Flavor Physics / FCNC at FCC-ee

- Physics at Z peak → $10^{12}/10^{13}$ Z's
- ... above WW threshold → $10^8$ W's
- ... above ZH threshold → $10^6$ H's
- ... above tt threshold → $10^6$ top's

RICH PHYSICS PROGRAM AT ANY $E_{cm}$ STAGE!

- (NOT A REVIEW !) some details on a few recent developments:
  - $B^0 \rightarrow K^{*0} \tau^+\tau^-$
  - FCNC in hadronic single top channel
  - FCNC mediated by dark-photons

b-had, c-had, top rare decays, CP violation, LFV, sterile v's

Barbara Mele

Rome, 12 April 2016
useful links to FCC-ee WG activities

**Flavor Physics WG**

https://twiki.cern.ch/twiki/bin/viewauth/FCC/FCCeeFlavourPhysics

https://indico.cern.ch/category/5663/

**Top Physics WG**

https://tlep.web.cern.ch/content/wg4-exp

**FCC-ee Physics Workshops**

https://indico.cern.ch/category/5684/

special thanks to J.Kamenik & S.Monteil
FCC-ee benefits not only from statistics

- clean exp. environment (moderate bckgrd) wrt LHCb
- excellent vertexing and PID ($\pi/K/p$ separation possible with dedicated detector)
- large boost wrt Belle II
- helps in controlling invisible (v) systems
- crucial comparing FCC-ee potential with reach at LHCb and Belle II, and lower energy experiments ( # of B mesons at FCC-ee comparable to Belle II)

- $O(150) \, B_s \rightarrow \mu\mu$ similar to LHCb.
- $O(20) \, B_d \rightarrow \mu\mu$ same comment in order.
- $O(\text{few } 10^{10}) \, \tau\tau$, yielding equivalent sensitivity as Belle II for LFV processes such as $\tau \rightarrow e\gamma, \mu\gamma, eee, \mu\mu\mu$. 

*These estimates account for a luminosity of $5.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, b-quark hadronisation fractions as measured at LEP and large reconstruction efficiencies.
1) Any leptonic or semileptonic decay mode involving $B_s$, $B_c$ or $b$-baryon, including electrons, in no particular order:

- $B_{d,s} \rightarrow ee, \mu\mu, \tau\tau$: if the second will be mostly covered by LHCb and CMS, the first can be searched for with a similar precision. The latter $B_s \rightarrow \tau\tau$ is most likely unique to FCC-ee and subjected to third family specific couplings.
- Leptonic decays in direct annihilation $B_{u,c} \rightarrow \mu\nu_\mu, \tau\nu_\tau$. The latter is a chance to get $|V_{cb}|$ with mild theoretical uncertainties.
- Radiative decays $B \rightarrow Xll (\tau\tau\tau$ at first): rare FCNC complementing the $B_d$ at $B$-factories.

2) Any decay mode involving $B_s$, $B_c$ or $b$-baryon with neutrals.

- $B_{d,s} \rightarrow \gamma\gamma$: theoretically difficult.
- $B_s \rightarrow K_SK_S$: CP violation studies. Also interesting for downstream tracking of $V^0$ in general.

3) Multibody (4 and more) hadronic $b$-hadron decays.

- $B_s \rightarrow \psi\eta^*$ or $\eta_c\Phi$: flavour tagging required for weak mixing phase.
- $B_s \rightarrow D_sK$: PID definitely required to isolate the signal.

4) Lepton Flavour Violating processes.

