ATLAS highlight 2: $t\bar{t}$(+jets) in ATLAS and a comparison with the CMS triple differential cross-section measurement, and $t\bar{t}$ in pPb collisions

Miguel Príncipe[1] and Henriette Aarup Petersen[2]
on behalf of ATLAS and CMS Collaborations
[1]Universidad Autónoma de Madrid
[2]DESY

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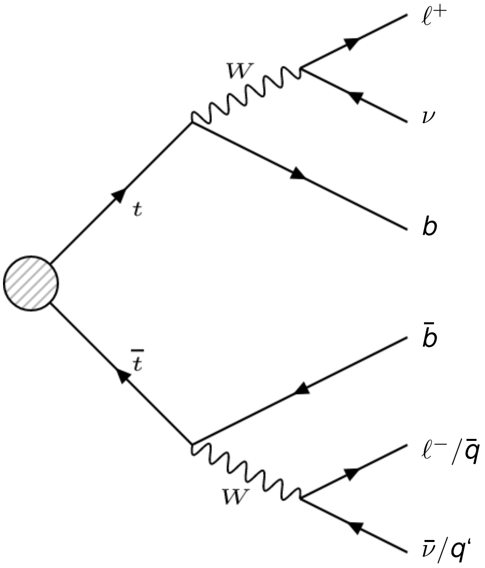
LHC TOP WG meeting

Overview



Analyses presented:

- ATLAS:
  - dilepton and ℓ+jets (pPb)
    ATLAS-CONF-2023-063
  - ℓ+jets (pp)
    ATLAS-CONF-2023-068
- CMS (only pp):
  - dilepton channel
    CMS-PAS-TOP-20-006
  - ℓ+jets channel
    Phys. Rev. D 104 (2021) 092013

Background in $t\bar{t}$ production (dilepton and ℓ+jets channels): single-top, fake leptons, Z+jets, diboson, W+jets (only in ℓ+jets), $t\bar{t}$+bosons

Introduction: ATLAS observation of $t\bar{t}$ in pPb collisions

Observation of $t\bar{t}$ production in ℓ+jets and dilepton channels: ATLAS-CONF-2023-063

- 165 nb^{-1} of pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV recorded by ATLAS
- dilepton and ℓ+jets decay modes
- Measurement of total cross-section
- Comparison with NLO and NNLO QCD predictions

Motivation

- Probes of nuclear-PDFs
- Information on the properties of the quark-gluon plasma
- Observation of the $t\bar{t}$ dileptonic channel in pPb collisions
  Previous analyses:
  - ℓ+jets by CMS with pPb collision at $\sqrt{s_{NN}} = 8.16$ TeV: 5σ Phys. Rev. Lett. 119 (2017) 242001
  - dilepton by CMS with PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV: 4σ Phys. Rev. Lett. 125 (2020) 222001

Selection and fit [ATLAS-CONF-2023-063]

Selection applied in six SR:

- $1e$ $1b$-jet
- 1μ $1b$-jet
- 2ℓ $1b$-jet
- $1e \geq 2b$-jet
- $1\mu \geq 2b$-jet
- $2\ell \geq 2b$-jet

ℓ+jets selection:

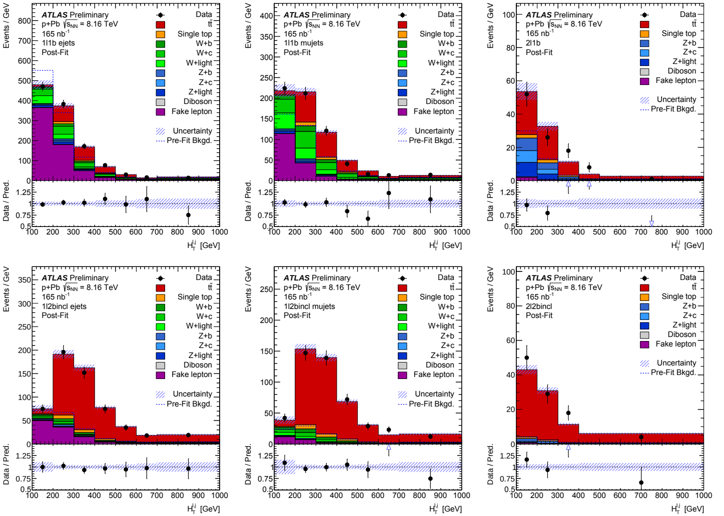
$p_{\mathrm{T}}^{\ell} > 18$ GeV; 4 jets ($p_{\mathrm{T}} > 20$ GeV)

dilepton selection:

OS $p_{\mathrm{T}}^{\ell} > 18$ GeV;
2 jets ($p_{\mathrm{T}} > 20$ GeV)

SF: $m_{\ell\ell} > 45$ GeV (veto $80 < m_{\ell\ell} < 100$ GeV)
OF: $m_{\ell\ell} > 15$ GeV

Fit performed using H_{T} distributions.



Uncertainties [ATLAS-CONF-2023-063]

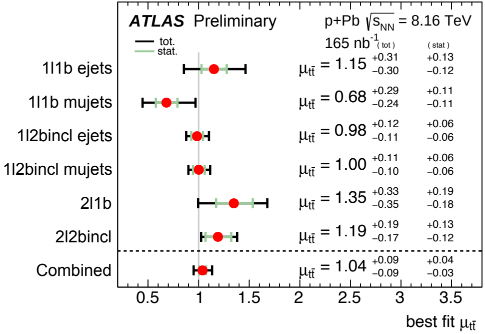
A total systematic uncertainty of 8% is achieved.

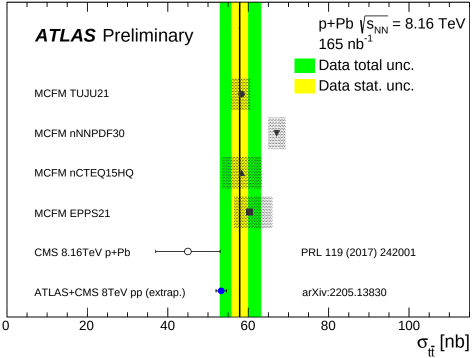
Statistical uncertainty is 3%.

JES and the modelling of the signal and backgrounds are the dominant sources of uncertainty.

