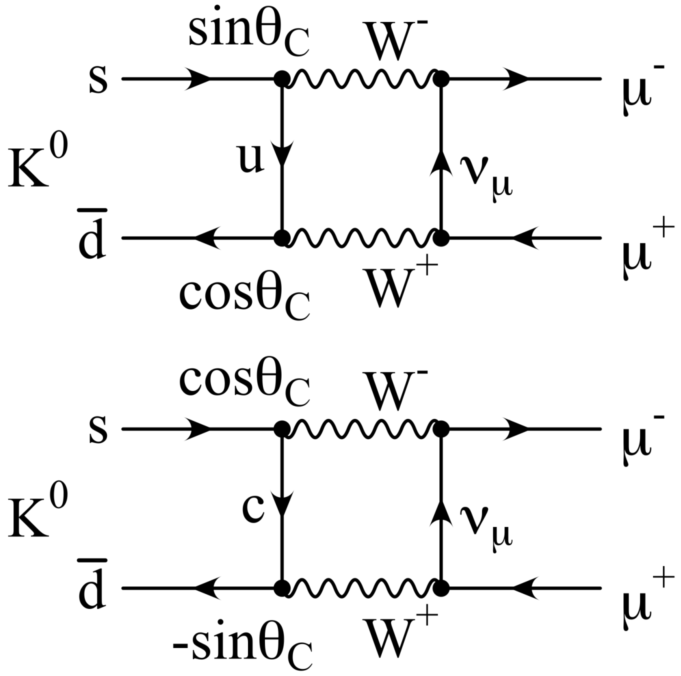


"Wow, I sure love box diagrams!"
-Everyone

FLAVOR CHANGING NEUTRAL CURRENTS in top decays

Patrick McCormack

March 6, 2019

Oh no, is this a GIM Mechanism lecture?

- Well not exactly, I’m going to assume we all know the 6 quarks
- Let’s just start from the Standard Model

Why are there no tree-level FCNC?

- Let’s only worry about quarks for now
- Fermions acquire mass via Yukawa type coupling with a scalar with a vev so:
  - $\mathcal{L} \supset \bar{Q}_L \, \phi \, q_R \supset \begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R$
- The left-handed fermions carry SU(2) charge so:
  - $\mathcal{L} \supset g \bar{Q}_L \, \gamma^\mu \, \tau_i \, W_\mu^i Q_L \approx g \begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} \gamma^\mu \begin{pmatrix} W_\mu^3 & W_\mu^+ \\ W_\mu^- & -W_\mu^3 \end{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
  - $\mathcal{L} \supset g \left(\bar{u}_L \, \gamma^\mu \, W_\mu^+ \, d_L \; - d_L \, \gamma^\mu \, W_\mu^3 \, d_L \right)$

Flavor changing charged current

Flavor conserving neutral current

So what’s the problem?

- Q: Are the mass eigenstates and the flavor eigenstates the same?
- A: No

Flavor states are linear combinations of mass states

- $\begin{bmatrix} u' \\ c' \\ t' \end{bmatrix} = V_u \begin{bmatrix} u \\ c \\ t \end{bmatrix}$
- So:

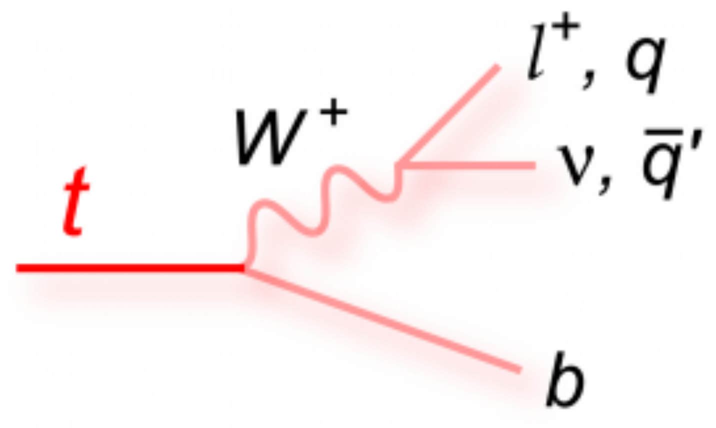
$$(\bar{u}'_L \, \gamma^\mu \, W_\mu^+ \, d'_L \; - d'_L \, \gamma^\mu \, W_\mu^3 \, d'_L) \rightarrow (\bar{u}_L V_u^\dagger \; \gamma^\mu \, W_\mu^+ \, V_d \, d_L \; - d_L V_d^\dagger \gamma^\mu \, W_\mu^3 \, V_d \, d_L)$$

