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Search for a top-philic heavy resonance produced in association with two top quarks

CMS China 13nd Sep.

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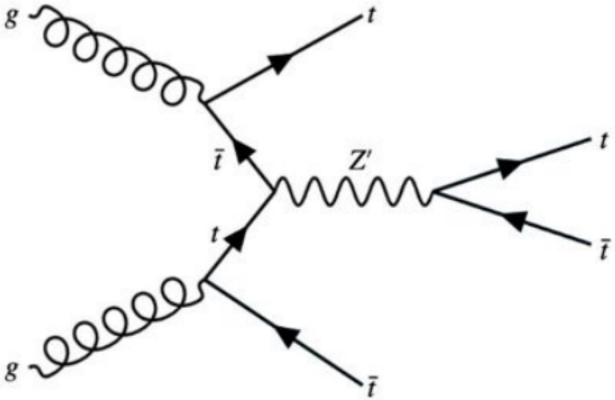
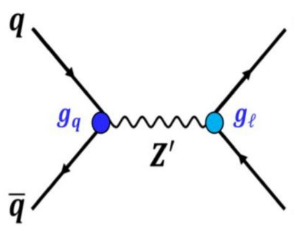


Motivation to search for an heavy neutral resonance

- A heavy neutral resonance, Z′, is common in many theories beyond the SM
  - Main production mechanism is through annihilation of qqbar pairs.
  - At the LHC this is mainly couplings to light-quarks

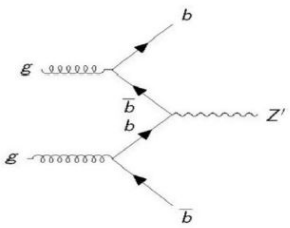
Drell-Yan



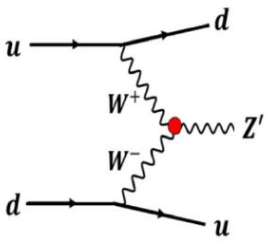
- A Z′ has been extensively searched for at CMS and the LHC,

setting strong limits on its existence up to several TeV
  - If couplings to light-quarks are suppressed and nature favors a Z′ coupling to higher fermion generation (D. Barbosa et al.) at the LHC energies, it is possible for a Z′ to manifest through unprecedented mechanisms and phase-space (P.J. Fox et al.)
  - Recent proposals for some new production mechanisms (EXO-22-006, EXO-21-015)
  - In this analysis we consider the most extreme scenario of a top-philic Z′, which leads to a 4th probe of investigation

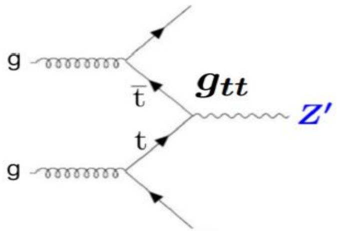
b-Quark Fusion



VBF



t-quark fusion



Top-philic Z′ in a simplified model

From J.H. Kin et al.

- We consider a color singlet vector particle (V1) which couples to top and antitop.
- The relevant interaction is given by the following renormalization Lagrangian.

$$\mathcal{L}_{int} = \bar{t}\gamma_\mu(c_L P_L + c_R P_R)tV_1^\mu = c_t\bar{t}\gamma_\mu(cos\theta P_L + sin\theta P_R)tV_1^\mu$$

$P_{R/L} = (1 \pm \gamma_5)/2$ is projection operators

$c_t = \sqrt{(c_L)^2 + (c_R)^2}$ is coupling of vector singlet with top quarks

$tan\theta = c_R / c_L$ tangent of the chirality angle

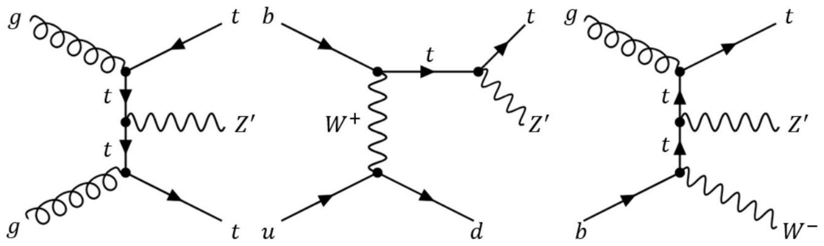
- There are three free parameters:
  - The V1 mass
  - The V1 coupling to top (Ct)
  - The V1 chirality (θ)

Refer to paper arXiv:1604.07421

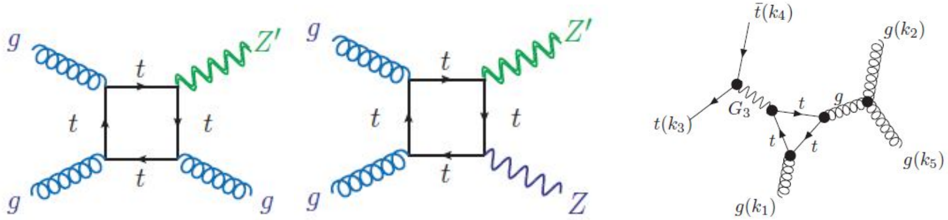
- Different production mechanisms dominates based on different chirality values

Production modes

- There are two ways to produce a top-philic resonance at the LHC: at tree level and one loop.
  - Tree level (we focus on in the reminder)



  - Loop level



chirality	Physics case	Experimental effect
0	Pure left-handed interaction	Largest xSec for tWb processes at higher masses
pi/2	Pure right-handed interaction	Smallest xSec for tWb processes
pi/4	No axial component in Z'	No Z'+j from quark-initiated
pi 3/4	Axial coupling	Max xSec for loop-induced (tt and Z'+j) production

- We rely on the Top-philic-Zprime UFO model
- We consider
  - θ = pi/4 and we focus on tree level processes (complementary to HIG-22-013)
  - the ttZ' process, as its production cross-section is independent from θ

Analysis strategy: single-lepton final state

- Possible to cover a vast experimental phase space

	0 t_{had}	1 t_{had}	2 t_{had}	3 t_{had}	4 t_{had}
0 lep				tjZ′ or tWZ′	ttZ′
1 lep			tjZ′ or tWZ′	**ttZ′** or tWZ′	
2 lep		tjZ′ or tWZ′	**ttZ′** or tWZ′		Our search!
3 lep	tjZ′ or tWZ′	ttZ′ or tWZ′			
4 lep	ttZ′ or tWZ′				

- In this analysis we cover the single lepton (electron, muon) final state:
  - mitigate the QCD multijet background and trigger events with a relatively low transverse momentum threshold
- Another team from DESY works on the di-lepton final state

Analysis strategy: samples and datasets

- Single lepton datasets with a luminosity of Full Run2 (138 fb^{-1})
- Background samples:
  - tt (tt_hadronic, tt_semi-leptonic, tt_di-leptonic)
  - other top bkg (ttt/tttW, tt + V/VV, single-top, tZq, t+V/VV)
  - tttt
  - non top bkg (V/VV/VVV/DY jets)

- Signal samples:
  - We have 4 different widths for each mass point: 4%, 10%, 20%, 50%.
  - Z' mass varies as follows:
    - From 500 to 2000 GeV in steps of 250 GeV
    - From 2000 to 3000 GeV in steps of 500 GeV
    - From 3000 to 4000 GeV in a step of 1000 GeV

  - In total we have 40 samples (10 masses x 4 widths)

Analysis strategy: signal selections

- triggers and lepton selection:
  - 1 tight muon with 0 extra loose leptons
  - 1 tight electron with 0 extra loose leptons

Year	Channel	Trigger
2018	muon	HLT_IsoMu24 HLT_IsoTkMu24
2017	muon	HLT_IsoMu27
2016	muon	HLT_IsoMu24 HLT_IsoTkMu24
2018	electron	HLT_Ele32_WPTight_Gsf
2017	electron	HLT_Ele32_WPTight_Gsf_L1DoubleEG with hltEGL1SingleEGOrFilter
2016	electron	HLT_Ele25_eta2p1_WPTight_Gsf

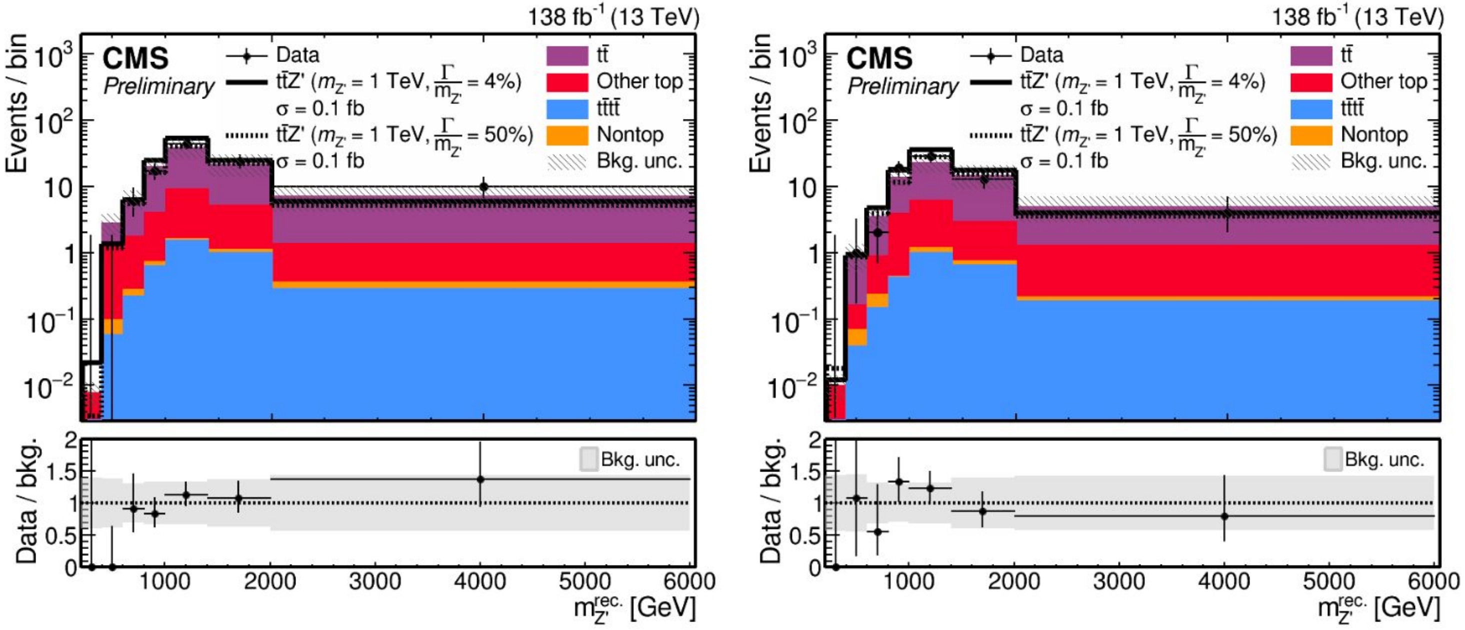
official corrections applied, link, link, link
approve corrections applied, link

