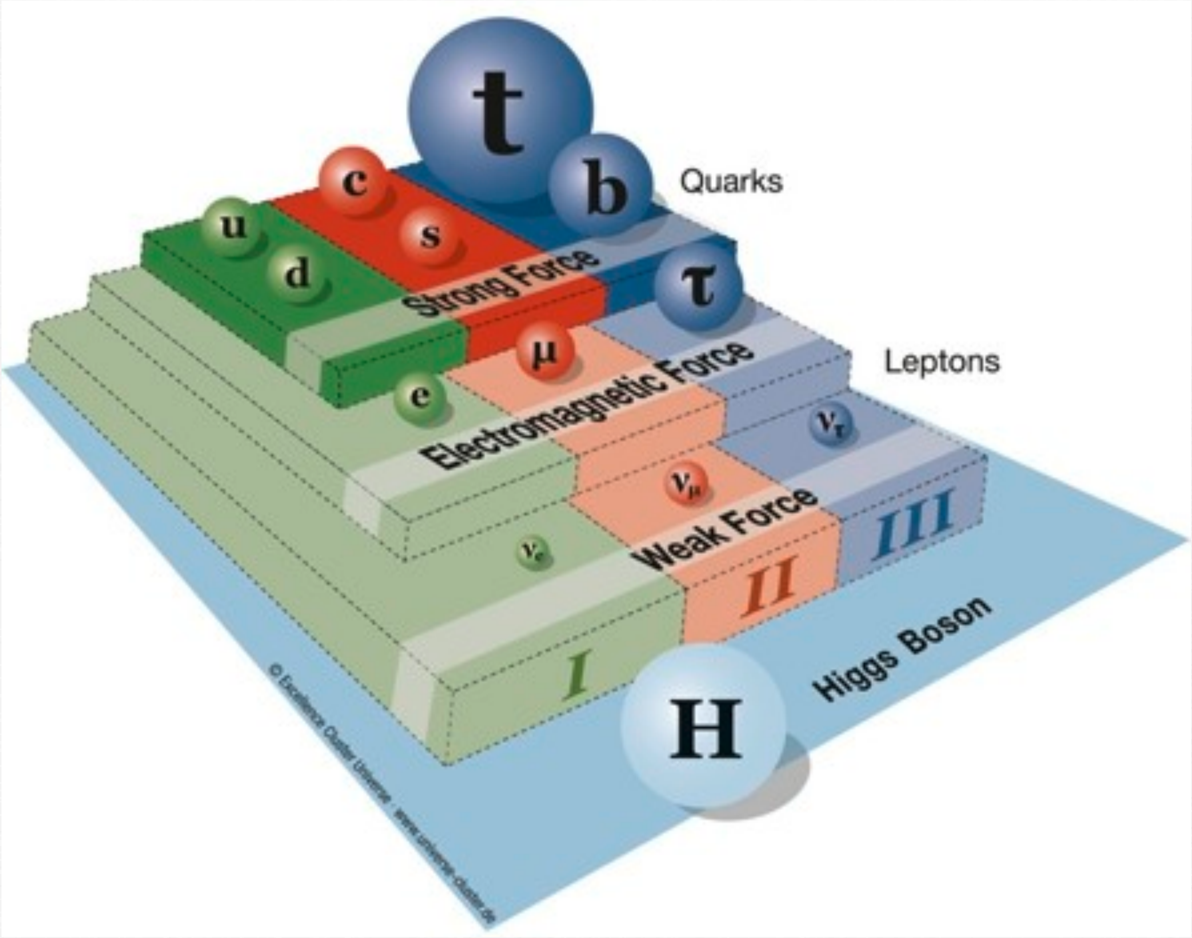
University of Southampton
School of Physics and Astronomy

Flavour Predictions from SUSY GUTs with Family Symmetry

Steve King, UK Flavour 2013, Durham

The Standard Model



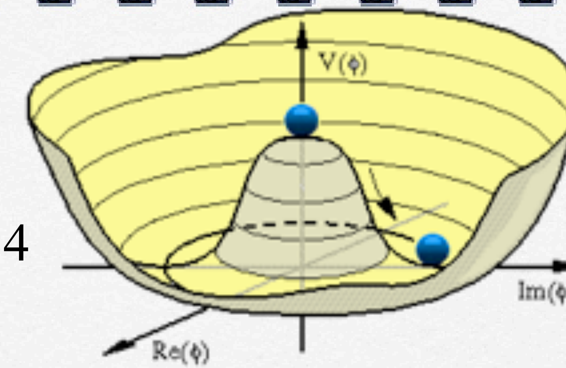
Standard Model Puzzles

1. The origin of mass - the origin of the weak scale, its stability under radiative corrections, and the solution to the hierarchy problem

2. The quest for unification - the question of whether the three known forces of the standard model may be related into a grand unified theory, and whether such a theory could also include a unification with gravity.

3. The problem of flavour - the problem of the undetermined fermion masses and mixing angles (including neutrino masses and mixing angles) together with the CP violating phases, in conjunction with the observed smallness of flavour changing neutral currents and very small strong CP violation.

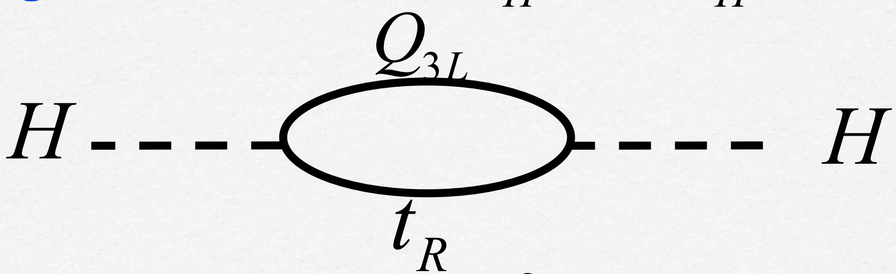
Higgs Theory in SM



Higgs potential $$V = m_H^2 |H|^2 + \tfrac{1}{2}\lambda |H|^4$$

Tree-level min cond $$m_H^2 = -\lambda v^2 = -\lambda (246\,GeV)^2$$

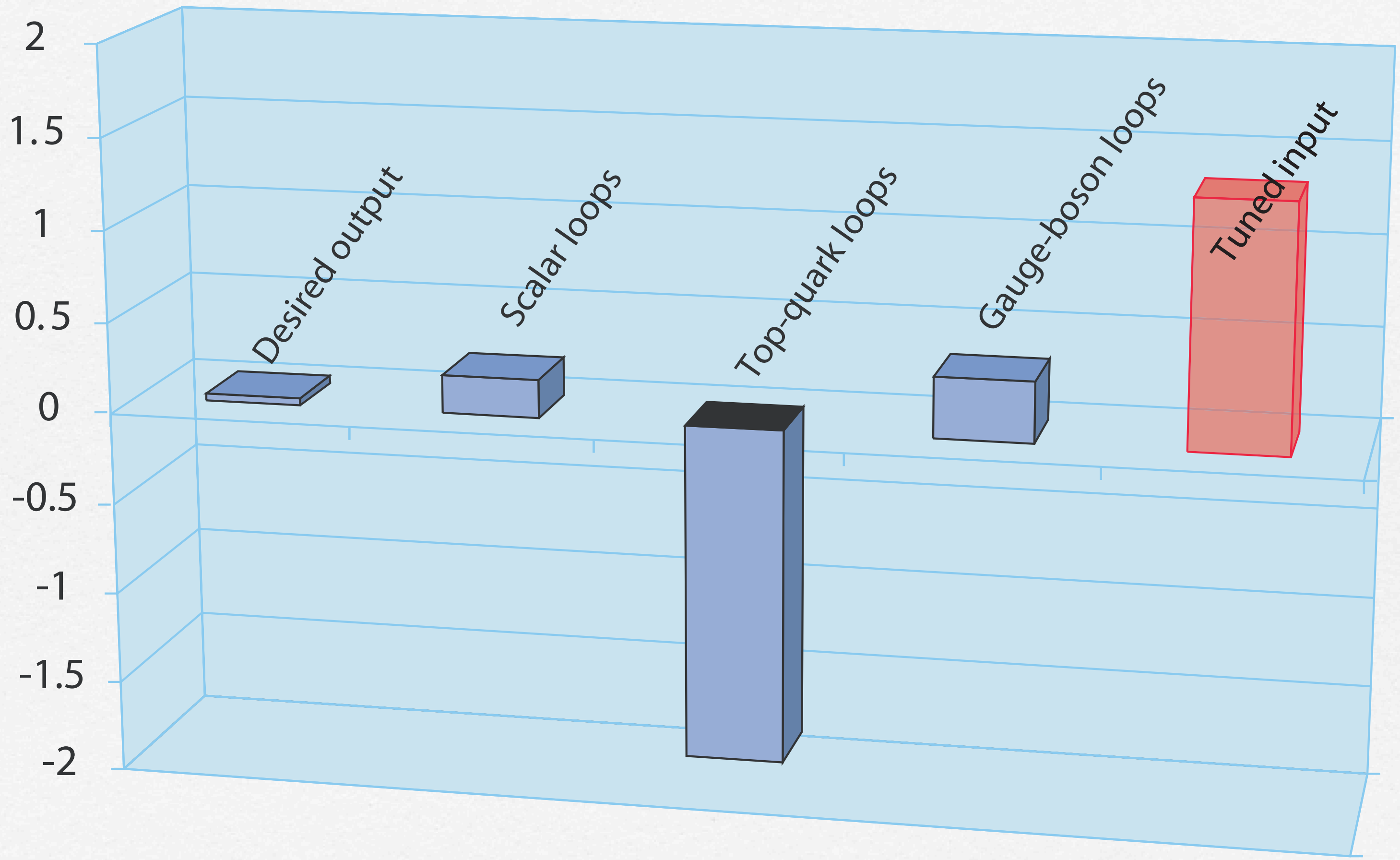
Including rad corr $$m_H^2 + \delta m_H^2 = -\lambda (246\,GeV)^2$$



$$\delta m_H^2 (top\,loop) = -\frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = -(100\,GeV)^2 \left(\frac{\Lambda}{1\,TeV}\right)^2$$

Fine-tuning is required if the cut-off $\Lambda \gg 1\,TeV$

Relative contributions to ΔM_H^2 for $\Lambda = 5$ TeV



Quigg 0704.2232

Complementarity of direct and indirect searches for new physics

Generic amplitude for flavor process

trivial kinematical factors

$$A = A_0 \left[c_{SM} \frac{1}{M_W^{\,2}} + c_{NP} \frac{1}{\Lambda^2} \right]$$

(adimensional) effective couplings

Flavor non-diagonal measured in LFV and heavy quark physics

LHC measures this!

