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

Snowmass on the Mississippi
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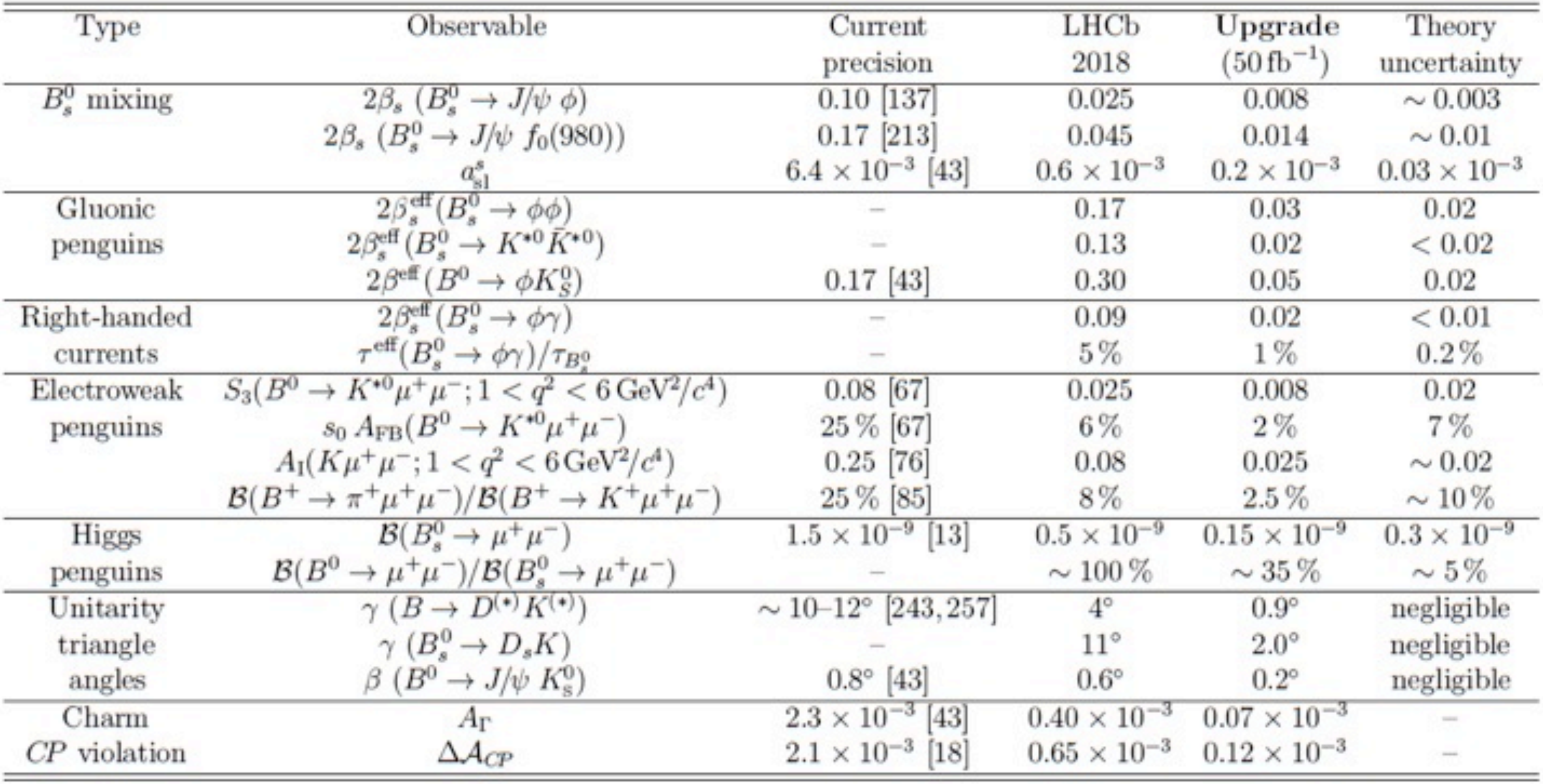
Flavor and CP Violation at the EF

- 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($B_{(s)} \rightarrow \mu\mu$),
  - $B \rightarrow K^{(*)}ll$ differential distributions,
  - CPV in $B_s \rightarrow J/\psi\ \phi$,
  - D^0 mixing and CPV,
  - τ LFV decays, etc.
- integrate estimated IF sensitivities together with EF results into constraints on NP models

Looked at IF projections: e.g. sensitivity of the upgraded LHCb experiment to key observables



Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	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	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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 %	$\sim 10\,\%$
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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [243, 257]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	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

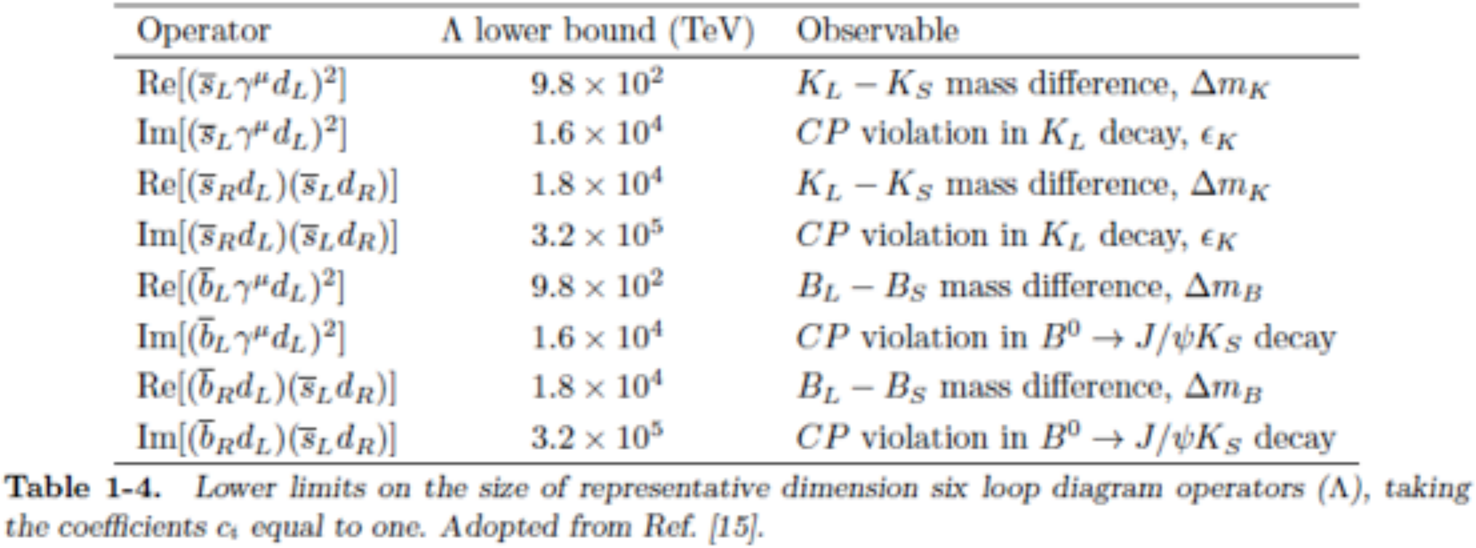
Flavor as a High Mass Probe

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)},$$

No sign of new physics in low-energy mixing and CPV measurements

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)

→ implies constraints on NP



Operator	Λ lower bound (TeV)	Observable
$\text{Re}[(\bar{s}_L\gamma^\mu d_L)^2]$	9.8×10^2	$K_L - K_S$ mass difference, Δm_K
$\text{Im}[(\bar{s}_L\gamma^\mu d_L)^2]$	1.6×10^4	CP violation in K_L decay, ϵ_K
$\text{Re}[(\bar{s}_R d_L)(\bar{s}_L d_R)]$	1.8×10^4	$K_L - K_S$ mass difference, Δm_K
$\text{Im}[(\bar{s}_R d_L)(\bar{s}_L d_R)]$	3.2×10^5	CP violation in K_L decay, ϵ_K
$\text{Re}[(\bar{b}_L\gamma^\mu d_L)^2]$	9.8×10^2	$B_L - B_S$ mass difference, Δm_B
$\text{Im}[(\bar{b}_L\gamma^\mu d_L)^2]$	1.6×10^4	CP violation in $B^0 \to J/\psi K_S$ decay
$\text{Re}[(\bar{b}_R d_L)(\bar{s}_L d_R)]$	1.8×10^4	$B_L - B_S$ mass difference, Δm_B
$\text{Im}[(\bar{b}_R d_L)(\bar{s}_L d_R)]$	3.2×10^5	CP violation in $B^0 \to J/\psi K_S$ decay

Table 1-4. *Lower limits on the size of representative dimension six loop diagram operators (Λ), taking the coefficients c_i equal to one. Adopted from Ref. [15].*

e.g. Improvement on new physics in $B_{d,s}$ mixing with LHCb upgrade+Belle II+lattice at least ~1.5-2 on scale (very preliminary)