- HT > 700 GeV (HT = the sum of the pT of all AK4 jets)
- MET_pT > 60 GeV with the Noise Filters (official recommendations link, link)
- ≥ 6 AK4 jets
- ≥ 2 boosted tops (AK8 jet with ParticleNet Medium ID and official corrections link)
- ≥ 1 loose b-jet (DeepJet, official corrections link, link)

Selection similar to 4 tops single lepton analysis except that we sought more stringent requirement on the N jets and HT and the presence of two boosted top quarks, because we are specifically interested on a Z' boson with high mass

Signal region distribution

- Signal Region plot



- Background completely dominated by top events, non top background minor

Background estimation (1)

- Find a region close to the phase space of the search region, but orthogonal to it and with negligible signal

Signal Region	Control Region
Exactly 1 lepton	Exactly 1 lepton
HLT	HLT
Noise filters	Noise filters
$HT > 700\,\text{GeV}$	$HT > 700\,\text{GeV}$
$MET_{p_T} > 60\,\text{GeV}$	$MET_{p_T} > 60\,\text{GeV}$
Number of jets$\geq$6	Number of jets$\geq$6
$\geq$2 boosted tops && $\geq$1 loose b jets.	$\geq$2 boosted tops && $<$1 loose b jet

- Efficiency comparison for signal samples

Efficiency	SR	CR
Mass 500 GeV, width 4%	0.15070%	0.02310%
Mass 3000 GeV, width 4%	2.48830%	0.22740%

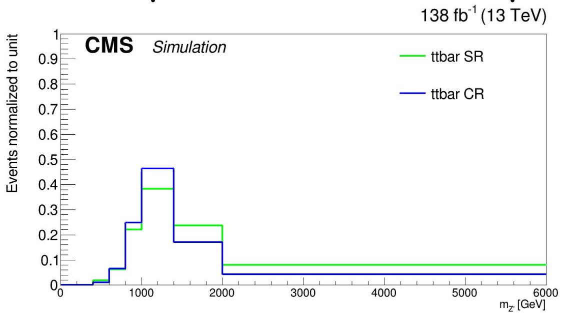
Signal is about a factor of 10 less in the CR -> SR+CR simultaneous fit

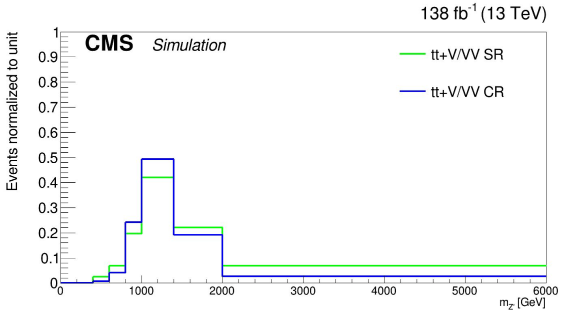
Background estimation (2)

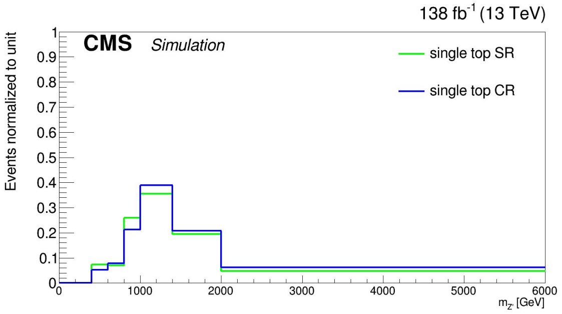
- Background composition in SR and CR

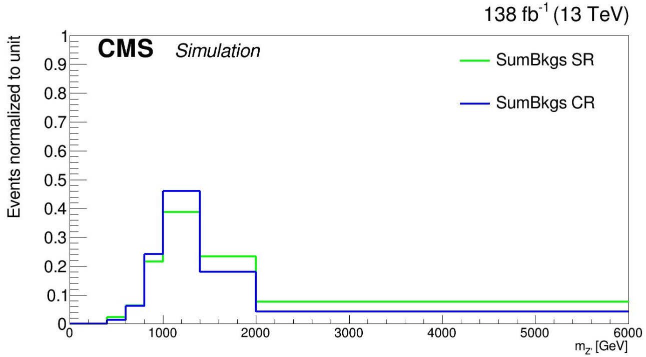
BKG samples	$t\bar{t}$	other top (ttt, tt+V/VV, single top)	tttt	Non top (V/VV/VVV/DY)
signal region	74.74%	20.72%	3.99%	0.55%
control region	67.86%	30.48%	0.51%	1.15%

- Shape distribution comparison









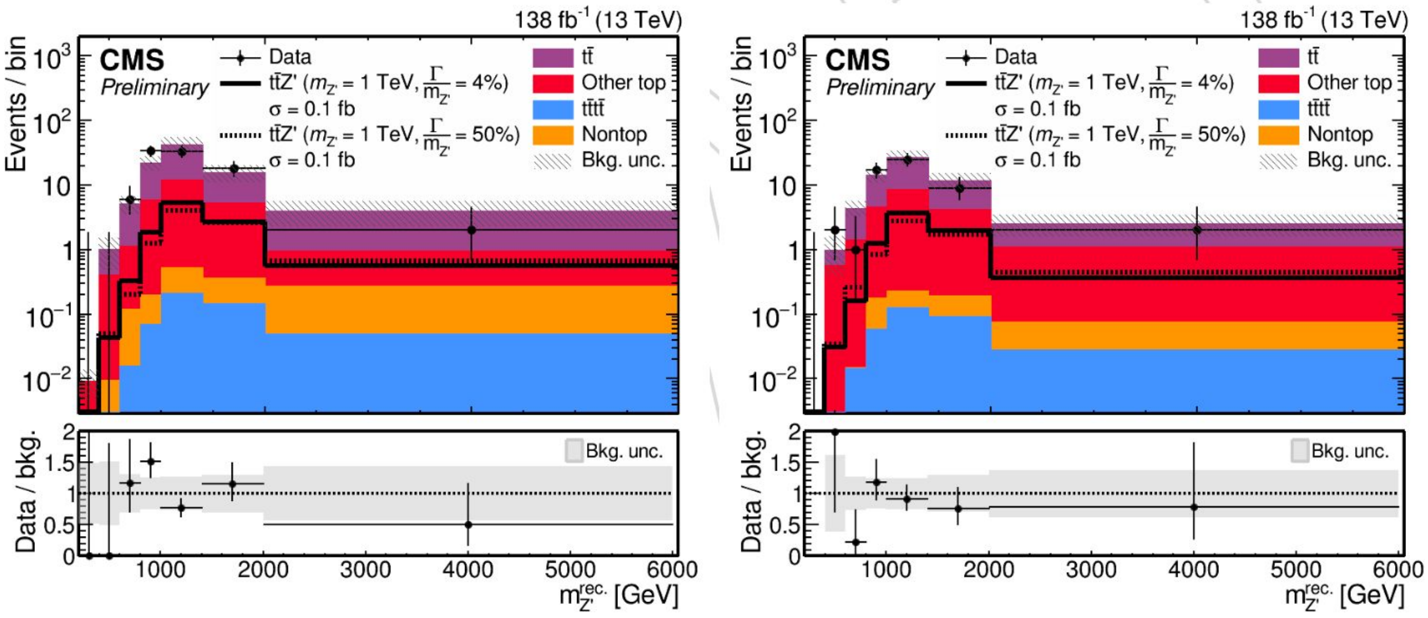
Good consistency is found!

-> Use rate parameter and scale all the background samples of each year

-> This normalization scale factor will be applied in the simultaneous fit with SR and CR together.