Indirect

Direct

Here's the problem

Masiero

$$M(B_d\text{-}\bar{B}_d) \sim \; c_{SM} \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^{\;2}} + c_{new} \frac{1}{\Lambda^2}$$

If $c_{new} \sim c_{SM} \sim 1$

Isidori

$\Lambda > 10^4$ TeV for $O^{(6)} \sim (\bar{s}\,d)^2$

[K^0-$\bar{K}^0$ mixing]

$\Lambda > 10^3$ TeV for $O^{(6)} \sim (\bar{b}\,d)^2$

[B^0-$\bar{B}^0$ mixing]

UV SM COMPLETION TO STABILIZE THE ELW. SYMM. BREAKING: $\Lambda_{UV} \sim O(1\ \text{TeV})$

2. EFT analysis of ΔF=2 transitions

Silvestrini, Bona

The mixing amplitudes $A_q e^{2i\phi_q} = \langle \bar{M}_q | H_{eff}^{\Delta F=2} | M_q \rangle$

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^{\alpha} \gamma_\mu b_L^{\alpha} \, \bar{q}_L^{\beta} \gamma^\mu b_L^{\beta} \qquad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^{\alpha} b_L^{\alpha} \, \bar{q}_R^{\beta} b_L^{\beta} \qquad Q_3 = \bar{q}_R^{\alpha} b_L^{\beta} \, \bar{q}_R^{\beta} b_L^{\alpha}$$

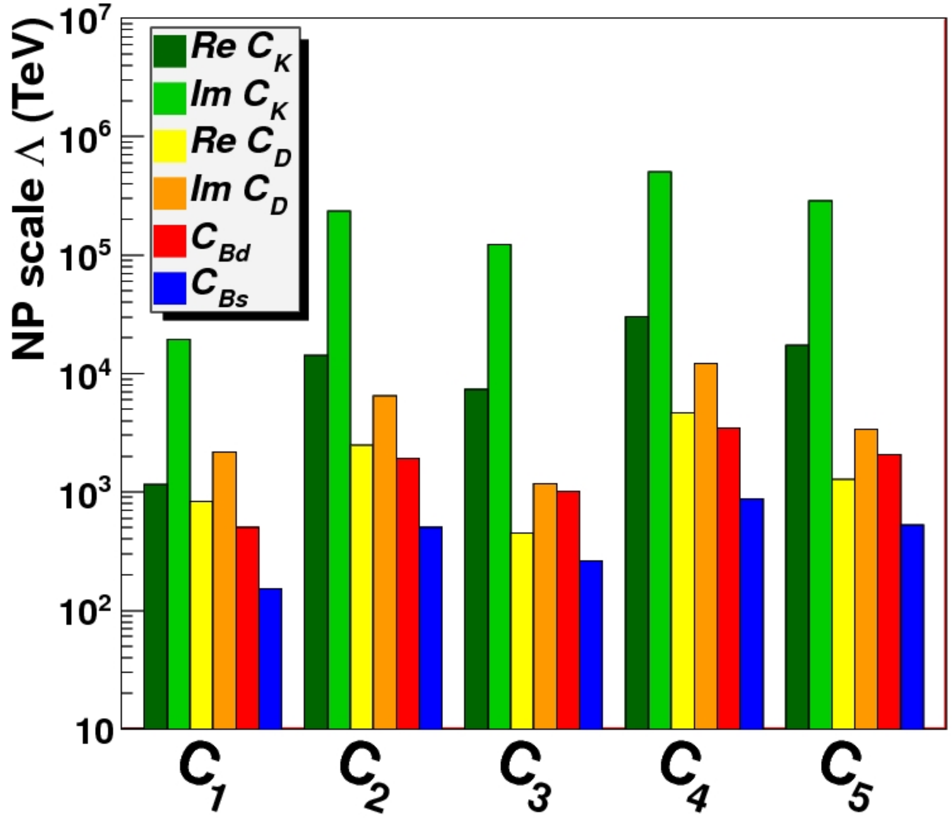
$$Q_4 = \bar{q}_R^{\alpha} b_L^{\alpha} \, \bar{q}_L^{\beta} b_R^{\beta} \qquad Q_5 = \bar{q}_R^{\alpha} b_L^{\beta} \, \bar{q}_L^{\beta} b_R^{\alpha}$$

$$\tilde{Q}_1 = \bar{q}_R^{\alpha} \gamma_\mu b_R^{\alpha} \, \bar{q}_R^{\beta} \gamma^\mu b_R^{\beta}$$

$$\tilde{Q}_2 = \bar{q}_L^{\alpha} b_R^{\alpha} \, \bar{q}_L^{\beta} b_R^{\beta} \qquad \tilde{Q}_3 = \bar{q}_L^{\alpha} b_R^{\beta} \, \bar{q}_L^{\beta} b_R^{\alpha}$$

7 new operators beyond MFV involving quarks with different chiralities

Silvestrini, Bona



General FV: $\Lambda > 5\ 10^5$ TeV

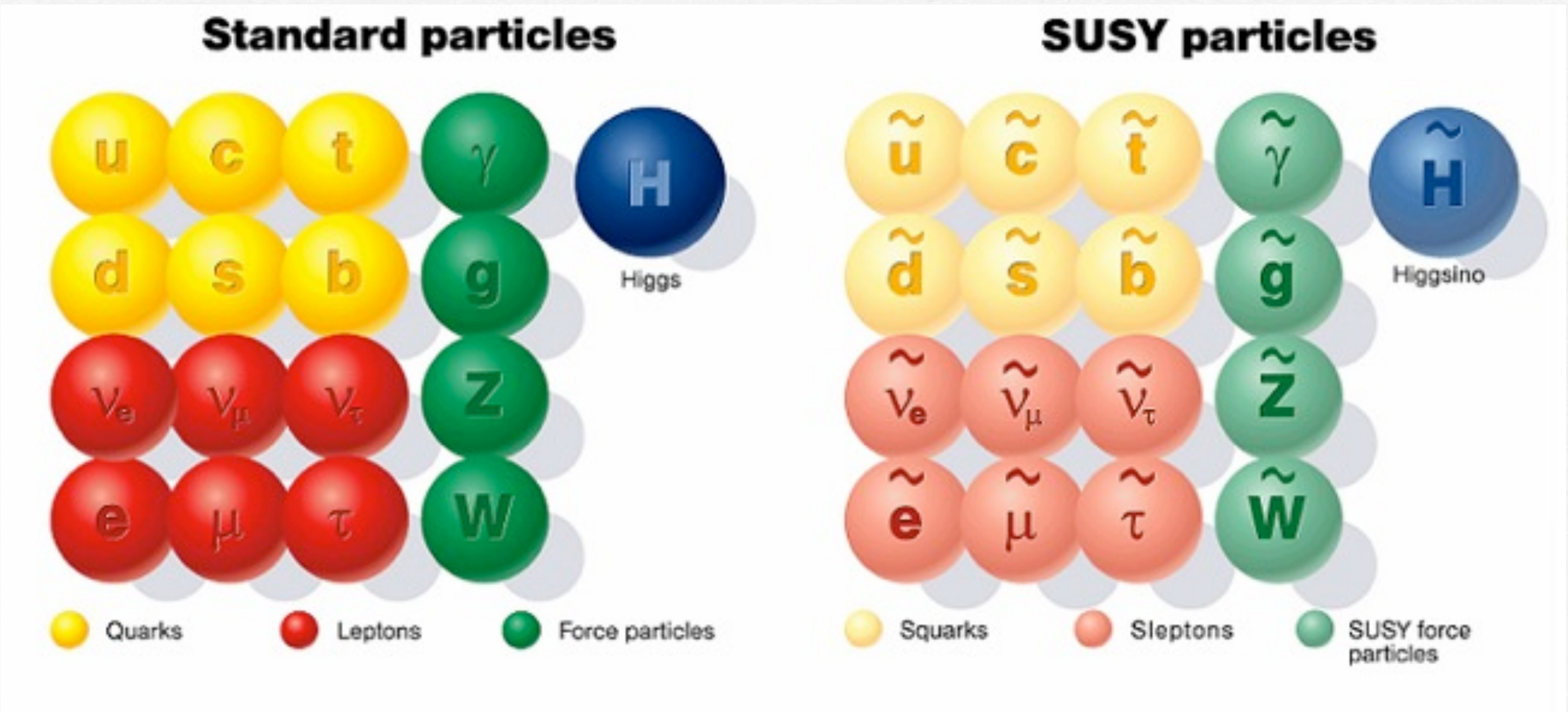
$$c_{new} \frac{1}{\Lambda^2}$$

=1

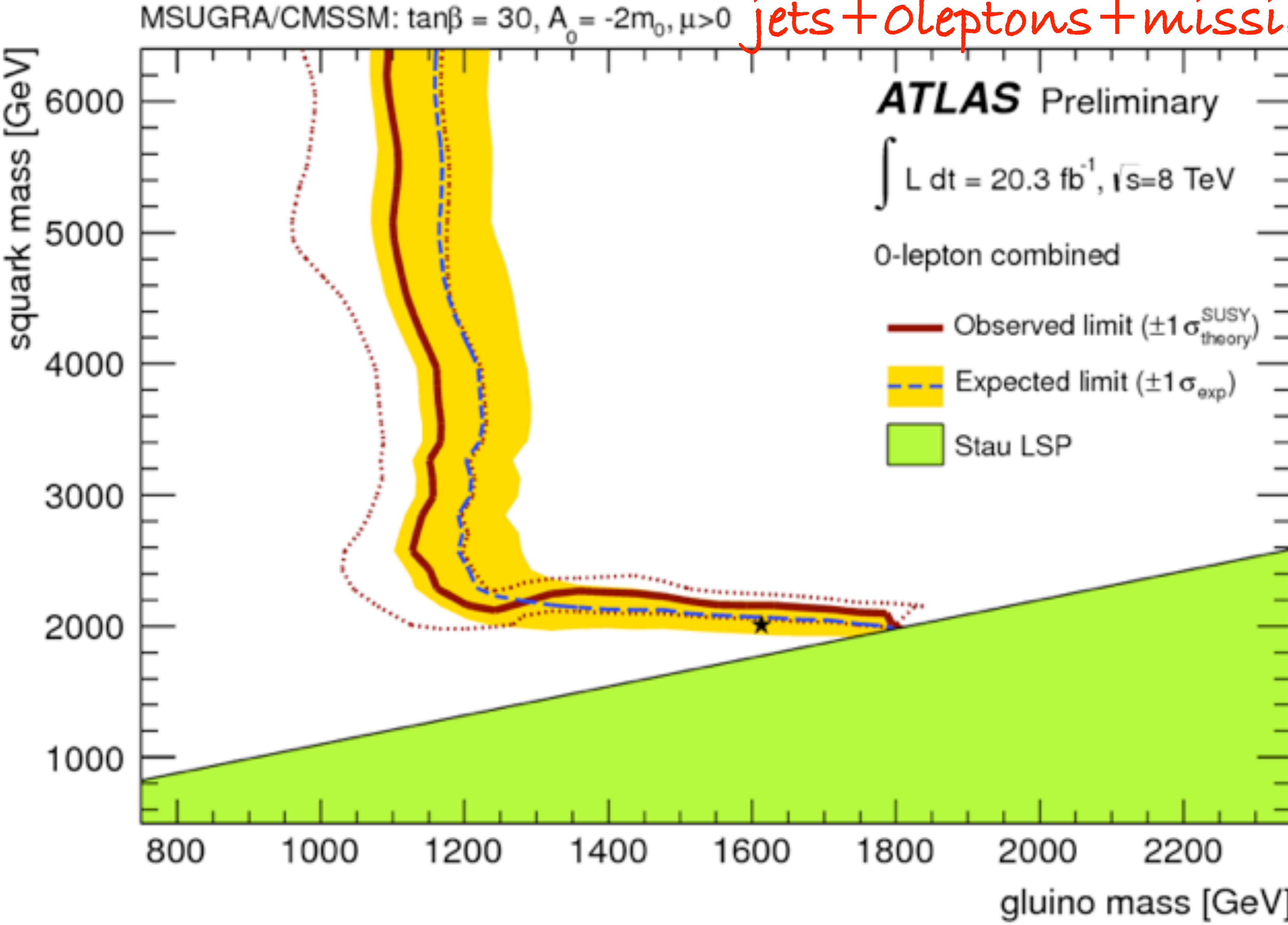
direct LHC searches > 1 TeV

Indirect constraints much better!?

