Rare top quark production at CMS
ttW, ttZ, ttγ, tZq, $t\gamma$q, tttt

Didar Dobur

University of Ghent

On behalf of the CMS Collaboration

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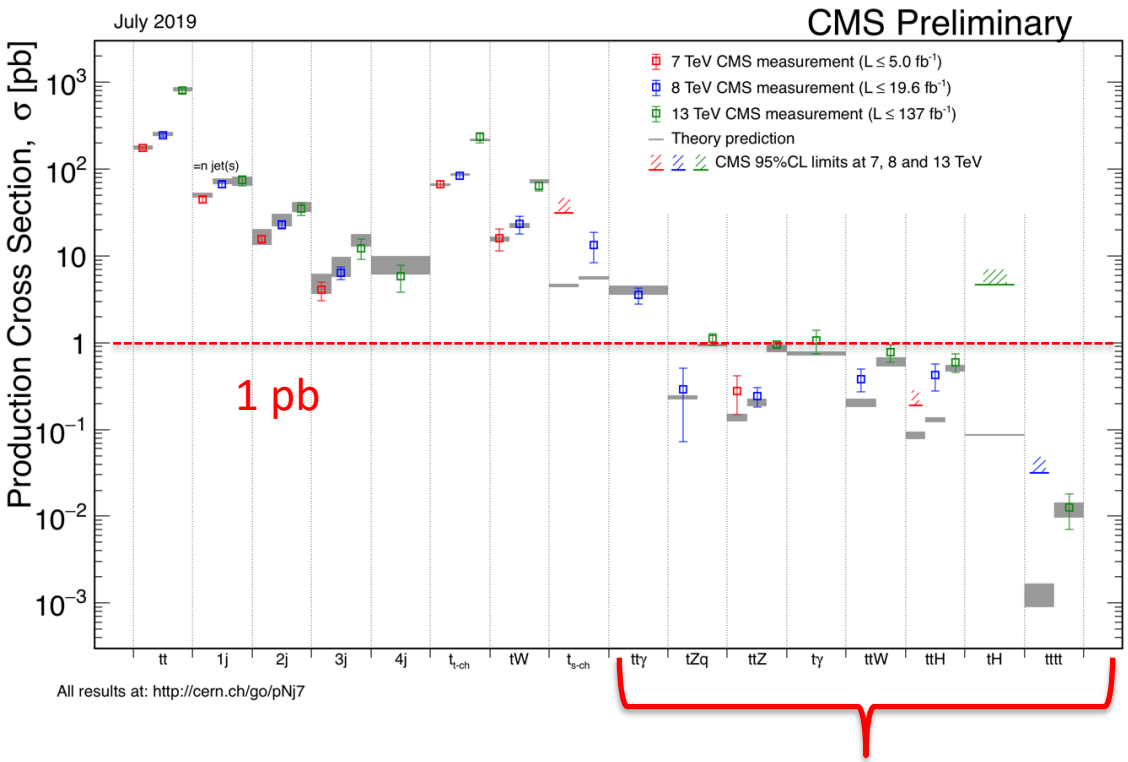
Toronto, 2019

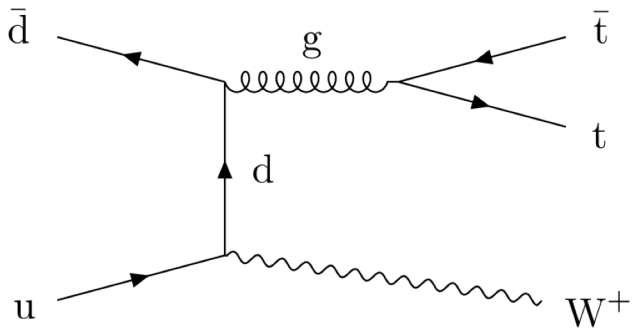
Top quark production



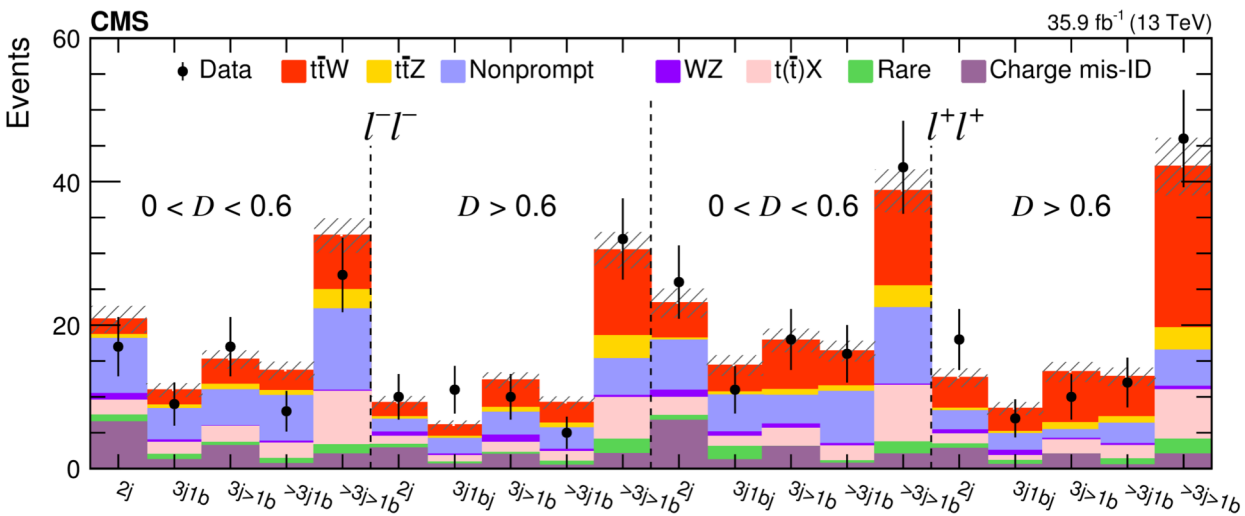
- $t\bar{t}+W$ (36 fb^{-1}) JHEP08(2018)011
- $t\bar{t}+Z$ (78 fb^{-1}) arXiv:1907.11270
- $t\bar{t}+\gamma$ (20 fb^{-1}) JHEP10(2017)006
- 4 top (137 fb^{-1}) CMS-TOP-18-003
  (36 fb^{-1}) CMS-TOP-17-019
- tZq (78 fb^{-1}) PRL122(2019)132003
- $t\gamma q$ (36 fb^{-1}) PRL 121 (2018)221802

Run II dataset allows to probe top quarks in its rarest rarest production modes

$t\bar{t} + W$ production



- 2 leptons with same charge
- $p_T(\ell) > 25 / 40$ GeV
- veto Z candidate
- At least two jets



- Large bkg. from nonprompt leptons, ttH
- BDT classifier for S/B separation
- Binned ML fit to all signal & background control regions

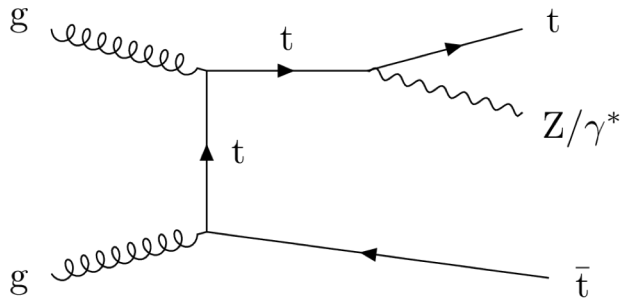
$$\sigma(t\bar{t}W) = 0.77 \pm 0.11(\text{stat}) \pm 0.13(\text{syst})\,\text{pb}$$

25% precision

- Main syst. from backgrounds
- Next : Full Run II data & detailed studies of charge asymmetries

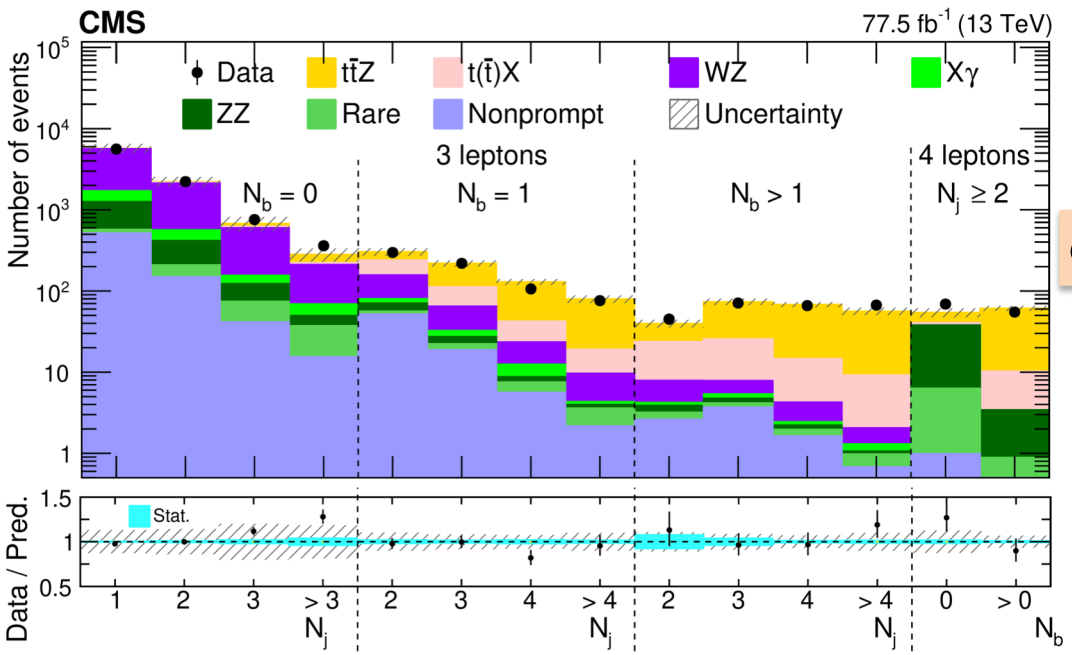
$t\bar{t} + Z$ production

Run II data



- 3/4 leptons
- $p_T(\ell) > 10,15,25$ GeV
- Z candidate $|m_{\ell\ell} - m_Z| < 15$ GeV

Best process to probe top-Z coupling and its structure



- Events categorized in jet bjet multiplicity → good S/B separation
- Simultaneous fit in Signal & bkg. enriched regions with nuisance parameters

8% precision !!!

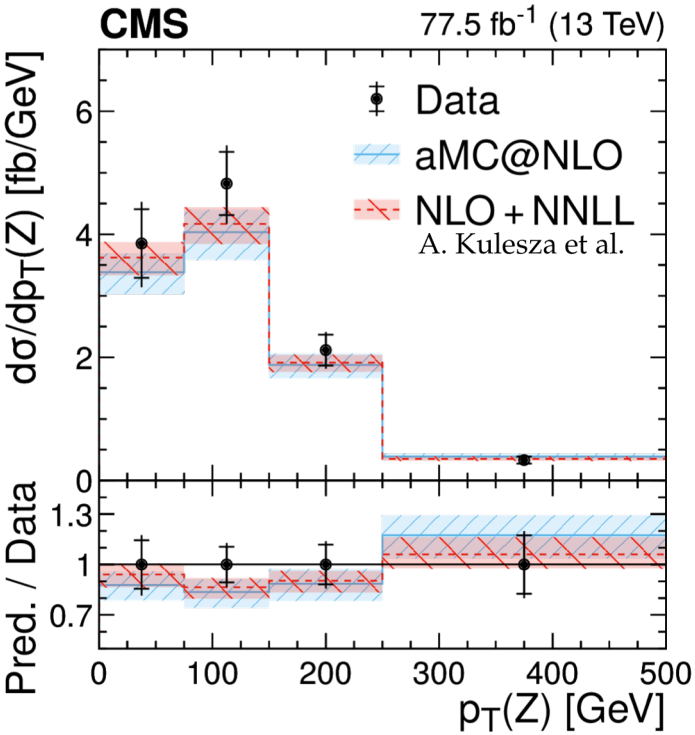
$$\sigma(t\bar{t}Z) = 0.95 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})\,\text{pb}$$

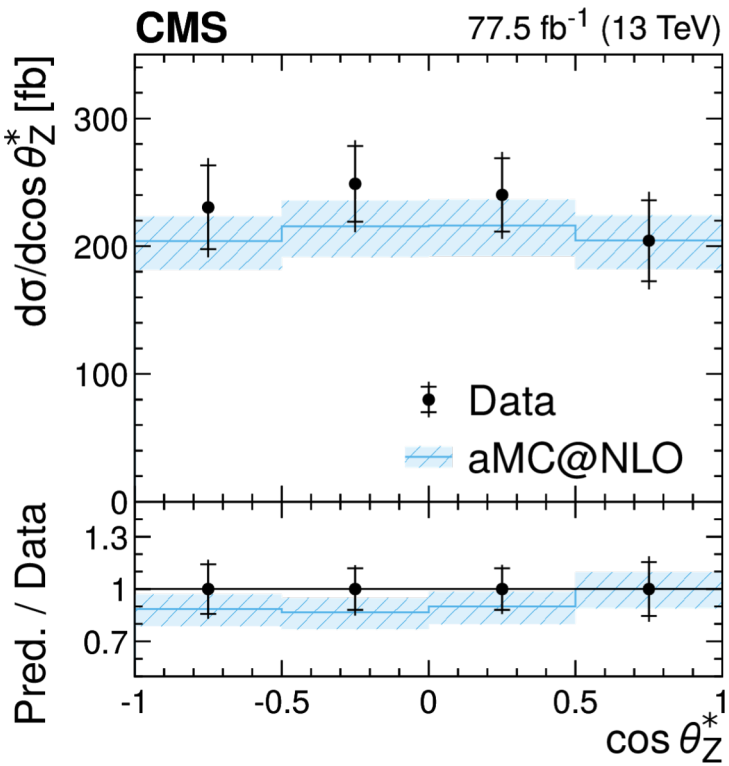
- Main systematic uncertainty modelling of signal acceptance related to leptons and ttX bkg.

