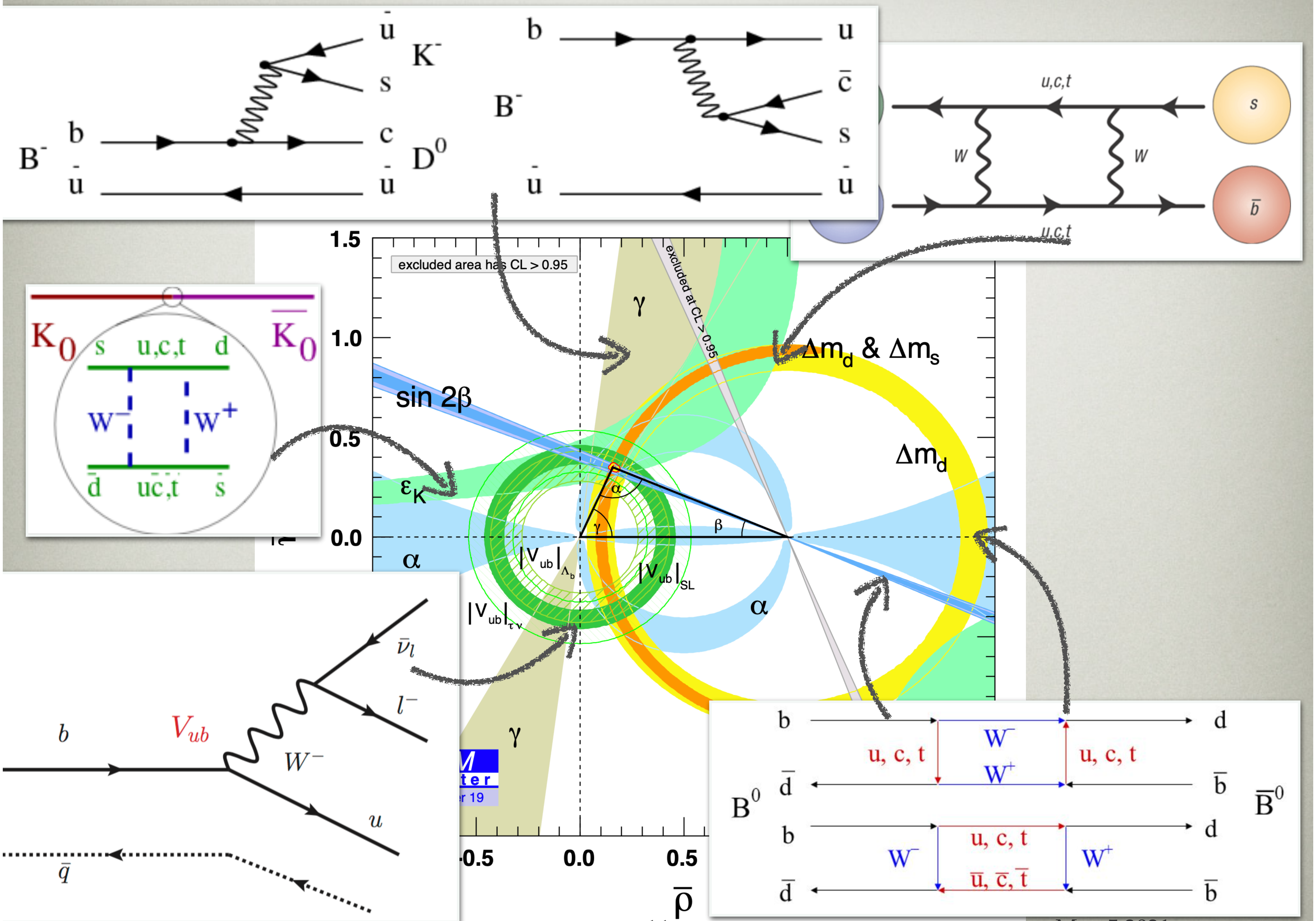
γ
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
β
$|V_{ub}|_{\Lambda_b}$
$|V_{ub}|_{SL}$
$|V_{ub}|_{\tau\nu}$
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
$\bar{\rho}$
K_0
$\overline{K}_0$
s
u,c,t
d
W^-
W^+
$\bar{d}$
$\bar{u},\bar{c},\bar{t}$
$\bar{s}$
b
s
$\bar{s}$
$\bar{b}$
u,c,t
W
W
b
V_{ub}
W^-
$\bar{\nu}_l$
l^-
u
$\bar{q}$
B^0
$\bar{B}^0$
b
d
$\bar{d}$
$\bar{b}$
u, c, t
W^-
W^+
$\bar{u}, \bar{c}, \bar{t}$


B⁻
b
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u
K⁻
s
c
D⁰
u
b
B⁻
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c̄
s
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u
u,c,t
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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
|V_ub|_{Λ_b}
|V_ub|_SL
|V_ub|_{τν}
α
α
γ
K_0
K̄_0
s
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄
b
V_ub
W⁻
ν̄_l
l⁻
u
q̄
1.5
1.0
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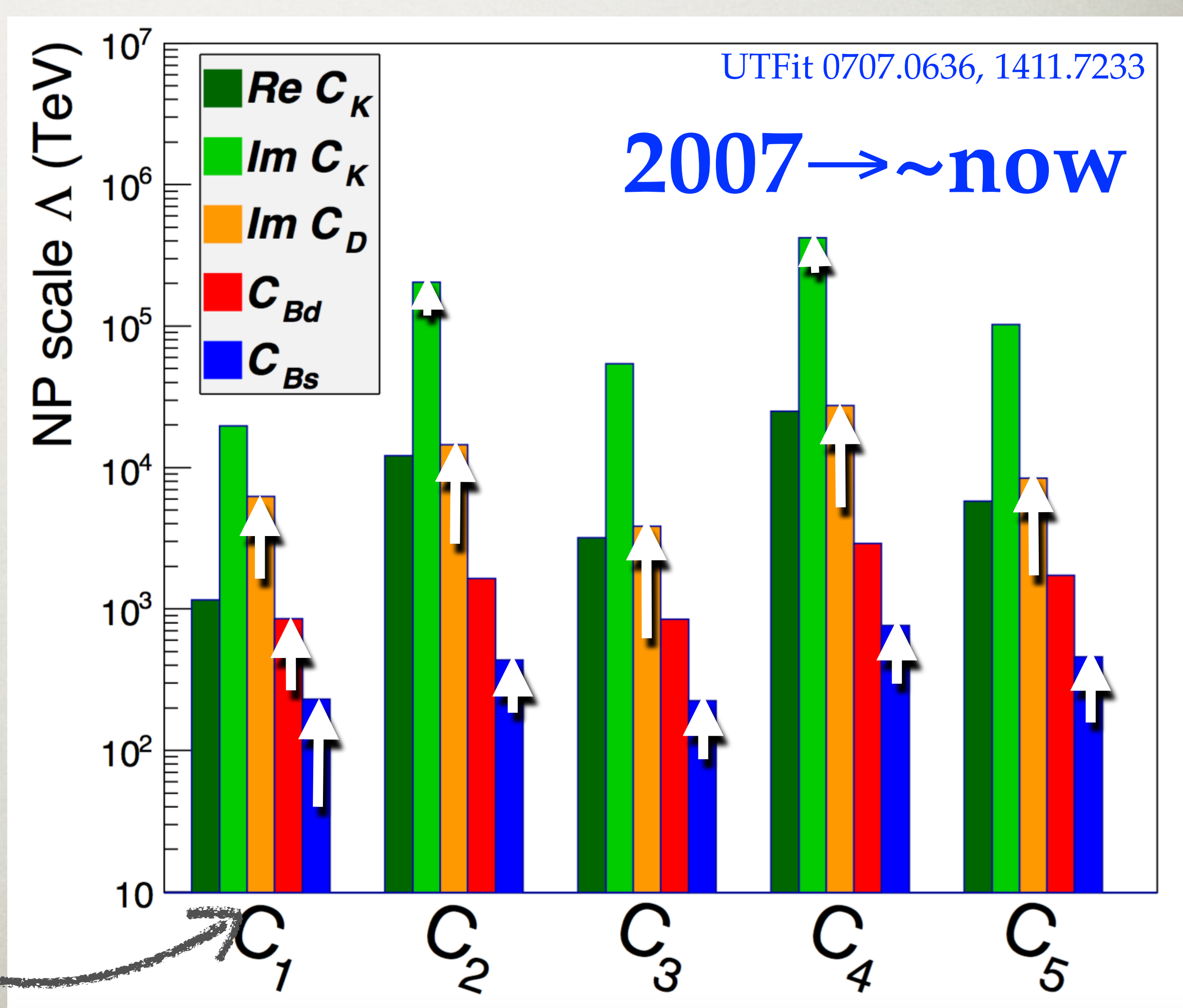
0.0
-0.5
0.0
0.5
ρ̄
b
d
u, c, t
W⁻
W⁺
u, c, t
d̄
b̄
B⁰
B̄⁰
b
d
u, c, t
W⁻
W⁺
ū, c̄, t̄
d̄
b̄

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 ($c\bar{u}$, $\bar{b}s$)
- also from ε_K ($\bar{d}s$)

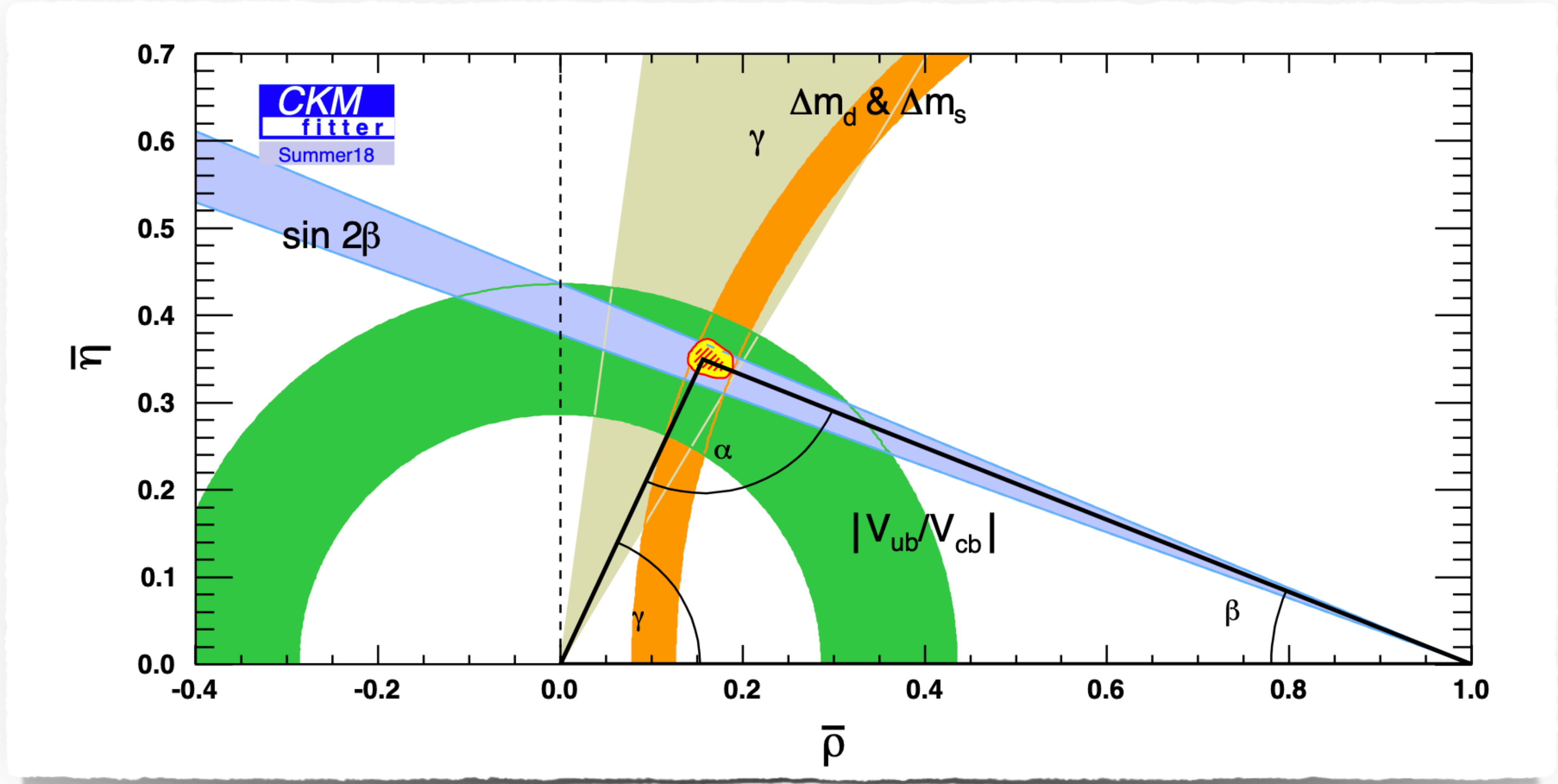
$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



THE (MID-TERM) FUTURE

Physics Briefing Book, 1910.11775

- just from LHCb:



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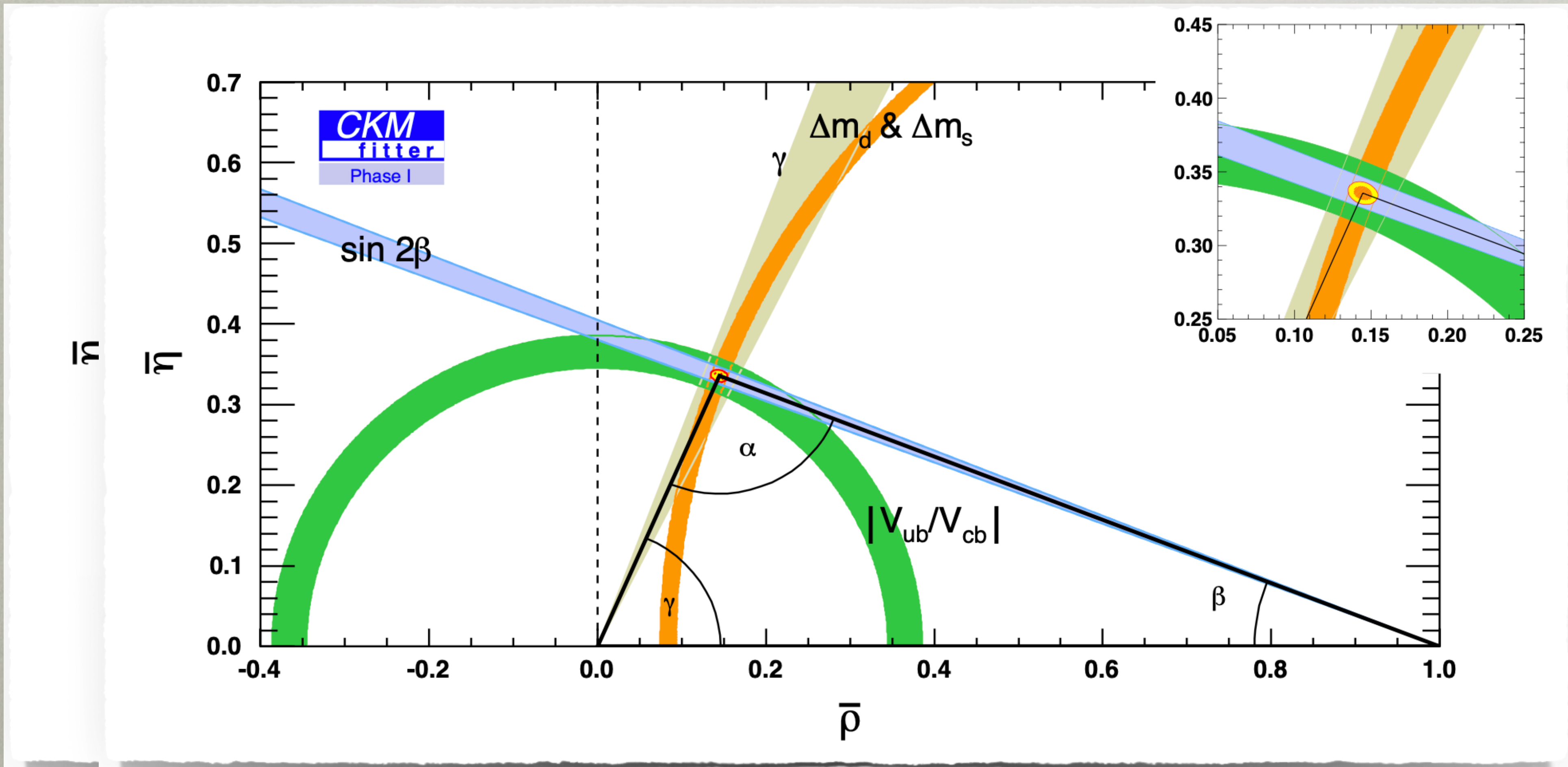

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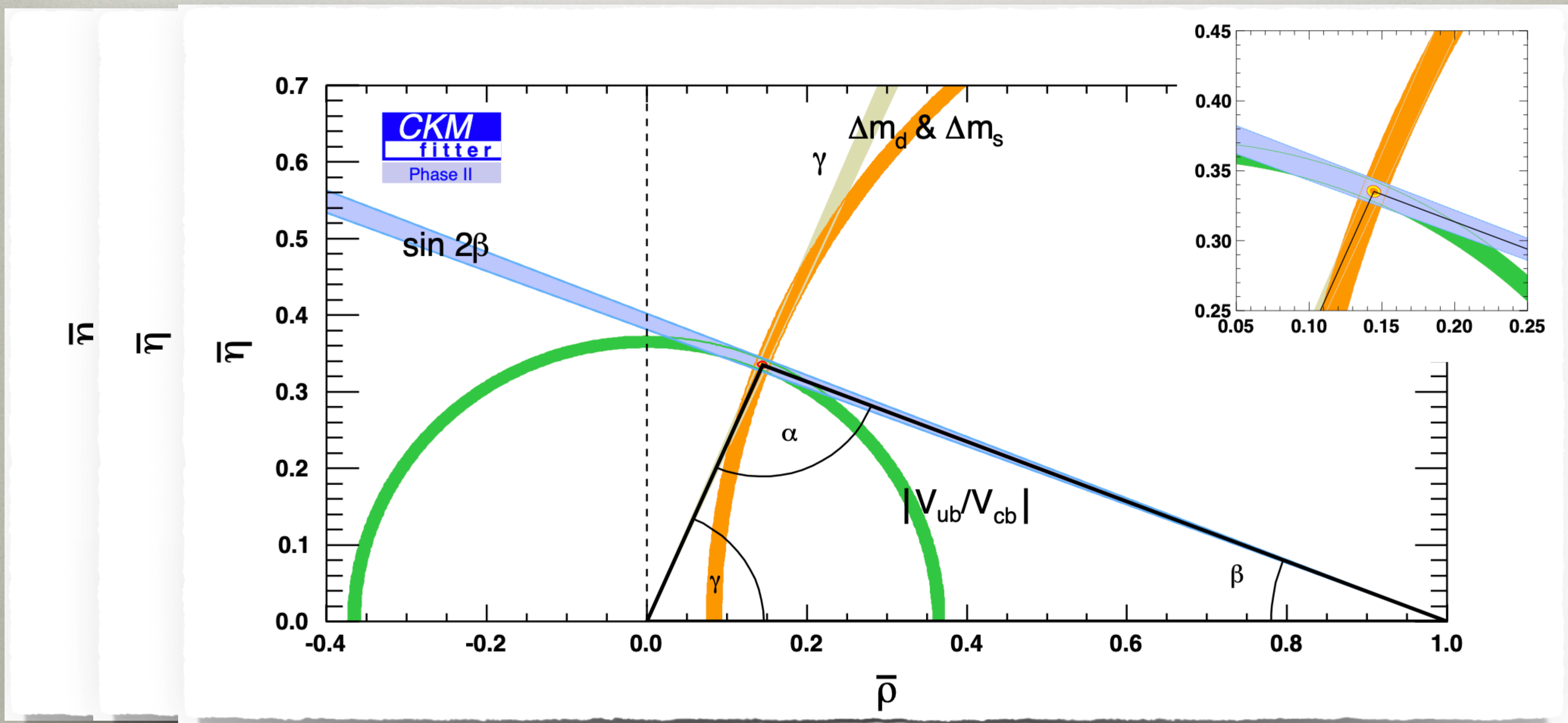

