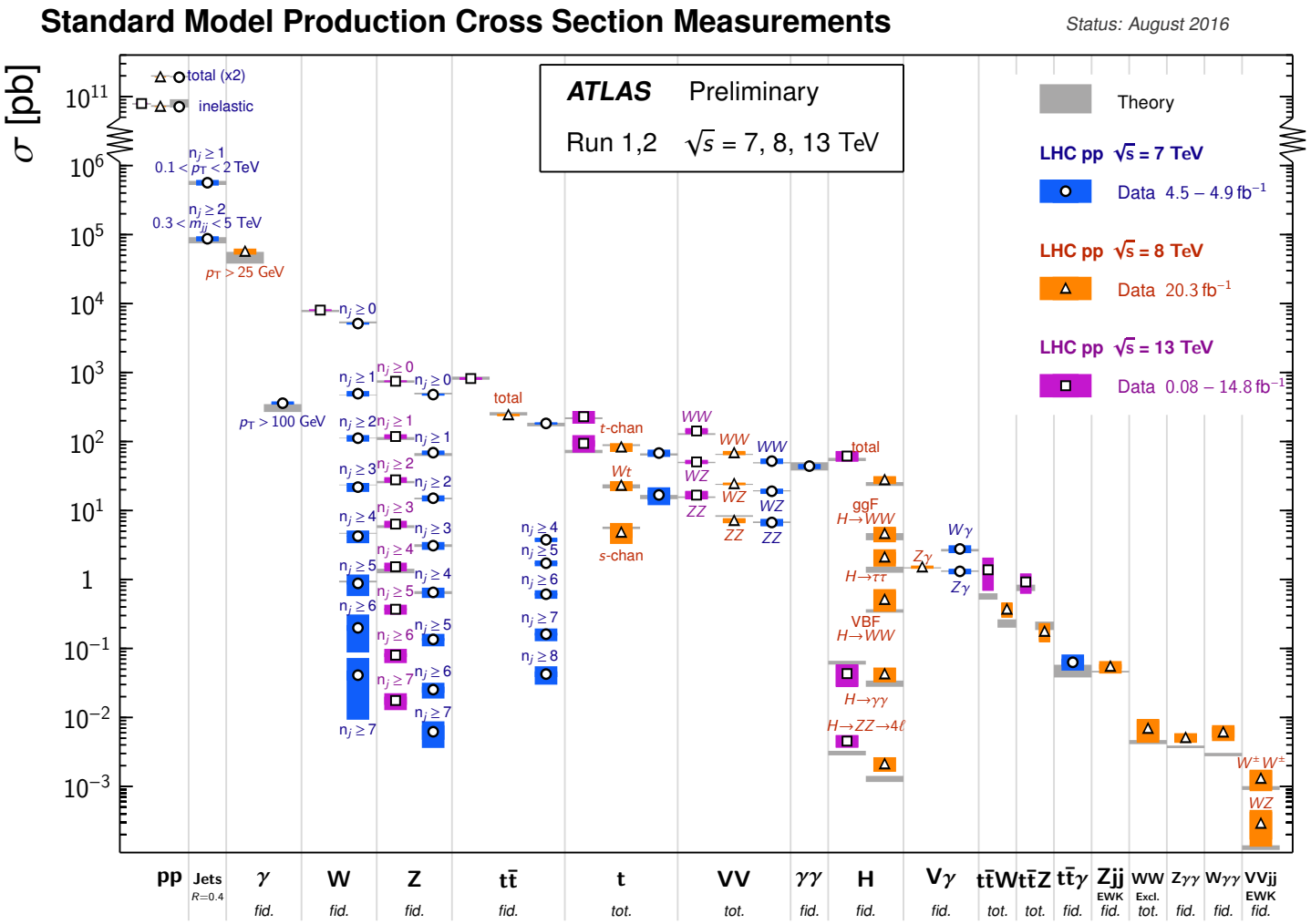
Transverse momentum distributions and jet cross sections at NNLO precision

Future Challenges for Precision QCD, Durham, 26.10.2016

Thomas Gehrmann, Universität Zürich

Standard Model processes at the LHC

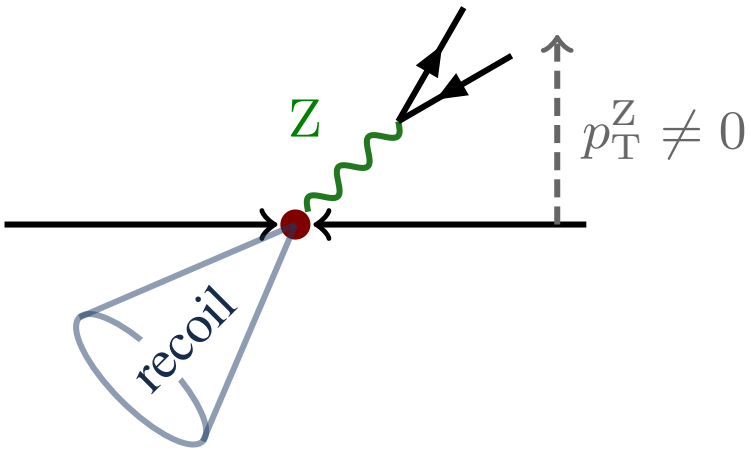


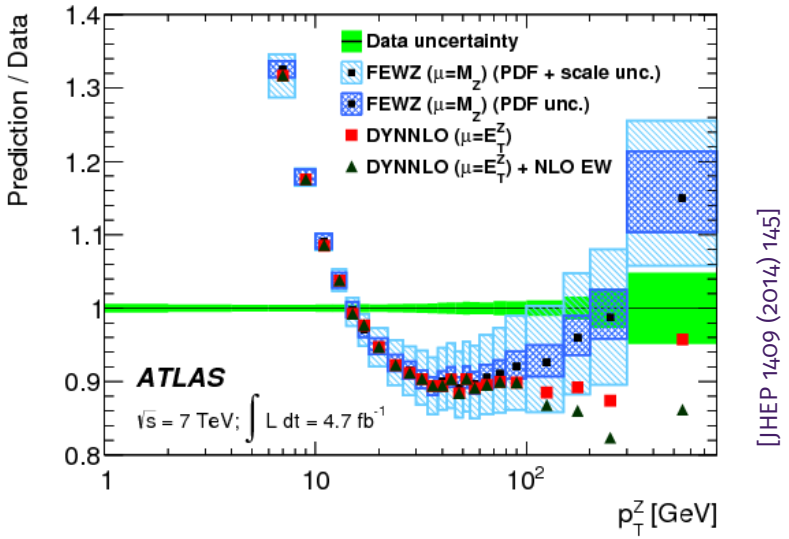
Benchmark processes: $2 \rightarrow 2$ reactions

