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Measurements of the associated production of top quark pairs with bosons or other top quarks

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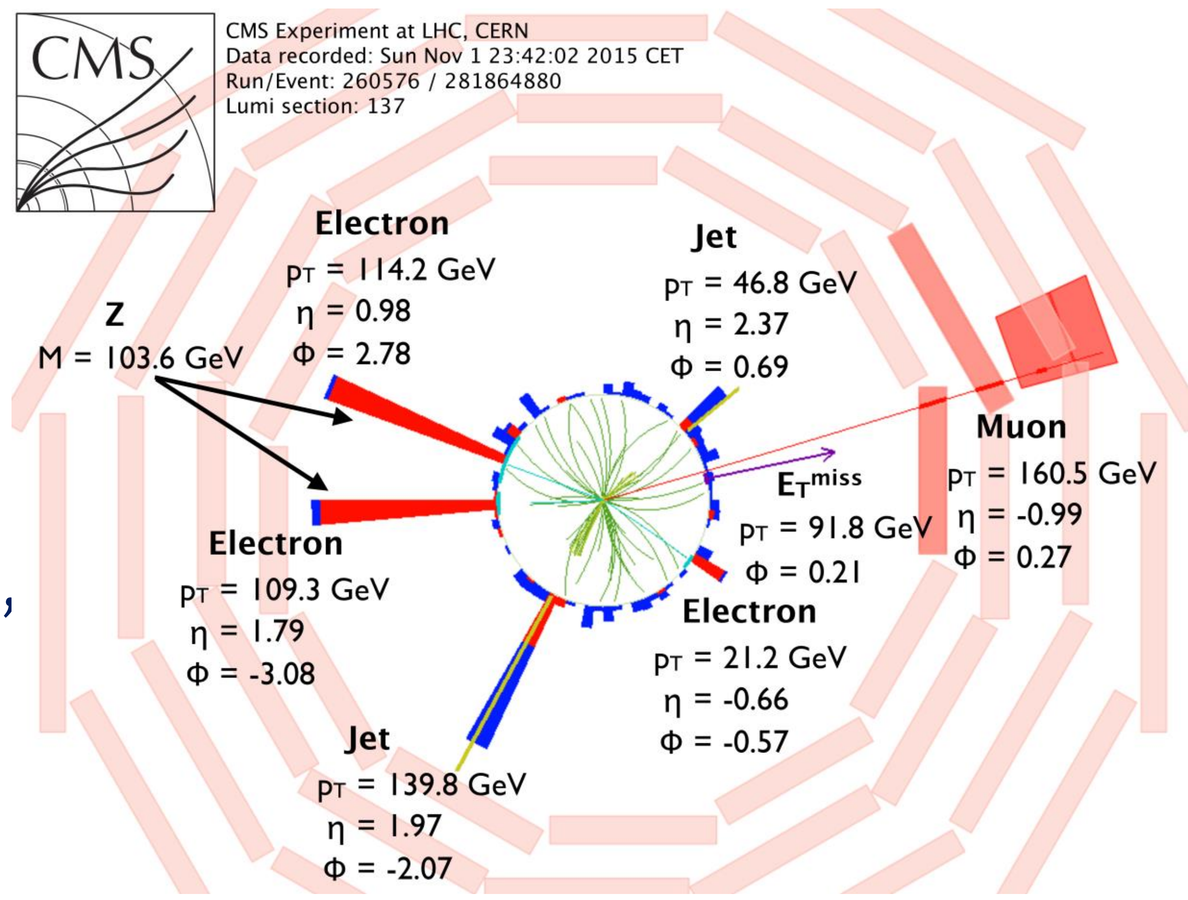
QCD@LHC 2017,
August 28th – Sep 1st 2017,
Debrecen, Hungary



Introduction

- The study of top quark production is of primordial interest at LHC.
  - Higgs and new physics scenarios involve top quarks.

- $t\bar{t}V$ is the main background for $t\bar{t}H$ and other BSM physics processes.
  - Effective field theories (EFT) provide a framework to interpret results in a model independent way if there is new physics at high energy.
  - Top quark pair production with an additional vector gauge boson is sensitive to most of the leading EFT operators that preserve charge-parity and flavor in neutral-currents.

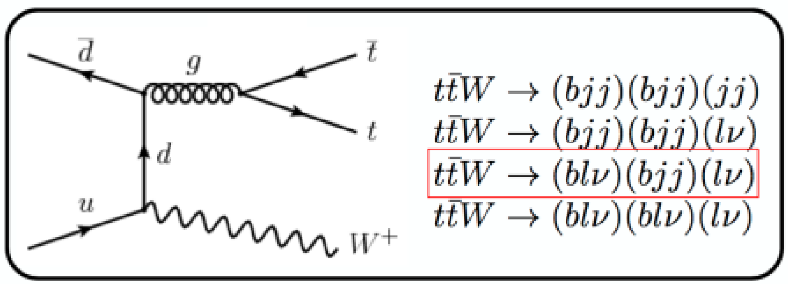
- Strength of the electromagnetic coupling of top quark and γ and top quark and Z boson can be probed.

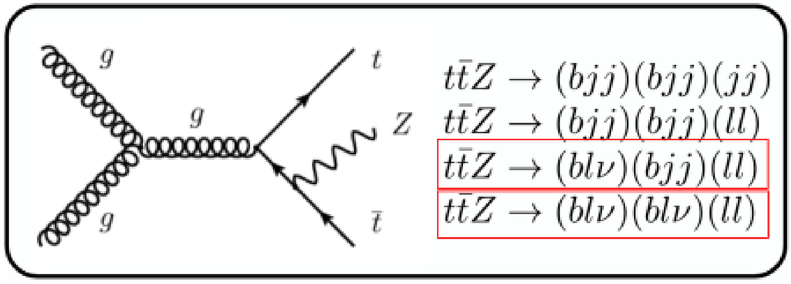
- $t\bar{t}$ $b\bar{b}$ is the main irreducible background for $t\bar{t}H$ searches in the H-> $b\bar{b}$ mode, $t\bar{t}$ jj is the reducible background faking b-jets.

- The $t\bar{t}t\bar{t}$ measurement provide a useful test of analytical higher order calculation of QCD.
  - BSM models could enhance the SM production.

