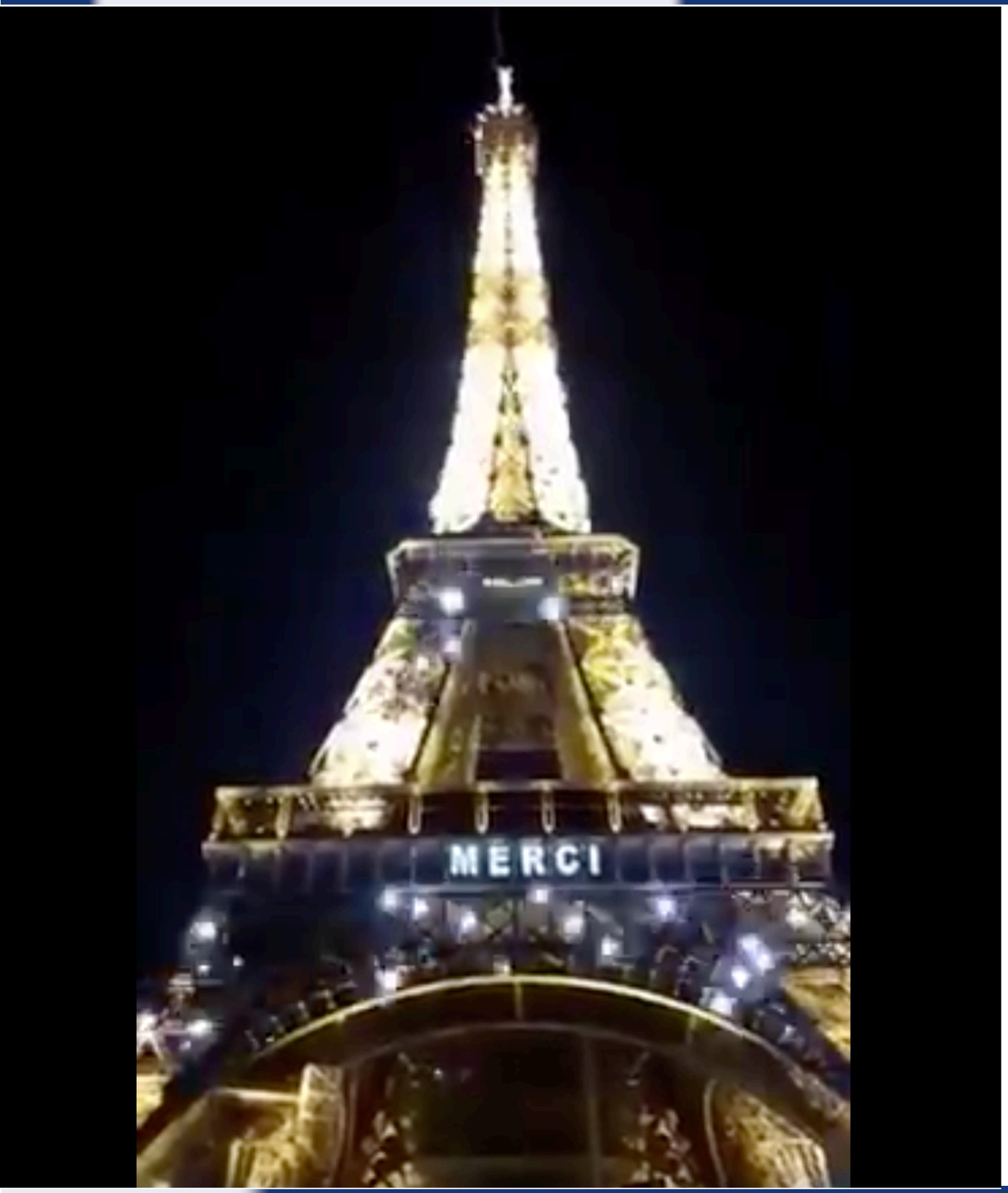
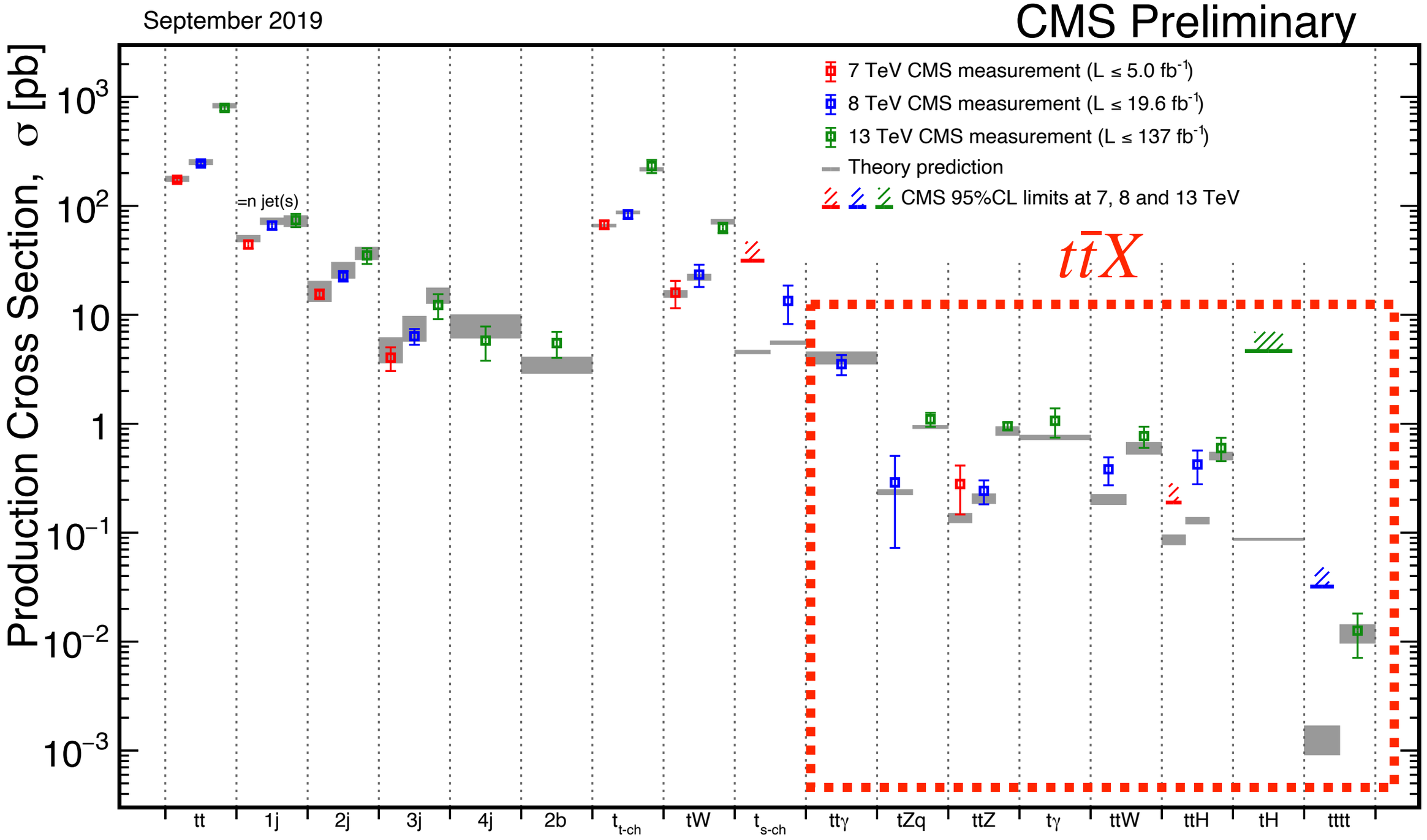


Rare top production processes, rare top decays

Elizaveta Shabalina
University of Göttingen

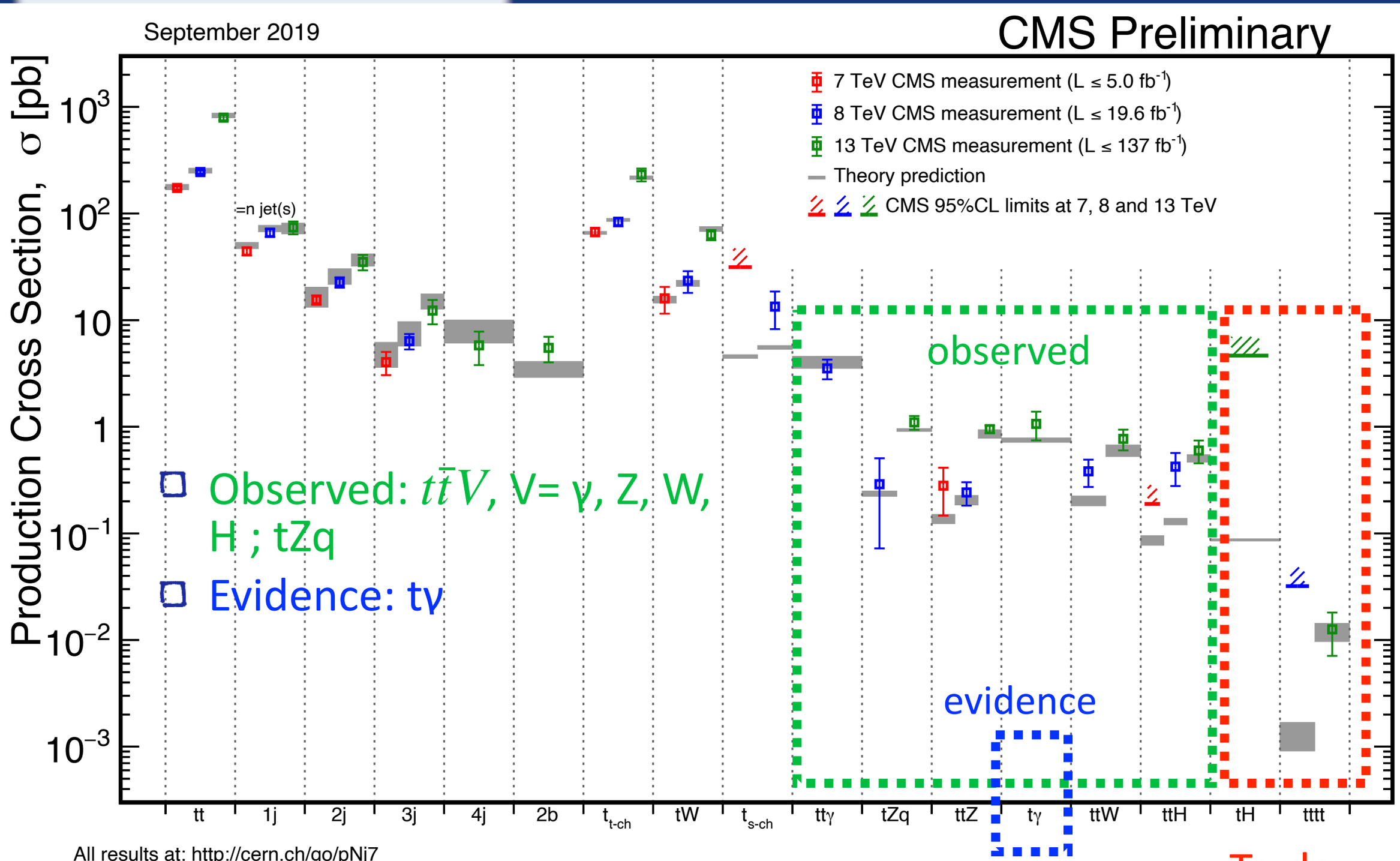
for ATLAS and CMS collaborations

Rare top processes status



- Very rich experimental field in Run 2 due to large statistics

Rare top processes status



- Observed: $t\bar{t}V$, V= γ, Z, W, H ; tZq
- Evidence: tγ

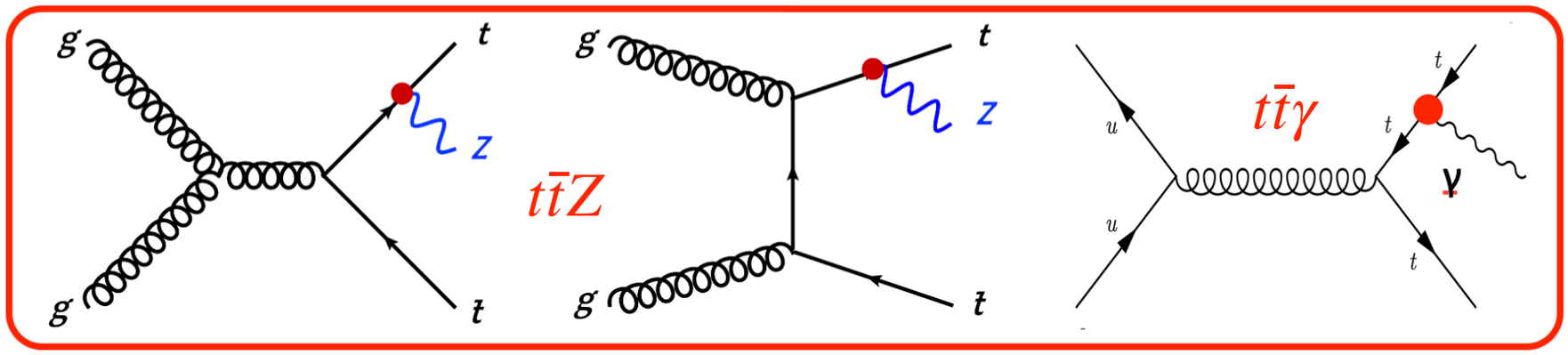
All results at: http://cern.ch/go/pNj7

To do: tH, $t\bar{t}t\bar{t}$

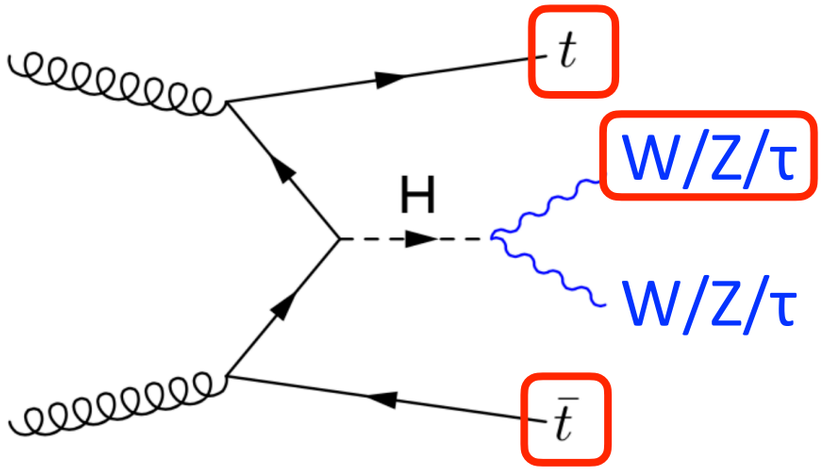
- Details in talks by P.Sabatini (ATLAS) and N.Chanon (CMS) in Top physics session on Friday 29/05

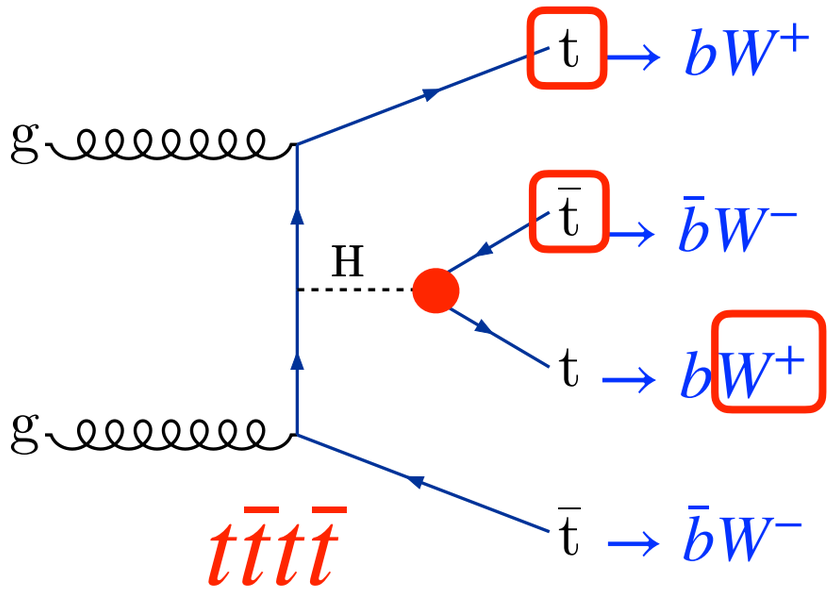
Rare top: signal and background

- Direct measurement of top quark coupling to gauge bosons
- It is sensitive to most of the leading EFT operators that preserve charge-parity and flavour in neutral currents



