NNLO predictions for jets and V+jet at the LHC

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Kobe, Japan
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work with J. Currie, R. Gauld, A. Gehrmann–De Ridder, T. Gehrmann, E.W.N. Glover, T.A. Morgan, J. Pires, and D.M. Walker

Outline

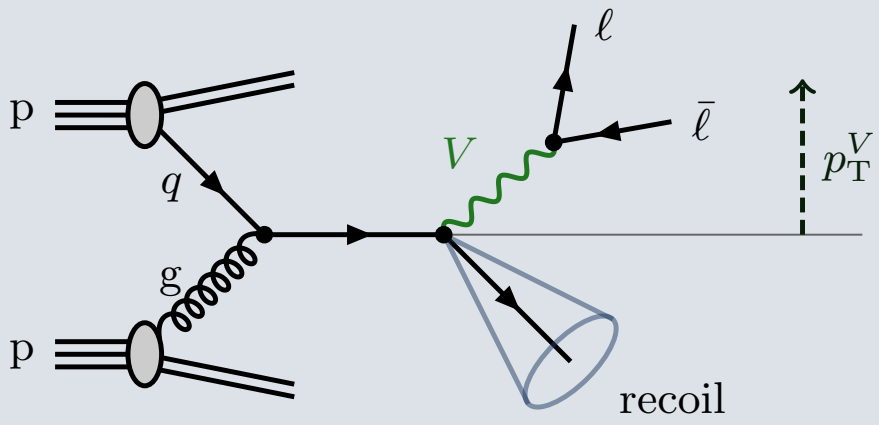
Part 1. **V+jet Production & Related Observables**

- ↪ The transverse momentum spectrum of gauge bosons
- ↪ Angular coefficients in $Z \to \ell^- \ell^+$ production

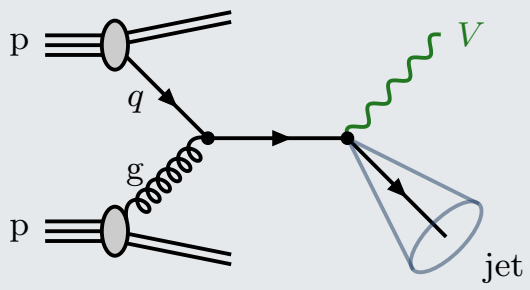
Part 2. **Jet Production at the LHC**

- ↪ Inclusive Jet Production
- ↪ Dijet Production

V+jet Production & Related Observables



Why $V + \text{jet}$ production?



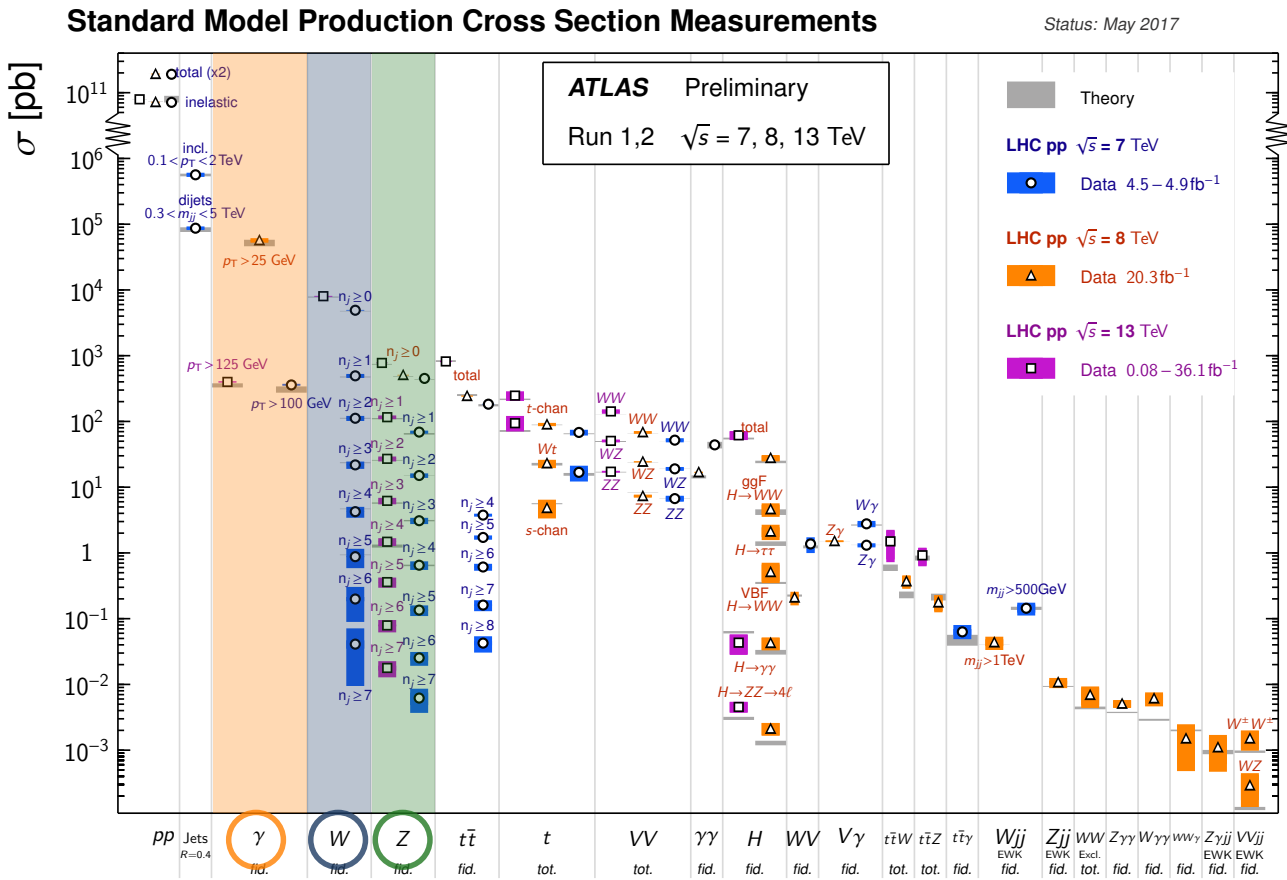
$$\mathrm{p\,p} \to V + \text{jet} \quad \begin{cases} V = \gamma \\ V = \mathrm{W} & \to \ell + \nu \\ V = \mathrm{Z}/\gamma^* & \to \ell + \bar{\ell} \end{cases}$$

- large cross section & clean signature

$+\textbf{jet} \rightsquigarrow$ sensitivity to α_s & gluon PDF

- precision measurements
  ↪ test pQCD
  ↪ constrain PDFs (gluon)
- detector calibration
  ↪ jet energy scale
- search for BSM physics

high-precision predictions mandatory!



Where do we stand?

Theory status — $V + \mathrm{jet}$ production (not exhaustive)

- **NLO QCD**

  Z & W ..... [Giele, Glover, Kosower '93]

  + threshold logs ..... [Becher, Lorentzen, Schwartz '12]

  γ ..... [Baer, Ohnemus, Owens '90] [Gordon, Vogelsang '94] [Catani, Fontannaz, Guillet, Pilon '02]

- **NLO EW**

  Z ..... [Kühn, Kulesza, Pozzorini, Schulze '05] [Denner, Dittmaier, Kasprzik, Mück '11]

  W ..... [Kühn, Kulesza, Pozzorini, Schulze '07] [Denner, Dittmaier, Kasprzik, Mück '09]

  V (Sudakov logs) ..... [Becher, Tormo '13, '15]

- **NLO QCD+EW** (+multijet merging) ..... [Kallweit, Lindert, Maierhofer, Pozzorini, Schönherr '15]

- **NNLO QCD** (this talk)

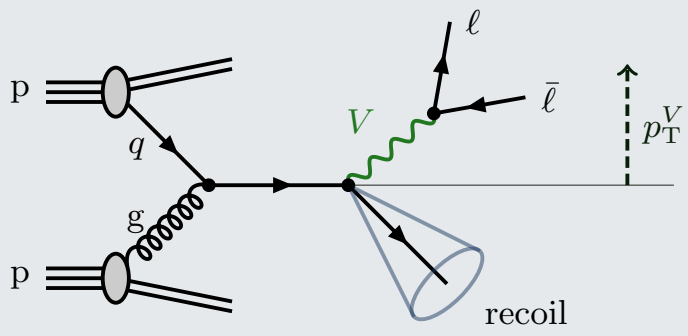
  Z ..... [Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15]
  [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]

  W ..... [Boughezal, Liu, Petriello '16]
  [Gehrmann-De Ridder, Gehrmann, Glover, AH, Walker '17]

  γ ..... [Campbell, Ellis, Williams '16]

$\rightsquigarrow$ all $V + \mathrm{jet}$ processes now known to **NNLO QCD**!

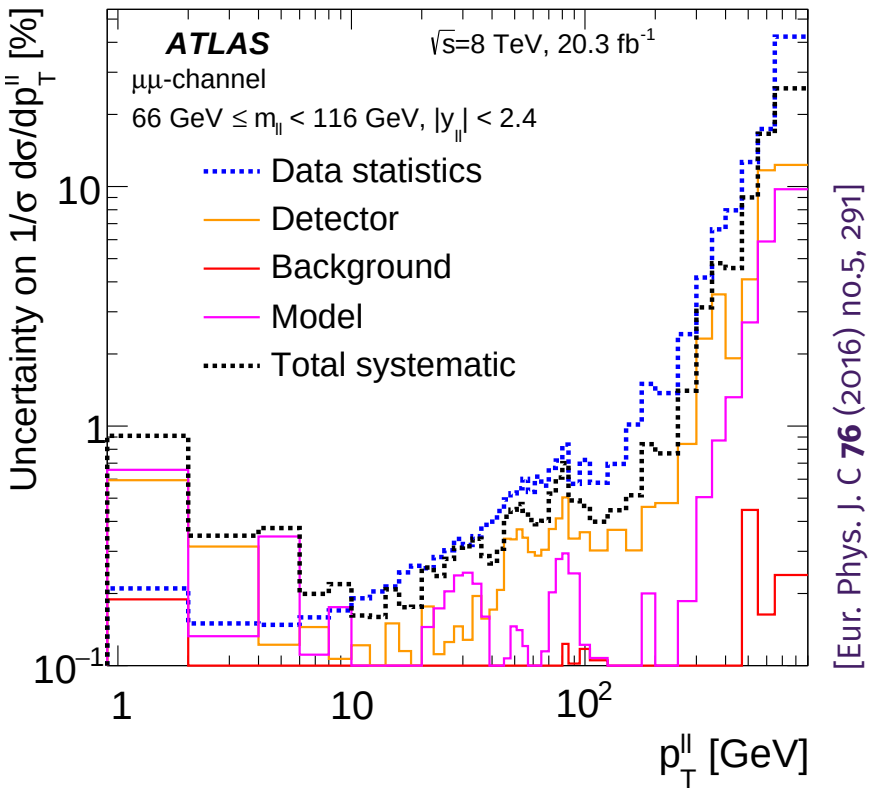
p_{T}^{V} — Towards precision phenomenology



$$\mathrm{p\,p} \to V + X \to \ell\,\bar{\ell} + X$$

- large cross section
- clean leptonic signature

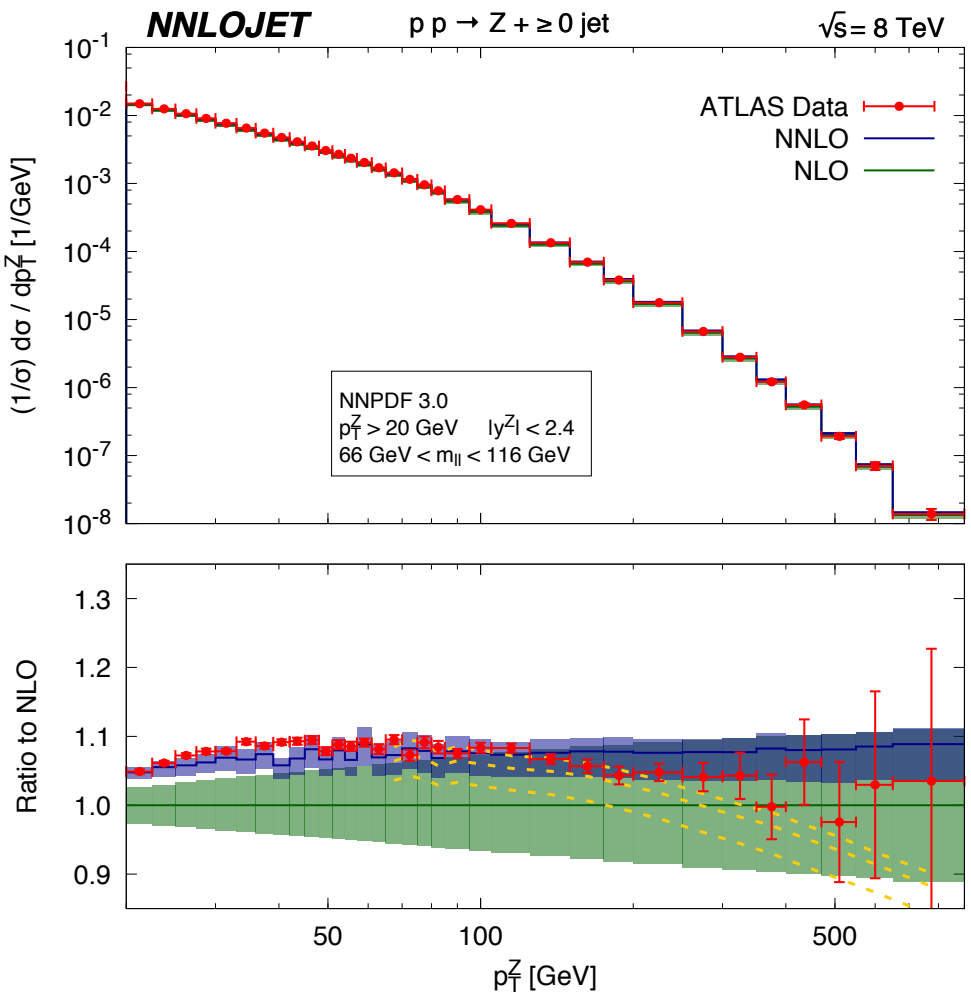
recoil ⇝ sensitivity to α_{s}, gluon PDF



- fully inclusive w.r.t. QCD radiation
- only reconstruct leptons
  ⇝ sub-% accuracy! (forZ)
- probes various aspects of theory predictions
- ratios: $(\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{V})/(\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{V'})$

FEWZ, DYNNLO } Only NLO accurate in this distribution

Inclusive p_{T} spectrum of Z/γ^*



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Morgan '16]

$$\frac{1}{\sigma} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

NLO

undershoots data by 5–10%

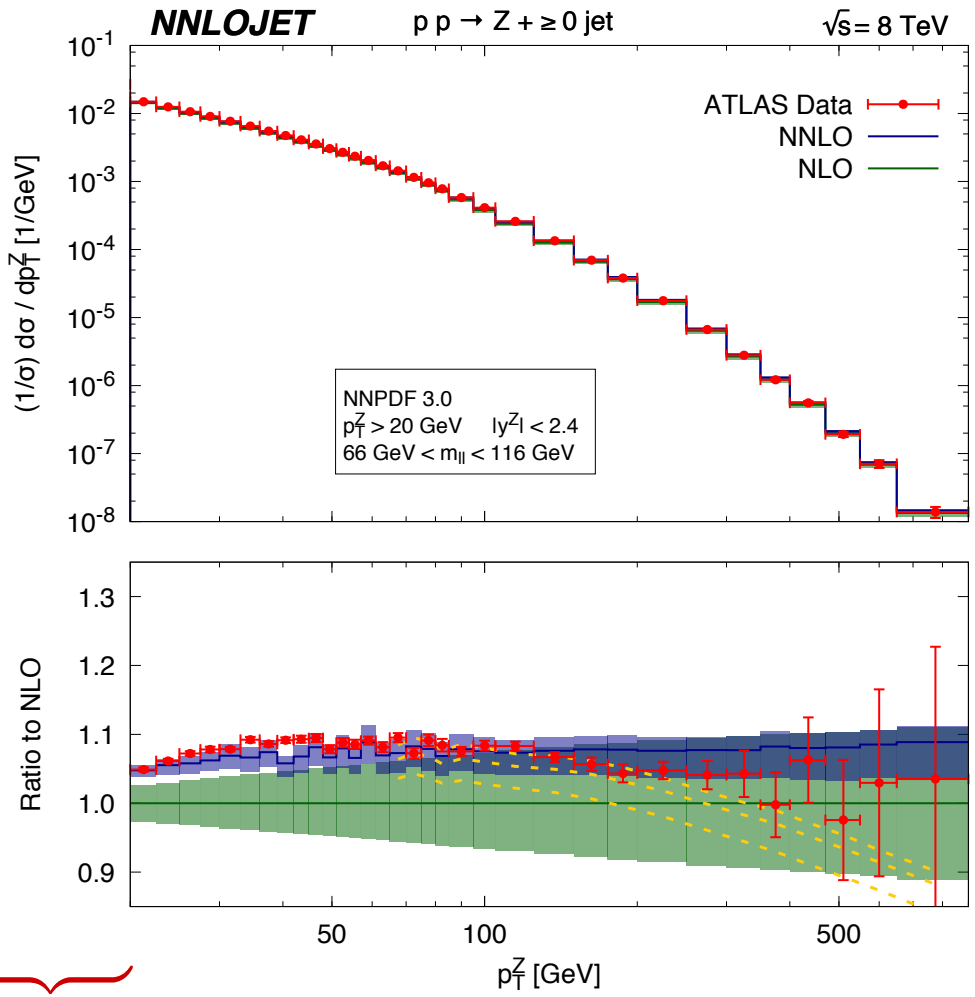
NNLO

significant improvement
in Data vs. Theory comparison

+ EW corrections: - - - -

[Denner, Dittmaier, Kasprzik, Mück '11]

