$t\bar{t}W$ measurement as a step towards $t\bar{t}H$ in the multilepton channel

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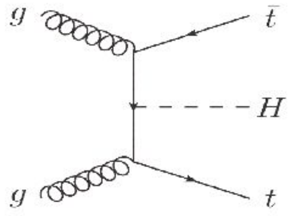
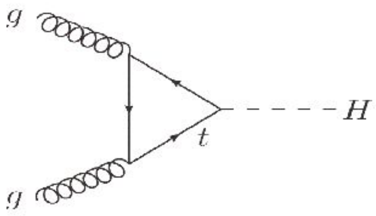
$t\bar{t}H$: motivation

- Top Yukawa coupling is the only coupling with the magnitude of order one in the Standard Model → idea about the scale of New Physics
- $t\bar{t}H$/tH production cross-section measurement is the only direct way to measure y_t
- $t\bar{t}H$ production also allows to probe the CP structure of the top-Higgs coupling



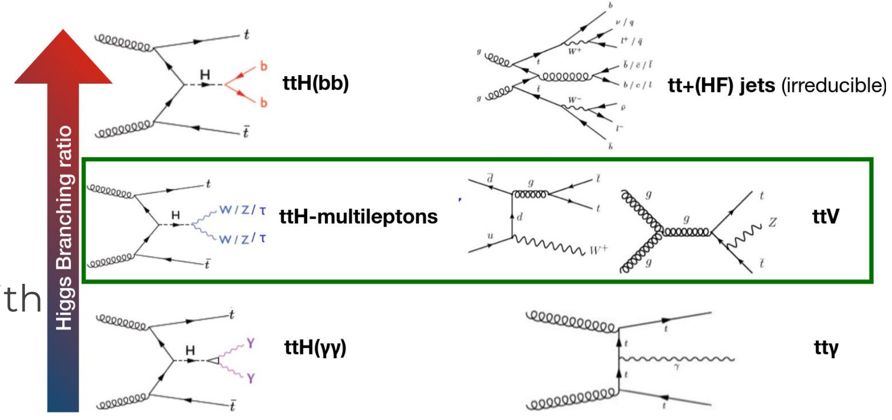
direct



indirect

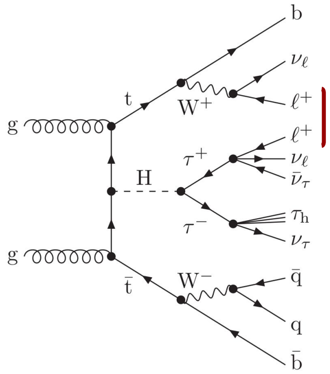
$t\bar{t}H$ in multilepton: motivation

- Production of $t\bar{t}H$ accounts for about 1% of the total rate
- Covering as many decay channels as possible: $t\bar{t}H(\gamma\gamma)$, $t\bar{t}H(b\bar{b})$, $t\bar{t}H(4\ell)$, $t\bar{t}H$(ML)
- $t\bar{t}H$ in multilepton final state: clean final state with leptons, moderate irreducible background

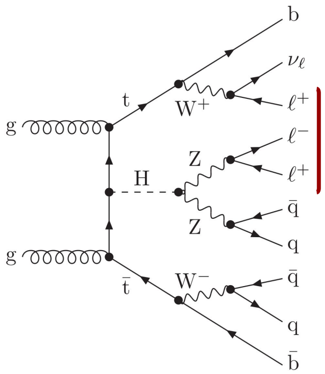


Signal *Background*

- Highest sensitivity : 2ℓ same-sign (SS) and 3ℓ



2ℓSS final state

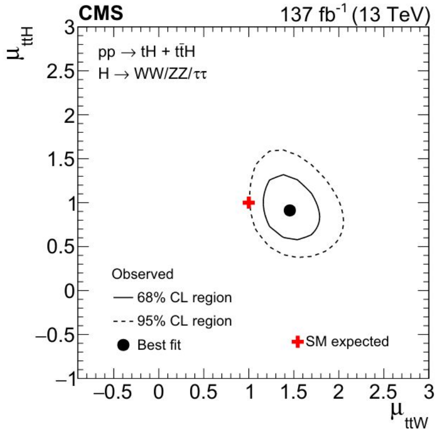


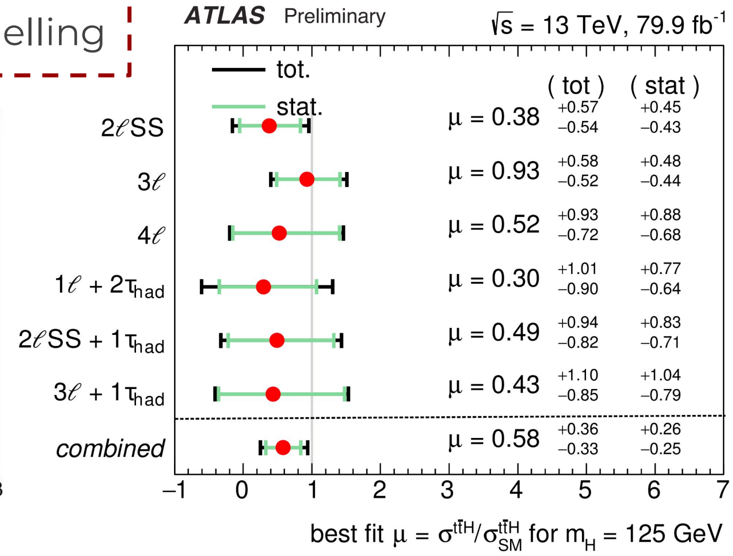
3ℓ final state

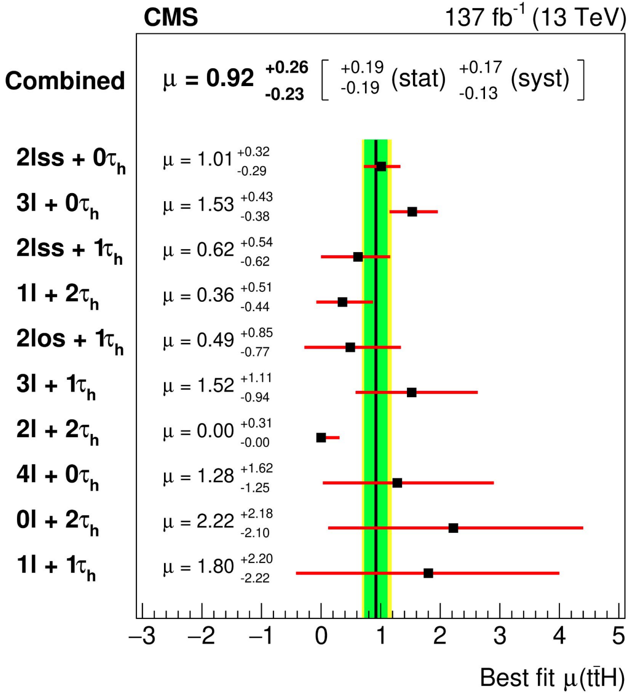
$t\bar{t}H$ in multilepton: current state