- $t\bar{t}W$ and $t\bar{t}Z$ are often dominant and irreducible backgrounds for many BSM searches and for $t\bar{t}H$





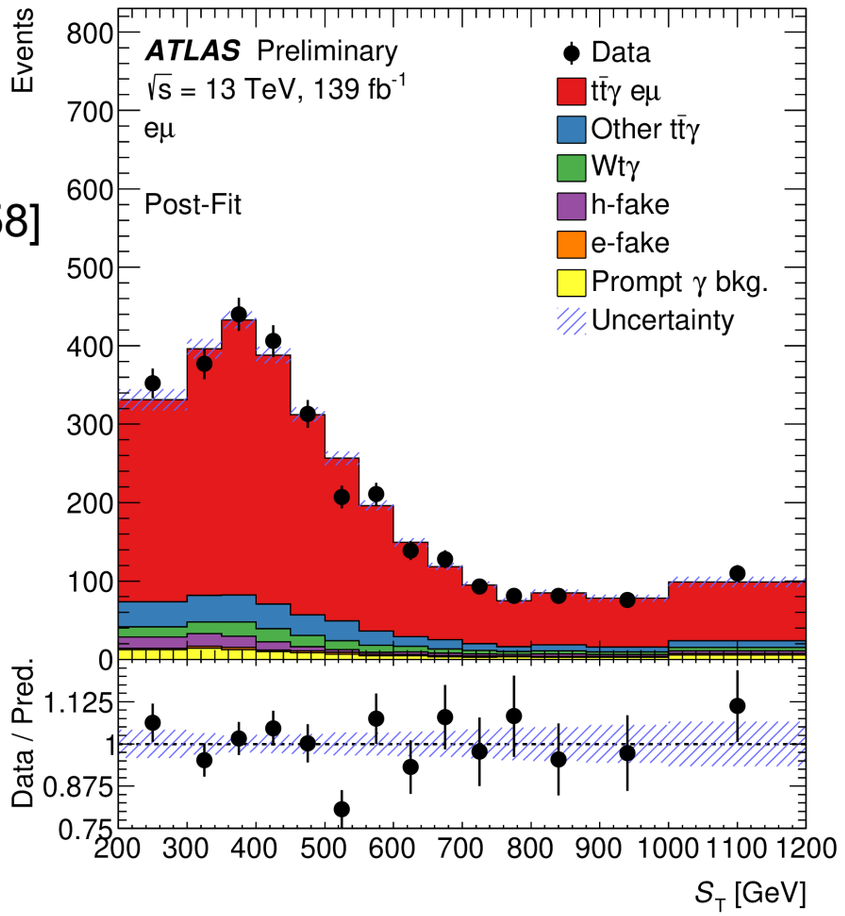
Heaviest particle final state

Measurements and searches with photons

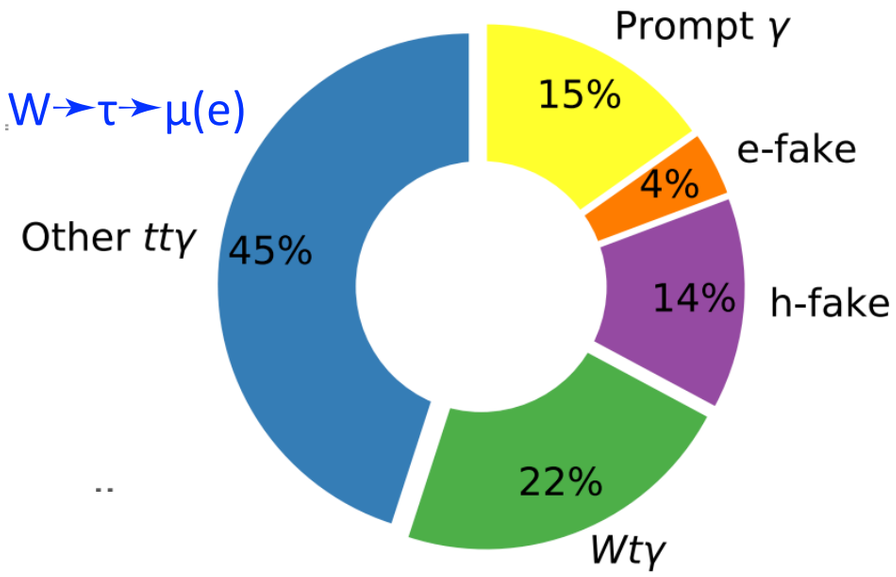
$t\bar{t}\gamma$ production

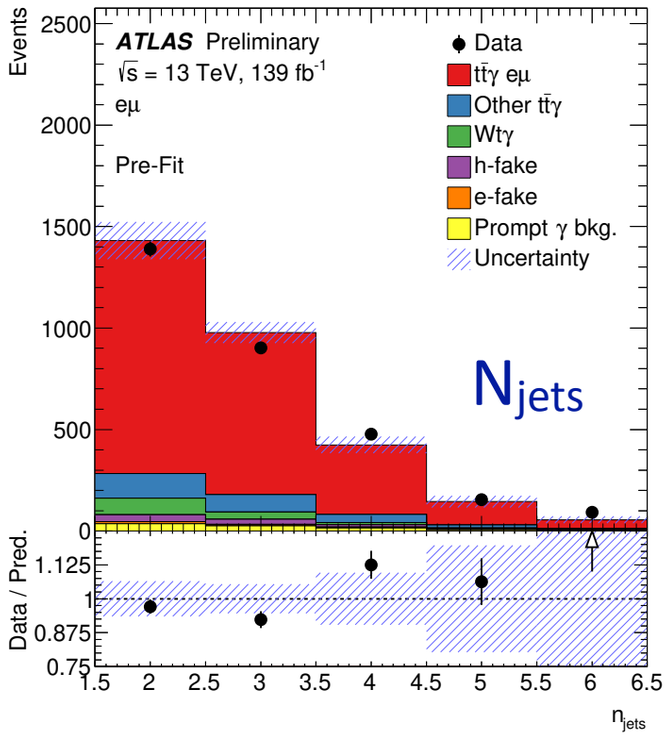
ATLAS-CONF-2019-042

- 139 fb^{-1}, eμ channel
- Highlight: comparison with fixed order NLO calculation including off-shell effects [JHEP 1810 (2018) 158]
- Selection: 1 e, 1 μ , 1 photon, $N_{jets} \geq 2$, $N_b \geq 1$
- Fiducial region defined to match theory calculation



Backgrounds





- Very pure channel - S/B ~ 4, 2.5K eμγ events

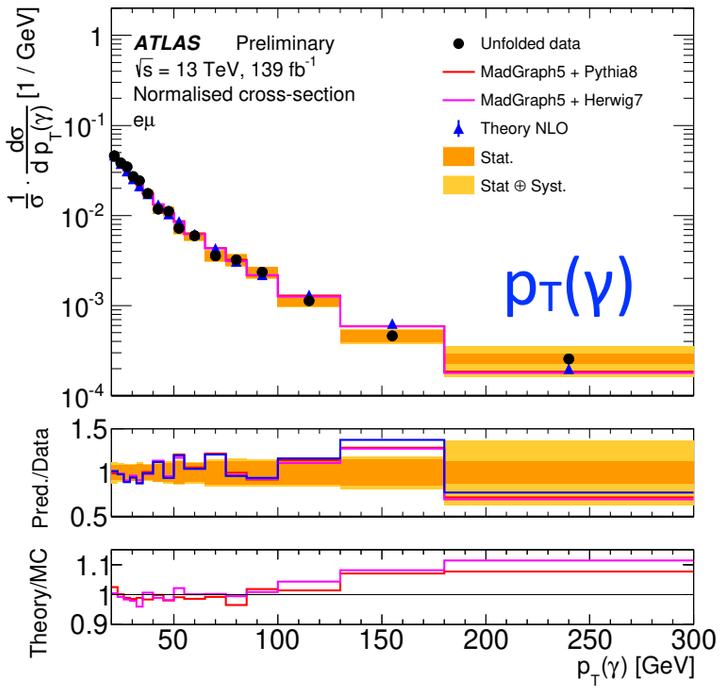
- Cross section extraction
  - Profile LH fit to S_T (scalar sum of all particle transverse momenta in event)

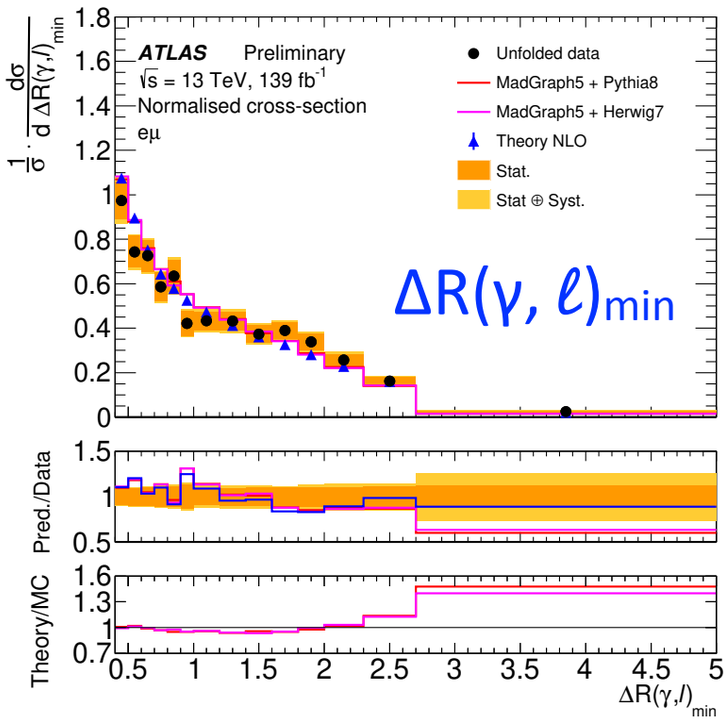
$$\sigma = 44.2 \pm 0.9(\text{stat})^{+2.6}_{-2.4}(\text{syst}) \text{ fb}$$ 6% relative uncertainty

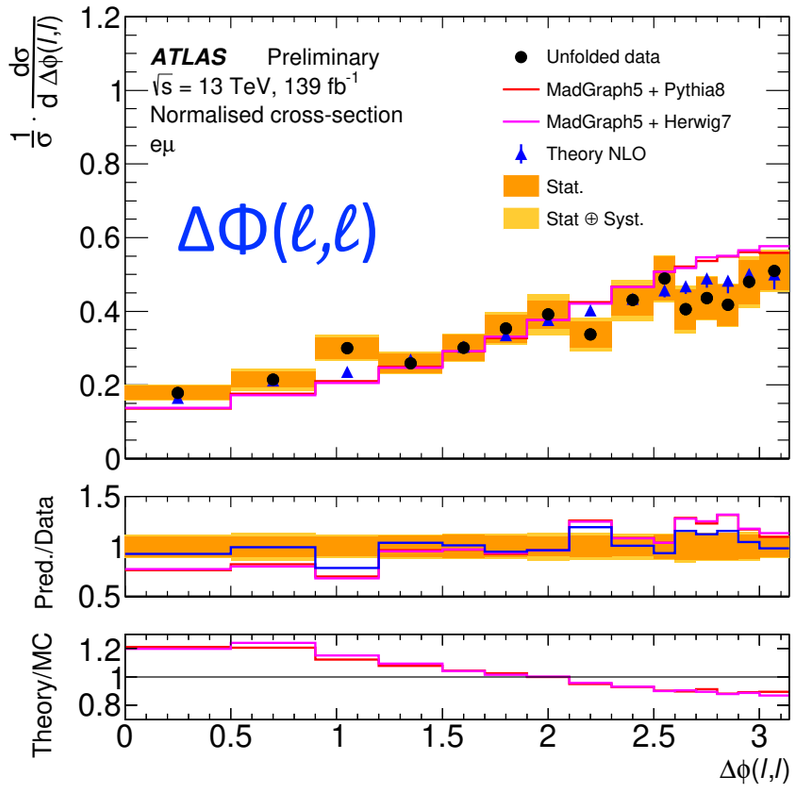
- Dominant systematics: MC modelling of ttγ (3.4%)

$t\bar{t}\gamma$ differential

- Variables:
  - photon p_T and $|\eta|$
  - $\Delta R(\gamma, \ell)_{min}$ - sensitive to $t\gamma$ coupling
  - $\Delta\phi(\ell,\ell)$ and $|\Delta\eta(\ell,\ell)|$
- Unfolded to parton level



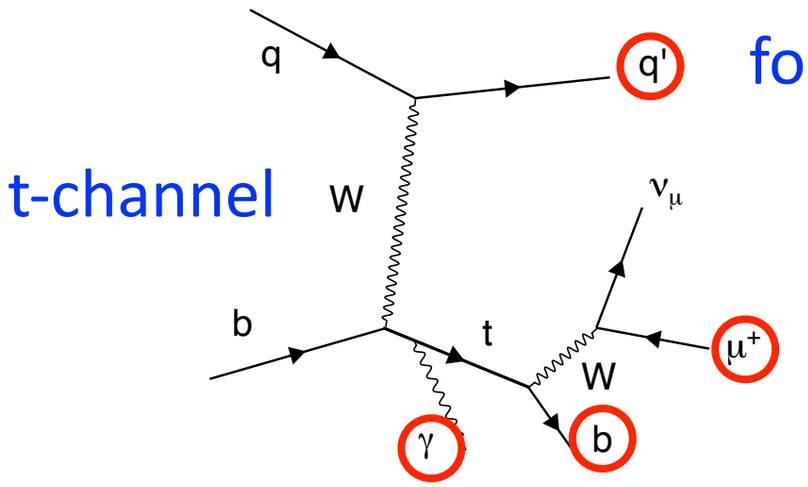




Predictions	$\Delta\phi(\ell,\ell)$ χ^2/ndf	p-value
MadGraph+Pythia8	35.2/14	<0.01
MadGraph+Herwig7	36.8/14	<0.01
Theory NLO	12.0/14	0.61

- Shapes are well described by both LO MadGraph 2->7 $t\bar{t}\gamma$ nominal simulation and NLO prediction
- The shape of the $\Delta\phi(\ell,\ell)$ is not perfectly modelled by the LO MadGraph simulation, NLO theory prediction gives better description

tγ production



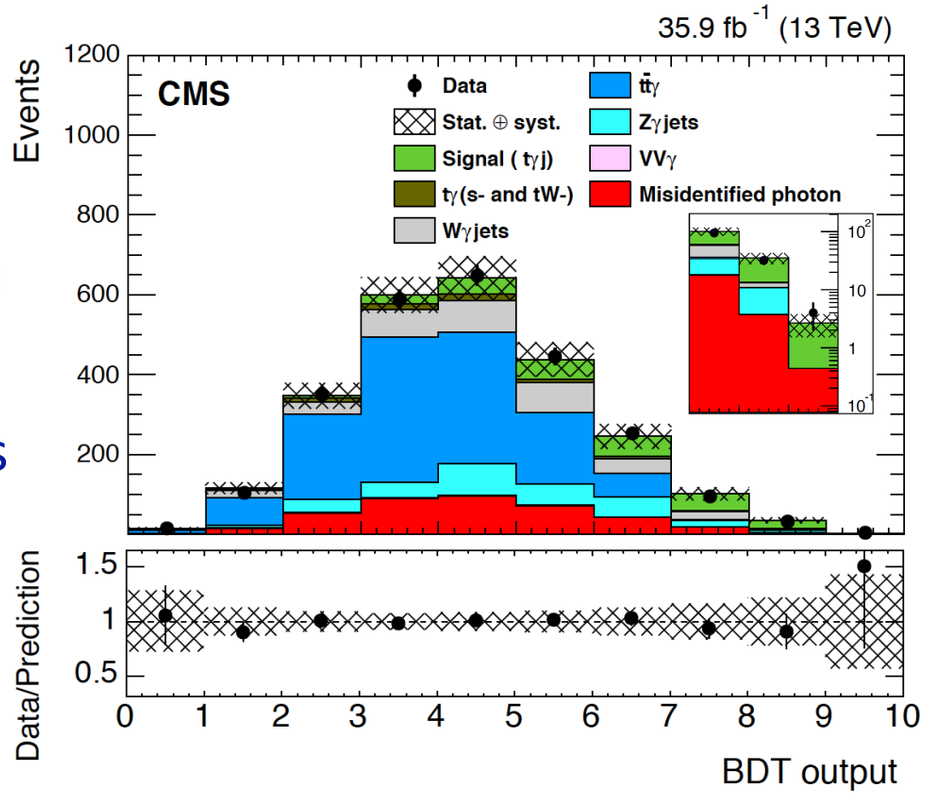
forward jet

- Selection:
  - 1 μ , 1 photon,
  - N_b=1, 1 forward jet
- Backgrounds:
  - irreducible
    - tγ : 9 times larger than expected signal
    - Zγ, Wγ : twice the signal
  - reducible
    - hadron (jet)—> photon fakes
    - determined from DD method