Take SUSY as an example



jets + 0leptons + missing



The down squark mass matrix

In the diagonal down quark basis (Super CKM basis)

$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d - \mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s - \mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b - \mu\tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

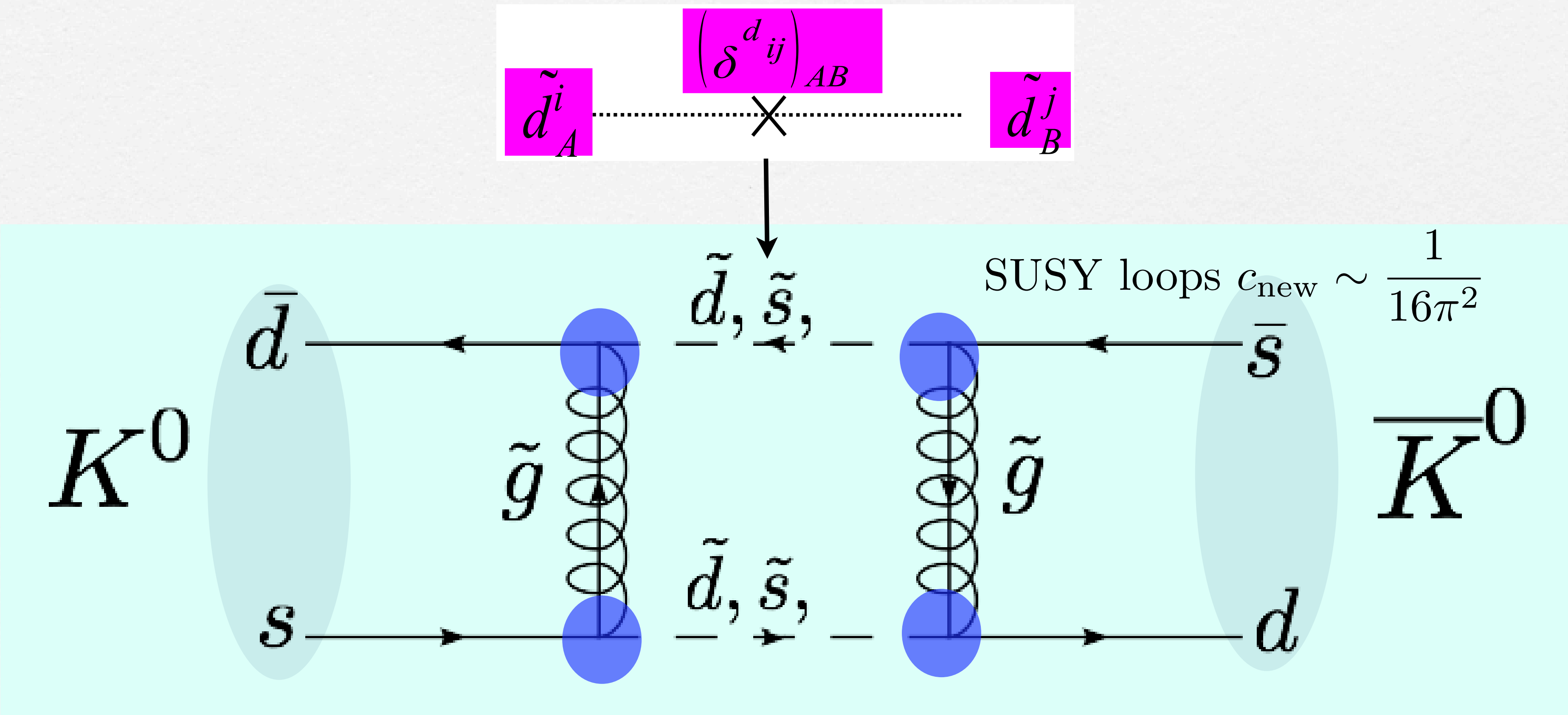
LHC direct measurement/limits

A diagonal matrix corresponds to "minimal flavour violation"
we say that SUSY is "flavour blind" (FBMSSM)

Constrain off-diagonal elements from rare/FC processes

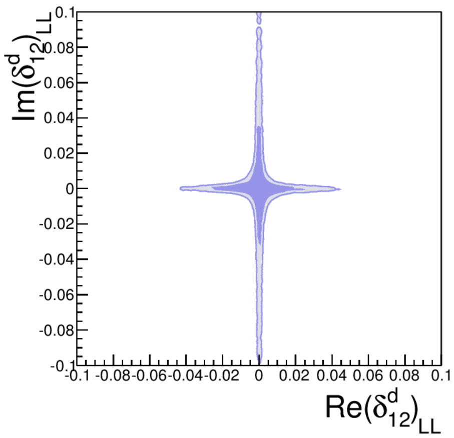
$$(\delta^d_{ij})_{LL} = \frac{(\Delta^d_{ij})_{LL}}{m_{\tilde{d}_{i\,L}} m_{\tilde{d}_{j\,L}}} \qquad (\delta^d_{ij})_{RR} = \frac{(\Delta^d_{ij})_{RR}}{m_{\tilde{d}_{i\,R}} m_{\tilde{d}_{j\,R}}} \qquad (\delta^d_{ij})_{LR} = \frac{(\Delta^d_{ij})_{LR}}{m_{\tilde{d}_{i\,L}} m_{\tilde{d}_{j\,R}}}$$

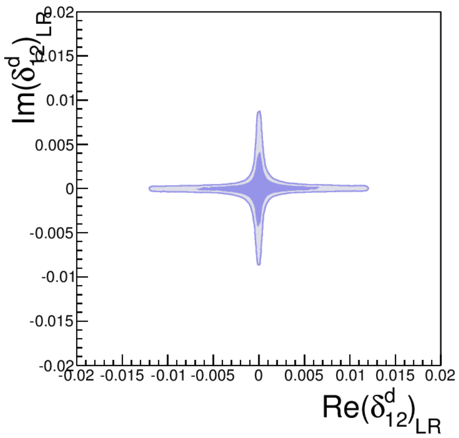
Mass insertion approximation

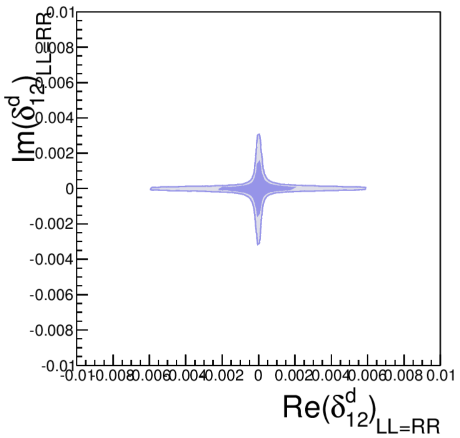


Silvestrini

KAON MIXING



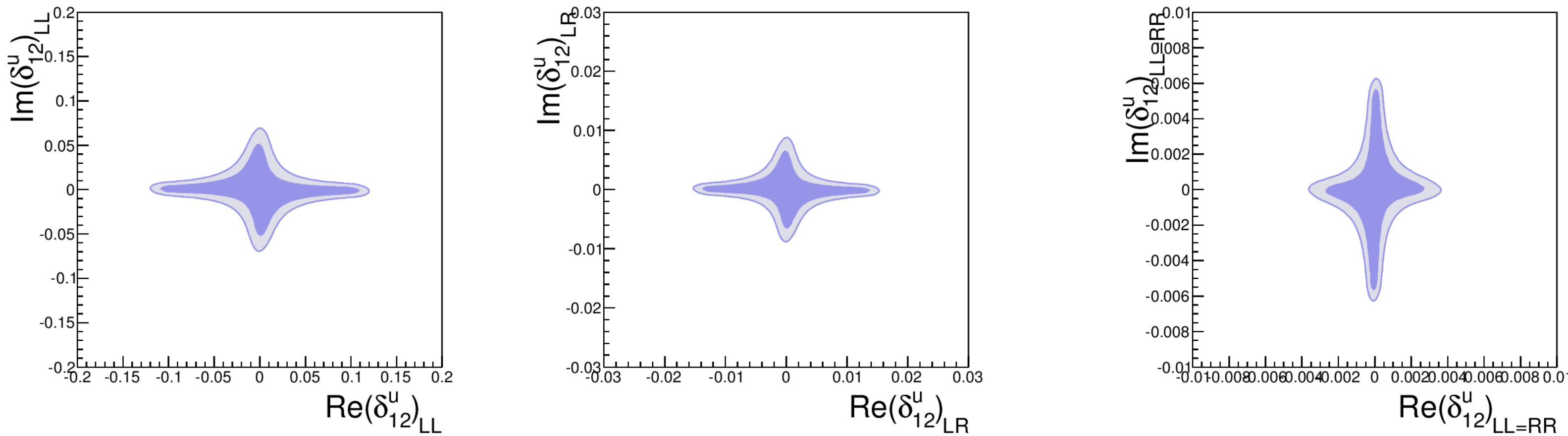




	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^d_{12})_{LL}\right]^2 \right\rvert}$	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^d_{12})_{LR}\right]^2 \right\rvert}$	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^d_{12})_{LL=RR}\right]^2 \right\rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	170
	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^d_{12})_{LL}\right]^2 \right\rvert}$	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^d_{12})_{LR}\right]^2 \right\rvert}$	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^d_{12})_{LL=RR}\right]^2 \right\rvert}$
bound on δ ($\tilde{m} = 1$ TeV)	$8 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$6 \cdot 10^{-4}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	100	$--$	1700

Silvestrini

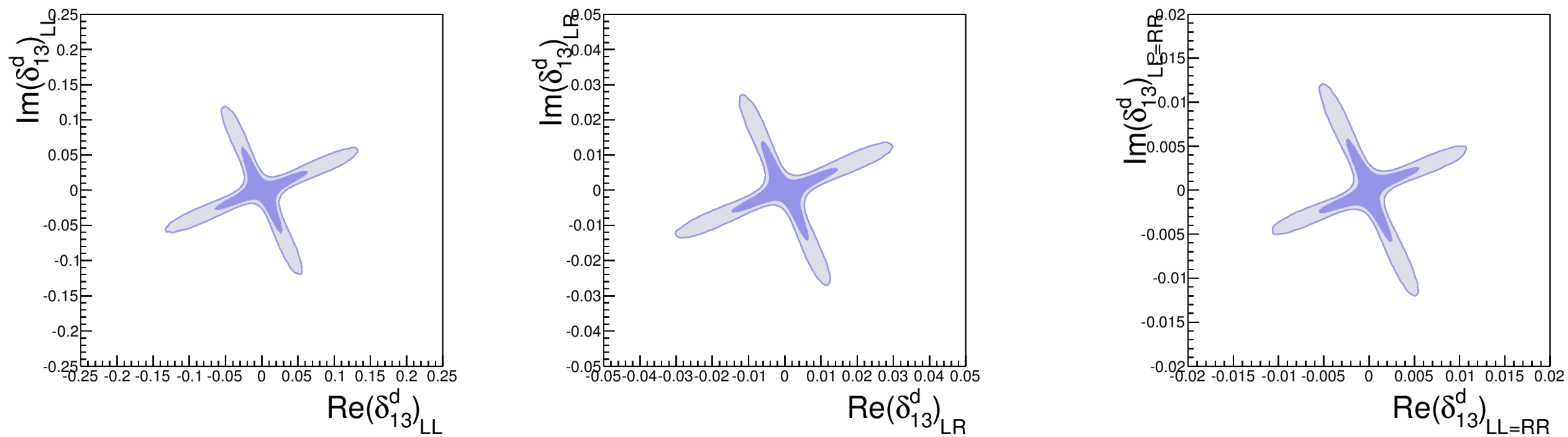
D MIXING



bound on δ ($\tilde{m} = 1$ TeV) bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^u_{12})_{LL}\right]^2 \right\rvert}$ $1 \cdot 10^{-1}$ 10	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^u_{12})_{LR}\right]^2 \right\rvert}$ $1 \cdot 10^{-2}$ $--$	$\sqrt{\left\lvert \mathrm{Re}\left[(\delta^u_{12})_{LL=RR}\right]^2 \right\rvert}$ $6 \cdot 10^{-3}$ 170
bound on δ ($\tilde{m} = 1$ TeV) bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^u_{12})_{LL}\right]^2 \right\rvert}$ $3 \cdot 10^{-2}$ 30	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^u_{12})_{LR}\right]^2 \right\rvert}$ $4 \cdot 10^{-3}$ $--$	$\sqrt{\left\lvert \mathrm{Im}\left[(\delta^u_{12})_{LL=RR}\right]^2 \right\rvert}$ $2 \cdot 10^{-3}$ 500

