Overview of progress with NNLOJET

Alexander Huss

LHC-EW WG meeting

Orsay — May 25th 2018

work with X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld,
A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, I. Majer,
T. Morgan, J. Niehues, J. Pires, and D. Walker

$p_{\mathrm{T}}^{\mathrm{Z}}$ & ϕ_η^*: [JHEP 1607 (2016) 133, JHEP 1611 (2016) 094] ,
A_i: [JHEP 1711 (2017) 003], $p_{\mathrm{T}}^{\mathrm{W}}$ & ratios: [PRL 120 (2018) no.12, 122001]

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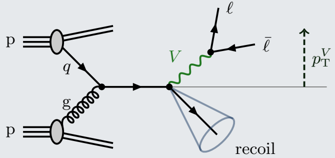
Common framework for NNLO calculations using Antenna Subtraction

- parton-level event generator
- based on antenna subtraction
- test & validation framework
- `APPLfast-NNLO` interface
  [Britzger, Gwenlan, AH, Morgan, Sutton, Rabbertz]
- first differential N^3LO: DIS 1-jet
- …

Processes:

- $\mathrm{pp} \to (\mathrm{Z} \to \ell^+\ell^-) + 0, 1$ jets
- $\mathrm{pp} \to (\mathrm{W}^\pm \to \ell\nu) + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} + 2$ jets (VBF)
  $\hookrightarrow \gamma\gamma,\ \ell^+\ell^-\gamma,\ 4\ell, \ldots$
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 1,\ 2$ jets
- $\mathrm{e}^+\mathrm{e}^- \to 3$ jets
- …

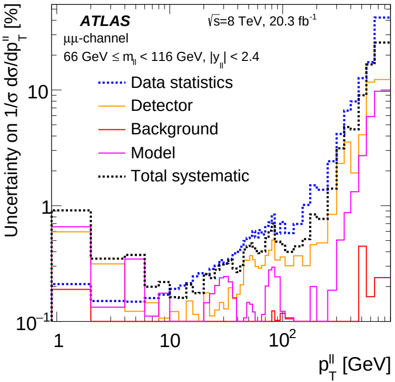
p_T^V — Towards precision phenomenology



$\mathrm{p\,p} \to V + X \to \ell\,\bar{\ell} + X$

- large cross section
- clean leptonic signature

recoil ⇝ sensitivity to α_s, gluon PDF



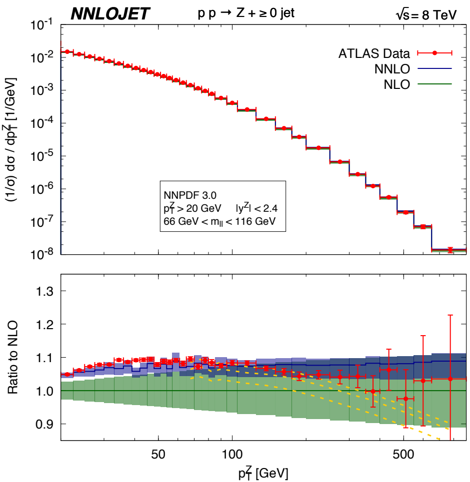
[Eur. Phys. J. C **76** (2016) no.5, 291]

- fully inclusive w.r.t. QCD radiation
- only reconstruct leptons

  ⇝ sub-% accuracy! (forZ)
- probes various aspects of theory predictions
- ratios: $(\mathrm{d}\sigma/\mathrm{d}p_T^V)/(\mathrm{d}\sigma/\mathrm{d}p_T^{V'})$

FEWZ
DYNNLO } Only NLO accurate in this distribution

Inclusive p_{T} spectrum of Z/γ^*



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

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

NLO

undershoots data by 5–10%

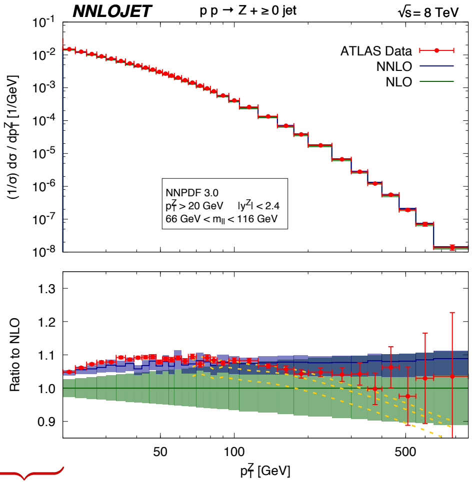
NNLO

significant improvement
in Data vs. Theory comparison

+ EW corrections: - - - -

[Denner, Dittmaier, Kasprzik, Mück '11]

