Rare Top Quark Decays

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ATLAS and CMS Collaborations
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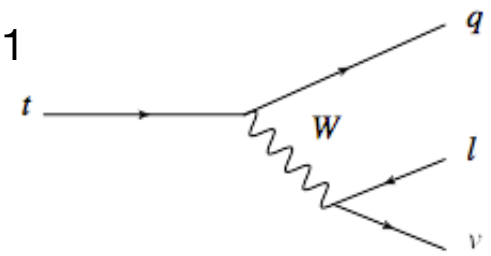
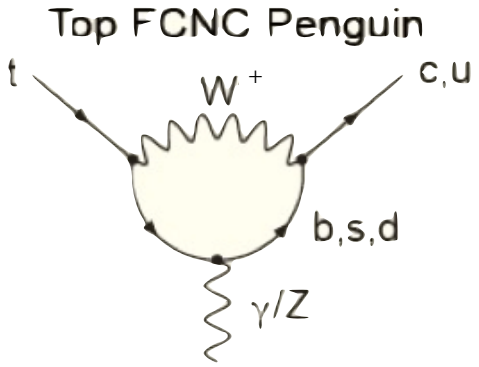
Introduction

❖ **In the standard model (SM):**

- The top decays to bW with branching ratio~1 due to $|V_{tb}|$~0.9991
- Flavor changing neutral currents (FCNC) are forbidden at tree level, and only allowed via high order corrections like penguin diagrams (suppressed by GIM mechanism).





❖ **Rare top quark decays**

Studies of rare top quark decays can not only test the SM, but also probe if a new physics exists. This talk includes rare decays via three kinds of ways,

- Via charged current :

  A challenge to measure B(**t → Wd**) or B(**t → Ws**), and more straightforward to measure $R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)}$

- Via FCNC :

  Including qg, qγ, qZ, and qH decays. Enhanced by new physics(MSSM, ~~R~~ SUSY..)

- Via baryon number violation (BNV) :

  Baryon number conserves in the SM, but a small violation can arise from non-perturbative effects[1]. Also, it can naturally occur with a new physics.

  $t \to \bar{b}\bar{u}e^+$ $(\bar{t} \to bue^-)$ and $t \to \bar{b}\bar{c}\mu^+$ $(\bar{t} \to bc\mu^-)$

[1] PhysRevLett.37.8 (1976)

Rare Decays via Charged Current

R = B(t → W + b)/B(t → W + q)

Pair Production

❖ Motivation :

- SM prediction (Phys. Rev. Lett. 37(1976) 8-11)

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.99830^{+0.00006}_{-0.00009}$$

- A tension with SM from D0 measurement (**PhysRevLett.107.121802**)

$$R = 0.90 \pm 0.04(\text{stat} + \text{syst})$$

$$|V_{tb}| = 0.95 \pm 0.02$$

❖ Event selection :

2 isolated leptons (e or μ), ≥ 2 jets, and MET

❖ Profile likelihood (λ) :

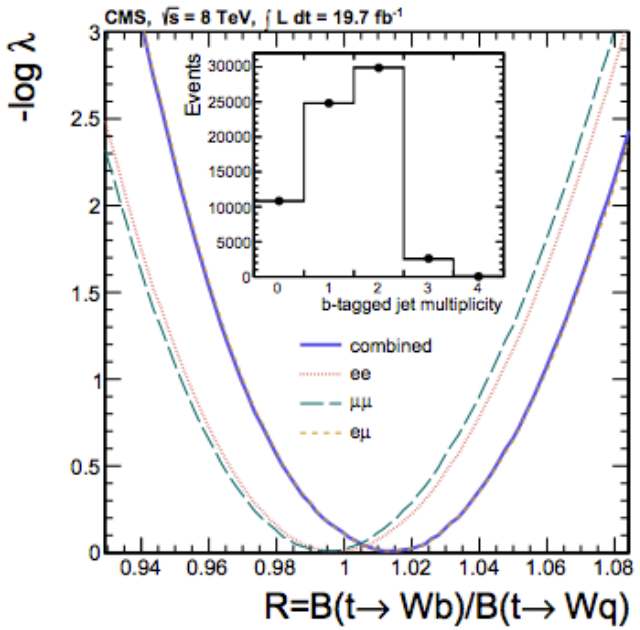
- Composed of signal purity, jet mis-assignment and probability of b-tagging as a function of R.

