Issues in multilepton final states in ttW production

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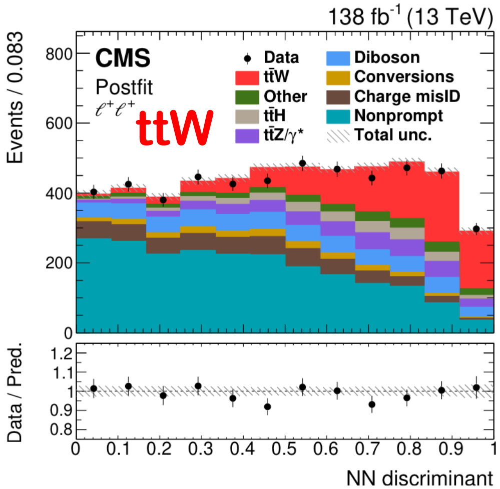
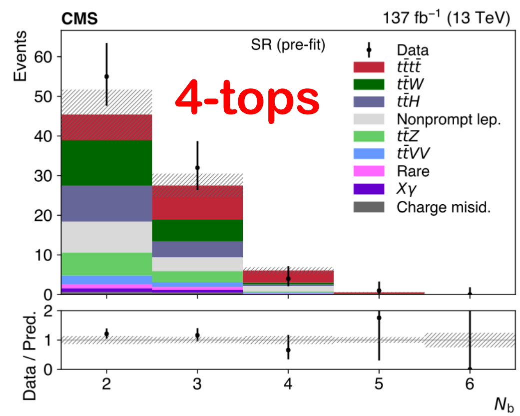
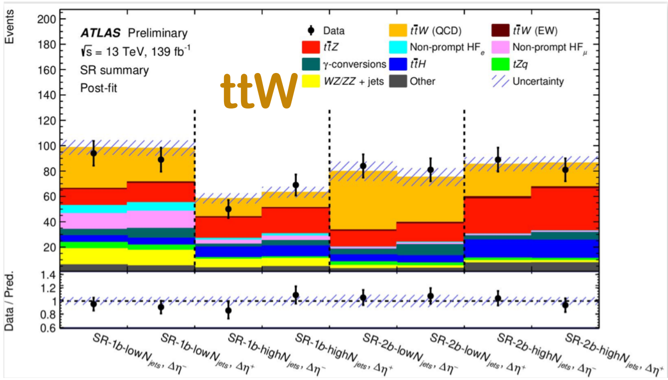
CERN, December 2022

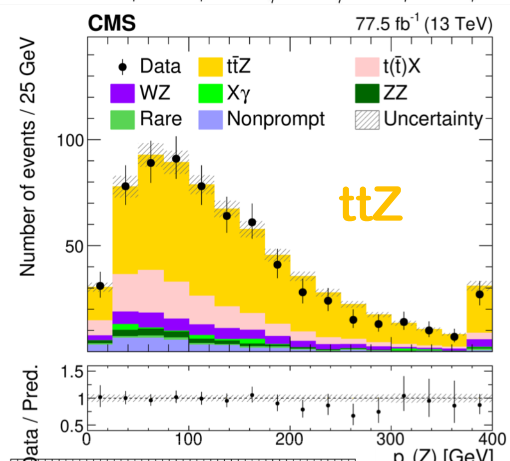
Last similar presentation: "What is wrong with multi-leptons + b-jets?" by Elizavetta at: https://indico.cern.ch/event/1138183

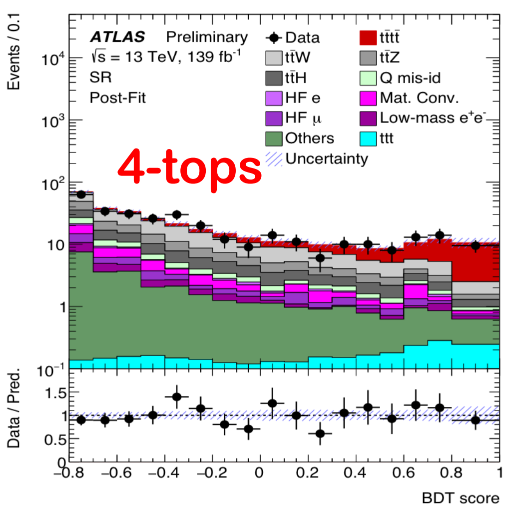
The issue… is the richness ?







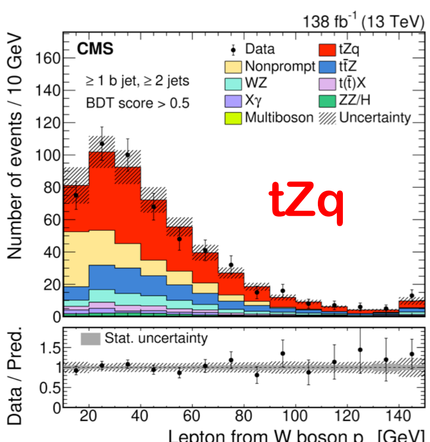


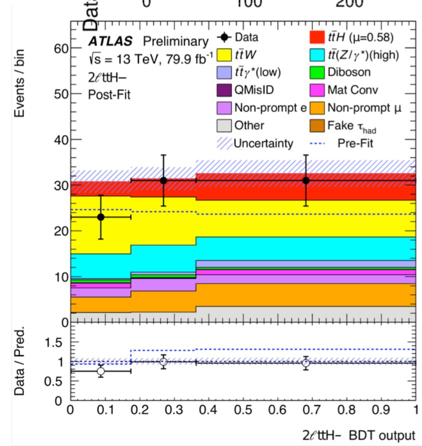


Same-Sign dileptons

&

Multi-leptons





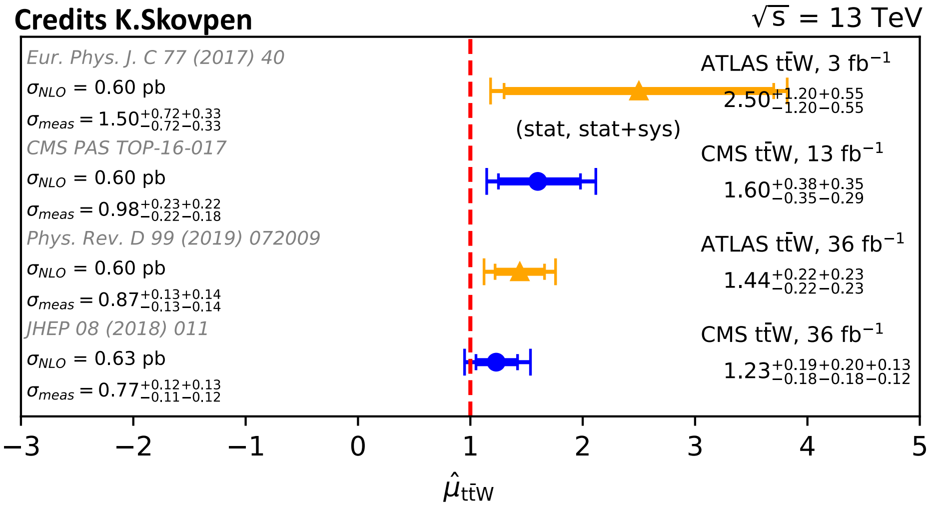
tWZ, tHq, ttVV, 3-tops ..

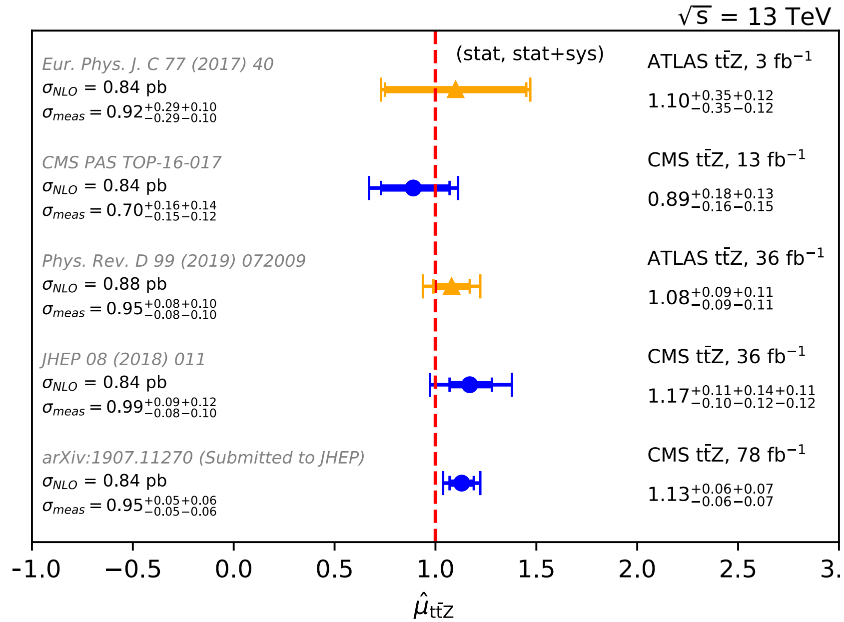
several "unknown" processes

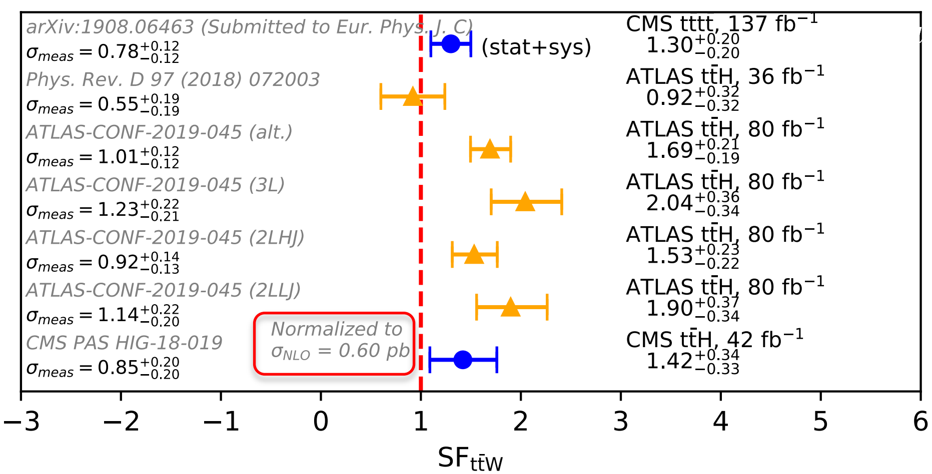
Summary of the μ/SF for ttW/Z

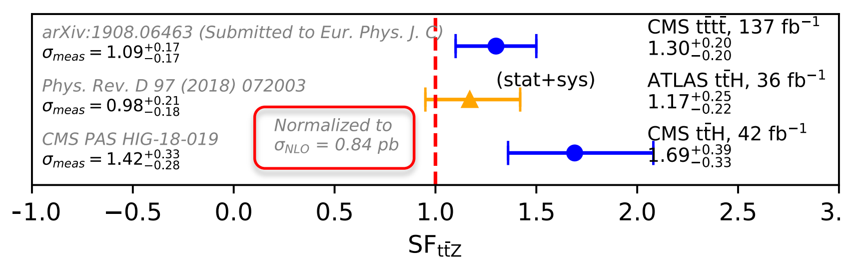
ttW **slide from 2019 TOPLHC WG** **ttZ**

Credits K.Skovpen









$$\mu_{ttW} = 1.47 \pm 0.11$$

- Most measurements in both experiments give slightly higher x-section than the theory
- Still large (statistical) uncertainties in particular for ttW

Summary of the μ/SF for ttW/Z

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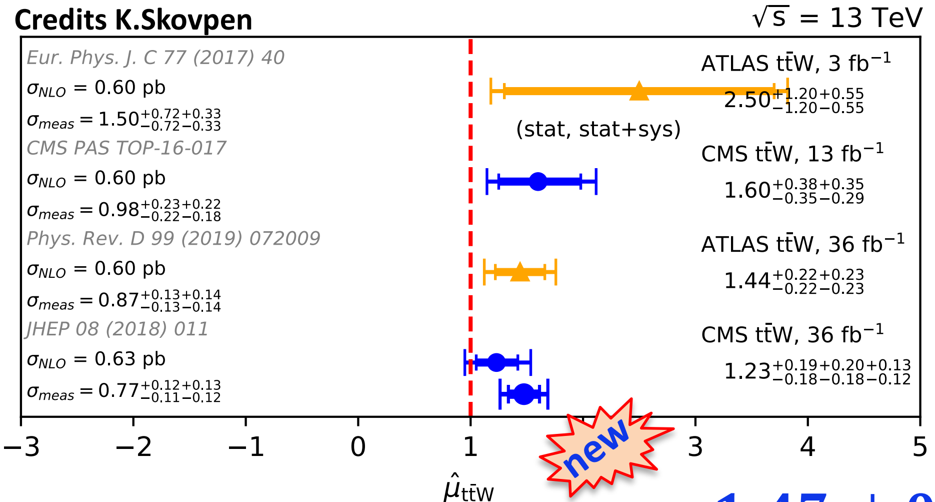