Background estimation (3)

- Post-fit results in CR



Good data-MC agreement

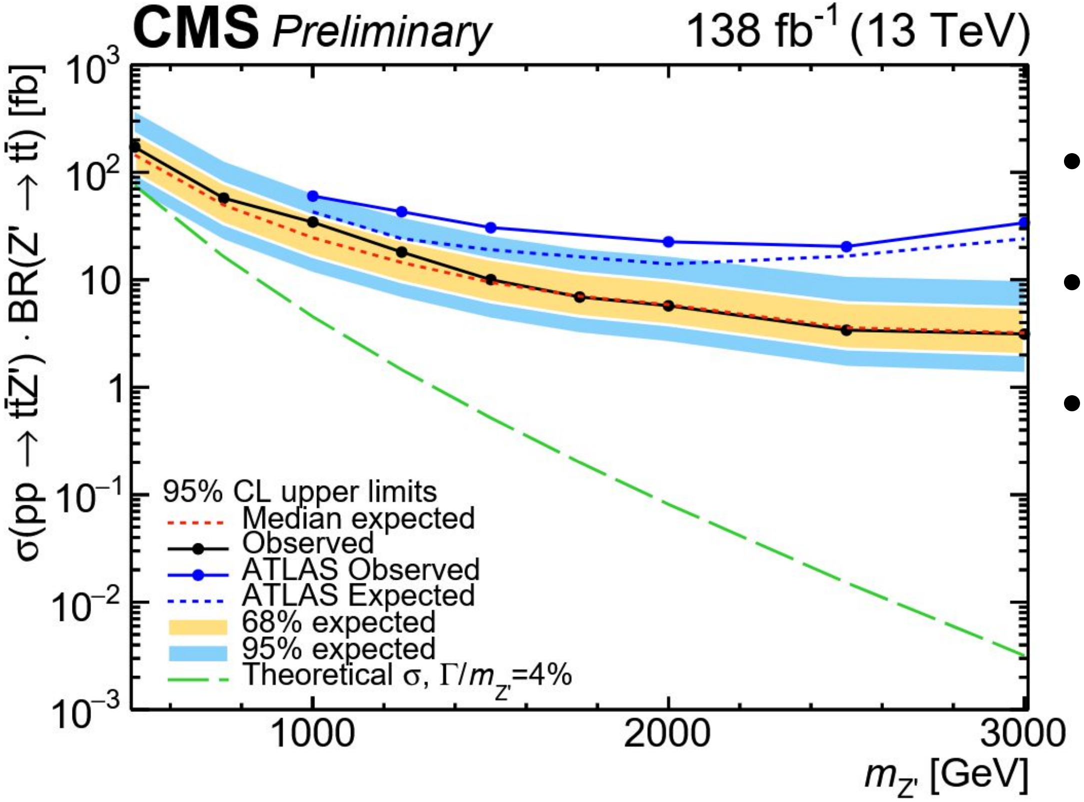
Systematic uncertainties

- Summary for all the systematics included

systematics	type	2016	2017	2018	process	year correlation
PDF	shape	✓	✓	✓	sig+bkg	correlated
QCDScale_sig	shape	✓	✓	✓	sig	correlated
QCDScale_tttt	shape	✓	✓	✓	tttt	correlated
QCDScale_ttbar	shape	✓	✓	✓	$t\bar{t}$	correlated
QCDScale_otherTop	shape	✓	✓	✓	otherTopBkg	correlated
QCDScale_VX	shape	✓	✓	✓	nonTopBkg	correlated
Trigger	norm+shape	✓	✓	✓	sig+bkg	partial correlated
lepton	norm+shape	✓	✓	✓	sig+bkg	correlated
pile-up	norm+shape	✓	✓	✓	sig+bkg	correlated
Prefiring	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
Jet resolution	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
Jet scale	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
b-tag_light_corr	norm+shape	✓	✓	✓	sig+bkg	correlated
b-tag_bc_corr	norm+shape	✓	✓	✓	sig+bkg	correlated
b-tag_bc	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
b-tag_light	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
boosted top	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
MET uncluster	norm+shape	✓	✓	✓	sig+bkg	uncorrelated
Lumi_Corr	norm	0.6%	0.9%	2.0%	sig+bkg	correlated
Lumi_UnCorr	norm	1.0%	2.0%	1.5%	sig+bkg	uncorrelated
Lumi_Corre_1718	norm	-	0.6%	0.2%	sig+bkg	correlated

All systematics are derived from official recommendations

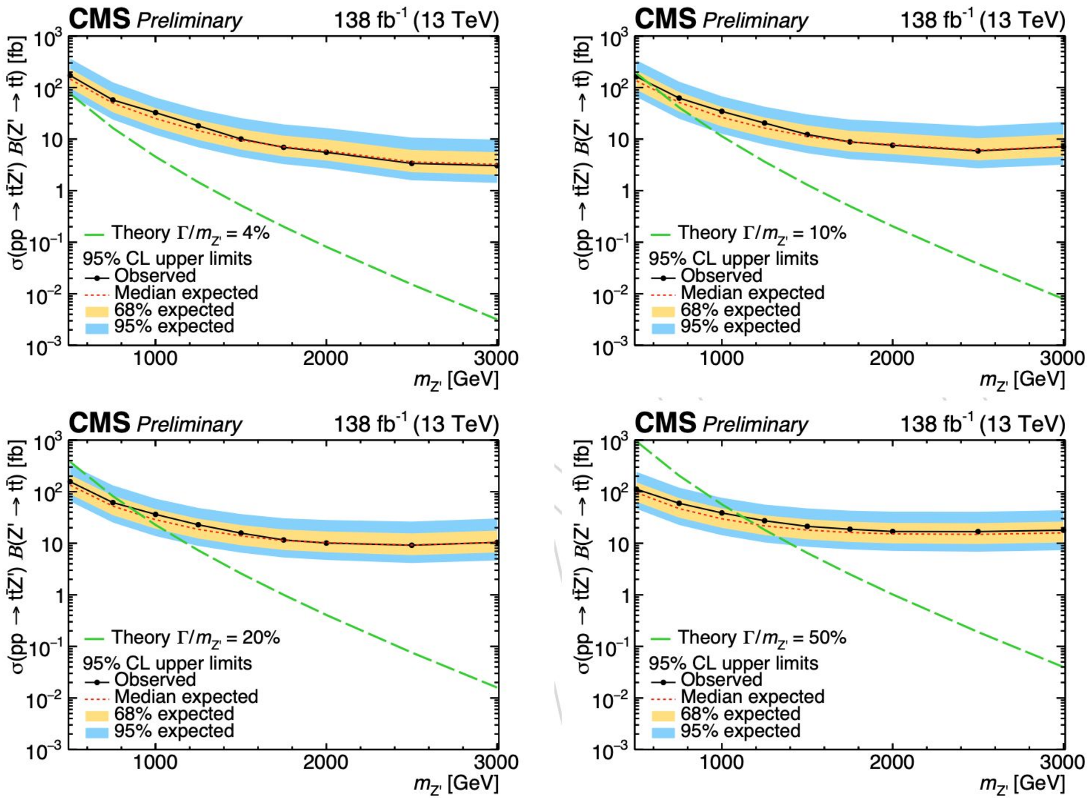
Observed upper limits and comparison with ATLAS



- We investigate a Z′ from 500 GeV, ATLAS from 1 TeV
- We have better limits over all mass range, especially at higher Z′ masses
- Increase in sensitivity driven by dedicated machine learning hadronic top identification (particleNet)

Observed upper limits

Observed upper limit on σ(pp → tt Z′) as a function to Z′ mass for all the width



Summary

- We have presented an analysis for a search of a top-philic Z′ produced with and decaying to 2 tops (4 top quarks in total). We use the Run 2 dataset.
- We focus on the single lepton (electron or muon) final state
- First search at CMS (together with the dilepton final state)
- Significant Z′-top quark mass splitting resulting in a boosted top quark
  - use of dedicated machine learning algorithm, crucial for the signal sensitivity
- Highest sensitivity at LHC, improving upon ATLAS's results and expanding the search down to 500 GeV
- We are now PAS-PUB
- Target journal: JHEP

Back up

Analysis strategy: object definition

- Objects definition relies on the official recommendations
  - Muon:
    - $|\eta| < 2.4$, $D_{xy} < 0.2$, $D_z < 0.5$
    - Loose: cutbase loose with Iso< 0.25, pT > 15 GeV
    - Tight: cutbased tight with Iso < 0.15, pT > 26 GeV (29 GeV for 2017)
    - Official corrections link, link, link
  - Electron:
    - $|\eta| < 2.5$, $1.4442 < |\eta| < 1.566$ is removed
    - Loose: MVA WP90Iso ID, pT > 15 GeV
    - Tight: MVA WP80Iso ID, pT > 33 GeV (26 GeV for 2016)
    - official corrections link
  - AK8 jets:
    - pT > 300 GeV, $|\eta| < 2.4$, overlap removal with leptons
  - AK4 jets:
    - pT ≥ 30 GeV, $|\eta| < 2.5$ (2.4 for 2016), overlap removal with leptons and AK8 jets
    - latest JEC and JER included link

Signal region distribution

- Signal Region efficiency table
  - Cumulative efficiency for 2018, results are in percentage

Selection	ttZ′ ($m_{Z'} = 500\ GeV, \Gamma/m = 4\%$) (mu)	ttZ′ ($m_{Z'} = 3\ TeV, \Gamma/m = 4\%$) (mu)	ttZ′ ($m_{Z'} = 500\ GeV, \Gamma/m = 4\%$) (e)	ttZ′ ($m_{Z'} = 3\ TeV, \Gamma/m = 4\%$) (e)
Ini evt	100.000±0.000	100.000±0.000	100.000±0.000	100.000±0.000
exactly 1 lepton	15.115±0.036	13.113±0.034	11.271±0.032	10.304±0.030
HLT	13.809±0.035	11.890±0.032	9.751±0.030	8.723±0.028
Noise Filter	13.788±0.034	11.751±0.032	9.733±0.030	8.629±0.028
$HT > 700$ GeV	9.130±0.029	11.648±0.032	6.570±0.025	8.549±0.028
$MET > 60$ GeV	6.696±0.025	10.523±0.031	4.792±0.021	7.693±0.027
$number\ of\ jets \geq 6$	6.385±0.024	9.468±0.029	4.558±0.021	6.909±0.025
$\geq 2\ boosted\ tops, \geq 1\ b-tagged\ jets$	0.151±0.004	2.488±0.016	0.102±0.003	1.781±0.013

