NNLO QCD corrections for Z+jet and related processes

Alexander Huss

in collaboration with

A. Gehrmann–De Ridder, T. Gehrmann,
E.W.N. Glover and T.A. Morgan

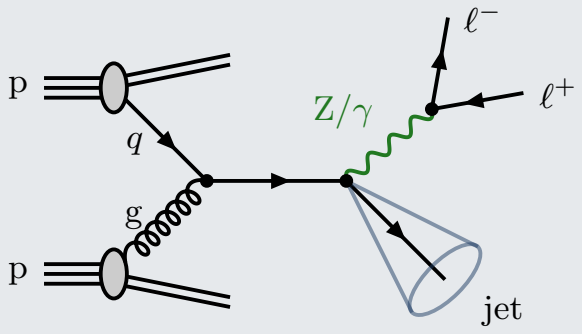
Seminar — UCL CP3 — Louvain, March 1st 2017

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

MC@NNLO

based on Phys. Rev. Lett. **117** (2016) 022001, JHEP **1607** (2016) 133, JHEP **1611** (2016) 094

Motivation — Why $\mathrm{Z}+\mathrm{jet}$ production?



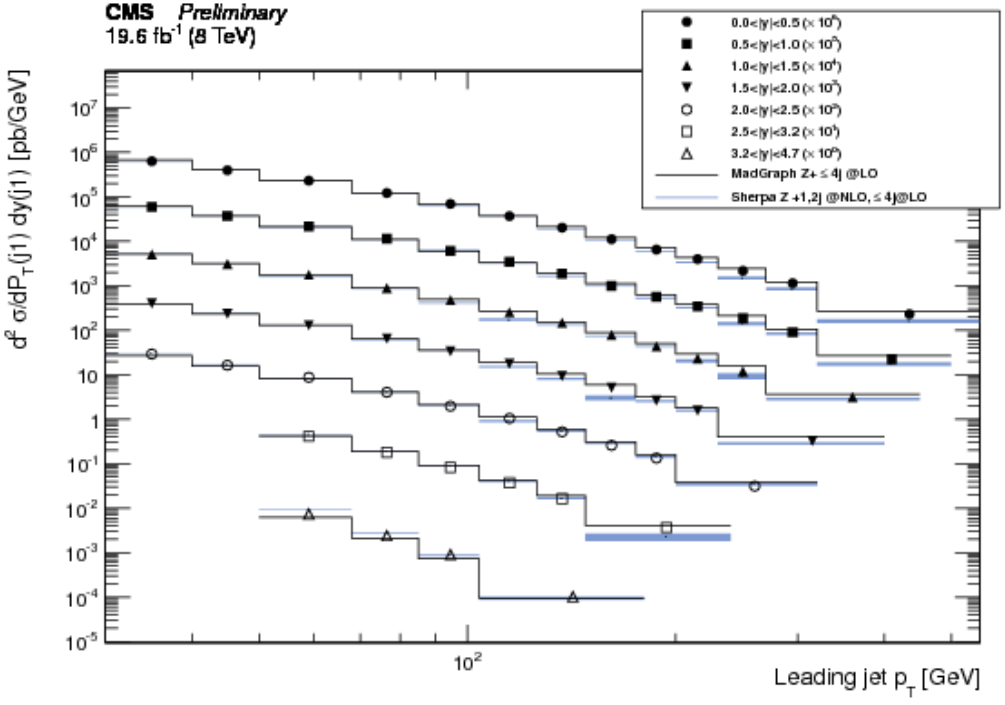
$$\mathrm{p\,p} \;\to\; \mathrm{Z}/\gamma^{*}+\mathrm{jet} \;\to\; \ell^{-}\ell^{+}+\mathrm{jet}+X$$

- large cross section
- clean leptonic signature

+jet $\rightsquigarrow$ sensitivity to α_{s}, gluon PDF

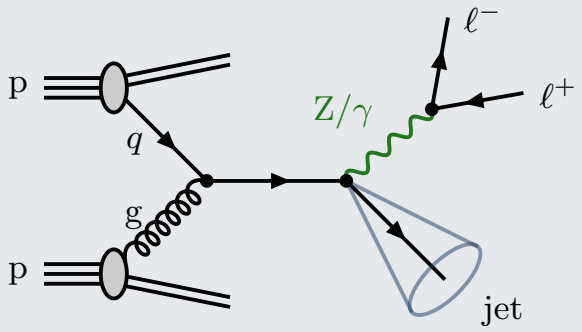
- precision measurements
  - ↪ test pQCD
  - ↪ constrain PDFs (gluon)
- detector calibration
  - ↪ jet energy scale
- searches for BSM physics

high-precision predictions mandatory!



[CMSPAS SMP-14-009]

Motivation — Why $\mathrm{Z}+\mathrm{jet}$ production?



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

- 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** ..... [Kühn, Kulesza, Pozzorini, Schulze '05] [Denner, Dittmaier, Kasprzik, Mück '11]
- **NLO QCD+EW** (+multijet merging) ..... [Kallweit, Lindert, Maierhofer, Pozzorini, Schönherr '15]
- **NNLO QCD** .....
  ↪ Antenna subtraction (this talk) [Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15, '16]
  ↪ N-jettiness ..... [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]
  [Boughezal, Liu, Petriello.'16]

  $\rightsquigarrow$ validation (✓) & opportunity for benchmarks

This talk

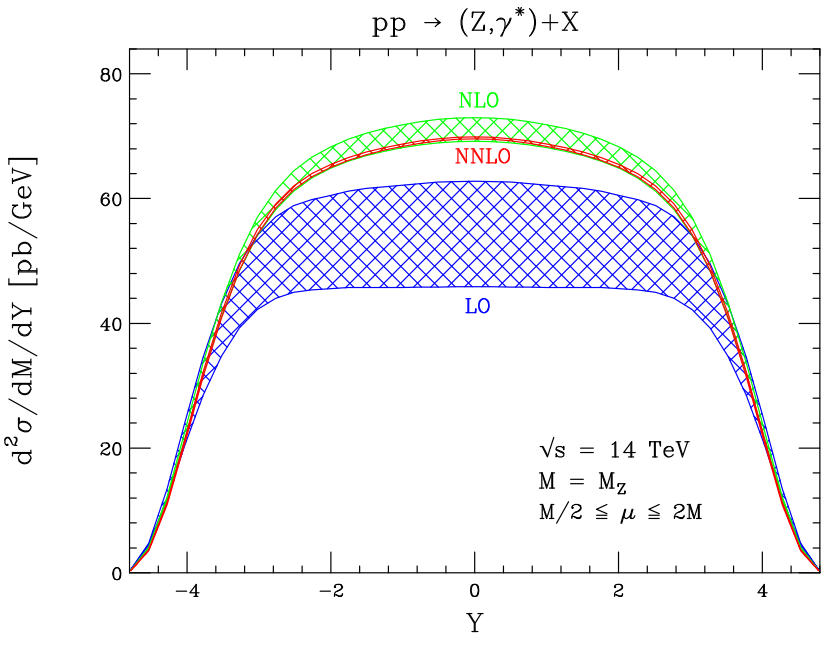
1. NNLO QCD corrections — Antenna Subtraction
2. $\mathrm{Z} + \mathrm{jet}$ production @ NNLO
3. Inclusive Z-boson production for $p_{\mathrm{T}} \neq 0$
4. The ϕ^*_η observable

NNLO QCD corrections
—
Antenna Subtraction



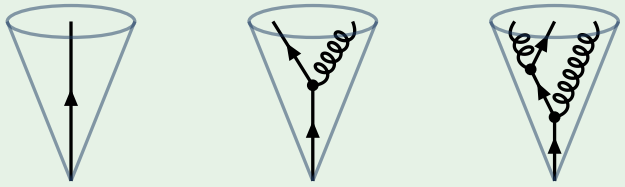
What NNLO might give you

- high-precision mandatory
  ↪ processes with large K-factors (H)
  ↪ "standard candles" (jets, V, t, …)
- reduction of scale uncertainties
  ↪ variation of μ_{R} & μ_{F}



[Anastasiou, Dixon, Melnikov, Petriello '04]

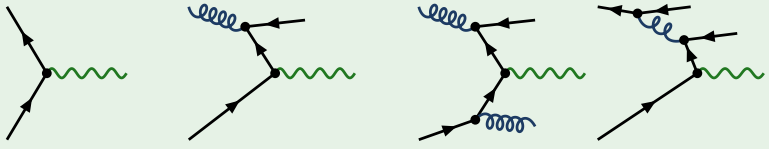
Jet clustering



LO NLO NNLO

- better modelling of jet algorithm between theory & experiment

Initial-state radiation



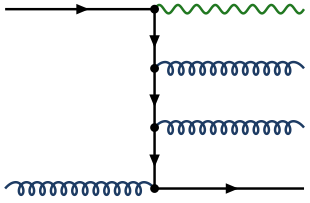
LO NLO NNLO

$q\bar{q}$ $\oplus\ qg,\ \bar{q}g$ $\oplus\ gg,\ qq',\ q\bar{q}',\ \bar{q}\bar{q}'$

- opening up of all channels
- more complicated p_{T} recoil

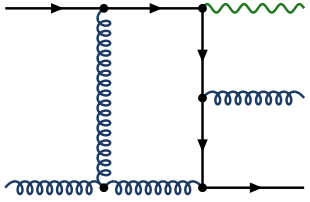
Anatomy of an NNLO calculation

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



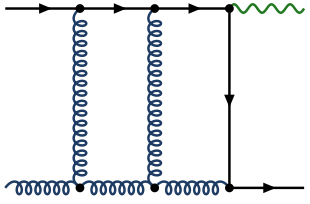
[Hagiwara, Zeppenfeld '89]
[Berends, Giele, Kuijf '89]
[Falck, Graudenz, Kramer '89]

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



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

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

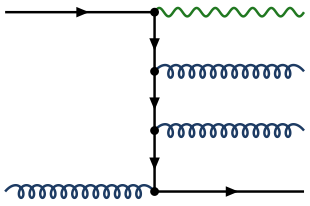


[Moch, Uwer, Weinzierl '02]
[Garland et al. '02]
[Gehrmann, Tancredi '12]

Individual building blocks known for a while

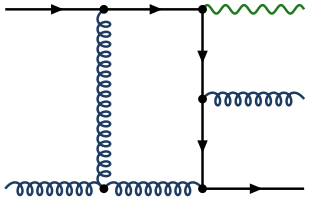
Anatomy of an NNLO calculation

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



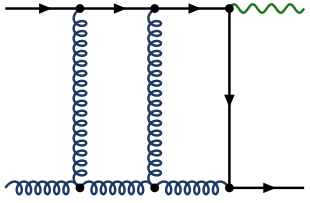
- single-unresolved
- double-unresolved

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



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

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



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

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

Non-trivial cancellation of infrared singularities

Anatomy of an NNLO calculation

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

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

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

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

Different methods:

- Antenna subtraction ..... [Gehrmann–De Ridder, Gehrmann, Glover '05]
- CoLorFul subtraction ..... [Del Duca, Somogyi, Trocsanyi '05]
- q_{T} subtraction ..... [Catani, Grazzini '07]
- Sector-improved residue subtraction ..... [Czakon '10], [Boughezal, Melnikov, Petriello '11]
- N-jettiness subtraction ..... [Gaunt, Stahlhofen, Tackmann, Walsh '15] [Boughezal, Focke, Liu, Petriello '15]

...

Approaches: subtraction, slicing

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

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

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

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

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

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

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

Antenna factorisation

- antenna formalism operates on colour-ordered amplitudes
- exploit universal factorisation properties in IR limits

$$\underbrace{|\mathcal{A}^0_{m+1}(\ldots,i,j,k,\ldots)|^2}_{\text{partial amplitude}} \xrightarrow{j \text{ unresolved}} \underbrace{X^0_3(i,j,k)}_{\text{antenna function}} \underbrace{|\mathcal{A}^0_m(\ldots,I,K,\ldots)|^2}_{\text{reduced ME}}$$

$+$ mapping $\{p_i,p_j,p_k\} \to \{p_I,p_K\}$

- captures multiple limits* and smoothly interpolates between them

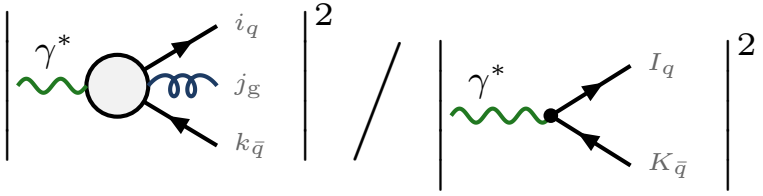
limit	$X^0_3(i,j,k)$	mapping
$p_j \to 0$	$\dfrac{2s_{ik}}{s_{ij}s_{jk}}$	$p_I \to p_i, p_K \to p_k$
$p_j \parallel p_i$	$\dfrac{1}{s_{ij}} P_{ij}(z)$	$p_I \to (p_i+p_j), p_K \to p_k$
$p_j \parallel p_k$	$\dfrac{1}{s_{jk}} P_{kj}(z)$	$p_I \to p_i, p_K \to (p_j+p_k)$

* c.f. dipoles: $X^0_3(i,j,k) \sim \mathcal{D}_{ij,k} + \mathcal{D}_{kj,i}$

Antenna subtraction

- $X(\ldots)$ based on physical matrix elements $\quad X = \overbrace{A,\ B,\ C}^{q\bar{q}}, \overbrace{D,\ E}^{qg}, \overbrace{F,\ G,\ H}^{gg}$

$$X_3^0(i,j,k) \sim \frac{|\mathcal{A}_3^0(i,j,k)|^2}{|\mathcal{A}_2^0(I,K)|^2}, \qquad A_3^0(i_q, j_g, k_{\bar{q}}) \sim$$



Use $X(\ldots)$ to construct subtraction terms example: $q\bar{q} \to \mathrm{gg}(+\mathrm{Z})$

$$|\mathcal{A}_4^0(1_q, i_g, j_g, 2_{\bar{q}})|^2 \mathcal{J}_1^{(2)}(p_i, p_j) - D_3^0(1_q, i_g, j_g)|\mathcal{A}_3^0(\widetilde{1}_q, \widetilde{(ij)}_g, 2_{\bar{q}})|^2 \mathcal{J}_1^{(1)}(\widetilde{p_{ij}})$$
$$- D_3^0(i_g, j_g, 2_q)|\mathcal{A}_3^0(1_q, \widetilde{(ij)}_g, \widetilde{2}_{\bar{q}})|^2 \mathcal{J}_1^{(1)}(\widetilde{p_{ij}})$$

- integrating the antennae $\longleftrightarrow$ phase-space factorization

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

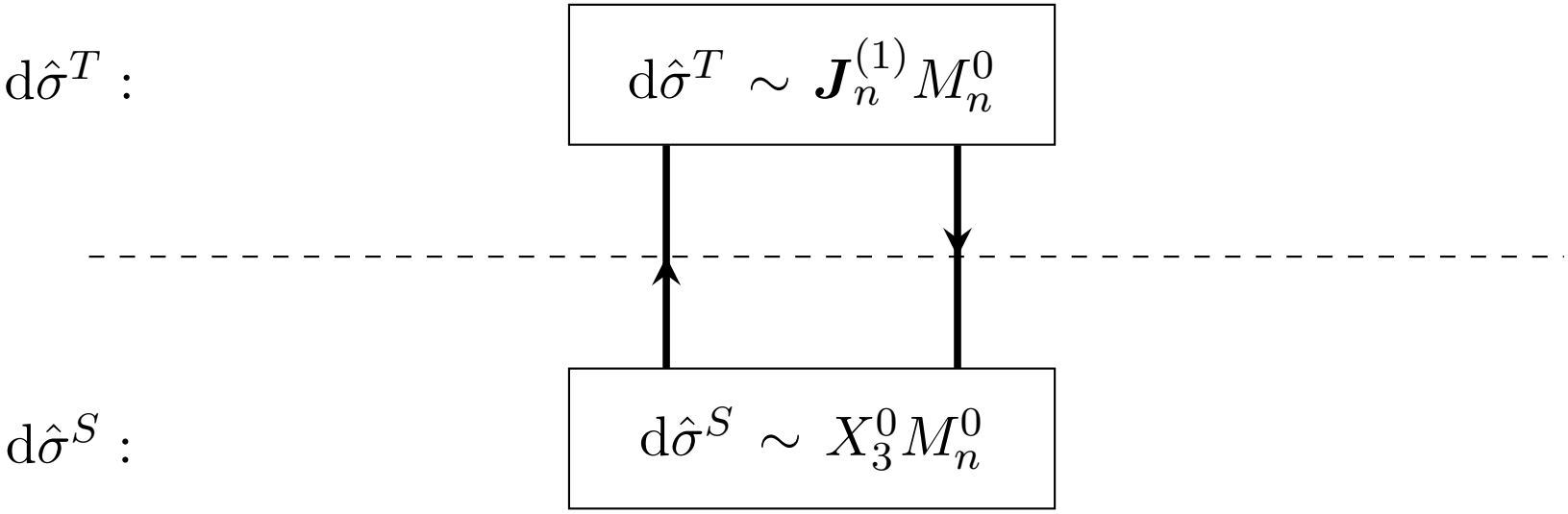
All building blocks available!

