Probing perturbative QCD at the ATLAS Experiment

Tibor Ženiš
Comenius University Bratislava

On behalf of the ATLAS collaboration

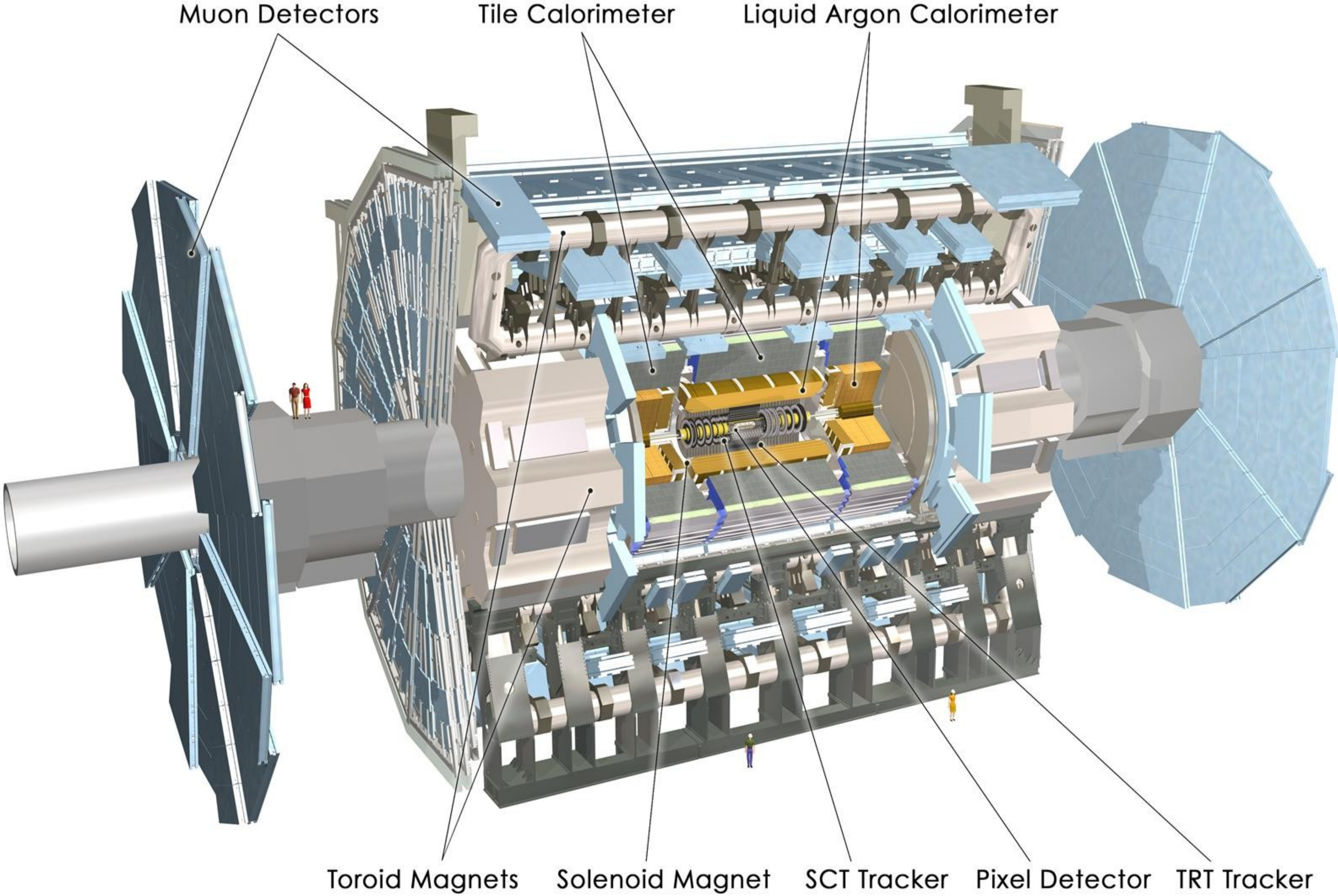
Overview

- Motivation
- Experiment ATLAS: brief description
- Samples of ATLAS perturbative QCD results:
  - Jets and dijets cross-sections
  - Photons in association with heavy flavors
  - Vector bosons in association with jets
  - Dijet correlations
  - Jet-substructure studies
- Conclusions

Motivation

- Perturbative QCD calculations at next-to-next-to leading order are available for many processes.
- Latest results from the ATLAS collaboration at center of mass energies of 8 and 13 TeV are presented and compared to the theory predictions.
- Results of the comparison:
  - consistency test of the Standard Model (SM),
  - extraction of fundamental parameters;
  - is sensitive to physics beyond SM;
  - tuning of the Monte-Carlo (MC) models.

The ATLAS Detector



The ATLAS Detector

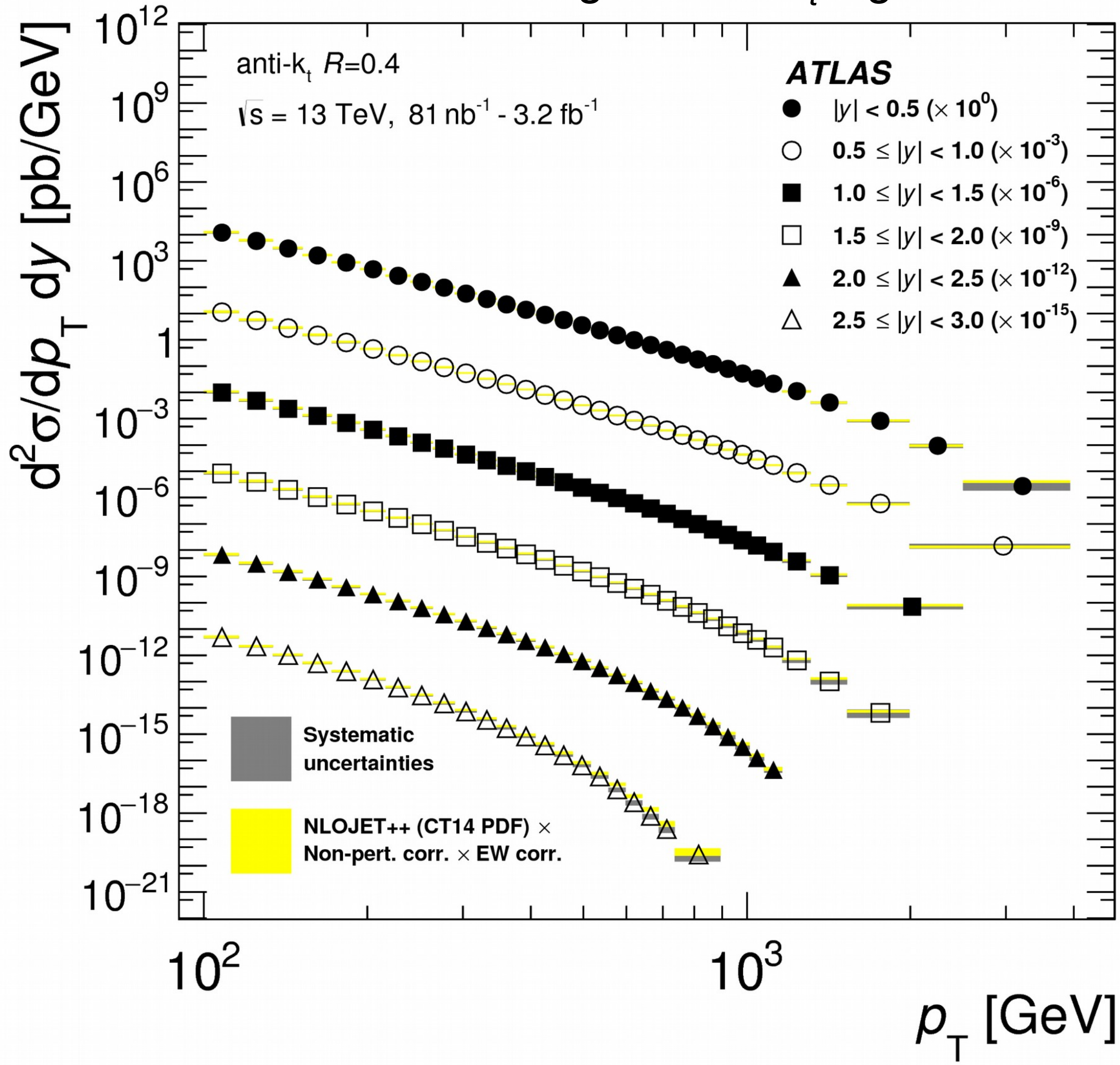
- Multipurpose particle physics detector with a forward-backward symmetric cylindrical geometry and a solid angle coverage of almost 4π.
- Inner tracking system:
  - pseudorapidity range $|\eta| < 2.5$
  - silicon pixel detector, silicon microstrip detector and, transition radiation tracker.
- Superconducting solenoid providing a 2 T magnetic field along the beam direction.
- Calorimeters:
  - High-granularity liquid-argon sampling electromagnetic calorimeter in region $|\eta| < 3.2$.
  - A steel/scintillator tile hadronic calorimeter in range $|\eta| < 1.7$.
  - The endcap and forward regions $1.5 < |\eta| < 4.9$: liquid-argon calorimeters for electromagnetic and hadronic measurements.
- Muon spectrometer:
  - Three large air-core superconducting toroid systems.
  - Separate trigger and high-precision tracking chambers for $|\eta| < 2.7$.
- The trigger system:
  - Three consecutive levels: from hardware-based level 1 to the event filter which uses reconstruction algorithms similar to the offline versions with the full detector granularity.

