THE ROYAL SOCIETY

University of Glasgow

Measurements with highly-boosted top quarks at ATLAS

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BOOST 2019, MIT, Boston

Outline

- Introduction
- Measurements of cross-sections of boosted tops
  - Selection & background estimate
  - Cross-section extraction
  - Systematics
  - Results
- 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?

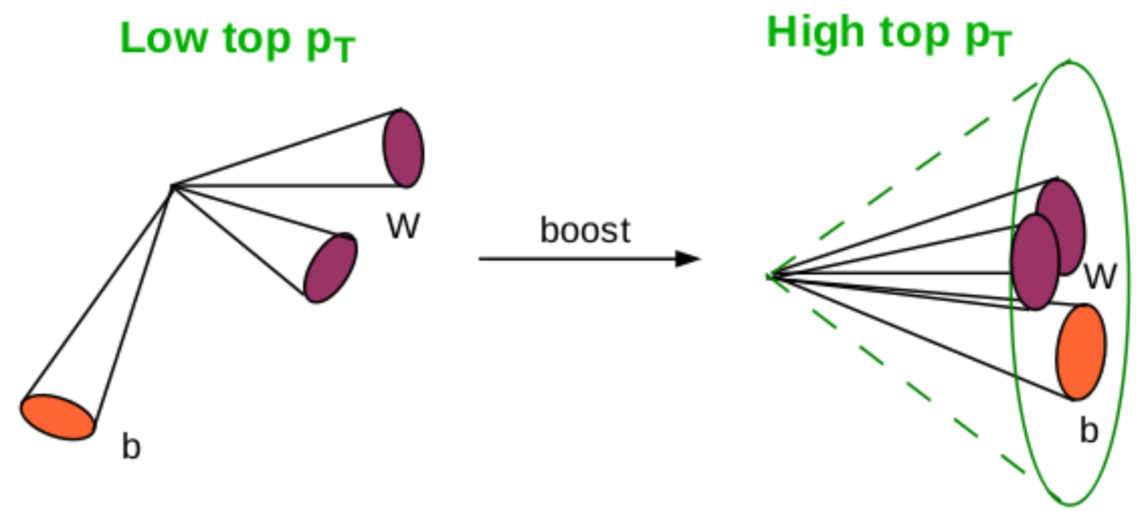
  2. That decays before hadronizing:

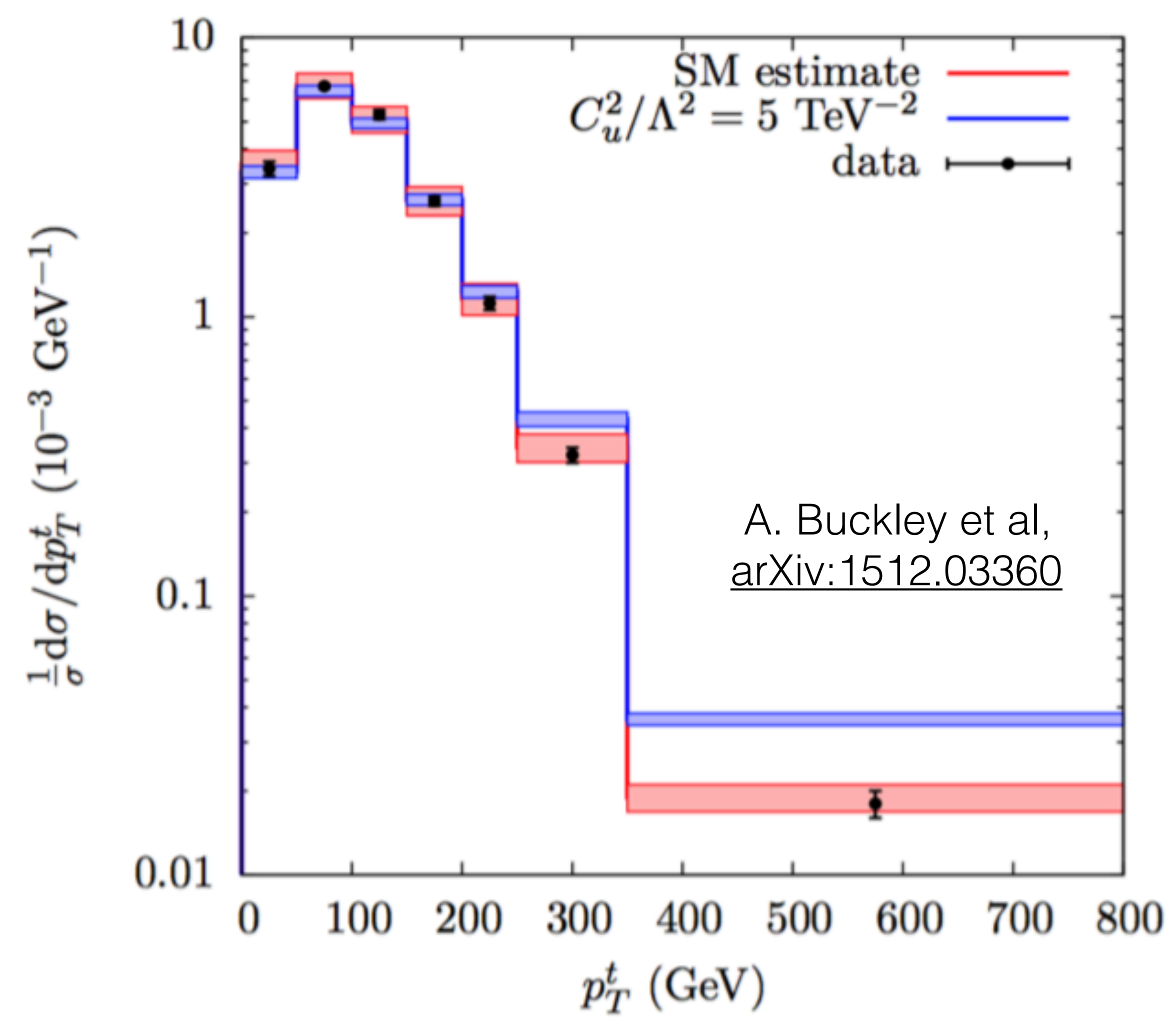
$$\tau_{had} \approx 2 \times 10^{-24} s$$
$$\tau_{top} \approx 5 \times 10^{-25} s$$

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

Why boosted top-quarks?

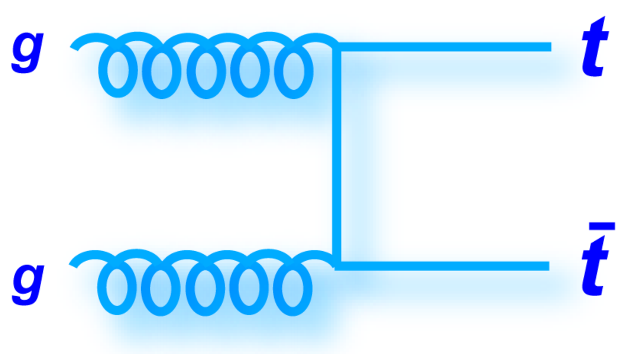
- Measurements of high pT (boosted) top-quarks interesting for a few reasons:
  - Potential for new physics contributions.
  - Probe QCD predictions in a phase space with multiple scales (p_T(top) > m(top) > p_T(j)).
  - Important phase space region for searches.



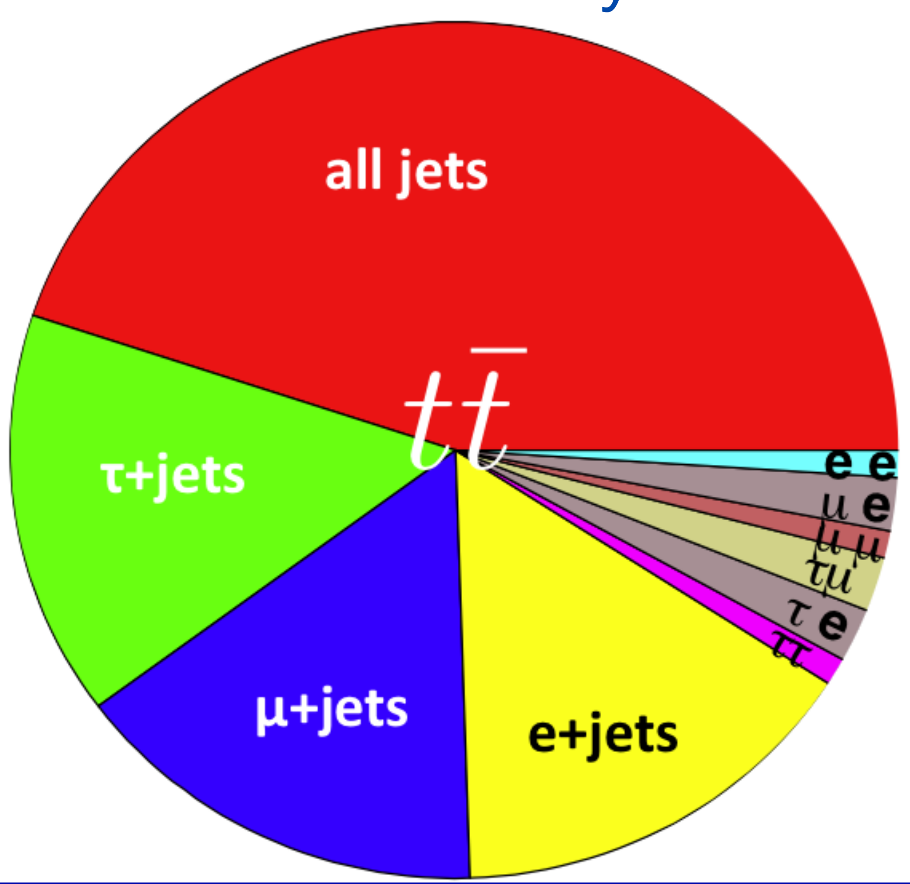


Top production and decay

- 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

Differential cross-section measurements

- Present two measurements of the differential cross-section of top-quark pair events with boosted top-quarks, in all-hadronic and lepton+jets channels.

New for this workshop!

Differential cross-section measurements

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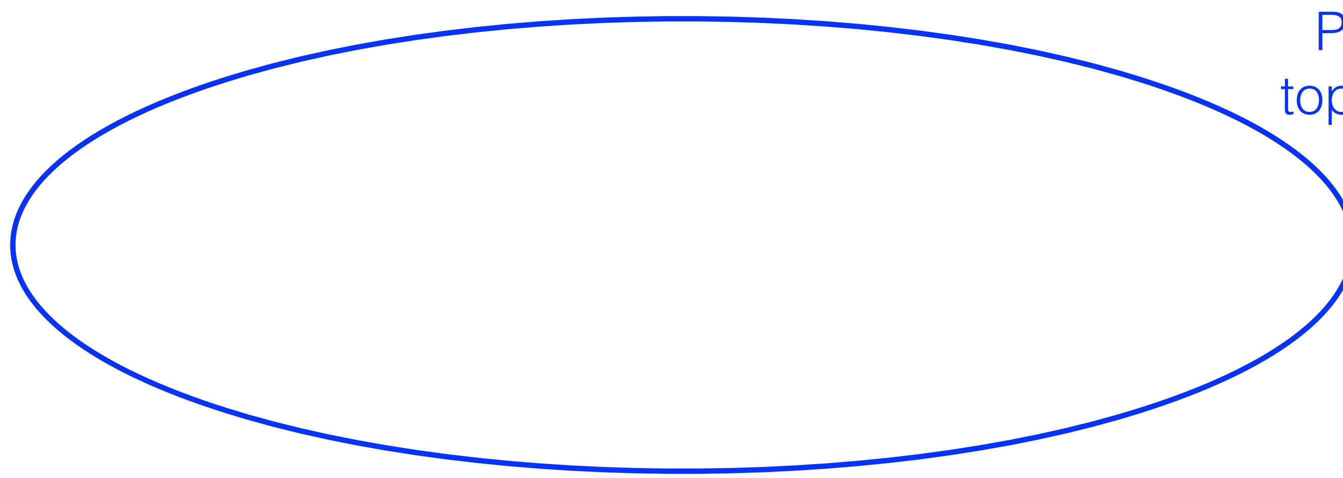
- Define measurements at two levels:
  - Parton-level: define ‘parton-tops’ directly before decay.
    - Compare to state-of-the-art QCD predictions for stable tops (NNLO).
    - Need MC to extrapolate from jets & leptons to parton-level:



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

Differential cross-section measurements

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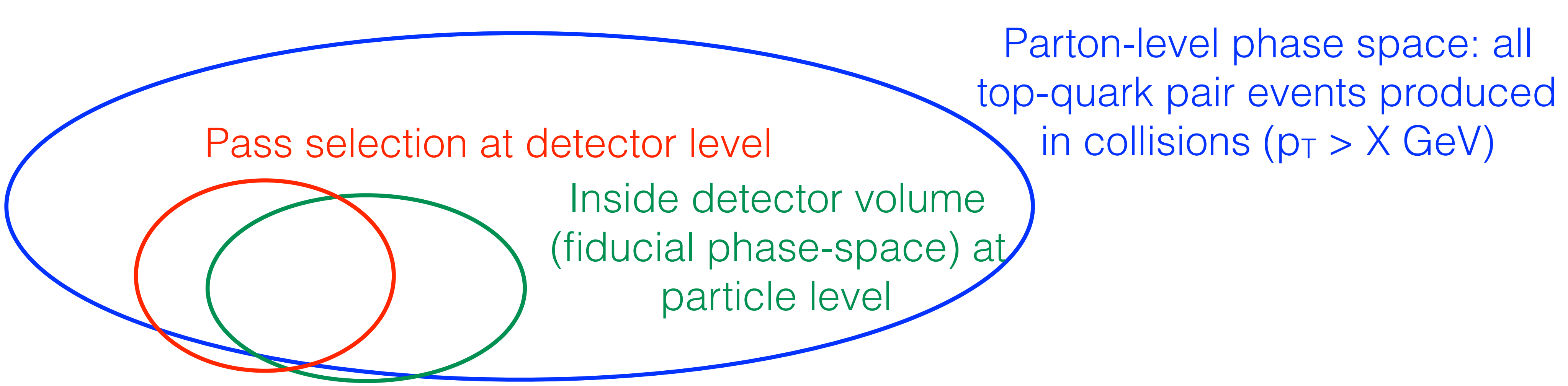
Differential cross-section measurements

- Present two measurements of the differential cross-section of top-quark pair events with boosted top-quarks, in all-hadronic and lepton+jets channels.

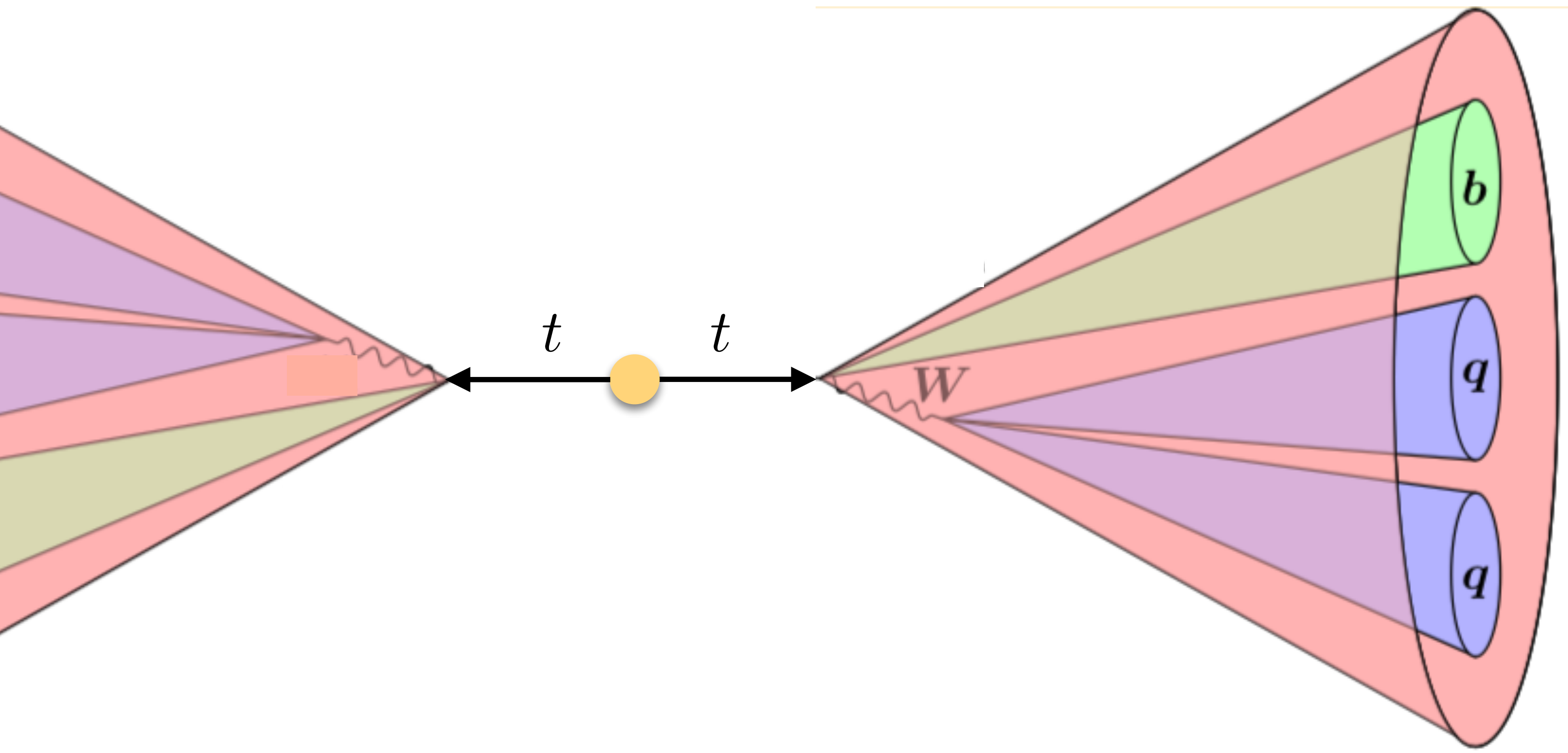
- Define measurements at two levels:
  - Particle-level: build ‘pseudo-tops’ from stable particles.
    - Close connection to particles observed in detector (same jet algos).
    - Reduced dependence on MC for measurement: smaller uncertainties.
    - Compare to MC models (hadron-level predictions).



arXiv:1801.02052

Event selection: all-hadronic

- Identify two boosted hadronic tops using anti-k_T R=1 jets.
    - Dedicated top-tagger is used to reject background.