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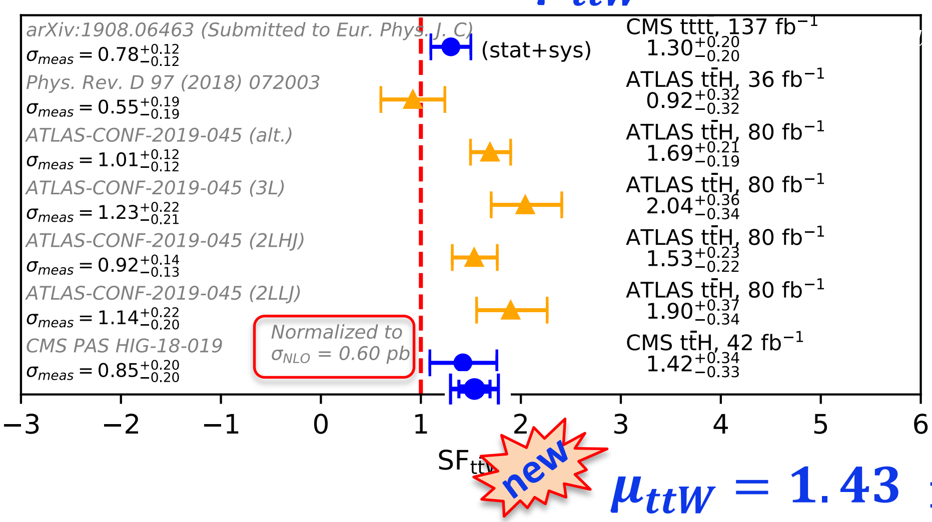
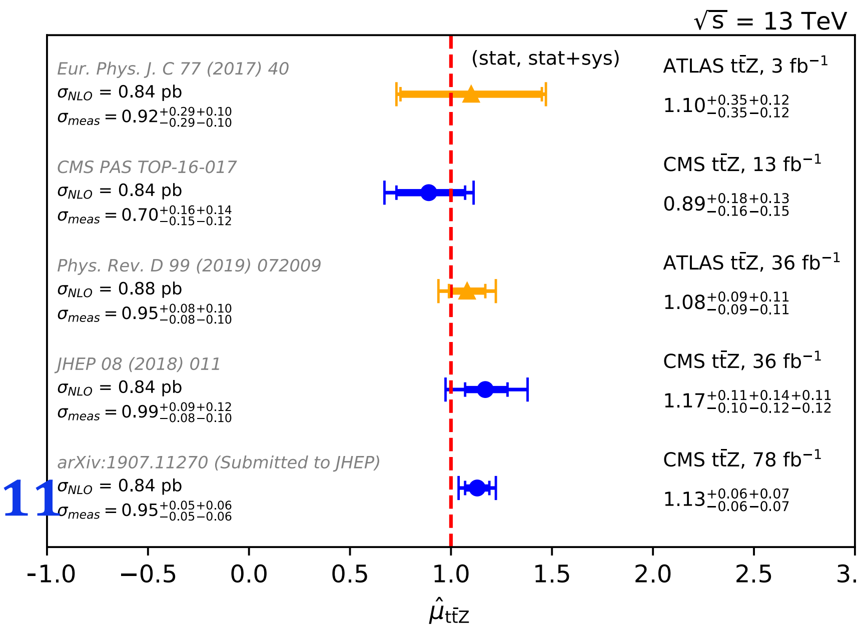
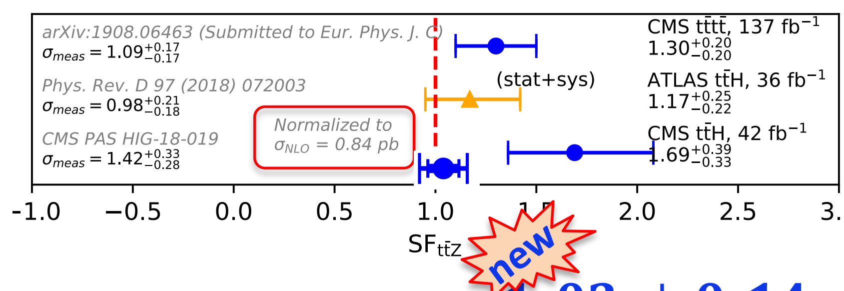


$\mu_{ttW} = 1.43 \pm 0.21$





$\mu_{ttZ} = 1.03 \pm 0.14$

Summary of the μ/SF for ttW/Z

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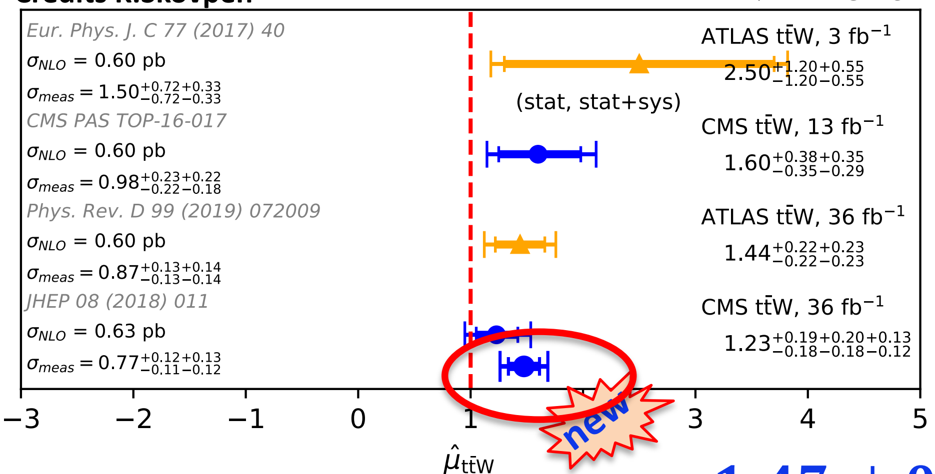

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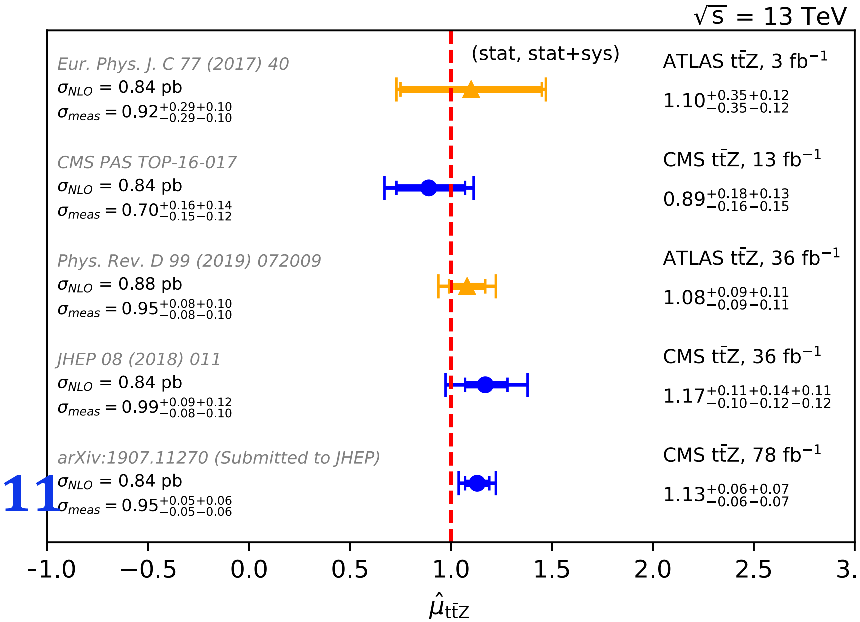
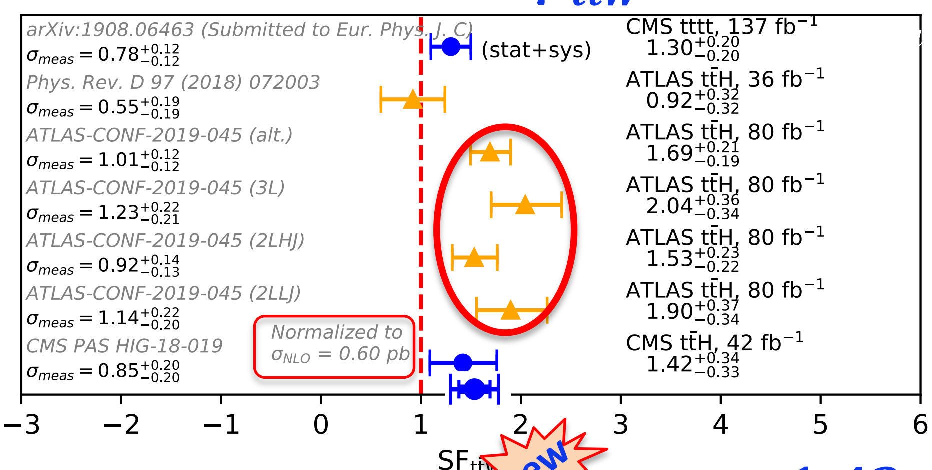
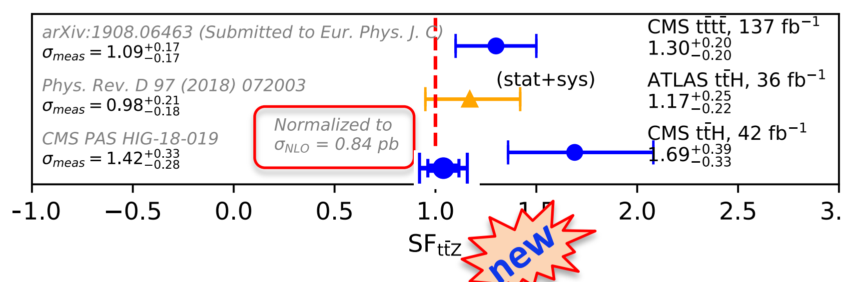




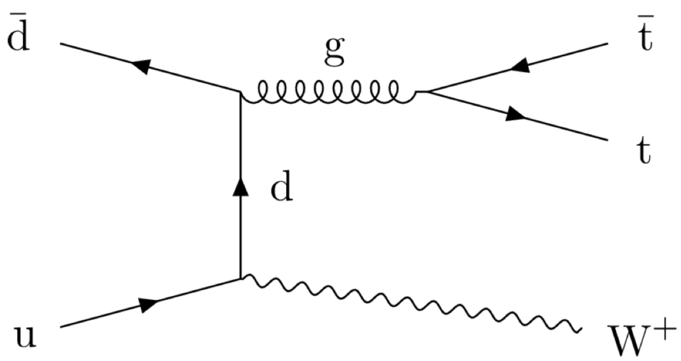


$\mu_{ttW} = 1.43 \pm 0.21$

$\mu_{ttZ} = 1.03 \pm 0.14$

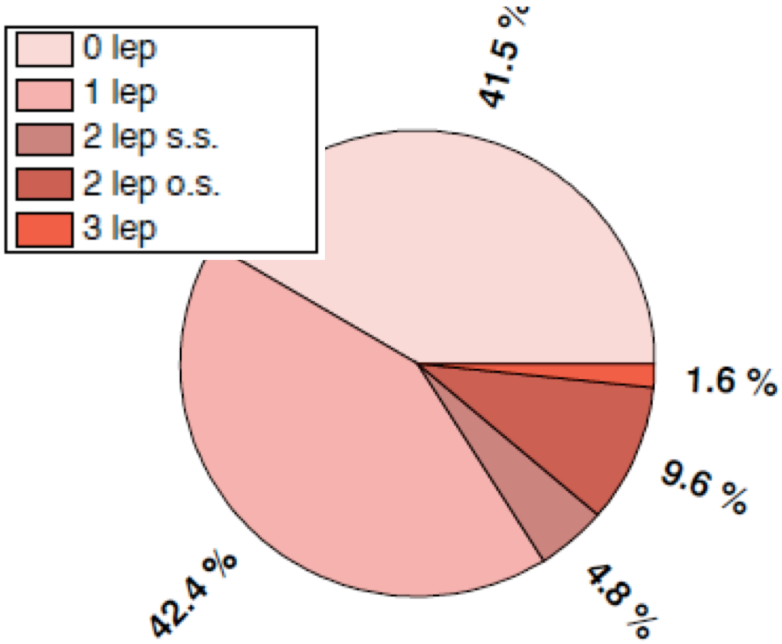
This talk: CMS-TOP-21-011 and ATLAS-CONF-2019-045

