3rd Lecture
Flavor physics at a TeV

- New physics and symmetries
- (Lepton flavor violation)
- Top FCNC at the LHC
- Minimal flavor violation

  Flavor at high-p_T, some sflavor physics
- Final thoughts

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- Final thoughts

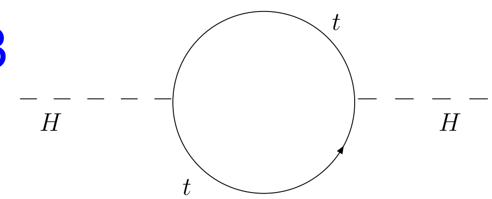
Excuse to talk about this: “Violation de CP et CKM” — possible that CKM violation ($\equiv$ non-MFV)
may first be seen by ATLAS & CMS

Reasons to pursue flavor physics

- Hopefully the LHC will discover new particles; some subleading couplings probably not measurable directly (we know V_{td} & V_{ts} only from B and not t decays)

  Important to figure out soft SUSY breaking terms $\Rightarrow$ SUSY breaking, mediation

- In many models: large $m_t \Rightarrow$ non-universal coupling to EWSB



  Motivated models: NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.

  Is the physics of 3rd–1st, 3rd–2nd, and 2nd–1st generation transitions the same?

- If no NP is seen in flavor sector, similar constraints as LEP tests of gauge sector

- If non-SM flavor physics is seen, try to distinguish between classes of models:
  - One / many sources of CPV?
  - In charged / neutral currents?
  - Modify SM operators / new operators?
  - Couples to up / down sector?
  - To 3rd / all generations?
  - Quarks / leptons / other sectors?

The new physics scale

- Baryon and lepton number violating operators (lack of proton decay), e.g.:

$$\frac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\,\mathrm{GeV}$$

May be an exact symmetry — small coefficients due to high scales or symmetries

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- Flavor and CP violating operators (new physics flavor problem), e.g.:

$$\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(4\ldots7)}\,\mathrm{GeV}$$

- Precision electroweak T parameter (little hierarchy problem):

$$\frac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda > \text{few} \times 10^3\,\mathrm{GeV}$$

Flavor and custodial symmetry are known to be broken already in the SM

- There cannot be an exact symmetry that forbids these higher dimension operators

And the winner is...

- Unique set of dimension-5 terms composed of SM fields:

$$\mathcal{L}_{\text{dim-5}} = \frac{1}{\Lambda}(L\phi)(L\phi) \to m_\nu\,\nu\nu\,, \qquad m_\nu \propto \frac{v^2}{\Lambda}$$ (see-saw mechanism)

... Gives Majorana masses for neutrinos

- Discovery of neutrino oscillations implies that SM has to be extended:
  (i) Dirac mass: need "sterile" right haded neutrino states (no weak interaction)
  (ii) Majorana mass: need nonrenormalizable terms to describe Nature

- Majorana mass: natural expectation if SM viewed as a low energy effective theory

  Suggests very high scales (assuming $\mathcal{O}(1)$ couplings), far beyond reach

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- Hierarchy $\Rightarrow \Lambda \sim 1\text{TeV}$; flavor / $CP \Rightarrow \Lambda \gtrsim 10^3\text{TeV}$; neutrino mass $\Rightarrow \Lambda \sim 10^{10}\text{TeV}$

  All have assumptions — we do not really know; hope to find NP at a TeV

Aside: lepton flavor violation

Neutrino masses: extending the SM

- It is often stated that the standard model (SM) implies $m_\nu = 0$ — if one defines:

  Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ ("forces")

  Particle content: quarks: $\left[Q_L(3,2)_{1/6}, \quad u_R(3,1)_{2/3}, \quad d_R(3,1)_{-1/3}\right] \times 3$ copies

  leptons: $\left[L_L(1,2)_{-1/2}, \quad \ell_R(1,1)_{-1}\right] \times 3$ copies

  Symmetry breaking: $SU(2)_L \times U(1)_Y \;\to\; U(1)_{\rm em}$ (due to Higgs vev)

  This definition predicts $m_\nu = 0$ for all 3 neutrinos

- Neutrino mass term similar to (up-type) quarks would require $\nu_R(1,1)_0$

$$\mathcal{L} = Y^\nu_{ij}\, \overline{L^I_{Li}}\, \widetilde{\phi}\, \nu^I_{Rj} \;\Rightarrow\; m\, \overline{\nu}\, \nu$$

  No evidence for ν_R — would be a SM singlet, have no weak interactions ("sterile")

  Can add it to the SM, then simplicity / minimalism lost — why not much heavier?

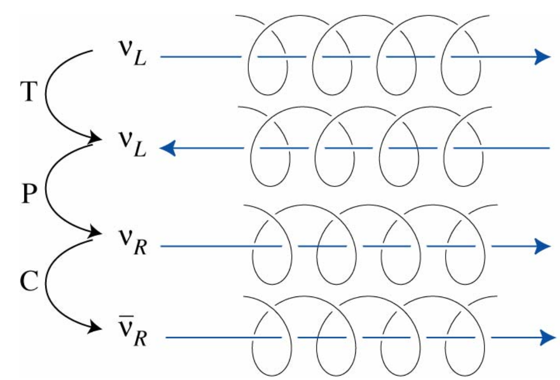
Particles masses and chirality

- Neutrinos have mass ⇒ cannot go with speed of light

- What is this right-handed particle?
  - "New" particle: right-handed neutrino (Dirac mass, previous page)
  - "Old" anti-particle: right-handed anti-neutrino (Majorana mass, next page)

- Under CPT transformation: $\nu_L \leftrightarrow \overline{\nu}_R$ and $\overline{\nu}_L \leftrightarrow \nu_R$

  For a particle which carries no additive conserved charge, these may be the same



Dirac vs. Majorana mass

- If there are no light ν_R states, masses can arise from dimension-5 operators:

$$\mathcal{L}_{\text{dim-5}} = \frac{1}{\Lambda}\,(L\phi)(L\phi) \to m_\nu\,\nu\nu\,, \qquad\qquad m_\nu \propto \frac{v^2}{\Lambda} \quad \text{(see-saw mechanism)}$$

$\dfrac{Y^\nu_{ij}}{v}\,\phi\phi L_{Li}L_{Lj}$ cannot arise from loops, e, μ, τ number are accidental symm's of SM

$B - L$ is non-anomalous, so nonperturbative terms can neither generate it

- Modern view of SM: the low energy effective theory of any underlying physics

  ... suggested scale is very high: $\Lambda \sim 10^{13}\,\text{GeV}$

- Majorana mass terms violate lepton number: $\Delta L = \Delta(B - L) = 2$

- Central question: Is lepton number conserved?

