QCD predictions for the production of a Z boson in association with a hadronic jet

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in collaboration with
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Rencontres de Moriond

QCD and High Energy Interactions

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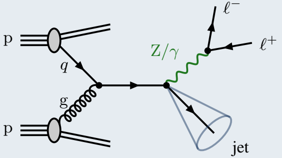
MC@NNLO

Motivation and Introduction

$\mathrm{Z} + \mathrm{jet}$ 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!

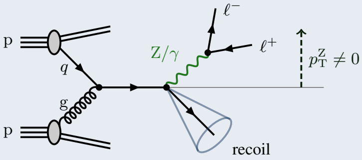
NNLO QCD ....

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

[Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]

[Boughezal, Liu, Petriello.'16]

Inclusive p_{T} spectrum of the Z boson $(p_{\mathrm{T}}^{\mathrm{Z}} > 0\ \mathrm{GeV})$



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

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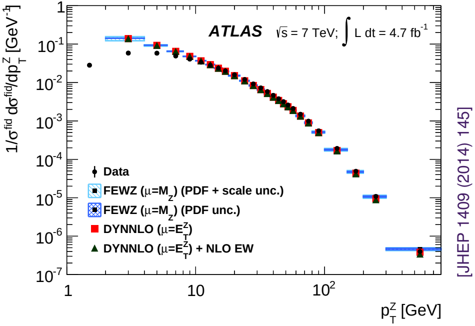
- clean leptonic signature



- 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]

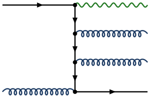
This talk

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

2. Results for the inclusive p_{T} spectrum of the Z boson

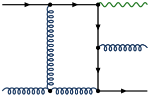
Anatomy of an NNLO calculation

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



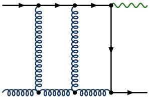
- single-unresolved
- double-unresolved

$$+ \int_{\Phi_{\text{Z}+2}} \mathrm{d}\sigma_{\text{NNLO}}^{\text{RV}}$$



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

$$+ \int_{\Phi_{\text{Z}+1}} \mathrm{d}\sigma_{\text{NNLO}}^{\text{VV}}$$



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

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

Non-trivial cancellation of infrared singularities

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

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

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

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

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

$\sum$ finite -0

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

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: $D = 4 - 2\epsilon$

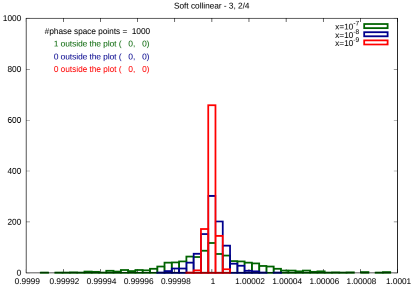
```
09:26:35  ...maple/process/Z
$ form autoqgB1g2ZgtoqU.frm
FORM 4.1 (Mar 13 2014) 64-bits
   #-

   poles = 0;

  6.58 sec out of 6.64 sec
```

Unresolved limits

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

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

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

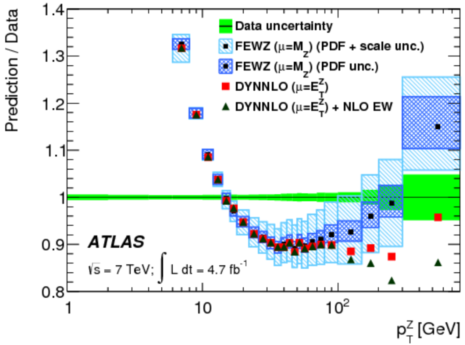


(approach singular limit: $x_i = 10^{-7}, 10^{-8}, 10^{-9}$)

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

2. Results for the inclusive p_{T} spectrum of the Z boson

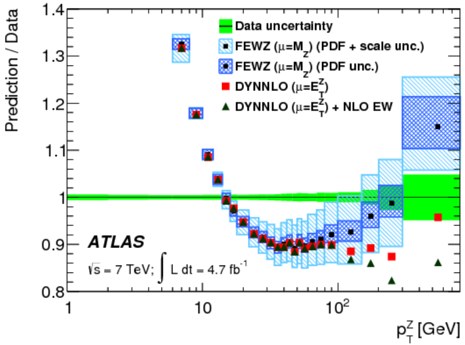
Inclusive p_T^Z at fixed order



[JHEP 1409 (2014) 145]

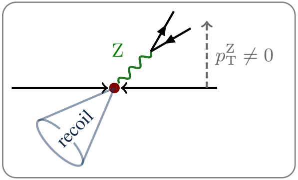
- low $p_T^Z \lesssim 10$ GeV: resummation required
- $p_T^Z \gtrsim 20$ GeV: fixed-order prediction $\sim 10\%$ below data!

