BERGISCHE UNIVERSITÄT WUPPERTAL

Tuesday, May 26th

Top-quark production

Highlights on recent LHC results

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On behalf of the ATLAS, CMS and LHCb collaborations

ATLAS EXPERIMENT

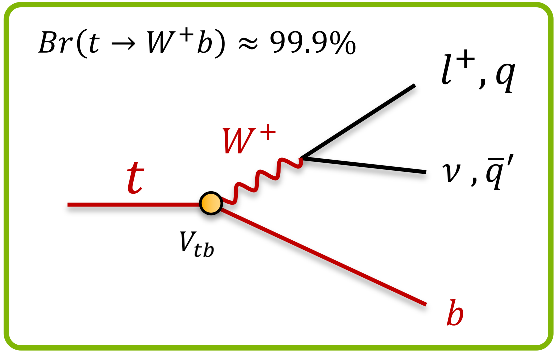
CMS

LHCb

Introduction

The top quark

- A unique particle
  - Most massive elementary particle: $m_t \approx 173$ GeV
  - Large coupling to Higgs boson & special role in EWSB
  - Decays before hadronising, allowing study of bare quarks



- An important probe for testing SM & BSM Physics
  - Test pQCD at NNLO precision (fixed-order)
  - Constrain Parton Distribution Functions (PDFs)
  - Determine SM parameters (m_t, $|V_{tb}|$) and measure rare processes (e.g. $t\bar{t} + V$, $t\bar{t} + H$, tV)
  - Constraint New Physics: Anomalous couplings, direct searches (e.g. $t\bar{t}$, $t\bar{b}$ resonances)

A particle abundantly produced at the LHC

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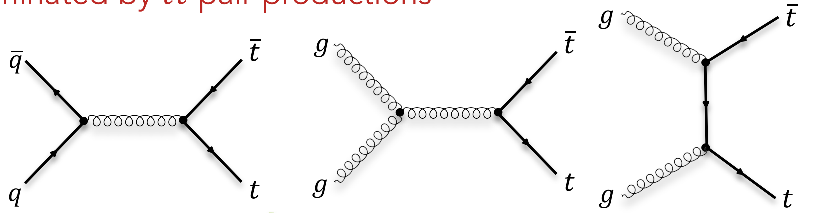
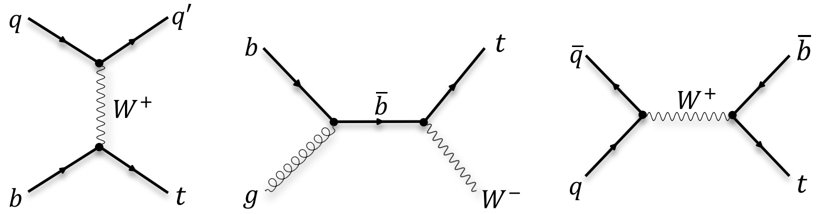
Dominated by $t\bar{t}$ pair productions



quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

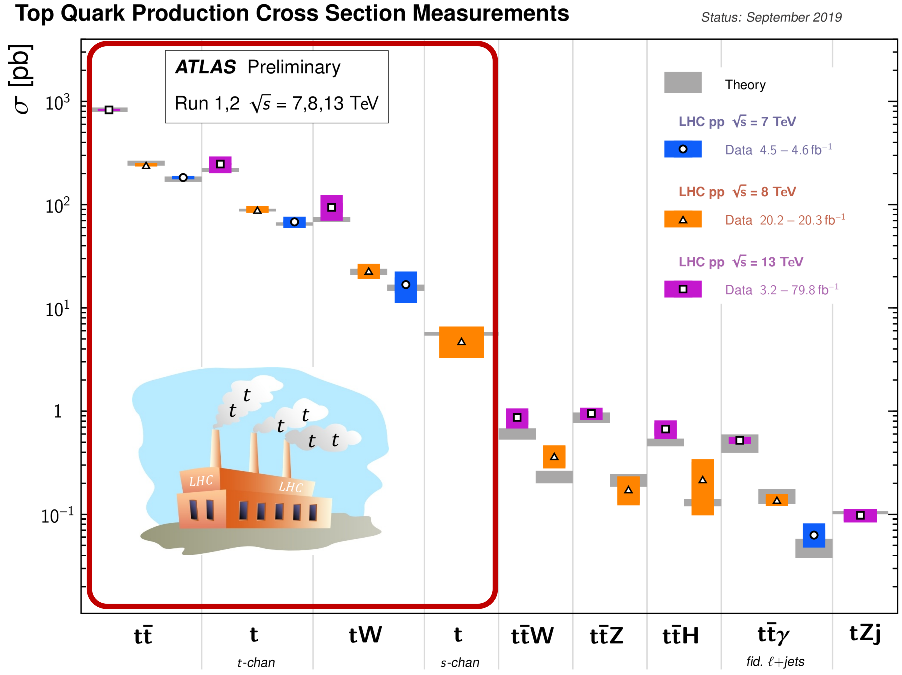
Single top-quark productions



t-channel (~73%)

tW associated production (~24%)

s-channel (~3%)



ATL-PHYS-PUB-2019-035

Top-quark pair production

Overview of recent inclusive and differential cross section measurements

Three main investigation channels

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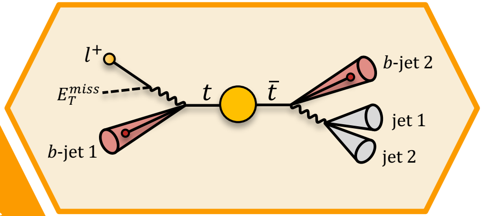
Compromise between signal statistics & background contamination

Backgrounds: t-channel, W+jets, Multi-jet
Possibility to exploit multiple control regions to constraint systematic uncertainties

$Br = 45\%$ (including e, μ, τ)

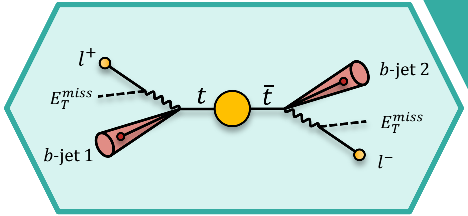


Lepton+jets

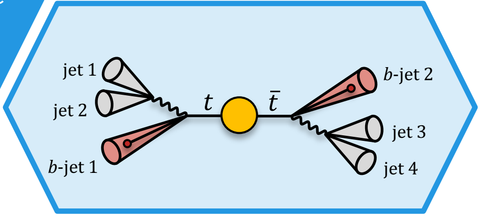
Di-lepton

All-hadronic

$Br = 9\%$ (including e, μ, τ)



$Br = 46\%$



Cleanest signature, but lower signal statistics

Most precise results in $e\mu$ final states
Backgrounds: Wt, fake leptons, VV, $Z \rightarrow \tau\tau$
Limited constraints on systematic uncertainties

Significantly less precise

Large multi-jet background uncertainty
Possibility to probe highly-boosted top quarks

Main systematic uncertainties

$t\bar{t}$ modelling
Generators, scales, radiation, hadronisation

Object efficiencies & calibrations
Leptons, jets, flavour-tagging

Background estimates

Luminosity (~2%)

A challenge for precision measurements
Different strategies

ATLAS
- Generator: Powheg+P8 vs. aMC@NLO+P8 or Sherpa 2.2.1
- Shower modelling: Powheg+P8 vs. Powheg+H7
- ISR/FSR: Powheg+P8 w/ more or less rad. (inc. ME scale & hdamp var.)
- Other: PDF, Heavy flavour variations

CMS
- ME scales: μ_R and μ_F scales varied by 2
- ME to PS matching: hdamp variations
- ISR/FSR: Scales in PS simulation (x2 for ISR and $\sqrt{2}$ for FSR)
- Other: PDF, colour reconnection, underlying events, b-quark frag.