- Large cross sections
  - Multiple-differential measurements
    - Di-jet production
    - Z+jet, W+jet
    - H+jet
- Detailed understanding of dynamics
  - Disentangle production processes
  - Probe parton distributions
- Transverse momentum distribution
  - Continuous transition from hard to soft region
  - Fixed order versus resummation

Z transverse momentum distribution

- Transverse momentum requires partonic recoil





- Mismatch of orders in perturbation theory
  - NNLO for inclusive Z is only NLO for p_T-distribution
  - Z+jet and Z p_T distribution closely related
- NLO fails to describe measurements in norm and shape

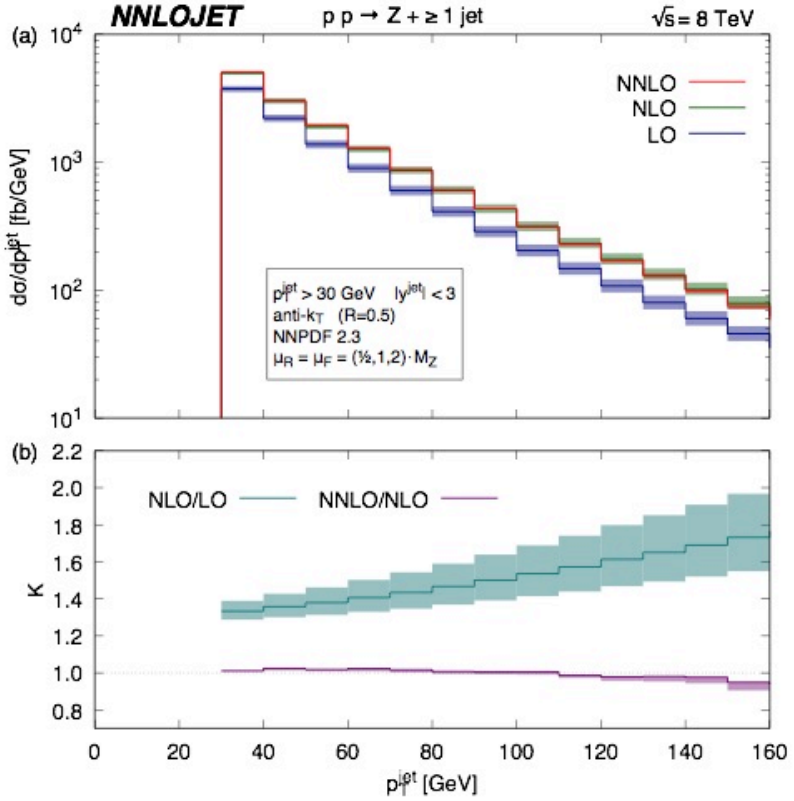
NNLOJET code

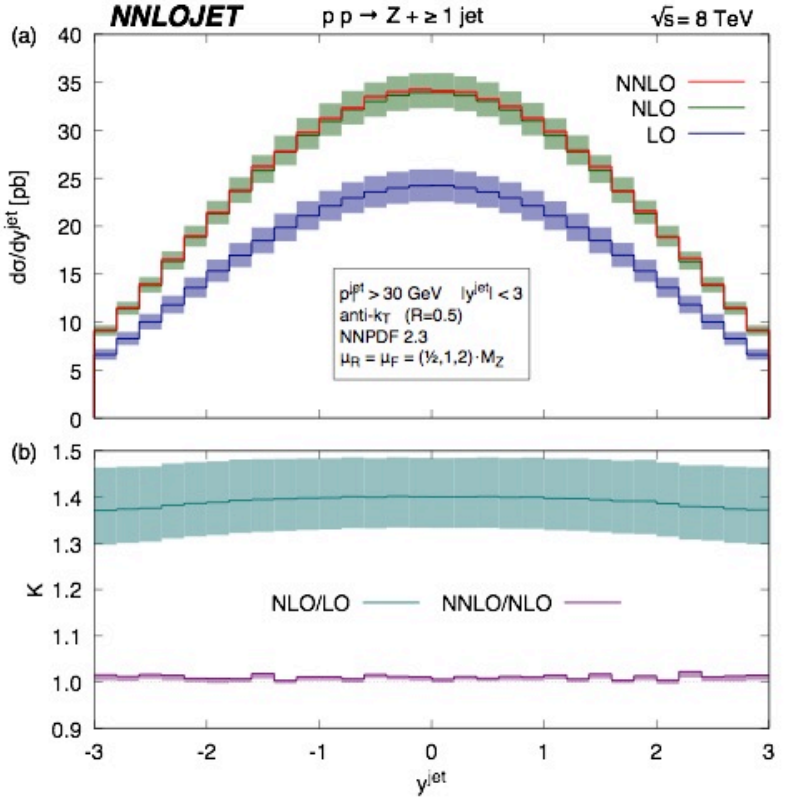
- NNLO parton level event generator
  - Based on antenna subtraction
- Provides infrastructure
  - Process management
  - Phase space, histogram routines
  - Validation and testing
  - Parallel computing (MPI) support for warm-up and production
  - ApplGrid/fastNLO interfaces in development
- Processes implemented at NNLO
  - Z+(0,1)jet, H+(0,1)jet, W+0jet
  - DIS-2j, LHC-2j (ongoing)

NNLOJET project:
X. Chen, J. Cruz-Martinez, J, Currie,
A. Gehrmann-De Ridder, E.W.N. Glover,
A. Huss, T. Morgan, J. Niehues, J. Pires,
M. Sutton, D. Walker, TG

Z+jet at NNLO

- Calculation based on antenna subtraction
  - In-depth validation of subsequent results (MCFM: R.Boughezal et al.)
  - Uncovering various issues, finally in agreement





