Drell Yan at NNLOPS

Work done in collaboration with Alexander Karlberg and Emanuele Re

Relies on previous work with Keith Hamilton, Paolo Nason, Carlo Oleari, Emanuele Re

Giulia Zanderighi
CERN & University of Oxford

Outline

- brief intro and motivation
- method used (POWHEG+MiNLO)
- results
  - validation
  - comparison to data
  - comparison to analytic resummations

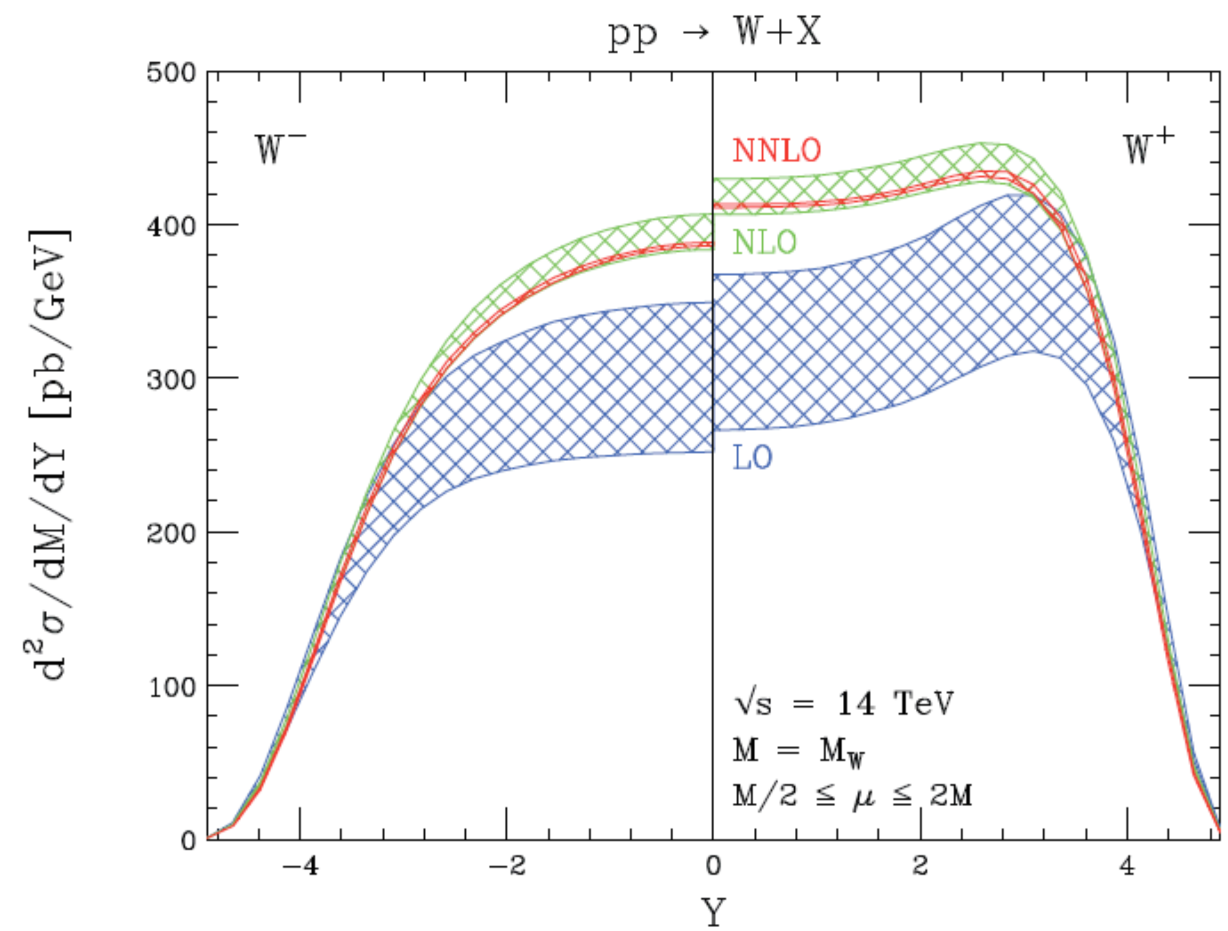
NLO+PS

- NLO revolution went hand in hand with the development of merging of NLO and parton showers via MC@NLO (Frixione & Webber ’02) or POWHEG (Nason ’04)
- Today, next-to-leading order parton showers (NLO+PS) have been realized as practical tools (POWHEG, MC@NLO, Sherpa) and are being today routinely used for LHC analyses
- First only processes with no associated jets in the final state, e.g. Drell-Yan, diboson, tt, VBF Higgs, ...
- Now associated jet production also included, e.g. for Drell Yan production in POWHEG there is
    - inclusive Drell Yan production
    - Drell Yan plus one jet
    - Drell Yan plus two jets

NNLO+PS

NLO not always enough

- high precision requires NNLO
- when NLO corrections are very large, even moderate precision requires NNLO (paramount example Higgs)
- NNLO is the frontier: first $2 \rightarrow 2$ calculations available



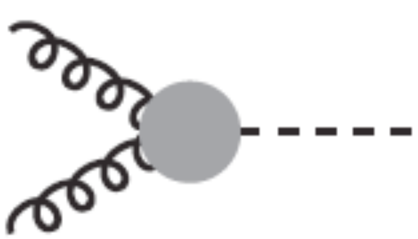
Anastasiou et al. ’03

Why merge NNLO + parton shower?

- realistic exclusive description of the final state (including MPI, resummation effects, hadronisation, U.E.) with state-of-the-art perturbative accuracy
- clearly a MUST for the upcoming LHC Higgs physics programme (important for precision studies in Drell Yan events)

NNLO: example Higgs

Ingredients for Higgs at NNLO



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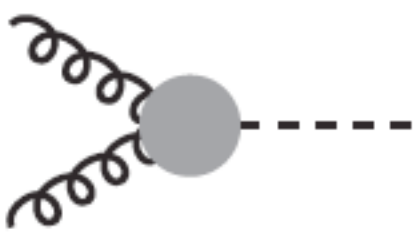
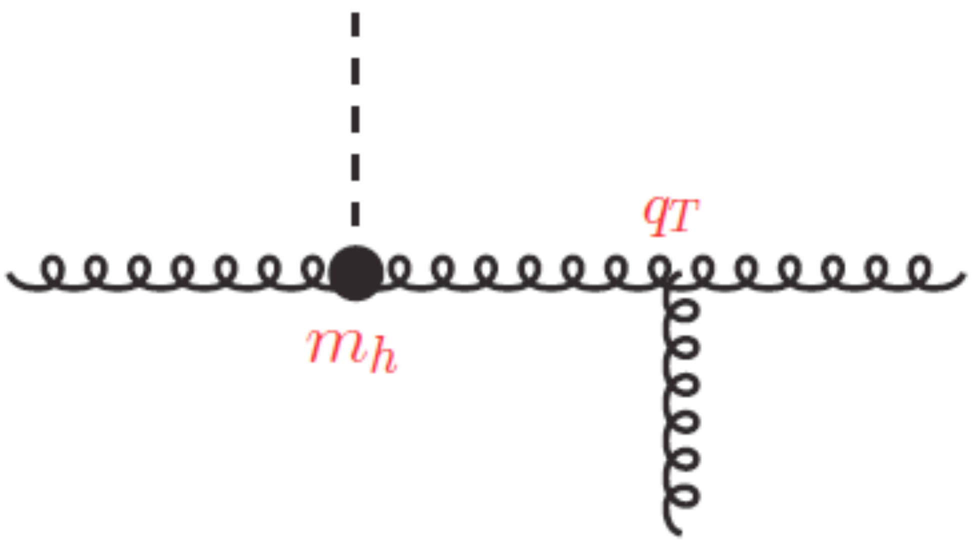
NNLO: example Higgs

Ingredients for Higgs at NNLO



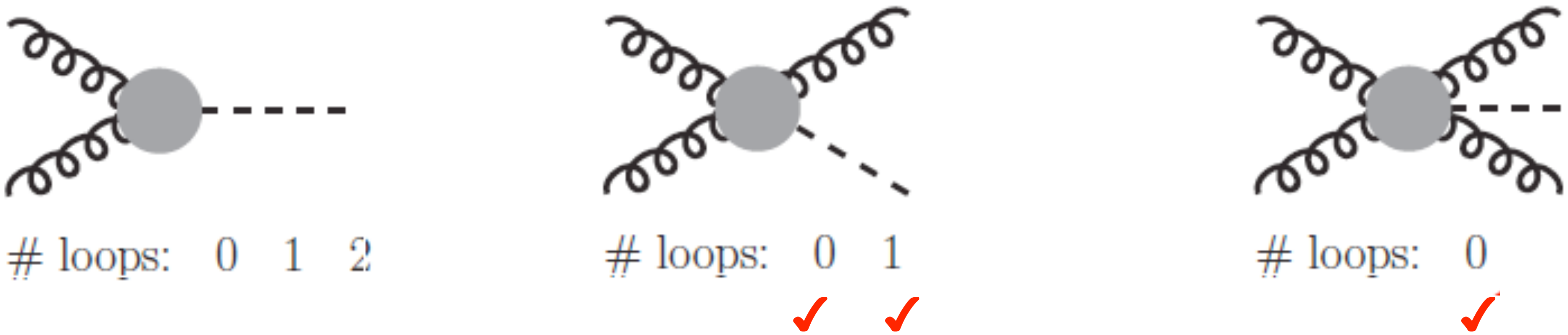
✓ NLO Higgs plus one jet calculation in POWHEG