State of the art of $t\bar{t}$ cross section measurements

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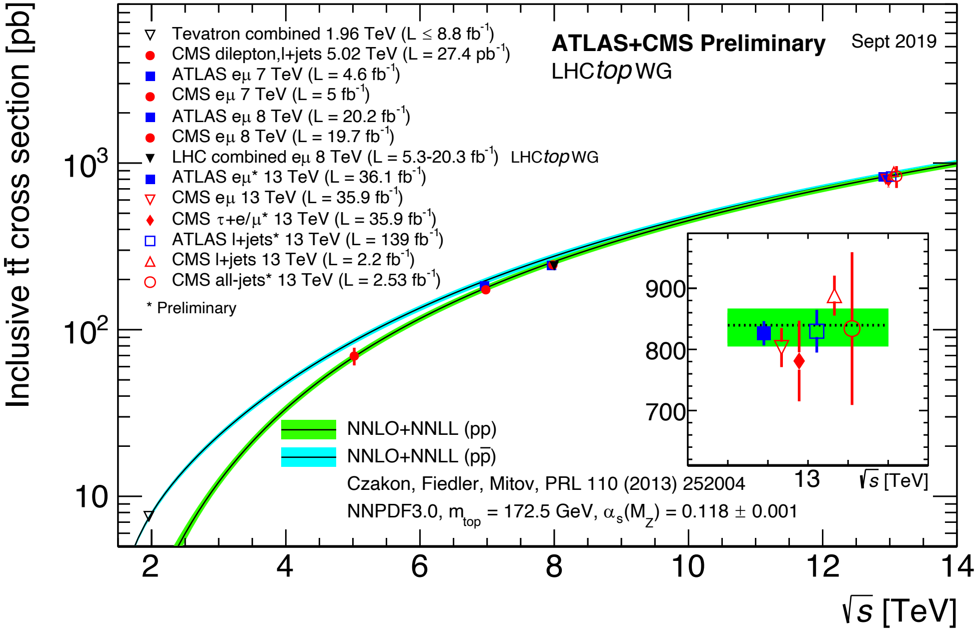
Many measurements performed by the LHC collaborations at $\sqrt{s}$ = 7, 8 and 13 TeV - LHCTopWG



Up to now, an impressive agreement between predictions and measurements

NB: Also, first LHCb measurement of forward $t\bar{t}$ pair production in di-lepton events at $\sqrt{s} = 13$ TeV - JHEP 08 (2018) 174

Among the latest inclusive measurements

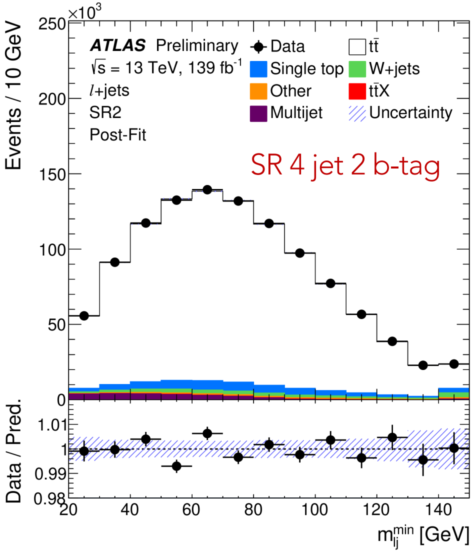
Inclusive and fiducial $t\bar{t}$ cross section in l+jets events at $\sqrt{s}$ = 13 TeV using $\mathcal{L}$ = 139 fb^{-1}

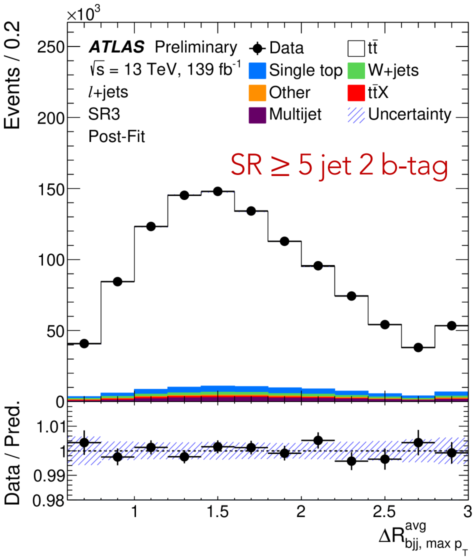
ATLAS-CONF-2019-44

Event selection: 1 lepton ($e^{\pm}$ or $\mu^{\pm}$) and ≥ 4 jets (≥ 1 b-tagged jets).

Strategy: PLH fit to different kinematics in ≥ 4 jet 1 b-tag, 4 jet 2 b-tag and ≥ 5 jet 2 b-tag regions.

Systematic uncertainties: Dominated by $t\bar{t}$ shower/hadronization (2.6%), scale variations (2.6%) and jet reconstruction (2.4%).





Results: XS measured at a precision of 4.6%.

In agreement with NNLO+NNLL prediction (unc. 5.7%)

$$\sigma_{\text{inc}} = 830.4 \pm 0.4\ (\text{stat.})\ ^{+38.2}_{-37.0}\ (\text{syst.})\ \text{pb} = 830^{+38}_{-37}\ (\text{tot.})\ \text{pb}.$$

NB: Similar result from CMS (with 3.8% precision)
JHEP 09 (2017) 051

Among the latest inclusive measurements

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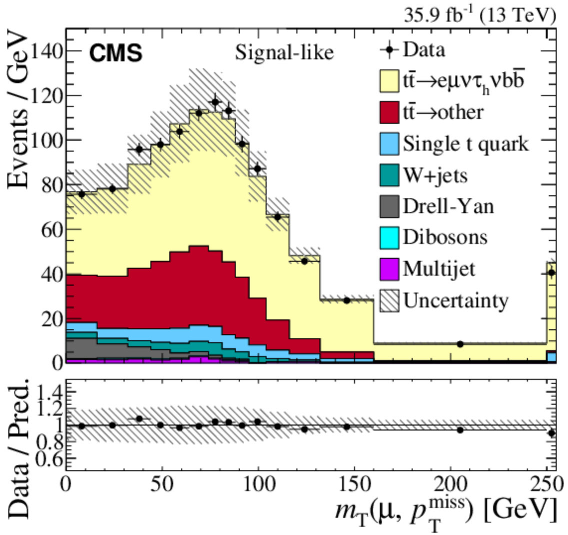
First Inclusive $t\bar{t}$ cross section in di-lepton events containing one τ lepton at $\sqrt{s} = 13$ TeV

JHEP 02 (2020) 191

Event selection: 1 lepton ($e^{\pm}$ or $\mu^{\pm}$) and ≥ 3 jets (≥ 1 b-tagged jets + 1 jet identified as hadronically decaying τ).

Strategy: PLH fit to $m_T(l, p_T^{miss})$ in two kinematic categories based on jet triplet distance for each $e\tau_h$ and $\mu\tau_h$ final state

Systematic uncertainties: Dominated by τ_{had} jet id. (4.5%), luminosity (2.5%), $t\bar{t}$ background norm. (2.3%) and pile-up (2.3%).



Results: XS measured at a precision of 8.3%.

In agreement with NNLO+NNLL prediction (unc. 5.7%)

$$\sigma_{tt}(l\tau_h) = 781 \pm 7(stat) \pm 62(syst) \pm 20(lumi)\ pb$$

In addition:

$$R_{l\tau_h/ll} = 0.973 \pm 0.009\ (stat) \pm 0.066(syst)$$

Consistent with lepton universality

$$\frac{\Gamma(t \to \tau v_\tau b)}{\Gamma_{total}} = 0.1050 \pm 0.0009\ (stat) \pm 0.0071(syst)$$

Improving precision comp. to previous measurements

Among the latest inclusive measurements

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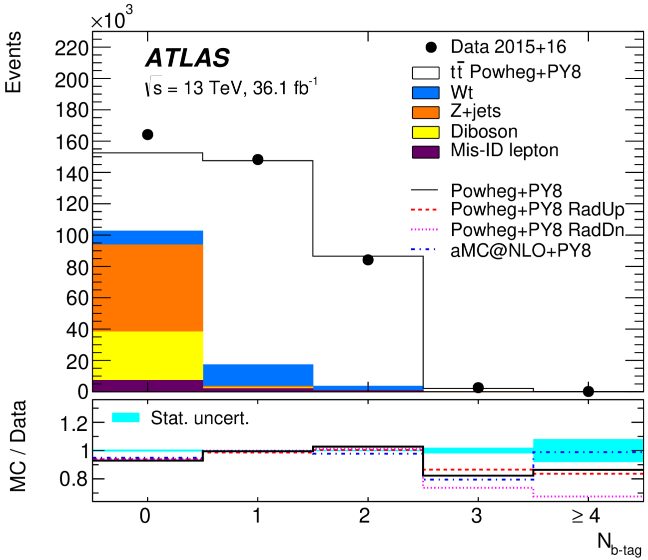
ATLAS EXPERIMENT

Inclusive and lepton differential $t\bar{t}$ cross section in di-lepton events at $\sqrt{s} = 13$ TeV
arXiv:1910.08819v1 – Accepted by Eur. Phys. J. C

Event selection: Isolated opposite sign $e\mu$ pair and 1 or 2 b-tagged jets.