154 ± 24 tγ events expected

220 ± 63 tγ events observed

Phys. Rev. Lett. 121 (2018) 221802



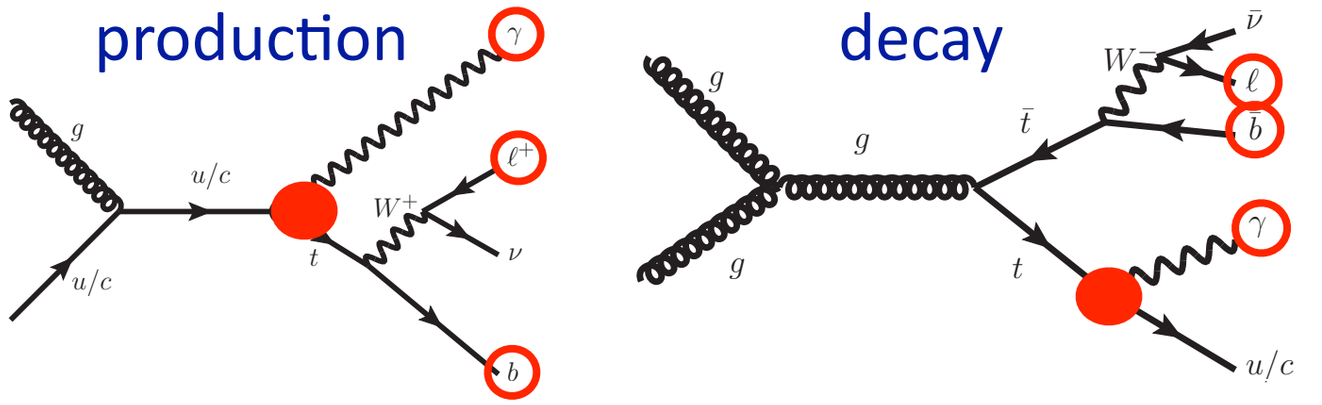
- BDT trained to separate signal
- ttγ shape determined from CR with N_b=2, included in the fit
- ttγ norm - free parameter the fit
- Main systematics: JES (12%), tγ model (9%)

Fiducial cross section (p_T^γ > 25 GeV, ΔR(X,γ)>0.5)

$$\sigma(pp \to t\gamma j) \times Br(t \to \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\ \text{fb}$$

Observed (expected) significance: 4.4 (3.0) σ

Search for FCNC: tqγ



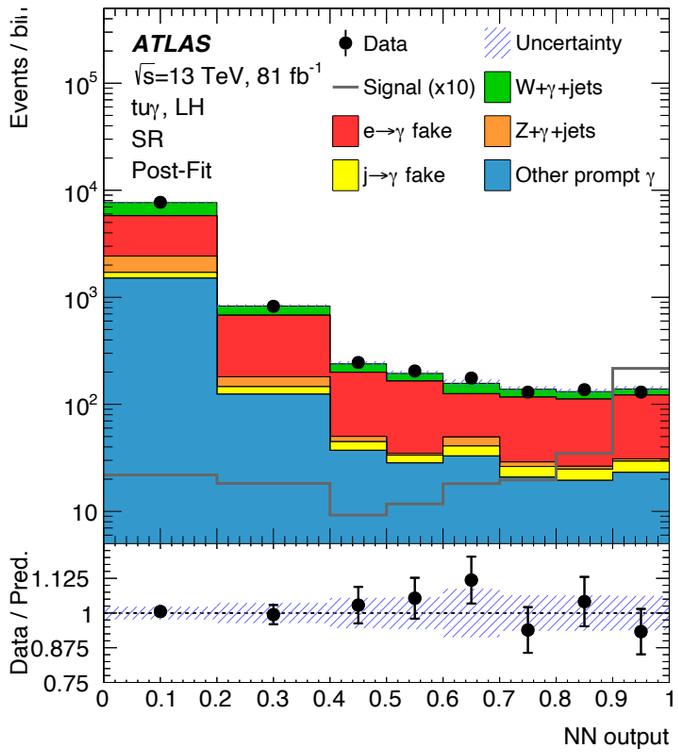
Forbidden in SM at tree level, suppressed at NLO

- Selection:
  - 1 e or μ , 1 photon, N_b=1
- Backgrounds:
  - reducible
    - e —> photon fakes from $t\bar{t}$
    - hadron fakes
    - determined from MC and data
  - irreducible
    - Wγ, Zγ
    - determined from MC and control regions
    - free parameters in the fit

- 4 NNs trained for tuγ, tcγ, LH, RH in production mode

ATLAS EXPERIMENT

Phys. Lett. B 800 (2019) 135082



Set limits on effective coupling parameters

Observable	Vertex	Coupling	Obs.	Exp.
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

Almost an order of magnitude improvement of limits over previous measurement

Measurements with Z bosons

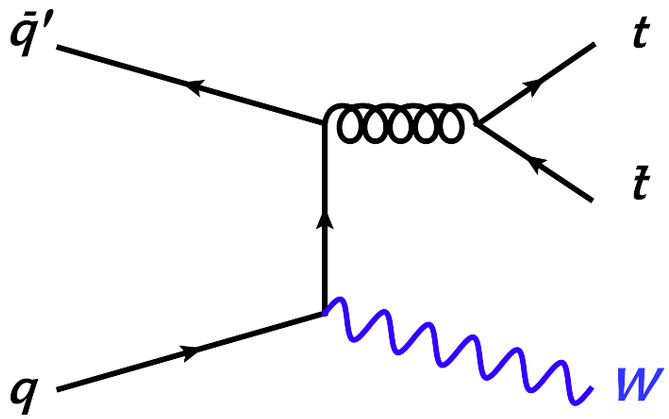
Measurements of ttV production

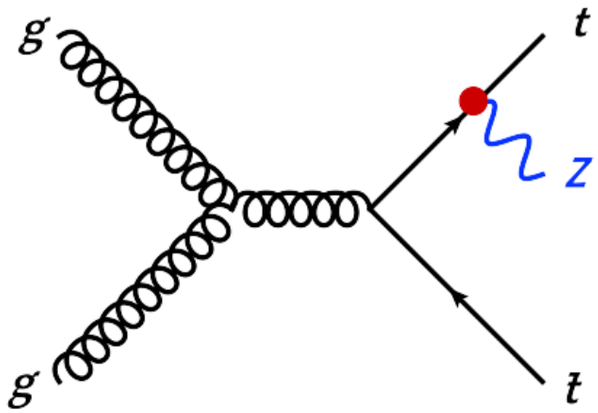
- Latest measurements use
  - $t\bar{t}W$ 36 fb^{-1}
  - $t\bar{t}Z$ 78 (36) fb^{-1} CMS (ATLAS)
- A lot of data still to analyse

Phys. Rev. D 99 (2019) 072009

JHEP 03 (2020) 056

JHEP 08 (2018) 011





σ = 0.60 pb

$\sim$90K $t\bar{t}W$ events

140 fb^{-1}

σ = 0.84 pb

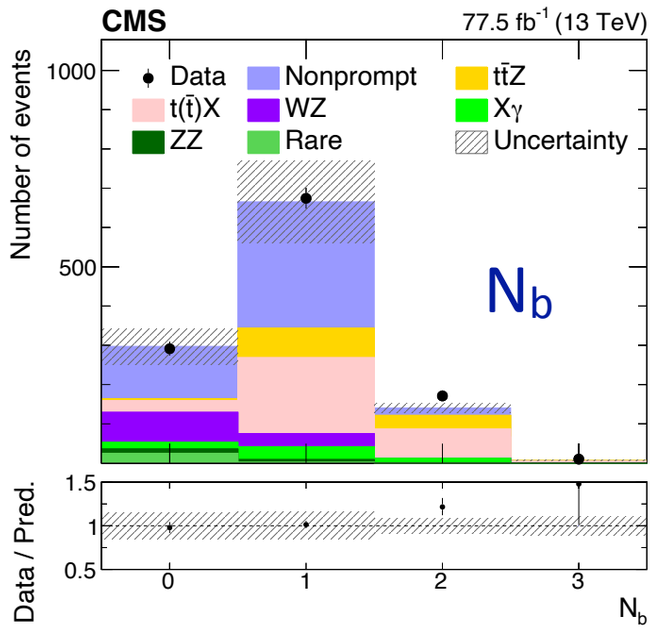
$\sim$120K $t\bar{t}Z$ events

Measurements in channels with low branching ratios

- Same-sign dilepton SS (4.8%)
- 3-lepton (1.6%)
- 3-lepton (2.8%)
- 4-lepton (0.5%)

ttZ measurement

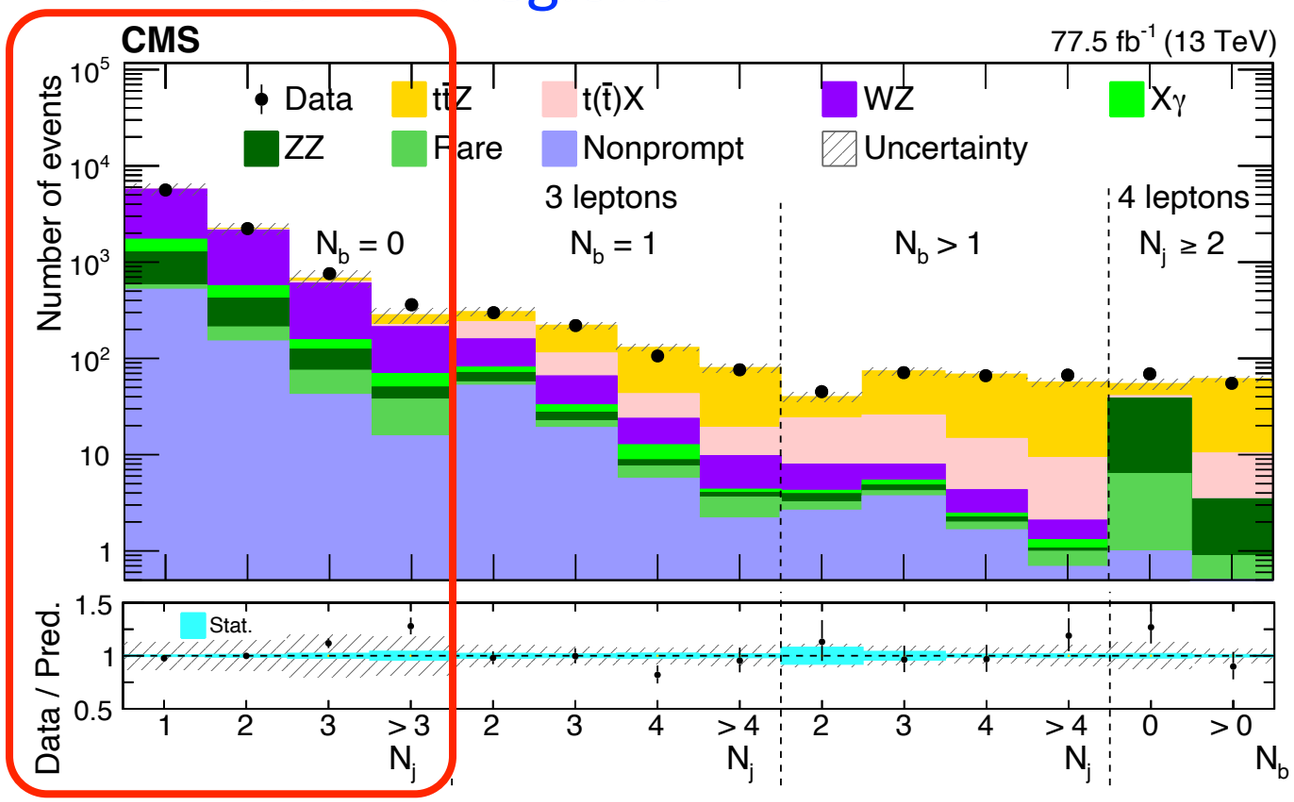
- Selection
  - 3 or 4 leptons
  - Z boson candidate
  - $N_{jets} \geq 2$, $N_b \geq 0$
- Backgrounds
  - t(t)+X
  - Diboson+b-jets
  - non-prompt leptons: DD fake factor method
- Diboson model validated in CRs included in the fit



Fakes and t(t)X enriched control region

JHEP 03 (2020) 056

- Signal extraction:
  - Simultaneous PL fit in multiple signal/ control regions



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

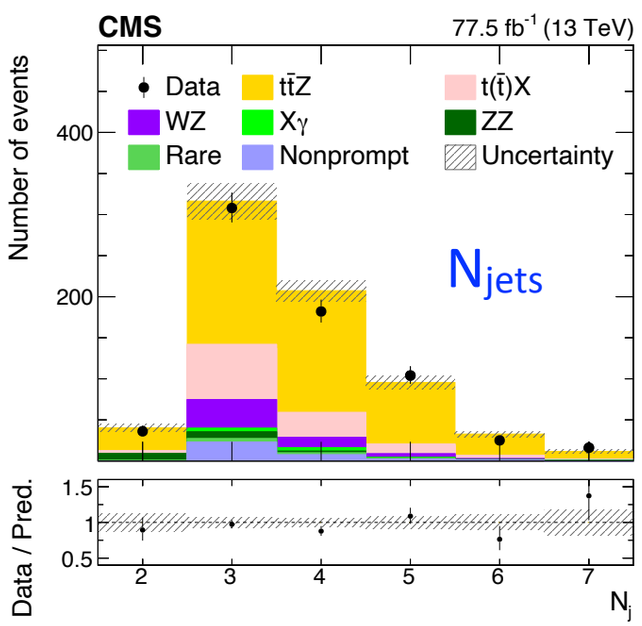
8% precision

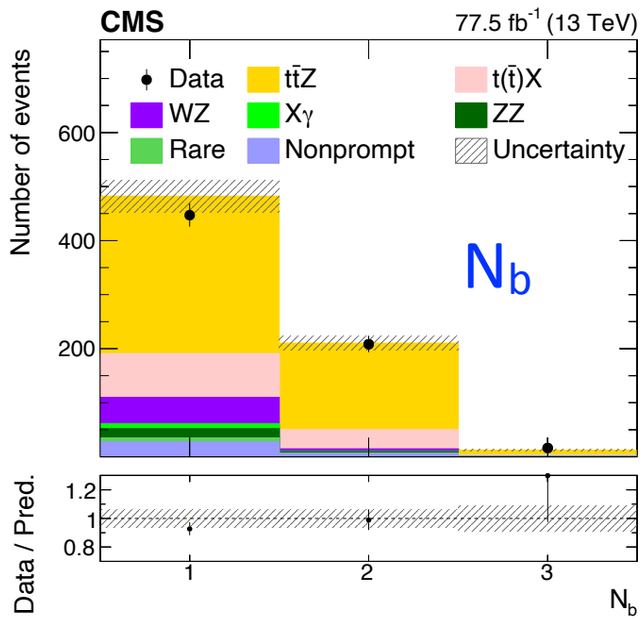
Main systematic uncertainties

- lepton identification (4%)
- WZ (3%) and t(t)X (3%)

ttZ: going differential

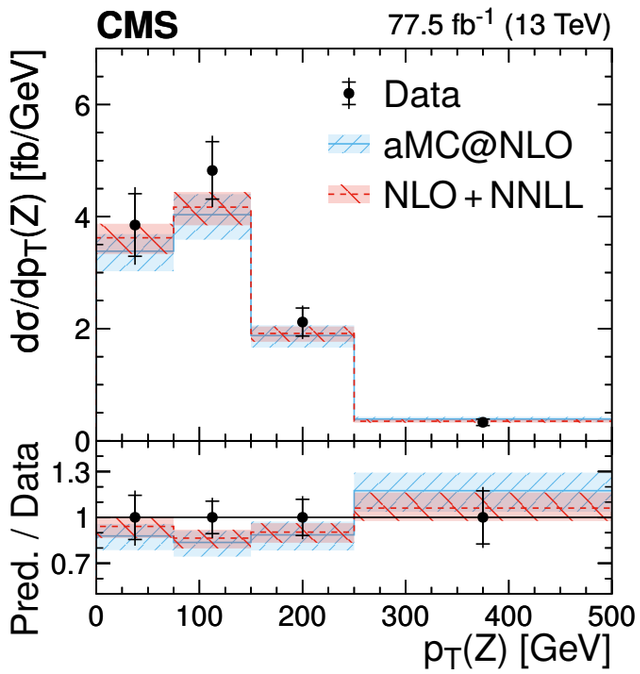
- Postfit distributions in ttZ enriched region

