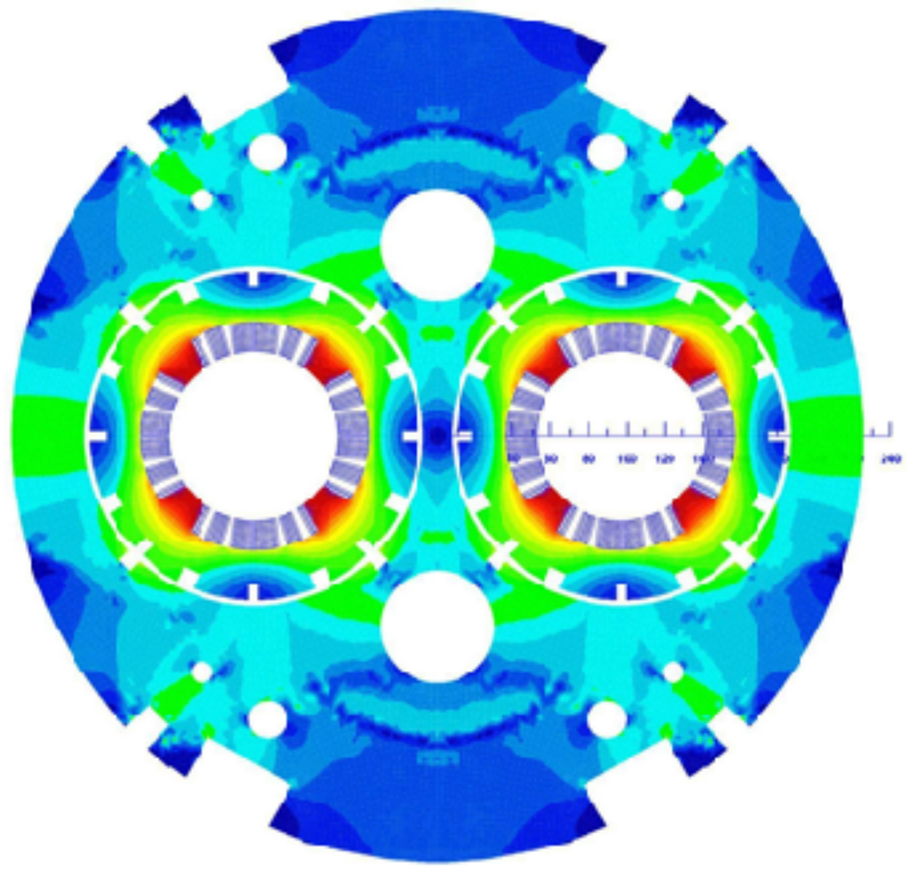
# Top Quark Properties at HL/HE-LHC

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Workshop on the physics of HL-LHC and perspectives at HE-LHC, November 1st, 2017


thanks for the inputs from M. Cristinziani, M. Mangano, M. Vos

# top quark statistics

- top quark samples

| | 13 TeV - 30 $fb^{-1}$ | 13/14 TeV - 3000 $fb^{-1}$ |
|---|---|---|
| **$t\bar{t}$** | 30 Mevts | 3 Gevts |
| **$t\bar{t}$ (fiducial)** | 1.55 Mevts | 155 Mevts |
| **$t\bar{t}$ with $M_{t\bar{t}} > 1$ TeV (fiducial)** | 30 kevts | 3 Mevts |
| **$t\bar{t}$ with $M_{t\bar{t}} > 2$ TeV (fiducial)** | 480 evts | 48 kevts |
| **t-channel** | 6 Mevts | 600 Mevts |
| **Wt-channel** | 2 Mevts | 200 Mevts |
| **s-channel** | 300 kevts | 30 Mevts |
| **ttV** | 30 kevts | 3 Mevts |
| **tZ** | 3 kevts | 300 kevts |
| **tH** | 300 evts | 30 kevts |

- top quark properties: search from deviation from SM predictions
  - top couplings
  - asymmetries
  - rare process, FCNC

# top-gluon coupling

J.A. Aguilar-Saavedra et al., arXiv:1412.6654

- chromo-electric and magnetic dipole moments:
  - dim-6 operator: effective modification of the top-gluon coupling (dV, dA)

$$\mathcal{L}_{tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t} \bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

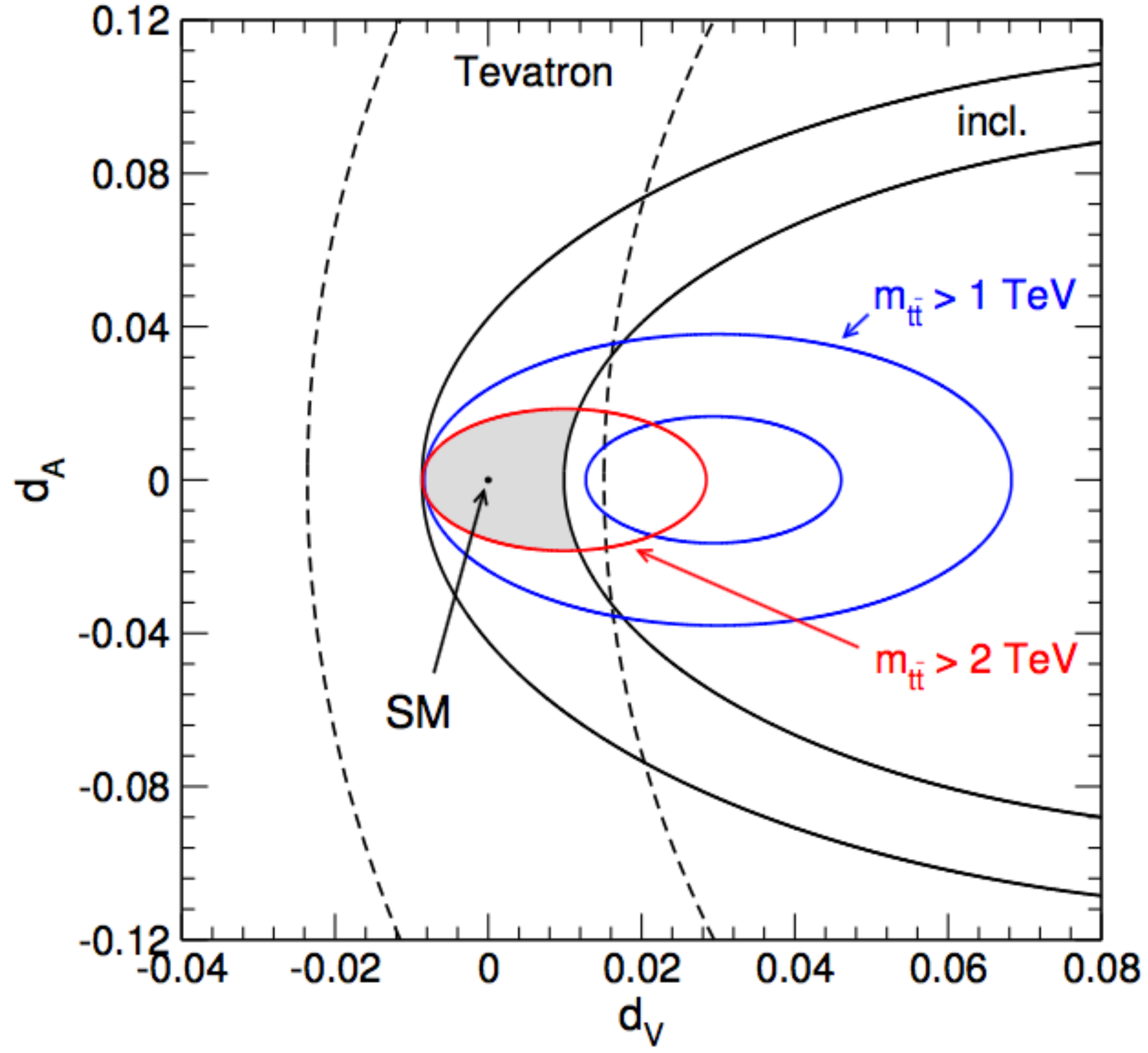
  - constrain coming from the $t\bar{t}$ inclusive cross section

- enhance sensitivity by using production at high invariant mass
  - using central events |η| < 2
  - events are boosted: top tagging (12.5% efficiency, 0.03% mistag)
  - background from mistagging of top (dijet)

- expect large gain due to the statistics in the boosted regime

| Invariant mass selection | $\sigma_{t\bar{t}}$ | $\sigma_{jj}$ | $\sqrt{S+B}/S$ |
|---|---|---|---|
| $m_{t\bar{t}}$ (or $m_{jj}$) $> 1$ TeV | 1.0 pb | 0.89 pb | 0.004 |
| $m_{t\bar{t}}$ (or $m_{jj}$) $> 2$ TeV | 16 fb | 40 fb | 0.047 |

normalized to 100 $fb^{-1}$



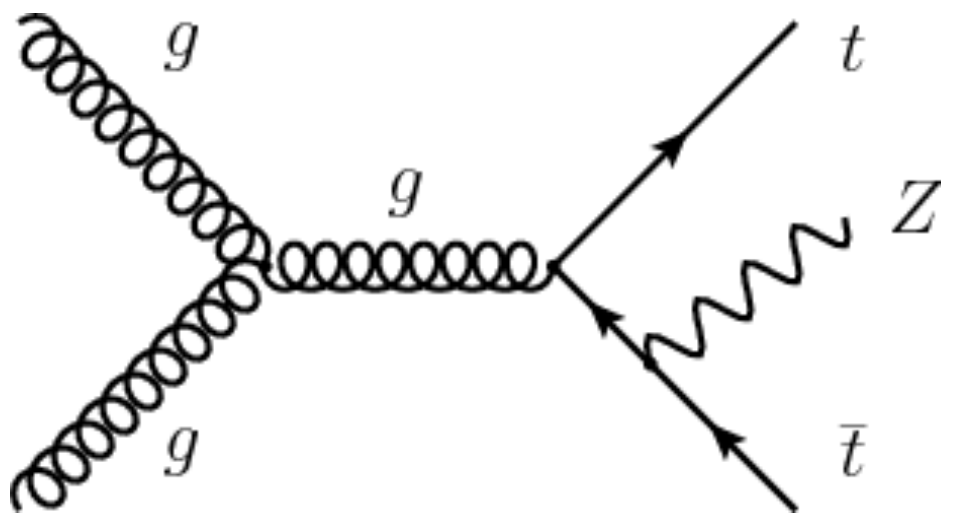
# top-Z coupling

R. Rontsch, M. Shulze, arXiv:1501.06939

- top-Z weak magnetic and electric dipole moments:

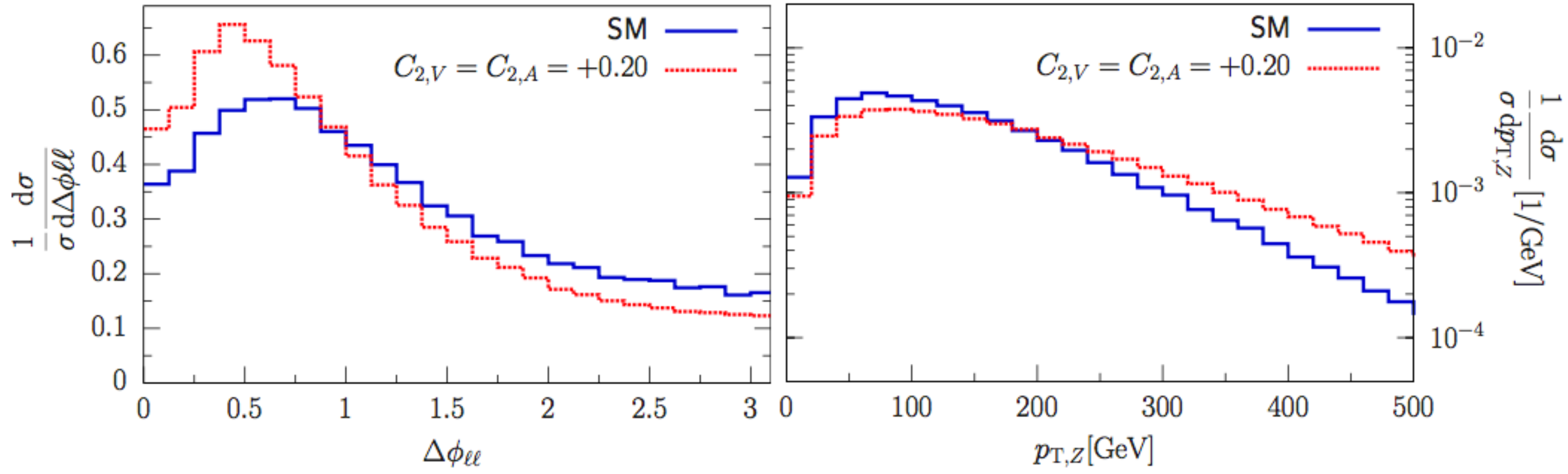
$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V}^Z + \gamma_5 C_{1,A}^Z\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V}^Z + i\gamma_5 C_{2,A}^Z\right)\right]v(p_{\bar{t}})Z_\mu$$

- $C^Z_{2,V}$: ~ $10^{-4}$ at NLO, $C^Z_{2,A}$: only at NNLO




- selection of ttZ events
  - 3 leptons
  - 4 jets, 2 b-tag

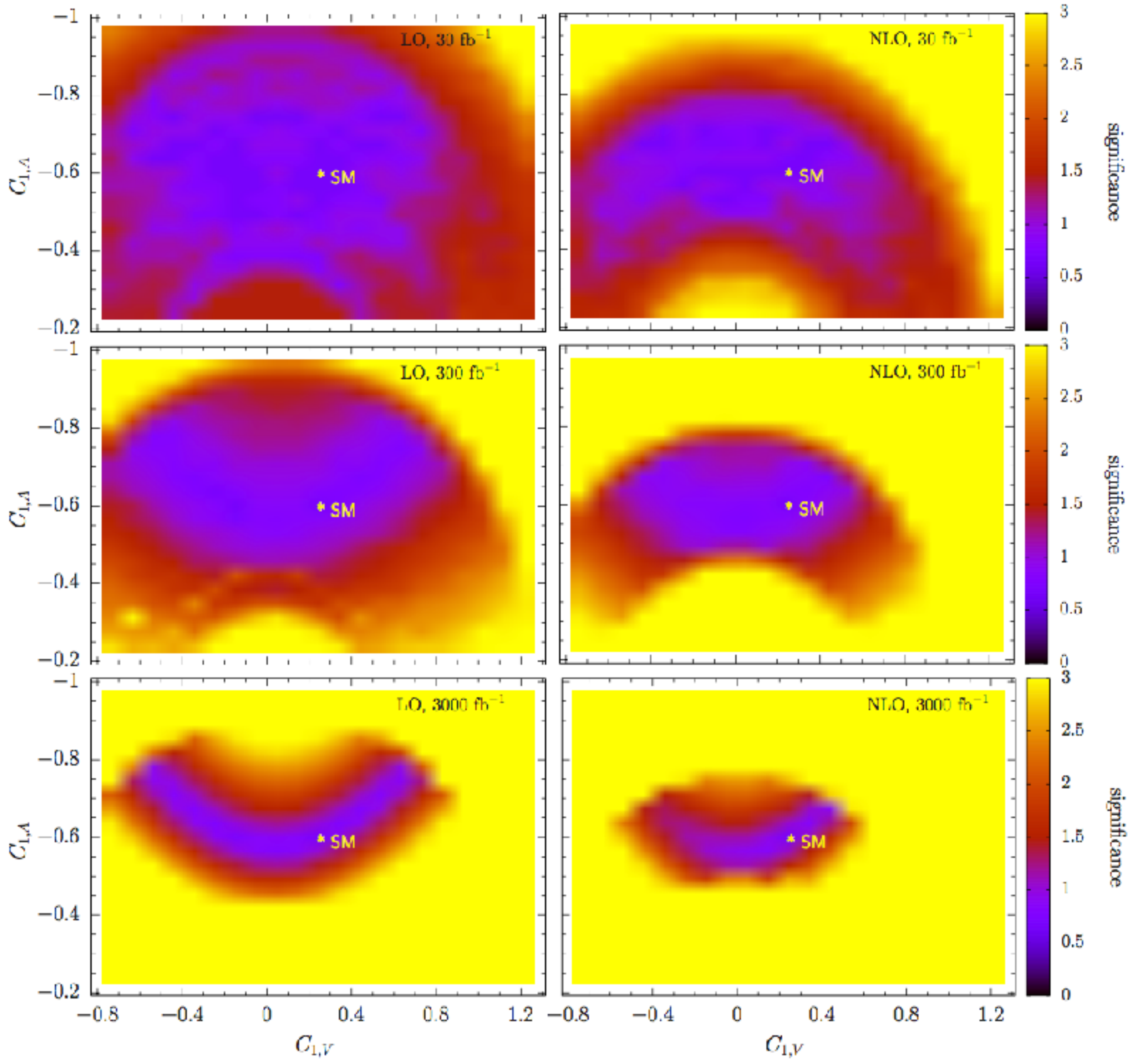
- limit settings using 2 observables with the highest sensitivity
  - $\Delta\Phi_{ll}$ for $C^Z_1$ and $p_tZ$ for $C^Z_2$

