Short recap

Last lecture (yesterday) we have learned that:

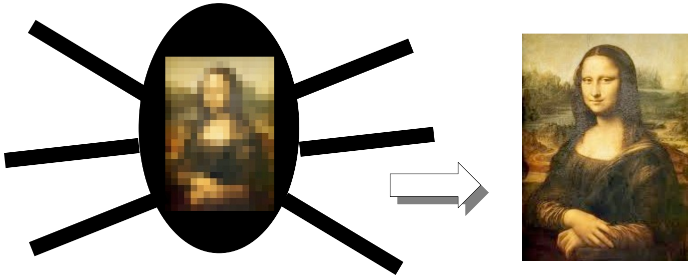
- (Effective) BSM models with TeV-scale new particles cannot have a generic flavor structure: NP flavor problem
- Effective Lagrangians that satisfy the Minimal Flavor violating hypothesis can satisfy experimental flavor constraints more easily
  ⇒ TeV scale NP is allowed
- MFV models are highly predictive (ex. $B_s \longrightarrow \mu^+\mu^- / B_d \longrightarrow \mu^+\mu^-$)

This lecture:

- (More) UV complete models: 2HDMs & SUSY
- Flavor physics at high energy:
  Higgs and top flavor violating decays
- Experimental prospects for the coming years

How to discover a new d.o.f.

High energy vs. high precision experiments



Synergy

Producing new particles on shell at high energy experiments

Collision of protons/electrons at high energy producing directly new particles and observe their decay products

Most recent examples from the past

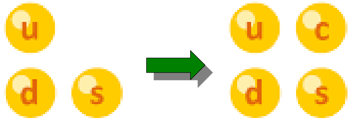
- Tevatron at Fermilab
  (center of mass energy 1.96 TeV)
  discovery of the top quark 1995
- Large Hadron Collider at CERN
  (center of mass energy 8 TeV)
  discovery of the Higgs boson 2012

What is next?

Testing new particles through flavor and CP transitions

Some examples from the past

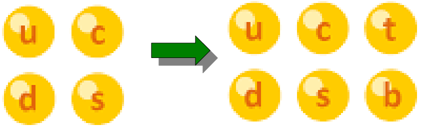
- Measurement of the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$



prediction of the charm quark
(Glashow, Iliopoulos, Maiani, 1970)

- Observation of CP violation in kaon anti-kaon oscillations

prediction of the 3rd generation
(Kobayashi, Maskawa, 1973)



What is next?

1. A Two Higgs Doublet Model (2HDM)

- Several extensions of the SM involve an extended Higgs sector, with more than one Higgs doublet.
  Most studied example: SUSY

SM doublet

- A two Higgs dublet: H_1= (1,2,-1/2), H_2= (1,2,1/2) ⇒ Physical fields: h, H, A, $H^{\pm}$

- Most general Lagrangian

$$V(H_1,H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + (bH_1H_2 + \mathrm{h.c}) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+ \lambda_4|H_1H_2|^2 + \left[\frac{\lambda_5}{2}(H_1H_2)^2 + \lambda_6|H_1|^2H_1H_2 + \lambda_7|H_2|^2H_1H_2 + \mathrm{h.c}\right]$$

These coefficients are generically complex.
Possible new sources of CP violation

$$\mathcal{H}_Y^{\mathrm{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

Each Higgs doublet can generically couple to up and down quarks.

FCNCs in 2HDMs

$$\mathcal{H}_Y^{\rm gen} = \underline{\bar{Q}_L X_{d1} D_R H_1} + \bar{Q}_L X_{u1} U_R H_1^c + \underline{\bar{Q}_L X_{d2} D_R H_2^c} + \bar{Q}_L X_{u2} U_R H_2$$

We can rotate to the basis in which only one Higgs has a VEV

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^c \end{pmatrix}$$

$$\langle \Phi_v^\dagger \Phi_v \rangle = v^2/2,$$

$$\langle \Phi_H^\dagger \Phi_H \rangle = 0$$

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R$$

$$\tan\beta \equiv \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

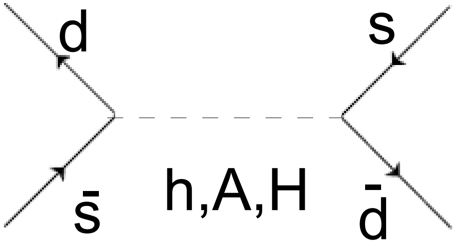
3x3 matrices

$$\begin{cases} Z_d = \cos\beta X_{d2} - \sin\beta X_{d1} \\ M_d = \dfrac{v}{\sqrt{2}} (\cos\beta X_{d1} + \sin\beta X_{d2}) \end{cases}$$

(analogous in the up sector)

Generically not proportional to each other! ⇨ It is not possible to diagonalize them simultaneously

Exercise: what are the conditions on X_{d1} and X_{d2} not to have FCNCs at tree level?



No loop suppression of the four fermion operators!

BAD!

