Higgs and Drell-Yan at NNLOPS

Work done in (various) collaborations with

Alexander Karlberg, Keith Hamilton, Paolo Nason, Carlo Oleari, Emanuele Re

Giulia Zanderighi

CERN & University of Oxford

Next-to-leading order

- Remarkable progress in NLO calculations over the past ten years. Goes under the name of the NLO revolution
- NLO wish-lists [ttbb,tttt, WWbb, bbbb, WWjj,W/Z+3,4,j, W+5j, 4j] are closed chapters
- Two main directions now
  - more legs: e.g. Blackhat focuses on pure n jets or W/Z + n jets pushing the frontier of n
  - more processes: towards a full automation of NLO calculations with codes like Helac, GoSam or MadLoop
- This progress went hand in hand with the development of merging of NLO and parton showers via MC@NLO (Frixione & Webber '02) or POWHEG (Nason '04)

NLO+PS

- 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 Higgs production in POWHEG there is
  - inclusive Higgs production
  - Higgs plus one jet
  - Higgs plus two jets

  [same for W and Z]

NNLO + parton shower

- Higgs and Drell-Yan known to NNLO since many years now
- 2013 is the year were the NNLO started: full or partial results for associated Higgs production, top-pairs, H+jet, dijet [...]
- these calculations pave the way to all 2 → 2 processes relevant for LHC physics
- similarly to what happened at NLO, natural to seeks for a method to compute NNLO+parton shower corrections
- first ideas towards NNLO+PS for inclusive Higgs production presented in Hamilton et al. 1212.4504
- first NNLO+PS for Higgs production in Hamilton et al. '13
- here: preliminary results for Drell-Yan production
- method based on MiNLO procedure for NLO and is intimately connected to the merging problem. So, start discussing those.

MiNLO: Multiscale Improved NLO

The idea behind MiNLO started as a spin-off of the NLO calculation of W+3jets

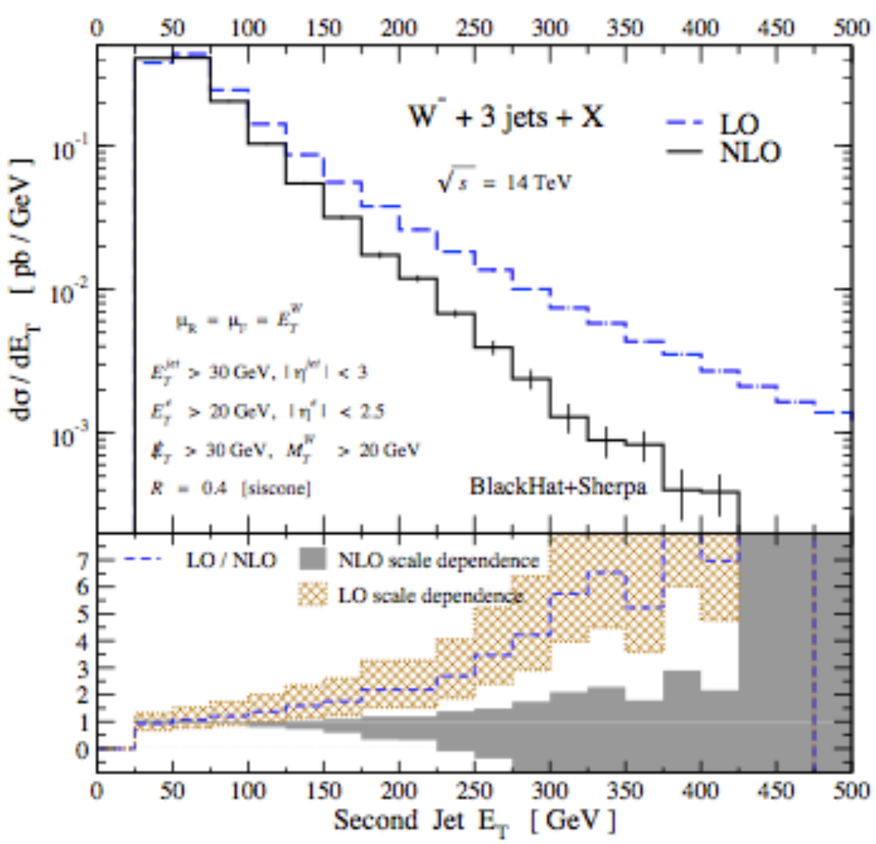
the impact of NLO calculations is often discussed using the same scale choice at LO and NLO, however more advanced LO calculations exist that rely on the CKKW procedure for scale setting and inclusion of Sudakov effects

Melnikov & GZ 0910.3671

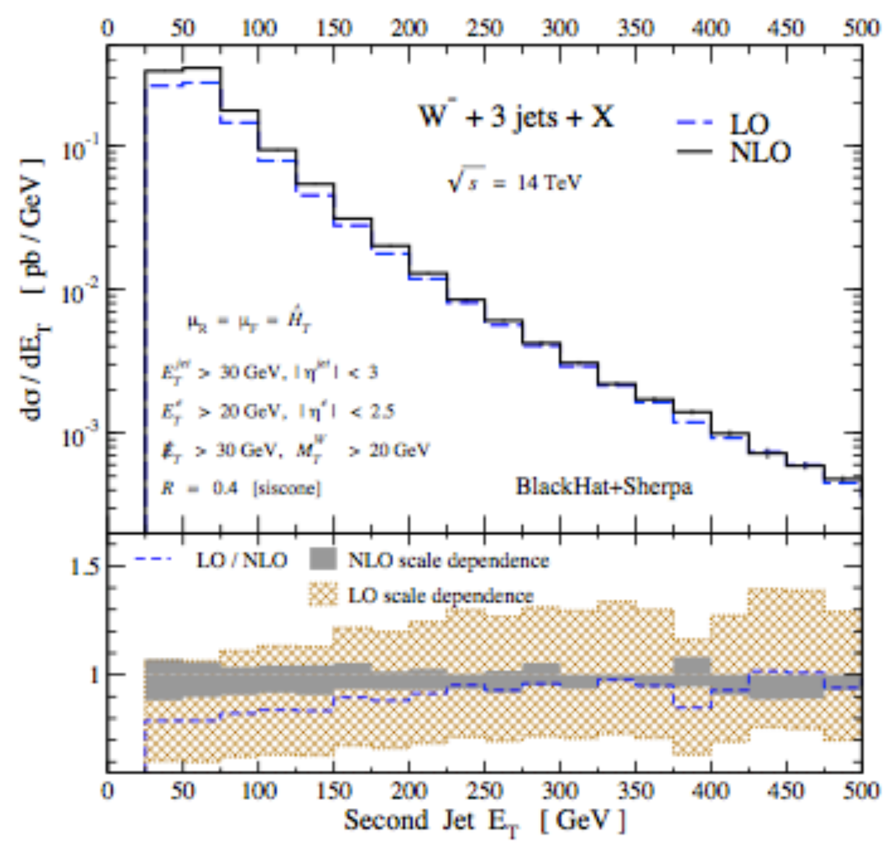
Even at NLO the scale choice is an issue. Different choices can lead to a different picture/contrasting conclusions, so it seemed natural to look for an extension of the CKKW method to NLO

Scale choice at NLO

Often a “good scale” is determined a posteriori, either by requiring NLO corrections to be small, or by looking where the sensitivity to the scale is minimized



bad scale



good scale

Scale choice at NLO

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Reason: bad scale ➠ large logs ➠ large NLO, large scale dependence

But we also know that large NLO ~~➠~~ bad scale choice, since NLO corrections can have a “genuine” physical origin
(new channels opening up, Sudakov logarithms, color factors, large gluon flux ...)

