EFT and **FCNC** interpretations with top quarks at CMS

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on behalf of the CMS Collaboration

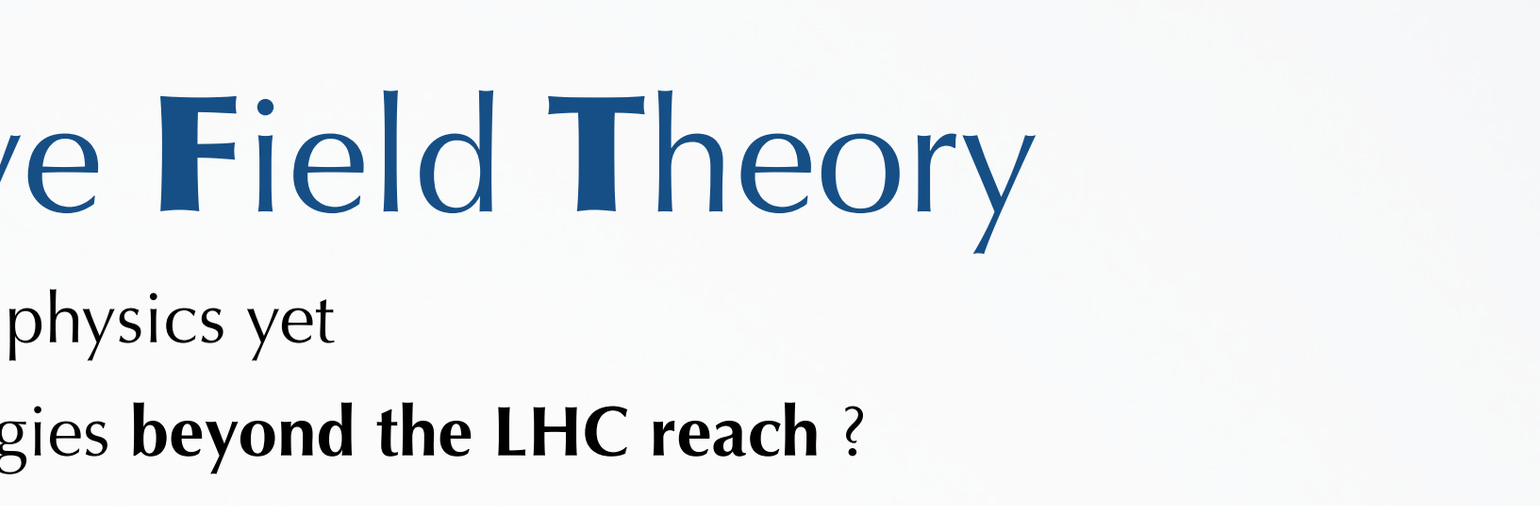
The **E**uropean **P**hysical **S**ociety Conference on **H**igh **E**nergy **P**hysics

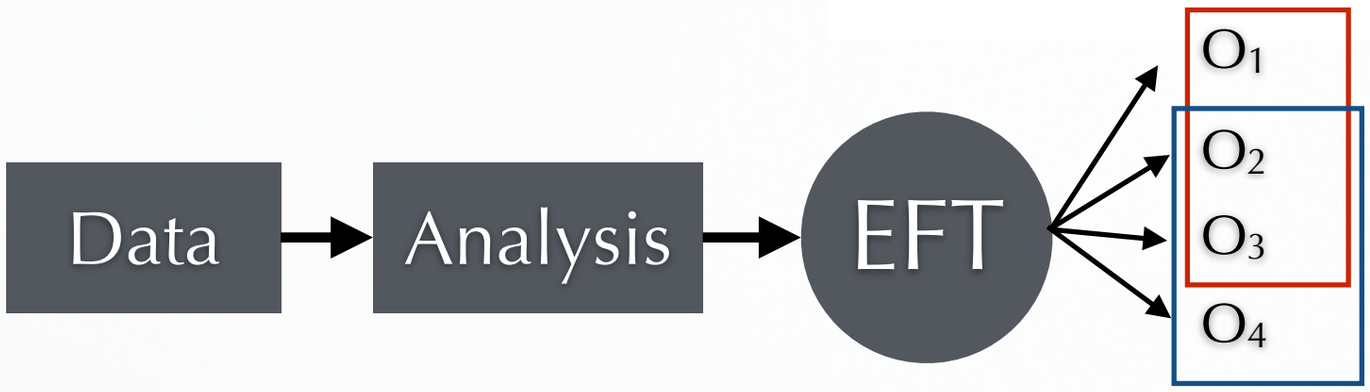
Ghent, July 10-17, 2019

Effective Field Theory

- We saw no evidence of new physics yet
- Can new physics live at energies **beyond the LHC reach** ?
- Think **w i d e !**
- **Interpret** the effects of new physics at higher energies with an **extended SM effective field theory (SMEFT)** applicable within the LHC reach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$

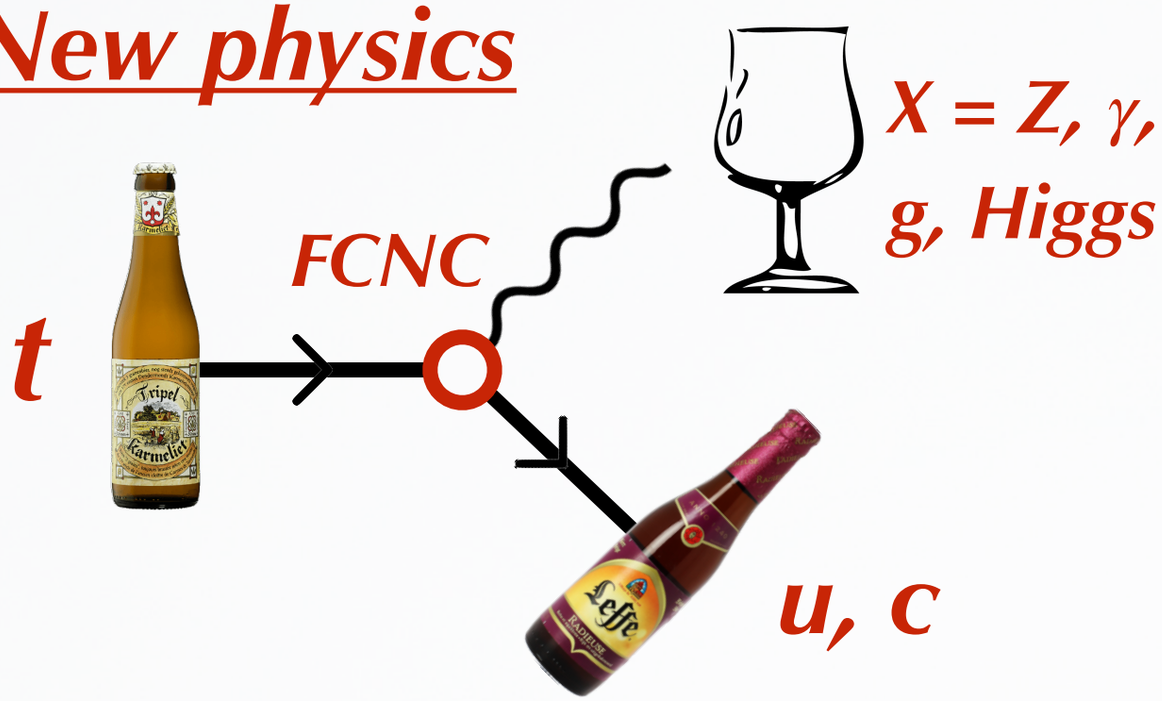




new physics breweries

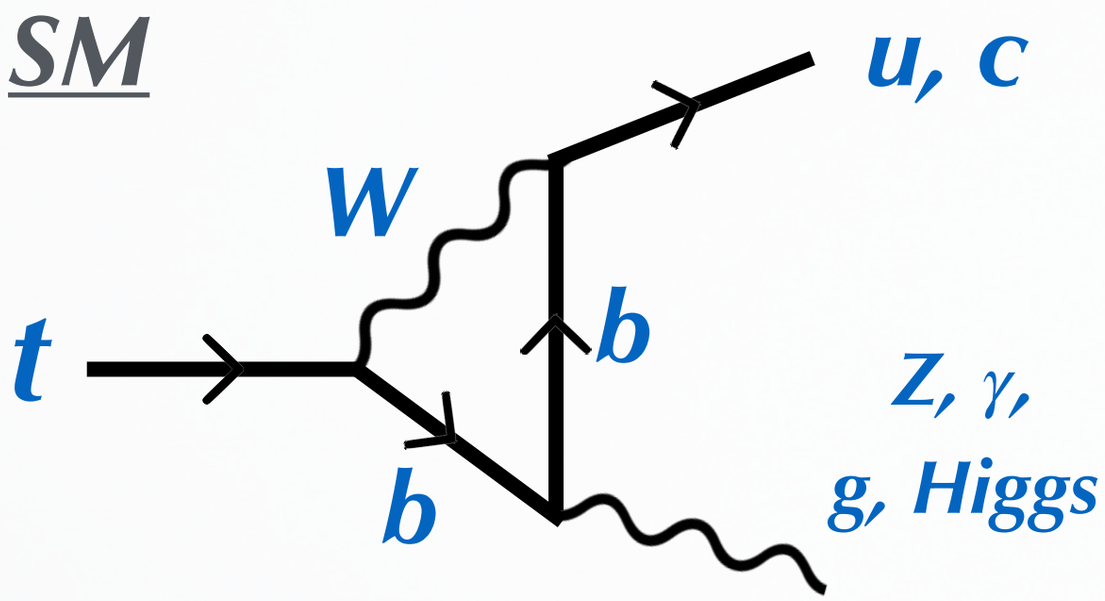
Flavour-Changing Neutral Currents

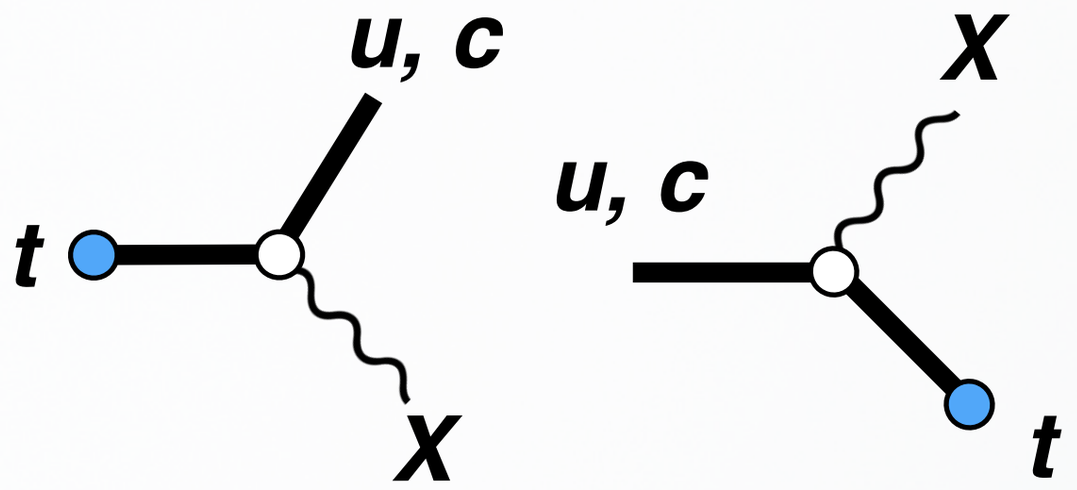
New physics



- **Forbidden** at tree level and heavily suppressed at higher orders in **SM** by GIM mechanism
- Many new physics models allow **FCNC** processes
- Searches in ***top decays*** and ***single top+X production***
- Interpretations via **anomalous** couplings and **SMEFT** framework

SM

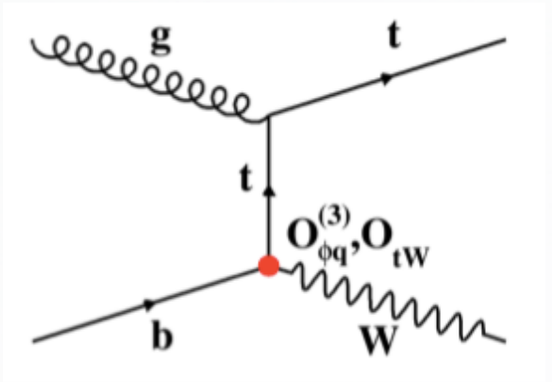


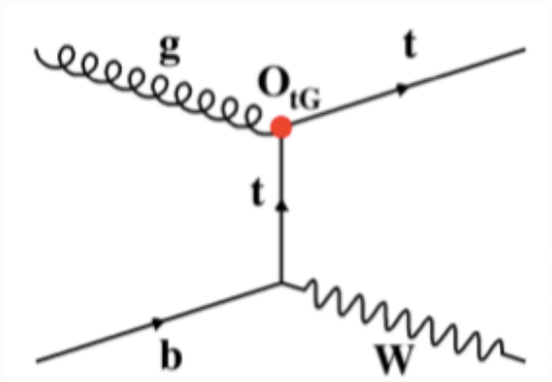


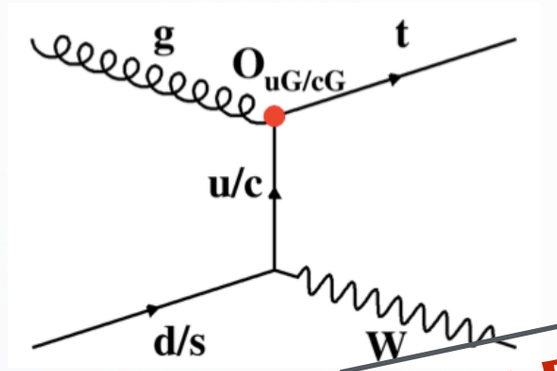
EFT in **dilepton** events with top quarks

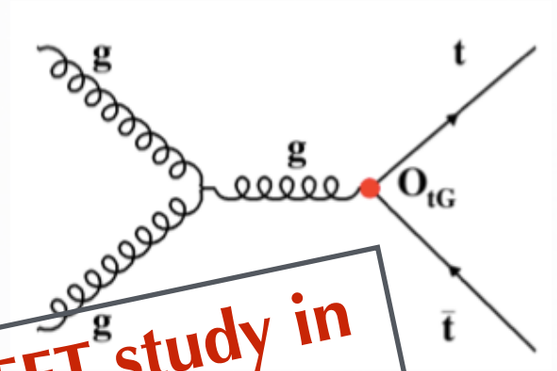
36 fb^{-1}, 13 TeV *arXiv:1903.11144 (Submitted to EPJC)*

- EFT interpretation for tW and ttbar using CP-even dimension-six operators
- Probe **Wtb**, **chromomagnetic dipole moment**, **triple gluon field**, and **FCNC** operators
- DS/DR for ttbar and tW interference at NLO
- Study rate and shape (for FCNC) information









First EFT study in tW channel

exclusive

Effective coupling	Channel	Observed [TeV^{-2}] Best fit	[68% CI]	[95% CI]
C_G/Λ^2	ee	−0.14	[−0.82, 0.51]	[−1.14, 0.83]
	$e\mu$	−0.18	[−0.73, 0.42]	[−1.01, 0.70]
	$\mu\mu$	−0.14	[−0.75, 0.44]	[−1.06, 0.75]
	Combined	−0.18	[−0.73, 0.42]	[−1.01, 0.70]
$C^{(3)}_{\phi q}/\Lambda^2$	ee	1.12	[−1.18, 2.89]	[−4.03, 4.37]
	$e\mu$	−0.70	[−2.16, 0.59]	[−3.74, 1.61]
	$\mu\mu$	1.13	[−0.87, 2.86]	[−3.58, 4.46]
	Combined	−1.52	[−2.71, −0.33]	[−3.82, 0.63]
C_{tW}/Λ^2	ee	6.18	[−3.02, 7.81]	[−4.16, 8.95]
	$e\mu$	1.64	[−0.80, 5.59]	[−1.89, 6.68]
	$\mu\mu$	−1.40	[−3.00, 7.79]	[−4.23, 9.01]
	Combined	2.38	[0.22, 4.57]	[−0.96, 5.74]
C_{tG}/Λ^2	ee	−0.19	[−0.40, 0.02]	[−0.65, 0.22]
	$e\mu$	−0.03	[−0.19, 0.11]	[−0.34, 0.27]
	$\mu\mu$	−0.15	[−0.34, 0.02]	[−0.53, 0.19]
	Combined	−0.13	[−0.27, 0.02]	[−0.41, 0.17]
C_{uG}/Λ^2	ee	−0.017	[−0.22, 0.22]	[−0.37, 0.37]
	$e\mu$	−0.017	[−0.17, 0.17]	[−0.29, 0.29]
	$\mu\mu$	−0.017	[−0.17, 0.17]	[−0.29, 0.29]
	Combined	−0.017	[−0.13, 0.13]	[−0.22, 0.22]
C_{cG}/Λ^2	ee	−0.032	[−0.47, 0.47]	[−0.78, 0.78]
	$e\mu$	−0.032	[−0.34, 0.34]	[−0.60, 0.60]
	$\mu\mu$	−0.032	[−0.36, 0.36]	[−0.63, 0.63]
	Combined	−0.032	[−0.26, 0.26]	[−0.46, 0.46]

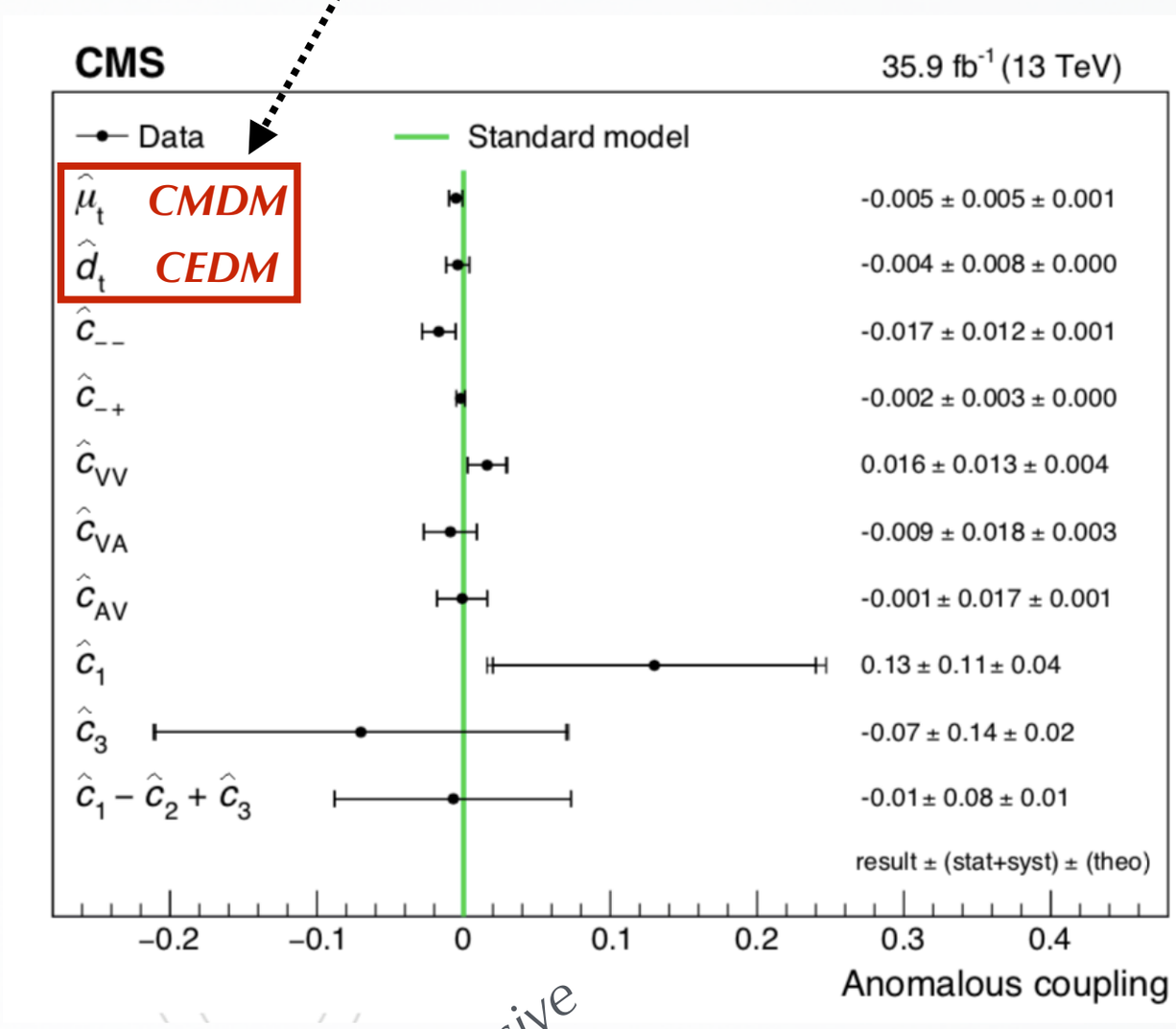
Anomalous couplings in **dilepton** ttbar events

