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Top quark precision measurements

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Large Hadron Collider Physics Conference
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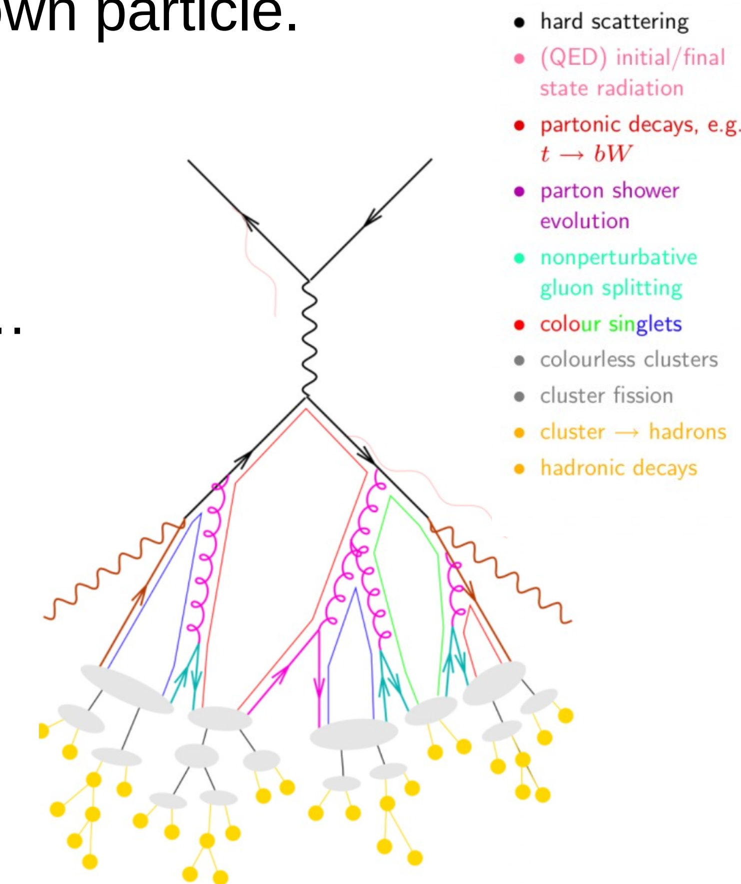
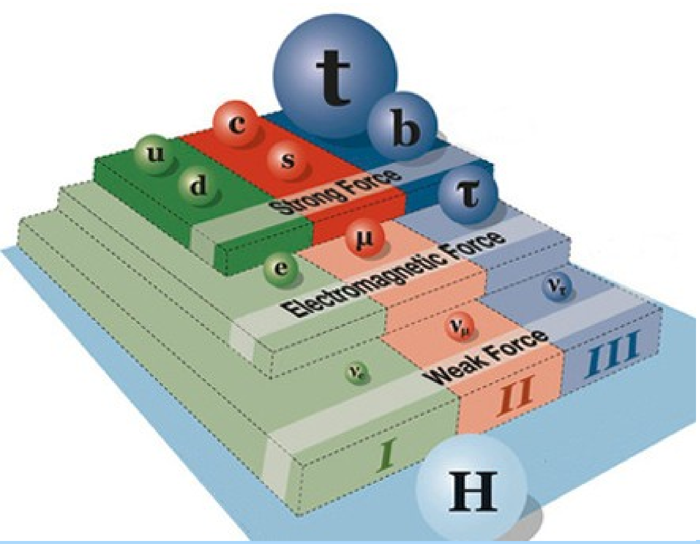
2022 LHCP TAIPEI ONLINE

Why top quarks?

- The top quark is the most massive known particle.
  - ➔ Largest coupling to Higgs boson
  - ➔ Sensitive to many BSM physics
- Sensitive to different QCD parameters:
  - ➔ α_s, proton PDFs, color reconnection…
- A key to new physics:
  - ➔ Crucial in many BSM searches
  - ➔ Allows us to test EFT interpretations



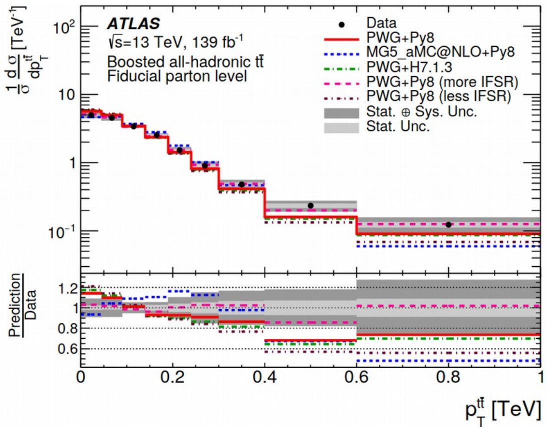


- Multiple final states. Key to understand b-tagging
  - ➔ Used to calibrate the detector

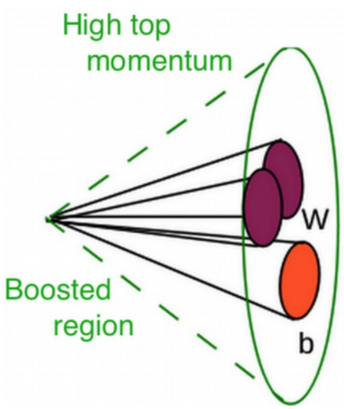
Top quark and precision

Precision era for top quark measurements

- Probe SM calculations with high precision
  - Beyond NLO calculations
- Check the agreement with different generators
  - Precision beyond theory

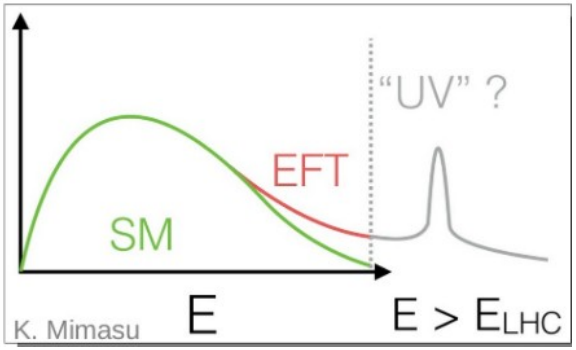


- Detect very rare processes
  - Associated production (see also talk from Mark)
  - Four tops (see talk from Nuno)
  - Exclusive production (see talk from Nuno)
- Explore corners of the kinematic phase space
  - Boosted regime
  - Multi-differential measurements



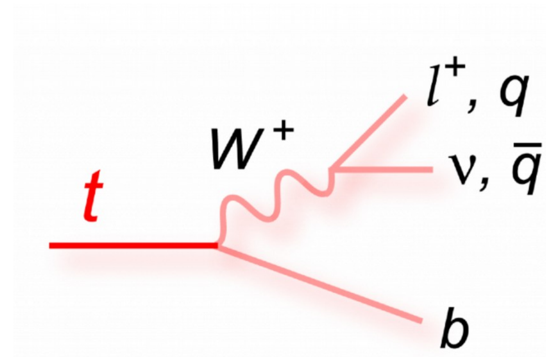
Details in parallel sessions

- New physics through top quarks
  - EFT interpretations
  - FCNC searches (see talk from Nuno)



Top quark at the LHC

Huge amount of data: ~138 fb^{-1} in the Run 2 at 13 TeV.
Top quarks in a wide range of $\sqrt{s}$: from 5.02 TeV to 13 TeV.



Production at the LHC:

Pair production

Main production process, huge cross section.

Sensitive to QCD.

Single top

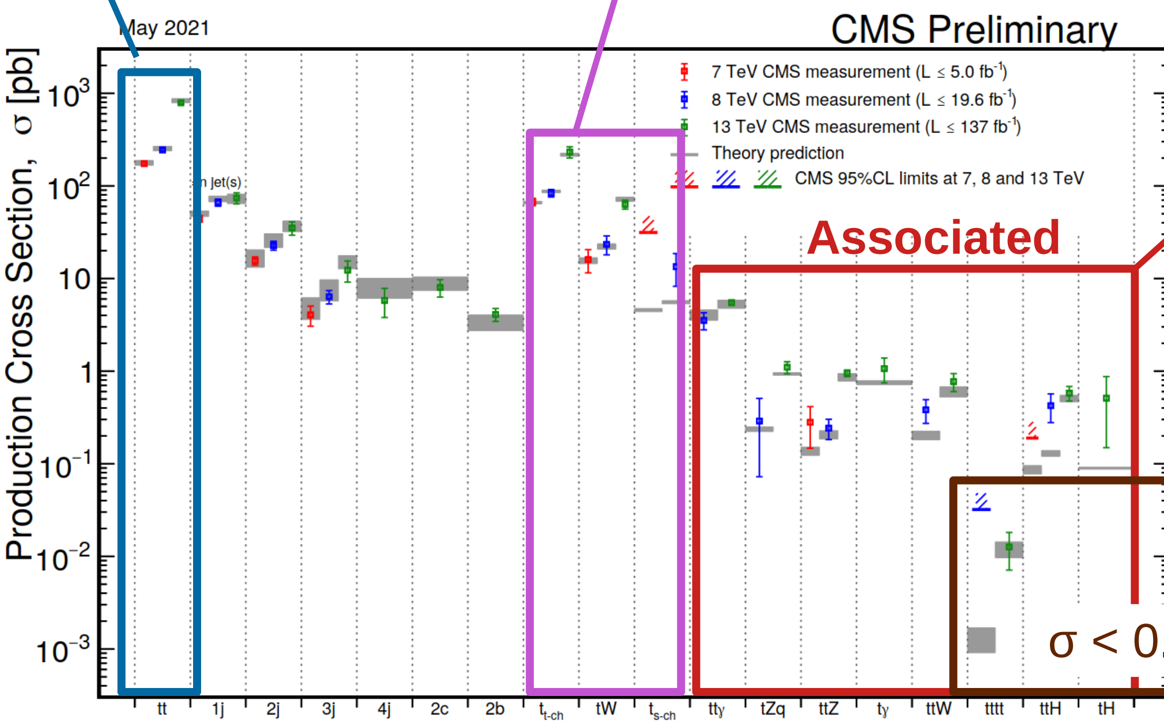
Probing EWK top quark production.

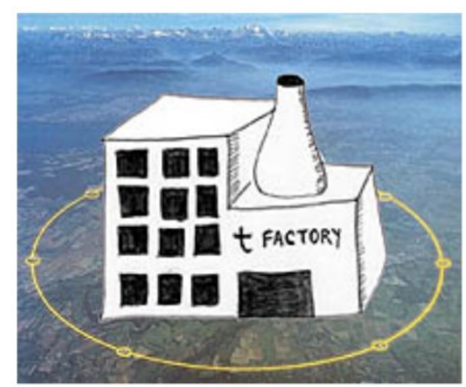
Associated

Small cross section, but precision is reached.

Rare

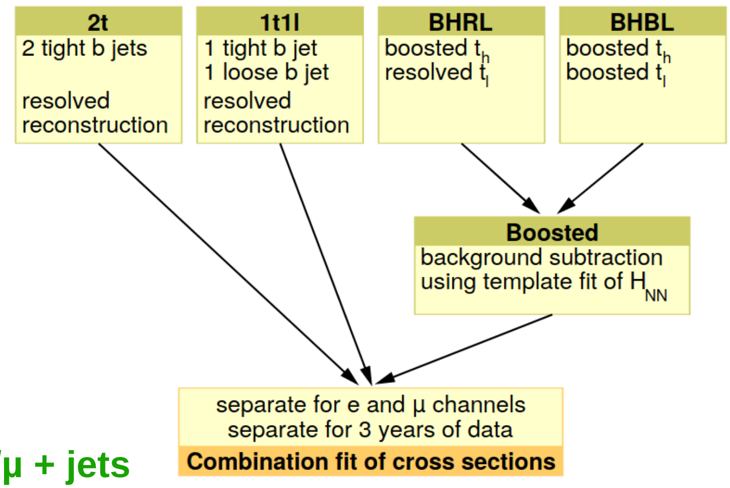
$\sigma < 0.1$ pb



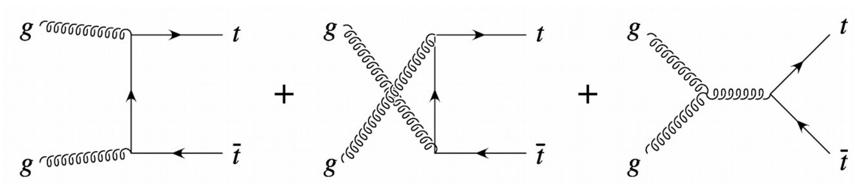


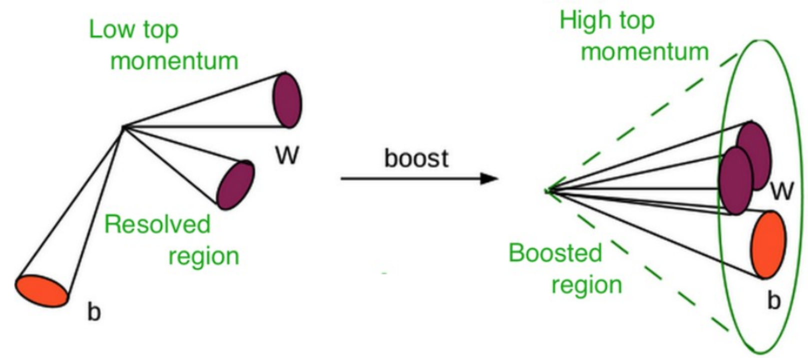
Most precise $t\bar{t}$ inclusive cross section at 13 TeV

For the first time, a combination of boosted + resolved topologies is used → provides constraints to systematic uncertainties.

