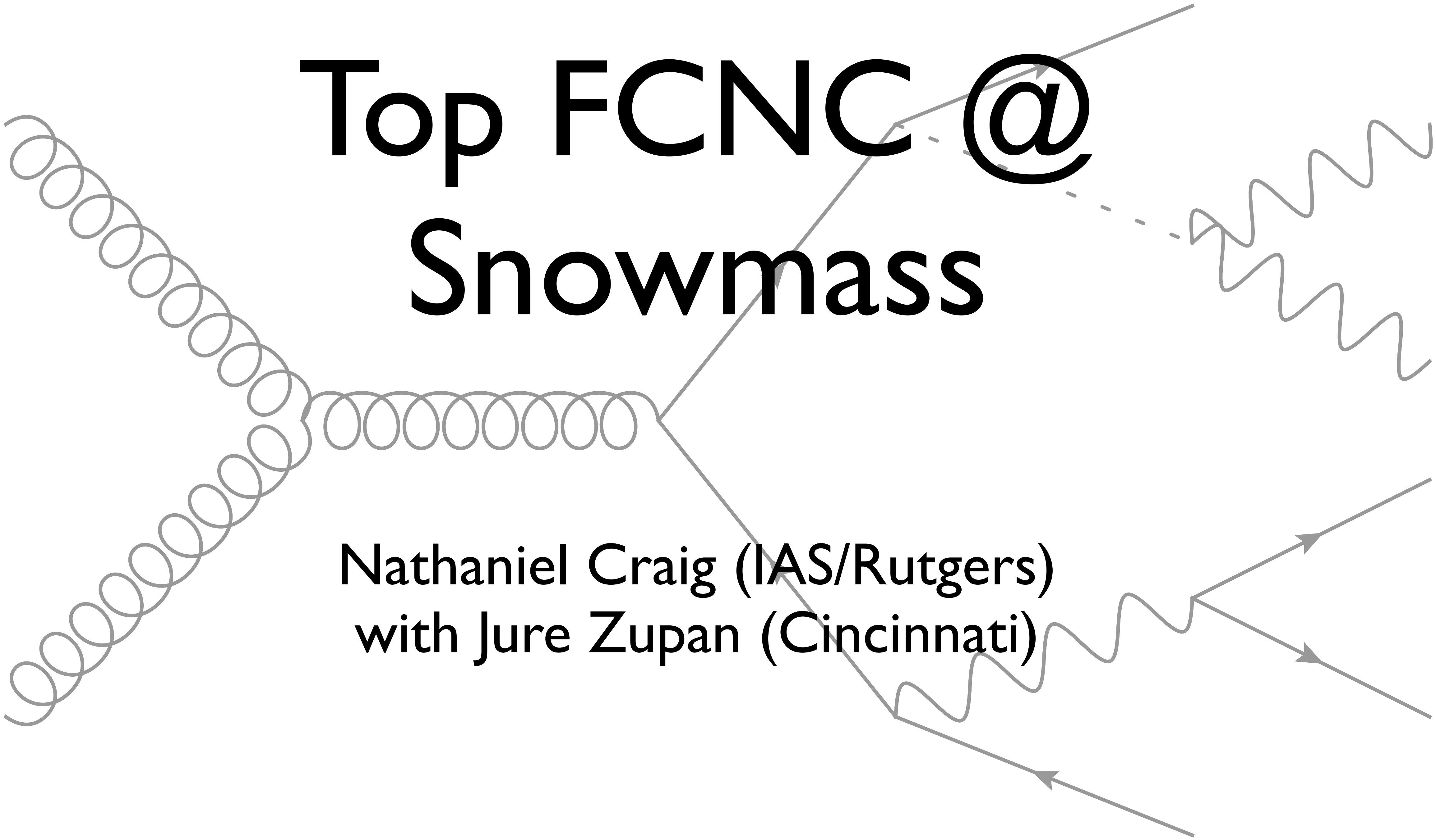
Top FCNC @ Snowmass



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with Jure Zupan (Cincinnati)

The top FCNC era

- Flavor violation in the top sector is poorly constrained...
- ...but one of the most likely flags of NP!
- LHC is a top factory; already making considerable progress, with much more to come. The era of top FCNC is upon us!
- Possible future colliders considered in the Snowmass process differ in capacity to provide a high-statistics top sample.

Top FCNC charge

- Does the top quark decay to exotic final states? SM-like or BSM-like? How well can these decays be measured/constrained at hadron and lepton colliders?
- What sensitivity needs to be reached for these decays in order to have a significant impact on models of physics beyond the SM?
- Can the small CKM-matrix elements Vts and Vtd be directly measured via top quark decays? To what precision?

Effective lagrangian for top FCNC

$$\mathcal{L}_{\text{eff}} = \frac{v}{\Lambda^2}\Big(b^Z_{LR}\mathcal{O}^Z_{LR} + b^\gamma_{LR}\mathcal{O}^\gamma_{LR} + b^g_{LR}\mathcal{O}^g_{LR}\Big)$$
$$+ \frac{v^2}{\Lambda^2}\Big(a^Z_L\mathcal{O}^Z_L + a^h_{LR}\mathcal{O}^h_{LR}\Big) + L \leftrightarrow R + h.c.$$

Dimension 5

$$\mathcal{O}^Z_{LR} = \frac{2e}{\sin 2\theta_W}\big(\bar{q}_L\sigma^{\mu\nu}t_R\big)Z_{\mu\nu}$$
$$\mathcal{O}^\gamma_{LR} = e\big(\bar{q}_L\sigma^{\mu\nu}t_R\big)F_{\mu\nu}$$
$$\mathcal{O}^g_{LR} = g_s\big(\bar{q}_L\sigma^{\mu\nu}T^a t_R\big)G^a_{\mu\nu}$$

Dimension 4

$$\mathcal{O}^Z_L = \frac{2e}{\sin 2\theta_W}\big(\bar{q}_L\gamma^\mu t_L\big)Z_\mu$$
$$\mathcal{O}^h_{LR} = \big(\bar{q}_L t_R\big)h$$

