Particle Physics

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DISCLAIMER

- This is an attempt to give an overview of what the theoretical physicists, members of IN2P3, are working on - presently and recently
- It is by no means meant to be exhaustive
- Purposefully biased by experimental hints of physics BSM 'unfortunately' called anomalies

TH particle physics at IN2P3 Laboratories

Laboratory	People
APC Paris (UMR 7164)	D. Semikoz, J. Serreau, M. C. Volpe
IJCLab Orsay (UMR 9012)	A. Abada, D. Bečirević, V. Bernard, B. Blossier, S. Descotes-Genon, A. Falkowski, S. Friot, E. Kou, G. Moreau, O. Sumensari
IP2I Lyon (UMR 5822)	A. Arbey, G. Cacciapaglia, A. Deandrea, F. N. Mahmoudi
IPHC Strasbourg (UMR 7178)	M. Rausch de Traubenberg
LPC Clermont (UMR 6533)	A. Goudelis, J.-F. Mathiot, V. Morénas, J. Orloff, A. M. Teixeira
LPSC Grenoble (UMR 5821)	S. Kraml, M. Mangin-Brinet, J. Quevillon, I. Schienbein, C. Smith
LUPM Montpellier (UMR 5299)	F. Brümmer, S. Davidson, C. Hugonie

Part I

In the Standard Model

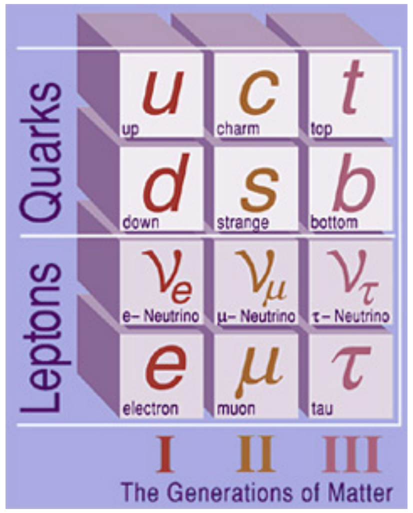
✘ Gauge sector entirely fixed by symmetry

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

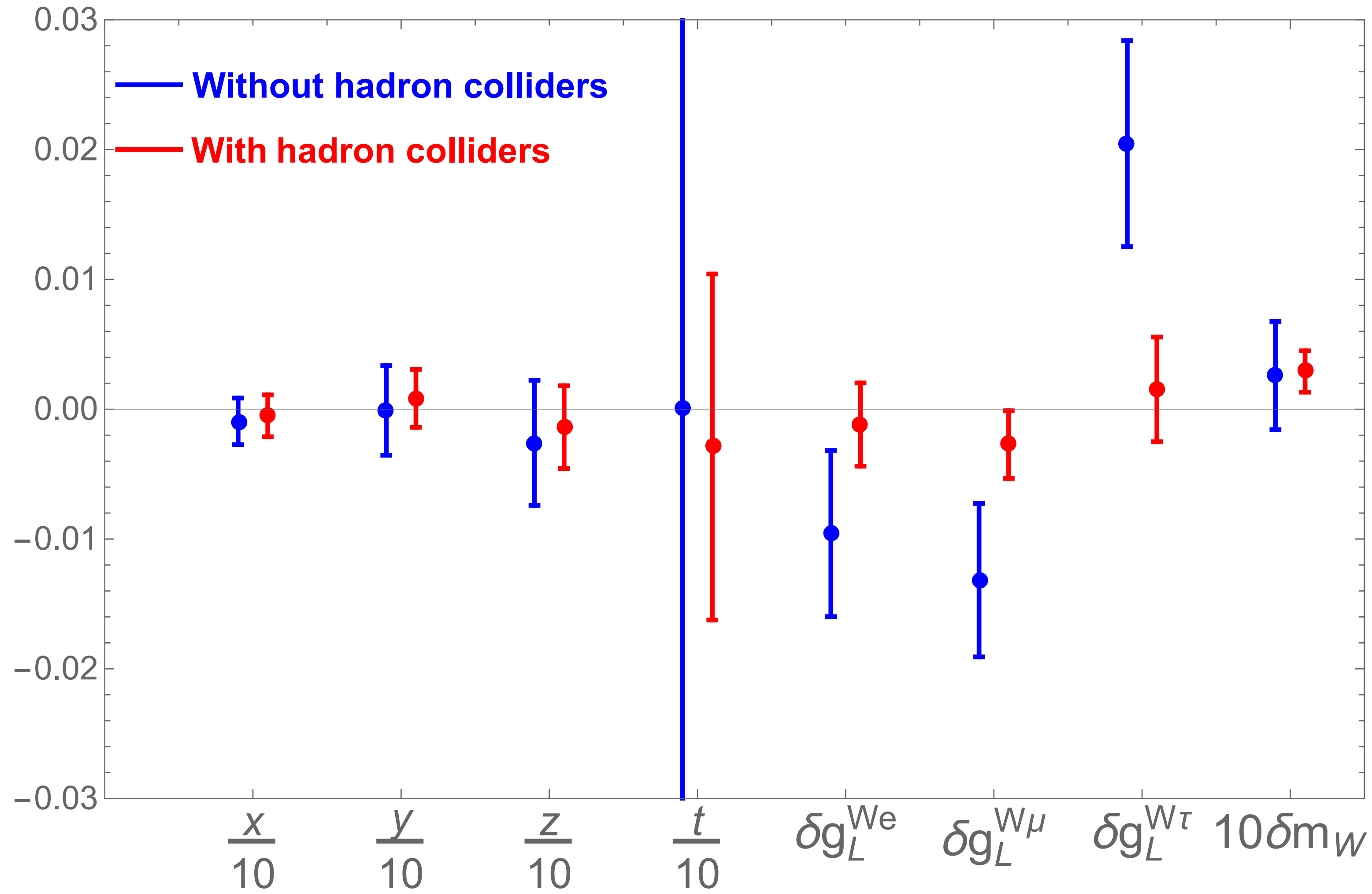
✘ Flavor sector loose (a bunch of parameters)

13 of 18 are fermion masses and mixing parameters

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



LHC PRECISION



$$\begin{pmatrix} x \\ y \\ z \\ t \end{pmatrix} = \begin{pmatrix} 0.93 & -0.29 & -0.23 & -0.01 \\ 0.18 & 0.87 & -0.33 & -0.33 \\ 0.27 & 0.18 & 0.90 & -0.29 \\ 0.17 & 0.37 & 0.17 & 0.90 \end{pmatrix} \begin{pmatrix} \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix}$$

$$\mathcal{L}_{\rm eff} = \overbrace{\mathcal{L}_{\rm gauge}(A,\Psi) + \mathcal{L}_{\rm Higgs}(A,\Psi,H)}^{\mathcal{L}_{\rm SM}\ \text{(renormalizable)}} + \underbrace{\sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}(A,\Psi,H)}_{\text{Operators of dim} \geq 5 \text{ made of SM fields}},$$

A. Falkowski

LHC PRECISION

- LHC precision observables: input from Higgs physics, top quark physics, W and Z mass, Drell-Yan processes, etc.
- LHC precision program is much broader than that of LEP. Well-defined and flexible theoretical framework - currently the **SMEFT** with d=5 and d=6 operators added to the SM.
- Huge and long-term collaborative task b/w theorists and experimentalists.
- Many technical problems to solve, e.g. how to include NLO **SMEFT** corrections, or how to simultaneously fit PDFs and d=6 operators.
- New measurements and new observables are still being proposed to optimise this task

A. Falkowski

Uncertainties: S. Kraml, I. Schienbein

Matching (loop corrections): J. Quevillon, C. Smith

Particular pheno issues: <<pretty much everyone>>

Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\lvert H^\dagger D_\mu H\right\rvert^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_W	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_G	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