Source	unc. up	unc. down
Jet energy scale	+0.048	-0.044
$t\bar{t}$ generator	+0.048	-0.043
Fake-lepton background	+0.030	-0.027
Background	+0.030	-0.025
Luminosity	+0.029	-0.025
Muon systs.	+0.024	-0.021
W+jets	+0.023	-0.020
b-tagging	+0.022	-0.021
Electron systs.	+0.018	-0.017
MC statistical uncertainties	+0.011	-0.010
Jet energy resolution	+0.005	-0.004
$t\bar{t}$ PDF	+0.001	-0.001
Total syst.	+0.088	-0.081

Results [ATLAS-CONF-2023-063]





Measurement: $\sigma_{t\bar{t}} = 57.9 \pm 2.0\ \text{(stat.)}^{+4.9}_{-4.5}\ \text{(syst.) nb}$

Signal strength is measured for 6 regions with a significance over 5σ in ℓ+jets and dilepton channels separately.

Measured cross-section agrees with calculations based on several nPDF sets.

Introduction: ATLAS $t\bar{t}$ and $t\bar{t}$+jets differential cross-sections

Measurements of $t\bar{t}$ and $t\bar{t}$+jets differential cross sections: ATLAS-CONF-2023-068

- 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by ATLAS
- ℓ+jets decay mode in resolved topology
- Focusing on jet observables
- Three channels: $t\bar{t}$ inclusive, $t\bar{t}$+1jet and $t\bar{t}$+2jets
- Absolute and normalised cross-sections at particle level
- Comparison with NLO and NNLO QCD predictions

Motivation

- Characterization of the kinematics and topology of the $t\bar{t}$ system
- Characterization of the kinematics, dynamics and topology of the two hardest QCD emissions
- Test of pQCD theory

Observables and predictions [ATLAS-CONF-2023-068]

Observables: Selected based on the sensitivity to the different predictions.

- $t\bar{t}$ inclusive: $p_{\mathrm{T}}^{\text{jet-W1}}$, $\left|y^{\text{jet-W1}}\right|$, $p_{\mathrm{T}}^{\text{jet-W2}}$, $\left|y^{\text{jet-W2}}\right|$, $\left|\Delta y^{\text{jet-W1—jet-W2}}\right|$ and $\left|\Delta\phi^{\text{jet-W1—jet-W2}}\right|$
- $t\bar{t}$+1jet: $p_{\mathrm{T}}^{\text{jet-rad1}}$, $\left|y^{\text{jet-rad1}}\right|$, $\left|\Delta\phi^{\text{jet-W1—jet-rad1}}\right|$, $\left|\Delta\phi^{\text{toplep—jet-rad1}}\right|$, $\left|\Delta\phi^{\text{tophad—jet-rad1}}\right|$ and $m^{t\bar{t}\text{—jet-rad1}}$
- $t\bar{t}$+2jet: $p_{\mathrm{T}}^{\text{jet-rad2}}$, $\left|y^{\text{jet-rad2}}\right|$, $\left|\Delta y^{\text{jet-rad1—jet-rad2}}\right|$, $\left|\Delta\phi^{\text{jet-rad1—jet-rad2}}\right|$, $\left|\Delta\phi^{\text{toplep—jet-rad2}}\right|$, $\left|\Delta\phi^{\text{tophad—jet-rad2}}\right|$ and $m^{\text{jet-rad1—jet-rad2}}$

Predictions:

- QCD NLO: POWHEG+PYTHIA8, POWHEG+HERWIG7, aMC@NLO+HERWIG7 and SHERPA 2.2.12
- QCD NNLO ($t\bar{t}$ system): POWHEG+PYTHIA8 using MINNLO$_{PS}$ scheme
- Normalisation from Top++2.0 at NNLO+NNLL ($m_t = 172.5$ GeV):

$$\sigma_{t\bar{t}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF}, \alpha_{\mathrm{S}}) \pm 23\,(m_t)\ \text{pb}$$

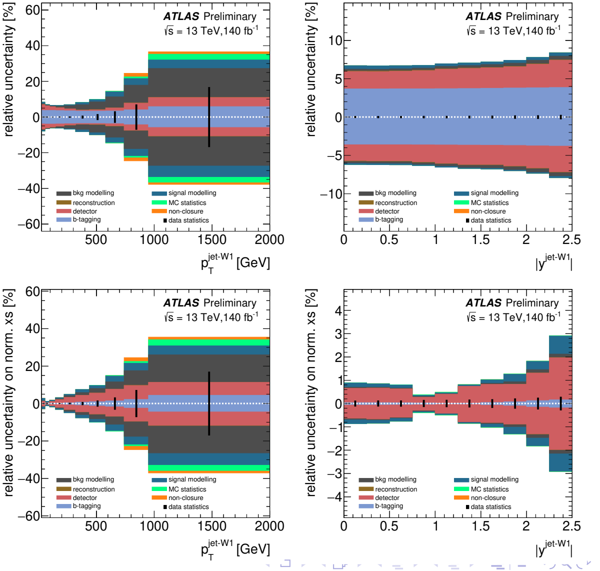
Systematic uncertainties [ATLAS-CONF-2023-068]

Dominant sources of systematic uncertainties:

- At low p_T, the b-tagging efficiency is the dominant source of uncertainty.
- In the high p_T region, background modelling becomes the dominant systematic.
- For normalised cross-sections, the b-tagging uncertainty decreases significantly and the detector energy scale and resolution becomes the main source of uncertainty at low p_T.

Total relative uncertainty: (normalised)

- $t\bar{t}$ inclusive: $\approx$ **7%** ($\approx$ 1%) at low-p_T
- $t\bar{t}$+1jet: $\approx$ **10%** ($\approx$ 1.5%) at low-p_T
- $t\bar{t}$+2jet: $\approx$ **13%** ($\approx$ 2%) at low-p_T



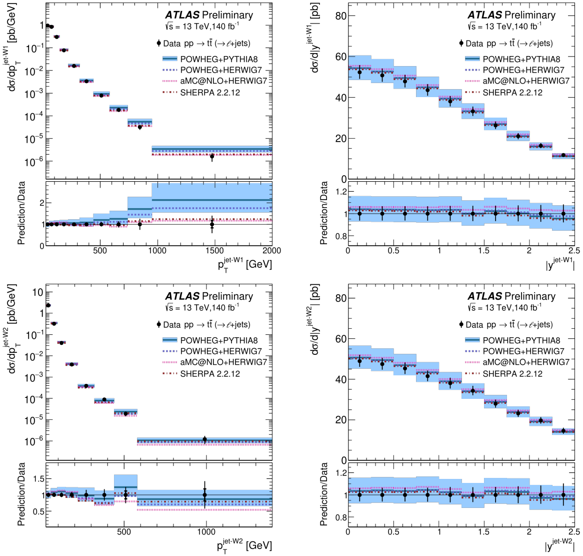
Results: $t\bar{t}$ inclusive [ATLAS-CONF-2023-068]

Measured cross section as a function of $p_T^{\text{jet-W1}}$ **has harder spectrum** than that of $p_T^{\text{jet-W2}}$.

