Studies of $t\bar{t}$+X at CMS

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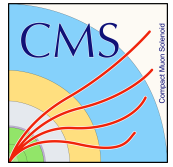
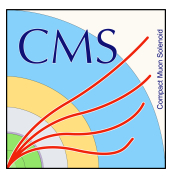
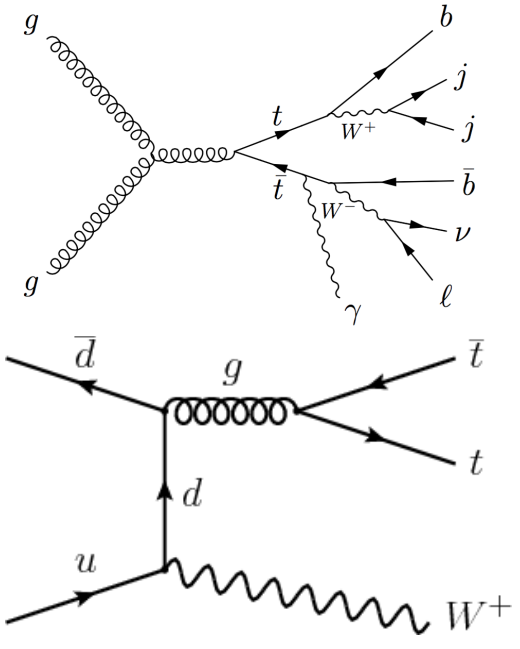


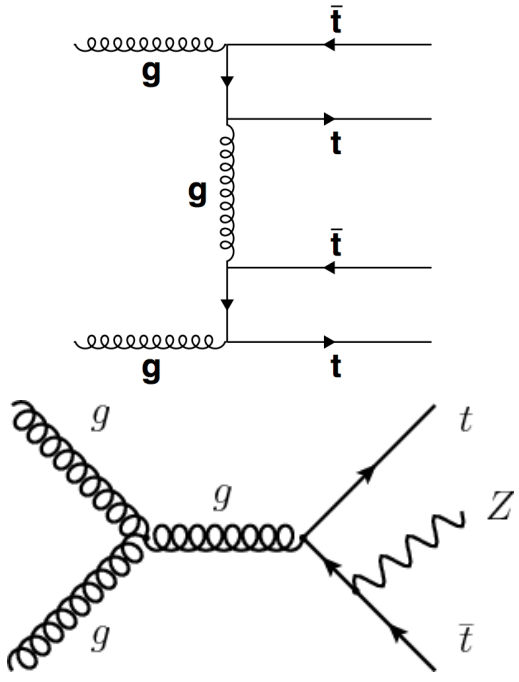
Overview

- Introduction and experimental status of $t\bar{t}t\bar{t}$, $t\bar{t}bb$, $t\bar{t}\gamma$, $t\bar{t}W$ and $t\bar{t}Z$ processes.
- Search for standard model four top-quark production at 13 TeV (2.3 fb^{-1}), Submitted to PLB (1702.06164) + (NEW) SUSY SS 2ℓ (1704.07323)
- Measurement of ttbb production at 13 TeV (2.3 fb^{-1}), to be submitted to PLB (CMS-TOP-16-010)
- Measurement of the ttγ production cross section at 8 TeV (19.7 fb^{-1}) (CMS-PAS-TOP-14-008)
- (NEW) Measurement of the top pair-production in association with a W or Z boson in pp collisions at 13 TeV (35.9 fb^{-1}) (CMS-PAS-TOP-17-005)



