Transverse momentum distributions and jet cross sections at NNLO precision

Eltville Workshop, 14.9.2016

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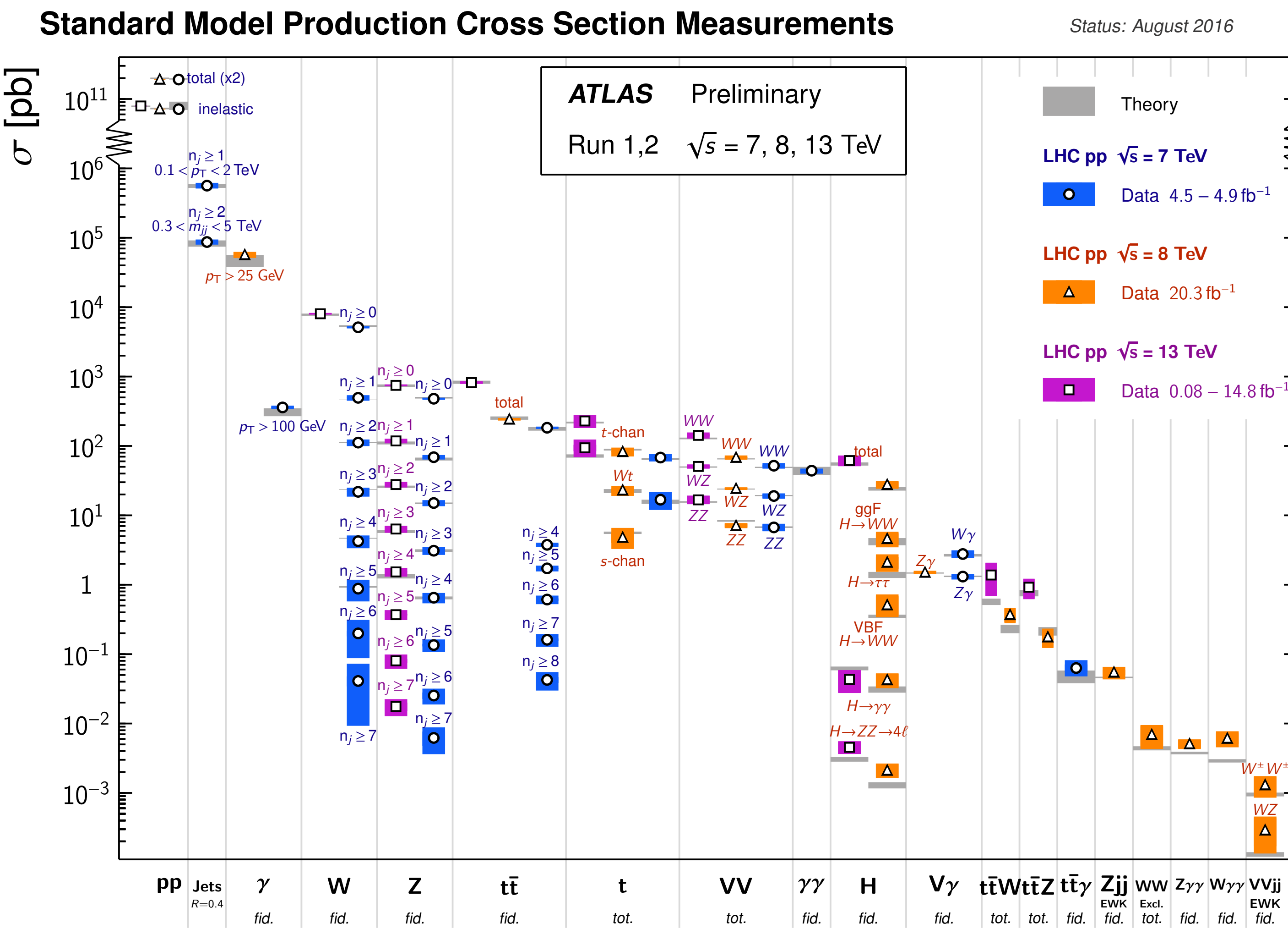
Standard Model processes at the LHC

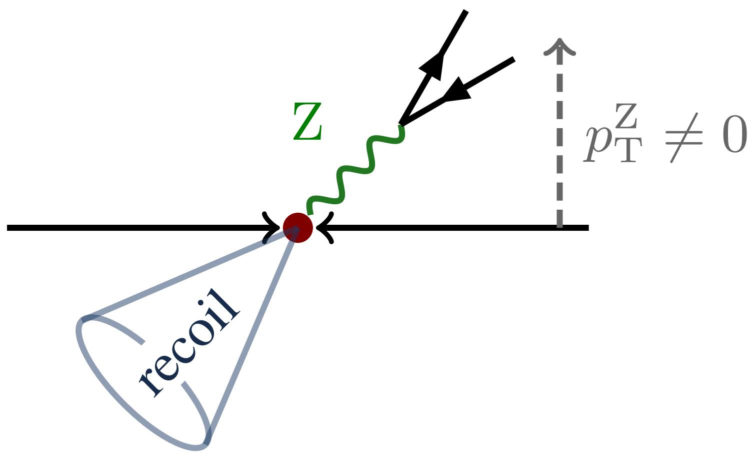


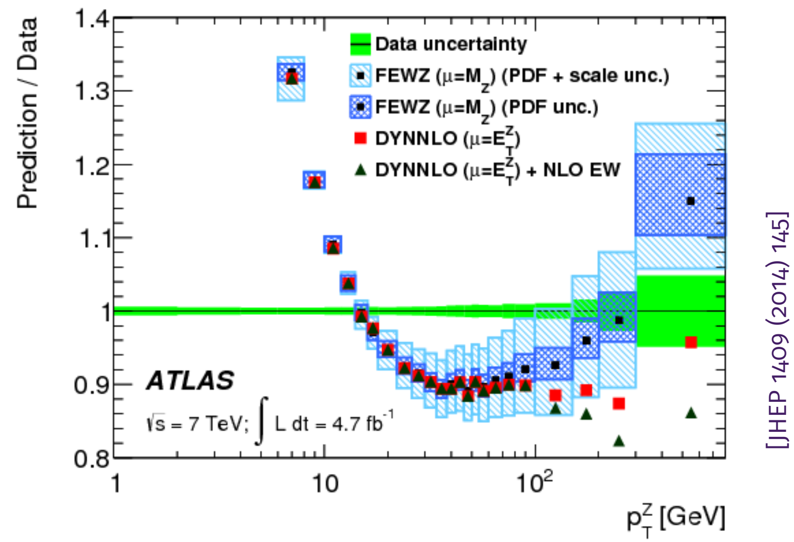
Benchmark processes: 2 → 2 reactions

- 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

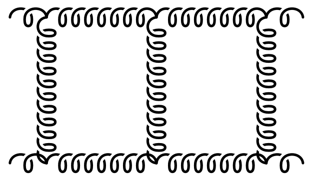




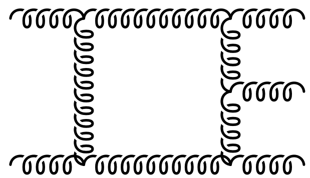
- Mismatch of orders in perturbation theory
  - NNLO for inclusive Z is only NLO for p_T-distribution
  - Z+jet and Z p_T distribution closely related
- NLO fails to describe measurements in norm and shape