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

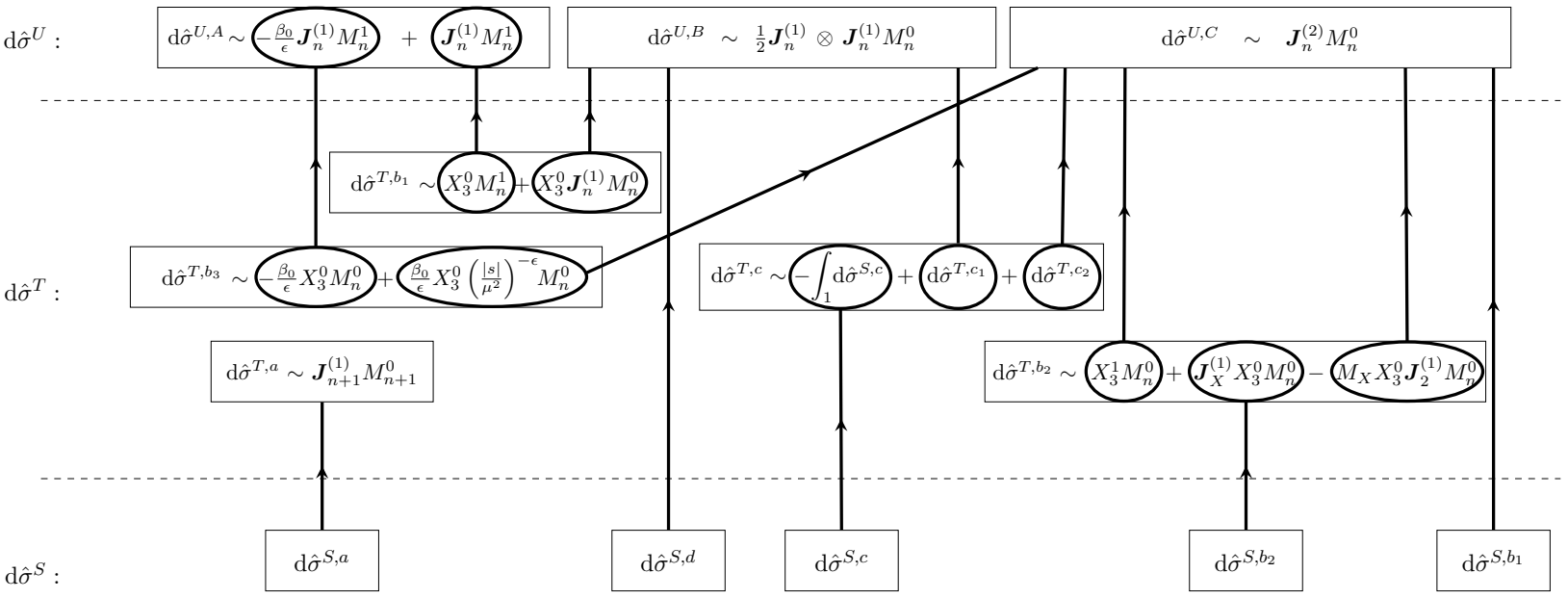
Antenna subtraction @ NLO

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



Antenna subtraction @ NNLO

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



Checks of the calculation — unresolved limits

Double-real level

- $\mathrm{d}\sigma^{\mathrm{S}} \to \mathrm{d}\sigma^{\mathrm{RR}}$

  (single- & double-unresolved)

Real–virtual level

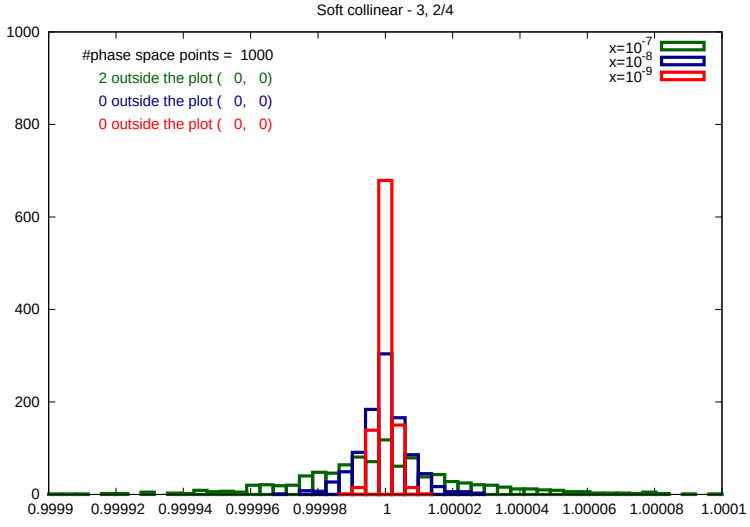
- $\mathrm{d}\sigma^{\mathrm{T}} \to \mathrm{d}\sigma^{\mathrm{RV}}$

  (single-unresolved)

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

$q\,\bar{q} \to \mathrm{Z} + \mathrm{g}_3\;\mathrm{g}_4\;\mathrm{g}_5$ @ tree

(g_3 soft & $\mathrm{g}_4 \parallel \bar{q}$)

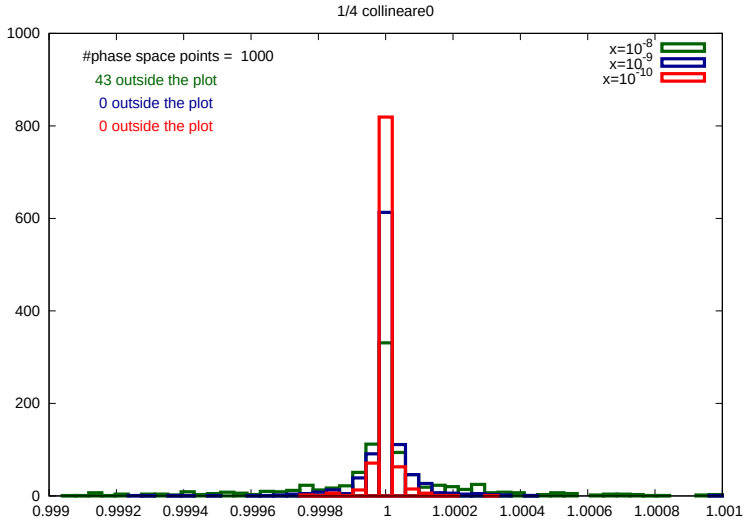


(approach limit: $x_i = 10^{-7},\ 10^{-8},\ 10^{-9}$)

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

$q\,\bar{q} \to \mathrm{Z} + \mathrm{g}_3\;\mathrm{g}_4$ @ 1-loop

($\mathrm{g}_4 \parallel q$)



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

Checks of the calculation — pole cancellation

DimReg: $D = 4 - 2\epsilon$

Double-virtual level

- Poles $\left(\mathrm{d}\sigma^{\mathrm{VV}} - \mathrm{d}\sigma^{\mathrm{U}}\right) = 0$

  2-loop, (1-loop)^2 $\rightsquigarrow$ $1/\epsilon^4, \ldots, 1/\epsilon$

Real–virtual level

- Poles $\left(\mathrm{d}\sigma^{\mathrm{RV}} - \mathrm{d}\sigma^{\mathrm{T}}\right) = 0$

  1-loop $\rightsquigarrow$ $1/\epsilon^2, 1/\epsilon$

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

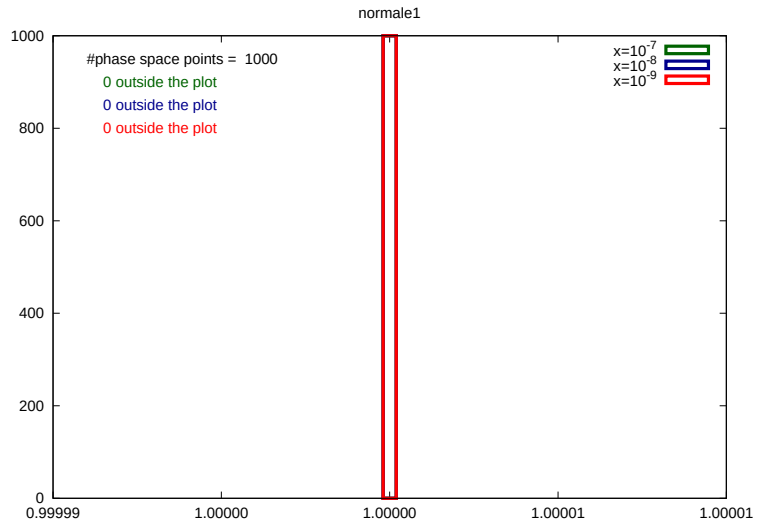
   poles = 0;

  6.58 sec out of 6.64 sec
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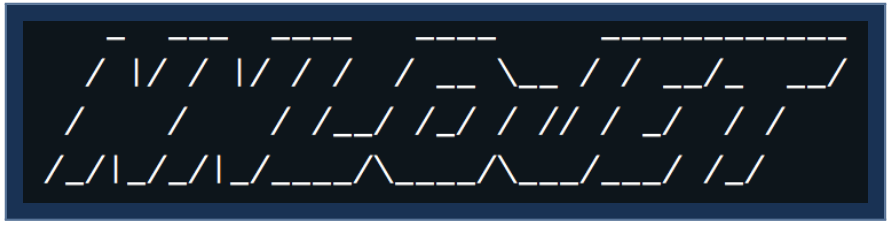
pole coefficient: $\mathrm{d}\sigma^{\mathrm{T}}/\mathrm{d}\sigma^{\mathrm{RV}} \equiv 1$

$q\,\bar{q} \to \mathrm{Z} + \mathrm{g}\,\mathrm{g}$ @ 1-loop

($1/\epsilon$ coefficient)



NNLOJET



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

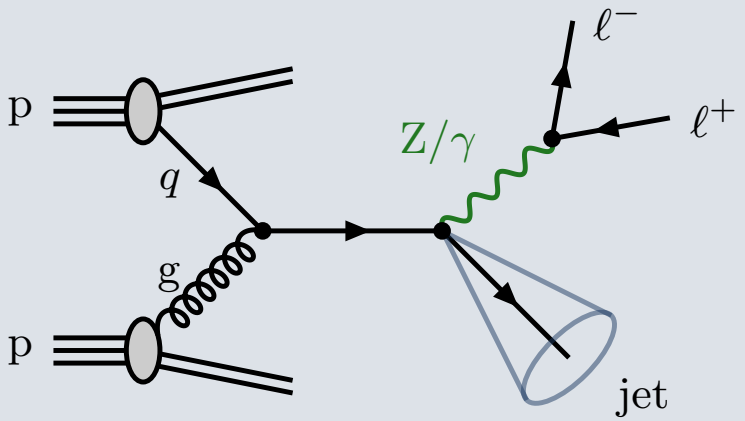
Common framework for NNLO corrections using Antenna Subtraction

- parton-level event generator
- based on antenna subtraction
- test & validation framework
- `APPLfast-NNLO` interface
  (Work in progress)
- ...

Processes:

- $\mathrm{pp} \to V \to \bar{\ell}\ell \ + 0, 1$ jets
- $\mathrm{pp} \to \mathrm{H} \ + 0, 1, 2$ jets
- $\mathrm{pp} \to$ dijets
- $\mathrm{ep} \to 1, \ 2$ jets
- $\mathrm{e}^+\mathrm{e}^- \to 3$ jets
- ...

$\mathrm{Z} + \mathrm{jet}$ production @ NNLO



$\mathrm{Z} + \mathrm{jet}$: Fiducial 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: $80\ \mathrm{GeV} < m_{\ell\ell} < 100\ \mathrm{GeV}, \quad |y^{\ell}| < 5$
- jets [anti-k_T ($R = 0.5$)]: $p_T^{\mathrm{jet}} > 30\ \mathrm{GeV}, \quad |y^{\mathrm{jet}}| < 3$
- scale choice: $\mu_F = \mu_R = M_Z \times [\frac{1}{2}, 1, 2]$

Fiducial cross section

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

$+40\%$

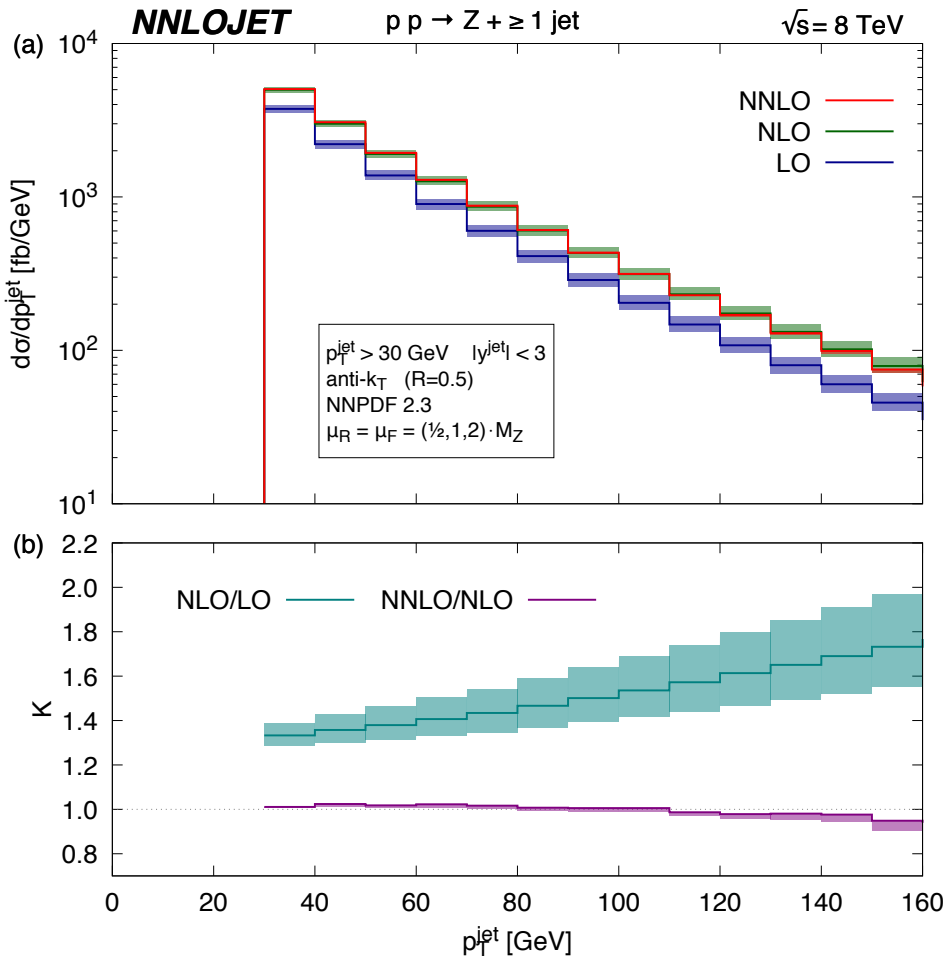
$$\sigma_{\mathrm{NLO}} = 144.4^{+9.0}_{-7.2}\ \mathrm{pb}$$