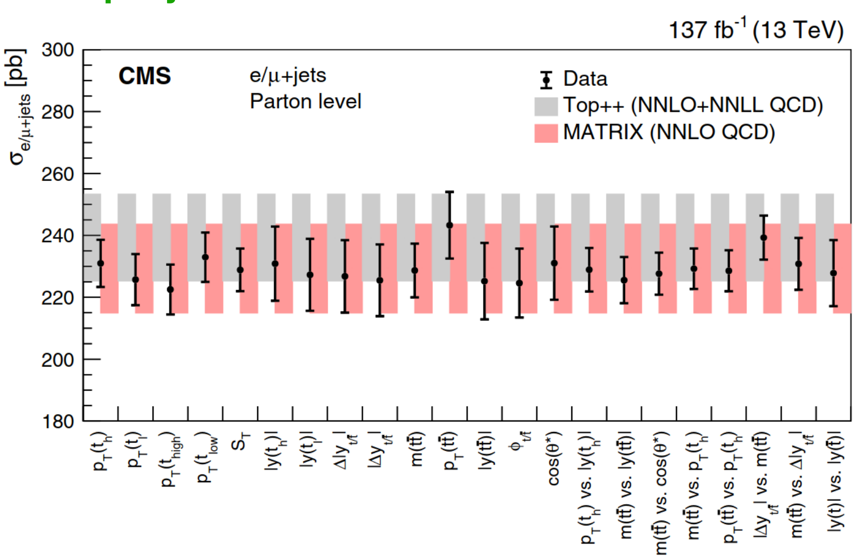


[Phys. Rev D 104 (2021) 092013](https://doi.org/10.1103/PhysRevD.104.092013)





e/μ + jets



Most precise measurement in the e/μ+jets:

$$\sigma_{t\bar{t}} = 791 \pm 1\ (\text{stat}) \pm 21\ (\text{syst}) \pm 14\ (\text{lumi})\ \text{pb}$$

$$\sigma_{MATRIX} = 797^{+39}_{-51}\ (\text{scale}) \pm 39\ (\text{PDF})\ \text{pb}$$

- Total relative uncertainty of 3.2%
- Dominant systematic: JES (1.38%)

$t\bar{t}$ cross section at 5 TeV in the eμ final state

JHEP 04 (2022) 144

Measurement with special conditions!

Special energy – sensitive to high-x gluon in proton PDFs!

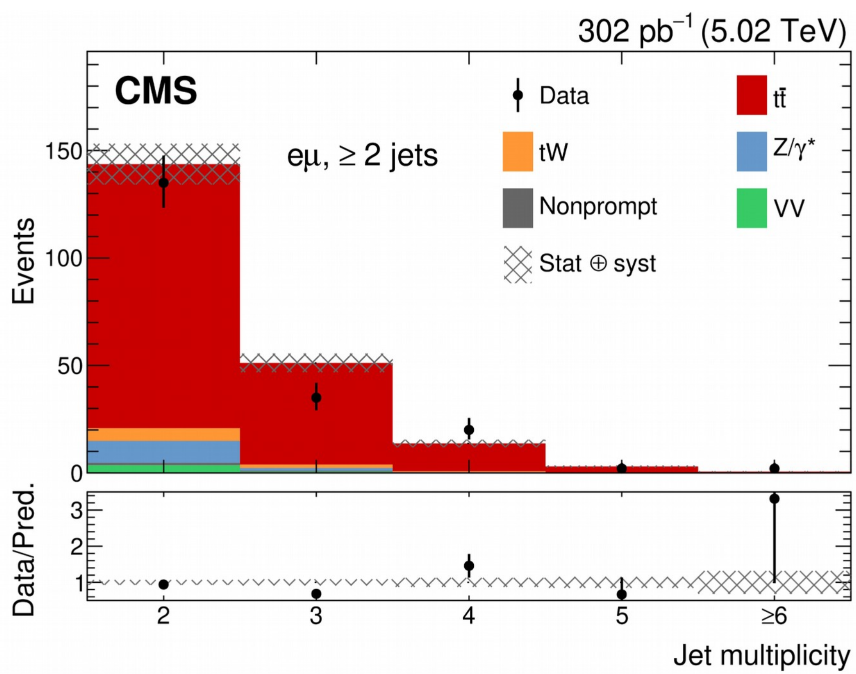
eμ final state, 302pb^{-1} of low-pu data at 5.02 TeV in pp collisions.

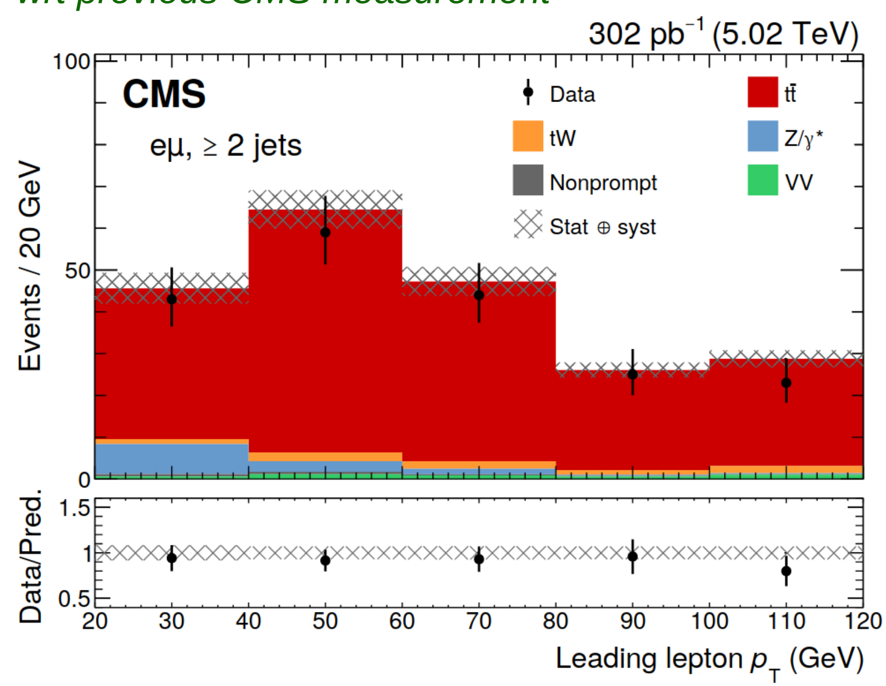
- eμ pair, at least 2 jets. No b-tagging requirement
- Cut-and-count method to extract the cross section
- Result combined with a previous measurement in l+jets final state

$$\sigma_{t\bar{t}} = 63.0 \pm 4.1\ (\text{stat}) \pm 3.0\ (\text{syst+lumi})\ \text{pb}$$

$\sigma_{NNLO} = 68.2 \pm 4.8\ (\text{PDF}+\alpha_s) \pm 2.2\ (\text{scale})$ pb

> 30% improvement in precision
wrt previous CMS measurement





$t\bar{t}$ cross section at 5 TeV in l+jets + dileptons

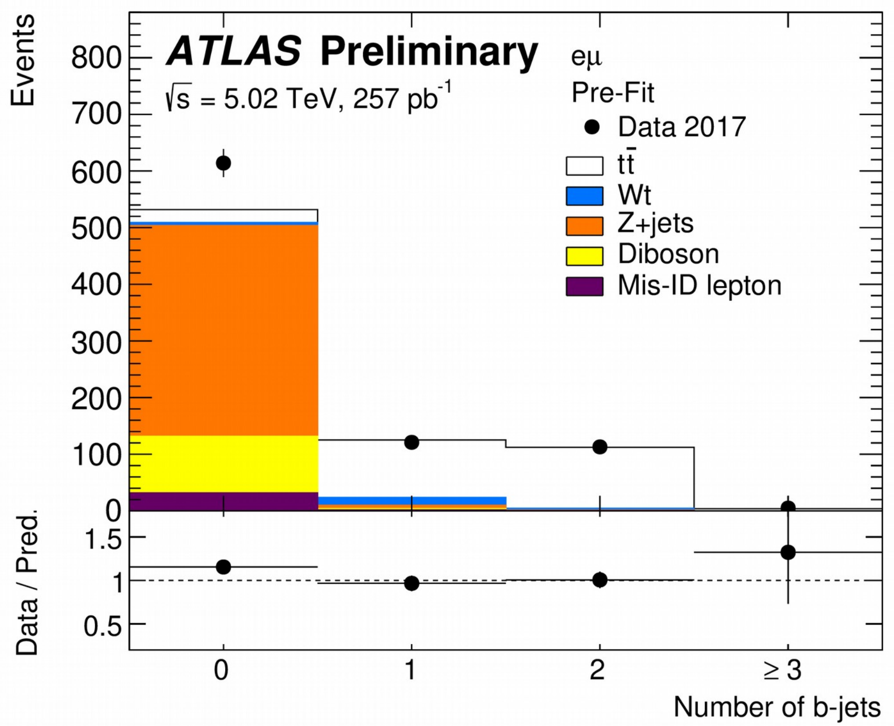
ATLAS-CONF-2022-031

Very precise result even with a small amount of events (257 pb^{-1}).
- Relaxed selection
- Optimized analysis using multivariate techniques
- Combination of different final states (dilepton, e/μ + jets)

NEW LHCP

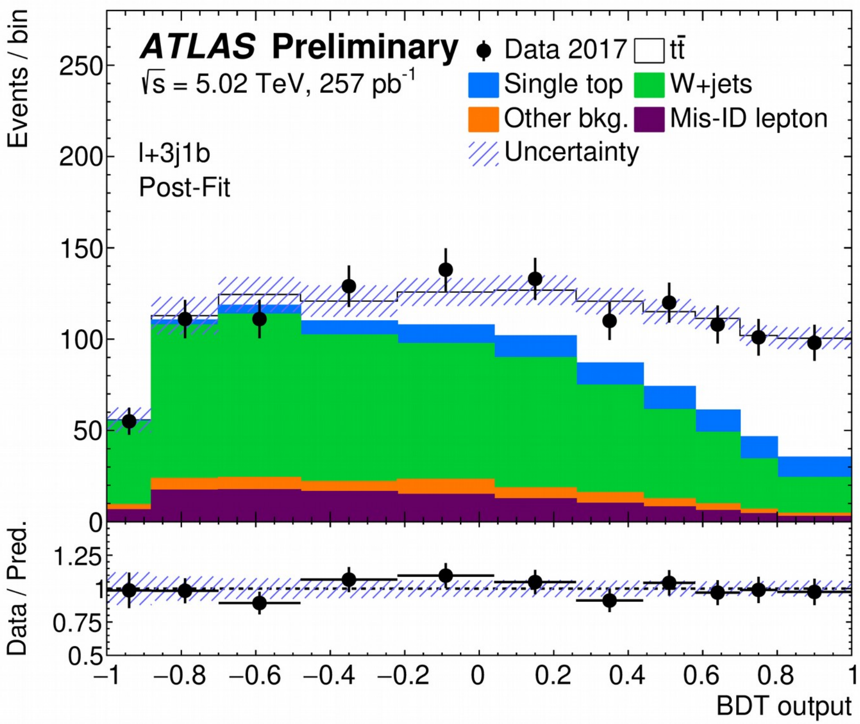
<u>dilepton</u>

Cross section from categories with 1 or 2 b-tagged jets in ee+μμ/eμ final states.



<u>e/μ + jets</u>

BDT in different regions depending on number of jets and b-tagged jets



$t\bar{t}$ cross section at 5 TeV in l+jets + dileptons

ATLAS-CONF-2022-031

Measured cross section with a total uncertainty of about 3.9%.

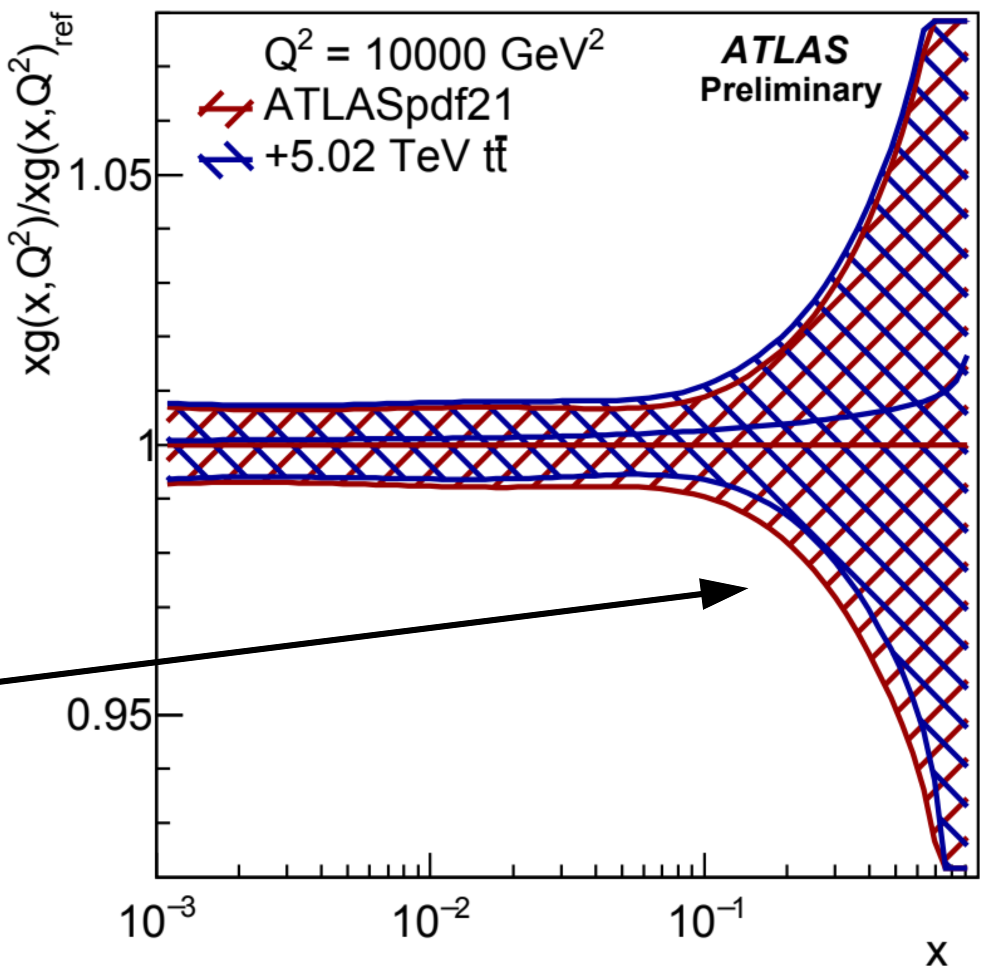
$\sigma_{t\bar{t}}$ = 67.5 ± 0.9 (stat) ± 2.3 (syst) ± 1.1(lumi) pb

