Minimal Flavour Violation and SU(5)-unification

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Invisibles15 Workshop
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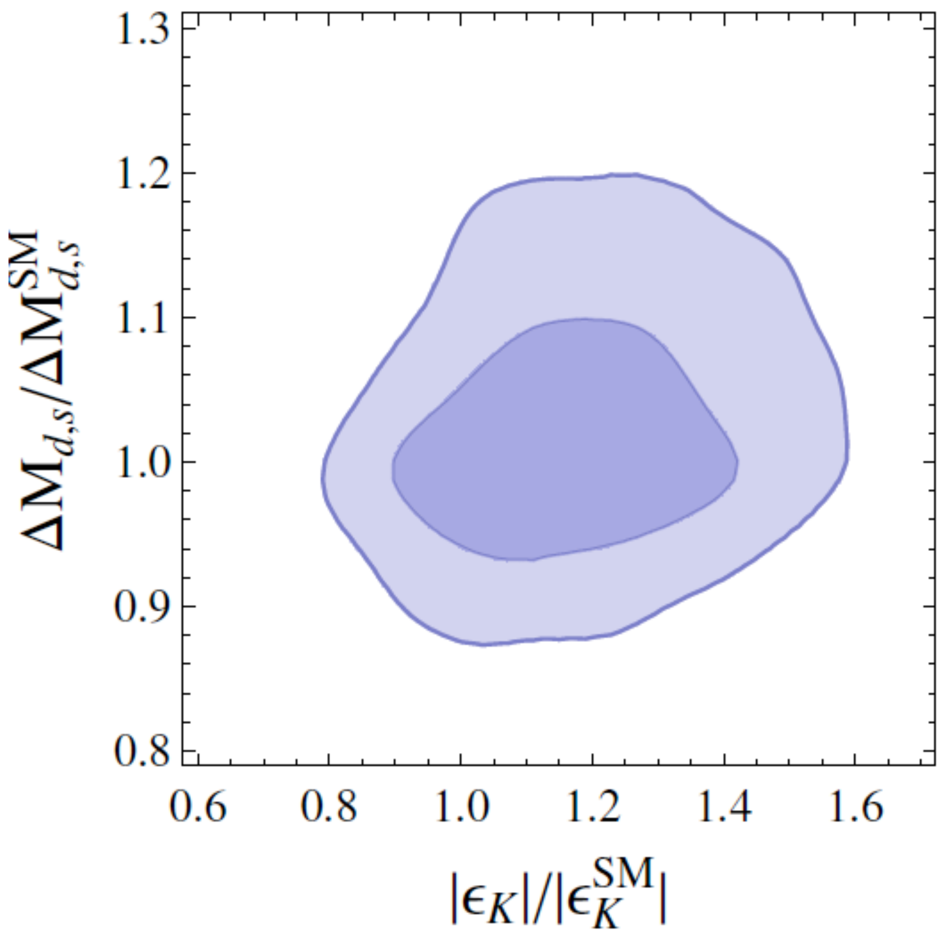
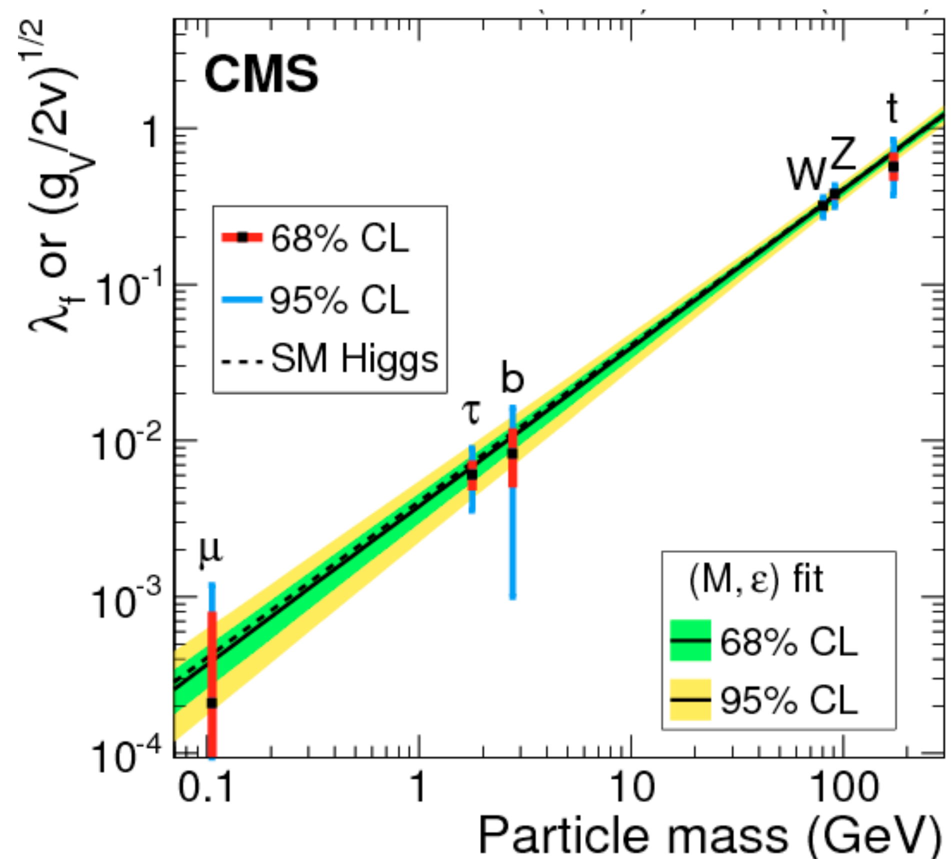
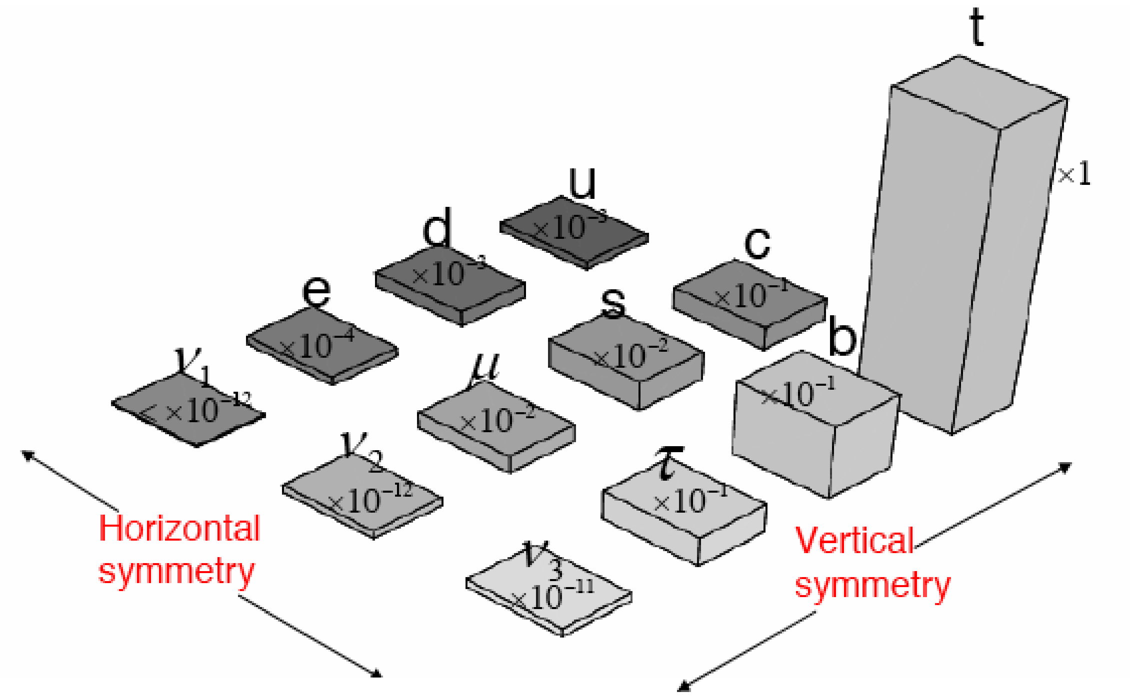
The flavour paradox

