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

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

RICH PHYSICS PROGRAM AT ANY E_{cm} STAGE !

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

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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 (π/K/p separation possible with dedicated detector)
- large boost wrt Belle II
  - helps in controlling invisible (ν) 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) $B_s \to \mu\mu$ similar to LHCb.
- O(20) $B_d \to \mu\mu$ same comment in order.
- O(few 10^{10}) $\tau\tau$, yielding equivalent sensitivity as Belle II for LFV processes such as $\tau \to e\gamma$, $\mu\gamma$, eee, $\mu\mu\mu$.

*These estimates account for a luminosity of 5.6 10^{35} $cm^{-2}s^{-1}$, b-quark hadronisation fractions as measured at LEP and large reconstruction efficiencies

Flavor Physics benchmarks at the Z pole

(Kamenik & Monteil)

1) Any leptonic or semileptonic decay mode involving B_s, B_c or b-baryon, including electrons, in no particular order:

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

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

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

- $B_s \to \psi\eta'$ or $\eta_c\Phi$: flavour tagging required for weak mixing phase.
- $B_s \to D_s K$: PID definitely required to isolate the signal.

4) Lepton Flavour Violating processes.

current experimental bounds:

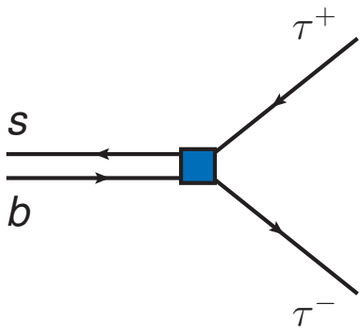
$$\mathcal{B}(Z \to e^\pm \mu^\mp) < 7.5\ 10^{-7}$$

$$\mathcal{B}(Z \to e^\pm \tau^\mp) < 9.8\ 10^{-6}$$

$$\mathcal{B}(Z \to \mu^\pm \tau^\mp) < 1.2\ 10^{-5}$$

- Direct LFV processes: $Z \to e\mu, e\tau, \tau\mu$. In terms of model constraints, this can be far richer than the current or foreseeable reach for $\mu \to e\gamma$ or $\tau \to \mu\gamma$ etc...
- Related to the large $\tau\tau$ production at the Z pole: $\tau \to e\gamma, \mu\gamma, eee, \mu\mu\mu$. 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→s τ+τ-



$B_s \to \tau^+\tau^-$

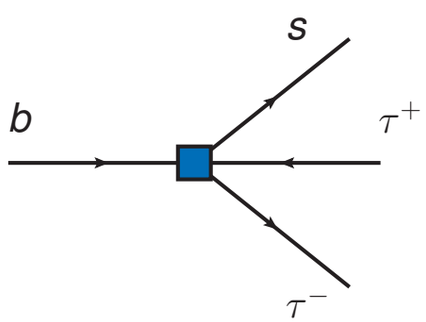
- purely tauonic decay
- recognized as "flagship mode" at a FCC-ee

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

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

$$\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.23,\mathrm{max}]} < 3.3 \times 10^{-3}$$

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



$B \to K\tau^+\tau^-$, $B \to K^*\tau^+\tau^-$

$B \to X_s\tau^+\tau^-$, $B_s \to \phi\tau^+\tau^-$

- semi-tauonic decays

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

SM predictions

restrict q^2 above the narrow charmonium resonances

$$\mathrm{BR}(B^0 \to K^{*0}\tau^+\tau^-)_{[15,\mathrm{max}]} = (0.91 \pm 0.11) \times 10^{-7}$$
$$\mathrm{BR}(B^+ \to K^{*+}\tau^+\tau^-)_{[15,\mathrm{max}]} = (0.99 \pm 0.12) \times 10^{-7}$$
$$\mathrm{BR}(B_s \to \phi\tau^+\tau^-)_{[15,\mathrm{max}]} = (0.73 \pm 0.09) \times 10^{-7}$$
$$\mathrm{BR}(B^0 \to K^0\tau^+\tau^-)_{[15,\mathrm{max}]} = (1.09 \pm 0.12) \times 10^{-7}$$
$$\mathrm{BR}(B^+ \to K^+\tau^+\tau^-)_{[15,\mathrm{max}]} = (1.18 \pm 0.13) \times 10^{-7}$$

Straub

LF Universality test

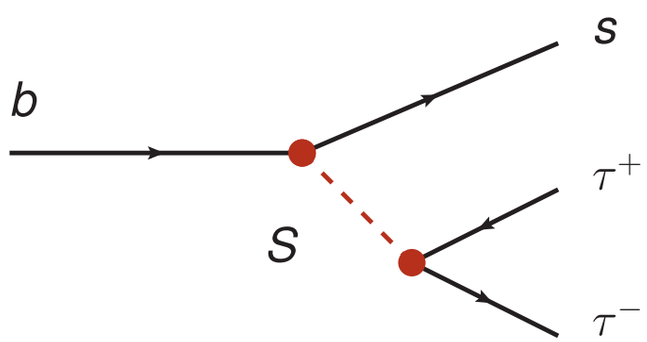
$$R_K^{\mu e} = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} = 1.00023 \pm 0.00063$$

$$R_K^{\tau e} = \frac{\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.18,\mathrm{max}]}}{\mathrm{BR}(B \to Ke^+e^-)_{[14.18,\mathrm{max}]}} = 1.161 \pm 0.040$$

$$R_K^{\tau\mu} = \frac{\mathrm{BR}(B \to K\tau^+\tau^-)_{[14.18,\mathrm{max}]}}{\mathrm{BR}(B \to K\mu^+\mu^-)_{[14.18,\mathrm{max}]}} = 1.158 \pm 0.039$$

(Bouchard et al. 1306.0434)

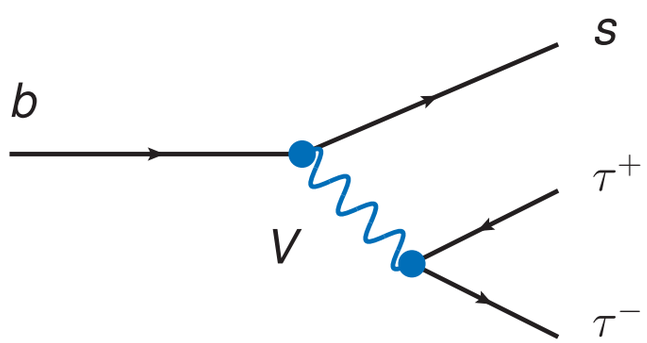
New Physics in $b \to s\tau\tau$ (models)



scalars (e.g. in 2HDMs)

if scalar couplings to leptons are prop. to the masses
$\Rightarrow B_s \to \tau^+\tau^-$ is the most important probe

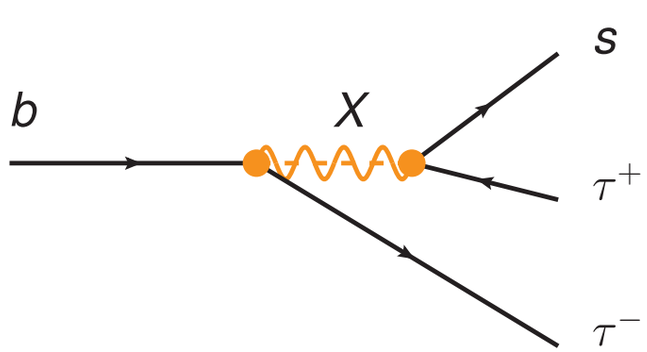
generic 2HDMs allow for much richer flavor structure
$\Rightarrow b \to s\tau^+\tau^-$ transitions can give important info



vectors

photon and Z are couple lepton flavor universaly
$\Rightarrow$ strong constraints from $b \to s\mu^+\mu^-$

Z' gauge bosons can violate lepton flavor universality
$\Rightarrow b \to s\tau^+\tau^-$ transitions are complementary probes



leptoquarks

generically no reason to expect
lepton flavor universality

$B^0 \to K^{*0}\,\tau^+\tau^-$ at the FCC-ee

- **tau final state unexplored so far !**

(Monteil, Semkiv, Altmanshoffer, Kamenik & Straub)