Require two top-jets:

$$p_T > 350 \text{ GeV}$$
$$p_T^{\text{lead}} > 500 \text{ GeV}$$
$$|\eta| < 2.0$$
$$|m - m_t| < 50 \text{ GeV}$$
$$\text{top} - \text{tagged}$$

Large-R jet must contain a b-tagged small-R jet.

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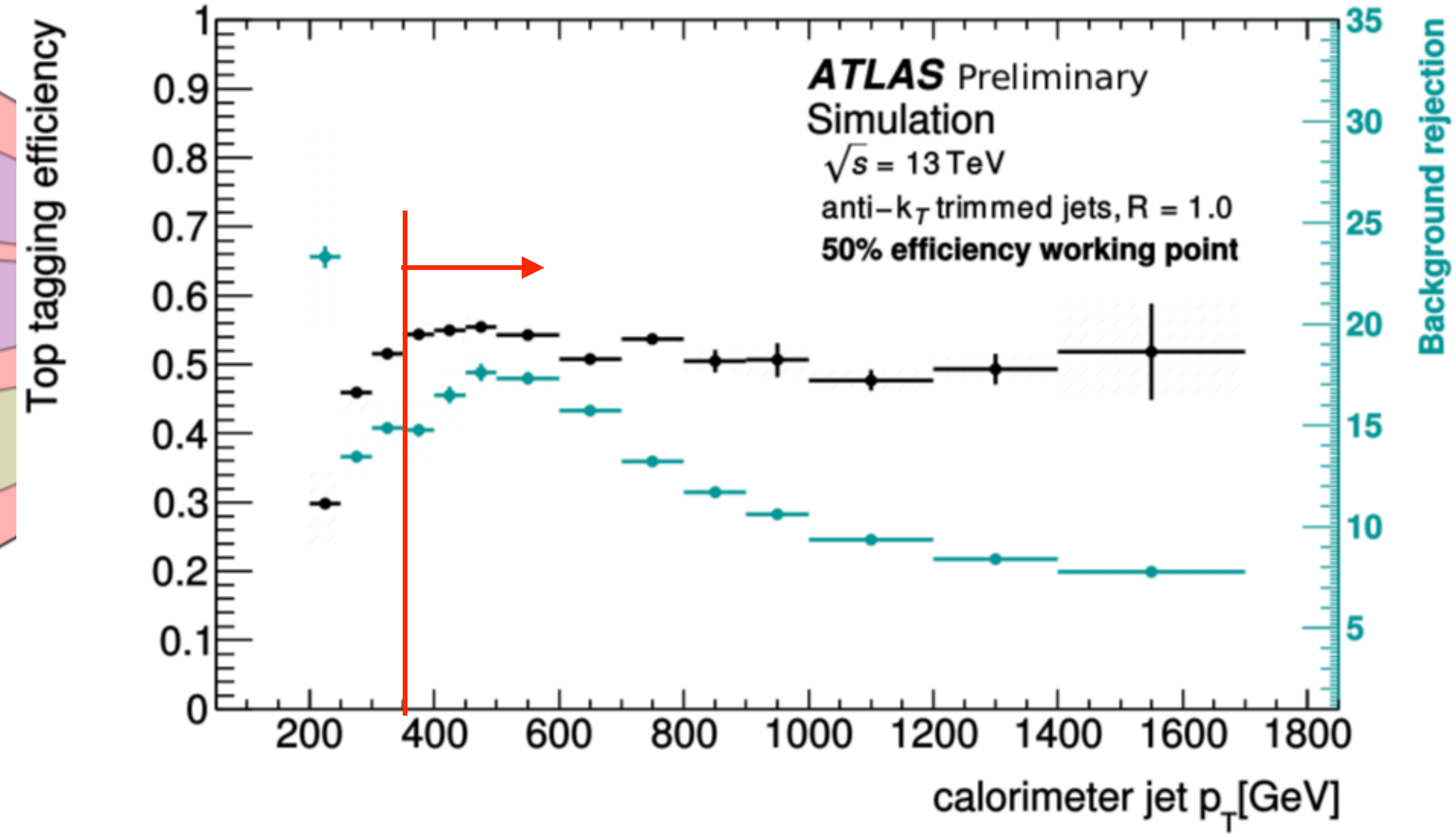

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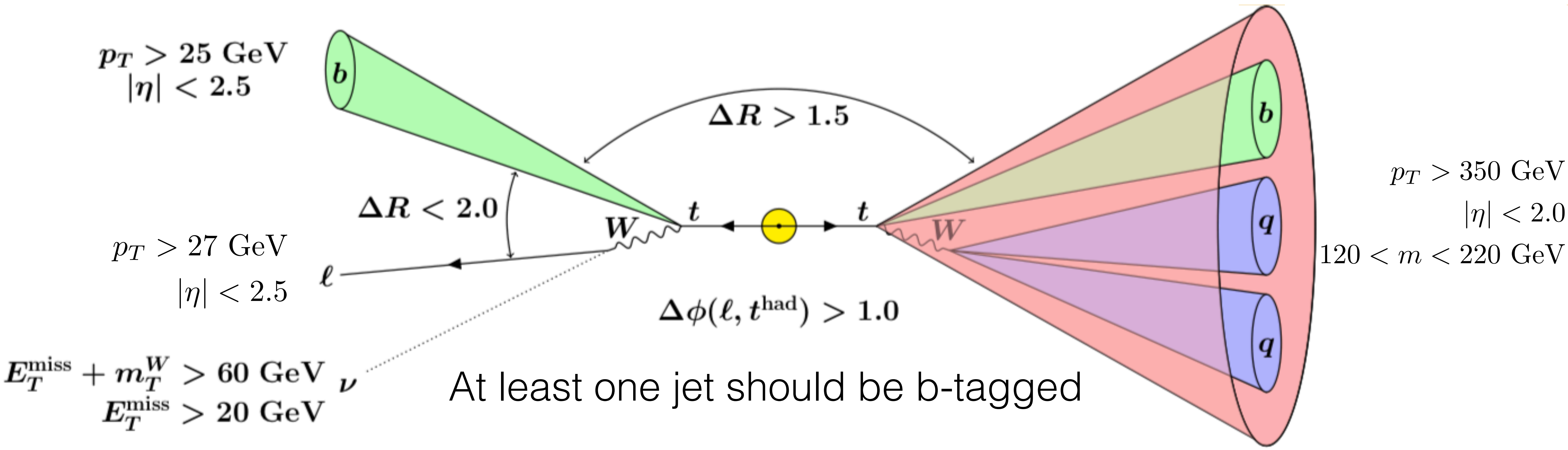
Large-R jet must contain a b-tagged small-R jet.

Event selection: lepton+jets

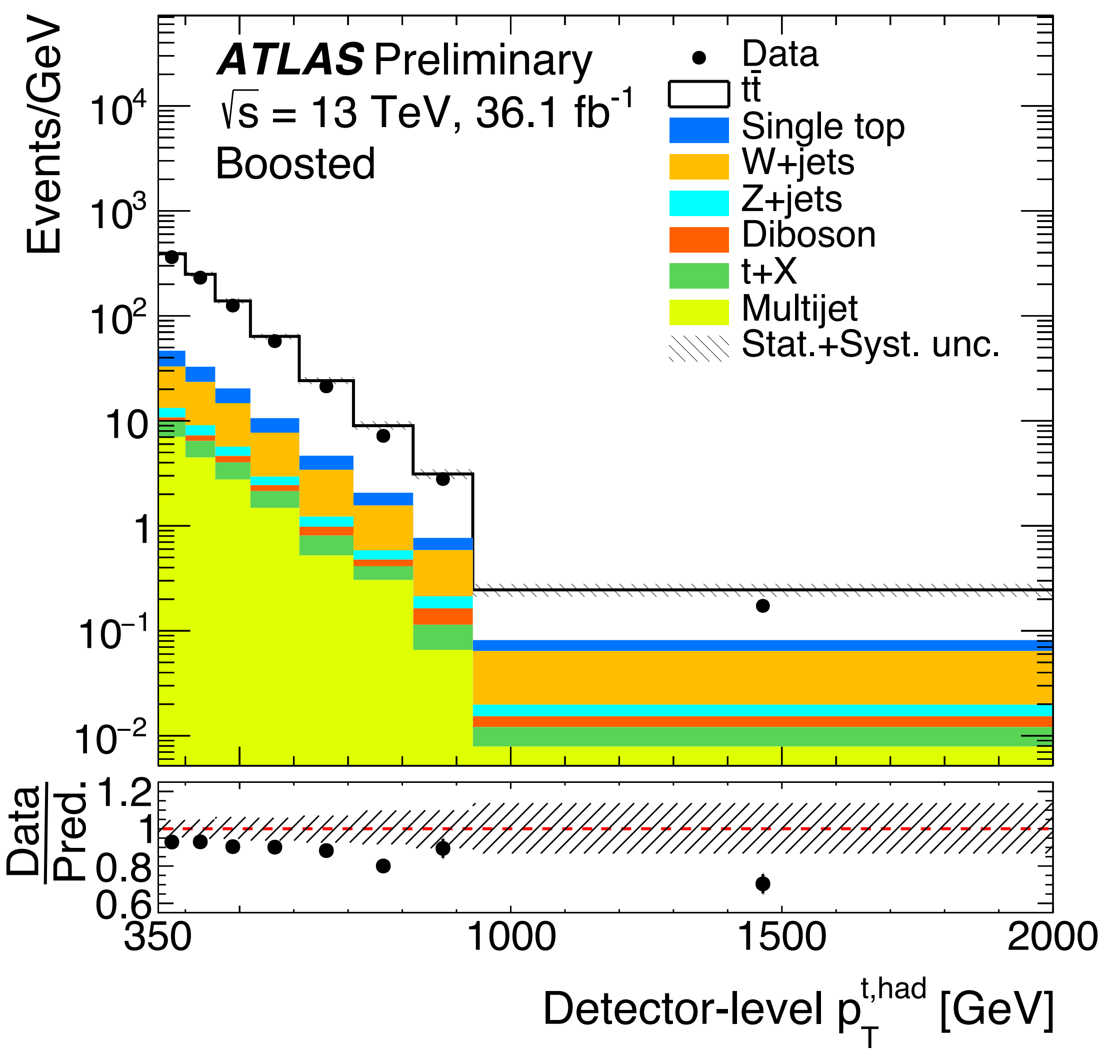
- Boosted hadronic top is identified by re-clustering 0.4 jets with anti-k_T R=1 algorithm.
    - Re-clustering allows propagation of small-R JES and a mass cut is sufficient for background rejection.



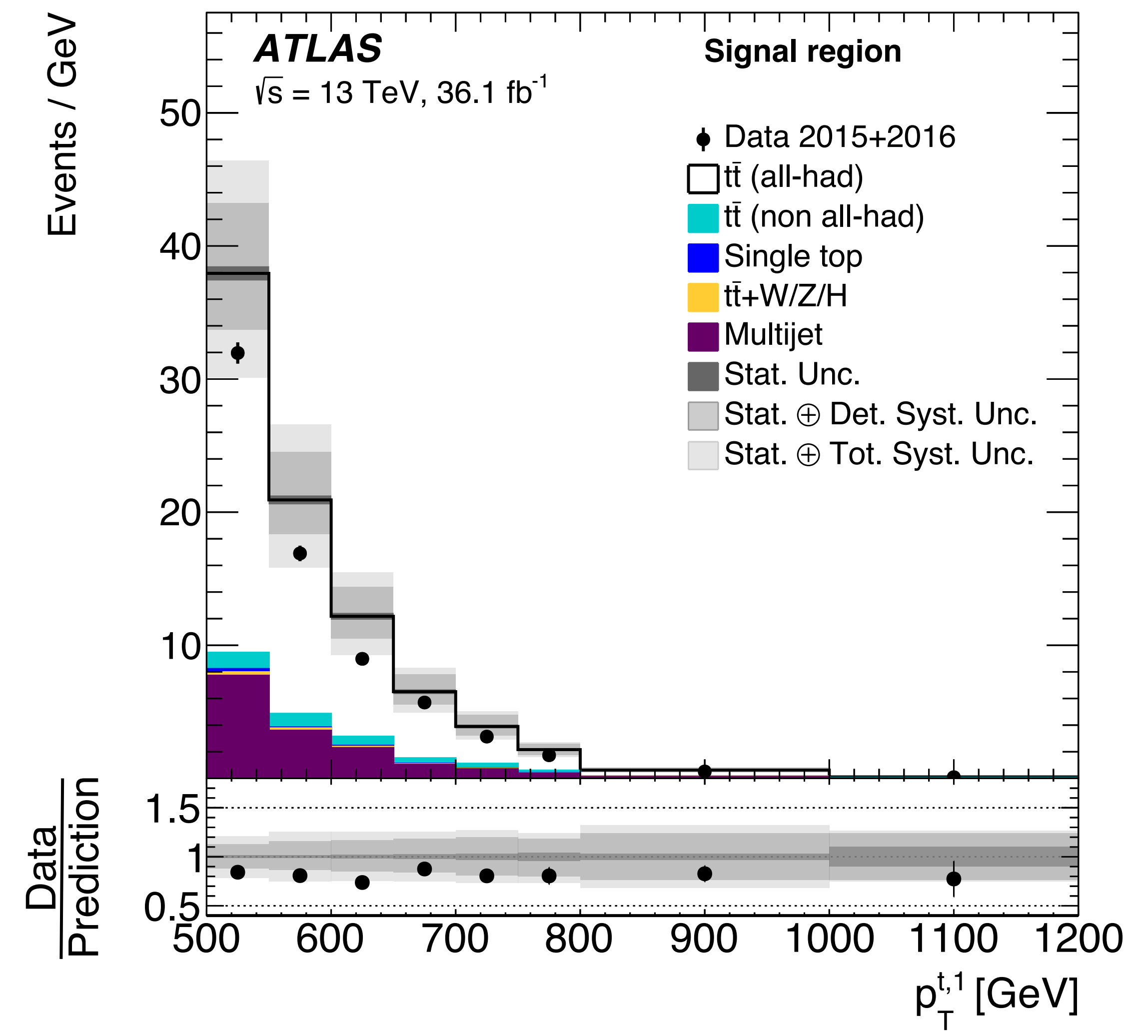
Note: possible to have events where the leptonic top is at lower p_T.

Background composition

lepton+jets



all-hadronic



- Backgrounds generally small in lepton+jets, with largest contributions from W+jets and single-top.
- Dominant background in all-hadronic is QCD multi jet production - estimated with a data-driven technique.

