$Z + \text{jet}$ production at NNLO

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

Loops and Legs
in Quantum Field Theory
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ETH
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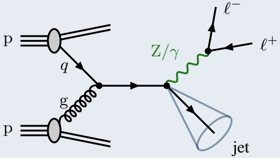
MC@NNLO

$\mathrm{Z} + \mathrm{jet}$ production at the LHC

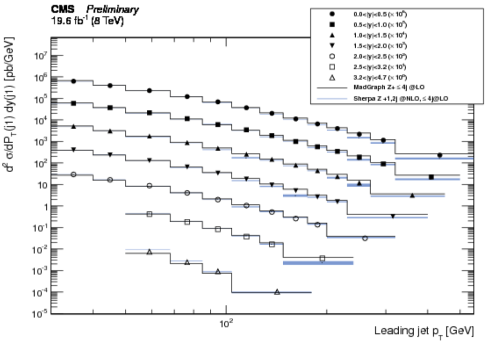


$$\mathrm{p\,p} \to \mathrm{Z}/\gamma^* + \mathrm{jet} \to \ell^-\ell^+ + \mathrm{jet} + X$$

- large cross section
- clean leptonic signature

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

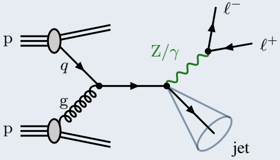
high-precision predictions mandatory!



[CMSPAS SMP-14-009]

Motivation

$\mathrm{Z} + \mathrm{jet}$ production at the LHC



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

- large cross section
- clean leptonic signature

Theory status

- **NLO QCD** .... [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] (talk by P. Maierhofer)
- **NNLO QCD** ....
  - ↪ Antenna subtraction ... (this talk) [Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15]
  - ↪ N-jettiness .... [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]
    (talk by K. Ellis) [Boughezal, Liu, Petriello.'16]

Outline

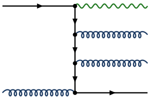
1. $\mathrm{Z} + \mathrm{jet}$ @ NNLO using Antenna Subtraction

2. Numerical results for $\mathrm{Z} + \mathrm{jet}$ production

3. The inclusive p_{T} spectrum of the Z boson

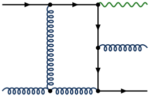
Anatomy of an NNLO calculation

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



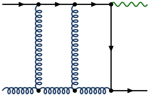
[Hagiwara, Zeppenfeld '89]
[Berends, Giele, Kuijf '89]
[Falck, Graudenz, Kramer '89]

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



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

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

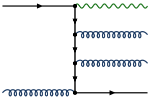


[Moch, Uwer, Weinzierl '02]
[Garlandet al. '02]
[Gehrmann, Tancredi '12]

Individual building blocks known for a while

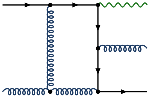
Anatomy of an NNLO calculation

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



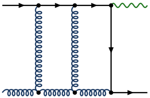
- single-unresolved
- double-unresolved

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



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

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



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

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

Non-trivial cancellation of infrared singularities

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

$$
\begin{aligned}
\sigma_{\text{NNLO}} = & \int_{\Phi_{Z+3}} \left(\mathrm{d}\sigma_{\text{NNLO}}^{\text{RR}} - \mathrm{d}\sigma_{\text{NNLO}}^{\text{S}} \right) \\
& + \int_{\Phi_{Z+2}} \left(\mathrm{d}\sigma_{\text{NNLO}}^{\text{RV}} - \mathrm{d}\sigma_{\text{NNLO}}^{\text{T}} \right) \\
& + \int_{\Phi_{Z+1}} \left(\mathrm{d}\sigma_{\text{NNLO}}^{\text{VV}} - \mathrm{d}\sigma_{\text{NNLO}}^{\text{U}} \right)
\end{aligned}
$$

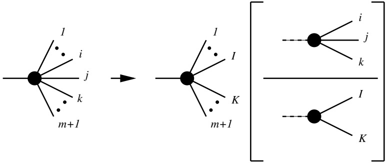
- $\mathrm{d}\sigma_{\text{NNLO}}^{\text{S}}, \mathrm{d}\sigma_{\text{NNLO}}^{\text{T}}$: mimic $\mathrm{d}\sigma_{\text{NNLO}}^{\text{RR}}, \mathrm{d}\sigma_{\text{NNLO}}^{\text{RV}}$ in unresolved limits
- $\mathrm{d}\sigma_{\text{NNLO}}^{\text{T}}, \mathrm{d}\sigma_{\text{NNLO}}^{\text{U}}$: analytic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