36 fb^{-1}, 13 TeV *arXiv:1907.03729 (Submitted to PRD)*

NEW

- Constrain anomalous **four-particle** effective couplings with top quarks
- Probe the top quark **chromomagnetic (CM)** and **chromoelectric (CE) dipole moments (DM)**
- The **EFT** study via the measurements of ttbar spin correlations and differential production cross sections
- Measure full spin density matrix and use all possible relevant observables
- Sensitivity to CMDM and CEDM **significantly improved** with respect to existing direct constraints

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^a t) \tilde{\phi} G^a_{\mu\nu}$$



exclusive

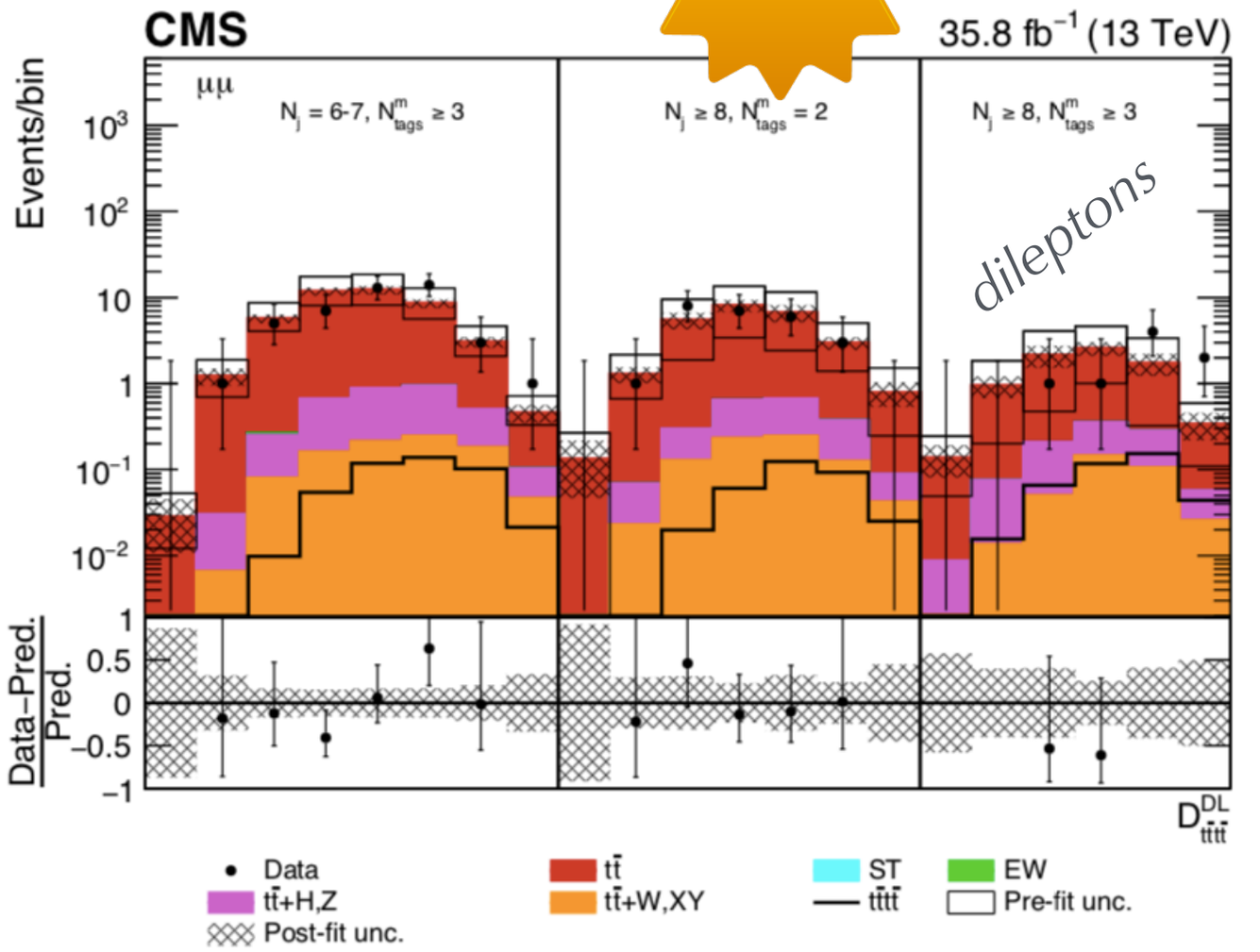
$-0.24 < C_{tG}/\Lambda^2 < 0.07$ TeV^{-2}
$-0.33 < C_{tG}^{[I]}/\Lambda^2 < 0.20$ TeV^{-2}

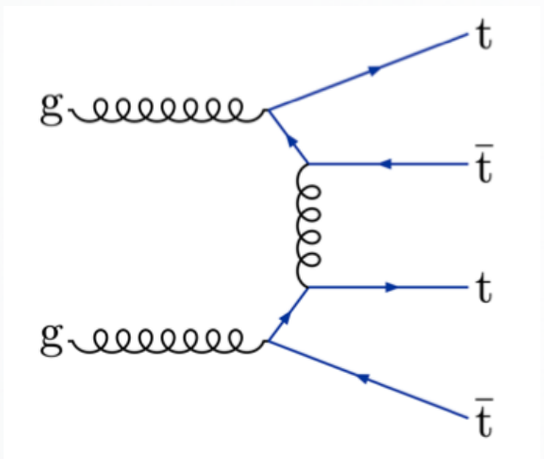
more results in the talk by Agostino De Iorio

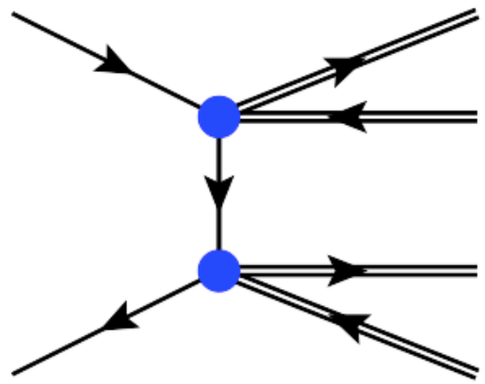
Search for **4 top** quark production

36 fb^{-1}, 13 TeV *arXiv:1906.02805 (Submitted to JHEP)* NEW

- Single lepton and dilepton OS
- **Combined** with previously published **dilepton SS** and **trilepton** analysis
- Dominant uncertainties from limited statistics, b tagging, jet reconstruction and modelling
- Combined sensitivity to 4 top production at **1.4 (1.1) σ**
- Constrain **four-fermion** operators via event rate for C_{tt}^1, C_{QQ}^1, C_{Qt}^1, C_{Qt}^8







Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}_{tt}^1$	$[-2.0, 1.9]$	$[-2.2, 2.1]$
$\mathcal{O}_{QQ}^1$	$[-2.0, 1.9]$	$[-2.2, 2.0]$
$\mathcal{O}_{Qt}^1$	$[-3.4, 3.3]$	$[-3.7, 3.5]$
$\mathcal{O}_{Qt}^8$	$[-7.4, 6.3]$	$[-8.0, 6.8]$

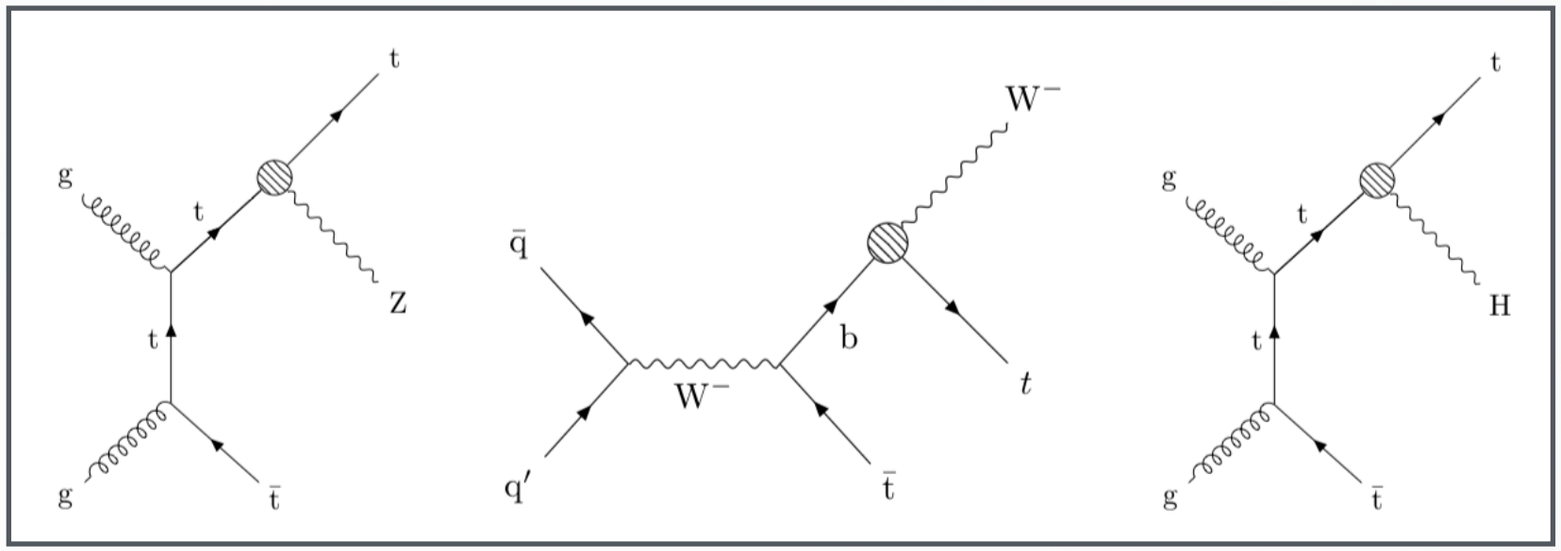
marginalised

more results in the talk by Sébastien Wertz

Study of **ttV** production

36 fb^{-1}, 13 TeV *JHEP 08 (2018) 011*

- Study new physics effects in ttW, ttZ ***and ttH*** production
- Set constraints on **top quark electroweak**, **triple gluon field** and **Higgs couplings**
  ttZ and **ttH**: C_{3G}, C_{2G}, C_{uB}
  ttZ: C_{Hu}
  ttH: C_H
  all processes: C_{uG}, C_{uW}



more results in the talk by Enrique Palencia

Wilson coefficient	Best fit [TeV^{-2}]	68% CL [TeV^{-2}]	95% CL [TeV^{-2}]
$\bar{c}_{uW}/\Lambda^2$	1.7	$[-2.4,-0.5]$ and $[0.4,2.4]$	$[-2.9,2.9]$
$\lvert\bar{c}_H/\Lambda^2 - 16.8\ \text{TeV}^{-2}\rvert$	15.6	$[0,23.0]$	$[0,28.5]$
$\lvert\widetilde{c}_{3G}/\Lambda^2\rvert$	0.5	$[0,0.7]$	$[0,0.9]$
$\bar{c}_{3G}/\Lambda^2$	−0.4	$[-0.6,0.1]$ and $[0.4,0.7]$	$[-0.7,1.0]$
$\bar{c}_{uG}/\Lambda^2$	0.2	$[0,0.3]$	$[-1.0,-0.9]$ and $[-0.3,0.4]$
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	$[0,2.2]$	$[0,2.7]$
$\bar{c}_{Hu}/\Lambda^2$	−9.3	$[-10.3,-8.0]$ and $[0,2.1]$	$[-11.1,-6.5]$ and $[-1.6,3.0]$
$\bar{c}_{2G}/\Lambda^2$	0.4	$[-0.9,-0.3]$ and $[-0.1,0.6]$	$[-1.1,0.8]$

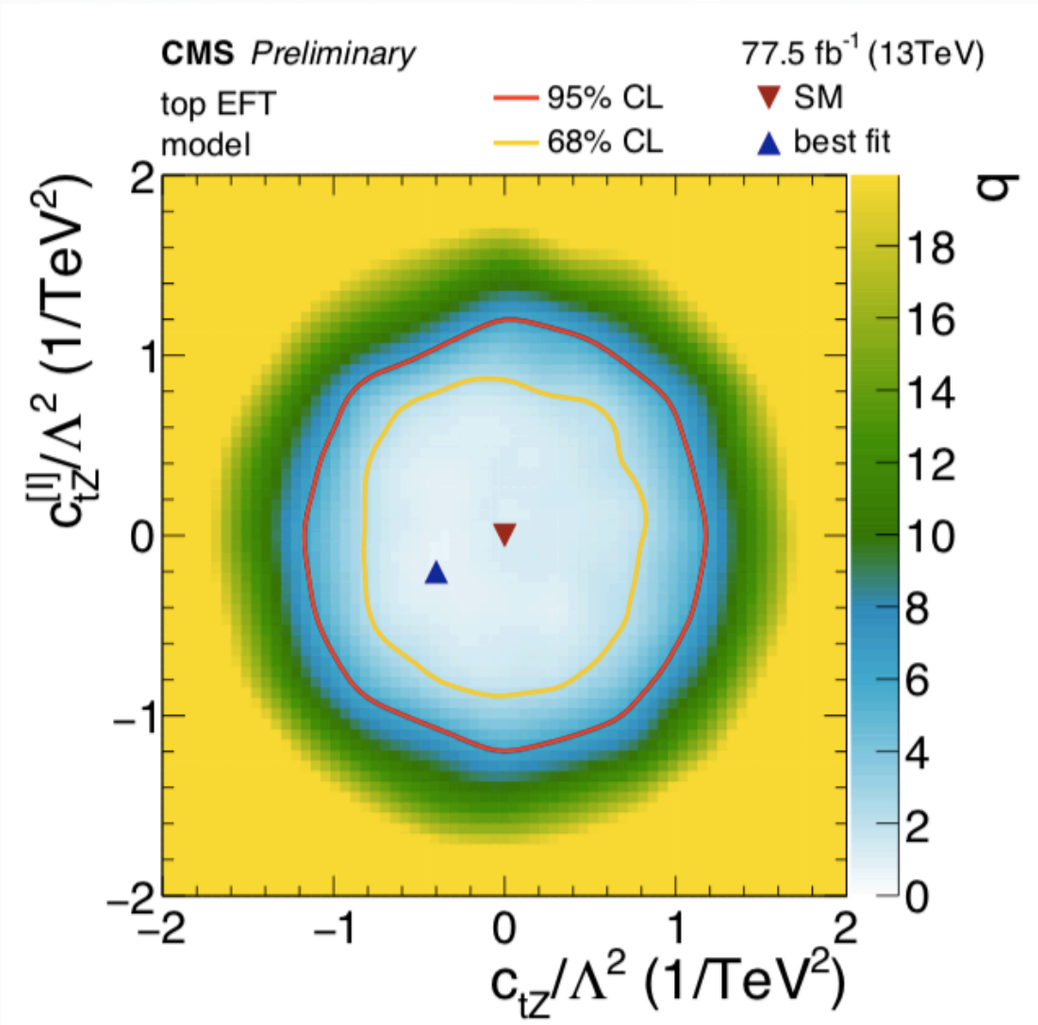
exclusive

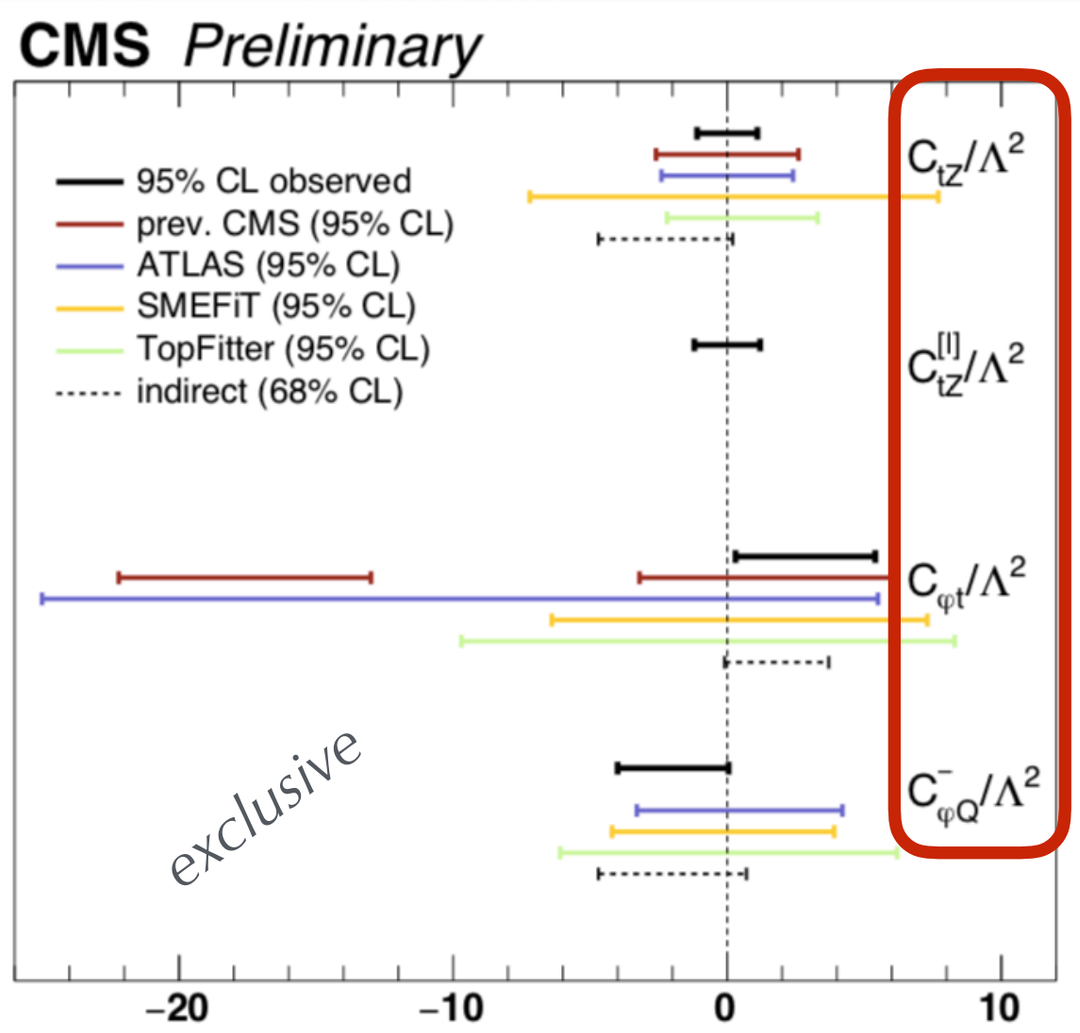
Differential **ttZ** cross section

78 fb^{-1}, 13 TeV ***CMS PAS TOP-18-009***

more results in the talk by Enrique Palencia

- Set constraints on
  - **EFT electroweak operators** (C_{tZ}, $C_{tZ}^{[I]}$, $C_{\varphi t}$, $C_{\varphi Q}$)
  - **Vector and axial-vector current couplings** ($C_{1A,V}$) and **electroweak dipole moments** ($C_{2A,V}$)



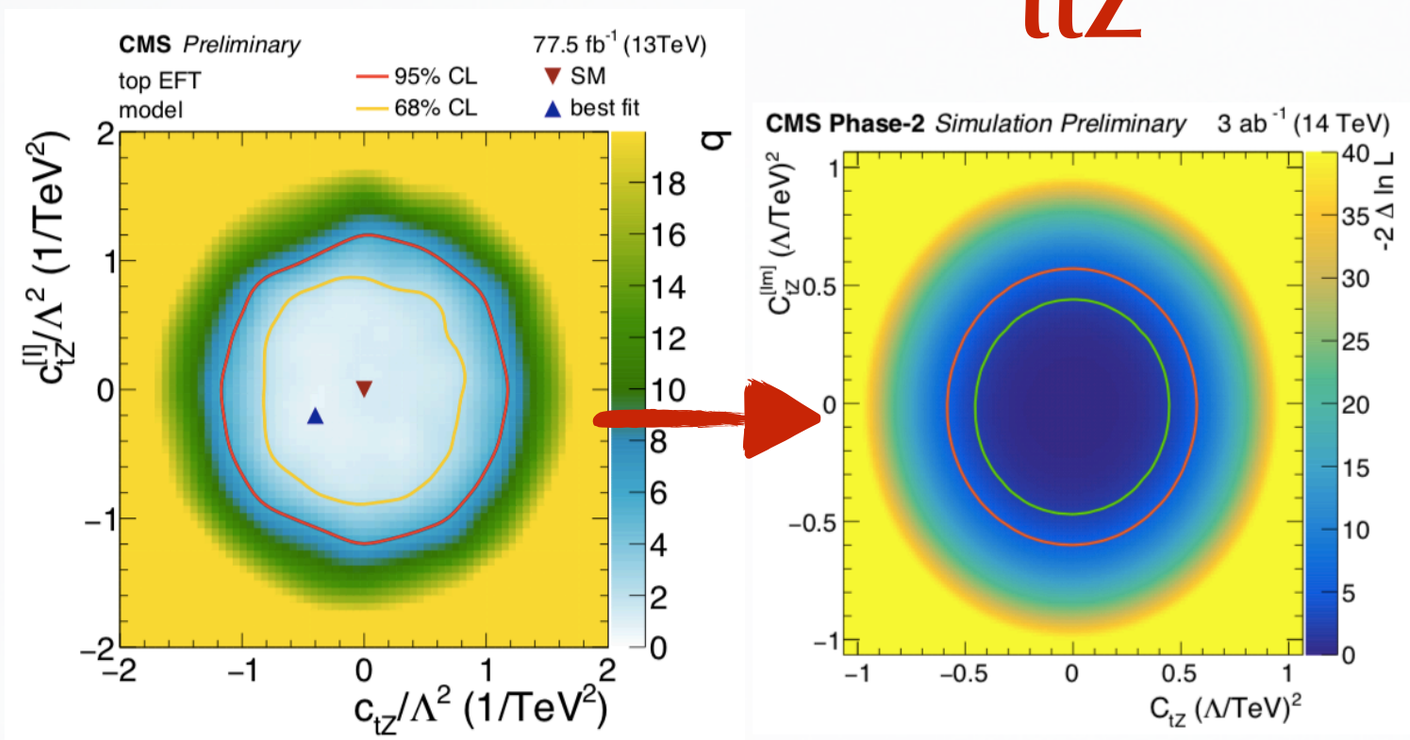


Future EFT projections

arXiv:1902.04070, CMS PAS FTR-18-031, CMS PAS FTR-18-036

Very good prospects for EFT interpretations in the top quark sector!