THE MID-TERM FUTURE

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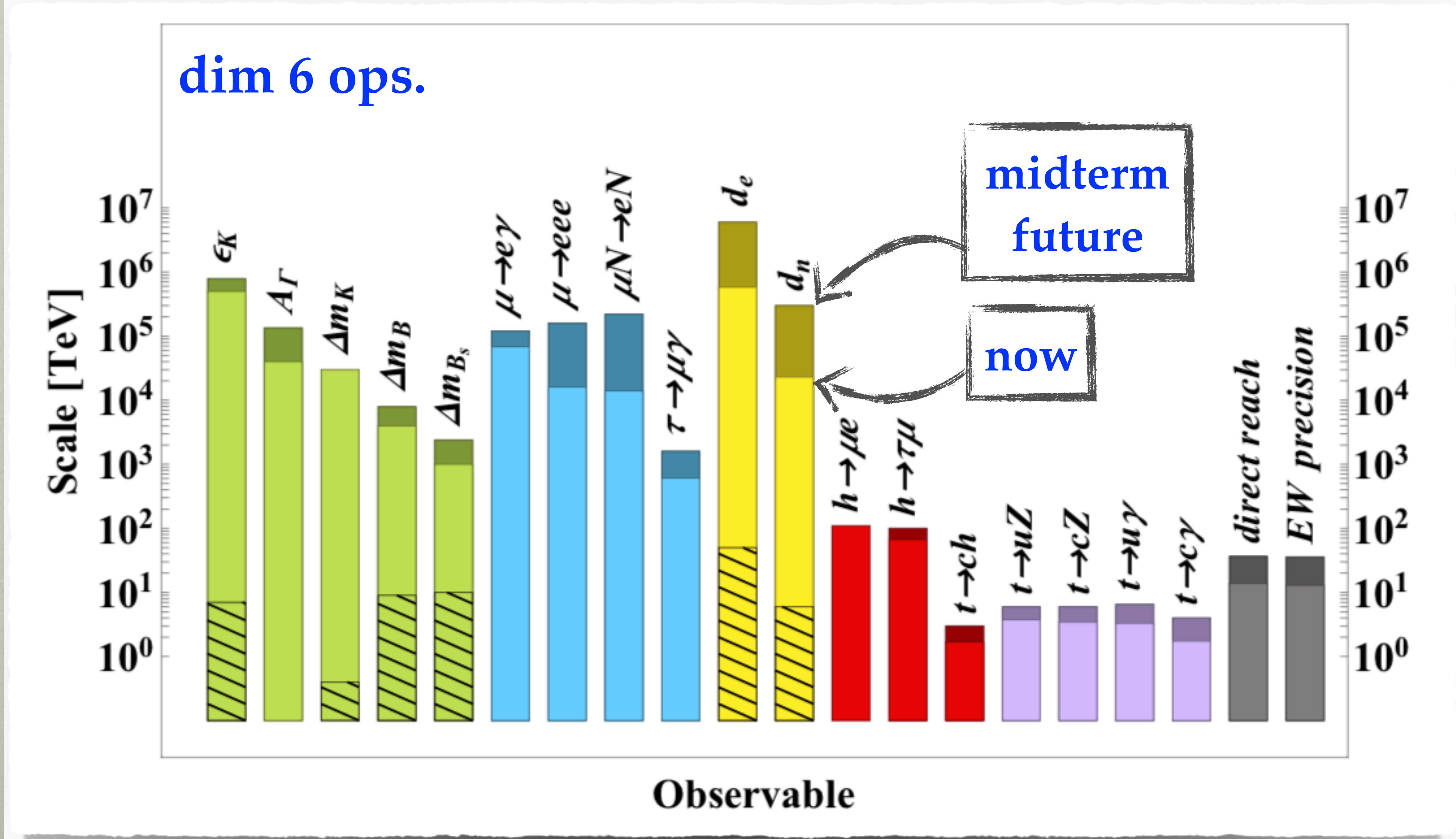


PROBING
LIGHT NEW PHYSICS

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

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

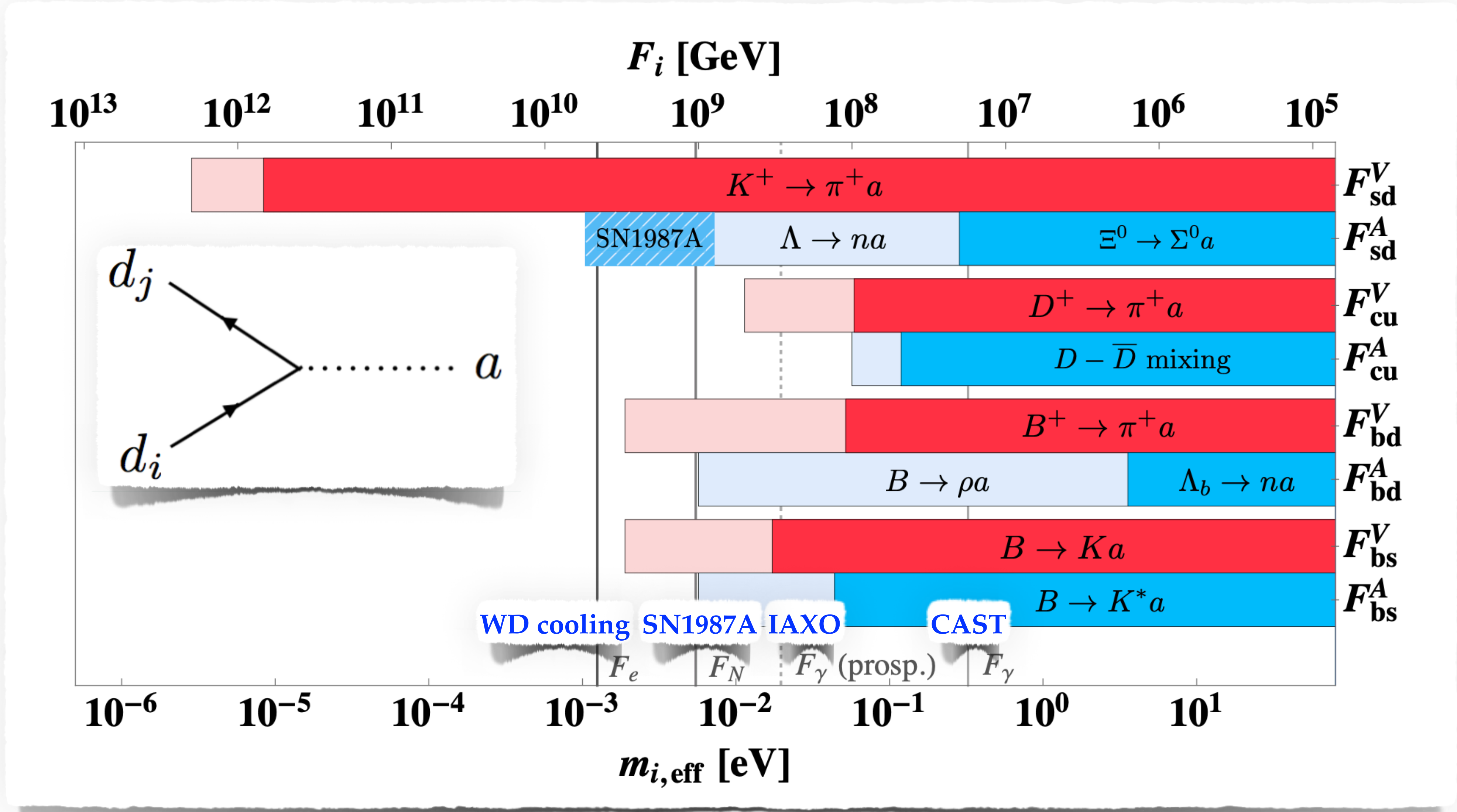
- in general the couplings can be flavor violating
  - since dim 5, FCNCs probe very high scales
  - even above astrophysics bounds
- concrete examples: FV QCD axion, axiflavon, majoron,...

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

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

BOUNDS ON FLAVOR VIOLATING QCD AXION



EXPERIMENTAL ANOMALIES

EXPERIMENTAL ANOMALIES IN PROCESSES WITH MUONS&TAUS

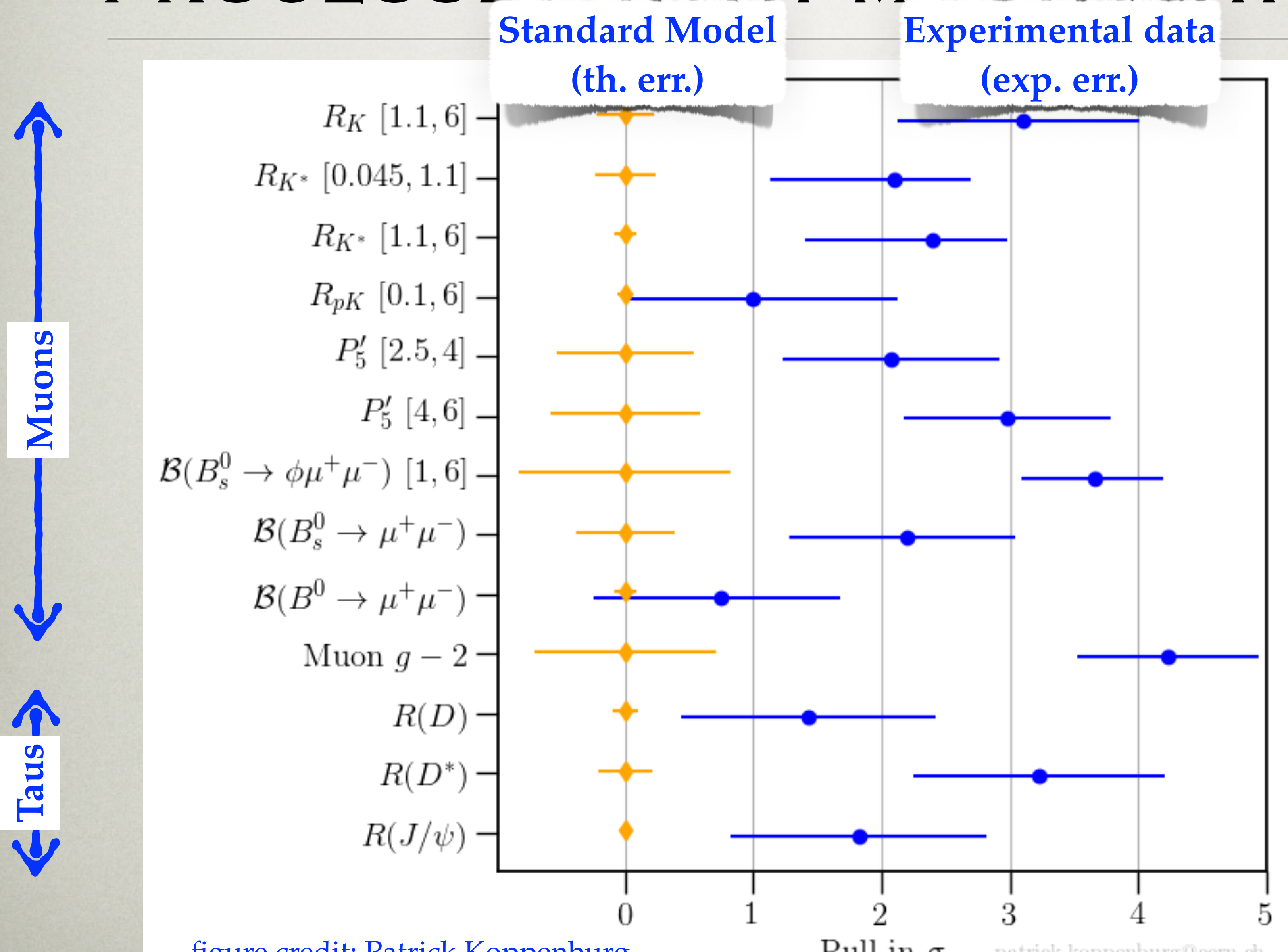


figure credit: Patrick Koppenburg

NEWS FROM THE LAST TWO MONTHS

- 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
- $(g-2)_\mu$ went from 3.7σ to 4.2σ

The Muon g–2 Collaboration , 2104.03281

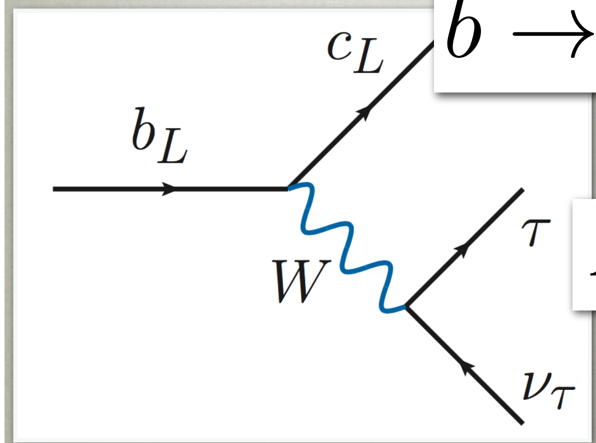
figure credit: J. Butterworth

IF NEW PHYSICS...

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

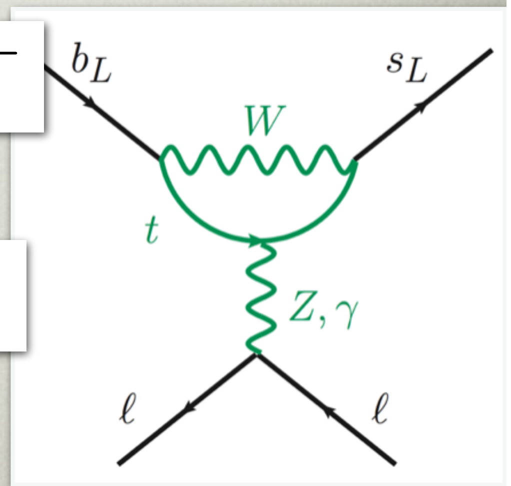
$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

$b \to c\tau\nu$



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

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



$\Lambda_{\rm NP} \sim 40$ 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?

$$(g-2)_\mu$$

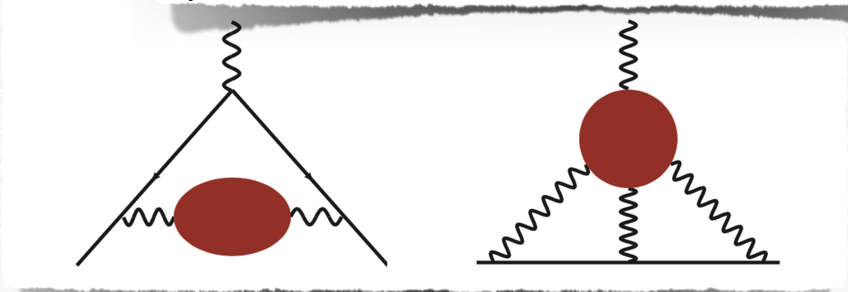
A DEVIATION?

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

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

- the SM theory error dominated by hadronic uncert.

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

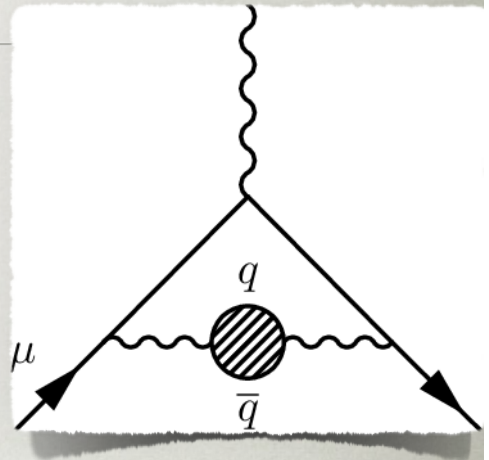


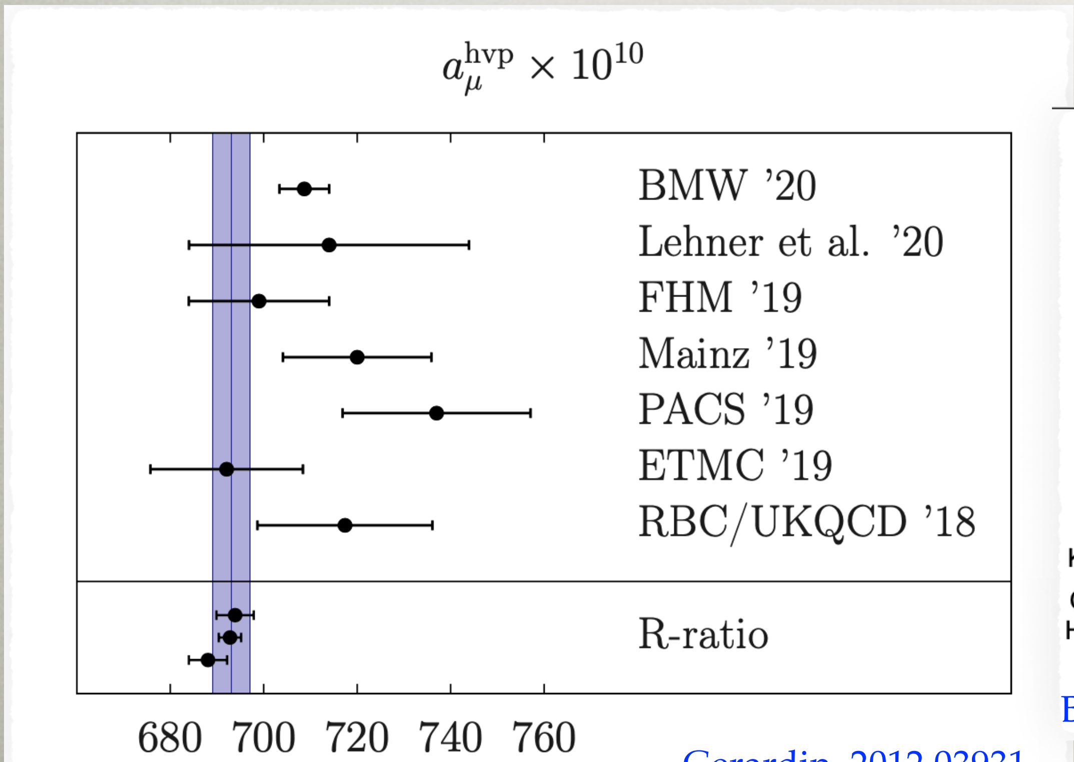
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)

The muon g-2 theory initiative, 2006.04822

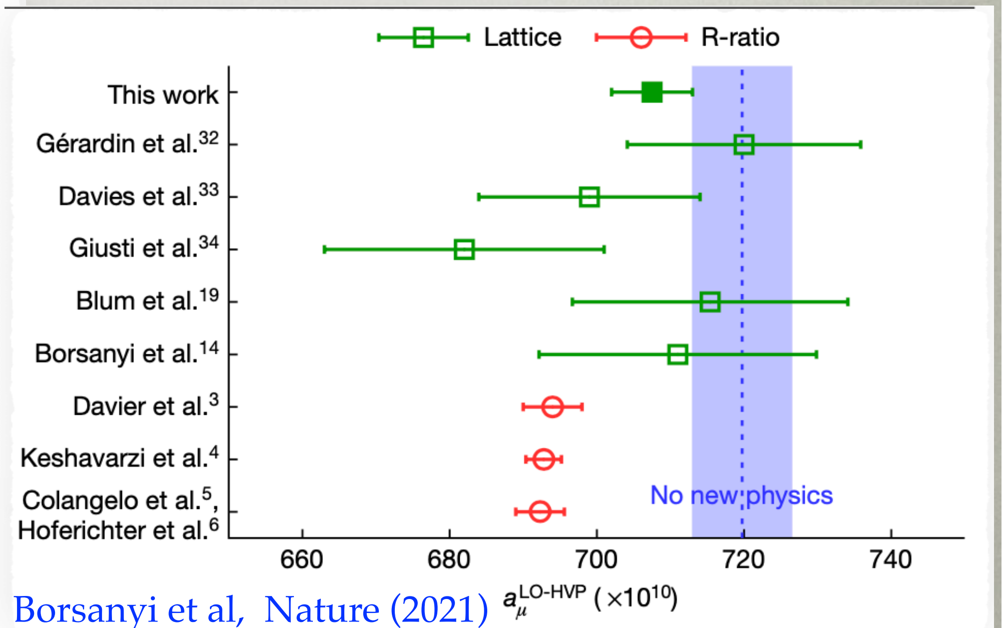
HADRONIC VACUUM POLARIZATION

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





Gerardin, 2012.03931



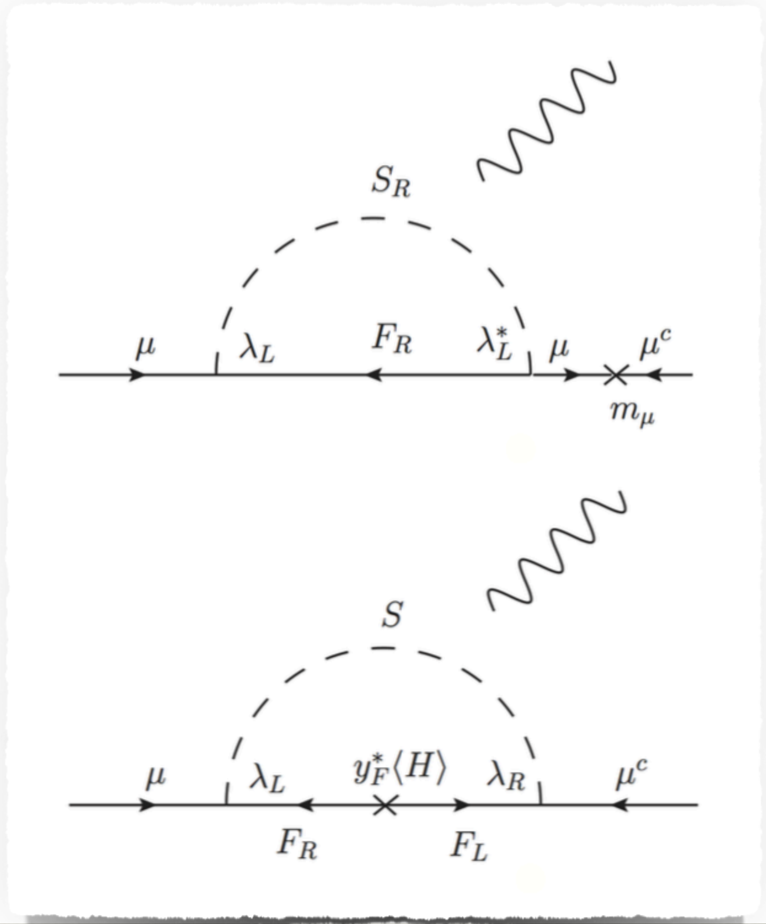
Borsanyi et al, Nature (2021)

IF NEW PHYSICS...

