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Jet cross sections with NNLOJET

Aude Gehrmann-De Ridder

Loops and Legs in Quantum Field Theory
St. Goar, 30.04.2018

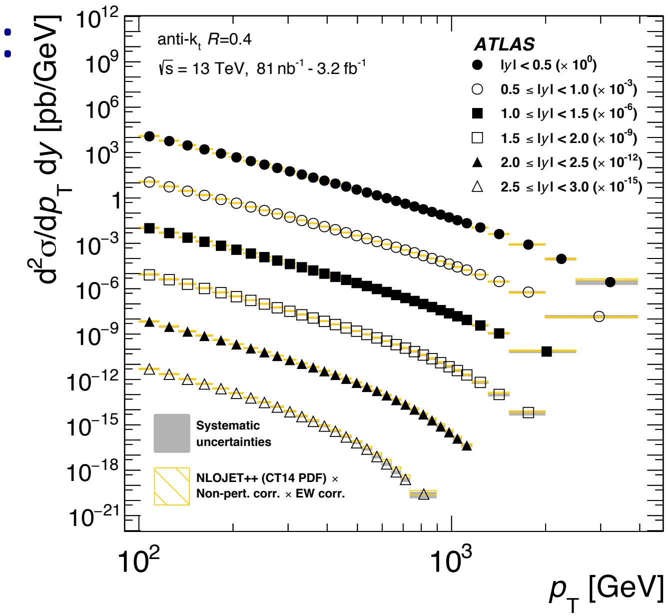
work with: J. Currie, T. Gehrmann, E.W.N. Glover, A. Huss, J. Pires

MC@NNLO

Jet production at the LHC

- Jet cross sections: measured differentially with per cent level uncertainties
- providing an ideal testing ground for QCD:
  - constrain PDFs (sensitive to gluon)
  - determine α_s
  - enable indirect BSM searches
- Mainly compared to NLO predictions
  - So far: no observed discrepancy within theory or experimental uncertainties
  - NLO here from NLOJET++

  (Z. Nagy, Phys. Rev. D 68 (2003) 094002)



Single jet inclusive: (pp->jet +X)
ATLAS@13TeV (arXiv:1711.02692)

Jet observables at LHC

- Single jet inclusive cross section: pp $\to$ jet +X
  - Is the sum of individual single jet cross sections
    - ❖ each jet in an event contributes separetely, leading to multiple entries of a single event in distributions
  - differential in transverse momentum p_T and rapidity y

- Di-jet cross section: pp $\to$ 2 jet +X
  - consider only two leading (in p_T) jets in event
    - ❖ single entry per event
  - Multi-differential measurements possible (M_{JJ}, $\langle p_T \rangle$, …)

Jet observables: Theory status

- Important steps and recent developments
  - NLO QCD [Ellis, Kunszt,Soper '92], [Giele,Glover,Kosower '94], [Nagy '03]
  - NLO QCD + PS (POWHEG) [Alioli, Hamilton, Nason, Oleari, Re '11]
  - NLO QCD + Resummation (threshold+jet radius) (talk by S. Moch)
  - NLO EW [Dittmaier, Huss, Speckner '12],[Campbell, Wackeroth, Zhou '16]
  - NLO QCD+EW [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '17]

  - NNLO QCD (this talk)

    [Gehrmann, Glover, Pires, AG '13], [Currie, Glover, Pires '16]

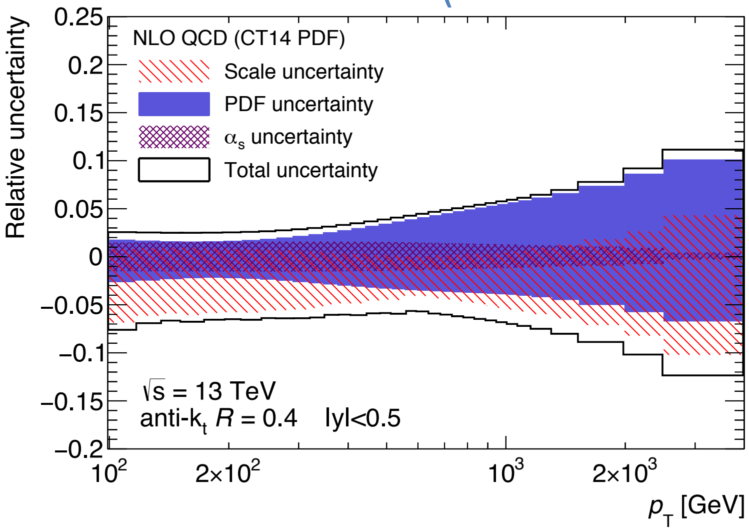
    [Currie, Gehrmann, Glover, Huss, Pires, AG '17]