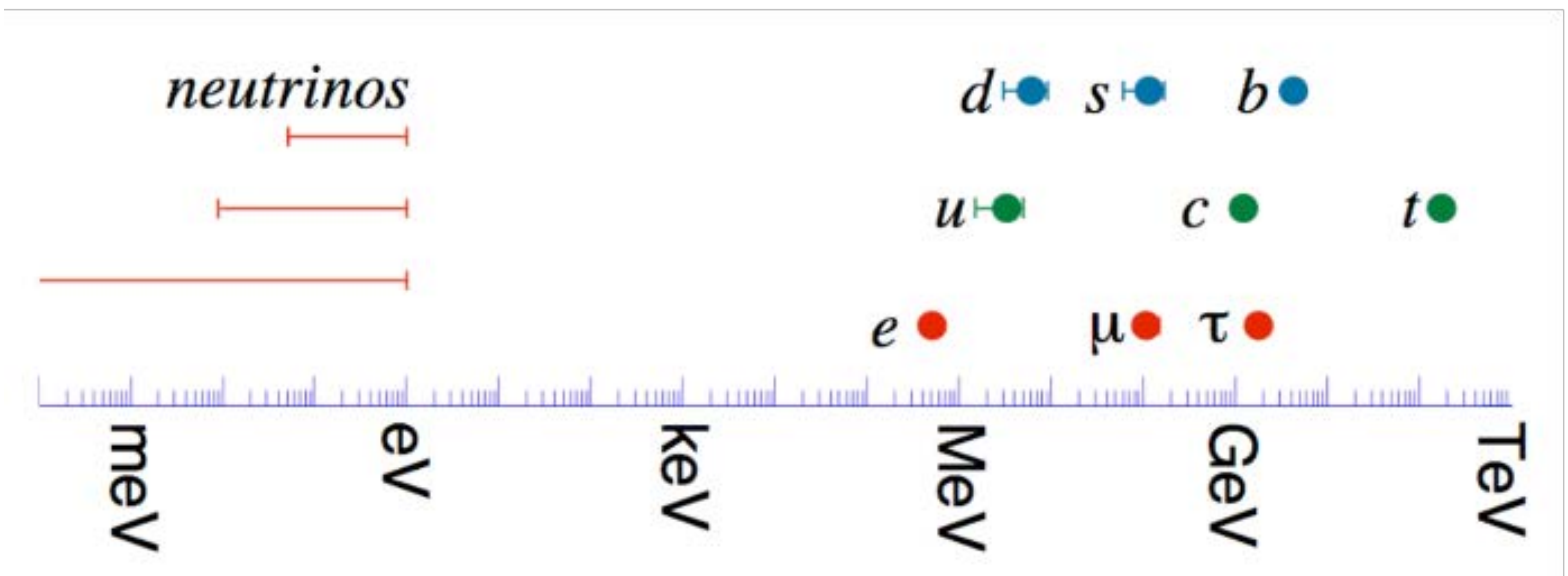
Vertex		Dipole	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D_\mu} H$	$[O^\dagger_{eW}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D_\mu} H$	$[O^\dagger_{eB}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$i e^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D_\mu} H$	$[O^\dagger_{uG}]_{IJ}$	$u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D_\mu} H$	$[O^\dagger_{uW}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D_\mu} H$	$[O^\dagger_{uB}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$i u^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D_\mu} H$	$[O^\dagger_{dG}]_{IJ}$	$d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$i d^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D_\mu} H$	$[O^\dagger_{dW}]_{IJ}$	$d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$i u^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O^\dagger_{dB}]_{IJ}$	$d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$	$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$	$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$	$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$	O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$	O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$	O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$	O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
		O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

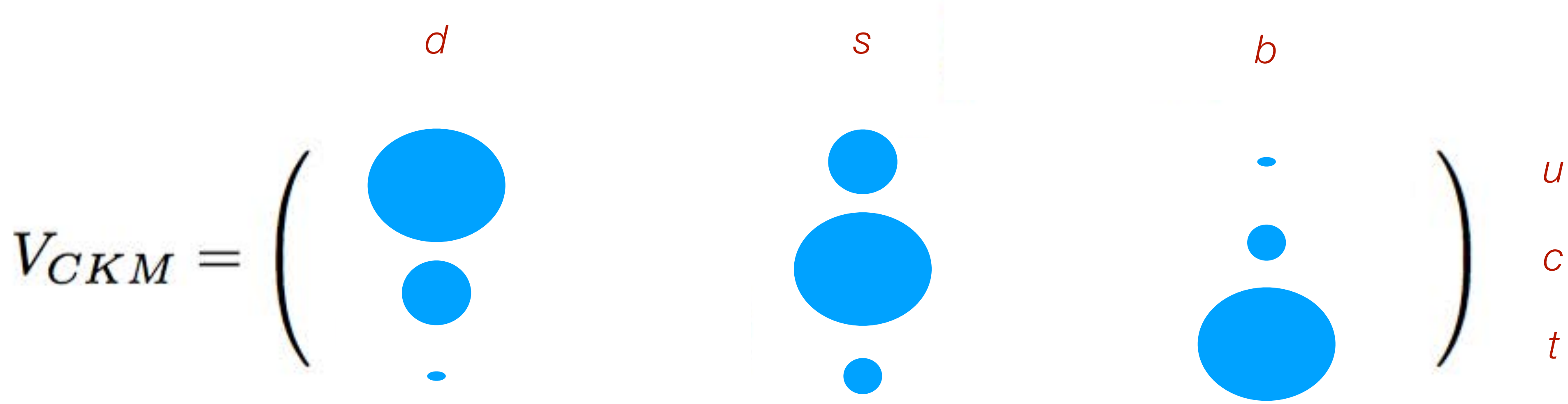
$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{L}R)$	
$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$	O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$	O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$	$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Flavor Physics

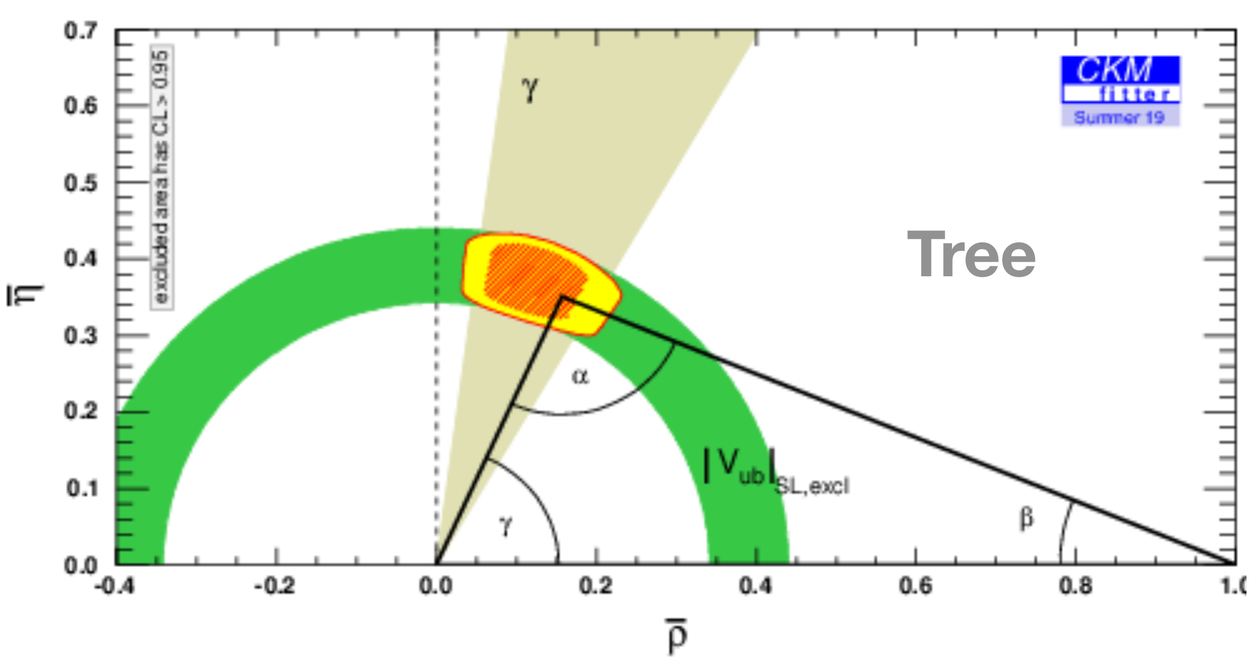
- ✘ Why three generations?
- ✘ Why such hierarchy of masses and mixing?
- ✘ Why so small CPV phase?