Samples of perturbative QCD results

- Results of data recorded by the ATLAS detector at LHC in CERN
- Common terms:
  - Anti-k_t: jet clustering algorithm, usually with a radius parameter $R = 0.4$
  - Rapidity: $y = 0.5 \times \ln[(E + p_z) / (E - p_z)]$
  - Half of rapidity separation: $y^* = |y_1 - y_2| / 2$
  - Transverse energy, momentum: E_T, p_T
  - Invariant mass of the dijet system: m_{jj}
  - Scalar sum of the transverse momenta of the two leading jets: H_{T2}
  - Calculation accuracy:
    - Leading order: LO
    - Next-to leading order: NLO
    - Next-to-next-to leading order: NNLO
    - Next-to-leading-logarithm NLL
    - Next-to-next-to-leading-logarithm NNLL

Jets and dijets measurements

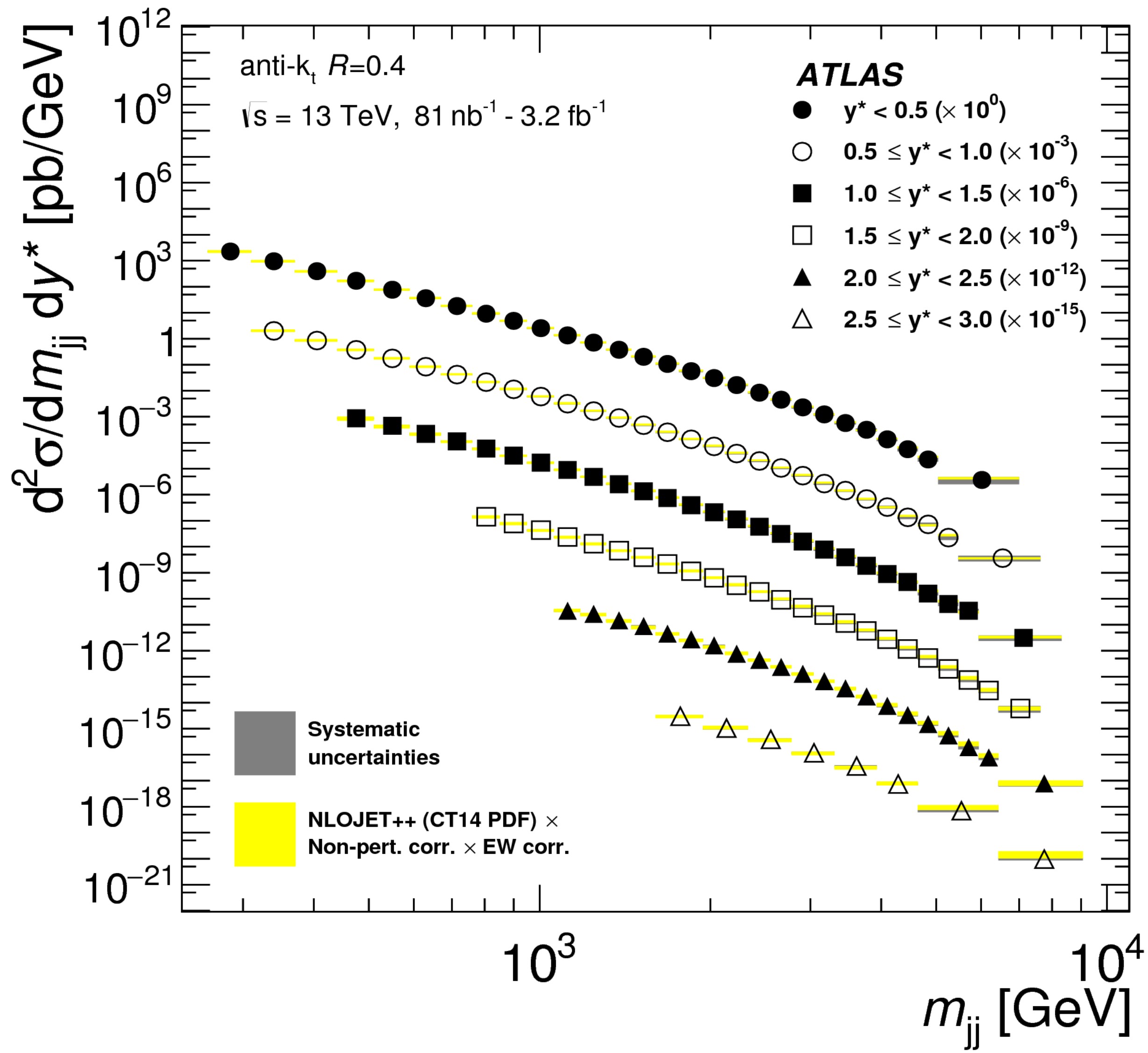
- Inclusive jet and dijet cross-sections measurements in p-p collisions at $\sqrt{s}$ = 13 TeV.
- Integrated luminosity of 3.2 fb^{-1} 2015 ATLAS data.
- Jets are identified using the anti-k_t algorithm.