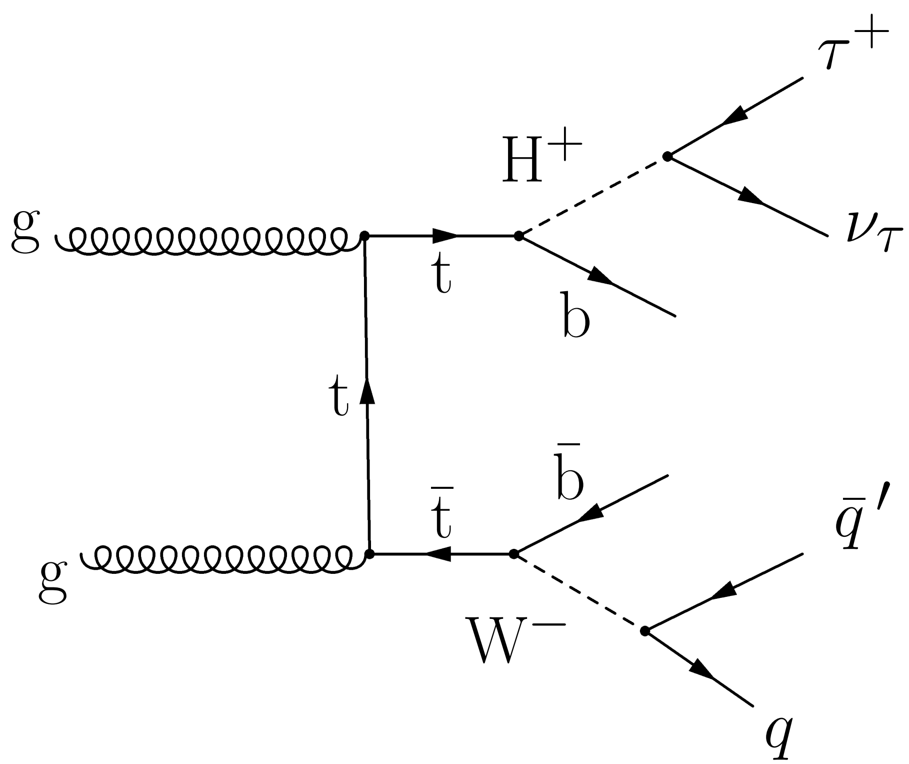
Look for $t \to Zq, t \to gq, t \to \gamma q, t \to hq$

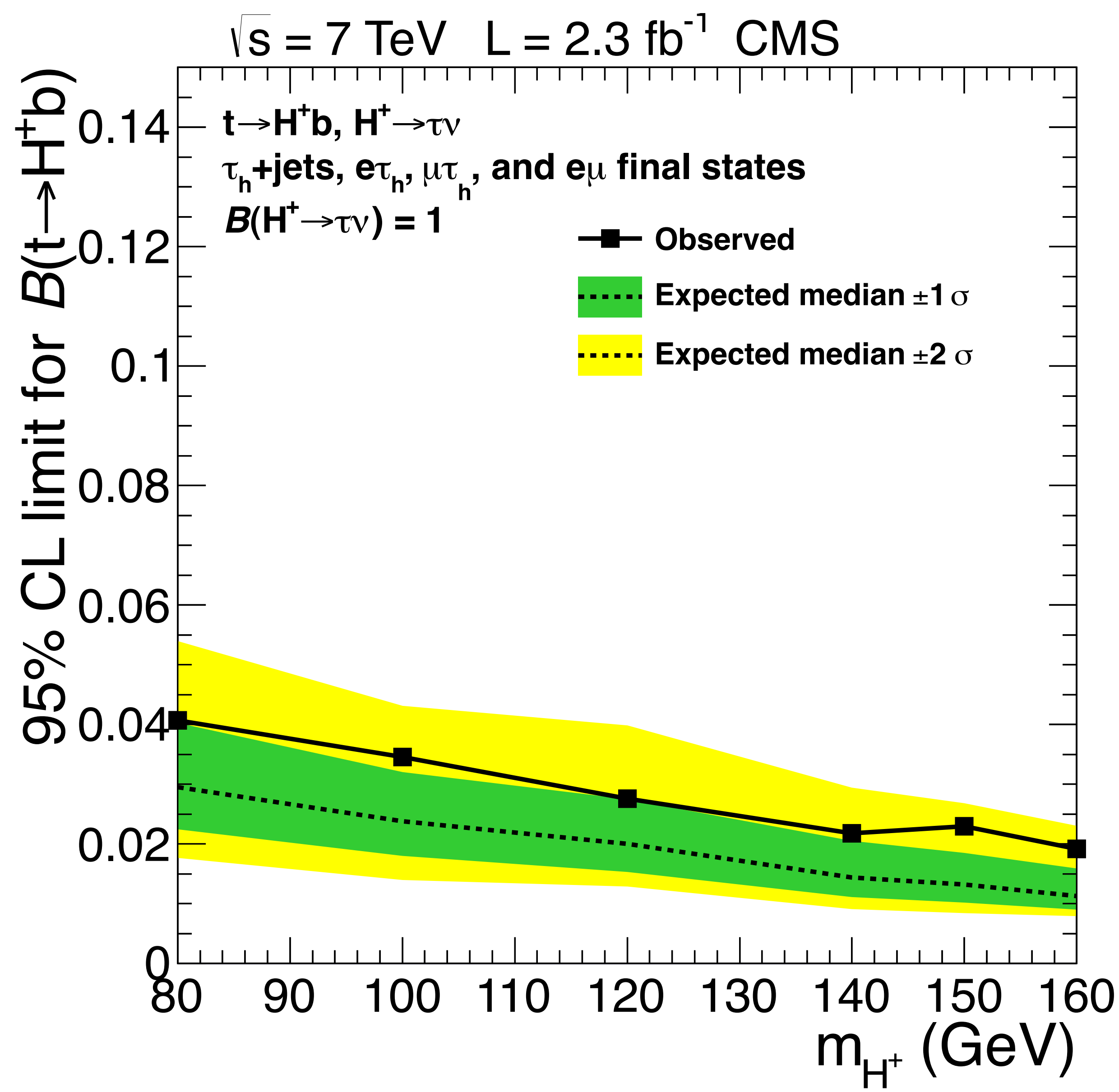
New states

Of course, effective Lagrangian is not quite the right tool if there are new states below the top mass...