Yukawa couplings: a piece of physical reality





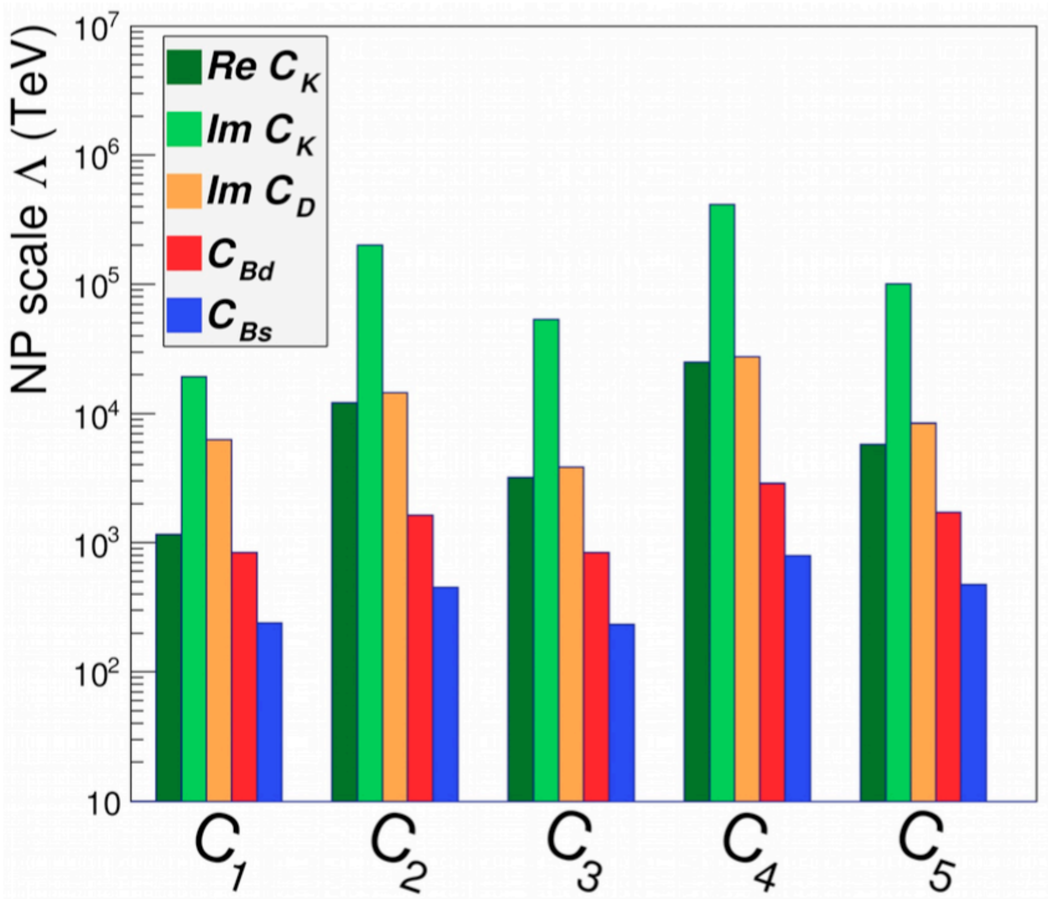
as opposed to:



?!?!?

Which direction to take?

1. High energy exploration



2. Putative anomalies in B-decays

$$V_{ub}\ exc/inc \quad B \to D(D^*)\tau\nu \quad B \to K\mu^+\mu^-/e^+e^-\ P_5'(B \to K^*\mu^+\mu^-)$$

3. Indirect signals of new physics at the TeV scale

Minimal Flavour Violation in the quark sector

Phenomenological Definition:

In EFT the only relevant op.s correspond to the FCNC loops of the SM, weighted by a single scale Λ and by the standard CKM factors (up to $O(1)$ coeff.s)

Strong MFV $U(3)_Q \times U(3)_u \times U(3)_d$

$$Y_u = (3, \bar{3}, 1) \to Y_u^D \qquad Y_d = (3, 1, \bar{3}) \to V Y_d^D$$

$$\Rightarrow \quad A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} (1 + a_1 (\frac{4\pi M_W}{\Lambda})^2)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} (1 + a_2 (\frac{4\pi M_W}{\Lambda})^2)$$

Weak MFV

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$y_b = (1,1,1)_{-1} \quad \lambda_u = (2,\bar{2},1)_0 \quad \lambda_d = (2,1,\bar{2})_0 \quad \mathbf{V} = (2,1,1)_0$$

$$\Rightarrow \quad Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline 0 & y_t \end{array}\right) \qquad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \qquad \mathbf{V} = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix} \qquad \lambda_{u,d} = U^{(12)}_{u,d} \lambda^D_{u,d}$$