- Inclusive jet cross-sections as a function of p_T and $|y|$.
- The data are compared to NLO pQCD predictions.
- Non-perturbative and electroweak corrections are applied to the predictions.
- Overall fair agreement between data and theoretical predictions in individual bins.

arXiv:1711.02692

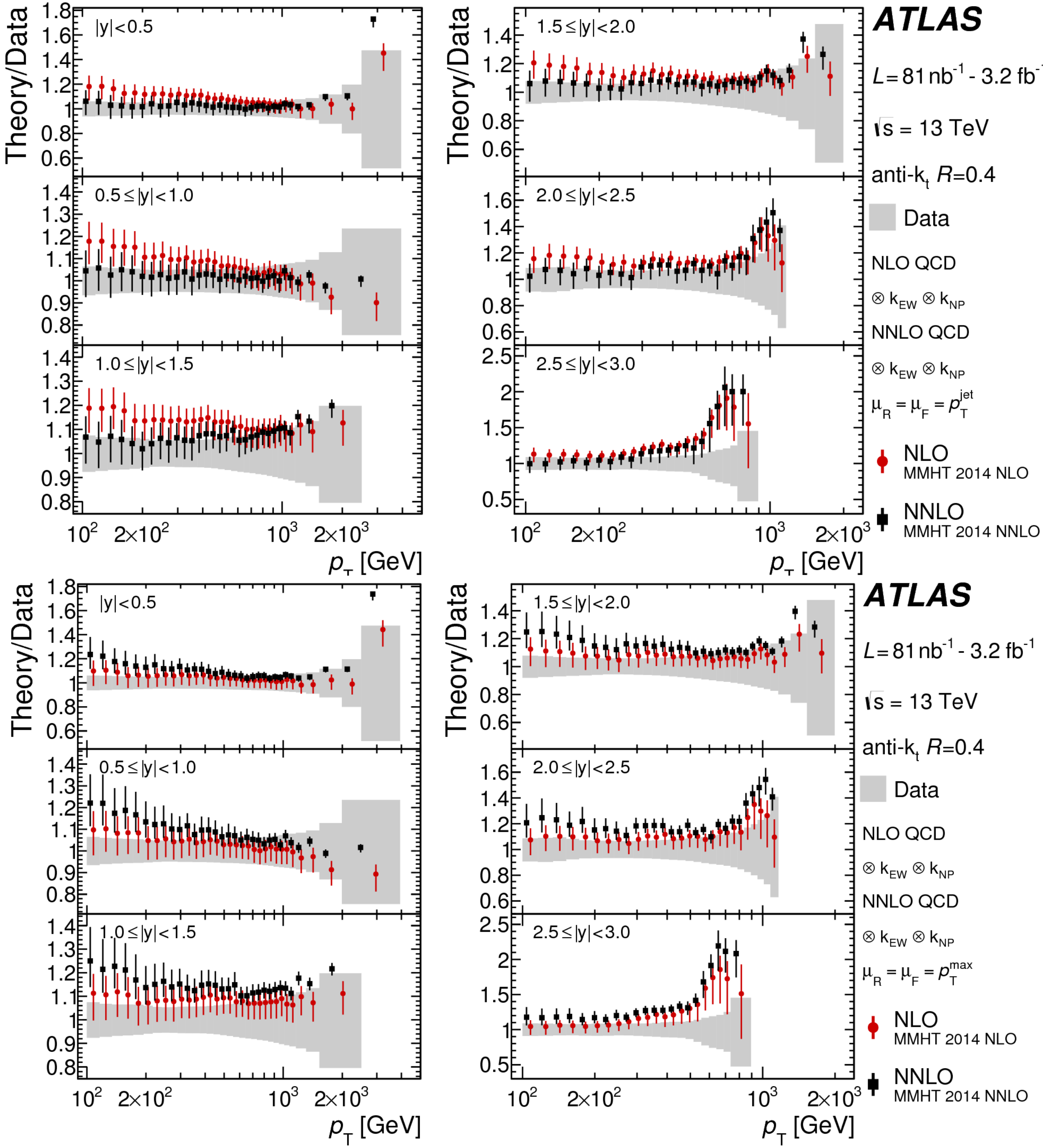
Jets and dijets measurements (2)



- Dijet cross-sections as a function of m_{jj} and y^*, for anti-k_t jets.
- The data are compared to NLO pQCD predictions with the QCD scale $p_T^{max}\exp(0.3\,y^*)$.
- Non-perturbative and electroweak corrections are applied to the prediction.
- Overall fair agreement between data and theoretical predictions.

arXiv:1711.02692

Jets and dijets measurements (3)

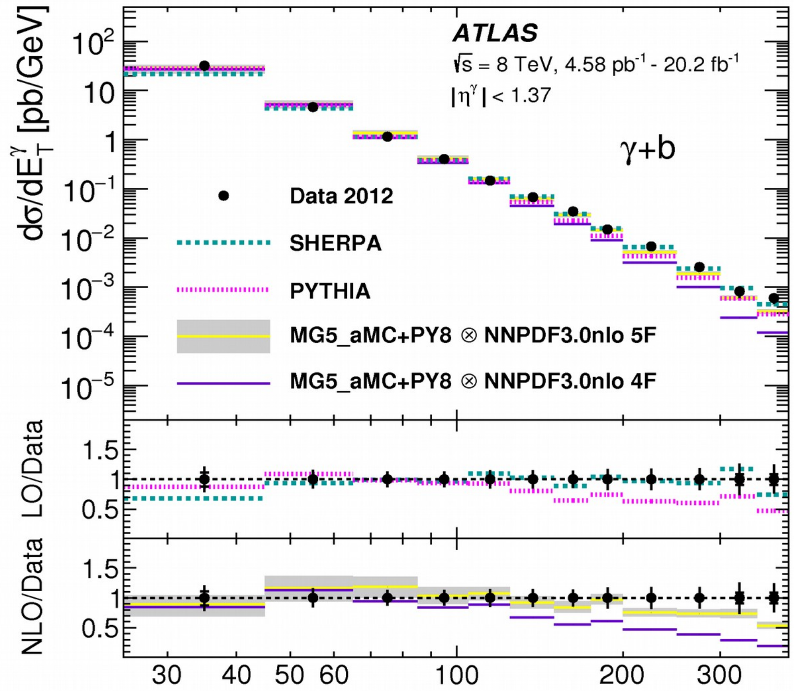


- Ratios of the NLO and NNLO pQCD predictions to the data as a function of the jet p_T in $|y|$ bins for two μ_R and μ_F scales.
- Non-perturbative and electroweak corrections are applied to the predictions.
- The NNLO pQCD predictions using p_T^{max} as the scales overestimate the measured inclusive jet cross-sections.

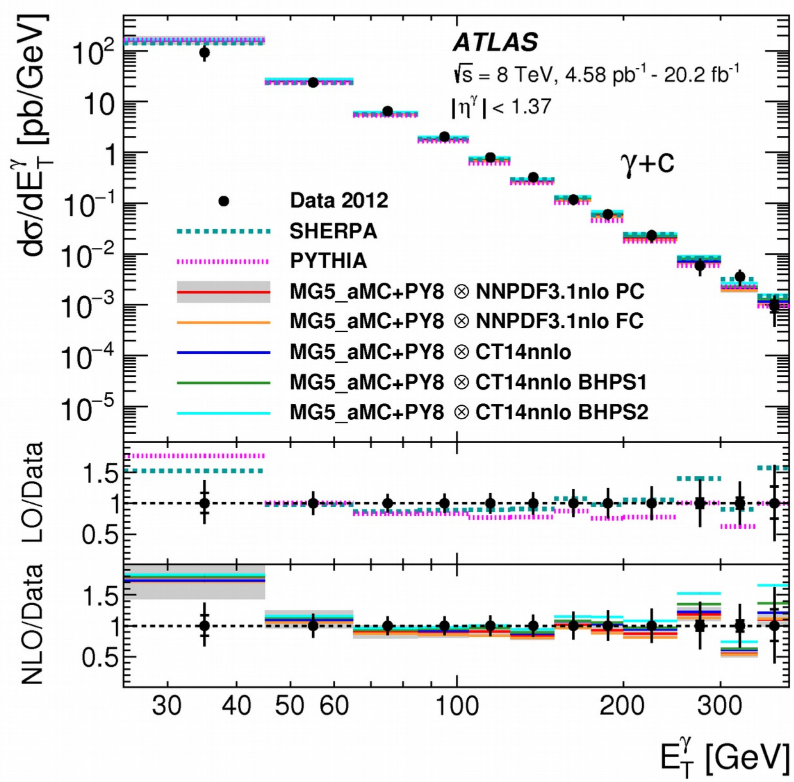
arXiv:1711.02692

Photons in association with heavy flavors

- Differential cross sections of isolated prompt photons in association with a b-jet or a c-jet.
- Sensitivity to the heavy-flavor content of the proton.
- p-p collision 2012 data at $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}.