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

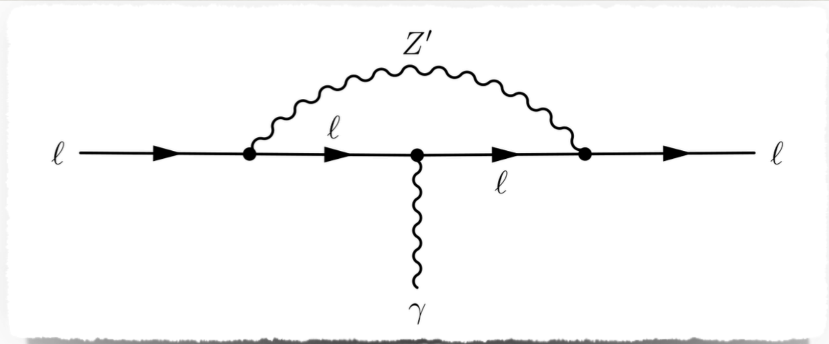
$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

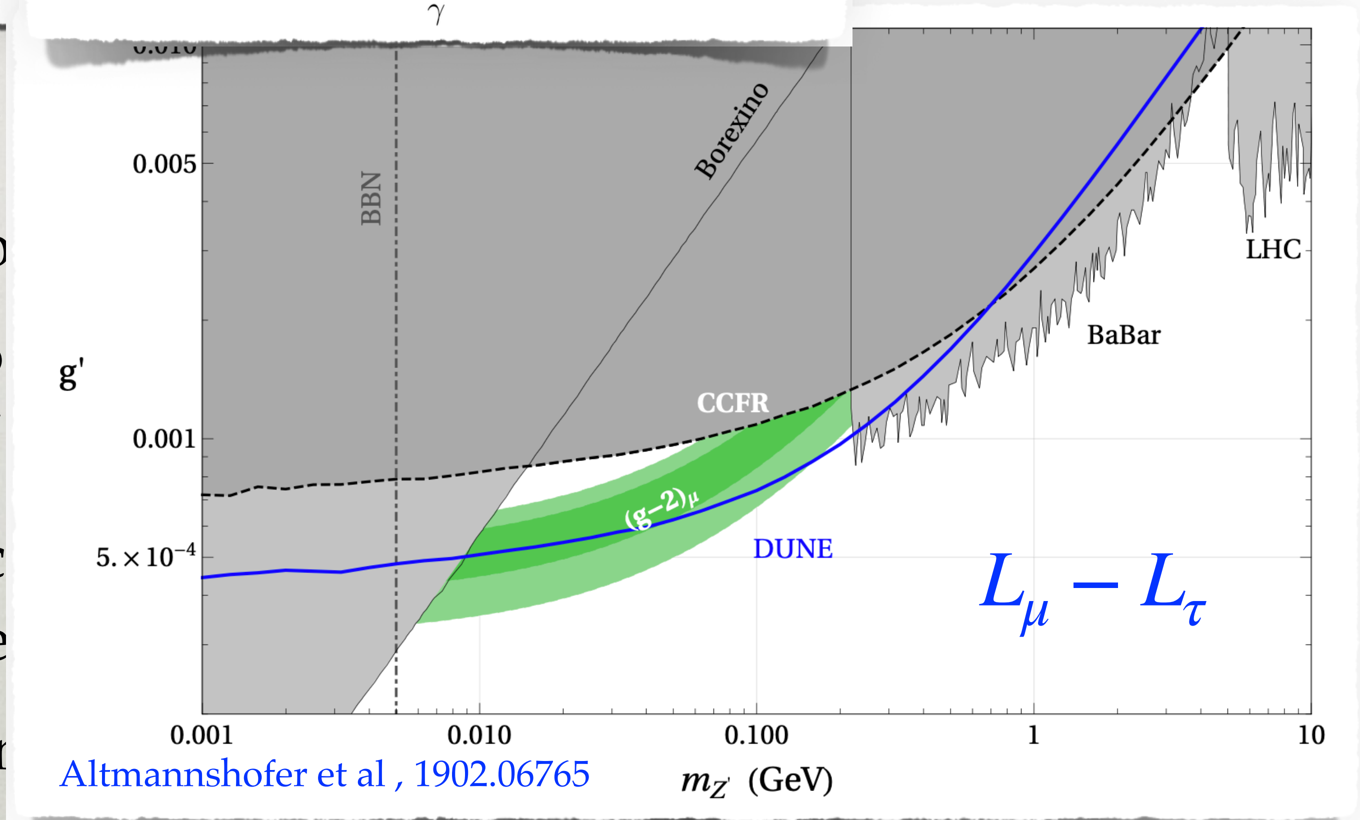
- NP models of two types
- chirality flip on SM fermion leg
    - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
    - NP can be much heavier
    - example: minimal models with DM



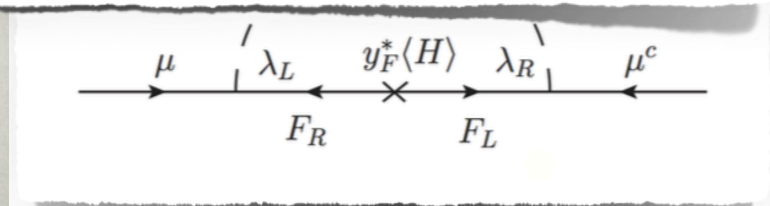
IF N… .

$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251($ … $(\bar\mu\sigma^{\mu\nu}\mu)F_{\mu\nu}$





- NP models of …
- chirality flip o…
  - NP need to …
    example: Z…
- chirality flip c…
  NP fermion le…
  - NP can be r…
  - example: minimal models with DM

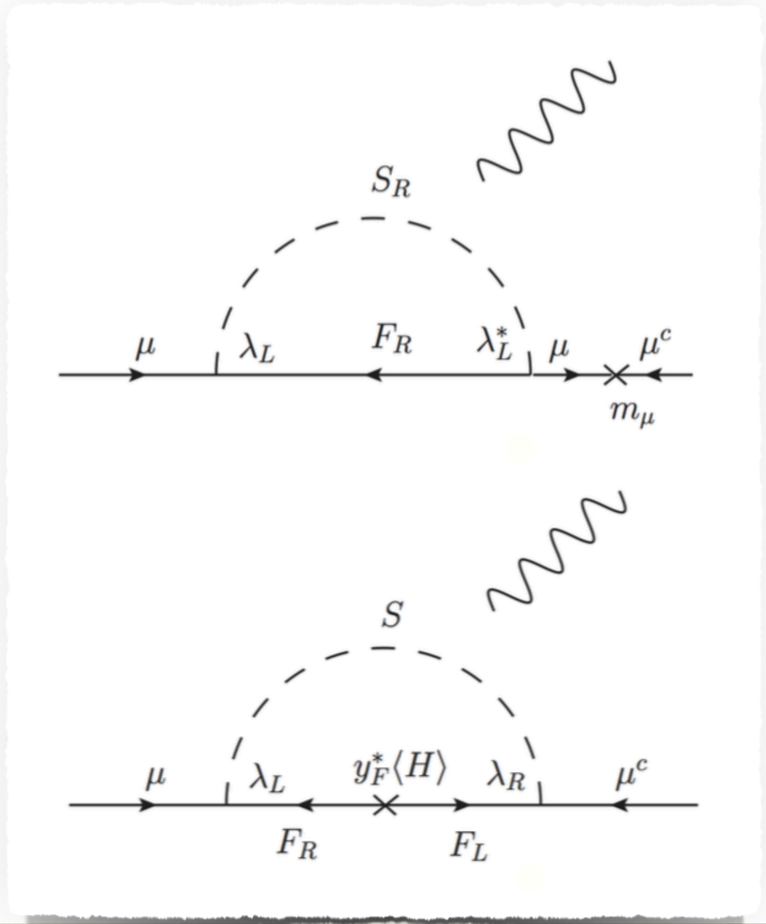


IF NEW PHYSICS...

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

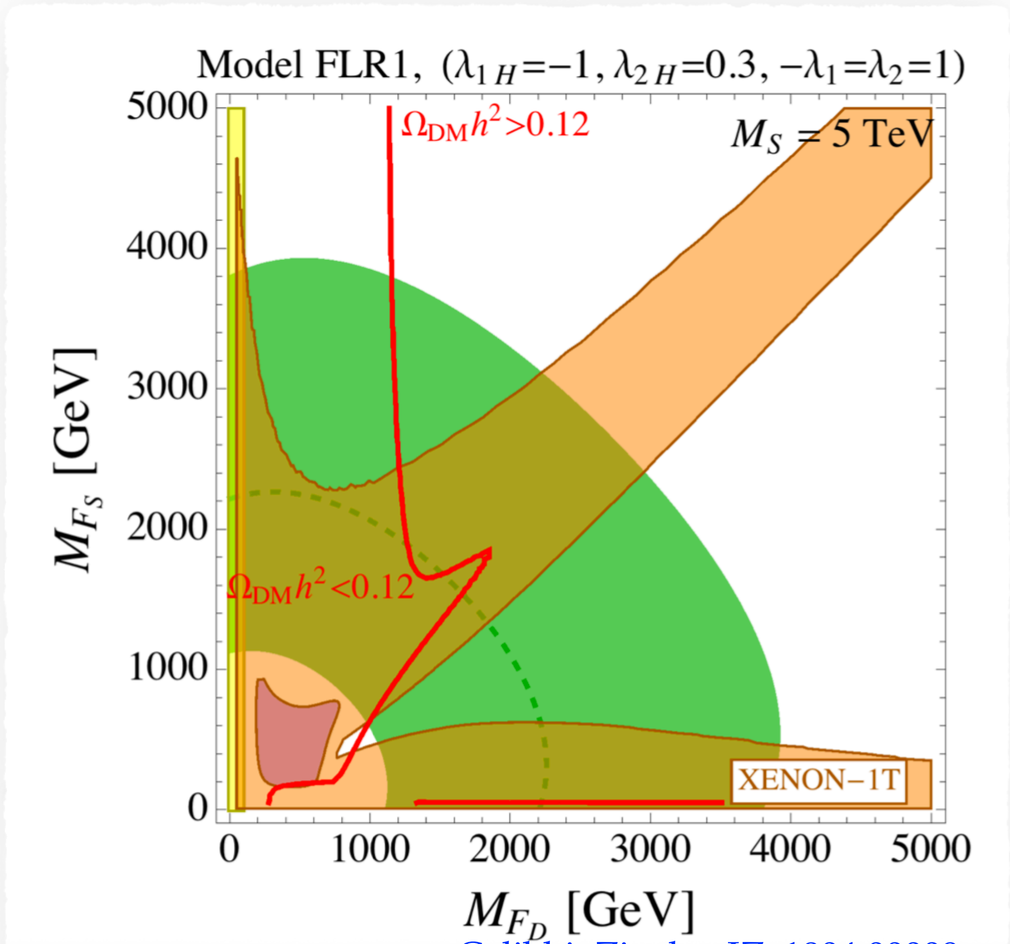
$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

- 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...

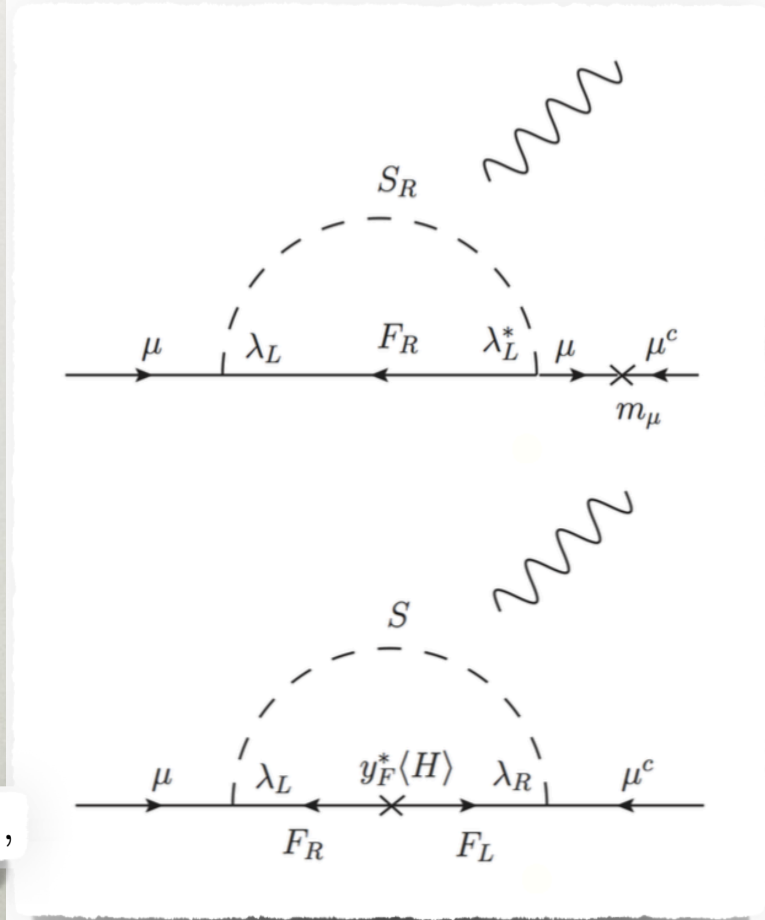
$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$



Calibbi, Ziegler, JZ, 1804.00009

leg

s



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

$b \rightarrow s\mu\mu$

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

UPSHOT

- $b \to sll$ flavor anomaly
  - theoretically clean, ~5σ excess
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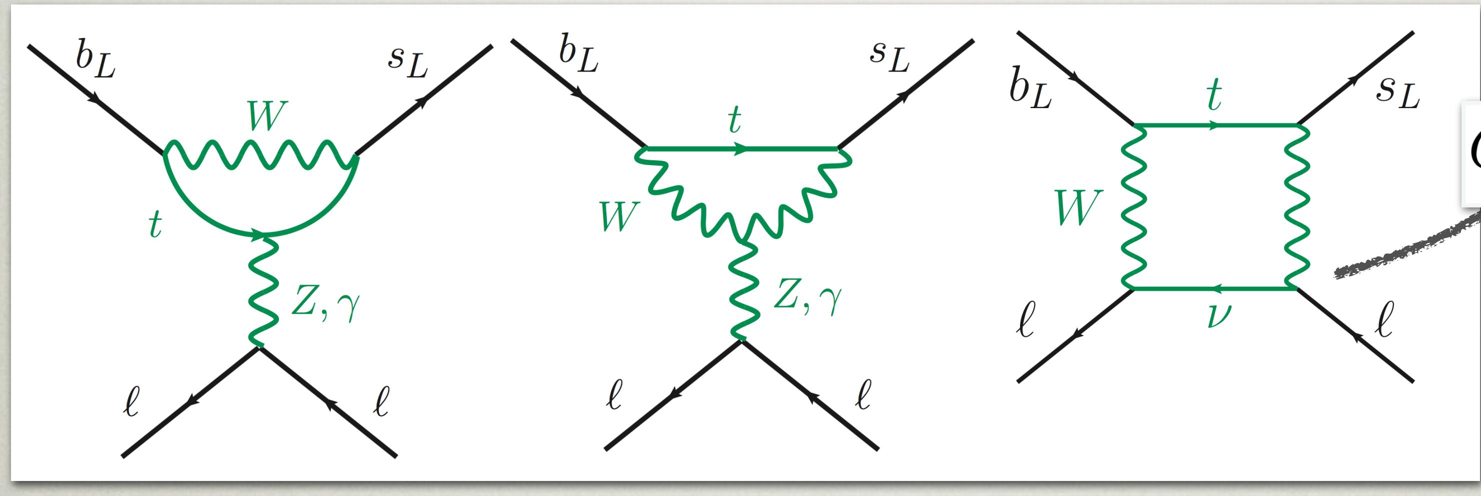
EXPERIMENTAL SITUATION

- $b \to sll$: 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 $b \to see$ the same as $b \to s\mu\mu$
- Lepton Flavor Universality in the SM

$b \to sll$: EXPERIMENT

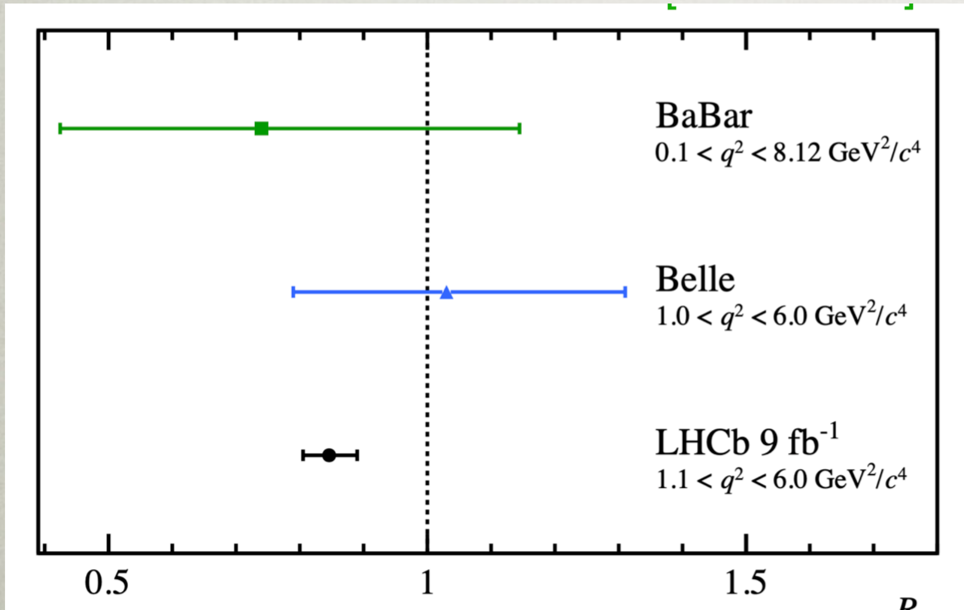
- three clean observables: R_K and R_{K^*}

two bins

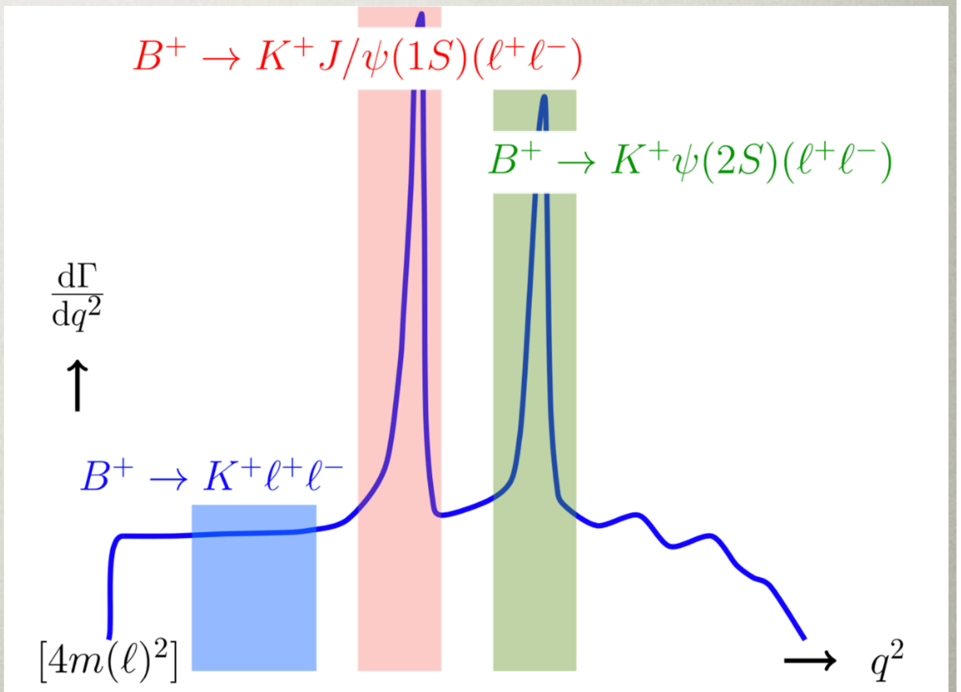
$$R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)}\bigg|_{[1,6]\mathrm{GeV}^2}$$