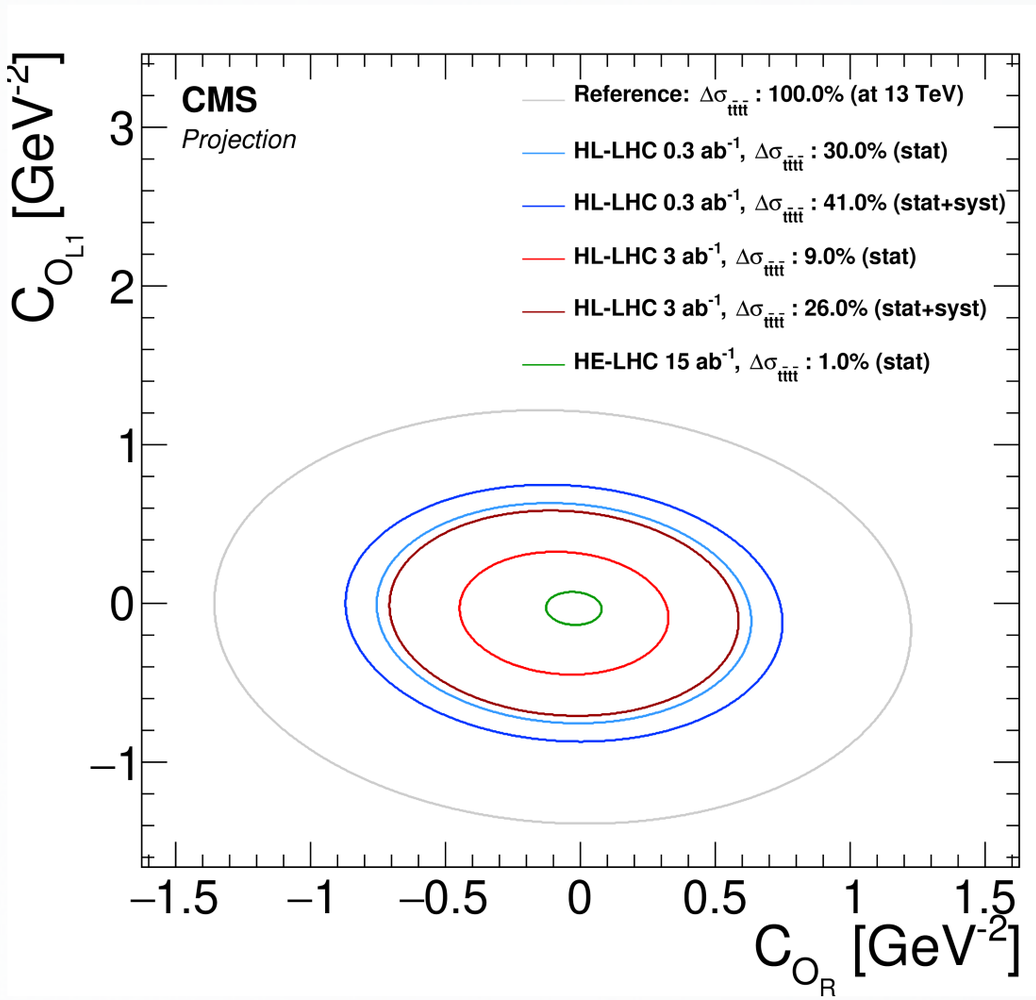
ttZ



different axis ranges!

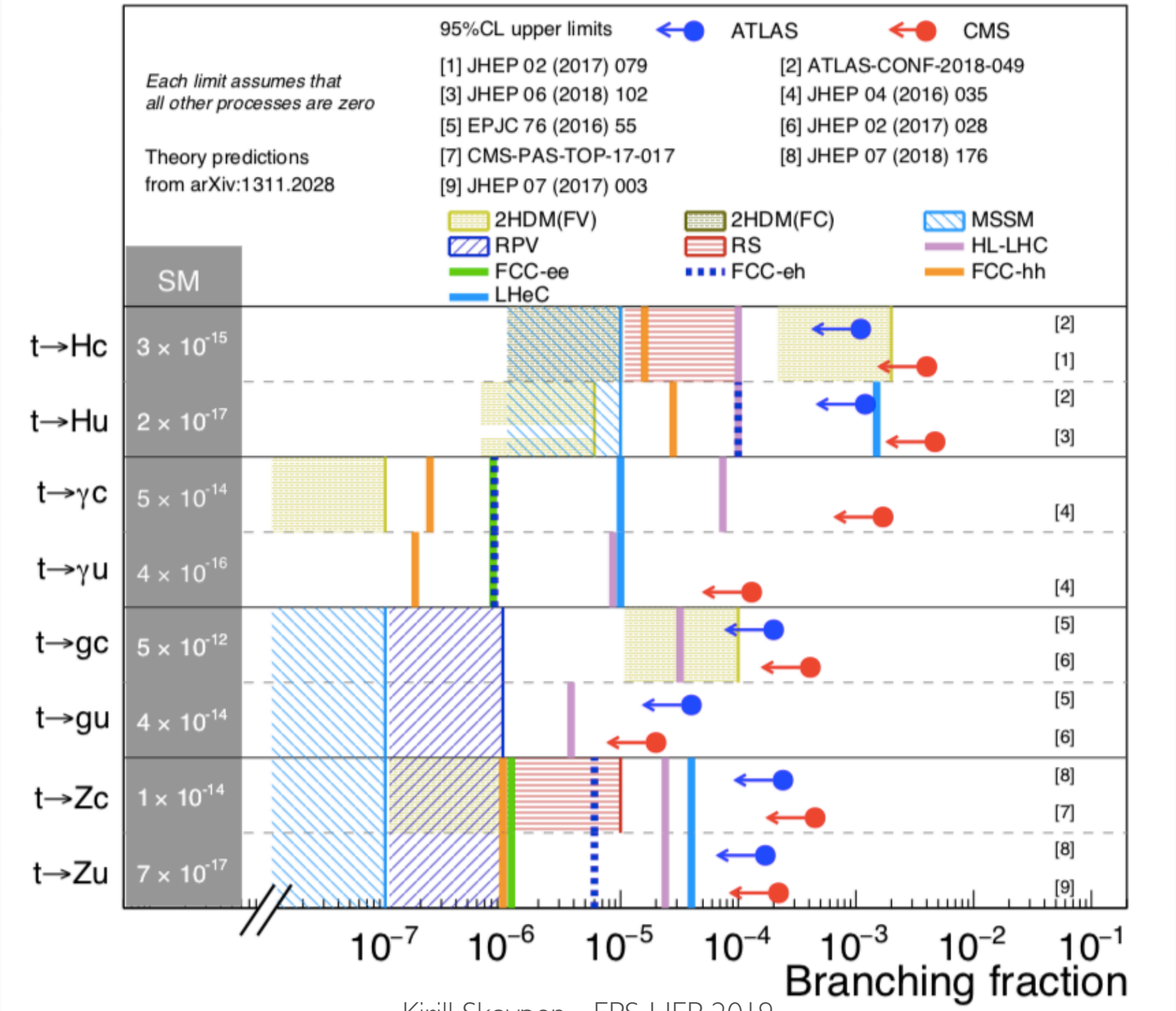
Wilson coefficient	68 % CL $(\Lambda/\text{TeV})^2$	95 % CL $(\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-0.47, 0.47]	[-0.89, 0.89]
$C_{\phi Q}$	[-0.38, 0.38]	[-0.75, 0.73]
C_{tZ}	[-0.37, 0.36]	[-0.52, 0.51]
$C_{tZ}^{[Im]}$	[-0.38, 0.36]	[-0.54, 0.51]

tttt



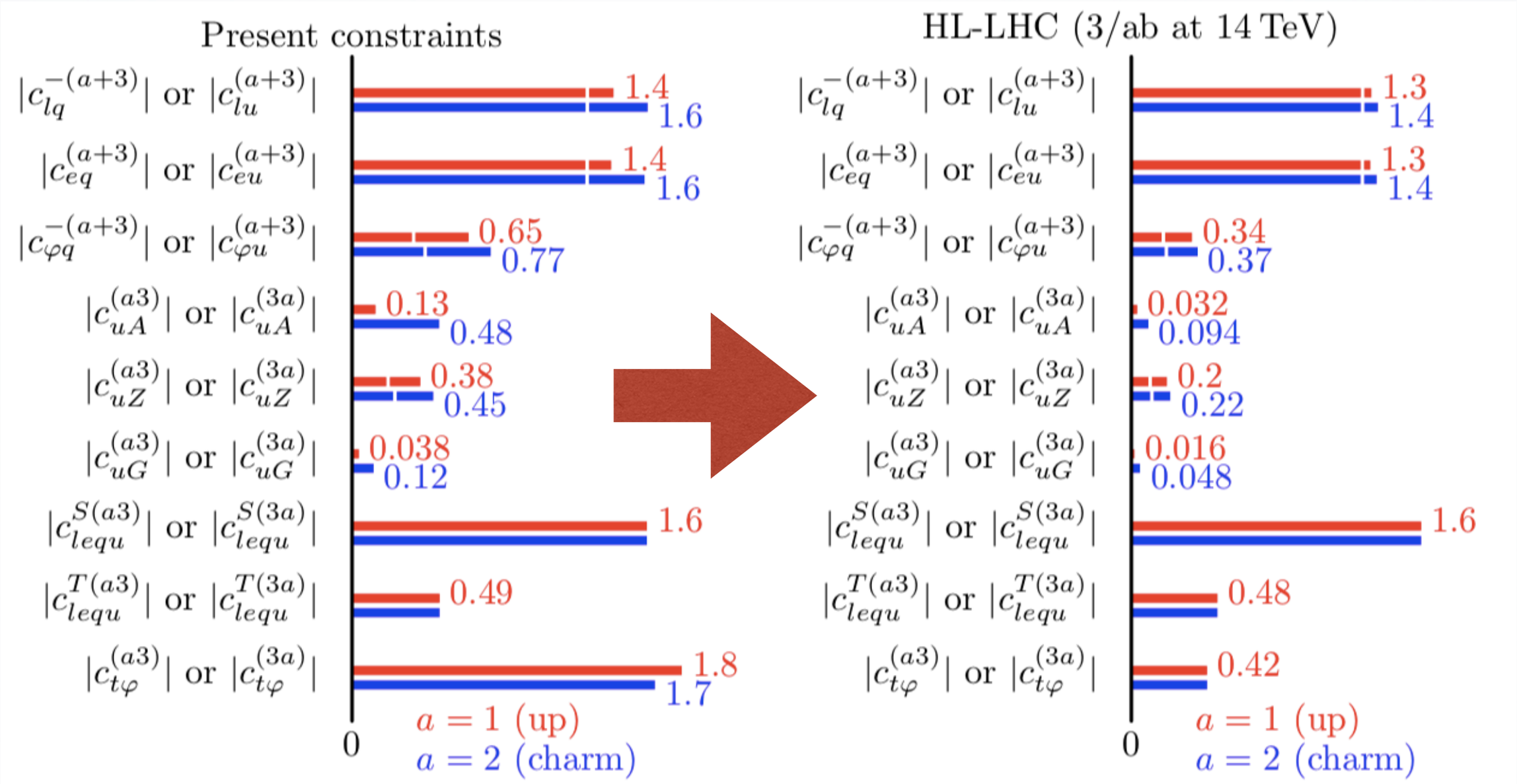
Present and future of **FCNC** searches

EPJC 79 (2019) 474



Future **FCNC EFT** projections

arXiv:1812.07638



Factor of ≈ 2 improvement in the constraints on several two-fermion FCNC operators

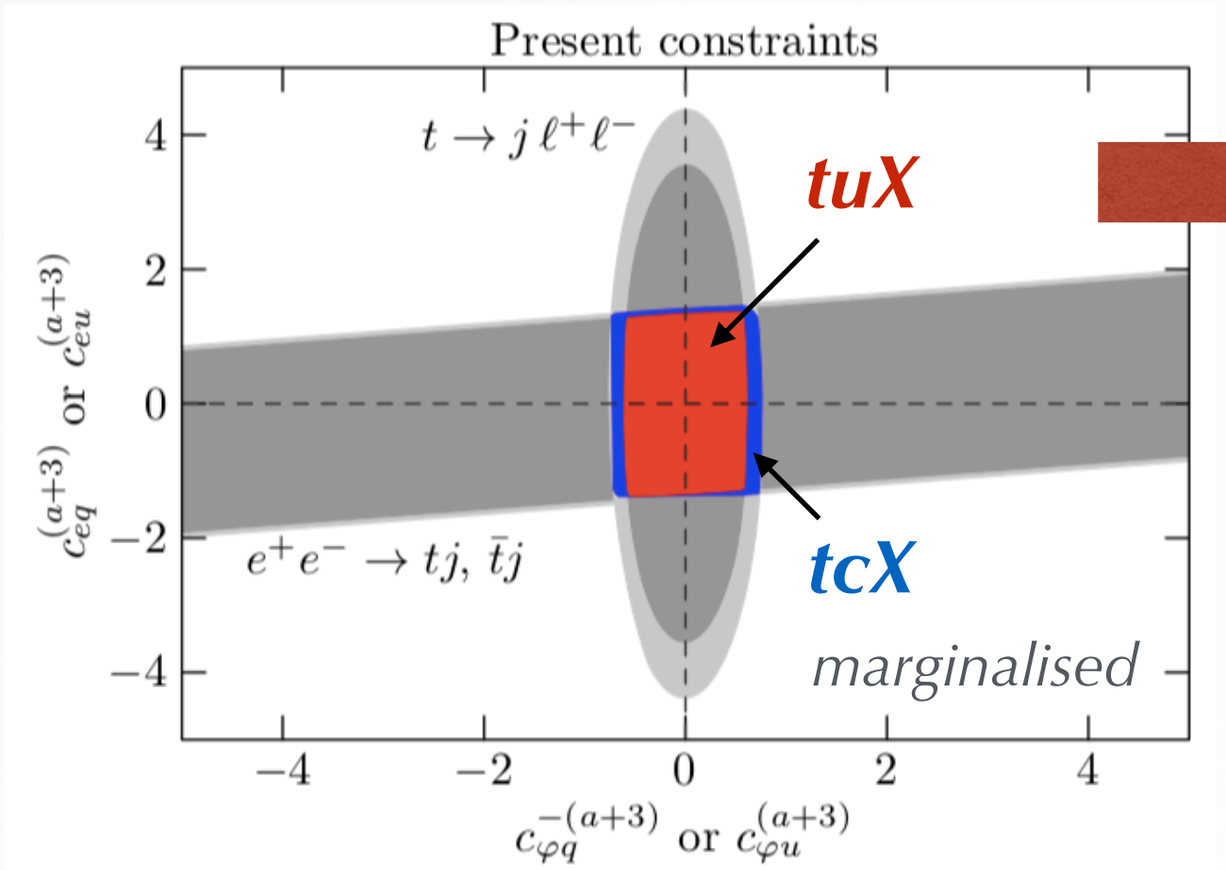
Conclusion

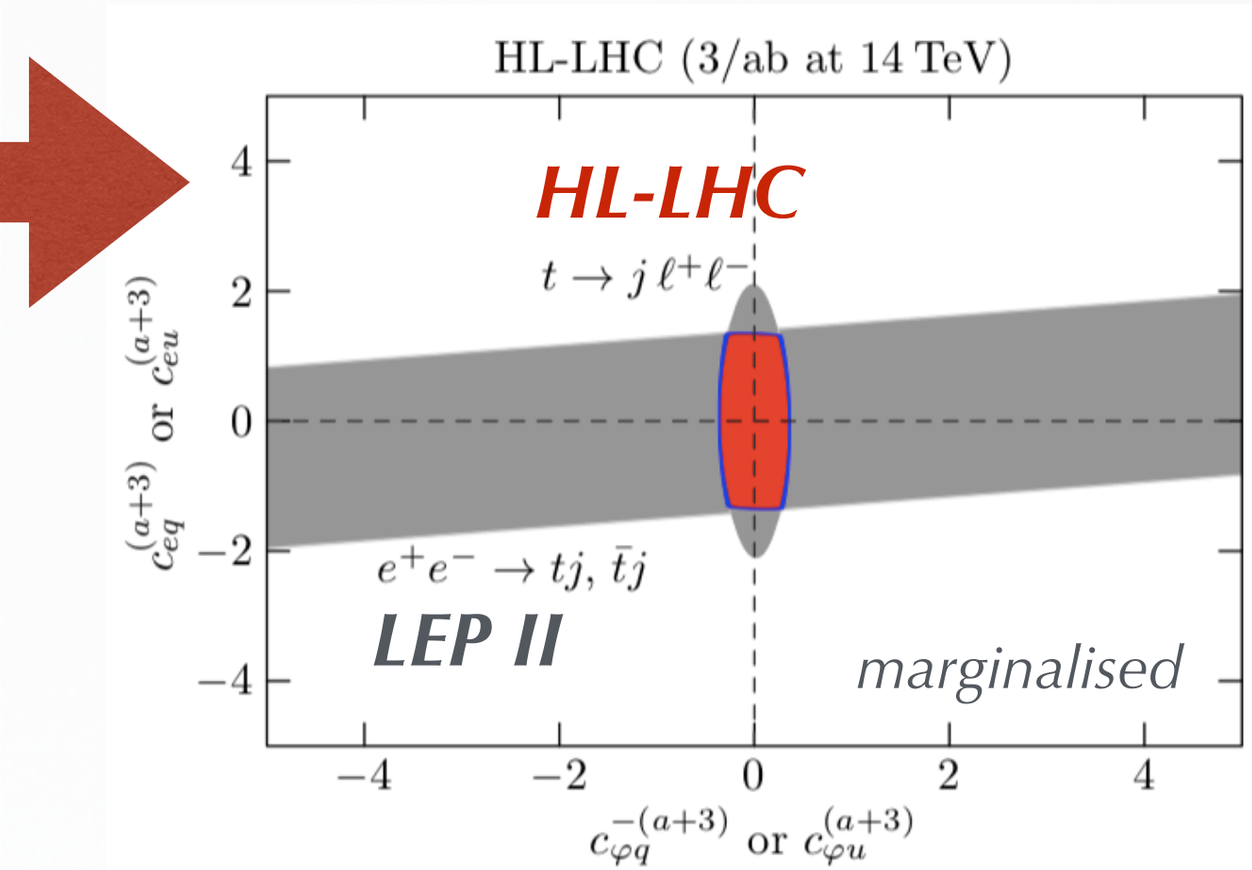
- Interpretation of the LHC experimental results in the **EFT** framework represents an important ***LHC legacy result*** for many years to come
- Presented several first **EFT** results for some very rare processes with top quarks
- Search for **FCNC** continues with setting strong limits
- Recent highlights from CMS:
  - **Comprehensive EFT interpretations from new ttZ differential cross section measurement and studies of the ttV production**
  - **First NLO EFT in the study of the tW process**
  - **Hunt for 4 top production in progress with probing four-fermion EFT operators**
  - **Good prospects for future EFT and FCNC studies at HL-LHC**
- Interpretations go easy with Belgian beer!

