3rd Lecture
Flavor at the TeV scale

- Known particles: leptons, top, Higgs
- SUSY and flavor

  MFV, squark searches
- Final thoughts

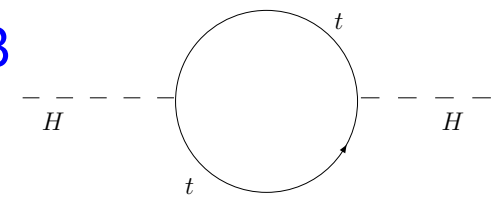
Reasons to pursue flavor physics

- 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

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

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

- 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)

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

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

Do neutrino mass terms violate lepton number, or are there "sterile" neutrinos?

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

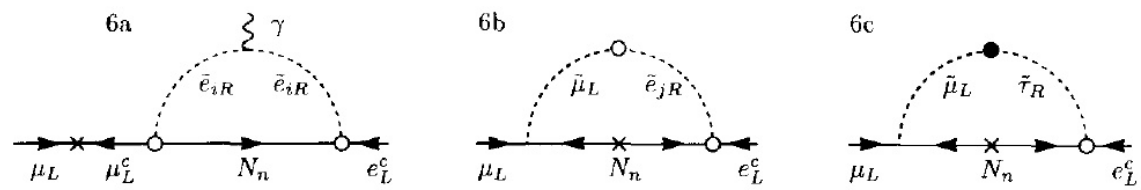
  SM predictions (penguins w/ neutrinos) are incredibly small and always negligible

Lepton flavor violation (in τ decays)

- $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$



  If a positive signal is seen, it's the tip of an iceberg $\Rightarrow$ trigger broad program

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (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

sensitivity with $75\,{\rm ab}^{-1}$ e^+e^- data

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: $\dfrac{m_\mu}{\Lambda^2}\,\bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta}e\,,\quad \dfrac{m_\mu}{\Lambda^2}\,\bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta}\mu$

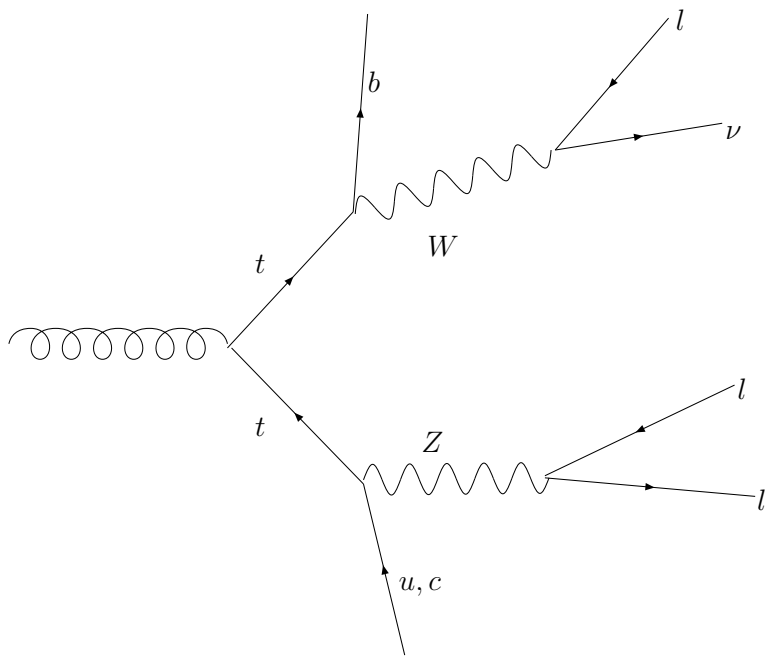
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