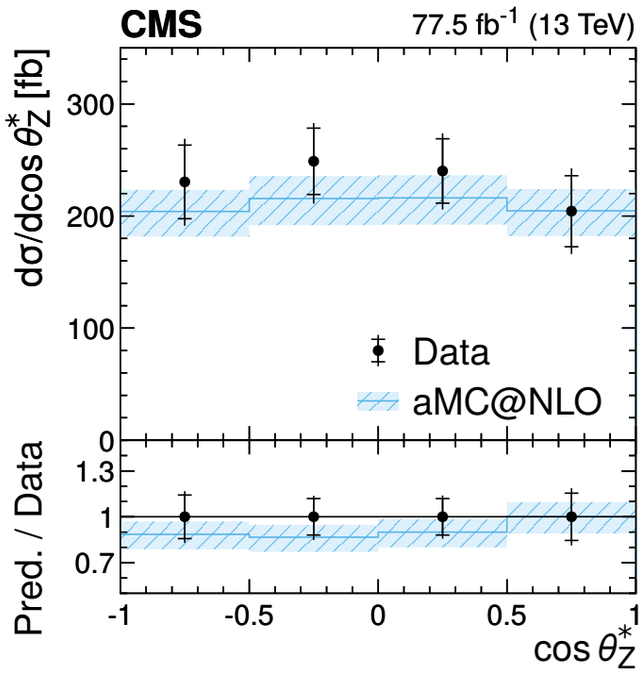


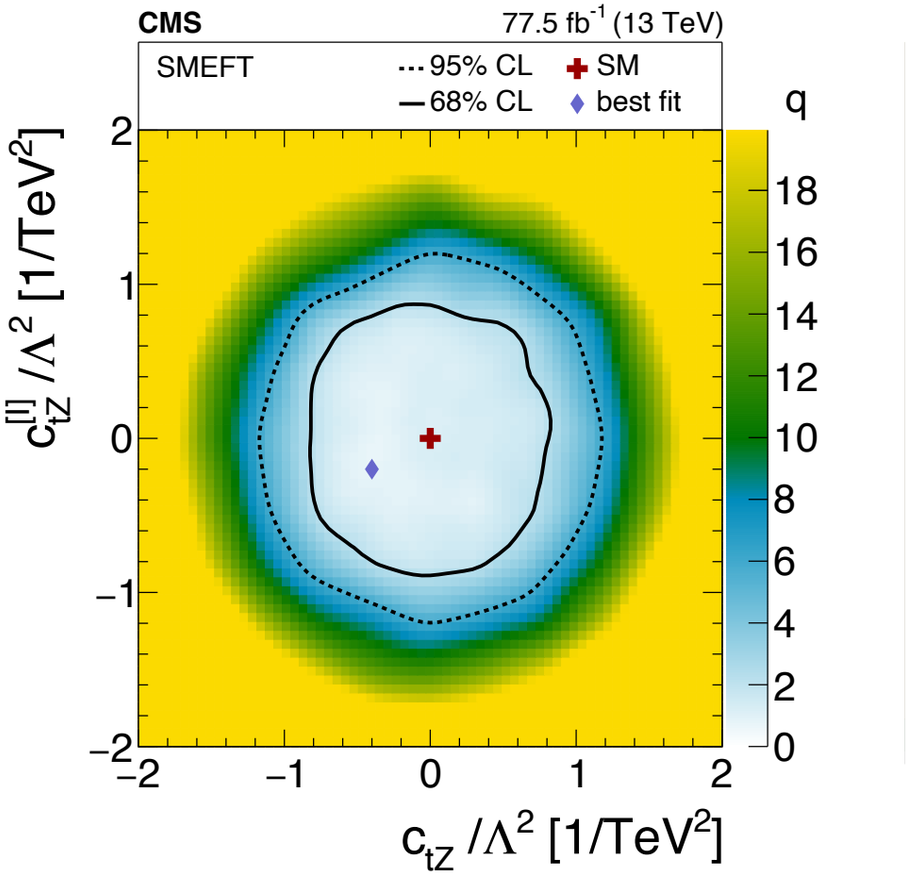


- Further splitting in bins of cos (θ_Z^*) and $p_T(Z)$ for BSM interpretations
  - SMEFT
  - limits on axial-vector and vector current coupling
  - electroweak dipole moment

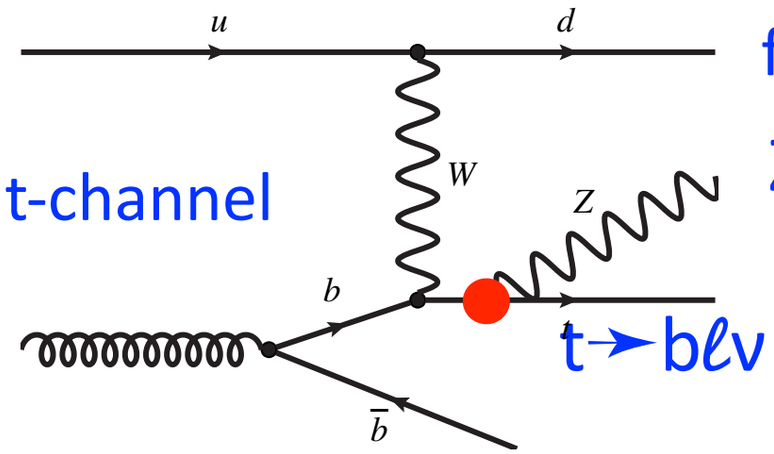
- Differential measurements to validate and improve $t\bar{t}Z$ MC models







tZq measurement



t-channel

forward jet

$Z(\ell\ell)$

$t \to b\ell\nu$

- Selection
  - 3 leptons
    - opposite sign same flavour pair within Z mass window
  - 2 to 4 jets with1 or 2 b-tags

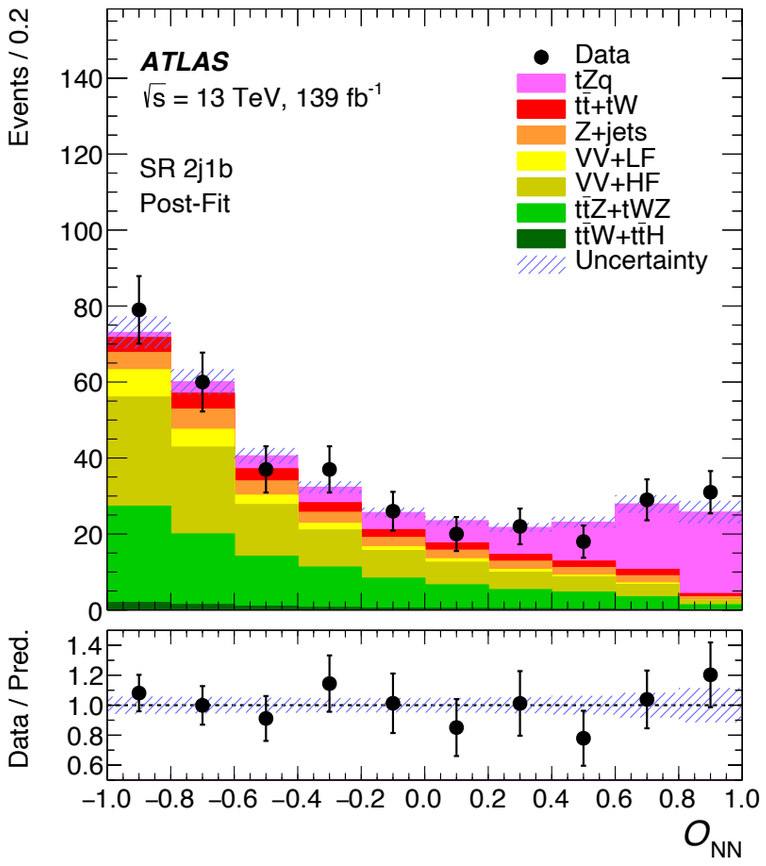
	2J	3J	4J
2b		CR ttZ (A)	CR ttZ (A) SR (CMS)
1b	SR	SR	SR (CMS)
0b	CR WZ	CR WZ	

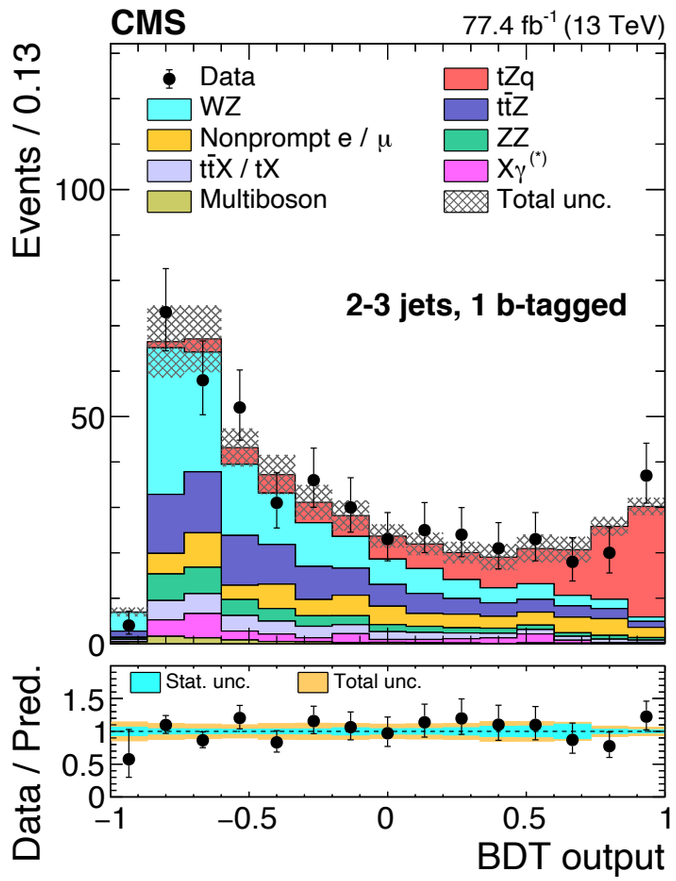
arXiv:2002.07546

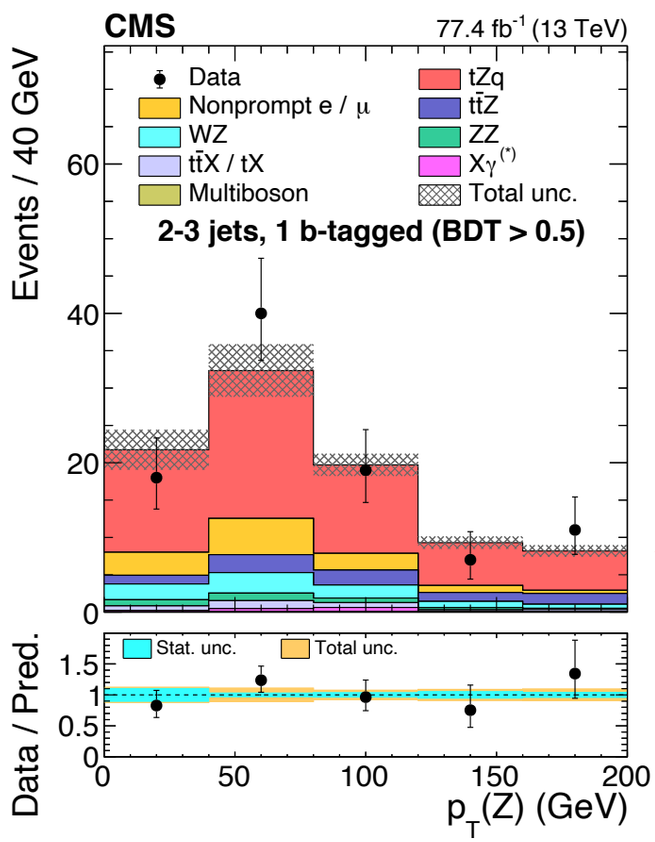
Phys. Rev. Lett. 122 (2019) 132003

- Backgrounds
  - non-prompt leptons
    - CMS: Data driven, fake factor method
    - ATLAS: MC-based shape, free floating normalisation from 2 dedicated CRs
  - WZ+b-jets
  - $t\bar{t}Z$
    - dominant background in 4j1b and 4j2b CMS SR regions
- Signal extraction
  - simultaneous fit to distributions in signal and control regions
    - MVA discriminant in SR
    - Event counting or kinematic distributions in control regions

tZq results







$p_T(Z)$

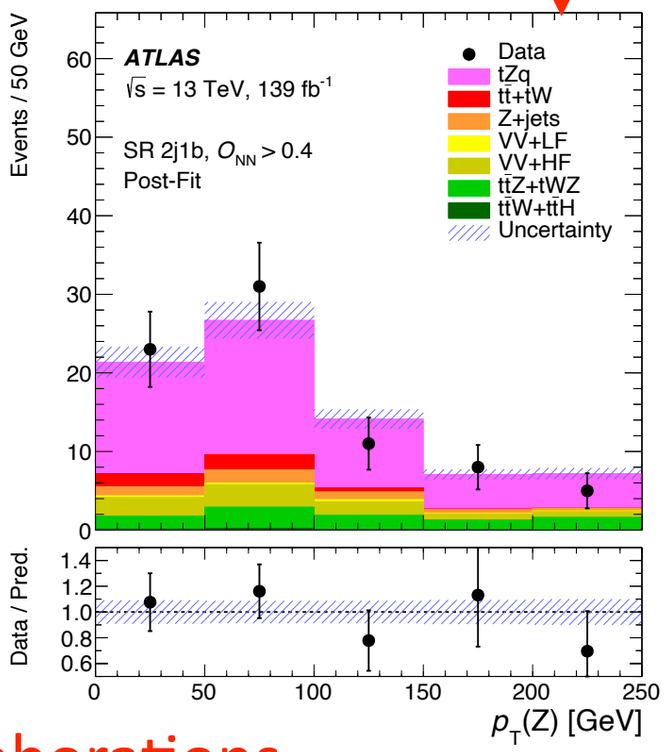
$$\sigma(pp \to t\ell^+\ell^- q) = 111 \pm 13(\text{stat})^{+11}_{-9}(\text{syst})\ \text{fb} \quad \text{CMS } 77.4\ \text{fb}^{-1}$$

$$\text{for } m(\ell^+\ell^-) > 30\ \text{GeV} \quad = 97 \pm 13(\text{stat}) \pm 7(\text{syst})\ \text{fb} \quad \text{ATLAS } 139\ \text{fb}^{-1}$$

Main systematic uncertainties

15% precision

- Prompt-lepton background (3-4%)
- Jets and E_T^{mis} (2-3%)
- Leptons reconstruction and ID (2-3%)

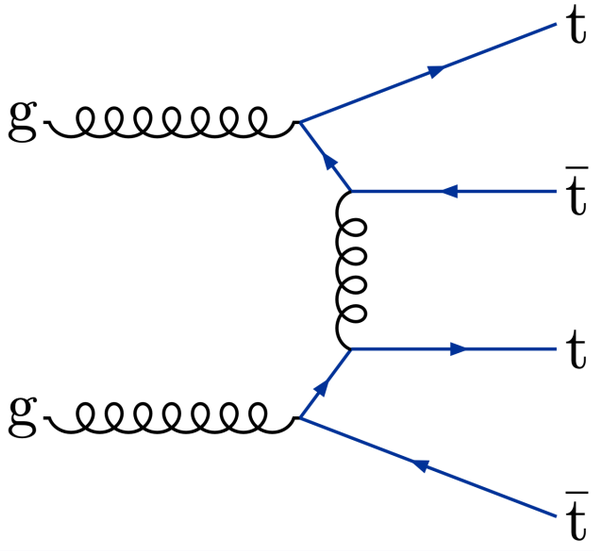


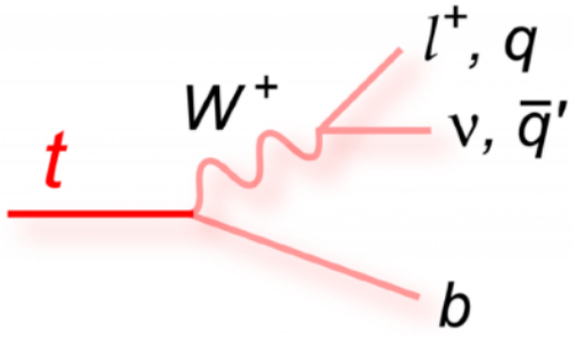
Observation of tZq production by both collaborations