NNLO calculations

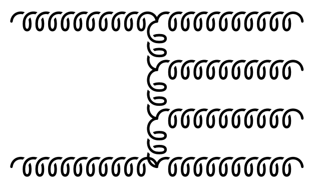
- Require three principal ingredients
  - two-loop matrix elements
    - explicit infrared poles from loop integral
      - known for all massless 2 → 2 processes



  - one-loop matrix elements
    - explicit infrared poles from loop integral
    - and implicit poles from single real emission
      - usually known from NLO calculations



  - tree-level matrix elements
    - implicit poles from double real emission
      - known from LO calculations



- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator
  - Need a method to extract implicit infrared poles

NNLO Infrared Subtraction

Structure of NNLO cross section

$$\begin{aligned}
\mathrm{d}\sigma_{NNLO} = & \int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^{R}_{NNLO} - \mathrm{d}\sigma^{S}_{NNLO}\right) \\
& + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{V,1}_{NNLO} - \mathrm{d}\sigma^{VS,1}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{MF,1}_{NNLO} \\
& + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{V,2}_{NNLO} + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{S}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{VS,1}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{MF,2}_{NNLO}
\end{aligned}$$

- Real and virtual contributions
- Subtraction term for double real radiation
- Subtraction term for one-loop single real radiation
- Mass factorization terms

- Each line finite and free of poles
  $\rightarrow$ numerical implementation

NNLO calculations for LHC processes

- Exclusive calculations, full final state information
  - Can apply experimental selection cuts
- $pp \to V$, $pp \to H$, $pp \to VH$, $pp \to \gamma\gamma$ (C. Anastasiou, K. Melnikov, F. Petriello; S. Catani, L. Cieri, D. de Florian, G. Ferrera, M. Grazzini, F. Tramontano)
- $pp \to V\gamma$, $pp \to Z^0Z^0$, $pp \to W^+W^-$ (F. Cascioli, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, M. Wiesemann, E. Weihs, TG)
- $pp \to$ top quark pairs (M. Czakon, D. Heymes, A. Mitov)
- $pp \to W^{\pm}+j$ (R. Boughezal, C. Focke, X. Liu, F. Petriello)
- $pp \to H+2j$ (VBF) (M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi)
- $pp \to Z^0+j$ (A. Gehrmann-De Ridder, E.W.N. Glover, A. Huss, T. Morgan, TG)
- $pp \to H+j$ (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze; X. Chen, E.W.N. Glover, M. Jaquier, TG)
- $pp \to 2j$ (J. Currie, A. Gehrmann-De Ridder, E.W.N. Glover, J. Pires, TG)

Real radiation at NNLO: methods

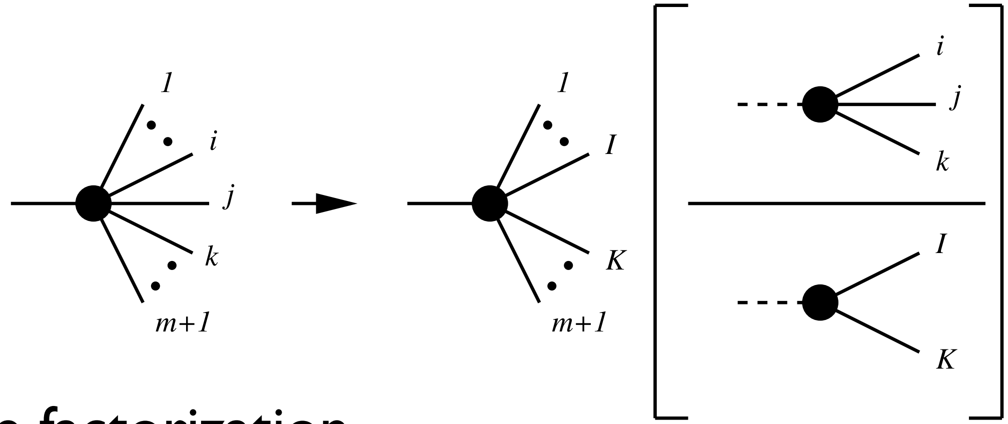
- N-Jettiness subtraction
  (R. Boughezal, X. Liu, F. Petriello; J. Gaunt, M. Stahlhofen, F. Tackmann, J.R. Walsh)
  - pp → H+j (R. Boughezal, C. Focke, W. Giele, X. Liu, F. Petriello)
  - pp → W+j (R. Boughezal, C. Focke, X. Liu, F. Petriello)
  - pp → Z+j (R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello)
- N-Jettiness variable: distance from N-parton configuration
  (I. Stewart, F. Tackmann, W. Waalewijn)

$$\mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2 q_i \cdot p_k}{Q_i} \right\}$$

  - Universal behaviour at small T_N from SCET resummation
  - Implementation: N+1jet calculation at NLO with cut-off on T_N

Antenna subtraction

- Subtraction terms constructed from antenna functions
  - Antenna function contains all emission between two partons



  - Phase space factorization

$$d\Phi_{m+1}(p_1,\ldots,p_{m+1};q) = d\Phi_m(p_1,\ldots,\tilde{p}_I,\tilde{p}_K,\ldots,p_{m+1};q)\cdot d\Phi_{X_{ijk}}(p_i,p_j,p_k;\tilde{p}_I+\tilde{p}_K)$$

  - Integrated subtraction term

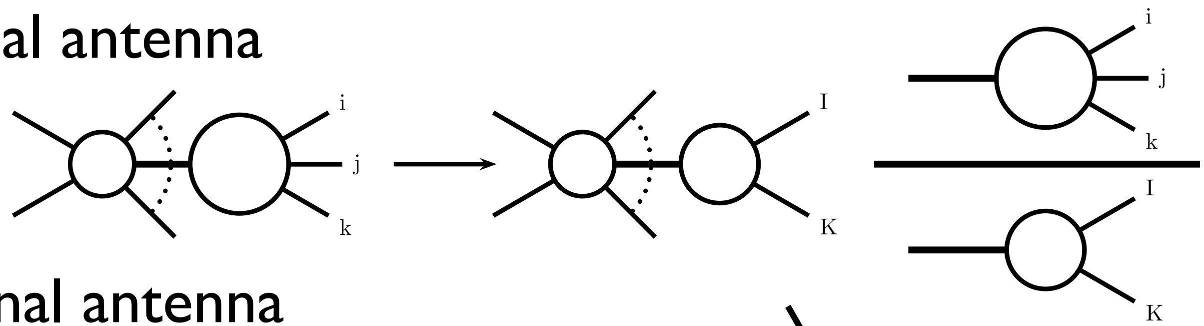
$$\mathcal{X}_{ijk} = \int d\Phi_{X_{ijk}} X_{ijk}$$

