RARE TOP DECAYS AT 100 TEV

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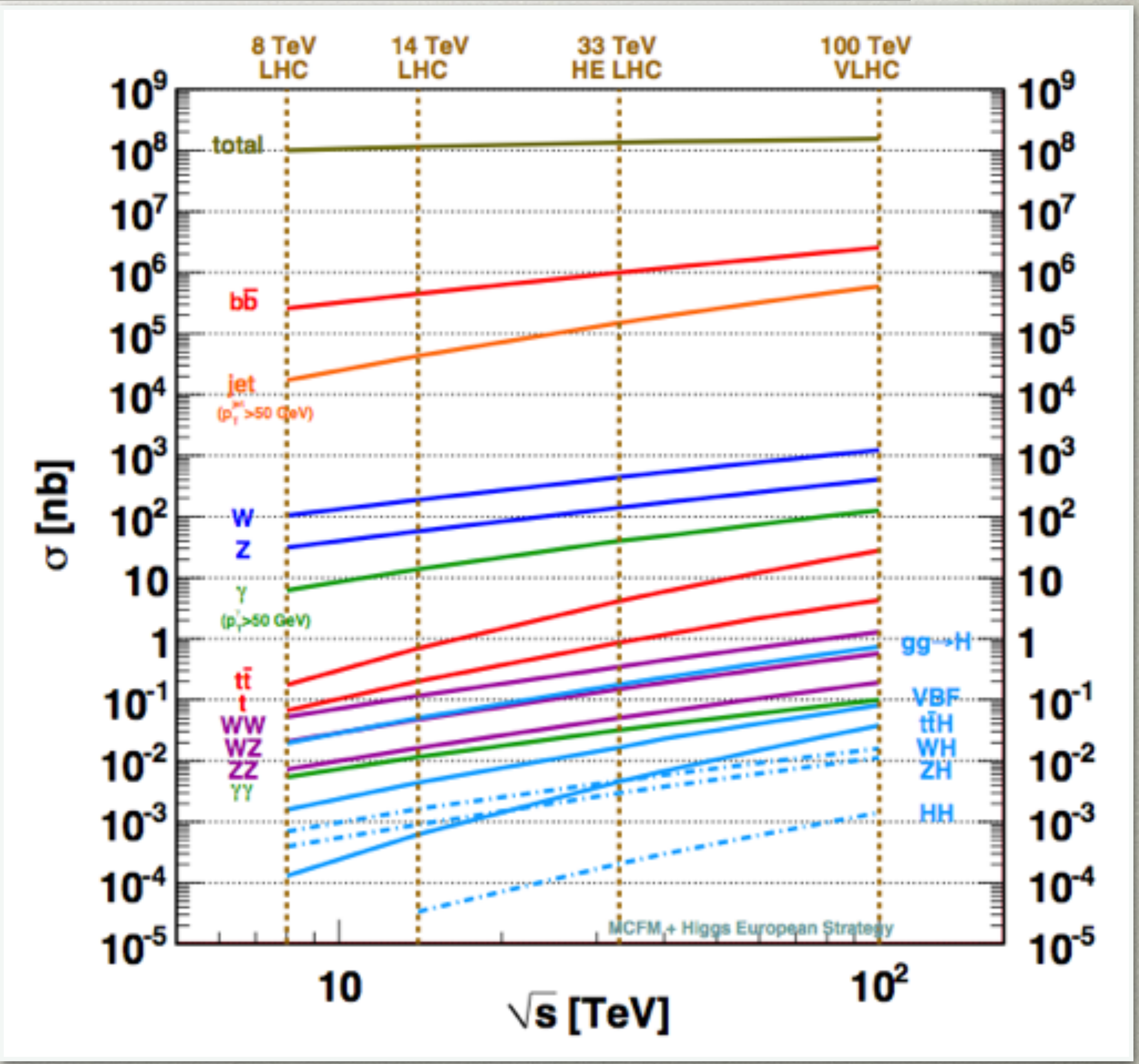
BSM Opportunities at 100 TeV, CERN, Feb 11 2014

MOTIVATION

- at 100TeV $\sigma(t\bar{t})$~$30nb$
  - 3×10^{10} $t\bar{t}$ for $1ab^{-1}$
  - 3×10^{11} $t\bar{t}$ for $10ab^{-1}$
- what would this mean for rare top decays
  - not just statistics, also different kinematics



Snowmass QCD report, 1310.5189

OUTLINE

- general considerations in EFT
- concrete models
- focus on top FCNCs at 100TeV
  - many statements apply also to the anomalous *tbW* couplings
- most importantly: everything is **very preliminary**

THE MODES

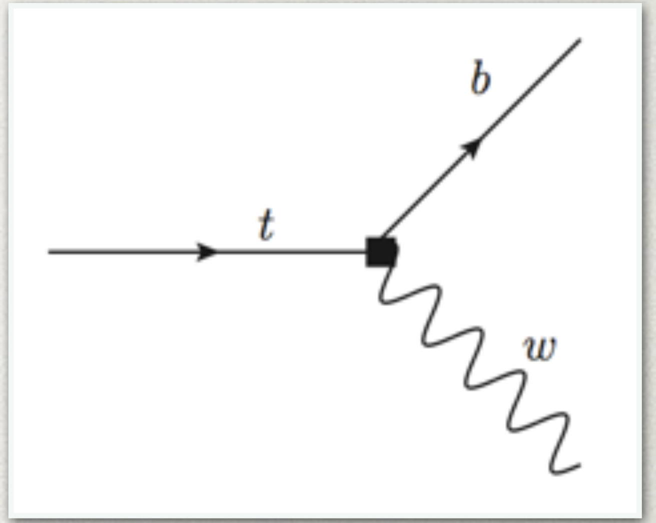
see also Snowmass 2013
Top quark WG report, 1311.2028

- top FCNC modes
  - $t \to cZ$
  - $t \to ch$
  - $t \to c\gamma$
  - $t \to cg$
  - $t \to c + MET$ (monotop)
- + the modes with *u*-quark

THE CHALLENGE

- top has unsuppressed decay width $t \to bW$

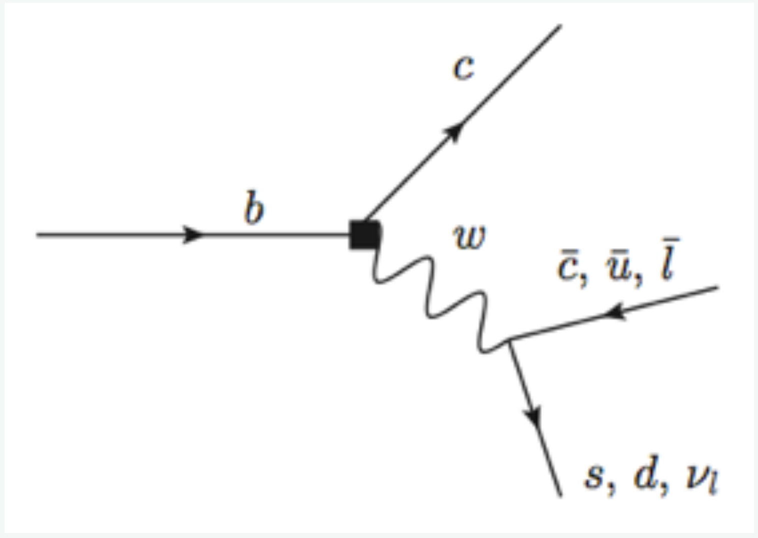
$$\Gamma_t = \frac{\lambda_t^2}{32\pi} m_t \simeq 1.4\ \text{GeV}$$



- this is much larger than *B,D,K* decay widths
  - for instance, for B_d

$$\Gamma_{b\to c\bar{l}\nu} = \frac{g^4}{32\pi}\frac{1}{16\pi^2}\frac{1}{12}\left(\frac{m_b}{m_w}\right)^4 |V_{cb}|^2 m_b$$

$$\Gamma_{B_d} \simeq 4.3 \times 10^{-13}\ \text{GeV}$$



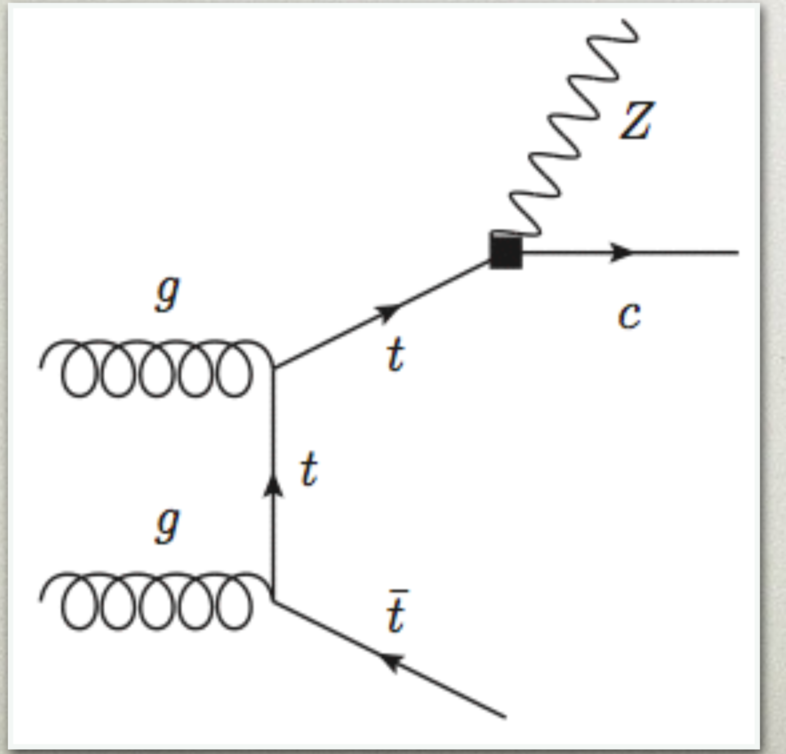
- if NP with <u>*anarchic FV*</u>
  - the same *Br* for tFCNC probes lower Λ_{NP} (<u>*in NDA*</u>) than bFCNC, cFCNC, sFCNC