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

- Generate: $e^+e^- \to Z \to b\bar{b}$ — Pythia 8 and HepMC (through pythiafcc)
- Fragmentation and hadronisation of the *b* quarks:
- Filter B^0 particles. — Selection in P8
- Force the B^0 decay: $B^0 \to K^{0*}\tau^+\tau^-$ — EvtGen
- Force the tau lepton decay in three prongs: — EvtGen (Pythia Interfaced)

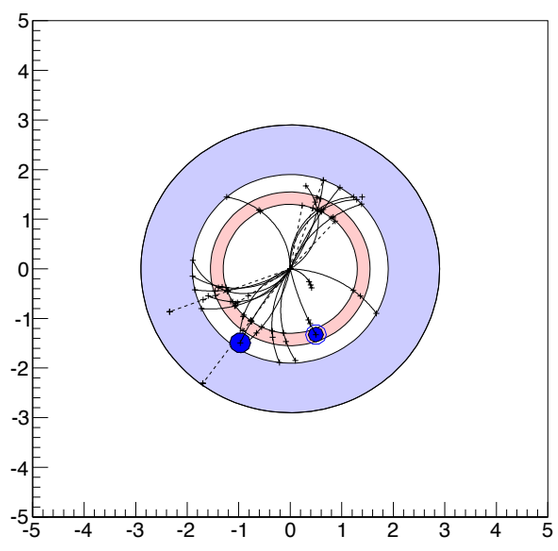
$$\tau^+ \to a_1^+\bar{\nu}_\tau \qquad K^{*0}(892) \to K^-\pi^+$$
$$a_1^+ \to \pi^+\pi^-\pi^+$$

- Write the output (tuples) in the Event Data Model — albers, fcc-albers, fcc-edm, heppy, fcc-heppy

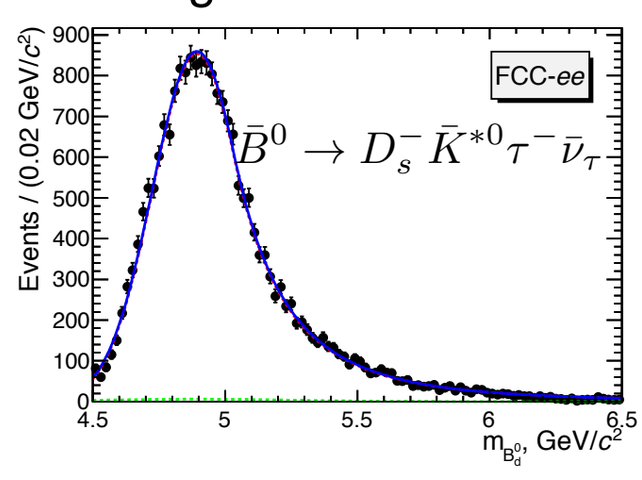
- **Partial Reconstruction** driven by resolutions on momenta, primary, secondary and tertiary vertices.

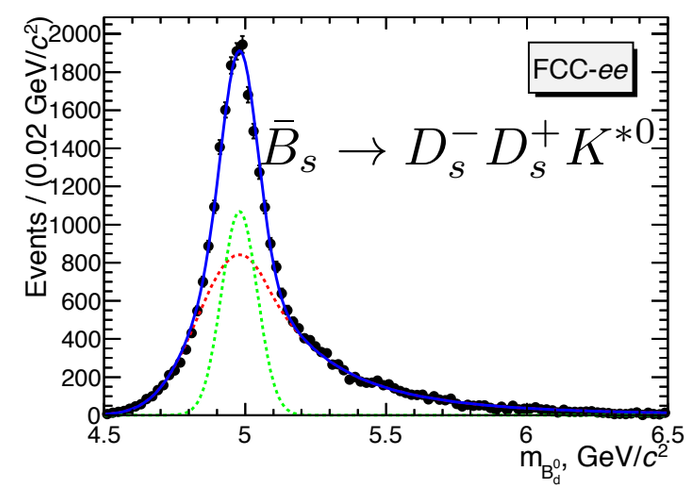
- assumed typical resolutions of ILD tracking system detector. MC truth outputs smeared according to following resolutions (~ state of the art) :
  - **Momentum** → 10 MeV
  - **Primary vertex** → 3 um
  - **Secondary vertex** → 7 um
  - **Tertiary vertex** → 5 um

- Generation in picture (B = 1 T).



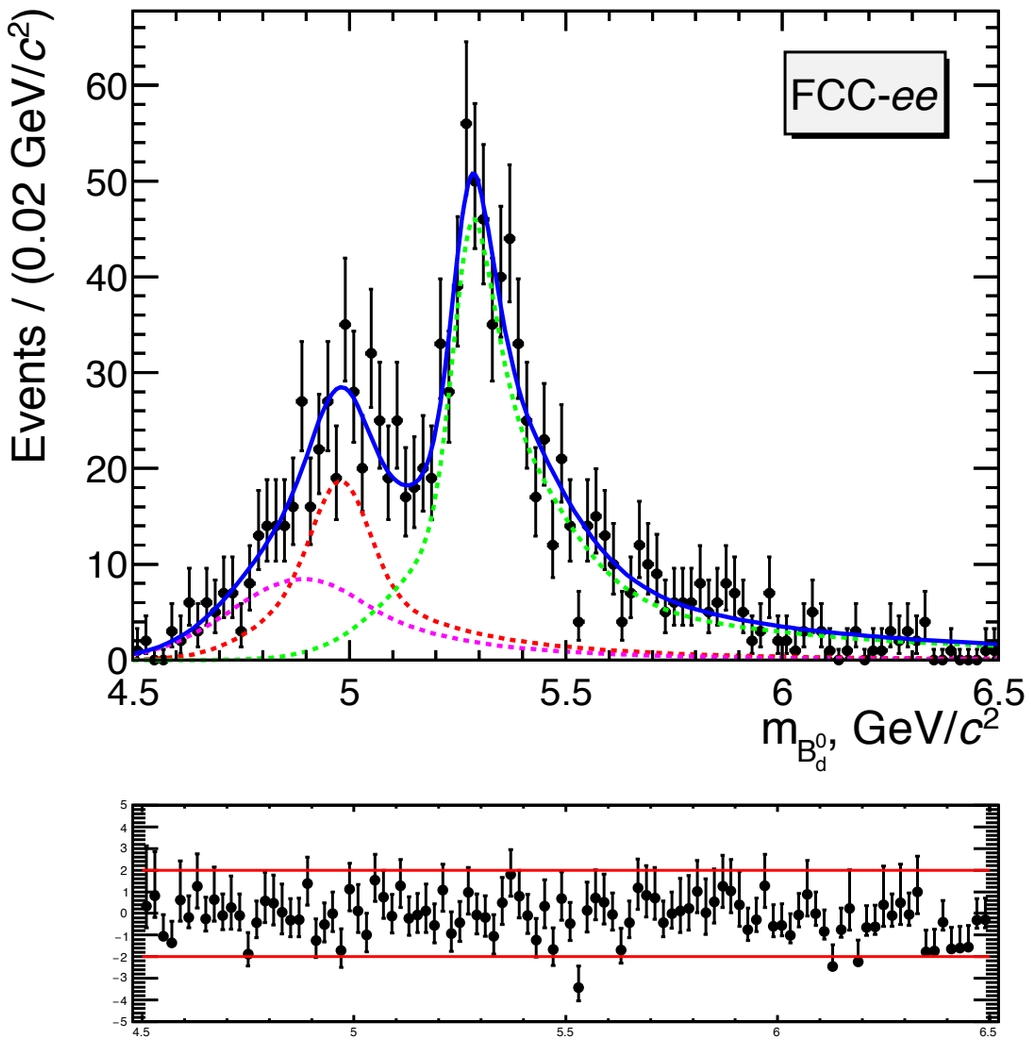
Backgrounds:





$B^0 \to K^{*0}\,\tau^+\tau^-$ at the FCC-ee

(Monteil, Semkiv, Altmanshoffer, Kamenik & Straub)



Conclusions:

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

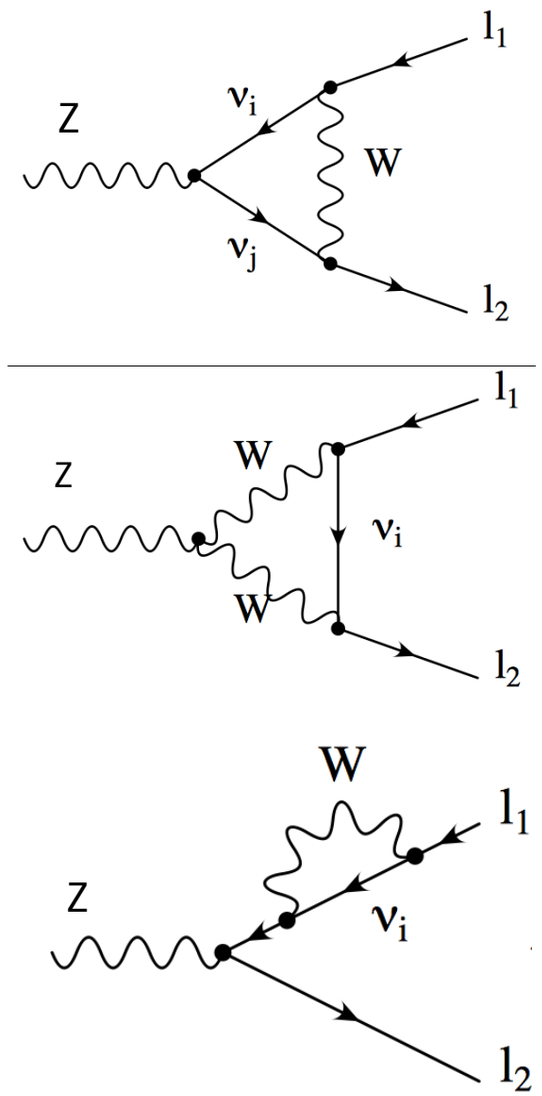
- FCC-*ee* likely unique to tackle this mode. Belle II experiment expects a handle of events.

- 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 ν'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:

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

- Steriles with mass above 80 GeV and mixings $O(10^{-5}\text{-}10^{-4})$ within FCCee reach.
- Low-energy experiment at work to probe the electron-muon sector
- FCC-*ee* provides the stringent constraint in tau-mu sectors.

top-quark rare decays : forewords

- 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

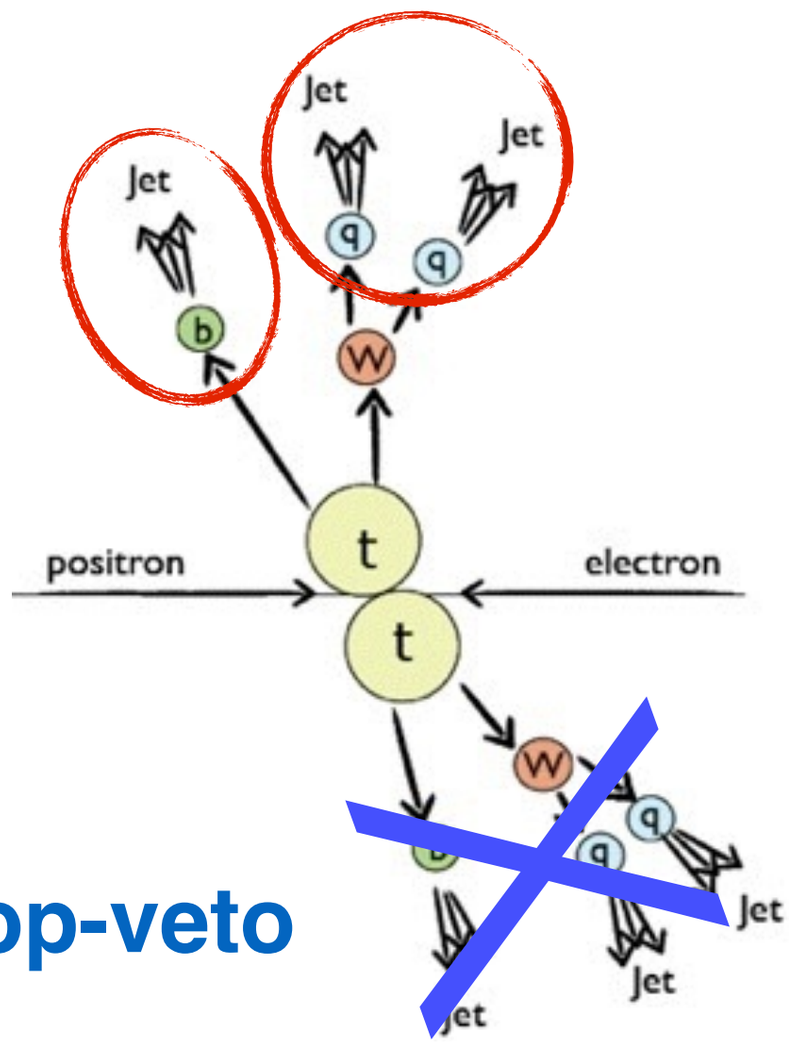
- this will open the opportunity to look at details of top production and kinematics that is unthinkable in hadron collisions
(relevant strategies mostly still to be developed …)

- rare top decays is one of the (many) top physics chapters that would widely benefit from such spectacularly clean environment !

one example →

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



top-veto

$E_{cm}(e+e-) \geq 350$ GeV

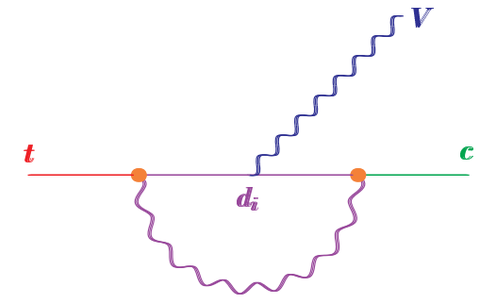
a) define criteria to tag
a Wb/Wj system
as a (SM) top quark

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

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

d) get model-independent
bounds on $BR(top)_{exotica}$!

FCNC top (really rare !) decays in the SM : NOT measurable !



GIM-suppressed by $(\frac{m_b}{M_W})^4$ + MFV (CKM matrix)

$(t \to ux)/(t \to cx) \simeq |V_{ub}/V_{cb}|^2 \simeq 0.008$

$\mathrm{BR}(t \to c\gamma) \simeq 5 \times 10^{-14}$

$\mathrm{BR}(t \to cg) \simeq 5 \times 10^{-12}$

$\mathrm{BR}(t \to cZ) \simeq 1 \times 10^{-14}$

$\mathrm{BR}(t \to ch) \simeq 3 \times 10^{-15}$

(Aguilar-Saavedra hep-ph/0409342)

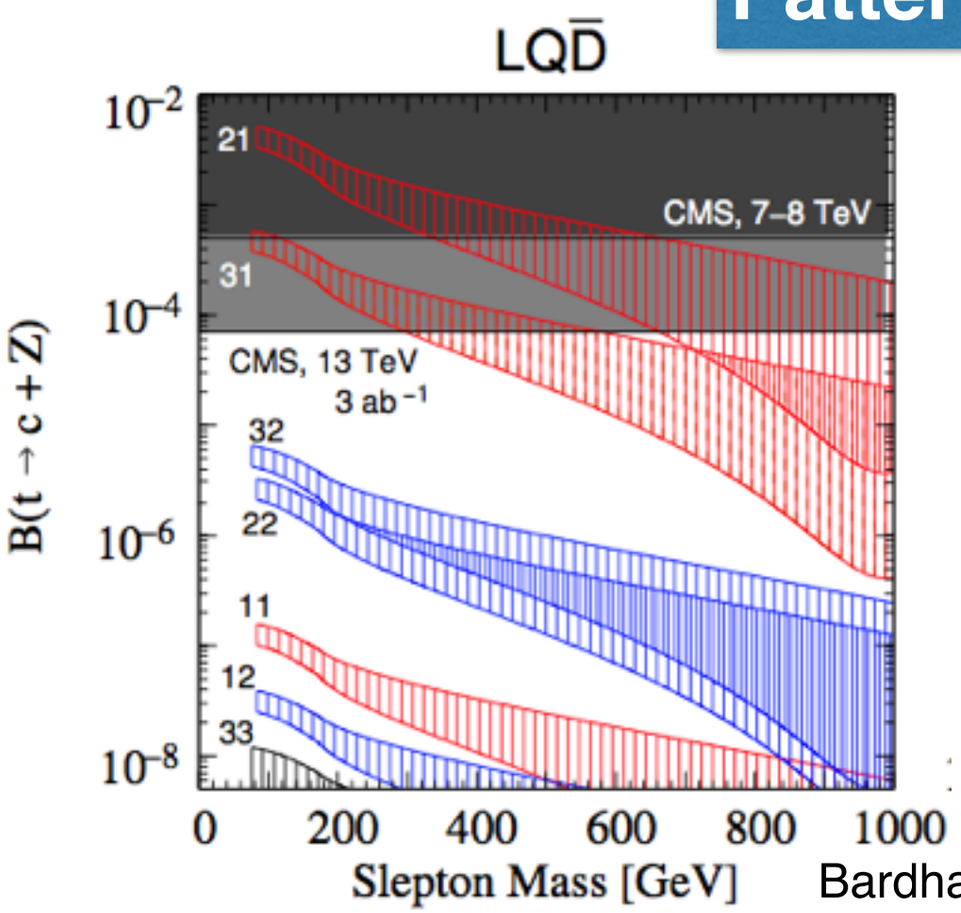
$\mathrm{BR}(t \to u\gamma) \simeq 4 \times 10^{-16}$

