THE ROYAL SOCIETY

University of Glasgow

Latest ATLAS & CMS top cross-section measurements

Mark Owen
The University of Glasgow
on behalf of the ATLAS & CMS Collaborations

SM@LHC 2021

CMS Top Results
ATLAS Top Results

Outline

- Introduction
- $t\bar{t}$ differential cross-section measurements
- $t\bar{t}$ inclusive cross-section measurements
- tW cross-section measurements
- Summary

Why the top quark?

- In the SM it's the only quark:

  1. With a natural mass:

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

  - Top quark interacts strongly with the Higgs sector - special role in EWSB?

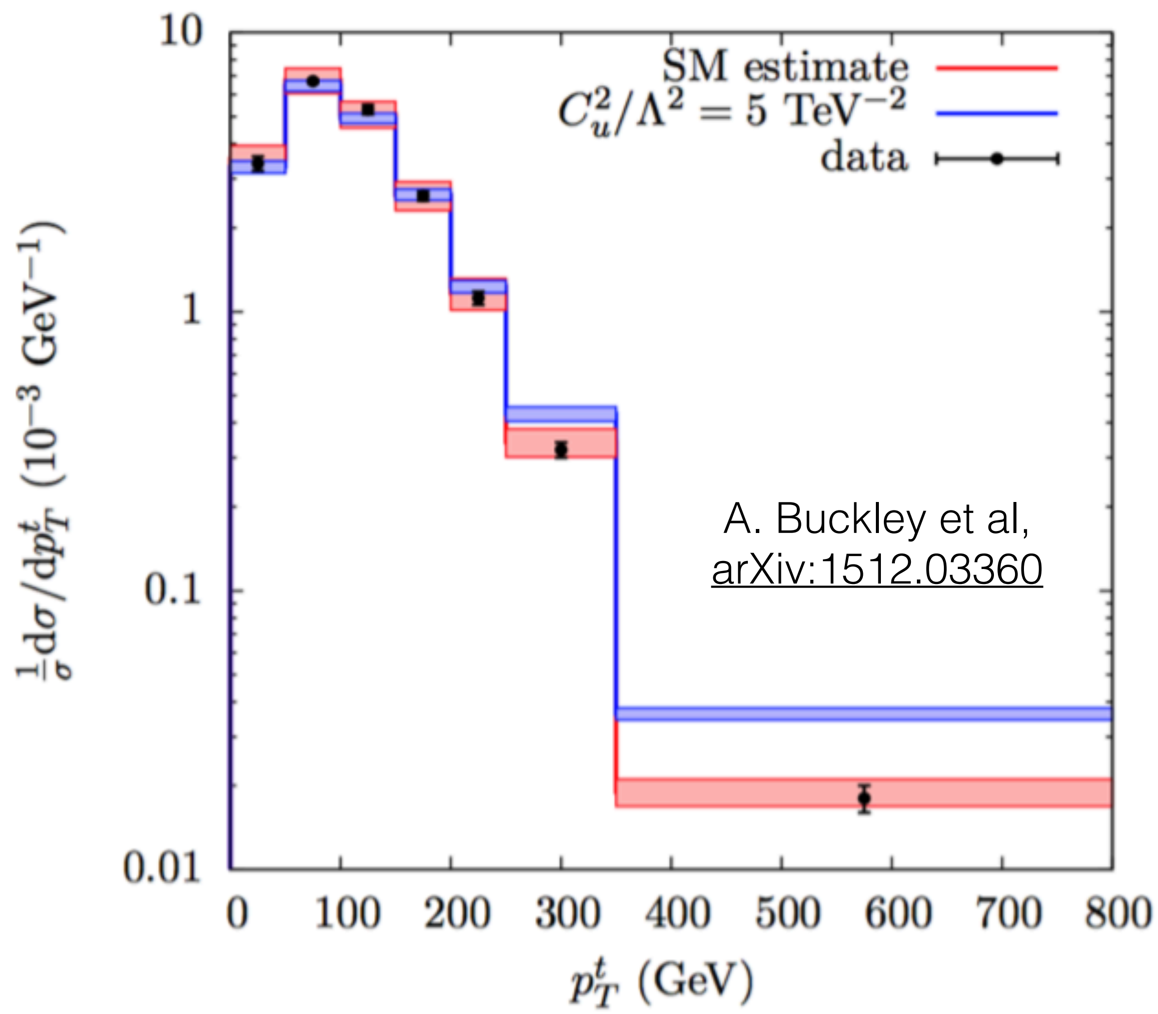
  2. That decays before hadronizing:

$$\tau_{had} \approx 2 \times 10^{-24} s$$
$$\tau_{top} \approx 5 \times 10^{-25} s$$

- Copious production rate at the LHC allows for precise tests of QCD involving multiple scales (pT(top), m(top), m(b)).

Why cross-section measurements?

- $t\bar{t}$ production:
  - Test state-of-the-art QCD predictions (cf Marius' talk).
  - Extraction of fundamental parameters (m_t, y_t, α_s).
  - Potential for new physics contributions.
- Single-top production:
  - Probe Wtb vertex for new physics.
  - Wt final-state can test modelling of off-shell tops / interference with $t\bar{t}$.



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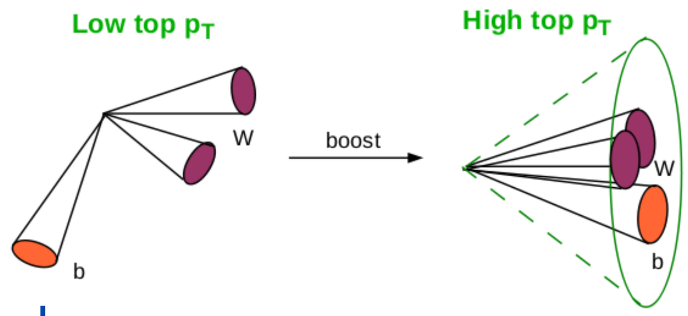
$t\bar{t}$ differential cross-section measurements

CMS l+jets differential cross-section

- Analysis uses dedicated selections and reconstruction for resolved and boosted tops.



- Resolved selection:
  - 1 lepton, >= 4 0.4 jets, 2 of which are b-tagged.
    - Events are split according to quality of second b-tag.

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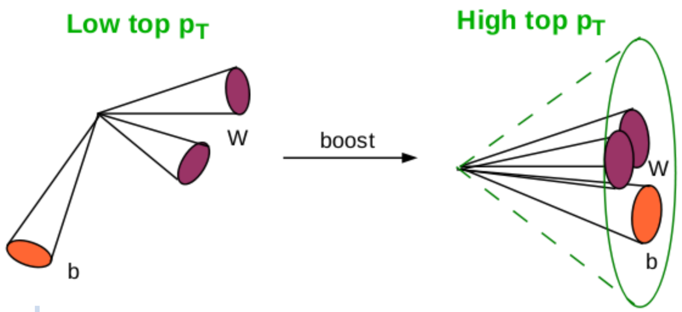

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  - 1 lepton, >= 4 0.4 jets, 2 of which are b-tagged.
    - Events are split according to quality of second b-tag.
- Boosted selections:
  - Anti-kT 0.8 jets with a 21 variable NN is used to identify boosted hadronic top decays (t_h^b).
  - Boosted leptonic top decays (t_l^b) are identified by using leptons (no isolation cuts) close to b-jets with a 5 variable NN.
  - Selections require a boosted hadronic top, leptonic side can be boosted or reconstructed with a standard lepton+b-jet requirement.

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Cross-section extraction

- The cross-section is extracted from a combined fit to the different channels, 3 selections x 2 lepton flavours x 3 data taking years.

$$\boldsymbol{s} = R\boldsymbol{\sigma} + \boldsymbol{b}$$

$$\chi^2(\boldsymbol{\sigma},\boldsymbol{v}) = \sum_y \sum_c \sum_\ell (\boldsymbol{m}_{yc\ell} - \boldsymbol{s}_{yc\ell}(\boldsymbol{\sigma},\boldsymbol{v}))^T C^{-1}_{yc\ell} (\boldsymbol{m}_{yc\ell} - \boldsymbol{s}_{yc\ell}(\boldsymbol{\sigma},\boldsymbol{v})) + \boldsymbol{v}^T Q^{-1} \boldsymbol{v}$$

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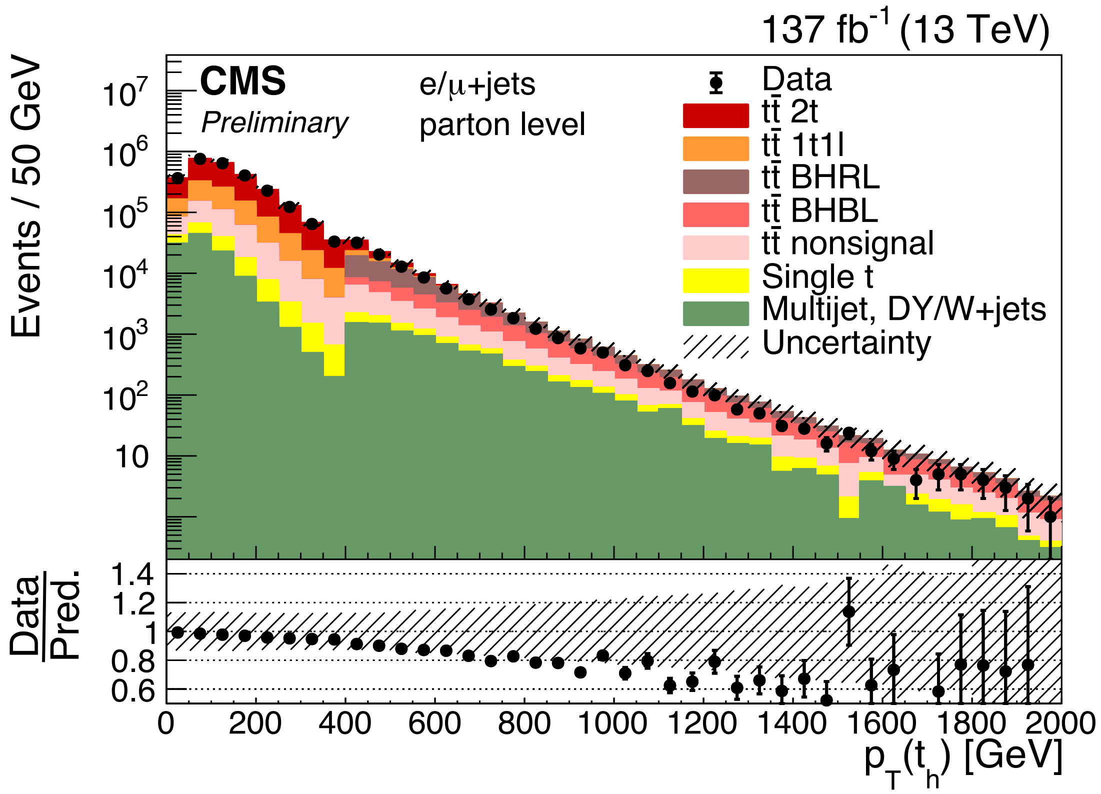

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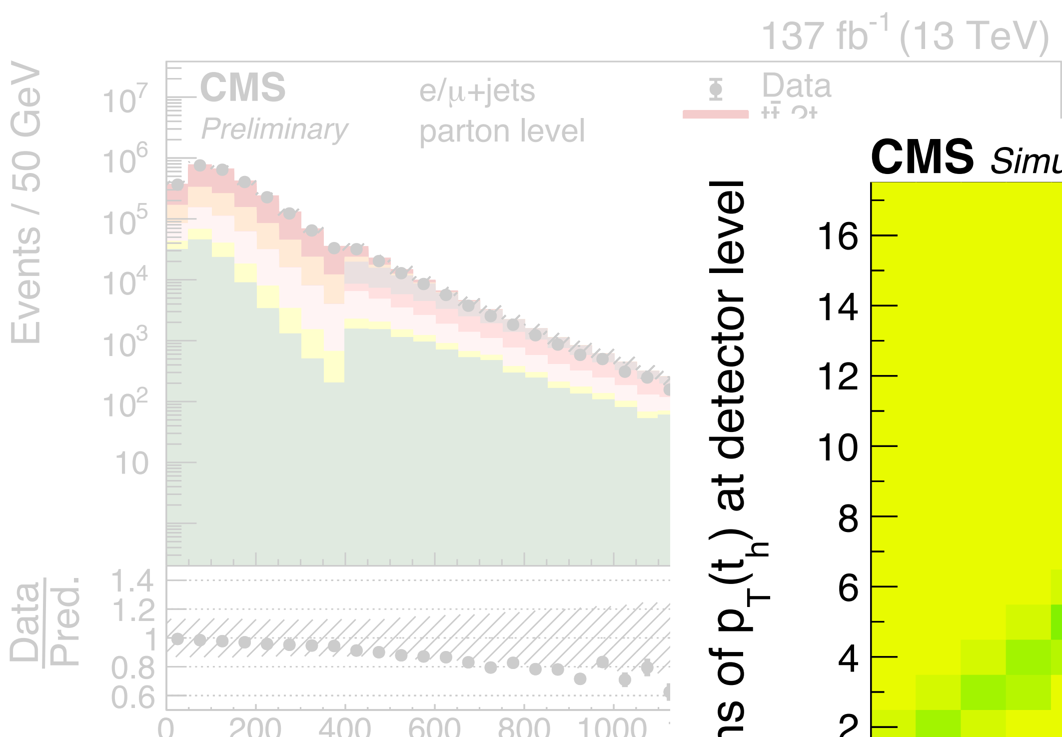

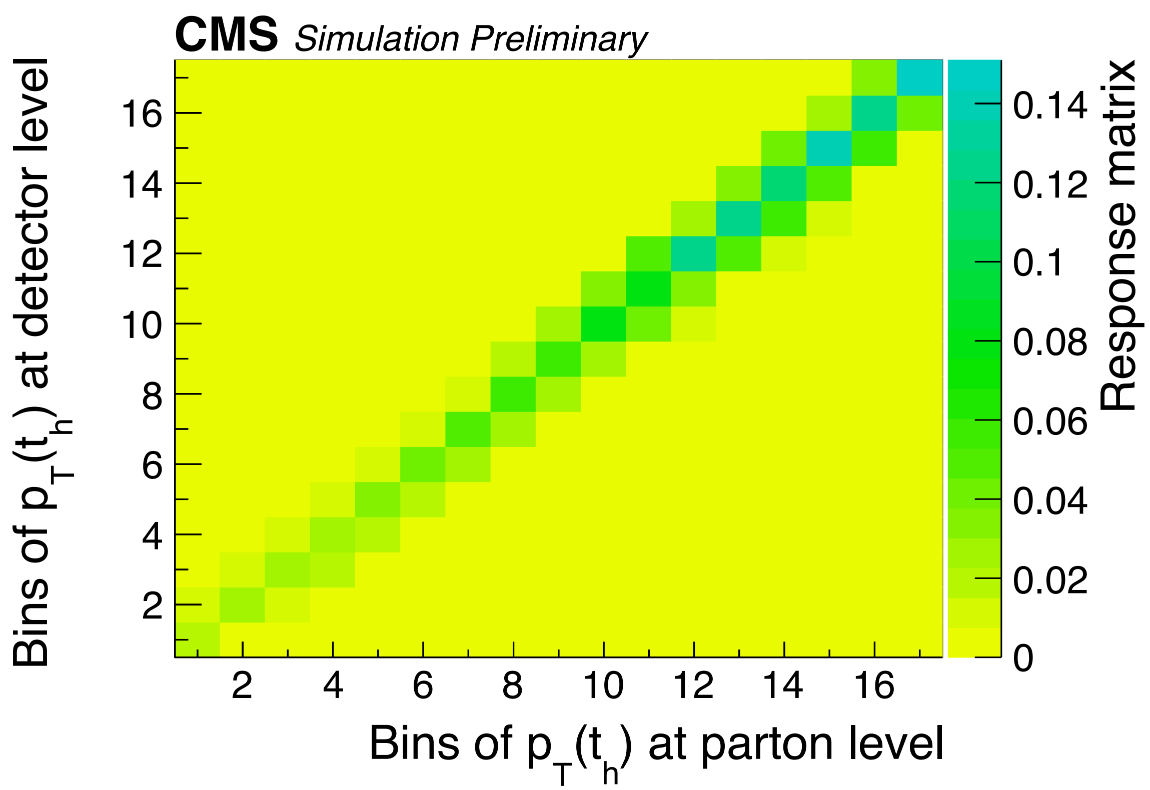

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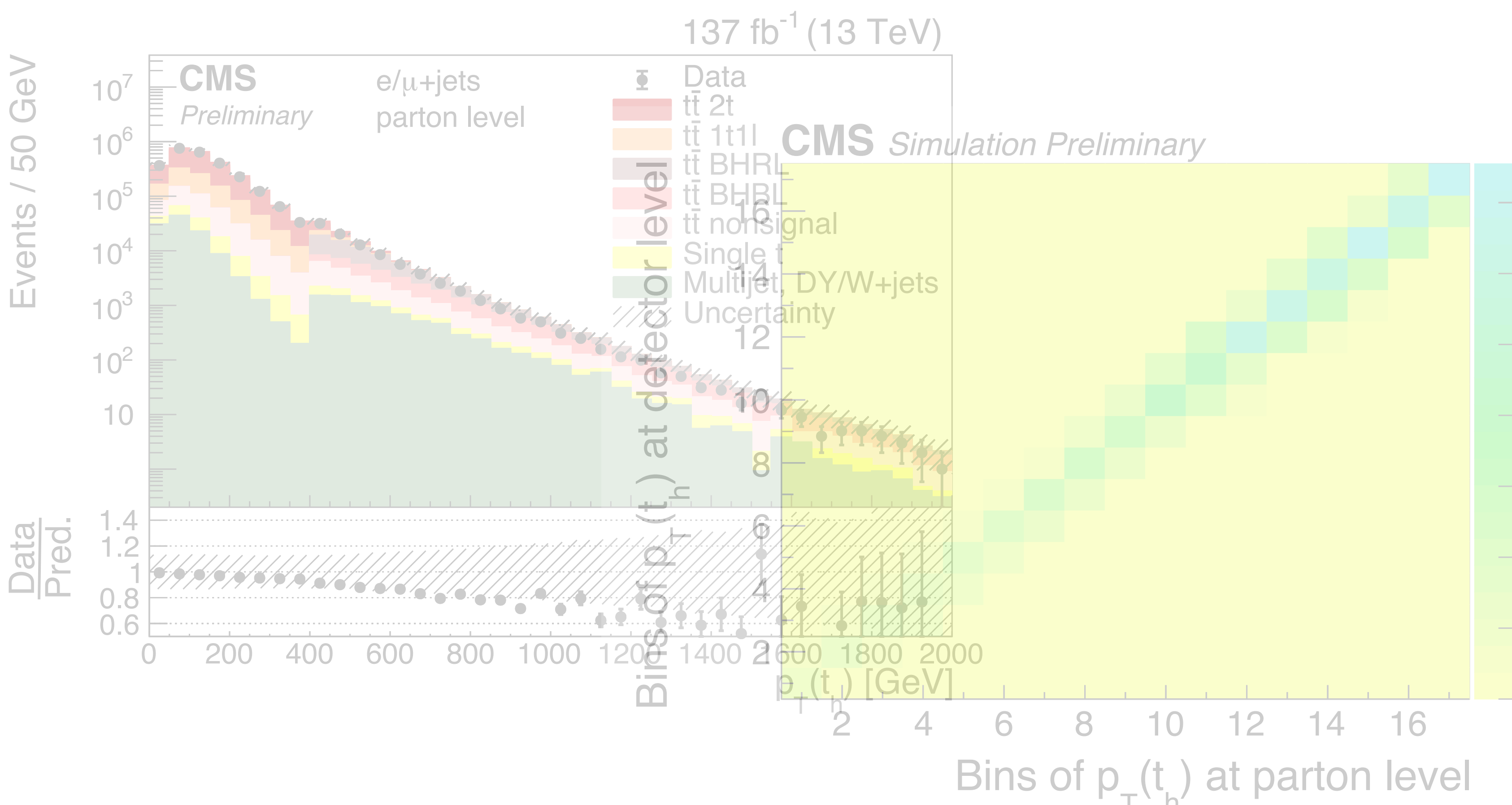

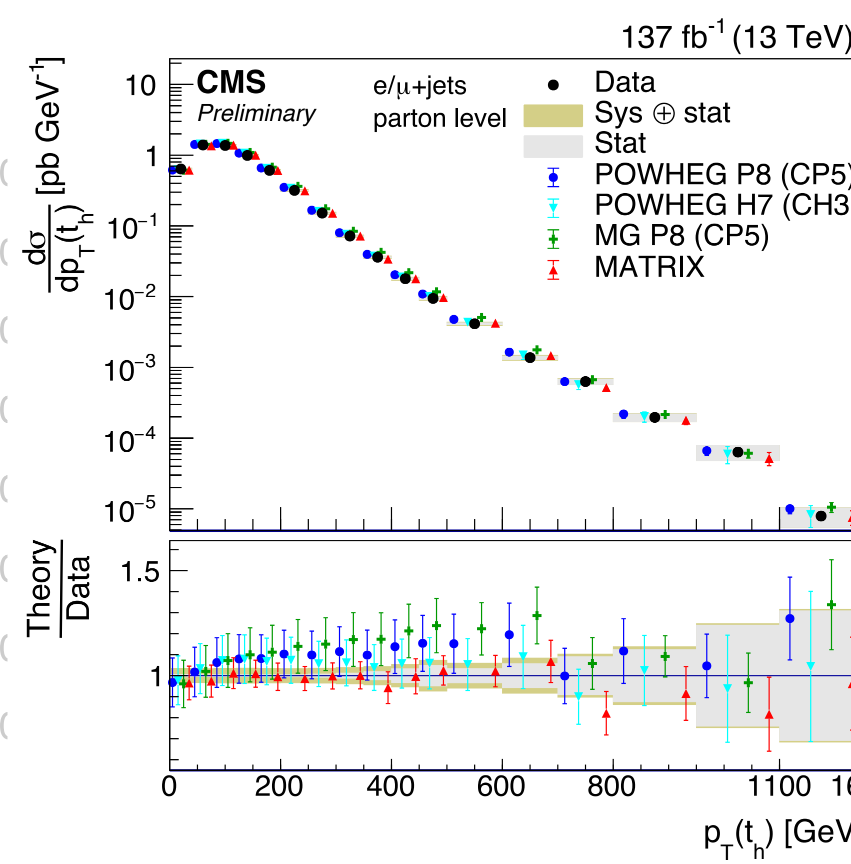

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- The cross-section is extracted from a combined fit to the different channels, 3 selections x 2 lepton flavours x 3 data taking years.