$\sum$ finite -0

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

Antenna Subtraction Formalism

- exploit <u>universal</u> factorization properties in the IR limits (colour-ordering):



- phase-space factorization

$$\mathrm{d}\Phi(\ldots,p_i,p_j,p_k,\ldots) = \mathrm{d}\Phi(\ldots,\tilde{p}_I,\tilde{p}_K,\ldots)\cdot \mathrm{d}\Phi_{X_{ijk}}(p_i,p_j,p_k;\tilde{p}_I+\tilde{p}_K)$$

All building blocks available!

X_3^0, X_4^0, X_3^1 and integrated counterparts $\mathcal{X}_3^0$, $\mathcal{X}_4^0$, $\mathcal{X}_3^1$

$\forall$ configurations relevant at hadron colliders
$\hookrightarrow$ final–final, initial–final, initial–initial

```
   _  ___  ____    ____     __________
  / |/ / |/ / /   / __ \__ / / __/_  __/
 /    /    / /__/ /_/ / // / _/  / /
/_/|_/_/|_/____/\____/\___/___/ /_/
```

X. Chen, J. Cruz-Martinez, J. Currie, A. Gehrmann–De Ridder, T. Gehrmann, E.W.N. Glover, AH, M. Jaquier, T. Morgan, J. Niehues, J. Pires

Common code base for NNLO corrections using Antenna Subtraction

- $\mathrm{pp} \to \mathrm{Z}/\gamma^* \to \ell^+\ell^- \ + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} \to \gamma\gamma \ + 0, 1, 2$ jets
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 2$ jets (talk by J. Niehues)
- ...

- Fully differential parton-level event generator
- Work in progress: Interface to `APPLgrid`, `fastNLO`

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: $D = 4 - 2\epsilon$

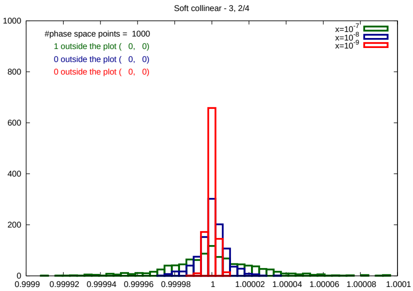
```
09:26:35  ...maple/process/Z
$ form autoqgB1g2ZgtoqU.frm
FORM 4.1 (Mar 13 2014) 64-bits
   #-

   poles = 0;

  6.58 sec out of 6.64 sec
```

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: $x_i = 10^{-7}, 10^{-8}, 10^{-9}$)

1. $\mathrm{Z}+\mathrm{jet}$ @ NNLO using Antenna Subtraction
2. Numerical results for $\mathrm{Z}+\mathrm{jet}$ production
3. The inclusive p_{T} spectrum of the Z boson

$Z + \text{jet}$: Total 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: $\mu_F = \mu_R = M_Z \times [\frac{1}{2}, 1, 2]$

Total Cross section

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

+40%

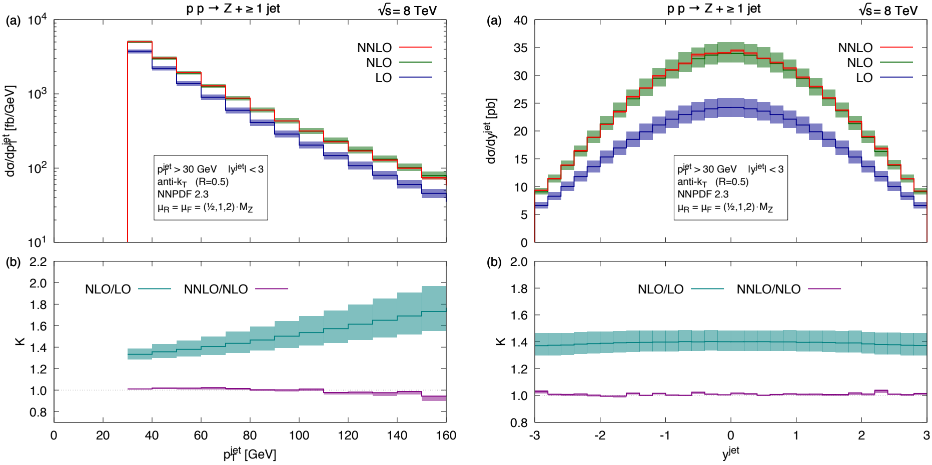
$$\sigma_{\text{NLO}} = 144.4^{+9.0}_{-7.2}\ \text{pb}$$

+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', ...