- Current experimental bounds:
  \[ \mathcal{B}(Z \rightarrow e^\pm \mu^\mp) < 7.5 \times 10^{-7} \]
  \[ \mathcal{B}(Z \rightarrow e^\pm \tau^\mp) < 9.8 \times 10^{-6} \]
  \[ \mathcal{B}(Z \rightarrow \mu^\pm \tau^\mp) < 1.2 \times 10^{-5} \]

- Direct LFV processes: $Z \rightarrow e\mu, e\tau, \tau\mu$. In terms of model constraints, this can be far richer than the current or foreseeable reach for $\mu \rightarrow e\gamma$ or $\tau \rightarrow \mu\gamma$ etc...
- Related to the large $\tau\tau$ production at the $Z$ pole: $\tau \rightarrow e\gamma, \mu\gamma, eee, \mu\mu$. Both LFV and Majorana neutrino. In the latter case, possibly rich like-sign dilepton searches in $b$-hadron decays as well.
**FCC-ee sensitivity study to $b \rightarrow s \tau^+ \tau^-$**

- **present exp anomalies in $b \rightarrow s \mu \mu$ ??**

- **strongest current bound** (BaBar, PoS ICHEP 2010, 234)

  \[
  \text{BR}(B \rightarrow K_{\tau^+ \tau^-})_{[14,23,\text{max}]} < 3.3 \times 10^{-3}
  \]

- **expected sensitivity at Belle II to BRs of $O(10^{-4}) \sim O(10^{-5})$**

- **constraints from $B \rightarrow K\nu\bar{\nu}$ can be avoided if e.g. only right handed taus involved**

**SM predictions**

- restrict $q^2$ above the narrow charmonium resonances

\[
\begin{align*}
\text{BR}(B^0 \rightarrow K^{*0}_{\tau^+ \tau^-})_{[15,\text{max}]} &= (0.91 \pm 0.11) \times 10^{-7} \\
\text{BR}(B^+ \rightarrow K^{*+}_{\tau^+ \tau^-})_{[15,\text{max}]} &= (0.99 \pm 0.12) \times 10^{-7} \\
\text{BR}(B_s \rightarrow \phi_{\tau^+ \tau^-})_{[15,\text{max}]} &= (0.73 \pm 0.09) \times 10^{-7} \\
\text{BR}(B^0 \rightarrow K^0_{\tau^+ \tau^-})_{[15,\text{max}]} &= (1.09 \pm 0.12) \times 10^{-7} \\
\text{BR}(B^+ \rightarrow K^{+}_{\tau^+ \tau^-})_{[15,\text{max}]} &= (1.18 \pm 0.13) \times 10^{-7}
\end{align*}
\]

- Straub

**LF Universality test**

\[
R^\mu_Ke = \frac{\text{BR}(B \rightarrow K_{\mu^+ \mu^-})_{[1,6]}}{\text{BR}(B \rightarrow Ke^+e^-)_{[1,6]}} = 1.00023 \pm 0.00063
\]

\[
R^\tau_Ke = \frac{\text{BR}(B \rightarrow K_{\tau^+ \tau^-})_{[14,18,\text{max}]} }{\text{BR}(B \rightarrow Ke^+e^-)_{[14,18,\text{max}]} } = 1.161 \pm 0.040
\]

\[
R^\tau_\mu = \frac{\text{BR}(B \rightarrow K_{\tau^+ \tau^-})_{[14,18,\text{max}]} }{\text{BR}(B \rightarrow K_{\mu^+ \mu^-})_{[14,18,\text{max}]} } = 1.158 \pm 0.039
\]

(Bouchard et al. 1306.0434)
New Physics in $b \rightarrow s\tau\tau$ (models)

**Scalars** (e.g. in 2HDMs)

If scalar couplings to leptons are proportional to the masses

$$\Rightarrow B_s \rightarrow \mu^+\mu^-$$

is the most important probe.

Generic 2HDMs allow for much richer flavor structure

$$\Rightarrow b \rightarrow s\tau^+\tau^-$$

transitions can give important information.

**Vectors**

Photon and $Z$ are coupled to lepton flavor universally

$$\Rightarrow$$ strong constraints from $b \rightarrow s\mu^+\mu^-$

$Z'$ gauge bosons can violate lepton flavor universality

$$\Rightarrow b \rightarrow s\tau^+\tau^-$$

transitions are complementary probes.