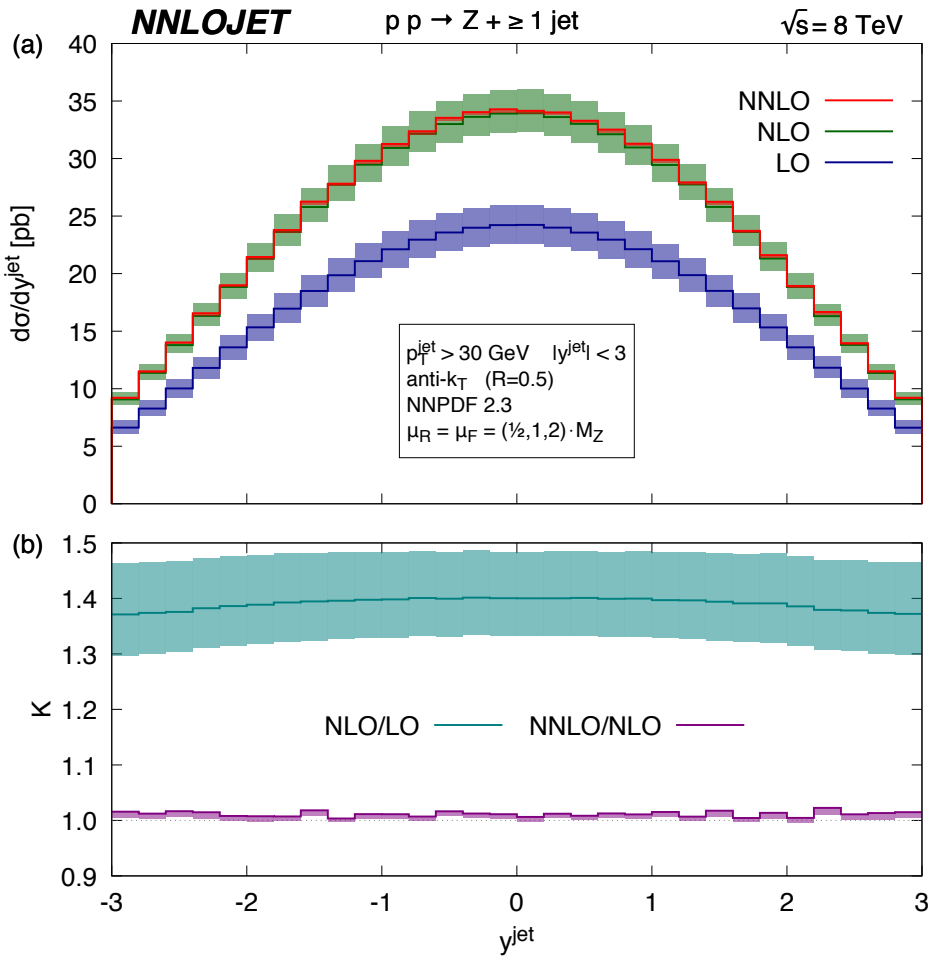
$+1\%$

$$\sigma_{\mathrm{NNLO}} = 145.8^{+0.0}_{-1.2}\ \mathrm{pb}$$

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

Distributions: Leading jet

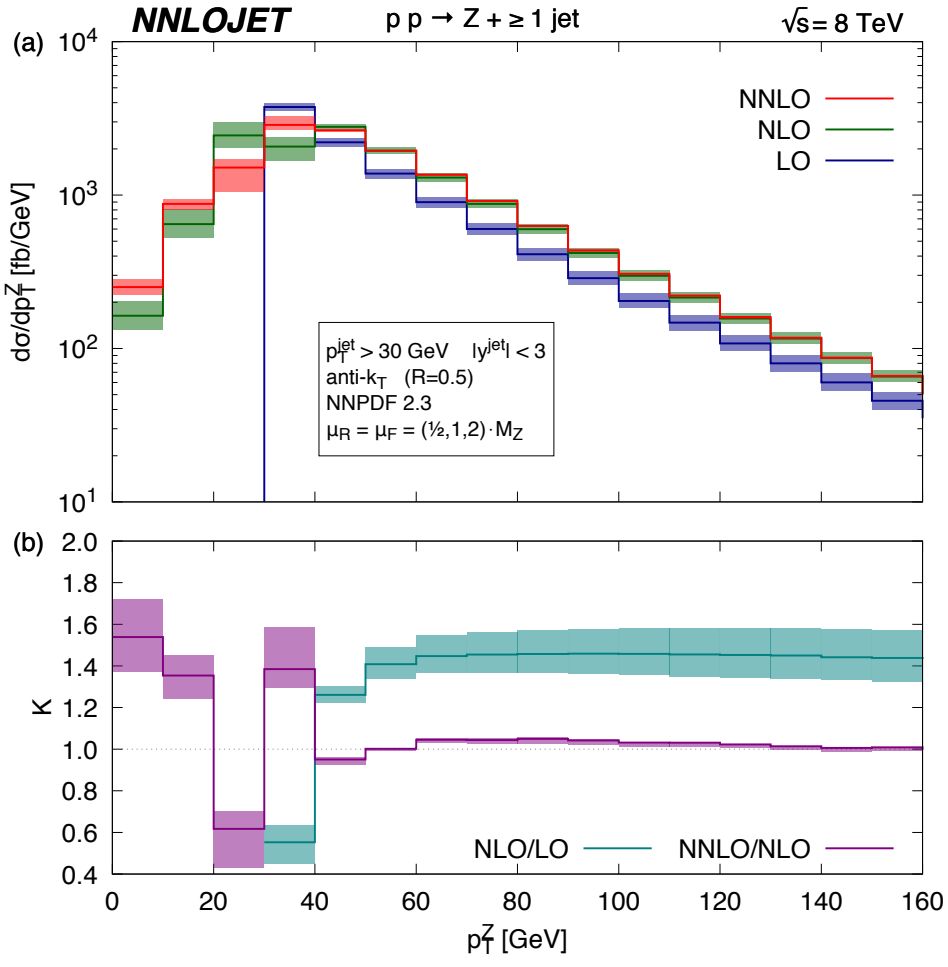


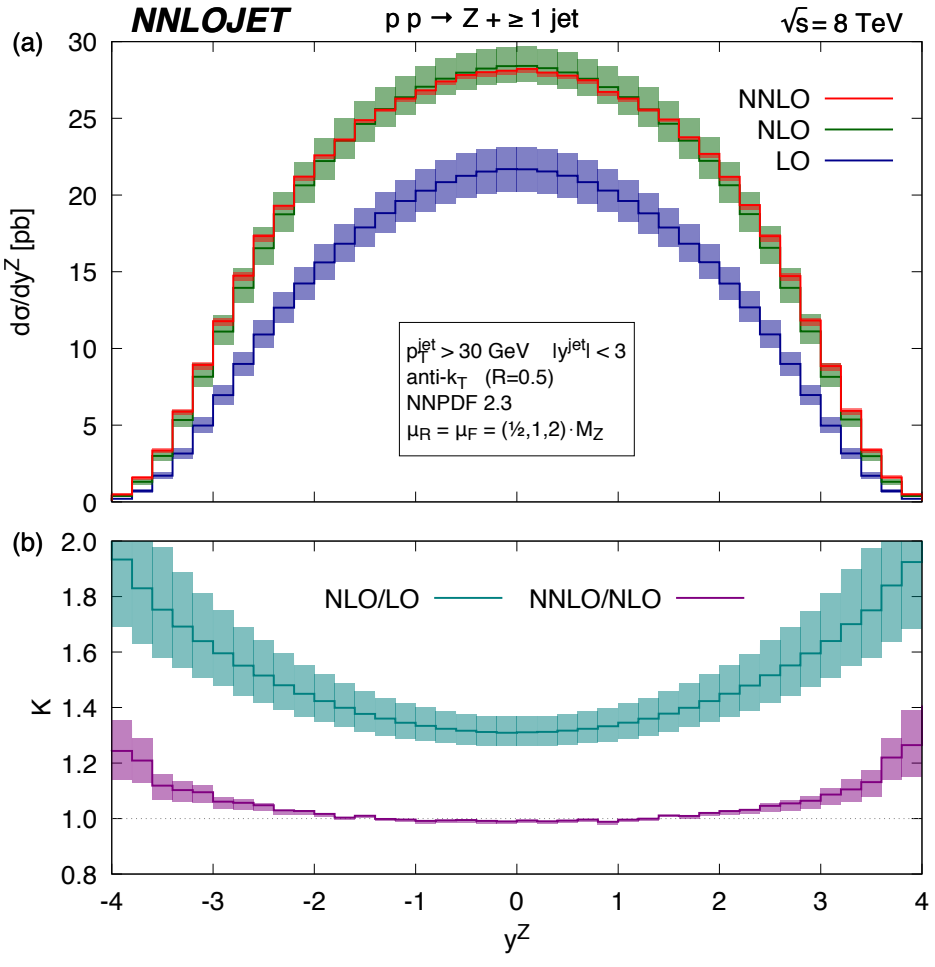


- NLO corrections $\gtrsim 40\%$ $\quad(\delta^{\mathrm{NLO}}_{\mathrm{scale}} \sim \delta^{\mathrm{LO}}_{\mathrm{scale}})$
- NNLO corrections $\lesssim 5\%$ (quite flat)
- significant reduction of scale uncertainty

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

Distributions: Z-boson

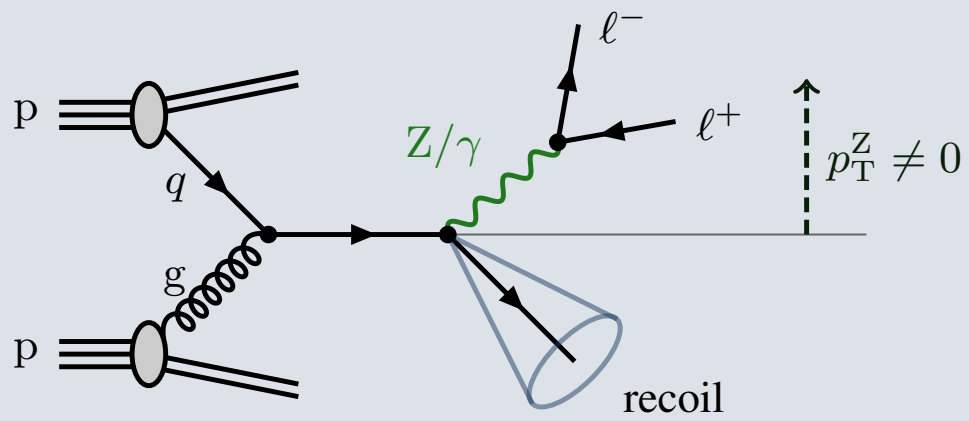




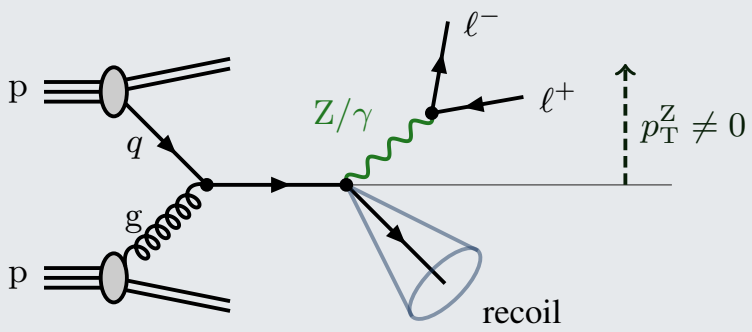
- "Sudakov shoulder" at $p_{\mathrm{T}}^{\mathrm{Z}} \sim 30\ \mathrm{GeV}$
- NNLO corrections not flat!
- significant reduction of scale uncertainty

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

Inclusive Z-boson production for $p_{\mathrm{T}} \neq 0$



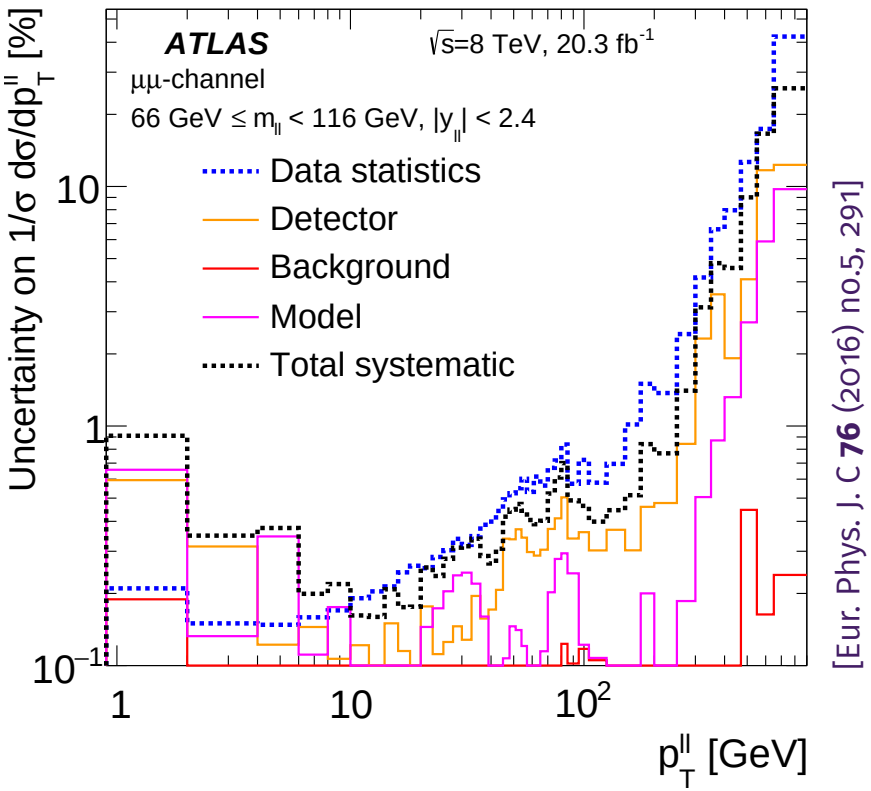
Motivation — Towards precision phenomenology