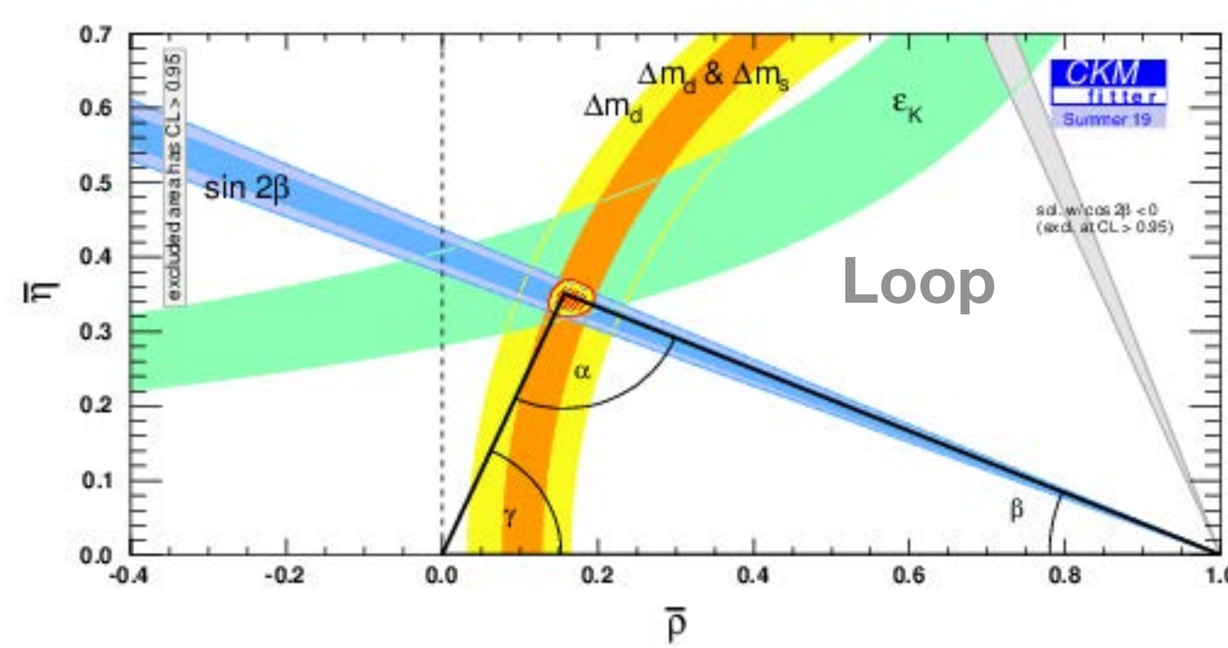


Quark Mixing

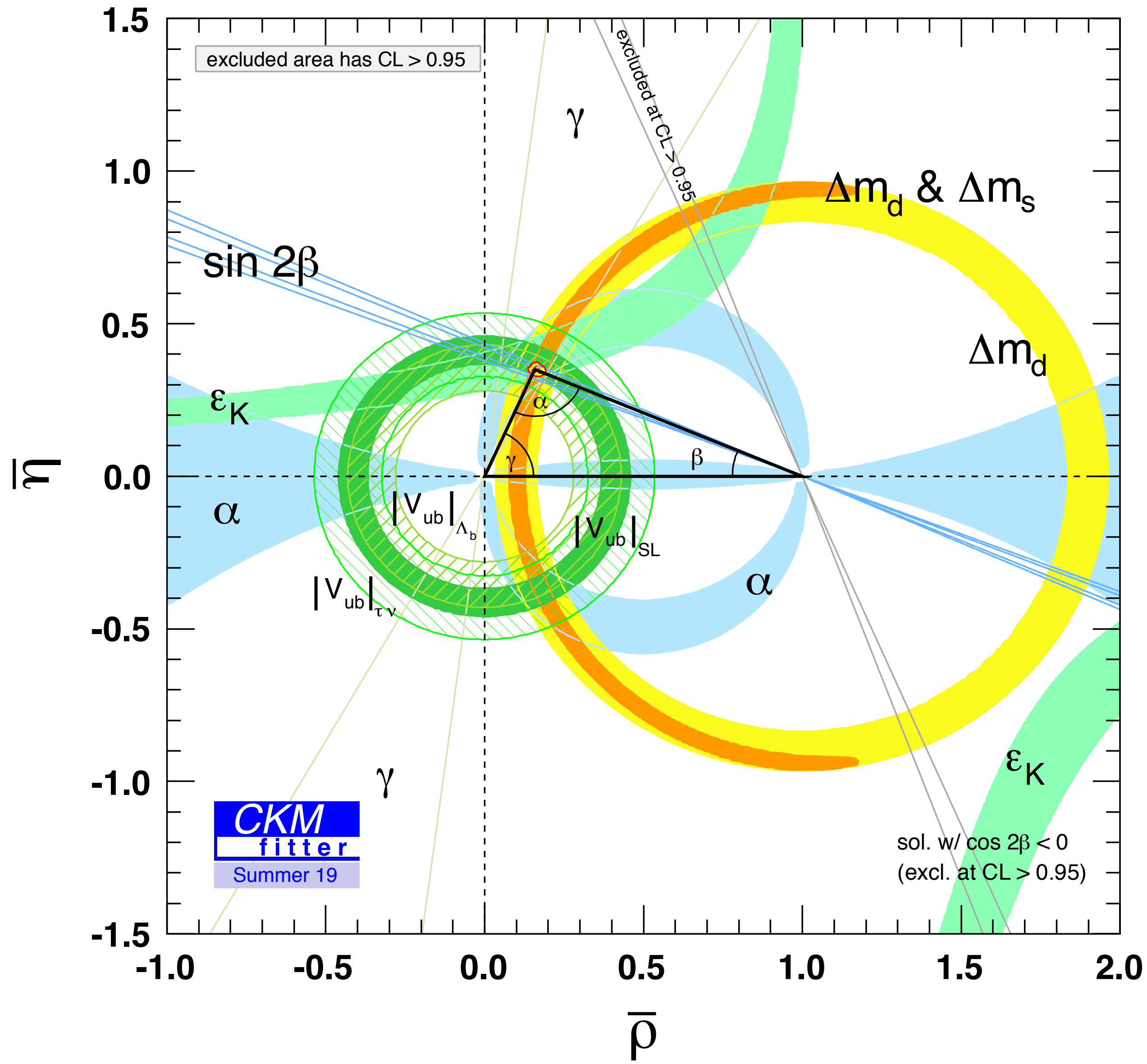


✘ Fix CKM entries through tree level processes & over-constrain by loop-induced ones [progress through precision!]





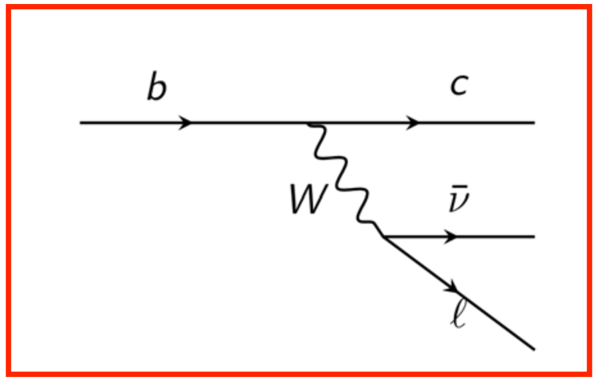
CKM-ology



S. Descotes-Genon
J. Orloff

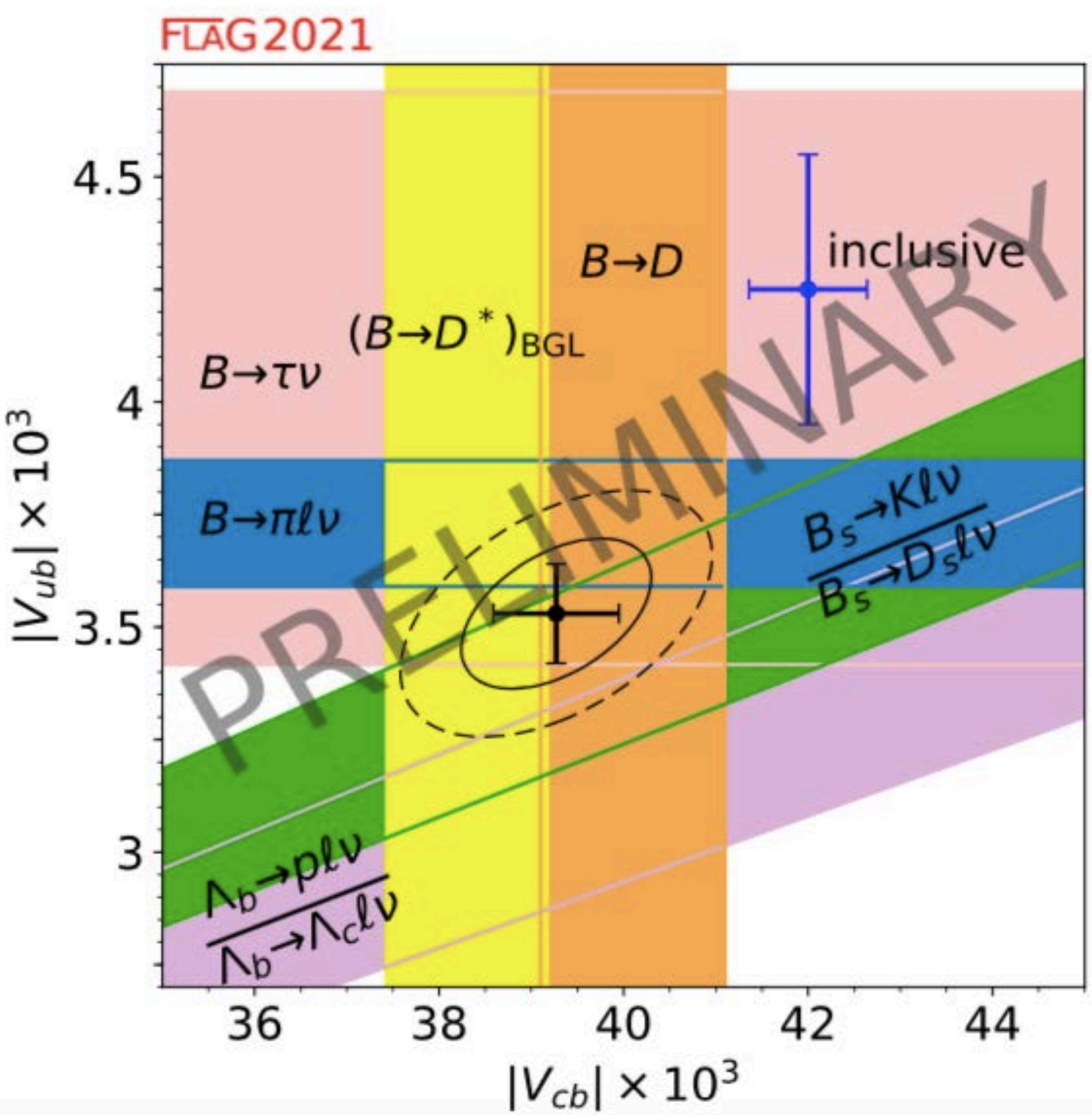
cf. http://ckmfitter.in2p3.fr

- ✘ 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)