Backup

Future **FCNC EFT** projections

arXiv:1812.07638





- Most stringent constraints on both **two-** and **four-fermion** operators expected at the **HL-LHC**
- Significant improvement for **two-fermion** operators at **HL-LHC** with reaching **LEP-II** sensitivity for **four-fermion** operators (mainly from other indirect constraints)

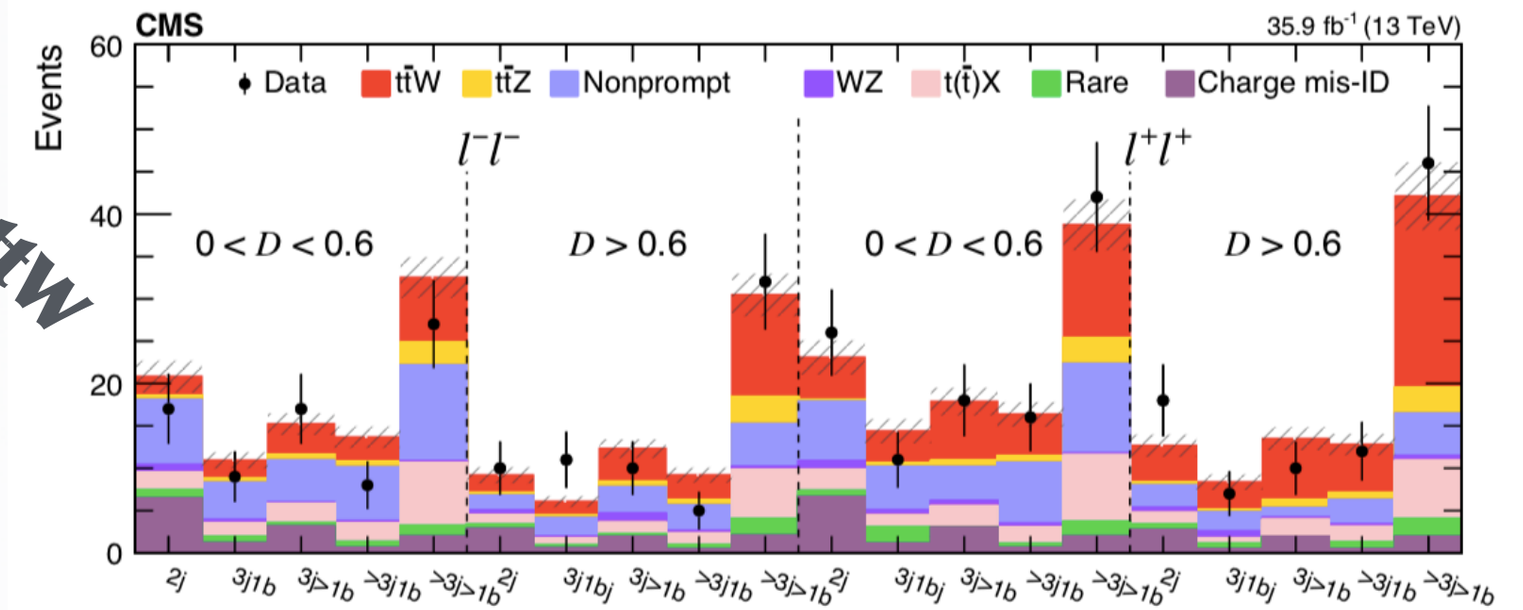
Study of **ttV** production

36 fb^{-1}, 13 TeV

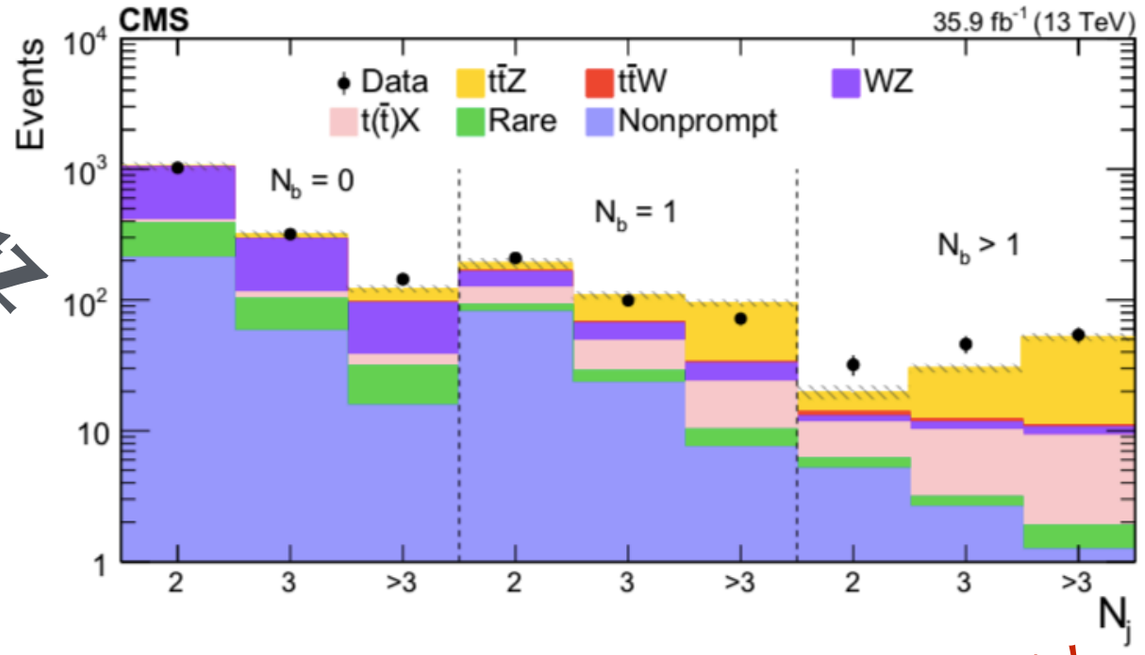
JHEP 08 (2018) 011

- Sensitive to **electroweak couplings** of the top quark
- Important background to ttH
- Prompt: WW, WZ
  Z+jets, ttbar
  (only in dilepton OS)
- Non-prompt: Z+jets, ttbar
  (except dilepton OS)
- **ttW** measured in dilepton SS
- **ttZ** extracted from trilepton and 4-lepton

ttW



ttZ



$$\sigma(\mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}$$

14% precision

$$\sigma(\mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.13}_{-0.12}\,(\mathrm{syst})\,\mathrm{pb}$$

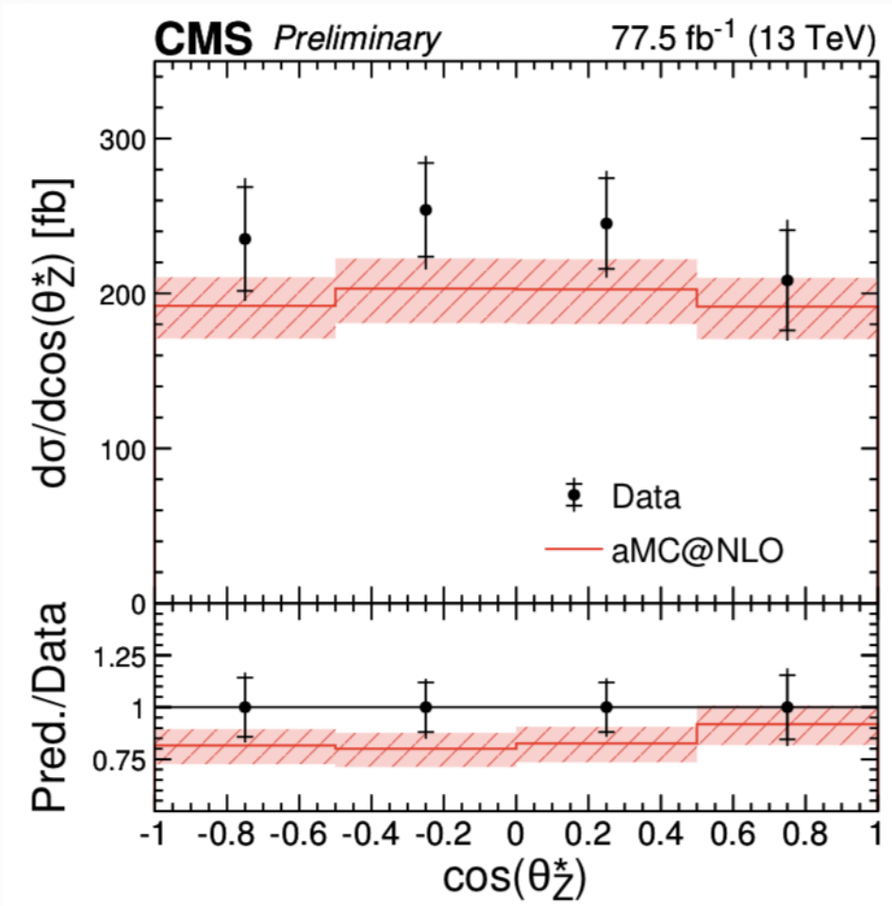
22% precision

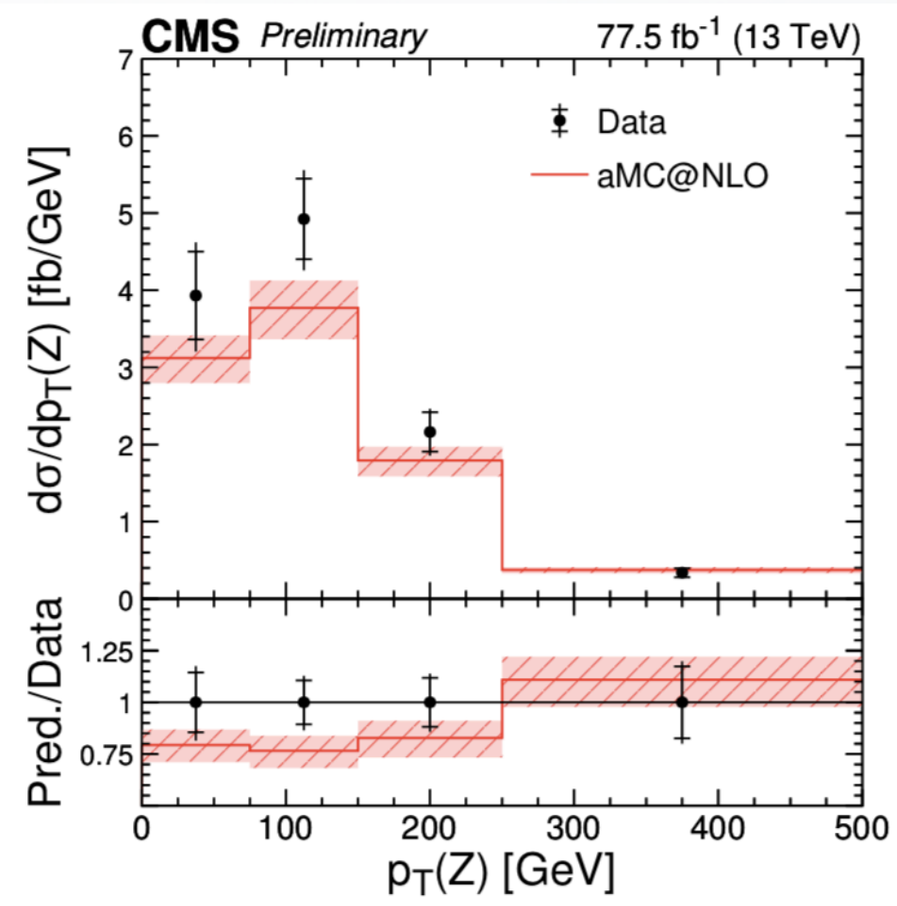
Good agreement with NLO predictions

Differential **ttZ** cross section

78 fb^{-1}, 13 TeV — *CMS PAS TOP-18-009*

- Cross sections measured wrt $\mathbf{p_T(Z)}$ and $\mathbf{\cos(\theta^*)}$ - angle between Z and negatively charged lepton from Z decay in Z rest frame
- Trilepton and 4-lepton
- Dominant systematics reduced by 2x due to **improved** lepton ID (≈15% higher prompt lepton efficiency)





10% precision

Better precision than in NLO calculations

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 1.00^{+0.06}_{-0.05}\,(\mathrm{stat})^{+0.07}_{-0.06}\,(\mathrm{syst})\,\mathrm{pb}$$

Anomalous couplings in **dilepton** ttbar events

36 fb^{-1}, 13 TeV *arXiv:1907.03729 (Submitted to PRD)*

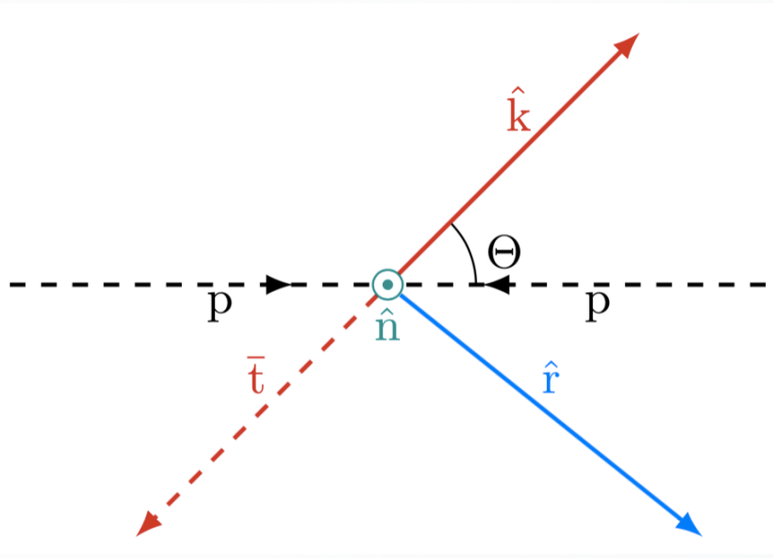
$$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b}))|^2 \sim Tr[\rho R \bar{\rho}]$$

spin matrix

$$R \propto \tilde{A}\mathbb{1}\otimes\mathbb{1} + \tilde{B}_i^+\sigma^i\otimes\mathbb{1} + \tilde{B}_i^-\mathbb{1}\otimes\sigma^i + \tilde{C}_{ij}\sigma^i\otimes\sigma^j$$

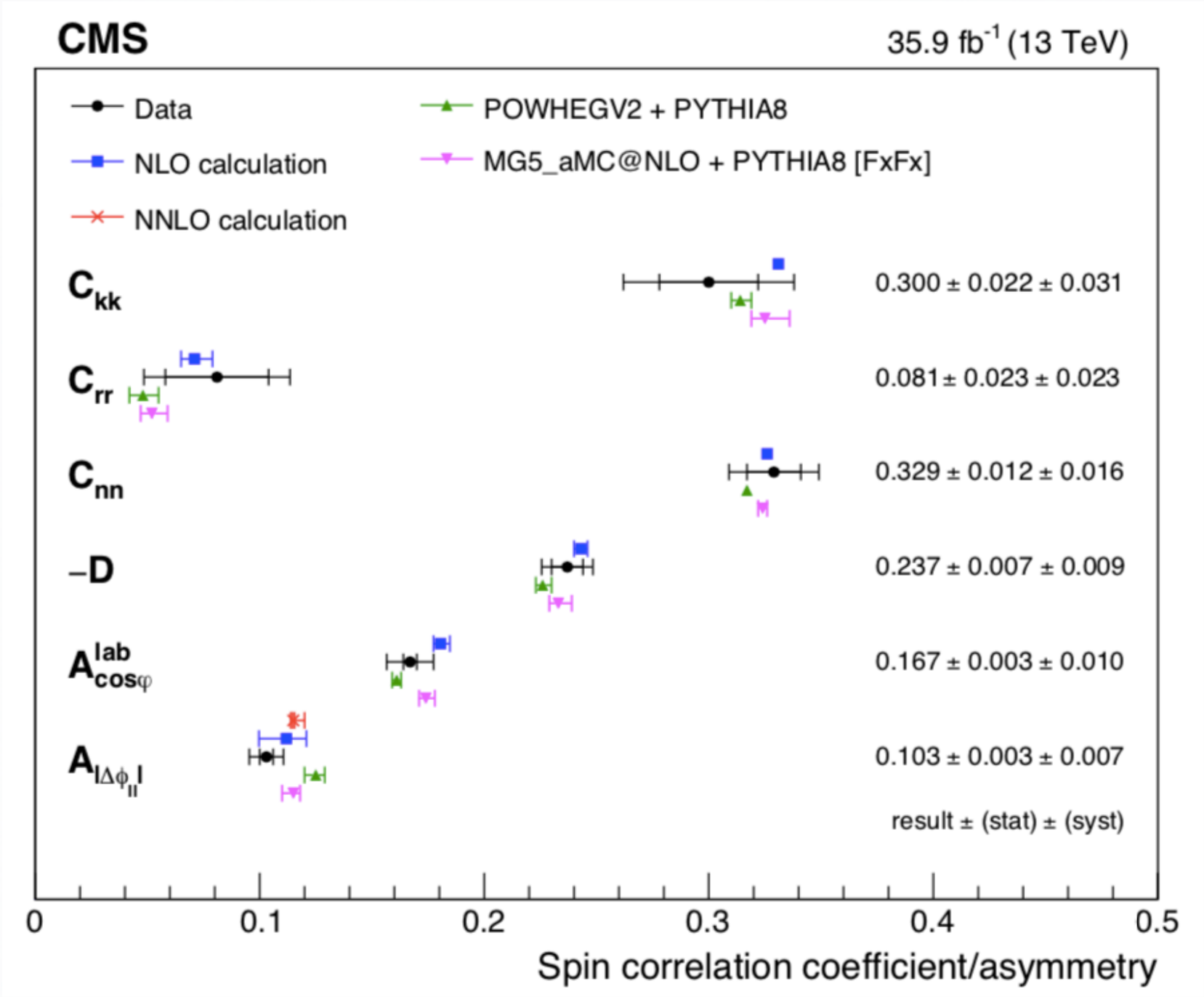
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2\right)$$

$$\begin{aligned}
\tilde{B}_i^{\pm} &= b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{r}_i + b_n^{\pm}\hat{n}_i,\\
\tilde{C}_{ij} &= c_{kk}\hat{k}_i\hat{k}_j + c_{rr}\hat{r}_i\hat{r}_j + c_{nn}\hat{n}_i\hat{n}_j\\
&\quad + c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j)\\
&\quad + c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j).
\end{aligned}$$



Anomalous couplings in dilepton ttbar events

36 fb^{-1}, 13 TeV *arXiv:1907.03729 (Submitted to PRD)*



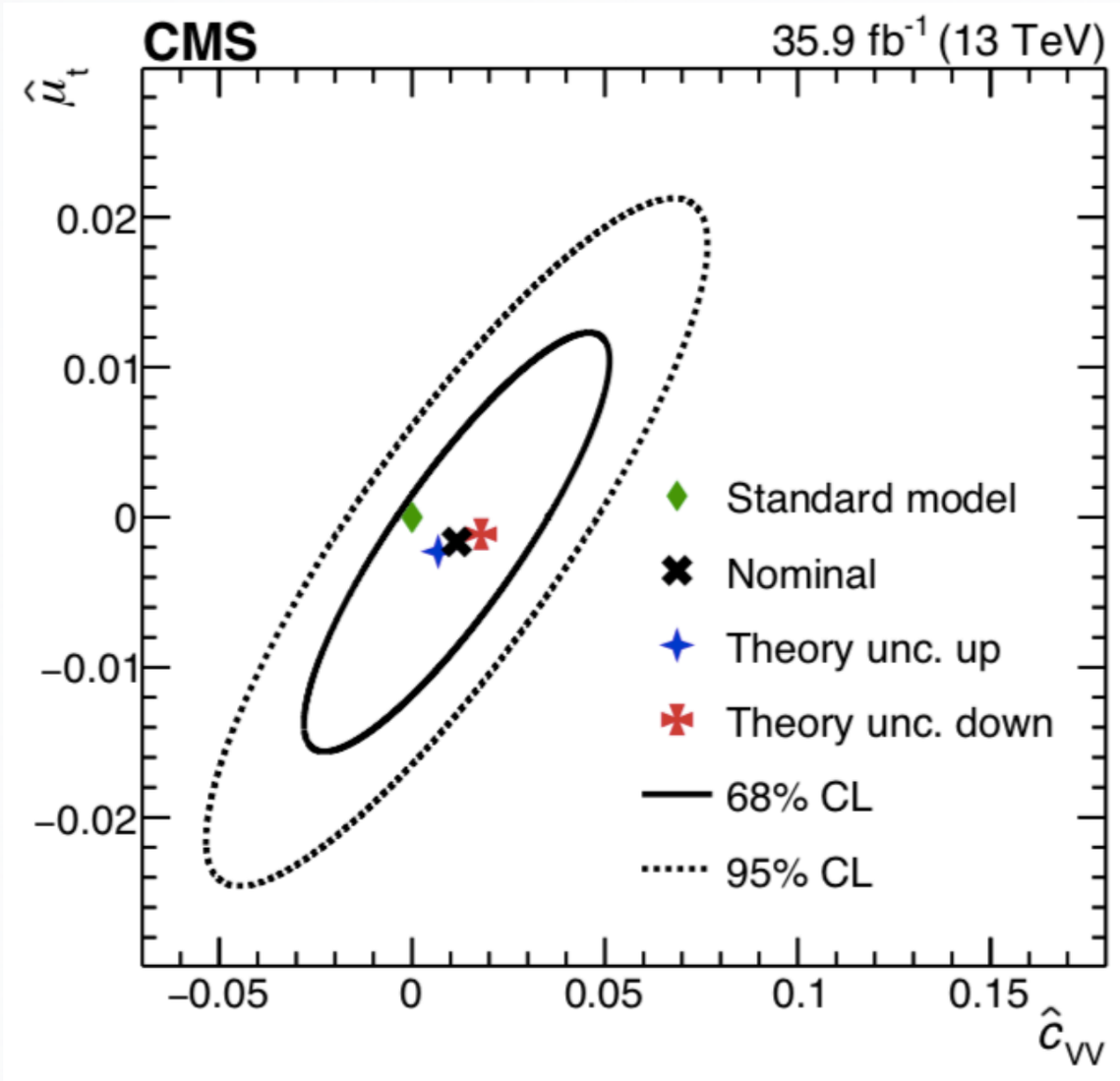
Anomalous couplings in **dilepton** ttbar events