$$\sigma(t\bar{t}Z)^{NLO} = 0.85 \pm 0.10$$

$t\bar{t} + Z$:differential measurement

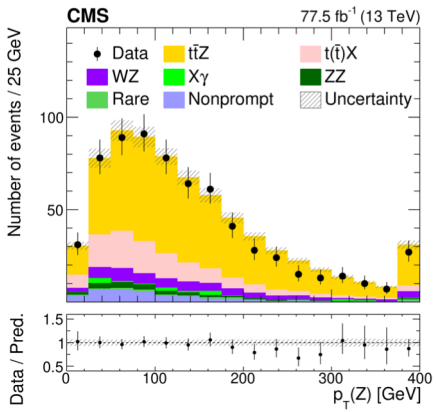
- Events with at least 1 bjet and 3 jets are used to measure the differential cross sections

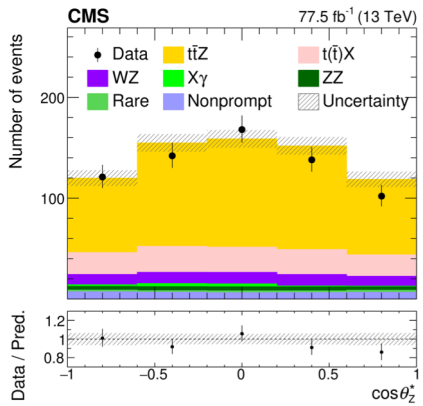




- Z boson p_T and $\cos\theta^*$ → sensitive to new physics effects!

$t\bar{t} + Z$: EFT interpretation



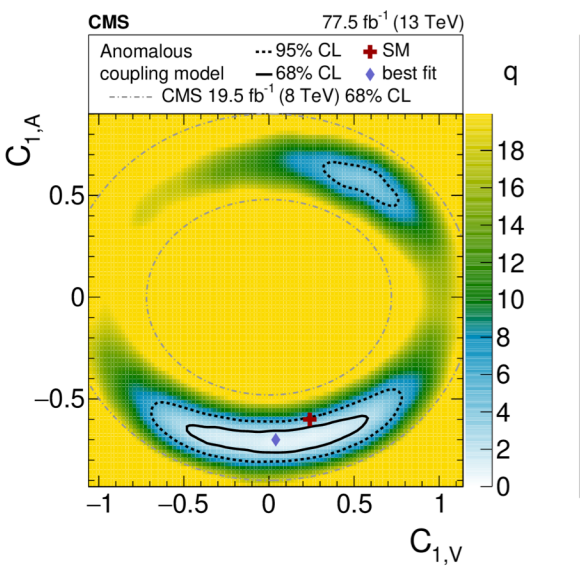


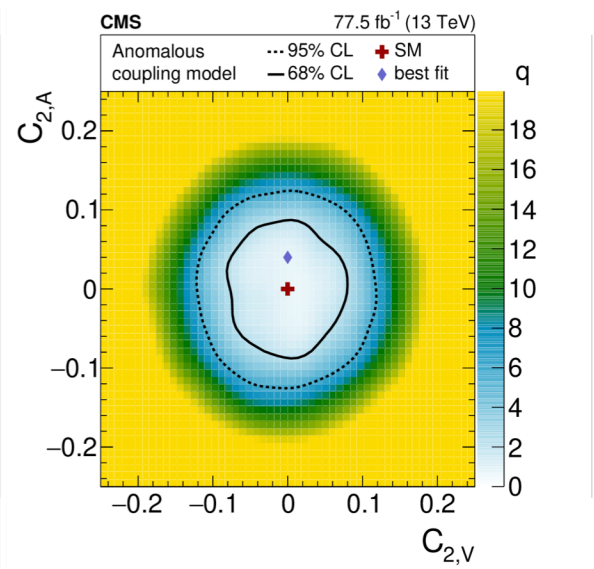
- Z p_T and cosθ^* are explored to probe anomalous top-Z couplings & top EW dipole moments

anomalous current interactions

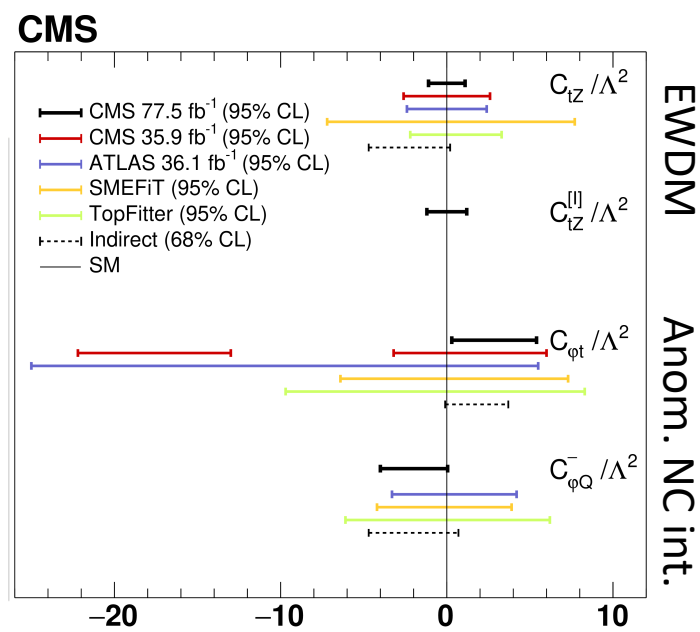
EW dipole interactions

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



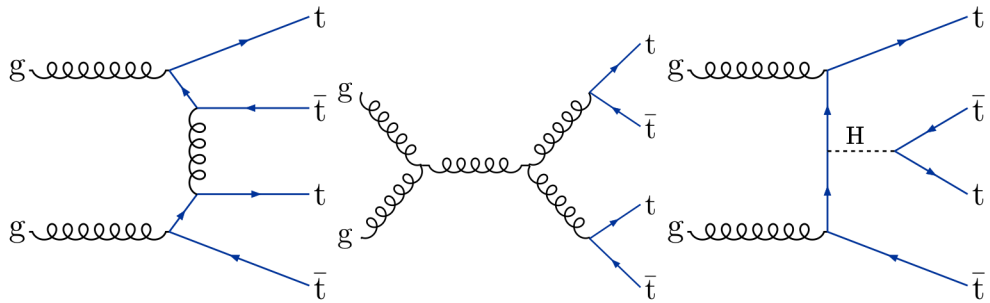


SMEFT interpretation to constraint four Wilson coefficients



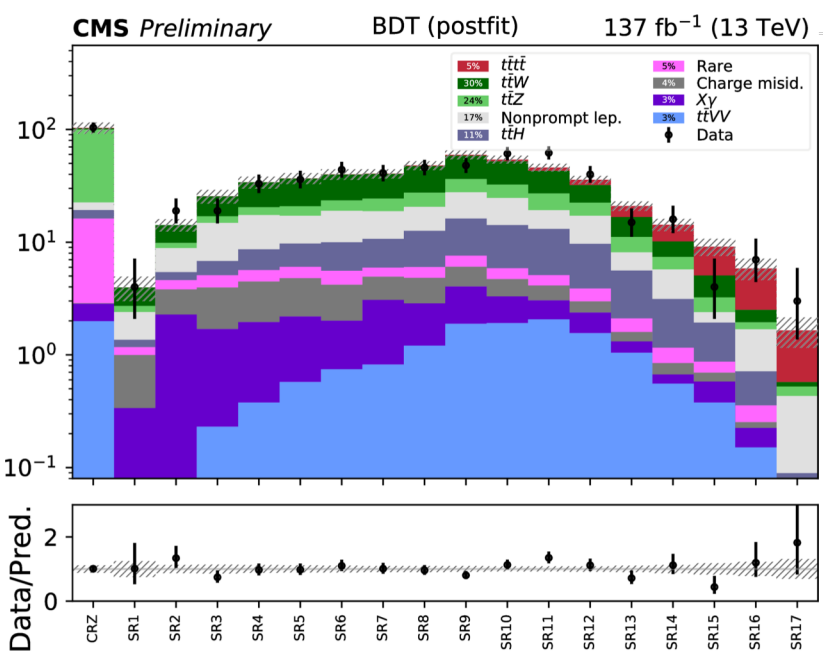
4top production

Run II data



- Rare process with a predicted cross section: $12.0^{+2.2}_{-2.5}$ fb

Sensitive to top Higgs Yukawa coupling & NP via BSM particles ie. a heavy (pseudo)scalar boson in association with a ttbar pair in 2HDM



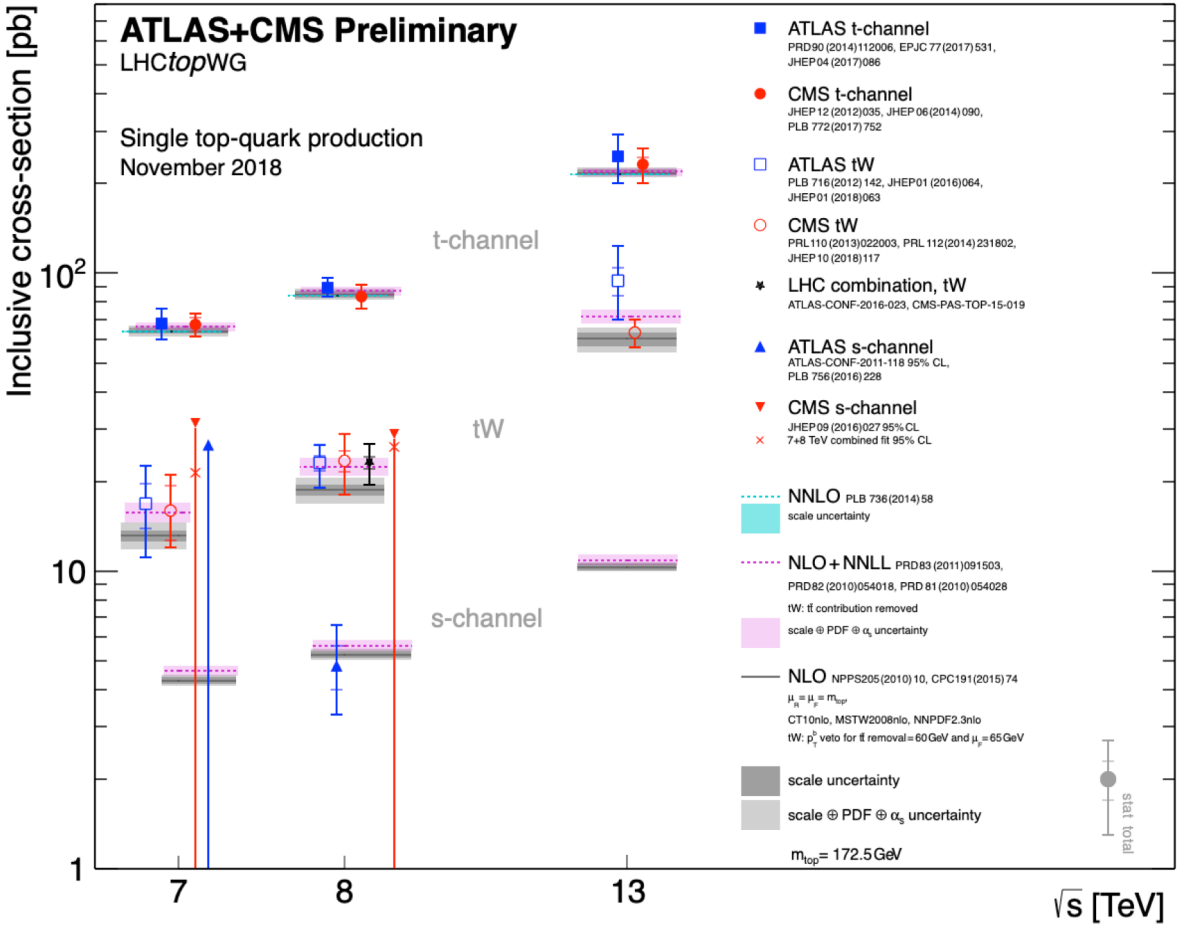
- Spectacular experimental signature, but small cross section
- Most sensitive channel: same-sign dileptons and multileptons