$t\bar{t}V$ (V=W,Z) 13 TeV

CMS-PAS-TOP-17-005





$t\bar{t}W$ SS2ℓ

- 2 same-sign leptons
- p^T > 40, 25(27)GeV
- 3rd lepton veto
- ≥ 2 jets, ≥ 1 b-tag
- MVA BDT

$t\bar{t}Z$ 3ℓ

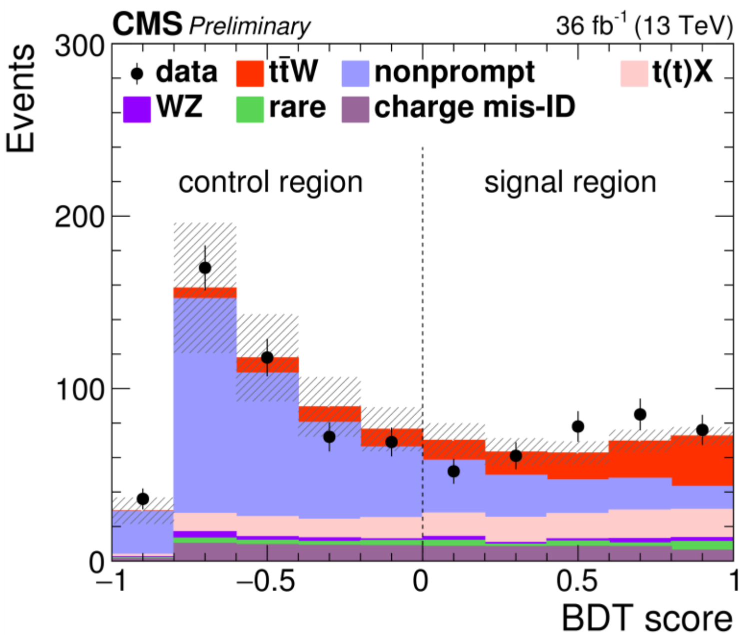
- 3 leptons
- p^T > 40, 20, 10 GeV
- ≥ 2 jets
- $|m_{\ell\ell} - M_Z| < 10$ GeV

$t\bar{t}Z$ 4ℓ

- 4 leptons
- p^T > 40, 10, 10, 10 GeV
- Sum of charges = 0
- ≥ 2 jets, ≥ 1 b-tag
- $|m_{\ell\ell} - M_Z| < 20$ GeV
- sequential analysis

$t\bar{t}W$ SS 2ℓ

- Events preselected with >=2 jets, 1 b-tag jet
- **MVA BDT** analysis based on the following variables:
  - Number of jets, number of b-tagged jets and the scalar sum of p^T of the jets
  - Leading and trailing lepton p^T, transverse invariant mass of each of the leptons and MET.
  - Leading and subleading jet p^T, missing transverse energy
  - ΔR between the trailing lepton and the nearest selected jet



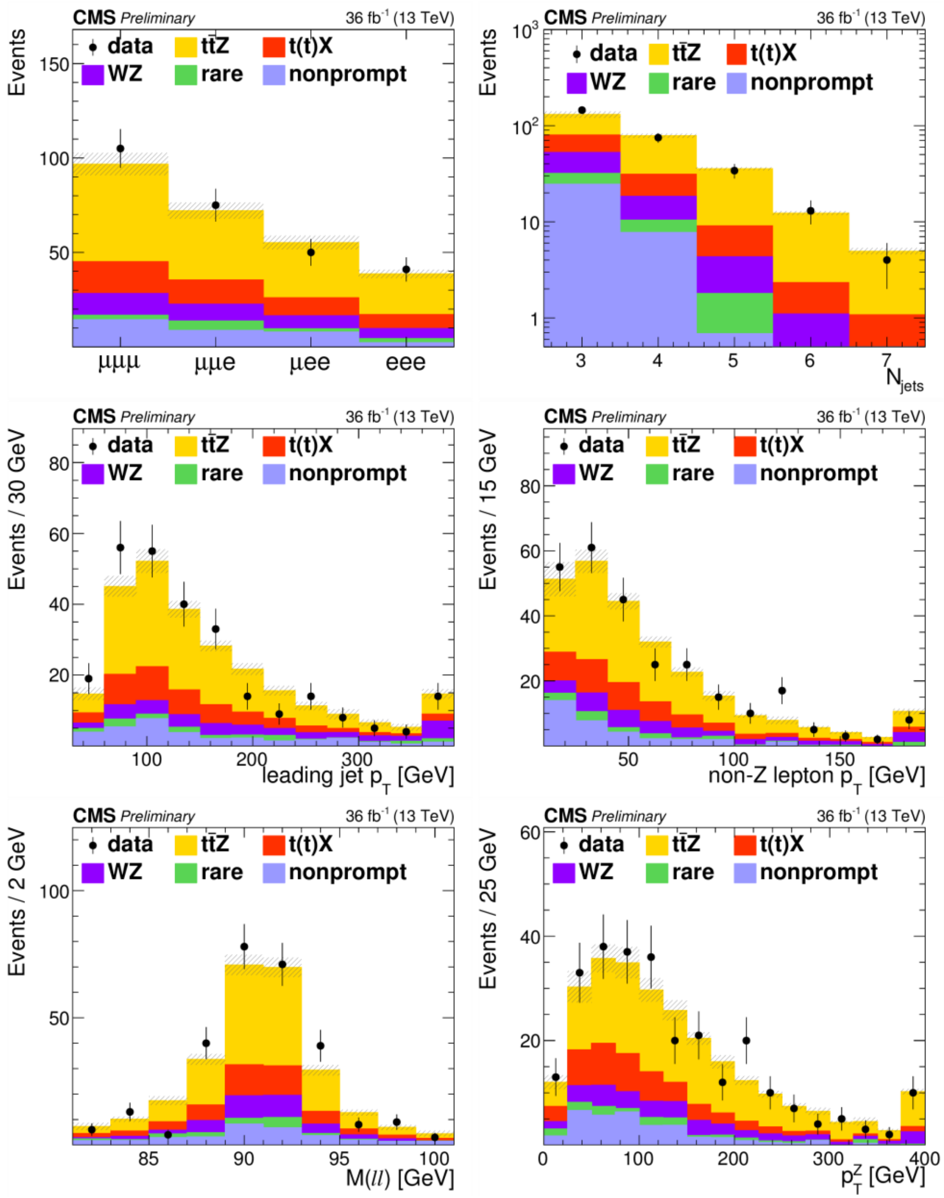
Event selection:

- BDT > 0 (suppress mainly the bkg. due to non-prompt leptons)
- split in number of jets, b-tag jets
- split in ++ and −−

Backgrounds

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

$t\bar{t}Z$ 3ℓ and 4ℓ



3ℓ channel

3ℓ channel:

9 exclusive SR:

2, 3 or ≥4 jets, 0, 1, ≥2 b jet

4ℓ channel:

2 categories, high and low S/B, ≥ 1 b-tag, or no b-tag

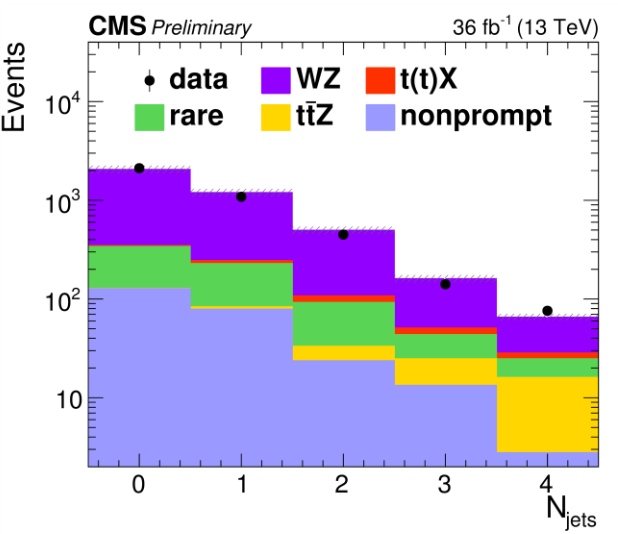
Main backgrounds:

- For the 3ℓ final state: non-prompt leptons, WZ, t(t)X (tZq, tWZ, ttH)
- For the 4ℓ final state, essentially ZZ

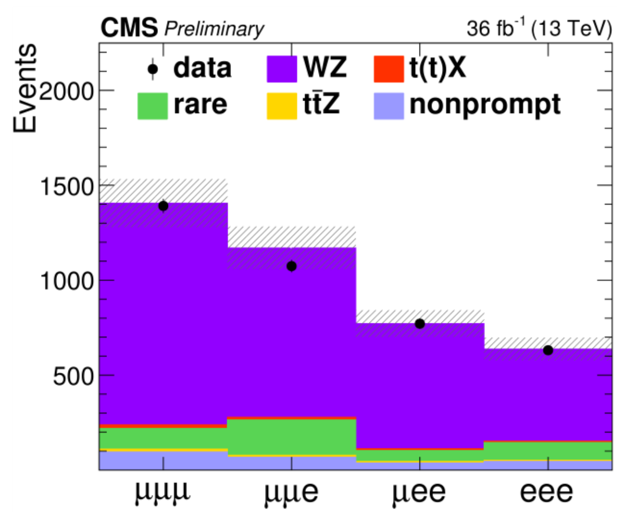
$t\bar{t}V$ (V=W,Z): WZ and ZZ background

- Estimated using MC, validation in WZ and ZZ enriched control regions in data:
  - 3 leptons(4 leptons), two of them form an (2) SF Opp. charge pair close to Z peak mass
  - 3ℓ , <= 2 jets and no b-tag jets, MET>30 GeV, m_T>50 GeV

