NNLO QCD predictions for single jet inclusive production at the LHC

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Based on work in [Phys. Rev. Lett. 118, 072002 (2017)] and new results

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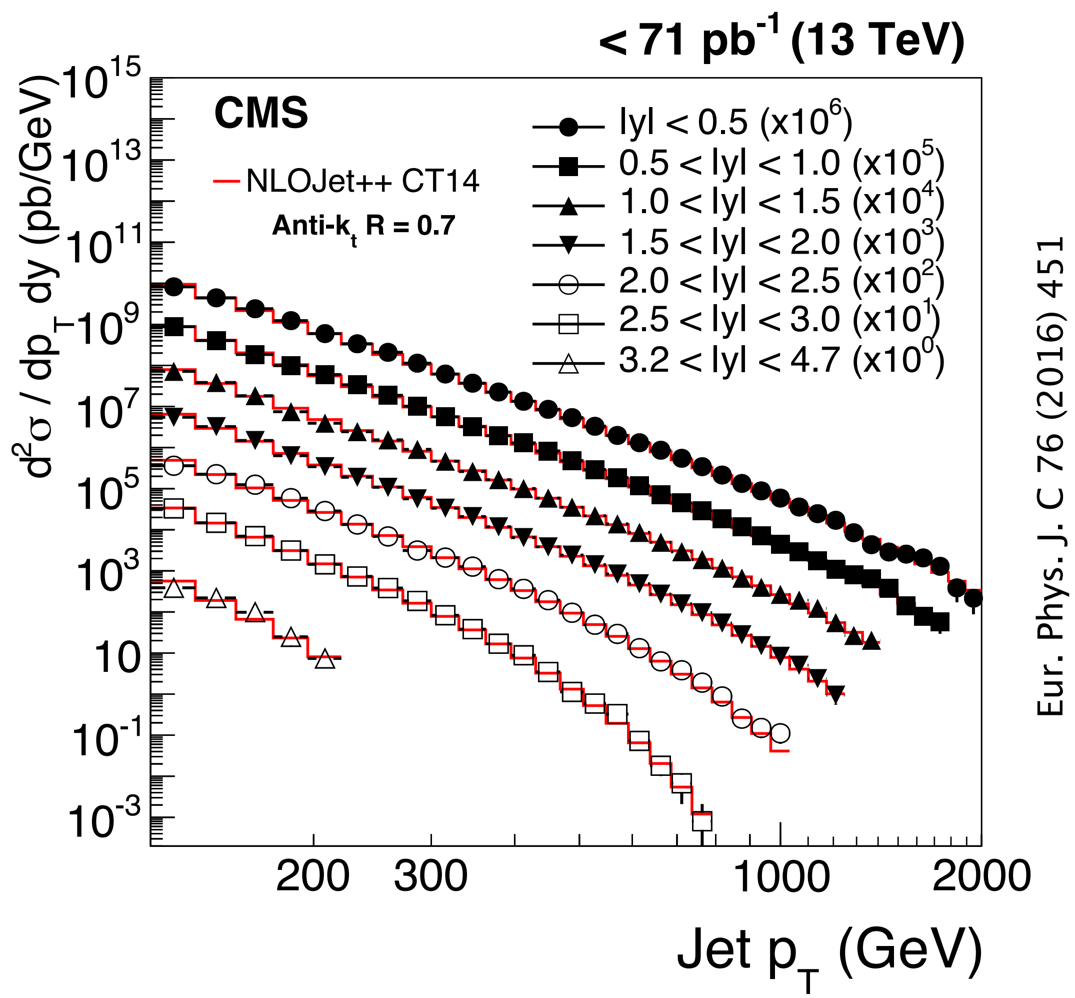
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

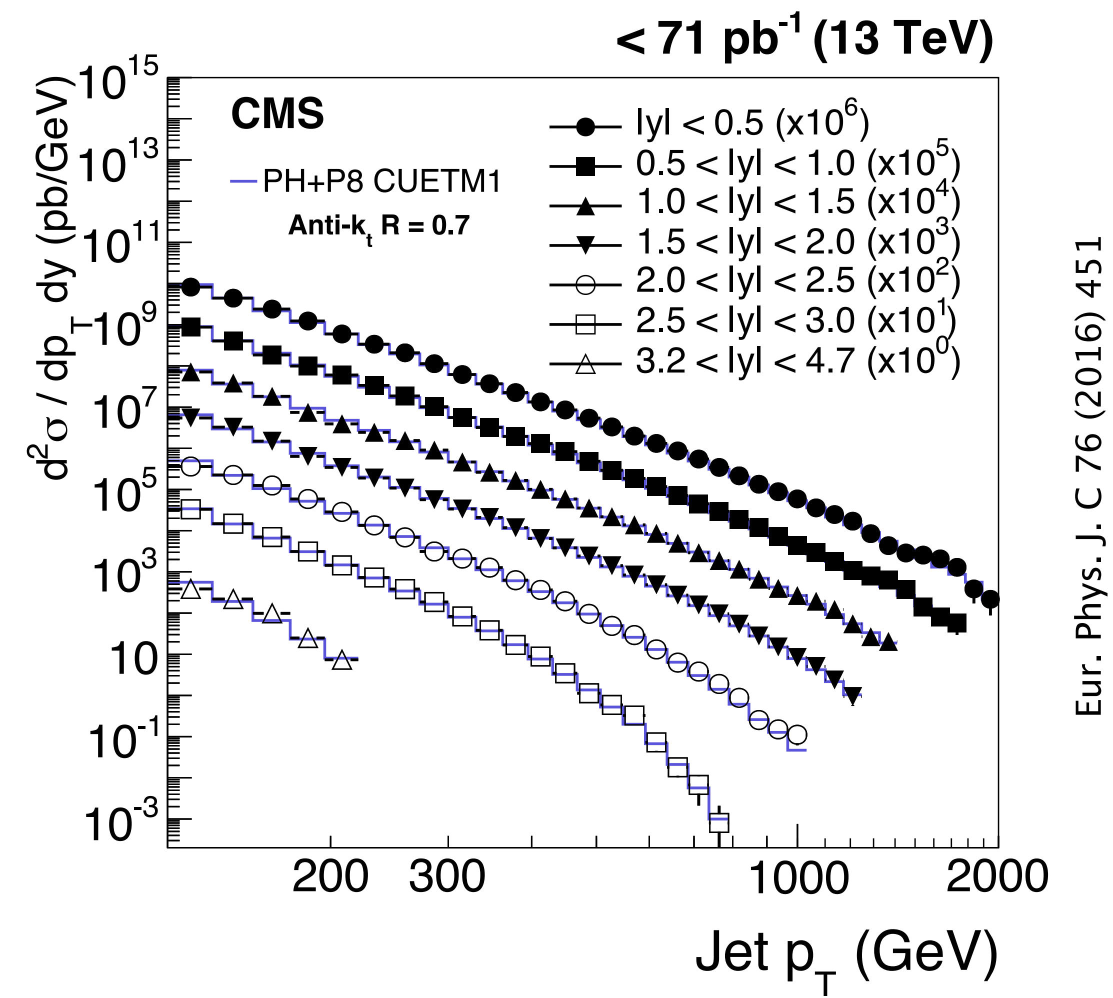
MAX-PLANCK-GESELLSCHAFT

Jets at the LHC

- look at production of jets of hadrons with large transverse energy
- for sufficiently high transverse momentum $p_T > 20$ GeV high rates and clean and simple cross section definition