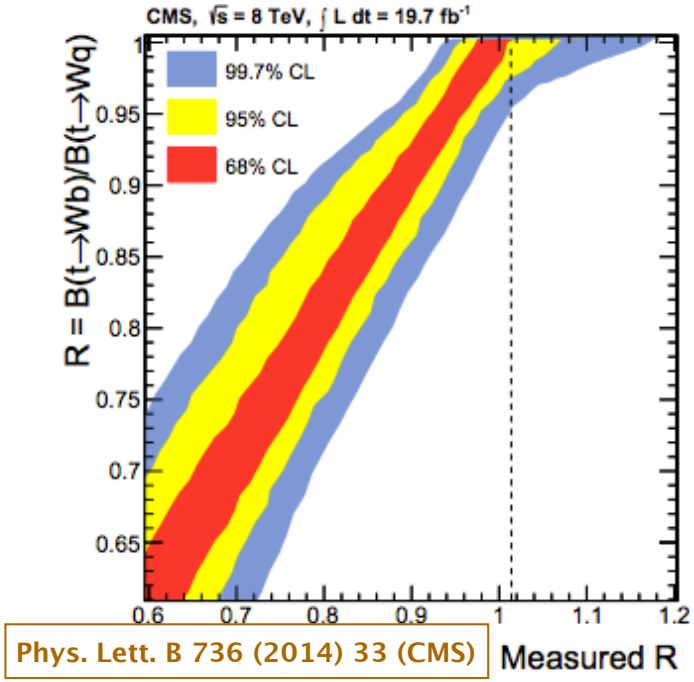
- R obtained by maximizing the profile likelihood.

❖ Result :

- Limit bands obtained from the Feldman-Cousins methods.

- If R ≤ 1, we obtain R > 0.955 at 95%C.L.
$|V_{tb}| > 0.975$





Phys. Lett. B 736 (2014) 33 (CMS)

Rare Decays via Flavor Changing Neutral Current (FCNC)

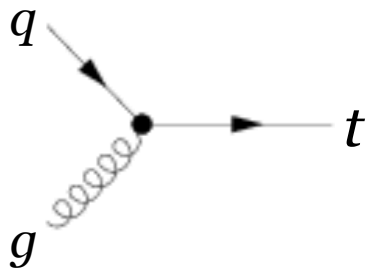
Search for single top-quark production via FCNC B(t → g + q)

Single top Production

❖ Motivation :

- FCNC top decays suppressed by SM (~10^{-14})
- Enhanced by new physics (new exotic quarks, SUSY, or technicolor) up to ~10^{-3}

❖ B(**t → g + q**) performed by searching for anomalous single top production (**qg → t**)



❖ Event selection :

Isolated lepton (e or μ), 1 b-jet, and MET

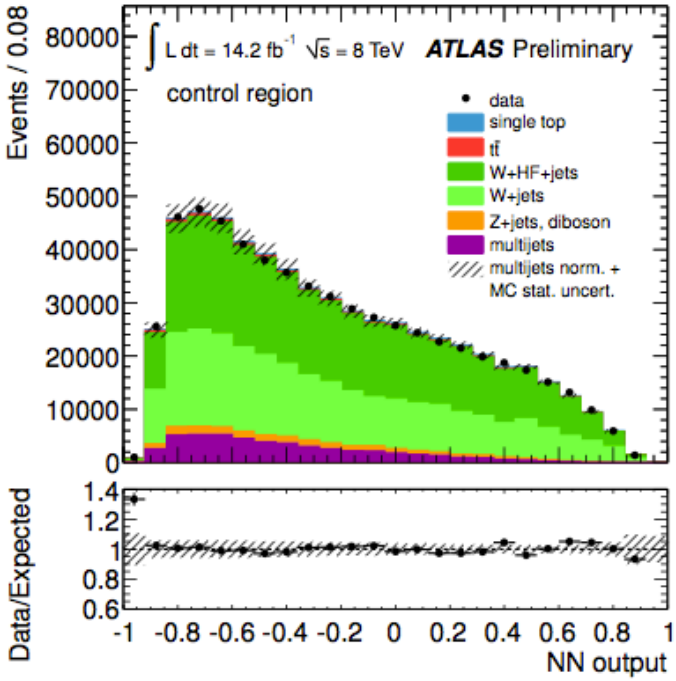
❖ Resulting plot :