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)

Probing flavor and CPV @ EF

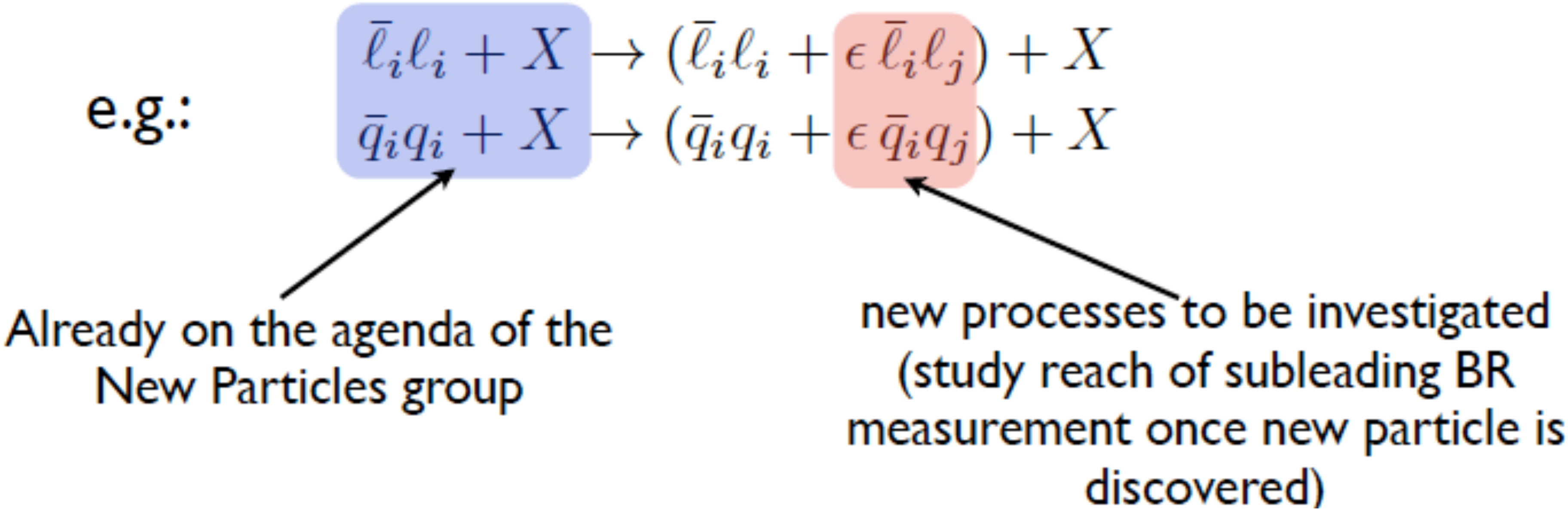
- Top and Higgs are already-discovered particles whose properties for flavor and CPV can be probed with next facilities → guaranteed target! (explored in other subgroups: top & Higgs)
- New particles:
  - mass spectrum contains important flavor information
  - other flavor information requires lots of statistics → in most of the cases it will be relevant only for early discoveries in the next LHC run

top flavor physics

- sensitivity studies for flavor-violating top decays have been coordinated by the EF top subgroup
  - e.g. top FCNC
    - t → Z q, t → γ q, t → g q, t → 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.:

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

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

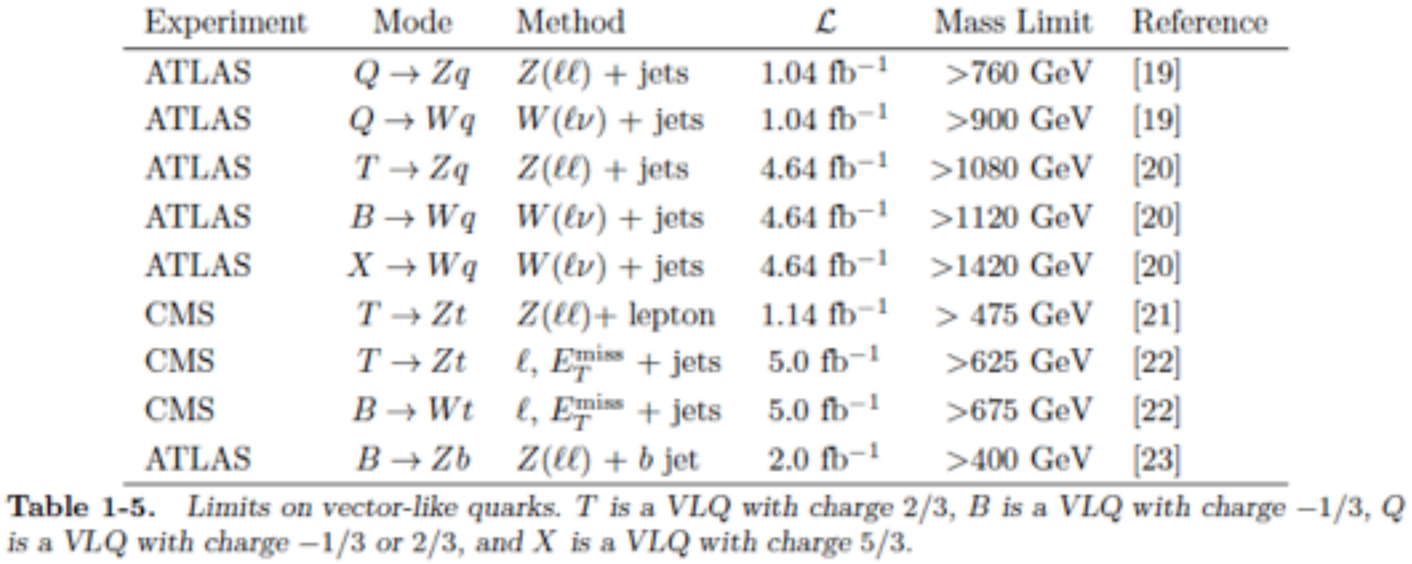
Already on the agenda of the New Particles group

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

- flavor–conserving modes are studied in expt's top, SUSY, Exotics physics groups and covered by EF top and NP subgroups
- no measurements available on (suppressed) flavor–violating modes via "asymmetric" decay

Vector-like quarks

- 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 plus single VLQ production with dominant light quark coupling studied by ATLAS and/or CMS and looked into by EF top/NP groups

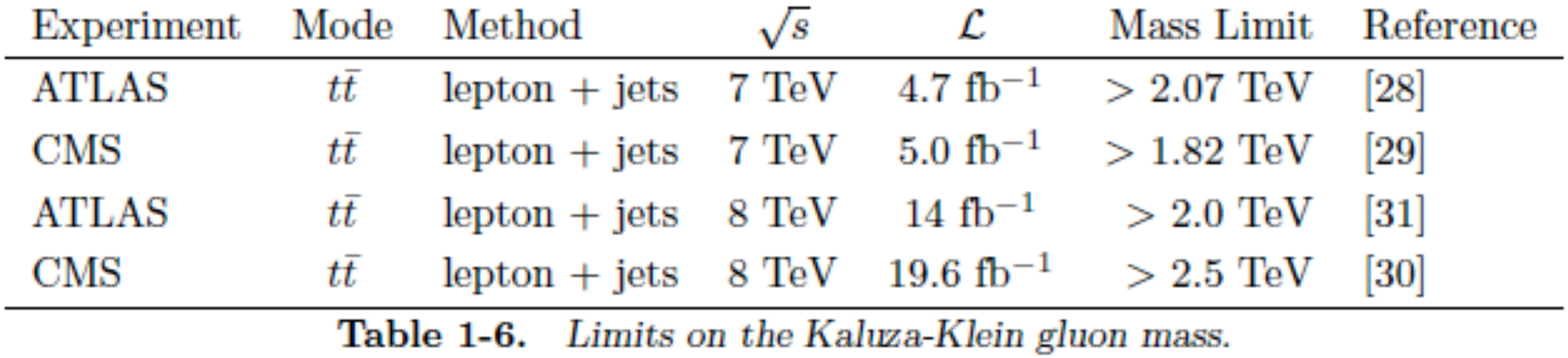


Experiment	Mode	Method	$\mathcal{L}$	Mass Limit	Reference
ATLAS	$Q \to Zq$	$Z(\ell\ell)$ + jets	1.04 fb^{-1}	>760 GeV	[19]
ATLAS	$Q \to Wq$	$W(\ell\nu)$ + jets	1.04 fb^{-1}	>900 GeV	[19]
ATLAS	$T \to Zq$	$Z(\ell\ell)$ + jets	4.64 fb^{-1}	>1080 GeV	[20]
ATLAS	$B \to Wq$	$W(\ell\nu)$ + jets	4.64 fb^{-1}	>1120 GeV	[20]
ATLAS	$X \to Wq$	$W(\ell\nu)$ + jets	4.64 fb^{-1}	>1420 GeV	[20]
CMS	$T \to Zt$	$Z(\ell\ell)$+ lepton	1.14 fb^{-1}	> 475 GeV	[21]
CMS	$T \to Zt$	ℓ, E_T^{miss} + jets	5.0 fb^{-1}	>625 GeV	[22]
CMS	$B \to Wt$	ℓ, E_T^{miss} + jets	5.0 fb^{-1}	>675 GeV	[22]
ATLAS	$B \to Zb$	$Z(\ell\ell)$ + b jet	2.0 fb^{-1}	>400 GeV	[23]