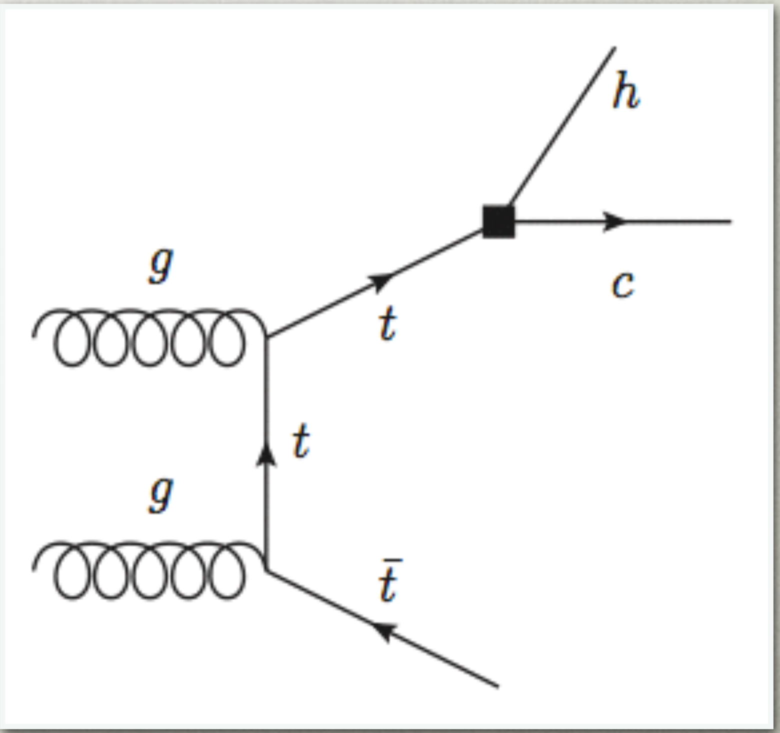
THE BENEFITS

- the above statement is too naive
  - in theories addressing naturalness there is nontrivial flavor structure
  - top often most sensitive to NP modifications
- will go through explicit NP models later

THE BENEFITS

- the benefit from experimental point of view
  - both tFCNC in production and decay are important
- tFCNC in decay
  - $t \to cZ$, $t \to uZ$
  - $t \to ch$





THE BENEFITS

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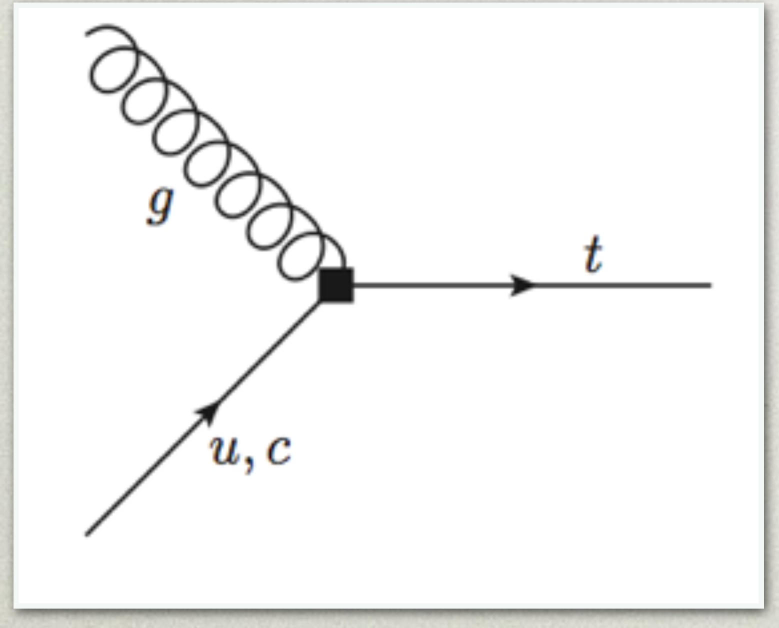
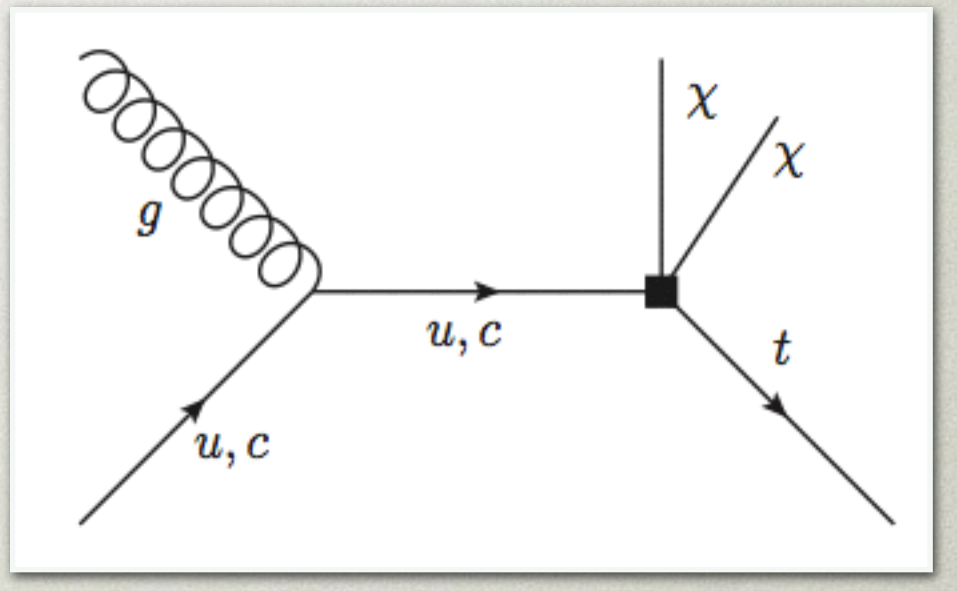
  - both tFCNC in production and decay are important
- tFCNC in production
  - $t \to cg$, $t \to ug$



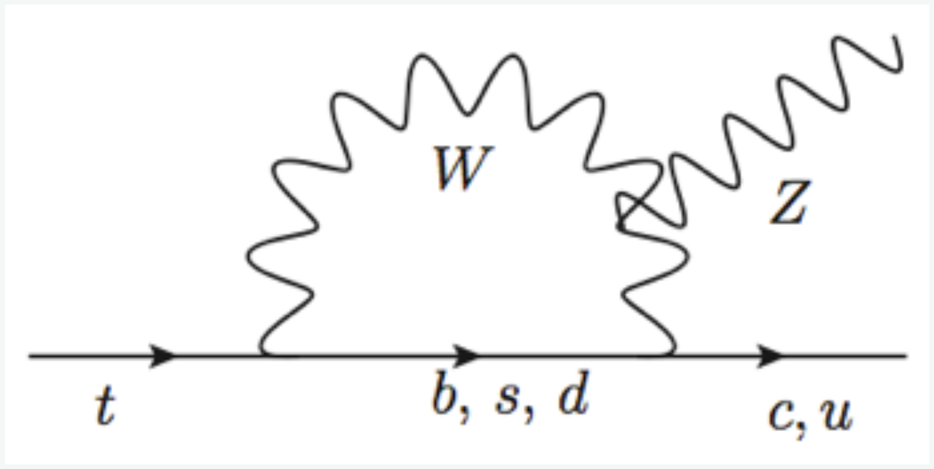
  - monotop



  - note: can distinguish between $t \to c$ and $t \to u$ from production!

SM values

- in the SM generated at 1-loop
  - GIM suppressed



Aguilar-Saavedra, hep-ph/0409342

$$Br(t \to u\gamma) \simeq 4 \times 10^{-16} \qquad Br(t \to c\gamma) \simeq 5 \times 10^{-14}$$

$$Br(t \to uZ) \simeq 8 \times 10^{-17} \qquad Br(t \to cZ) \simeq 10^{-14}$$

$$Br(t \to uh) \simeq 2 \times 10^{-17} \qquad Br(t \to ch) \simeq 3 \times 10^{-15}$$

$$Br(t \to ug) \simeq 4 \times 10^{-14} \qquad Br(t \to cg) \simeq 5 \times 10^{-12}$$

$$\frac{Br(t \to uX)}{Br(t \to cX)} \simeq \left|\frac{V_{ub}}{V_{cb}}\right|^2 \simeq 0.008$$

EFT ANALYSIS

- tFCNC arise from dim-6 operators
  - useful operator basis is above EWSB
  - makes e.g. explicit that $Br(t\to cZ)$ is $\sim v^2$
- basis from Fox et al., 0704.1482

$$\mathcal{O}^u_{LL} = i[\bar{Q}_3\tilde{H}][(\not{D}\tilde{H})^\dagger Q_2] - i[\bar{Q}_3(\not{D}\tilde{H})][\tilde{H}^\dagger Q_2] + \text{h.c.}$$
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$$\mathcal{O}^u_{RR} = i\bar{t}_R\gamma^\mu c_R[H^\dagger \overleftrightarrow{D}_\mu H] + \text{h.c.}$$

  - +Higgs and gluon ops.

$$\mathcal{O}^g_{RL} = g_s[\bar{Q}_2\sigma^{\mu\nu}\tilde{H}]T^A t_R G^A_{\mu\nu} + \text{h.c.}$$
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focus on these three opers. as examples

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EXPERIMENTAL CONSTRAINTS

- experimental constraints

$Br(t \to cZ) < 0.05\%$ CMS

$Br(t \to cg) < 1.6 \times 10^{-4}$ ATLAS

$Br(t \to ch) < 0.83\%$ ATLAS

$Br(t \to uZ) < 0.05\%$ CMS

$Br(t \to ug) < 3.1 \times 10^{-5}$ ATLAS

$Br(t \to uh) < 0.83\%$ ATLAS

- can probe TeV scale physics (taking $C_n=1$)

	$t \to c$	$t \to u$
$\mathcal{O}^w_{LR}$	$\Lambda > 0.75$ TeV	$\Lambda > 0.75$ TeV
$\mathcal{O}^g_{RL}$	$\Lambda > 4.0$ TeV	$\Lambda > 5.8$ TeV
$\mathcal{O}^{h^3}_{RL}$	$\Lambda > 0.73$ TeV	$\Lambda > 0.73$ TeV

$$\mathcal{L} = \sum_n \frac{C_n}{\Lambda^2} \mathcal{O}_n$$

- this essentially assumes large mixing angles
- no loop factors for magnetic operators
- later: how large are $t \to cZ$, $t \to c\gamma$, $t \to cg$ and $t \to ch$ in NP models

