Flavor Physics
theory - emphasis on LFUV in b-decays

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GRADUATE SCHOOL Physique

P2I
Physique des deux Infinis

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IJClab, Orsay, Bât. 200, Auditorium Pierre Lehmann

In the Standard Model

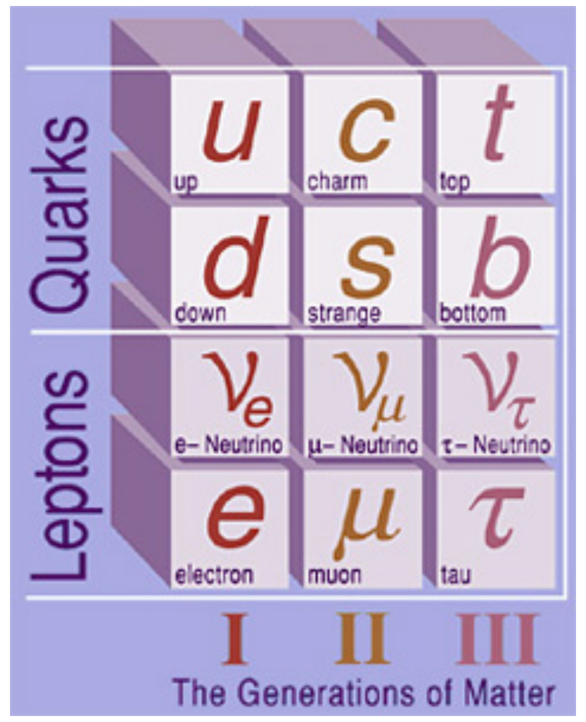
- ✗ Gauge sector entirely fixed by symmetry

$$i\bar{\psi}\not{D}\psi \qquad D_\mu = \partial_\mu - ig_s t_a A^a_\mu - ig\mathbf{T}\cdot\mathbf{W}_\mu - ig'\frac{Y}{2}B_\mu$$

- ✗ Flavor sector loose (a bunch of parameters)

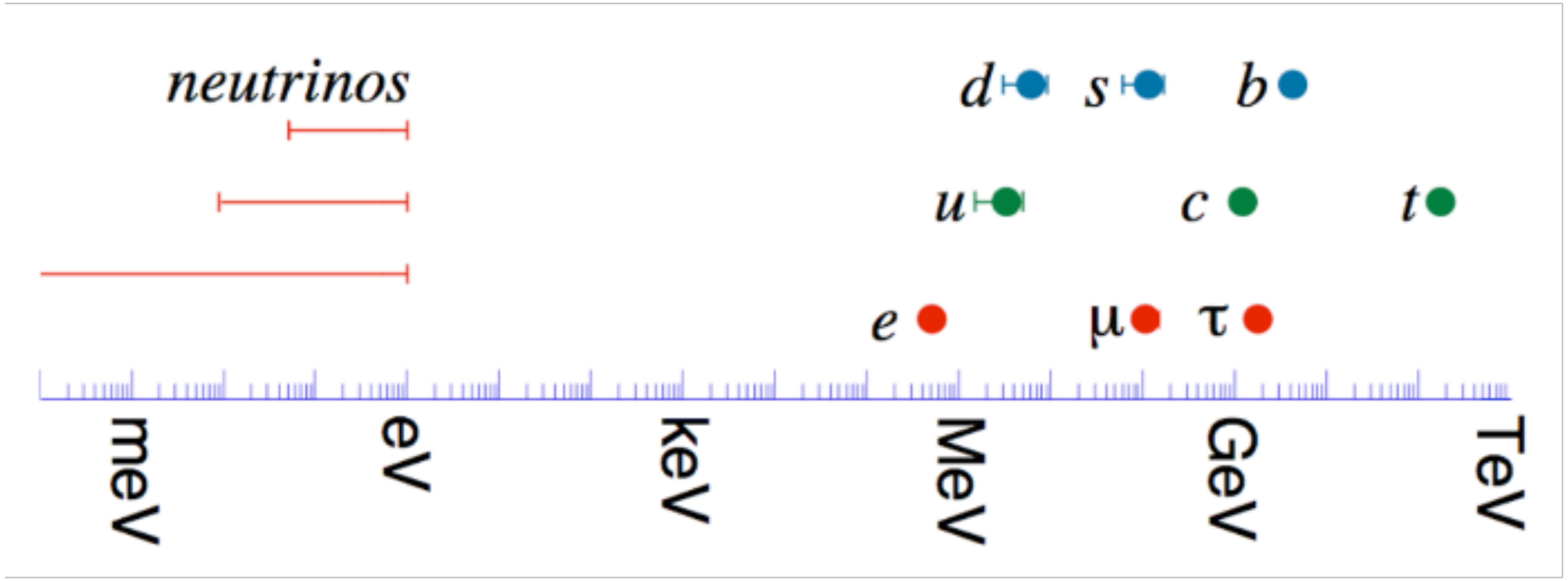
13 of 18 parameters are fermion masses and mixing parameters

$$-\sum_{i=1}^{3}\sum_{j=1}^{3}\left[y^u_{ij}\bar{u}_{Ri}\tilde{\Phi}^\dagger Q_{Lj} + y^d_{ij}\bar{d}_{Ri}\Phi^\dagger Q_{Lj}\right] + \text{h.c.}$$

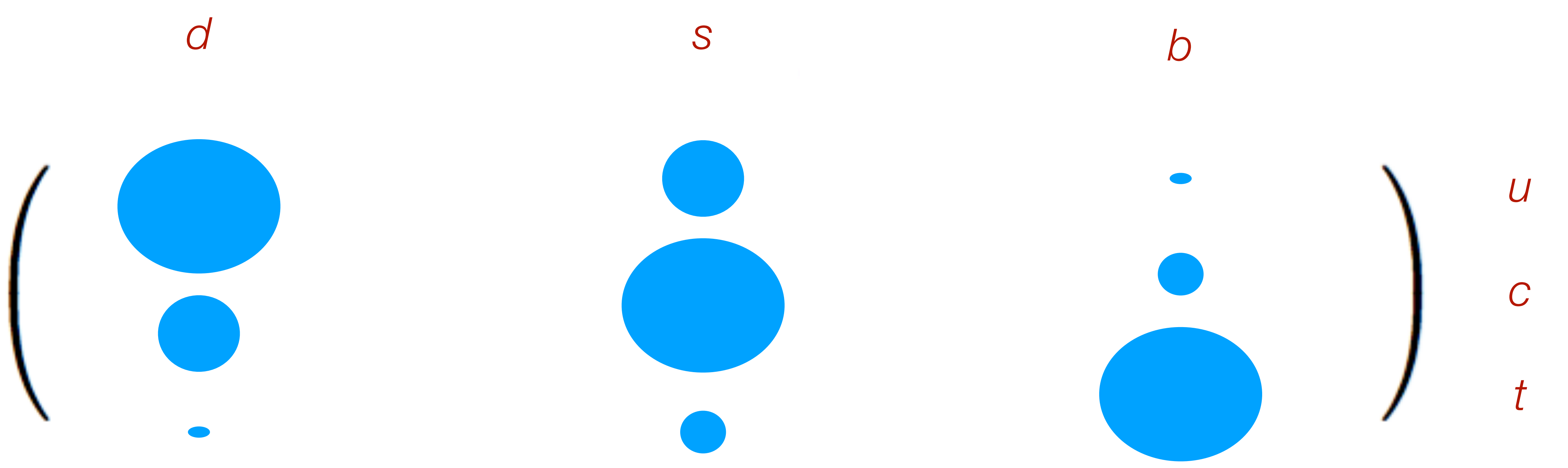


Flavor Physics

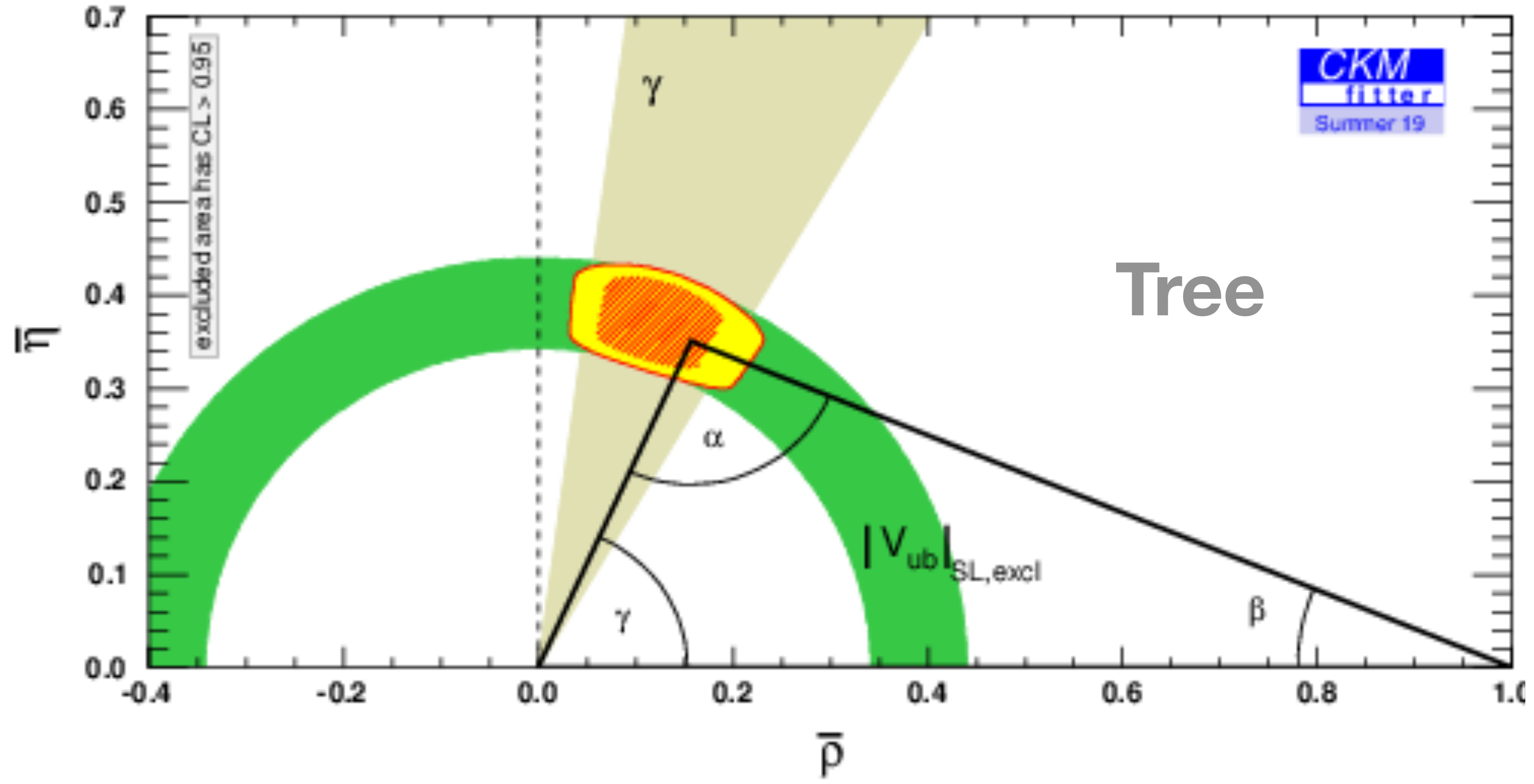
- ✘ Why three generations?
- ✘ Why such hierarchy of masses and mixing?
- ✘ Why so small CPV phase?

