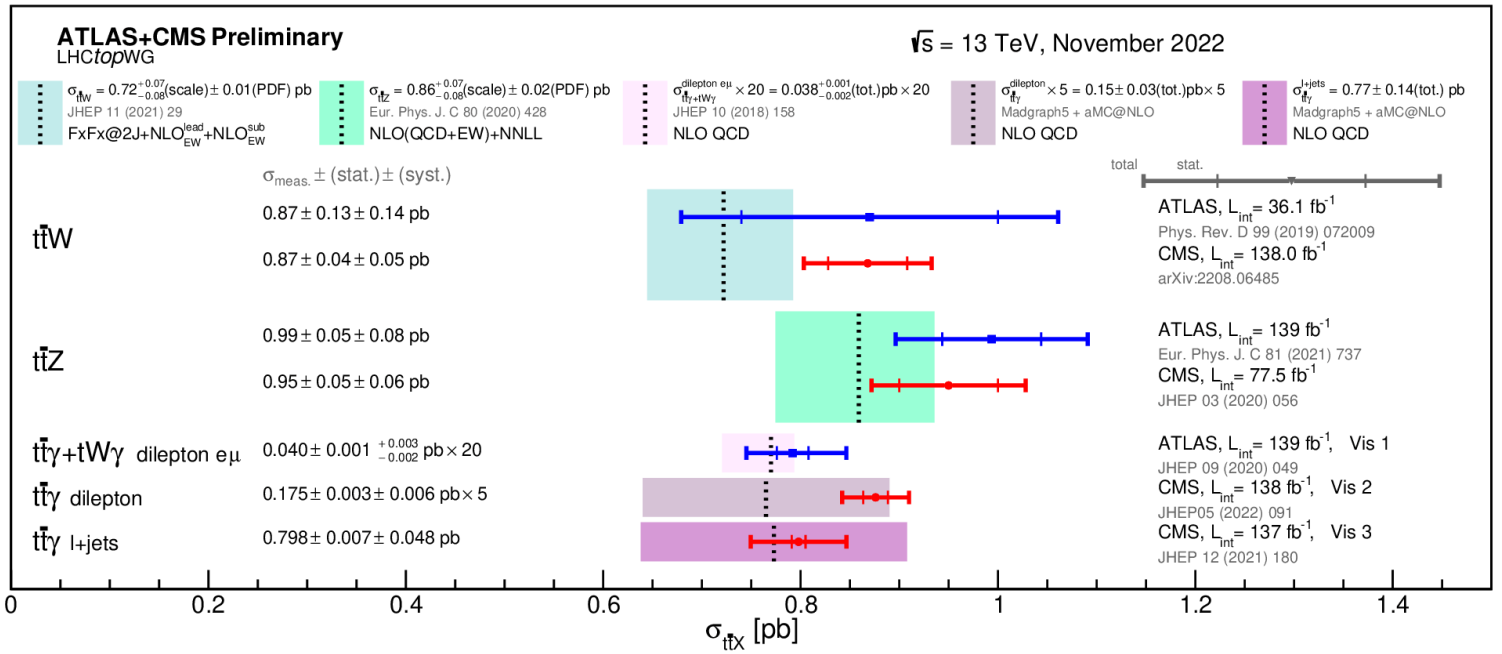
tX and $t\bar{t}X$ and their EFT interpretation in ATLAS and CMS

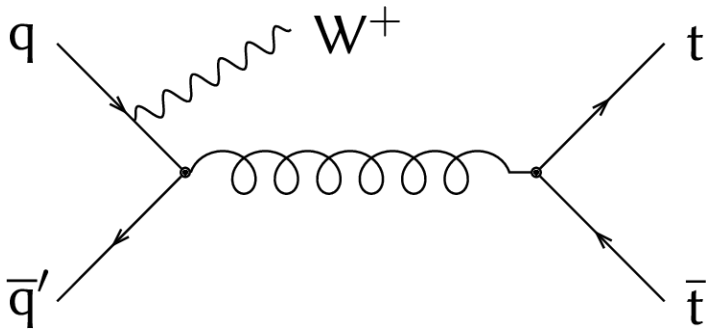
F. FABBRI, on behalf of the ATLAS and CMS collaborations

Motivations for tX and $t\bar{t}X$

- Both ATLAS and CMS have now collected enough data to measure very rare (<1 pb vs 800 pb in $t\bar{t}$) processes:
  - 4top, tγ, differential tZ
- Test the SM predictions, very challenging calculations.
- High potential for new physics discovery:
  - Sensitive to several EFT operators: t-V coupling and four fermions' operators.
  - BSM models foresee a larger cross-section for *tX* and $t\bar{t}X$.
- Irreducible background to BSM searches and other SM rare processes (e.g. $t\bar{t}H$).

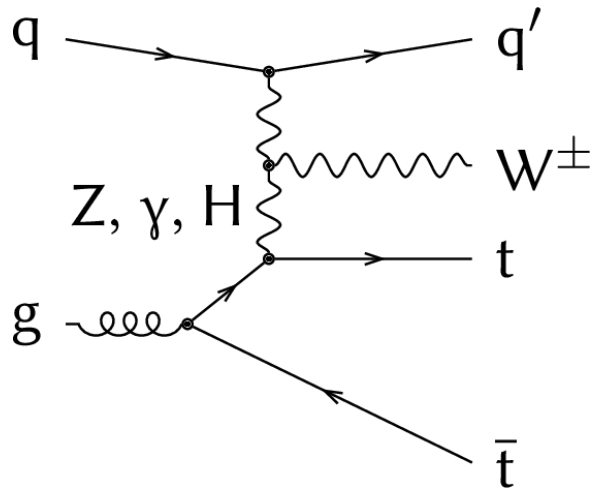


$t\bar{t}W$



- Unlike in $t\bar{t}Z$ or $t\bar{t}\gamma$ the boson can not be radiated by the top quark.
- Receives much larger contributions by the EW corrections.

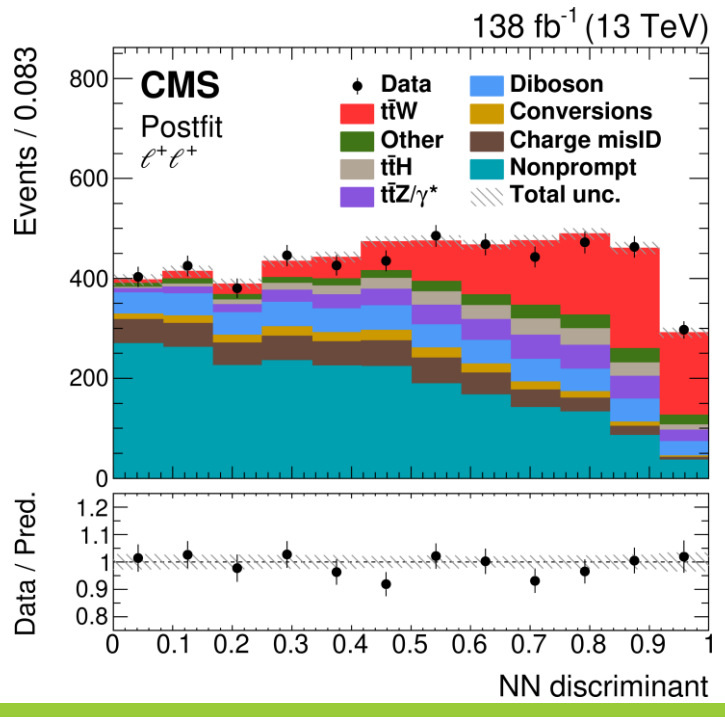
ATLAS- ATLAS-CONF-2023-019 , arXiv:2301.04245
CMS-arxiv:2208.06485

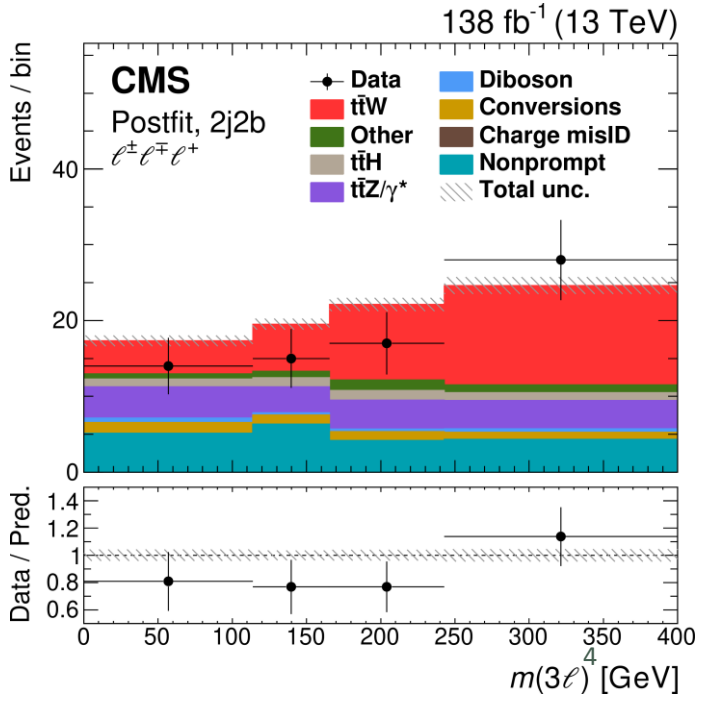


arXiv:2208.06485

$t\bar{t}W$ inclusive σ

- Events selected in two main regions:
- *2 SS leptons (semi-leptonic $t\bar{t}$ decay) :*
  - Dominant bkg from: $t\bar{t}H$ & $t\bar{t}Z$, charge mis-ID, non-prompt lepton.
  - Dedicated multiclass NN to separate signal and bkgs.
- *3 leptons (dileptonic $t\bar{t}$ decay) :*
  - Events categorized based on the number of b jets and lepton charge.
- $t\bar{t}W$ extracted doing a fit to all SRs and CR.
  - NN score used in 2l and m(3l) in 3l.
  - Dominant uncertainty from e charge mis-ID, **lumi**, b-tagging and **normalization of $t\bar{t}H$** , VVV and $t\bar{t}VV$.
  - Uncertainty constrained thanks to the large number of regions employed in the fit.
  - σ measured for $t\bar{t}W$ and independently for $t\bar{t}W^+$ and $t\bar{t}W^-$, measured also the ratio $t\bar{t}W^+ / t\bar{t}W^-$