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

- large cross section
- clean leptonic signature

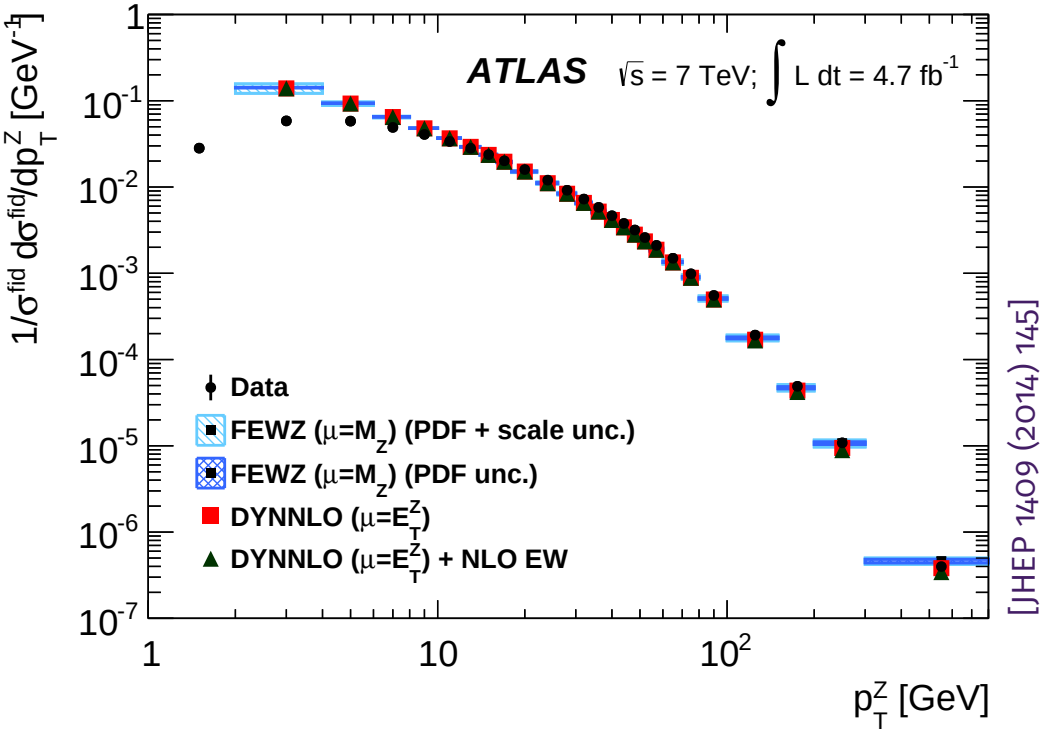
recoil ⇝ sensitivity to α_s, gluon PDF



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

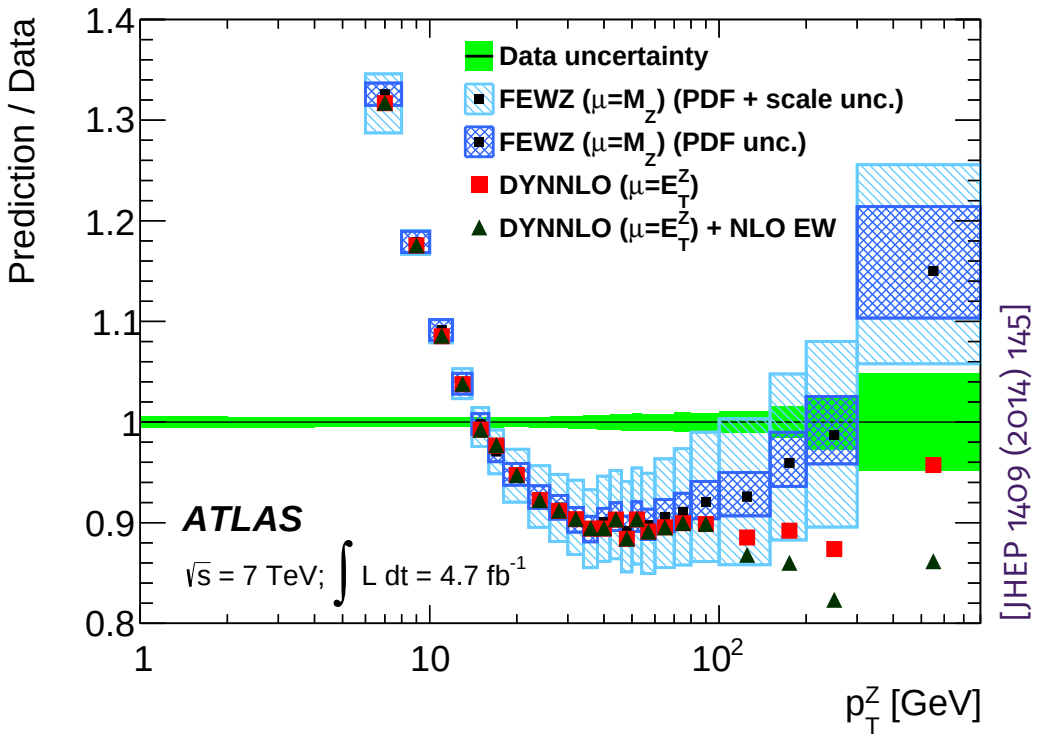
- fully inclusive w.r.t. QCD radiation
- only reconstruct ℓ^+, ℓ^-
  ⇝ sub-% accuracy!
- potential to constrain gluon PDFs
  ⇝ NNLO needed! [Malik, Watt '14]

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



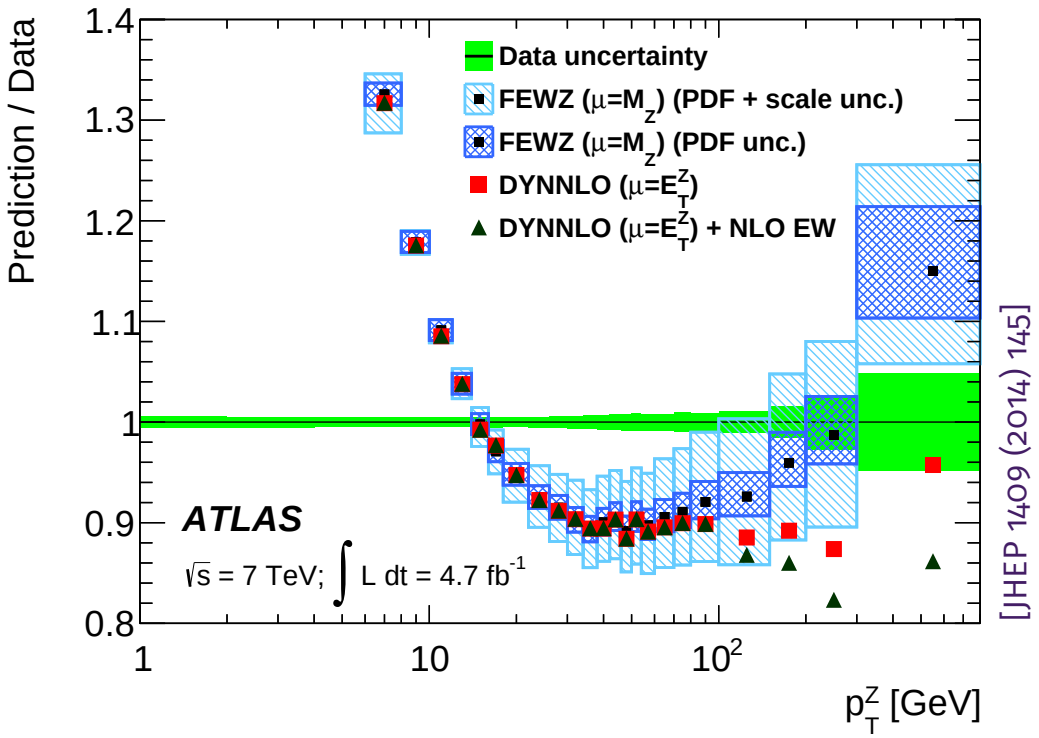
- low $p_{\mathrm{T}}^{\mathrm{Z}} \lesssim 10\ \mathrm{GeV}$: resummation required
- $p_{\mathrm{T}}^{\mathrm{Z}} \gtrsim 20\ \mathrm{GeV}$: fixed-order prediction $\sim 10\%$ below data!
- high $p_{\mathrm{T}}^{\mathrm{Z}} \gtrsim 500\ \mathrm{GeV}$: EW corrections ~ -5 - 10%

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

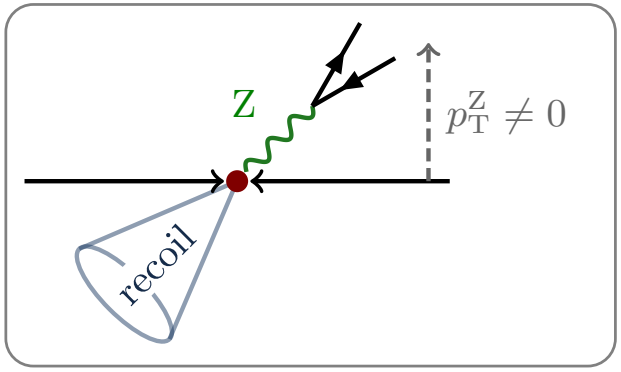


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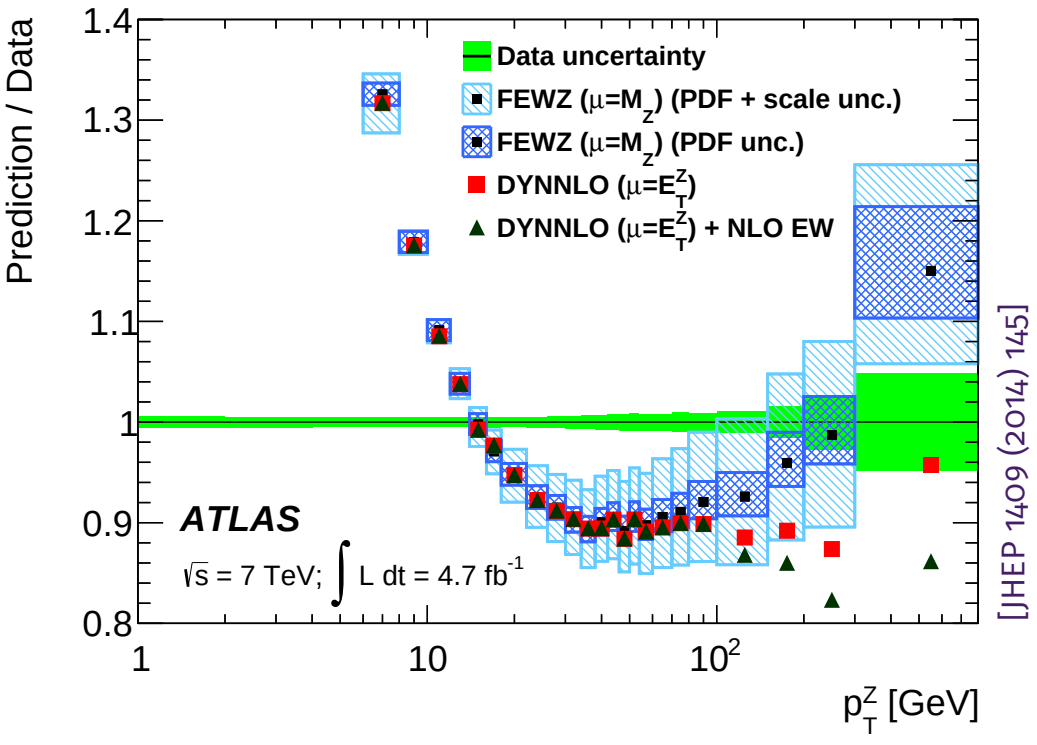


FEWZ
DYNNLO
} $\mathrm{Z}+0\,\mathrm{jet}$ @ NNLO

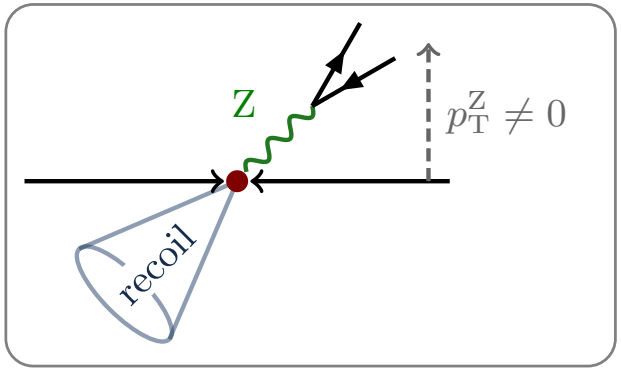


↪ Only NLO accurate
in this distribution!

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



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



↪ Only NLO accurate in this distribution!

NNLO

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

- requires hadronic recoil

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

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

Calculational setup

- LHC @ 8 TeV
- PDF: `NNPDF3.0` $\alpha_{\mathrm{s}}(M_{\mathrm{Z}}) = 0.118$
- ~~jet cuts~~ $\longleftrightarrow$ fully inclusive w.r.t. QCD radiation
- $p_{\mathrm{T}}^{\mathrm{Z}} > 20$ GeV
- scale choice (dynamical)

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

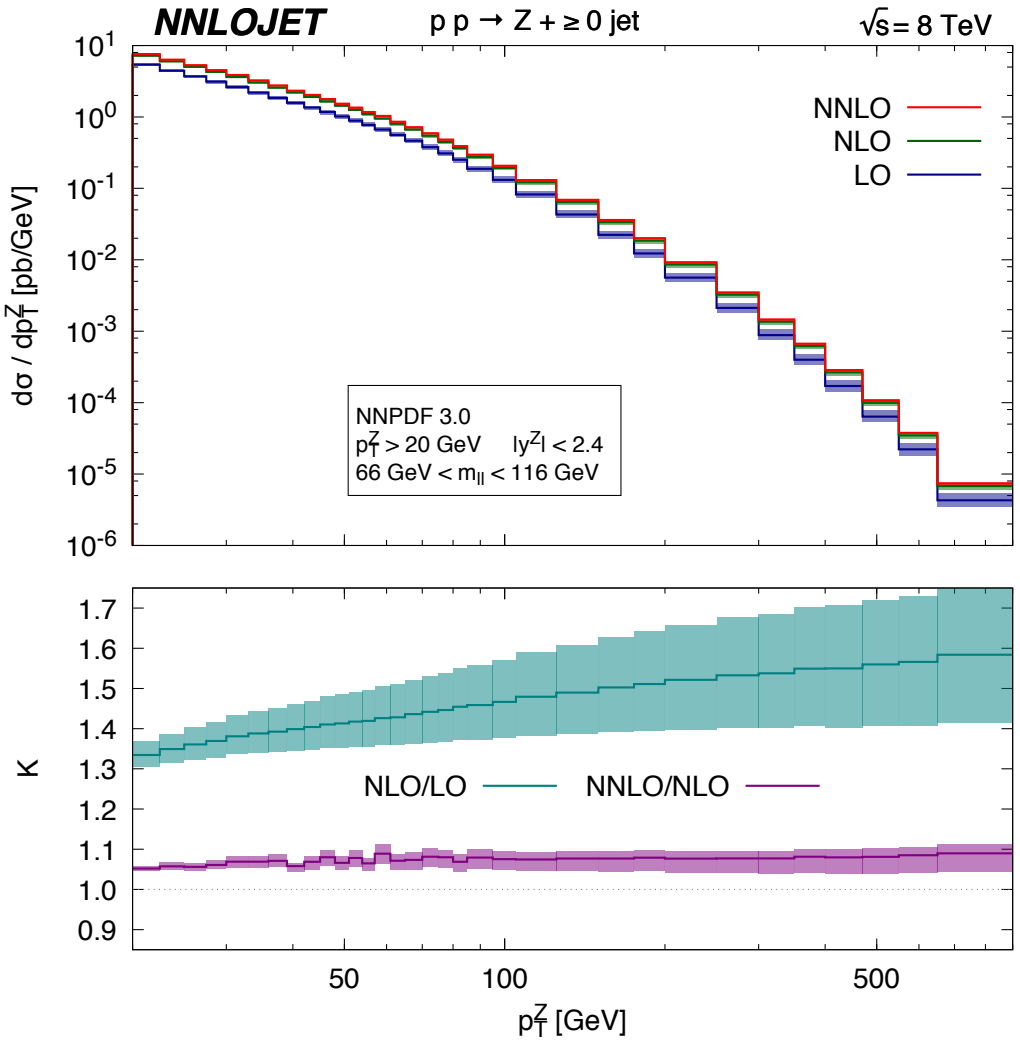
ATLAS setup [arXiv:1512.02192]