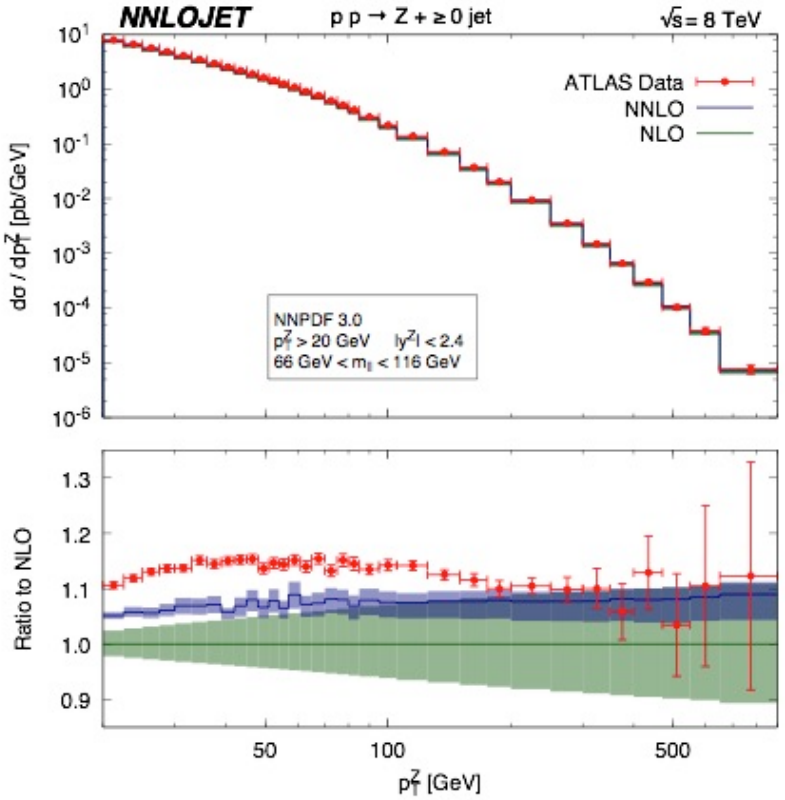
Z p_T-distribution at NNLO

- Using calculation for Z+jet inclusively on partons
  - No jet requirement
  - Including leptonic Z-decay
  - Lower cut on transverse momentum
  - Compute fiducial cross sections

	ATLAS	CMS
leading lepton	$\lvert\eta_{\ell_1}\rvert < 2.4$	$\lvert\eta_{\ell_1}\rvert < 2.1$
	$p_T^{\ell_1} > 20$ GeV	$p_T^{\ell_1} > 25$ GeV
sub-leading lepton	$\lvert\eta_{\ell_2}\rvert < 2.4$	$\lvert\eta_{\ell_2}\rvert < 2.4$
	$p_T^{\ell_2} > 20$ GeV	$p_{T,2}^{\ell_2} > 10$ GeV

Z p_T-distribution at NNLO

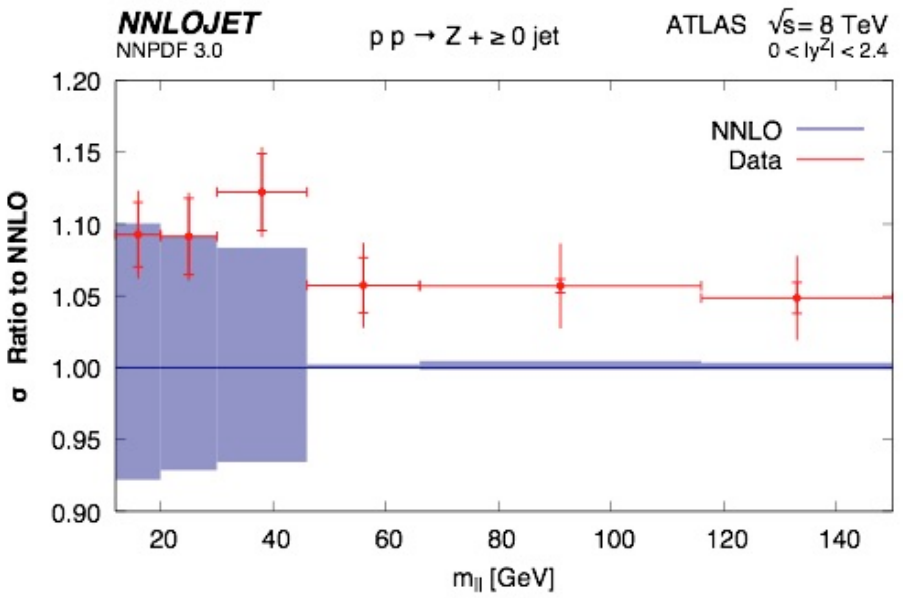
- NNLO effects
  - Around 5% corrections, modify shape of p_T distribution
  - Normalization of data not described correctly (both CMS/ATLAS)

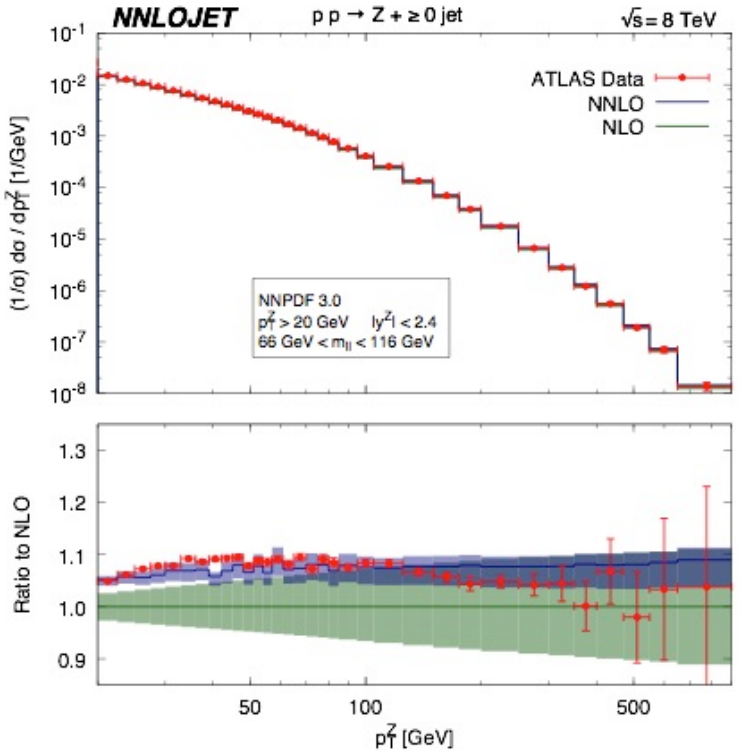


A. Gehrmann-De Ridder,, E.W.N. Glover, A. Huss, T. Morgan, TG

Z p_T-distribution at NNLO

- Compute inclusive fiducial cross section at NNLO
  - Corresponds to Z+0j calculation
  - Observe same discrepancy