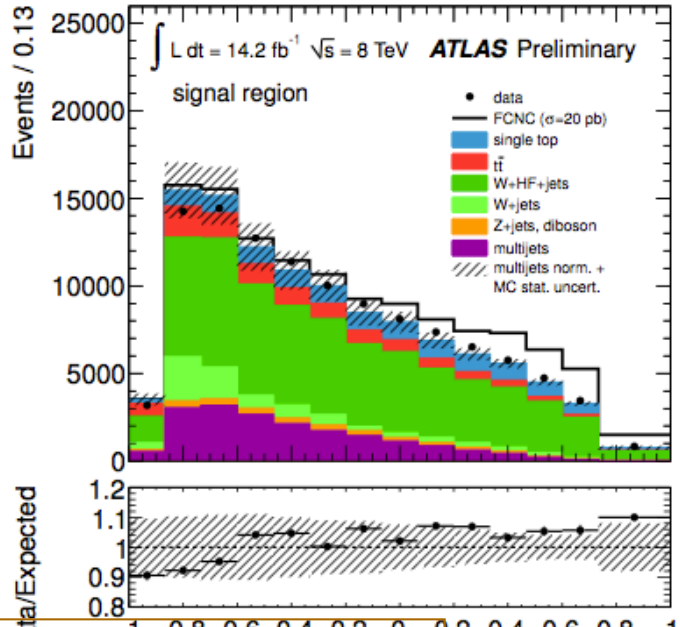
Neutral network output used to distinguish signal from background.

❖ Result :

- B(t → g + u) < 3.1x10^{-5} (assuming B(t → gc)=0)
- B(t → g + c) < 1.6x10^{-4} (assuming B(t→ gu)=0)

(Compared to 7TeV result: B(t →gu) ≤ 0.56% & B(t →gc) ≤ 7.12%, reference to CMS PAS-TOP-12-021)





ATLAS CONF-2013-063

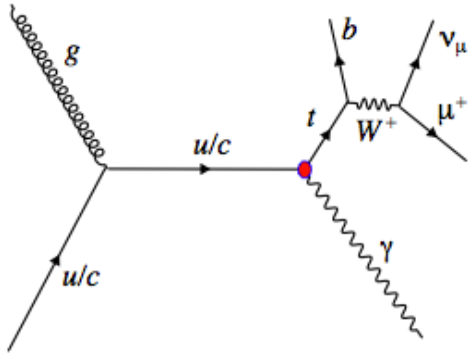
Search for single top-quark production via FCNC B(t → γ + q)

Single top Production

❖ Motivation :

- FCNC top decays suppressed by SM (~10^{-14})
- Enhanced by new physics (two-Higgs doublet model (2HDM), SUSY, or technicolor) up to ~10^{-5}

❖ Analysis performed using single top production



❖ Event selection :

Isolated muon with a photon, 1 b-jet, and MET

❖ Background estimation :

