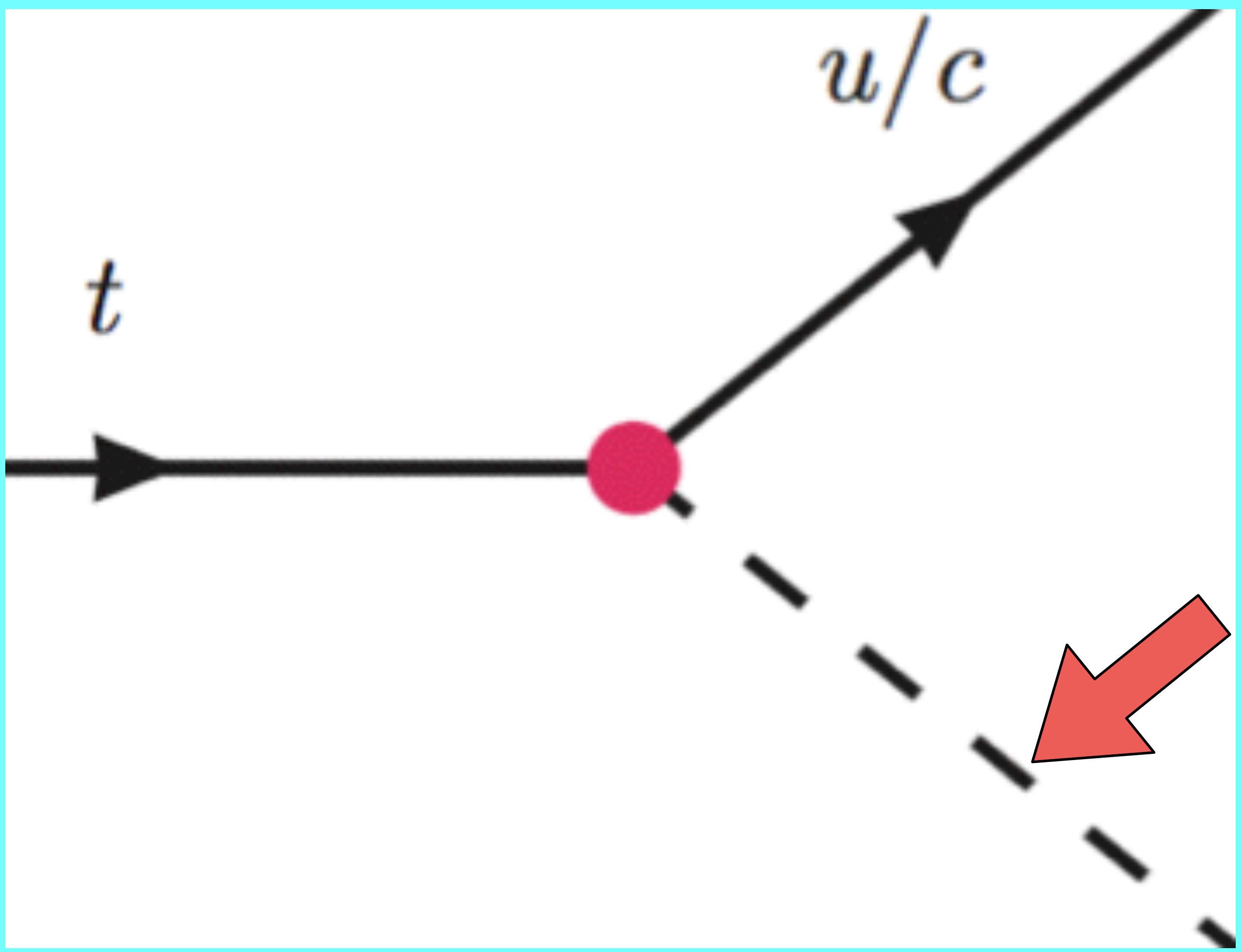
FCC-ee Mini-Workshop: "Physics Behind Precision"
2-3 February 2016, CERN

(top) FCNC at the FCC-ee



$\gamma, Z, g, H, \text{“}X\text{”}$

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CERN, 3 February 2016

Outline

- Forewords
- LHC: present and future bounds on top FCNC
- FCC-ee : two running phases relevant for top FCNC :
  - $\sqrt{S} \geq 350$ GeV ➜ 10^6 top pairs above ttbar threshold

    (➜ BR~10^{-5} for rare decays with distinctive signatures)
  - $\sqrt{S} = 240$ GeV with $\int L \sim 10\ ab^{-1}$ ➜ single top $ee \to t\ q$
- NOT A REVIEW ! Details on two recent developments:
  - $ee \to t\ q$ (hadronic top channel) (Biswas, Margaroli, BM)
  - $t \to q\ \bar{\gamma}$ ➜ new BSM FCNC signature !

    jet + dark-photon m_{top} resonance !

    (Gabrielli, BM, Raidal, Venturini)
- Outlook

special thanks to S.Biswas and E.Gabrielli

Outlook

BM, talk at 7th FCC-ee Phys. WS June 2014

- 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

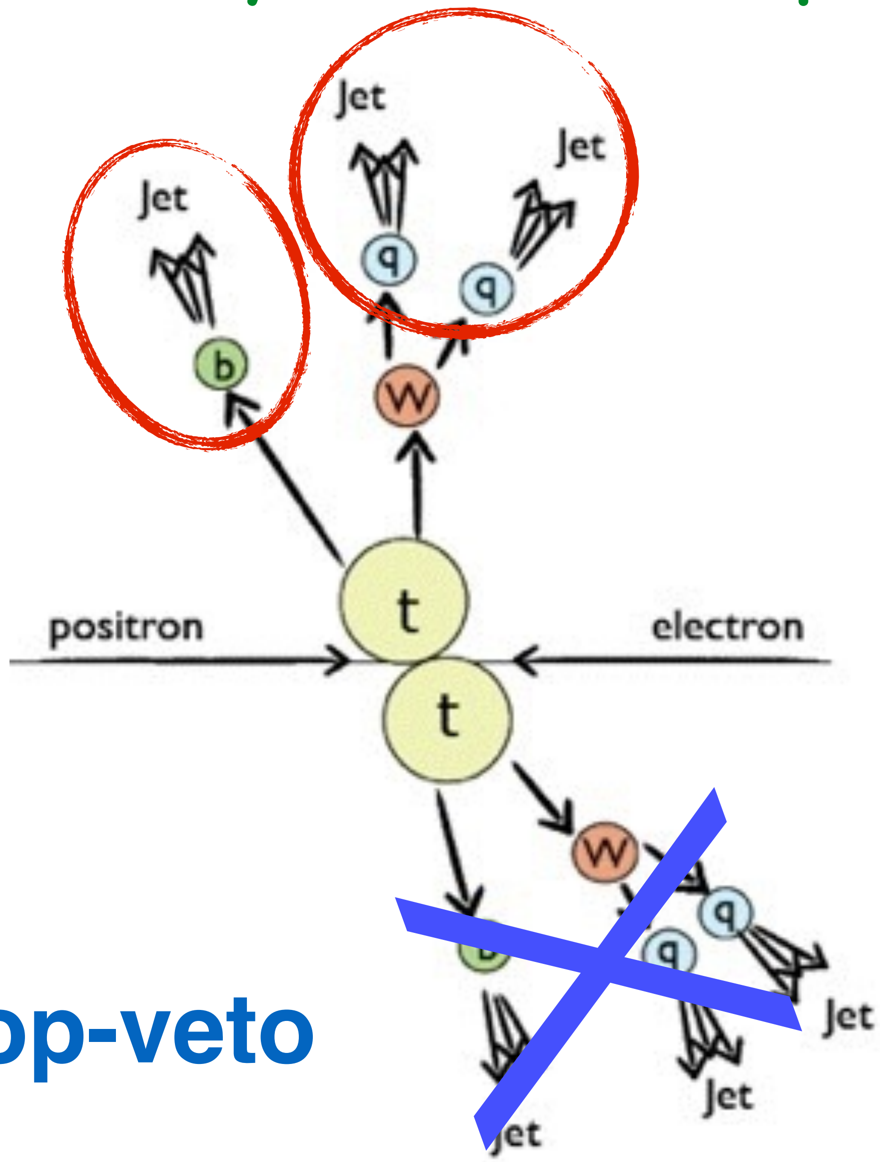
- this will open the opportunity to look at details of top production and kinematics that is unthinkable in hadron collisions
(relevant strategies mostly still to be developed …)