If $V_d^\dagger V_d = 1$, there are still no tree-level FCNC

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

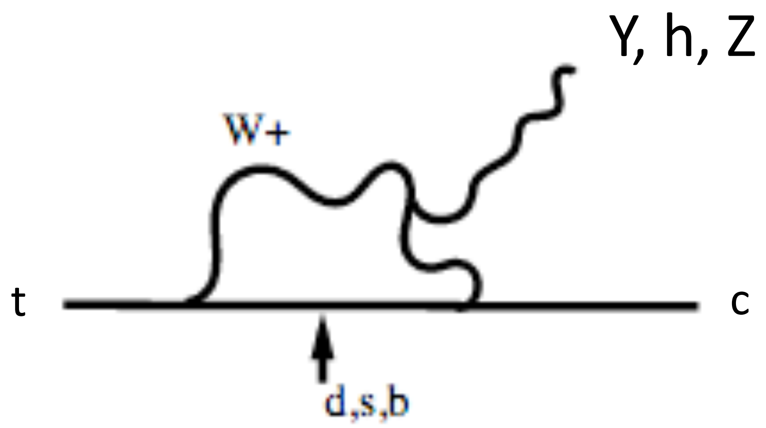
Top decays

- We can get our top decays from $\bar{u}_L V_u^\dagger\ \gamma^\mu\ W_\mu^+\ V_d\ d_L$
- The CKM matrix value here is basically 1: $V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$
- So the only process that ever really happens in the SM is



Top decays- with loops!

- Here's a diagram we could draw:

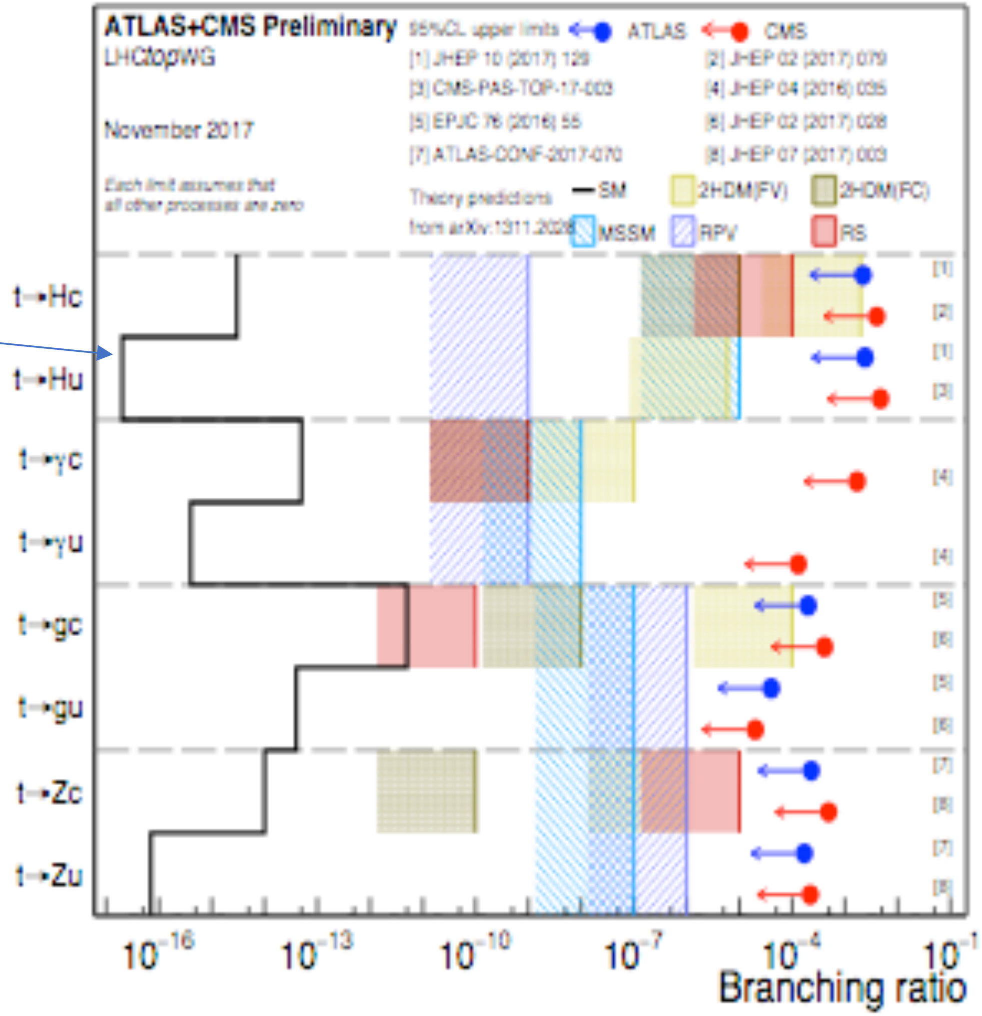


- But wait!

