NNLO $V + \text{jet}$

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in collaboration with
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E.W.N. Glover and T.A. Morgan

ZPW2017 — **The second run of the LHC**

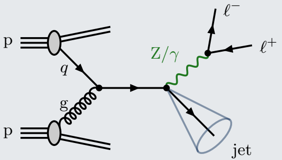
Zurich, January 10th 2017

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

MC@NNLO

based on Phys. Rev. Lett. **117** (2016) 022001, JHEP **1607** (2016) 133, JHEP **1611** (2016) 094

Motivation — Why $Z + \text{jet}$ production?



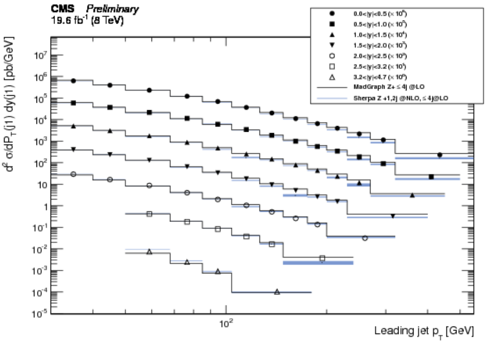
$$\mathrm{p\,p} \to Z/\gamma^* + \text{jet} \to \ell^-\ell^+ + \text{jet} + X$$

- large cross section
- clean leptonic signature

+jet ⇝ sensitivity to α_s, gluon PDF

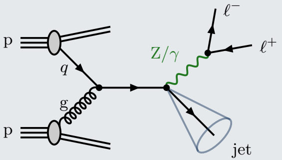
- precision measurements
  - ↪ test pQCD
  - ↪ constrain PDFs (gluon)
- detector calibration
  - ↪ jet energy scale
- searches for BSM physics

high-precision predictions mandatory!



[CMSPAS SMP-14-009]

Motivation — Why $\mathrm{Z} + \mathrm{jet}$ production?



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

- large cross section
- clean leptonic signature

+jet $\rightsquigarrow$ sensitivity to α_s, gluon PDF

Where do we stand?

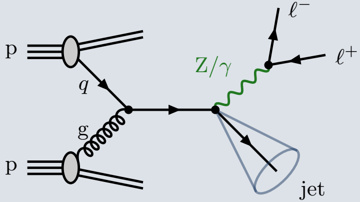
- **NLO QCD** .... [Ellis, Kunszt, Soper '92] [Giele, Glover, Kosower '93]
- **NLO EW** .... [Kühn, Kulesza, Pozzorini, Schulze '05] [Denner, Dittmaier, Kasprzik, Mück '11]
- **NLO QCD+EW** (+multijet merging) .... [Kallweit, Lindert, Maierhofer, Pozzorini, Schönherr '15]
- **NNLO QCD** ....
  ↪ Antenna subtraction (this talk) [Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15, '16]
  ↪ N-jettiness .... [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]
  [Boughezal, Liu, Petriello.'16]

$\rightsquigarrow$ validation (✓) & opportunity for benchmarks

This talk

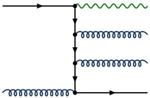
1. $\mathrm{Z} + \mathrm{jet}$ production @ NNLO
2. Inclusive Z-boson production for $p_{\mathrm{T}} \neq 0$
3. The ϕ^*_η observable

$\mathrm{Z} + \mathrm{jet}$ production @ NNLO



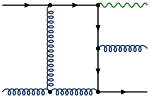
Anatomy of an NNLO calculation

$$\sigma_{\mathrm{NNLO}} = \int_{\Phi_{\mathrm{Z}+3}} \mathrm{d}\sigma^{\mathrm{RR}}_{\mathrm{NNLO}}$$



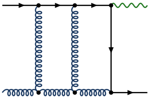
[Hagiwara, Zeppenfeld '89]
[Berends, Giele, Kuijf '89]
[Falck, Graudenz, Kramer '89]

$$+ \int_{\Phi_{\mathrm{Z}+2}} \mathrm{d}\sigma^{\mathrm{RV}}_{\mathrm{NNLO}}$$



[Glover, Miller '97]
[Bern, Dixon, Kosower, Weinzierl '97]
[Campbell, Glover, Miller '97]
[Bern, Dixon, Kosower '98]

$$+ \int_{\Phi_{\mathrm{Z}+1}} \mathrm{d}\sigma^{\mathrm{VV}}_{\mathrm{NNLO}}$$

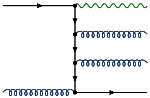


[Moch, Uwer, Weinzierl '02]
[Garlandet al. '02]
[Gehrmann, Tancredi '12]

Individual building blocks known for a while

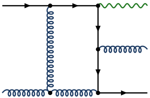
Anatomy of an NNLO calculation

$$\sigma_{\mathrm{NNLO}} = \int_{\Phi_{\mathrm{Z+3}}} \mathrm{d}\sigma^{\mathrm{RR}}_{\mathrm{NNLO}}$$



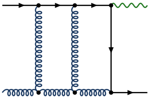
- single-unresolved
- double-unresolved

$$+ \int_{\Phi_{\mathrm{Z+2}}} \mathrm{d}\sigma^{\mathrm{RV}}_{\mathrm{NNLO}}$$



- single-unresolved
- $1/\epsilon^2$, $1/\epsilon$

$$+ \int_{\Phi_{\mathrm{Z+1}}} \mathrm{d}\sigma^{\mathrm{VV}}_{\mathrm{NNLO}}$$



- $1/\epsilon^4$, $1/\epsilon^3$, $1/\epsilon^2$, $1/\epsilon$

$\sum$ finite (Kinoshita–Lee–Nauenberg & factorization)

Non-trivial cancellation of infrared singularities

Anatomy of an NNLO calculation

$$\sigma_{\rm NNLO} = \int_{\Phi_{\rm Z+3}} d\sigma^{\rm RR}_{\rm NNLO}$$

$$+ \int_{\Phi_{\rm Z+2}} d\sigma^{\rm RV}_{\rm NNLO}$$

$$+ \int_{\Phi_{\rm Z+1}} d\sigma^{\rm VV}_{\rm NNLO}$$

$$\sum \qquad \text{finite}$$

Different methods:

- Antenna subtraction .... [Gehrmann–De Ridder, Gehrmann, Glover '05]
- CoLorFul subtraction .... [Del Duca, Somogyi, Trocsanyi '05]
- q_T subtraction .... [Catani, Grazzini '07]
- Sector-improved residue subtraction ..... [Czakon '10], [Boughezal, Melnikov, Petriello '11]
- N-jettiness subtraction .... [Gaunt, Stahlhofen, Tackmann, Walsh '15] [Boughezal, Focke, Liu, Petriello '15]

...