- $t\bar{t}H$ observation by ATLAS and CMS in 2018 with partial Run 2 datasets
- $t\bar{t}H$ in multilepton by ATLAS (80 fb^{-1}) and CMS (137 fb^{-1})

Observed $t\bar{t}W$ mismodelling

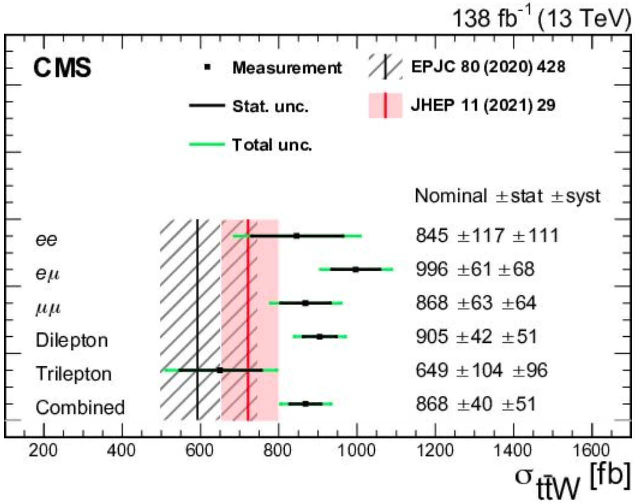


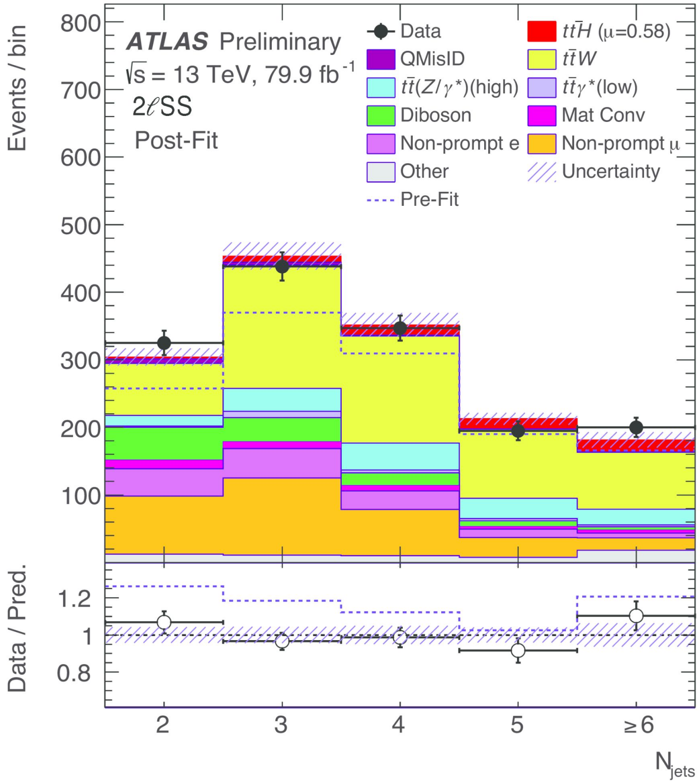




$t\bar{t}H$ and $t\bar{t}W$ in multilepton

- $t\bar{t}W$ mismodelling observed in $t\bar{t}H$ ATLAS analysis, and $t\bar{t}W$ CMS measurement: 20-50% larger cross section than predicted
- $t\bar{t}W$ is the main background for $t\bar{t}H$ in multilepton
- $t\bar{t}H$ analysis closely follows the $t\bar{t}W$ analysis





$t\bar{t}W$: current state by ATLAS

Measure $t\bar{t}W$ production cross-section in the 2ℓSS and 3ℓ channels with 140 fb^{-1} Run II dataset:

- Inclusive and fiducial cross sections
- Differential cross section of 9 observables
- Cross sections for $t\bar{t}W^{+/-}$ and their ratio

$$R = \frac{\sigma(t\bar{t}W^{+})}{\sigma(t\bar{t}W^{-})}$$

- Charge asymmetry

$$A_{\mathrm{C}}^{\mathrm{rel}} = \frac{\sigma(t\bar{t}W^{+}) - \sigma(t\bar{t}W^{-})}{\sigma(t\bar{t}W^{+}) + \sigma(t\bar{t}W^{-})}$$

ATLAS CONF Note

ATLAS-CONF-2023-019

29th March 2023

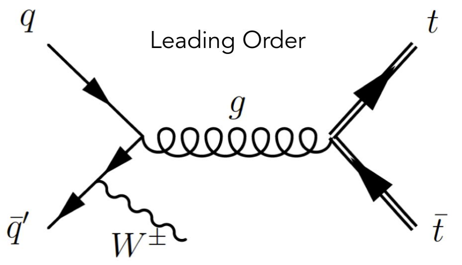
Measurement of the total and differential cross-sections of $t\bar{t}W$ production in pp collisions at 13 TeV with the ATLAS detector

The ATLAS Collaboration

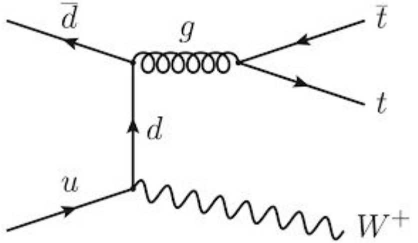
Measurements of the inclusive and differential production cross-sections of a top-quark-antiquark pair in association with a W boson ($t\bar{t}W$) are presented. The measurements are performed by targeting final states with two same-sign or three isolated leptons (electrons or muons) and are based on $\sqrt{s}$ = 13 TeV proton–proton collision data with an integrated luminosity of 140 fb^{-1}, recorded from 2015 to 2018 with the ATLAS detector at the Large Hadron Collider. The inclusive $t\bar{t}W$ production cross-section is measured to be 890 ± 80 fb, compared to the reference theoretical prediction of 722 $^{+70}_{-78}$ (scale) ± 7 (PDF) fb. Differential cross-section measurements characterise this process in detail for the first time. Several particle-level observables are compared to a variety of theoretical predictions which are generally in good agreement with the normalised differential cross-section results.