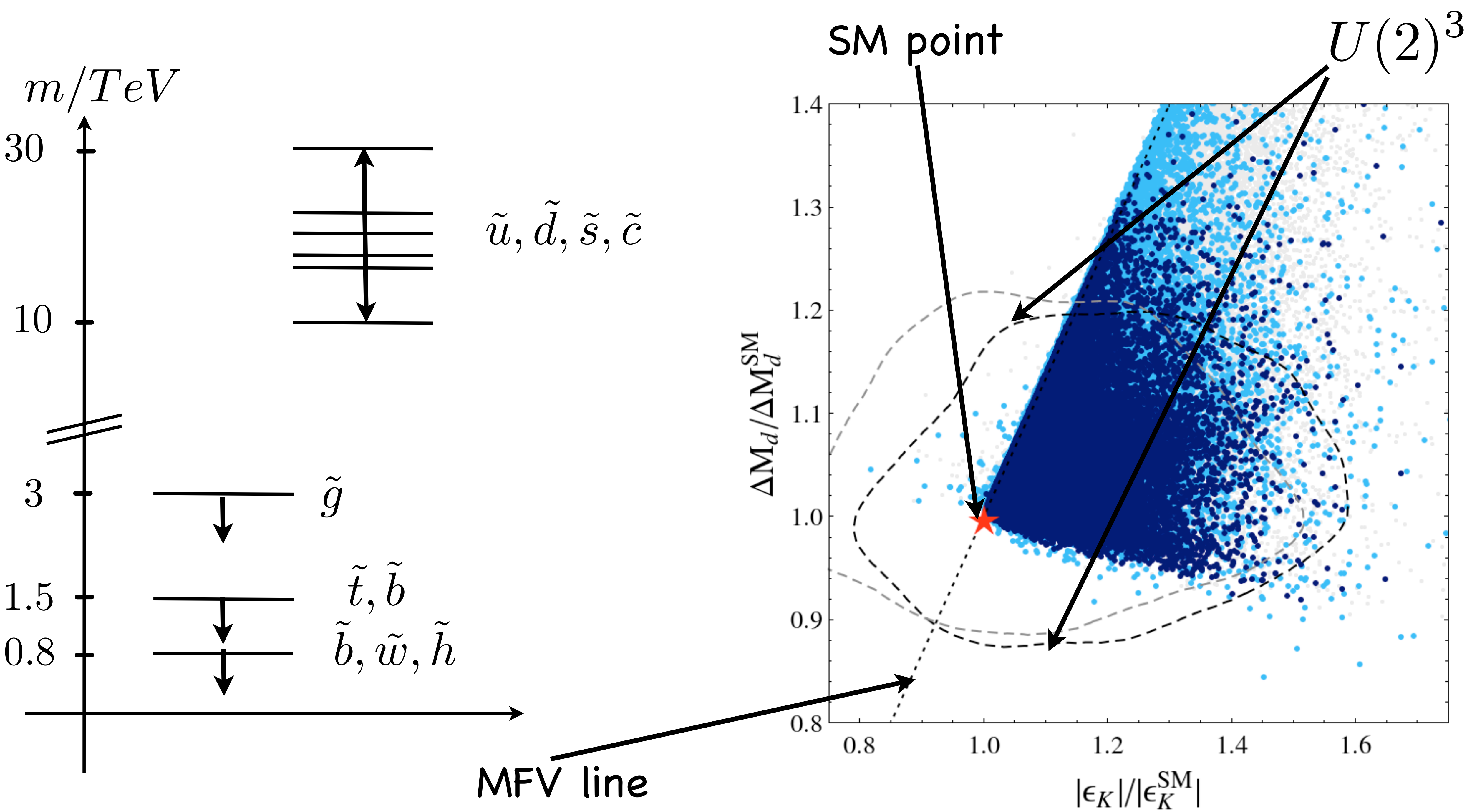
$$Y_u \approx U_u Y_u^D \qquad Y_d \approx U_d Y_d^D \qquad U_{u,d} \approx U^{(23)}_{u,d} U^{(12)}_{u,d}$$

$$V_{CKM} = U_u^+ U_d = \begin{pmatrix} c_L^u c_L^d & \lambda & s_L^u s\, e^{-i\delta} \\ -\lambda & c_L^u c_L^d & c_L^u s \\ -s_L^d s\, e^{i(\delta+\phi)} & -c_L^d s & 1 \end{pmatrix} \qquad \begin{array}{c} s \sim O(\epsilon) \\ s_L^u c_L^d - s_L^d c_L^u e^{i\phi} = \lambda e^{i\delta} \end{array}$$

$$A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} \left(1 + (a_{1b}, a_{1s}) \left(\frac{4\pi M_W}{\Lambda}\right)^2\right)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} \left(1 + (a_{2b}, a_{2s}) \left(\frac{4\pi M_W}{\Lambda}\right)^2\right)$$

An example: "Natural" SUSY



points allowed by present ATLAS/CMS

light points: "compressed spectra" $m_{\tilde{g}} - m_{\chi_1^0} \lesssim 350\,\text{GeV}$ or $m_{\tilde{t}} - m_{\chi_1^0} \lesssim 150\,\text{GeV}$

dark points: "naive" bounds $m_{\tilde{g}} \gtrsim 1.4\,\text{TeV}$, $m_{\tilde{t},\tilde{b}} \gtrsim 0.7\,\text{TeV}$

How to extend this picture to leptons?

1. Include neutrinos. E.g.

$$\bar{L} Y_e e + \bar{L} Y_N N + N M N \qquad U(3)_L \times U(3)_e \times U(3)_N$$

$$\Rightarrow \quad Y_e = Y_e^D \qquad M_N = M_N^D \qquad Y_N = U_L Y_N^D U_R$$

both physical (U_L, U_R)

2. Assume that neutrinos do not affect LFV in charged lepton sector and go to unification $\Leftarrow$

Technically OK if $|M_{ij}| \lesssim 10^{11}\ GeV$

since $|Y_N Y_N^+| \lesssim 10^{-4} \dfrac{m_\nu}{0.1\ eV} \dfrac{M}{10^{11}\ GeV}$

MFV and SU(5)-unification

$U(3)_T \times U(3)_{\bar{F}} \equiv U(3)^2$

$$\mathcal{L}_Y^{U(3)} = TY_uTH_5 + TY_1\bar{F}H_{\bar{5}} + TY_2\bar{F}H_{45}$$

$Y_1,\ Y_2 = (\bar{3},\bar{3})$ both crucial for $\mu - s,\ e - d$ mass difference

$\Rightarrow$ at low energy $Y_u \to Y_u^D$ $Y_d \to VY_d^D$ as in $U(3)^3$

but $Y_e = V_L Y_e^D V_R$

both physical

Cirigliano, Grinstein, Isidori, Wise

MFV and SU(5)-unification

$$U(2)_T \times U(2)_{\bar F} \times U(1)_{\bar F 3} \equiv U(2)^2$$

$$\mathcal{L}_Y^{U(2)} = y_t T_3 T_3 H_5 + y_t x_t \mathbf{T}\mathbf{V} T_3 H_5 + \mathbf{T}\Delta_u \mathbf{T} H_5$$
$$+ y_b T_3 \bar F_3 H_{\bar 5} + y_b x_b \mathbf{T}\mathbf{V} \bar F_3 H_{\bar 5} + \mathbf{T}\Delta_1 \bar{\mathbf{F}} H_{\bar 5} + \mathbf{T}\Delta_2 \bar{\mathbf{F}} H_{45}$$