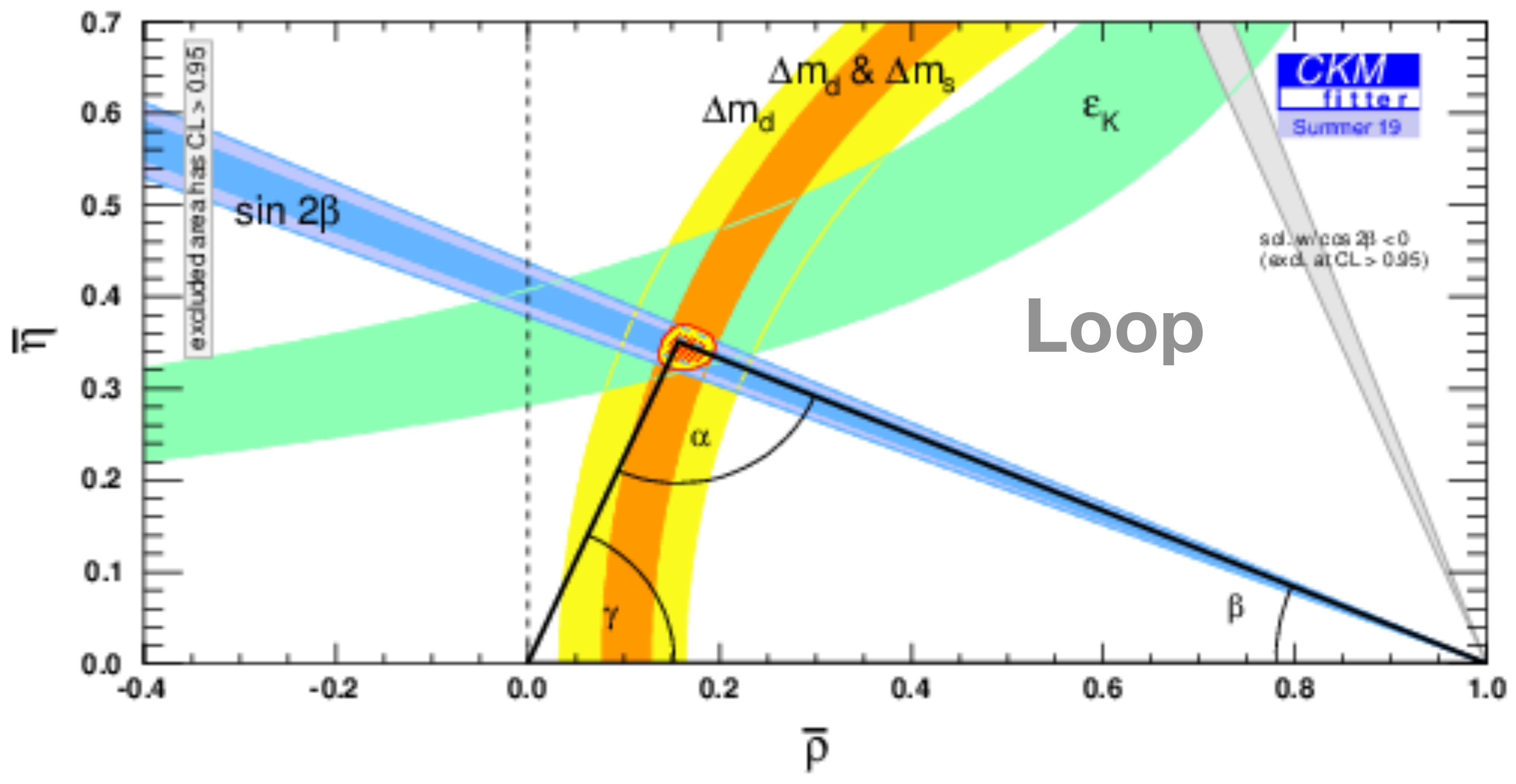


Quark Mixing

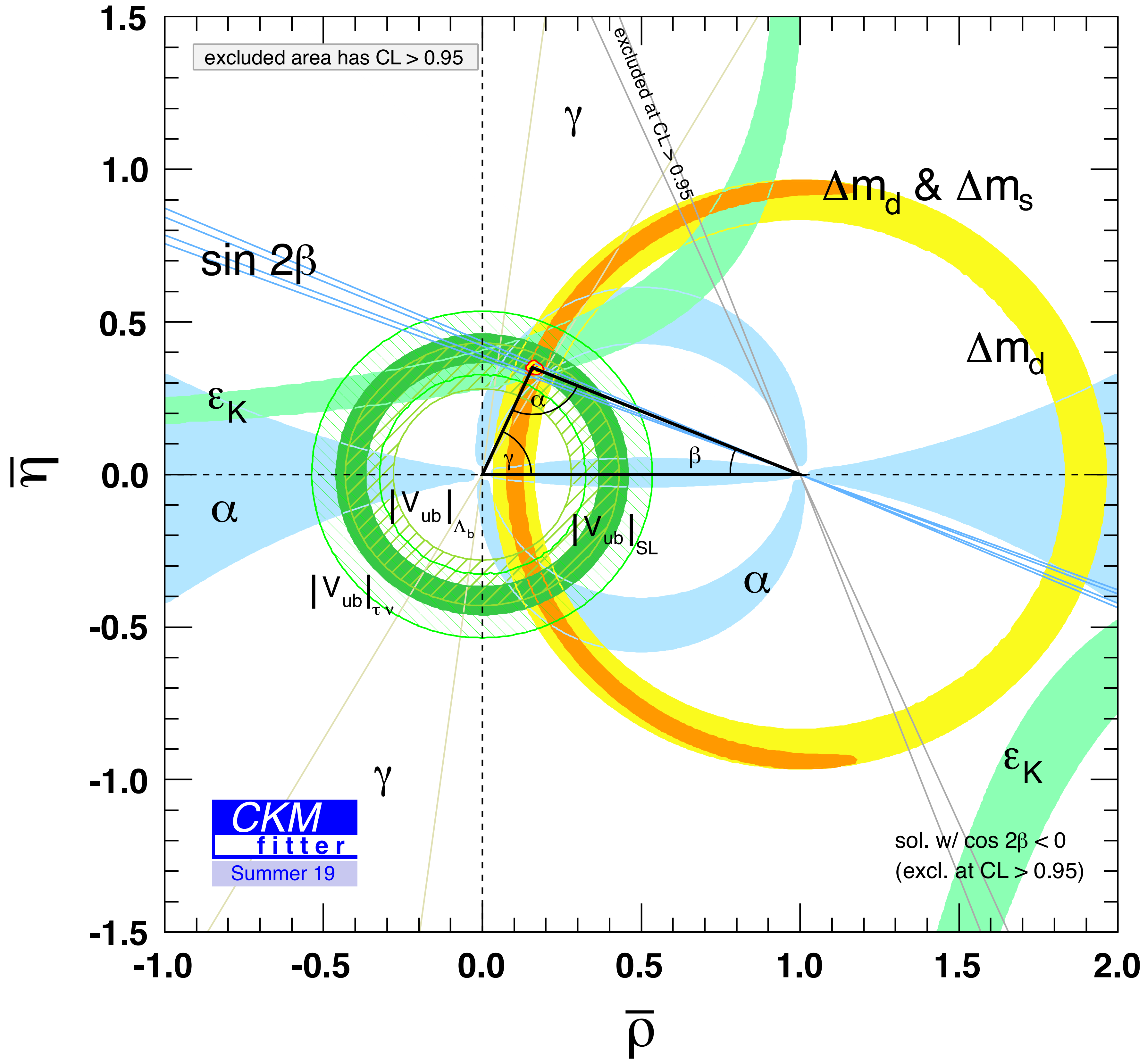
$V_{CKM} =$ 

- ✘ Fix CKM entries through tree level processes & over-constrain by loop-induced ones [progress through precision!]



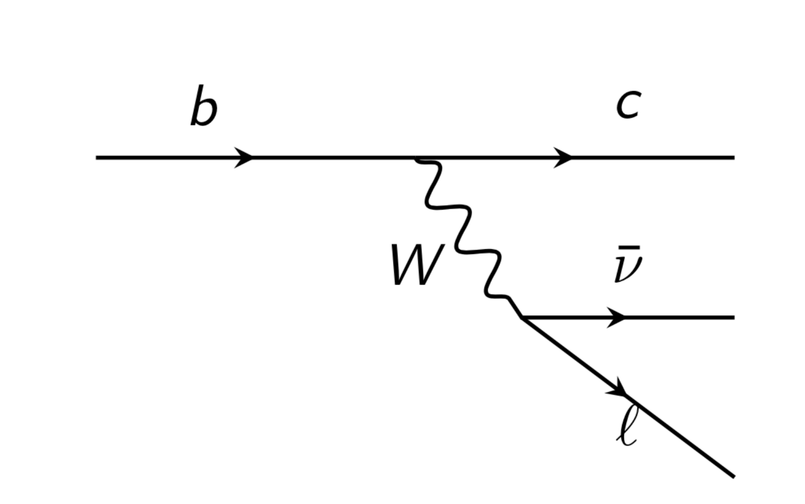


CKM-ology



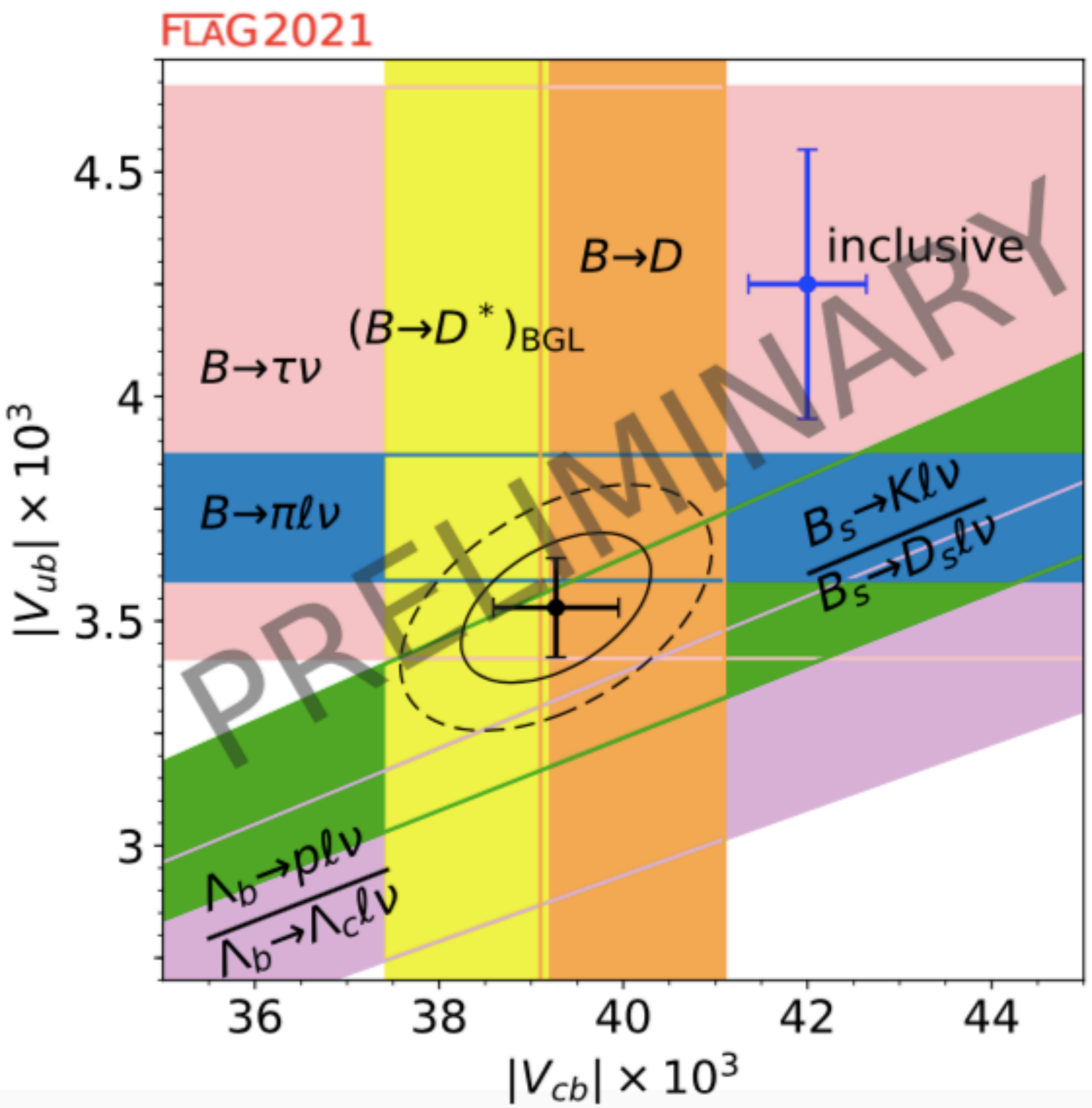
cf. http://ckmfitter.in2p3.fr

✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?
Is V_{ud} well controlled? V_{us} keeps coming back (EM)…



CKM-ology - Small flavor ‘anomaly’

- ✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?