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Expected events in detector ($\boldsymbol{s}$); Response matrix (R); Cross-section to extract ($\boldsymbol{\sigma}$); background ($\boldsymbol{b}$)

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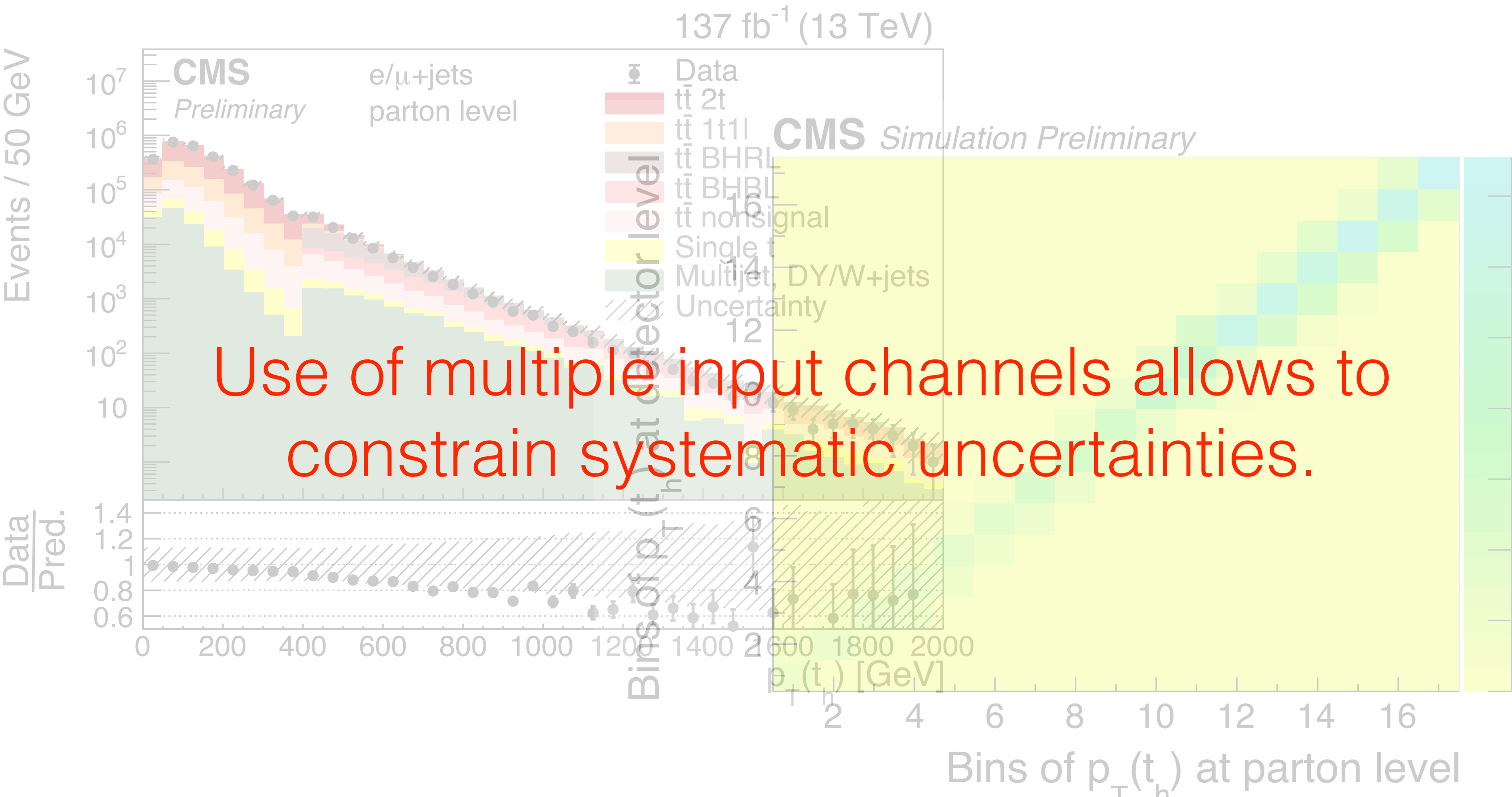
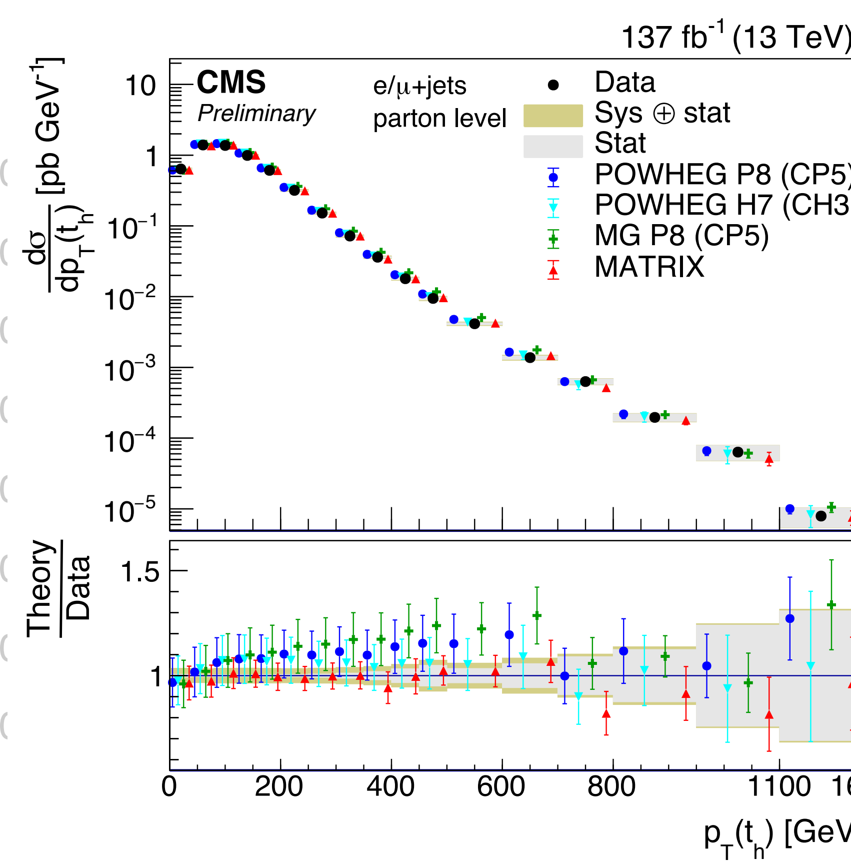
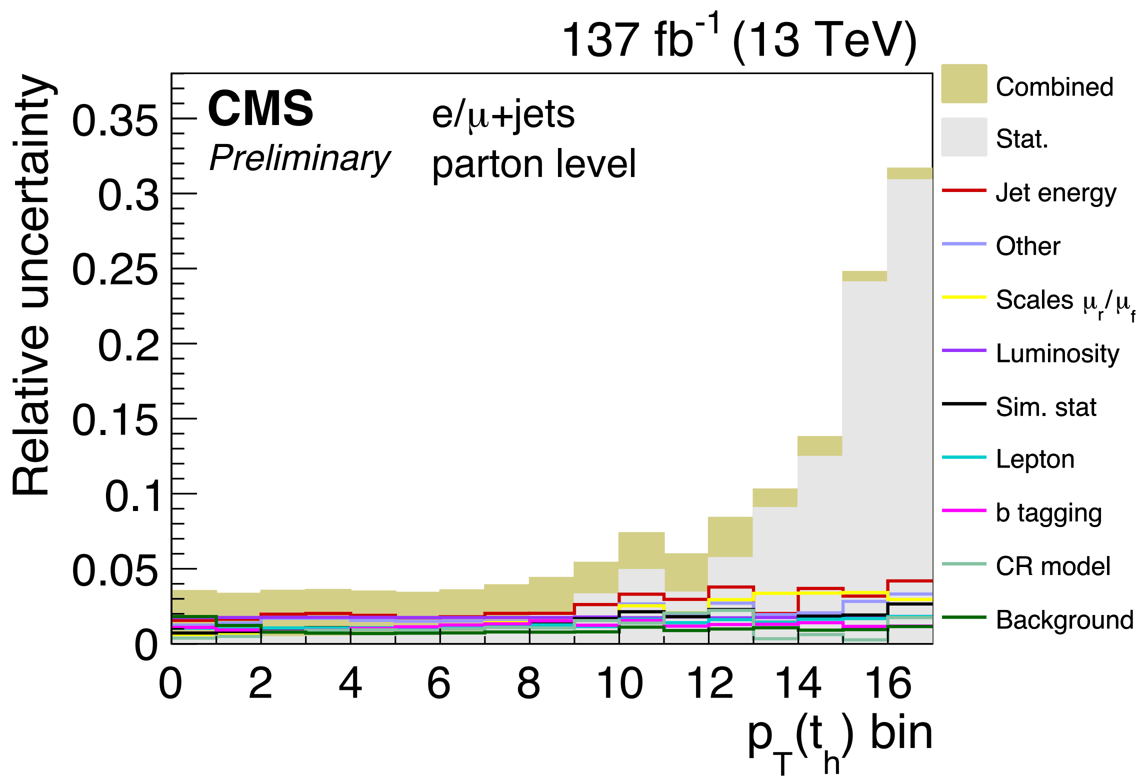
Measured events in detector ($\boldsymbol{m}_{yc\ell}$); Expected events in detector ($\boldsymbol{s}_{yc\ell}$); Statistical uncertainty of data ($C_{yc\ell}$); Systematic uncertainties (Q)

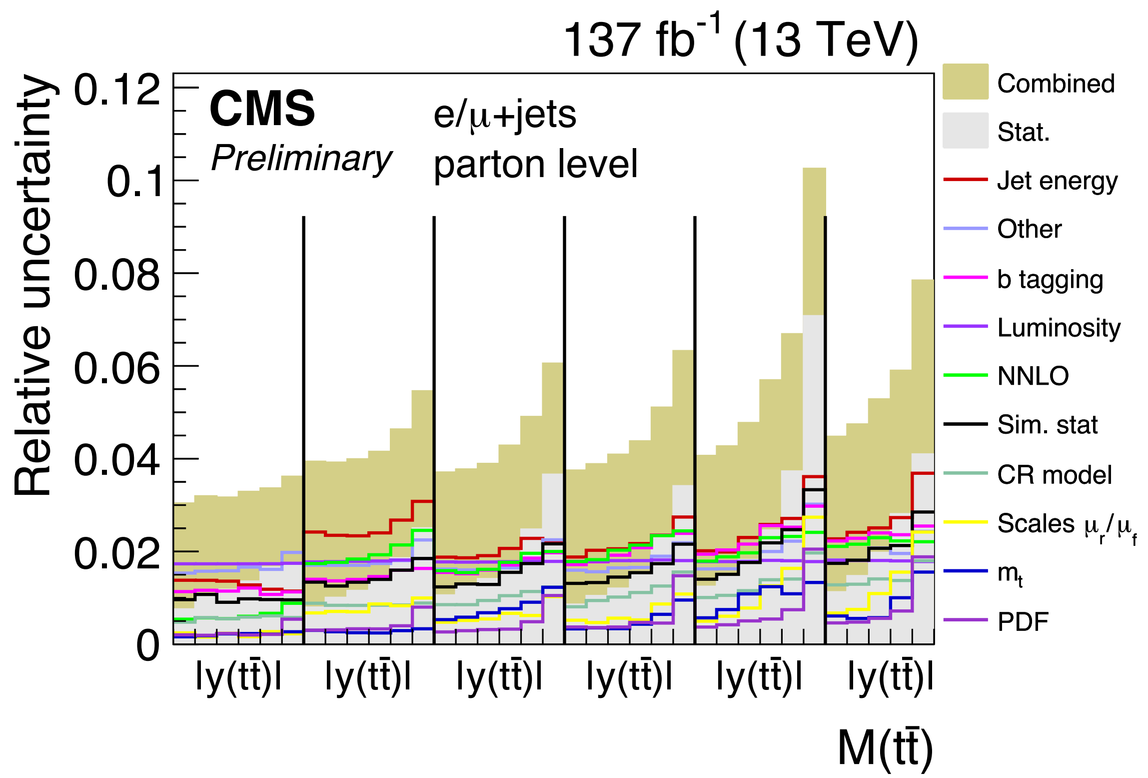


Use of multiple input channels allows to constrain systematic uncertainties.



Uncertainties





- Measurement has very good precision: < 5% in many bins.
- Largest systematics from jet energy scale & modelling of $t\bar{t}$ production.
- Statistical uncertainty matters in the high p_T / mass tails.

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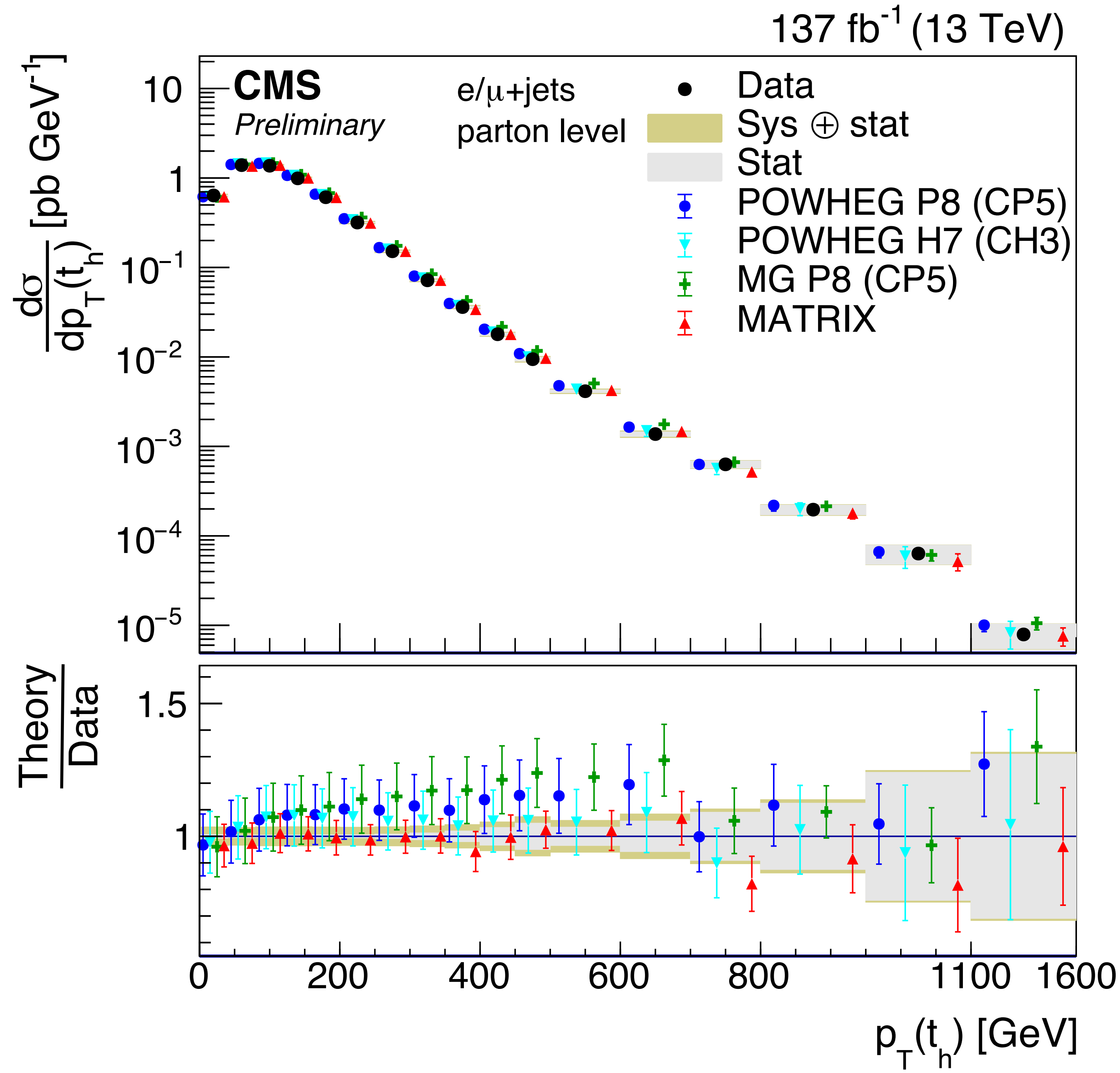
Results

- NNLO improves agreement with top pT distribution:



Note all MC are normalised to NNLO+NNLL.

Matrix is NNLO.

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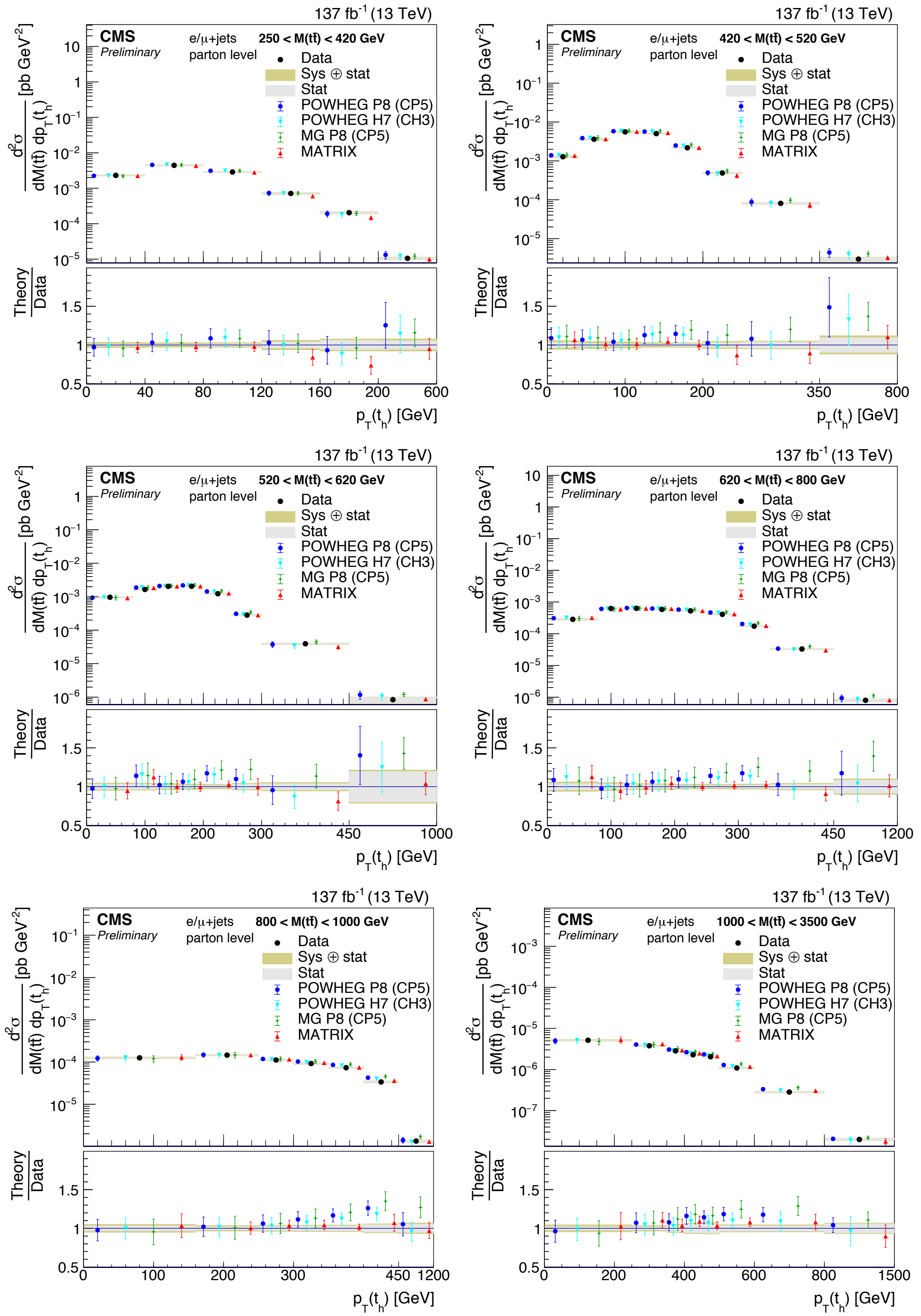
Results

- Double differential, e.g. $p_T(t)$ vs $m(t\bar{t})$:
- Many variables well modelled, but $p_T(t)$ vs $m(t\bar{t})$ shows poor agreement (χ^2 calculation).



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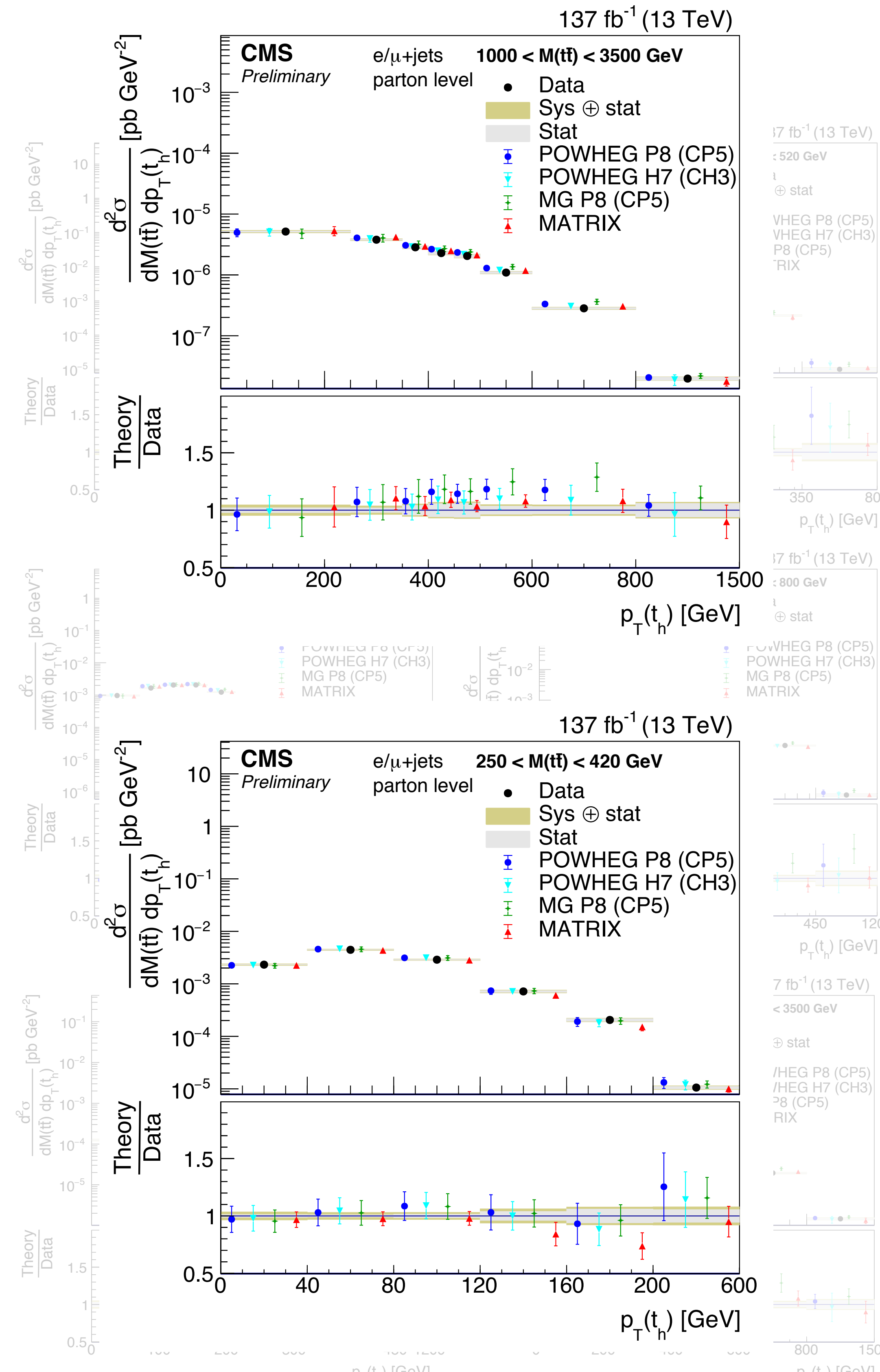

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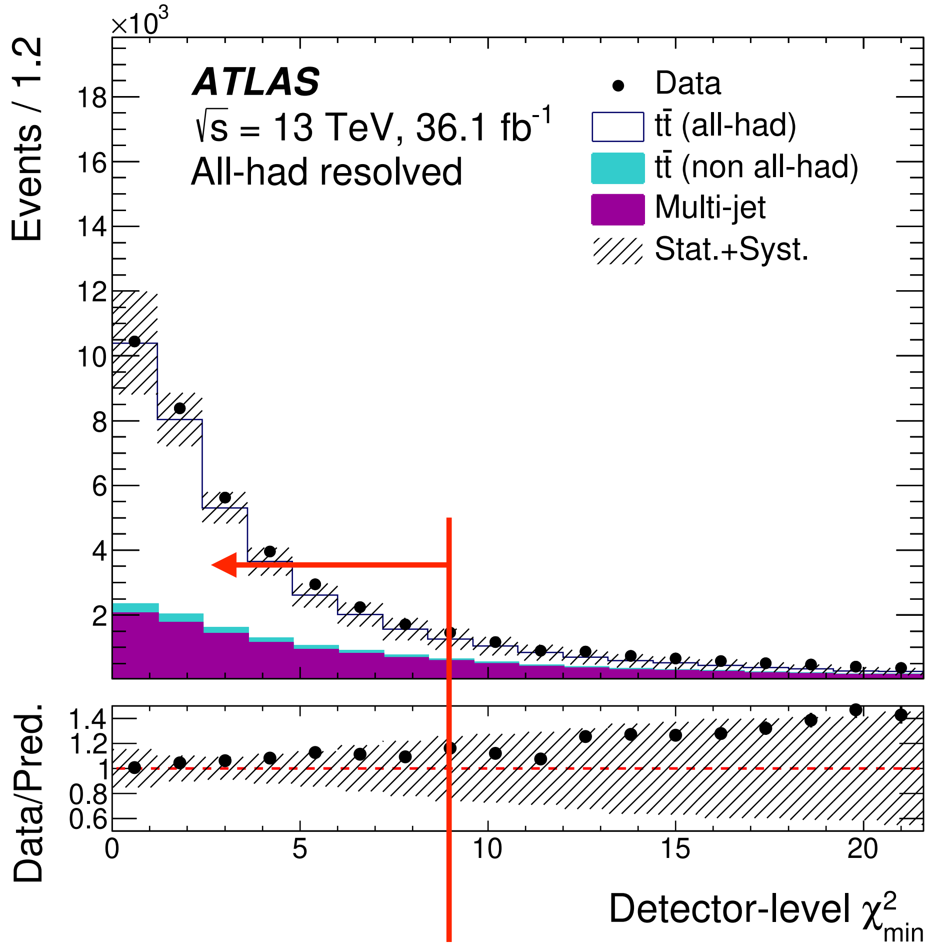
ATLAS all-hadronic differential cross-section

- Important to test all decay modes to differentiate modelling effects in hadronic top decays.
- Recent ATLAS measurement selects all-hadronic events with >=6 jets (p_T > 55 GeV), two of which are b-tagged.
- Selections on the top reconstruction suppress backgrounds:



JHEP 01 (2021) 033

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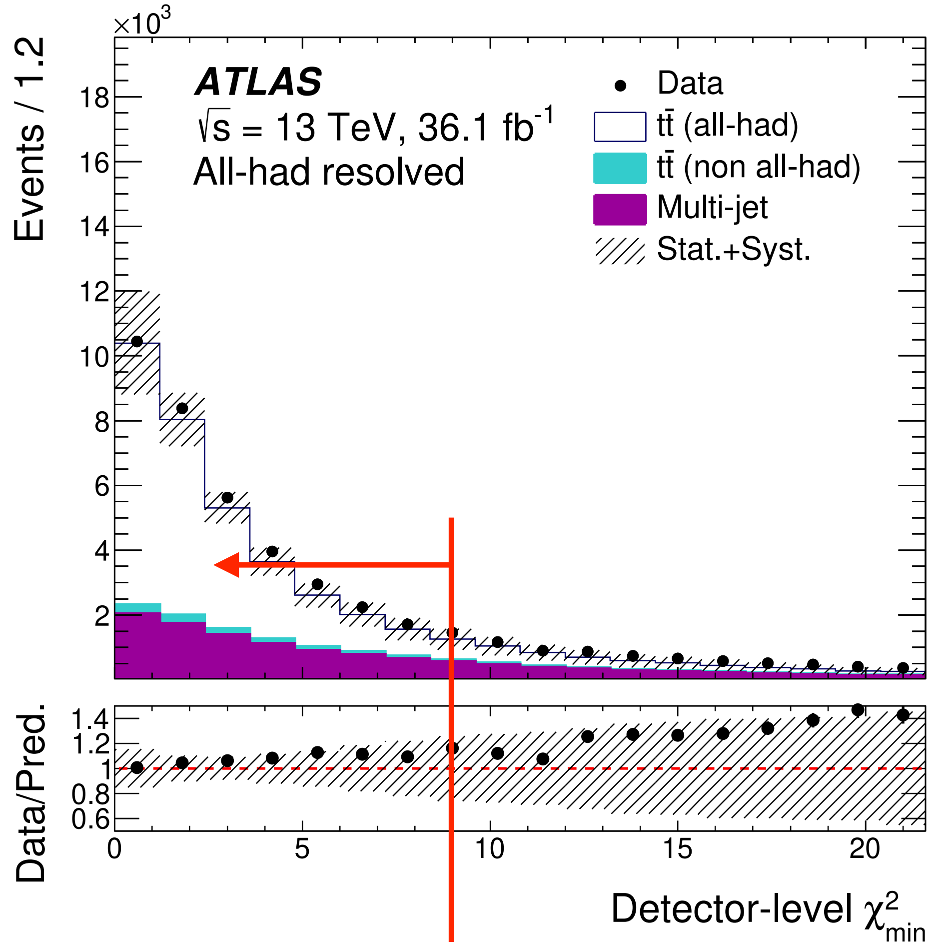

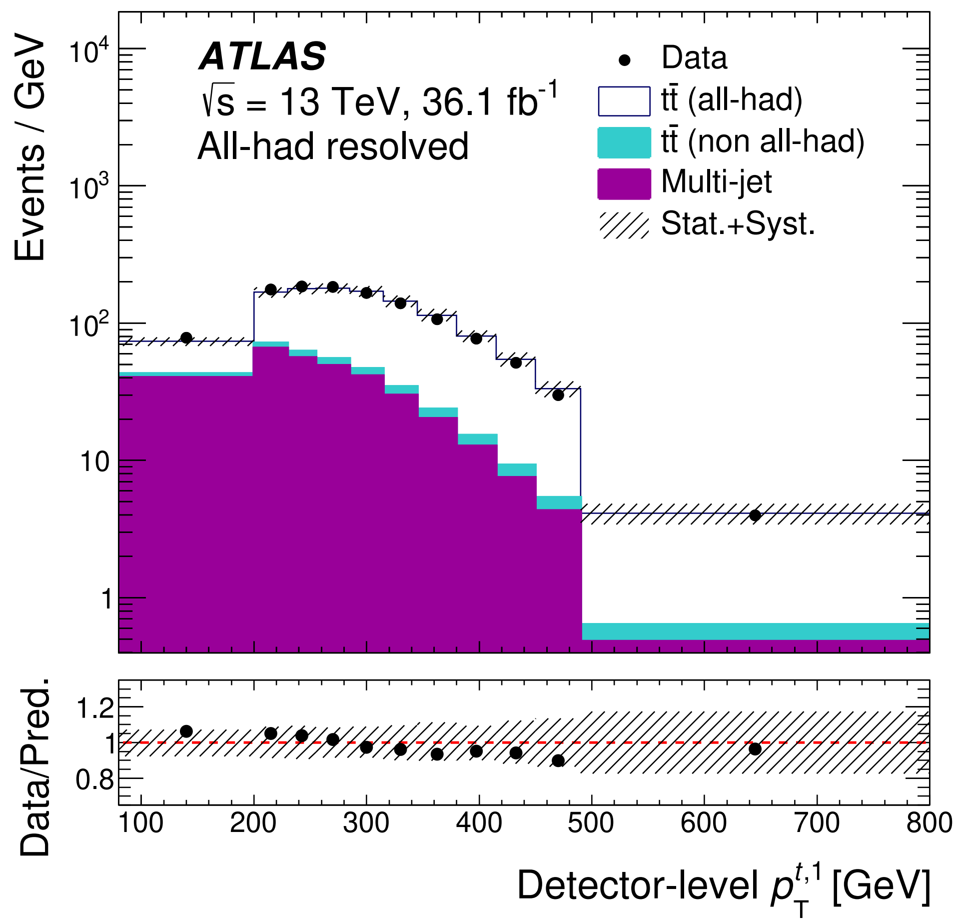

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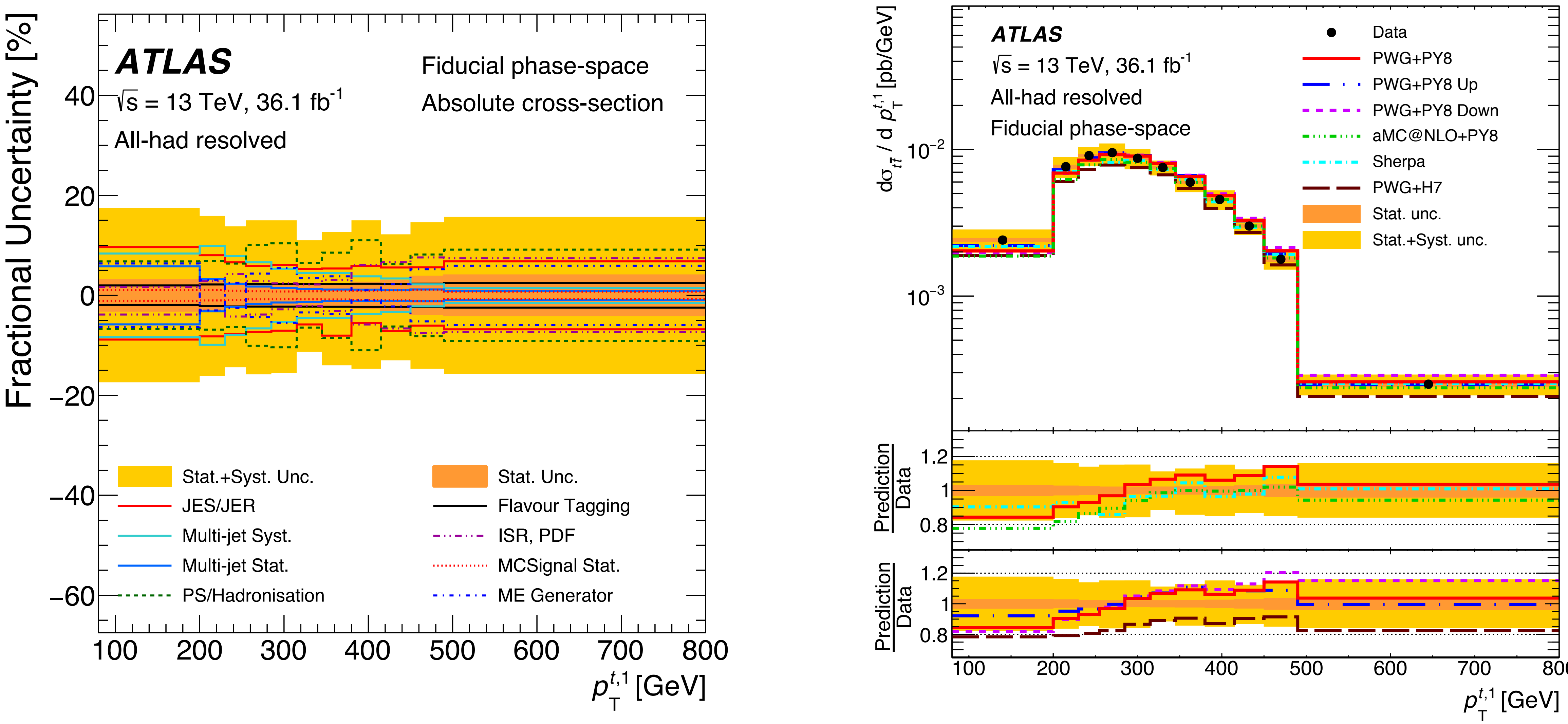
Results

- Less precision than l+jets results, but same trend in top p_T is seen:



- The publication includes several variables sensitive to additional QCD radiation.

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ATLAS dilepton differential

- The number of events with 1 and 2 b-tagged jets are used to determine the $t\bar{t}$ differential cross-section inclusive of all jet-activity:

$$N_1^i = L\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i (1 - C_b^i \epsilon_b^i) + N_1^{i,\mathrm{bkg}},$$

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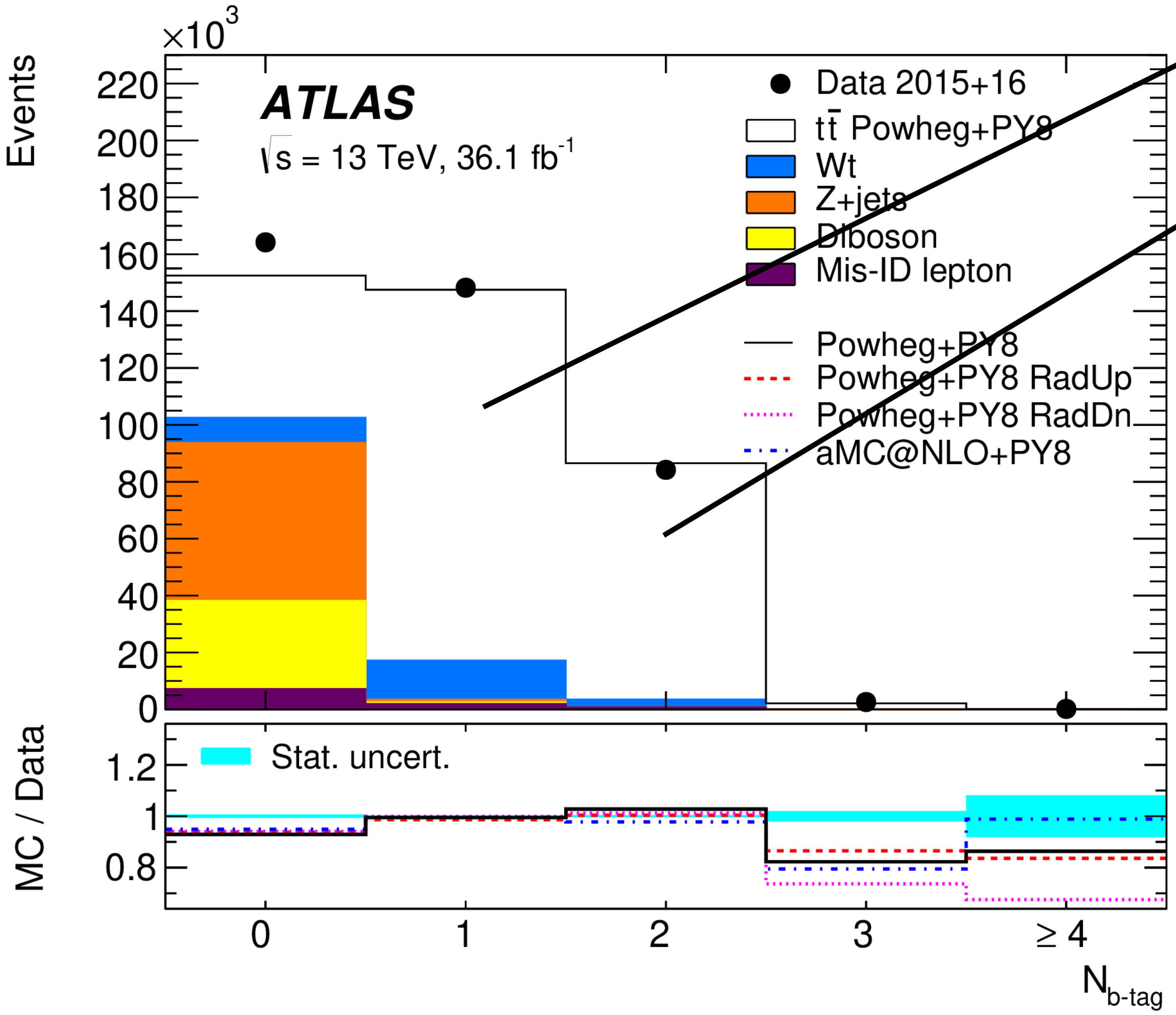

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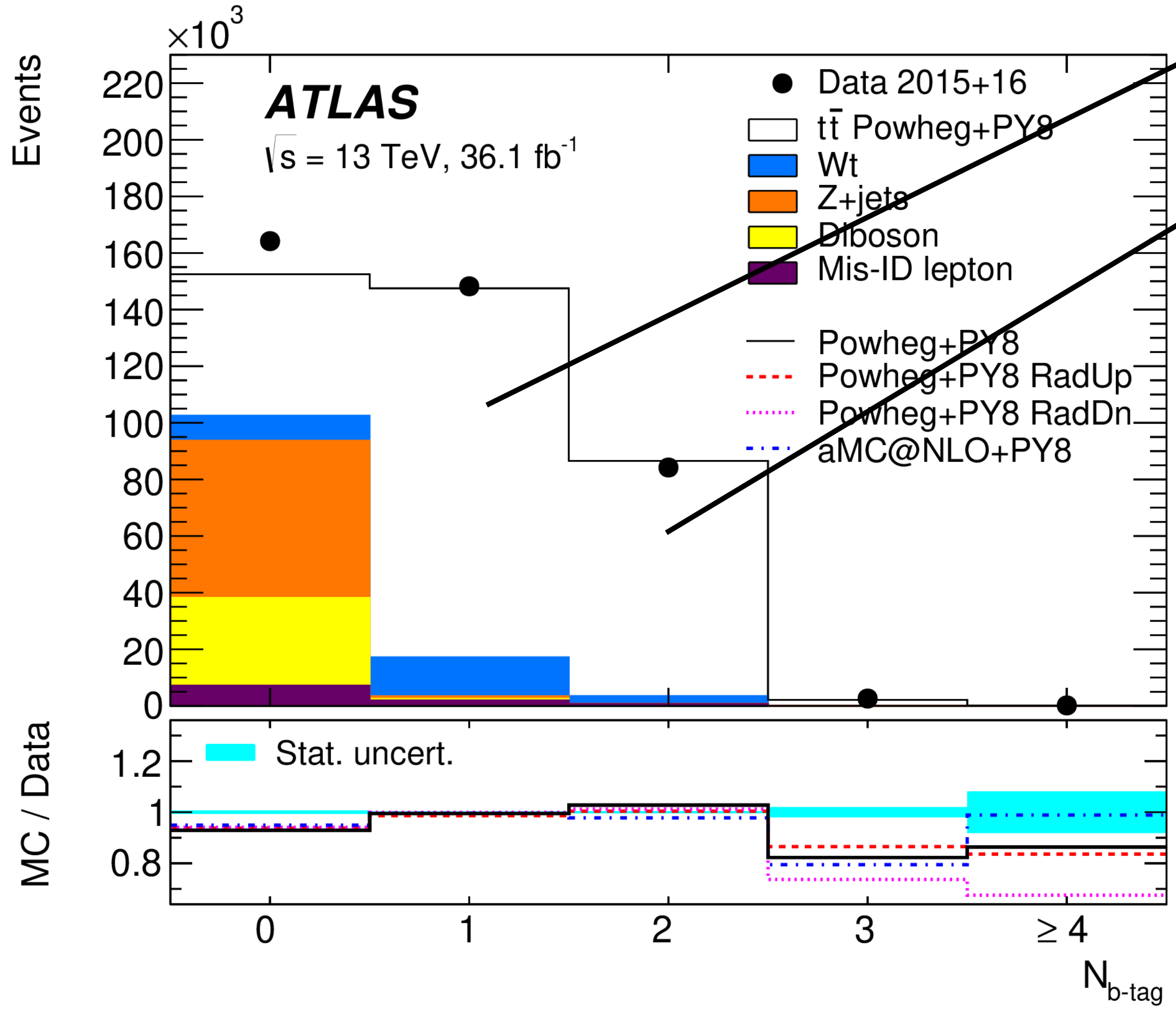

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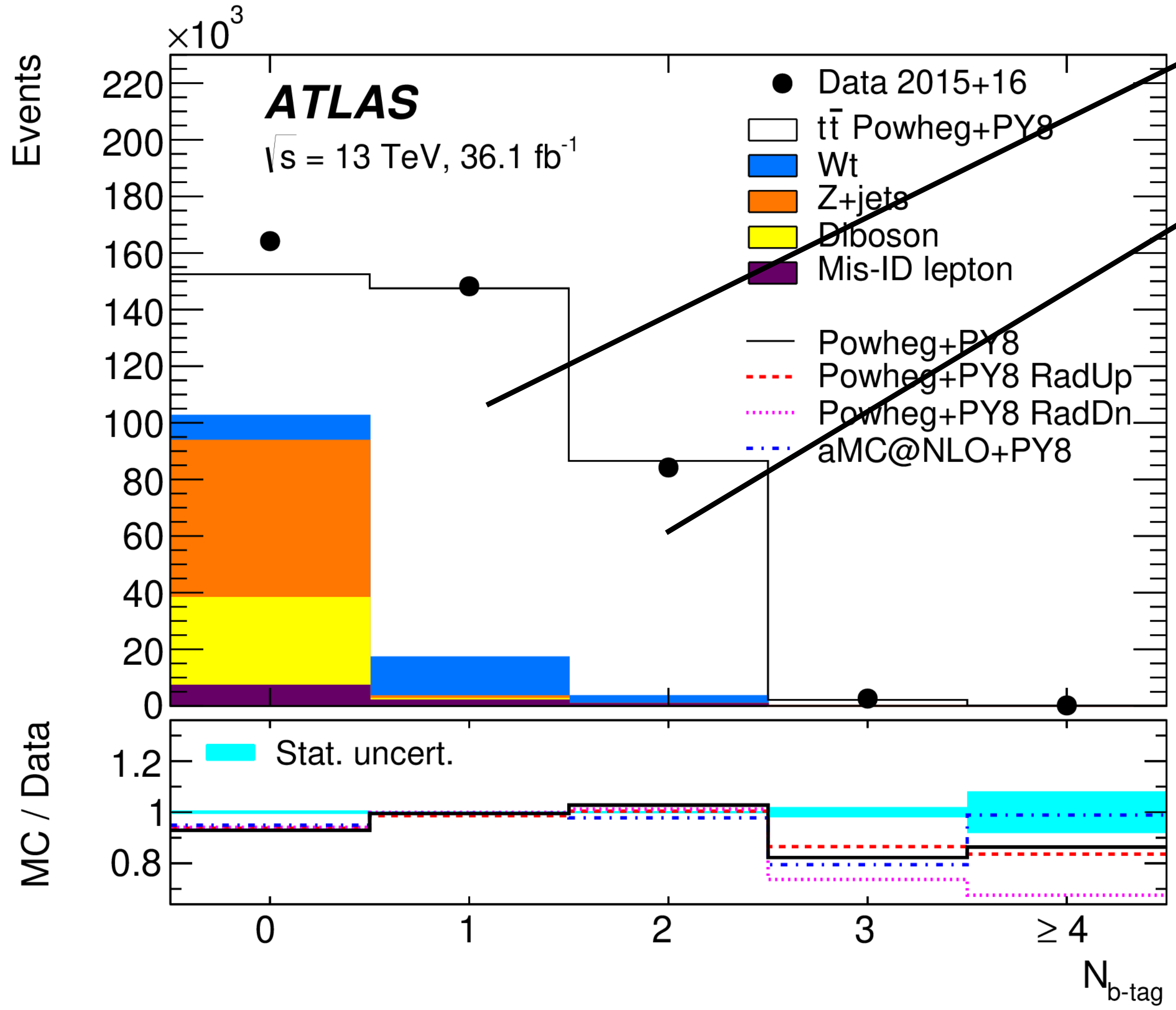

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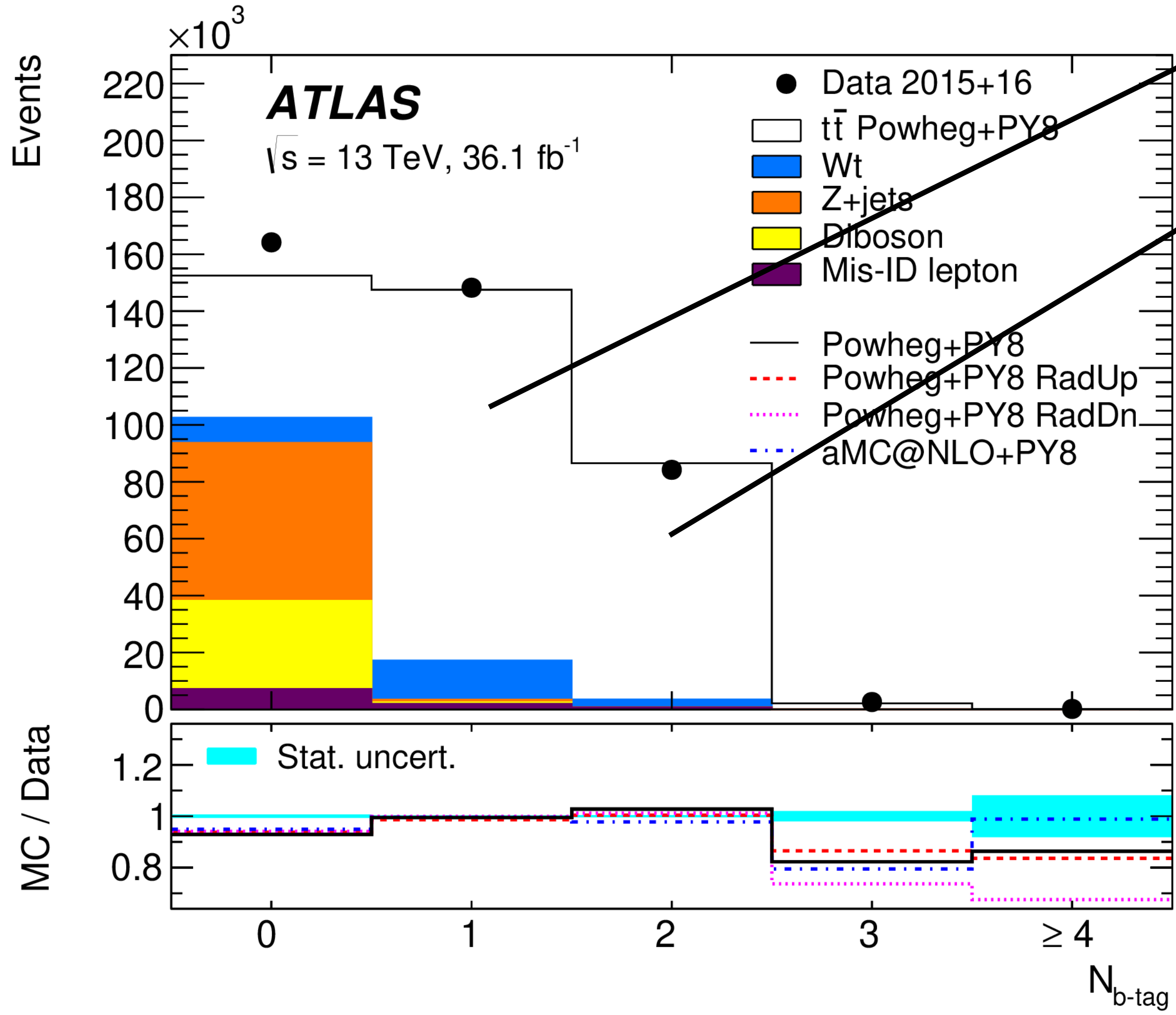