  To decide: neutrinoless double beta decay

Aside: ν oscillation measurements

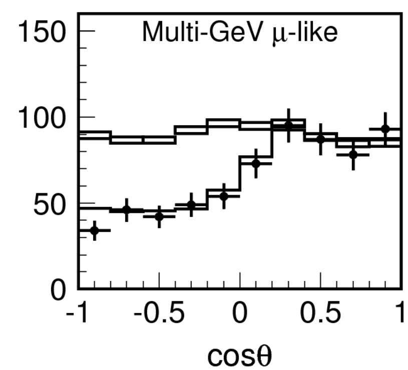
- Two large mixing angles observed
- Oscillation between two flavors $(\delta m^2 = m_1^2 - m_2^2)$

$$P_{\rm osc} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\delta m^2}{\rm eV^2}\,\frac{L}{\rm km}\,\frac{\rm GeV}{E}\right)$$

- Atmospheric neutrinos:

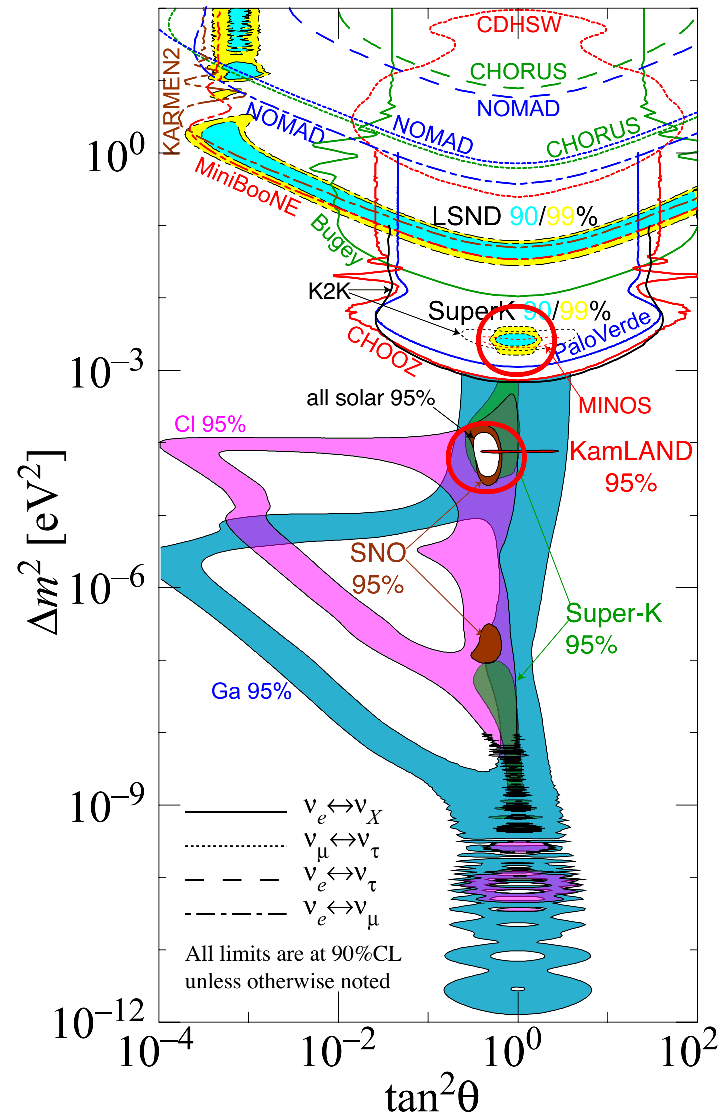
  $1 \sim (10^{-3}) \times (10^{1\ldots4}) \,/\, (10^{0\pm1})$

  half of up-going ν_μ get lost



- Solar neutrinos: $\delta m^2\, L/E \gg 1$
- Two mixing angles and two mass-squared differences are known, but not the absolute mass scale

From WMAP: $\sum m_i < 1\,{\rm eV}$



Aside: Neutrino mixing parameters

- Usual parameterization — just like the CKM matrix:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23} \approx 45^\circ \text{ (atm)}} \underbrace{\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}}_{\theta_{13} \lesssim 10^\circ,\ \delta \text{ unknown}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}}_{\theta_{12} \approx 34^\circ \text{ (solar)}}$$

- If neutrinos are Majorana, multiply by: $\mathrm{diag}\,(e^{i\alpha_1/2},\, e^{i\alpha_2/2},\, 1)$
  The “new” CPV phases, $\alpha_{1,2}$, do not affect oscillation experiments

  Neutrino mass effects are tiny $m_\nu/E_\nu \sim \mathrm{meV/MeV} \sim 10^{-9} \Rightarrow$ interference

- Think of quarks in terms of (physical) mass eigenstates, no confusion between $D \to \pi K$ and $D \to \pi\pi$; if neutrino masses were larger, we would have gotten used to thinking of $\pi \to \mu\bar{\nu}_2$ and $\pi \to \mu\bar{\nu}_3$ instead of $\pi \to \mu\bar{\nu}_\mu$

- In the quark sector (CKM matrix): $\theta_{12} \approx 13^\circ$, $\theta_{23} \approx 2.4^\circ$, $\theta_{13} \approx 0.2^\circ$, and $\delta \approx 68^\circ$

Related to TeV scale physics?

- In its simplest version with $m_\nu = 0$, SM predicted lepton flavor conservation

  This is now known not to be the case — so there is no reason to impose it as a symmetry on new physics

- If there are new TeV-scale particles that carry lepton number (sleptons), then they have their own mixing matrices and give rise to charged lepton flavor violation

  Most often discussed: $\mu \to e\gamma$, $\mu \to e\bar{e}e$, $\tau \to \mu\gamma$, $\tau \to \ell\ell\ell$

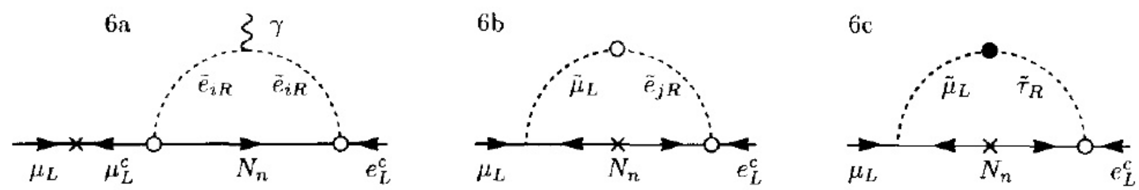
  SM predictions (penguins w/ neutrinos) are incredibly small and always negligible

Lepton flavor violation (in τ decays)

- $\mu \to e\gamma$ vs. $\tau \to \mu\gamma$ (few $\times 10^{-9}$)?

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{3\pm2}$



  In many models best bet is $\mu \to e\gamma$, but there are many exceptions

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (few $\times 10^{-10}$) vs. $\tau \to \mu\gamma$?