Strategy: Cut & count analysis based on *double b-tagging* technique to suppress jet and flavour-tagging uncertainties.

$$N_1 = L\sigma_{tt}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{bkg} \;;\; N_2 = L\sigma_{tt}\epsilon_{e\mu}2\epsilon_b^2 + N_2^{bkg}$$



BLUE combination of 2015 & 2016 data leading to 9% reduction on total uncertainty due to uncorrelated uncertainties.

Systematic uncertainties: Dominated luminosity (1.9%), bkg. cross section (0.5%), $t\bar{t}$ shower/hadronization (0.5%) and ISF/FSR (<0.5%)

Results: XS measured at a precision of 2.4%.
In agreement with NNLO+NNLL prediction (unc. 5.7%)

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\ (\text{stat}) \pm 11.5\ (\text{syst}) \pm 15.7\ (\text{lumi}) \pm 1.9\ (\text{beam})\ \text{pb}$$

NB: Similar result from CMS with 3.9% precision - EPJC 79 (2019) 368

Beyond baseline $t\bar{t}$ cross section measurements

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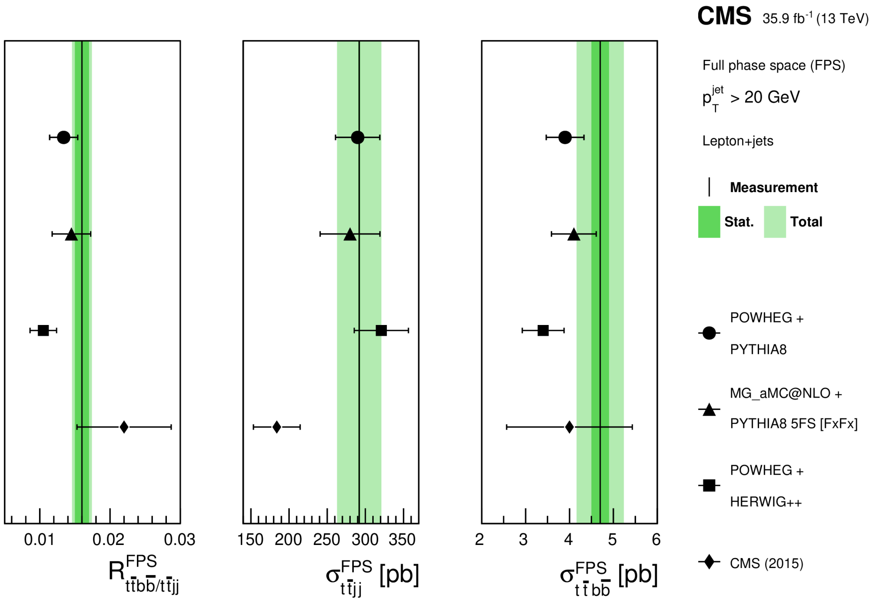
Inclusive $t\bar{t}+b\bar{b}$ and $t\bar{t}+jj$ cross section in di-lepton and lepton+jets events at $\sqrt{s}=13$ TeV
arXiv:2003.06467 – Submitted to J. High Energy Phys.

Strategy: $t\bar{t}+jj$ XS and $t\bar{t}+b\bar{b}$ / $t\bar{t}+jj$ XS ratio measured in fiducial phase space via PLH fit to b-tagging discriminant distribution of additional jets, inferring $t\bar{t}+b\bar{b}$ XS. Extrapolation to full phase space after acceptance corrections.



Results: Inclusive $t\bar{t}+b\bar{b}$ XS and XS ratios for both decay channels measured higher than, but consistent with, several MC generators.

$t\bar{t}+b\bar{b}$ XS is measured as a precision of 13% (12%) in dilepton (lepton+jets) channel.

NB: Similar result from ATLAS with 13% (17%) precision in dilepton (lepton+jets) channel - JHEP 03 (2019) 046

Studying $t\bar{t}$ production in nuclear interactions

Evidence of $t\bar{t}$ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
CMS-PAS-HIN-19-001

Event selection: At least 1 isolated $l^{\pm}l^{\mp}$ ($l = e \text{ or } \mu$) and 2 b-tagged jets
Strategy: PLH fit to BDT distributions in different leptonic categories w/ or w/o b-tagged jet multiplicity information.
Systematic uncertainties: Dominated by statistical uncertainty (28%), background norm. (12%).

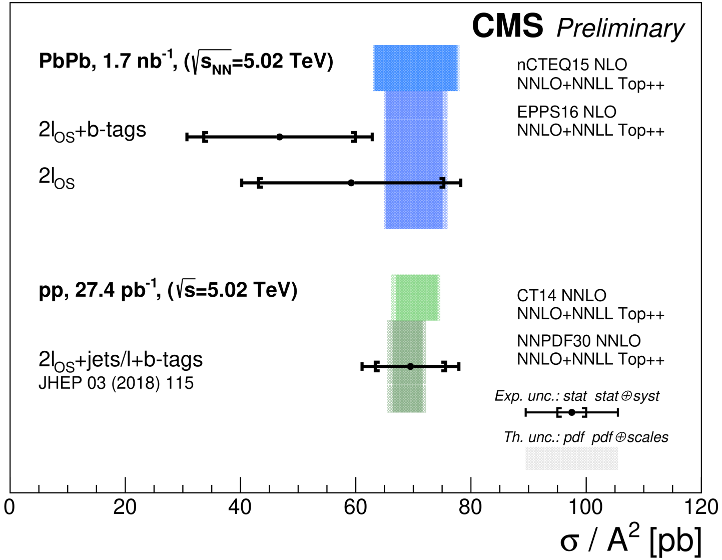
Results: Observed (expected) significances

$2l_{OS}$+b-tags: 4.0 (6.0) σ ; $2l_{OS}$: 3.8 (4.8) σ

Measured XS lower but still compatible with scaled pp data expectation and pQCD calculations.

$2l_{OS}+b$-tags: $\sigma_{tt} = 2.02 \pm 0.69\ (tot)\mu b$

$2l_{OS}$: $\sigma_{tt} = 2.02 \pm 0.69\ (tot)\mu b$



Towards differential measurements

Interface between state-of-the-art theory calculation, Mont Carlo generators and experiments

Stringent test of perturbative theory

Several observables sensitive to different effects (matrix element, radiation, hadronisation)

Allow simulation improvements

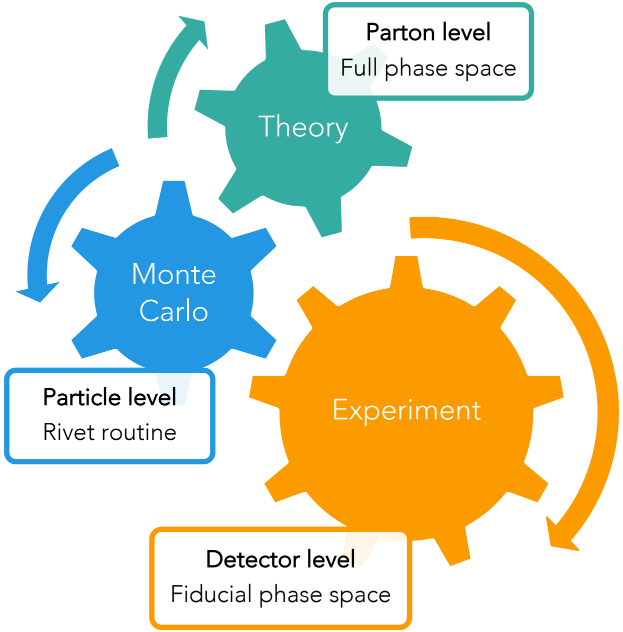
Via MC generator tuning

Probe New Physics not modifying inclusive XS

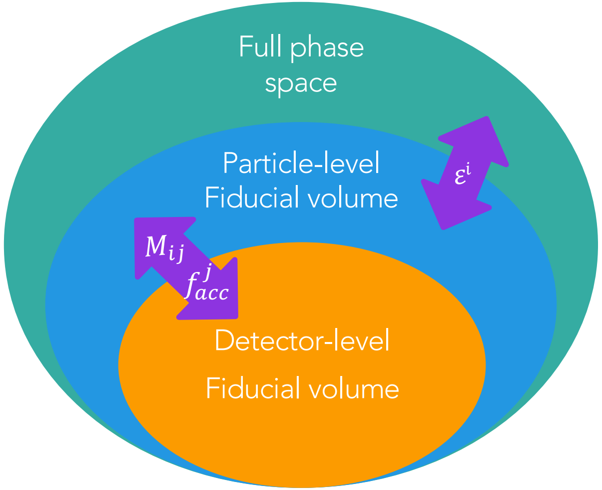
Via Effective Field Theory interpretation