Using BDT analysis

- Measured cross section is $12.6^{+5.8}_{-5.2}$ fb
- Obs. significance of 2.6 σ

Combination with other channels important

Single top-quark production

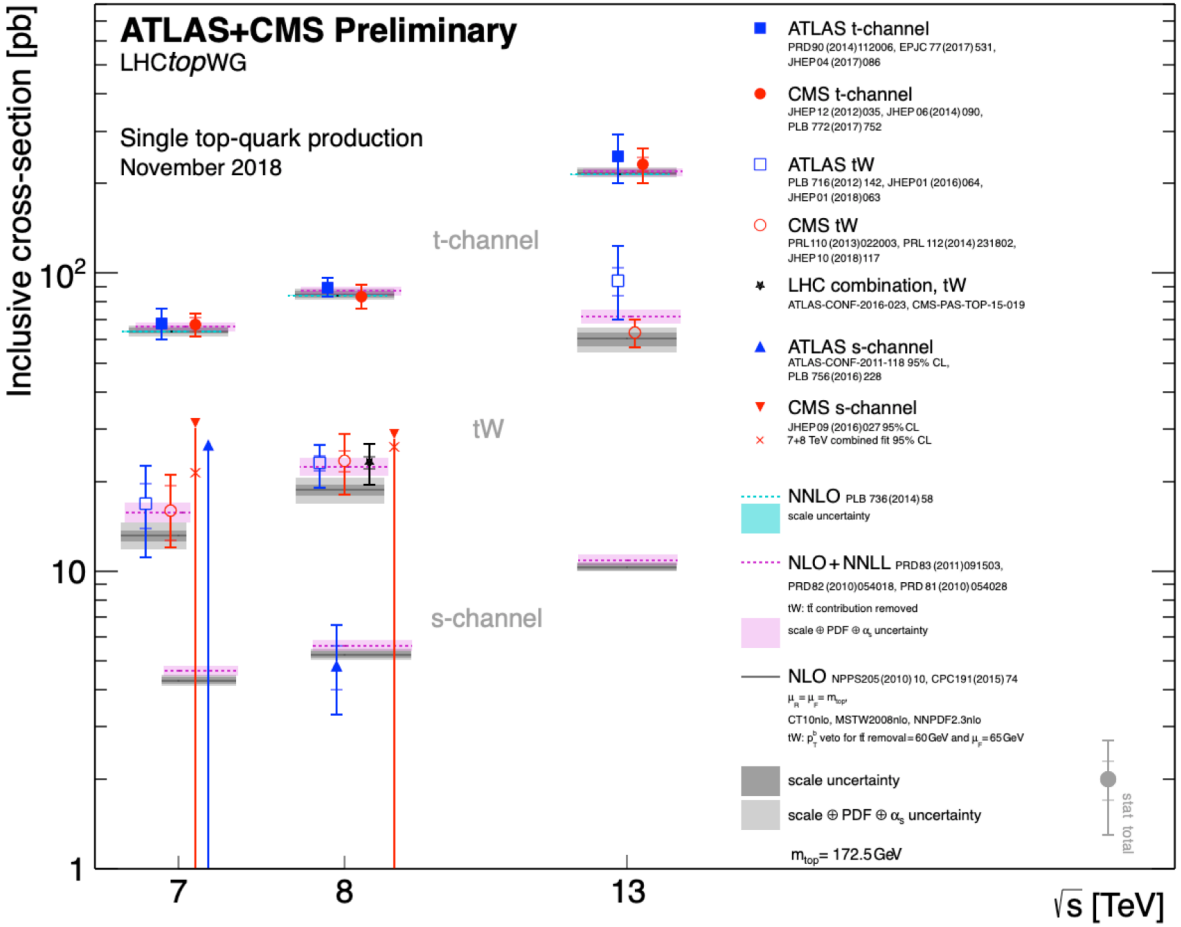


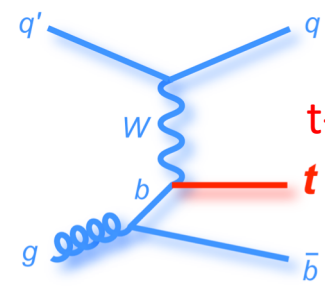
- Production via EWK interaction

  → smaller cross sections, large backgrounds

- Precise determination of |Vtb|, constrain PDFs, FCNC

Single top-quark production

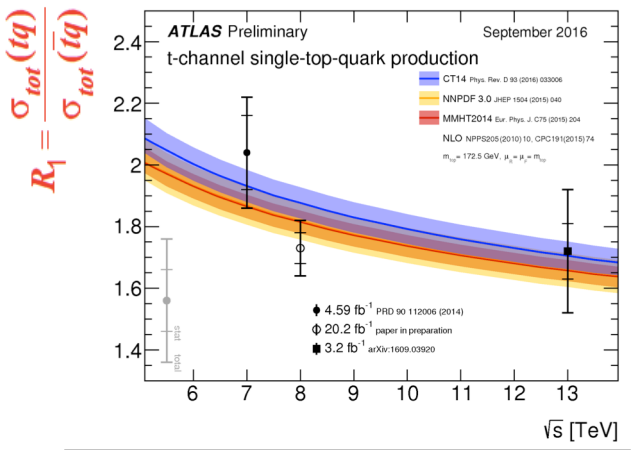




t-channnel

$\sigma(tq) = 136 \pm 1 \pm 22\,\text{pb}$

$\sigma(\bar{t}q) = 82 \pm 1 \pm 14\,\text{pb}$



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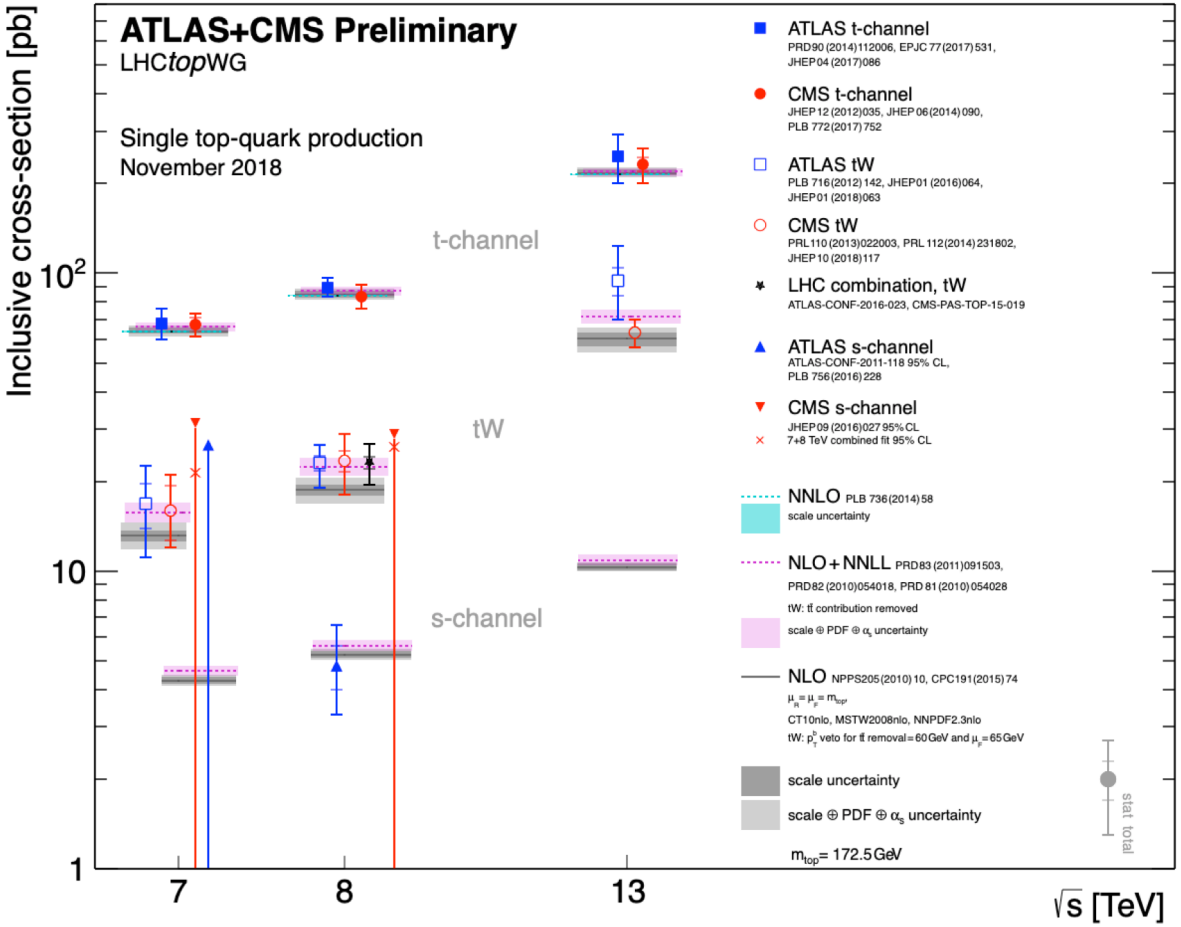

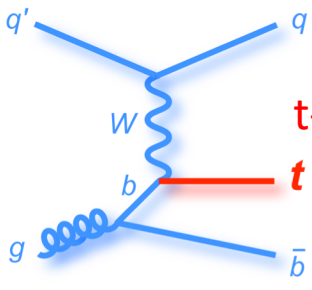

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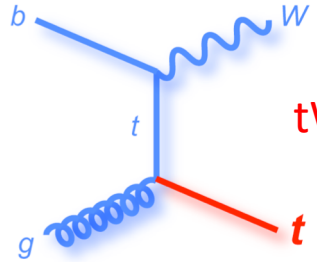

tW-channel

$\sigma(tW) = 63 \pm 2 \pm 7\,\mathrm{pb}$

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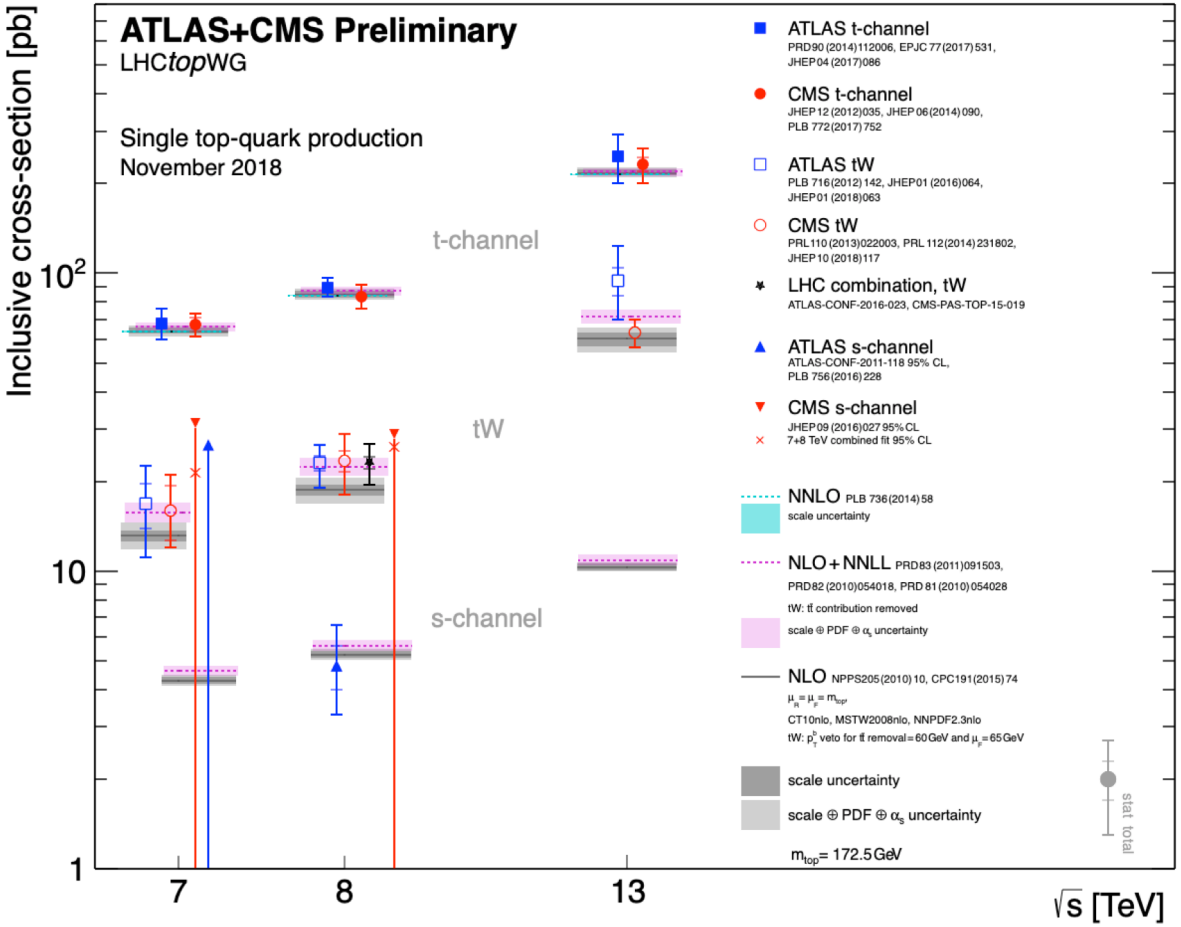
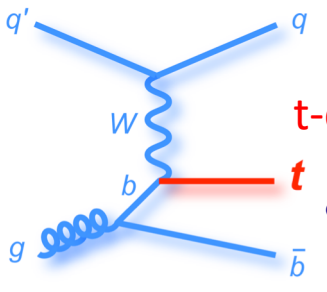
Single top-quark production





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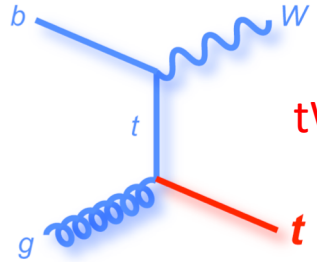