Inclusive p_T^Z at fixed order



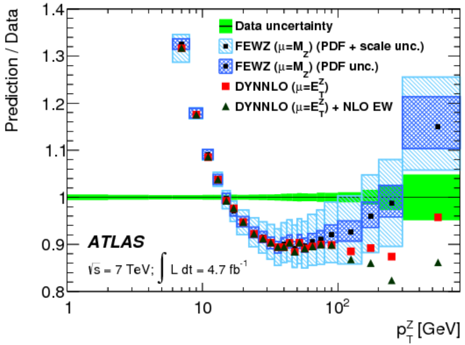
[JHEP 1409 (2014) 145]

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



$\hookrightarrow$ Only NLO accurate in this distribution!

Inclusive p_T^Z at fixed order



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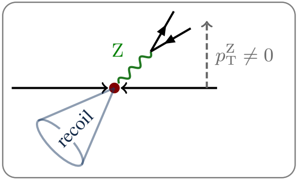

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NNLO

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

- requires hadronic recoil

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

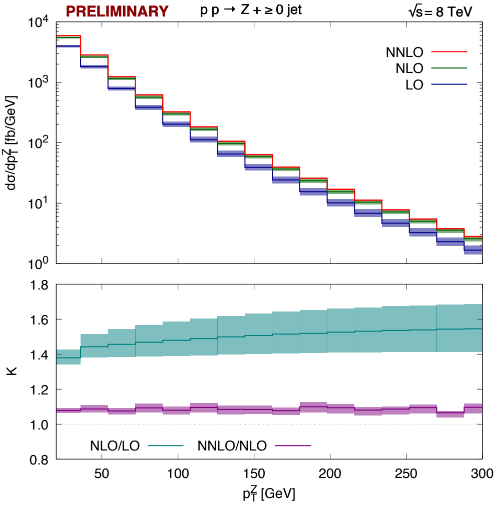
Inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum: Setup

Calculational setup

- LHC @ 8 TeV
- PDF: `NNPDF2.3` $\alpha_{\mathrm{s}}(M_{\mathrm{Z}}) = 0.118$
- ~~jet cuts~~ $\longleftrightarrow$ fully inclusive w.r.t. QCD radiation
- $p_{\mathrm{T}}^{\mathrm{Z}} > 20\ \mathrm{GeV}$
- $p_{\mathrm{T}}^{\ell_1} > 20\ \mathrm{GeV}, \quad p_{\mathrm{T}}^{\ell_2} > 10\ \mathrm{GeV}, \quad |y^{\ell^\pm}| < 2.4, \quad 12\ \mathrm{GeV} < m_{\ell\ell} < 150\ \mathrm{GeV}$
- scale choice (dynamical)

$$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sqrt{m_{\ell\ell}^2 + p_{\mathrm{T,Z}}^2} \times \left[\tfrac{1}{2}, 1, 2\right]$$

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 $\rightarrow$ 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: `NNPDF2.3` $\alpha_s(M_Z) = 0.118$
- ~~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)

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

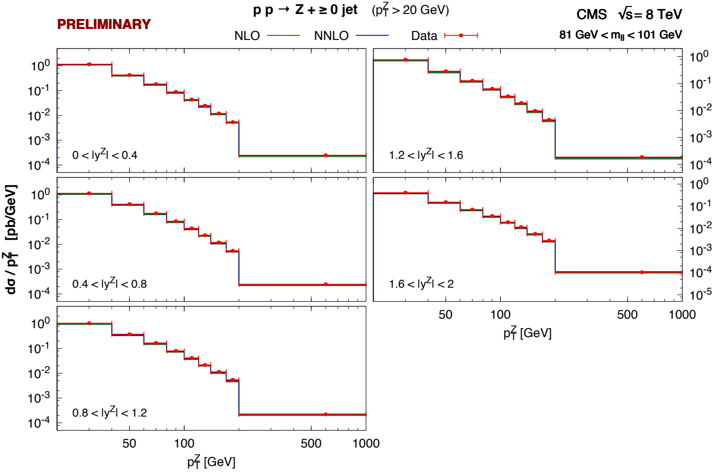
CMS setup [arXiv:1504.03511]