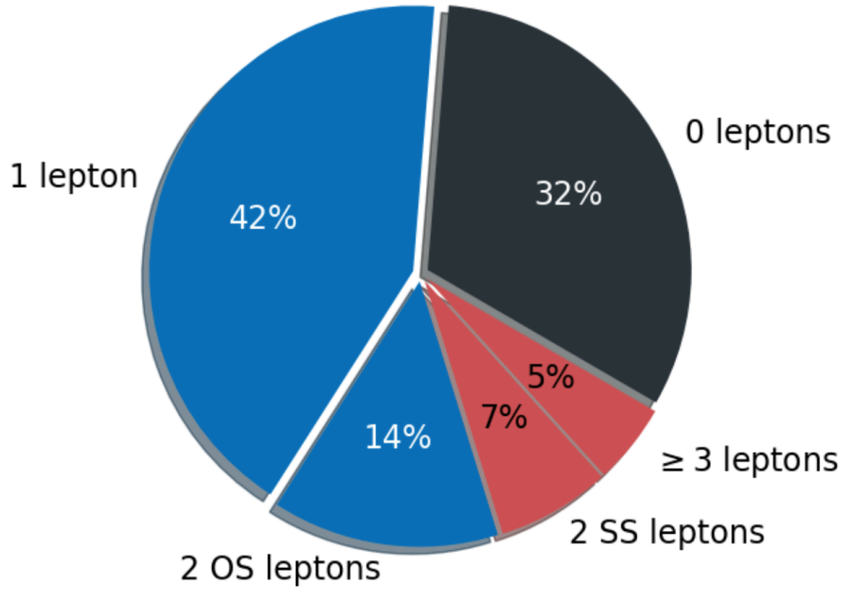
Searches for 4-top quark production

Introduction

- Final state with high jet and b-jet multiplicity







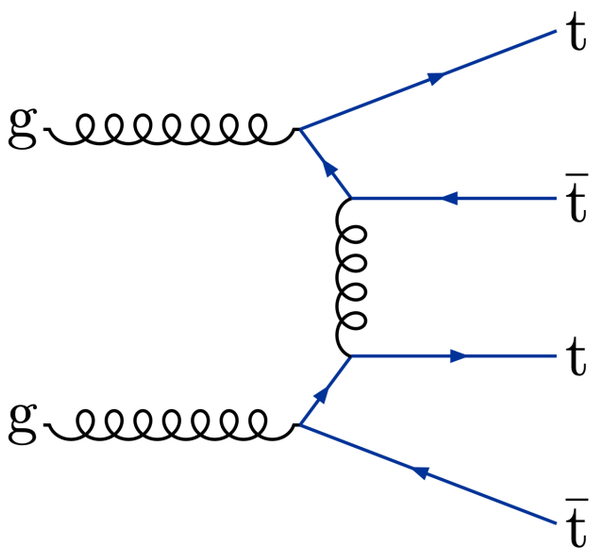
- Single and two lepton opposite sign
  - larger branching fraction (56%)
  - large irreducible background
    - $t\bar{t}$+light jets, $t\bar{t}$+heavy flavour jets
- Same-sign charge lepton and multilepton (SS/ML)
  - small branching fraction (12%)
  - lower backgrounds
    - $t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons, charge misidentification

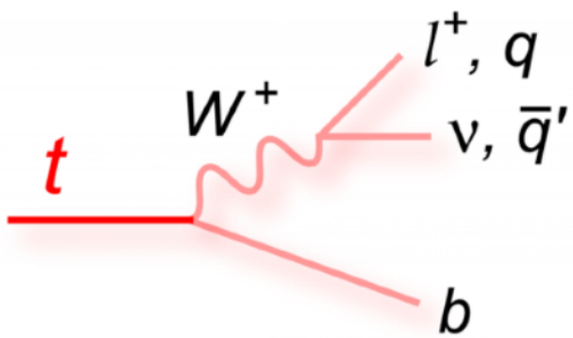
lepton	total jets	light/c jets	b jets
1L	10	6	4
OS	8	4	
SS			
ML	6	2	

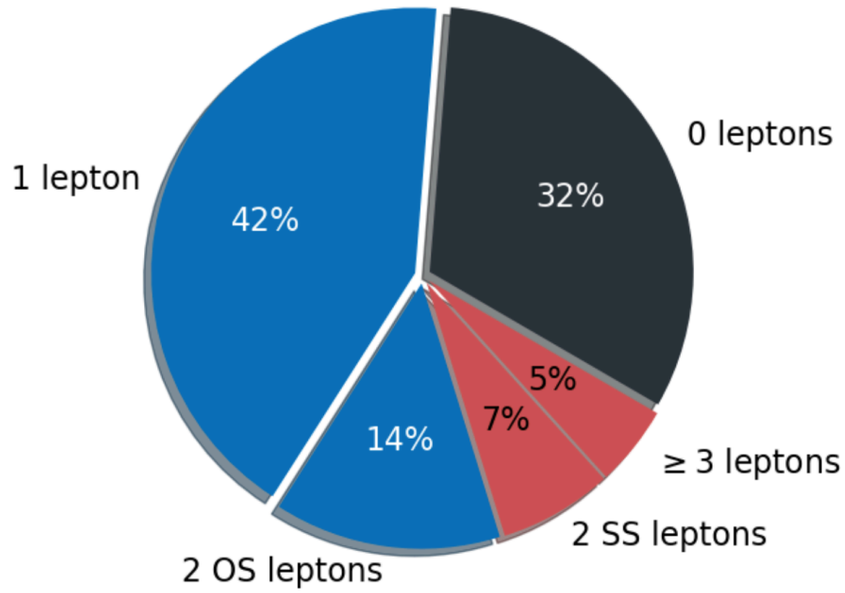
- Analysis strategy depends on the final state

Introduction

- Final state with high jet and b-jet multiplicity







- Single and two lepton opposite sign
  - larger branching fraction (56%)
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  - small branching fraction (12%)
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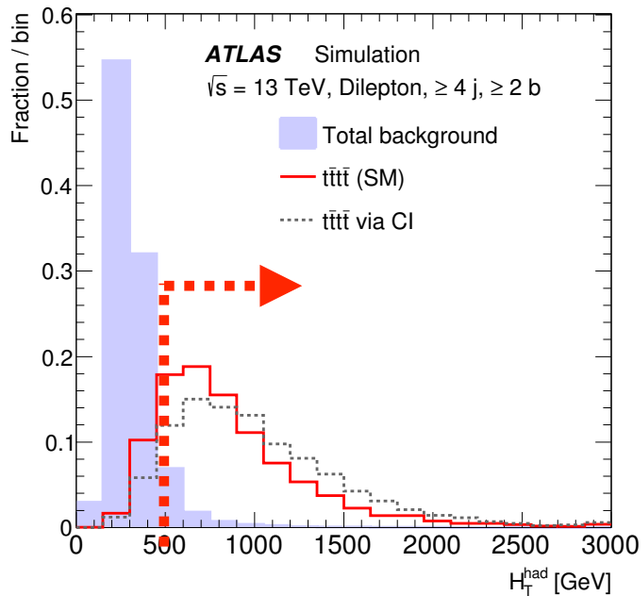
lepton	total jets	light/c jets	b jets
1L	10	6	4
OS	8	4	
SS			
ML	6	2	

SS/ML is the most sensitive channel

4-top: 1LOS channel

- Selection
  - 1 e/μ or 2 e/μ, $N_b \geq 2$
  - CMS:
    - $N_{jets} \geq 7(8)$ (1L), $N_{jets} \geq 4$ (2L), $H_T > 500$ GeV
  - ATLAS
    - $N_{jets} \geq 5$ (1L), $N_{jets} \geq 4$ (2L)



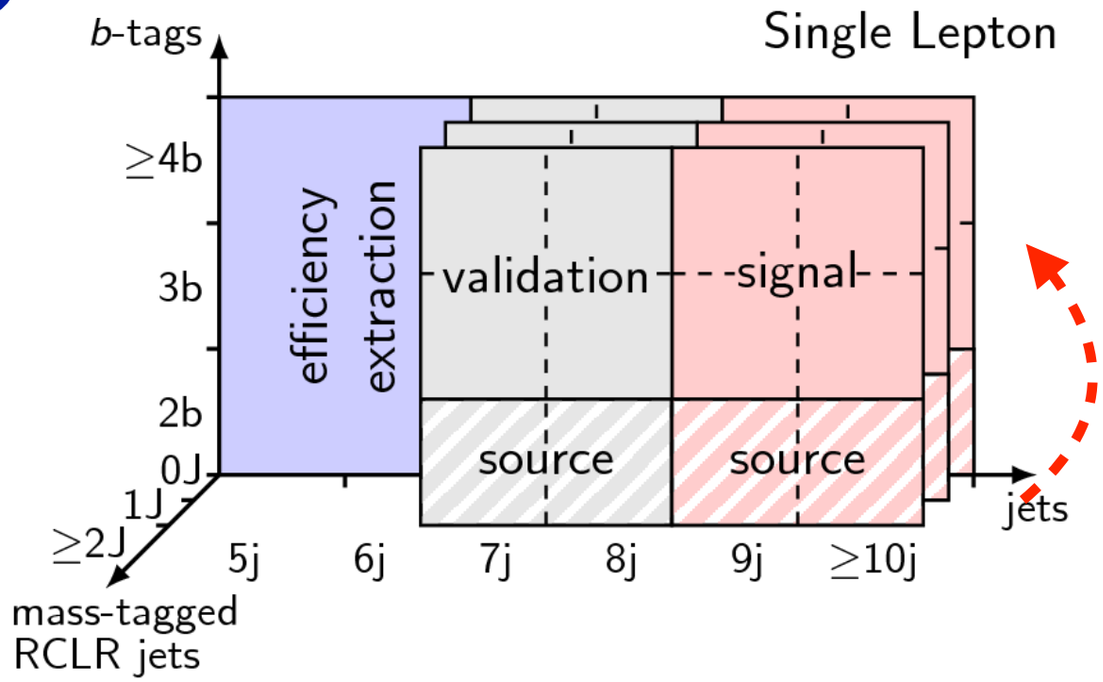
ATLAS EXPERIMENT

CMS

36 fb^{-1}

JHEP 11 (2019) 082
Phys. Rev. D 99 (2019) 052009

- Analysis strategy
  - categorise events N_{jets}, N_b
  - ATLAS adds categories based on N_{RC}
- Background estimate
  - CMS:
    - MC-based with DD corrections
  - ATLAS:
    - data-driven method (ttTRF)



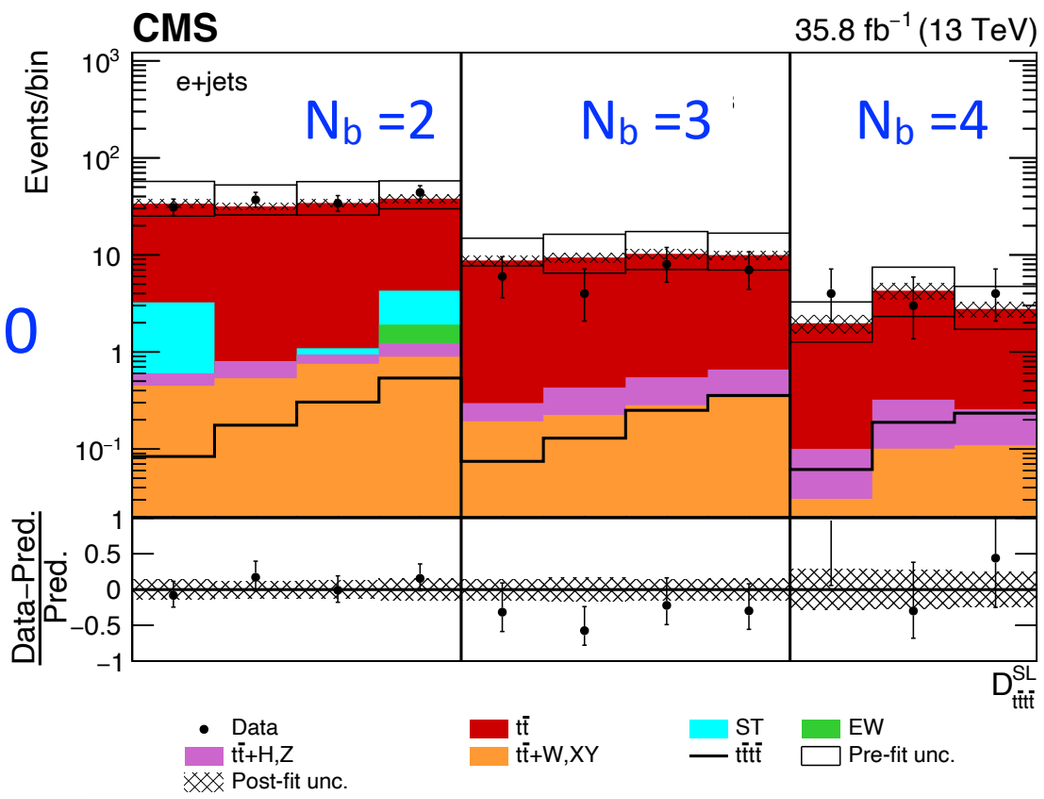
- extract effective tagging efficiency (p_T^{jet},ΔR^{jet}) from low N_{jet} region
- apply to low source regions to promote events to higher N_b

Signal extraction

- Simultaneous fit to discriminating variables in multiple signal regions
- ATLAS:
  - fit H_T distributions in each region
- CMS:
  - 2 BDTs to improve sensitivity
  - BDT 1: distinguish 3 jets from hadronically decaying top from other 3 jet combinations
  - BDT 2: separates signal from the background

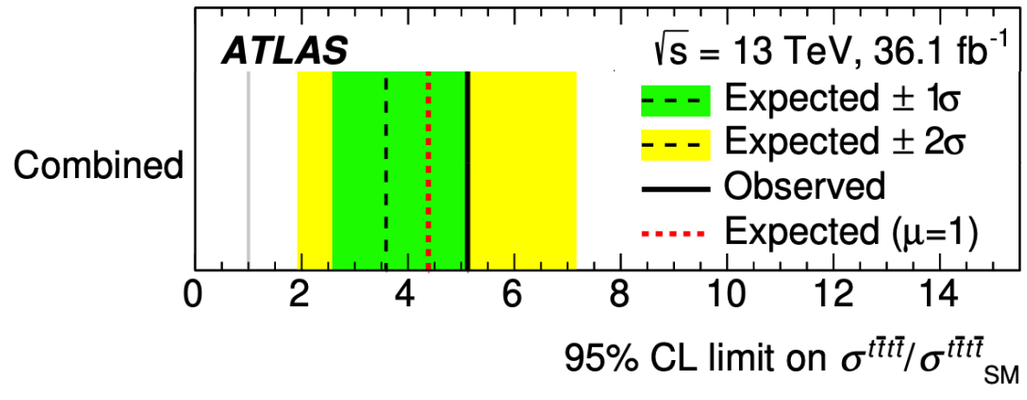
BDT 2 score

N_{jets} =10



Limits on μ:

CMS: obs (exp): $5.2(5.7^{+2.9}_{-1.8})$



	significance obs (exp)
CMS	0.0 (0.4)
ATLAS	1.0 (0.6)

CMS combination with SS/ML channel 36 fb^{-1} :

$$\sigma(t\bar{t}t\bar{t}) = 13^{+11}_{-9}\ \text{fb}$$

observed significance 1.4

4-top: SS/ML channel

- 2ℓSS and 3ℓ channel signature
  - 4 b-jets from 4 top quarks
  - 4 or 2 jets from W
- Selection
  - ≥2 jets, ≥2 b-jets
  - H_T>300 GeV, E_T^{miss} > 50 GeV
  - Z($\ell^+\ell^-$) mass window veto
- Backgrounds
  - DD methods for non-prompt and charge misID leptons
  - $t\bar{t}Z/t\bar{t}W$ MC based with DD corrections
    - jet multiplicity: based on data/MC comparison of $t\bar{t}$ jet multiplicity spectrum
    - corrections vary between 1.46 and 0.77 for 1 to 4 additional jets
    - factor of 1.7±0.6 is applied to improve modelling of extra heavy flavour jet based on measured ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ ratio