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

- 3.1σ anomaly in R_K



LHCb, 2103.11769

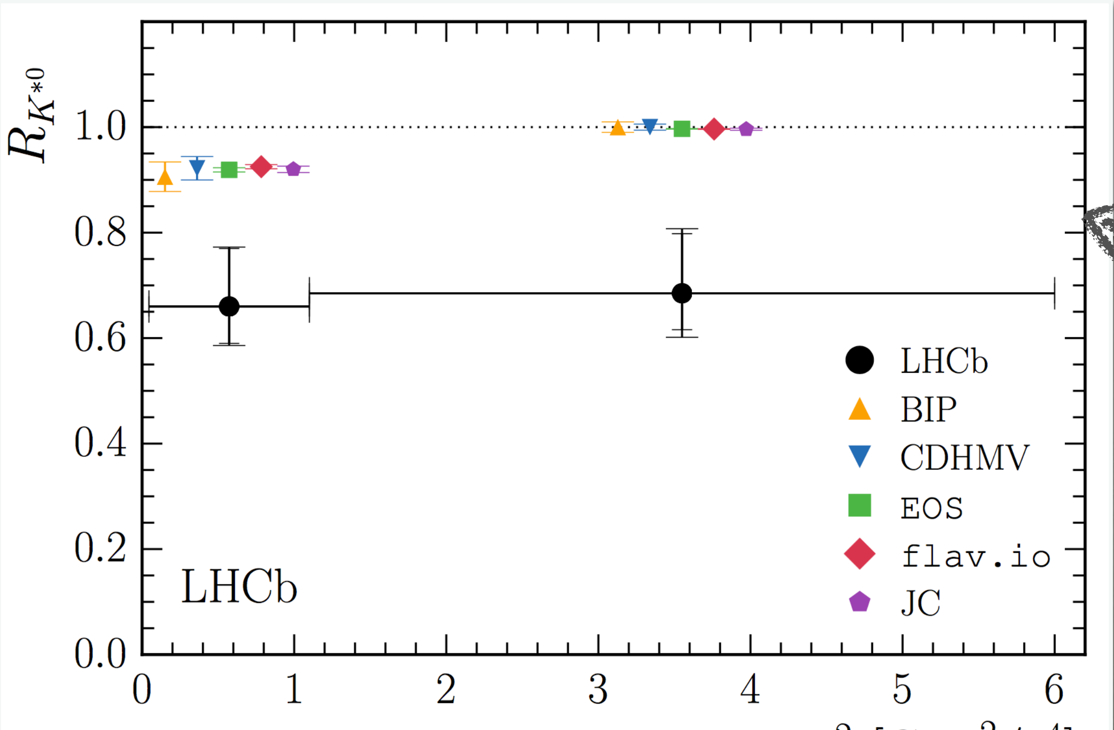


$b \to sll$: EXPERIMENT

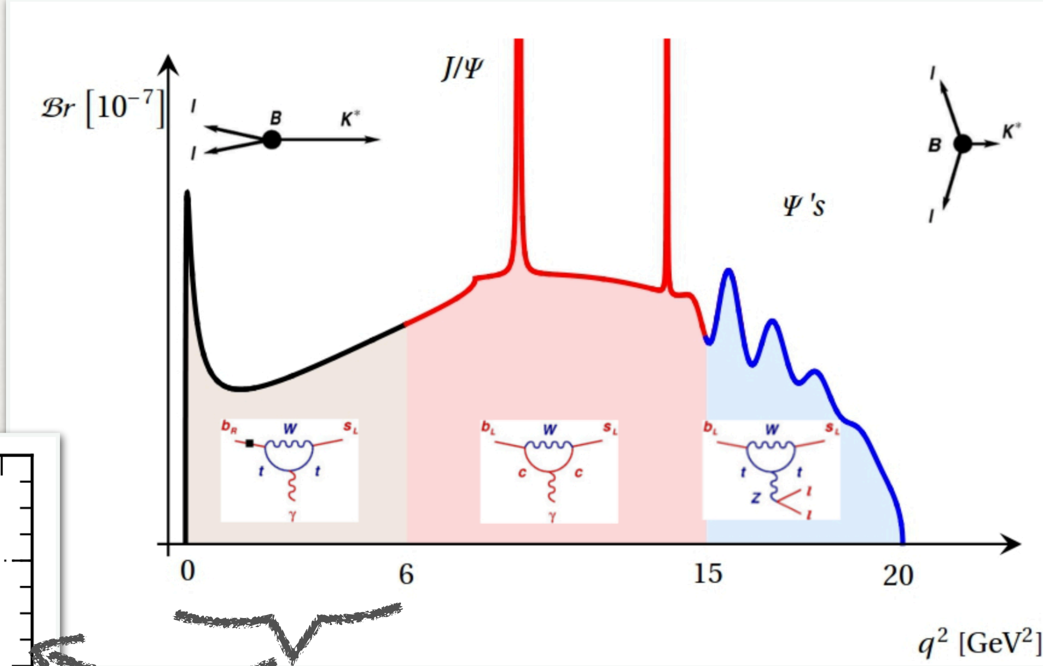
- 2 bins in R_{K^*}

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

- *2.2-2.5σ* deviation in each



LHCb, 1705.05802



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

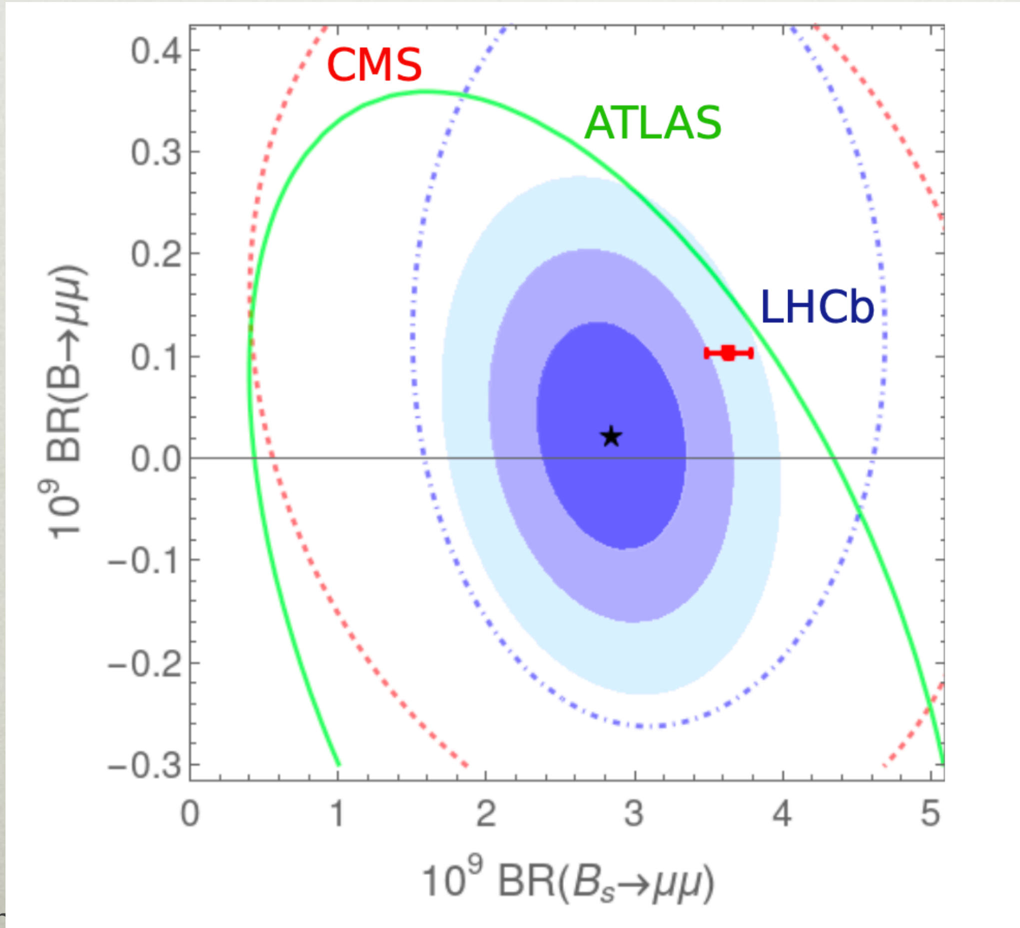
$$R_{K^*[0.045,\ 1.1]\ \mathrm{GeV}^2} = 0.660^{+0.110}_{-0.070} \pm 0.024,$$

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

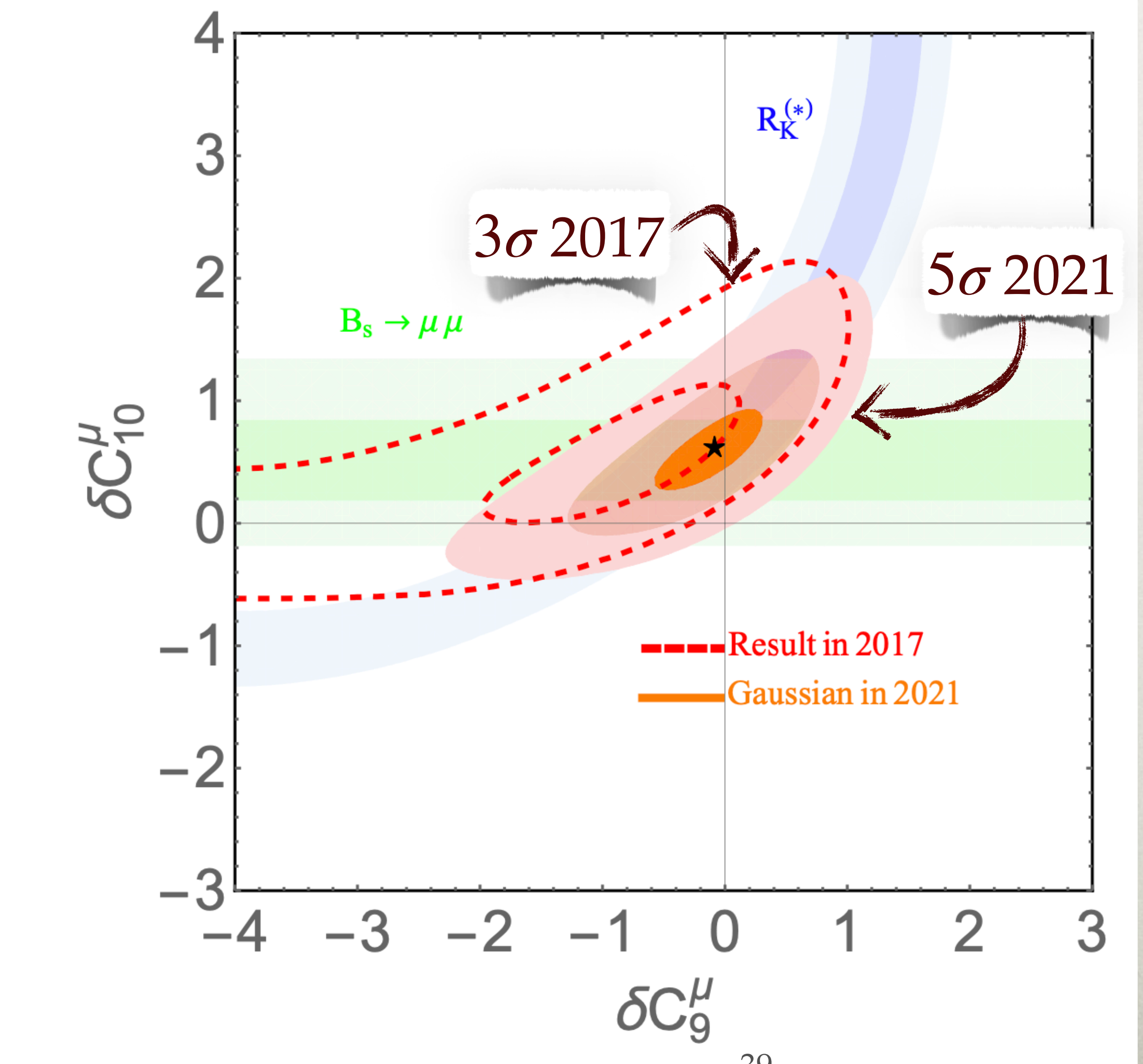
PREFERENCE FOR NP IN MUONS?

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

Geng et al., 2103.12738



FIT TO CLEAN OBSERVABLES



Geng et al., 2103.12738

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

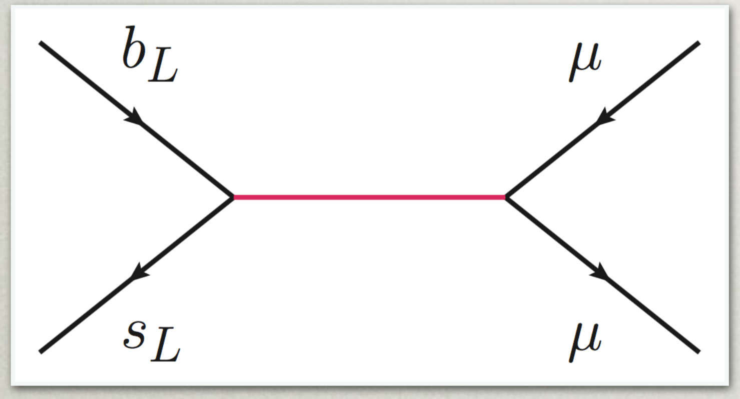
$$V_{tb}V_{ts}^{*}\frac{\alpha_{\rm em}}{4\pi v^2}C_I = \frac{C_I}{(36\,\text{TeV})^2}$$

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

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

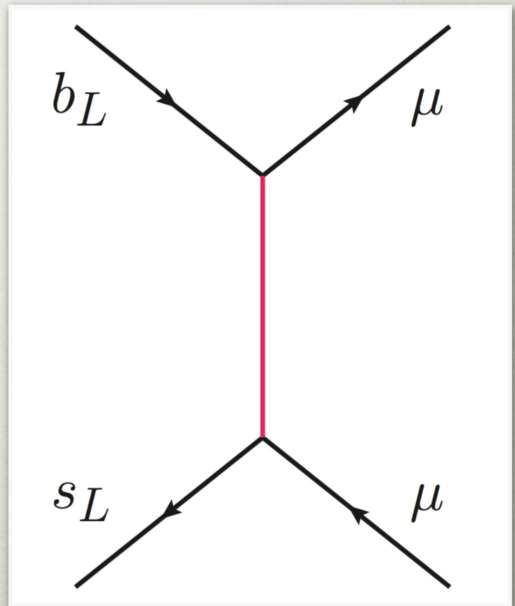
TREE LEVEL

- 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

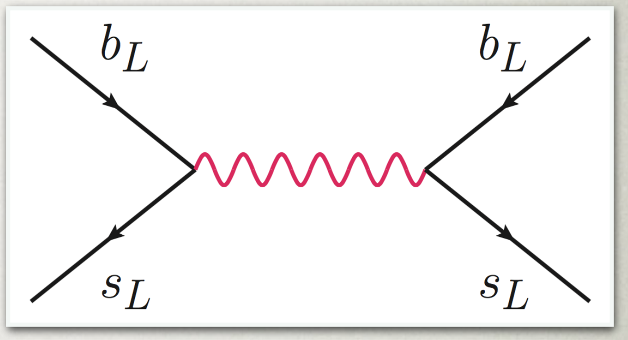


see, e.g., Hiller, Nisandzic, 1704.05444;
Hiller, Schmaltz, 1411.4773; +many refs

GENERAL CONSIDERATIONS ABOUT Z'

- nontrivial constraint from B_s mixing

Altmannshofer, Straub, 1308.1501; 1411.3161



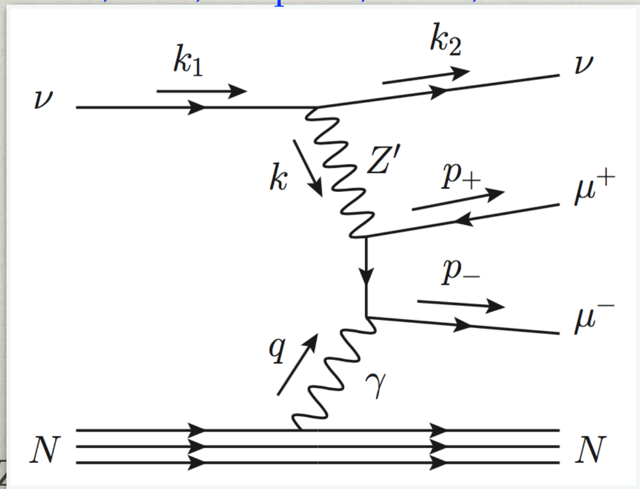
$$\frac{g_{bsZ'}}{m_{Z'}} \lesssim \frac{0.01}{2.5\ \mathrm{TeV}}$$