Introduction

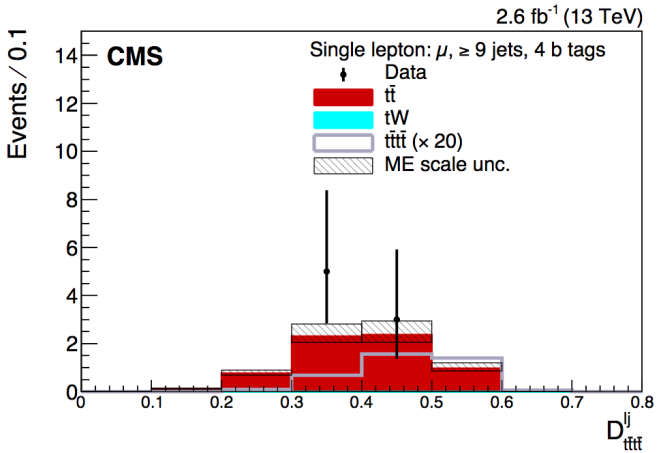


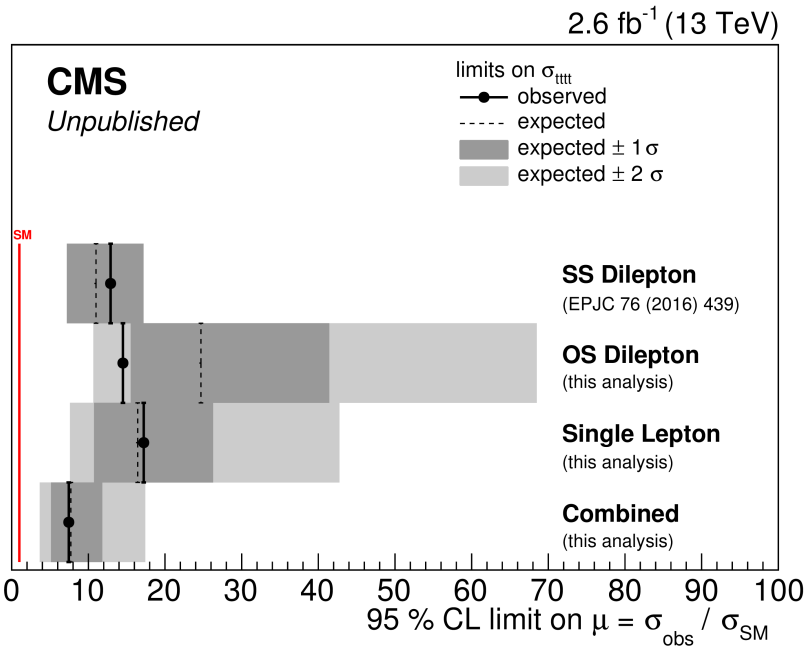


- The observed yields and measured cross-sections could be altered by new physics, the main background for $t\bar{t}H$ and for BSM processes
- Strength of the electromagnetic coupling of top quark and γ and top quark and Z boson can be probed
- The $t\bar{t}t\bar{t}$ measurement provide a useful test of analytical higher order calculation of QCD

Search for $t\bar{t}t\bar{t}$

- Selection: 1 or 2 leptons, high hadron activity
- The discrimination power is provided by number of top and b quarks, event activity and topology
- Highest systematics uncertainty comes from variation of QCD scale choice at ME
- No deviation from background-only is expected and observed the limits on cross-section are set

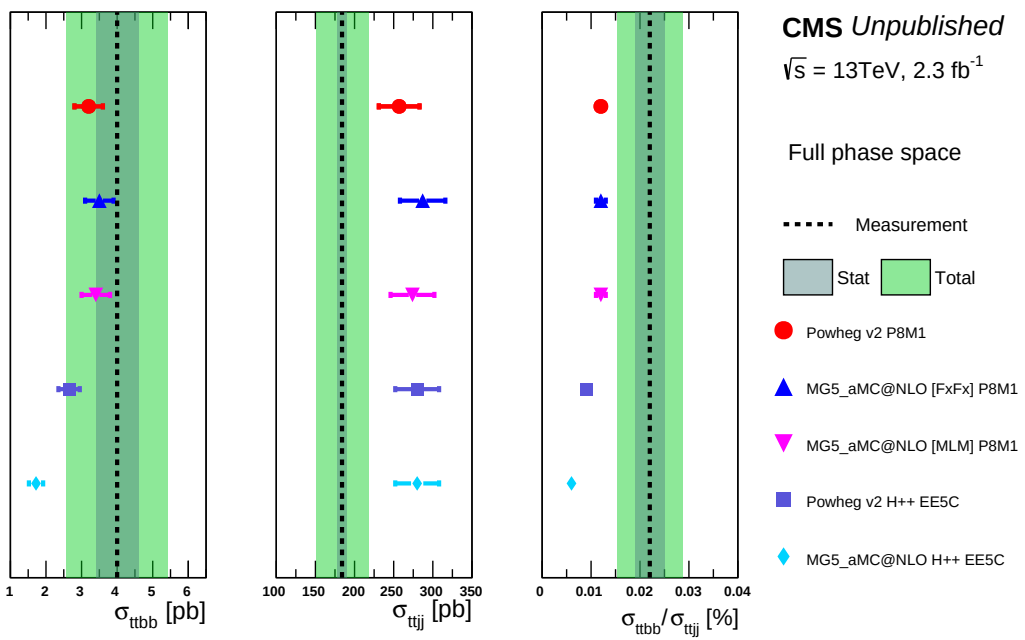


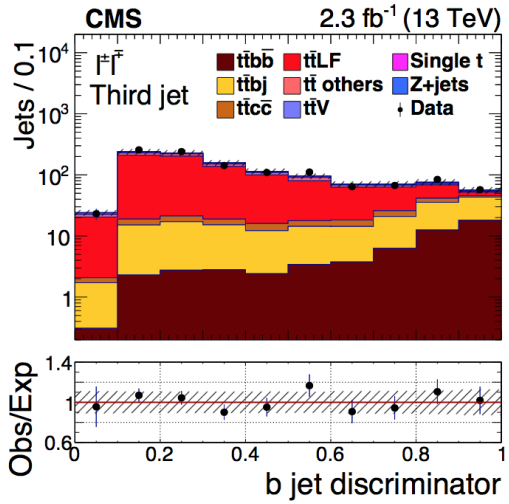


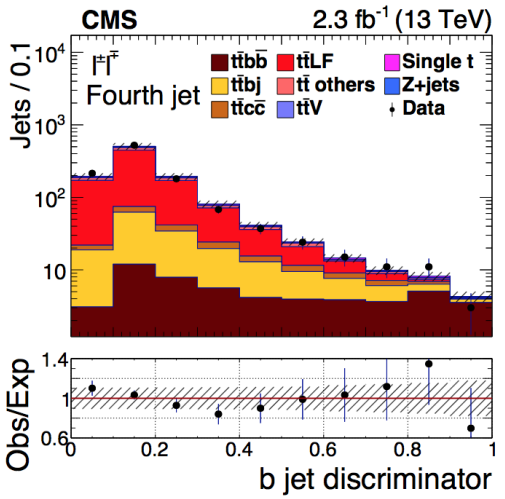
- NEW! SUSY same charge 2ℓ (1704.07323) with 35.9 / fb
- Observed (Expected) limit is $4.6\ (2.9^{+1.4}_{-0.9}) \times \sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}t\bar{t}}}$
- With new data still a place to improve! Stay tuned!