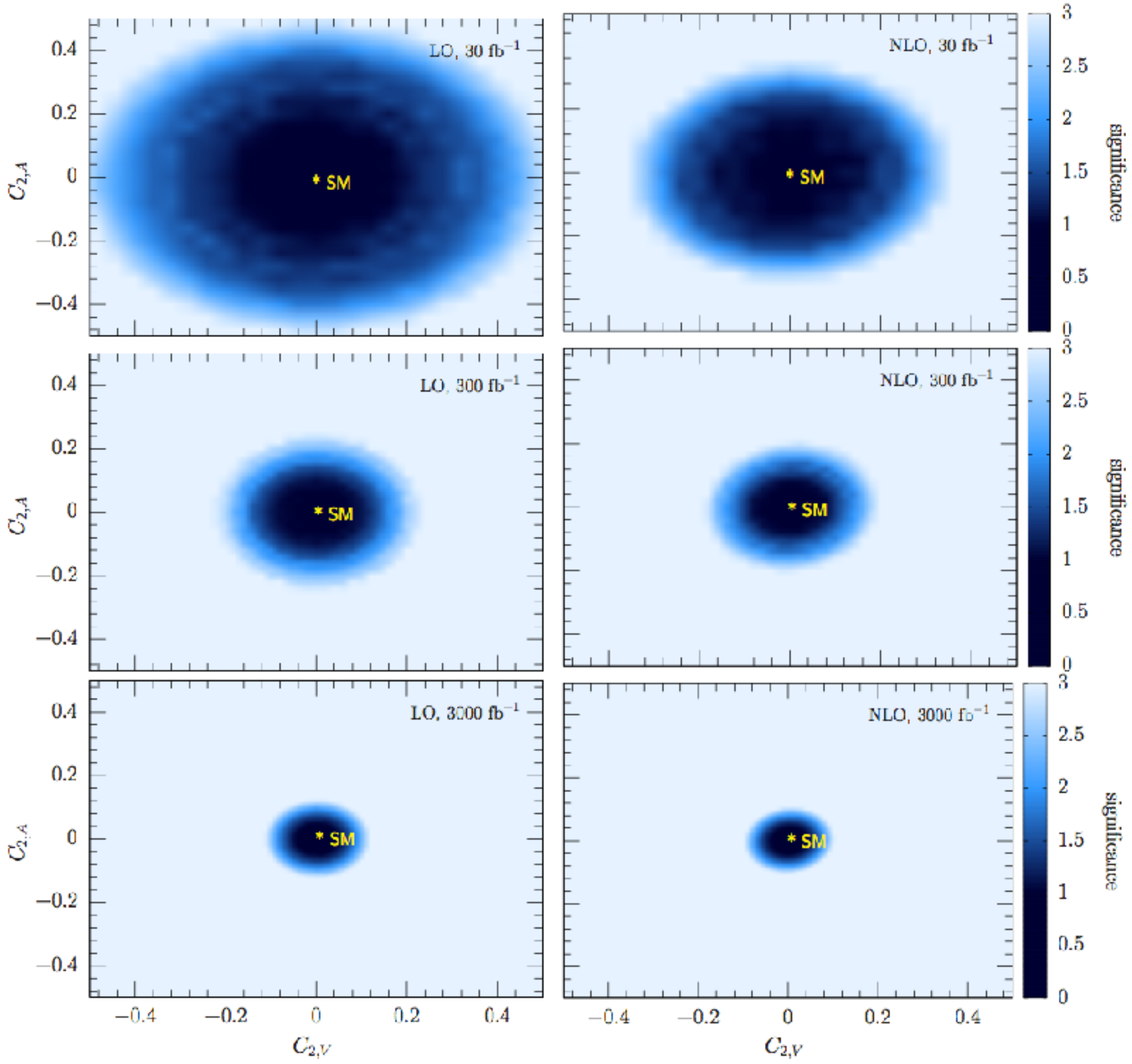


# top-Z coupling sensitivity

R. Rontsch, M. Shulze,
arXiv:1501.06939

- results:
  - including NLO corrections improves the constraints by 20-40%
  - constraints down to 0.08
  - can go further by using tt̄Z/tt̄ ratio (and tt̄γ/tt̄) to constrain 3 electroweak dipole moments (arXiv: 1603.08911)



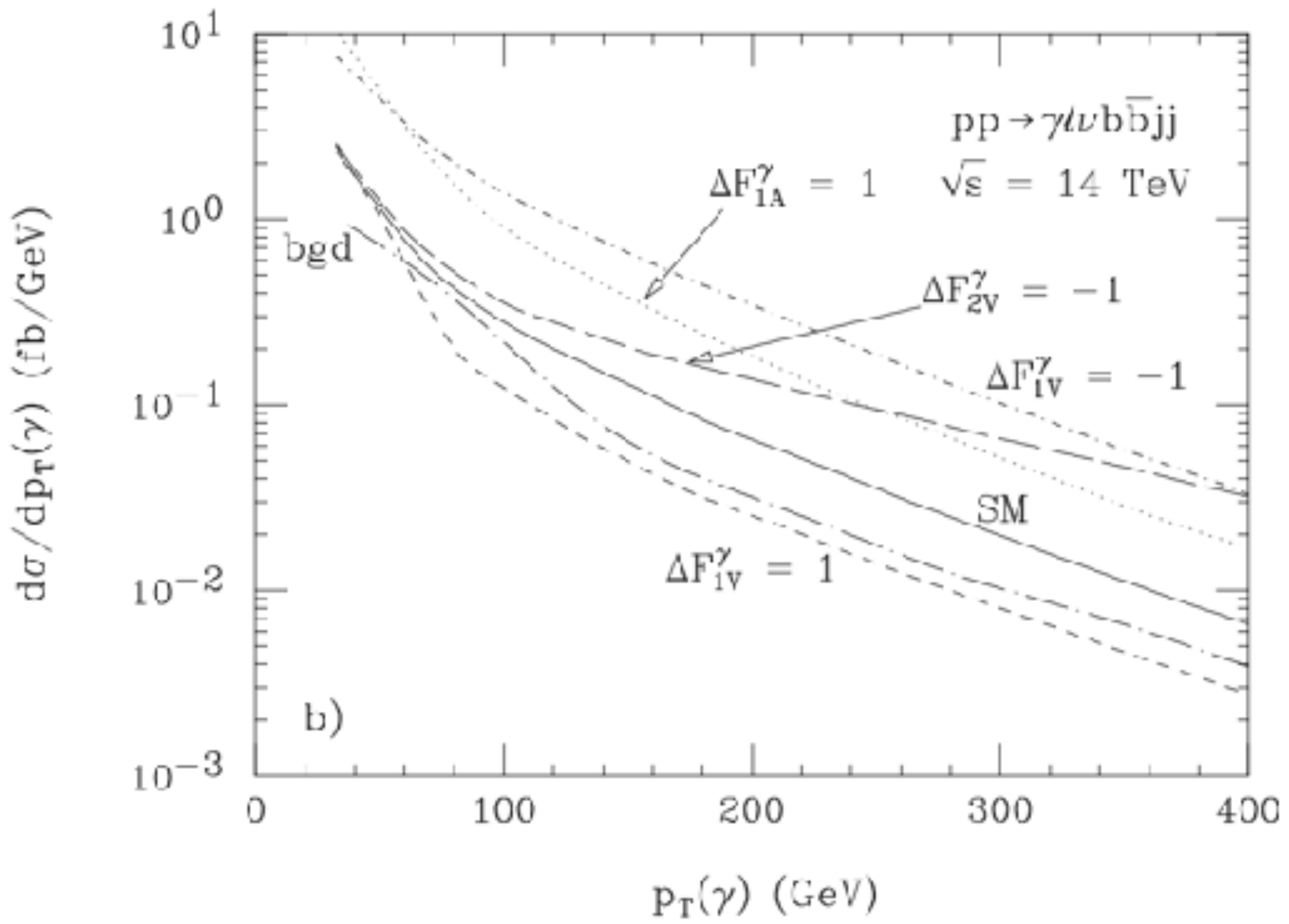

ot, HL-

# top-γ coupling

U. Baur et al, arXiv: hep-ph/0412021

- anomalous form factors:

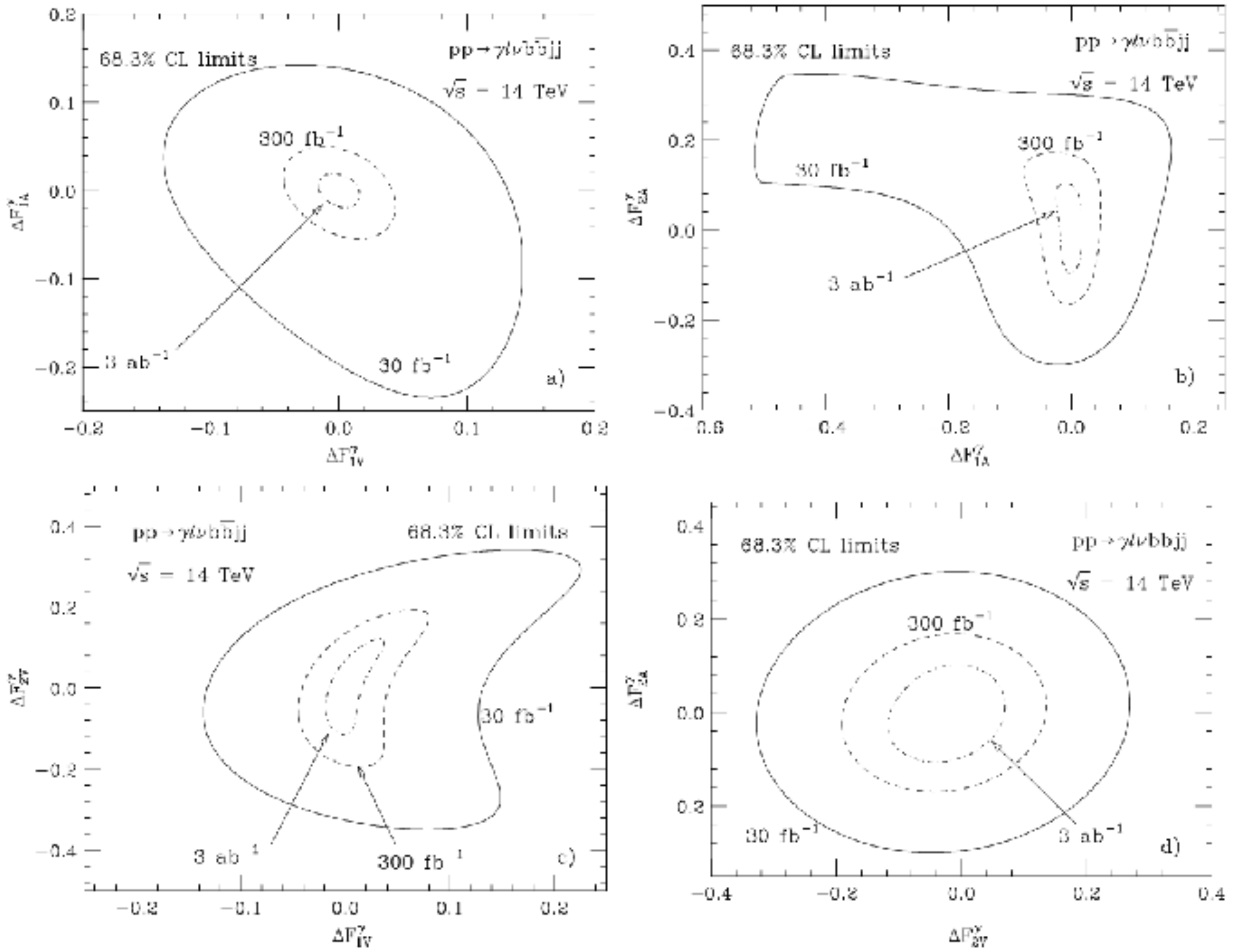
$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(k^2)+\gamma_5 F_{1A}^V(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(k^2)+\gamma_5 F_{2A}^V(k^2)\right)\right\}$$




- selection of ttγ events
  - 1 lepton, 4 jets, 2 b-tag
  - 1 well separated photon
  - main background from fake photon

- results
  - constraints on the vector/axial couplings $F^\gamma_1$ to 2-3%, $F^\gamma_2$ to 10%

| coupling | 30 fb$^{-1}$ | 300 fb$^{-1}$ | 3000 fb$^{-1}$ |
|---|---|---|---|
| $\Delta F^\gamma_{1V}$ | $+0.23$ $-0.14$ | $+0.079$ $-0.045$ | $+0.037$ $-0.019$ |
| $\Delta F^\gamma_{1A}$ | $+0.17$ $-0.52$ | $+0.051$ $-0.077$ | $+0.018$ $-0.024$ |
| $\Delta F^\gamma_{2V}$ | $+0.34$ $-0.35$ | $+0.19$ $-0.20$ | $+0.12$ $-0.12$ |
| $\Delta F^\gamma_{2A}$ | $+0.35$ $-0.36$ | $+0.19$ $-0.21$ | $+0.11$ $-0.14$ |