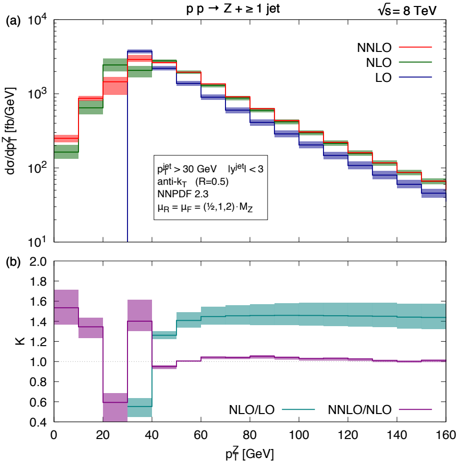
Distributions: Leading jet

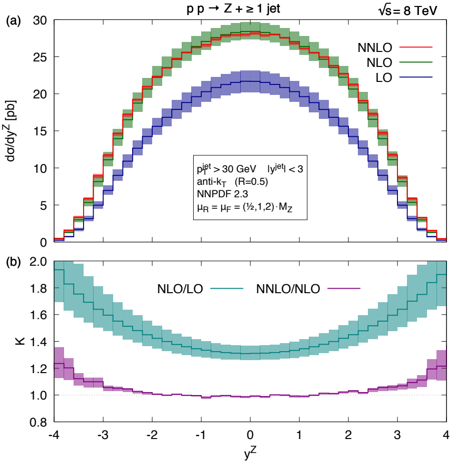


- NLO corrections $\gtrsim 40\%$
- NNLO corrections $\lesssim 5\%$ (quite flat)
- significant reduction of scale uncertainty

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

Distributions: Z-boson



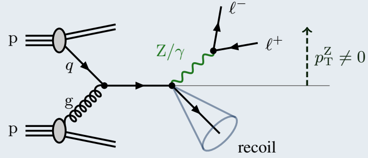


- “Sudakov shoulder” at $p_T^Z \sim 30$ GeV
- significant reduction of scale uncertainty

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

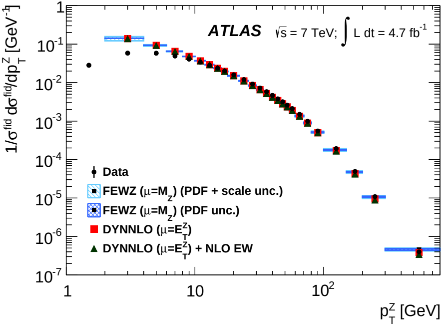
Motivation

Inclusive p_T spectrum of the Z boson $(p_T^Z > 0\ \text{GeV})$



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

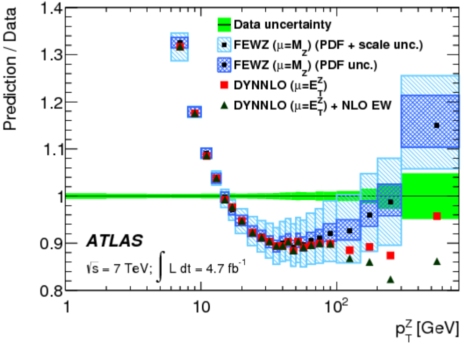
- large cross section
- clean leptonic signature



[JHEP 1409 (2014) 145]

- fully inclusive w.r.t. QCD radiation
- only reconstruct ℓ^+, ℓ^-
  - ↪ very clean & precise measurement
- potential to constrain gluon PDFs
  - ↪ **NNLO needed** [Malik, Watt ’14]