Unfolding detector level observables measured in fiducial phase space to particle or parton levels

At the heart of the measurement strategy



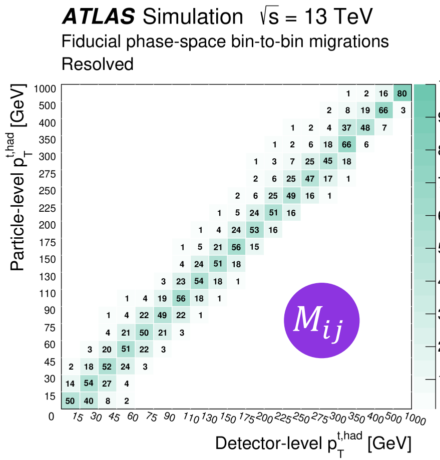
Unfolding, the general approach



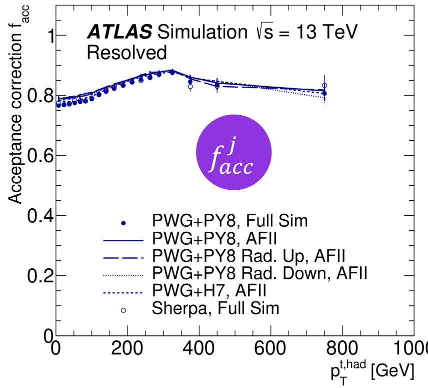
$$N_i^{unfolded} = \frac{1}{\varepsilon^i} \sum_j M_{ij}^{-1} \cdot f_{match}^j \cdot f_{acc}^j \cdot \left(N_{det}^j - N_{bkg}^j\right)$$

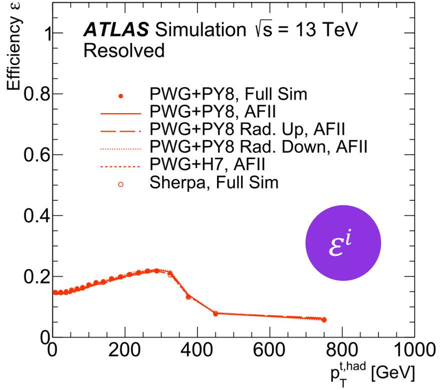
Differential XS

$$\frac{d\sigma}{dX_i} = \frac{1}{\mathcal{L} \cdot \Delta X_i} \cdot N_i^{unfolded} \quad \& \quad \frac{d^2\sigma}{dX_i dY_j} = \frac{1}{\mathcal{L} \cdot \Delta X_i \Delta Y_j} \cdot N_{ij}^{unfolded}$$



Eur. Phys. J. C 79 (2019) 1028

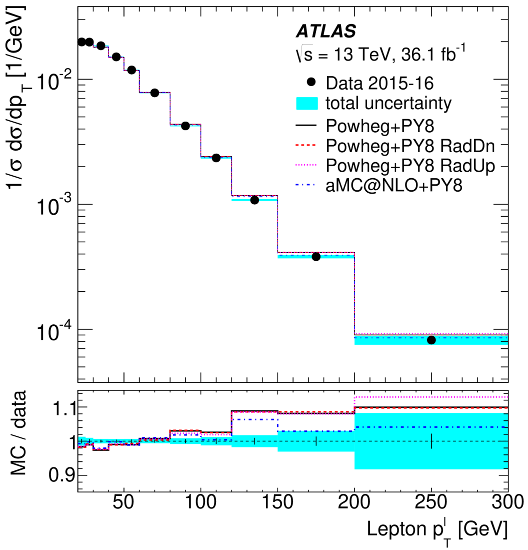


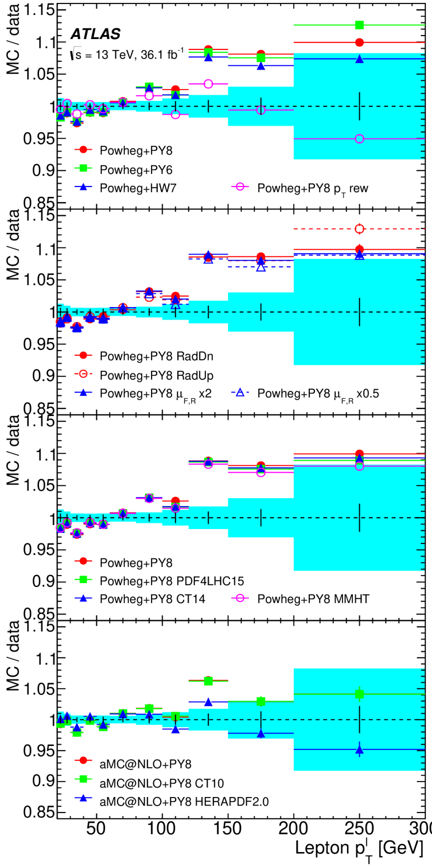


Lepton distributions at a glance

Inclusive and lepton differential $t\bar{t}$ cross section in di-lepton events at $\sqrt{s} = 13$ TeV
arXiv:1910.08819v1 – Accepted by Eur. Phys. J. C

Strategy: Similar to inclusive measurement, counting events per bin of lepton kinematics.
Normalised differential cross-sections compared to particle-level predictions.





Among the main conclusions

Softer lepton p_T and more forward η distributions in data.

Dependence to lepton p_T improved by aMC@NLO+PY8, especially using HERA PDF

Top-quark distributions at a glance

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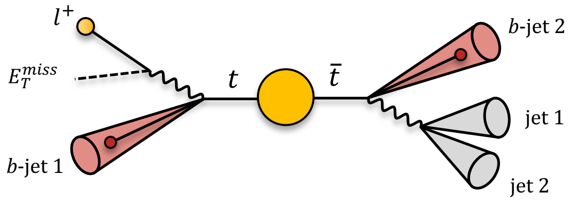
ATLAS EXPERIMENT

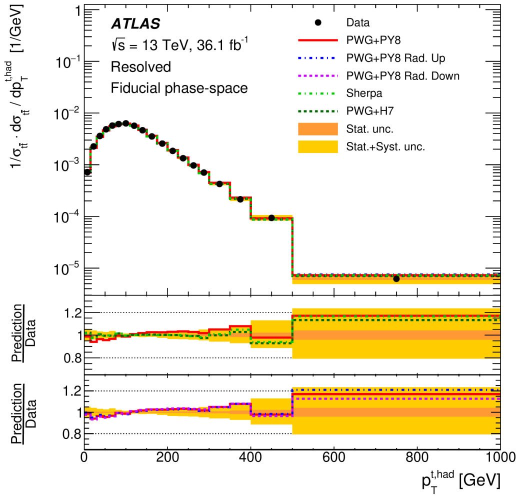
Differential and double differential $t\bar{t}$ cross section in l+jets events at $\sqrt{s} = 13$ TeV