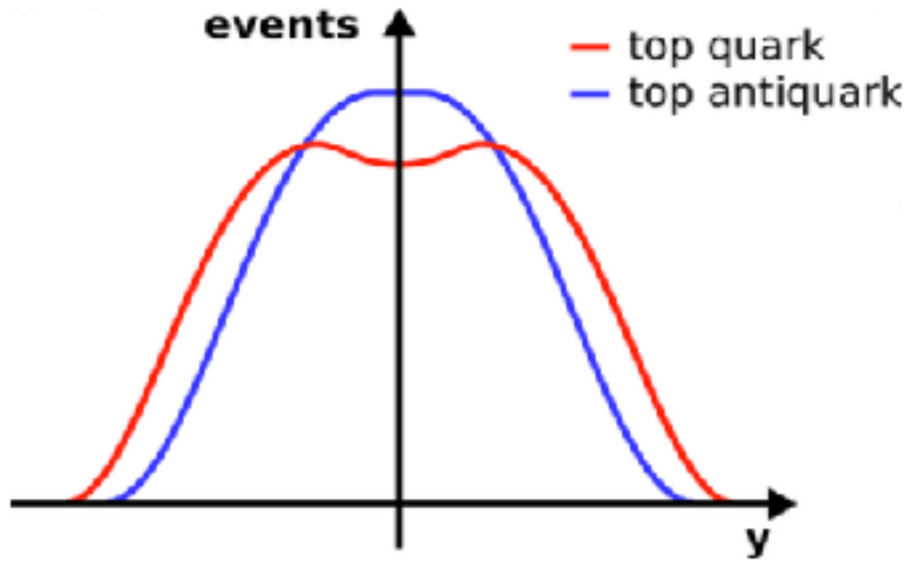


# $t\bar{t}$ charge asymmetry

- charge asymmetry small in the SM:
  - ~ 1%, can be enhanced by looking at boosted channel

| | | $M_c = 2m_t$ | 0.5 TeV | 1 TeV | 2 TeV |
|---|---|---|---|---|---|
| 14 TeV | QCD: $A_C^{\Delta\|y\|}$ (%) | 0.58 (3) | 0.74 (3) | 1.11 (5) | 1.72 (10) |
| | QCD + EW: $A_C^{\Delta\|y\|}$ (%) | 0.67 (4) | 0.86 (5) | 1.32 (8) | 2.12 (10) |

W. Bernreuther et al., arXiv:1205.6580

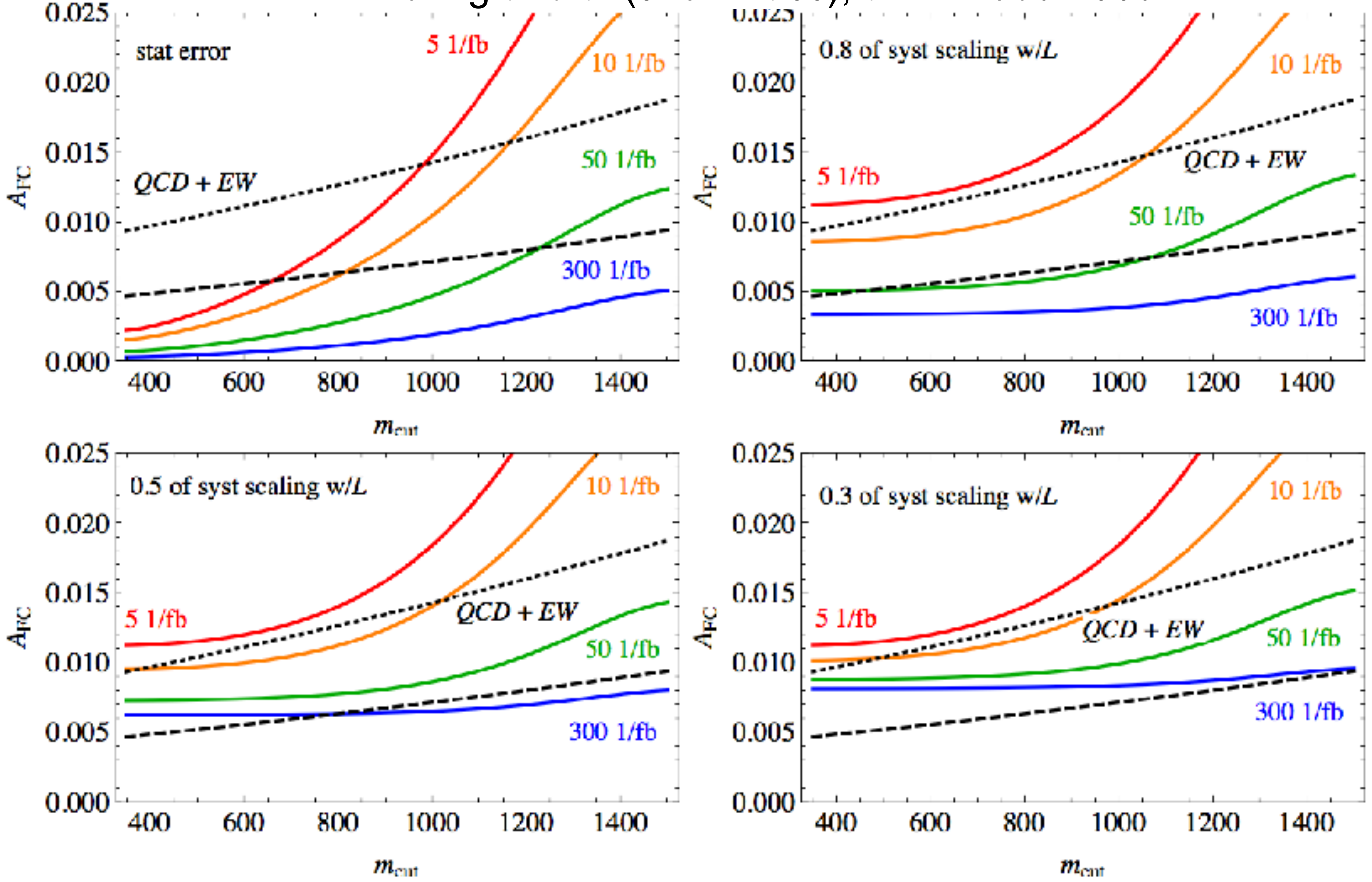



$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

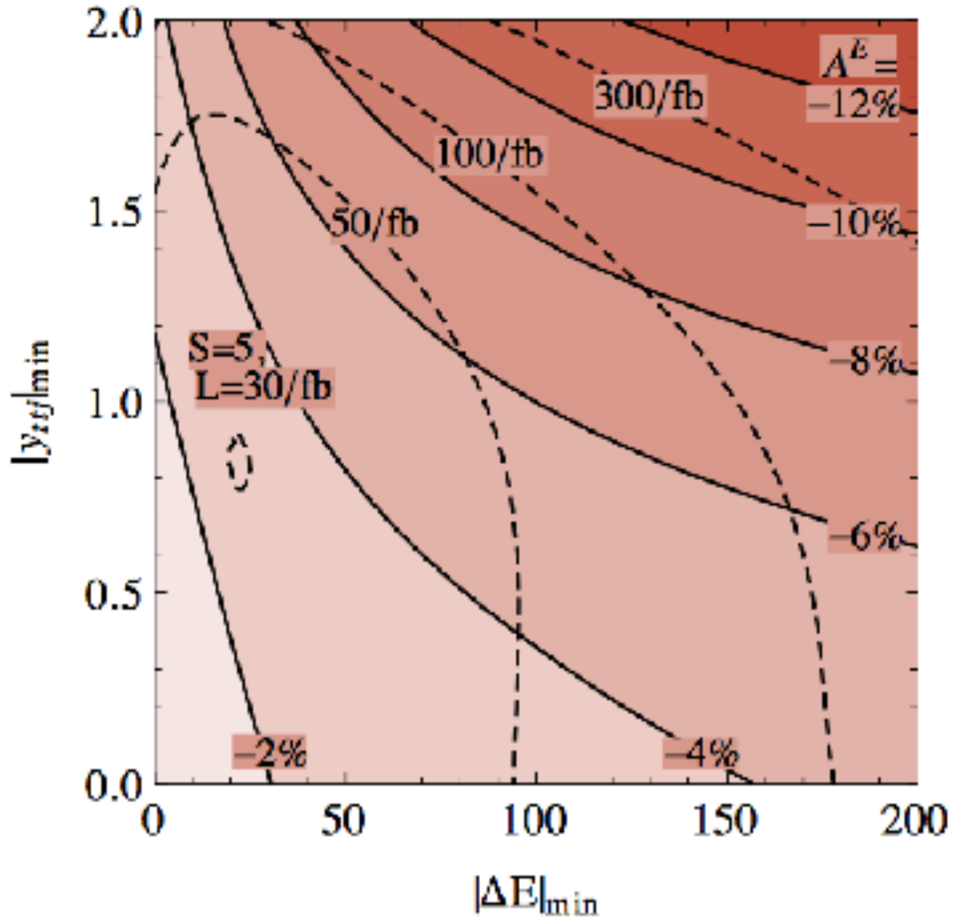
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

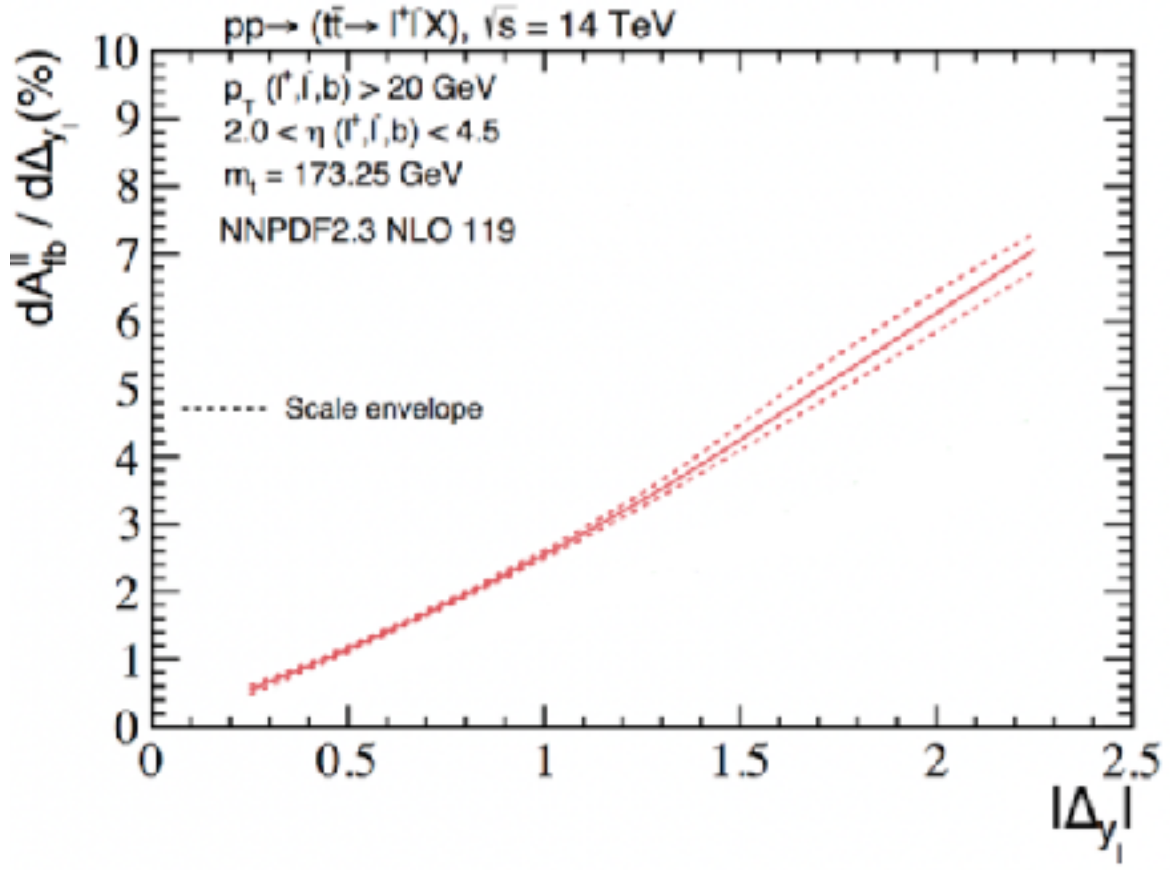
- sensitivity studies:
  - for different assumptions on the scaling of the systematic uncertainties
  - observation of SM asymmetry might be possible, need to improve modeling

A. Jung and al (snowmass), arXiv:1309.2889




- alternatives:
  - Can also use the other asymmetries (energy or inclined asymmetry) based on $t\bar{t}$+jet: could be observed with 16σ with 3000 fb$^{-1}$ (Berge & Westhoff, arXiv:1307.6225)
  - LHCb can also measure a forward asymmetry. Might be sensitive to complementary new physics models



