

Z + jet production at NNLO QCD

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in collaboration with

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LoopFest XV

University at Buffalo

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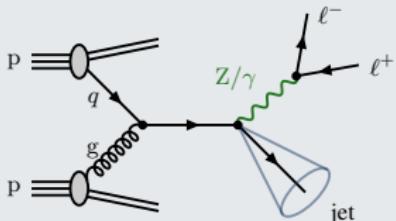
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



MC@NNLO

Motivation

Z + jet production at the LHC

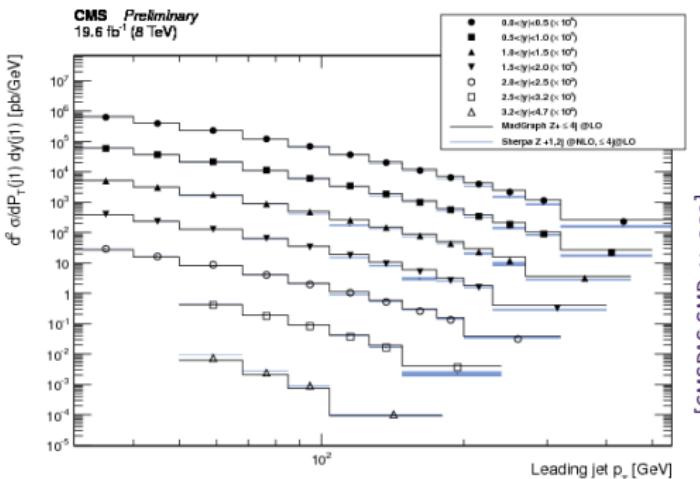


$$p \ p \rightarrow Z/\gamma^* + \text{jet} \rightarrow l^- l^+ + \text{jet} + X$$

- ▶ large cross section
- ▶ clean leptonic signature
- +jet ↼ sensitivity to α_s , gluon PDF,...

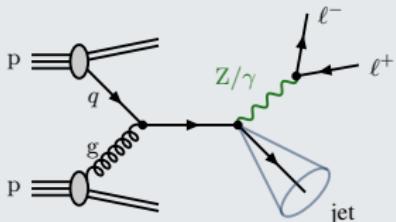
- ▶ precision measurements
 - ↪ test pQCD
 - ↪ constrain PDFs (gluon)
- ▶ detector calibration
 - ↪ jet energy scale
- ▶ searches for BSM physics

high-precision predictions
mandatory!



Motivation

Z + jet production at the LHC



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

- ▶ large cross section
- ▶ clean leptonic signature
- +jet \rightsquigarrow sensitivity to α_s , gluon PDF,...

Where do we stand?

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

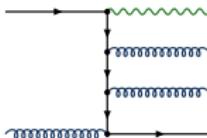
\rightsquigarrow validation (✓) & opportunity for benchmarks

This talk

- ① NNLO QCD corrections — Antenna Subtraction
- ② Numerical results for $Z + \text{jet}$ production @ NNLO
- ③ Inclusive Z -boson production at large p_T

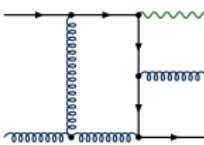
Anatomy of an NNLO calculation

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



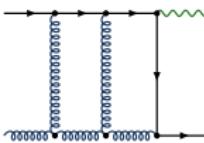
[Hagiwara, Zeppenfeld '89]
[Berends, Giele, Kuijf '89]
[Falck, Graudenz, Kramer '89]

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



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

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

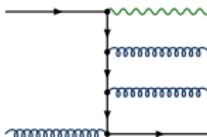


[Moch, Uwer, Weinzierl '02]
[Garlandet al. '02]
[Gehrmann, Tancredi '12]

Individual building blocks known for a while

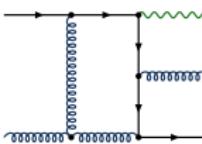
Anatomy of an NNLO calculation

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



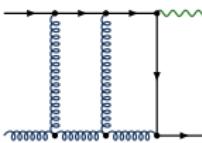
- ▶ single-unresolved
- ▶ double-unresolved

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



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

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



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

 \sum

finite (Kinoshita–Lee–Nauenberg & factorization)

Non-trivial cancellation of infrared singularities

Anatomy of an NNLO calculation

$$\begin{aligned}\sigma_{\text{NNLO}} = & \int_{\Phi_{Z+3}} d\sigma_{\text{NNLO}}^{\text{RR}} \\ & + \int_{\Phi_{Z+2}} d\sigma_{\text{NNLO}}^{\text{RV}} \\ & + \int_{\Phi_{Z+1}} d\sigma_{\text{NNLO}}^{\text{VV}}\end{aligned}$$

Different methods:

- ▶ Antenna subtraction
[Gehrmann–De Ridder, Gehrmann, Glover '05]
 - ▶ CoLoRful subtraction
[Del Duca, Somogyi, Trocsanyi '05]
 - ▶ q_T subtraction
[Catani, Grazzini '07]
(talk by M. Wiesemann)
 - ▶ Sector-improved residue subtraction
[Czakon '10], [Boughezal, Melnikov, Petriello '11]
(talk by D. Heymes)
 - ▶ N -jettiness subtraction
[Gaunt, Stahlhofen, Tackmann, Walsh '15]
[Boughezal, Focke, Liu, Petriello '15]
(talk by W. Giele, X. Liu)
 - ▶ Projection to Born
[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]
- ...

 \sum finite

Approaches: subtraction, slicing

Z + jet @ NNLO using Antenna

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

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

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

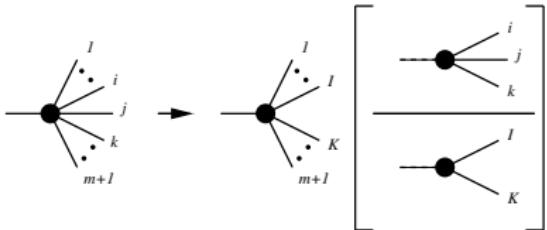
- $d\sigma_{\text{NNLO}}^{\text{S}}, d\sigma_{\text{NNLO}}^{\text{T}}$:
mimic $d\sigma_{\text{NNLO}}^{\text{RR}}, d\sigma_{\text{NNLO}}^{\text{RV}}$
in unresolved limits
- $d\sigma_{\text{NNLO}}^{\text{T}}, d\sigma_{\text{NNLO}}^{\text{U}}$:
analytic cancellation of
poles in $d\sigma_{\text{NNLO}}^{\text{RV}},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

$$\sum \quad \text{finite} \quad -0$$

⇒ each line suitable for numerical evaluation in $D = 4$

Antenna Subtraction Formalism

- ▶ exploit universal factorization properties in the IR limits (colour-ordering):



- ▶ phase-space factorization

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

All building blocks known!

antennae: X_3^0, X_4^0, X_3^1

integrated antennae: $\mathcal{X}_3^0, \mathcal{X}_4^0, \mathcal{X}_3^1$

∀ configurations relevant at hadron colliders
→ 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

Antenna subtraction – Checks of the calculation

Analytic pole cancellation

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

DimReg: $D = 4 - 2\epsilon$

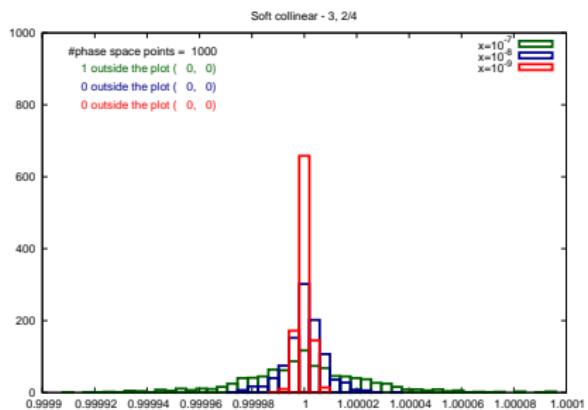
Unresolved limits

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

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

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

```
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
```