**Leptoquarks**

Generically, no reason to expect lepton flavor universality.
B^0 \rightarrow K^{*0} \tau^+\tau^- \text{ at the FCC-ee}

• tau final state unexplored so far!

• aim at:
  • measuring BR
  • studying angular distributions (needs reconstruction of particle decay without explicit reconstruction of one or several particles of the decay chain)
    \[ \rightarrow \text{Partial Reconstruction Technique} \text{ makes use of vertices exp information} \]
  • \( b \rightarrow s\tau^+\tau^- \) fully solvable in exclusive \( B^0 \rightarrow K^{*0} \tau^+\tau^- \), if one tau vertex can be reconstructed!
  • can be generalized to decays where secondary vertex is NOT reconstructed (\( B^0_s \rightarrow \tau^+\tau^- \))

• Generate:
  \[ e^+e^- \rightarrow Z \rightarrow b\bar{b} \]

• Fragmentation and hadronisation of the \( b \) quarks:
  • Pythia 8 and HepMC (through pythiafcc)

• Filter \( B^0 \) particles.
  • Selection in P8

• Force the \( B^0 \) decay:
  \[ B^0 \rightarrow K^{*0}\tau^+\tau^- \]

• Force the tau lepton decay in three prongs:
  \[ \tau^+ \rightarrow a_1^+\bar{\nu}_\tau \quad K^{*0}(892) \rightarrow K^-\pi^+ \]
  \[ a_1^+ \rightarrow \pi^+\pi^-\pi^+ \]

• Write the output (tuples) in the Event Data Model
  • EvtGen (Pythia Interfaced)
  • albers, fcc-albers, fcc-edm, heppy, fcc-heppy

• Partial Reconstruction driven by resolutions on momenta, primary, secondary and tertiary vertices.

  • assumed typical resolutions of ILD tracking system detector. MC truth outputs smeared according to following resolutions (~state of the art):
    • Momentum \( \rightarrow 10 \text{ MeV} \)
    • Primary vertex \( \rightarrow 3 \text{ um} \)
    • Secondary vertex \( \rightarrow 7 \text{ um} \)
    • Tertiary vertex \( \rightarrow 5 \text{ um} \)

Backgrounds:

\begin{align*}
\bar{B}^0 \rightarrow D_s^- K^{*0} \tau^-\bar{\nu}_\tau \\
\bar{B}_s \rightarrow D_s^- D_s^+ K^{*0}
\end{align*}
Conclusions:

- **500 - 1000 events** of reconstructed signals (~10^{13} Z decays). Backgrounds so far seem tractable (invariant mass shape peaking below signal).

- FCC-ee likely unique to tackle this mode. Belle II experiment expects a handle of events.

- Opens the way for a more ambitious analysis than signal establishment
  - angular analysis of the decay
  - tau polarization

- Plans for a paper gathering exp and pheno studies.
LFV in rare Z-decays: additional “light” sterile v’s

(Abada, De Romeri, Monteil & Teixeira, in progress)

Studies for the Giga-Z (Wilson, DESY-EFCA LC workshop (1998-1999), J. I. Illana and T. Riemann, Phys. Rev. D63 (2001) ... are revisited taking into account:

- $\theta_{13}$ and other neutrino data
- new contributions of sterile states are severely constrained:
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double $\beta$ decays
  - invisible $Z$-width