E. Kou

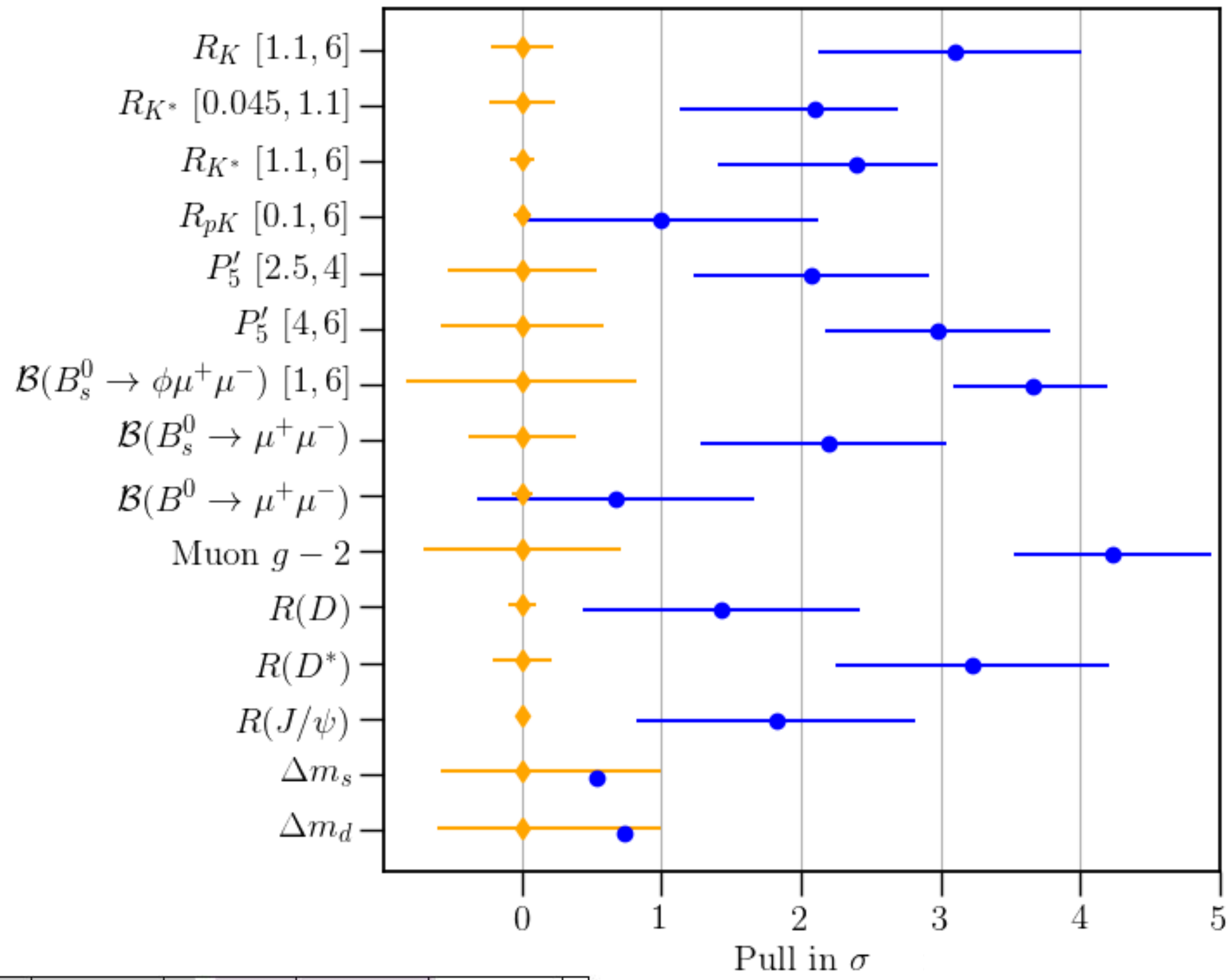
- QCD on very fine lattices
  B → D and B → D* at *w*=*1*

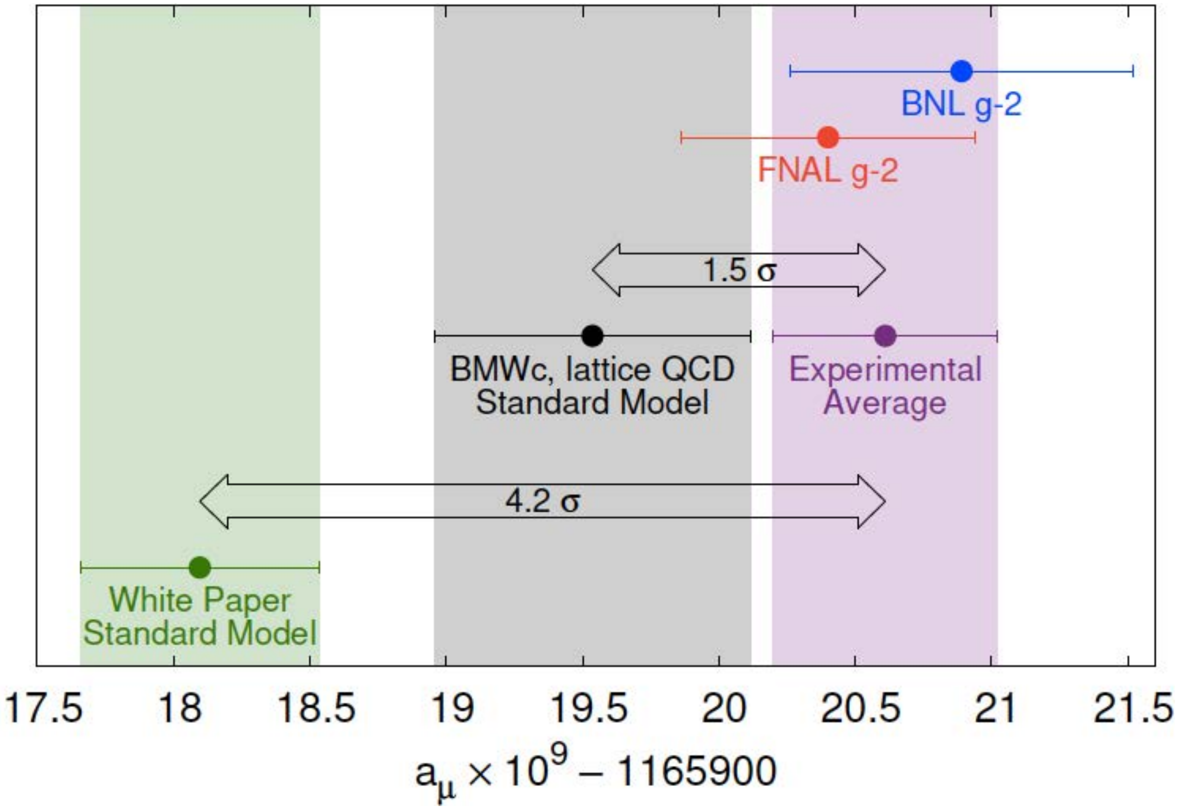
B. Blossier

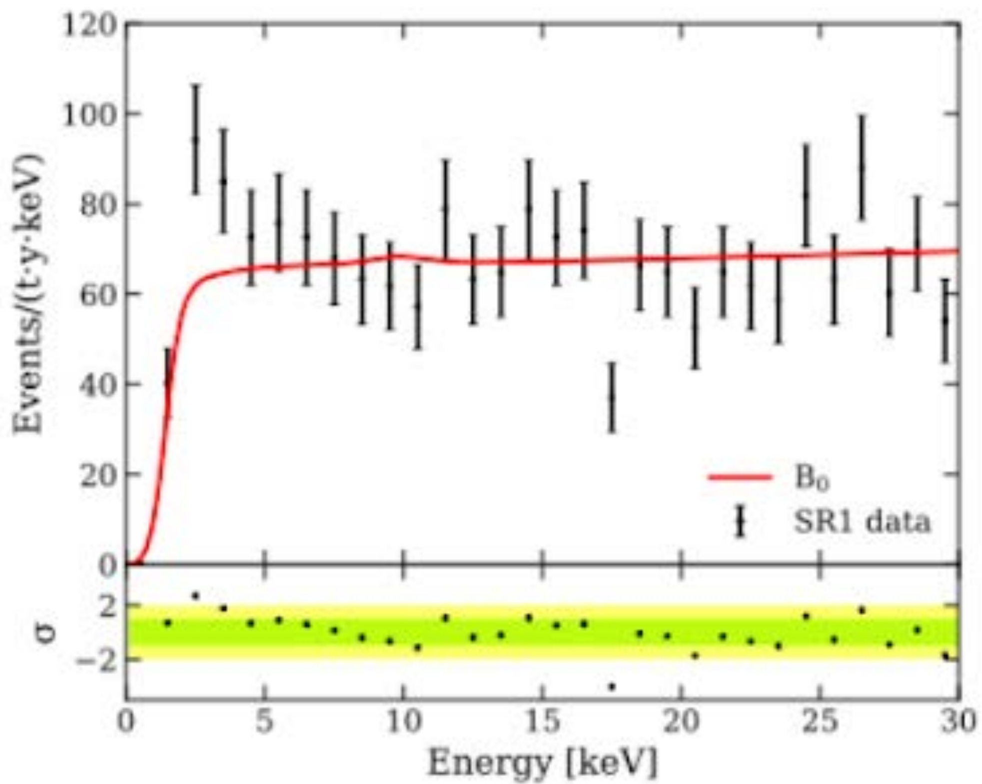
D. B.