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}}{\Delta p_T \Delta y}$$





Jets at the LHC

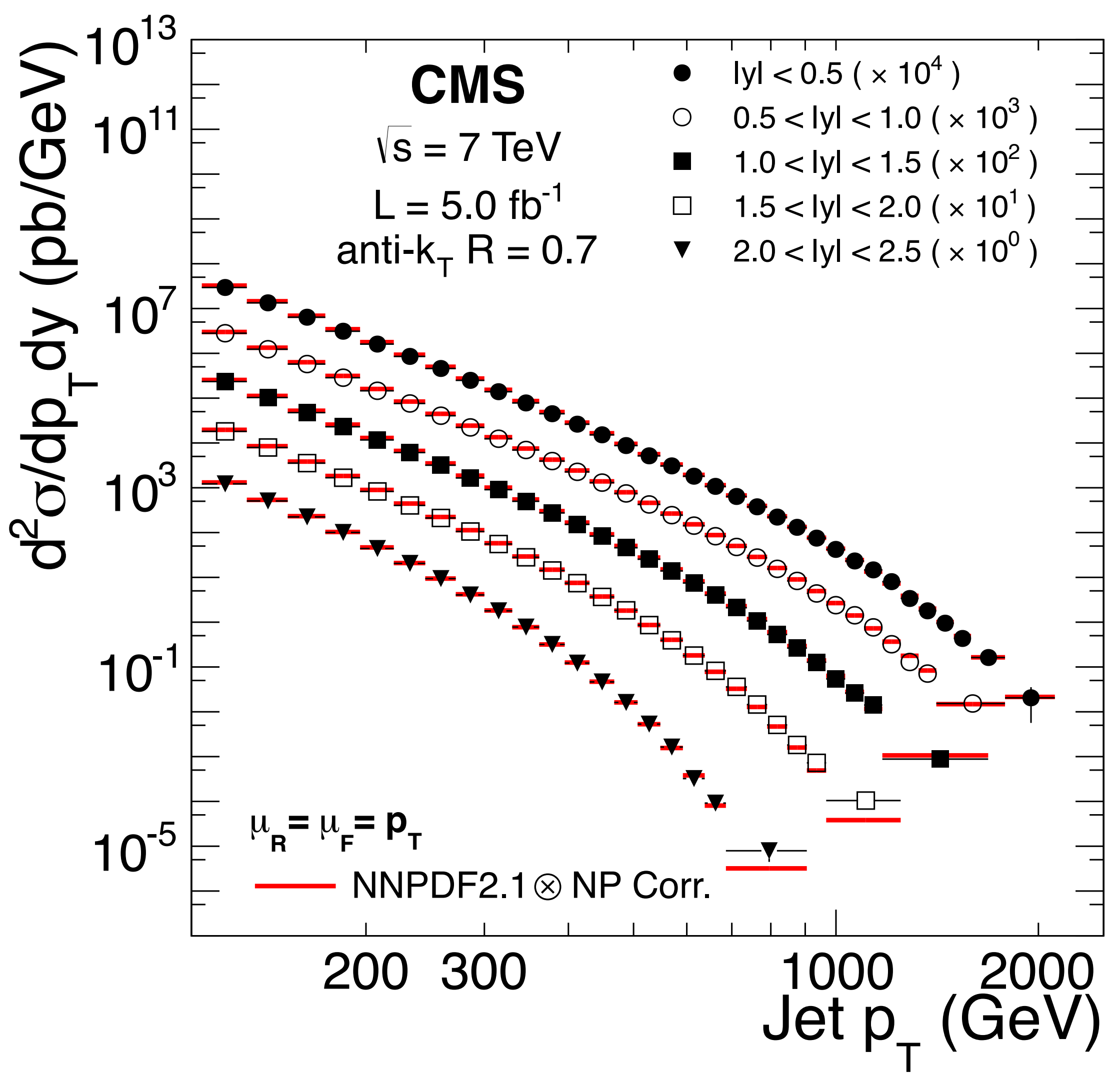
$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu^2), s/\mu^2, s/\mu_F^2)$$

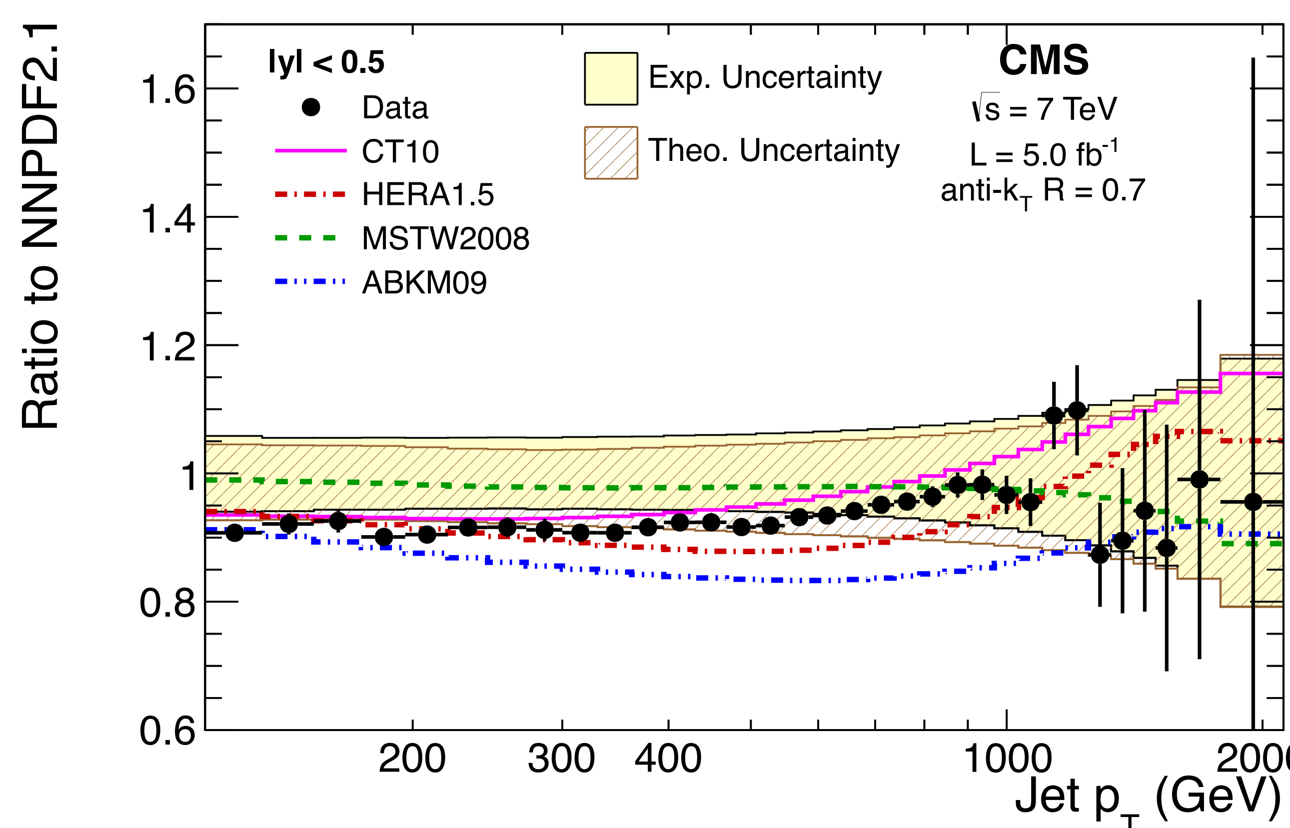
- Inputs from physical parameters
  - PDF's ; strong coupling
- Unphysical inputs
  - renormalization and factorization scales
- Partonic cross section calculable in perturbation theory

$$\hat{\sigma}_{ij} = \hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s}{2\pi}\right) \hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3)$$

Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
  - Rigorous tests of pQCD dynamics across a huge range of kinematics
  - Constrain PDF’s