Cross-section extraction

- Correct data to particle or parton level:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} = \frac{1}{\mathcal{L} \cdot \Delta X_i \cdot \varepsilon^i_{\mathrm{eff}}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{detector}} - N^j_{\mathrm{bkg}} \right)$$

Cross-section extraction

- Correct data to particle or parton level:

Data events

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Subtract background

Cross-section extraction

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Subtract background

Correct for top events that are outside the fiducial region (e.g. $p^t_T < 350$ GeV)

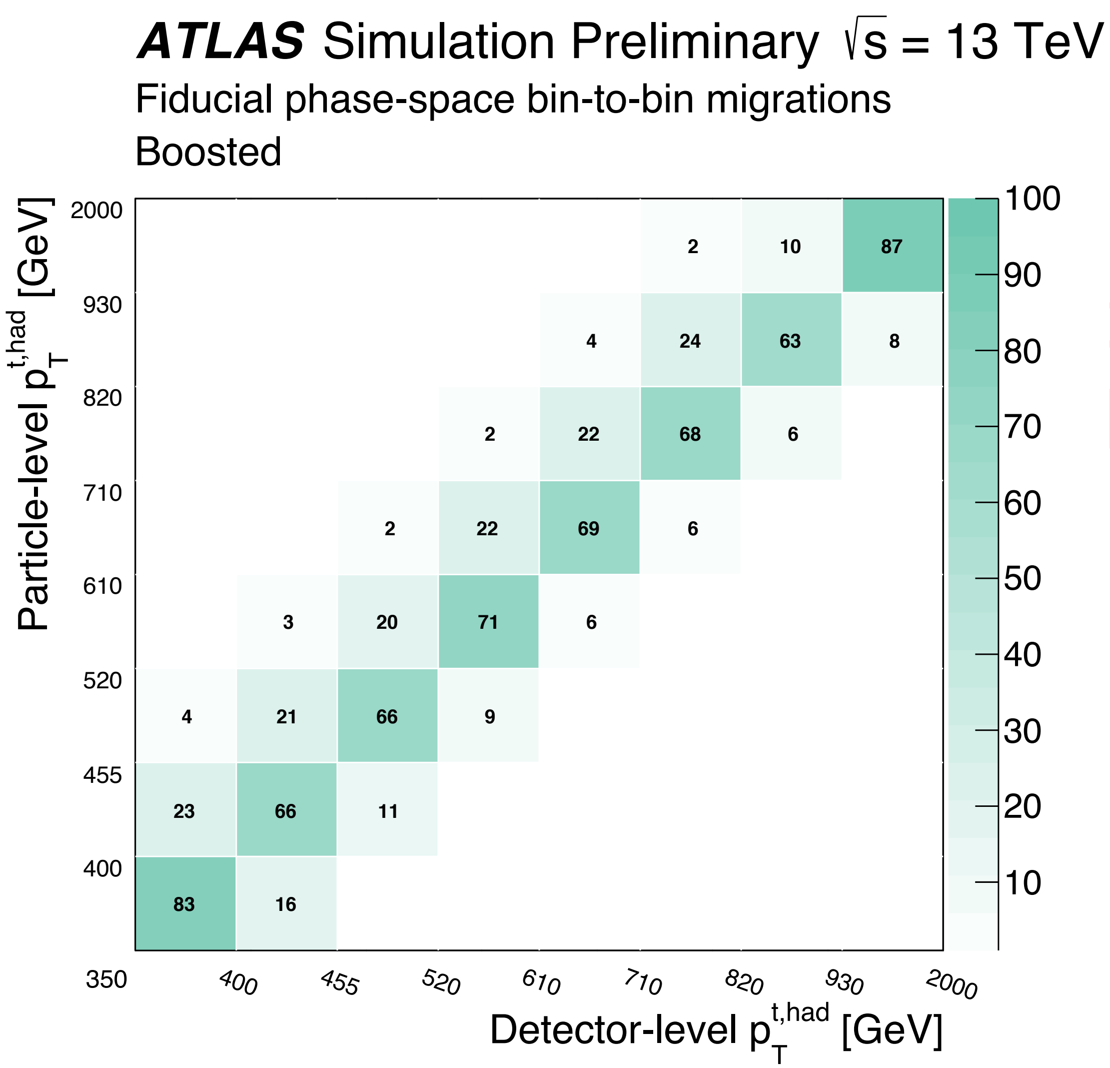
Cross-section extraction

- Correct data to particle or parton level:

Correct for detector resolution

Data events

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} = \frac{1}{\mathcal{L} \cdot \Delta X_i \cdot \varepsilon^i_{\mathrm{eff}}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{detector}} - N^j_{\mathrm{bkg}} \right)$$



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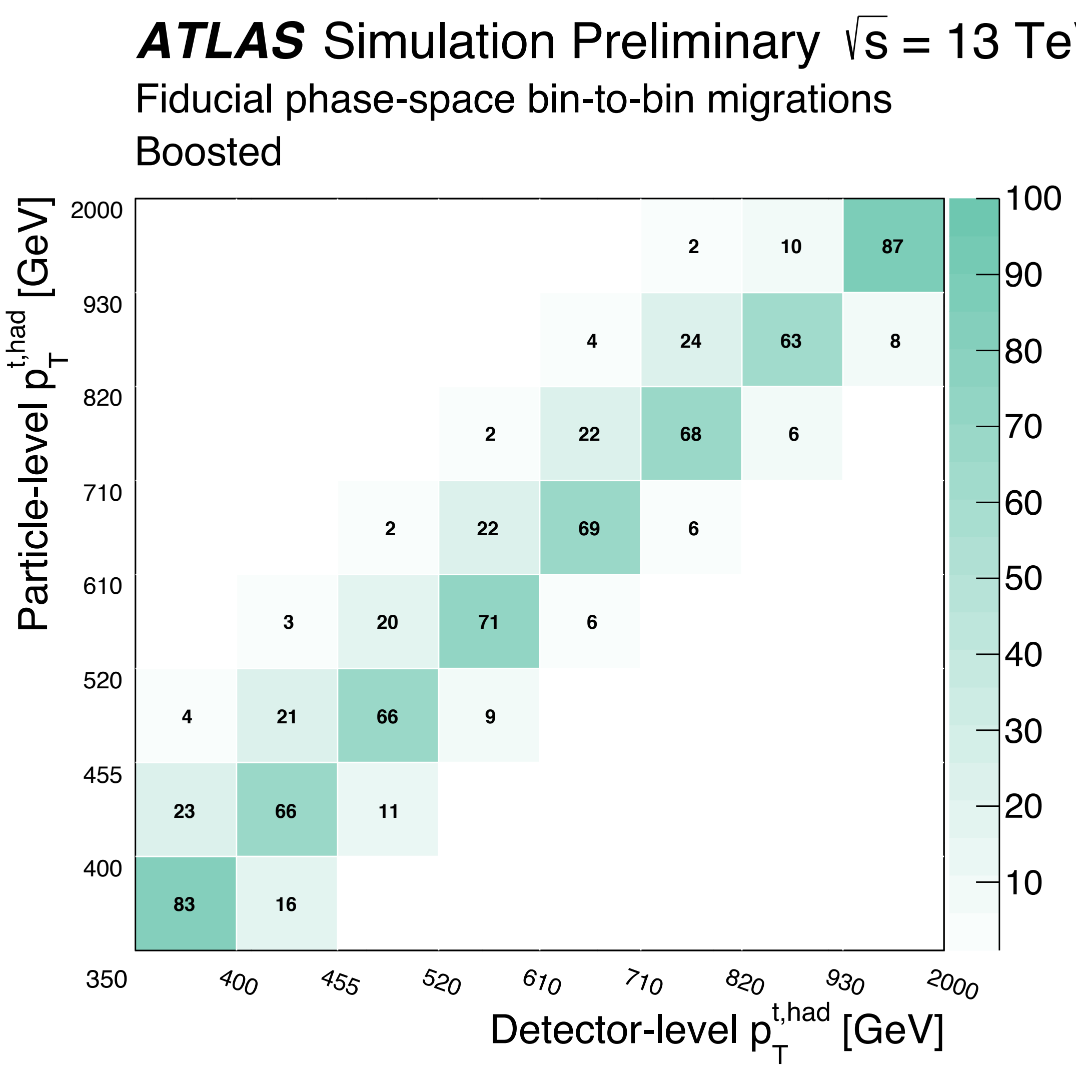
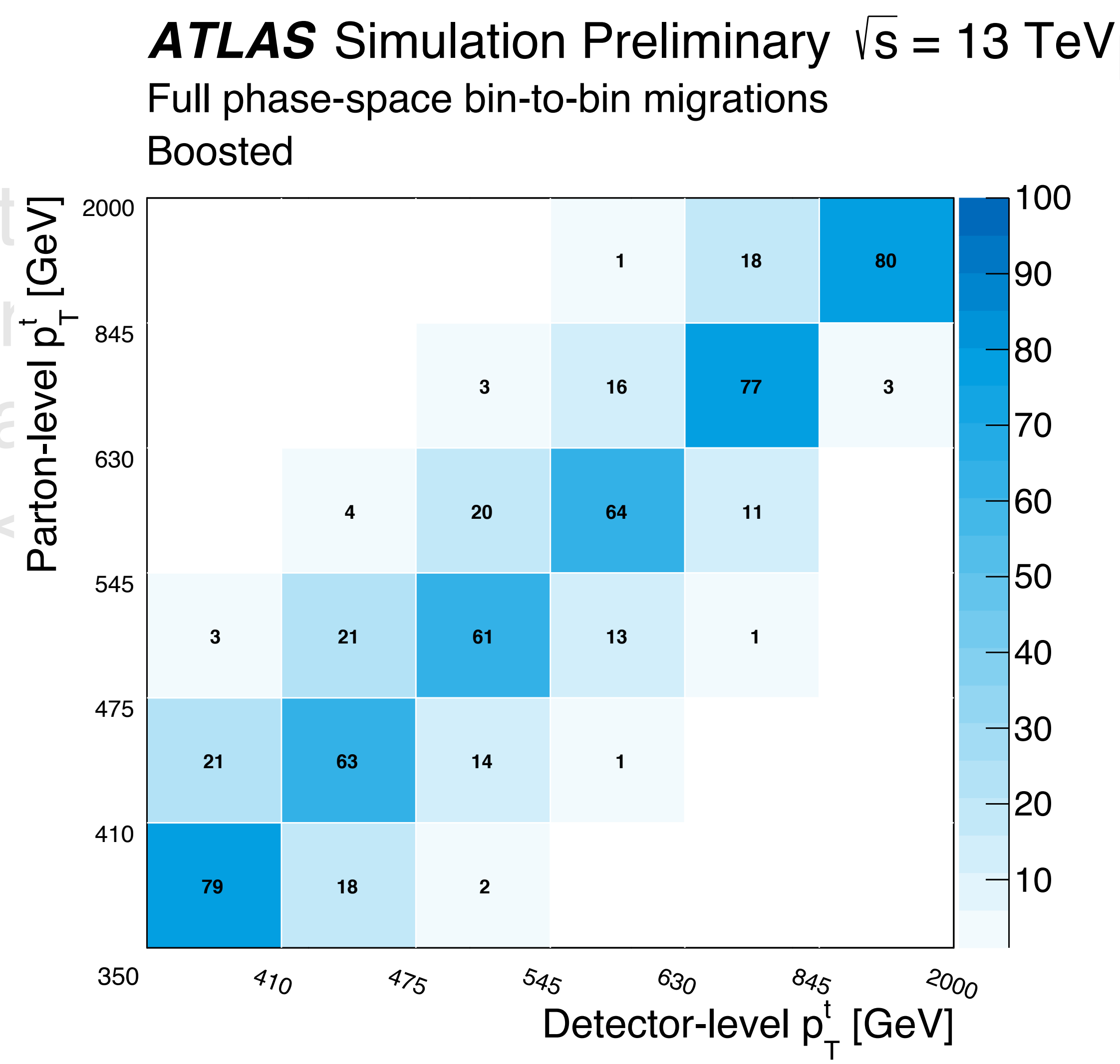




Cross-section extraction

- Correct data to particle or parton level:

Data events

Correct for detector resolution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} = \frac{1}{\mathcal{L} \cdot \Delta X_i \cdot \varepsilon^i_{\mathrm{eff}}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{detector}} - N^j_{\mathrm{bkg}} \right)$$

Correct for detector inefficiency

Subtract background

Correct for top events that are outside the fiducial region (e.g. pT < 350 GeV)

Cross-section extraction

- Correct data to particle or parton level:

Data events

Correct for detector resolution

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} = \frac{1}{\sigma \cdot \mathcal{L} \cdot \Delta X_i \cdot \varepsilon^i_{\mathrm{eff}}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{detector}} - N^j_{\mathrm{bkg}} \right)$$

Correct for detector inefficiency

Subtract background

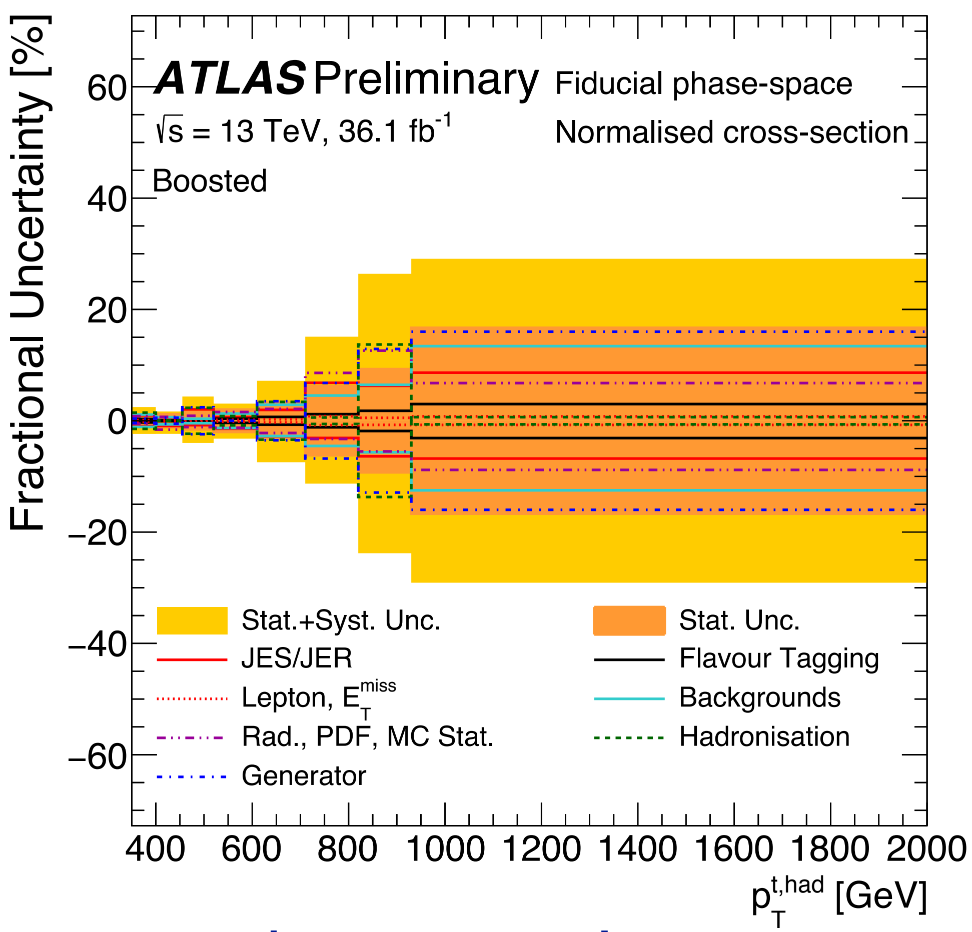
Correct for top events that are outside the fiducial region (e.g. pT < 350 GeV)

Measure both absolute and normalised cross-sections

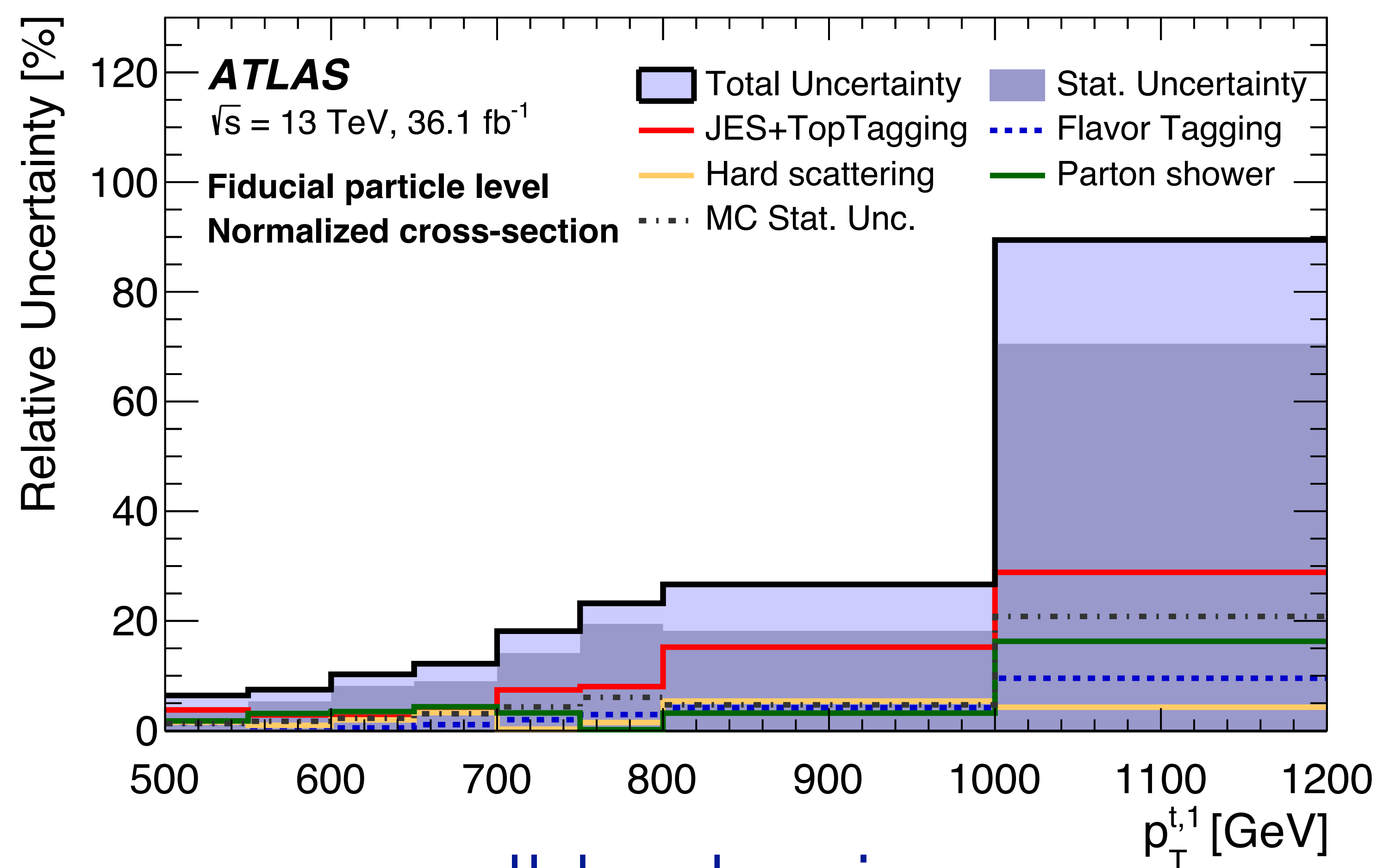
Result for total fiducial cross-section σ also provided.