Approaches: subtraction, slicing

$Z + \text{jet}$ @ NNLO using Antenna

$$\sigma_{\rm NNLO} = \int_{\Phi_{Z+3}} \left(\mathrm{d}\sigma^{\rm RR}_{\rm NNLO} - \mathrm{d}\sigma^{\rm S}_{\rm NNLO}\right)$$

$$+ \int_{\Phi_{Z+2}} \left(\mathrm{d}\sigma^{\rm RV}_{\rm NNLO} - \mathrm{d}\sigma^{\rm T}_{\rm NNLO}\right)$$

$$+ \int_{\Phi_{Z+1}} \left(\mathrm{d}\sigma^{\rm VV}_{\rm NNLO} - \mathrm{d}\sigma^{\rm U}_{\rm NNLO}\right)$$

- $\mathrm{d}\sigma^{\rm S}_{\rm NNLO}$, $\mathrm{d}\sigma^{\rm T}_{\rm NNLO}$: mimic $\mathrm{d}\sigma^{\rm RR}_{\rm NNLO}$, $\mathrm{d}\sigma^{\rm RV}_{\rm NNLO}$ in unresolved limits
- $\mathrm{d}\sigma^{\rm T}_{\rm NNLO}$, $\mathrm{d}\sigma^{\rm U}_{\rm NNLO}$: analytic cancellation of poles in $\mathrm{d}\sigma^{\rm RV}_{\rm NNLO}$, $\mathrm{d}\sigma^{\rm VV}_{\rm NNLO}$

$\sum$ finite -0

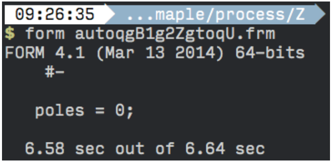
$\Rightarrow$ each line suitable for numerical evaluation in $D = 4$

Antenna subtraction — Checks of the calculation

Analytic pole cancellation

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

DimReg: $D = 4 - 2\epsilon$

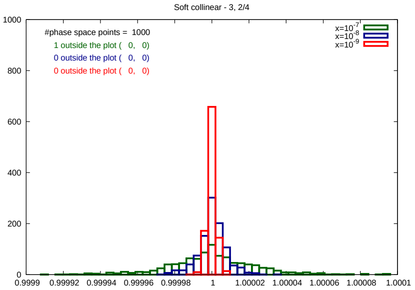


Unresolved limits

- $\mathrm{d}\sigma^{\mathrm{S}} \rightarrow \mathrm{d}\sigma^{\mathrm{RR}}$ (single- & double-unresolved)
- $\mathrm{d}\sigma^{\mathrm{T}} \rightarrow \mathrm{d}\sigma^{\mathrm{RV}}$ (single-unresolved)

bin the ratio: $\mathrm{d}\sigma^{\mathrm{S}}/\mathrm{d}\sigma^{\mathrm{RR}} \xrightarrow{\text{unresolved}} 1$

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



(approach singular limit: $x_i = 10^{-7}, 10^{-8}, 10^{-9}$)

X. Chen, J. Cruz-Martinez, J. Currie, A. Gehrmann-De Ridder, T. Gehrmann,
E.W.N. Glover, AH, 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
  (Work in progress)
- …

Processes:

- $\mathrm{pp} \to V \to \bar{\ell}\ell \; + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} \; + 0, 1, 2$ jets
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 1, \; 2$ jets
- $\mathrm{e}^+\mathrm{e}^- \to 3$ jets
- …

$Z + \text{jet}$: Fiducial cross section

Calculational setup

[Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15]

- LHC @ 8 TeV [NNPDF2.3]: $\alpha_s(M_Z) = 0.118$
- select resonant Z bosons: $80\ \text{GeV} < m_{\ell\ell} < 100\ \text{GeV}, \quad |y^\ell| < 5$
- jets [anti-k_T ($R = 0.5$)]: $p_T^{\text{jet}} > 30\ \text{GeV}, \quad |y^{\text{jet}}| < 3$
- scale choice: $\mu_F = \mu_R = M_Z \times [\frac{1}{2}, 1, 2]$

Fiducial cross section

$$\sigma_{\text{LO}} = 103.6^{+7.7}_{-7.5}\ \text{pb}$$

+40%

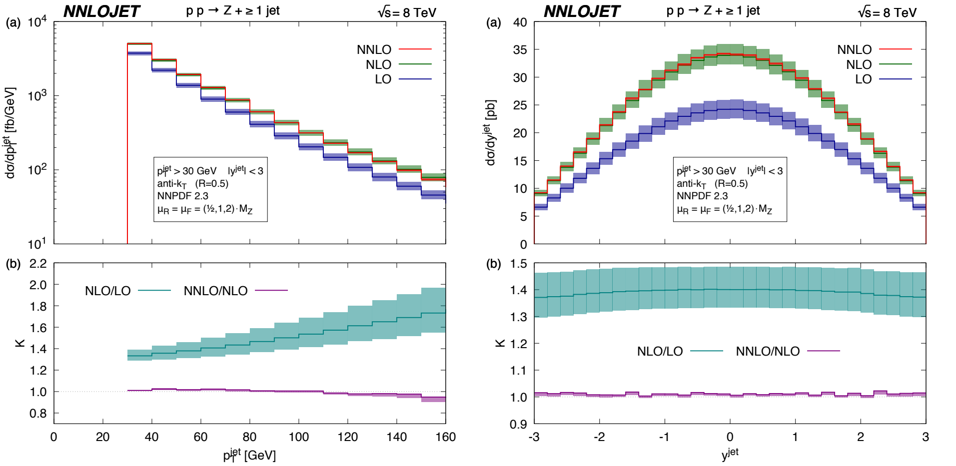
$$\sigma_{\text{NLO}} = 144.4^{+9.0}_{-7.2}\ \text{pb}$$