✗ **but standard** NLO Higgs plus one jet calculation diverges without a transverse momentum cut on the jet



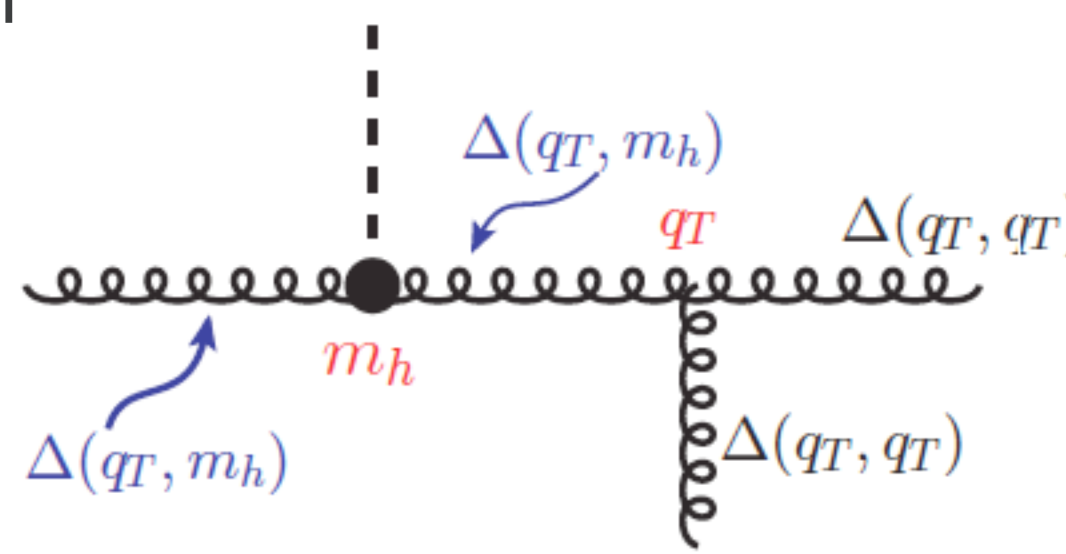
NNLO: example Higgs

Ingredients for Higgs at NNLO



✓ NLO Higgs plus one jet calculation in POWHEG

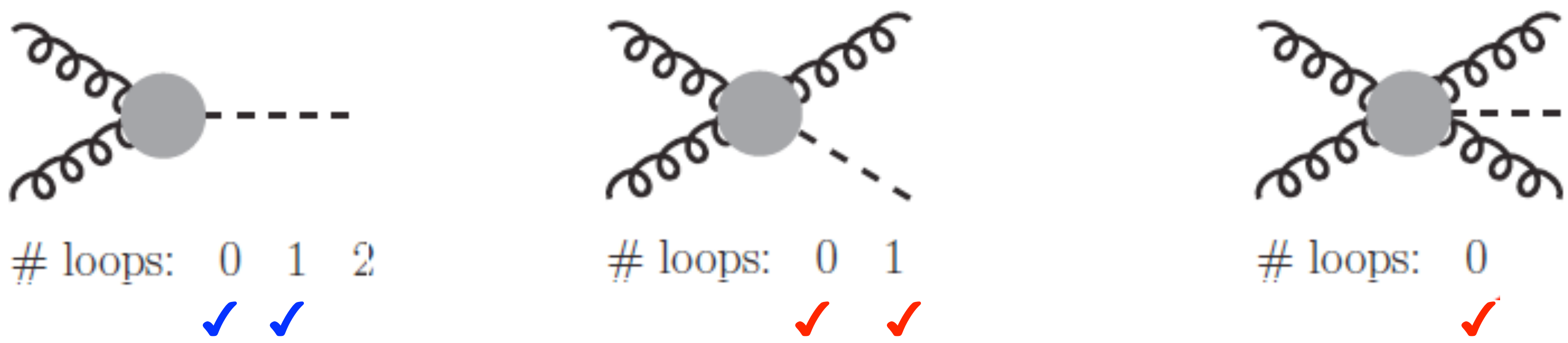
✓ NLO H+1jet calculation upgraded with MiNLO is finite upon integration over q_T



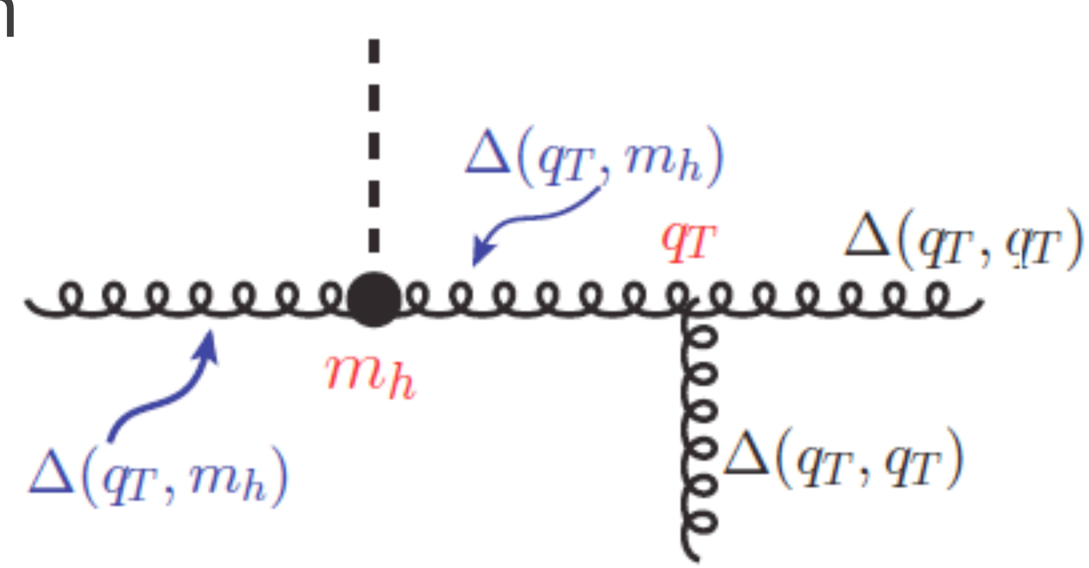
Hamilton et al. 1206.3542

NNLO: example Higgs

Ingredients for Higgs at NNLO



- ✓ NLO Higgs plus one jet calculation in POWHEG
- ✓ NLO H+1jet calculation upgraded with MiNLO is finite upon integration over q_T
- ✓ MiNLO procedure can be formulated such that the integral is the NLO inclusive Higgs cross-section

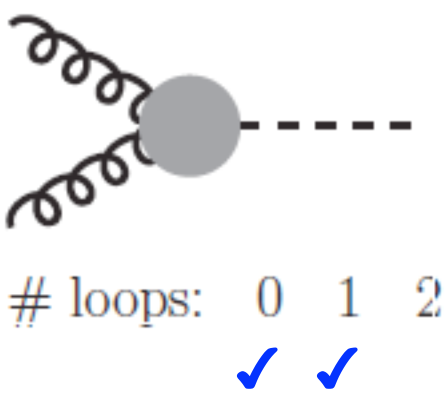


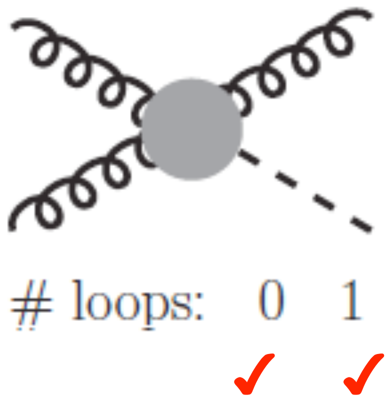
Hamilton et al. 1206.3542

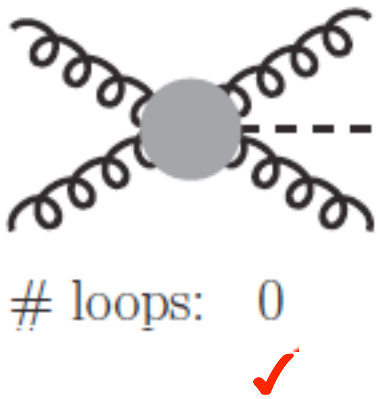
Hamilton et al. 1212.4504

NNLO: example Higgs

Ingredients for Higgs at NNLO







✗ still missing double virtual contribution

Merging and NNLO

Example: let's take

- Higgs at NLO+PS: H-NLOPS
- Higgs + one jet at NLO+PS: HJ-NLOPS
- a merged generator that is NLO+PS for H and HJ: H+HJ-NLOPS
- Higgs at NNLO+PS: H-NNLOPS

	inclusive H	H+1jet (inclusive)	H+2jets (inclusive)
H-NLOPS	NLO	LO	soft-col. approx
HJ-NLOPS	divergent	NLO	LO
H+HJ-NLOPS	NLO	NLO	LO
H-NNLOPS	NNLO	NLO	LO