Silvestrini

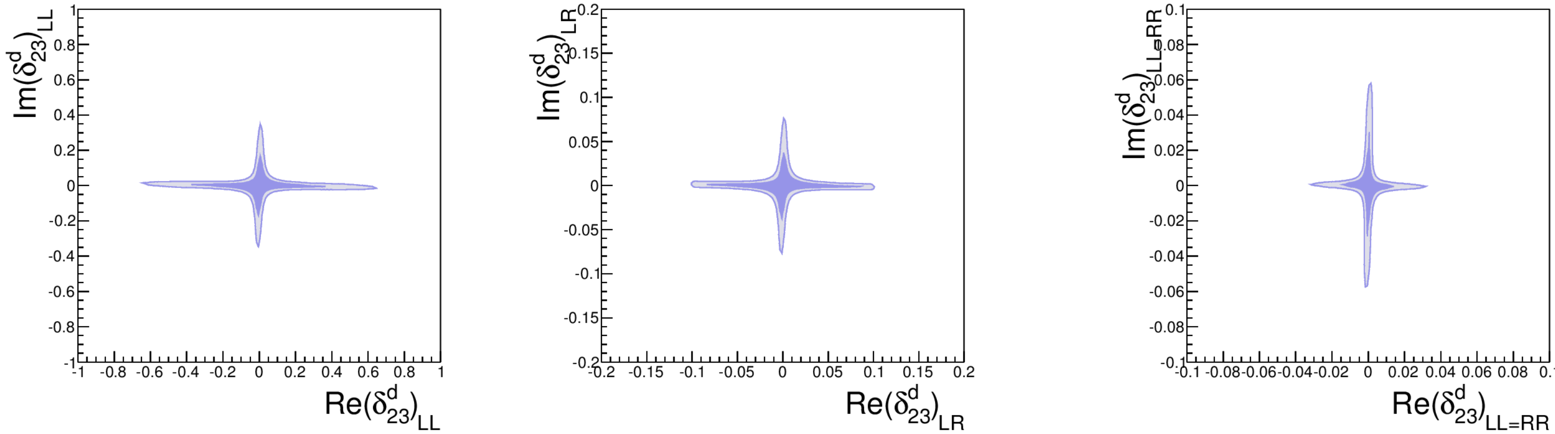
B_d MIXING



	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{13})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{13})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{13})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$9 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$8 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	125
	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{13})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{13})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{13})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$9 \cdot 10^{-3}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	110

Silvestrini

B_s MIXING



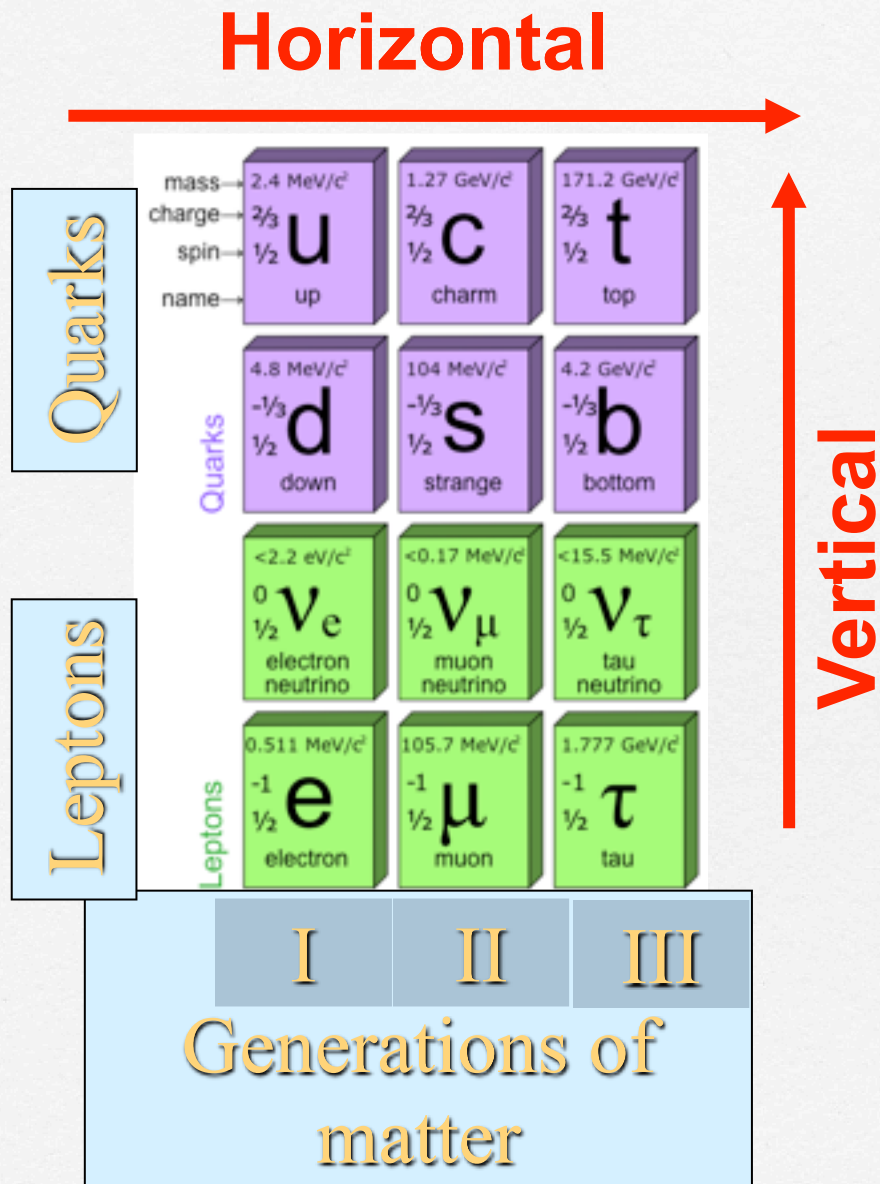
	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{23})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{23})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Re}\left[(\delta^d_{23})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$6 \cdot 10^{-1}$	$1 \cdot 10^{-1}$	$5 \cdot 10^{-2}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	1.7	$--$	20
	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{23})_{LL}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{23})_{LR}\right]^2\right\|}$	$\sqrt{\left\|\mathrm{Im}\left[(\delta^d_{23})_{LL=RR}\right]^2\right\|}$
bound on δ ($\tilde{m} = 1$ TeV)	$1 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-2}$
bound on $\tilde{m}$ (TeV) for $\delta_{\mathrm{LL,RR}} = 1$	10	$--$	100

Why are the off-diagonal squark masses so small?

- Maybe not small - just very heavy squarks (especially first and second family)
- Some alignment mechanism as in GMSB or AMSB
- mSUGRA ? But not well motivated...
- In general SUGRA need a theory of flavour to understand this - involving a family symmetry

The Flavour Problem

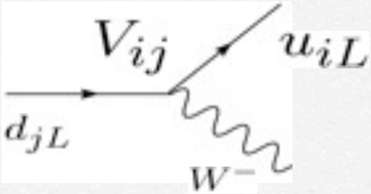
Why are there three families of quarks and leptons?



The Flavour Problem

Why is quark mixing so small?

Cabibbo
Kobayashi
Maskawa



$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\left.\begin{aligned} \theta_{12} &= 13^\circ \pm 0.1^\circ \\ \theta_{23} &= 2.4^\circ \pm 0.1^\circ \\ \theta_{13} &= 0.20^\circ \pm 0.05^\circ \end{aligned}\right\}$$

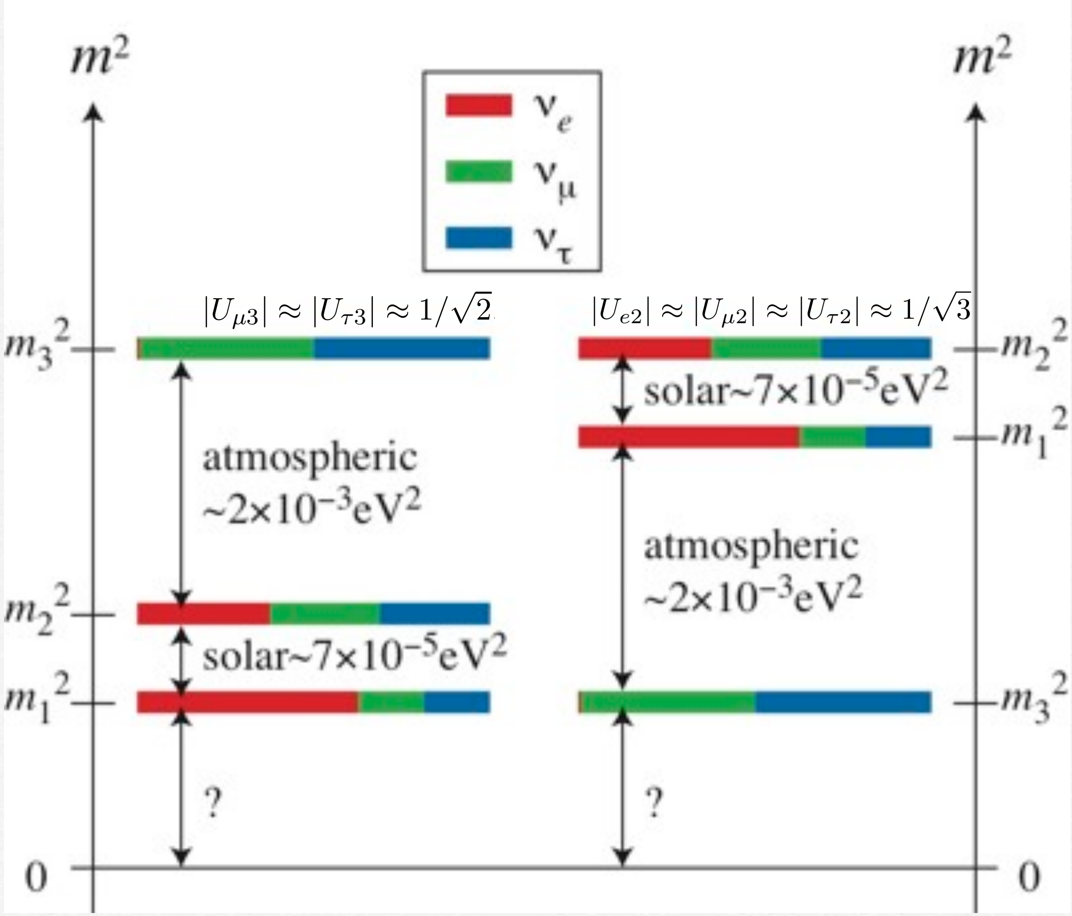
All these angles are pretty small – why?