# $t\bar{t}W$ asymmetry

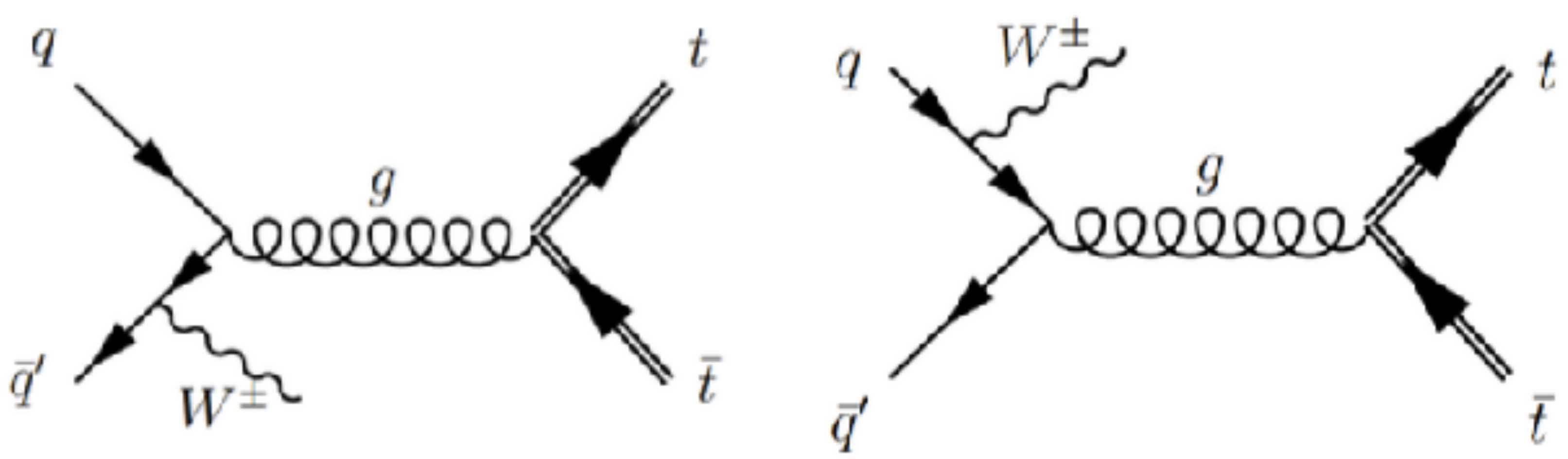
F. Maltoni et al., arXiv:1406.3262

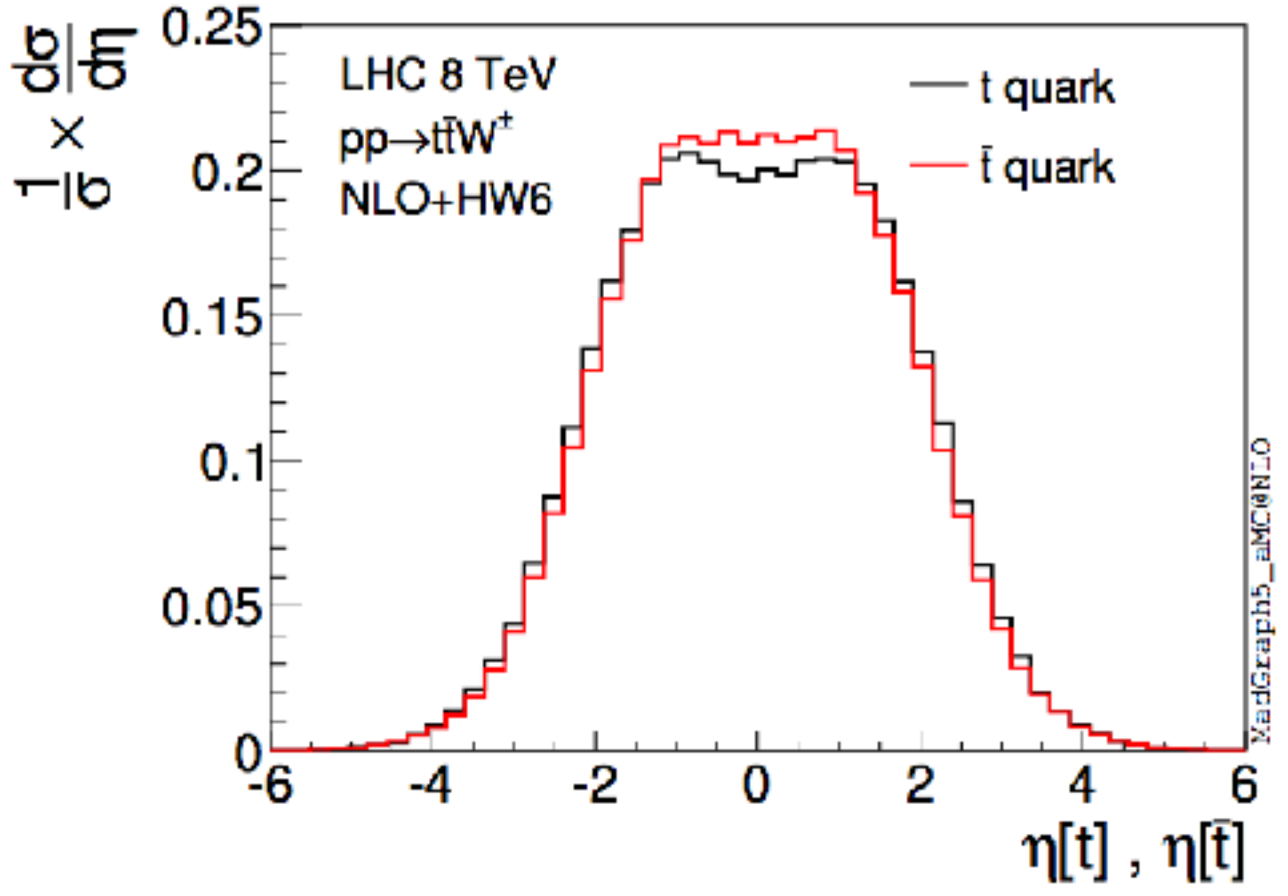
- $t\bar{t}W$ production
  - like for $t\bar{t}$ : symmetric at LO, asymmetry at NLO
  - but can only occur from $q\bar{q}$ annihilation (no gg contribution until NNLO): larger asymmetry than for $t\bar{t}$
  - W emission: polarizer for quark/antiquark ⇒ polarised top/antitop production (asymmetric rapidity distribution at LO)

- asymmetry
  - top based
  - b or lepton based

- variation with beam energy
  - decrease slower than the $t\bar{t}$ asymmetry

- $t\bar{t}W$ asymmetry
  - larger than $t\bar{t}$ asymmetry but need statistics
  - sensitive to chirality of NP




- 14 TeV ($\mathcal{L} = 300$ fb$^{-1}$):

  $\delta_{\rm rel} A_c^t = 45\%, \delta_{\rm rel} A_c^b = 13\%, \delta_{\rm rel} A_c^\ell = 8\%$

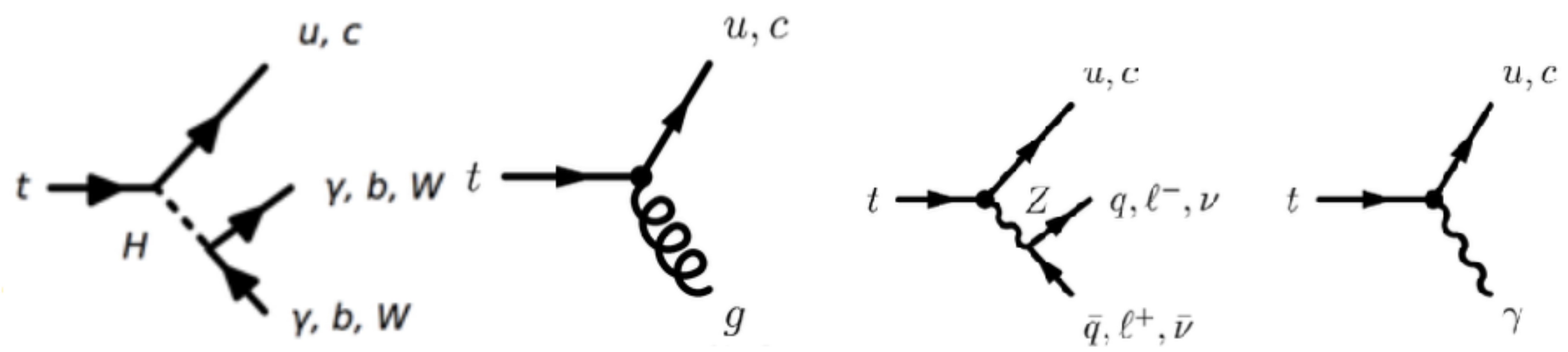
- 14 TeV ($\mathcal{L} = 3000$ fb$^{-1}$):

  $\delta_{\rm rel} A_c^t = 14\%, \delta_{\rm rel} A_c^b = 4\%, \delta_{\rm rel} A_c^\ell = 2\%$

| | | 8 TeV | 13 TeV | 14 TeV | 33 TeV | 100 TeV |
|---|---|---|---|---|---|---|
| $t\bar{t}$ | $\sigma$(pb) | $198^{+15\%}_{-14\%}$ | $661^{+15\%}_{-13\%}$ | $786^{+14\%}_{-13\%}$ | $4630^{+12\%}_{-11\%}$ | $30700^{+13\%}_{-13\%}$ |
| | $A_c^t(\%)$ | $0.72^{+0.14}_{-0.09}$ | $0.45^{+0.09}_{-0.06}$ | $0.43^{+0.08}_{-0.05}$ | $0.26^{+0.04}_{-0.03}$ | $0.12^{+0.03}_{-0.02}$ |
| $t\bar{t}W^\pm$ | $\sigma$(fb) | $210^{+11\%}_{-11\%}$ | $587^{+13\%}_{-12\%}$ | $678^{+14\%}_{-12\%}$ | $3220^{+17\%}_{-13\%}$ | $19000^{+20\%}_{-17\%}$ |
| | $A_c^t(\%)$ | $2.37^{+0.56}_{-0.38}$ | $2.24^{+0.43}_{-0.32}$ | $2.23^{+0.43}_{-0.33}$ | $1.95^{+0.28}_{-0.23}$ | $1.85^{+0.21}_{-0.17}$ |
| | $A_c^b(\%)$ | $8.50^{+0.15}_{-0.10}$ | $7.54^{+0.19}_{-0.17}$ | $7.50^{+0.24}_{-0.22}$ | $5.37^{+0.22}_{-0.30}$ | $3.36^{+0.15}_{-0.19}$ |
| | $A_c^\ell(\%)$ | $-14.83^{-0.65}_{+0.95}$ | $-13.16^{-0.81}_{+1.12}$ | $-12.84^{-0.81}_{+1.11}$ | $-9.21^{-0.87}_{+1.05}$ | $-4.94^{-0.63}_{+0.72}$ |

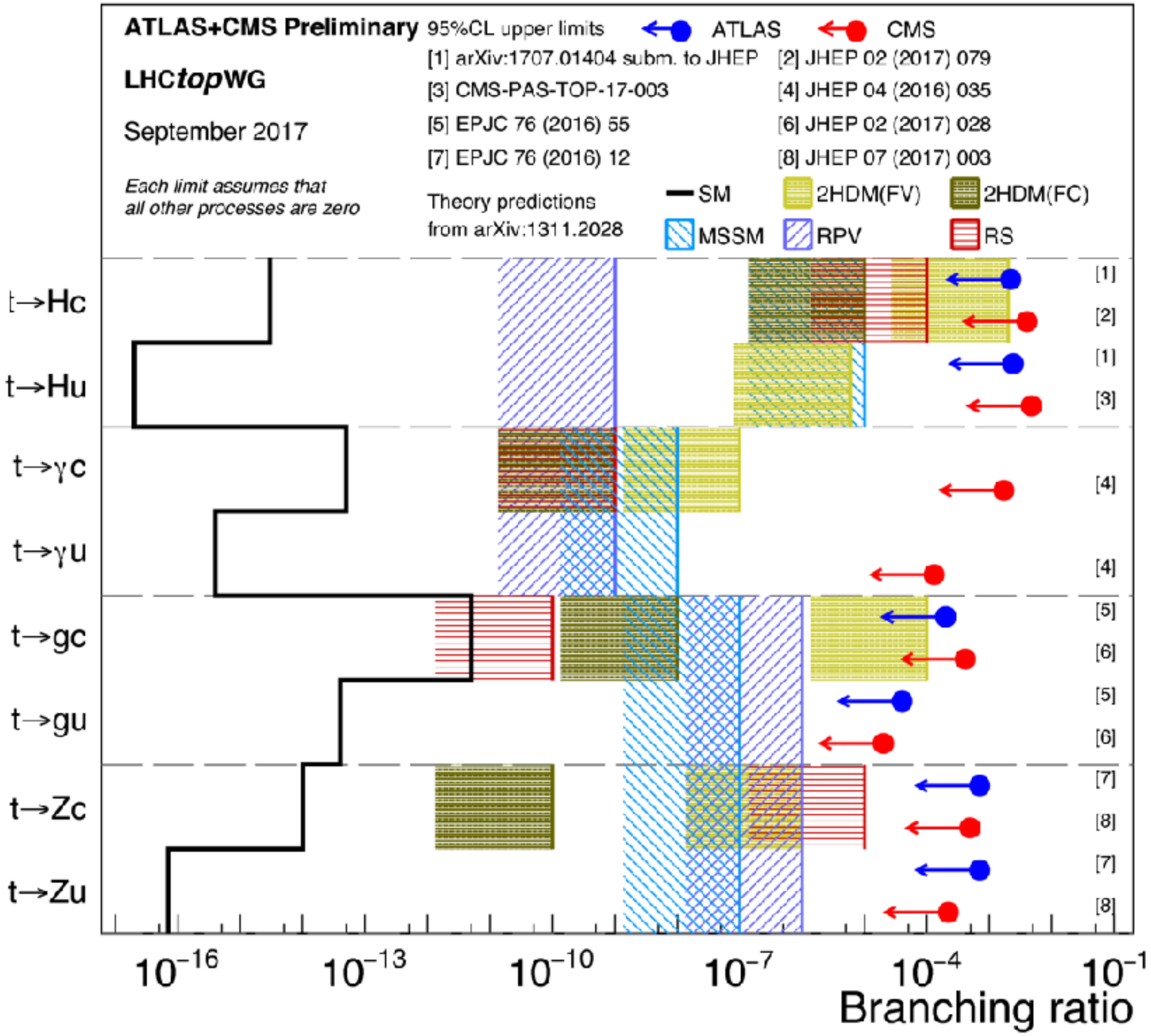
# Top Flavour Changing Neutral Current

- ‘golden’ physics case for HL-LHC top physics
  - Forbidden at tree level in the SM, appearing only in loops but highly suppressed
  - heavily rely on data statistics




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

snowmass, arXiv:13011.2028



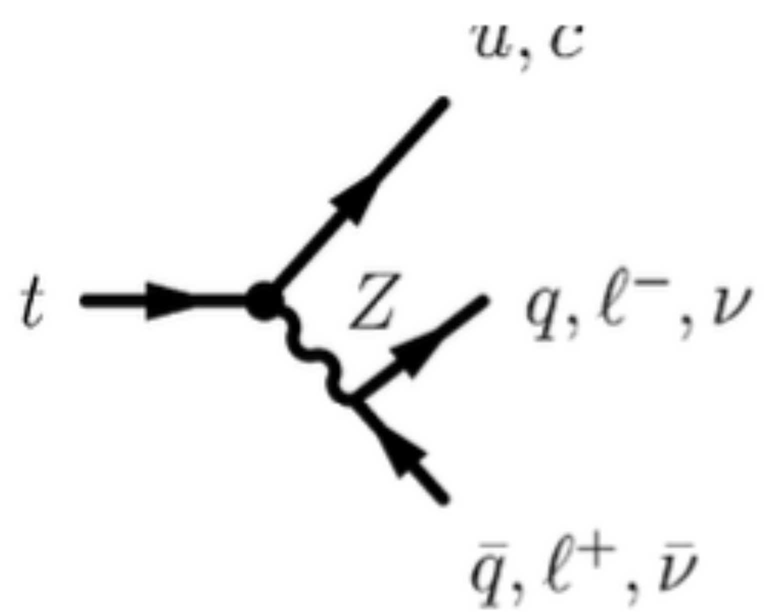

- HL-LHC experimental studies
  - t ⟶ Zq, t ⟶ Hq, t ⟶ qγ

# ATLAS t ⟶ Zq Sensitivity

ATL-PHYS-PUB-2016-019

- t ⟶ Zq FCNC parametrized with 4 independent couplings:

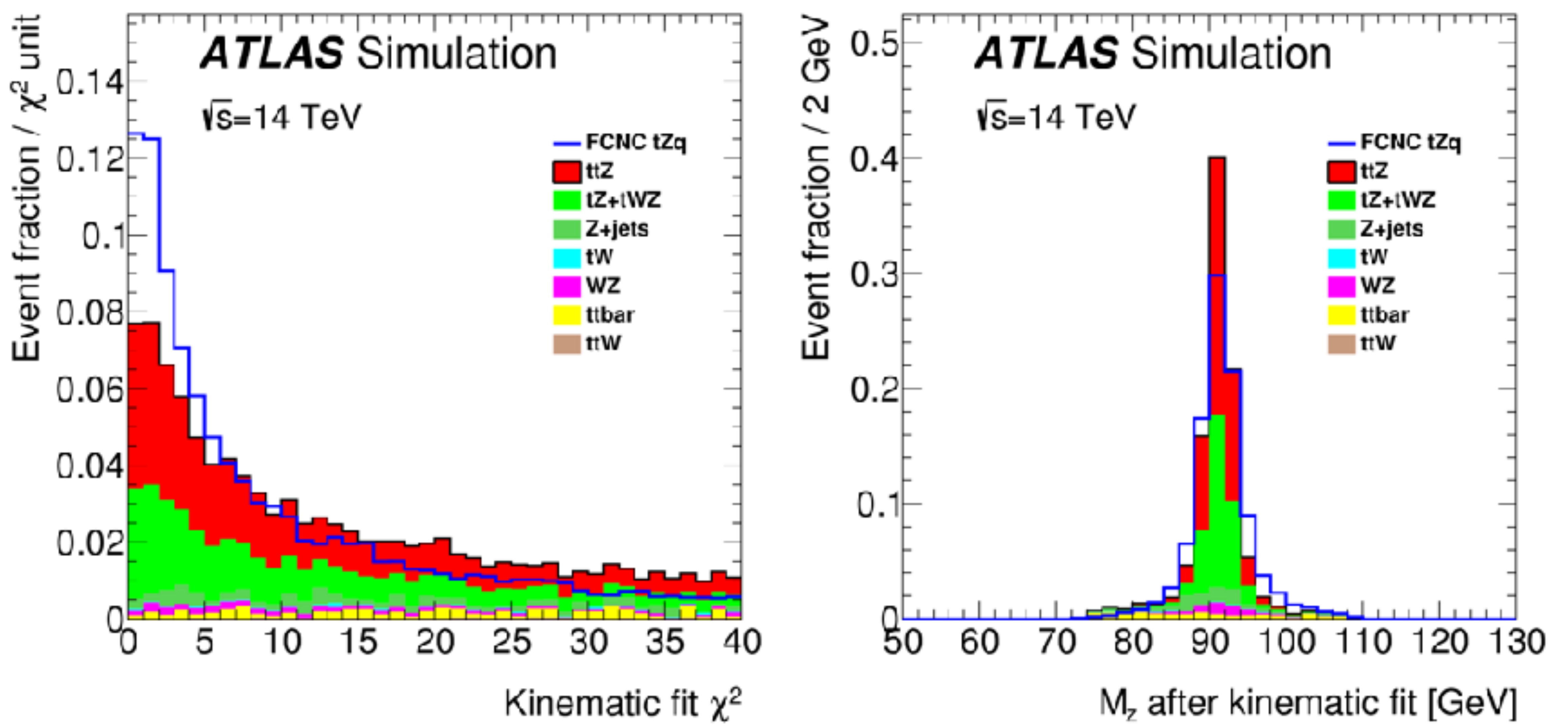
$$\mathcal{L}_{tZu} = -\frac{g}{2c_W}\bar{u}\gamma^{\mu}\left(X^L P_L + X^R P_R\right)tZ_{\mu} - \frac{g}{2c_W}\bar{u}\frac{i\sigma^{\mu\nu}(p_t^{\nu} - p_u^{\nu})}{M_Z}\left(\kappa^L P_L + \kappa^R P_R\right)tZ_{\mu} + h.c.,$$



