Snowmass EF subgroup:
Flavor mixing and CP violation at high energy

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http://www.snowmass2013.org/tiki-index.php?page=Flavor+Mixing+and+CP+Violation+at+High+Energy

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Flavor and CP Violation at the EF

- our group looked into the sensitivity to New Physics through flavor- and/or CP-violating observables in high-energy systems
- original plan was to cover studies of
  - high-pt flavor-violating physics
  - "low-pt flavor-violating physics at high-energy experiments" (e.g. LHCb, ATLAS and CMS's contributions to flavor and CP violation in bottom, charm, tau physics, etc.)
- connect direct searches at high energy with indirect searches in low-energy systems and combine constraints on New Physics models

Low-energy measurements

- LHC b, c, τ results complementary to e^+e^- super flavor factory experiments (Belle II)
- decided at CPM2012 that all sensitivity studies regarding bottom, charm and tau physics would take place in the Intensity Frontier (IF) subgroups
  - $BR(B_{(s)} \to \mu\mu)$,
  - $B \to K^{(*)}ll$ differential distributions,
  - CPV in $B_s \to J/\psi\ \varphi$,
  - D^0 mixing and CPV,
  - τ LFV decays, etc.
- integrate estimated IF sensitivities together with EF results into constraints on NP models

Sensitivity of the upgraded LHCb experiment to key observables

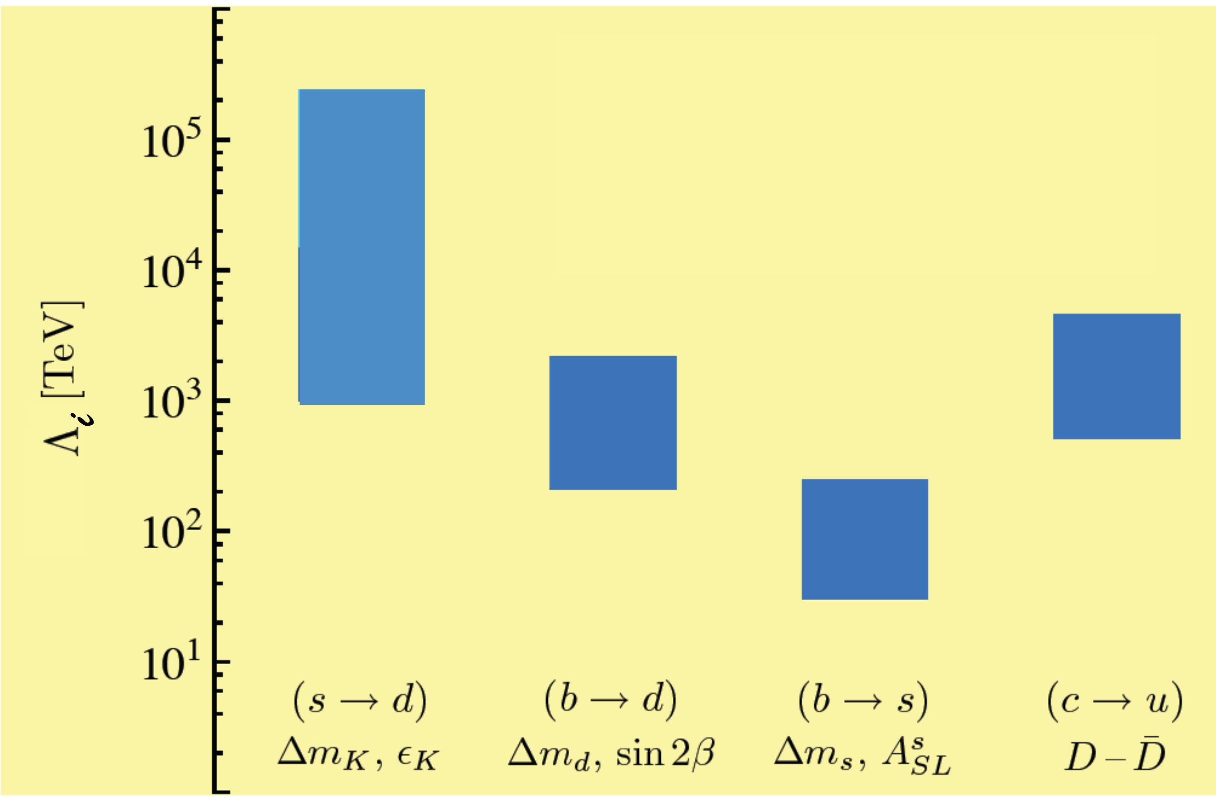
Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [213]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [243, 257]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Implications of LHCb measurements and future prospects, LHCB-PAPER-2012-031

