p_T^V at NNLO QCD

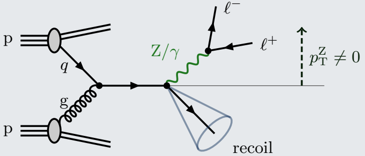
Alexander Huss

p_T^Z and p_T^W theory meeting

CERN — January 25th 2018

work with A. Gehrmann–De Ridder,
T. Gehrmann, E.W.N. Glover, and D.M. Walker.

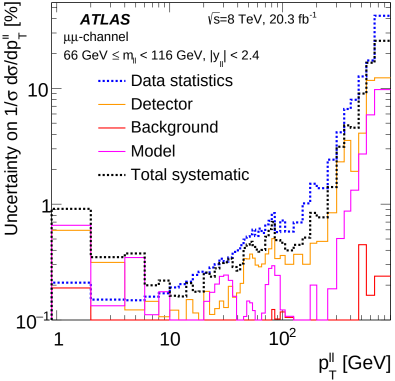
Motivation



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

- large cross section
- clean leptonic signature

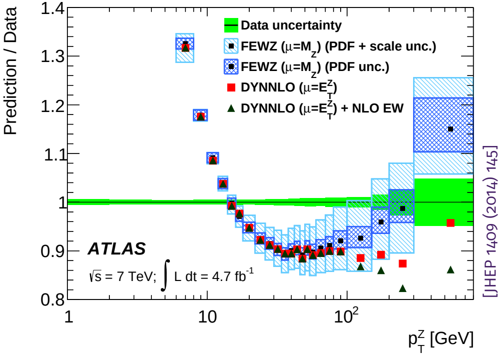
recoil ⇝ sensitivity to α_s, gluon PDF



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

- fully inclusive w.r.t. QCD radiation
- only reconstruct ℓ^+, ℓ^-
  ⇝ sub-% accuracy!
- important constraints in PDF fits
  [Boughezal et al. '17]

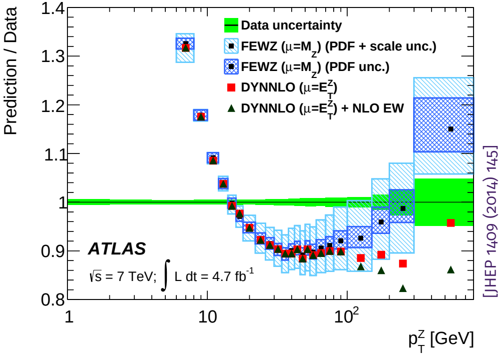
Inclusive p_T^Z at fixed order



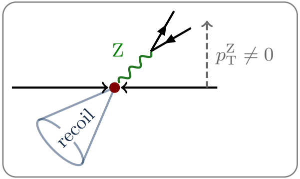
probe various aspects:

- very low p_T^Z: non-perturbative effects
- low $p_T^Z \lesssim 20\text{–}50$ GeV: resummation required
- $p_T^Z \gtrsim 20\text{–}50$ GeV: fixed-order prediction
- high $p_T^Z \gtrsim 500$ GeV: EW corrections

Inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ at fixed order



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



↪ Only NLO accurate in this distribution!