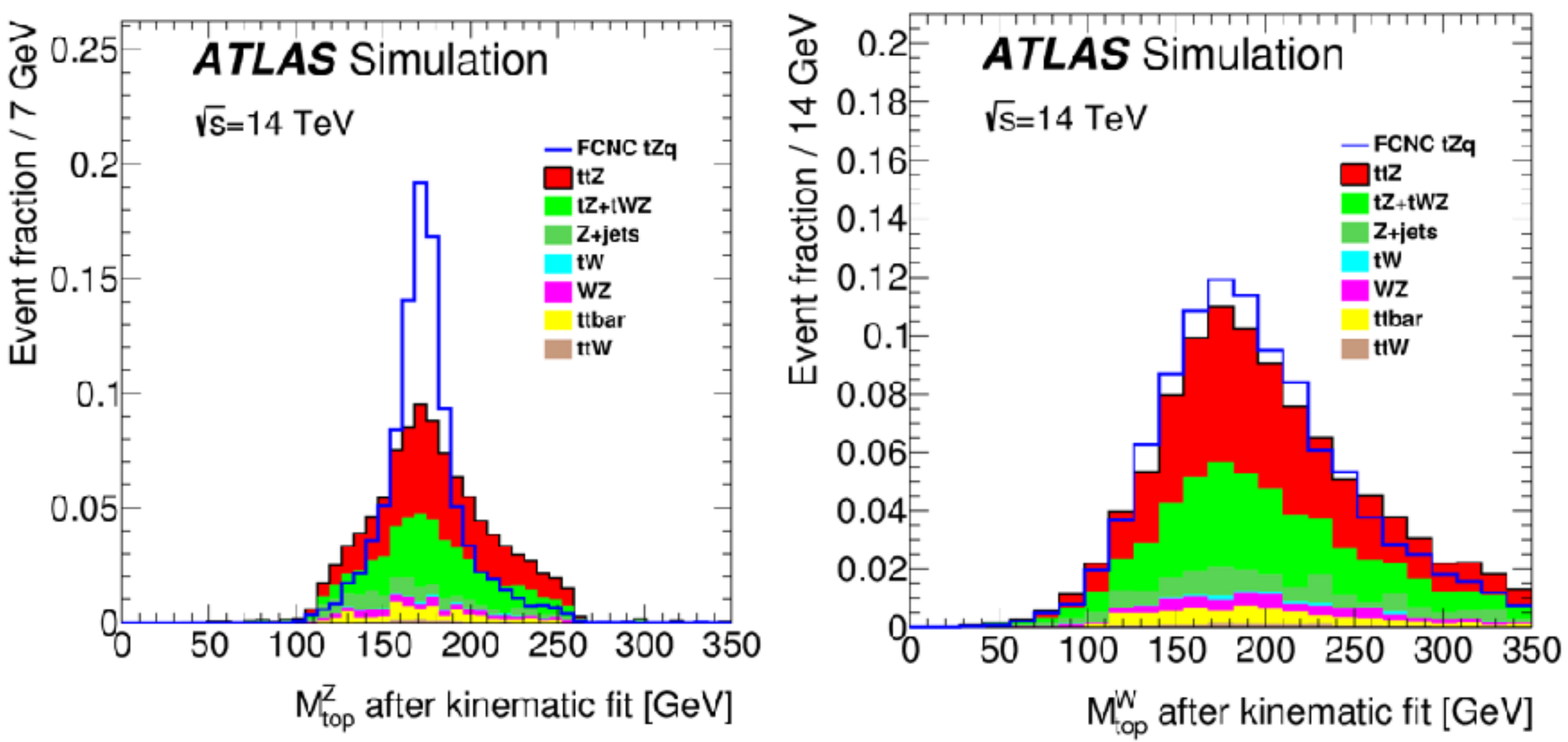

- event selection
  - using the detector with the full |η|<4 coverage
  - 3 leptons, 2 opposite signed around the Z mass
  - at least 2 jets: 1 b-tag, 1 non b-tag
  - kinematic reconstruction via a $X^2$

$$\chi^2 = \frac{\left(m_Z - m_{\ell_1\ell_2}^{\mathrm{reco}}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m_{\ell_3\nu}^{\mathrm{reco}}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m_{\ell_3\nu j_b}^{\mathrm{reco}}\right)^2}{\sigma_{t\to Wb}^2} + \frac{\left(m_t - m_{\ell_1\ell_2 j_u}^{\mathrm{reco}}\right)^2}{\sigma_{t\to Zq}^2}$$

reference scenario, unit normalisation



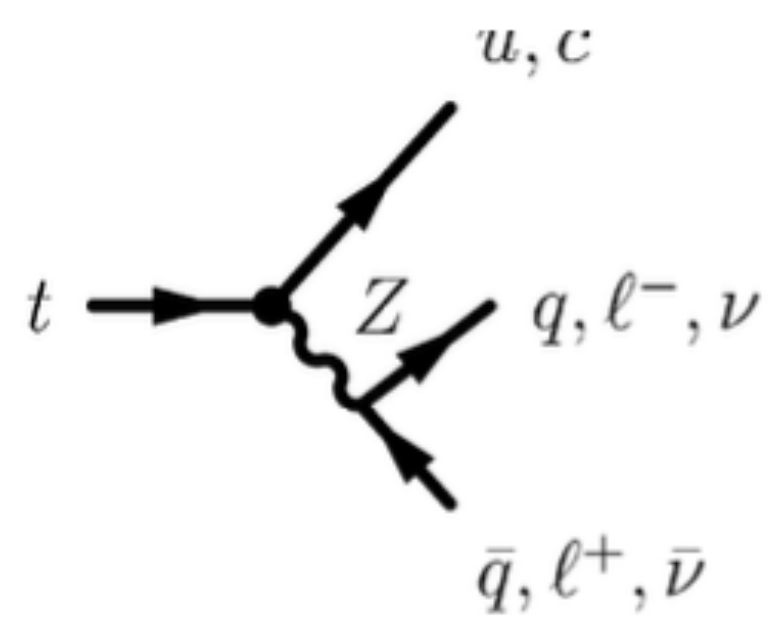

HL-LHC



# $t \longrightarrow Zq$ Sensitivity Results

ATL-PHYS-PUB-2016-019

CMS PAS FTR-13-016




- **ATLAS limit extraction:**
  - maximum likelihood fit of the $X^2$ distribution

- **ATLAS stat only limits**

| "$\gamma$" $t \to Zu$ | "$\sigma$" $t \to Zu$ | "$\gamma$" $t \to Zc$ | "$\sigma$" $t \to Zc$ | "$\gamma$" $t \to Zu+Zc$ | "$\sigma$" $t \to Zu+Zc$ |
|---|---|---|---|---|---|
| $4.3 \cdot 10^{-5}$ | $4.3 \cdot 10^{-5}$ | $5.6 \cdot 10^{-5}$ | $5.8 \cdot 10^{-5}$ | $2.4 \cdot 10^{-5}$ | $2.5 \cdot 10^{-5}$ |

- **ATLAS limit with systematics:**
  - Set A: 5-6 times worse limit than stat only
    - based on 8 TeV result
  - Set B: 3-4 times worse limit than stat only
    - 50% improvements in the uncertainty on the data driven fake estimation
    - 10% uncertainty on the tZ/tW cross sections, 6% on the ttV cross section

| Set | "$\gamma$" $t \to Zu$ | "$\sigma$" $t \to Zu$ | "$\gamma$" $t \to Zc$ | "$\sigma$" $t \to Zc$ | "$\gamma$" $t \to Zu+Zc$ | "$\sigma$" $t \to Zu+Zc$ |
|---|---|---|---|---|---|---|
| A | $18 \cdot 10^{-5}$ | $16 \cdot 10^{-5}$ | $41 \cdot 10^{-5}$ | $36 \cdot 10^{-5}$ | $13 \cdot 10^{-5}$ | $12 \cdot 10^{-5}$ |
| B | $13 \cdot 10^{-5}$ | $13 \cdot 10^{-5}$ | $24 \cdot 10^{-5}$ | $23 \cdot 10^{-5}$ | $8.9 \cdot 10^{-5}$ | $8.3 \cdot 10^{-5}$ |

sensitivity largely defined by systematic errors

- **CMS projection:**
  - pileup: 140
  - based on the 8 TeV result
  - cut and count approach
  - systematic uncertainty assumption
    - signal: 20%
    - background: scaling with luminosity (limit to at most a factor of 4 better)

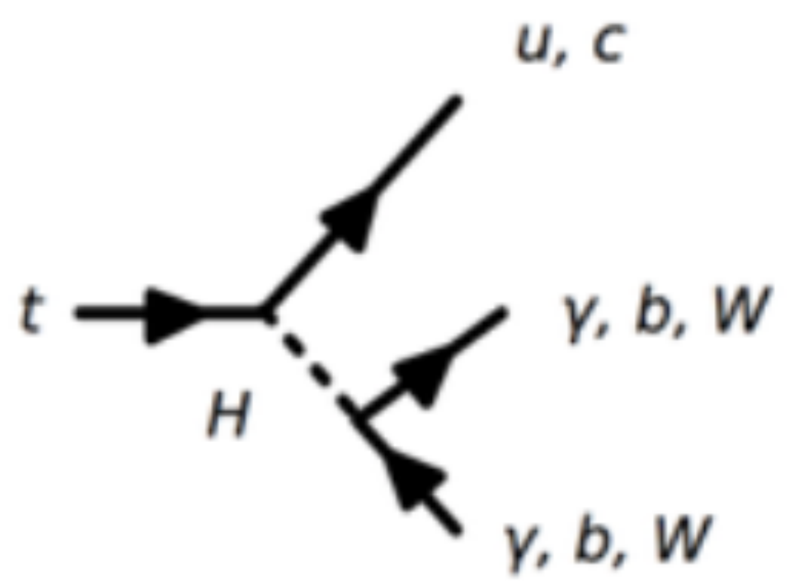
| $\mathcal{B}(t \to Zq)$ | $19.5\,\mathrm{fb}^{-1}$ @ 8 TeV | $300\,\mathrm{fb}^{-1}$ @ 14 TeV | $3000\,\mathrm{fb}^{-1}$ @ 14 TeV |
|---|---|---|---|
| Exp. bkg. yield | 3.2 | 26.8 | 268 |
| Expected limit | $< 0.10\%$ | $< 0.027\%$ | $< 0.010\%$ |
| $1\,\sigma$ range | $0.06 - 0.13\%$ | $0.018 - 0.038\%$ | $0.007 - 0.014\%$ |
| $2\,\sigma$ range | $0.05 - 0.20\%$ | $0.013 - 0.051\%$ | $0.005 - 0.020\%$ |

# ATLAS t ⟶ Hq Sensitivity

ATL-PHYS-PUB-2016-019

- t ⟶ Zq FCNC parametrized with 2 (scalar, pseudo-scalar) couplings:

$$\mathcal{L}_{tHu} = -\frac{1}{\sqrt{2}}\bar{u}\left(\eta^L P_L + \eta^R P_R\right) tH + h.c.$$