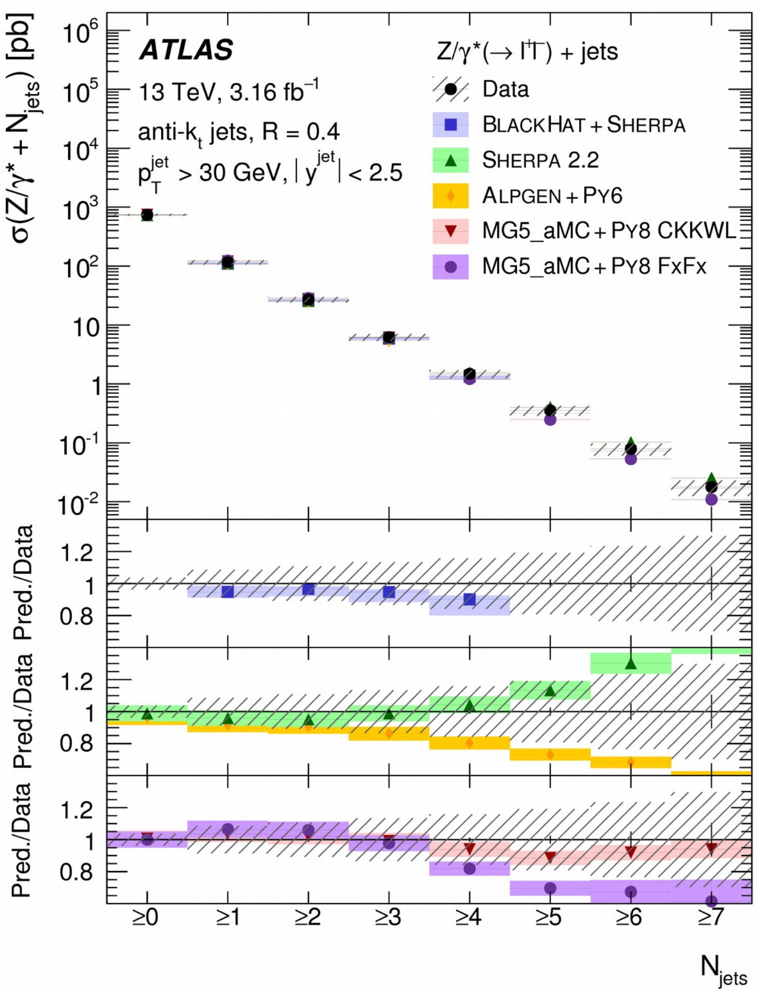
- Differential cross sections as a function of the E_T^{γ}, for γ+b and γ+c in the central region.
- γ+b best described by LO Sherpa in 5F scheme (3 additional quarks). NLO underestimate data at highest p_T.
- High measurement uncertainties of the γ+c data. All prediction in agreement with data.

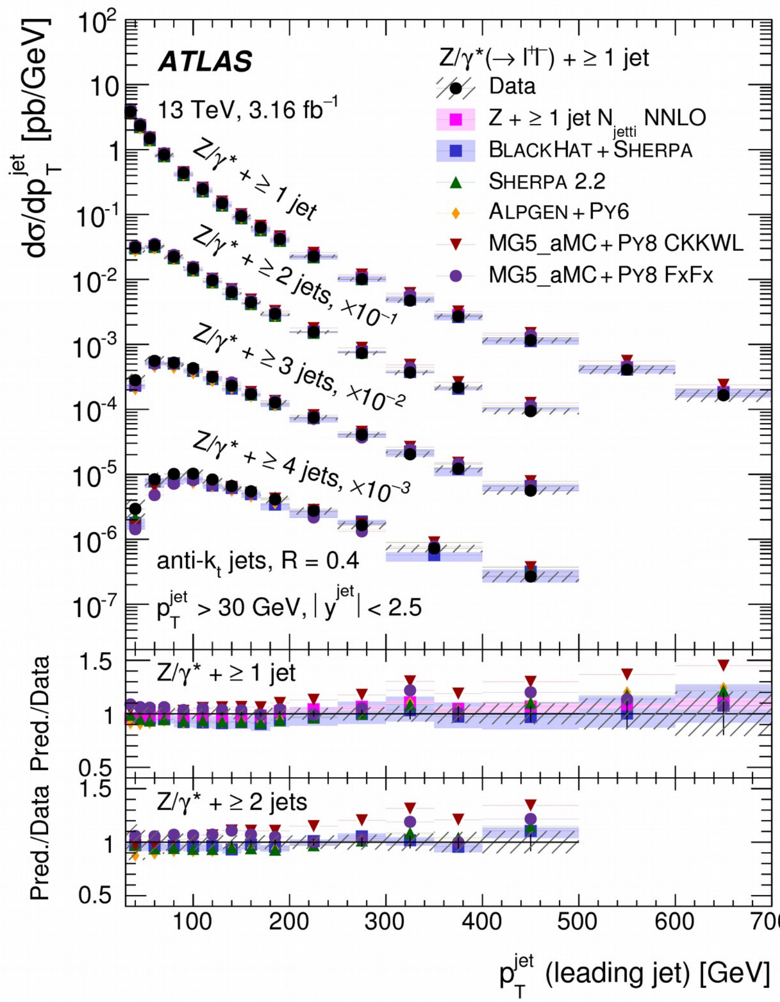


arXiv:1710.09560

Z boson in association with jets

- Cross section of a Z boson in association with jets in p-p collisions at $\sqrt{s}$ = 13 TeV, 3.16 fb^{-1}, 2015 data.
- Events with Z decaying to electron and muon pairs (p_T > 25 GeV) with one or more jets (p_T > 30 GeV).





Measured cross section as a function of the inclusive jet multiplicity and leading jet p_T compared with theoretical predictions.

Good agreement between data and prediction.

In case of single-jet dominance: well modeling with fixed order NLO.

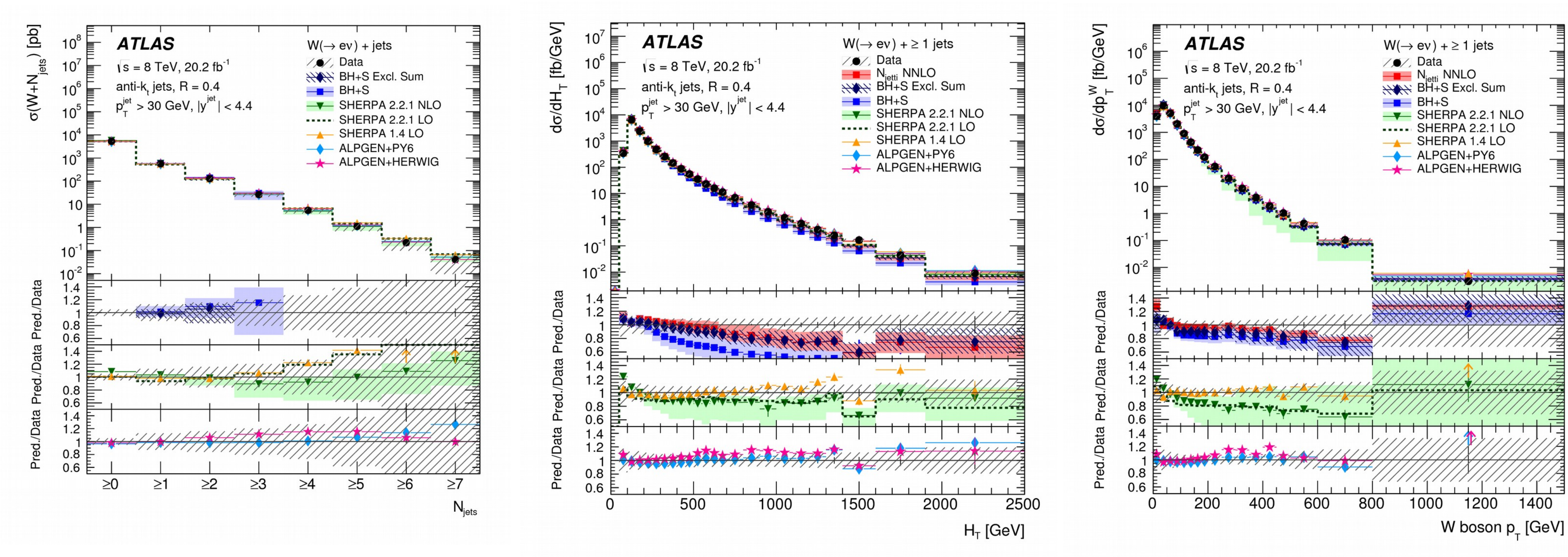
Z + ≥ 1 jets: NNLO describe well key distributions.