$m_\tau \approx m_b$ small enough for $m_e \approx m_s/3$ $m_\mu \approx 3 m_s$

⇒ at low energy

$$Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline y_t x_t \mathbf{V}^T & y_t. \end{array}\right) \qquad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \qquad Y_e = \left(\begin{array}{c|c} \lambda_e & 0 \\ \hline y_\tau x_\tau \mathbf{V}^T & y_\tau \end{array}\right)$$

with λ_e and λ_d almost aligned

⇒ LFV predicted in terms of the CKM angles

RB, Senia

Main new effects (bounds)

$$\mathcal{L}_i = \frac{c_i\ \xi^i_{CKM}}{\Lambda^2}\mathcal{O}_i$$

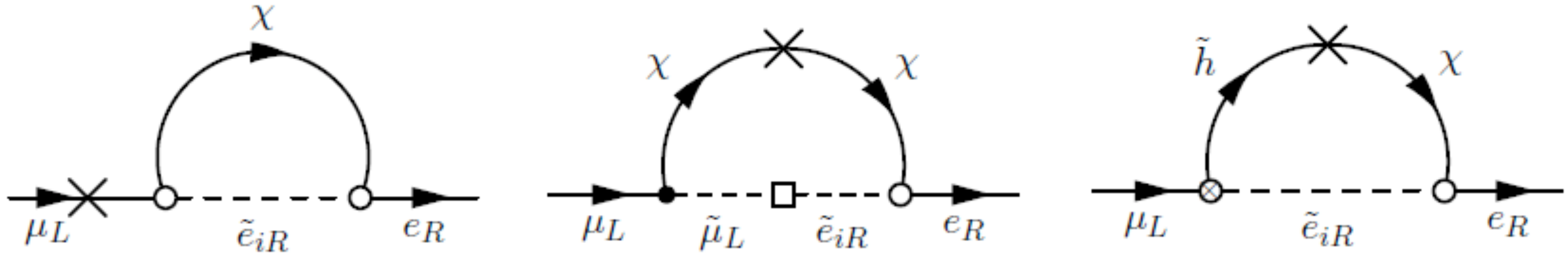
Observable	$\mu \to e\gamma$ ×	e EDM	u EDM	d EDM	ϵ' ×	$A_{CP}^{\Delta C=1}$ ×
Coefficient	$\lvert c^{\mu\to e\gamma}\rvert$	$\lvert \mathrm{Im}(\tilde{c}_e^{EDM})\rvert$	$\lvert \mathrm{Im}(\tilde{c}_u^{EDM})\rvert$	$\lvert \mathrm{Im}(c_d^{EDM})\rvert$	$\lvert c^{\Delta S=1}\sin\phi\rvert$	$\lvert c^{\Delta C=1}\rvert$
Upper bound	5×10^{-4}	1.6×10^{-5}	1.2×10^{-2}	5.6×10^{-3}	6.5×10^{-2}	0.2