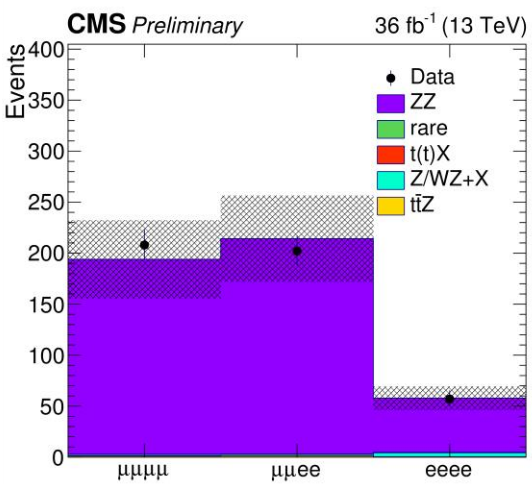
$t\bar{t}Z$: 3ℓ channel



$t\bar{t}Z$: 3ℓ channel

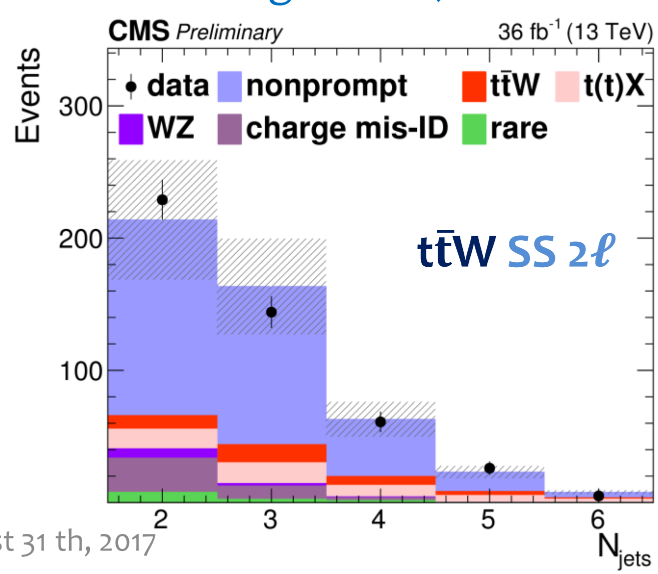


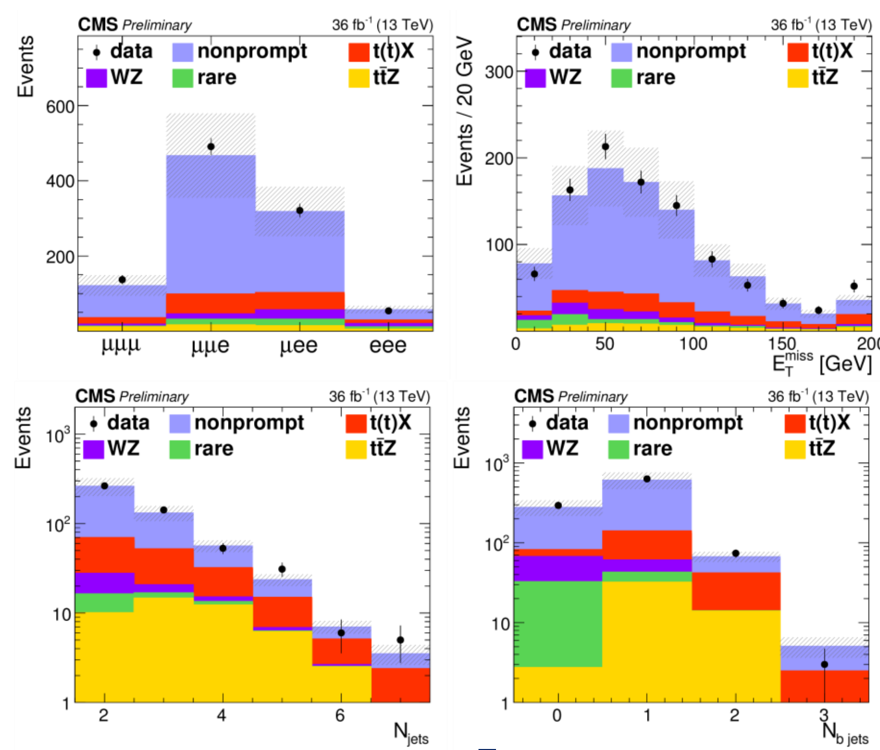
$t\bar{t}Z$: 4ℓ channel



tt̄V: non-prompt lepton background

- Non-prompt leptons are expected to come mostly from tt̄ and Drell-Yan with an additional 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 **id/iso** requirements is calculated in respective enriched region and validated in Monte-Carlo simulation and in data: **30% systematic uncertainty**
- Data control regions, exclusive to the signal extraction region and enriched by the processes with non-prompt leptons, are formed to check any other potential source of uncertainties:
  - **2ℓ : BDT < 0**
  - **3ℓ : absence of an SFOC lepton pair or off-Z**
- Other backgrounds, estimated from MC.





