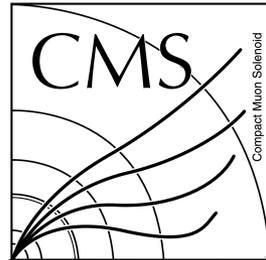


Overview of FCNC Searches in Top Events from CMS and ATLAS

Boris Lemmer



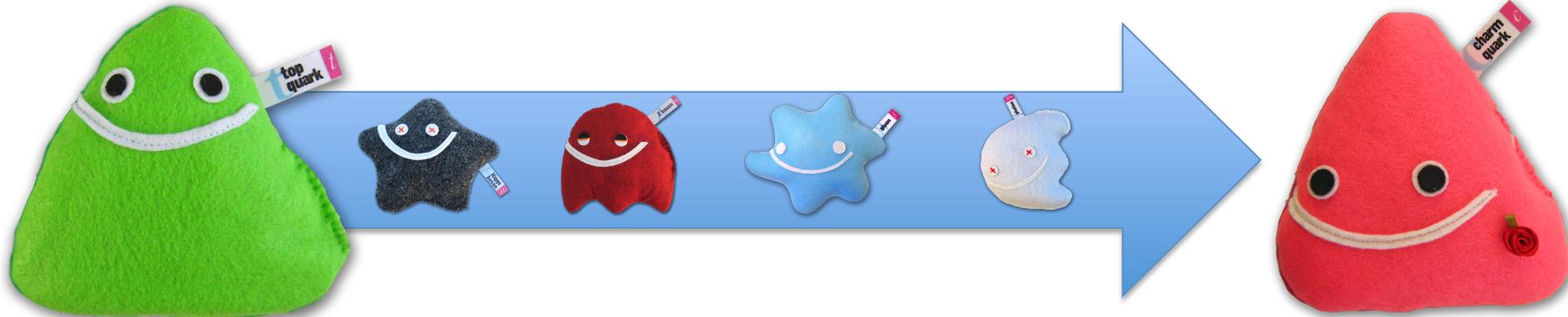
On behalf of the CMS and ATLAS collaborations



LHCP 2015

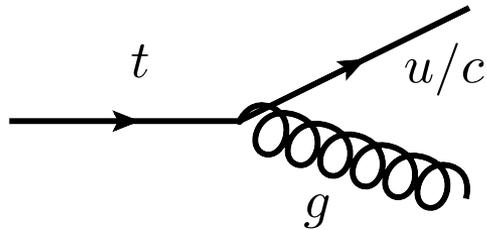
St. Petersburg, 2. September 2015

- Latest FCNC results from ATLAS and CMS
- Short description of
 - Selection
 - Dominant background sources
 - Analysis strategy
 - Dominant uncertainties
 - Results
- Summary: Where are we?



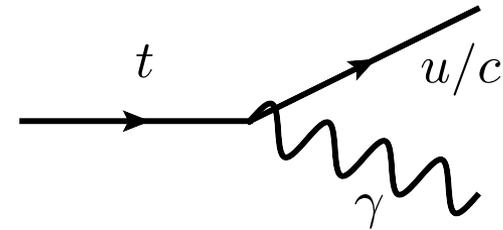
- SM: No FCNC at tree level, very low contributions (GIM suppression)
- Modeling via anomalous couplings in effective Lagrangians
- Easier comparison using branching ratios

$$\text{SM: } \mathcal{B}(t \rightarrow u/c + g) \lesssim 10^{-12}$$



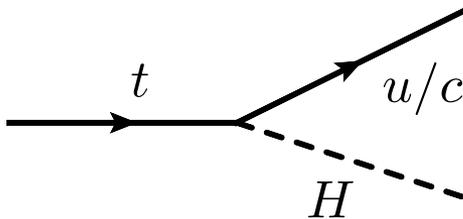
$$\mathcal{L}_{gtc} = -g_s \bar{c} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (\zeta_{ct}^L P_L + \zeta_{ct}^R P_R) t G_\mu^a \quad [1]$$

$$\text{SM: } \mathcal{B}(t \rightarrow u/c + \gamma) \lesssim 10^{-14}$$



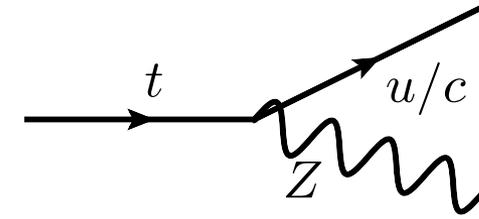
$$\mathcal{L}_{\gamma tc} = -e \bar{c} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} (\lambda_{ct}^L P_L + \lambda_{ct}^R P_R) t A_\mu + \text{H.c.} \quad [1]$$

$$\text{SM: } \mathcal{B}(t \rightarrow u/c + H) \lesssim 10^{-15}$$



$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}} \bar{c} (\eta_{ct}^L P_L + \eta_{ct}^R P_R) t H + \text{H.c.} \quad [2]$$

$$\text{SM: } \mathcal{B}(t \rightarrow u/c + Z) \lesssim 10^{-14}$$

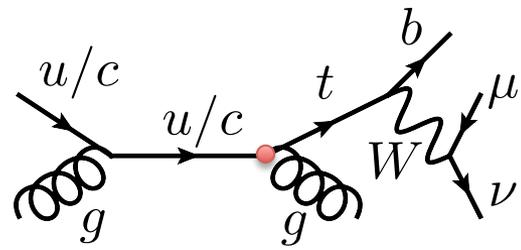


$$\mathcal{L}_{Ztc} = -\frac{g}{2c_W} \bar{c} \gamma^\mu (X_{ct}^L P_L + X_{ct}^R P_R) t Z_\mu \quad [1]$$

$$-\frac{g}{2c_W} \bar{c} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (\kappa_{ct}^L P_L + \kappa_{ct}^R P_R) t Z_\mu + \text{H.c.}$$



$t \rightarrow ug$ and $t \rightarrow cg$ (Single Top)



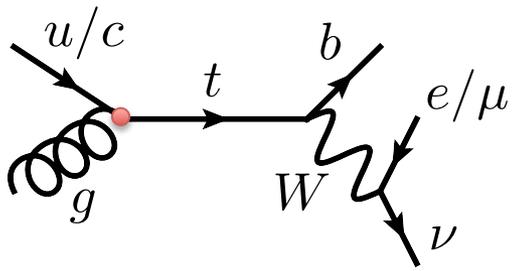
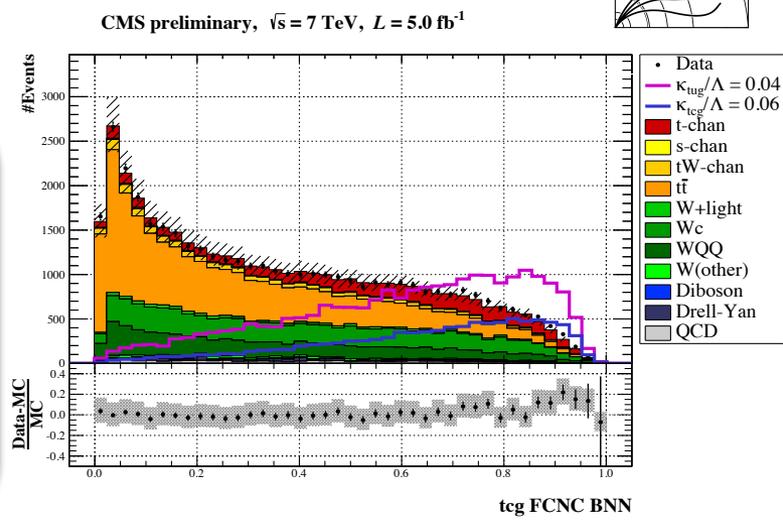
CMS PAS TOP-14-007

$\sqrt{s} = 7 \text{ TeV}, 5 \text{ fb}^{-1}$

- 1 isolated μ
- 2-3 jets (≥ 1 b-tag, ≥ 1 veto)
- NN for QCD Suppression

W+jets, $t\bar{t}$, single top

- Several neural networks:
 - SM t-channel single top vs. backgrounds
 - tcg FCNC vs. SM
 - tuc FCNC vs. SM
- 1D/2D limits on κ_{tug}/Λ and κ_{tcg}/Λ



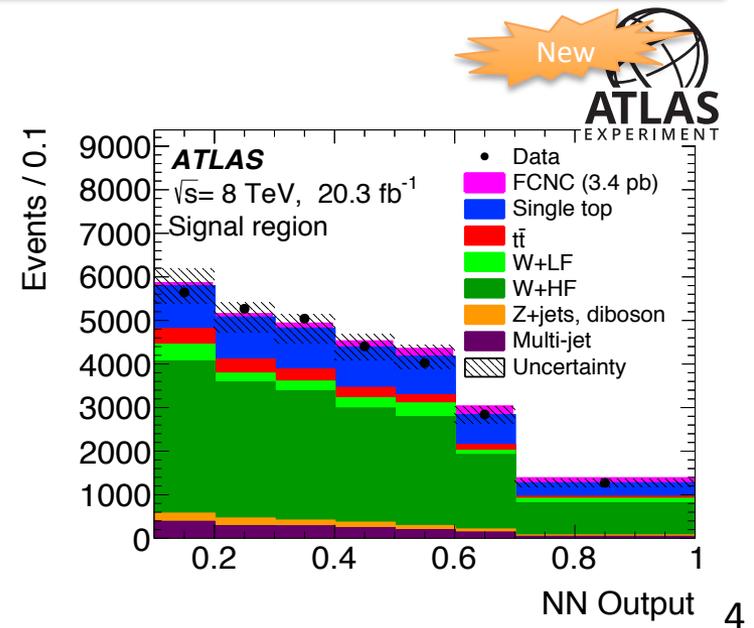
arxiv:1509.00294 (submitted to EPJC)