Input for optimization of the MC generators.

arXiv:1702.05725

W boson in association with jets

- W + jets production cross sectiion in proton-proton collisions at $\sqrt{s}$ = 8 TeV, 20.2 fb^{-1}.
- Sensitive test for modeling parton showers and parton structure of proton.
- One electron and missing transverse momentum in final states.

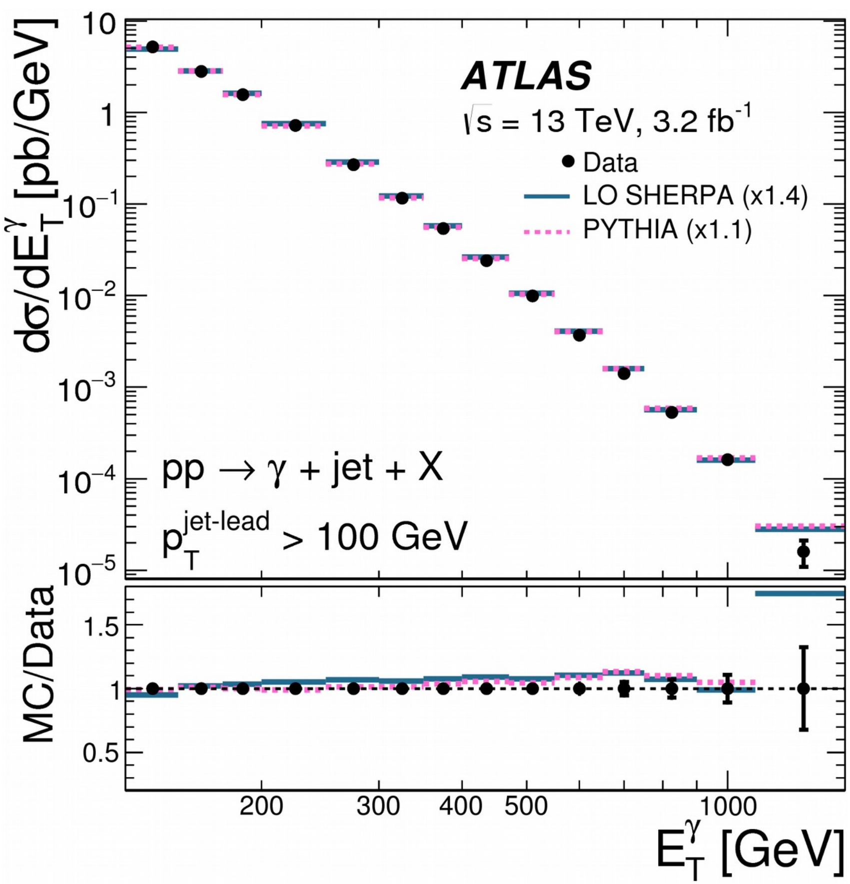


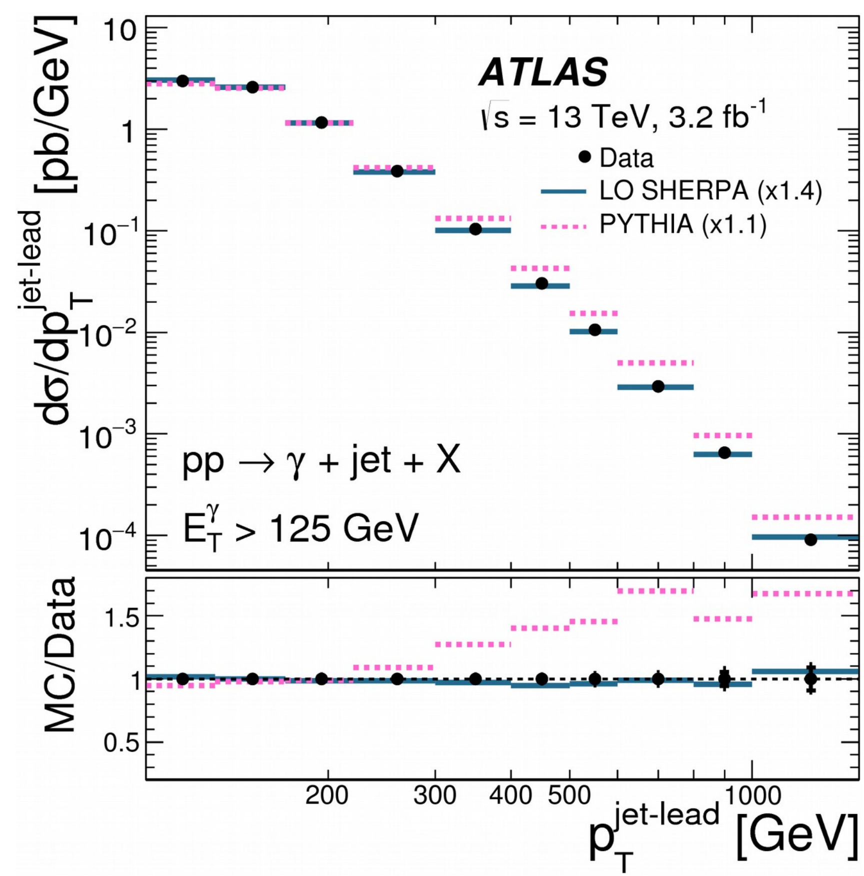
- Measured cross section as a function of the inclusive jet multiplicity, jets H_{T2} and W-boson p_T compared with theoretical predictions.
- The NNLO and NLO predictions are able to describe the data with exception of extreme cases.