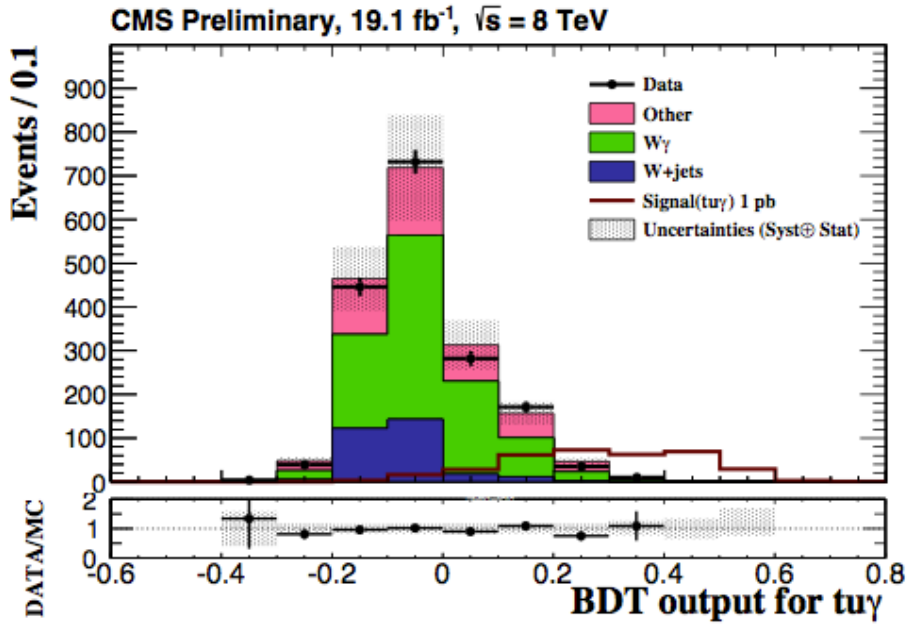
- Wγ / W + jets obtained using a data-driven method (template fit)
- Others from simulation

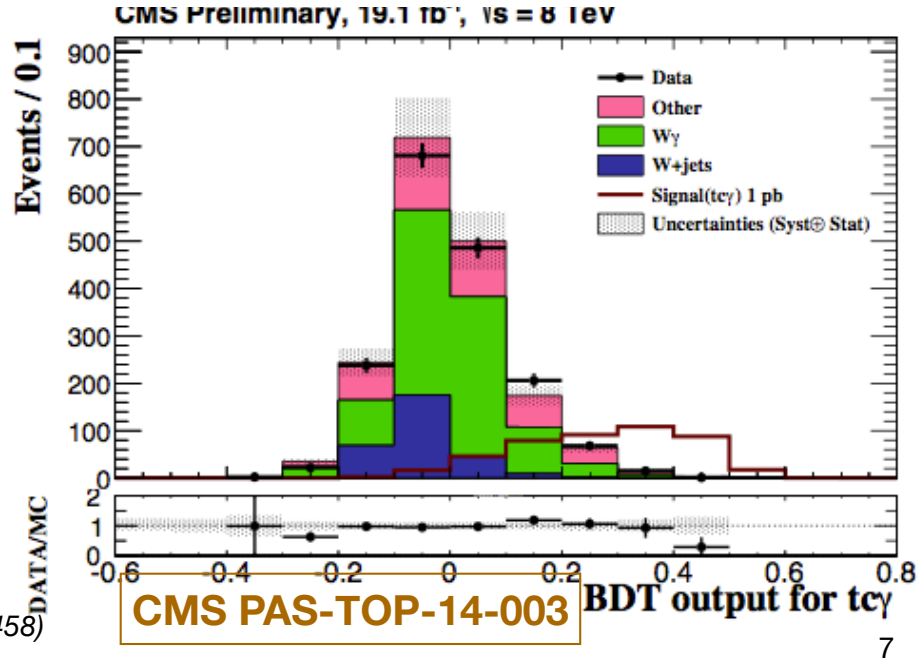
❖ A boosted decision tree (BDT) used to distinguish signal from background.

❖ Result :

- B(t → γ + u) < 0.0161% (assuming B(t → γc)=0)
- B(t → γ + c) < 0.182% (assuming B(t→ γu)=0)

(Compared to HERA result: B(t →γu) < 0.64%, Phys. Letters B 678 (2009) 450–458)





CMS PAS-TOP-14-003

Searching for FCNC in t → Z + q

Pair Production

❖ Motivation :

- Highly suppressed in the SM by GIM ($\sim 10^{-14}$)
- Enhanced in R-parity violating SUSY, top color assisted technicolor models ($\sim 10^{-4}$)

❖ Event selection :

Two opposite-site isolated leptons (e or μ), one extra lepton, and exactly 1 b-jet

❖ Mass reconstruction :