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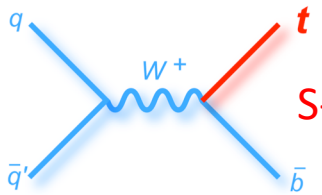


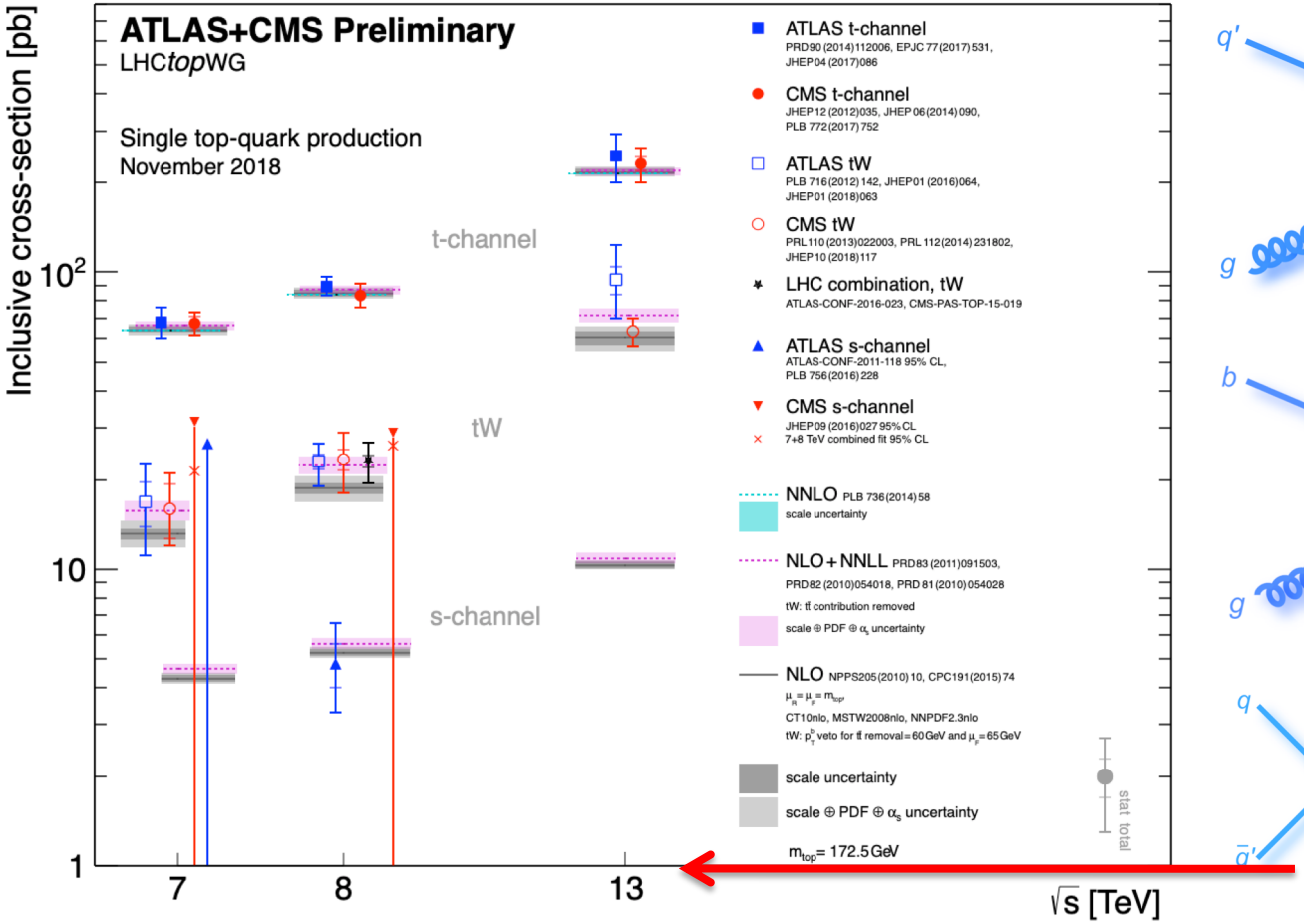
S-channel

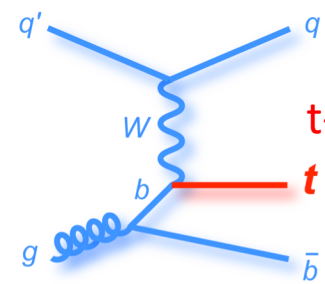
- Production via EWK interaction

  → smaller cross sections, large backgrounds

- Precise determination of |Vtb|, constrain PDFs, FCNC

Single top-quark production





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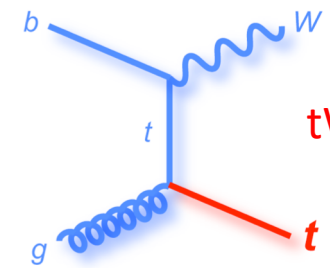

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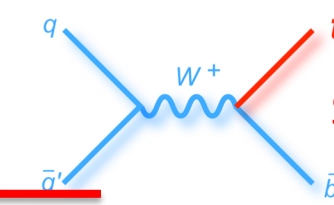
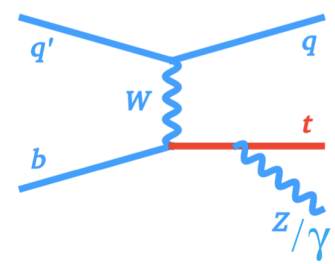


S-channel

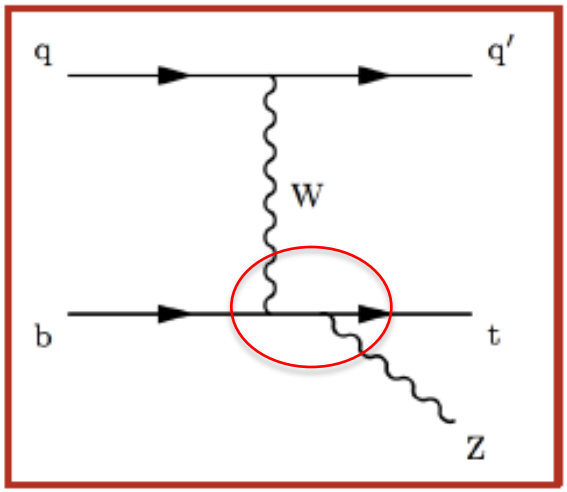
$\sigma(tZq) \sim 1\,\text{pb}$ **Rare!!!**

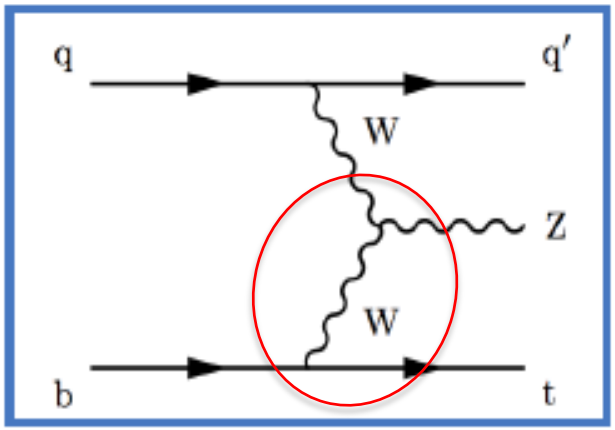
$\sigma(t\gamma q) \sim 3\,\text{pb}$

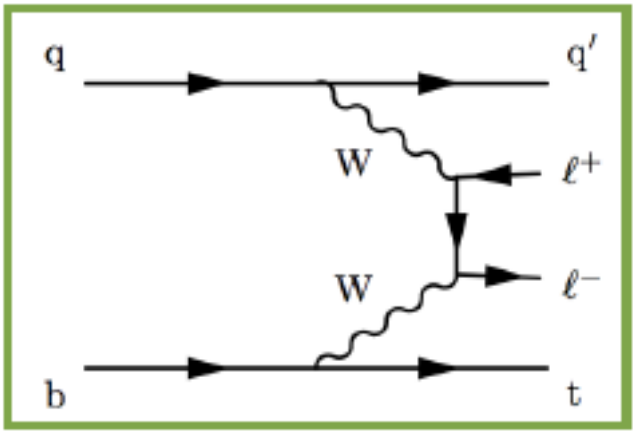


tZq

single-top + Z production



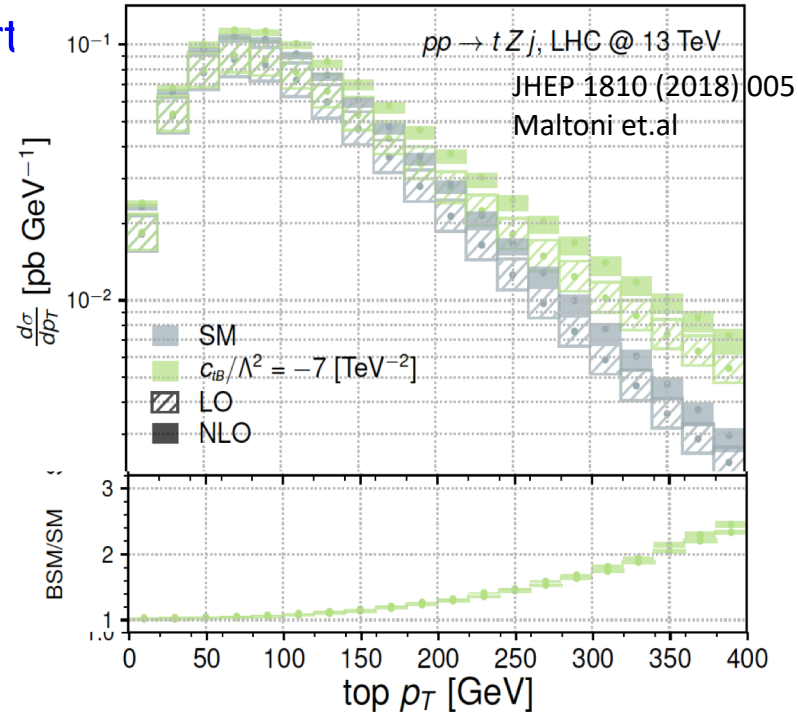




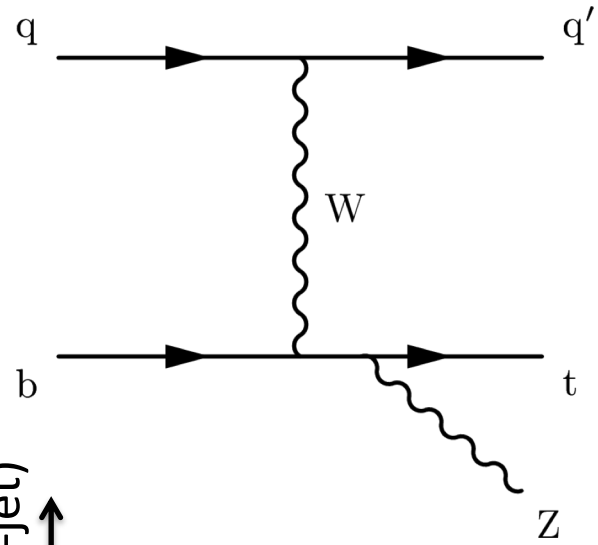
Top-Z coupling, complementary to ttZ

Sensitive to WWZ vert

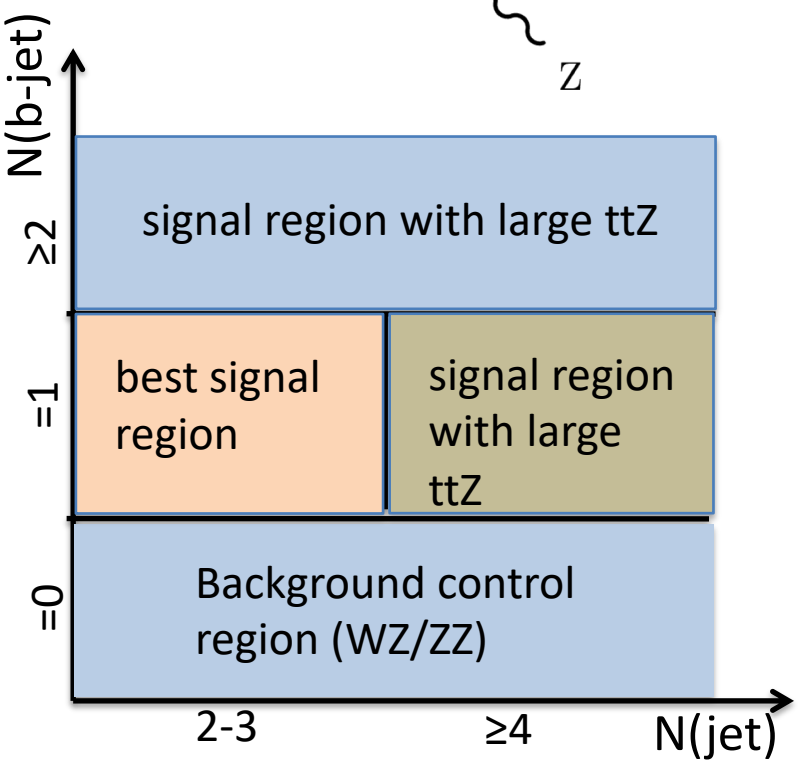
- Unique sensitivity to some EFT operators due to Wb→tZ vertex
- FCNC