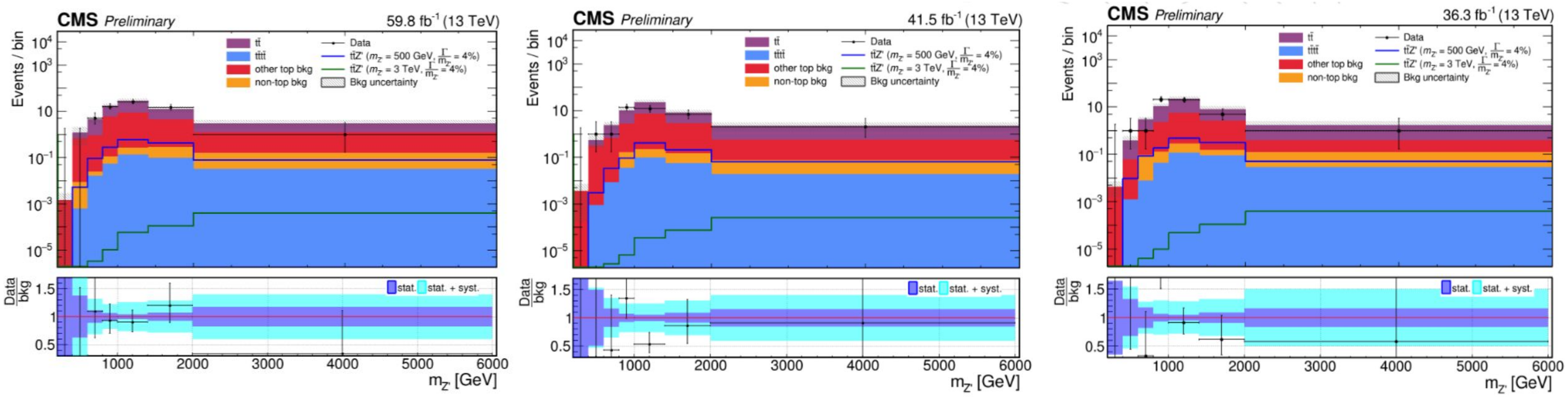
  - Relative efficiency for 2018, results are in percentage

Selection	ttZ′ ($m_{Z'} = 500\ GeV, \Gamma/m = 4\%$) (mu)	ttZ′ ($m_{Z'} = 3\ TeV, \Gamma/m = 4\%$) (mu)	ttZ′ ($m_{Z'} = 500\ GeV, \Gamma/m = 4\%$) (e)	ttZ′ ($m_{Z'} = 3\ TeV, \Gamma/m = 4\%$) (e)
Ini evt	100.000±0.000	1100.000±0.000	100.000±0.000	100.000±0.000
exactly 1 lepton	15.115±0.036	13.113±0.034	11.271±0.032	10.304±0.030
HLT	91.360±0.072	90.673±0.080	86.512±0.102	84.657±0.112
Noise Filters	99.844±0.011	98.830±0.031	99.818±0.014	98.926±0.035
$HT > 700$ GeV	66.221±0.127	99.128±0.027	67.497±0.150	99.075±0.033
$MET > 60$ GeV	73.337±0.146	90.339±0.087	72.944±0.173	89.981±0.103
$number\ of\ jets \geq 6$	95.358±0.081	89.978±0.093	95.117±0.098	89.808±0.109
$\geq 2\ boosted\ tops, \geq 1\ b-tagged\ jets$	2.412±0.061	27.891±0.146	2.288±0.070	27.383±0.170

- Single lepton selection includes 4 top branching ratio to 1 lepton
- Cumulative efficiency higher at higher masses because of enhanced efficiency in selecting boosted tops

Background estimation

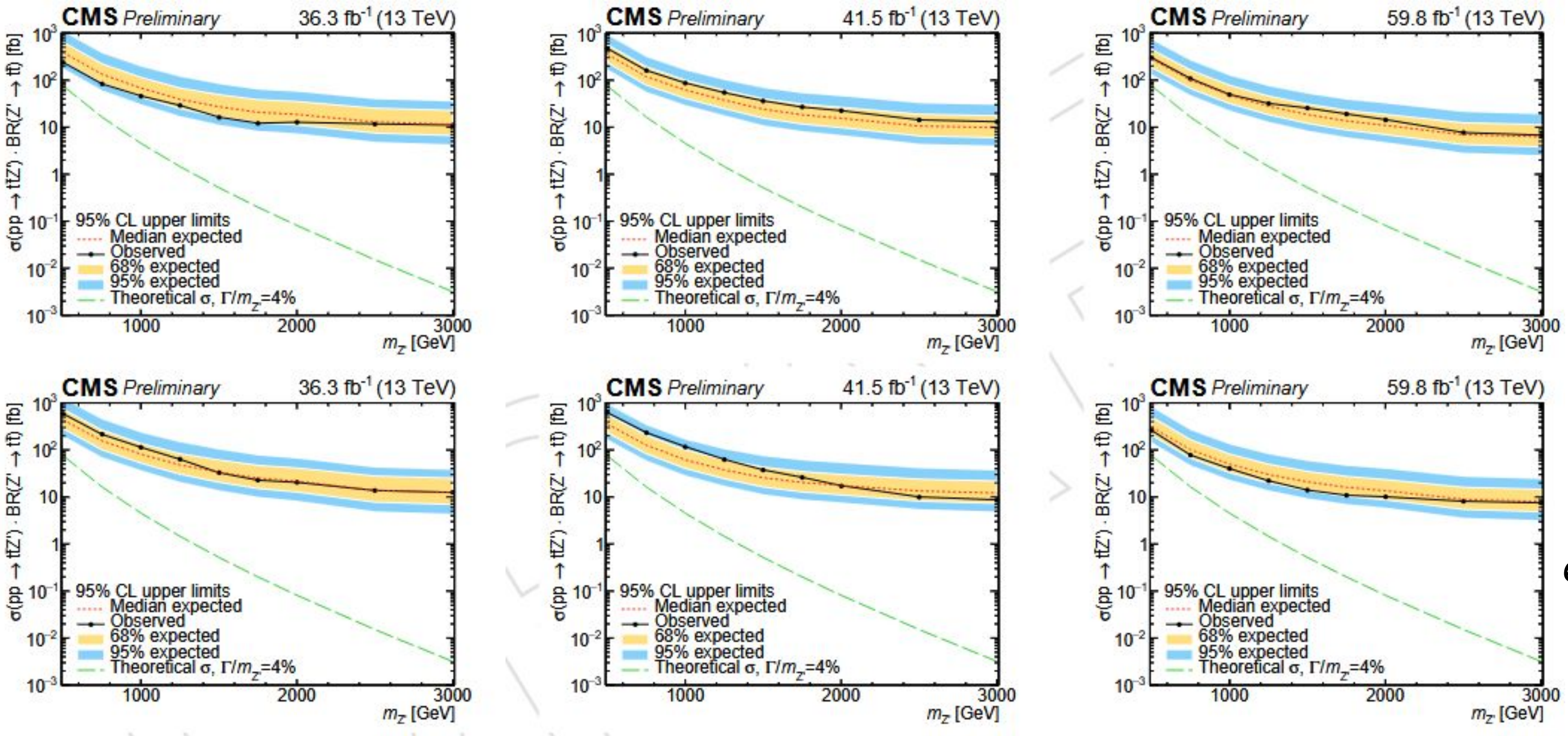
- Data to background simulation modeling in CR:



- Use rate parameter and scale all the background samples of each year
  - This normalization scale factor will be applied in the simultaneous fit with SR and CR together.