Canonical example:

$$t \to H^+ b$$





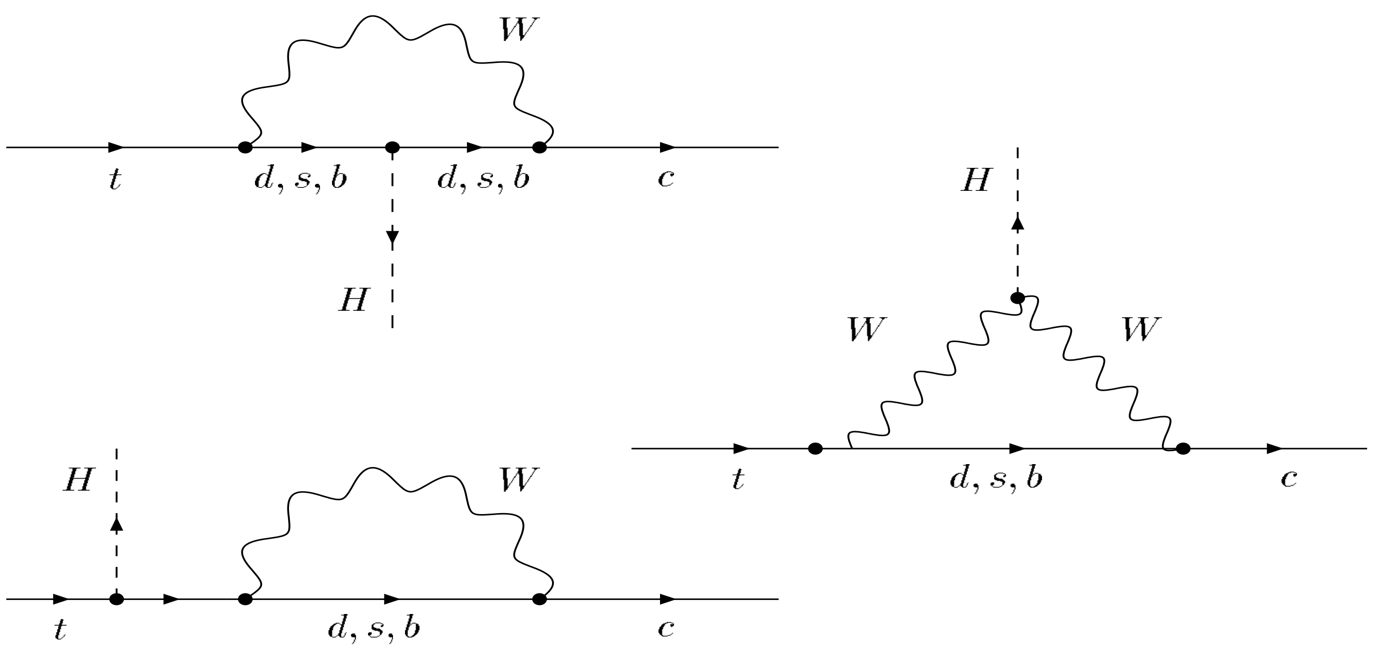
Models

Standard Model

SM prediction for top FCNC vanishingly small; suppressed by GIM mechanism and large total width

$t \to Zu$	7×10^{-17}
$t \to Zc$	1×10^{-14}
$t \to gu$	4×10^{-14}
$t \to gc$	5×10^{-12}
$t \to \gamma u$	4×10^{-16}
$t \to \gamma c$	5×10^{-14}
$t \to hu$	2×10^{-17}
$t \to hc$	3×10^{-15}

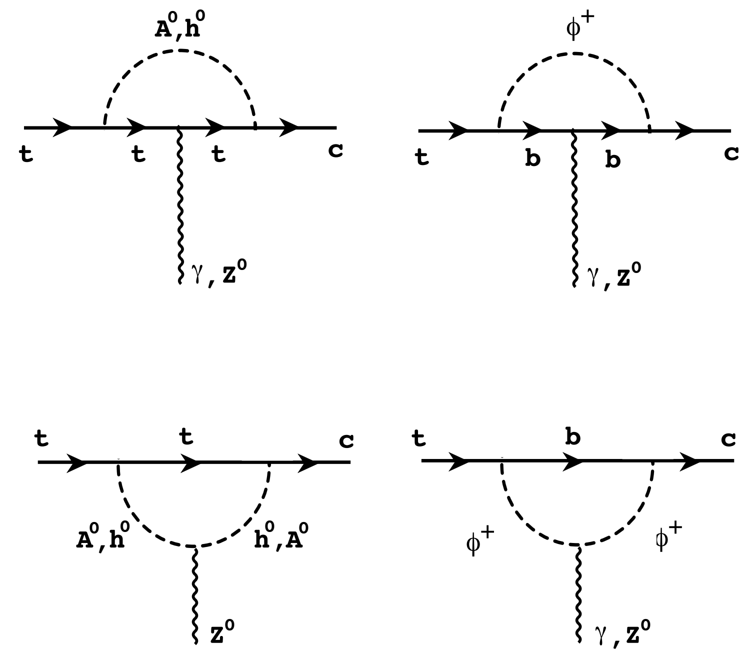
[Aguilar-Saavedra, hep-ph/0409342]



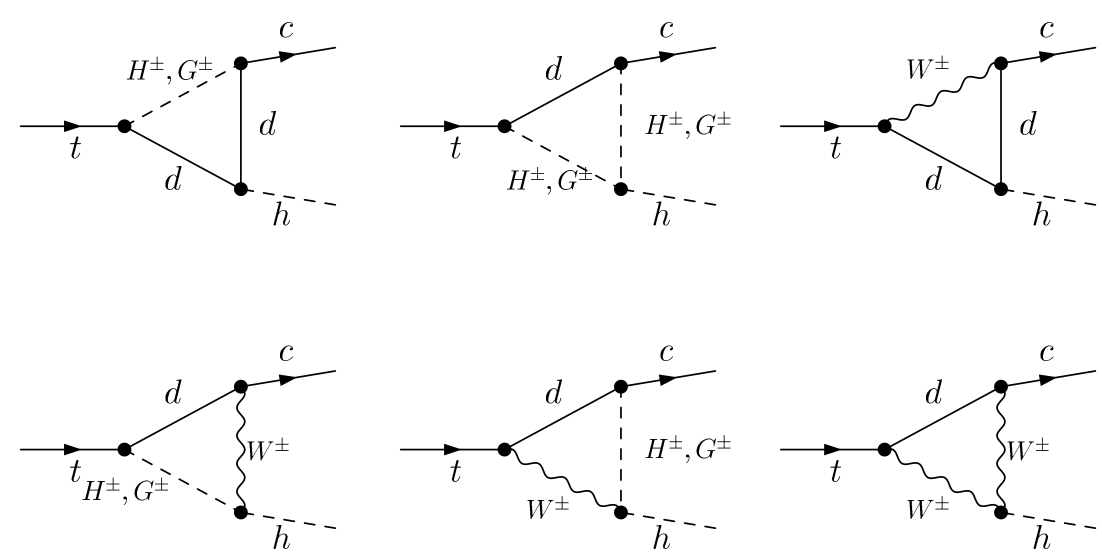
SM rate beyond reach of Snowmass options, but any signal is NP.