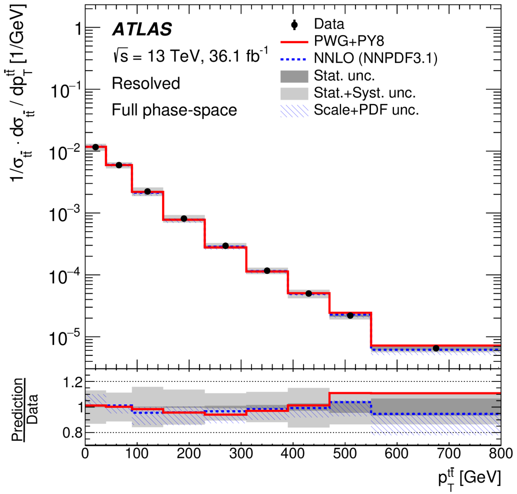
Eur. Phys. J. C 79 (2019) 1028

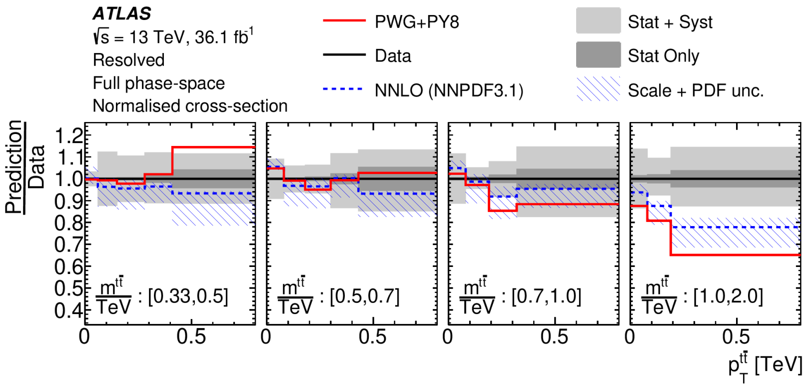
Strategy: Exploring resolved and boosted topologies

(1) 1 lepton ($e^{\pm}/\mu^{\pm}$), ≥ 4 R=0.4 jets (≥ 2 b-tagged jets)









Among the main conclusions

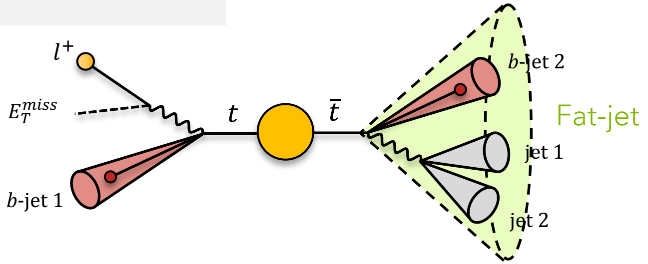
Powheg+PY8 best top p_T description. However, double dif. Measurement able to reveal discrepancies between data and MC.

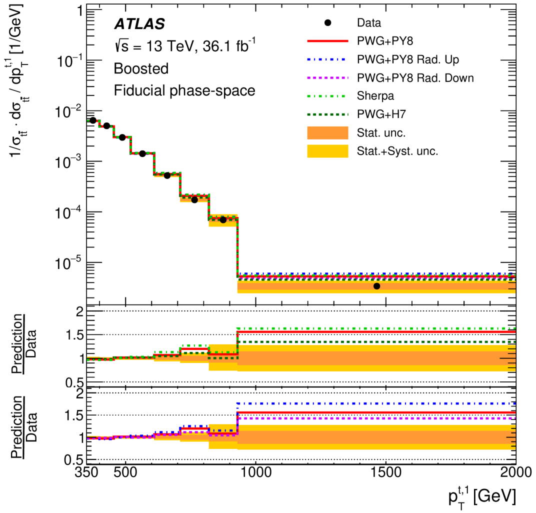
Overlap between resolved and boosted regimes

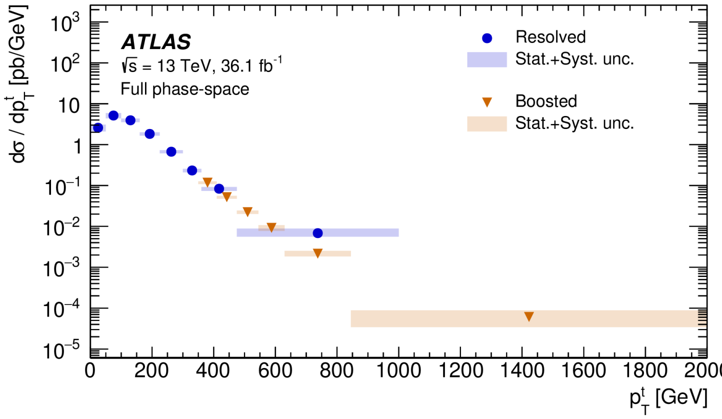
Differential and double differential $t\bar{t}$ cross section in l+jets events at $\sqrt{s}$ = 13 TeV
Eur. Phys. J. C 79 (2019) 1028

Strategy: Exploring resolved and boosted topologies

(2) 1 lepton ($e^{\pm}/\mu^{\pm}$), ≥ 1 R=1.0 trimmed jets (re-clustered from R=0.4 jets) with p_T>350 GeV. Top-tag jet requiring 120<m_{jet}<220, corr. to 60% top-tagging eff.







Further observations

Good overlap between resolved and boosted regime.

However, direct comparison impossible at particle level given different object definitions.

Further investigations in all-hadronic final states

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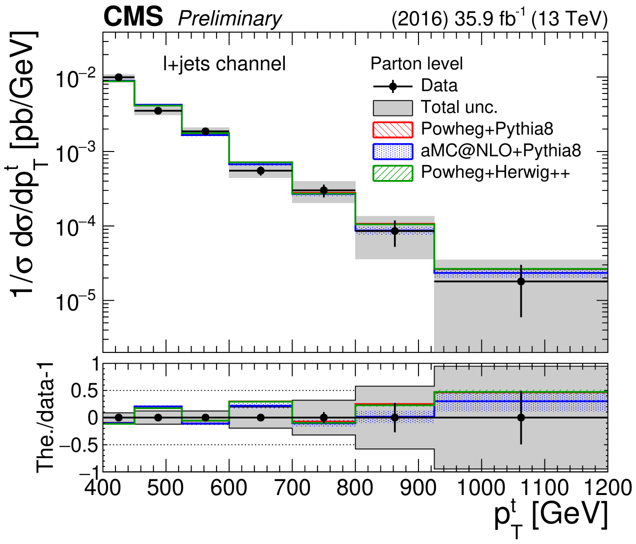
Differential $t\bar{t}$ cross section for high-p_T top quark at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}
CMS PAS TOP-18-013

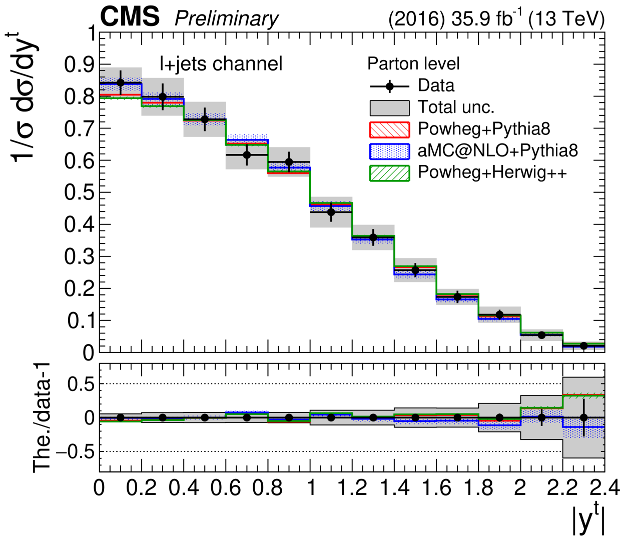
New

Strategy: Selection of one or two hadronically decaying top quark clustered in single large-R jet, with p_T>400 GeV.

(1) Hadronic final state: 2 Large-R jets; **(2) Lepton+jets final state**: 1 Large-R jets, 1 lepton ($e^{\pm}/\mu^{\pm}$), 1 b-tagged jets, MET.

Absolute and normalised differential XS measured at particle and parton levels.





Among the main conclusions

Differential distributions generally well described.

Models overpredict absolute cross sections by 20%.