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

- 1 NNLO QCD corrections — Antenna Subtraction
- 2 Numerical results for $Z + \text{jet}$ production @ NNLO
- 3 Inclusive Z -boson production at large p_T

Z + jet: Fiducial cross section

Calculational setup

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

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

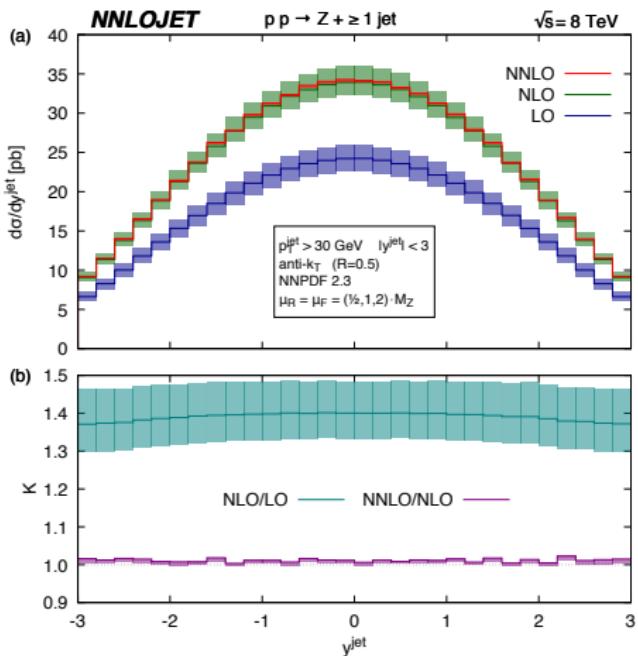
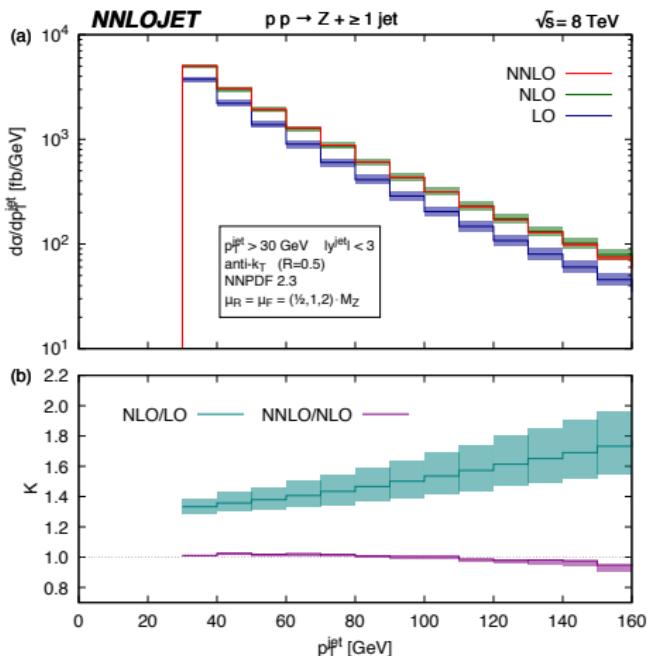
Fiducial cross section

$$\begin{aligned}\sigma_{\text{LO}} &= 103.6^{+7.7}_{-7.5} \text{ pb} \\ \sigma_{\text{NLO}} &= 144.4^{+9.0}_{-7.2} \text{ pb} \\ \sigma_{\text{NNLO}} &= 145.8^{+0.0}_{-1.2} \text{ pb}\end{aligned}$$

The diagram shows three horizontal curly braces on the right side of the cross-section values. The top brace is labeled '+40%', the middle brace is labeled '+1%', and the bottom brace is labeled '+0.0%'.

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

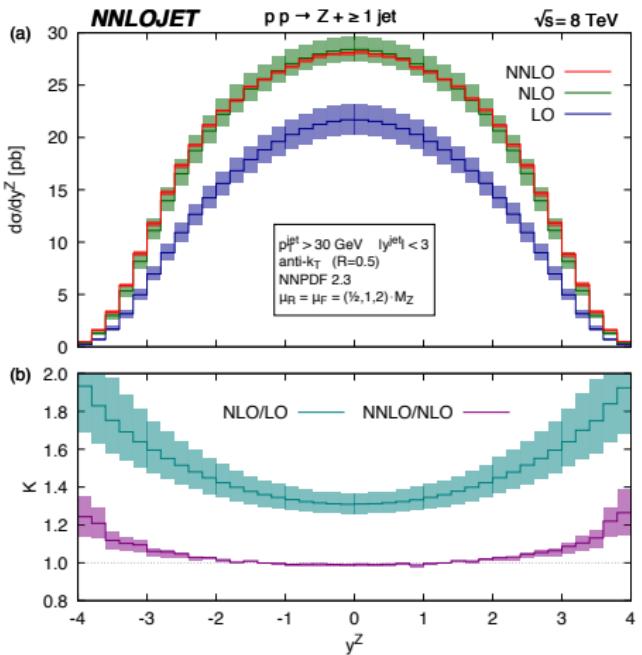
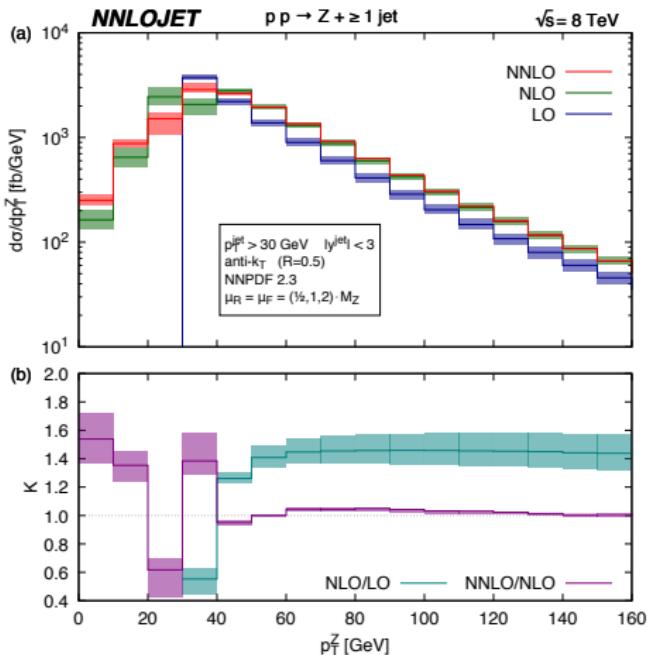
Distributions: Leading jet



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

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

Distributions: Z-boson



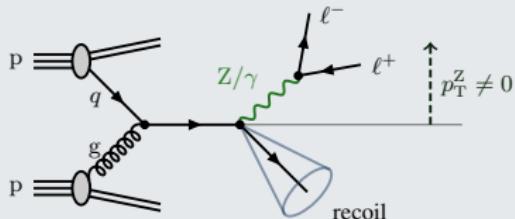
- ▶ “Sudakov shoulder” at $p_T^Z \sim 30 \text{ GeV}$
- ▶ **NNLO** corrections not flat!
- ▶ significant reduction of scale uncertainty