$$A \sim \propto \sum_{q} V_{tq}^{*} V_{cq} = 0$$

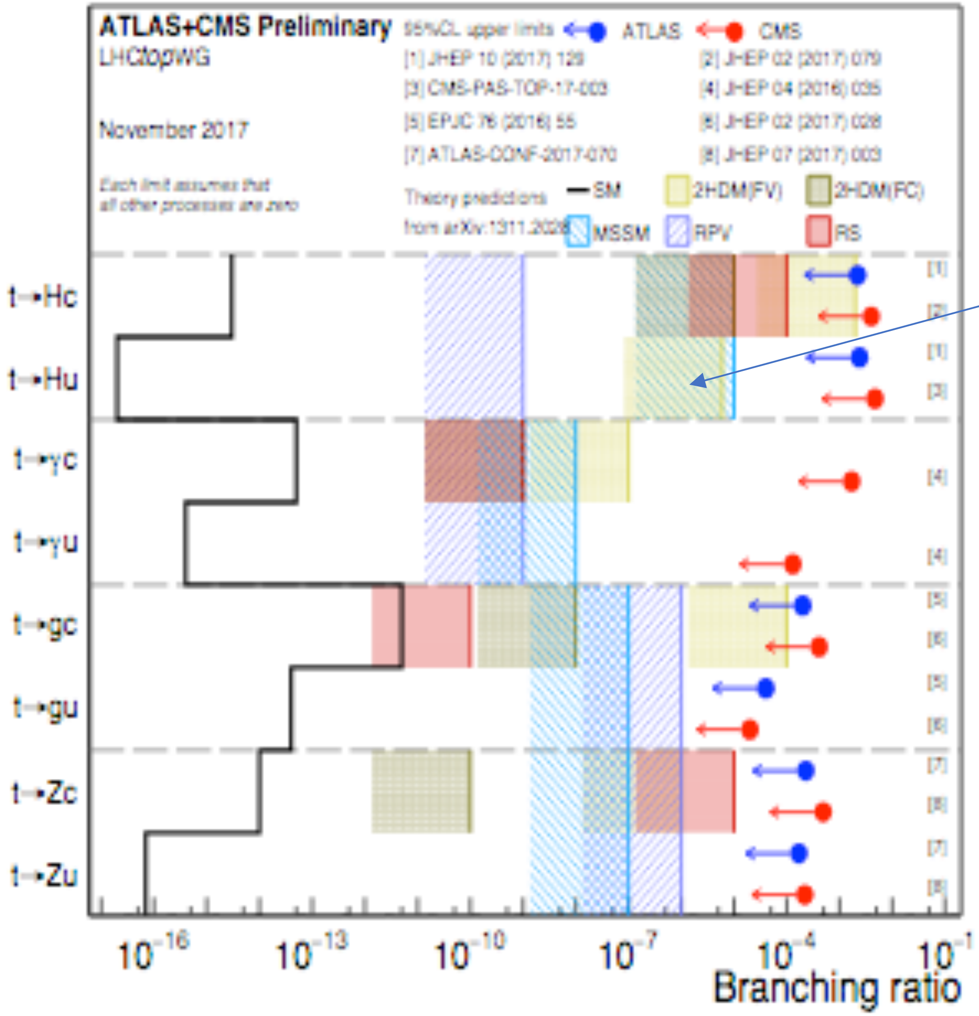
So why should I care?

Standard model branching ratios in black



You will (probably) never see something with a branching ratio that small

So why should I care?