- 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 exotic top final states
(unexpected signatures "hard" at LHC !)
➜ global analysis of a top
recoil system with a top-veto



top-veto

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

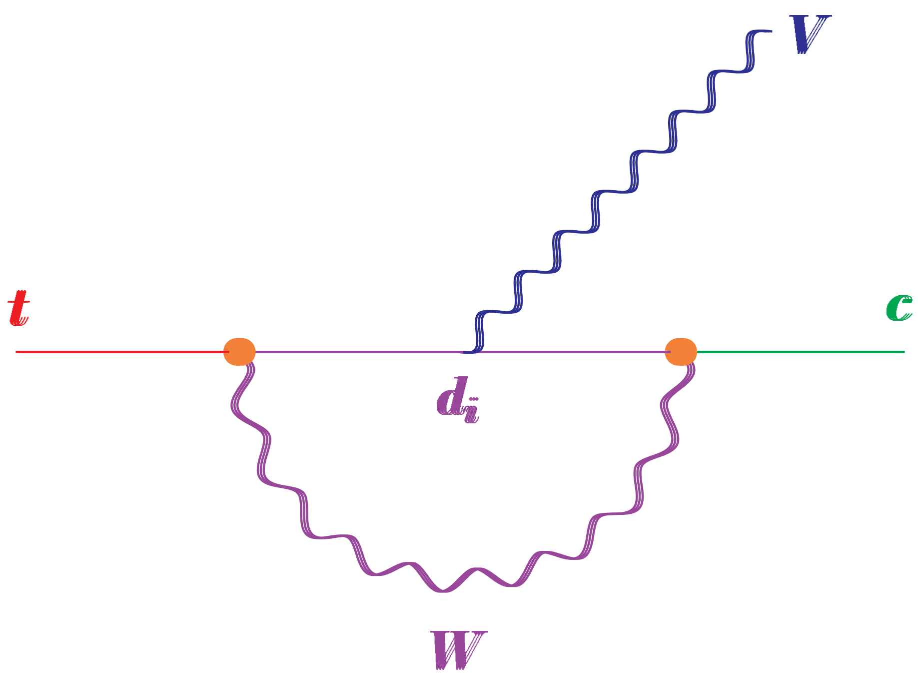
a) define criteria to tag
a Wb/Wj system
as a (SM) top quark

b) look for events containing
a top-system with
a veto on a 2^{nd} 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 $\left(\frac{m_b}{M_W}\right)^4$

+ MFV (CKM matrix)

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

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

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

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

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

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

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

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

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

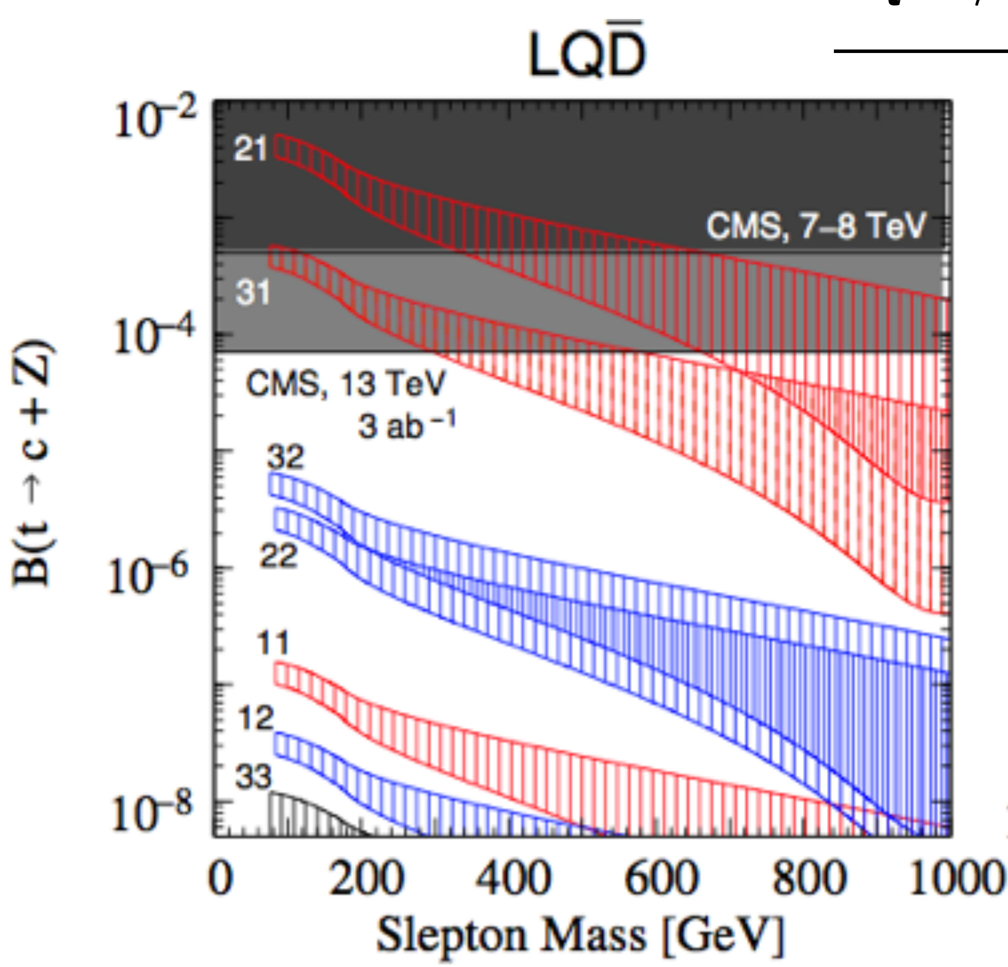
(Aguilar-Saavedra hep-ph/0409342)

New Physics can hugely enhance predictions !

Pattern of enhancements is model dependent !