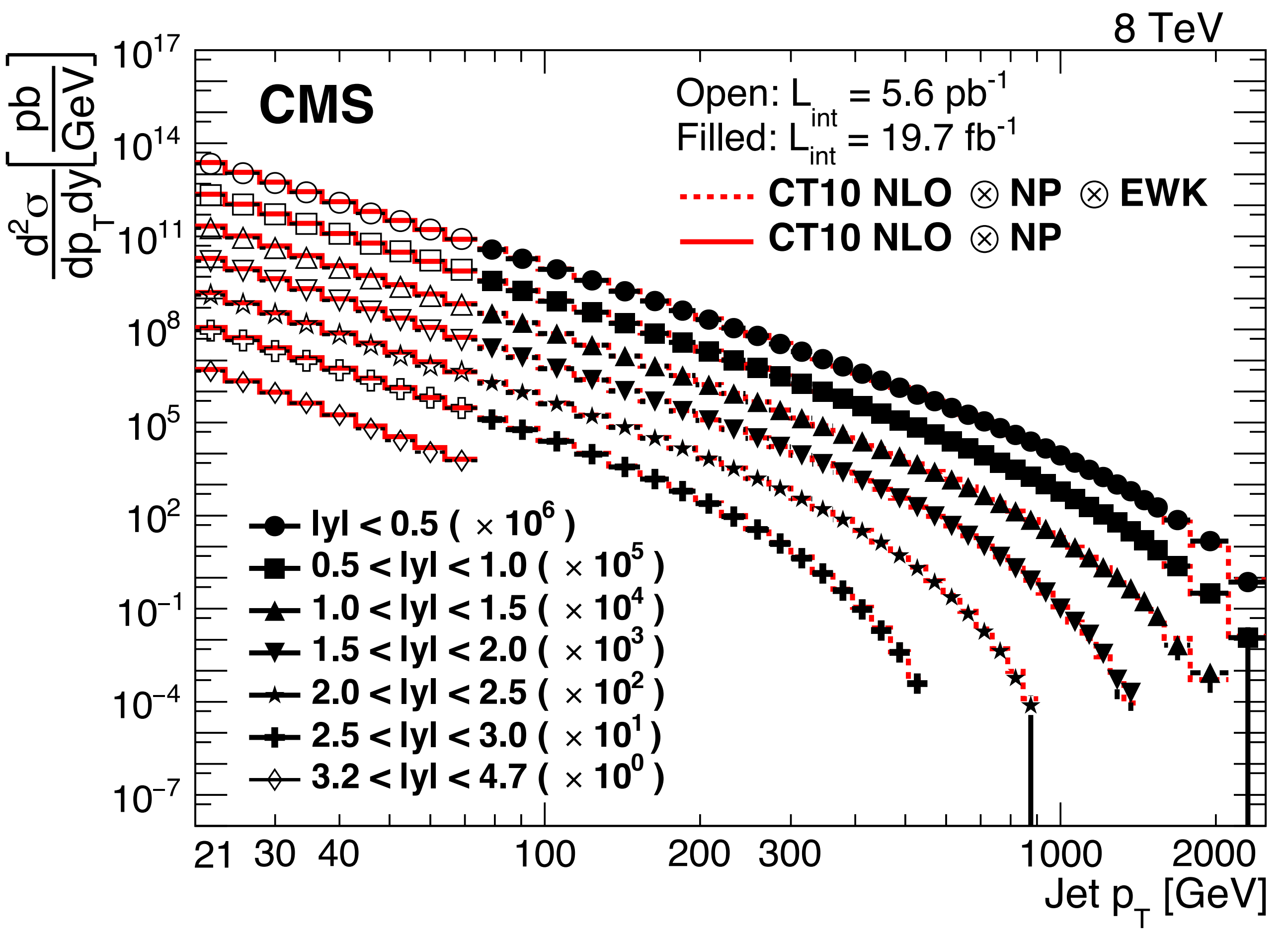


(NLO theory input)

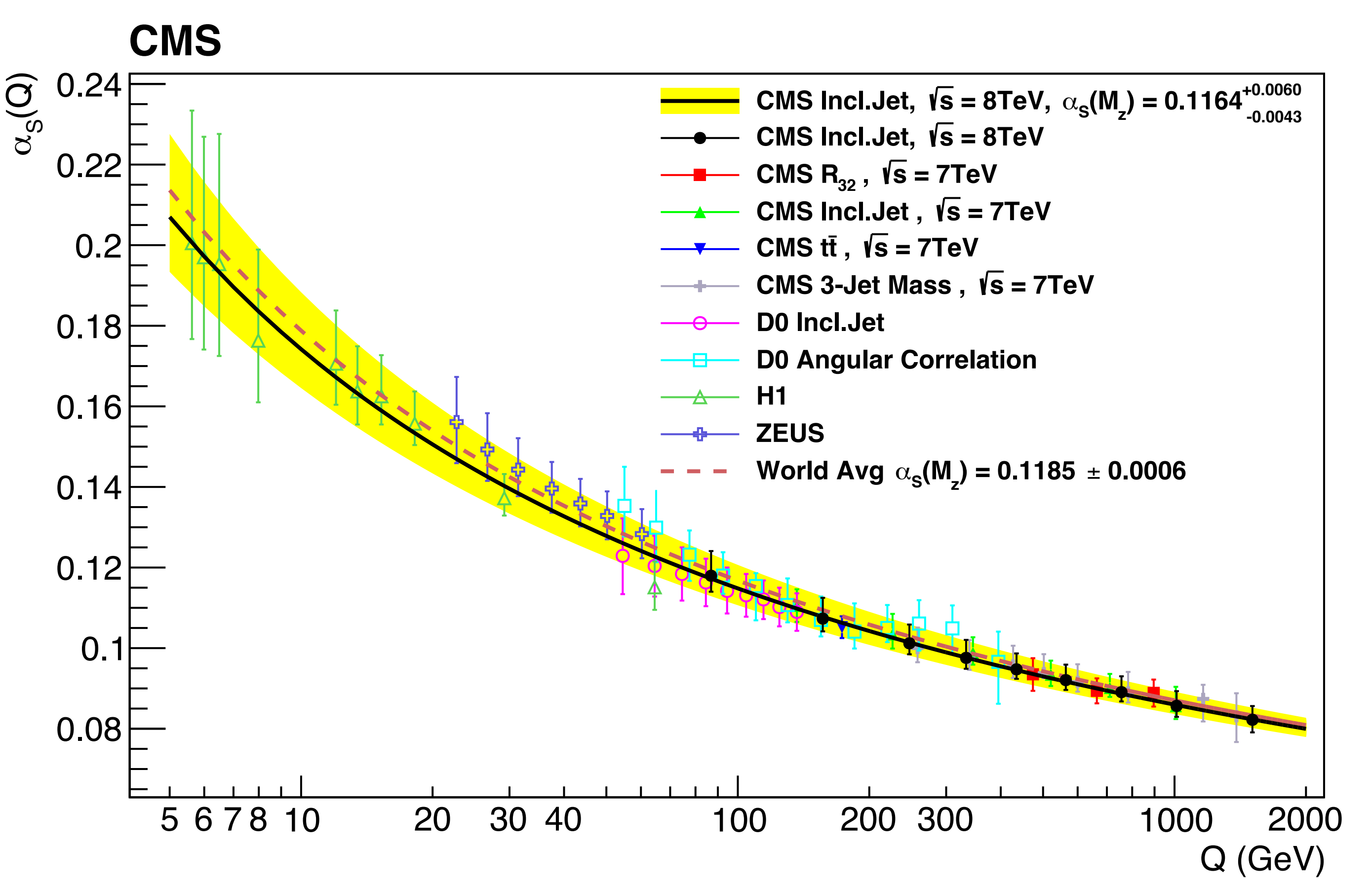
Phys. Rev. D 87 (2013) 112002

Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
  - Rigorous tests of pQCD dynamics across a huge range of kinematics
  - Constrain PDF's
  - Determine $\alpha_s(M_Z)$ and running coupling from a single experiment