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

- 1 NNLO QCD corrections — Antenna Subtraction
- 2 Numerical results for $Z + \text{jet}$ production @ NNLO
- 3 Inclusive Z-boson production at large p_T

Motivation

Inclusive p_T spectrum of the Z boson ($p_T^Z > 0$ GeV)

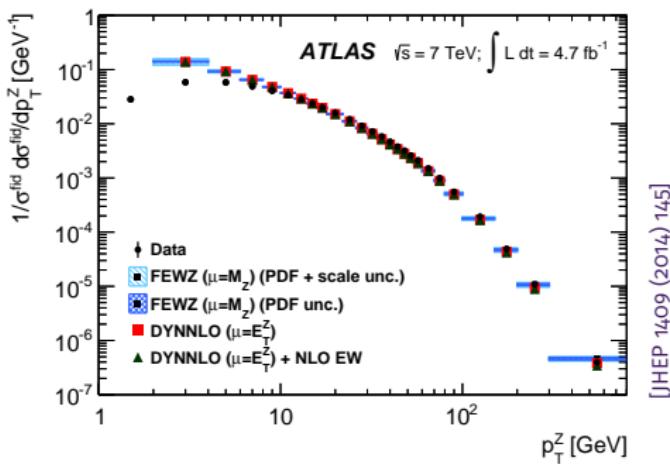


$$p + p \rightarrow Z/\gamma^* + X \rightarrow \ell^- \ell^+ + X$$

- ▶ large cross section

- ▶ clean leptonic signature

recoil \rightsquigarrow sensitivity to α_s , gluon PDF,...



- ▶ fully inclusive w.r.t. QCD radiation

- ▶ only reconstruct ℓ^+, ℓ^-

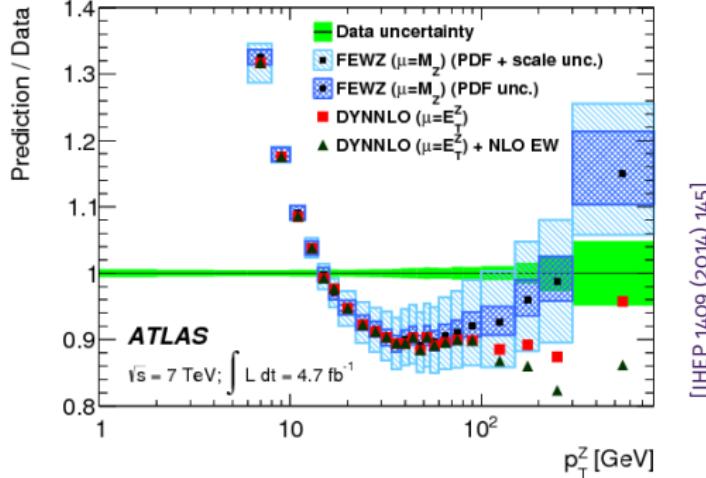
- ▶ \rightsquigarrow clean & precise measurement

- ▶ potential to constrain gluon PDFs

- ▶ **NNLO needed**

[Malik, Watt '14]

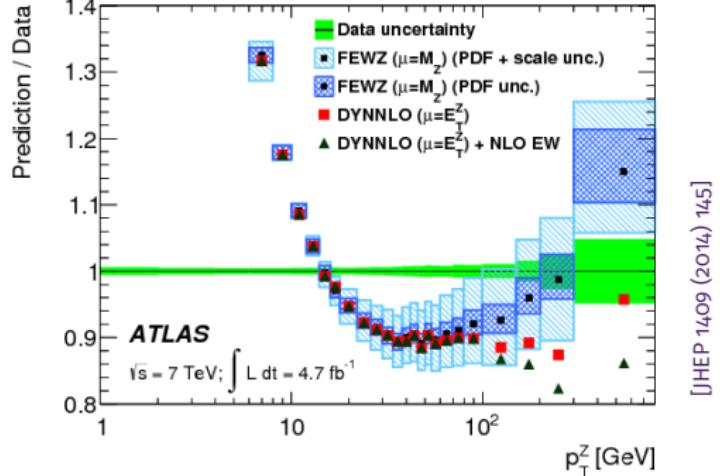
Inclusive p_T^Z at fixed order



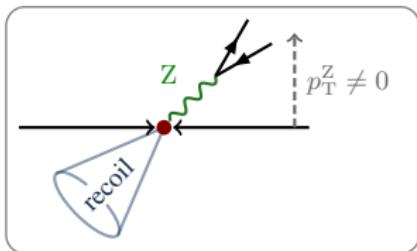
[JHEP1409(2014)145]

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

Inclusive p_T^Z at fixed order

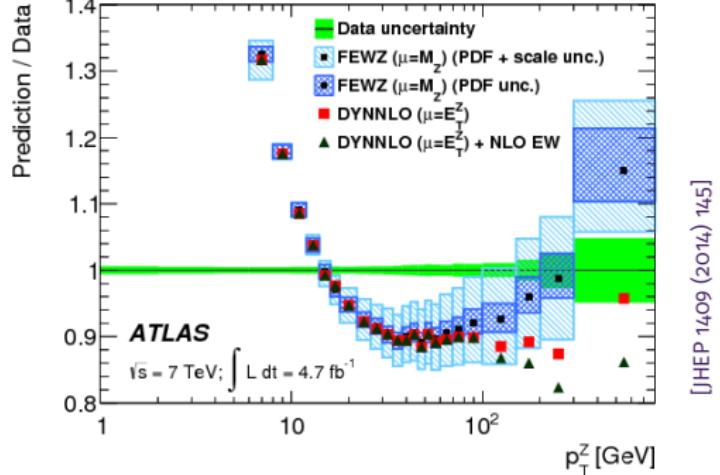


FEWZ
DYNNLO } $Z + 0 \text{ jet} @ \text{NNLO}$

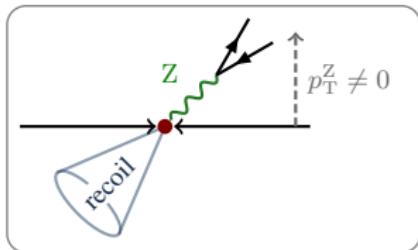


↪ Only NLO accurate
in this distribution!

Inclusive p_T^Z at fixed order



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



Only NLO accurate
in this distribution!