BSM models might enhance the BR

Let’s look at some models

- Preface: most of these models are meant to solve some open problem (e.g. CP violation, hierarchy problem, dark matter, grand unification)
- FCNC top decays end up being a testable prediction
- People aren’t just making theories to explain some FCNC phenomenon that hasn’t been observed yet

Let’s look at some models – Just EFT

- We can generically think of the SM as an effective theory with some cutoff scale of applicability
- Terms in Lagrangian with mass dimension in fields > 4 flow to 0 as cutoff $\rightarrow \infty$ (see “renormalization group” in your fav QFT book)
- In our low energy regime, specifics of “UV completion” don’t really matter than much

Let's look at some models – Just EFT

- Add terms like: $O_y = \frac{\tilde{y}^d_{ij}}{\Lambda^2}\,\bar{q}_{L\,i} H d_{R\,j}(H^\dagger H) + h.c.$

$$O_q = \frac{\kappa^q_{ij}}{\Lambda^2}\,\bar{q}_{L\,i}\, i\not{D} q_{L\,j}(H^\dagger H) + h.c.$$

$$O'_q = \frac{\kappa'^q_{ij}}{\Lambda^2}\,\bar{q}_{L\,i}\, H H^\dagger i\not{D} q_{L\,j} + h.c.$$

$$O_d = \frac{\kappa^d_{ij}}{\Lambda^2}\,\bar{d}_{R\,i}\, i\not{D} d_{R\,j}(H^\dagger H) + h.c.$$

- In SM, mass eigenstates are flavor-diagonalized
- These terms allows some off-diagonalization
  - See https://arxiv.org/pdf/0906.1542.pdf for derivation

Let's look at some models – Composite Higgs

- In this model, our regular higgs doublet is a bound state (like a pion) of some new dynamics
- SM fermions couple to the new sector, e.g.: $\lambda_L \bar{\psi}_L O_R + \lambda_R \bar{\psi}_R O_L + h.c.$
- Then you end up with coefficients like

$$y^d \sim y_* \frac{\lambda_L \lambda_R}{16\pi^2} \qquad \tilde{y}^d \sim y_*^3 \frac{\lambda_L \lambda_R}{16\pi^2} \qquad \kappa^q, \kappa'^q \sim y_*^2 \frac{\lambda_L^2}{16\pi^2} \qquad \kappa^d \sim y_*^2 \frac{\lambda_R^2}{16\pi^2}$$

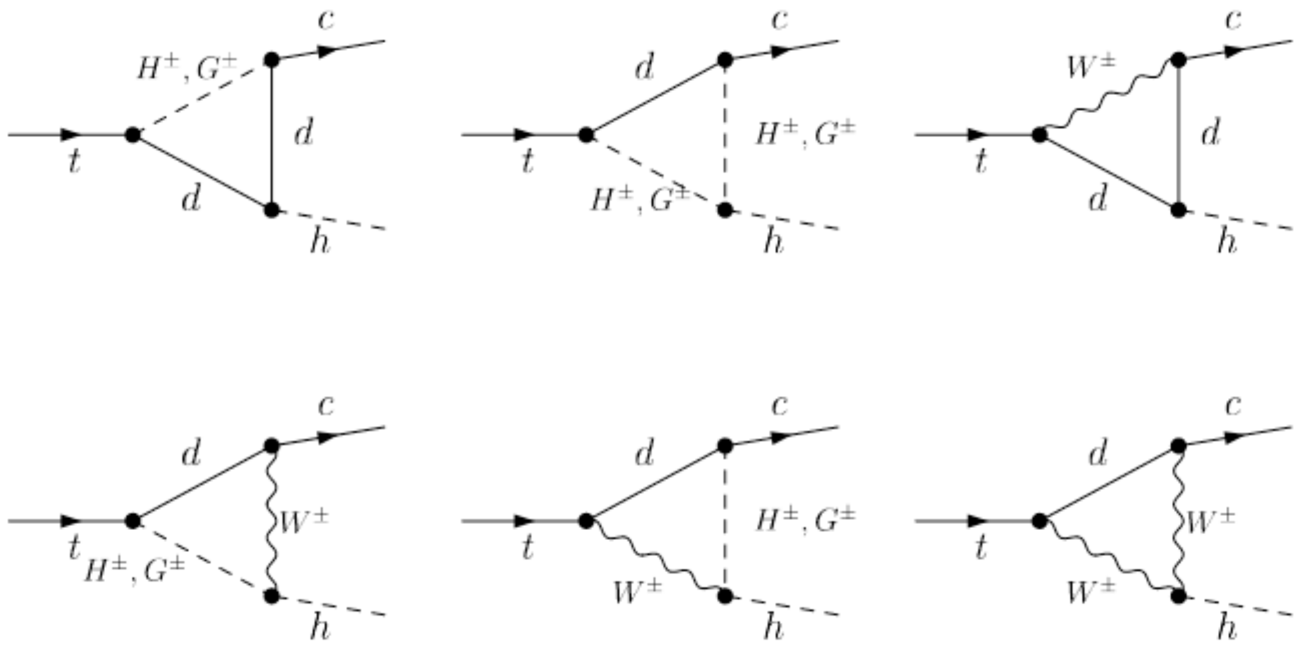
for last slide's EFT (see https://arxiv.org/pdf/0906.1542.pdf again)