+1%

$$\sigma_{\text{NNLO}} = 145.8^{+0.0}_{-1.2}\ \text{pb}$$

starting from NLO, all partonic channels open up: qg, $q\bar{q}$, gg, qq', …

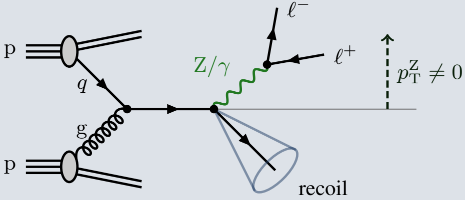
Distributions: Leading jet



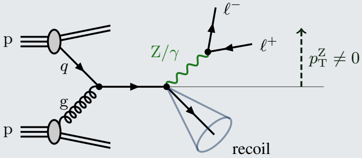
- NLO corrections $\gtrsim 40\%$ $\quad (\delta_{\text{scale}}^{\text{NLO}} \sim \delta_{\text{scale}}^{\text{LO}})$
- NNLO corrections $\lesssim 5\%$ (quite flat)
- significant reduction of scale uncertainty

$$K = \frac{\mathrm{d}\sigma^{\mathrm{(N)NLO}}(\mu)}{\mathrm{d}\sigma^{\mathrm{(N)LO}}(\mu = M_Z)}$$

Inclusive Z-boson production for $p_{\mathrm{T}} \neq 0$



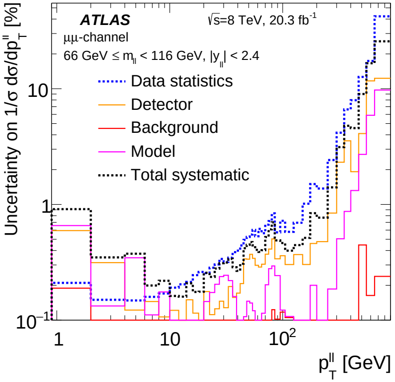
Motivation — Towards precision phenomenology



$$p\,p \rightarrow Z/\gamma^* + X \rightarrow \ell^-\ell^+ + X$$

- large cross section
- clean leptonic signature

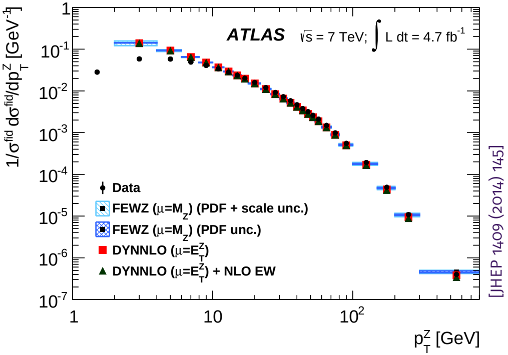
recoil ⇝ sensitivity to α_s, gluon PDF



[Eur. Phys. J. C **76** (2016) no.5, 291]

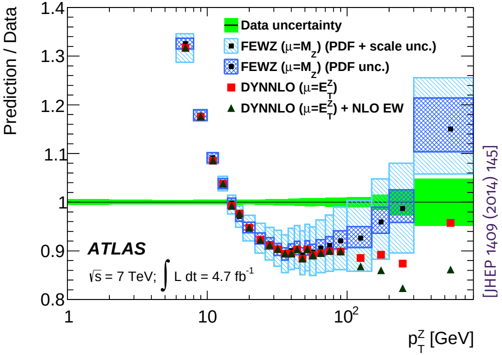
- fully inclusive w.r.t. QCD radiation
- only reconstruct ℓ^+, ℓ^-
  - ⇝ sub-% accuracy!
- potential to constrain gluon PDFs
  - ⇝ NNLO needed! [Malik, Watt '14]

Inclusive p_T^Z at fixed order



- low $p_T^Z \lesssim 10$ GeV: resummation required
- $p_T^Z \gtrsim 20$ GeV: fixed-order prediction $\sim 10\%$ below data!
- high $p_T^Z \gtrsim 500$ GeV: EW corrections ~ -5 - 10%

Inclusive p_T^Z at fixed order



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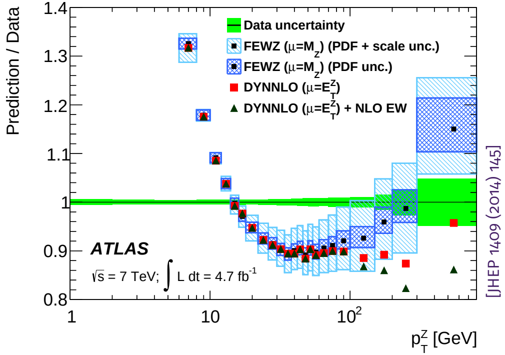
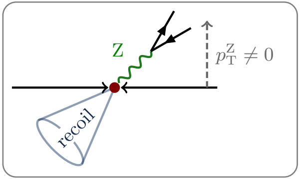
Inclusive p_{T}^{Z} at fixed order

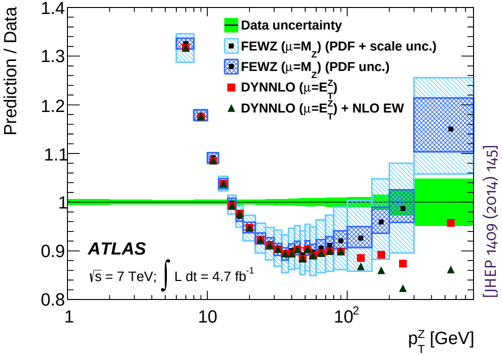


FEWZ
DYNNLO } $\mathrm{Z} + 0\,\mathrm{jet}$ @ NNLO

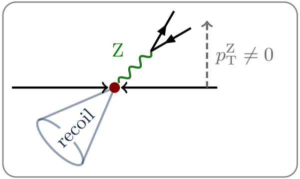


↪ Only NLO accurate in this distribution!