$\mathrm{BR}(t \to ug) \simeq 4 \times 10^{-14}$

$\mathrm{BR}(t \to uZ) \simeq 8 \times 10^{-17}$

$\mathrm{BR}(t \to uh) \simeq 2 \times 10^{-17}$

New Physics can hugely enhance predictions !



Bardhan et al., arXiv:1601.04165

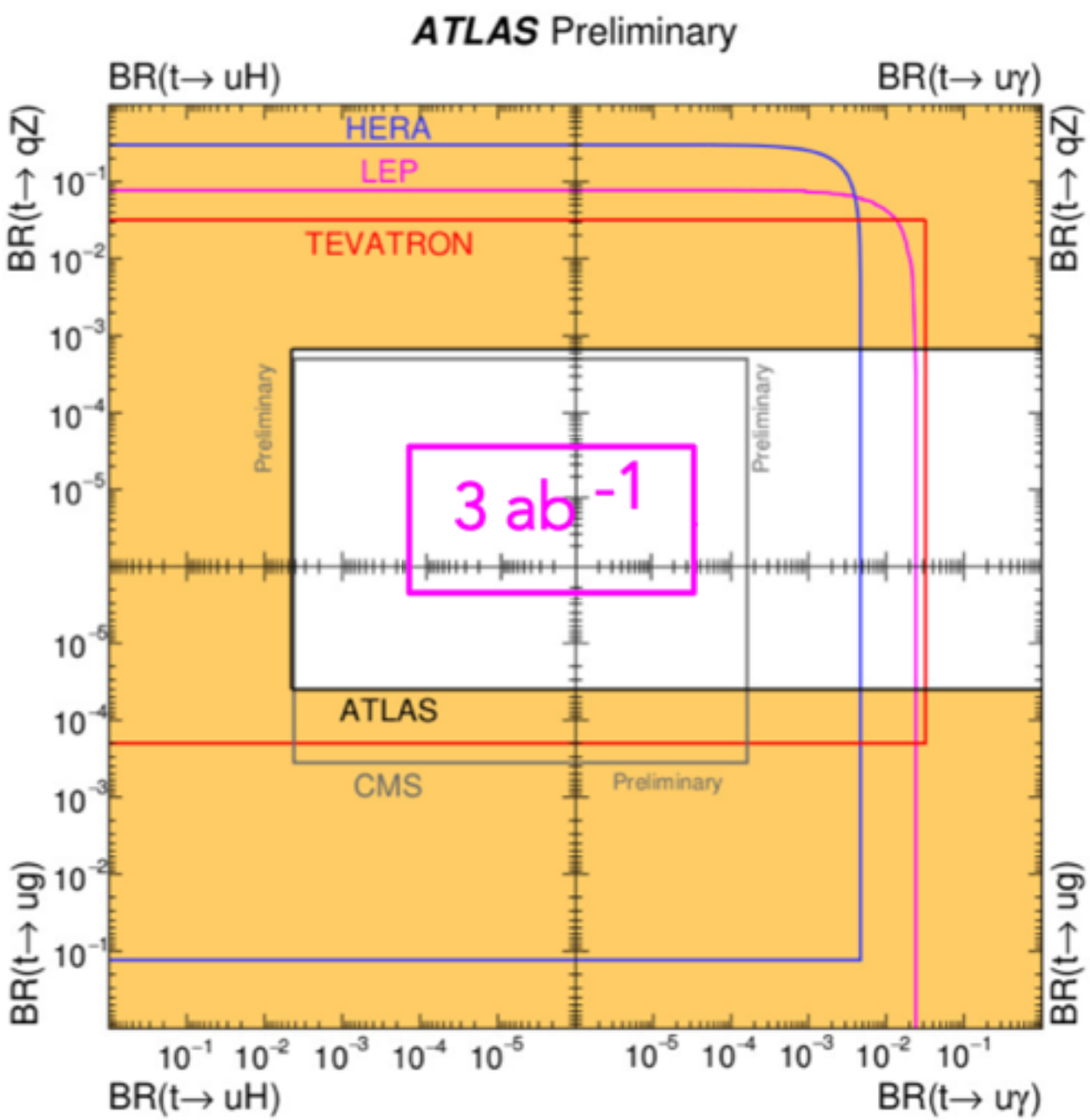
Pattern of enhancements is model dependent !

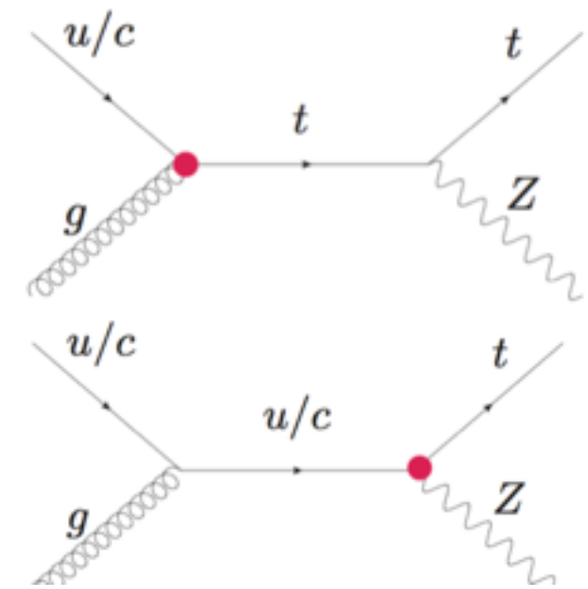
	2HDM	MSSM	RS
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Snowmass Top Quark Working Group Report 1311.2028

Present LHC bounds from $t\bar{t} \xrightarrow{\text{FCNC}} (Z/\gamma/g/h + j)(Wb)$
plus single-top anomalous production $qg \to t(Z/\gamma/H)$

single-top production more sensitive to u-type vertex





BR(t→ug)	0.004 %	ATLAS 1509.00294v1
BR(t→cg)	0.017 %	ATLAS 1509.00294v1
BR(t→qZ)	0.05 %	Phys. Rev. Lett. 112 (2014) 171802
BR(t→uγ)	0.013 %	CMS 1511.03951
BR(t→cγ)	0.17 %	CMS 1511.03951
BR(t→uH)	0.42 %	CMS-PAS-TOP-14-019
BR(t→cH)	0.46 %	ATLAS CERN-PH-EP-2015-229

most general effective Lagrangian for FC tqV(H) interactions with terms up to dim 5

$$-\mathcal{L}^{\rm eff} = \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu(x^L_{qt}P_L + x^R_{qt}P_R)tZ^\mu + \frac{g}{2c_W}\kappa_{qt}\,\bar{q}(\kappa^v_{qt} + \kappa^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tZ^\mu$$
$$+ e\lambda_{qt}\,\bar{q}(\lambda^v_{qt} + \lambda^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}tA^\mu + g_s\zeta_{qt}\,\bar{q}(\zeta^v_{tq} + \zeta^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t}T^a qG^{a\mu}$$
$$+ \frac{g}{2\sqrt{2}}g_{qt}\,\bar{q}(g^v_{qt} + g^a_{qt}\gamma_5)tH + \text{H.c.}\,,$$