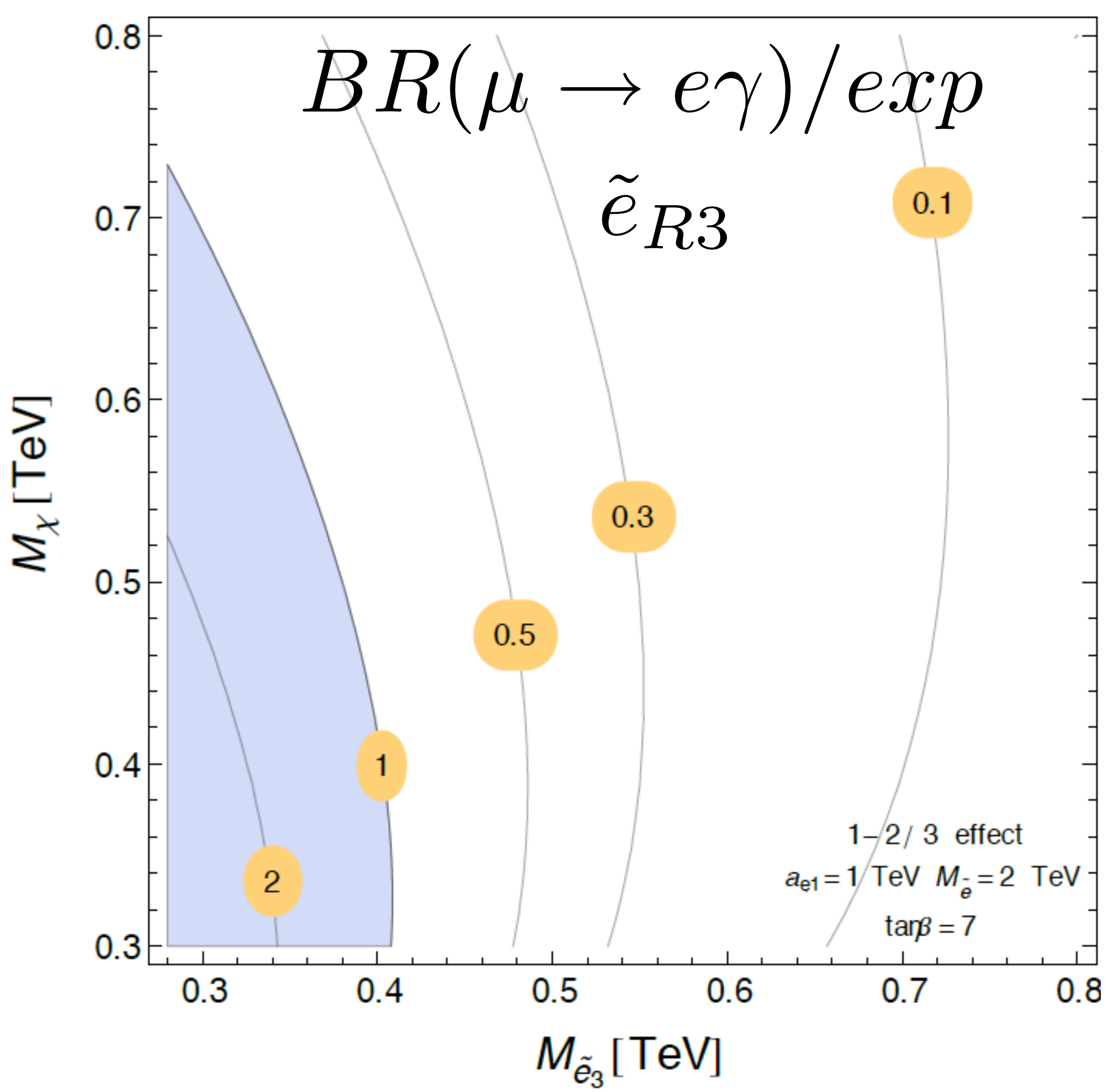
normalized at $\Lambda = 3\ TeV$

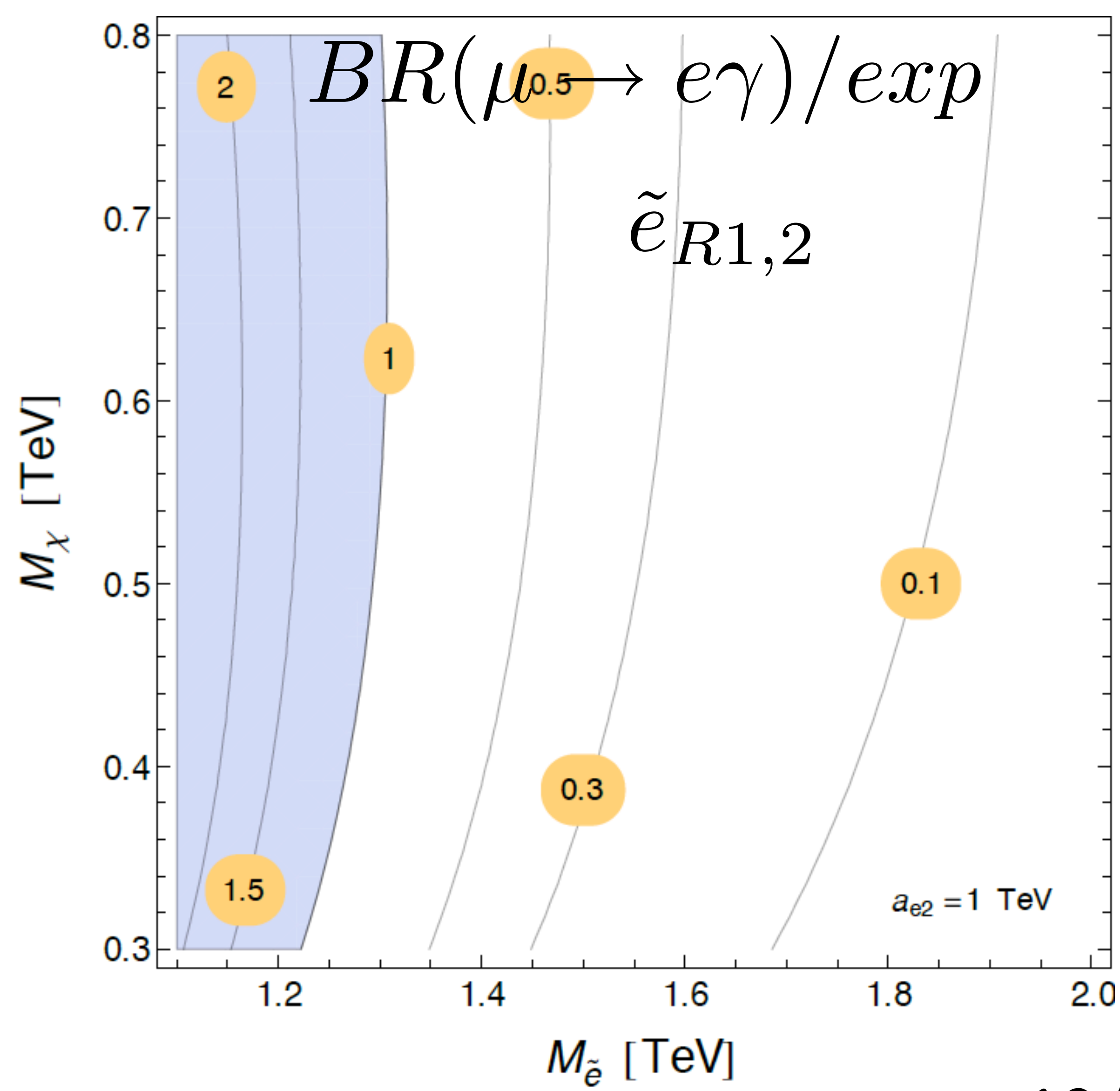
Coefficients of other FCNF effects $(\Delta B = 2,1;\ \Delta S = 1,2)$ as in $U(2)^3$ are at typical $10^{-(1\div2)}$ level, depending on their phases