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

Heavy SM particles: t and h

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

- The best place to probe FCNC top decays



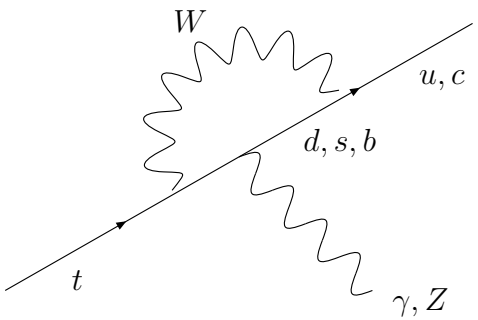
channel	$t \to Zu(c)$	$t \to \gamma u(c)$	$t \to gu(c)$		
			(3 jets)	(4 jets)	(combined)
upper limit on BR ($L = 10$ fb^{-1})	3.4×10^{-4}	6.6×10^{-5}	1.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}
upper limit on BR ($L = 100$ fb^{-1})	6.5×10^{-5}	1.8×10^{-5}	5.0×10^{-4}	8.0×10^{-4}	4.3×10^{-4}

$\Uparrow$ $\Uparrow$

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

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, DØ: $\mathcal{B}(t \to qZ) < 3\%$
  - CMS, ATLAS: $\mathcal{B}(t \to qZ) < 0.3\%$

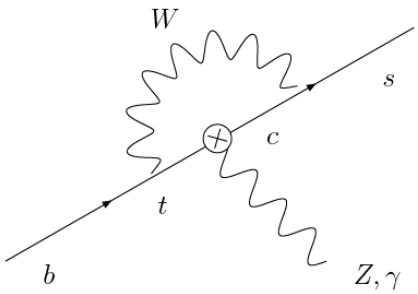
NP in the top sector?

- Indirect constraints: $t_L \leftrightarrow b_L$ — tight bounds from B decays

  Top FCNC's could affect other observables

- B factory data constrain some of the relevant operators (some beyond the LHC reach)

  Right-handed operators may still give rise to LHC signals



[e.g., arXiv:0704.1482]

- If top FCNC is seen, LHC & B decay data will probe the NP responsible for it

  Similarly large body of literature on $t \to cg$, single top production, etc.

- Forward-backward asymmetry: I fear we may never understand Tevatron signals

  Models have implications and are constrained by both flavor and collider data

  especially if want flavor structure (MFV, etc.), and not postulate something ad-hoc

Higgs couplings

- Many papers on constraining flavor non-universal and non-diagonal couplings

  Measuring $hf\bar{f}$ couplings is by definition flavor physics (distinguish generations)

- We know that $\mathcal{B}(h \to \mu^+\mu^-) < 10\times$ SM, so $\ll \mathcal{B}(h \to \tau^+\tau^-)$ [ATLAS-CONF-2013-010]

  Of the tree-level couplings (NP can enter in loops), I think this is the first / strongest evidence of non-universal coupling to fermions

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- One can also search for $h \to \mu^+\tau^-$ and other modes absent in the SM

  It's all interesting. It's all flavor physics. We'll skip it.

SUSY and flavor

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 supersymmetry seems to be the most interesting
  - How is supersymmetry broken?
  - How is SUSY breaking mediated to MSSM?
  - Predict soft SUSY breaking terms?

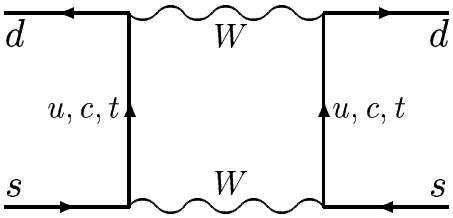
- Details of interactions of new particles with quarks and leptons will be important to understand underlying physics

- In SUSY, CP violation possible in squark & slepton couplings, flavor diagonal processes (e, n EDM's), neutral currents; may enhance FCNCs ($b \to s\gamma$, $\mu \to e\gamma$)

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

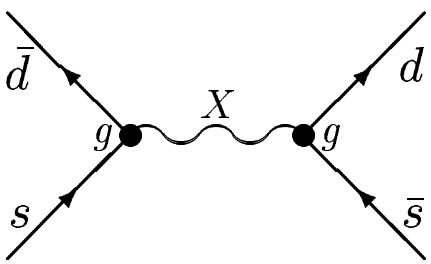
- In the SM: $\Delta m_K \sim \alpha_w^2 \, |V_{cs} V_{cd}|^2 \, \dfrac{m_c^2}{m_W^4} \, f_K^2 \, m_K$