While the CP phase is quite large

$\delta_{CP} \approx 70^\circ \pm 5^\circ$

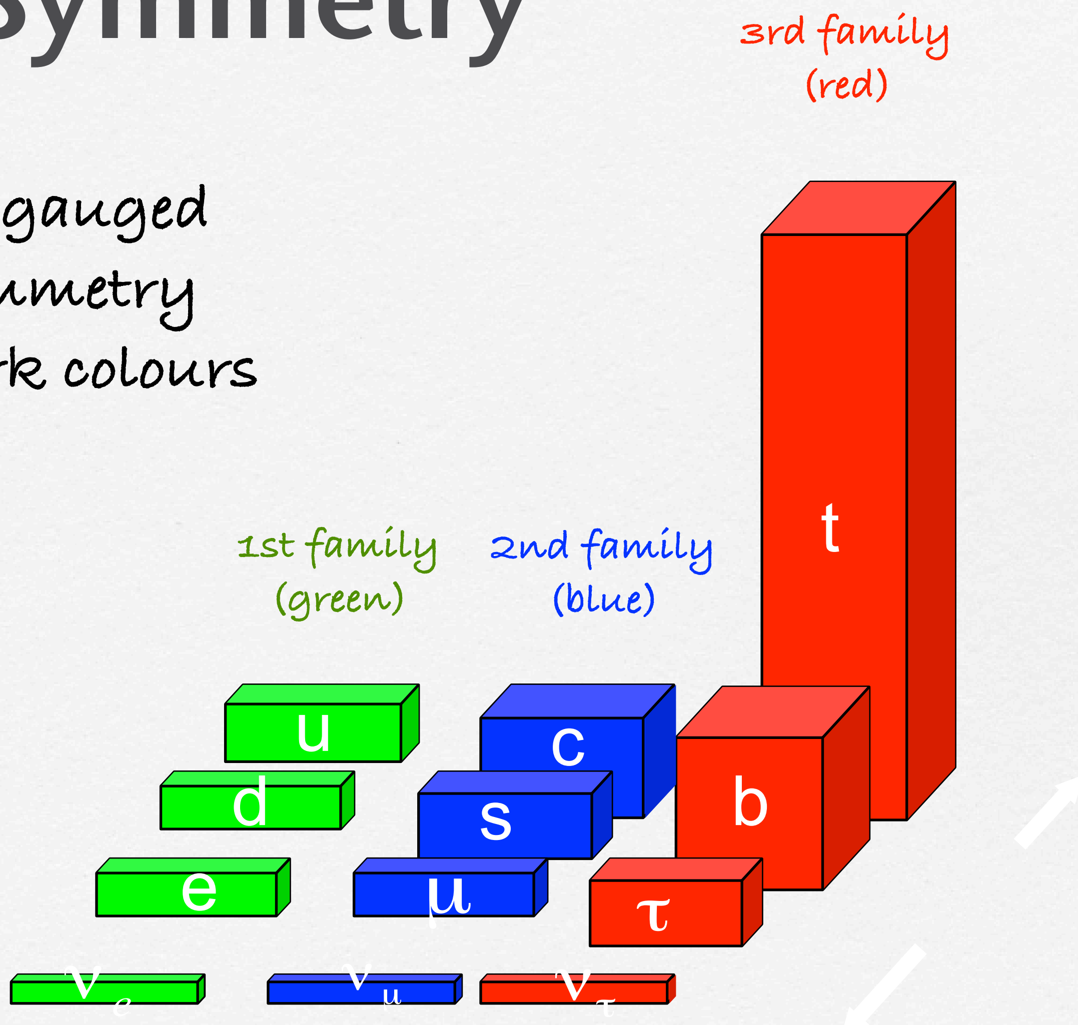
The Flavour Problem

Why is lepton mixing so large?



Family Symmetry

E.g. SU(3) gauged
family symmetry
c.f. QCD quark colours



SU(3) Family Symmetry and Soft Masses

$\psi_i \in (Q_i, L_i) \sim \mathbf{3}$ Flavons $\phi \sim \bar{3}$

SFK,Ross; Ross,Velasco-Sevilla,Vives
Antusch, SFK, Malinsky

Yukawas

$$\frac{b_3}{M^2}\phi_3^i\psi_i\phi_3^j\psi_j H + \frac{b_{23}}{M^2}\phi_{23}^i\psi_i\phi_{23}^j\psi_j H + \ldots$$

Soft masses

$$m^2 = m_0^2\left(\delta_{ij} + c_3\frac{\phi_3^*\phi_3}{M'^2} + c_{23}\frac{\phi_{23}^*\phi_{23}}{M'^2} + \ldots\right)$$

$$m^2 \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} m_0^2 + \begin{pmatrix} 0 & & \\ & 0 & \\ & & \varepsilon_3^2 \end{pmatrix} m_3^3 + \begin{pmatrix} 0 & & \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2 \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2 \end{pmatrix} m_{23}^3 + \ldots$$

- Leading order universal due to $SU(3)_{fam}$
- Sub-leading mainly (2,3) flavour violation controlled by flavons

The SUSY CP Problem

Abel, Khalil, Lebedev;
Ross, Vives;
Antusch, SFK, Malinsky, Ross

- SUSY neutron EDM $d_n \sim \left(\frac{300 \text{ GeV}}{M}\right)^2 \sin\phi \times 10^{-24} e \text{ cm}$

$$\phi_\mu \sim \phi_A \equiv \phi \ll 1,\ \tan\beta \sim 3 \quad \rightarrow \phi < 10^{-2}$$

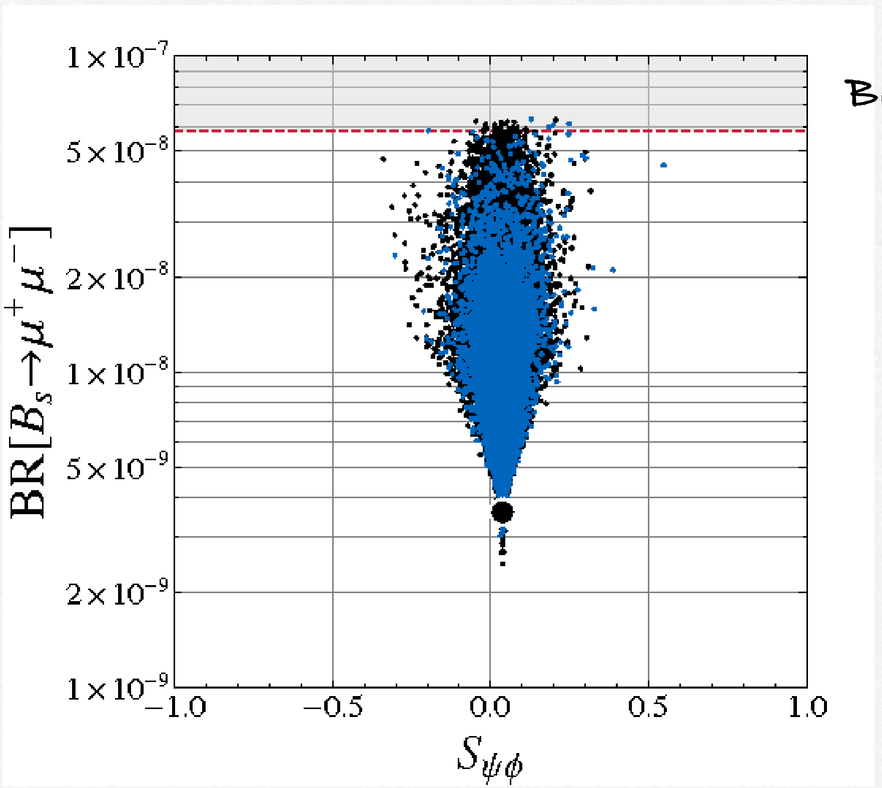
Why are SUSY phases so small?

- Postulate CP conservation (e.g. $\mu H_u H_d$ real) with CP is spontaneously broken by flavon vevs
- Trilinear soft

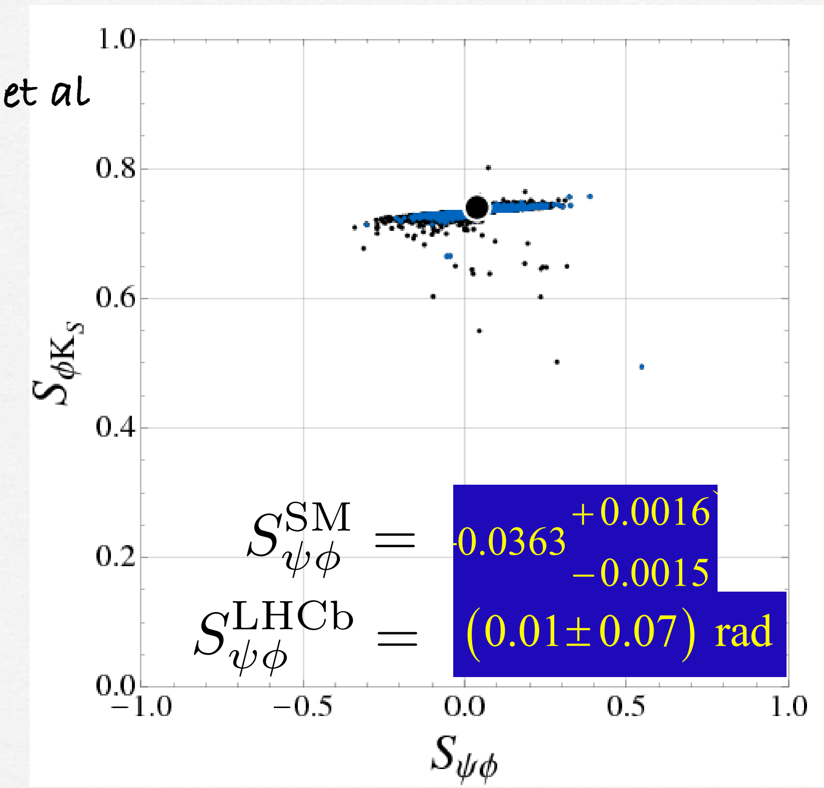
$$\tilde{A}_{ij} = A_0\left(a_3 \frac{\phi_3^i \phi_3^j}{M^2} + a_{23} \frac{\phi_{23}^i \phi_{23}^j}{M^2} + \ldots\right)$$

A_0 , a_3 , a_{23} , real gives real soft masses times complex Yukawa elements → no soft phases at leading order