2HDM (FV/FC)

Significant contributions in 2hdm both with & without tree-level flavor violation.



	FV	*FC*
$t \to Zu$	$-$	$-$
$t \to Zc$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to gu$	$-$	$-$
$t \to gc$	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$
$t \to \gamma u$	$-$	$-$
$t \to \gamma c$	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$
$t \to hu$	6×10^{-6}	$-$
$t \to hc$	2×10^{-3}	$\lesssim 10^{-5}$

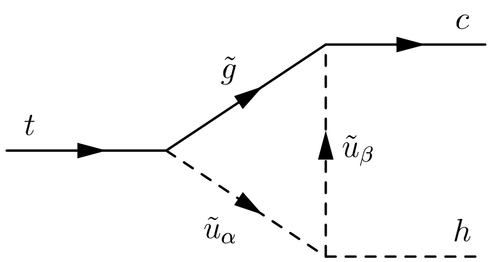


[Aguilar-Saavedra, hep-ph/0409342]
[Atwood, Reina, Soni hep-ph/9609279]
[Bejar, hep-ph/0606138]

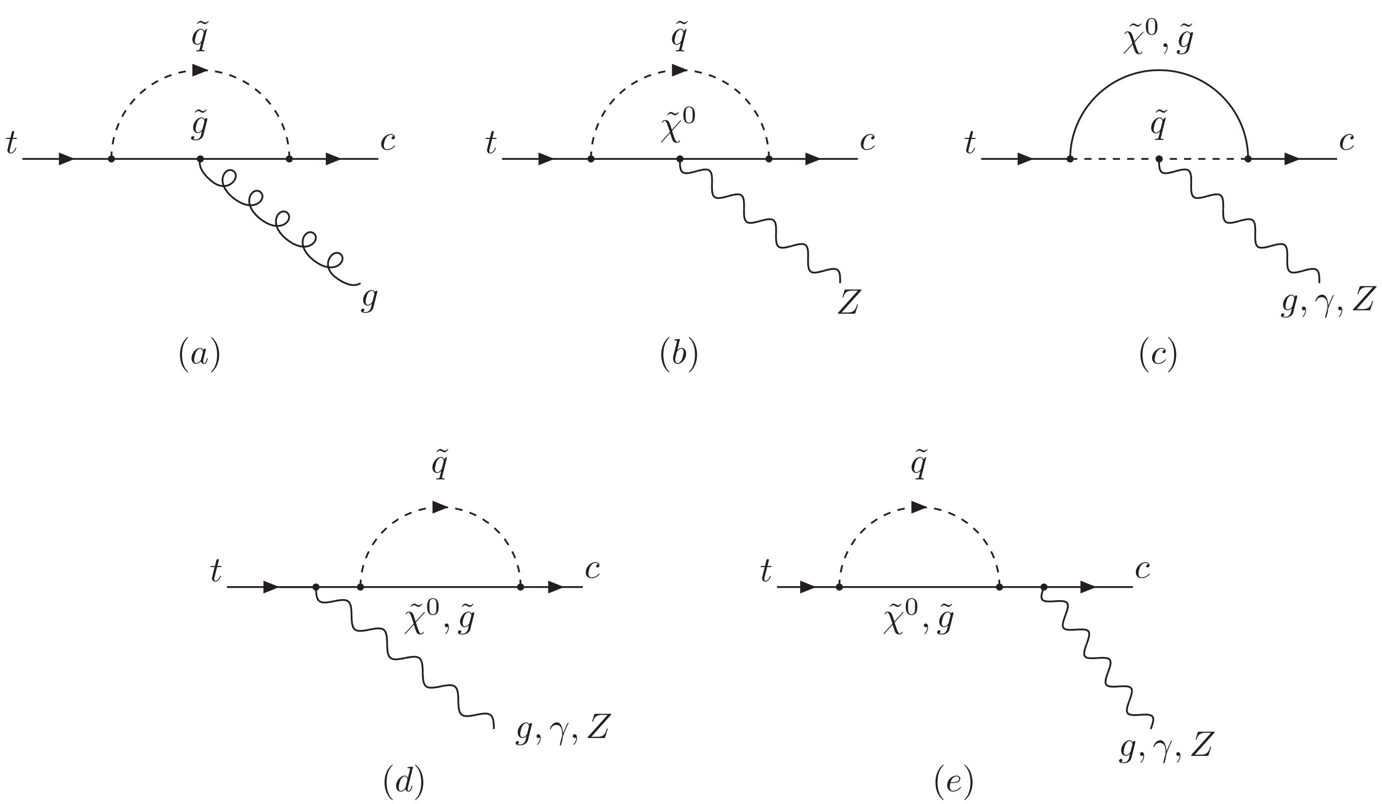
Signal range may be altered by Higgs coupling fits

MSSM

Significant rates possible due to squark FV, consistent with indirect limits if predominantly in stop sector



(rates assuming $m_{\tilde{g}} \sim m_{\tilde{q}} \sim 1\ \mathrm{TeV}$)



$$
\begin{aligned}
t &\to Zu & \lesssim 10^{-7} \\
t &\to Zc & \lesssim 10^{-7} \\
t &\to gu & \lesssim 10^{-7} \\
t &\to gc & \lesssim 10^{-7} \\
t &\to \gamma u & \lesssim 10^{-8} \\
t &\to \gamma c & \lesssim 10^{-8} \\
t &\to hu & \lesssim 10^{-5} \\
t &\to hc & \lesssim 10^{-5}
\end{aligned}
$$