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{nu}

$$\mathrm{Br}(t\to qZ)_\gamma = 0.472\, X^2_{qt},$$
$$\mathrm{Br}(t\to qZ)_\sigma = 0.367\, \kappa^2_{qt},$$
$$\mathrm{Br}(t\to q\gamma) = 0.428\, \lambda^2_{qt},$$
$$\mathrm{Br}(t\to qg) = 7.93\, \zeta^2_{qt},$$
$$\mathrm{Br}(t\to qH) = 3.88\times 10^{-2}\, g^2_{qt}$$

(Aguilar-Saavedra hep-ph/0409342)

bounds on tqZ and $tq\gamma$

ILC versus full LHC

Process	Br Limit	Search	Dataset
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV
$t \to Zq$	$5\,(2) \times 10^{-4}$ *	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 250 GeV
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 500 GeV
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 500 GeV
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV
$t \to \gamma q$	6×10^{-5} *	ILC single top	500 fb^{-1} 250 GeV
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1} 500 GeV
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1} 500 GeV

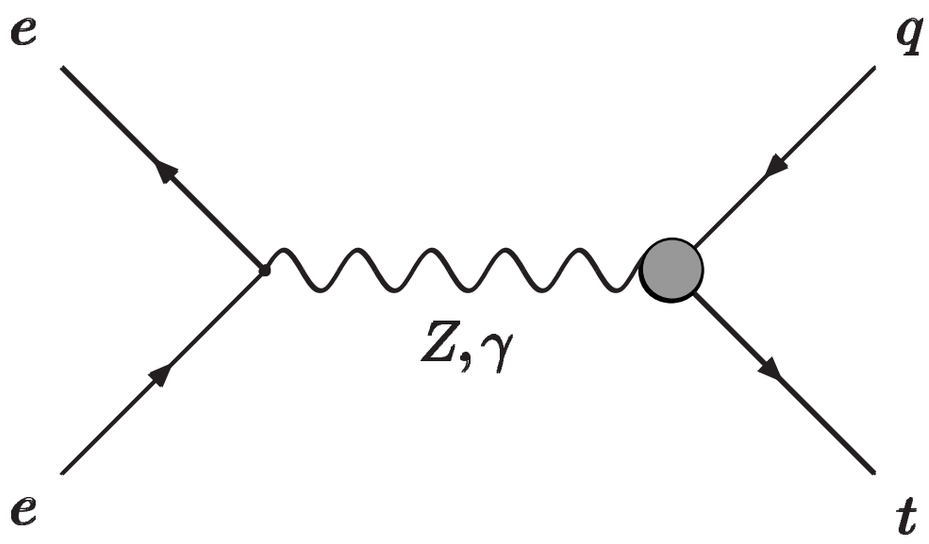
Snowmass Top Quark Working Group Report 1311.2028

*** extrapolated**

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{mu} **(~ √S in single top)**

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

$$e^+e^- \to \gamma, Z(q^\mu) \to tq$$



(LEP2 and ILC)

Han and Hewett 9811237

Bar-Shalom, Wudka 9905407

Aguilar-Saavedra, Riemann 0102197

(FCC-ee, leptonic top $t \to b\ell\nu$)

Khanpour at al. 1408.2090

main background from W j j

√S= 240 GeV

(large σ's and large lumi (~10 ab $^{-1}$) at the FCC-ee)

σ (fb)	γ	4811.7 $\lvert\lambda_{qt}\rvert^2$
	Z,γ_μ	2057.4 $\lvert\mathcal{X}_{qt}\rvert^2$
	$Z,\sigma_{\mu\nu}$	3218.0 $\lvert\kappa_{qt}\rvert^2$

New Analysis

FCC-ee, Hadronic top $t \to bjj$ **(Biswas, Margaroli, BM)**

Simulation

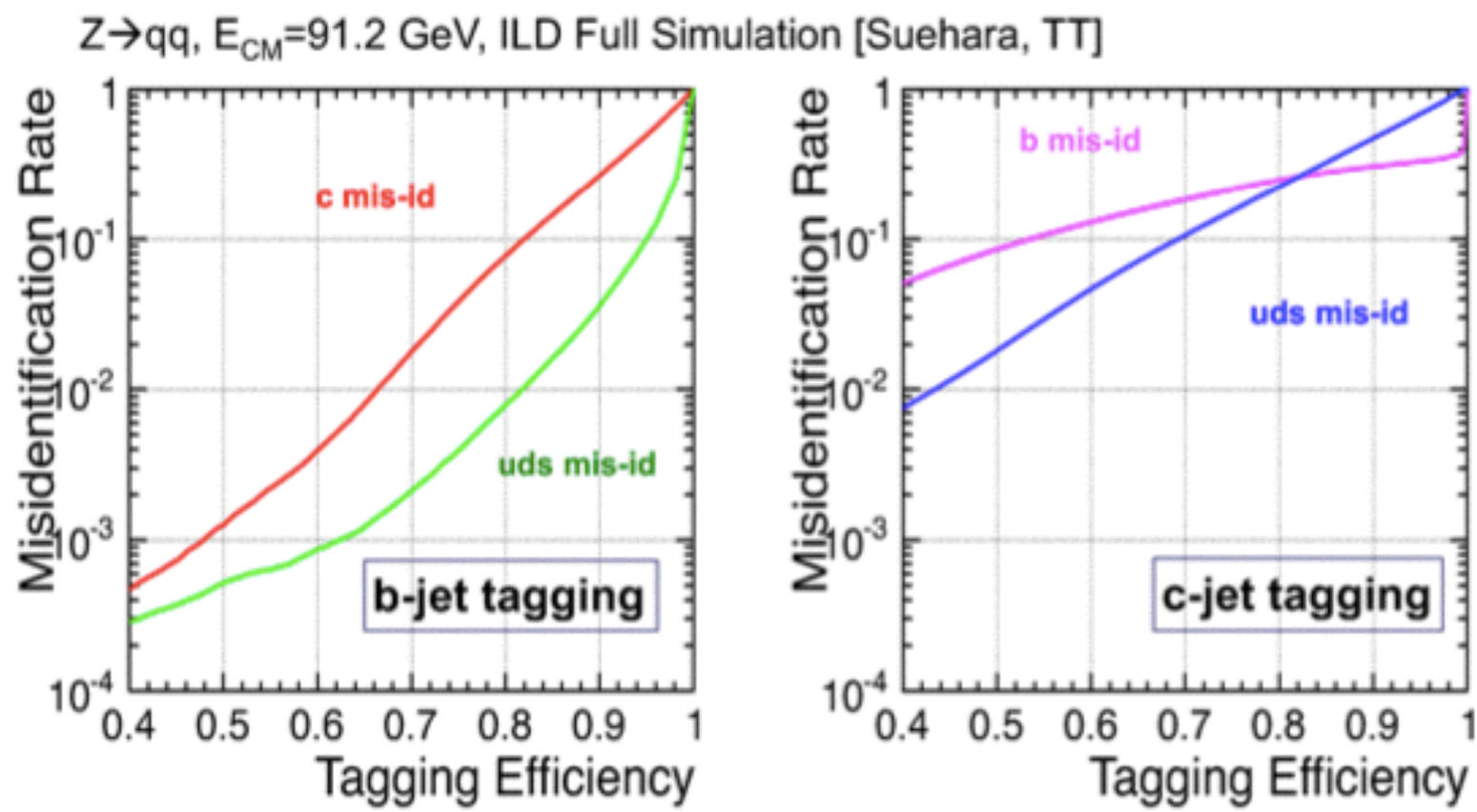
- Model file for FCNC interactions has been implemented using FeynRules and MadGraph5_aMC@NLO interface.
- Signal (tj) and Background (Wjj) events are generated in MadGraph5_aMC@NLO then interfaced with PYTHIA for showering and hadronization.
- Jets are defined by the iterative cone algorithm of PYTHIA with a cone size of $R = 0.4$
- Jet energy resolution as for ILC detectors $\boxed{\frac{\sigma(E)}{E} = 30\%/\sqrt{E}}$
- 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 ϵ_b.

b-tagging

[CLICdp-Note-2014-002, Taikan Suehara, ICHEP-2014]