Conclusion: the H+HJ-NLOPS generator almost does the right job

NB: merging achieved by extending the validity of the NLO with a jet down to the region where the jet is unresolved (no merging scale)

NNLOPS generator with MiNLO

Hamilton et al. 1309.0017

For Higgs production, the Born kinematics is fully specified by the Higgs rapidity. So consider the following distributions:

$\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}} \longrightarrow$ inclusive Higgs rapidity computed at NNLO

$\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ-MiNLO}} \longrightarrow$ inclusive Higgs rapidity from H+1jet-MiNLO

Since H+1jet-MiNLO (HJ-MiNLO) is NLO accurate, it follows that

$$\frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ\text{-}MiNLO}}} = \frac{c_2\alpha_s^2 + c_3\alpha_s^3 + c_4\alpha_s^4}{c_2\alpha_s^2 + c_3\alpha_s^3 + d_4\alpha_s^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

Thus, re-weighing `HJ-MiNLO+Pythia` results with this factor one obtains NNLO+PS accuracy

Proof of NNLO accuracy

<u>Theorem:</u>

A parton level Higgs boson production generator that

1) is accurate at $O(\alpha_s^4)$ for all IR safe observables that vanish with the transverse momenta of all light partons, and

2) that also reaches $O(\alpha_s^4)$ accuracy for the inclusive Higgs rapidity distribution,

achieves the same level of precision for all IR safe observables, i.e. it is fully NNLO accurate.

Proof of the theorem

- take any infrared safe observable F. It's value is $\langle F \rangle = \int d\Phi \frac{d\sigma}{d\Phi} F(\Phi)$
- because of infrared safety, F has a smooth limit when the momenta or all light partons vanish. This limit can depend only on the Higgs rapidity, call it F_y.
- write $\langle F \rangle = \langle F - F_y \rangle + \langle F_y \rangle$
- since $\langle F - F_y \rangle$ vanishes when momenta of all light partons vanish, it is described at NNLO accuracy
- on the other hand $\langle F_y \rangle = \int dy' \frac{d\sigma}{dy'} F_y(y')$ and so it is also NNLO accurate
- thus, $\langle F \rangle = \langle F - F_y \rangle + \langle F_y \rangle$ is NNLO accurate

q.e.d.

Proof of NNLO accuracy

Theorem:

A parton level Higgs boson production generator that

1) is accurate at $O(\alpha_s^4)$ for all IR safe observables that vanish with the transverse momenta of all light partons, and

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- The `HJ-MiNLO` generator satisfies property 1).
- The re-scaling with $\mathcal{W}(y)$ trivially also guarantees property 2).
- Finally, since `POWHEG` preserves NLO accuracy of the HJ calculation, further emissions from the shower give rise to terms beyond $O(\alpha_s^4)$

Variants of the method possible: freedom to distribute the NNLO/NLO K-factor only over the small-medium p_t region

Extension to Drell Yan

Karlberg, Re, Zanderighi '14

Extension to Drell-Yan is relatively straightforward

- because of spin-correlations in the decays of the boson need to perform a rescaling in terms of the variables specifying the Born process pp → 2 leptons
- this requires a rescaling in terms 3 independent variables, rather than just the Higgs rapidity as in Higgs production
- freedom in the choice of independent variables, but important to choose variables/binning so that bins are populated uniformly
  [we use y_Z, angle between electron and beam in frame where $p_{l,Z}=0$ and $\mathrm{atan}((m_{ll}^2-M_Z^2)/\Gamma_Z M_Z)$]

Other approaches to Drell Yan at NNLOPS: Hoeche, Li, Prestel '14; Alioli, Bauer et al '14

NNLO accuracy:DY

Theorem:

A parton level Drell Yan boson production generator that

1) is accurate at $O(\alpha_s^2)$ for all IR safe observables that vanish with the transverse momenta of all light partons, and

2) that also reaches $O(\alpha_s^2)$ accuracy for the three Born variables in Drell Yan production, achieves the same level of precision for all IR safe observables, i.e. it is fully NNLO accurate.

The proof proceeds exactly in the same way as for Higgs production

Settings

Karlberg, Re, Zanderighi '14

- MSTW2008NNLO pdfs
- NNLO from DYNNLO [Catani, Cieri, Ferrera, Grrazzini '09] at central scale M_V, MiNLO has it's own scale
- rescaling factor smoothly approaching 1 at $p_t \gtrsim M_V$
- tune: PYTHIA6 "Perugia P12-M8LO; PYTHIA8 Monash 2013

Uncertainty definition

Vary

- $\mu_R = \mu_F$ in NNLO by factor 2 up and down around $m_V/2$ (3 scales)
- μ_R, μ_F in VJ-MiNLO event generation by factor 2 up and down avoiding μ_R/μ_F = 1/4, 4 (7 scales)

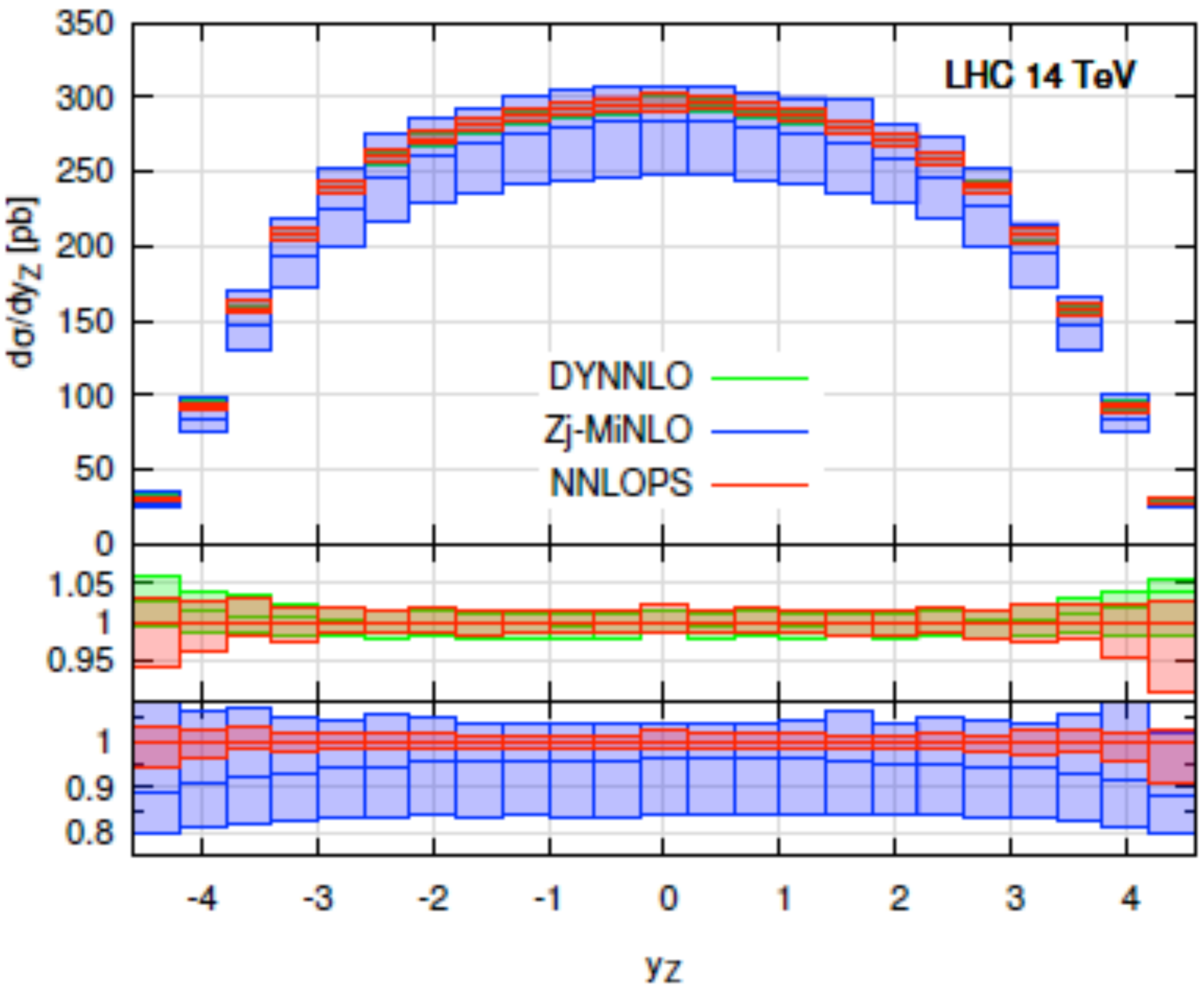
Take the envelope of the 21 scale choices