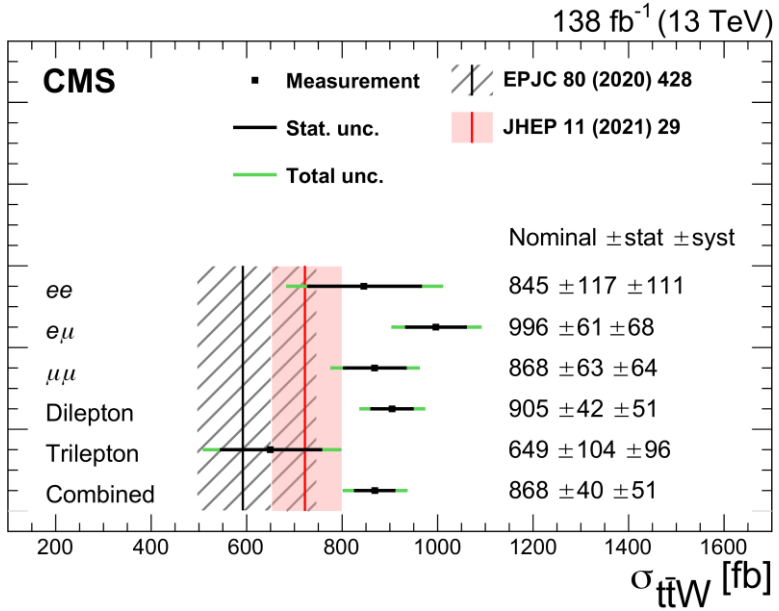


$t\bar{t}W$ inclusive σ

arXiv:2208.06485

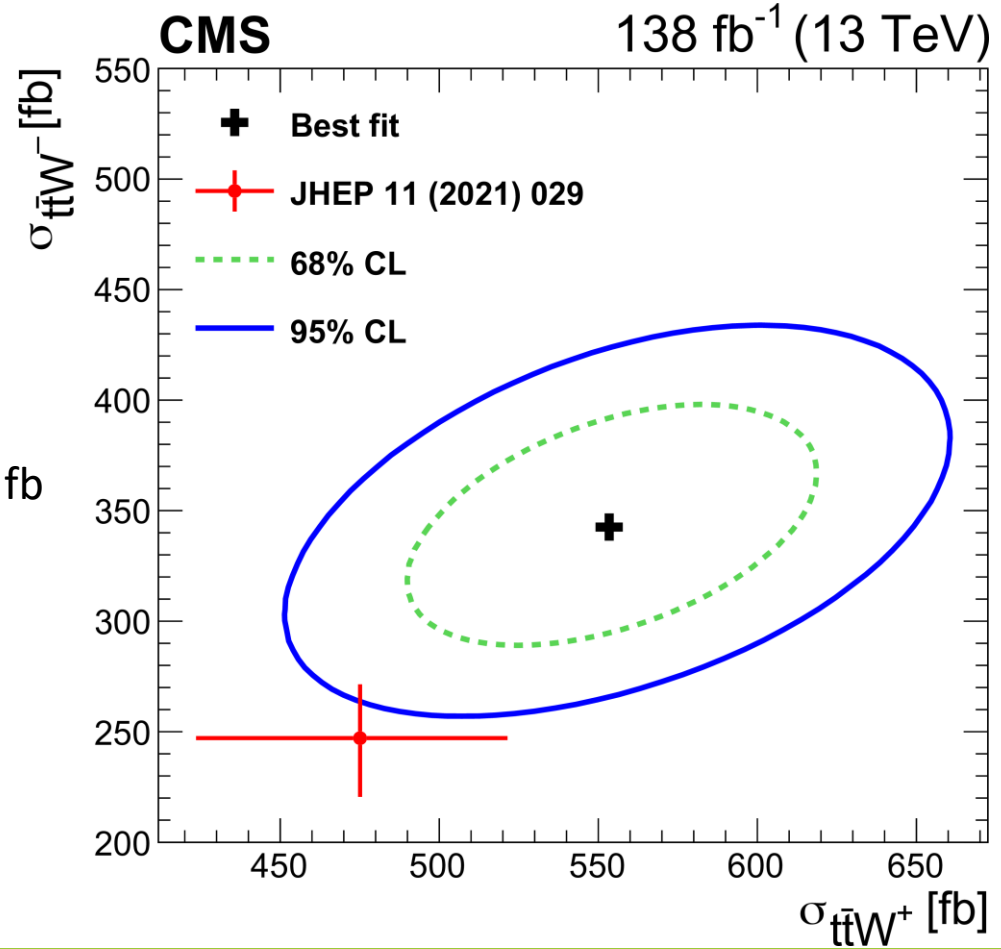
Measured $\sigma^{t\bar{t}W}$ slightly higher wrt the SM expectations:

- Better compatibility with the NLO (EW&QCD) prediction obtained with an improved NLO FxFx-merging scheme.
- Consistent with observation in $t\bar{t}H$ and $t\bar{t}t\bar{t}$.
- Agreement at 2σ level on $\sigma^{t\bar{t}W+}/\sigma^{t\bar{t}W-}$ with the SM prediction.



$\sigma^{t\bar{t}W}$=868±40(stat) ±51(syst) fb
Stat: 4.6% Syst:5.9%

$\sigma^{t\bar{t}W}_{SM}(FxFx)$:=$722^{+71}_{-78}$fb

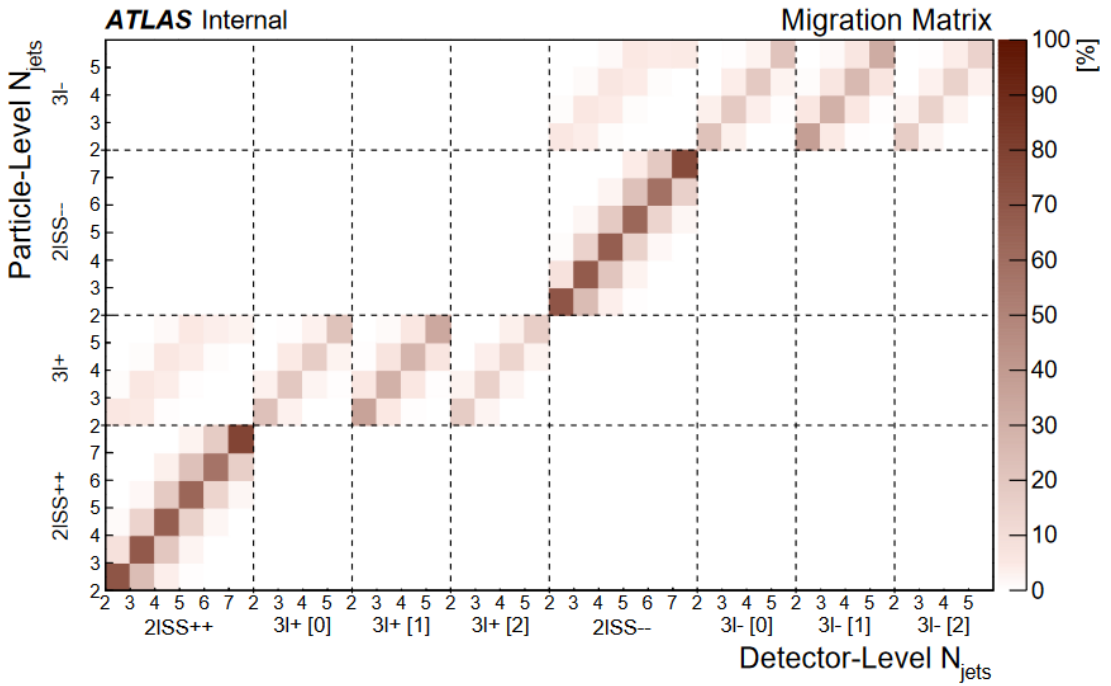


NEW

$t\bar{t}W$ differential – method

ATLAS-CONF-2023-019

- Following the same approach of the inclusive measurement presented in F. Deliot talk.
- Fiducial phase space definition:
  - Particle level objects defined starting by quasi-stable object
  - Closely follows the detector level definition
- Unfolding performed using a profile likelihood approach:
  - Signal extracted in each particle-level bin by a fit to the detector level events in multiple signal regions
  - Main background normalization ($t\bar{t}Z$, *VV, non-prompt lepton backgrounds)* free floating in the fit
- Dominant uncertainties:
  - Statistical
  - Different generator used for $t\bar{t}W$ (Sherpa vs Madgraph FxFx+PY8).
  - Showering (Pythia vs Herwig7).
  - Background modelling



Several variables measured:

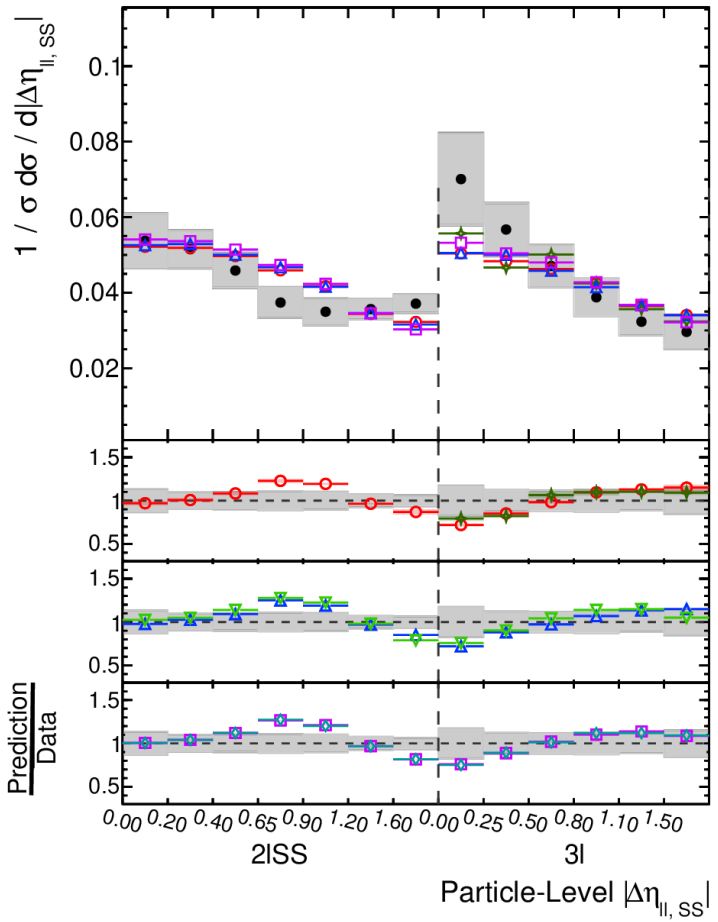
$N_{jets}, H_{T.jets}, H_{T,lep}, \Delta R(lb, lead), |\Delta\varphi_{ll,SS}|, |\Delta\eta_{ll,SS}|$