New! $t\bar{t}bb$ / $t\bar{t}jj$ ratio measurement

- Selection: exactly 2 OS leptons, at least 4 jets (at least 2 b jet)
- The leading and sub-leading in the b-tag discriminator value jet corresponds to the b jet from top in 85% cases
- The b tagging discriminator for 3rd and 4th jets are used to separate $t\bar{t}bb$ from other processes and for the fit
- Main uncertainties: JES & JER, b tagging, the choice of MC generator and scale in parton shower

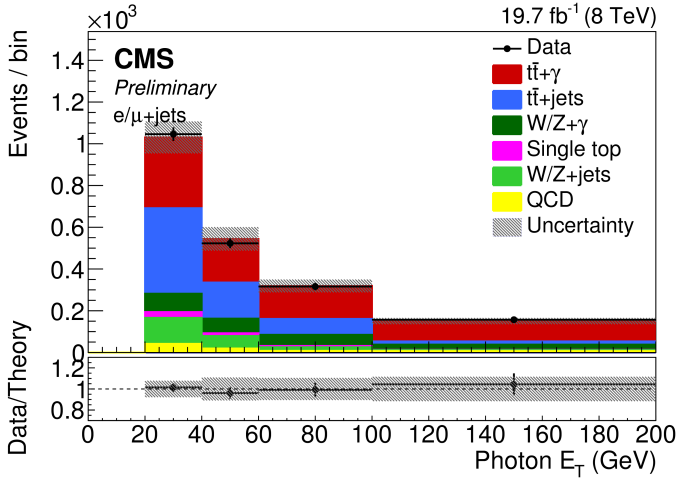






$t\bar{t}\gamma$ cross section measurement

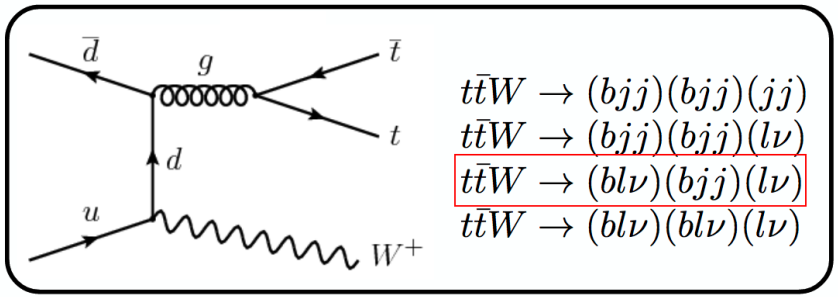
- Measure $t\bar{t}\gamma$ cross-section relative to the $t\bar{t}$ cross section
- Selection: exactly 1 lepton, at least 3 jets (1 b jet) and 1 photon
- Two categories of background:
  - Top events with fake photon ($t\bar{t}$)
  - Non-top events with real photon (Wγ, Zγ)

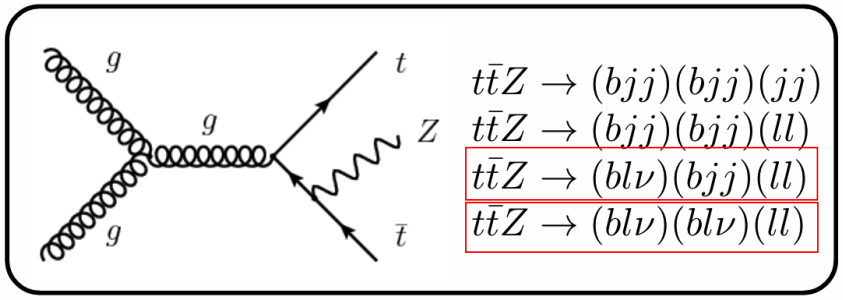


- Measure the **top quark purity** after top quark and photon selection using a fit in an invariant mass of three jets with highest $\mathrm{p_T}$ (M3)
- Measure the **photon purity** using a fit to the photon charged hadron isolation, separates real photon events from other backgrounds (data-driven approach)
- Apply likelihood fit to the **top quark purity, photon purity and number of top quark events** simultaneously to extract number of $t\bar{t}\gamma$ events

Category	R	$\sigma^{\mathrm{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma} \times \mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	139 ± 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	-	-	$592 \pm 71(\mathrm{scale}) \pm 30(\mathrm{PDF})$

New! ttV: strategy and event selection





$t\bar{t}W$, SS2ℓ

- 2 same-sign leptons
- $p_T > 40, 25(27)$GeV
- veto 3rd lepton
- at least 2 jets, 1 b-tag jet
- BDT analysis

$t\bar{t}Z$, 3ℓ

- 3 leptons
- $p_T >$ 40, 20, 10 GeV
- at least 2 jets
- $|m_{\ell\ell} - M_Z| <$ 10 GeV
- C&C analysis