NAIVE 100 TeV REACH

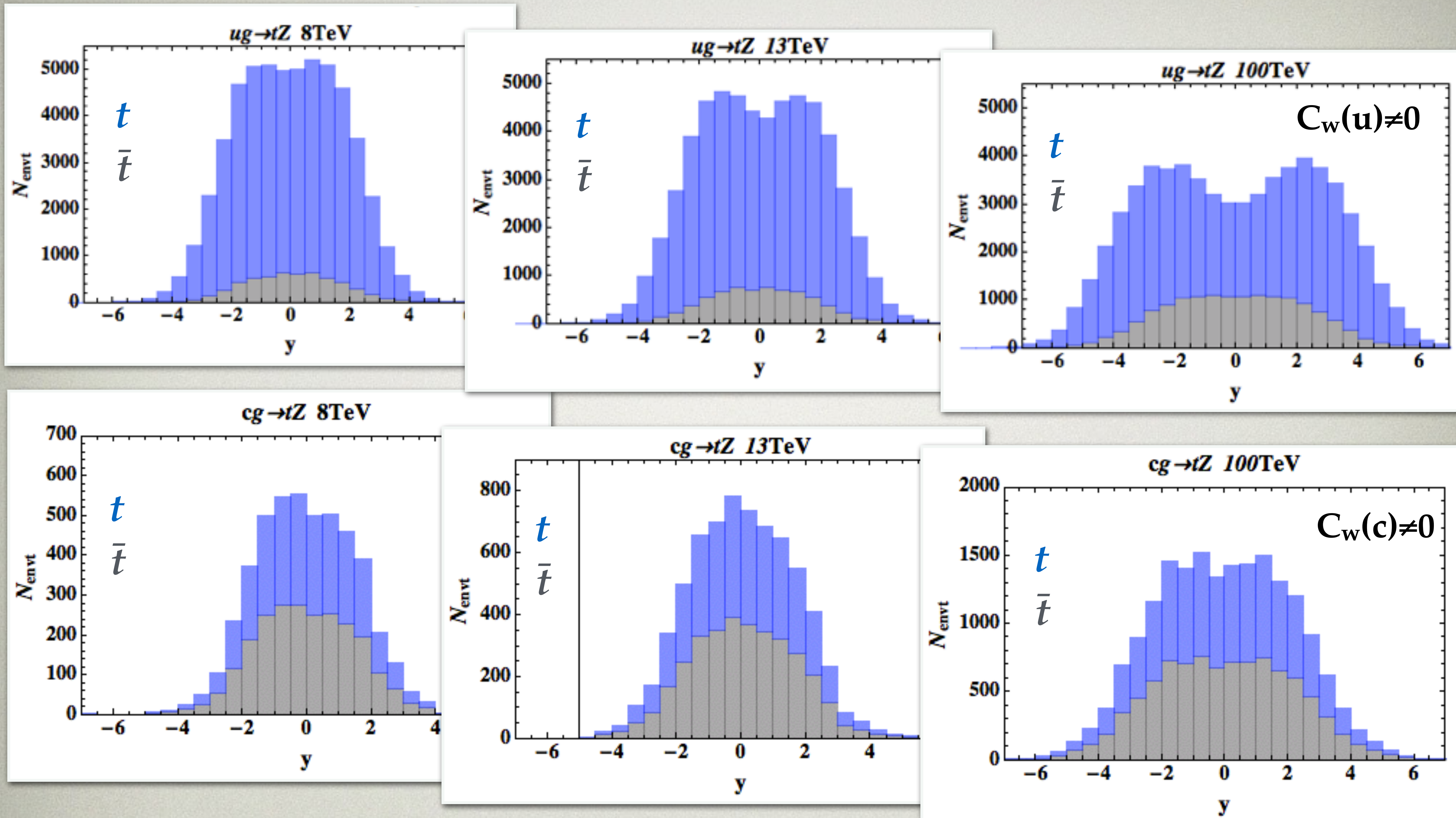
- trivially rescaling by the statistics for $10ab^{-1}$ at 100 TeV
  - assuming exactly the same efficiencies as at the LHC right now
  - can potentially be improved (for $t \to ch, uh$ by having other h decays beside $h \to \gamma\gamma$)
  - for $1ab^{-1}$ the bounds $10^{1/4} \simeq 1.8$ smaller

	$t \to c$	$t \to u$
$\mathcal{O}^{w}_{LR}$	$\Lambda \gtrsim 13$ TeV	$\Lambda \gtrsim 13$ TeV
$\mathcal{O}^{g}_{RL}$	$\Lambda \gtrsim 70$ TeV	$\Lambda \gtrsim 80$ TeV
$\mathcal{O}^{h^3}_{RL}$	$\Lambda \gtrsim 13$ TeV	$\Lambda \gtrsim 13$ TeV

- note: bckg. can completely change this naive extrapolation
  - e.g. $\sigma(t)_{SM}/\sigma(t)_{utG}$ grows from ~30 for present bound at 8TeV to ~200 at 100TeV

DIFFERENT KINEMATICS

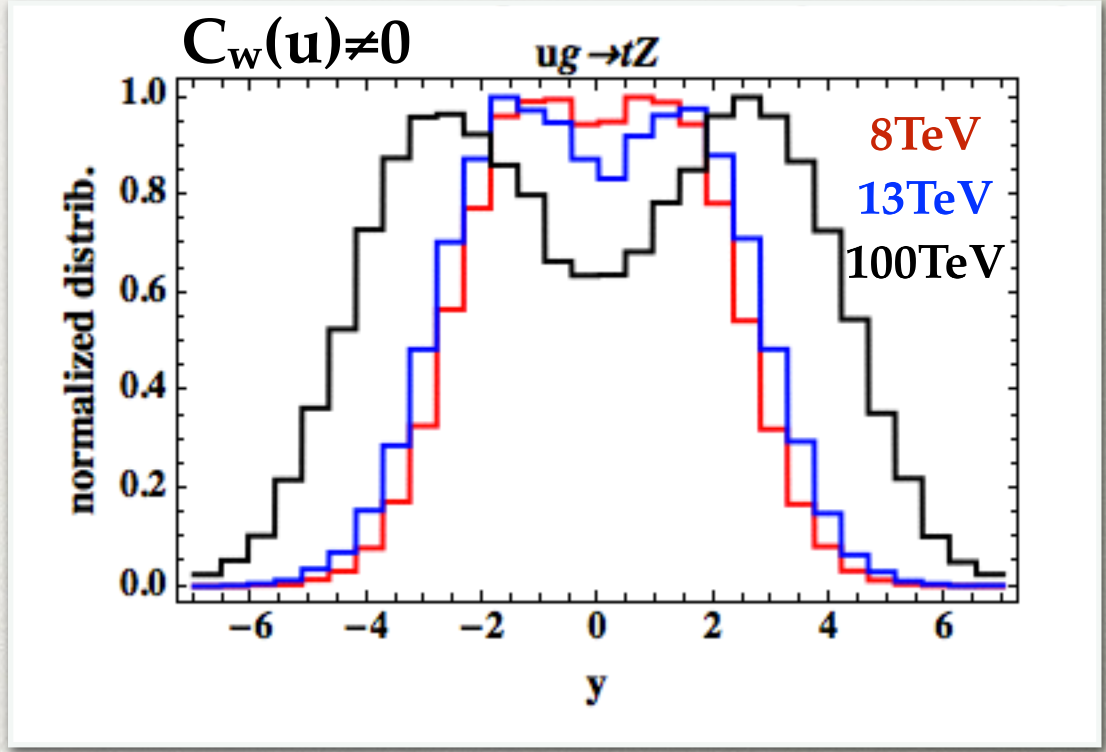
- there are gains/differences beyond the statistics
- the relative sea vs. valence quark decomposition changes
  - do we still have $u \to tX$ vs. $c \to tX$ separation?
- it is easy to produce tops+X (top pdf.)
  - can we use this?

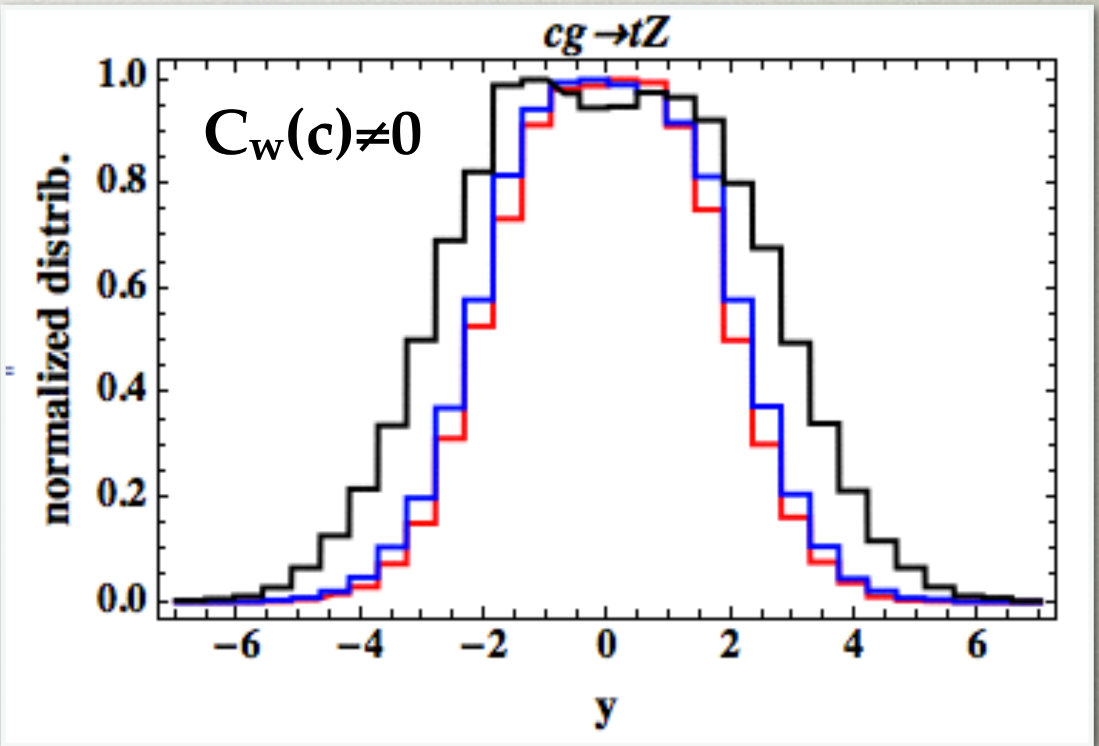


- the charge asymmetry in $ug \to tZ$ remains
  - $\sigma(tZ)/\sigma(\bar{t}Z)=(0.11,0.14,0.29)$ for $(8,13,100)$TeV

$ug\to tZ$ AND $cg\to tZ$

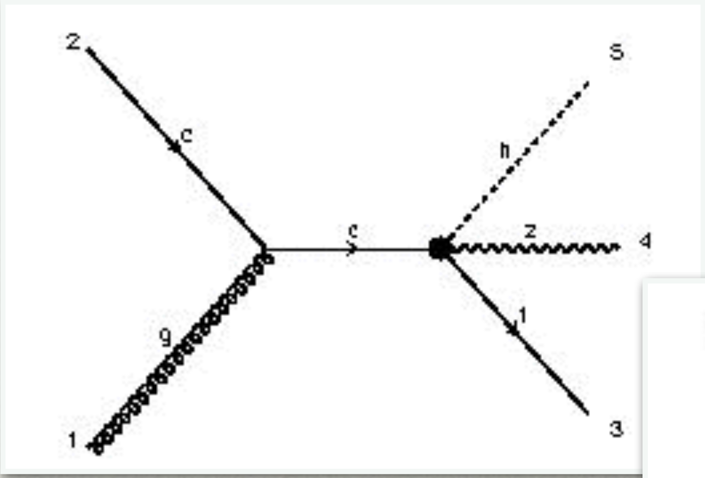
- top becomes less central
  - any implications for detector (LHCb→FCCt)?
- the charm content of a proton increases
  - for $C_w(u)=C_w(c)=1/(0.73TeV)^2$:
    - $\sigma(ug\to tZ)/\sigma(cg\to tZ)=7(19)\%$ at $13(100)TeV$
    - or in terms of presently allowed xsec at 100TeV $\sigma(ug\to tZ)=8(170)pb$, $\sigma(cg\to tZ)=0.5(30)pb$

