Progress in NNLO computations for processes with jets

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IP3

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MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

HiggsTools 2016, Granada
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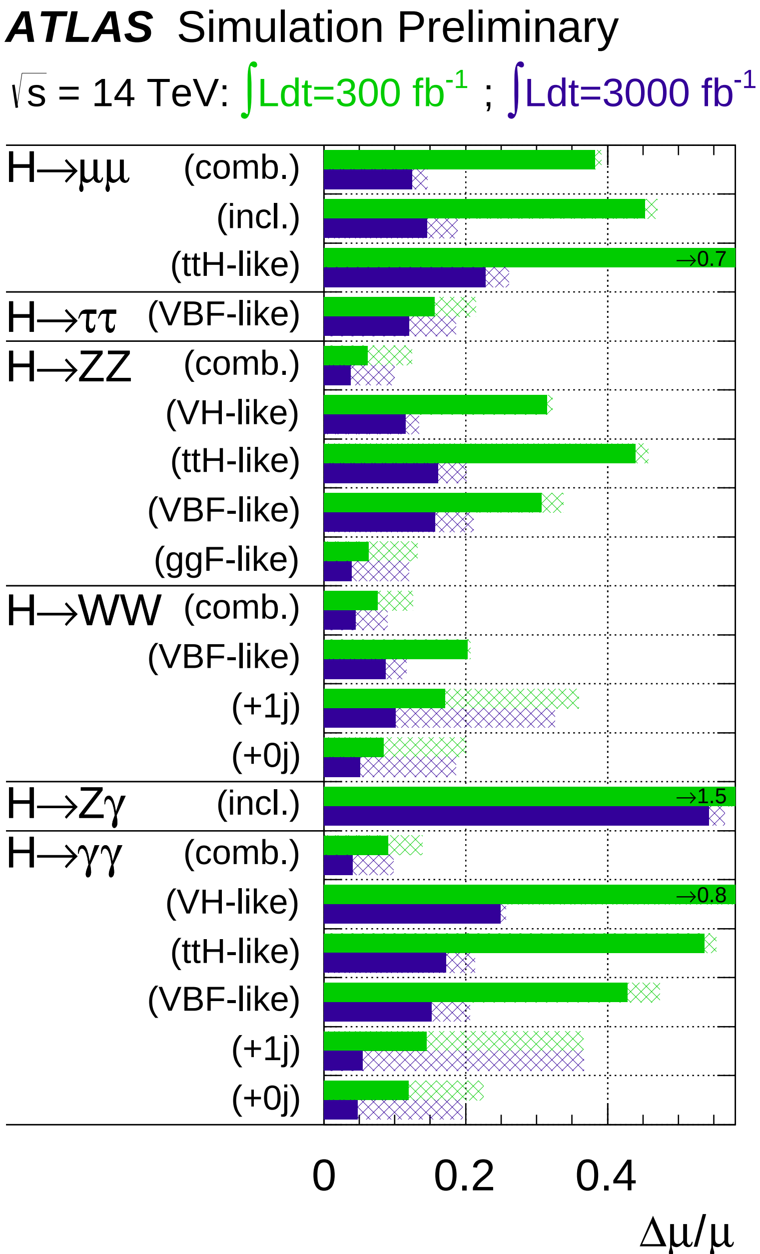
Motivation for more precise theoretical calculations

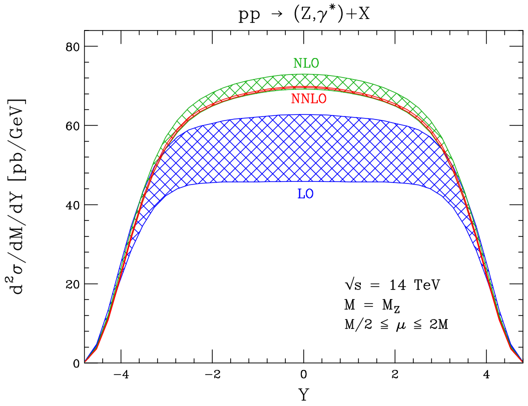
- ✓ Theory uncertainty has big impact on quality of measurement
- ✘ *NLO QCD is clearly insufficiently precise for SM, top (and even Higgs) measurements*, D. Froidevaux, HiggsTools School
- ⇒ Revised wishlist of theoretical predictions for
  - ✚ Higgs processes
  - ✚ Processes with vector bosons
  - ✚ Processes with top or jets

Les Houches 2013, arXiv:1405.1067

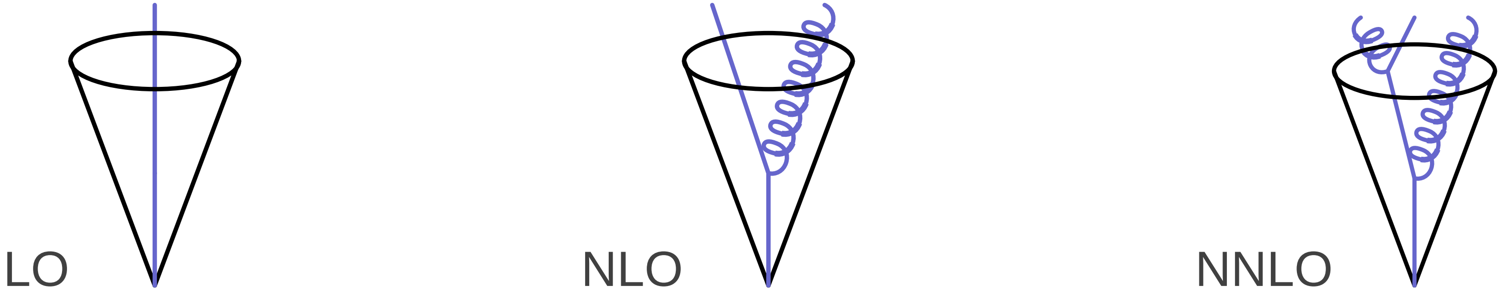


What NNLO might give you (1)

✓ Reduced renormalisation scale dependence



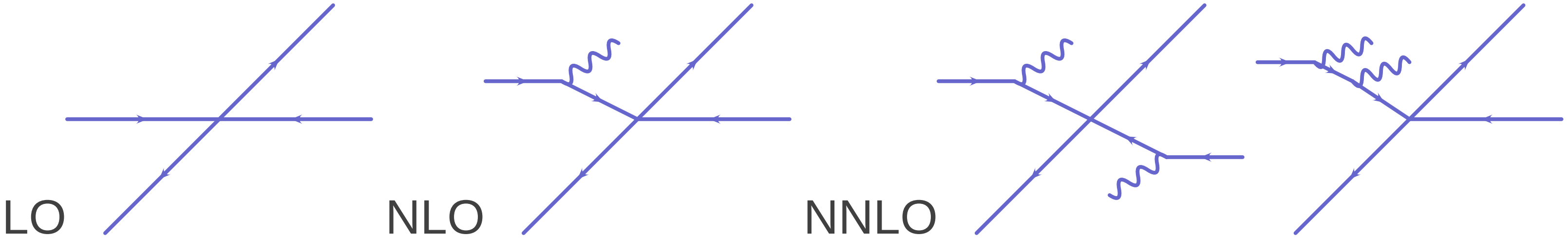
✓ Event has more partons in the final state so perturbation theory can start to reconstruct the shower
⇒ better matching of jet algorithm between theory and experiment



✓ Reduced power correction as higher perturbative powers of $1/\ln(Q/\Lambda)$ mimic genuine power corrections like $1/Q$

What NNLO might give you (2)

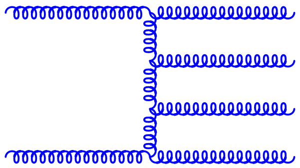
- ✓ Better description of transverse momentum of final state due to double radiation off initial state



  - ✓ At LO, final state has no transverse momentum
  - ✓ Single hard radiation gives final state transverse momentum, even if no additional jet
  - ✓ Double radiation on one side, or single radiation of each incoming particle gives more complicated transverse momentum to final state
- ✓ NNLO provides the first serious estimate of the theoretical uncertainty

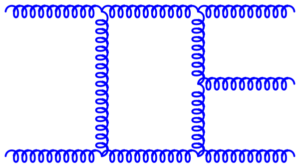
✓✓✓ and most importantly, the volume and quality of the LHC data!!