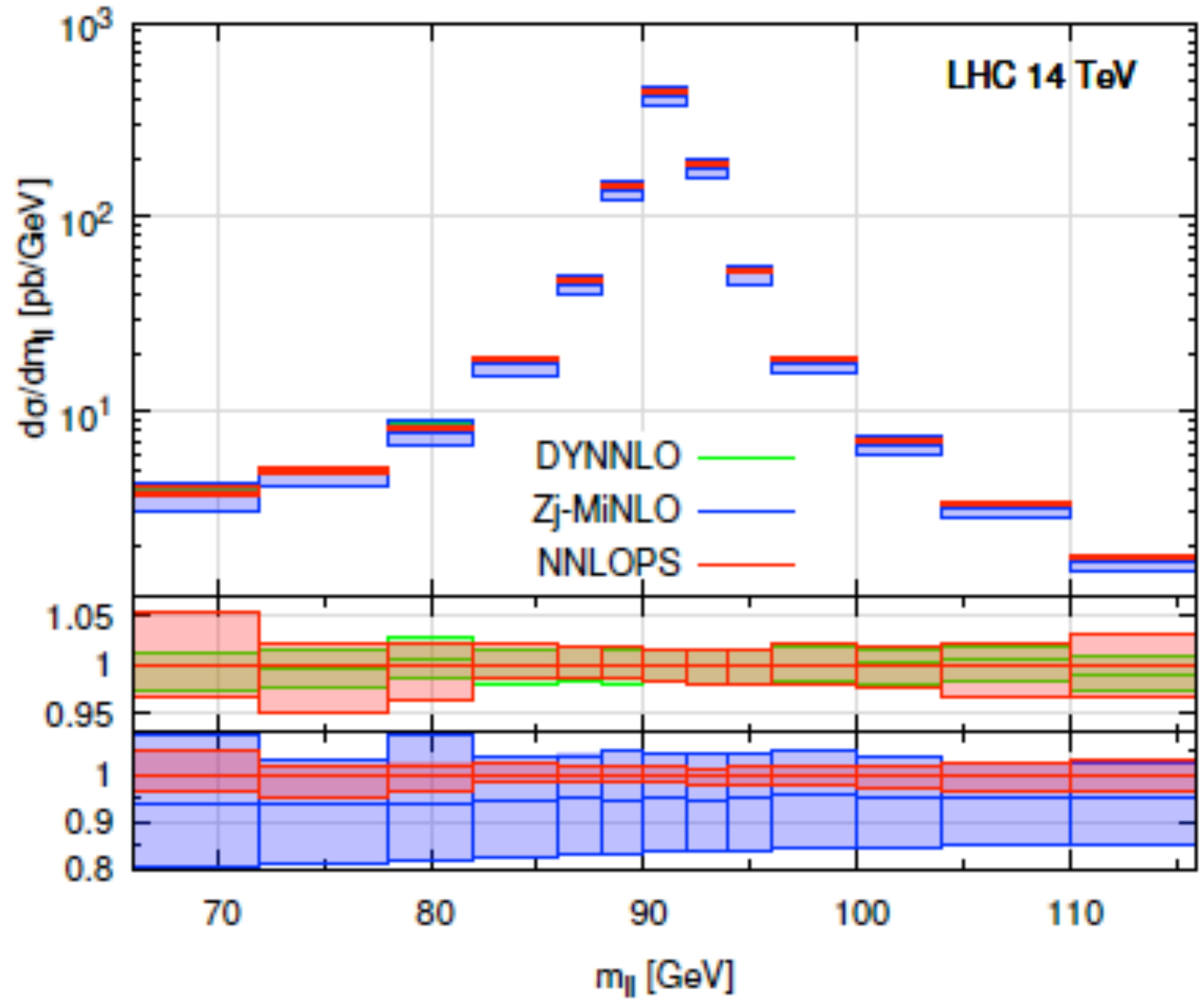
(Conservative) motivation to consider scale variations both in NNLO and in VJ-MiNLO independently is to consider uncertainties in normalization (NNLO) and shape (MiNLO) as independent (similar to efficiency method for cross-sections with jet-veto)

NB: 7scales in MiNLO obtained using POWHEG's reweighting procedure

Results for Higgs production at NNLOPS: validation plots and comparisons to other results available in Hamilton et al. 1309.0017

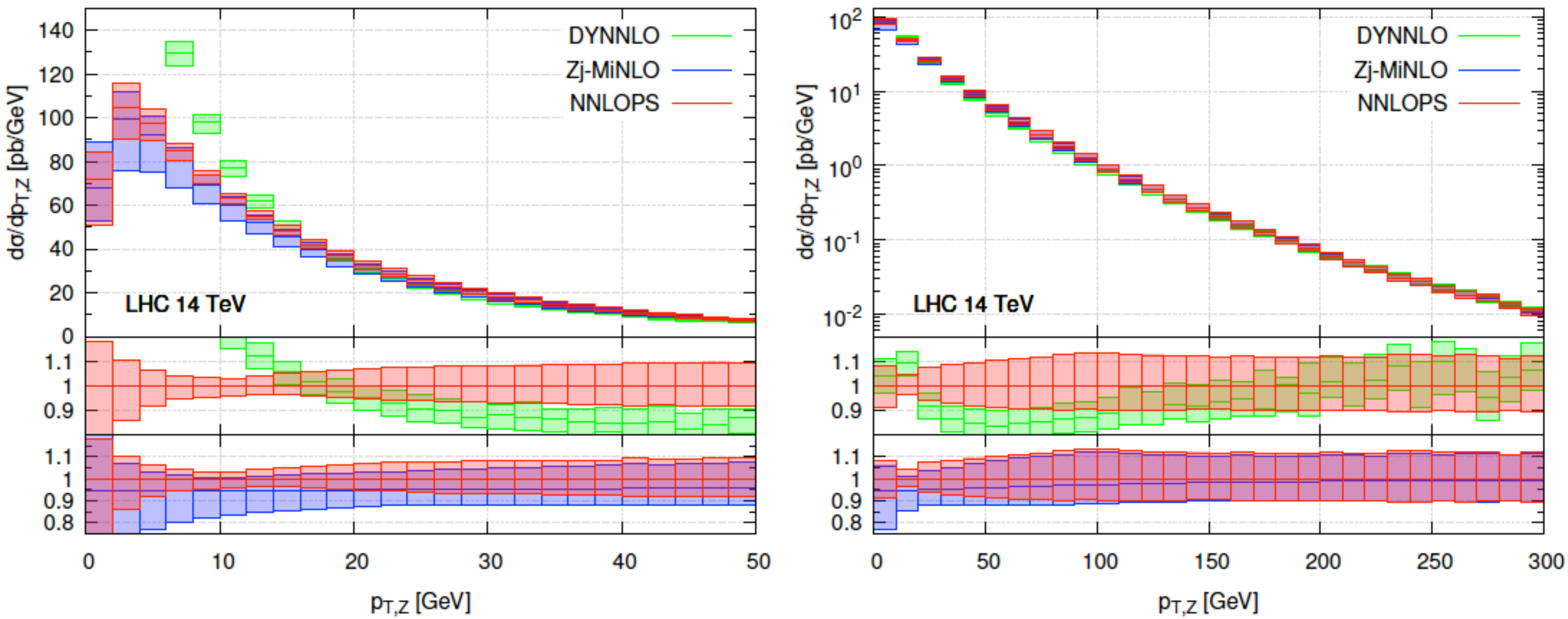
NNLOPS for Z production





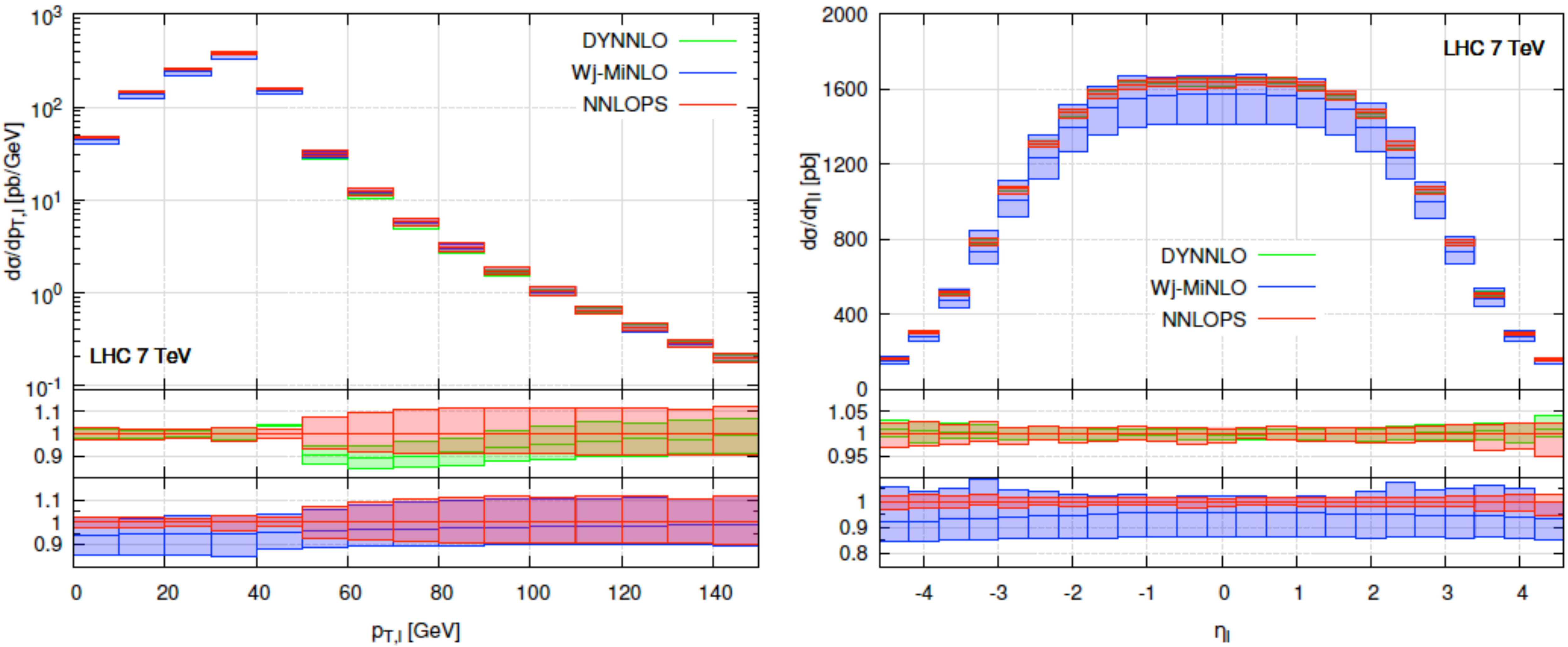
- 7 scales in DYNNLO, 21 in NNLOPS
- agreement with DYNNLO (validation)
- reduction of uncertainty wrt to ZJ+MiNLO