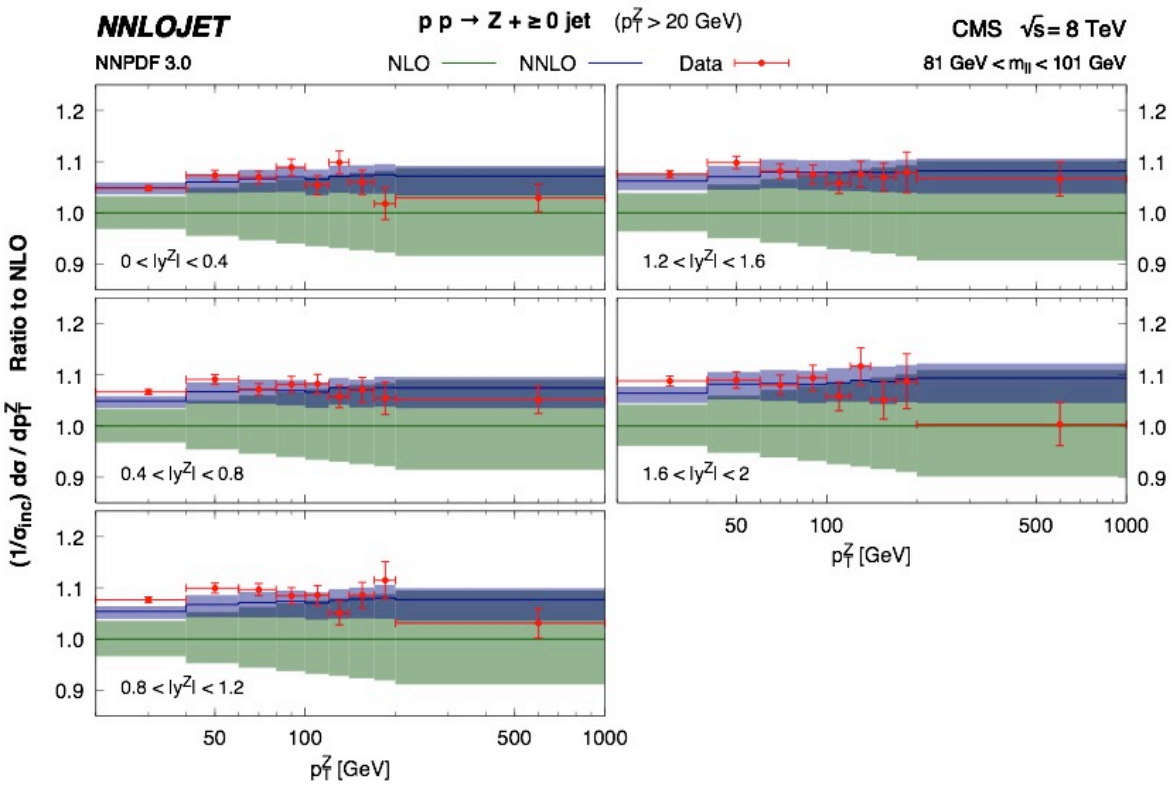




- Consider normalized p_T distribution

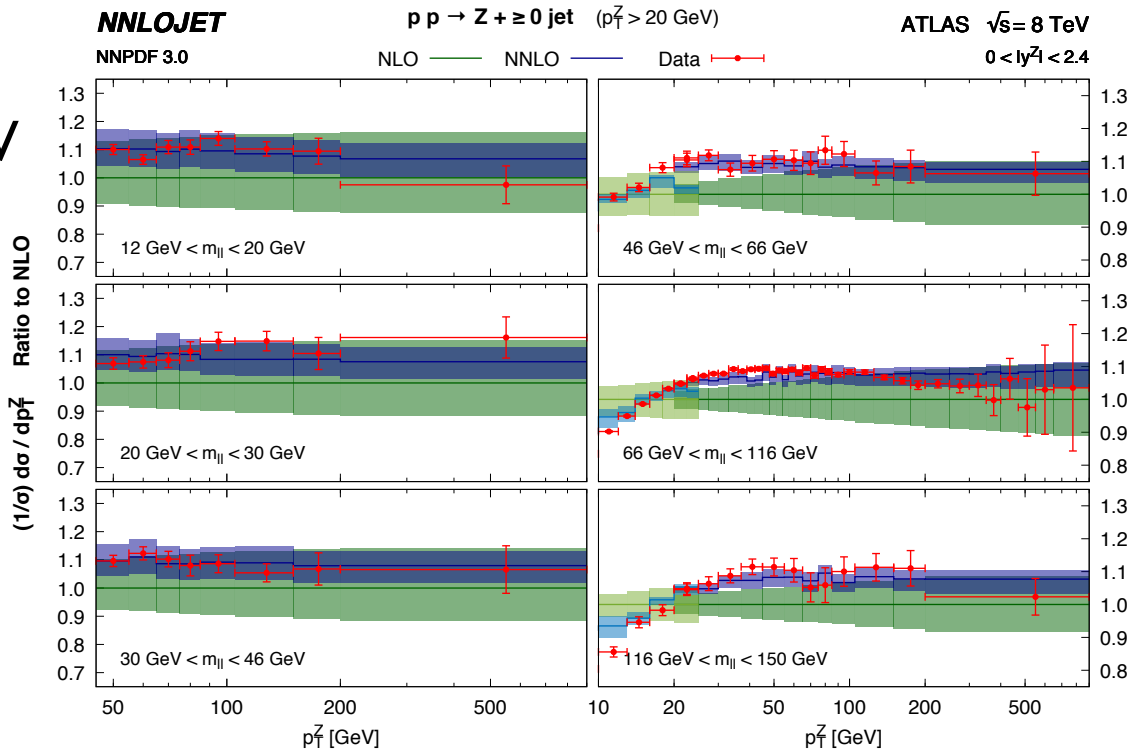
Z p_T-distribution at NNLO

- Double differential distributions
  - (p_T,m_{ll}), (p_T,y)
  - Good agreement for normalized distributions
  - Revisit ingredients
    - Luminosity
    - Parton distributions