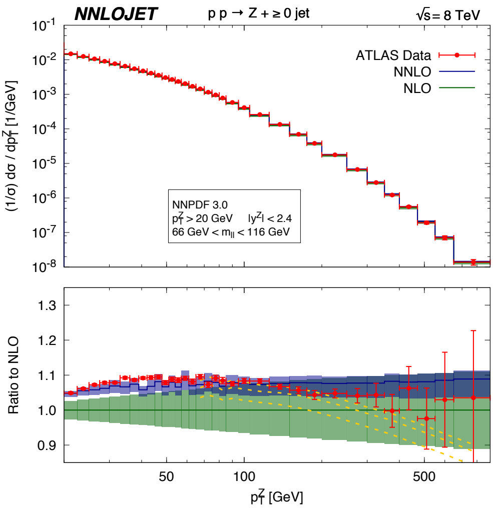
NNLO

$p_{\mathrm{T}}^{\mathrm{Z}} > p_{\mathrm{T,cut}}^{\mathrm{Z}}$

- requires hadronic recoil

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

Inclusive p_{T} spectrum of Z/γ^*



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

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

- removes luminosity error $(\sim 3\%)$

NLO

undershoots data by 5–10%

NNLO

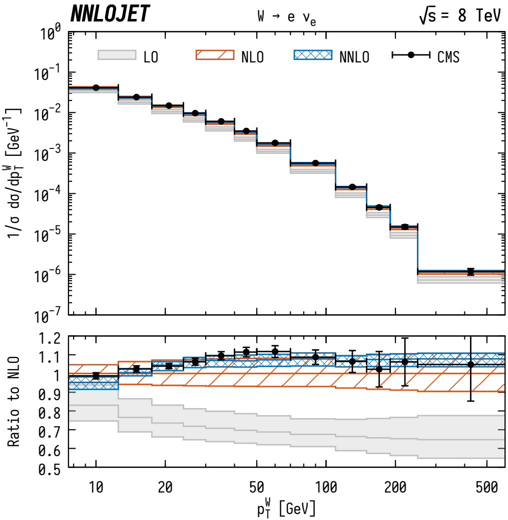
significant improvement
in Data vs. Theory comparison

+ EW corrections: - - - -

[Denner, Dittmaier, Kasprzik, Mück '11]

$\Rightarrow$ large impact in the high-p_{T} tail
$\sim -20\%$ for $p_{\mathrm{T}}^{\mathrm{Z}} \sim 900$ GeV
(Sudakov logatithms)

Inclusive p_T spectrum of $W^{\pm}$



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

NLO

↪ shape differences 5–10%

↪ scale uncertainties 5–10%

NNLO

↪ shape distortion

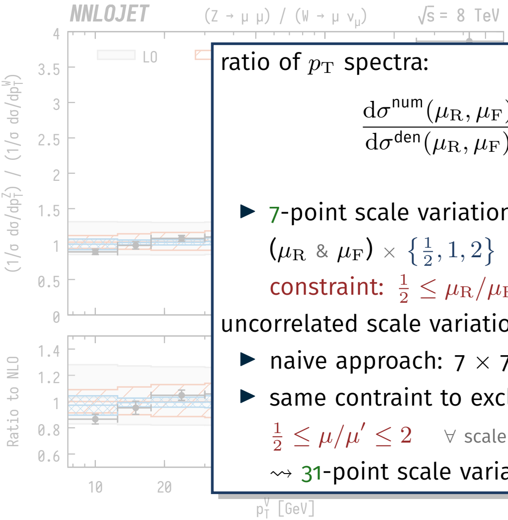
↪ reduction of scale uncertainties

↪ good agreement with data

▶ similar corrections to p_T^Z

Ratio of p_T spectra: Z/W

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



ratio of p_T spectra:

$$\frac{d\sigma^{\text{num}}(\mu_R,\mu_F)/dp_T}{d\sigma^{\text{den}}(\mu_R,\mu_F)/dp_T}$$

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

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

1 (very stable)

ns similar: Z vs. W

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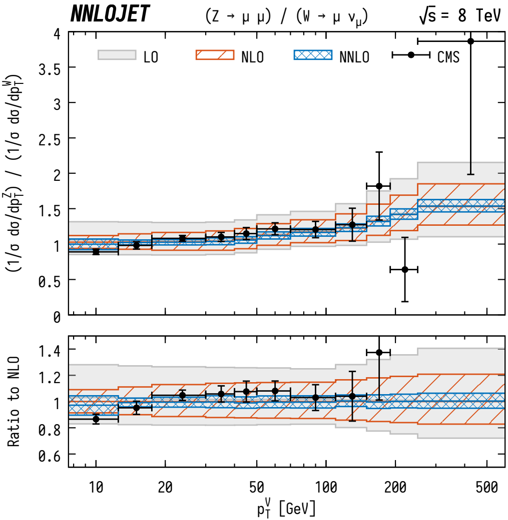
nties ± 10–20%

nties ± 5–8%

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 ± 10–20%

NNLO

↪ scale uncertainties ± 5–8%

Summary & Outlook

Summary

- $V + \text{jet}$ @ NNLO $\rightsquigarrow$ p_{T}^{V} spectrum at $\mathcal{O}(\alpha_{\mathrm{s}}^{3})$ for $p_{\mathrm{T}}^{V} > p_{\mathrm{T,cut}}^{V}$
  - $\hookrightarrow$ significant reduction in scale uncertainties
  - $\hookrightarrow$ substantial improvement in theory vs. data comparison
- Ratios of p_{T}^{V} spectra
  - $\hookrightarrow$ uncorrelated scale variation with: $\frac{1}{2} \leq \mu/\mu' \leq 2$ $\forall$ scale pairs
  - $\hookrightarrow$ scale uncertainties reduced by typically a factor of two or more
  - $\hookrightarrow$ remarkable stability w.r.t. QCD corrections

Outlook

- matching to resummation
- extend MiNLO $\rightsquigarrow$ MiNNLO
- inclusion of EW corrections