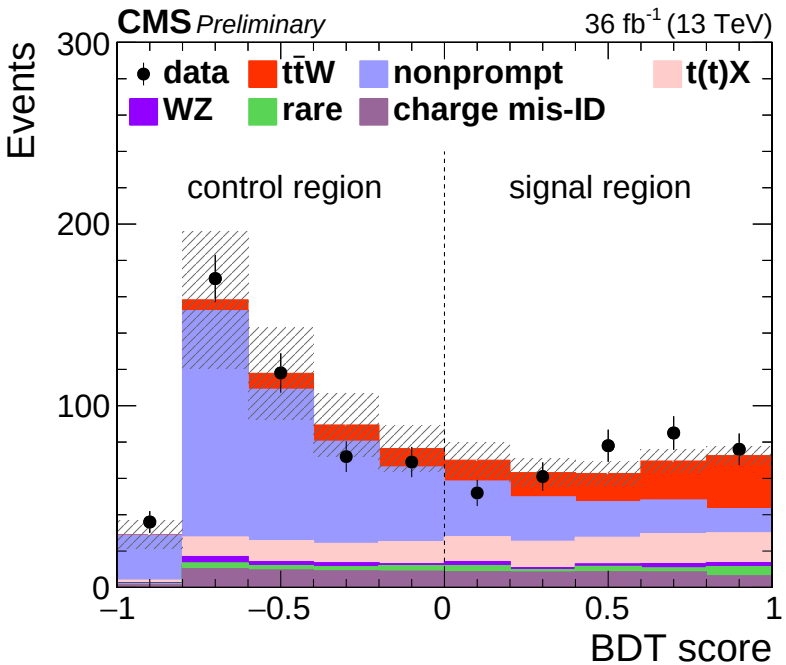
$t\bar{t}Z$, 4ℓ

- 3 leptons
- $p_T >$ 40, 10, 10, 10 GeV
- Sum of charges = 0
- at least 2 jets
- $|m_{\ell\ell} - M_Z| <$ 20 GeV
- C&C analysis

- To maximise significance the number of jets and b-tagged jets are used to form signal regions

ttV: $t\bar{t}W$ in SS 2ℓ

- For $t\bar{t}W$ in same-sign dilepton channel BDT analysis was developed
- BDT input:
  - Number of jets; number of medium b-tagged jets; the sum of p_T of the jets
  - Leading and trailing lepton p_T, transverse invariant mass of both leptons
  - Leading and subleading jet p_T, missing transverse energy
  - ΔR between the trailing lepton and the nearest selected jet



Event selection

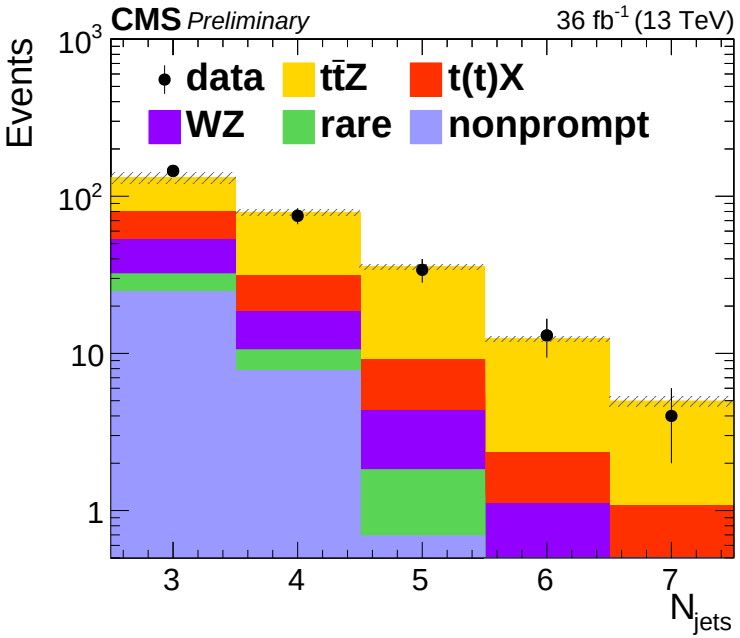
- BDT > 0
- Further split in number of jets, b-tag jets
- Split in $++$ and $--$