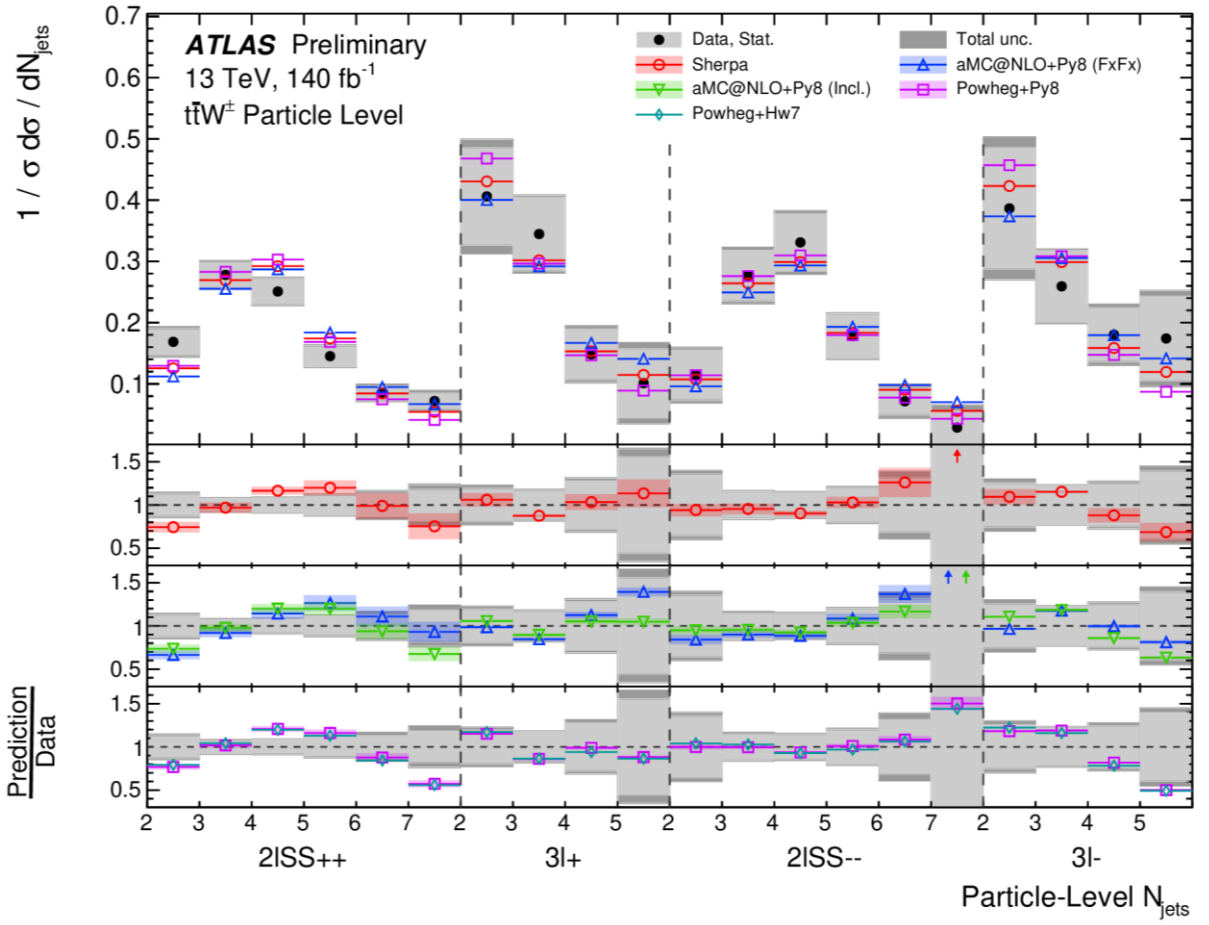
$M_{jj,lead}$

NEW

$t\bar{t}W$ – differential σ

ATLAS-CONF-2023-019

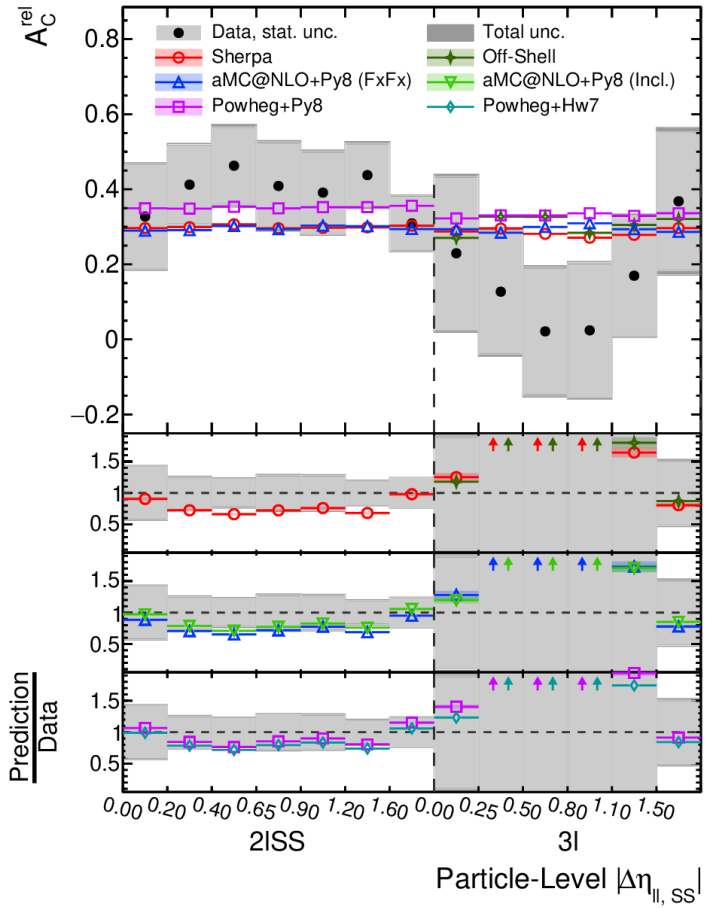


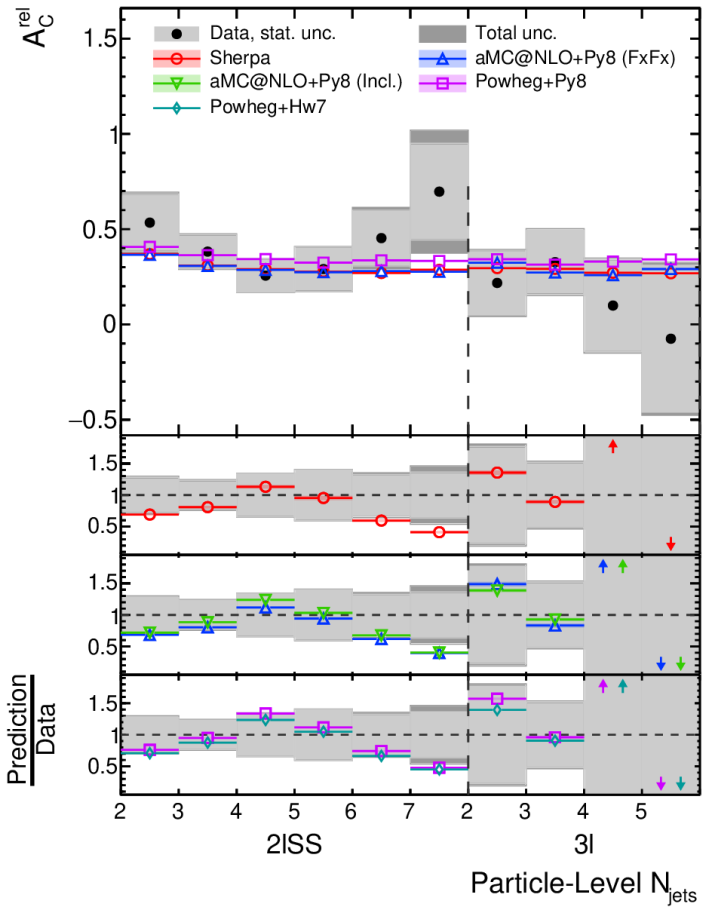


NEW

$t\bar{t}W$ — $A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$

ATLAS-CONF-2023-019





Dedicated off-shell calculation compared with results in the 3l channel (Eur. Phys. J. C 81 (2021) 675)

NEW

$t\bar{t}W$ — $A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$

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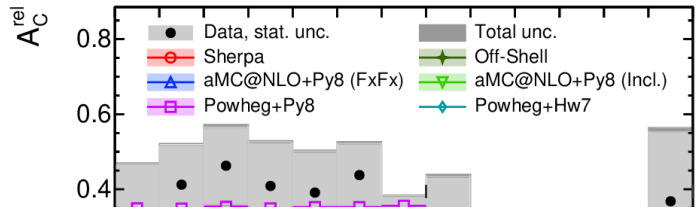

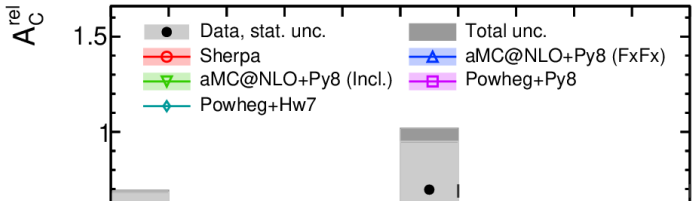

- The absolute distribution show a difference on the normalization – observed also in the inclusive xs.

- Some tensions are observed in the normalized xs and relative asymmetry but the quantitative agreement obtained considering the statistical and systematic correlation is generally good (p-value > 0.5)

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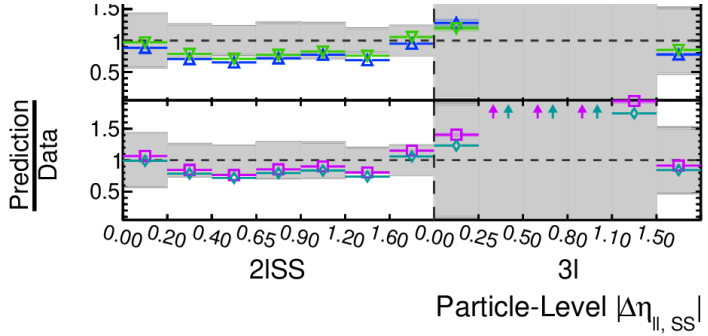
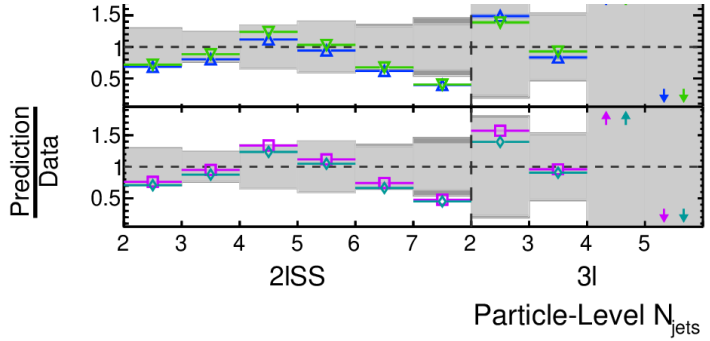
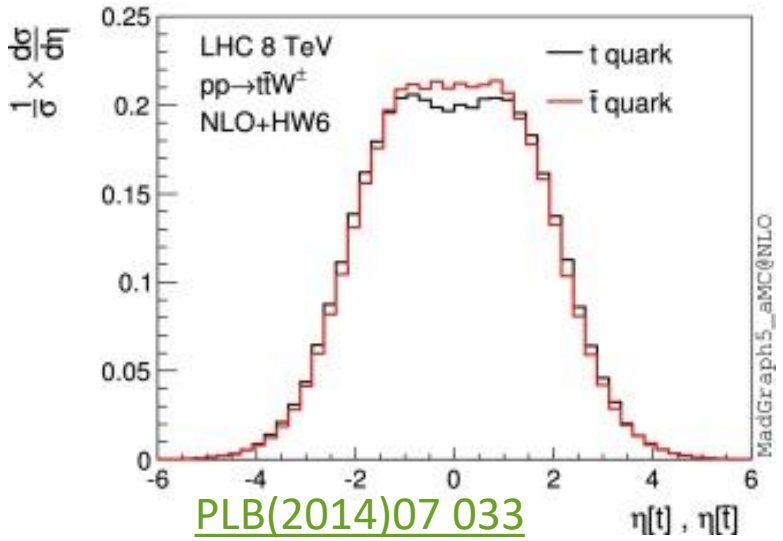




$t\bar{t}W$ Charge Asymmetry

arXiv:2301.04245

- $(\bar{t})$ t are preferably generated in the direction of the incoming $(\bar{q})$q
  - Result in a central-forward rapidity charge asymmetry (CA).
  - Subtle effect at LHC for $t\bar{t}$ (dominated by gg production).
- Larger CA expected in $t\bar{t}W$ wrt $t\bar{t}$:
  - Production dominated by qq' (positive CA).
  - Radiation of W polarize qq' → $t\bar{t}$ → enhance the asymmetry between the decay products (negative CA).
- Asymmetry measured using leptons from the $t\bar{t}$ decay.
  - Identified with a BDT.
  - ${A_{CA}}^{l}$ extracted at detector and particle level.