Inclusive p_{T} spectrum of Z/γ^*



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Morgan '16]

$$\frac{1}{\sigma}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

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+ EW corrections: - - - -

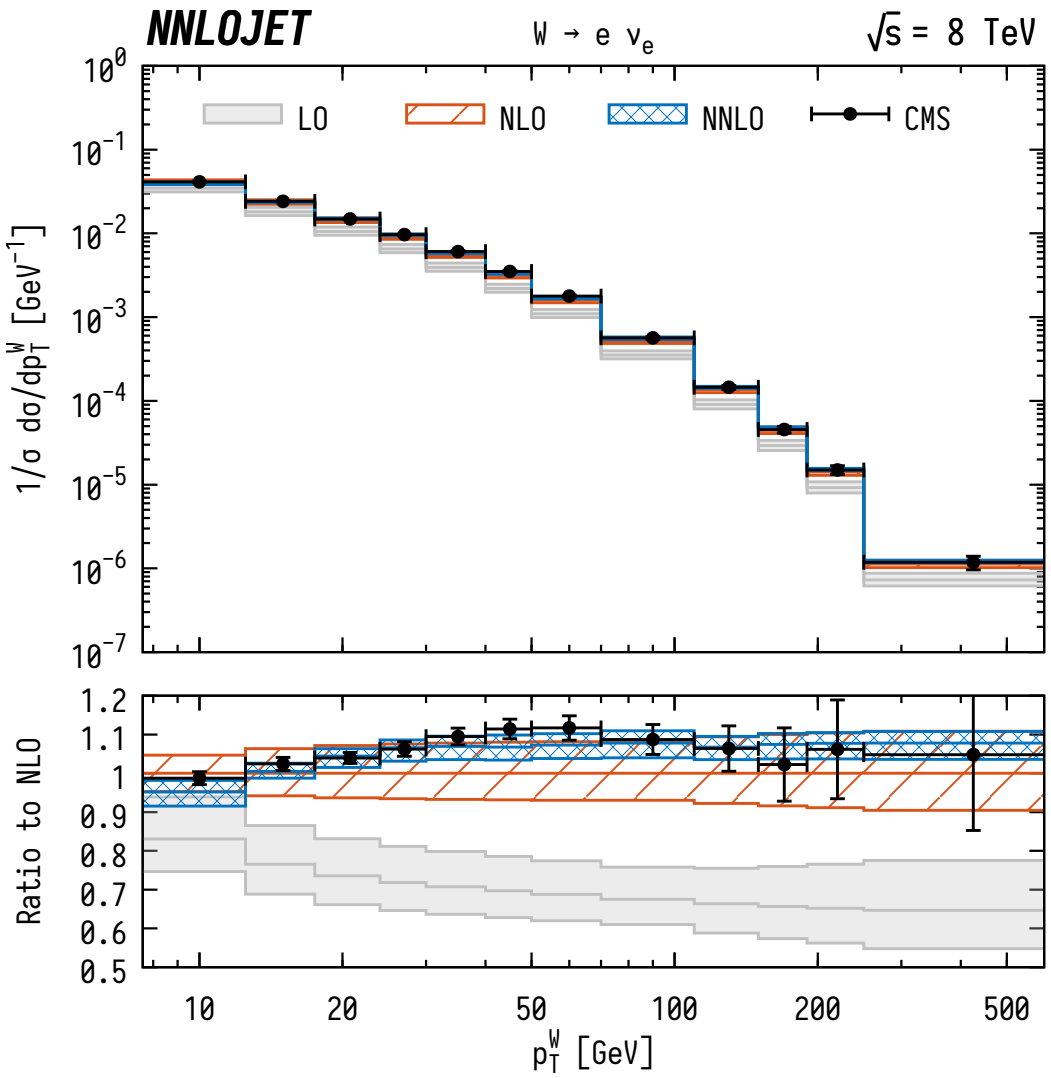
[Denner, Dittmaier, Kasprzik, Mück '11]

f.o. divergent
for $p_{\mathrm{T,Z}} \to 0$

resummation $\alpha_{\mathrm{s}}^n \log^k(p_{\mathrm{T}}/M)$

- RADISH [with Bizon, Monni, Re, Rottoli, Torrielli]
- NNLO matched to N^{3}LL (talk by P.F. Monni)

Inclusive p_{T} spectrum of $\mathrm{W}^{\pm}$



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Walker '17]

NLO

↪ shape differences 5–10%

↪ scale uncertainties 5–10%

NNLO

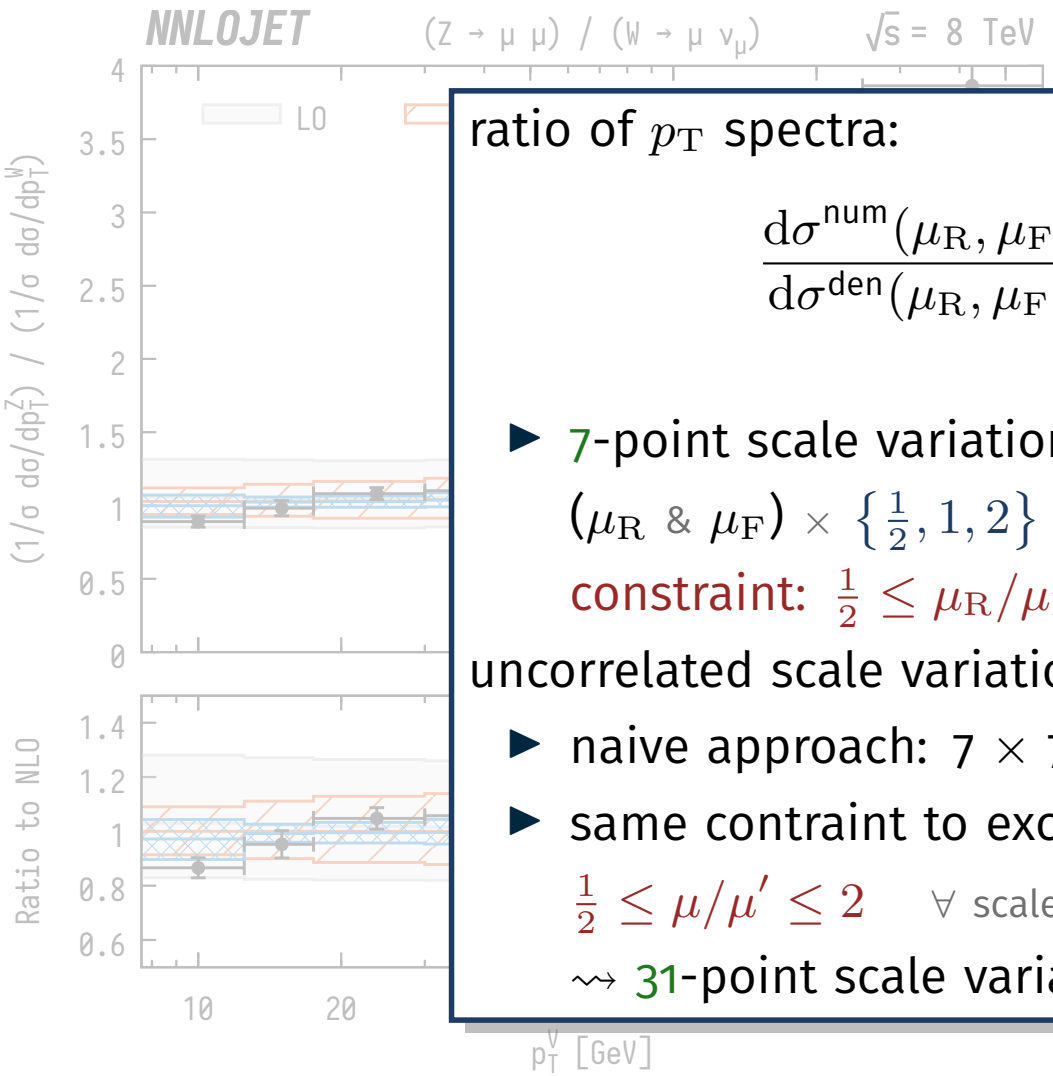
↪ shape distortion

↪ reduction of scale uncertainties

↪ good agreement with data

- similar corrections to $p_{\mathrm{T}}^{\mathrm{Z}}$

Ratio of p_{T} spectra: Z/W



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Walker '17]

1 (very stable)

s similar: Z vs. W

ibed

es

ties ± 10–20%

ties ± 5–8%

ratio of p_{T} spectra:

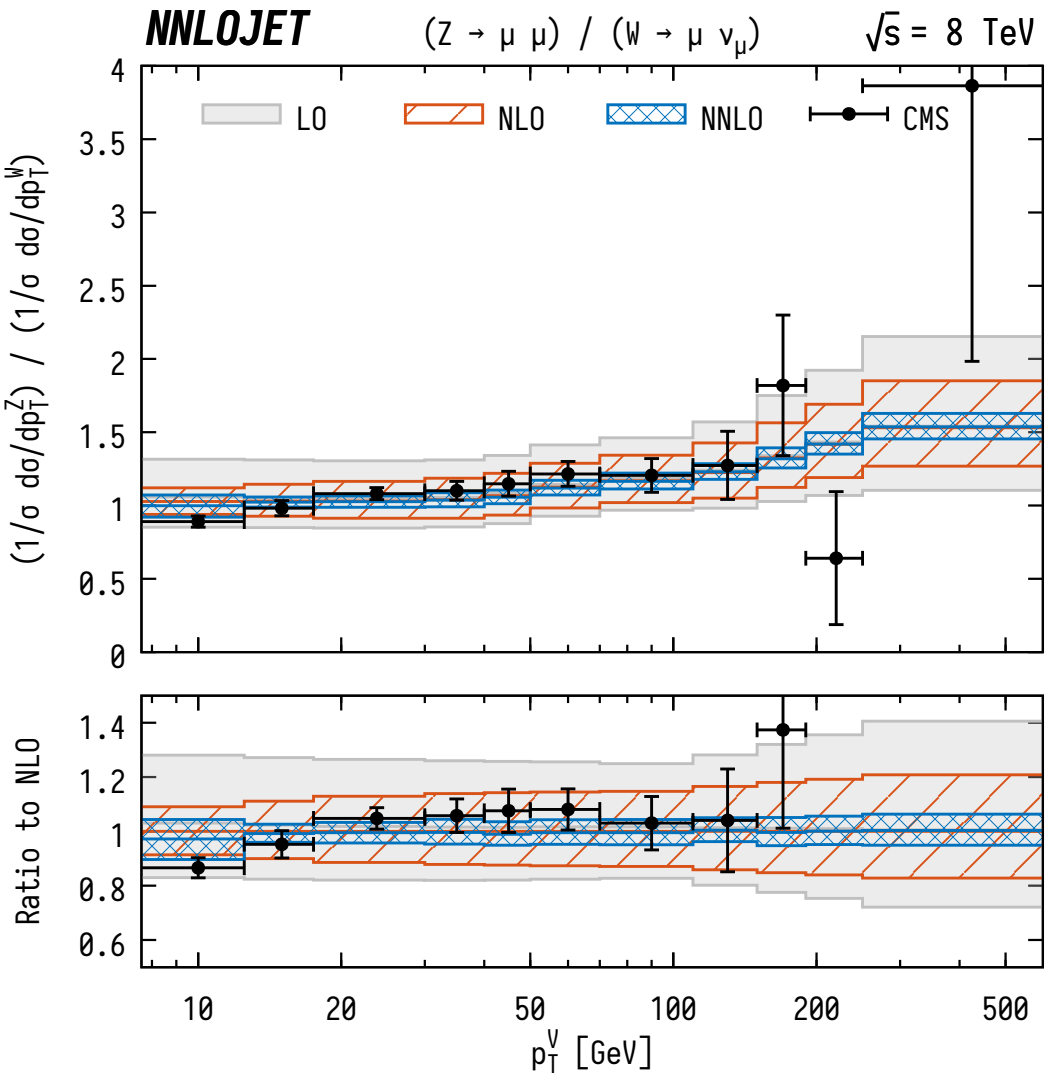
$$\frac{\mathrm{d}\sigma^{\mathrm{num}}(\mu_{\mathrm{R}}, \mu_{\mathrm{F}})/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{\mathrm{den}}(\mu_{\mathrm{R}}, \mu_{\mathrm{F}})/\mathrm{d}p_{\mathrm{T}}}$$

- 7-point scale variation for $\mathrm{d}\sigma$:
  $(\mu_{\mathrm{R}}\ \&\ \mu_{\mathrm{F}}) \times \{\frac{1}{2}, 1, 2\}$
  constraint: $\frac{1}{2} \leq \mu_{\mathrm{R}}/\mu_{\mathrm{F}} \leq 2$

uncorrelated scale variation:

- naive approach: $7 \times 7 = 49$ points
- same contraint to exclude extremes:
  $\frac{1}{2} \leq \mu/\mu' \leq 2 \quad \forall$ scale pairs
  $\rightsquigarrow$ 31-point scale variation

Ratio of p_{T} spectra: Z/W



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Walker '17]

- $K_{\text{(N)NLO / (N)LO}} \sim 1$ (very stable)

↪ QCD corrections similar: Z vs. W

- data well described by central values

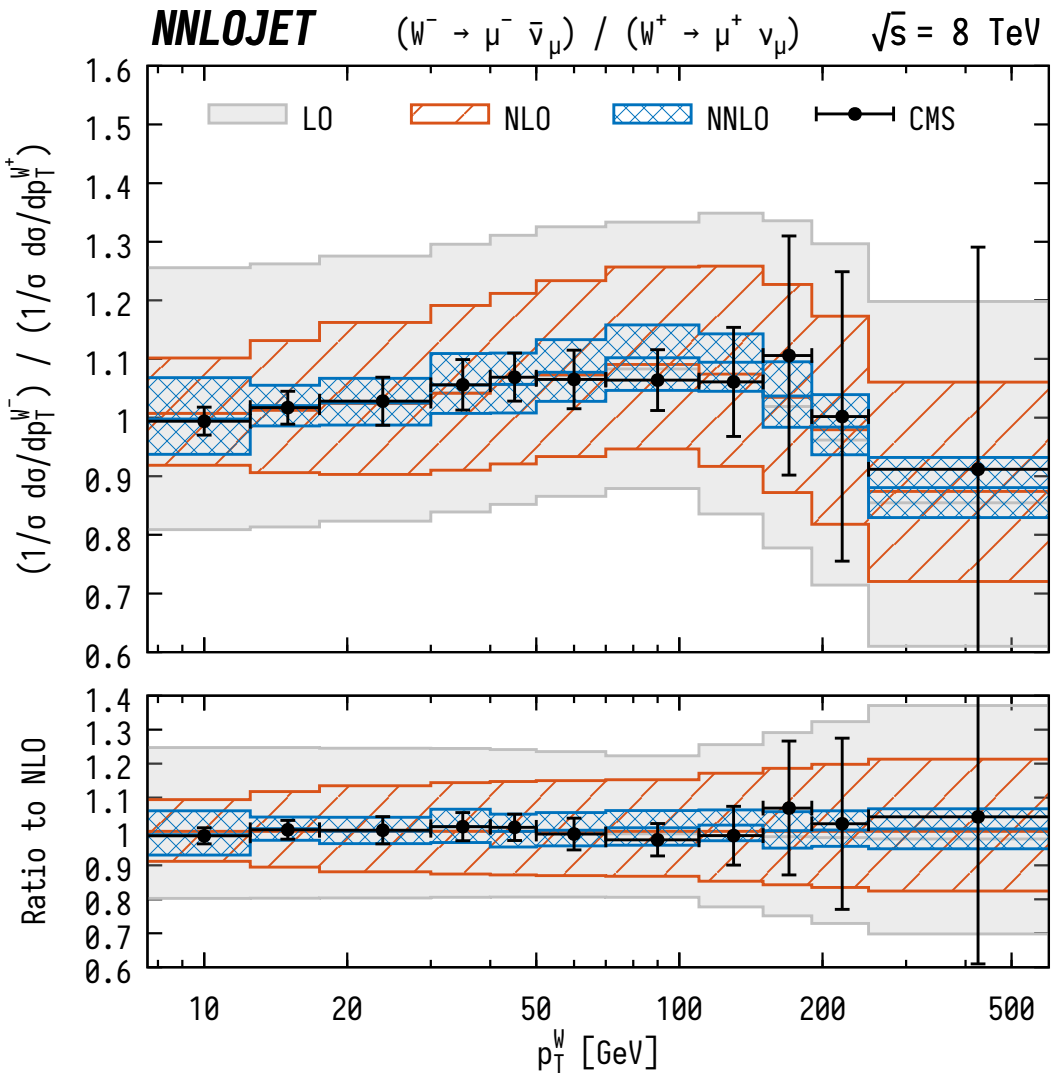
NLO

↪ scale uncertainties $\pm 10\text{–}20\%$

NNLO

↪ scale uncertainties $\pm 5\text{–}8\%$

Ratio of p_{T} spectra: $\mathrm{W}^-/\mathrm{W}^+$



[Gehrmann–De Ridder, Gehrmann, Glover, AH, Walker '17]

- $K_{\text{(N)NLO / (N)LO}} \sim 1$ (very stable)

↪ QCD corrections similar: W^- vs. W^+

- data well described by central values

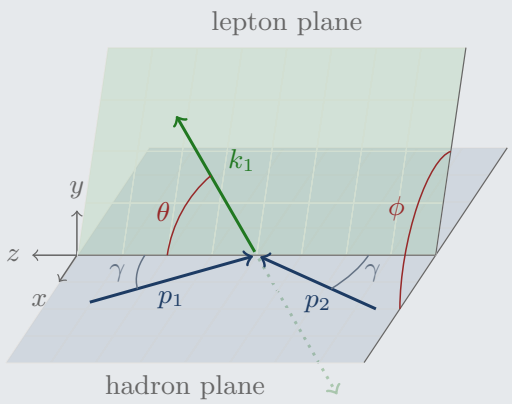
NLO

↪ scale uncertainties $\pm 10\text{–}20\%$

NNLO

↪ scale uncertainties $\pm 5\text{–}8\%$

Angular coefficients — going beyond rate measurements



$$\mathrm{p\,p} \to \mathrm{Z}/\gamma^* + X \to \ell^-\ell^+ + X$$

- lepton angular distributions (θ, ϕ)
- probe production dynamics & polarisation
- M_W & $\sin^2\theta_\mathrm{w}$ measurement

[Gauld, Gehrmann–De Ridder, Gehrmann, Glover, AH '17]