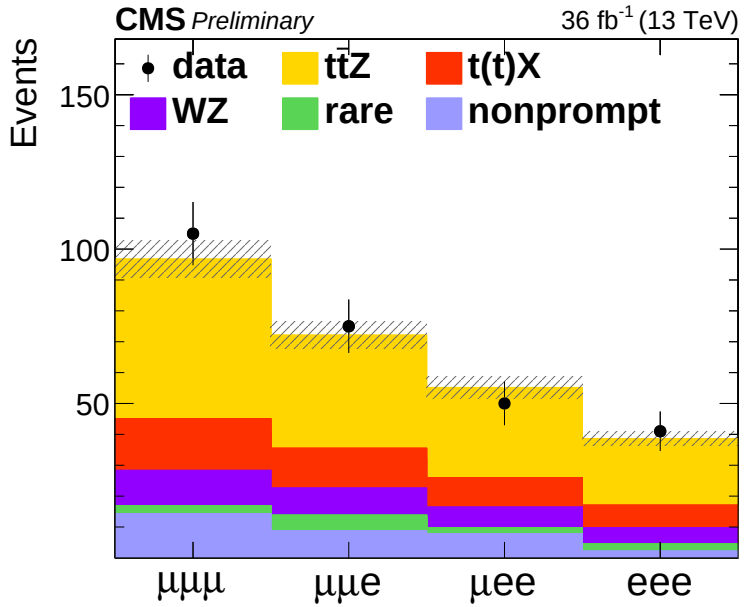
Backgrounds

- misidentified leptons, $t\bar{t}$
- $t\bar{t}Z$ and $t\bar{t}H$

ttV: $t\bar{t}Z$ in 3ℓ and 4ℓ

3ℓ channel in enriched $t\bar{t}Z$ region: $\geq$ 3 jets, $\geq$ 1 b jet





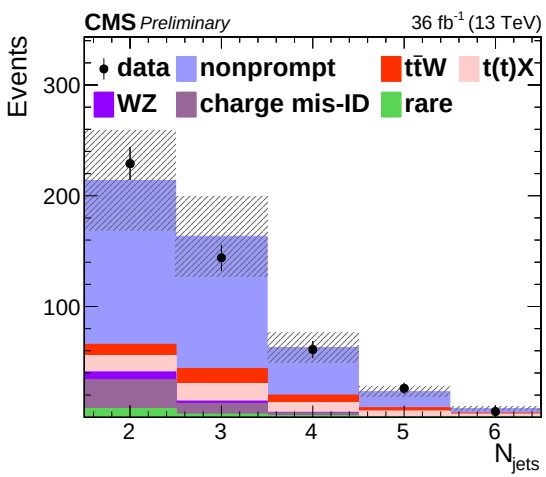
Main backgrounds:

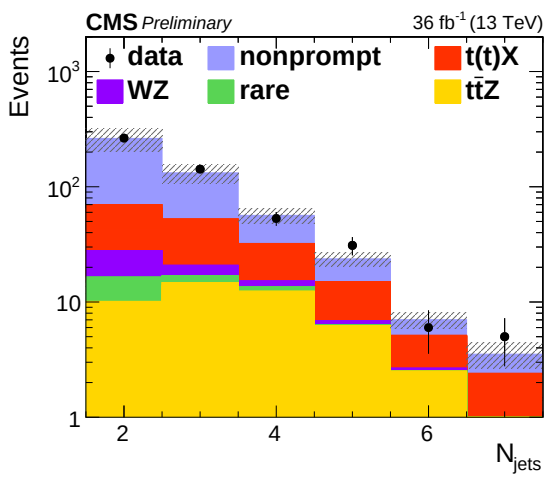
- nonprompt, WZ and t(t)X (tZq, tWZ, ttH) is relevant for 3ℓ
- ZZ for 4ℓ

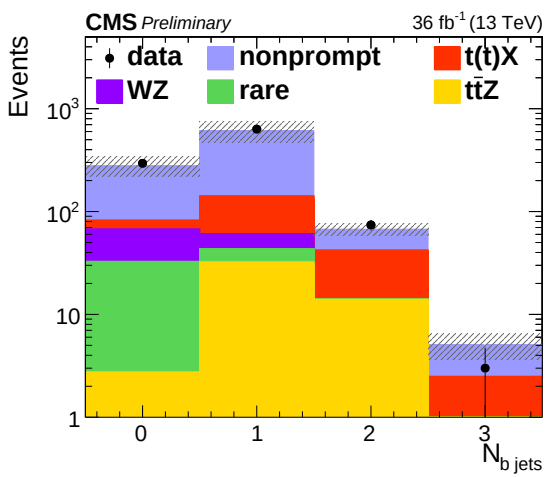
ttV: nonprompt lepton background

- Nonprompt background are expected to occur mostly in $t\bar{t}$ and Drell-Yan production: an additional nonprompt lepton from the semi-leptonic decays of a b-hadron, or additional jets misidentified as lepton
- The probability of loosely identified lepton to pass the full set of identification/isolation requirements is calculated in respective enriched region and validated in Monte-Carlo simulation and data:
  - 2ℓ: BDT < 0
  - 3ℓ: absence of an SFOC lepton pair or off-Z