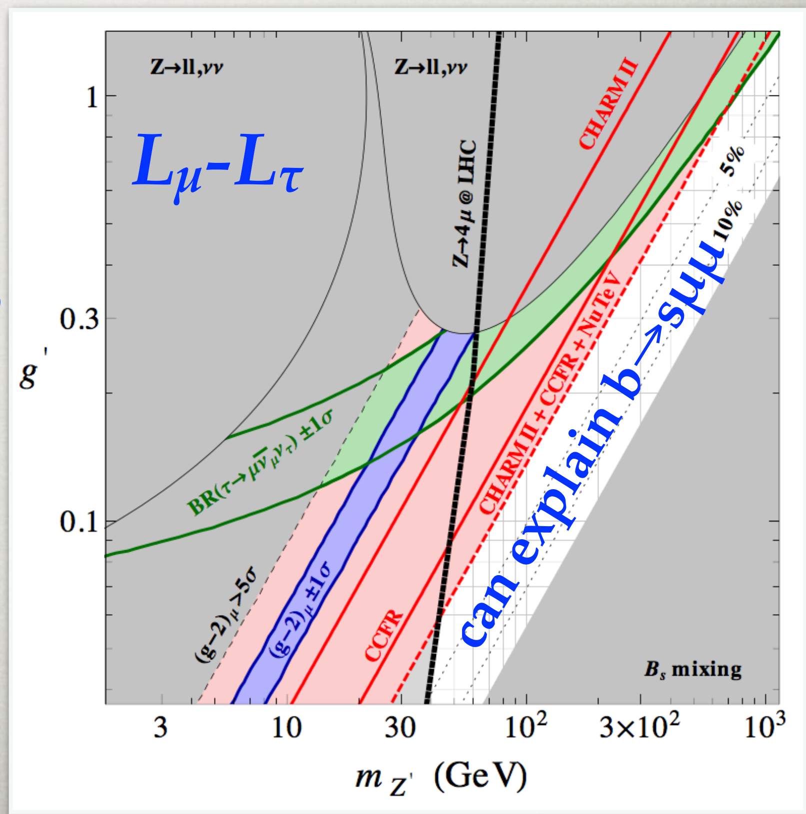
compare: $V_{ts} \simeq 0.04$

- 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

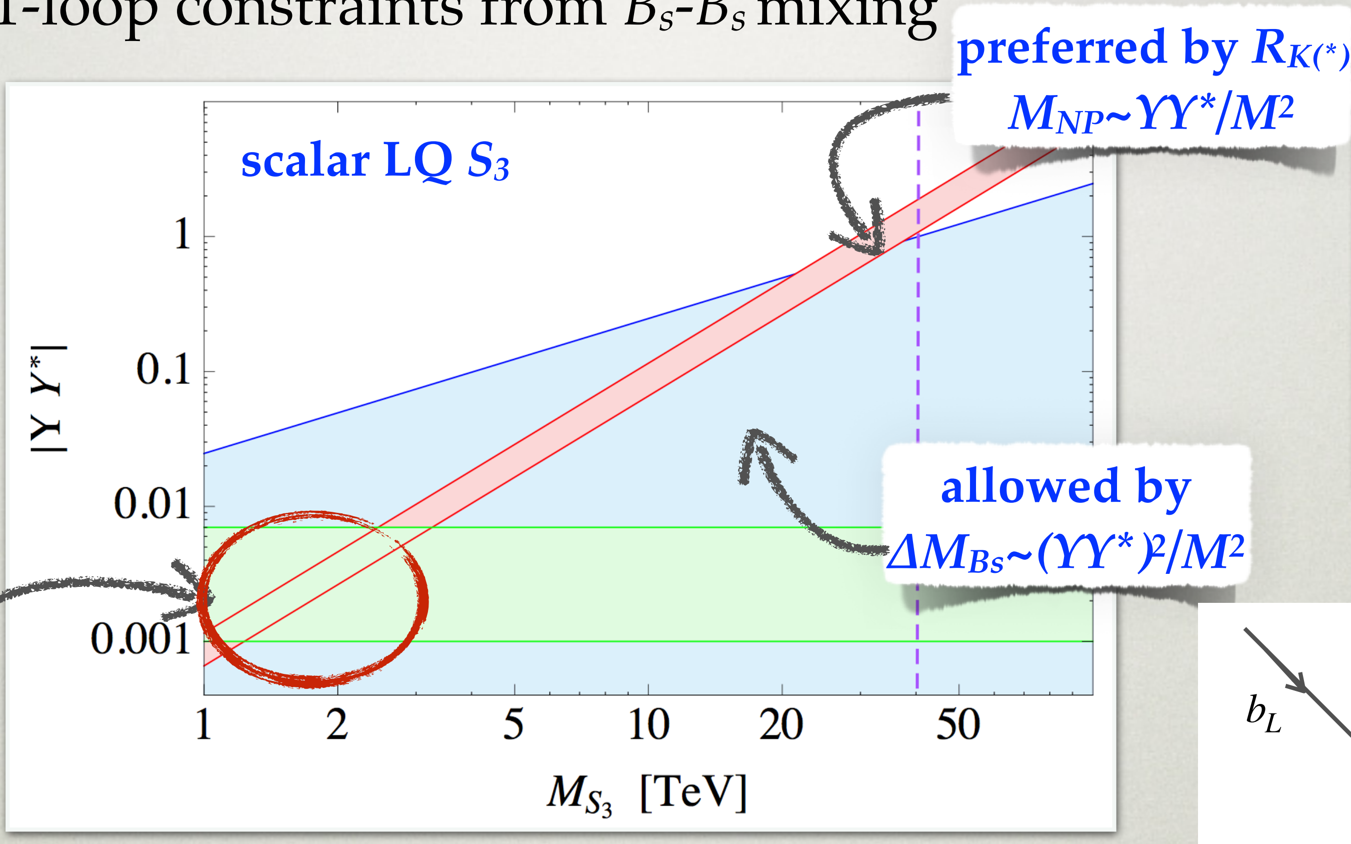




LEPTOQUARKS

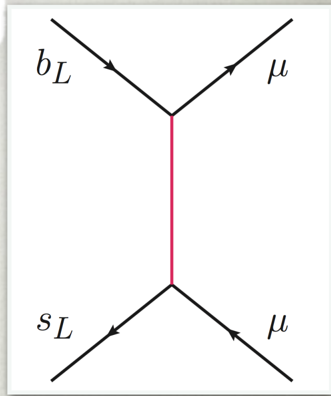
Hiller, Nisandzic, 1704.05444

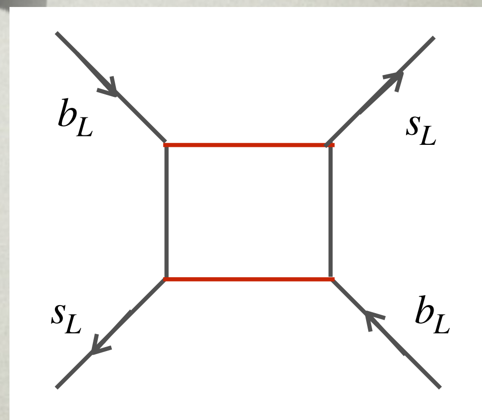
- at 1-loop constraints from B_s-$\bar{B}_s$ mixing



preferred by flavor models

Hiller et al, 1503.01084





- 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

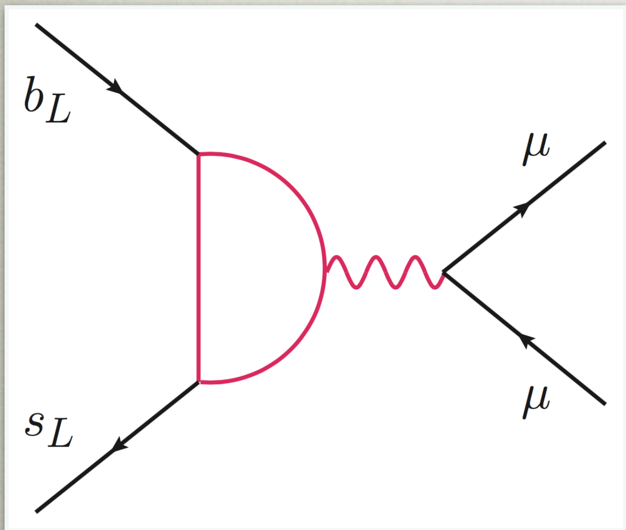
Gripaios, Nardecchia, Renner, 1412.1791; Gripaios, 0910.1789; Alonso et al, 1505.05164; Barbieri et al, 1512.01560, 1611.04930

LOOP LEVEL

in general in tension with direct searches

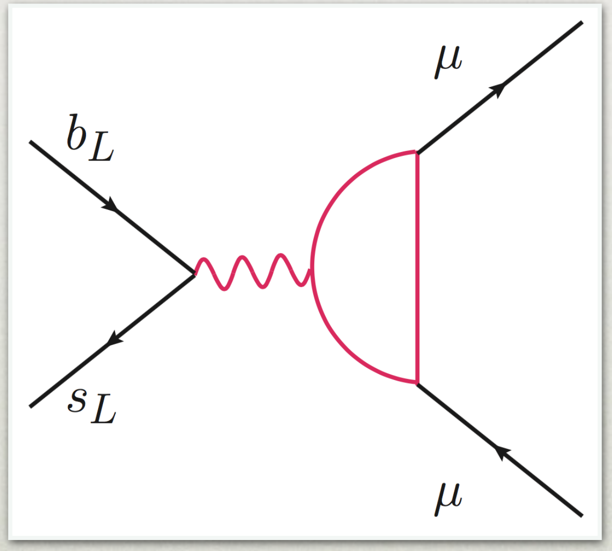
- three distinct options

- Z' w/ loop to bs



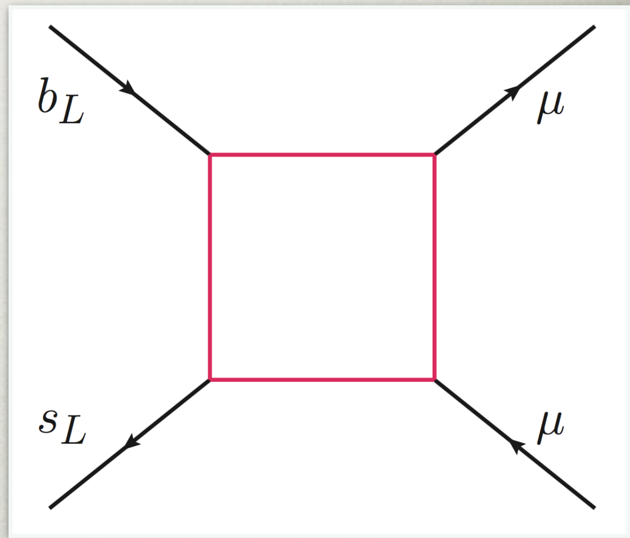
Kamenik, Soreq, JZ, 1704.06005

- Z' w/ loop to $\mu\mu$



Bélanger, Delaunay, 1603.03333

- box w/ NP fields

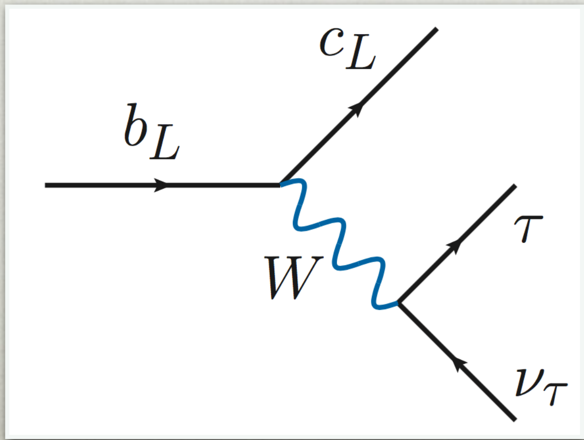


Gripaios, Nardecchia, Renner, 1509.05020; Bauer, Neubert, 1511.01900; Becirevic, Sumensari, 1704.05835

$b \to c\tau\nu$

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

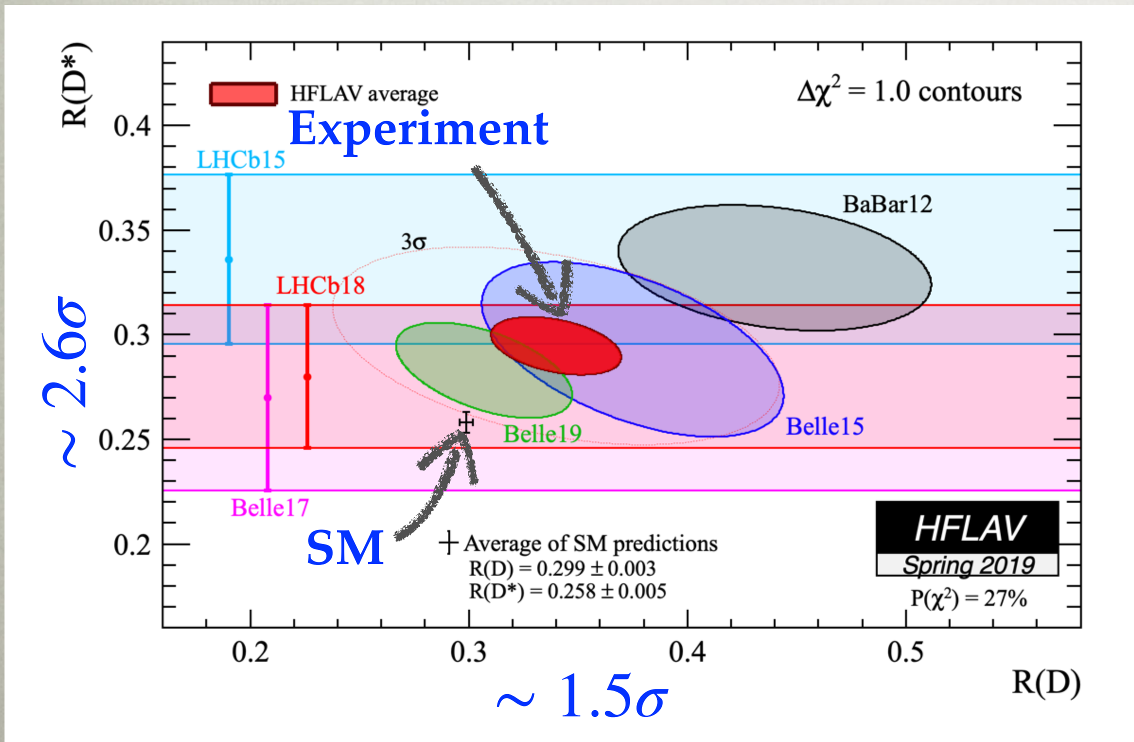


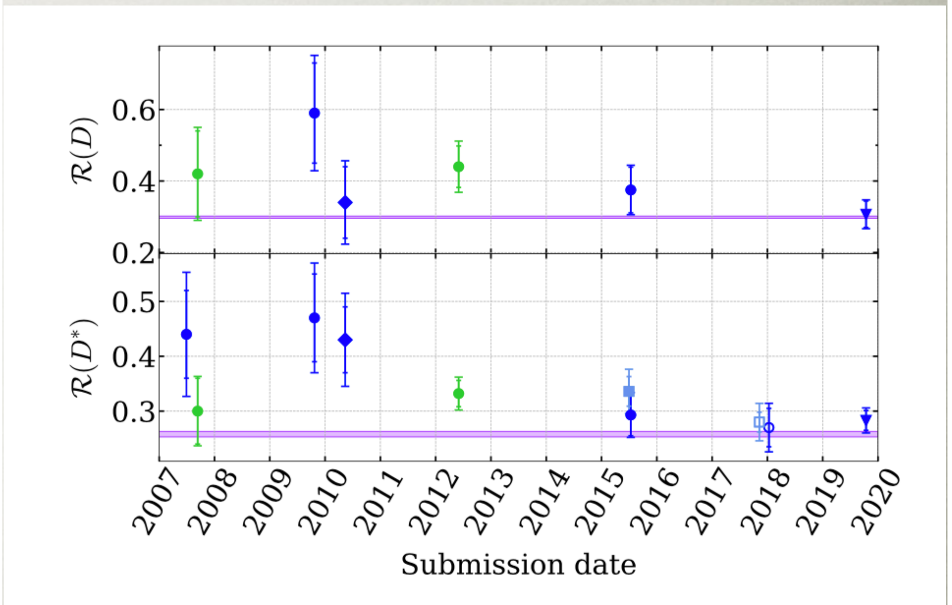
EXPERIMENTAL SITUATION

- 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

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



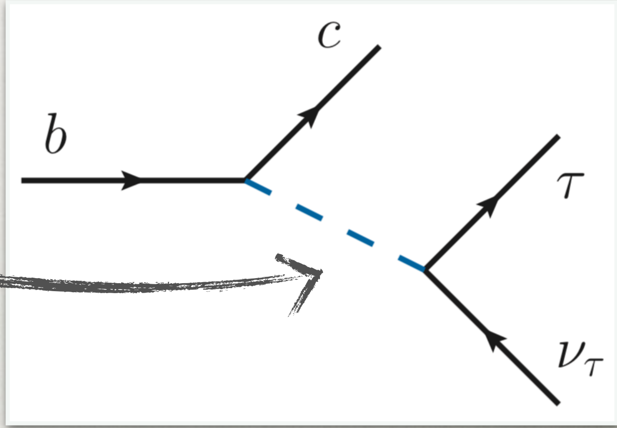


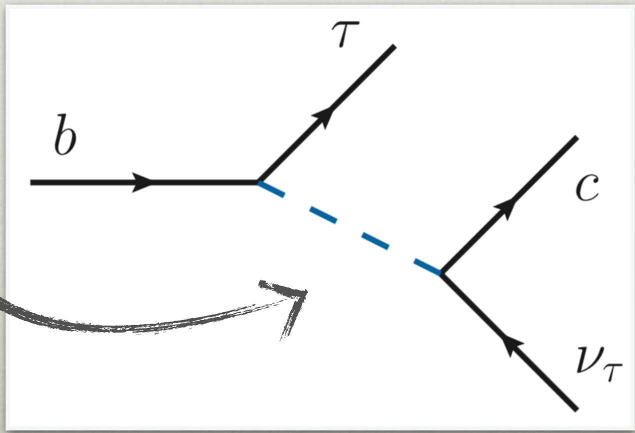
MODELS WITH SM NEUTRINO

Freytsis, Ligeti, Ruderman, 1506.08896

Faroughy, Greljo, Kamenik, 1609.07138

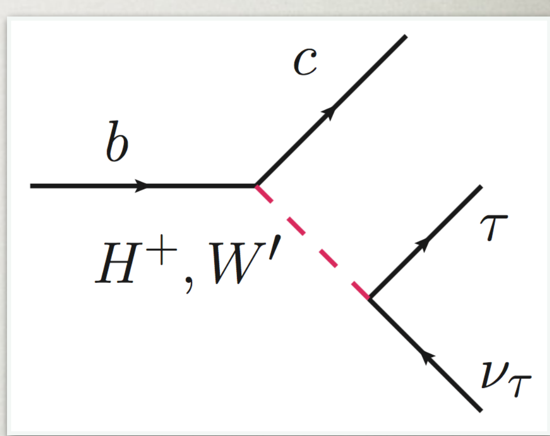
- big effect, needs to be tree level
- two types of exchanges
  - color singlet (W', H^+)
  - color octet (leptoquarks)

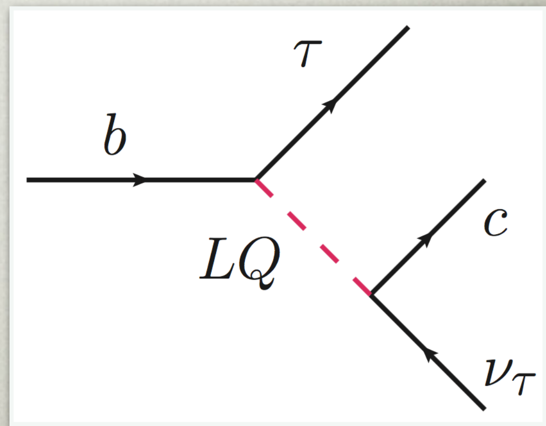




NEW PHYSICS INTERPRETATIONS

- the most obvious candidates ruled out
  - charged Higgs: total B_c lifetime, $b \to c\tau\nu$ 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





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 $(g-2)_\mu$

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

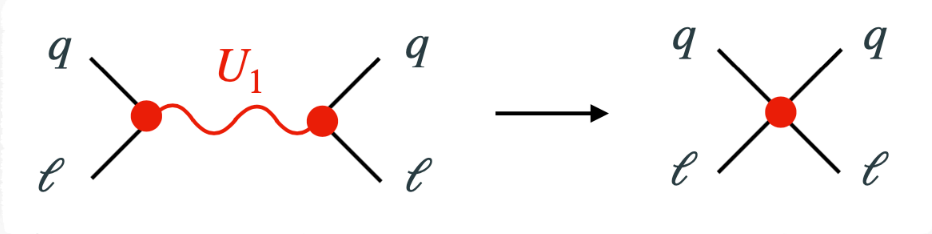
figure credits, talk by Fuentes Moriond 2021

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

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

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

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

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

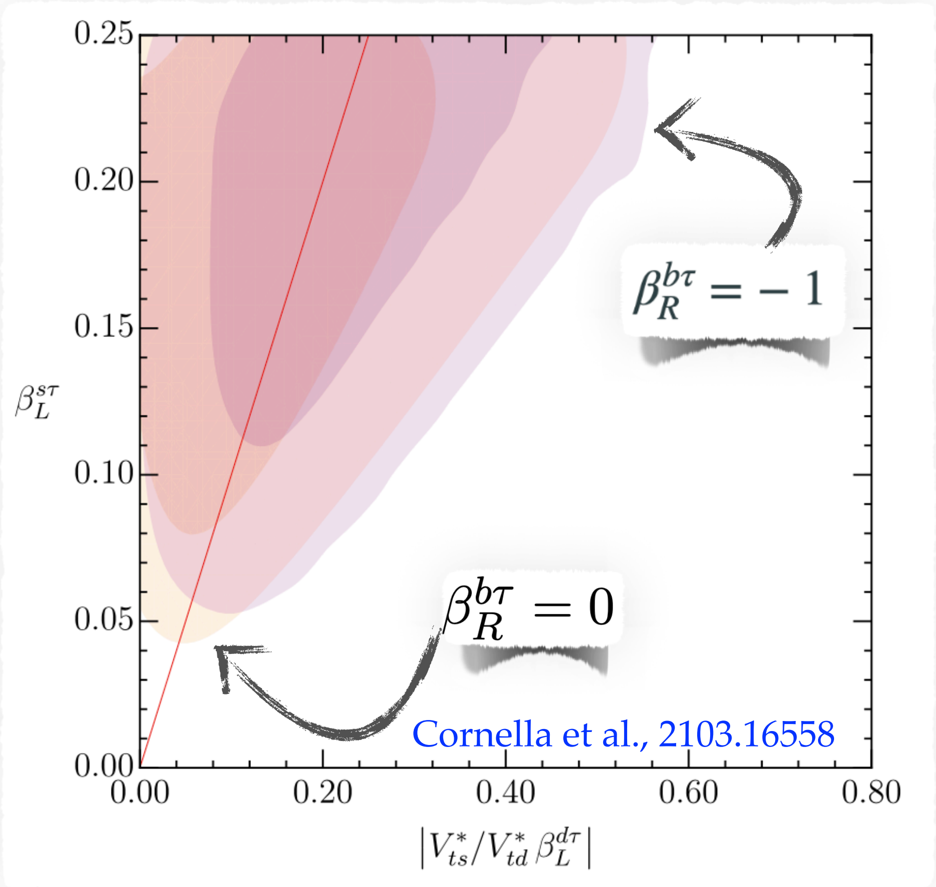
figure credits, talk by Fuentes Moriond 2021