Anatomy of a NNLO calculation e.g. pp to JJ



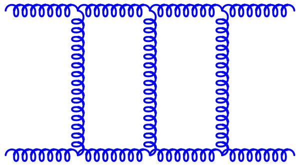
✓ double real radiation matrix elements $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}$

- ✚ implicit poles from double unresolved emission



✓ single radiation one-loop matrix elements $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}$

- ✚ explicit infrared poles from loop integral
- ✚ implicit poles from soft/collinear emission



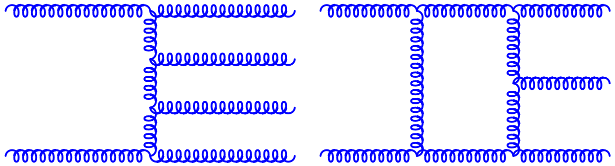
✓ two-loop matrix elements $\mathrm{d}\hat{\sigma}^{VV}_{NNLO}$

- ✚ explicit infrared poles from loop integral

$$\mathrm{d}\hat{\sigma}_{NNLO} \quad \sim \quad \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\hat{\sigma}^{RR}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\hat{\sigma}^{RV}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\hat{\sigma}^{VV}_{NNLO}$$

Anatomy of a NNLO calculation e.g. pp to JJ

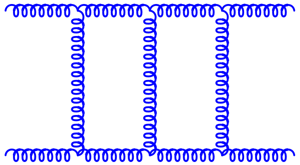
- ✓ Double real and real-virtual contributions used in NLO calculation of X+1 jet



  Can exploit NLO automation

  . . . but needs to be evaluated in regions of phase space where extra jet is not resolved

- ✚ Two loop amplitudes - very limited set known



  . . . currently far from automation

- ✚ Method for cancelling explicit and implicit IR poles - overlapping divergences

  . . . currently not automated

IR cancellation at NNLO

- ✓ The aim is to recast the NNLO cross section in the form

$$\begin{aligned} \mathrm{d}\hat{\sigma}_{NNLO} &= \int_{\mathrm{d}\Phi_{m+2}} \left[\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO}\right] \\ &+ \int_{\mathrm{d}\Phi_{m+1}} \left[\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{T}_{NNLO}\right] \\ &+ \int_{\mathrm{d}\Phi_{m}} \left[\mathrm{d}\hat{\sigma}^{VV}_{NNLO} - \mathrm{d}\hat{\sigma}^{U}_{NNLO}\right] \end{aligned}$$

  where the terms in each of the square brackets is finite, well behaved in the infrared singular regions and can be evaluated numerically.

- ✓ $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$ and $\mathrm{d}\hat{\sigma}^{T}_{NNLO}$

must cancel the implicit divergences in regions of phase space where $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}$ and $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}$ are singular (subtraction)

or restrict the phase space to avoid these regions (slicing)

NNLO - IR cancellation schemes

Unlike at NLO, we do not have a fully general NNLO IR cancellation scheme

- Antenna subtraction — Gehrmann, Gehrmann-De Ridder, NG (05)
- Colourful subtraction — Del Duca, Somogyi, Trocsanyi (05)
- q_T subtraction — Catani, Grazzini (07)
- STRIPPER (sector subtraction) — Czakon (10); Boughezal et al (11); Czakon, Heymes (14)
- N-jettiness subtraction — Boughezal, Focke, Liu, Petriello (15); Gaunt, Stahlhofen, Tackmann, Walsh (15)
- Projection to Born — Cacciari, Dreyer, Karlberg, Salam, Zanderighi (15)

Each method has its advantages and disadvantages

	Analytic	FS colour	IS colour	Azimuthal	Approach
Antenna	✓	✓	✓	✗	Subtraction
Colourful	✓	✓	✗	✓	Subtraction
q_T	✓	✗ (✓)	✓	–	Slicing
STRIPPER	✗	✓	✓	✓	Subtraction
N-jettiness	✓	✓	✓	–	Slicing
P2B	✓	✓	✓	–	Slicing

NNLOJET

X. Chen, J. Cruz-Martinez, J. Currie, A. Gehrmann-De Ridder, T. Gehrmann,
NG, A. Huss, M. Jaquier, T. Morgan, J. Niehues, J. Pires

UDUR, ETH, UZH, MPI, Peking University

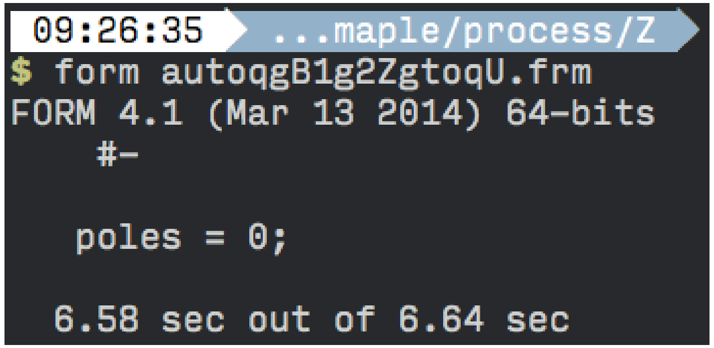
Implementing NNLO corrections using Antenna subtraction for

- ✓ $pp \to H \to \gamma\gamma$ plus 0, 1, 2 jets
- ✓ $pp \to e^+e^-$ plus 0, 1 jets
- ✓ $pp \to$ dijets
- ✓ $ep \to 2(+1)$ jets
- ✓ $\ldots$

Checks

- ✓ Analytic pole cancellations for RV, VV

$$\begin{aligned}\text{Poles}\left(d\sigma^{RV} - d\sigma^{T}\right) &= 0\\ \text{Poles}\left(d\sigma^{VV} - d\sigma^{U}\right) &= 0\end{aligned}$$