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

- 1 isolated e/μ
- 1 b-tagged jet
- E_t^{miss} and $m_T(W)$ cut

W+jets, single top, $t\bar{t}$

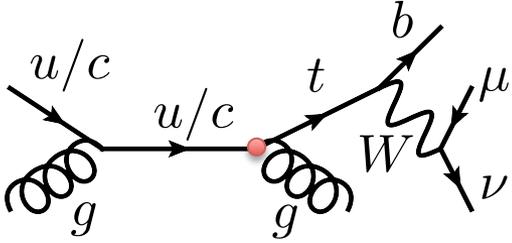
- Neural Network:
 - Softer top p_T
 - High p_T W
 - Charge asymmetry: $\sigma_t/\sigma_{\bar{t}}$ higher in FCNC w.r.t. SM





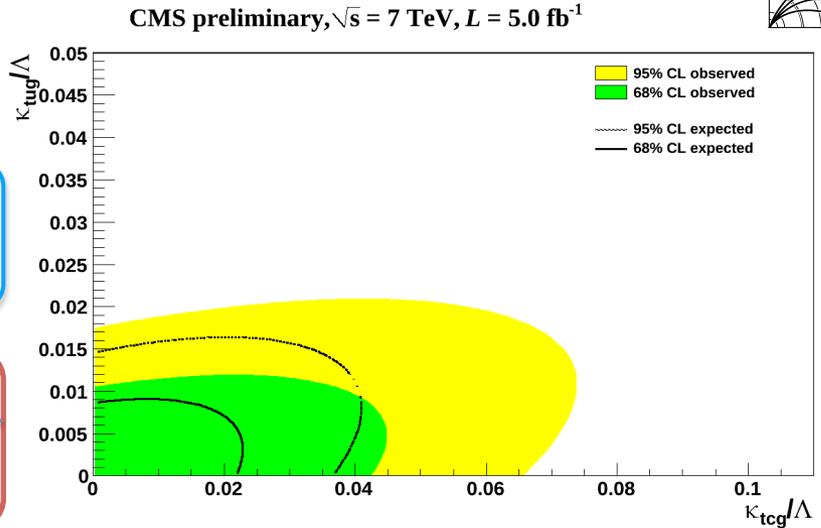
$t \rightarrow ug$ and $t \rightarrow cg$ (Single Top)

CMS PAS TOP-14-007

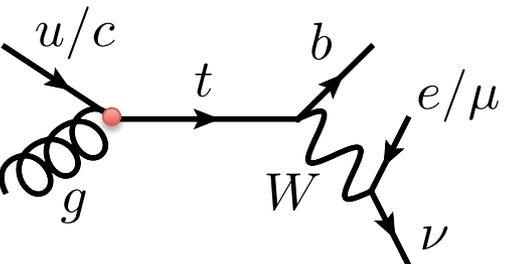


- PDF
- Signal modeling

- 95% CL observed (expected) limits, other BR set to 0
- $B(t \rightarrow u + g) < 3.55 \cdot 10^{-4}$ ($1.58 \cdot 10^{-4}$)
- $B(t \rightarrow c + g) < 3.44 \cdot 10^{-3}$ ($1.05 \cdot 10^{-3}$)

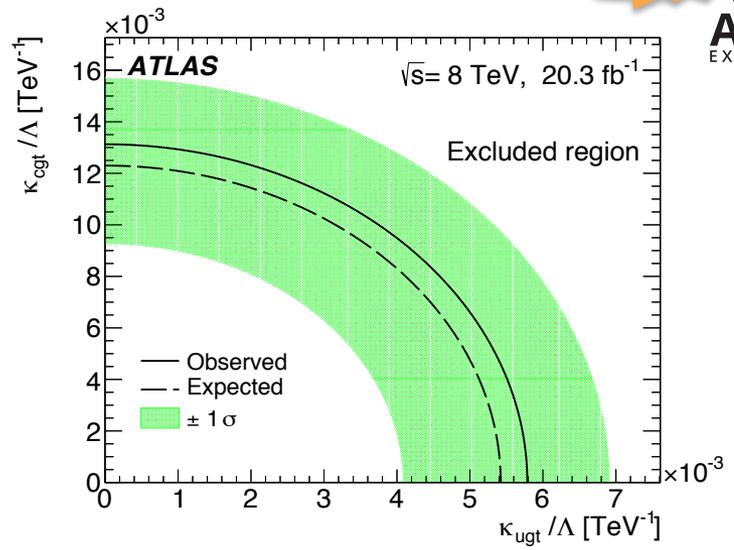


arxiv:1509.00294 (submitted to EPJC)

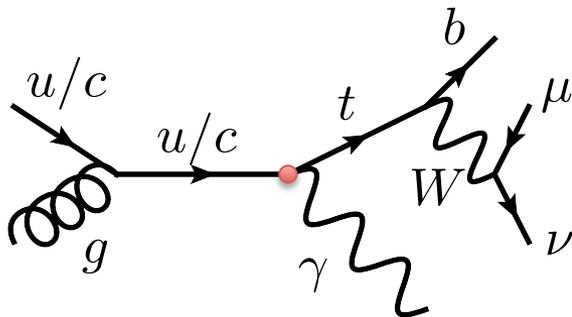


- JER
- E_T^{miss} modeling
- Multijet background modeling

- 95% CL observed (expected) limits, other BR set to 0
- $B(t \rightarrow u + g) < 4 \cdot 10^{-5}$ ($3 \cdot 10^{-5}$)
- $B(t \rightarrow c + g) < 17 \cdot 10^{-5}$ ($15 \cdot 10^{-5}$)



$t \rightarrow u\gamma$ and $t \rightarrow c\gamma$ (Single Top)



CMS PAS TOP-14-003

$\sqrt{s} = 8 \text{ TeV}, 19.1 \text{ fb}^{-1}$

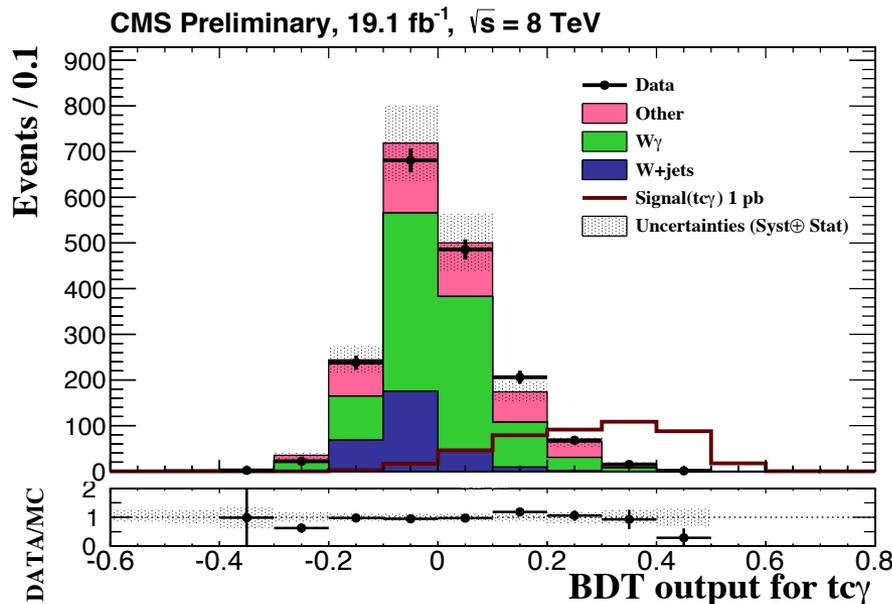
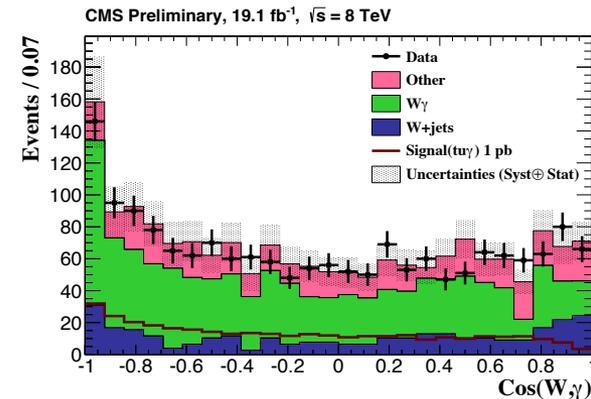
- Data driven $W\gamma$ +jets yield estimate
- BDT for signal vs. background discrimination:
 - Photon p_T
 - b-jet p_T
 - $\mu p_T + 5$ others