$m(l+\nu)=m_W$, $m(b+l+\nu)\leftrightarrow m_{Wb}$, $m(Z(ll)+\text{another j})$

❖ Background Estimation :

$$
\begin{aligned}
N_{all} &= N_{0b} + N_{1b} + N_{2b}, \\
N_{0tag} &= \alpha_1 N_{0b} + \alpha_2 N_{1b} + \alpha_3 N_{2b}, \\
N_{1tag} &= \beta_1 N_{0b} + \beta_2 N_{1b} + \beta_3 N_{2b},
\end{aligned}
$$

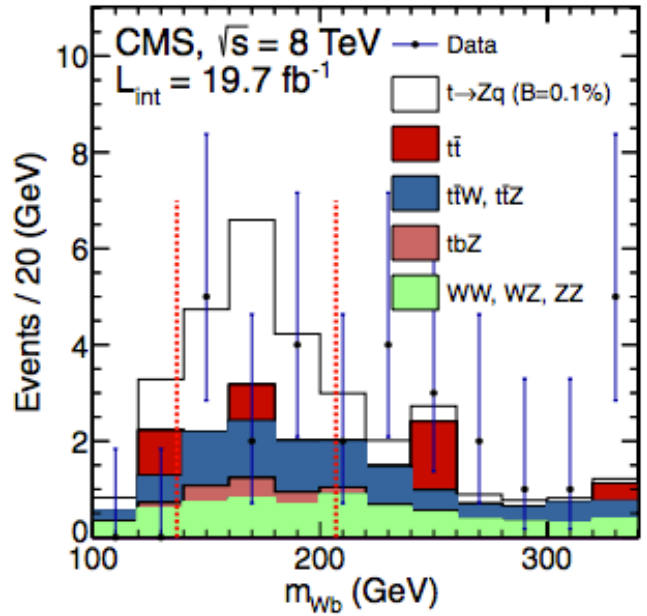
α_i : b-tag efficiency
β_i : fake rate

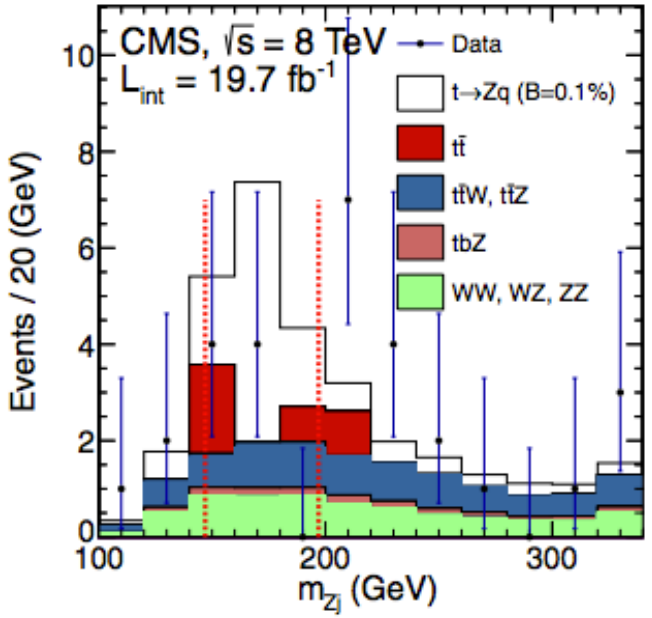
❖ Result :

observed (expected) limit on

B(t → Z + q)<0.05% (0.09%)

(Compared to 7TeV result: B(t →Zq) ≤ 0.73%, JHEP09(2012)139)





Phys. Rev. Lett. 112 (2014) 171802 (CMS)

Searching for FCNC in t → H + c

Pair Production

❖ Motivation:

Relatively large σ_{tt} and top having the largest coupling to the Higgs sector

❖ FCNC top decay including:

t → c +

$H \to WW^* \to \ell\nu\ell\nu$,
$H \to \tau\tau$,
$H \to ZZ^* \to jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$,
$H \to \gamma\gamma$.