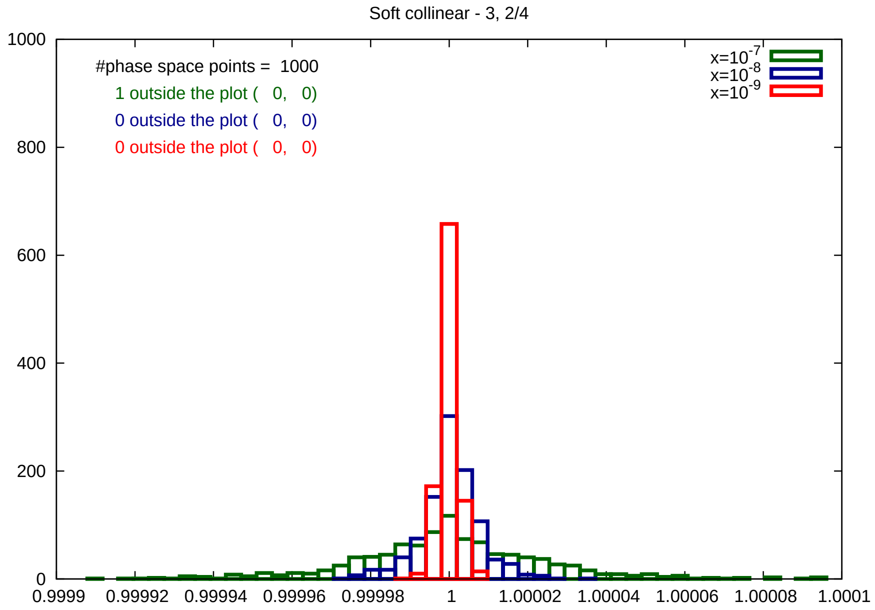
```
09:26:35  ...maple/process/Z
$ form autoqgB1g2ZgtoqU.frm
FORM 4.1 (Mar 13 2014) 64-bits
    #-

   poles = 0;

  6.58 sec out of 6.64 sec
```

- ✓ Partially autogenerated code using Maple scripting language

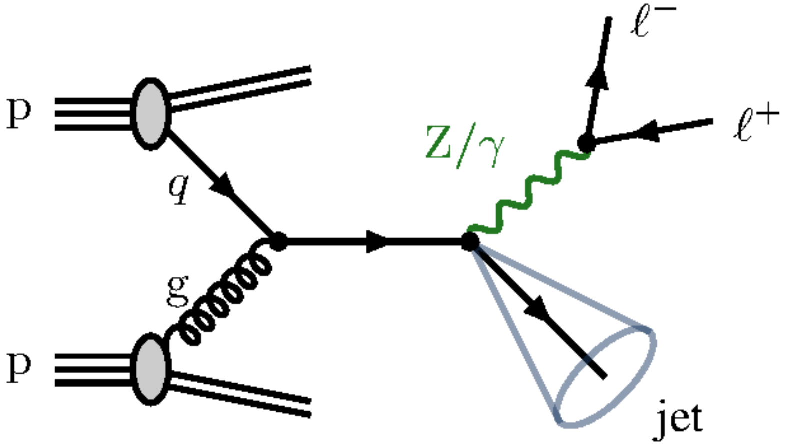
- ✓ Unresolved limits for RR, RV

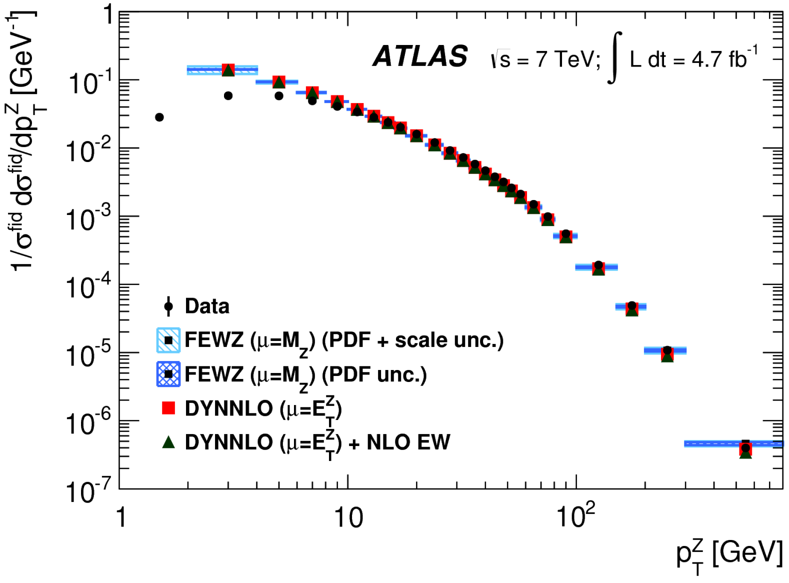
$$\begin{aligned} d\sigma^{S} &\longrightarrow d\sigma^{RR}\\ d\sigma^{T} &\longrightarrow d\sigma^{RV}\end{aligned}$$

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



Example: Inclusive p_T spectrum of Z





$$pp \to Z/\gamma^* \to \ell^+\ell^- + X$$

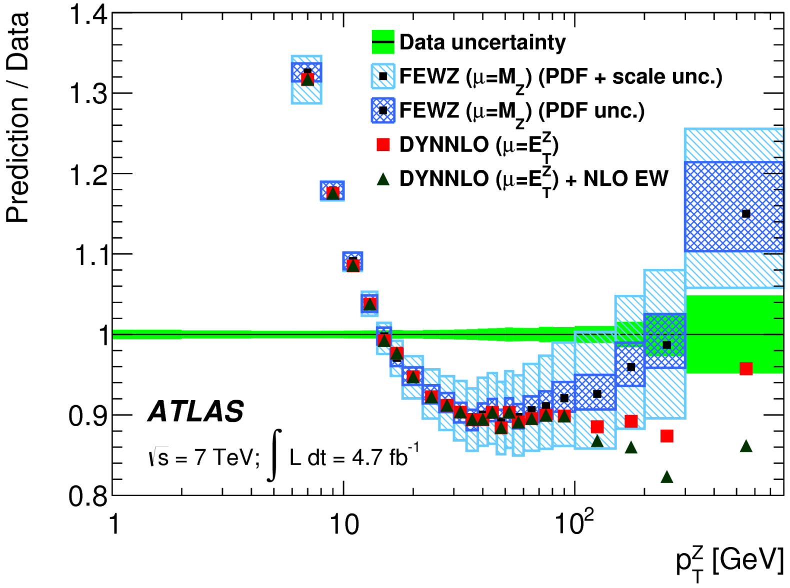
- large cross section
- clean leptonic signature

- fully inclusive wrt QCD radiation
- only reconstruct ℓ^+, ℓ^- so clean and precise measurement
- potential to constrain gluon PDFs

NNLO QCD Z+Jet

Gehrmann-De Ridder, Gehrmann, NG, Huss, Morgan (15)
Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello (15)
Boughezal, Liu, Petriello (16)

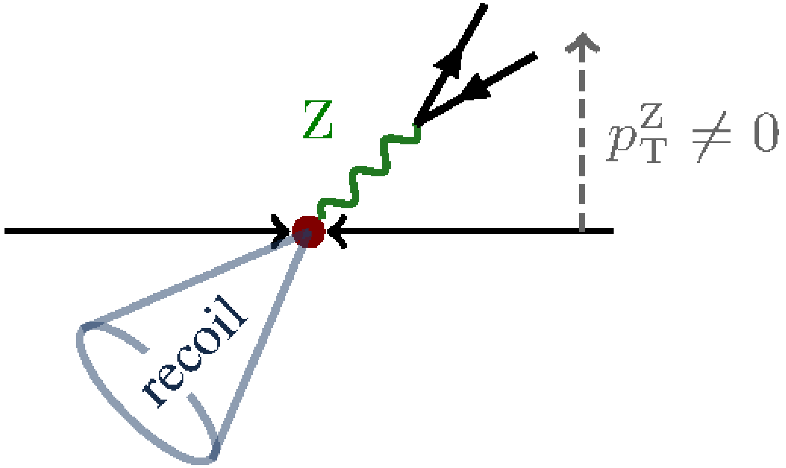
Example: Inclusive p_T spectrum of Z



✚ low $p_T^Z \leq 10$ GeV, resummation required

✚ $p_T^Z \geq 20$ GeV, fixed order prediction about 10% below data

✘ *Very precise measurement of Z p_T poses problems to theory*, D. Froidevaux, HiggsTools School