Higgs Hadronic Decays: Flavor Tagging

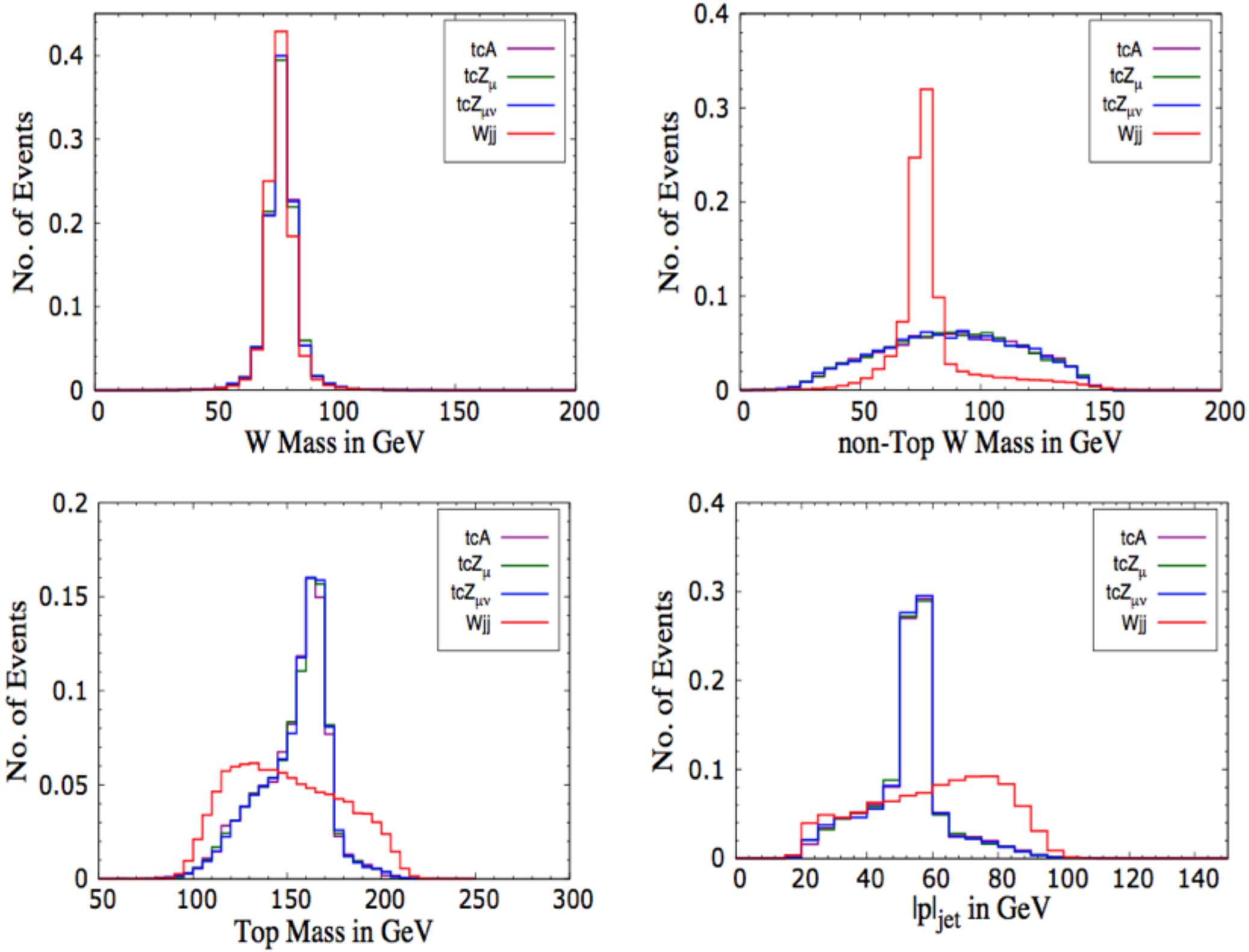
- b-tagging is crucial as background does not contain any b-quark initiated jet.
- An optimised choice of fake jet rejection may be more useful than a large b-tagging efficiency.



ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

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 ϵ_b =80%]



FCNC Exclusion Limits (95% CL):

Single top (hadronic)

Biswas, Margaroli, BM

$\sqrt{S} = 240$ GeV [0.1, 0.5, 10 ab^{-1}]

tqA:

Luminosity (fb^{-1})	$\epsilon_b = 60\%$		$\epsilon_b = 80\%$	
	λ_{qt}	BR	λ_{qt}	BR
100	$2.79 \cdot 10^{-02}$	$3.33 \cdot 10^{-04}$	$4.99 \cdot 10^{-02}$	$1.07 \cdot 10^{-03}$
500	$1.83 \cdot 10^{-02}$	$1.43 \cdot 10^{-04}$	$3.32 \cdot 10^{-02}$	$4.72 \cdot 10^{-04}$
10^4	$8.60 \cdot 10^{-03}$	$3.17 \cdot 10^{-05}$	$1.57 \cdot 10^{-02}$	$1.06 \cdot 10^{-04}$

tqZ, γ_μ:

Luminosity (fb^{-1})	$\epsilon_b = 60\%$		$\epsilon_b = 80\%$	
	$\mathcal{X}_{qt}$	BR	$\mathcal{X}_{qt}$	BR
100	$4.30 \cdot 10^{-02}$	$8.77 \cdot 10^{-04}$	$7.73 \cdot 10^{-02}$	$2.82 \cdot 10^{-03}$
500	$2.83 \cdot 10^{-02}$	$3.78 \cdot 10^{-04}$	$5.15 \cdot 10^{-02}$	$1.25 \cdot 10^{-03}$
10^4	$1.32 \cdot 10^{-02}$	$8.22 \cdot 10^{-05}$	$2.43 \cdot 10^{-02}$	$2.79 \cdot 10^{-04}$

$tqZ, \sigma_{\mu\nu}$:

Luminosity (fb^{-1})	$\epsilon_b = 60\%$		$\epsilon_b = 80\%$	
	κ_{qt}	BR	κ_{qt}	BR
100	$3.43 \cdot 10^{-02}$	$4.32 \cdot 10^{-04}$	$6.13 \cdot 10^{-02}$	$1.38 \cdot 10^{-03}$
500	$2.25 \cdot 10^{-02}$	$1.86 \cdot 10^{-04}$	$4.08 \cdot 10^{-02}$	$6.11 \cdot 10^{-04}$
10^4	$1.06 \cdot 10^{-02}$	$4.12 \cdot 10^{-05}$	$1.93 \cdot 10^{-02}$	$1.37 \cdot 10^{-04}$

$$e^+e^- \to \gamma, Z(q^\mu) \to tq$$

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

(leptonic channel)	$(100\ fb^{-1})$	(hadronic channel)
$\sqrt{s}$ (GeV)	240	
$Br(t \to q\gamma)$	5.9×10^{-4}	3.3×10^{-4}
$Br(t \to qZ)\ (\sigma_{\mu\nu})$	8.8×10^{-4}	4.3×10^{-4}
$Br(t \to qZ)\ (\gamma_\mu)$	1.4×10^{-3}	8.8×10^{-4}

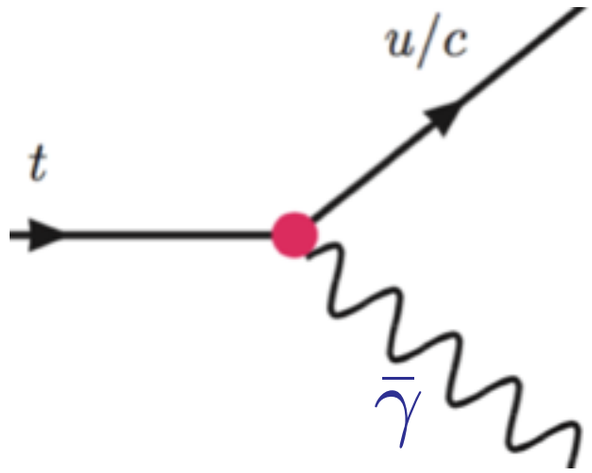
Khanpour at al. 1408.2090

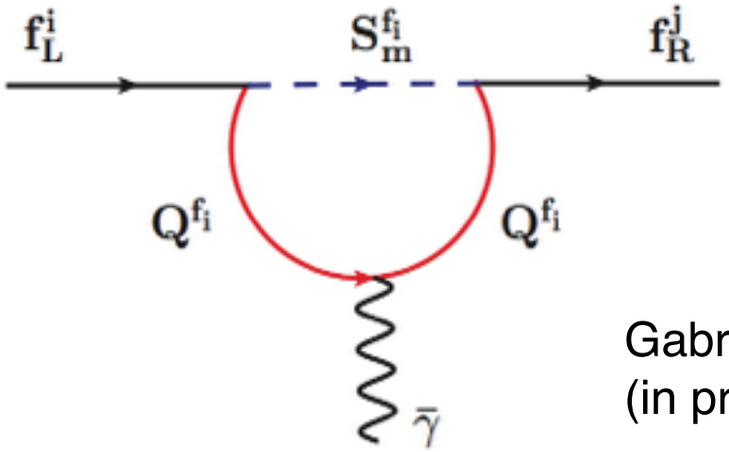
FCNC's mediated by Dark Photons

$t \to q\,\bar{\gamma}$

$b \to s\,\bar{\gamma}$

$\ell \to \ell'\,\bar{\gamma}$





Gabrielli, BM, Raidal, Venturini (in preparation)