Furthermore, double logarithmic corrections can never be absorbed by a choice of scale (single log). So a “stability criterion” can be misleading

Scale choice at LO

LO calculations in matrix elements generators that follow the CKKW procedure are quite sophisticated in the scale choice:

they use optimized/local scales at each vertex and Sudakov form factors at internal/external lines

Catani,Krauss, Kuehn, Webber ’01
extension to hh collisions ***Krauss ’02***

Reminder:
a Sudakov form factor encodes the probability of evolving from one scale to the next without branching above a resolution scale Q_0

Recap at CKKW procedure

The CKKW prescription in brief:

- use the k_t algorithm to reconstruct the most likely branching history
- evaluate each α_s at the local transverse momentum of the splitting
- for each internal line between nodes at scale Q_i and Q_j include a Sudakov form factor $\Delta_{ij}=D(Q_0,Q_i)/D(Q_0,Q_j)$ that encodes the probability of evolving from scale Q_i to scale Q_j without emitting. For external lines include the Sudakov factor $\Delta_i=D(Q_0,Q_i)$
- match to a parton shower to include radiation below Q_0

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Scale choice intertwined with inclusion of Sudakov form factors

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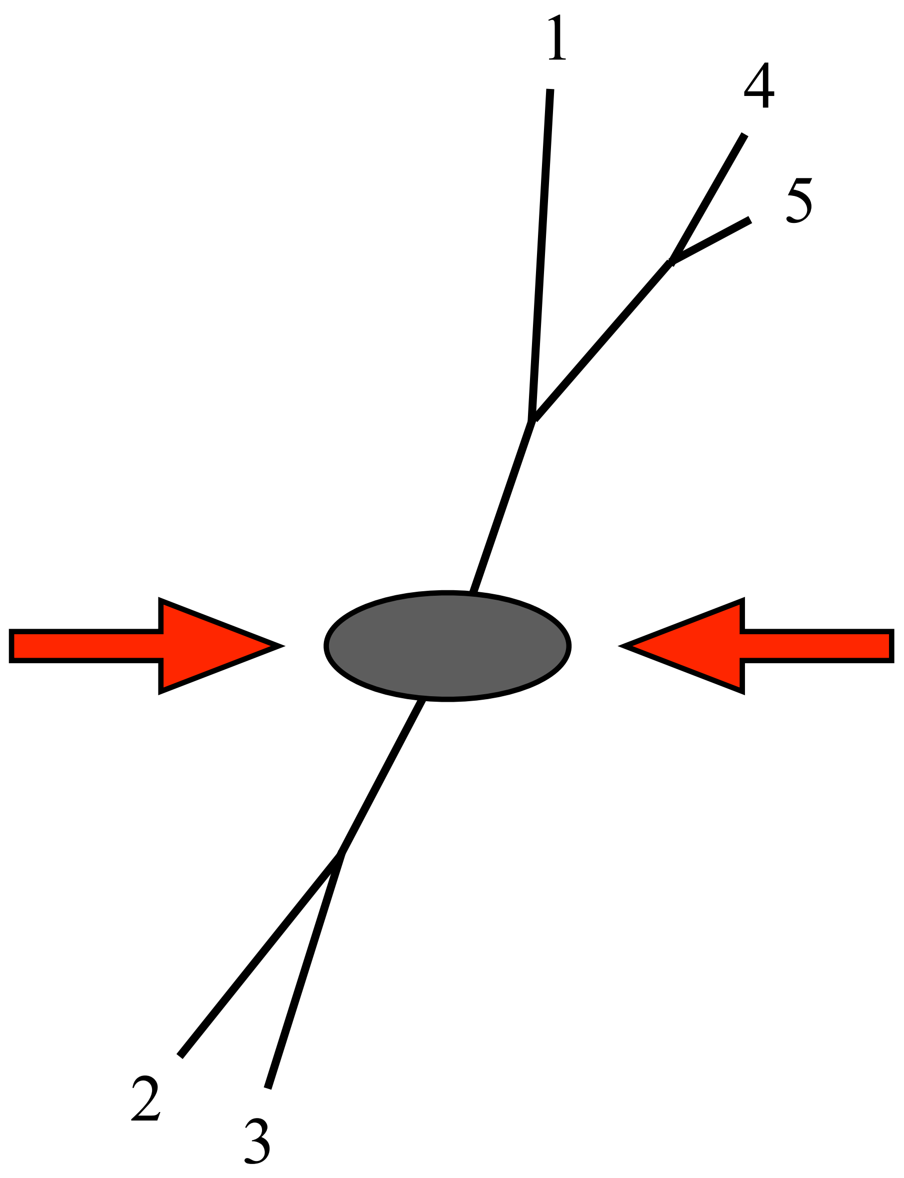

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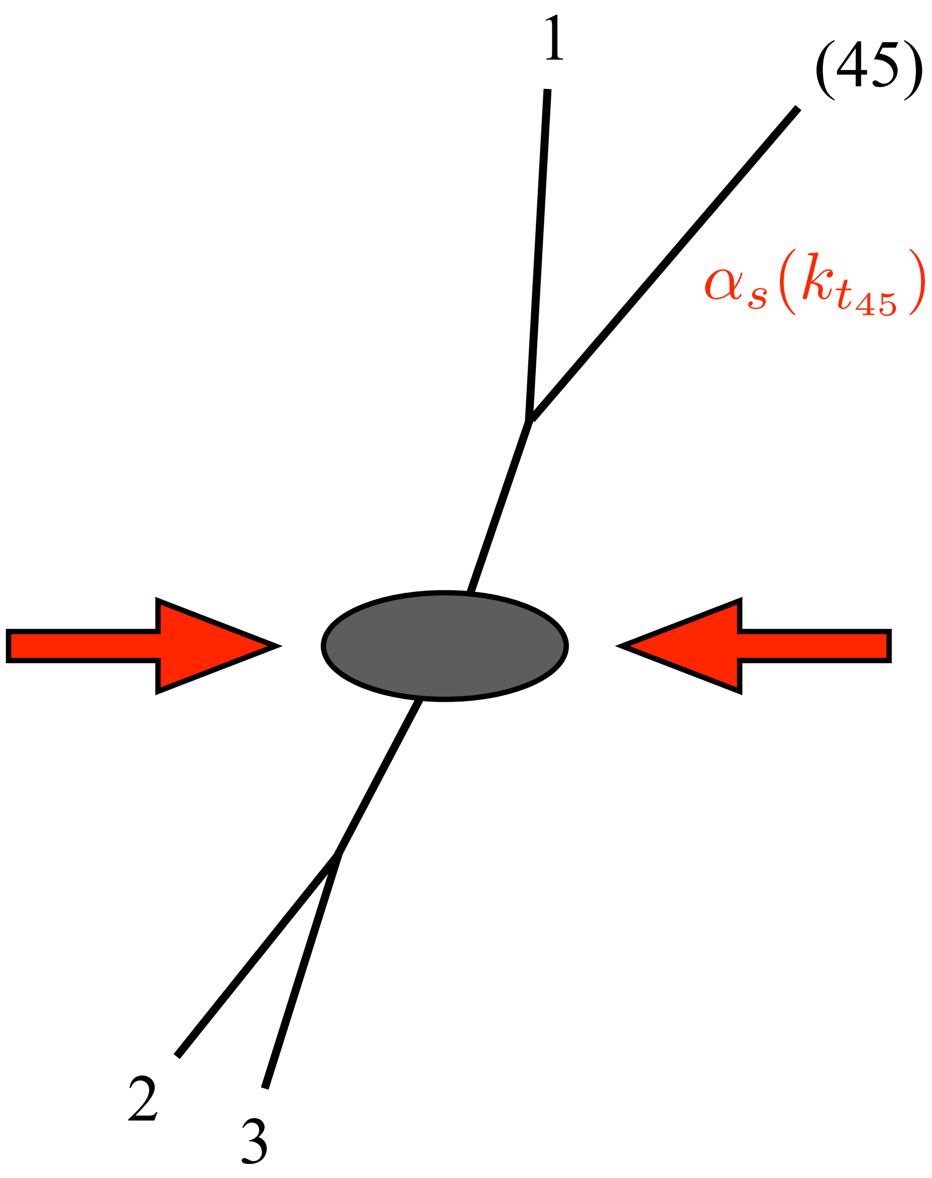