- ✘ Belle II (excl + incl), LHCb (excl)
- ✘ QCD on very fine lattices
  B → D and B → D*

cf. updates at http://flag.unibe.ch

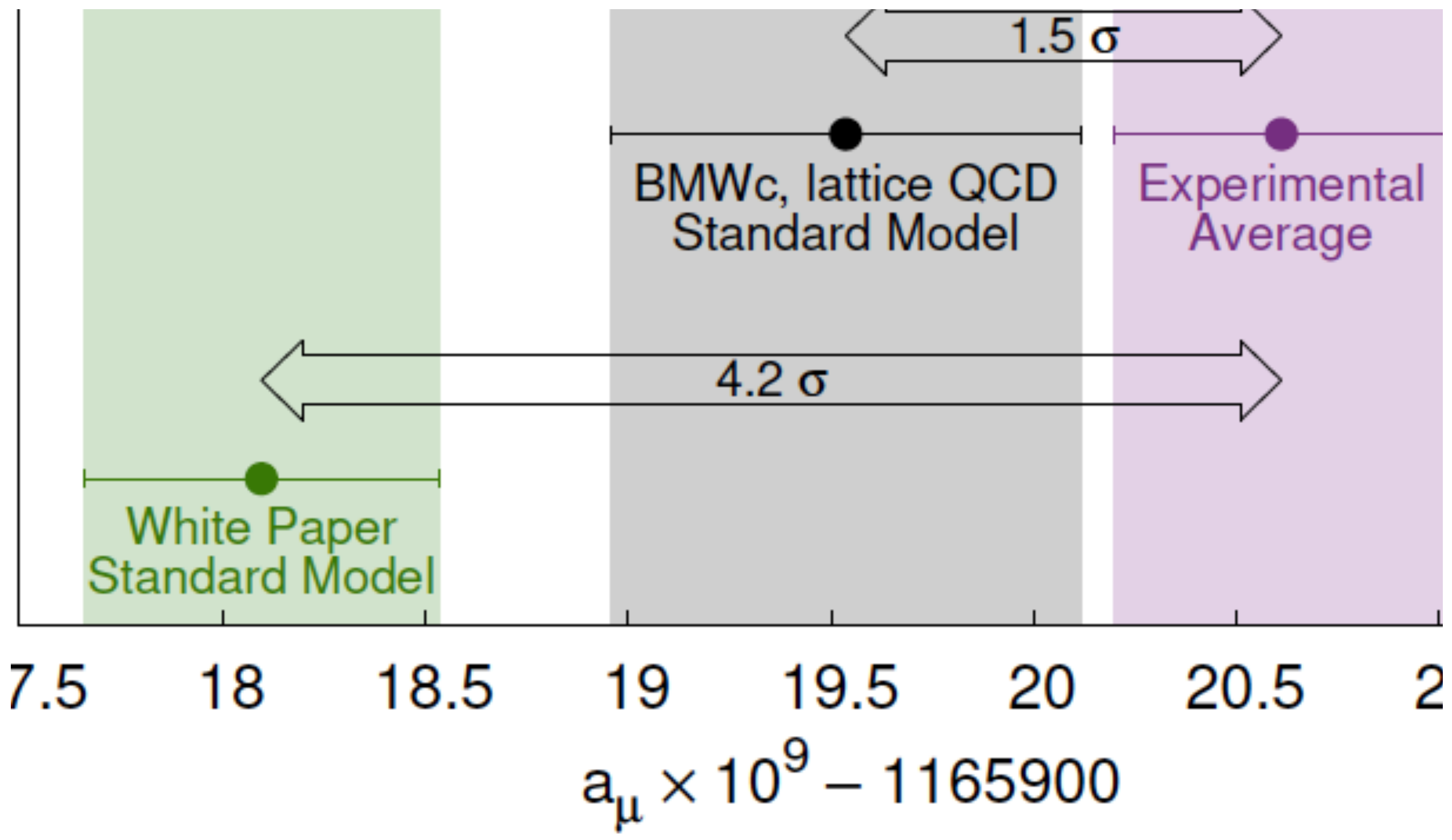
Experiment essential...

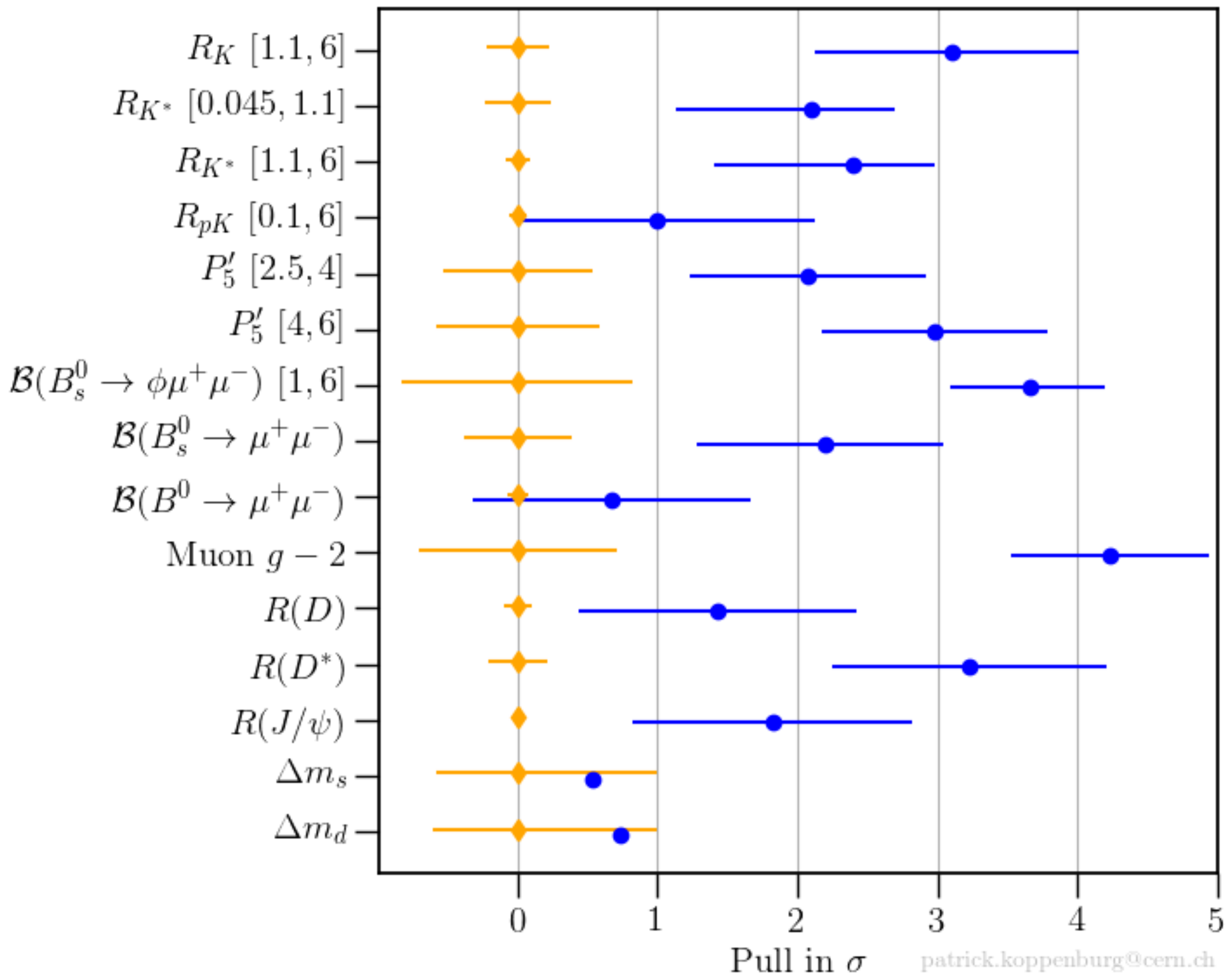
Phenomenology... bridge b/w theory and experiment

Look for quantities - observables:

- ✘ (Highly) Sensitive to contributions of physics BSM
- ✘ Mildly (or not) sensitive to hadronic uncertainties
- ✘ Accessible in current and/or (near) future experiments

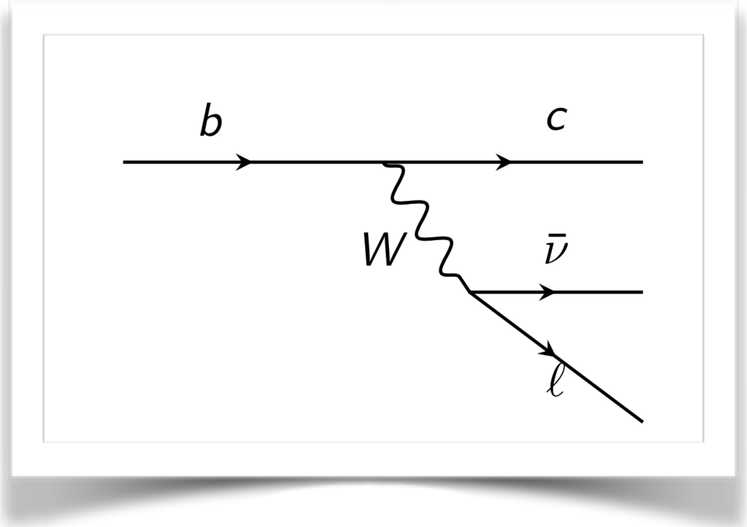
Flavor Anomalies



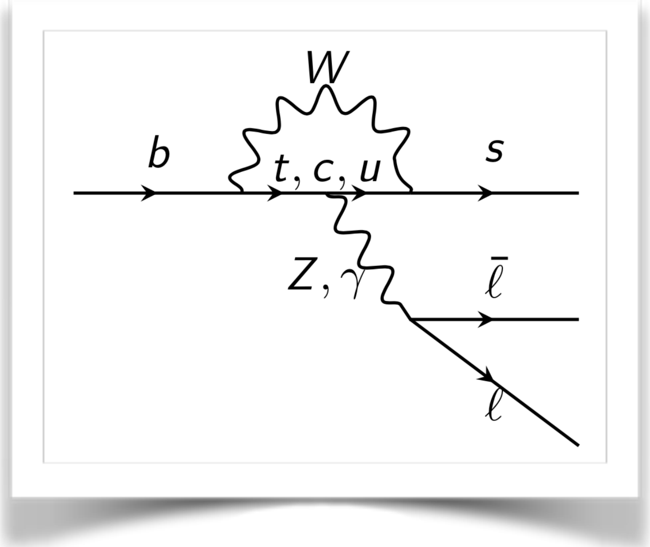


Lepton Flavor Universality Violation

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$



$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$



2019

Exp : $R_D = 0.340 \pm 0.030\,, \quad R_{D^*} = 0.295 \pm 0.014$

SM : $R_D^{\rm SM} = 0.293 \pm 0.008\,, \quad R_{D^*}^{\rm SM} = 0.257 \pm 0.003$

LHCb 2021

$R_K^{[1.1,6]} = 0.847(42)^{\rm LHCb}$ vs $R_K^{[1,6]} = 1.00(1)^{\rm SM}$

LHCb 2017

$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb}$ vs $R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$

LFUV: Experimentally?