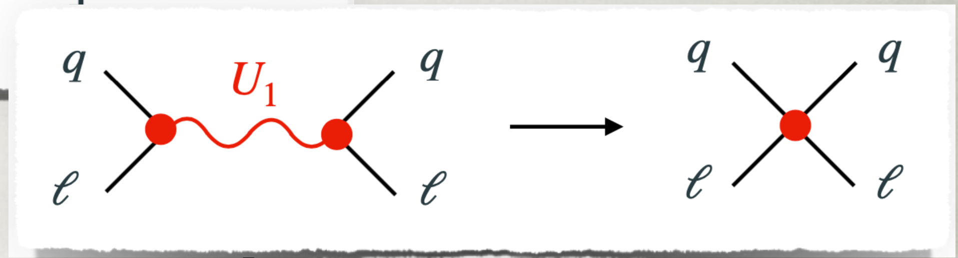
VECTOR LEPTOQUARK U_1 FOR $R_{K^{(*)}}$ AND $R_{D^{(*)}}$

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

Cornella et al., 2103.16558+many refs

$$(\bar{d}_R^i \gamma_\mu e_R^\alpha)\Big] + \mathrm{h.c.}$$





cture assumed

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

a for U_1 as well

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

$U(2)_\ell$

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

$U(2)_e$

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

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

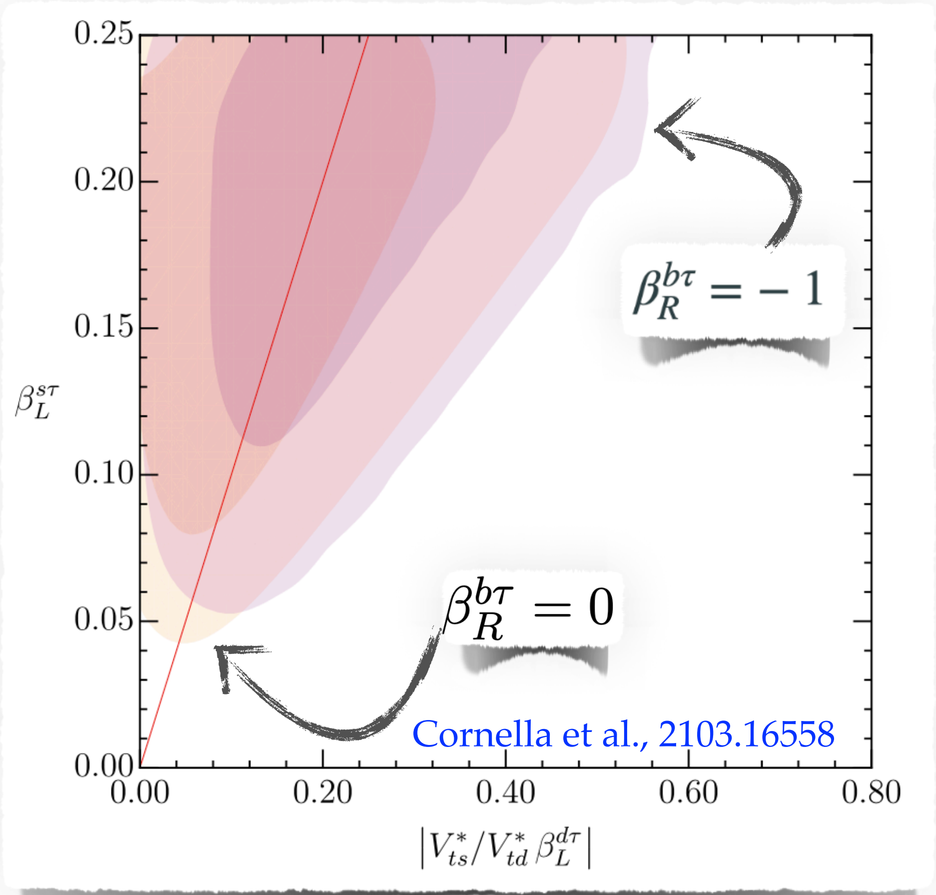
$(\bar{d}^i_R \gamma_\mu e^\alpha_R$

ture as

a for U

Y_e =

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



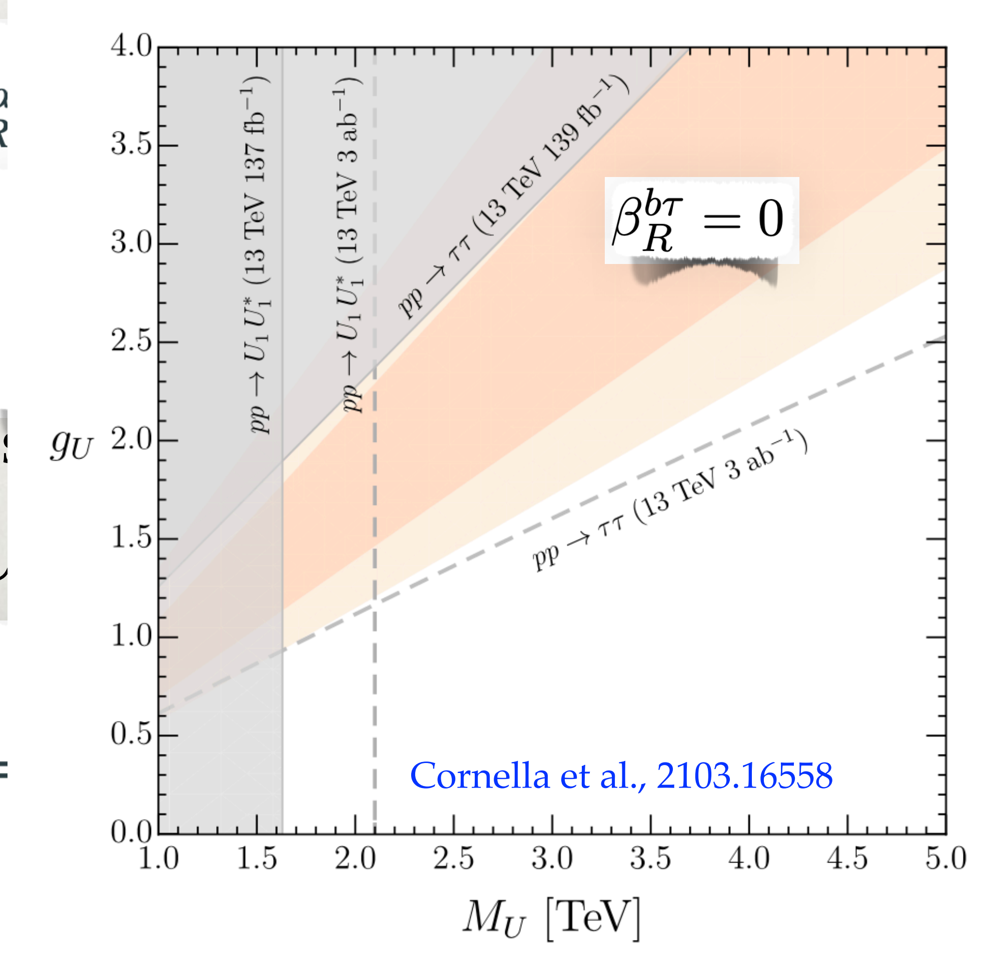
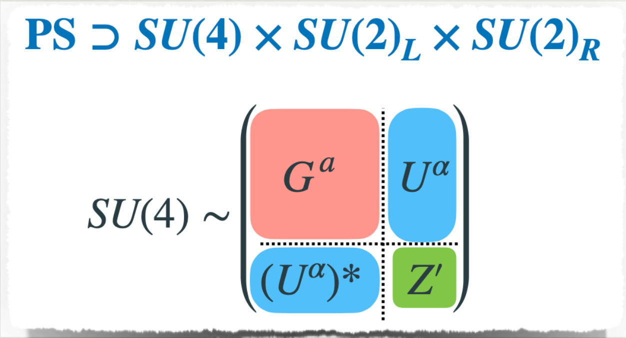


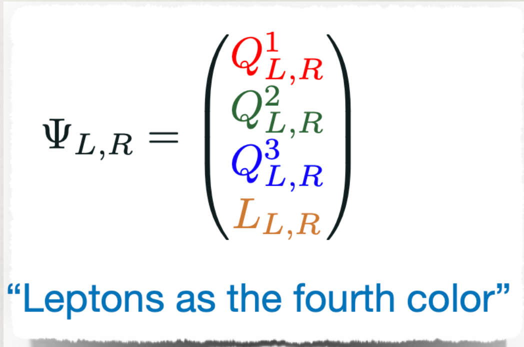
figure credits, talk by Fuentes Moriond 2021

4321 model

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

- U_1 gauge boson arises in Pati-Salam unification

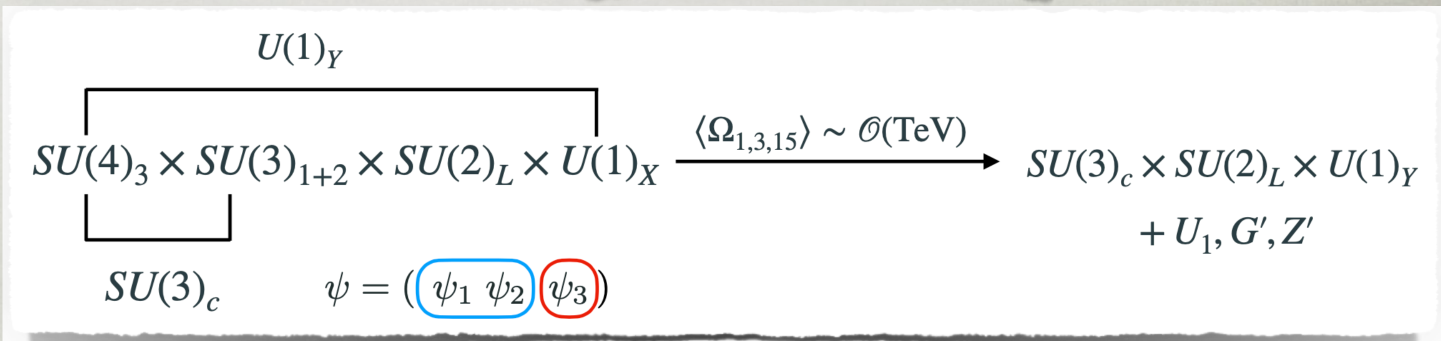




- 4321 model

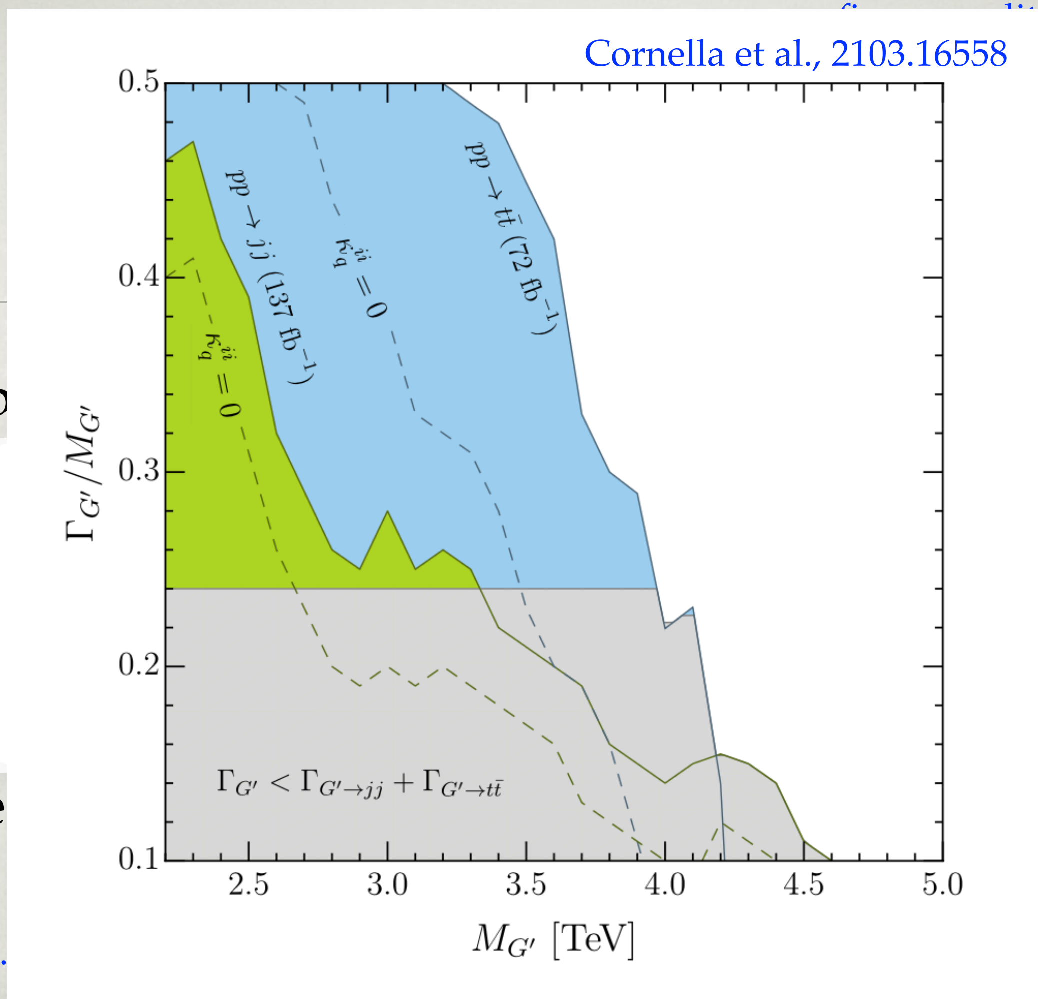
Di Luzio et al, 1708.08450

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 $M_U > 100$ TeV
- 3rd generation gauged under SU(4)
- additional states: G', Z'

...s, talk by Fuentes Moriond 2021



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

- U_1 gauge b...

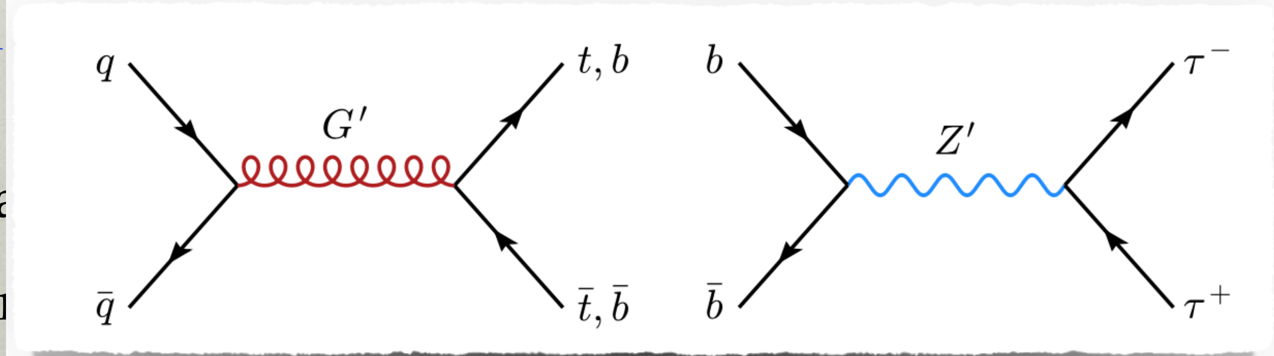
...h color"

- 4321 mode...

Di Luzio et al, 1708.08450

Bordone et al, 1712.01368, 1805....
Greljo, Stefanek, 1802.04274:
Cornella et al, 1903.1...

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



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

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,

CONCLUSIONS

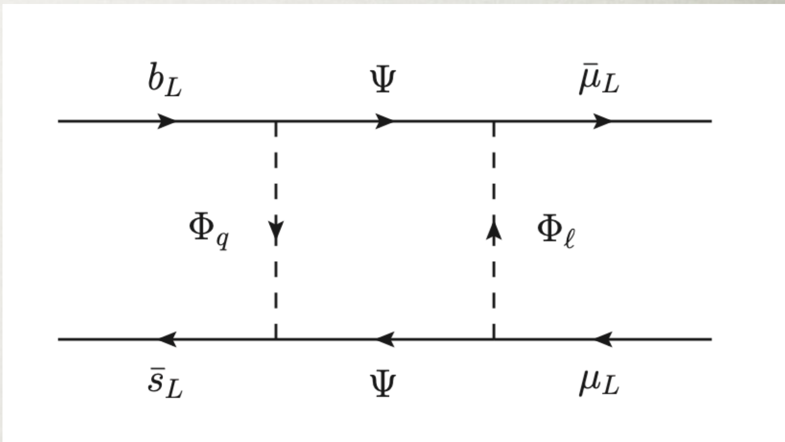
- FCNCs very sensitive probes of new physics
- growing tensions in $(g-2)_\mu$, $R_{K^{(*)}}$
  - evidence of new physics?

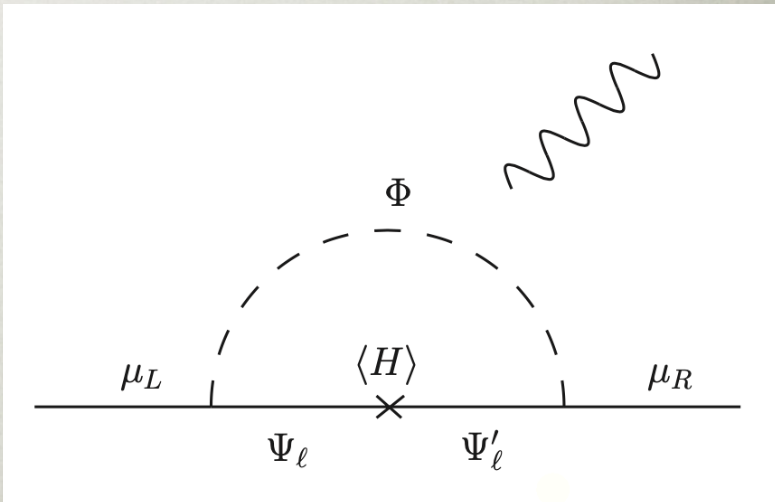
BACKUP SLIDES

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



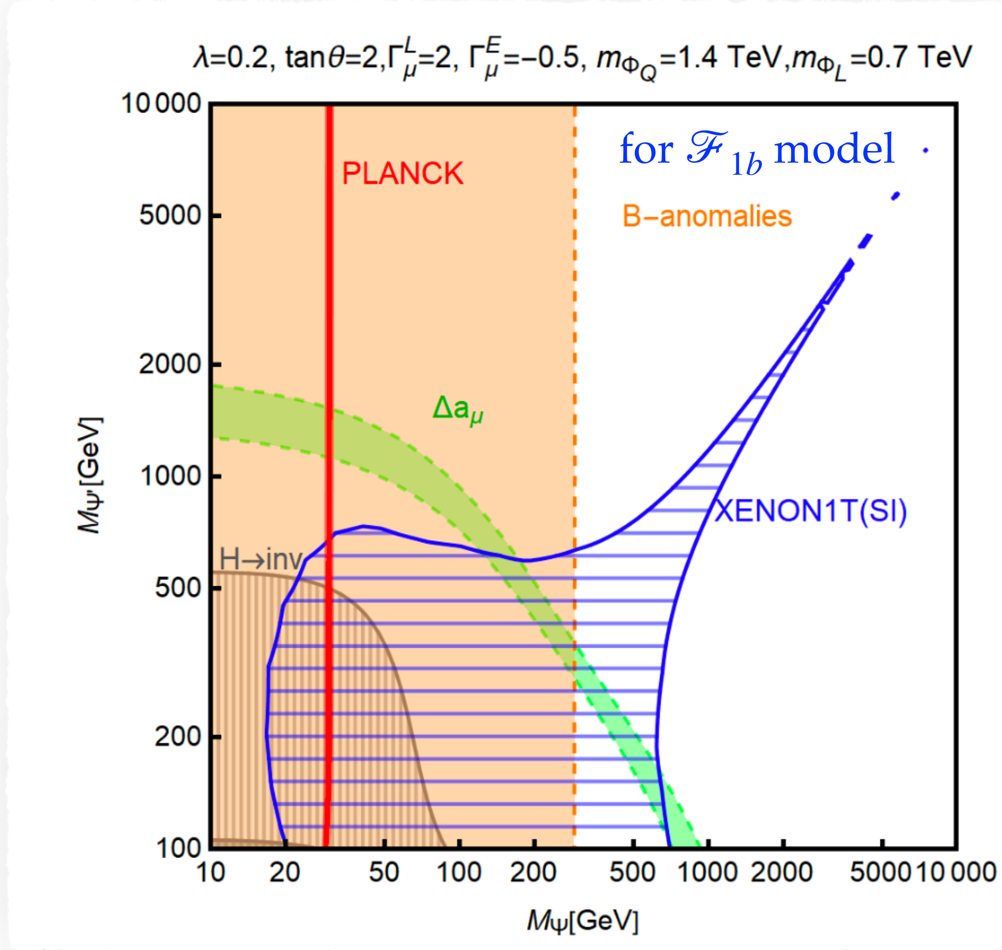


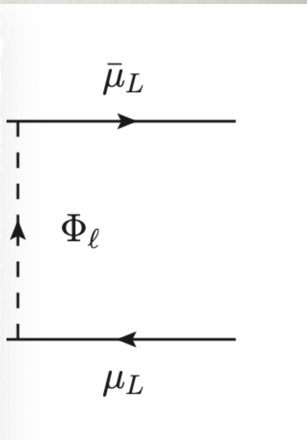
Label	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ'_ℓ/Ψ'_ℓ	Ψ'/Φ'
$\mathcal{F}_{\rm Ia}/\mathcal{S}_{\rm Ia}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{1},-1)$	–
$\mathcal{F}_{\rm Ib}/\mathcal{S}_{\rm Ib}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$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