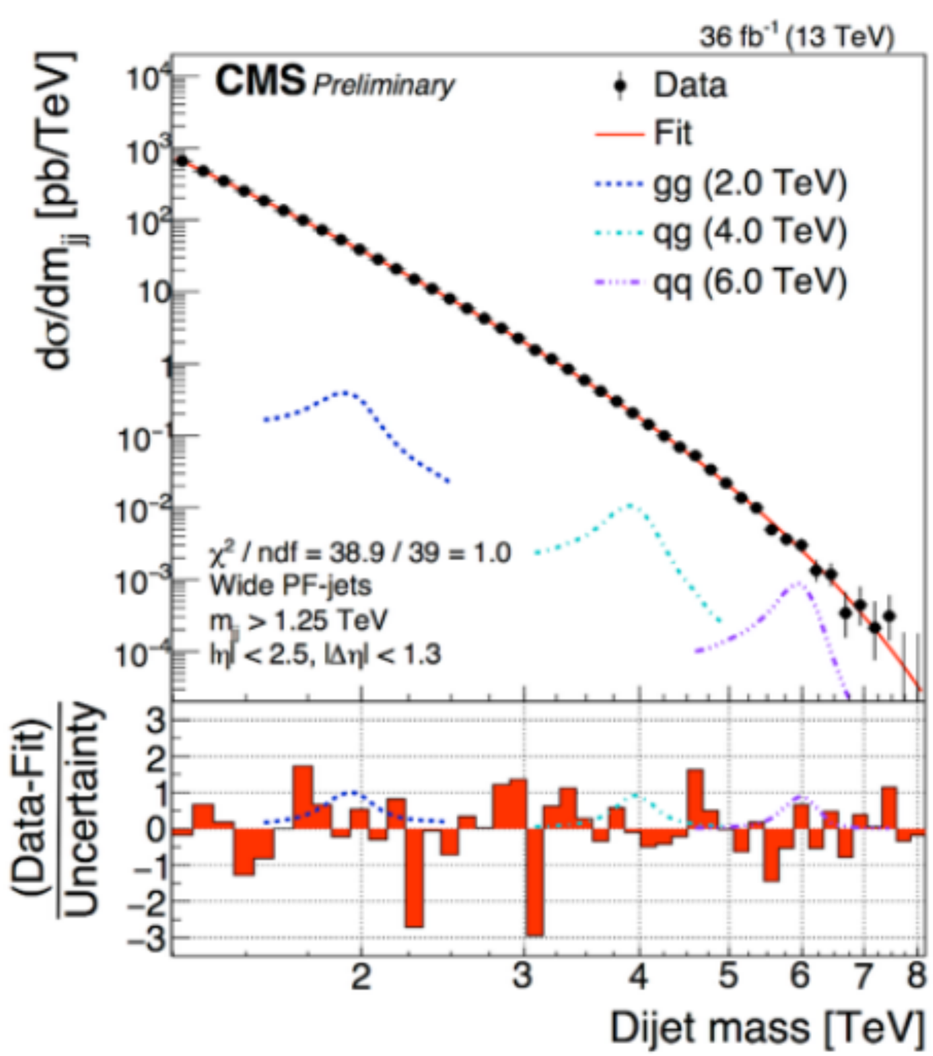
CMS-SMP-14-001



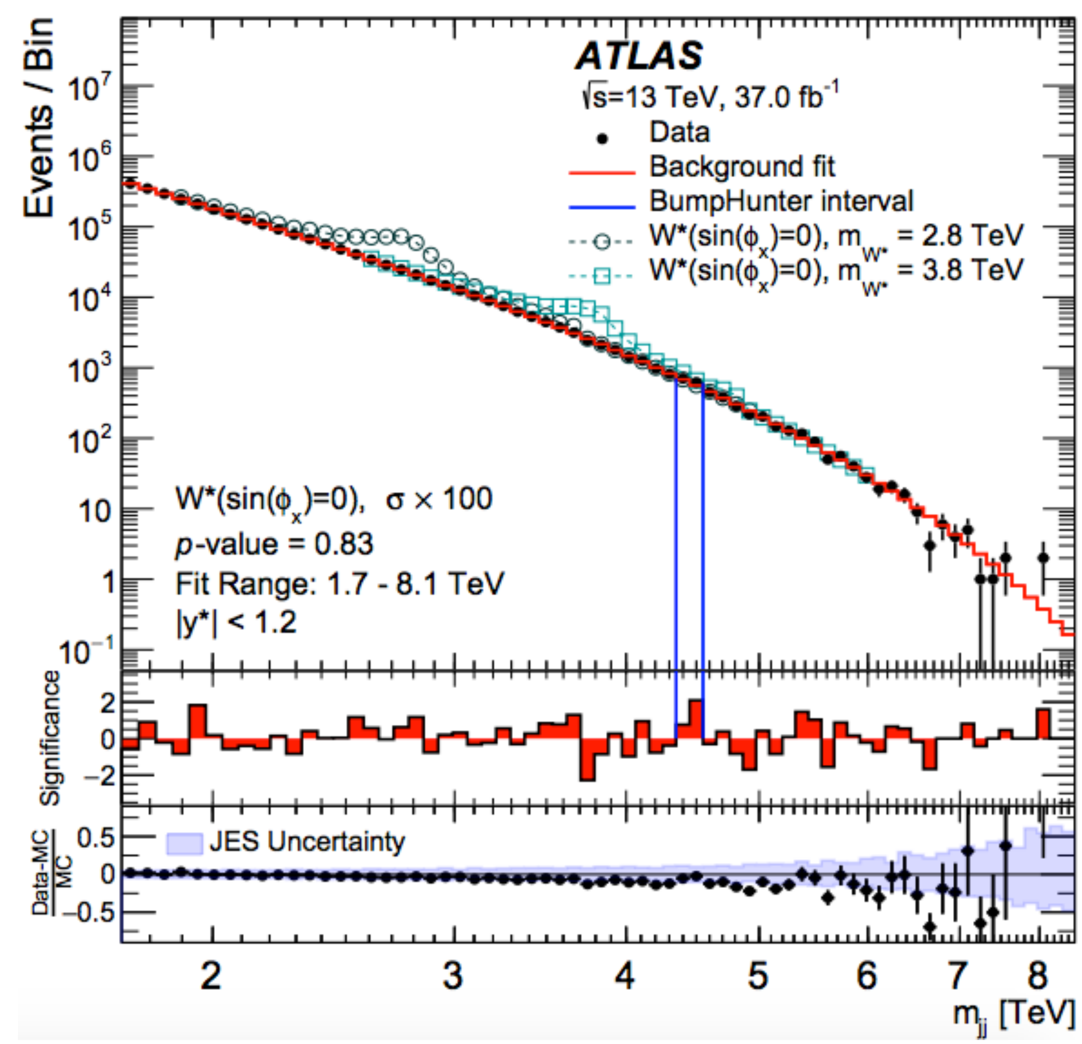
(NLO theory input)

Jets at the LHC

- Percent level experimental accuracy in jet production is a reality at the LHC
  - Rigorous tests of pQCD dynamics across a huge range of kinematics
  - Constrain PDF’s
  - Background to high mass resonances decaying to dijet final states



arXiv:1703.09127



Theory state of the art

- NLO QCD [Ellis, Kunszt, Soper ’92] [Giele, Glover, Kosower ’94] [Nagy 02]
- NLO QCD + PS (POWHEG) [Alioli, Hamilton, Nason, Oleari, Re ’11]
- NLO EW [Dittmaier, Huss, Speckner ’13] [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro ’16]
- NNLO QCD [Gehrmann-De Ridder, Gehrmann, Glover, JP ’13] [Currie, Gehrmann-De Ridder, Glover, JP ’13] [Currie, Glover, JP ’16]

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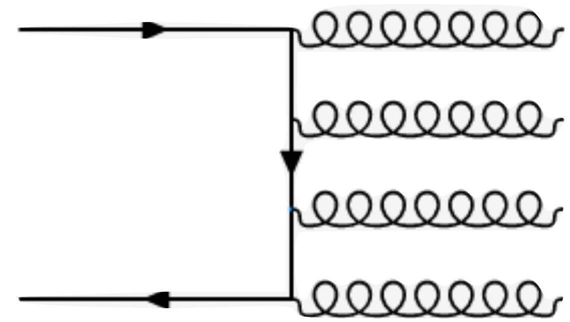
New approach to look at jet data at the LHC (this talk)

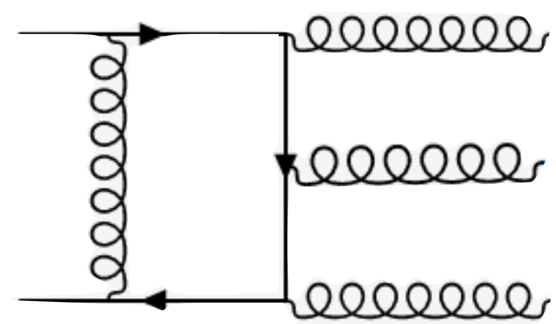
Anatomy of an NNLO calculation

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \mathrm{d}\hat{\sigma}^{RR}_{NNLO}$$