Systematic Uncertainties

- Major sources of uncertainty:
  - Jet energy scale.
  - Statistics (all-hadronic).
  - b-tagging.
  - Modelling of top-quark pair events.
  - Backgrounds.

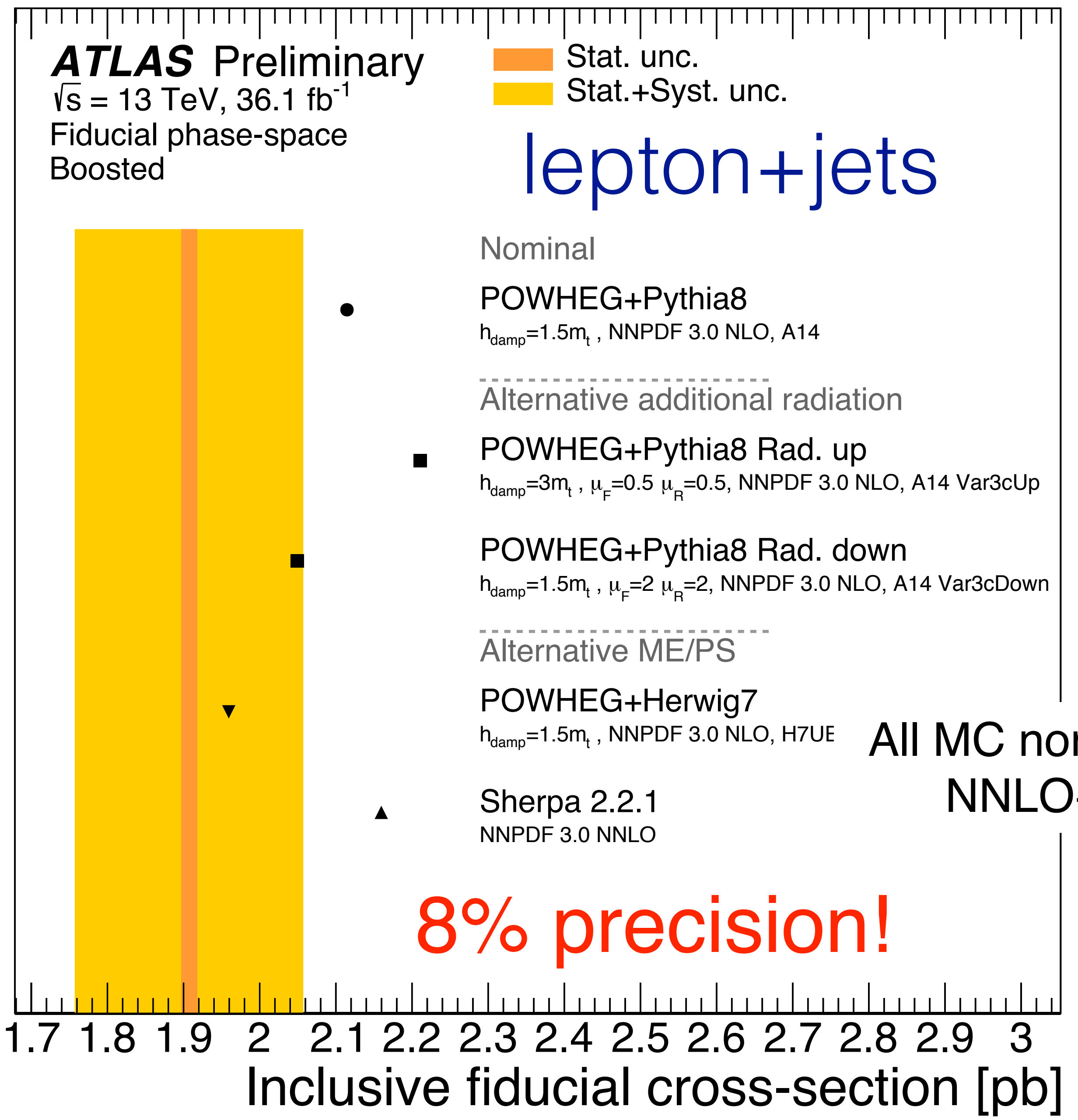


lepton+jets

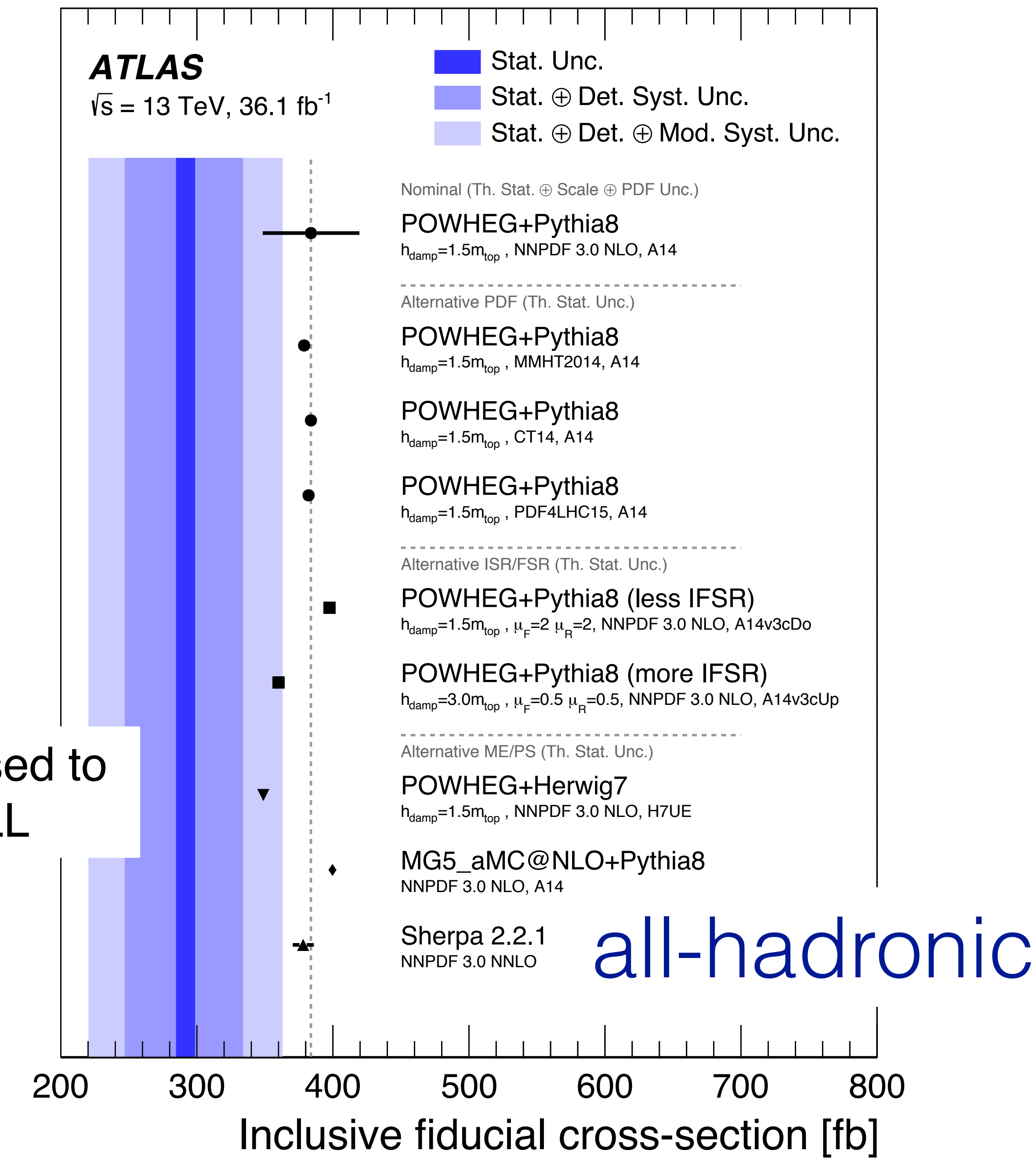


all-hadronic

Particle-level cross-section at high p_T



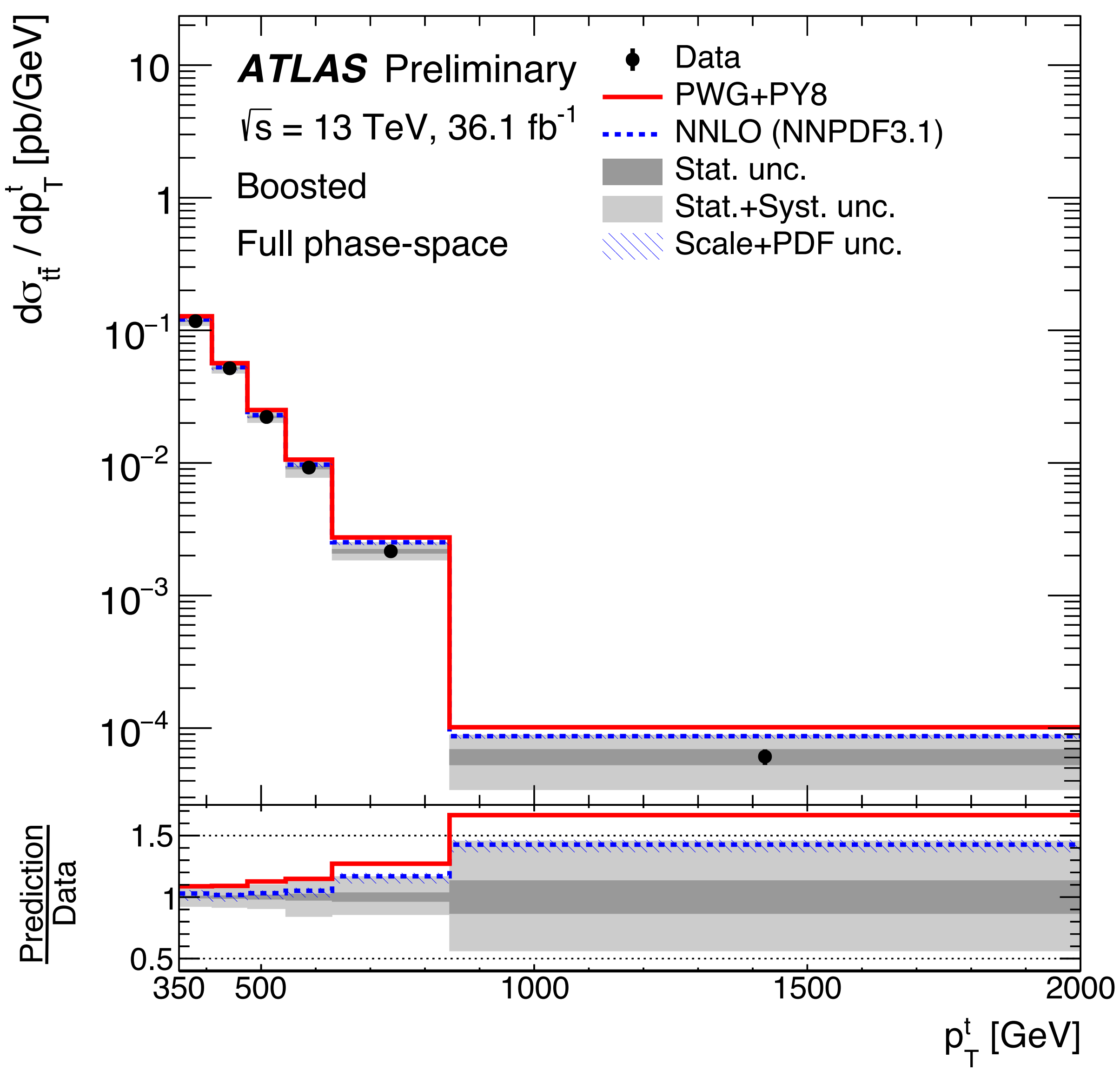
All MC normalised to NNLO+NNLL



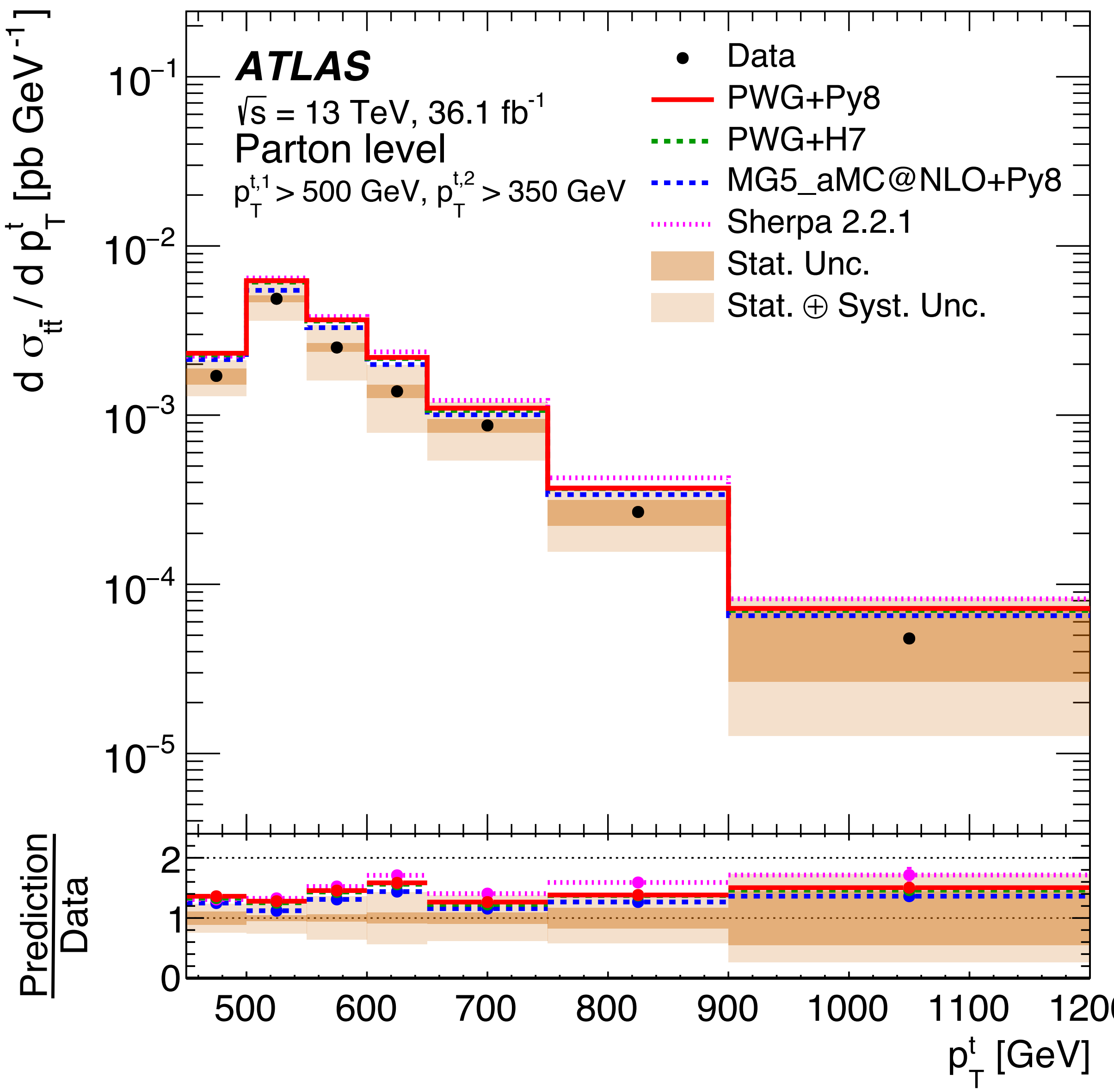
- Both measurements slightly below the theory.
- Larger uncertainty in all-hadronic mainly from top-tagging, b-tagging and top modelling.
- NB different fiducial requirements in two channels.