Jet cross sections: uncertainties

- Two types: parametric (PDF, α_s) and perturbative (truncation)
- Perturbative uncertainty: quantified by scale variation
  - Vary renormalization μ_R and factorization μ_F scales by factors [1/2;2] around some pre-defined central scale
  - Important limiting factor for using jet data in PDF fits

(arXiv:1711.02692)

- Size of uncertainties at NLO
  - Scale uncertainty important
    - ❖ (p_T and y dependent)

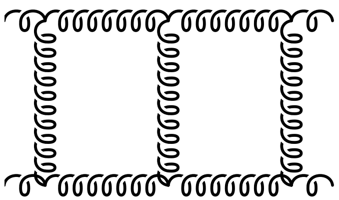


Single jet inclusive: (Central y)

- NNLO corrections needed
  - for precise determination PDFs and α_s

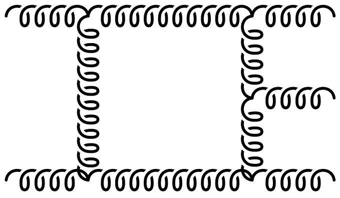
Ingredients to jet production at NNLO

$\mathrm{d}\sigma^{VV}_{NNLO}$ with two-loop matrix elements



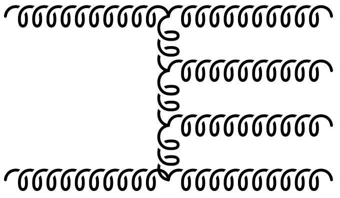
- explicit infrared poles from loop integral

$\mathrm{d}\sigma^{RV}_{NNLO}$ with one-loop matrix elements



- explicit infrared poles from loop integral and implicit poles from single real emission

$\mathrm{d}\sigma^{RR}_{NNLO}$ with tree-level matrix elements



- implicit poles from single and double real emission

- Infrared poles cancel in the sum

Antenna subtraction at NNLO

- Parton level NNLO cross section with m-jets in the final state

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\phi_{m+2}} \left[\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO}\right] + \int_{\mathrm{d}\phi_{m+1}} \left[\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right] + \int_{\mathrm{d}\phi_{m}} \left[\mathrm{d}\hat{\sigma}^{VV}_{NNLO} - \mathrm{d}\hat{\sigma}^{U}_{NNLO}\right]$$

- Unintegrated subtraction terms in $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{T}_{NNLO}$
  - Mimic double real (RR) and real-virtual (RV) contributions in all infrared limits
- Integrated subtraction terms in $\mathrm{d}\hat{\sigma}^{T}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{U}_{NNLO}$
  - Cancel explicit infrared poles in real-virtual (RV) and double virtual (VV)
- Terms in square brackets are
  - finite, well-behaved in all infrared regions
  - evaluated numerically with a parton level event generator
- Implementation in NNLOJET

NNLOJET

- NNLO parton level event generator
  - based on antenna subtraction
- Infrastructure
  - Process management
  - Phase space, histogram routines
  - Validation and testing
  - ApplFast interface in progress
- Processes implemented at NNLO
  - Z+(0,1)jet, W+(0,1)jet (talk by D.Walker)
  - H+(0,1)jet (X.Chen et al.)
  - DIS-2j (J. Niehues et al.)
  - VBF H+2jet (talk by J. Cruz-Martinez)
  - Jet production (this talk)