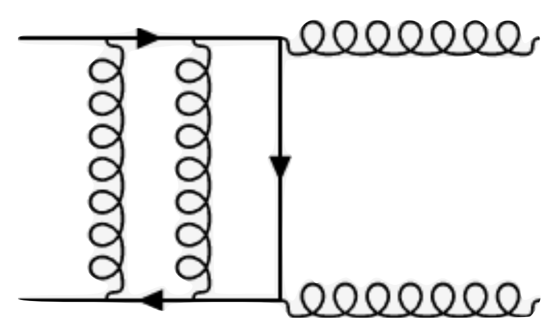
- double-unresolved
- single-unresolved

$$+ \int_{\mathrm{d}\Phi_3} \mathrm{d}\hat{\sigma}^{RV}_{NNLO}$$



- single-unresolved
- $1/\varepsilon^2$; $1/\varepsilon$

$$+ \int_{\mathrm{d}\Phi_2} \mathrm{d}\hat{\sigma}^{VV}_{NNLO}$$



- $1/\varepsilon^4$; $1/\varepsilon^3$; $1/\varepsilon^2$; $1/\varepsilon$;

- 6 parton tree level [Berends, Giele ’87] [Mangano, Parke, Xu ’87] [Britto, Cachazo, Feng ’06]
- 5 parton one-loop [Bern, Dixon, Kosower ’93]
- 4 parton two-loop [Anastasiou, Glover, Oleari, Tejeda-Yeomans ’01][Bern,De Freitas Dixon ‘02]
- non-trivial cancellation of infrared singularities at NNLO

NNLO antenna subtraction

$$\mathrm{d}\hat{\sigma}_{NNLO} = \int_{\mathrm{d}\Phi_4} \left(\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO}\right) + \int_{\mathrm{d}\Phi_3} \left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right) + \int_{\mathrm{d}\Phi_2} \left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} - \mathrm{d}\hat{\sigma}^{U}_{NNLO}\right)$$

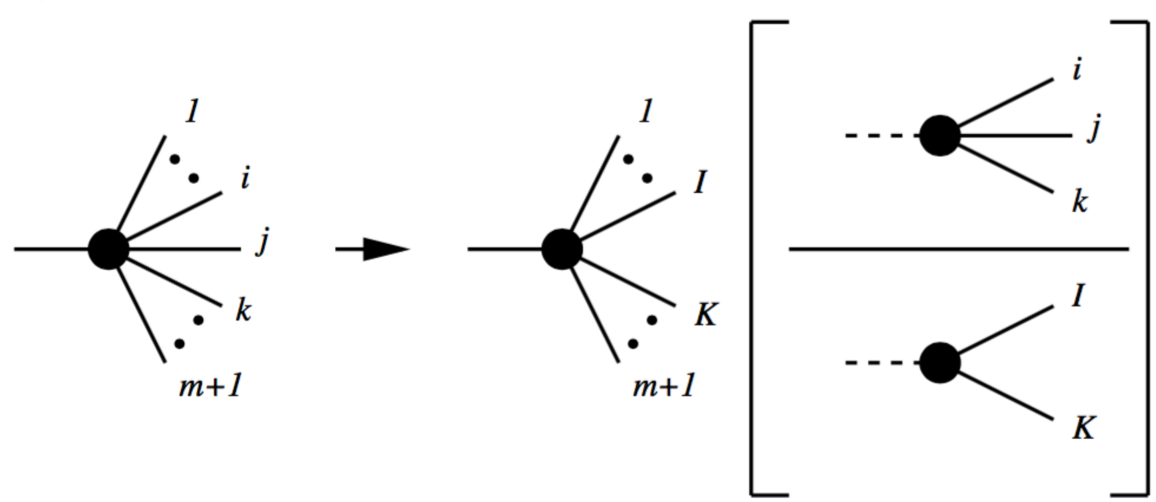
$\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ $\mathrm{d}\hat{\sigma}^{T}_{NNLO}$

- mimic RR,RV in unresolved limits

$\mathrm{d}\hat{\sigma}^{T}_{NNLO}$ $\mathrm{d}\hat{\sigma}^{U}_{NNLO}$

- analytically cancel the poles in RV and VV matrix elements

- universal factorization properties in IR limits



- phase space factorization

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

NNLO antenna subtraction

$$
\begin{aligned}
d\hat{\sigma}_{NNLO} &= \int_{d\Phi_4} \left(d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO} \right) \\
&+ \int_{d\Phi_3} \left(d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO} \right) \\
&+ \int_{d\Phi_2} \left(d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO} \right)
\end{aligned}
$$

$d\hat{\sigma}^{S}_{NNLO}$ $d\hat{\sigma}^{T}_{NNLO}$

- mimic RR,RV in unresolved limits

$d\hat{\sigma}^{T}_{NNLO}$ $d\hat{\sigma}^{U}_{NNLO}$

- analytically cancel the poles in RV and VV matrix elements

For pp->jet +X

- all subprocesses included through leading colour $\alpha_s^2 N^2, \alpha_s^2 N N_F, \alpha_s^2 N_F^2$

$$\{gg, qg, q\bar{q}, qq, qq^{'}, q\bar{q}^{'}\}$$

- subleading colour contributions to the NNLO coefficient neglected

NNLOJET parton level generator

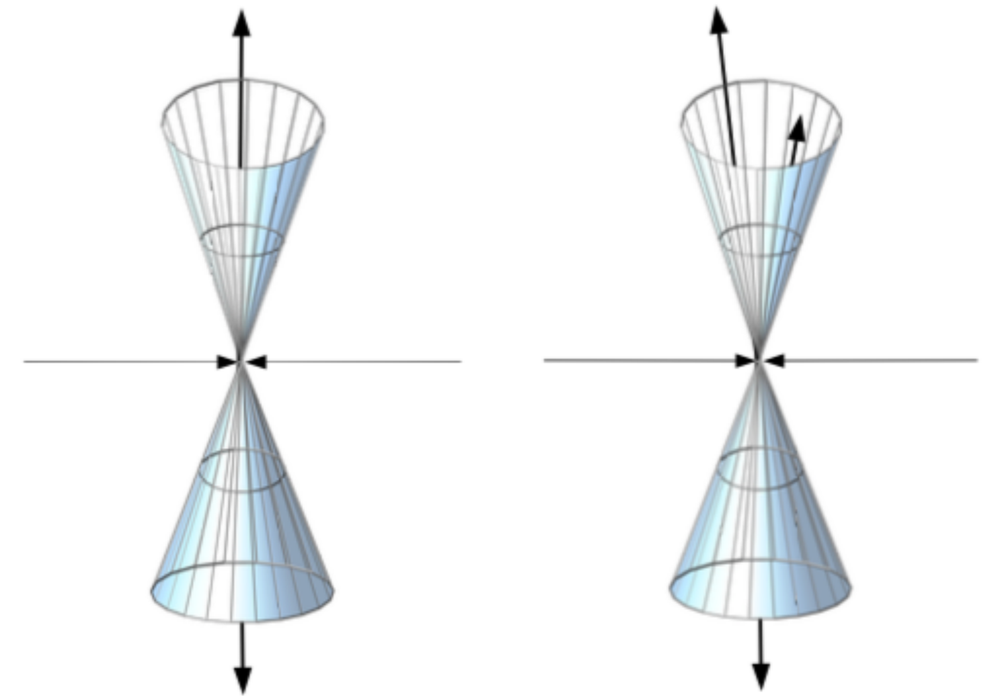
[X. Chen, J. Cruz-Martinez, J.Currie, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, M.Jaquier, T.Morgan, J. Niehues, JP]

- parton level generator based on antenna subtraction to compute fully differential cross sections at NNLO in QCD
  - pp -> H+jet
  - pp -> Z+jet
  - pp -> 2 jets
  - pp->H,W,Z
  - ep-> 2 jets → Jan Niehues talk
- interface to applfast nnlo tables → Daniel Britzger's talk

Single jet inclusive scale choice

two widely used scale choices:

- $\mu_R = \mu_F = \{p_{T1}, p_T\}$
    - leading jet p_T in the event p_{T1}
    - individual jet p_T
- high p_T jets are back to back ⇒ $p_T \longrightarrow p_{T1}$