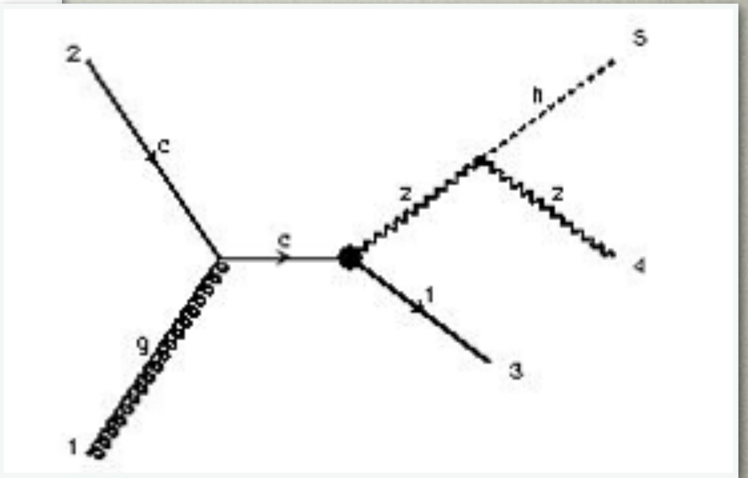




ASSOCIATED HIGGS PROD.

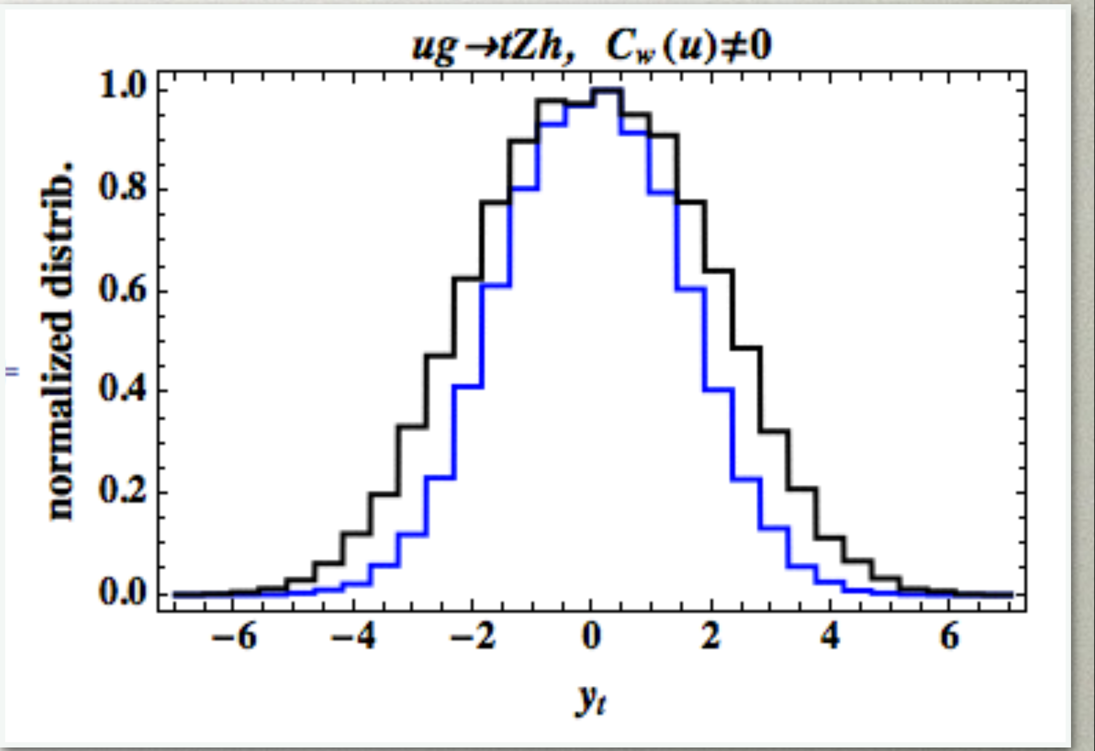
- note: for each of $t \to cZ$, $t \to c\gamma$, $t \to cg$, $t \to ch$ there is and associated decay
  - $t \to cZ^* h$, $t \to c\gamma h$, $t \to cgh$, $t \to chh$
  - if $t \to cZ(\ldots)$ dominat. by one oper. $\Rightarrow$ $t \to cZh$ completely fixed
  - NDA estimate $$Br(t \to cZh) \simeq \frac{1}{16\pi^2} Br(t \to cZ) \simeq 10^{-2} Br(t \to cZ)$$
- if more opers. $\Rightarrow$ these decays can give further info.
  - out of reach of LHC but maybe at 100 TeV?
  - at 100TeV one can look also at $ug \to tZh$, $ug \to t\gamma h$, $ug \to thh$ or even $tu \to hh$

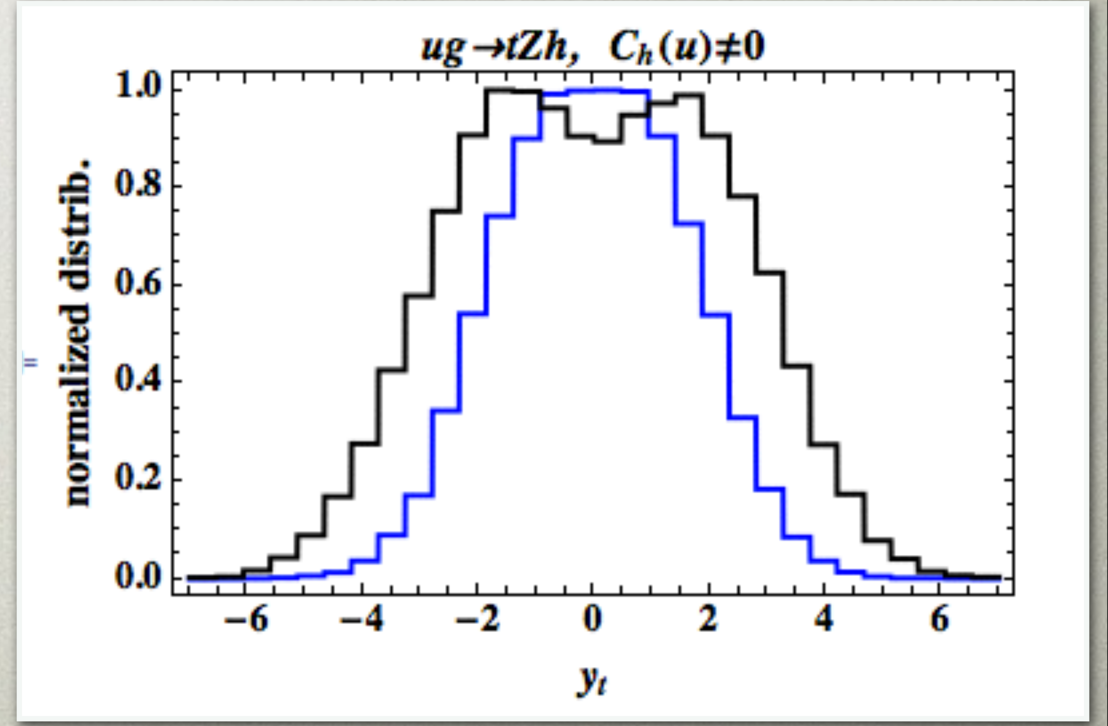




ASSOCIATED HIGGS PRODUCTION

- instead of looking at three-body decay can use assoc. prod
- the $ug \to tZh$ has much larger xsec at 100TeV
  - $C_w \neq 0$: $\sigma_{13TeV} \simeq 0.09pb \to \sigma_{100TeV} \simeq 11pb$
  - $C_h \neq 0$: $\sigma_{13TeV} \simeq 9fb \to \sigma_{100TeV} \simeq 400fb$
- what are the bckg?
  - bremsstrahlung of Z, h in single top prod.
  - presumably top much more forward?
- can one tag forward top?





TOP FCNC IN NEW PHYSICS MODELS

NP MODELS

- will consider the following NP models
  - type II 2HDM
  - MSSM with general FV
  - monotop from dark sector
  - Z′ for $A_{FB}{}^t$
  - RS flavor

TYPE III 2HDM

- two scalar doublets with completely general Yukawas

$$\mathcal{L} = Y_{ij}^u \bar{Q}_{L,i} \tilde{\varphi}_1 u_{R,j} + Y_{ij}^d \bar{Q}_{L,i} \varphi_1 d_{R,j} + (Y \to Y', \varphi_1 \to \varphi_2) + \text{h.c.}$$

Atwood, Reina, Soni, hep-ph/9609279

- can rotate such that only φ_1 obtains vev
- mass eigenbasis related by

$$\varphi_1^0 = H\cos\alpha - h\sin\alpha$$
$$\varphi_2^0 = h\cos\alpha + H\sin\alpha$$

note: the decoupling limit is $\alpha=-\pi/2$

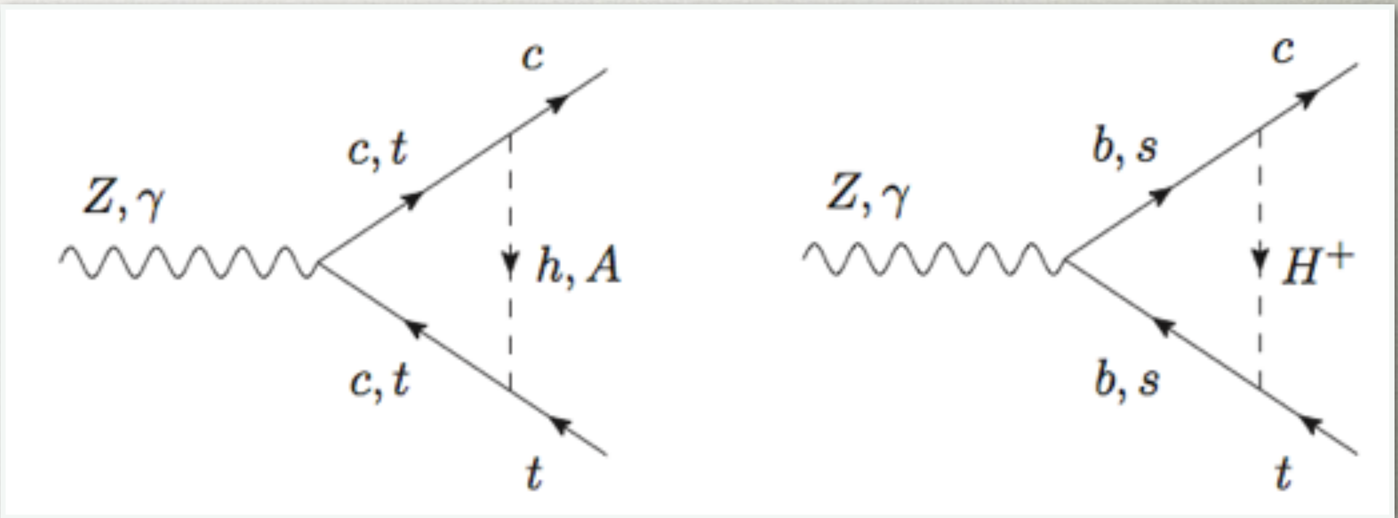
- there can be tree level FCNCs

$$\mathcal{L} \supset \hat{Y}_{ij}^h \bar{f}_i f_j h + \hat{Y}_{ij}^H \bar{f}_i f_j H + \hat{Y}'_{ij} \bar{f}_i \gamma_5 f_j A + \text{h.c.}\,.$$