NNLO
 $p_T^Z > p_{T,\text{cut}}^Z = 20 \text{ GeV}$
▶ requires hadronic recoil
~~~  $Z + \geq 1\text{jet} @ \text{NNLO}$

# 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
- ▶  $p_T^Z > 20 \text{ GeV}$
- ▶ scale choice (dynamical)

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

### ATLAS setup

[arXiv:1512.02192]

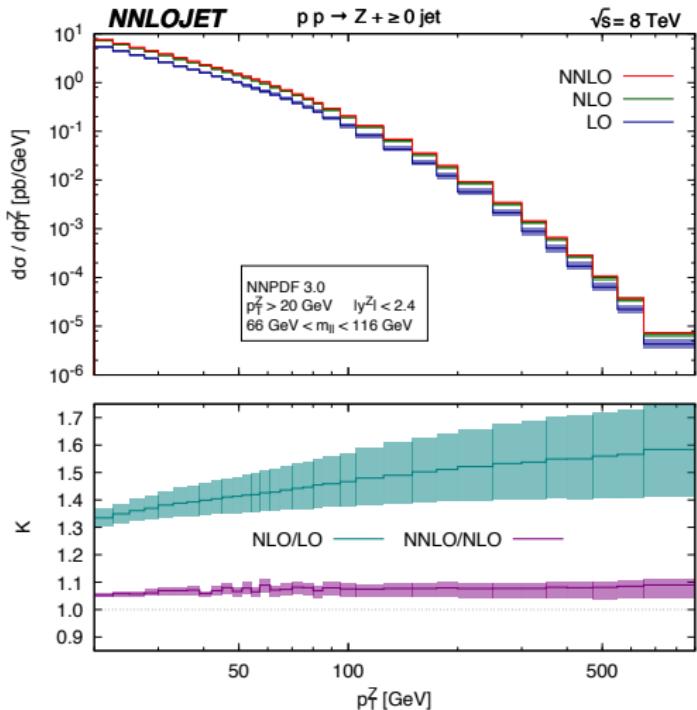
- ▶  $p_T^{\ell^\pm} > 20 \text{ GeV}, |y^{\ell^\pm}| < 2.4$
- ▶  $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$   
+ binning in  $y^Z$
- ▶  $|y^Z| < 2.4$  + binning in  $m_{\ell\ell}$

### 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  $y^Z$

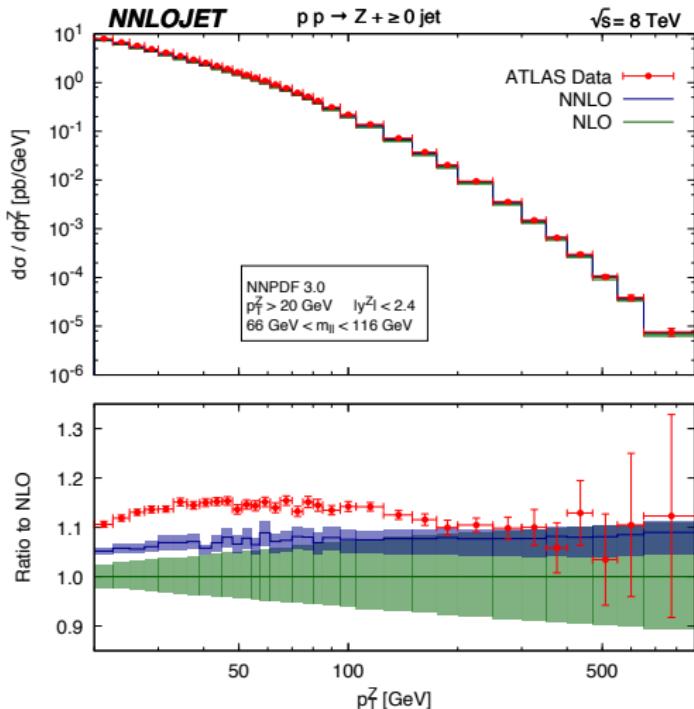
# Inclusive $p_T$ spectrum of $Z/\gamma^*$



- ▶ NLO corrections  $\sim 40 - 60\%$
- ▶ significant reduction of scale uncertainties NLO  $\rightarrow$  NNLO
- ▶ NNLO corrections:  
relatively flat  $\sim 5 - 10\%$

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

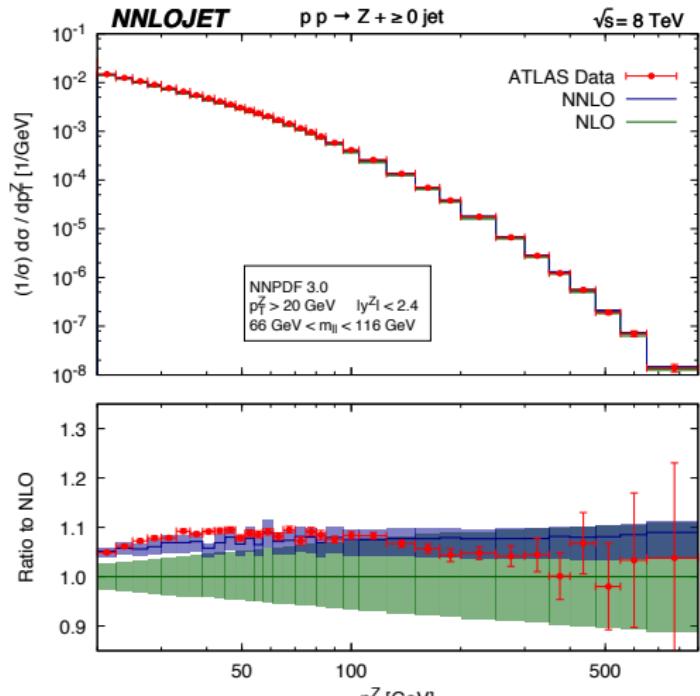
# Inclusive $p_T$ spectrum of $Z/\gamma^*$



- ▶ 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

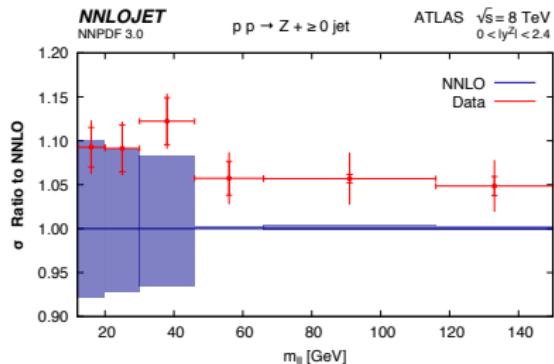