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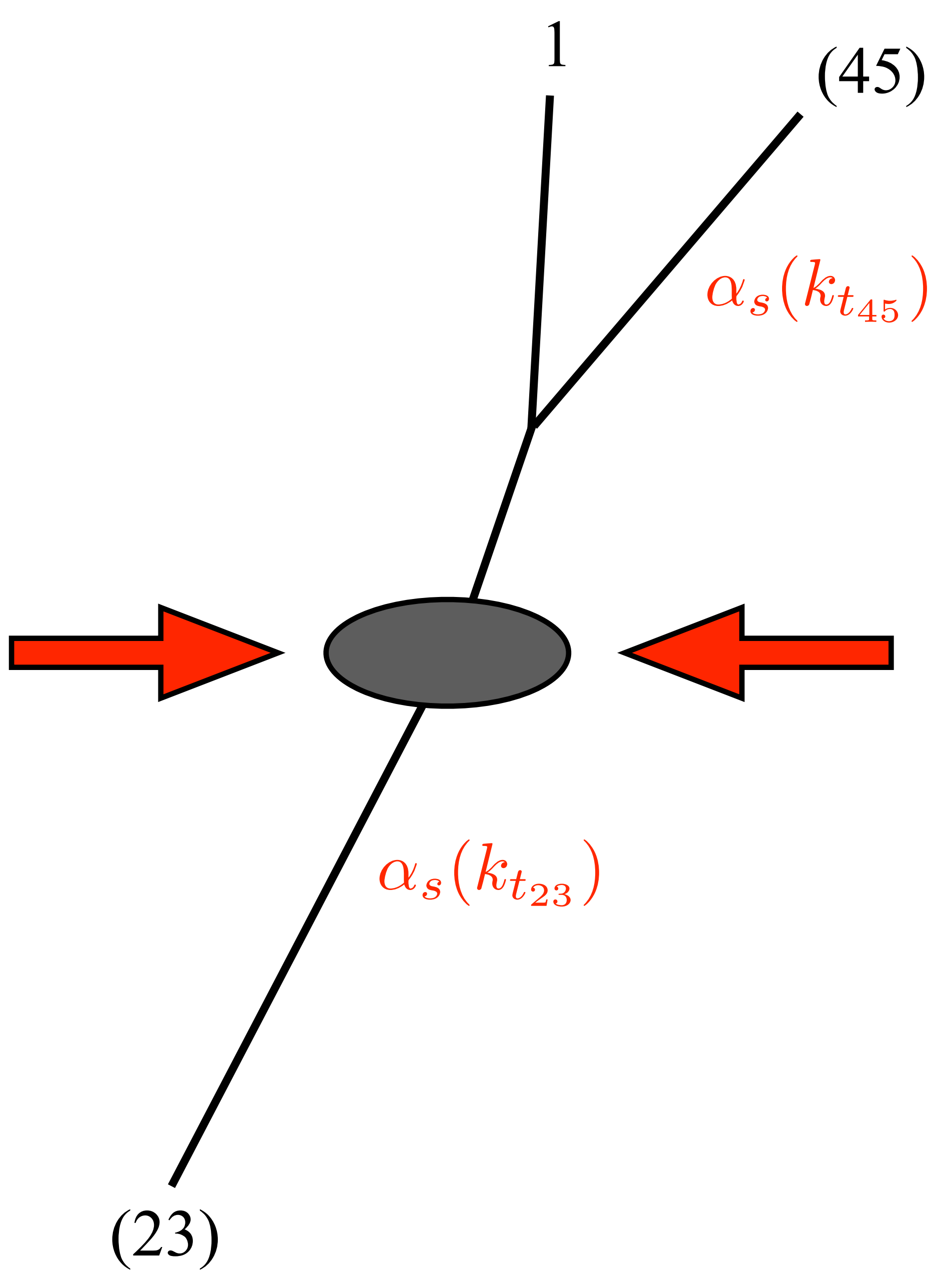

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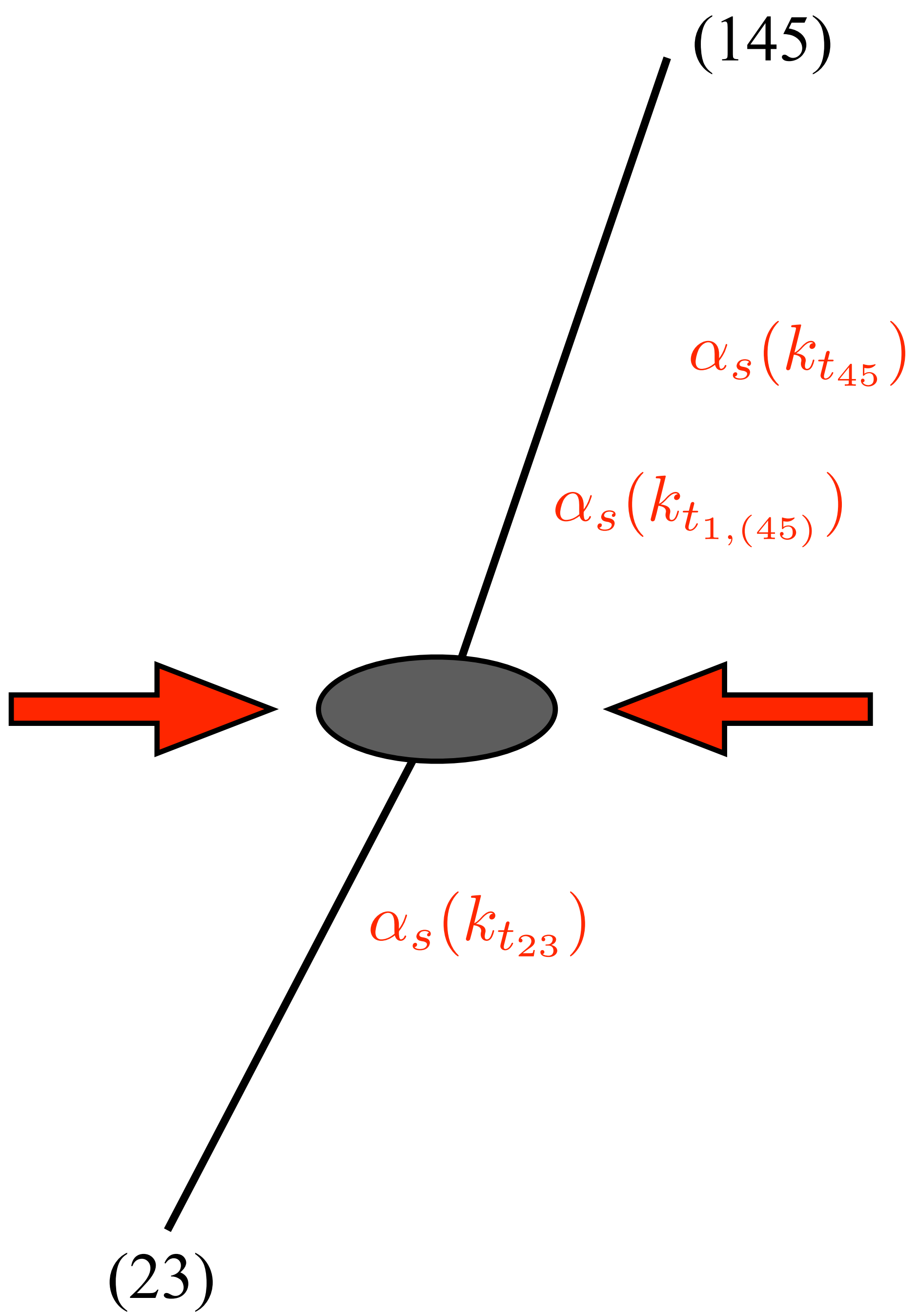

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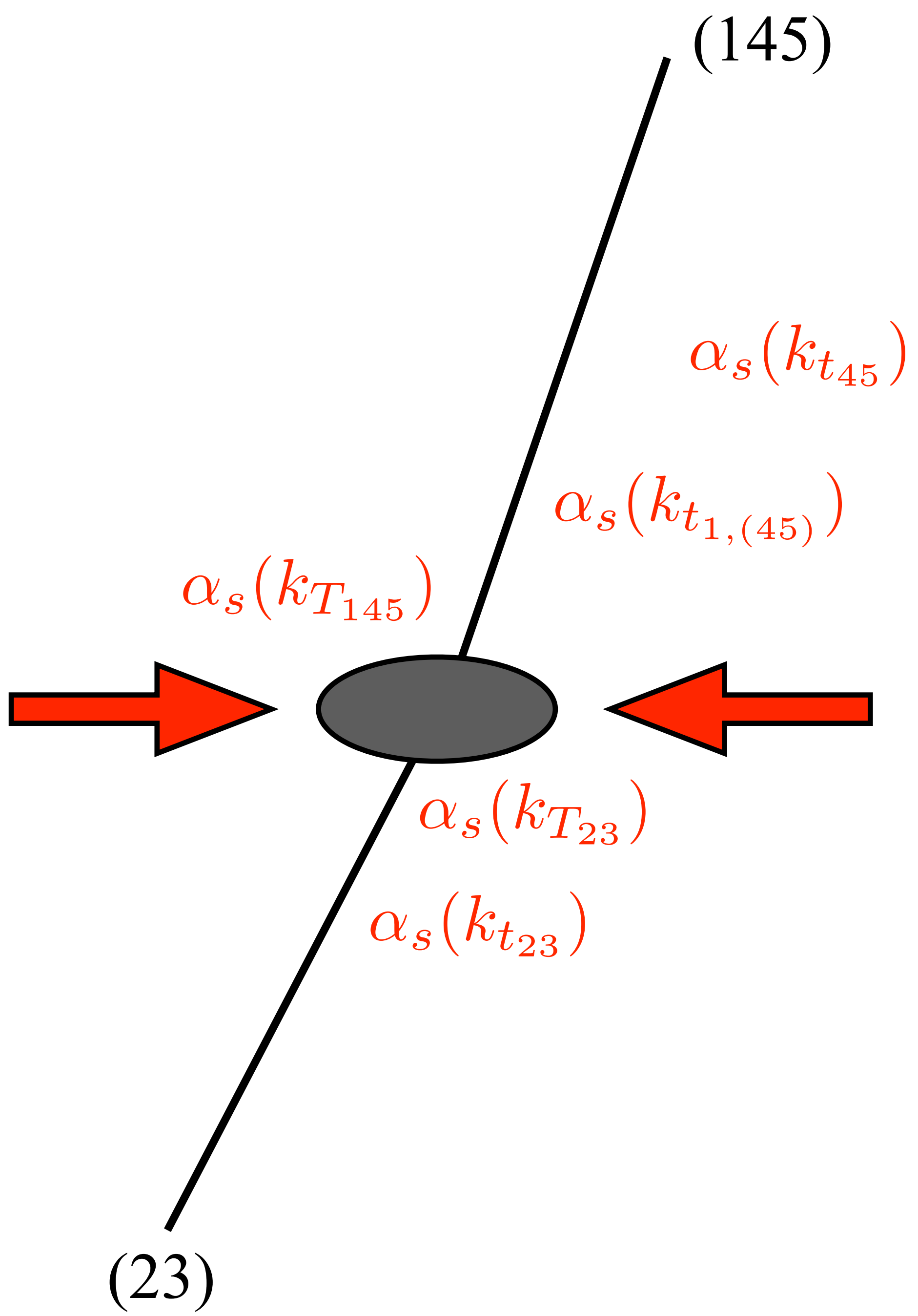