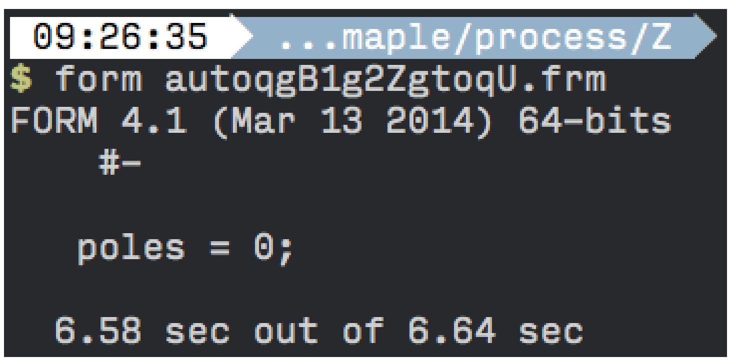
NNLOJET project:
X. Chen, J. Cruz-Martinez, J. Currie,
R. Gauld, T.Gehrmann, E.W.N. Glover,
M. Höfer, A.Huss, T.Morgan, I. Majer
J.Niehues, J. Pires, D. Walker, AG

Antenna subtraction: Checks

- Analytic pole cancellation

$$Poles(\mathrm{d}\sigma^{RV} - \mathrm{d}\sigma^{T}) = 0$$

$$Poles(\mathrm{d}\sigma^{VV} - \mathrm{d}\sigma^{U}) = 0$$



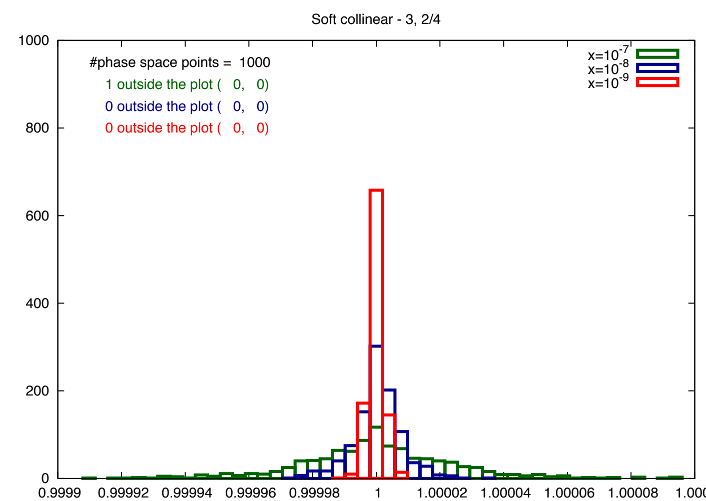
- Unresolved limits for RR, RV

$$\mathrm{d}\sigma^{S} \to \mathrm{d}\sigma^{RR}$$

$$\mathrm{d}\sigma^{T} \to \mathrm{d}\sigma^{RV}$$

Example $q\bar{q} \to Z + g_3 g_4 g_5 \; (g_3 \,\mathrm{soft}, g_4 \parallel \bar{q})$

Ratio $\mathrm{d}\sigma^{S}/\mathrm{d}\sigma^{RR} \to 1$ approaching singular limit



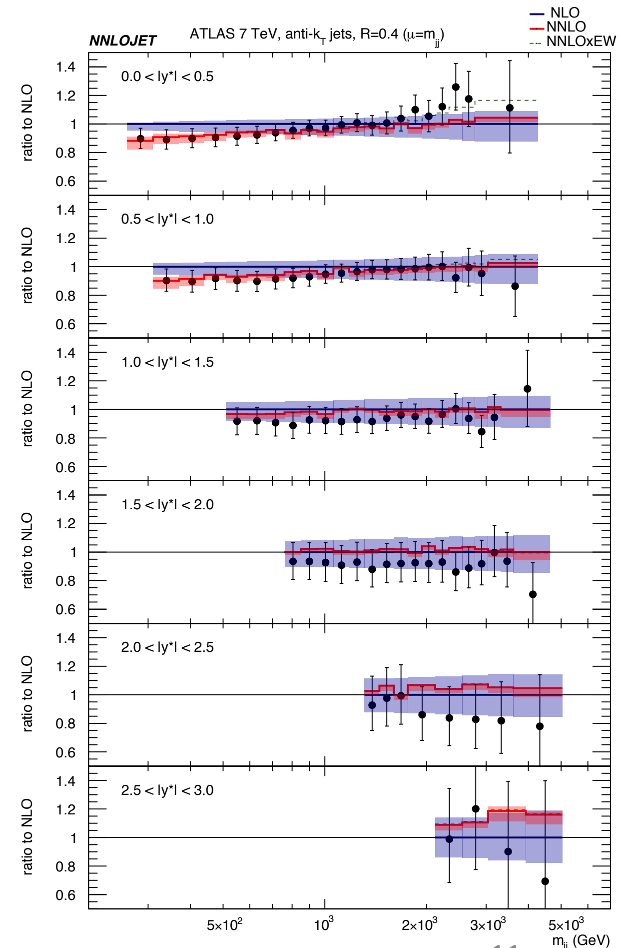
Di-jet production at NNLO

- Most complicated 2 → 2 process: pp → 2 jets +X
  - large number of parton-level sub-processes
  - Four QCD partons at tree level
  - Many more unresolved configurations than in V +jet
- NNLO corrections known:

  (Currie, Gehrmann, Glover, Huss, Pires, AG '17)
  - All channels at leading color (N^2,NN_F, N_F^2)
  - Gluon-gluon channel with full colour
  - Subleading colour contributions: (a priori suppressed by $1/N^2$)
    - ❖ below two percent at NLO (all channels)
    - ❖ around ten percent of full NNLO contribution in gg channel

Di-jet invariant mass distribution

- ATLAS measurement @ 7TeV [JHEP 1405.059 (2014)]
  - double differential in invariant mass of the di-jet system m_{JJ} and rapidity difference y^*:
    - ❖ At least two reconstructed jets with: $p_{T1} > 100$ GeV, $p_{T2} > 50$ GeV and $|y_j|<3$

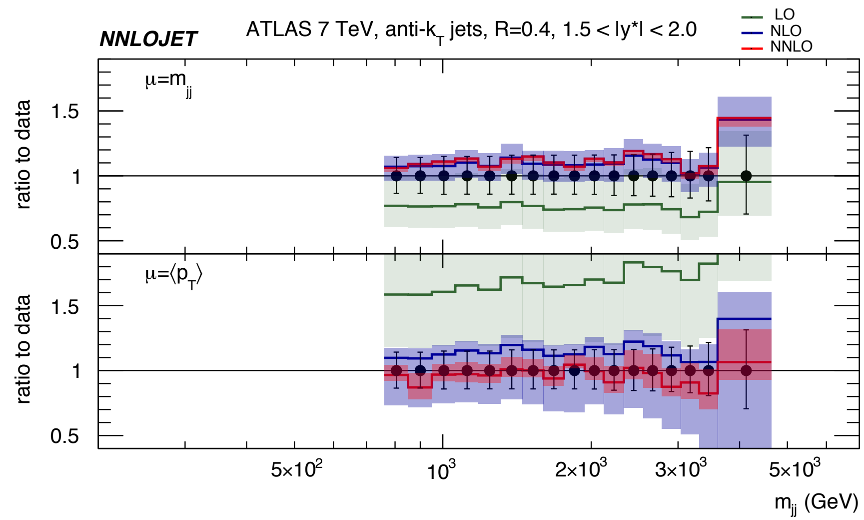


- Di-jet@NNLO
  - Central scale: $\mu_F = \mu_R = \mu = m_{JJ}$
  - Scale dependence
    - ❖ Independent 7-scale variation of μ_F, μ_R

✔ Good agreement in shape and normalisation even at low m_{JJ} and low $|y^*|$ where NLO fails

Di-jet production: scale choice

- Common central scale choices
  - invariant mass m_{jj}
  - average transverse momentum of two leading jets $\langle p_T \rangle$
- Compare predictions (normalised to data)
  - NLO: Spread of predictions
    - ❖ m_{jj} Small positive corrections, small uncertainties
    - ❖ $\langle p_T \rangle$: Large negative corrections, large uncertainties
  - NNLO: Scale choice issue resolved
    - ❖ Stabilization and convergence of predictions with small residual scale uncertainties
    - ❖ better choice: m_{jj}