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

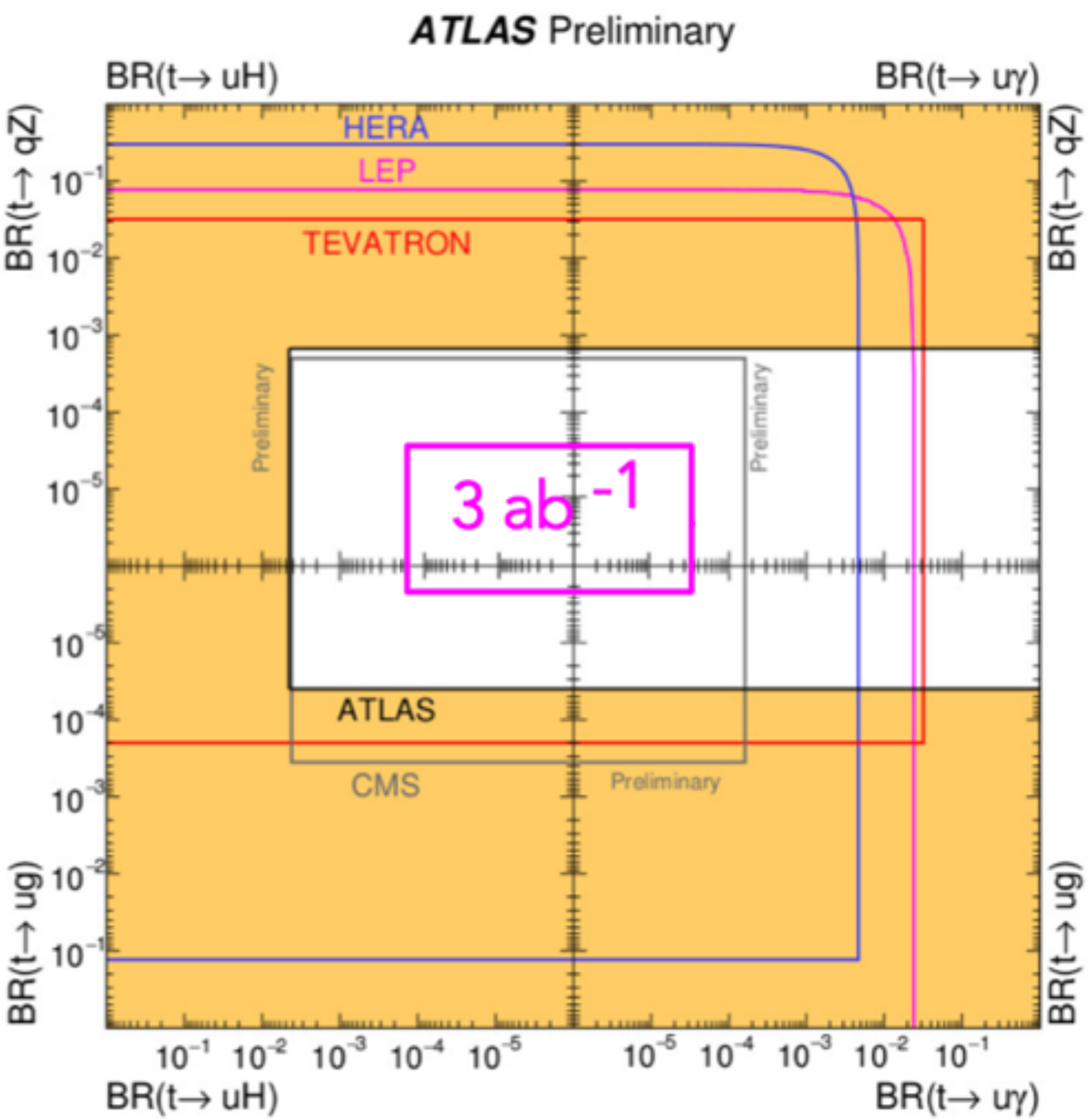
Snowmass Top Quark Working Group Report 1311.2028

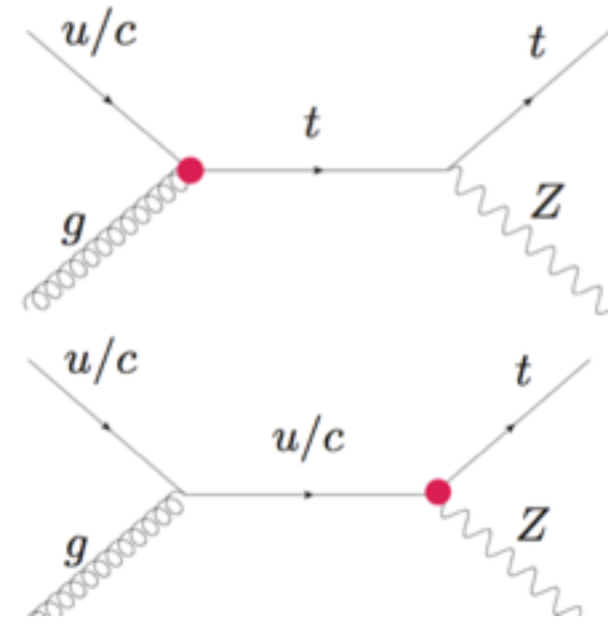


Bardhan et al., arXiv:1601.04165

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

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

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

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

(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

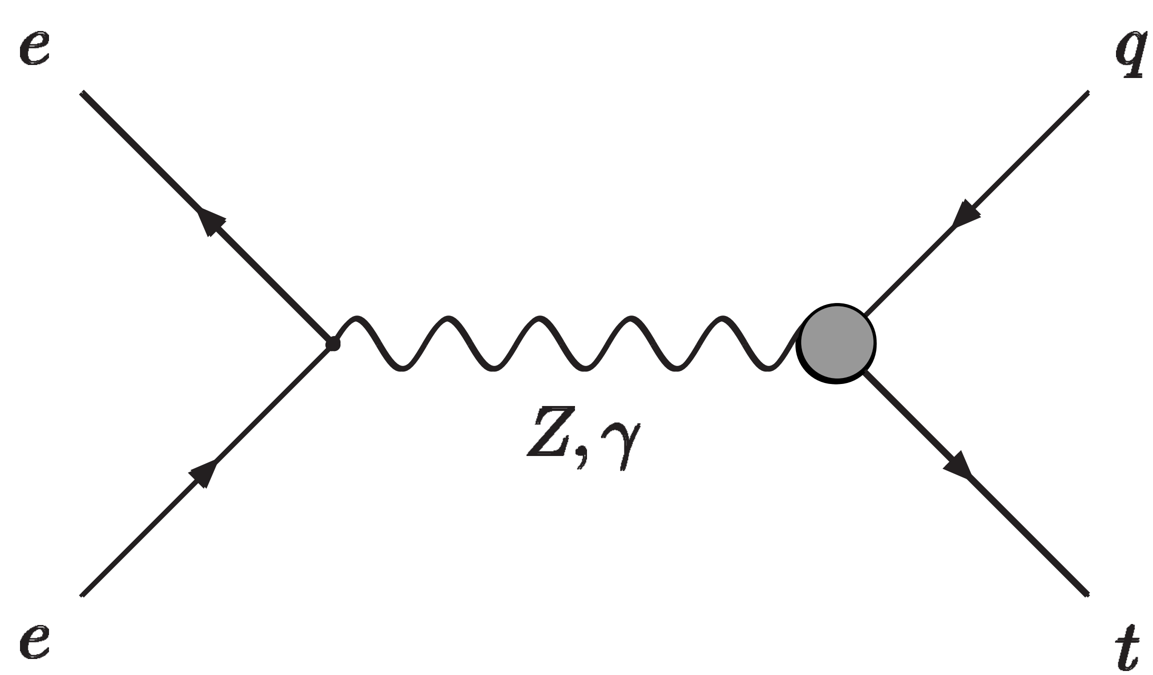
Snowmass Top Quark Working Group Report 1311.2028