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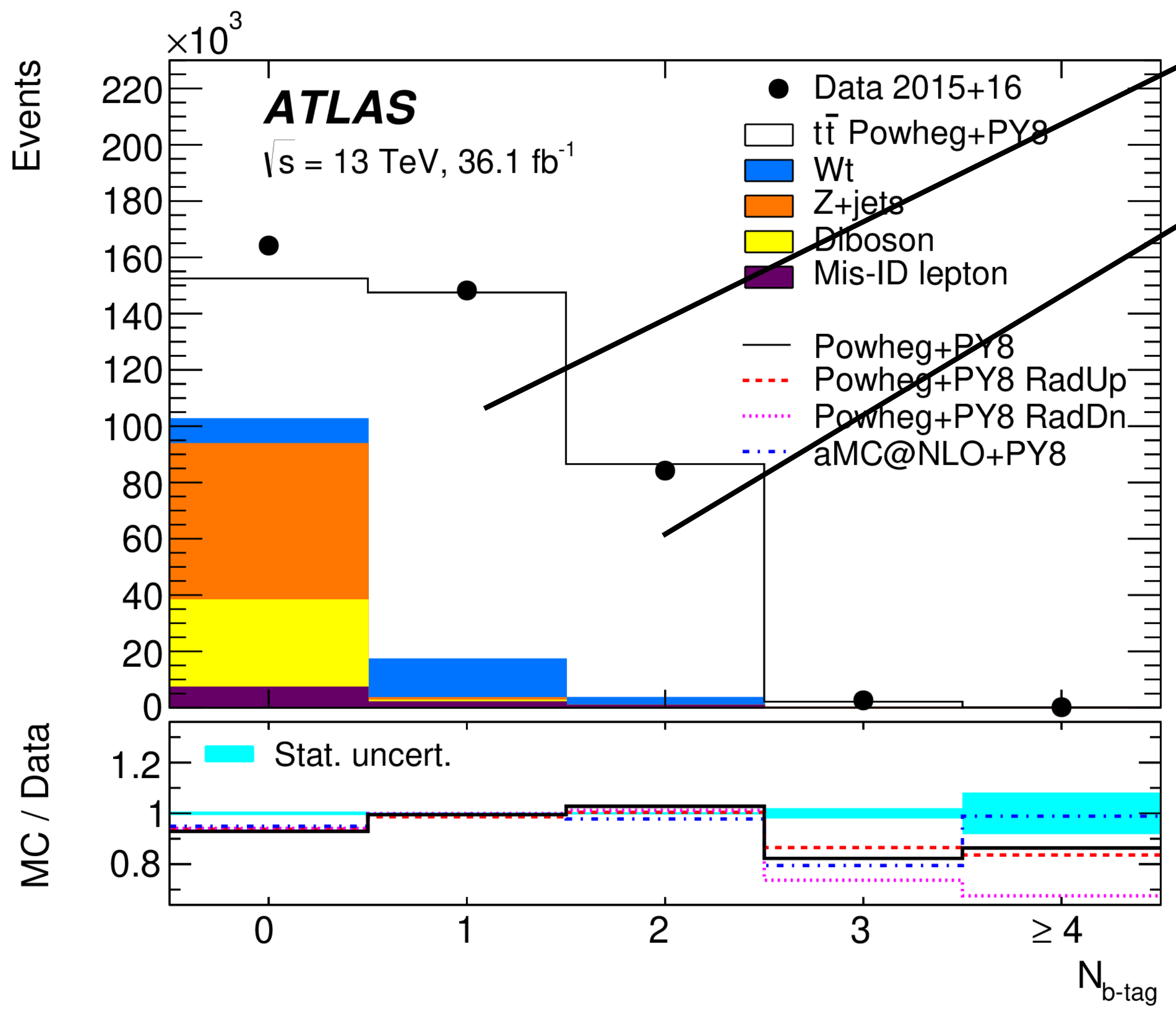

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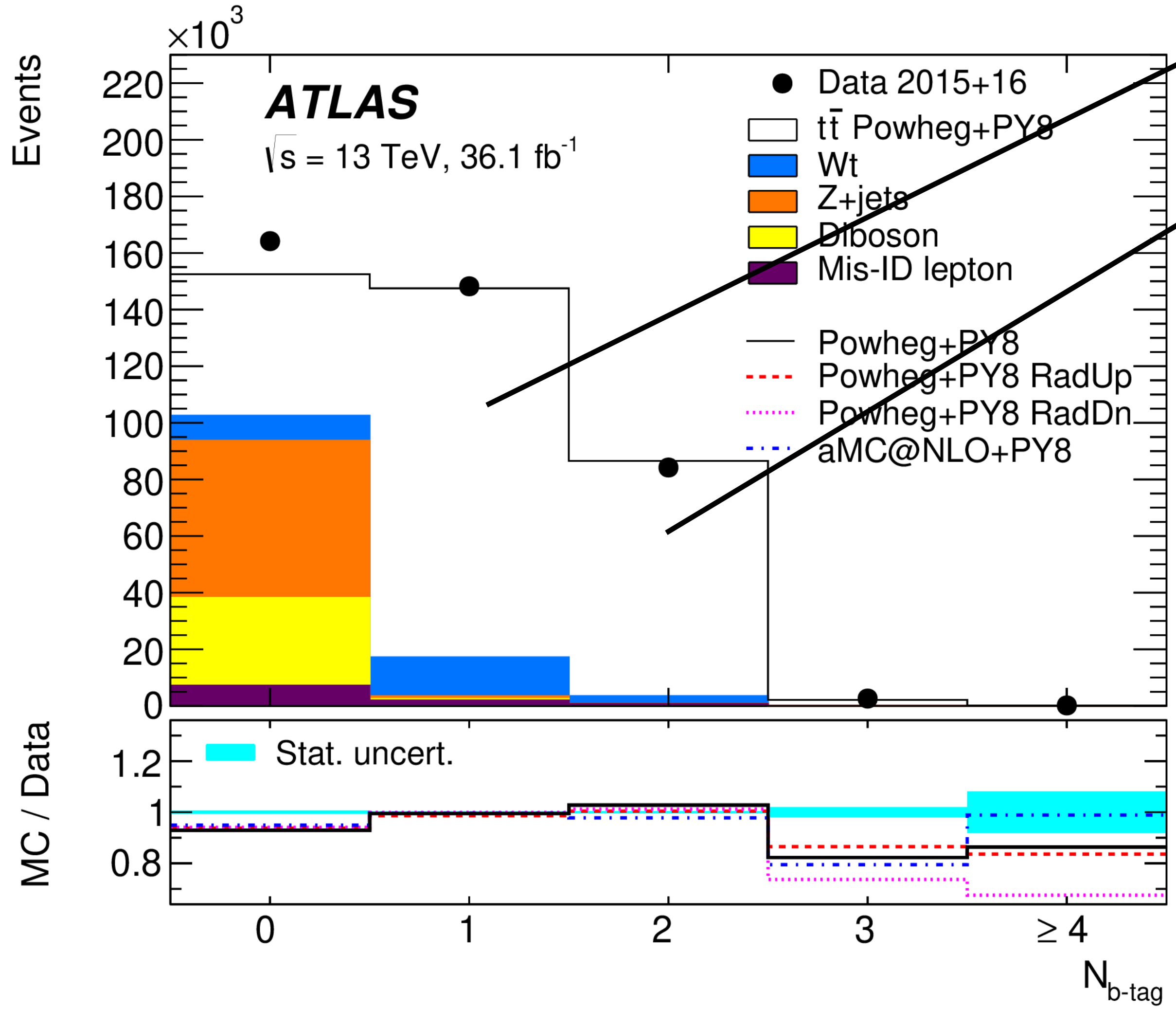

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Simultaneous fit for $\sigma_{t\bar{t}}^i$ and ϵ_b.

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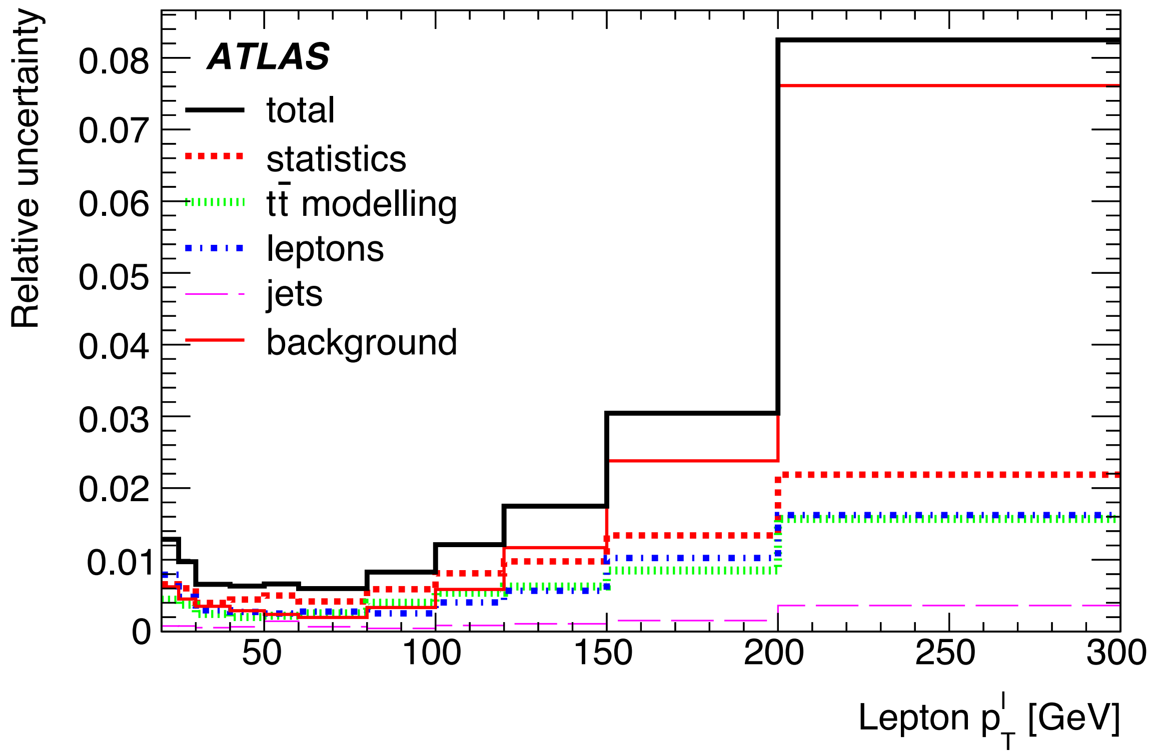
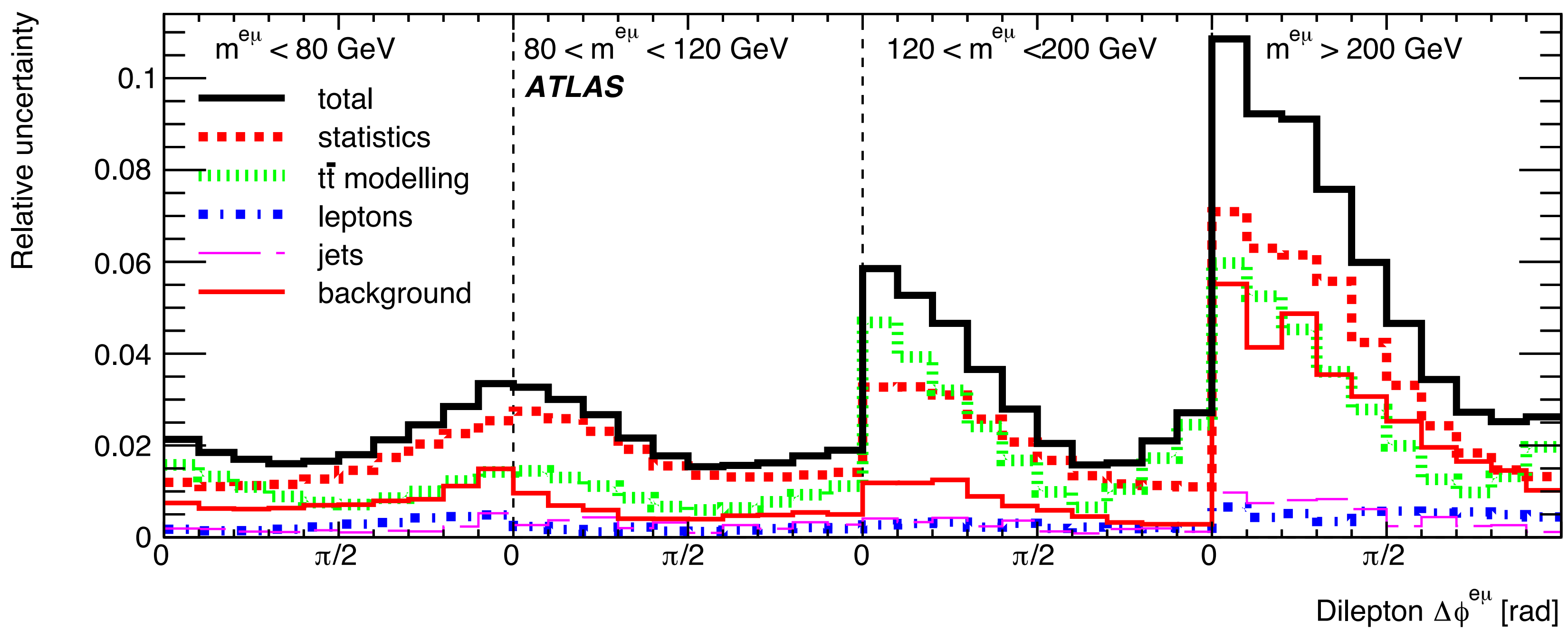
Uncertainties

- High precision measurement, reaching %-level on shape:





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Results

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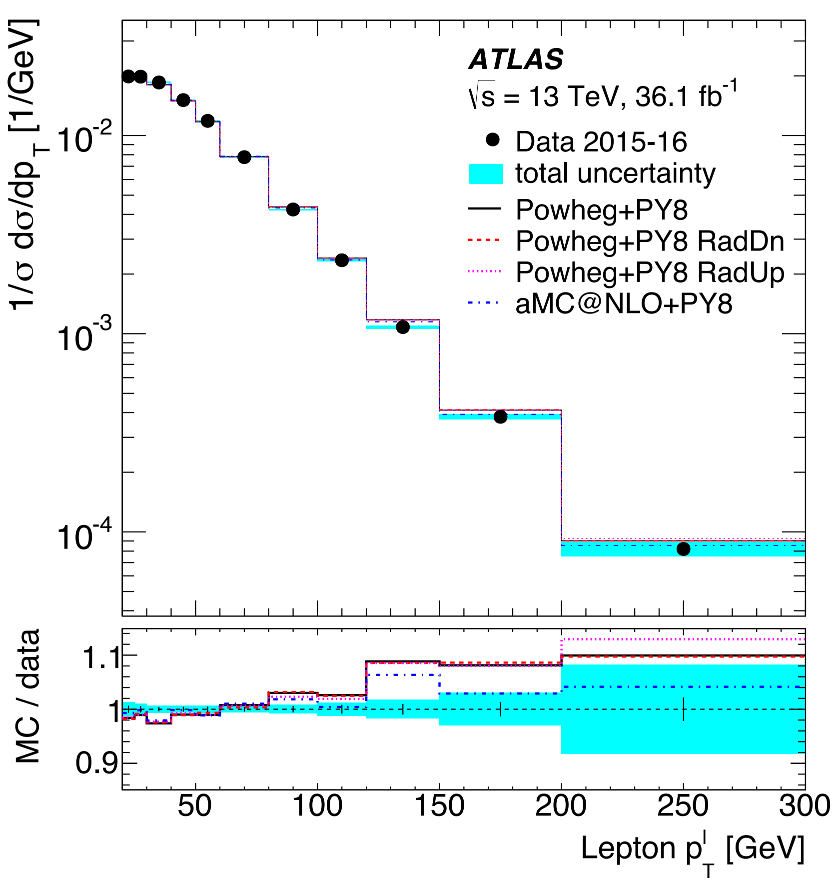

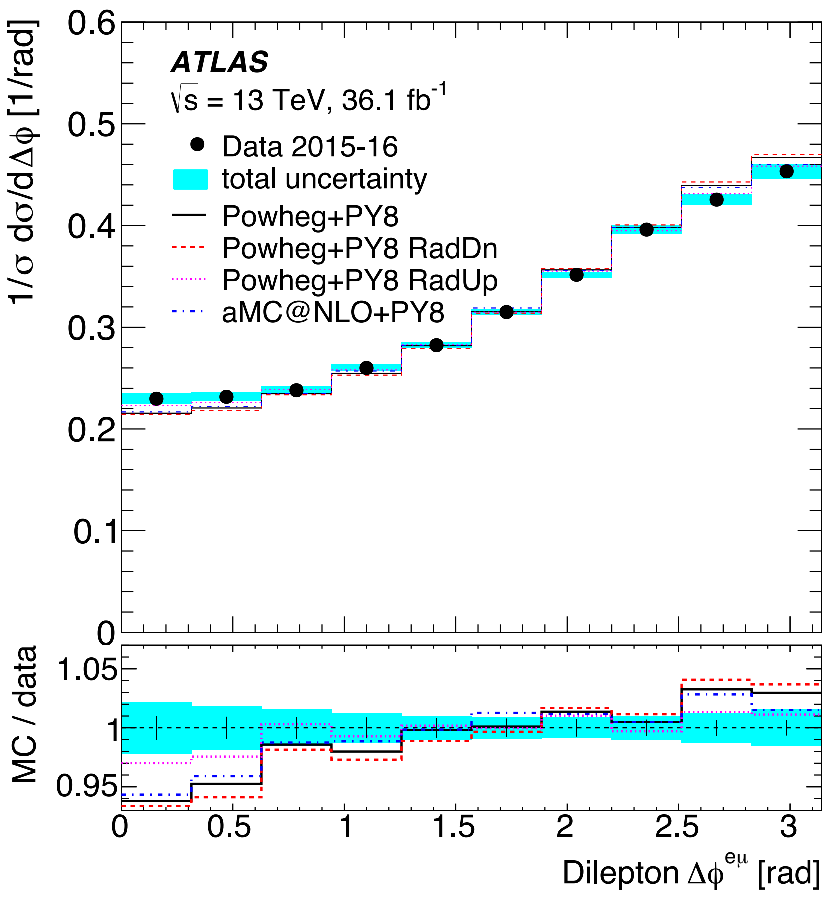

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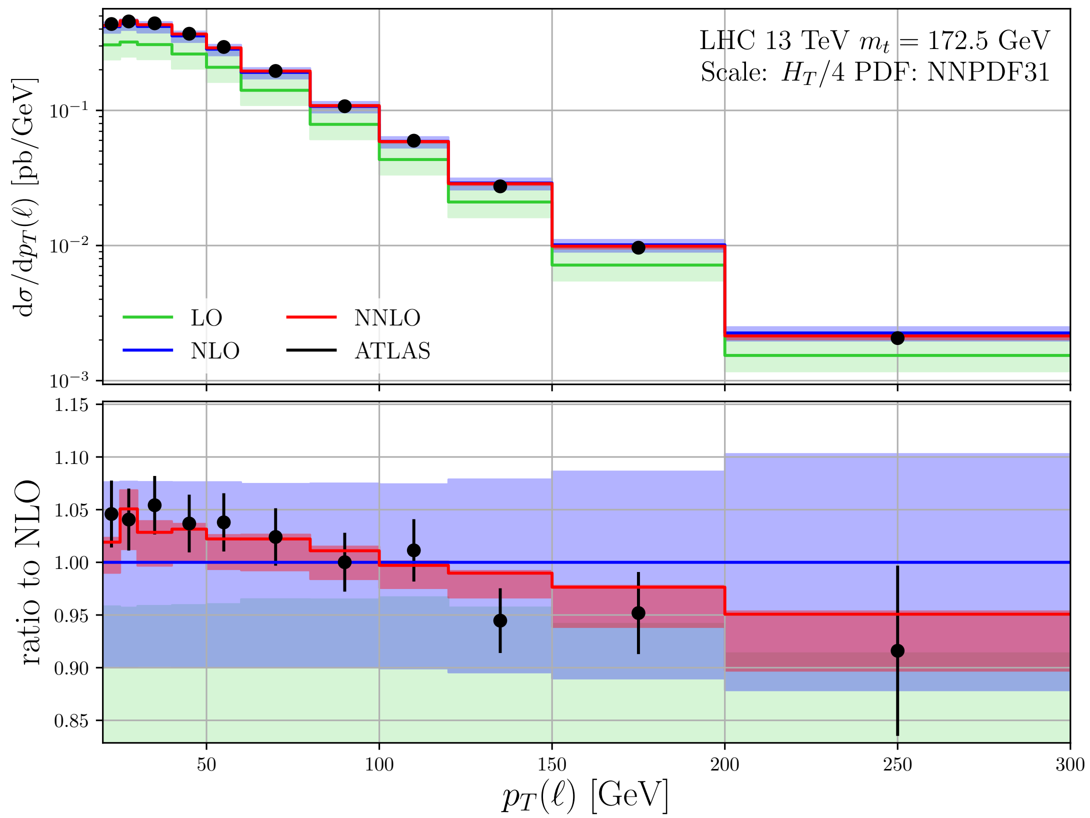
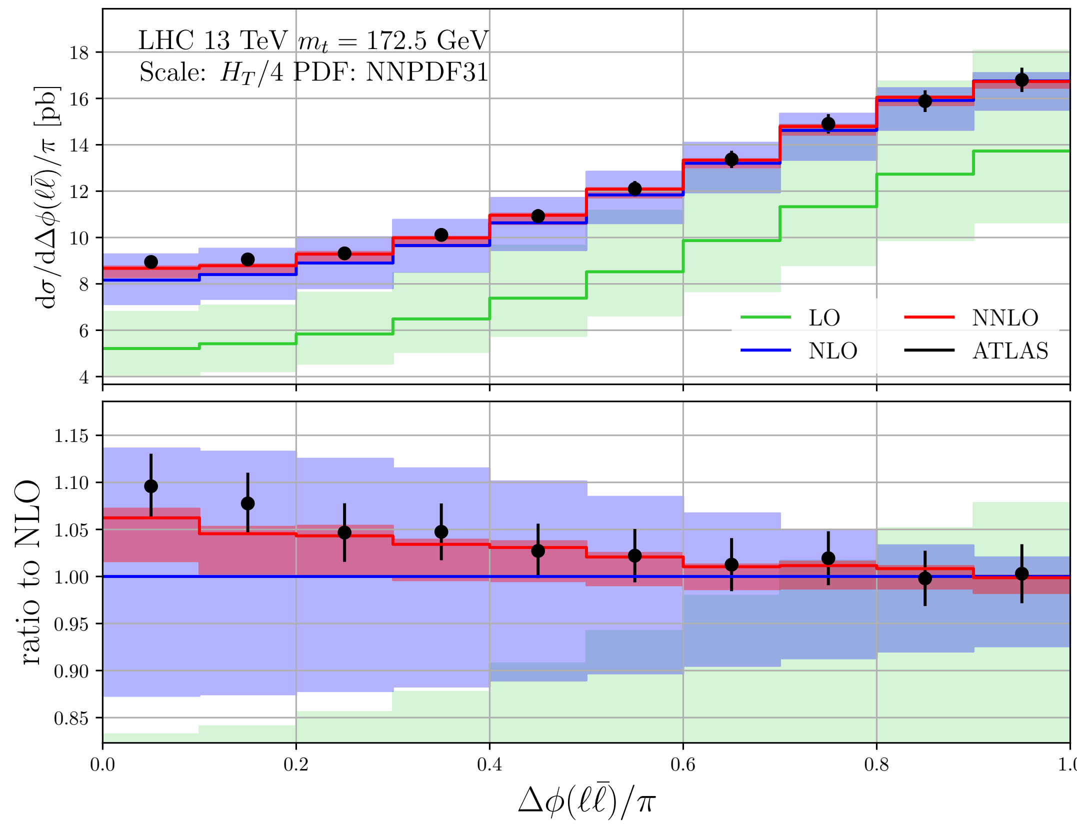
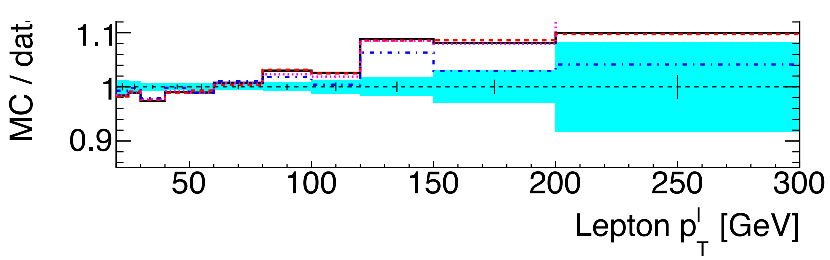
arXiv:2008.11133

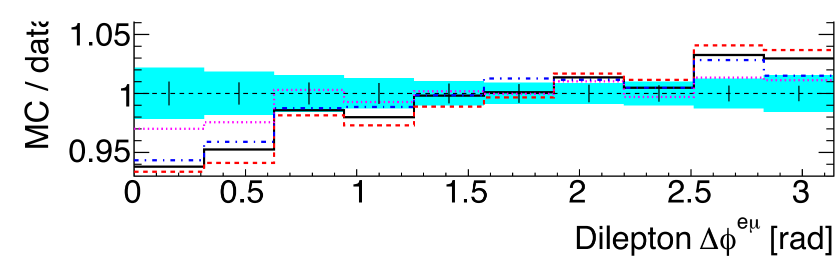
Results

- Precision motivates to go beyond NLO+PS precision:









Eur. Phys. J. C 80 (2020) 528

arXiv:2008.11133

Summary of $t\bar{t}$ differential cross-section measurements

- Impressive range of measurements - many channels & many (2D) distributions.
- There is a consistent picture that the NLO+PS generators predict a harder top pT distribution than observed.
- The most precise measurements (i.e. CMS l+jets, ATLAS dilepton) seem to point to needing NNLO to fully describe the data.
- Much interesting work on interpreting the data (top mass, Y_t, EFT), which will continue to be expanded - see Soureek's talk.