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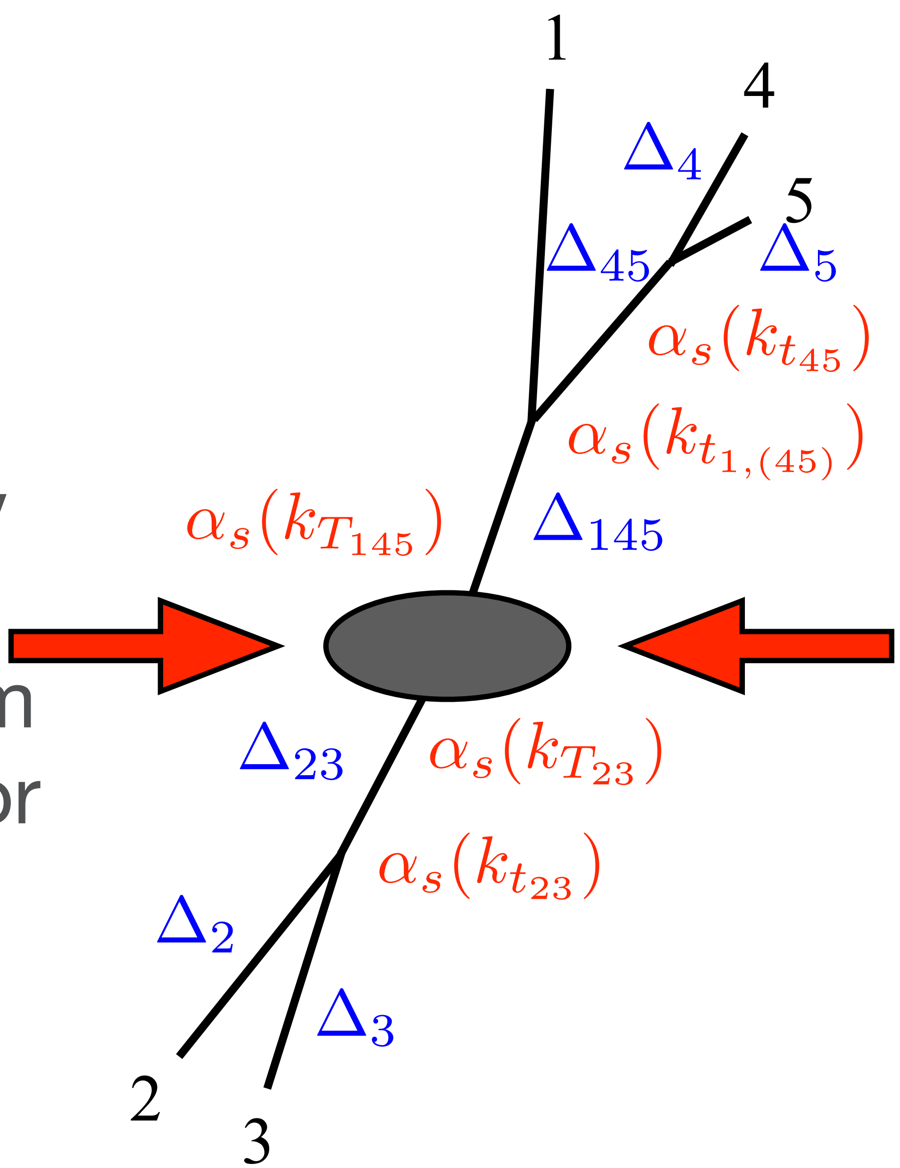

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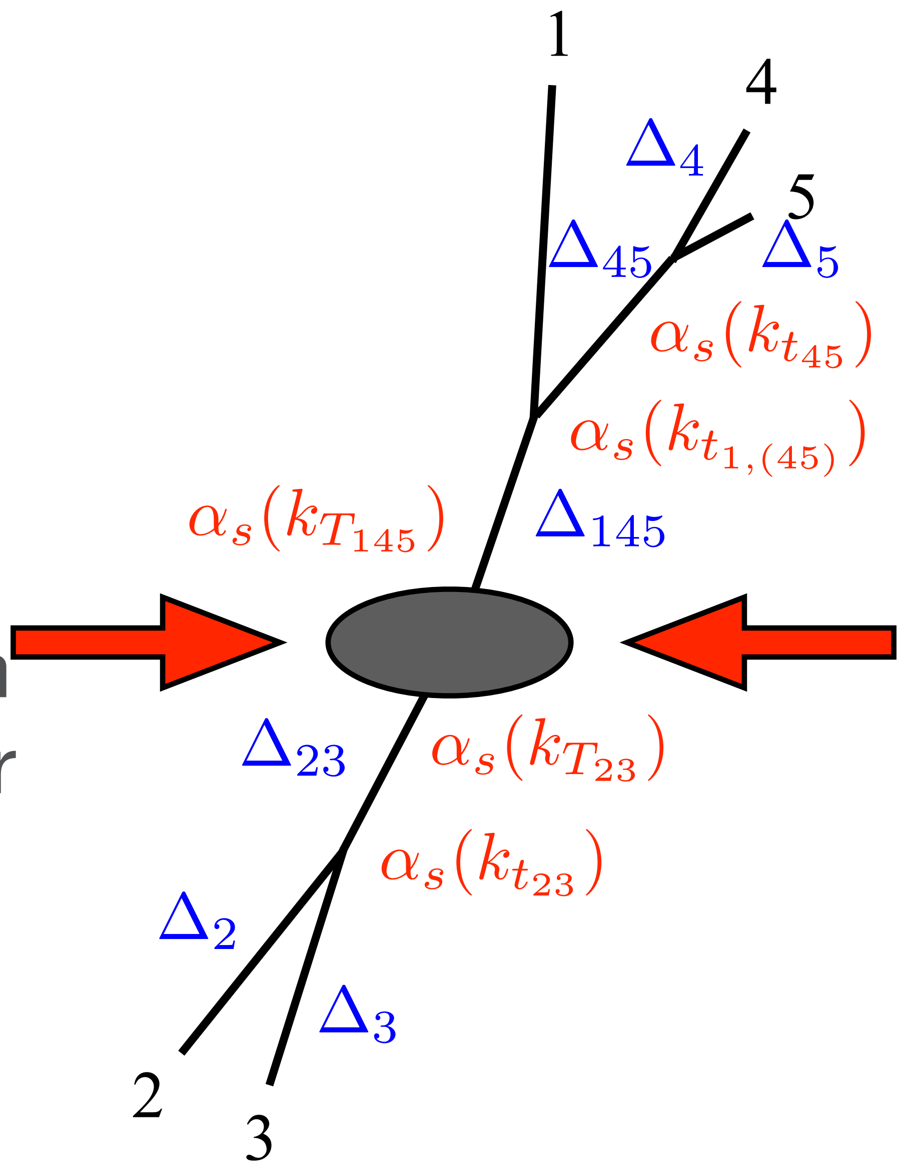