Minimal Flavor Violating 2HDMs

$$\mathcal{H}_Y^{\text{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

$$\left\{\begin{array}{lcl} X_{d1} & = & Y_d \\ X_{u1} & = & \epsilon_u Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \cdots \\ X_{d2} & = & \epsilon_b Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \cdots \\ X_{u2} & = & Y_u \end{array}\right.$$

higher orders in the small Yukawa couplings

The ϵ_i are in general complex coefficients

Exercise: convince your-self that the several terms are invariant under

$$SU(3)_Q \times SU(3)_U \times SU(3)_D$$

Minimal Flavor Violating 2HDMs

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

$$\left\{ \begin{array}{lcl} X_{d1} & = & Y_d \\ X_{u1} & = & \epsilon_u Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \cdots \\ X_{d2} & = & \epsilon_b Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \cdots \\ X_{u2} & = & Y_u \end{array} \right.$$

higher orders in the small Yukawa couplings

The ε_i are in general complex coefficients

- The most studied 2HDMs are the so called Type I, II, III, IV: these are models where up and down quarks only couple to one Higgs type.

Example: Type II: U_R only couple to H_2 and D_R only coupled to H_1 ($X_{u1} = X_{d2} = 0$)

- All these models are a particular limit of a MFV 2HDM

Footnote:
The MSSM can be approximated with a Type II 2HDM

Flavor phenomenology of MFV 2HDMs

- Constraints from meson mixing observables

Kaon $\sim \frac{A_0}{M_H^2}\tan^4\beta\, m_s m_d [V_{ts}^* V_{td}]^2$

$B_d \sim \frac{A_1}{M_H^2}\tan^4\beta\, m_b m_d [V_{tb}^* V_{td}]^2$

$B_s \sim \frac{A_2}{M_H^2}\tan^4\beta\, m_b m_s [V_{tb}^* V_{ts}]^2$

Larger NP effect

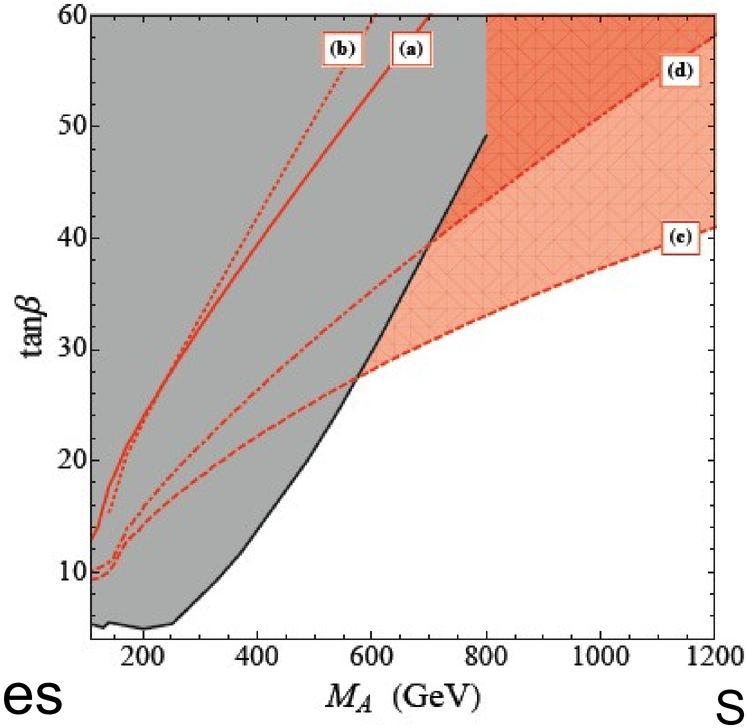
A_i are combinations of the ε_i of the previous slide

- Some possible NP in rare B-decays

$$\frac{\mathrm{Br}(B_q \to \mu^+\mu^-)}{\mathrm{Br}(B_q \to \mu^+\mu^-)_{\mathrm{SM}}} = (|1 + R_q|^2 + |R_q|^2)$$

$$R_q \propto \frac{M_{B_q}^2 t_\beta^3}{M_H^2}$$

Altmannshofer et al. 1211.1976

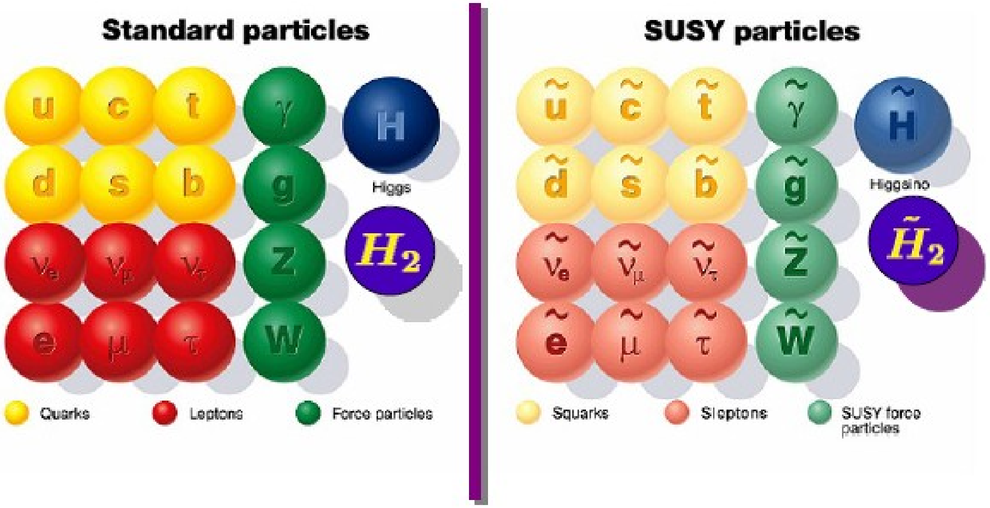


Interplay
with direct searches

2. SUSY models (intro). The MSSM

The Minimal Supersymmetric extension of the SM includes:

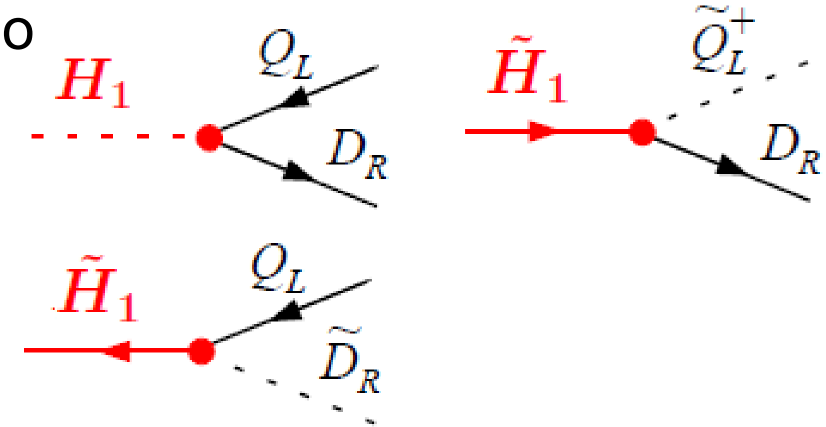
(i) scalar partners of the ordinary quarks and leptons;
(ii) spin-1/2 partners of the ordinary gauge bosons [*gauginos*];
(iii)Two Higgs doublets [H_1 , H_2]
with their corresponding spin 1/2 partners



- The SUSY version of L_{gauge} is completely determined by its symmetry properties

- The SUSY version of L_{Yukawa} ($\mathcal{L}_Y^{\text{MSSM}}$) is also strongly constrained

$$\mathcal{L}_Y^{\text{MSSM}} = \bar{Q}_L Y_D D_R H_1 + \bar{Q}_L Y_U U_R H_2 + \tilde{Q}_L^{+} Y_D D_R \tilde{H}_1 + \tilde{Q}_L^{+} Y_U U_R \tilde{H}_2 + \cdots$$



SUSY models & new sources of FCNCs

"Problems" arise when we consider SUSY breaking.
Large number of degrees of freedom!

$$\mathcal{L}_{soft} = (M_f)_{ij}\,\chi_i\,\chi_j + (M_s{}^2)_{ij}\,\phi_i\,\phi_j + A_{ijk}\,\phi_i\,\phi_i\,\phi_k$$

gaugino/higgsino masses

squark/slepton masses

trilinear scalar couplings

Potential new sources of flavor symmetry breaking

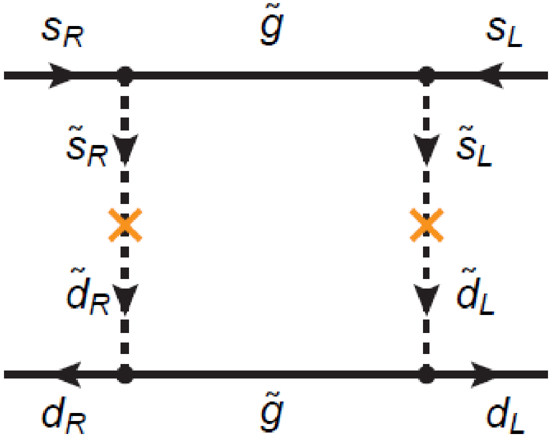
For example, in the down-squark sector:

$$\left(\tilde{Q}_L^i \quad \tilde{D}_R^i \right) \begin{pmatrix} (M_{LL}^2)_{ij} & (M_{LR}^2)_{ij} \\ (M_{LR}^2)_{ij}^\dagger & (M_{RR}^2)_{ij} \end{pmatrix} \begin{pmatrix} \tilde{Q}_L^i \\ \tilde{D}_R^i \end{pmatrix}$$

If the off-diagonal entries in these mass matrices are not sufficiently small, the model is ruled out by flavor physics...

The SUSY flavor problem

Going back to our meson mixings...



If these mass parameters are of O(1):

$$\mathcal{M} = M_{\tilde{q}} \begin{pmatrix} \mathcal{O}(1)_{3\times3} & \mathcal{O}(1)_{3\times3} \\ \mathcal{O}(1)_{3\times3} & \mathcal{O}(1)_{3\times3} \end{pmatrix}$$

squark masses have to be larger than ~10^3 TeV

Tension with the idea of TeV-scale SUSY ⇒ SUSY flavor problem

If we take a MFV SUSY scenario, the soft masses are highly non-generic:

$$\begin{cases} M^2_{LL} = \tilde{m}^2_Q \left(\mathrm{I}_{3\times3} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + \right. \\ \qquad \left. + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + b_3^* Y_u Y_u^\dagger Y_d Y_d^\dagger + \ldots \right) \\ M^2_{RR} = \tilde{m}^2_D \left(\mathrm{I}_{3\times3} + b_5 Y_d^\dagger Y_d + \ldots \right) \end{cases}$$

⇒ **Squark masses as light as few hundred GeV are allowed!**

Take home messages (for NP models)

- Complete NP models generically show a rich flavor structure
  ⇒ too large breaking of the flavor symmetry
  of the SM gauge interactions

- If we ask for MFV, it is easier to evade the constraints.
  At the same time it is possible to have deviations from the SM prediction of some flavor observables
  (example: $B_s \longrightarrow \mu^+\mu^-$ vs. $B_d \longrightarrow \mu^+\mu^-$)

- Complementarity with LHC direct searches of new physics particles
  (example: additional Higgs bosons, ...)