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

More Flavor Anomalies







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

LFUV: Experimentally?

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

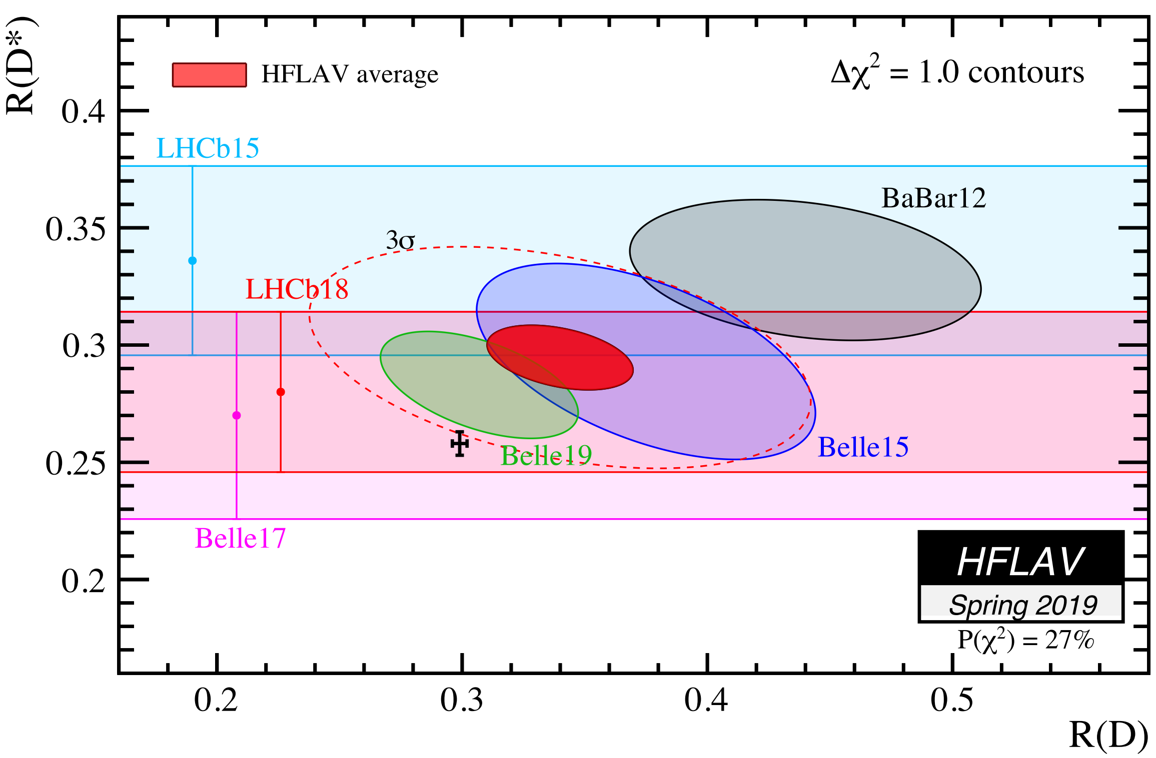
$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

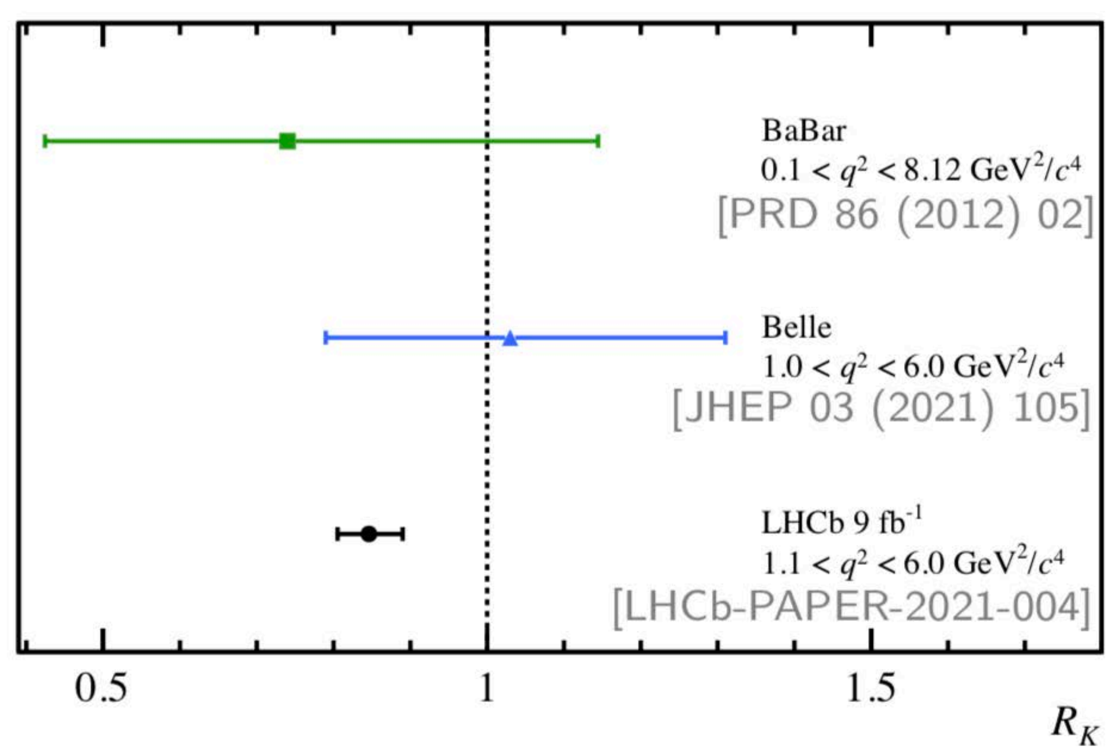
$\text{Exp}: \quad R_D = 0.340\pm0.030\,, \quad R_{D^*} = 0.295\pm0.014$

$\text{SM}: \quad R_D^{\rm SM} = 0.293\pm0.008\,, \quad R_{D^*}^{\rm SM} = 0.257\pm0.003$

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

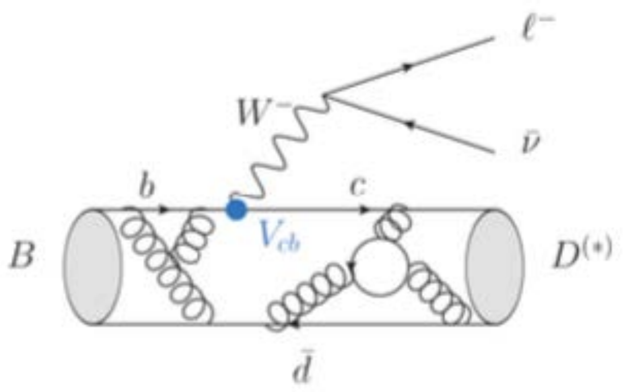
$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb} \quad \text{vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$