Let’s look at some models – Extra Dimensions

- Common extra dimensional models result in a “Kaluza-Klein tower” of particles, essentially giving heavy copies of SM particles
- There’s shift in the top’s coupling to heavier Z’s
  - See https://arxiv.org/pdf/hep-ph/0606293.pdf
  - Involves branes?
- Get a term like $\mathcal{L}^t_{\mathrm{FC}} \ni \left(g_1 \bar{t}_R \gamma_\mu c_R + g_2 \bar{t}_L \gamma_\mu c_L\right) Z^\mu g_Z$

Let’s look at some (super) models – 2 Higgs Doublets

- If a theory involves 2 Higgs doublets, that’s 8 KG fields
  - 3 eaten by W’s and Z
  - 5 real scalar particles left!
- These introduce many new loops to e.g. t->hc
  - Don’t necessarily suffer from GIM-type suppression, leading to enhanced branching ratio!



Let's look at some (super) models

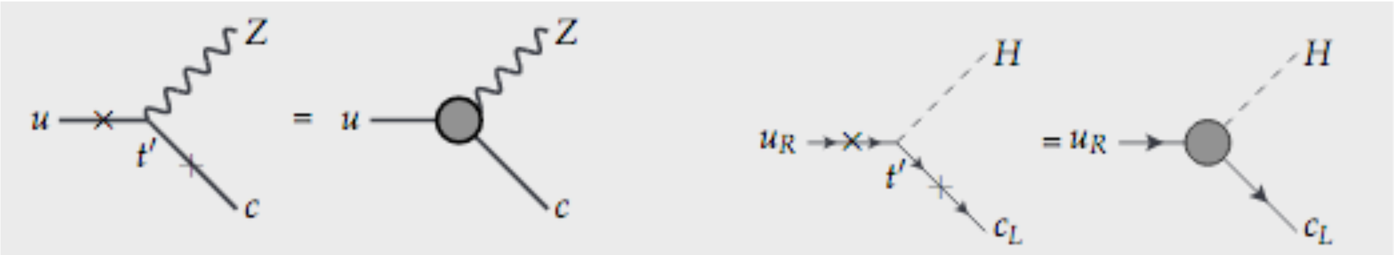
Table 1-7. *SM and new physics model predictions for branching ratios of top FCNC decays. The SM predictions are taken from [119], on 2HDM with flavor violating Yukawa couplings [119, 120] (2HDM (FV) column), the 2HDM flavor conserving (FC) case from [121], the MSSM with 1TeV squarks and gluinos from [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}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

https://arxiv.org/pdf/1311.2028.pdf

Let’s look at some models – Vector Quarks

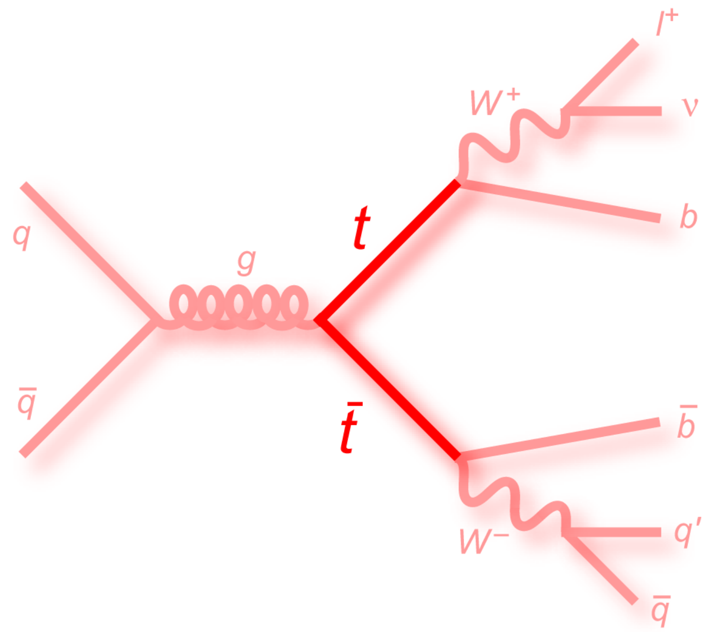
- See Jennet’s talk from last week for actual description of vector quarks
    - Main takeaway for this: we get heavy quark
- You can generically get couplings like:



- You can also make loops with these vertices, which might get around the GIM mechanism

Actually looking for FCNC top decays

- At any pp (or $p\bar{p}$) collider of adequate energy, you'll make a lot of $t\bar{t}$ pairs
  - LHC produces ~1,000,000 per year
- Fairly distinct experimental signature: 2 b-jets and 2 W's



Actually looking for FCNC top decays

- Since we're looking for FCNC top decays, the main channel of interest is $t\bar{t}$, where one of the tops goes t->hc
- You want to get as distinct a signal as possible, so probably look for higgs decays with multiple leptons (WW*, ZZ*, $\tau\bar{\tau}$)
- Main backgrounds end up being:

  - $t\bar{t}W$, $t\bar{t}(Z/\gamma^* \to \ell\ell)$, $t\bar{t}H$, and $t\bar{t}WW$;
  - $t\bar{t}t$ and $t\bar{t}t\bar{t}$;
  - single top quark production in the s- and t-channels, tW, tZ, tWZ, tHb, and tHW;
  - production of two or three W or Z/γ^* bosons.

Experimental challenges

- How hard can it be to just find an event with e.g.
  - A charm jet
  - A b-jet
  - A lepton and neutrino that add up to an on-shell W
  - Four leptons that add up to an on-shell h

Experimental challenges

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  - A charm jet
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ALL OF THESE OBJECTS SUFFER FROM SOME KIND OF SMEARING

Experimental challenges

- How often will the background signals really contaminate your signal?
  - That’s a good question-> you have to estimate
- The same smearing effects that make the signal hard to tag will make the background look like signal!

Experimental challenges

- How often will the background signals really contaminate your signal?
  - That’s a good question-> you have to estimate
- The same smearing effects that make the signal hard to tag will make the background look like signal!

Process	Cross section [pb]
$t\bar{t}W$	0.60
$t\bar{t}(Z/\gamma^* \rightarrow \ell\ell)$	0.12
$t\bar{t}H$	0.51
$t\bar{t}t\bar{t}$	0.0092
$t\bar{t}W^+W^-$	0.0099
$tHqb$	0.074
tHW	0.015
tZ	0.61
tWZ	0.16
s-, t-channel,	10, 217
Wt single top	72
$t\bar{t}$	832
$t\bar{t}\gamma$	5.7
$VV(\rightarrow \ell\ell XX)$	37
$Z \rightarrow \ell^+\ell^-$	2070

And there’s a lot of background! (relatively)

Experimental challenges

Category		Non-prompt leptons	$t\bar{t}V$	$t\bar{t}H$	Diboson	Other prompt SM	Total SM	FCNC	Data
				$t \to Hu$					
$2\ell SS$	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	61 ± 13	514
	Post-fit	240 ± 37	167 ± 18	43 ± 4	24 ± 14	28 ± 6	502 ± 33	13 ± 21	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	32 ± 6	258
	Post-fit	104 ± 20	84 ± 8	23 ± 3	19 ± 10	24 ± 5	254 ± 18	7 ± 11	
				$t \to Hc$					
$2\ell SS$	Pre-fit	266 ± 40	165 ± 19	43 ± 4	25 ± 15	28 ± 6	526 ± 39	62 ± 13	514
	Post-fit	264 ± 41	165 ± 18	42 ± 4	20 ± 11	28 ± 6	520 ± 36	-3 ± 25	
3ℓ	Pre-fit	126 ± 31	84 ± 8	23 ± 3	20 ± 11	24 ± 5	276 ± 33	30 ± 6	258
	Post-fit	116 ± 21	84 ± 8	23 ± 3	15 ± 8	23 ± 5	262 ± 19	-1 ± 12	

ATLAS trained a BDT to distinguish FCNC events from background

Yields if BR(t->hc) = 0.2%

What you’d hope to see

- With SM, you don’t expect to see direct evidence of FCNC top decays
- The “smoking gun” would be an excess in the number of observed events in the signal region
- If you don’t see it, all you can do is give an upper limit to the BR based on your sensitivity

Historical results

Table 1. The most stringent experimental upper bounds on the top quark FCNC branching ratios at 95% CL obtained in CDF, D0, ATLAS and CMS from different channels.