Z p_T-distribution at NNLO

- Low p_T
  - measurements to 1 GeV
  - Challenge for NNLO calculation: stability
  - NNLO reliable to around 5 GeV

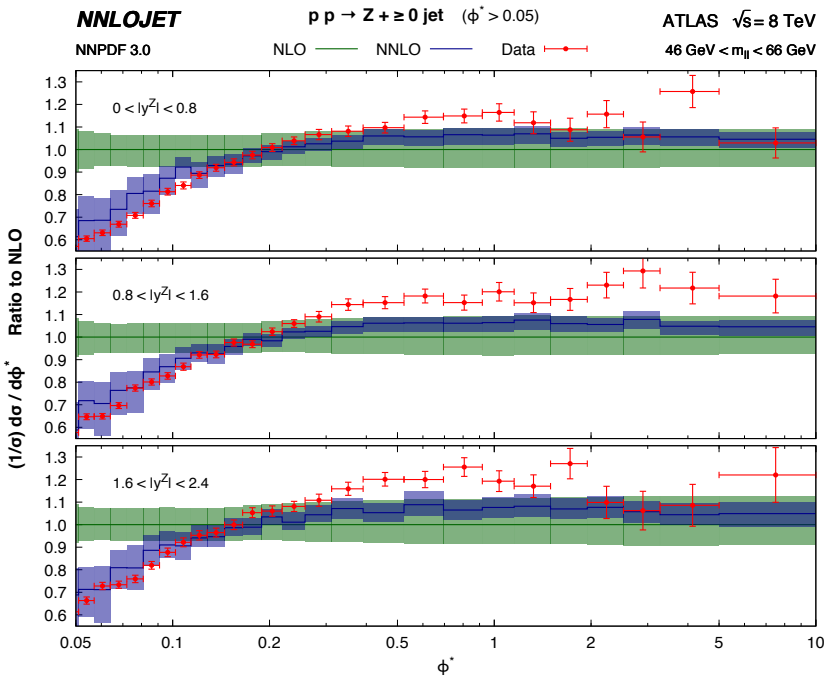


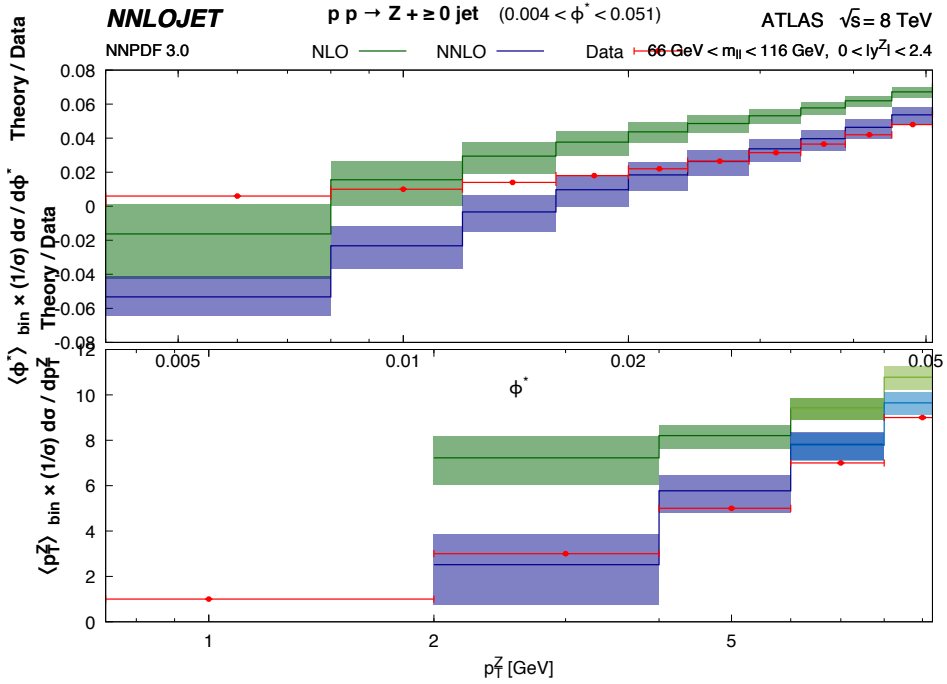
- Related observable (purely from lepton directions)

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta_\eta^*) \approx \frac{p_T^Z}{2m_{ll}}$$

Z ϕ^*-distribution at NNLO

- Leptonic variable ϕ^* allows higher resolution
  - Observe breakdown of fixed order similar to p_T-distribution
  - Eagerly awaiting matching to resummation