NNLOPS for Z production



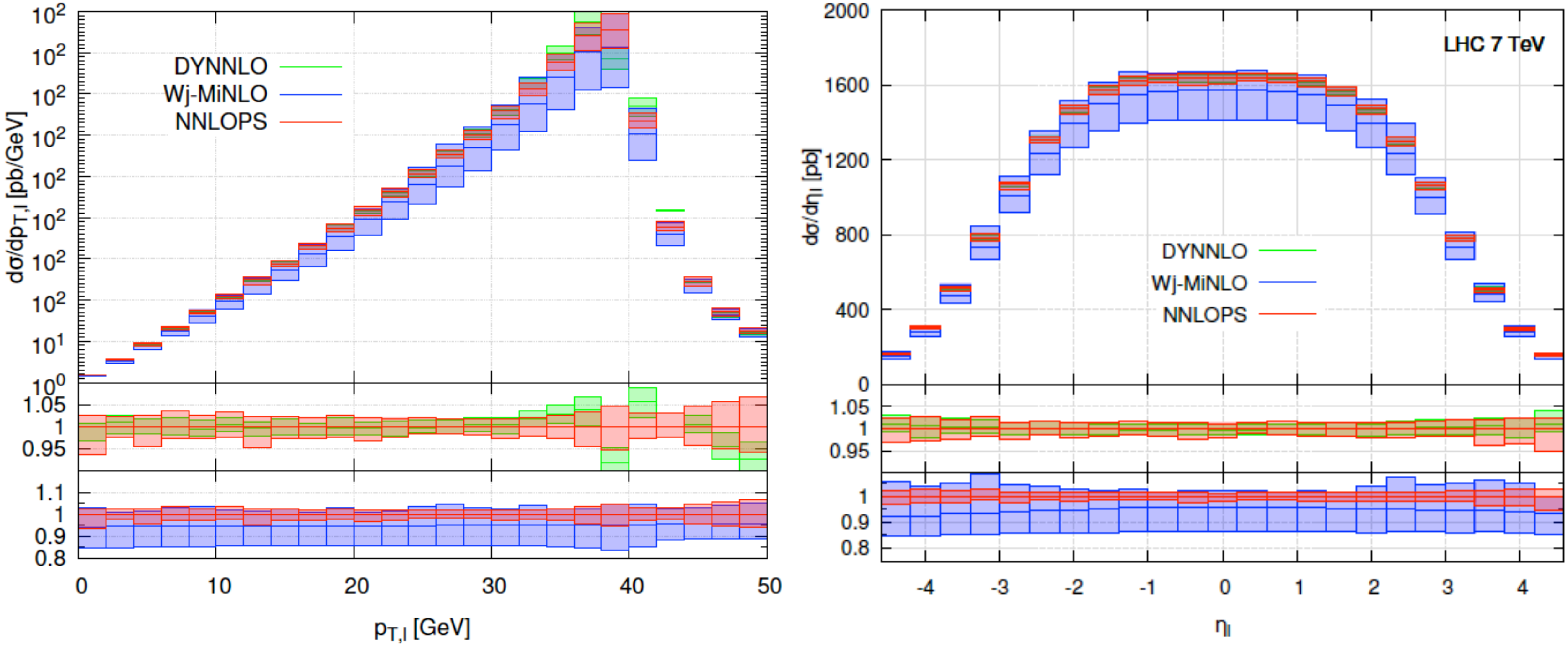
- NNLOPS smooth behavior where DYNNLO diverges
- DYNNLO uncertainty too small at low p_t
- at high p_t all calculations comparable (but use different scales)

NNLOPS for W production



- *not* the observables used in the reweighting
- lepton rapidity NNLO everywhere
- lepton transverse momentum NNLO only at $p_{t,l} < M_W/2$ (uncertainty band reflects this), smooth behavior close to Jacobian peak

NNLOPS for W production



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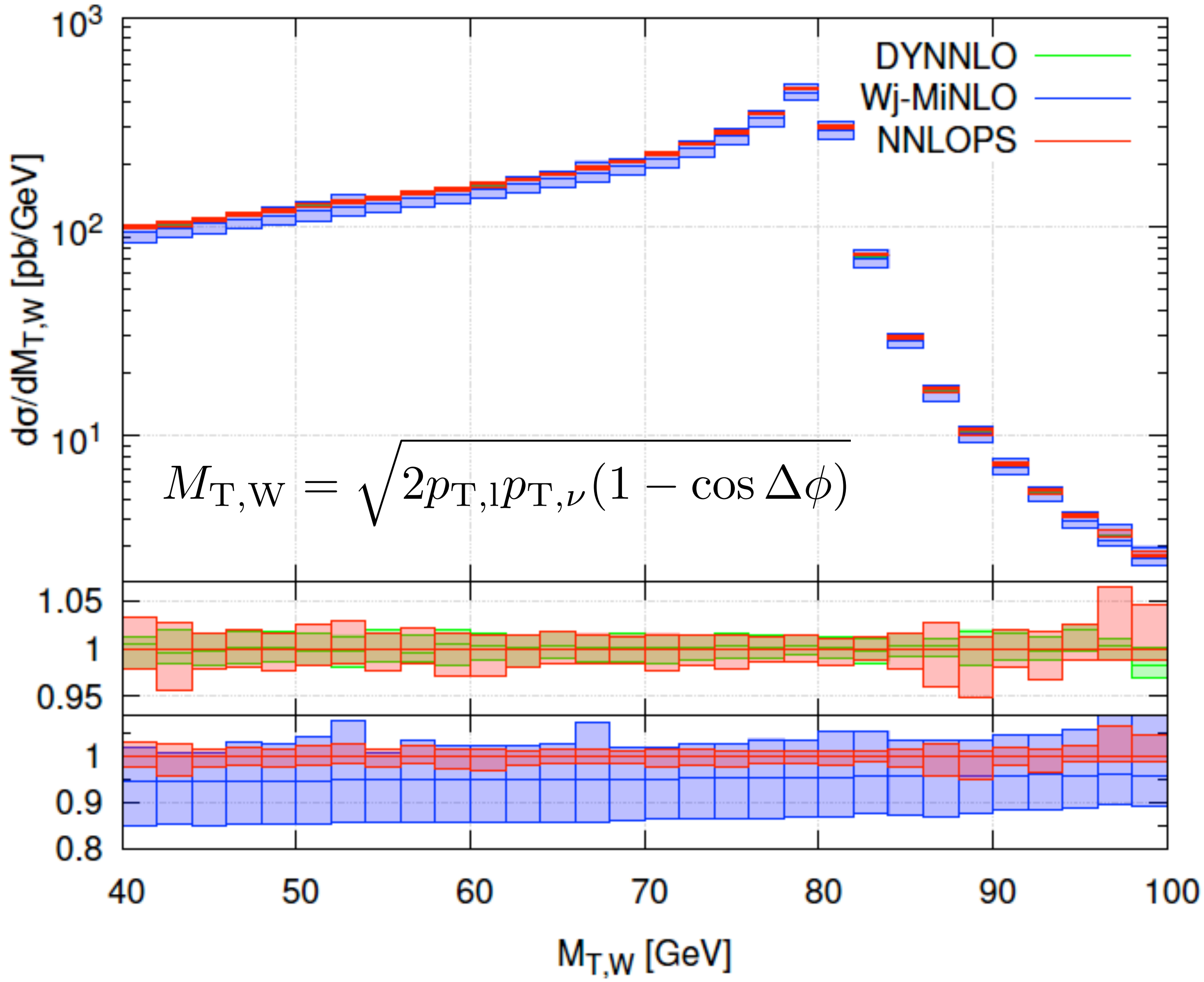
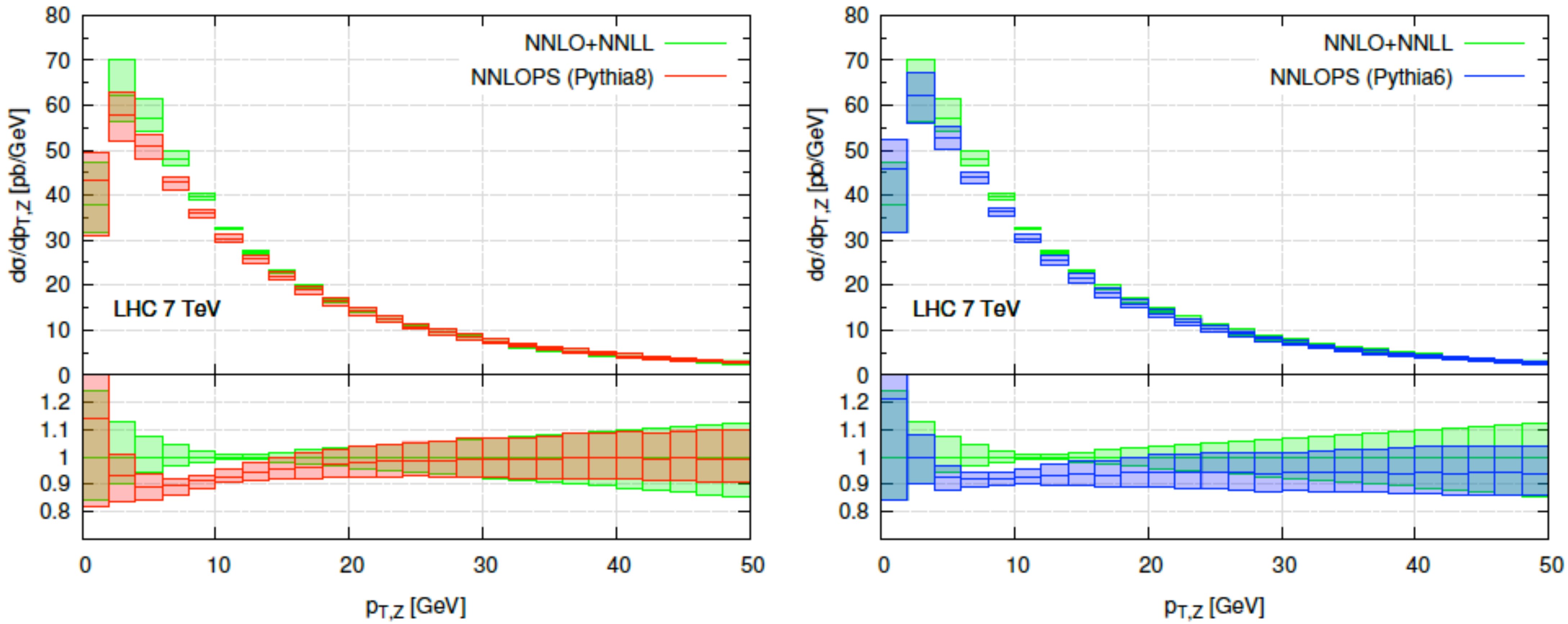