Inclusive p_{T} spectrum of Z/γ^*



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

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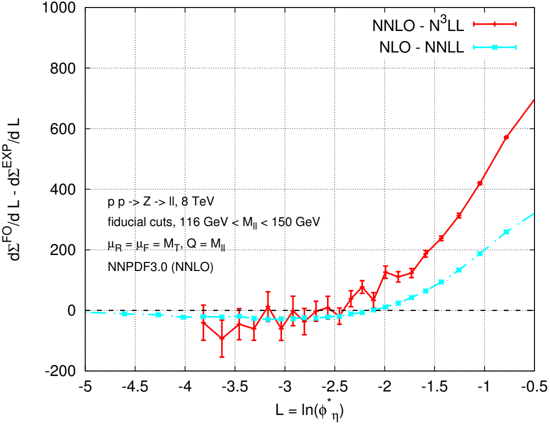
[Denner, Dittmaier, Kasprzik, Mück '11]

f.o. divergent
for $p_{\mathrm{T,Z}} \to 0$

resummation $\alpha_s^n \log^k(p_{\mathrm{T}}/M)$

- RADISH [with Bizon, Monni, Re, Rottoli, Torrielli]
- NNLO matched to N^{3}LL (talk by P.F. Monni)

Comparing the logs — fixed-order & resummation



- for $p_T^Z \to 0$: difference $\to 0$
  - ↪ excellent agreement within stat. errors
  - ↪ challenging numerics
- very important *cross check*
- convergence much delayed vs. inclusive setups

fixed-order: $p_T^Z \neq 0$

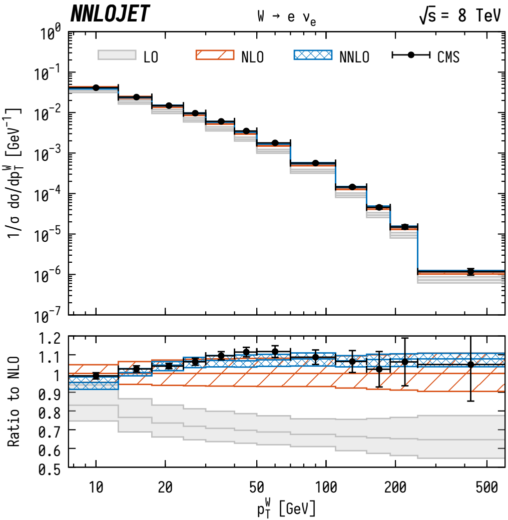
- fiducial cuts $(p_T^{\ell+} \neq p_T^{\ell-}, \ldots)$
- $\mu^2 = E_T^2 = m_{\ell\ell}^2 + (p_T^Z)^2$

$\longleftrightarrow$

resummation: $p_T^Z = 0$

- fiducial cuts $(p_T^{\ell+} = p_T^{\ell-}, \ldots)$
- $\mu^2 = m_{\ell\ell}^2$

Inclusive $p_{\rm T}$ spectrum of $\mathrm{W}^{\pm}$



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

NLO

↪ shape differences $5\text{–}10\%$

↪ scale uncertainties $5\text{–}10\%$

NNLO

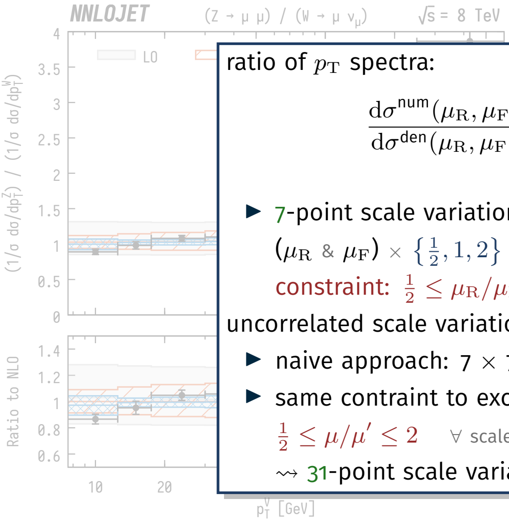
↪ shape distortion

↪ reduction of scale uncertainties

↪ good agreement with data

- similar corrections to $p_{\rm T}^{\rm Z}$

Ratio of p_{T} spectra: Z/W



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

ratio of p_{T} spectra:

$$\frac{\mathrm{d}\sigma^{\text{num}}(\mu_{\mathrm{R}},\mu_{\mathrm{F}})/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma^{\text{den}}(\mu_{\mathrm{R}},\mu_{\mathrm{F}})/\mathrm{d}p_{\mathrm{T}}}$$

- 7-point scale variation for $\mathrm{d}\sigma$:
  (μ_{R} & μ_{F}) $\times \{\frac{1}{2}, 1, 2\}$
  constraint: $\frac{1}{2} \leq \mu_{\mathrm{R}}/\mu_{\mathrm{F}} \leq 2$

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)

s similar: Z vs. W

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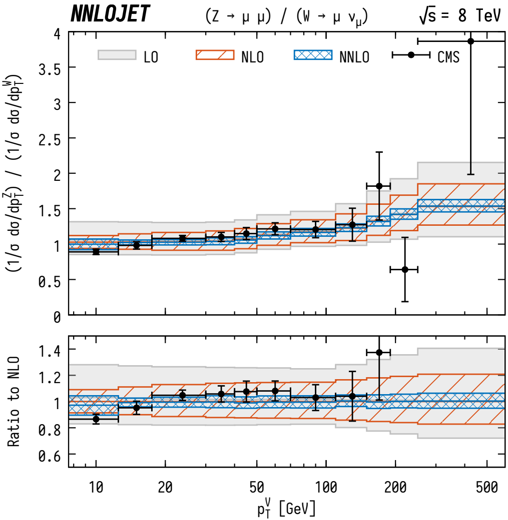
es

ties ± 10–20%

ties ± 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

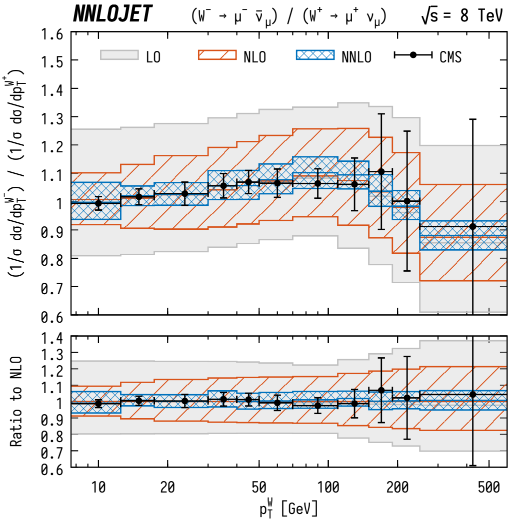
NLO

↪ scale uncertainties ± 10–20%

NNLO

↪ scale uncertainties ± 5–8%

Ratio of p_T spectra: W^-/W^+



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

- $K_{\text{(N)NLO / (N)LO}} \sim 1$ (very stable)

↪ QCD corrections similar: W^- vs. W^+

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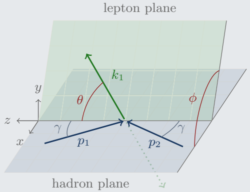
NLO

↪ scale uncertainties $\pm 10\text{–}20\%$

NNLO

↪ scale uncertainties $\pm 5\text{–}8\%$

Angular coefficients



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

- lepton angular distributions (θ, ϕ)
- probe production dynamics & polarisation
- M_W & $\sin^2\theta_\mathrm{w}$ measurement