Inclusive p_T^Z at fixed order



FEWZ
DYNNLO
} $\mathrm{Z} + 0\,\mathrm{jet}$ @ NNLO



↪ Only NLO accurate in this distribution!

NNLO

$p_T^Z > p_{T,\mathrm{cut}}^Z = 20\ \mathrm{GeV}$

- requires hadronic recoil

⇝ $\mathrm{Z} + \geq 1\mathrm{jet}$ @ NNLO

Inclusive p_T^Z spectrum: Setup

Calculational setup

- LHC @ 8 TeV
- PDF: `NNPDF3.0` $\alpha_s(M_Z) = 0.118$
- ~~jet cuts~~ $\longleftrightarrow$ fully inclusive w.r.t. QCD radiation
- $p_T^Z > 20$ GeV
- scale choice (dynamical)

$$\mu_F = \mu_R = \sqrt{m_{\ell\ell}^2 + p_{T,Z}^2} \times \left[\tfrac{1}{2}, 1, 2\right]$$

ATLAS setup

[arXiv:1512.02192]

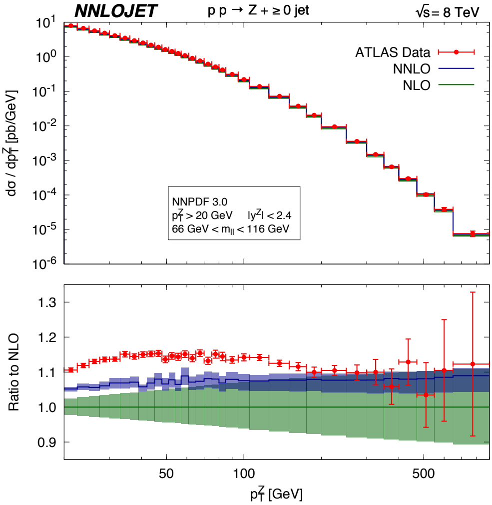
- $p_T^{\ell^\pm} > 20$ GeV, $|y^{\ell^\pm}| < 2.4$
- 66 GeV $< m_{\ell\ell} <$ 116 GeV
  + binning in y^Z
- $|y^Z| < 2.4$ + binning in $m_{\ell\ell}$

CMS setup

[arXiv:1504.03511]

- $p_T^{\ell_1} > 25$ GeV, $|y^{\ell_1}| < 2.1$
- $p_T^{\ell_2} > 10$ GeV, $|y^{\ell_2}| < 2.4$
- 81 GeV $< m_{\ell\ell} <$ 101 GeV
  + binning in y^Z

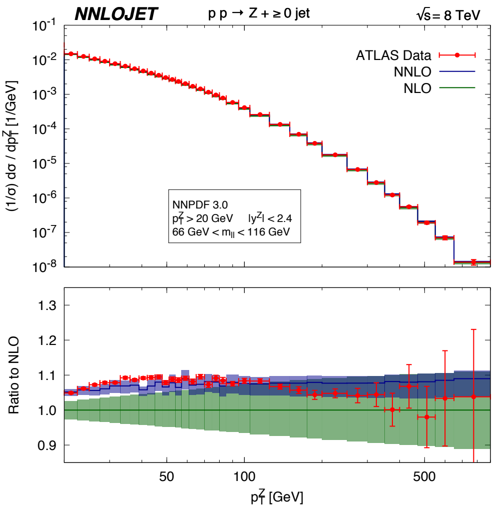
Inclusive p_{T} spectrum of Z/γ^*



- NNLO corrections
  ↪ goes into right direction
- still undershoots data by $\sim 5\%$
- Note: data does not include the $\pm 2.8\%$ luminosity error!
  ↪ use normalised distributions

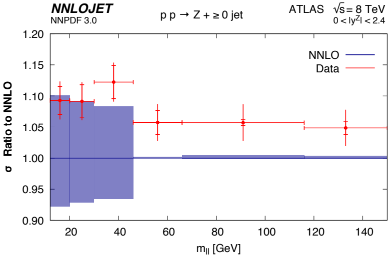
$$\frac{1}{\sigma} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

Inclusive p_{T} spectrum of Z/γ^*

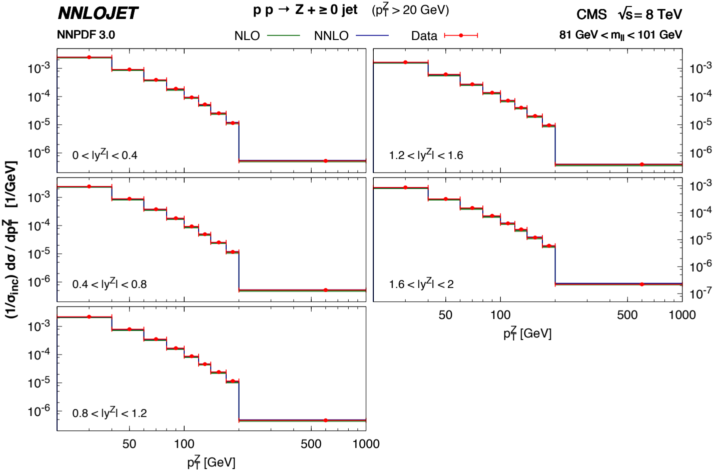


$$\frac{1}{\sigma} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

- uncorrelated scale variation $\leftrightarrow$ numerator & denominator
- significant improvement in Data vs. Theory