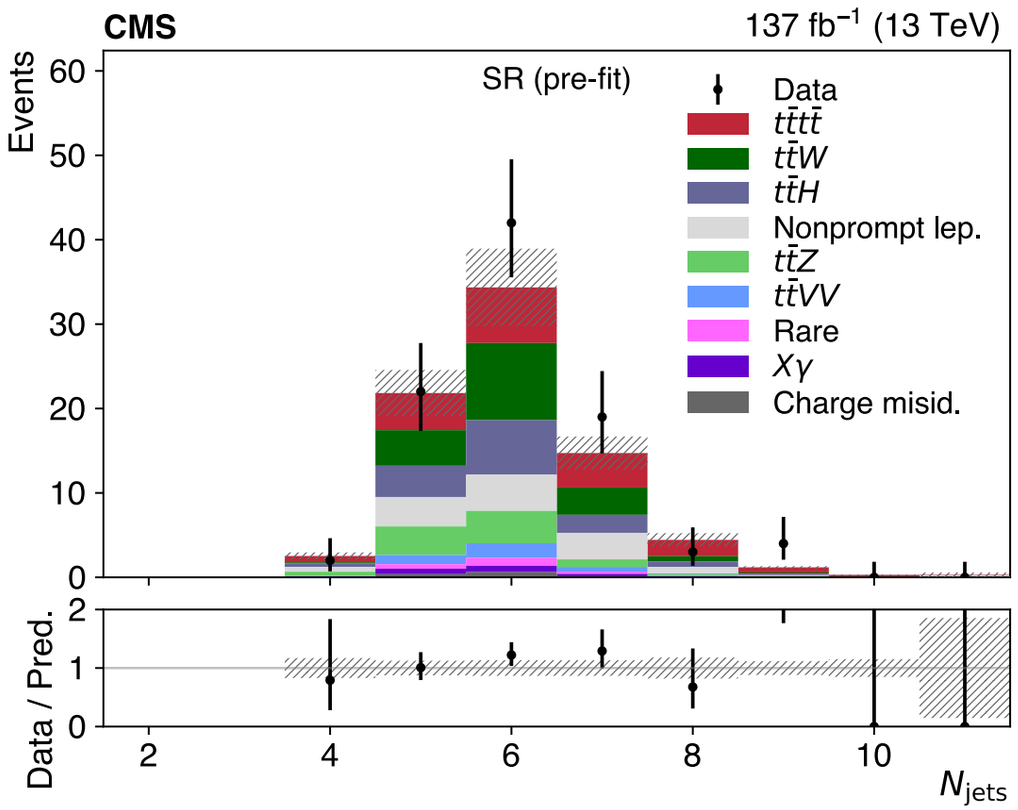
EPJC 80 (2020) 75

137 fb^{-1}

Two analyses: categorisation and BDT based

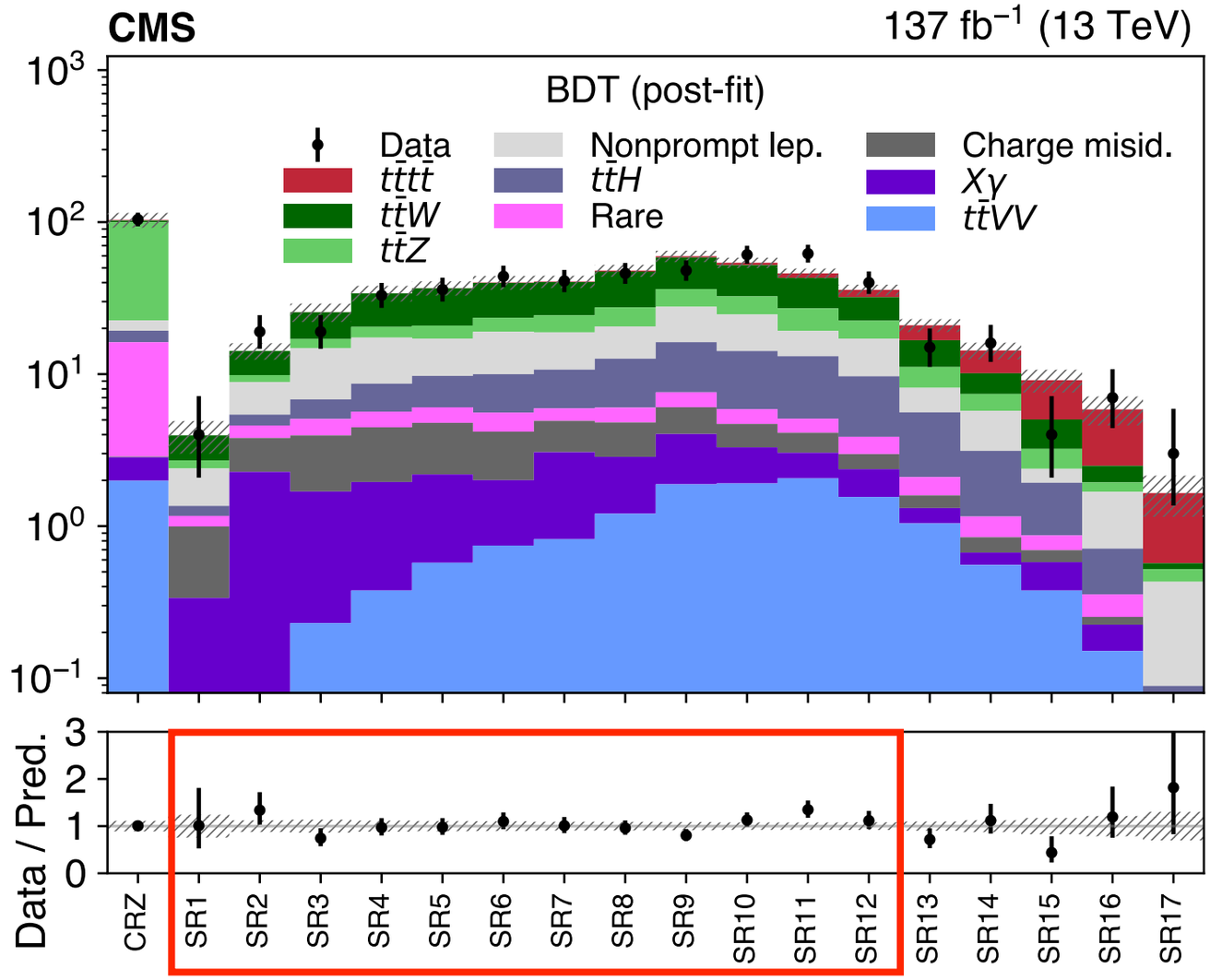
N_ℓ	N_b	N_{jets}	Region
		≤5	CRW
2	2	6	SR1
		7	SR2
		≥8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥8	SR7
	≥ 4	≥5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥7	SR11
	≥ 3	4	SR12
		5	SR13
		≥6	SR14
Inverted resonance veto			CRZ

4-top search result



Post-fit $t\bar{t}W/t\bar{t}Z$ scaled by 1.3±0.2

- Dominant systematics:
  - modelling of additional b-jets (11%)
  - JES (9%) JER (6%)
  - b-tagging (6%)



- In BDT analysis ttW is constrained by regions with low BDT score

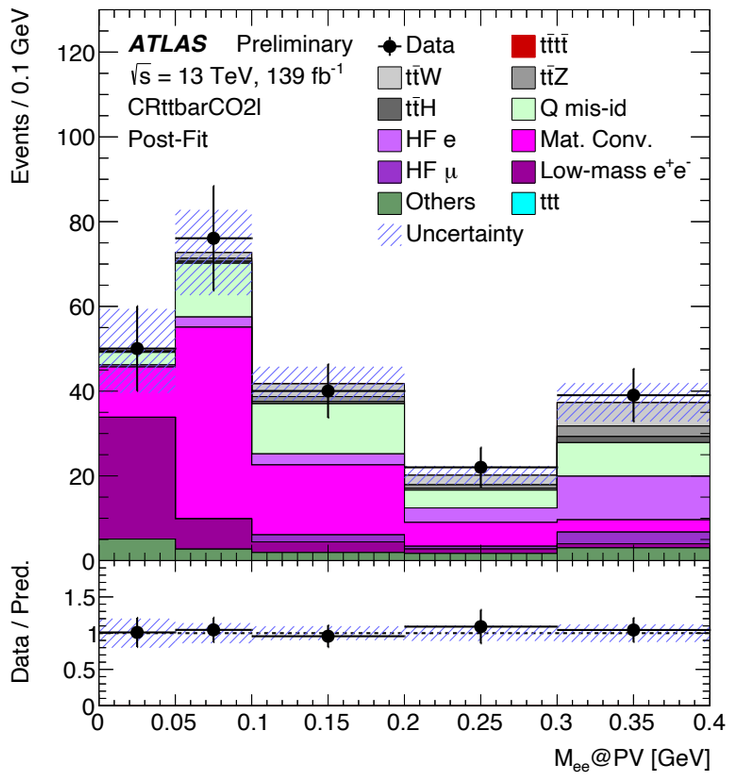
$$\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}\ \text{fb}$$

2.6 (2.7) σ observed (expected) significance

4-top: SS/ML channel

ATLAS-CONF-2020-013 139 fb^{-1}

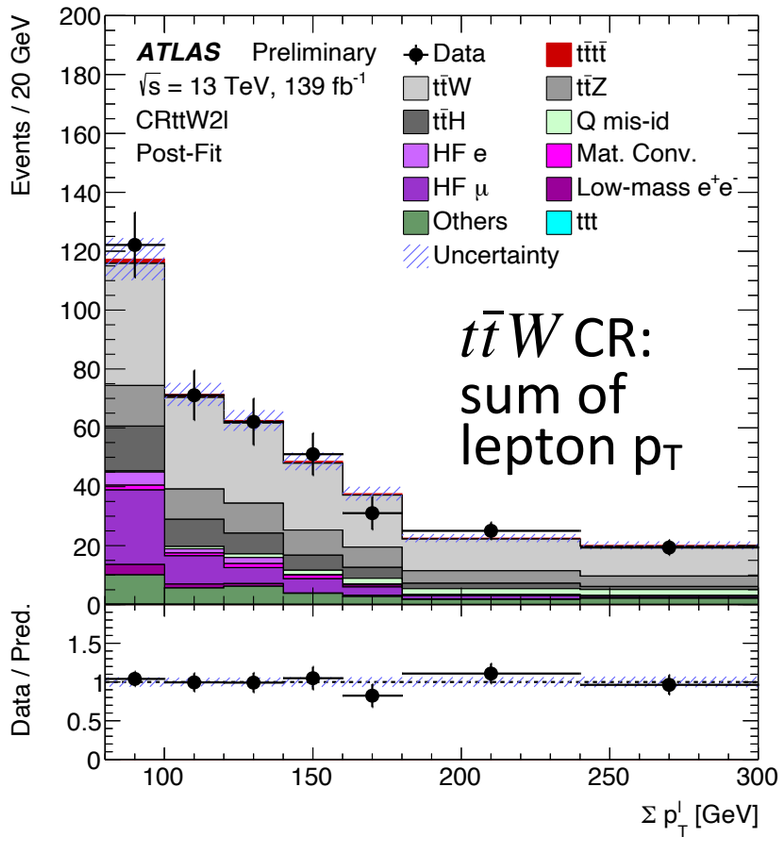
- Basic selection
  - ≥4 jets, ≥1 b-jets
  - $|m_{\ell\ell} - m_Z| > 10$ GeV for OS SF pairs in 3L selection
- Fake background estimate motivates CR definition
- MC-based template method with 4 free parameters included in the signal extraction fit
  - HF electron, HF muon
  - material conversions
  - internal conversions
- $t\bar{t}W$ background normalisation is free in the fit



ATLAS EXPERIMENT

new

Material conversion CR

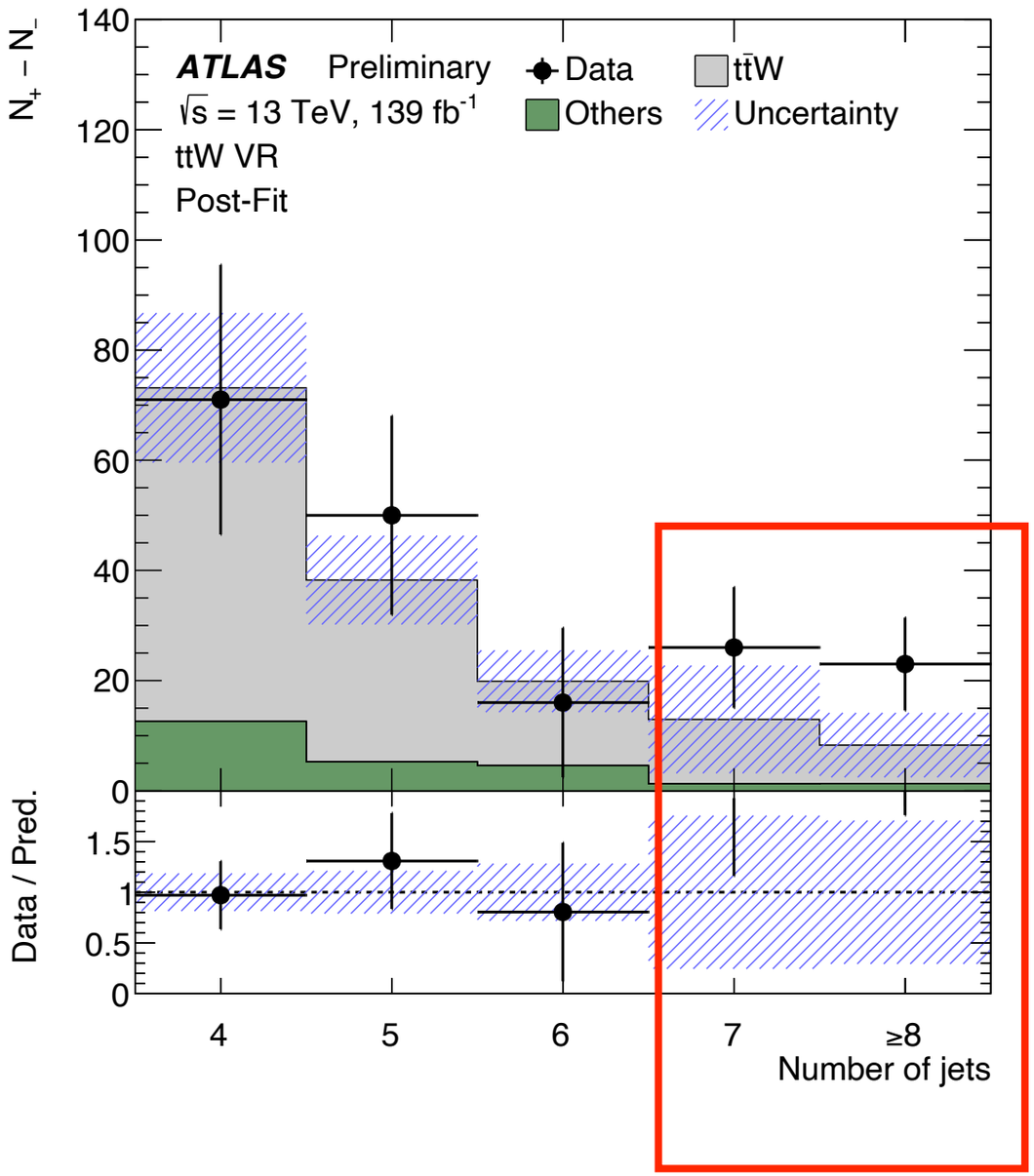


$t\bar{t}W$ CR: sum of lepton p_T

Parameter	$NF_{t\bar{t}W}$	NF_{CO}	NF_{γ^*}	NF_{HFe}	$NF_{HF\mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