Antenna functions

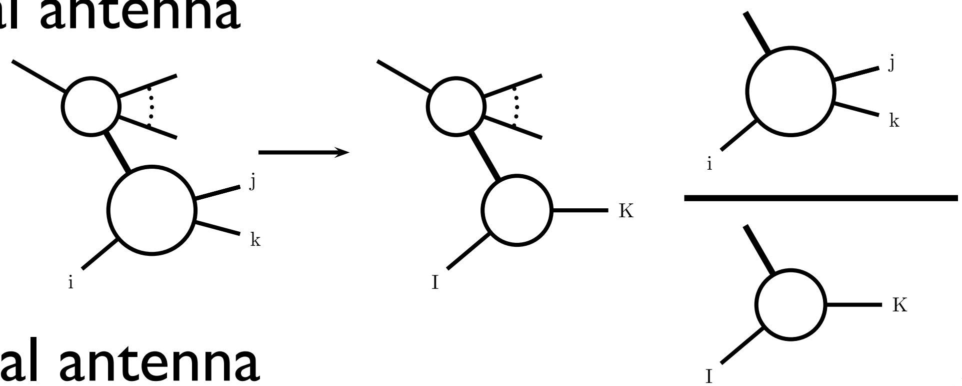
- Colour-ordered pair of hard partons (radiators)
  - Hard quark-antiquark pair
  - Hard quark-gluon pair
  - Hard gluon-gluon pair
- NLO (D. Kosower; J. Campbell, M. Cullen, E.W.N. Glover)
  - Three-parton antenna: one unresolved parton
- NNLO (A. Gehrmann-De Ridder, E.W.N. Glover, TG)
  - Four-parton antenna: two unresolved partons
  - Three-parton antenna at one loop
  - Products of NLO antenna functions
  - Soft antenna function

Antenna subtraction: incoming hadrons

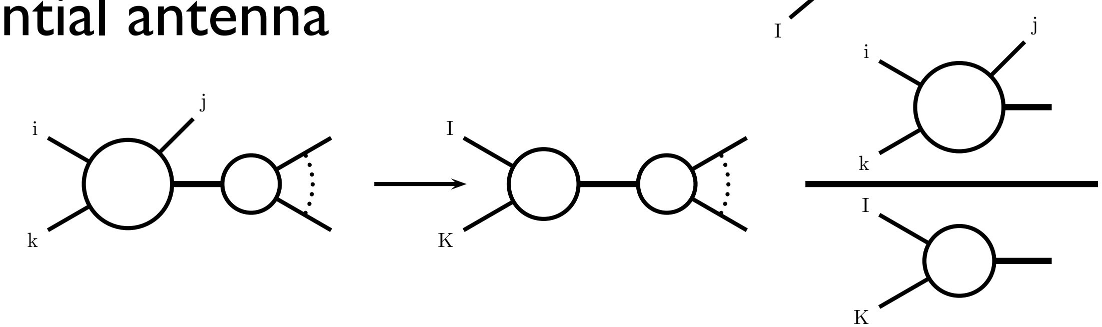
- Three antenna types (A. Daleo, D. Maitre, TG; J. Currie, N. Glover, S. Wells)
  - Final-final antenna