Observed limits

Observed limits per year per channel

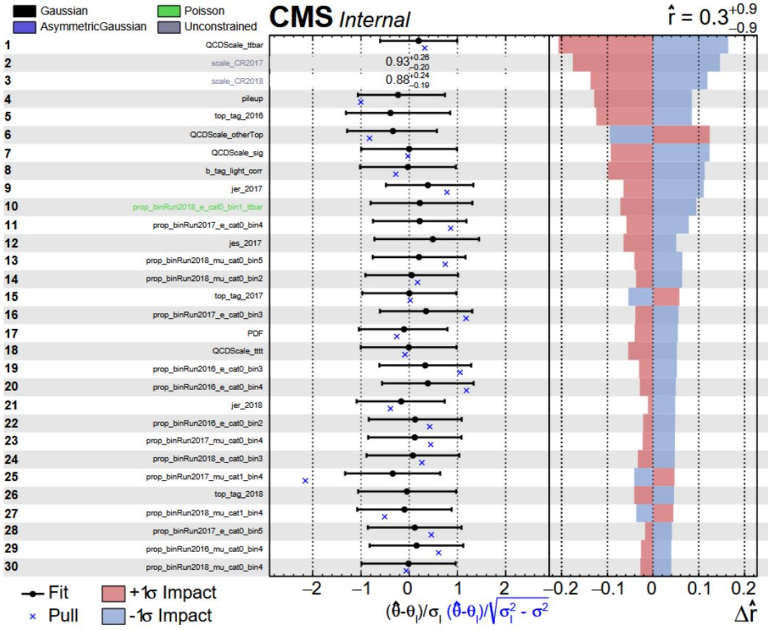


muon

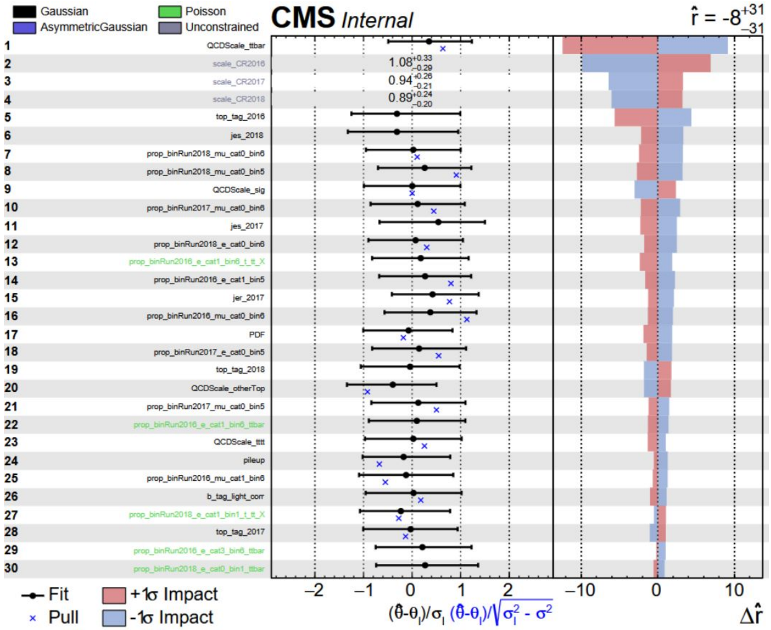
electron

Impacts

- Low mass point of 500 GeV



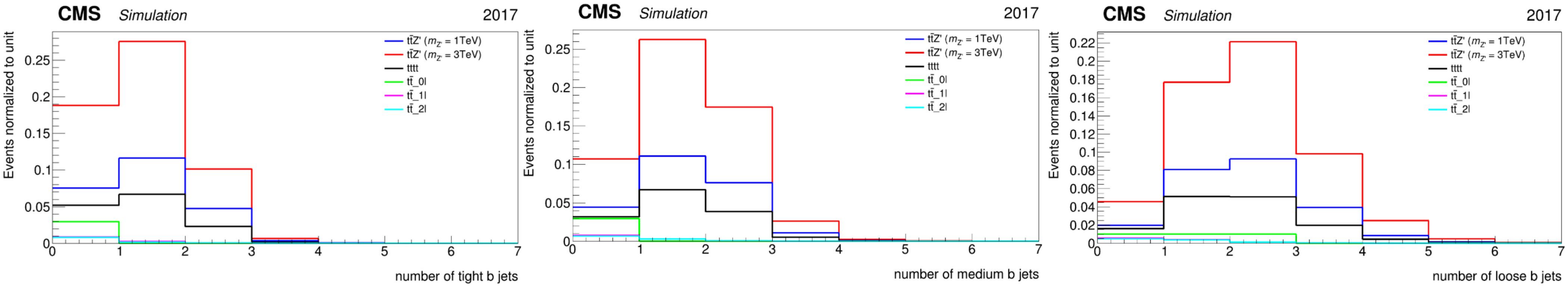
High mass point of 2 TeV



- QCD scale has a big impact and also observed this situation in ttbar resonance search (link)
- Background normalization plays an important role in our analysis

event categorization

- >=2 boosted tops category



>= 1 loose b jets can keep most of the signal samples

cross triggers study (1)

- please provide more detailed cut-flow information on how you estimated trigger improvement from including HT HLT path

The same cross triggers with 4top analysis: (single lepton + HT triggers)

Year	Electron	Muon
2016	HLT_Ele32_eta2p1_WPTight_Gsf_v*	HLT_IsoMu24_v* HLT_IsoTkMu24_v*
2017	HLT_Ele15_IsoVVVL_PFHT450_v* HLT_Ele50_IsoVVVL_PFHT450_v* HLT_Ele15_IsoVVVL_PFHT600_v* HLT_Ele35_WPTight_Gsf_v* HLT_Ele38_WPTight_Gsf_v*	HLT_Mu15_IsoVVVL_PFHT450_v* HLT_Mu50_IsoVVVL_PFHT450_v* HLT_Mu15_IsoVVVL_PFHT600_v* HLT_Mu50_v*
2018	HLT_Ele15_IsoVVVL_PFHT450_v* HLT_Ele50_IsoVVVL_PFHT450_v* HLT_Ele15_IsoVVVL_PFHT600_v* HLT_Ele15_IsoVVVL_PFHT450_PFMET50_v* HLT_Ele35_WPTight_Gsf_v* HLT_Ele38_WPTight_Gsf_v*	HLT_Mu15_IsoVVVL_PFHT450_v* HLT_Mu50_IsoVVVL_PFHT450_v* HLT_Mu15_IsoVVVL_PFHT600_v* HLT_Mu15_IsoVVVL_PFHT450_PFMET50_v* HLT_Mu50_v* HLT_TkMu50_v*

TOP-21-005

Detailed contents

also keep the same lepton definition with 4top analysis for this test (mini-isolation)

cross triggers study (2)

- **Efficiency comparison (2018 muon channel) (Relative eff.)**

official single lepton triggers

Selection	ttZ′ ($m_{Z'} = 500\ GeV, \Gamma/m = 4\%$) (mu)
Ini evt	100.00000±0.00000
exactly 1 lepton	15.11530±0.03582
HLT	91.35975±0.07227
Noise Filters	99.84358±0.01063
$HT > 700$ GeV	66.22062±0.12737
$MET > 60$ GeV	73.33713±0.14634
$number\ of\ jets \geq 6$	95.35835±0.08130
$\geq 2\ boosted\ tops, \geq 1\ b-tagged\ jets$	2.41187±0.06071
$ST > 200$ GeV	100.00000±0.00000

cross triggers

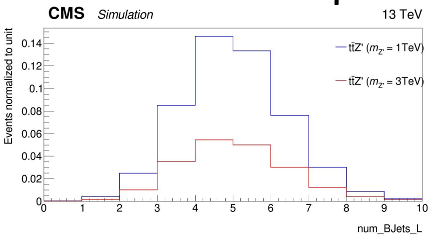
Selection	TTZprime_M500W4
Ini evt	100.00000±0.00000
exactly 1 lepton	18.58370±0.03890
HLT	93.54111±0.05702
$HT > 700$	69.21201±0.11072
$MET_{Pt} > 60$	72.29749±0.12902
$numberofjets >= 6$	94.93125±0.07438
$>= 2boostedtops, >= 1b - taggedjets$	2.50023±0.06183
$ST > 200GeV$	100.00000±0.00000

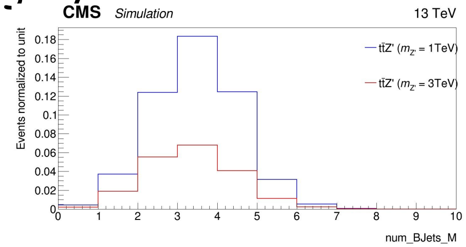
Efficiency not improve so much.
Cross triggers don't have official SFs

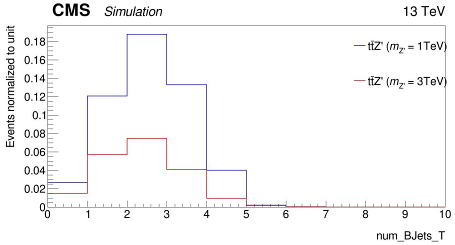
Category study (1)

- **Event categorization**

❖ 0 boosted top category:

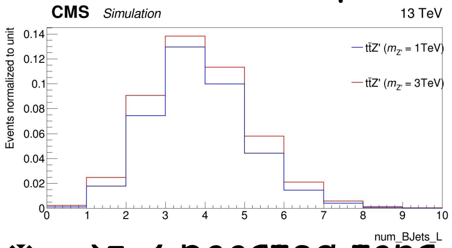


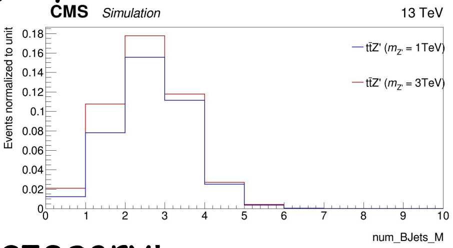


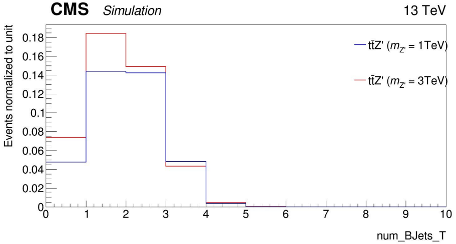


>= 3 loose b jets, >= 2 medium b jets, >= 1 tight b jets

❖ 1 boosted top category:

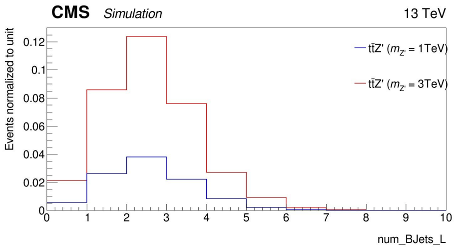


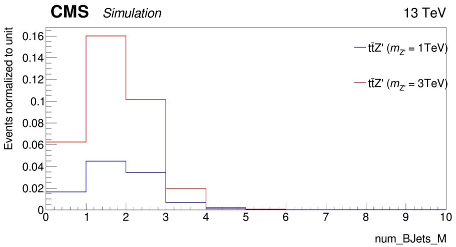


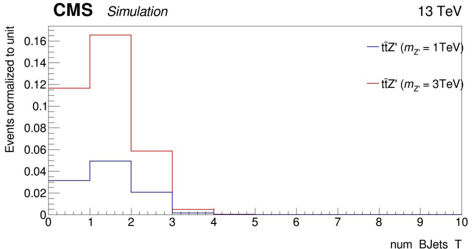


>= 2 loose b jets, >= 1 medium b jets

❖ >= 2 boosted tops category:





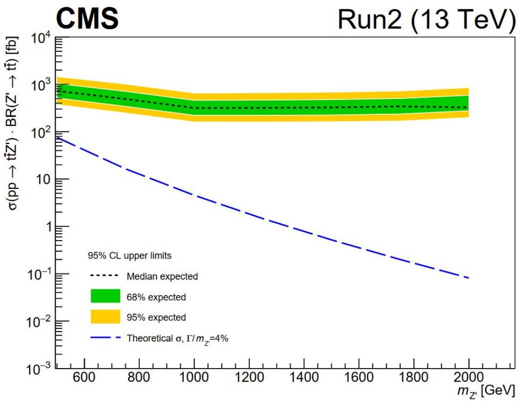


>= 1 loose b jets

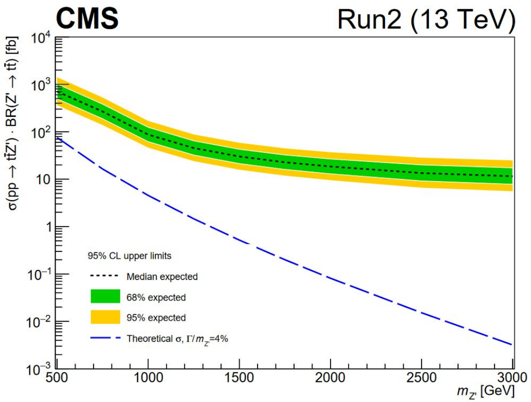
Category study (2)