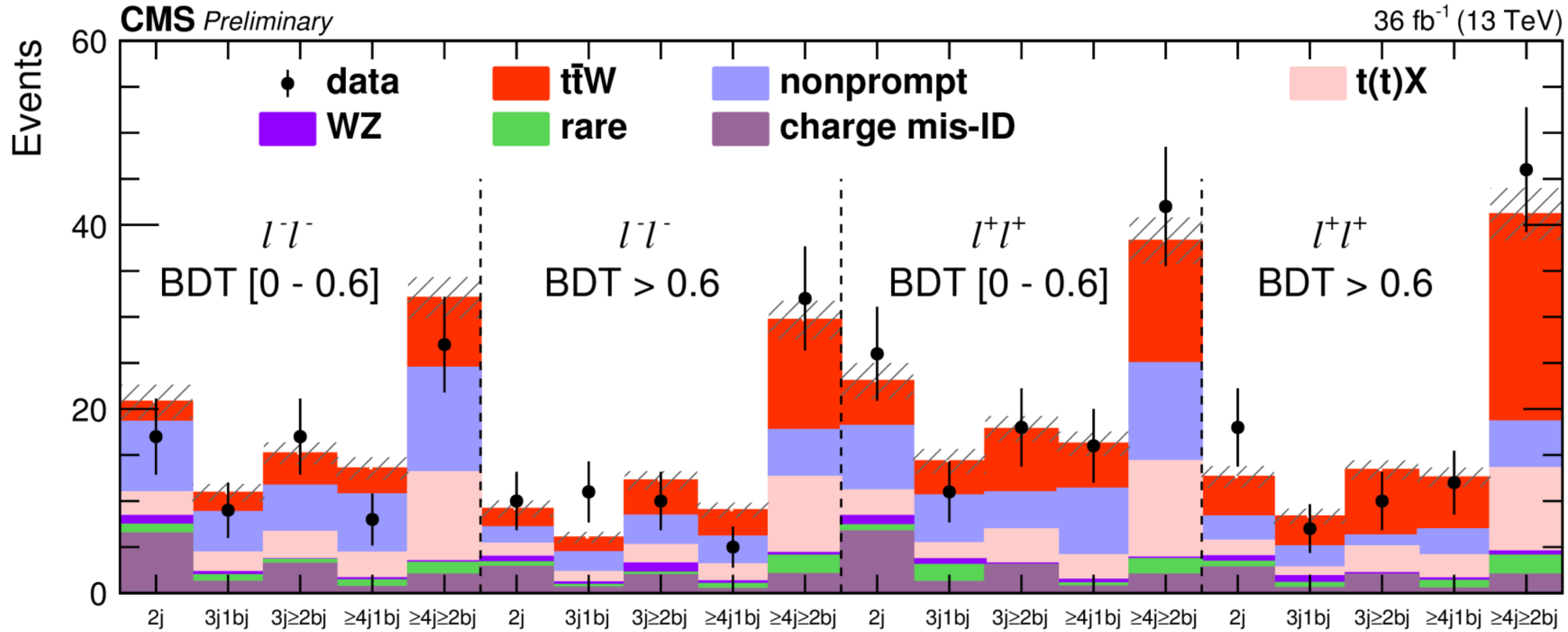
tt̄Z: 3ℓ channel

$t\bar{t}V$: systematic uncertainties

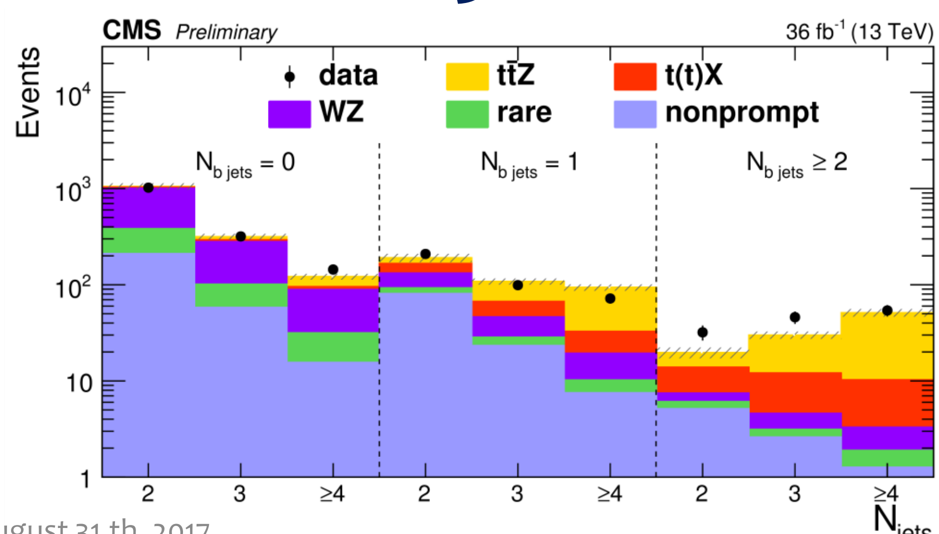
Source	Uncertainty range	Impact on ttW cross-section	Impact on ttZ cross-section
Luminosity	2.5%	4%	3%
Jet Energy Scale/Resolution	2-5%	3%	3%
Trigger	2-4%	4-5%	5%
B tagging	1-5%	2-5%	4-5%
PU modeling	1%	1%	1%
Lepton ID, efficiency	2-7%	3%	6-7%
μ_R/μ_F scale choice	1%	<1%	1%
PDF choice	1%	<1%	1%
Nonprompt 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 largest effect on the $t\bar{t}W$ and $t\bar{t}$ Z cross-section measurement.
- The uncertainty on non-prompt background gives a significant contribution to the systematic uncertainty of the $t\bar{t}W$ cross section measurement.
- **The systematic uncertainty for $t\bar{t}W$ and $t\bar{t}Z$ becomes dominant**

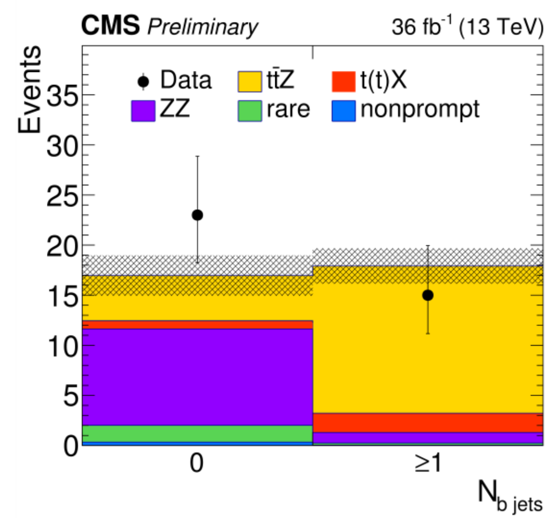
$t\bar{t}V$: results



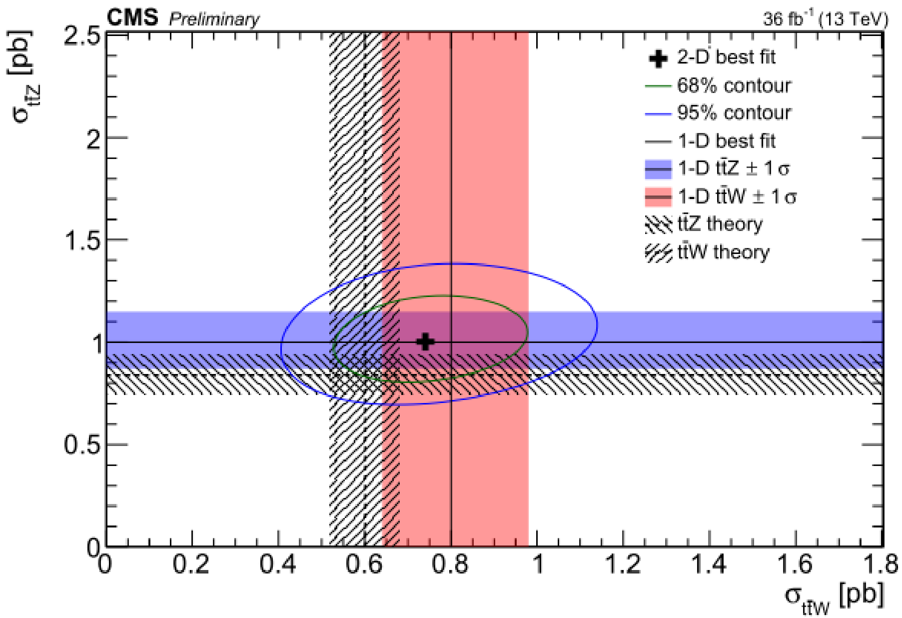
$t\bar{t}Z$: 3ℓ channel



4ℓ channel



$t\bar{t}V$: 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

Signal strengths:

$t\bar{t}W : 1.28^{+0.19}_{-0.18}$ (stat.)$^{+0.20}_{-0.18}$ (syst.)$^{+0.13}_{-0.12}$(theo.)

$t\bar{t}Z : 1.18^{+0.11}_{-0.10}$ (stat.)$^{+0.14}_{-0.12}$ (syst.)$^{+0.13}_{-0.12}$(theo.)

Cross sections:

$t\bar{t}W^+ : 0.58^{+0.09}_{-0.09}$ (stat.)$^{+0.09}_{-0.08}$ (syst.) pb

$t\bar{t}W^- : 0.19^{+0.07}_{-0.07}$ (stat.)$^{+0.06}_{-0.06}$ (syst.) pb

$t\bar{t}W : 0.80^{+0.12}_{-0.11}$ (stat.)$^{+0.13}_{-0.12}$ (syst.) pb

$t\bar{t}Z : 1.00^{+0.09}_{-0.08}$ (stat.)$^{+0.12}_{-0.10}$ (syst.) pb

theoretical cross sections:

ttW: 601^{+56}_{-51}(scale)$^{+25}_{-25}$ (pdf)$^{+25}_{-25}$(α_s) fb

ttZ(γ*): 839^{+80}_{-92}(scale)$^{+9}_{-9}$ (pdf)$^{+11}_{-11}$(α_s) fb

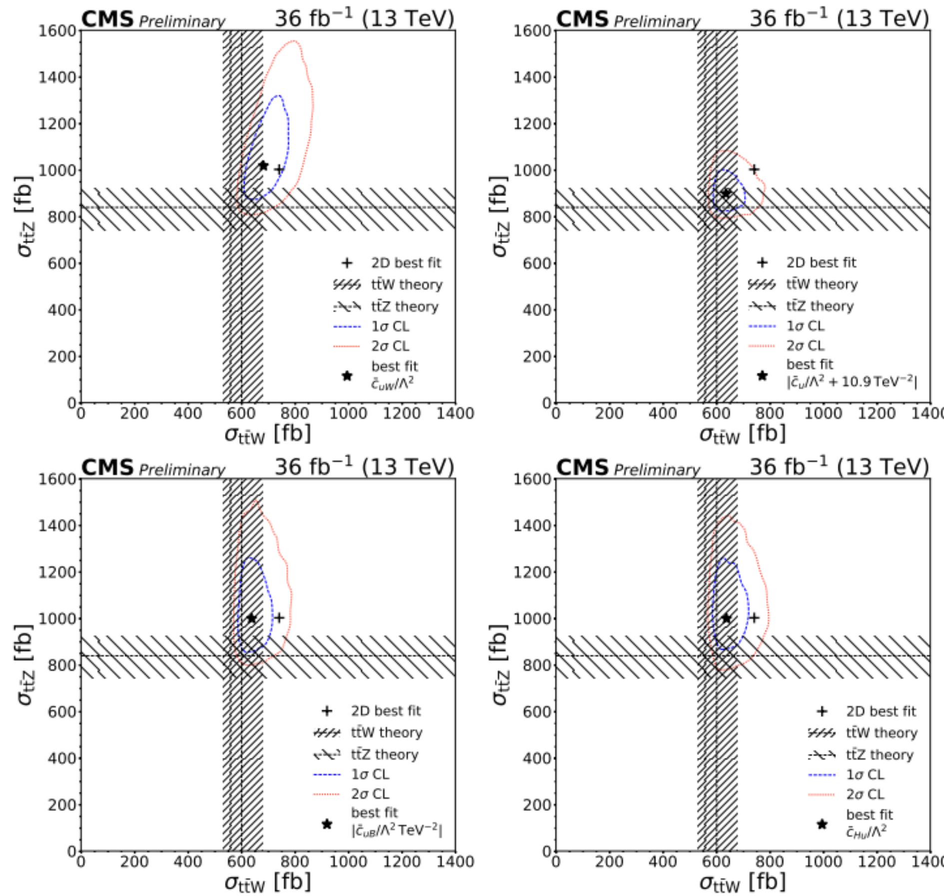
> 5σ for both processes simultaneously at 13 TeV

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

- Effective field theories (EFT), allow to use $t\bar{t}V$ cross section measurements to search in a model- independent way for **new physics (NP)** at energy scales which are not yet experimentally accessible.

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

- Only dimension-6 operators are considered: $\mathbf{c_j}$. One operator is considered each time.
- NP effects on $t\bar{t}H$ as well as $t\bar{t}W$ and $t\bar{t}Z$. Operators which caused significant cross section scaling for tt, inclusive Higgs, WW, or WZ are excluded.
- Expected 1σ and 2σ CL and observed best fit values for selected Wilson coefficients.

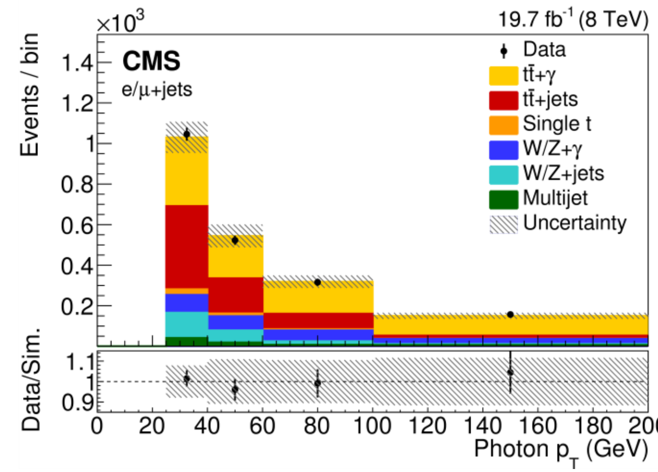


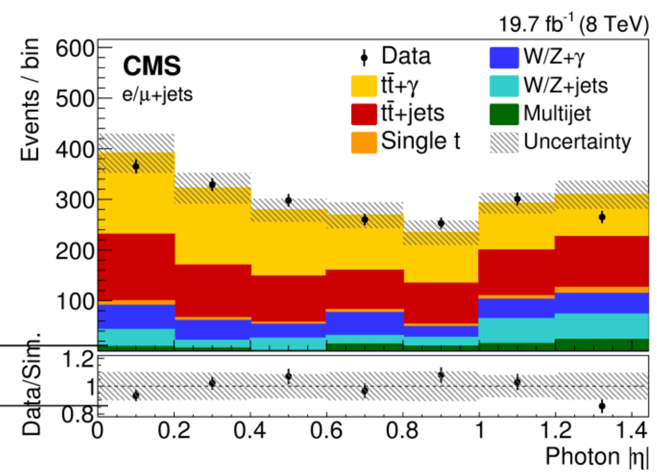
Wilson coefficient	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	[0.0, 1.5]	[0.0, 2.1]	1.6	[0.0, 2.3]	[0.0, 2.8]
$\lvert\bar{c}_{u}/\Lambda^2 + 10.9\ \text{TeV}^{-2}\rvert$	[2.3, 15.2]	[0.0, 18.6]	11.1	[2.7, 15.6]	[0.0, 19.1]
$\bar{c}_{uW}/\Lambda^2$	[-1.6, 1.5]	[-2.2, 2.1]	1.8	[-2.4, -0.8] and [0.7, 2.4]	[-3.0, 2.9]
$\bar{c}_{Hu}/\Lambda^2$	[-9.1, -6.5] and [-1.6, 1.1]	[-10.1, 2.0]	-9.4	[-10.3, -8.1] and [0.1, 2.1]	[-11.2, -6.6] and [-1.5, 3.0]

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

CMS-TOP-14-008, 1706.08128, sub. to **JHEP**

- **Measure $t\bar{t}\gamma$ cross-section relative to the $t\bar{t}$ cross section**
- Event 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 pT (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