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

(Gabrielli, Raidal, arXiv:1310.1090; Ma, arXiv:1311.3213)

- HS contains N_f heavy fermions (Df=Dark Matter ?) charged under Dark $U(1)_F$
- Chiral Simmetry spont. broken in HS via non-perturbative effects (higher-derivative in DP field ~ $1/\Lambda$ ➜ Lee-Wick ghosts)

  ➜ Dark fermions get M_{Df} masses depending on their $U(1)_F$ charge q_{Df} ➜ exponentially-spread Df spectrum if integer charges q_{Df}=1, 2, 3, 4...
- Flavor and Chiral Sym Breaking transferred to (radiative) Yukawa couplings at one-loop via (heavy) squark/slepton-like scalar messangers

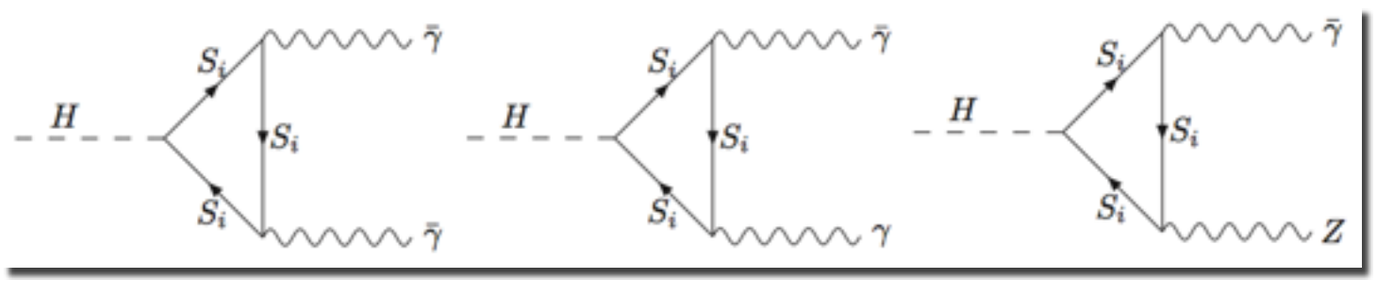
➜ Yukawa hierarchy appears in visible sector, too !

→ plenty of new signatures at colliders involving stable dark photons

exploration just started !

massless and invisible → ν-like

- in H decays : $H \to \gamma\bar{\gamma}$

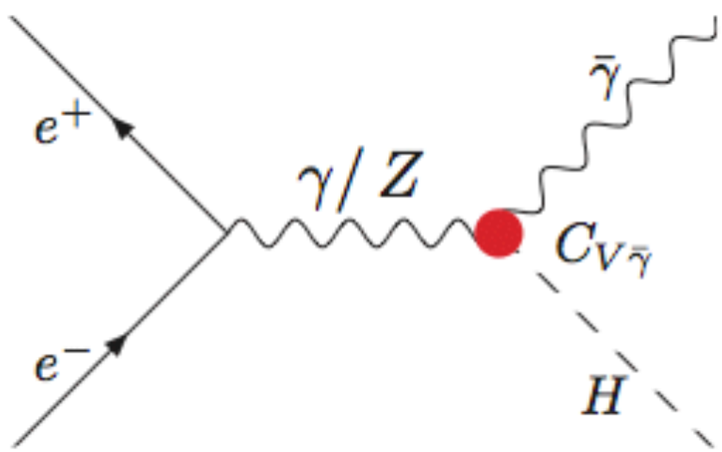


mono-photon resonant signature

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

Gabrielli,Heikinheimo, BM, Raidal, arXiv:1405.5196

- in H production

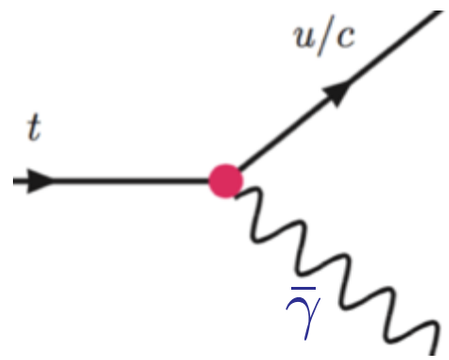


Higgs momentum balanced by a massless invisible system

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1503.05836

top FCNC's mediated by Dark Photons

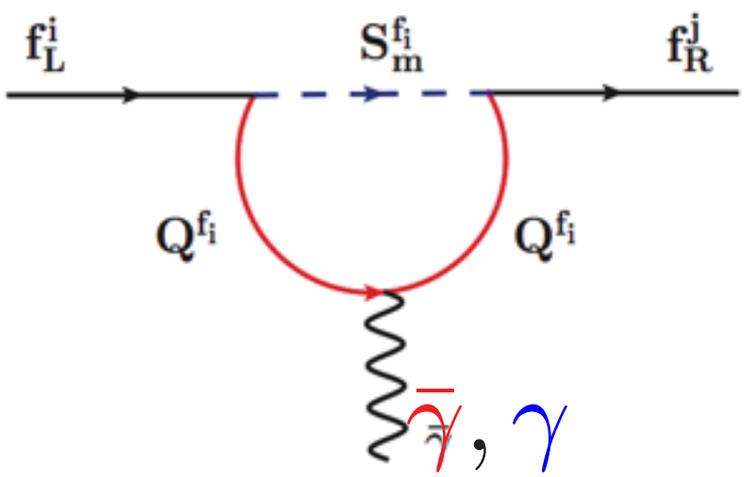
$$t \to (c,u)\,\bar{\gamma}$$



Gabrielli, BM, Raidal, Venturini
(in preparation)

also : $b \to s\,\bar{\gamma}$
vs $b \to s\,\gamma$

$t \to q\,\bar{\gamma}$ **versus** $t \to q\,\gamma$



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

$$\mathrm{BR}(t \to (c,u)\,\bar{\gamma}) \;=\; \frac{\bar{\alpha}}{\alpha}\left(\frac{q_3^U\, f_2(x_3^U,\xi_U)}{e_U\, \bar{f}_2(x_3^U,\xi_U)}\right)^2 \mathrm{BR}(t \to (c,u)\,\gamma)$$

LHC (present bounds):

$$\mathrm{BR}^{\mathrm{exp}}(t \to u\,\gamma) \;<\; 1.3 \times 10^{-4}$$
$$\mathrm{BR}^{\mathrm{exp}}(t \to c\,\gamma) \;<\; 1.7 \times 10^{-3}$$

$$\mathrm{BR}^{(t\to u\gamma)}(t \to u\,\bar{\gamma}) \;<\; 1.8 \times 10^{-2}\left(\frac{\bar{\alpha}}{0.1}\right)$$
$$\mathrm{BR}^{(t\to c\gamma)}(t \to c\,\bar{\gamma}) \;<\; 2.3 \times 10^{-1}\left(\frac{\bar{\alpha}}{0.1}\right)$$