- Steriles with mass above 80 GeV and mixings $O(10^{-5}-10^{-4})$ within FCCee reach.
- Low-energy experiment at work to probe the electron-muon sector
- FCC-ee provides the stringent constraint in tau-mu sectors.
ever since its discovery, the top quark has never been produced and studied in such a clean environment as the one expected in $e^+e^-$ collisions

e$^+e^-$ collisions will almost allow to trace back top-quark final states on an event-by-event basis

this will open the opportunity to look at details of top production and kinematics that is unthinkable in hadron collisions (relevant strategies mostly still to be developed …)

rare top decays is one of the (many) top physics chapters that would widely benefit from such spectacularly clean environment!
inclusive searches for exotic t decays via recoil system

large variety
of possible exotic top final states
(unexpected signatures “hard” at LHC !)
→ global analysis of the top recoil system with a top-veto

a) define criteria to tag
   a Wb/Wj system
   as a (SM) top quark

b) look for events containing
   a top-system with
   a veto on a 2\textsuperscript{nd} tag
   (i.e. recoil system does not pass
   the SM top-system criteria)

c) full simulation needed to
   assess sensitivity ( \(<% \sigma\) ?)

d) get model-independent
   bounds on BR(top)\textsubscript{exotica} !

E_{cm}(e^+e^-) \geq 350 \text{ GeV}
Standard Model Predictions

**FCNC top (really rare !) decays in the SM :**

**NOT measurable !**

GIM-suppressed by

\[ \text{BR}(t \rightarrow c\gamma) \approx 5 \times 10^{-14} \]
\[ \text{BR}(t \rightarrow cg) \approx 5 \times 10^{-12} \]
\[ \text{BR}(t \rightarrow cZ) \approx 1 \times 10^{-14} \]
\[ \text{BR}(t \rightarrow ch) \approx 3 \times 10^{-15} \]

\[ \left( \frac{m_b}{M_W} \right)^4 + \text{MFV (CKM matrix)} \]

\[ |V_{ub}/V_{cb}|^2 \approx 0.008 \]

\[ \text{BR}(t \rightarrow u\gamma) \approx 4 \times 10^{-16} \]
\[ \text{BR}(t \rightarrow ug) \approx 4 \times 10^{-14} \]
\[ \text{BR}(t \rightarrow uZ) \approx 8 \times 10^{-17} \]
\[ \text{BR}(t \rightarrow uh) \approx 2 \times 10^{-17} \]

(Aguilar-Saavedra hep-ph/0409342)

New Physics can hugely enhance predictions!

Pattern of enhancements is model dependent!

<table>
<thead>
<tr>
<th></th>
<th>2HDM</th>
<th>MSSM</th>
<th>RS</th>
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</thead>
<tbody>
<tr>
<td>( t \rightarrow cZ )</td>
<td>( \lesssim 10^{-6} )</td>
<td>( \lesssim 10^{-7} )</td>
<td>( \lesssim 10^{-5} )</td>
</tr>
<tr>
<td>( t \rightarrow c\gamma )</td>
<td>( \lesssim 10^{-7} )</td>
<td>( \lesssim 10^{-8} )</td>
<td>( \lesssim 10^{-9} )</td>
</tr>
<tr>
<td>( t \rightarrow cg )</td>
<td>( \lesssim 10^{-5} )</td>
<td>( \lesssim 10^{-7} )</td>
<td>( \lesssim 10^{-10} )</td>
</tr>
<tr>
<td>( t \rightarrow ch )</td>
<td>( \lesssim 10^{-2} )</td>
<td>( \lesssim 10^{-5} )</td>
<td>( \lesssim 10^{-4} )</td>
</tr>
</tbody>
</table>

Snowmass Top Quark Working Group Report 1311.2028

Barbara Mele

Roma, 12 April 2016
Present LHC bounds from single-top production more sensitive to $u$-type vertex
most general effective Lagrangian for FC tqV(H) interactions with terms up to dim 5