- 1 isolated μ ,
- Jets (max 1 b-tag)
- 1 high p_T photon
- E_T^{miss}

- $W\gamma$ +jets, W +jets, $t\bar{t}$

- Data driven background estimate

- 95% CL observed (expected) limits
- $\mathcal{B}(t \rightarrow u + \gamma) < 0.0108 \text{ (0.0205)\%}$
- $\mathcal{B}(t \rightarrow c + \gamma) < 0.132 \text{ (0.193)\%}$



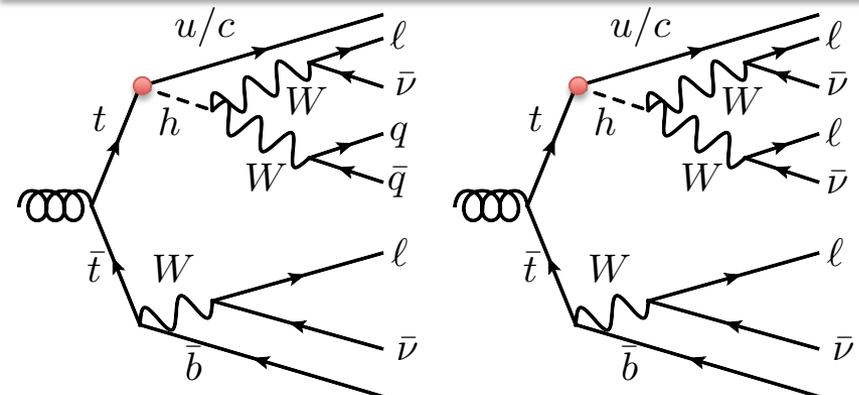
$t \rightarrow Hc (t\bar{t})$



CMS PAS TOP-13-017

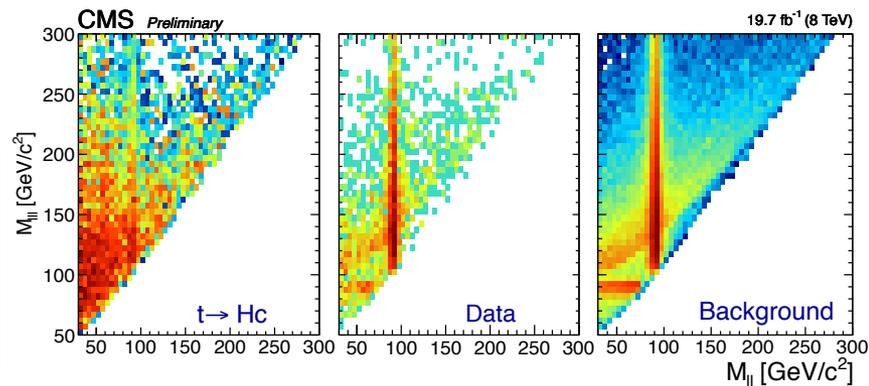
$\sqrt{s} = 8 \text{ TeV}, 19.7 \text{ fb}^{-1}$

• WZ (3L), non-prompt leptons (2L), rare SM



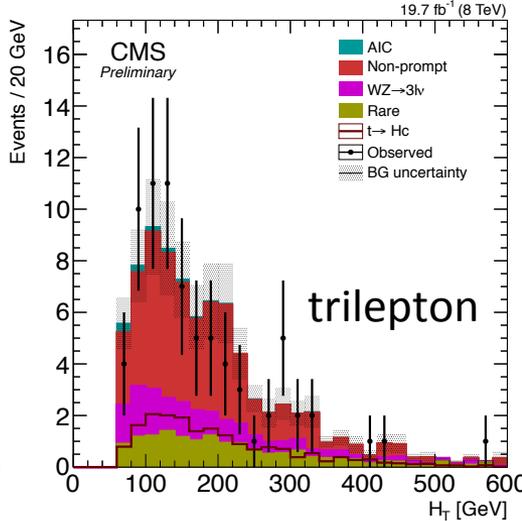
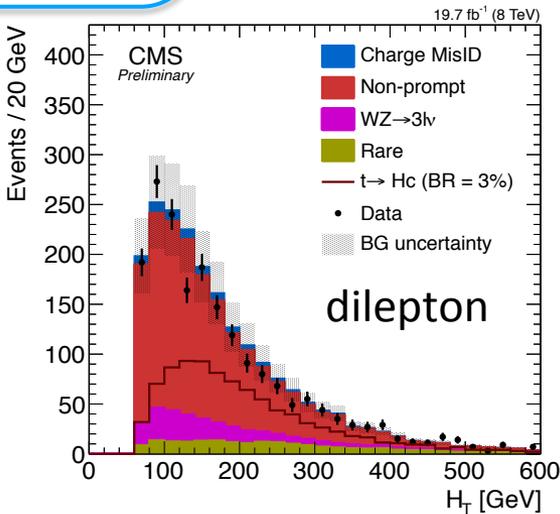
- 3 or 2 (same sign of electric charge) isolated leptons (e,μ)
- Jets
- E_T^{miss}, H_T and mass cuts
- Z veto

- Considering $H \rightarrow WW, ZZ, \tau\tau$
- Data driven estimate of $Z \rightarrow 3\ell$ and charge-misidentification



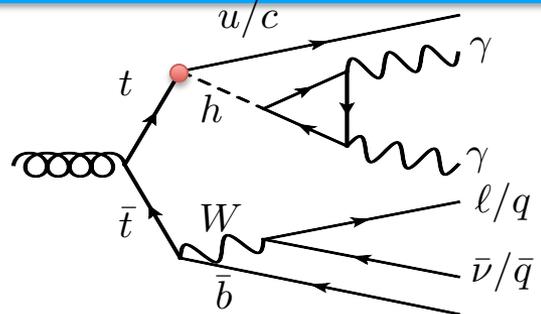
- Electron charge misidentification
- Lepton misidentification
- Background modeling

| 95% CL limit on $\mathcal{B}(t \rightarrow c + H)$ | $-\sigma$ | Exp. | $+\sigma$ | Obs. |
|--|-----------|--------|-----------|--------|
| Trilepton | 0.95 % | 1.33 % | 1.87 % | 1.26 % |
| Same Sign Dilepton | 0.68 % | 0.93 % | 1.26 % | 0.99 % |
| Combined | 0.65 % | 0.89 % | 1.22 % | 0.93 % |



Also: 95% CL limit of $\mathcal{B}(t \rightarrow c + H) < 1.3\% (1.2\%)$ in PRD 90 (2014) 032006 (mulepton final states)

$t \rightarrow Hq$ with $H \rightarrow \gamma\gamma$



CMS PAS TOP-14-019

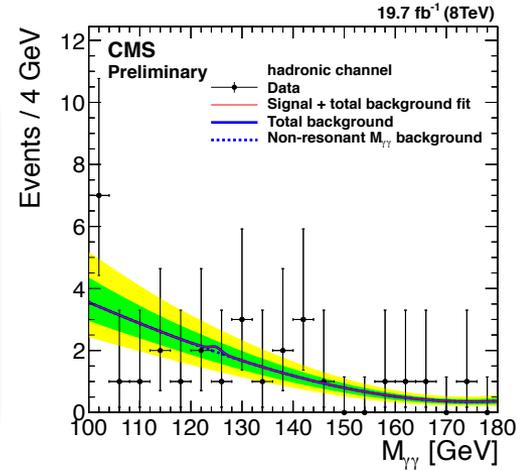
$\sqrt{s} = 8 \text{ TeV}, 19.7 \text{ fb}^{-1}$



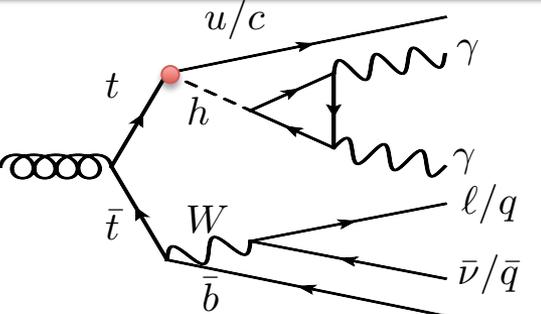
- ≥ 2 photons
- Had: ≥ 4 jets, 1 b-tag
- Lep: 1 isolated e/μ , ≥ 2 jets, 1 b-tag
- Top mass cuts



- Non-resonant di-photon background shape from data: fitted by function with lowest bias on test data
- Max. likelihood fit incl. Hc and Hu