  (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 $[g \sim \mathcal{O}(10^{-2})]$

SUSY in $K^0 - \overline{K}^0$ mixing (oversimplified)

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde{m}}\right)^2 \left(\frac{\Delta \tilde{m}^2_{12}}{\tilde{m}^2}\right)^2 {\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$$

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

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

- Classes of models to suppress each factors

  (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)

- All models incorporate some of the above — has been known since the '70s

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: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

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

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

$5\, m^2_S$ 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

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 $U(3)^3$ 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]

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

  ... their background values are the only source of $U(3)^3$ 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

MFV and flavor change in SUSY

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

  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, $B \to X_s\gamma,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ B \to \tau\nu,\ g-2,\ \Omega h^2$

- Additional subtleties, e.g., in 2HDM at large $\tan\beta$

Flavor effects at the TeV scale

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

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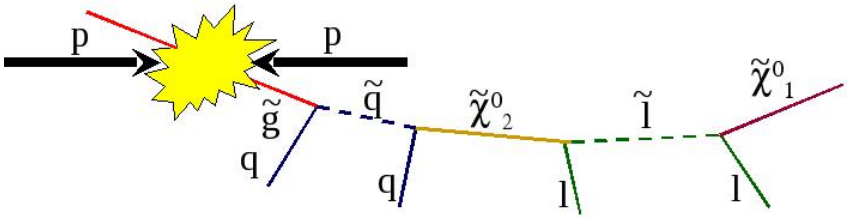
- More and more studies to test MFV in specific models with a given particle content

  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

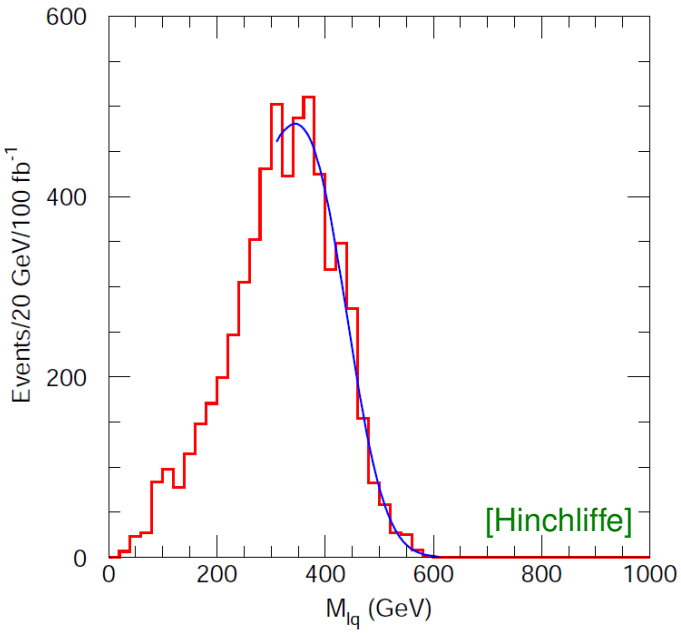
- At each vertex two supersymmetric particles
  Lightest SUSY particle (LSP) undetected



- 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



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

Flavorful SUSY models

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

  Many studies over the last few years (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