  Consider operators: $\bar\tau_R \sigma_{\alpha\beta} F^{\alpha\beta} \mu_L, \ (\bar\tau_L \gamma^\alpha \mu_L)(\bar\mu_L \gamma_\alpha \mu_L)$

  Suppression of $\mu\gamma$ and $\mu\mu\mu$ final states by $\alpha_{\rm em}$ opposite for these two operators $\Rightarrow$ winner is model dependent

Super B sensitivity with $75\,\mathrm{ab}^{-1}$

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- $\mu \to e\gamma$ and $(g-2)_\mu$ operators are very similar: $\dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} e\,, \quad \dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

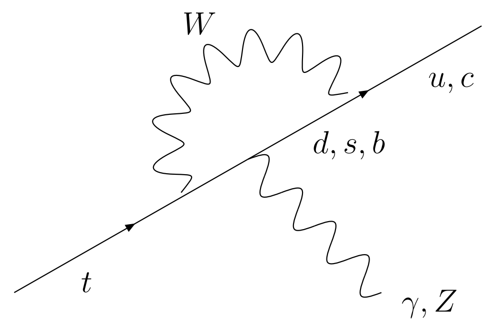
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

Top flavor violation

FCNC in top decays

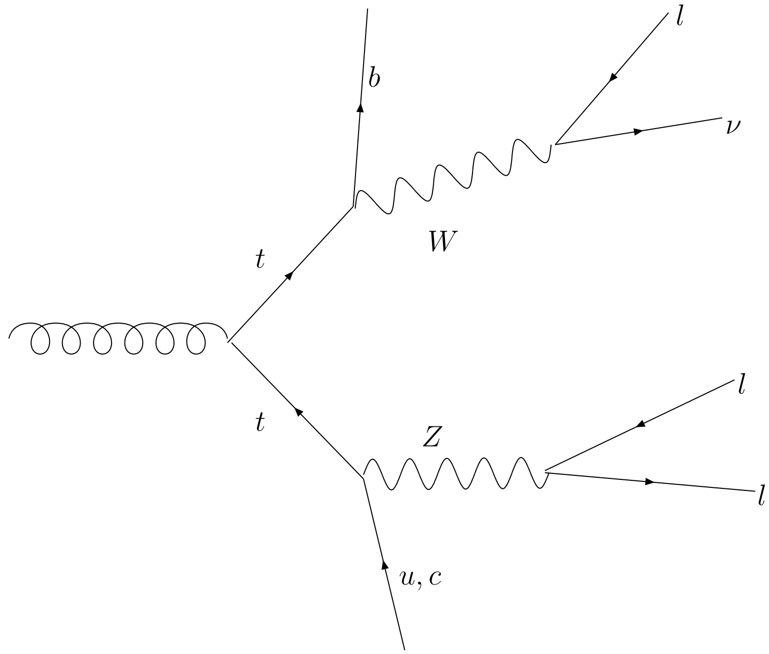
- Rare top decays
  - $t \to qZ \qquad (q = u, c)$
  - $t \to q\gamma$
  - $t \to qg$
  - $t \to qh \qquad \longleftarrow$ more model dependent



- Tiny in SM: $\mathcal{B}(t \to cZ) \sim \mathcal{B}(t \to c\gamma) \sim 10^{-13}$ — good place to look for NP
- Direct bounds on top FCNC's are weak (95% CL)
  - LEP2: $e^+e^- \to tc: \quad \mathcal{B}(t \to qZ) < 13.7\%$
  - Hera: $e^-p \to te^-: \quad \mathcal{B}(t \to u\gamma) < 0.6\%$
  - CDF: $\mathcal{B}(t \to qZ) < 3\%$

LHC is a top factory: $1\ t\bar{t}$ pair / sec

- The best place to probe FCNC top decays



channel	$t \to Zu(c)$	$t \to \gamma u(c)$	$t \to gu(c)$		
			(3 jets)	(4 jets)	(combined)
upper limit on BR ($L = 10$ fb^{-1})	3.4×10^{-4}	6.6×10^{-5}	1.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}
upper limit on BR ($L = 100$ fb^{-1})	6.5×10^{-5}	1.8×10^{-5}	5.0×10^{-4}	8.0×10^{-4}	4.3×10^{-4}

⇑ ⇑

[Carvalho, Castro, Onofre, Veloso, ATLAS note, 2005]

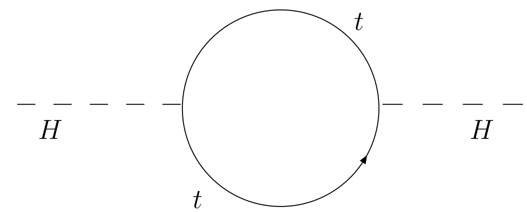
NP in the top sector?

- NP at TEV scale to stabilize electroweak scale

  ... it may interact with the top

  New flavor violation if:

  NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.

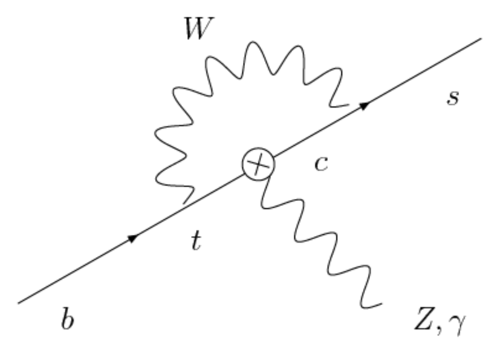


- Search for flavor violation in top sector

- Indirect constraints: $t_L \leftrightarrow b_L$ — there are tight bounds from B decays
- Top FCNC's could affect other observables

  What are the present bounds?

  Could the LHC still see something?



A model independent analysis

- The SM gauge symmetries relate some operators to B decay processes

  Our motivation: be less model dependent than previous analyses

  - Consider SM $+$ all possible dimension-6 operators respecting $SU(2) \times U(1)$ invariance that contribute to top FCNCs
  - Assume a valid perturbative expansion in v/Λ (NP scale above electroweak)
  - "No CP violation" ($\sim$ be conservative with CPV)
  - Look at all possible indirect bounds

[Fox, ZL, Papucci, Perez, Schwartz]

List of operators

- $2\ LL$ operators:

$$O^u_{LL} = i\left[\overline{Q}_3\tilde{H}\right]\left[\left(\not{D}\tilde{H}^\dagger\right)Q_2\right] - i\left[\overline{Q}_3\left(\not{D}\tilde{H}\right)\right]\left[\tilde{H}^\dagger Q_2\right] + \mathrm{h.c.}$$
$$O^h_{LL} = i\left[\overline{Q}_3\gamma^\mu Q_2\right]\left[H^\dagger D_\mu H\right] + \mathrm{h.c.}$$

- $4\ LR$ operators:

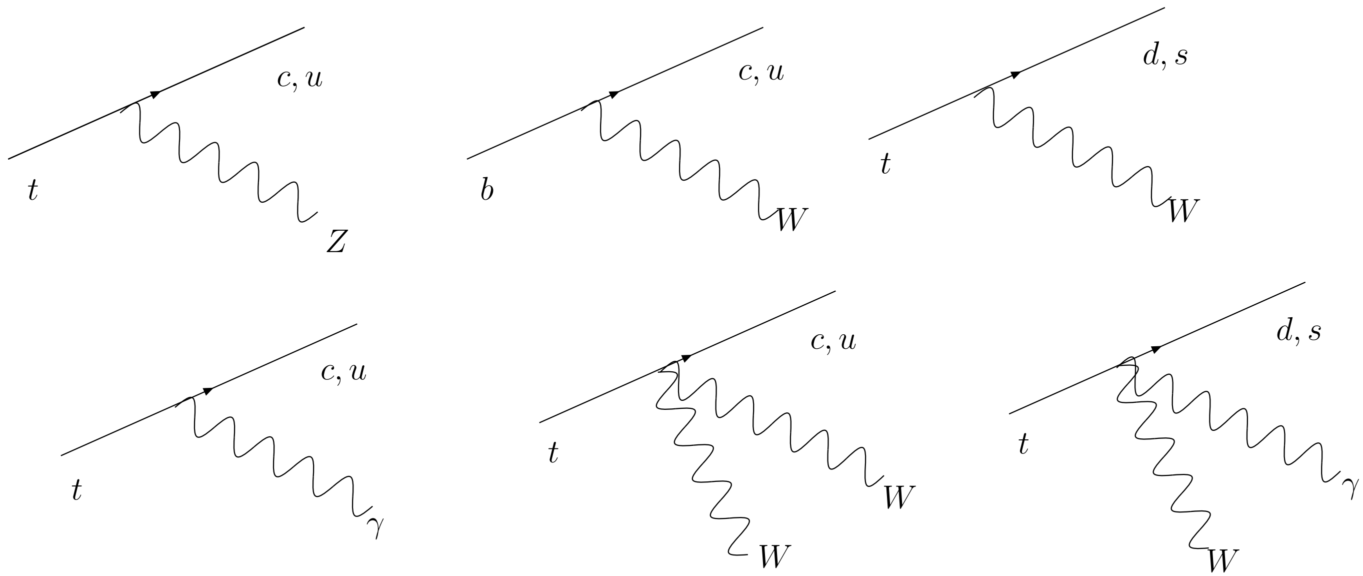
$$O^w_{LR} = g\left[\overline{Q}_3\sigma^{\mu\nu}\sigma^a\tilde{H}\right]c_R W^a_{\mu\nu} + \mathrm{h.c.}$$
$$O^w_{RL} = g\left[\overline{Q}_2\sigma^{\mu\nu}\sigma^a\tilde{H}\right]t_R W^a_{\mu\nu} + \mathrm{h.c.}$$
$$O^b_{RL} = g'\left[\overline{Q}_2\sigma^{\mu\nu}\tilde{H}\right]t_R B_{\mu\nu} + \mathrm{h.c.}$$
$$O^b_{LR} = g'\left[\overline{Q}_3\sigma^{\mu\nu}\tilde{H}\right]c_R B_{\mu\nu} + \mathrm{h.c.}$$

- $1\ RR$ operator:

$$O^u_{RR} = i\,\bar{t}_R\gamma^\mu c_R\left[H^\dagger D_\mu H\right] + \mathrm{h.c.}$$

- Many four-fermion operators ($q\bar{q}\ell\bar{\ell}$ and $q\bar{q}q\bar{q}$)

After electroweak symmetry breaking



- Constraints from:
  - EW precision tests: $T,\ U,\ V$
  - B decays: semileptonic decays ($B \to X_{c,u}\ell\bar{\nu}$, $D^{(*)}\ell\bar{\nu}$, $\pi\ell\bar{\nu}$), mixing ($\Delta F = 2$)
    rare decays: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, $B \to \rho\gamma$, $B \to \ell^+\ell^-$
- Subtlety: tree-level measurements modified — whole CKM fit has to be redone

Open sources of top FCNC

	C^u_{LL}	C^h_{LL}	C^w_{RL}	C^b_{RL}	C^w_{LR}	C^b_{LR}	C^u_{RR}
direct bound	9.0	9.0	6.3	6.3	6.3	6.3	9.0
LHC sensitivity	0.20	0.20	0.15	0.15	0.15	0.15	0.20
$B \to X_s\gamma,\ X_s\ell^+\ell^-$	$[-0.07,\ 0.036]$	$[-0.017,\ -0.01]$ $[-0.005,\ 0.003]$	$[-0.09, 0.18]$	$[-0.12, 0.24]$	$[-14, 7]$	$[-10, 19]$	—
$\Delta F = 2$	0.07	0.014	0.14	—	—	—	—
semileptonic	—	—	—	—	$[0.3, 1.7]$	—	—
best bound	0.07	0.014	0.15	0.24	1.7	6.3	9.0
Λ for $C_i = 1$ (min)	3.9 TeV	8.3 TeV	2.6 TeV	2.0 TeV	0.8 TeV	0.4 TeV	0.3 TeV
$\mathcal{B}(t \to cZ)$ (max)	7.1×10^{-6}	3.5×10^{-7}	3.4×10^{-5}	8.4×10^{-6}	4.5×10^{-3}	5.6×10^{-3}	0.14
$\mathcal{B}(t \to c\gamma)$ (max)	—	—	1.8×10^{-5}	4.8×10^{-5}	2.3×10^{-3}	3.2×10^{-2}	—
LHC Window	Closed*	Closed*	Ajar	Ajar	Open	Open	Open

- The LHC will probe FCNC top decays down to (few $\times$) 10^{-5}
- The NP involved in EWSB may induce new flavor violation observable in top decay
- B factory data constrain the relevant operators (some beyond the LHC reach)
- If top FCNC is seen, LHC & B decay data will probe the NP responsible for it

Minimal flavor violation

Supersymmetry and flavor at the LHC

- After the LHC discovers new particles (and the champagne is gone):

  What are their properties: mass, decay modes, spin, production cross section?

- My prejudice: I hope the LHC will discover something unexpected
  Of the known scenarios I view supersymmetry as most interesting

  – How is supersymmetry broken?
  – How is SUSY breaking mediated to MSSM?
  – Predict soft SUSY breaking terms?

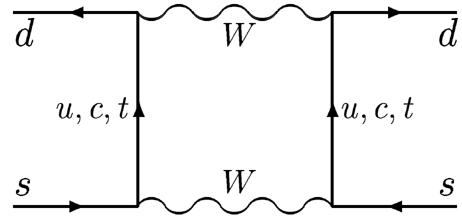
- Details of interactions of new particles with quarks and leptons will be important to understand underlying physics

- Does flavor matter at ATLAS & CMS? Can we probe (s)flavor directly at high p_T?

Saw this: Δm_K, ϵ_K built in NP models since 70's

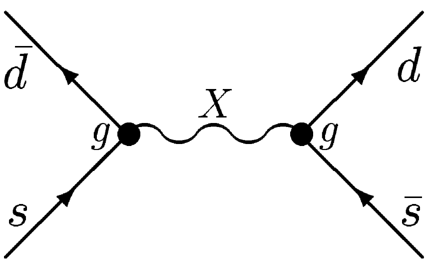
- In the SM: $\Delta m_K \sim \alpha_w^2\, |V_{cs}V_{cd}|^2\, \frac{m_c^2}{m_W^4}\, f_K^2\, m_K$

  (severe suppressions!)