  - Initial-final antenna



  - Initial-intial antenna



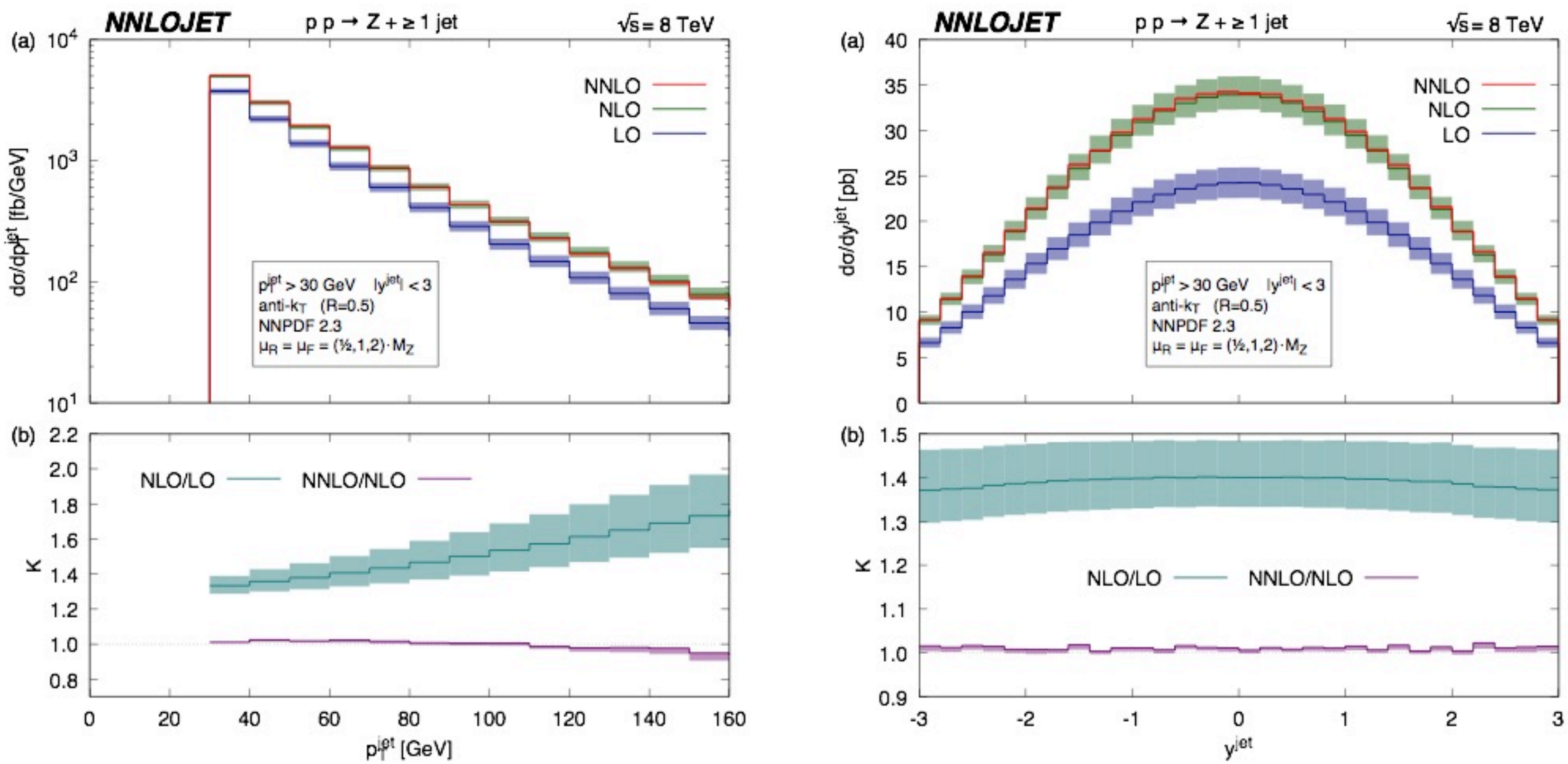
NNLOJET code

- 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



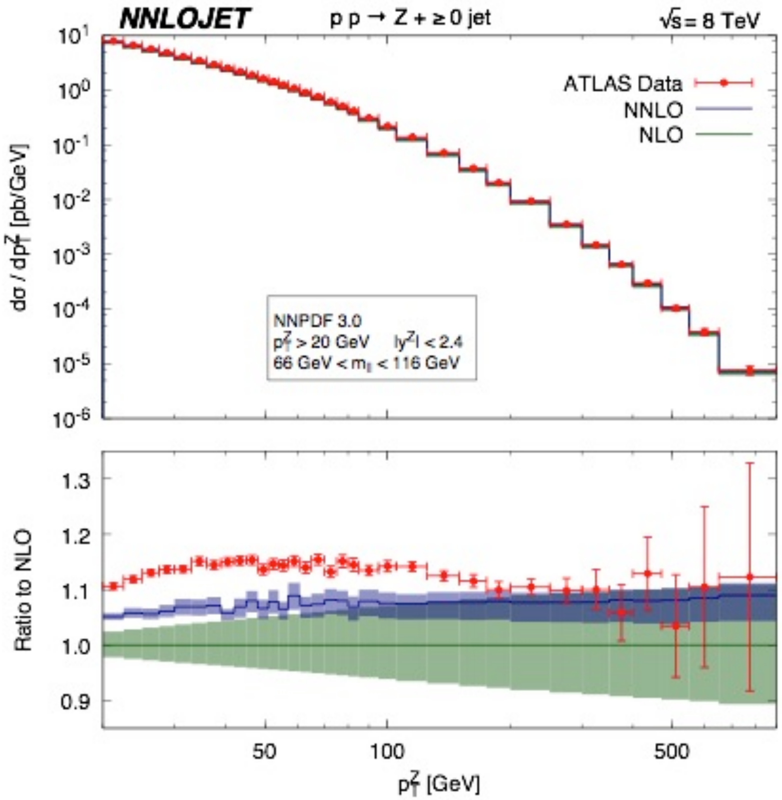
Z p_T-distribution at NNLO

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

Z p_T-distribution at NNLO

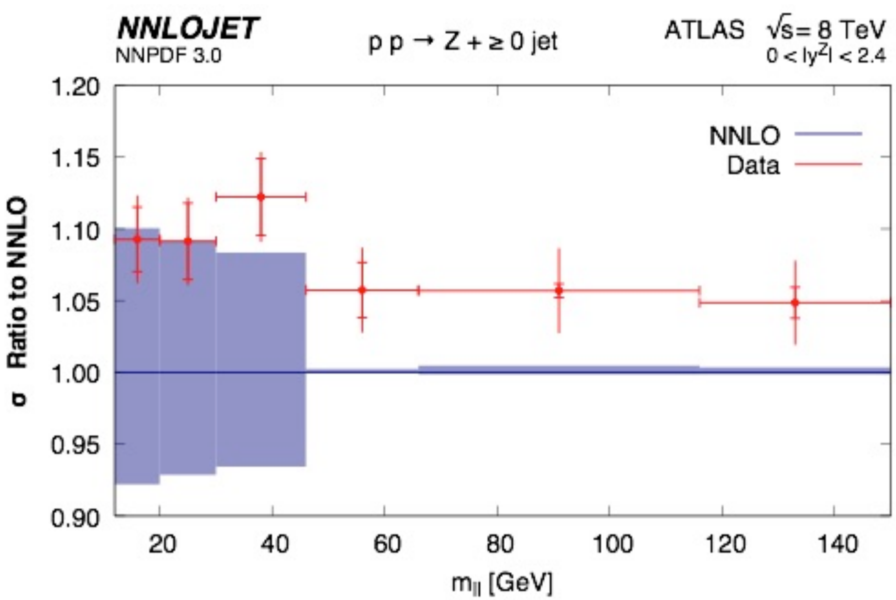
- NNLO effects
  - Around 5% corrections, modify shape of p_T distribution
  - Normalization of data not described correctly (both CMS/ATLAS)