PLB(2014)07 033

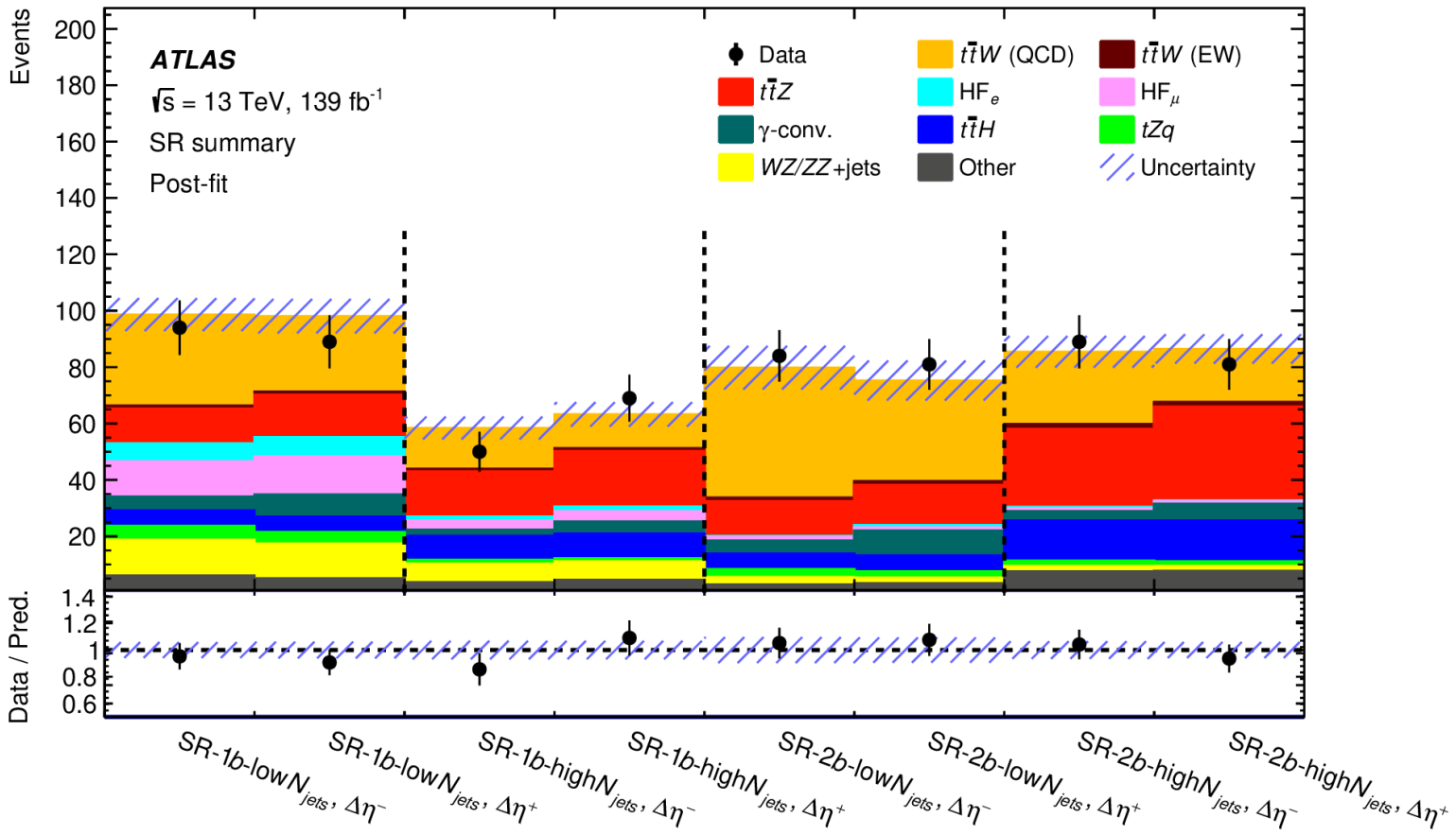
$$ {A_{CA}}^{l} = \frac{N(\Delta\eta^{l} > 0) - N(\Delta\eta^{l} < 0)}{N(\Delta\eta^{l} > 0) + N(\Delta\eta^{l} < 0)} $$

$$ \Delta\eta^{l} = |\eta^{l}| - |\eta^{\bar{l}}| $$

$t\bar{t}W$ Charge Asymmetry

arXiv:2301.04245

- Events with ==3 leptons (p_T>15,20,30 GeV).
- Events categorized in CRs and SRs
  - each separated in $\Delta\eta^l$ >(<) 0.
- CR used to extract the normalization of the major backgrounds: HFe/μ, γ-conv, $t\bar{t}Z$.
- ${A_{CA}}^l$ extracted from a simultaneous fit in all regions
  - For the particle level result considering the response from the fiducial region.



$t\bar{t}W$ Charge Asymmetry

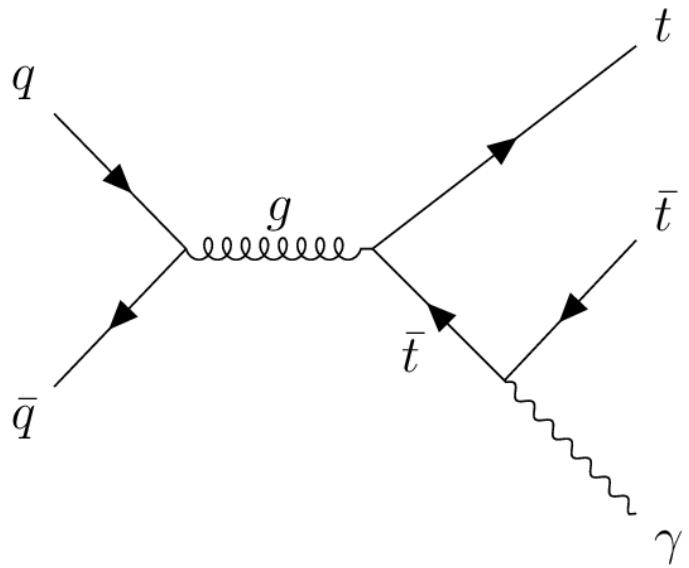
The CA measured at particle level in in the fiducial region is:

$$A_{CA}^{l}(t\bar{t}W)^{PL} = -0.112 \pm 0.170\,(stat.) \pm 0.054\,(syst.)$$

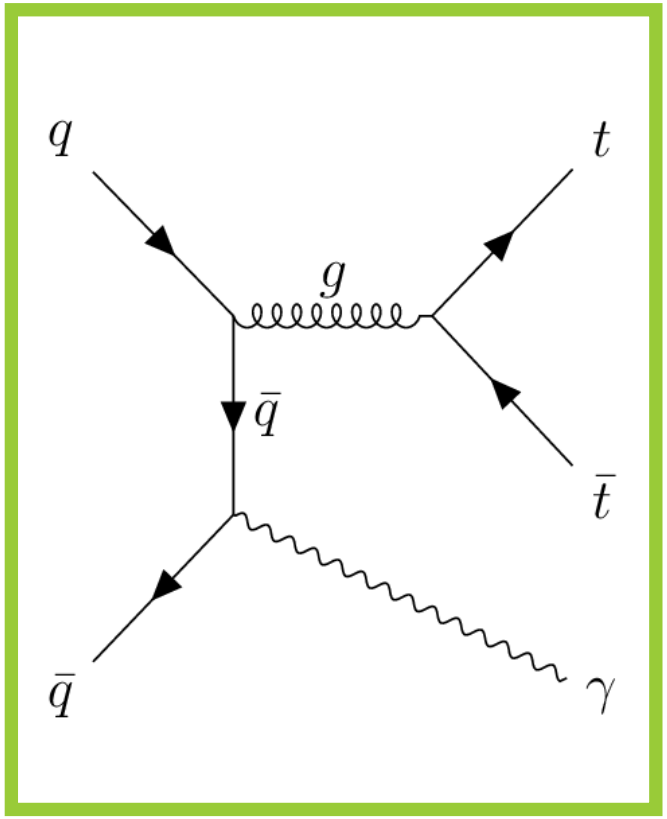
Consistent with the SM expectation $A_{CA}^{l}(t\bar{t}W)^{PL} = -0.063^{+0.007}_{-0.004}\,(scale) \pm 0.004(MC\ stat.)$.

Analysis limited by the statistical uncertainty.

$t\bar{t}\gamma$



ATLAS - [arXiv:2212.10552]

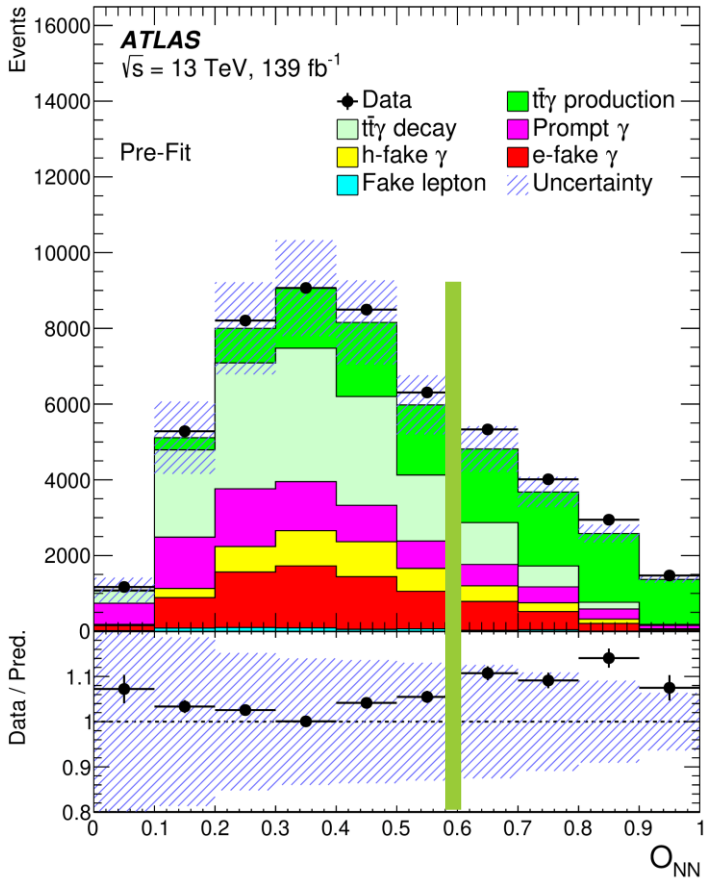


$$A_{CA} = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

$t\bar{t}\gamma$ Charge Asymmetry

arXiv:2212.10552

- Measure of the charge asymmetry between the t and $\bar{t}$ quarks in $t\bar{t}\gamma$ events:
  - Main CA contribution from QED interference in events where the γ is radiated by the qq or $t\bar{t}$ →signal.
  - CA diluted in events where the γ is radiated by decay products → bkg.
- Events selected with ==1 lepton, ==1 γ, >= 4jets(>=1b-jet)
- t and $\bar{t}$ γ are reconstructed from the decay products using a constrained (m^t,m^W) kinematic fitted algorithm (top quark reconstruction ~68%).
- Enhance purity using a NN to separate signal and bkg:
  - Main bkg: $t\bar{t}\gamma$ – decay and other bkg with a prompt γ.
  - The NN score is used to separate the events in 2 regions.