2ℓ 3ℓ 3ℓ



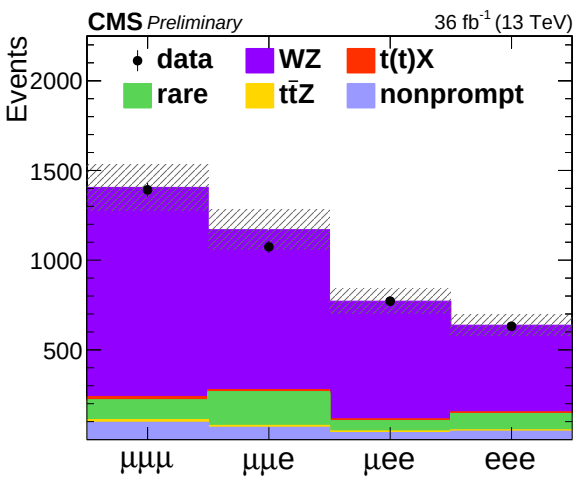




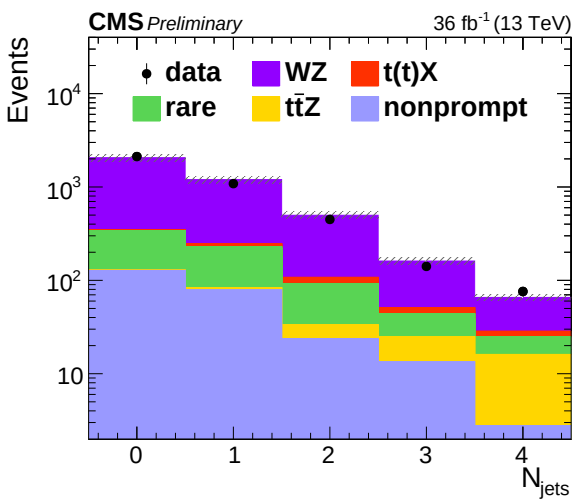
ttV: WZ and ZZ background

- MC is used for estimation, validate WZ and ZZ in enriched control region:
  - 3 leptons(4 leptons), 2 of the form an (2)SFOC pair close to Z peak mass
  - in 3ℓ the cut that excludes b-tag jets is used