- Non-resonant di-photon BG, $t\bar{t}H$



JHEP 1406 (2014) 008

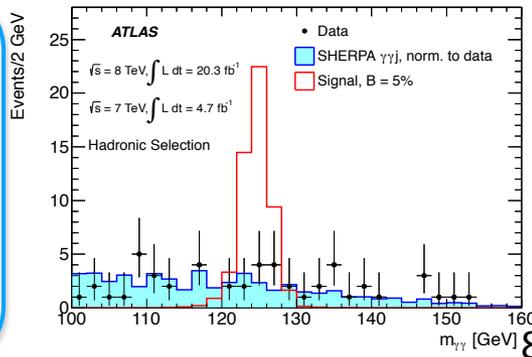
$\sqrt{s} = 7 \text{ TeV}, 4.7 \text{ fb}^{-1}$
 $\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$



- ≥ 2 photons
- Had: ≥ 4 jets, ≥ 1 b-tag, top mass cuts
- Lep: 1 isolated e/μ , ≥ 2 jets, ≥ 1 b-tag, $m_T(W)$ and top mass cuts



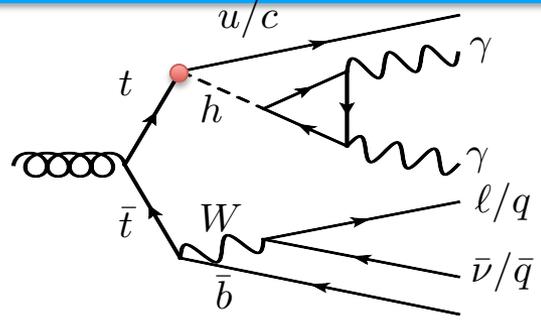
- Non-resonant di-photon bkg. shape from data: fitted by function with lowest bias on smoothed Sherpa $\gamma\gamma j$ events
- Lep: only 8 TeV
- Max. likelihood fit of combined Hc and Hu (Lep: event counting)



- Non-resonant di-photon BG, $t\bar{t}H$

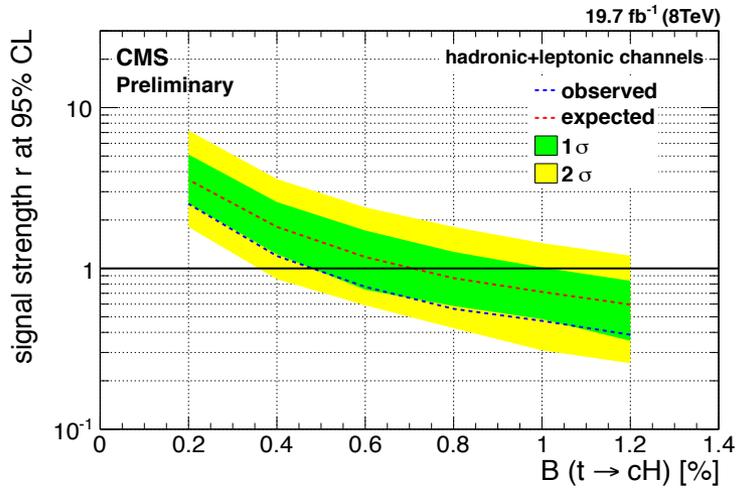
$t \rightarrow Hq$ with $H \rightarrow \gamma\gamma$

CMS PAS TOP-14-019

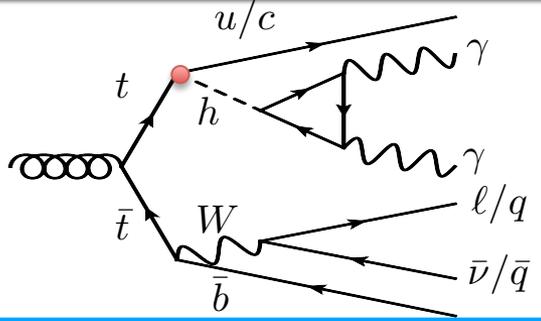


- $t\bar{t}$ and $t\bar{t}H$ modeling, photon ID

- 95% CL observed (expected) limits
 $B(t \rightarrow u + H) < 0.42\% (0.65\%)$
 $B(t \rightarrow c + H) < 0.47\% (0.71\%)$

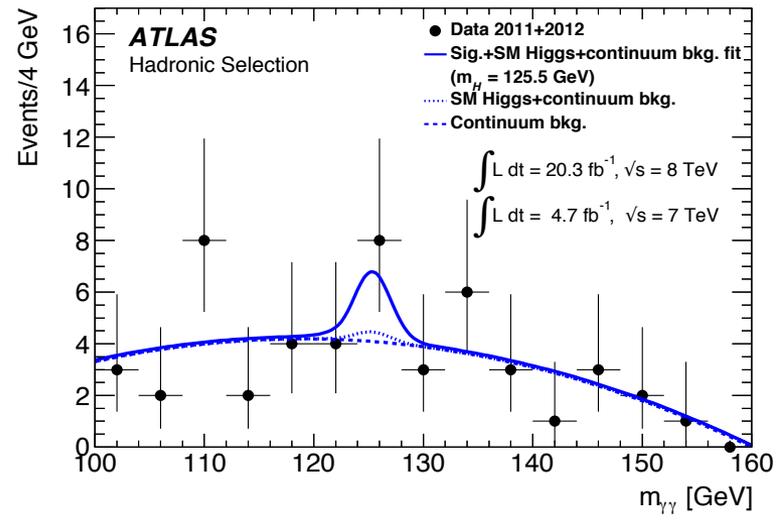


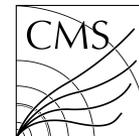
JHEP 06 (2014) 008



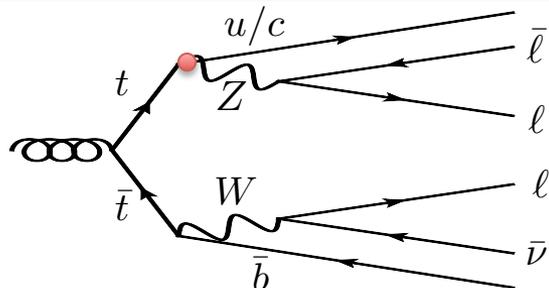
- $t\bar{t}$ and $t\bar{t}H$ modeling, photon ID

- 95% CL observed (expected) limits
 $B(t \rightarrow H + q) < 0.79\% (0.51\%)$





$t \rightarrow Zq$ in $t\bar{t}$

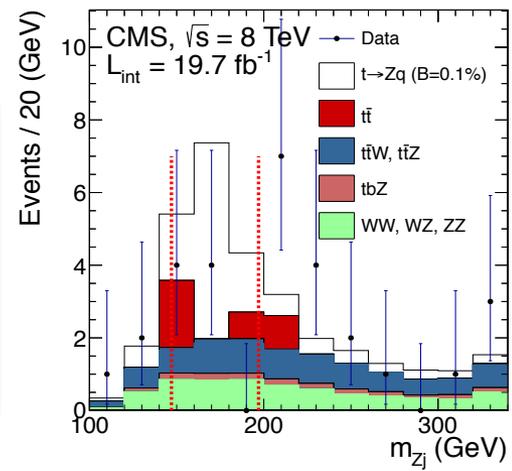


Phys. Rev. Lett. 112 (2014) 171802

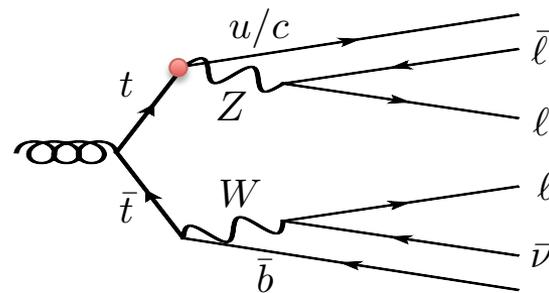
$\sqrt{s} = 8 \text{ TeV}, 19.7 \text{ fb}^{-1}$

- 3 isolated e, μ
- ≥ 2 jets, 1 b-tag
- E_T^{miss} and mass cuts

- Data driven background estimation by yield comparison in b-tag bins (0: Diboson, 1: FCNC, 2: $t\bar{t} + X$)
- CL_s limits from the yields
- Combination with 7 TeV result



- $t\bar{t}Z, WZ, t\bar{t}$

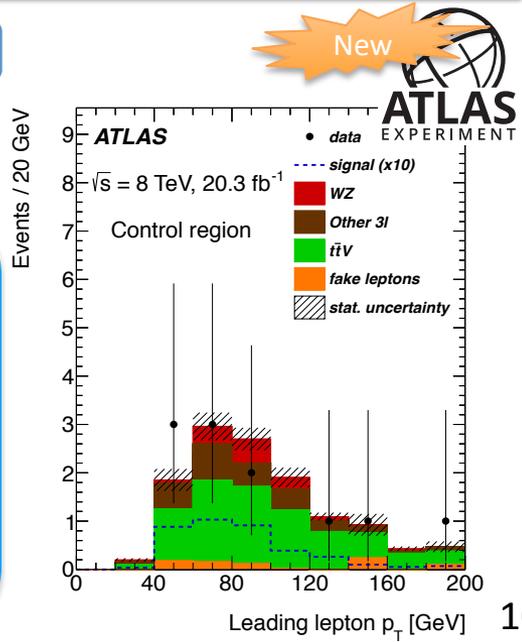


arXiv:1508.05796 (submitted to EPJC)