- variable important for W mass determination
- perturbative instabilities in the presence of leptonic cuts alleviated in NNLO+PS approach

Comparison to resummation: $p_{t,Z}$

Comparison to NNLL+NNLO for $p_{t,Z}$ [Bozzi et al. 1007.2351]

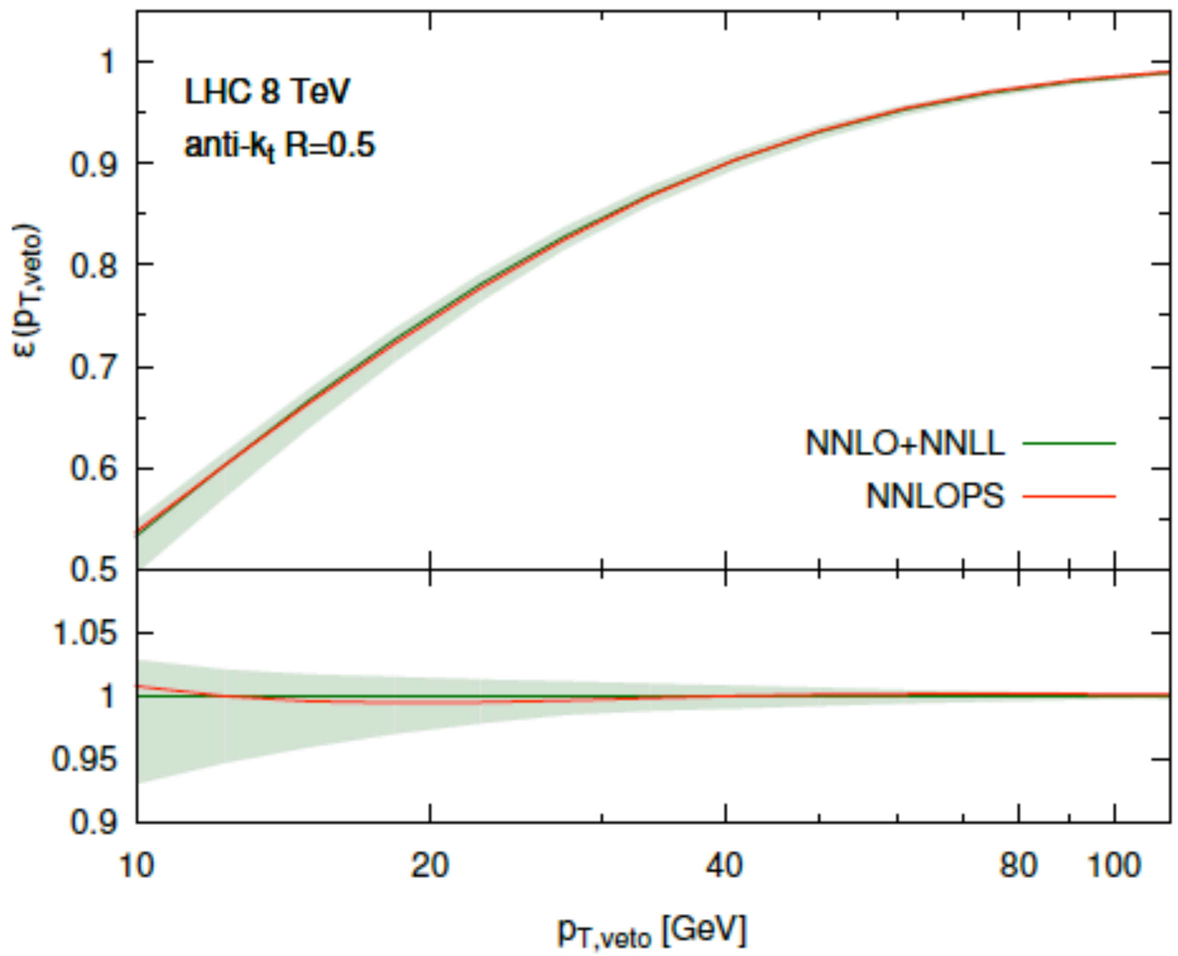


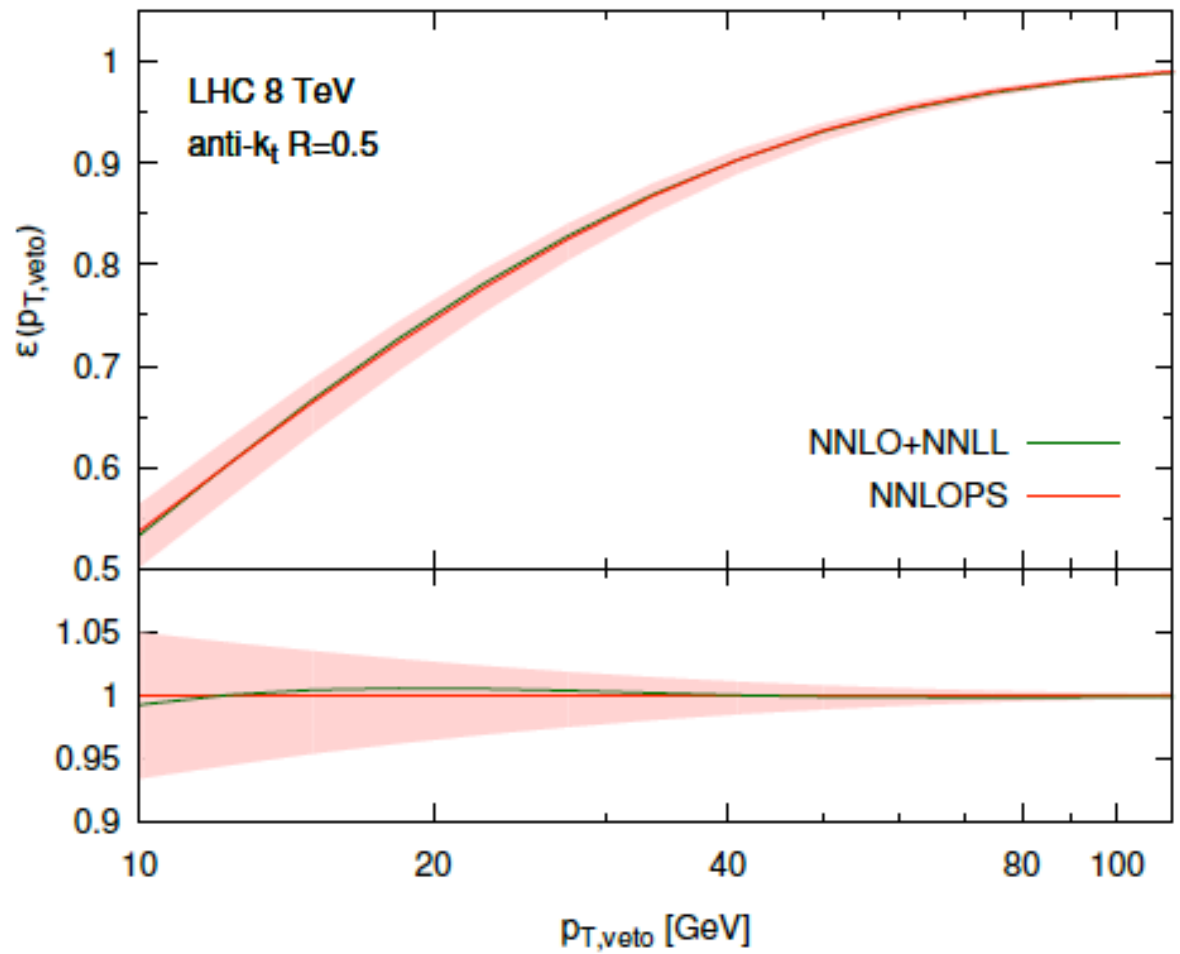
- agreement good but not perfect (shrinking of bands makes it look worse?). Formal accuracy in logarithmic region different.
- uncertainty bands might underestimate true uncertainty
- differences between Pythia6 and Pythia8 suggest that impact of non-perturbative (tune) not negligible at low $p_{t,Z}$