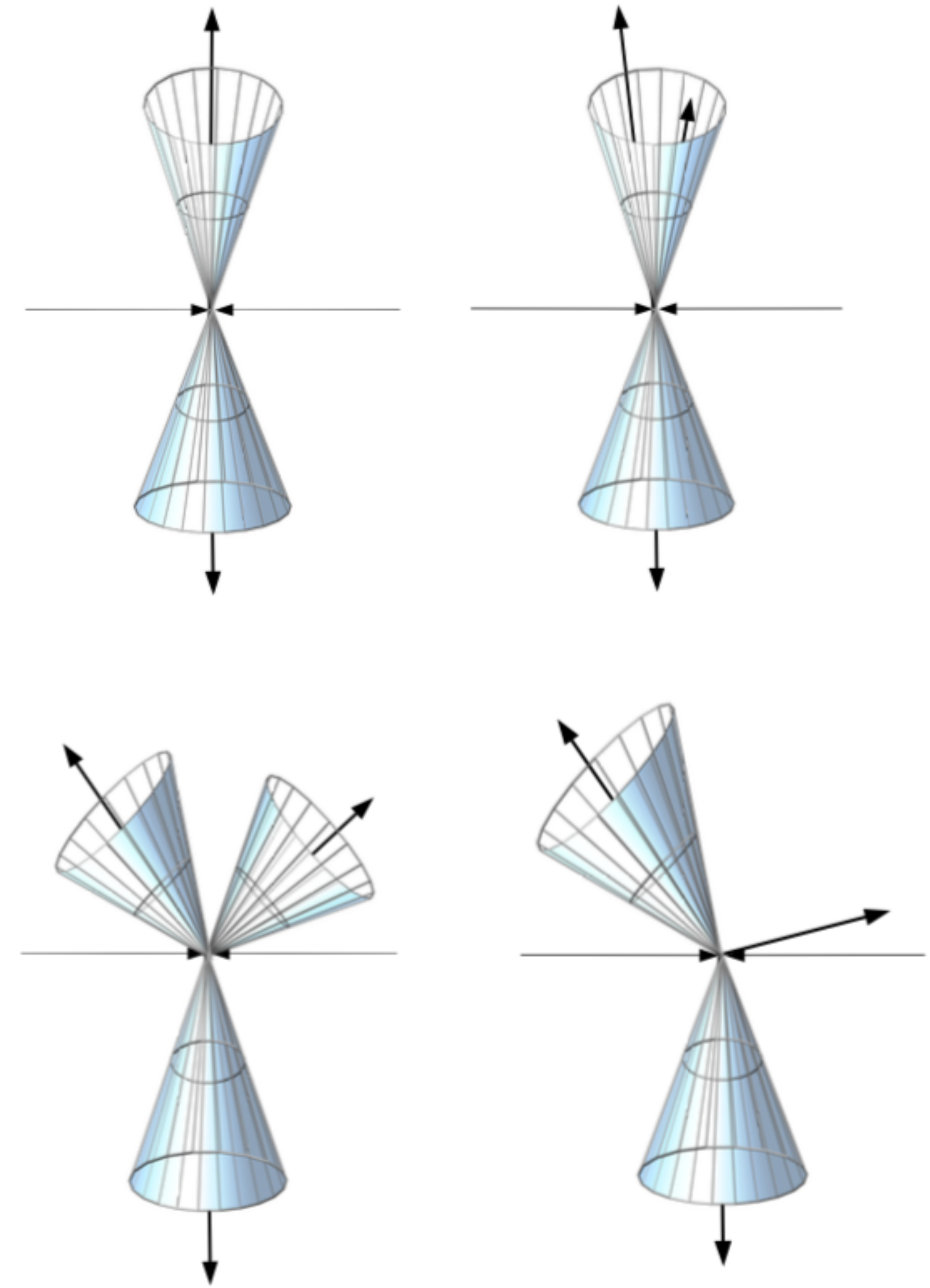


Single jet inclusive scale choice

two widely used scale choices:

- $\mu_R=\mu_F=\{p_{T1}, p_T\}$
    - leading jet p_T in the event p_{T1}
    - individual jet p_T
- high p_T jets are back to back ⇒ p_T —> p_{T1}
- $p_T!=p_{T1}$ for:
    - 3jet events
    - 3rd jet outside fiducial jet cuts

  ⇒ with p_T choice the real emission event with different R gives rise to a different scale ⇒ larger R ⇒ harder scale ⇒ p_T —> p_{T1}
- at NLO the p_{T1} scale choice generates the same hard scale for the event independent of the value of R



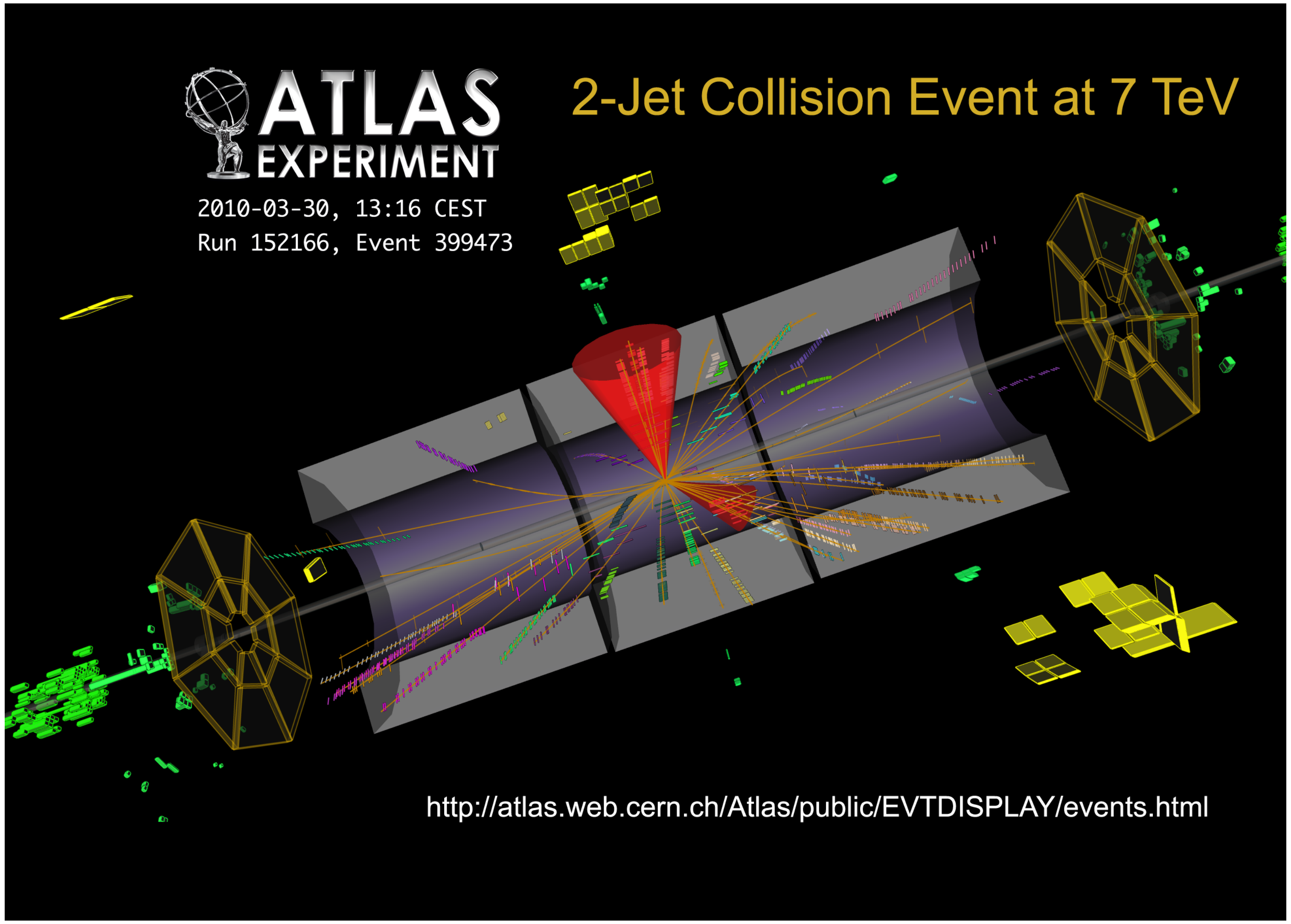
ATLAS jets

Theory setup

- NNPDF3.0_nnlo
- anti-k_T jet algorithm
- $\mu_R=\mu_F=\{p_{T1}, p_T\}$
- vary scales by factors of 2 and 1/2