Higgs+jet at NNLO

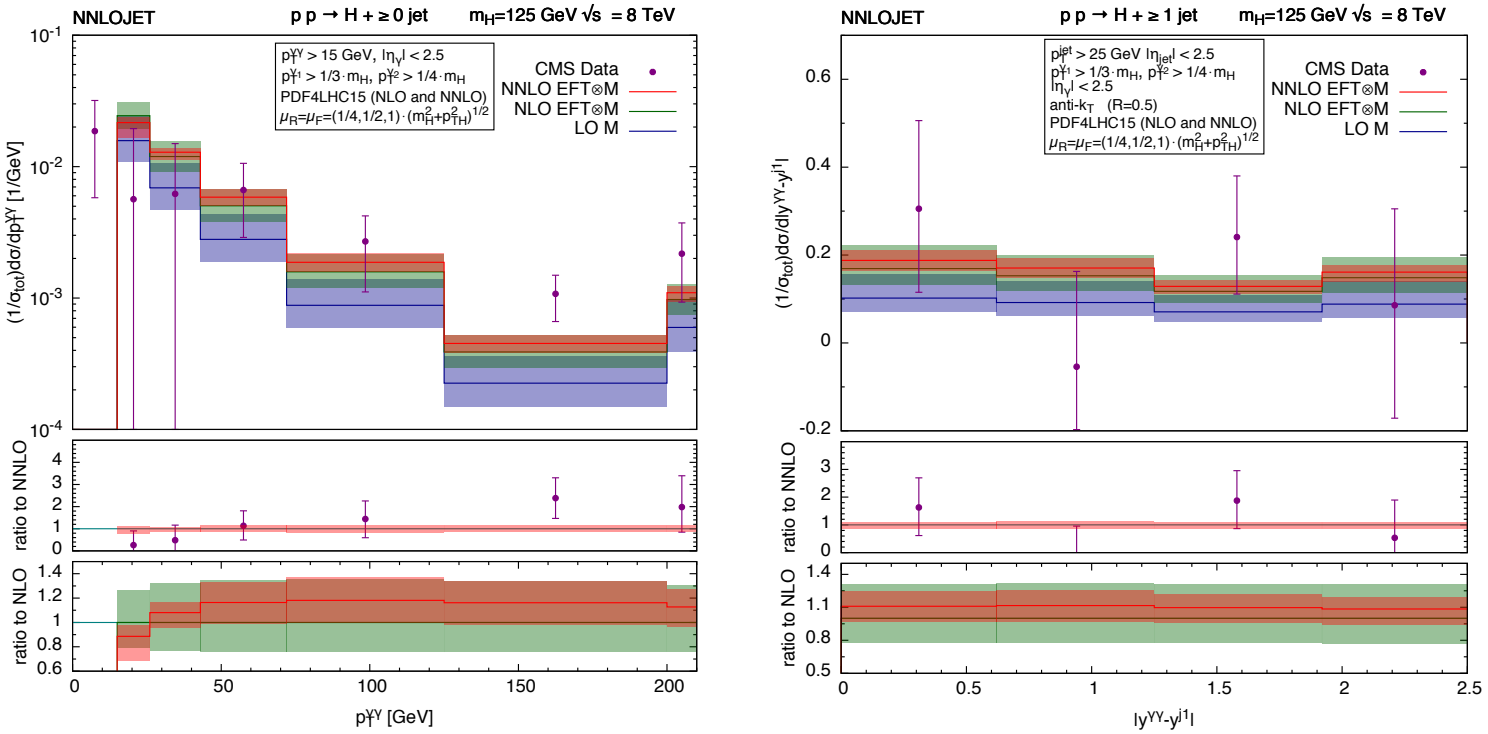
- Calculation based on antenna subtraction
  - Agreement (0.4%) with residue-subtraction (F. Caola, K. Melnikov, M. Schulze)
  - Discrepancy with Njettiness (R. Boughezal, C. Focke, X. Liu, F. Petriello)
- Fiducal cross sections

	ATLAS	CMS
leading photon	$\lvert\eta_{\gamma_1}\rvert < 2.37$	$\lvert\eta_{\gamma_1}\rvert < 2.5$
	$p_T^{\gamma_1} > 0.35\, m_H$	$p_T^{\gamma_1} > 0.33\, m_H$
sub-leading photon	$\lvert\eta_{\gamma_2}\rvert < 2.37$	$\lvert\eta_{\gamma_2}\rvert < 2.5$
	$p_T^{\gamma_2} > 0.25\, m_H$	$p_T^{\gamma_2} > 0.25\, m_H$
photon isolation	$R_\gamma = 0.4$	$R_\gamma = 0.4$
	$\sum_i E_{Ti} < 14$ GeV	$\sum_i E_{Ti} < 10$ GeV
anti-k_T jets	$R = 0.4$	$R = 0.5$
	$\lvert\eta_j\rvert < 4.4$	$\lvert\eta_j\rvert < 2.5$
	$p_T^j > 30$ GeV	$p_T^j > 25$ GeV

- Consider normalization inclusive fiducal cross section
- Input to HXSWG Yellow Report 4