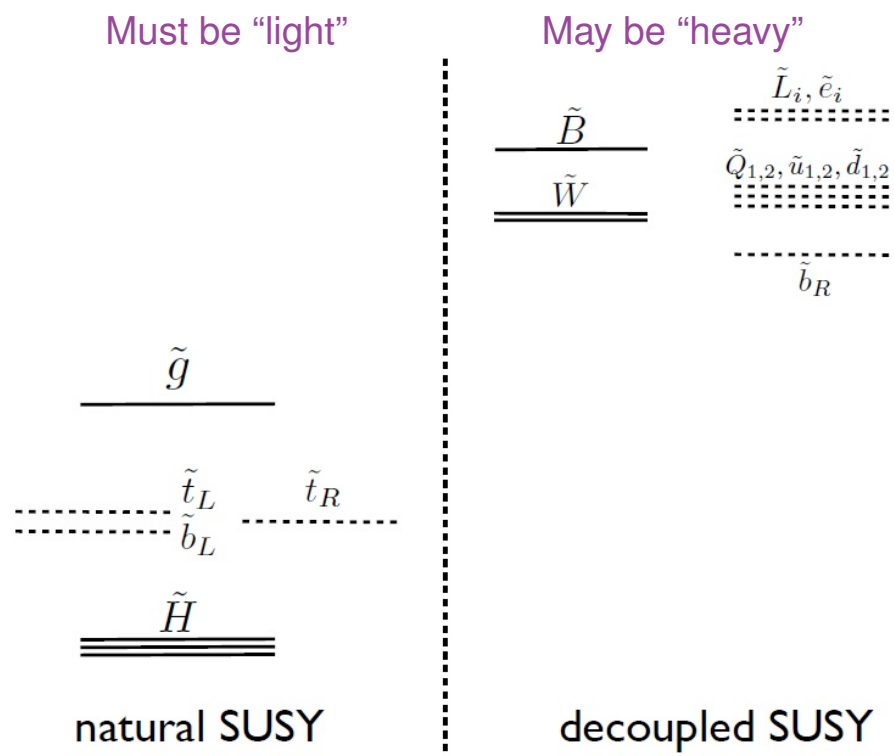
Natural SUSY and $m_h = 126\,\mathrm{GeV}$

- Naturalness has been main motivation for TeV-scale NP — leave no stone unturned!

  Simplest bottom-up approach:
  Light $\tilde{t}$, 1st & 2nd generation (a lot) heavier

  [Cohen, Kaplan, Nelson, 90-s; Papucci, Ruderman, Weiler, 1110.6926]

- Accommodating $m_h = 126\,\mathrm{GeV}$ pushes models toward NMSSM or large A terms; latter has interesting flavor implications



- LHC is probing weak-scale natural SUSY; with no BSM signal, increasing focus on RPV, stealth/squashed and split spectra (many models)

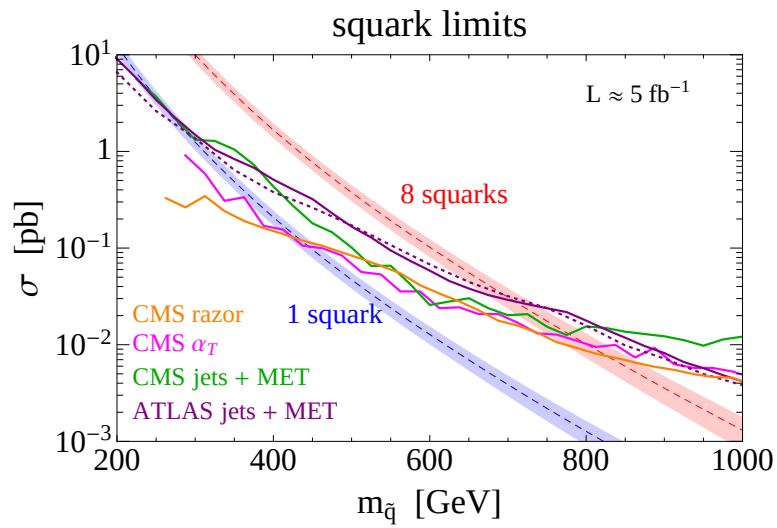
  Can have (SUSY) GIM, (approximate) MFV, etc., but as the first two generations are pushed heavier, expect larger flavor non-universality, and more flavor signals