Limit results:

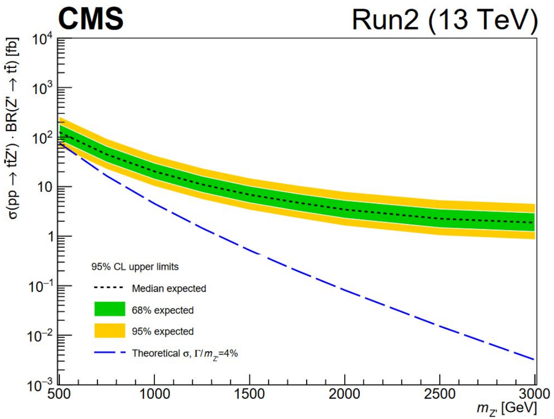
0 boosted top category



1 boosted top category



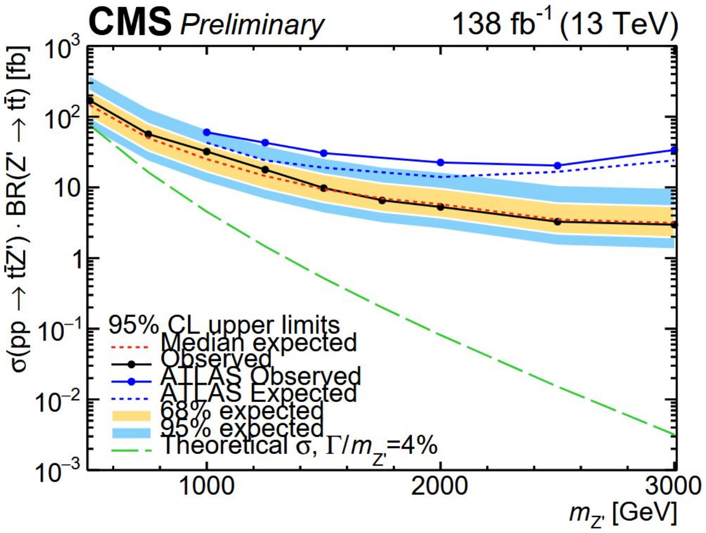
>= 2 boosted tops category



>= 2 boosted tops category drives our sensitivity
Other 2 categories didn't contribute too much

Fake Top Study (1)

- Cross check for the rate parameter origin
  - -> mismodeling of the fake top tagging efficiency for particleNet algorithm
- Add a new shape uncertainty that scales to the number of fake tops in the event
  - applied to every process including signal
  - set a 40% uncertainty for each fake top (slightly higher than a typical uncertainty on fake objects around 20% to 30%)
- Limit results:



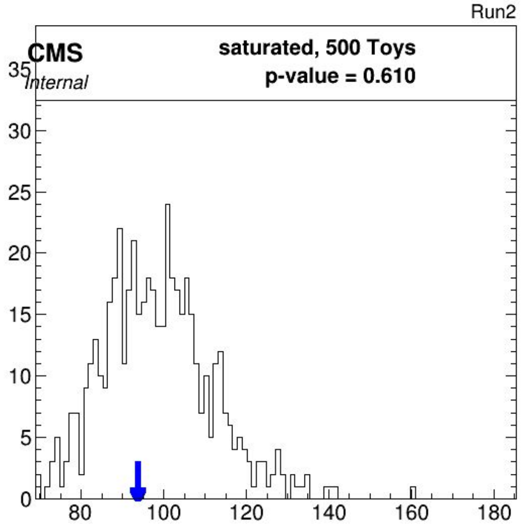
Quite similar with our rate-param-based modeling

Thanks to our ARC !

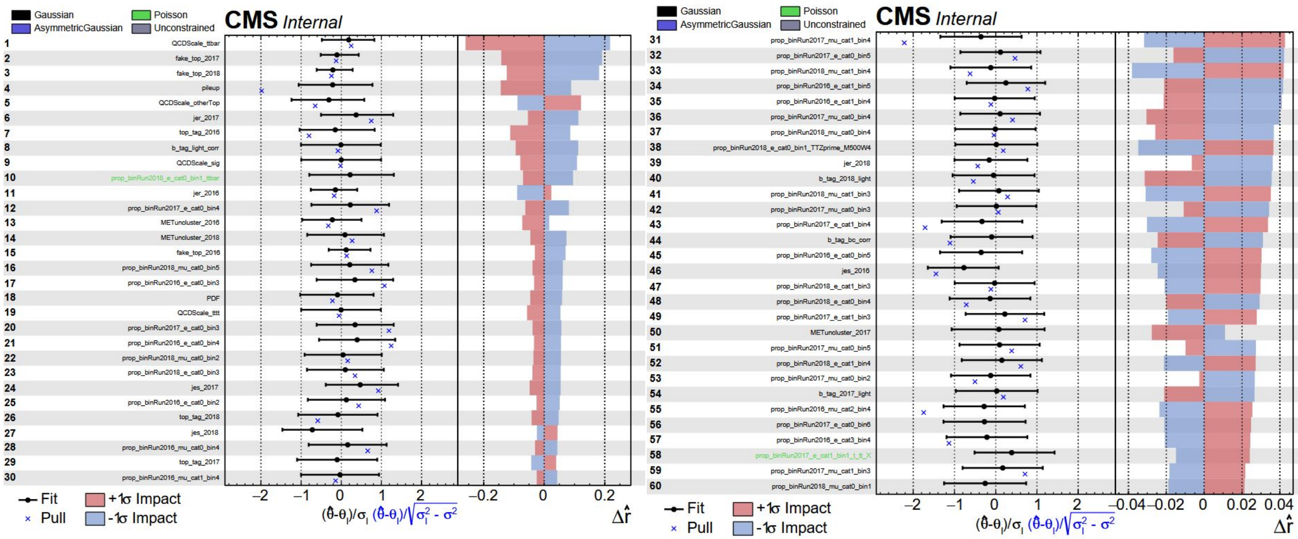
Fake Top Study (2)

- Comparison for Full Run2:

Goodness of Fit



Impacts plot for mass 500 GeV

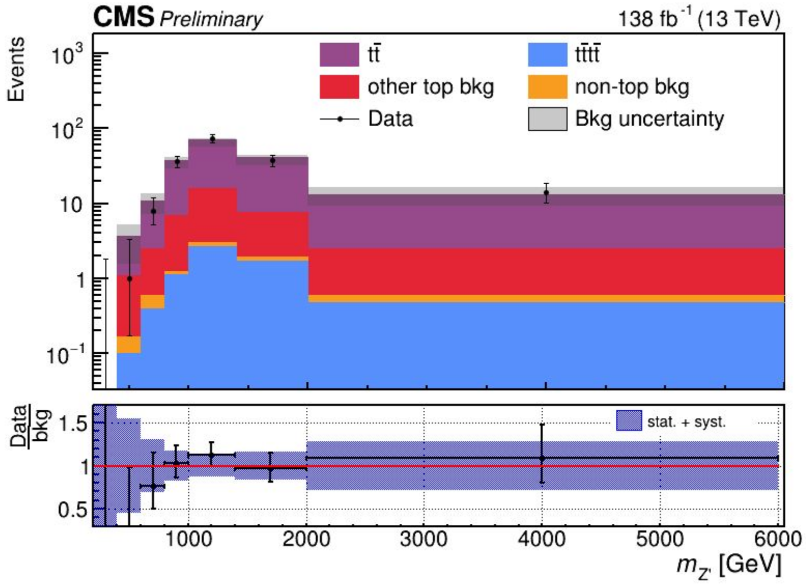


Statistical tests are fine and similar with using rate-para-based modeling

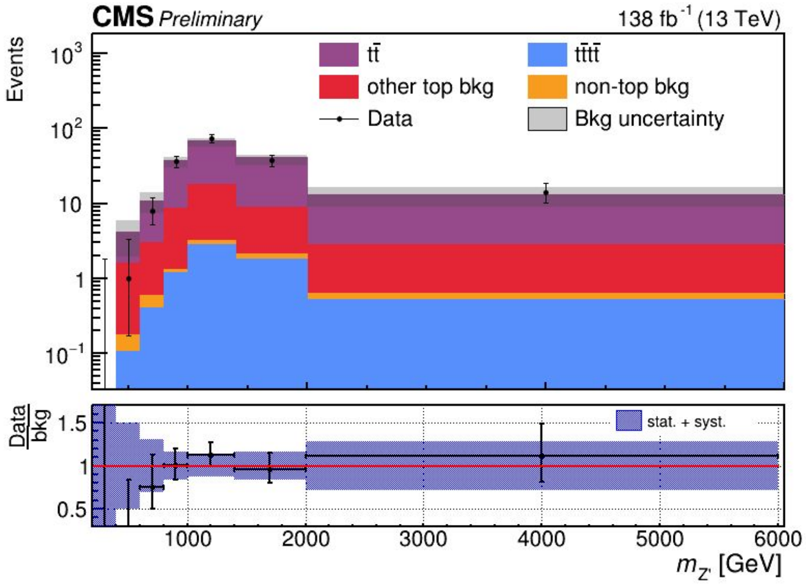
Fake Top Study (3)