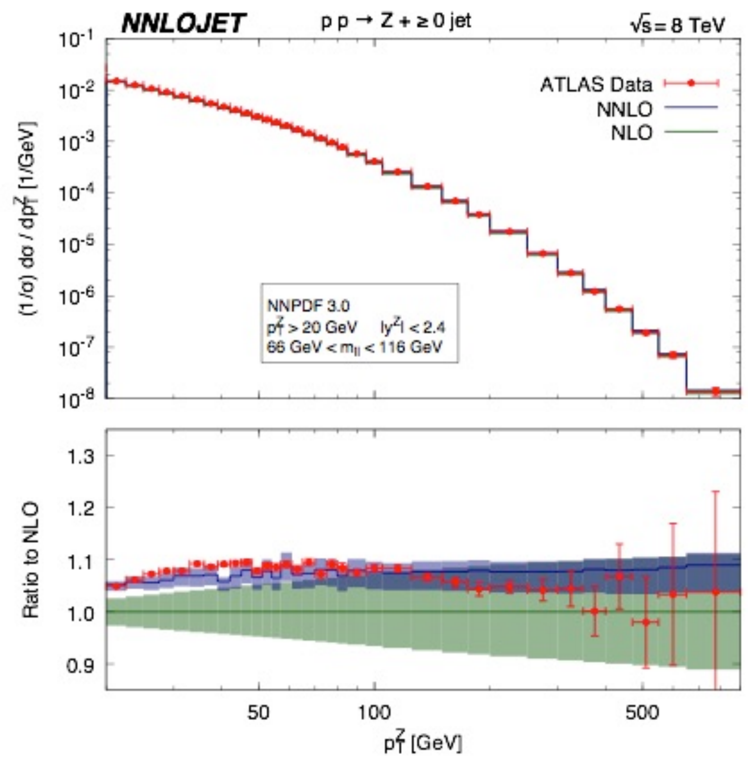


A. Gehrmann-De Ridder,, E.W.N. Glover, A. Huss, T. Morgan, TG

Z p_T-distribution at NNLO

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

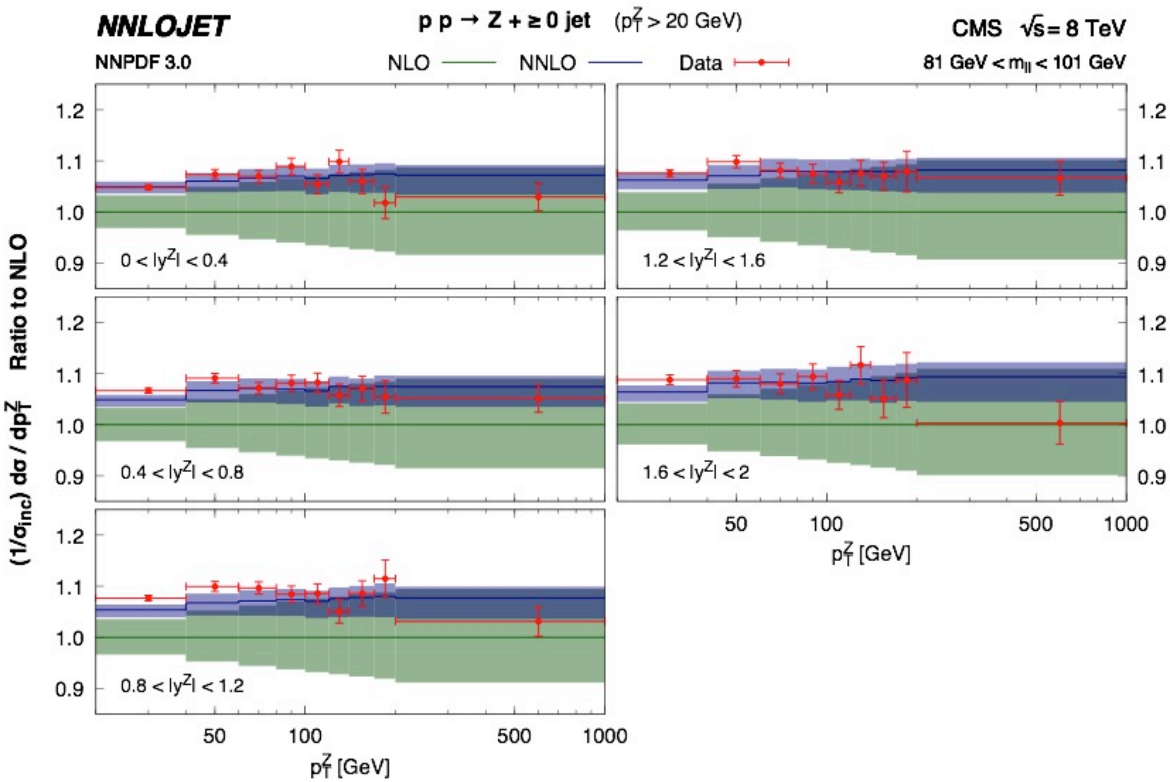




- Consider normalized p_T distribution

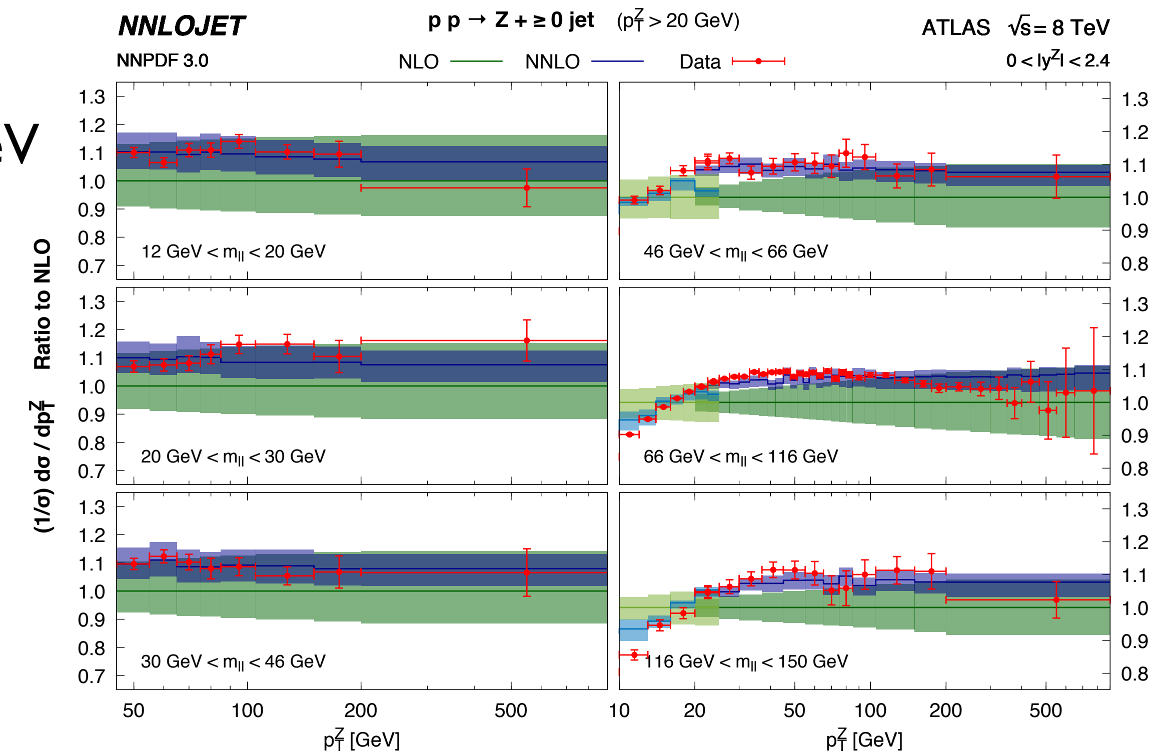
Z p_T-distribution at NNLO

- 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 10 GeV

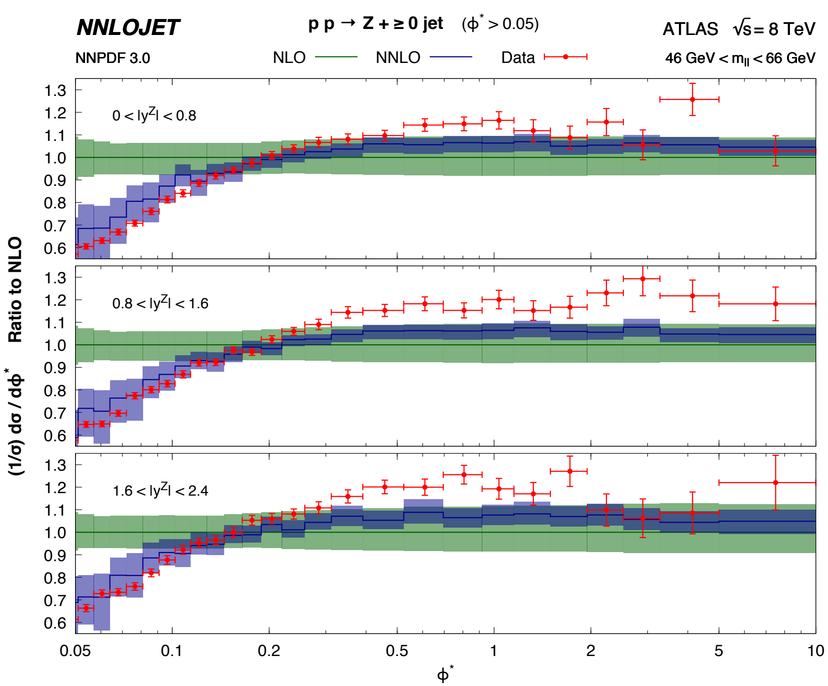