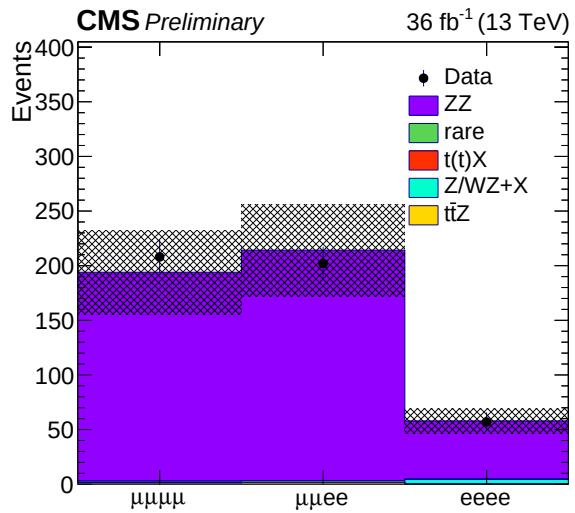
3ℓ



3ℓ



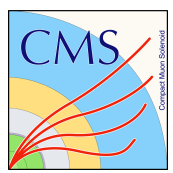
4ℓ



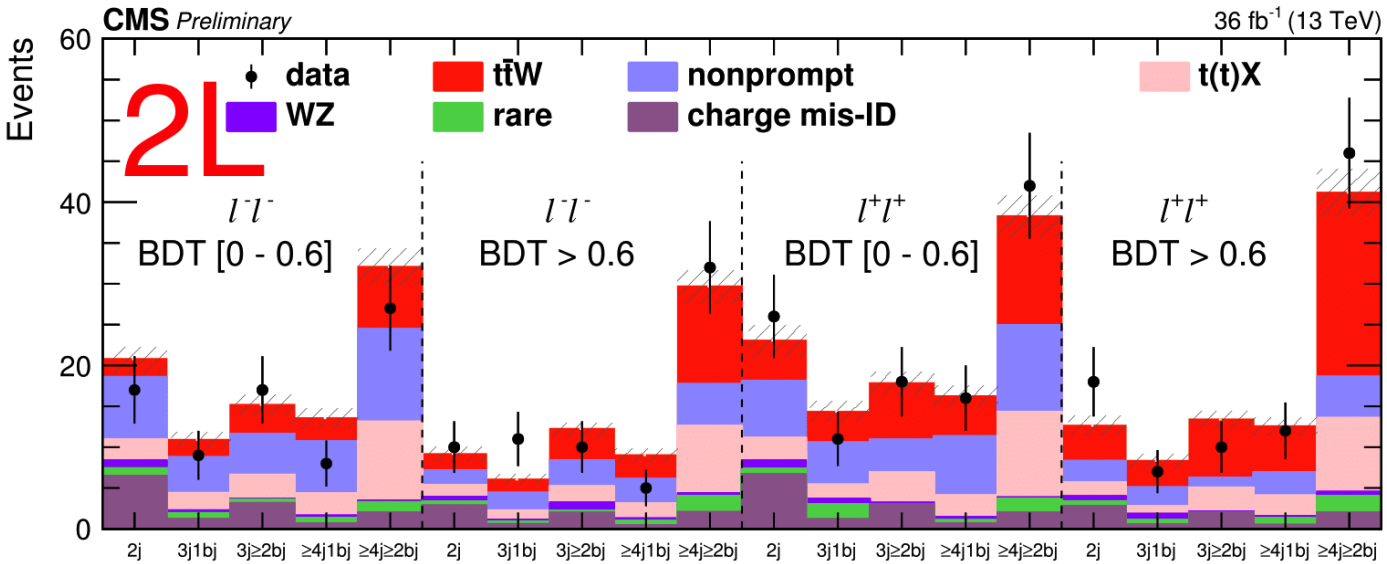
ttV: systematic uncertainties

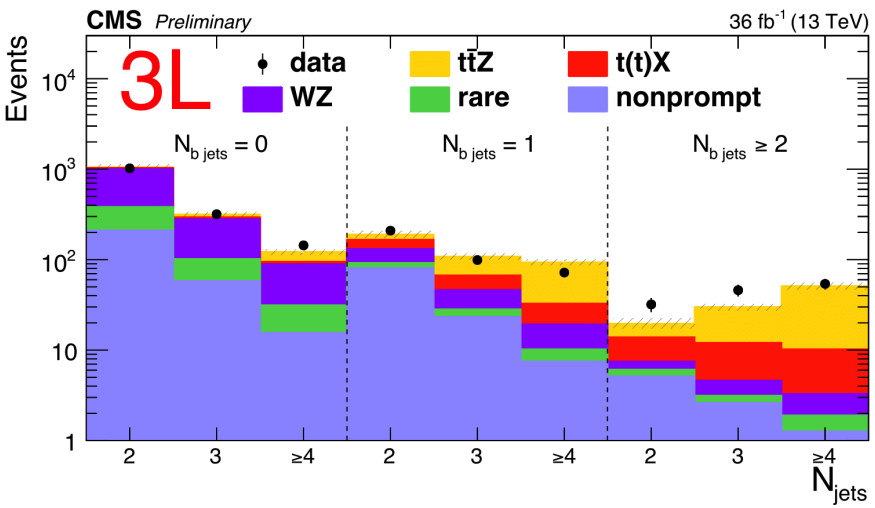
Source	Uncertainty range	Impact on ttW cross-section	Impact on ttZ cross-section
Luminosity	2.5%	4%	3%
Jet Energy Scale/Resolution	2-5%	3%	3%
Trigger	2-4%	4-5%	5%
B tagging	1-5%	2-5%	4-5%
PU modeling	1%	1%	1%
Lepton ID, efficiency	2-7%	3%	6-7%
μ_R/μ_F scale choice	1%	<1%	1%
PDF choice	1%	<1%	1%
Nonprompt background	30%	4%	< 2%
WZ cross section	10-20%	<1%	2%
ZZ cross section	20%	-	1%
Charge misidentification	20%	3%	-
Rare SM background	50%	2%	2%
ttX background	10-15%	4%	3%
Stat. unc. for nonprompt	5-50%	4%	2%
Stat. unc. rare SM processes	20-100%	1%	< 1%
Total systematic	-	14%	12%

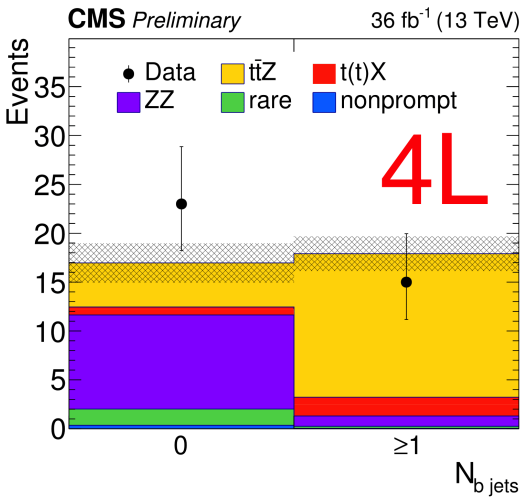
- Uncertainties on the lepton reconstruction, b tagging and trigger efficiency have the greatest effect both on the $t\bar{t}W$ and $t\bar{t}Z$ cross-section measurement.
- The uncertainty on nonprompt background gives a significant contribution to the systematic uncertainty of $t\bar{t}W$ cross section measurement.
- The systematic uncertainty for $t\bar{t}W$ and $t\bar{t}Z$ becomes dominant!



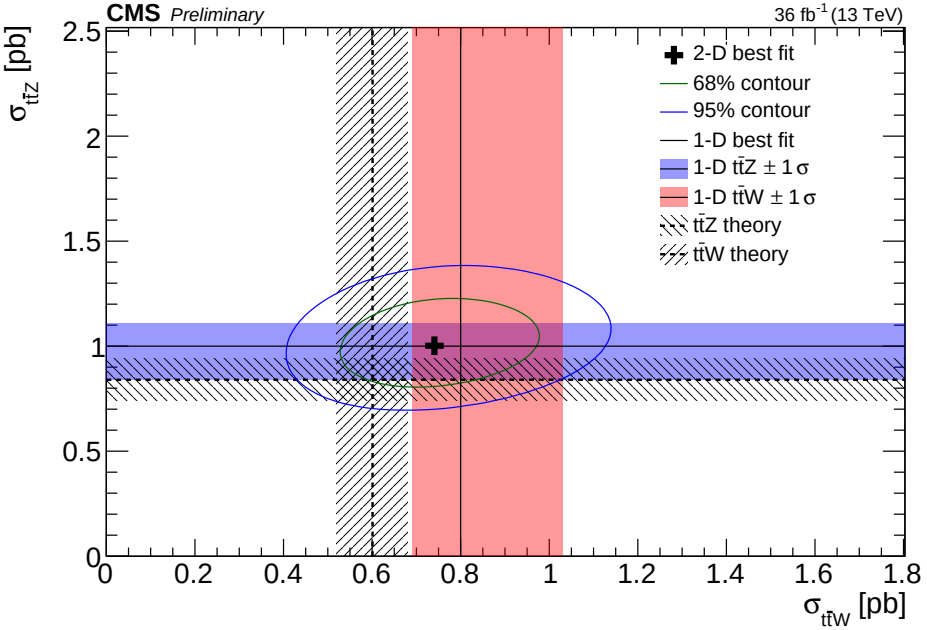
$t\bar{t}V$ results







$t\bar{t}V$ results



Channel	Expected significance	Observed significance
$2\ell ss$ analysis $t\bar{t}W^-$	2.4	2.3
$2\ell ss$ analysis $t\bar{t}W^+$	4.3	5.9
$2\ell ss$ analysis ($t\bar{t}W$)	4.6	5.5
3ℓ analysis ($t\bar{t}Z$)	8.4	8.7
4ℓ analysis ($t\bar{t}Z$)	4.8	4.6
3ℓ and 4ℓ combined ($t\bar{t}Z$)	9.5	9.9