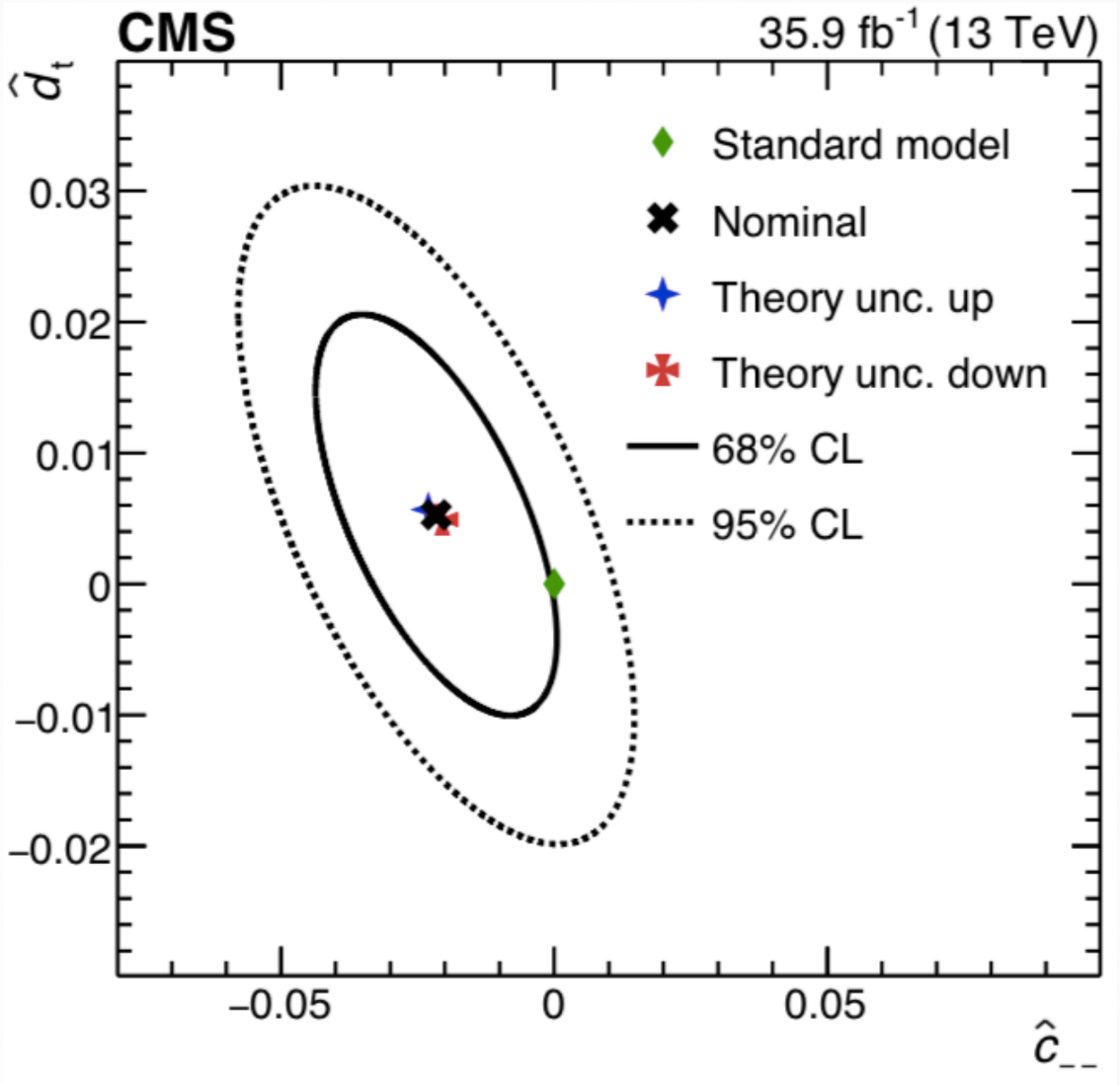
36 fb^{-1}, 13 TeV *arXiv:1907.03729 (Submitted to PRD)*

Coupling	Operator type	Symmetry properties
$\hat{\mu}_t$	2 quarks plus gluon(s)	P-even, CP-even
$\hat{d}_t$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{--}$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{-+}$	2 quarks plus gluon(s)	P-even, CP-odd
$\hat{c}_{VV}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_{VA}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AV}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AA}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_1$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_2$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_3$	4 quarks (weak isospin 1)	CP-even

Anomalous couplings in **dilepton** ttbar events

36 fb^{-1}, 13 TeV *arXiv:1907.03729 (Submitted to PRD)*

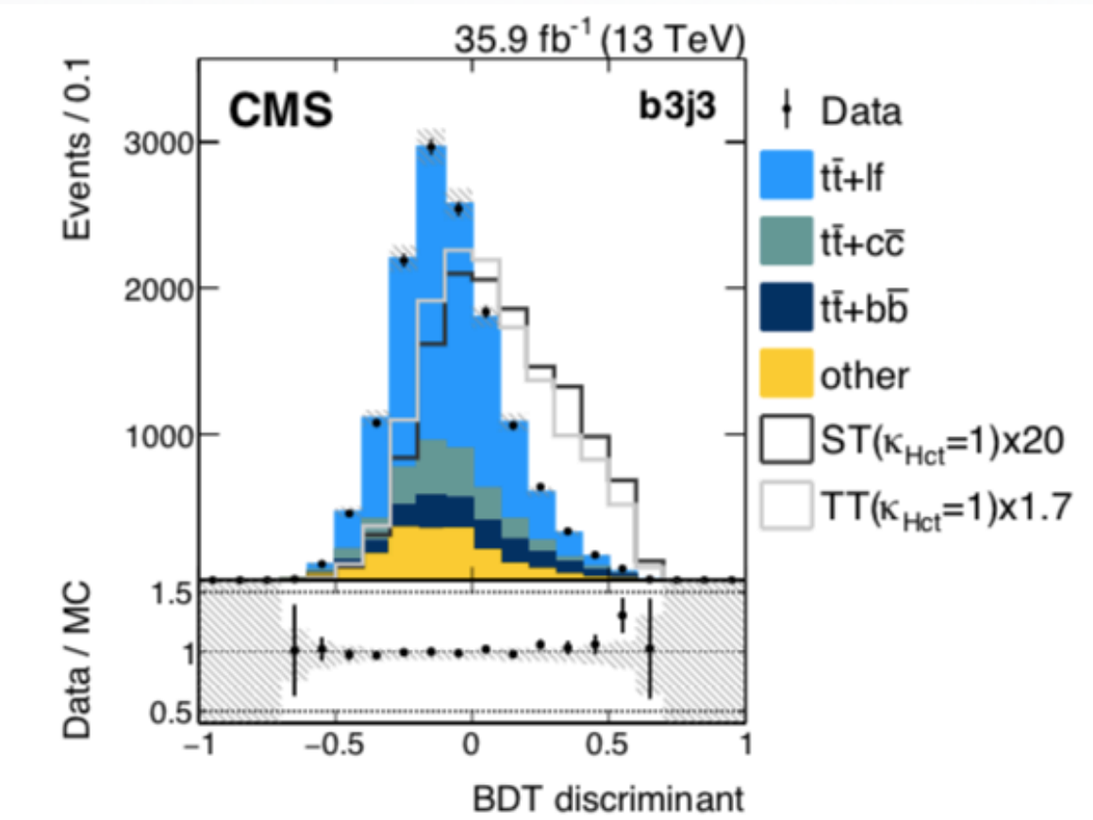




Search for *top-Higgs* **FCNC**

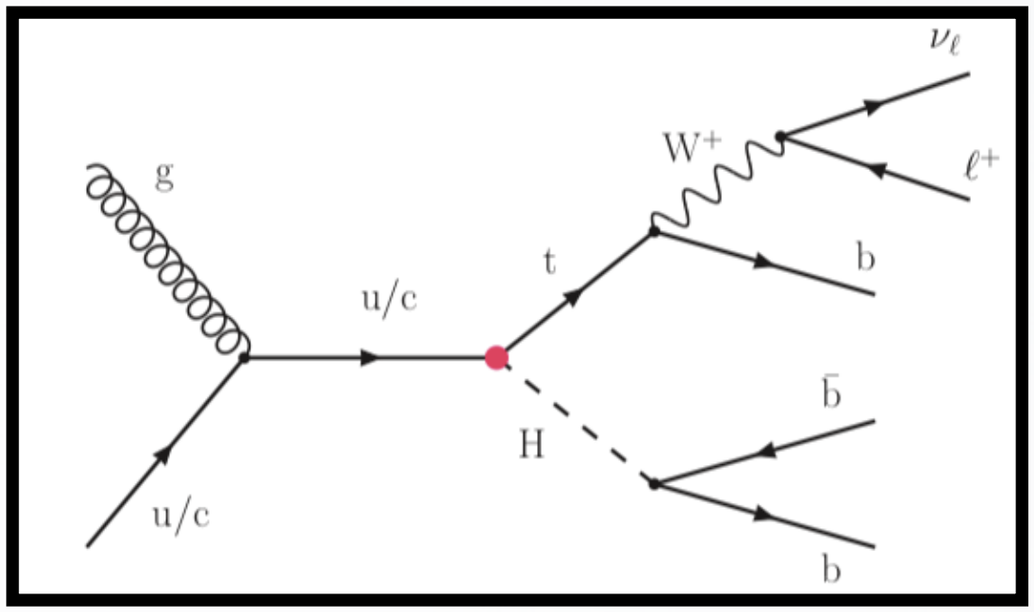
JHEP 06 (2018) 102

- Probe tH (H→bb) FCNC in lepton+jets events
- Use of BDT and event categorisation to deal with the dominant ttbar+jets background

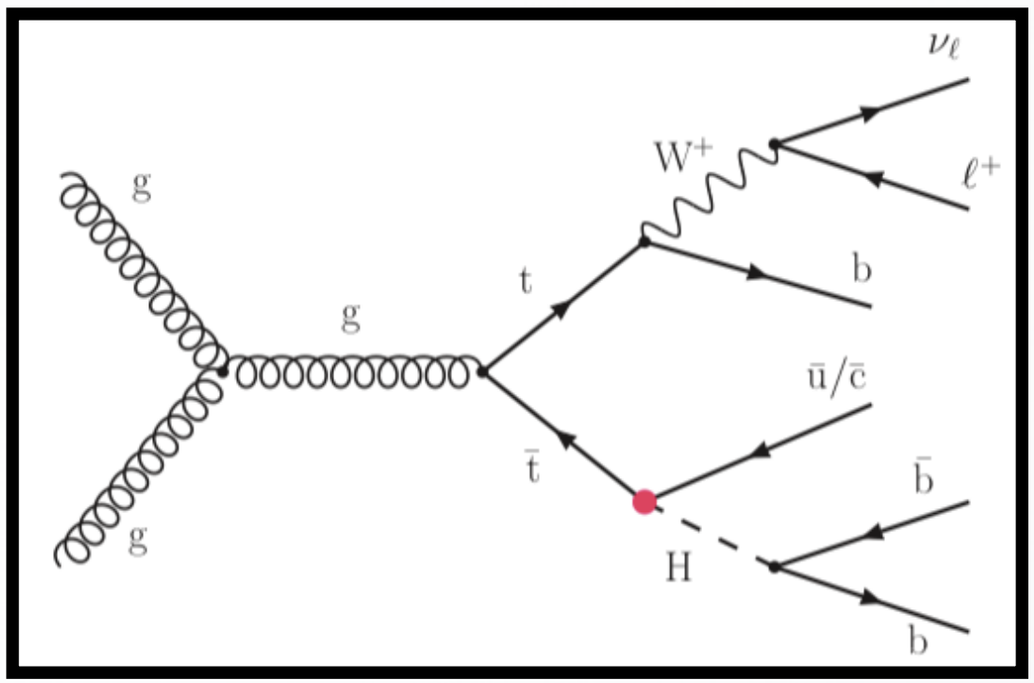


B(t→uH) < 0.47 (0.34) %
B(t→cH) < 0.47 (0.44) %

tH FCNC



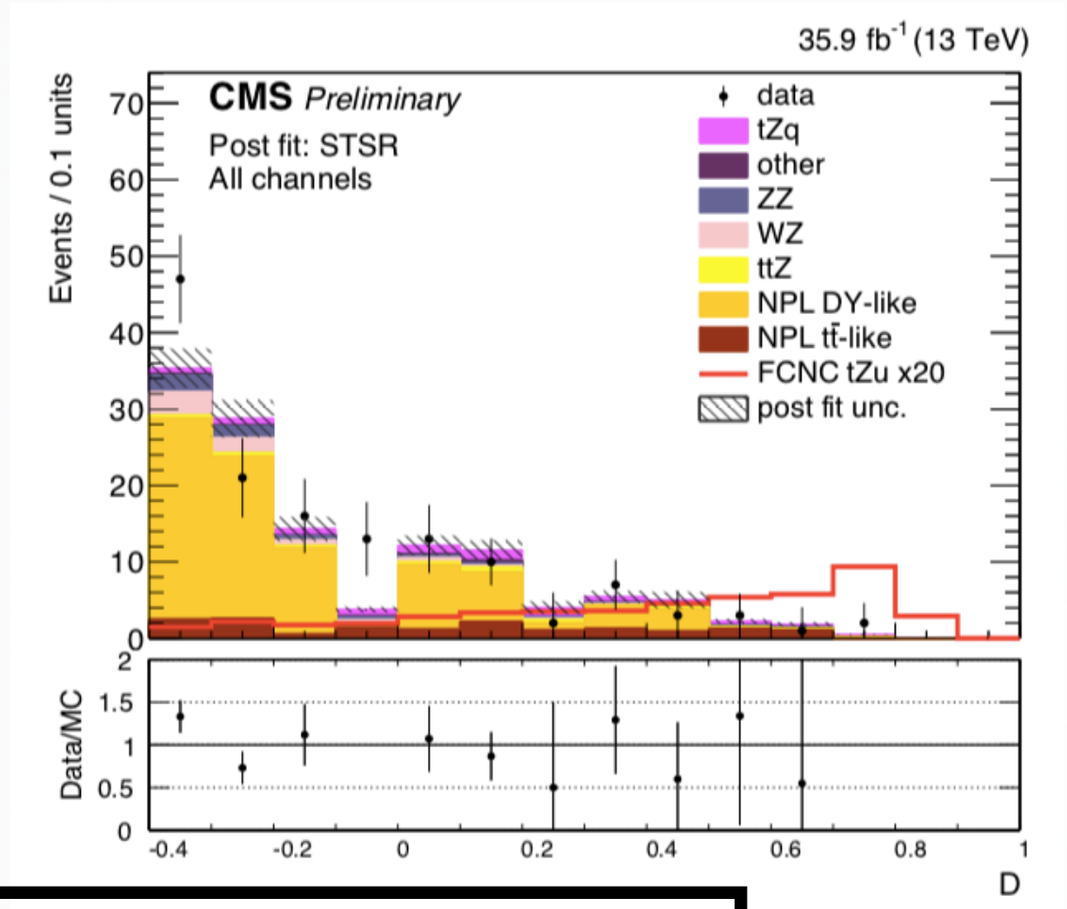
ttbar FCNC



Search for *top-Z* **FCNC**

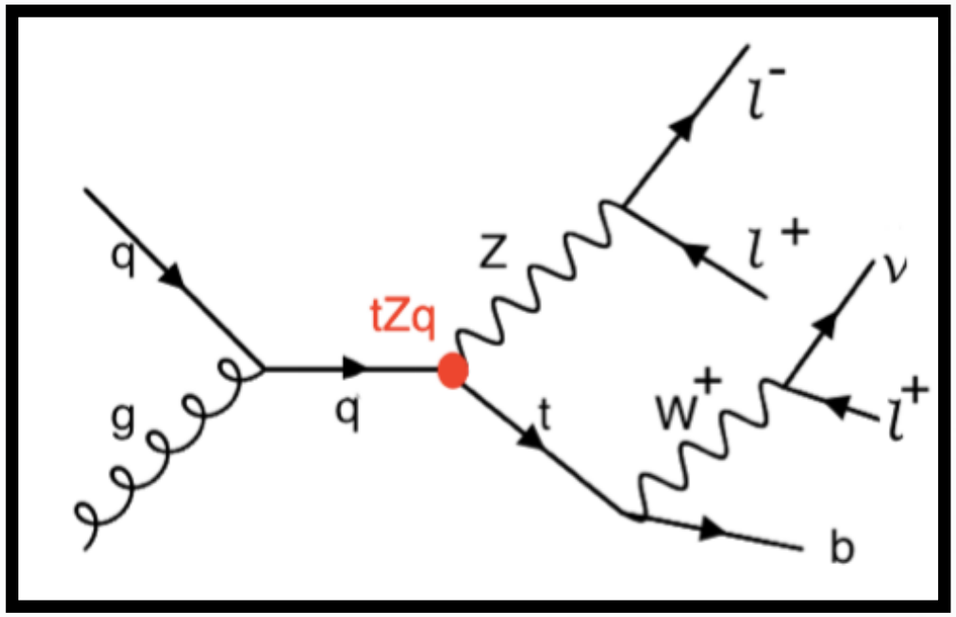
CMS PAS TOP-17-017

- Probe tZ (Z→ll) FCNC in trilepton events
- BDT as the final selection with non-prompt lepton background controlled via additionally defined kinematic regions (WZ and ttbar)