$U(2)^2$ in supersymmetry

As above in SUSY SU(5) with soft terms as in SUGRA

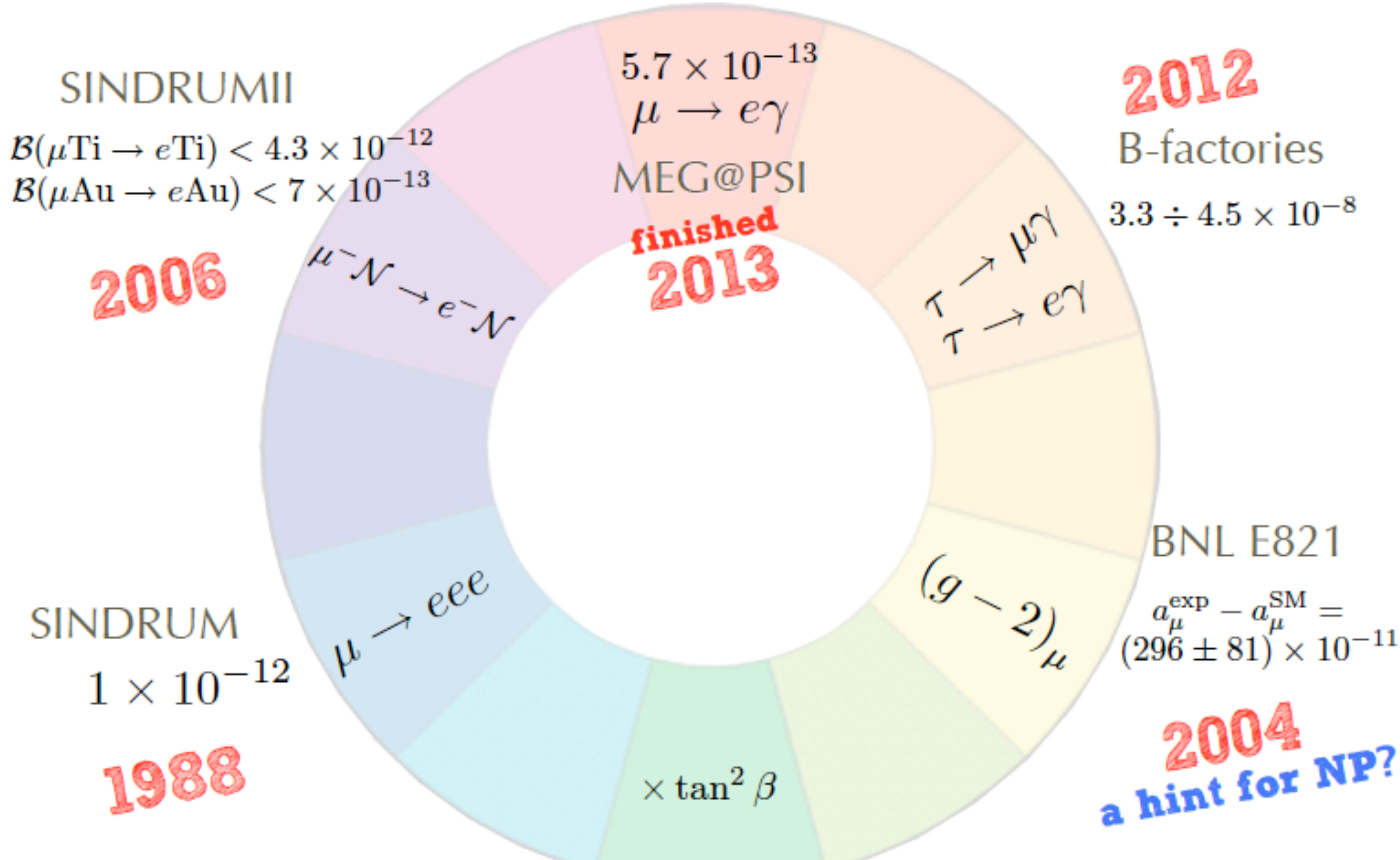




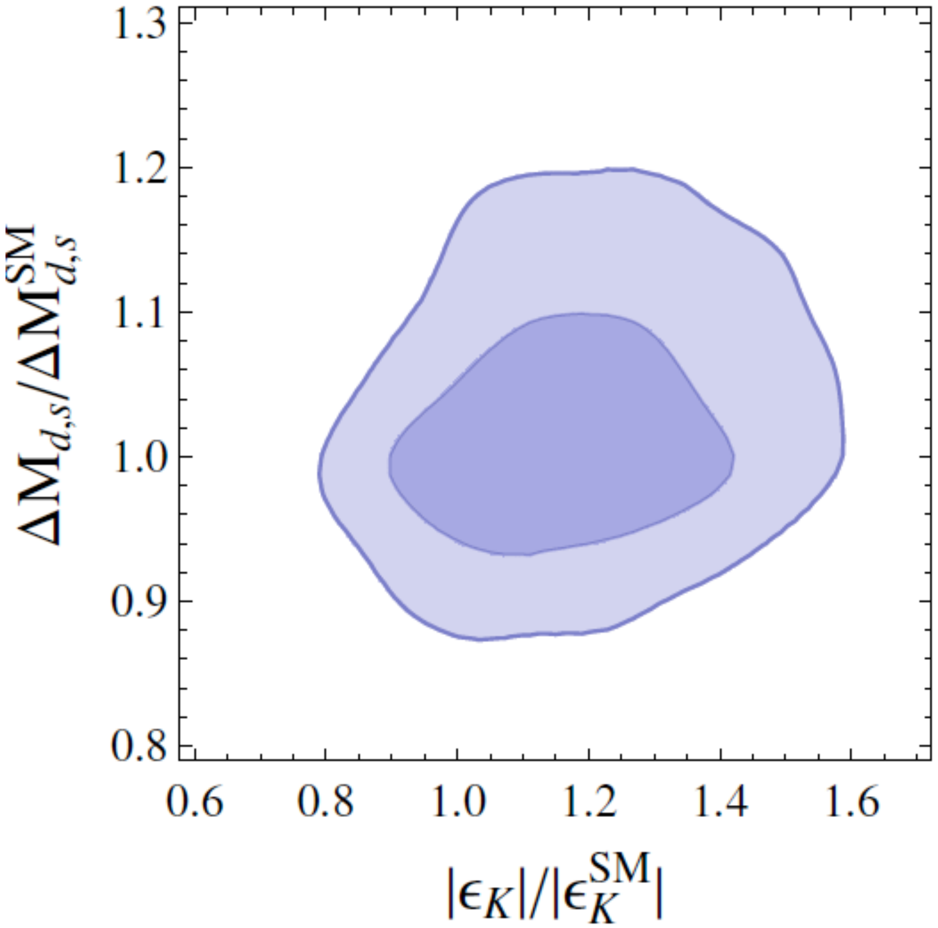


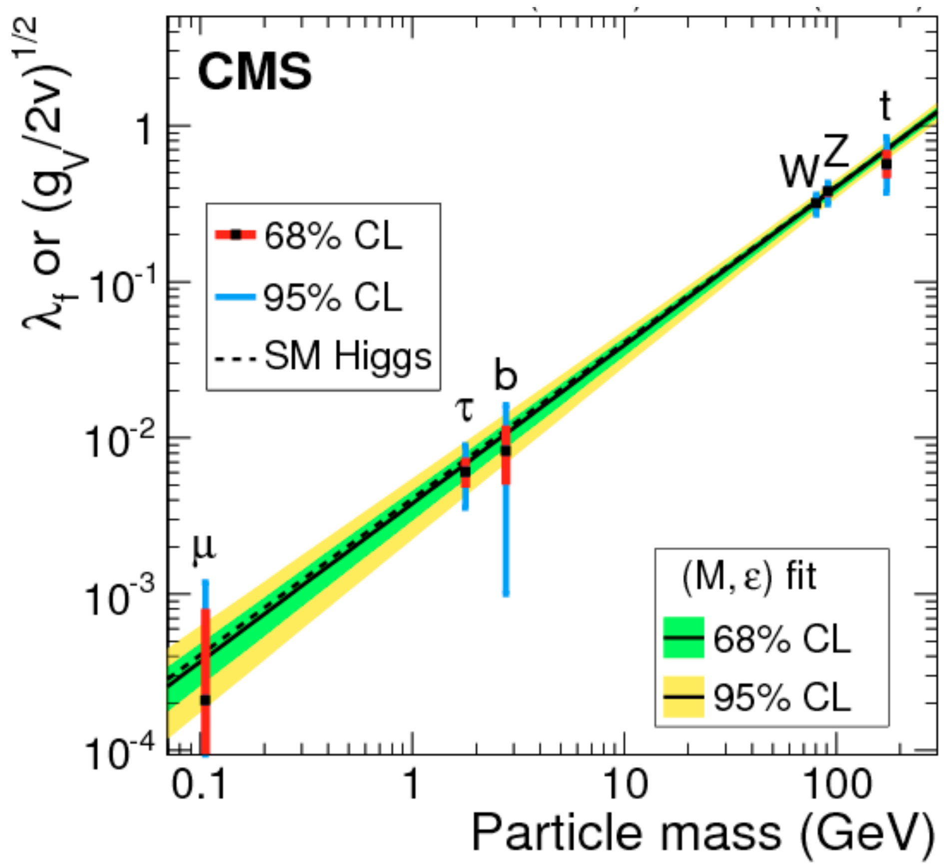
(up to O(1) uncertainty in the amplitude)