$t\bar{t}$ inclusive cross-section measurements

Inclusive cross-section measurements

- The techniques outlined earlier for the CMS l+jets and ATLAS dilepton measurements also give the most precise inclusive cross-section measurements:

$$\sigma^{\mathrm{NNLO+NNLL}} = 832 \pm 42 \text{ pb}$$

CMS

Source	Uncertainty [pb] (%)
Jet energy	10.9 (1.38)
Branching fraction	8.80 (1.11)
Lepton	7.78 (0.98)
NNLO	7.56 (0.96)
b tagging	6.96 (0.88)
Sim. stat	6.46 (0.82)
Background	6.10 (0.77)
CR model	5.45 (0.69)
Jet energy res.	3.36 (0.43)
Scales μ_r/μ_f	3.24 (0.41)
ISR scale	3.19 (0.40)
FSR scale	2.71 (0.34)
Subjet energy	2.42 (0.31)
Mistagging	2.20 (0.28)
Tune	2.16 (0.27)
m_t	2.08 (0.26)
PDF	1.94 (0.25)
h_{damp}	1.51 (0.19)
L1 prefire	0.53 (0.07)
Pileup	0.40 (0.05)
Sys	21.1 (2.66)
Stat	0.56 (0.07)
Luminosity	13.8 (1.75)

$$\sigma = 791 \pm 25 \text{ pb}$$

CMS-PAS-TOP-20-001

ATLAS

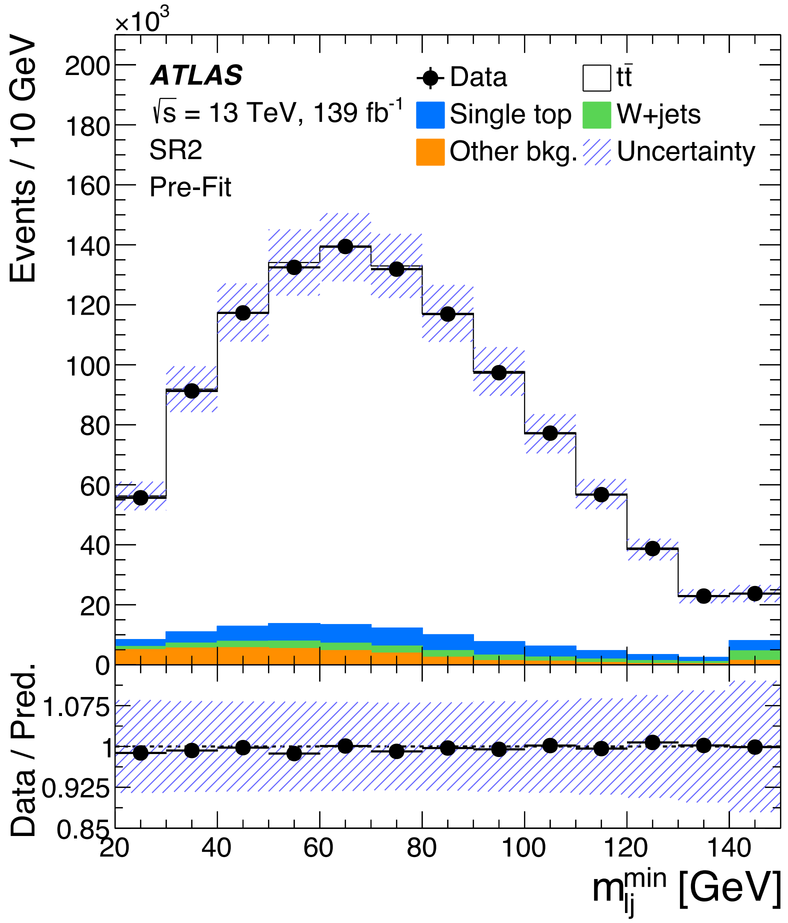
	Uncertainty source	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
	Data statistics	0.44
$t\bar{t}$ mod.	$t\bar{t}$ generator	0.43
	$t\bar{t}$ hadronisation	0.49
	Initial/final-state radiation	0.45
	$t\bar{t}$ heavy-flavour production	0.26
	Parton distribution functions	0.45
	Simulation statistics	0.22
Lept.	Electron energy scale	0.06
	Electron energy resolution	0.01
	Electron identification	0.37
	Electron charge mis-id	0.10
	Electron isolation	0.24
	Muon momentum scale	0.03
	Muon momentum resolution	0.01
	Muon identification	0.30
	Muon isolation	0.18
	Lepton trigger	0.14
Jet/b	Jet energy scale	0.03
	Jet energy resolution	0.01
	Pileup jet veto	0.02
	b-tagging efficiency	0.20
	b-tag mistagging	0.06
Bkg.	Single-top cross-section	0.52
	Single-top/$t\bar{t}$ interference	0.15
	Single-top modelling	0.34
	Z+jets extrapolation	0.09
	Diboson cross-sections	0.02
	Diboson modelling	0.03
	Misidentified leptons	0.43
	Analysis systematics	1.39
L/E_b	Integrated luminosity	1.90
	Beam energy	0.23
	Total uncertainty	2.40

$$\sigma = 826 \pm 20 \text{ pb}$$

Eur. Phys. J. C 80 (2020) 528

ATLAS l+jets inclusive cross-section

- Recent dedicated ATLAS analysis on inclusive cross-section.
- Events must have 1 lepton, >=4 jets & 1 or 2 b-jets and are split into signal regions:
    - SR1: >=4 jets, == 1 b-jet.
    - SR2: ==4 jets, == 2 b-jets.
    - SR3: >=5 jets, == 2 b-jets.



- Cross-section is extracted from a profile-likelihood fit to kinematic variables in the 3 regions.

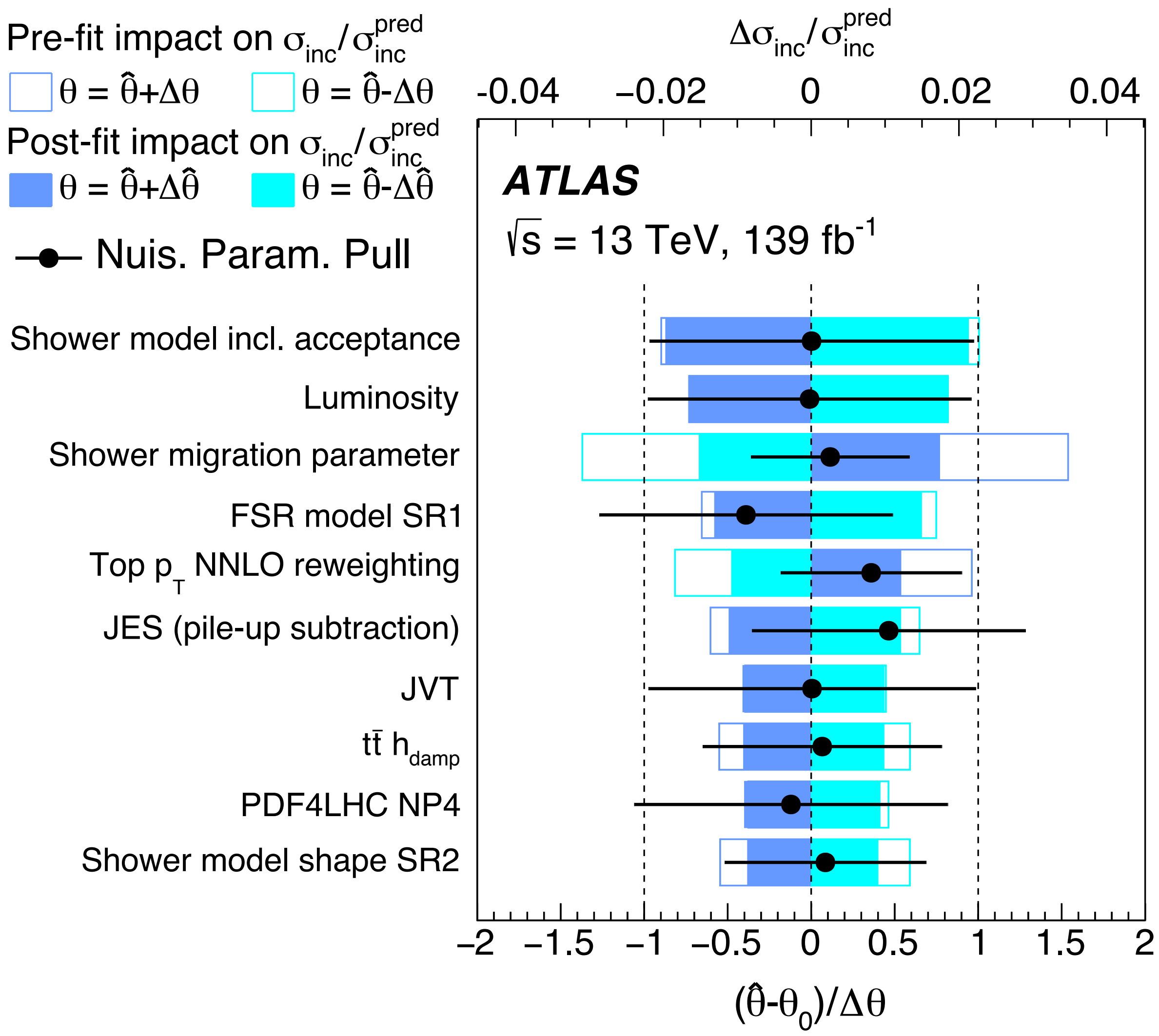
Phys. Lett. B 810 (2020) 135797

ATLAS l+jets inclusive cross-section

- The fit can constrain the systematic uncertainties and reaches a precision of 4.6%:

$$\sigma^{\text{NNLO+NNLL}} = 832 \pm 42 \text{ pb}$$

$$\sigma = 830 \pm 39 \text{ pb}$$



- Good agreement with theory & dilepton measurement.

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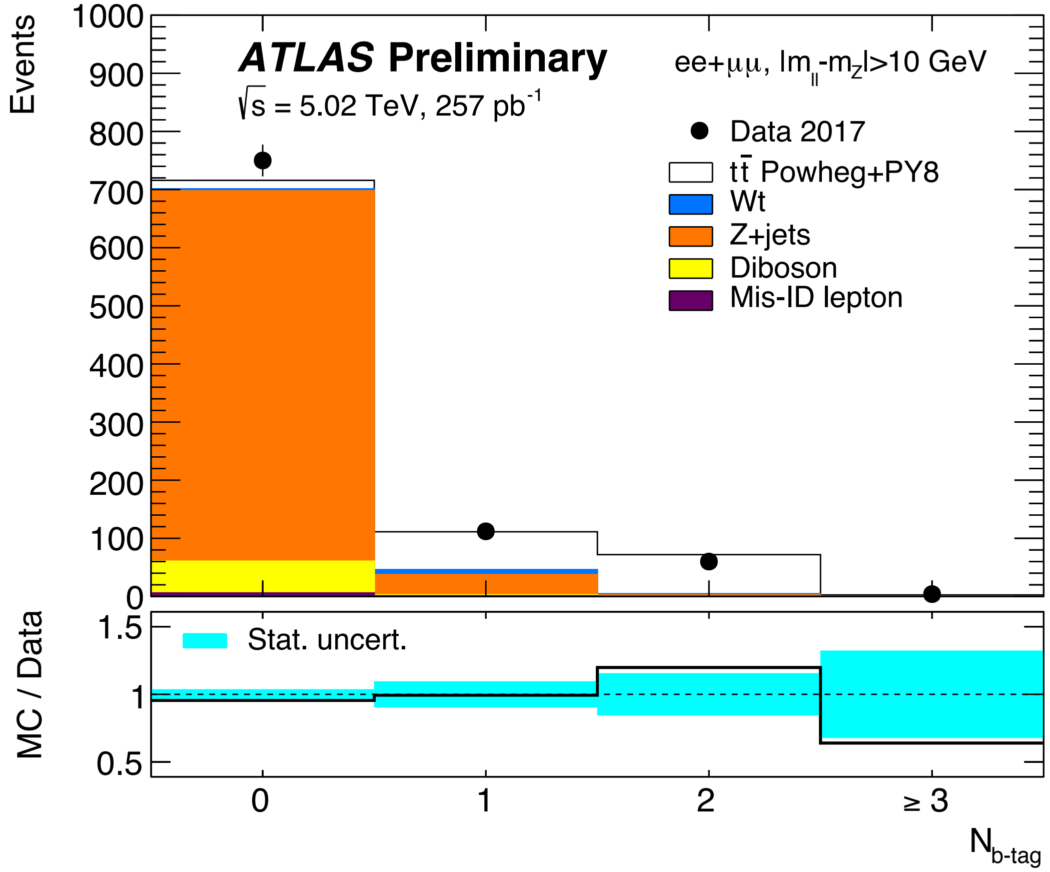
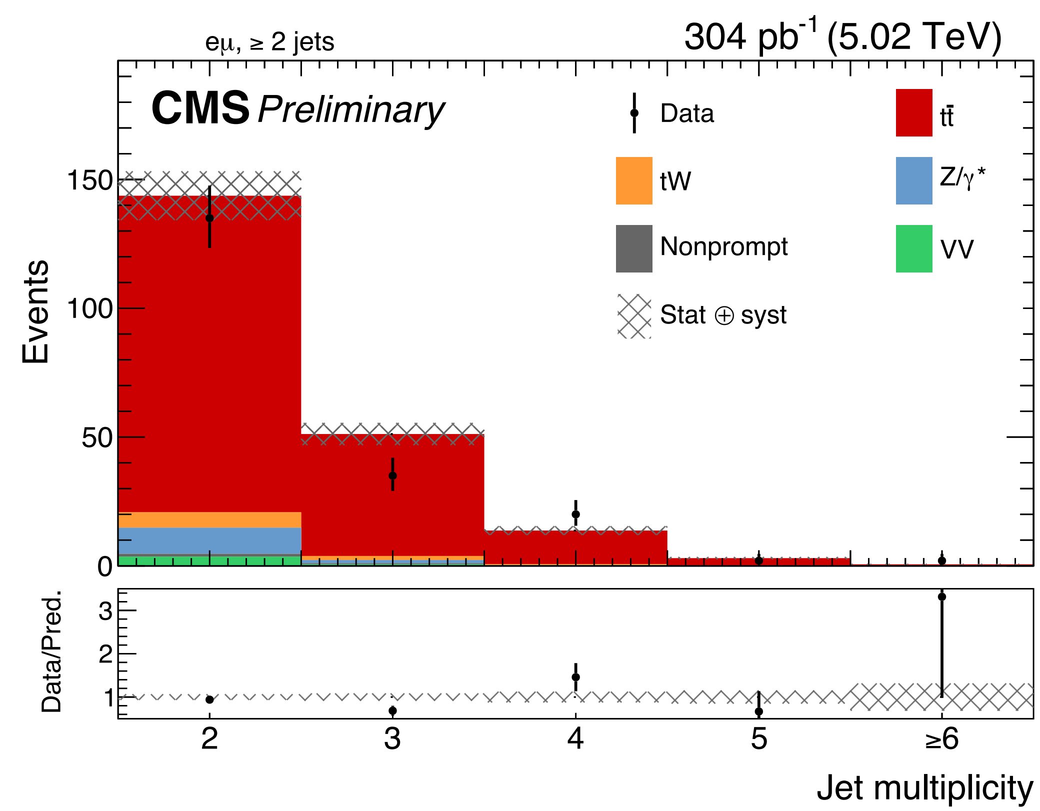
$t\bar{t}$ cross-section @ 5 TeV

- Both collaborations have new dilepton measurements @ 5 TeV.
  - ATLAS: $ee, \mu\mu, e\mu$ events using the 1 and 2 b-jet fit procedure presented earlier.
  - CMS: counting experiment with $e\mu$ events.



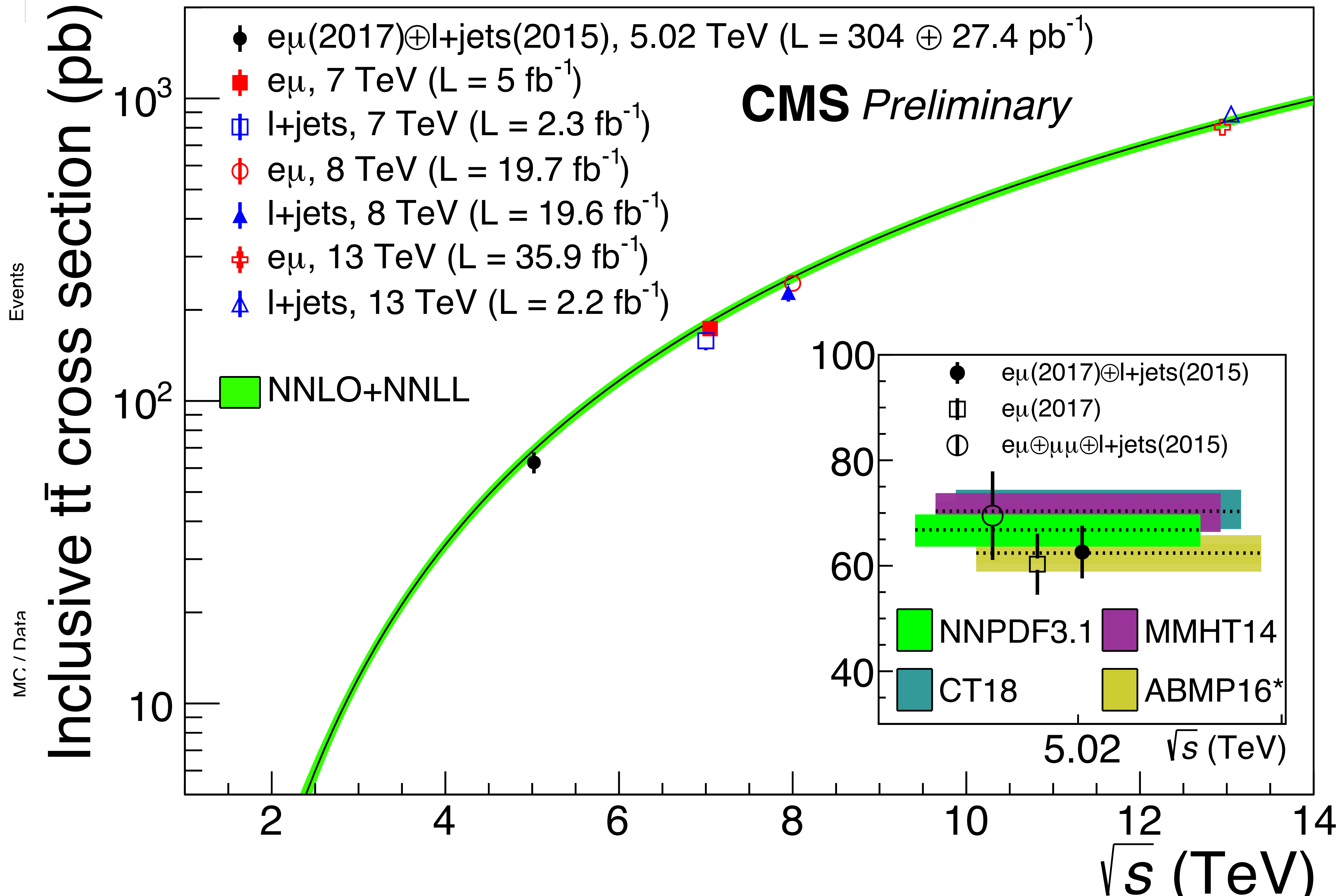
$$\sigma = 66.0 \pm 4.5\ (\text{stat}) \pm 2.0\ (\text{syst})\ \text{pb}$$



$$\sigma = 60.3 \pm 5.0\ (\text{stat}) \pm 2.9\ (\text{syst})\ \text{pb}$$

$$\sigma^{\text{NNLO+NNLL}} = 68.2 \pm 5.2\ \text{pb}$$

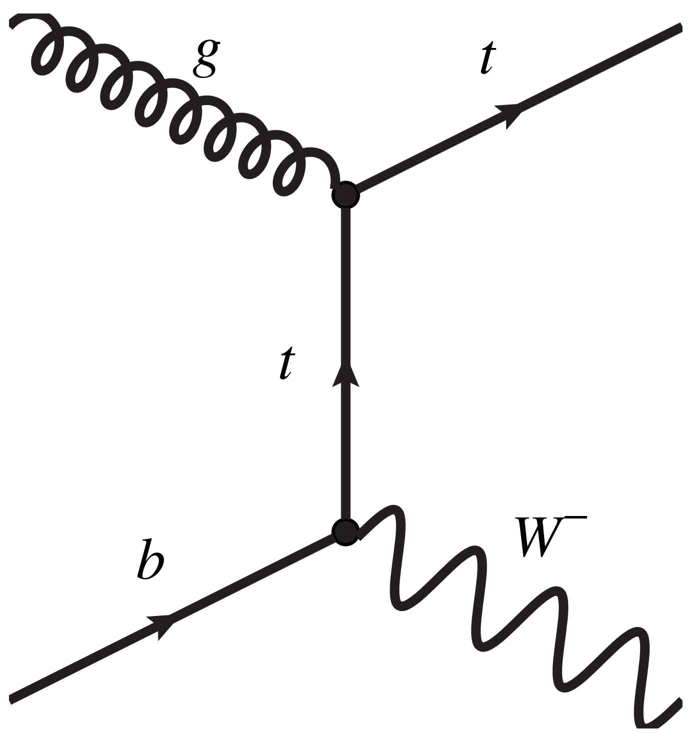
$t\bar{t}$ cross-section @ 5 TeV



tW cross-section measurements

tW in l+jets

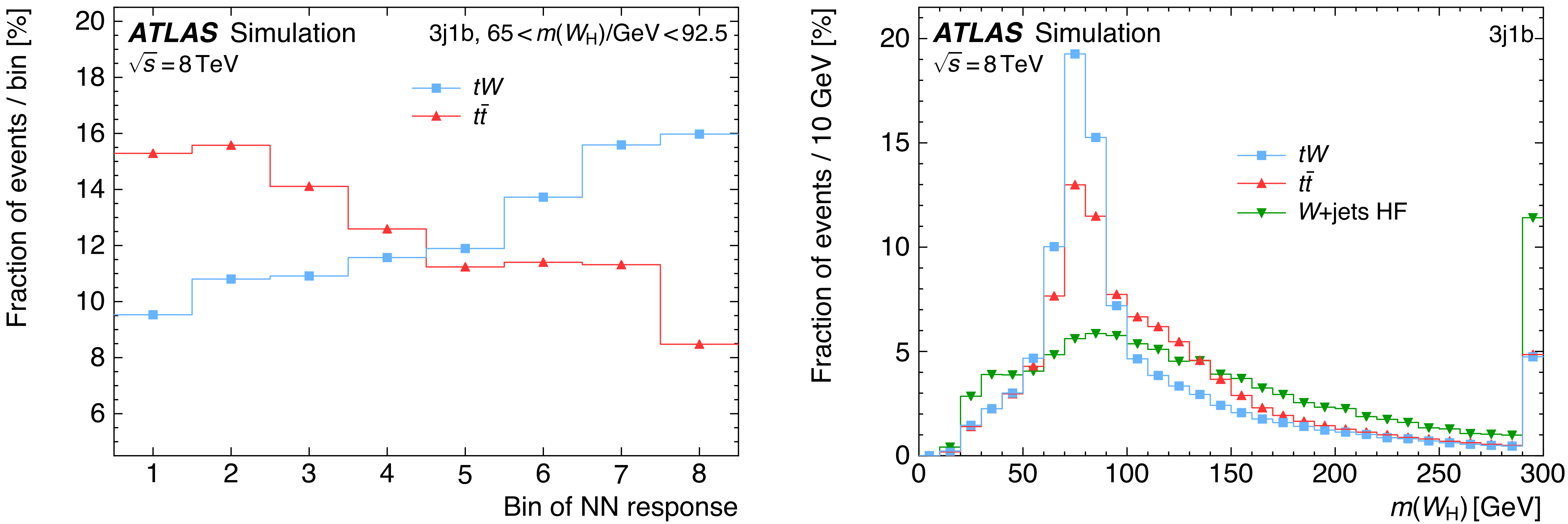
- tW is an interesting process as it probes the Wtb coupling & interferes with $t\bar{t}$ at NLO.



- Most measurements to date use dilepton channel, present here two recent measurements using 1 lepton events.