single-top + Z production

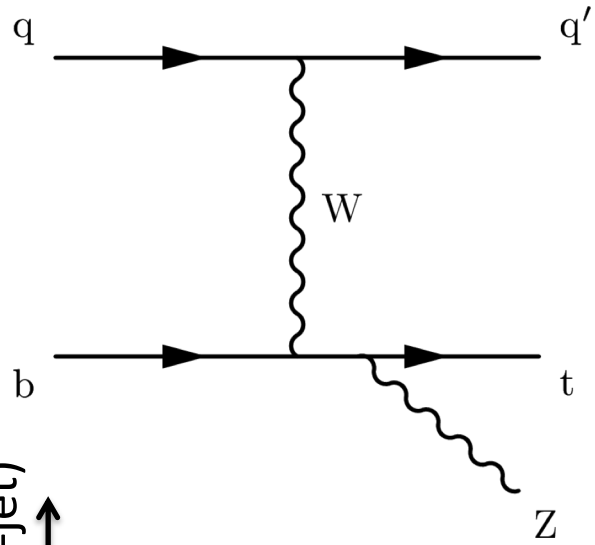


- 3 leptons
- $p_T(\ell) > 10,15,25$ GeV
- Z candidate $|m_{\ell\ell} - m_Z| < 15$ GeV
- At least two jets with $p_T > 25(60)$ GeV



single-top + Z production

Run II data



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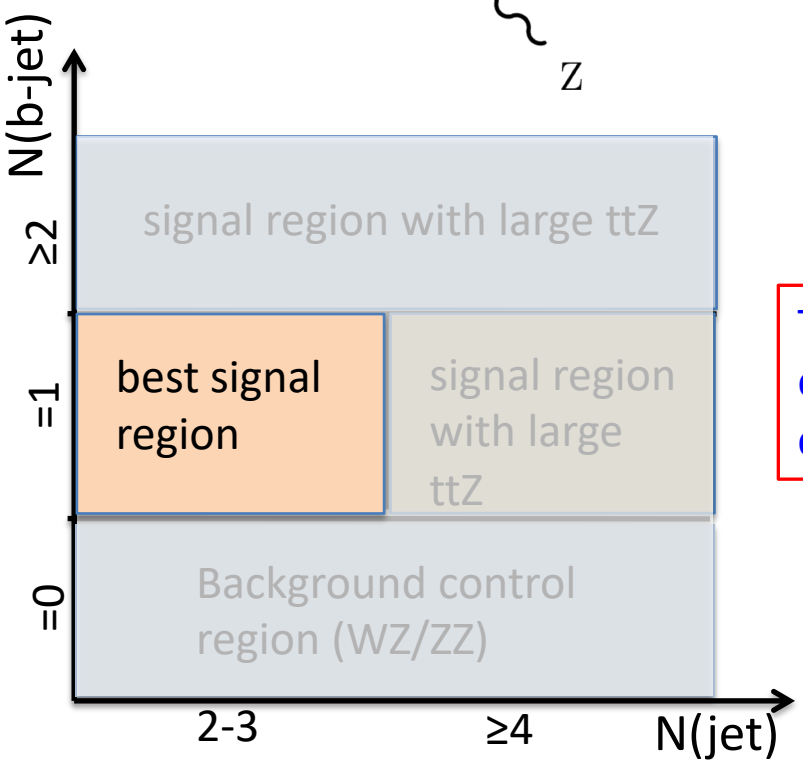
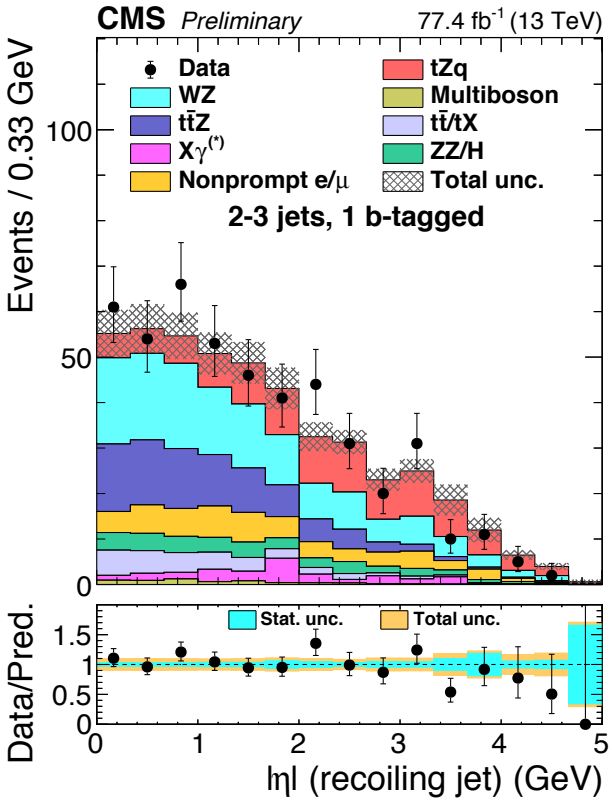
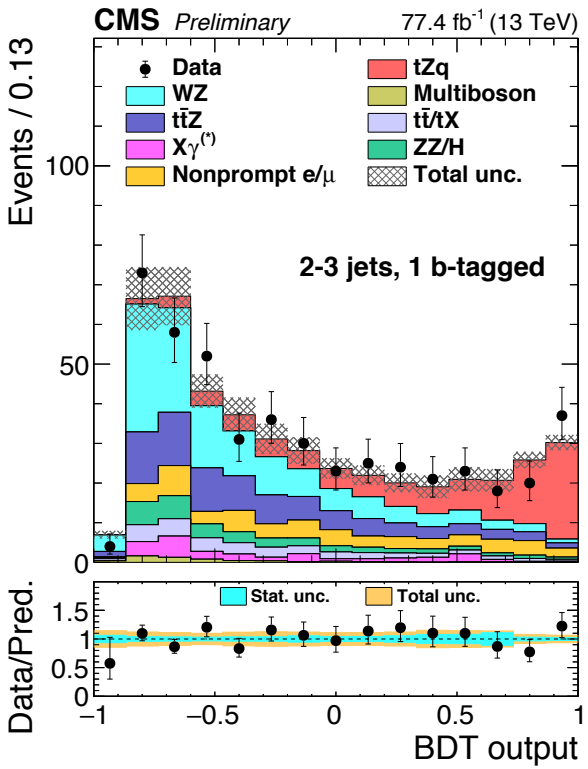


Train BDT in each signal category



single-top + Z production



- Binned ML fit to all signal & bkg. control regions

obs.(exp.) significance $8.2(7.7)\sigma$

First observation !

Measured cross section

$$\sigma(tZq \to t\ell^+\ell^-q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\,\text{fb}$$

15% precision

NLO SM prediction 94.2 ± 3.1 fb

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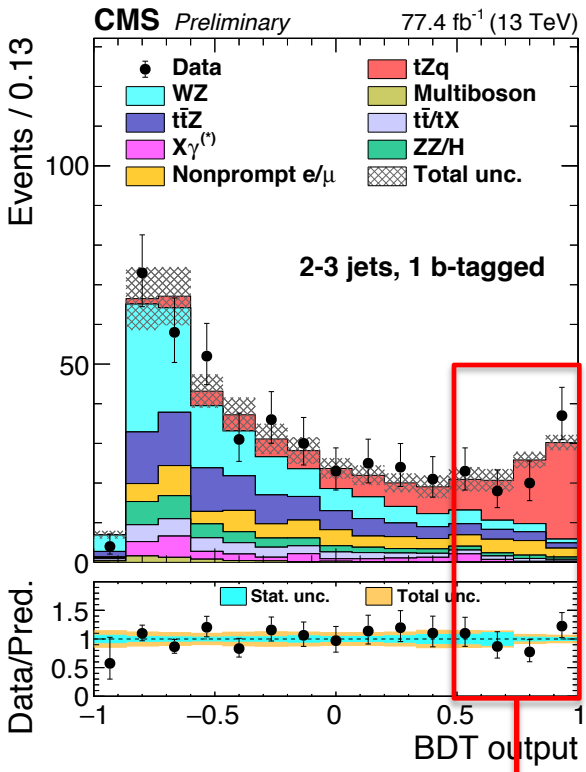
single-top + Z production



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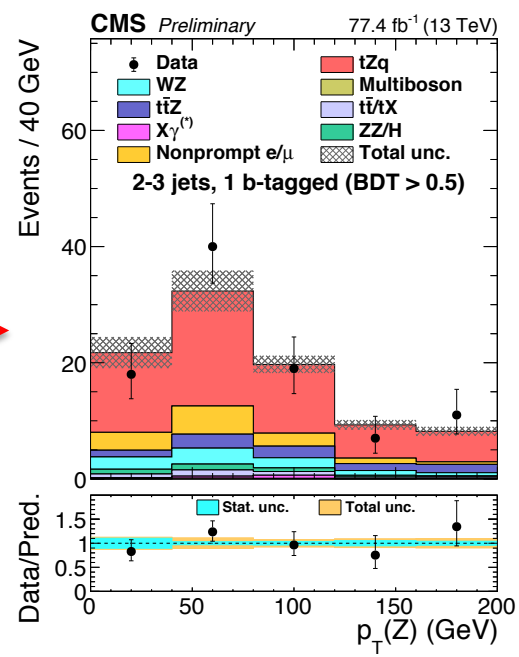
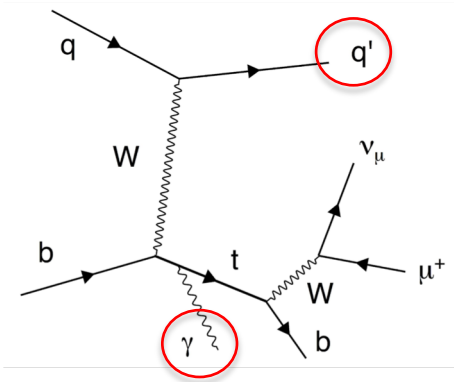


- Relatively pure signal sample → next the differential measurement!

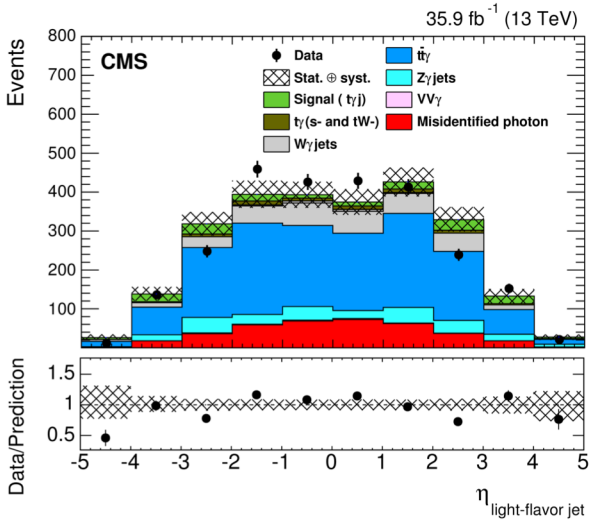
single-top + γ production

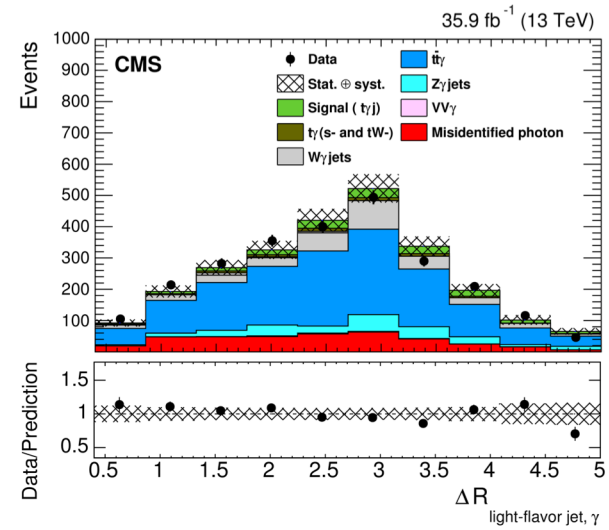
Run II data



- Sensitive to the top quark charge and the top quark electric and magnetic dipole moments
  - Single-muon, $p_T > 30$ GeV
  - Photon $p_T > 30$ GeV , 2 jets, 1 bjet

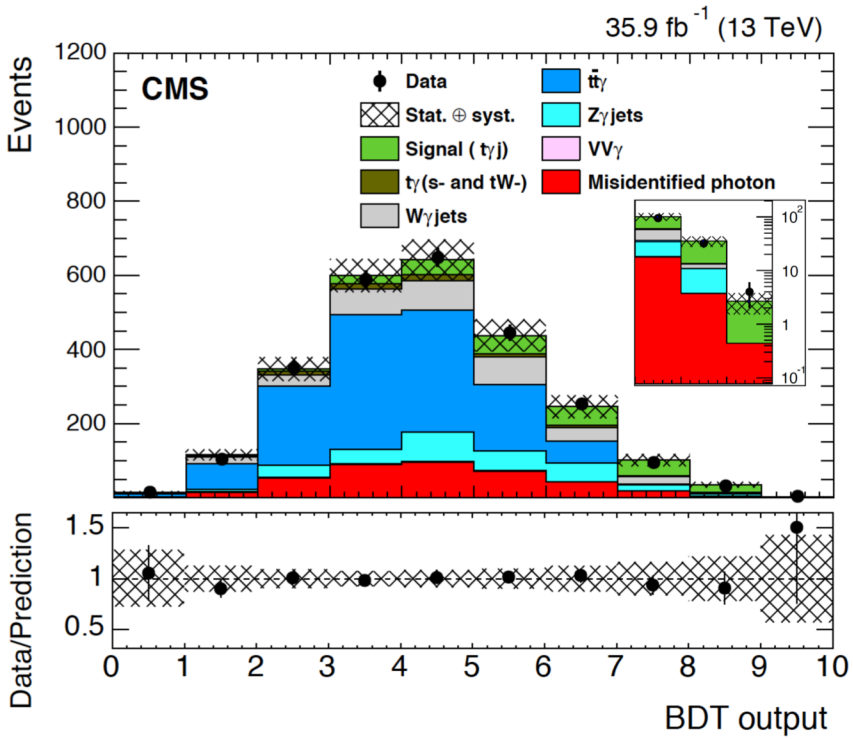
BDT to discriminate signal from backgrounds





- largest background from $t\bar{t}\gamma$, **template from 2 b-tag data**
- misidentified photons **predicted from data** by measuring jet misidentification rate as a function of p_T

single-top + γ production



Binned likelihood fit is performed to the BDT in the SR and the tt+γ CR

obs.(exp.) significance $4.4(3.0)\sigma$

First evidence !