❖ Event selection :

Multi-leptons (≥3leptons)

Di-photons+lepton

❖ Background estimation :

Multi-leptons (≥3leptons)

Use fake rate to estimate dominant bkg(Z+jets)

Di-photons+lepton

Use the sidebands around Mγγ using an exponential function

❖ Result :

observed (expected) limit on B(**t → H + c**)<0.56% (0.65%) --> $\sqrt{|\lambda_{tc}^H|^2 + |\lambda_{ct}^H|^2} < 0.14$

Multi-leptons

OSSF pair	$N_{\tau_{had}}$	E_T^{miss} [GeV]	H_T [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
below Z	0	50–100	0–200	≥ 1	48	48 ± 23	9.5 ± 2.3	10.3 ± 2.5
n/a	0	50–100	0–200	≥ 1	29	26 ± 13	5.9 ± 1.3	6.4 ± 1.4
below Z	0	0–50	0–200	≥ 1	34	42 ± 11	5.9 ± 1.2	6.4 ± 1.3
n/a	0	0–50	0–200	≥ 1	29	23 ± 10	4.3 ± 1.1	4.7 ± 1.2
below Z	0	50–100	> 200	≥ 1	10	9.9 ± 3.7	3.0 ± 1.1	3.3 ± 1.2
below Z	0	0–50	> 200	≥ 1	5	10 ± 2.5	2.8 ± 0.8	3.1 ± 0.9
below Z	0	50–100	0–200	0	142	125 ± 27	9.7 ± 2.1	10.6 ± 2.3
n/a	1	0–50	0–200	≥ 1	237	240 ± 113	13.1 ± 2.6	14.3 ± 2.8
n/a	0	50–100	0–200	0	35	38 ± 15	4.3 ± 1.1	4.7 ± 1.2
above Z	0	0–50	0–200	≥ 1	17	18 ± 6.7	2.8 ± 0.8	3.1 ± 0.9

Assuming B(t → H + c) at 1%

Di-photons + lepton

$N_{\tau_{had}}$	E_T^{miss} [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
0	50–100	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39	3.1 ± 0.4
0	30–50	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30	2.4 ± 0.3
0	0–30	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24	1.9 ± 0.3
0	50–100	0	7	9.5 ± 4.4	2.22 ± 0.31	2.4 ± 0.3
0	> 100	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14	1.0 ± 0.2
0	> 100	0	1	2.2 ± 1.0	0.94 ± 0.17	1.0 ± 0.2
0	30–50	0	29	21 ± 10	1.51 ± 0.22	1.6 ± 0.2
1	30–50	≥ 1	2	2.1 ± 1.2	0.43 ± 0.09	0.5 ± 0.1
1	0–30	≥ 1	6	6.4 ± 3.3	0.48 ± 0.12	0.5 ± 0.1
1	50–100	≥ 1	1	1.5 ± 0.8	0.30 ± 0.08	0.3 ± 0.1

Assuming B(t → H + c) at 1%

CMS PAS-HIG-13-034

Searching for FCNC in t → H + q

Pair Production

❖ Enhanced by Quark-singlet model(QS), 2HDM of type I with explicit flavour conservation (FC-2HDM), or 2HDM of type II (like MSSM), 2HDM without explicit flavour conservation (2HDM-III)

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

❖ Top quark decays to an up-type (c,u) quark + a Higgs

❖ Event selection :