Top-quark distributions at a glance

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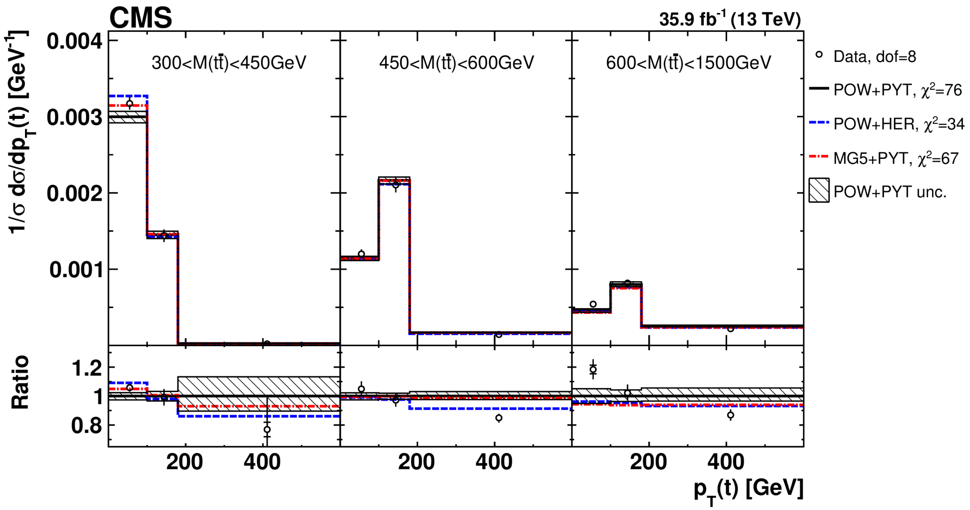
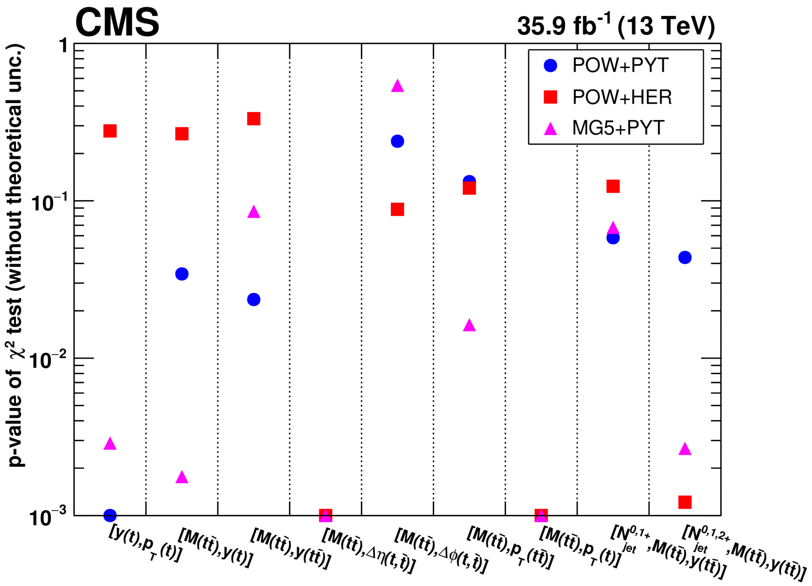
Multi-differential $t\bar{t}$ cross section in di-lepton events at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}
arXiv:1904.05237 – Accepted by Eur. Phys. J. C

Strategy: Normalised $t\bar{t}$ XS measured in opposite sign $e\mu$ pair events.





Among the main conclusions

None predictions able to describe all distributions.
Softer $p_T(t)$ distribution enhanced at high $M(t\bar{t})$.

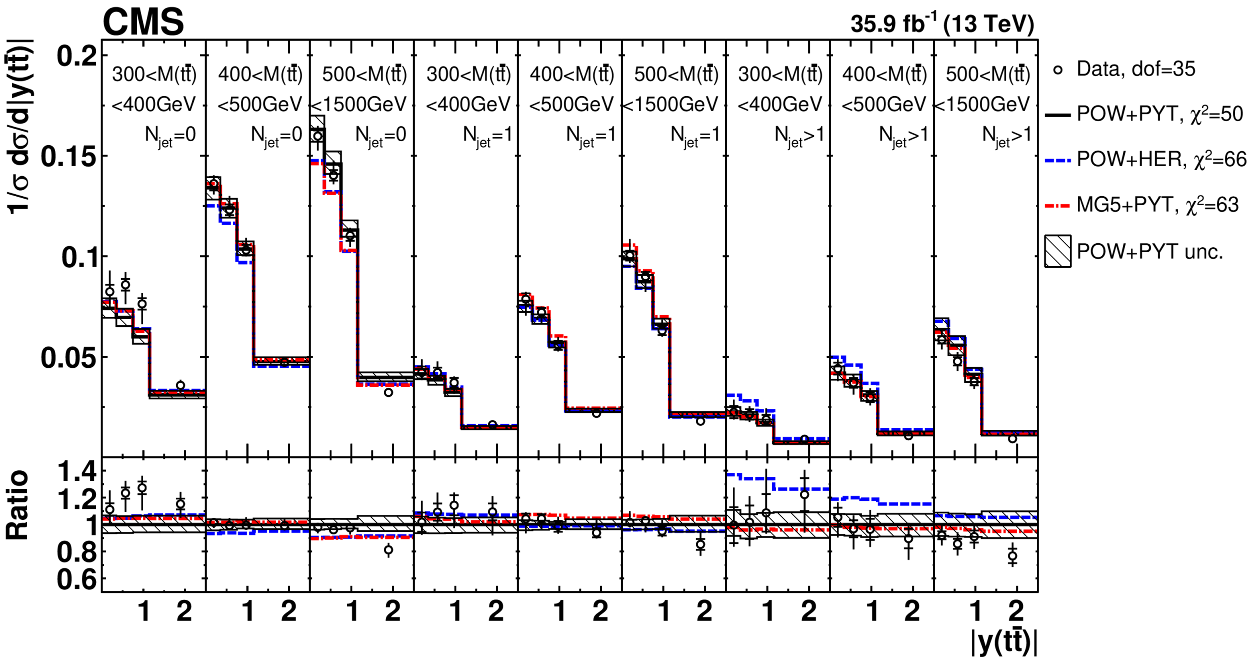
Top-quark distributions at a glance

Multi-differential $t\bar{t}$ cross section in di-lepton events at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}

arXiv:1904.05237 – Accepted by Eur. Phys. J. C

First triple differential measurements

All predictions ok up to $N_{jet} = 1$.
Serious advantage for Poweg+PY8 at $N_{jet} > 1$.



Further investigations in all-hadronic final states

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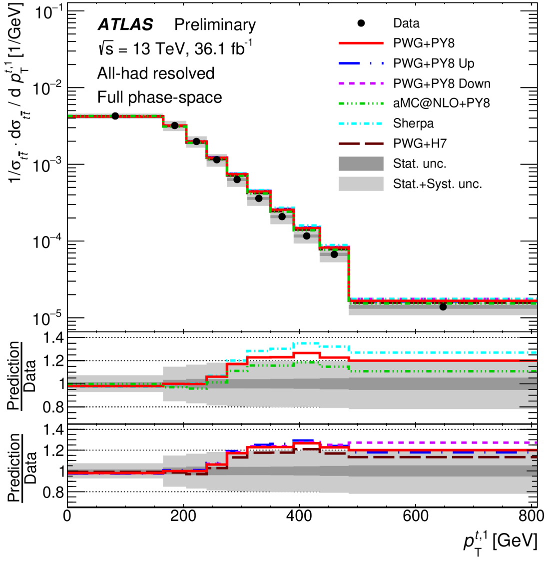
Differential and double differential $t\bar{t}$ cross section in all-hadronic events at $\sqrt{s} = 13$ TeV
ATLAS-CONF-2020-001

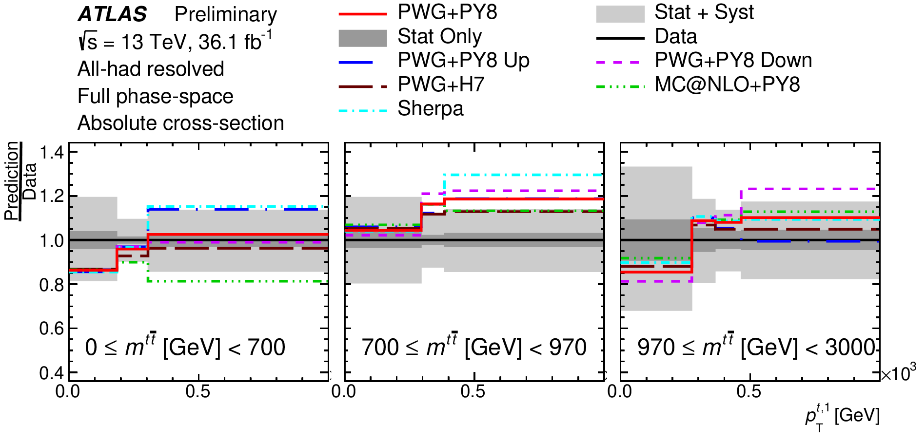
New

Strategy: Selection of ≥ 6 jets (=2 b-tag jets), Kinematic fit based on χ^2 minimisation to top quark pairs.
Differential XS measured at particle and parton levels.