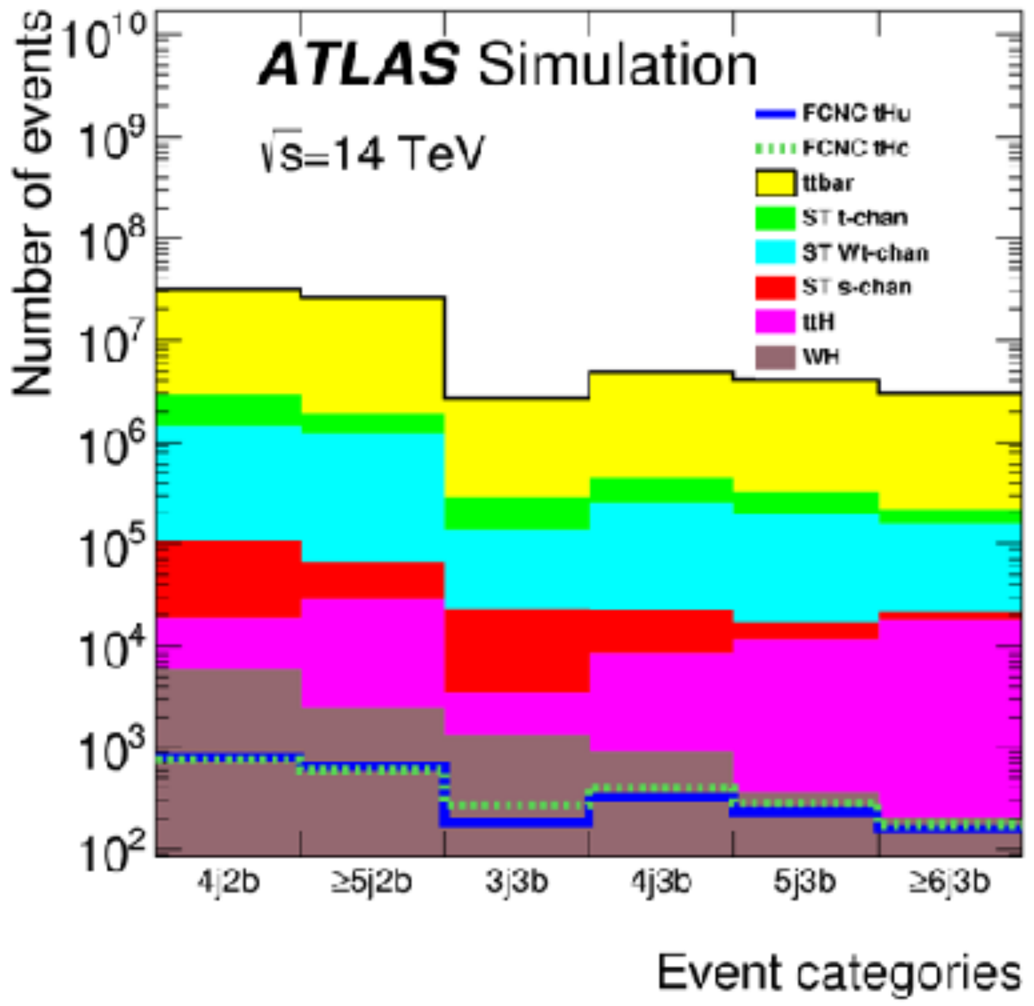

- event selection
  - 1 lepton, at least 3 jets, 1 or 2 b-jets

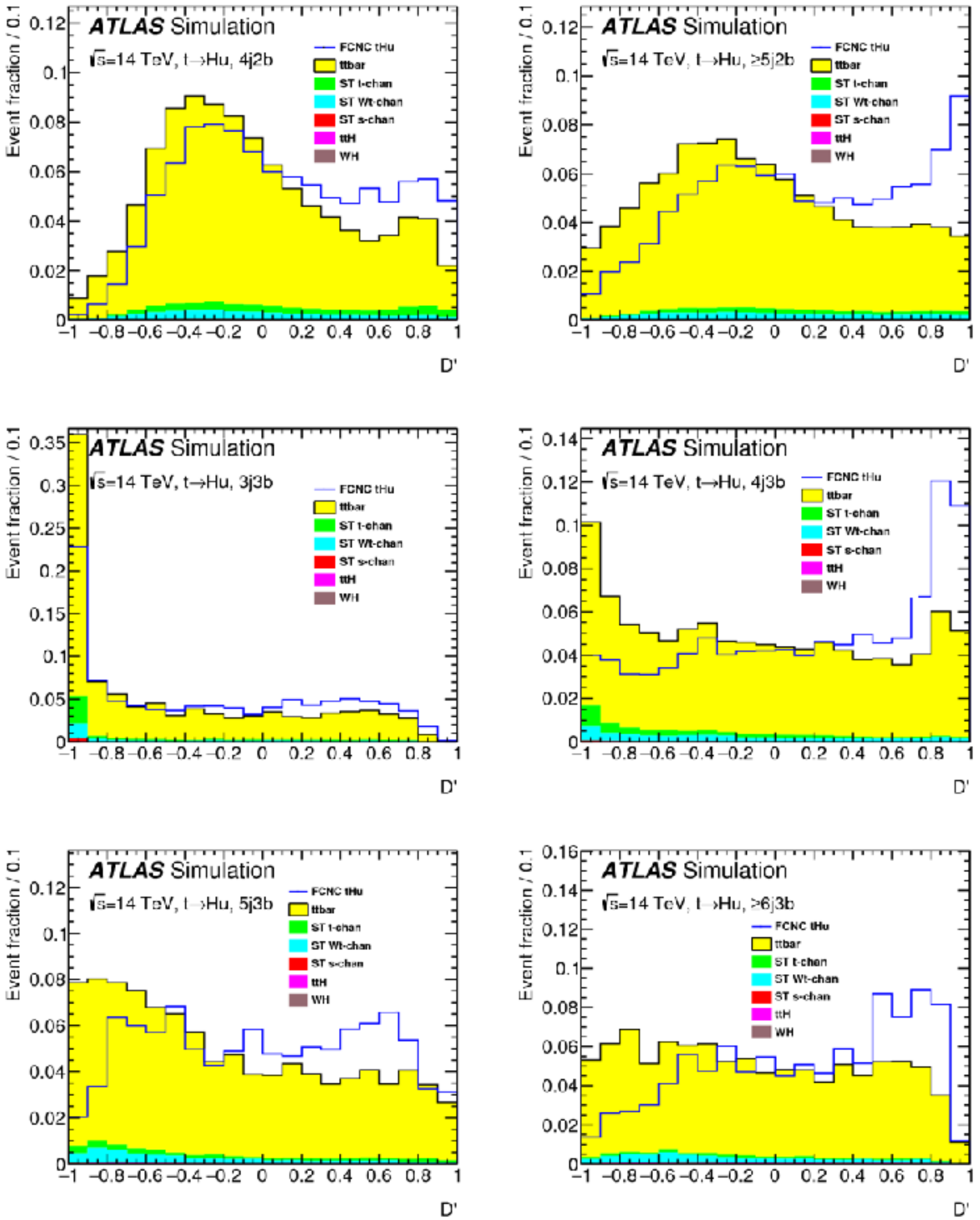
- main background
  - $t\bar{t}$+jets/HF

- analysis strategy
  - discriminant variable built from pdf calculated for every permutations in each signal category taking into account the reconstruction probability

$$\mathcal{P}^{\mathrm{Sig}} = M^t(b_1, \ell, E_{\mathrm{T}}^{\mathrm{miss}}) \cdot M^H(b_2, b_3) \cdot M^t(b_2, b_3, j) \cdot p_{\mathrm{T}}(j)$$

coupling: 0.01

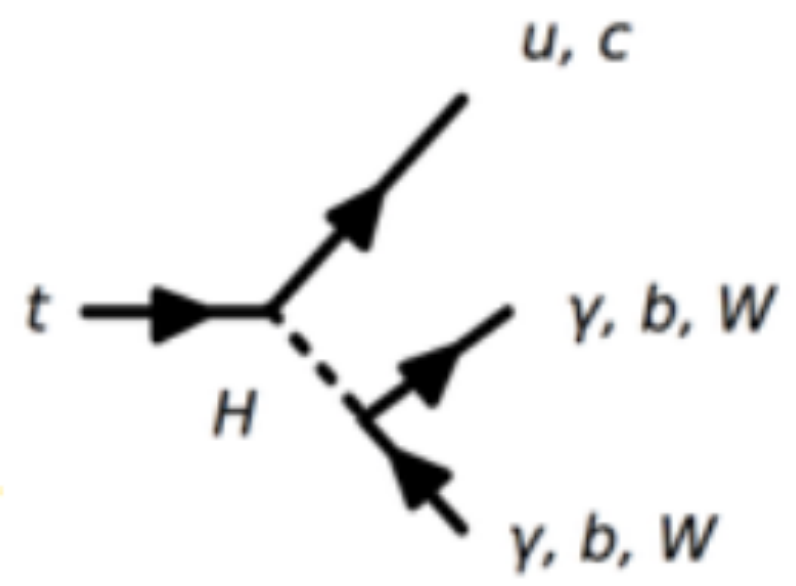


# ATLAS t ⟶ Hq Sensitivity Results

ATL-PHYS-PUB-2016-019

- Limit extraction:
  - maximum likelihood fit of the discriminant




- stat only limits

| $t \to Hu$ | $t \to Hc$ | $t \to Hu+Hc$ |
|---|---|---|
| $1.2 \cdot 10^{-4}$ | $1.0 \cdot 10^{-4}$ | $0.55 \cdot 10^{-4}$ |

- Limit with systematics:
  - Set A: 2 times worse limit than stat only
    - based on 8 TeV result
  - Set B: 2 times worse limit than stat only
    - 2% uncertainty on the b-tagging efficiency
    - 10% uncertainty in the light fake rate

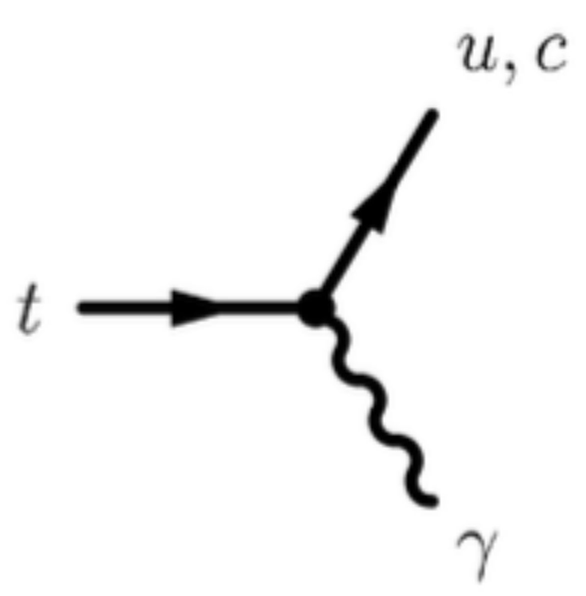
| Set | $t \to Hu$ | $t \to Hc$ | $t \to Hu+Hc$ |
|---|---|---|---|
| A | $2.4 \cdot 10^{-4}$ | $2.0 \cdot 10^{-4}$ | $1.1 \cdot 10^{-4}$ |
| B | $2.4 \cdot 10^{-4}$ | $2.0 \cdot 10^{-4}$ | $1.1 \cdot 10^{-4}$ |

reduced impact of the systematic uncertainties due to profiling
strongly constrain expected with large HL-LHC control region dataset

# CMS $t \longrightarrow q\gamma$ Sensitivity

CMS PAS FTR-16-006

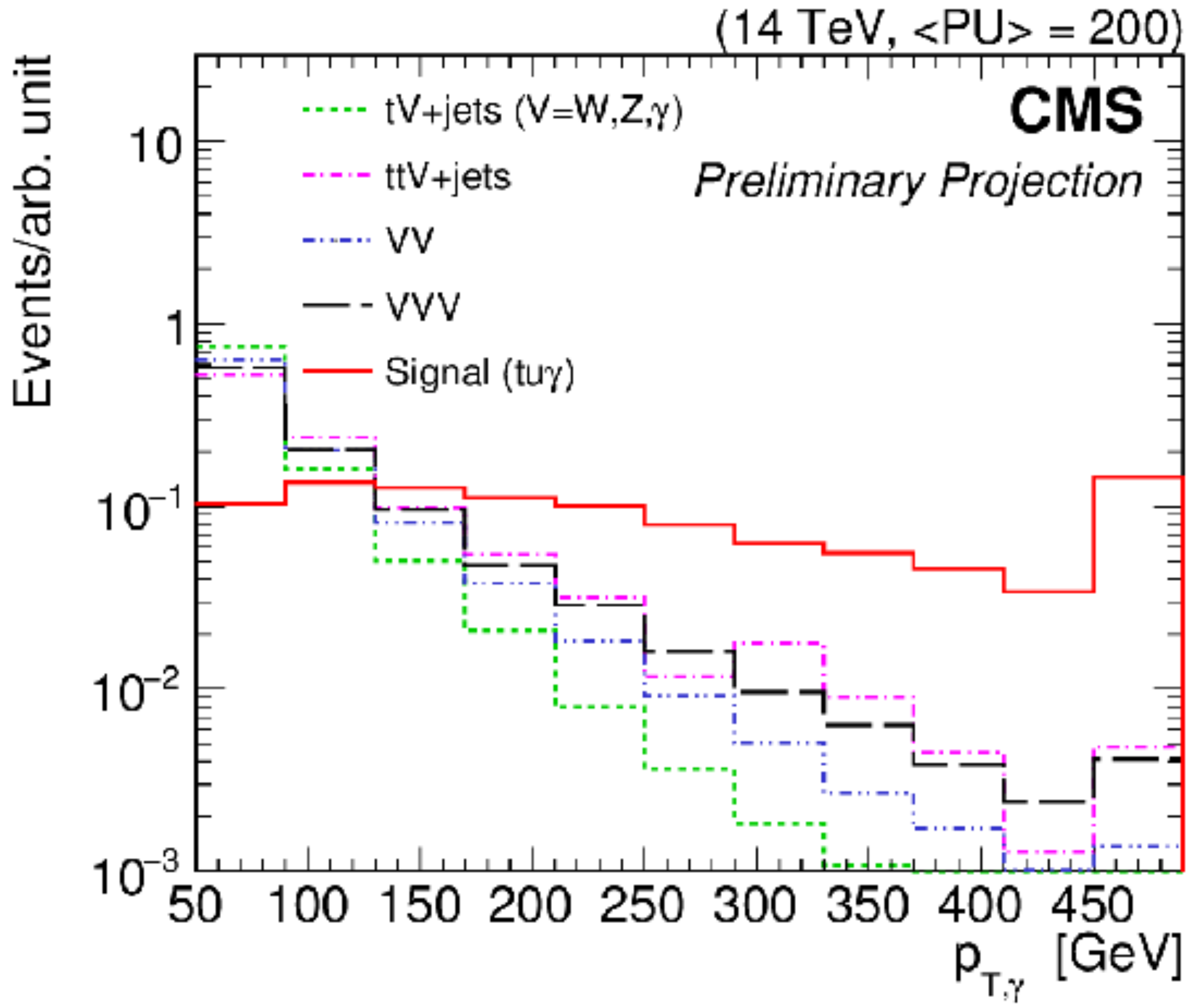
- channels
  - both single top with photon and $t\bar{t}$ with one FCNC $t \longrightarrow q\gamma$ decay

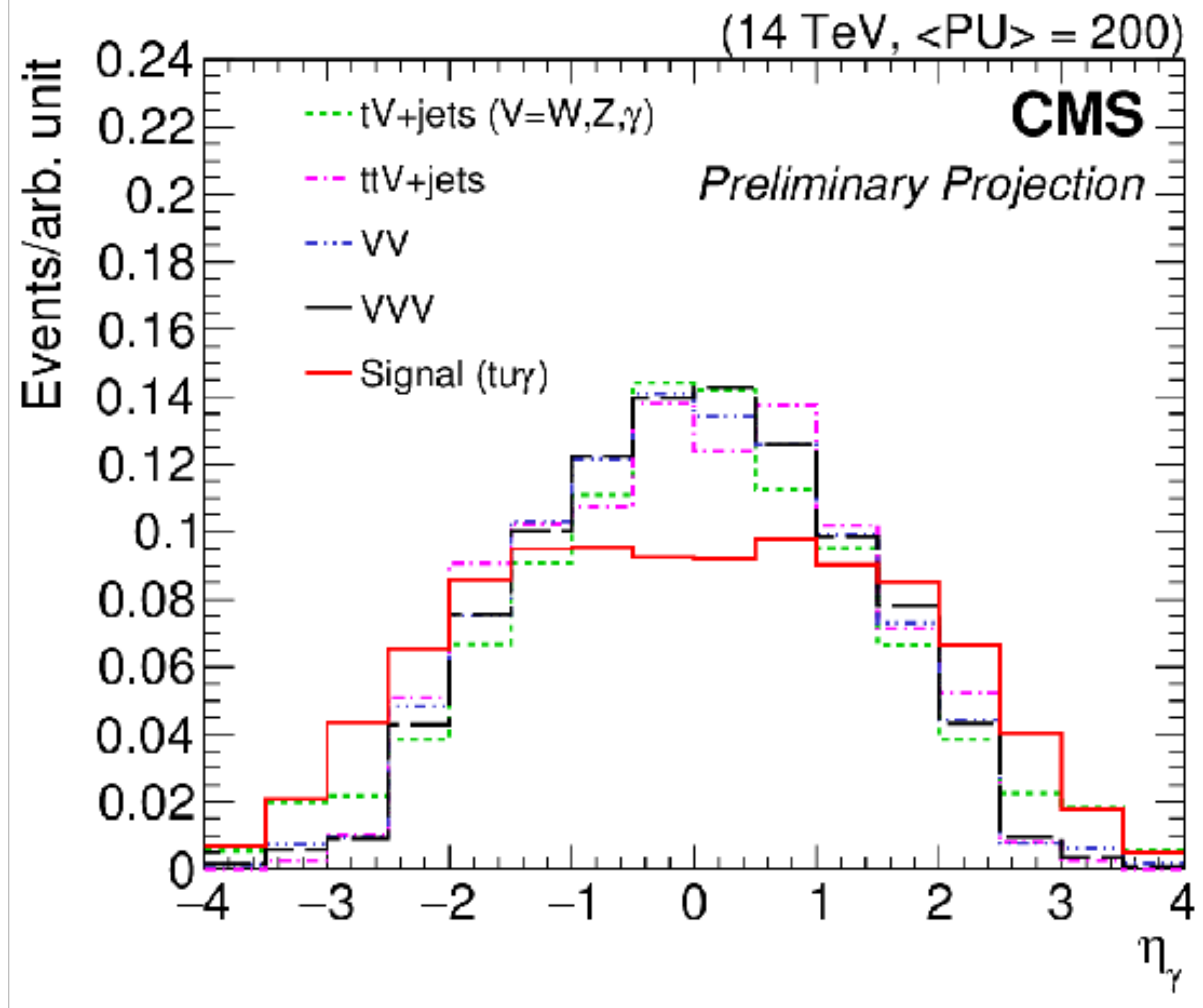



- selection
  - 1 muon, 1 b-tag jet, 1 photon separated from the muon and the jet
  - top kinematic reconstruction using muon, b-jet, MET 4-momenta
  - not fully exploits eta coverage yet