- $p_T^{\ell_1} > 25$ 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

ATLAS setup [arXiv:1512.02192]

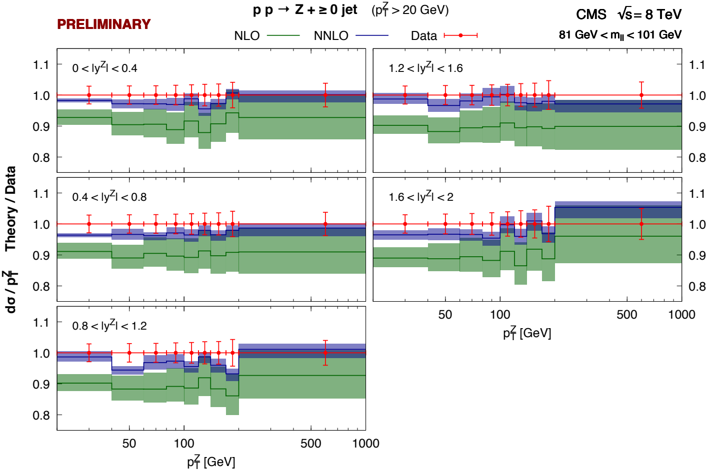
- $p_T^{\ell^\pm} > 20$ GeV, $|y^{\ell^\pm}| < 2.4$
- 66 GeV $< m_{\ell\ell} < 116$ GeV
  $+$ binning in y^Z
- $|y^Z| < 2.4$ $+$ binning in $m_{\ell\ell}$

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}: $[0,\, 0.4]$ $[0.4,\, 0.8]$ $[0.8,\, 1.2]$ $[1.2,\, 1.6]$ $[1.6,\, 2]$

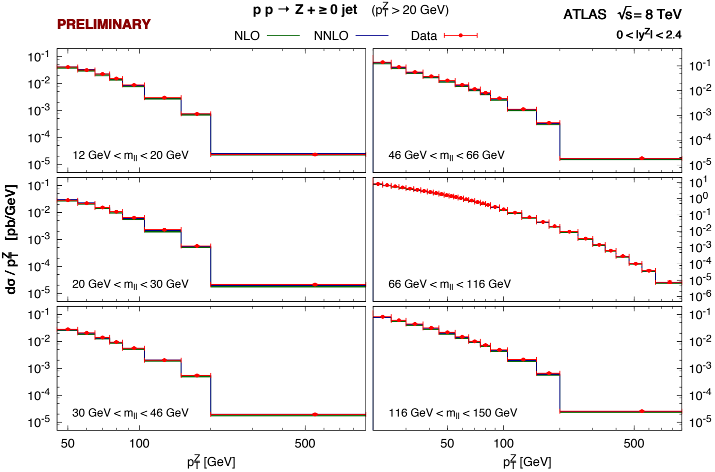
Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^\mathrm{Z}$ binned in y^Z — CMS