Comparison to data

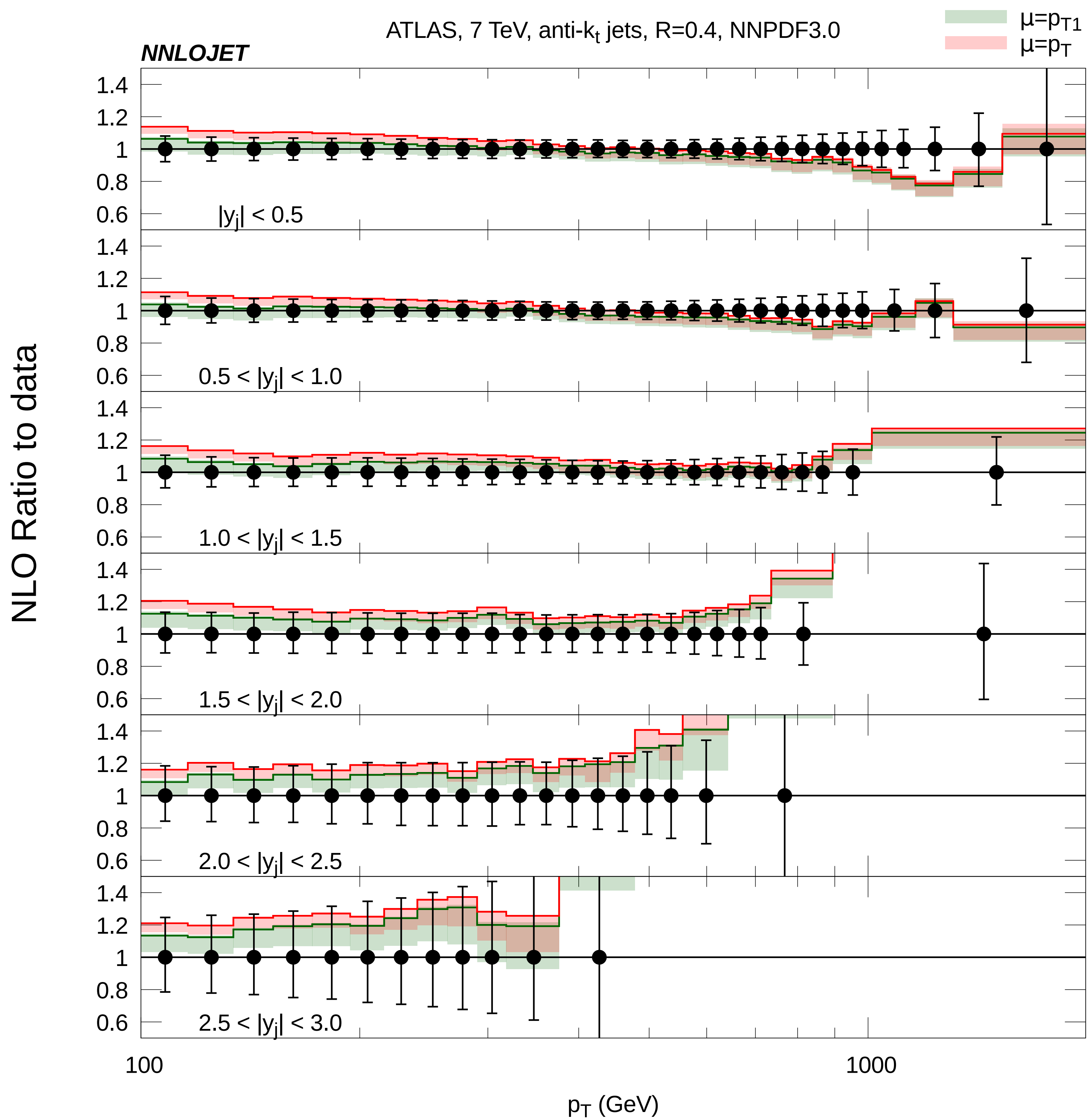
- ATLAS 7 TeV 4.5 fb^{-1}
- R=0.4



[Currie, Gehrmann, Glover, Huss, JP (in preparation)]

Ratio to NLO

- asymmetric scale band variation
- underestimated at small pT due to turn over of the NLO coefficient
- 20% uncertainty for central high pT jets rising to 40% for forward jets



Comparison to data

- non perturbative effects < 2% effect [JHEP 1509, 141 (2015)]
- data favours the pT1 scale choice at NLO

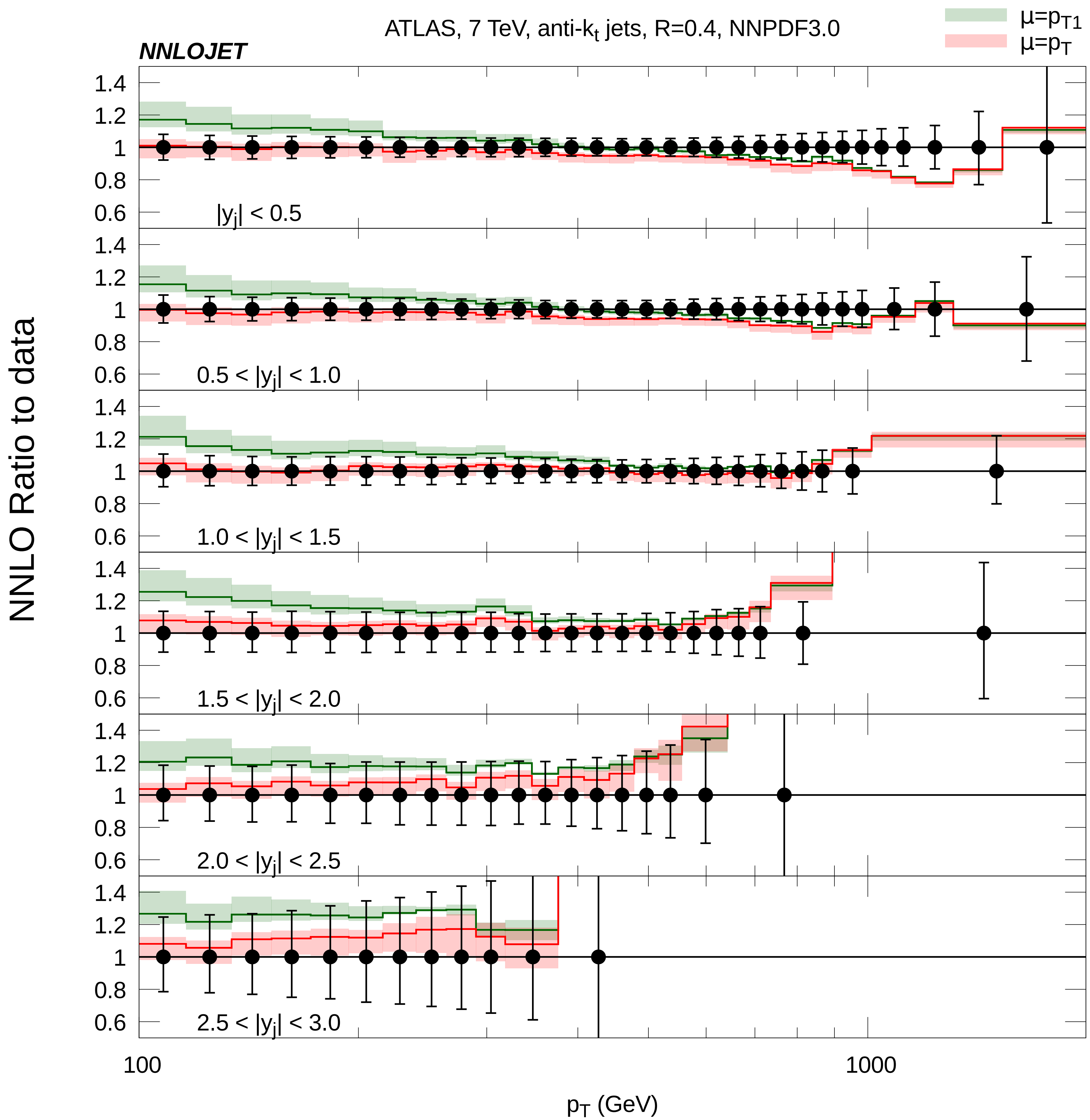
[Currie, Gehrmann, Glover, Huss, JP (in preparation)]

Ratio to NNLO

- symmetric scale band variation
- pT1!=pT effects enlarged at NNLO
- 10% scale uncertainty at low pT and percent level scale uncertainty at high pT