Some discrepancy. Hints for NP?

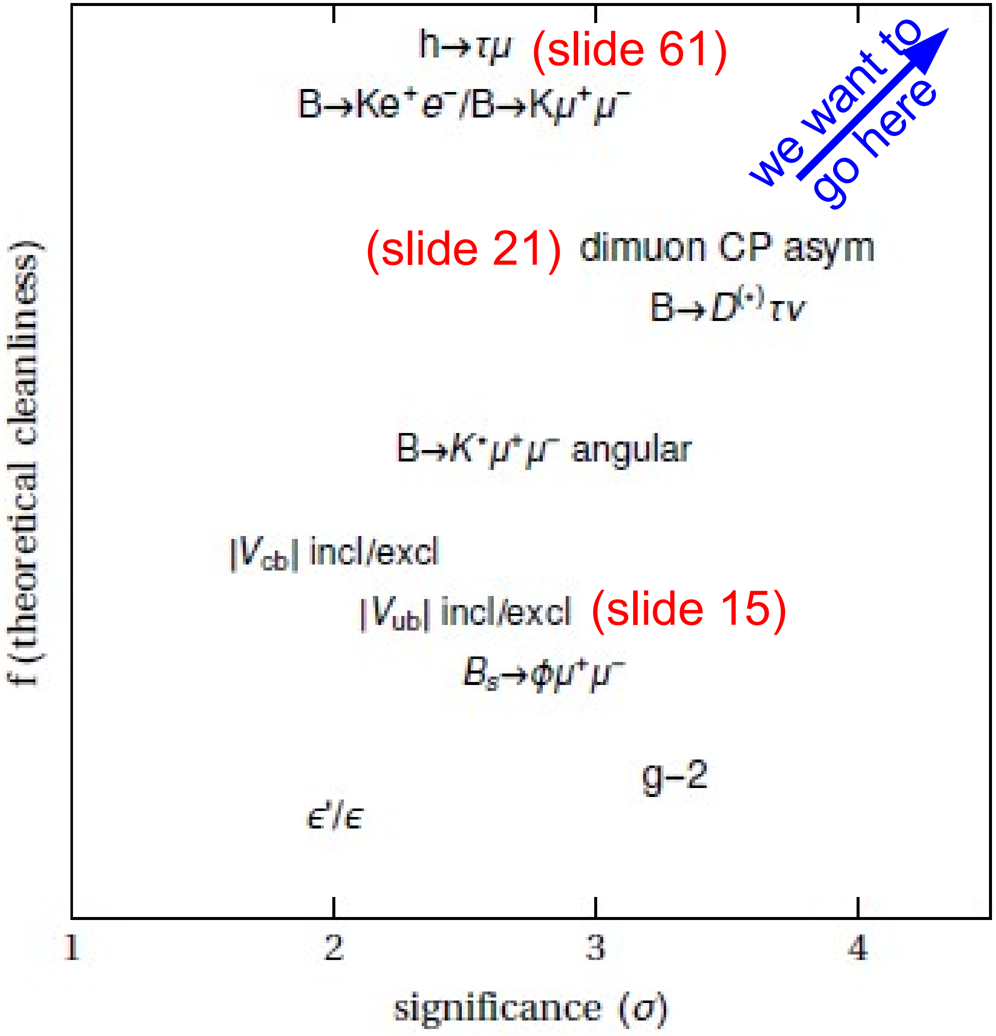
In the last ~30 years, there have been a tremendous experimental progress in testing the flavor structure of the SM

Overall, we have a good agreement

Neverthless

There are some measurements of flavor observables that show some (small?) deviation with respect to the SM prediction

Z.Ligeti



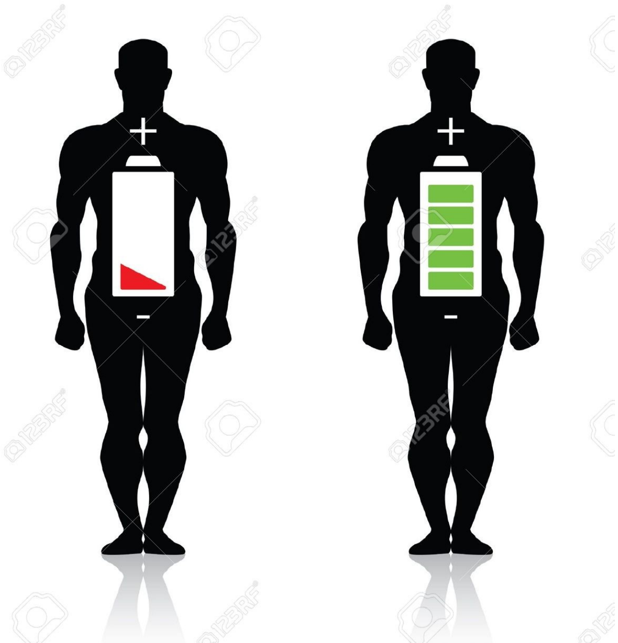
Some would be unambiguous NP signals

Except for theoretically cleanest modes, cross-checks needed to build a robust case for NP

Flavor at high energy?