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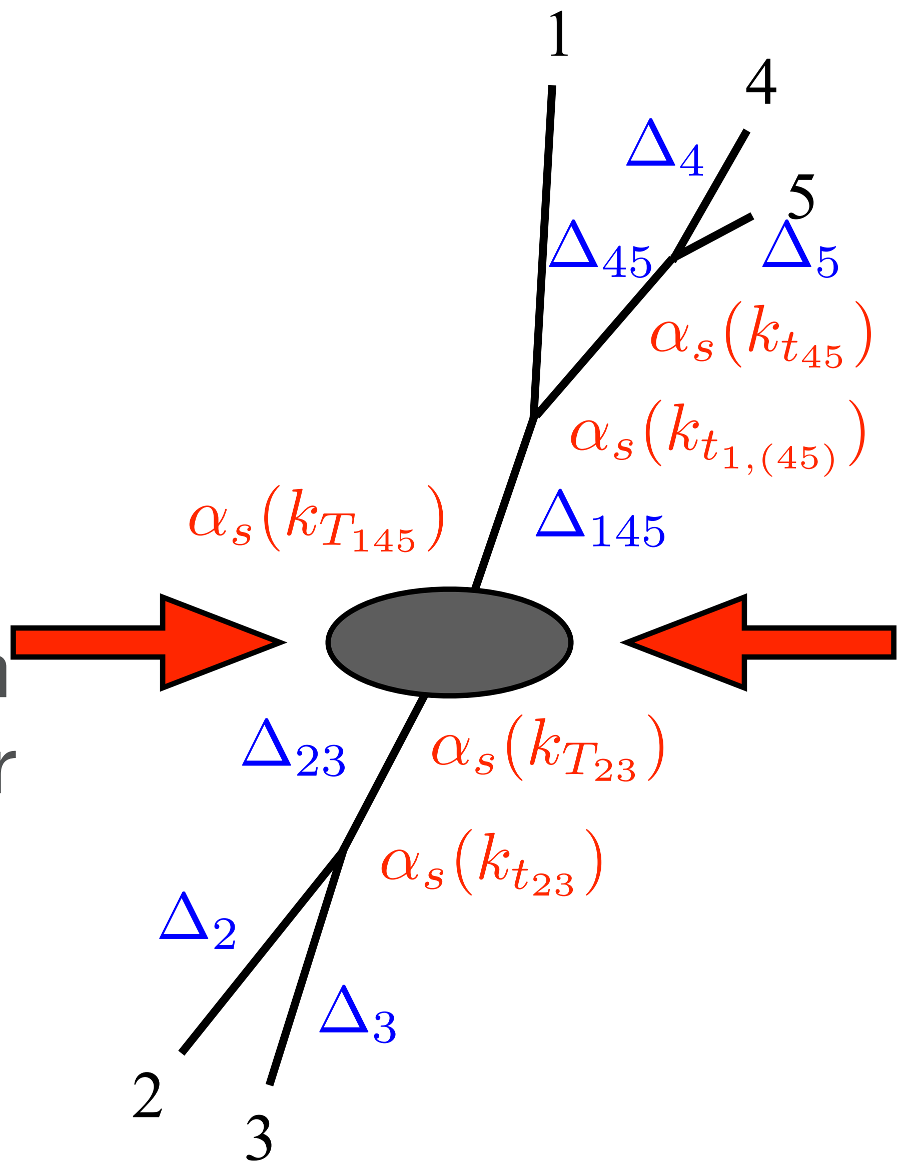


Scale choice intervened with inclusion of Sudakov form factors

MiNLO

MiNLO Born as an extension to NLO of the CKKW procedure, such that the procedure to fix the scales is unbiased and decided ***a priori***

In particular, the focus is on processes involving **many scales** (e.g. X+multi-jet production) and on soft/collinear branchings, i.e. on the region where it is more likely that associated jets are produced

Two observations

1. A generic NLO cross-section has the form

$$\alpha_S^n(\mu_R)\,B + \alpha_S^{n+1}(\mu_R)\left(V(Q) + n b_0 \log\frac{\mu_R^2}{Q^2} B(Q)\right) + \alpha_S^{n+1}(\mu_R)\,R$$

   Adopting CKKW scales at LO, this becomes naturally

$$\alpha_s(\mu_1)\dots\alpha_s(\mu_n)B + \alpha_s^{n+1}(\mu_R')\left(V(Q) + b_0 \log\frac{\mu_1^2\dots\mu_n^2}{Q^{2n}} B\right) + \alpha_s^{n+1}(\mu_R'')R$$

   and the scale choices μ_R’ and μ_R” are irrelevant for the scale cancelation

2. Sudakov corrections included at LO via the CKKW procedure lead to NLO corrections that need to be subtracted to preserve NLO accuracy

The MiNLO procedure

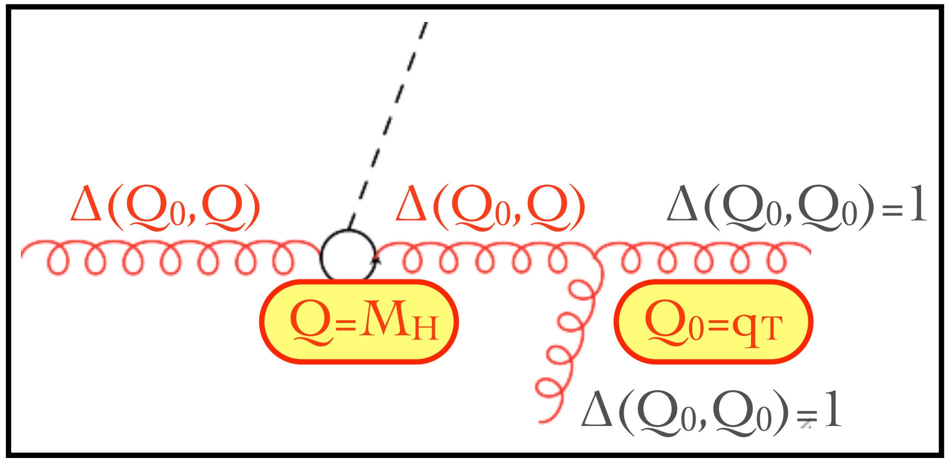
1. Find the CKKW n clustering scales $Q_1 < \ldots < Q_n$. Fix the hard scale of the process Q to the system invariant mass after clustering. Set Q_0 to Q_1 (inclusive on radiation below Q_1)
2. Evaluate the n coupling constants at the scales Q_i (times a factor to probe scale variation)
3. Set μ_R in the virtual to the geometric average of these scales and μ_F to the softest scale Q_1
4. Include Sudakov form factors for Born and virtual terms, and for the real term after the first branching
5. Subtract the NLO bit present in the CKKW Sudakov of the Born
6. Give a prescription for the $(n+1)^{th}$ power of α_s in the real and virtual terms

MiNLO in one equation

<u>Example:</u> take e.g. HJ

In POWHEG it is customary to discuss the $\bar{\mathrm{B}}$ function, which for HJ is defined as

$$\bar{B} = \alpha_s^3(\mu_R)\left[B + V(\mu_R) + \int d\Phi_{\rm rad}\, R\right]$$



With MiNLO this function becomes

$$\bar{B} = \alpha_s^2\left(M_H^2\right)\alpha_s\left(q_T^2\right)\Delta_g^2\left(M_H, q_T\right)\left[B\left(1 - 2\Delta_g^{(1)}\left(M_H, q_T\right)\right) + V(\mu') + \int d\Phi_{\rm rad}\, R\right]$$

Properties of MiNLO

MiNLO has the following properties

- the result is accurate at NLO, i.e. the scale dependence is NNLO
- the smooth behaviour of the CKKW scheme in the singular regions is preserved, in particular the X+n-jet cross-sections are finite even without jet cuts (do not need generation cuts or Born suppression factors)
- the procedure is simple to implement in any NLO calculation, i.e. the improvement requires only a very modest amount of work

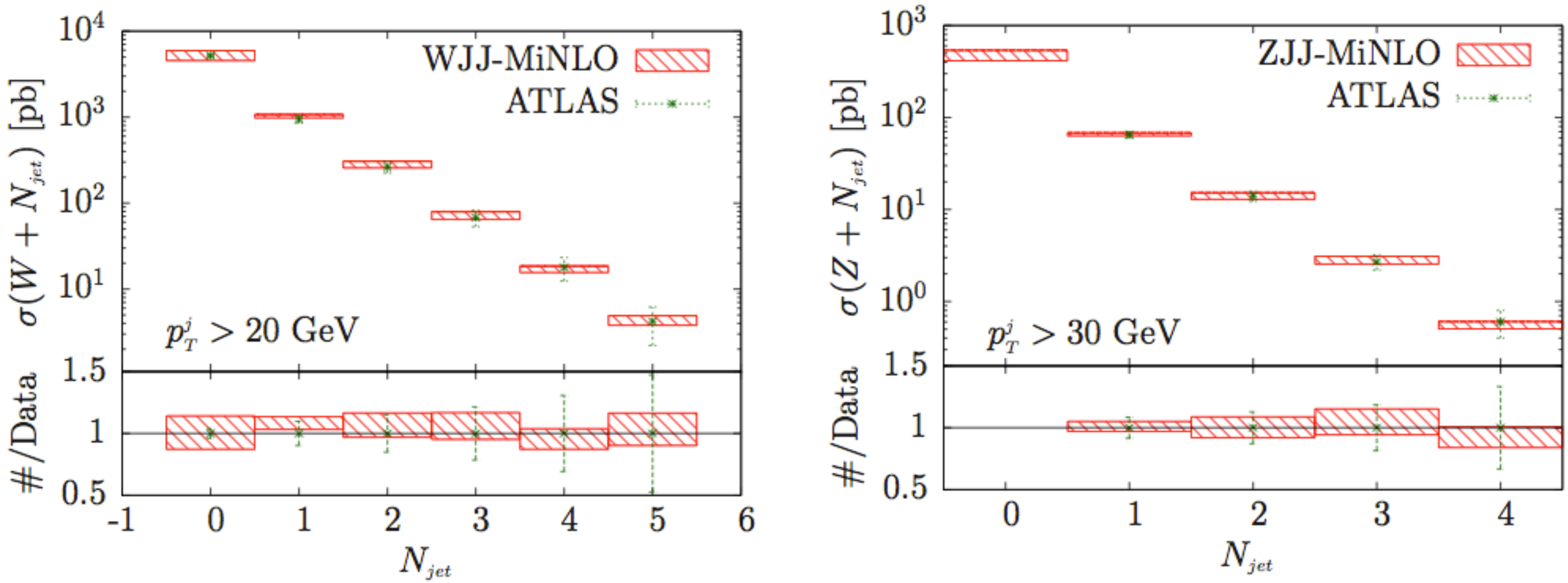
MiNLO applied to W/Z+2jets

We implemented W/Z + 2 jets in POWHEG, and compared the WJJ/ZJJ-MiNLO generators against ATLAS data from 0 to 5 jets