\[- \mathcal{L}^{\text{eff}} = \frac{g}{2c_W} X_{qt} \bar{q} \gamma_\mu (x_{qt}^L P_L + x_{qt}^R P_R) t Z^\mu + \frac{g}{2c_W} \kappa_{qt} \bar{q} (\kappa_{qt}^v + \kappa_{qt}^a \gamma_5) \frac{i \sigma_{\mu \nu} q^\nu}{m_t} t Z^\mu + e \lambda_{qt} \bar{q} (\lambda_{qt}^v + \lambda_{qt}^a \gamma_5) \frac{i \sigma_{\mu \nu} q^\nu}{m_t} t A^\mu + g_s \zeta_{qt} \bar{q} (\zeta_{qt}^v + \zeta_{qt}^a \gamma_5) \frac{i \sigma_{\mu \nu} q^\nu}{m_t} T^a q G^{a \mu} + \frac{g}{2 \sqrt{2}} g_{qt} \bar{q} (g_{qt}^v + g_{qt}^a \gamma_5) t H + \text{H.c. ,}
\]

\[\sigma_{\mu \nu} \text{ terms grow with } V^\mu \text{ momentum } q^{\nu} \]

\[
\begin{align*}
\text{Br}(t \to q Z)_\gamma &= 0.472 X_{qt}^2, \\
\text{Br}(t \to q Z)_\sigma &= 0.367 \kappa_{qt}^2, \\
\text{Br}(t \to q \gamma) &= 0.428 \lambda_{qt}^2, \\
\text{Br}(t \to q g) &= 7.93 \zeta_{qt}^2, \\
\text{Br}(t \to q H) &= 3.88 \times 10^{-2} g_{qt}^2
\end{align*}
\]

(Aguilar-Saavedra hep-ph/0409342)
### bounds on $tqZ$ and $tq\gamma$

<table>
<thead>
<tr>
<th>Process</th>
<th>Br Limit</th>
<th>Search</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \to Zq$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$</td>
<td>300 fb$^{-1}$, 14 TeV</td>
</tr>
<tr>
<td>$t \to Zq$</td>
<td>$7 \times 10^{-5}$</td>
<td>ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$</td>
<td>3000 fb$^{-1}$, 14 TeV</td>
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<tr>
<td>$t \to Zq$</td>
<td>$5 (2) \times 10^{-4}$ *</td>
<td>ILC single top, $\gamma_{\mu} (\sigma_{\mu\nu})$</td>
<td>500 fb$^{-1}$</td>
</tr>
<tr>
<td>$t \to Zq$</td>
<td>$1.5 (1.1) \times 10^{-4} (-5)$</td>
<td>ILC single top, $\gamma_{\mu} (\sigma_{\mu\nu})$</td>
<td>500 fb$^{-1}$</td>
</tr>
<tr>
<td>$t \to Zq$</td>
<td>$1.6 (1.7) \times 10^{-3}$</td>
<td>ILC $t\bar{t}$, $\gamma_{\mu} (\sigma_{\mu\nu})$</td>
<td>500 fb$^{-1}$</td>
</tr>
<tr>
<td>$t \to \gamma q$</td>
<td>$8 \times 10^{-5}$</td>
<td>ATLAS $t\bar{t} \to Wb + \gamma q$</td>
<td>300 fb$^{-1}$, 14 TeV</td>
</tr>
<tr>
<td>$t \to \gamma q$</td>
<td>$2.5 \times 10^{-5}$</td>
<td>ATLAS $t\bar{t} \to Wb + \gamma q$</td>
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</tr>
<tr>
<td>$t \to \gamma q$</td>
<td>$6 \times 10^{-5}$ *</td>
<td>ILC single top</td>
<td>500 fb$^{-1}$</td>
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<tr>
<td>$t \to \gamma q$</td>
<td>$6.4 \times 10^{-6}$</td>
<td>ILC single top</td>
<td>500 fb$^{-1}$</td>
</tr>
<tr>
<td>$t \to \gamma q$</td>
<td>$1.0 \times 10^{-4}$</td>
<td>ILC $t\bar{t}$</td>
<td>500 fb$^{-1}$</td>
</tr>
</tbody>
</table>

* extrapolated

**Snowmass Top Quark Working Group Report 1311.2028**

$\sigma_{\mu\nu}$ terms grow with $V^\mu$ momentum $q^{\mu} \sim \sqrt{s}$ in single top