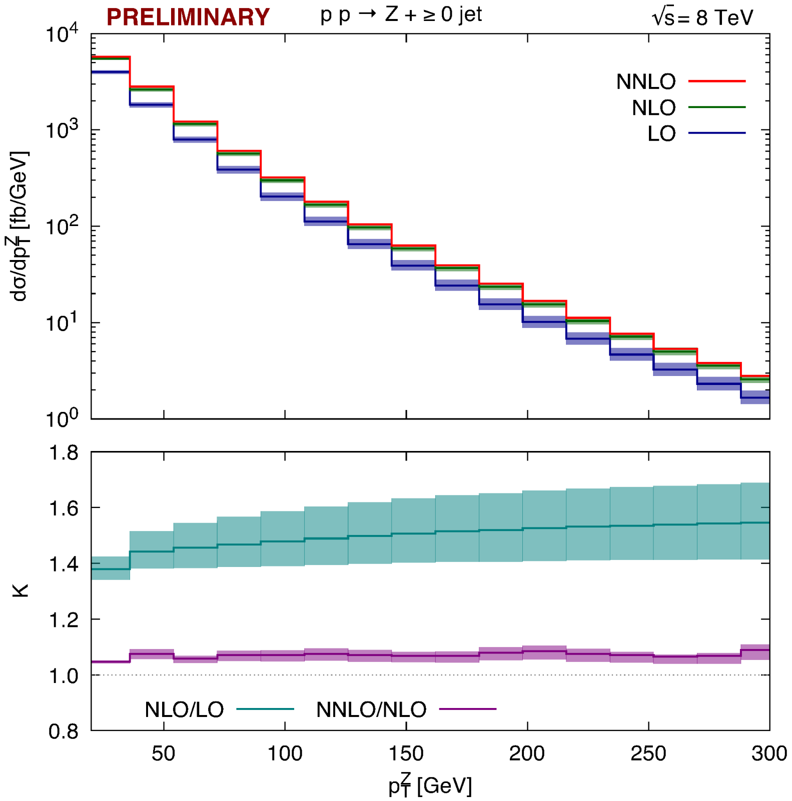


FEWZ/DYNNLO are Z + 0 jet @ NNLO

✘ Only NLO accurate in this distribution

✓ Requiring recoil means Z + 1 jet @ NNLO required

Example: Inclusive p_T spectrum of Z



- ✓ NLO corrections $\sim 40 - 60\%$
- ✓ significant reduction of scale uncertainties NLO $\rightarrow$ NNLO
- ✓ NNLO corrections relatively flat $\sim 4 - 8\%$

Can the NNLO corrections resolve the discrepancy in theory v data?

Inclusive p_T^Z spectrum: Setup

Calculational setup

- ✓ LHC @ 8 TeV
- ✓ PDF: NNPDF2.3 $\alpha_s(M_Z)$ = 0.118
- ✓ fully inclusive wrt QCD radiation
- ✓ $p_T^Z > 20$ GeV
- ✓ $p_T^{\ell_1} > 20$ GeV, $p_T^{\ell_1} > 10$ GeV, $|y^{\ell^\pm}| < 2.4$, 12 GeV $< m_{\ell\ell} < 150$ GeV
- ✓ dynamical scale choice