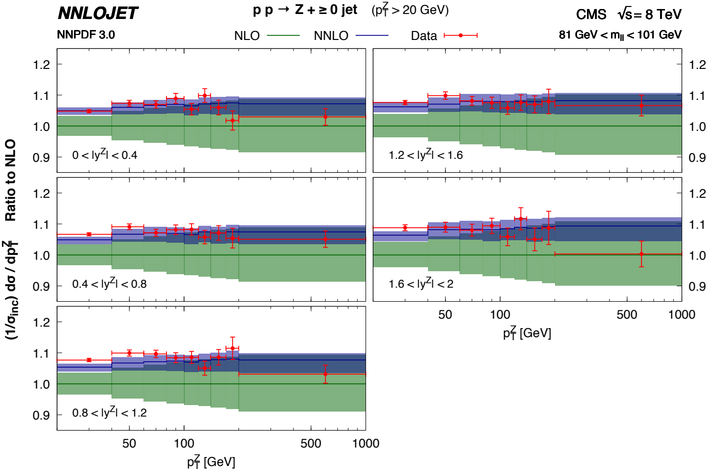


Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^\mathrm{Z}$ binned in y^Z — CMS



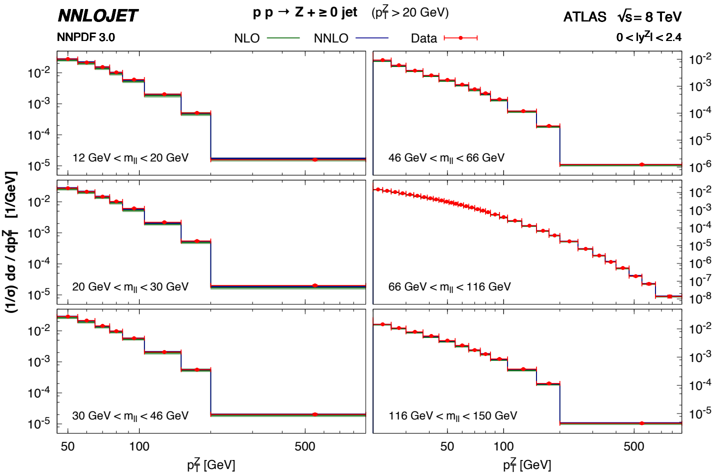
- $81\ \mathrm{GeV} < m_{\ell\ell} < 101\ \mathrm{GeV}$ (narrower mass window than ATLAS)
- 5 bins in y^Z: $[0,\ 0.4]$ $[0.4,\ 0.8]$ $[0.8,\ 1.2]$ $[1.2,\ 1.6]$ $[1.6,\ 2]$

Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{Z}$ binned in y^{Z} — CMS



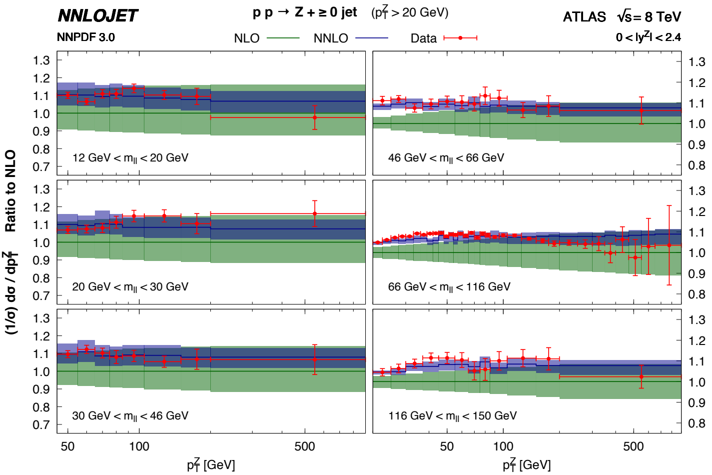
- ▶ NLO prediction systematically undershoots data, NNLO corrections ~ 5–10%
- ▶ improvement in **theory** vs. **data** comparison
- ▶ reduction of scale uncertainties

Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}$ binned in $m_{\ell\ell}$ — ATLAS



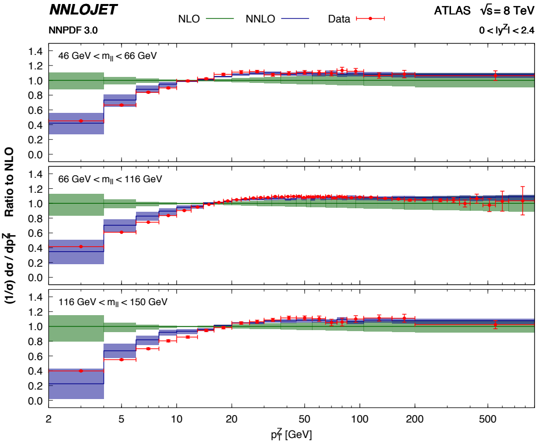
- $0 < |y^{\mathrm{Z}}| < 2.4$
- 6 bins in $m_{\ell\ell}$ [GeV]: [12, 20] [20, 30] [30, 46] [46, 66] [66, 116] [116, 150]

Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}$ binned in $m_{\ell\ell}$ — ATLAS



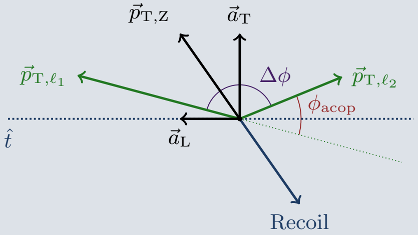
- significant tension between NLO prediction and data $(m_{\ell\ell} \geq 46\ \mathrm{GeV})$
- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties

low-p_T^Z region: $d\sigma/dp_T^Z$ binned in $m_{\ell\ell}$ — ATLAS

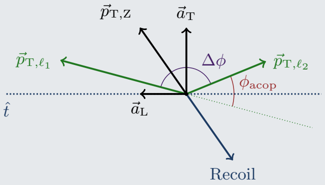


- $p_T^Z > 2\text{ GeV}$ (first bin $\in [0, 2]$ GeV)
- **NLO:** bad description below $p_T^Z \lesssim 40\text{ GeV}$
- **NNLO:** shape well reproduced down to $p_T^Z \sim 5\text{ GeV}$
- deviation @ lower values: onset of large logarithmic corrections