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

further upper bounds from $f \to f' \gamma$ constraints

$$\mathrm{BR}^{\mathrm{exp}}(\bar{B} \to X_S \gamma) \;=\; (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

$$\Rightarrow \quad \mathrm{BR}^{(b\to s\gamma)}(b \to s\,\bar{\gamma}) \;<\; 8.5 \times 10^{-3} \left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}(\tau^- \to e^- \gamma) \;<\; 3.3 \times 10^{-8}$$

$$\mathrm{BR}(\tau^- \to \mu^- \gamma) \;<\; 4.4 \times 10^{-8}$$

$$\Rightarrow \quad \mathrm{BR}^{(\tau\to\mu\gamma)}(\tau \to \mu\,\bar{\gamma}) \;<\; 5.9 \times 10^{-6} \left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}^{(\tau\to e\gamma)}(\tau \to e\,\bar{\gamma}) \;<\; 1.1 \times 10^{-5} \left(\frac{\bar{\alpha}}{0.1}\right)$$

Gabrielli, BM, Raidal, Venturini

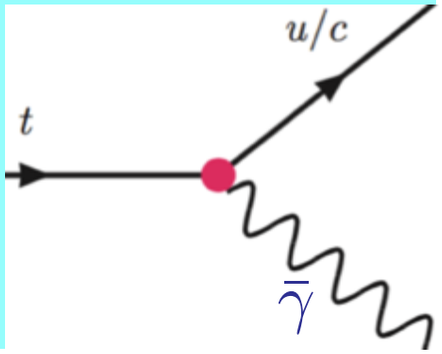
➜ new class of (very distinctive) FCNC signatures at ee colliders

$$f \to f' \bar{\gamma}$$

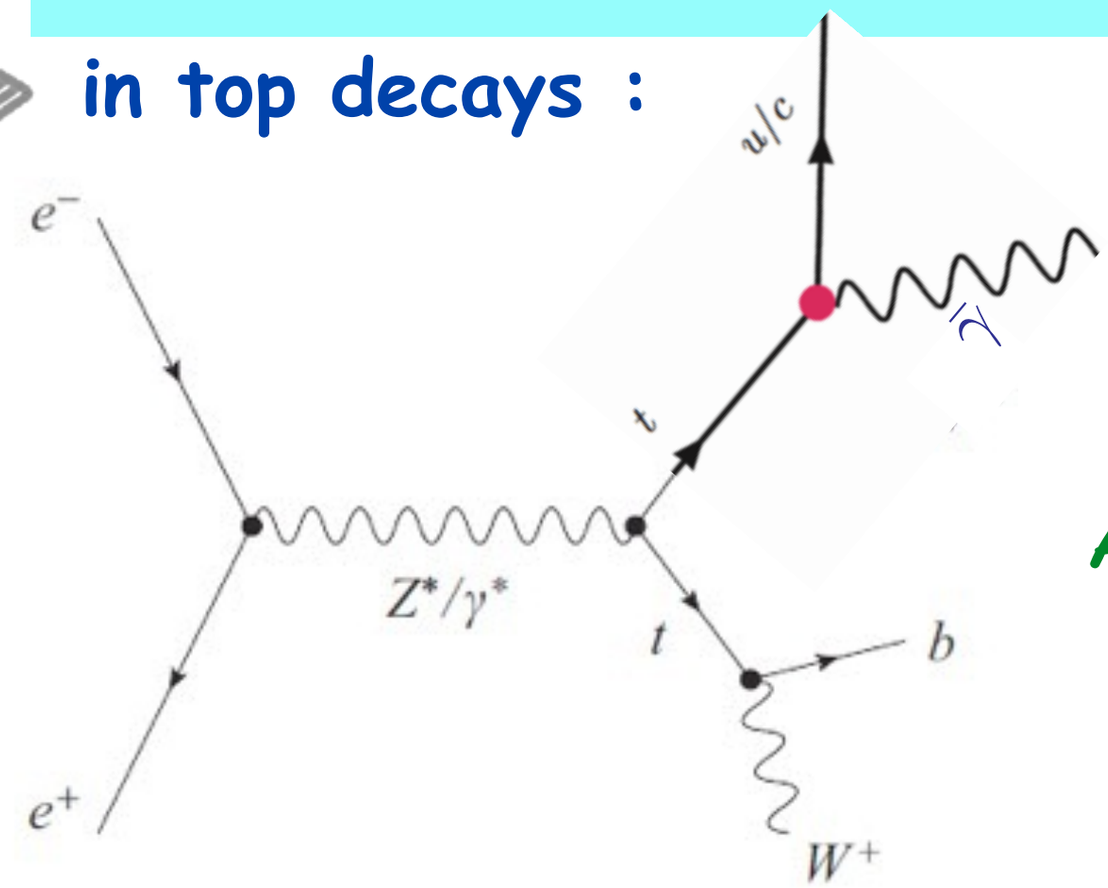
for light fermions, $E_{miss} \sim E_{f'} \sim E_f/2$

Sensitivity is likely just statistics limited !

(10^6 top pairs ➜ $BR_{top} \sim 10^{-5}$)
(10^{11} b pairs ➜ $BR_b \sim 10^{-10}$)
(10^{10} tau pairs ➜ $BR_{tau} \sim 10^{-9}$)



- in top decays :



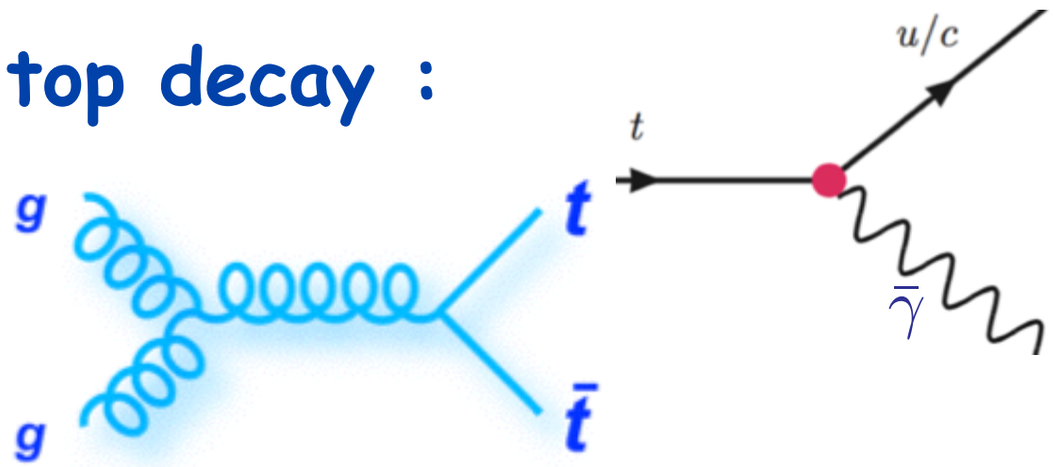
"top" + (mono-j + E_{miss})
resonant at m_{top}

At tt threshold : ~ large monochr. E_{miss}
$E_{miss} \sim E_q \sim m_{top}/2$

Biswas, Gabrielli, BM, in progress

➜ at the LHC new FCNC signatures in BOTH top decay AND top production

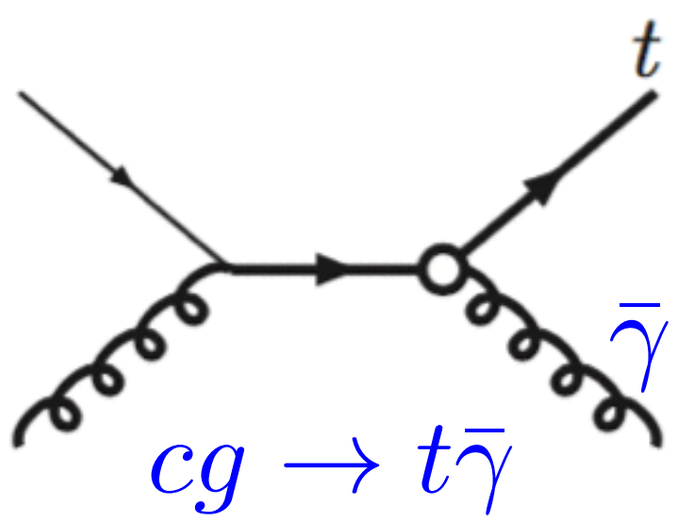
- in top decay :



"top" + (mono-j + E^T_{miss})
resonant at m_{top}

[stop-like, for massless χ^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. $B^0 \to K^{*0}\,\tau^+\tau^-$
- 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)γ / 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 ➜ bounds expected to be just limited by statistics ! (to be looked at)