Parton-level p_T(top)

lepton+jets



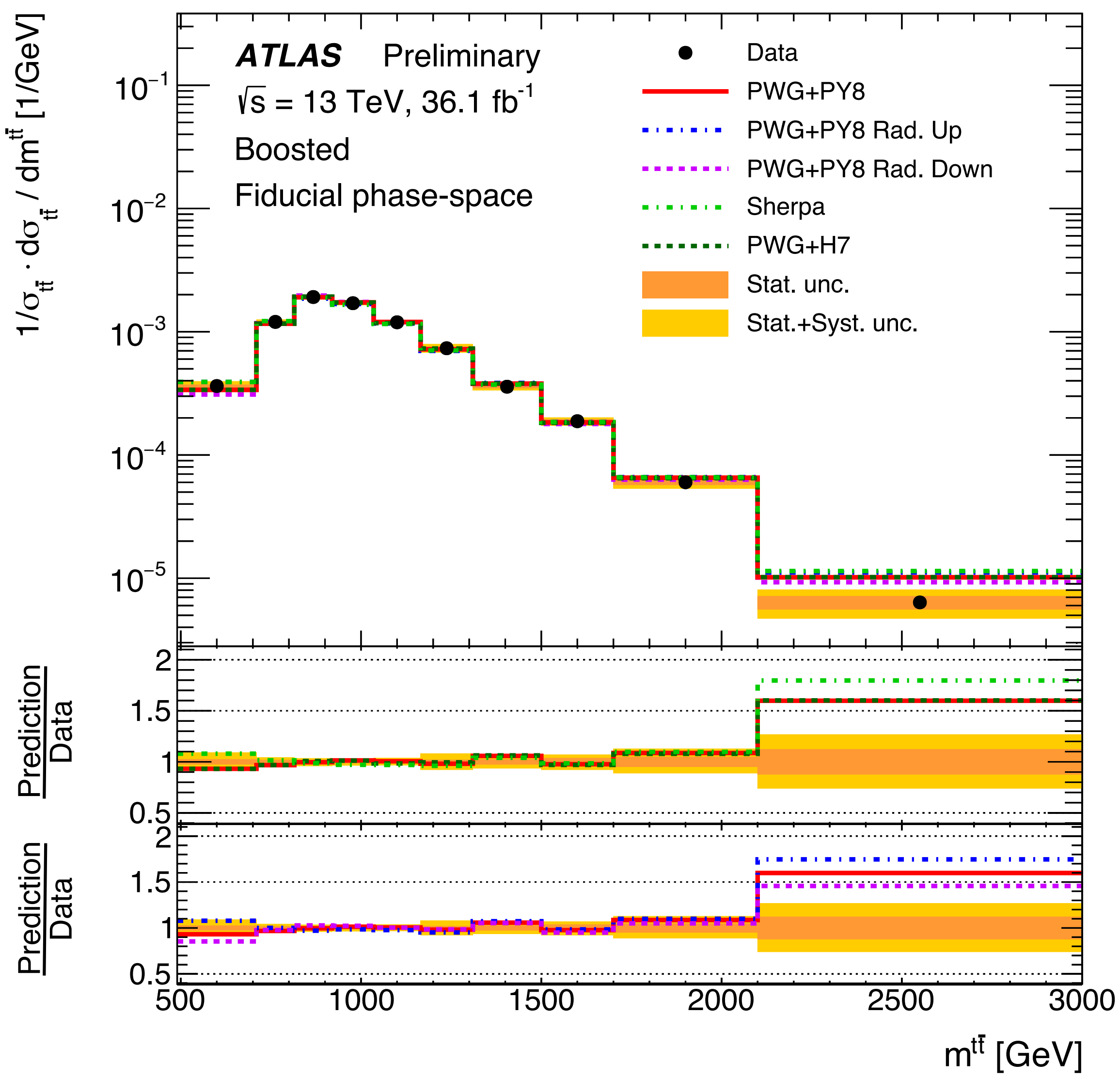
all-hadronic



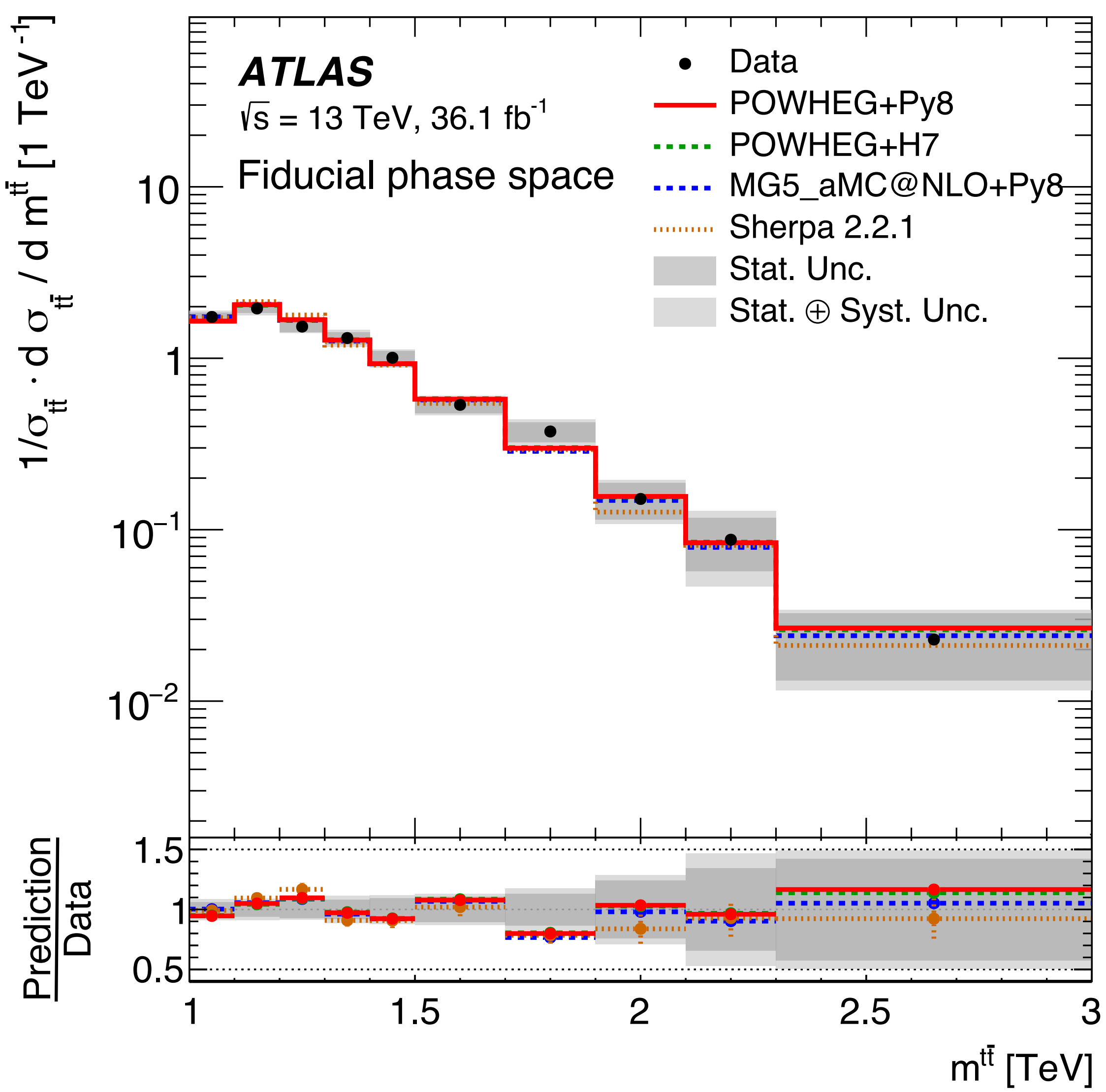
- Full NNLO calculation improves agreement in both normalisation and shape for l+jets data.
- All-hadronic shape appears in better agreement with MC, however note the larger uncertainties on the data

Particle-level m(ttbar)

lepton+jets



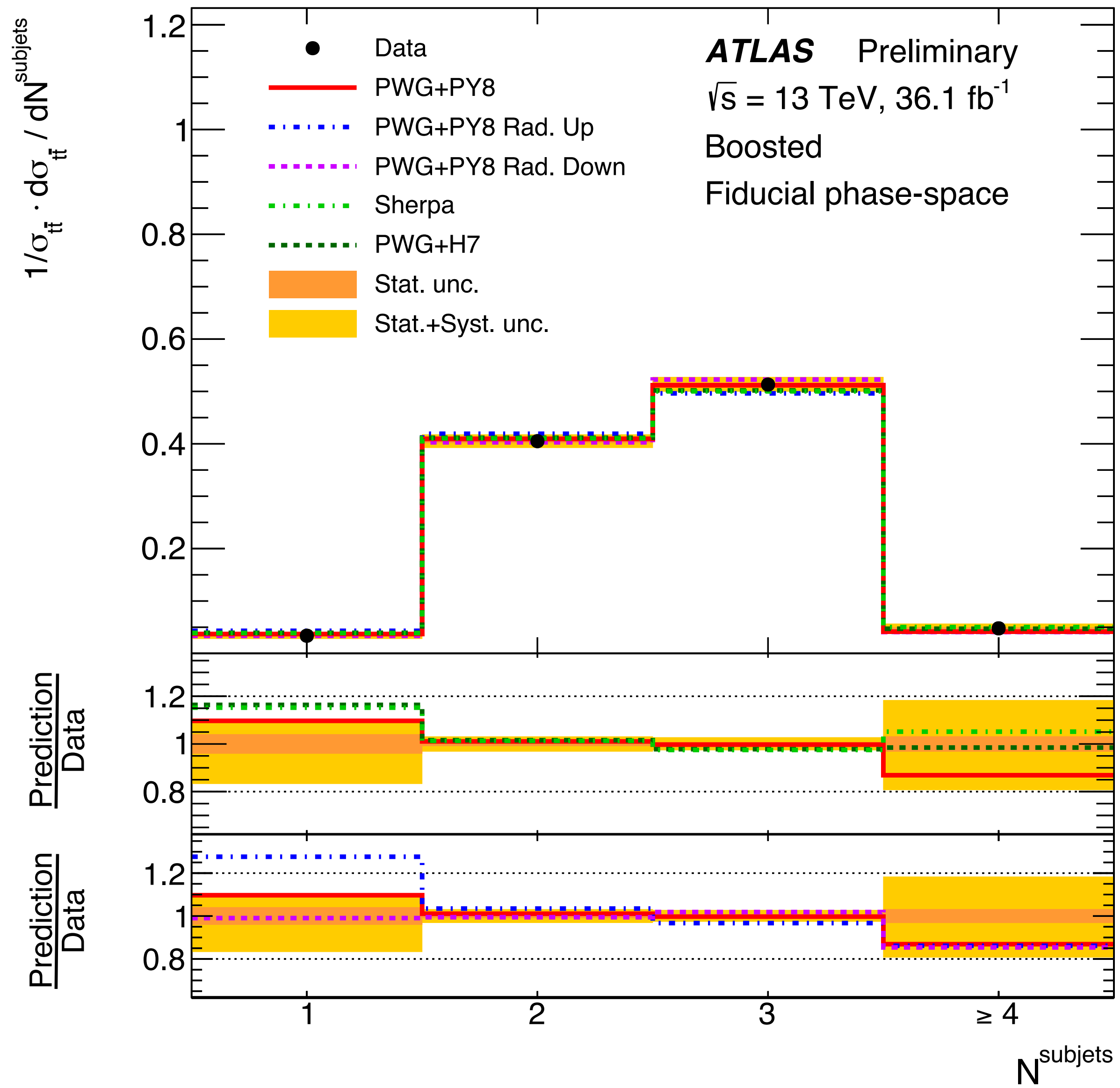
all-hadronic



- Good modelling of the shape of the distribution by NLO generators.
- Now probing m(ttbar) > 2 TeV.

Looking inside a boosted top:

- Measure the number of R=0.4 sub-jets (p_T > 25 GeV) inside the selected top-jet (anti-kT 1.0 with R=0.4 jets as input).



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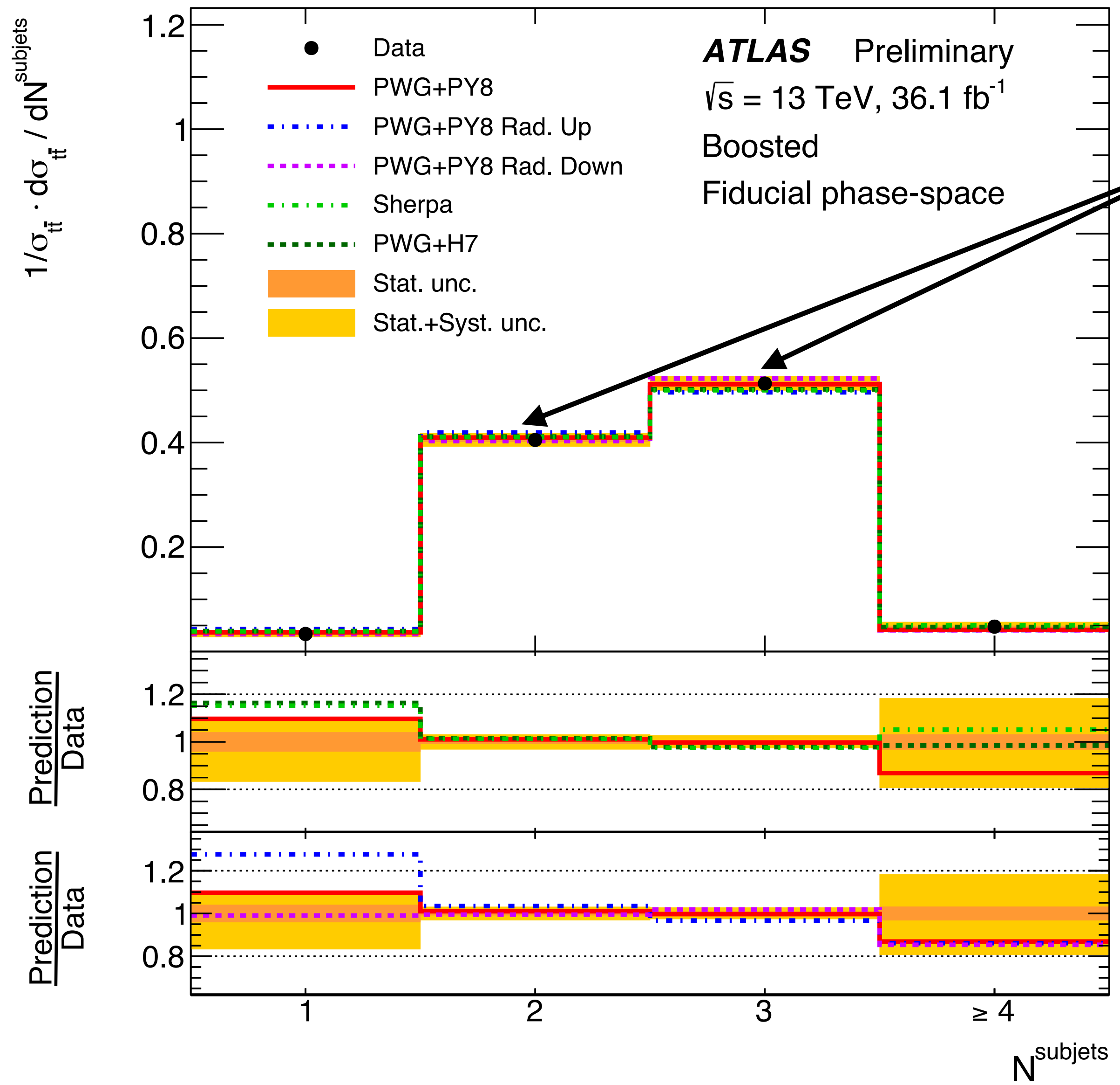

Quite even splits between jets with 2 and 3 subjets.