  - $Y_{tc,tu}^h$ and $Y_{ct,tu}^h$ are not restricted in general
  - can saturate the present exp. bounds for $t \to ch$, $t \to uh$

TYPE III 2HDM

- the decays $t \to cZ, c\gamma$ arise at 1 loop
  - are smaller by a loop factor $1/(16\pi^2)^2 \sim 10^{-4}$
  - H^+ loop also contribs. without FV



- scanning $m_S \in [200 GeV, 1 TeV]$, taking $Y_{ij}^h = 1$ gives
  - note: $Y_{ij}^h = 1$ gives $Br(t \to ch) \approx 30\%$
  - allowed Br's thus at least $O(10)$ smaller

Atwood, Reina, Soni, hep-ph/9609279

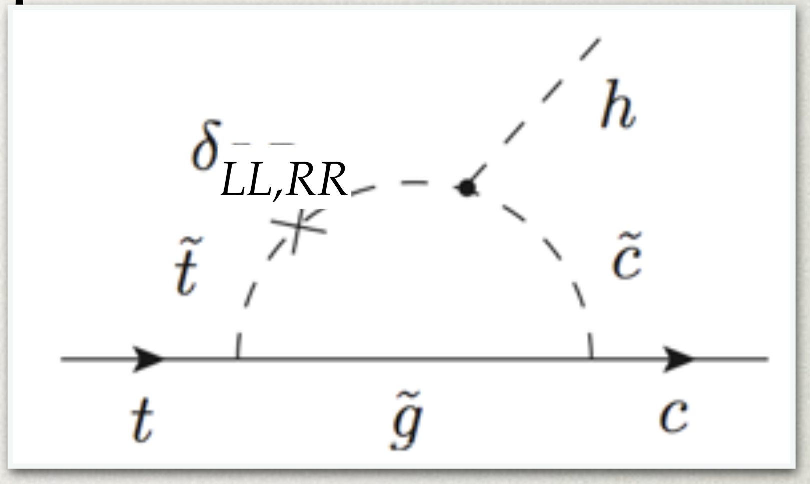
$$\mathrm{Br}(t \to c\gamma) \approx 10^{-12} - 10^{-7},$$

$$\mathrm{Br}(t \to cZ) \approx 10^{-8} - 10^{-6},$$

$$\mathrm{Br}(t \to cg) \approx 10^{-8} - 10^{-4}.$$

MSSM WITH GENERAL FV

- MSSM Higgs sector at tree level is type II 2HDM
  - no tree-level FCNCs
  - $t \to ch$ generated at one loop



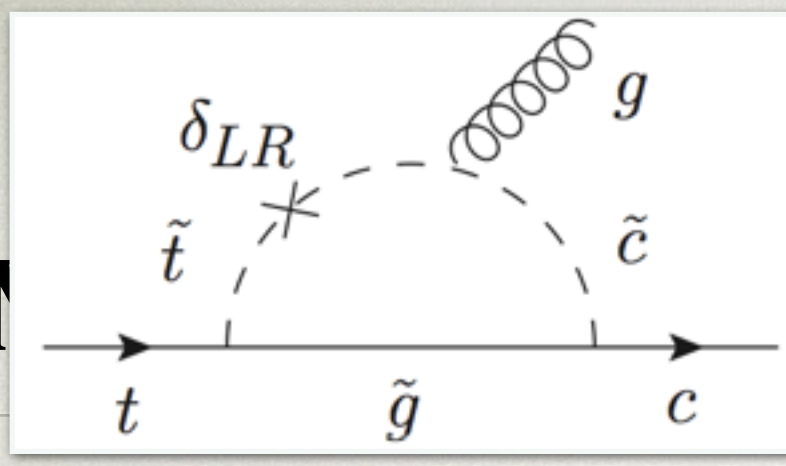
- also $t \to cg, cZ, c\gamma$ at 1-loop
  - scan shows $\delta_{LR} \neq 0$ generically largest

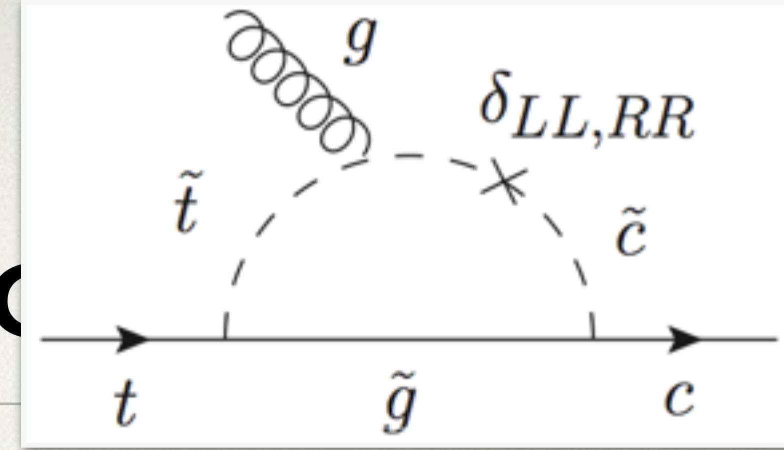
Cao et al., hep-ph/0702264

$$\mathrm{Br}(t \to cg) \approx 3 \cdot 10^{-5}\,,$$
$$\mathrm{Br}(t \to ch) \approx 6 \cdot 10^{-5}\,,$$

$$\mathrm{Br}(t \to cZ) \approx 10^{-6}\,,$$
$$\mathrm{Br}(t \to c\gamma) \approx 5 \cdot 10^{-7}\,.$$

  - require $m_{\tilde{g}} \approx 200\ GeV$ (ruled out), $m_{\tilde{t}} \approx 200\ GeV$, large mixing
  - from plots: pushing $m_{\tilde{g}} \to 1-2\ TeV \Rightarrow O(10)$ reduction of the predicted branching ratios.





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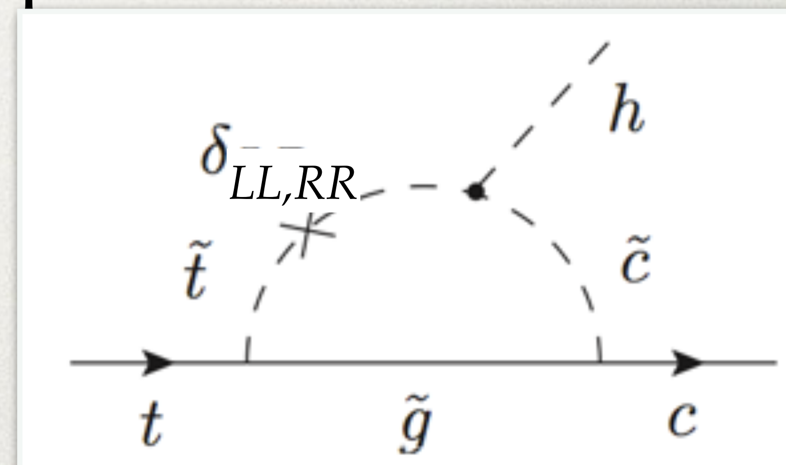

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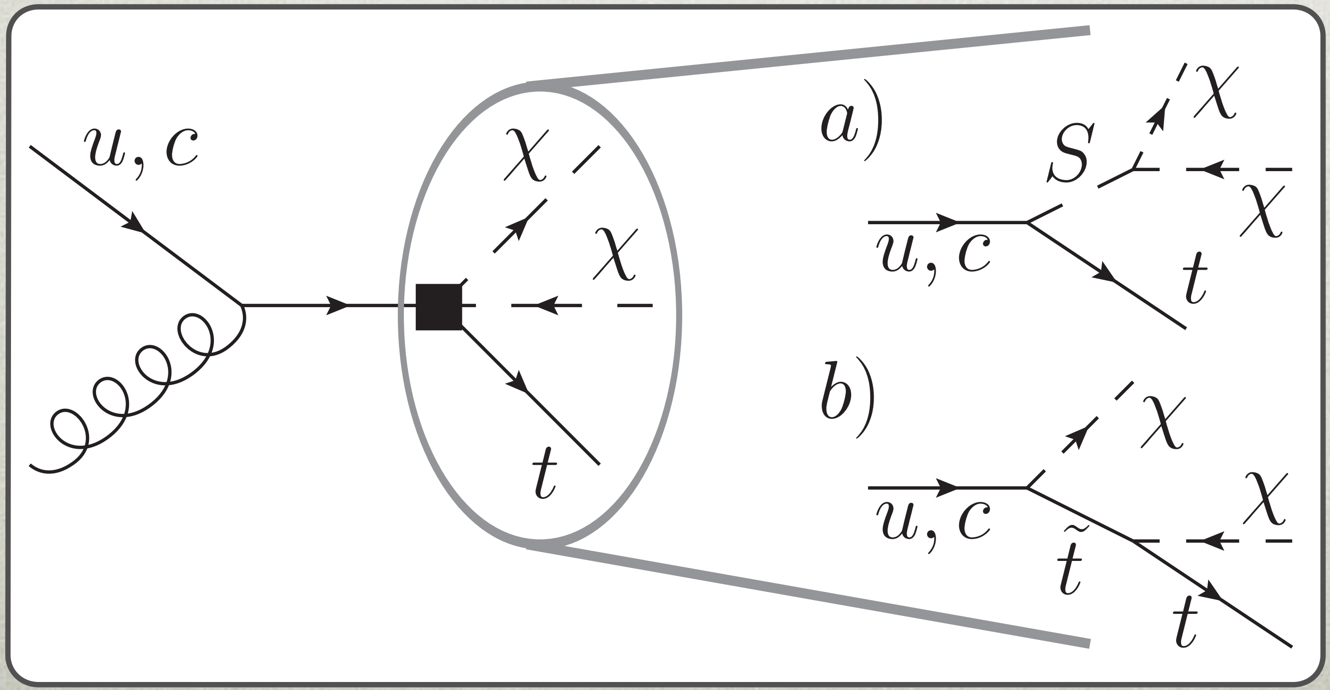
  - from plots: pushing $m_{\tilde{g}} \to 1 - 2$ *TeV* $\Rightarrow$ *O(10)* reduction of the predicted branching ratios.