Hadronically decaying top quark

2γ, ≥ 4 jets, and ≥ 1 b-jet

Leptonically decaying top quark

2γ, an isolated lepton(e or μ), ≥ 2 jets, and ≥ 1 b-jet

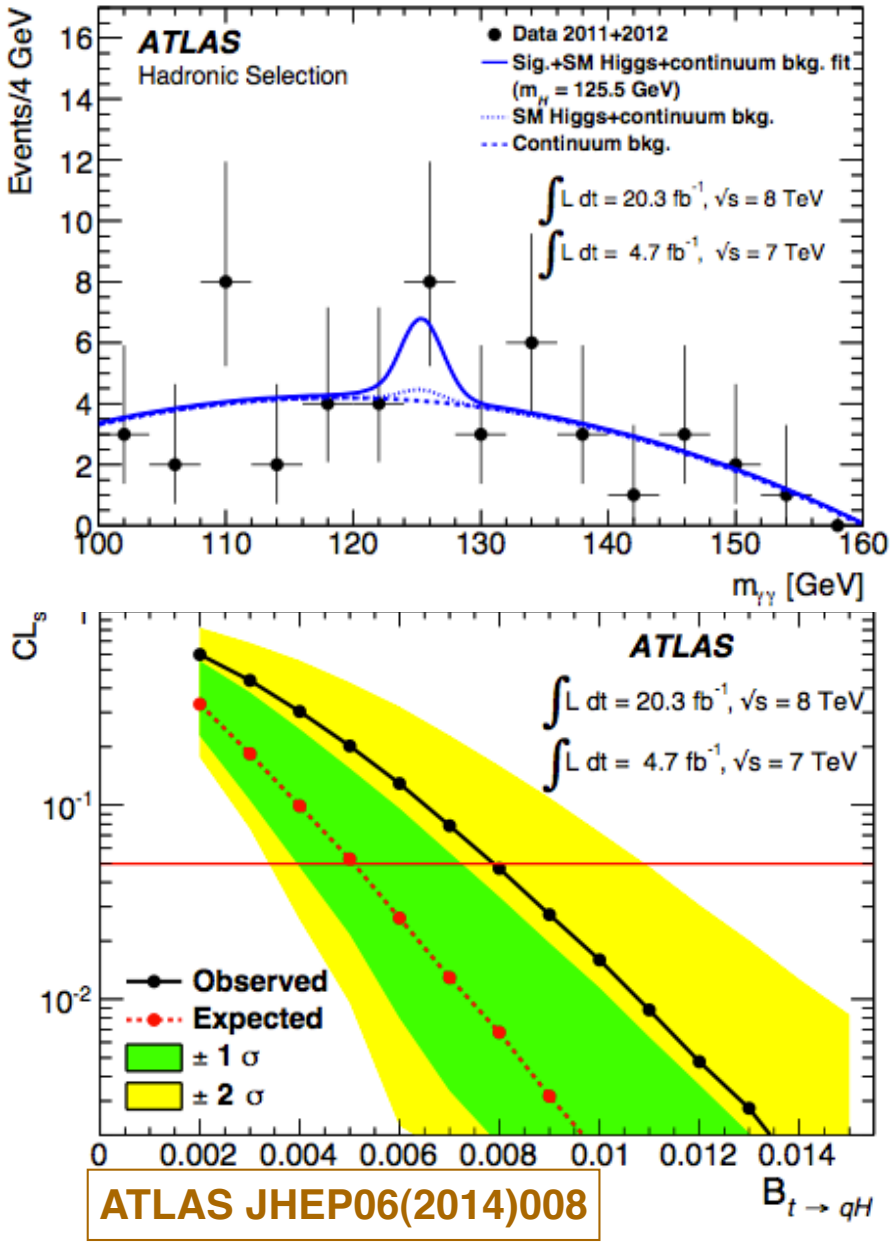
❖ Signal & Background modeling for $M_{\gamma\gamma}$:

Signal shape : Gaussian + Crystal Ball

Bkg shape : Polynomial function

❖ Result

observed (expected) limit on B(**t → H + q**)<0.79% (0.51%) --> $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$ (0.14)



Rare Decays via Baryon Number Violation (BNV)

Search for baryon number violating top decays
$t \rightarrow b + u + e$ (or $b + c + \mu$)

Pair Production

❖ Motivation :

- Small BNV can arise from non-perturbative effects in the SM ~ too small to be realistically measurable (BNV top decays ~1fb ~B(10^{-6}), arXiv:1107.3805).
- Naturally occurs in new physics (SUSY, grand unified theories, and black hole)

❖ BNV top decays :

$$t \rightarrow \bar{b}\bar{u}e^{+} \; (\bar{t} \rightarrow bue^{-})$$
$$t \rightarrow \bar{b}\bar{c}\mu^{+} \; (\bar{t} \rightarrow bc\mu^{-})$$

❖ Event selection :

An isolated lepton (e or μ), ≥ 5 jets, and lower MET

❖ Background modeling :

Top and electro-weak backgrounds (MC)