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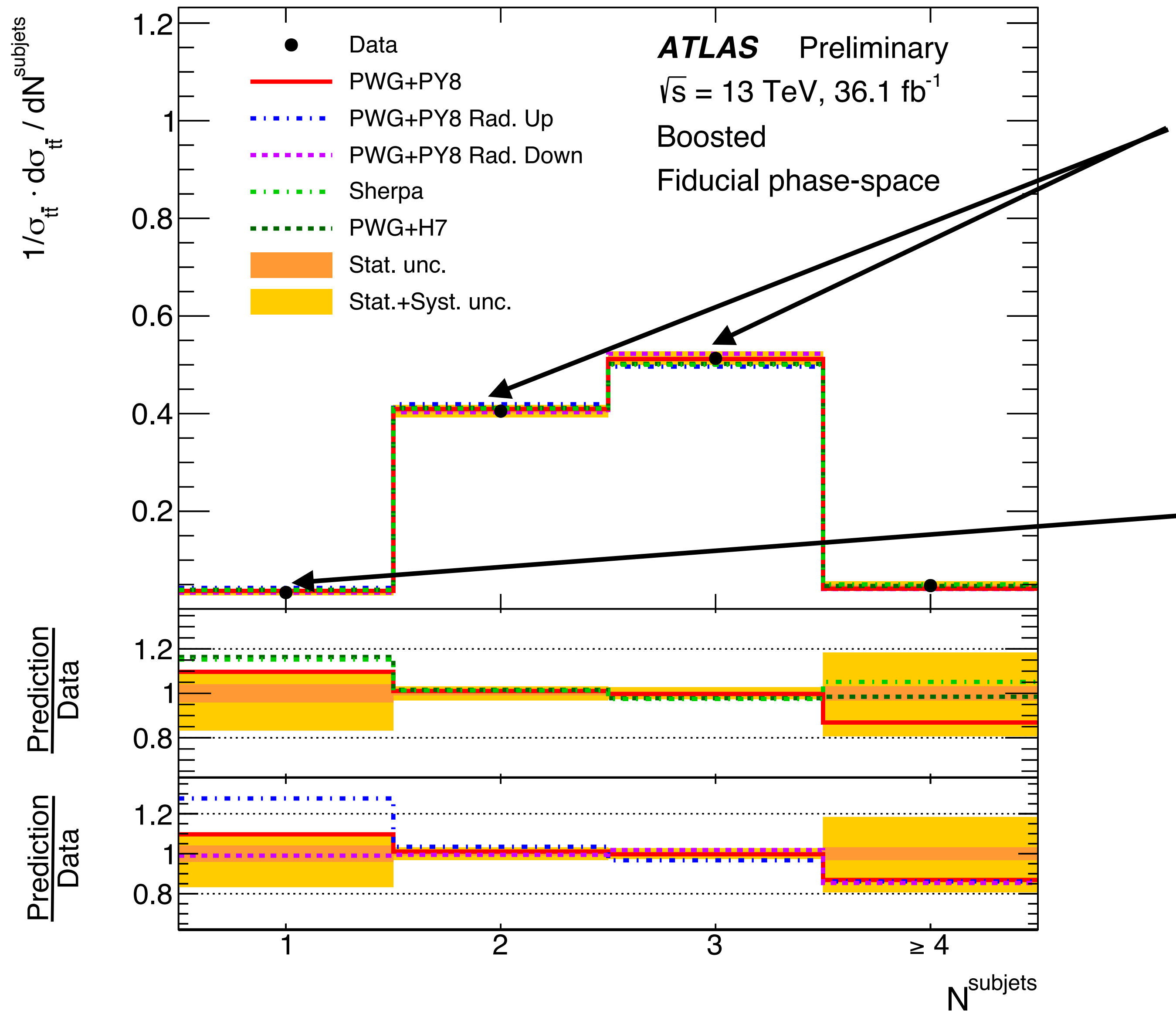

Quite even splits between jets with 2 and 3 subjets.

Highly boosted events?

Looking inside a boosted top:

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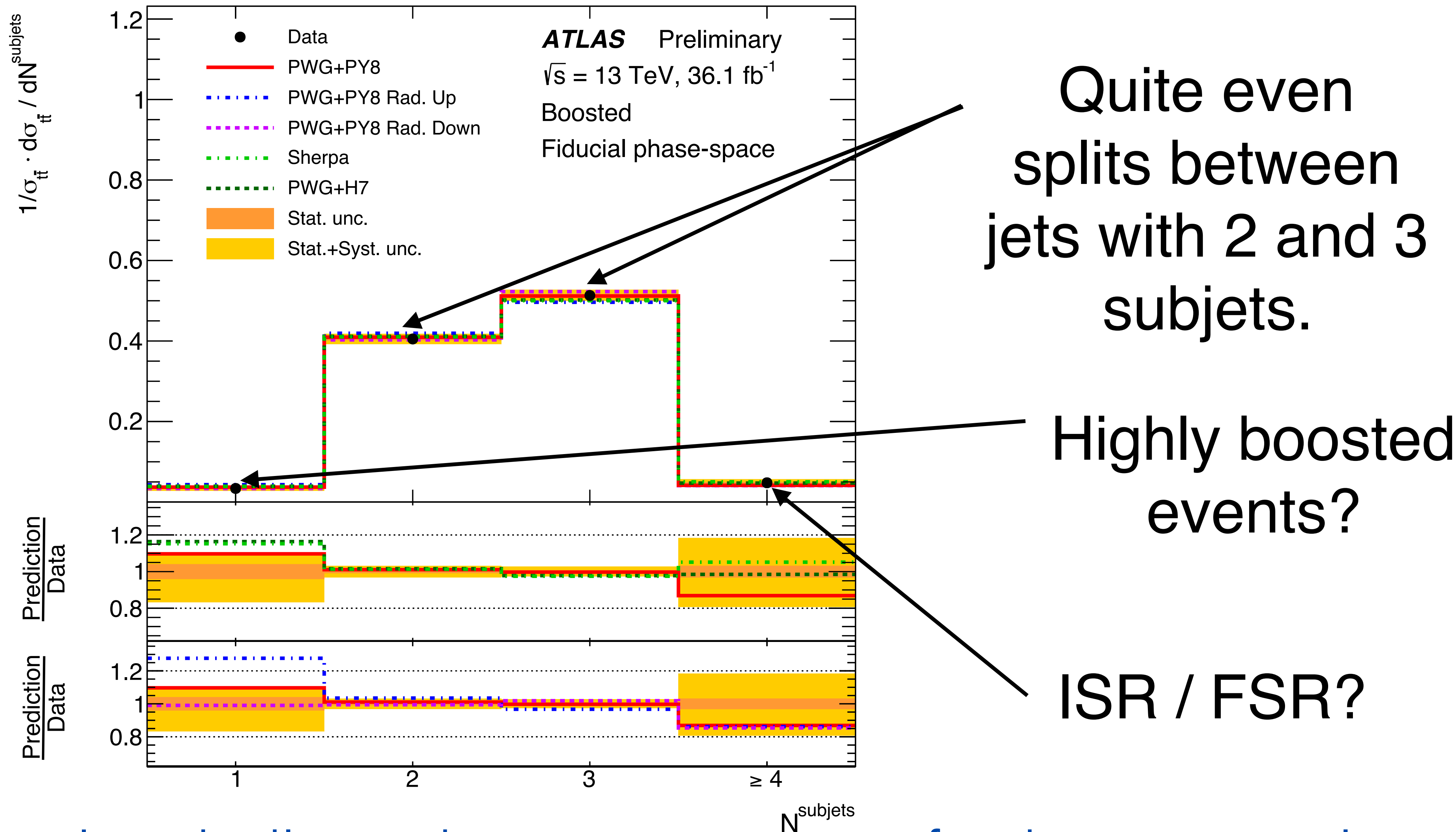
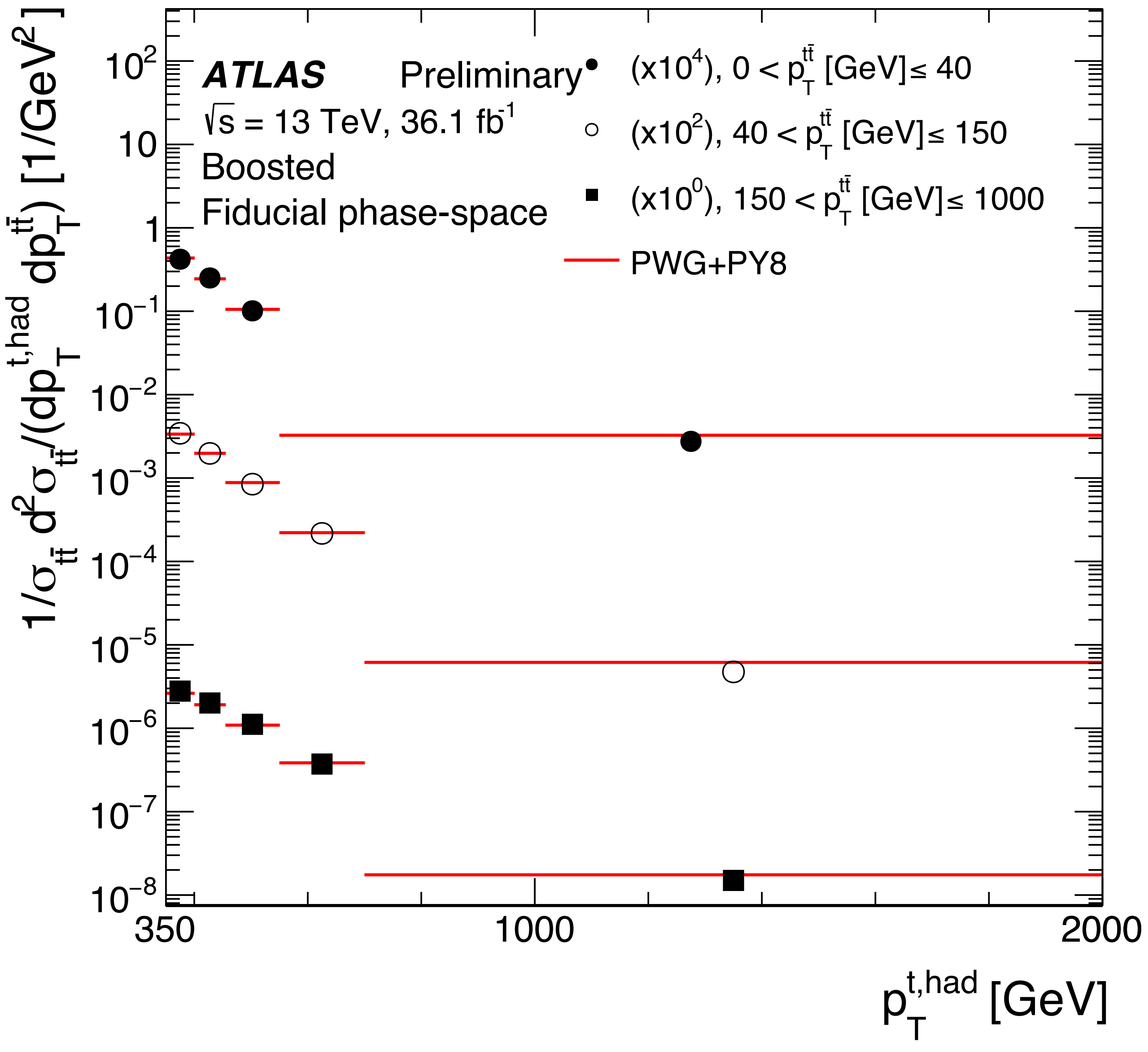


- See also dedicated measurements of sub-structure in Jennifer's talk.

First double differential measurements of boosted tops:

- Measure the top p_T in bins of p_T(ttbar):



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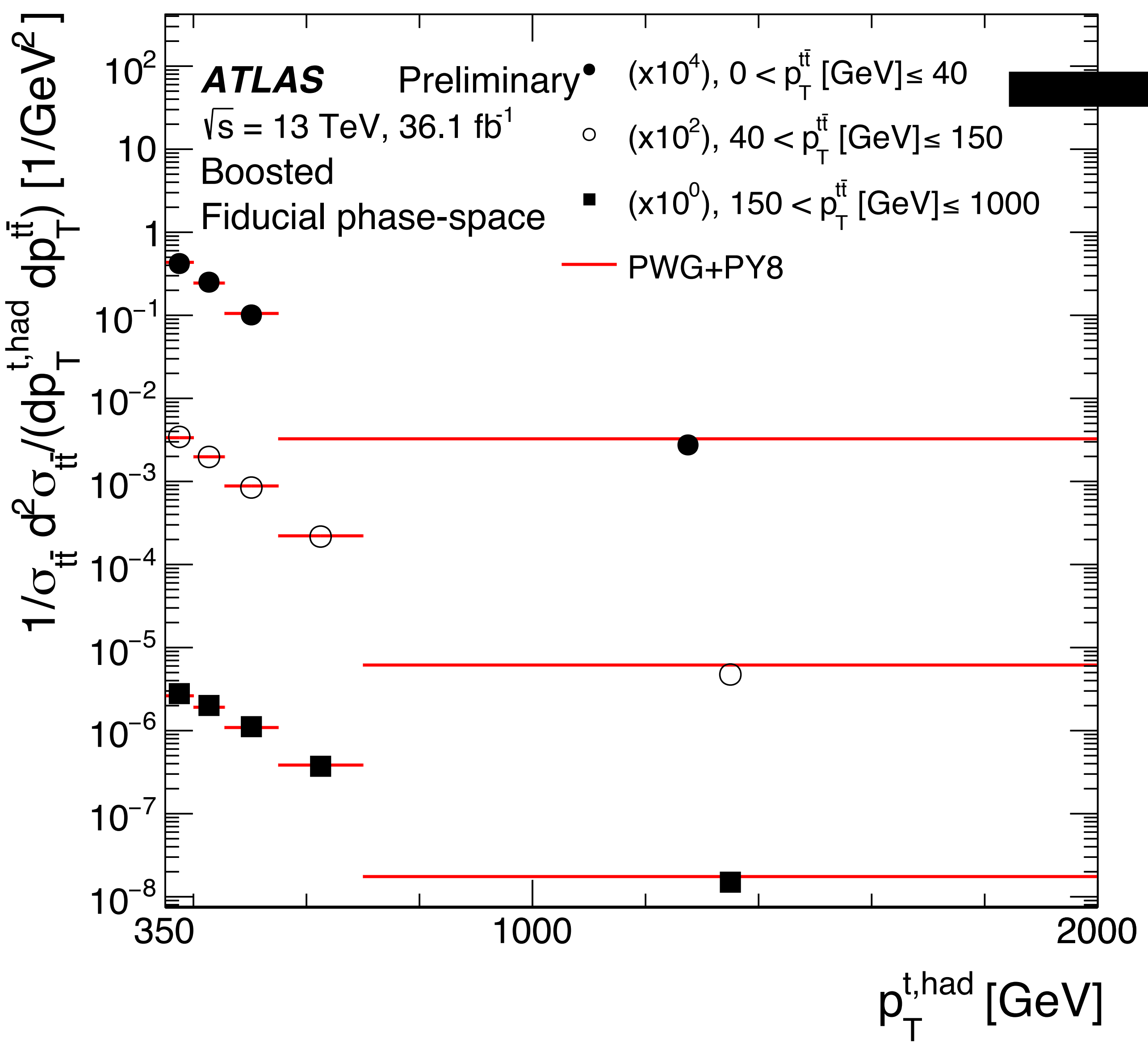