MONOTOP

- monojets a standard DM search at the LHC
- however, monotop can be the leading signal
  - despite coming from FV coupling
  - DM needs to couple to quarks through scalar interactions
  - the size depends on flavor model

Kamenik, JZ, 1107.0623

Andrea, Fuks, Maltoni, 1106.6199

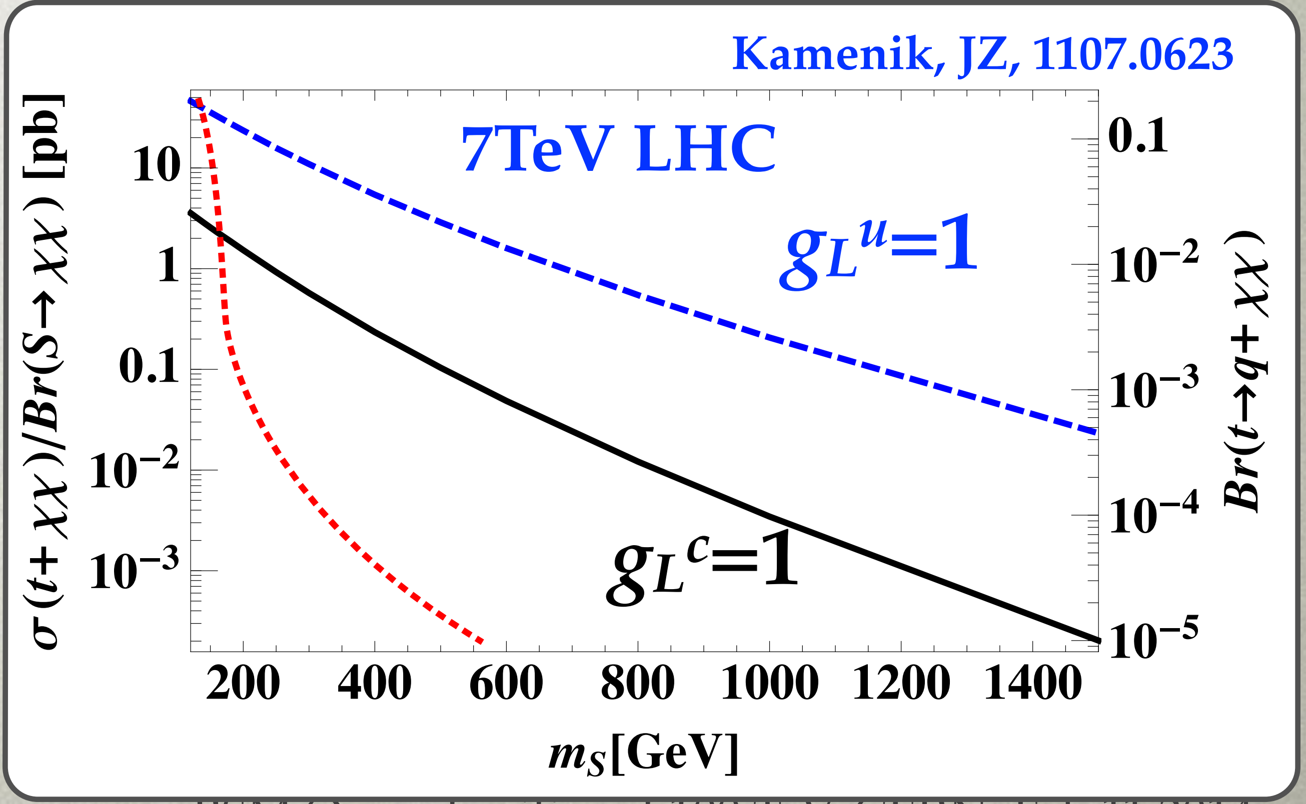


MONOTOP

- an example flavor model
  - abelian horizontal symmetries
  - the yukawas are given by Leurer, Nir, Seiberg hep-ph/9212278; hep-ph/9310320

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \quad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}$$

  - dark sector not charged under horizont. symm.
- viable SM Yukawas give $g_L^u \sim \lambda^3$, $g_L^c \sim \lambda$
- the big gain for 100TeV: top pdf large, no need to use FV coupling

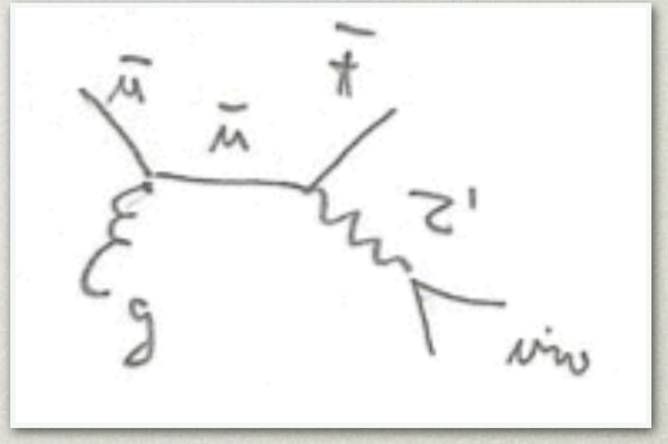


Z' FOR A_{FB}^t

- consider Z' solution to A_{FB}^t **Drobnik et al., 1209.4872**

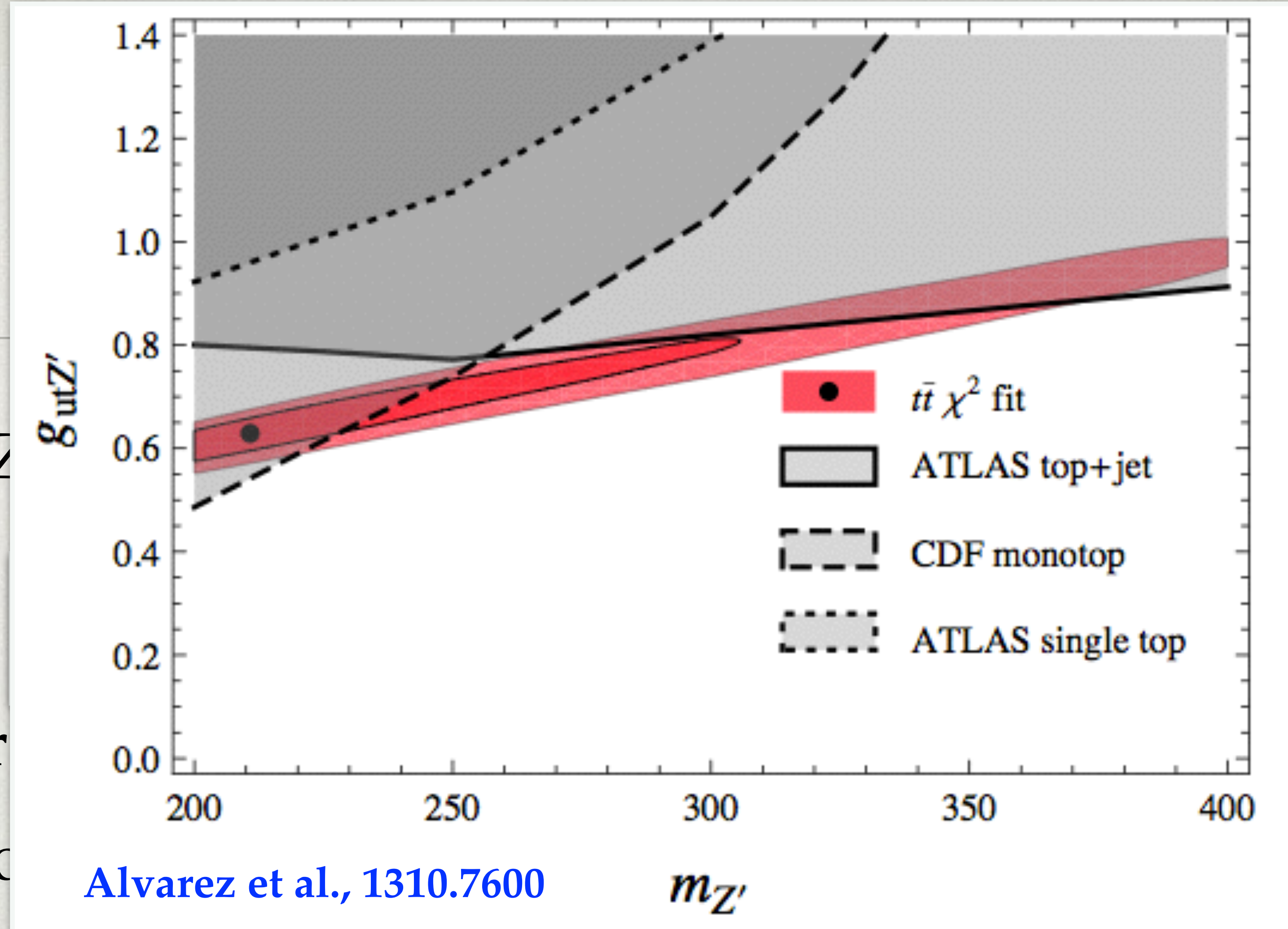
$$\mathcal{L} = g_{utZ'}\, \bar{u} \not{Z}' P_R t + \text{h.c.}$$

  - appears to be flavor violating (need not be in the full model)
  - Z' is not Hermitean, $M_{Z'} \approx 300\ GeV$
  - assoc. production $ug \to Z't \to u\bar{t}t$ decreases A_C at LHC
- viable option: $Br(Z \to \bar{t}u) \approx 30\%$, the rest to invisible
  - CDF monotop search excludes part of the phase space
  - monotop searches with existing data can exclude that