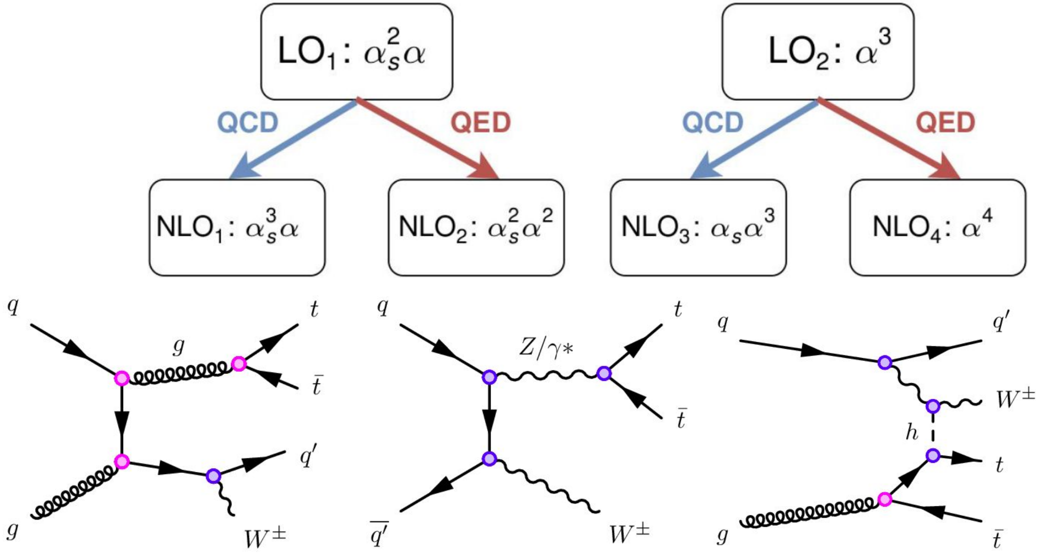
$t\bar{t}W$: signal

- Nominal MC sample is Sherpa
  - Alternative samples: MG5_aMC, Powheg



$$\mathcal{R} = 1.81 \pm 0.03 \text{ (scale)} \pm 0.03 \text{(PDF)}$$





$t\bar{t}W$: signal regions

Signal region: split by lepton charges, lepton flavours, jet and b-jet multiplicities : 48 $2\ell SS$ + 8 3ℓ signal regions

Signal region preselection	$2\ell SS$	3ℓ
Lepton definition	TT	LTT
Lepton p_{T} [GeV]	(20, 20)	(10, 20, 20)
N_{jets}	≥ 2	
$N_{b\text{-jets}}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	
$m^{\mathrm{SF}}_{\ell^\pm\ell^\pm}$ or $m^{\mathrm{SF}}_{\ell^+\ell^-}$ [GeV]	> 12	
$\lvert m^{\mathrm{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	–	> 10
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	–	> 10
	Inclusive cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Lepton flavour split	$(\mu\mu, e\mu, \mu e, ee)$	-
Jet multiplicity split	(3, 4, ≥5)	(2, ≥3)
b-jet multiplicity split	(1, ≥2)	
Total inclusive SRs	48	8
	Differential cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Number of OS-SF pairs split	–	(0, 1, 2)
Total differential SRs	2	6

$t\bar{t}W$: selection at reconstruction level

Object pre-selection

Reconstruction-level

Using lowest p_T un-prescaled dilepton triggers

Object preselection:

- Leptons: p_T>10 GeV, $|\eta_e| < 2.47$, $|\eta_\mu| < 2.5$; veto electrons in LAr crack region (FCLoose, Loose/LooseLH ID)
- Jets: reconstruct with PFlow anti-k_T w/ R=0.4, p_T>25 GeV; pass JVT; tag b-jets with PCT DL1r NN tagger
- "B-jet aware" overlap removal:
  - e/μ: if $\Delta R(e, \mu) < 0.1$ remove muon if Calo Tagged, else remove electron
  - e/jet: $\Delta R(e, \text{jet}) < 0.2$ remove electron **if jet is b-tagged**, else remove jet
  - μ/jet: if ghost-matched and $\Delta R(\mu, \text{jet}) < 0.4 \rightarrow$ remove muon if jet is b-tagged, else remove jet
  - If $\Delta R(\ell, \text{jet}) < \min(0.4, 0.04 + 10/p_{T,\ell})$, remove ℓ

Event selection

Reconstruction-level

- "Tight" lepton definition applied for SS leptons
  - TightLH (Medium) e(μ) ID, electron ambiguity cuts, p_T > 20 GeV
  - Apply PLIV(+ECIDS) VeryTight working point
- N_{jet}≥2, $N_{b\text{-}jet}$≥1
  - Hybrid b-tagging, 1@60% OR ≥2@77%
- $M_{\ell\ell}$>12 GeV in $2\ell SS$
- $M_{\ell\ell}$>12 GeV, $|M_{\ell\ell} - M_Z| > 10$ GeV (SFOS), $|M_{3\ell} - M_Z| > 10$, in 3ℓ

PLIV – Prompt Lepton Improved Veto
ECIDS –Electron Charge ID selector

$t\bar{t}W$: selection at particle level

Object pre-selection

Fiducial Particle-level

Adopt similar fiducial phase space as defined for detector-level to minimize extrapolation uncertainty

- Leptons: p_T>10 GeV, $|\eta_e| < 2.47$, $|\eta_\mu| < 2.5$; veto electrons in LAr crack region
- Jets: reconstruct with anti-k_T w/ R=0.4, p_T>25 GeV; tag b-jets containing a B-hadron
- "B-jet aware" overlap removal:
  - Skip e/μ step
  - e/jet: $\Delta R(e, \text{jet}) < 0.2$ remove electron **if jet has B-hadron**, else remove jet
  - Skip μ/jet step (checked that impact is minor)
  - If $\Delta R(\ell, \text{jet}) < \min(0.4, 0.04 + 10/p_{T,\ell})$, remove ℓ

Event selection

Fiducial Particle-level

Adopt similar fiducial phase space as defined for detector-level to minimize extrapolation uncertainty

- Exactly 2(3) leptons, total charge ±2(±1)
  - SS lepton p_T > 20 GeV, OS p_T > 10 GeV
- $N_{jet} \geq 2$, $N_{b\text{-}jet} \geq 1$ (defined by presence of b-hadron)
- $M_{\ell\ell}$>12 GeV in $2\ell SS$
- $M_{\ell\ell}$>12 GeV, $|M_{\ell\ell} - M_Z| > 10$ GeV (SFOS), $|M_{3\ell} - M_Z| > 10$, in 3ℓ

$t\bar{t}W$: backgrounds

Physical background:

- $t\bar{t}Z$, diboson (in particular WZ)

Instrumental background:

- Events with non-prompt or fake leptons: electrons from conversion and leptons from heavy flavour quark decays
- Process with charge mis-identified

$t\bar{t}W$: backgrounds

Physical background:

- $t\bar{t}Z$, diboson (in particular WZ)

Instrumental background:

- Events with non-prompt or fake leptons: electrons from conversion and leptons from heavy flavour quark decays
- Process with charge mis-identified →
  - negligible for muons
  - data-driven from $Z \rightarrow e^{\pm}e^{\pm}/e^{\pm}e^{\mp}$

$t\bar{t}W$: backgrounds

Physical background:

- $t\bar{t}Z$, diboson (in particular WZ) →

Instrumental background:

- Events with non-prompt or fake leptons: → electrons from conversion and leptons from heavy flavour quark decays
- Process with charge mis-identified

Template method:
estimated using MC with their normalisation determined from data by the likelihood fit (together with the signal) using 10 control regions

$t\bar{t}W$: template method

Physical background:

- $t\bar{t}Z$, diboson (in particular WZ)

Instrumental background:

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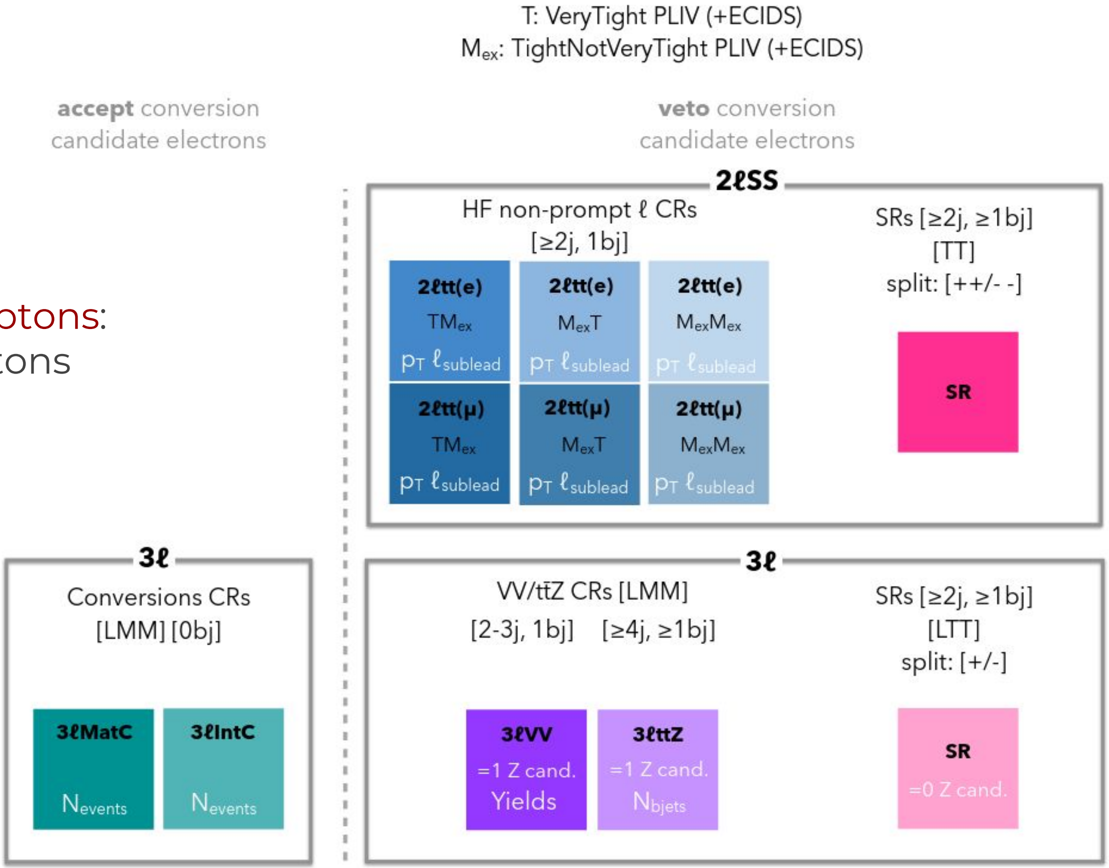

$t\bar{t}W$: template method

Physical background:

- $t\bar{t}Z$, diboson (in particular WZ)

Instrumental background:

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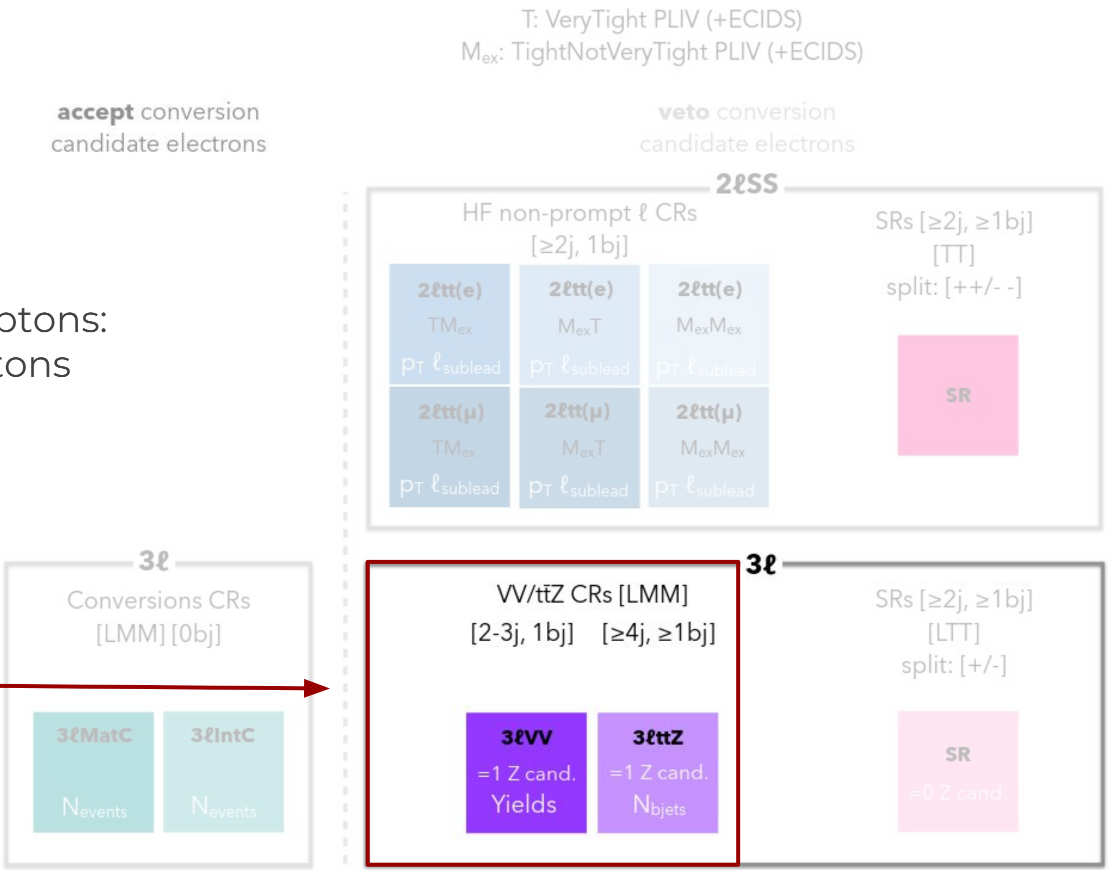
- Process with charge mis-identified