The experimental signatures



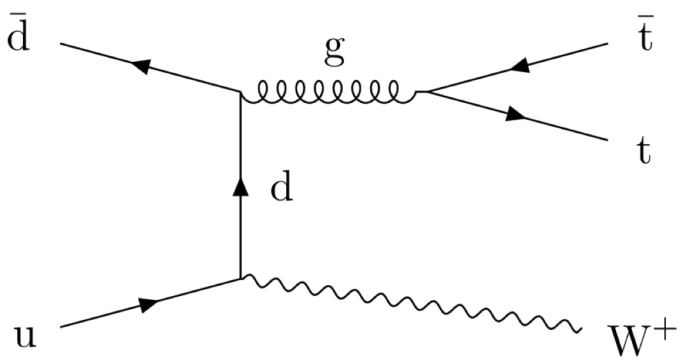
$$\sigma_{ttW} = 0.60\,\text{pb}$$

~100K ttW events @ 140 fb-1



- Same-Sign di-leptons & 3-leptons → most sensitive
- Channels with large BR are so far untouched → large backgrounds, but potential strong cross-check

The experimental signatures



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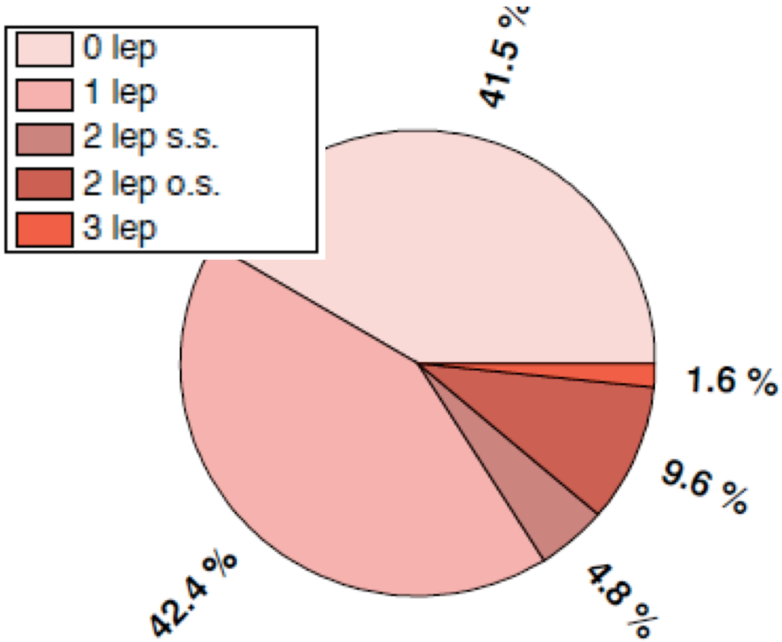


- CMS (in ttW measurement)
  - MadGraph5_aMC 2.6.0 at NLO in QCD with $\alpha_s^3\alpha$ term included
  - The $\alpha^3\alpha_s$ term is simulated separately by MadGraph5_aMC

  x-section 592^{+155}_{-97} fb
- ATLAS (in ttH analysis)
  - Sherpa 2.2.1 NLO + 1p@NLO +2p@LO

  x-section: 727 ± 92 fb.

ttW measurements in ATLAS & CMS

CMS-TOP-21-011

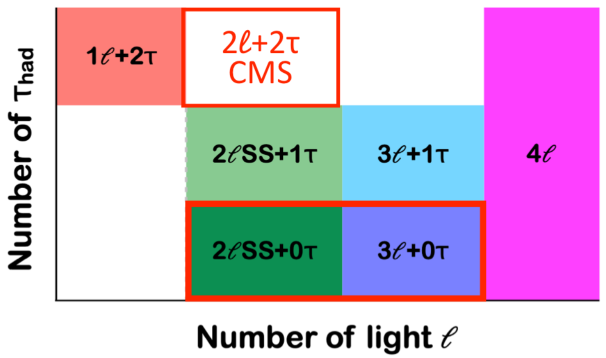
CMS: dedicated ttW measurement

- Selection
  - 2 same-sign or 3 leptons
  - Z veto (ee, μμ) in 3L and in (eeSS)
  - $N_{jets} \geq 2$
  - 1b medium or 2b loose in 2LSS
  - at least 1b medium in 3L
  - Large E_T^{mis} in 2LSS

ATLAS-CONF-2019-045

ATLAS: ttW in the context of ttH

2LSS	3L
$N_{jets} \geq 4$, $N_b \geq 1$	$N_{jets} \geq 2$, $N_b \geq 1$ $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV



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ttW measurements in ATLAS & CMS

CMS-TOP-21-011

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ATLAS-CONF-2019-045

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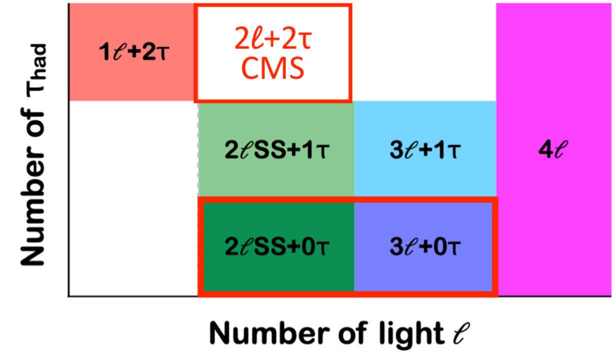
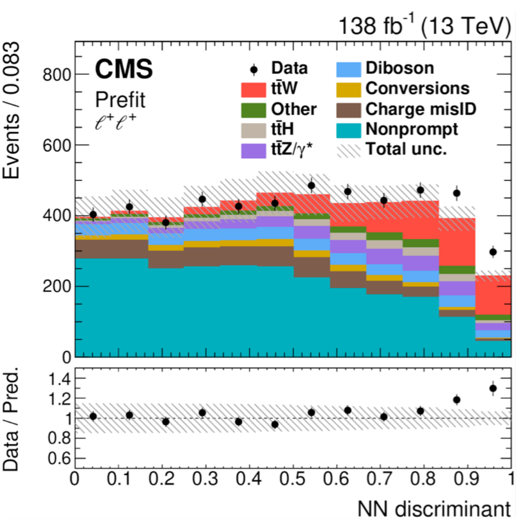
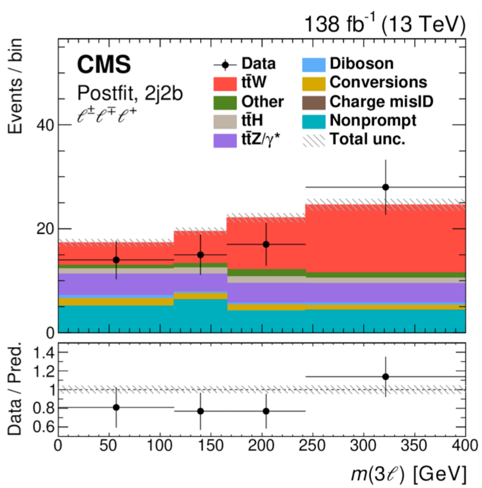
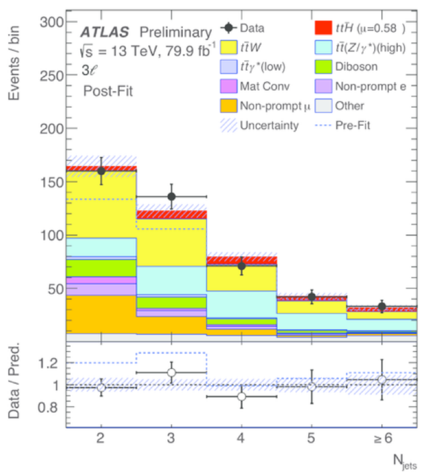
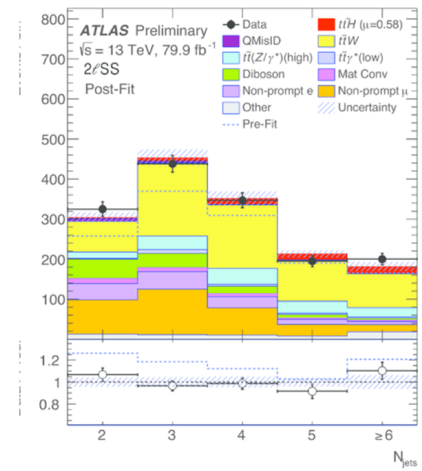


BDT training to separate ttW, ttH and ttBar

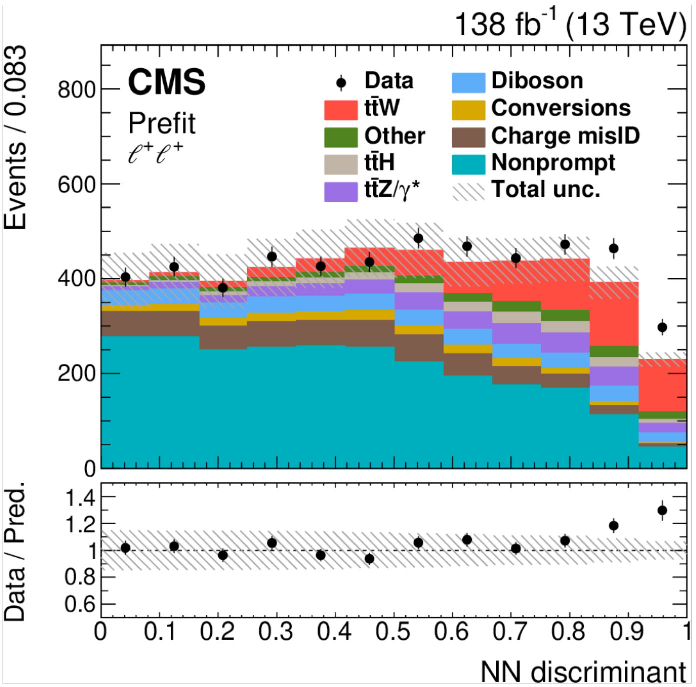


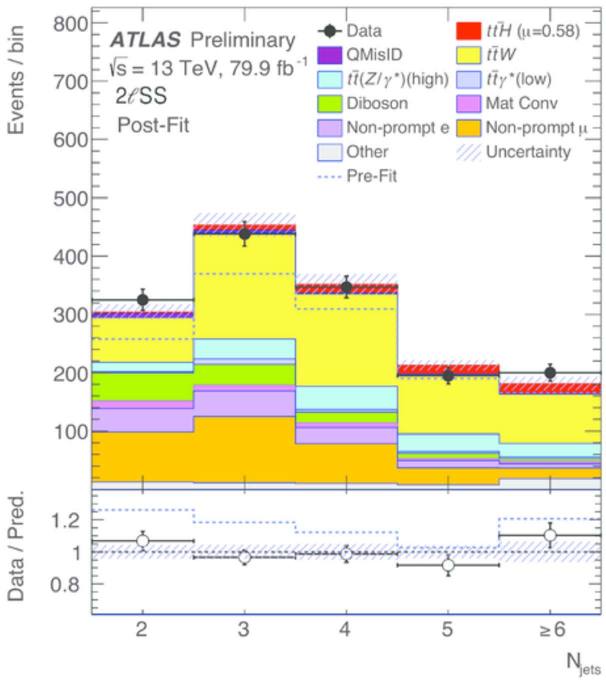






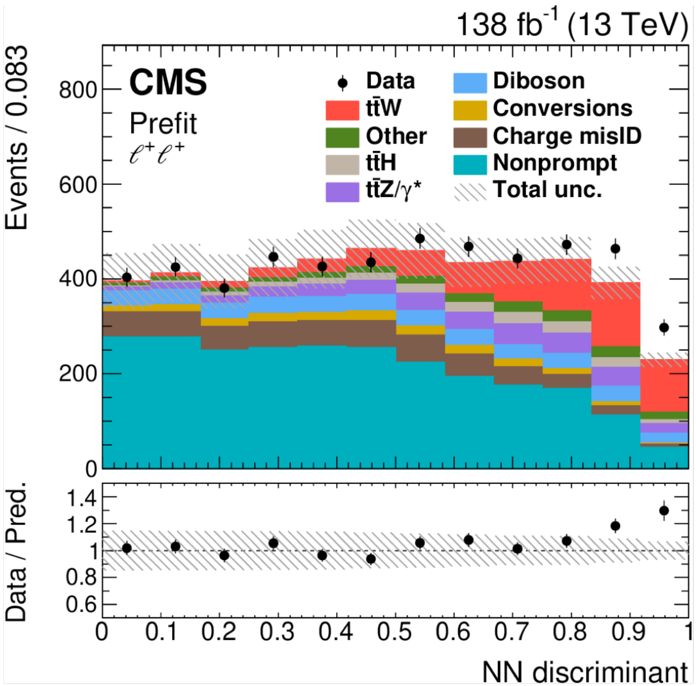
State-of-the-art on the measurements

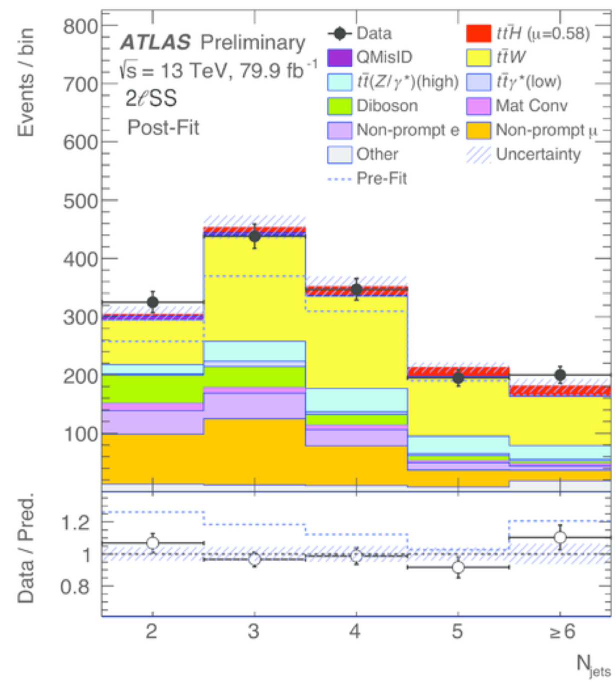




- Nonprompt leptons: Either fully from data or fits to MC template
- Lepton charge mismeasurement: Estimated using semi-data-driven method
- Conversions(X+γ): Simulation with validations in CR
- WZ/ZZ/ttZ background: Simulation validated in CR and/or extracted from the fit