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

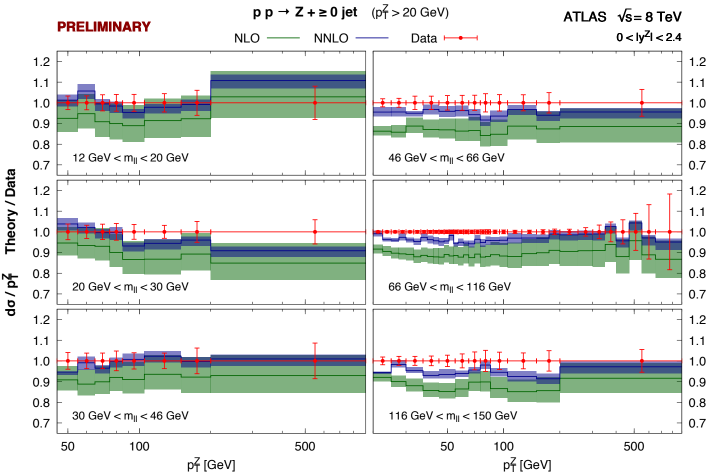
* fluctuations in "NLO/Data" from Data

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



- $0 < |y^Z| < 2.4$
- 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



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Summary & Outlook

Summary

- The inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum is an important observable at hadron colliders: Powerful testing ground for QCD predictions, modelling of Z/W backgrounds, potential to constrain PDFs, ...
- We have used our recent $\mathrm{Z}+\mathrm{jet}$ calculation to predict this distribution to NNLO accuracy for $p_{\mathrm{T}}^{\mathrm{Z}} > p_{\mathrm{T,cut}}^{\mathrm{Z}}$
- We observe a reduction of the scale uncertainty and a significant improvement in the theory vs. data comparison

Outlook

- Repeat calculation with different PDF sets
  $\hookrightarrow$ study potential of data to constrain PDF sets
- work in progress: interface to `APPLgrid`, `fastNLO`

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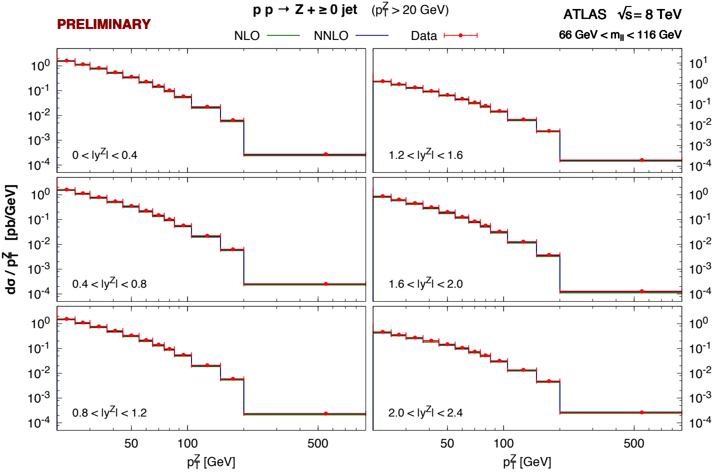
Thank you

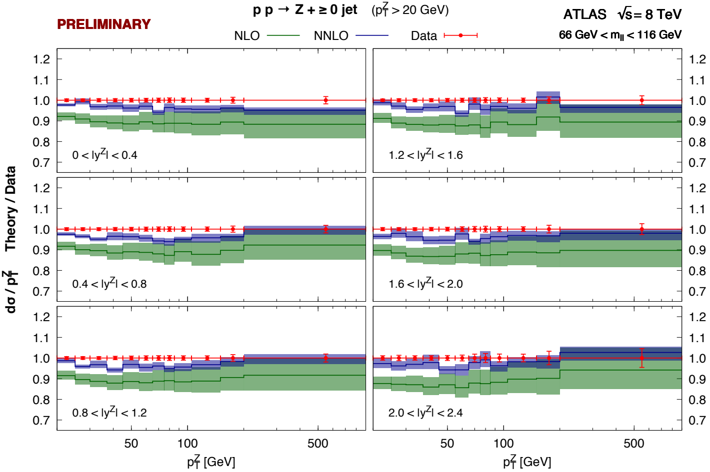
Backup Slides

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}: $[0,\,0.4]$ $[0.4,\,0.8]$ $[0.8,\,1.2]$ $[1.2,\,1.6]$ $[1.6,\,2]$ $[2,\,2.4]$

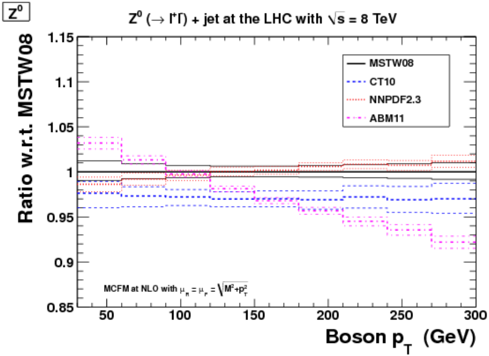
Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_T^Z$ binned in y^Z — ATLAS



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

* ATLAS errors significantly smaller compared to CMS

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: $\mathrm{Z} + \mathrm{b}(\mathrm{b}) \leftrightarrow$ constrain b-quark PDFs