$$\frac{1}{\sigma} \cdot \frac{d\sigma}{dp_T^Z}$$

# Inclusive $p_T$ spectrum of $Z/\gamma^*$

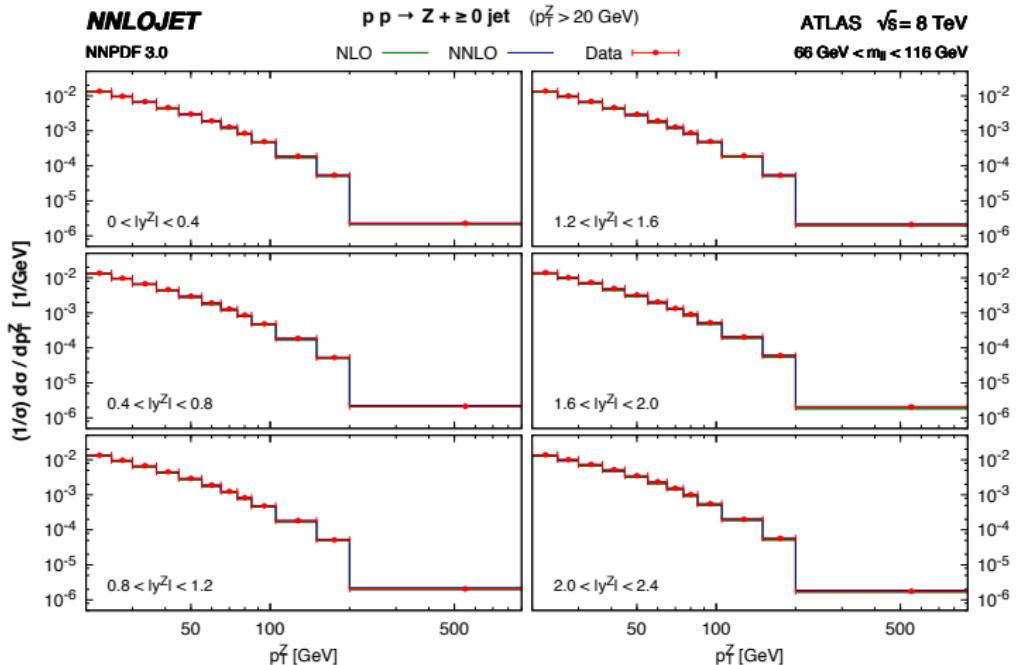


$$\frac{1}{\sigma} \cdot \frac{d\sigma}{dp_T^Z}$$

- uncorrelated scale variation  
↔ numerator & denominator
- significant improvement  
in **Data** vs. **Theory**

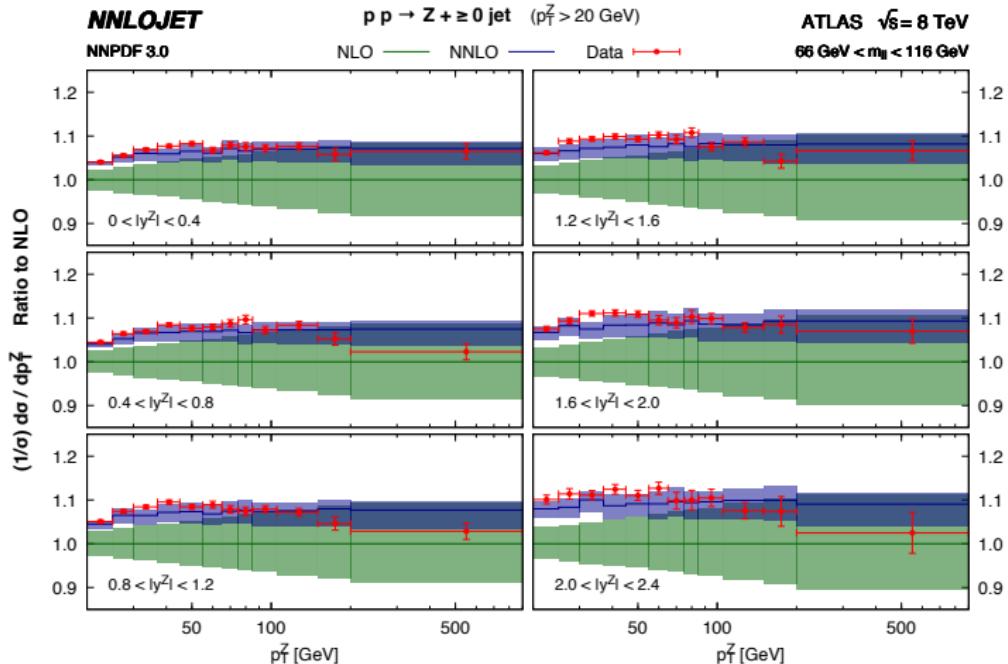


# Double-differential: $d\sigma/dp_T^Z$ binned in $y^Z$ — ATLAS



- ▶  $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$
- ▶ 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: $d\sigma/dp_T^Z$ binned in $y^Z$ — ATLAS



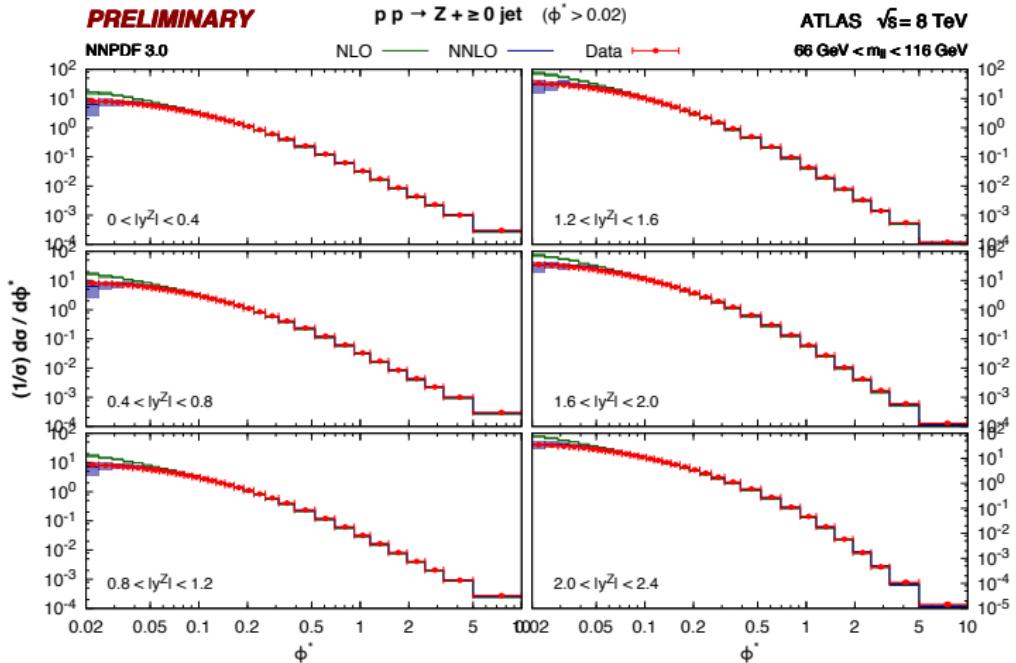
- ▶ NLO prediction systematically undershoots data, NNLO corrections  $\sim 5\text{--}10\%$
- ▶ improvement in theory vs. data comparison % $\Delta$ fill (+5–10% NNLO corrections)
- ▶ reduction of scale uncertainties

# The $\phi_\eta^*$ distribution

$$\phi_\eta^* = \tan\left(\frac{\phi_{\text{acop}}}{2}\right) \cdot \sin(\theta_\eta^*)$$

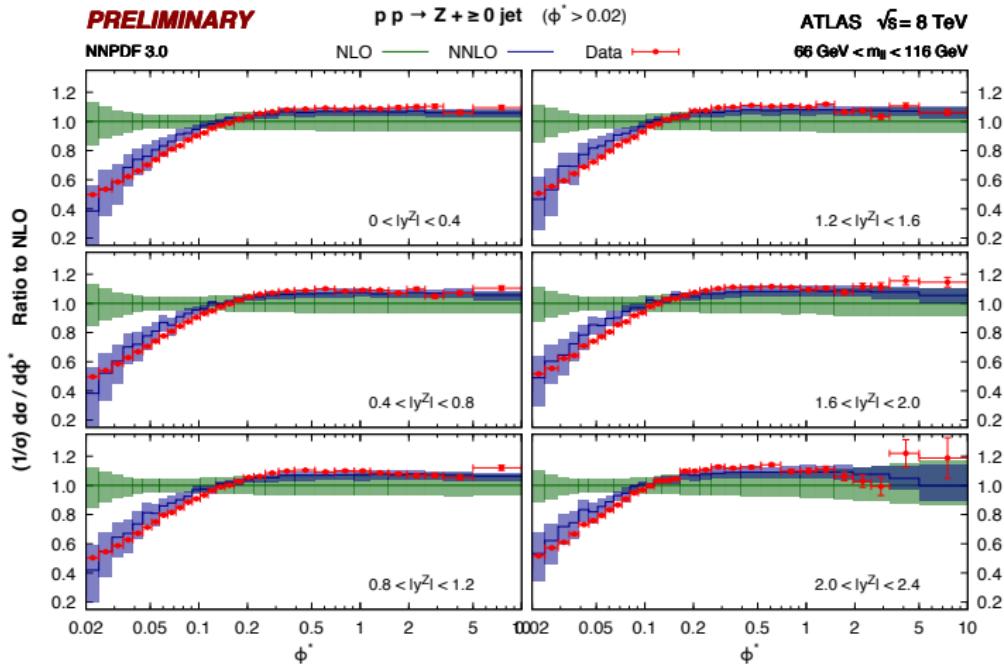
- ▶  $\phi_{\text{acop}} = \pi - \Delta\phi$ ,  $\cos(\theta_\eta^*) = \tanh[(\eta^{\ell^-} - \eta^{\ell^+})/2]$