Antusch, SK, Malinsky (AKM) Predictions

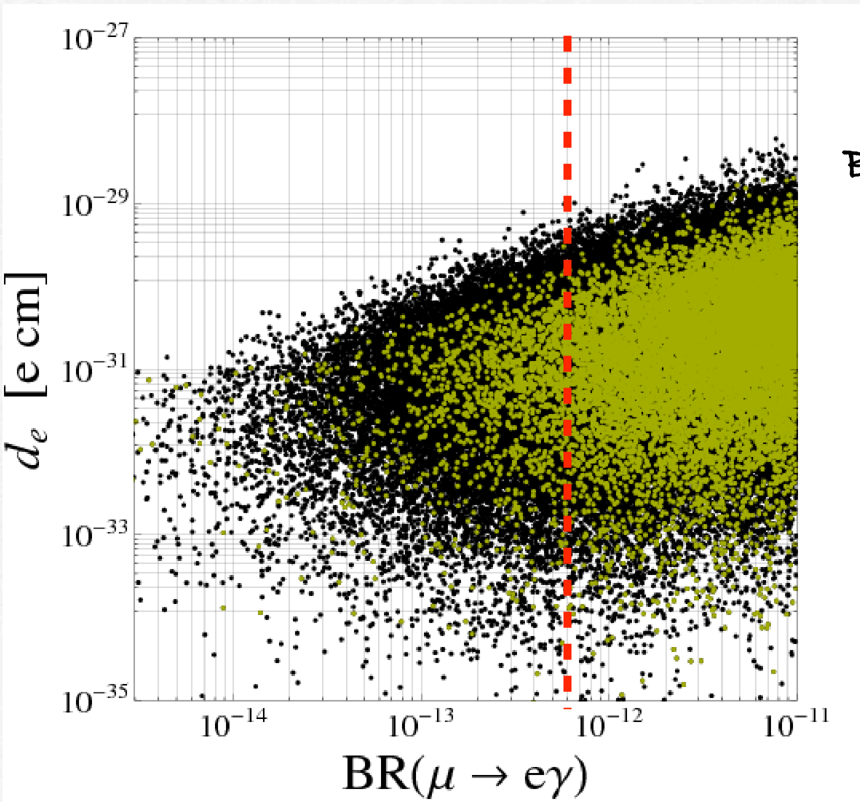


Buras et al

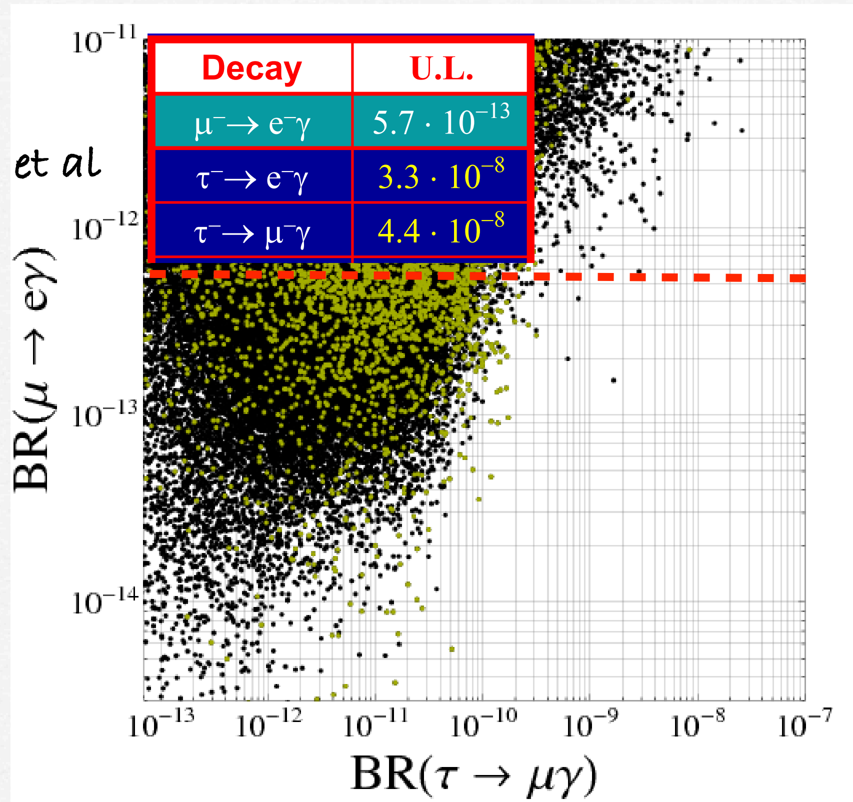


$$A^s_{\mathrm{CP}}(\psi\phi,t) \equiv \frac{\Gamma(\bar{B}_s(t)\to\psi\phi)-\Gamma(B_s(t)\to\psi\phi)}{\Gamma(\bar{B}_s(t)\to\psi\phi)+\Gamma(B_s(t)\to\psi\phi)} \simeq S_{\psi\phi}\sin(\Delta M_s t)$$

Antusch, SK, Malinsky (AKM) Predictions



Buras et al



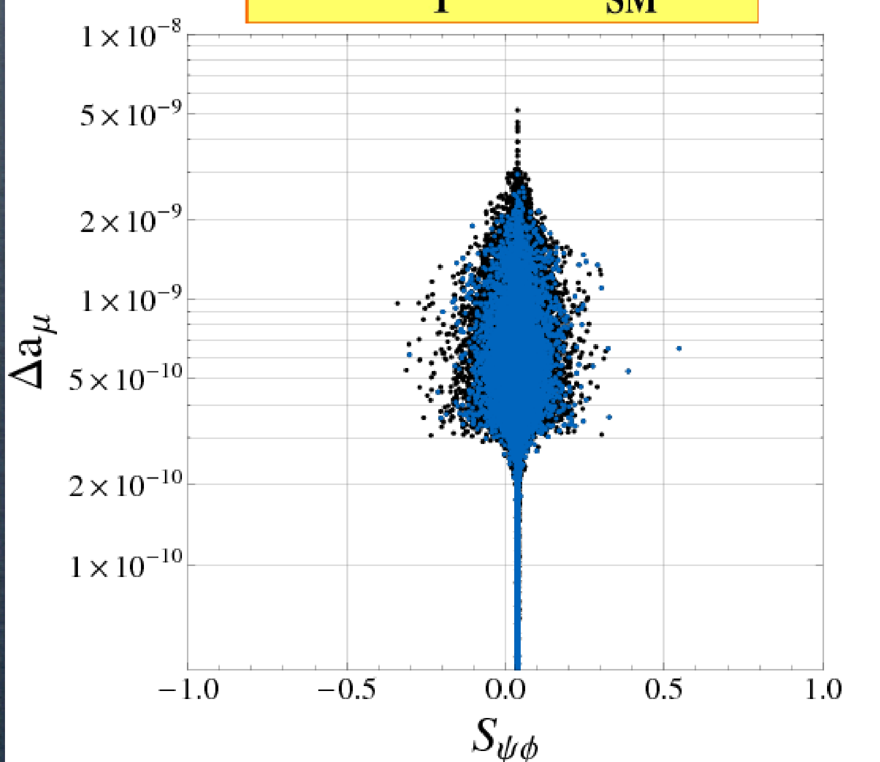
Decay	U.L.
$\mu^- \to e^- \gamma$	$5.7 \cdot 10^{-13}$
$\tau^- \to e^- \gamma$	$3.3 \cdot 10^{-8}$
$\tau^- \to \mu^- \gamma$	$4.4 \cdot 10^{-8}$

Antusch, SK, Malinsky (AKM) Predictions

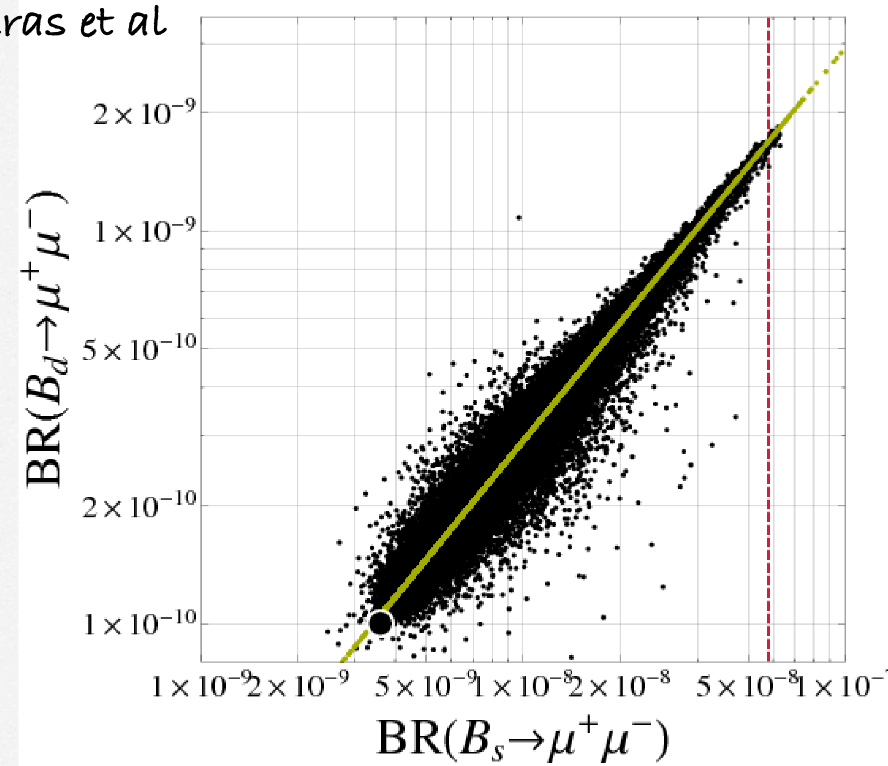
$$\mathcal{B}r\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.2^{+1.5}_{-1.2}\right)\cdot 10^{-9}$$
$$\mathcal{B}r\left(B^0 \to \mu^+\mu^-\right) < 9.4\cdot 10^{-10} \text{ at } 95\% \text{ C.L.}$$

$$S_{\psi\varphi} = \sin\left(2\left|\beta_s\right| - 2\varphi_s^{new}\right) \overset{\varphi_s^{new}=0}{\approx} 0.04$$