$\Rightarrow e^+e^- \to \gamma, Z(q^\mu) \to tq$ at ILC, most sensitive channel (!)
\[e^+e^- \rightarrow \gamma, Z(q^\mu) \rightarrow tq\]

**Figure 1:** Feynman diagrams for 2 generation signals and backgrounds

- **Cancellation between signals**
- **The top is assumed to decay via W**
- **Introducing a new HELAS-like subroutine**

In order to describe the FCN couplings among the top, a light quark (q) or antiquark (\(\bar{q}\)) and a Z boson or a photon. This correction is suppressed because it does not have the enhancement due to the charge conjugate processes. For the vertex, this new routine has been checked by hand. In all cases where the top decays, we only consider the first terms in the expansion in momenta. The terms of dimension 5. The couplings are constants corresponding to the FCN coupling (see Fig. 2). This gives the signals that led to a suppression of this signal.

For top decays we study the SM process of electron and muon decays.

For single top production we study the process of...

- **For the leptonic top** \(t \rightarrow b\ell\nu\)
  - **Khanpour at al. 1408.2090**

**Main background from Wjj**

\[\sqrt{S} = 240 \text{ GeV}\]

- **(large \(\sigma\)'s and large lumi (~10 ab\(^{-1}\) ) at the FCC-ee)**

| \(\gamma\) | 4811.7 | \(|\lambda_{qt}|^2\) |
| \(Z, \gamma_{\mu}\) | 2057.4 | \(|\lambda'_{qt}|^2\) |
| \(Z, \sigma_{\mu\nu}\) | 3218.0 | \(|\kappa_{qt}|^2\) |

**New Analysis**

**FCC-ee, Hadronic top** \(t \rightarrow bjj\)

- **(Biswa, Margaroli, BM)**
Simulation

- Model file for FCNC interactions has been implemented using FeynRules and MadGraph5_aMC@NLO interface.
- Signal ($tj$) and Background ($Wjj$) events are generated in MadGraph5_aMC@NLO then interfaced with PYTHIA for showering and hadronization.
- Jets are defined by the iterative cone algorithm of PYTHIA with a cone size of $R = 0.4$
- Jet energy resolution as for ILC detectors $\frac{\sigma(E)}{E} = 30\%/\sqrt{E}$
- True $b$-jet tagging efficiency and fake jet rejection for $c$ and light quark jets have been incorporated by generating random numbers on an event-by-event basis according to a given efficiency $\epsilon_b$. 
b-tagging

- b-tagging is crucial as background does not contain any b-quark initiated jet.
- An optimised choice of fake jet rejection may be more useful than a large b-tagging efficiency.

We have worked with true b-jet tagging efficiency of 60% and 80% and corresponding c (light)-jet rejection factor of 250 (1000) and 10 (100), respectively.
Event topology: Signal $tcA$ (magenta), $tcZ,\mu$ (green), $tcZ,\mu\nu$ (blue) and background $Wjj$ (red) kinematics at $\sqrt{s} = 240$ GeV [assumes $\epsilon_b = 80\%$]
FCNC Exclusion Limits (95% CL):
Single top (hadronic)
$\sqrt{S} = 240$ GeV  [0.1, 0.5, 10 ab$^{-1}$]