In agreement with NNLO+NNLL SM cross section from TOP++ of:

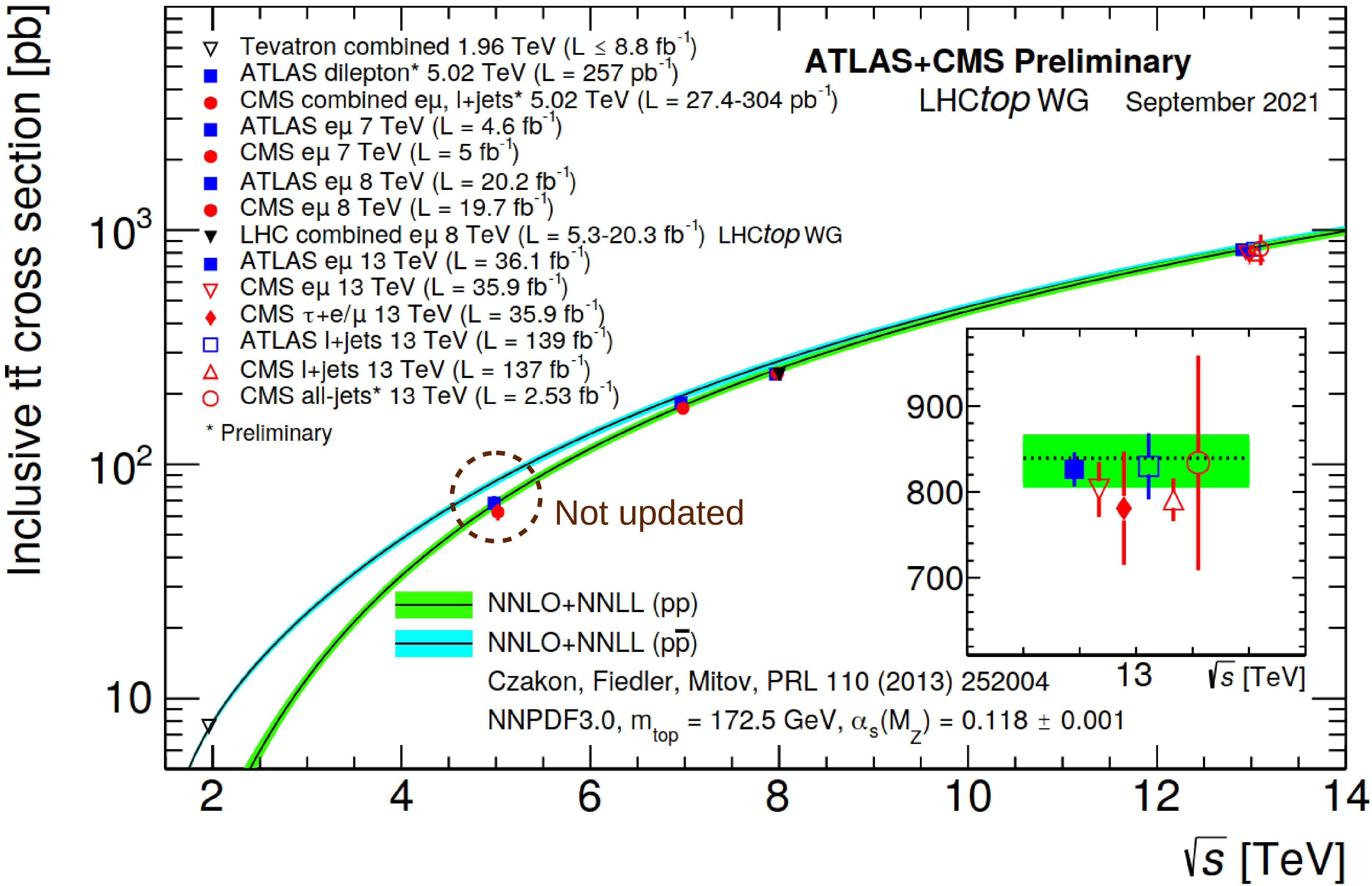
σ_{NNLO} = 68.2 ± 4.8 (PDF+α_s) ± 2.2 (scale) pb

Measured uncertainty below NNLO predictions!

QCD fit performed to show the result is sensitive to high-x_g in proton PDF.



Summary of inclusive cross sections



Differential cross section in the dilepton channel

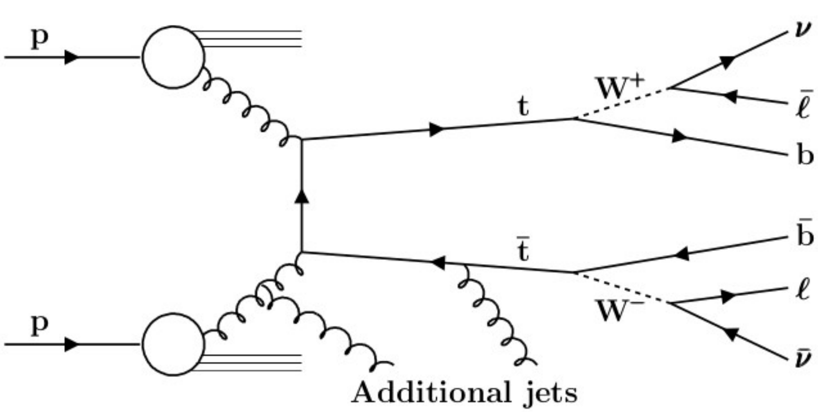
Let's go differential!

NEW

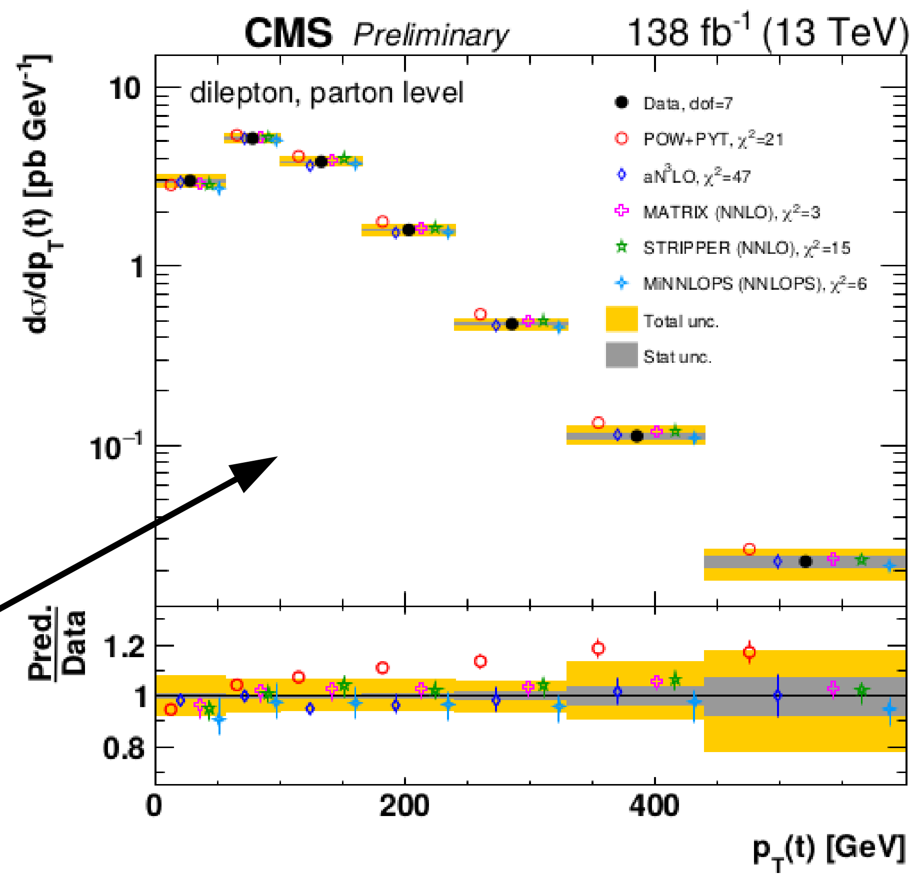
CMS-PAS-TOP-20-006

Exploiting full Run 2 data to explore top kinematics with high precision.

$t\bar{t}$ differential cross section is measured in the dilepton final state as a function of different kinematic observables.



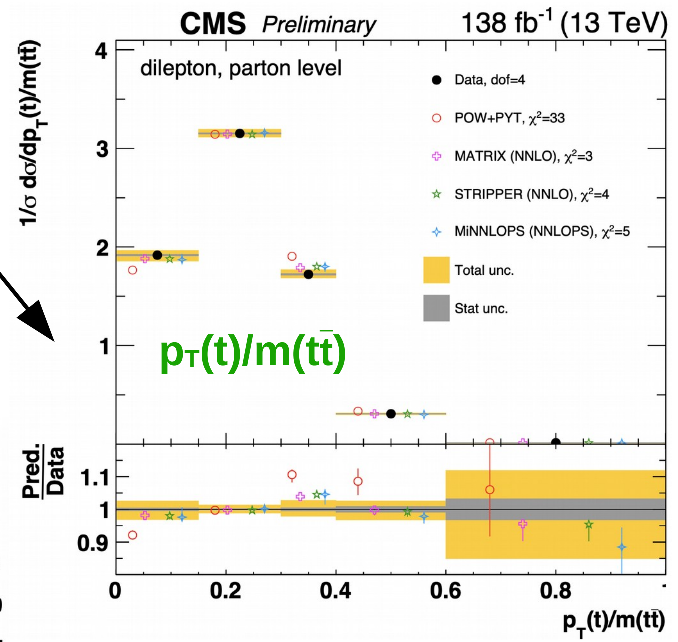
Comparisons with beyond NLO calculations, including NNLOPS for the first time.

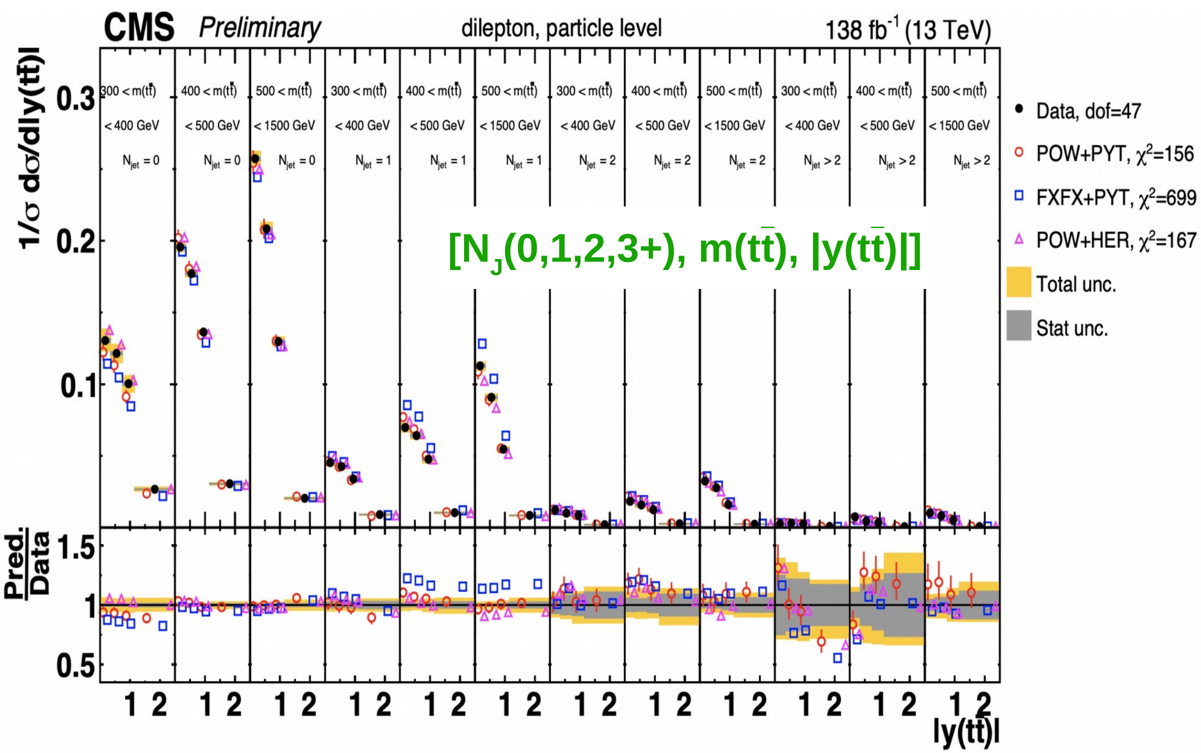


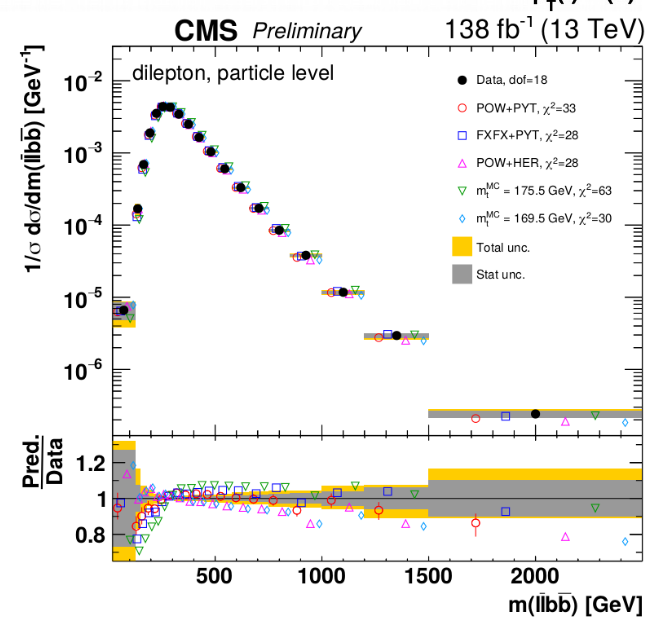
$t\bar{t}$+jets differential cross section