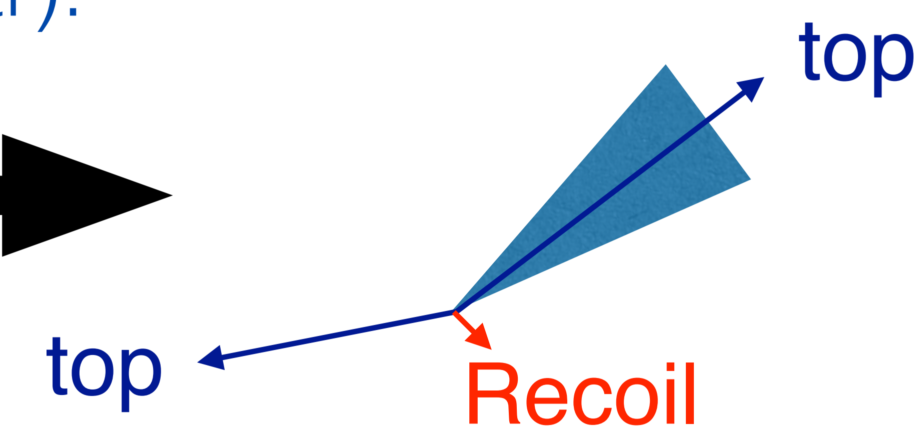

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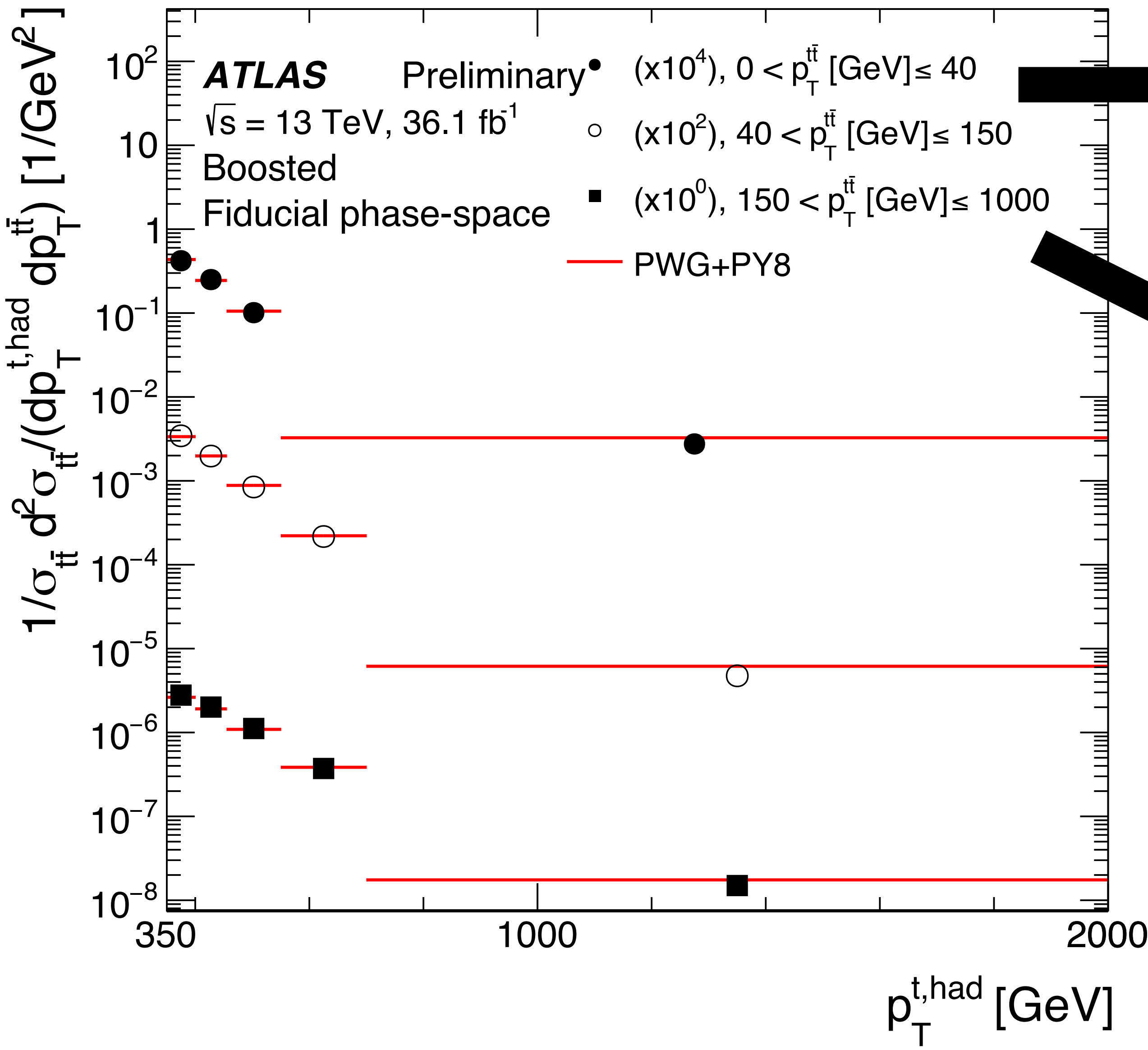

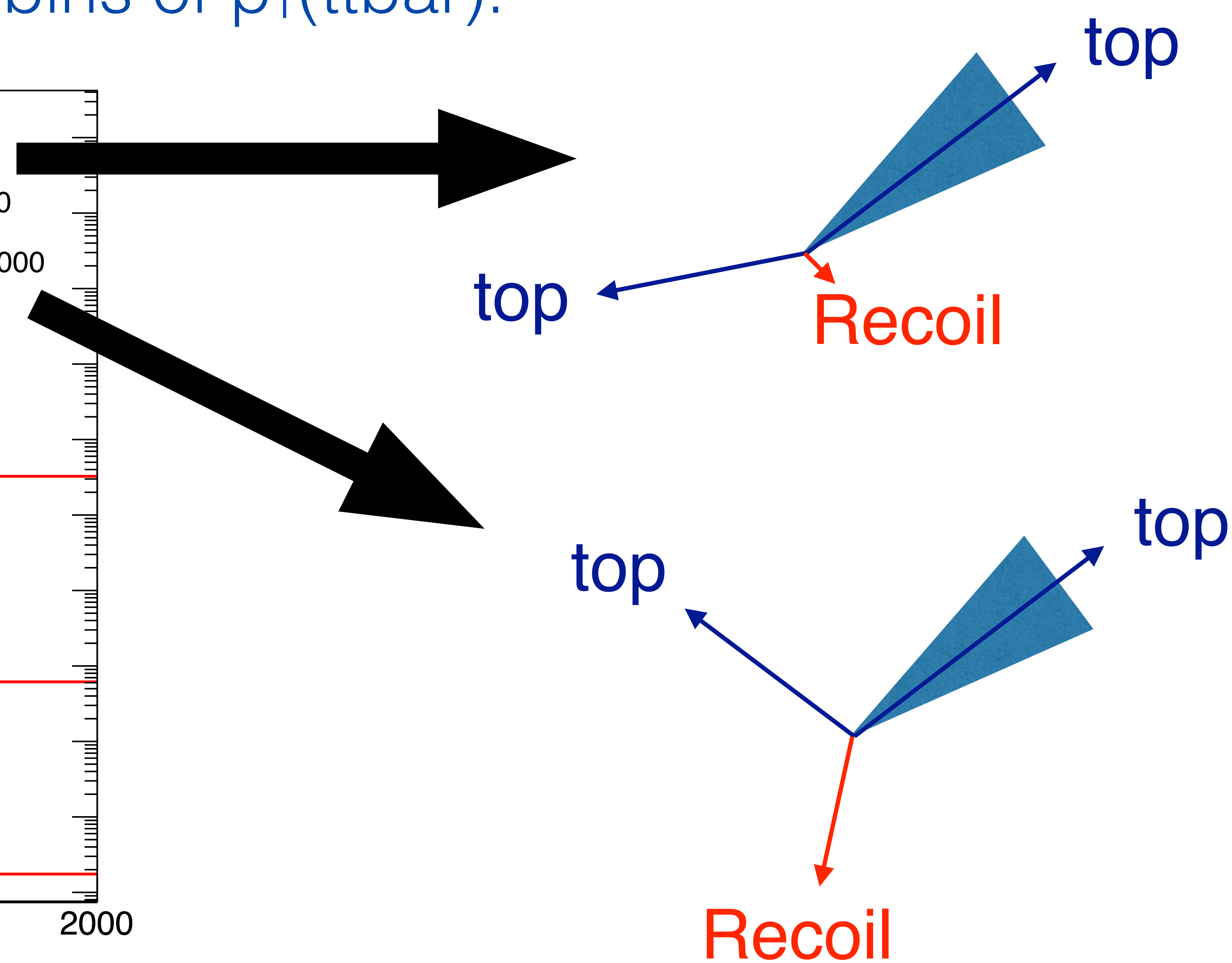

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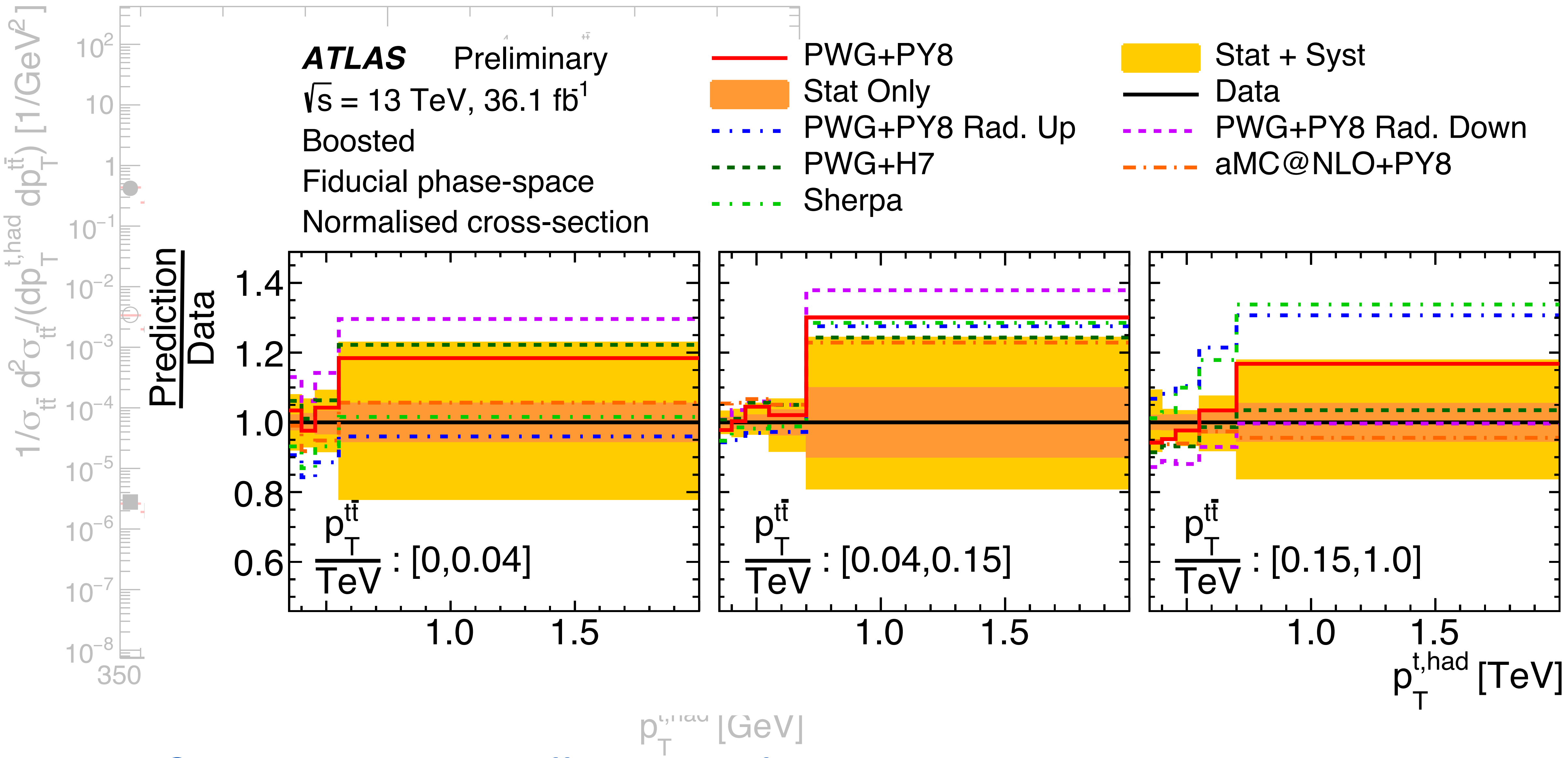
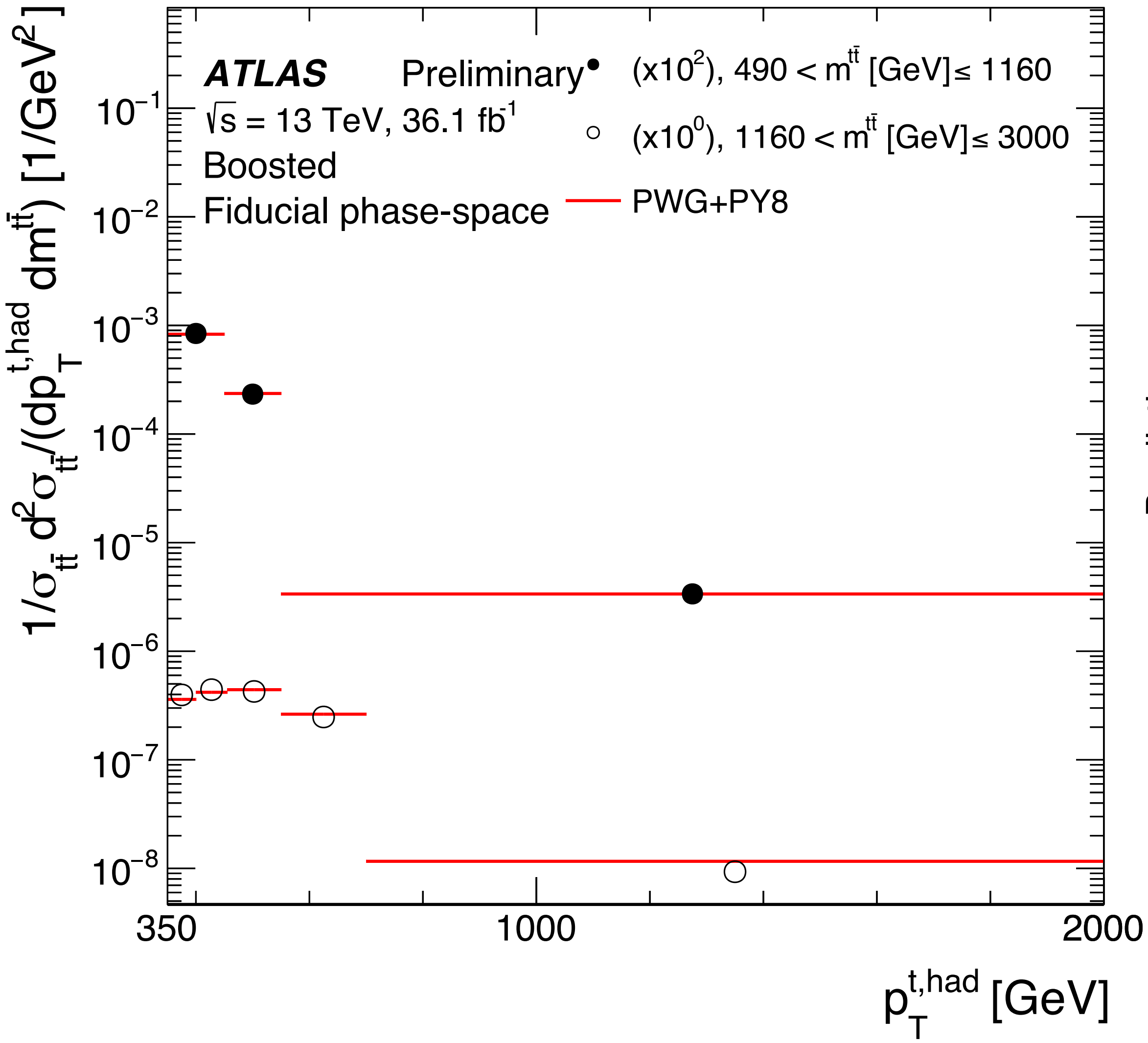
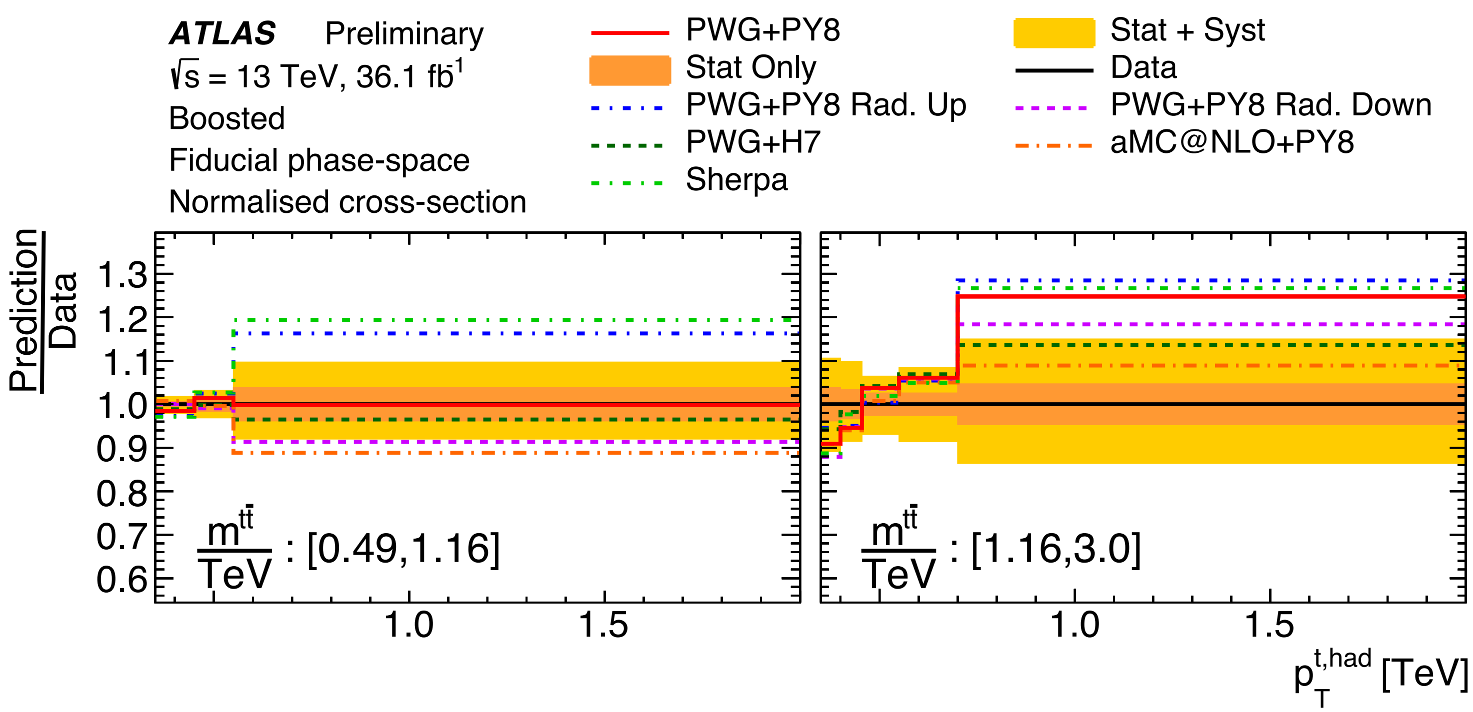