Measured cross section as a function of $|y^{\text{jet-W1}}|$ and $|y^{\text{jet-W2}}|$ **have very similar shape and normalisation**.

Comparison with NLO QCD predictions:

- Good description of $p_T^{\text{jet-W1}}$ by SHERPA and aMC@NLO+HERWIG7.
- $p_T^{\text{jet-W2}}$ is well described by NLO predictions.
- Rapidity distributions are well described by all predictions.



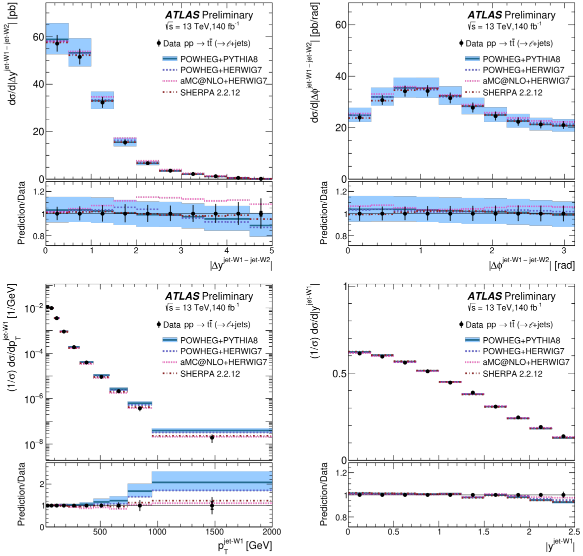
Measured cross sections as functions of **angular correlations exhibit peaks** around $\left|\Delta y^{\text{jet-W1—jetW2}}\right| = 0$ and $\left|\Delta\phi^{\text{jet-W1—jetW2}}\right| = 1$.

Comparison with NLO QCD predictions:

- Angular correlation distributions are well described by the predictions.

Normalised cross-sections:

- Reduced uncertainties at low-p_{T}.
- Uncertainties considerably suppressed for angular distributions.

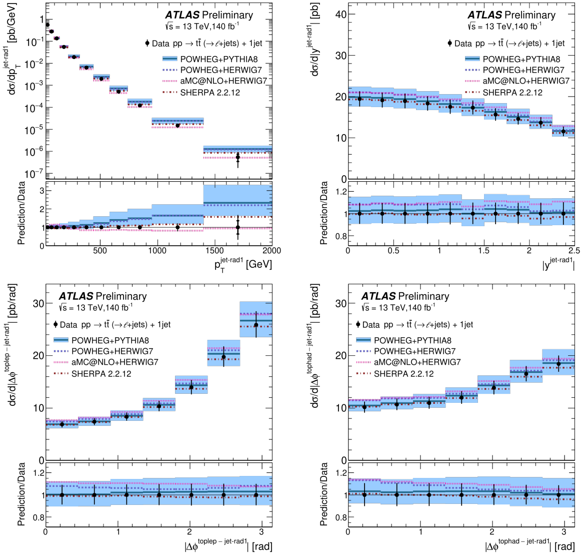


Measured cross section as a function of $|y^{\text{jet-rad1}}|$ **is more isotropic** than that of $|y^{\text{jet-W1}}|$.

Measured cross sections as functions of $|\Delta\phi^{\text{toplep—jet-rad1}}|$ and $|\Delta\phi^{\text{tophad—jet-rad1}}|$ have different shapes. **jet-rad1 tends to be farther in ϕ from toplep than from tophad**.

Comparison with NLO QCD predictions:

- Good description of $p_T^{\text{jet-rad1}}$ by SHERPA and aMC@NLO+HERWIG7.
- $|y^{\text{jet-rad1}}|$ and angular correlation distributions are well described by the predictions.



Results: $t\bar{t} + 1$jet [ATLAS-CONF-2023-068]

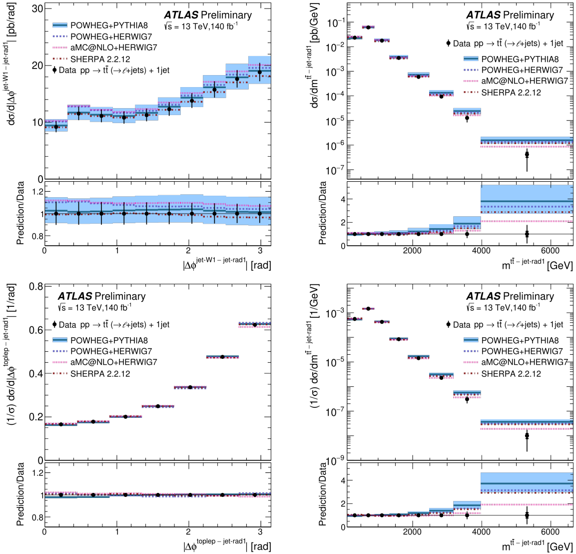
Measured cross section as a function of $\left|\Delta\phi^{\text{jet-W1—jet-rad1}}\right|$ **shows a peak at π and around 0.5**.

Comparison with NLO QCD predictions:

- $\left|\Delta\phi^{\text{jet-W1—jet-rad1}}\right|$ distribution is well described by the predictions.
- $m^{t\bar{t}\text{—jet-rad1}}$ cross-section is well described for $m^{t\bar{t}\text{—jet-rad1}} < 3$ TeV .

Normalised cross-sections:

- Similar conclusions than those for $t\bar{t}$ inclusive.