Summary & Outlook

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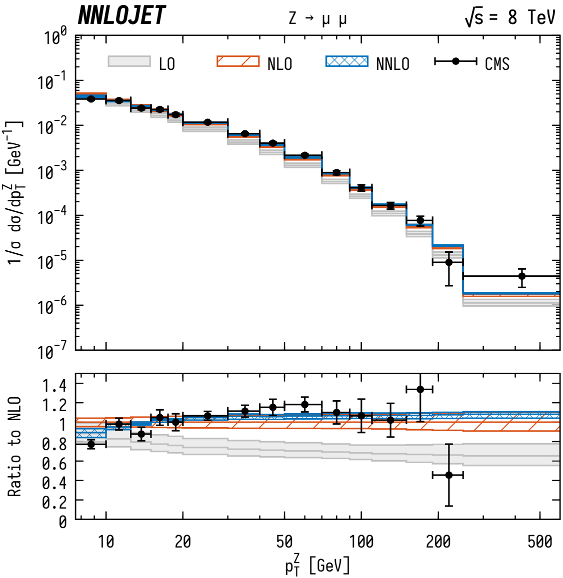
Thank you

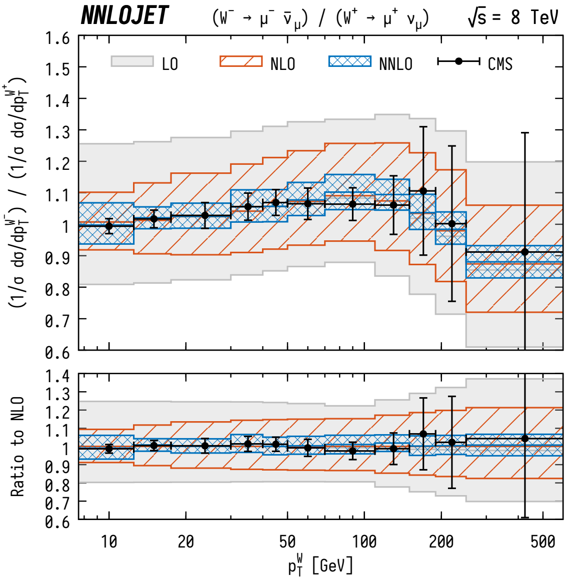
Backup Slides

CMS: p_T^Z



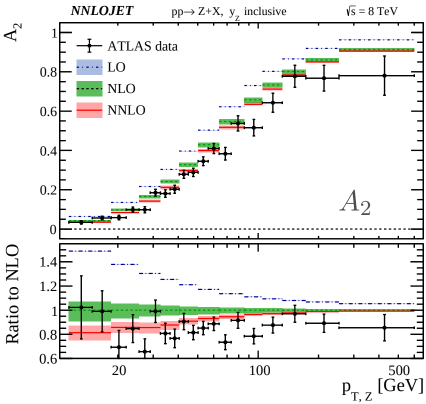
NNLOJET
Z → μ μ
√s = 8 TeV
LO
NLO
NNLO
CMS
1/σ dσ/dp$_T^Z$ [GeV^{-1}]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Ratio to NLO
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
20
50
100
200
500
p$_T^Z$ [GeV]

CMS: ratio W^-/W^+

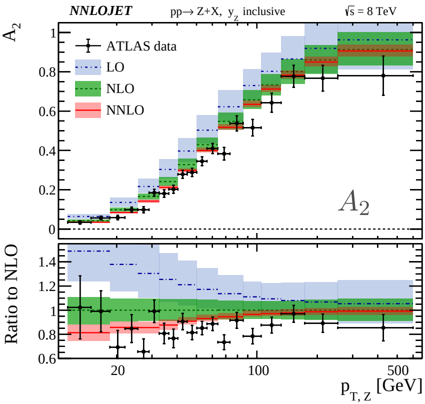

NNLOJET
(W⁻ → μ⁻ ν̄μ) / (W⁺ → μ⁺ νμ)
√s = 8 TeV
LO
NLO
NNLO
CMS
(1/σ dσ/dpT^W⁻) / (1/σ dσ/dpT^W⁺)
Ratio to NLO
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
20
50
100
200
500
pT^W [GeV]

Ratios — correlated vs. uncorrelated (ang. coefficients)

correlated:



uncorrelated:



- **LO** α_s cancels in correlated case ⇝ almost no scale bands
- **NLO** substantial differences in correlated vs. uncorrelated
- **NNLO** similar uncertainty estimates

uncorrelated exhibits more realistic behaviour ⇝ default choice