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

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$$\text{Exp}: \quad R_D = 0.340\pm0.030\,, \quad R_{D^*} = 0.295\pm0.014$$

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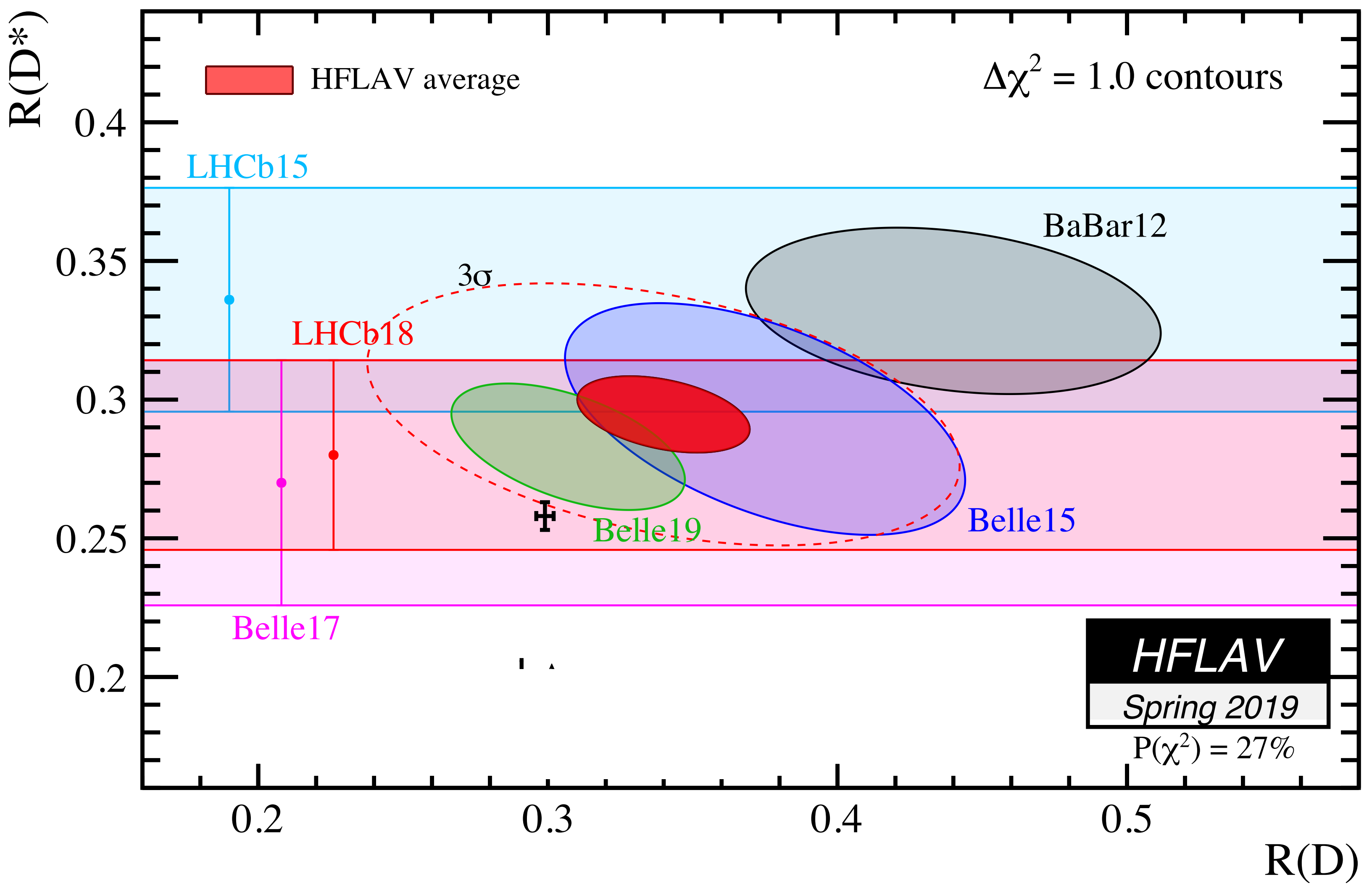
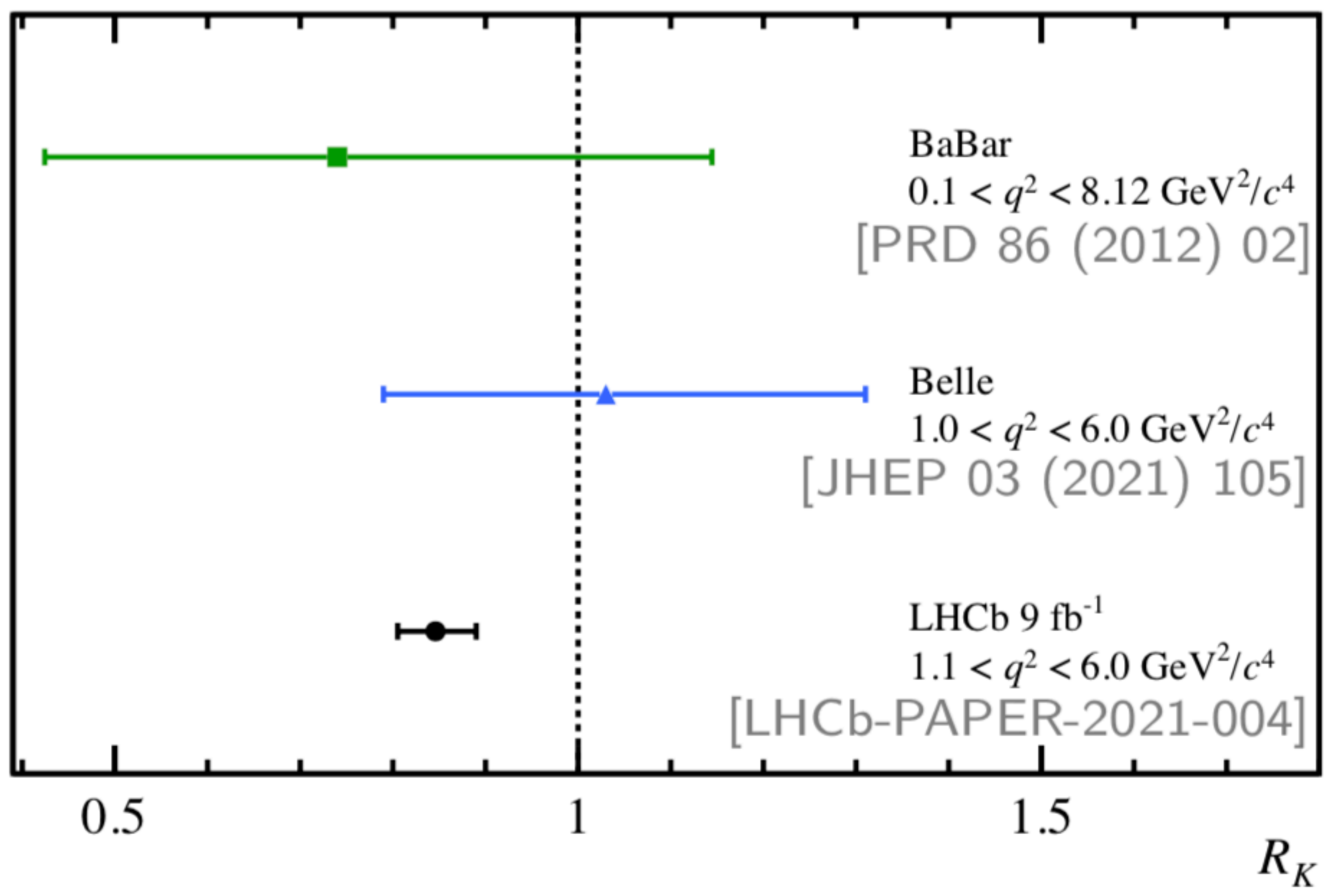
$$R_K^{[1.1,6]} = 0.847(42)^{\rm LHCb} \quad \text{vs} \quad R_K^{[1,6]} = 1.00(1)^{\rm SM}$$

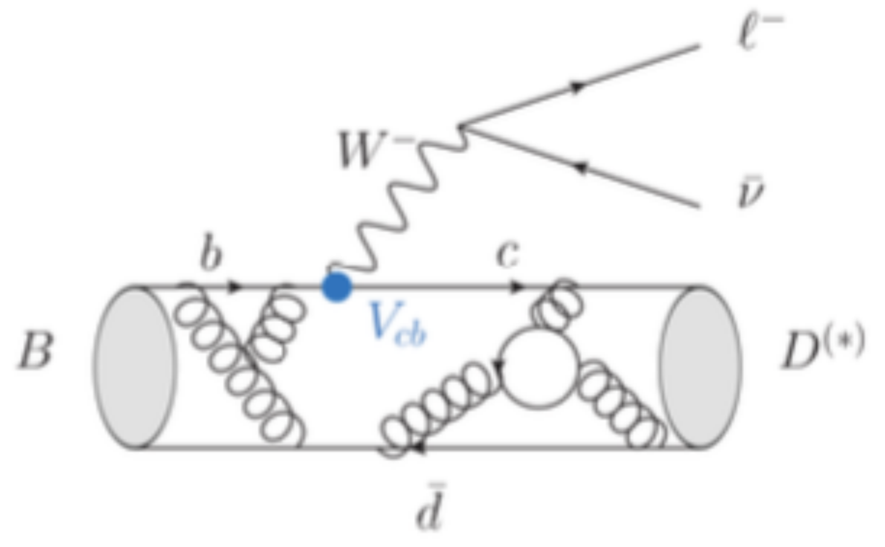
$$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb} \quad \text{vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$$



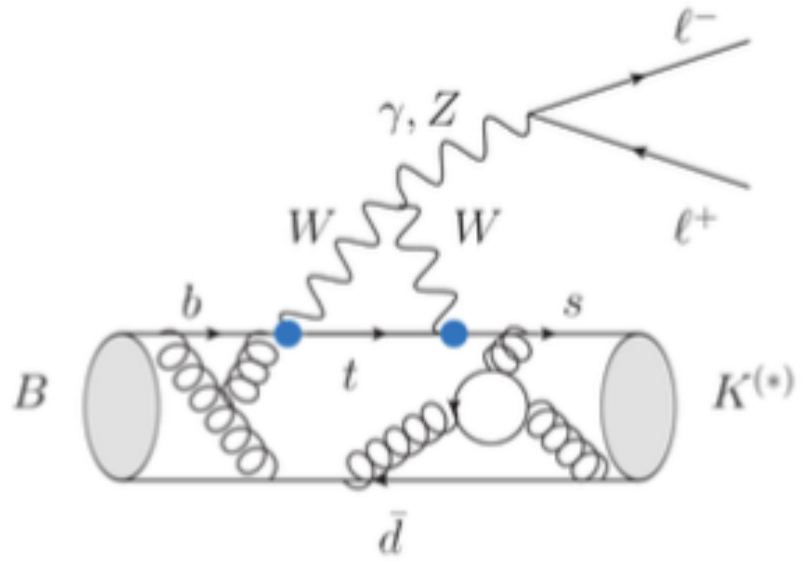


Lepton Flavor Universality Violation

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$



$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$



$$\text{Exp}: \quad R_D = 0.340\pm0.030\,, \quad R_{D^*} = 0.295\pm0.014$$

$$\text{SM}: \quad R_D = 0.293\pm0.008\,, \quad R_{D^*} = 0.248\pm0.001$$

$$R_K^{[1.1,6]} = 0.847(42)^{\rm LHCb} \quad \text{vs} \quad R_K^{[1,6]} = 1.00(1)^{\rm SM}$$

$$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb} \quad \text{vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$$