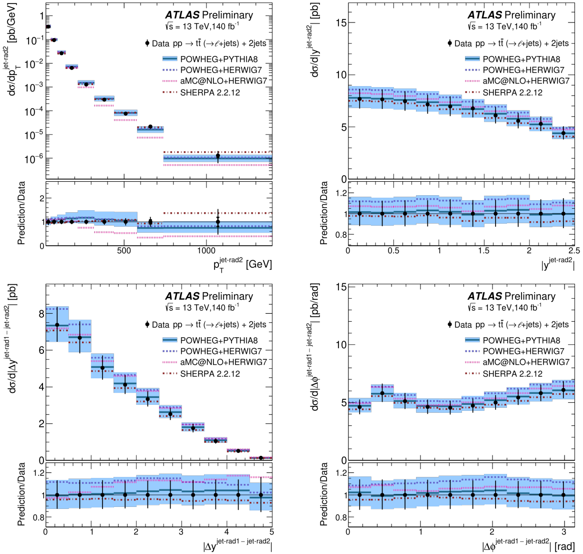
Results: $t\bar{t} + 2$jets [ATLAS-CONF-2023-068]

Measured cross section as a function of $|y^{\text{jet-rad2}}|$ **is similar** to that of jet-rad1.

Measured cross sections as functions of $|\Delta y^{\text{jet-rad1—jet-rad2}}|$ and $|\Delta \phi^{\text{jet-rad1—jet-rad2}}|$ **have different shapes** than those for jet-W1—jet-W2.

Comparison with NLO QCD predictions:

- Good description of $p_T^{\text{jet-rad2}}$ by SHERPA and POWHEG.
- $|y^{\text{jet-rad2}}|$ and angular correlation distributions are well described by the predictions.



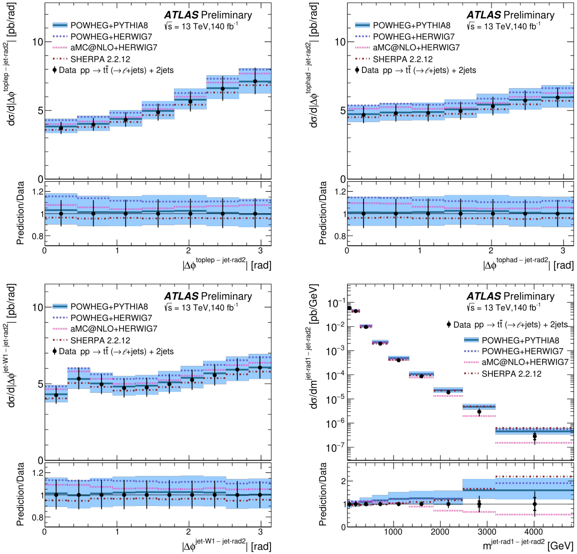
Results: $t\bar{t}$ + 2jets [ATLAS-CONF-2023-068]

Measured cross sections as functions of $|\Delta\phi^{\text{toplep—jet-rad2}}|$ and $|\Delta\phi^{\text{tophad—jet-rad2}}|$ **are more isotropic** than those for jet-rad1.

Measured cross section as a function of $|\Delta\phi^{\text{jet-W1—jet-rad2}}|$ **shows similar features** than that wrt jet-rad1.

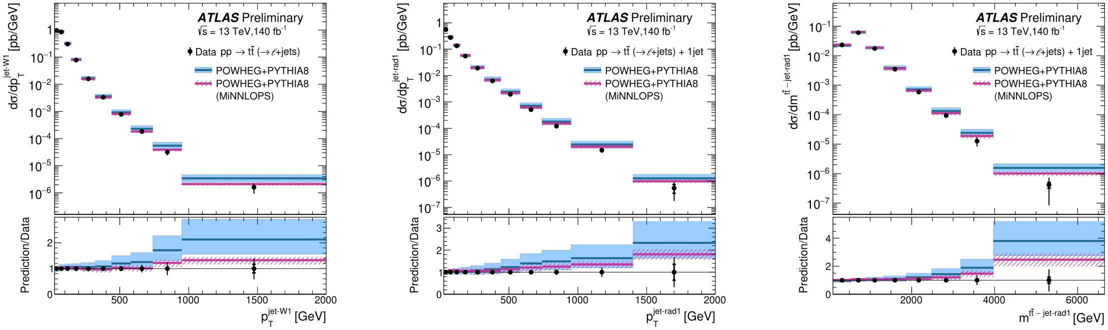
Comparison with NLO QCD predictions:

- Angular correlation distributions are well described by the predictions.
- Good description of $m^{\text{jet-rad1—jet-rad2}}$ by SHERPA and POWHEG.



Results: NNLO comparison [ATLAS-CONF-2023-068]

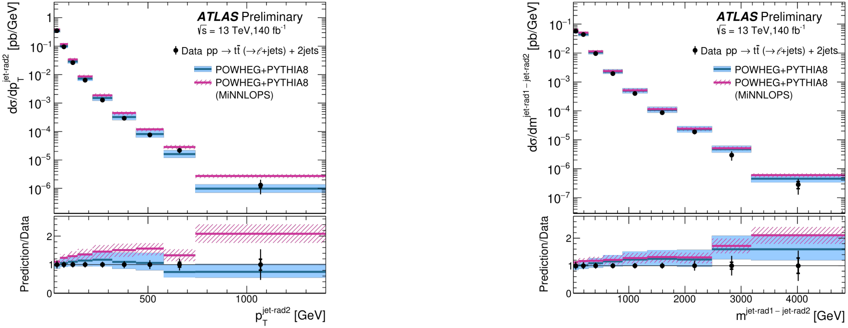
Absolute differential cross-sections in the $t\bar{t}$ inclusive and $t\bar{t}$+1jet channels



A **significant improvement in the description** of the $p_T^{\text{jet-W1}}$, $p_T^{\text{jet-rad1}}$ and $m^{t\bar{t}\text{—jet-rad1}}$ is achieved with NNLO QCD predictions.

Results: NNLO comparison [ATLAS-CONF-2023-068]

Absolute differential cross-sections in the $t\bar{t}$+2jet channel



NNLO predictions do not provide an improved description of $p_{\mathrm{T}}^{\text{jet-rad2}}$ and $m^{\text{jet-rad1—jet-rad2}}$ observables.