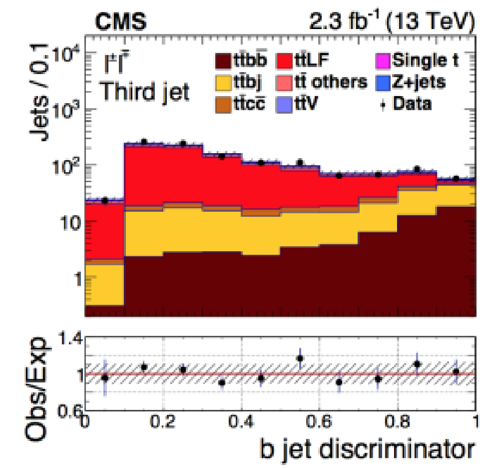


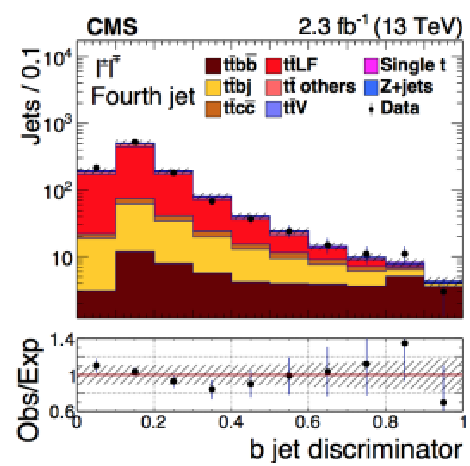
Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales)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

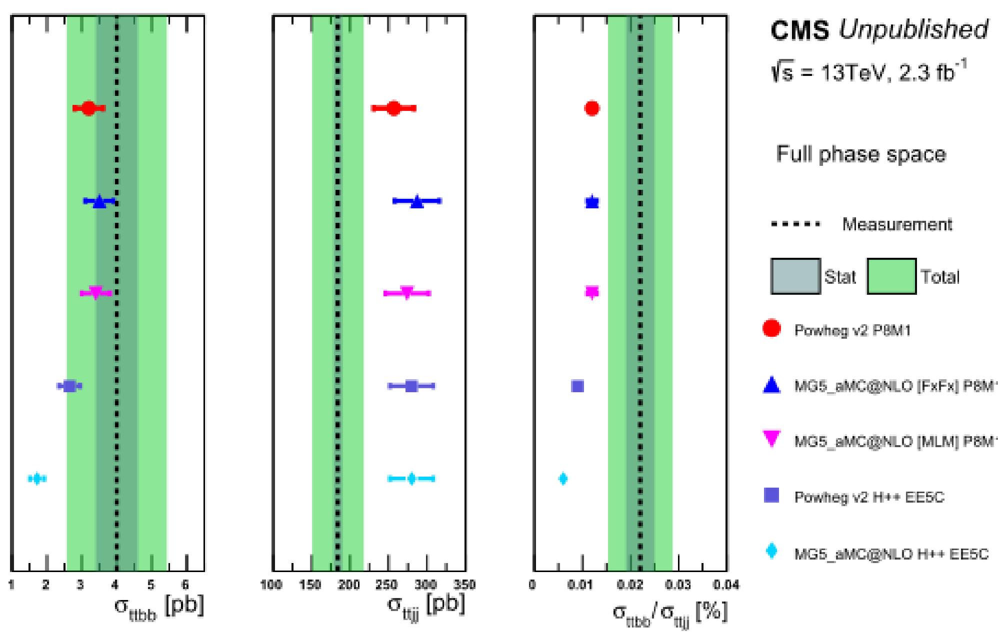
$t\bar{t}bb$, $t\bar{t}jj$ and ratio measurements

CMS-TOP-16-010
1705.10141 sub. to **PLB**

- Essential to understand the $t\bar{t}$ bb and $t\bar{t}$ jj processes for the study of the $t\bar{t}H(b\bar{b})$ production mode of the Higgs.
  - $t\bar{t}\,b\bar{b}$ is the main irreducible background for $t\bar{t}H$ searches in the H-> $b\bar{b}$ mode, $t\bar{t}$ jj is the reducible background faking b-jets.
- Event 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.