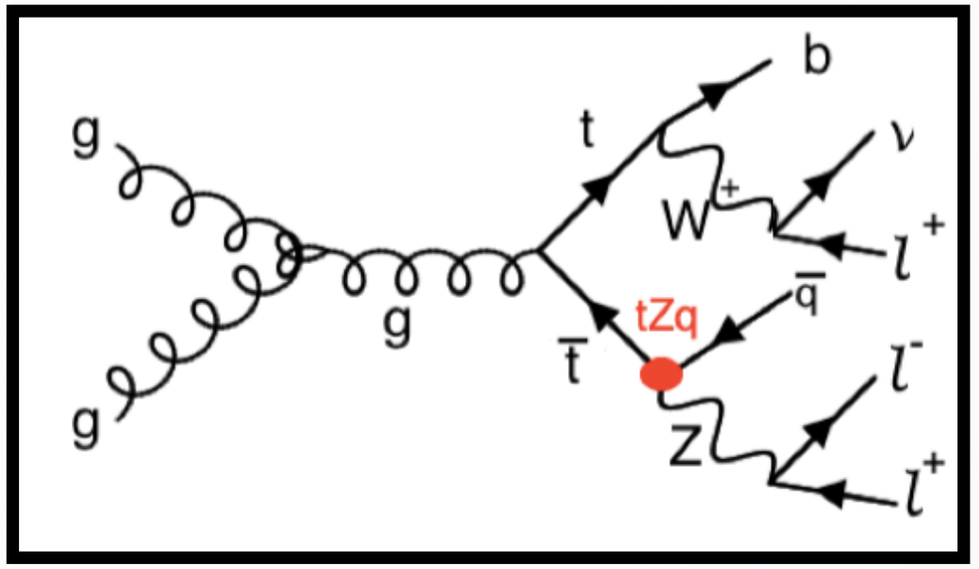


B(t→uZ) < 0.024 (0.015) %
B(t→cZ) < 0.045 (0.037) %

tZ FCNC



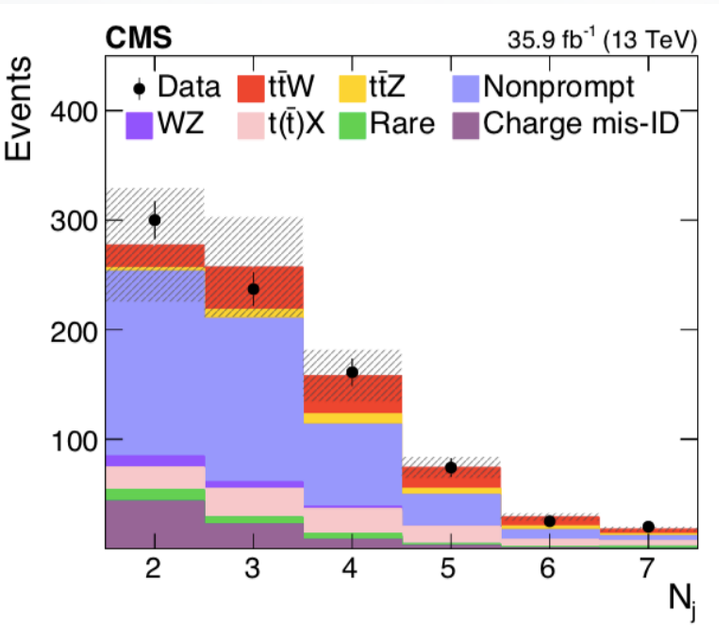
ttbar FCNC

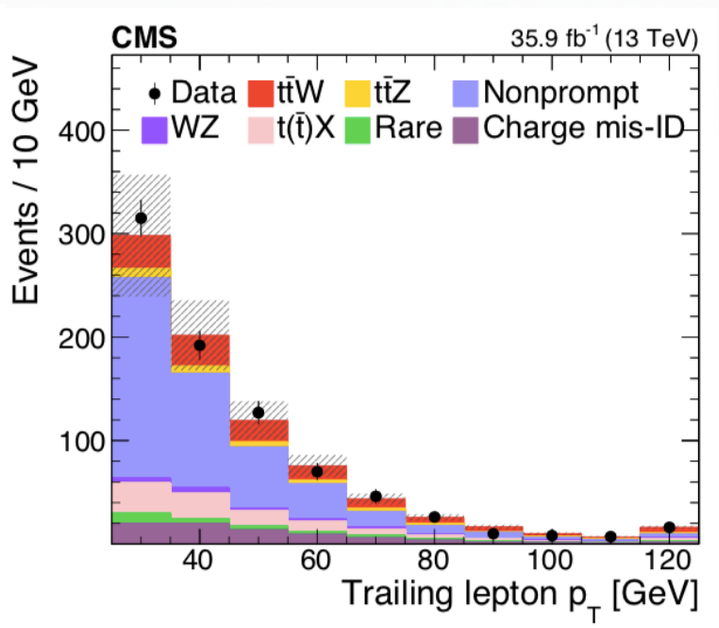


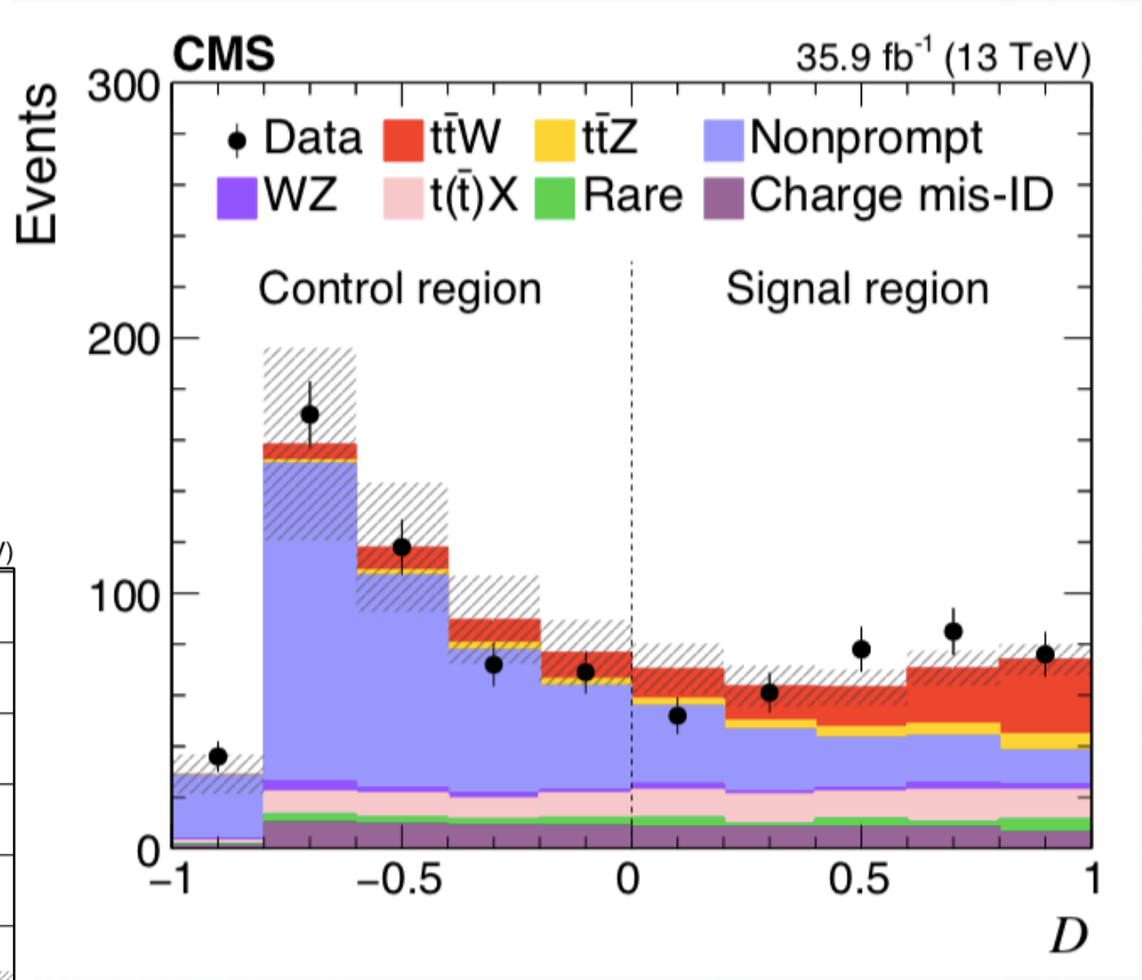
Study of ttV production

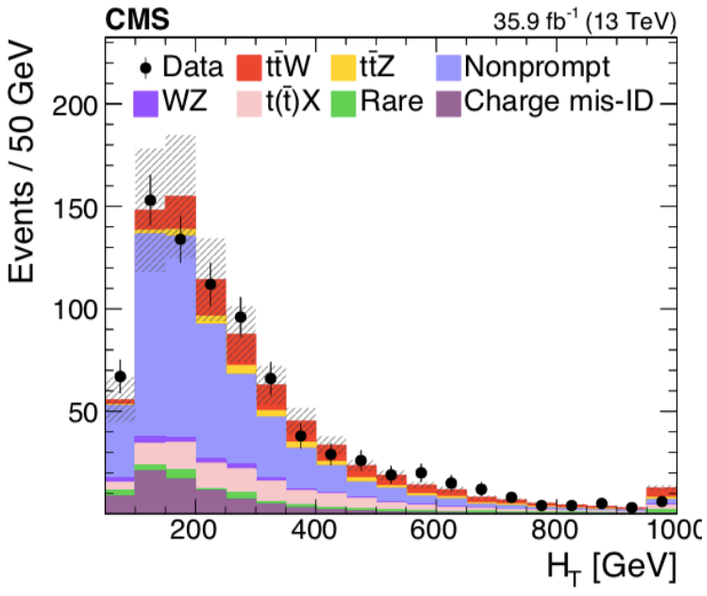
36 fb^{-1}, 13 TeV *JHEP 08 (2018) 011*

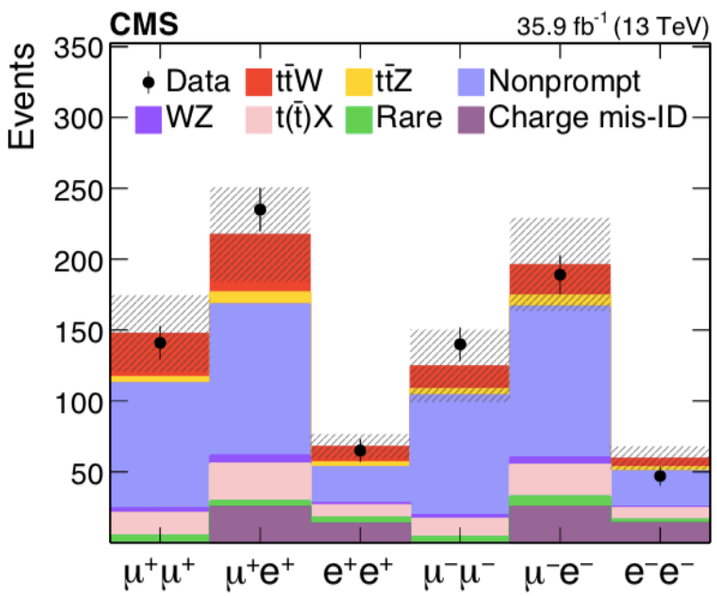
Pre-fit data/MC comparisons in SS dilepton