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

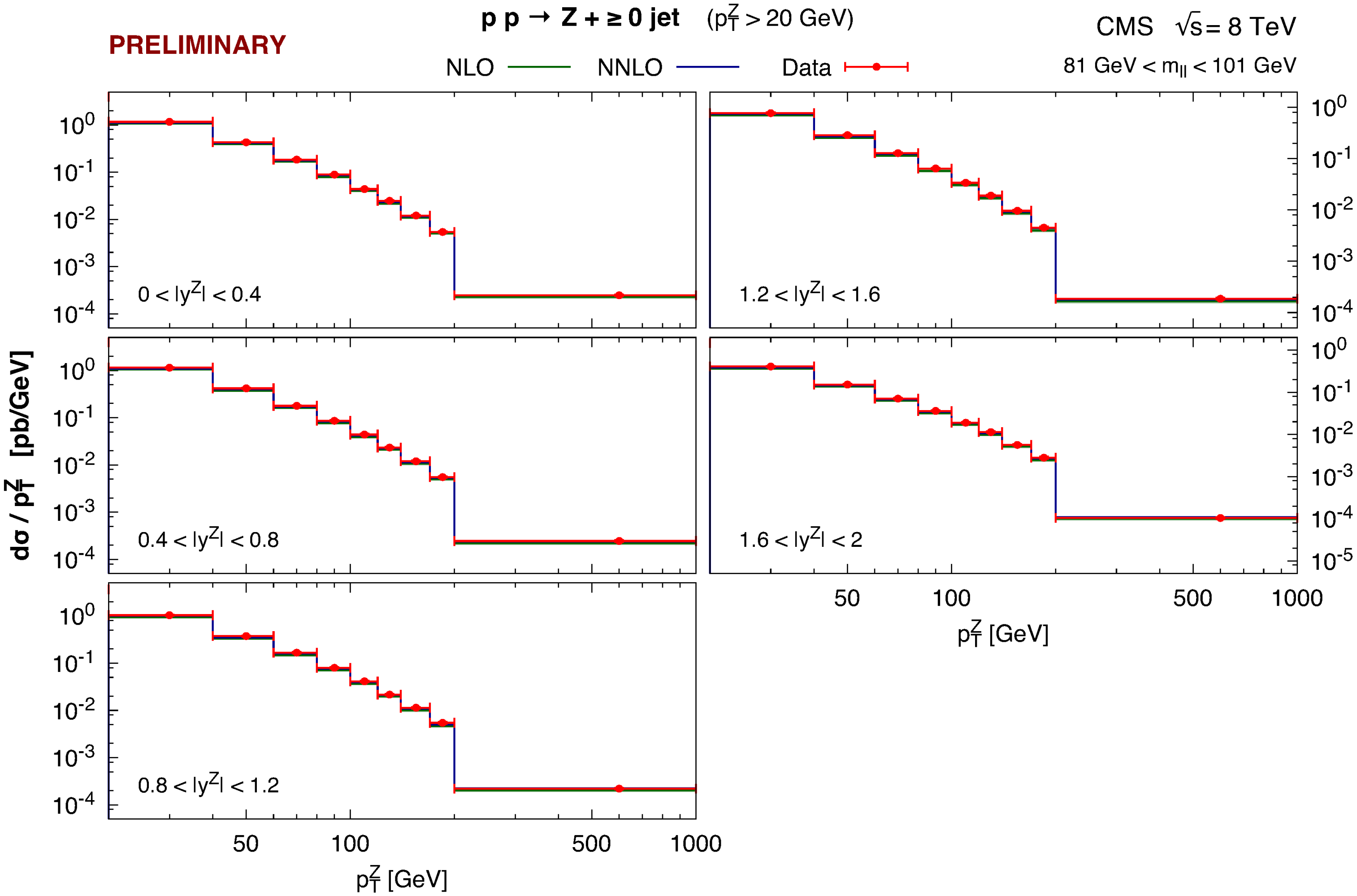
CMS setup arXiv:1504.03511

- $p_T^{\ell_1} > 25$ 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

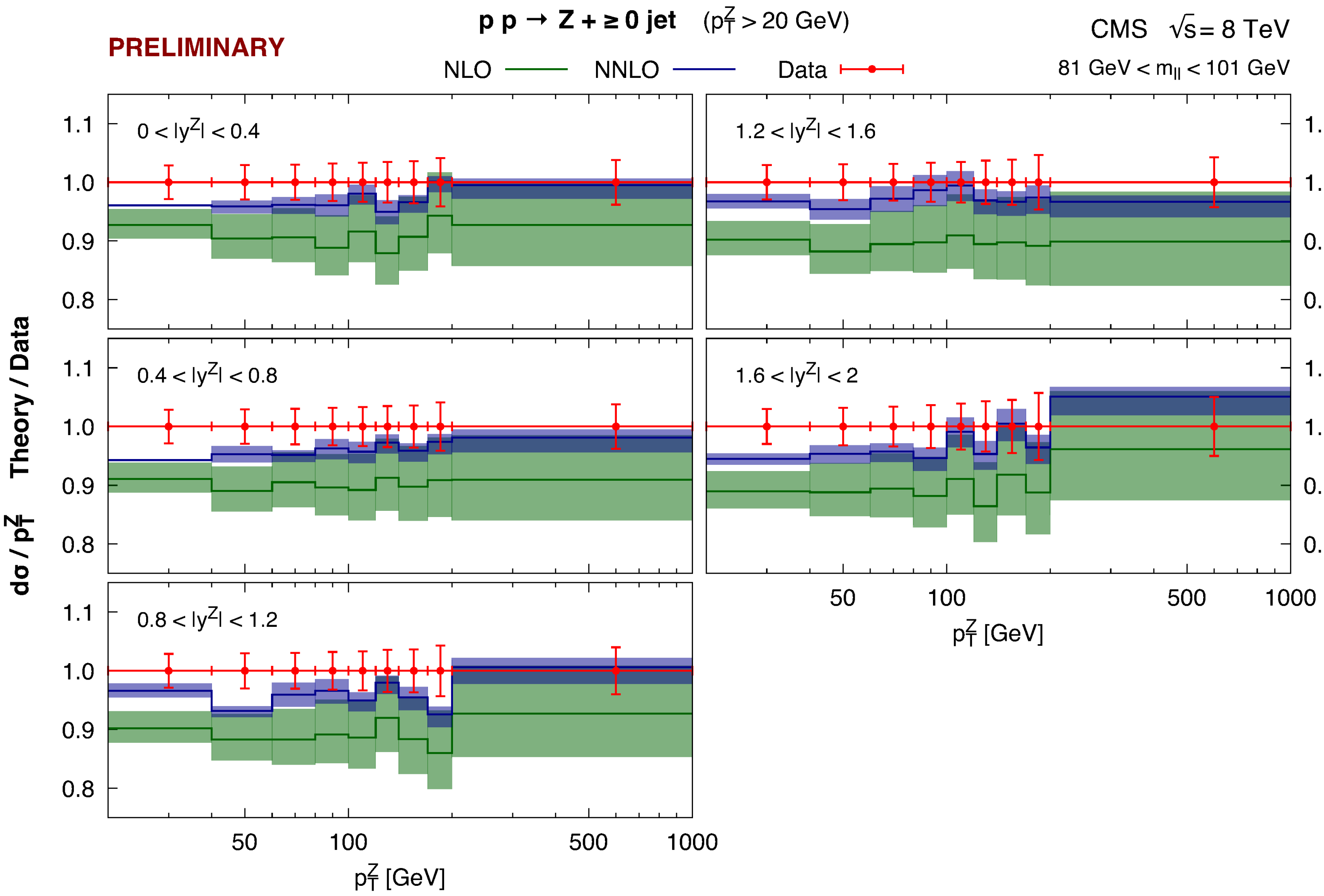
- $p_T^{\ell^\pm} > 20$ GeV, $|y^{\ell^\pm}| < 2.4$
- 66 GeV $< m_{\ell\ell} < 116$ GeV + binning in y^Z
- $|y^Z| < 2.4$ + binning in $m_{\ell\ell}$

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



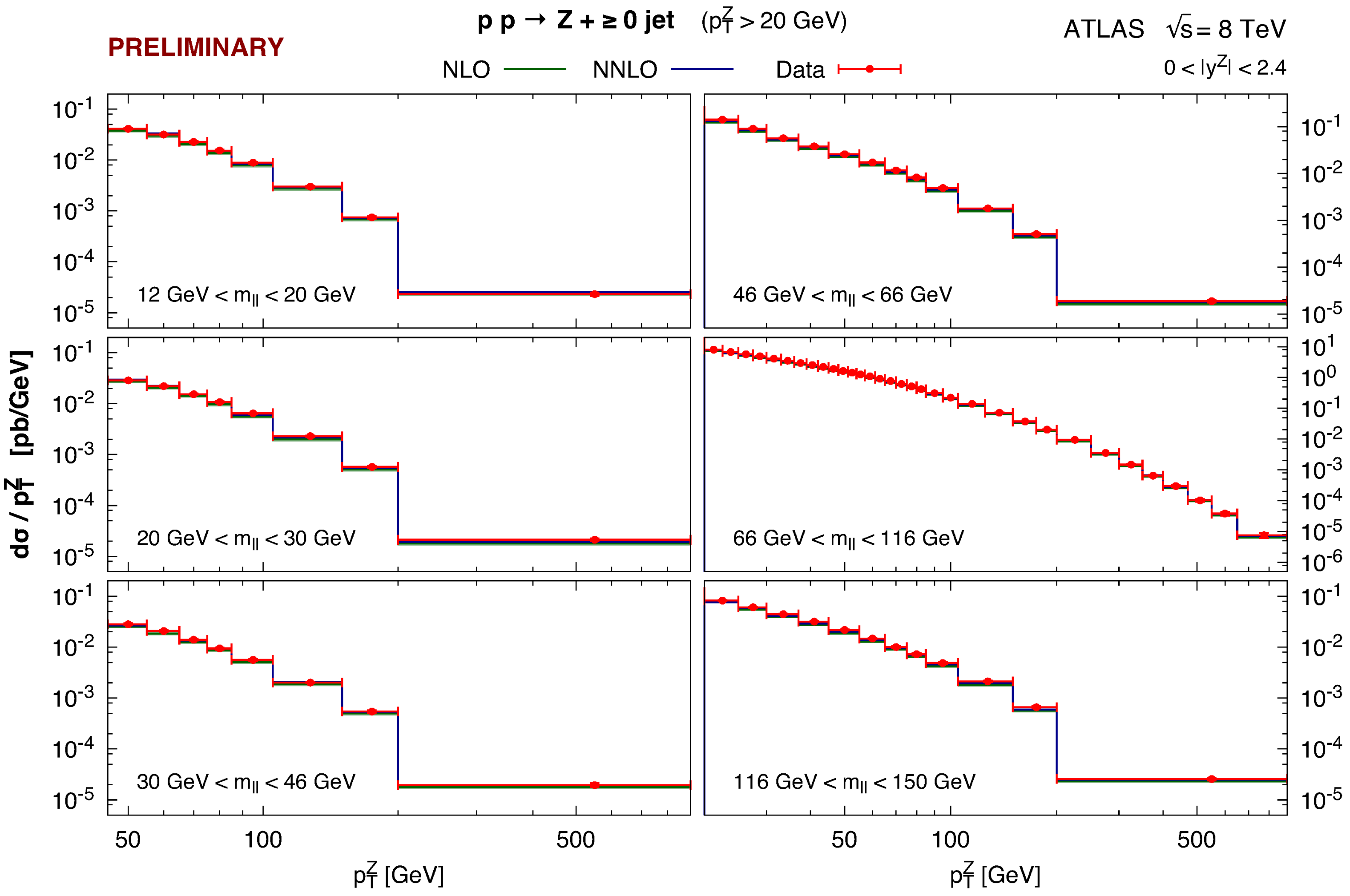
- $81\ \text{GeV} < m_{\ell\ell} < 101\ \text{GeV}$
- 5 bins in y^Z: [0,0.4], [0.4,0.8], [0.8,1.2], [1.2,1.6], [1.6,2.0]