[CMS-PAS-TOP-20-006](CMS-PAS-TOP-20-006)

- New distributions – ratios such as $p_T(t)/m(t\bar{t})$ shown for the first time
- Factor ~2 improvement on uncertainties w.r.t. previous results
- Up to 3D differential cross sections







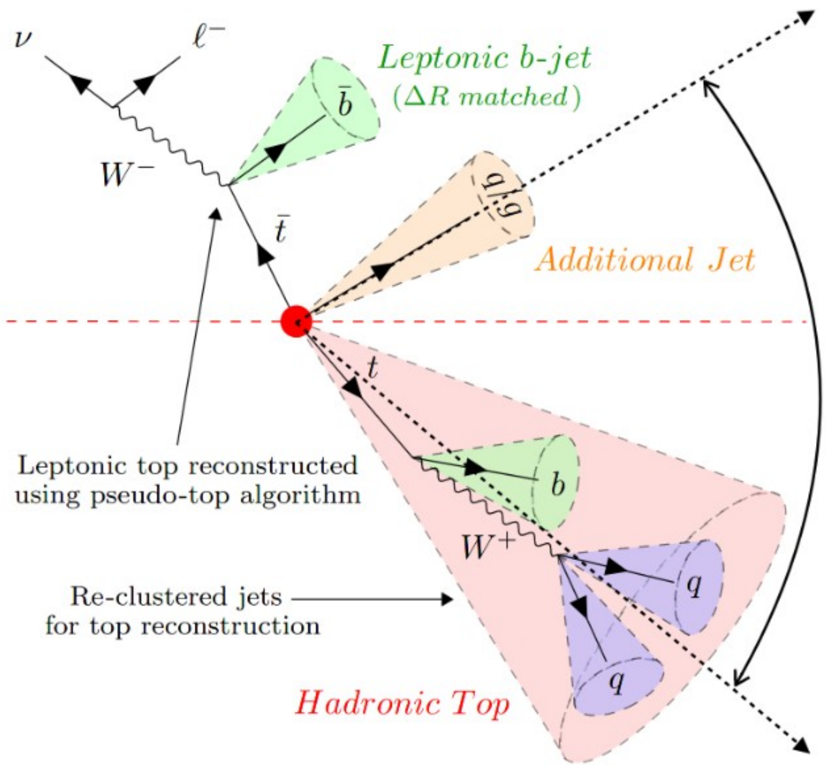
- Data best described by beyond-NLO calculations

Boosted differential $t\bar{t}$ cross section in the l+jets channel

Submitted to JHEP
arXiv:2202.12134

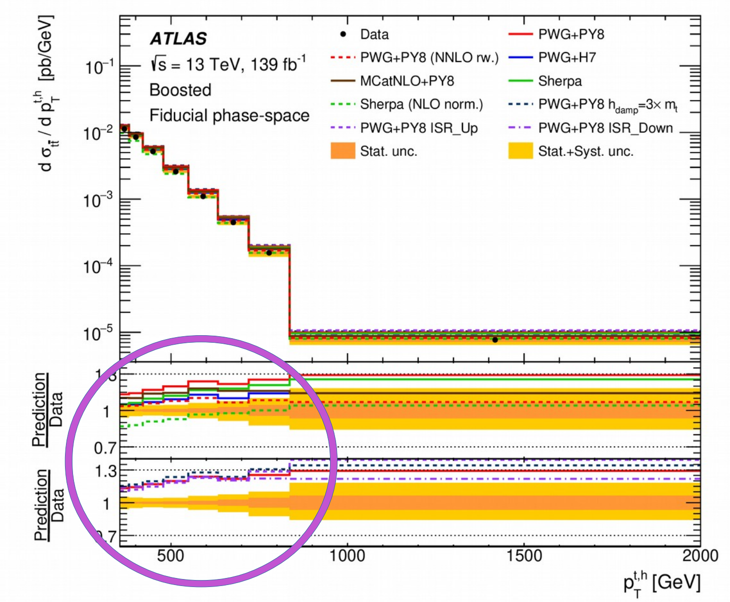
Let's go differential and boosted!

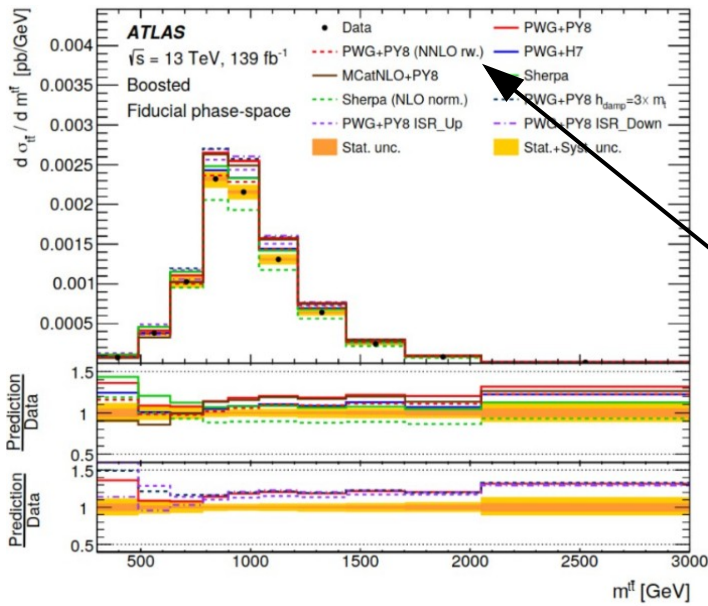
Boosted regime, 1D and 2D differential cross sections are measured.



- Hadronic (boosted) top, p_T > 355 GeV
- Leptonic top quark reconstructed from lepton, MET and associated b-tagged jet
- Cross sections for multiple observables related to kinematics of the top quarks and $t\bar{t}$ system

Boosted differential $t\bar{t}$ cross section in the l+jets channel

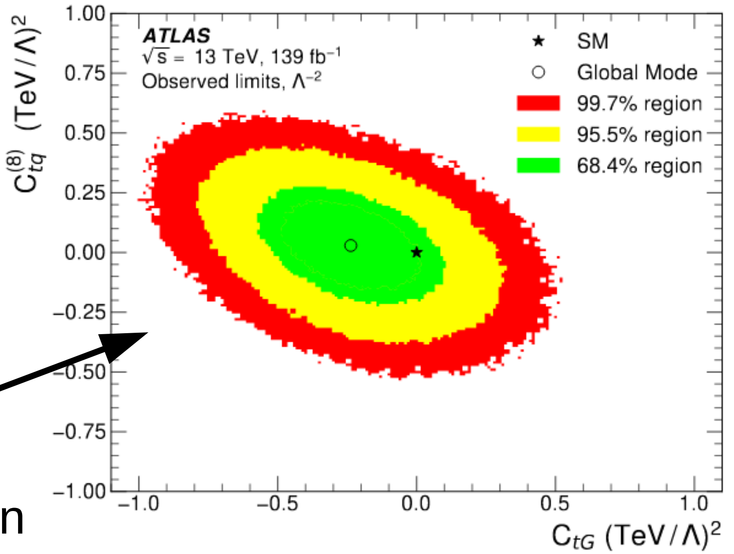




Submitted to JHEP
arXiv:2202.12134

NNLO reweighting improves the agreement!

- Theory predictions tested at high top p_T
- $m^{t,h}$ distribution used to reduce JES unc.
- Top p_T softer than predictions
- Perfect agreement is not reached with any of the MC simulations



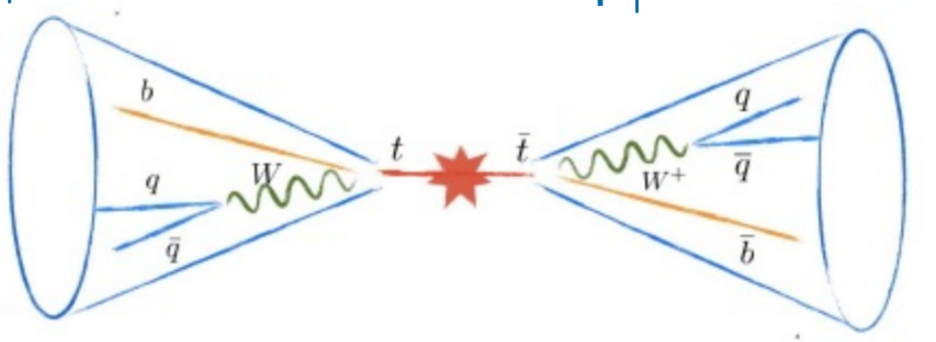
- EFT interpretations for $C_{tq}^{(8)}$ and C_{tG} WCs using the $p_T^{t,h}$ distribution

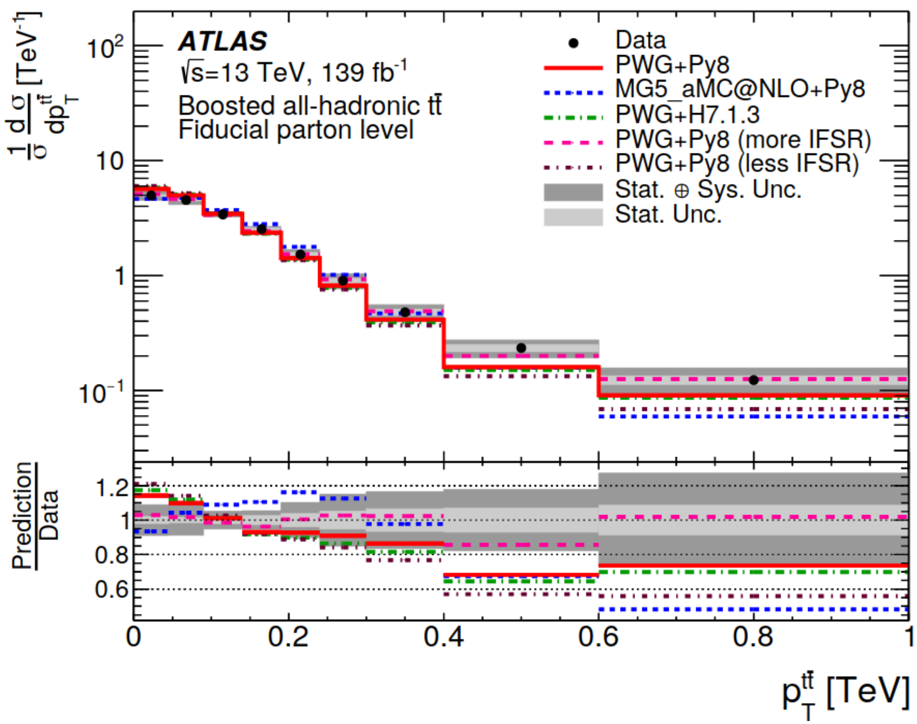
Boosted differential $t\bar{t}$ cross section in the all had channel