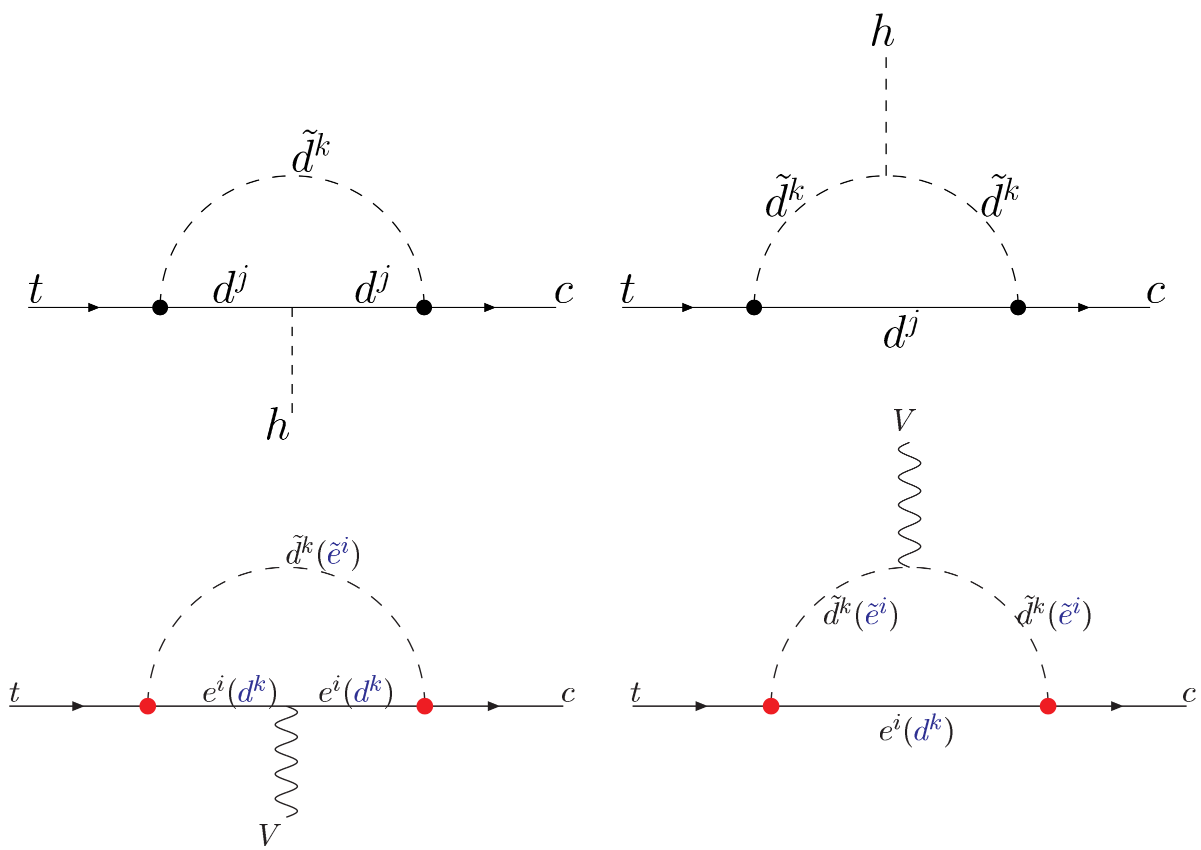
Comprehensive update with LHC limits is needed.

[Cao et al., hep-ph/0702264]

RPV

Additional SUSY contributions possible if R-parity is broken due to flavor-violating RPV couplings

(rates assuming $m_{\tilde{q}} \sim 1\ \mathrm{TeV}$)



$$
\begin{aligned}
t &\to Zu & &\lesssim 10^{-6} \\
t &\to Zc & &\lesssim 10^{-6} \\
t &\to gu & &\lesssim 10^{-6} \\
t &\to gc & &\lesssim 10^{-6} \\
t &\to \gamma u & &\lesssim 10^{-9} \\
t &\to \gamma c & &\lesssim 10^{-9} \\
t &\to hu & &\lesssim 10^{-9} \\
t &\to hc & &\lesssim 10^{-9}
\end{aligned}
$$

Comprehensive update with LHC limits is needed.

[Yang et al., hep-ph/9705341]

[Eilam et al., hep-ph/0102037]

Just scratching the surface

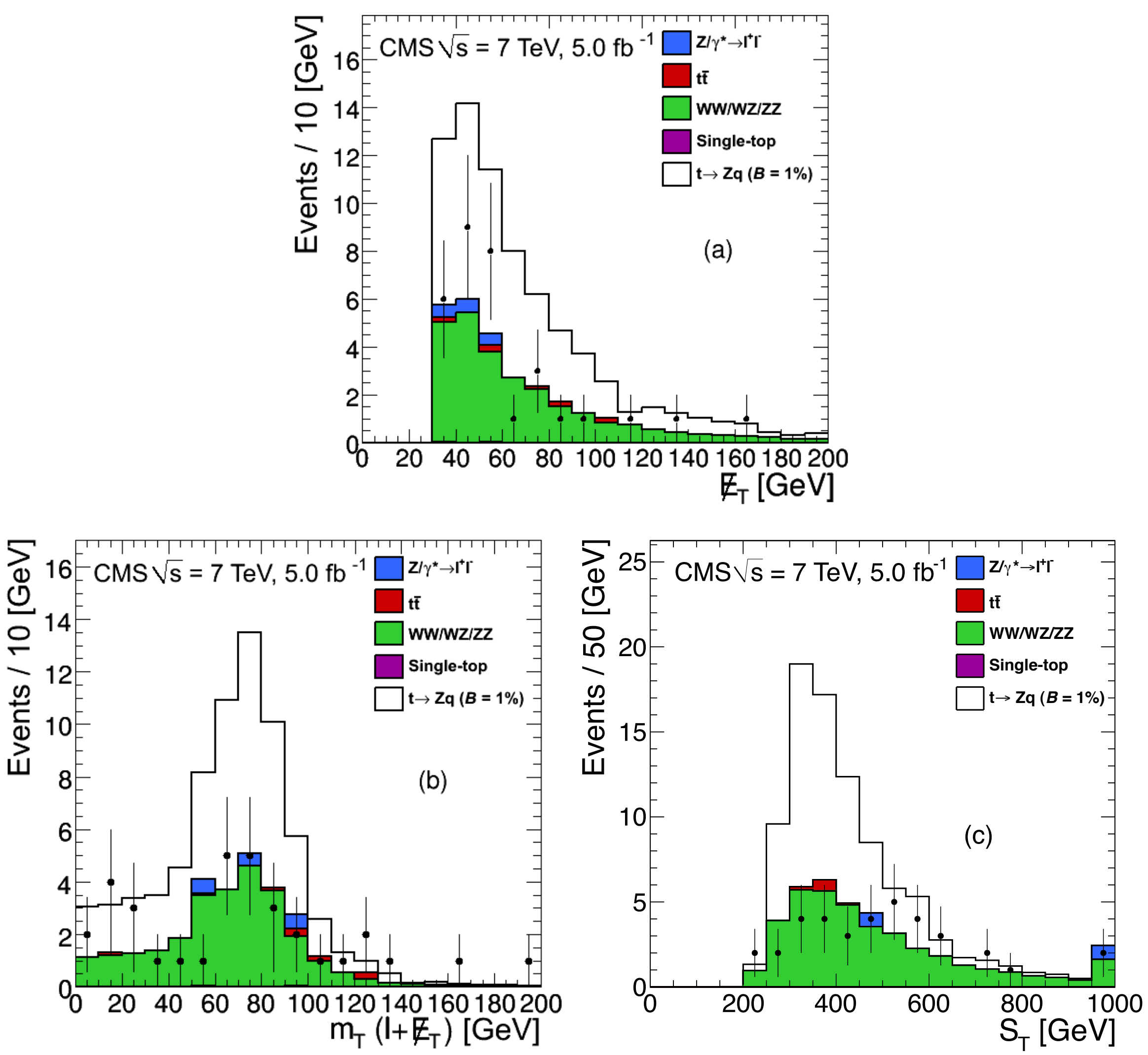
- Folded SUSY
- Topcolor
- Randall-Sundrum
- MFV scenarios
- ...