* 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 cross section and large lumi at FCC-ee)***

versus

√S= 350, 500 GeV **(lower bckgd and more sensitive to $\sigma_{\mu\nu}$ terms)**

√S = 240 GeV

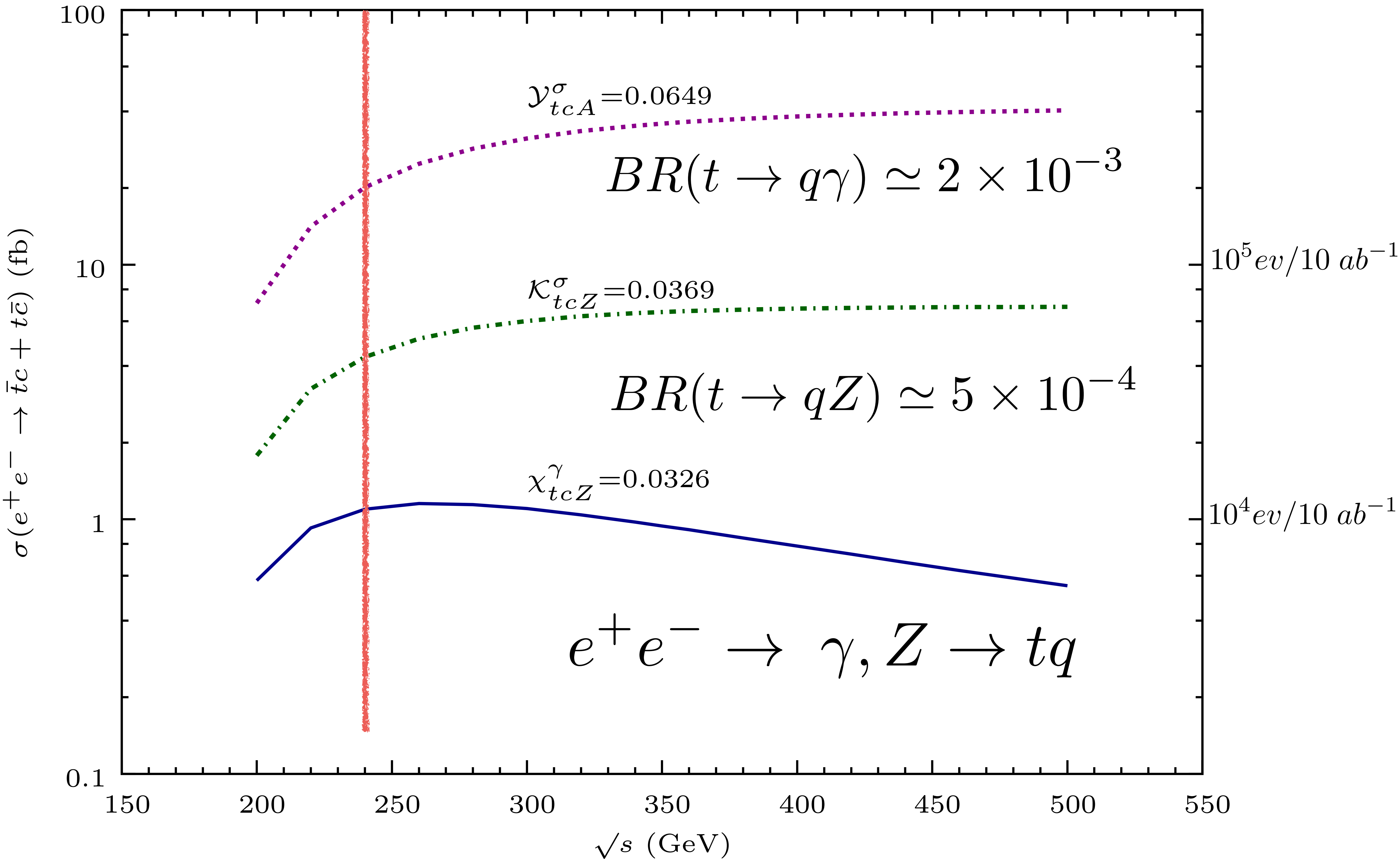
x-sections (fb)

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)** →

maximum allowed σ's by presents bounds on BR(top)^{FCNC}



Simulation

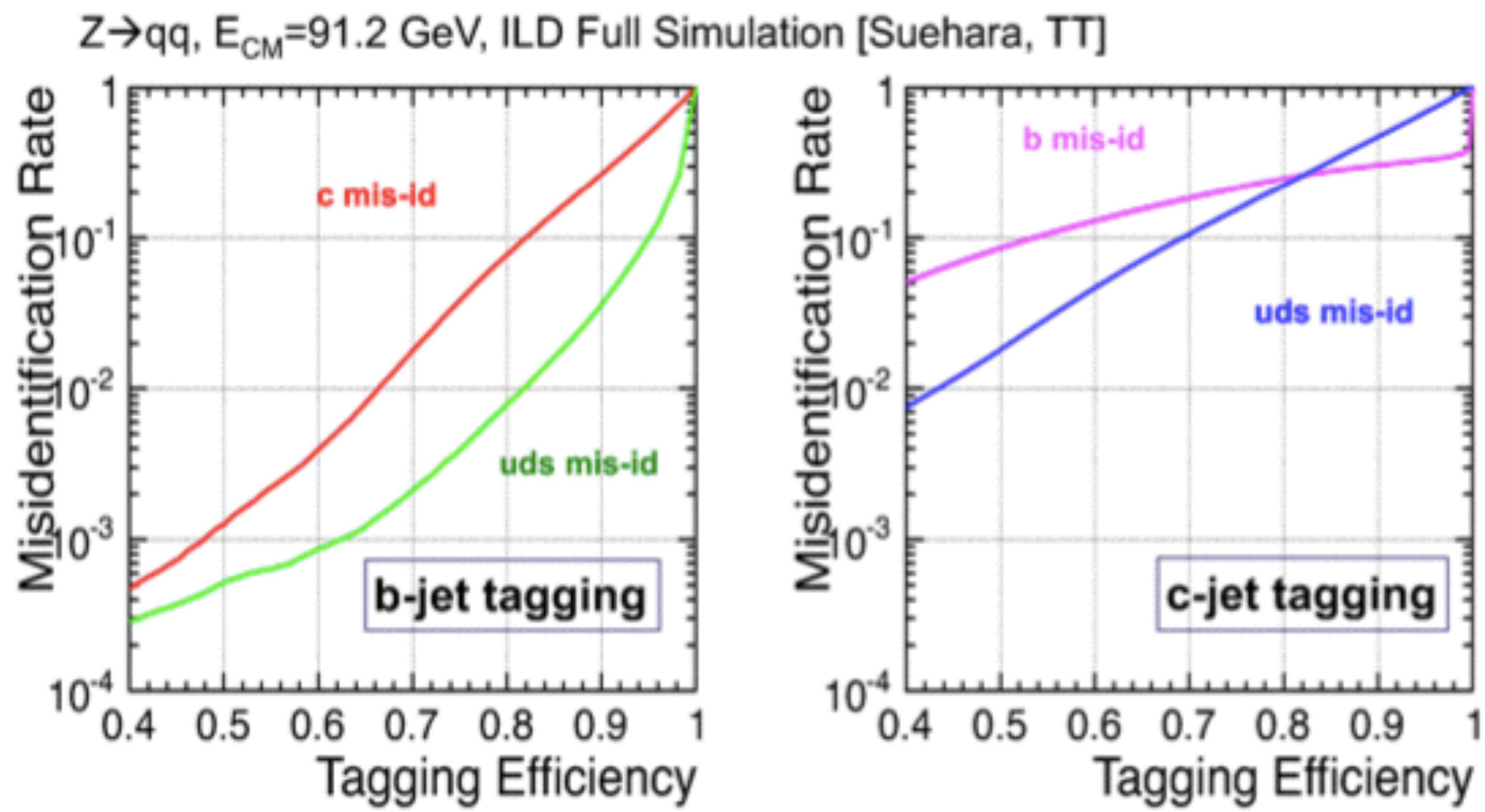
- Model file for FCNC interactions has been implemented using FeynRules and MadGraph5_aMC@NLO interface.
- Signal (tj) and Background (Wjj) events are generated in MadGraph5_aMC@NLO then interfaced with PYTHIA for showering and hadronization.
- Jets are defined by the iterative cone algorithm of PYTHIA 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 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.