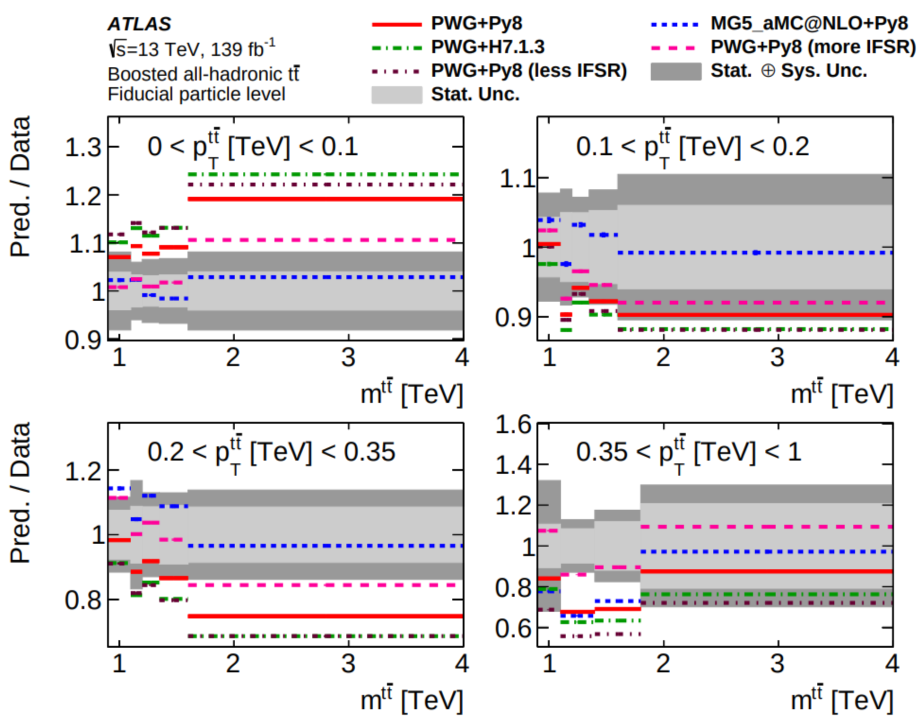
Boosted regime, all hadronic

Submitted to JHEP
arXiv:2205.02817

p_T > 500 GeV p_T > 350 GeV



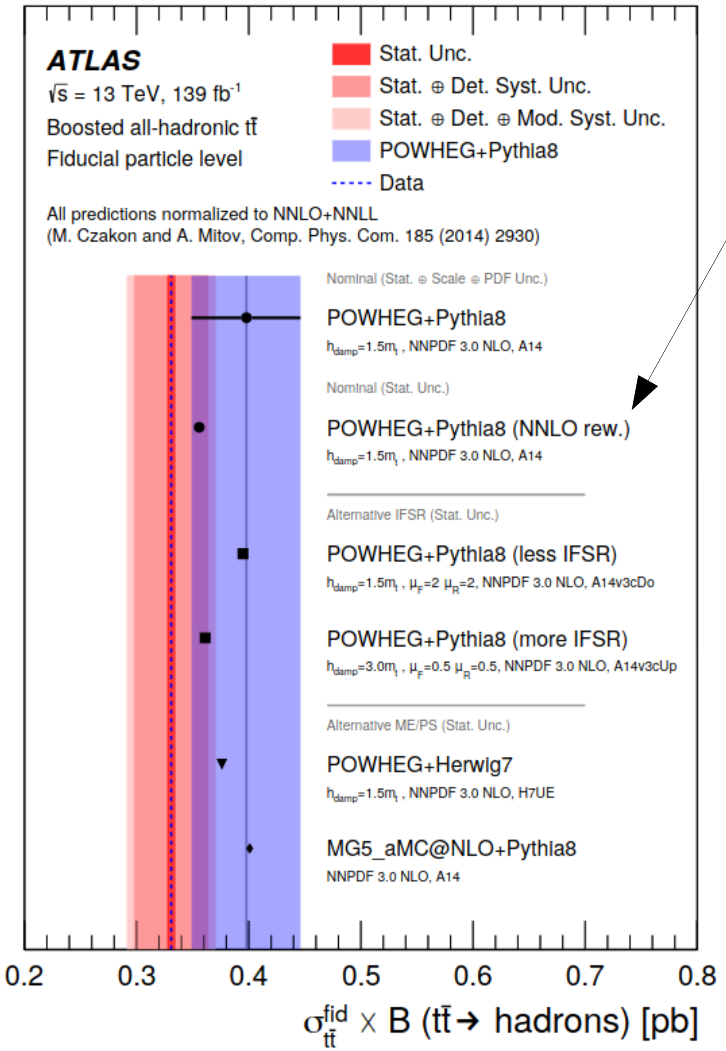




Boosted differential $t\bar{t}$ cross section in the all had channel

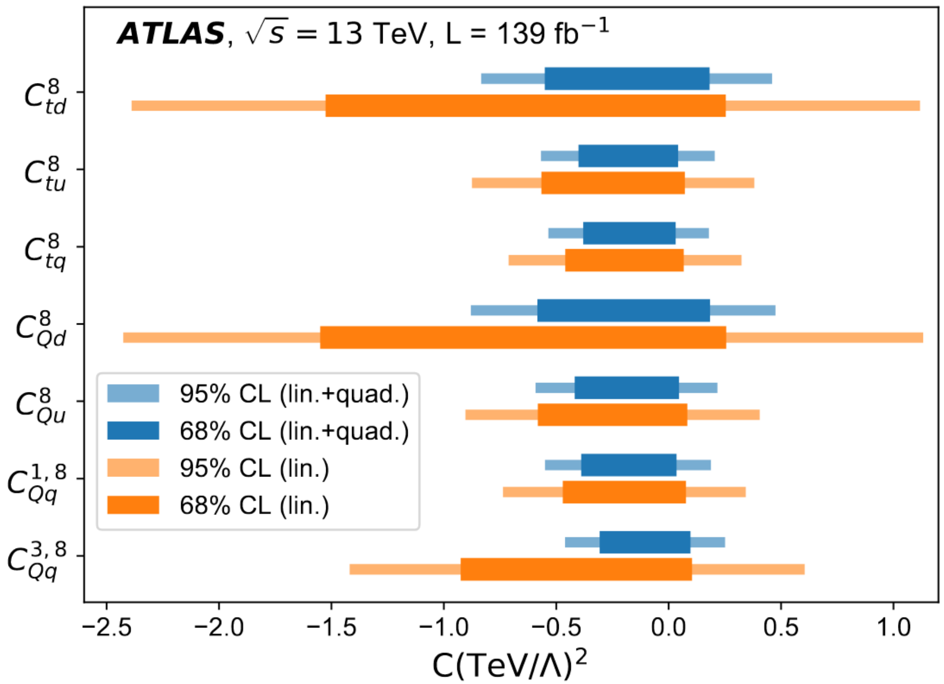
Fiducial cross section ~20% below nominal prediction, but compatible within the uncertainties.

Submitted to JHEP
arXiv:2205.02817



Comparison to different generators. NNLO reweighting improves the agreement of POWHEG+Pythia8 prediction.

EFT operators are constrained using the differential measurements.



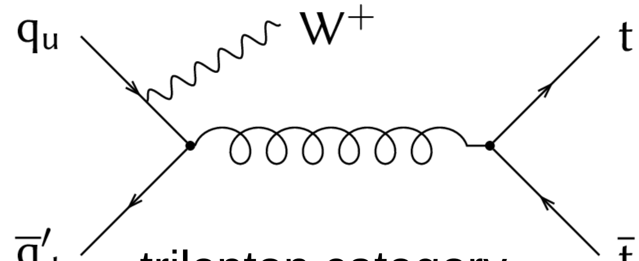
$t\bar{t}W$ cross section measurement

[CMS-PAS-TOP-21-011](CMS-PAS-TOP-21-011)

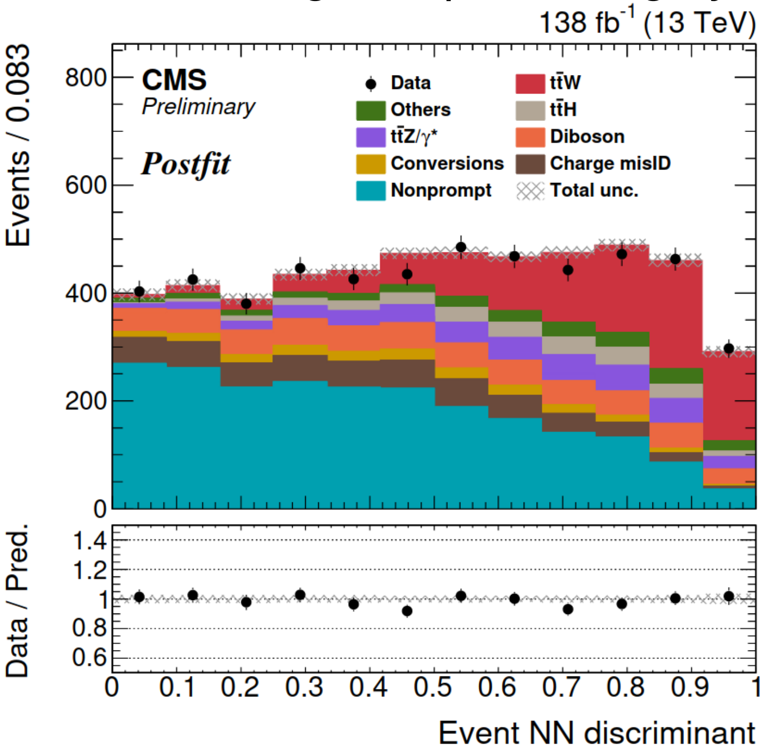
NEW

$t\bar{t}$ + W associated production

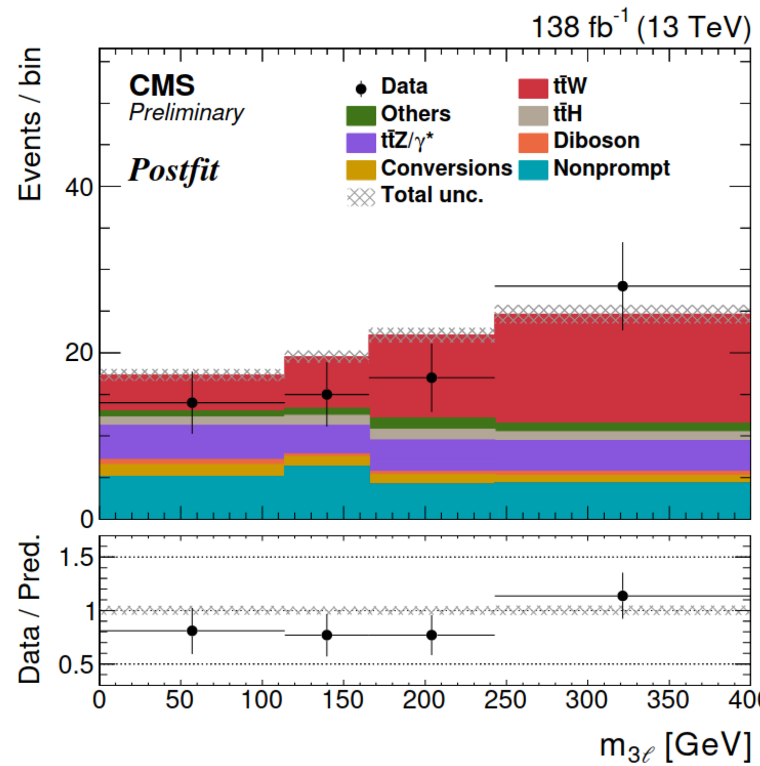
- Precise measurement of the $t\bar{t}W$ process: understanding W association production in detail
- Test the newest NLO predictions



same-sign dilepton category



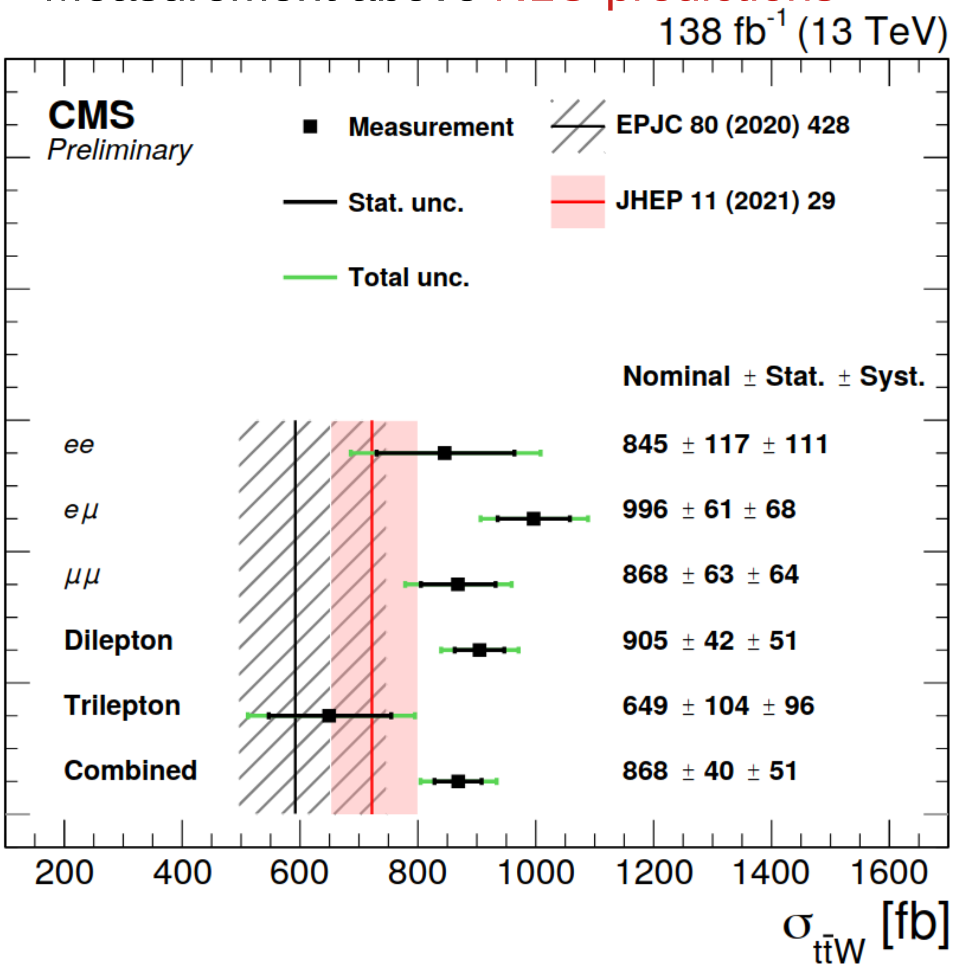
trilepton category



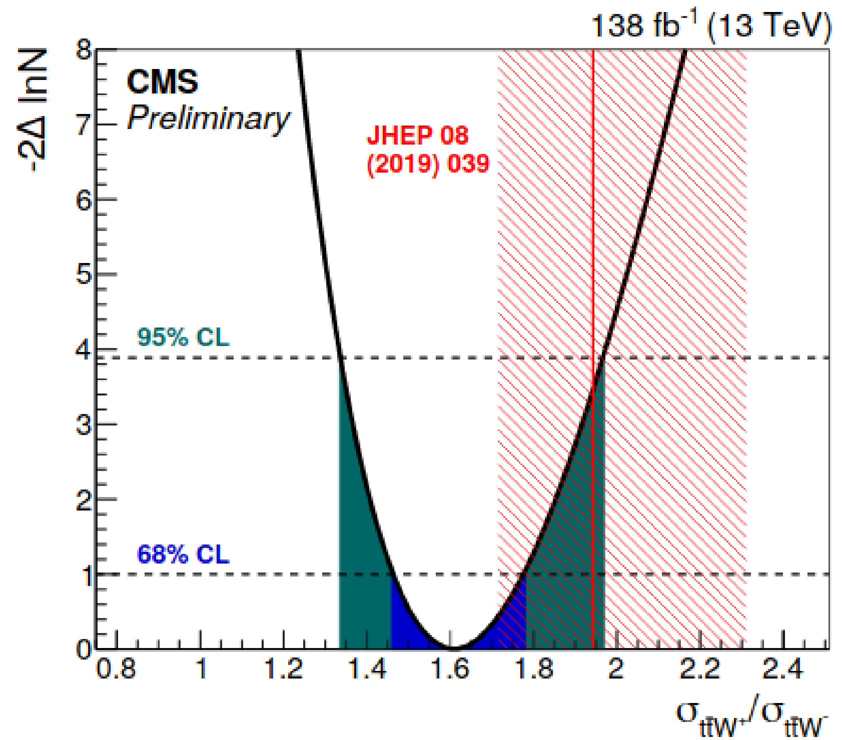
$t\bar{t}W$ cross section and $t\bar{t}W^+/t\bar{t}W^-$