Need to survey the motivated set of models and update signals to account for direct and indirect LHC limits

Searches

Searches

Process	Br Limit	Search	Dataset
$t \to Zq$	2.4×10^{-3}	CMS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$5\ \mathrm{fb}^{-1}$, 7 TeV
$t \to Zq$	7.3×10^{-3}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	$2.1\ \mathrm{fb}^{-1}$, 7 TeV



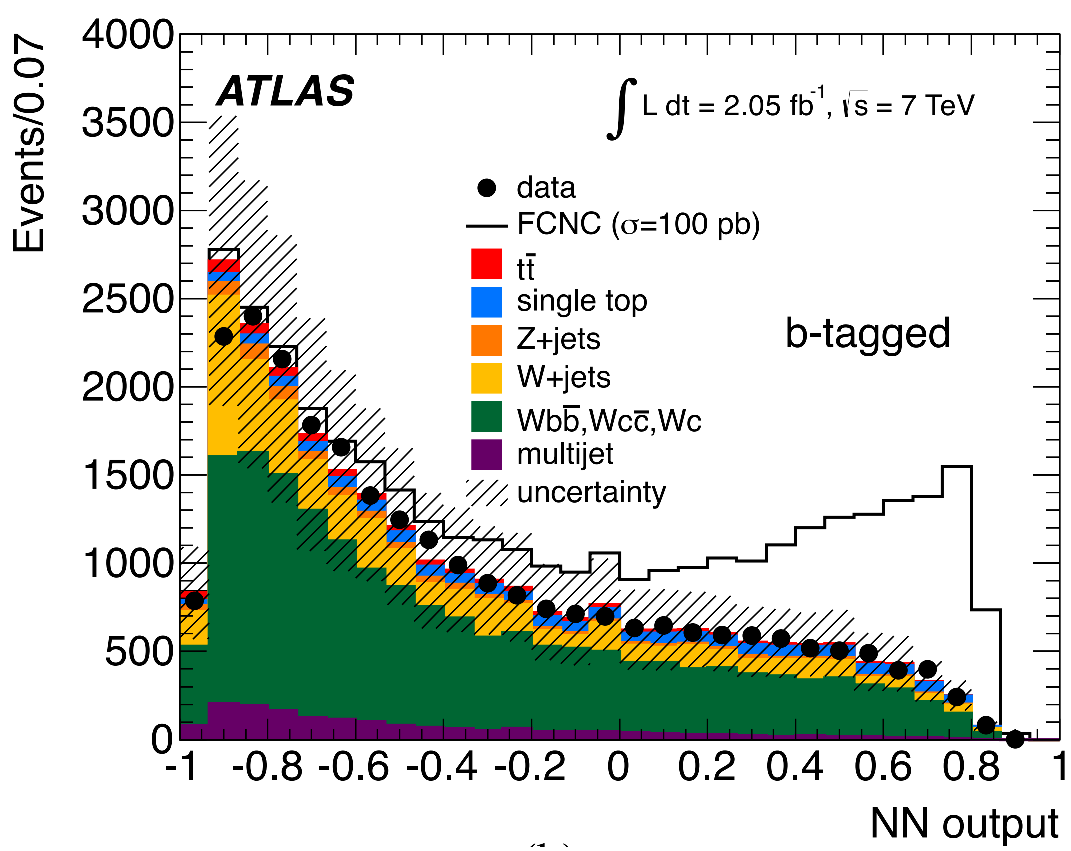
Canonical search for trilepton final states, generally with one OSSF pair reconstructing the Z and one b-tag.