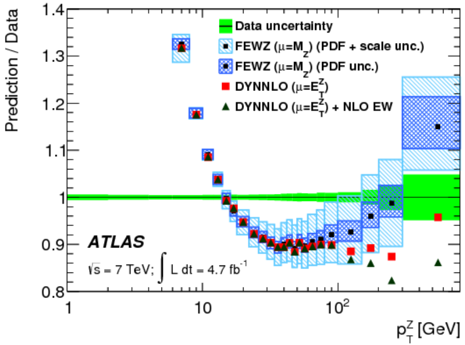
Inclusive p_T^Z at fixed order



[JHEP 1409 (2014) 145]

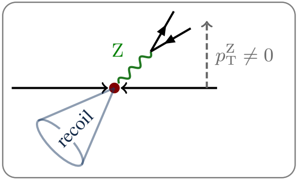
- low $p_T^Z \lesssim 10$ GeV: resummation required
- $p_T^Z \gtrsim 20$ GeV: fixed-order prediction $\sim 10\%$ below data!
- high $p_T^Z \gtrsim 500$ GeV: EW corrections ~ -5 - 10%

Inclusive p_T^Z at fixed order



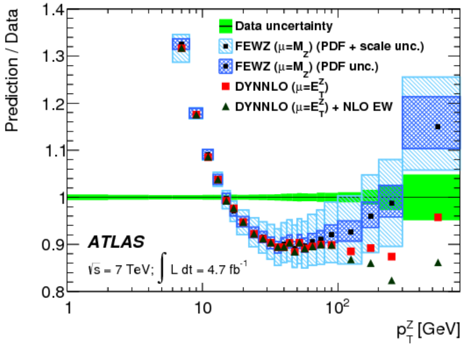
[JHEP 1409 (2014) 145]

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



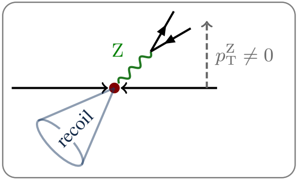
$\hookrightarrow$ Only NLO accurate in this distribution!

Inclusive p_T^Z at fixed order



[JHEP 1409 (2014) 145]

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



$\hookrightarrow$ Only NLO accurate in this distribution!

NNLO

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

- requires hadronic recoil

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

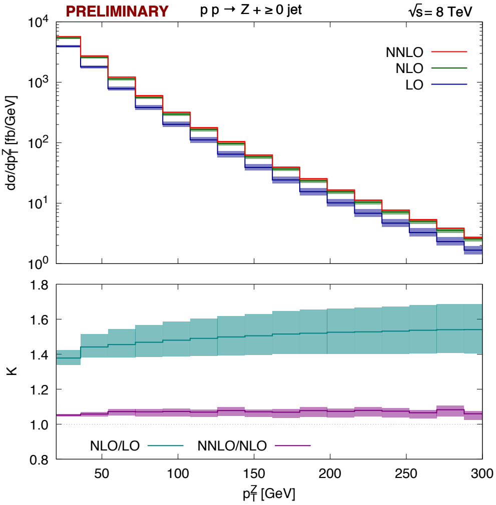
Inclusive p_T^Z spectrum: Setup

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
- $p_T^{\ell_1} > 20$ GeV, $p_T^{\ell_2} > 10$ GeV, $|y^{\ell^\pm}| < 2.4$, 12 GeV $< m_{\ell\ell} <$ 150 GeV
- scale choice (dynamical)

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

Inclusive p_T spectrum of Z/γ^*



$(12\ \mathrm{GeV} < m_{\ell\ell} < 150\ \mathrm{GeV})$

- NLO corrections ~ 40 - 60%
- significant reduction of scale uncertainties NLO $\to$ NNLO
- NNLO corrections: relatively flat ~ 5 - 10%

Can this resolve the discrepancy in theory vs. data?!