CMS-PAS-TOP-21-011

- 50% improvement on the uncertainty w.r.t. the previous CMS (2016) result
  - ➔ Improved lepton uncertainties, control of background events
- Measurement above NLO predictions



- First steps towards a precise measurement of the W^+/W^- asymmetry in $t\bar{t}W$ production
- The results are compatible within 2 sigma with predictions

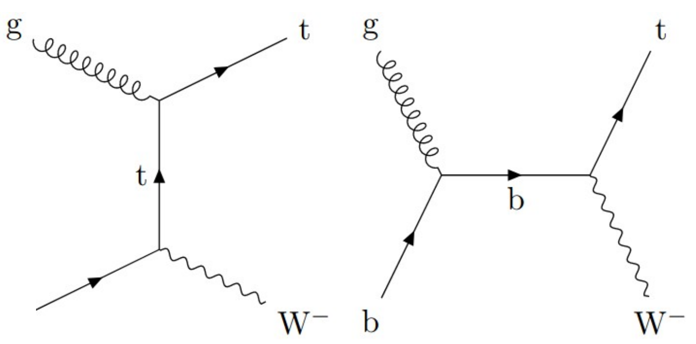


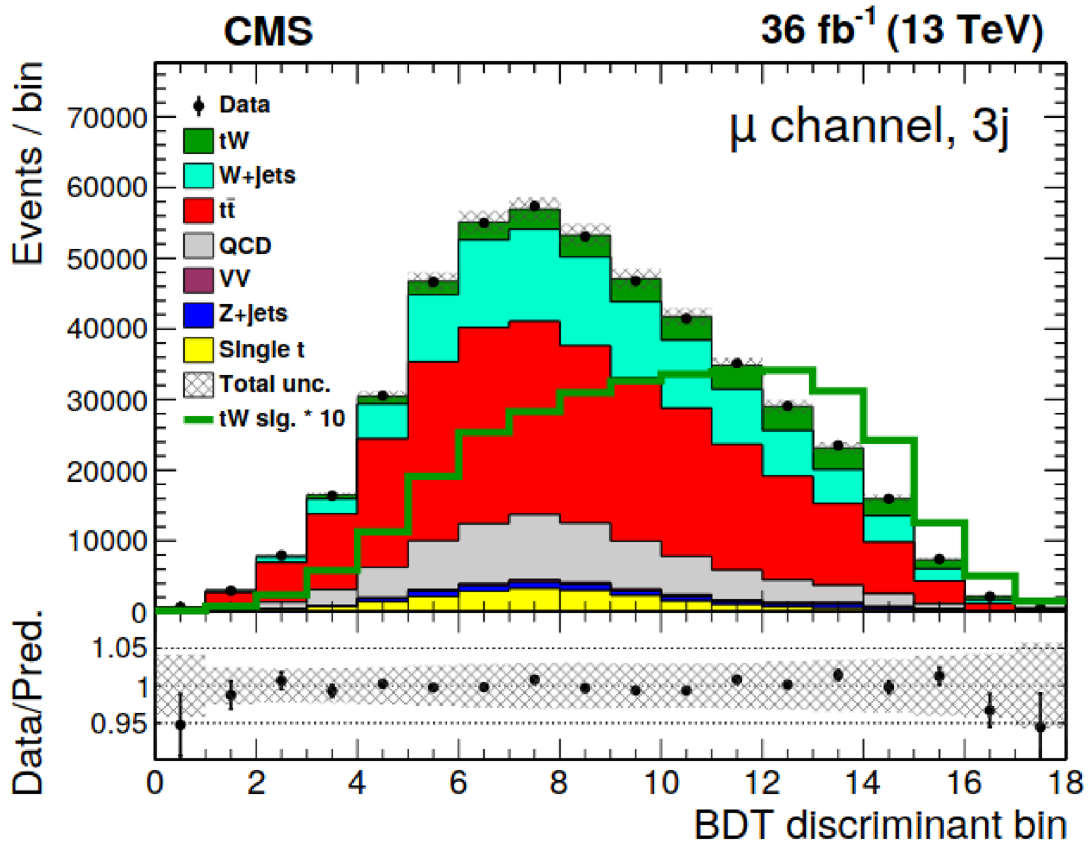
tW cross section in lepton+jets

JHEP 11 (2021) 111

t + W associated production

- Top quark + W: EWK sector of top quark production
- First observation of tW in l+jets channel





- BDT used to discriminate tW from $t\bar{t}$ background
- Result:

$\sigma_{t\bar{t}}$ = 89 ± 4 (stat) ± 12 (syst) pb

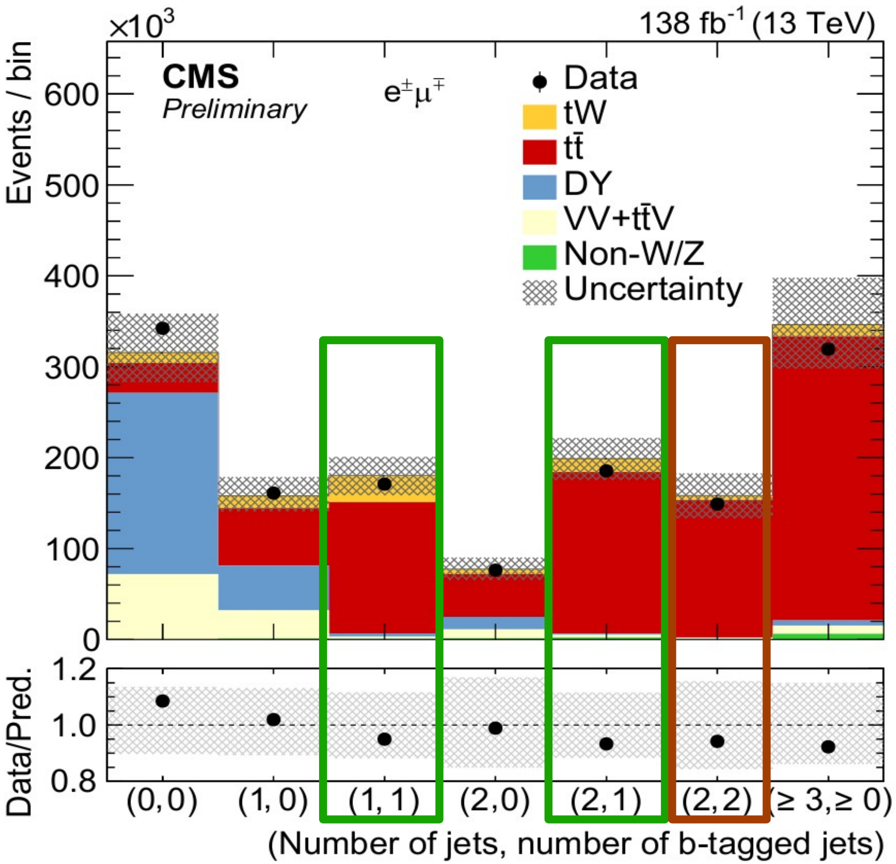
σ_{aNNLO} = 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb

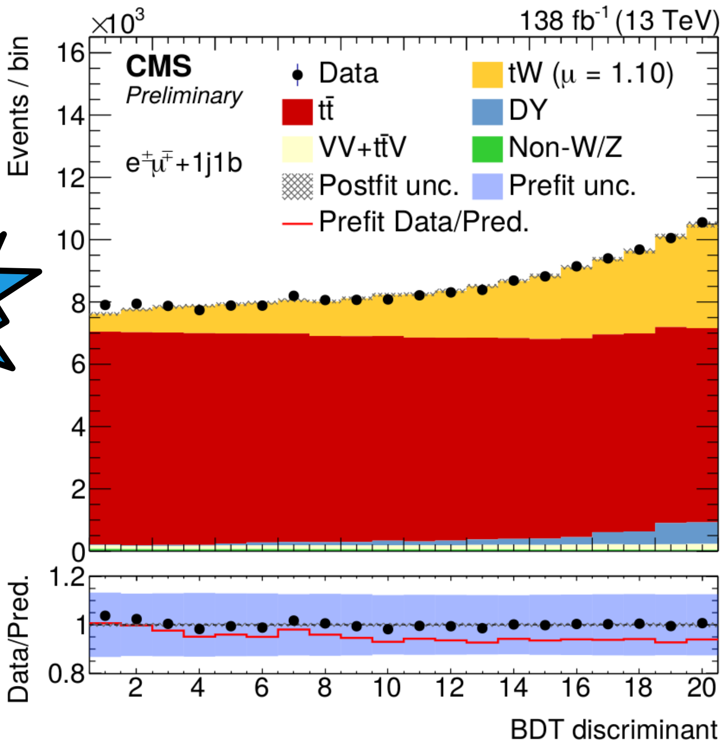
- Measured cross section in agreement with predictions, with a total uncertainty of 15%

tW cross section in the dilepton final state

CMS-PAS-TOP-21-010

- Most precise measurement of the tW inclusive cross section
- About 10% improvement w.r.t. the previous result
- Getting close to theory uncertainty





σ_{tW} = 79.2 ± 0.8 (stat) ± 7.1 (syst) ± 1.1 (lumi) pb

σ_{aNNLO} = 71.7 ± 1.8 (scale) ± 3.4 (PDF) pb

Main sources of uncertainties:

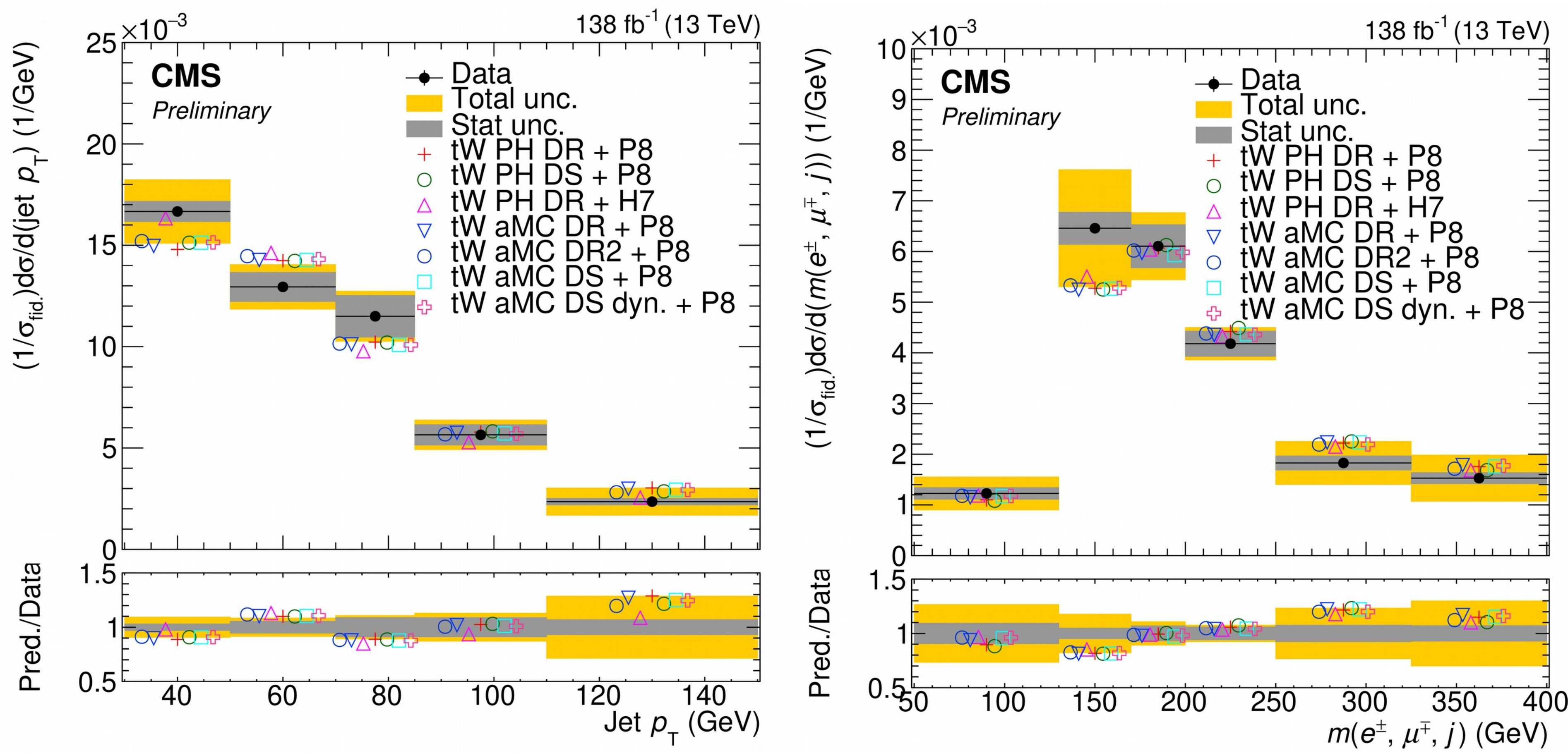
JES, FSR, ME scales.

tW cross section in the dilepton final state

CMS-PAS-TOP-21-010

Normalized differential cross sections are also measured.