The ϕ_η^* observable



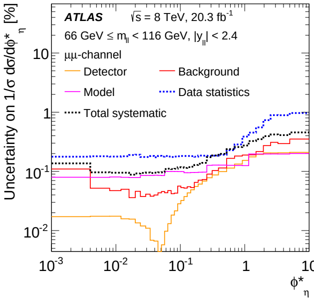
Motivation — A precision probe in the low-p_T^Z regime



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

- large cross section
- clean leptonic signature

recoil $\rightsquigarrow$ sensitivity to α_s, gluon PDF



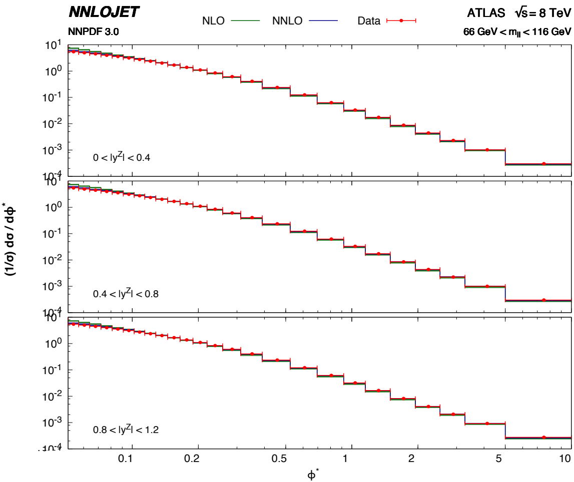
[Eur. Phys. J. C **76** (2016) no.5, 291]

$$\phi^*_\eta = \tan\left(\frac{\phi_{acop}}{2}\right)\cdot\sin(\theta^*_\eta)$$

- $\phi_{acop} = \pi - \Delta\phi, \quad \cos(\theta^*_\eta) = \tanh[(\eta^{\ell^-} - \eta^{\ell^+})/2]$
- only depends on $\ell^\pm$ directions (not energies)

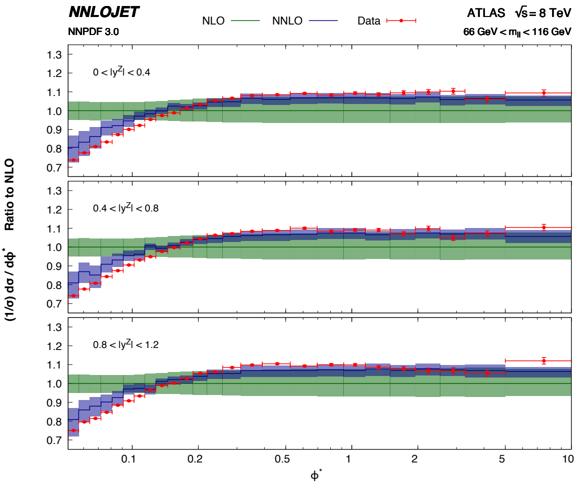
  $\rightsquigarrow$ better experimental resolution
- similar to p_T^Z: $\phi^*_\eta > 0 \quad \Rightarrow \quad Z + \text{jets}$

$\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ binned in y^Z — high ϕ^*_η (> 0.051)



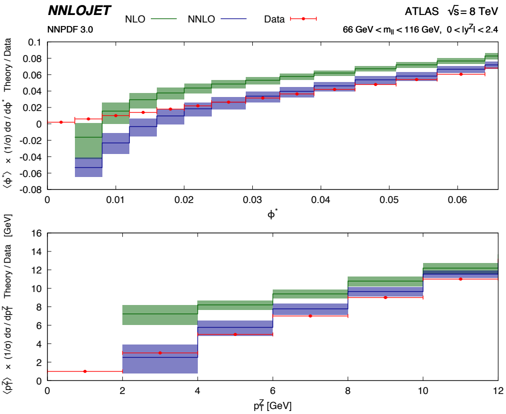
- $66~\mathrm{GeV} < m_{\ell\ell} < 116~\mathrm{GeV}$
- 6 bins in y^Z: $[0,\ 0.4]$ $[0.4,\ 0.8]$ $[0.8,\ 1.2]$ $[1.2,\ 1.6]$ $[1.6,\ 2]$ $[2,\ 2.4]$

$d\sigma/d\phi^*_\eta$ binned in y^Z — high ϕ^*_η (> 0.051)



- high ϕ^*_η: NNLO corrections $\sim 10\%$, low ϕ^*_η: significant shape distortion
- improvement in **theory** vs. **data** comparison & reduction of scale uncertainties
- extends validity of fixed-order predictions before resummation takes over

$\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ vs. $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^\mathrm{Z}$ — small ϕ^*_η



- relation between ϕ^*_η & p_T^Z: $\phi^*_\eta \approx \frac{p_\mathrm{T}^\mathrm{Z}}{2m_{\ell\ell}}$ $\rightsquigarrow$ align x-ranges
- **NLO:** does not describe data in plotting range
- **NNLO:** reliable down to $\phi^*_\eta \sim 0.02 \quad \leftrightarrow \quad p_\mathrm{T}^\mathrm{Z} \sim 4\,\mathrm{GeV}$

Summary & Outlook

Summary

- NNLO corrections to $\mathrm{Z}+\mathrm{jet}$ production completed
- implementation in a flexible parton-level event generator NNLOJET
- related observables: inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum, ϕ_{η}^{*}
  - ↪ improvement in the theory vs. data comparison
  - ↪ NNLO extends range of validity

Outlook

- further studies:
  - ↪ angular coefficients, PDF fits, …
- development on NNLOJET
  - ↪ interface to `APPLfast-NNLO`, more processes, performance, …

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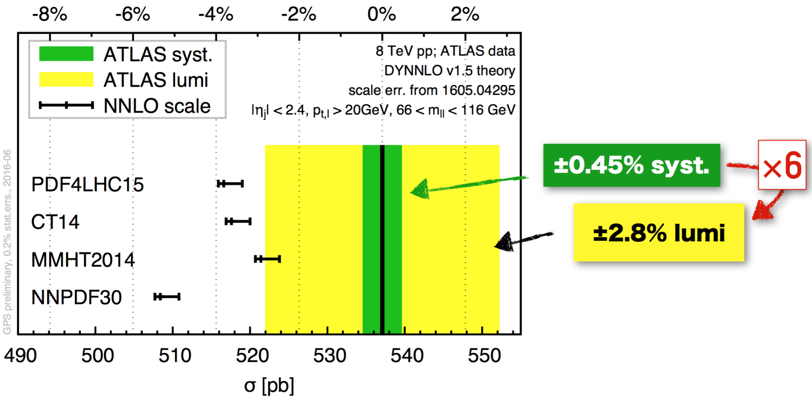
Thank you