State-of-the-art on the measurements





- Nonprompt leptons: Either fully from data or fits to MC template
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- Conversions(X+γ): Simulation with validations in CR
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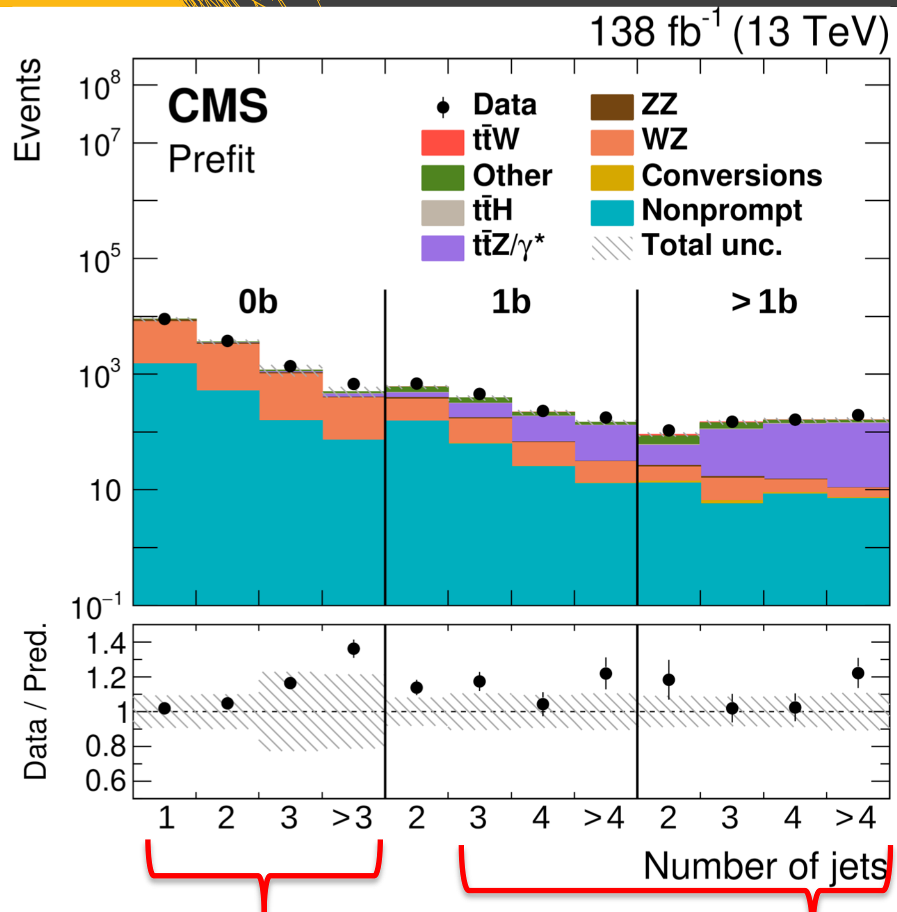
- Rare processes & tt+X : ttH, tZq, ttG, tWZ, tH, multiboson → simulations with NLO x-section
  - CMS : tZq (10%), ttH(20%), tWZ(11%), VVV/tHW/tHq/ttVV(50%)…
  - ATLAS: tZq (15%), ttH(measured), tWZ(10%), VVV/ttVV(50%)…

ttZ & WZ background



Pure in WZ → overall normalization of WZ & Njet dependence

ttZ

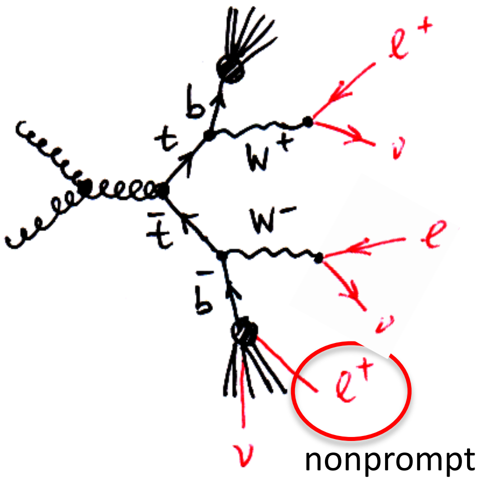
ATLAS: SHERPA (+up to 3 partons)

- WZ/ttZ normalization let to float in the fit
- Systematic uncertainty for WZ+HF→ 10-40%

- CMS: Madgraph NLO (up to 1 partons)
  - WZ/ttZ normalization let to float in the fit
  - Systematic uncertainty for WZ+HF→ 10-40% & 30% for Njet>=3

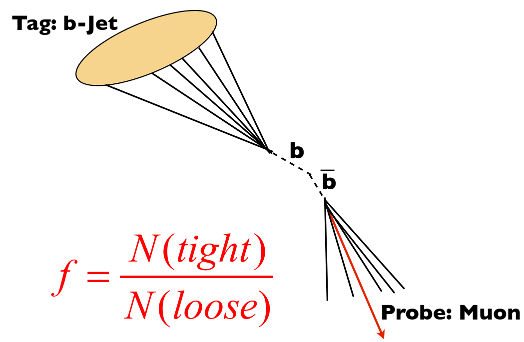
- ttZ signal strength obtained is consistent with the dedicated measurements

Nonprompt lepton background



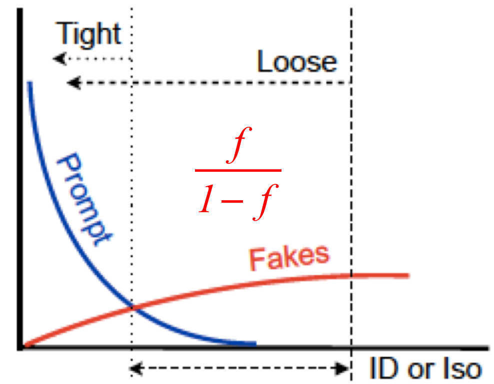
- **Mainly from $t\bar{t}$, W+jets and DY:**
  - ➜ Use events with at least 1 ℓ fails “tight” selection but
  - ➜ passes the “loose” selection → “Tight-to-Loose” (TL)
  - ➜ Need to evaluate TL probability (f)

Measure in QCD di-jet events



$$f = \frac{N(tight)}{N(loose)}$$

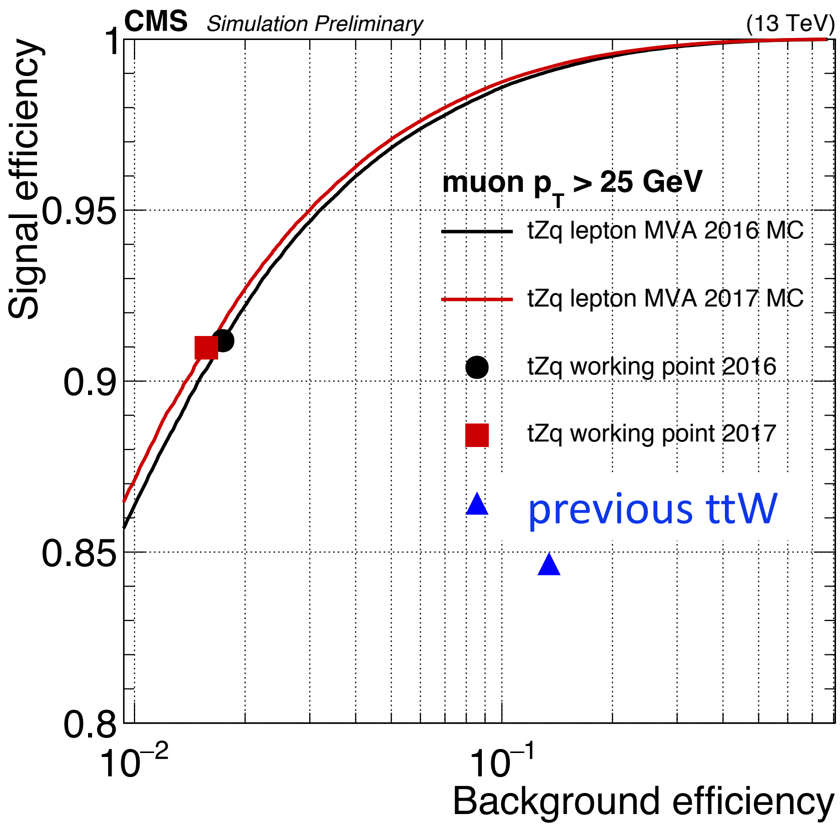
Apply in the signal region



➜ CMS : f is measured in a QCD di-→ potential signal contamination

➜ ATLAS: More use of MC simulation, MC based template fit

Lepton identification

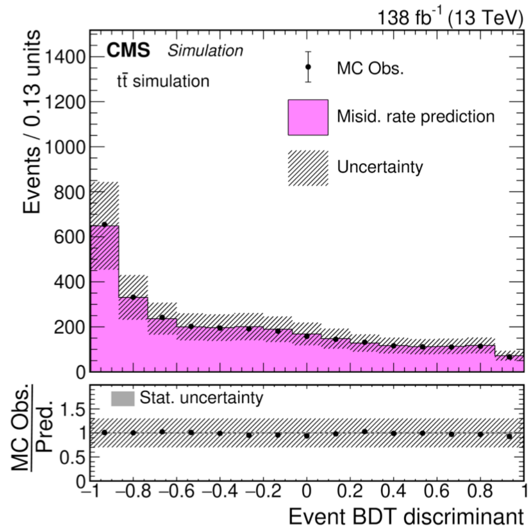


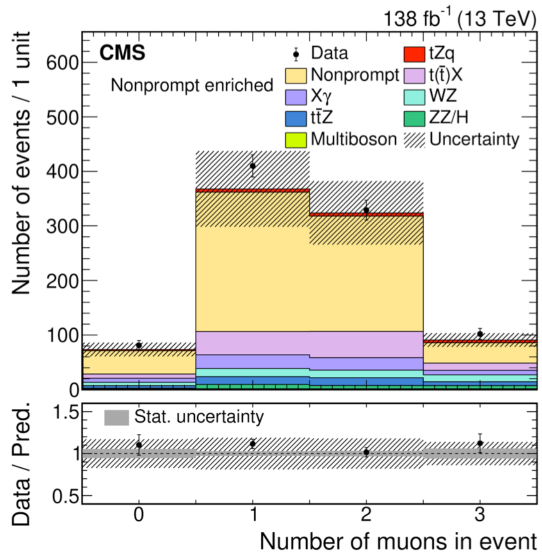
- Improved lepton selection using MVA wrt. C&C type is.
- nearly all CMS ttV, ttH analyses use
- strongly reduced nonprompt leptons

Challenges:

- modelling of lepton id efficiencies
- difficult to find a data CR to measure the TL-ratio or pure validation region

nonprompt background validation





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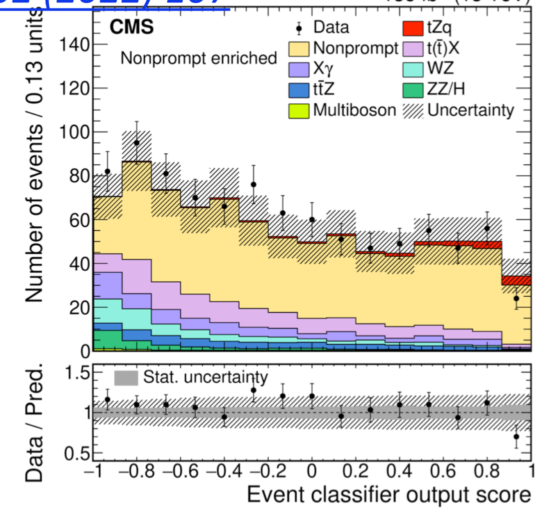
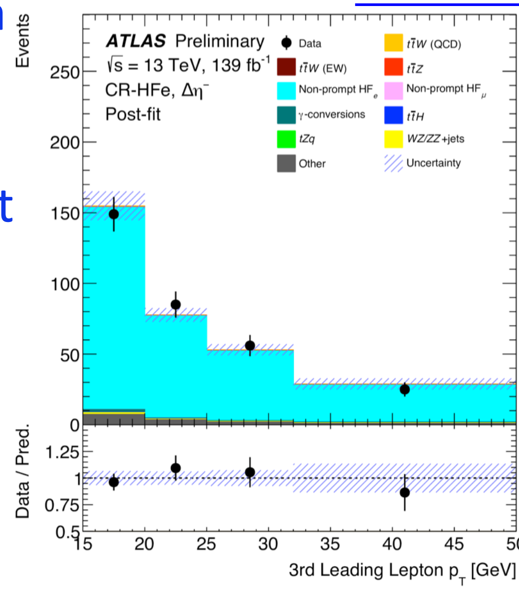


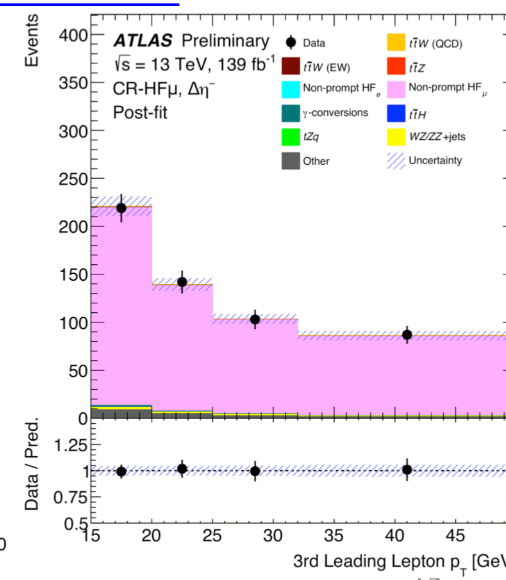
- MC closure test & validation in data
- CMS: various systematic unct.(rate & shape) accounting also for statistical unct. in the measurement region (20% +)
- ATLAS: MC template fit with normalization parameters

$$\hat{\lambda}_e^{4\ell,\mathrm{had}} = 0.89 \pm 0.41$$

$$\hat{\lambda}_\mu^{4\ell,\mathrm{had}} = 1.07 \pm 0.43$$

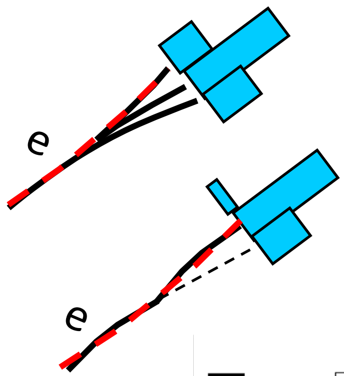
[ATLAS-CONF-2022-062](#)





Charge mis-id background

Brem.&conversion or multiple scattering in the tracker



muons: negligible (rate ~10^{-5})

electrons: Use Z events to predict changre mis-id rate: depending on the pseudorapidity & p_T it varies $10^{-3} - 10^{-4}$

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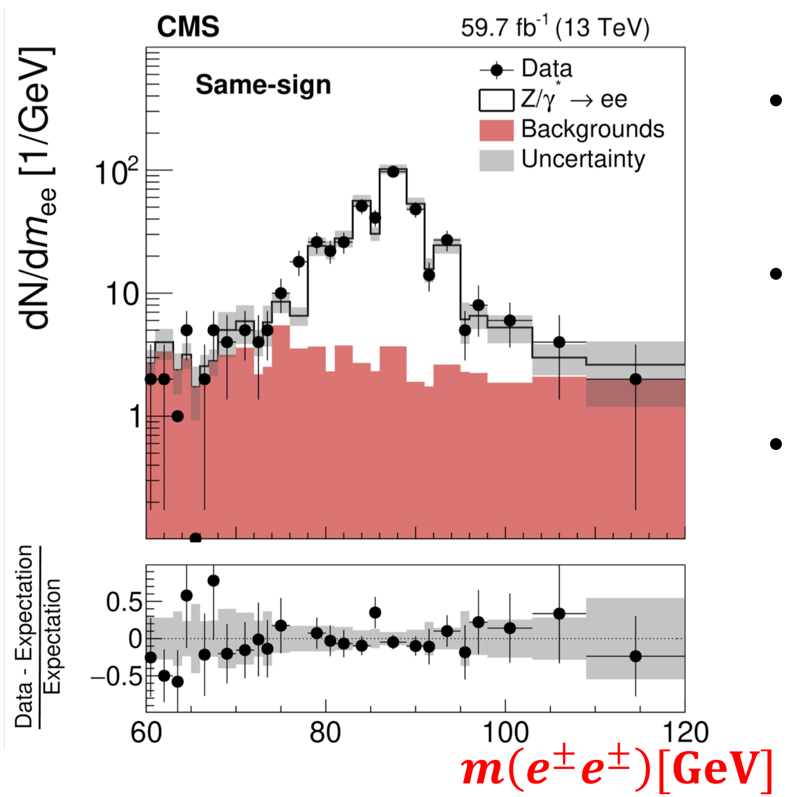

- Rather common to use DY events to measure/validate charge mis-id rate
- Measured charge mis-id rates are used to estimate the background in the SR
- Systematic uncertainty:
  CMS (20%),
  ATLAS (30%)

Background due to γ-conversion

- Internal or ext. conversion:
- $tt\gamma^{(*)}$
  - main contributor
  - well measured by both collaborations (4-6%)
- $Z\gamma^{(*)}, W\gamma^{(*)}$
  - rather negligible, but extra b/c production modeling important

- Photon conversion in the detector
  - requires a good modeling of material budget
  - validation of photon conversion in data

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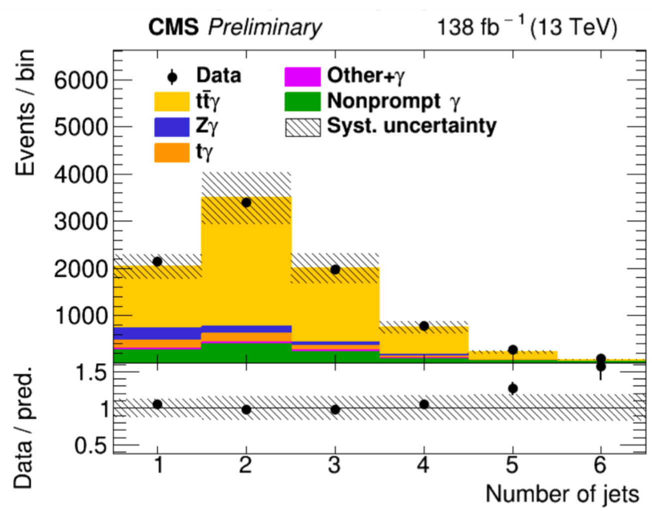

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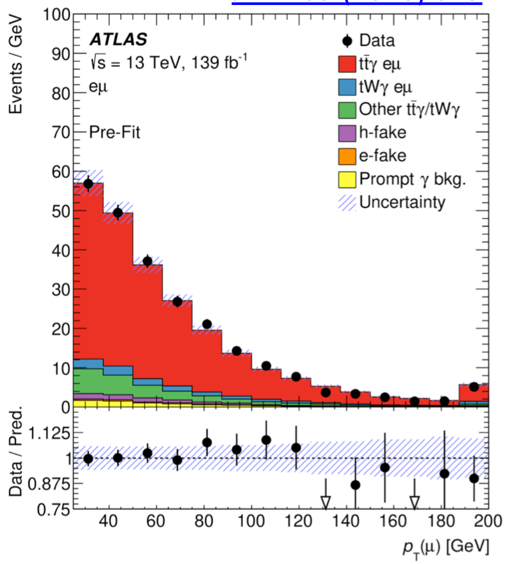
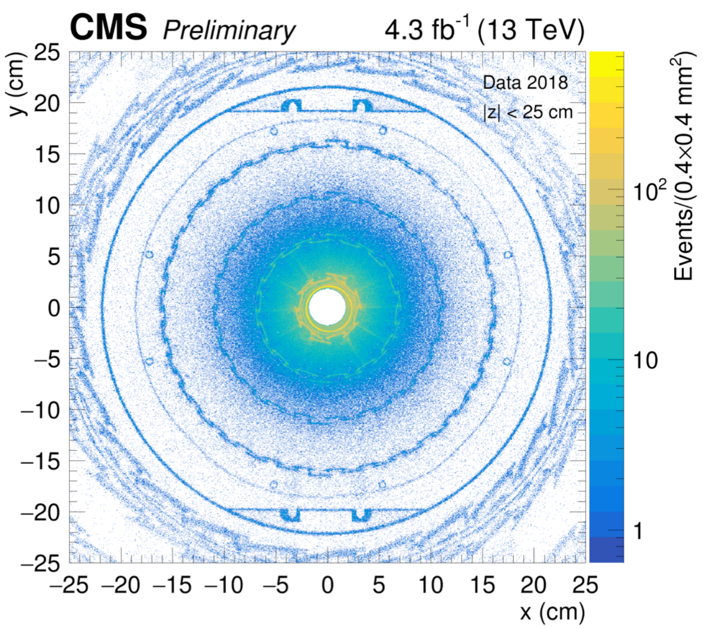
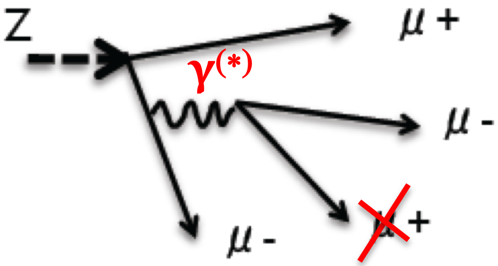




Background due to γ-conversion

- Tri-lepton control region to validate



$$m(\ell\ell\ell) \sim m(Z)$$

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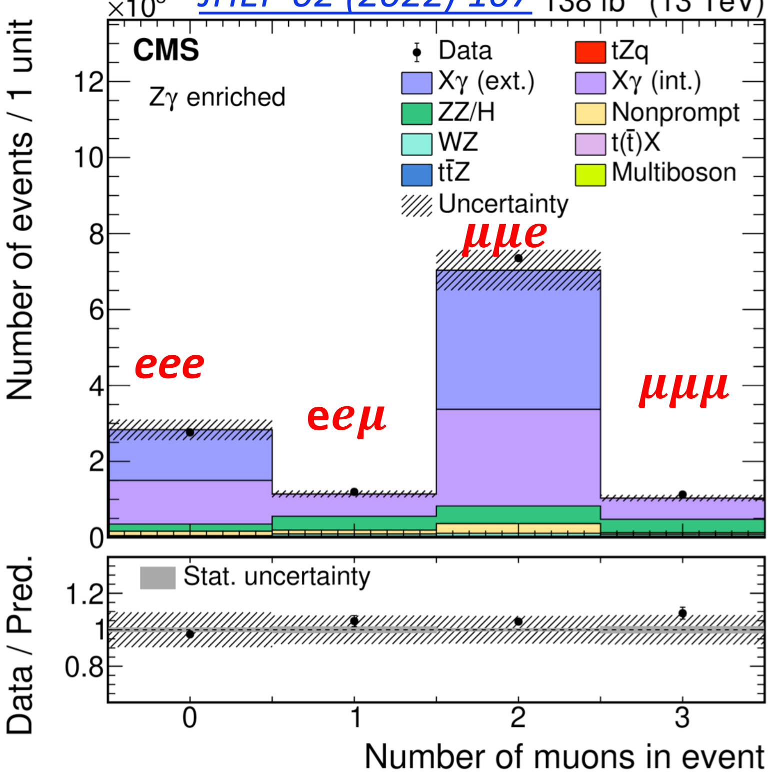
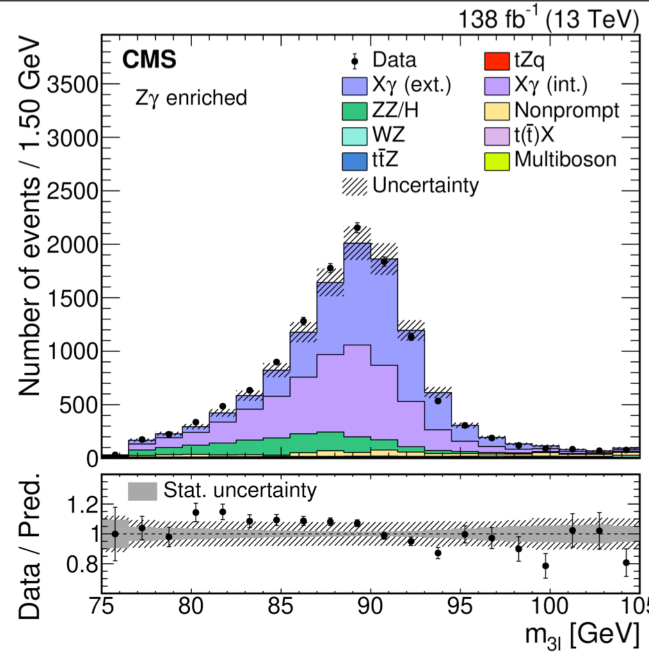