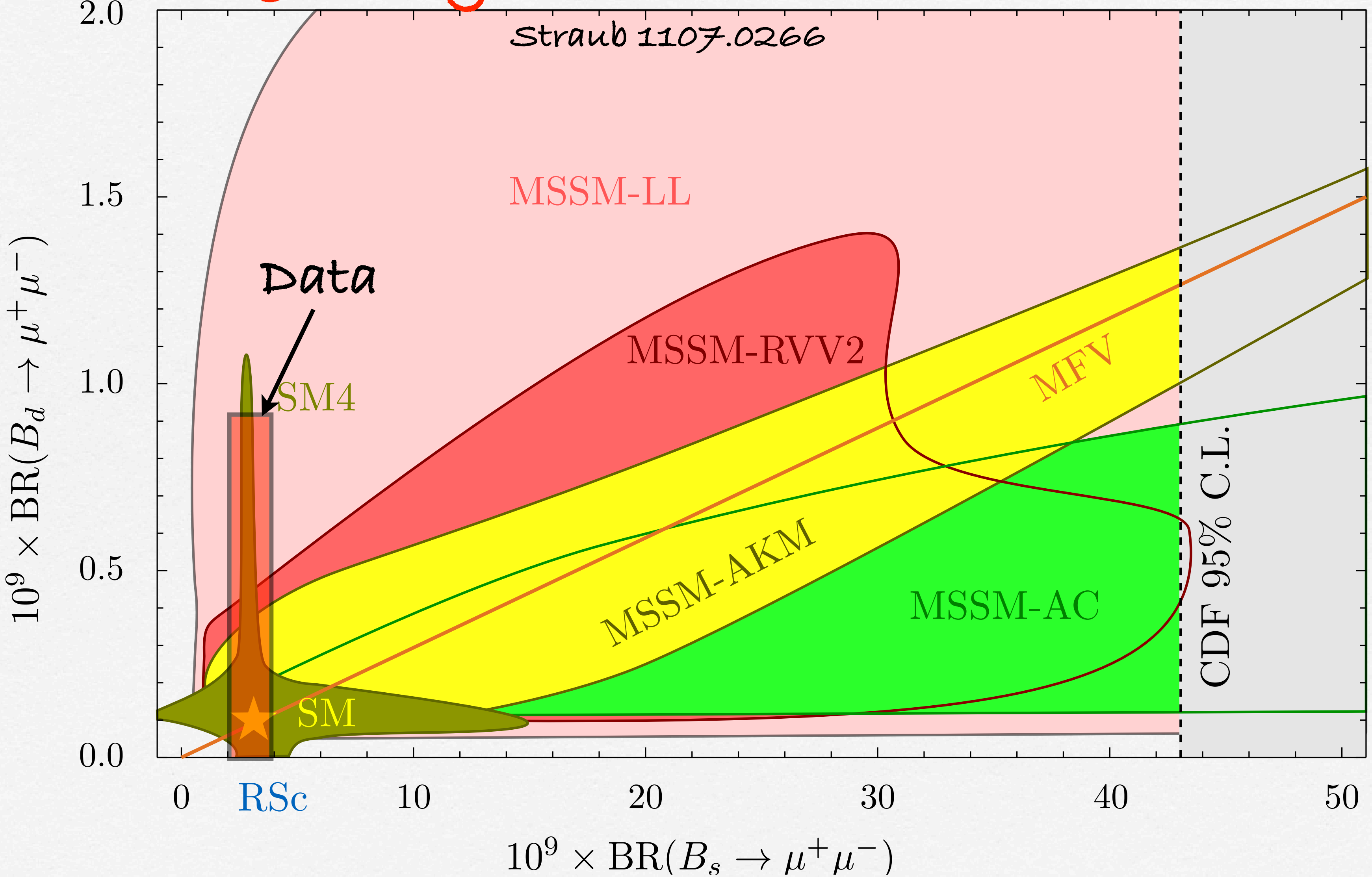
1° SM



Buras et al

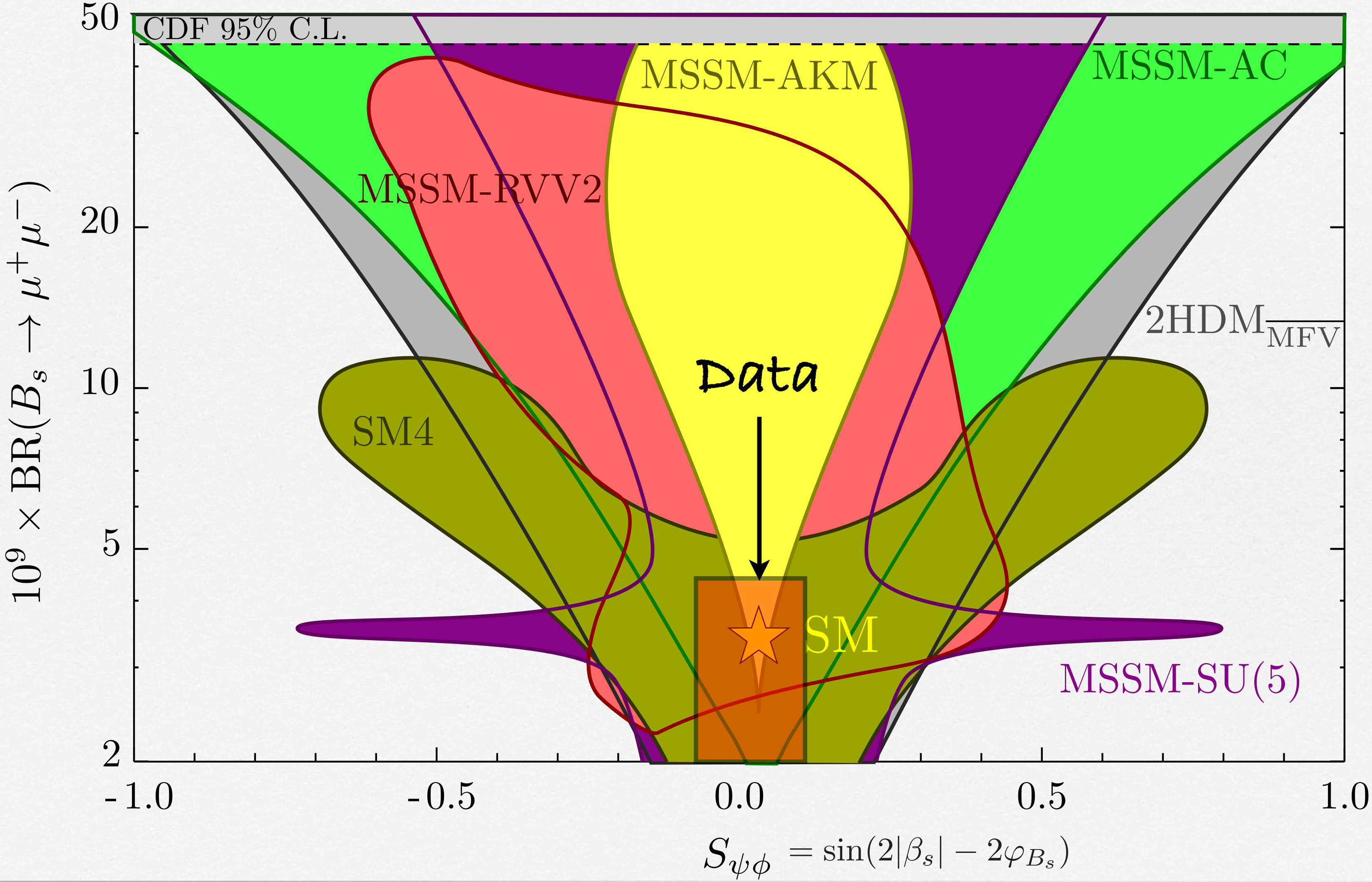


Data greatly constrains these models



Data greatly constrains these models

Straub 1107.0266



SUSY GUTs

$$m^2_Q = m^2_{\tilde{e}^c} = m^2_{\tilde{u}^c} = m^2_{\mathbf{10}}$$

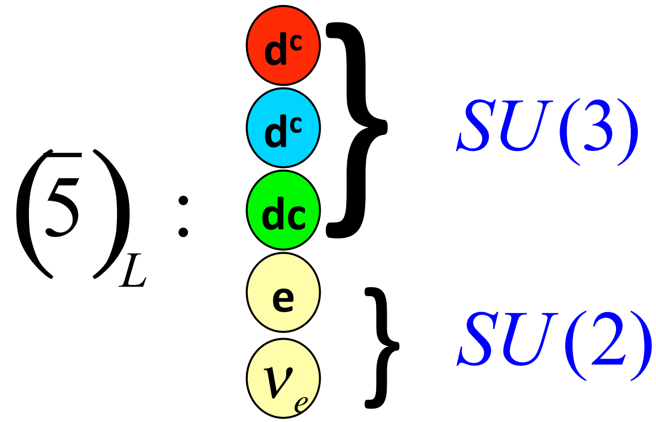
$$m^2_{\tilde{d}^c} = m^2_L = m^2_{\bar{\mathbf{5}}}$$

$$A^e_{ij} = A^d_{ji}\,.$$

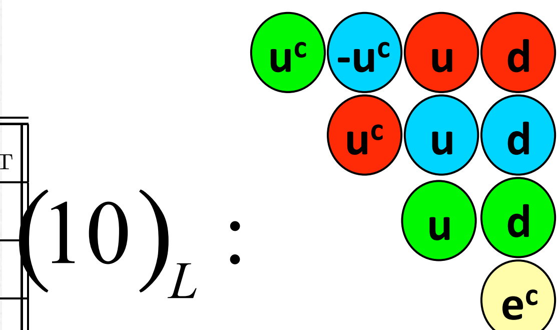
$$(\Delta^u_{ij})_{\mathrm{LL}} = (\Delta^u_{ij})_{\mathrm{RR}} = (\Delta^d_{ij})_{\mathrm{LL}} = (\Delta^l_{ij})_{\mathrm{RR}}$$

$$(\Delta^d_{ij})_{\mathrm{RR}} = (\Delta^l_{ij})_{\mathrm{LL}}$$

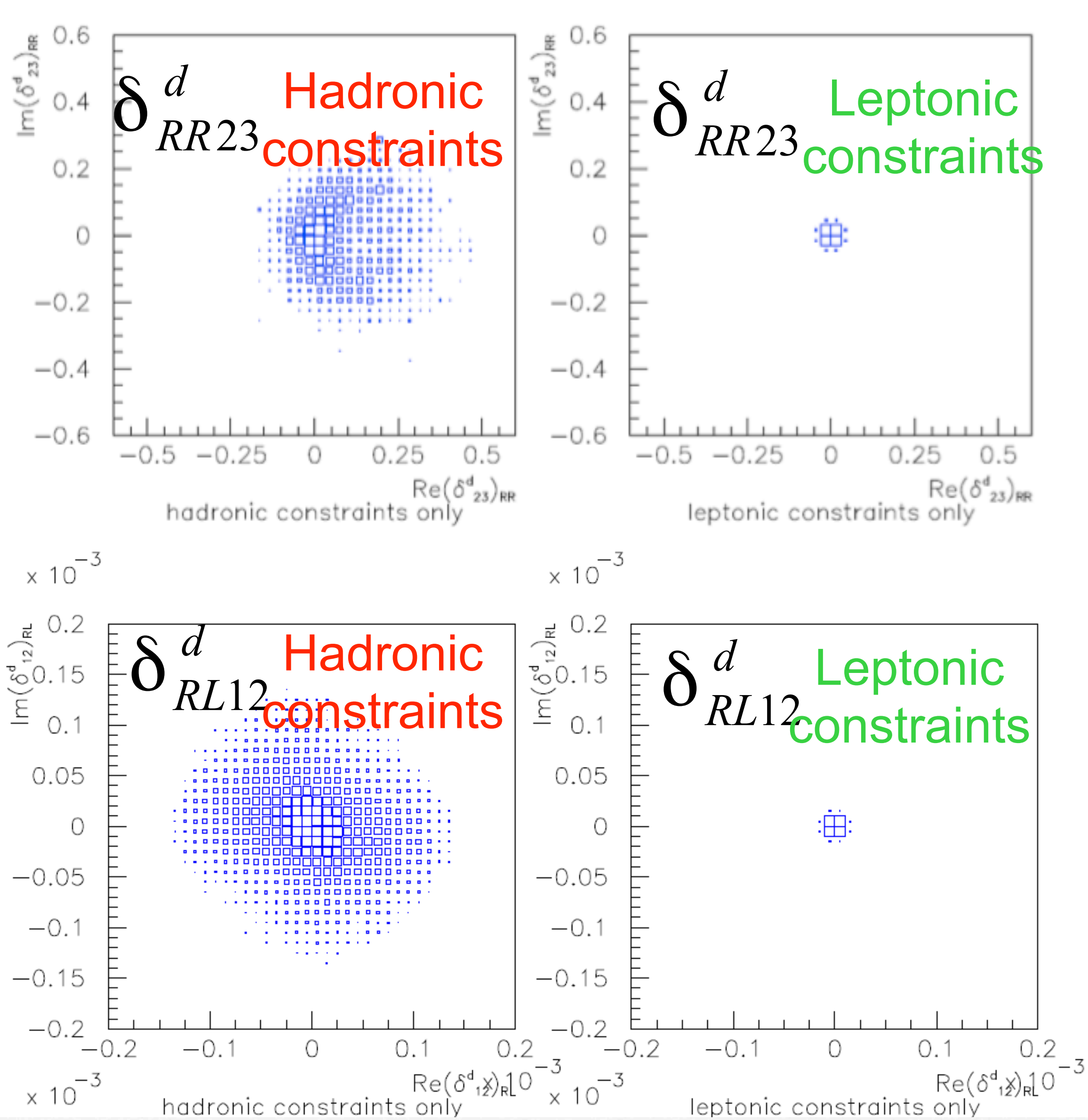
$$(\Delta^d_{ij})_{\mathrm{LR}} = (\Delta^l_{ji})_{\mathrm{LR}} = (\Delta^l_{ij})^\star_{\mathrm{RL}}$$



Relations at the weak scale	Relations at M_{GUT}
$(\delta^u_{ij})_{\mathrm{RR}} \approx (m^2_{e^c}/m^2_{u^c})\ (\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{u^c{}_0} = m^2_{e^c{}_0}$
$(\delta^q_{ij})_{\mathrm{LL}} \approx (m^2_{e^c}/m^2_Q)\ (\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{Q_0} = m^2_{e^c{}_0}$
$(\delta^d_{ij})_{\mathrm{RR}} \approx (m^2_L/m^2_{d^c})\ (\delta^l_{ij})_{\mathrm{LL}}$	$m^2_{d^c{}_0} = m^2_{L_0}$
$(\delta^d_{ij})_{\mathrm{LR}} \approx (m^2_{L_{avg}}/m^2_{Q_{avg}})\ (m_b/m_\tau)\ (\delta^l_{ij})^\star_{\mathrm{LR}}$	$A^e_{ij_0} = A^d_{ji_0}$