Campbell, Ellis, Nason, Zanderighi 1303.5447
Wjj also in Frederix et al. 1110.5502; Zjj in Re 1204.5433

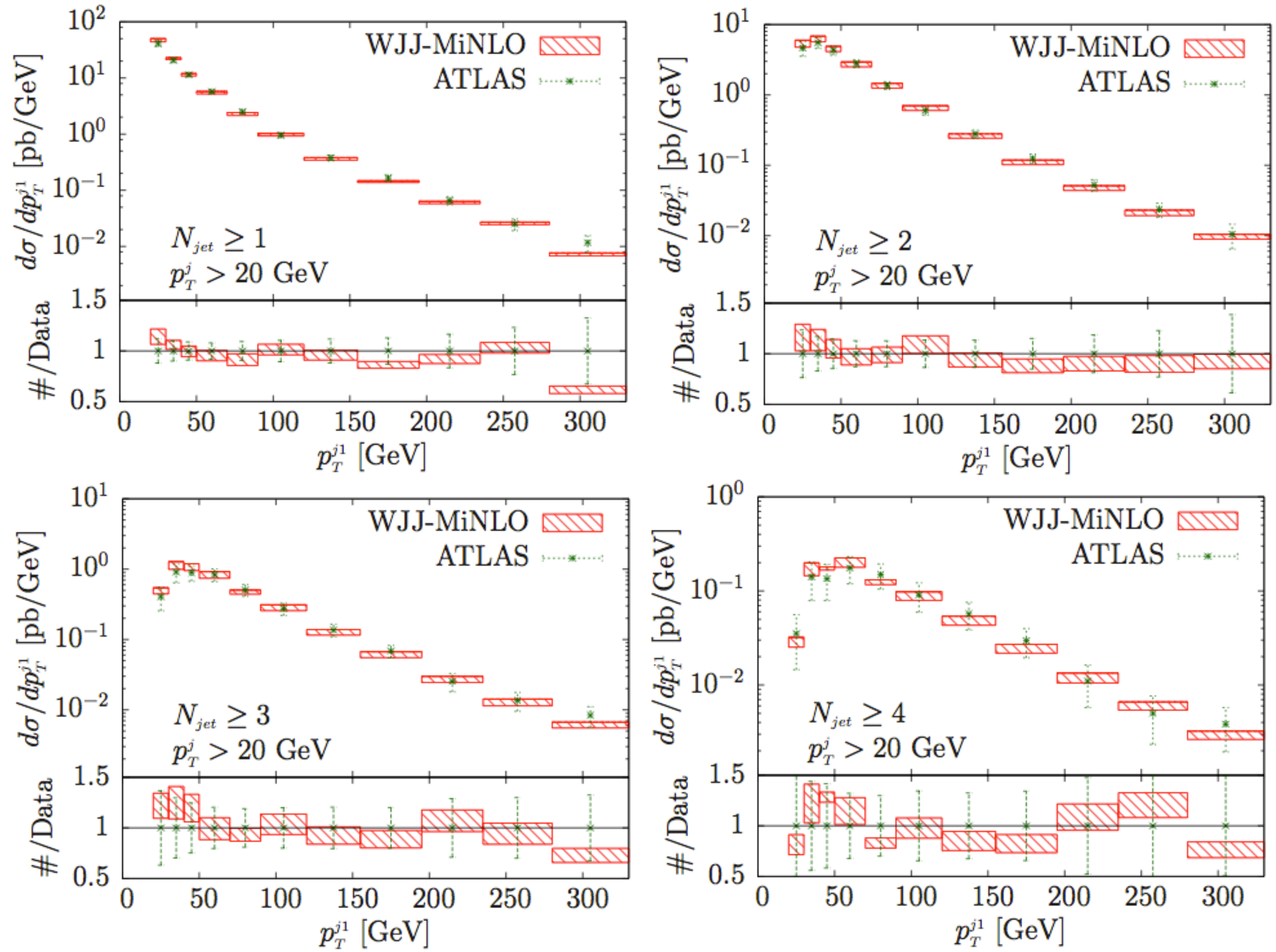
Cuts for W production
Jets defined using the anti-k_t algorithm ($R = 0.4$), with $p_t^{\min} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.4$;
One lepton required with $p_t^{(l)} > 20\,\mathrm{GeV}$, $\lvert\eta_l\rvert < 2.5$;
Lepton isolation required: ΔR_{lj} for all jets (as defined above) > 0.5;
One neutrino (missing E_t) required with $p_t^{(\nu)} > 25\,\mathrm{GeV}$;
Transverse mass constraint required: $\sqrt{2p_t^{(l)}p_t^{(\nu)}(1-\cos\phi_{l,\nu})} > 40\,\mathrm{GeV}$;
Events are classified according to the number of jets, as defined above.

MiNLO-VJJ versus data



Results out of the box. Nothing has been tuned here.

MiNLO-VJJ versus data



All comparison with data very good (many more plots in 1303.5447)

Merging with MiNLO

Hamilton et al. 1212.4504

We have shown that it is possibly to modify the original MiNLO procedure in such a way that the H+1jet (or Drell+Yan +1 jet) calculation, upgraded with MiNLO, is NLO accurate also for fully inclusive quantities
[e.g. you can look at the Higgs transverse momentum or Higgs rapidity (without any jet cut) and will get NLO accurate results]

This means that MiNLO on H+1jet merges the H+1jet and the inclusive Higgs calculations without using any merging scale (unlike most other approaches)

Sketch of the proof

Hamilton et al. 1212.4504

NNLL$_\Sigma$ Higgs q_T resummation at fixed rapidity can be written as

$$\frac{d\sigma}{dy dq_T^2} = \sigma_0 \frac{d}{dq_T^2}\Big\{ \left[C_{ga} \otimes f_{a/A}\right](x_A, q_T) \times \left[C_{gb} \otimes f_{b/B}\right](x_B, q_T) \times \exp \mathcal{S}(Q, q_T)\, \mathcal{F} \Big\} + R_f$$

Integrating in q_T one gets

$$\frac{d\sigma}{dy} = \sigma_0 \left[C_{ga} \otimes f_{a/A}\right](x_A, Q) \times \left[C_{gb} \otimes f_{b/B}\right](x_B, Q) + \int dq_T^2\, R_f + \dots$$

i.e. the formula is NLO$^{(0)}$ accurate if O(α_s) corrections to the coefficient functions are included and R_f is LO$^{(1)}$ accurate

Now, need to show that if the derivative is taken explicitly, and some higher orders are neglected, NLO$^{(0)}$ accuracy is maintained.

Sketch of the proof

Hamilton et al. 1212.4504

Generic form of the Sudakov form factor (at next-to-leading log)

$$e^{\mathcal{S}(Q,Q_0)} = e^{-\int_{Q_0^2}^{Q^2} \frac{dq^2}{q^2} A(\alpha_s(q^2)) \ln \frac{Q^2}{q^2} + B(\alpha_s(q^2))}$$

where the functions A and B can be expanded in powers of the coupling constant

$$A(\alpha_s) = \sum_{i=1}^{\infty} A_i \alpha_s^i \qquad B(\alpha_s) = \sum_{i=1}^{\infty} B_i \alpha_s^i$$

Sketch of the proof

Hamilton et al. 1212.4504

So, taking the derivative one gets

$$\sigma_0 \frac{1}{q_T^2} \left[\alpha_s,\, \alpha_s^2,\, \alpha_s^3,\, \alpha_s^4,\, \alpha_s L,\, \alpha_s^2 L,\, \alpha_s^3 L,\, \alpha_s^4 L\right] \exp \mathcal{S}\left(Q, q_T\right)$$

Sketch of the proof

Hamilton et al. 1212.4504

So, taking the derivative one gets

$$\sigma_0 \frac{1}{q_T^2} \left[\underbrace{\alpha_s}_{B_1},\, \alpha_s^2,\, \alpha_s^3,\, \alpha_s^4,\, \alpha_s L,\, \alpha_s^2 L,\, \alpha_s^3 L,\, \alpha_s^4 L\right] \exp \mathcal{S}\left(Q, q_T\right)$$