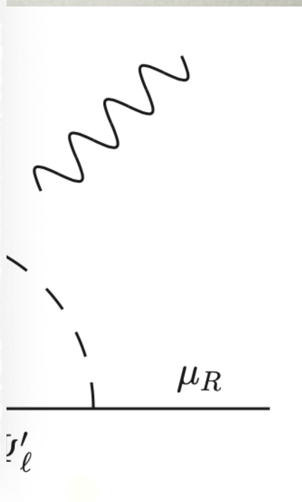
SIMPLIFIED DM MODELS FOR $R_{K^{(*)}}$ AND $(g-2)_\mu$

Arcadi, Calibbi, Fedele, Mescia, 2104.03228

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





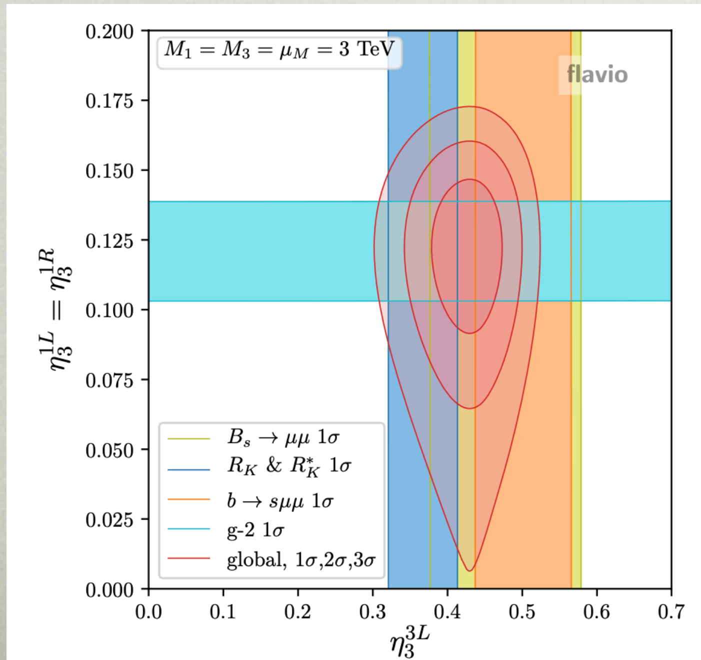


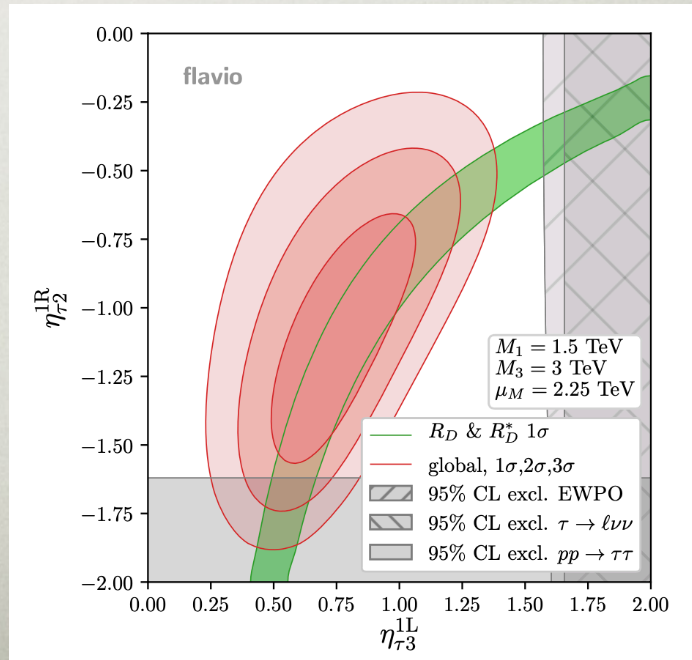
Label	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ		
$\mathcal{F}_{\rm Ia}/\mathcal{S}_{\rm Ia}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$		
$\mathcal{F}_{\rm Ib}/\mathcal{S}_{\rm Ib}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$		
$\mathcal{F}_{\rm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

S_1 AND S_3 LEPTOQUARKS
$R_{K^{(*)}}$ 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

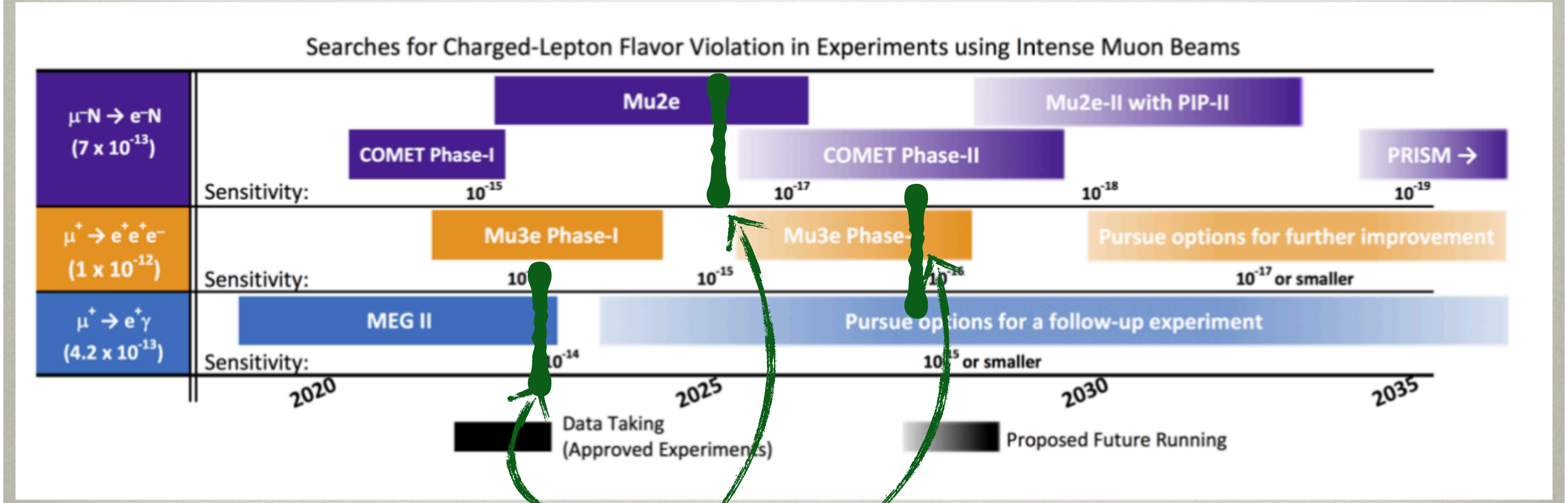




EXPERIMENTAL PROGRESS

Physics Briefing Book, 1910.11775

- further orders of magnitude experimental progress expected in CLFV transitions

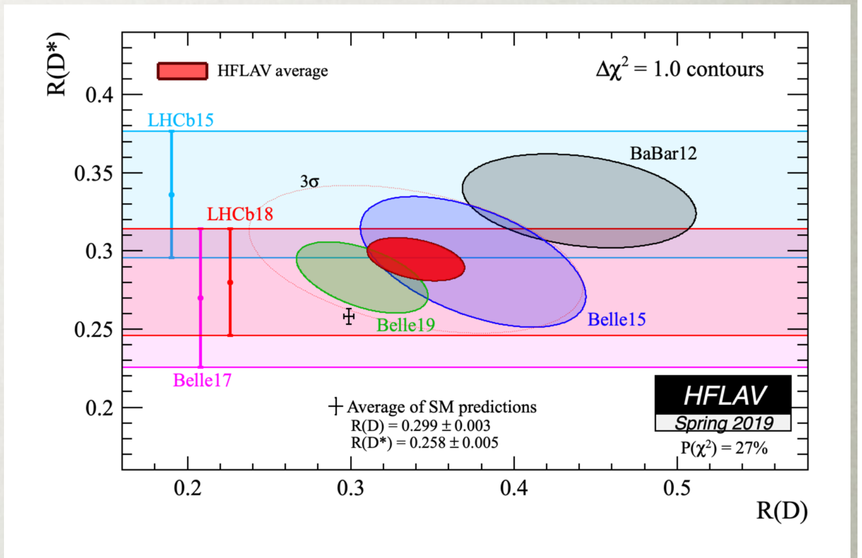


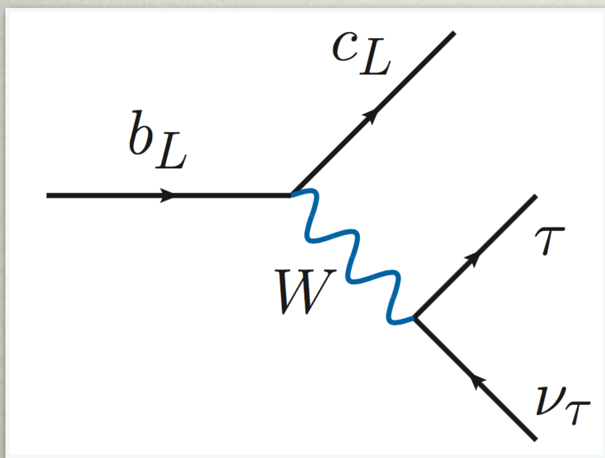
assumed sensitivies in the previous slide

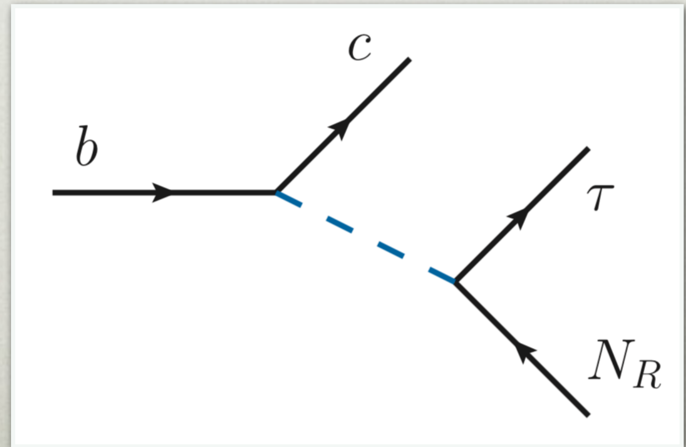
MODELS WITH RIGHT HANDED NEUTRINO

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

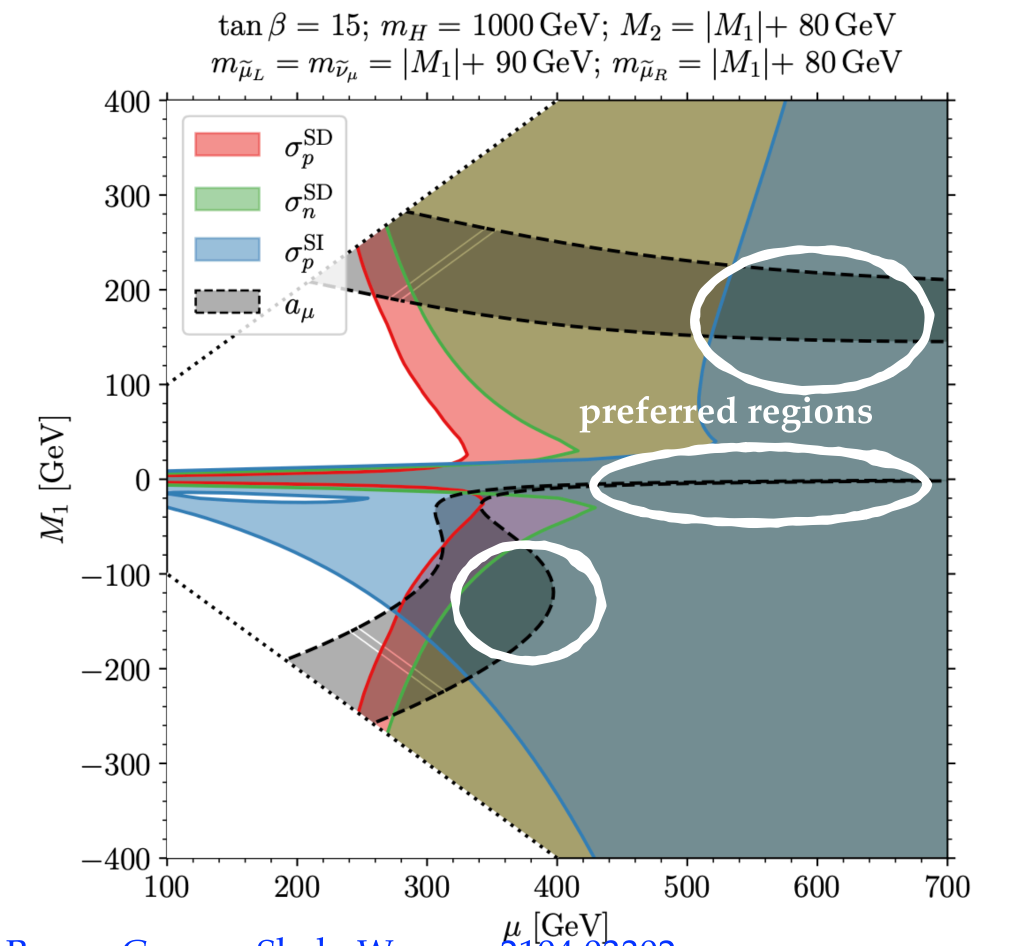






SUSY?

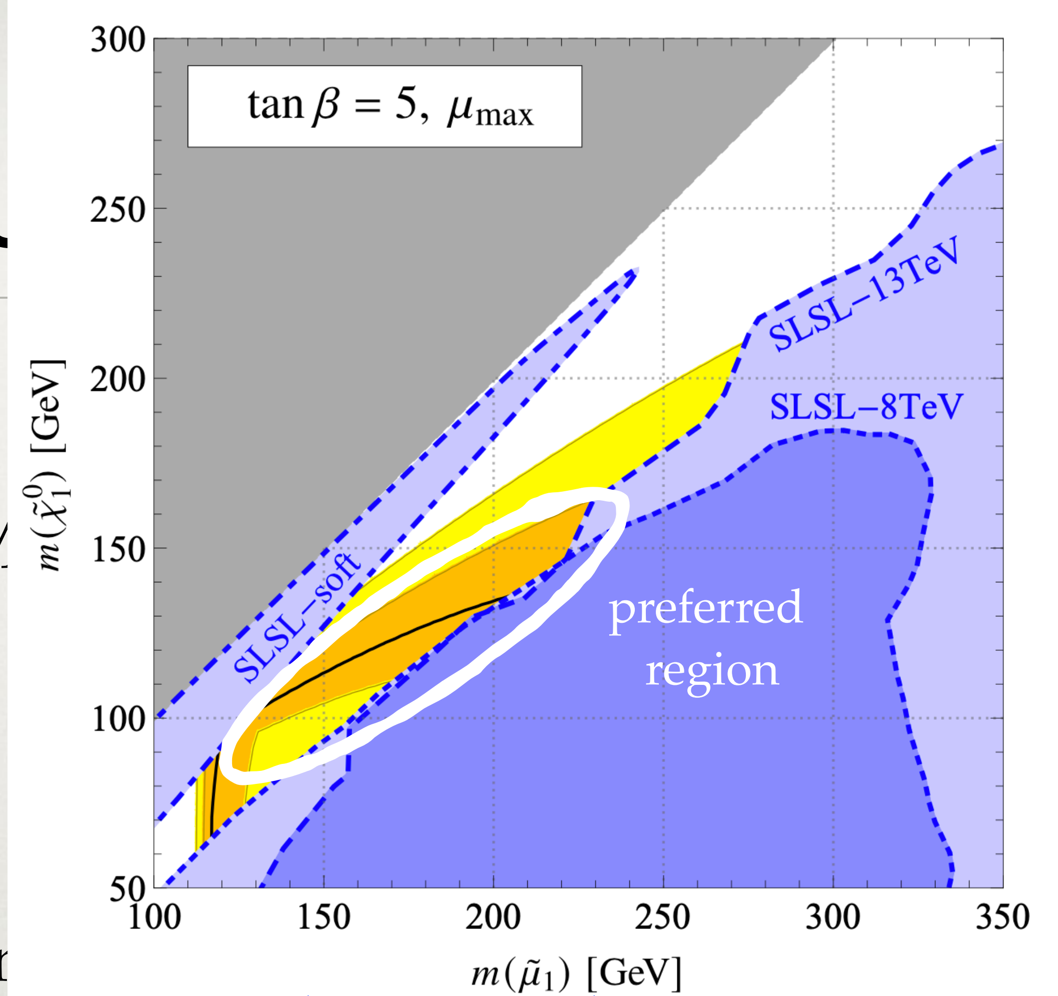
- a_μ via chargino-sneutrino and neutralino-smuon loops
- bino-like neutralino is DM
- requires cancellations in DM direct detection xsec
  - "blind spot": h and H exch. with opposite signs
- can evade LHC constraints in the soft region



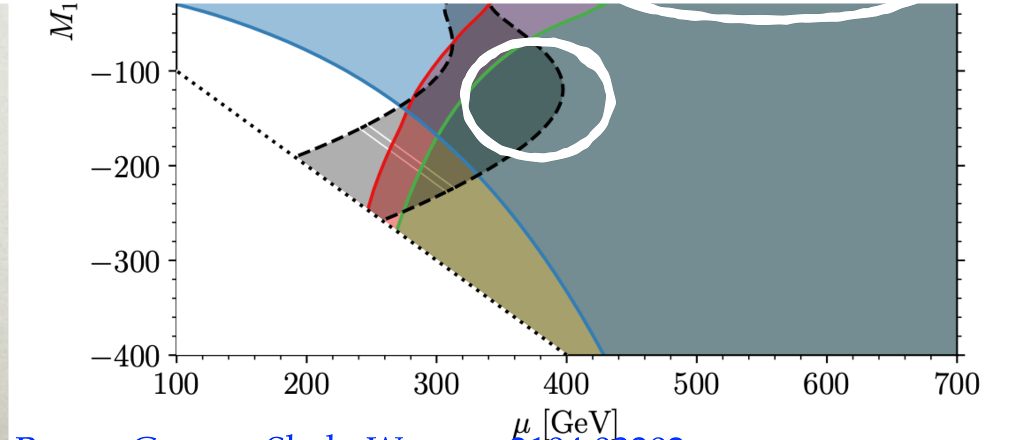
Baum, Carena, Shah, Wagner, 2104.03302

SU

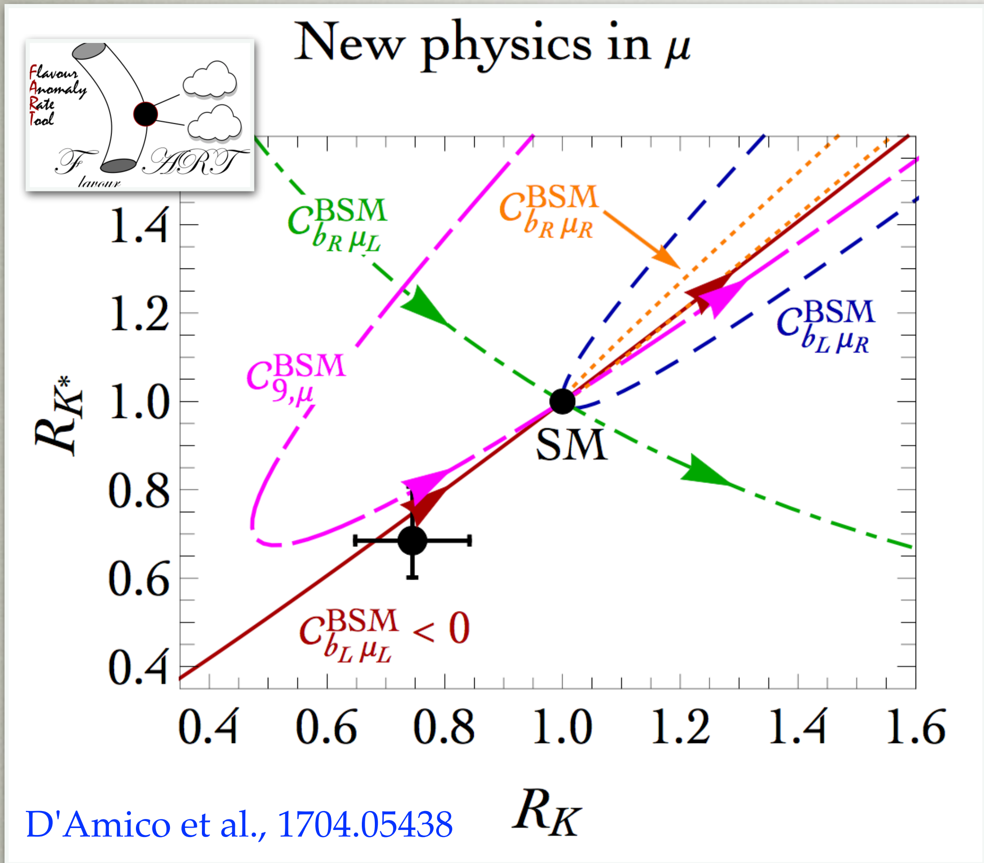
- a_μ via chargino-sneutrino
- bino-like neutralino is DM
- requires cancellations in DM direct detection xsec
    - "blind spot": h and H exch. with opposite sign
- can evade LHC constraints in the soft region