Measured cross section in a fiducial region:

$$p_T(\gamma) > 25\text{GeV}, \quad |\eta(\gamma)| < 1.44, \quad \Delta R(X,\gamma) > 0.5$$

$$\sigma(t\gamma q) * BR(t \to \mu\nu b) = 115 \pm 17(stat) \pm 30(syst) \text{ fb}$$

30% precision

NLO SM prediction

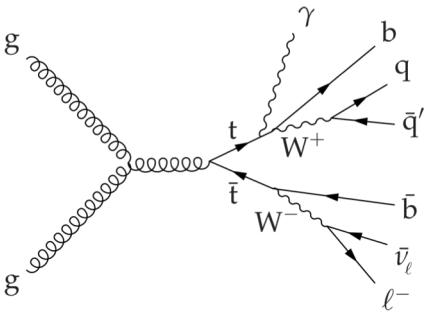
$\sigma_{t\gamma}$(NLO) = 81 ± 4(scale+PDF) fb

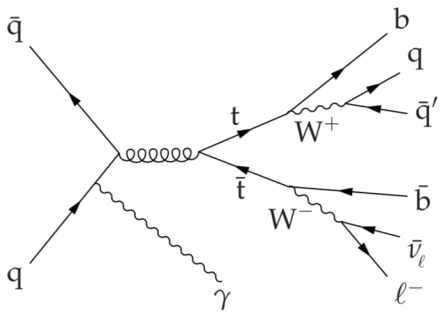
Summary & outlook

- tt+V measurements are becoming precise and challenge the theoretical precision
- First differential measurements of ttZ
- Observation of tZq and evidence for tγq
- EFT interpretations play more central role in using top events to look for new physics effects! → More systematic results to come

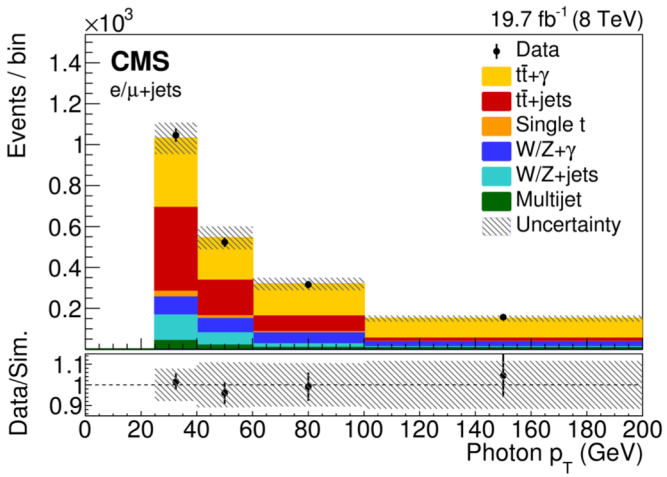
Backup

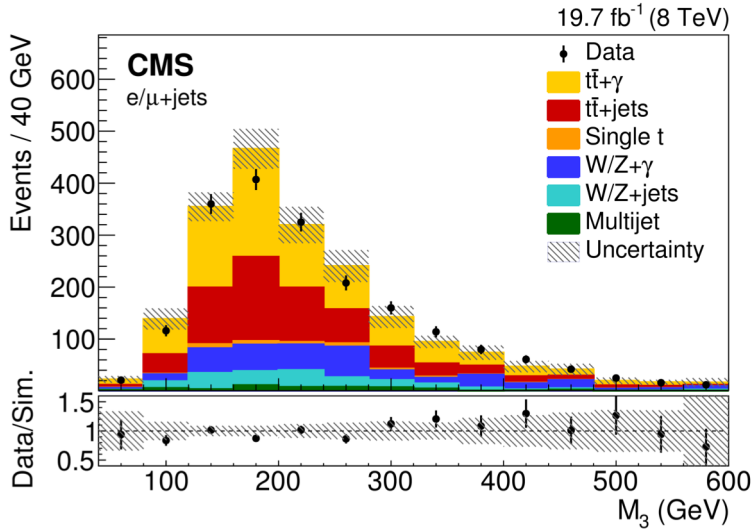
$t\bar{t} + \gamma$ production





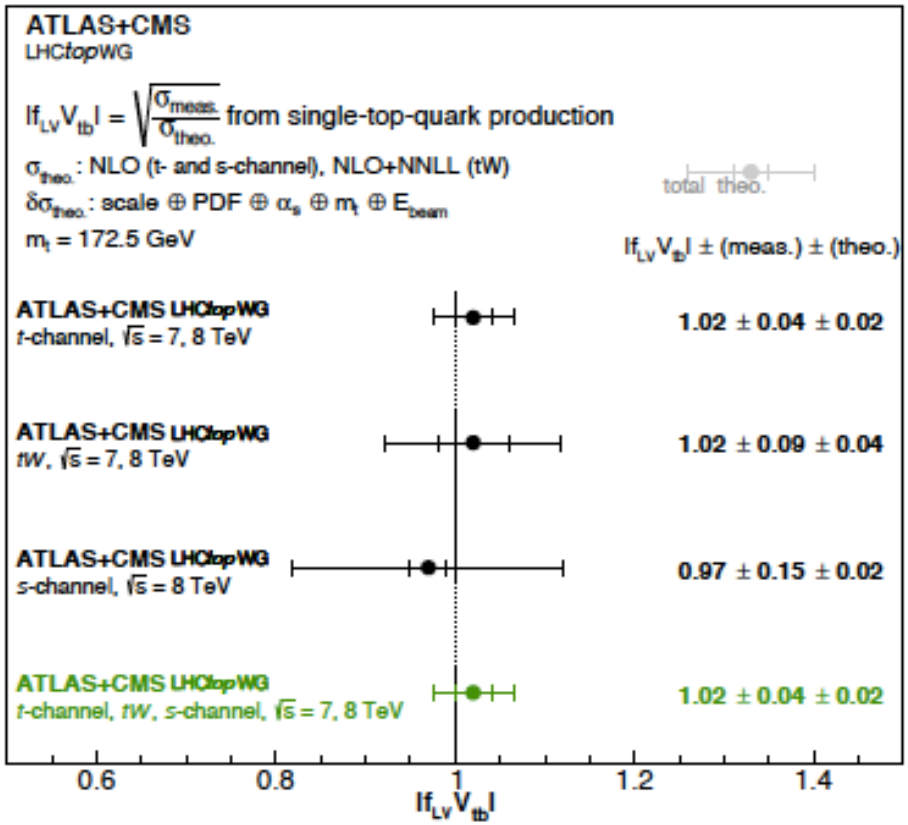
- Only one lepton ($p_T(e,\mu)$ > 35, 26 GeV), at least 3 jets (p_T > 30 GeV) one b-tagged, MET > 20 GeV and at least one photon (p_T > 25 GeV)

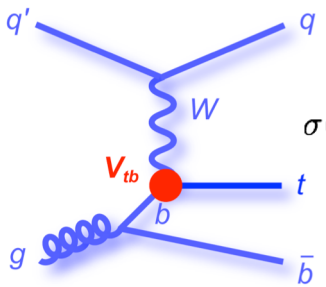




Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales) ± 30 (PDFs)

Vtb extraction





V_{tq} enter in production and decay vertices

$$\sigma(\mathrm{tj}+\bar{\mathrm{t}}\mathrm{j}) = \sum_{\mathrm{q=b,d,s}} \alpha_{\mathrm{tq}} \cdot |V_{\mathrm{tq}}|^2 \cdot \mathcal{B}(\mathrm{t} \to \mathrm{Wq})$$

Deviations from the SM are parameterized with f_{LV}

$$|f_{LV} \cdot V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{predicted}}}$$

Best measurement is obtained from 7 & 8 TeV combination with ~4% uncertainty

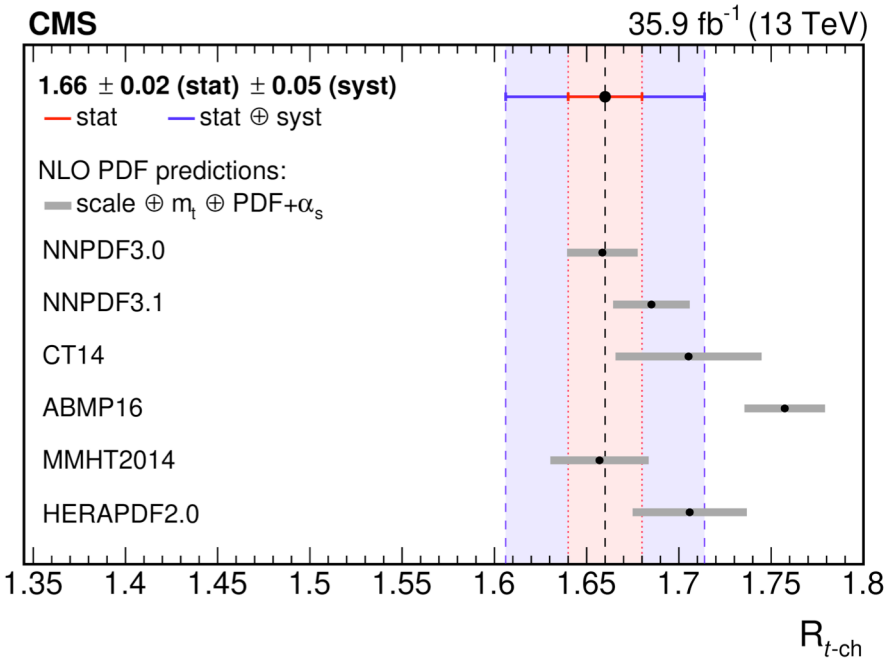
- Expect to improve with luminosity
- limited by theory (~3% at NNLO)

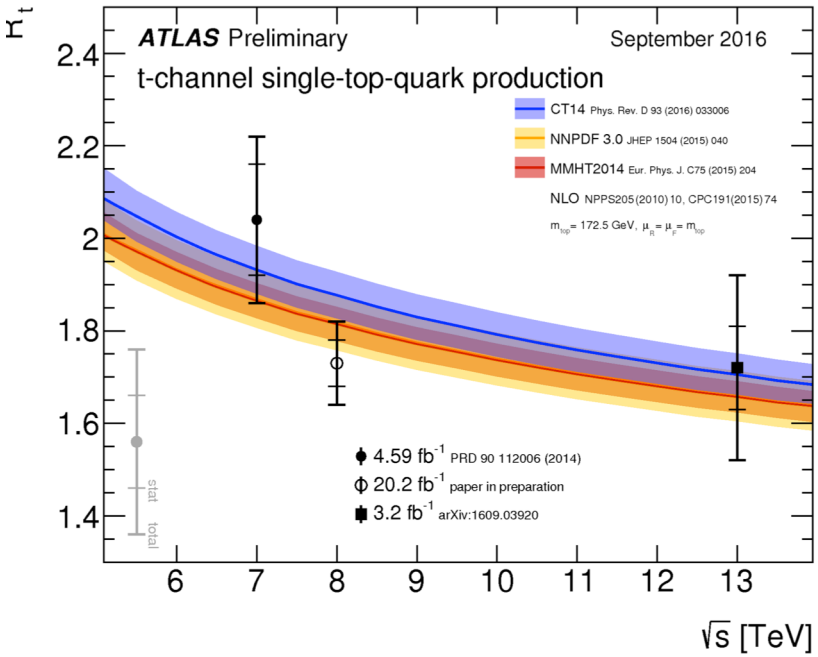
Single-top t-channel production

$$R_1 = \frac{\sigma_{tot}(tq)}{\sigma_{tot}(\bar{t}q)} = 1.66 \pm 0.02\ (\text{stat}) \pm 0.05\ (\text{syst})$$