Among the main conclusions

In general, mis-modelling in hardness of leading 3 jet emissions, leading to $p_T(t)$ and $p_T(t\bar{t})$ distributions incompatible with several theory predictions.



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Differential $t\bar{t}$ cross section for high-p_T top quark at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}
CMS PAS TOP-18-013

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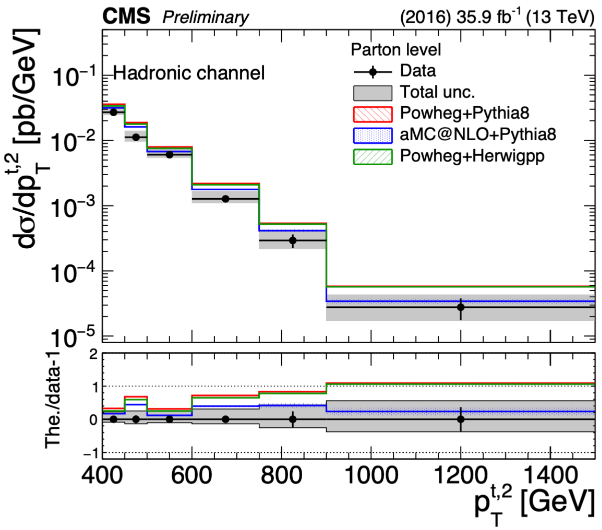
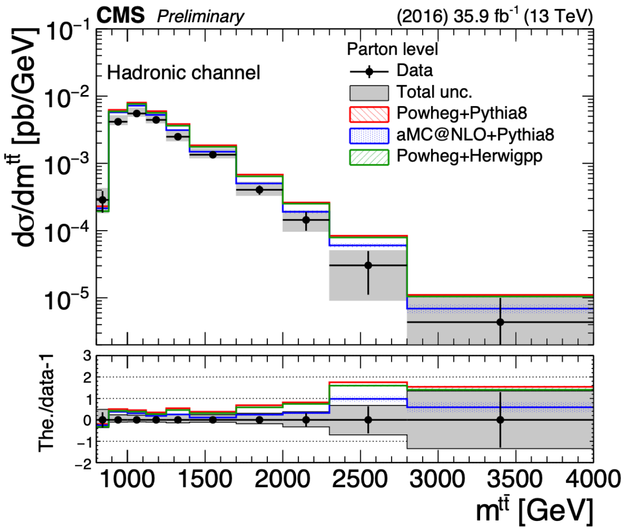
Absolute and normalised differential XS measured at particle and parton levels.





Among the main conclusions

Models overpredict absolute cross sections by 35%.

Describing consistently differential distributions.

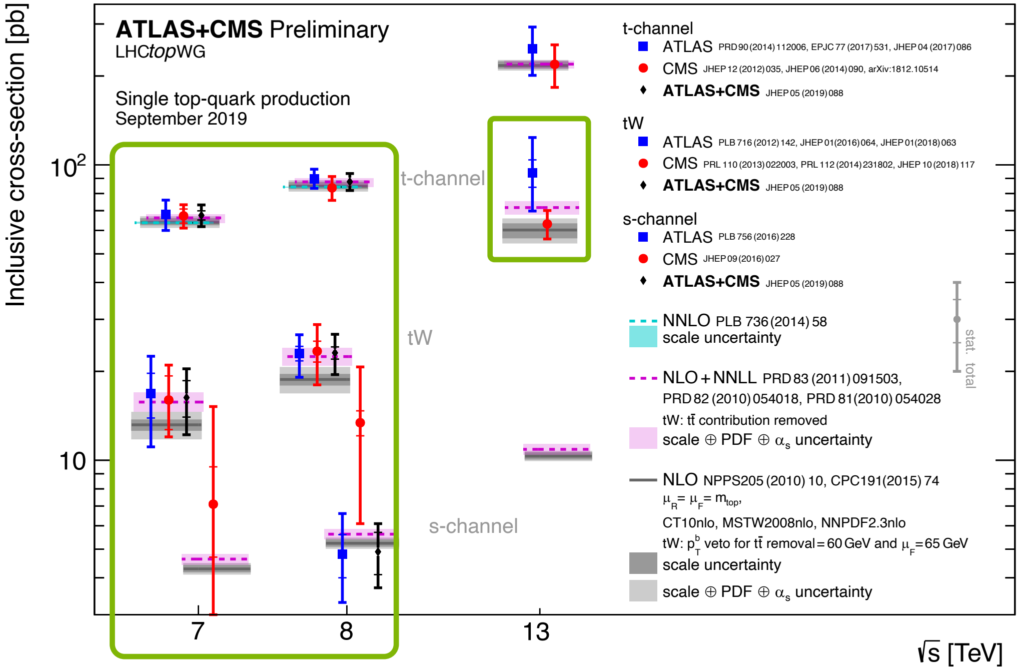
Most important discrepancy observed in hadronic channel

Single top-quark productions

Focus on Run I combination and new measurements at $\sqrt{s} = 13$ TeV

Stat of the heart of Single top-quark production

- Many measurements performed by the ATLAS and CMS collaborations at $\sqrt{s}$ = 7, 8 and 13 TeV



Here as well, predictions impressively in agreement measurements

LHCTopWG

Combining Run 1 measurements

Single top cross section combination and $|f_{LV}V_{tb}|$ determination at $\sqrt{s} = 7$ and 8 TeV
JHEP 05 (2019) 089

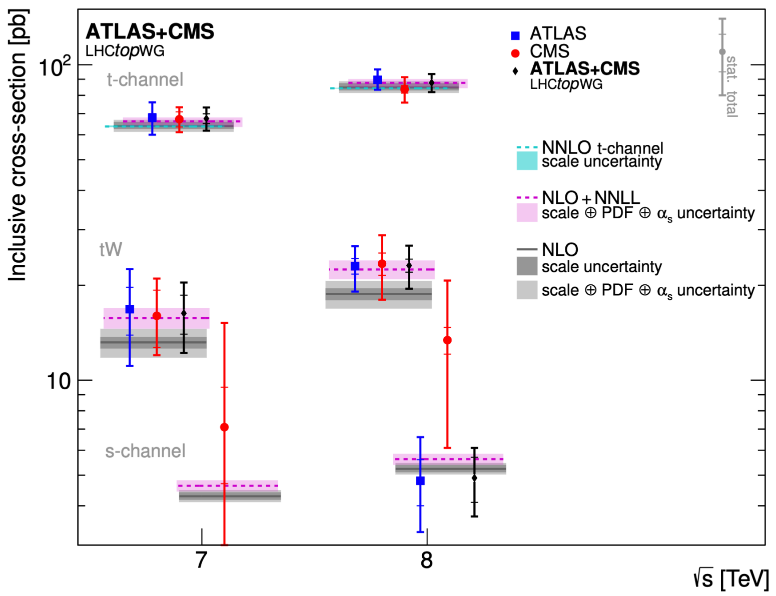
Strategy: BLUE combination of 10 inclusive measurements per production and centre-of-mass energy.

Systematic uncertainties: Experimental uncertainties and correlations carefully taken into account.

Dominated by theory modelling, detector modelling, Jets reconstruction, data statistics (for s-channel)

NB: Uncertainties on the top-quark mass dependence not included.