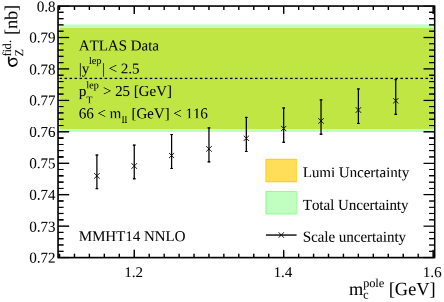
Backup Slides

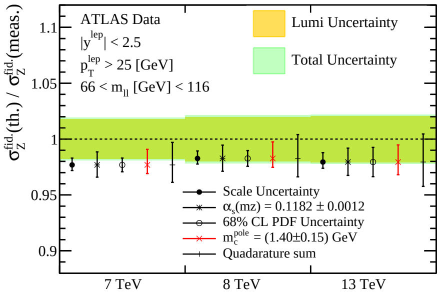
The fiducial Drell–Yan cross section



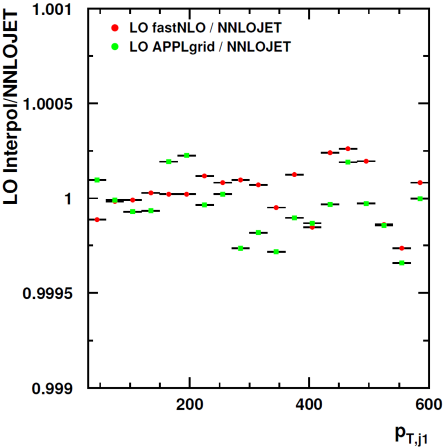
[talk by Gavin Salam, LHCP 2016]

The fiducial Drell–Yan cross section — m_c dep.





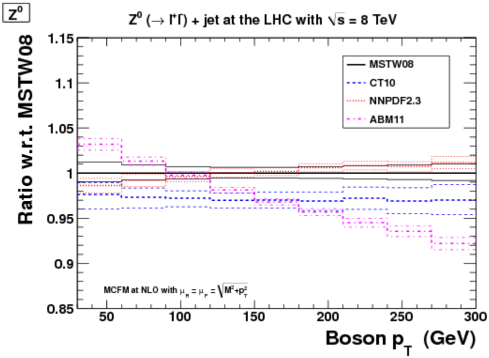
APPLfast-NNLO



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

- single interface between NNLOJET
  + APPLgrid
  + fastNLO
- proof-of-concept implementation ✓
- closure test for all parts (VV, RV, RR) ✓
- todo: phase-space optimisation, merging of runs, performance, …

PDF constraints from $p_{\mathrm{T}}^{\mathrm{Z}}$



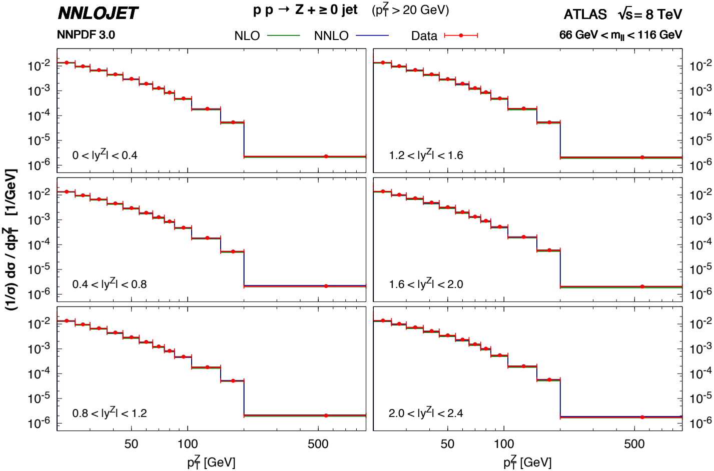
- $p_{\mathrm{T}}^{\mathrm{Z}} \gtrsim M_{\mathrm{Z}} \rightsquigarrow$ fixed-order reliable
- left: only PDF uncertainties!
  (NLO scale uncertainty: $\sim 10\%$)
- potential to constrain gluon PDFs

$\Rightarrow$ NNLO calculation needed!

[Malik, Watt '14]

- repeat study at NNLO using newest generation of PDF sets
- work in progress: interface to `APPLgrid`, `fastNLO`
- tag flavour: $\mathrm{Z} + \mathrm{b}(\mathrm{b}) \leftrightarrow$ constrain b-quark PDFs

Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}$ binned in y^{Z} — ATLAS



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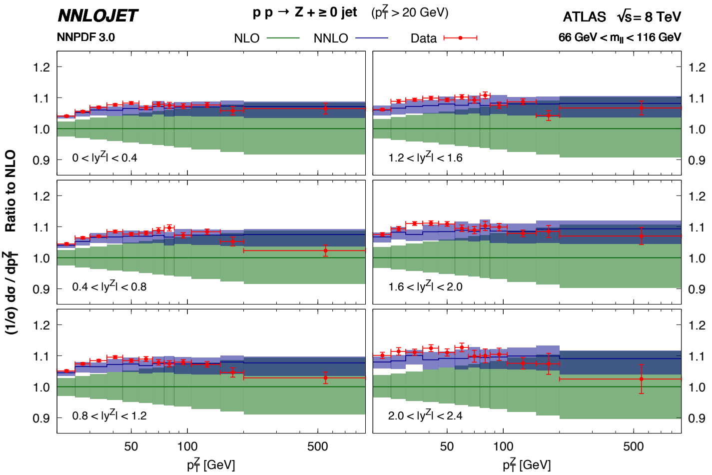