- main background
  - fake photon (% taken from the 8 TeV analysis)
  - tV+jets, triboson

- analysis strategy
  - counting method

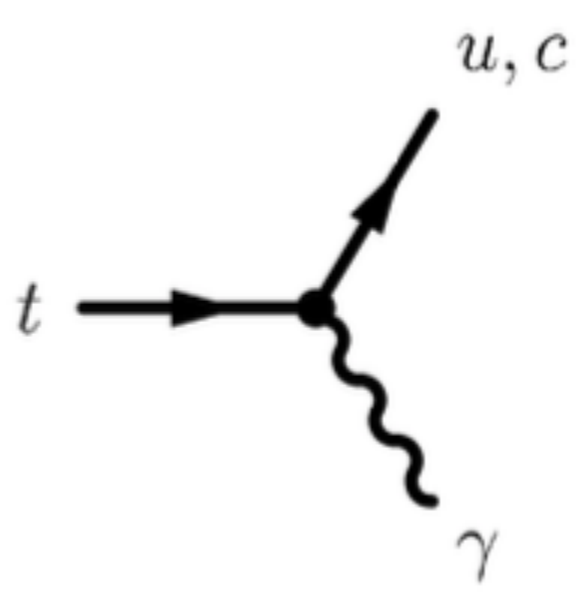


# CMS t ⟶ qγ Sensitivity Results

CMS PAS FTR-16-006

- systematic uncertainties in the 8 TeV analysis
  - tuγ / tcγ : 11.5 / 11 % (theory uncertainties: 4.1 % / 2.8 %)

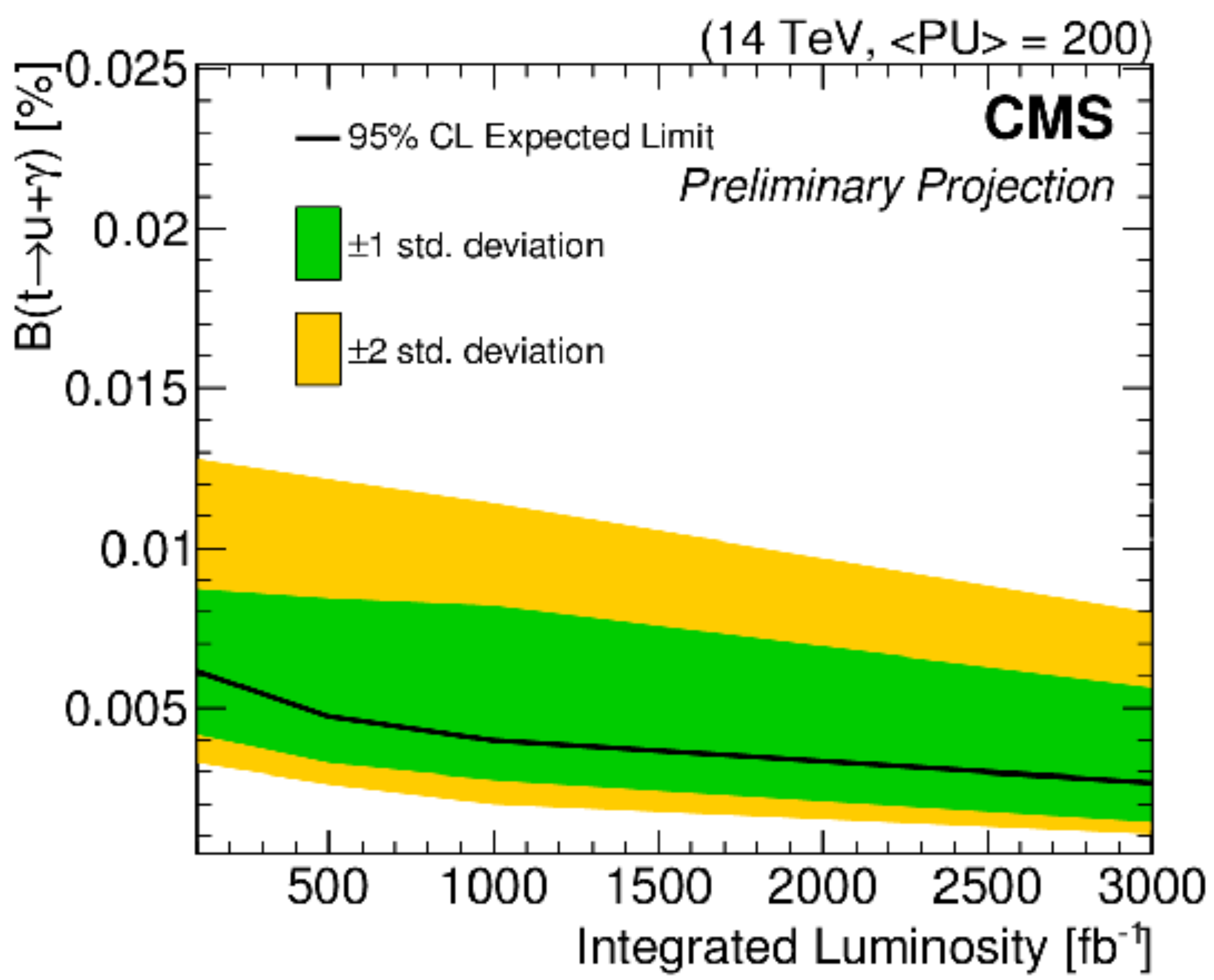


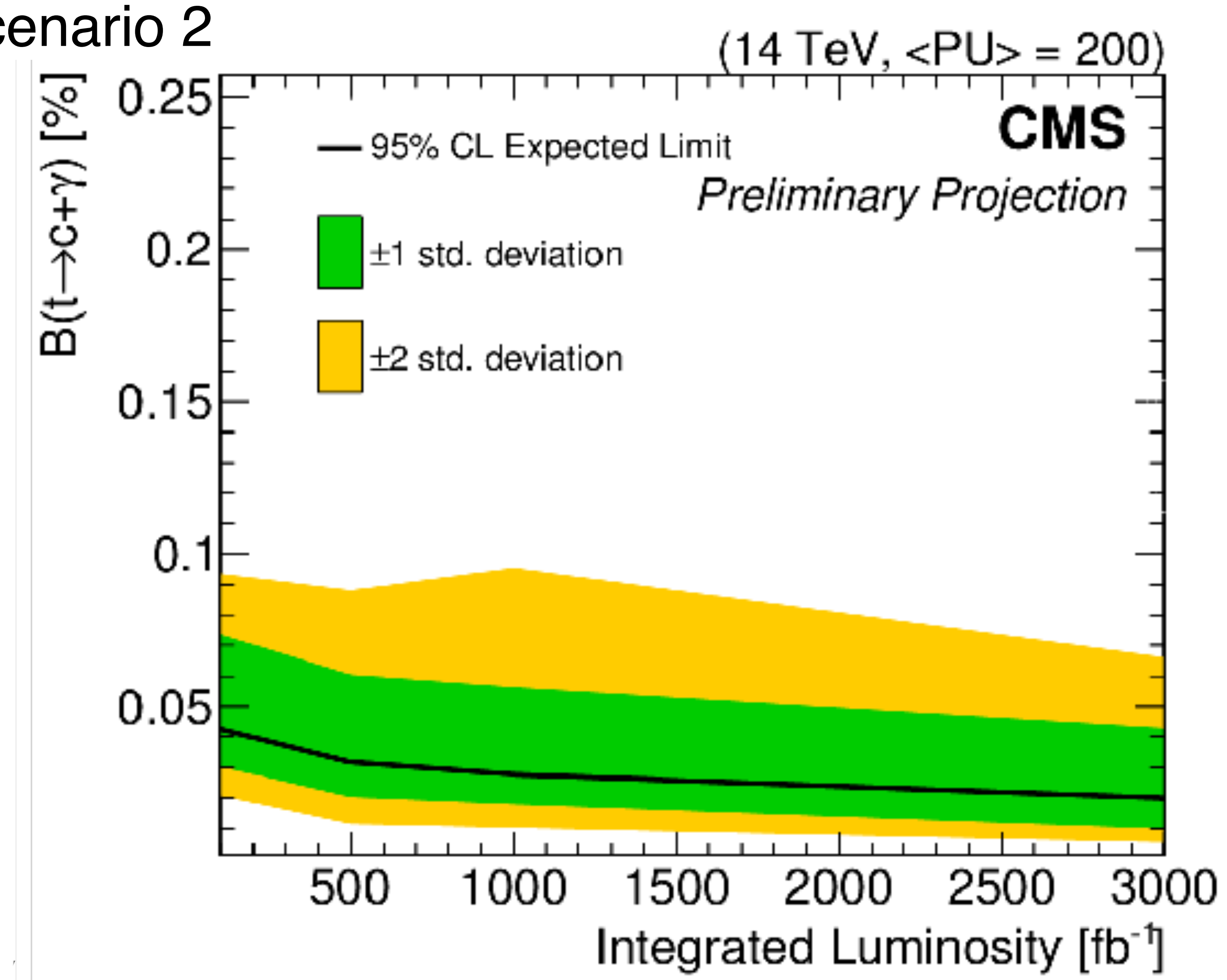

- extrapolation of systematics
  - scenario 1: same as at 8 TeV
  - scenario 2:
    - theory uncertainty reduced by 50%
    - experimental uncertainties: 1% uncertainty on b-tagging, 2% on c/light misidentification, 1% on lepton/JES, 1.5% luminosity uncertainty

- upper limits

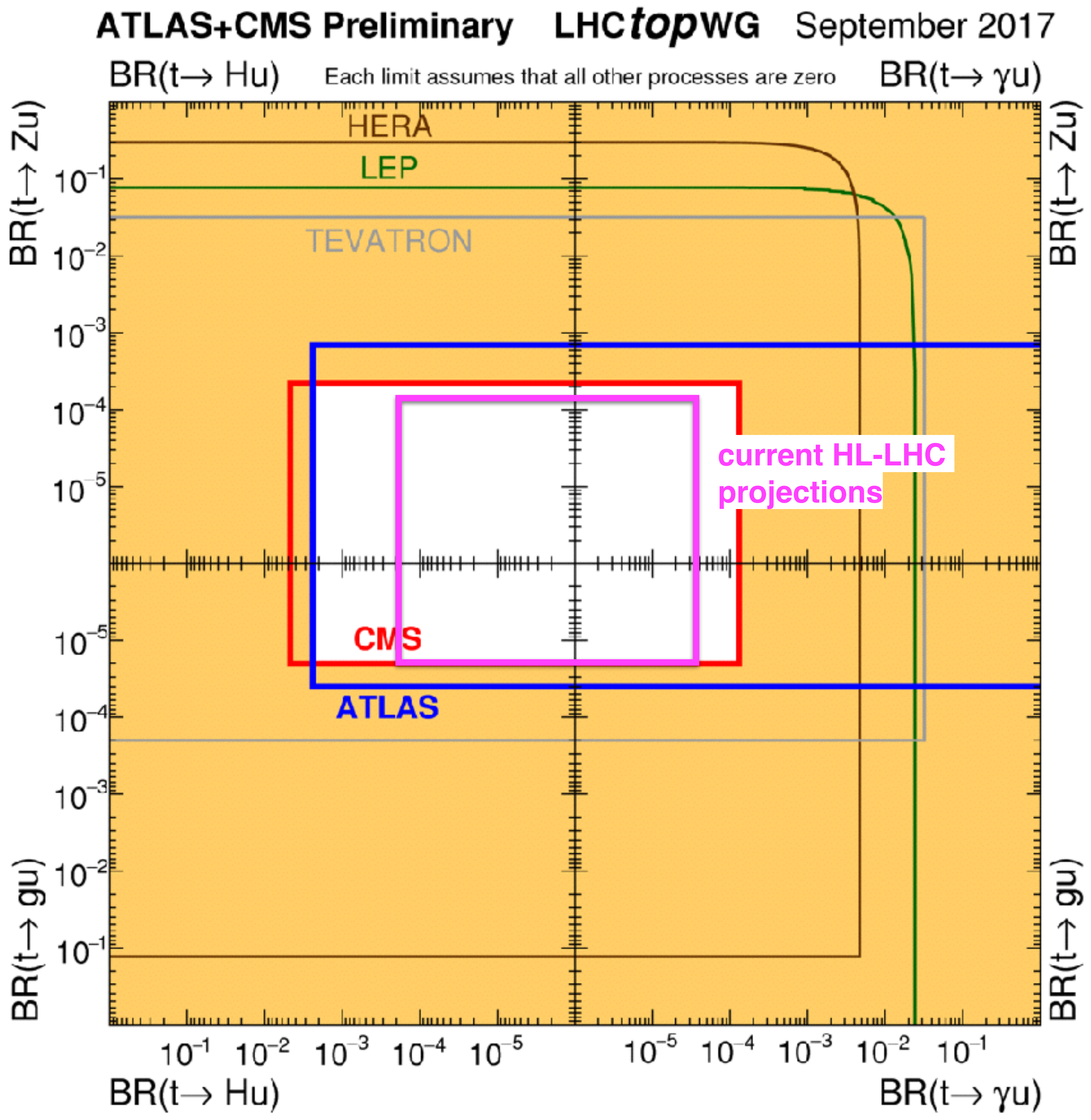
| | 19.7 $fb^{-1}$ at 8 TeV | 3 $ab^{-1}$ at 14 TeV (Scenario 1) | 3 $ab^{-1}$ at 14 TeV (Scenario 2) |
|---|---|---|---|
| $B(t\to u+\gamma)$ | $1.7 \times 10^{-4}$ | $4.6 \times 10^{-5}$ | $2.7 \times 10^{-5}$ |
| $B(t\to c+\gamma)$ | $2.2 \times 10^{-3}$ | $3.4 \times 10^{-4}$ | $2.0 \times 10^{-4}$ |

scenario 2



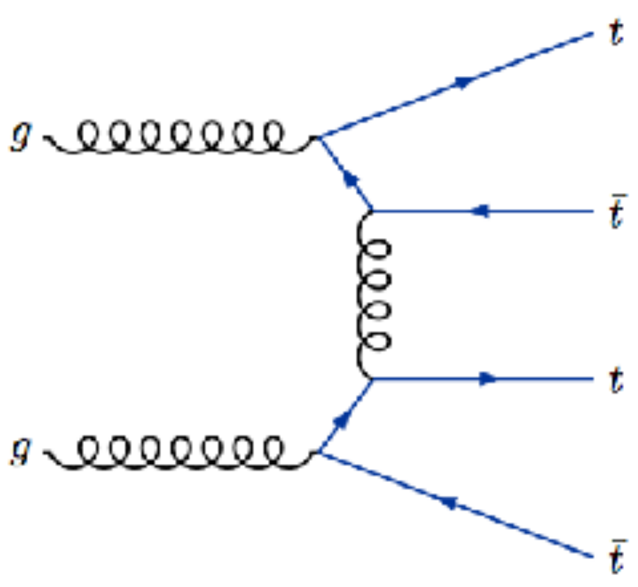



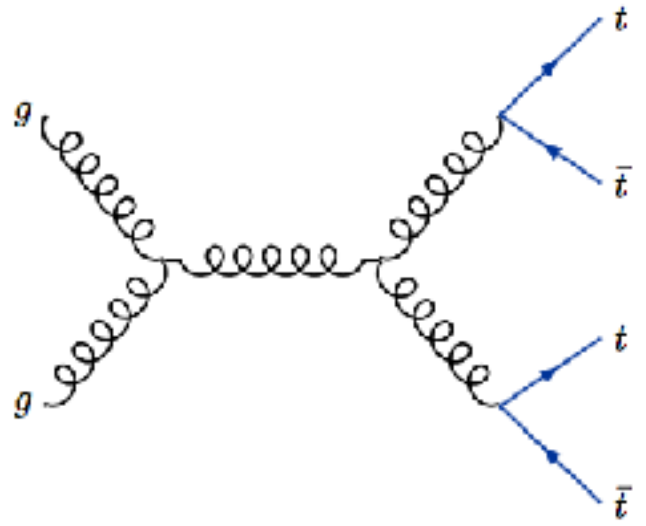
# FCNC Sensitivity Summary

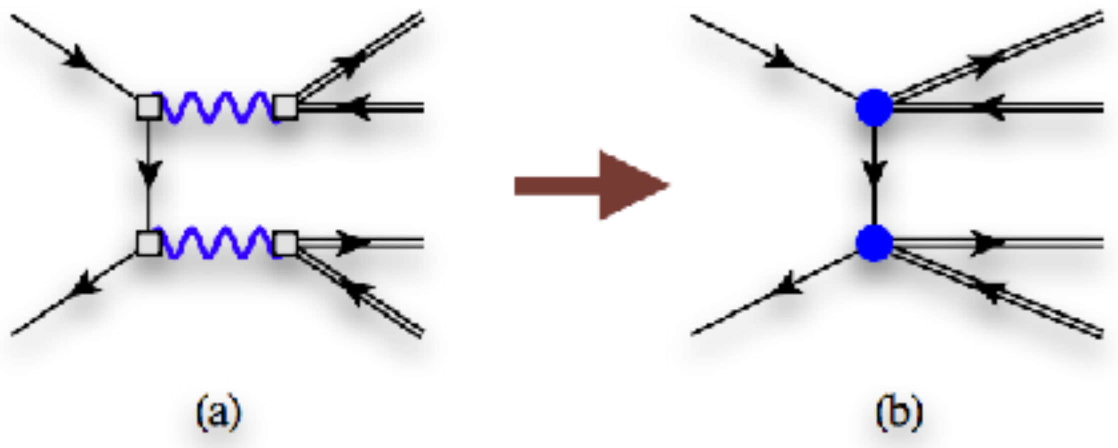


# 4 tops

- very sensitive to New Physics
  - New resonances, e.g. color-octet/singlet vectors/scalars
  - Top compositeness
  - EFT
  - 4t operator is not constrained elsewhere