- Post-fit results comparison:

rate parameter method



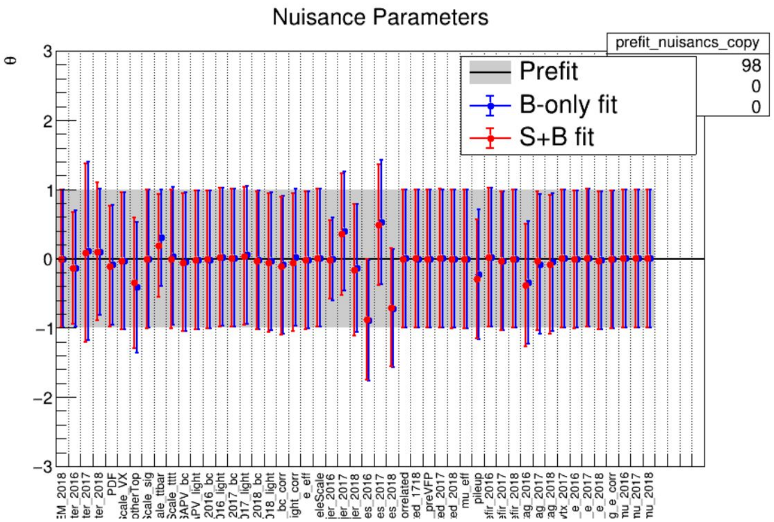
fake top method



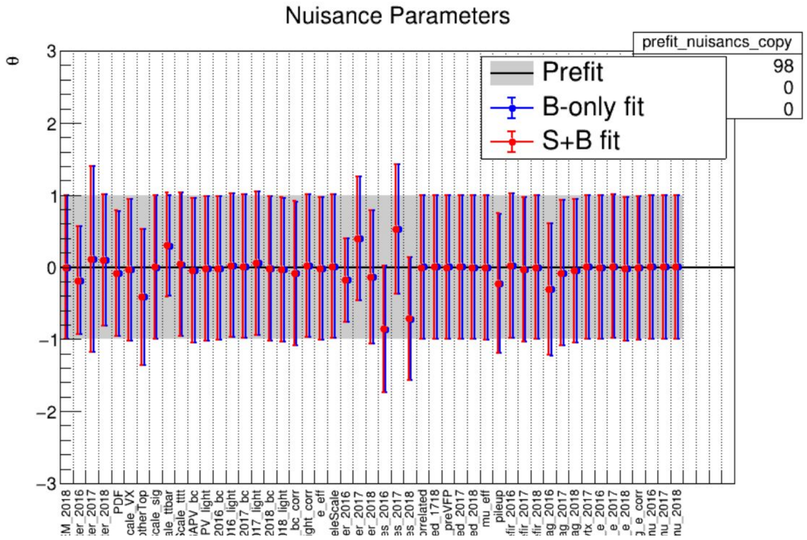
Post-fit background shapes and normalizations are compatible between the two methods
-> This test validate the used methods

- Nuisance parameter pull tests:

Mass 500 GeV



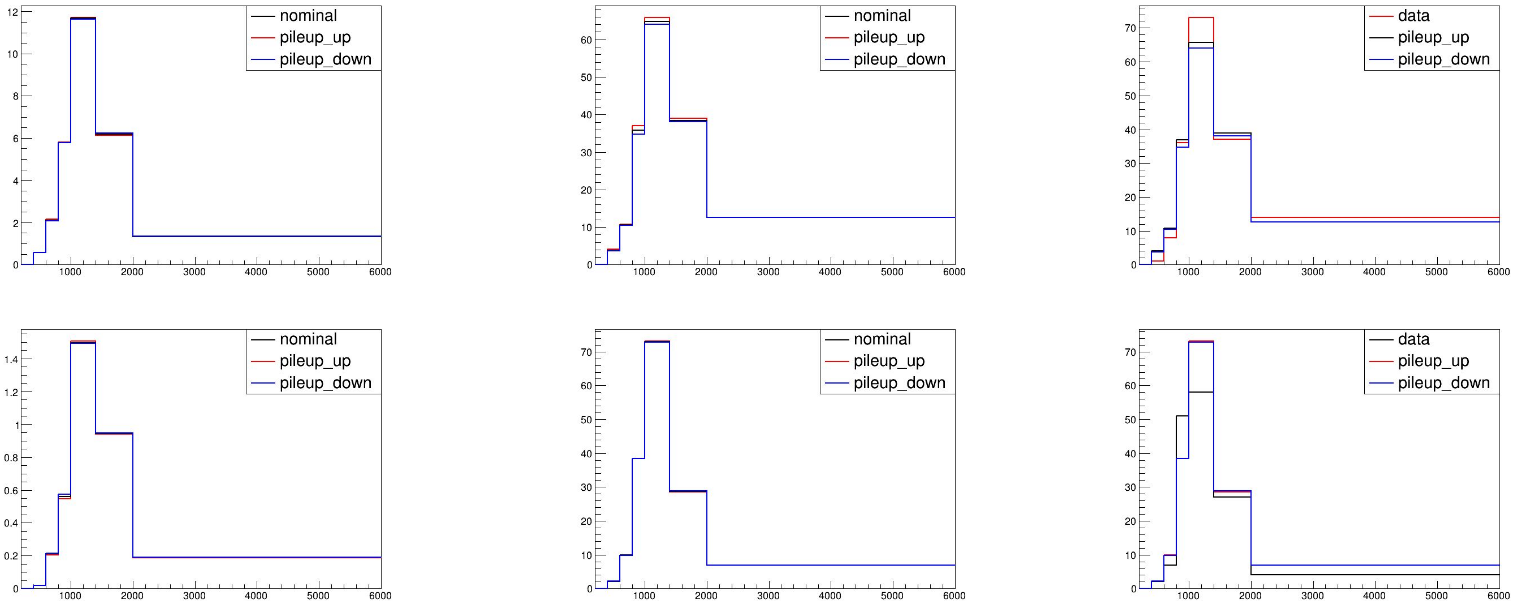
Mass 3 TeV



Statistical tests (2)

- Templates for some variables which have high impacts:

signal mass 500 GeV | all the background | data + up/down from all the bkg



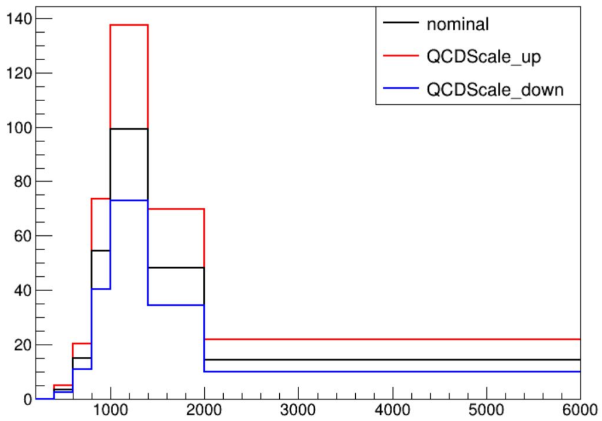
SR

CR

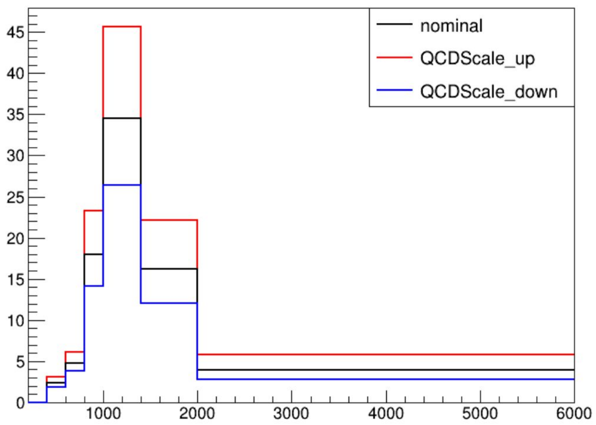
Statistical tests (3)

- Templates for some variables which have high impacts:

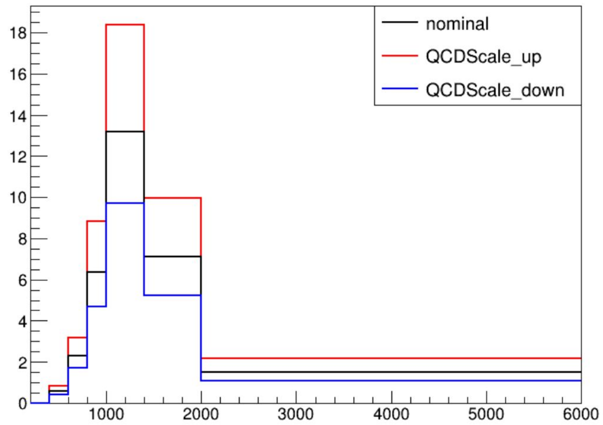
QCD Scale for ttbar



QCD Scale for other tops



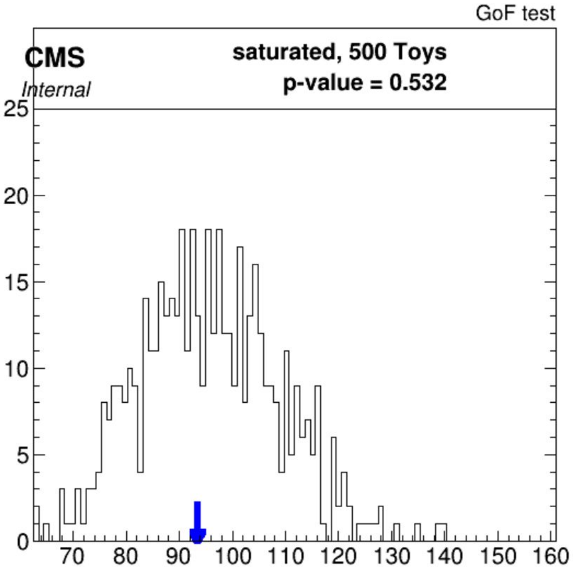
QCD Scale for signal



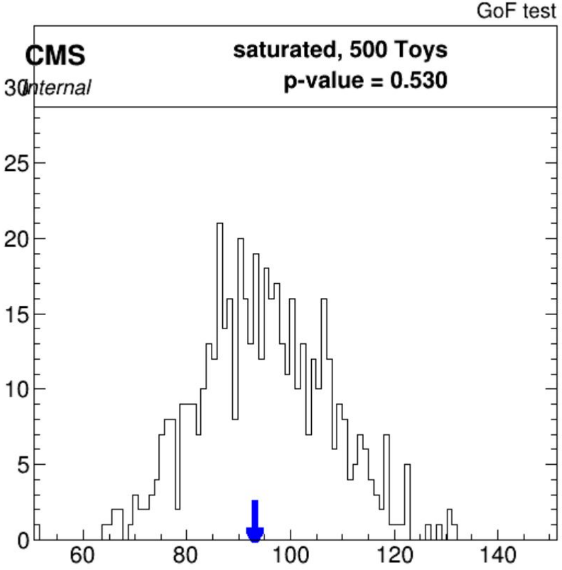
Statistical tests (4)