Hide flavor signals ⇔ hide LHC signals

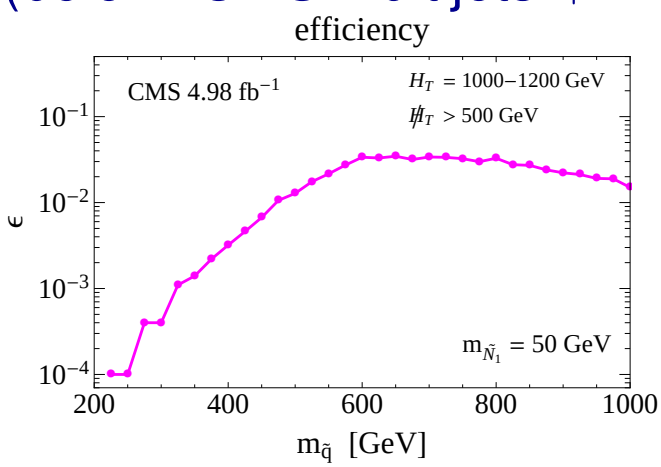
- Despite lore, squarks need not be nearly as degenerate as widely believed (triggered by studying charm CPV) [Gedalia, Kamenik, ZL, Perez, 1202.5038]

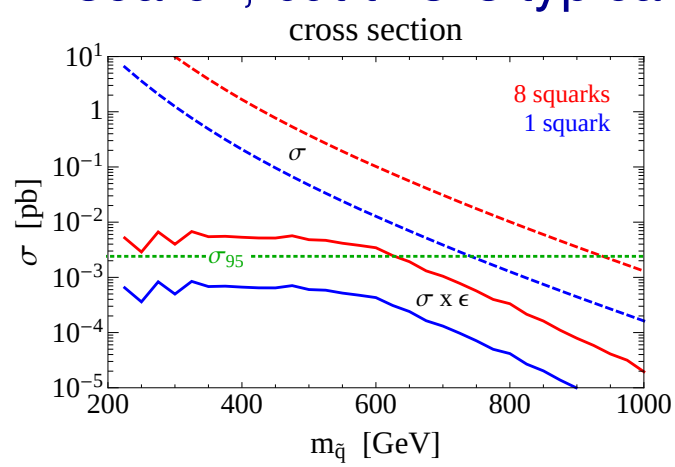
  Right plot: each LHC search gets much weaker

  [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]



- Not only due to cross sections, but steeply falling efficiencies at lower mass, due to hard cuts (below: CMS multijets + MET search, but this is typical behavior)