$$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3 \text{ TeV}$$

$$R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 30 \text{ TeV}$$

naive NP scale

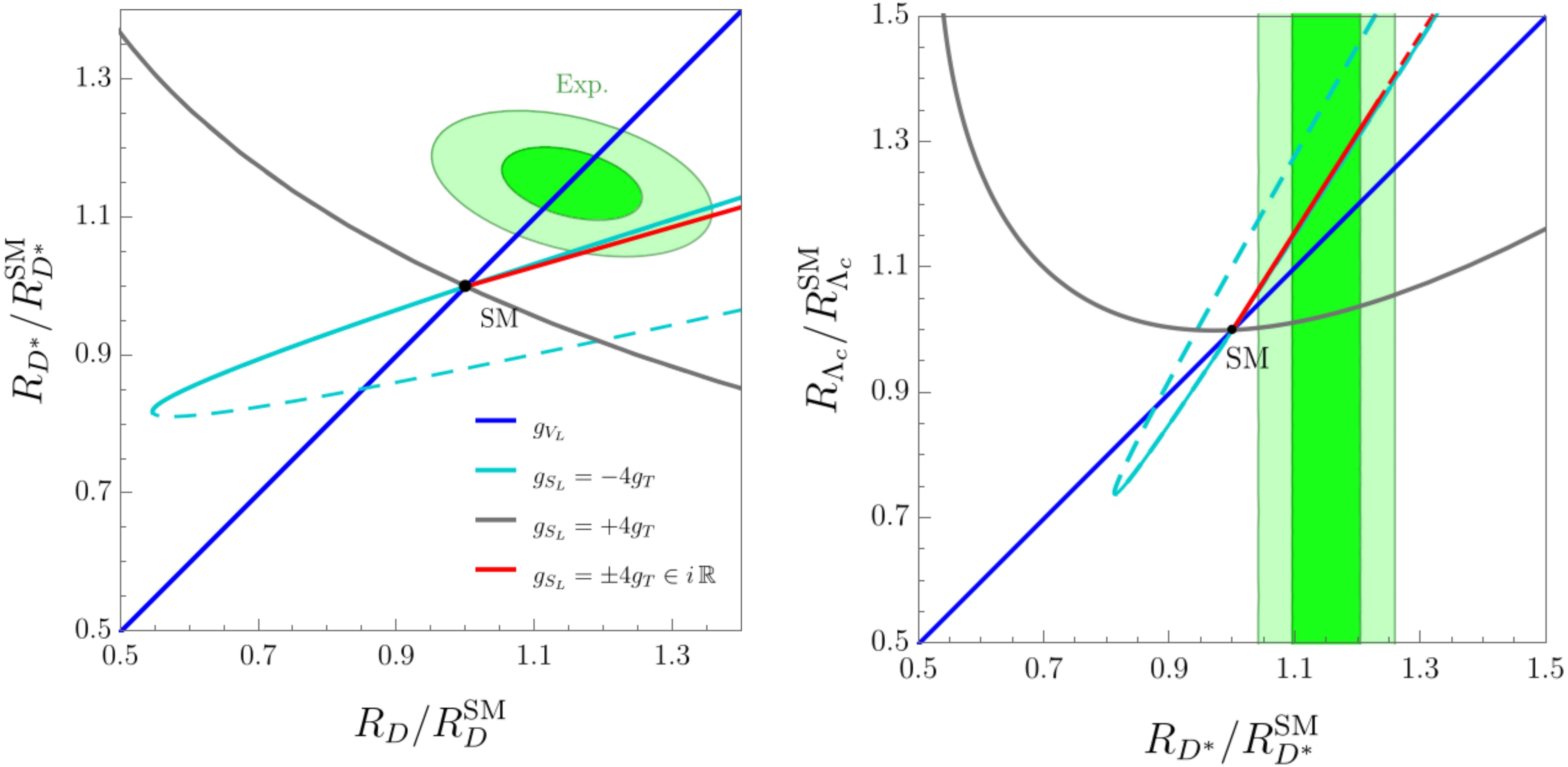
EFT - exclusive $b \to c\ell\nu$

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W\bar{c}_R b_R$ vertex).
  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.

EFT - exclusive $b \to c\ell\nu$

$$\mathcal{L}_{\rm eff} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$



EFT - exclusive $b \to s\ell\ell$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \left(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \right) \right] + \text{h.c.}$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

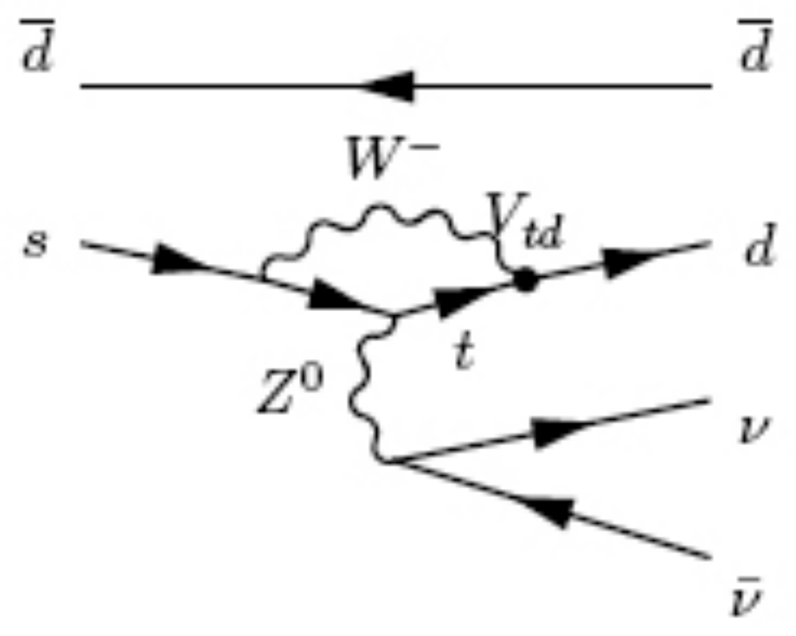
$$\mathcal{O}_7^{(\prime)} = m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

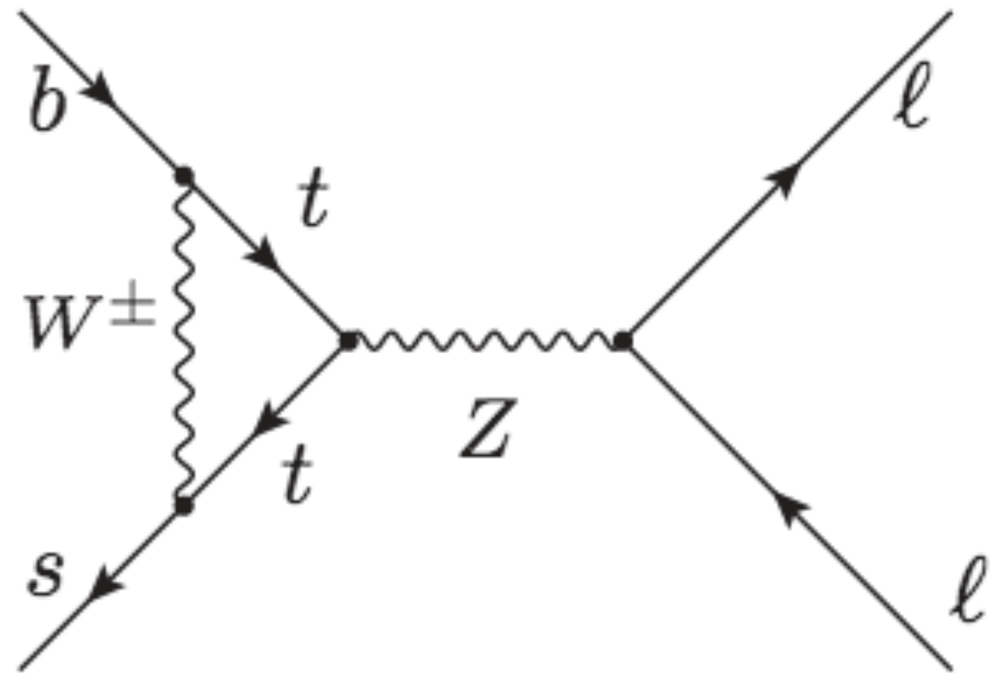
Exp : $\mathcal{B}(B_s \to \mu\mu) = (2.85 \pm 0.33) \times 10^{-9}$

SM : $\mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

Probing BSM...

Strategy:
fix V_{ij} by tree level processes, then look for NP in FCNC





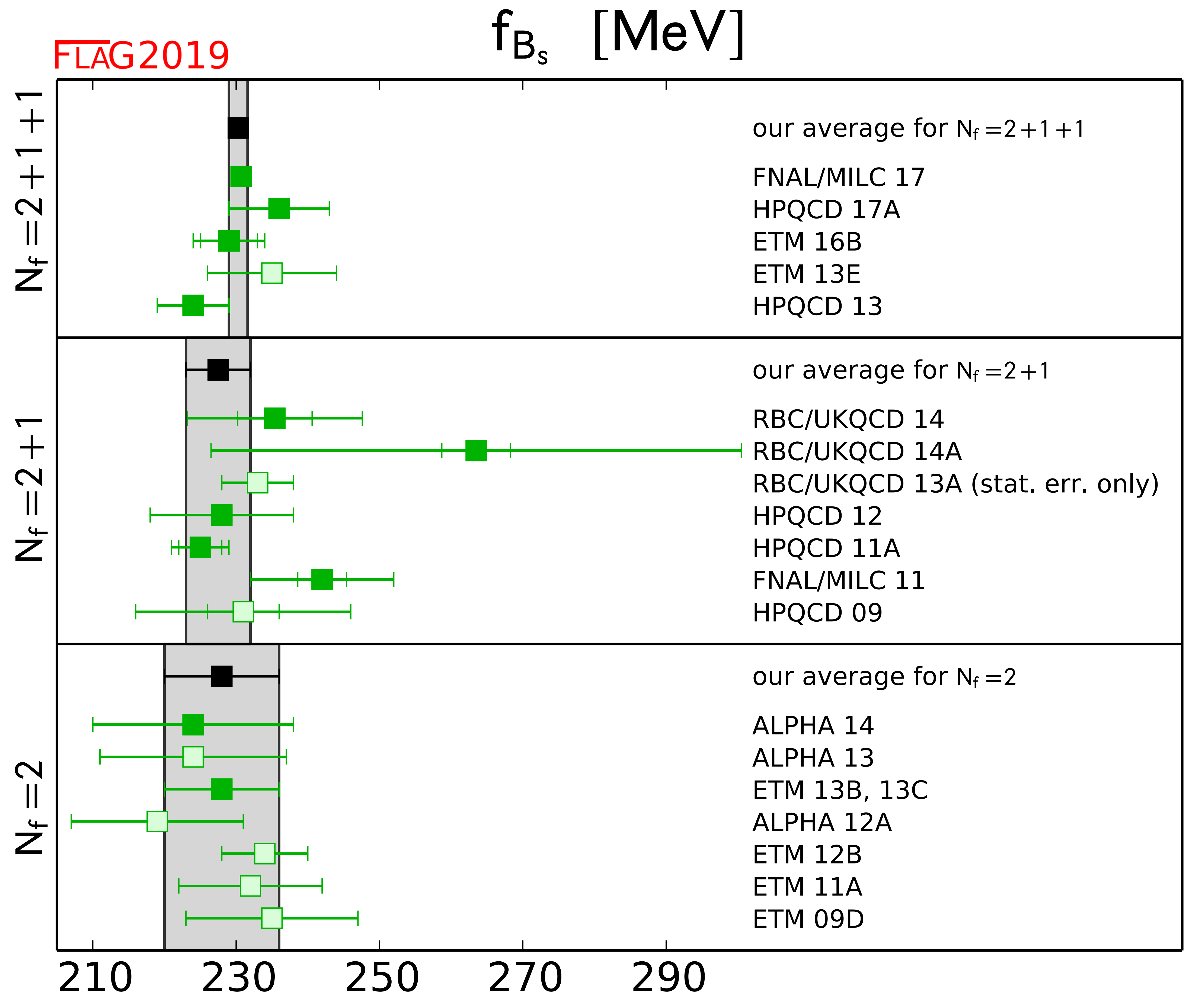
$\text{Exp}: \mathcal{B}(B_s \to \mu\mu) = (2.85 \pm 0.33) \times 10^{-9}$ 12%