Focus: Region of large rapidity differences: $1.5 < |y^*| < 2.0$

Single jet inclusive production at NNLO

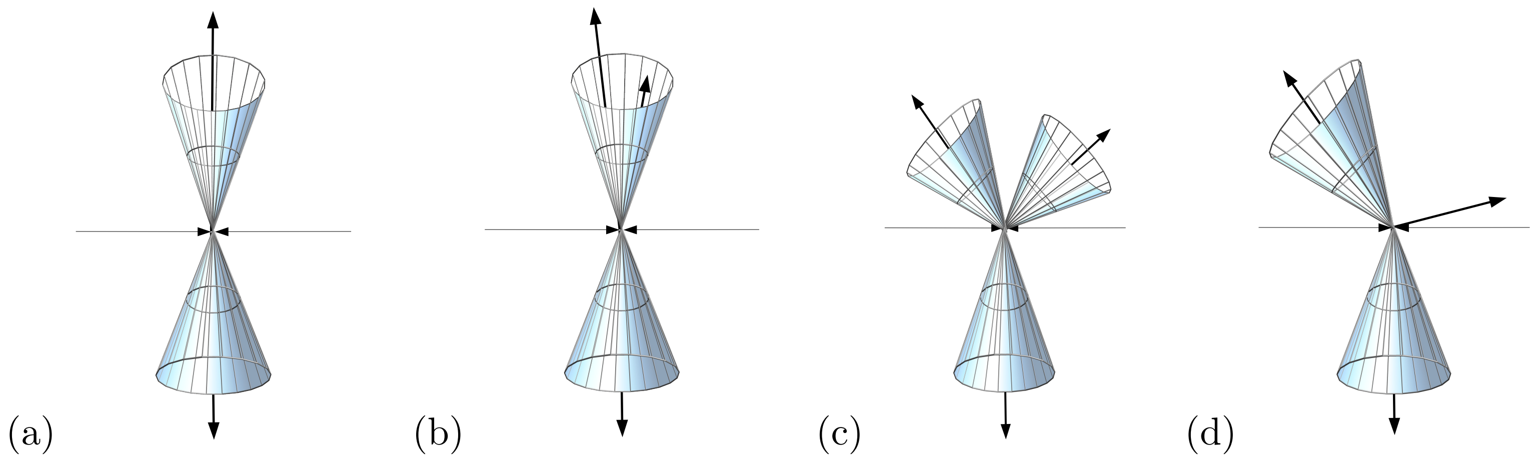
- Single jet inclusive cross section: pp $\rightarrow$ jet +X
  - Is the sum of separate single jet cross sections
- Central scale setting choices: Two categories
  - jet-based: scale different for each jet in an event
    - ex: p_T : transverse momentum of the individual jets
  - event-based: common scale for all jets in an event
    - ex: p_{T1}: transverse momentum of the leading jet
- At $O(\alpha_s^4)$

$$\frac{d\sigma}{dp_T}(\mu = p_T) = \frac{d\sigma}{dp_{T1}}(\mu = p_{T1}) + \frac{d\sigma}{dp_{T2}}(\mu = p_{T2}) + \frac{d\sigma}{dp_{T3}}(\mu = p_{T3}) + \frac{d\sigma}{dp_{T4}}(\mu = p_{T4})$$

$$\frac{d\sigma}{dp_T}(\mu = p_{T1}) = \frac{d\sigma}{dp_{T1}}(\mu = p_{T1}) + \frac{d\sigma}{dp_{T2}}(\mu = p_{T1}) + \frac{d\sigma}{dp_{T3}}(\mu = p_{T1}) + \frac{d\sigma}{dp_{T4}}(\mu = p_{T1})$$