- improvement in **theory** vs. **data** comparison $(+5\text{–}10\%$ NNLO corrections$)$
- reduction of scale uncertainties

The small ϕ^*_η region

- domain of large logarithms
  - ↪ breakdown of fixed-order predictions
- relation between p_T^Z & ϕ^*_η
  - ↪ compare leading-logarithmic behaviour

$$p_\mathrm{T}^\mathrm{Z}\left(\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}^\mathrm{Z}}\right)_\mathrm{LL} \sim -4C_F\frac{\alpha_\mathrm{s}}{\pi}\ln\left(\frac{(p_\mathrm{T}^\mathrm{Z})^2}{m_{\ell\ell}^2}\right) + 2C_F^2\left(\frac{\alpha_\mathrm{s}}{\pi}\right)^2\ln^3\left(\frac{(p_\mathrm{T}^\mathrm{Z})^2}{m_{\ell\ell}^2}\right) + \ldots$$

$$\phi^*_\eta\left(\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi^*_\eta}\right)_\mathrm{LL} \sim -4C_F\frac{\alpha_\mathrm{s}}{\pi}\ln\left(4(\phi^*_\eta)^2\right) + 2C_F^2\left(\frac{\alpha_\mathrm{s}}{\pi}\right)^2\ln^3\left(4(\phi^*_\eta)^2\right) + \ldots$$

$$\Rightarrow \quad \phi^*_\eta \approx \frac{p_\mathrm{T}^\mathrm{Z}}{2m_{\ell\ell}}$$

Z+jet: Channel breakdown

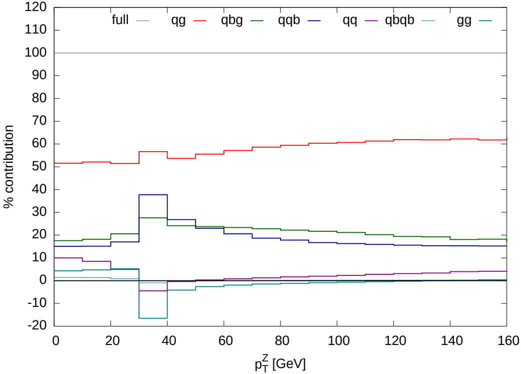
Variety of partonic channels contribute to Z+jet production

↪ what are the most important sub-processes?

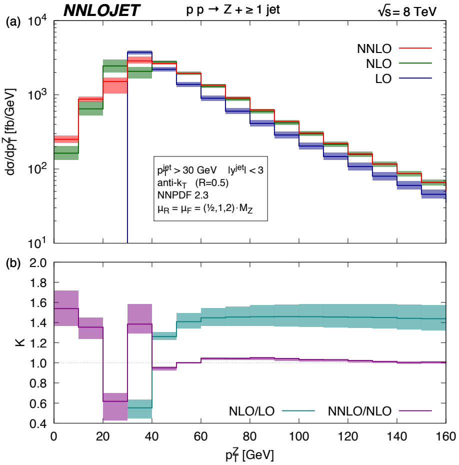
↪ channel breakdown @ NLO (default cuts & scale choice)

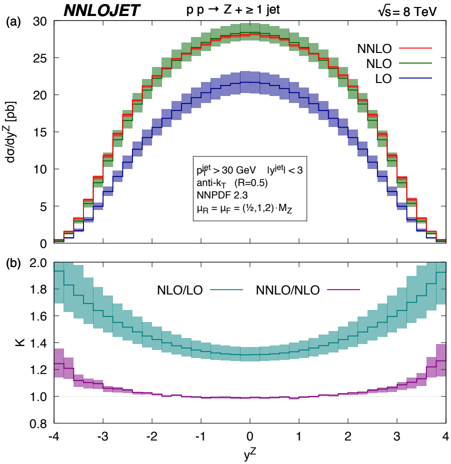
Total cross section

initial state	contribution
qg	56%
$q\bar{q}$	23%
$\bar{q}g$	23%
gg	−3%
qq	1%
$\bar{q}\bar{q}$	0.1%



Distributions: Z-boson

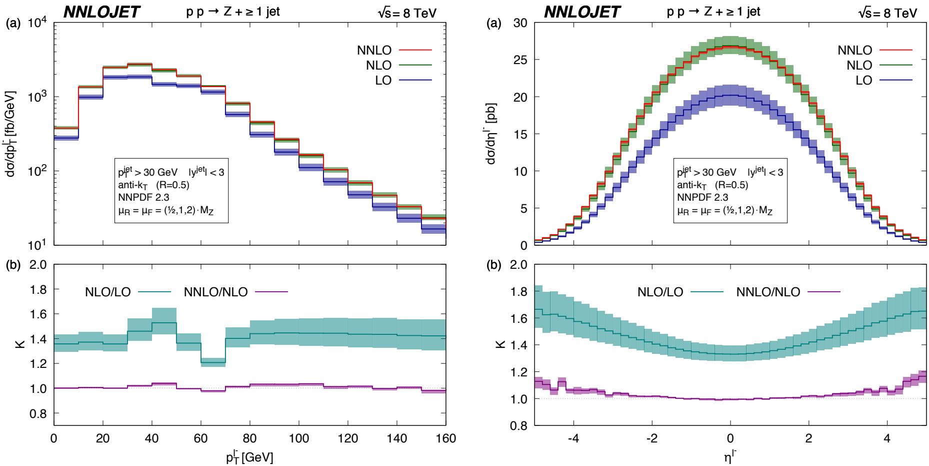




- "Sudakov shoulder" at $p_T^Z \sim 30$ GeV
- NNLO corrections not flat!
- significant reduction of scale uncertainty

$$K = \frac{d\sigma^{(N)NLO}(\mu)}{d\sigma^{(N)LO}(\mu = M_Z)}$$

Distributions: lepton ℓ^-



- significant reduction of scale uncertainty

$$K = \frac{d\sigma^{(N)NLO}(\mu)}{d\sigma^{(N)LO}(\mu = M_Z)}$$