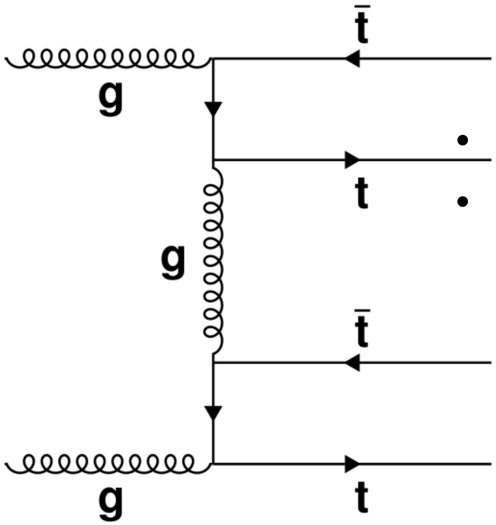




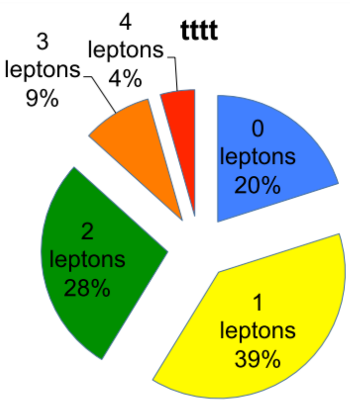


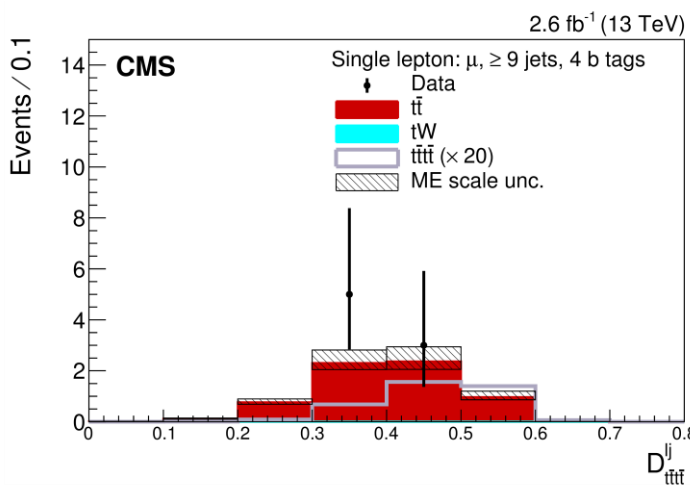
Search for $t\bar{t}t\bar{t}$

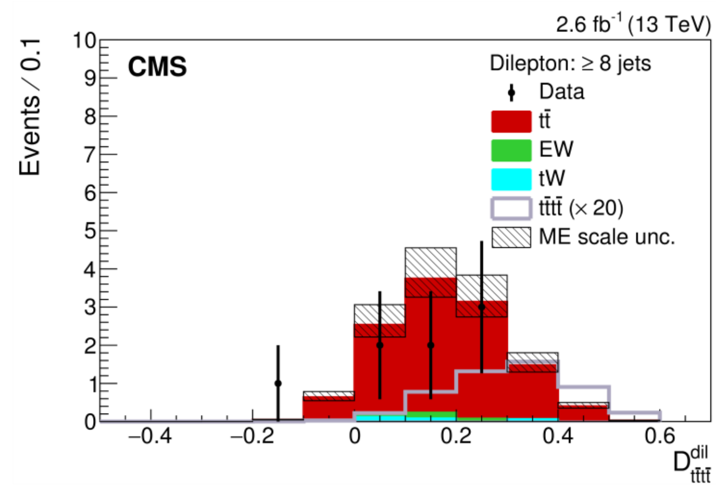
1702.06164, sub. to **PLB**
SUSY SS 2l (1704.07323), sub. to **EPJC**



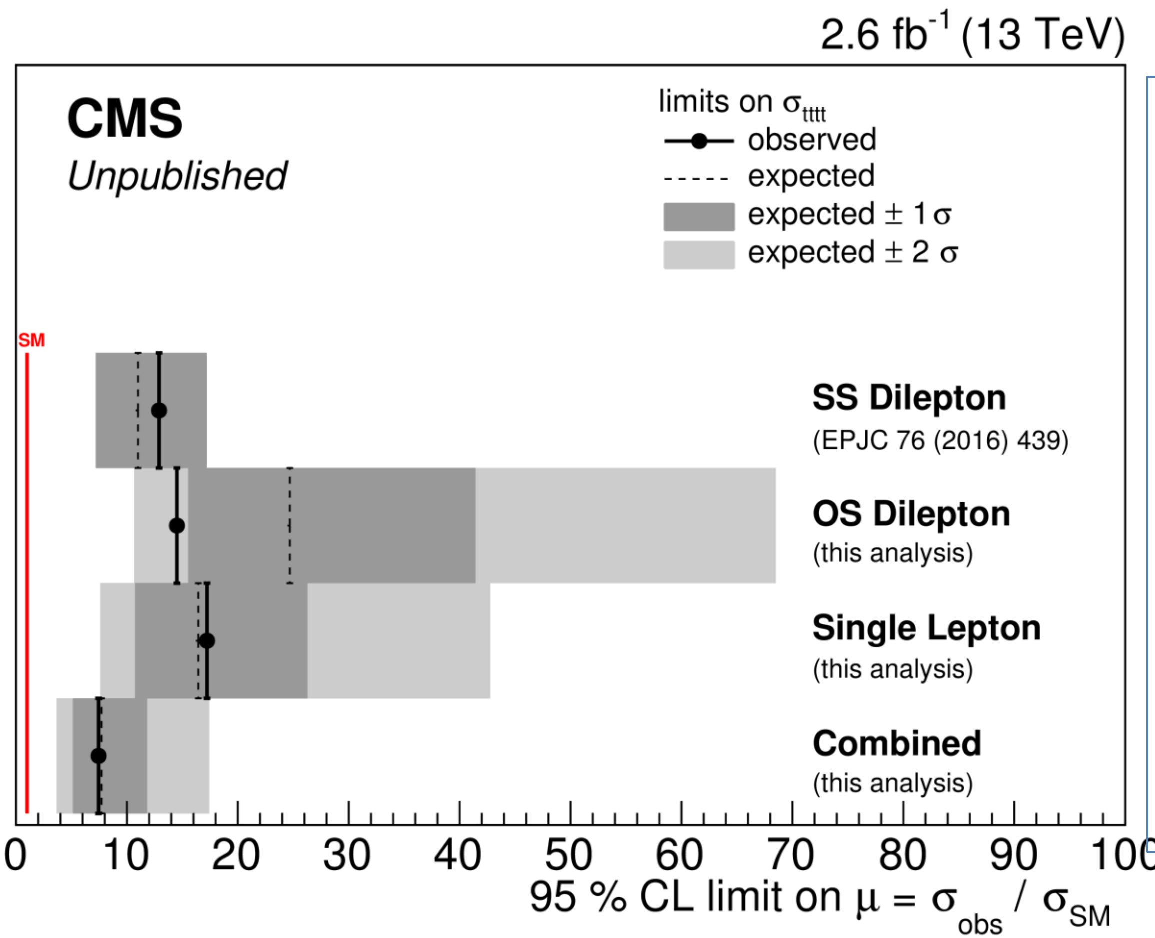
- Measure the cross-section, **SM expectation: $9.2^{+2.9}_{-2.4}$ fb**
- BSM models leads to enhanced four top production cross-section
  - Selection: 1 or 2 isolated leptons (W decay), large jet and b-jet multiplicity and hadronic energy. Discrimination comes from the number of top and b quarks, event activity and topology
  - Main background, $t\bar{t}$ +jets, other backgrounds: DY, W+jets, single top, ttW, ttZ, ttH
  - Presence of additional hadronically decaying top quarks distinguishes $t\bar{t}t\bar{t}$ from $t\bar{t}$. Use a BDT to rank reconstructed tops built from tri-jet candidates. Largest systematic uncertainty: variation of QCD scale choice at ME
  - No deviation from background-only is expected and observed the limits on cross-section are set
  - Splitting the BDT distribution into categories significantly improves the sensitivity of the limit fit.







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



SUSY same charge 2l
1704.07323, 36 / fb

when treating this process as signal, its observed (expected) cross section limit is determined to be **42 (27^{+13}_{-8}) fb at 95% CL,** to be compared to the SM expectation of **$9.2^{+2.9}_{-2.4}$ fb**

Summary

- Measurement of $t\bar{t}V$ (V=W,Z) cross-sections were performed by CMS at 13 TeV with comparable statistical and systematic uncertainties of about 15%.
  - EFT operators in the top sector started to be studied and constrained.
- $t\bar{t}t\bar{t}$ and $t\bar{t}\gamma$ are statistical limited and with new data measurements will be improved.
- $t\bar{t}bb$, $t\bar{t}jj$ and and its ratio has been measured.
- The production of top pairs with associated bosons or other top or b quarks is a very active research field at the LHC.