Angular coefficients: $A_i(p_\mathrm{T}^\mathrm{Z}, y^\mathrm{Z}, m_{\ell\ell})$ (Collins–Soper frame)

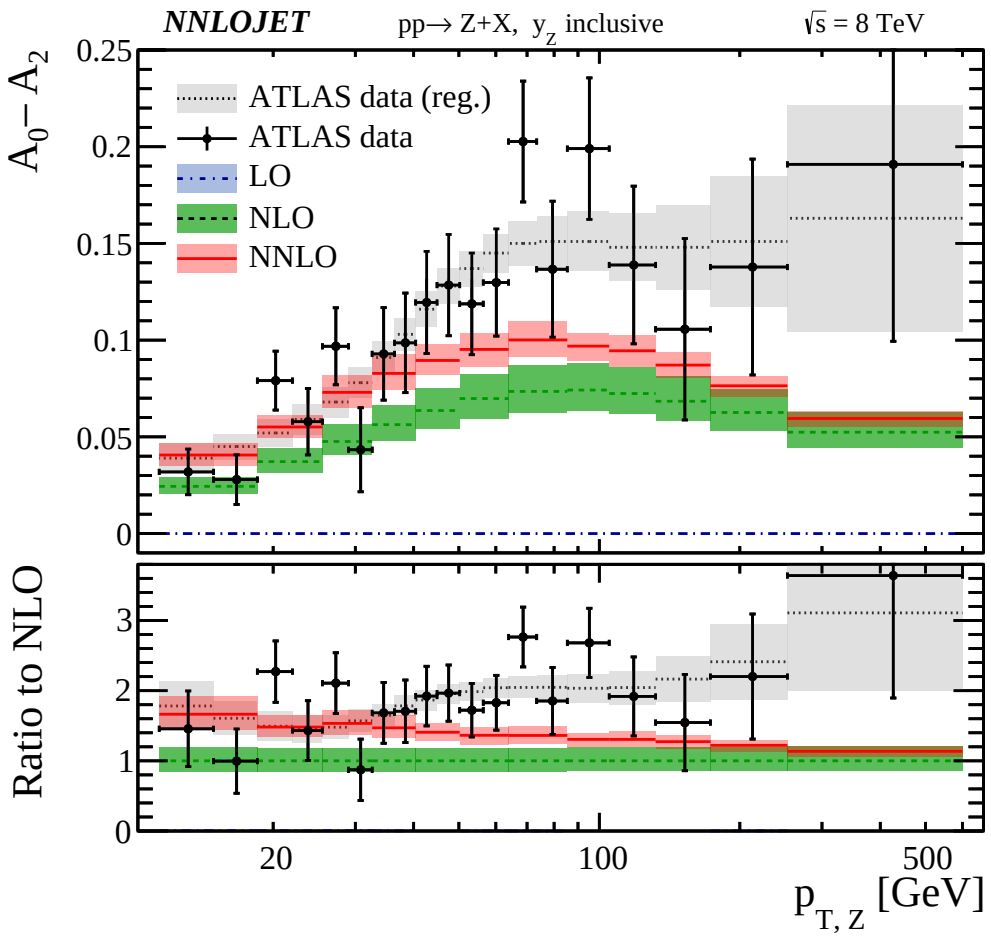
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}^\mathrm{Z}\,\mathrm{d}y^\mathrm{Z}\,\mathrm{d}m_{\ell\ell}\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\,\frac{\mathrm{d}\sigma^\mathrm{unpol.}}{\mathrm{d}p_\mathrm{T}^\mathrm{Z}\,\mathrm{d}y^\mathrm{Z}\,\mathrm{d}m_{\ell\ell}}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta)$$
$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}$$

Lam–Tung relation

$$A_0 - A_2 = 0$$

- analogue of Callen–Gross relation in DIS
- not affected by $\mathcal{O}(\alpha_\mathrm{s})$ corrections

Angular coefficients — ATLAS @ 8 TeV



$\mathcal{O}(\alpha_s)$ prediction:
↪ vanishes (Lam–Tung)

$\mathcal{O}(\alpha_s^2)$ prediction:
↪ $\simeq$ DYNNLO (NNLO)
↪ tension with data
↪ $\chi^2/N_{\text{dat.}} \sim 4.89$

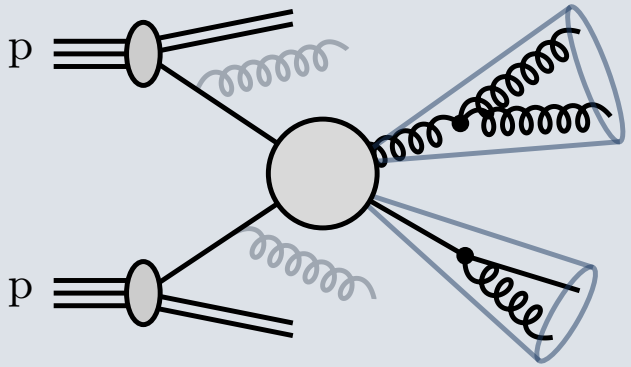
$\mathcal{O}(\alpha_s^3)$ prediction:
↪ large positive corrections
↪ $\chi^2/N_{\text{dat}} \sim 1.75$

- data: [ATLAS arXiv:1606.00689]
  ↪ applies "regularization"

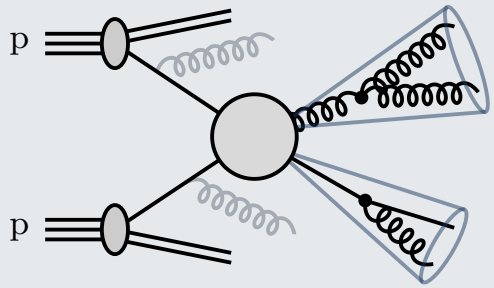
No significant data* vs. theory disagreement between
(un-regularized) ATLAS & **theory @ $\mathcal{O}(\alpha_s^3)$**

$$^*\ \chi^2 = \sum_{i,j}^{N_{\text{dat.}}} (O^i_{\text{exp}} - O^i_{\text{th.}})\sigma^{-1}_{ij}(O^j_{\text{exp}} - O^j_{\text{th.}})$$

Jet Production at the LHC



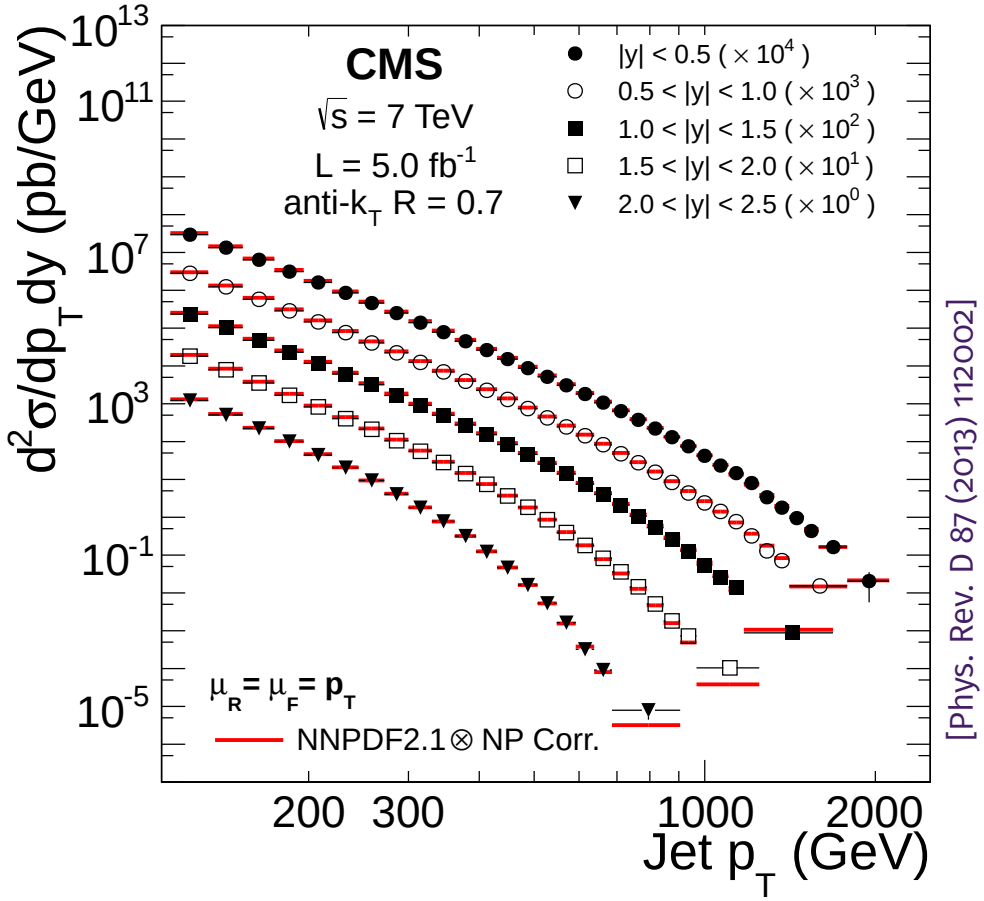
Jet Production at the LHC



$\mathrm{p} + \mathrm{p} \;\rightarrow\; \mathrm{jet(s)} + X$

- jets produced in abundance
- precise measurements $(p_{\mathrm{T},j} \gtrsim 20\ \mathrm{GeV})$
- wide kinematic range accessible

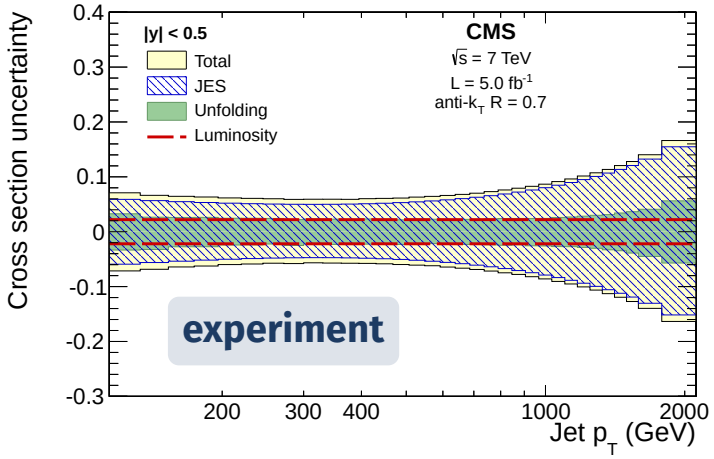
- test perturbative QCD
  $\hookrightarrow$ study scale choices
- constrain PDFs (talk by R. Thorne)
  $\hookrightarrow$ sensitive to *gluon*
  $\hookrightarrow$ probe wide x-range
- determine $\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$ and *running*
- search for BSM physics

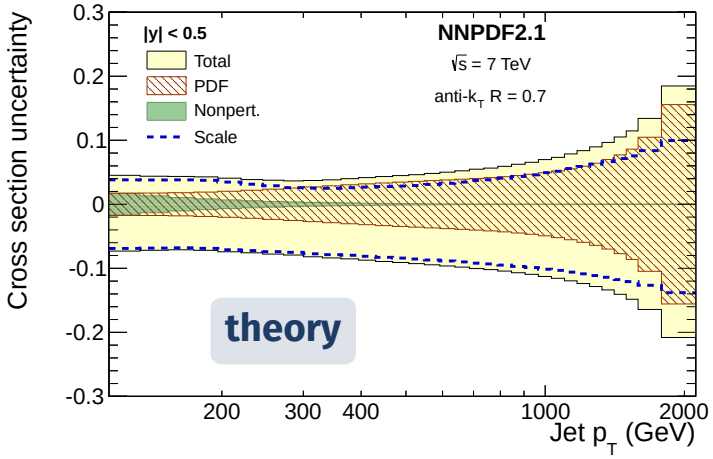


Jet Production — Where do we stand?

(*very* incomplete list!)

- **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 F. Ringer) .. [Liu, Moch, Ringer '17]
- **NLO EW** ..... [Dittmaier, AH, Speckner '12] [Campbell, Wackeroth, Zhou '16] [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '17]
- **NNLO QCD** (this talk) ..... [Gehrmann-De Ridder, Gehrmann, Glover, Pires '13] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, Pires, Wells '14] [Currie, Glover, Pires '16] [Currie, Gehrmann-De Ridder, Gehrmann, Glover, AH, Pires '17]





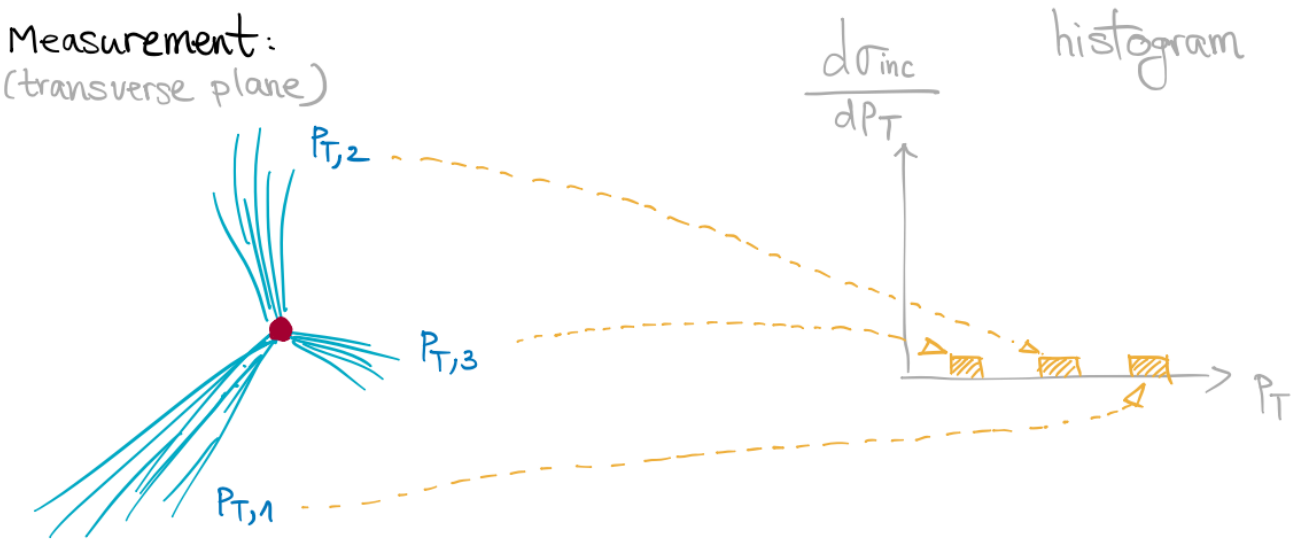
- up to $\sim 2\ \mathrm{TeV}$: sys. uncert. dominant

jet energy scale ± 5–10%

- - - NLO scale uncert. $\sim 10\ \%$
(limiting factor in α_s & PDF extraction)

- **NNLO needed!**

Inclusive Jet Production

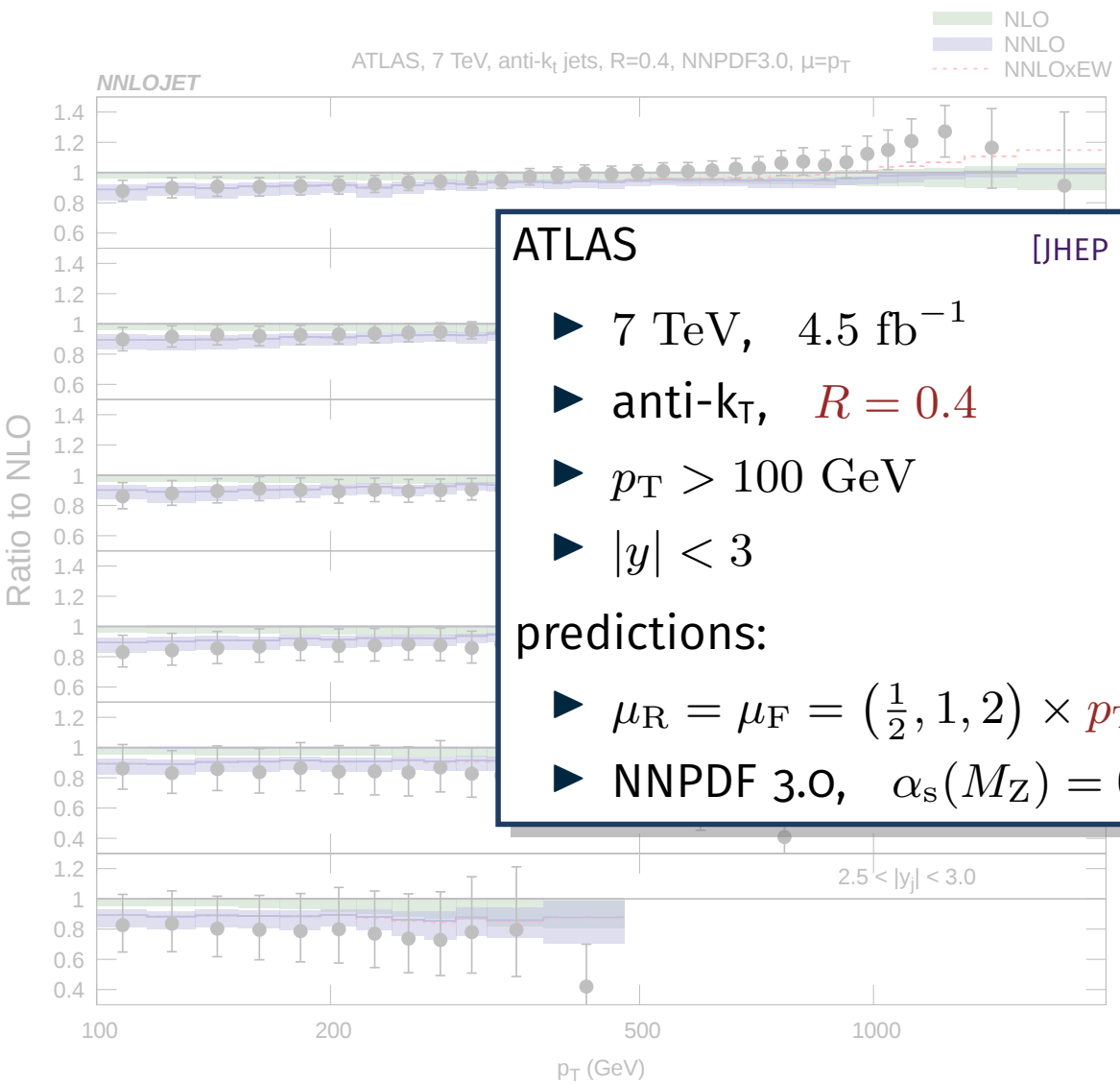


$$\left\{ \begin{array}{c} n \text{ reconstructed jets} \\ \text{in the event} \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} n \text{ binnings to} \\ \text{the histogram} \end{array} \right\} \Rightarrow \sum_{\text{bins}} \frac{\mathrm{d}\sigma_{\text{inc}}}{\mathrm{d}p_{\mathrm{T}}} \neq \sigma_{\text{tot}}$$

scale choices $\leftrightsquigarrow$ **binning of *individual jets* vs. *events***

- "global" scales (event): $p_{\mathrm{T,max}}$, $\langle p_{\mathrm{T}} \rangle, \ldots$
- "local" scales (jet): $p_{\mathrm{T}}, \ldots$

Inclusive Jet Production — ATLAS @ 7 TeV



ATLAS [JHEP 1502 (2015) 153]

- 7 TeV, $4.5\ \mathrm{fb}^{-1}$
- anti-k_T, $R = 0.4$
- $p_T > 100$ GeV
- $|y| < 3$

predictions:

- $\mu_R = \mu_F = \left(\frac{1}{2}, 1, 2\right) \times p_T \quad (p_{T,\max})$
- NNPDF 3.0, $\alpha_s(M_Z) = 0.118$

NLO ($\rightsquigarrow 1$)

NNLO

$\hookrightarrow$ high p_T:

orrections: few %

on of scale uncert.

gence of pert. series

rapidity)

e corrections: -10%

rapidity bins)

ands: NNLO $\gtrsim$ NLO

erlapping)

mmetric scale bands!