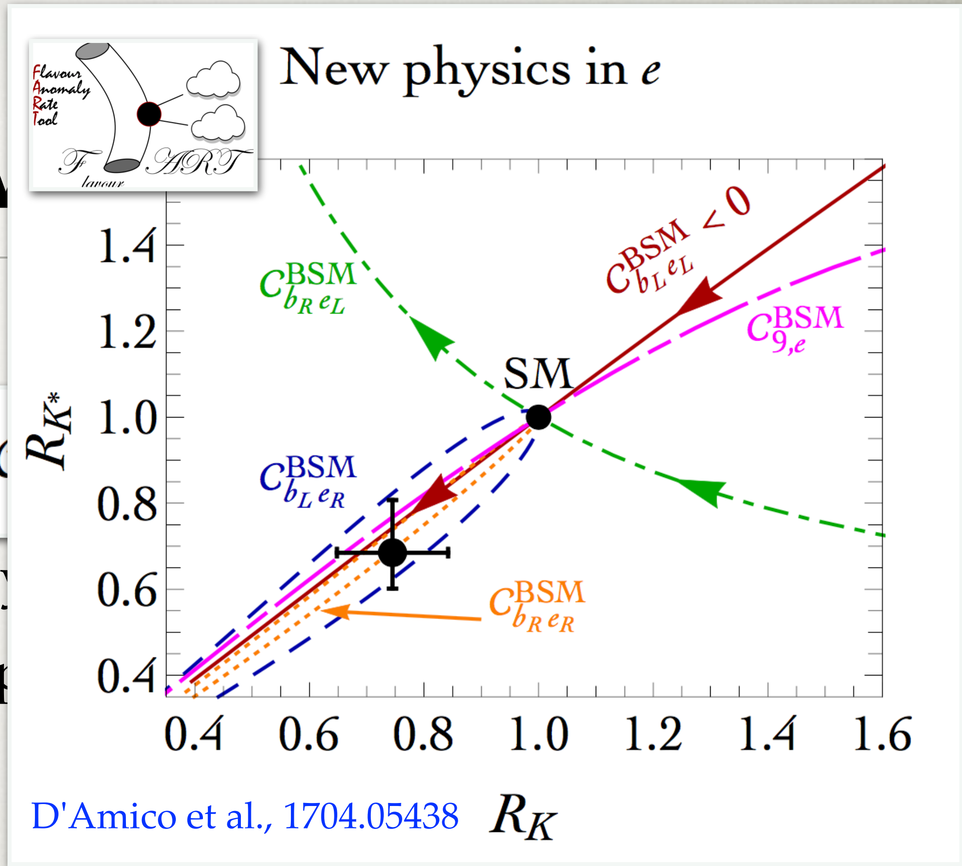


Endo, Hamaguchi, Iwamoto, Kitahara, 2104.03217



Baum, Carena, Shah, Wagner, 2104.03302





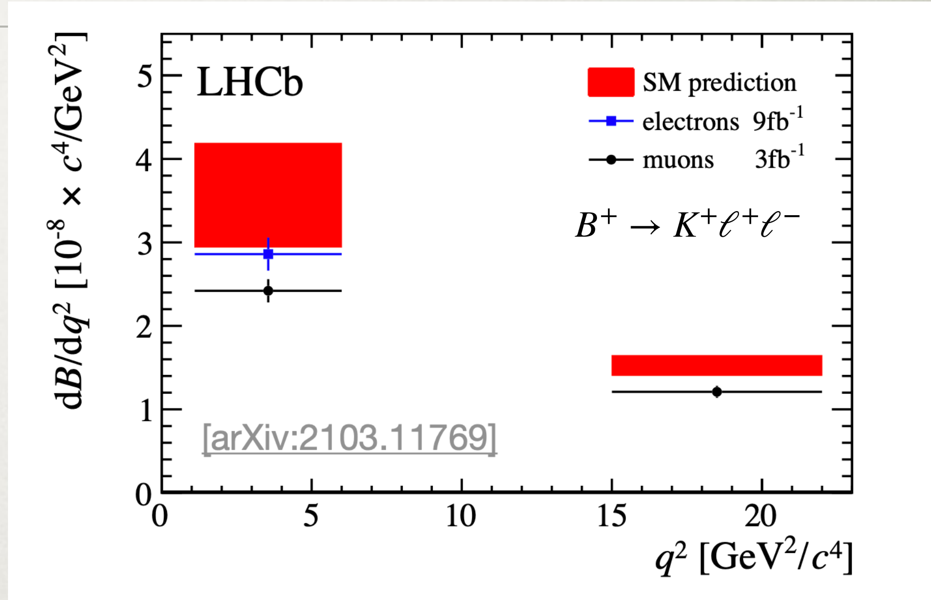
see, e.g., D'Amico et al., 1704.05438

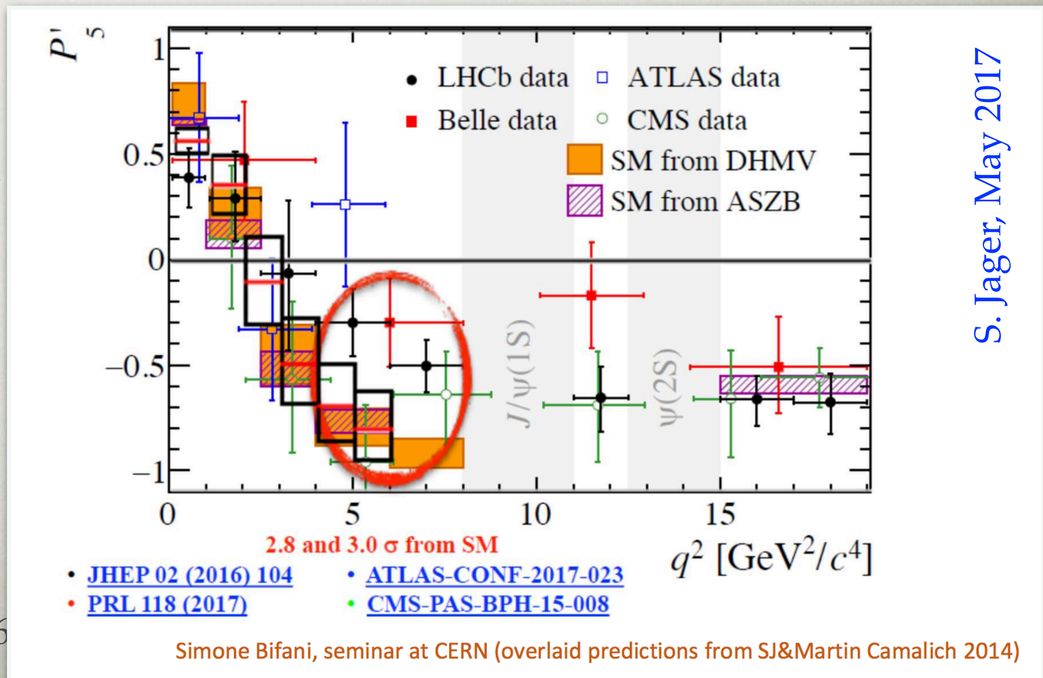
- from ratios: NP can be either in muons or electrons
  - in both cases $(\bar{s}b)_L$ ok
  - for electrons also $(\bar{s}b)_R(\bar{e}e)_R$ possible (from quadratic dep.)
- combined signif. from "clean" observables >4σ

Altmannshofer, Stangl, Straub, 1704.05435; D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano, 1704.05438; Capdevila, Crivellin, Descotes-Genon, Matias, Virto, 1704.05340; Hiller, Nisandzic, 1704.05444; Geng, Grinstein, Jager, Martin Camalich, Ren, Shi, 1704.05446; Chobanova, Hurth, Mahmoudi, Neshatpour, Santos, 1705.10730

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





GLOBAL

- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
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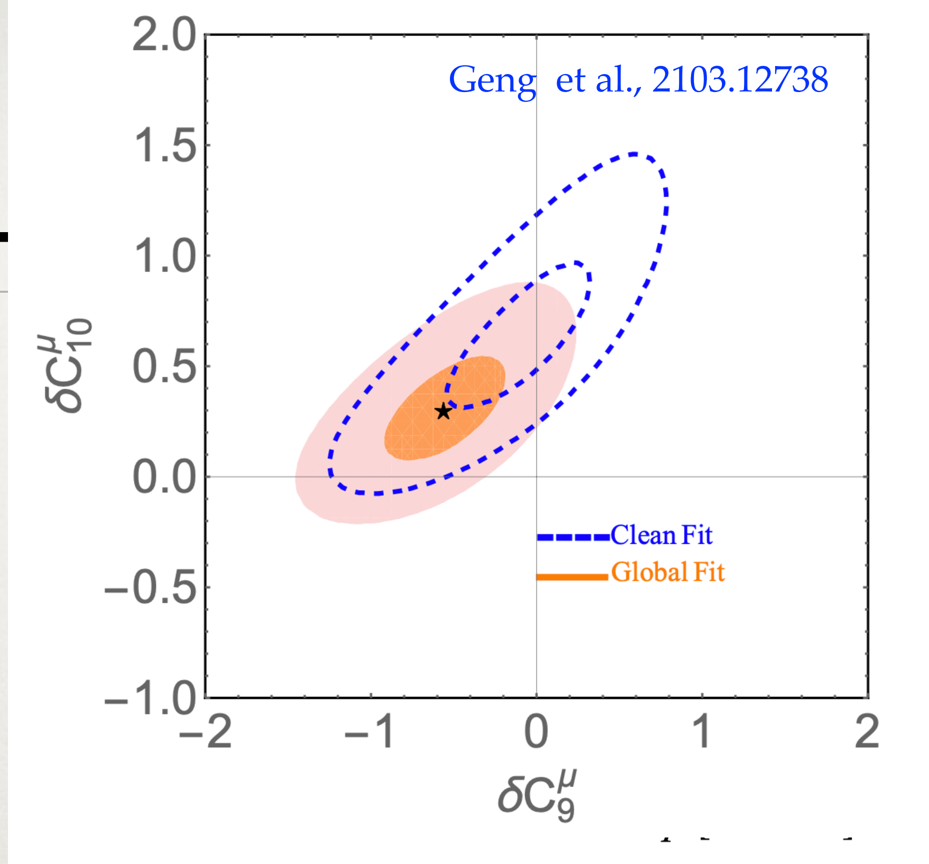
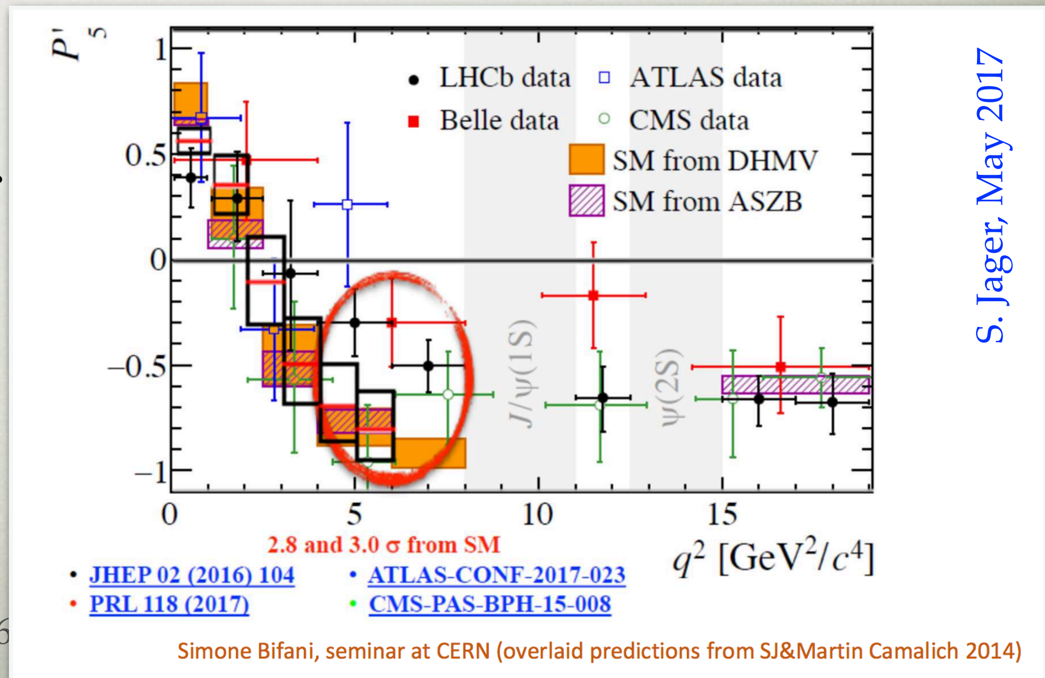
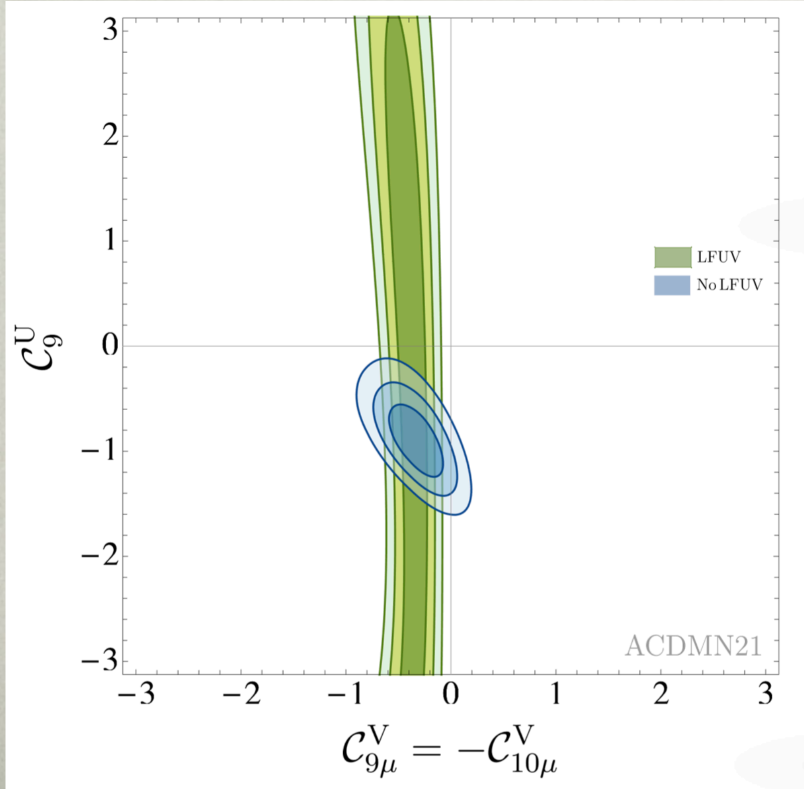




NP just in muons?

- 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

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

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

LEPTOQUARKS

Hiller, Nisandzic, 1704.05444

- 3 options if a single LQ dominates

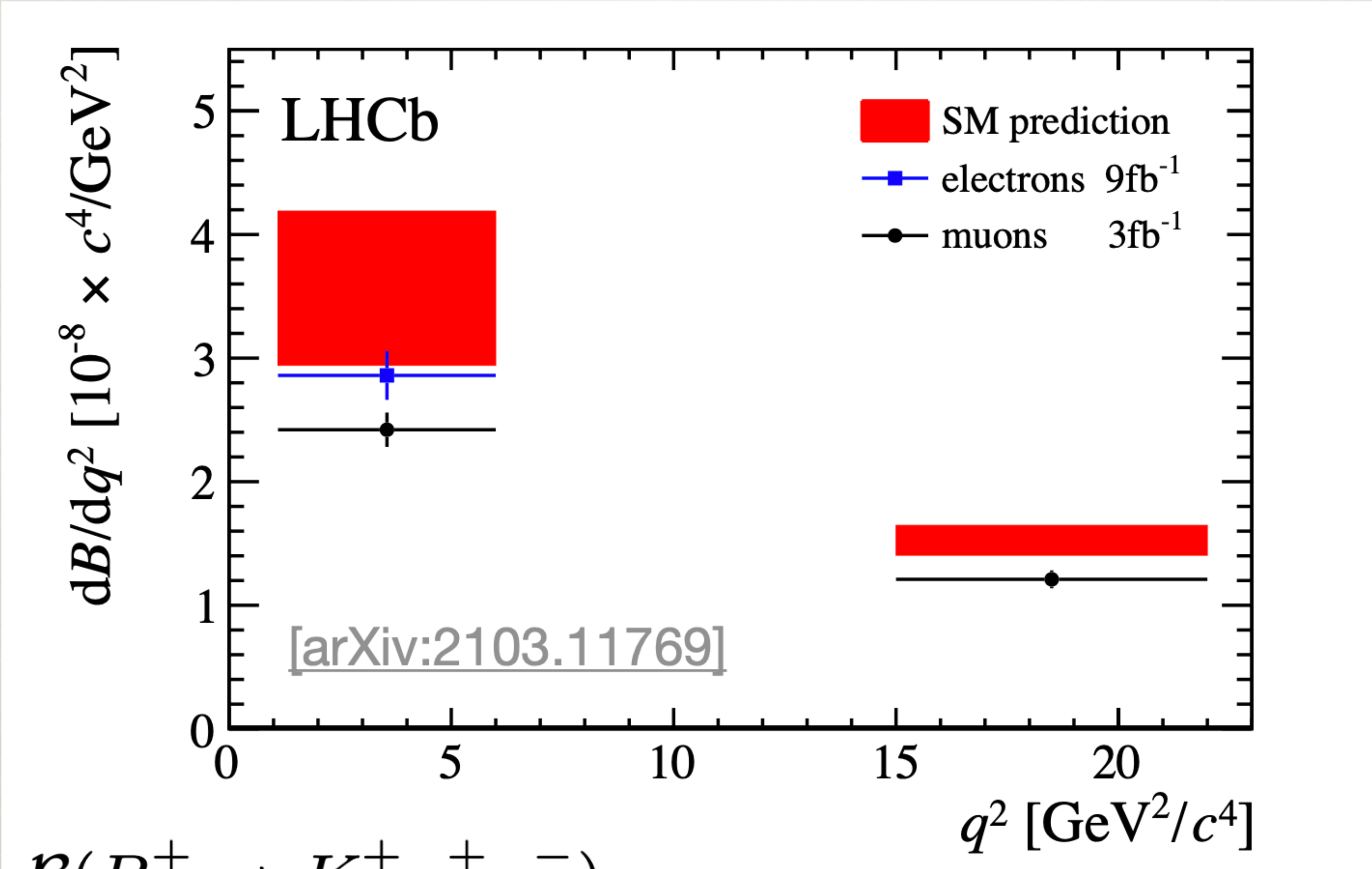
$SU(3)_C \times SU(2)_L \times U(1)_Y$

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	$(\bar{3}, 3, 1/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1.$
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	$(3, 1, 2/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$
		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	$(3, 3, -2/3)$	$C_{LL}^{\rm NP}$	$C_9 = -C_{10}$	$R_K \simeq R_{K^*} < 1$



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