arXiv:1711.03296

Photon in association with jets

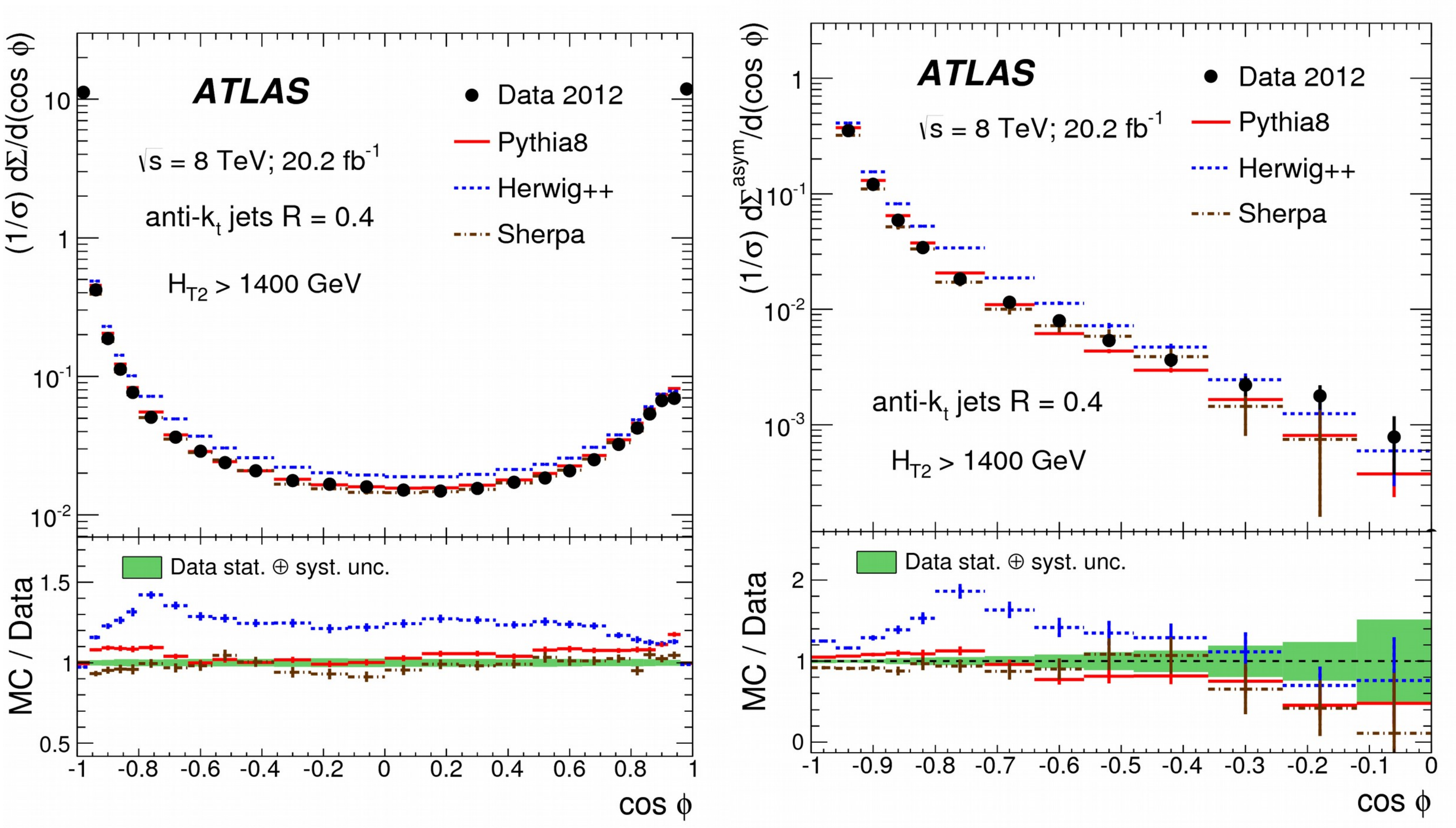
- Isolated-photon production in association with a jet in p-p collisions at $\sqrt{s}$ = 13 TeV, 3.2 fb^{-1} 2015 data.
- Photon with E_T > 125 GeV.
- Anti-kt jets with p_T > 100 GeV.
- Isolated-photon plus jet cross sections as functions of the leading-photon E_T and the leading-jet p_T compared to tree-level plus parton-shower predictions and NLO QCD predictions.
- The predictions of the tree-level plus parton-shower MC models by Pythia and LO Sherpa give a satisfactory description of the shape of the data distributions



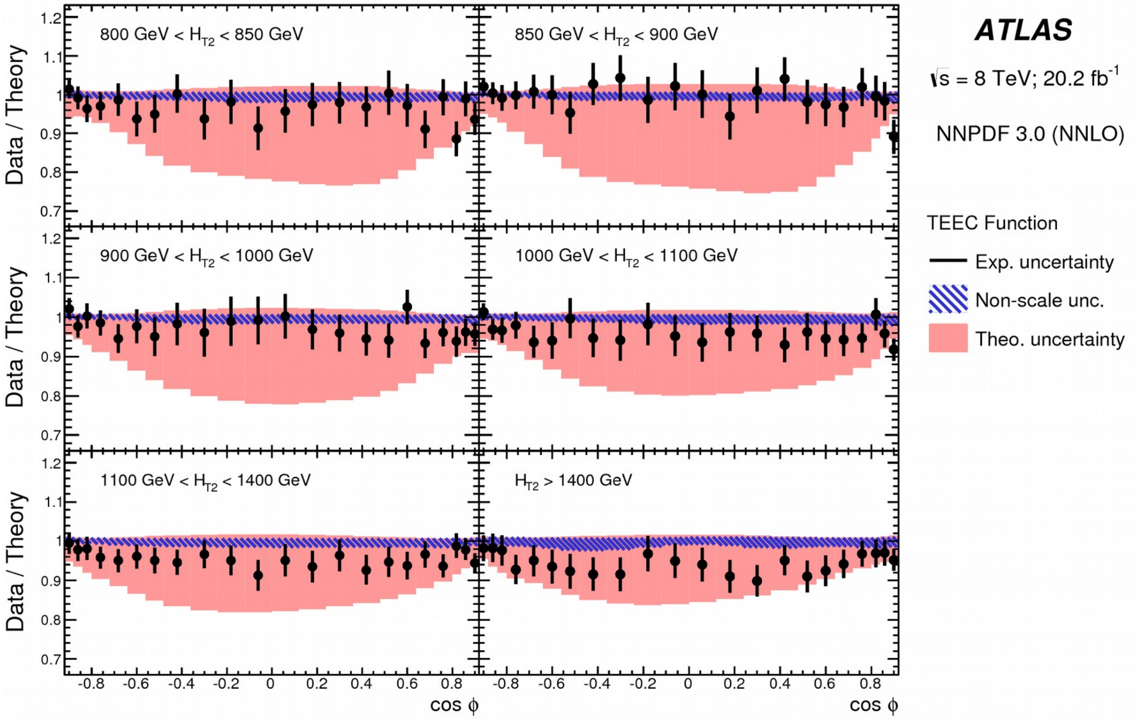


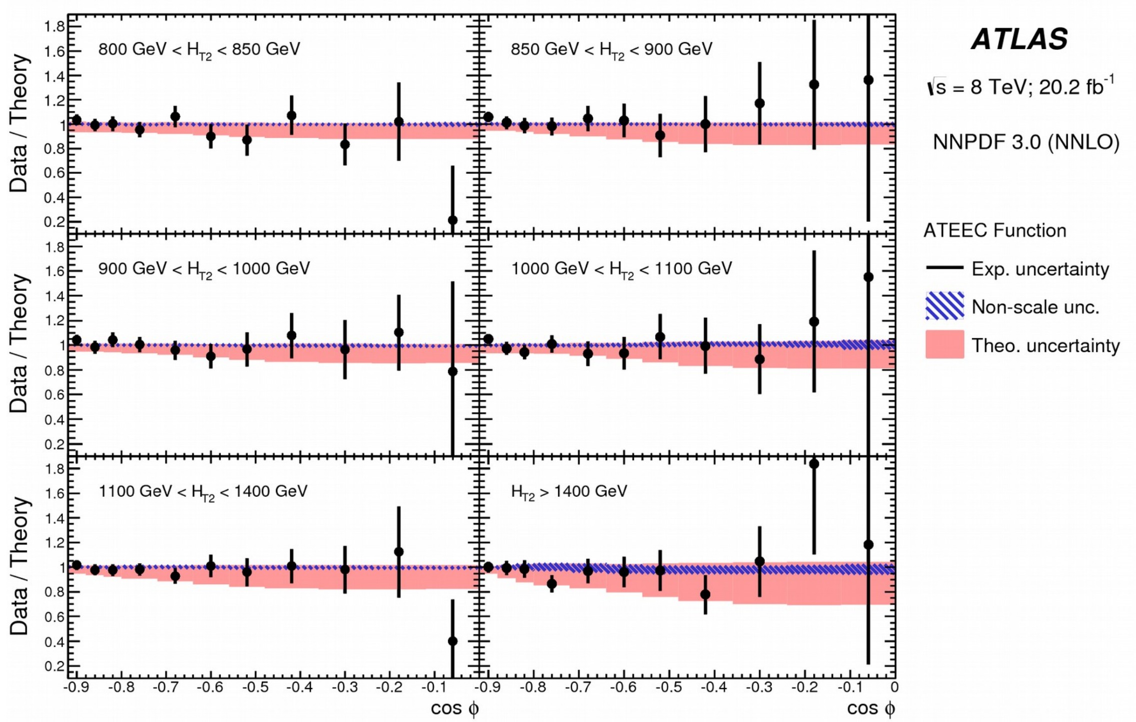
Dijet correlations

- Measurements of transverse energy-energy correlations (TEEC) and their associated asymmetries (ATEEC) in multi-jet events at $\sqrt{s}$ = 8 TeV p-p collisions, 20.2 fb^{-1}, 2012 data.
- The data are used to determine the strong coupling constant α_s.
- Detector-level distributions for the TEEC and ATEEC functions for one H_{T2} intervals, together with MC predictions from Pythia8, Herwig++ and Sherpa.