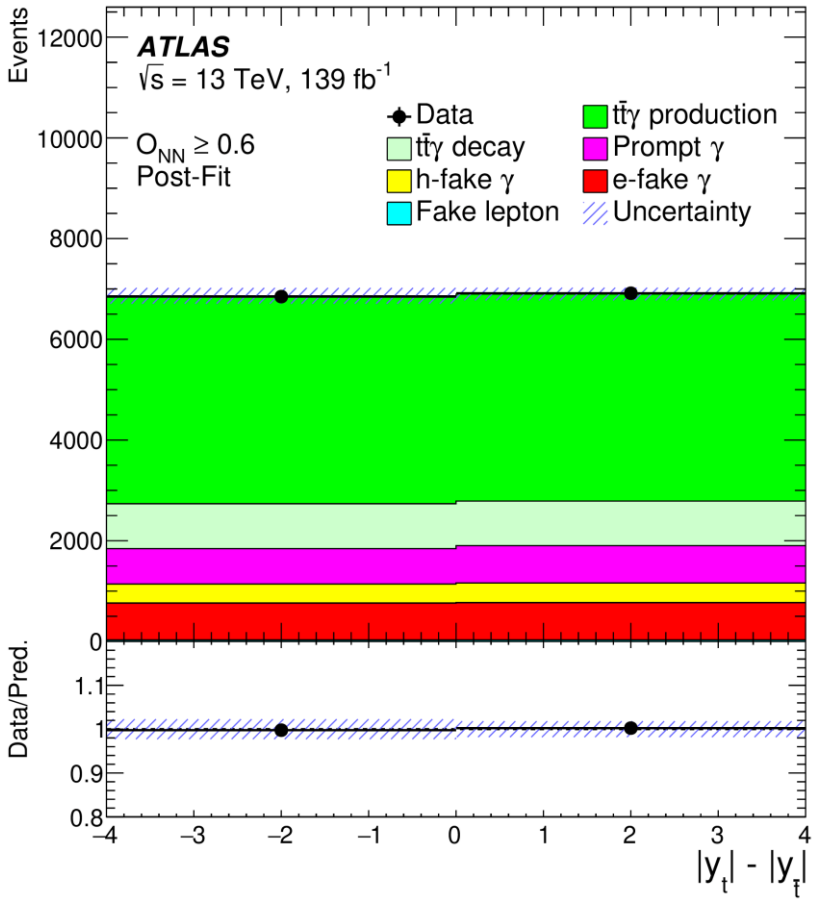
$t\bar{t}\gamma$ Charge Asymmetry

arXiv:2212.10552

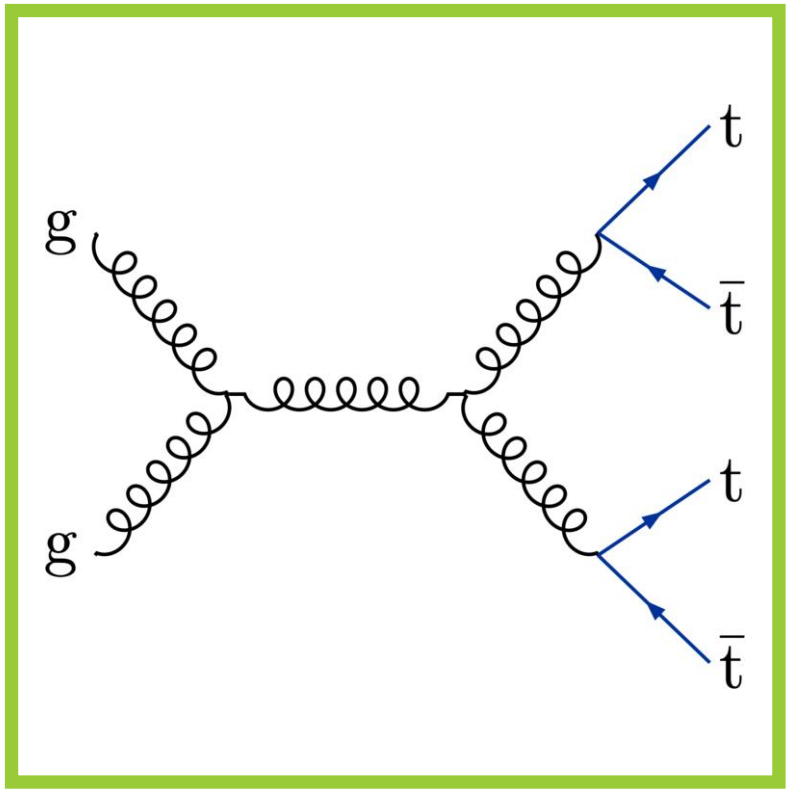
- A_{CA} extracted at particle level using a profile likelihood fit on $|y_t| - |y_{\bar{t}}|$ in both regions.
- The result is:

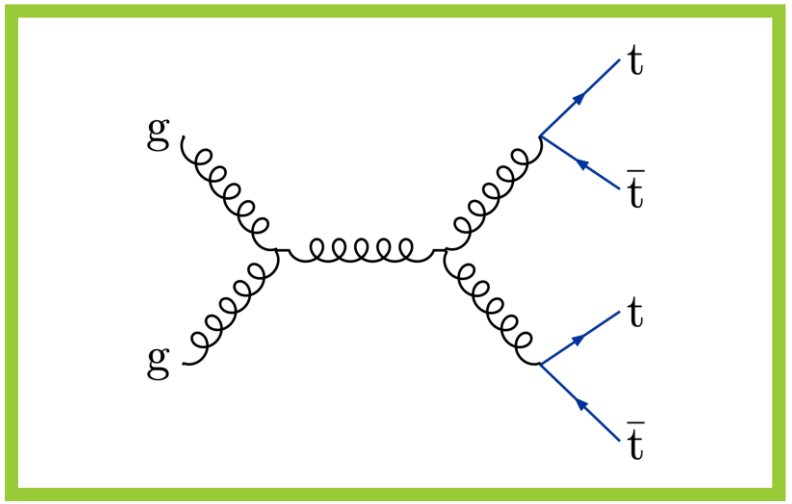
$$A_{CA}(t\bar{t}\gamma) = -0.003 \pm 0.024\,(stat.) \pm 0.017\,(syst.)$$

- Compatible with the SM MC prediction: $A_{CA}(t\bar{t}\gamma) = -0.014 \pm 0.001\,(scale)$
- The result is limited by the statistical uncertainties.
- The largest detector uncertainties are on jets and missing transverse energy.



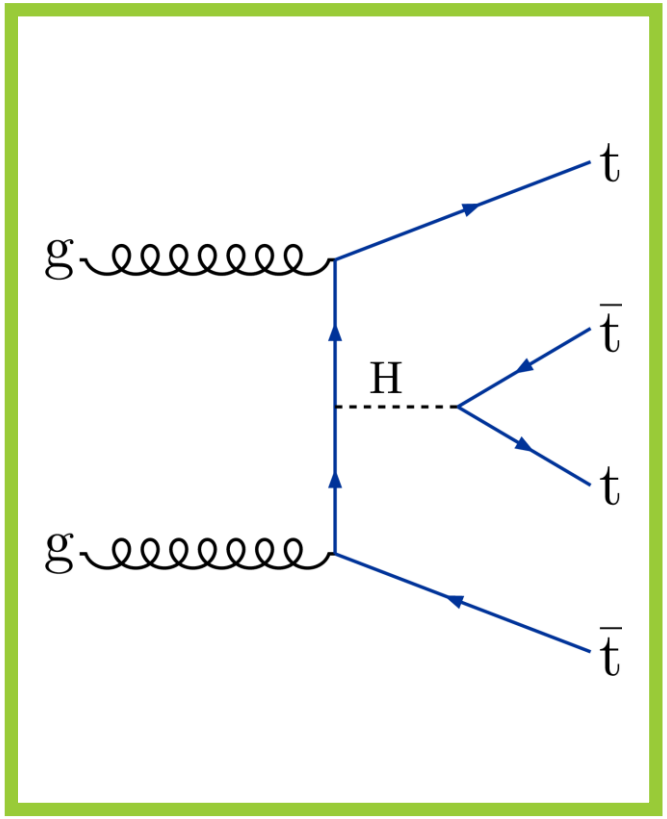
$t\bar{t}t\bar{t}$





ATLAS - **(Covered in F. Deliot talk)**

CMS- CMS-PAS-TOP-22-013

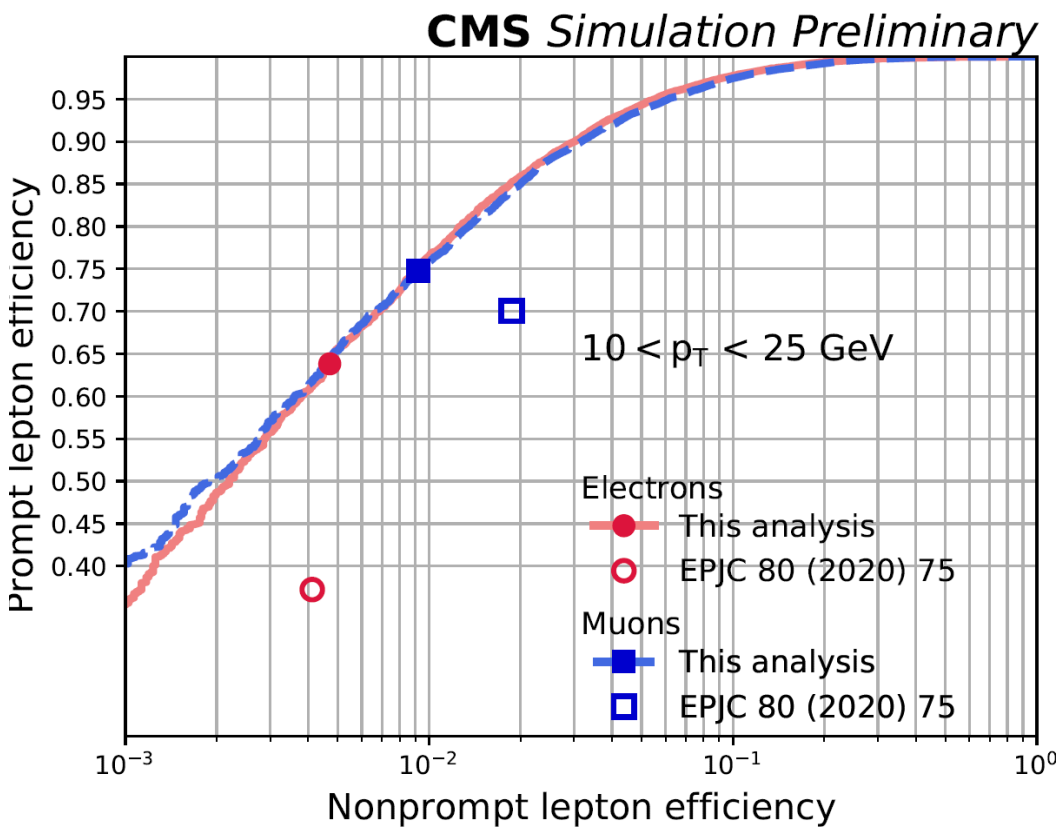


NEW

Observation of $t\bar{t}t\bar{t}$

CMS-PAS-TOP-22-013

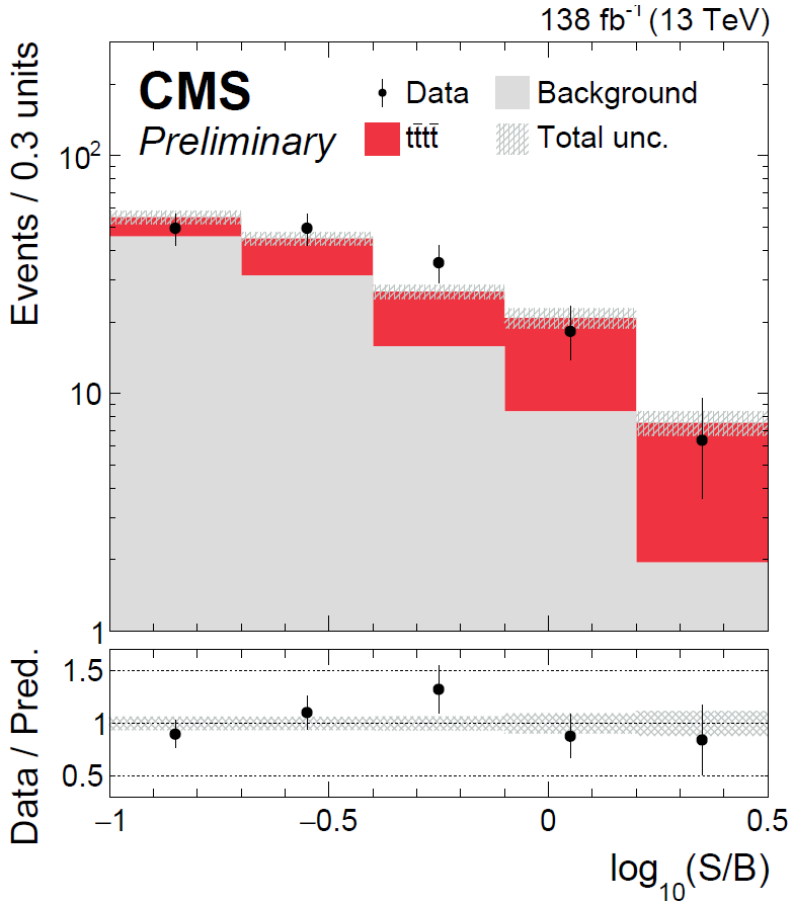
- CMS already had evidence of $t\bar{t}t\bar{t}$ production (combining channels with 0 to 4 leptons) with 4.0 (3.2)σ observed and expected significance
- This measurement represents a huge improvement with respect to the search in the multilepton channel(Eur. Phys. J.C 80 (2020) 75) that reached 2.6(2.7) σ observed and expected significance
  - Improved b-jet identification
  - Improved leptons reconstruction
    - Allow to loose the requirements on the lepton pT.
  - Improved discrimination between signal and bkg
    - BDT multiclassifier designed to identify three classes: $t\bar{t}t\bar{t}$, $t\bar{t}$X (events with a prompt lepton), and $t\bar{t}$ (events with no leptons)
    - BDT trained separately in 2l and 3l+4l regions.