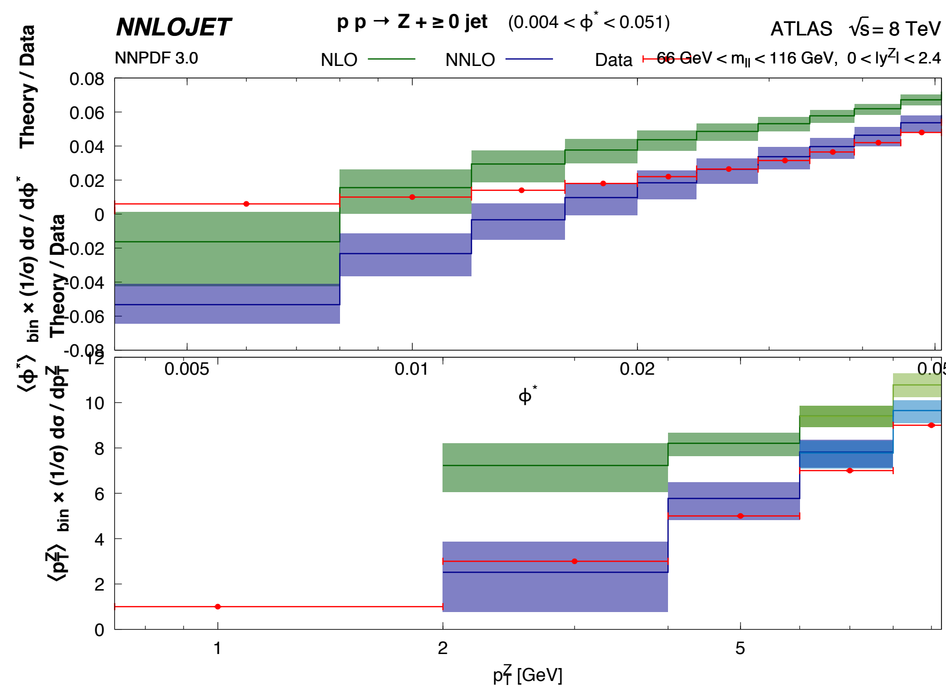
- Related observable (purely from lepton directions)

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

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

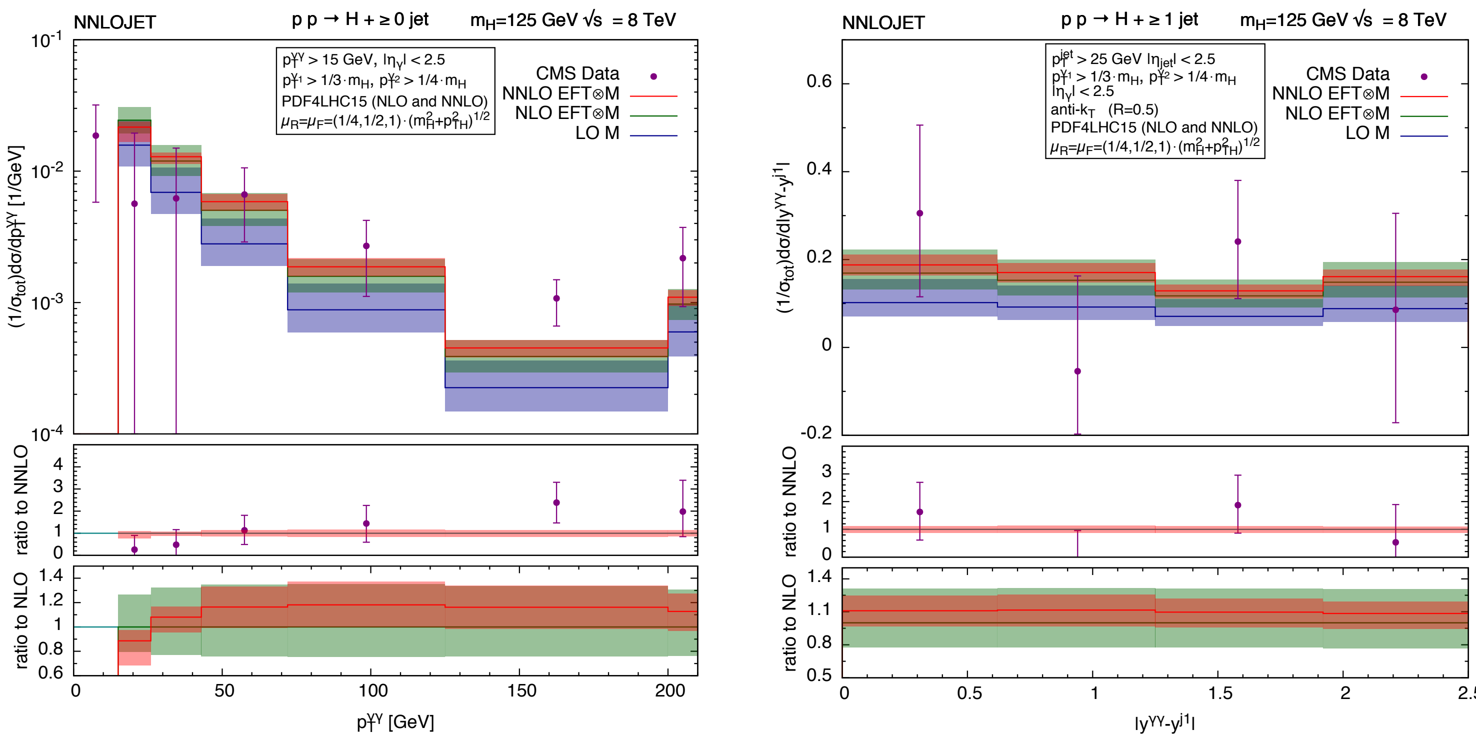
- Calculation based on antenna subtraction
  - Agreement (0.4%) with residue-subtraction (F. Caola, K. Melnikov, M. Schulze)
  - Validation against Njettiness ongoing (R. Boughezal, C. Focke, X. Liu, F. Petriello)
- Fiducal cross sections