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

- 3 isolated e, μ
- 2-3 jets, 1-2 b-tags
- E_T^{miss} and χ^2 cut (from masses)

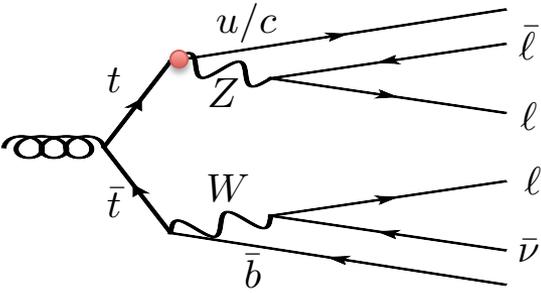
- Backgrounds from simulation, validated in dedicated control regions
- CL_s limits from the yields
- Limit from $t \rightarrow Z + c$ signal (more conservative than $t \rightarrow Z + u$)



- $t\bar{t}Z, WZ, tZ$



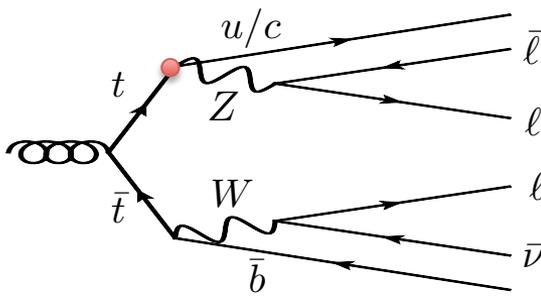
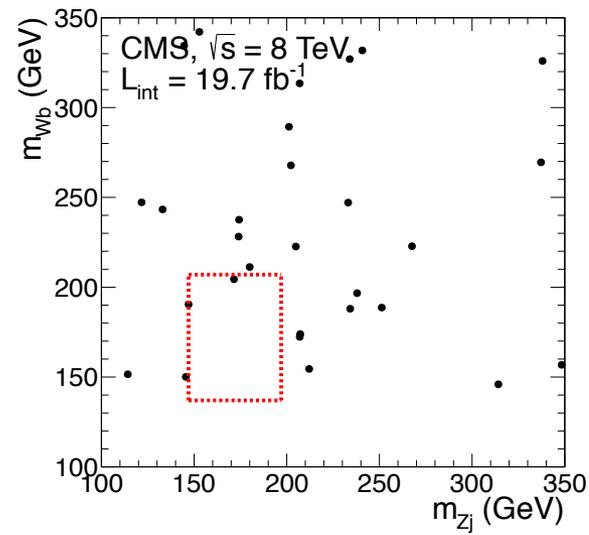
$t \rightarrow Zq$ in $t\bar{t}$



Phys. Rev. Lett. 112 (2014) 171802

- Background: b-tagging
- Signal: renormalization/factorization scale, PDF

| 95% CL limit on $t \rightarrow Z + q$ | $-\sigma$ | Exp. | $+\sigma$ | Obs. |
|---------------------------------------|-----------|--------|-----------|--------|
| 8 TeV | 0.06 % | 0.10 % | 0.13 % | 0.06 % |
| 7 TeV + 8 TeV | 0.06 % | 0.09 % | 0.13 % | 0.05 % |

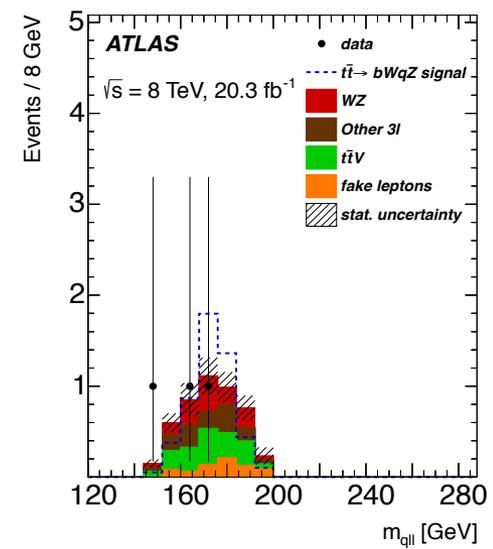


arXiv:1508.05796 (submitted to EPJC)