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

CMS setup [arXiv:1504.03511]

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

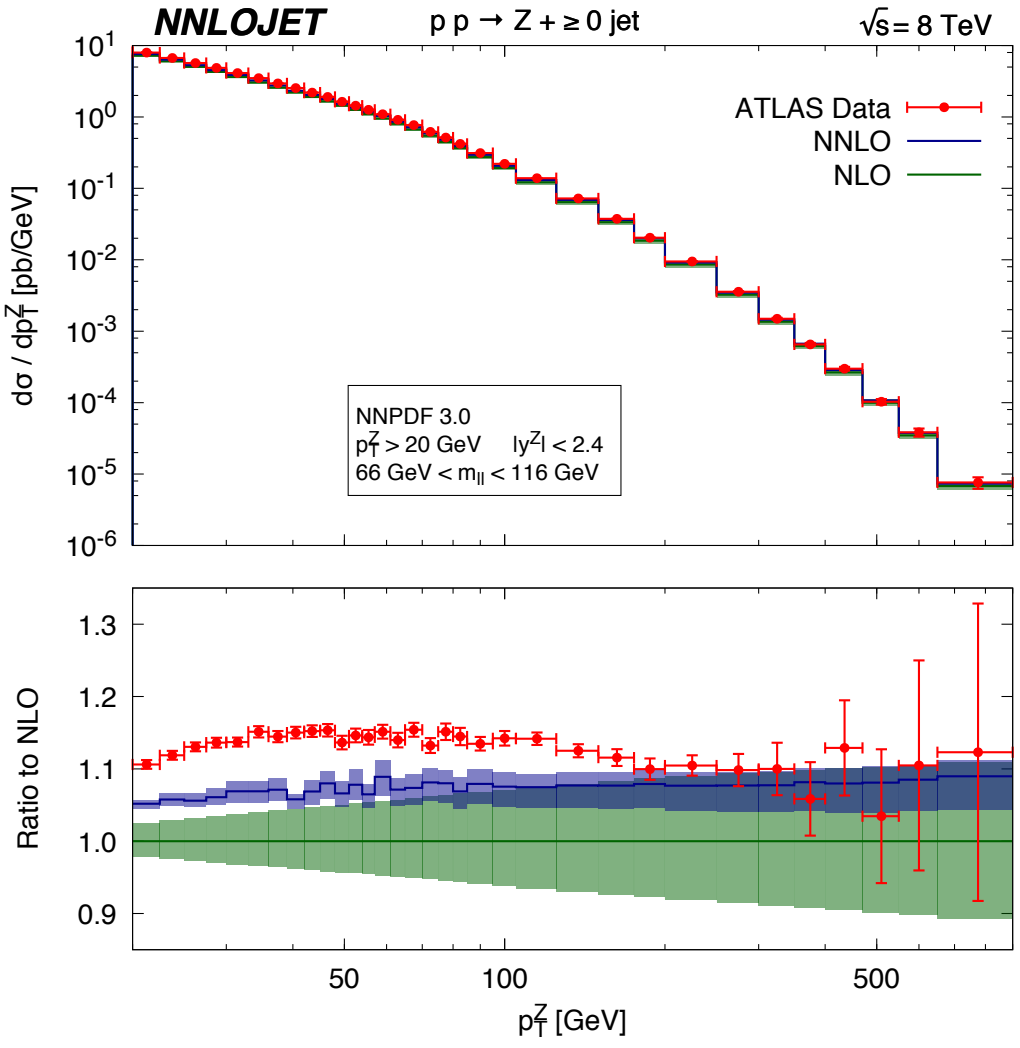
Inclusive p_{T} spectrum of Z/γ^*



- 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?!

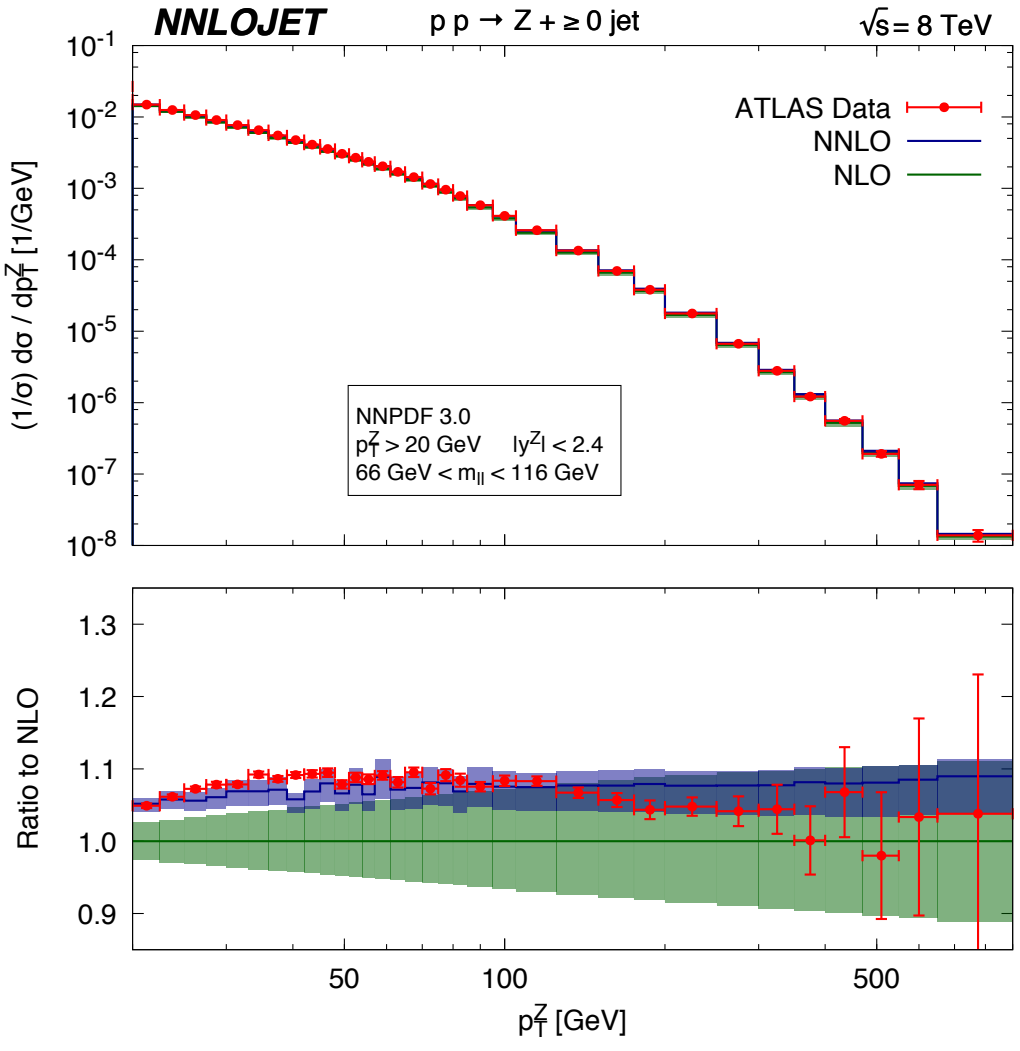
Inclusive p_{T} spectrum of Z/γ^*



- 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

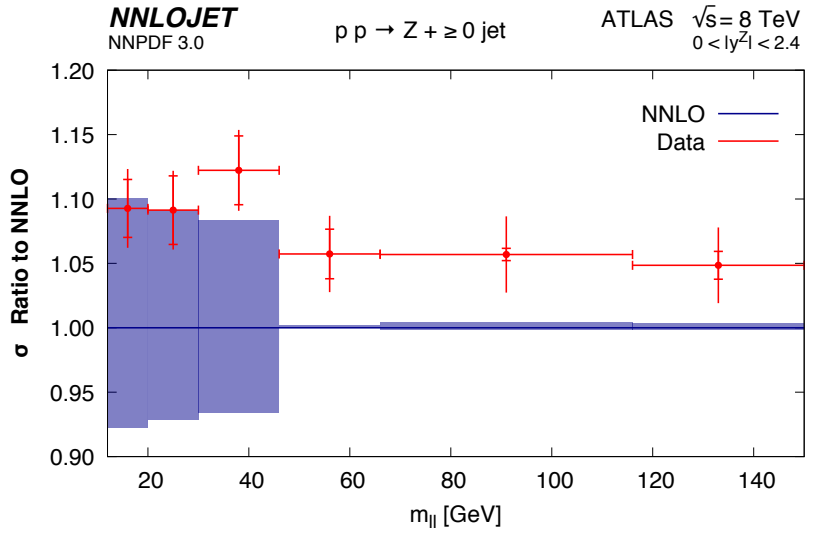
$$\frac{1}{\sigma} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

Inclusive p_{T} spectrum of Z/γ^*

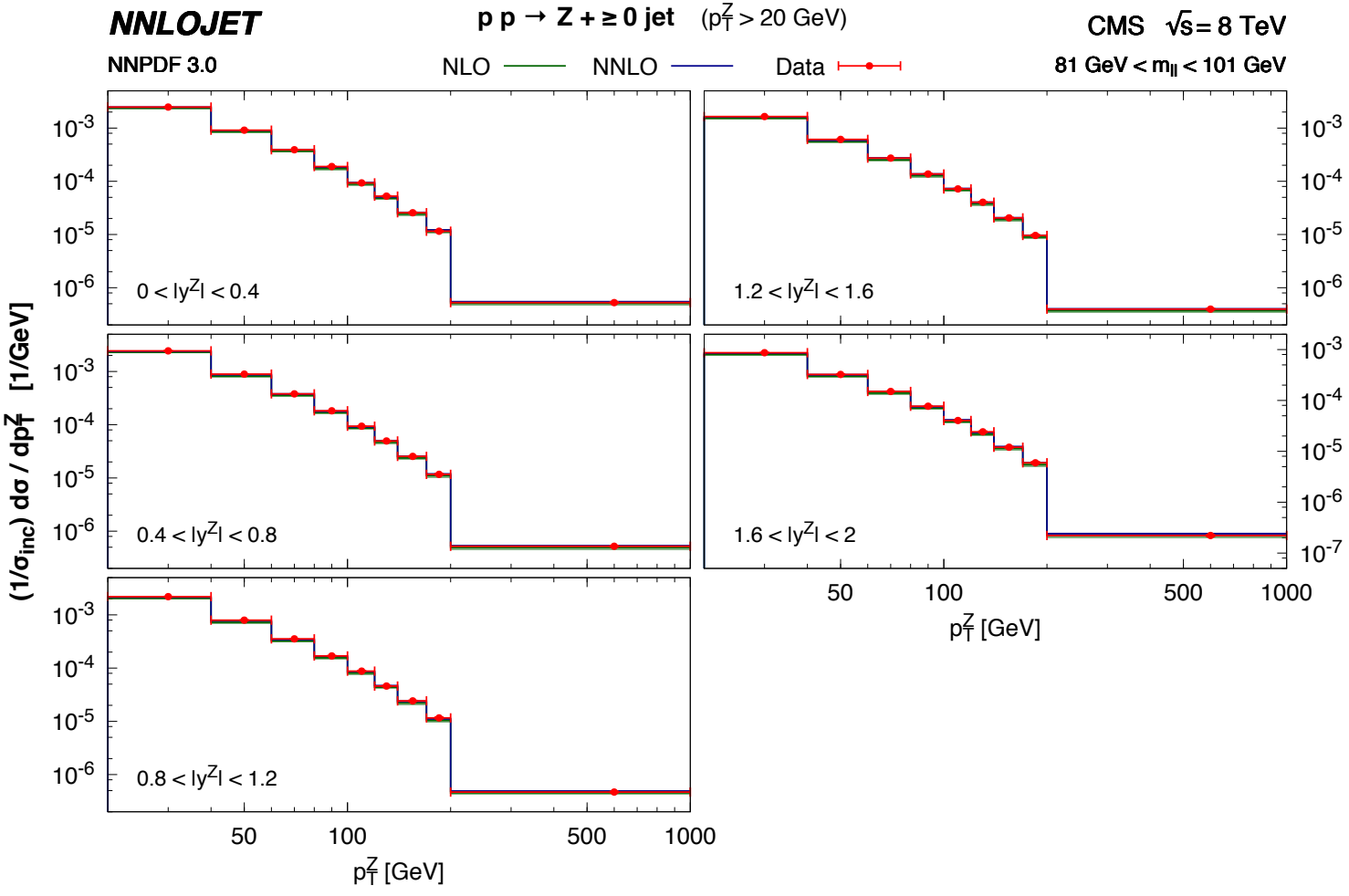


$$\frac{1}{\sigma} \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}}$$

- uncorrelated scale variation $\leftrightarrow$ numerator & denominator
- significant improvement in Data vs. Theory

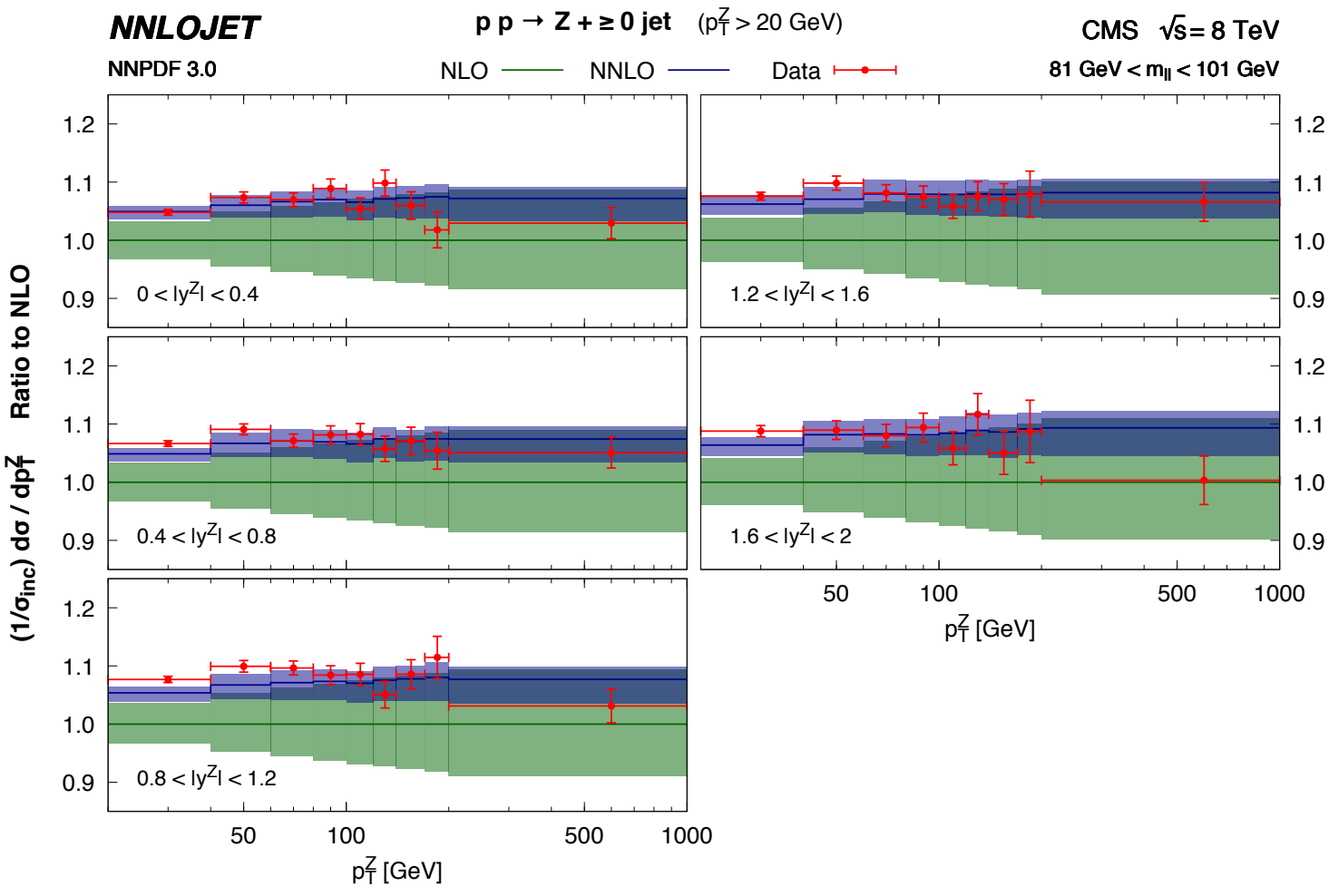


Double-differential: $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}$ binned in y^{Z} — CMS