1\. Up to now we have learned about low energy flavor observables

2\. Can we say something using more massive particles?
Can we test flavor transitions at high energy environments?



Low energy

We have studied:
Meson transitions

High energy

We will study:
Top & Higgs

S.Gori

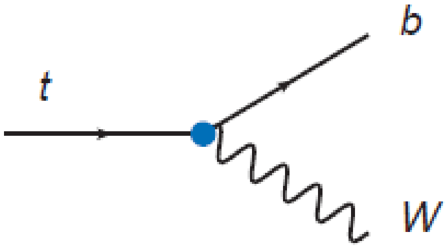
Top flavor changing decays

- The top was discovered in 1995 at Tevatron.
  By now, we know its properties quite well BUT...
- Let us compare the top quark to the bottom quark

Top | **Bottom**

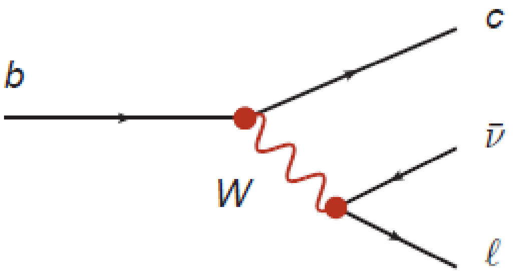
Main decay mode

Top



$$\frac{\Gamma_t}{m_t} \simeq 1\%$$

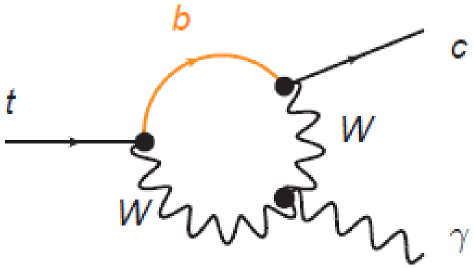
Bottom



$$\frac{\Gamma_{B_d}}{m_{B_d}} \simeq 8.2 \times 10^{-13}$$

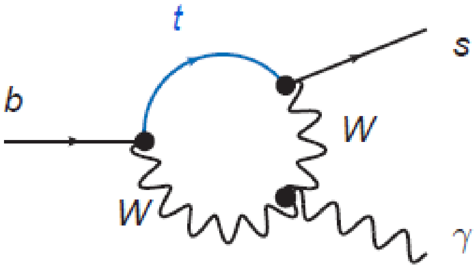
Some possible Rare decay

Top



$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{m_W^2}V_{tb}V_{cb}^*$$

Bottom



$$\mathcal{A}_{b\to s\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^*$$

Top flavor changing decays

- The top was discovered in 1995 at Tevatron.
  By now, we know its properties quite well BUT...

- Let us compare the top quark to the bottom quark

Top | **Bottom**

Main d
moc

SM predictions:

Aguilar-Saavedra 0409342

$$\mathrm{BR}(t \to c\gamma) \simeq 5 \times 10^{-14} \quad , \quad \mathrm{BR}(t \to u\gamma) \simeq 4 \times 10^{-16}$$

$$\mathrm{BR}(t \to cg) \simeq 5 \times 10^{-12} \quad , \quad \mathrm{BR}(t \to ug) \simeq 4 \times 10^{-14}$$

$$\mathrm{BR}(t \to cZ) \simeq 1 \times 10^{-14} \quad , \quad \mathrm{BR}(t \to uZ) \simeq 8 \times 10^{-17}$$

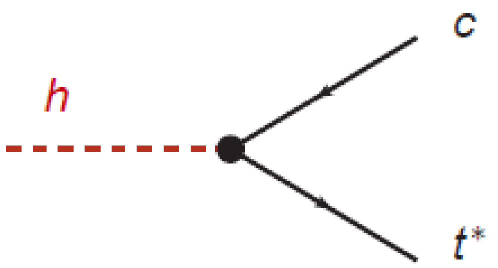
$$\mathrm{BR}(t \to ch) \simeq 3 \times 10^{-15} \quad , \quad \mathrm{BR}(t \to uh) \simeq 2 \times 10^{-17}$$

Som
possi
Rare decay

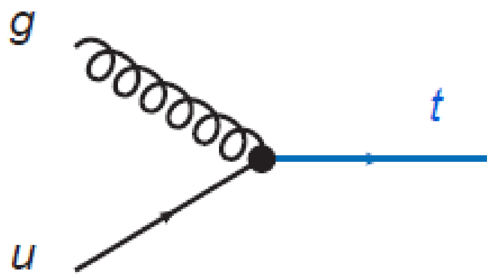
$$\mathcal{A}_{t\to c\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_b^2}{m_W^2}V_{tb}V_{cb}^* \qquad \mathcal{A}_{b\to s\gamma} \propto \frac{e}{16\pi^2}\frac{G_F}{\sqrt{2}}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^*$$

Top flavor changing couplings at LHC

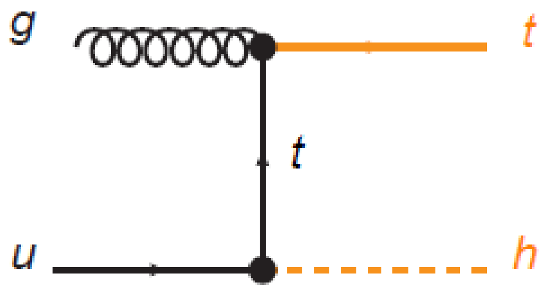
Flavor changing top interactions are not only probed by searches of rare top decays. Other probes include:



Higgs decay



Single top production



Single top+Higgs production

Process	Br Limit	Search	Dataset
$t \to Zq$	5×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.7 fb^{-1}, 8 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV
$t \to \gamma u$	1.6×10^{-4}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to \gamma c$	1.8×10^{-3}	CMS $qg \to t\gamma \to Wb\gamma$	19.1 fb^{-1}, 8 TeV
$t \to hq$	7.9×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV
$t \to hq$	5.6×10^{-3}	CMS $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	19.5 fb^{-1}, 8 TeV

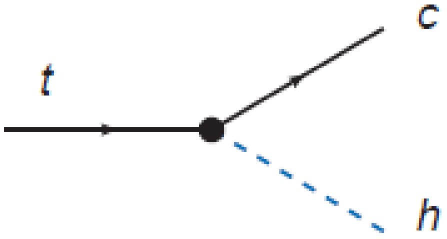
Bounds are much much larger than the SM prediction

NP models and top flavor changing decays

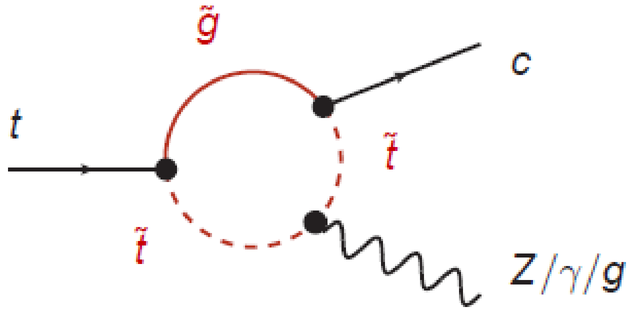
- Several NP models can sizably enhance the BR for top flavor changing decays, while satisfying direct and "indirect" low energy constraints

Some example:

2HDM

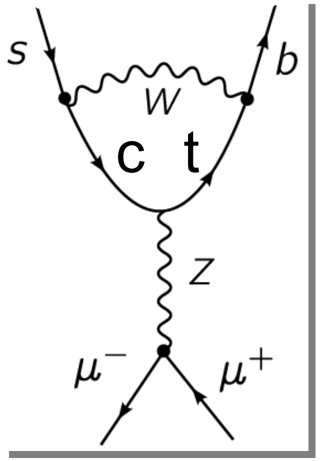


MSSM



	2HDM[1)]	MSSM[2)]	Reminder for the SM:
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	10^{-14}
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	5×10^{-14}
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	5×10^{-12}
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	3×10^{-15}

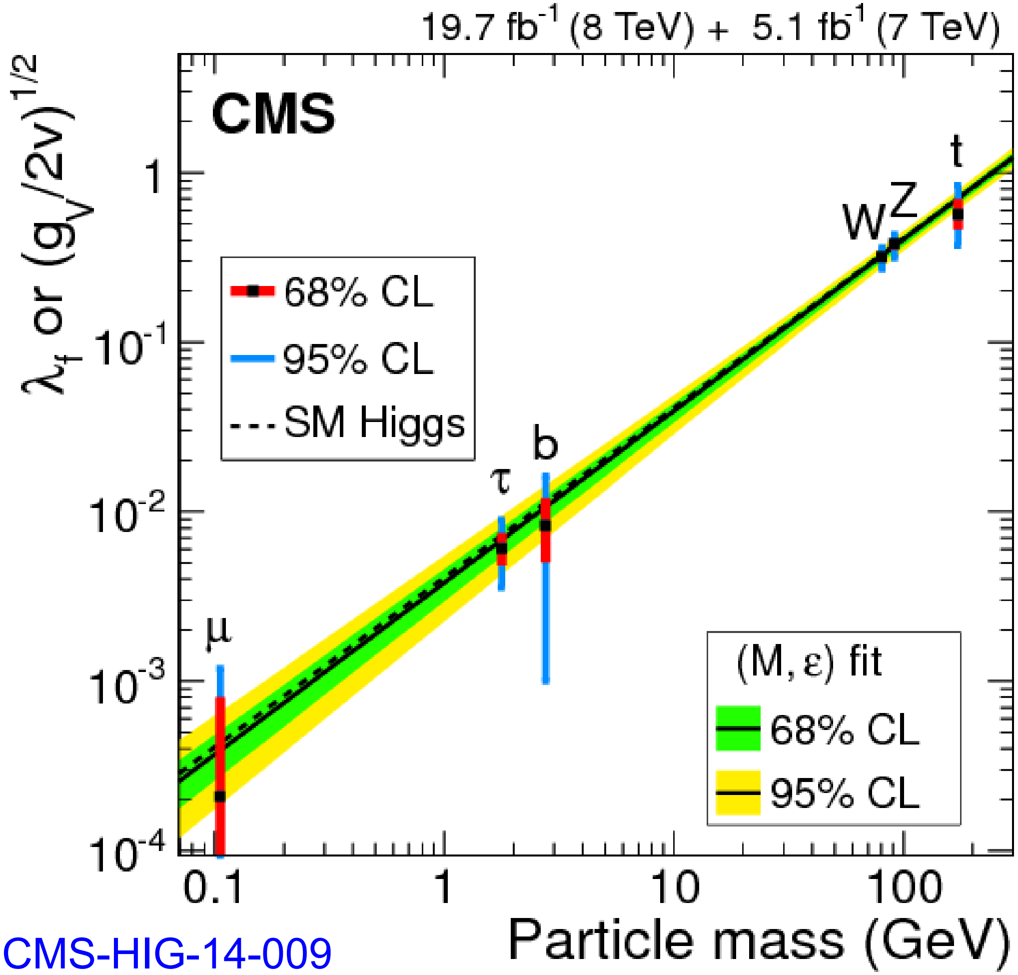
Example of indirect constraint:



$B_s \to \mu^+\mu^-$

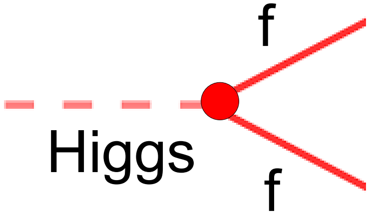
The Higgs flavor conserving couplings

- LHC will measure more and more precisely the couplings of the Higgs to the massive particles of the SM



CMS-HIG-14-009

LHC RunI tests for the relations



$\propto m_f$

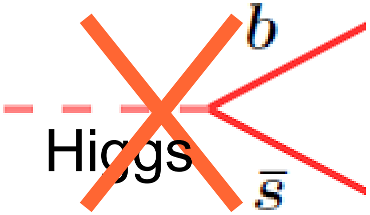
(note: we are speaking about flavor conserving couplings!)

We do not know (yet) how the Higgs couples to light flavors (muons? electrons? charm quarks?)

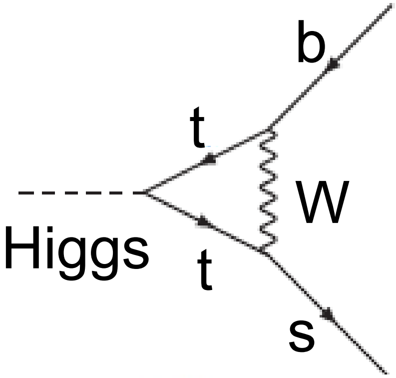
We know, for example, that it couples non-universally with muons and taus but we do not know more than this...

The Higgs flavor violating couplings (1)

- We have seen that, in the SM, the Higgs does not have flavor changing couplings at the tree level



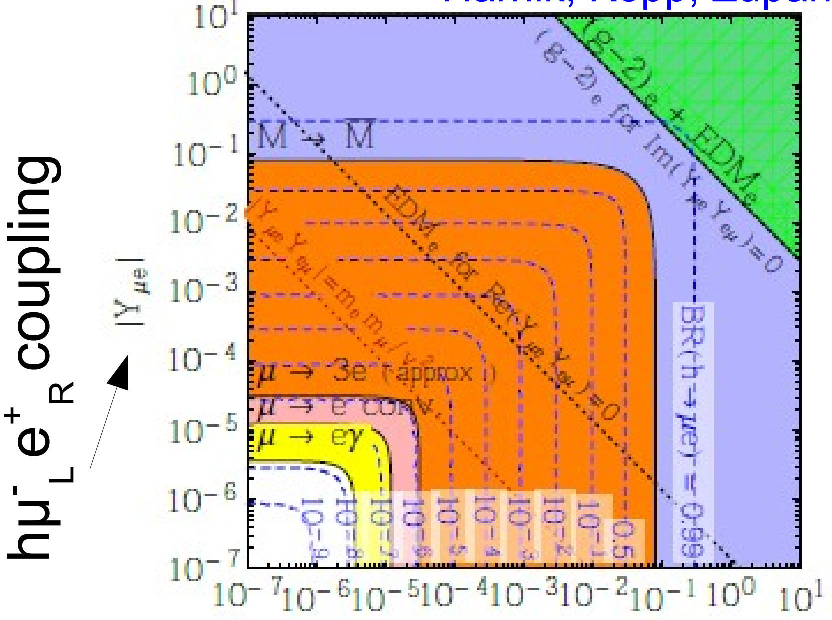
Still, these couplings are generated at one loop in perturbation theory:



Tiny BRs are predicted by the SM

- Some of these "effective" couplings are strongly constrained by low energy measurements:

Harnik, Kopp, Zupan, 1209.1397

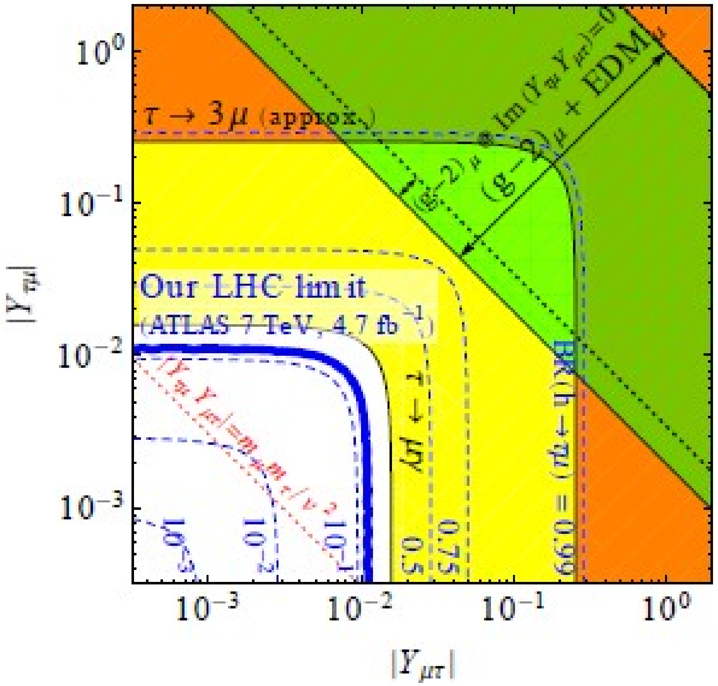


$he^-_L \mu^+_R$ coupling → $|Y_{e\mu}|$

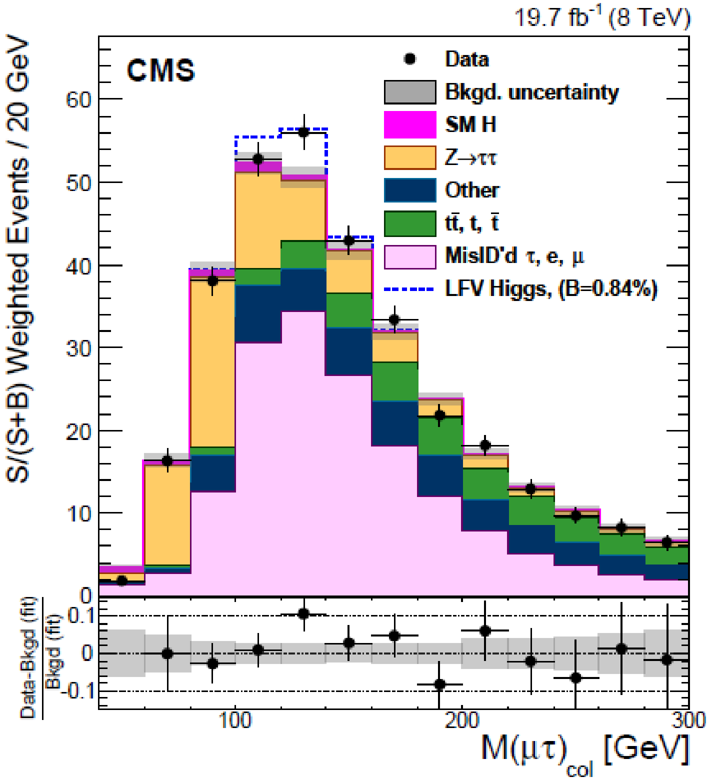
The Higgs flavor violating couplings (2)

- Some other coupling is instead much more weakly constrained by low energy measurements

Harnik, Kopp, Zupan, 1209.1397



- Some interesting ATLAS and CMS search...



- CMS, 1502.07400

$$\mathrm{BR}(h \to \mu\tau) \ < \ 1.51\%, \ \ 95\% \ \mathrm{C.L.}$$

$$\mathrm{BR}(h \to \mu\tau) \ = \ (0.84^{+0.39}_{-0.37})\%$$

- ATLAS, 1508.03372

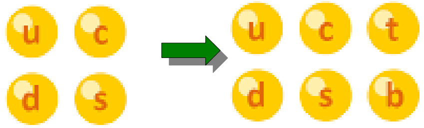
$$\mathrm{BR}(h \to \mu\tau) \ < \ 1.85\%, \ \ 95\% \ \mathrm{C.L.}$$

$$\mathrm{BR}(h \to \mu\tau) \ = \ (0.77 \pm 0.62)\%$$

Take home messages

- The measurements of a few low energy flavor observables seem to show some (small) discrepancy, if compared to the SM prediction... Looking for a theory and experimentally clean observables not agreeing with the SM prediction!

We want to repeat:



- Opportunity of testing flavor, performing high energy measurements: top and Higgs flavor changing couplings

- The Higgs is the ultimate source of flavor. Importance of testing its flavor structure (both flavor diagonal and off-diagonal couplings)

A rich flavor experimental program ahead

Observables fulfilling the criteria:
(i) sensitive to different NP,
(ii) measurements can improve by order(s) of magnitude,
(iii) not limited by hadronic uncertainties

Belle II and LHCb (some highlight)

- Difference of CP asymmetries $S_{\Psi Ks}$, $S_{\Phi ks}$, $S_{\Psi\Phi}$ etc.
- γ from CP asymmetries in tree-level decays (e.g. $B \longrightarrow D K$)
- CP asymmetry in semileptonic B decays
- CP asymmetry in the radiative decay $S_{K_s\pi^0\gamma}$
- B meson decay searches: $B_{s,d} \longrightarrow \mu\mu$, $B_{s,d} \longrightarrow \tau\ \tau$, $B^{\pm} \longrightarrow \tau\ \nu$, $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, ...
- Search for CP violation in $D - \bar{D}$ mixing
- Search for charged lepton flavor violation

LHC (some highlight)

High energy measurements

- Top flavor changing couplings (in decay and in production)
- Couplings of the Higgs to light Generation quarks/leptons?
- Flavor changing Higgs couplings

Concluding remarks on flavor/CP

- We cannot (yet) predict the SM flavor/CP structure
- from first principles (SM flavor puzzle)

- The SM is very well tested by low energy flavor measurements

  ⇨ Overall good consistency

- Great opportunity for testing NP using low and high energy flavor measurements

Evidence for BSM?		FLAVOR	
		yes	no
ATLAS & CMS	yes	Complementary info	Distinguish models
	no	Tells us where to look next	Flavor is the best probe