- ▶ only depends on  $\ell^\pm$  directions (not energies)  $\rightsquigarrow$  better exp. resolution
- ▶ similarly to  $p_T^Z$ :  $\phi_\eta^* \geq \phi_{\eta, \text{cut}}^* > 0 \Rightarrow Z + \text{jets}$

# Double-differential: $d\sigma/d\phi^*$ binned in $y^Z$ — ATLAS



- ▶  $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$
- ▶ 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: $d\sigma/d\phi^*$ binned in $y^Z$ — ATLAS



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

# Summary & Outlook

## Summary

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

## Outlook

- ▶ development on NNLOJET
  - ↪ interface to **APPLgrid & fastNLO**, performance, more processes, ...
- ▶ different PDF sets  $\rightsquigarrow$  potential to constrain PDFs?
- ▶ complete  $W + \text{jet}$  (subtraction terms almost identical to  $Z + \text{jet}$ )

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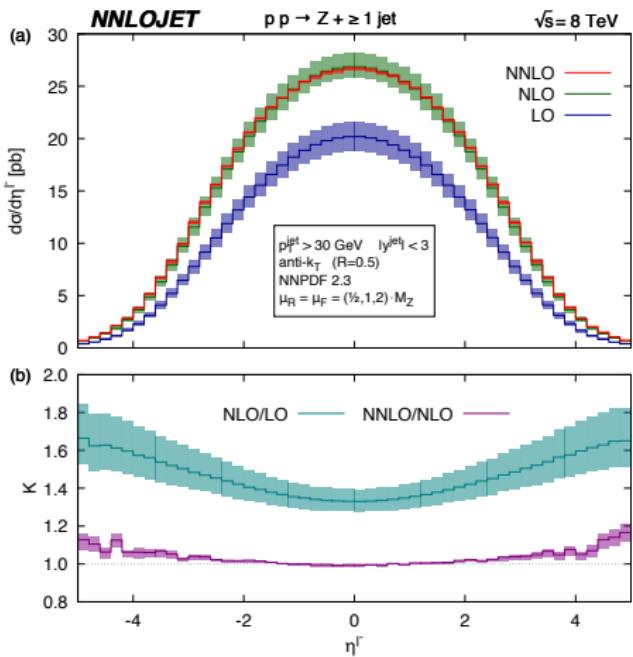
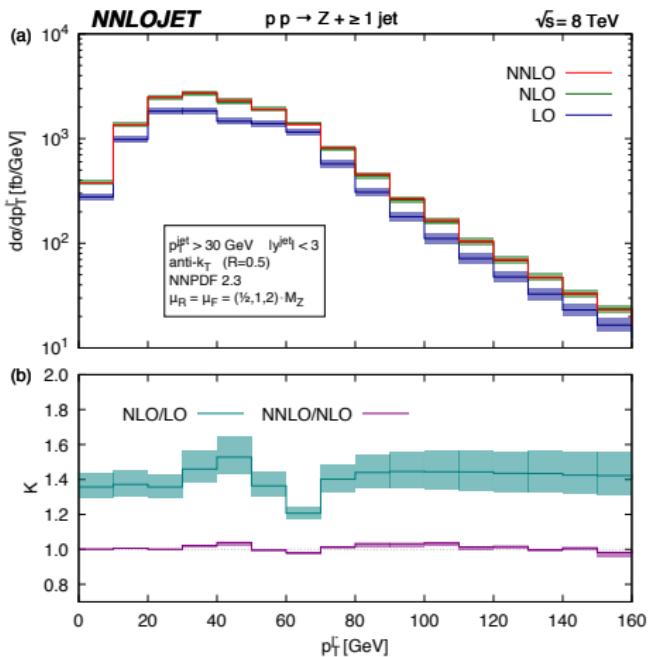
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Thank you

# Backup Slides

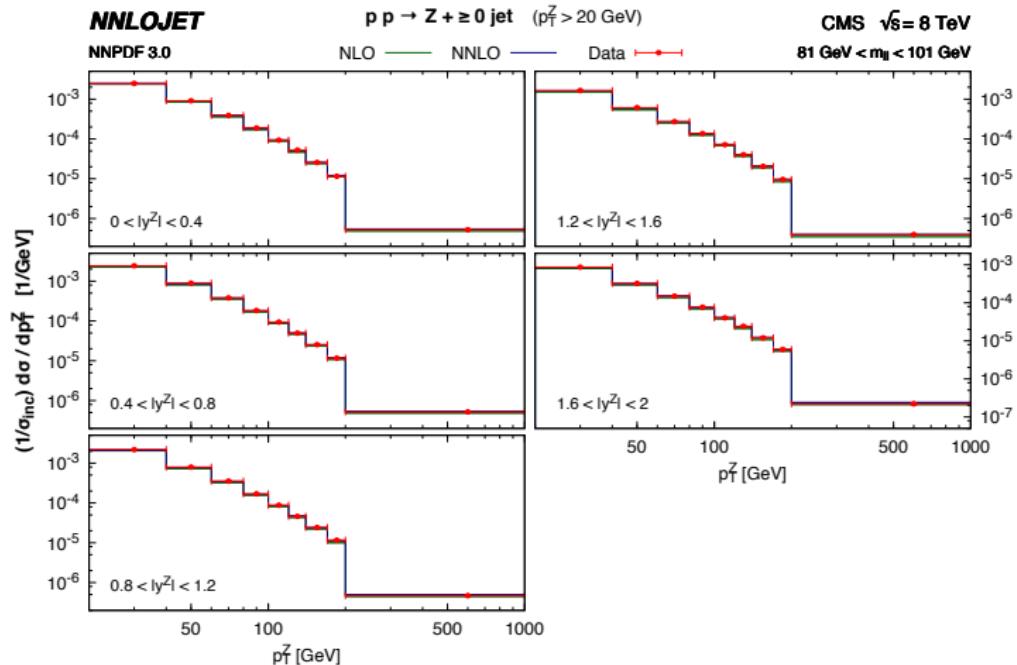