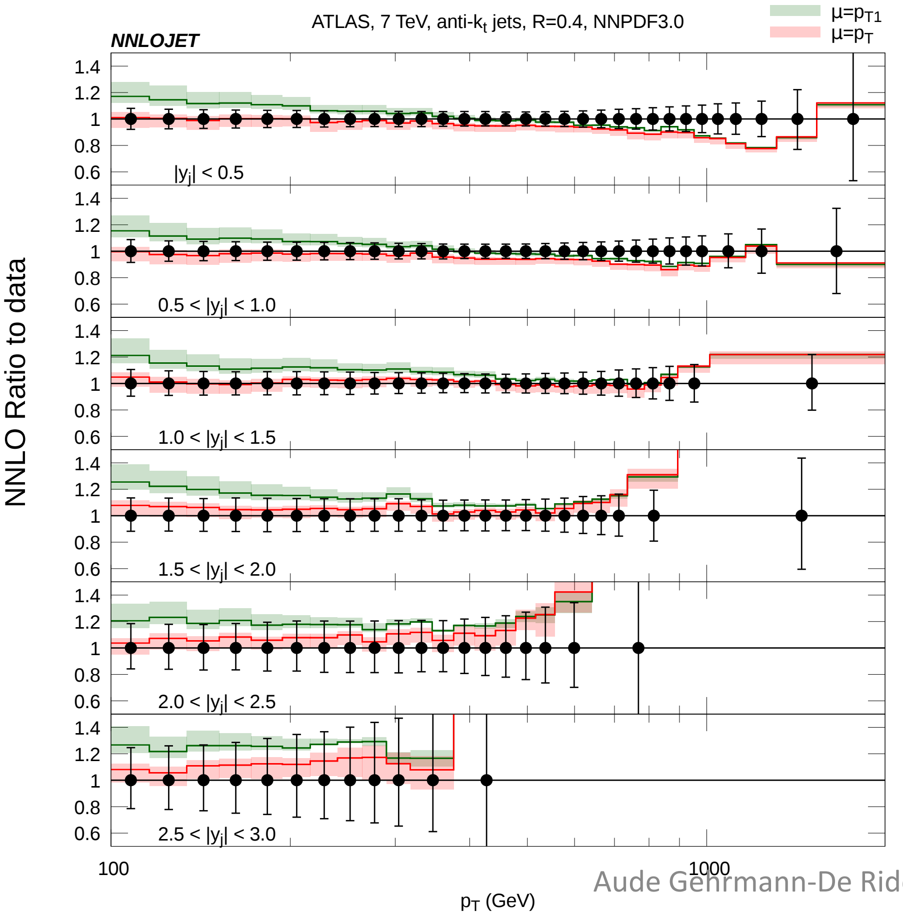
p_T versus p_{T1}: Similarities and Differences

- $p_T = p_{T1}$
  - for leading order (2→2 kinematics)
  - for high p_T-jets (back-to-back)
- $p_T \neq p_{T1}$
  - for events with three or more jets
  - for events with jets outside the fiducial cuts



Single jet inclusive production - p_T vs. p_{T1}

- Compare NNLO predictions with scales $\mu = p_T$ or $\mu = p_{T1}$ with ATLAS @ 7 TeV (R=0.4) [JHEP 1502 153 (2015)]
  - At least one reconstructed jet with: $p_T > 100$ GeV and $|y|<3$



Single jet at NNLO:

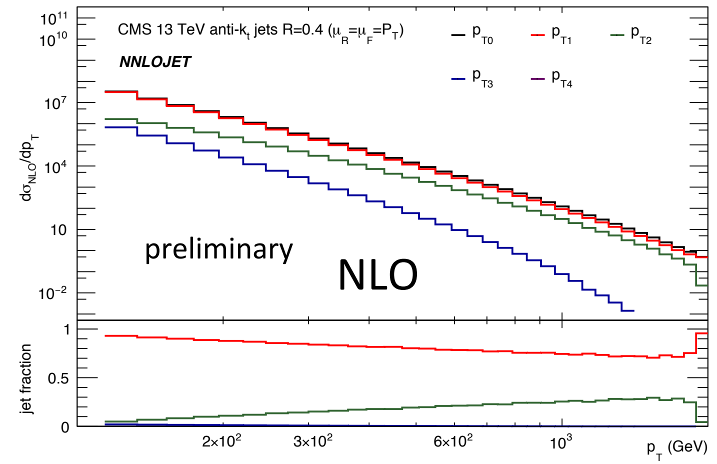
- high p_T: Stabilization and agreement of predictions
- low p_T : Significant differences: 15-20% with large uncertainty bands for both scale choices

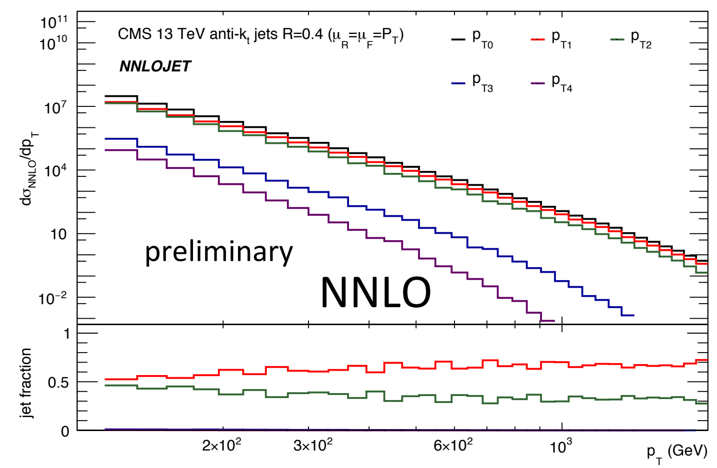
⇒ Large effects from scale ambiguity remain at NNLO (unlike in di-jet production)