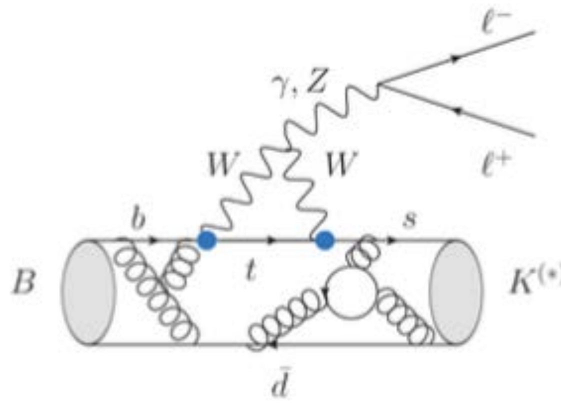


Lepton Flavor Universality Violation

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



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



NEW

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

SM : $R_D = 0.293 \pm 0.008\,, \quad R_{D^*} = 0.248 \pm 0.001$

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

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

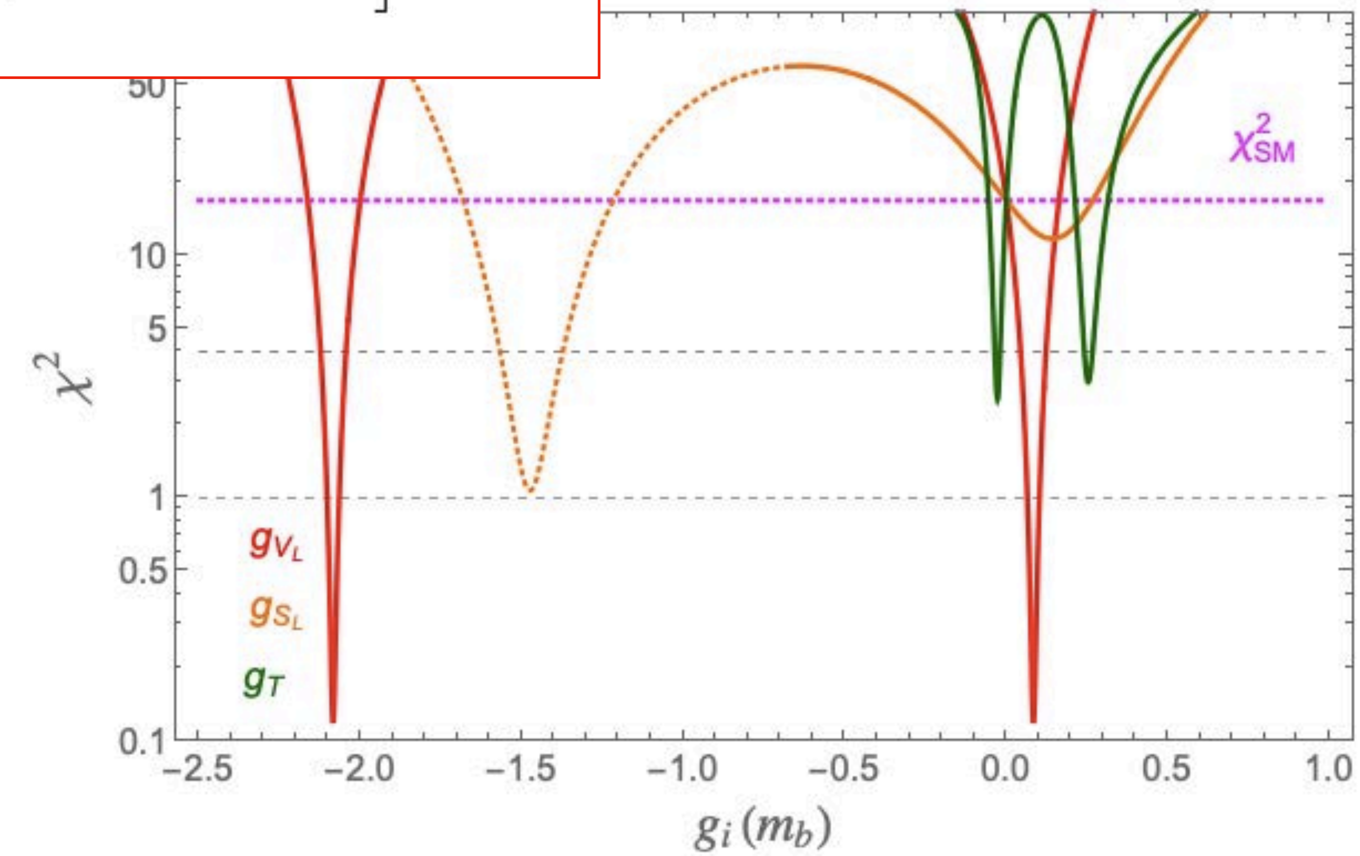
$$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3 \text{ TeV}$$

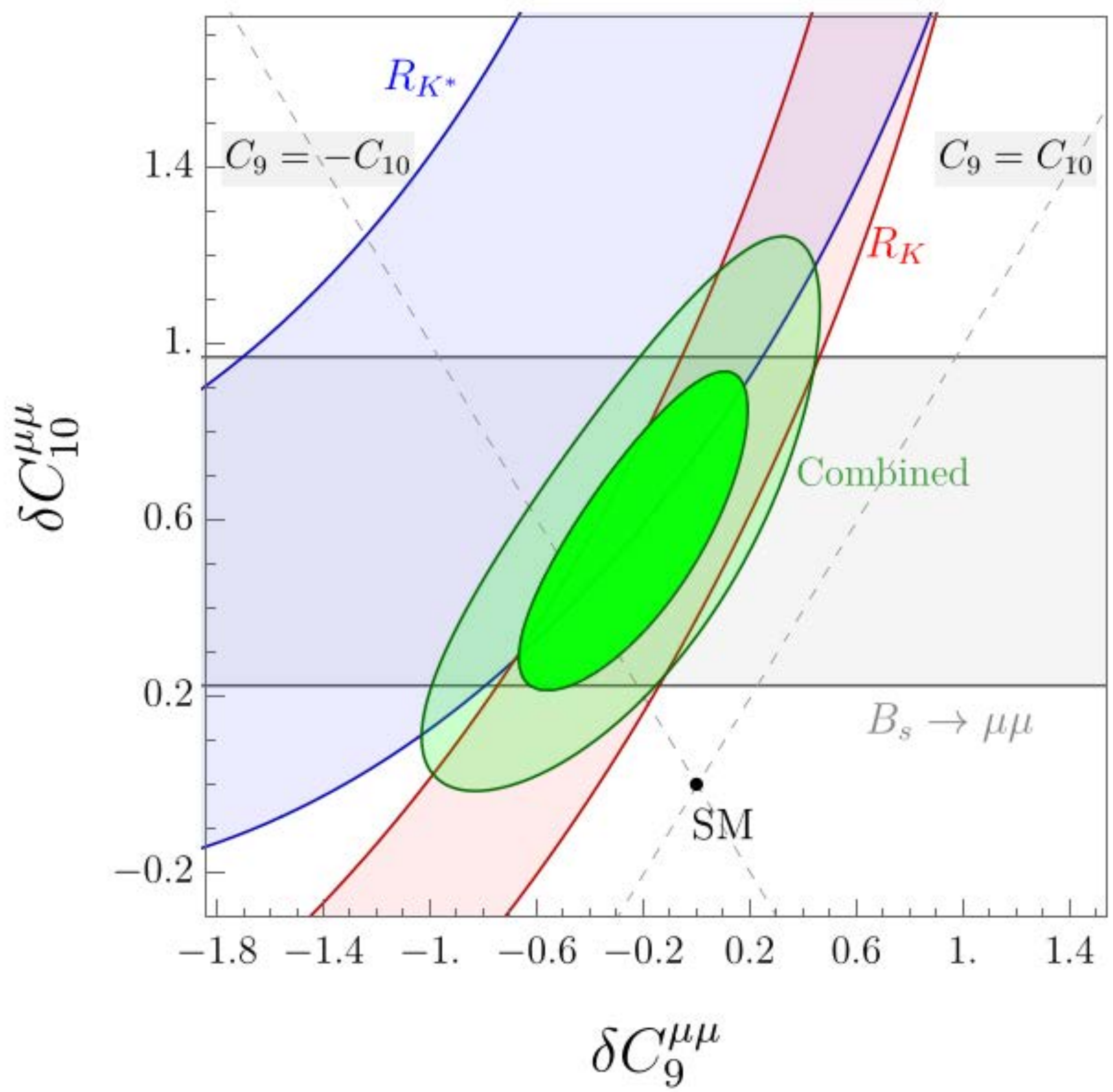
$$R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 30 \text{ TeV}$$

naive NP scale

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

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





$b \to s\mu\mu$

$$\mathcal{L}'_{\rm eff} \supset \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i\,\mathcal{O}_i + \text{h.c.}$$