- Comparison to predictions with multiple generators
- Overall agreement within the uncertainties (10-50%)



Summary

- Run 2 has provided a huge amount of data to explore top quark production in phase space corners and inclusively with unprecedented precision:
  - Boosted and resolved topologies
  - Multidifferential cross sections
  - Comparison to beyond NLO predictions

- Associated production cross section measurements with improved uncertainties

- New precision measurement at a center-of-mass energy of 5.02 TeV

- In general, agreement with the SM, favoring higher-order predictions

  Experimental precision beyond theory in inclusive cross sections!

- Wide top physics program by ATLAS and CMS – stay tuned!

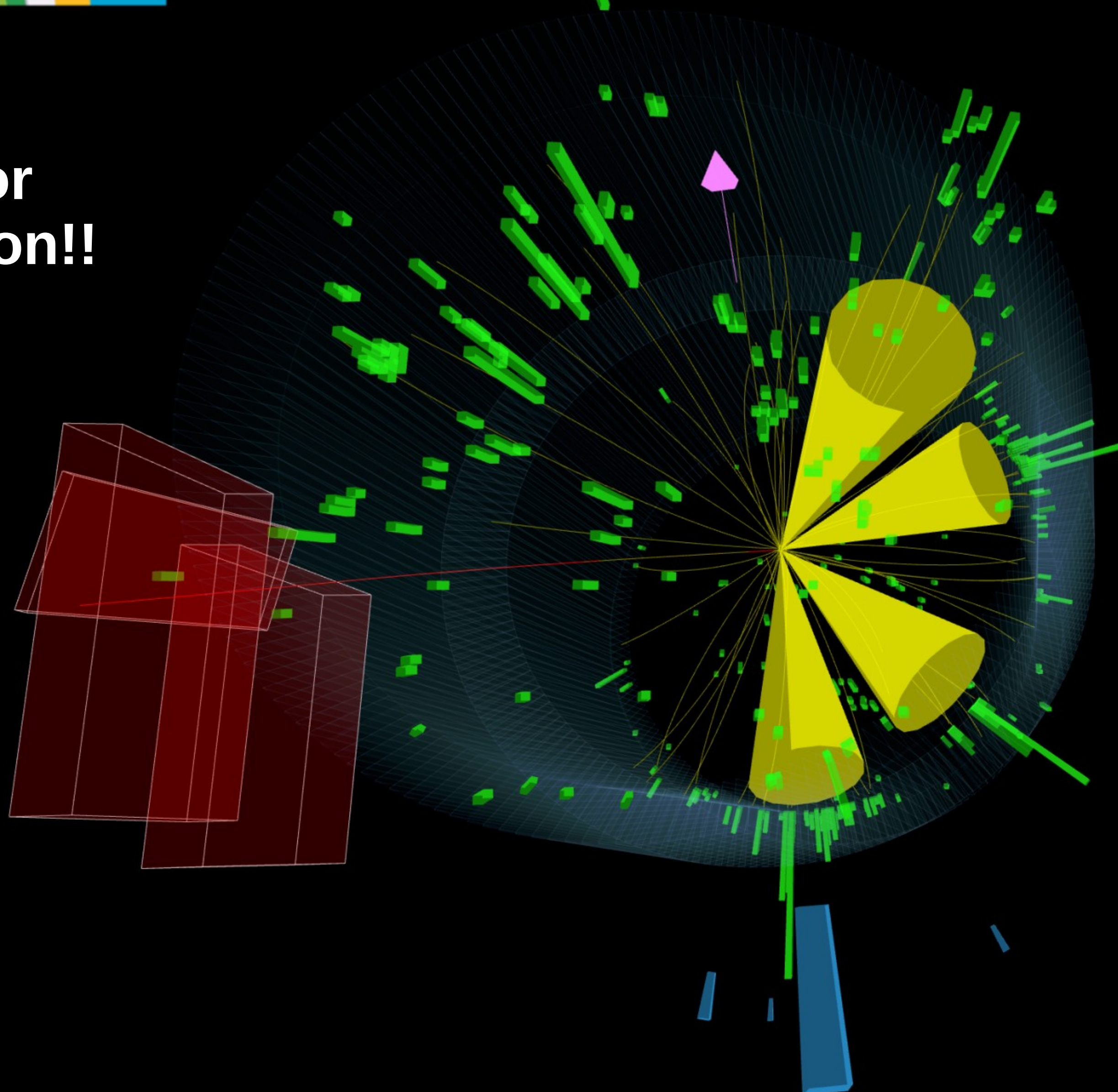
More top quark physics results:

http://cms-results.web.cern.ch/cms-results/

http://atlasresults.web.cern.ch/atlasresults/

CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-17 08:01:23.065024 GMT
Run / Event / LS: 278969 / 229126383 / 184

Thanks for your attention!!

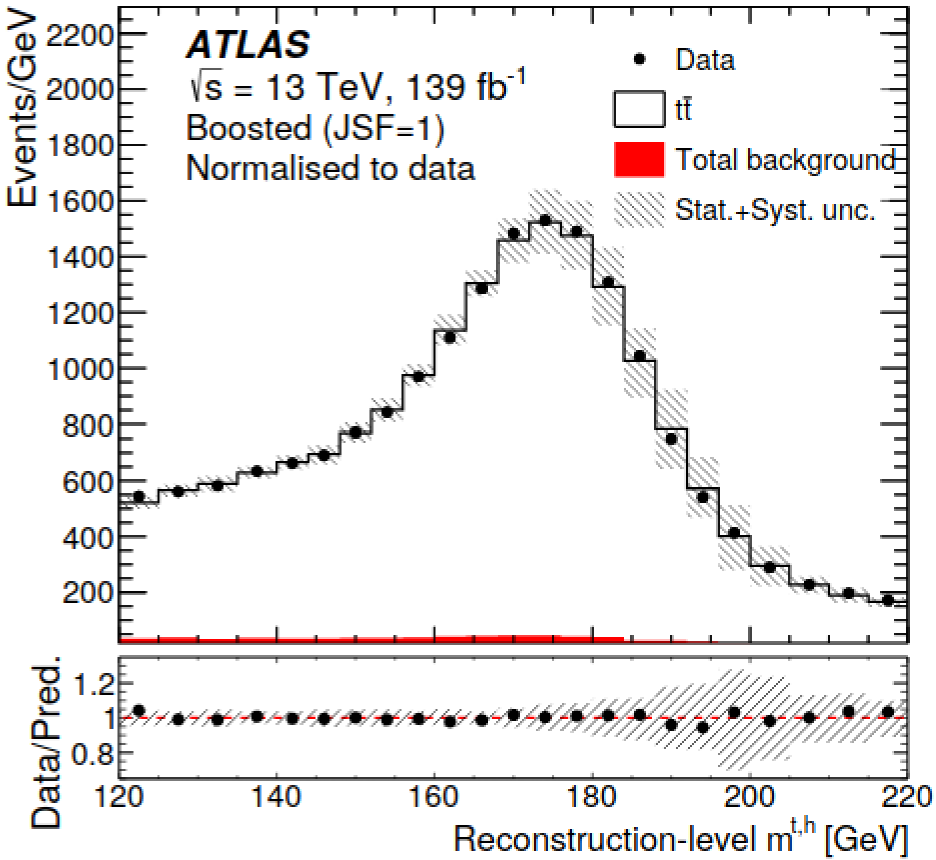


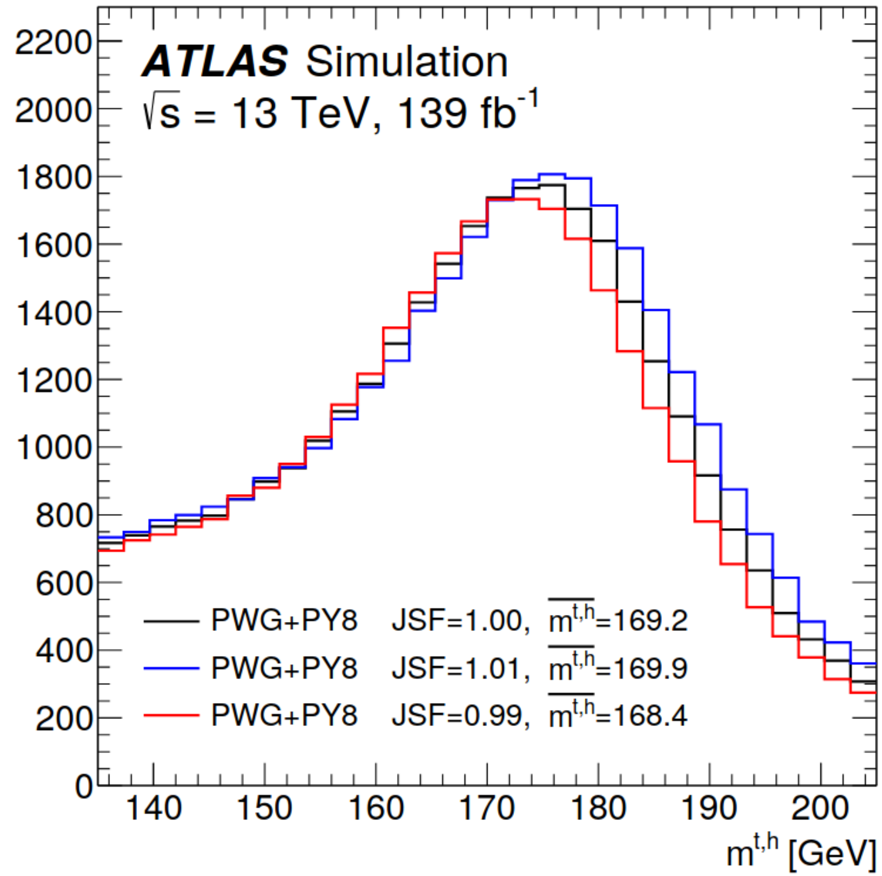
Back up

Boosted cross section in l+jets

Submitted to JHEP
arXiv:2202.12134

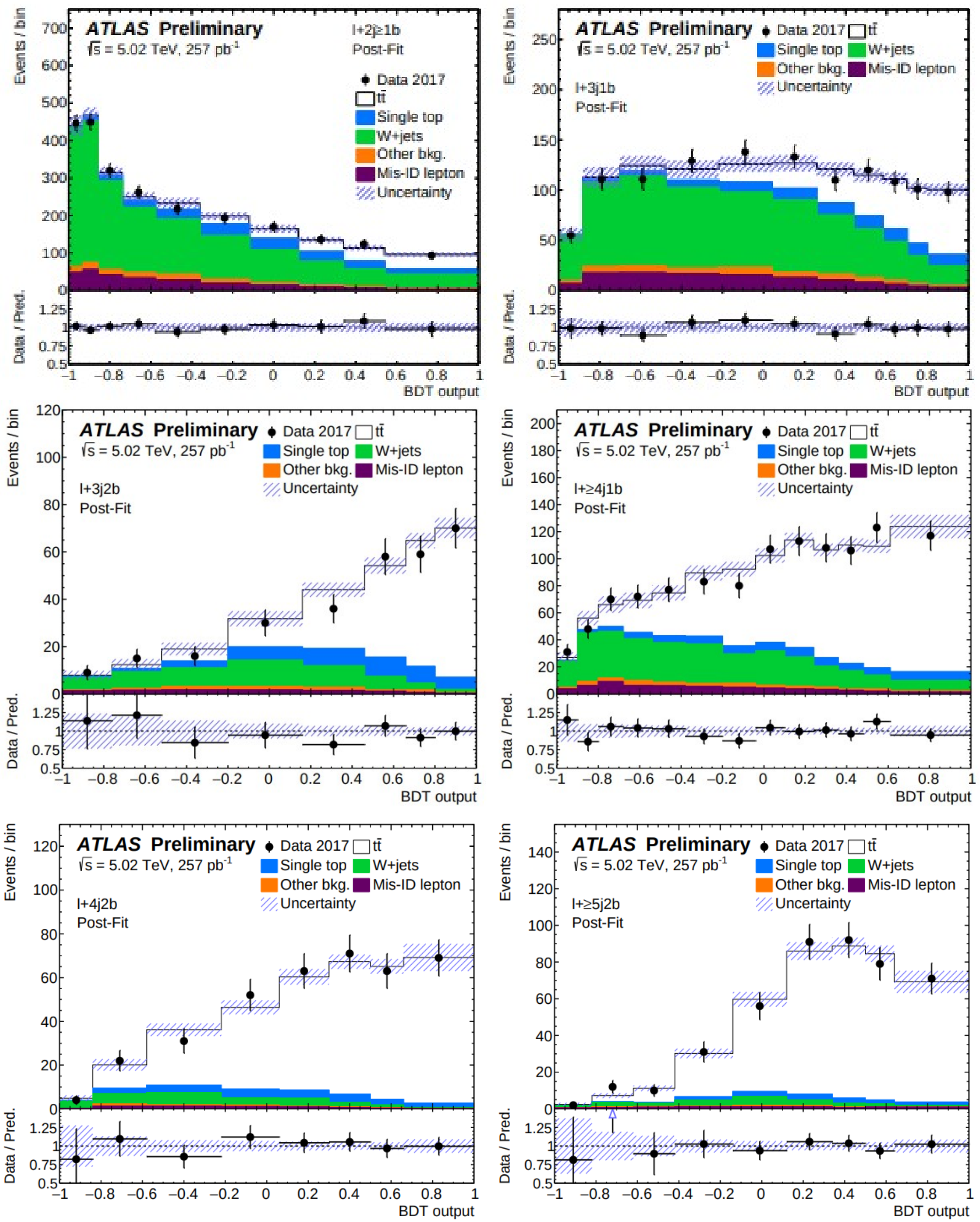
- Invariant mass of the top-tagged hadronic jet.