<table>
<thead>
<tr>
<th>Luminosity (fb$^{-1}$)</th>
<th>$\epsilon_b = 60%$</th>
<th>$\epsilon_b = 80%$</th>
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<tbody>
<tr>
<td></td>
<td>$\lambda_{qt}$</td>
<td>BR</td>
</tr>
<tr>
<td>100</td>
<td>2.79·10$^{-02}$</td>
<td>3.33·10$^{-04}$</td>
</tr>
<tr>
<td>500</td>
<td>1.83·10$^{-02}$</td>
<td>1.43·10$^{-04}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>8.60·10$^{-03}$</td>
<td>3.17·10$^{-05}$</td>
</tr>
<tr>
<td></td>
<td>$\chi_{qt}$</td>
<td>BR</td>
</tr>
<tr>
<td>100</td>
<td>4.30·10$^{-02}$</td>
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<td>$10^4$</td>
<td>1.32·10$^{-02}$</td>
<td>8.22·10$^{-05}$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_{qt}$</td>
<td>BR</td>
</tr>
<tr>
<td>100</td>
<td>3.43·10$^{-02}$</td>
<td>4.32·10$^{-04}$</td>
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<tr>
<td>500</td>
<td>2.25·10$^{-02}$</td>
<td>1.86·10$^{-04}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>1.06·10$^{-02}$</td>
<td>4.12·10$^{-05}$</td>
</tr>
</tbody>
</table>
\[ e^+ e^- \rightarrow \gamma, Z(q^\mu) \rightarrow tq \]

**hadronic top twice as sensitive to \( \text{BR}(\text{top})^{\text{FCNC}} \) as leptonic top**

<table>
<thead>
<tr>
<th>(leptonic channel)</th>
<th>(100 fb(^{-1}))</th>
<th>(hadronic channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} ) (GeV)</td>
<td>240</td>
<td>3.3 \times 10^{-4}</td>
</tr>
<tr>
<td>( \text{Br}(t \rightarrow q\gamma) )</td>
<td>5.9 \times 10^{-4}</td>
<td>4.3 \times 10^{-4}</td>
</tr>
<tr>
<td>( \text{Br}(t \rightarrow qZ) (\sigma_{\mu\nu}) )</td>
<td>8.8 \times 10^{-4}</td>
<td>8.8 \times 10^{-4}</td>
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<tr>
<td>( \text{Br}(t \rightarrow qZ) (\gamma_{\mu}) )</td>
<td>1.4 \times 10^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

Khanpour at al. 1408.2090
FCNC’s mediated by Dark Photons

\[ t \rightarrow q \bar{\gamma} \]
\[ b \rightarrow s \bar{\gamma} \]
\[ \ell \rightarrow \ell' \bar{\gamma} \]

Based on NP Model explaining Yukawa hierarchy via a Hidden Sector (HS) with extra unbroken Dark \( U(1)_F \) \( \Rightarrow \) massless dark photon

(HS contains \( N_f \) heavy fermions (\( D_f = \) Dark Matter ?) charged under Dark \( U(1)_F \)

Chiral Simmetry spontaneously broken in HS via non-perturbative effects (higher-derivative in DP field \( \sim 1/\Lambda \) \( \Rightarrow \) Lee-Wick ghosts)

\( \Rightarrow \) Dark fermions get \( M_{D_f} \) masses depending on their \( U(1)_F \) charge \( q_{D_f} \) \( \Rightarrow \) exponentially-spread \( D_f \) spectrum if integer charges \( q_{D_f} = 1, 2, 3, 4 \ldots \)

Flavor and Chiral Sym Breaking transferred to (radiative) Yukawa couplings at one-loop via (heavy) squark/slepton-like scalar messangers

\( \Rightarrow \) Yukawa hierarchy appears in visible sector, too!

Gabrielli, BM, Raidal, Venturini (in preparation)


Barbara Mele
Roma, 12 April 2016

22
→ plenty of new signatures at colliders involving stable dark photons

exploration just started!

mono-photon resonant signature

Higgs non-decoupling effects (just as in SM) can enhance BR

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196

Higgs momentum balanced by a massless invisible system

top FCNC’s mediated by Dark Photons

\[ t \rightarrow (c, u) \bar{\gamma} \]

\[ t \rightarrow q \bar{\gamma} \text{ versus } t \rightarrow q \gamma \]

new heavy states in loops contribute with same flavor matrix (but different U(1) charges) to FCNC decays into photon and dark photon

\[
\text{BR}(t \rightarrow (c, u) \bar{\gamma}) = \frac{\bar{\alpha}}{\alpha} \left( \frac{q^U_3 f_2(x^U_3, \xi_U)}{e_U f_2(x^U_3, \xi_U)} \right)^2 \text{BR}(t \rightarrow (c, u) \gamma)
\]