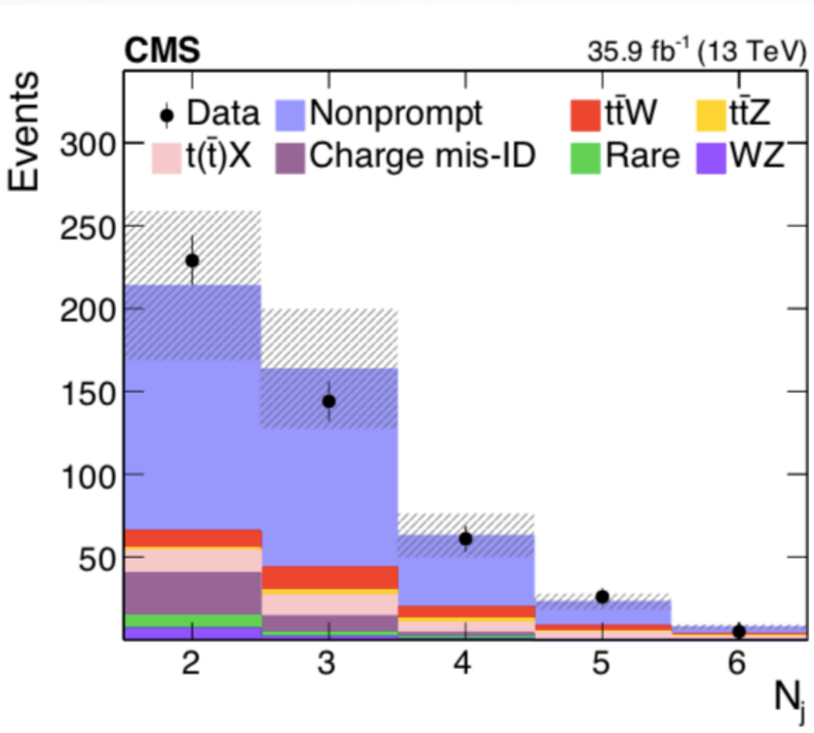




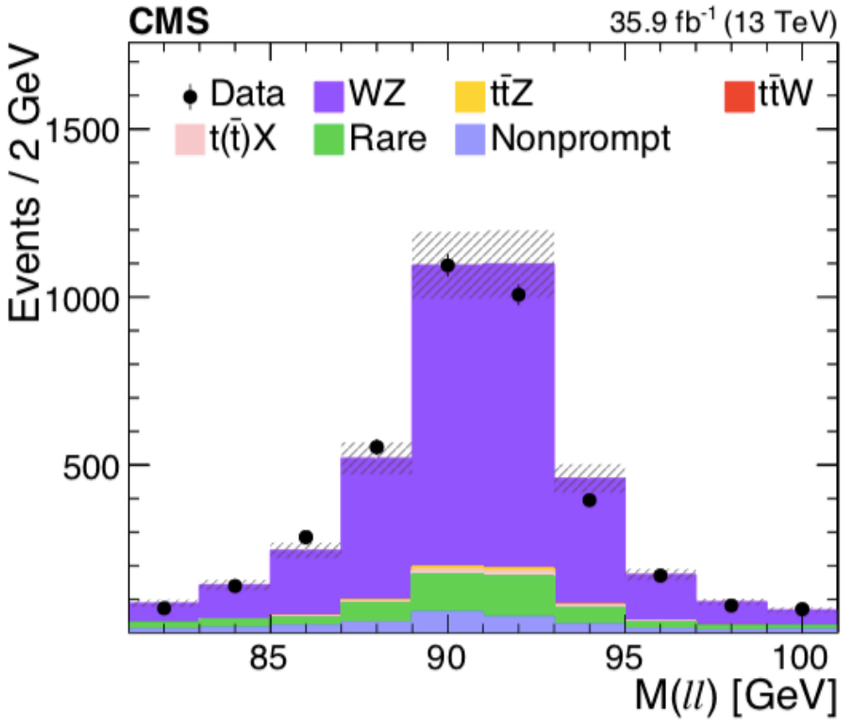
Study of ttV production

36 fb^{-1}, 13 TeV *JHEP 08 (2018) 011*

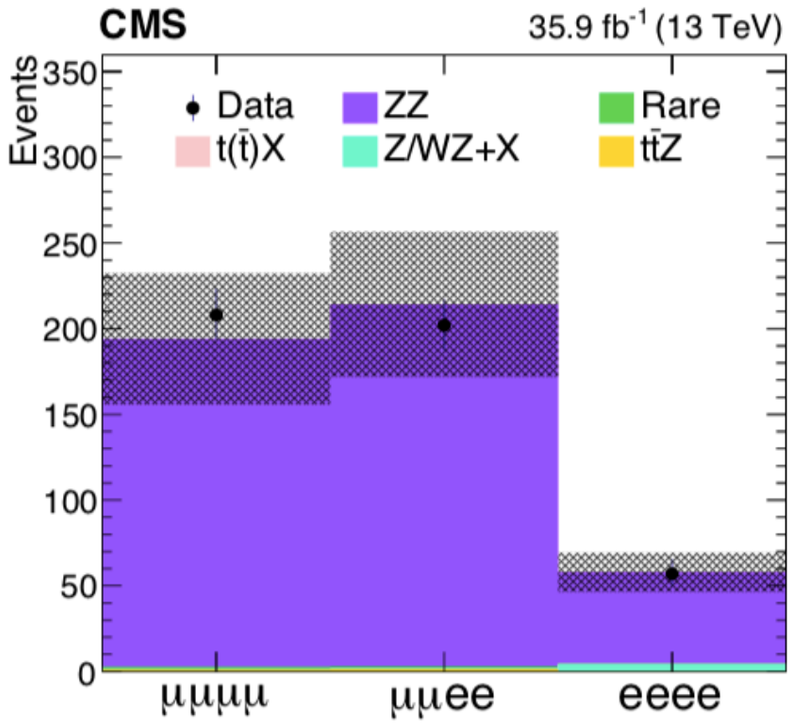
Background validation



Non-prompt
2L SS, D < 0



WZ
3L with 2L OSSF, $N_j < 2$, b tag veto

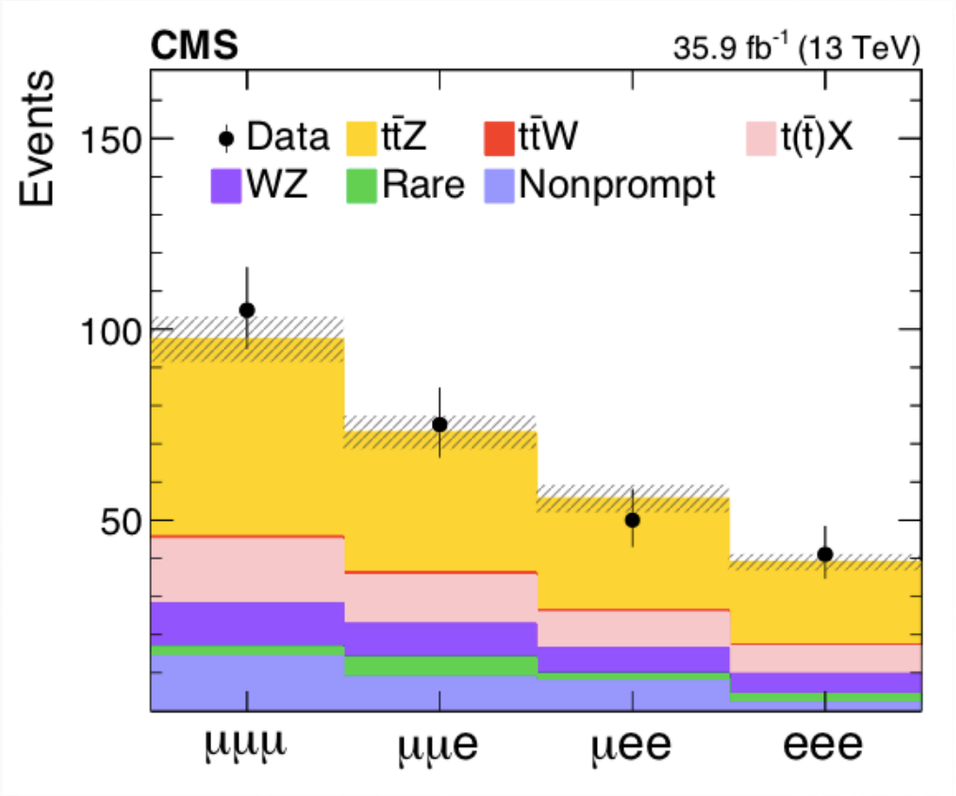


ZZ
4L with 2L OSSF

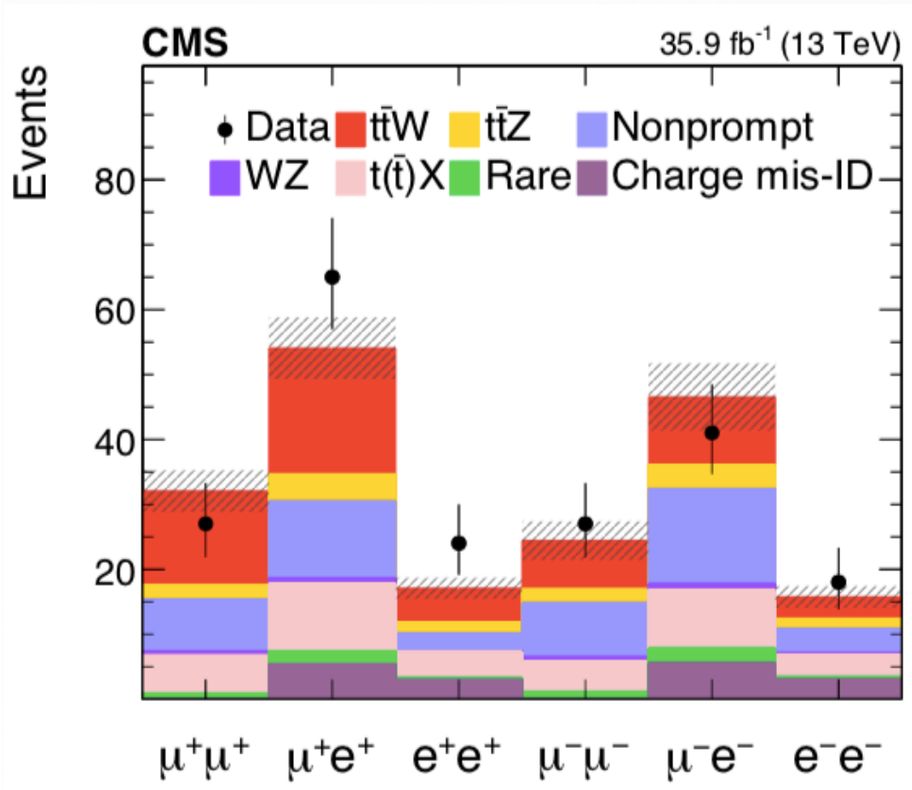
Study of ttV production

36 fb^{-1}, 13 TeV *JHEP 08 (2018) 011*

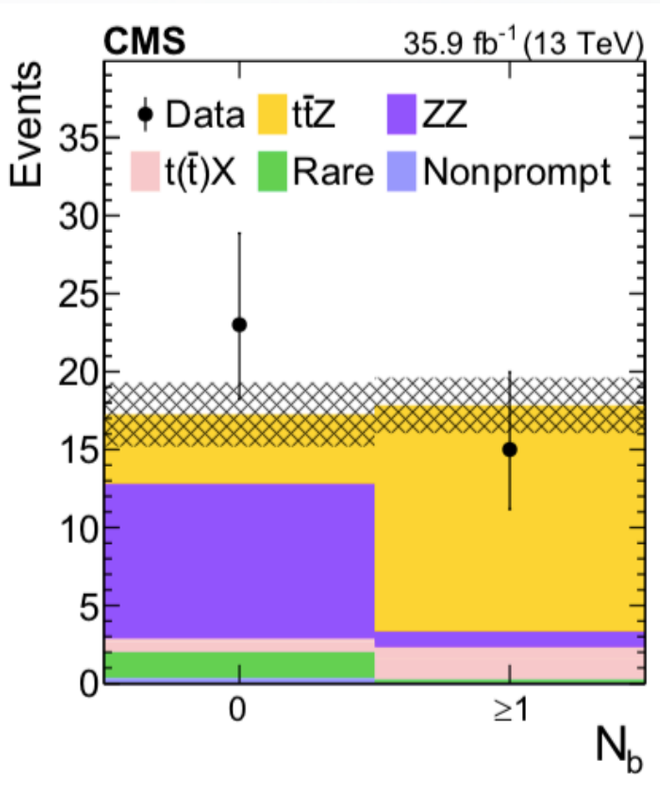
Post-fit data/MC comparisons



3L



2L SS

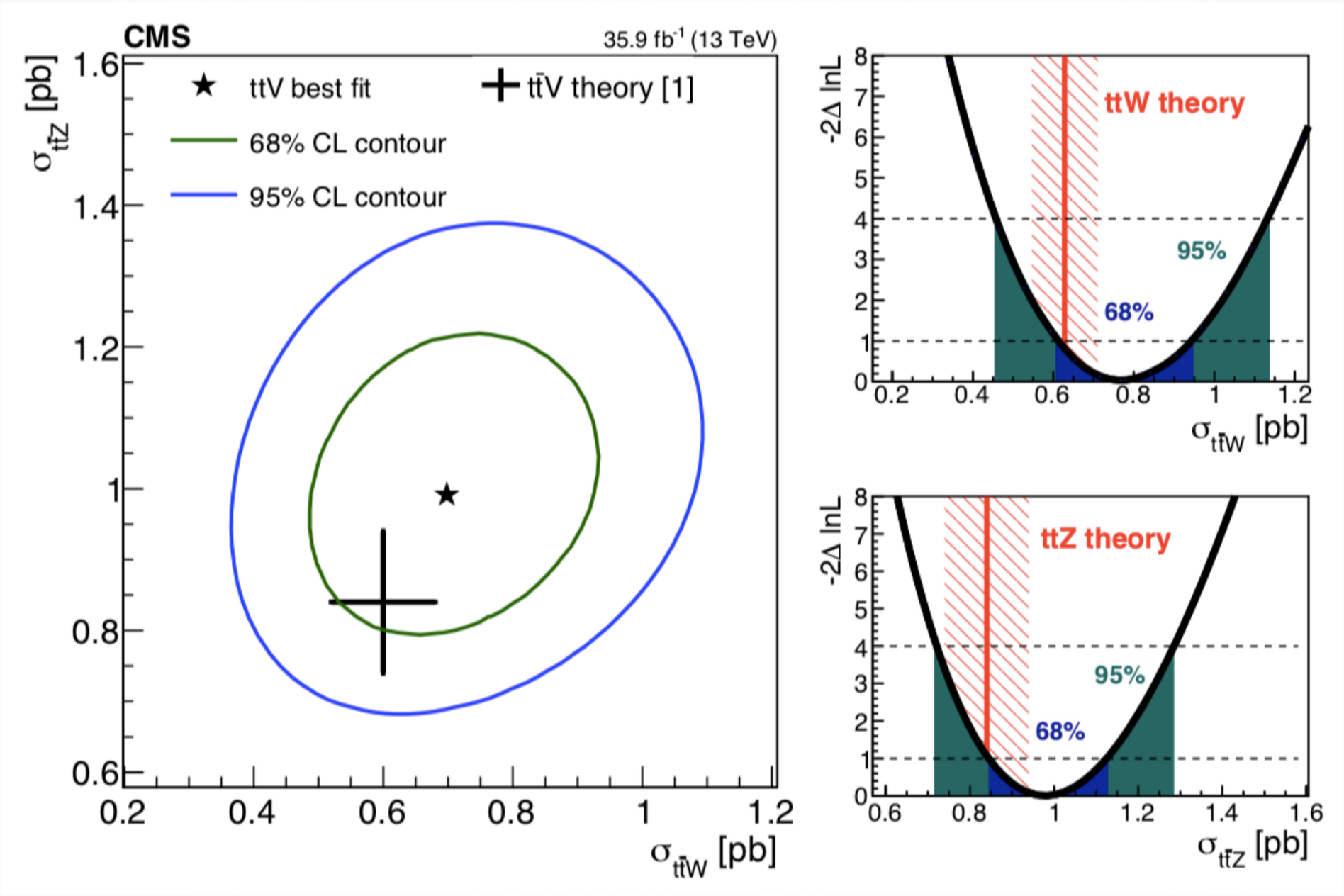


4L

Study of ttV production

36 fb^{-1}, 13 TeV *JHEP 08 (2018) 011*

Cross section extraction



Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

Systematics

Source	Uncertainty range (%)	Correlated in 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
B tagging light flavor	0–4	×	1
B tagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	1
Color reconnection	1.5	✓	< 1
Parton shower	1–8	✓	1
WZ cross section	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ bg.	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	< 1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bg.	5–50	×	< 1
Stat. unc. in rare SM bg.	5–100	×	< 1
Total uncertainty			7

Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

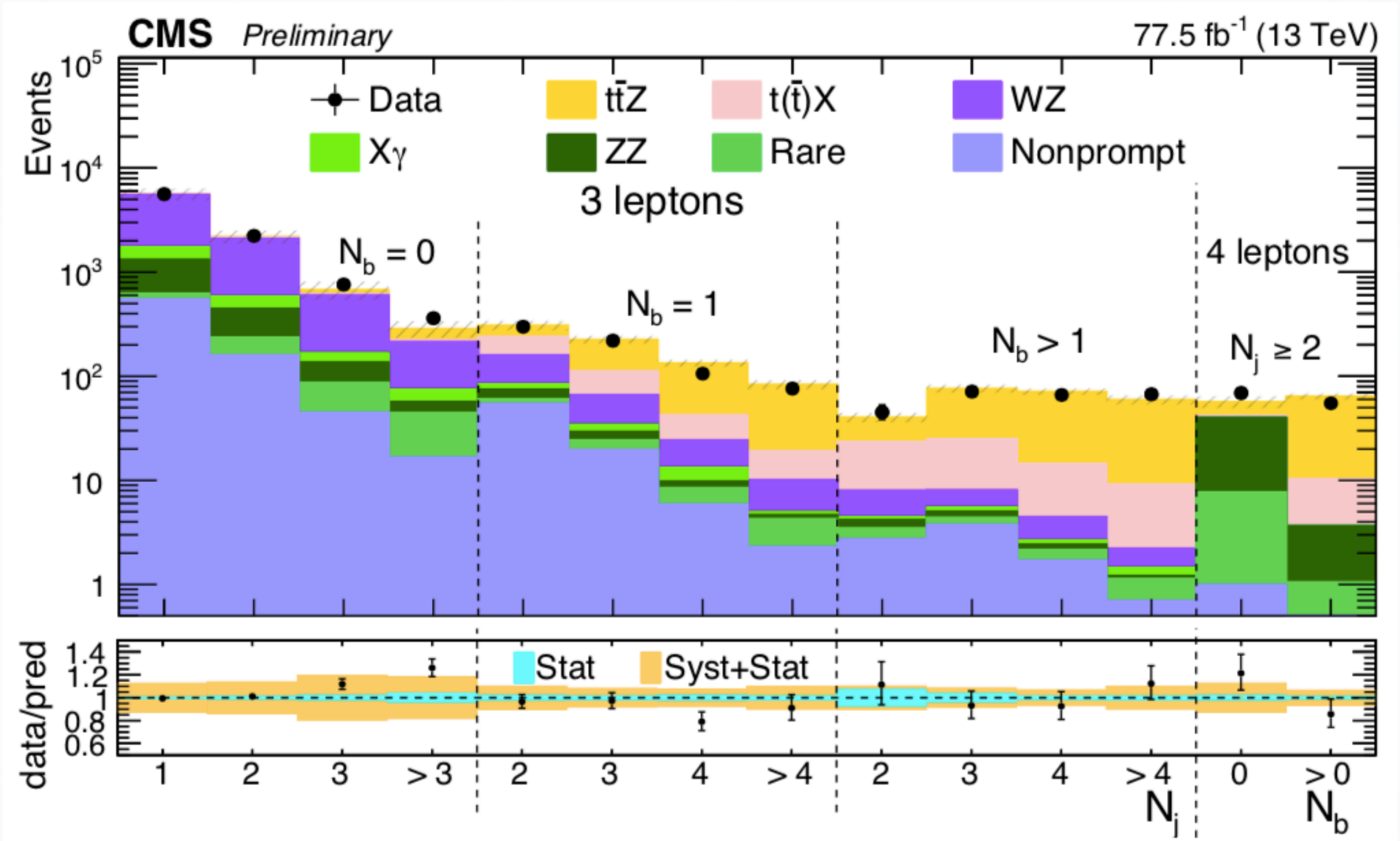
$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},
\end{aligned}
$$

Coefficient	Expected		Observed		Previous CMS constraints		Indirect constraints
	68% CL	95% CL	68% CL	95% CL	Exp, 95% CL	Obs, 95% CL	68% CL
c_{tZ}/Λ^2	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 0.5]$	$[-1.1, 1.1]$	$[-2.0, 2.0]$	$[-2.6, 2.6]$	$[-4.7, 0.2]$
$c_{tZ}^{[I]}/\Lambda^2$	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 1.0]$	$[-1.2, 1.2]$	–	–	–
$c_{\phi t}/\Lambda^2$	$[-1.6, 1.4]$	$[-3.4, 2.8]$	$[2.2, 4.7]$	$[0.7, 5.9]$	$[-20.2, 4.0]$	$[-22.2, -13.0]$ $[-3.2, 6.0]$	$[-0.1, 3.7]$
$c_{\phi Q}^{-}/\Lambda^2$	$[-1.1, 1.1]$	$[-2.1, 2.2]$	$[-3.0, -1.0]$	$[-4.0, 0.0]$	–	–	$[-4.7, 0.7]$

Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

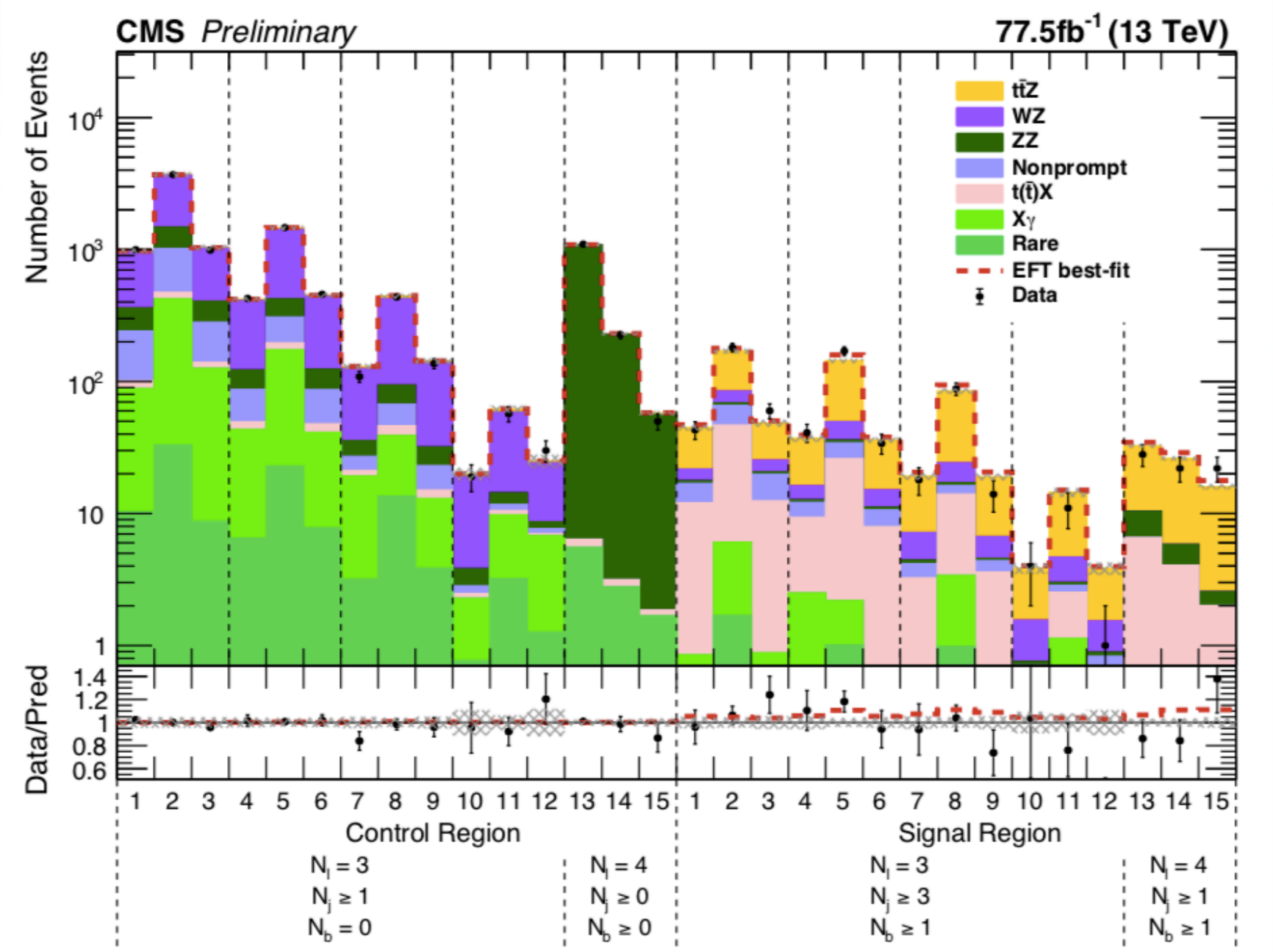
Data/MC comparison



Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

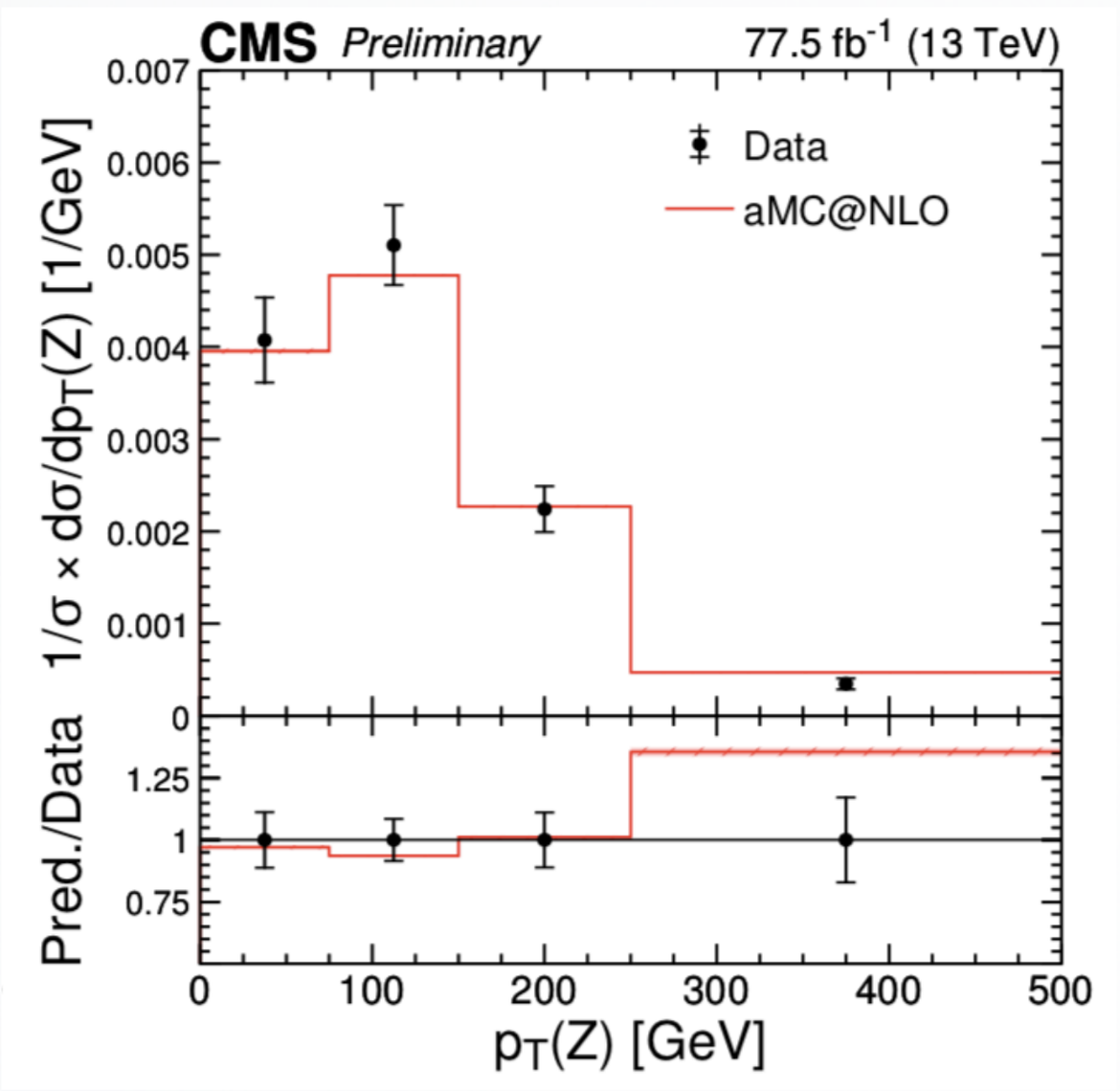
Data/MC comparison

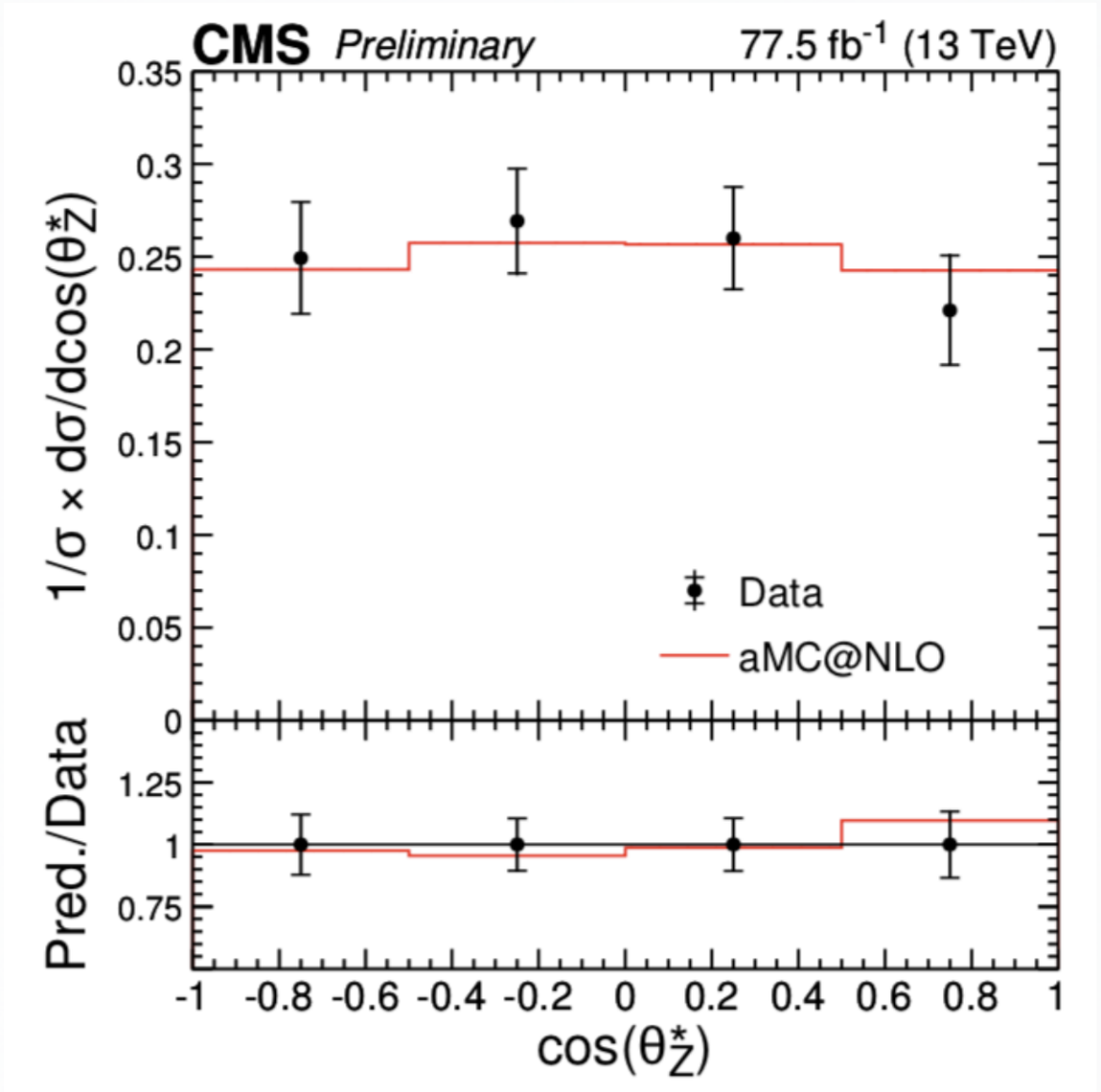


Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

Normalized differential cross sections

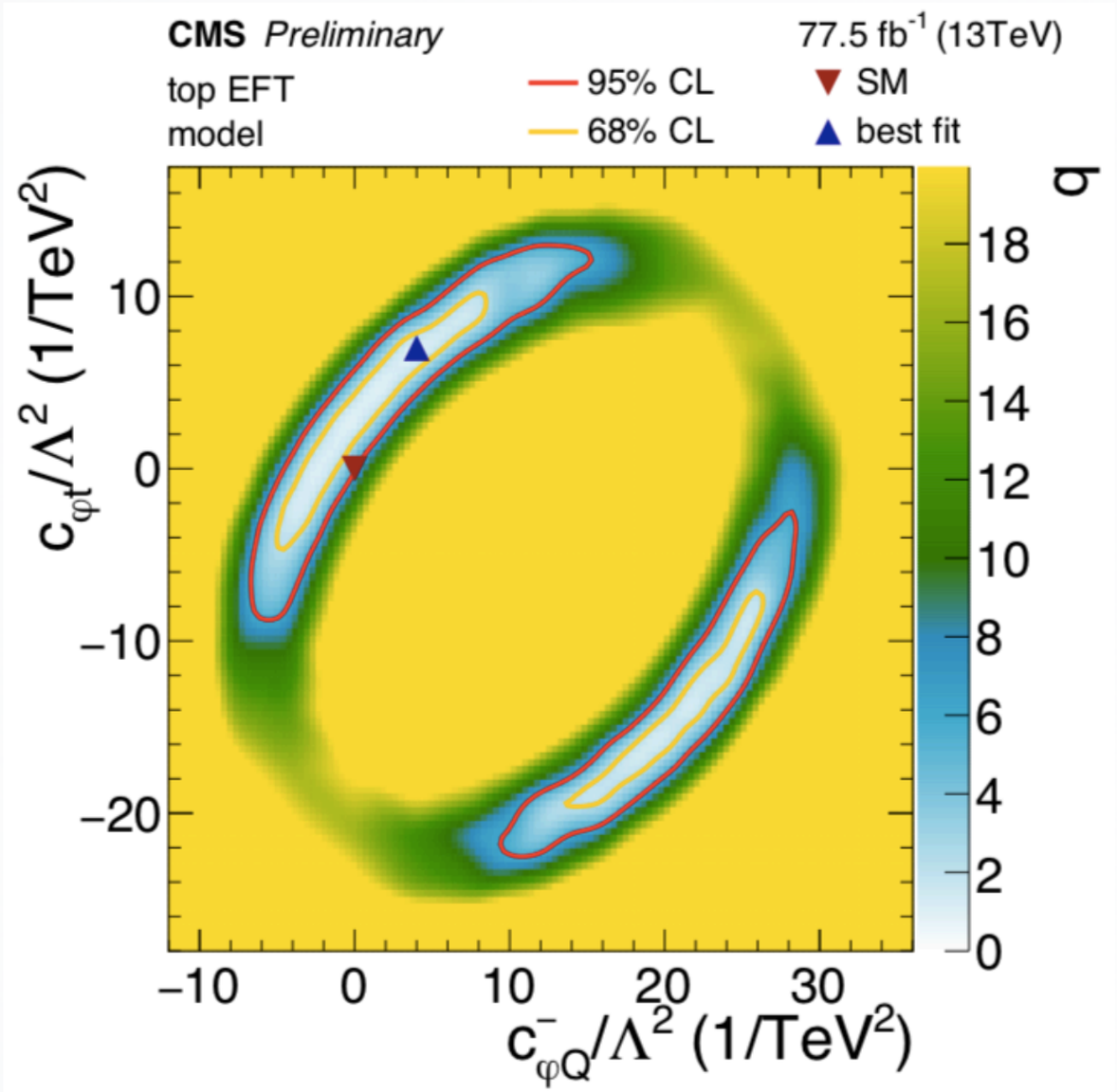


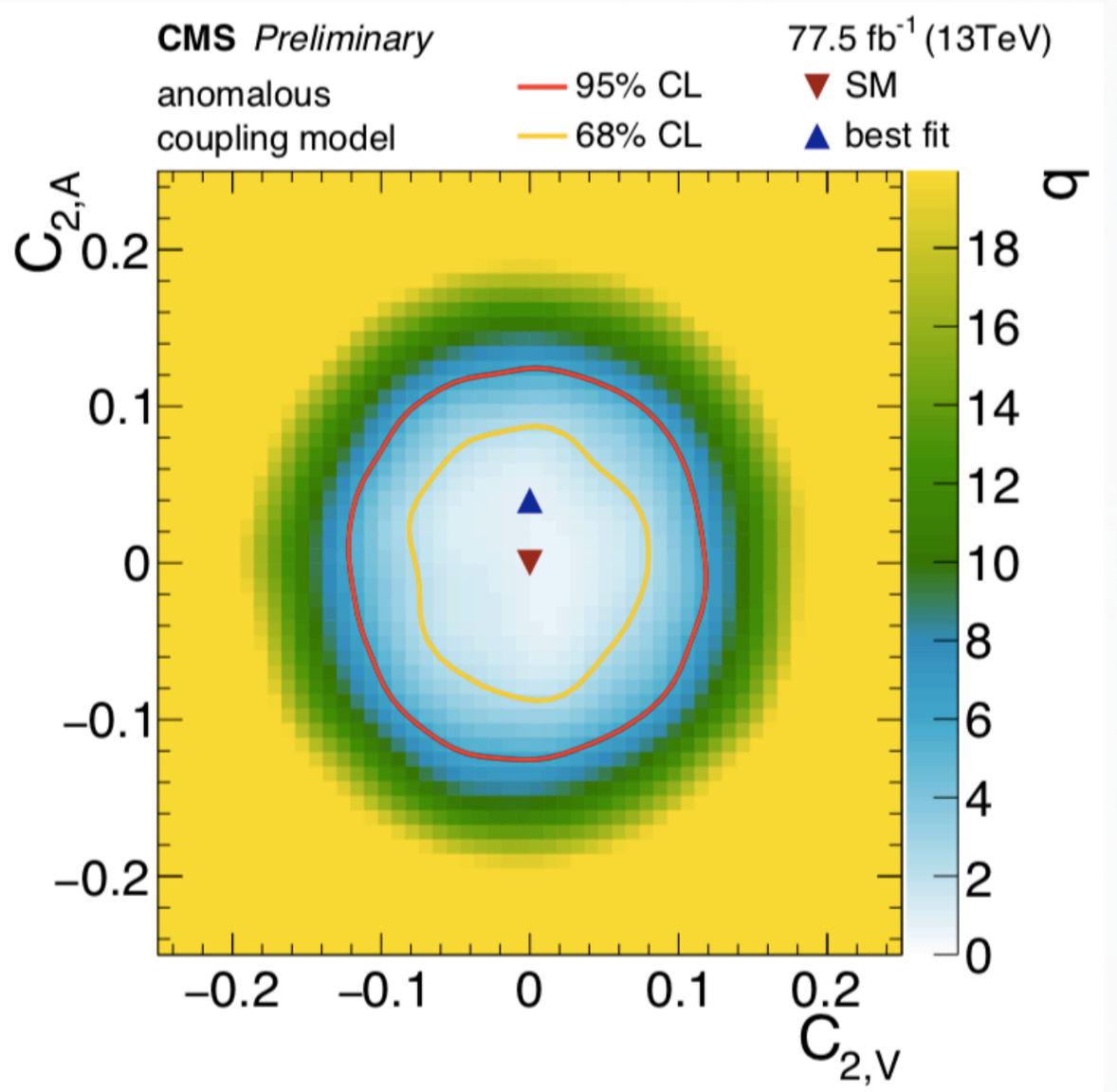


Differential ttZ cross section

78 fb^{-1}, 13 TeV *CMS PAS TOP-18-009*

EFT constraints

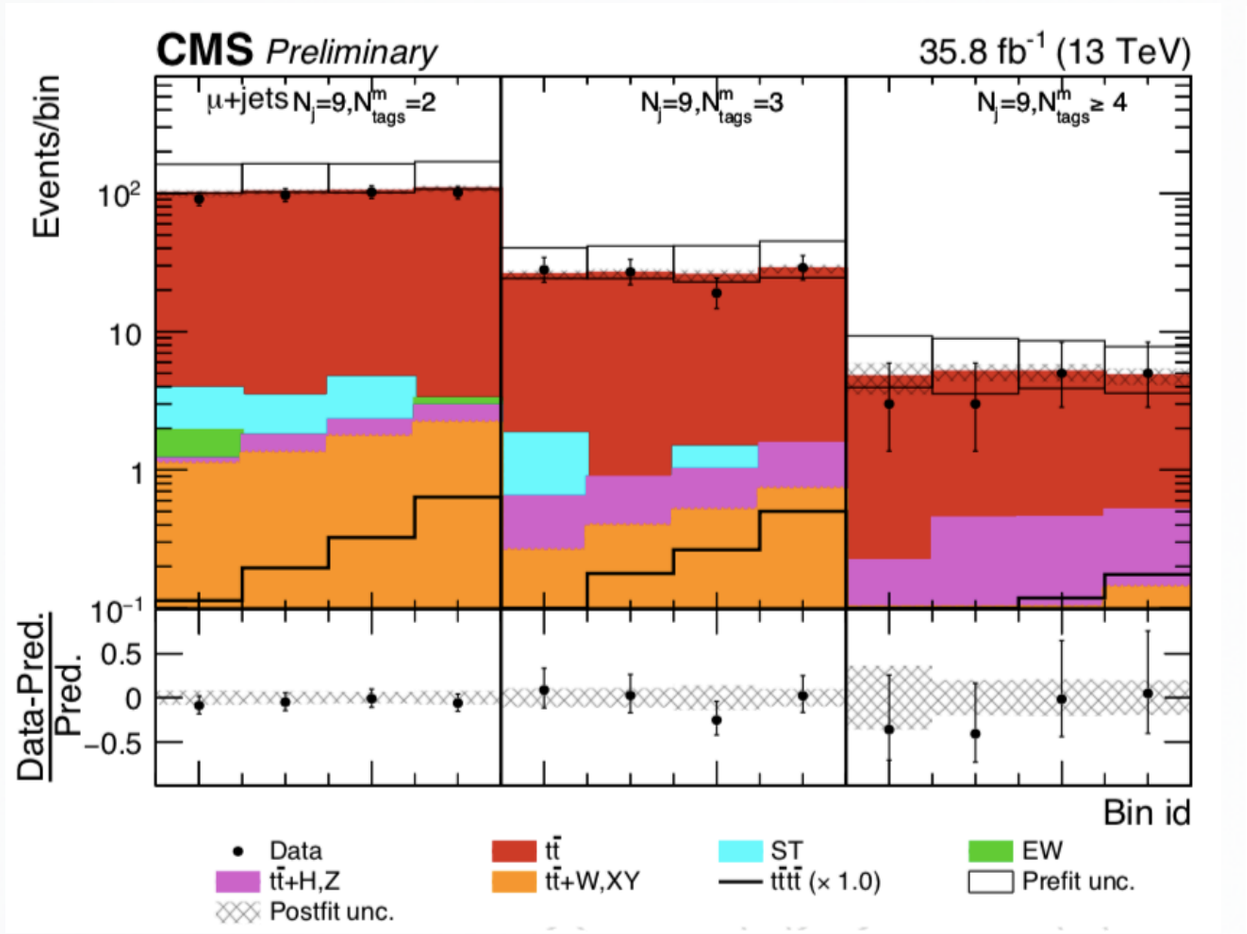


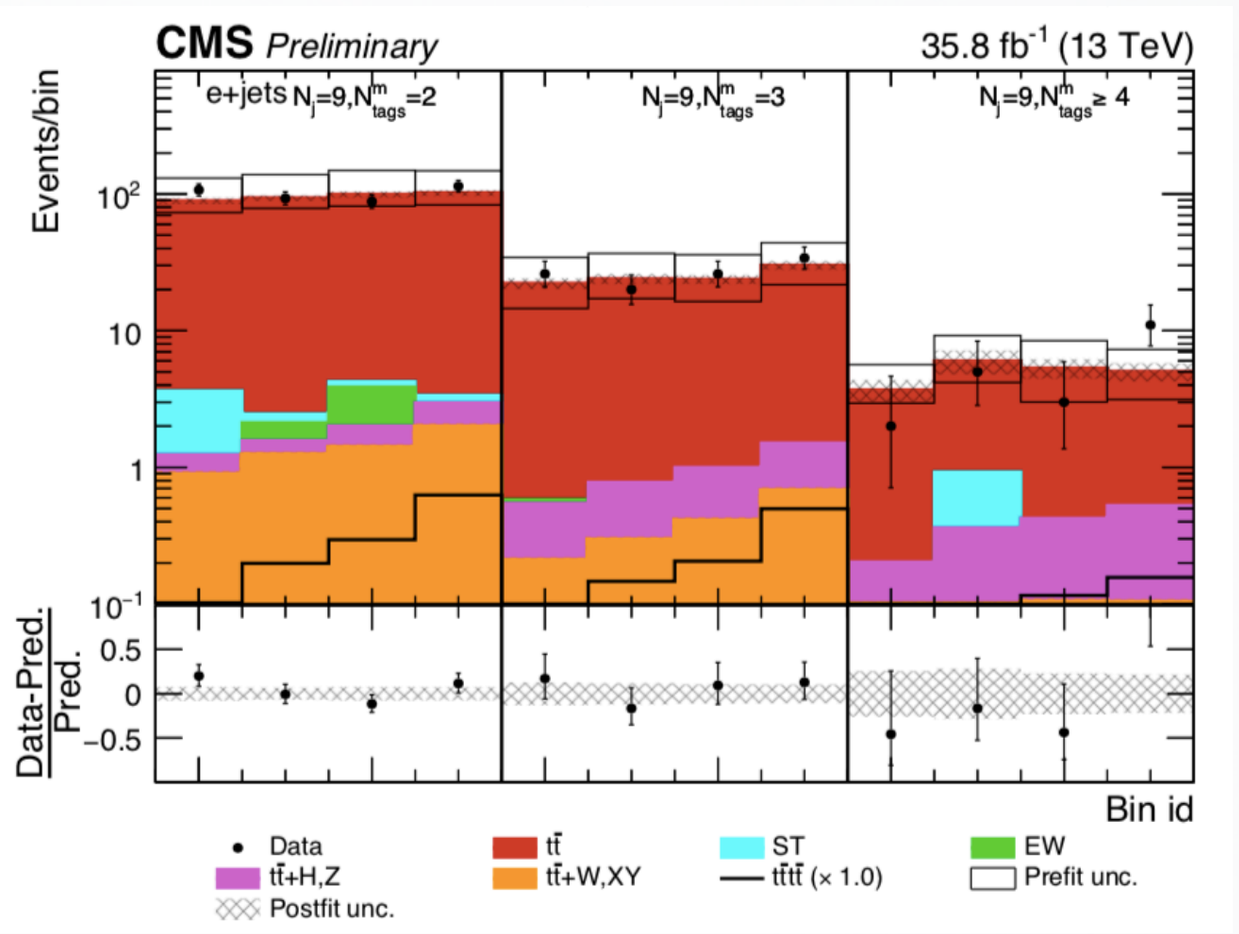


Search for 4 tops

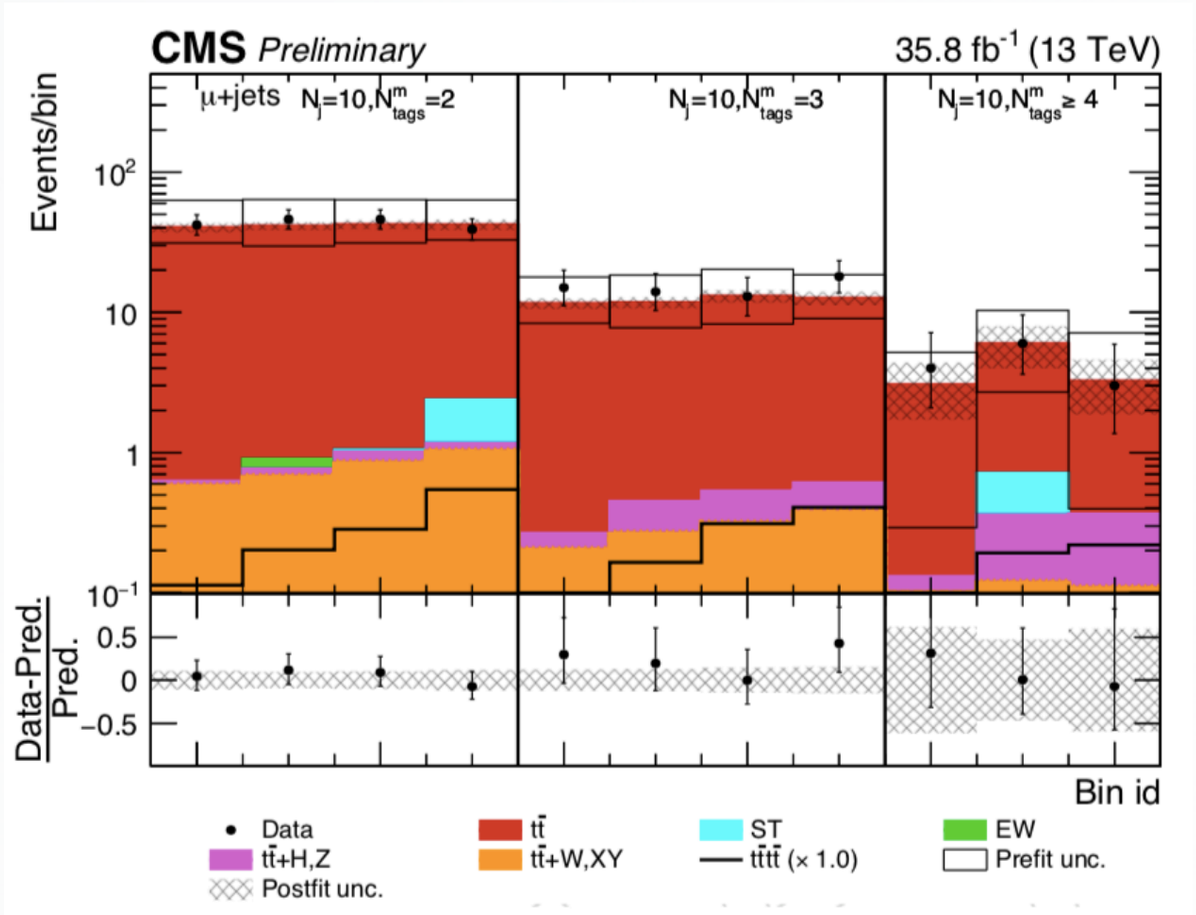
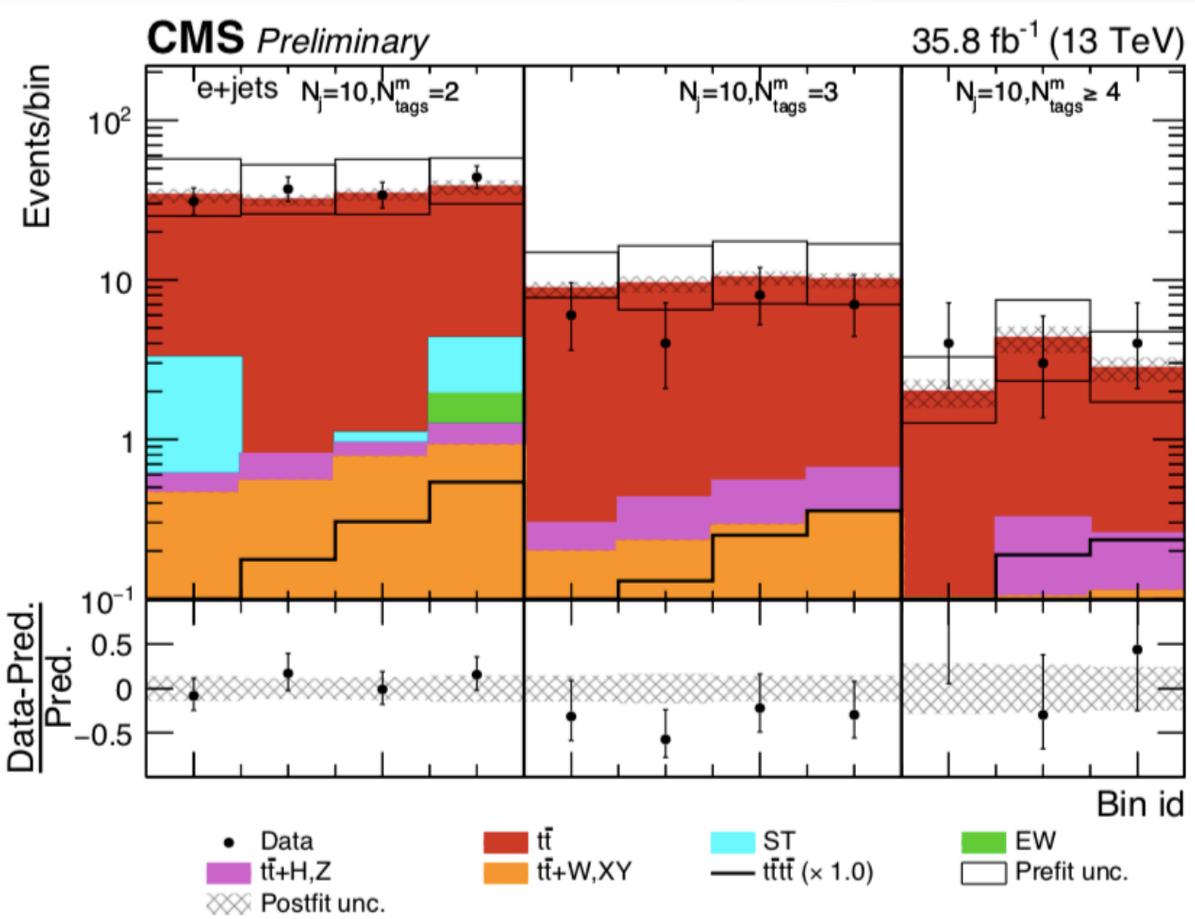
36 fb^{-1}, 13 TeV *CMS PAS TOP-17-019*

Data/MC comparison in single lepton (post-fit)





Search for 4 tops

36 fb^{-1}, 13 TeV *CMS PAS TOP-17-019*

Data/MC comparison in single lepton (post-fit)