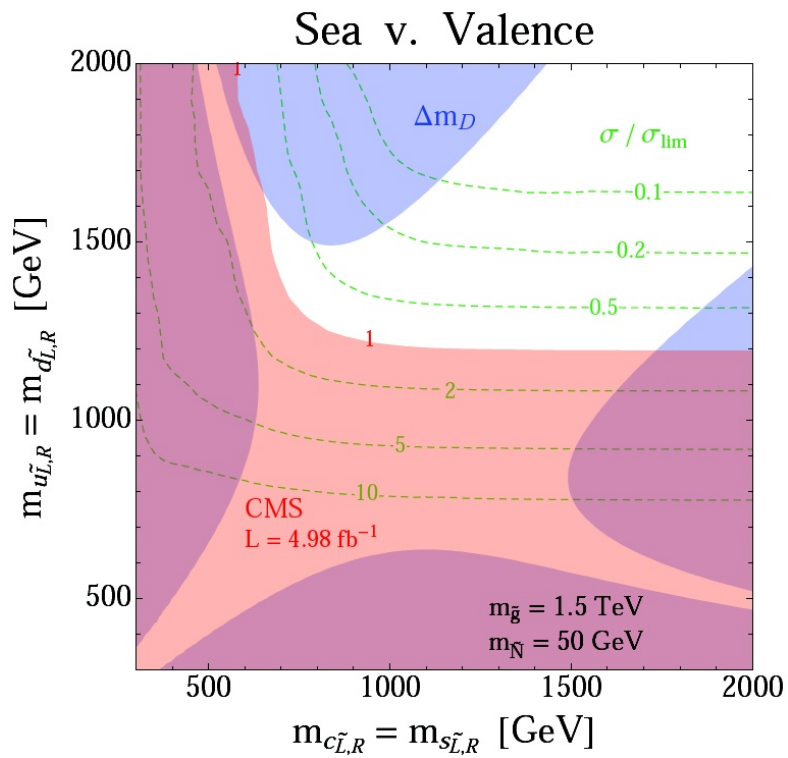


Hide flavor signals ⇔ hide LHC signals

- If 4 pairs of u, d, s, c squarks not degenerate, lot weaker LHC bounds: $1.2\,\mathrm{TeV} \Rightarrow \sim 0.5\,\mathrm{TeV}$

  E.g., assume that 4–4 squarks (1st and 2nd generation, but not all 8) are degenerate