⇒ Data better described with $\mu = p_T$ choice

Individual jet contributions and jet fractions

- NLO
  - Leading jet dominates
  - Third jet negligible
  - Second jet sizeable
    - ❖ high p_T: as significant as leading jet
    - ❖ low p_T: negligible
- NNLO
  - Leading and second jet similar over whole p_T range
    - ❖ substantial increase of second jet contribution at low p_T
- Large alternating corrections to second jet distribution

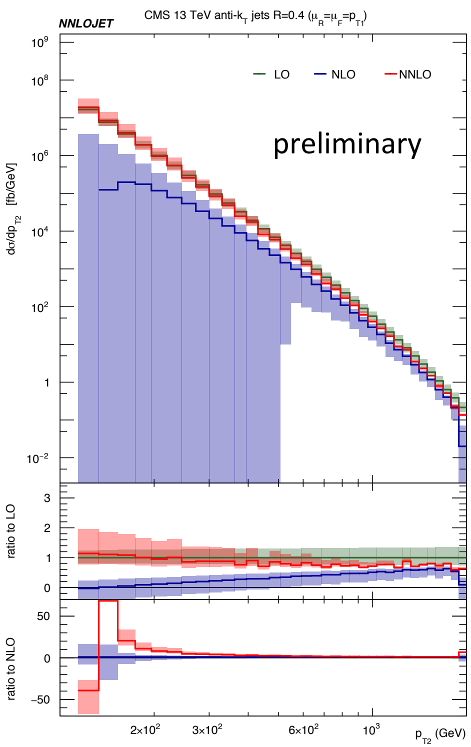




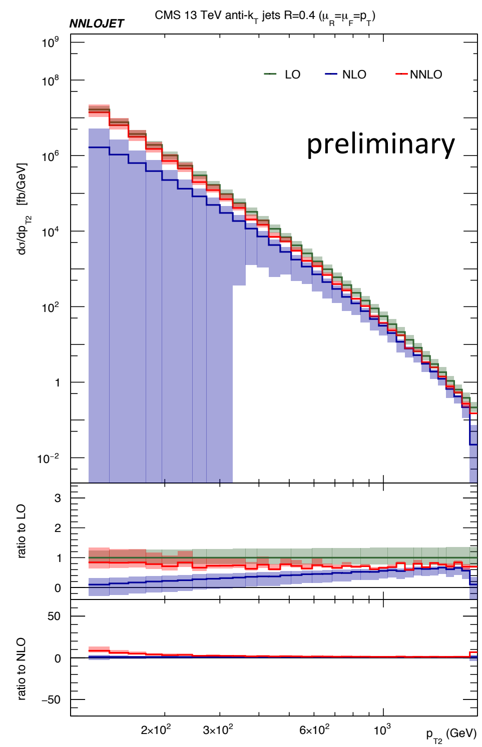
$\mu_R = \mu_F = p_T$

Second jet transverse momentum distribution

- Corrections to second jet distribution
  - NLO: Large and negative with huge uncertainty
  - NNLO: Large and positive
- Ratios show
  - NLO problematic for both scales
  - but much worse for $\mu = p_{T1}$
  - Stabilisation at NNLO (in line with LO)
  - better choice: $\mu = p_T$



$\mu = p_{T1}$



$\mu = p_T$

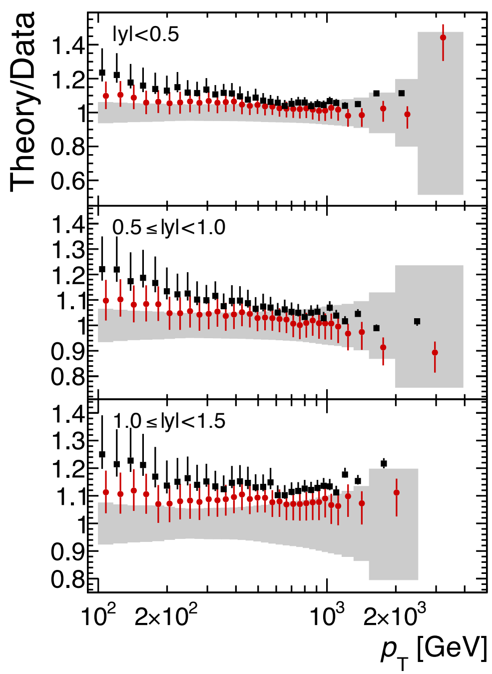
Scale setting issue in single jet production