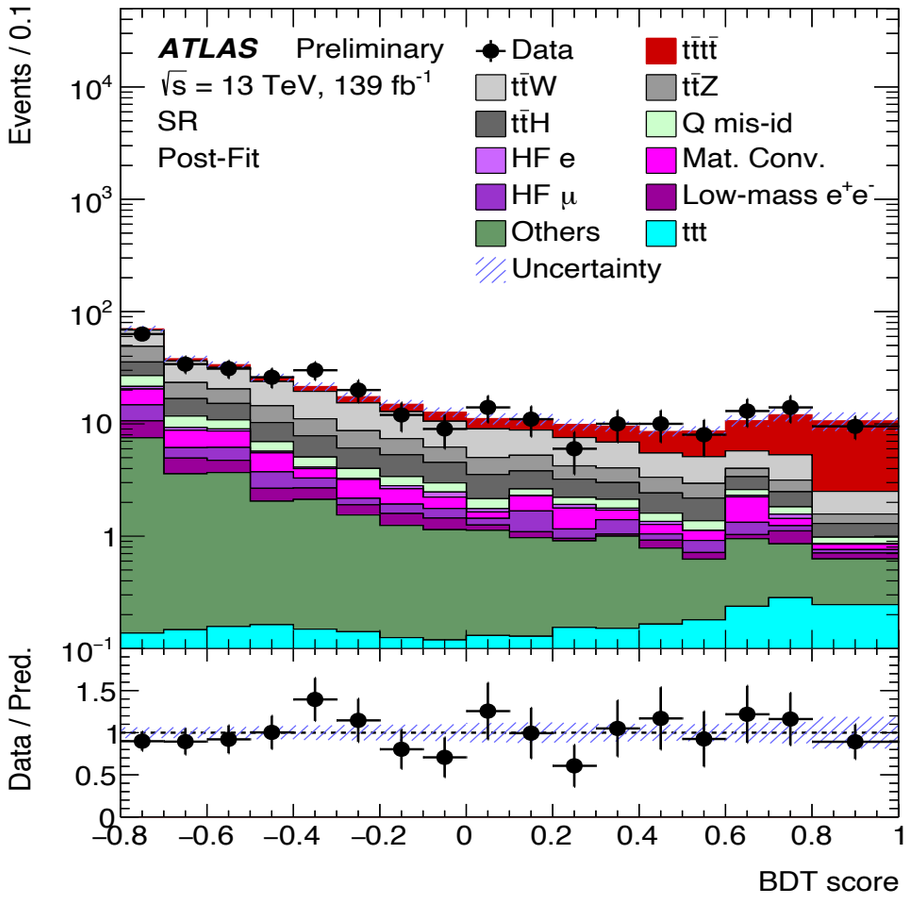
ttX background model

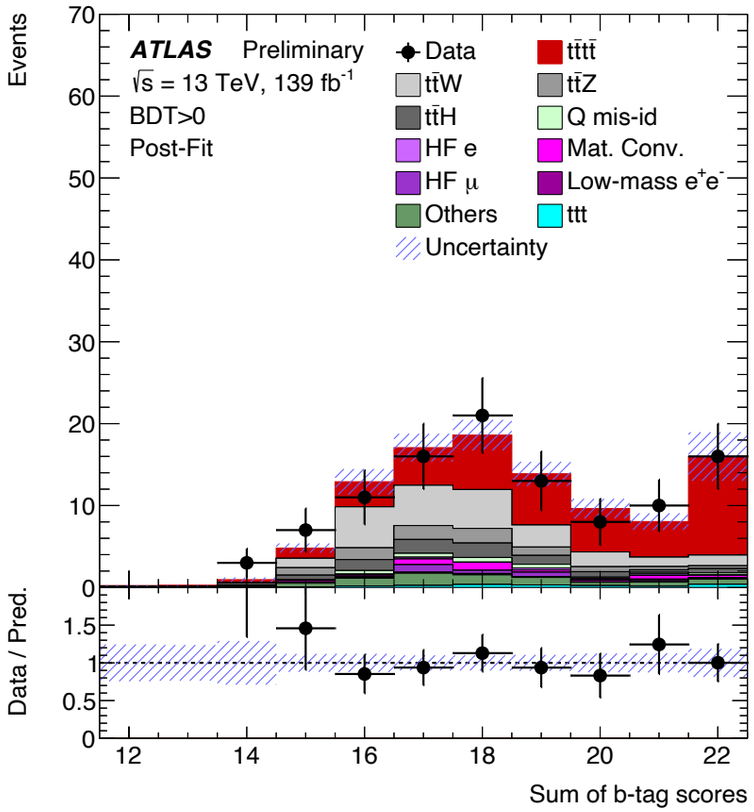
- $t\bar{t}W$ validation region:
  - ≥4 jets, ≥2 b-jets
  - plot $N_+ - N_-$ to suppress all charge symmetric backgrounds
- Systematic uncertainties on $t\bar{t}W$:
  - 125% on $t\bar{t}W$+7 jets
  - 300% on $t\bar{t}W$+8 jets
  - 50% on $t\bar{t}W$+3b, $t\bar{t}W$≥4b
- Additional 50% uncertainty is applied to $t\bar{t}Z$ and $t\bar{t}H$ with 3 and ≥4b jets
- 100% uncertainty on 3-top cross section and additional 50% on ttt+b

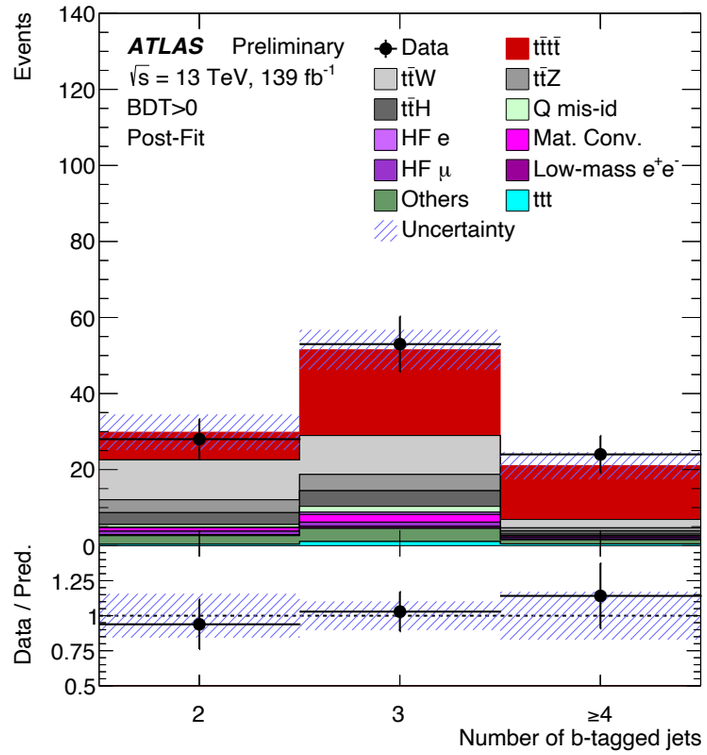


4-top search result

- Inclusive signal region
  - ≥6 jets, ≥2 b-jets, H_T>500 GeV
  - BDT is trained to separate signal from background
- Signal extraction
  - simultaneous fit to BDT and distributions in 4 CRs







$$\sigma(t\bar{t}t\bar{t}) = 24^{+7}_{-6}\ \text{fb}$$

$$\mu = 2.0^{+0.4}_{-0.4}\ (\text{stat})^{+0.7}_{-0.5}\ (\text{syst})\ \text{fb}$$

4.3 (2.4) σ observed (expected) significance

Evidence for the 4-top quark production

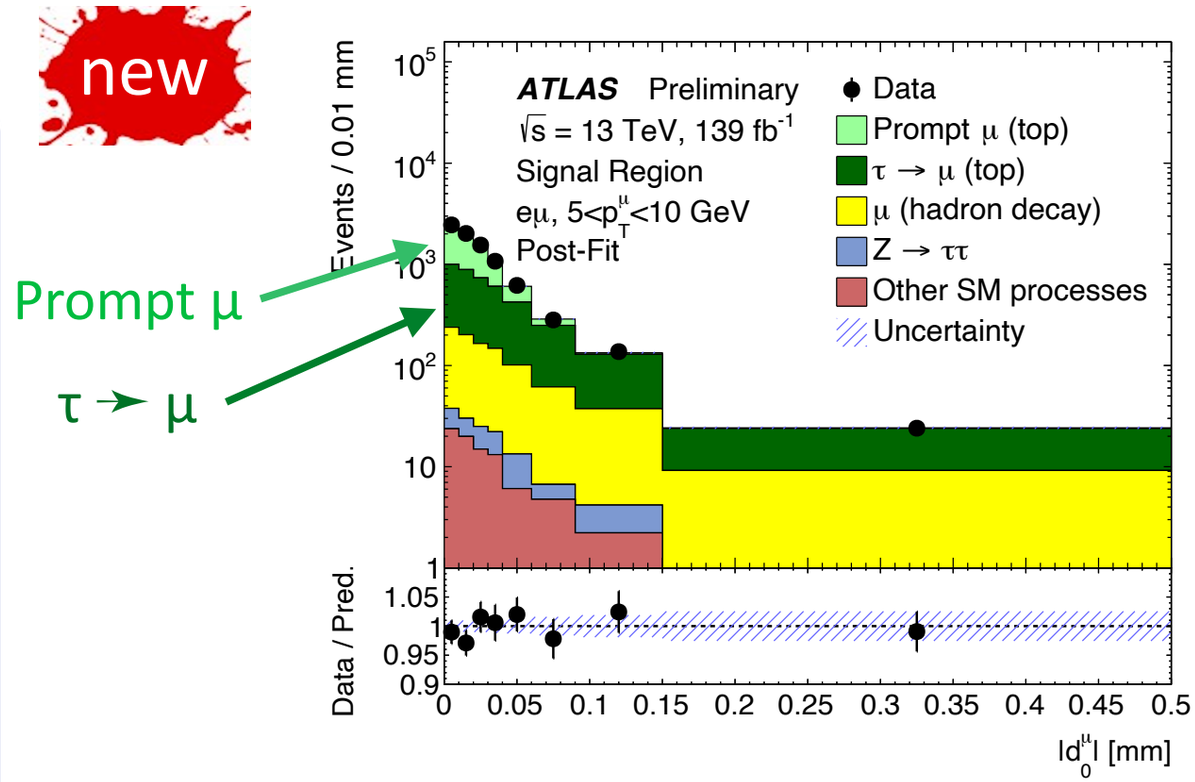
Consistent with SM prediction at 1.7 σ

Lepton coupling universality

ATLAS-CONF-2020-014 139 fb^{-1}

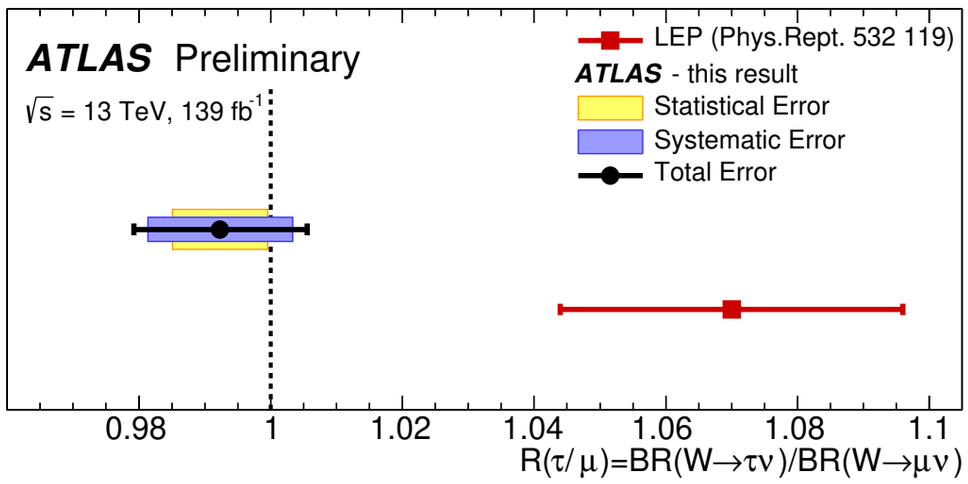
- W decays in dilepton $t\bar{t}$ events are used to measure ratio
  R(τ/μ) = BR(W➔τν)/BR(W➔μν)
- 2.7σ deviation from SM at LEP
- Separate direct muons from W from W➔τ➔μ
  - difference between p_T spectra of W➔μ and W➔τ➔μ
  - τ-lepton lifetime (transverse impact parameter d_0)
- Tag (e or μ) and probe (μ, p_T>5 GeV) approach
- R(τ/μ) extraction:
  - fit in 3 p_T bins and 8 d_0 bins of probe muon
  - normalisation k($t\bar{t}$) of $(t\bar{t} + tW)$ is free in the fit

new



R = 0.992 ± 0.013 [±0.007 (stat) ± 0.011 (syst)]

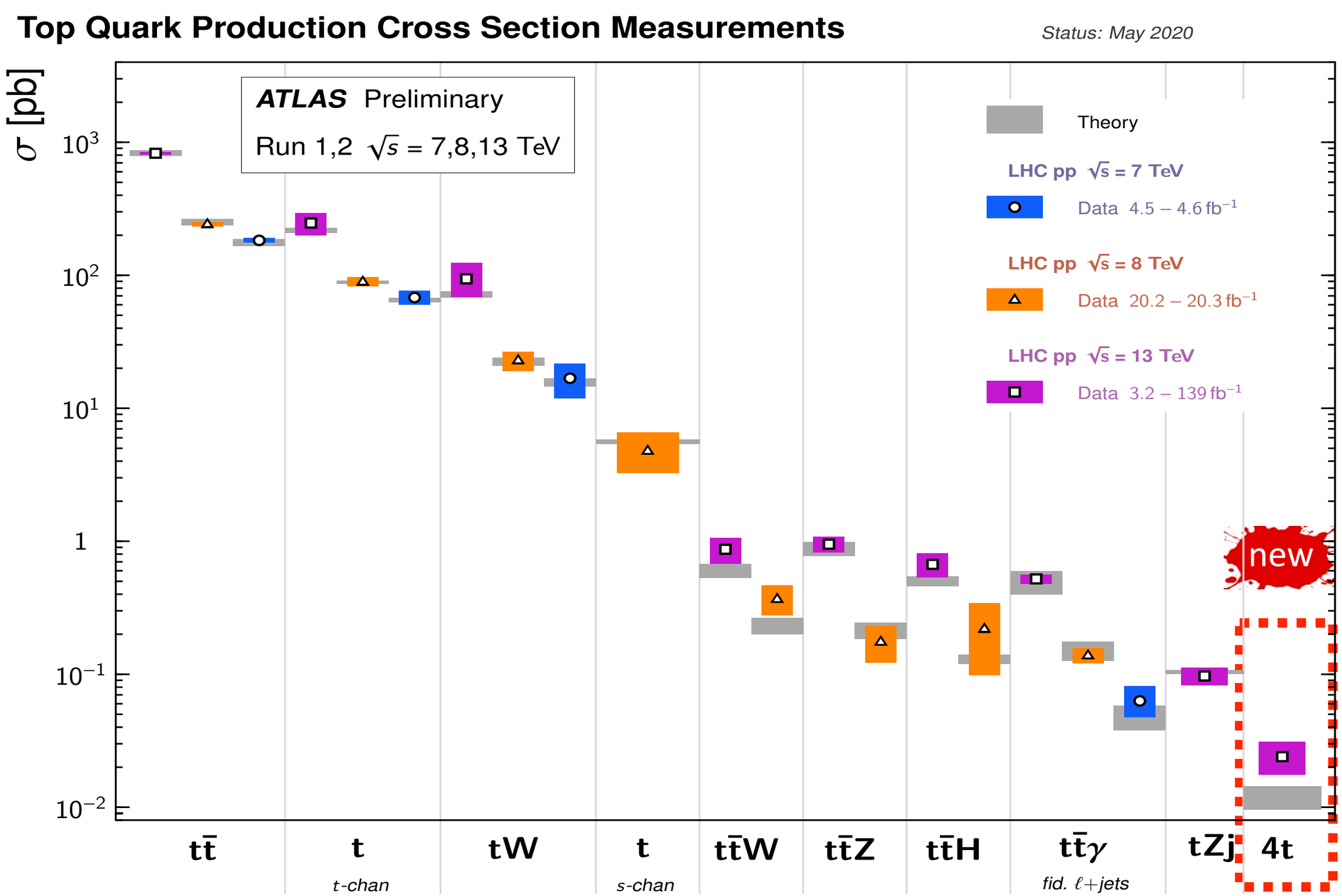
1.3% total uncertainty



Twice more precise than LEP !