LHC (present bounds):

\[
\begin{align*}
\text{BR}^{\exp}(t \rightarrow u \gamma) & < 1.3 \times 10^{-4} \\
\text{BR}^{\exp}(t \rightarrow c \gamma) & < 1.7 \times 10^{-3}
\end{align*}
\]

but imposing vacuum-stability and dark-matter bounds gives \( \text{BR}(t \rightarrow q \bar{\gamma}) < 10^{-4} \)

Gabrielli, BM, Raidal, Venturini (in preparation)

also : \( b \rightarrow s \bar{\gamma} \) vs \( b \rightarrow s \gamma \)
further upper bounds from $f \to f' \gamma$ constraints

\[
\text{BR}^{\text{exp}}(\bar{B} \to X_S\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}
\]

\[
\begin{align*}
\text{BR}^{(b\to s\gamma)}(b \to s \bar{\gamma}) &< 8.5 \times 10^{-3} \left(\frac{\bar{\alpha}}{0.1}\right) \\
\text{BR}(\tau^- \to e^-\gamma) &< 3.3 \times 10^{-8} \\
\text{BR}(\tau^- \to \mu^-\gamma) &< 4.4 \times 10^{-8} \\
\text{BR}^{(\tau\to\mu\gamma)}(\tau \to \mu \bar{\gamma}) &< 5.9 \times 10^{-6} \left(\frac{\bar{\alpha}}{0.1}\right) \\
\text{BR}^{(\tau\to e\gamma)}(\tau \to e \bar{\gamma}) &< 1.1 \times 10^{-5} \left(\frac{\bar{\alpha}}{0.1}\right)
\end{align*}
\]

Gabrielli, BM, Raidal, Venturini
new class of (very distinctive) FCNC signatures at ee colliders:

\[ f \rightarrow f' \bar{\gamma} \]

for light fermions, \( E_{\text{miss}} \sim E_{f'} \sim E_f/2 \)

Sensitivity is likely just statistics limited!

( 10^6 top pairs \( \rightarrow \) \( \text{BR}_{\text{top}} \sim 10^{-5} \) )
( 10^{11} b pairs \( \rightarrow \) \( \text{BR}_b \sim 10^{-10} \) )
( 10^{10} tau pairs \( \rightarrow \) \( \text{BR}_{\tau} \sim 10^{-9} \) )

in top decays:

“In top” + (mono-j + \( E_{\text{miss}} \))

resonant at \( m_{\text{top}} \)

At \( tt \) threshold: \( \sim \) large monochr. \( E_{\text{miss}} \)
\[ E_{\text{miss}} \sim E_q \sim m_{\text{top}}/2 \]

Biswa, Gabrielli, BM, in progress
at the LHC new FCNC signatures in BOTH top decay AND top production

in top decay:

“top” + (mono-j + $E_{T\text{miss}}$)
resonant at $m_{\text{top}}$

[stop-like, for massless $\chi^0$]

in top production:

“top” plus massless invisible system
Outlook

- Z factory with $10^{12}/10^{13}$ Z's equals $10^6$-LEP's potential!
- opens up new frontiers in HF/lepton precision physics
- present effort to pinpoint FCC-ee “exclusive” search area (not covered by Belle II / LHCb) e.g. $B^0 \rightarrow K^{*0} \tau^+\tau^-$
- great control on bckgrs makes ee colliders excellent tools for looking at top rare decays inclusively!
- FCC-ee at 240 GeV has potential on $tc(u)\gamma$ / $tc(u)Z$ via single-top production comparable to HL-LHC
- new class of FCNC signatures from top, b, tau, mu decays into a massless dark photon
- very distinctive $\rightarrow$ bounds expected to be just limited by statistics! (to be looked at)