- Change in NNLO predictions using $\mu = p_T$ or $\mu = p_{T1}$ at low p_T due to:
  - Increased importance of p_{T2} contribution from NLO to NNLO
  - p_{T2} distribution potentially sensitive on IR effects
    - presence of potentially large logs
  - p_{T2} distribution better behaved for $\mu = p_T$

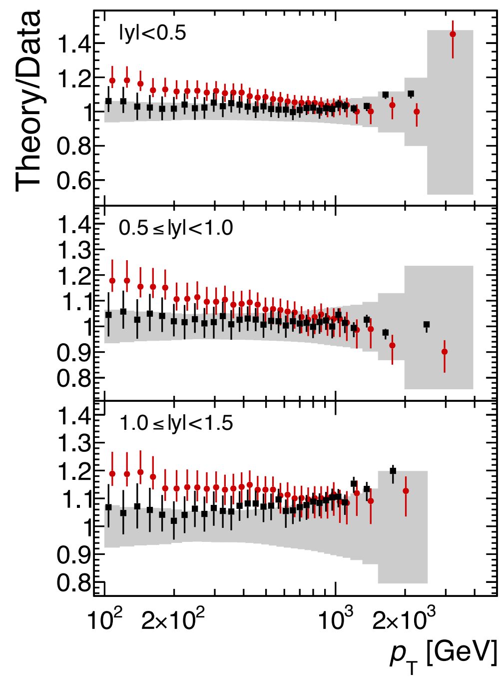
- Tentative recommendation
  - Use (jet-based) central scale $\mu = p_T$ in NNLO predictions for single jet inclusive p_T distributions

Comparison with LHC data

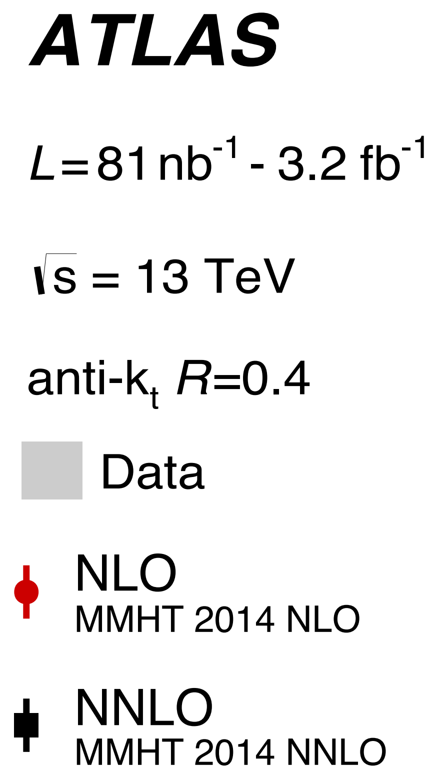
- Conclusions in agreement with recent measurements



p_{T1}



p_T



NNLO Theory: from NNLOJET

[arXiv:1711.02692]

Conclusions

- NNLO corrections to LHC jet production sizeable
- Perturbative convergence and impact of scale choices
  - Di-jets
    - ❖ NNLO corrections largely remove scale ambiguities
    - ❖ $\mu=m_{jj}$: preferred choice (stability and convergence)
  - Single jet inclusive
    - ❖ jet-based versus event-based scales
    - ❖ scale ambiguities persist at NNLO
    - ❖ contribution from second jet perturbatively unstable
    - ❖ $\mu=p_T$: appears as best choice (convergence)

Outlook: Next steps

- Dissemination of NNLO results
  - Determination of (PDFs, α_s) require NNLO predictions to be computed multiple times (varying PDF sets, scales, etc.)
  - Repeated running of NNLO parton-level calculation is not realistically feasible
  - Grid generation using APPLfast-NNLO interface in progress (D. Britzger, C. Gwenlan, K. Rabbertz, M. Sutton)
    - ❖ First application: H1 determination of α_s from jet production in DIS (H1: arXiv:1709.07251)
- Precision phenomenology with NNLO jet observables is just starting