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

Angular coefficients: $A_i(p_\mathrm{T}^\mathrm{Z}, y^\mathrm{Z}, m_{\ell\ell})$ $\quad Y_{lm}(\theta,\phi),\; l = 0,1,2$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\text{unpol.}}}{\mathrm{d}^4q}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0\,(1-3\cos^2\theta)$$
$$+ A_1\,\sin(2\theta)\cos\phi + \frac{1}{2}A_2\,\sin^2\theta\,\cos(2\phi)$$
$$+ A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\,\sin(2\phi)$$
$$+ A_6\,\sin(2\theta)\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}$$

$A_i(q)$ $+\,\sigma^{\text{unpol.}}$ — production dynamics

$Y_{lm}(\theta,\phi)$ — lepton kinematics

$l = 0:$	$m = 0$
$l = 1:$	$m = \pm1,\ 0$
$l = 2:$	$m = \pm2,\ \pm1,\ 0$
total:	9

Angular coefficients

- extraction of A_i though projections: $\int \mathrm{d}\Omega \; Y_{lm} Y^*_{l'm'} = \delta_{ll'}\,\delta_{mm'}$

$$\langle f(\theta,\phi)\rangle = \frac{1}{\sigma}\int_{-1}^{1}\mathrm{d}\cos\theta\int_0^{2\pi}\mathrm{d}\phi\;\frac{\mathrm{d}\sigma(\theta,\phi)}{\mathrm{d}\cos\theta\,\mathrm{d}\phi}\;f(\theta,\phi)$$

$A_0 = 4 - 10\,\langle\cos^2\theta\rangle$, $A_1 = 5\,\langle\sin^2\theta\cos(2\phi)\rangle$, $A_2 = 10\,\langle\sin^2\theta\cos(2\phi)\rangle$,
$A_3 = 4\,\langle\sin\theta\cos\phi\rangle$, $A_4 = 4\,\langle\cos\theta\rangle$, ...

$\hookrightarrow$ **very** challenging numerics!

- dominant coefficients: $A_{0,\ldots,4}$

$A_{0,1,2}$: parity even $\rightsquigarrow$ probed by γ^* & Z exchange
$A_{3,4}$: parity odd $\rightsquigarrow$ sensitive to $\sin^2\theta_{\mathrm{w}}$, $A_4 \leftrightarrow A_{\mathrm{FB}}$

Lam–Tung relation

$$A_0 - A_2 = 0$$

- analogue of Callen–Gross relation in DIS $(F_2 = 2xF_1)$
- not affected by $\mathcal{O}(\alpha_{\mathrm{s}})$ corrections
  $\hookrightarrow$ violation starting from $\mathcal{O}(\alpha_{\mathrm{s}}^2)$

Calculational setup

LHC @ $8\,\mathrm{TeV}$:	ATLAS [arXiv:1606.00689], CMS [arXiv:1504.03512], LHCb
region & accuracy:	$p_{\mathrm{T,Z}} > 10\,\mathrm{GeV}$ & $\mathcal{O}(\alpha_s^3)$ (using $\mathrm{Z}+\mathrm{jet}$ @ NNLO)
PDF & α_s:	`PDF4LHC15_nnlo_30` & $\alpha_s(M_Z) = 0.118$
scale choice:	$\mu_0 \equiv E_{\mathrm{T,Z}} = \sqrt{m_{\ell\ell}^2 + p_{\mathrm{T},\ell\ell}^2}$

Scale variation

independent variation of μ_R & μ_R with $\frac{1}{2} \leq \mu_R/\mu_F \leq 2$ ⇝ 7 points

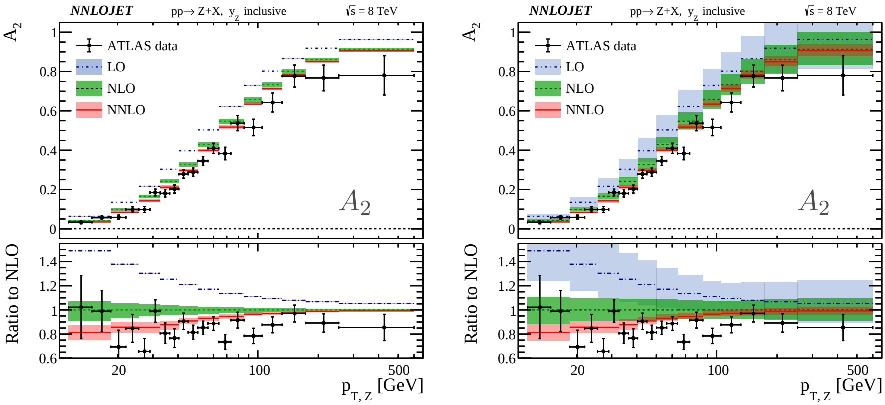
A_i defined through ratios:

$$\langle f(\theta,\phi)\rangle = \frac{\int \mathrm{d}\Omega\; \mathrm{d}\sigma(\mu_F^{\mathrm{num.}}, \mu_R^{\mathrm{num.}})\; f(\theta,\phi)}{\int \mathrm{d}\Omega\; \mathrm{d}\sigma(\mu_F^{\mathrm{den.}}, \mu_R^{\mathrm{den.}})}$$

- **correlated:** $\mu_{F,R}^{\mathrm{num.}} = \mu_{F,R}^{\mathrm{den.}}$ ⇝ 7 points
- **uncorrelated:** $\frac{1}{2} \leq \mu_a^i/\mu_b^j \leq 2$ ⇝ 31 points

Ratios — correlated vs. uncorrelated

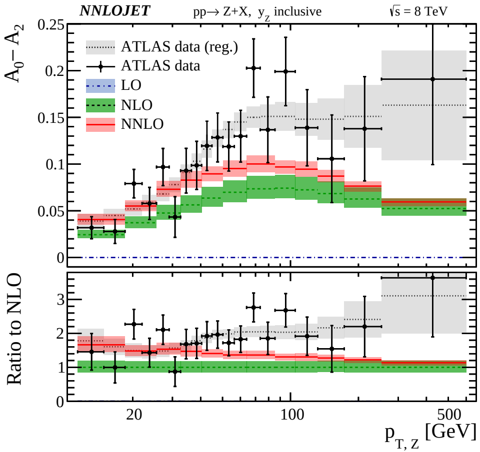
correlated: **uncorrelated:**



- **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

Angular coefficients — ATLAS @ 8 TeV



$\mathcal{O}(\alpha_s)$ prediction:
↪ vanishes (Lam–Tung)

$\mathcal{O}(\alpha_s^2)$ prediction:
↪ ≃ DYNNLO (NNLO)
↪ tension with data
↪ $\chi^2/N_{\mathrm{dat.}} \sim 4.89$

$\mathcal{O}(\alpha_s^3)$ prediction:
↪ large positive corrections
↪ $\chi^2/N_{\mathrm{dat}} \sim 1.75$

- data: [ATLAS arXiv:1606.00689]
  ↪ applies "regularization"

No significant data* vs. theory disagreement between
(un-regularized) ATLAS & theory @ $\mathcal{O}(\alpha_s^3)$

$$^*\ \chi^2 = \sum_{i,j}^{N_{\mathrm{dat.}}} (O^i_{\mathrm{exp}} - O^i_{\mathrm{th.}})\sigma^{-1}_{ij}(O^j_{\mathrm{exp}} - O^j_{\mathrm{th.}})$$

Summary & Outlook

Summary

- $\mathcal{O}(\alpha_s^3)$ **NNLO QCD** predictions: p_T^Z & $p_T^{W^\pm}$ for $p_T > p_{T,\,\mathrm{cut}}$
  - ↪ significant reduction in scale uncertainties ($\sim \pm$ few %)
  - ↪ improved data vs. theory agreement
  - ↪ p_T^Z matched to **N³LL** resummation with `RadISH` (talk by P.F. Monni)
- Ratio of p_T^V spectra
  - ↪ very stable w.r.t. QCD corrections: $K_{\text{(N)NLO / (N)LO}} \sim 1$
  - ↪ **NLO** ⇝ **NNLO**: substantial reduction of scale uncertainties
- angular coefficients A_i directly probe production dynamics
  - ↪ first clear evidence of *Lam–Tung* violation $(A_0 - A_2 \neq 0)$ by ATLAS & CMS
  - ↪ **NNLO**: large impact on A_0, A_1, and A_2
  - ↪ substantial improvement in agreement with data for $A_0 - A_2$

Outlook

- **N³LL** + **NNLO** for $p_T^{W^\pm}$ & ratios

Thank you