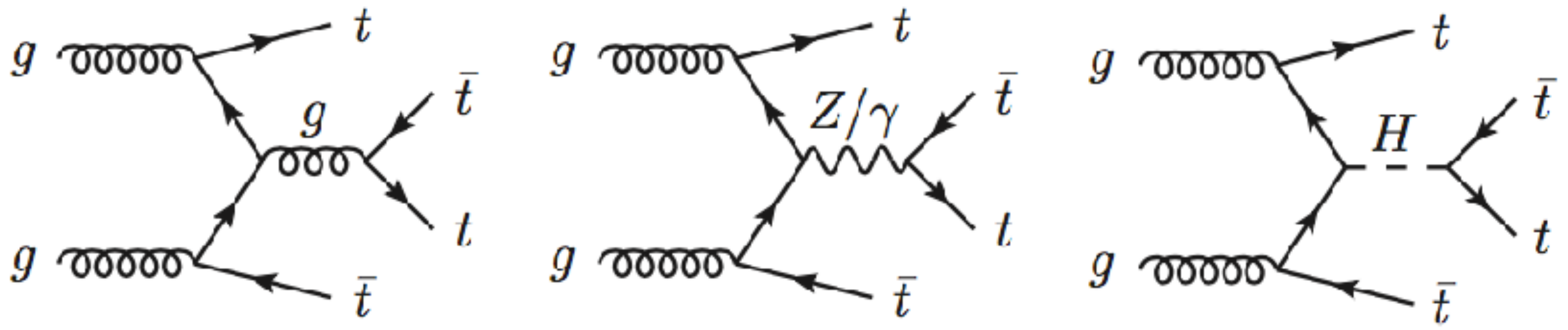






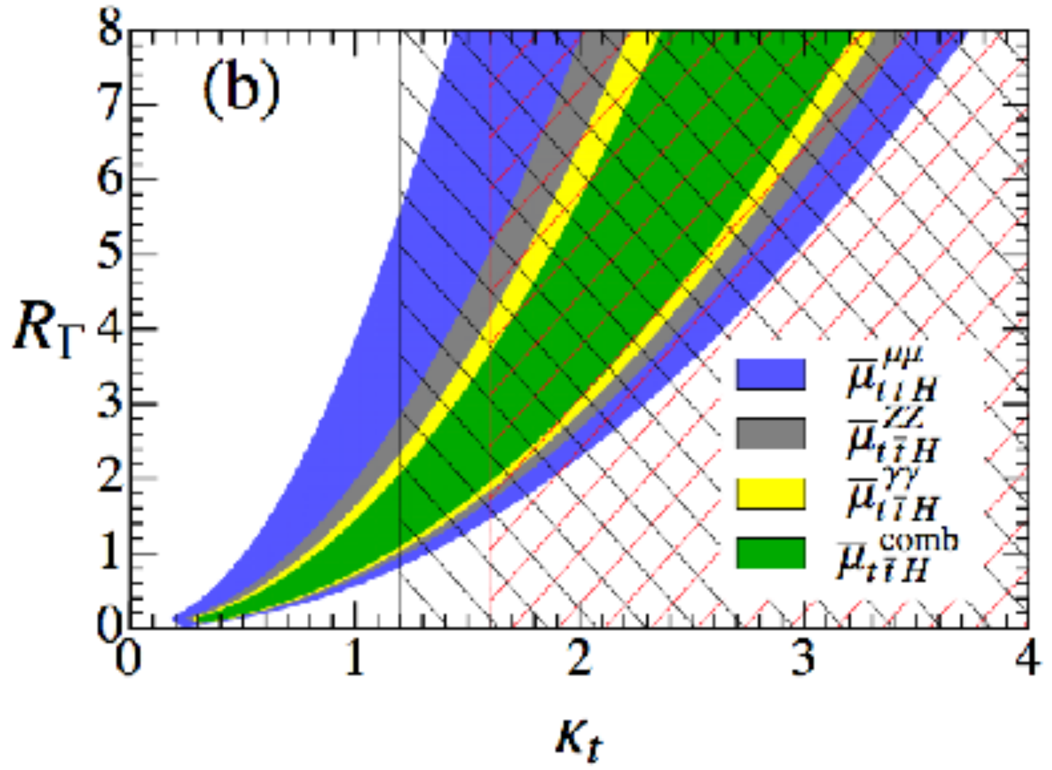

Two dim-6

- Higgs width
  - Off-shell Higgs also contributes significantly to 4 tops



| | 8 TeV | 14 TeV |
|---|---|---|
| $\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$ : | 1.193 fb, | 12.390 fb, |
| $\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H}$ : | 0.166 fb, | 1.477 fb, |
| $\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$ : | −0.229 fb, | −2.060 fb. |

arXiv:1602.01934




- Experimental search:
  - SM NLO prediction: ~ 9 fb @ 13 TeV
  - current significance (30 fb$^{-1}$): ~ 1 sigma
    - not sure we can reach 5 sigma before HL-LHC

  - SM NLO prediction: ~ 104 fb @ 27 TeV

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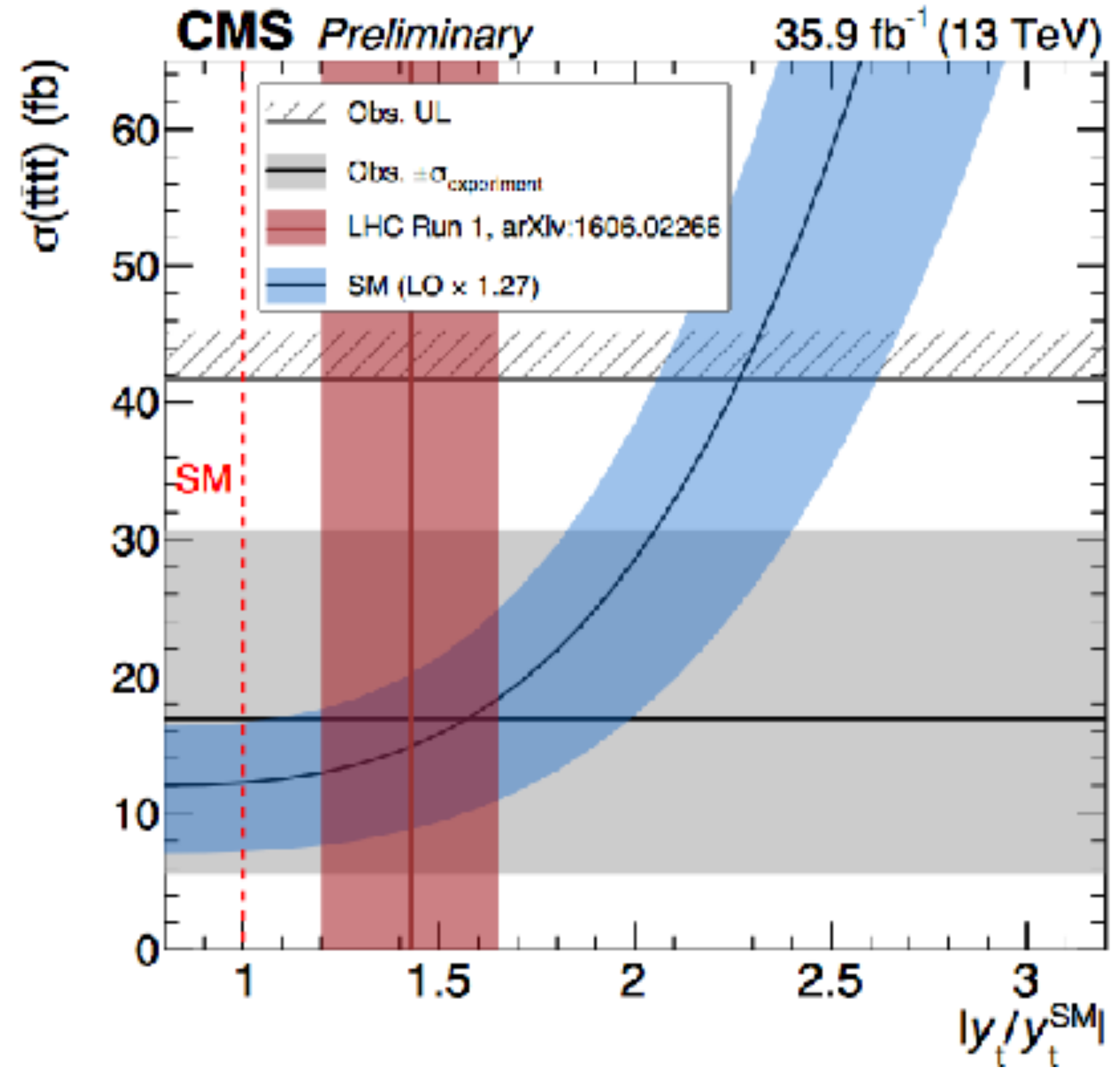
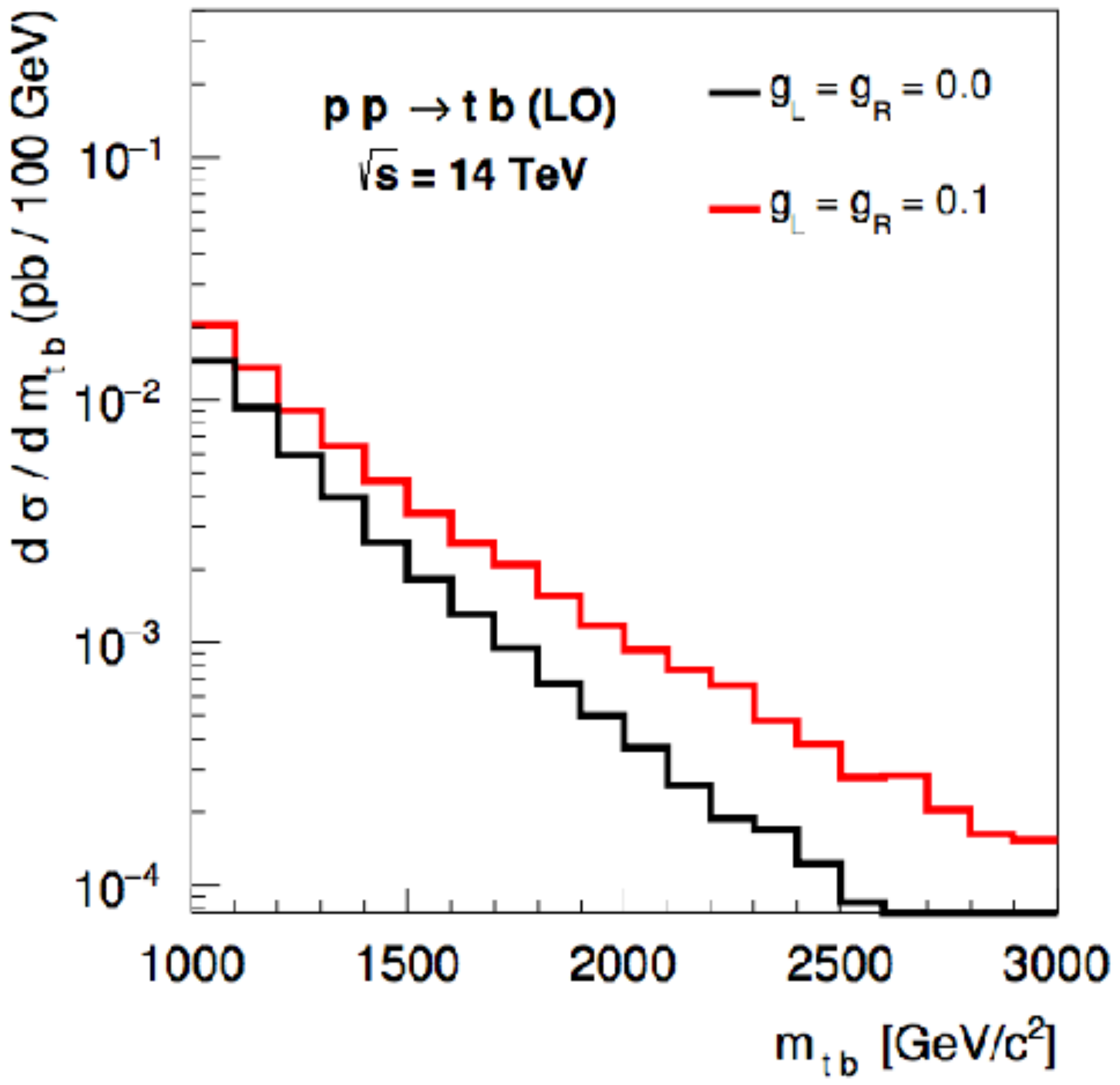


# Other properties

- measurements of Vts and Vtd
  - using ratio of top decays with different b-tagging requirement and rapidity of the t-channel single top production (arXiv:1002.4718)
  - limited by systematics: overall precision down to 0.05 ?

- Wtb coupling
  - testing the anomalous tensor-like coupling using single top s-channel production at large momentum transfer (arXiv:1512.04807)

    $|g_{A,V}| < 0.10$ with 3000 $fb^{-1}$ using $\sigma(m_{tb} > 2TeV)$



# Conclusion

- Top FCNC is the 'obvious' search that will benefit from the HL-LHC statistics
  - experimental projection done
- Studies of top couplings will also gain from statistics
  - important gain expected in constraining EFT operators
- We can go beyond that
  - asymmetries
  - other properties in the boosted regime ?
- Need to develop the HE-LHC physics case for the top sector
  - 4 tops
  - ….