Two CR with different jets multiplicity and with a same flavour dilepton invariant mass near the Z peak



$t\bar{t}W$: template method

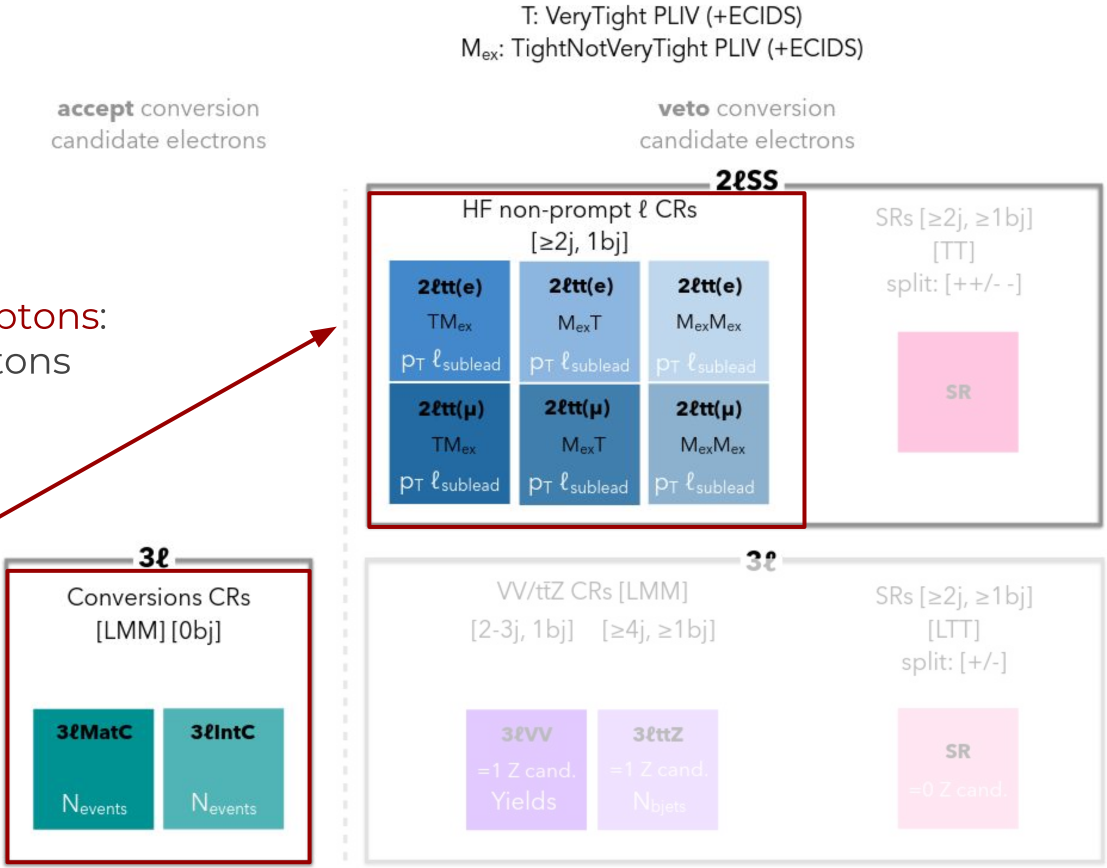
Physical background:

- $t\bar{t}Z$, diboson (in particular WZ)

Instrumental background:

- Events with non-prompt or fake leptons: electrons from conversion and leptons from heavy flavour quark decays
- Process with charge mis-identified

6 HF CR regions defined by BDT-based isolation working points M_{ex},
2 conversion CR depend on the electron track reconstructed displaced vertex



$t\bar{t}W$: inclusive and fiducial cross sections

Simultaneous profile likelihood fit to data in the 56 SR and the 10 CR

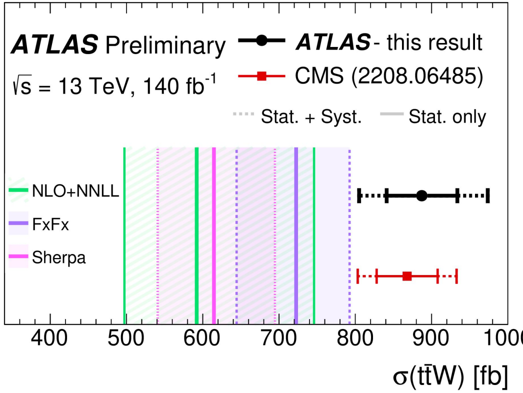
$$\sigma(t\bar{t}W) = 890\ \pm 50\ \text{(stat.)}\ \pm 70\ \text{(syst.)} = 890\ \pm 80\ \text{(tot.) fb}$$

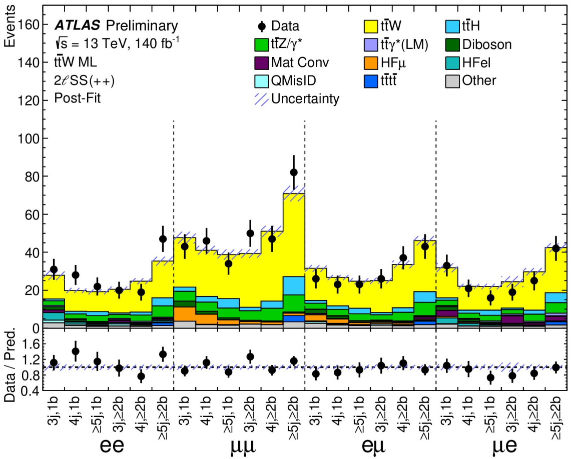
consistent at 1.5σ with theory:

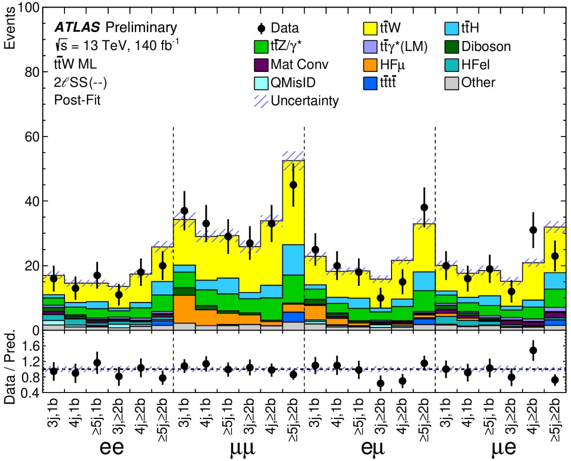
$$\sigma_{t\bar{t}W}^{\text{NLO+NNLL}} = 592^{+26.1\%+2.1\%}_{-16.2\%-2.1\%}\ \text{fb}$$

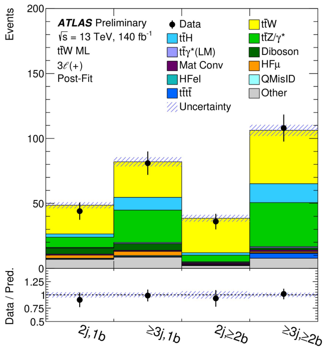
Fiducal cross section:

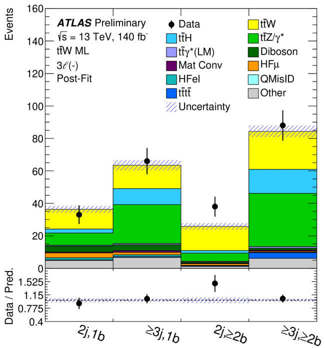
$$\sigma_{\text{fid}}(t\bar{t}W) = 21.7\ ^{+1.1}_{-1.1}\ \text{(stat.)}\ ^{+2.1}_{-1.9}\ \text{(syst.)} = 21.7\ ^{+2.4}_{-2.2}\ \text{(tot.) fb}$$











2ℓSS (48 regions)

Split by: Charge (++,--)
Flavour (ee, $e\mu$, μe, $\mu\mu$)
N_{jets} ($= 3$, $= 4$, ≥ 5)
$N_{b-\text{jets}}$ ($= 1$, ≥ 2)

3ℓ (8 regions)

Split by: Charge (+,-)
N_{jets} ($= 2$, ≥ 3)
$N_{b-\text{jets}}$ ($= 1$, ≥ 2)

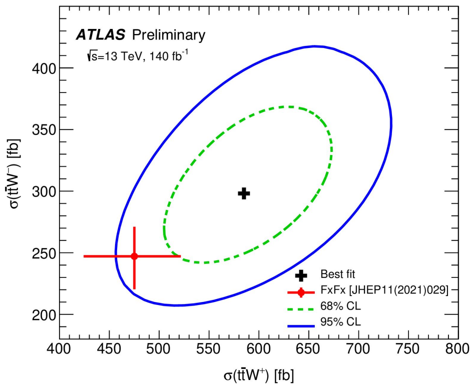
$t\bar{t}W$: ratios and asymmetry

Measured:

$$\sigma(t\bar{t}W^+) = 585\ ^{+35}_{-34}\ \text{(stat.)}\ ^{+47}_{-44}\ \text{(syst.)}$$

$$\sigma(t\bar{t}W^-) = 301\ ^{+28}_{-27}\ \text{(stat.)}\ ^{+35}_{-31}\ \text{(syst.)}$$

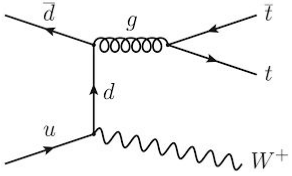
$$R(t\bar{t}W) = 1.95^{+0.21}_{-0.18}\ \text{(stat.)}^{+0.16}_{-0.13}\ \text{(syst.)} = 1.95^{+0.26}_{-0.22}\ \text{(tot.)}$$



Good agreement with MC prediction:

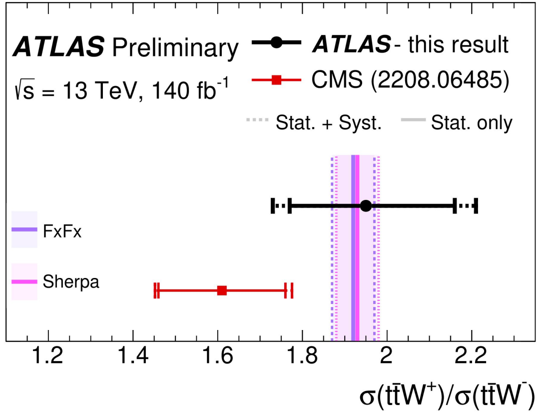
$$\mathcal{R} = 1.81 \pm 0.03\ \text{(scale)} \pm 0.03\text{(PDF)}$$

Ratio computed with the full off-shell effects at NLO in QCD



CMS result:

$\sigma_{t\bar{t}W+}$	$553 \pm 30\,\text{(stat)} \pm 30\,\text{(syst)}$ fb
$\sigma_{t\bar{t}W-}$	$343 \pm 26\,\text{(stat)} \pm 25\,\text{(syst)}$ fb
$\sigma_{t\bar{t}W+}/\sigma_{t\bar{t}W-}$	$1.61 \pm 0.15\,\text{(stat)}\ ^{+0.07}_{-0.05}\,\text{(syst)}$



$t\bar{t}W$: uncertainties

Largest systematic uncertainties:

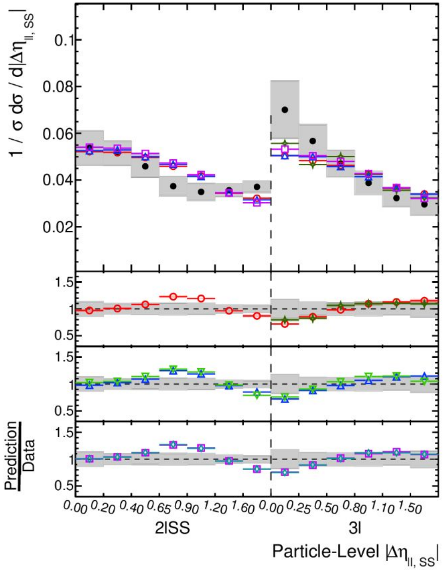
- $t\bar{t}W$ modelling
- $t\bar{t}H$, four-top background normalisation
- non-prompt isolation BDT calibration