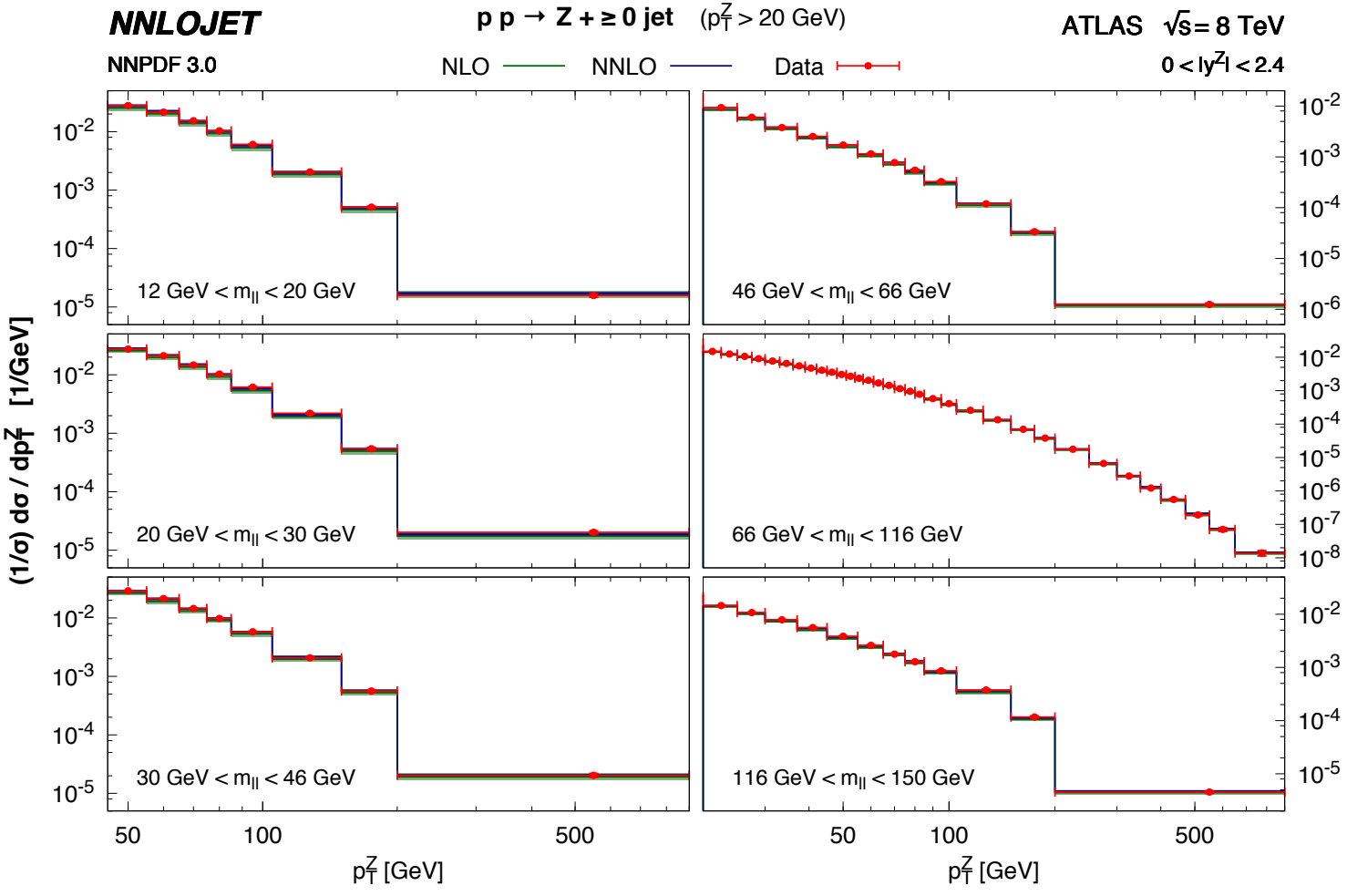
- $81\ \mathrm{GeV} < m_{\ell\ell} < 101\ \mathrm{GeV}$ (narrower mass window than ATLAS)
- 5 bins in y^{Z}: $[0,\ 0.4]$ $[0.4,\ 0.8]$ $[0.8,\ 1.2]$ $[1.2,\ 1.6]$ $[1.6,\ 2]$

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



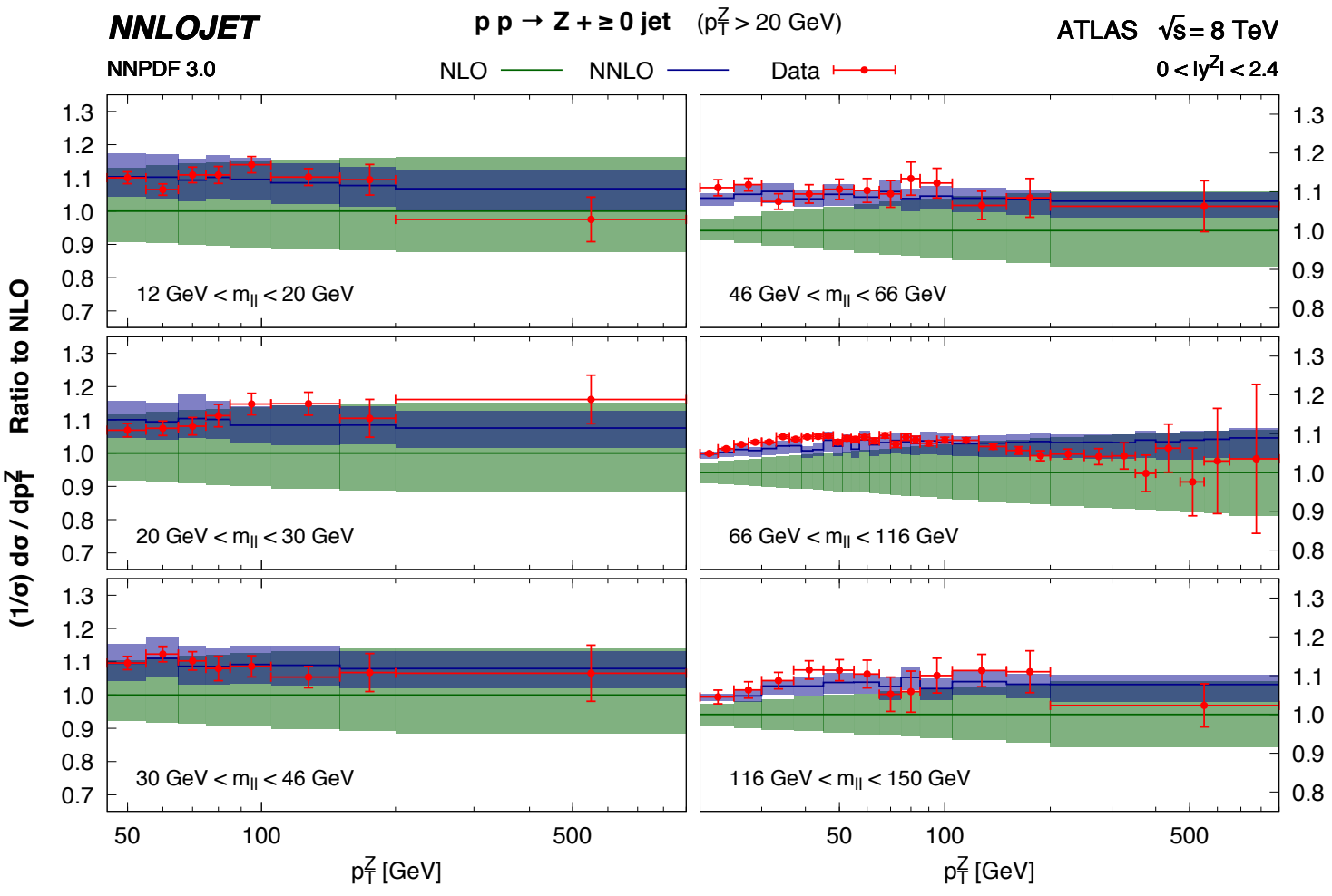
- NLO prediction systematically undershoots data, NNLO corrections ~ 5–10%
- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties

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



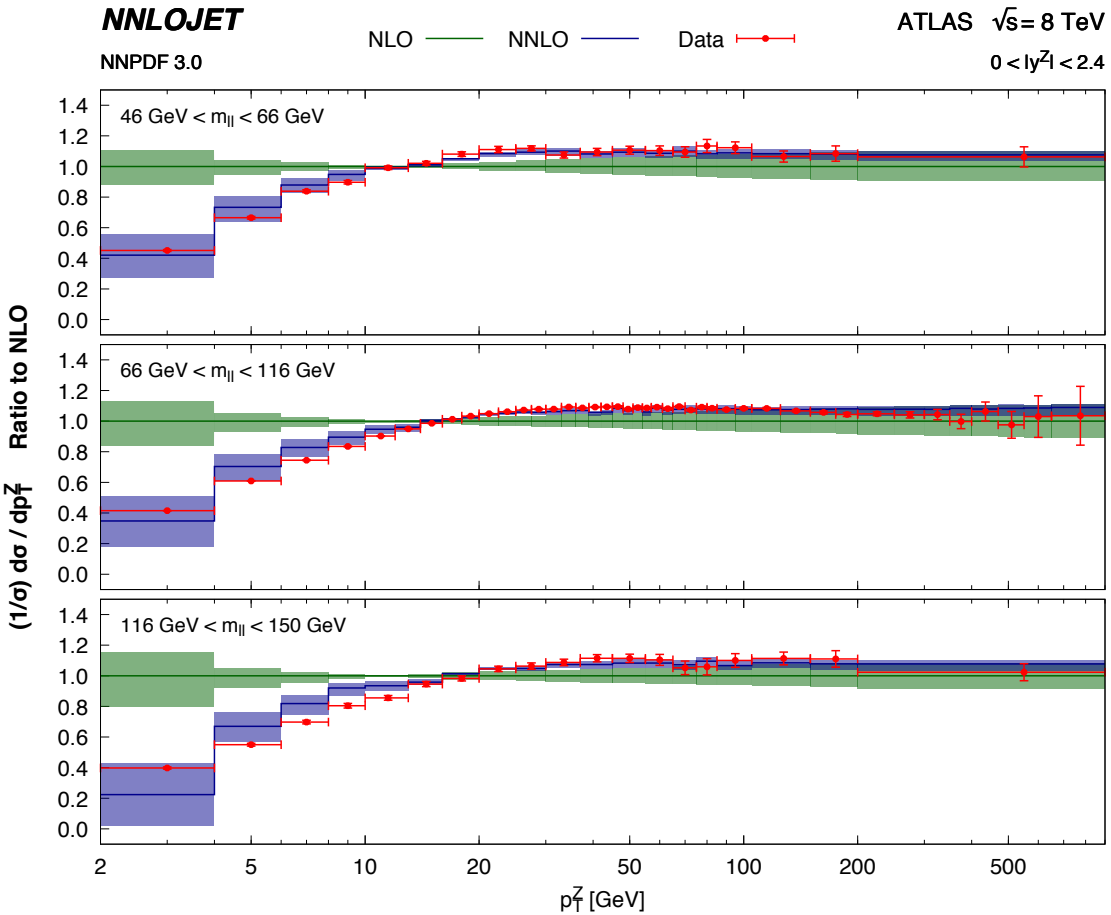
- $0 < |y^{\mathrm{Z}}| < 2.4$
- 6 bins in $m_{\ell\ell}$ [GeV]: [12, 20] [20, 30] [30, 46] [46, 66] [66, 116] [116, 150]

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



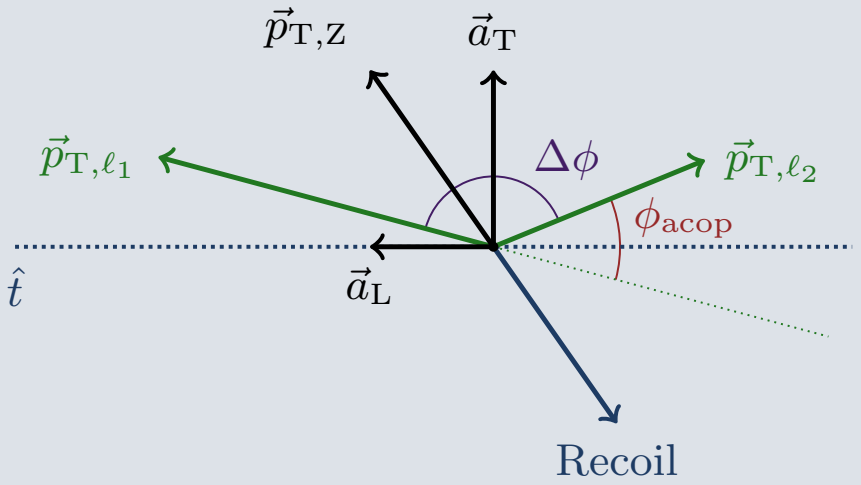
- significant tension between NLO prediction and data $(m_{\ell\ell} \geq 46\ \mathrm{GeV})$
- improvement in **theory** vs. **data** comparison
- reduction of scale uncertainties

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

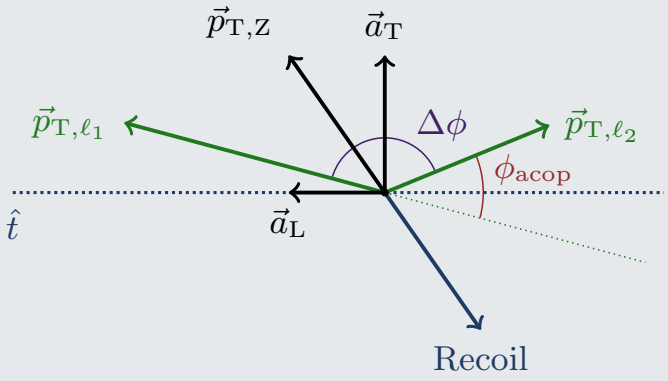


- $p_{\mathrm{T}}^{\mathrm{Z}} > 2\ \mathrm{GeV}$ (first bin $\in [0, 2]\ \mathrm{GeV}$)
- **NLO:** bad description below $p_{\mathrm{T}}^{\mathrm{Z}} \lesssim 40\ \mathrm{GeV}$
- **NNLO:** shape well reproduced down to $p_{\mathrm{T}}^{\mathrm{Z}} \sim 5\ \mathrm{GeV}$
- deviation @ lower values: onset of large logarithmic corrections