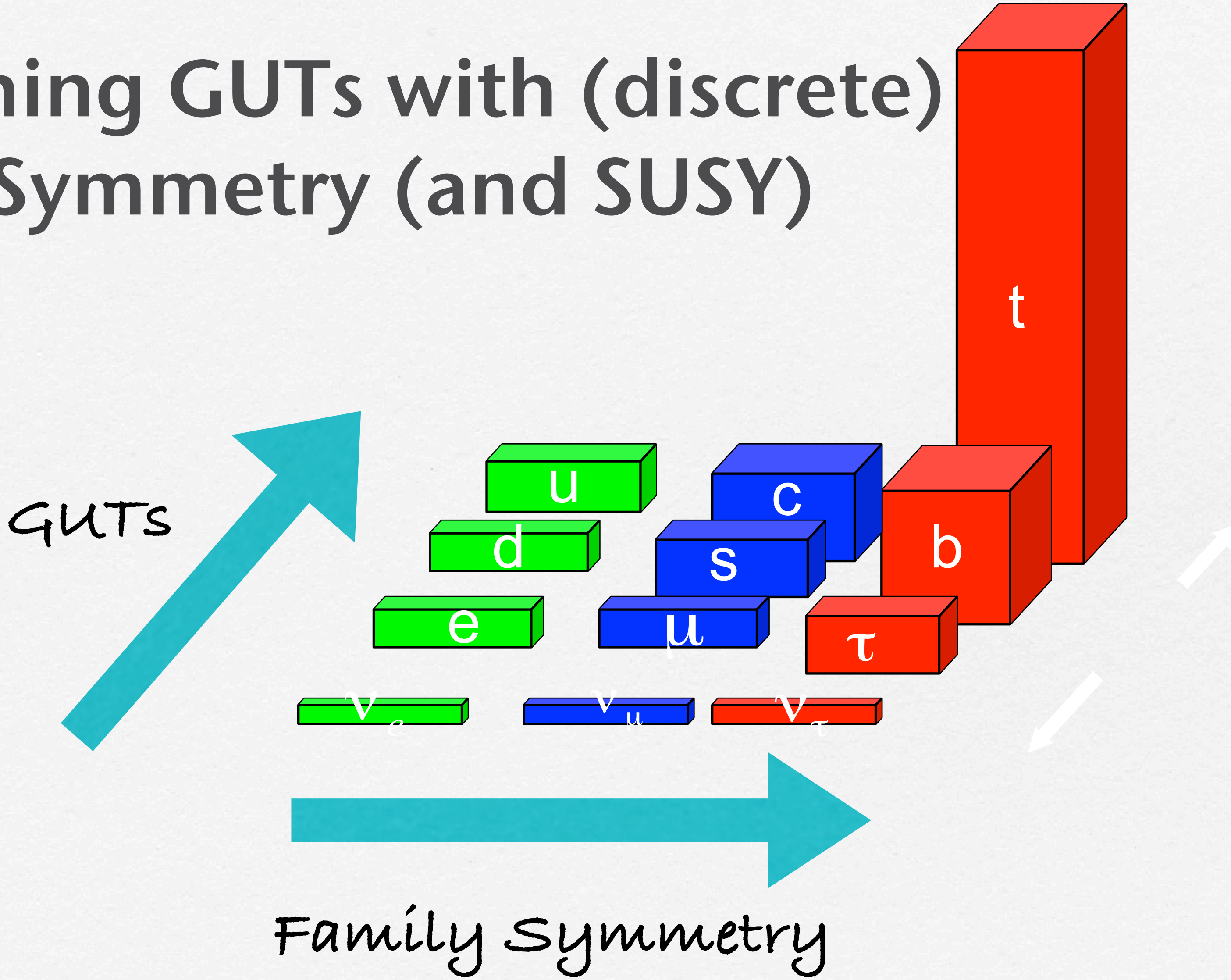
Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives



Quark-lepton connection:

LFV processes can constrain Quark Flavour Violation via GUTs

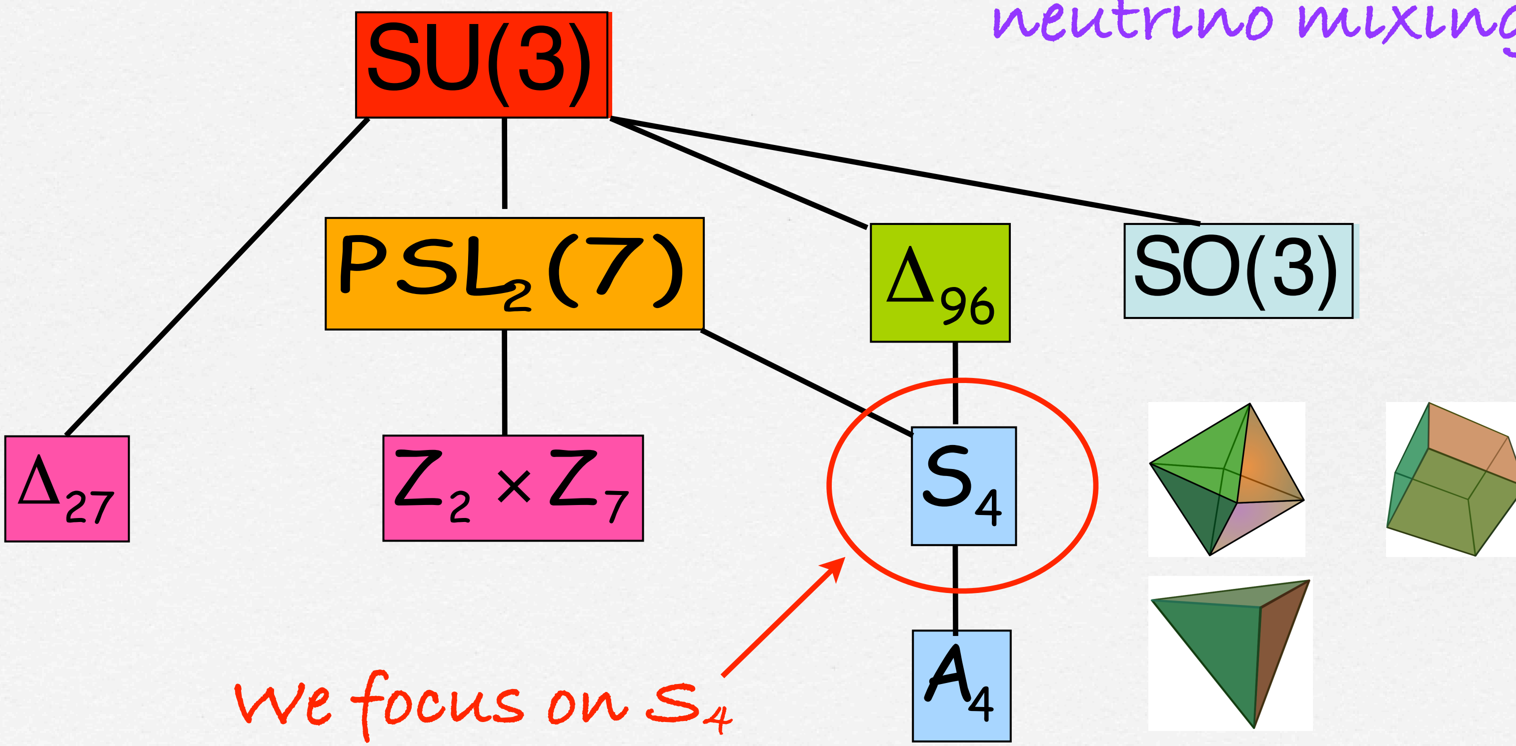
Combining GUTs with (discrete) Family Symmetry (and SUSY)



Merle, Zwicky

SU "Tree"

Discrete subgroups of SU(3) family symmetry have been used to explain large neutrino mixing



$S_4 \times SU(5) \times U(1)$

Hagedorn, SK, Luhn
+ work in progress with Dimou

	Matter fields				Higgs fields			Flavon fields								
	T_3	T	F	ν^c	$H_{\mathbf{5}}$	$H_{\bar{\mathbf{5}}}$	$H_{\overline{\mathbf{45}}}$	ϕ_2^u	$\tilde{\phi}_2^u$	ϕ_3^d	$\tilde{\phi}_3^d$	ϕ_2^d	$\phi_{3'}^\nu$	ϕ_2^ν	ϕ_1^ν	η
$SU(5)$	$\mathbf{10}$	$\mathbf{10}$	$\bar{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{5}$	$\bar{\mathbf{5}}$	$\overline{\mathbf{45}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
S_4	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{3'}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)$	0	5	4	-4	0	0	1	-10	0	-4	-11	1	8	8	8	7

Yukawa couplings

$$Y^u = \begin{pmatrix} y_1^u\lambda^8 & 0 & 0 \\ 0 & y_2^u\lambda^4 & 0 \\ 0 & 0 & y_3^u \end{pmatrix},$$

$$\frac{A^u}{A_0} = \begin{pmatrix} a_1^u\lambda^8 & 0 & 0 \\ 0 & a_2^u\lambda^4 & 0 \\ 0 & 0 & a_3^u \end{pmatrix},$$

Soft SUSY breaking trilinears

$$Y^d = \begin{pmatrix} 0 & y_3^d\lambda^5 & -y_3^d\lambda^5 \\ -y_3^d\lambda^5 & y_1^d\lambda^4 & (y_3^d - yd_1)\lambda^4 \\ 0 & 0 & y_2^d\lambda^2 \end{pmatrix},$$

$$\frac{A^d}{A_0} = \begin{pmatrix} 0 & a_3^d\lambda^5 & -a_3^d\lambda^5 \\ -a_3^d\lambda^5 & a_1^d\lambda^4 & (a_3^d - a_1^d)\lambda^4 \\ 0 & 0 & a_2^d\lambda^2 \end{pmatrix}$$

$$Y^e = \begin{pmatrix} 0 & -y_3^e\lambda^5 & 0 \\ y_3^e\lambda^5 & -3y_1^e\lambda^4 & 0 \\ -y_3^e\lambda^5 & (3y_1^e + y_3^e)\lambda^4 & y_2^e\lambda^2 \end{pmatrix},$$

$$\frac{A^e}{A_0} = \begin{pmatrix} 0 & -a_3^e\lambda^5 & 0 \\ a_3^e\lambda^5 & -3a_1^e\lambda^4 & 0 \\ -a_3^e\lambda^5 & (3a_1^e + a_3^e)\lambda^4 & a_2^e\lambda^2 \end{pmatrix},$$

Squark and slepton mass matrices (at M_{GUT} in non-diagonal Yukawa basis)

$$M_F^2 \sim m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + m_0^2 \begin{pmatrix} \lambda^4 & \lambda^4 & \lambda^4 \\ \lambda^4 & \lambda^4 & \lambda^4 \\ \lambda^4 & \lambda^4 & \lambda^4 \end{pmatrix}$$

$$M_T^2 \sim m_0^2 \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix} + m_0^2 \begin{pmatrix} \lambda^2 & \lambda^4 & \lambda^7 \\ \lambda^4 & \lambda^2 & \lambda^5 \\ \lambda^7 & \lambda^5 & 0 \end{pmatrix}$$

Model predicts very small off-diagonal masses with non-universal stop squark masses

Mass insertion parameters

(at M_{GUT} in the diagonal Yukawa basis)

$$(\delta^u)_{LL} = \begin{pmatrix} 1 & \lambda^4 & \lambda^7 \\ \cdot & 1 & \lambda^5 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^u)_{RR} = \begin{pmatrix} 1 & \lambda^4 & \lambda^7 \\ \cdot & 1 & \lambda^5 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^u)_{LR} = \begin{pmatrix} \lambda^8 & 0 & 0 \\ 0 & \lambda^4 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(\delta^d)_{LL} = \begin{pmatrix} 1 & \lambda^3 & \lambda^4 \\ \cdot & 1 & \lambda^2 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^d)_{RR} = \begin{pmatrix} 1 & \lambda^4 & \lambda^4 \\ \cdot & 1 & \lambda^6 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^d)_{LR} = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^7 & \lambda^6 & \lambda^2 \end{pmatrix}$$

$$(\delta^e)_{LL} = \begin{pmatrix} 1 & \lambda^4 & \lambda^4 \\ \cdot & 1 & \lambda^6 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^e)_{RR} = \begin{pmatrix} 1 & \lambda^3 & \lambda^4 \\ \cdot & 1 & \lambda^2 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad (\delta^e)_{LR} = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^7 \\ \lambda^5 & \lambda^4 & \lambda^6 \\ \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix}$$

Model predicts very small mass insertion parameters close to the MFV limit

Summary

- No evidence for NP, but SM puzzles remain: origin of mass, quest for unification, problem of flavour
- Higgs mass stabilization requires NP at ~ 1 TeV (current LHC limit)
- How do we reconcile this with general flavour analyses limits of ~100 TeV?
- We have focussed on SUSY where strong constraints may be derived on the off-diagonal squark masses in the diagonal quark basis
- Since SUSY particles appear in loops (R-parity) the constraints are not quite so strong but still require small mass insertion parameters
- SUSY models with family symmetry which describe fermion masses and mixings naturally have small off-diagonal squark masses
- In SU(5) GUTs off-diagonal squark and slepton masses may be related
- In S_4 discrete family symmetry with SU(5) GUTs we find small mass insertion parameters close to the MFV case, allowing TeV scale NP