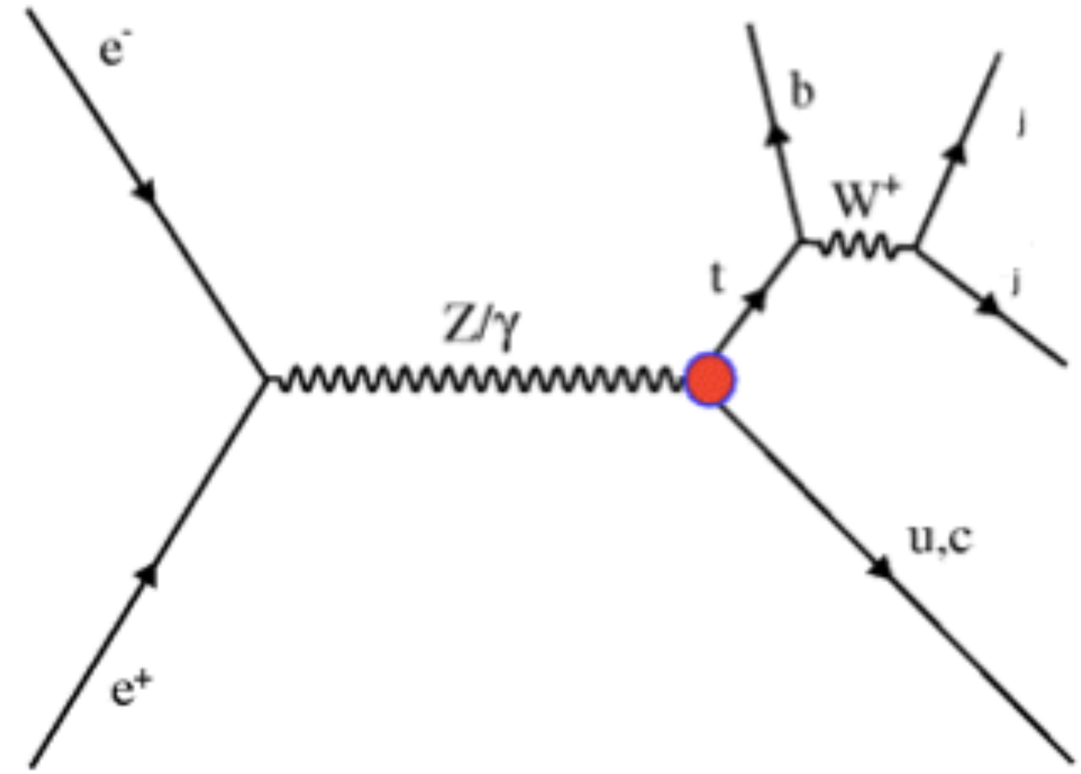
ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

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.

Signal

$e^+e^- \rightarrow tj + h.c. \rightarrow bWj \rightarrow bjjj$

basic cuts on jets : $p_T^{j,b} > 20$ GeV, $|\eta^{j,b}| < 2.5$, and $\Delta R(jj, bb, bj) > 0.4$



Background

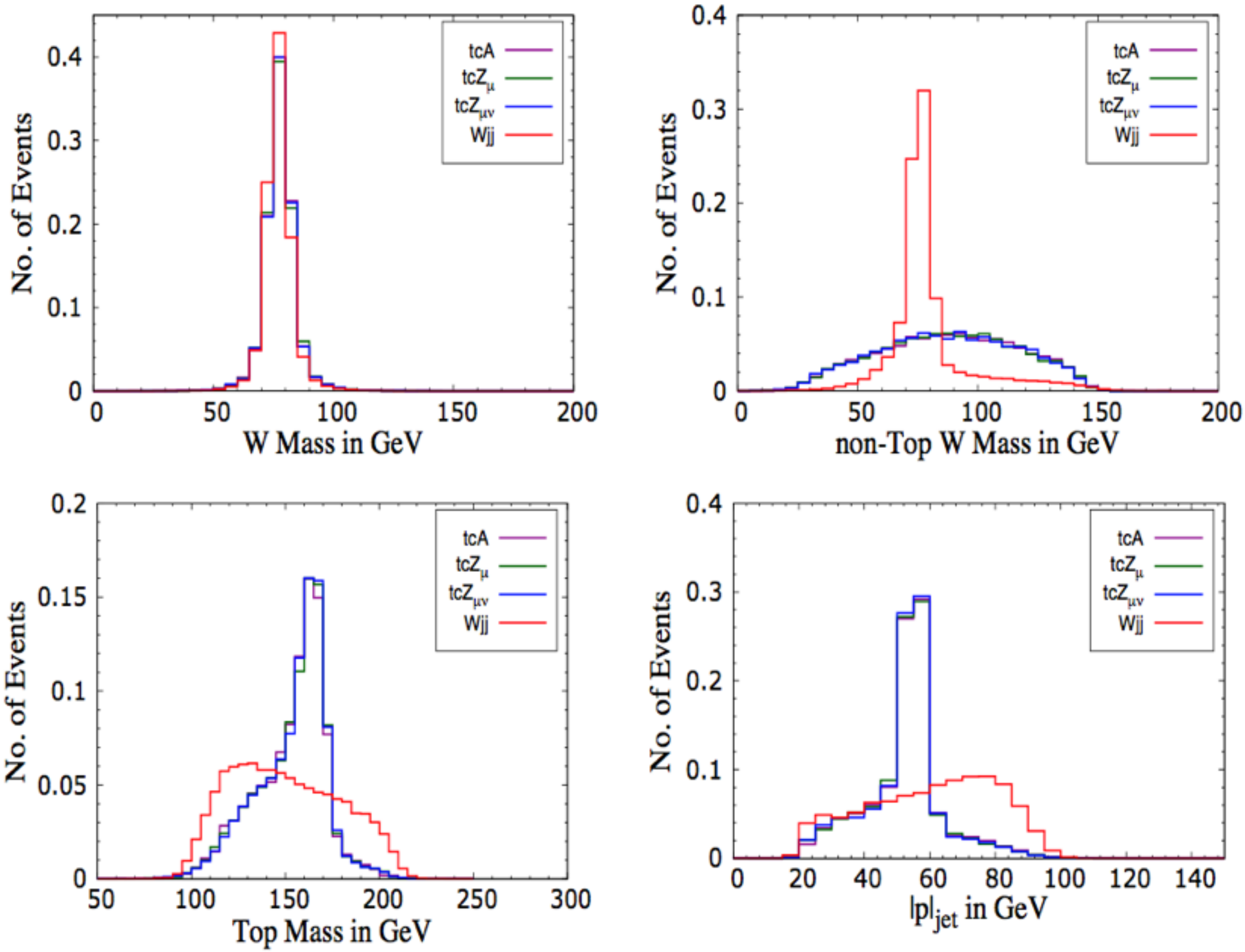
Dominant background : $e^+e^- \rightarrow Wjj \rightarrow jjjj$

Other 4-jets background (*e.g.* $q\bar{q}b\bar{b}$) checked to be small.