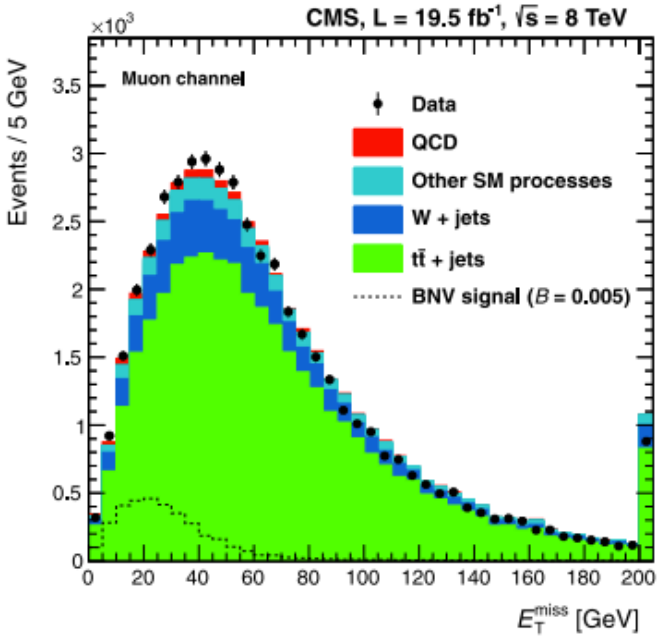
QCD background (data-driven)

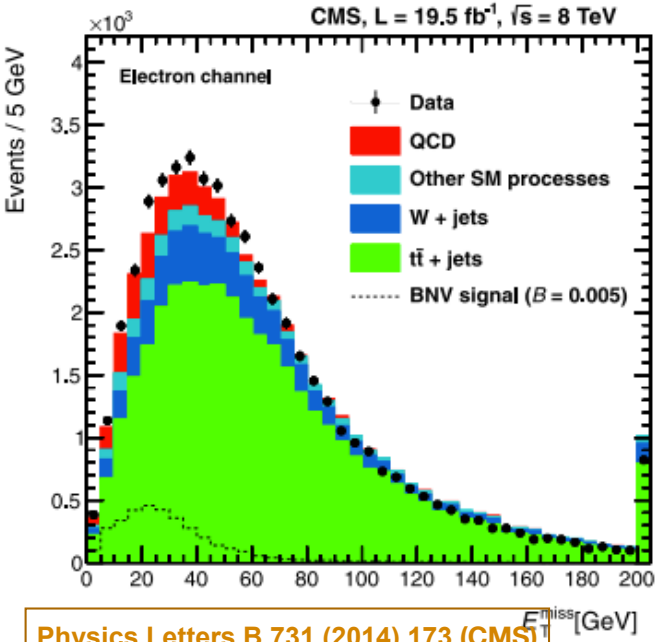
$$N_{QCD} = R(N_{data}^{anti-iso} - N_{non-QCD}^{anti-iso})$$

$$R = f/(1-f)$$ fake rate

❖ Result :

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0046]
Electron	0.0017	0.0030	[0.0017, 0.0047]
Combined	0.0015	0.0028	[0.0016, 0.0046]





Physics Letters B 731 (2014) 173 (CMS)

Summary

❖ The ATLAS and CMS collaborations have performed a number of studies for rare top quark decays.

- No significant excess of events over the expected yields from the SM processes

- Set limits on the (branching) ratios :

Interaction	Model	Result		
Charged Current	$\frac{B(t\to Wb)}{B(t\to Wq)}$	> 0.955	19.7 fb^{-1} @8 TeV	Phys. Lett. B 736 (2014) 33 (CMS)
FCNC	t→gc(u)	< 1.6x10^{-4} (3.1x10^{-5})	14.2 fb^{-1} @8 TeV	ATLAS CONF-2013-063
	t→γc(u)	<0.182% (0.0161%)	19.1 fb^{-1} @8 TeV	CMS PAS-TOP-14-003
	t→Zq	< 0.05%	5.0 fb^{-1} + 19.7 fb^{-1} @7 and 8 TeV	Phys. Rev. Lett. 112 (2014) 171802 (CMS)
	t→Hc(q)	< 0.56% (0.79%)	19.5 fb^{-1} @8 TeV (20.3+4.7 fb^{-1} @8 and 7 TeV)	CMS PAS-HIG-13-034 (ATLAS JHEP06(2014)008)
BNV	t→b u e (or b c μ)	< 0.15%	19.5 fb^{-1} @8 TeV	Physics Letters B 731 (2014) 173 (CMS)

Thank you for your attention!