... Even more suppressions for ϵ_K, which involves all 3 generation

- If tree-level exchange of a heavy gauge boson was responsible for a significant fraction of the measured value of Δm_K



$$\left|\frac{M_{12}^{(X)}}{\Delta m_K}\right| \sim \left|\frac{g^2\, \Lambda_{\rm QCD}^3}{M_X^2\, \Delta m_K}\right| \;\Rightarrow\; M_X \gtrsim g \times 2\cdot 10^3\ \text{TeV}$$

Similarly, from $B^0 - \overline{B}^0$ mixing: $M_X \gtrsim g \times 3\cdot 10^2\ \text{TeV}$

- Or new particles at TeV scale can have large contributions in loops $[g \sim \mathcal{O}(10^{-2})]$

$K^0 - \overline{K}^0$ mixing and supersymmetry

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm EXP}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m^2_{12}}{\tilde m^2}\right)^2 {\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Constraint from ϵ_K: replace $10^4\,{\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$ with $\sim 10^6\,{\rm Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

- Solutions to supersymmetric flavor problems:

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q,\tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

  The CP problems ($\epsilon_K^{(\prime)}$, EDM's) are alleviated if relevant CPV phases $\ll 1$

- Has driven SUSY model building, all models incorporate some of the above

Flavor and CP violation in SUSY

- Superpotential: [Haber, hep-ph/9709450]

$$W = \sum_{i,j} \left(Y^u_{ij} H_u\, Q_{Li} \bar{U}_{Lj} + Y^d_{ij} H_d\, Q_{Li} \bar{D}_{Lj} + Y^\ell_{ij} H_d\, L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$$

- Soft SUSY breaking terms: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

$$\mathcal{L}_{\rm soft} = -\left(A^u_{ij} H_u \tilde{Q}_{Li} \tilde{\bar{U}}_{Lj} + A^d_{ij} H_d \tilde{Q}_{Li} \tilde{\bar{D}}_{Lj} + A^\ell_{ij} H_d \tilde{L}_{Li} \tilde{\bar{E}}_{Lj} + B H_u H_d \right)$$
$$- \sum_{\rm scalars} (m_S^2)_{ij}\, S_i \bar{S}_j - \frac{1}{2} \left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} \right)$$

$3\ Y^f$ Yukawa and $3\ A^f$ matrices — $6\times(9$ real $+\ 9$ imaginary) parameters

$5\ m_S^2$ hermitian sfermion mass-squared matrices — $5\times(6$ real $+\ 3$ imag.) param's

Gauge and Higgs sectors: $g_{1,2,3},\, \theta_{\rm QCD},\, M_{1,2,3},\, m^2_{h_{u,d}},\, \mu,\, B$ — 11 real $+\ 5$ imag.

Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\rm PQ} \times U(1)_R \to U(1)_B \times U(1)_L$

- 44 CPV phases: CKM $+\ 3$ in M_1, M_2, μ (set $\mu B^*, M_3$ real) $+\ 40$ in mixing matrices of fermion-sfermion-gaugino couplings $(+80$ real param's)

Minimal flavor violation (MFV)

- What are the minimal flavor physics effects of new physics at $\Lambda_{\rm NP}$ scale?

  Assume that only source of flavor violation are the SM Yukawa couplings

  Unrealistic to demand that all higher dimension operators are flavor invariant and contain only SM fields (and not Y), since $U(3)^5$ is not a symmetry of the SM

- MFV: treat Y's as spurions [Chivukula & Georgi '87; Hall & Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]

  $$Y_u \sim (3,\overline{3},1)\,,\ Y_d \sim (3,1,\overline{3})\,,\ Y_e \sim (3,\overline{3})$$ [under $SU(3)_Q\times SU(3)_u\times SU(3)_d$]

  ... their background values are the only source of $U(3)^5$ breaking and CPV

- EFT like analyses, e.g., terms for down quarks

  $$\bar Q_L Y_u Y_u^\dagger Q_L, \quad \bar d_R Y_d^\dagger Y_u Y_u^\dagger Q_L, \quad \bar d_R Y_d^\dagger Y_u Y_u^\dagger Y_d d_R$$

Convenient to choose $Y_d \sim {\rm diag}(m_d, m_s, m_b)$, then $Y_u \sim V^\dagger\, {\rm diag}(m_u, m_c, m_t)$

Examples of MFV at work

- Δm_K: operator $(X/\Lambda_{\rm NP}^2)\,(\bar s_L\gamma_\mu d_L)^2$

  $\bar s_L(\bar 3,1,1),\ d_L(3,1,1) \Rightarrow (\bar s_L d_L) \in (8,1,1)$ must be $\propto (Y_u Y_u^\dagger)_{21} = y_c^2\, V_{cd}^* V_{cs}$

  $\Rightarrow$ In MFV: $X \propto y_c^4\,|V_{cd}^* V_{cs}|^2$ — similarly, $\Delta m_{B_{d,s}}$ are proportional to $y_t^4\,|V_{tb}^* V_{tq}|^2$

- $\Gamma(b\to s\gamma)$: operator $(X/\Lambda_{\rm NP})\,(\bar s_L \sigma_{\mu\nu} F^{\mu\nu} b_R)$

  $\bar s_L b_R$ is not invariant under $U(3)^3$

  $\bar s_L\, Y_d\, b_R \to \bar s_L\, m_d^{\rm diag}\, b_R$ is flavor diagonal

  $\bar s_L\, Y_u Y_u^\dagger Y_d\, b_R \to \bar s_L\, V^\dagger (m_u^{\rm diag})^2\, V m_d^{\rm diag}\, b_R \to \bar s_L\, V_{ts}^* V_{tb}\, y_t^2\, m_b\, b_R$

  $\Rightarrow$ In MFV: $X \propto (m_b/\Lambda_{\rm NP})\, y_t^2\, |V_{tb}^* V_{ts}|^2$

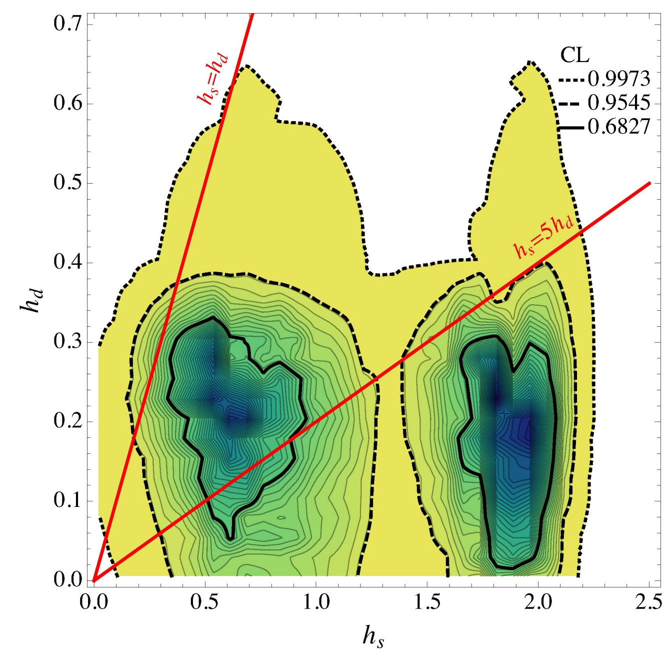
As in SM: Suppressed by m_b; FCNC's vanish for degenerate quark masses (GIM)
Need at least two CKM elements, one of which must be off-diagonal