	$\epsilon_b = 60\%$	$\epsilon_b = 80\%$
tcA	$903.05\lvert\lambda_{qt}\rvert^2$	$1073.96\lvert\lambda_{qt}\rvert^2$
tcZ, γ_μ	$378.93\lvert\mathcal{X}_{qt}\rvert^2$	$446.41\lvert\mathcal{X}_{qt}\rvert^2$
$tcZ, \sigma_{\mu\nu}$	$596.11\lvert\kappa_{qt}\rvert^2$	$710.16\lvert\kappa_{qt}\rvert^2$
Wjj	47.72	686.77

Table : Cross section normalisation (in fb) for 4-jet final states after basic cuts, including b-tagging and $W \rightarrow jj$ BR

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%]



Cut flow

After applying basic selection cuts, we model signal events with the following (ordered) set of cuts:

- Select all events in which a di-jet system passes the W requirement with $65\ \text{GeV} < M_{jj} < 90\ \text{GeV}$
- Rejects events if the invariant mass of the remaining dijet system peaks around a second W within a mass window $65\ \text{GeV} < M_{jj} < 85\ \text{GeV}$
- A jet, which is tagged as a b-jet, is then combined with the reconstructed W to get a top system satisfying $150\ \text{GeV} < M_{bW} < 175\ \text{GeV}$
- Finally, the jet which is neither a b-jet nor a jet coming from a W-decay is required to have $|\vec{p}_{jet}| < 65\ \text{GeV}$

Efficiency:
47% for signal
5% for bckgr
(for $\epsilon_b = 60\%$)

	$\epsilon_b = 60\%$	$\epsilon_b = 80\%$
tcA	$426.17\|\lambda_{qt}\|^2$	$479.28\|\lambda_{qt}\|^2$
tcZ, γ_μ	$178.82\|\mathcal{X}_{qt}\|^2$	$199.22\|\mathcal{X}_{qt}\|^2$
$tcZ, \sigma_{\mu\nu}$	$281.32\|\kappa_{qt}\|^2$	$316.92\|\kappa_{qt}\|^2$
Wjj	2.40	34.35

Cross section normalisation (in fb) after complete cut flow

FCNC Exclusion Limits (95% CL):

Single top (hadronic)

Biswas, Margaroli, BM

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

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	$1.06 \cdot 10^{-02}$	$4.12 \cdot 10^{-05}$	$1.93 \cdot 10^{-02}$	$1.37 \cdot 10^{-04}$

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

(leptonic channel) $(100\ fb^{-1})$ (hadronic)

$\sqrt{s}$ (GeV)	240	(hadronic)
$Br(t \to q\gamma)$	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

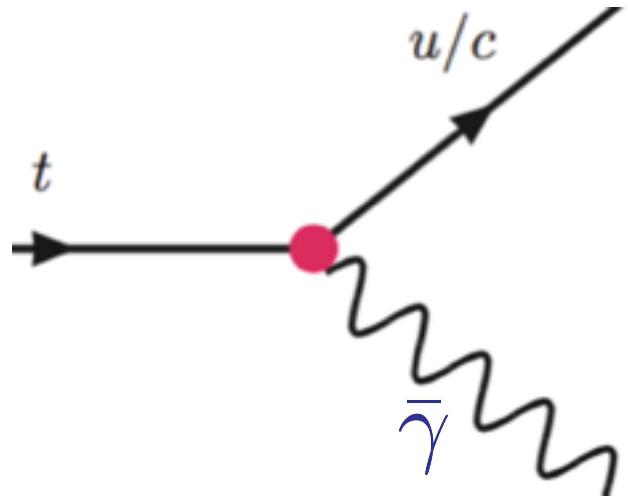
a little stronger bounds expected at $E_{cm}(e+e-) \sim 350$ GeV

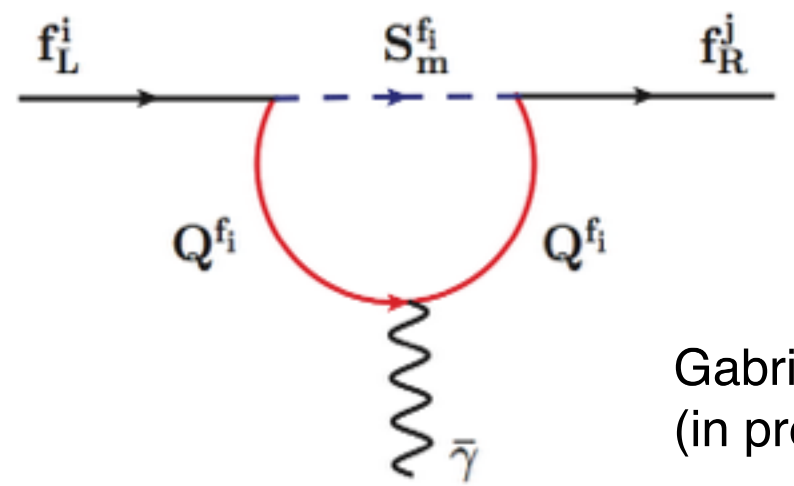
FCNC's mediated by Dark Photons

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

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

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





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 (for integer charges q_{Df}=1, 2, 3, 4...)

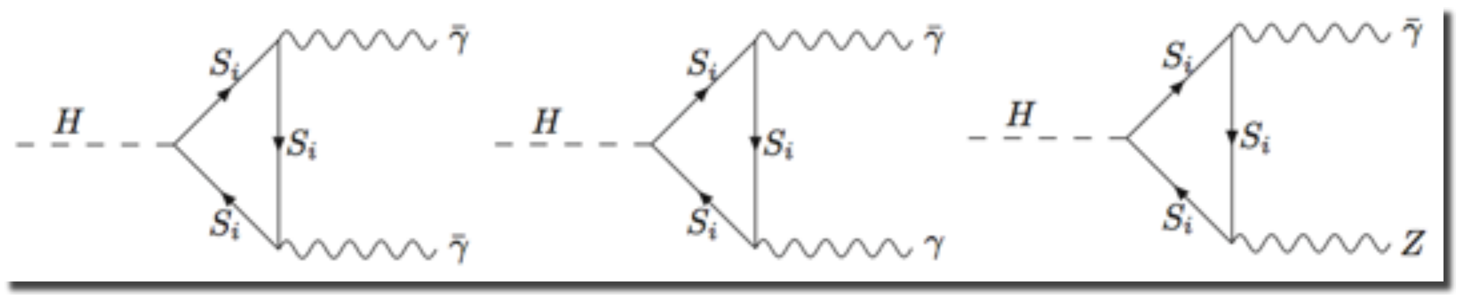
- Flavor and Chiral Sym Breaking transferred to (radiative) Yukawa couplings at one-loop via (heavy) squark/slepton-like scalar messangers

  ➜ Yukawa hierarchy appears in visible sector, too !

➜ plenty of new signatures at colliders involving stable dark photons (invisible and massless)

(exploration just started !)