The ϕ^*_η observable



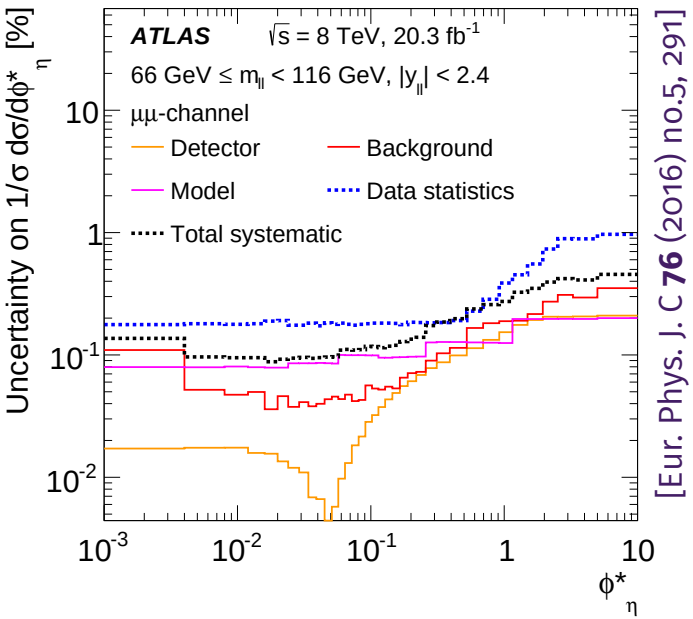
Motivation — A precision probe in the low-$p_{\mathrm{T}}^{\mathrm{Z}}$ regime



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

- large cross section
- clean leptonic signature

recoil $\rightsquigarrow$ sensitivity to α_{s}, gluon PDF

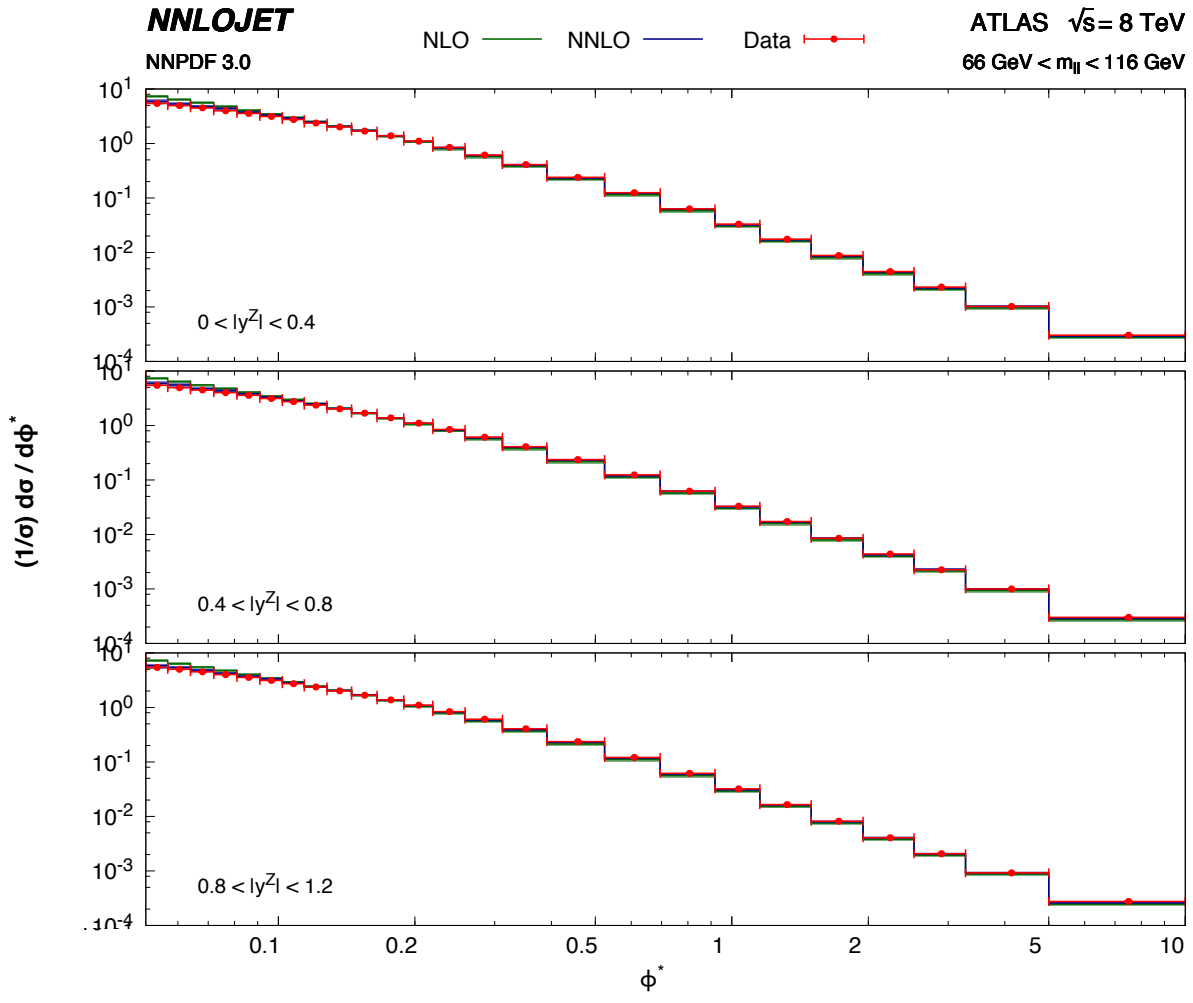


$$\phi_\eta^* = \tan\left(\frac{\phi_{\mathrm{acop}}}{2}\right) \cdot \sin(\theta_\eta^*)$$

- $\phi_{\mathrm{acop}} = \pi - \Delta\phi, \quad \cos(\theta_\eta^*) = \tanh[(\eta^{\ell^-} - \eta^{\ell^+})/2]$
- only depends on $\ell^\pm$ directions (not energies)

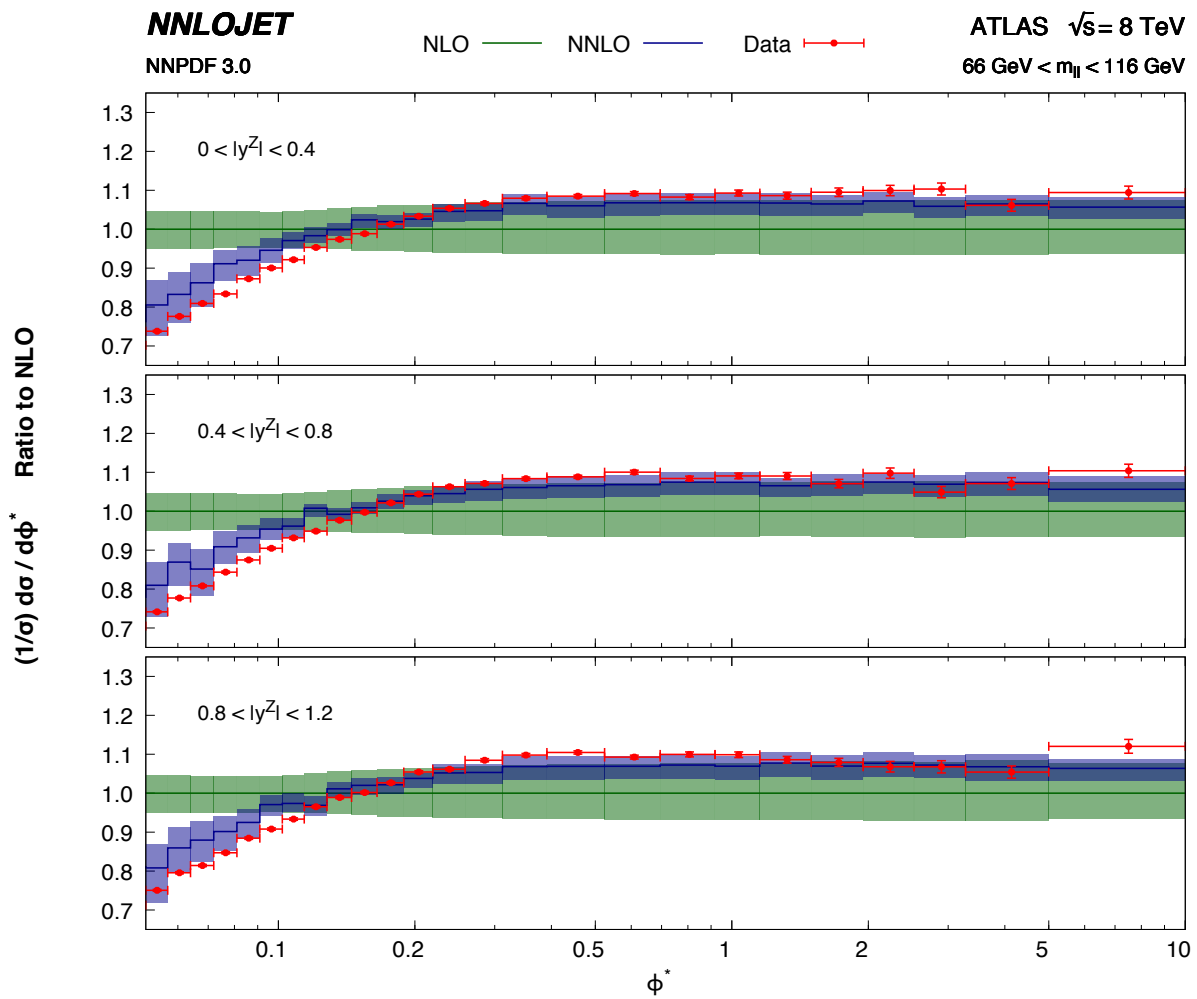
  $\rightsquigarrow$ better experimental resolution
- similar to $p_{\mathrm{T}}^{\mathrm{Z}}$: $\phi_\eta^* > 0 \quad \Rightarrow \quad \mathrm{Z} + \mathrm{jets}$

$\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ binned in y^{Z} — high ϕ^*_η (> 0.051)



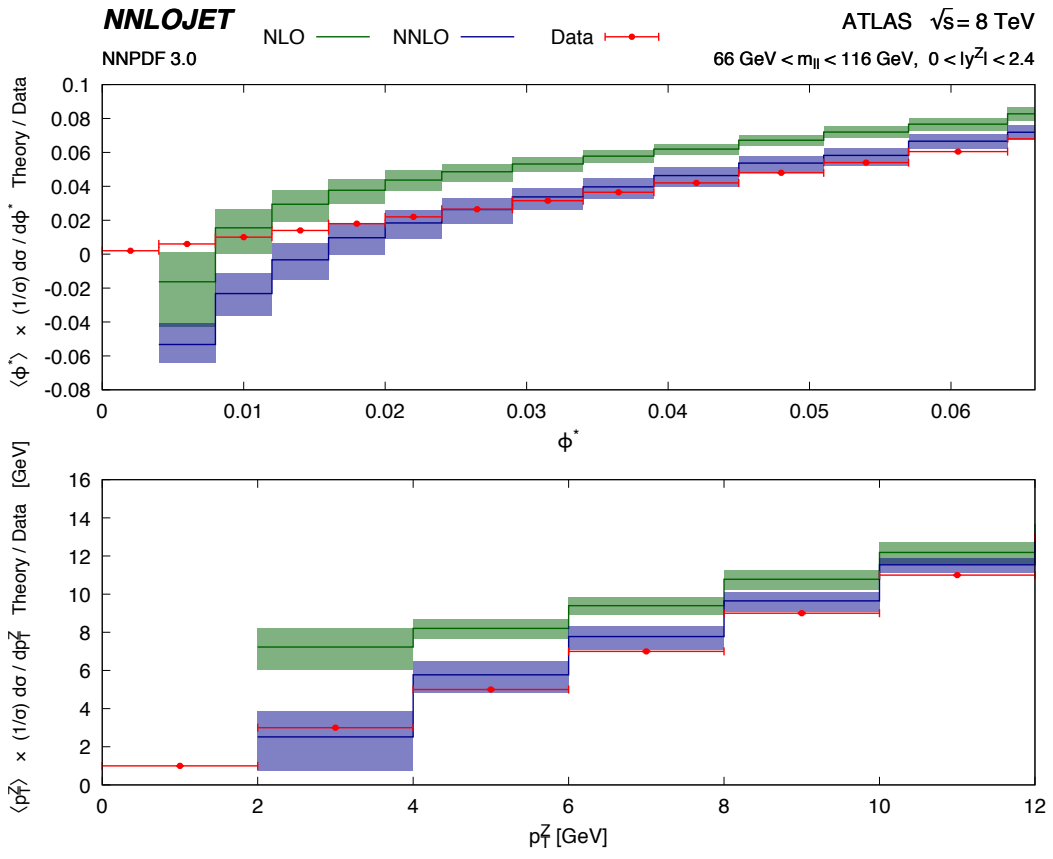
- $66\ \mathrm{GeV} < m_{\ell\ell} < 116\ \mathrm{GeV}$
- 6 bins in y^{Z}: [0, 0.4] [0.4, 0.8] [0.8, 1.2] [1.2, 1.6] [1.6, 2] [2, 2.4]

$\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ binned in y^Z — high ϕ^*_η (> 0.051)



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

$\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ vs. $\mathrm{d}\sigma/\mathrm{d}p^{\mathrm{Z}}_{\mathrm{T}}$ — small ϕ^*_η



- relation between ϕ^*_η & $p^{\mathrm{Z}}_{\mathrm{T}}$: $\phi^*_\eta \approx \dfrac{p^{\mathrm{Z}}_{\mathrm{T}}}{2m_{\ell\ell}}$ $\rightsquigarrow$ align x-ranges
- **NLO:** does not describe data in plotting range
- **NNLO:** reliable down to $\phi^*_\eta \sim 0.02 \leftrightarrow p^{\mathrm{Z}}_{\mathrm{T}} \sim 4\,\mathrm{GeV}$

Summary & Outlook

Summary

- NNLO corrections to $\mathrm{Z} + \mathrm{jet}$ production completed
- implementation in a flexible parton-level event generator NNLOJET
- related observables: inclusive $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum, ϕ_{η}^{*}
  - ↪ improvement in the theory vs. data comparison
  - ↪ NNLO extends range of validity

Outlook

- further studies:
  - ↪ angular coefficients, `MiNNLO`, PDF fits, ...
- development on NNLOJET
  - ↪ interface to `APPLfast-NNLO`, more processes, performance, ...