NEW

Observation of $t\bar{t}t\bar{t}$

CMS-PAS-TOP-22-013



- Signal extracted with a profile likelihood fit on the signal and CRs
  - defined based on l multiplicities, charge and the event classes defined by the BDT.
- $t\bar{t}$W and $t\bar{t}$Z cross section extracted at the same time, leading to a small excess wrt to the SM (~2.2σ)
- Observation of $t\bar{t}t\bar{t}$ the process with significance 5.5 (4.9)σ
- Measured cross section:

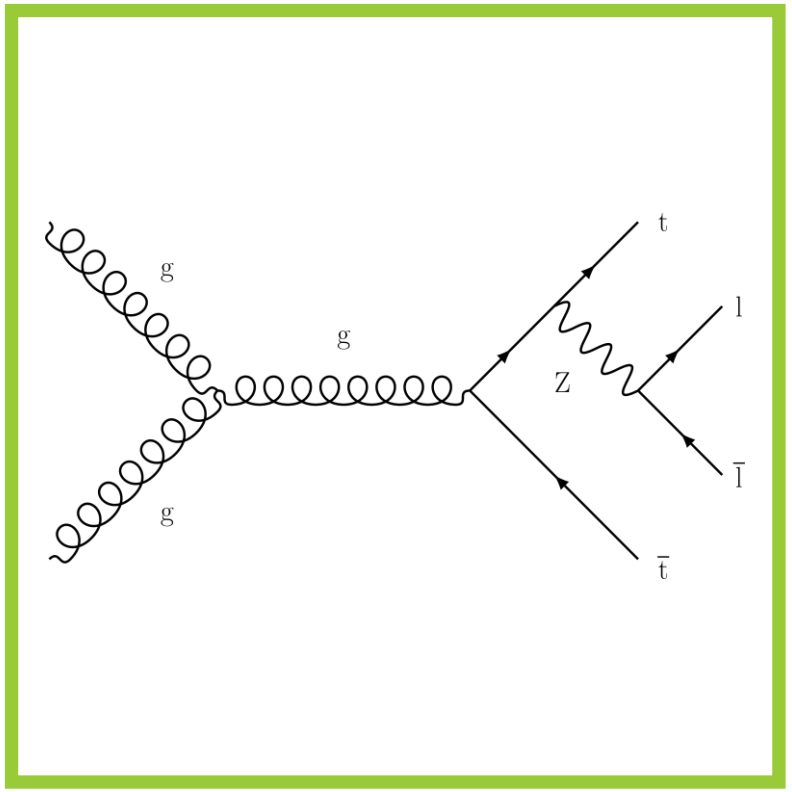
$$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}(stat)\ ^{+2.4}_{-2.1}(syst)\ \text{fb}$$

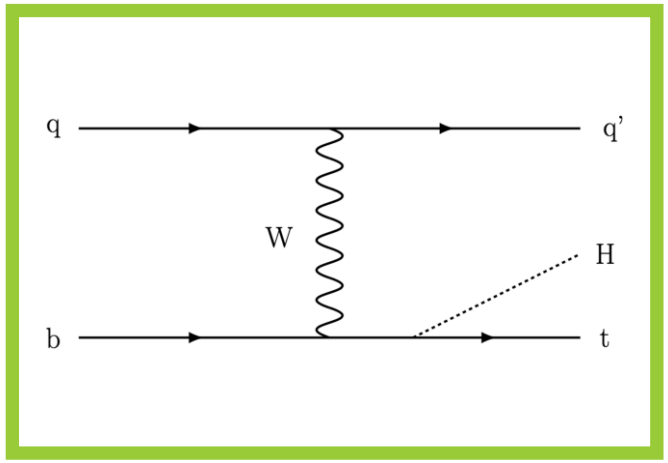
$$\sigma_{t\bar{t}t\bar{t}}(SM) = 13.4^{+1.0}_{-1.8}\ \text{fb}$$

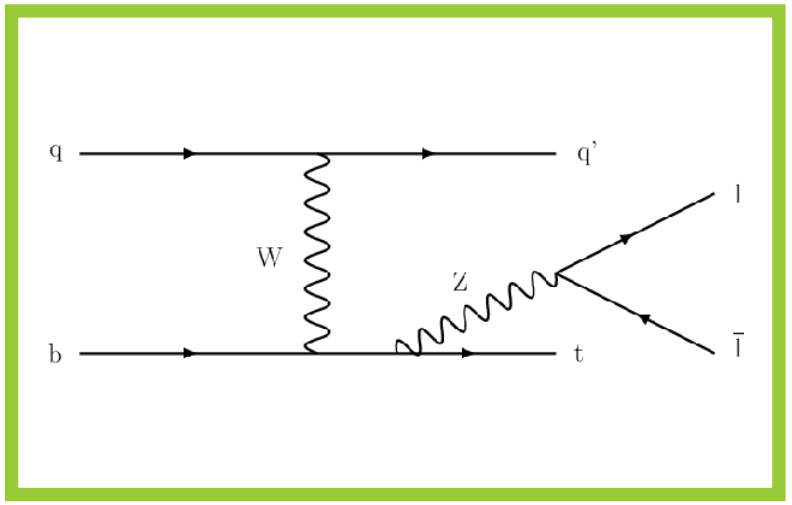
- Dominated by statistical uncertainty
  - Dominant modelling uncertainty is the additional jets in $t\bar{t}$X and the scale uncertainty in $t\bar{t}t\bar{t}$

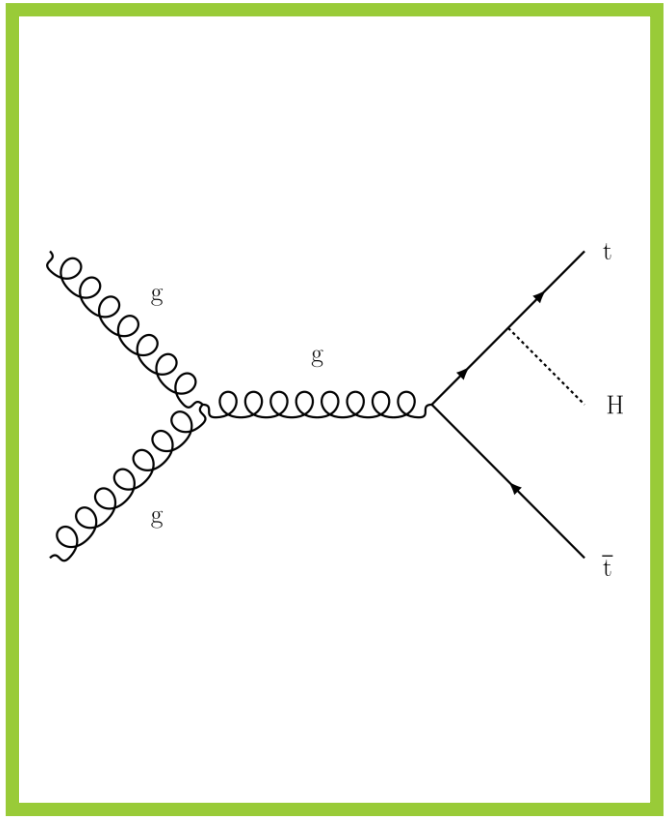
EFT search in $t(\bar{t})$+leptons

CMS-PAS-TOP-22-006





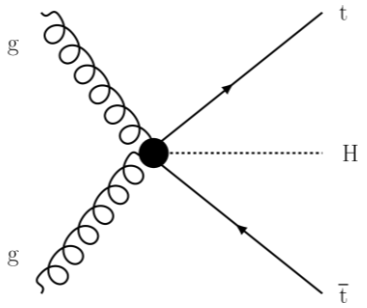




EFT interpretation

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d,j} \frac{c_j^d}{\Lambda^d} O_j^d$$

- Assume the SM is an effective theory :
  - New physics is added under the form of new operators.
  - Operators are scaled by a coefficient (c_j) and the new physics scale (Λ).
- Only dimension 6 operator considered (main effect).

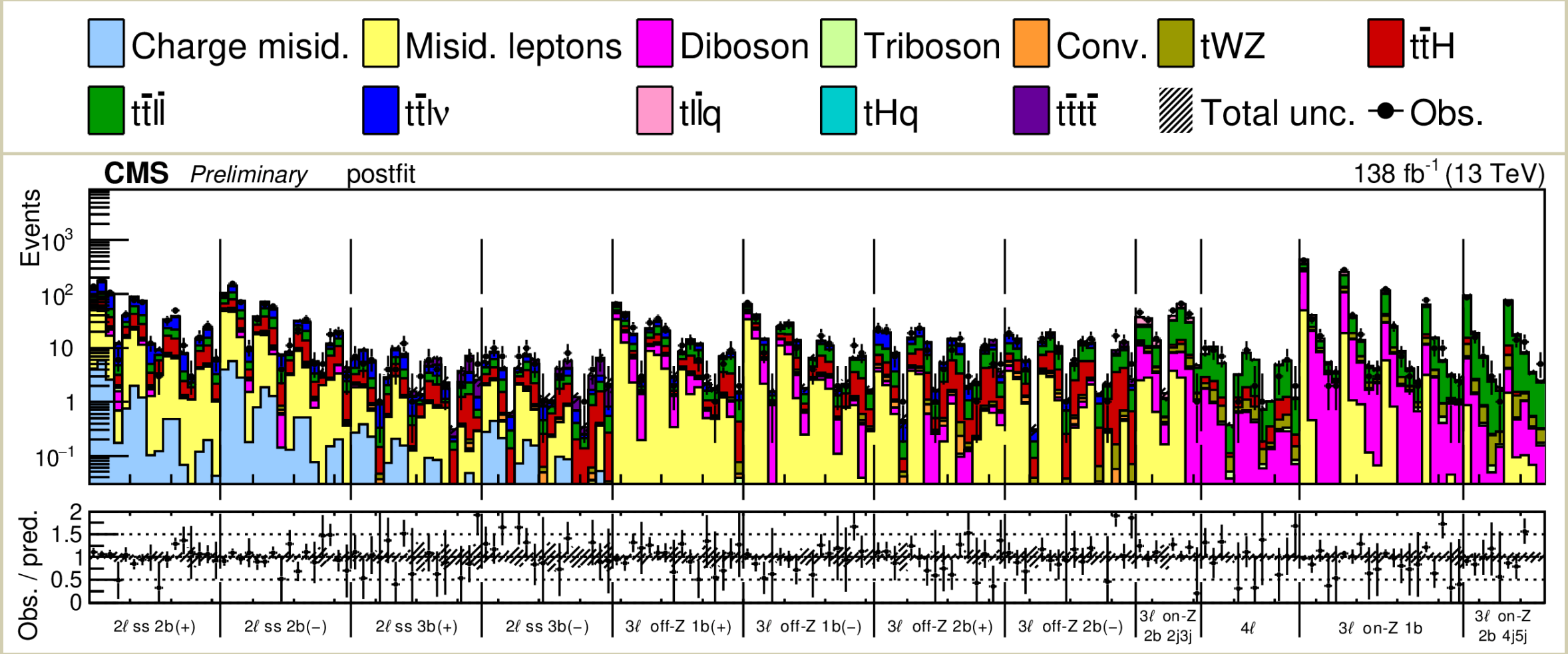


- The effects of the new physics on the yield/cross section can be parametrized with a second order polynomial:

Int. with SM — Pure EFT contribution

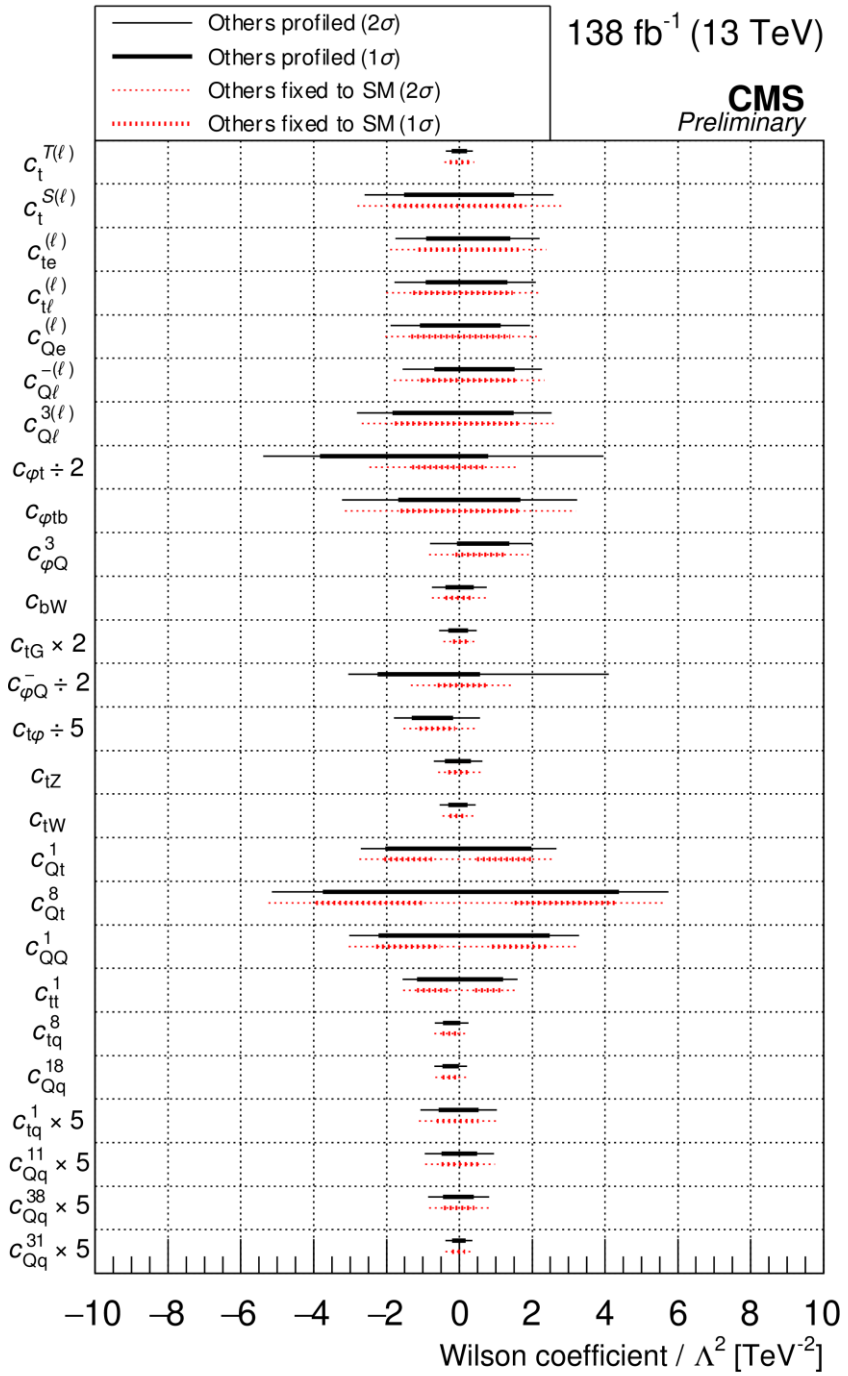
$$N\left(\frac{\vec{c}}{\Lambda}\right) = N_{SM} + \sum_j \frac{c_j}{\Lambda^2} N_j + \sum_{j,k} \frac{c_j c_k}{\Lambda^4} N_j N_k$$

- The same operator can affect multiple processes
  - EFT interpretation can be used to combine several processes and analysis and derive a single picture on the presence of new physics.



CMS-PAS-TOP-22-006

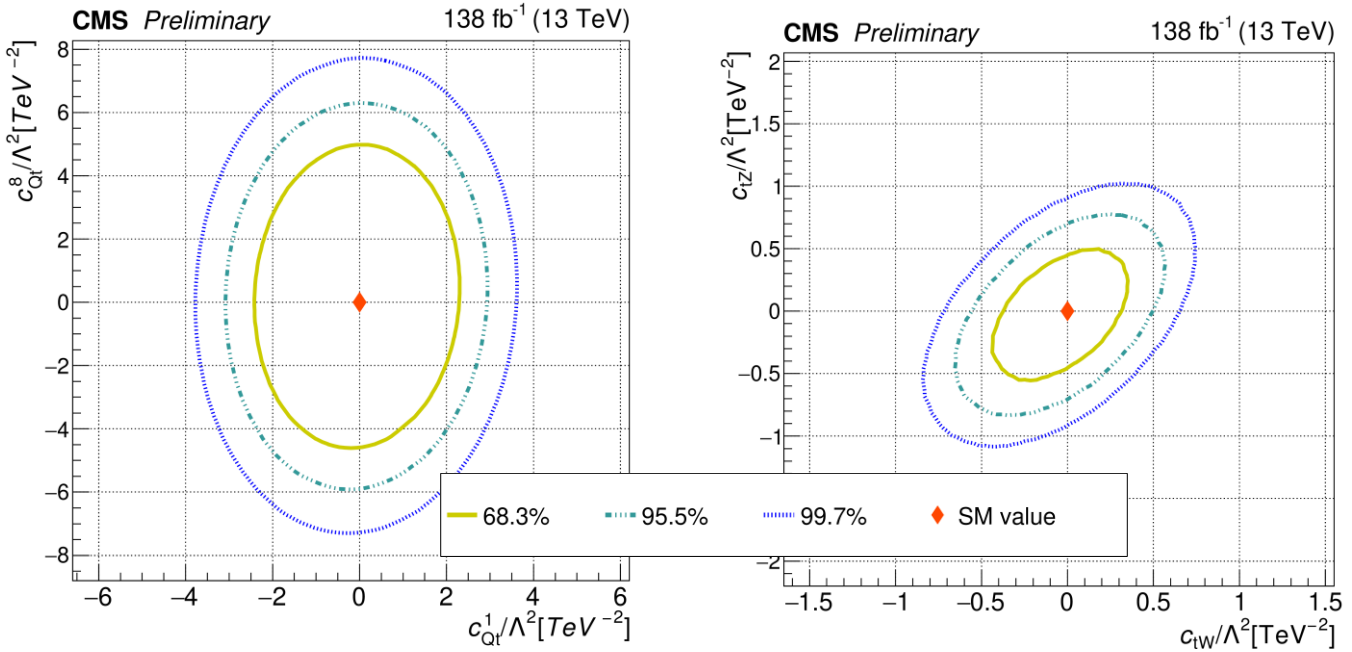
- Search targeting $t(\bar{t})$+leptons (includes $t\bar{t}$H, $t\bar{t}$ll, $t\bar{t}$lv,tllq,tHq, $t\bar{t}t\bar{t}$) final states to perform a simultaneous fit on 26 EFT operators
- The events divided in 43 categories based on n. of jets and bjets, lepton charge. A kinematic variable is used as input to the fit in each category (leading p_T of pair of objects and p_T Z)



CMS-PAS-TOP-22-006

Results

- All c_j agrees with the SM expectation value of 0.
- Result significantly improved wrt JHEP03(2021)095.
- The sensitivity is dominated by the statistical uncertainty in most operators
  - The dominant systematic uncertainty is on the processes' normalization.



Conclusions

ATLAS and CMS have reached an impressive precision in measuring extremely rare SM processes:

- The $t\bar{t}W$ production is measured, also differential, and a slight excess is observed with respect to the SM. Disagreement reduced by recent FxFx calculations.
- The charge asymmetries are measured by ATLAS in $t\bar{t}\gamma$ and $t\bar{t}W$ without significant deviations with respect to the SM expectations.
- Both experiments have now observation of the $t\bar{t}t\bar{t}$ production process.
- The associated production of top quarks and leptons has been employed in CMS to perform a large scale EFT study fit, without significant deviation with the SM observed.

Several of the analyses presented today are statistically limited, looking forward to analyse Run3 data!

Back-up

$t\bar{t}\gamma$ Charge Asymmetry

- The measured $t\bar{t}\gamma$ CA depends on the CA assumed for the $t\bar{t}$ process (entering in fake h- γ and $t\bar{t}\gamma$ deacy)
- The dependence resulted linear

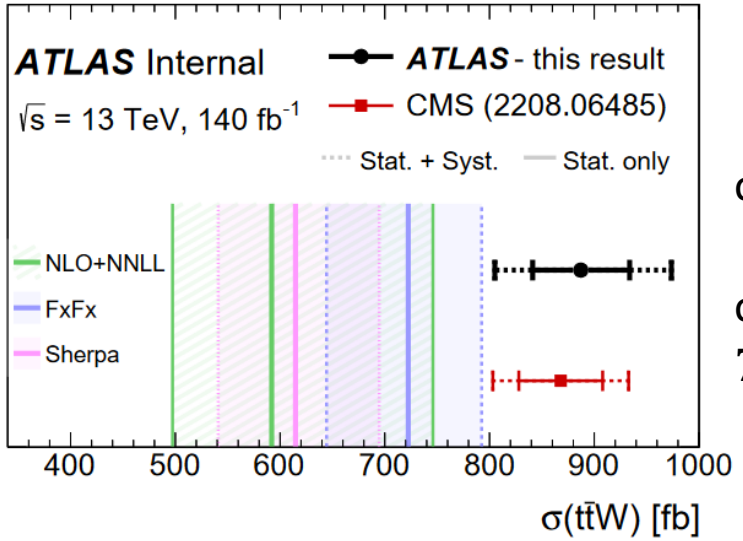
$$A_{CA}^{t\bar{t}\gamma} = -0.57 \times A_{CA}^{t\bar{t}} + 0.0005$$