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell)$$

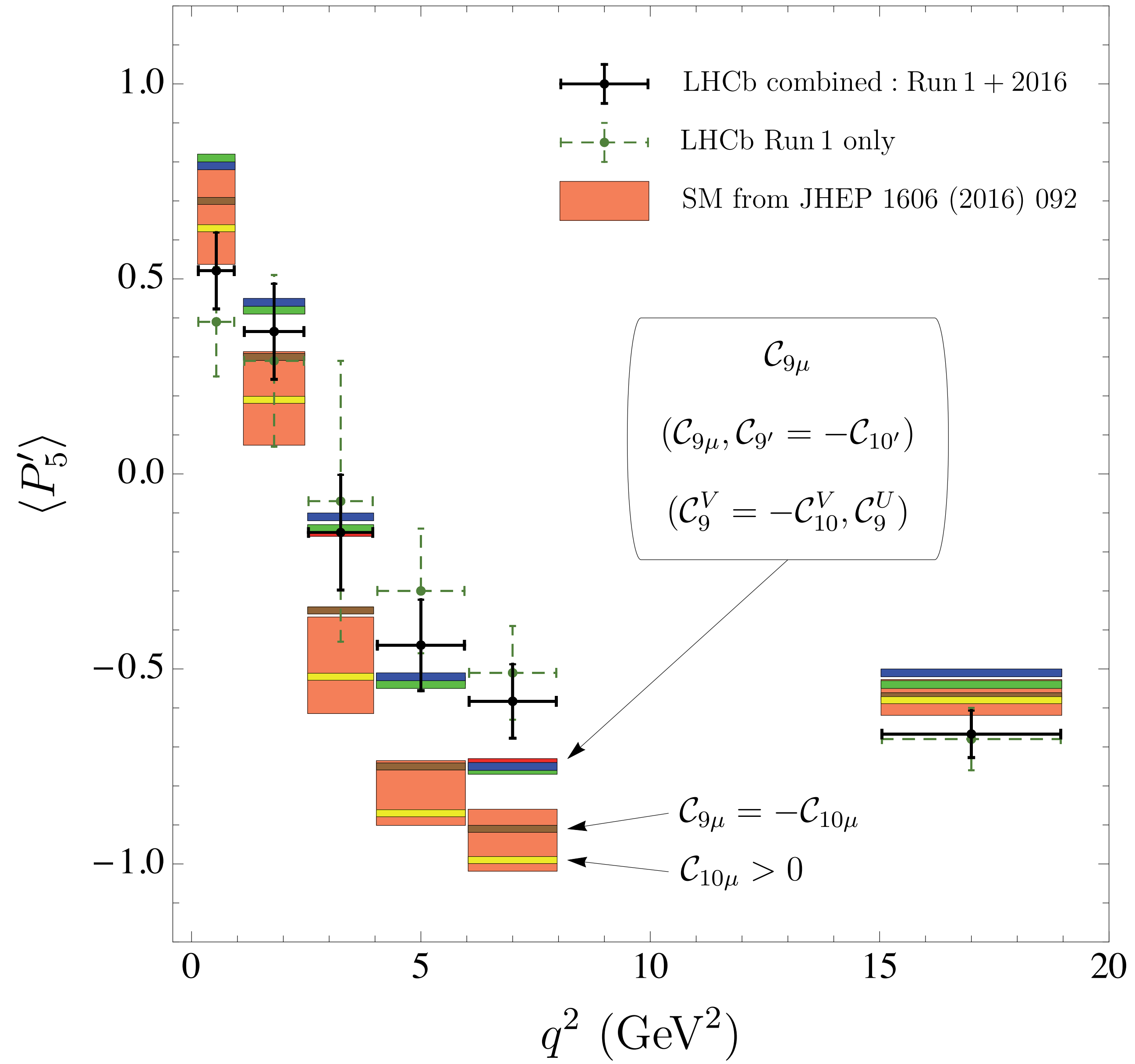
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$

S. Descotes-Genon, N. Mahmoudi, A. Arbey, O. Sumensari, D.B.

Detailed angular distribution can help…

More Observables

$b \to s\mu\mu$



Debate over Hadronic Uncertainties…

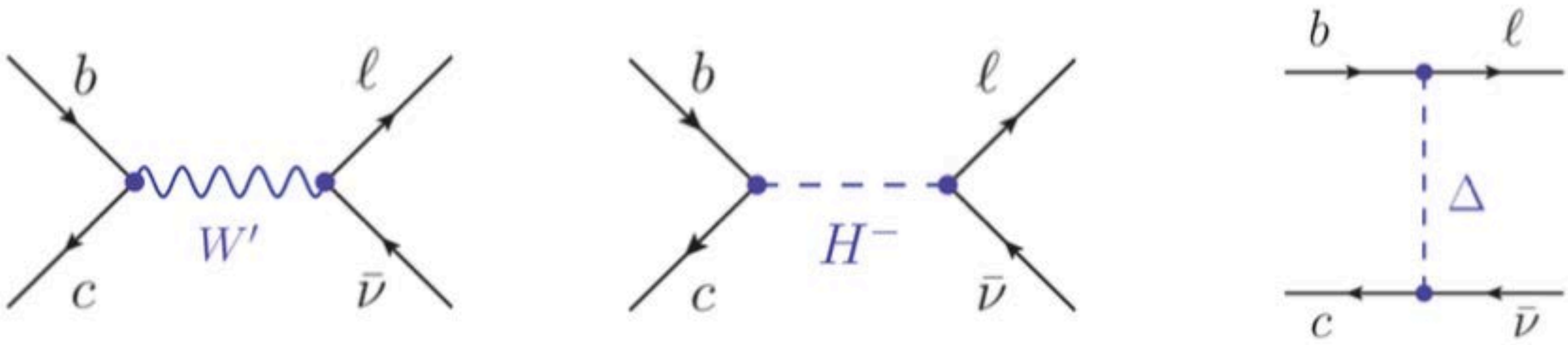
$b \to c\tau\bar{\nu}$

Stay tuned (early results from Belle…)

S. Descotes-Genon, N. Mahmoudi, A. Arbey, E. Kou (γ), O. Sumensari, D.B.

Building a NP model…

E.g. $b \to c\tau\bar{\nu}$



Only a model with $\mathcal{O}$(TeV) leptoquark can simultaneously accommodate

✔ both types of *B* anomalies

✔ wealth of LE flavor physics observables

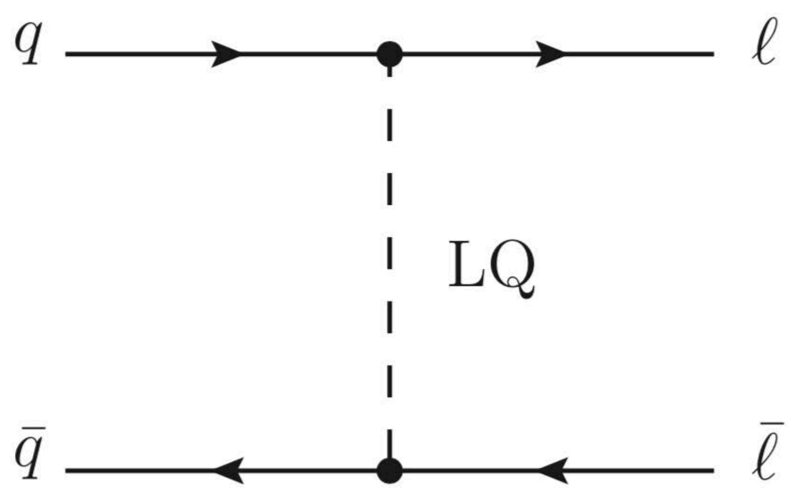
✔ EWPT

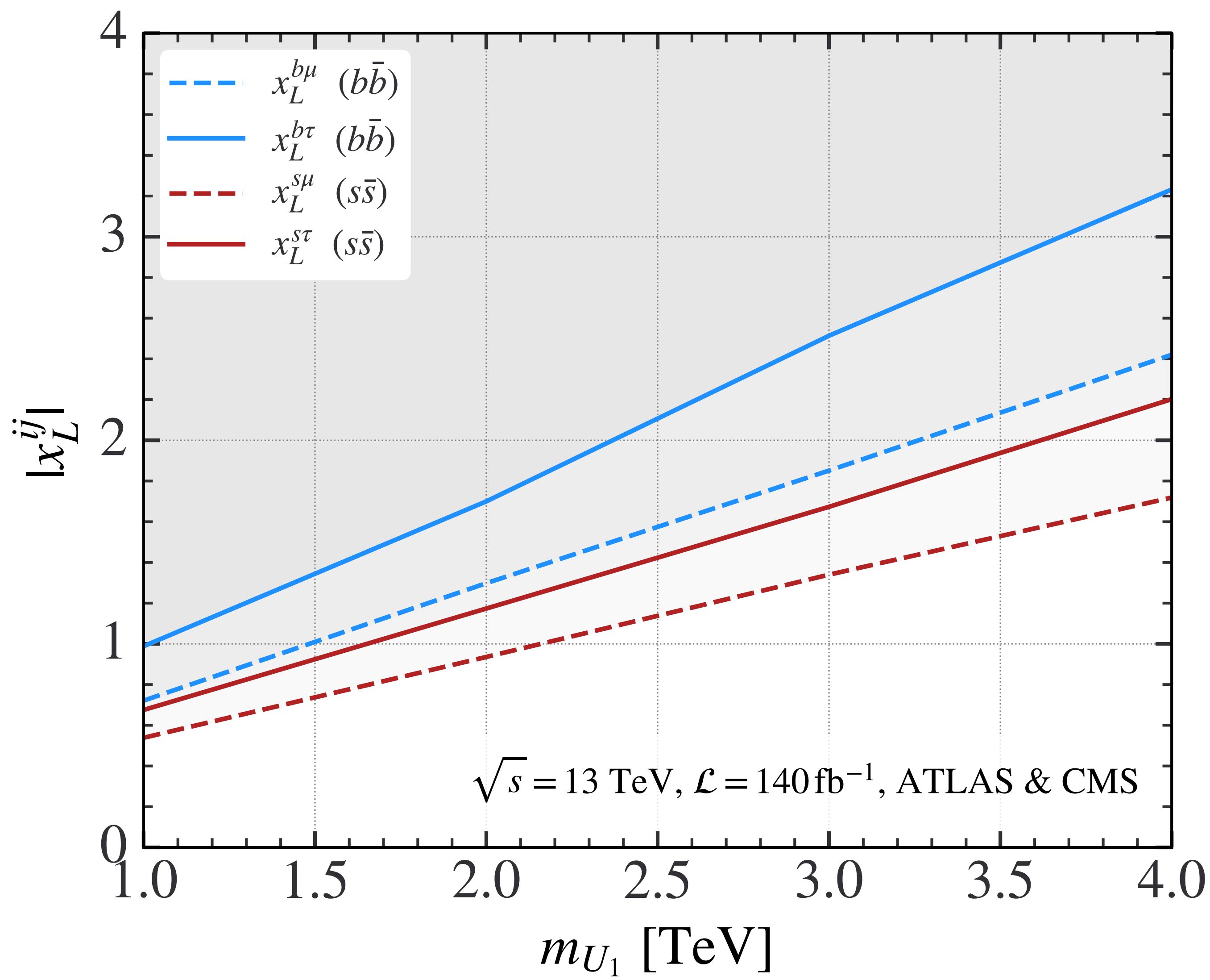
✔ direct LHC searches

If we stick to a minimal extensions (least # of NP parameters)

S. Descotes-Genon, N. Mahmoudi, A. Arbey, A. Teixeira, J. Orloff, A. Deandrea, G. Cacciapaglia O. Sumensari, A. Falkowski, D.B.