General / next-to-minimal flavor violation

- In some cases one cannot capture the main effects by Taylor expanding to low orders in $Y_{u,d}$ (e.g., strongly coupled NP sector, large $\tan\beta$ effects, large RGEs)
- The full function $f_{ij}(Y_u, Y_d)$ may give flavor violation beyond MFV — but additional sources of flavor and CP violation are still functions of the Yukawas

[Agashe, Papucci, Perez, Pirjol, 2005; Kagan, Perez, Volansky, Zupan, 2009]

- Some consequences:
  - Possible to get CPV in $B_s >$ CPV in B_d
  - Possible to get $h_s \gg h_d$
    e.g., even $h_s/h_d \sim m_s/m_d$ could be (G)MFV
    (made interesting by central values of recent data)
- Without MFV, constraints from K and D mixing are very severe



MFV and flavor change in SUSY

- For generic parameters, way too much flavor change, unless scale $\gg \text{TeV}$

E.g., even if at some scale: $m_U^2 = \begin{pmatrix} m_{\tilde u}^2 & 0 & 0 \\ 0 & m_{\tilde c}^2 & 0 \\ 0 & 0 & m_{\tilde t}^2 \end{pmatrix}$

– Run a little and $m_U^2 =$ generic... Why 0's are set at a certain scale?

– How do these terms know about quark basis? SUSY breaking about Yukawas?

- Imposing MFV solves this in a RGE invariant way, e.g., $m_U^2 = \tilde m^2 (a\, 1 + b\, Y_u Y_u^\dagger + \ldots)$
- Even imposing MFV, some observables may still receive sizable corrections: precision electroweak, $g-2,\ B \to X_s\gamma,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ B \to \tau\nu,\ \Omega h^2$
- Additional subtleties, e.g., in 2HDM at large $\tan\beta$

Flavor effects at the TeV scale

- Does flavor matter? Can we access flavor at high p_T?
- Some flavor aspects of LHC:
  - $p = g + u, d, s, c, b, \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ — has flavor
  - Hard to bound flavor properties of new particles (e.g., $Z' \to b\bar{b}$ vs. $Z' \to b\bar{s}$?)
  - Little particle ID: b (displaced vertex), t (which p_T range?), and all the others
- Flavor data the LHC can give us:
  - Spectrum (degeneracies) which mass splittings can be probed?
  - Information on some (dominant?) decay widths
  - Production cross sections
- As in QCD, spectroscopy can give dynamical information

Some MFV predictions

- Spectra: $y_{u,d,s,c} \ll 1$, so there is an approximate $SU(2)_q^3$ symmetry

  Indeed, in GMSB, the squarks in the first two generations are quasi-degenerate

- Mixing: Only source is the CKM matrix

$$V_{\rm CKM}^{({\rm high}-p_T)} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  New particles decay to either 3rd or non-3rd generation quarks, but not to both

---

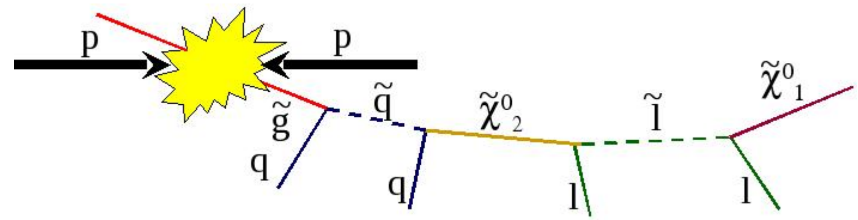
- Emerging studies of testing MFV in specific models with a given particle content

  E.g.: extra down type quarks $B'_{L,R}(3,1)_{-1/3}$, each transforming as $(3,1)$ or $(1,3)$ of $U(3)_Q \times U(3)_d$ [Grossman, Nir, Thaler, Volansky, Zupan, arXiv:0706.1845]

Detection of SUSY particles

- At each vertex two supersymmetric particles

  Lightest SUSY particle (LSP) undetected

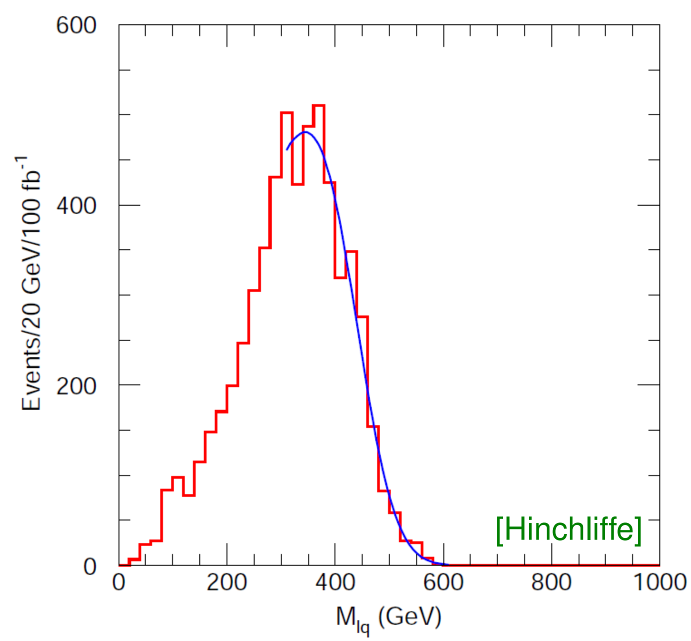


- Reconstruct masses via kinematic endpoints

- Most experimental studies use reference points which set flavor (i.e., generation) off-diagonal rates to zero (and $\tilde{m}_1^2 = \tilde{m}_2^2 \neq \tilde{m}_3^2$)

- Some off-diagonal rates can still be $10-20\%$ or more, consistent with all low energy data

  [E.g.: Hurth & Porod, hep-ph/0311075]



- Flavor can complicate determination of sparticle masses from cascade decays by smearing out endpoints ... can modify the discovery potential of some particles

Other developments: flavorful SUSY models

- Emerging non-MFV models w/ interesting flavor structure, consistent with all data