arXiv:1707.02562



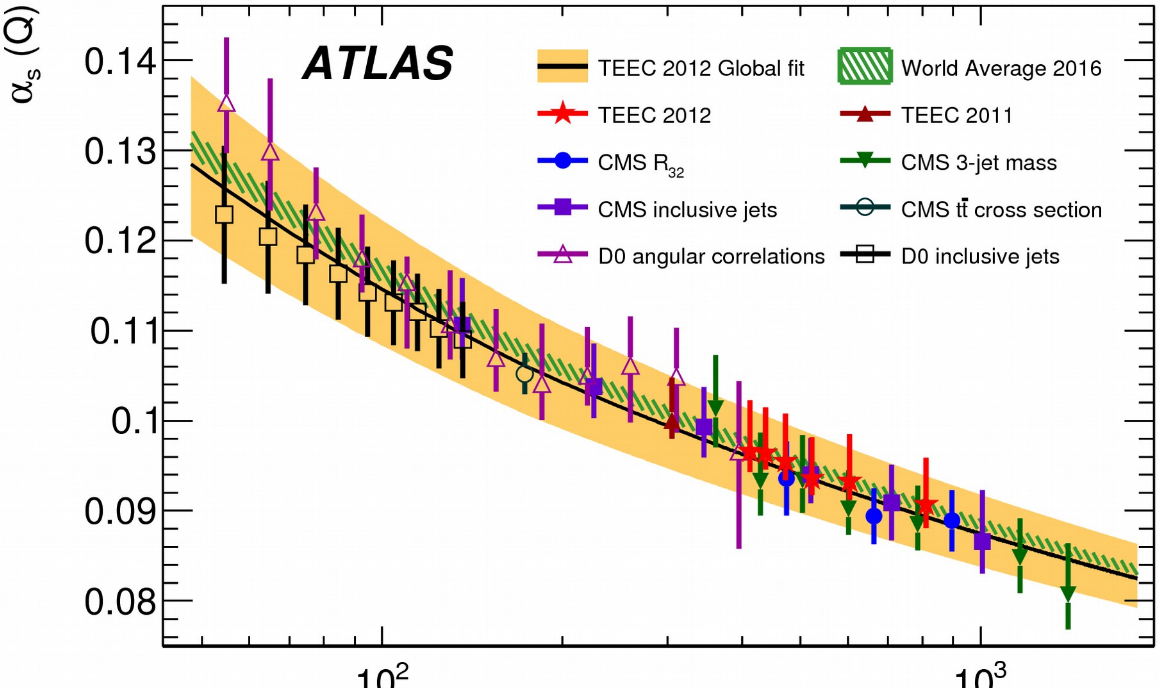


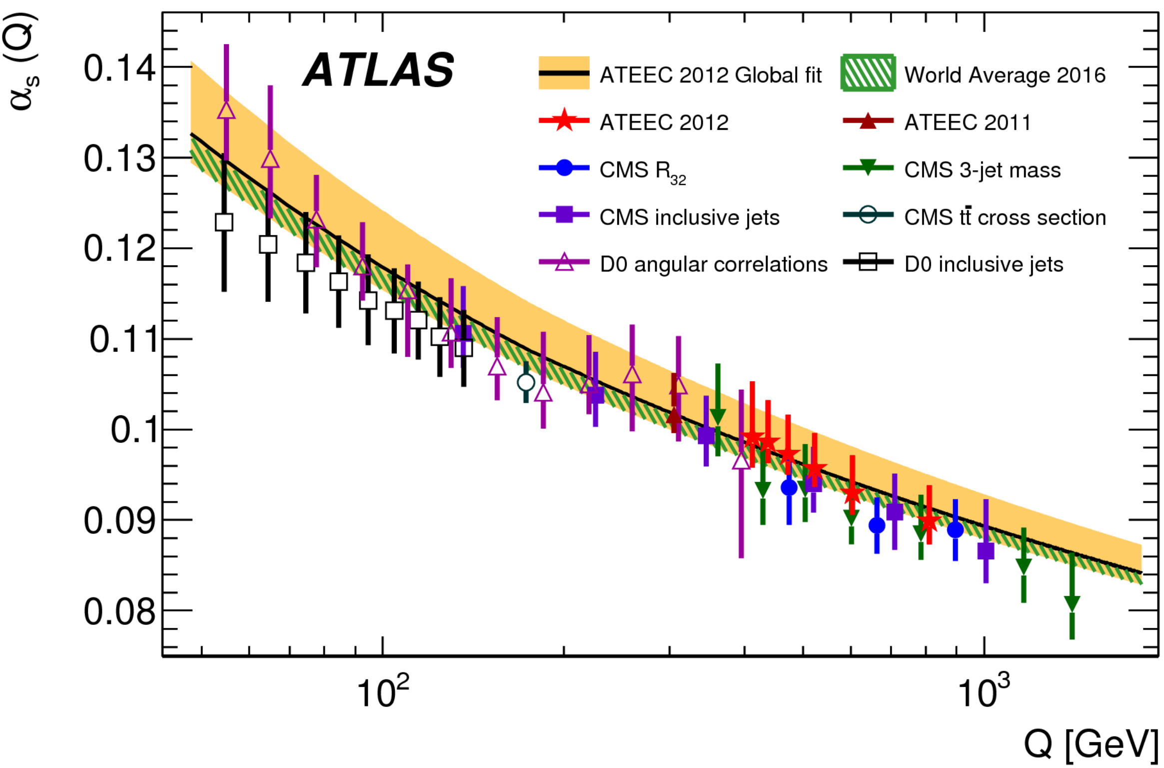
Dijet correlations (2)

- Ratios of the TEEC and ATEEC data, unfolded to the particle level, in each H_{T2} bin to the NLO pQCD predictions, corrected for non-perturbative effects.
- The value of the strong coupling constant is extracted for different energy regimes, testing the running of $\alpha_s(\mu)$ predicted in QCD up to scales over 1 TeV.

arXiv:1707.02562

Dijet correlations (3)





- Comparison of the values of $\alpha_s(Q)$ obtained from the TEEC and the ATEEC functions at the energy scales $\langle H_{T2} \rangle / 2$ (red star points) with the uncertainty band from the global fit and the 2016 world average.

- Determinations from other experiments are also shown. The strong coupling constant is assumed to run according to the two-loop solution of the re-normalization group equations (RGE).