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



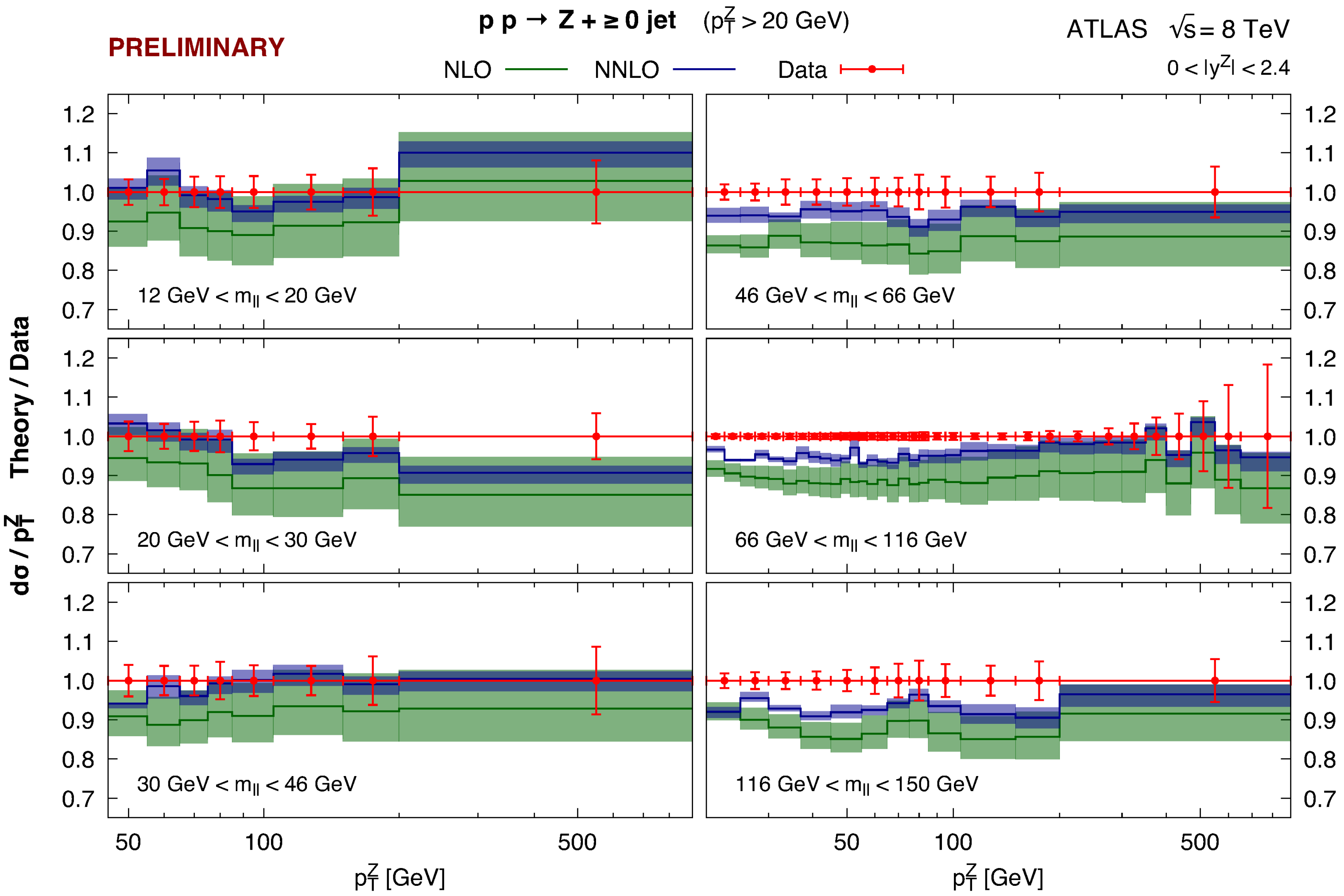
- improvement of theory vs. data comparison
- significant reduction of scale uncertainties

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



- $0 < |y^Z| < 2.4$
- 6 bins in $m_{\ell\ell}$: [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 of theory vs. data comparison
- significant reduction of scale uncertainties

Example H + jet production, large mass limit

NNLO QCD H+Jet

Boughezal, Caola, Melnikov, Petriello, Schulze (13,15)
Chen, Gehrmann, NG, Jaquier (14)
Boughezal, Focke, Giele, Liu, Petriello (15)
Caola, Melnikov, Schulze (15)

- ✓ large K-factor

$$\begin{aligned} \sigma_{NLO}/\sigma_{LO} &\sim 1.6 \\ \sigma_{NNLO}/\sigma_{NLO} &\sim 1.3 \end{aligned}$$

- ✓ significantly reduced scale dependence $\mathcal{O}(4\%)$

- ✓ Three independent computations:
  - ✚ STRIPPER
  - ✚ Antenna
  - ✚ N-jettiness

- ✓ allows for benchmarking of methods (for gg, qg and $\bar{q}g$ processes)
  - ✚ $\sigma^{NNLO} = 9.45^{+0.58}_{-0.82}$ fb

    Caola, Melnikov, Schulze (15)
  - ✚ $\sigma^{NNLO} = 9.44^{+0.59}_{-0.85}$ fb

    Chen, Gehrmann, NG, Jaquier (16)