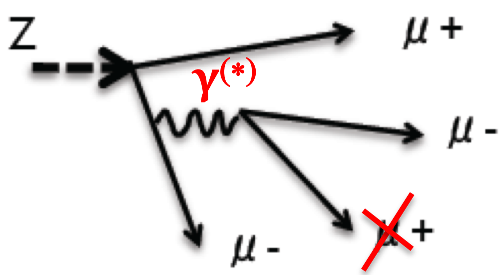
$\mu\mu\mu + ee\mu \rightarrow$ internal γ^* conversion

$eee + \mu\mu e \rightarrow$ int./ext. $\gamma^{(*)}$ conversion

- **In all cases very well modeled!**
- (CMS)rather conservative 30% systematic uncertainty

Background due to γ-conversion

- Tri-lepton control region to validate



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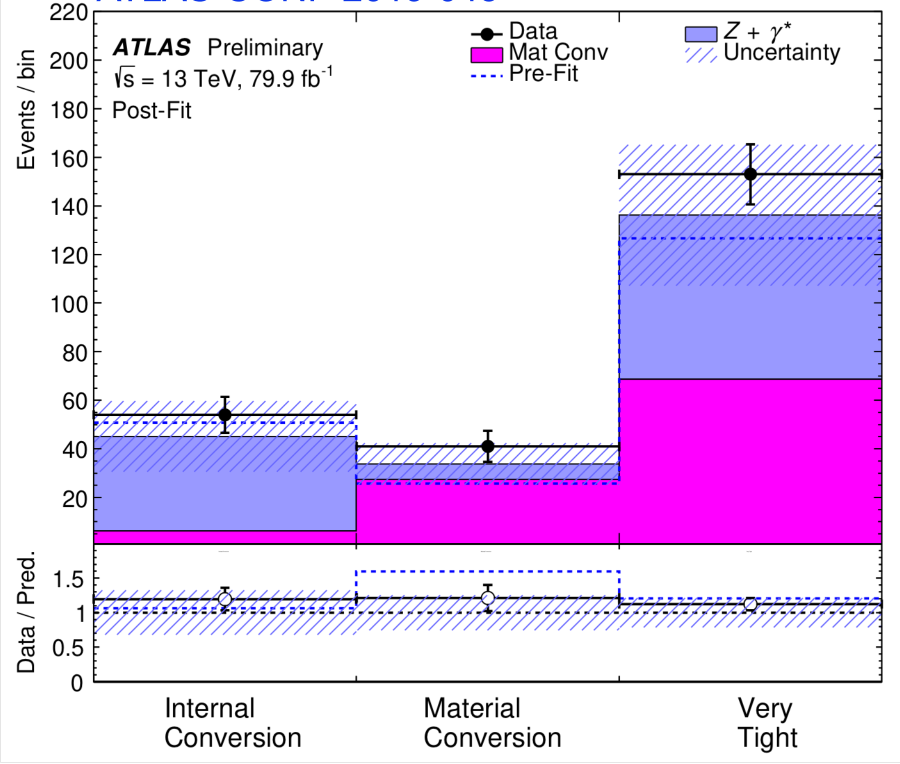
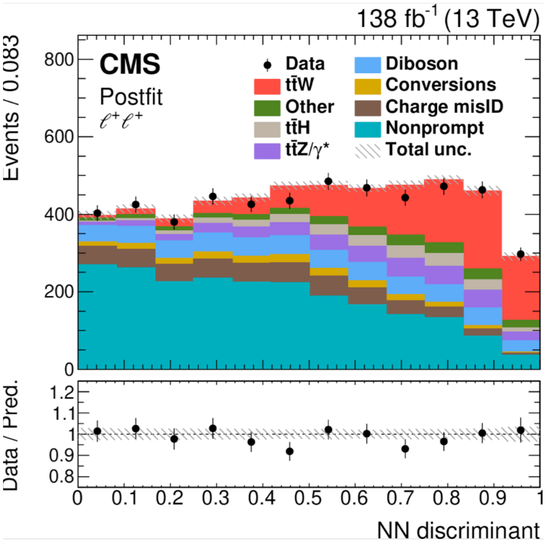
ATLAS-CONF-2019-045

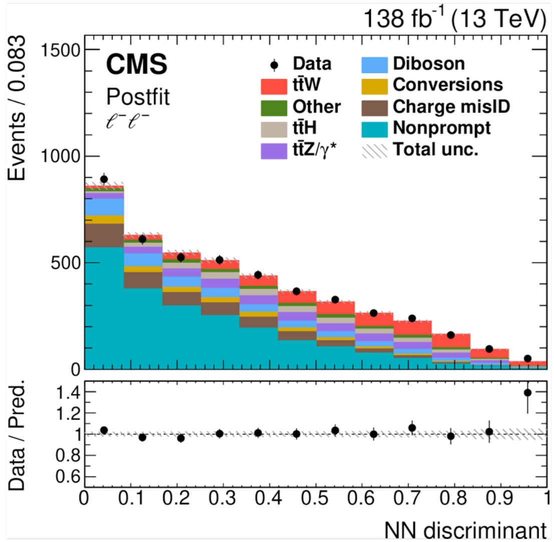


ATLAS: similar control regions in enriched in internal and material conversion

- some mismodeling in pre-fit
- 25% uncertainty

ttW results CMS

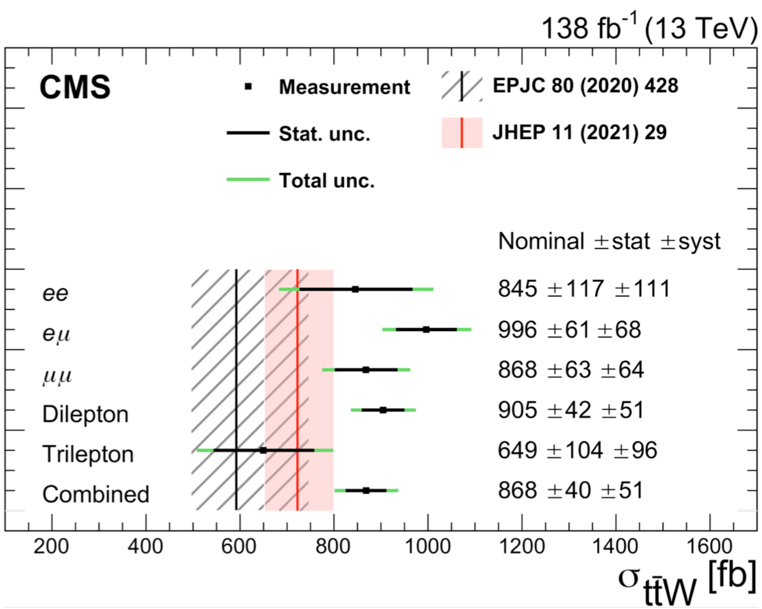




- PL fit to various distributions in SS,3L SR and CR
- Postfit distributions look good

$$\mu_{ttW} = 1.47 \pm 0.11$$

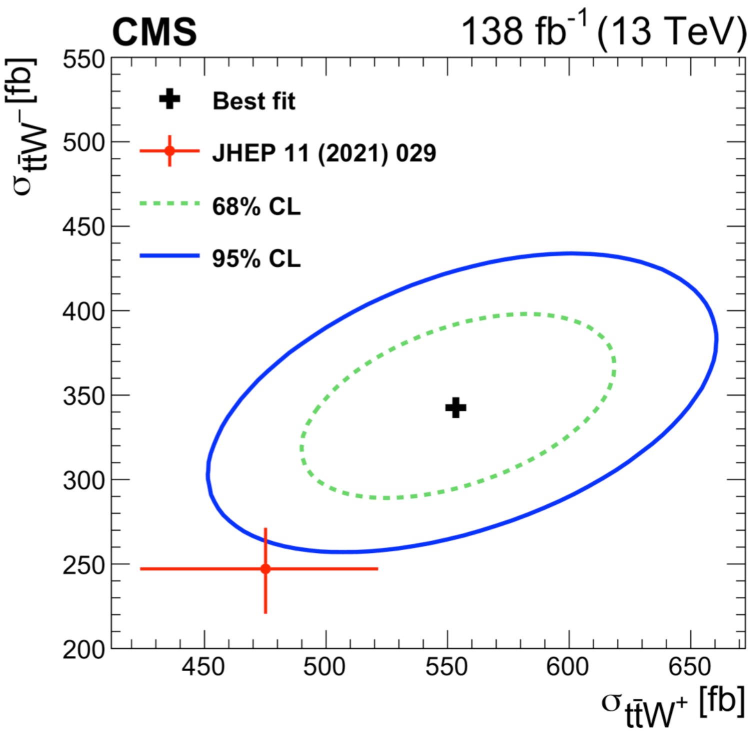
similar to ATLAS and other CMS results

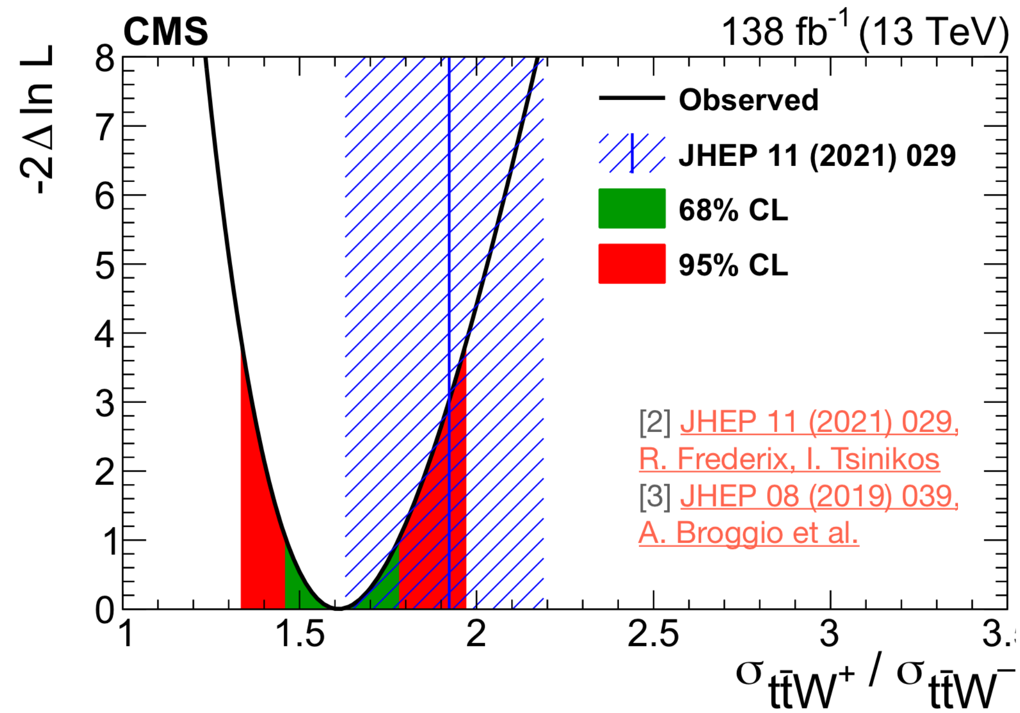


Experimental uncertainties	
Integrated luminosity	1.9
b tagging efficiency	1.6
Trigger efficiency	1.2
Pileup reweighting	1.0
Modeling uncertainties	
tt̄W scale	1.8
tt̄W color reconnection	1.0
ISR & FSR scale for tt̄W	0.8
Simulation statistical uncertainty	1.8

Background uncertainties	
tt̄H normalization	2.6
Charge misidentification	1.6
Nonprompt leptons	1.3
VVV normalization	1.2
tt̄VV normalization	1.2