  Unshaded region still allowed

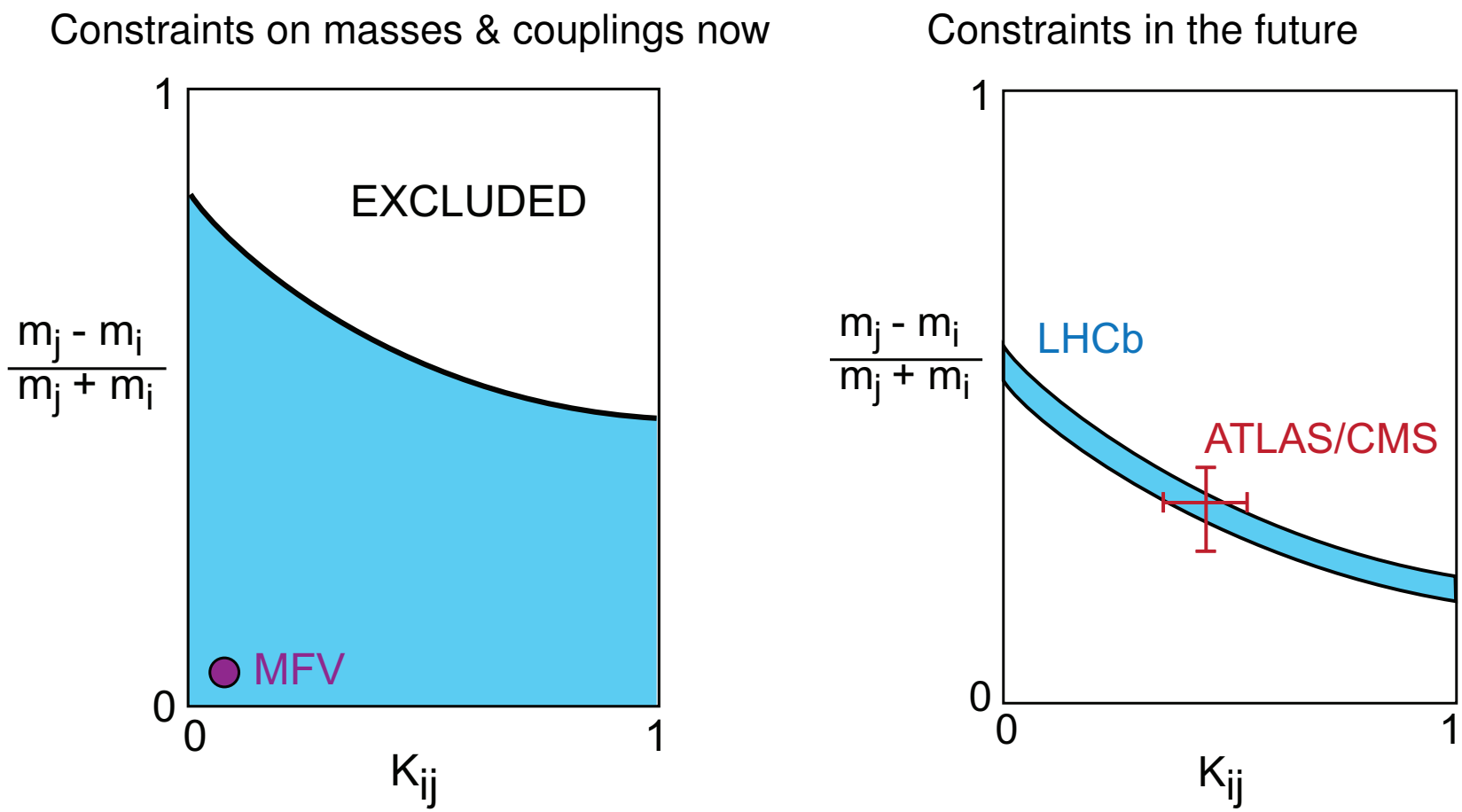


- Modify search strategies to improve coverage

- Ways for naturalness to survive — can give up many assumptions before abandoning key principles (many new LHC studies are yet to be devised and done)

Possible pictures in a few years

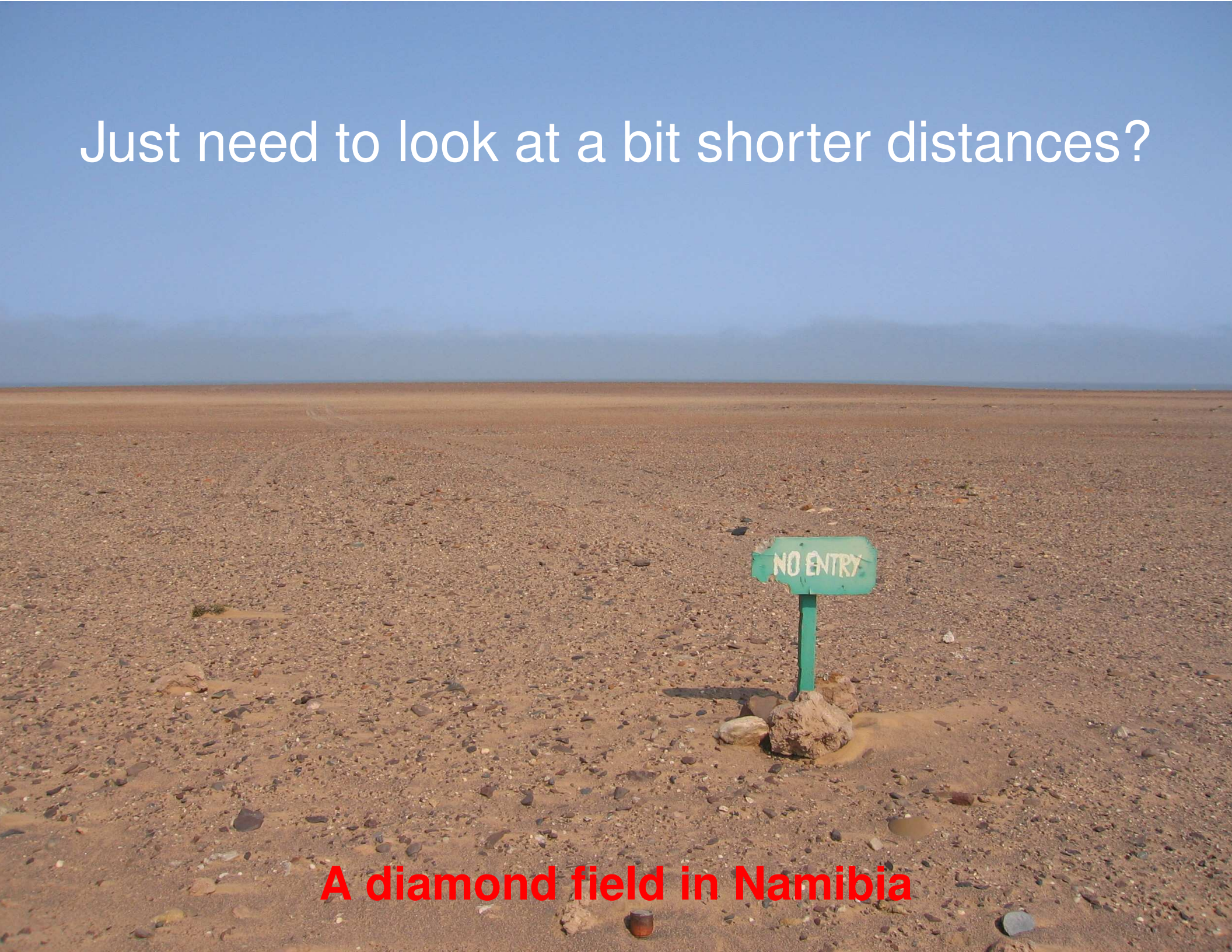
- Combination of LHC and flavor physics measurements can be very powerful to discriminate between models