Measured signal strength:

- $t\bar{t}W$:
  $1.28\ ^{+0.19}_{-0.18}(\text{stat.})\ ^{+0.20}_{-0.18}(\text{sys.})\ ^{+0.13}_{-0.12}(\text{theo.})$
- $t\bar{t}Z$:
  $1.18\ ^{+0.11}_{-0.10}(\text{stat.})\ ^{+0.14}_{-0.12}(\text{sys})\ ^{+0.11}_{-0.12}(\text{theo.})$

Measured cross sections:

- $t\bar{t}W^+$: $0.58\ ^{+0.09}_{-0.09}(\text{stat.})\ ^{+0.09}_{-0.08}(\text{sys.})$ pb
- $t\bar{t}W^-$: $0.19\ ^{+0.07}_{-0.07}(\text{stat.})\ ^{+0.06}_{-0.06}(\text{sys.})$ pb
- $t\bar{t}W$: $0.80\ ^{+0.12}_{-0.11}(\text{stat.})\ ^{+0.13}_{-0.12}(\text{sys.})$ pb
- $t\bar{t}Z$: $1.00^{+0.09}_{-0.08}(\text{stat.})\ ^{+0.12}_{-0.10}(\text{sys.})$ pb

$\Rightarrow$ First time a single experiment achieves $> 5\sigma$ for both processes simultaneously at 13 TeV

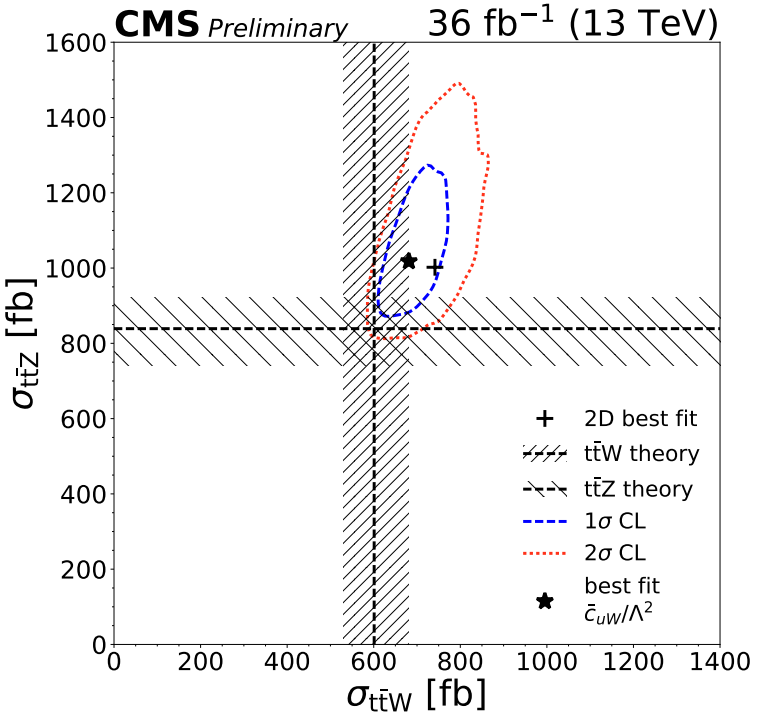
$\Rightarrow$ First time ttV reaches $> 5\sigma$ at 13 TeV

$t\bar{t}V$: EFT interpretations

EFT Lagrangian:

$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i\mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j\mathcal{O}_j + \cdots$

- $\mathcal{M} = \mathcal{M}_0 + \sum c_j\mathcal{M}_j$, consider one operator at a time
- Do not consider all NP couplings to the first two generations, as well operators which caused significant cross section scaling for $t\bar{t}$, inclusive Higgs, WW or WZ
- Considered NP effects on $t\bar{t}H$ as well as $t\bar{t}W$ and $t\bar{t}Z$
- Construct a profile likelihood test statistic $q(c_j)$, maximize to find the asymptotic best-fit c_j



Wilson coefficient	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	3.2	[0.0, 4.4]	[0.0, 5.4]
$\lvert\bar{c}_u/\Lambda^2 + 18.7\,\text{TeV}^{-2}\rvert$	18.9	[5.2, 26.6]	[0.0, 32.6]
$\bar{c}_{uW}/\Lambda^2$	3.0	[-4.1, -1.5] and [1.2, 4.1]	[-5.1, 5.0]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]	[-11.1, -6.6] and [-1.4, 3.0]

Conclusions

- Both results for $t\bar{t}t\bar{t}$ and $t\bar{t}\gamma$ are statistical limited, with new data will be improved!
- Measurement of $t\bar{t}$ + V cross-section is done at 13 TeV with statistical uncertainty O(15%) and systematic uncertainty O(15%)
- Next step is to measure differential cross-section for $t\bar{t}Z$ and the tZ coupling
- We are excited to have more data already in 2017-2018!