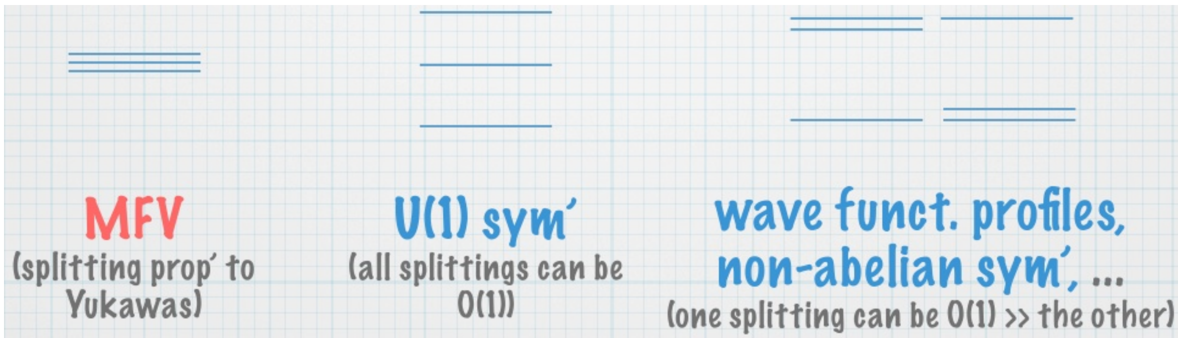
  Many studies over the last year (and in progress), mostly based on SUSY

- “Dilute” (but not completely eliminate) SUSY flavor violation with
  - mixed gauge / gravity mediated SUSY breaking [Feng *et al.*; Nomura, Papucci, Stolarski; Hiller *et al.*]
  - heavy Dirac gaugino masses (going beyond the MSSM) [Kribs, Poppitz, Weiner]

- Emerging themes:
  - Viable model space $\gg$ often thought; sizable flavor non-universalities possible
  - Easier to tag lepton than quark flavor $\Rightarrow$ slepton sflavor violation probably more accessible than squark sflavor violation

Flavor information from spectra

- E.g.: RH slepton spectrum and branching ratios may contain useful info on flavor
  Some possibilities in MFV, $U(1)$ horizontal symmetry, extra dimensional models

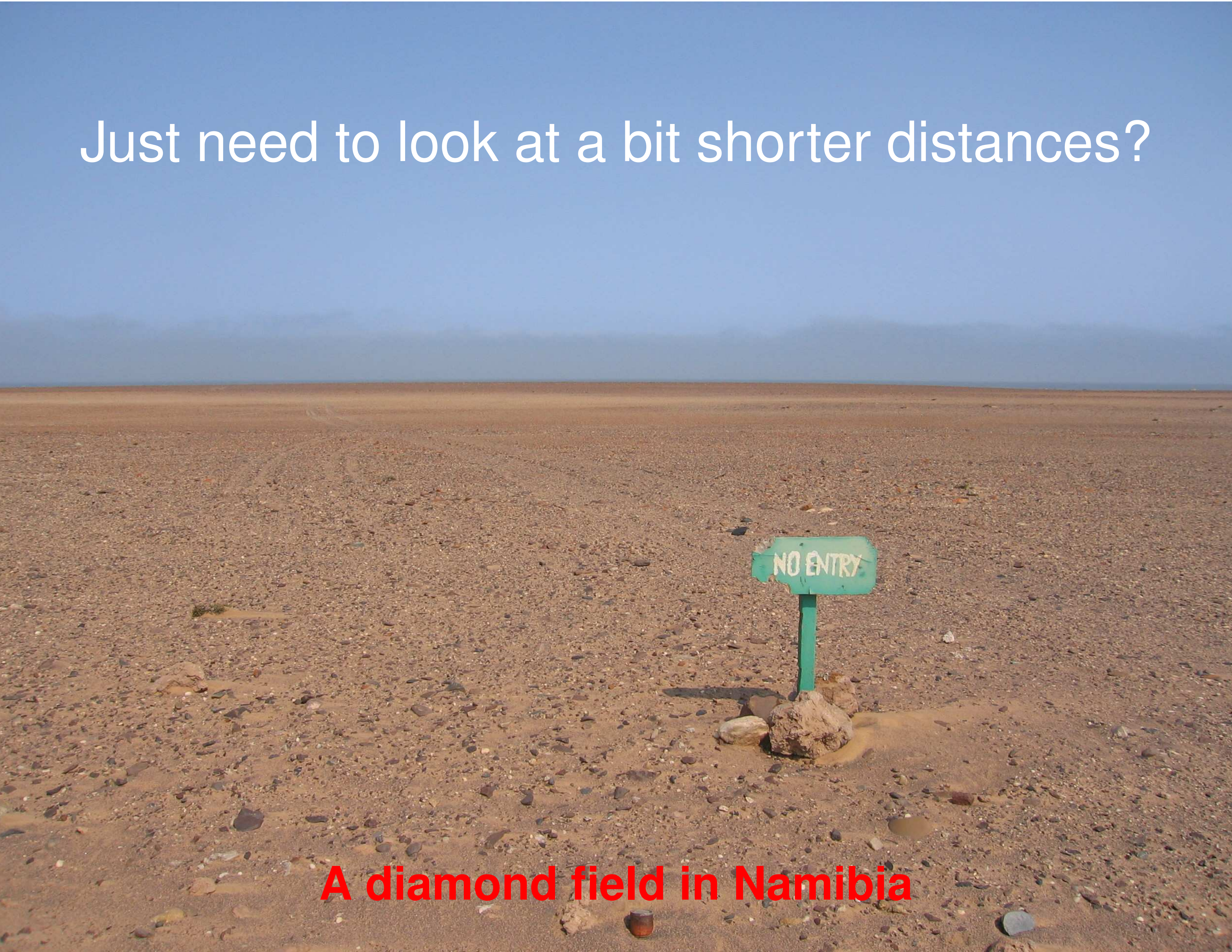


stau lightest — any slepton can be the lightest — [M. Papucci]

- Who is the (N)LSP? Interesting cases with different LHC signatures & prospects:
  - LSP: gravitino; NLSP: bino
  - LSP: gravitino; NLSP: slepton
    slepton NLSP may be long lived $\Rightarrow$ stable charged tracks
    if NLSP is $\tilde{e}$ or $\tilde{\mu}$, it may be easier to reconstruct that $\tilde{\tau}$ NLSP in standard GMSB

Final comments

We know there is exciting physics out there


Just need to look at a bit shorter distances?
NO ENTRY
A diamond field in Namibia

Back to dark matter, dark energy

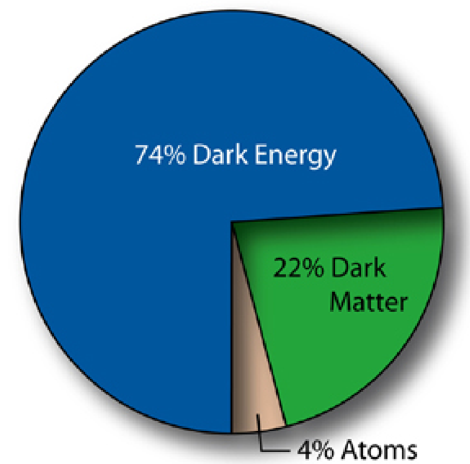
- Wanted to understand matter – antimatter asymmetry
  The LHC may help (new particles, new CP violation)