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
- $p_T^Z > 20\ \text{GeV}$
- $p_T^{\ell_1} > 20\ \text{GeV}, \quad p_T^{\ell_2} > 10\ \text{GeV}, \quad |y^{\ell^\pm}| < 2.4, \quad 12\ \text{GeV} < m_{\ell\ell} < 150\ \text{GeV}$
- scale choice (dynamical)

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

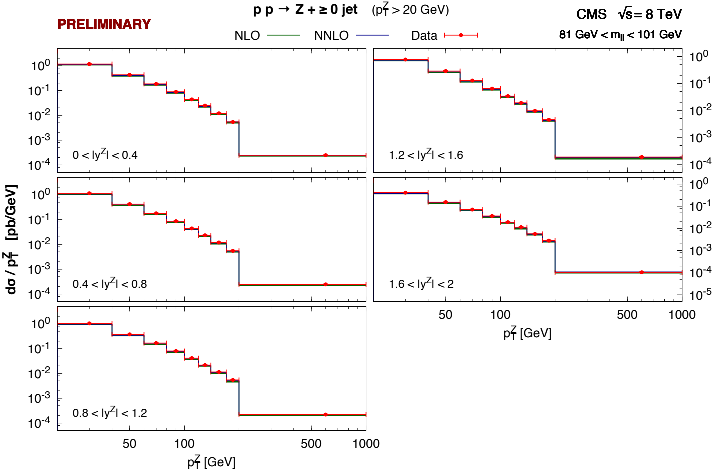
CMS setup [arXiv:1504.03511]

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

ATLAS setup [arXiv:1512.02192]

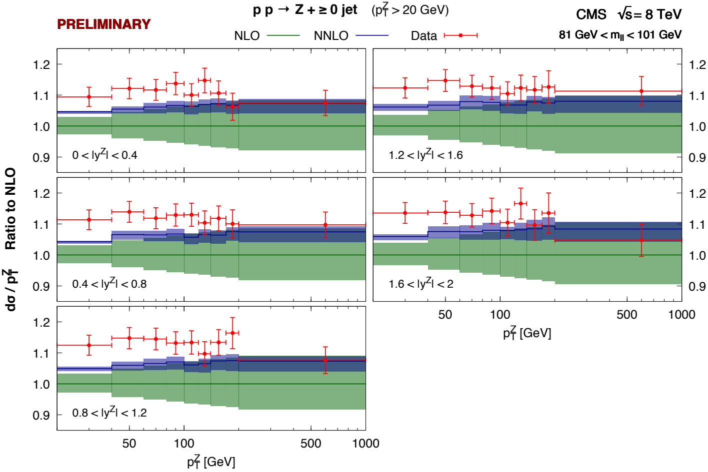
- $p_T^{\ell^\pm} > 20\ \text{GeV}, \ |y^{\ell^\pm}| < 2.4$
- $66\ \text{GeV} < m_{\ell\ell} < 116\ \text{GeV}$
  $+$ binning in y^Z
- $|y^Z| < 2.4$ $+$ binning in $m_{\ell\ell}$

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



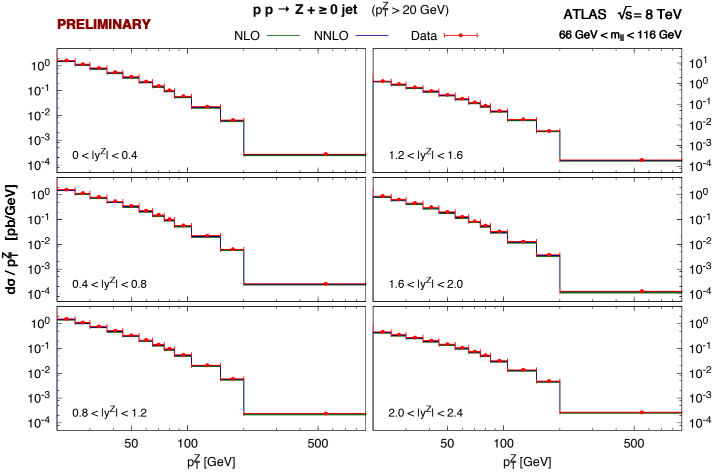
- $81\ \mathrm{GeV} < m_{\ell\ell} < 101\ \mathrm{GeV}$
- 5 bins in y^{Z}: $[0,\ 0.4]$ $[0.4,\ 0.8]$ $[0.8,\ 1.2]$ $[1.2,\ 1.6]$ $[1.6,\ 2]$