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

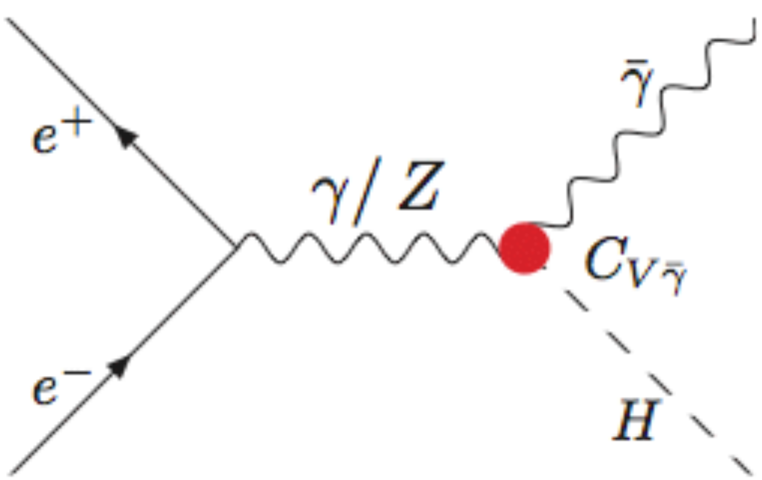


mono-photon resonant signature

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

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196

- in production :



Higgs momentum balanced by a massless invisible system

Biswas, Gabrielli, Heikinheimo, BM,1503.05836

resonant mono-photon signature (LHC)

(A_1) 50 GeV $< p_T^\gamma <$ 63 GeV (A_2) 60 GeV $< p_T^\gamma <$ 63 GeV

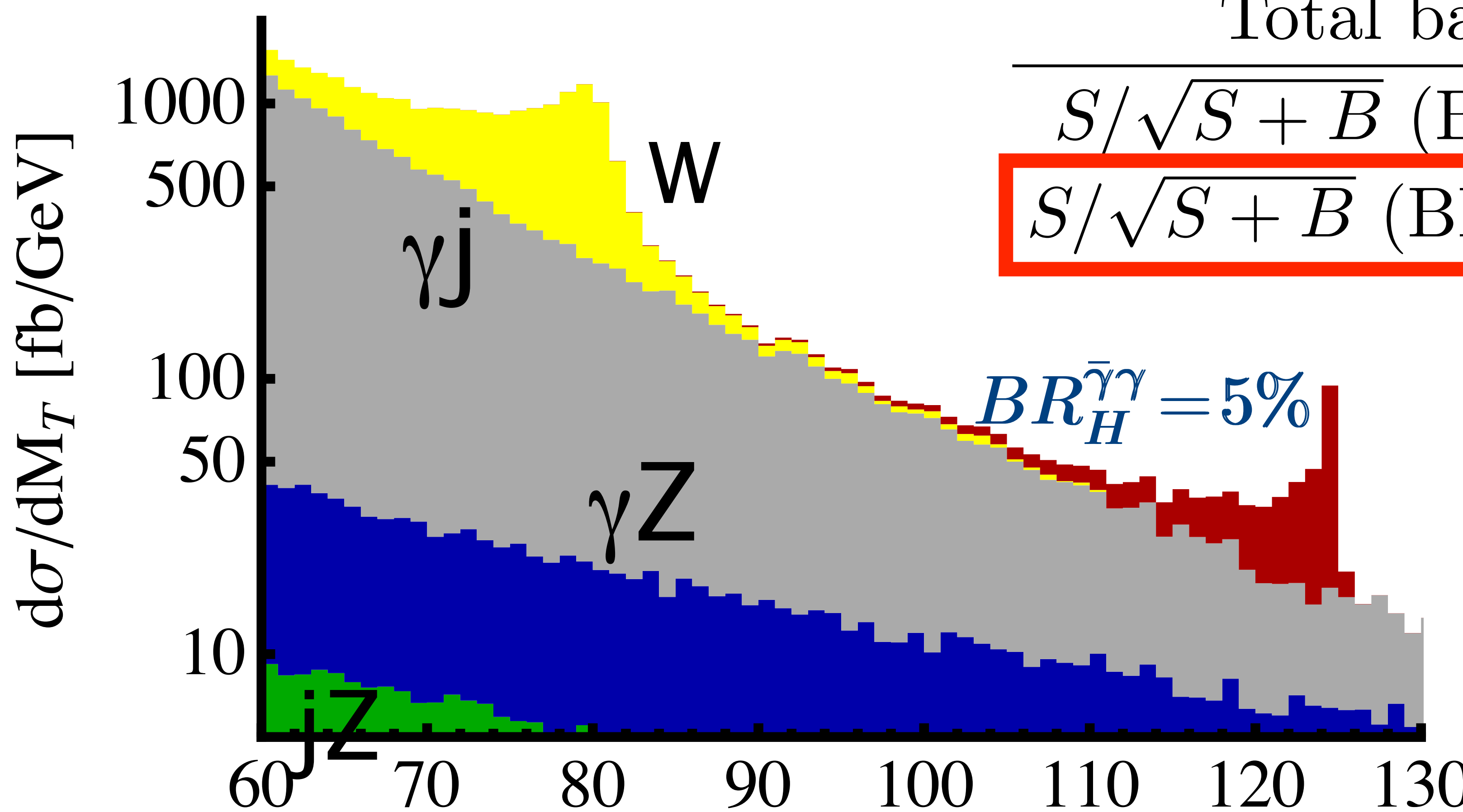
$$H \to \bar{\gamma}\gamma$$

$E_{miss} \sim E_\gamma \sim m_H/2$

σ (fb)	$\sigma \times A_1$	$\sigma \times A_2$
Signal $\mathrm{BR}_{H\to\gamma\bar{\gamma}} = 1\%$	65	34
γj	715	65
$\gamma Z \to \gamma\nu\bar{\nu}$	157	27
$jZ \to j\nu\bar{\nu}$	63	11
$W \to e\nu$	22	0
Total background	957	103
$S/\sqrt{S+B}$ $(\mathrm{BR}_{H\to\gamma\bar{\gamma}} = 1\%)$	9.1	13.0
$S/\sqrt{S+B}$ $(\mathrm{BR}_{H\to\gamma\bar{\gamma}} = 0.5\%)$	4.6	6.9

(8TeV/20fb^{-1})

$$M_T = \sqrt{2p_T^\gamma \not{E}_T(1-\cos\Delta\phi)}$$



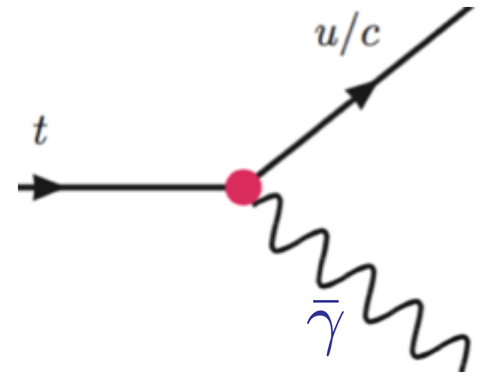
(parton-level analysis)

model-independent measurement of BR$_{DP}$!