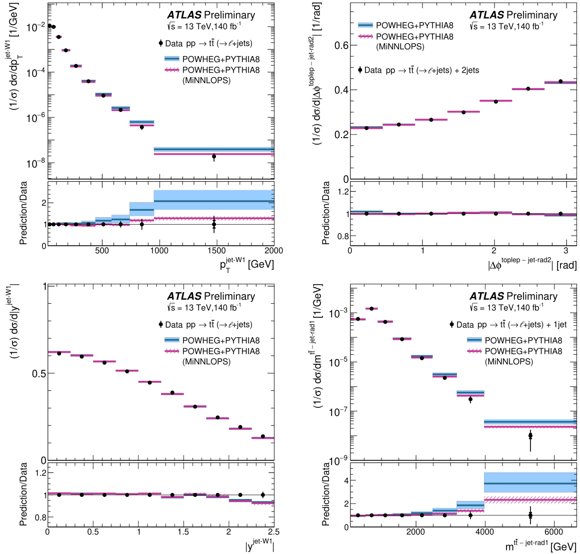
MiNNLO$_{PS}$ prediction is only lowest order for second emission.

Results: NNLO comparison [ATLAS-CONF-2023-068]

Normalised differential cross-sections

Good description by MiNNLO$_{PS}$ with reduced theoretical uncertainties is seen for some observables, e. g. $p_{\mathrm{T}}^{\mathrm{jet\text{-}W1}}$ and $\left|\Delta\phi^{\mathrm{toplep—jet\text{-}rad2}}\right|$.

With reduced uncertainties, differences between the measurement and the prediction are seen in some regions of the phase space of some observables, e. g. $\left|y^{\mathrm{jet\text{-}W1}}\right|$ and $m^{t\bar{t}—\mathrm{jet\text{-}rad1}}$.



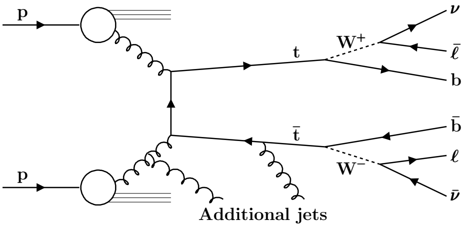
CMS dilepton differential cross-sections [CMS-PAS-TOP-20-006]

Measurement of differential cross sections for the production of top quark pairs and of additional jets: CMS-PAS-TOP-20-006

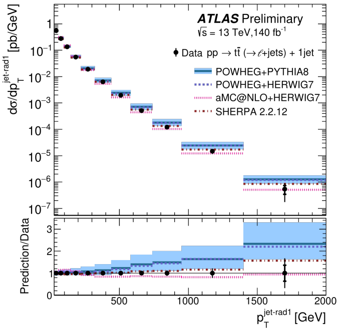
- 138 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by CMS
- dilepton decay mode: e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$
- absolute and normalised differential cross-sections (single, double and triple)
- cross-sections unfolded to particle and parton levels
- comparisons with NLO and NNLO predictions and different PDFs

Motivation: Comprehensive measurements of kinematic and topological properties of $t\bar{t}$ events:

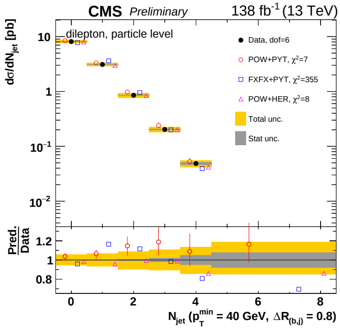
- t, $\bar{t}$ and $t\bar{t}$ observables.
- ℓ and b-jets observables.
- events with additional jets (correlation with t and $t\bar{t}$ kinematics).



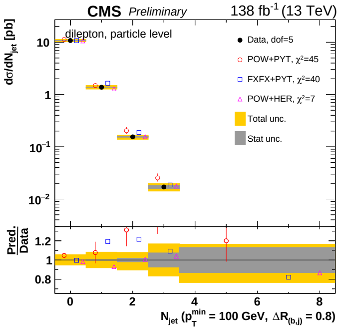
Comparison between ATLAS and CMS



ATLAS-CONF-2023-068



CMS-PAS-TOP-20-006



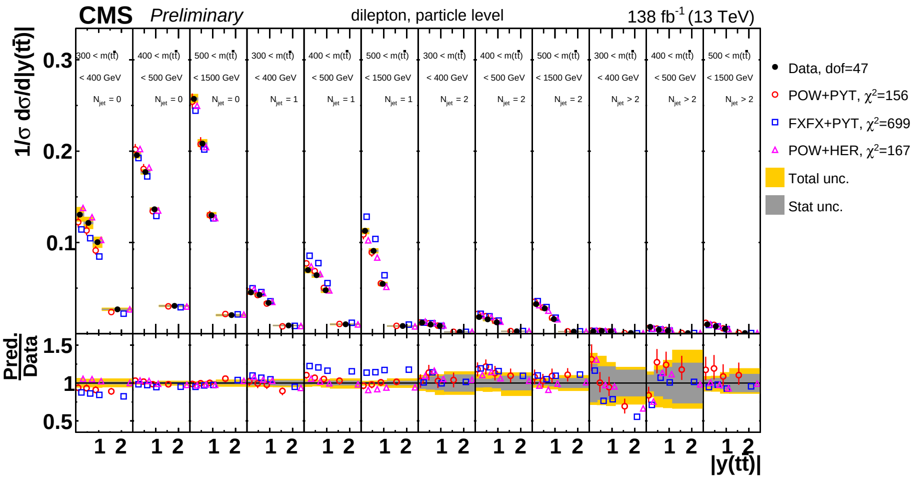
CMS-PAS-TOP-20-006

CMS has measured the additional jet multiplicity at different jet p_T thresholds.

POW+PYT and POW+HER describe the data within uncertainties at $p_T^{min} = 40$ GeV while POW+PYT exhibits a significantly worse description at $p_T^{min} = 100$ GeV.

ATLAS measurement of $p_T^{jet\text{-}rad1}$ shows a similar description of the data by POW+PYT and POW+HER up to 2 TeV.