<table>
<tr><th>EXP</th><th>$\sqrt{s}$TeV</th><th>$\mathcal{L}(fb^{-1})$</th><th>Br</th><th>(q=u)%</th><th>(q=c)%</th><th>Ref</th></tr>
<tr><td>ATLAS</td><td>7&8</td><td>25</td><td rowspan="2">$t \to qH$</td><td colspan="2">0.79</td><td>[9]</td></tr>
<tr><td>CMS</td><td>8</td><td>19.5</td><td colspan="2">0.56</td><td>[10]</td></tr>
<tr><td>CDF</td><td>1.8</td><td>0.11</td><td rowspan="2">$t \to q\gamma$</td><td colspan="2">3.2</td><td>[15]</td></tr>
<tr><td>CMS</td><td>8</td><td>19.1</td><td>0.0161</td><td>0.182</td><td>[19]</td></tr>
<tr><td>CDF</td><td>1.96</td><td>2.2</td><td rowspan="5">$t \to qg$</td><td>0.039</td><td>0.57</td><td>[20]</td></tr>
<tr><td>D0</td><td>1.96</td><td>2.3</td><td>0.02</td><td>0.39</td><td>[28]</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.56</td><td>7.12</td><td>[26]</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.035</td><td>0.34</td><td>[25]</td></tr>
<tr><td>ATLAS</td><td>8</td><td>14.2</td><td>0.0031</td><td>0.016</td><td>[21]</td></tr>
<tr><td>CDF</td><td>1.96</td><td>1.9</td><td rowspan="5">$t \to qZ$</td><td colspan="2">3.7</td><td>[27]</td></tr>
<tr><td>D0</td><td>1.96</td><td>4.1</td><td colspan="2">3.2</td><td>[28]</td></tr>
<tr><td>CMS</td><td>7</td><td>4.9</td><td>0.51</td><td>11.40</td><td>[26]</td></tr>
<tr><td>ATLAS</td><td>7</td><td>2.1</td><td colspan="2">0.73</td><td>[29]</td></tr>
<tr><td>CMS</td><td>7&8</td><td>24.7</td><td colspan="2">0.05</td><td>[30]</td></tr>
</table>