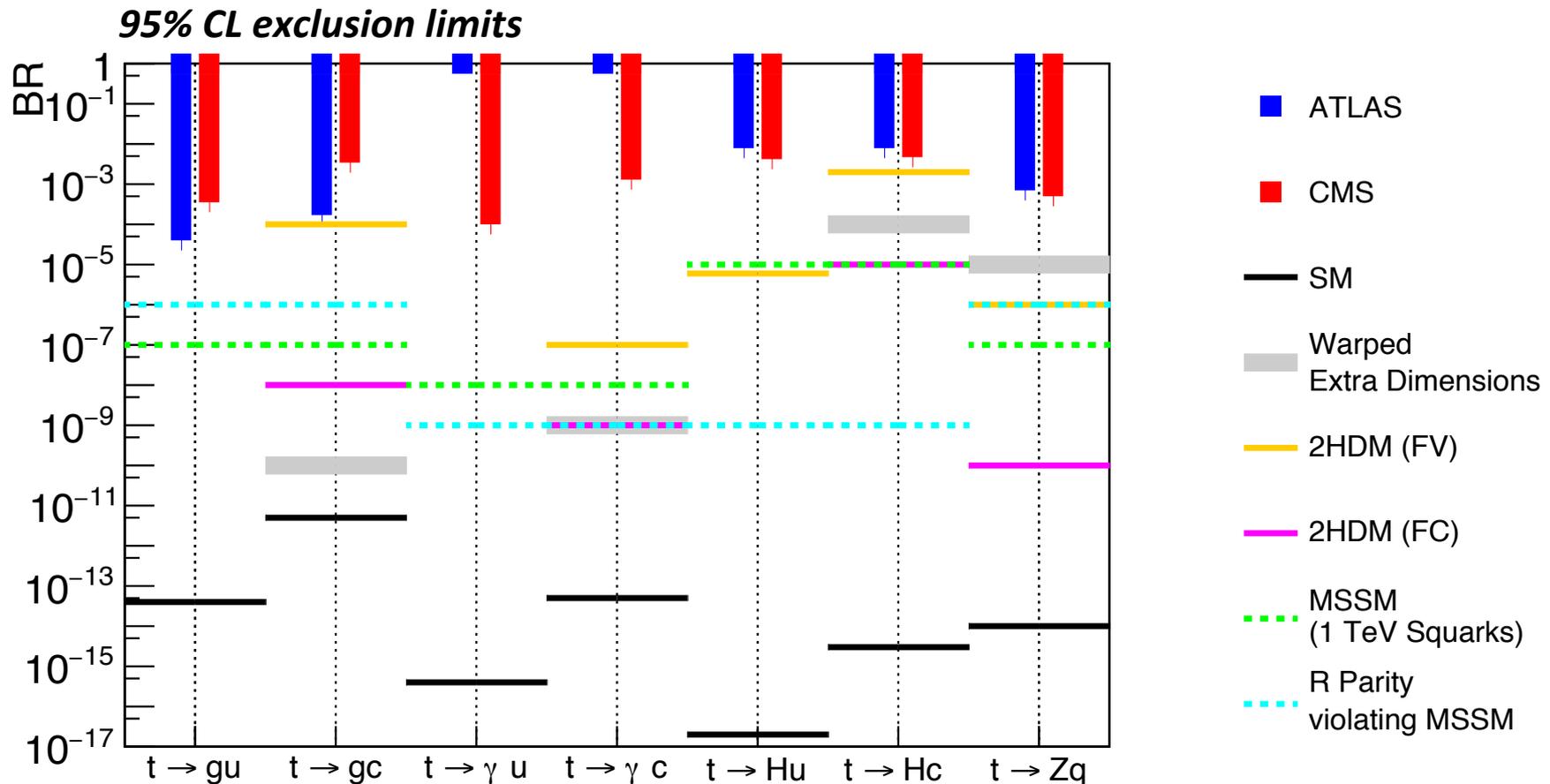


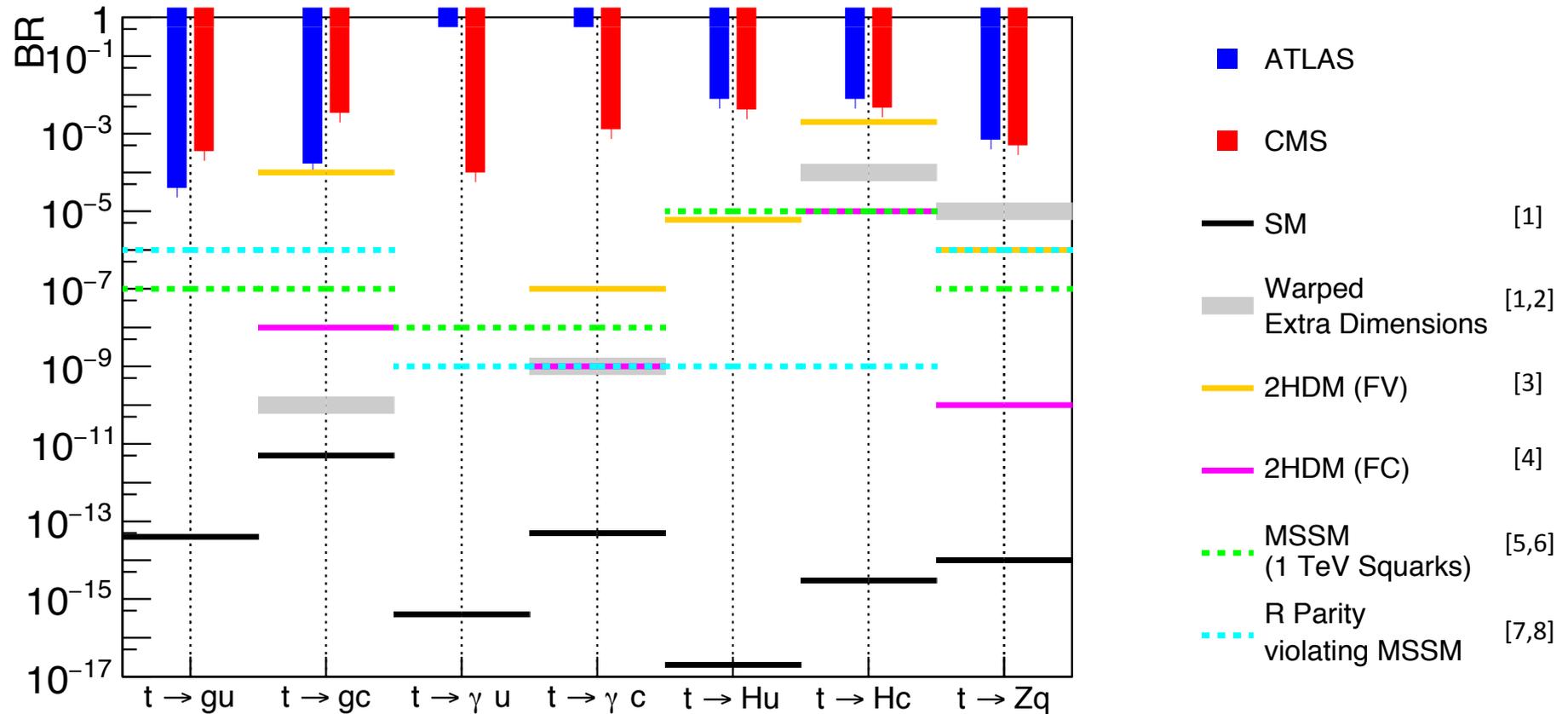
- Background (dominating): modeling
- Signal: b-tagging
- Both: Jet energy scale

| 95% CL limit on $t \rightarrow Z + q$ | $-\sigma$ | Exp. | $+\sigma$ | Obs. |
|---------------------------------------|-----------|--------|-----------|--------|
| 8 TeV | 0.06 % | 0.08 % | 0.12 % | 0.07 % |



- FCNC: Complex final states with tough background modeling
 - Still far above SM prediction, but BSM sensitivity close
 - Limited by signal and background modeling
 - No sign of deviations from the SM yet





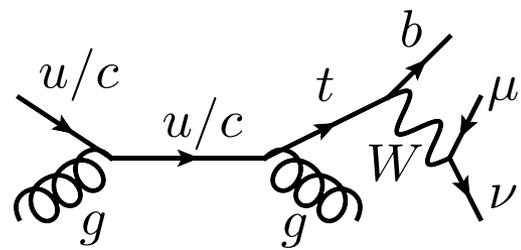
BSM: Summary/extrapolation from arXiv:1311.2028

- [1] Acta Phys.Polon., B35:2695-2710, 2004, hep-ph/0409342
- [2] Phys.Rev., D55:3156-3176, 1997, hep-ph/9609279
- [3] hep-ph/0606138
- [4] Phys.Rev., D75:075021, 2007, hep-ph/0702264
- [5] Phys.Rev., D58:055001, 1998, hep-ph/9705341
- [6] Phys.Lett., B510:227-235, 2001, hep-ph/0102037
- [7] Phys.Rev., D75:015002, 2007, hep-ph/0606293
- [8] Phys.Rev., D80:075016,2009, 0906.1542



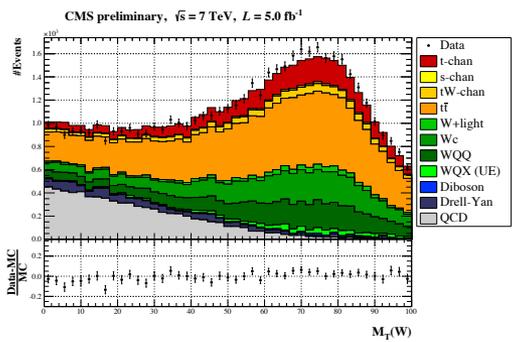
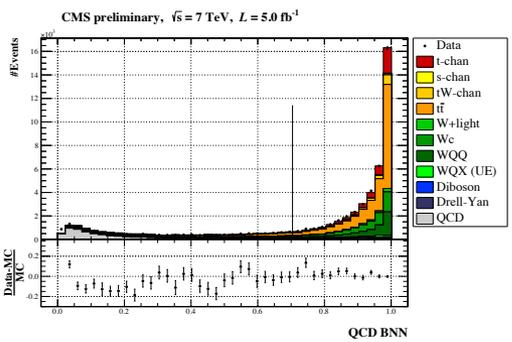
$t \rightarrow ug$ and $t \rightarrow cg$ (Single Top)

CMS PAS TOP-14-007

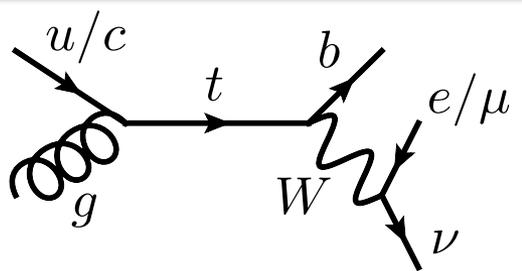


- 1 isolated μ
- 2-3 jets, $p_T > 30$ GeV, 1 b-tag, 1 veto
- NN for QCD Suppression

- FCNC via CompHEP + eff. NLO ext.



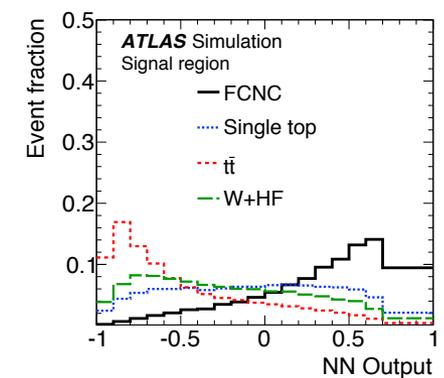
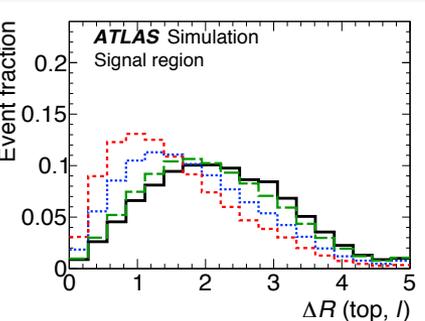
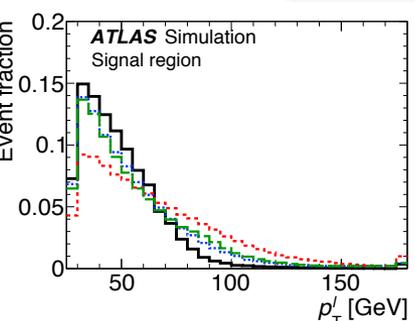
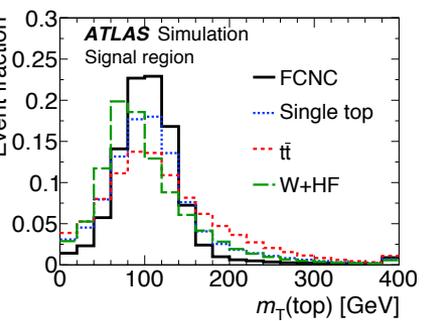
| Process | Basic selection | QCD BNN > 0.7 | Cross section |
|------------------|--|--|--|
| s-channel | $373.3^{+16.3}_{-14.5}$ | $302.2^{+13.1}_{-11.8}$ | $4.63^{+0.2}_{-0.18}$ pb |
| tW-channel | $2079.0^{+154.5}_{-159.9}$ | $1753.4^{+130.3}_{-134.8}$ | $15.74^{+7.43}_{-7.69}$ pb |
| $t\bar{t}$ | $20750.1^{+778.1}_{-908.9}$ | $17593.7^{+659.8}_{-770.6}$ | $172.0^{+6.5}_{-7.6}$ pb |
| W+jets | 15286.1 ± 761.2 | 12083.2 ± 601.7 | 31314 ± 1558 pb |
| Diboson | 378.4 ± 13.6 | 300.8 ± 10.9 | 67.1 ± 1.7 pb |
| Drell-Yan | 1601.7 ± 87.1 | 704.0 ± 38.3 | 4998 ± 272 pb |
| QCD | 7338.1 | 740.5 | - |
| t-channel | $5563.1^{+222.5}_{-161.9}$ | $4545.5^{+181.8}_{-132.3}$ | $64.57^{+2.58}_{-1.88}$ pb |
| Simulation | $53369.9^{+1125.3}_{-1210.5}$ | $38023.3^{+921.5}_{-996.6}$ | |
| Data | 56145 | 40681 | |



arxiv:1509.00294 (submitted to EPJC)