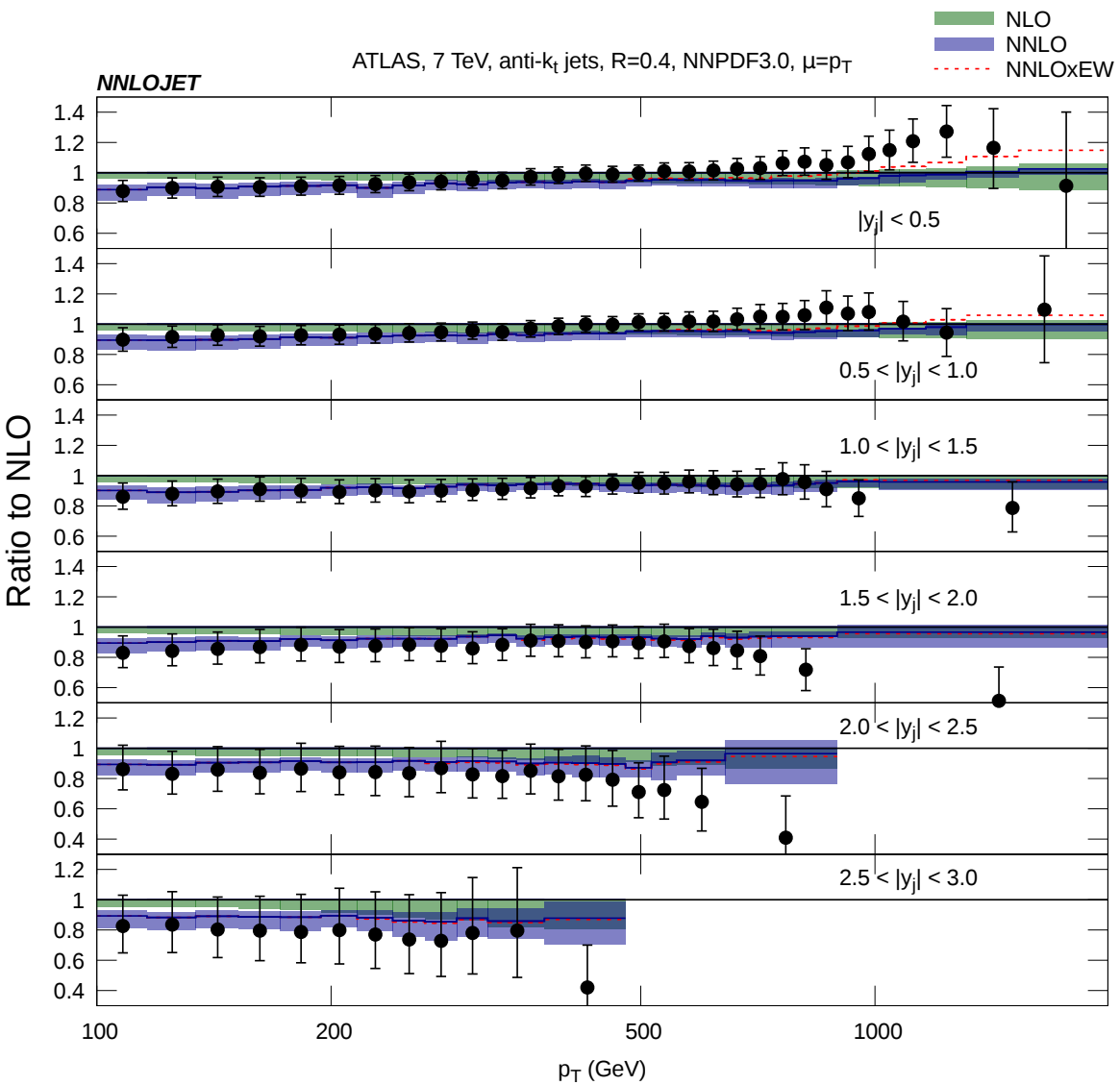
EW corrections - - - -

small – moderate @

high p_T & central rapidity

* no non-pert. corrections

Inclusive Jet Production — ATLAS @ 7 TeV



NLO ($\rightsquigarrow 1$)

NNLO

↪ high p_T:

- small corrections: few %
- reduction of scale uncert.
- convergence of pert. series (central rapidity)

↪ low p_T:

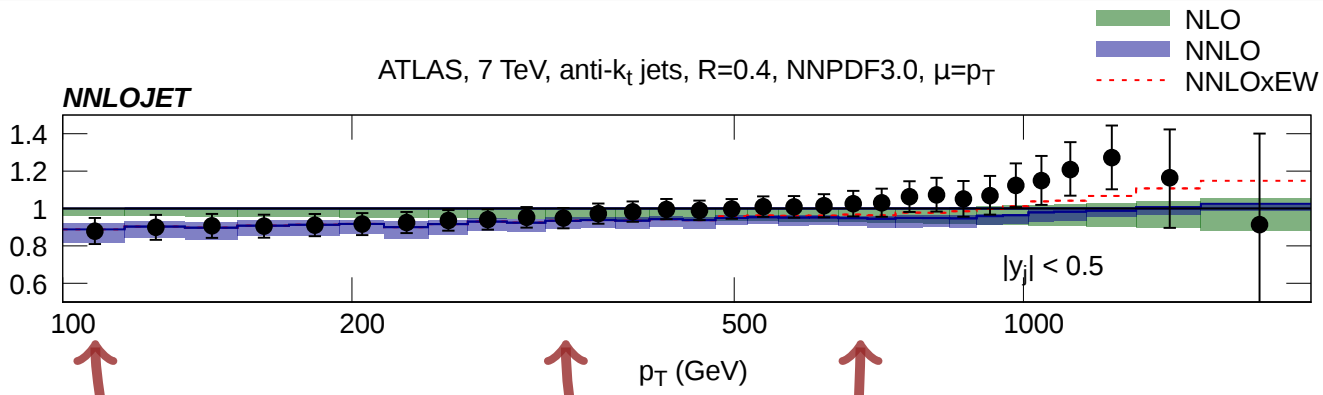
- sizeable corrections: -10% (across rapidity bins)
- scale bands: NNLO $\gtrsim$ NLO (non-overlapping)
- NLO: asymmetric scale bands!

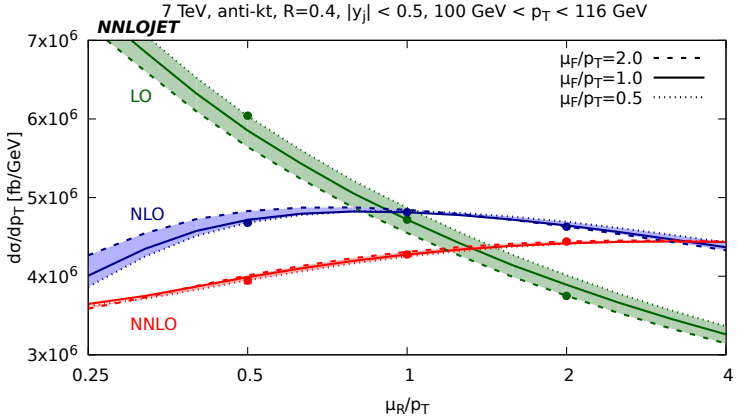
EW corrections - - - -
small – moderate @ high p_T & central rapidity

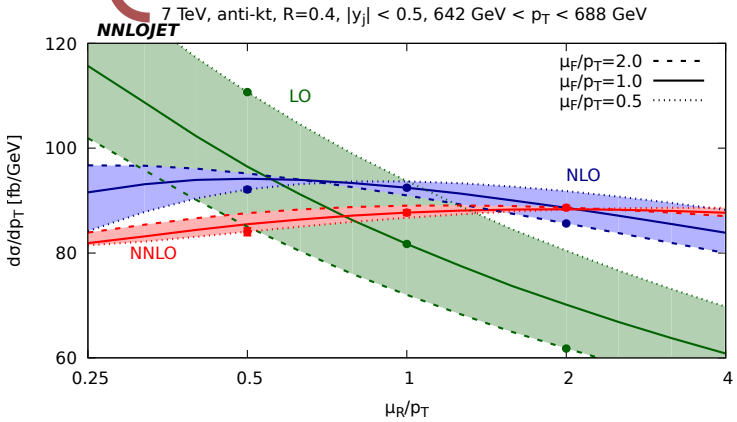
* no non-pert. corrections

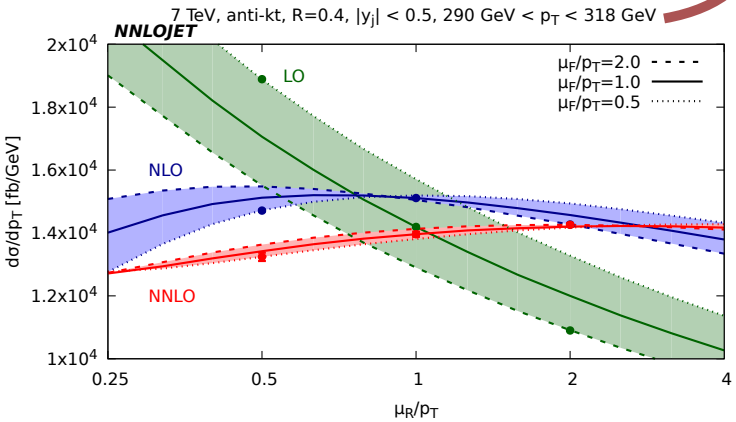
Inclusive Jet Production — Scale Variation

$|y_j| < 0.5$









NLO: turn-over @ $\mu_R/p_T \sim 0.5$–1
↪ asymmetric bands
↪ pert. uncert. underestimated?!

NNLO: monotonic behaviour
↪ symmetric bands

solid: analytic RGE, *points:* NNLOJET

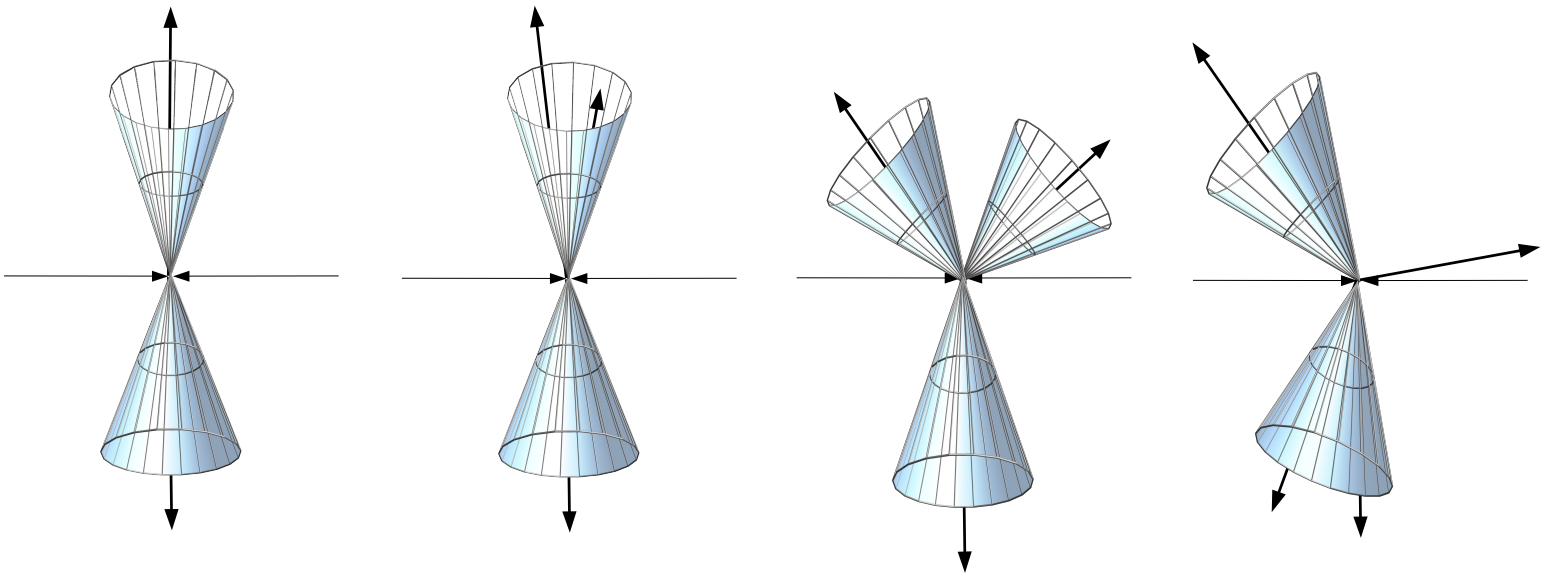
Inclusive Jet Production — Scale Choices

Two common scale choices

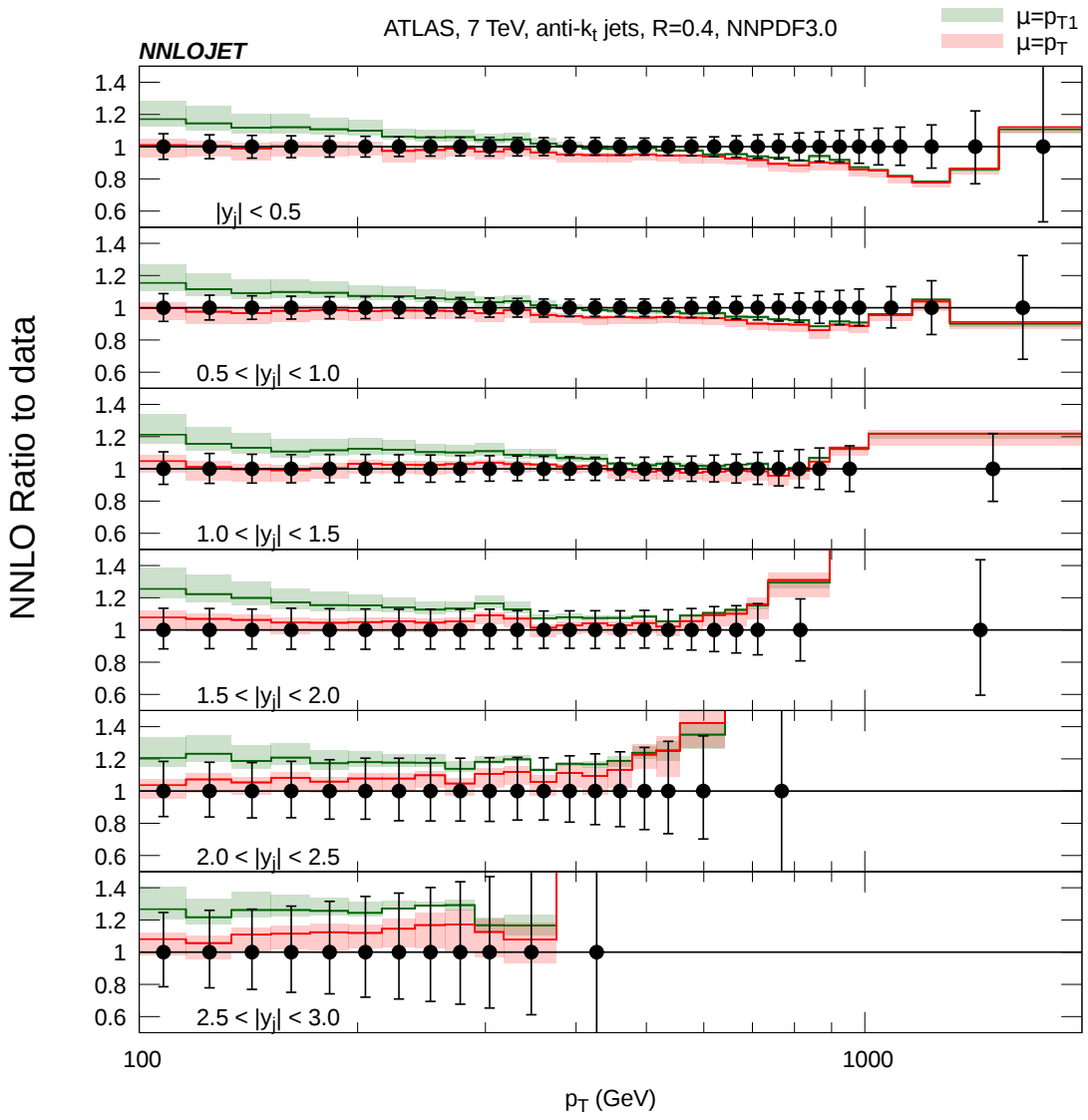
$p_{\mathrm{T,max}}$ the *leading-jet* transverse momentum

p_{T} transverse momentum of the *individual jets*

- identical at LO ($2 \to 2$ kinematics)
- high-p_{T} jets are mostly back-to-back: $\Rightarrow$ $p_{\mathrm{T,max}} \sim p_{\mathrm{T}}$
- differences:
  $\hookrightarrow$ ≥ 3 jets in the event
  $\hookrightarrow$ jets outside of fiducial cuts
- sensitive to the cone size R