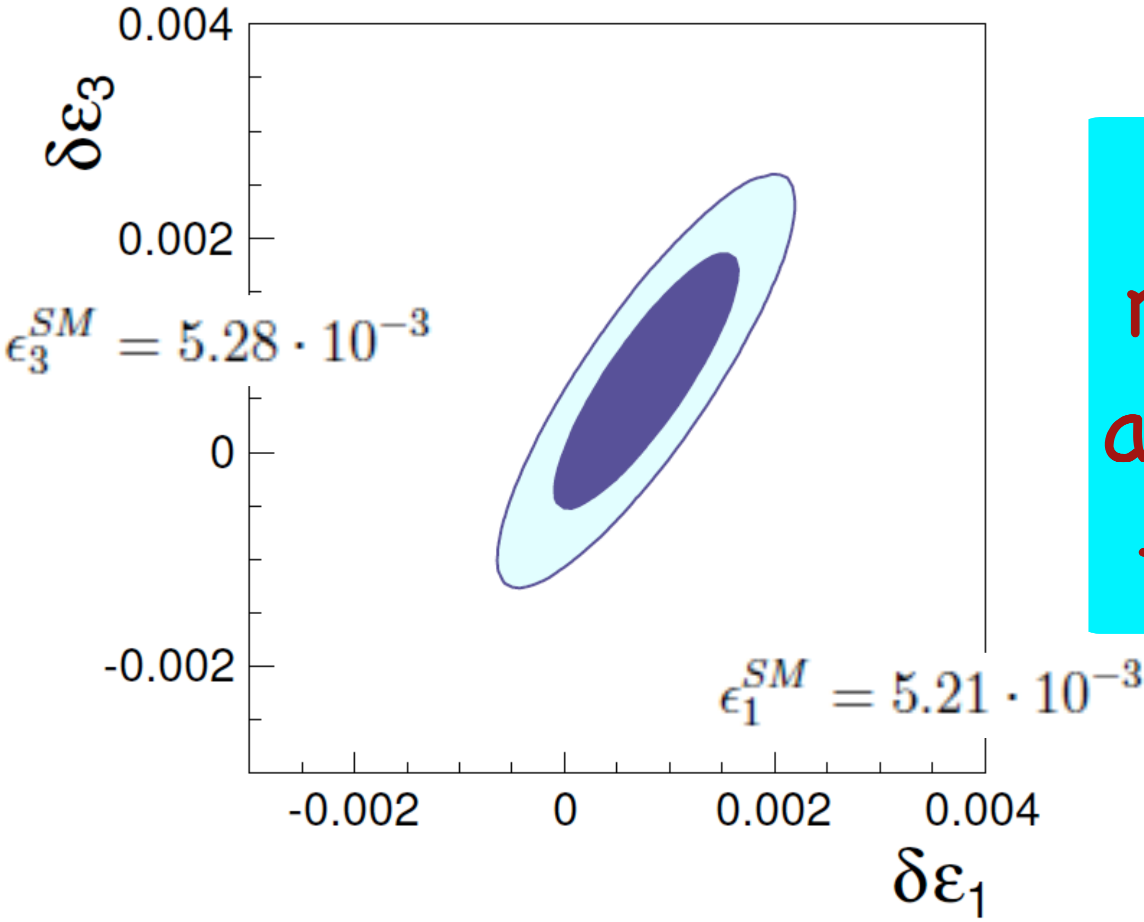
Current limits



time for improvement





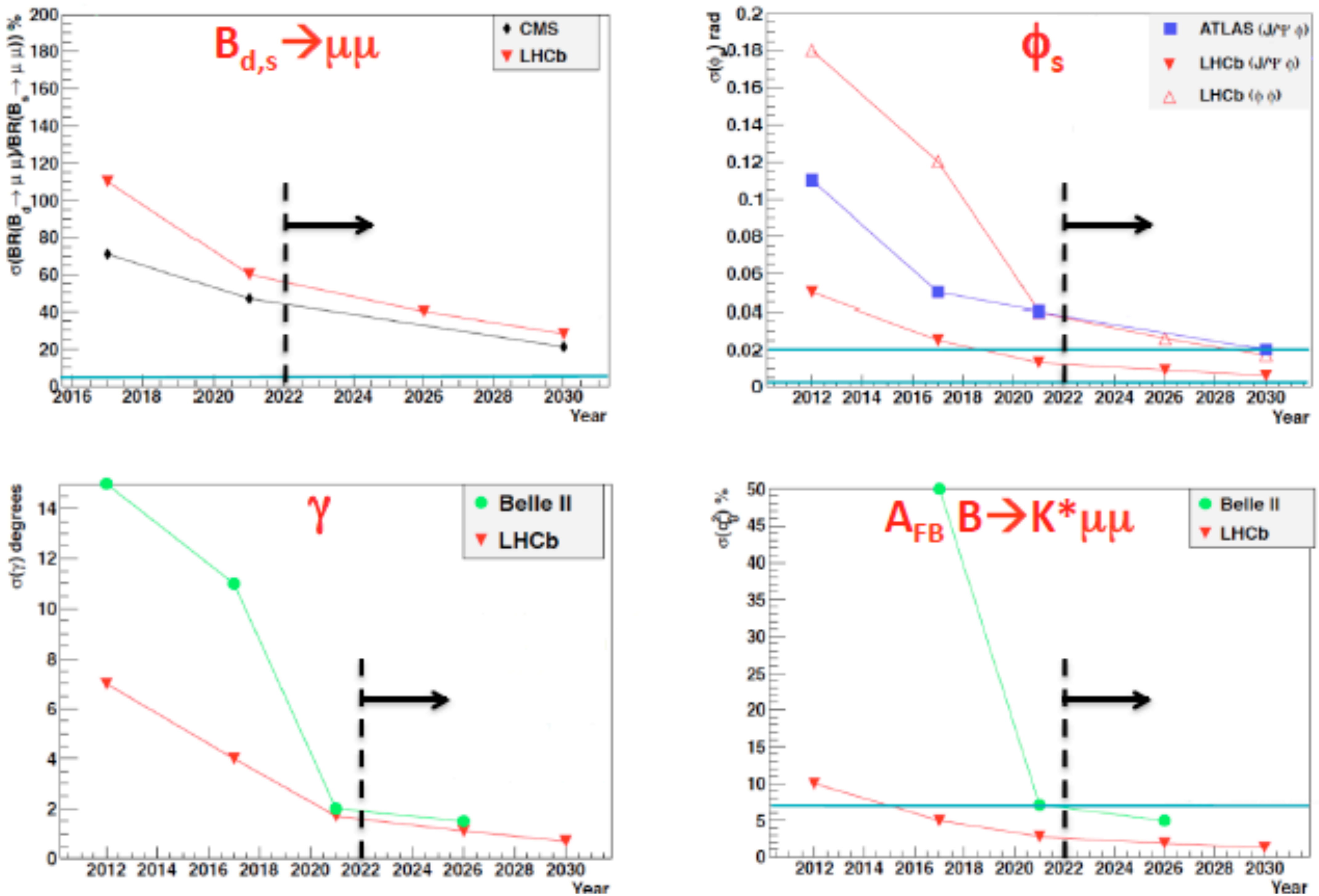


A suitable flavour program can reduce errors on CKM tests from about 20% (now, similar to $\delta\epsilon_i/\epsilon_i^{SM}$) to $\lesssim$ 1% (in a decade?)

An "Extreme Flavour" experiment?