Comparison to resummation: $p_{t,veto}$

Comparison to JetVHeto (NNLL+NNLO) for jet-veto efficiency

[Banfi et al. '12]

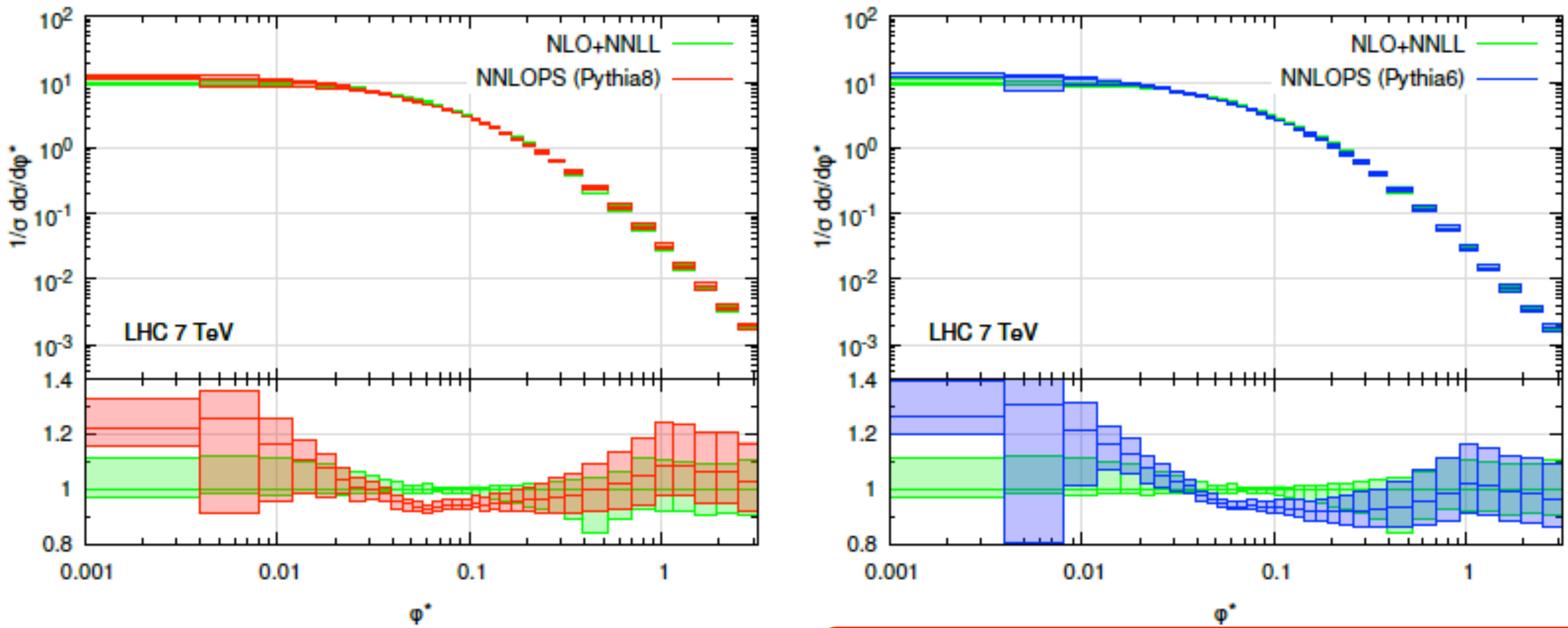




- agreement very good, at the level of 2-3%
- but level of agreement depends on radius (worsen at large R)

Comparison to resummation: φ^*

Comparison to NNLL+NNLO resummation for φ^* [Banfi et al. 1205.4760]



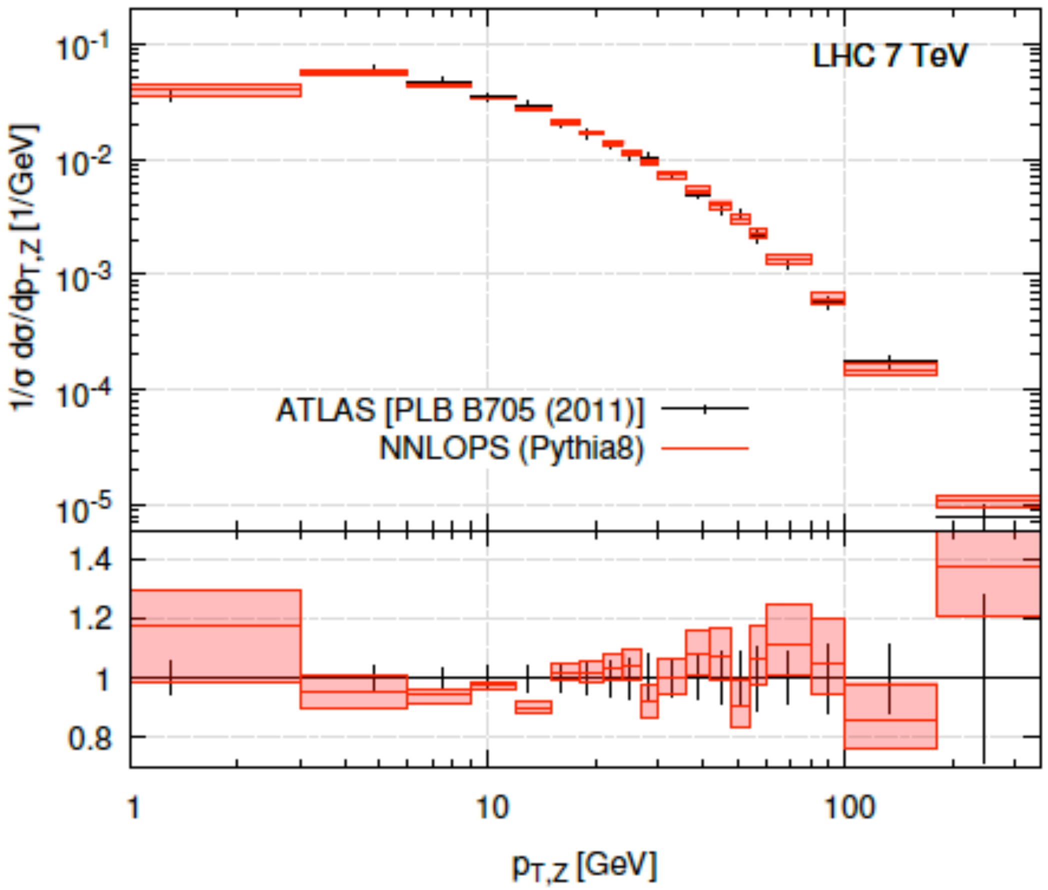
$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin\theta^*$$