Inclusive Jet Production — $p_{\mathrm{T,max}}$ vs. p_{T}



Inclusive Jets @ NNLO

$\mu_0 = p_{\mathrm{T,max}}$

$\mu_0 = p_{\mathrm{T}}$

high p_{T}: both scales coincide

(as expected)

low p_{T}: significant differences 15–20%

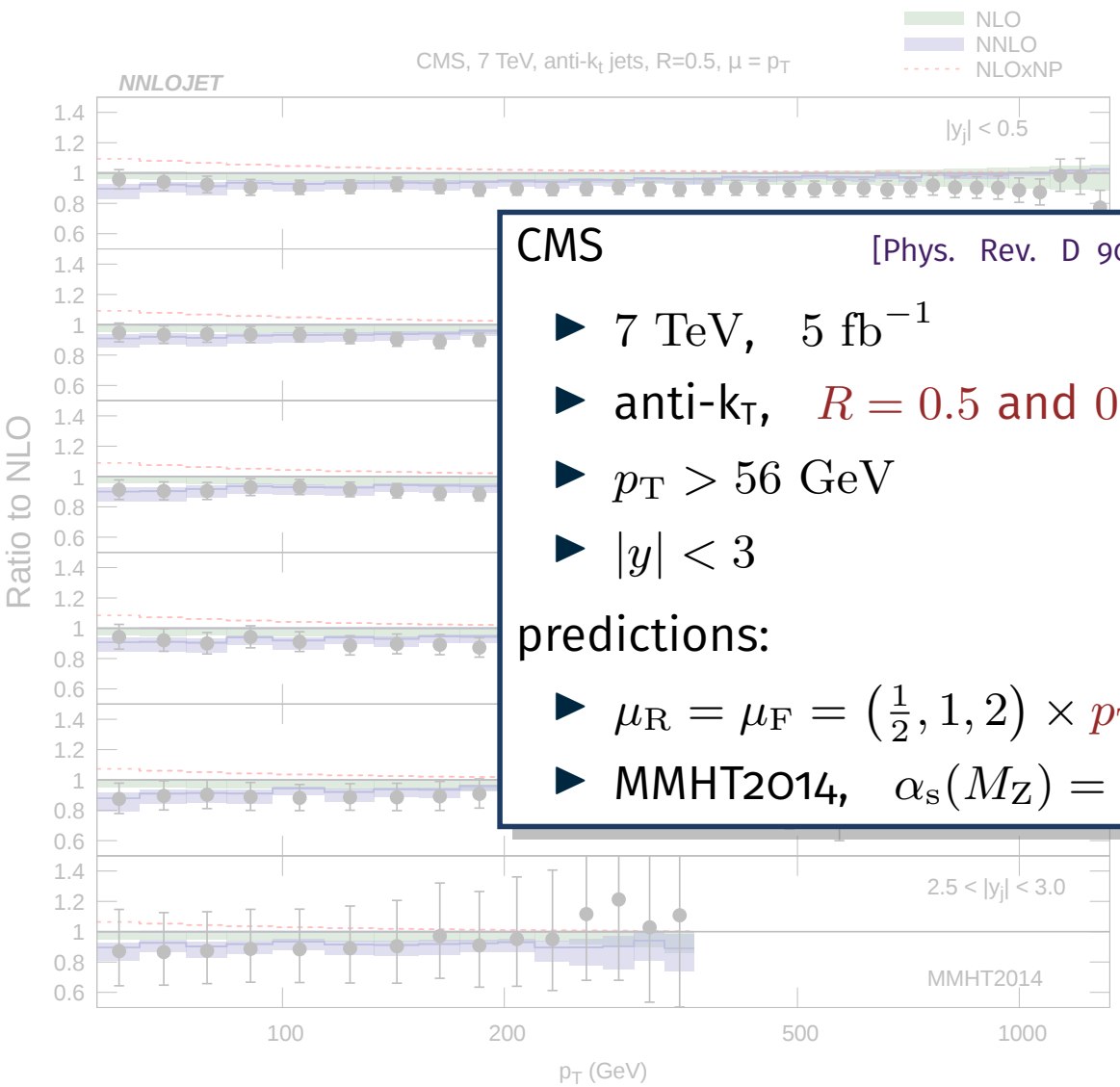
$\hookrightarrow$ $p_{\mathrm{T,max}}$ away from data

$\hookrightarrow$ p_{T} in line with data

(non-overlapping bands)

large effects from scale ambiguity!

Inclusive Jet Production — CMS @ 7 TeV



CMS [Phys. Rev. D 90 (2014) 072006]

- 7 TeV, $5\ \mathrm{fb}^{-1}$
- anti-k_T, $R = 0.5$ and 0.7
- $p_T > 56$ GeV
- $|y| < 3$

predictions:

- $\mu_R = \mu_F = \left(\frac{1}{2}, 1, 2\right) \times p_T$
- MMHT2014, $\alpha_s(M_Z) = 0.118$

NLO ($\rightsquigarrow 1$)

NNLO

NLO × NP

orrections: few %

on of scale uncert.

gence of pert. series

rapidity)

e corrections: -10%

rapidity bins)

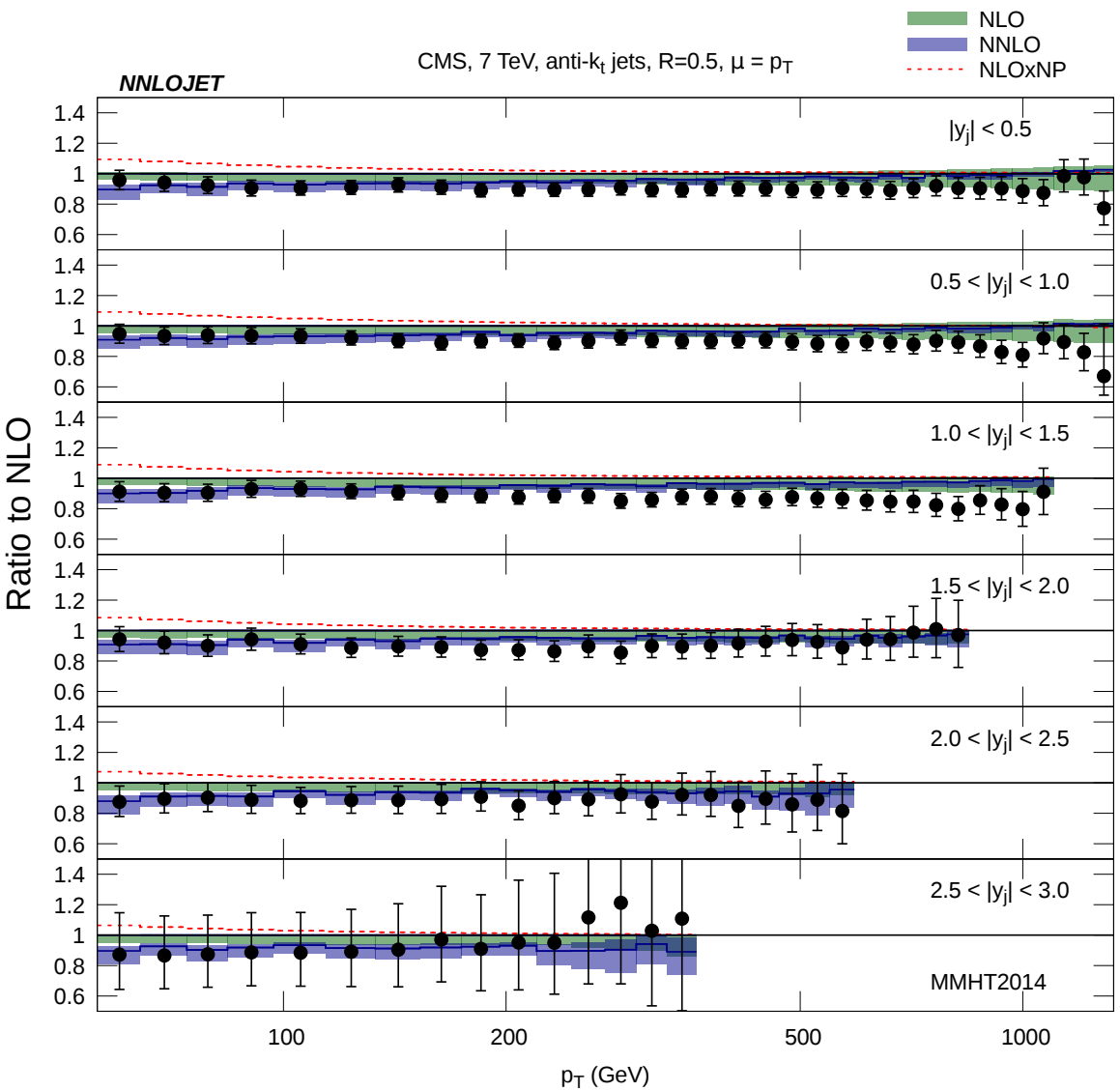
ands: NNLO $\simeq$ NLO

erlapping)

- NP effects relevant for $p_T \lesssim 100$ GeV
- NLO: asymmetric scale bands!

similar to ATLAS ($R = 0.4$)

Inclusive Jet Production — CMS @ 7 TeV $(R = 0.5)$



NLO $(\rightsquigarrow 1)$

NNLO

NLO $\times$ NP

↪ high p_{T}:

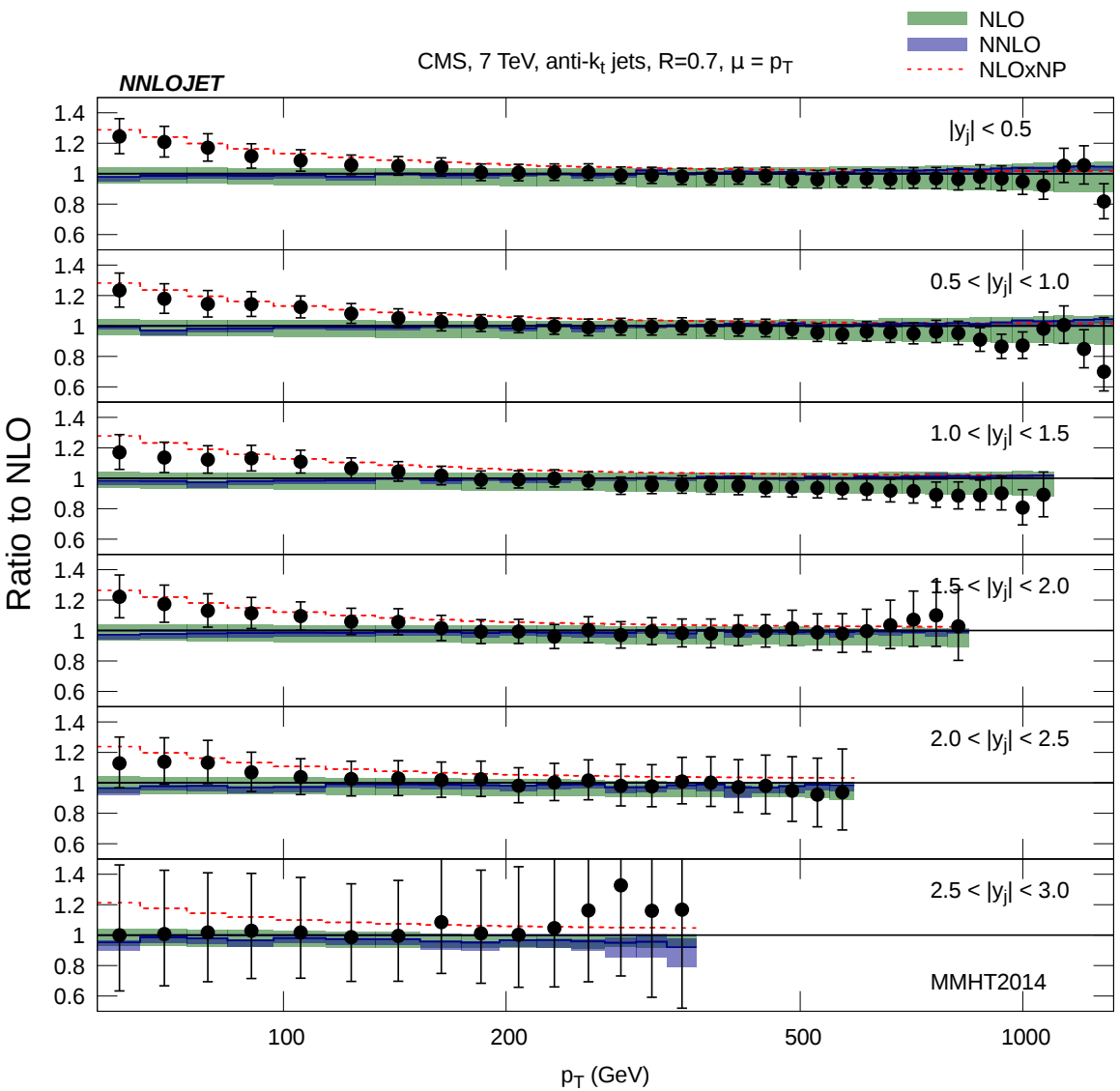
- small corrections: few %
- reduction of scale uncert.
- convergence of pert. series (central rapidity)

↪ low p_{T}:

- sizeable corrections: -10% (across rapidity bins)
- scale bands: NNLO $\simeq$ NLO (non-overlapping)
- NP effects relevant for $p_{\mathrm{T}} \lesssim 100$ GeV
- NLO: asymmetric scale bands!

similar to ATLAS $(R = 0.4)$

Inclusive Jet Production — CMS @ 7 TeV $(R = 0.7)$



NLO $(\rightsquigarrow 1)$

NNLO

NLO × NP

↪ stabilization of corrections:

- small NNLO corrections
- reduction of scale uncert.
- good pert. convergence
- across *all* p_T

↪ NP corrections:

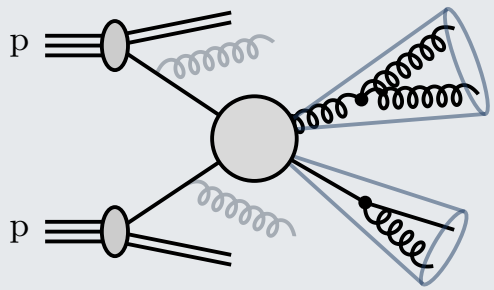
- more sizable at low-p_T $(R = 0.7)$

↪ attention:

- NNLO: asymmetric scale bands!

NNLO/NLO for $\mu = p_{T,\max}$ stable

Dijet Production



$\mathrm{p} + \mathrm{p} \;\to\; 2\text{ jets} + X$ (# jets ≥ 2)

j_1: leading jet
j_2: sub-leading jet

$\rightsquigarrow$ dijet system

- $m_{jj} = (p_{j_1} + p_{j_2})^2$
- $y^* = \frac{1}{2}(y_{j_1} - y_{j_2})$

$m_{jj} = 2\, p_{\mathrm{T}} \cosh y^*$ (back-to-back)

$\hookrightarrow$ scattering angle in part. system $\leftrightarrow$ x smeared out

- sensitivity to x:

$\bar{y} = \frac{1}{2}(y_{j_1} + y_{j_2})$ longitudinal boost

$y_{\max} = \max(y_{j_1}, y_{j_2})$ scattering angle in lab

scale choices

m_{jj}, $\langle p_{\mathrm{T}} \rangle = \frac{1}{2}(p_{\mathrm{T},1} + p_{\mathrm{T},2})$, $p_{\mathrm{T},1}$, $p_{\mathrm{T},1}\, \mathrm{e}^{-0.3y^*}$, $m_{jj}/2, \ldots$

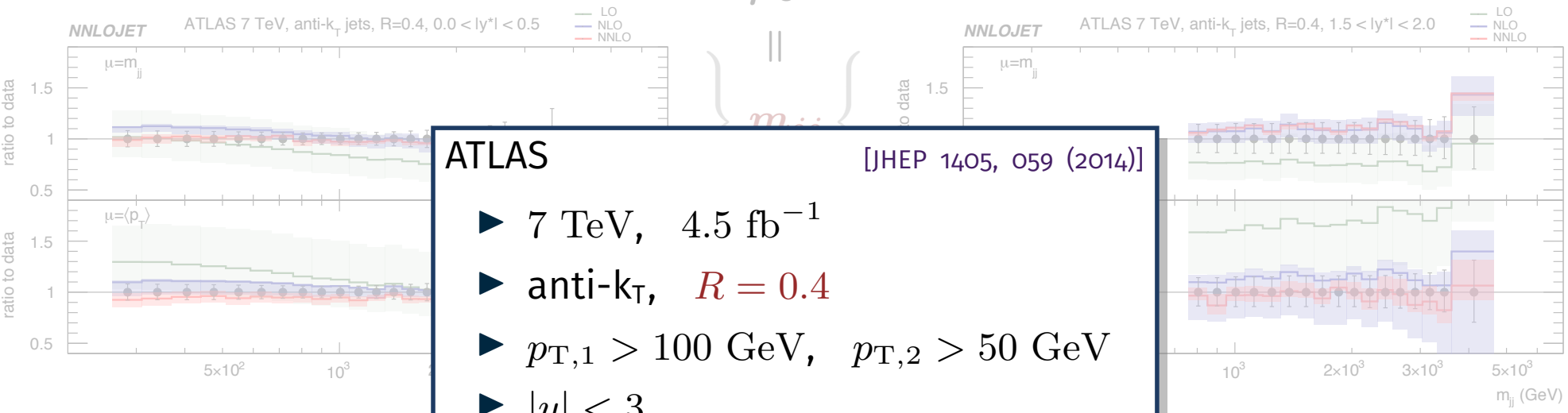
Dijet Production — m_{jj} vs. $\langle p_{\mathrm{T}} \rangle$