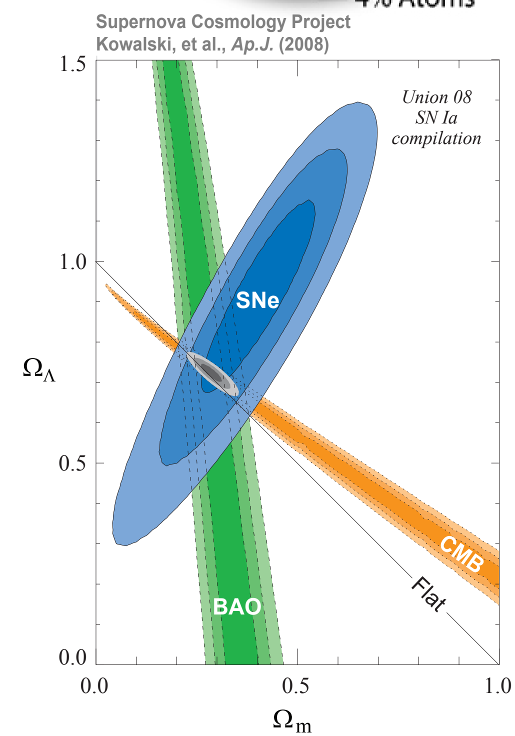
- We hope to also understand what dark matter is
  Promising candidate: lightest supersymmetric particle
  (superpartner of a gauge boson in most models)

- Dark energy: accelerating expansion discovered (1998)
  $\Lambda_{\rm cc} \sim 10^{-29}\,{\rm g/cm^3} = 10^{-47}\,{\rm GeV^4} = 10^{-120}$ (Planck units)
  (positive vacuum energy density $=$ negative pressure)

- The LHC won't directly address the cosmological constant problem, but it will tell us if we (mis)understand fine-tuning

  Is it just a coincidence that $\Lambda_{cc} \sim (1\,{\rm TeV}^2/M_{\rm Pl})^4$?





Conclusions — GeV scale

- Our knowledge of the flavor sector and CPV improved tremendously
  CKM phase is the dominant source of CPV in flavor changing processes

- If NP is seen: Study it in as many different operators as possible:
  One / many sources of CPV? Only in CC interactions? NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or 1?

- If NP is not seen: Achieve what is theoretically possible
  Could teach us a lot about the NP seen (or not) at LHC

- Low energy tests of the flavor sector will continue to improve in the next decade
  Sensitivity to lepton flavor violation will improve by $10-1000$, and also and EDMs

- Progress in theory toward model independently understanding more observables

- To learn as much as possible from flavor, need both super-B and LHCb (upgrade)

Conclusions — TeV scale

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
  $\Rightarrow$ New physics could show up any time measurements improve

- If new particles discovered, their flavor properties can teach us about $\gg \mathrm{TeV}$; masses (degeneracies), decay rates (flavor decomposition), cross sections

- We may learn how the NP flavor problem is (not) solved; MFV may be excluded

- Possible convergence between (s)quark and (s)lepton flavor physics

- Interplay between direct & indirect probes of NP will provide important information
  – synergy in reconstructing the fundamental theory (distinguish between models)
  – complementary coverage of param. space (subleading couplings, $\gg$TeV scales)

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Thank you!

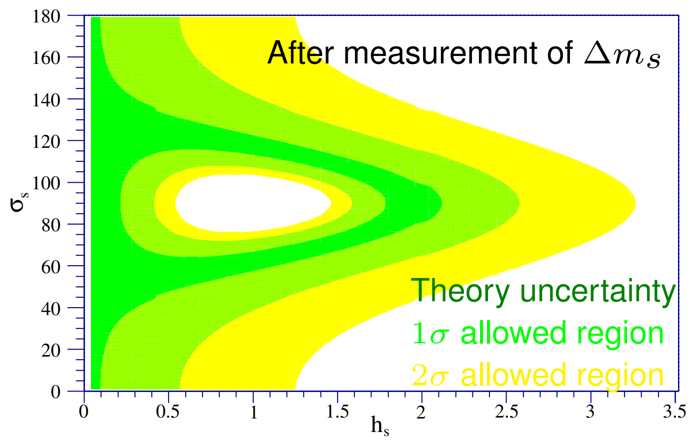
Backup slides

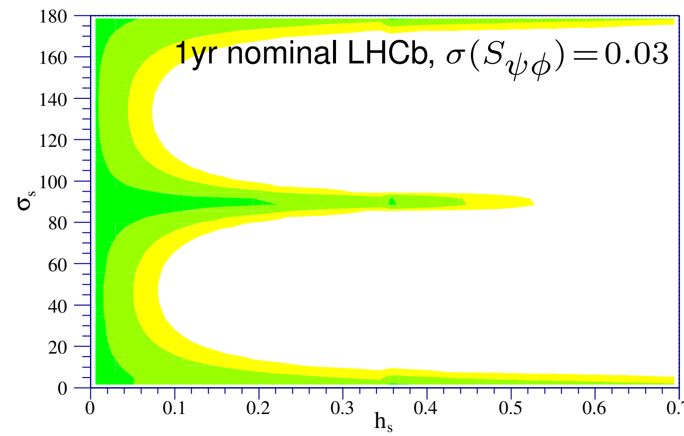
A personal super-B best buy list

- Want observables: (i) sensitive to different NP, (ii) measurements can improve by an order of magnitude, and (iii) not limited by hadronic uncertainties:
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d / \Delta m_s$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - The CP asymmetry in semileptonic decay, $A_{\rm SL}$
  - The CP asymmetry in the radiative decay, $S_{K^*\gamma}$
  - Search for not yet seen FCNC decays and refinements: $b \to s\nu\bar\nu$, $B \to \tau\bar\nu$, etc.
- Any one of these measurements has the potential to establish new physics

A personal LHCb best buy list

- After Δm_s measurement, large NP contribution to B_s mixing is still allowed





LHCb will probe B_s sector at a level comparable to B_d

- Difference of CP asymmetries, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
- $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
- 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma$, ... — test Dirac structure, BSM op's
- γ from $B \to DK$ and $B_s \to D_s K$ (for α probably super-B wins)
- [Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.]

Looking for surprises

- Will LHC see new particles beyond a Higgs?
  SUSY, something else, understand in detail?

- Will NP be seen in the quark sector?
  B_s: large $A_{\rm SL}^s$, β_s or $B_s \to \mu^+\mu^-$?
  B: Semileptonic $|V_{ub}|$ and $B \to \tau\nu$ agree, in conflict with $\sin 2\beta$?
  D: CPV in D^0–$\overline{D}^0$ mixing?

- Will NP be seen in the lepton sector?
  $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, ...?

- I don't know, but I'm sure it's worth finding out...! Want to keep looking broadly