ATLAS tW @ 8 TeV

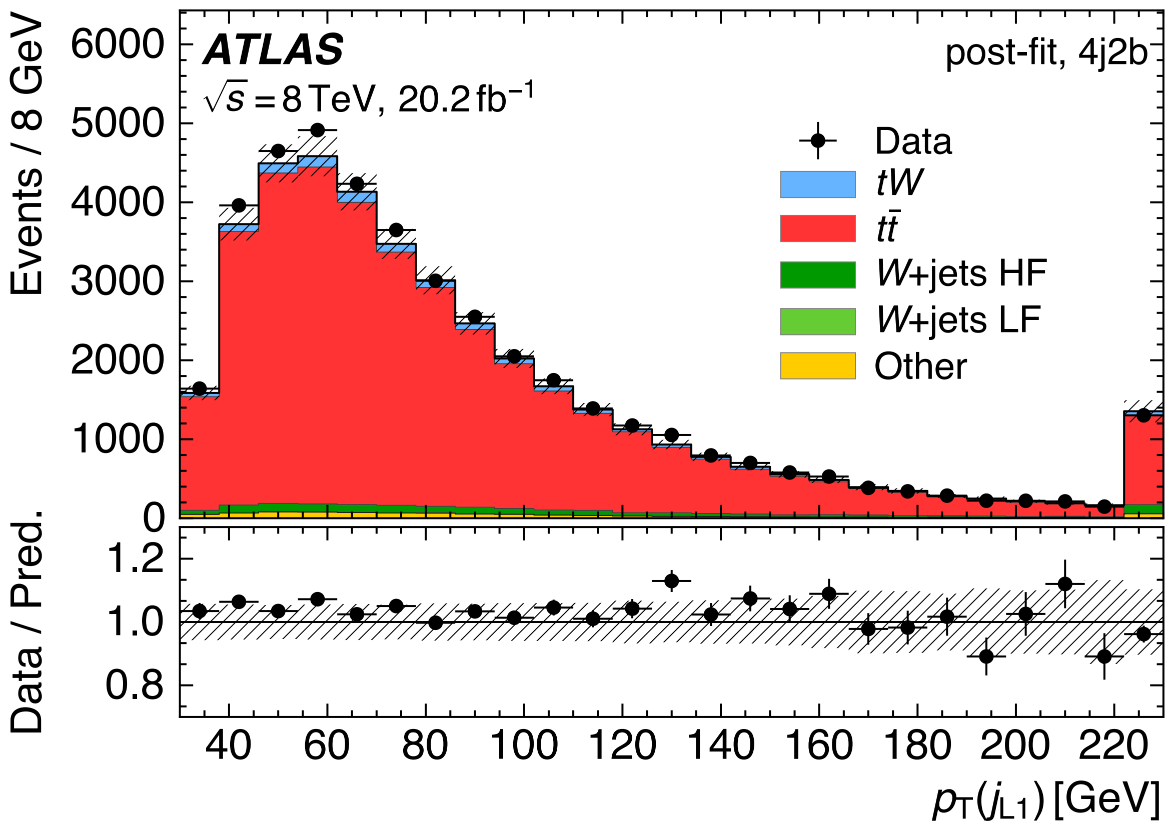
- Events are selected with 1 lepton and >=3 jet:
  - Signal region: Events with 3 jets, including ==1 b-jet.
  - $t\bar{t}$ validation region: Events with 4 jets, including ==2 b-jets.
- Neural network as well as the reconstructed W boson mass is used to separate signal from background:



arXiv:2007.01554

ATLAS tW @ 8 TeV

- Profile-likelihood to signal region is used to extract the cross-section.
- Fit parameters are propagated to validation region to check background modelling.



$$\sigma^{\mathrm{NLO+NNLL}} = 22.4 \pm 1.5 \text{ pb}$$

arXiv:2007.01554

Phys. Part. Nucl. 45 714 (2014)

ATLAS tW @ 8 TeV

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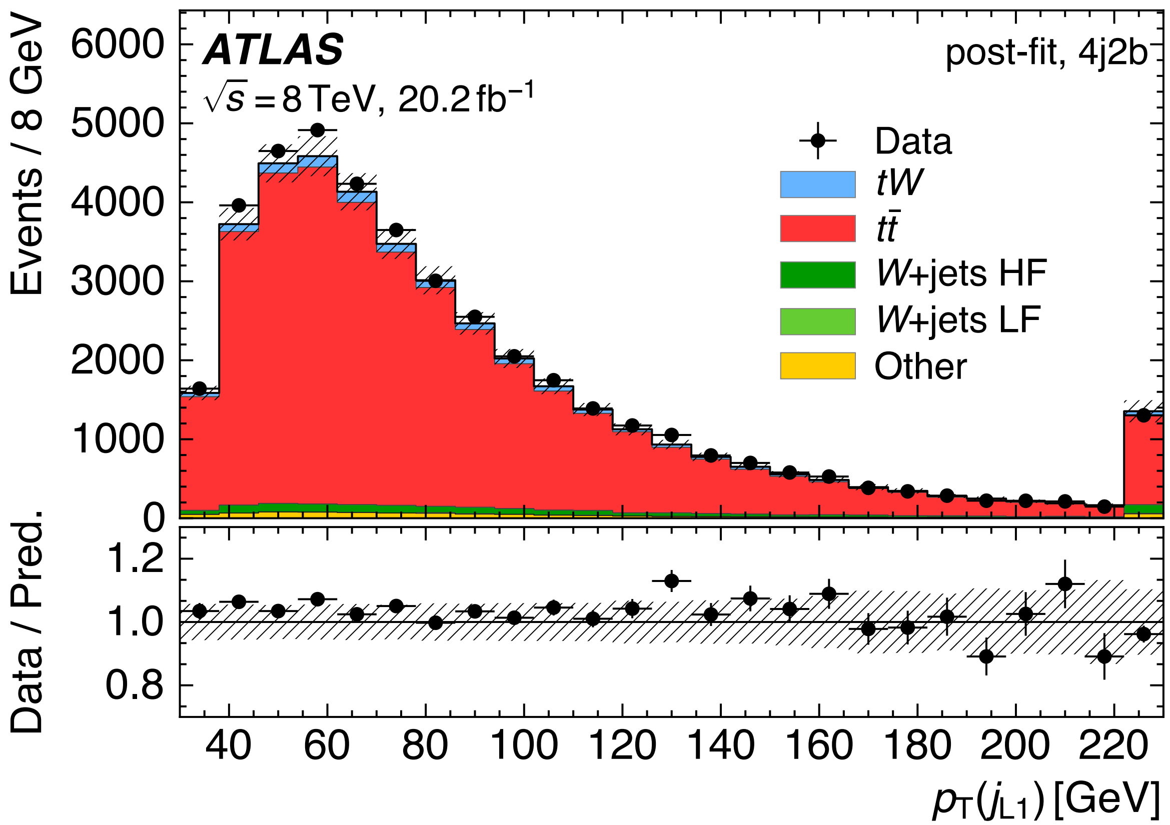

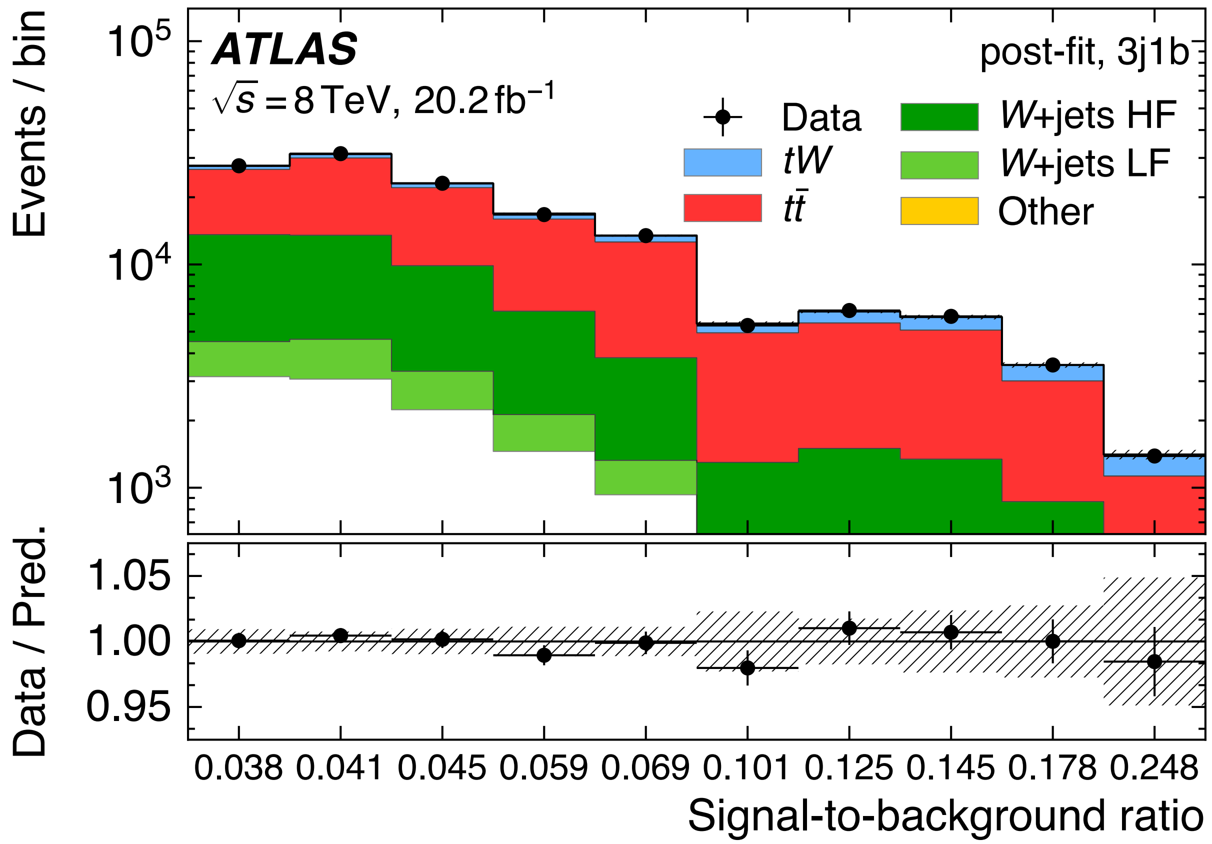

$$\sigma^{\text{NLO+NNLL}} = 22.4 \pm 1.5 \text{ pb}$$

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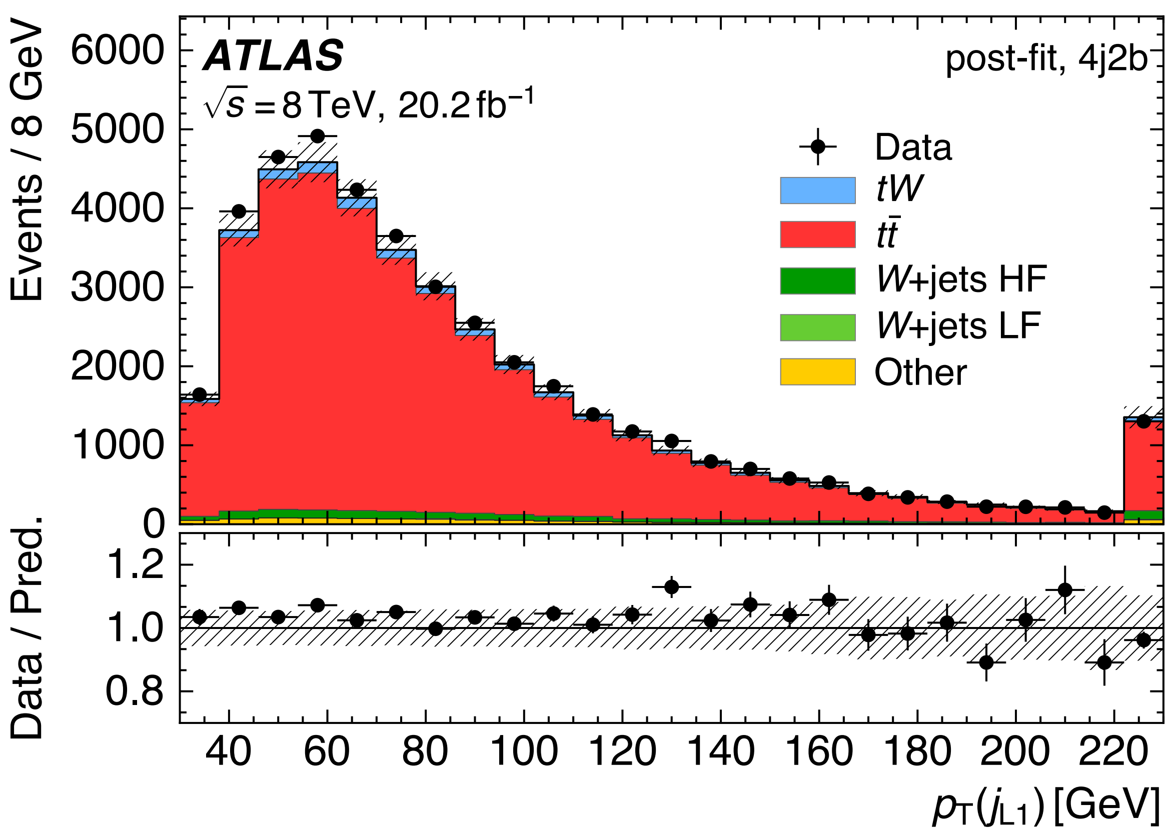

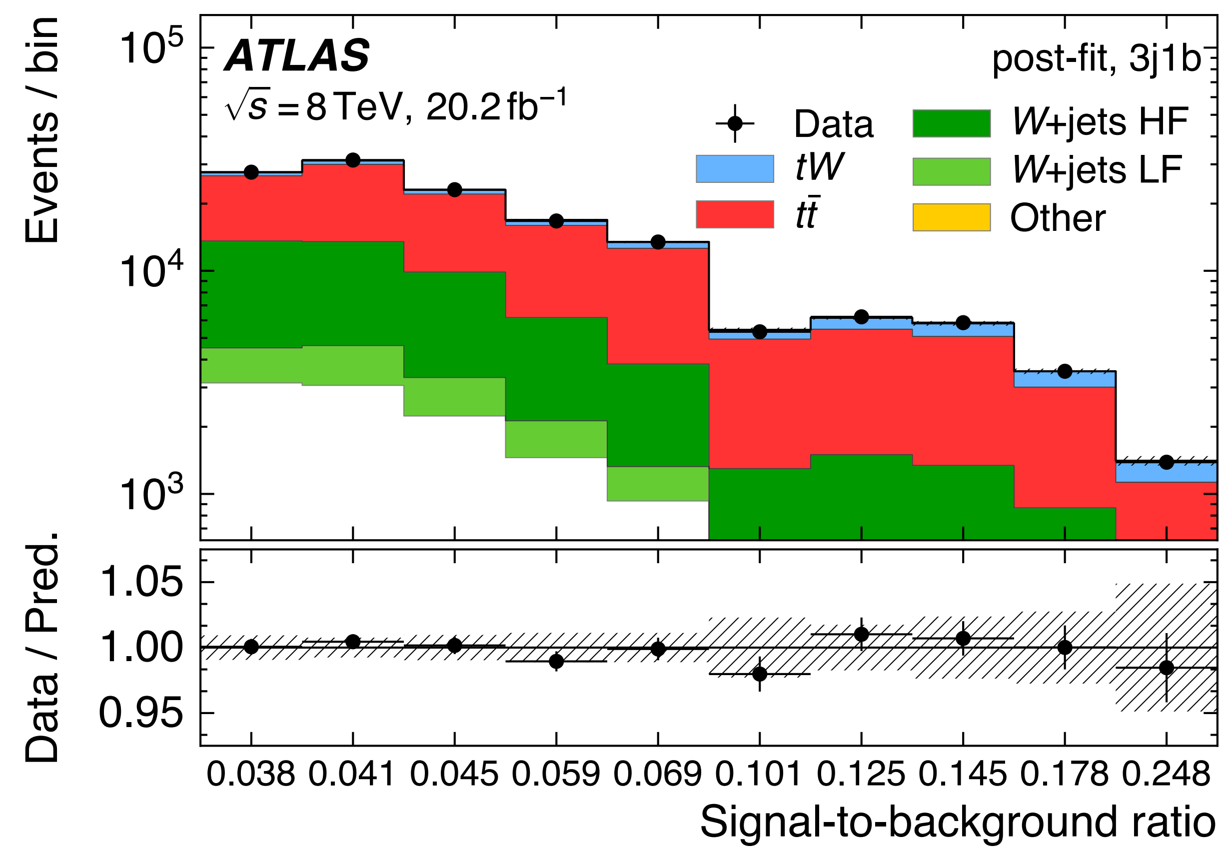

$$\sigma = 26 \pm 7 \text{ pb}$$

Good agreement with SM

$$\sigma^{\text{NLO+NNLL}} = 22.4 \pm 1.5 \text{ pb}$$

arXiv:2007.01554

Phys. Part. Nucl. 45 714 (2014)

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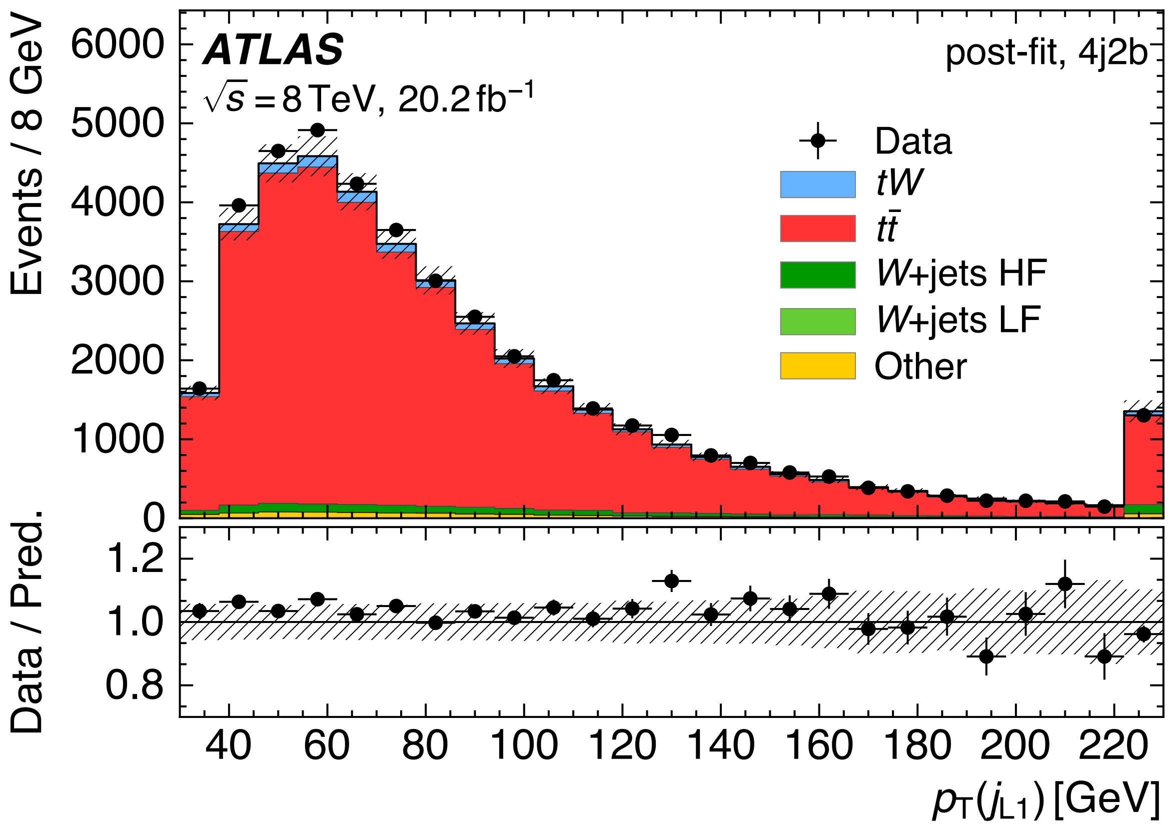
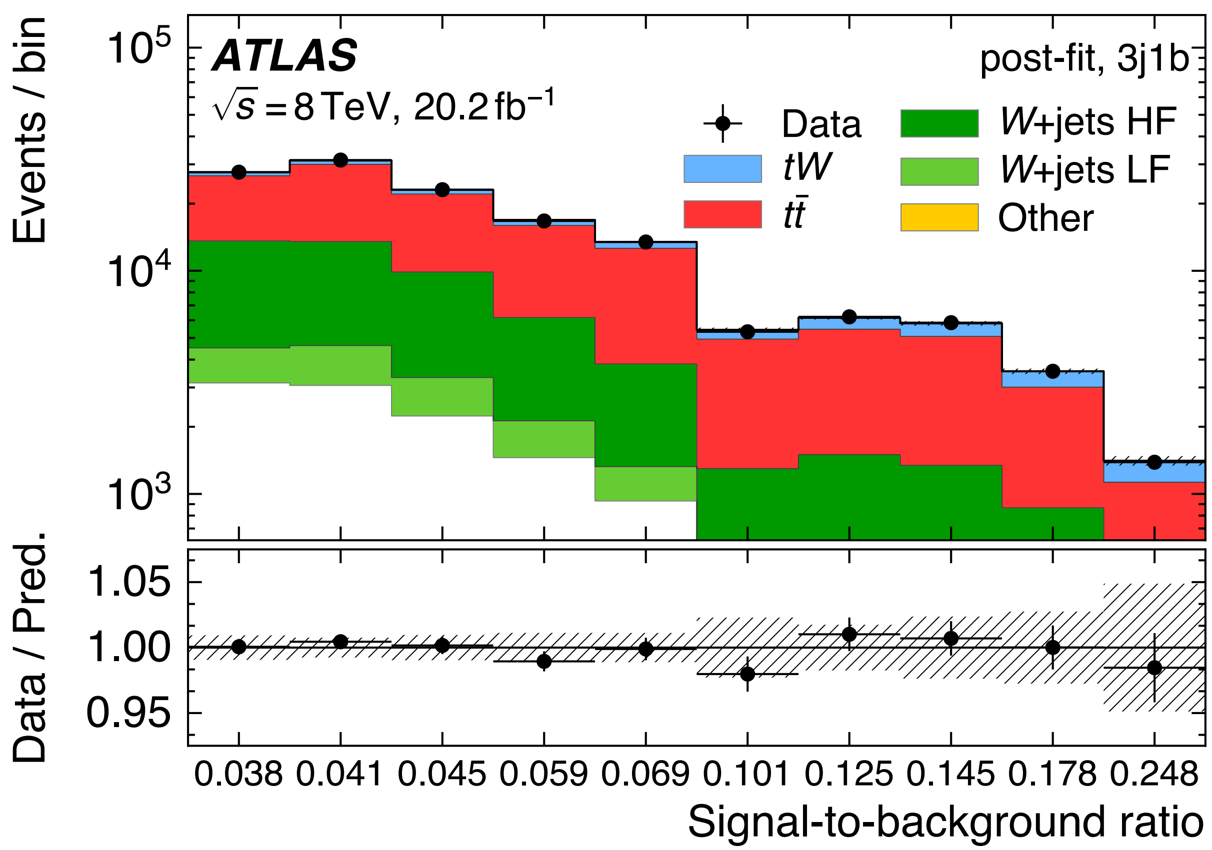




$$\sigma = 26 \pm 7 \text{ pb}$$

Good agreement with SM

$$\sigma^{\text{NLO+NNLL}} = 22.4 \pm 1.5 \text{ pb}$$

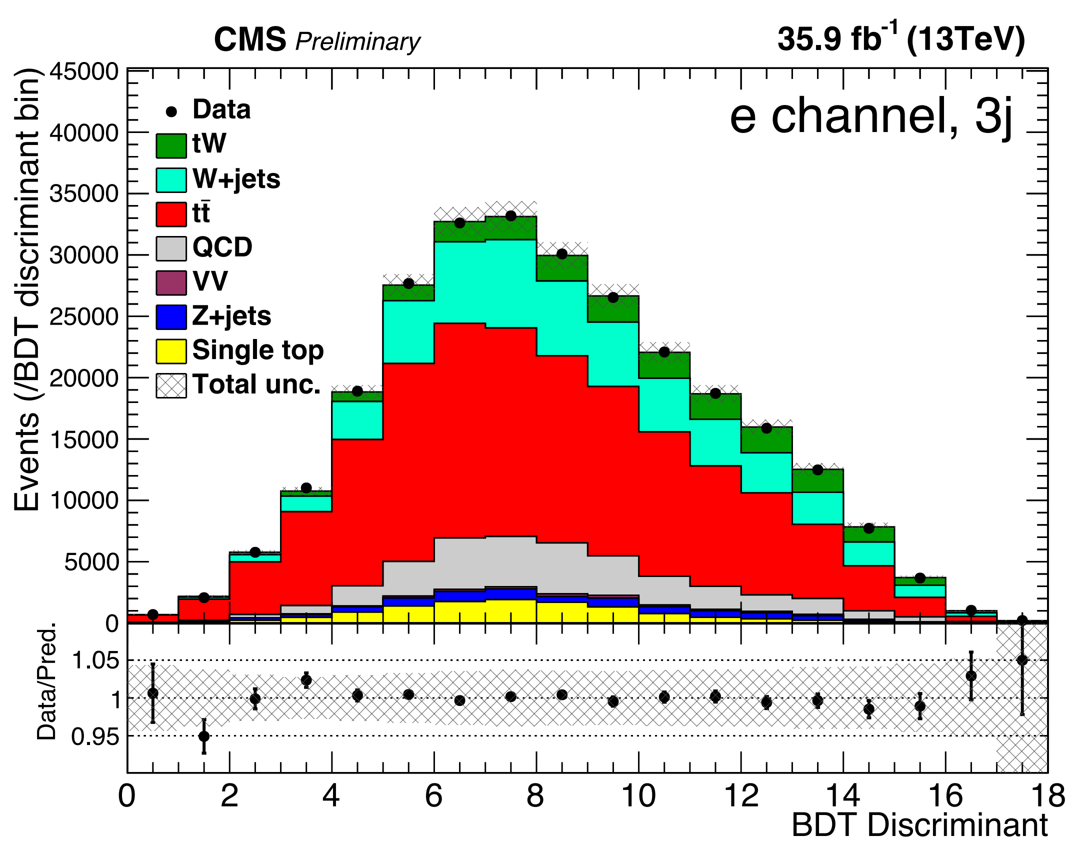
Significance:
4.5σ (3.9σ expected)