# Distributions: lepton $\ell^-$



- significant reduction of scale uncertainty

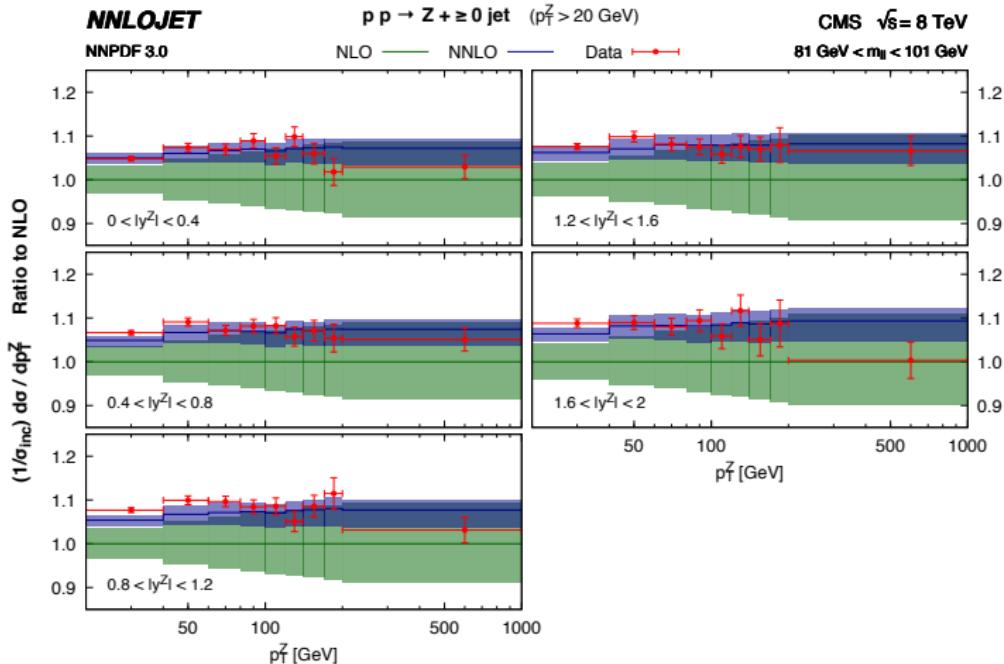
$$K = \frac{d\sigma^{(N)\text{NLO}}(\mu)}{d\sigma^{(N)\text{LO}}(\mu = M_Z)}$$

# Double-differential: $d\sigma/dp_T^Z$ binned in $y^Z$ — CMS



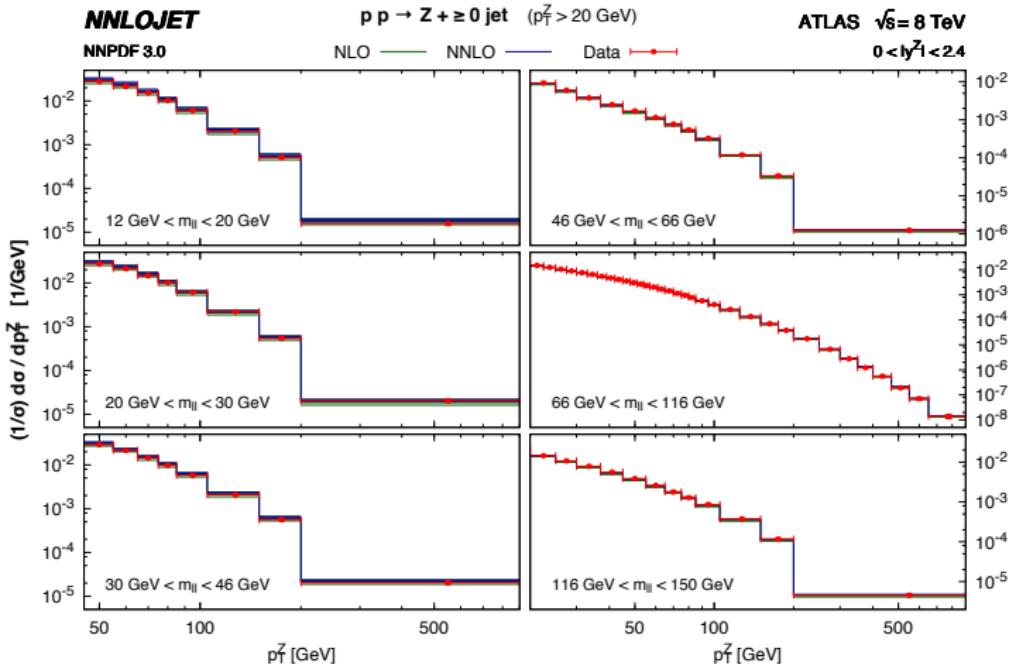
- $81 \text{ GeV} < m_{ll} < 101 \text{ GeV}$  (narrower mass window than ATLAS)
- 5 bins in  $y^Z$ :  $[0, 0.4]$   $[0.4, 0.8]$   $[0.8, 1.2]$   $[1.2, 1.6]$   $[1.6, 2]$

# Double-differential: $d\sigma/dp_T^Z$ binned in $y^Z$ — CMS



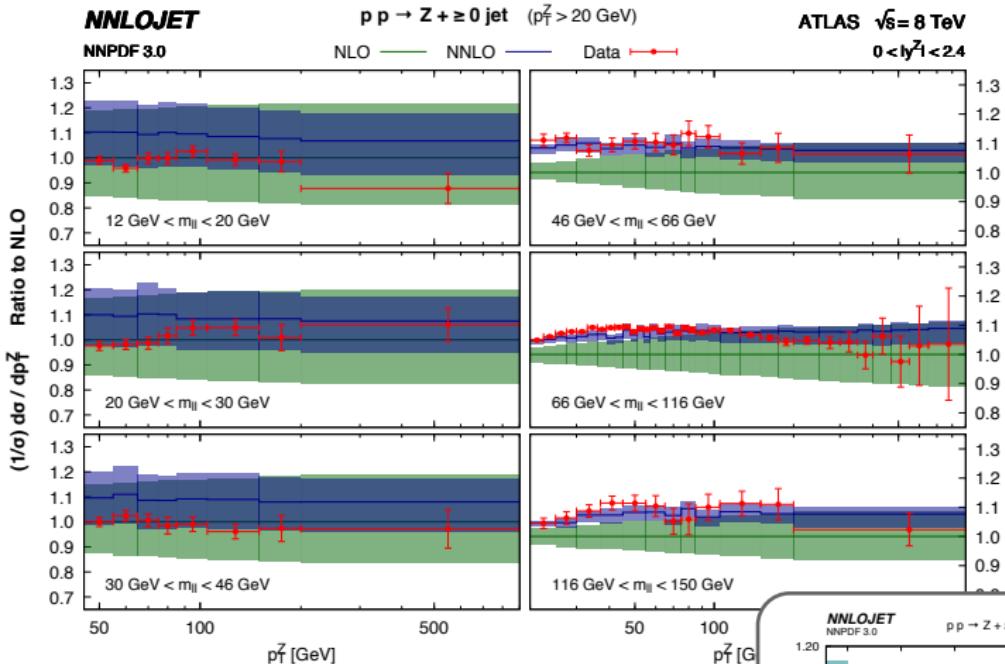
- ▶ NLO prediction systematically undershoots data, NNLO corrections  $\sim 5\text{--}10\%$
- ▶ improvement in theory vs. data comparison
- ▶ reduction of scale uncertainties

# Double-differential: $d\sigma/dp_T^Z$ binned in $m_{\ell\ell}$ — ATLAS

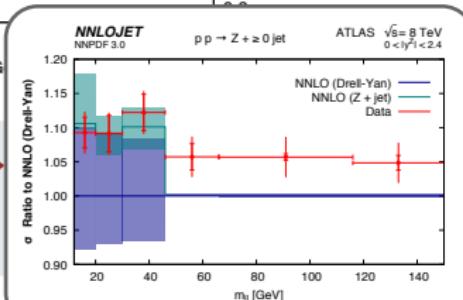


- $0 < |y^Z| < 2.4$
- 6 bins in  $m_{\ell\ell}$  [GeV]: [12, 20] [20, 30] [30, 46] [46, 66] [66, 116] [116, 150]

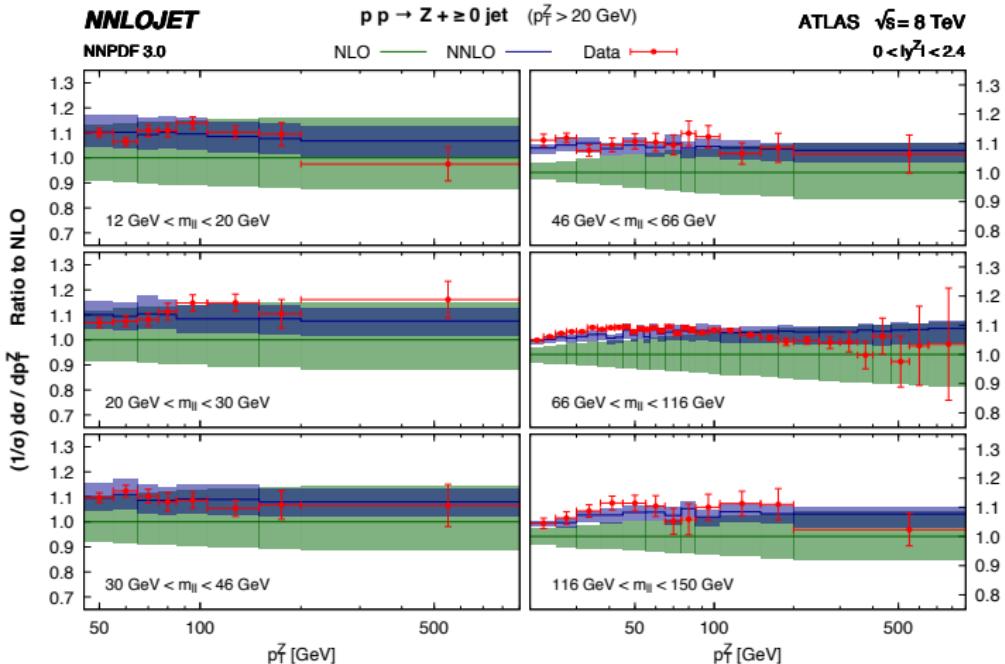