$0.0 < |y^*| < 0.5$ $\qquad$ $1.5 < |y^*| < 2.0$

μ_0

$\|$

$\{ m_{jj} \}$



ATLAS [JHEP 1405, 059 (2014)]

- 7 TeV, $4.5\ \mathrm{fb}^{-1}$
- anti-k_T, $R = 0.4$
- $p_{\mathrm{T},1} > 100$ GeV, $p_{\mathrm{T},2} > 50$ GeV
- $|y| < 3$
- binned in $|y^*|$

predictions:

- $\mu_0 = m_{jj}$ vs. $\langle p_{\mathrm{T}} \rangle$
- MMHT2014, $\alpha_{\mathrm{s}}(M_{\mathrm{Z}}) = 0.118$

small $|y^*|$:

- both scales g
  - ↪ overlappin

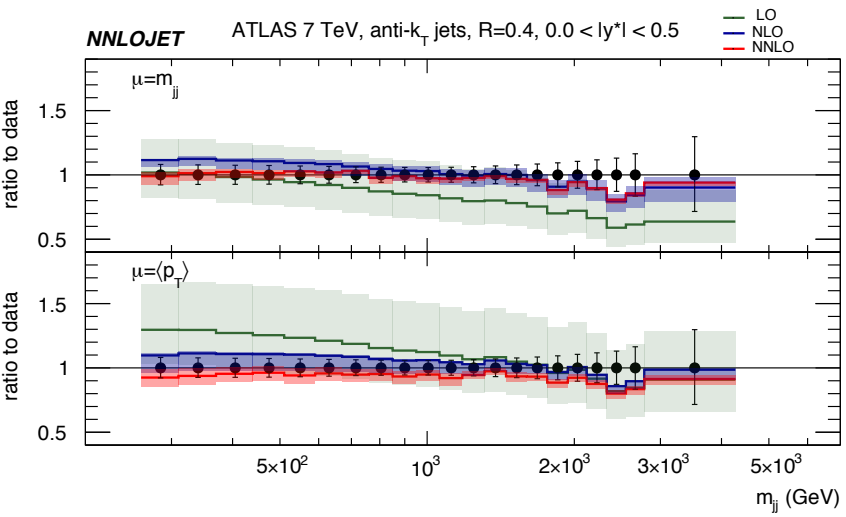
large $|y^*|$:

- m_{jj}: similarly good to small $|y^*|$
- $\langle p_{\mathrm{T}} \rangle$: large NLO corrections with huge scale uncertainties
  - ↪ for $|y^*| > 2.0$ even *negative* cross sections @ NLO!
  - ↪ inclusion of NNLO resolves these issues

⇝ choose $\mu_0 = m_{jj}$ (based on pert. convergence and residual scale uncertainties)

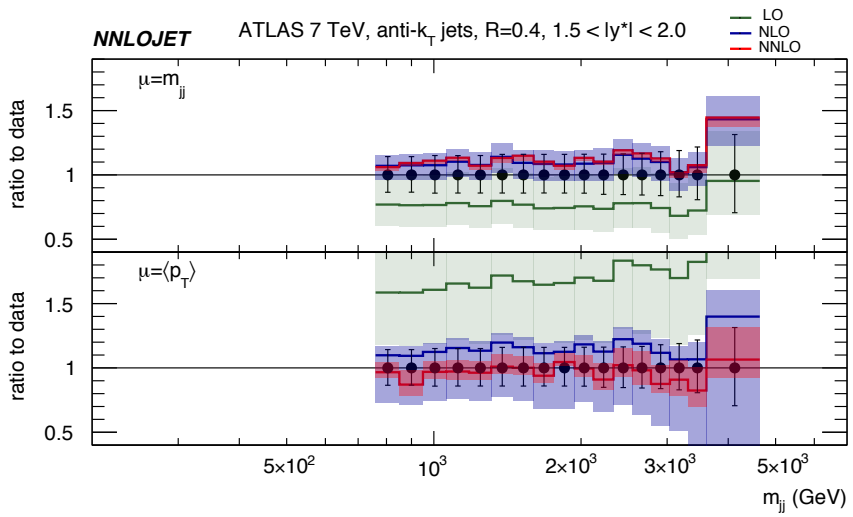
Dijet Production — m_{jj} vs. $\langle p_{\mathrm{T}} \rangle$

$0.0 < |y^*| < 0.5$ $\qquad$ $\boldsymbol{\mu_0}$ $\qquad$ $1.5 < |y^*| < 2.0$



$\boldsymbol{m_{jj}}$

$\boldsymbol{\langle p_{\mathrm{T}} \rangle}$



LO **NLO** **NNLO**

small $|y^*|$:

- both scales give reasonable predictions:
  - ↪ overlapping bands, perturbateive convergence, …

large $|y^*|$:

- m_{jj}: similarly good to small $|y^*|$
- $\langle p_{\mathrm{T}} \rangle$: large NLO corrections with huge scale uncertainties
  - ↪ for $|y^*| > 2.0$ even *negative* cross sections @ NLO!
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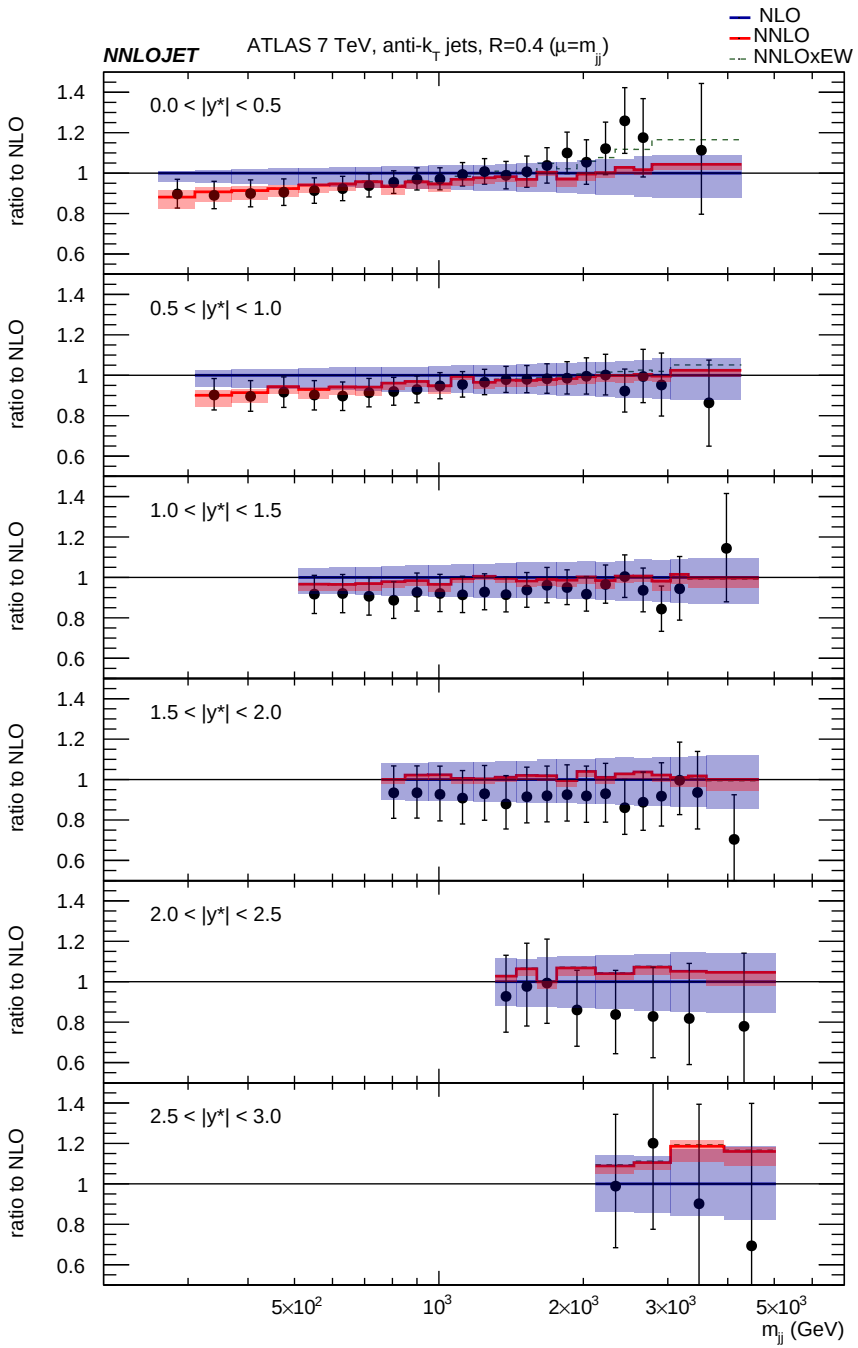
Dijet Production — ATLAS @ 7 TeV



NLO ($\rightsquigarrow 1$)

NNLO

- typically $\lesssim 10\%$
- relatively flat
- large reduction of scale uncert.

$\hookrightarrow$ low m_{jj} & low $|y^*|$:

- shape distorted by NNLO
- scale bands: NNLO $\simeq$ NLO
  (NLO: asymmetric again)
- better data–theory agreement

scales in dijet production
better behaved

Summary & Outlook

- theoretical predictions for $V + \mathrm{jet}$ in good shape!
- **NNLO QCD** now available $\forall \quad V = \mathrm{W}^{\pm}, \mathrm{Z}/\gamma^{*}, \gamma$
  - $\hookrightarrow$ significant reduction in scale uncertainties ($\sim$ few %)
  - $\hookrightarrow$ resolve / reduce long-standing tension with data: H_{T}, p_{T}, ang. coefficients, ...

- **NNLO QCD** corrections completed for jet production ($N_C^2, N_C N_F, N_F^2$)
- inclusive jet production:
  - $\hookrightarrow$ intermediate – high p_{T}: good perturbative convergence (NLO $\rightarrow$ NNLO)
  - $\hookrightarrow$ low p_{T}: larger scale uncertainties & scale ambiguities ($p_{\mathrm{T,max}}$ vs. p_{T})
- dijet production:
  - $\hookrightarrow$ inclusion of NNLO largely removes scale ambiguities (even for $\langle p_{\mathrm{T}} \rangle$)
  - $\Rightarrow$ $\mu_0 = m_{jj}$ provides good convergence & reduced scale uncertainties
  - $\hookrightarrow$ improvement in comparison to data

Summary & Outlook

- theoretical predictions for $V + \mathrm{jet}$ in good shape!
- **NNLO QCD** now available $\forall \quad V = \mathrm{W}^{\pm}, \mathrm{Z}/\gamma^{*}, \gamma$

  ↪
  ↪

- **NN** … N_F^2)
- in…
  ↪ …LO)
  ↪ …$_F$)
- di…
  ↪
  ⇒
  ↪ improvement in comparison to data

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X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld,
A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, AH,
I. Majer, T. Morgan, J. Niehues, J. Pires, D. Walker

`APPLfast-NNLO` interface: (talk by C. Gwenlan)

[Britzger, Gwenlan, AH, Morgan, Sutton, Rabbertz]

Summary & Outlook

- theoretical predictions for $V + \mathrm{jet}$ in good shape!
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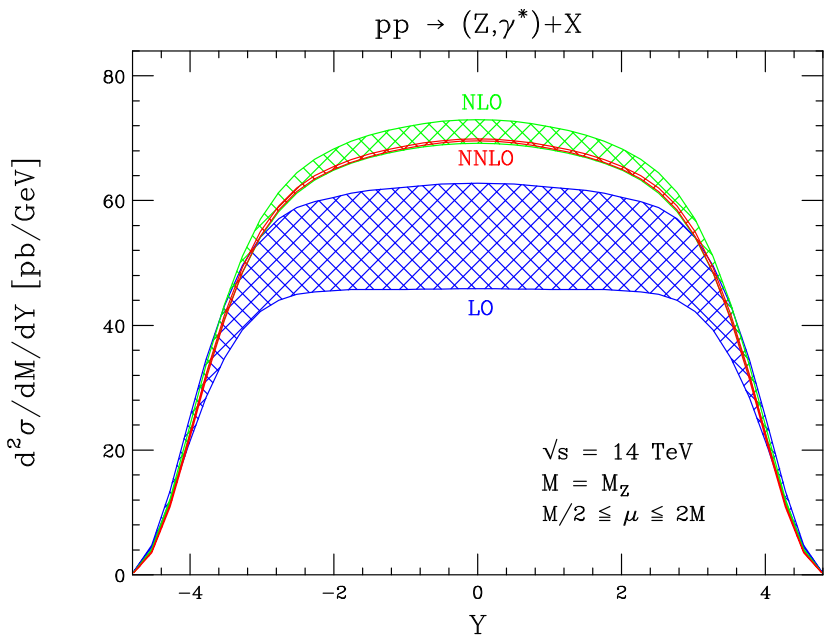
  - $\hookrightarrow$ improvement in comparison to data

Thank you

Backup Slides

Why Higer-Order Corrections?

- high-precision mandatory
  ↪ processes with large K-factors (H)
  ↪ "standard candles" (jets, V, t, …)
- reduction of scale uncertainties
  ↪ variation of μ_{R} & μ_{F}

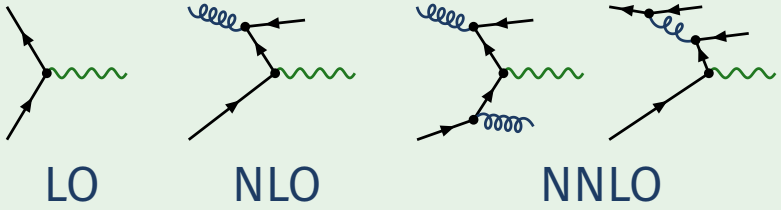


[Anastasiou, Dixon, Melnikov, Petriello '04]

Jet clustering

- better modelling of jet algorithm between theory & experiment

Initial-state radiation



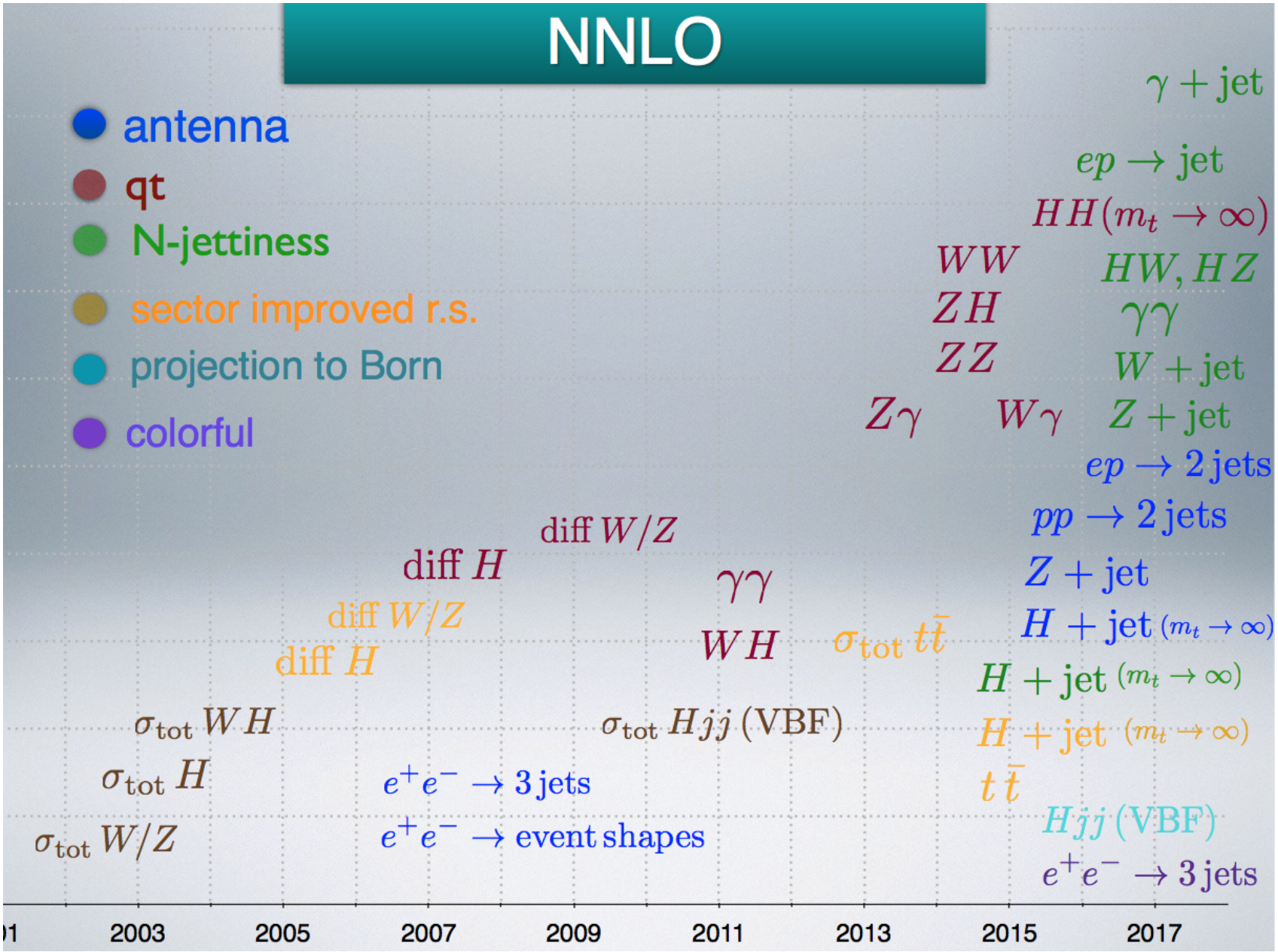
- opening up of all channels
- more complicated p_{T} recoil

NNLO Subtraction Methods

remarkable progress in the development of methods to perform NNLO computations

(not an exhaustive list)	local subtraction	analytic	pp collisions	final-state jet(s)
Antenna	✗ (local after rot^n)	✓	✓	✓
CoLorFul	✓	✓	✗	✓
q_T-Subtr.	✗	✓	✓	✗ (only t)
Sector-improved Residue Subtr.	✓	✗	✓	✓
N-jettiness	✗	✓	✓	✓ ($\leq$ 1 jet so far)

NNLO Timeline



[slide by Gudrun Heinrich, CERN Colloquium '17]