Higgs p_T distribution at NNLO

- Normalized results in good agreement with 8TeV data

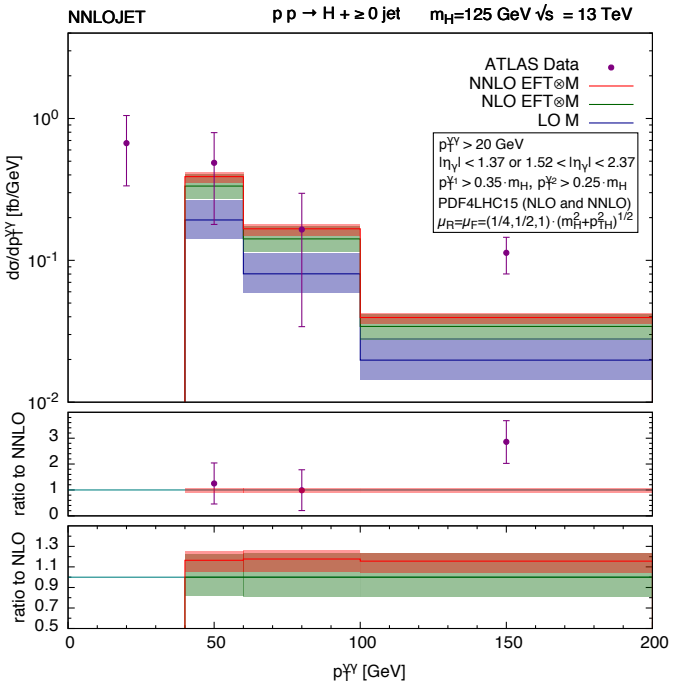


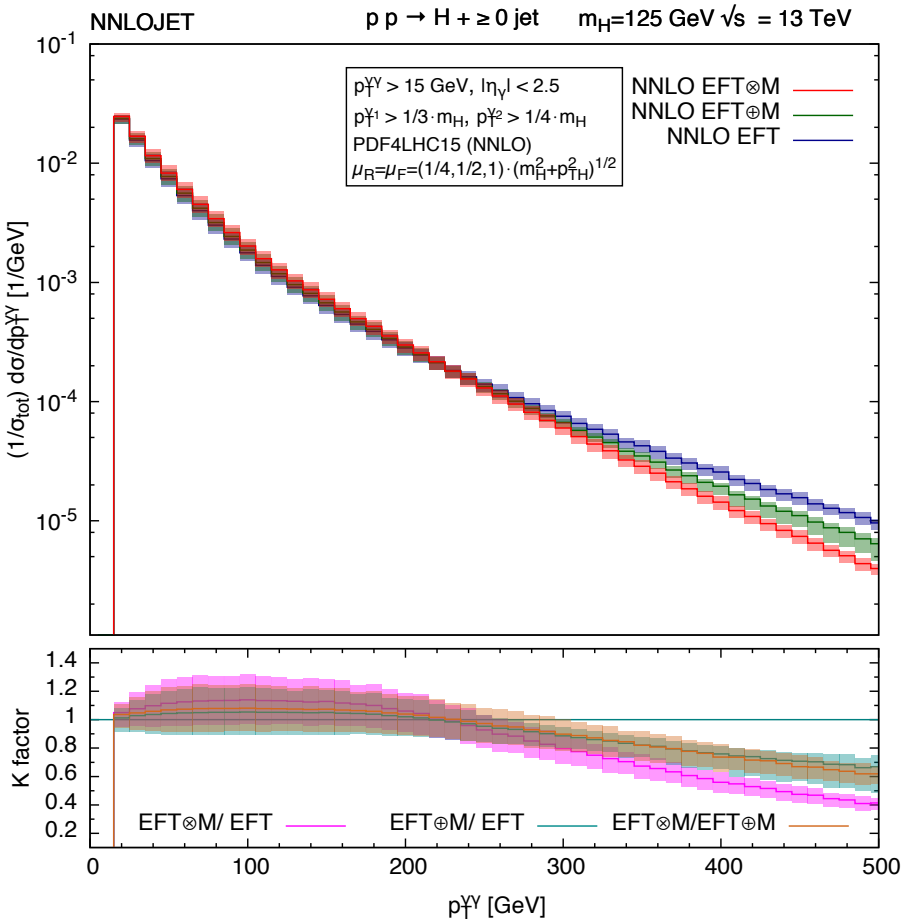
- Prepare for precision studies at higher energy

X. Chen, J. Cruz-Martinez, E.W.N. Glover, M. Jaquier, TG

Higgs p_T distribution at NNLO

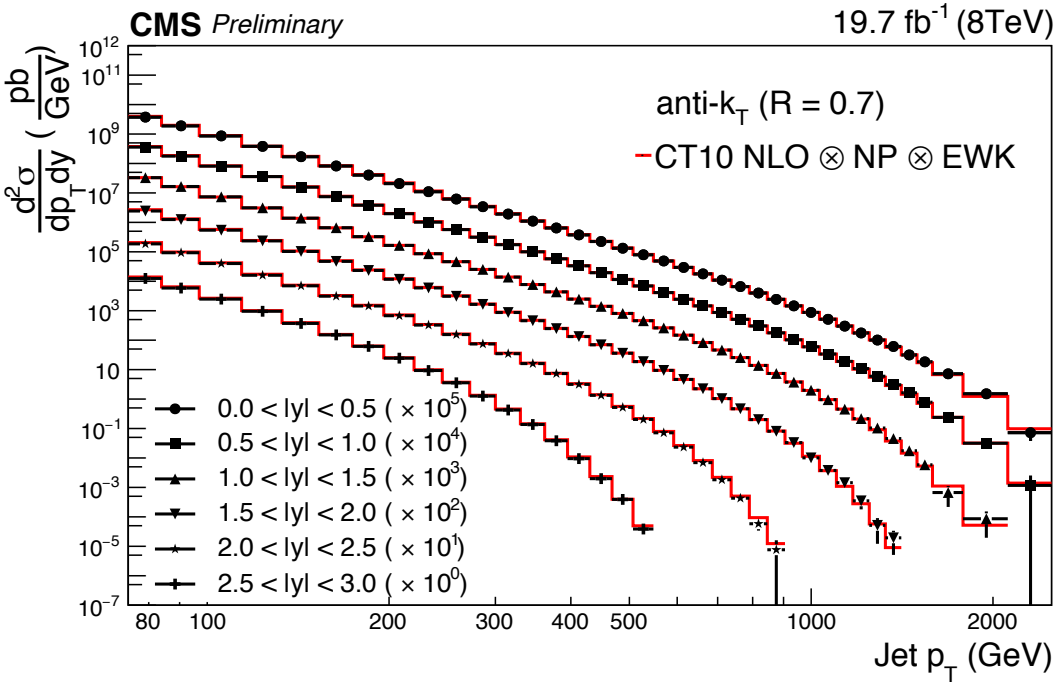
- EFT description of Higgs-gluon coupling breaks down at large transverse momenta
  - Need finite mass corrections
  - Only known at LO so far