Alvarez et al., 1310.7600

- consider Z … robnik et al., 1209.4872



Alvarez et al., 1310.7600

  - appear … l model)
  - Z' is nc
  - assoc. production $ug \to Z't \to u\bar{t}t$ decreases A_C at LHC
- viable option: $Br(Z \to \bar{t}u) \approx 30\%$, the rest to invisible
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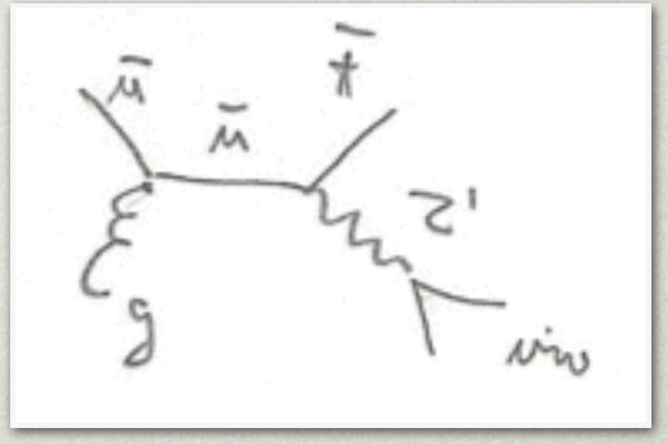
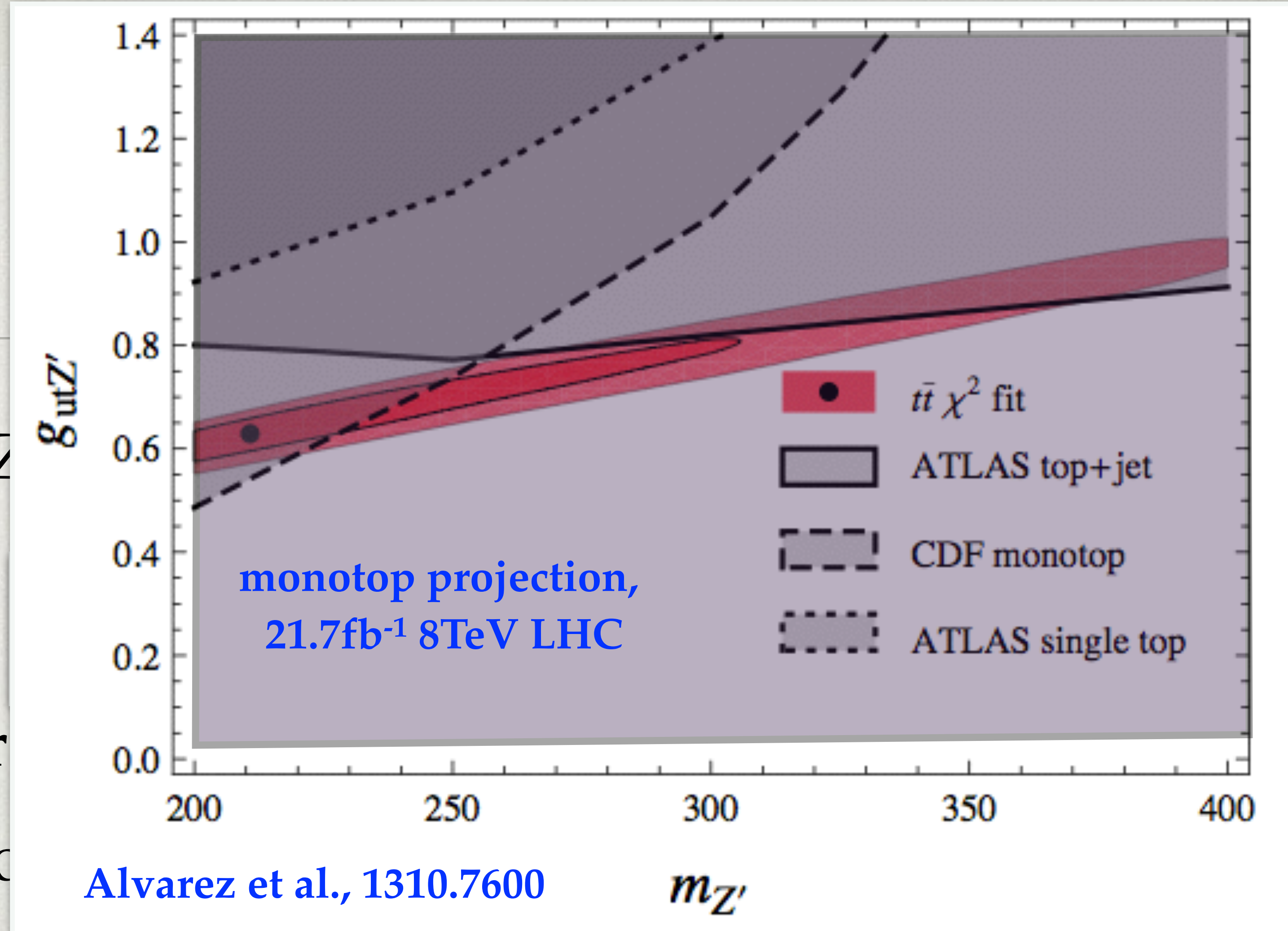


Alvarez et al., 1310.7600



- consider Z

robnik et al., 1209.4872

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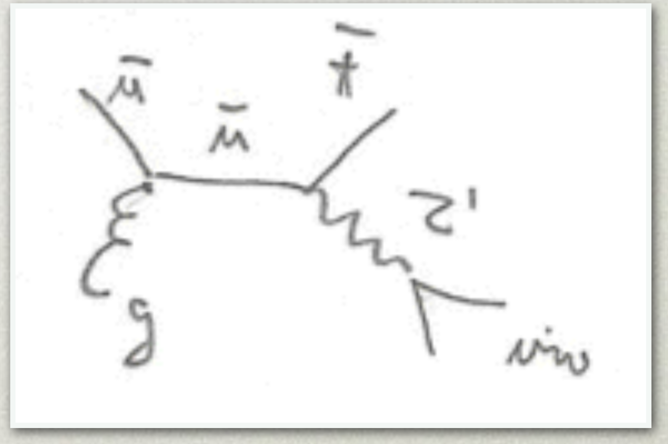


Alvarez et al., 1310.7600

RS FLAVOR

- flavor structure from profiles of zero modes in 5th dim.
  - t_R, c_R, u_R close to IR brane
  - (t_L, b_L) ~ close to IR brane
  - (c_L, s_L), (u_L, d_L) close to UV brane
- the leading effect in $t \to cZ$ determined by

Agashe et al., hep- ph/0612015

$$\mathcal{L}_{tc}^{Z} \supset g_Z \left(g_1 \bar{t}_R \not{Z} c_R + g_2 \bar{t}_L \not{Z} c_L \right)$$

$$(g_1, g_2) \sim \left(5 \cdot 10^{-3} \frac{(U_R)_{23}}{0.1}, 4 \cdot 10^{-4} \frac{(U_L)_{23}}{0.04} \right) \left(\frac{3\,\mathrm{TeV}}{m_{KK}} \right)^2$$

- mixing mostly in right-handed sector

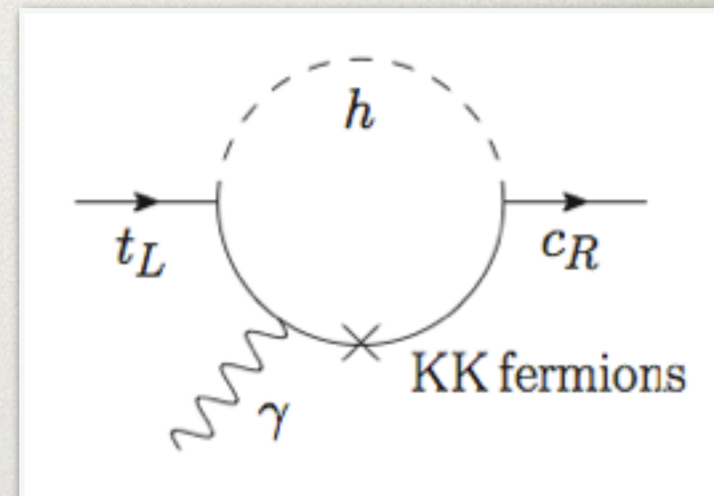
$$\mathrm{Br}(t \to cZ) \sim 10^{-5} \left(\frac{3\,\mathrm{TeV}}{m_{KK}} \right)^4 \left(\frac{(U_R)_{23}}{0.1} \right)^2$$

RS FLAVOR

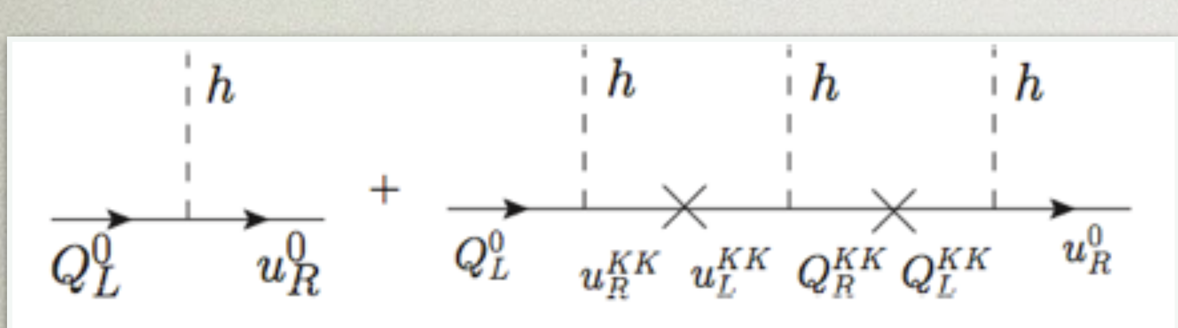
Agashe et al., hep- ph/0606295

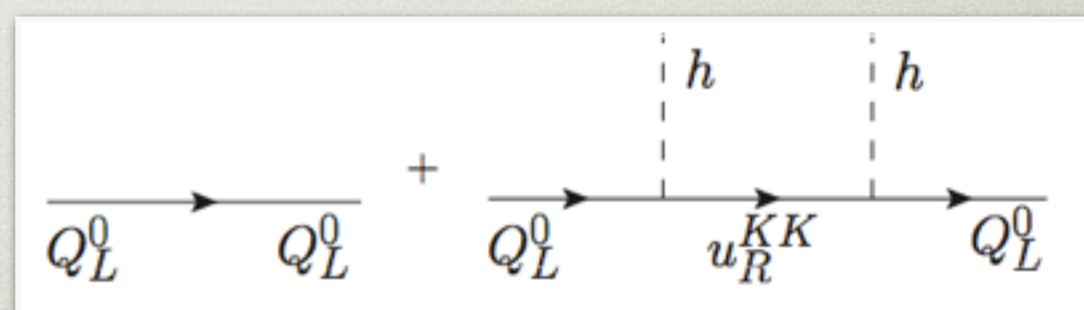
- Radiative processes require a chirality flip
  - they could arise from loop diagrams

$$\mathrm{Br}(t \to c\gamma, cg) \sim 10^{-9,-10} \left(\frac{3\,\mathrm{TeV}}{m_{KK}}\right)^4 \left(\frac{(U_R)_{23}}{0.1}\right)^2 \left(\frac{\lambda_{5D}}{4}\right)^4$$



- the KK fermions correct Yukawas and the kinetic terms





  - for reasonable parameters one could potentially have $Br(t \to ch) \simeq 5 \cdot 10^{-5}$