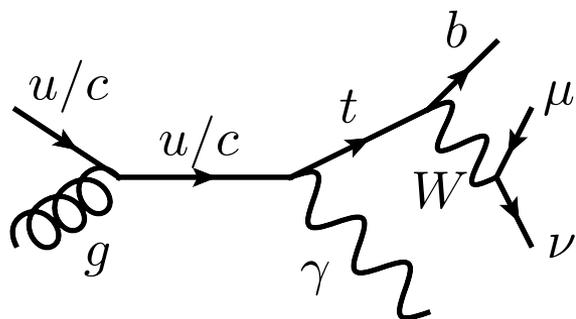
- 1 isolated e/μ ($p_T > 25$ GeV)
- Add. ϕ dep. p_T cut on lepton
- 1 b-tagged jet ($\epsilon = 50\%$), $p_T > 30$ GeV
- $E_{T,miss} > 30$ GeV
- $m_T(W) > 50$ GeV

- Assuming NLO σ_{FCNC} and $B(t \rightarrow Wb) = 1$ for κ_{ugt}/Λ derivation



$t \rightarrow u\gamma$ and $t \rightarrow c\gamma$ (Single Top)

CMS PAS TOP-14-003



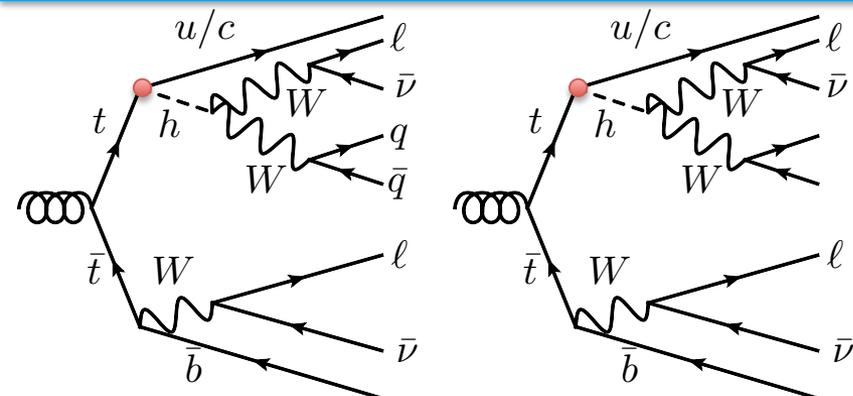
- 1 isolated μ ($p_T > 26$ GeV)
- Jets w. $p_T > 30$ GeV, max 1 b-tag
- 1 high p_T photon > 50 GeV
- $\Delta R(\mu, \gamma) > 0.7, \Delta R(\text{b-jet}, \gamma) > 0.7$
- $E_T^{\text{miss}} > 30$ GeV
- $130 \text{ GeV} < m_{\text{top}} < 220 \text{ GeV}$

- $t_{u\gamma}, t_{c\gamma}$ signal via PROTONS (LO)

| | Exp. limit (LO) | Obs. limit (LO) | Exp. limit (NLO) | Obs. limit (NLO) |
|--|-----------------|-----------------|------------------|------------------|
| $\sigma_{t_{u\gamma}} \times Br(W \rightarrow l\nu_l)$ | 0.0404 pb | 0.0234 pb | 0.0408 pb | 0.0217 pb |
| $\sigma_{t_{c\gamma}} \times Br(W \rightarrow l\nu_l)$ | 0.0411 pb | 0.0281 pb | 0.0410 pb | 0.0279 pb |
| $\kappa_{t_{u\gamma}}$ | 0.0367 | 0.0279 | 0.0315 | 0.0229 |
| $\kappa_{t_{c\gamma}}$ | 0.113 | 0.094 | 0.0790 | 0.0652 |
| $Br(t \rightarrow u\gamma)$ | 0.0279% | 0.0161% | 0.0205% | 0.0108% |
| $Br(t \rightarrow c\gamma)$ | 0.261% | 0.182% | 0.193% | 0.132% |



CMS PAS TOP-13-017



• Signal via Pythia6

- 3 or 2 (same sign) isol. leptons (e,μ), $p_T > 20$ GeV (1st), > 10 GeV (2nd and 3rd)
- Jet $p_T > 30$ GeV
- 2L: $n_{jet} > 2$, $|m_{ee} - m_Z| > 15$ GeV, $E_T^{miss} > 40$ GeV, $[E_T^{miss}, H_T]$ cuts
- 3L: $|m_{ll} - m_Z| > 15$ GeV, $|m_{lll} - m_Z| > 10$ GeV for $m_{lll} > 40$ GeV



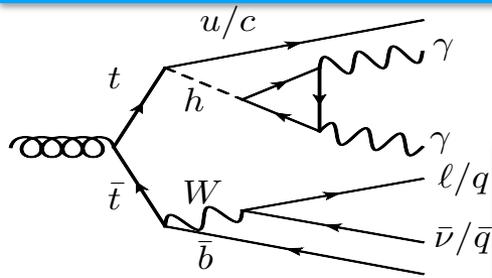
| process | trilepton | Z removal | ≥ 2 jets |
|-----------------------------|--------------------|------------------|----------------|
| Rare | 380.4 ± 11.9 | 54.3 ± 2.1 | 19.6 ± 1.4 |
| $WZ \rightarrow 3l\nu$ | 1451.9 ± 93.4 | 117.0 ± 7.6 | 15.8 ± 1.1 |
| Non-prompt | 613.4 ± 97.3 | 148.8 ± 25.7 | 49.4 ± 9.0 |
| BG | 2598.3 ± 135.5 | 339.4 ± 27.0 | 86.2 ± 9.3 |
| Observed | 2555 | 309 | 79 |
| $FCNH \rightarrow WW$ | 27.9 ± 1.9 | 21.0 ± 1.5 | 14.4 ± 1.1 |
| $FCNH \rightarrow \tau\tau$ | 9.1 ± 0.6 | 6.4 ± 0.4 | 4.4 ± 0.3 |
| $FCNH \rightarrow ZZ$ | 2.9 ± 0.2 | 0.5 ± 0.0 | 0.4 ± 0.0 |

| process | same-sign dilepton | Z removal | ≥ 2 jets | MET-dependent HT |
|-----------------------------|----------------------|----------------------|--------------------|------------------|
| Rare | 512.3 ± 12.9 | 495.6 ± 12.5 | 225.5 ± 9.7 | 128.1 ± 6.4 |
| $WZ \rightarrow 3l\nu$ | 1080.1 ± 68.4 | 1041.9 ± 66.0 | 242.2 ± 15.4 | 83.9 ± 5.4 |
| Charge MisID | 4407.3 ± 881.7 | 521.1 ± 104.3 | 101.6 ± 20.3 | 32.1 ± 6.4 |
| Non-prompt | 10644.2 ± 1574.7 | 10493.7 ± 1568.4 | 1561.4 ± 248.9 | 409.8 ± 72.3 |
| BG | 16643.9 ± 1806.3 | 12552.3 ± 1573.5 | 2130.7 ± 250.6 | 654.3 ± 73.1 |
| Observed | 16790 | 12686 | 2032 | 631 |
| $FCNH \rightarrow WW$ | 307.8 ± 19.2 | 295.4 ± 18.4 | 246.2 ± 15.4 | 112.2 ± 7.1 |
| $FCNH \rightarrow \tau\tau$ | 82.0 ± 5.1 | 79.4 ± 4.9 | 65.0 ± 4.0 | 30.8 ± 1.9 |
| $FCNH \rightarrow ZZ$ | 3.4 ± 0.2 | 3.2 ± 0.2 | 2.9 ± 0.2 | 1.1 ± 0.1 |



$t \rightarrow Hq$ with $H \rightarrow \gamma\gamma$

CMS PAS TOP-14-019



- ≥ 2 photons, ($p_T^1 > 33$ GeV, $p_T^2 > 25$ GeV, $p_T^1/m_{\gamma\gamma} > 1/3$, $p_T^2/m_{\gamma\gamma} > 1/3$)
- Had: ≥ 4 jets ($p_T > 20$ GeV), 1 b-tag ($\epsilon=66\%$)
- Lep: 1 iso. e/ μ ($p_T > 20$ GeV), ≥ 2 jets, 1 b-tag
- $158 < m_t^{\gamma\gamma} < 202$ GeV, $142 < m_t^{SM} < 222$ GeV