NNLOJET

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X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder,
T. Gehrmann, E.W.N. Glover, AH, I. Majer, T. Morgan, J. Niehues, J. Pires, D. Walker

Common framework for NNLO corrections using Antenna Subtraction

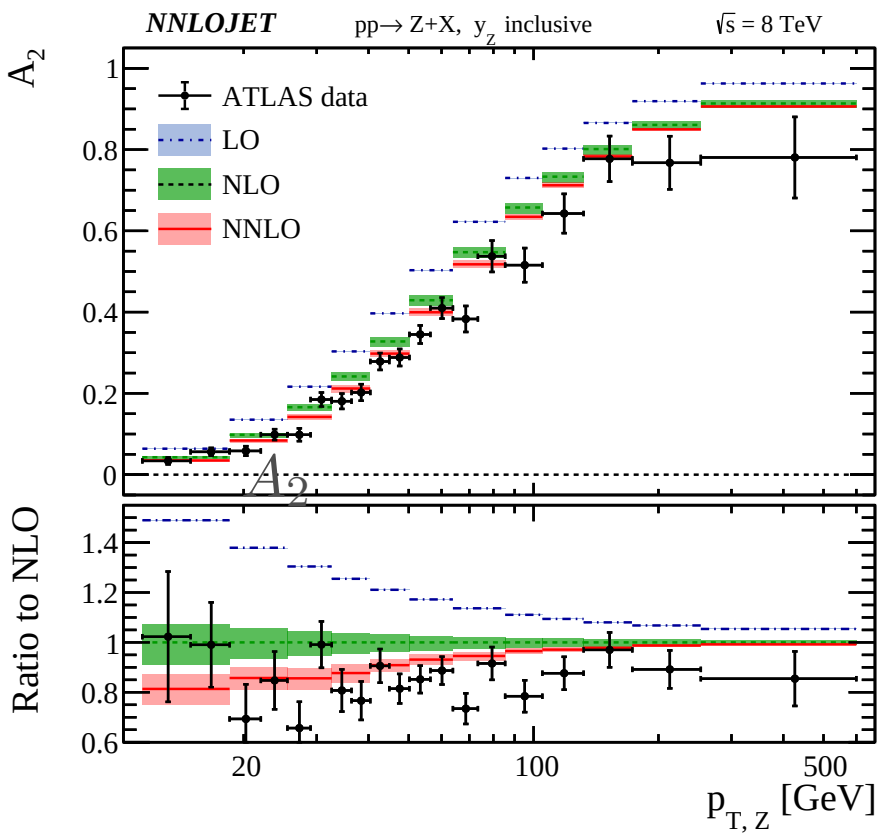
- parton-level event generator
- based on antenna subtraction
- test & validation framework
- `APPLfast-NNLO` interface
  [Britzger, Gwenlan, AH, Morgan, Sutton, Rabbertz]
  (talk by C. Gwenlan)
- ...

Processes:

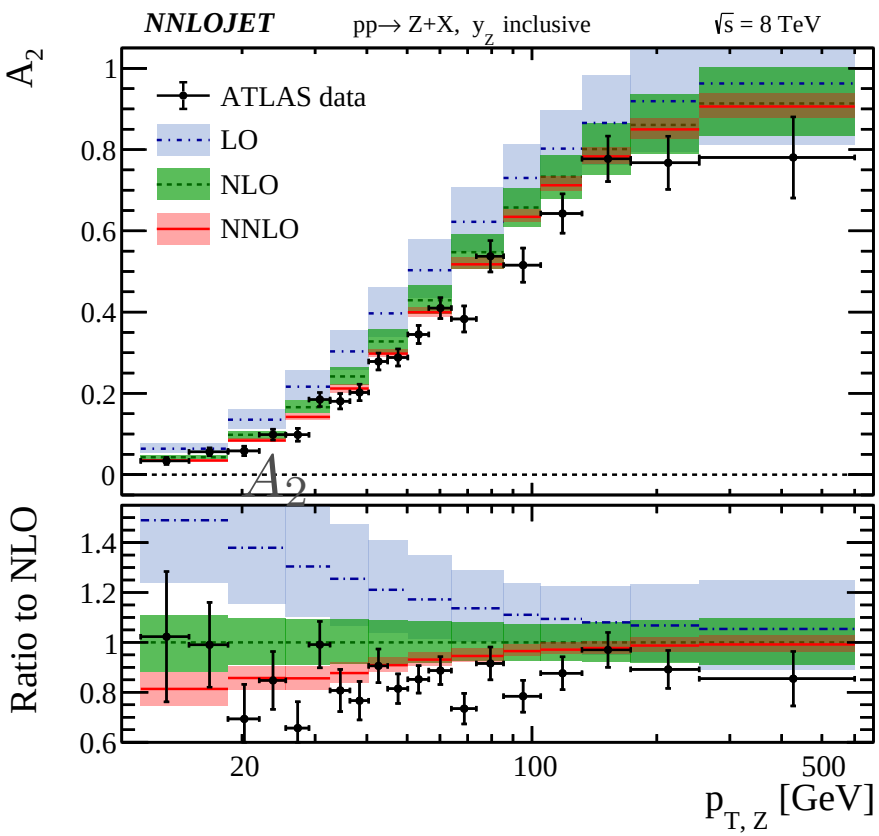
- $\mathrm{pp} \to (\mathrm{Z} \to \ell^+\ell^-) \; + 0, 1$ jets
- $\mathrm{pp} \to (\mathrm{W}^\pm \to \ell\nu) \; + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} \; + 0, 1$ jets, VBF
  $\hookrightarrow \gamma\gamma, \;\; \ell^+\ell^-\gamma, \;\; 4\ell, \ldots$
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 1, \; 2$ jets
- $\mathrm{e}^+\mathrm{e}^- \to 3$ jets
- ...

Ratios — correlated vs. uncorrelated

correlated:



uncorrelated:



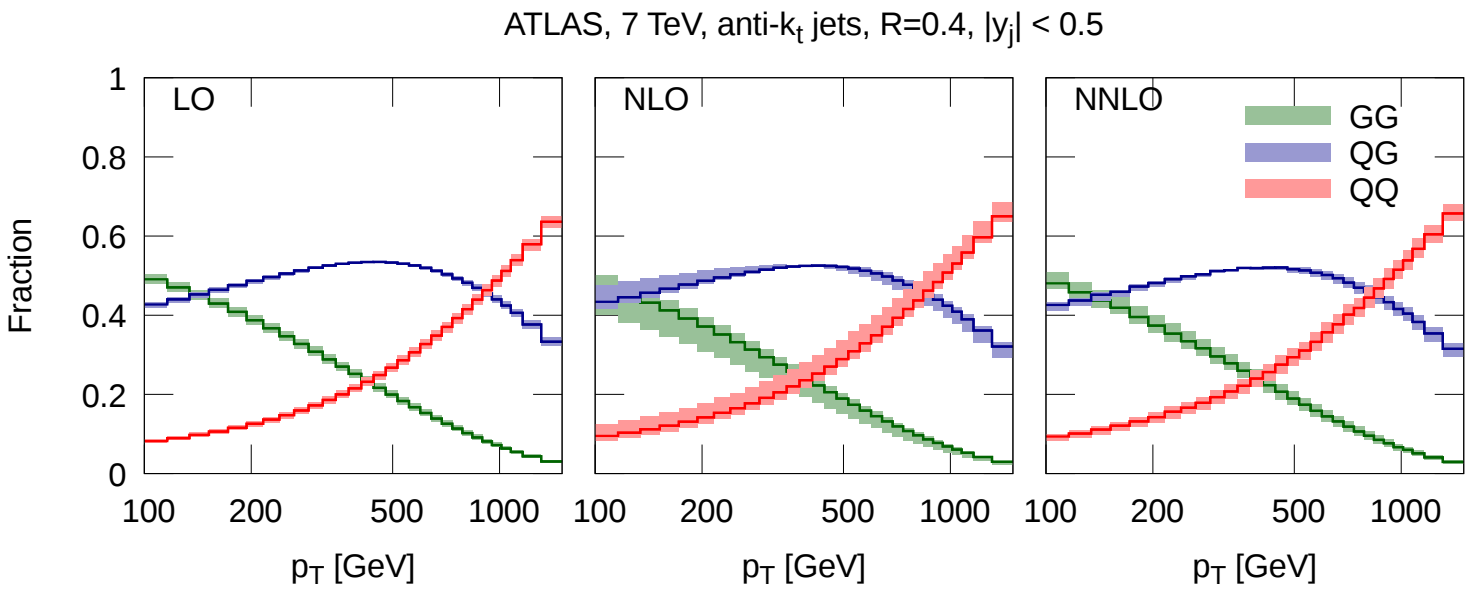
LO α_s cancels in correlated case $\rightsquigarrow$ almost no scale bands

NLO substantial differences in correlated vs. uncorrelated

NNLO similar uncertainty estimates

uncorrelated exhibits more realistic behaviour $\rightsquigarrow$ default choice

Jet Production — Channel Breakdown



gluon–gluon [LC '13] [SLC '14]
↪ low p_T

quark–gluon [LC '16]
↪ low – intermediate p_T

quark–quark [LC '16]
↪ high p_T

*LC = leading colour

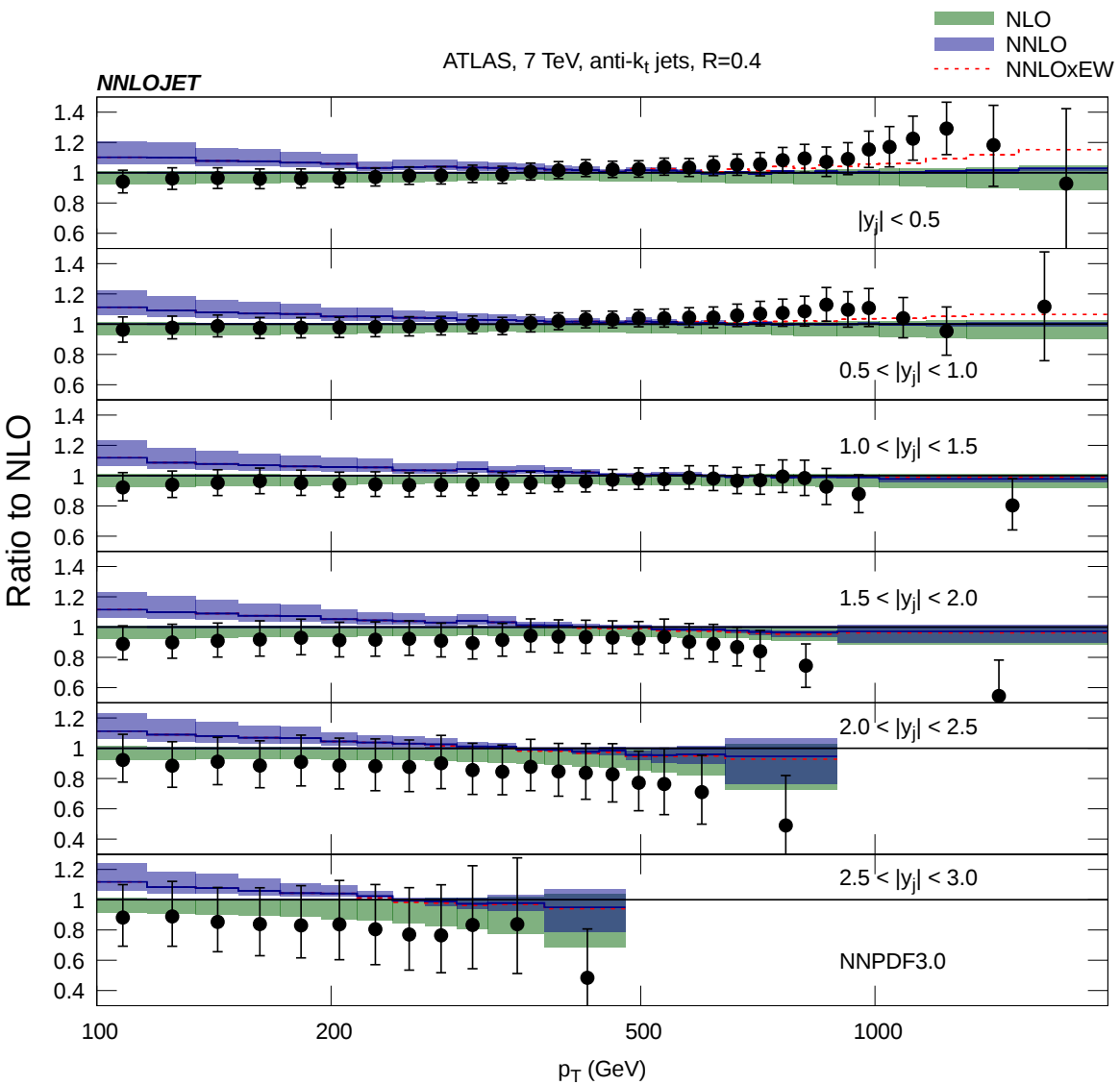
*SLC = sub-leading colour

Analytic Scale Variation

- $L_R = \ln(\mu^2/\mu_0^2)$

$$
\begin{aligned}
\sigma(\mu, \mu_0, \alpha_\mathrm{s}(\mu)) = \quad & \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^2 f_i(\mu_0) \otimes \sigma_{ij}^0 \otimes f_j(\mu_0) \\
& + \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^3 f_i(\mu_0) \otimes \left[\sigma_{ij}^1 + 2\beta_0 L_R \sigma_{ij}^0\right] \otimes f_j(\mu_0) \\
& + \left(\frac{\alpha_\mathrm{s}(\mu)}{2\pi}\right)^4 f_i(\mu_0) \\
& \quad \otimes \left[\sigma_{ij}^2 + 3\beta_0 L_R \sigma_{ij}^1 + (2\beta_1 L_R + 3\beta_0^2 L_R^2)\sigma_{ij}^0\right] \otimes f_j(\mu_0)
\end{aligned}
$$

Inclusive Jet Production — ATLAS @ 7 TeV $(\mu = p_{\mathrm{T,max}})$



NLO $(\rightsquigarrow 1)$

NNLO

↪ high p_{T}:

- small corrections: 1–2%
- reduction of scale uncert.
- convergence of pert. series (esp. central rapidity)

↪ low p_{T}:

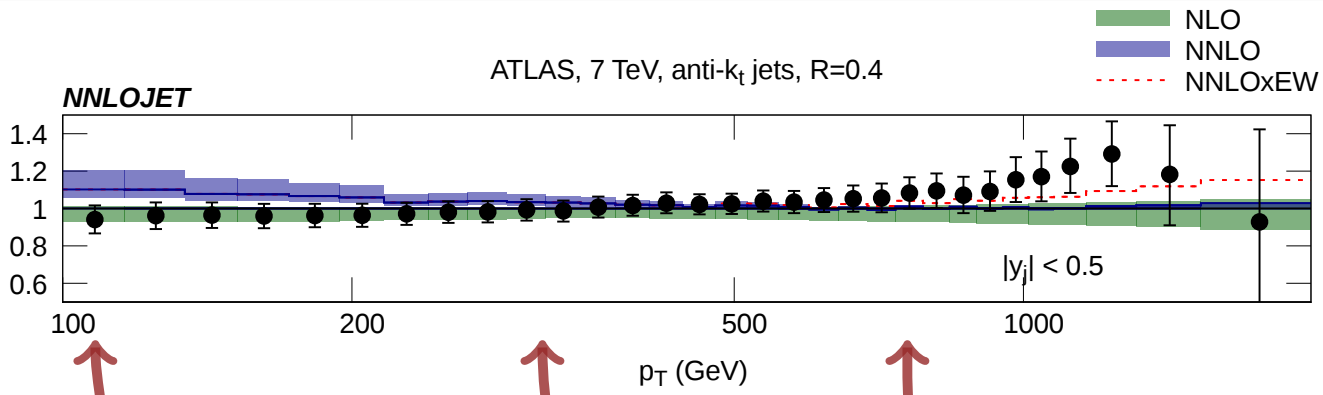
- sizeable corrections: $+10\%$ (across rapidity bins)
- scale bands: NNLO $\simeq$ NLO (non-overlapping)
- NLO: asymmetric scale bands!