- A global fit to the TEEC distributions:

  $$\alpha_s(m_Z) = 0.1162 \pm 0.0011\,(\text{exp.})^{+0.0084}_{-0.0070}\,(\text{theo.})$$

- A global fit to the ATEEC distributions:

  $$\alpha_s(m_Z) = 0.1196 \pm 0.0013\,(\text{exp.})^{+0.0075}_{-0.0045}\,(\text{theo.})$$

- In good agreement with the current world average $\alpha_s(m_Z) = 0.1181 \pm 0.0011$.

arXiv:1707.02562

Jet-substructure studies

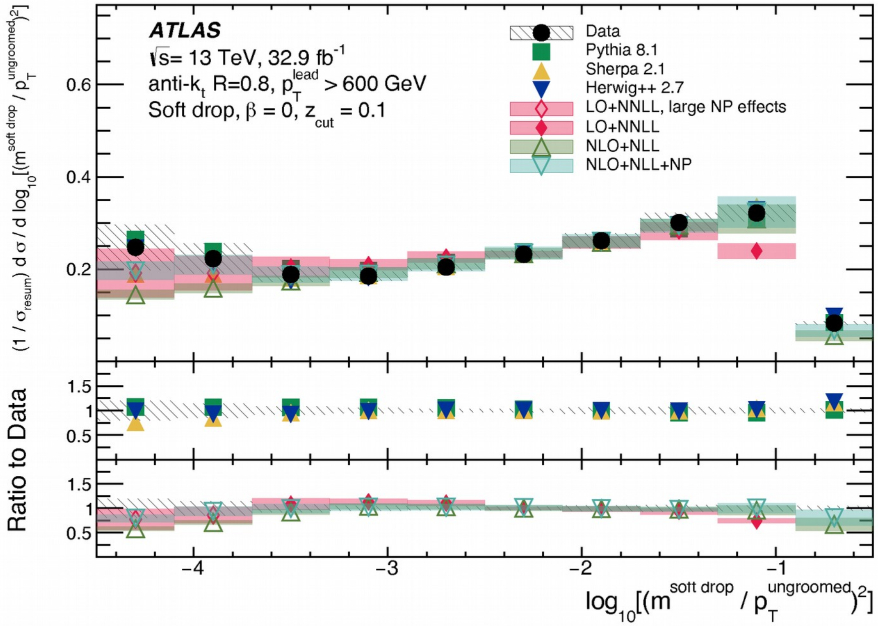
- p-p, $\sqrt{s}$ = 13 TeV, 2012 data, 32.9 fb^{-1}.
- Events with a minimum of two jets, at least one p_T > 600 GeV, $p_{T,1} / p_{T,2} < 1.5$.
- The jet mass cannot be predicted completely in LL accuracy:
  - Presence of non-global logarithms (NGLs): resummation terms associated with particles that radiate out of, and then radiate back into, jets (NLL terms).
- A new jet soft-drop grooming procedure insensitive to NGLs is introduced:
  - The distribution of the soft-drop mass has been calculated at both next-to-leading order (NLO) with NLL and LO with NNLL accuracy.
  - The soft-drop algorithm starts by re-clustering an anti-k_t jets (R = 0.8) constituents.
  - Branches with smaller p_T not satisfied next criteria are removed:

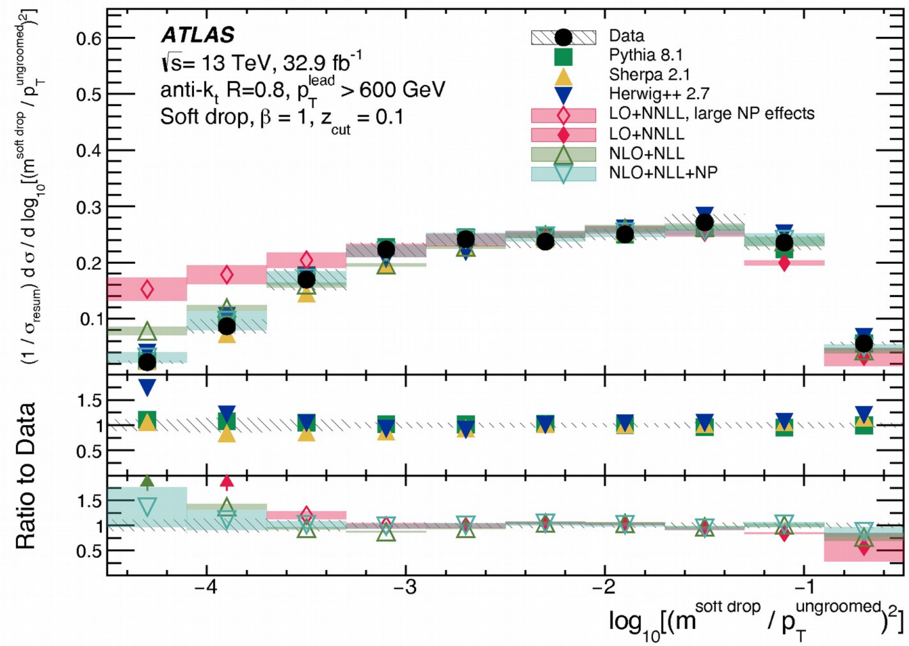
$$\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

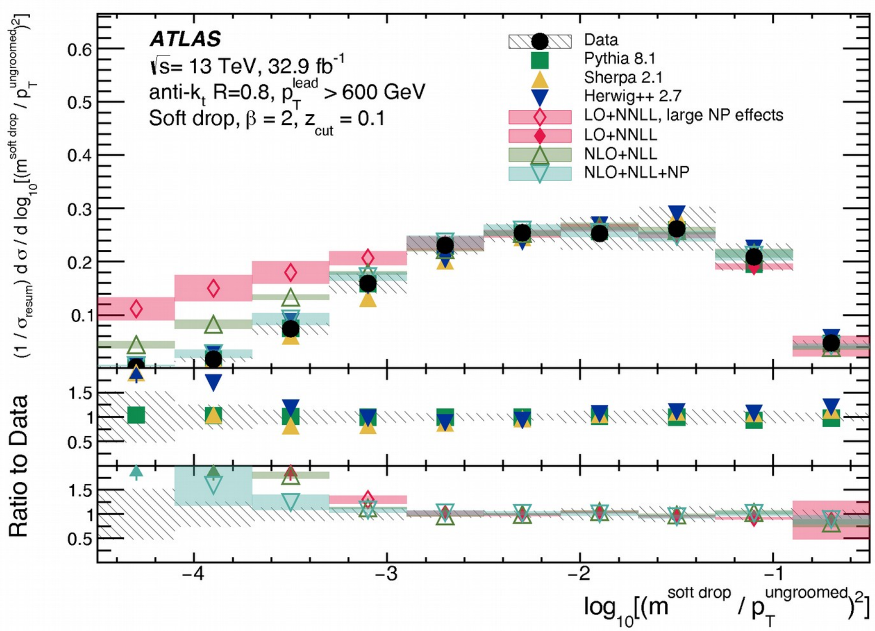
  - z_{cut} sets the scale of the energy removed by the algorithm.
  - β tunes the sensitivity of the algorithm to wide-angle radiation.
- ρ is the ratio of the soft-drop mass to the ungroomed (anti-k_t) jet p_T - insensitive to NGLs.

arXiv:1711.08341

Jet-substructure studies (2)







- The data are unfolded to correct for detector effects and compared to precise QCD calculations and LL particle-level Monte Carlo simulations.
- Where the calculations are well defined perturbatively, they agree well with the data.
- In regions where non-perturbative effects are expected to be significant, the calculations disagree with the data and the predictions from MC simulation are better able to reproduce the data.

arXiv:1711.08341

Conclusions

- Various recent ATLAS measurements sensitive to the perturbative Standard model including jet and dijets cross sections, vector bosons and jet cross sections measured at center of mass energies of 8 and 13 TeV were presented and compared to the theoretical expectations calculated to the NNLO accuracy.
- Measurements of dijet energy-energy correlations allowing to test the renormalization group equation and extracting the strong coupling constant were presented.
- The latest results of jet-substructure studies at 13 TeV, the measurement of the jet soft-drop mass as a first jet-substructure observable which can be predicted with perturbative calculations were shown.
- The results are compared to the theoretical calculations and MC predictions. In many cases the calculations and predictions describe data successfully, in extreme cases a tuning is needed.
- More ATLAS QCD results are available here:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ StandardModelPublicResults