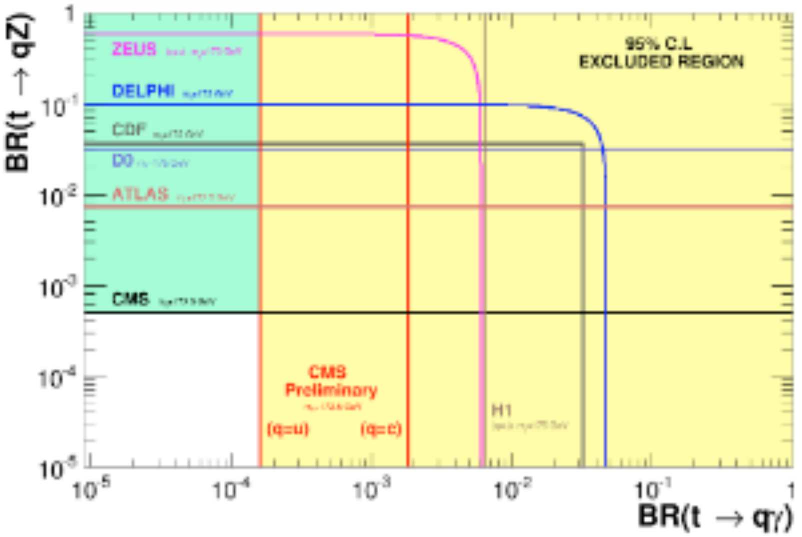
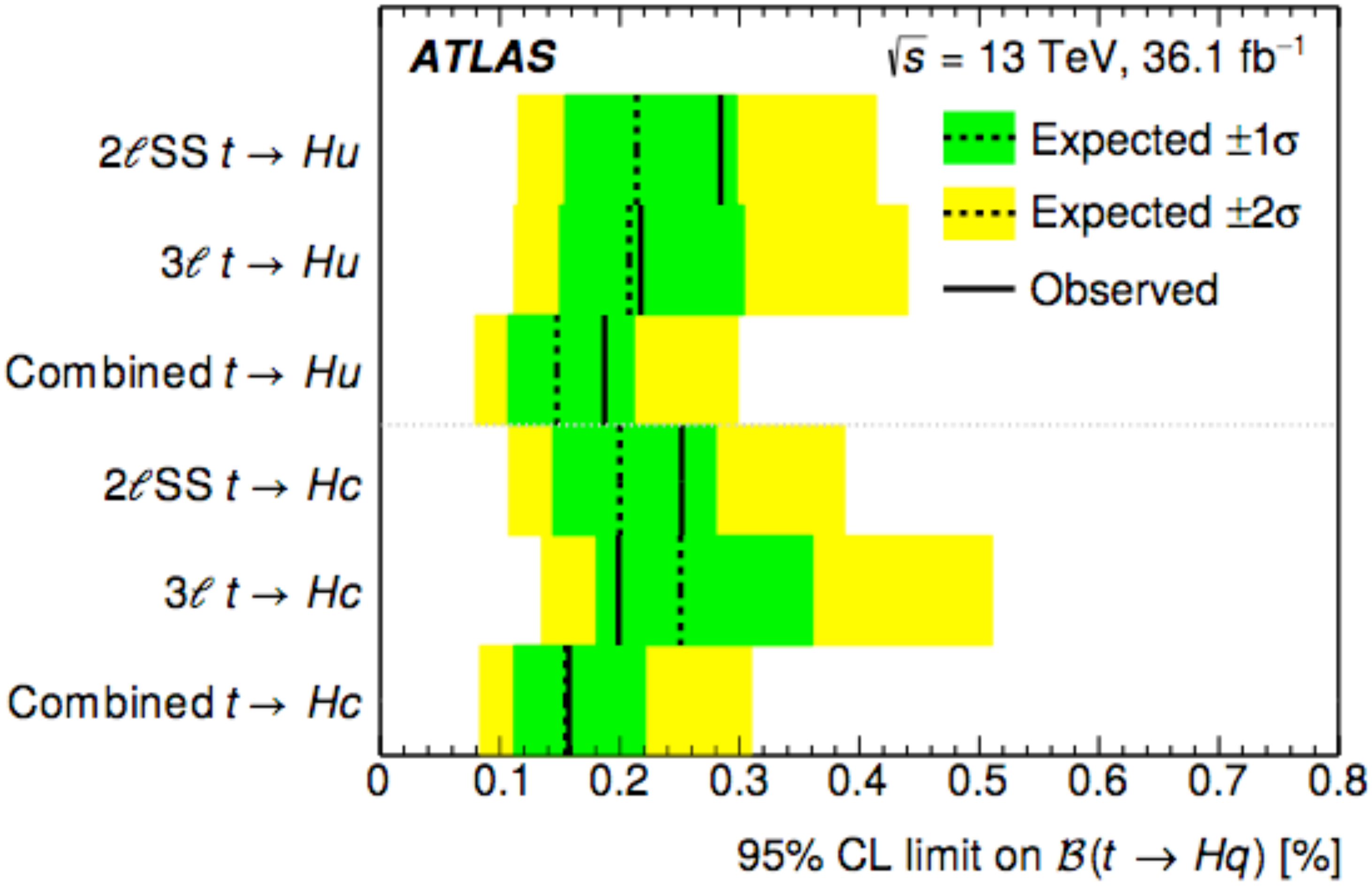


Figure 3. The observed 95% C.L. upper limit on the $BR(t \to q\gamma)$ vs $BR(t \to qZ)$ for the DELPHI, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations.

https://arxiv.org/pdf/1412.2524.pdf

2018 ATLAS paper



https://arxiv.org/pdf/1805.03483.pdf

Summary and conclusions

- SM predicts that we should not see FCNC top decays
- If we DID, that'd be a sign of BSM physics
- As of now, current experiments aren't really able to rule out popular models that would give FCNC enhancements
- With increasing statistics, BR constraints should be come stronger

References

- Theory:
  - EFT and composite higgs: https://arxiv.org/pdf/0906.1542.pdf
  - Extra dimensions: https://arxiv.org/pdf/hep-ph/0606293.pdf
  - MSSM: https://arxiv.org/pdf/hep-ph/9906268.pdf
  - General 2HDM: https://arxiv.org/pdf/hep-ph/0011091.pdf
  - Vector quarks: http://www.ectstar.eu/sites/www.ectstar.eu/files/talks/Panizzi.pdf
- Experiment:
  - Top quark studies: https://arxiv.org/pdf/1311.2028.pdf
  - Contains historical results: https://arxiv.org/pdf/1412.2524.pdf
  - 2018 ATLAS paper: https://arxiv.org/pdf/1805.03483.pdf