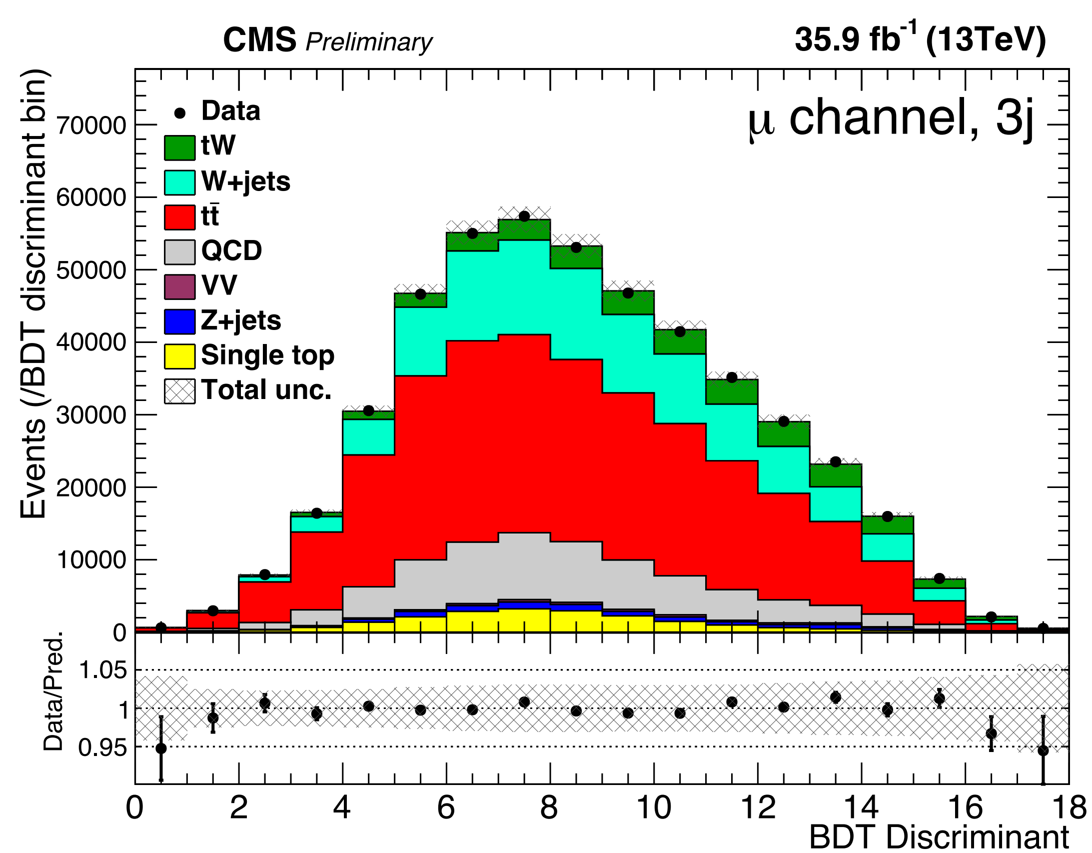
arXiv:2007.01554

Phys. Part. Nucl. 45 714 (2014)

CMS tW @ 13 TeV

- Events are selected with 1 lepton and >=2 jets:
  - Signal region: Events with 3 jets, including ==1 b-jet.
  - $t\bar{t}$ control region: Events with 4 jets, including ==1 b-jets.
  - W+jets control region: Events with 2 jets, including ==1 b-jets.
- BDT is used to separate signal from background:

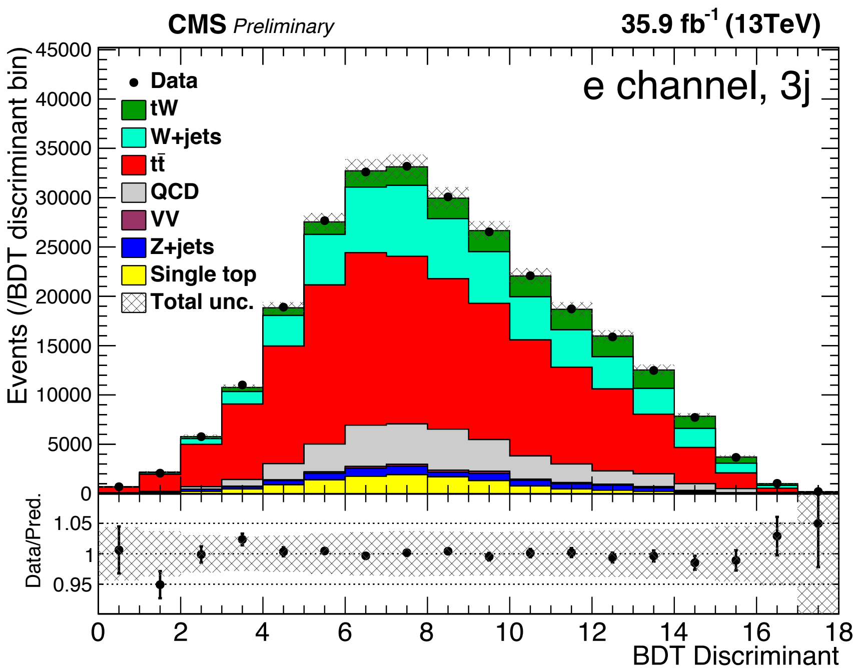


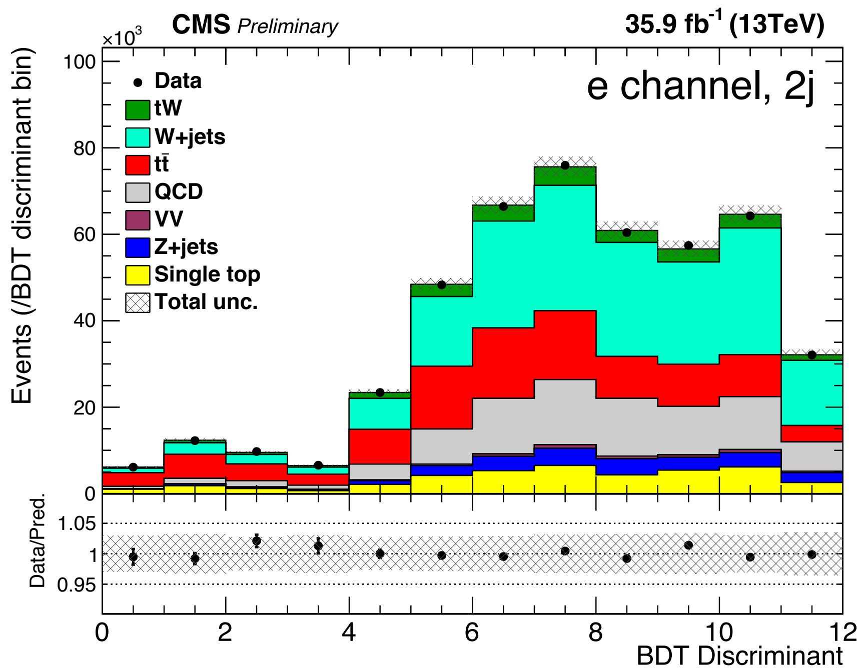


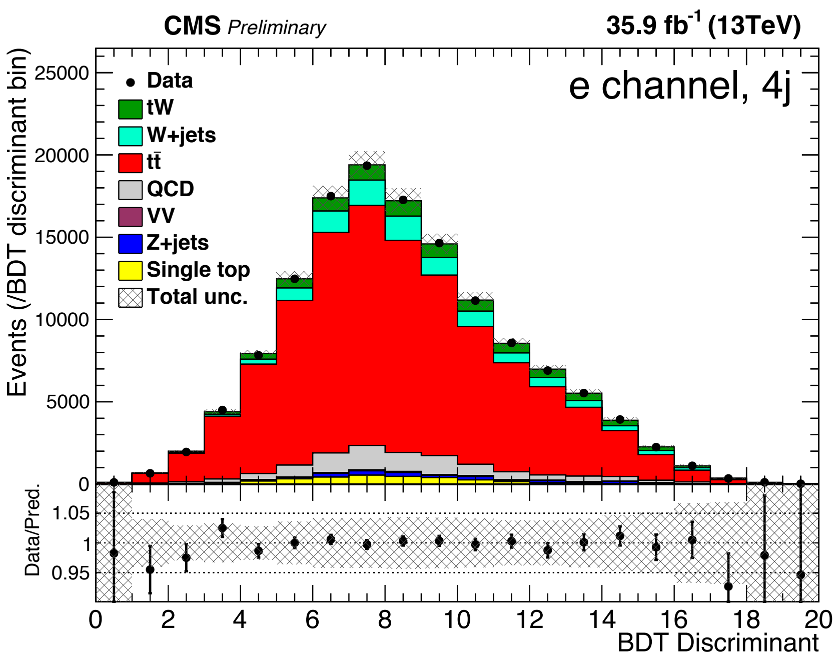
CMS-PAS-TOP-20-002

CMS tW @ 13 TeV

- Profile-likelihood to signal & control regions is used to extract the cross-section.







$$\sigma^{\text{NLO+NNLL}} = 71.7 \pm 3.8 \text{ pb}$$

CMS-PAS-TOP-20-002

CMS tW @ 13 TeV

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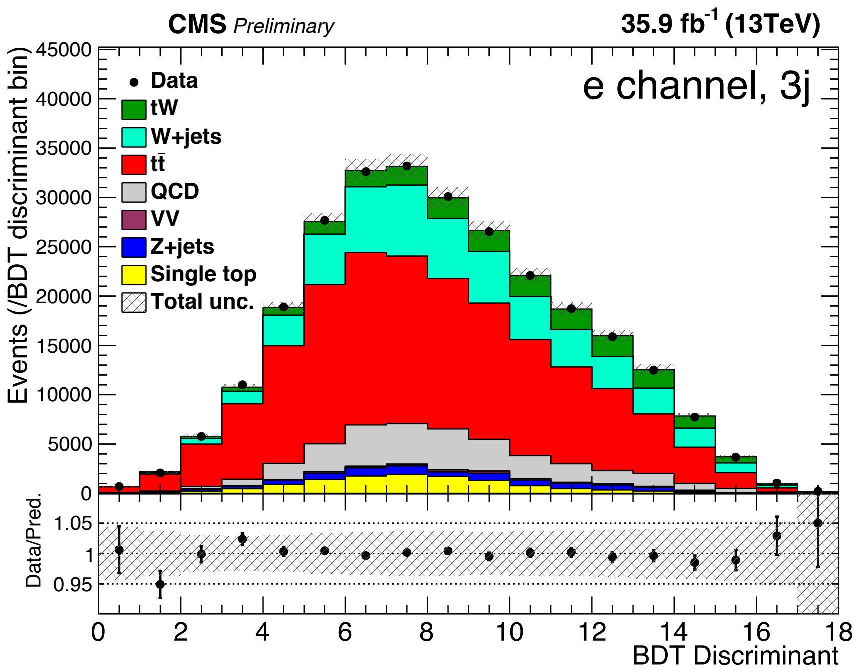

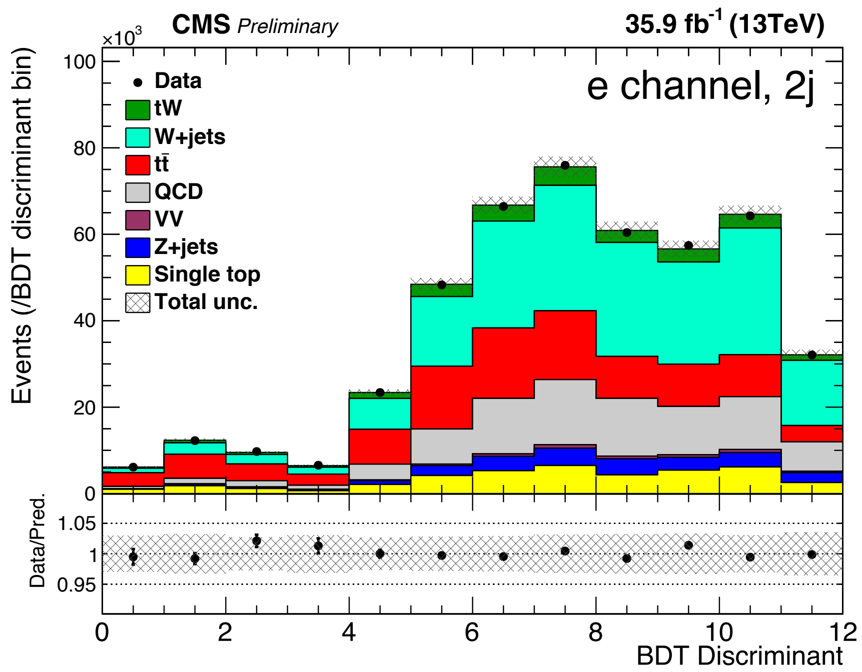

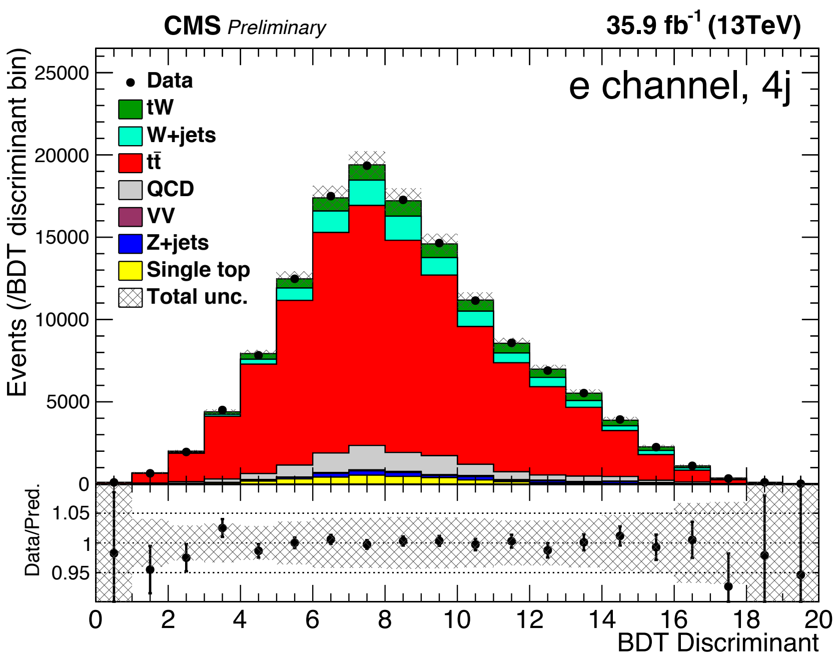

$$\sigma = 89 \pm 13 \text{ pb}$$

Good agreement with SM

$$\sigma^{\text{NLO+NNLL}} = 71.7 \pm 3.8 \text{ pb}$$

CMS-PAS-TOP-20-002

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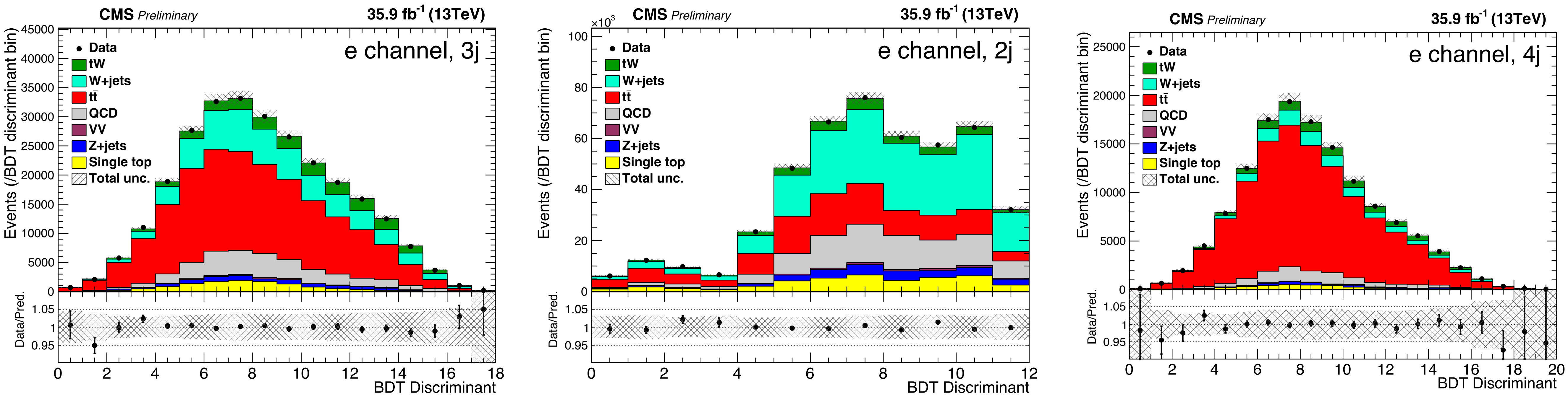


$$\sigma = 89 \pm 13 \text{ pb}$$

Good agreement with SM

$$\sigma^{\text{NLO+NNLL}} = 71.7 \pm 3.8 \text{ pb}$$

Significance:

$> 5\sigma$ (as expected)

CMS-PAS-TOP-20-002

Summary

- Impressive breadth of measurements exploiting our top factory (LHC).

- $t\bar{t}$ differential cross-section measurements reach high precision (%-level) and point towards the need for NNLO predictions.

- $t\bar{t}$ inclusive cross-section is measured at all energies - good agreement with NNLO+NNLL predictions.

- Latest single top analyses observe tW in the l+jets channel and see good agreement with the SM.

- Many analyses still to do with the full run-2 dataset: stay tuned!

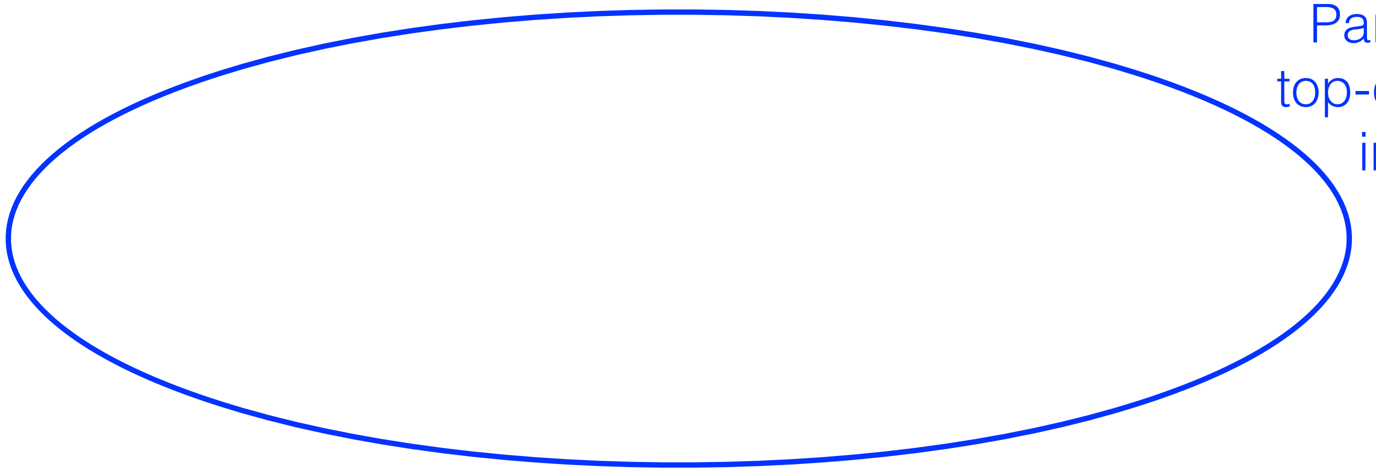
Backup

Differential cross-section measurements

- Will present several measurements of the differential cross-section of top-quark pair events.

Differential cross-section measurements

- Will present several measurements of the differential cross-section of top-quark pair events.
- Define measurements at two levels:
  - Parton-level: define 'parton-tops' directly before decay.
    - Compare to state-of-the-art QCD predictions for stable tops (NNLO).
    - Need MC to extrapolate from jets & leptons to parton-level:



Parton-level phase space: all top-quark pair events produced in collisions (p_T > X GeV)

Differential cross-section measurements

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- Define measurements at two levels:
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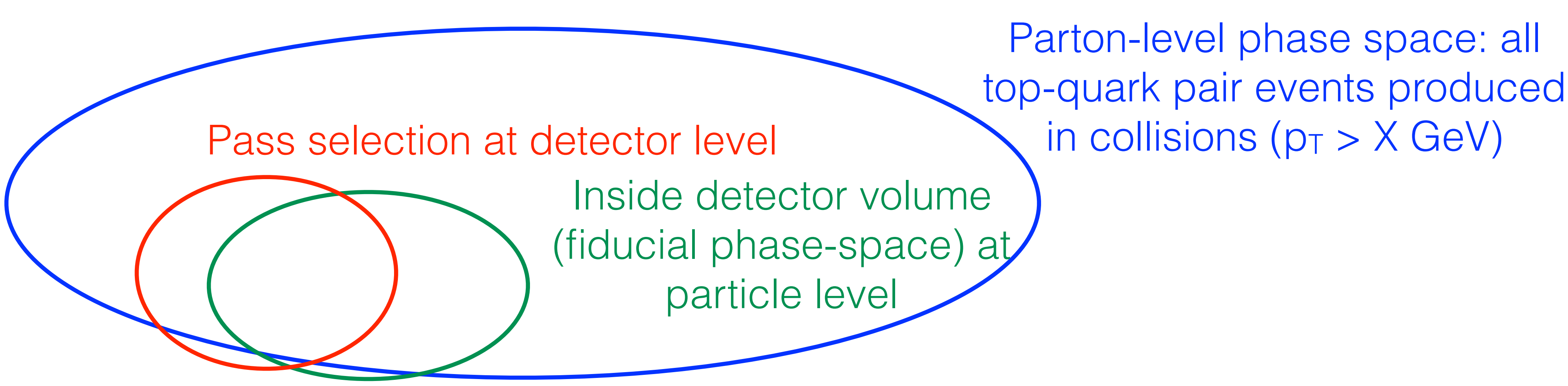
Differential cross-section measurements

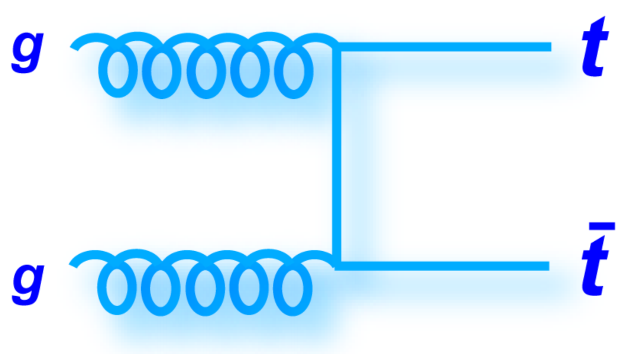
- Will present several measurements of the differential cross-section of top-quark pair events.

- Define measurements at two levels:
  - Particle-level: build 'pseudo-tops' from stable particles.
    - Close connection to particles observed in detector (same jet algos).
    - Reduced dependence on MC for measurement: smaller uncertainties.
    - Compare to MC models (hadron-level predictions).