Details in talk by C.Young (ATLAS) in on Wednesday 27/05

Rare top processes status



- Observed: $t\bar{t}V$, V= γ, Z, W, H ; tZq
- Evidence: tv. $t\bar{t}t\bar{t}$

Summary and conclusions

- Measurements of $t\bar{t}X/tX$ (X=V,H,γ,$t\bar{t}$) processes are a large part of the current CMS and ATLAS programs
  - sensitive to top quark couplings
- Improved limits on the FCNC rare processes
- Measurements of $t\bar{t}V$ and $t\bar{t}\gamma$ differential distributions using full run 2 dataset
  - improve our understanding of their modelling
  - allow to explore parameters of EFT and other BSM models
- Observation of tZq production by both collaborations
- Evidence for the 4-top quark production has been achieved with 4.3σ significance

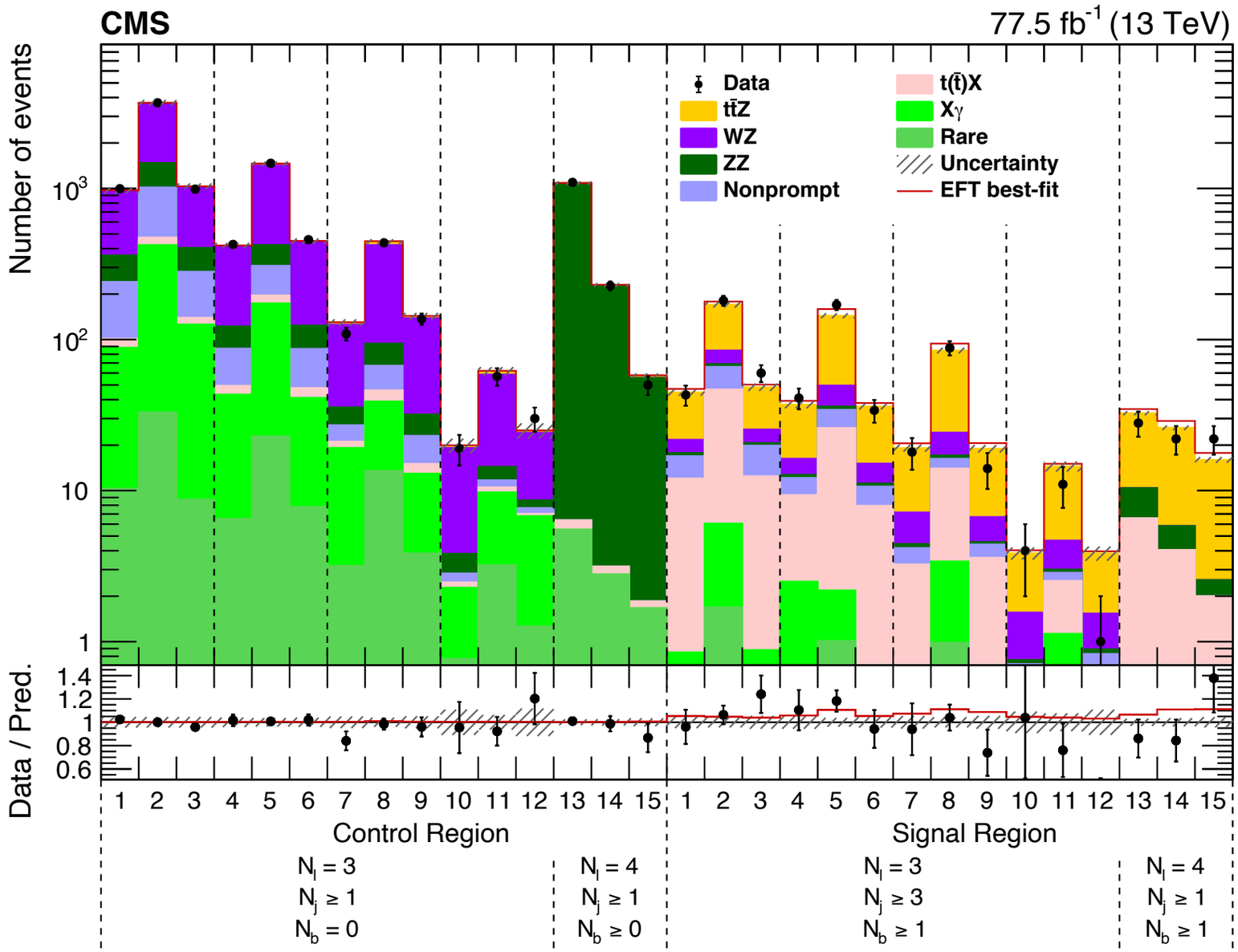
new

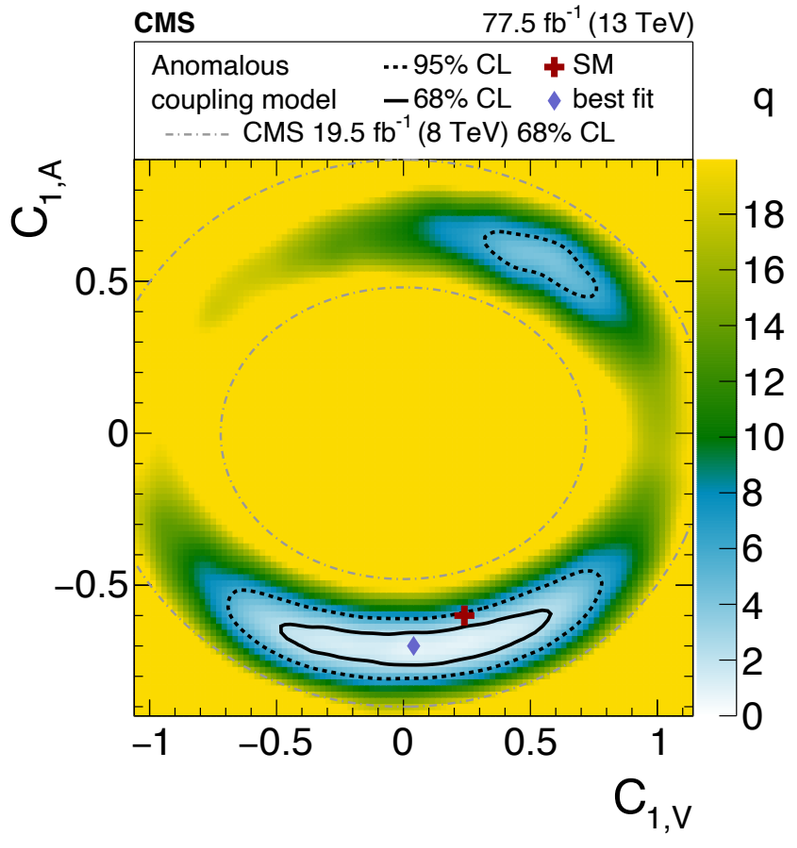
- The new measurement of lepton universality is in agreement with the SM and is the most precise measurement of R(τ/μ) to date

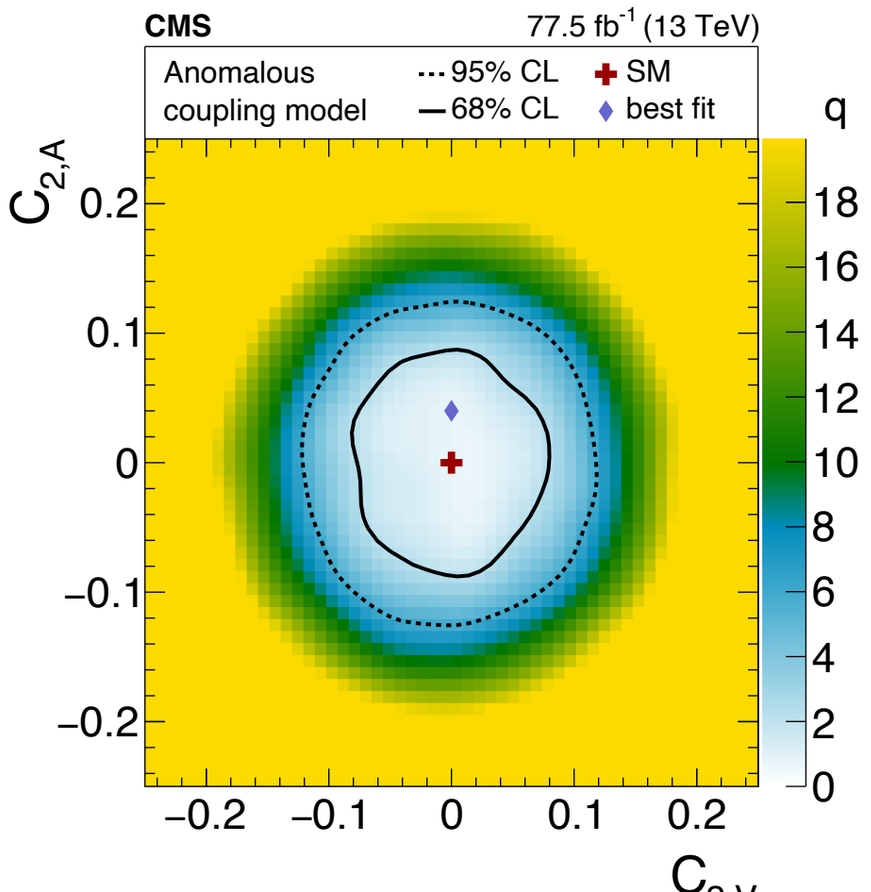
new

More results with full Run 2 data are yet to come

Backup

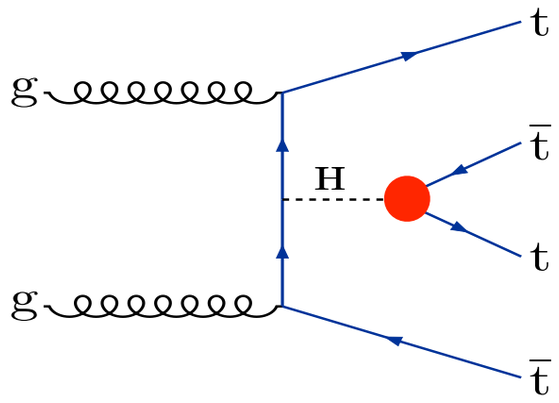






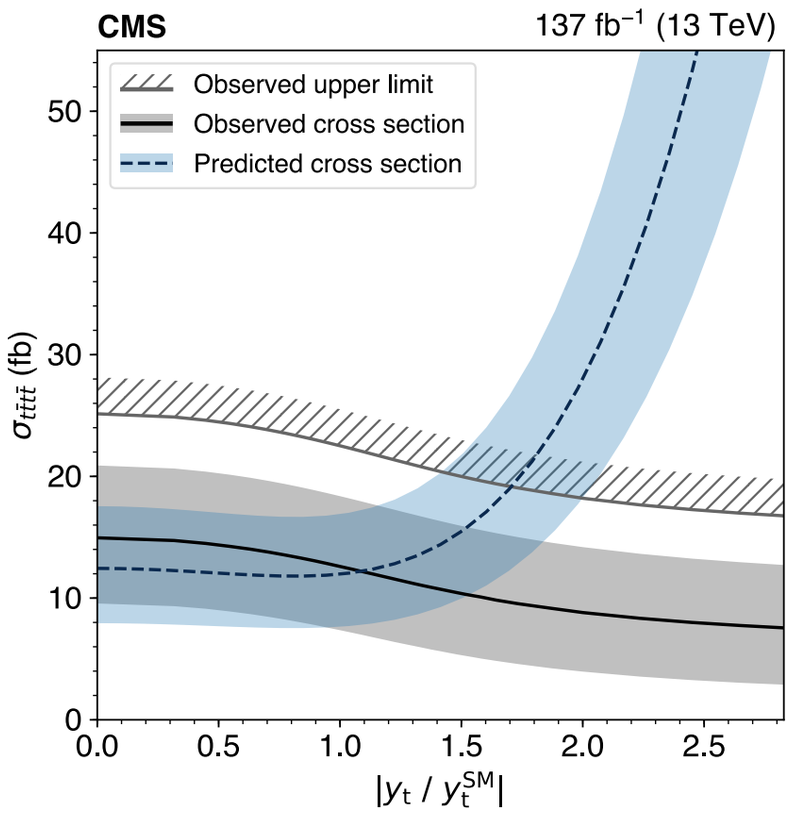
- Scan in axial-vector and vector current coupling plane
- Scan in the electroweak dipole moment plane

4-top search result

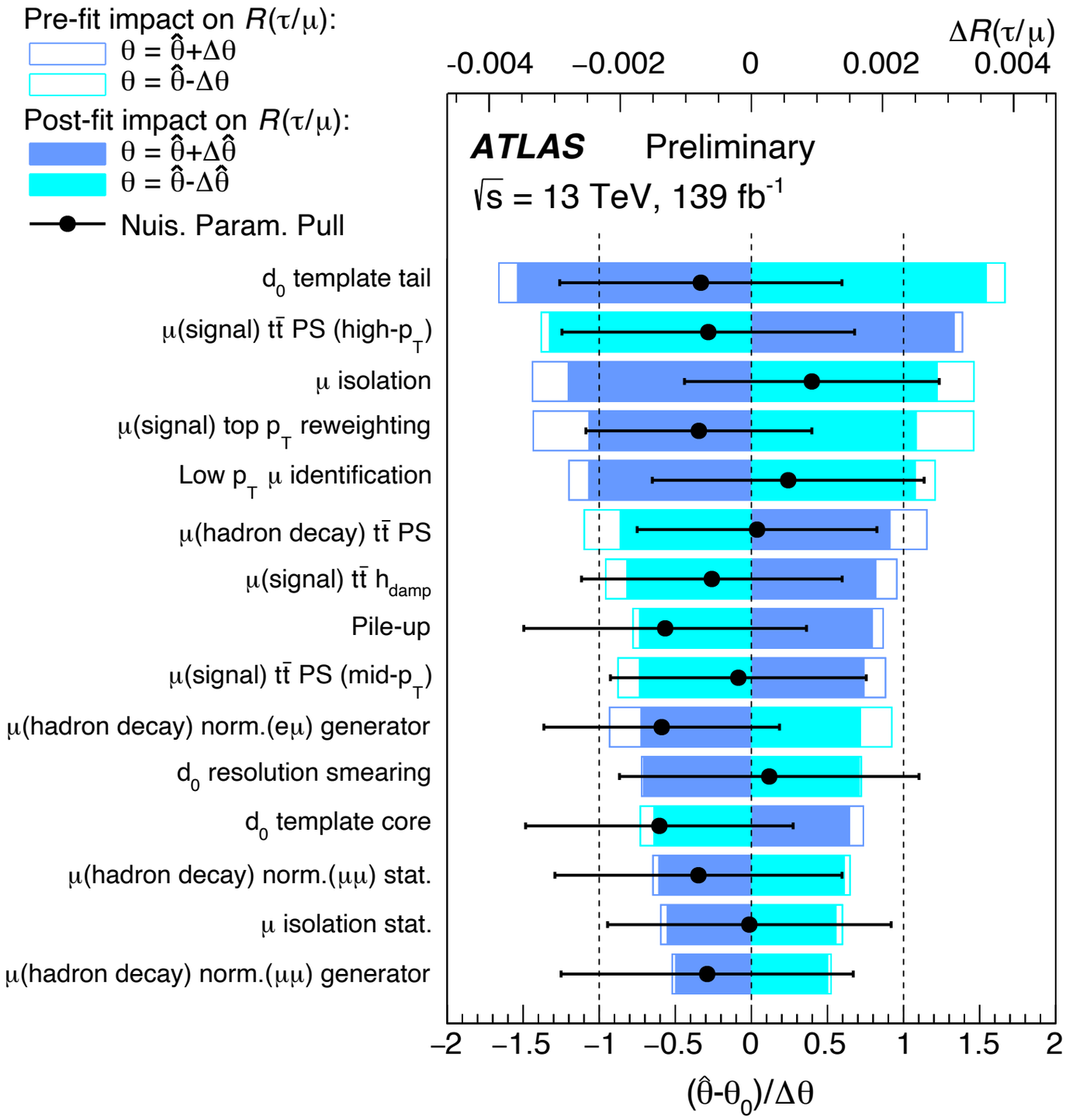


Upper limit on $\sigma_{t\bar{t}t\bar{t}}$ is translated into a limit on Yukawa coupling:

$|y_t/y_t^{SM}| < 1.7$ at 95% CL



LFV in dilepton events



4-top: 1LOS channel

36 fb^{-1}

- Background estimate
  - derive scale factors from low jet multiplicity regions to correct MC
  - apply to high multiplicity regions
  - heavy flavour component correction based on to $t\bar{t}b\bar{b}$ ratio measurement $t\bar{t}jj$

tZq measurement

arXiv:2002.07546

Phys. Rev. Lett. 122 (2019) 132003

- Backgrounds
  - non-prompt leptons
    - CMS: Data driven
    - ATLAS: MC-based shape, free floating normalisation from 2 dedicated CRs
  - WZ+b-jets
  - ttZ
    - dominant background in 4j1b and 4j2b CMS SR regions
- Signal extraction
  - simultaneous fit to distributions in signal and control regions
  - MVA discriminant in SR
  - ATLAS:
    - counting in CRs for non-prompt lepton background
    - M_T^W in WZ CRs
    - NN in ttZ CRs
  - CMS: counting in WZ and ZZ CRs