CMS dilepton differential cross-sections [CMS-PAS-TOP-20-006]



FxFx+PYT has poor description for $N_{\text{jet}} = 1$ in all rapidity bins at $m_{t\bar{t}} > 500$ GeV.
POW+PYT and POW+HER has largest discrepancy w.r.t data for $N_{\text{jet}} > 2$ at $m_{t\bar{t}} < 500$ GeV

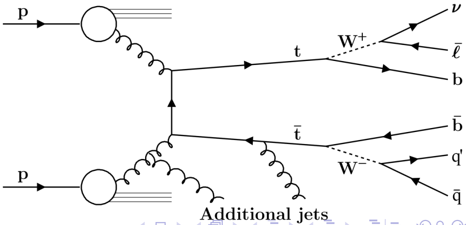
CMS ℓ+jets differential cross-sections [Phys. Rev. D 104 (2021) 092013]

Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using ℓ+jets events: Phys. Rev. D 104 (2021) 092013

- 137 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by CMS.
- absolute and normalised cross-sections
- cross-sections unfolded to particle and parton levels
- focus on observables describing top-quarks and $t\bar{t}$ system
- comparison only with NLO predictions

Motivation: CMS Run-2 paper on differential cross-sections of $t\bar{t}$ production at 13 TeV:

- study of full kinematic range in the ℓ+jets channel.
- combination of resolved and boosted topologies.



CMS ℓ+jets differential cross-sections [Phys. Rev. D 104 (2021) 092013]

Additional jet observables:

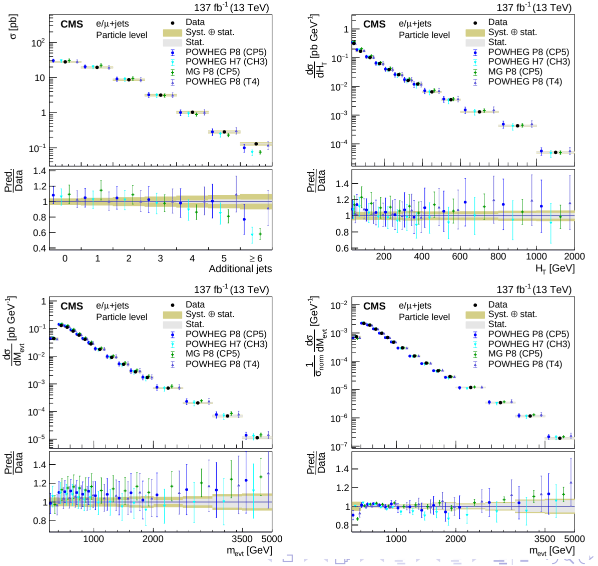
Three cross-sections measured as functions of jet observables.

For the additional jets distributions all predictions describe the measurement, but $N_{jet} \geq 6$ POW+PYT has the best description.

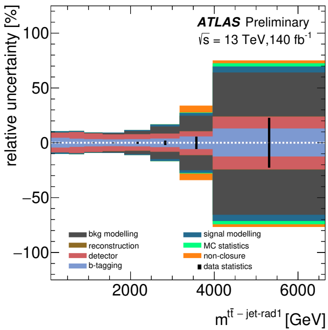
The cross-section as a function of H_T, the scalar p_T sum of the additional jets, is measured and well described by NLO predictions.

The cross-section as a function of m_{evt} (similar to $m^{t\bar{t}\text{—jet-rad1}}$ from ATLAS) is measured. It is defined as the invariant mas of the $t\bar{t}$ and all additional jets.

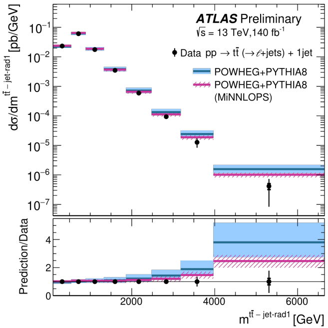
NLO predictions describe well the m_{evt} distribution except at low m_{evt} (normalised) where POW+PYT has the best description.



Comparison between ATLAS and CMS



ATLAS-CONF-2023-068



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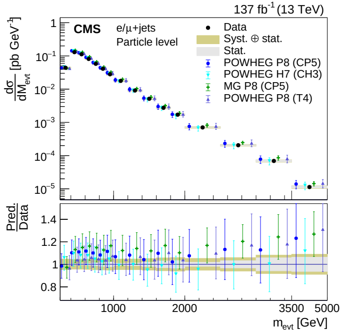

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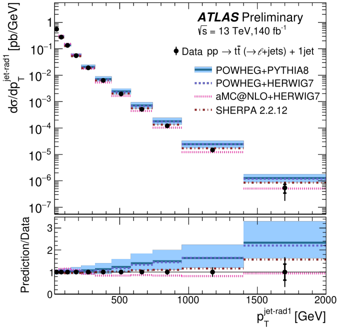
CMS measures up to 5 TeV, whereas ATLAS measures up to 6.5 TeV.
→ In the common region, NLO and NNLO predictions describe the data within uncertainties.

Differences between data and NLO prediction are observed for $m > 4$ TeV (ATLAS)
→ NNLO is closer to data in this region with smaller uncertainties than NLO.

Experimental uncertainties similar for both measurements in common region: $\sim 10 - 15\%$
→ for $m > 4$ TeV (ATLAS) statistical fluctuations becomes a relevant source of uncertainty.

Comparison between ATLAS and CMS



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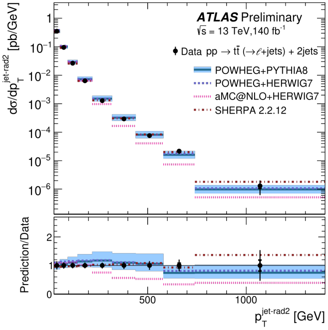

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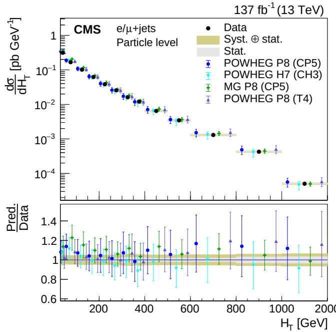

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QCD radiation kinematics is measured by $p_T^{\text{jet-rad1}}$ and $p_T^{\text{jet-rad2}}$ (ATLAS) and H_T (CMS) distributions.

POW+PYT and POW+HER exhibit a reasonable description of H_T up to 2 TeV within uncertainties. POW+PYT and POW+HER has a larger disagreement with data in the last bins of $p_T^{\text{jet-rad1}}$, while for $p_T^{\text{jet-rad2}}$ the description is good.