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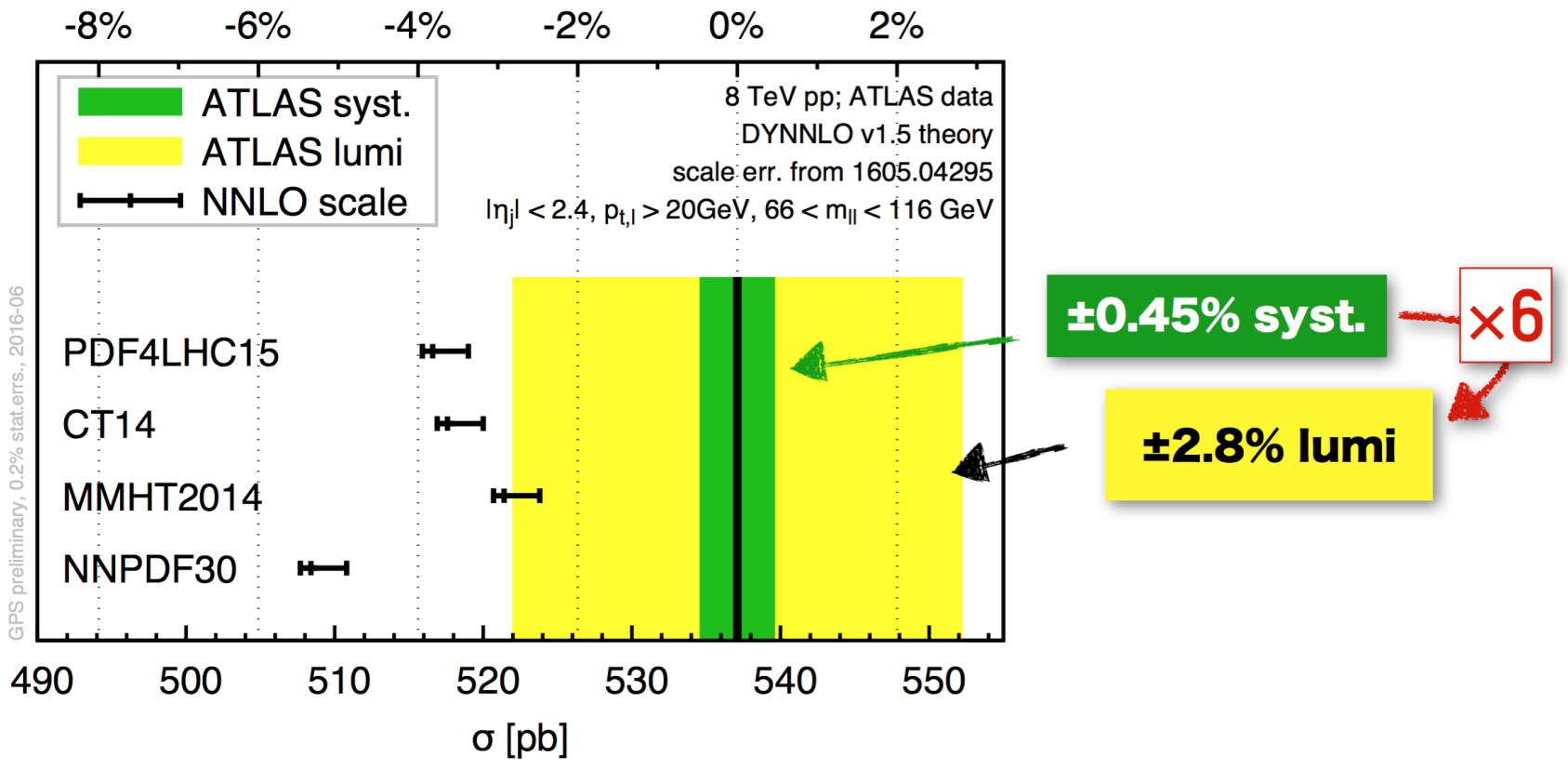
Outlook

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Thank you

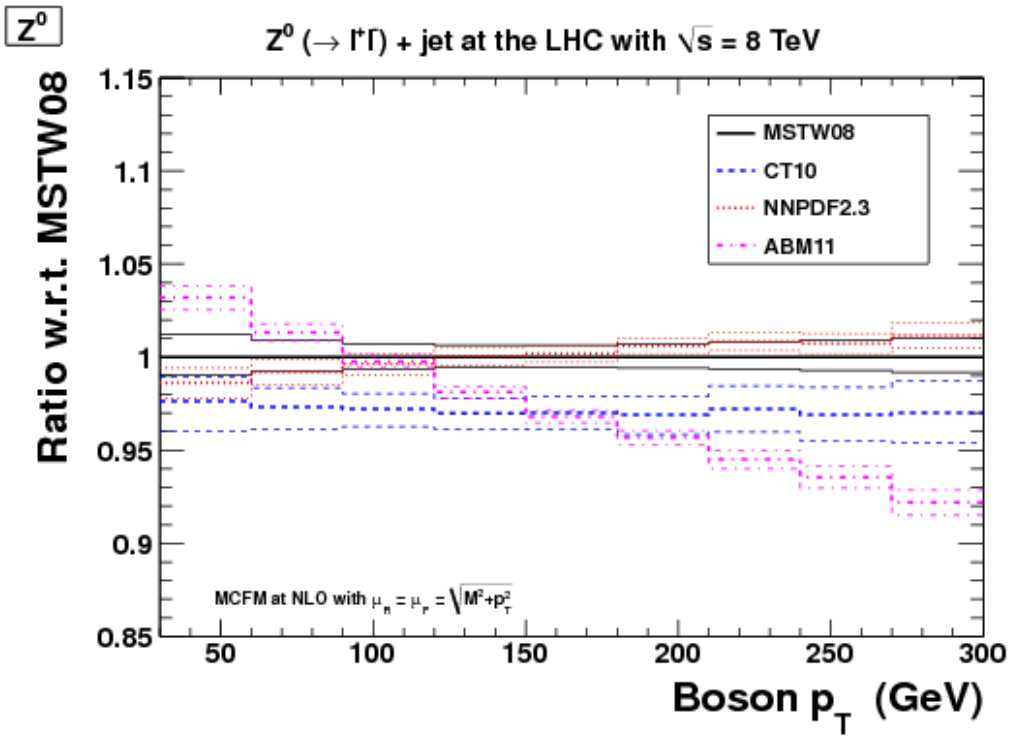
Backup Slides

The fiducial Drell–Yan cross section



[talk by Gavin Salam, LHCP 2016]

PDF constraints from $p_{\mathrm{T}}^{\mathrm{Z}}$



- $p_{\mathrm{T}}^{\mathrm{Z}} \gtrsim M_{\mathrm{Z}} \rightsquigarrow$ 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

The small ϕ_η^* region

- domain of large logarithms
  - ↪ breakdown of fixed-order predictions
- relation between $p_{\mathrm{T}}^{\mathrm{Z}}$ & ϕ_η^*
  - ↪ compare leading-logarithmic behaviour

$$p_{\mathrm{T}}^{\mathrm{Z}} \left(\frac{1}{\sigma_0} \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}} \right)_{\mathrm{LL}} \sim -4C_F \frac{\alpha_{\mathrm{s}}}{\pi} \ln \left(\frac{(p_{\mathrm{T}}^{\mathrm{Z}})^2}{m_{\ell\ell}^2} \right) + 2C_F^2 \left(\frac{\alpha_{\mathrm{s}}}{\pi} \right)^2 \ln^3 \left(\frac{(p_{\mathrm{T}}^{\mathrm{Z}})^2}{m_{\ell\ell}^2} \right) + \dots$$

$$\phi_\eta^* \left(\frac{1}{\sigma_0} \frac{\mathrm{d}\sigma}{\mathrm{d}\phi_\eta^*} \right)_{\mathrm{LL}} \sim -4C_F \frac{\alpha_{\mathrm{s}}}{\pi} \ln \left(4(\phi_\eta^*)^2 \right) + 2C_F^2 \left(\frac{\alpha_{\mathrm{s}}}{\pi} \right)^2 \ln^3 \left(4(\phi_\eta^*)^2 \right) + \dots$$

$$\Rightarrow \quad \phi_\eta^* \approx \frac{p_{\mathrm{T}}^{\mathrm{Z}}}{2m_{\ell\ell}}$$

Z+jet: Channel breakdown

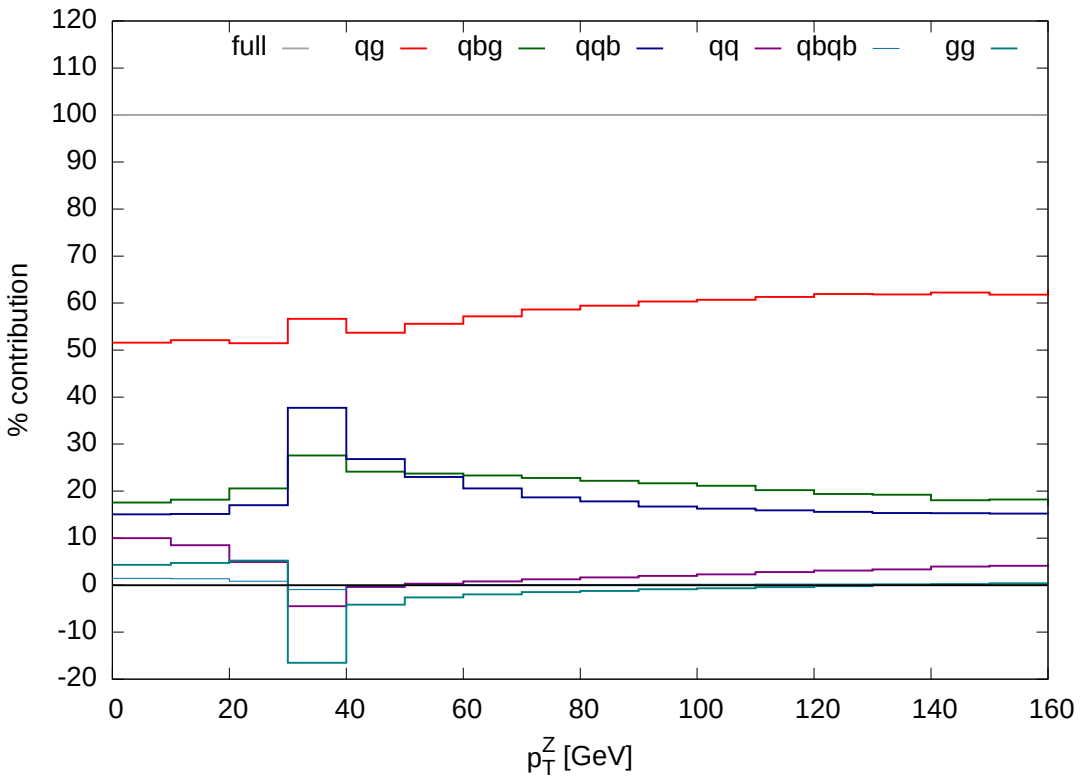
Variety of partonic channels contribute to Z+jet production

↪ what are the most important sub-processes?

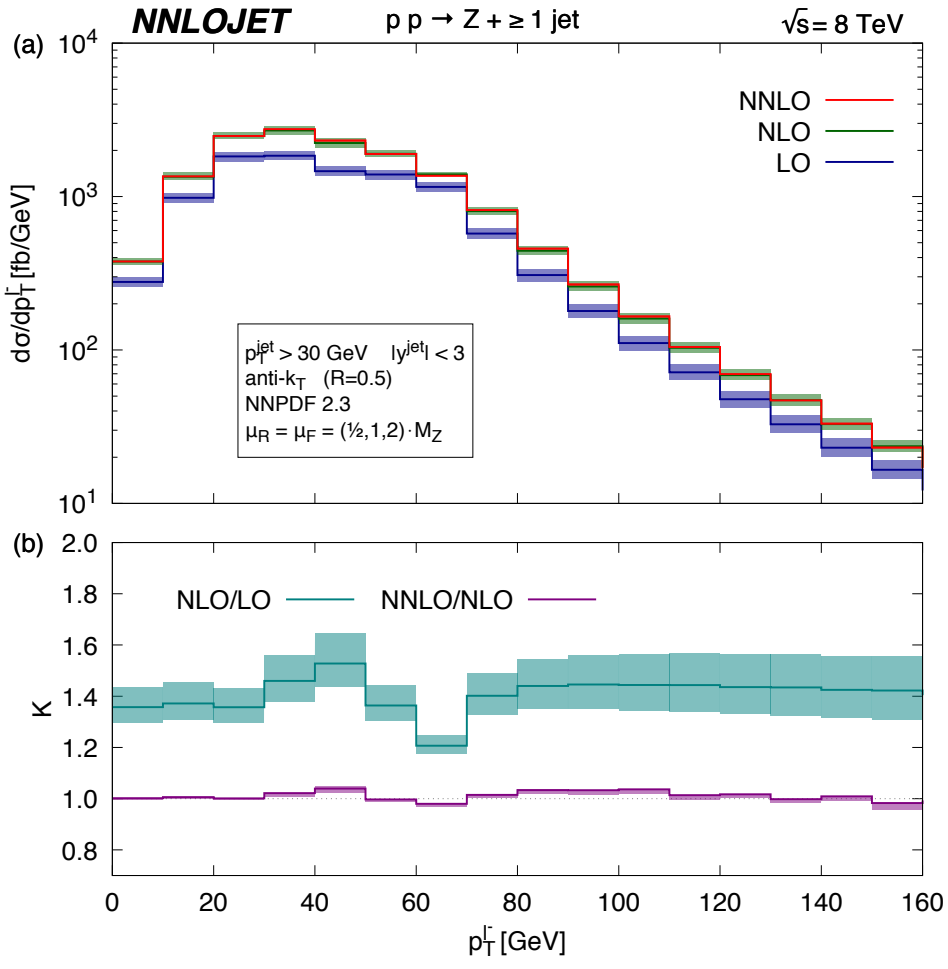
↪ channel breakdown @ NLO (default cuts & scale choice)

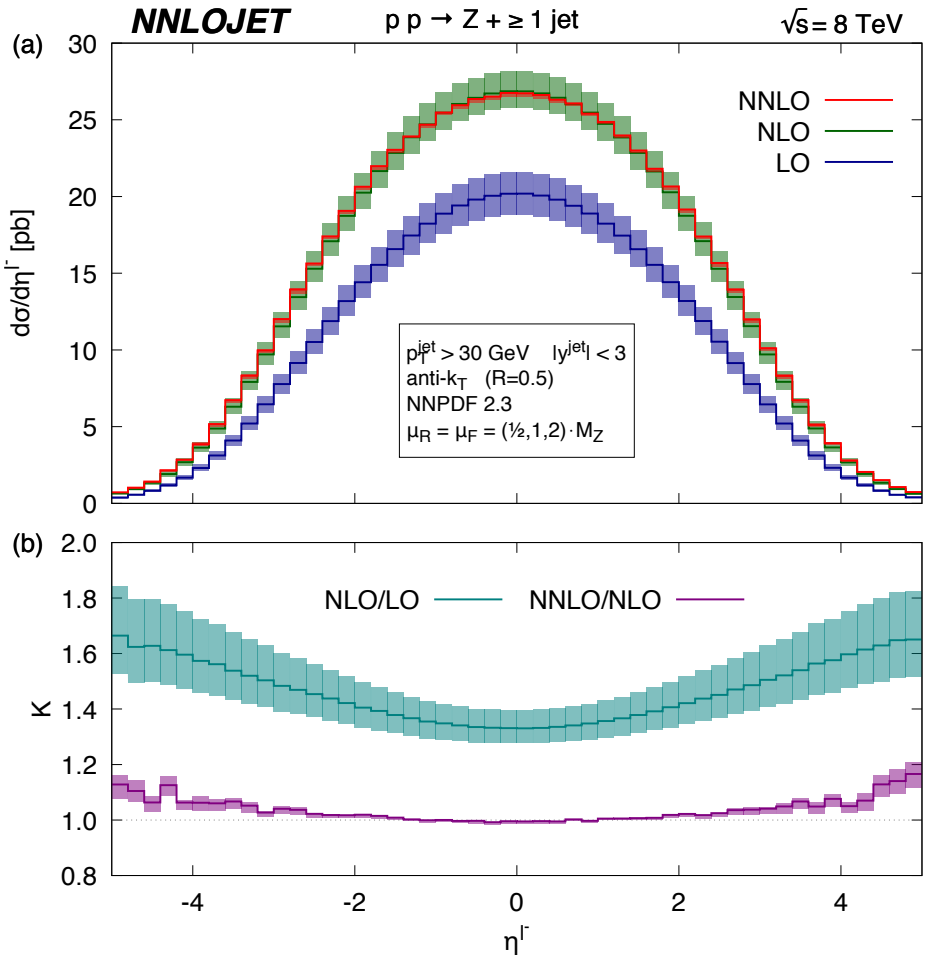
Total cross section

initial state	contribution
qg	56%
$q\bar{q}$	23%
$\bar{q}g$	23%
gg	-3%
qq	1%
$\bar{q}\bar{q}$	0.1%



Distributions: lepton ℓ^-





- significant reduction of scale uncertainty

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