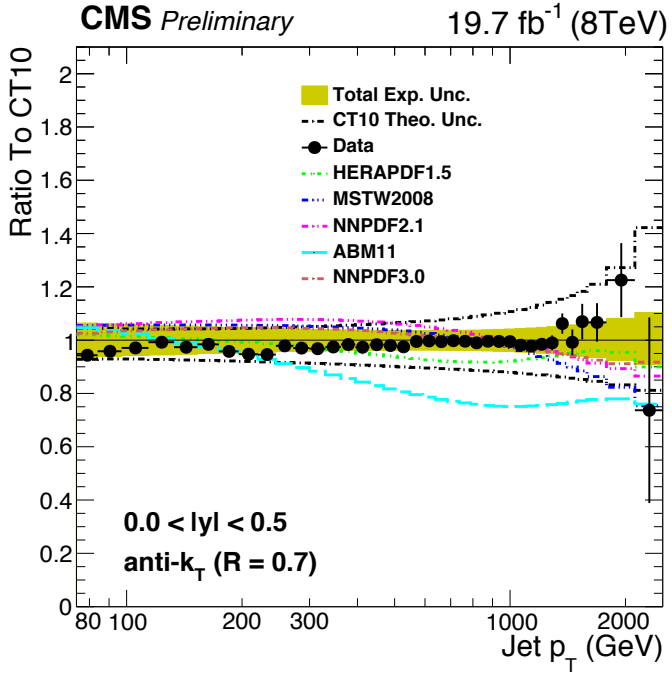




Jet cross sections at hadron colliders

CMS results: single jet inclusive

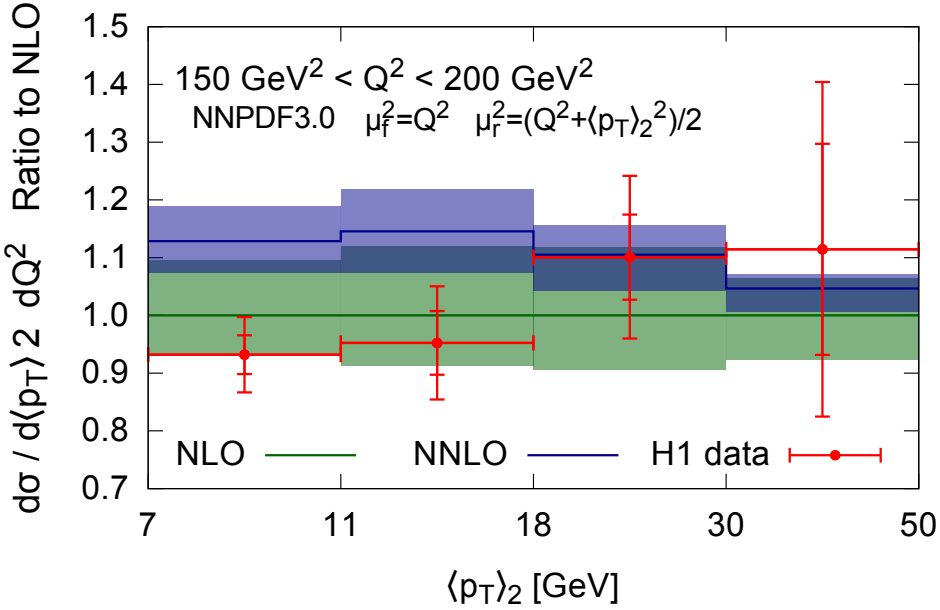




- uncertainty on NLO prediction larger than spread from partons
- need improved theory for precise extraction of parton distributions from jets

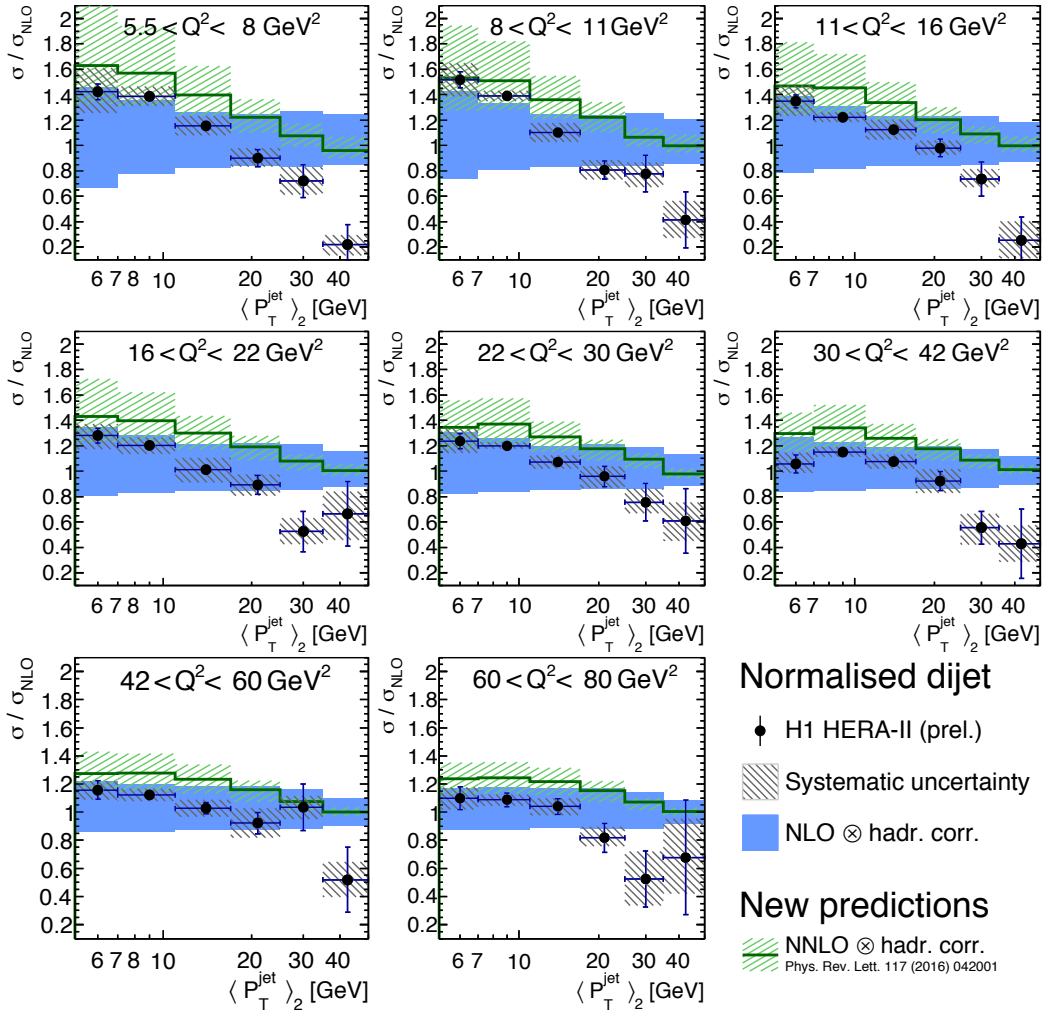
Jet cross sections at NNLO

- NNLO corrections to di-jet production in DIS
  - Recently completed (J. Currie, J. Niehues, TG)
  - Implemented in NNLOJET
  - Substantial NNLO effects
  - Uncovered infrared-sensitive interplay of H1 event selection
    - Combination of jet-pT and di-jet mass restricts LO/NLO phase space
  - Will become input to PDF fits
    - Require APPLGrid/FastNLO



- NNLO corrections to di-jets at hadron colliders ongoing (J. Currie, E.W.N. Glover, J. Pires)

Jet cross sections in DIS



New H1 measurement at low Q^2 (preliminary)

NNLO with NNPDF3.0

Conclusions and outlook

- NNLO corrections to precision observables at LHC
  - Various methods have been applied successfully
  - Healthy competition between groups
  - Dissemination of results remains a challenge (ApplGrid, fast[N]NLO)

- Current frontier: $2 \to 2$ QCD processes
  - Substantial number of calculations completed in the past two years
  - More results coming (require in part new two-loop amplitudes)

- Precision phenomenology starting
  - Parton distributions from multiple-differential measurements
  - Transverse momentum distributions