Comparison to data

- data favours the pT scale choice at NNLO
- NLO EW effects around 15% for central high pT jets



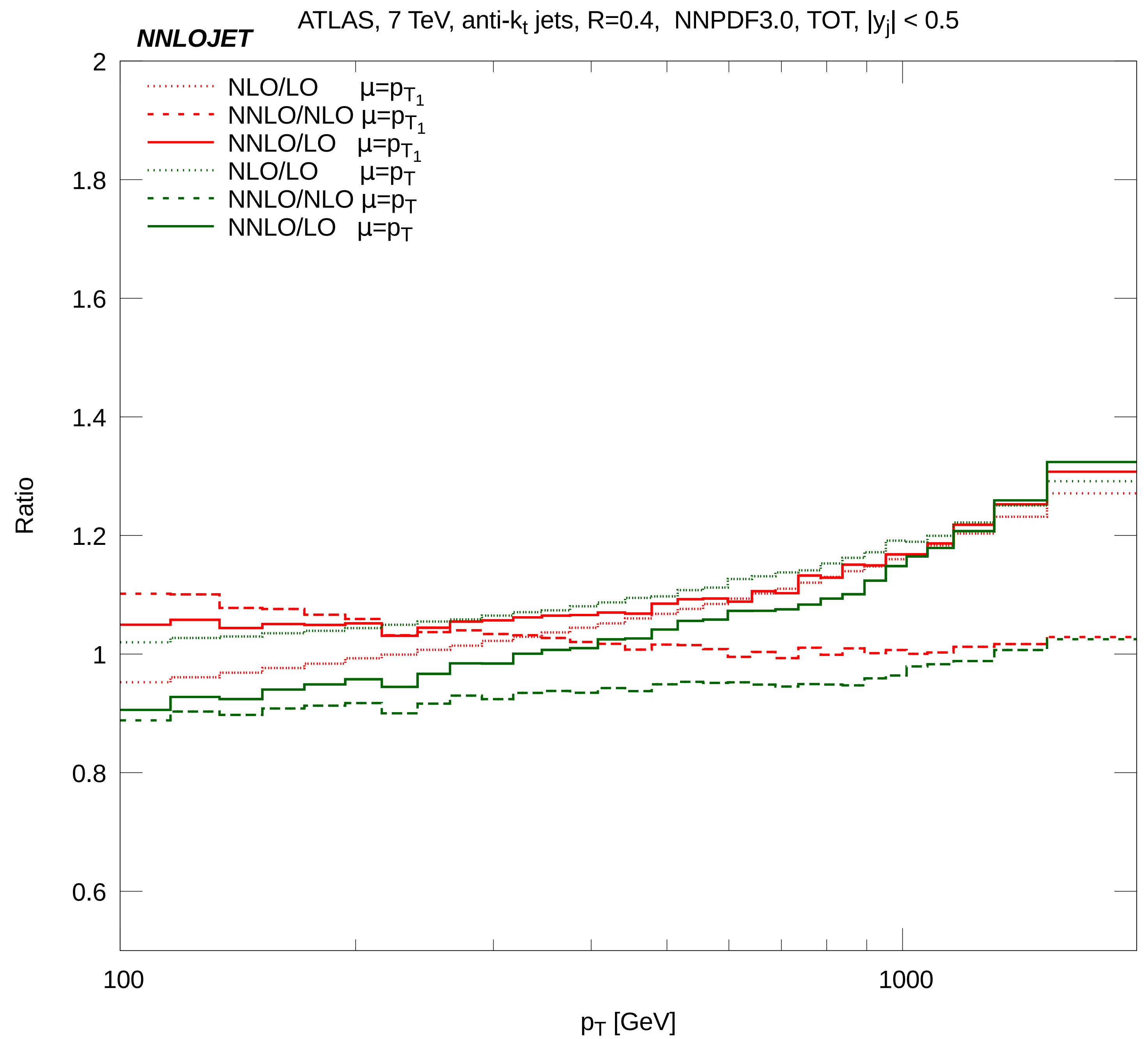
[Currie, Gehrmann, Glover, Huss, JP (in preparation)]

K-factor plot

- pT1!=pT effects enlarged at NNLO at low pT
  - decrease for larger R values

Sensible criteria for scale choice for single jet inclusive production

- perturbative stability
- data driven scale choice



Future steps

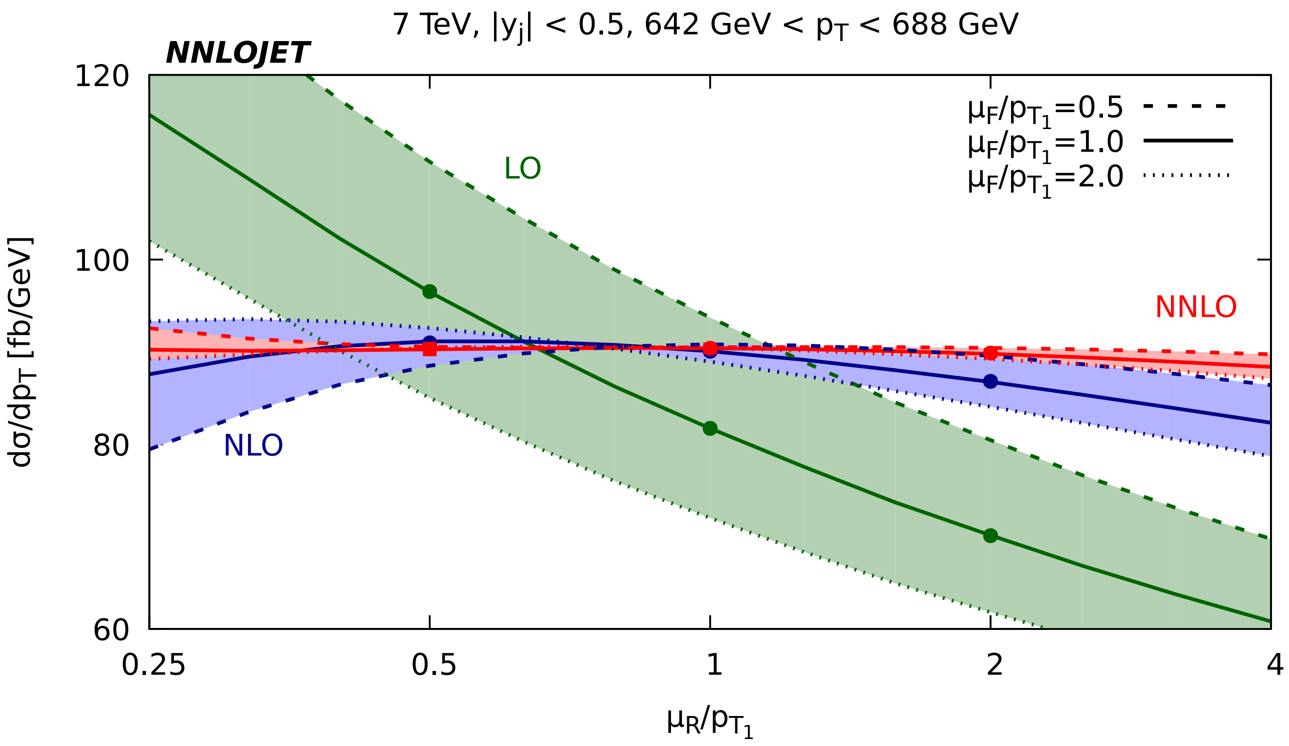
- compare with CMS jet data; change R value ; change $\sqrt{s}$

- Obtain consistent description of jet data at NNLO for all jet data sets at low and high pT in the central and forward regions for multiple R values

Summary

- Presented a new approach to look at jet data at the LHC with NNLO QCD using antenna subtraction implemented in a new parton level generator NNLOJET

- Percent level experimental accuracy in jet production is a reality at the LHC



- Percent level theory scale uncertainty for high pT jet production at NNLO below PDF and $\alpha_s(M_Z)$ uncertainties on the cross section

- Observed significant ambiguity at small pT due to scale choice (underestimated at NLO) which requires further phenomenological studies

- In future: 8 TeV, 13 TeV, CDF data, different PDFs etc… gateway to NNLO jet phenomenology