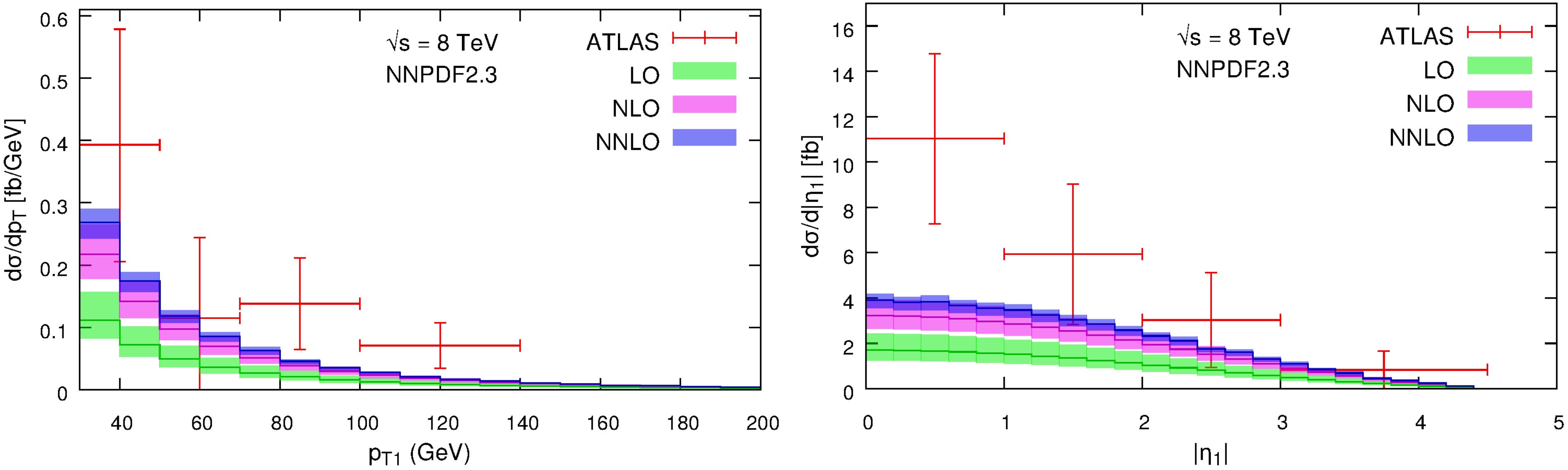
Higgs plus Jet: ATLAS

ATLAS setup

arXiv:1407.4222

- ✓ LHC @ 8 TeV
- ✓ anti-k_T algorithm, $R = 0.4$, $p_T^J > 30$ GeV, $|\eta_J| < 4.4$
- ✓ $p_T^{\gamma_1} > 43.75$ GeV, $p_T^{\gamma_2} > 31.25$ GeV, $|\eta_\gamma| < 2.37$
- ✓ isolation criterion $\Delta R(J, \gamma) > 0.4$ in $[\eta, \phi]$
- ✚ NNPDF2.3, $\alpha_s(M_Z)$ = 0.118 and fixed scale choice

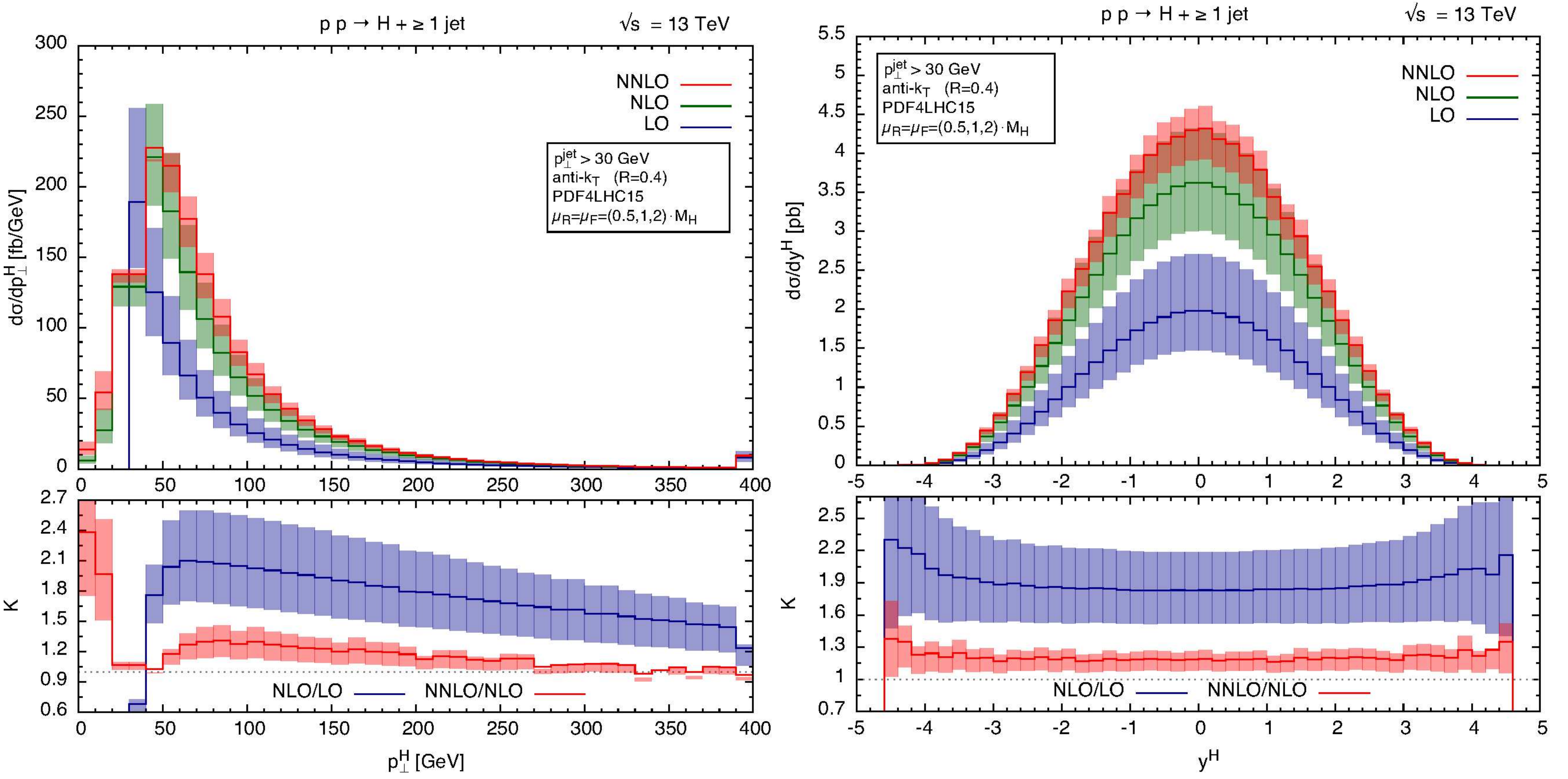
$$\mu_R = \mu_F = m_H \times \left[\frac{1}{2}, 1, 2\right]$$