Table 1-5. *Limits on vector-like quarks. T is a VLQ with charge 2/3, B is a VLQ with charge −1/3, Q is a VLQ with charge −1/3 or 2/3, and X is a VLQ with charge 5/3.*

Randall-Sundrum models

- flavor-violating decay of KK gluon g_{KK} → ct
  - limits on flavor-conserving decay g_{KK} → tt from ATLAS/CMS, sensitivities for future experiments studied by top/NP groups
  - decay similar to W' → tb (also studied by top/NP group), convert sensitivities for W' into limits on g_{KK}
  - preliminary results: exclude BR(gKK→tc) down to ~5% for M_{KK} = 1-2TeV and ~20% for M_{KK} = 3-4TeV with 300fb^{-1} (better for 3ab^{-1})



Experiment	Mode	Method	$\sqrt{s}$	$\mathcal{L}$	Mass Limit	Reference
ATLAS	$t\bar{t}$	lepton + jets	7 TeV	4.7 fb^{-1}	> 2.07 TeV	[28]
CMS	$t\bar{t}$	lepton + jets	7 TeV	5.0 fb^{-1}	> 1.82 TeV	[29]
ATLAS	$t\bar{t}$	lepton + jets	8 TeV	14 fb^{-1}	> 2.0 TeV	[31]
CMS	$t\bar{t}$	lepton + jets	8 TeV	19.6 fb^{-1}	> 2.5 TeV	[30]

Table 1-6. *Limits on the Kaluza-Klein gluon mass.*

Lepton Flavor Violation

- Heavy leptons in Type III see-saw models
  - heavy lepton (neutrino or charged lepton) decays into gauge boson + lepton
  - flavor violation: pair production + decay in opposite flavor leptons
  - interplay with neutrino mixing parameters
  - expect limits for 14 TeV and 33 TeV LHC

SUSY (simplified models)

- 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
- Hadronic modes:
    - direct stop pair production, with one stop decaying to top + neutralino (dominant) and the other decaying to charm + neutralino (suppressed)

SUSY RPV

- R-parity violating operators provide many possibilities for flavor violation. For example:
  - 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

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
- EF facilities are indirect probes of FV
- main signature would be 3-body gluino decay in two quarks and missing energy
- flavor conserving decays: gluino→ttχ, bbχ, jjχ, are probed by ATLAS and CMS (covered by EF NP subgroup)
- corresponding flavor violating decays: gluino→tcχ, gluino→bjχ
- given heaviness of squarks, relatively large FV BR’s possible

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
  - Future IF facilities (LHCb upgrade, Belle II) will improve by a factor of 2-3 on NP even on most “mature” cases e.g. $B_{d,s}$ mixing (preliminary conclusion)
- 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)
  - Potential reach for probing FV mixing matrices is in many cases new mixing matirce "V_{ij}" ~ can be probed down to O(0.1) ~ λ (if early LHC discovery).
  - Generically not competitive if already probed at IF (LHCb upgrade, Belle II, …)
  - New complementary information for those entries which are difficult to probe at IF (e.g. RR-mixing in up-sector, etc.)

Conclusions (3)

- leptonic machines
  - precision spectrum measurements for important information on flavor structure
  - important for precision flavor studies if lepton partners (e.g. sleptons) found, especially if found in the next run of the LHC
  - SUSY bilinear RPV precision study at ILC white paper → precision on $\sin^2\theta_{23}$ comparable or better than current neutrino expts.
  - only ≥ 1TeV option relevant for quark flavor violation (given current LHC results)

EF Flavor and CPV at Snowmass

- Results not ready yet (hopefully some this week, likely after the meeting)
- Work meetings to finalize write-up
  - Wed 8:30 – 10:00
    - Soni talk on “Repercussions of a geometric theory of flavor for future directions in High Energy Physics”
  - Fri 8:30 – 12:00
  - Sat 8:30 – 12:00