Results: Combined measurements at the precisions of
8.4% and 25% for t and Wt channels at $\sqrt{s} = 7$ TeV
6.7%, 16%, 30% for t, Wt and s channels at $\sqrt{s} = 8$ TeV



Combining Run 1 measurements

Single top cross section combination and $|f_{LV}V_{tb}|$ determination at $\sqrt{s} = 7$ and 8 TeV
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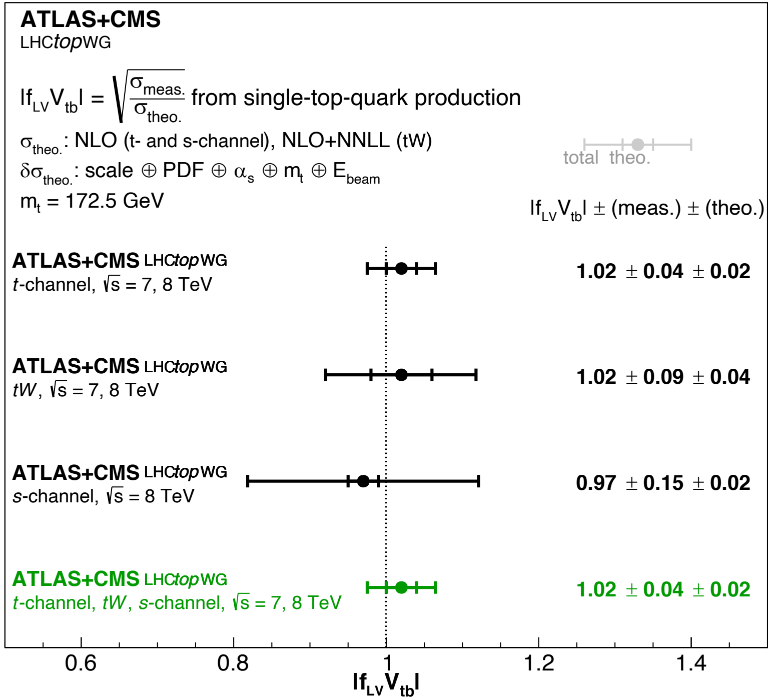
$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$ **extraction:** Determined for each production mode and full combination. Combining $|f_{LV}V_{tb}|^2$ given the linear dependence with the cross section.

Systematic uncertainties : Dominated by

- Theory modelling (4.5%),
- Theoretical cross section (4.3%)
- Jets reconstruction (2.4%).

NB: Uncertainties on the top-quark mass dependence included.

Results: Combined measurement at a precision of 3.7%.
Driven by t-channel cross section measurements



Differential tW cross section in di-lepton ($e^{\pm}\mu^{\pm}$) events at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}
CMS-PAS-TOP-19-003

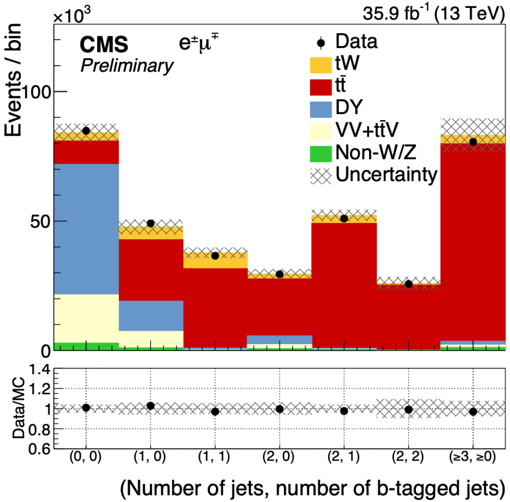
New

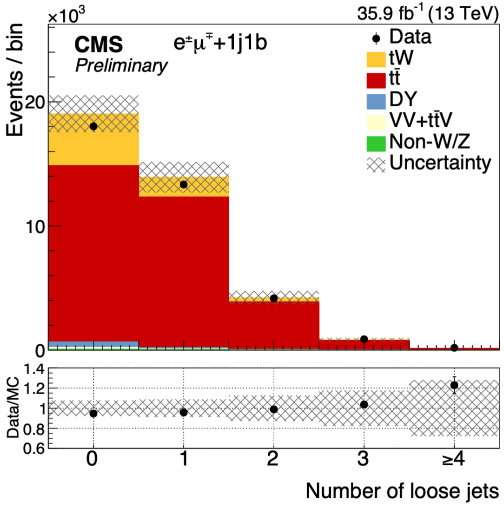
Main selection: $e^{\pm}\mu^{\pm}$ pair with $m_{ll} > 20$ GeV. Event classification based on jet and b-tag jet multiplicities.

Strategy: Normalised differential XS measured as a function of various properties. Unfolding procedure based on bin-by-bin corrections.

Systematic uncertainties:

Dominated by jet reconstruction and the theoretical modelling, driven by overwhelming $t\bar{t}$ background.





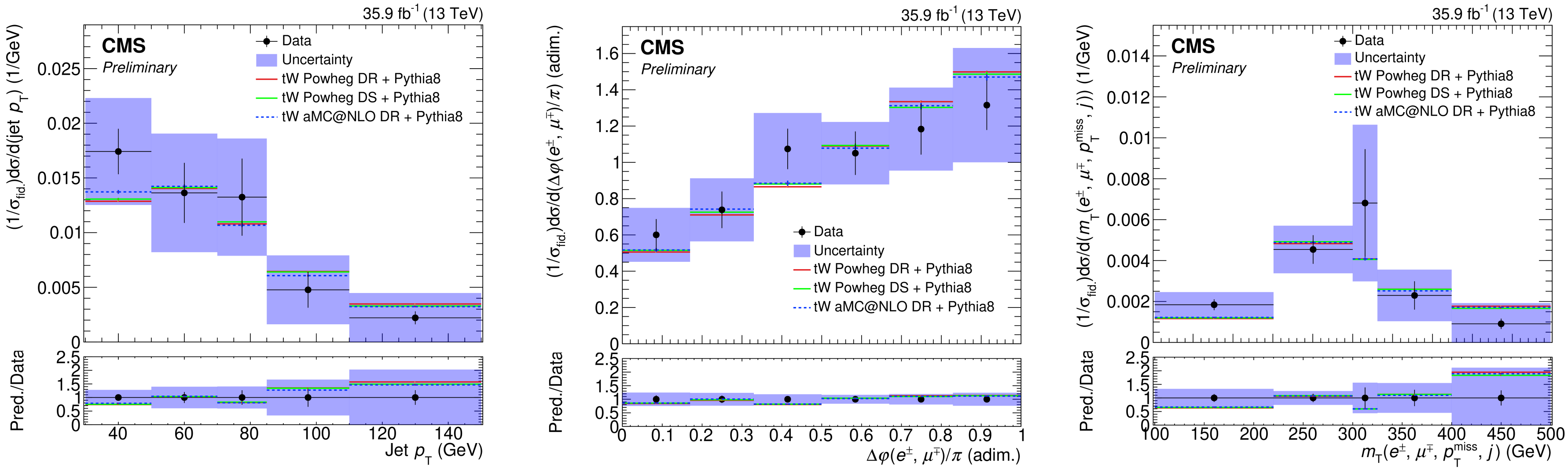
NB: Similar result from ATLAS – Eur. Phys. J. C 78 (2018) 186

tW cross section measurement

Differential tW cross section in di-lepton ($e^{\pm}\mu^{\pm}$) events at $\sqrt{s}$ = 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1}

CMS-PAS TOP-19-003

New



Among the main conclusions

Results consistent with model expectations (Powheg and Madgraph5 aMC@NLO) used for modelling tW signal.

NB: Similar result from ATLAS
Eur. Phys. J. C 78 (2018) 186

Summary

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- LHC Run I and II provided high statistics top-quark data.
  - Many precision measurements performed.

- Recent measurements confirm good agreements with SM expectations.
  - Improving precisions (e.g. exploiting larger data statistics and via ATLAS+CMS combinations).
  - Probing new kinematic regimes (e.g. in highly-boosted top quark final states).

- Better understanding of physics modelling and detector effects.
  - Largest experimental uncertainties and a real challenge for precision measurements.
  - Differential cross section measurements at the heart of the latest investigations.
  - In particular, multi-differential measurements extremely useful for improving MC predictions.

Thank you for your attention