- At higher $\sqrt{s}$, R_1 approaches 1 As "sea quarks" become important

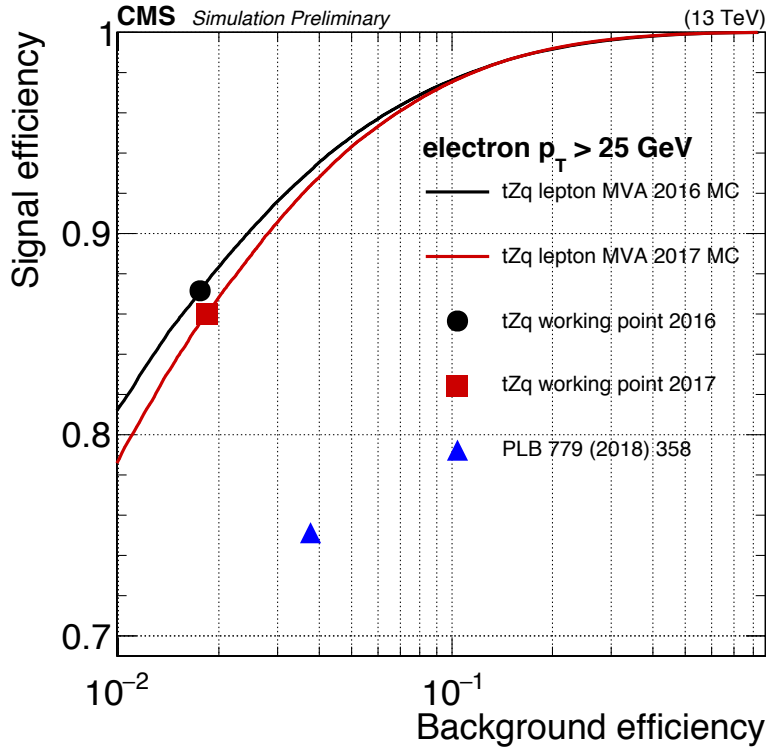
arXiv:1812.10514

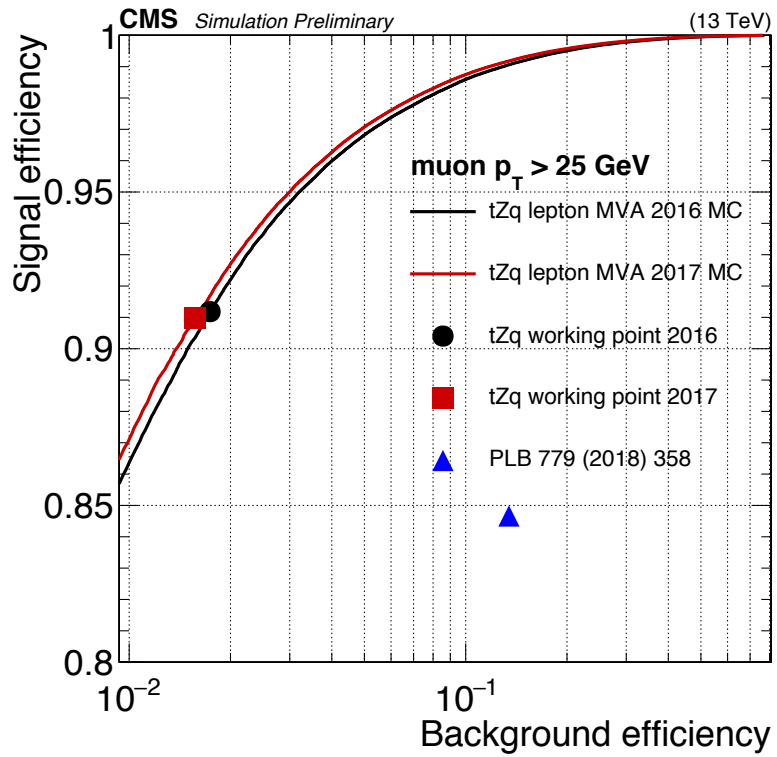




Lepton identification

- Dedicated lepton selection using MVA for this analysis
- Crucial for reducing backgrounds from nonprompt leptons
- Input variables: jets closest to lepton, impact parameters, isolation, lepton p_T, η, +usual identification variables

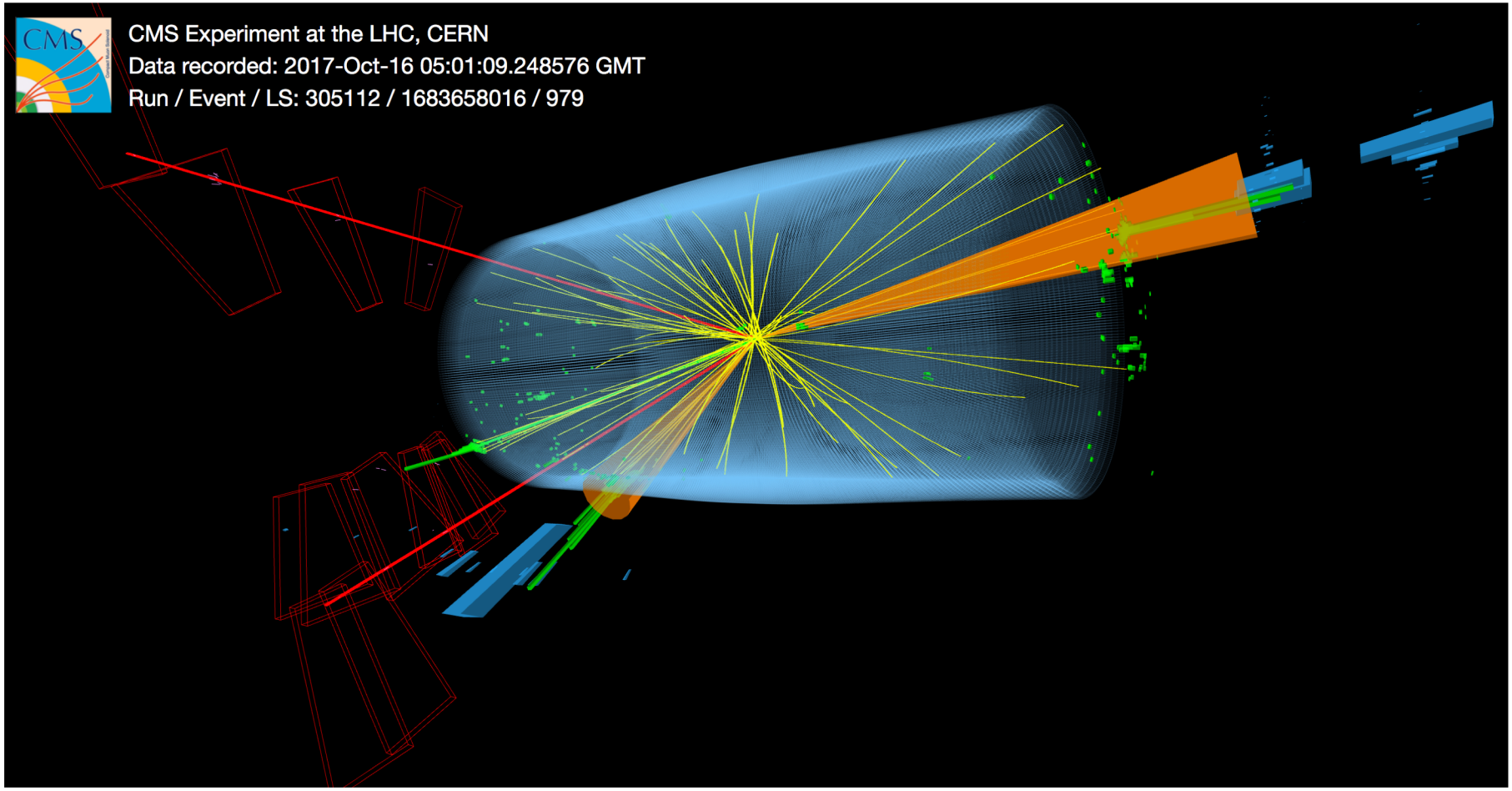




→ 8-12% gain per signal lepton efficiency

→ factor 2(8) reduction in nonprompt electron (muon) background

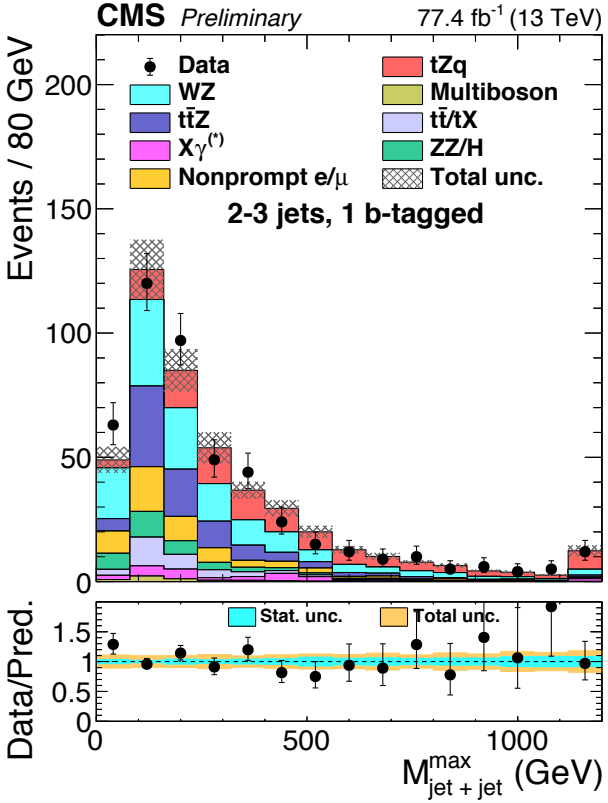
tZq event candidate

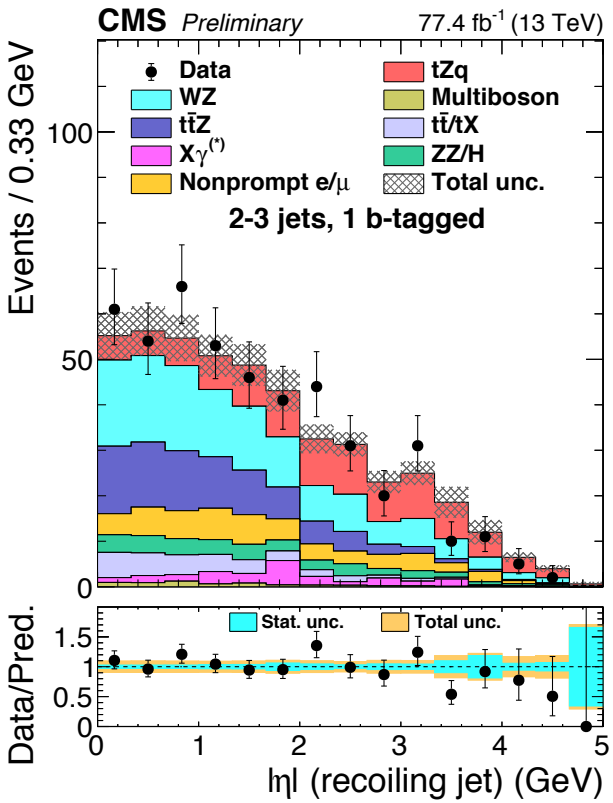


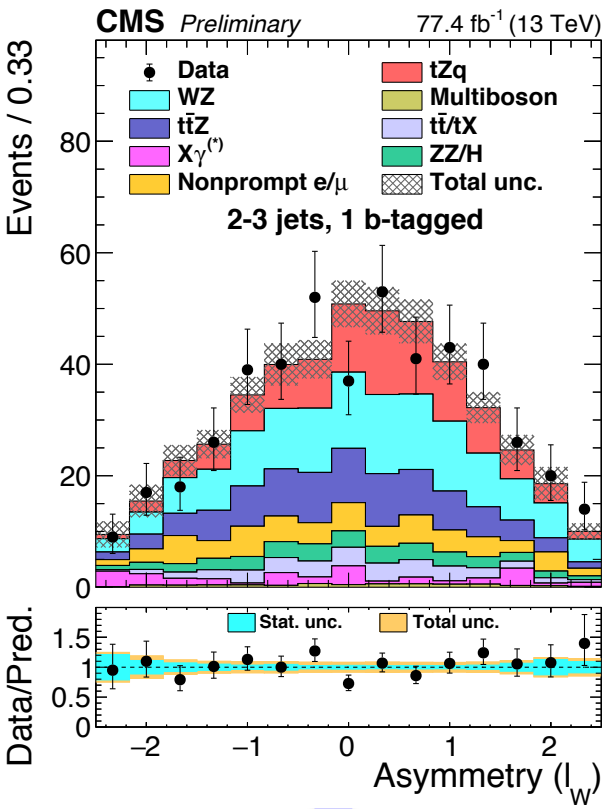
single-top + Z production

$N_{jets} = 2,3 \quad N_{bjets} = 1$

Most sensitive kinematic variables:







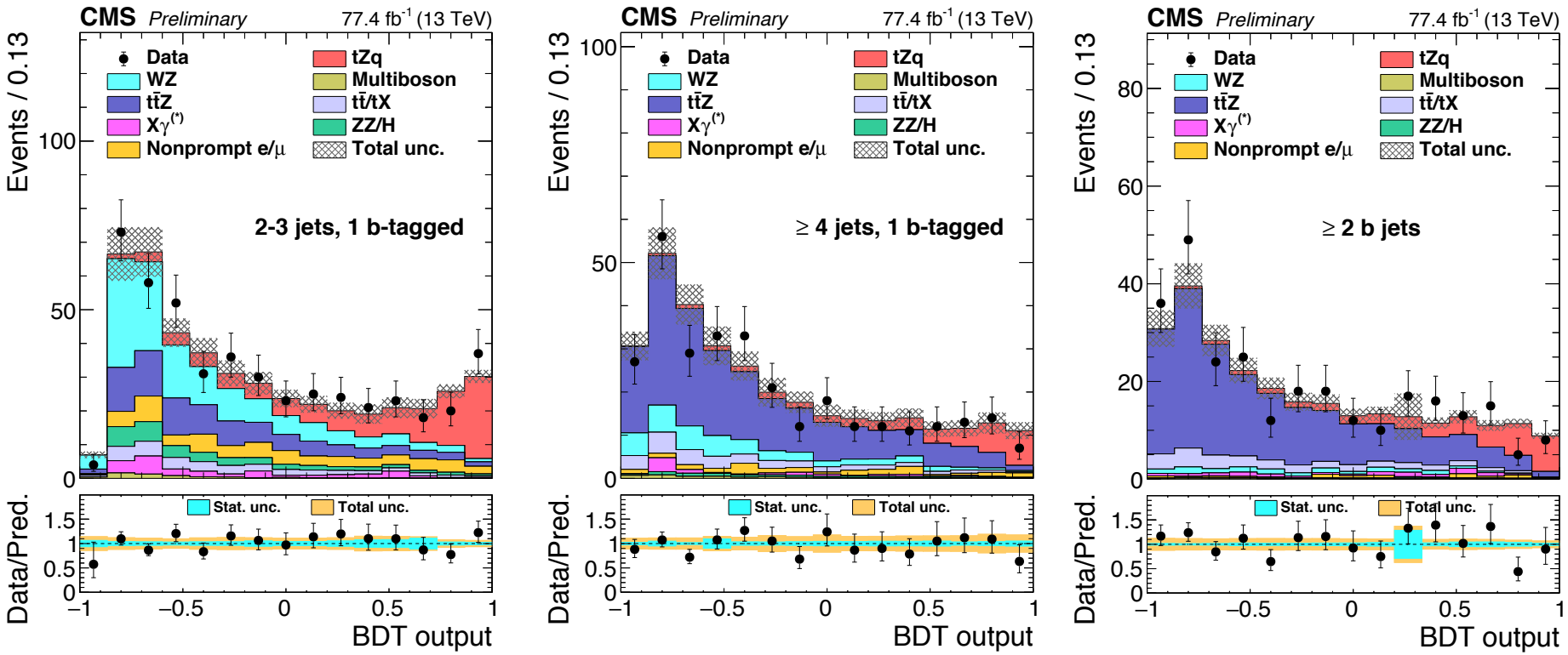
Maximum di-jet invariant mass

η of the jet recoiling top

$|\eta| \times \mathrm{charge}(\ell_W)$

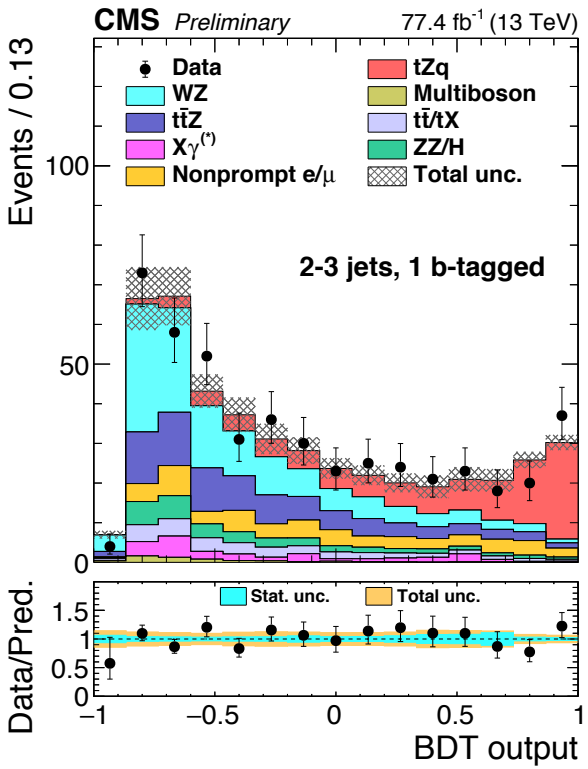
Main backgrounds: WZ, ttZ and nonprompt lepton

single-top + Z production



- Binned maximum-likelihood fit to all three distributions & WZ and ZZ control regions
- Nuisance parameters for normalization and shape uncertainties
- Good agreement between prediction and observed data

single-top + Z production



- Binned maximum-likelihood fit to all three distributions & WZ and ZZ control regions

$$\mu = 1.36^{+0.22}_{-0.20}(\text{stat})\,^{+0.14}_{-0.12}(\text{sys})$$ 2016 data

$$\mu = 1.03^{+0.18}_{-0.17}(\text{stat})\,^{+0.14}_{-0.12}(\text{sys})$$ 2017 data

$$\mu = 1.18^{+0.14}_{-0.13}(\text{stat})\,^{+0.11}_{-0.10}(\text{sys})$$

observed(expected) significance $8.2(7.7)\sigma$

Asymptotic CLs approach

First observation of tZq process !

Measured cross section

$$\sigma(tZq \to t\ell^+\ell^- q) = 111 \pm 13(stat)\,^{+11}_{-9}(syst)\ \text{fb}$$

NLO SM prediction

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$$94.2 \pm 3.1\ \text{fb}$$

15% precision

single-top + Z production

Measured cross section

$$\sigma(tZq \to t\ell^+\ell^-q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\,\text{fb}$$

15% precision

Source	impact (±%)
Nonprompt bkg.	4.1
Lepton selection	3.2
Jet Energy Scale 2016(2017)	0.9(3.1)
Parton Shower Mod.	2
QCD Scale choice (tZq)	2
Pile Up	1.9
QCD Scale choice (ttZ)	1.4

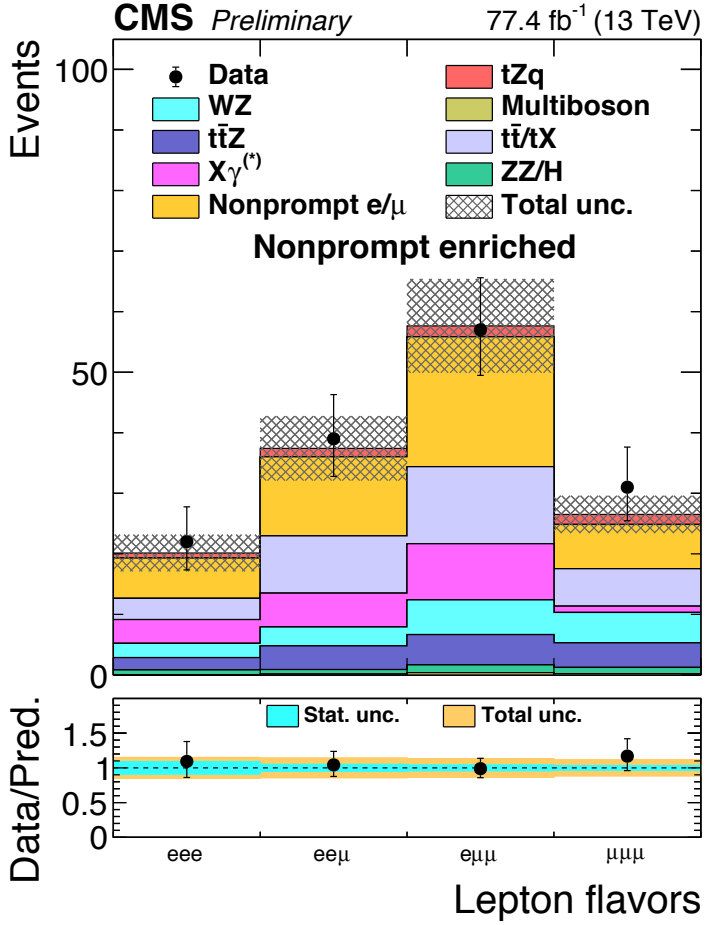
- Several improvements in the analysis paid off
- In particular nonprompt lepton background reduction
- Still statistical uncertainties dominate

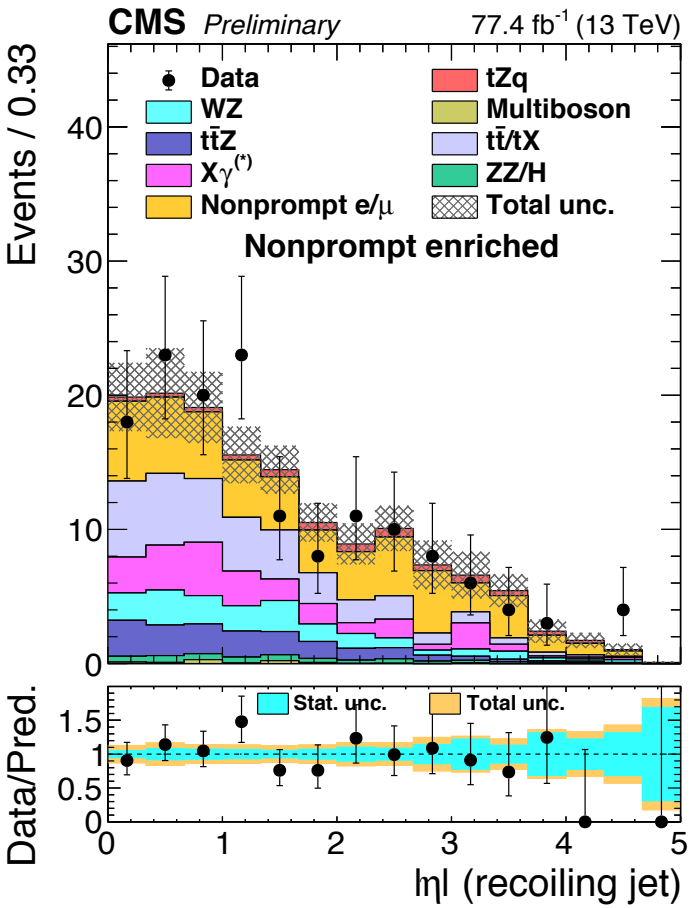
Ttgamma systematics

Source	Uncertainty (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7
ME/PS matching threshold	3.9
Photon energy scale	2.4
JER	2.3
Multijet estimate	2.0
Electron misid. rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top quark p_T reweighting	0.4
b tagging scale factor	0.3
Muon efficiency	0.3
Electron efficiency	0.1
PDFs	0.1
Muon energy scale	0.1
Electron energy scale	0.1
Total	20.7

Nonprompt lepton bkg. validation

No OSSF pair or $m(\ell\ell)$ outside Z mass window





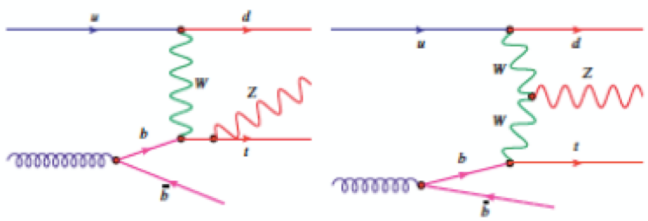
- Low statistics -> powerful lepton selection
- 30% systematic uncertainty + stat uncertainty in the control region

Lidia Dell'Asta
TOPWG November 2017

Signal samples & theory cross section

ATLAS

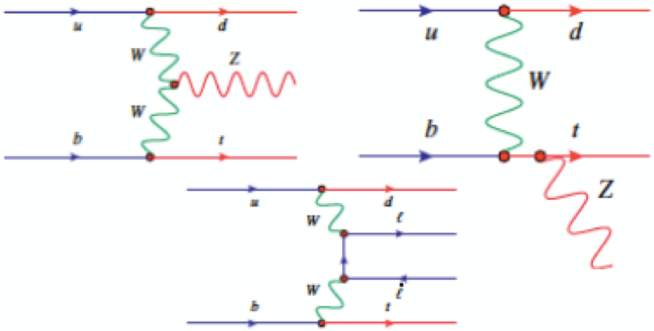
- Signal MC: LO rescaled to NLO.
- Theory cross section:
  - Z boson is forced to be on shell,
  - no cuts are applied,
  - 4-flavour scheme.
- $\sigma_{NLO}(tZq)$ = 800 fb
  - ±6/7% scale



- Tau leptonic decays included.
- Different scale choice between ATLAS and CMS.
- Theory paper https://arxiv.org/abs/1302.3856
  - $\sigma_{NLO}(tZq)$ ~ 820 fb.

CMS

- Signal MC: NLO.
- Theory cross section:
  - Z boson can be off shell/γ* is also included,
  - m_{ll} > 30 GeV,
  - 5-flavour scheme (4FS for MC generation).
- $\sigma_{NLO}(tllq)$ = 94 fb
  - ±2% scale
  - ±2.5% PDF



BDT discriminator

Signal& Background discriminating variables

- Maximum di-jet invariant mass
- η of the jet recoiling top
- $|\eta| \times \mathrm{charge}(\ell_W)$
- highest btag discriminator
- $\max \Delta\phi(\ell\ell)$
- $\min \Delta R(\mathrm{jet}, \ell_W)$
- $\max p_T(\mathrm{jet}, \mathrm{jet})$
- $\mathrm{m}(\ell\ell\ell)$, m_T, H_T, N_{jets}, ...

- 6 BDTs in total: 3 for each category and separate for 2016/2017 data
- Training against the sum of all backgrounds
- Good discrimination power in all categories