$\text{SM}: \mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$ 4%

C_{ij}	1	$V_{ti}V_{tj}^*$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV

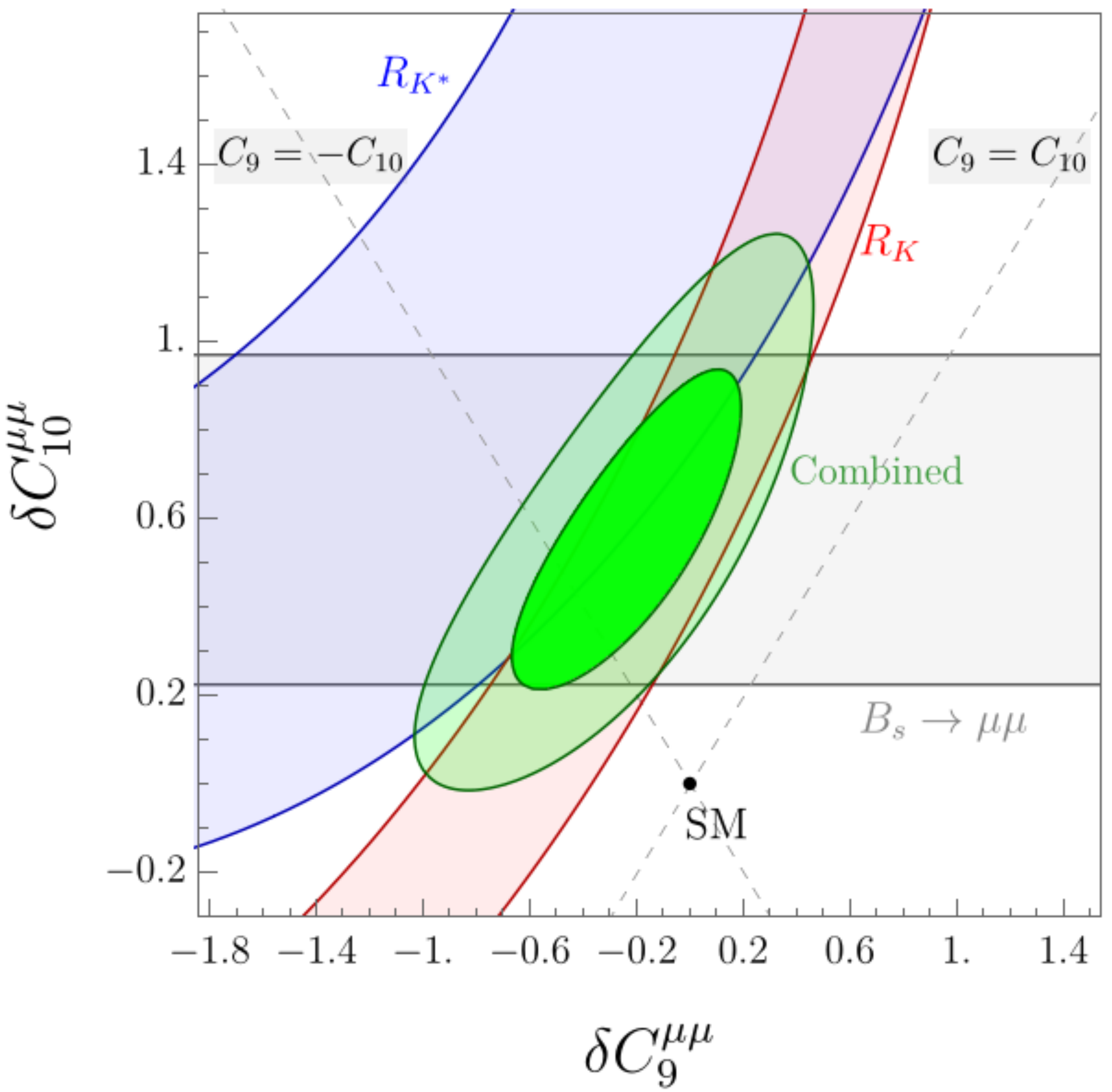
$$O = \frac{1}{\Lambda^2} C_{ij} \bar{Q}_i \gamma^\mu Q_j H^\dagger D_\mu H$$

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B_s(p)\rangle = i f_{B_s}\, p^\mu$$



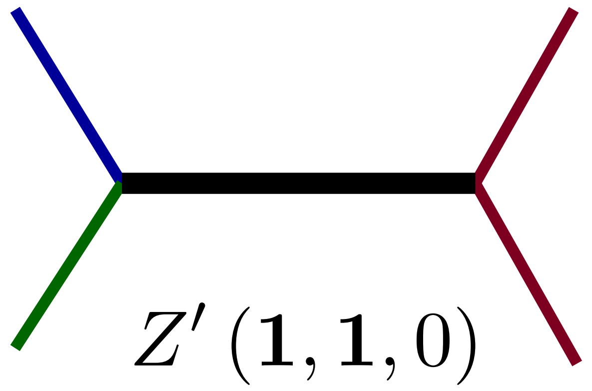
cf. updates at http://flag.unibe.ch

Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$ EFT for $b \to s\ell\ell$



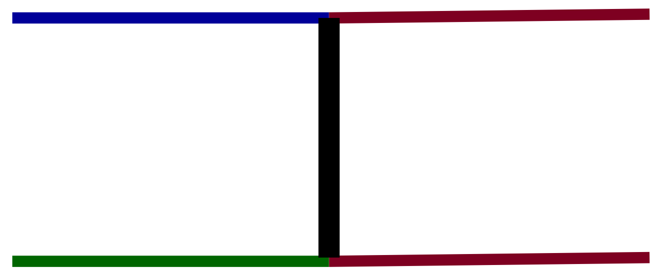
Concrete Scenarios of Physics BSM

1. Vector singlet

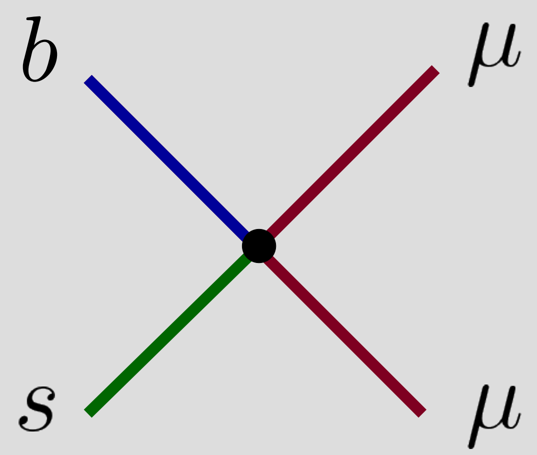


$Z' \, (\mathbf{1}, \mathbf{1}, 0)$

3. Vector Leptoquarks

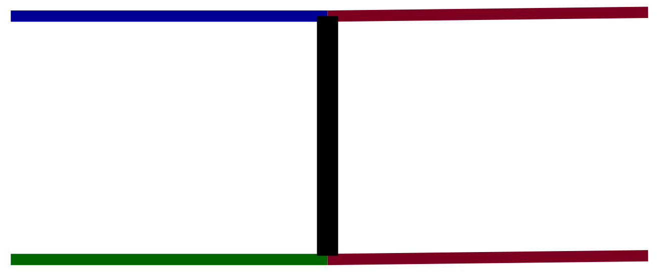


$U_1 \, (\mathbf{3}, \mathbf{1}, 2/3)$
$U_3 \, (\mathbf{3}, \mathbf{3}, 2/3)$



$$\frac{1}{\Lambda^2} \, (\bar{b}\, \gamma^\mu P_L\, s)(\bar{\ell}\gamma_\mu P_{L,R}\ell)$$

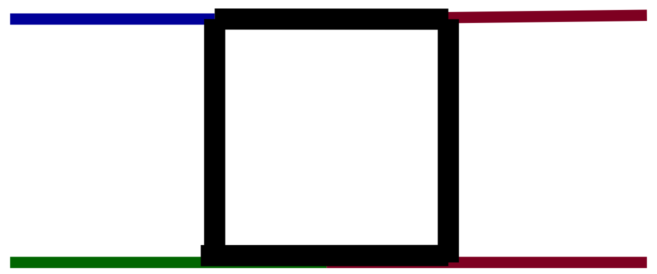
2. Scalar Leptoquarks



$S_3 \, (\mathbf{3}, \mathbf{3}, -1/3)$

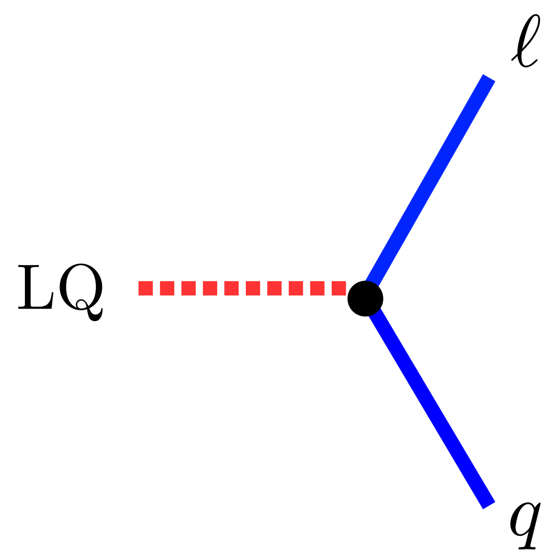
Beware: essentially **ALL** models contain **additional states** when UV-completing!

4. In the Loop



$Z' \, (\mathbf{1}, \mathbf{1}, 0)$, VL fermions
$S_1 \, (\mathbf{3}, \mathbf{1}, -1/3)$, $R_2 \, (\mathbf{3}, \mathbf{2}, 7/3)$ ...

Leptoquarks



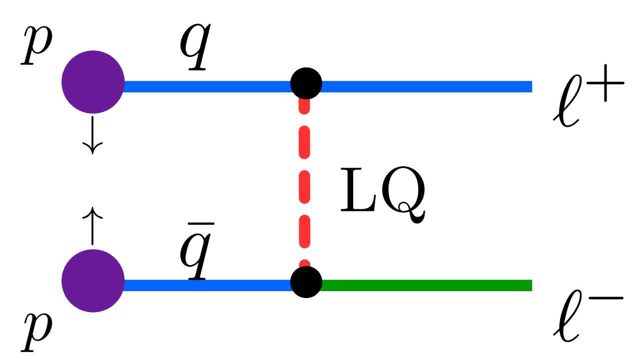
Color triplet

Scalar / Vector boson

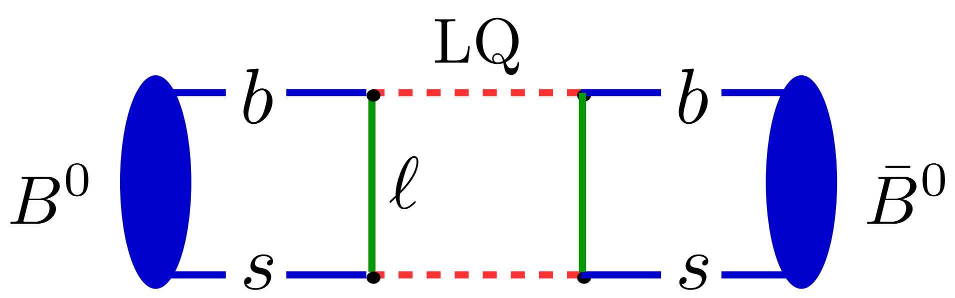
$(SU(3), SU(2), U(1))$	Spin	Symbol
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$

Some good and bad features:

- Non-resonant Drell-Yan production
- No 4-quark / 4-lepton effective interactions at tree level
- Violate SM accidental symmetries!