Summary and Conclusions

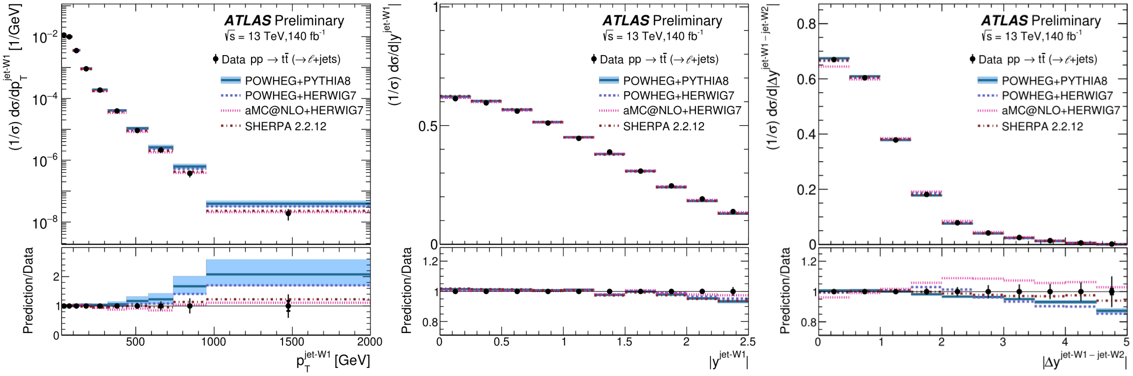
- $t\bar{t}$ cross-section has been measured in *p*Pb collisions with $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. Both dilepton and ℓ+jets channels have a significance over 5σ.

- Absolute and normalised differential cross sections at particle level measured for $t\bar{t}$(+jets) production in ℓ+jets decay mode using 140 fb^{-1} of ATLAS *pp* data at $\sqrt{s} = 13$ TeV.
  - Cross-sections are measured as functions of jet transverse momenta, jet angular correlations and invariant masses in the $t\bar{t}$ inclusive, $t\bar{t}$+1jet and $t\bar{t}$+2jets channels.
  - NLO QCD predictions describe well the shape of the angular observables, but the transverse momenta and invariant masses are described in general only by SHERPA.
  - NNLO QCD predictions give an improved description with reduced the theoretical uncertainties.
  - The normalised cross sections show there are regions of phase space where predictions fail to describe the data.

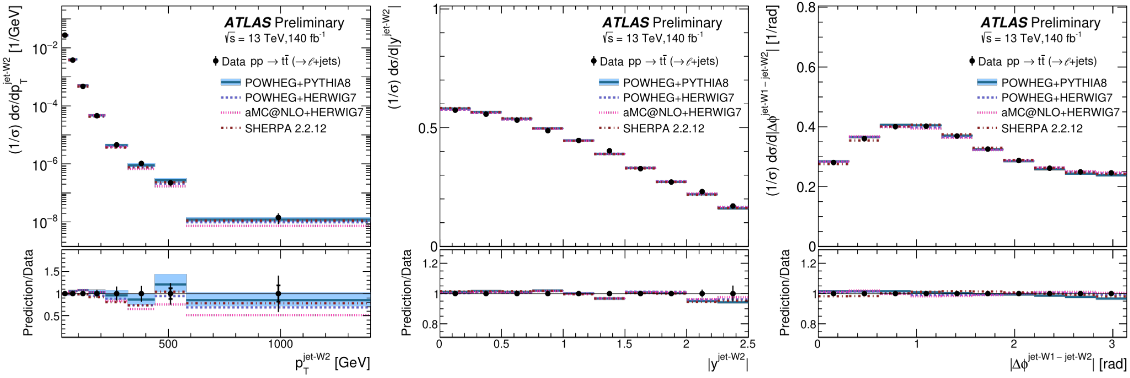
- The comparison between ATLAS and CMS measurements shows similar behaviour for the NLO predictions in the transverse momentum observables.

Back-up

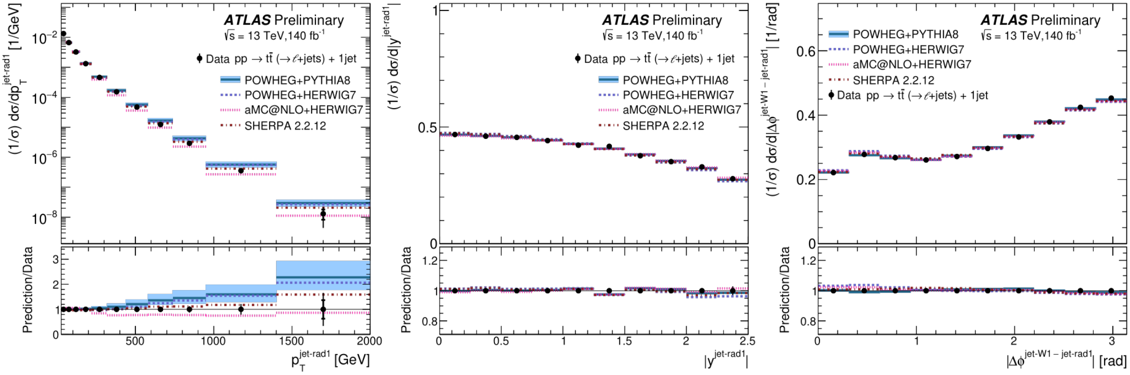
Normalised cross-sections ($t\bar{t}$ inclusive) [ATLAS-CONF-2023-068]



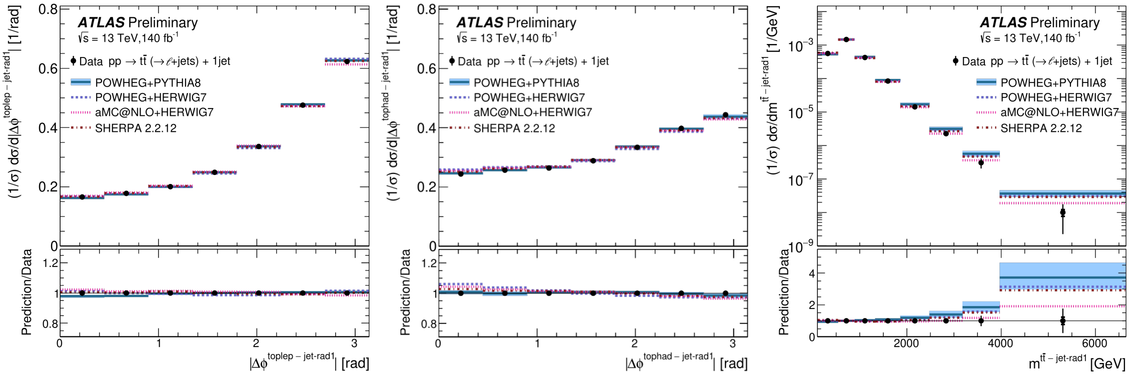
Normalised cross-sections ($t\bar{t}$ inclusive) [ATLAS-CONF-2023-068]