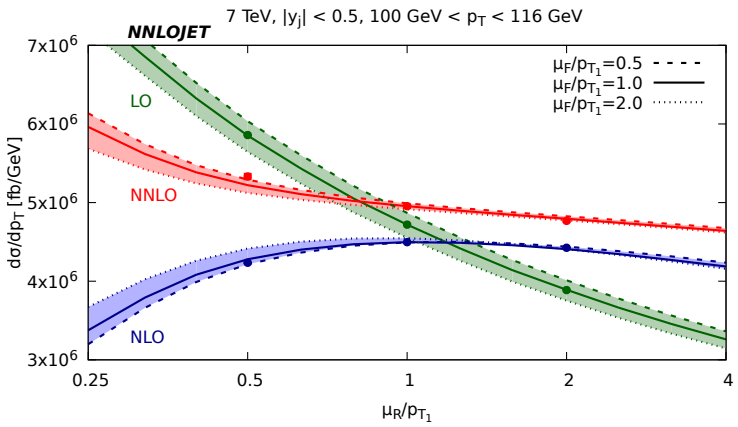
EW corrections - - - -
small – moderate @ high p_{T} & central rapidity

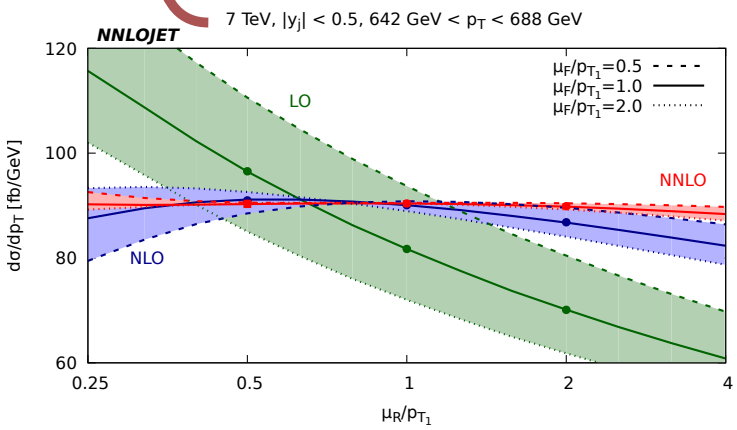
* no non-pert. corrections

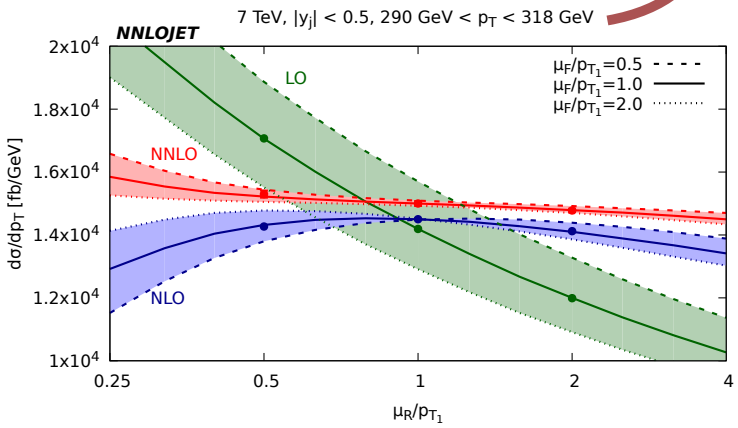
Inclusive Jet Production — Scale Variation $(\mu = p_{\mathrm{T,max}})$

$|y_j| < 0.5$







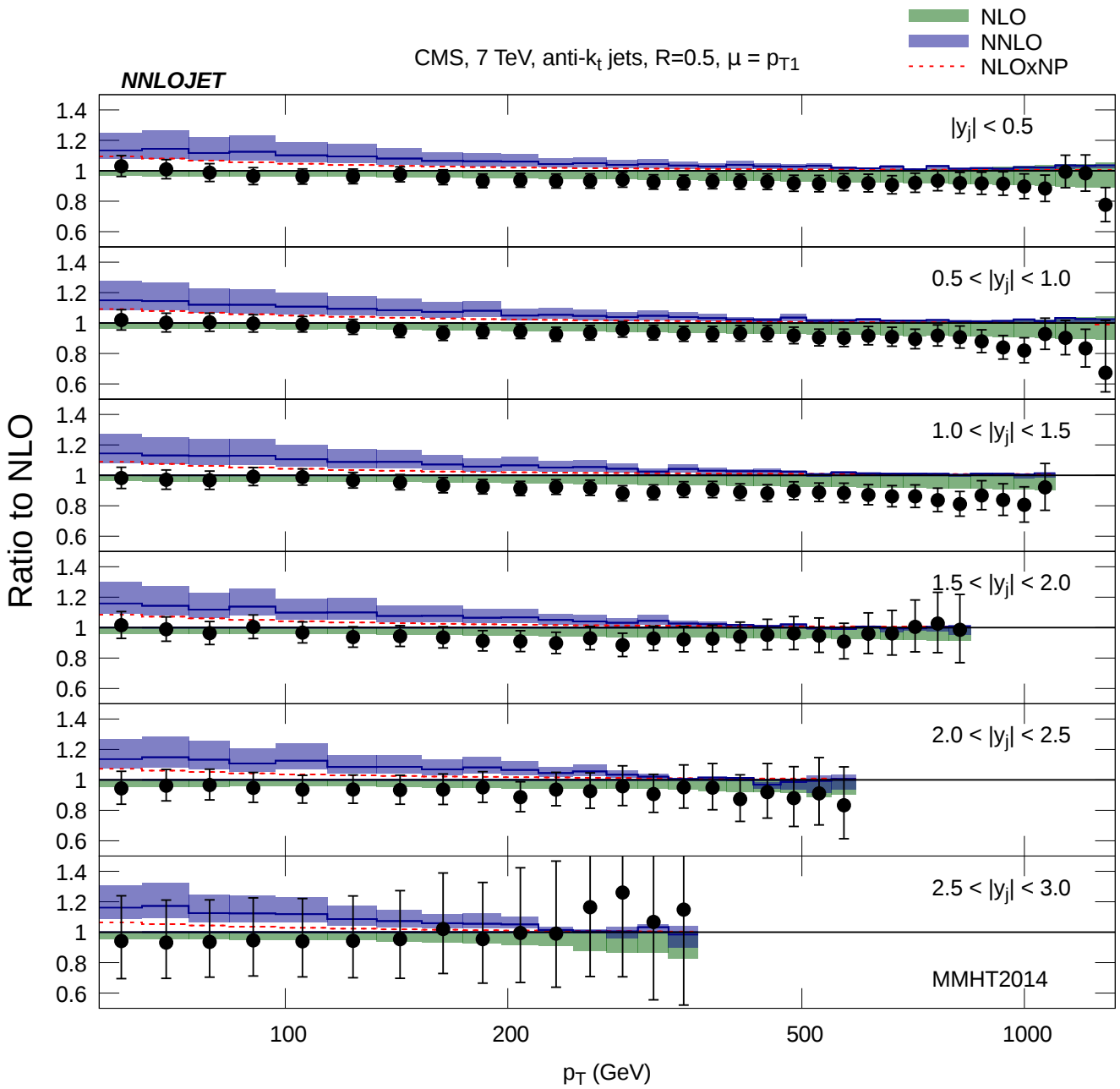


NLO: turn-over @ $\mu_R/p_{T,1} \sim 0.5$–1
↪ asymmetric bands
↪ pert. uncert. underestimated?

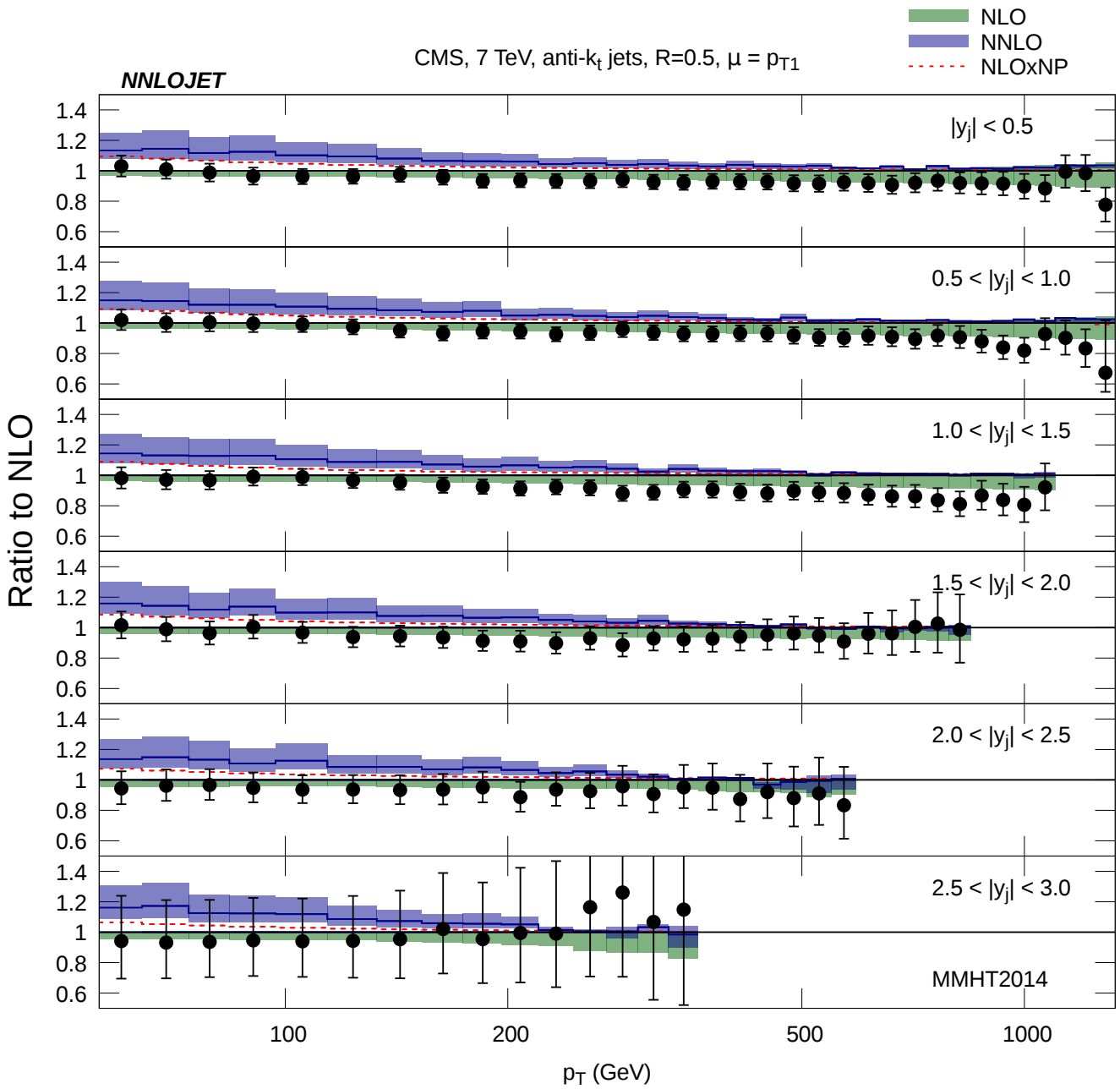
NNLO: monotonically decreasing
↪ symmetric bands

solid: analytic RGE, *points:* NNLOJET

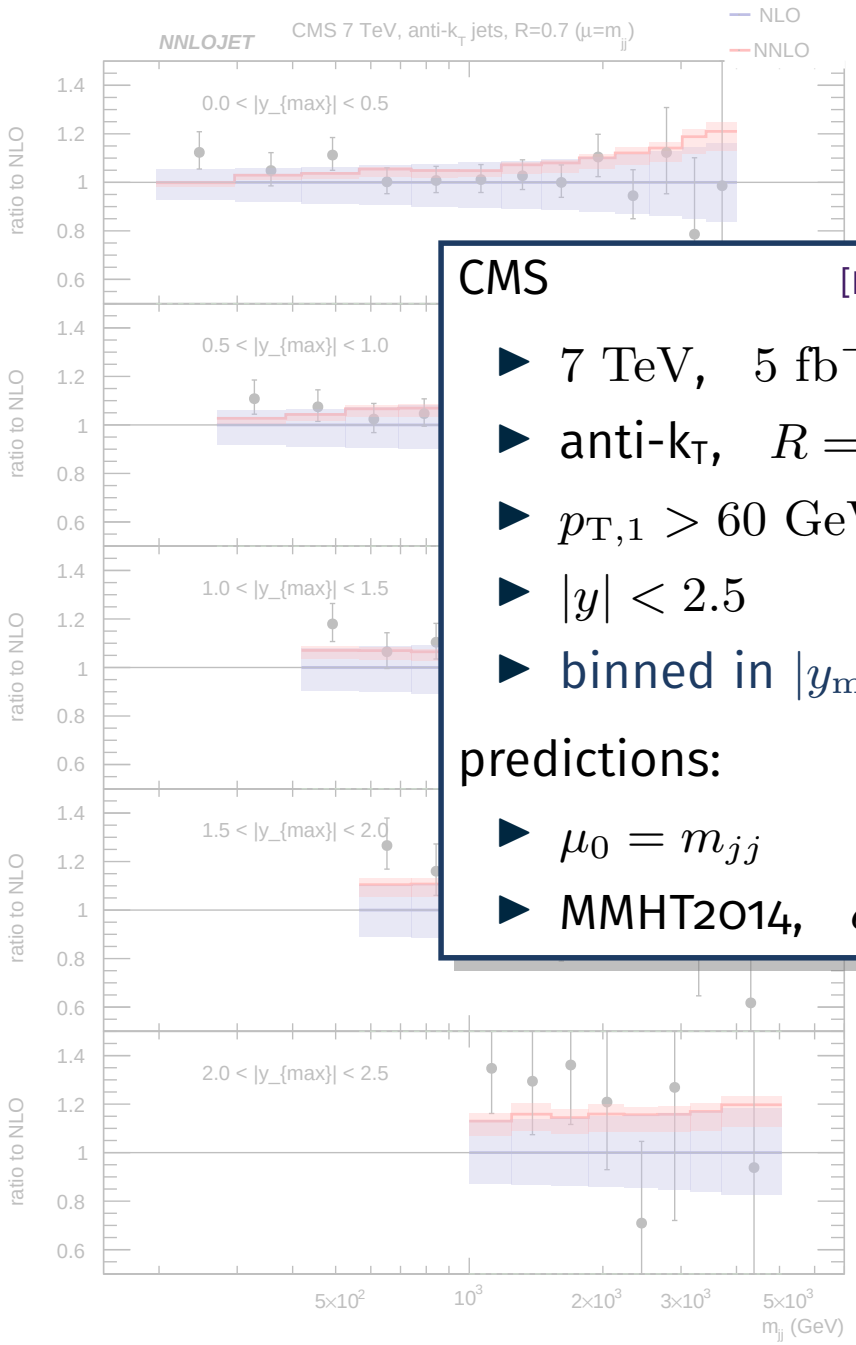
Inc. Jet Production — CMS @ 7 TeV $(R = 0.5)$ $(\mu = p_{\mathrm{T,max}})$



Inc. Jet Production — CMS @ 7 TeV $(R = 0.7)$ $(\mu = p_{\mathrm{T,max}})$



Dijet Production — CMS @ 7 TeV



NLO ($\rightsquigarrow 1$)

NNLO

CMS [Phys. Rev. D 87 (2013) 112002]

- 7 TeV, $5\ \mathrm{fb}^{-1}$
- anti-k_T, $R = 0.7$
- $p_{\mathrm{T},1} > 60\ \mathrm{GeV}$, $p_{\mathrm{T},2} > 30\ \mathrm{GeV}$
- $|y| < 2.5$
- binned in $|y_{\max}|$

predictions:

- $\mu_0 = m_{jj}$
- MMHT2014, $\alpha_s(M_Z) = 0.118$

of scale uncert.

ands

d by NNLO

m_{jj}

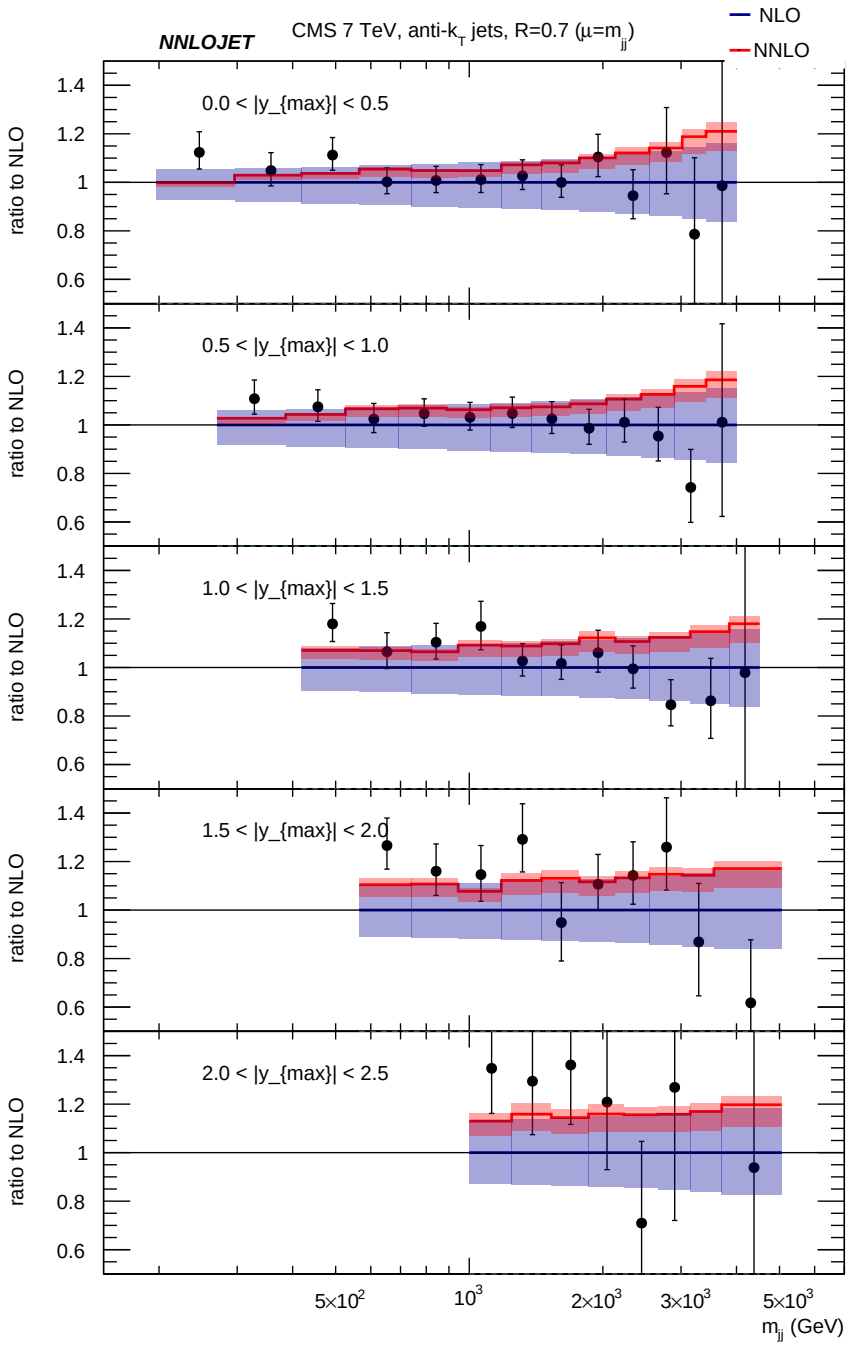
m_{jj}

10–20%

$\sim$ 5–10% @ low-m_{jj}

scales in dijet production
better behaved

Dijet Production — CMS @ 7 TeV



NLO ($\rightsquigarrow 1$)

NNLO

- large reduction of scale uncert.
- overlapping bands

$\hookrightarrow$ low $|y_{\max}|$:

- shape distorted by NNLO
- small @ low-m_{jj}
- $+20\%$ @ high-m_{jj}

$\hookrightarrow$ high $|y_{\max}|$:

- relatively flat: 10–20%

$\hookrightarrow$ NP corrections ~ 5–10% @ low-m_{jj}

scales in dijet production
better behaved