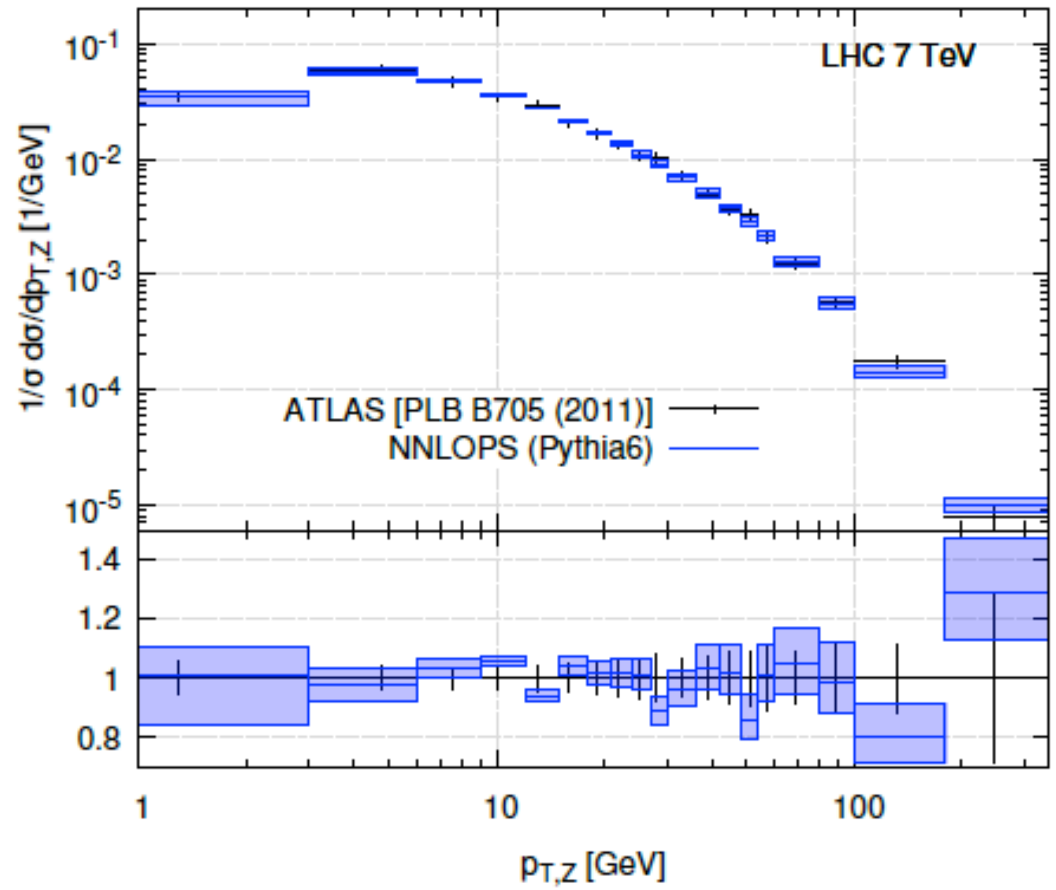
θ*: angle between lepton and beam in Z-rest frame

- agreement not very good at small φ^*
- non-perturbative effects important (agreement with data better when they are included)

Comparison to data

Comparison to ATLAS data for $p_{t,Z}$

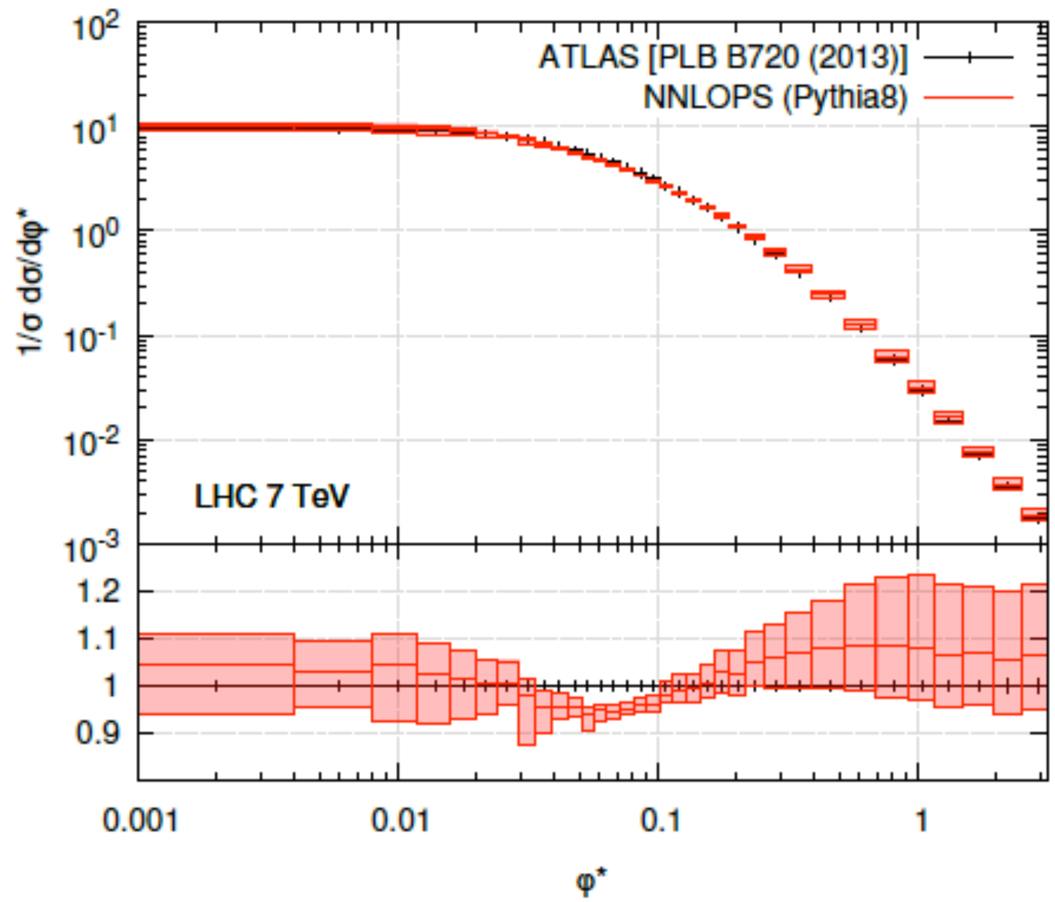


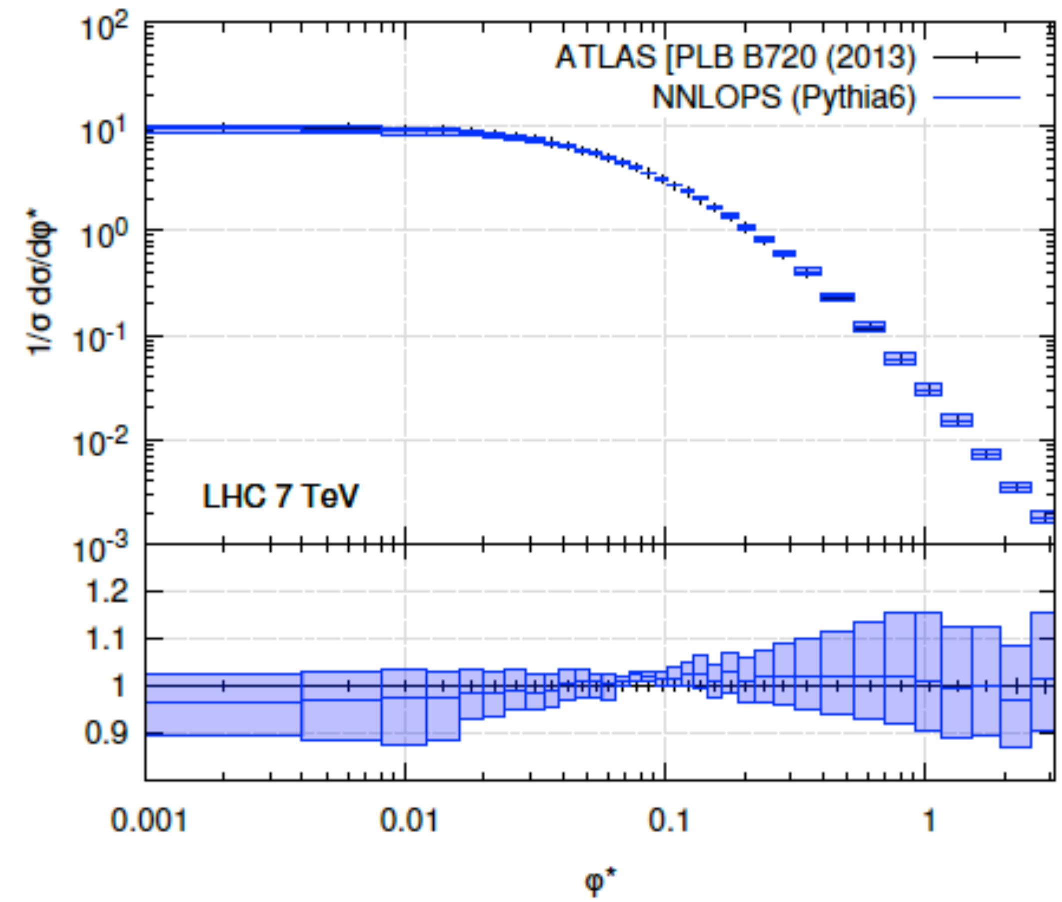


- agreement good, but depends on tune, shower etc (slightly better with Pythia6)
- similar agreement for $p_{t,W}$

Comparison to data

Comparison to ATLAS data for φ^*





- agreement good, but depends on tune, shower etc (slightly better with Pythia6)
- more comparisons to data shown in Karlberg et al. 1707.2940

Conclusions

- MiNLO born as a scale-setting procedure à-la CKKW, but inclusion of Sudakov form factor turns out to have great benefits and deep implications
  - no need for generation cuts or Born suppression factors
  - allows merging of different jet-multiplicities (0-jet and 1-jet for now)
  - a path to NNLOPS
- NNLOPS generator for Higgs and Drell Yan production
  Public code in `POWHEG-BOX V2` repository for `HJ` process, `VJ` released soon