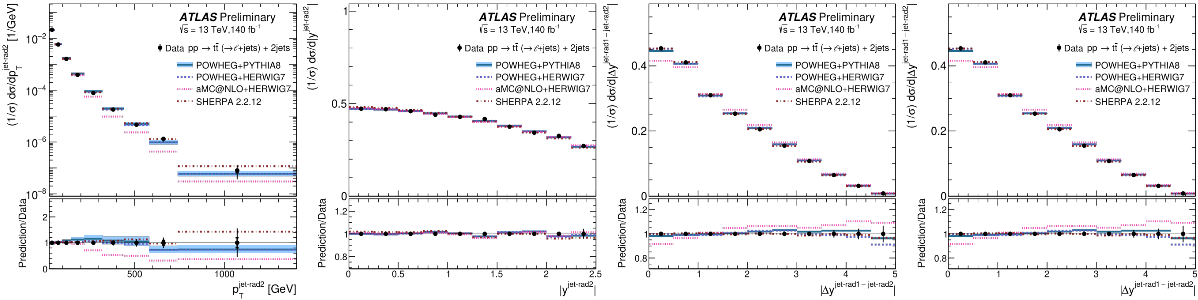
Normalised cross-sections ($t\bar{t}$+1jet) [ATLAS-CONF-2023-068]



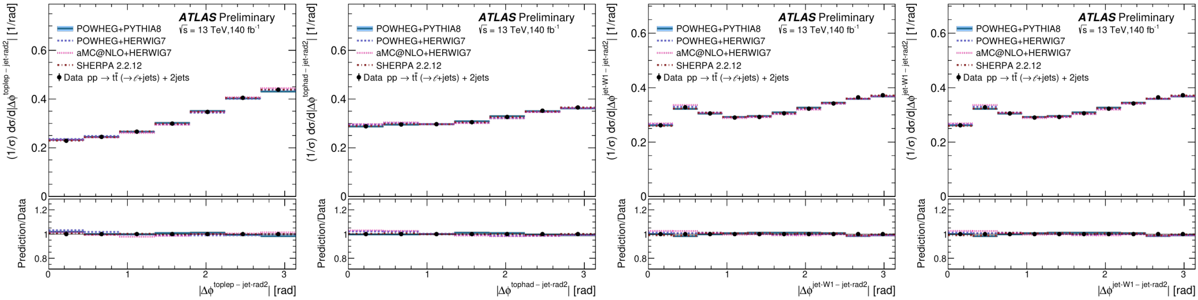
Normalised cross-sections ($t\bar{t}$+1jet) [ATLAS-CONF-2023-068]



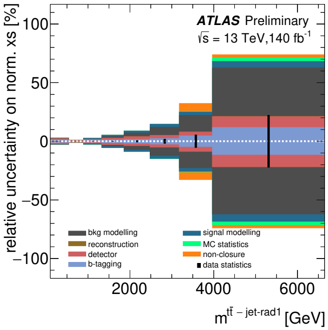
Normalised cross-sections ($t\bar{t}$+2jet) [ATLAS-CONF-2023-068]



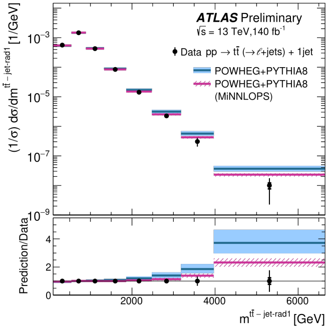
Normalised cross-sections ($t\bar{t}$+2jet) [ATLAS-CONF-2023-068]



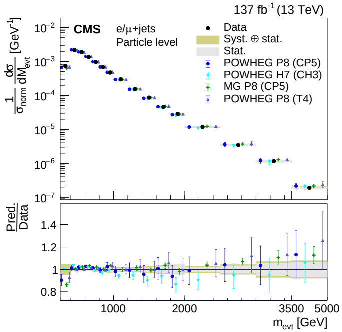
Comparison between ATLAS and CMS



ATLAS-CONF-2023-068



ATLAS-CONF-2023-068



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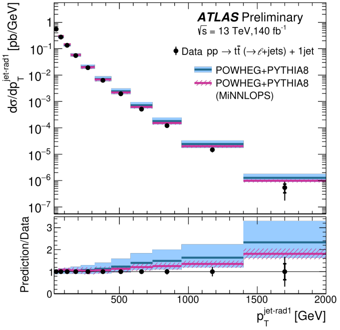
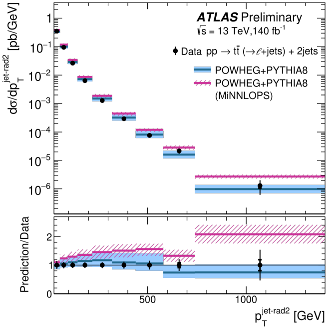
Measurements of normalised cross-sections have reduced uncertainties at low values of the invariant masses.

ATLAS measurements are in agreement with NLO and NNLO predictions below 5 TeV. For CMS measurements, differences are seen for $m < 400$ GeV.

Comparison between ATLAS and CMS



ATLAS-CONF-2023-068



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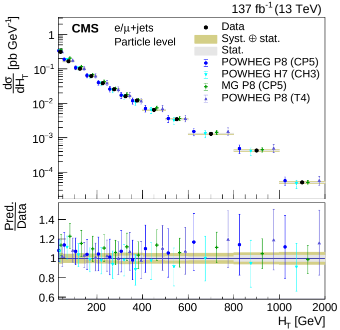

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QCD radiation kinematics is measured by $p_T^{\text{jet-rad1}}$ and $p_T^{\text{jet-rad2}}$ (ATLAS) and H_T (CMS) distributions.

The CMS measurement covers a range up to 2 TeV.

The combination of $p_T^{\text{jet-rad1}}$ (up to 2 TeV) and $p_T^{\text{jet-rad2}}$ (up to 1.4 TeV) probes a more energetic phase space area.