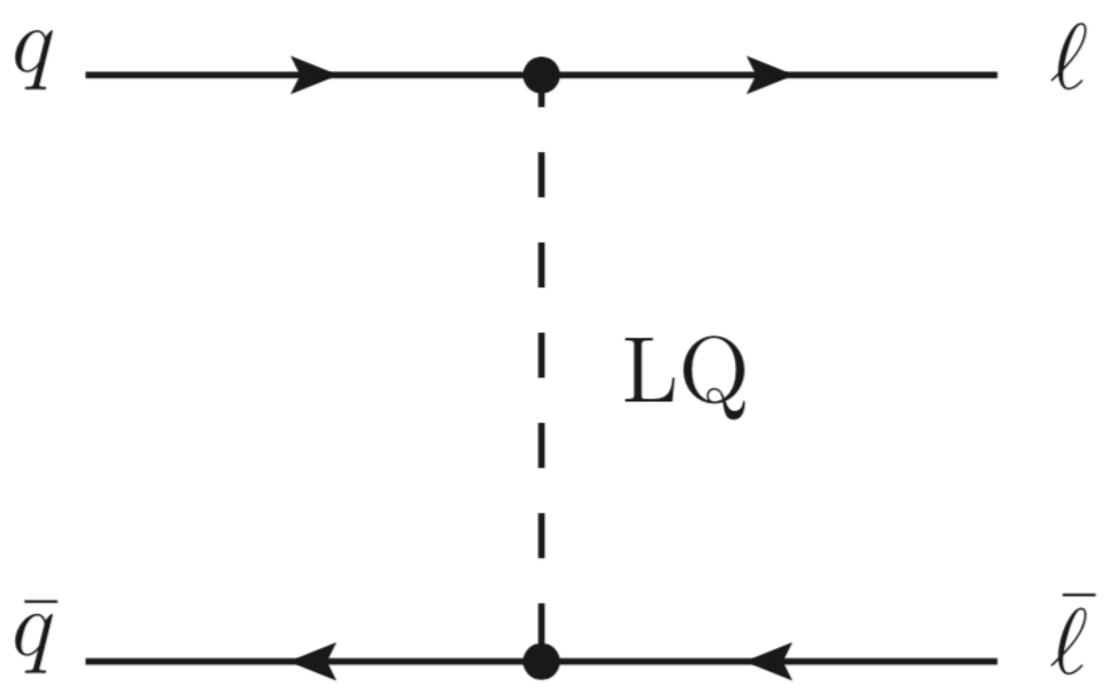


t-channel

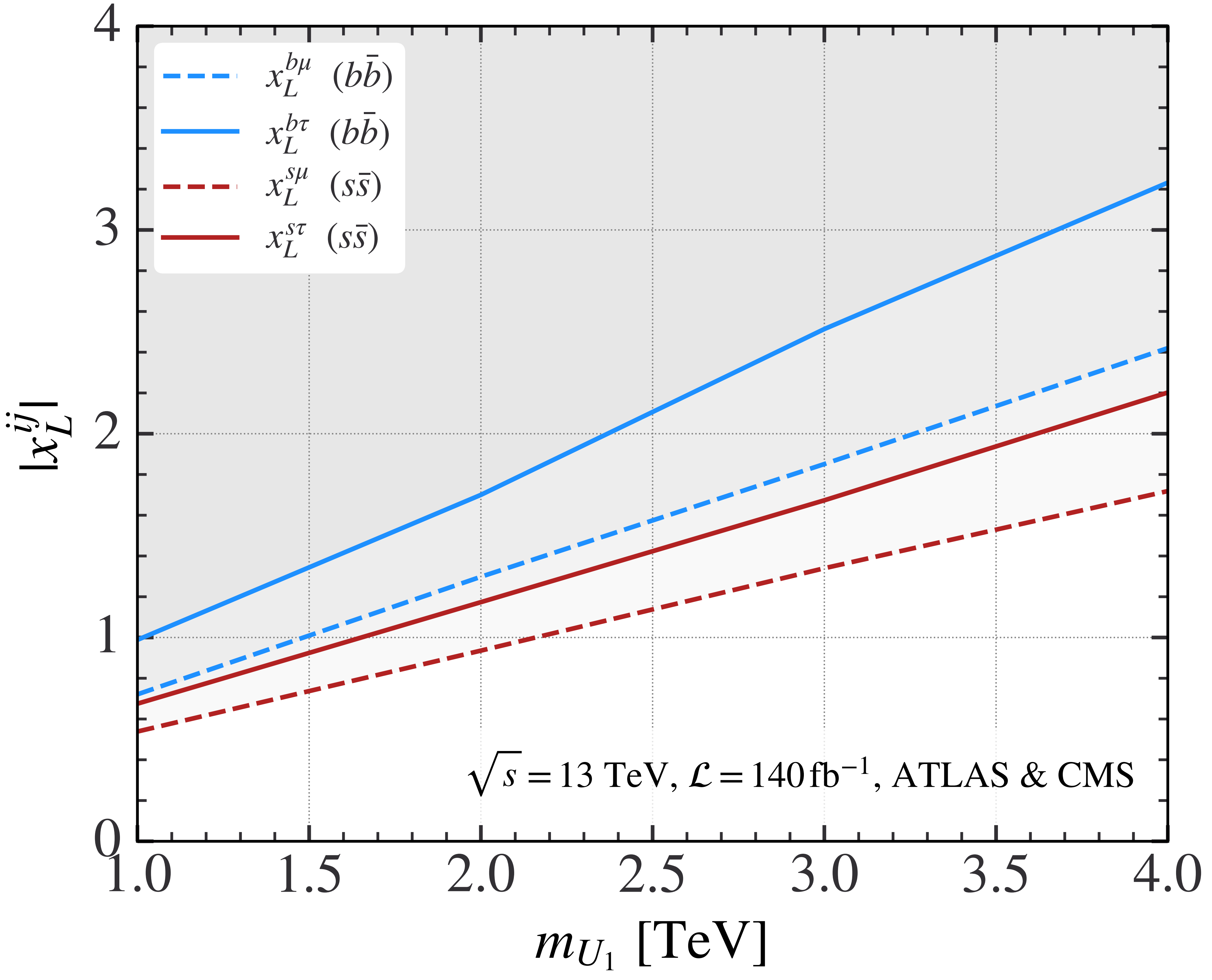


Loop level

From dilepton spectra at high p_T
Atlas and CMS 2018-2020



Example U1



$$\mathcal{L}_{U_1} = x_L^{ij}\, \overline{Q}_i \gamma_\mu L_j\, U_1^\mu + x_R^{ij}\, \overline{d}_{R_i} \gamma_\mu \ell_{Rj} U_1^\mu + \text{h.c.}$$

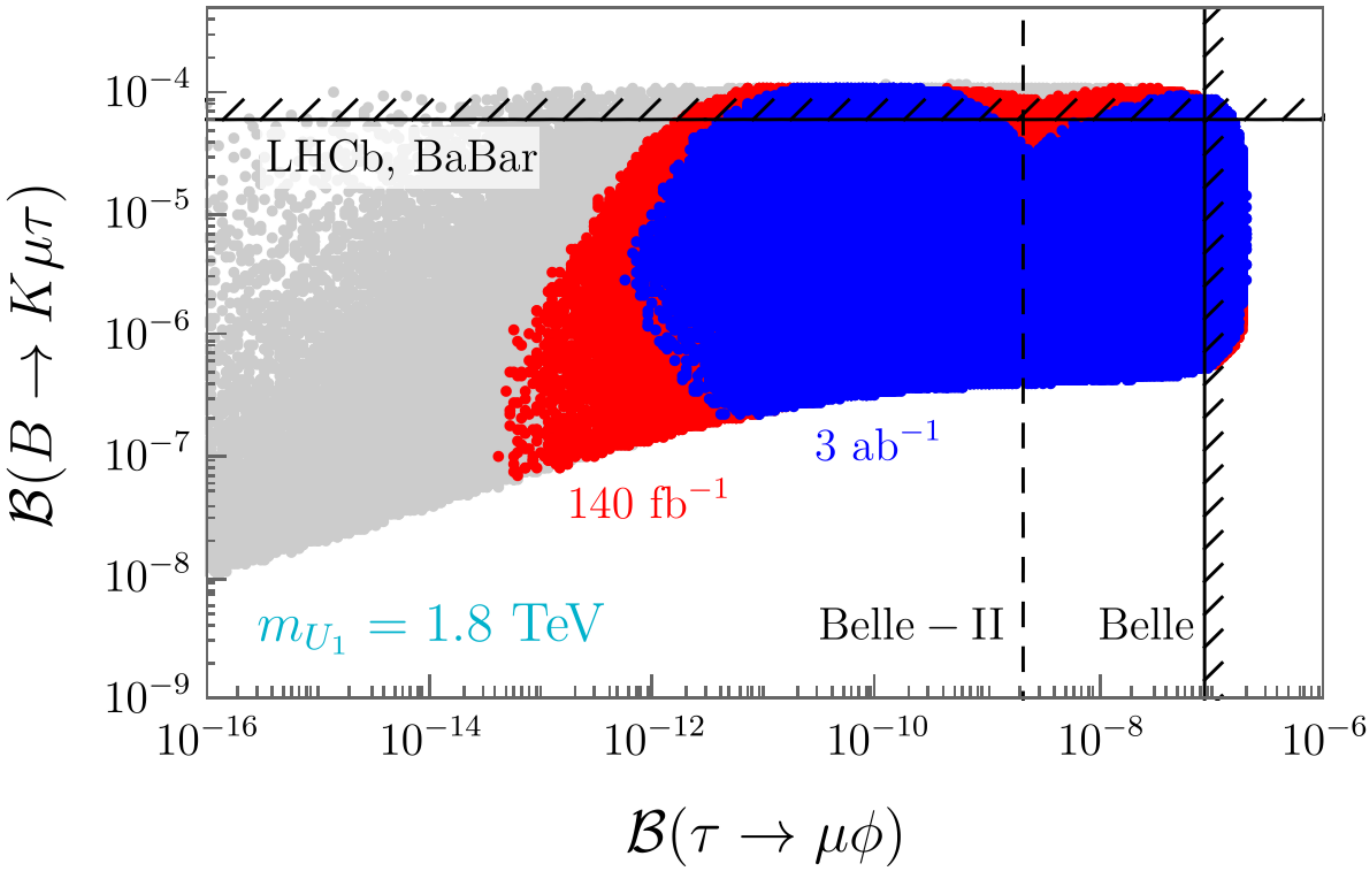
What LQ scenario?

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

N.B. U_1 is the only one to accommodate both!

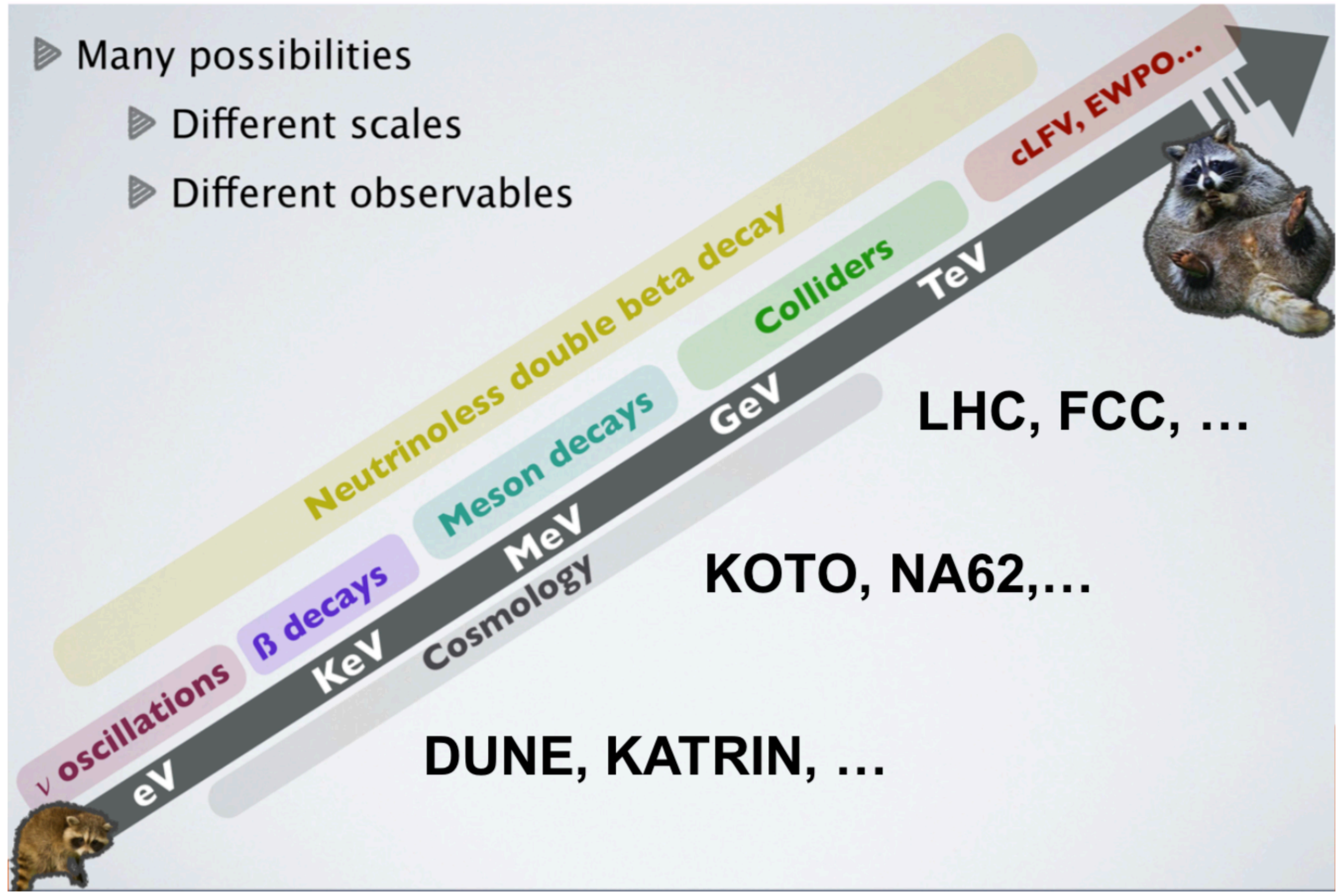
Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