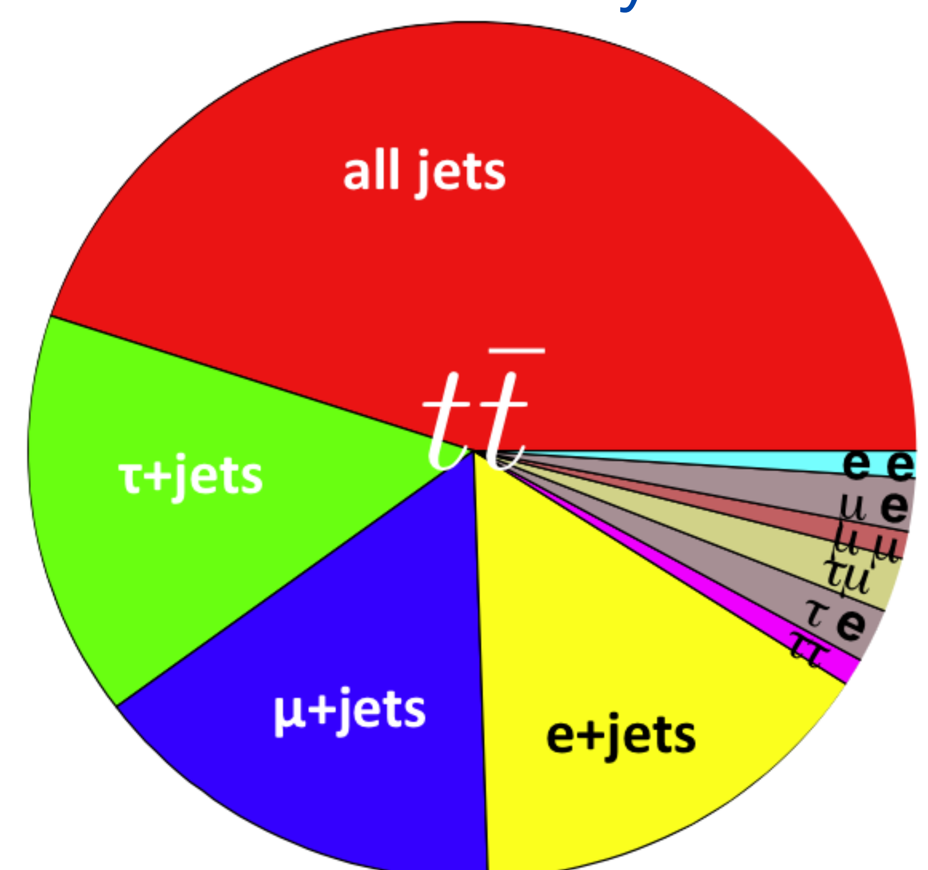


Top production and decay

- Top pair production is dominant mode at LHC:



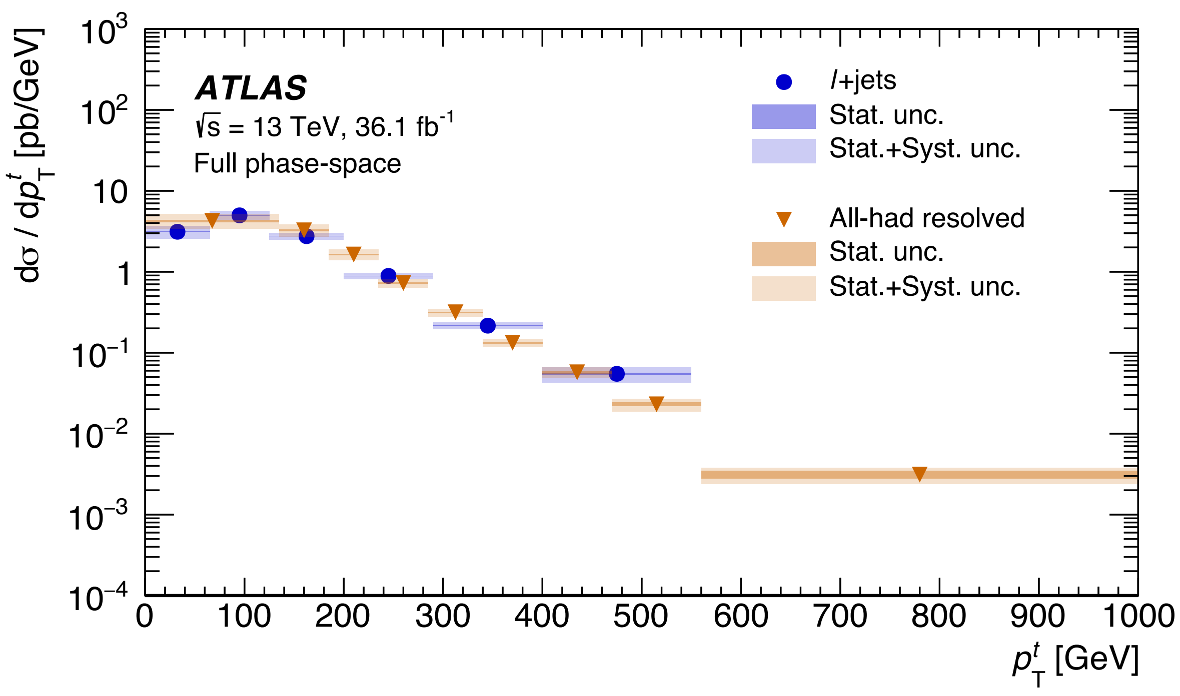
- Top decays to Wb in SM, final state determined by W decays:

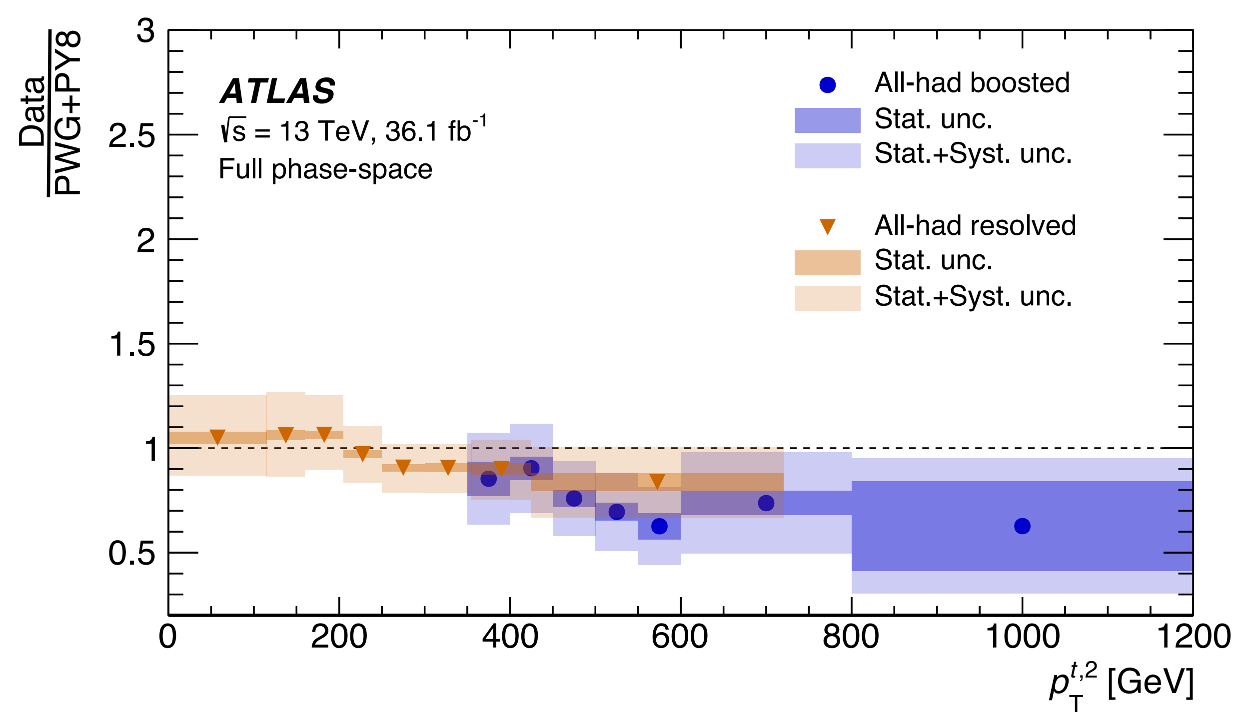


- All hadronic:
  - 2 b-jets + 4 q-jets
  - High Br
  - Large multijet background
- Lepton-plus-jets:
  - e / μ + ν + 2 b-jets + 2 q-jets
  - Good Br
  - Manageable backgrounds
- Di-lepton:
  - ee / μμ / eμ + νν + 2 b-jets
  - Small Br
  - Small backgrounds

ATLAS l+jets & all-hadronic

- Comparison of ATLAS l+jets & all-hadronic and boosted & resolved results generally shows good agreement:





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- Events must have 1 lepton, >=4 jets & 1 or 2 b-jets and are split into signal regions:
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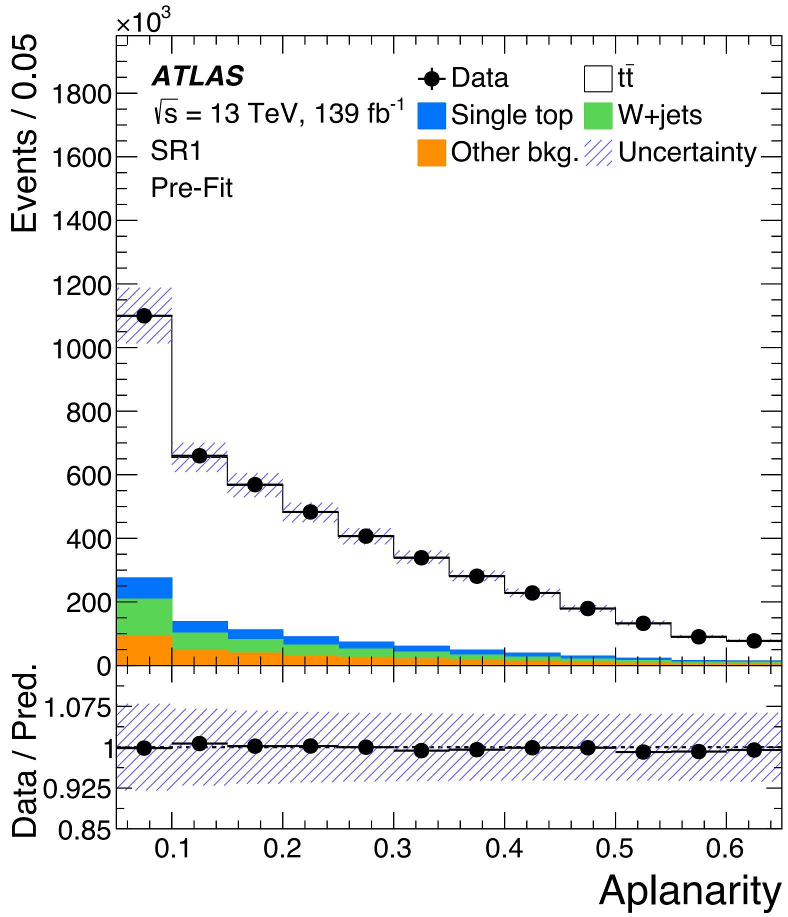

- Cross-section is extracted from a profile-likelihood fit to kinematic variables in the 3 regions.

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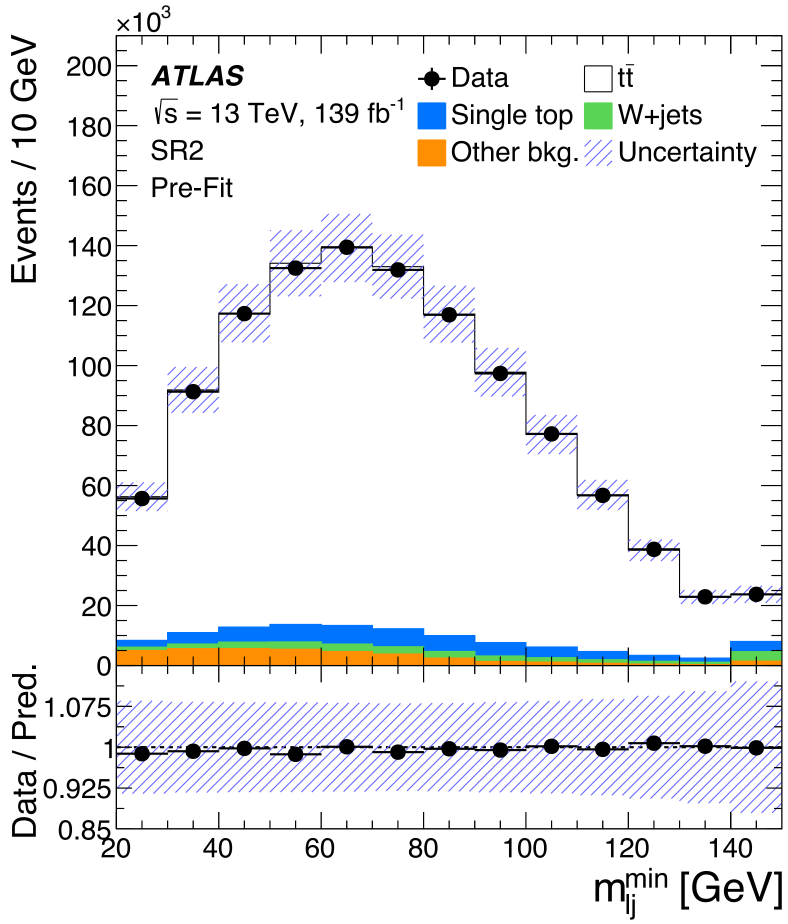

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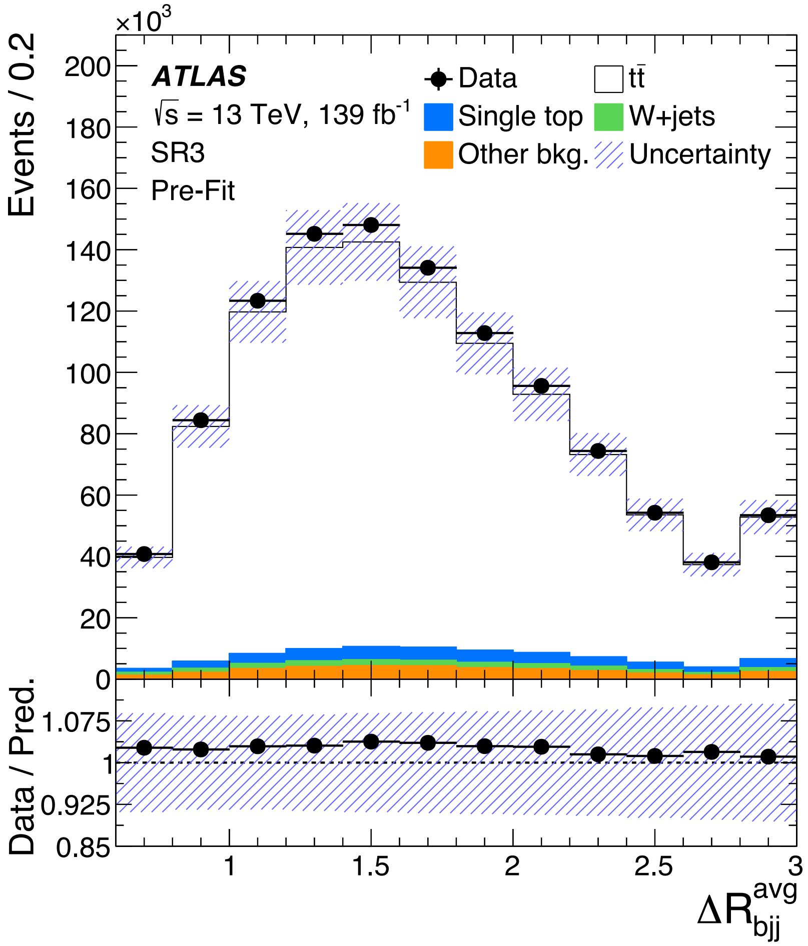

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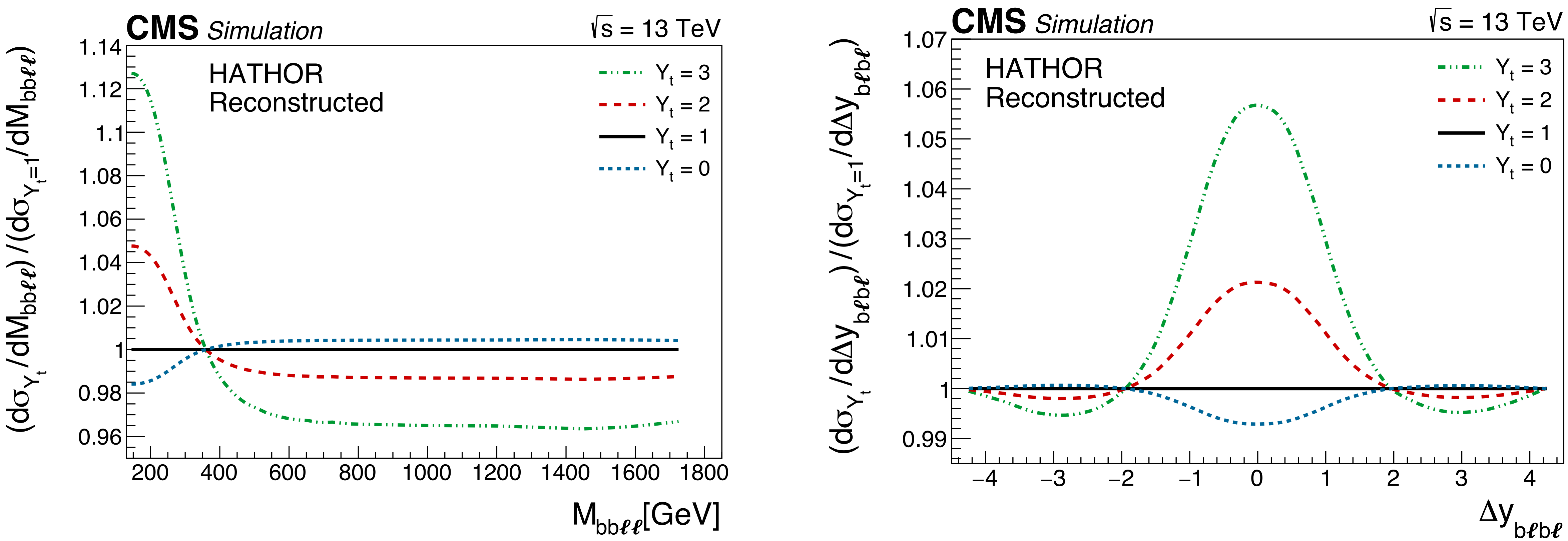
Differential cross-section & parameter extraction

- $t\bar{t}$ differential distributions have sensitivity to Y_t, m_t, α_s.
- Recent extraction of Yt from CMS from the $t\bar{t}$ distributions in the dilepton channel:



Phys. Rev. D 102 (2020) 092013

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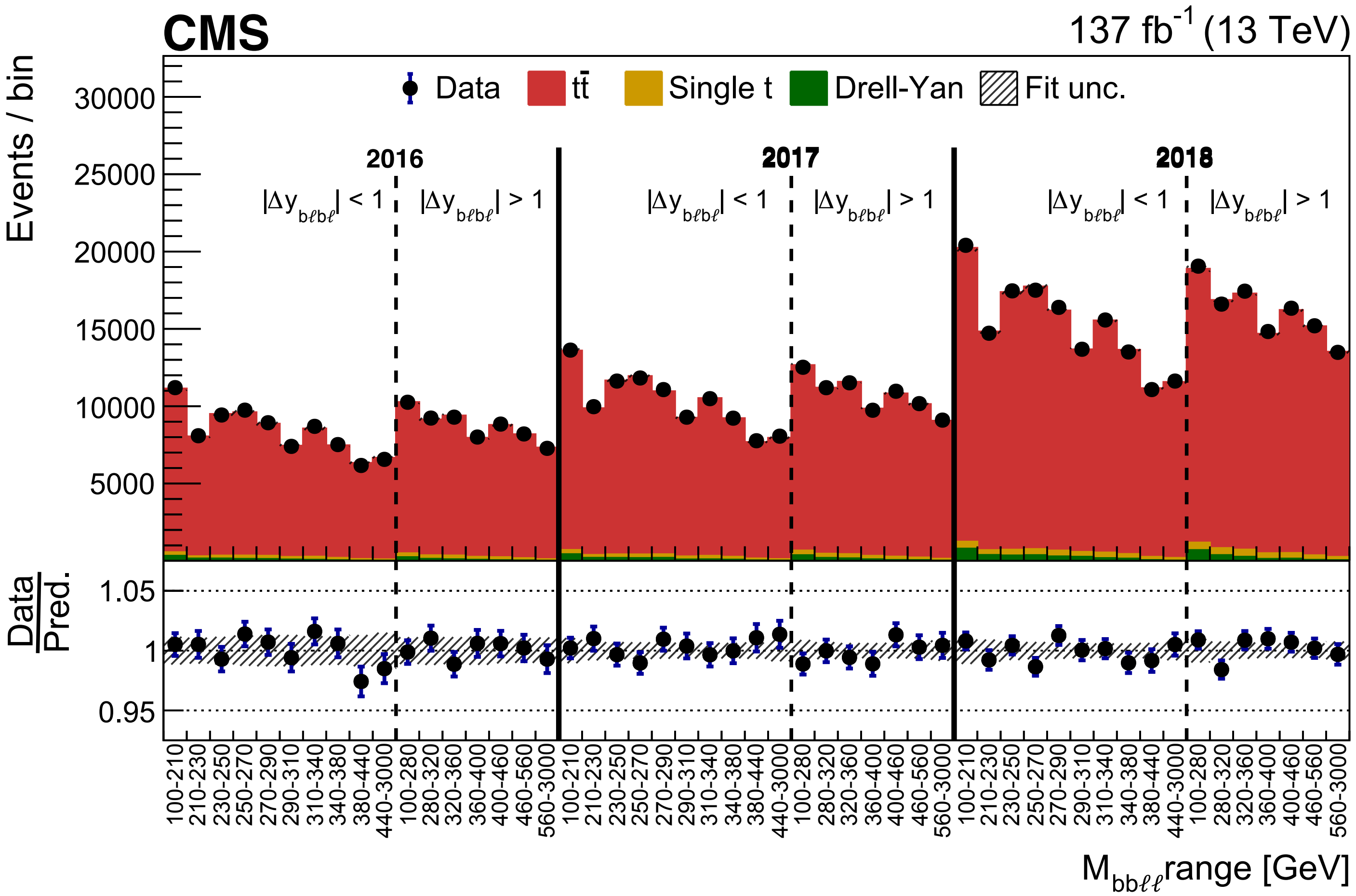

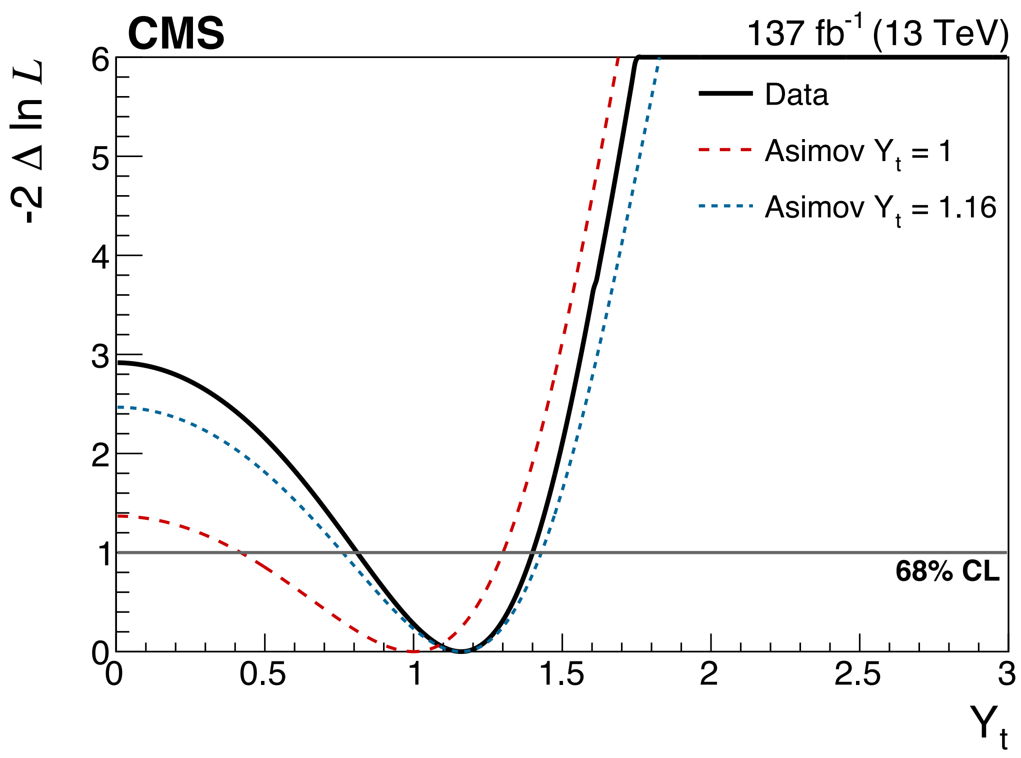

$$Y_t = 1.16^{+0.24}_{-0.35}$$

Phys. Rev. D 102 (2020) 092013