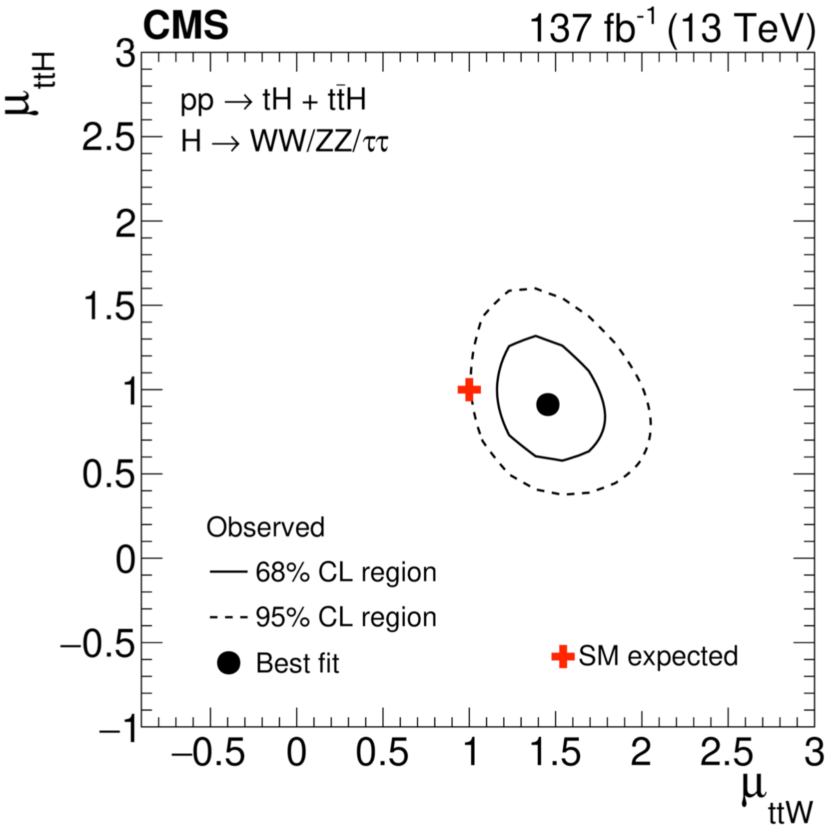
ttW+ vs. ttW-





Observable	Measurement	SM prediction NLO + NNLL [3]	SM prediction NLO + FxFx [2]
$\sigma_{t\bar{t}W}$	$868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb	$592\,^{+155}_{-97}$ fb	$722\,^{+71}_{-78}$ fb
$\sigma_{t\bar{t}W+}$	$553 \pm 30\,(\text{stat}) \pm 30\,(\text{syst})$ fb	$384\,^{+53}_{-33}$ fb	$475\,^{+46}_{-52}$ fb
$\sigma_{t\bar{t}W-}$	$343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})$ fb	$198\,^{+26}_{-17}$ fb	$247\,^{+24}_{-27}$ fb
$\sigma_{t\bar{t}W+} / \sigma_{t\bar{t}W-}$	$1.61 \pm 0.15\,(\text{stat})\,^{+0.07}_{-0.05}\,(\text{syst})$	$1.94\,^{+0.37}_{-0.24}$	$1.92\,^{+0.27}_{-0.29}$

Summary & outlook

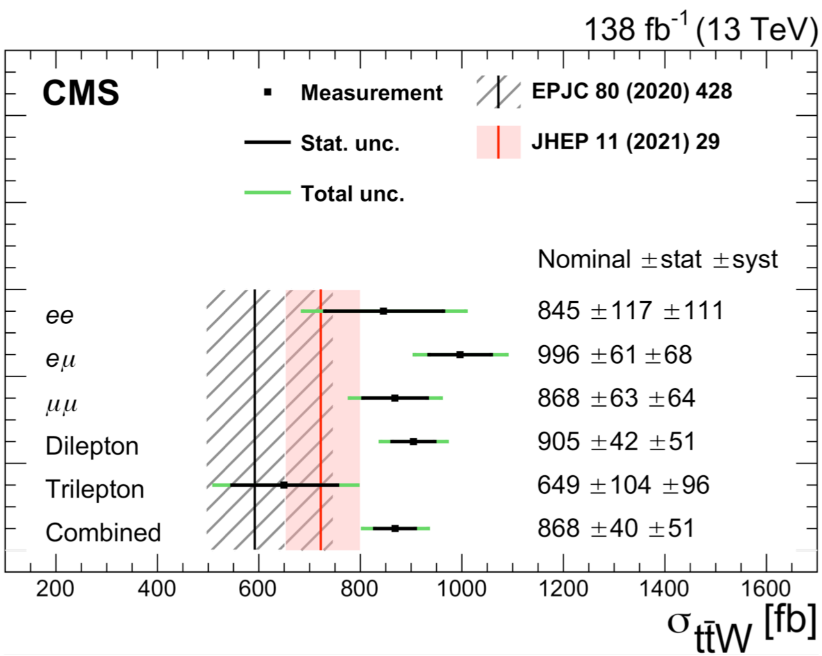


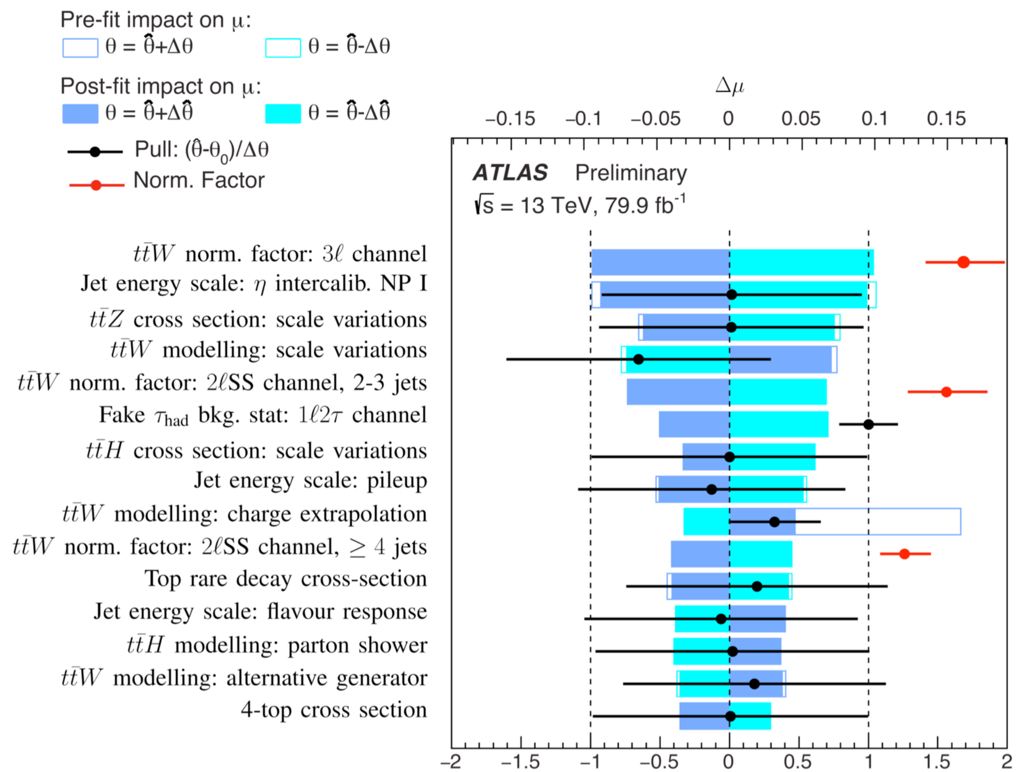
- Good understanding of ttW is a key for very interesting rare processes: ttH, 4-tops, ttVV, tWZ
- Difficult to isolate one process free of backgrounds → correlations, tails

- ATLAS&CMS results are consistent, but clear differences in modelling uncertainties
- Robust techniques for understanding the backgrounds
- Looking forward to the new ATLAS measurement with full Run II ☺

Backup

ttW ATLAS&CMS results





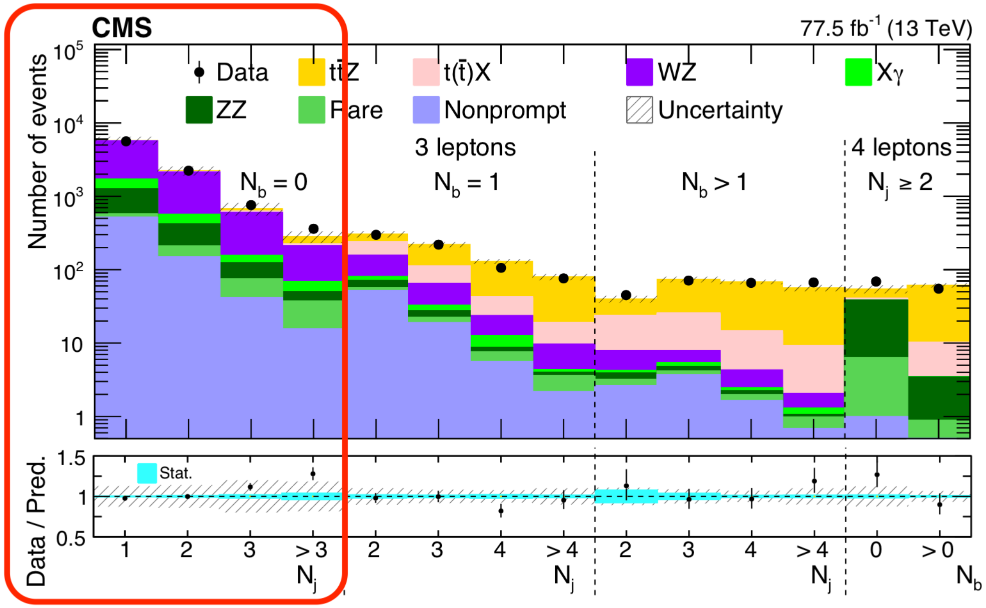
ATLAS 3L ttW charge asymmetry

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-062/

	Pre-selection			
N_ℓ ($\ell = e/\mu$)	$= 3$			
p_T^ℓ ($1^{st}/2^{nd}/3^{rd}$)	≥ 30 GeV, ≥ 20 GeV, ≥ 15 GeV			
Sum of lepton charges	± 1			
$m_{\ell\ell}^{OSSF}$	≥ 30 GeV			
	Region-specific requirements			
	SR-1b-lowN_{jets}	**SR-1b-highN_{jets}**	**SR-2b-lowN_{jets}**	**SR-2b-highN_{jets}**
N_{jets}	$[2, 3]$	≥ 4	$[2, 3]$	≥ 4
$N_{b\text{-jets}}$	$= 1$	$= 1$	≥ 2	≥ 2
E_T^{miss}	≥ 50 GeV	≥ 50 GeV	–	–
$N_{Z\text{-cand.}}$	$= 0$			
Tight leptons	TTT			
e/γ ambiguity-cuts	all pass			
	CR-$t\bar{t}Z$	**CR-HF$_e$**	**CR-HF$_\mu$**	**CR-γ-conv**
$\ell^{1st/2nd/3rd}$	$\ell\ell\ell$	$\ell\ell e$	$\ell\ell\mu$	$\ell\ell e$, $\ell e\ell$, $e\ell\ell$
N_{jets}	≥ 4	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$	≥ 2	$= 1$	$= 1$	≥ 1
E_T^{miss}	–	< 50 GeV	< 50 GeV	< 50 GeV
$N_{Z\text{-cand.}}$	$= 1$	$= 0$	$= 0$	$= 0$
Tight leptons	TTT	$TT\overline{T}$	$TT\overline{T}$	TTT
e/γ ambiguity-cuts	all pass	all pass	all pass	≥ 1 fail

ttZ in CMS & ATLAS

- Simultaneous profile likelihood fit in multiple signal/control regions



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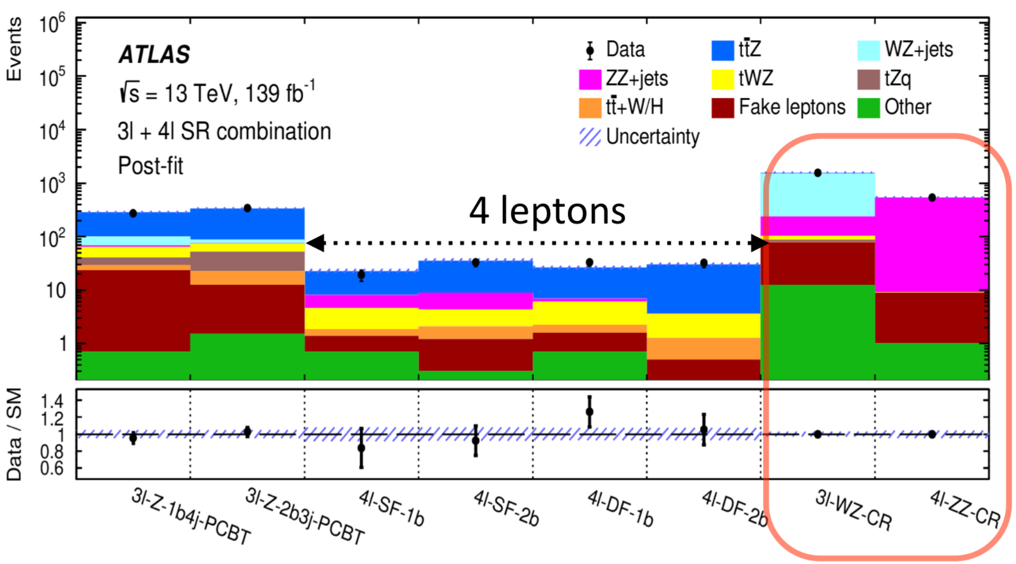
$$\mu = 1.13 \pm 0.06(\text{stat}) \pm 0.07(\text{syst})\ \text{pb}$$