Flavor as a High Mass Probe

$$L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$

- Already excluded ranges



See: Isidori, Nir
& Perez arXiv:1002.0900; Neubert EPS 2011 talk

Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constraints on NP

High-pT flavor physics

- Snowmass EF subgroups are well aligned with ATLAS and CMS physics analysis groups, except that there are no dedicated (high-pt) flavor & CP groups in ATLAS or CMS
- analyses of high-pt flavor-violating processes use the same methods and techniques as flavor-conserving processes
  - analyses and experts are scattered across several physics groups (top, SUSY, Exotics, Higgs)

top flavor physics

- sensitivity studies for flavor-violating top decays are coordinated by the HE Frontier top subgroup (see top sub-group talk)
  - e.g. top FCNC
    - $t \rightarrow Z\,q$, $t \rightarrow \gamma\,q$, $t \rightarrow g\,q$, $t \rightarrow H\,q$ can be measured at LHC and ILC with similar sensitivity and limits down to 10^{-5}
    - single top production at ILC can provide constraints on FCNC BRs
- integrate top FCNC limits into constraints on NP models

Direct searches for flavor-violating decays of *new particles*

- Studies for probing flavor generically involve:

e.g.:

$$\bar{\ell}_i \ell_i + X \to (\bar{\ell}_i \ell_i + \epsilon\, \bar{\ell}_i \ell_j) + X$$

$$\bar{q}_i q_i + X \to (\bar{q}_i q_i + \epsilon\, \bar{q}_i q_j) + X$$

Already on the agenda of the New Particles group

new processes to be investigated (study reach of subleading BR measurement once new particle is discovered)

- flavor-conserving modes are studied in expt's SUSY and Exotics physics groups and covered by EF New Particles subgroup
- convert these results into limits on corresponding flavor-violating processes

Models considered (1)

- RS models
  - flavor-violating decay of KK gluon $g_{KK} \to c\bar{t}$ (& c.c.)
    - flavor-conserving decay $g_{KK} \to t\bar{t}$ studied by NP group
    - decay similar to W' → tb (also studied by NP group), might be able to convert limit on W' into limit on g_{KK}
- Vector-like 3rd generation partners
  - dominant decays to 3rd generation quarks T → t Z, t h & T→ W b, B → W t & B → b Z, b h already studied
  - replace t or b with light quark jet to get corresponding flavor-violating decays
  - assume pair production followed by asymmetric decay (dominant + sub-leading)

Models considered (2)

- Heavy leptons in Type III see-saw models
  - decay into gauge boson + lepton
  - flavor violation: pair production + decay in opposite flavor leptons
  - interplay with neutrino mixing parameters

Models considered (3)

- SUSY (simplified models)
  - Hadronic modes:
    - direct stop pair production, with one stop decaying to top + neutralino (dominant) and the other decaying to charm + neutralino (suppressed)
  - Leptonic modes:
    - slepton (stau_R) direct pair production, with decays into e, μ, τ + χ final states
    - squark → jet + χ, χ → lepton slepton, slepton → lepton gravitino

Models considered (4)

- SUSY RPV
  - R-parity violating operators provide many possibilities for flavor violation. Study two representatives:
    - Bilinear RPV with Higgsino LSP (LH3): Higgsino decays to W+lepton. Investigate both W+μ and W+τ decays
    - stop LSP decaying into two quarks via the UDD operator:probe both stop -> jet + b and stop -> 2jets decays

Models considered (5)

- Decoupled SUSY ("mini-split”)
  - in this scenario squarks are in the 10-20 TeV range and maybe only relevant for the LHC energy upgrade, while gluino and neutralinos may still be relatively light
  - main signature would be 3-body gluino decay in two quarks and missing energy
  - flavor conserving decays: gluino -> t t χ, bb χ, jj χ, are probed by ATLAS and CMS (covered by EF NP subgroup)
  - corresponding flavor violating decays: gluino -> t c χ, gluino-> b j χ

Conclusions (1)

- low energy flavor and CP violation observables narrow the parameter space of various models of New Physics at the TeV scale
  – New physics has to have either a non-trivial flavor structure (i.e. not introduce flavor breaking much different than the Yukawa couplings) or be flavor blind
- the NP flavor structure can also be probed at high energy
  – studies generally require (considerably) more statistics than just discovery of new particles because in most cases the FV modes are sub-leading
  – there are a few cases which O(1) effects are not excluded by existing IF measurements

Conclusions (2)

- high energy probes provide complementary information to low energy measurements
  - flavor violation involves new mixing matrices (many parameters). Not all of them are experimentally accessible at IF and EF future facilities. Cases where IF and EF observables are probing the same parameters exists but most often IF and EF measurements constrain different couplings.
- leptonic machines
  - important for precision flavor studies if lepton partners (e.g. sleptons) found, especially if found the next run of the LHC
  - only ≥ 1TeV option relevant for quark flavor violation (given current LHC results)