LFV predictions



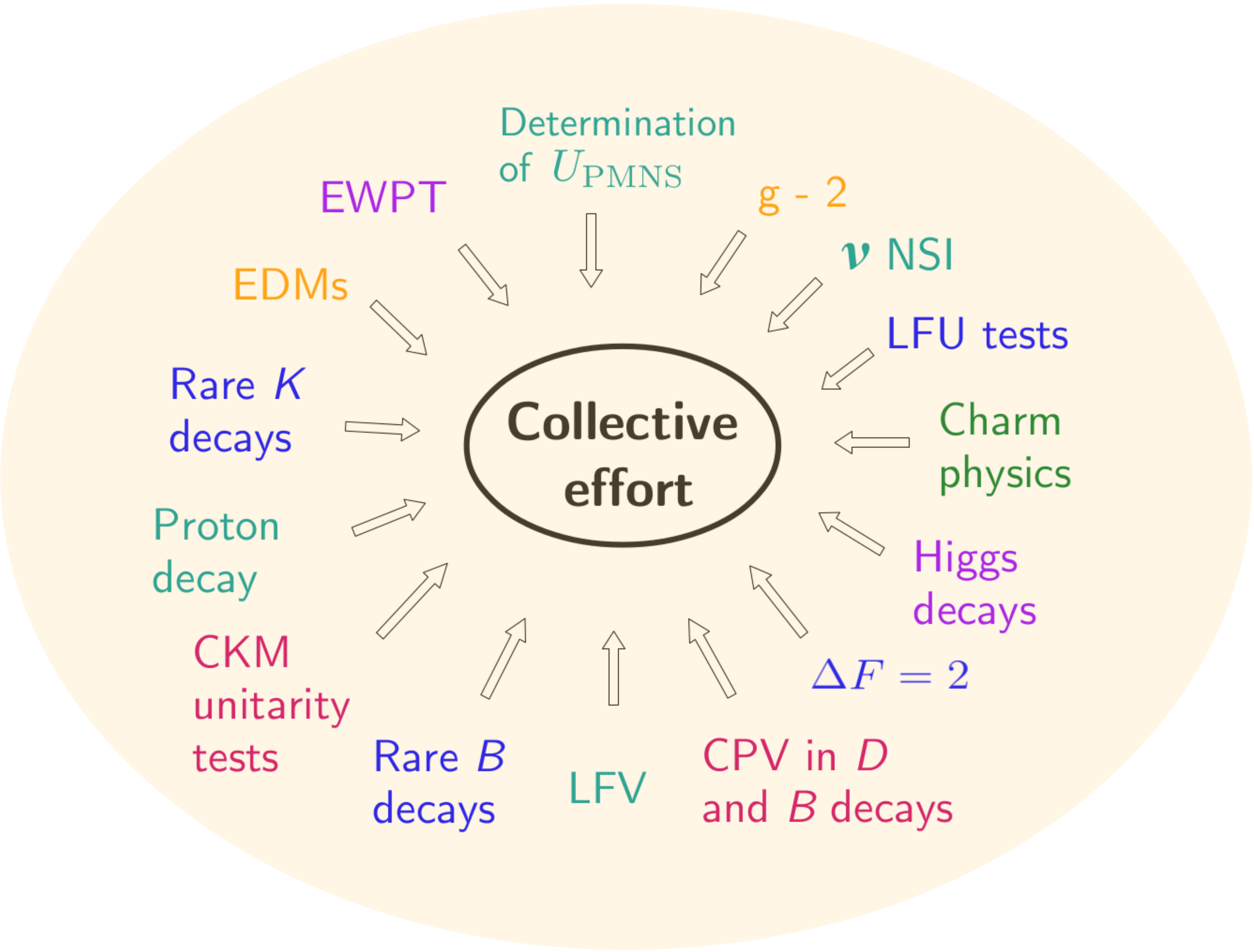
BSM from the lepton side…

- **Neutrino masses and mixings → call for New Physics**
- **Many BSM candidates** → motivated by theoretical and observational arguments
  Simultaneously address: BAU, DM and neutrino mass generation
- **Majorana** sterile fermions: appealing **New Physics** candidates
  Potentially **"visible"** NP portal: **imprints from colliders to flavour LE**
  LE experiments and CPV searches, ...

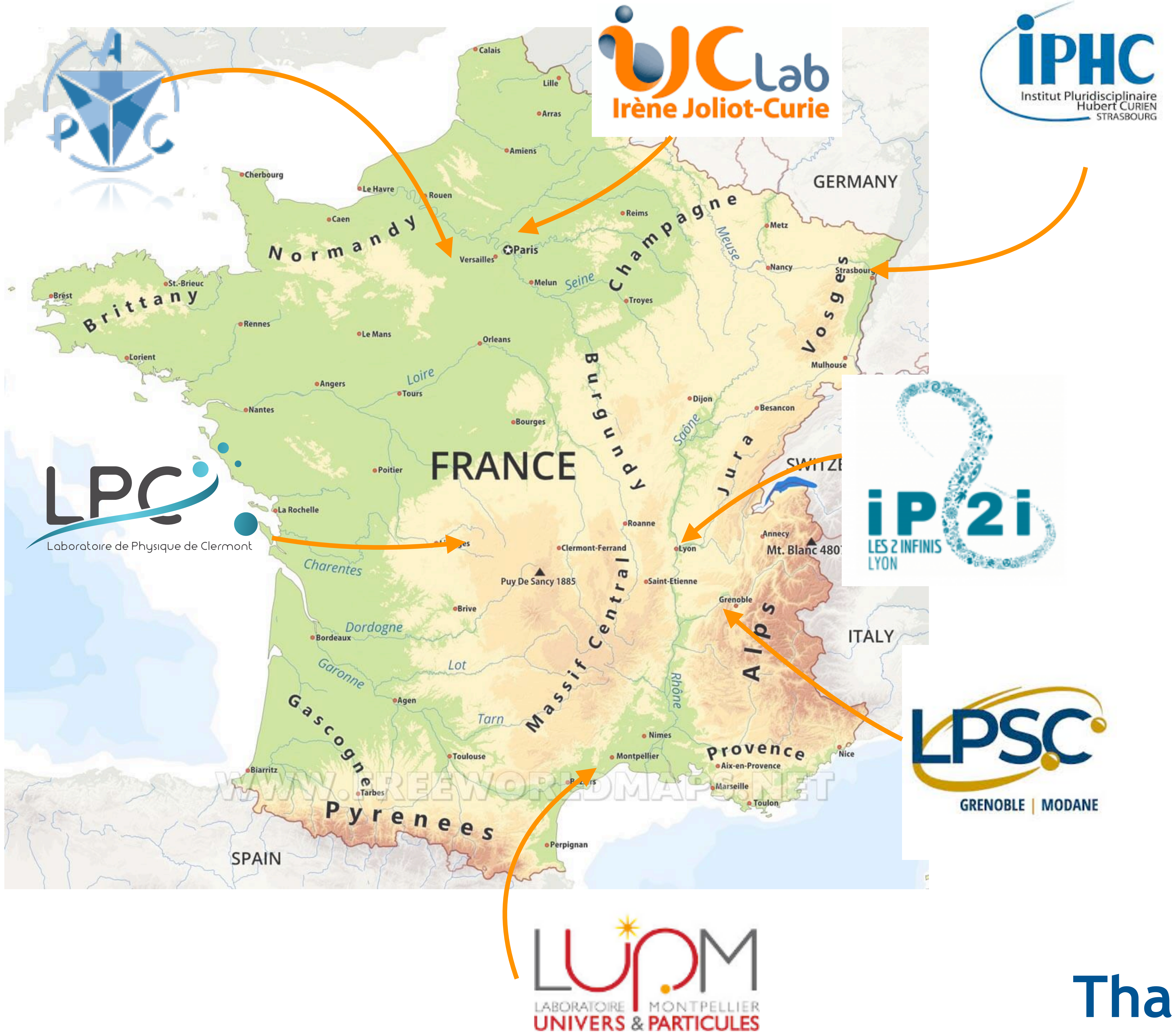


Interest & phenomenological implications

- **eV scale** ↔ extra neutrinos suggested by oscillation anomalies;
- **keV scale** ↔ warm dark matter candidates & astrophysical puzzles;
- **MeV-TeV scale** ↔ exp. tests, high-intensity expts and colliders (but also BAU, DM, ...);
- Beyond 10^{16} GeV ↔ theoretical appeal: standard seesaw, BAU, GUTs


Collective effort
Determination of U_{PMNS}
EWPT
g - 2
ν NSI
EDMs
LFU tests
Rare K decays
Charm physics
Proton decay
Higgs decays
CKM unitarity tests
$\Delta F = 2$
Rare B decays
LFV
CPV in D and B decays

Flavor physics at IN2P3 Laboratories



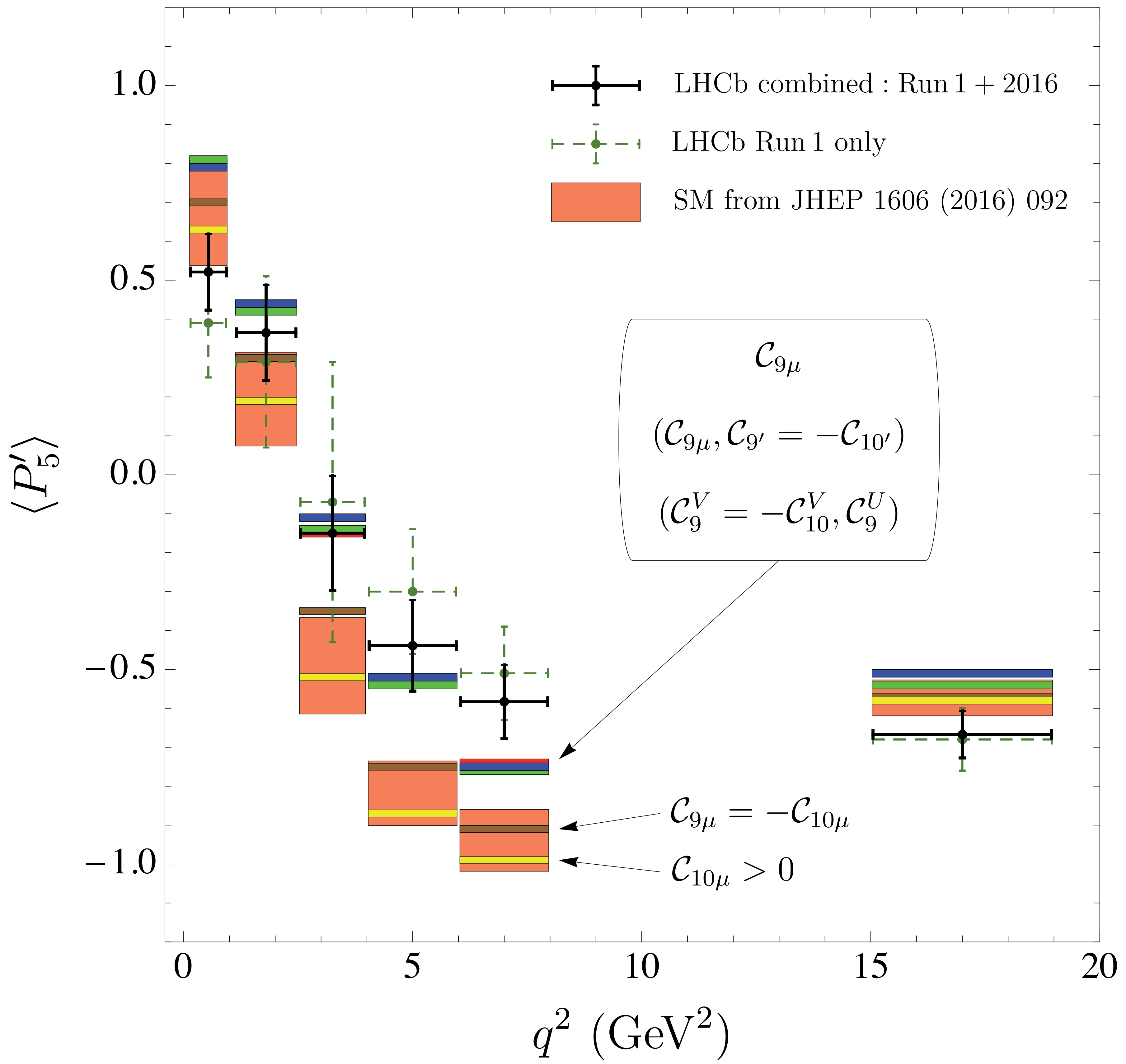
Thanks for your attention!

Extra Page

Detailed angular distribution can help…

More Observables

$b \to s\mu\mu$



Debate over Hadronic Uncertainties…

$b \to c\tau\bar{\nu}$

Stay tuned (early results from Belle…)