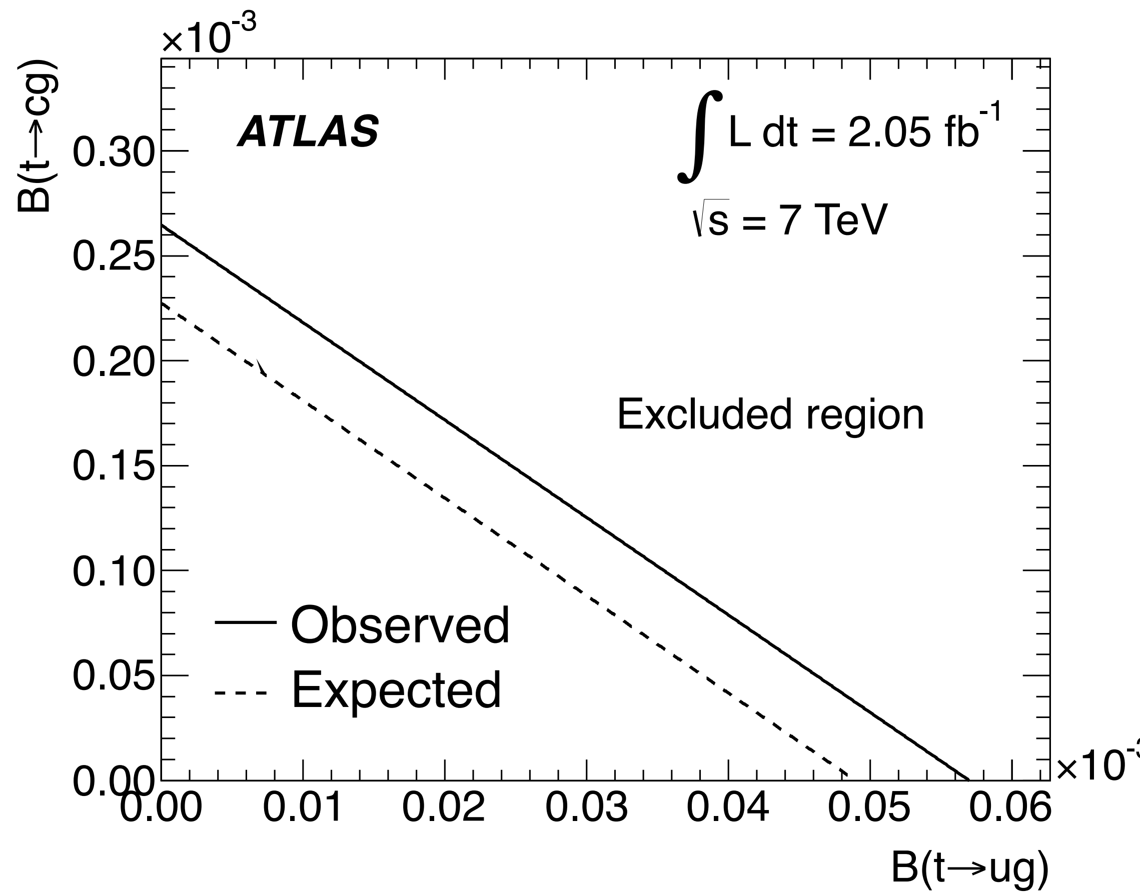
Should be fairly straightforward to estimate future sensitivities.

Searches

Process	Br Limit	Search	Dataset
$t \to gu$	5.7×10^{-5}	ATLAS $qg \to t \to Wb$	$2.05\ \mathrm{fb}^{-1}$, 7 TeV
$t \to gc$	2.7×10^{-4}	ATLAS $qg \to t \to Wb$	$2.05\ \mathrm{fb}^{-1}$, 7 TeV

Use NN to distinguish signal from SM single top.

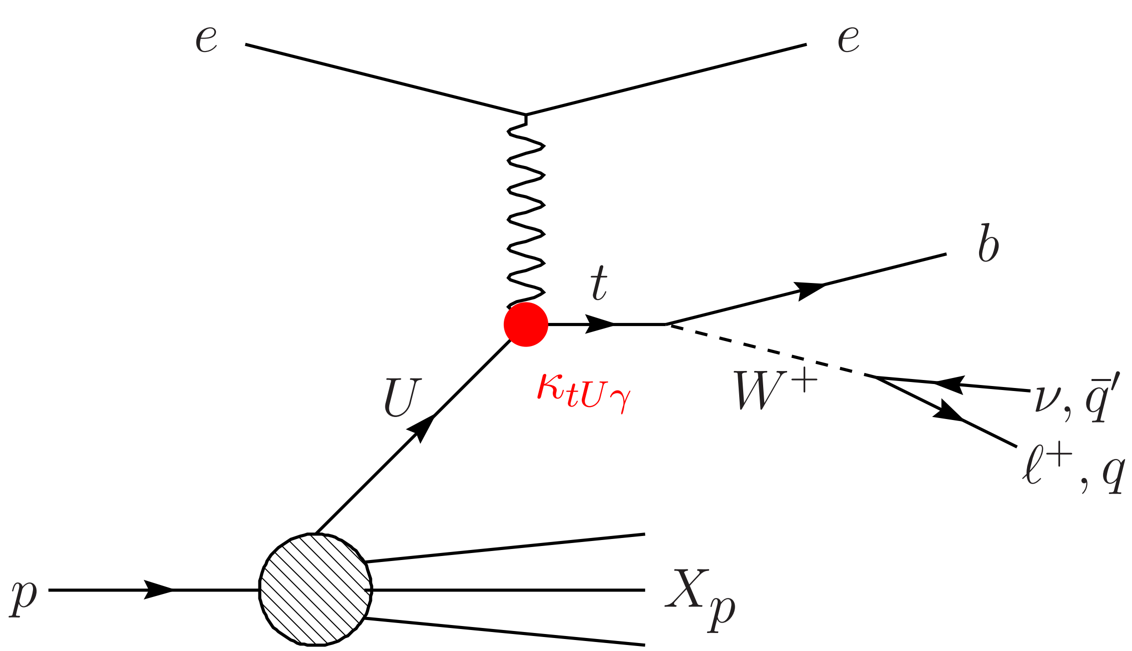




Future sensitivity may be harder to project...