8% precision

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

Main systematic uncertainties

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



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$$\mu = 1.19 \pm 0.06(\text{stat}) \pm 0.10(\text{syst})\ \text{pb}$$

10% precision

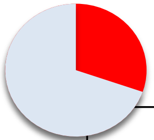
$$\sigma = 0.99 \pm 0.05(\text{stat}) \pm 0.08(\text{syst})\ \text{pb}$$

Main systematic uncertainties

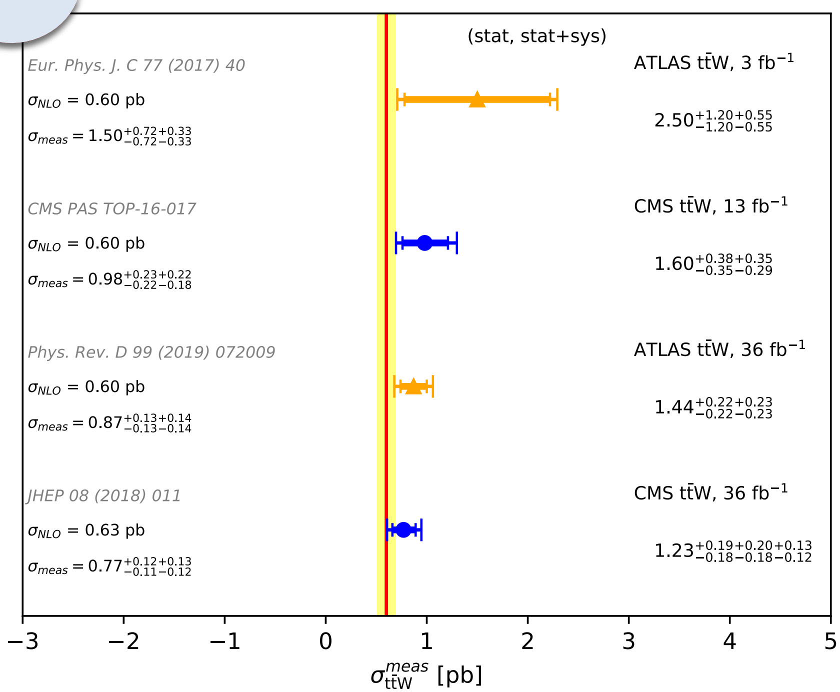
- ttZ parton shower model (3.1%)
- tWZ model, b-tagging (2.9% each)
- flavour tagging (2.8%)

Measured ttW/Z cross sections @ 13 TeV

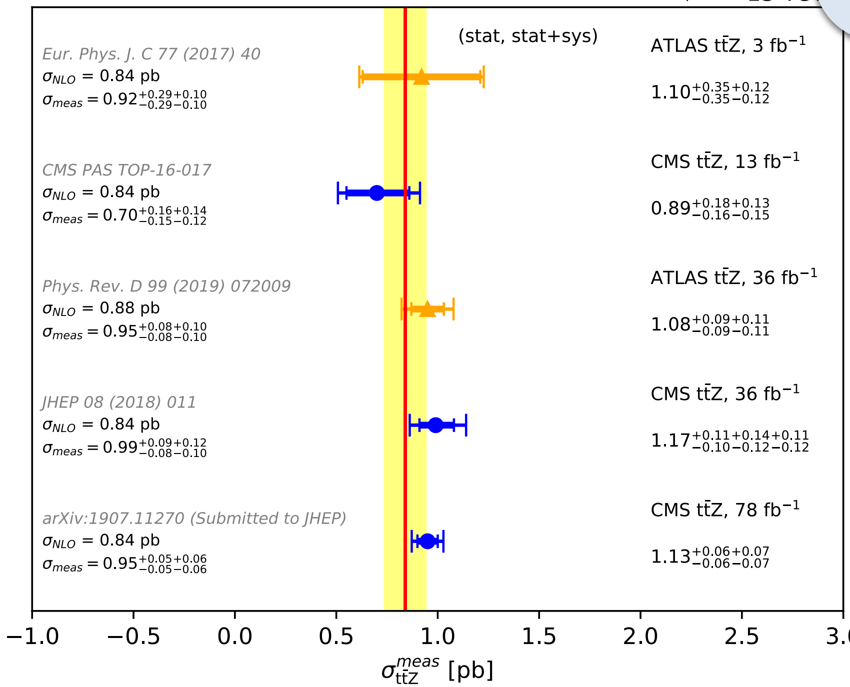
Used Run II data



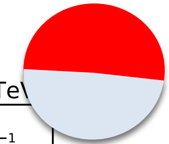
ttW measurements



ttZ measurements



Used Run II data



- Most measurements in both experiments give slightly higher x-section than the theory
- Still large (statistical) uncertainties in particular for ttW
- ttW: 36 fb^{-1}, ttZ: 78(36) fb^{-1}
- Which theory cross section should we compare our measurements ?

Samples CMS

Table 1: Event generators used to simulate events for the various processes. For each of the simulated processes shown, the order of the cross section normalization, the event generator used, the perturbative order of the generator calculation, and the NNPDF versions at NLO and at next-to-next-to-leading order (NNLO) used in simulating samples for the 2016 (2017) data sets.

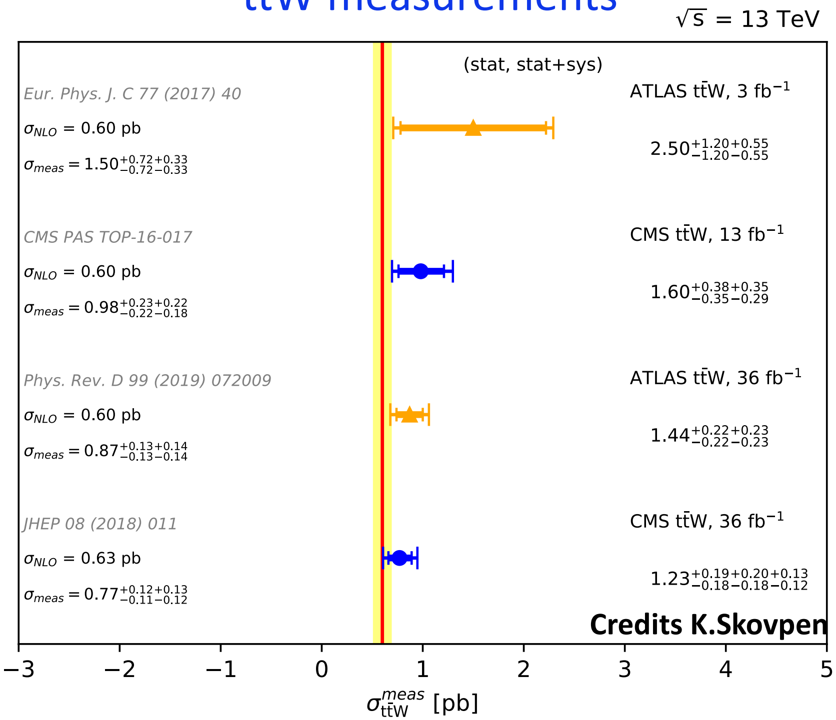
Process	Cross section normalization	Event generator	Perturbative order	NNPDF version
$t\bar{t}Z$, tZq, $t\bar{t}W$, WZ, Z+jets, VVV, $t\bar{t}\gamma^{(*)}$, $W\gamma^{(*)}$, $Z\gamma^{(*)}$	NLO	MADGRAPH5_aMC@NLO v2.2.3 (v2.4.2)	NLO	3.0 NLO (3.1 NNLO)
$gg \to ZZ$	NLO [32]	MCFM v7.0.1 [33] JHUGEN v7.0.11 [34]	LO	3.0 LO (3.1LO)
$q\bar{q} \to ZZ$	NNLO [35]	POWHEG v2 [36, 37]	NLO	3.0 NLO (3.1 NNLO)
WH, ZH	NLO	POWHEG v2 MINLO HVJ [38] JHUGEN v7.0.11 [34]	NLO	3.0 NLO (3.1 NNLO)
VBF H	NLO	POWHEG v2	NLO	3.0 NLO (3.1 NNLO)
$t\bar{t}H$	NLO	POWHEG v2 [39]	NLO	3.0 NLO (3.1 NNLO)
$t\bar{t}$	NNLO+NNLL [40]	POWHEG v2	NLO	3.0 NLO (3.1 NNLO)
$t\bar{t}VV$, tHW, tHq, tWZ	LO	MADGRAPH5_aMC@NLO	LO	3.0 LO (3.1 NNLO)

ttW

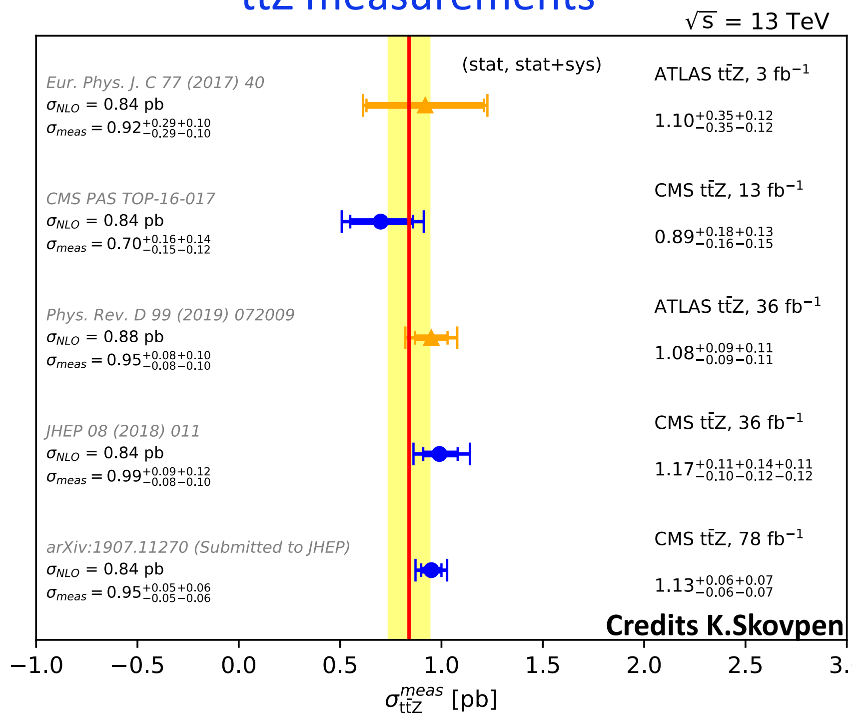
Process	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^\pm\ell^\mp\ell^+$	$\ell^\pm\ell^\mp\ell^-$	Postfit/Prefit
$t\bar{t}W$	677 ± 21	355 ± 12	119.4 ± 9.2	65.3 ± 5.4	1.49
Nonprompt	2490 ± 600	2360 ± 570	325 ± 75	298 ± 71	0.91
Charge misID	520 ± 110	520 ± 111	—	—	0.91
$t\bar{t}H$	167 ± 34	169 ± 34	56 ± 12	57 ± 12	1.35
$t\bar{t}Z/\gamma^*$	335 ± 26	333 ± 26	145 ± 13	147 ± 13	1.10
Diboson	382 ± 88	285 ± 65	46.8 ± 9.1	38.0 ± 7.5	1.07
Other	178 ± 34	126 ± 27	43.4 ± 8.2	33.5 ± 7.4	1.20
Conversions	177 ± 54	192 ± 59	22.9 ± 7.1	24.0 ± 7.4	1.01
Total background	4250 ± 620	4000 ± 590	639 ± 80	600 ± 76	1.03
Total prediction	4920 ± 620	4350 ± 590	758 ± 81	663 ± 76	1.05
Data	5143	4486	834	744	—

State-of-the-art on the measurements

ttW measurements



ttZ measurements



- Most measurements in both experiments give slightly higher x-section than the theory
- Still large (statistical) uncertainties in particular for ttW

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