- Goodness of Fit:

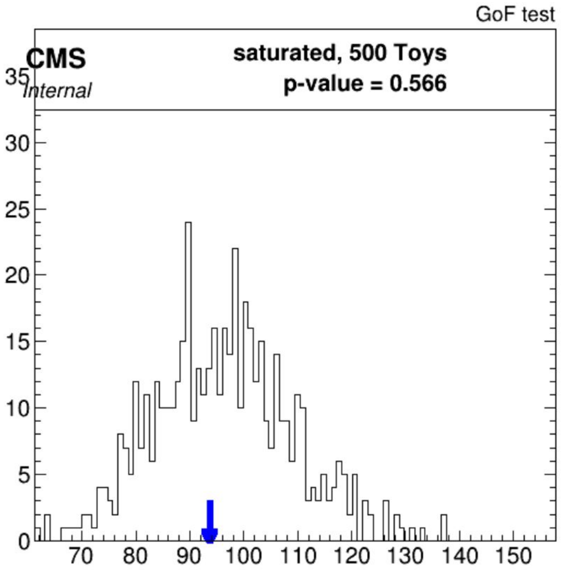
Mass 500 GeV



Mass 1 TeV

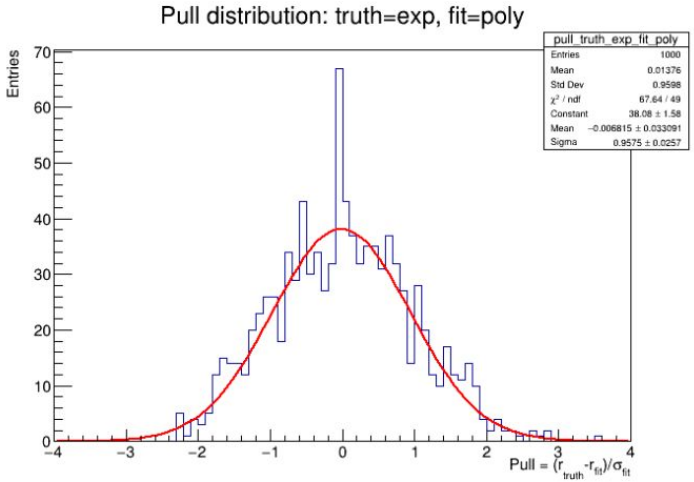


Mass 3 TeV

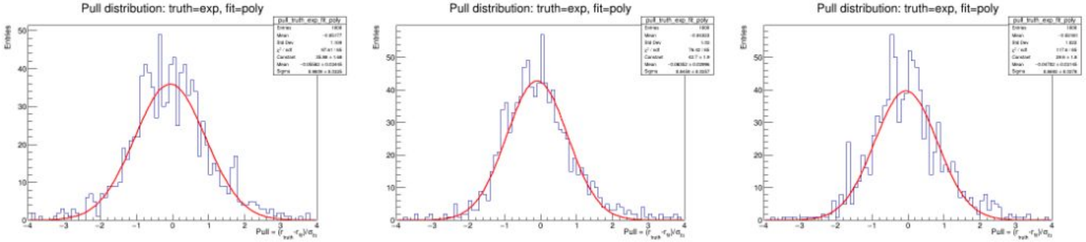


Statistical tests (5)

- Signal injection tests:
  Mass 500 GeV

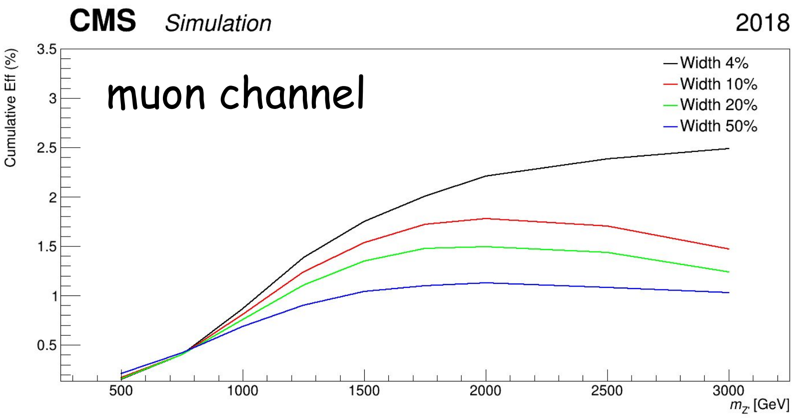


r = 0



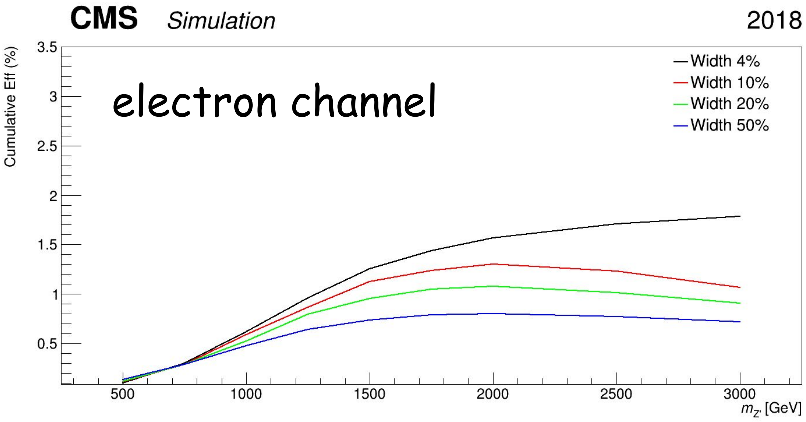
r = lower, median, upper limits

Signal efficiency



Selection	TTZprime_M500W4	TTZprime_M500W10	TTZprime_M500W20	TTZprime_M500W50
Ini evt	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000
1 lepton (with HLT)	13.80982±0.03450	13.78525±0.03447	13.79638±0.03449	13.80672±0.03450
MET requirement	10.06874±0.03009	10.07119±0.03009	10.09001±0.03012	10.16014±0.03021
$number\ of\ jets >= 6$	8.82655±0.02837	8.82040±0.02836	8.86322±0.02842	8.94735±0.02854
$HT > 700$	6.39016±0.02446	6.37353±0.02443	6.48784±0.02463	6.72286±0.02504
$>= 1\ b\ jets$	6.35336±0.02439	6.33713±0.02436	6.45014±0.02456	6.67936±0.02497
$>= 2\ boosted\ tops$	0.15140±0.00389	0.16710±0.00408	0.15910±0.00399	0.20990±0.00458

Selection	TTZprime_M3000W4	TTZprime_M3000W10	TTZprime_M3000W20	TTZprime_M3000W50
Ini evt	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000
1 lepton (with HLT)	11.89008±0.03237	13.03830±0.03369	13.36039±0.03402	13.67123±0.03437
MET requirement	10.60508±0.03079	10.86023±0.03113	10.94509±0.03122	11.05953±0.03138
$number\ of\ jets >= 6$	9.51518±0.02934	9.79266±0.02974	9.90279±0.02987	10.02980±0.03005
$HT > 700$	9.46668±0.02928	9.12970±0.02882	9.10369±0.02877	9.08936±0.02876
$>= 1\ b\ jets$	9.20018±0.02890	8.96554±0.02858	8.96129±0.02856	8.96063±0.02858
$>= 2\ boosted\ tops$	2.48680±0.01557	1.47297±0.01205	1.23760±0.01106	1.02983±0.01010



Selection	TTZprime_M500W4	TTZprime_M500W10	TTZprime_M500W20	TTZprime_M500W50
Ini evt	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000
1 lepton (with HLT)	9.75092±0.02966	9.66479±0.02955	9.66765±0.02955	9.71305±0.02961
MET requirement	7.07257±0.02564	7.01618±0.02554	7.03292±0.02557	7.10672±0.02569
$number\ of\ jets >= 6$	6.18689±0.02409	6.13210±0.02399	6.14474±0.02401	6.23834±0.02418
$HT > 700$	4.55472±0.02085	4.56935±0.02088	4.60378±0.02096	4.78898±0.02135
$>= 1\ b\ jets$	4.52892±0.02079	4.54225±0.02082	4.57518±0.02089	4.75878±0.02129
$>= 2\ boosted\ tops$	0.10200±0.00319	0.11470±0.00338	0.11790±0.00343	0.13480±0.00367

Selection	TTZprime_M3000W4	TTZprime_M3000W10	TTZprime_M3000W20	TTZprime_M500W50
Ini evt	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000	100.00000±0.00000
1 lepton (with HLT)	8.72243±0.02822	9.49921±0.02933	9.71420±0.02961	9.83074±0.02979
MET requirement	7.75944±0.02675	7.89744±0.02698	7.94703±0.02705	7.91518±0.02701
$number\ of\ jets >= 6$	6.94836±0.02543	7.11187±0.02571	7.17875±0.02581	7.15914±0.02579
$HT > 700$	6.91026±0.02536	6.67784±0.02498	6.65546±0.02492	6.53204±0.02472
$>= 1\ b\ jets$	6.70677±0.02501	6.54581±0.02475	6.54106±0.02472	6.43855±0.02456
$>= 2\ boosted\ tops$	1.78246±0.01323	1.06645±0.01028	0.90668±0.00948	0.71880±0.00845