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196

top FCNC's mediated by Dark Photons

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

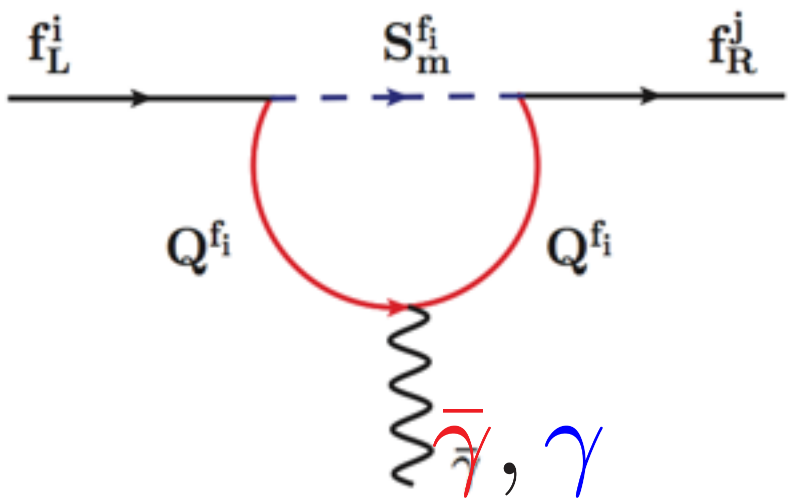


Gabrielli, BM, Raidal, Venturini
(in preparation)

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

also :

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



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):

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

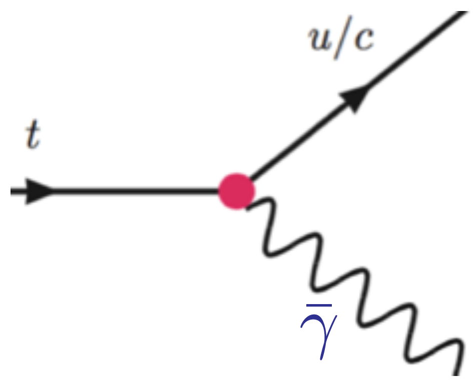
$\Rightarrow$

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

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

→ new FCNC signatures at LHC in top production from stable and invisible dark photons

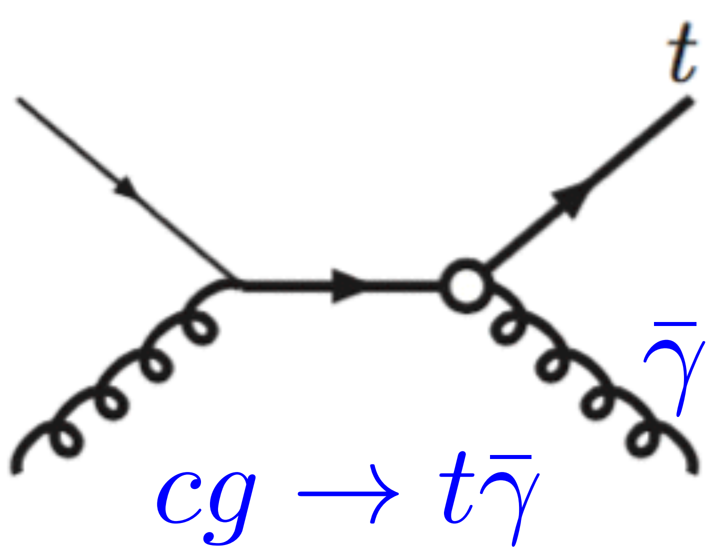
- in decays :



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

[stop-like, if massless neutralino]

- in production :



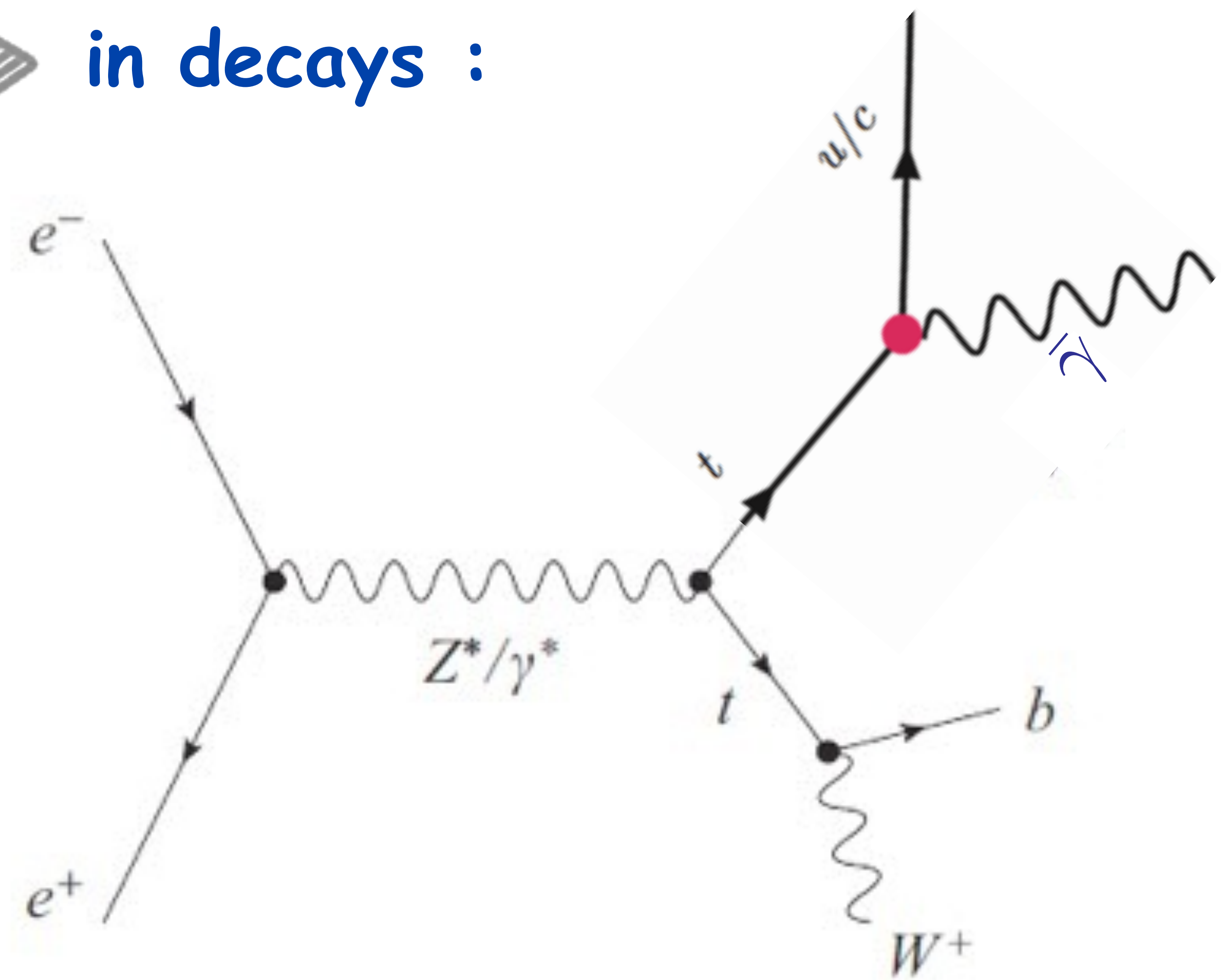
"top" plus massless invisible system

→ new FCNC signature at FCC-ee

(10^6 top pairs → BR ~ 10^{-5})

invisible and massless dark photons

- **in decays :**



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

at tt threshold :

~ large monochromatic E_{miss}
E_{miss}~ E_q~ $m_{top}/2$

Biswas, Gabrielli, BM, in progress

Outlook

- great control on bckgrs makes ee colliders excellent tools for looking at top rare decays !
- top FCNC signals at colliders only from BSM effects !
- FCC-ee at 240 GeV has potential on tc(u)γ / tc(u)Z via single-top production comparable to HL-LHC
  ➜ 350 GeV run expected to be slightly better
  (and benefits from top-pair channel, too !)
- new FCNC top signatures from top decay into a massless dark photon
  - very distinctive signature ➜ bounds expected to be just limited by statistics (studies ongoing) !