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



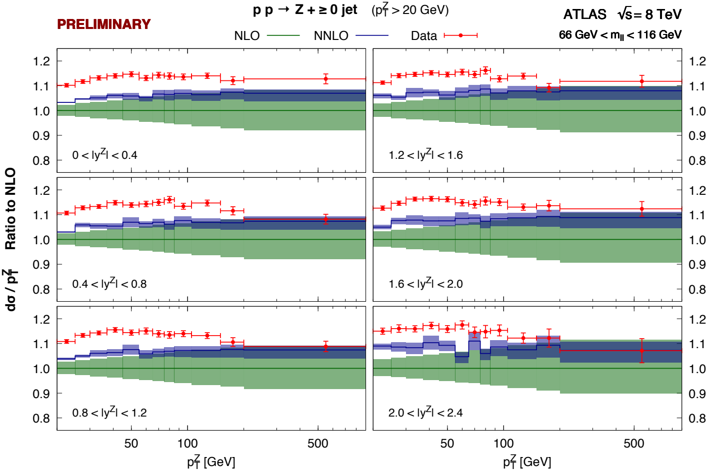
- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties

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



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

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



- improvement in **theory** vs. **data*** comparison
- reduction of scale uncertainties

* ATLAS errors significantly smaller compared to CMS (includes e and μ)

Summary & Outlook

Summary

- We have computed NNLO corrections to $\mathrm{Z} + \mathrm{jet}$ production
  ↪ reduction of scale uncertainties ($\sim 1\%$)
- Results implemented in a flexible parton-level event generator **NNLOJET**
- We have used our $\mathrm{Z} + \mathrm{jet}$ calculation to predict the inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum to NNLO accuracy for $p_{\mathrm{T}}^{\mathrm{Z}} > p_{\mathrm{T,cut}}^{\mathrm{Z}}$
  ↪ improvement in the theory vs. data comparison

Outlook

- Development on **NNLOJET**
  ↪ performance, interface to `APPLgrid`, `fastNLO`, more processes, ...
- Different PDF sets $\rightsquigarrow$ potential to constrain PDFs?
- Complete $\mathrm{W} + \mathrm{jet}$ (subtraction terms almost identical to $\mathrm{Z} + \mathrm{jet}$)

Summary & Outlook

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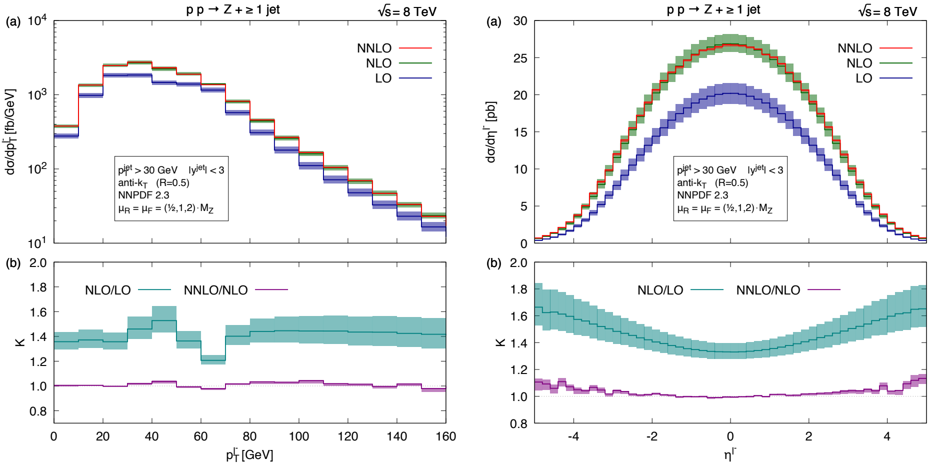
Thank you

Backup Slides

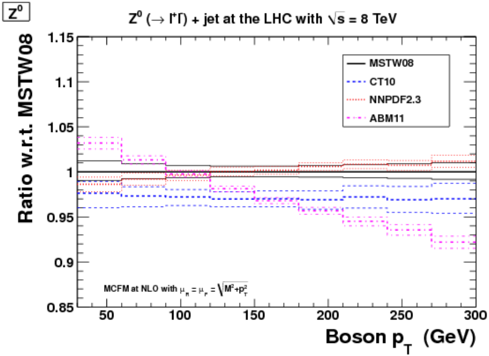
Distributions: lepton ℓ^-



- significant reduction of scale uncertainty

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

PDF constraints from p_T^Z



- $p_T^Z \gtrsim M_Z \rightsquigarrow$ 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: $\mathrm{Z} + \mathrm{b(b)} \leftrightarrow$ constrain b-quark PDFs