Azatov, Toharia, Zhu, 0906.1990

Casagrande, 1005.4315

CONCLUDING THOUGHTS

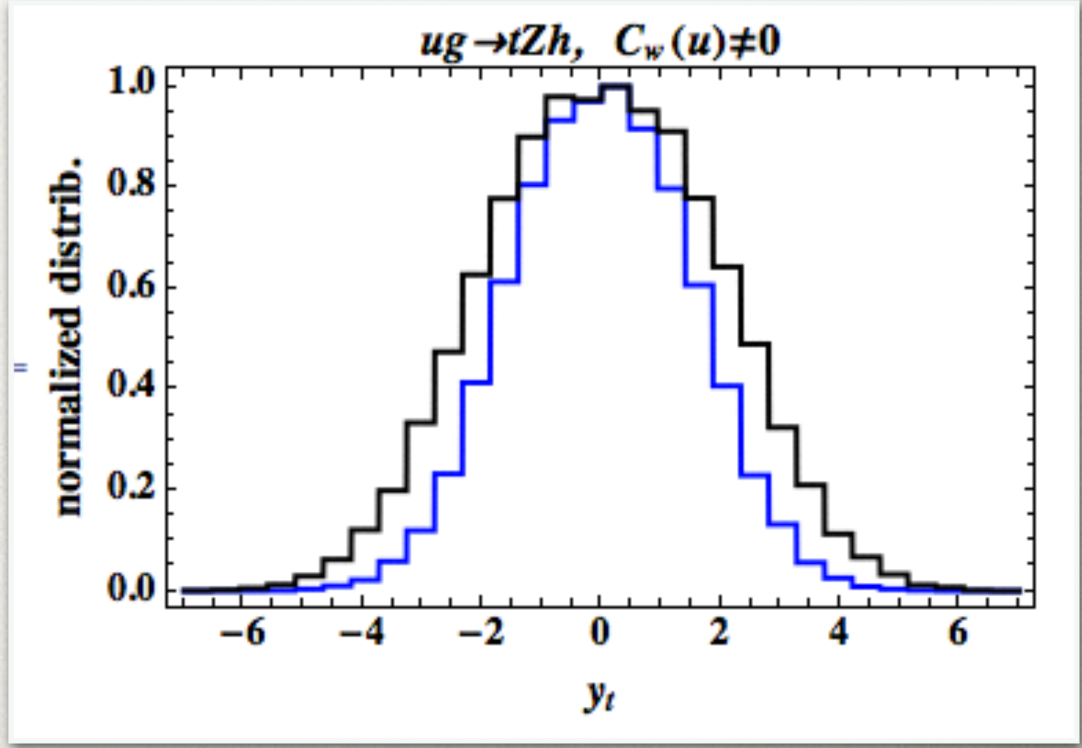
- can tFCNC aid in discovery?
  - does on-shell production have higher reach?
    - tFCNC reach at 100TeV needs to be made more quantitative

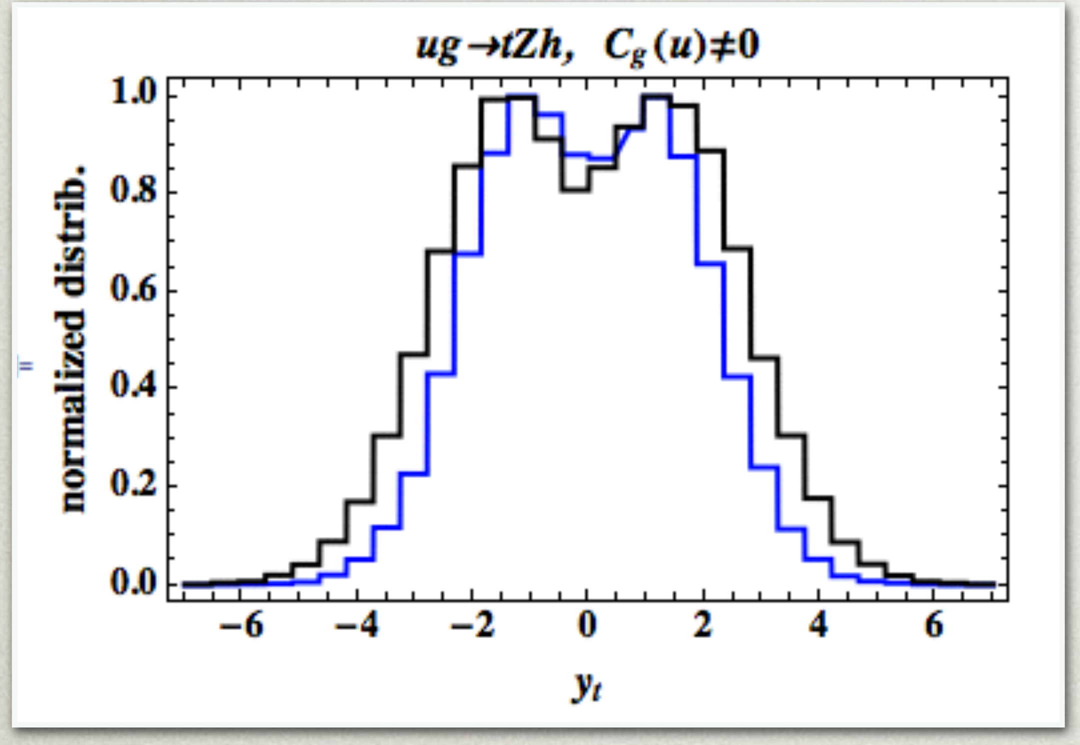
Altmannshofer, Blanke, Brod, Gori, Uttarayat, JZ, work in progress

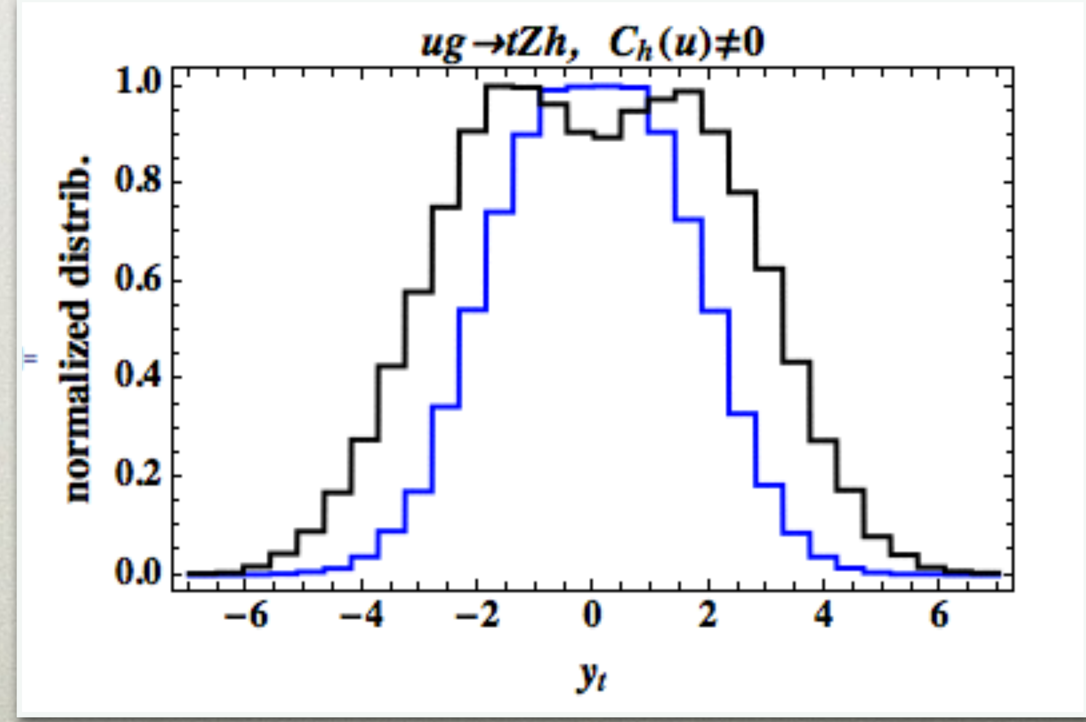
  - it is also important to keep FV in searches
    - cf. the single squark case, flavored naturalness, …
- since it is due to virtual effects tFCNC is more inclusive
  - its reach crucially depend on systematics

BACKUP SLIDES

ASSOCIATED TOP+Z+HIGGS PRODUCTION







CURIOSITY

- one of the solutions to $B \to D^{(*)}\tau\nu$ anomaly
  - if entirely due to $O^{w}{}_{LR}$
    $\Rightarrow$ requires $\Lambda^{w}{}_{LR} \simeq 0.37$ TeV

$$\mathcal{O}^w_{LR} = g_2[\bar{Q}_3\sigma^{\mu\nu}\sigma^a\tilde{H}]c_R W^a_{\mu\nu} + \text{h.c.}$$

  - corresponds to $Br(t \to cZ) \simeq 0.8\%$
    - excluded by an order of magnitude
- illustrates the bounds on NP models
  - of course not model independent (requires charged current)

Snowmass 2013
Top quark WG report, 1311.2028

Table 1-7. *SM and new physics model predictions for branching ratios of top FCNC decays. The SM predictions are taken from [119], on 2HDM with flavor violating Yukawa couplings [119, 120] (2HDM (FV) column), the 2HDM flavor conserving (FC) case from [121], the MSSM with 1 TeV squarks and gluinos from [122], the MSSM for the R-parity violating case from [123, 124], and warped extra dimensions (RS) from [125, 126] .*

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Snowmass 2013
Top quark WG report, 1311.2028

Table 1-8. *Current direct limits on top FCNCs. (*) denotes unofficial limits obtained from public results. The q in the final state denotes sum over $q = u, c$.*

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	7×10^{-4}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	19.5 fb^{-1}, 8 TeV	[130]
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	2.1 fb^{-1}, 7 TeV	[137]
$t \to gu$	3.1×10^{-5}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to gc$	1.6×10^{-4}	ATLAS $qg \to t \to Wb$	14.2 fb^{-1}, 8 TeV	[131]
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	474 pb^{-1}, 300 GeV	[134]
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	110 pb^{-1}, 1.8 TeV	[132]
$t \to hq$	8.3×10^{-3}	ATLAS $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	20 fb^{-1}, 8 TeV	[135]
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	5 fb^{-1}, 7 TeV	[136]
$t \to$ invis.	9×10^{-2}	CDF $t\bar{t} \to Wb$	1.9 fb^{-1}, 1.96 TeV	[133]

Table 1-9. *Projected limits on top FCNCs at the LHC and ILC. "Extrap." denotes estimates based on extrapolation as described in the text. For the ILC/CLIC, limits for various tensor couplings (i.e., with $\sigma_{\mu\nu}$ structure) are shown inside ().*

Process	Br Limit	Search	Dataset	Reference
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV	[140]
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV	[140]
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 250 GeV	Extrap.
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	[141]
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ ($\sigma_{\mu\nu}$)	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV	[140]
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV	Extrap.
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV	[141]
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV	[141]
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV	Extrap.
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV	Extrap.
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV	Extrap.