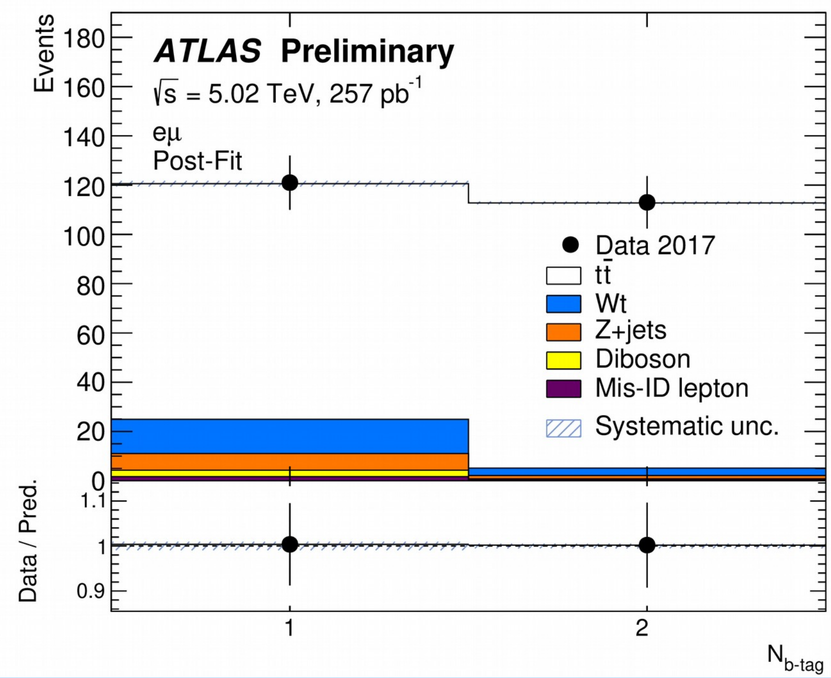


$t\bar{t}$ cross section at 5 TeV in l+jets + dileptons

ATLAS-CONF-2022-031



- Postfit plots.
- The invariant mass in ee/μμ final states are also used in the cross section extraction.



$t\bar{t}$ cross section at 5 TeV in l+jets + dileptons

ATLAS-CONF-2022-031

ATLAS EXPERIMENT

Category	$\delta\sigma_{t\bar{t}}$ [%]		
	Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ parton-shower/hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s} = 5.02$ TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

Uncertainties

$t\bar{t}W$ cross section measurement

CMS-PAS-TOP-21-011

Uncertainties

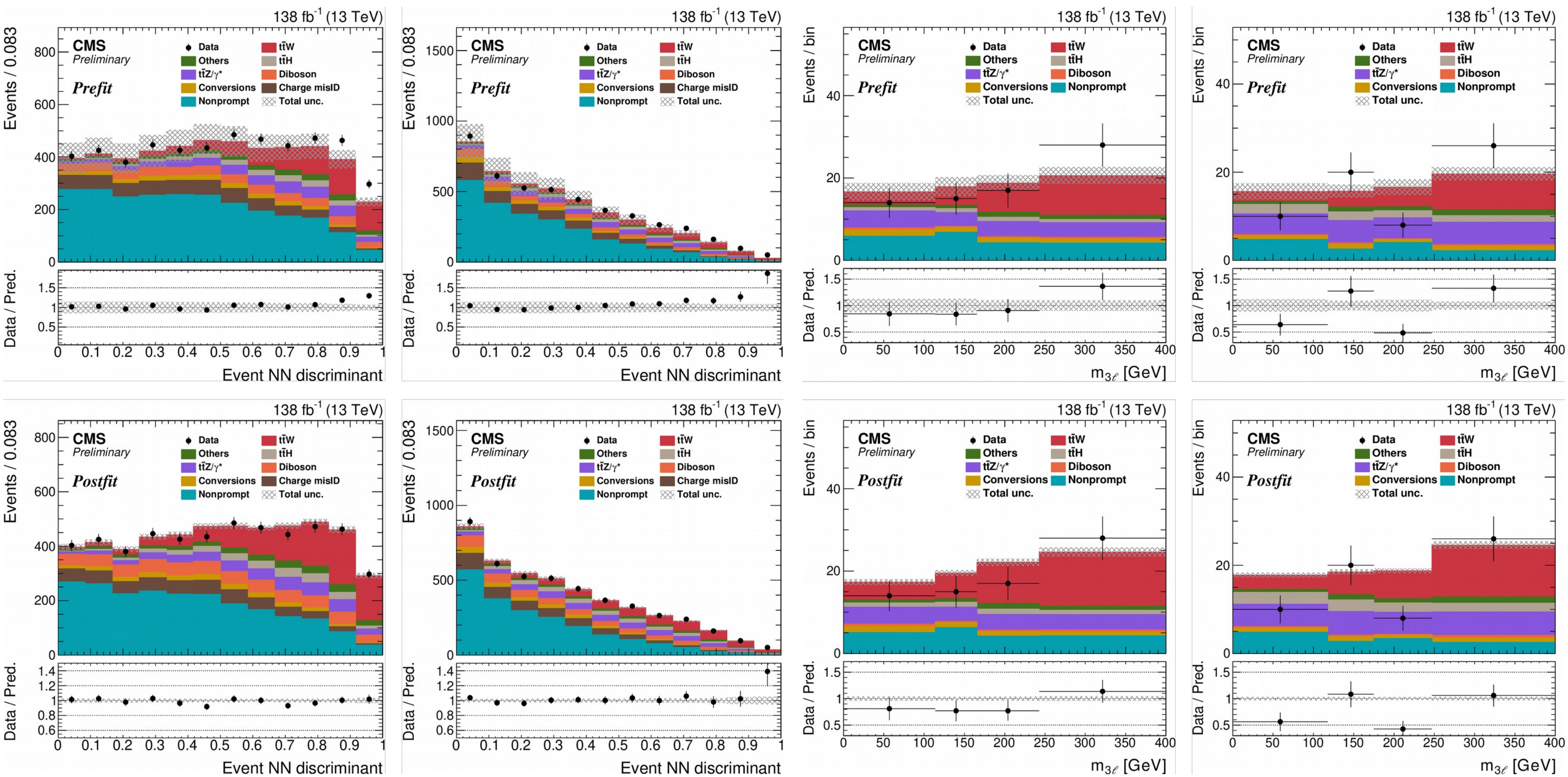
Uncertainty type	Relative value (%)
Experimental	
Integrated luminosity	1.9
Charge misidentification	1.6
bjet identification	1.6
Nonprompt lepton background	1.3
Trigger efficiencies	1.2
Pileup	1.0
Trigger prefiring	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton efficiencies	0.4
Normalizations	
$t\bar{t}H$	2.6
VVV	1.2
$t\bar{t}VV$	1.2
Conversions	0.7
$t\bar{t}\gamma$	0.6
ZZ	0.6
Others	0.5
$t\bar{t}Z$	0.3
WZ	0.2
tZq	0.2
tHq	0.2
Modelling	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ colour reconnection	1.0
ISR/FSR for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Statistical uncertainty	1.8

Yields

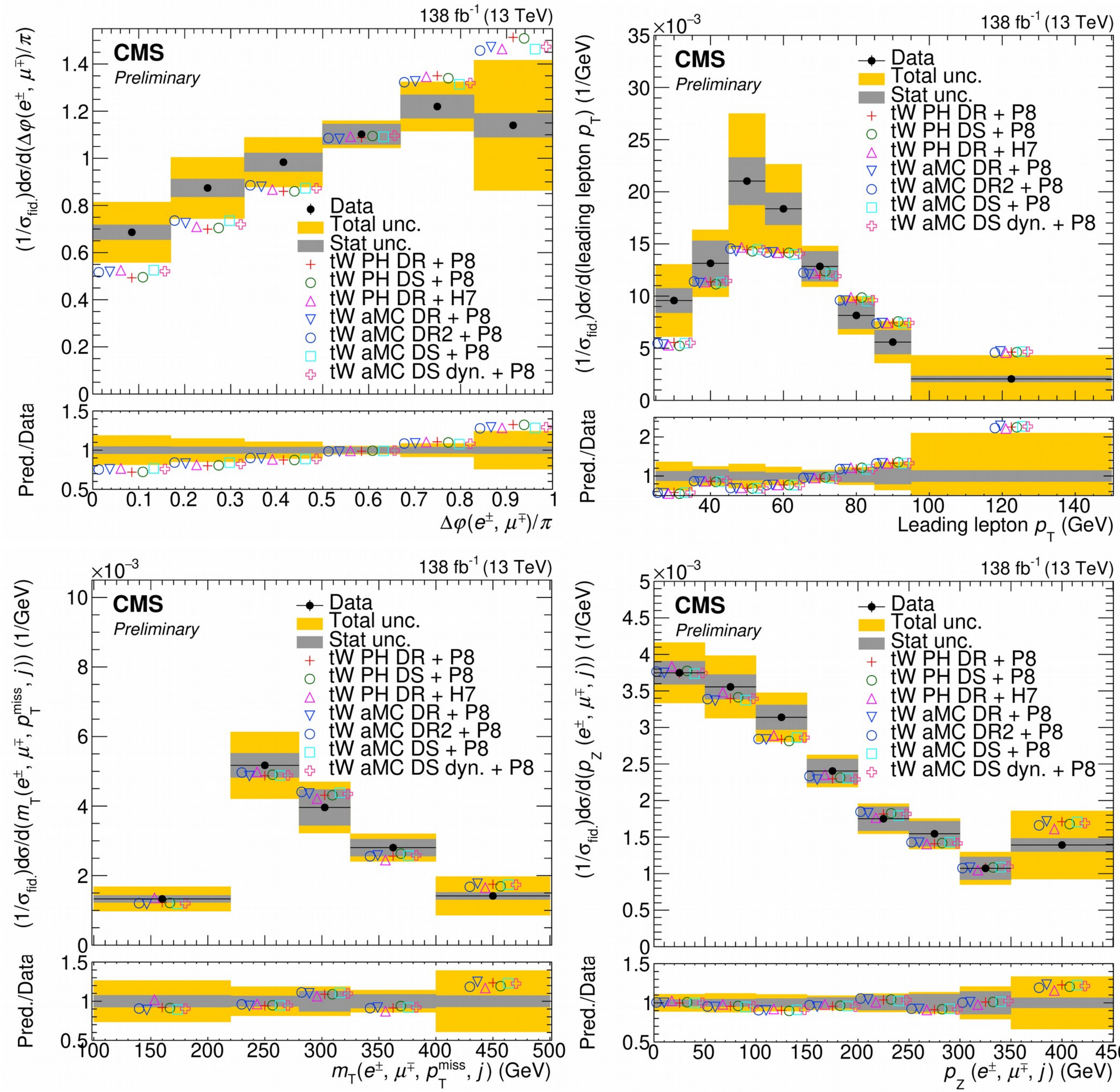
Process	$\ell^+\ell^+$	$\ell^-\ell^-$	$\ell^\pm\ell^\mp\ell^+$	$\ell^\pm\ell^\mp\ell^-$	Postfit/Prefit
$t\bar{t}W$	677 ± 21	355 ± 12	119 ± 9	65 ± 5	1.49
Nonprompt	2486 ± 598	2364 ± 570	325 ± 75	298 ± 71	0.91
Charge misID	521 ± 110	523 ± 111	—	—	0.91
$t\bar{t}H$	167 ± 34	169 ± 34	56 ± 12	57 ± 12	1.35
$t\bar{t}Z/\gamma^*$	335 ± 26	333 ± 26	145 ± 13	147 ± 13	1.10
Diboson	382 ± 88	285 ± 65	47 ± 9	38 ± 8	1.07
Others	178 ± 34	126 ± 27	43 ± 8	34 ± 7	1.20
Conversions	177 ± 54	192 ± 59	23 ± 7	24 ± 7	1.01
Total backgrounds	4246 ± 621	3993 ± 591	639 ± 80	597 ± 76	1.03
Total prediction	4922 ± 623	4348 ± 591	758 ± 81	663 ± 76	1.05
Data	5143	4486	834	744	

$t\bar{t}W$ cross section measurement

CMS-PAS-TOP-21-011



tW differential cross section



CMS-PAS-TOP-21-010