NEW

$t\bar{t}W$ – inclusive σ

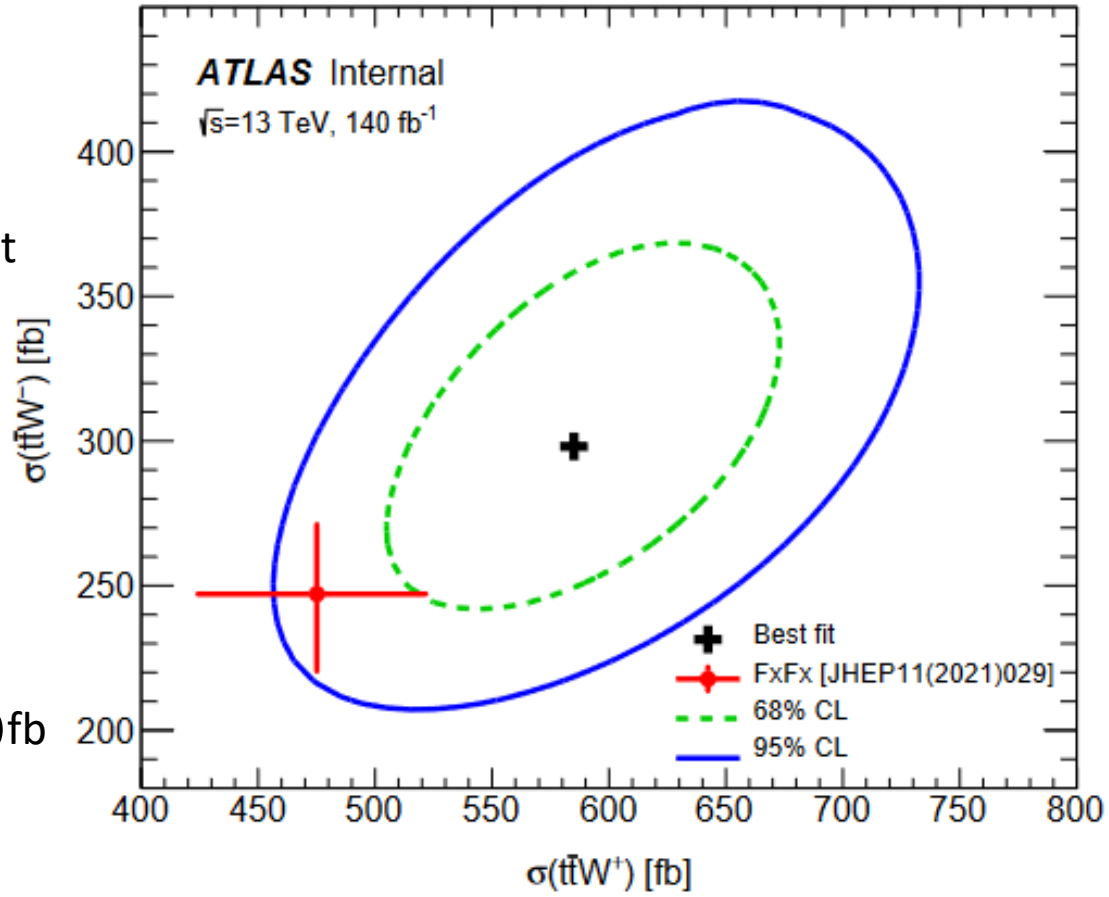
TBD

- $\sigma^{t\bar{t}W}$ slightly exceed the SM expectations (by X.XX σ)
  - The agreement is improved by the FxFx calc.
- The result is in XXX agreement with CMS.
- The total uncertainties are XX% (XX% w/o gen. and sh.).
- The measurement includes also $t\bar{t}W$ charge asymmetry that agrees with the SM.



$\sigma^{t\bar{t}W}$=XXXfb

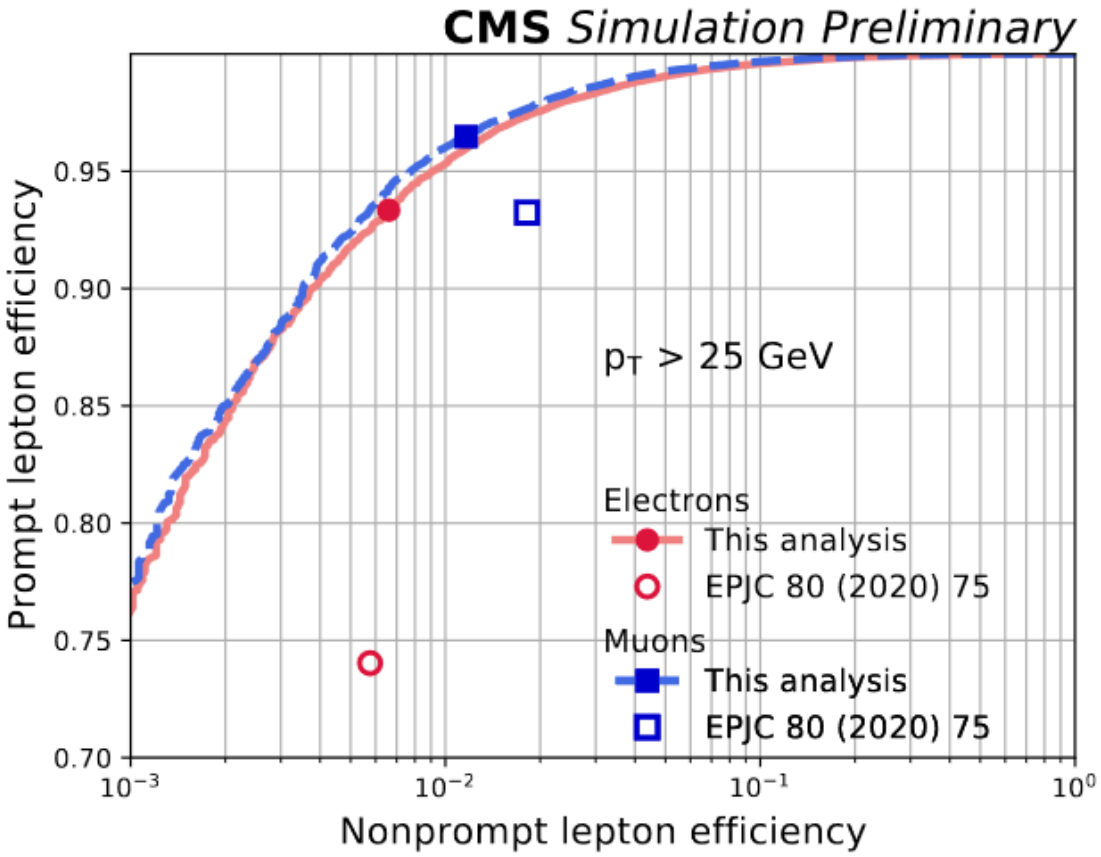
$\sigma_{SM}^{t\bar{t}W}(FxFx := 722^{+70}_{-78}(scale) \pm 7(PDF)$fb

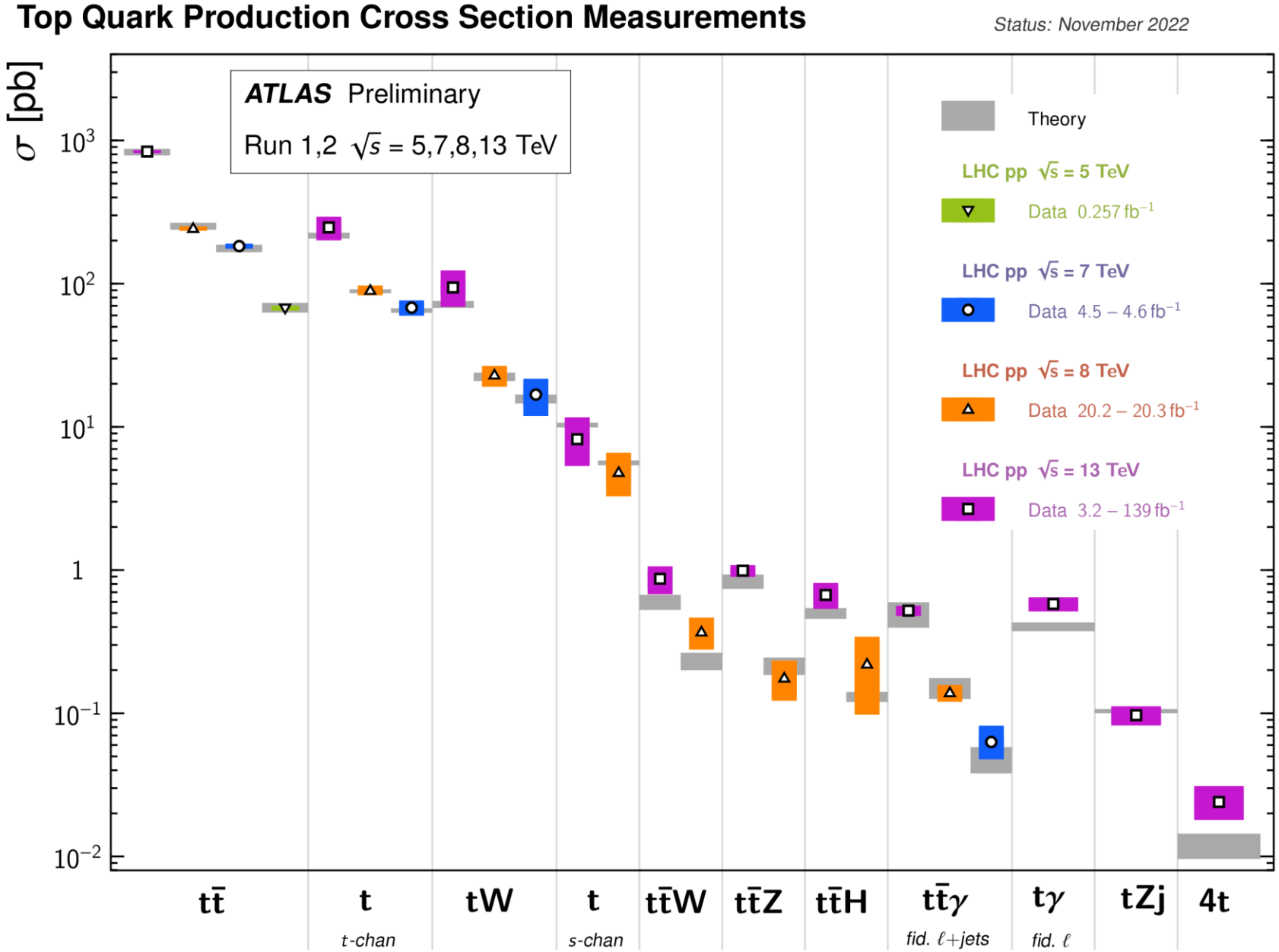


Observation of $t\bar{t}t\bar{t}$

Channel	Obs. (exp.) significance	$\sigma(pp \to t\bar{t}t\bar{t})$
2ℓ	4.1 (4.1) s.d.	$17.6\,^{+4.7}_{-4.3}\,(stat)\,^{+2.8}_{-2.7}\,(syst)$ fb
3ℓ	3.5 (3.0) s.d.	$19.4\,^{+7.1}_{-6.4}\,(stat)\,^{+2.9}_{-2.3}\,(syst)$ fb
4ℓ	0.0 (0.8) s.d.	—
Combined	5.5 (4.9) s.d.	$17.9\,^{+3.7}_{-3.5}\,(stat)\,^{+2.4}_{-2.1}\,(syst)$ fb

$$\sigma(pp \to t\bar{t}t\bar{t}) = 17.9\,^{+3.7}_{-3.5}\,(stat)\,^{+2.4}_{-2.1}\,(syst)\,fb,$$
$$\sigma(pp \to t\bar{t}W) = 997 \pm 58\,(stat)\,^{+79}_{-72}\,(syst)\,fb,$$
$$\sigma(pp \to t\bar{t}Z) = 1134\,^{+52}_{-43}\,(stat) \pm 86\,(syst)\,fb.$$




Top Quark Production Cross Section Measurements
Status: November 2022
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 5 TeV
Data 0.257 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
tt̄
t
t-chan
tW
t
s-chan
tt̄W
tt̄Z
tt̄H
tt̄γ
fid. ℓ+jets
tγ
fid. ℓ
tZj
4t