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}$ $cm^{-2}s^{-1}$

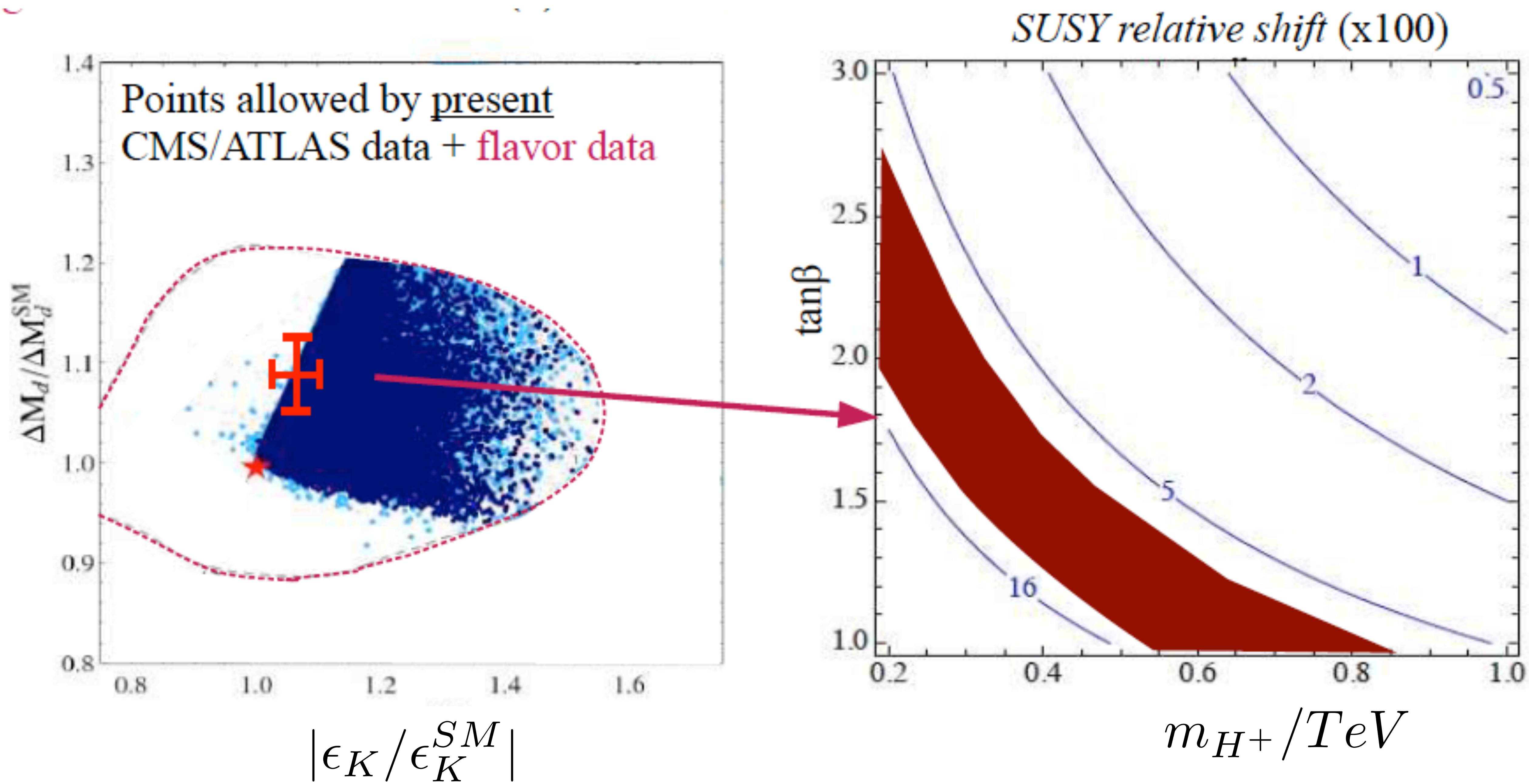
Nice prospects in the quark sector …



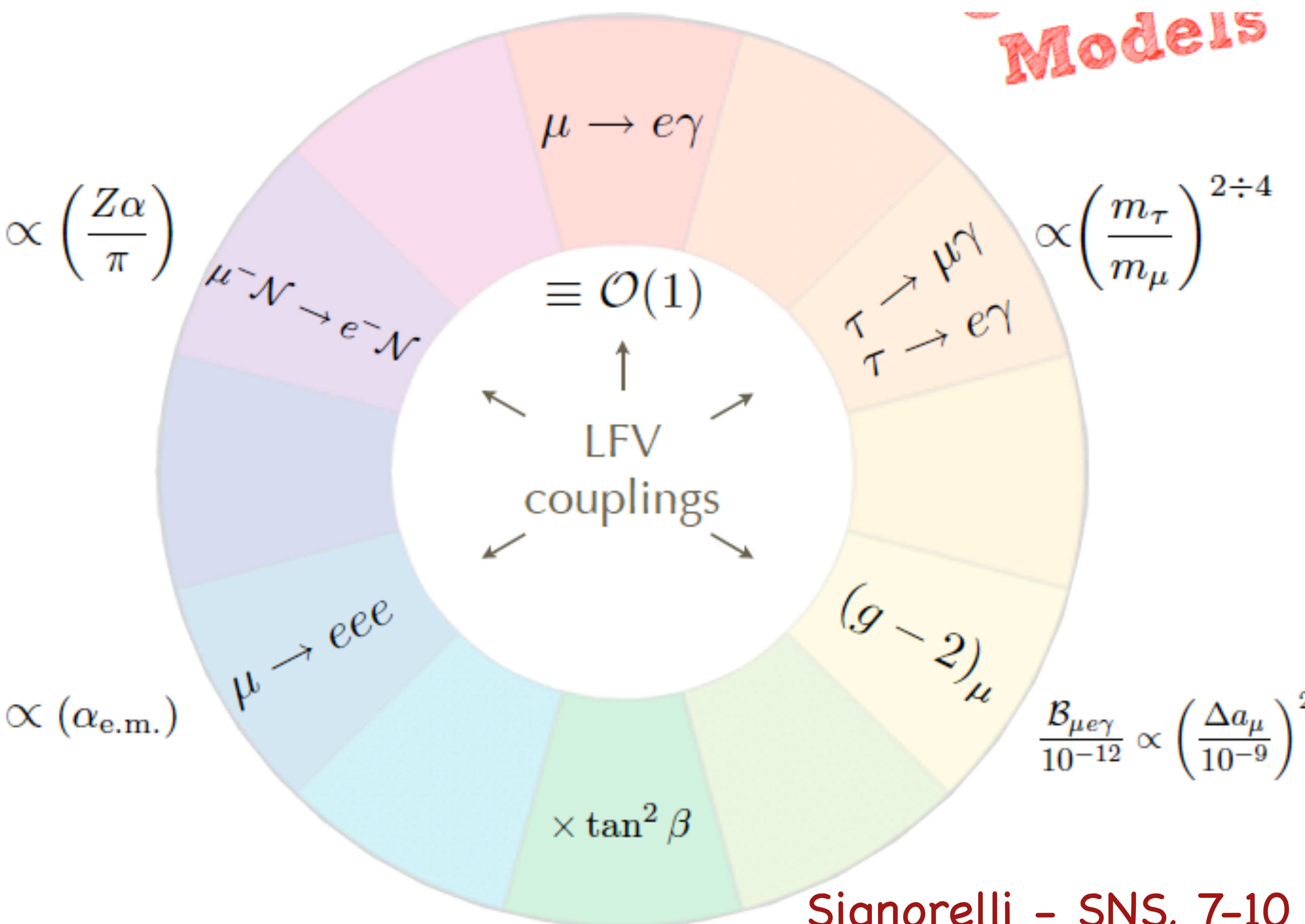
...but flattening out after ~2022

“Natural” SUSY

Flavour constraints on top of direct searches



Lepton Flavour Violation



Signorelli - SNS, 7-10 Dec 2014

Motivation: extra degrees of freedom + unification

Outlook of the Outlook

In the current confusing state of fundamental physics useful/necessary to have a diversified program (LHC, precision, flavour, astro-cosmo-particle, DM)