	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

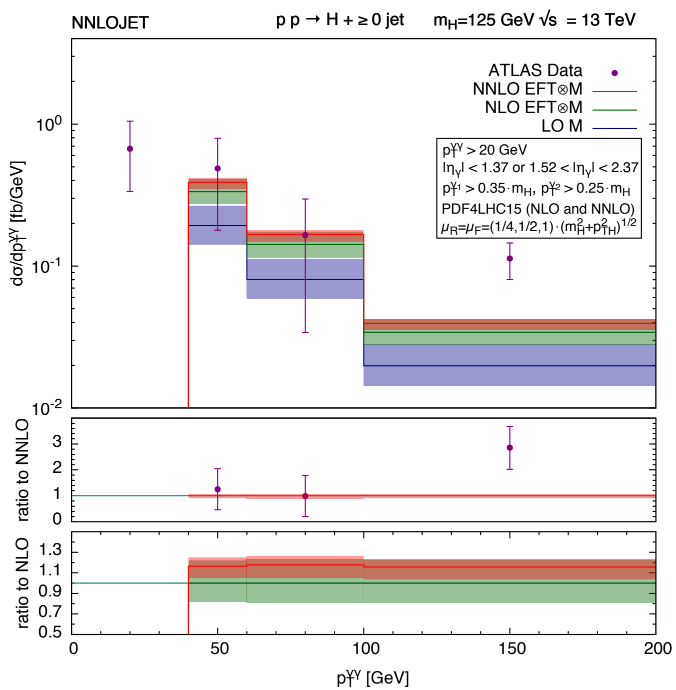


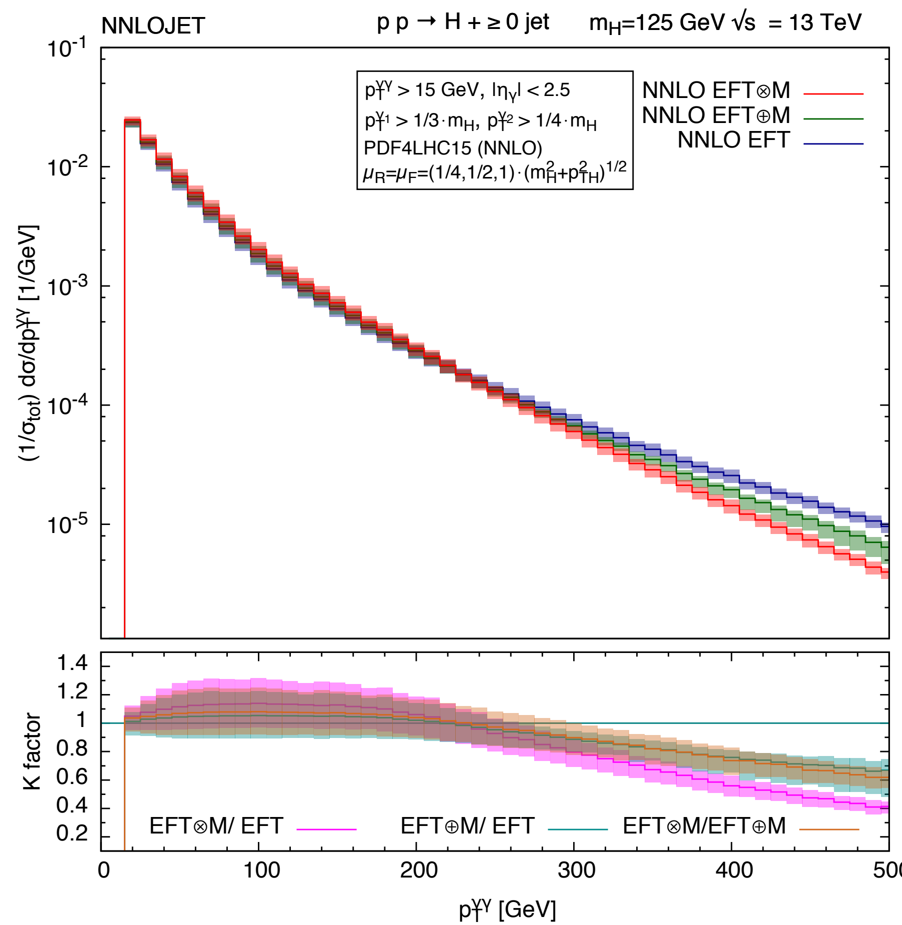
- Prepare for precision studies at higher energy

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

Higgs p_T distribution at NNLO

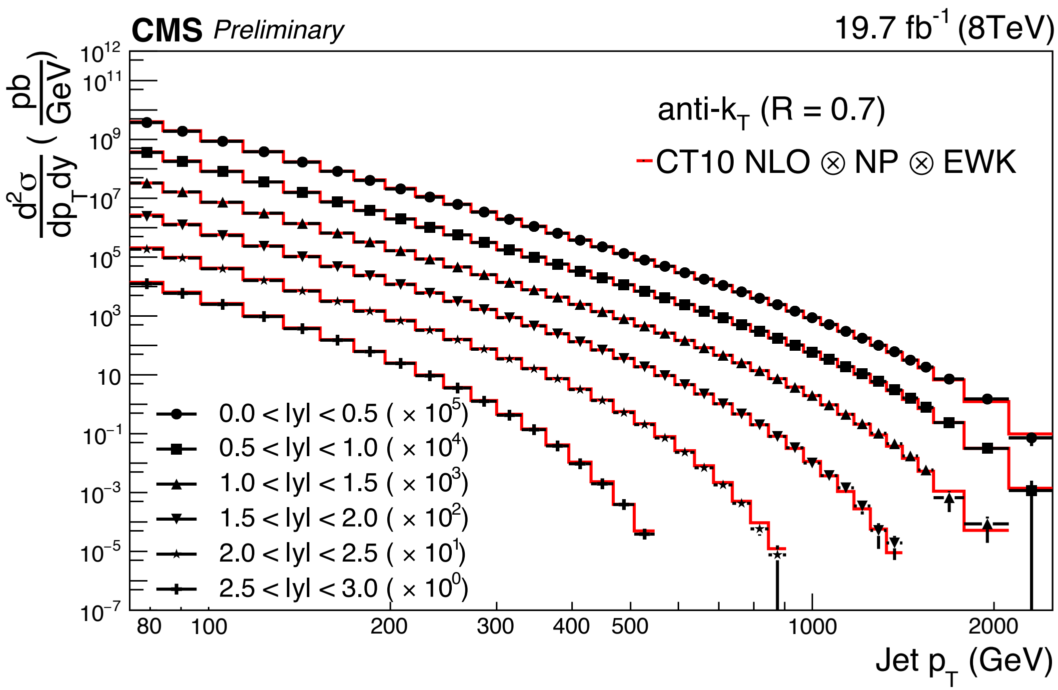
- EFT description of Higgs-gluon coupling breaks down at large transverse momenta
  - Need finite mass corrections
  - Only known at LO so far