Final comments

We know there is exciting physics out there

Just need to look at a bit shorter distances?



A diamond field in Namibia

Conclusions — GeV scale

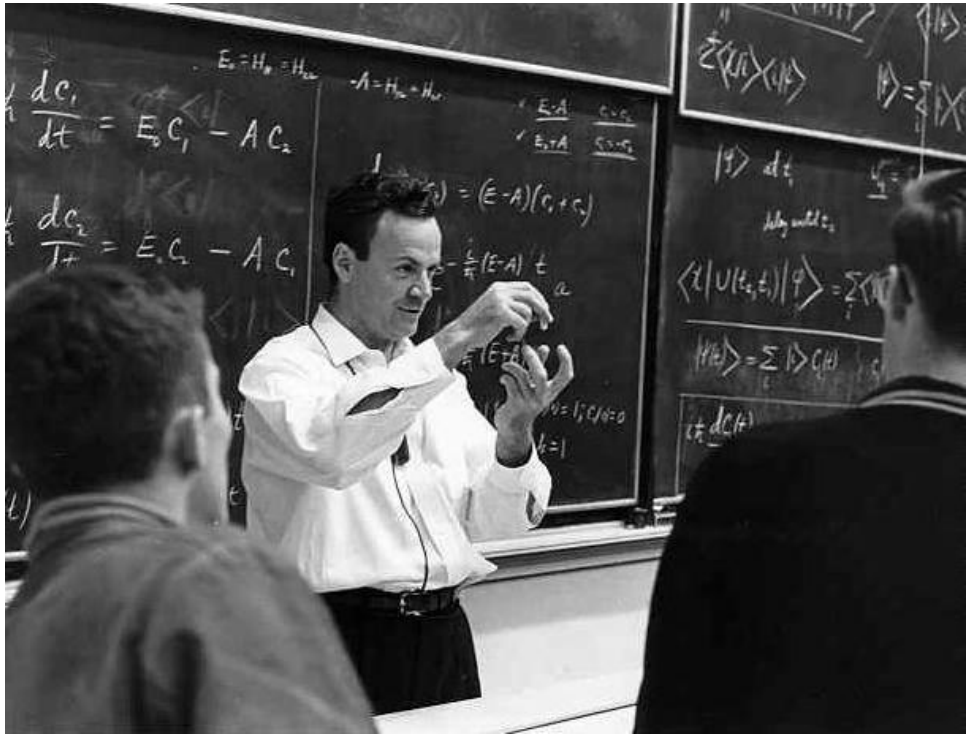
- CKM phase is the dominant source of CPV in flavor changing processes
  However, new physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM
- Few hints of discrepancies — existing data could have shown new physics, compelling reasons to continue (theoretical uncertainties won't be limiting)
- If NP is seen: Study it in as many different operators as possible:
- If NP is not seen: Achieve what is theoretically possible; will teach us a lot about the NP seen (or not) at LHC
- Progress in theory toward model independently understanding more observables
- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb upgrade, Belle II, K, lepton flavor viol.

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)

“I can live with doubt, and uncertainty, and not knowing. I think it’s much more interesting to live not knowing than to have answers which might be wrong.”

[R.P. Feynman]



Some of YOU will hopefully reduce what we do not know — the good news: lot to find out!