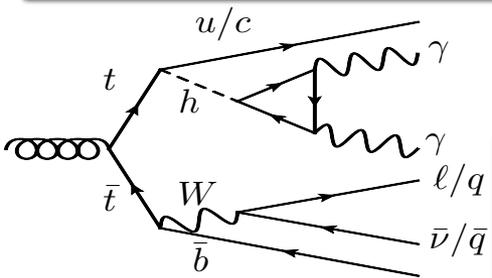


FCNC signal via Madgraph+Pythia

| | Hadronic channel | Leptonic channel |
|--|---------------------------|---------------------------|
| Data | 29 | 8 |
| Resonant diphoton background | 0.152 ± 0.021 (stat.) | 0.038 ± 0.008 (stat.) |
| Non-resonant diphoton background | 28.9 ± 5.4 (stat.) | 8.0 ± 2.8 (stat.) |
| expected signal yields for $\mathcal{B}(t \rightarrow cH) = 1\%$ | 6.26 ± 0.07 (stat.) | 1.91 ± 0.04 (stat.) |
| expected signal yields for $\mathcal{B}(t \rightarrow uH) = 1\%$ | 7.09 ± 0.08 (stat.) | 2.02 ± 0.04 (stat.) |

| source of the systematic uncertainty | hadronic channel | leptonic channel |
|--|------------------|------------------|
| Effect on signal yield [%] | | |
| integrated luminosity | 2.6 | 2.6 |
| pileup | 0.3 | 0.8 |
| trigger efficiency | 1 | 1 |
| photon identification efficiency | 5.2 | 5.2 |
| electron identification efficiency | - | 0.3 |
| muon identification efficiency | - | 0.3 |
| H cross section | 5.7 | 5.7 |
| PDF for signal kinematics | 5.9 | 5.2 |
| tt pr reweighting | 1.4 | 3.2 |
| branching fraction $\mathcal{B}(H \rightarrow \gamma\gamma)$ | 5 | 5 |
| jet identification efficiency | 2 | 2 |
| jet energy correction | 1.2 | 1.0 |
| jet energy resolution | 2.7 | 0.4 |
| b tagging efficiency | 2.9 | 3.5 |
| per photon [%] | | |
| photon energy scale | 0.1 | 0.1 |
| photon energy resolution | 0.1 | 0.1 |
| photon energy scale from the material mis-modeling | 0.34 | 0.34 |
| photon energy scale non-linearity | 0.1 | 0.1 |
| Effect on background estimation [%] | | |
| production cross section PDF for SM Higgs background | 8.1 | 8.1 |
| production cross section scale for SM Higgs background | 9.3 | 9.3 |

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- ≥ 2 photons, ($p_T^1 > 40$ GeV, $p_T^2 > 30$ GeV)
- Had: ≥ 4 jets ($p_T > 20$ GeV), ≥ 1 b-tag ($\epsilon=70\%$)
 $156 < m_t^{\gamma\gamma} < 191$ GeV, $130 < m_t^{SM} < 210$ GeV
- Lep: 1 iso. e/ μ ($p_T > 15/10$ GeV), ≥ 2 jets, 1 b-tag, $m_T(W) > 30$ GeV
 $156 < m_t^{\gamma\gamma} < 191$ GeV, $135 < m_t^{SM} < 205$ GeV



FCNC signal via Protos+Pythia

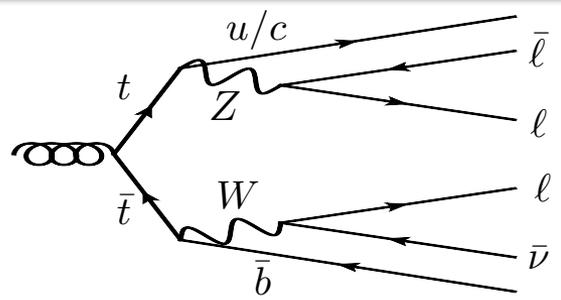
| | $t \rightarrow cH$ (%) | | Data (events) | |
|--------------------------|------------------------|---------------|---------------|--------|
| | 7 TeV | 8 TeV | 7 TeV | 8 TeV |
| $\gamma\gamma$ selection | 34.5 | 34.2 | 23683 | 118500 |
| $N_{\text{jets}} \geq 4$ | 15.2 | 15.1 | 227 | 1349 |
| Mass requirements | 5.9 | 6.1 | 36 | 210 |
| At least 1 b-tag | 4.2 ± 0.1 | 4.0 ± 0.1 | 7 | 43 |

| Selection | Hadronic | | Leptonic |
|---------------------------|--------------------|-------------------|-------------------|
| | 7 TeV | 8 TeV | 8 TeV |
| Centre of mass energy | 7 TeV | 8 TeV | 8 TeV |
| Trigger efficiency | ± 0.2 | ± 0.5 | ± 0.5 |
| Photon identification | ± 9.3 | ± 4.6 | ± 2.4 |
| Photon isolation | ± 3.0 | | ± 1.0 |
| Jet Energy Scale | ± 5.4 | $+7.4$ -4.5 | $+3.2$ -2.8 |
| Jet Energy Resolution | ± 0.2 | | ± 0.2 |
| Jet Vertex Fraction | ± 1.0 | | ± 1.0 |
| b-tagging | ± 3.5 | ± 4.8 | ± 5.2 |
| Lepton reco./ID/scale | — | — | ± 0.6 |
| E_T^{miss} scale | — | — | $+1.4$ -0.4 |
| ISR/FSR | $+7.0$ -3.0 | | $+8.0$ -2.0 |
| Underlying event | ± 3.5 | | ± 1.8 |
| Combined uncertainty | $+14.1$ -12.6 | $+13.1$ -9.8 | $+10.6$ -7.1 |





$t \rightarrow Zq$ in $t\bar{t}$

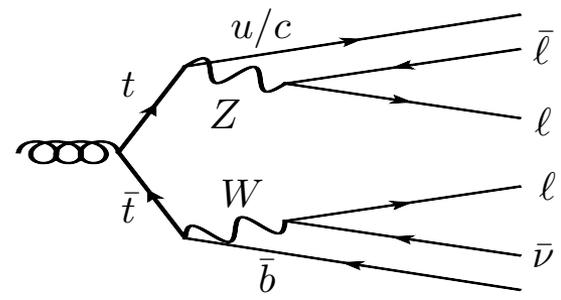


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- FCNC signal via Madgraph with $t \rightarrow Z + u/c$ (50/50)

| Process | Estimation from data | MC prediction |
|--|-----------------------|-----------------------------|
| $t \rightarrow Zq$ ($\mathcal{B} = 0.1\%$) | — | $6.4 \pm 0.1 \pm 1.3$ |
| WZ | — | $0.9 \pm 0.1 \pm 0.3$ |
| ZZ | $1.4 \pm 0.1 \pm 0.3$ | < 0.1 |
| Drell-Yan | — | < 0.1 |
| $t\bar{t}$ | — | $0.7^{+1.1}_{-0.4} \pm 1.2$ |
| $t\bar{t}Z$ | — | $1.1 \pm 0.1 \pm 0.8$ |
| $t\bar{t}W$ | $1.7 \pm 0.8 \pm 0.4$ | $0.1 \pm 0.1 \pm 0.1$ |
| $t\bar{t}Z$ | — | $0.3 \pm 0.1 \pm 0.2$ |
| Total background | $3.1 \pm 0.8 \pm 0.8$ | $3.2 \pm 1.2 \pm 1.5$ |
| Observed events | 1 | — |

| Source | Uncertainty % |
|--------------------------------------|---------------|
| Renormalization/factorization scales | 12 |
| Parton distribution functions | 7 |
| $t\bar{t}$ cross section | 7 |
| Parton matching threshold | 6 |
| Lepton selection | 6 |
| Trigger efficiency | 5 |
| b-tagging | 5 |
| Top-quark mass | 4 |
| Jet energy scale | 4 |
| Missing transverse energy resolution | 3 |
| Pileup modeling | 3 |
| Total | 20 |



arXiv:1508.05796 (submitted to EPJC)

- FCNC signal via PROTOS + $t\bar{t}$ p_T reweighting



| Source | Background [%] | Signal [%] |
|----------------------|----------------|------------|
| Background modelling | 17 | — |
| Signal modelling | — | 5.5 |
| Leptons | 4.7 | 2.9 |
| Jets | 7.7 | 4.9 |
| b-tagging | 3.9 | 7.2 |
| E_T^{miss} | 3.2 | 1.5 |
| Luminosity | 2.4 | 2.8 |
| Statistical | 8.1 | 1.5 |

| Sample | Yields |
|--|-----------------------|
| WZ | $1.3 \pm 0.2 \pm 0.6$ |
| $t\bar{t}V$ | $1.5 \pm 0.1 \pm 0.5$ |
| tZ | $1.0 \pm 0.1 \pm 0.5$ |
| Fake leptons | $0.7 \pm 0.3 \pm 0.4$ |
| Other backgrounds | $0.2 \pm 0.1 \pm 0.1$ |
| Total background | $4.7 \pm 0.4 \pm 1.0$ |
| Data | 3 |
| Signal efficiency [$\times 10^{-4}$] | $7.8 \pm 0.1 \pm 0.8$ |