# Double-differential: $d\sigma/dp_T^Z$ binned in $m_{\ell\ell}$ — ATLAS



- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties
- three low-mass bins:  $p_T^Z > 45$  GeV

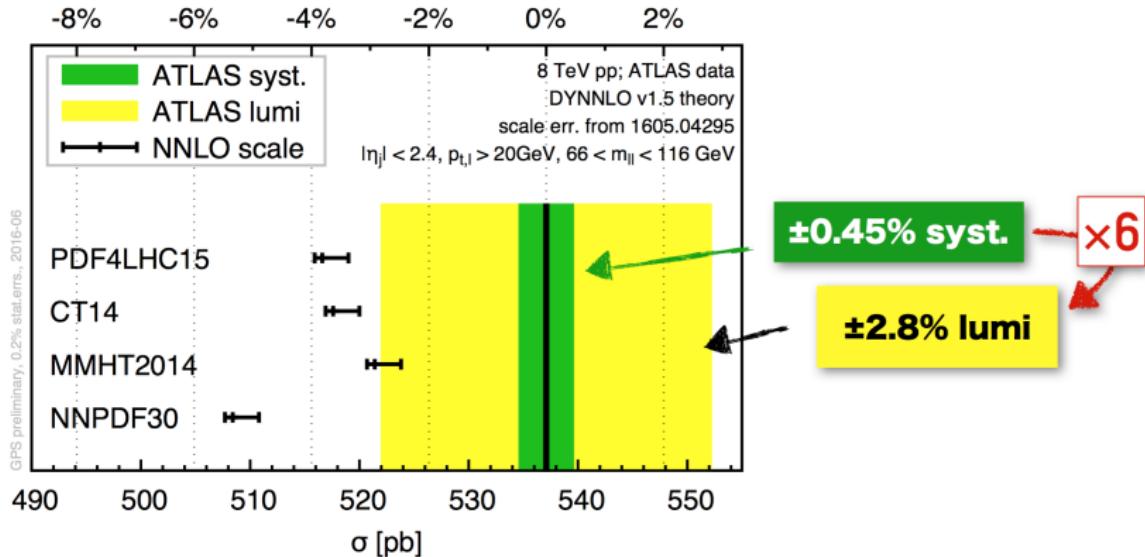


# Double-differential: $d\sigma/dp_T^Z$ binned in $m_{\ell\ell}$ — ATLAS



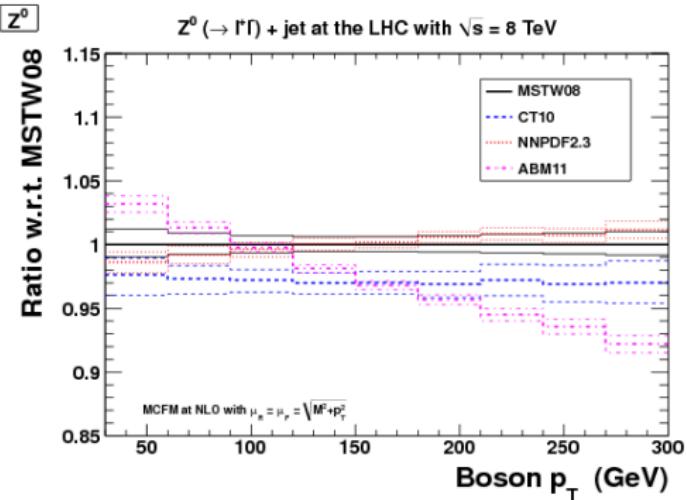
- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties
- three low-mass bins: **use Z + jet @ NNLO**

# The fiducial Drell-Yan cross section



[talk by Gavin Salam, LHCP 2016]

# 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
- ⇒ 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:  $Z + b(b) \leftrightarrow$  constrain b-quark PDFs

# Z+jet: Channel breakdown

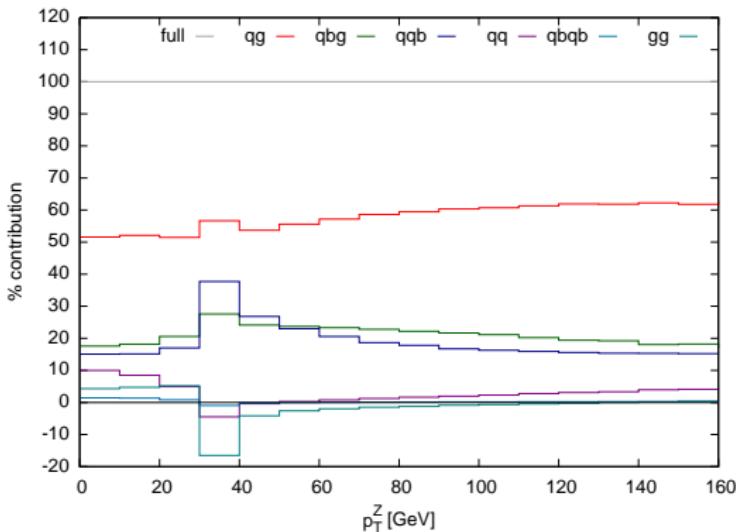
Variety of partonic channels contribute to Z+jet production

↪ 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%         |



# Antenna subtraction @ NLO

[J. Currie , E.W.N. Glover, S. Wells '13]

$d\hat{\sigma}^T :$

$$d\hat{\sigma}^T \sim \mathbf{J}_n^{(1)} M_n^0$$



$d\hat{\sigma}^S :$

$$d\hat{\sigma}^S \sim X_3^0 M_n^0$$

# Antenna subtraction @ NNLO

[J. Currie , E.W.N. Glover, S. Wells '13]