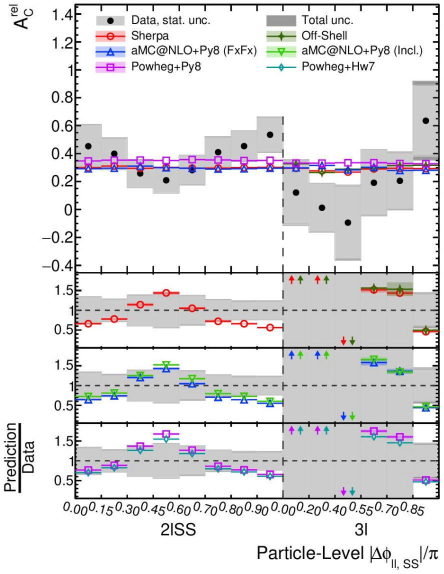
	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{fid}(t\bar{t}W)}{\sigma_{fid}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_C^{rel}}{A_C^{rel}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

$t\bar{t}W$: differential measurement

- Profile likelihood unfolding to measure differential cross-sections at particle level in the fiducial phase-space for one observable at a time
- Same background model and CR included in the fit
- Tikhonov regularisation with optimised strength for each variable
- Unfolding all channels simultaneously handles 10% migration effects

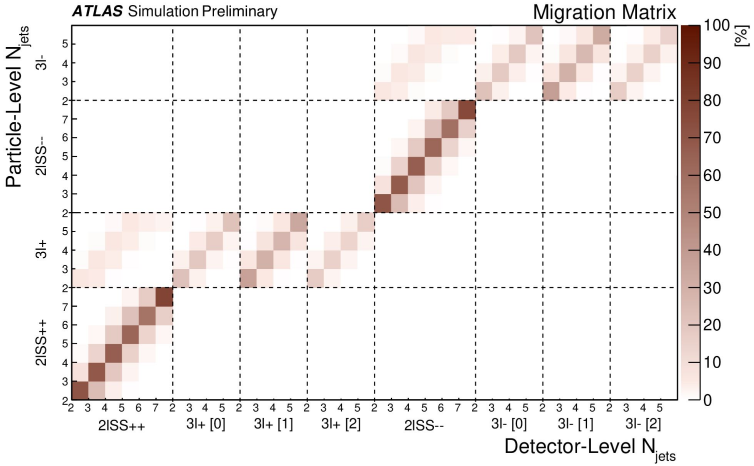
N_{jets}	Number of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{T,\text{jets}}$	Scalar sum of the transverse momenta of selected jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{T,\text{lep}}$	Scalar sum of the transverse momenta of selected leptons
$\Delta R_{lb,\text{ lead}}$	Angular distance between the leading lepton and the leading b-tagged jet
$\lvert\Delta\phi_{ll,\text{ SS}}\rvert$	Absolute azimuthal separation between the two leptons of the same-sign pair
$\lvert\Delta\eta_{ll,\text{ SS}}\rvert$	Absolute pseudo-rapidity separation between the two leptons of the same-sign pair
$M_{jj,\text{ lead}}$	Invariant mass of the two leading jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$





$t\bar{t}W$: profile likelihood unfolding

- Define sub-samples of signal process corresponding to set of bins at truth level
- Fold each bin forward to detector-level using response matrix
- Apply normalization factor independently to each truth bin, float in a fit to data



$$N_i^{\text{Det}} = \frac{1}{\alpha_i} \underbrace{\sum_j \epsilon_j M_{ij}}_{R_{ij}} N_j^{\text{Fid}}$$

Response matrix

$$M_{ij} = \frac{N_{ij}^{\text{Det}\cap\text{Fid}}}{N_j^{\text{Det}\cap\text{Fid}}}, \quad \alpha_i = \frac{N_i^{\text{Det}\cap\text{Fid}}}{N_i^{\text{Det}}}, \quad \epsilon_j = \frac{N_j^{\text{Det}\cap\text{Fid}}}{N_j^{\text{Fid}}}$$

Migration matrix

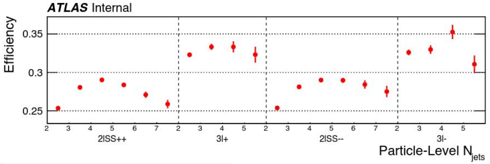
"How much of fiducial truth bin i ended up in reco bin j?"

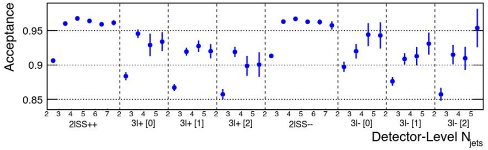
Acceptance correction

"How much of reco bin j originated from fiducial region?"

Efficiency correction

"How much of fiducial truth bin i was reconstructed?"