Searches

Process	Br Limit	Search	Dataset
$t \to \gamma u$	6.4×10^{-3}	ZEUS $e^{\pm}p \to (t \text{ or } \bar{t}) + X$	$474\ \text{pb}^{-1}$, 300 GeV
$t \to \gamma q$	3.2×10^{-2}	CDF $t\bar{t} \to Wb + \gamma q$	$110\ \text{pb}^{-1}$, 1.8 TeV

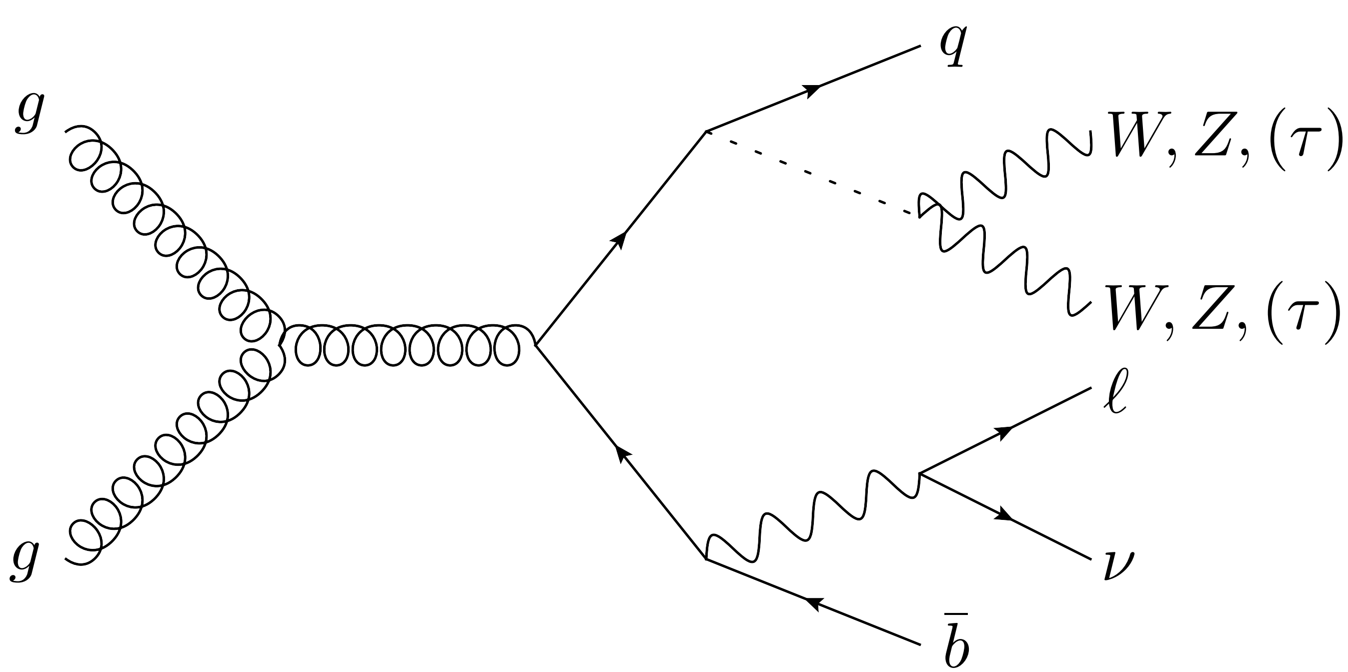


ZEUS exploited production vertex; CDF searched for final state.

Room for improvement! Timeline for LHC measurement (presumably in final state) is unclear.

Searches

Process	Br Limit	Search	Dataset
$t \to hq$	2.7×10^{-2}	CMS* $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	$5\ \mathrm{fb}^{-1}$, 7 TeV



Assuming SM-like decays of *h*.
Same-sign dilepton limit is comparable.

Should improve significantly using 8 TeV search which includes *b*-tagged categories; hopefully will become an official LHC interpretation at ATLAS/CMS

Limits

Translate current direct limits to effective lagrangian:

Operator	Limit	State
a^Z/Λ^2	$< 0.62\ \mathrm{TeV}^{-2}$	$q = u, c$
b^Z/Λ^2	$< 0.69\ \mathrm{TeV}^{-2}$	$q = u, c$
b^g/Λ^2	$< 2.8 \times 10^{-2}\ \mathrm{TeV}^{-2}$	$q = u$
b^g/Λ^2	$< 6.5 \times 10^{-2}\ \mathrm{TeV}^{-2}$	$q = c$
b^γ/Λ^2	$< 0.86\ \mathrm{TeV}^{-2}$	$q = u$
b^γ/Λ^2	$< 1.93\ \mathrm{TeV}^{-2}$	$q = c$
a^h/Λ^2	$< 3.6\ \mathrm{TeV}^{-2}$	$q = u, c$

Just beginning to graze TeV scale.

Indirect limits still competitive for a^h

Vts and Vtd

Fairly tightly constrained assuming unitarity of CKM matrix, but lots of NP models would violate this.

E.g. 4th gen quarks (vector or chiral), RS, etc.

Models also have correlated predictions for top FCNC.

Various handles on direct measurement:

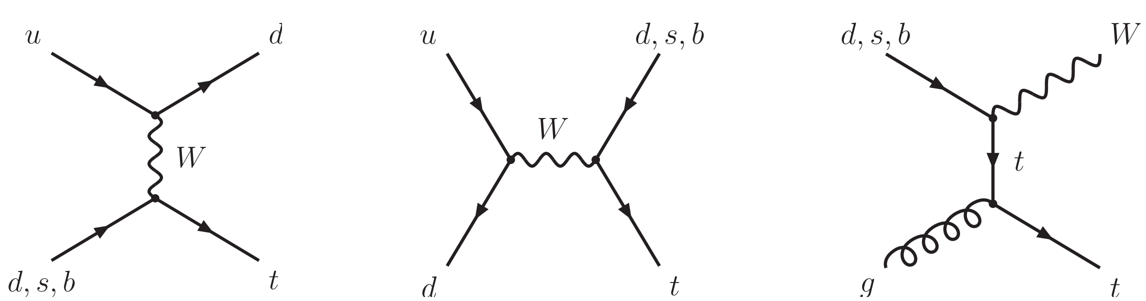
$$R = \frac{\mathrm{Br}(t \to Wb)}{\mathrm{Br}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

Top pair production

$$R' = \frac{\mathrm{Br}(t \to Ws)}{\mathrm{Br}(t \to Wb)} = \frac{|V_{ts}|^2}{|V_{tb}|^2}$$

s-tagging at LHC?

$$\sigma = A_d|V_{td}|^2 + A_s|V_{ts}|^2 + A_b|V_{tb}|^2$$



Single top production

Future prospects?
Additional variables?
Complementary colliders?

Future

- Update NP signal expectations to reflect current LHC limits on model spectra (and potential limits by end of LHC run). *Need this to know the target.*
- Perform detailed study of indirect limits on $t \to hq$ operator. *Indirect limits may be competitive.*
- Determine sensitivity of Snowmass benchmark colliders to top FCNC (trilepton, Wb, Wb+γq)
- Develop strategy for optimal determination of Vts and Vtd at LHC and other colliders.