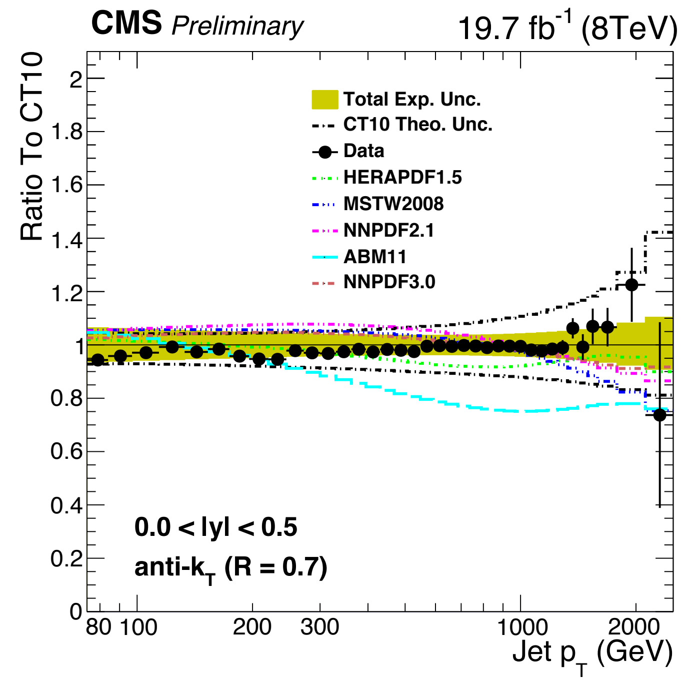




Jet cross sections at hadron colliders

CMS results: single jet inclusive

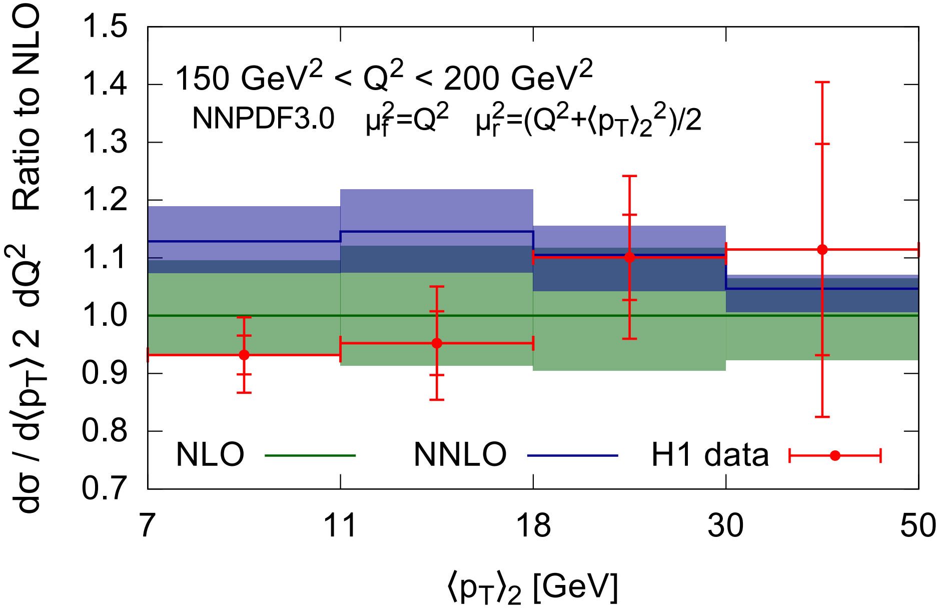




- uncertainty on NLO prediction larger than spread from partons
- need improved theory for precise extraction of parton distributions from jets

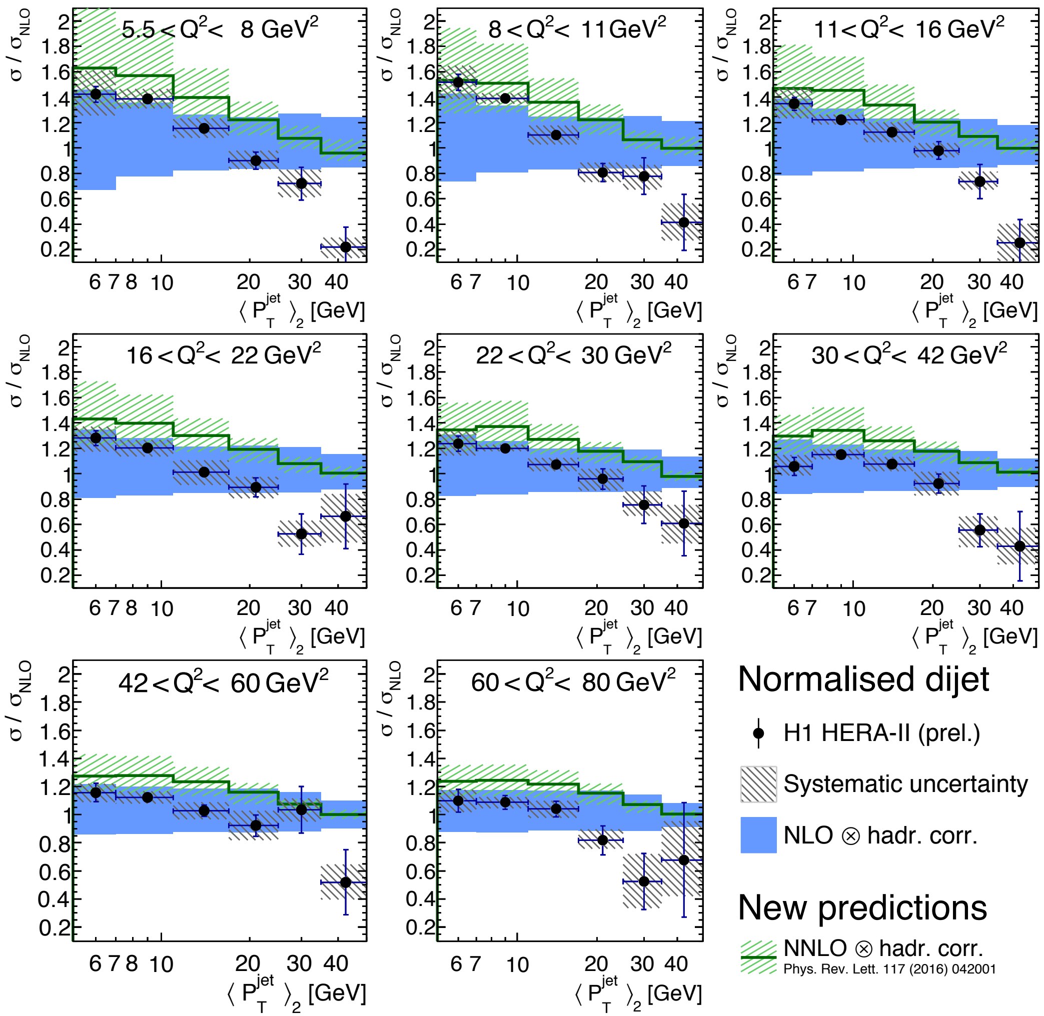
Jet cross sections at NNLO

- 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

- Current frontier: $2 \rightarrow 2$ 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
  - Indirect new physics searches