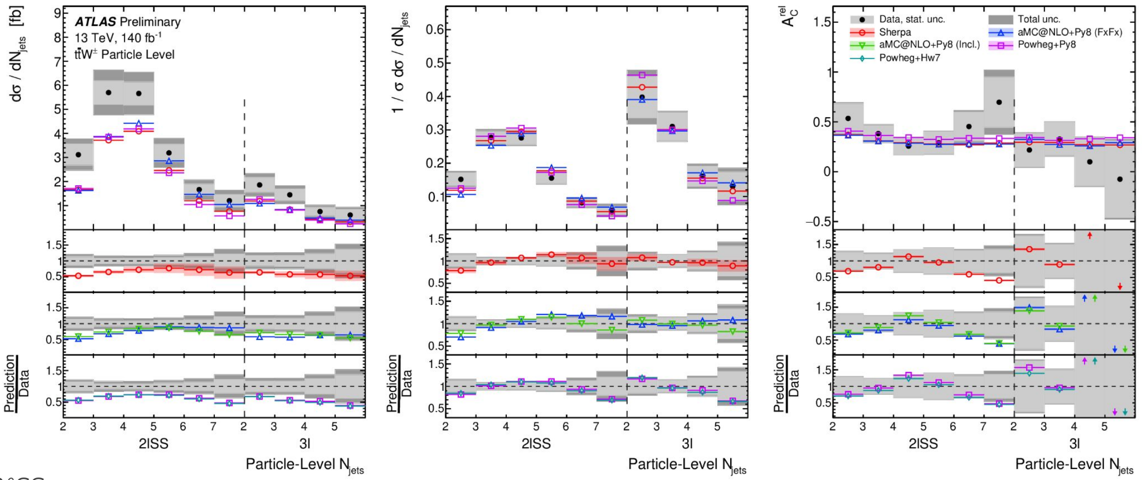




$t\bar{t}W$: differential measurement

Good agreement of unfolded data with all MC setups

- Slight tension in $\Delta\eta_{\ell\ell}$

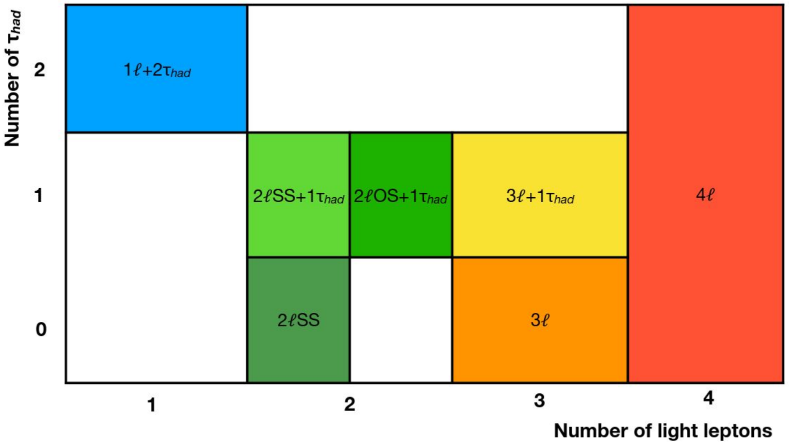


For unfolded normalised cross-section distributions in the 2ℓSS

Observable	NDF	Sherpa 2.2.10		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Pythia8		Powheg+Herwig7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	5	2.4	0.79	4.2	0.52	2.8	0.73	2.9	0.72	2.6	0.76
$H_{\text{T,jets}}$	5	0.7	0.98	1.1	0.95	0.8	0.98	1.5	0.91	2.0	0.85
$H_{\text{T,lep}}$	7	3.6	0.82	3.8	0.80	3.4	0.84	3.4	0.85	3.5	0.84
$\Delta R_{\text{lb, lead}}$	7	2.0	0.96	2.4	0.93	2.6	0.92	2.6	0.92	2.5	0.93
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	7	0.6	1.00	0.7	1.00	0.9	1.00	0.8	1.00	0.9	1.00
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	6	6.5	0.37	7.3	0.29	11.4	0.08	9.5	0.15	9.4	0.15
$M_{\text{jj, lead}}$	6	4.9	0.56	2.7	0.84	7.2	0.30	9.0	0.17	10.9	0.09

$t\bar{t}W$ vs $t\bar{t}H$

- Both $t\bar{t}H$ and $t\bar{t}W$ has similar CR
- There are no final states with 4ℓ or τ in $t\bar{t}W$, but these channels are in $t\bar{t}H$



Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
$2\ell SS$	Two same-charge (SS) very tight (T*) leptons, $p_T > 20$ GeV No τ_{had} candidates $m(\ell^{\pm}\ell^{\pm}) > 12$ GeV **13 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_T > 10$ GeV; sum of light-lepton charges = ±1 Two SS very tight (T*) leptons, $p_T > 15$ GeV One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_T > 10$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOS pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV **7 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv
4ℓ	Four loose-isolated (L*) leptons; sum of light lepton charges = 0 $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOS pairs $m(4\ell) < 115$ GeV or $m(4\ell) > 130$ GeV **2 categories**: Zenr (Z-enriched;1 or 2 SFOS pairs) or Zdep (Z-depleted; 0 SFOS pairs)
$1\ell 2\tau_{\text{had}}$	One tight (T) lepton, $p_T > 27$ GeV Two OS τ_{had} candidates At least one tight τ_{had} candidate $N_{\text{jets}} \geq 3$
$2\ell SS1\tau_{\text{had}}$	$2\ell SS$ selection, except: One medium τ_{had} candidate $N_{\text{jets}} \geq 4$
$3\ell 1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, of opposite charge to the total charge of the light leptons Two SS tight (T) leptons

Conclusion

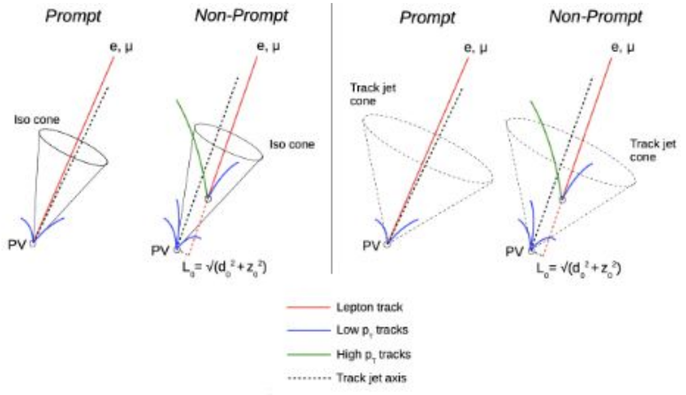
- ttW **inclusive** cross section measurement confirms mild tension in inclusive cross section that is consistent with CMS
- The **ratio** of $t\bar{t}W^{+}/t\bar{t}W^{-}$ is measured to be consistent with the SM prediction, in disagreement with what is reported by CMS
- The first **differential** cross section measurements are performed on $t\bar{t}W$ and it is found that all MC generators agree with unfolded data within uncertainties
    - However, for the moment the uncertainty on the unfolded measurement is still too large to distinguish between the MC generators

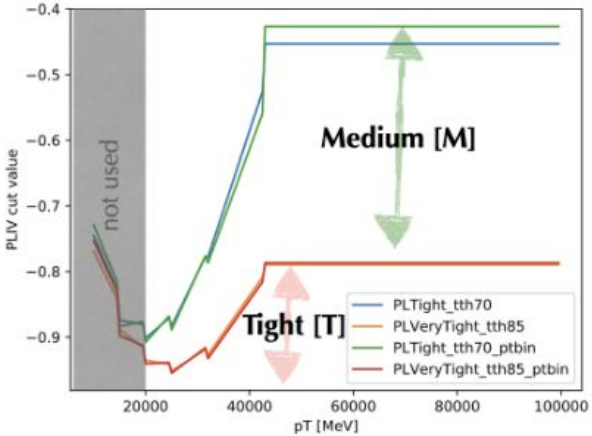
- Big contribution from $t\bar{t}W$ to $t\bar{t}H$ analysis. The work is actively on-going

Backup

PLIV

- MVA lepton isolation discriminant using track-jet variables
- Define and calibrate (with ECIDS for electrons) VeryTight and TightNotVeryTight exclusive working points
  - Tight and VeryTight WP are recommended by IFF
- p_T-dependent cuts on PLIV WP boundaries for smooth efficiency as a function of p_T





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