- Starting to probe different configurations.
- pT(ttbar) is non-trivial to model in MC.

Double differential:

- Measure the top p_T in two bins of m(ttbar):





- Slope relative to MC appears stronger in high m(ttbar) bin.
- Approx 20% difference between MC models at high pT and low mass - data starts to discriminate between the models.

Summary

- Detailed measurements of high-pT top-production in two independent channels.
  - Highest precision achieved with l+jets channel, precision better than 10%.
- Some hints that the full differential NNLO prediction provides improved modelling compared to NLO MC+PS.
- First double differential measurements probe details of the top kinematics.
- All results to be provided in HepData / Rivet for easy use.
- Looking ahead: exploit full run-2 data to improve systematic uncertainties and extend p_T reach.

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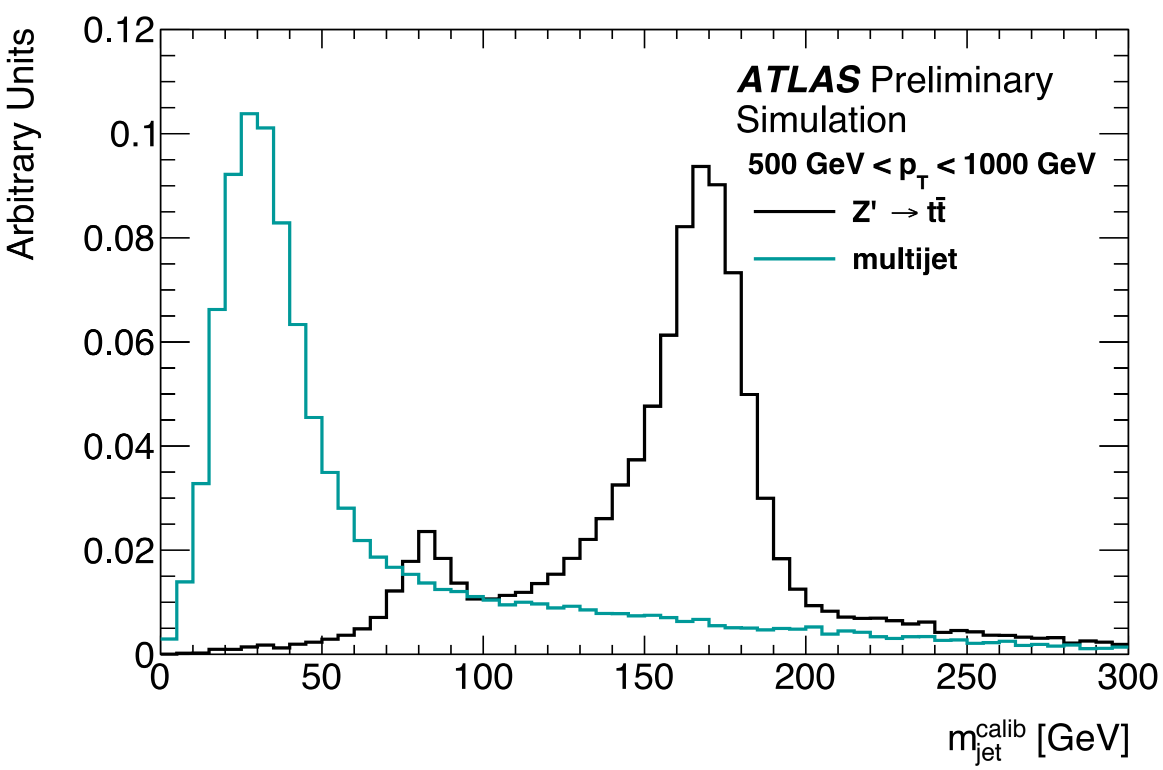
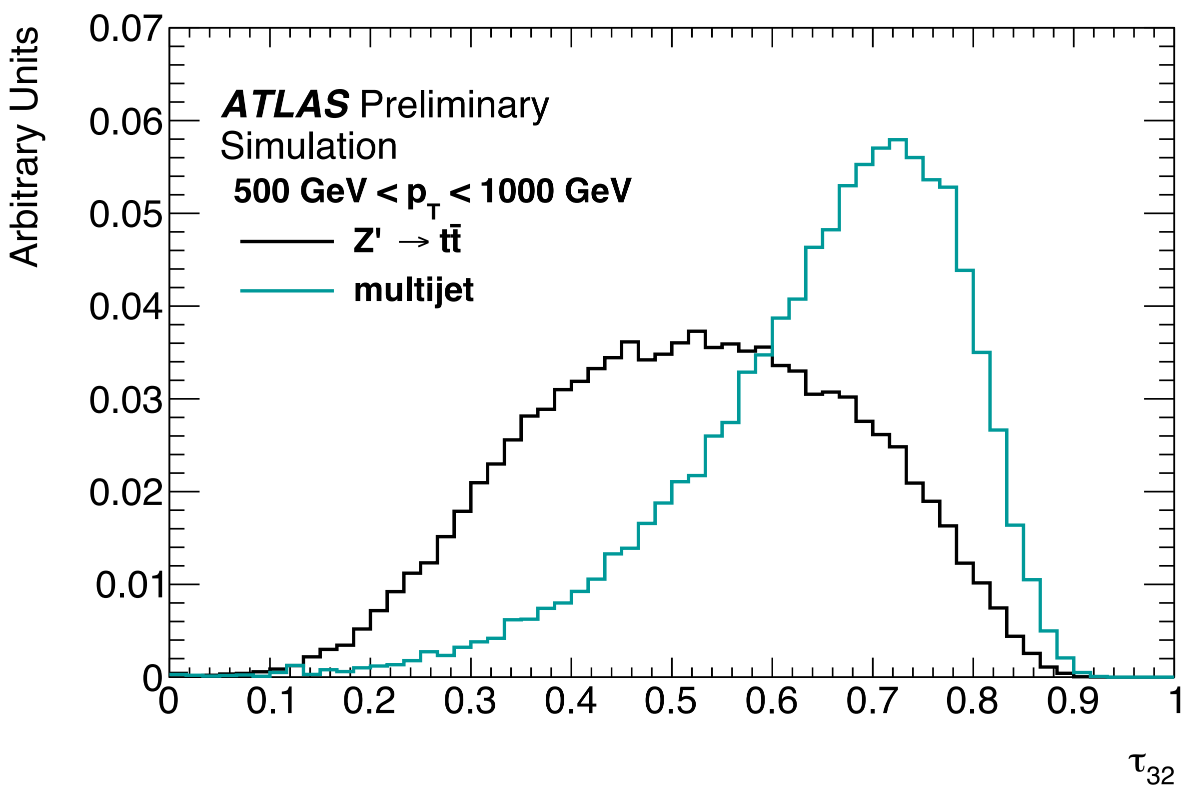
Backup

Top-tagging in all-hadronic

- Anti-kT R=1.0 jets built from calorimeter clusters (LCW).
- Jets are trimmed with R_{sub} = 0.2, f_{cut} = 0.05, based on studies of the impact of pileup.
- Tagging algorithm uses m_{jet} and τ_{32}.





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Multijet estimate in all-hadronic

- Use largely un-correlated b-tagging and top-tagging to estimate background:

2nd large-R jet				
1t1b	J (7.6%)	K (21%)	L (42%)	S
0t1b	B (2.2%)	D (5.8%)	H (13%)	N (47%)
1t0b	E (0.7%)	F (2.4%)	G (6.4%)	M (30%)
0t0b	A (0.2%)	C (0.8%)	I (2.2%)	O (11%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

$$S = \frac{J \times O}{A}$$

- Account for correlations:

$$S = \frac{J \times O}{A} \cdot \frac{D \times A}{B \times C} \cdot \frac{G \times A}{E \times I} \cdot \frac{F \times A}{E \times C} \cdot \frac{H \times A}{B \times I}$$

- Uncertainty from limited number of data events and subtraction of non-multijet events from control regions.

Multijet estimate in all-hadronic

- Validate in L and N regions:

2nd large-R jet				
1t1b	J (7.6%)	K (21%)	L (42%)	S
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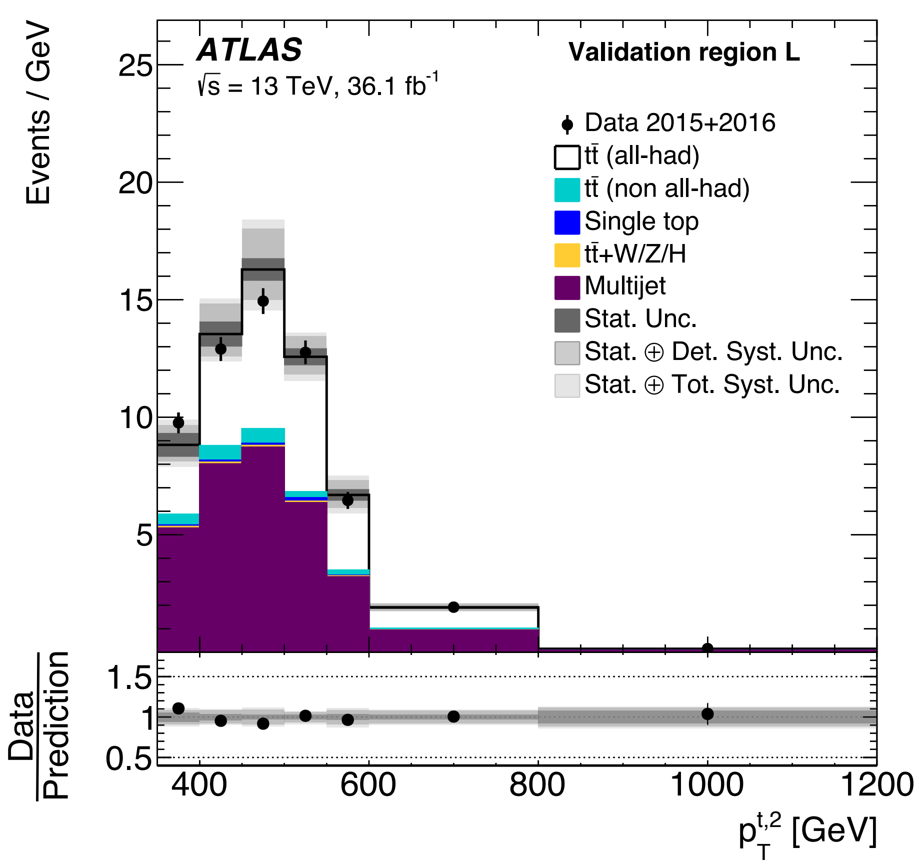
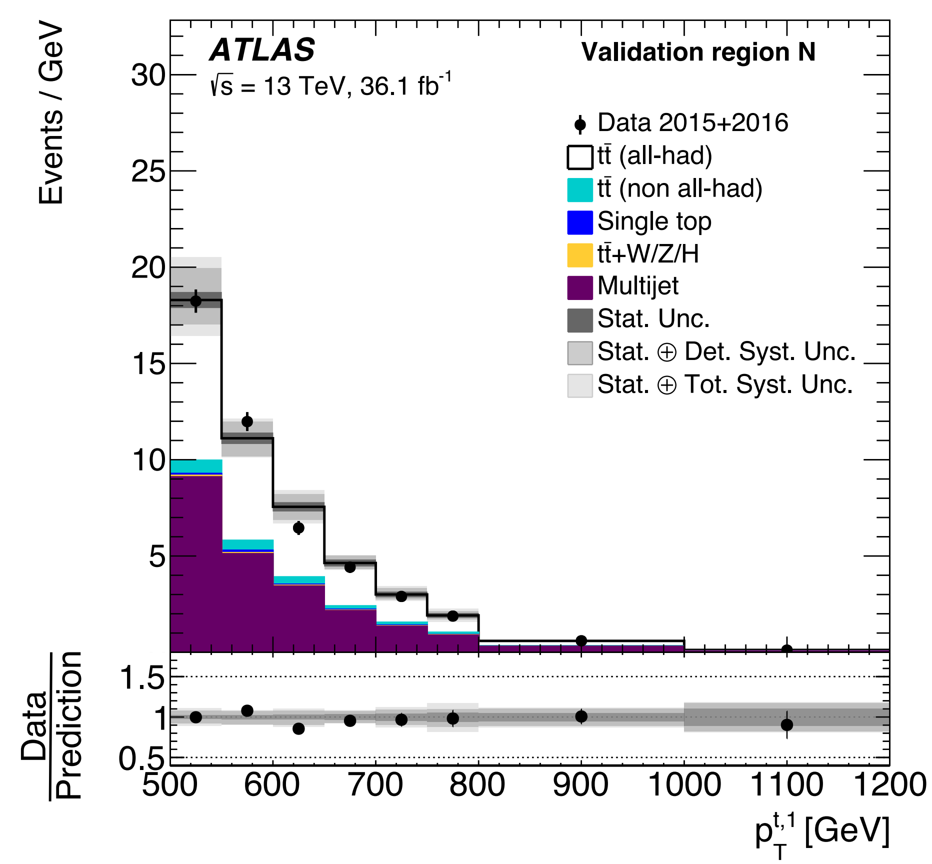
Leading large-R jet





MC Setups

- PWG+PY8: Powheg + Pythia 8.210, NNPDF3.0, ttbar production at NLO, h_{damp}=1.5m_t (tuned to previous ttbar data), A14 tune.
- PWG+PY8 Rad. Up: Powheg + Pythia8, ttbar production at NLO, h_{damp}=3mt, factorisation & renormalisation scales 0.5*nominal, Var 3c up A14 eigentune.
- PWG+PY8 Rad. Down: Powheg + Pythia8, ttbar production at NLO, h_{damp}=1.5mt, factorisation & renormalisation scales 2*nominal, Var 3c down A14 eigentune.
- PWG+H7: Powheg + Herwig 7.01, NNPDF3.0, ttbar production at NLO, H7-UE-MMHT tune.
- Sherpa: Sherpa 2.2.1, NNPDF3.0, ttbar production at NLO for 0 and 1 additional-jets, up-to 4 additional jets at LO, merged with MEPS@NLO, default Sherpa tune.
- aMC@NLO+PY8: MadGraph5_aMC@NLO 2.6.0 + Pythia 8.230, NNPDF3.0, shower starting scale set to HT/2 (tuned to previous ttbar data), A14 tune.