p_T of leading jet

Rapidity of leading jet

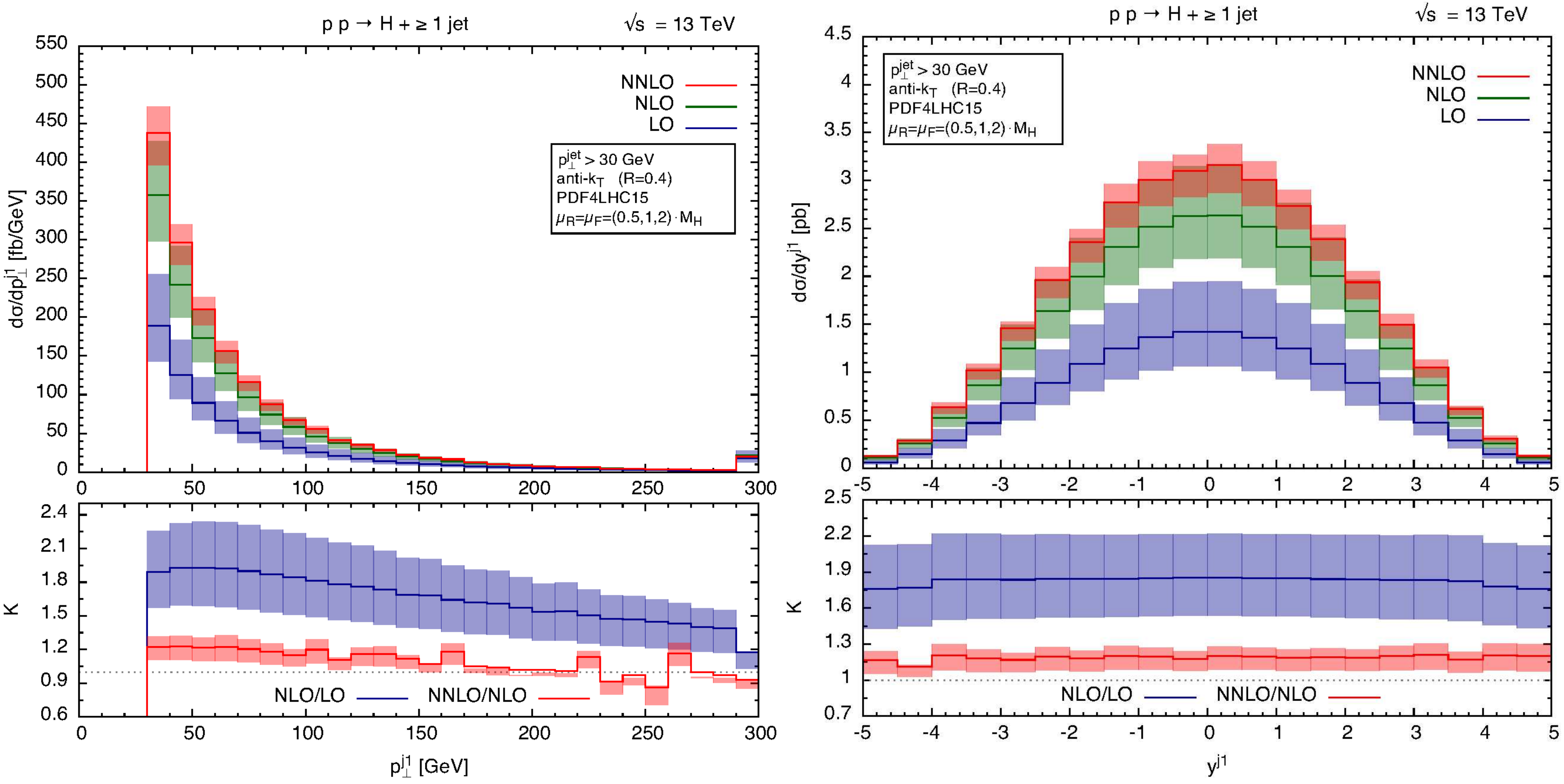
HXSWG



Higgs p_T and rapidity distributions

$\sqrt{s} = 13$ TeV, PDF4LHC15, $p_T^{jet} > 30$ GeV, anti-k_T, $R = 0.4$, $\mu_F = \mu_R = (0.5, 1, 2)m_H$

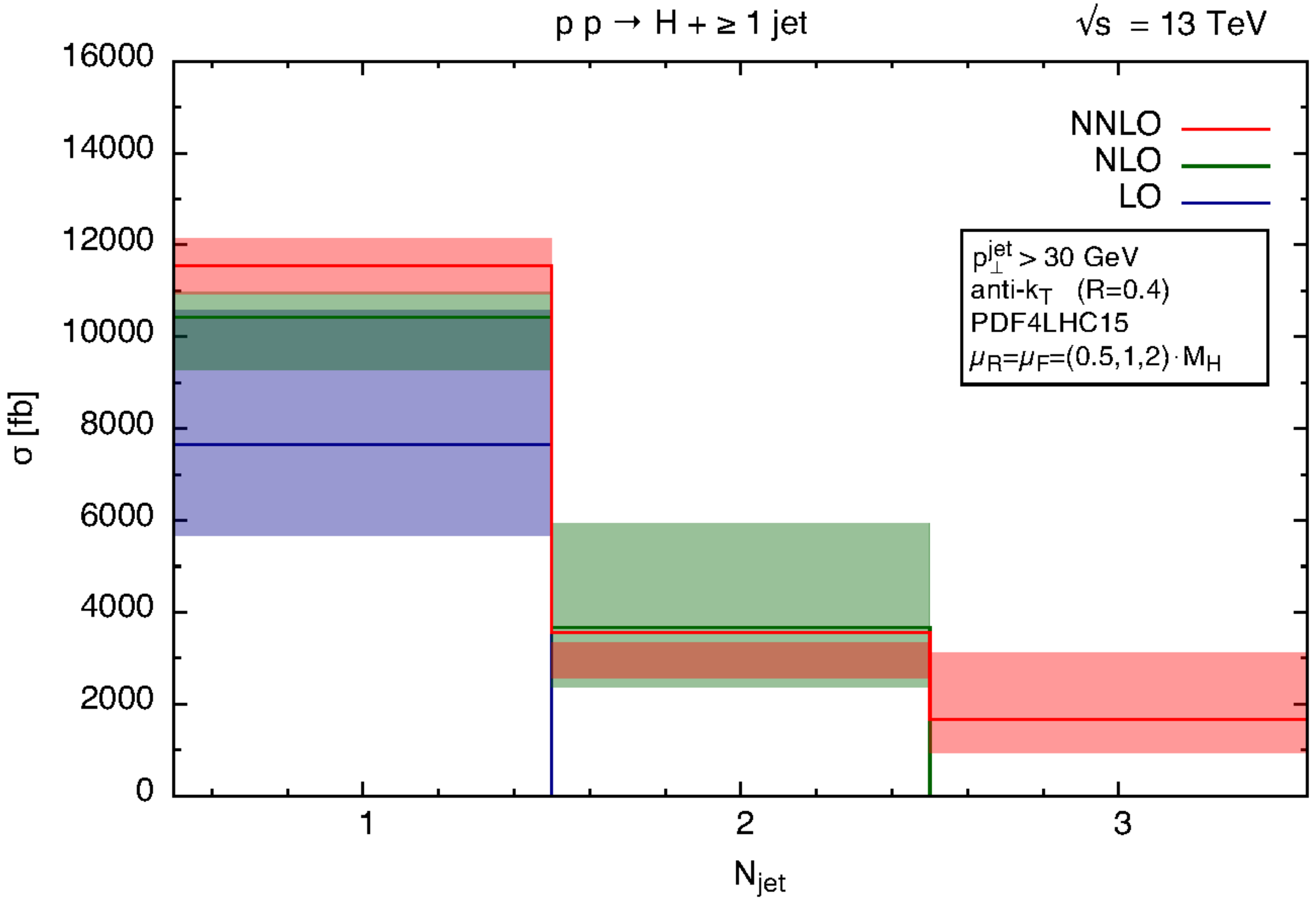
HXSWG



Leading jet p_T and rapidity distributions

$\sqrt{s} = 13$ TeV, PDF4LHC15, $p_T^{jet} > 30$ GeV, anti-k_T, $R = 0.4$, $\mu_F = \mu_R = (0.5, 1, 2)m_H$

HXSWG



Exclusive $H + nJ$ cross sections

$\sqrt{s} = 13$ TeV, PDF4LHC15, $p_T^{jet} > 30$ GeV, anti-k_T, $R = 0.4$, $\mu_F = \mu_R = (0.5, 1, 2)m_H$

Summary

- ✓ `NNLOJET` is able to make fully differential NNLO predictions that can be compared with data
- ✓ Z+jet
  - ✚ The inclusive p_T^Z spectrum is a powerful testing ground for QCD predictions, modelling of Z/W backgrounds, potential to constrain PDFs, . . .
  - ✚ We have predicted this distribution to NNLO accuracy for $p_T^Z > p_{T,\mathrm{cut}}^Z$
  - ✚ We observe a reduction of the scale uncertainty and an improvement in the theory vs. data comparison
- ✓ H+jet
  - ✚ Validated against calculation using different IR subtraction
  - ✚ Large corrections, but still some tension with inclusive H+J data

Work in progress:

- ✓ Including other processes, such as dijets, other Higgs decays, etc
- ✓ Studying potential of data to constrain PDF sets and interface to `APPLgrid`, `fastNLO`