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



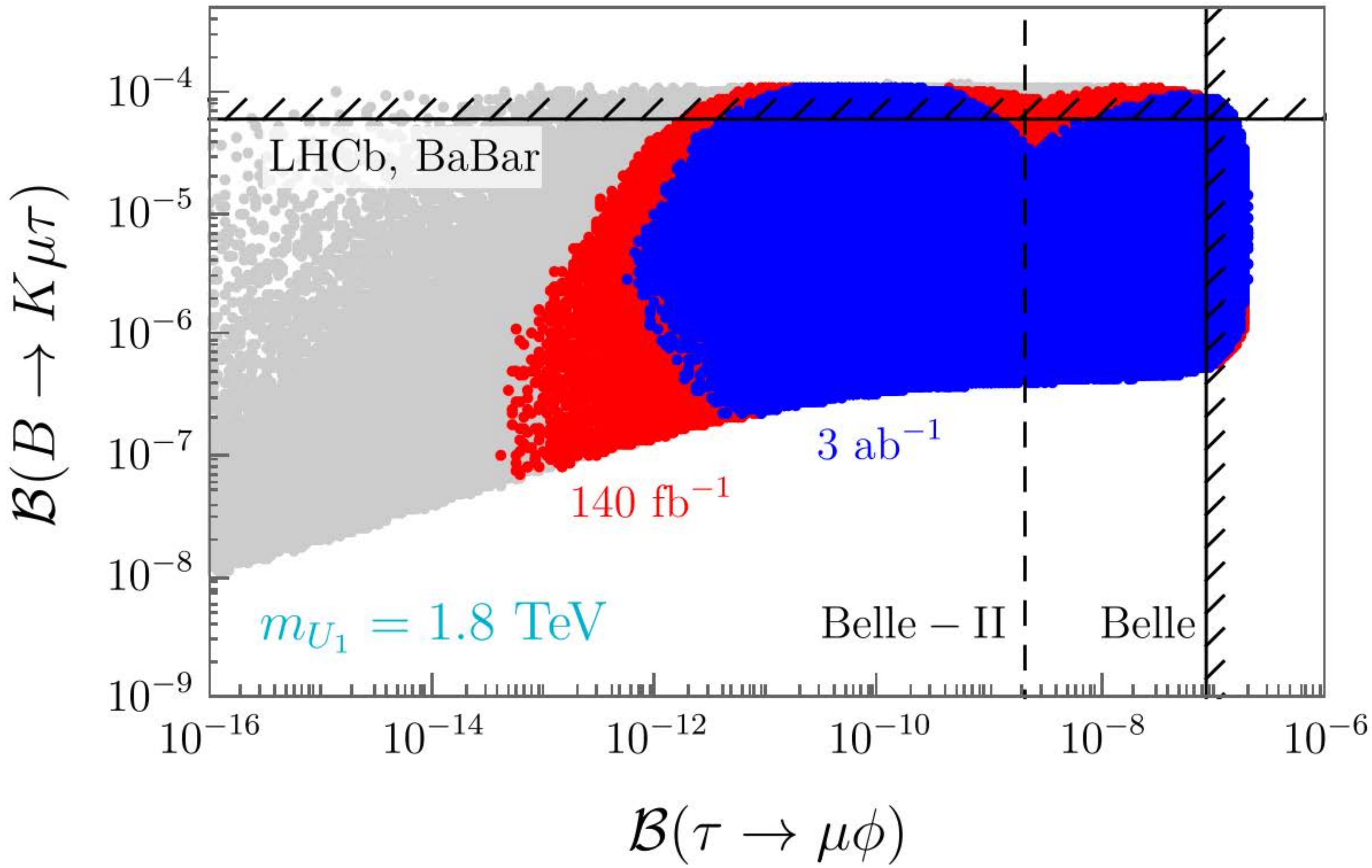


Example U_1

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

O. Sumensari, D.B.

Predictions… LFV



- Way to go 1: Combine two scalar LQs [S_1 with S_3, or R_2 with S_3]
- Way to go 2: Vector LQ (U_1)
  Non-renormalizable and thus requires UV-completion which can be an opportunity to tackle the hierarchy problem!

Compositeness - Alternative

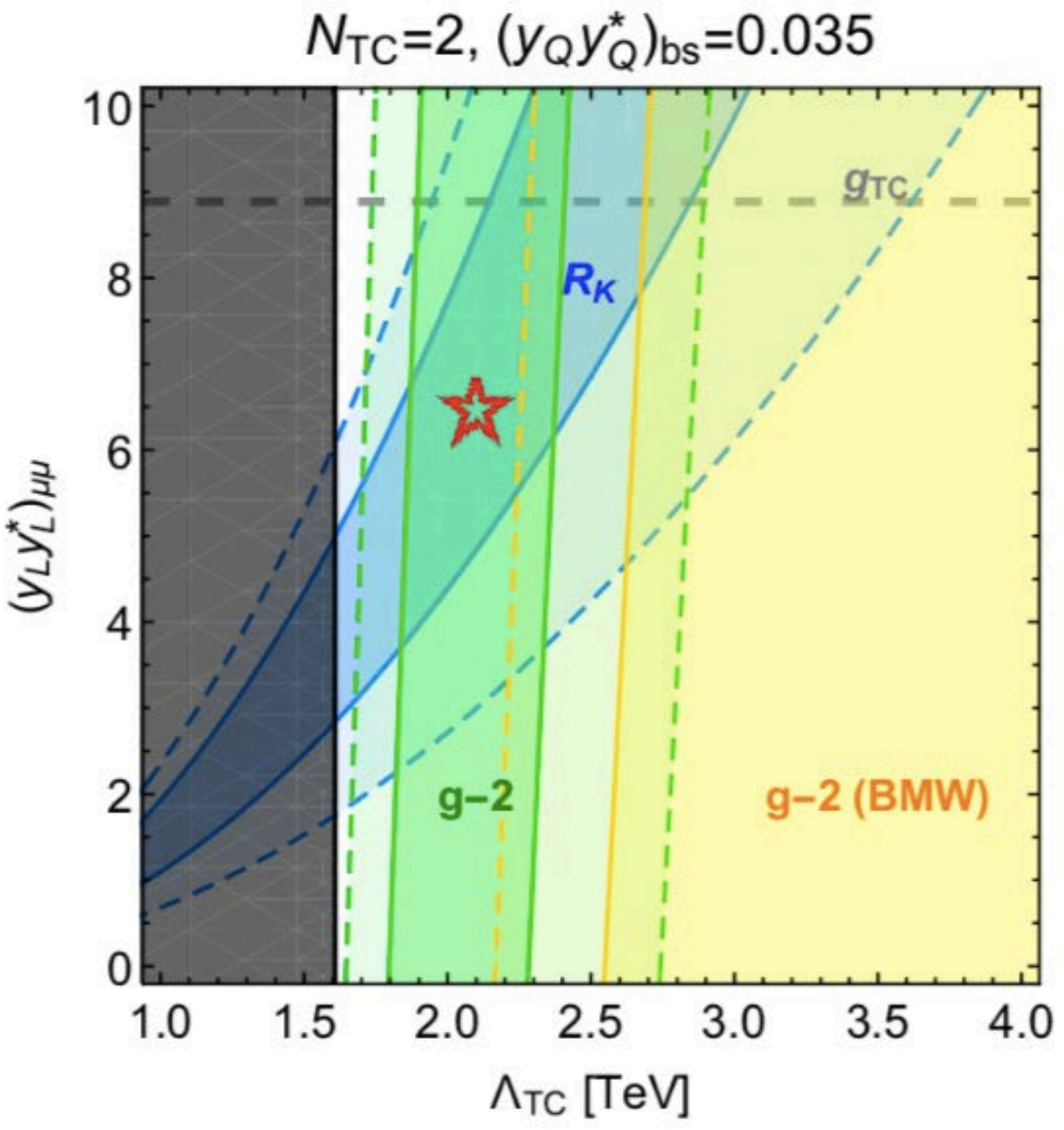
- Composite Higgs
  hierarchy is no more a problem

- Vacuum misalignment along one direction for EWSB, $\sin\theta = v/f$

- Scenario, reminiscing walking TC, constructed to describe "μ anomalies" while staying consistent with LHC data

- Collider phenomenology to be probed at LHC and FCC-ee

- Phenomenology with ALPs
  $m_a \sim \mathcal{O}(10\,\mathrm{GeV})$



A. Deandrea, G. Cacciapaglia