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Hamilton et al. 1212.4504

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$$\sigma_0 \frac{1}{q_T^2} \left[\underbrace{\alpha_s}_{B_1}, \underbrace{\alpha_s^2}_{B_2}, \alpha_s^3, \alpha_s^4, \alpha_s L, \alpha_s^2 L, \alpha_s^3 L, \alpha_s^4 L\right] \exp \mathcal{S}(Q, q_T)$$

Sketch of the proof

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So, taking the derivative one gets

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Sketch of the proof

Hamilton et al. 1212.4504

So, taking the derivative one gets

$$\sigma_0 \frac{1}{q_T^2} \left[\underset{B_1}{\alpha_s}, \underset{B_2}{\alpha_s^2}, \underset{\cdots}{\alpha_s^3}, \alpha_s^4, \underset{A_1}{\alpha_s L}, \alpha_s^2 L, \alpha_s^3 L, \alpha_s^4 L\right] \exp \mathcal{S}\left(Q, q_T\right)$$

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B_1 B_2 $\cdots$ $A_1 \cdots$

Sketch of the proof

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So, taking the derivative one gets

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$B_1 \quad B_2 \quad \cdots \quad A_1 \cdots \quad C_1 \otimes C_1 \otimes A_1$

Sketch of the proof

Hamilton et al. 1212.4504

So, taking the derivative one gets

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$$B_1 \quad B_2 \quad \cdots \quad A_1 \cdots \quad C_1 \otimes C_1 \otimes A_1 \quad \cdots$$

After integration with the Sudakov weight, the counting is set by $L \sim dL \sim 1/\sqrt{\alpha_s}$. So these terms contribute, e.g.

$$\sigma_0 \int dL \left[\alpha_s, \alpha_s^2, \alpha_s^3, \alpha_s^4, \alpha_s L, \alpha_s^2 L, \alpha_s^3 L, \alpha_s^4 L \right] \exp \mathcal{S}(Q, q_T)$$

Need B_2 in Sudakov to reach NLO$^{(0)}$ accuracy

$\mathcal{O}(\alpha_s^{3/2})$

$\mathcal{O}(\alpha_s^2)$

All higher order terms can be safety dropped maintaining NLO$^{(0)}$ accuracy

Sketch of the proof

Hamilton et al. 1212.4504

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$\mathcal{O}(\alpha_s^2)$

All higher order terms can be safety dropped maintaining NLO$^{(0)}$ accuracy

Similarly, the scale in V and R gives the largest difference in the α_s^2L term, where they give an α_s^3L^2 variation. This contributes O($\alpha_s^{3/2}$). So an effect of the same size to B_2.

Q.E.D.

Hamilton et al. 1212.4504

Conclusion:

☛ The original MiNLO prescription is less than NLO accurate in the description of inclusive quantities, in that it neglects O($\alpha_s^{3/2}$) terms

☛ achieve NLO accuracy from HJ also for inclusive Higgs observables by

✔ including the B_2 term in the Sudakov form factors

✔ taking the scale in the coupling constant in the real, virtual and subtraction terms equal to the Higgs transverse momentum

Provided this is done, the HJ describes both H and H+j at NLO, i.e. merging of H and HJ is effectively achieved without doing any merging

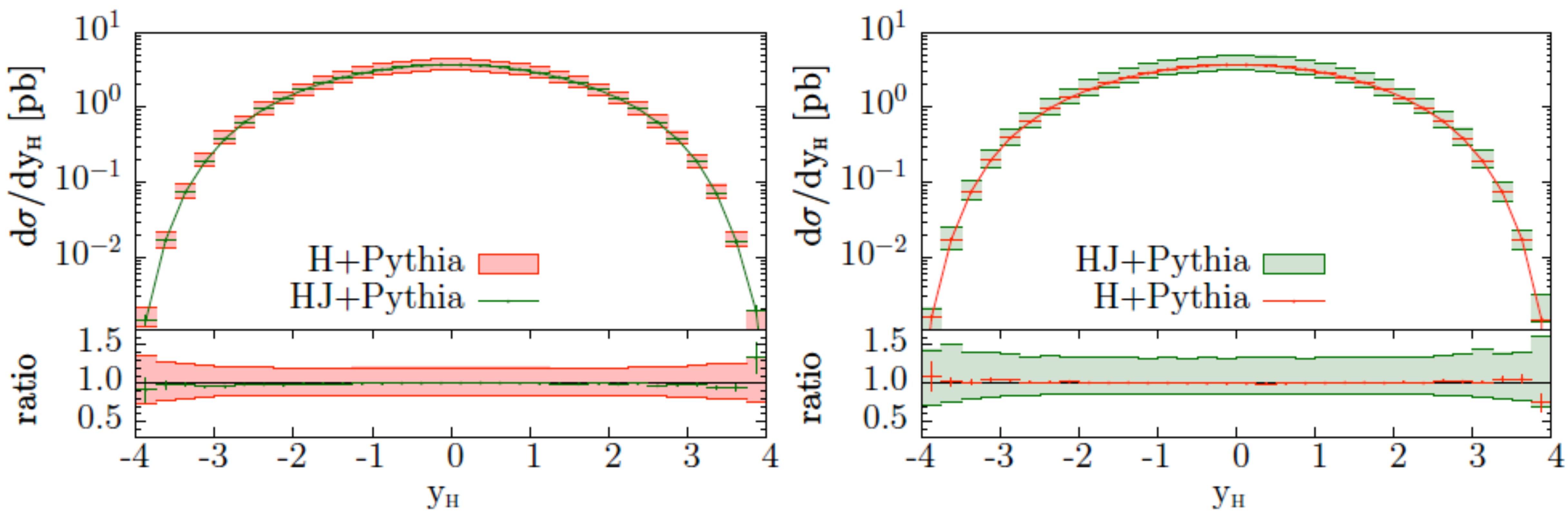
NB: thus unlike other approaches, no merging scale is introduced

Merging with MiNLO

Hamilton et al. 1212.4504

Sample results for Higgs (sample Z/W results also available)

Higgs rapidity:



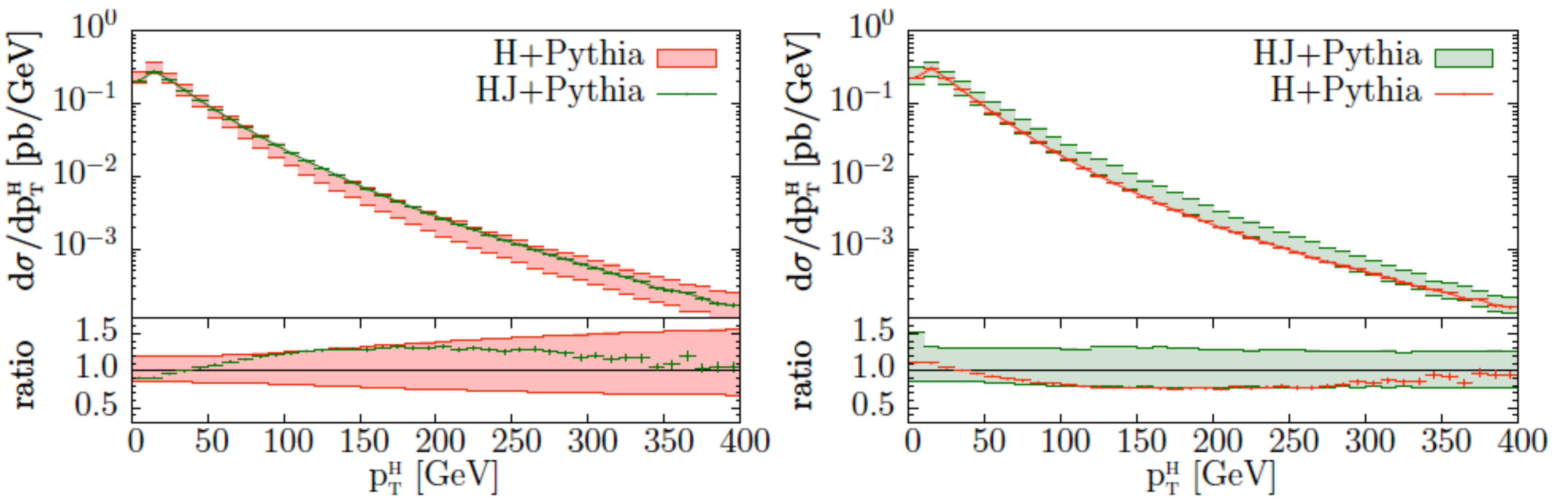
Nice agreement between standard Higgs NLO result and HJ-MiNLO

Merging with MiNLO

Hamilton et al. 1212.4504

Sample results for Higgs (sample Z/W results also available)

Higgs transverse momentum:



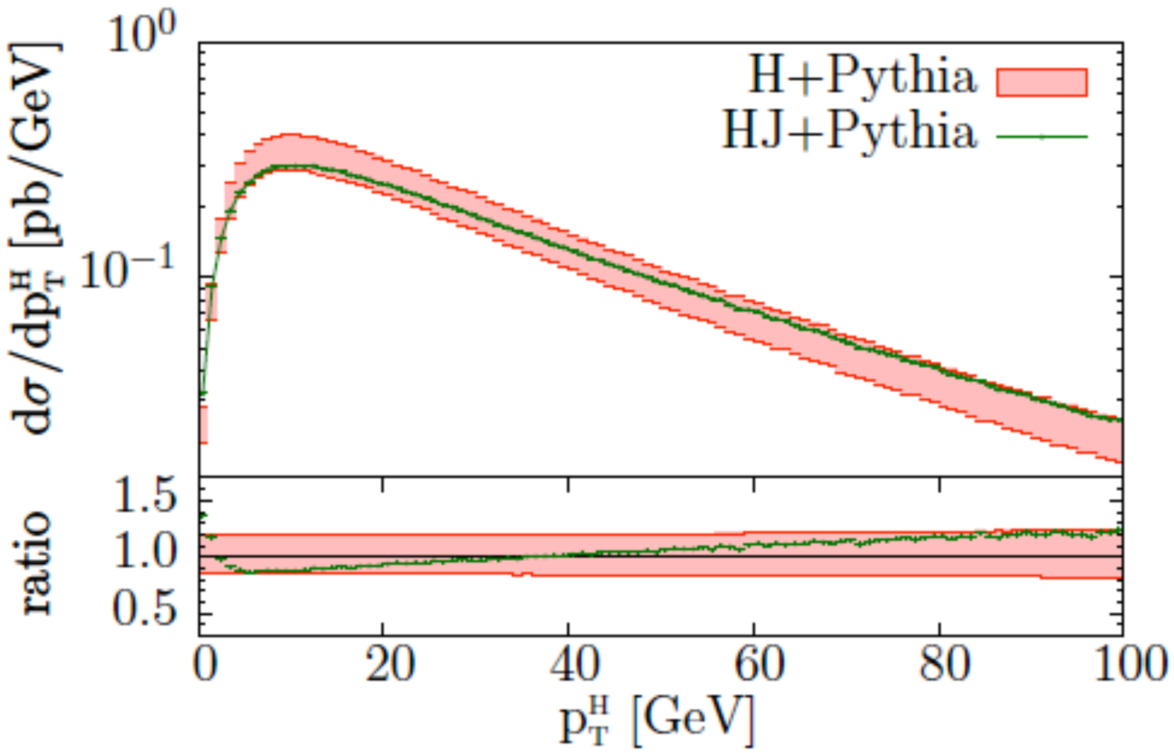
Nice agreement at intermediate values. At high transverse momenta H calculation is only LO accurate (band widens). HJ-MiNLO remains NLO accurate

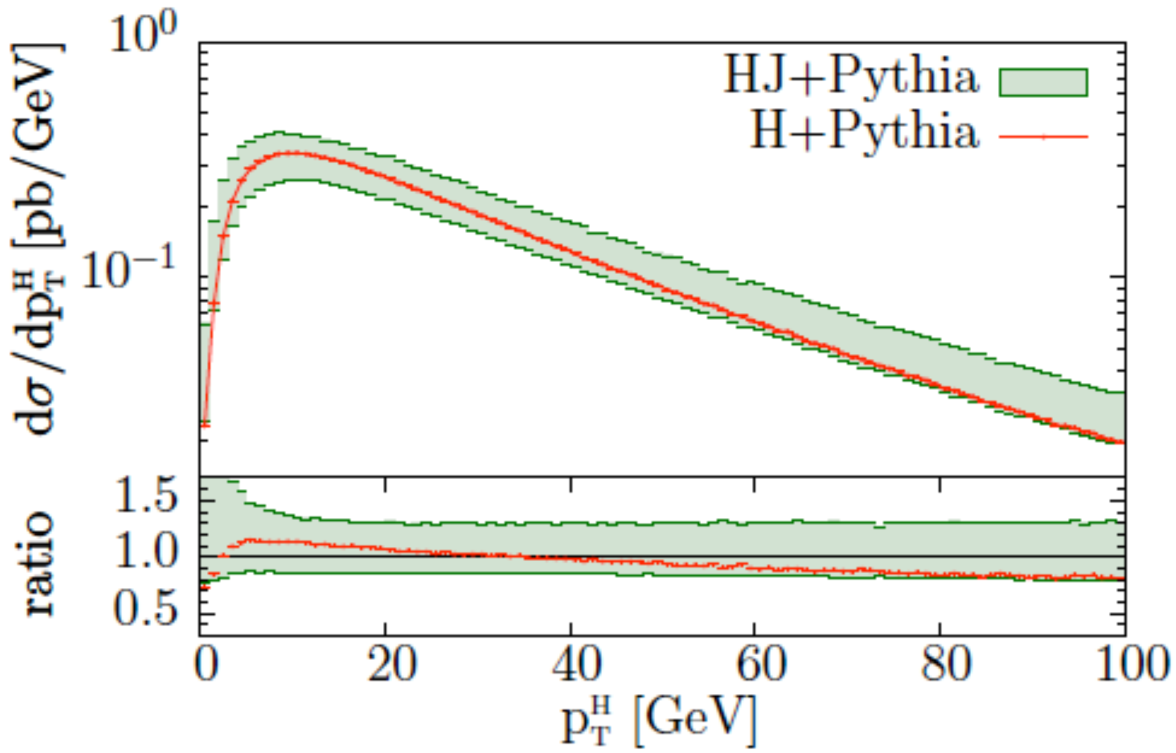
Merging with MiNLO

Hamilton et al. 1212.4504

Sample results for Higgs (sample Z/W results also available)

Higgs transverse momentum:





Nice agreement at intermediate values. At small transverse momenta HJ-MiNLO band widens, as approaching strong coupling regime. H uncertainty not realistic (too small).

NNLOPS generator with MiNLO

Hamilton et al. 1309.0017

Consider the case of Higgs production

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

$\left(\frac{d\sigma}{dy}\right)_{\rm HJ-MiNLO}$ $\Longrightarrow$ inclusive Higgs rapidity from HJ-MINLO generator

Since HJ-MINLO is NLO accurate, it follows that

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

It is possible to use this reweighing factor to promote HJ-MiNLO to NNLO. Because the re-weighting factor is $1+O(\alpha_s^2)$ it does not spoil NLO accuracy (unlike usual re-weighting procedures)

NNLOPS generator with MiNLO

Hamilton et al. 1309.0017

Consider the case of Higgs production

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

$$\left(\frac{d\sigma}{dy}\right)_{\rm HJ-MiNLO} \Longrightarrow$$ inclusive Higgs rapidity from HJ-MINLO generator

Since HJ-MINLO is NLO accurate, it follows that

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

Thus, reweighing HJ-MINLO results with this factor one obtains NNLO+PS accuracy, exactly in the same way as MC@NLO or POWHEG are NLO+PS accurate

Variants

Hamilton et al. 1309.0017

It is possible to define variants of the method. One defines

$$d\sigma = d\sigma_A + d\sigma_B \qquad d\sigma_A = d\sigma \cdot h(p_T) \qquad d\sigma_B = d\sigma \cdot (1 - h(p_T))$$

with h a function between 1 and 0, e.g. $h(p_T) = \frac{(c\, m_H)^\gamma}{(c\, m_H)^\gamma + p_T^\gamma}$

And one can re-weight the HJ-MiNLO events with the factor

$$\mathcal{W}(y, p_T) = h(p_T) \frac{\int d\sigma_A^{\rm NNLO} \delta(y - y(\Phi))}{\int d\sigma_A^{\rm MiNLO} \delta(y - y(\Phi))} + (1 - h(p_T))$$

This ensures that

$$\boxed{\left(\frac{d\sigma}{dy}\right)^{\rm NNLOPS} = \left(\frac{d\sigma_A}{dy}\right)^{\rm NNLO} + \left(\frac{d\sigma_B}{dy}\right)^{\rm MiNLO}}$$

The idea is to distribute the virtual correction only in the low-p_t region (in the high p_t region no improvement)

Variants

Hamilton et al. 1309.0017

Alternatively, one might want to preserve the NNLO cross-section exactly. In that case, one can use a reweighting factor

$$\mathcal{W}(y, p_T) = h(p_T)\frac{\int d\sigma^{\mathrm{NNLO}}\delta(y - y(\Phi)) - \int d\sigma_B^{\mathrm{MiNLO}}\delta(y - y(\Phi))}{\int d\sigma_A^{\mathrm{MiNLO}}\delta(y - y(\Phi))} + (1 - h(p_T))$$

Which ensures that the NNLO cross-section is preserved exactly

$$\boxed{\left(\frac{d\sigma}{dy}\right)^{\mathrm{NNLOPS}} = \left(\frac{d\sigma}{dy}\right)^{\mathrm{NNLO}}}$$

Uncertainty definition

Vary

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

Take the envelope of the 21 scale choices

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

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

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

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

  ✓ rapidity of the Z boson y_Z

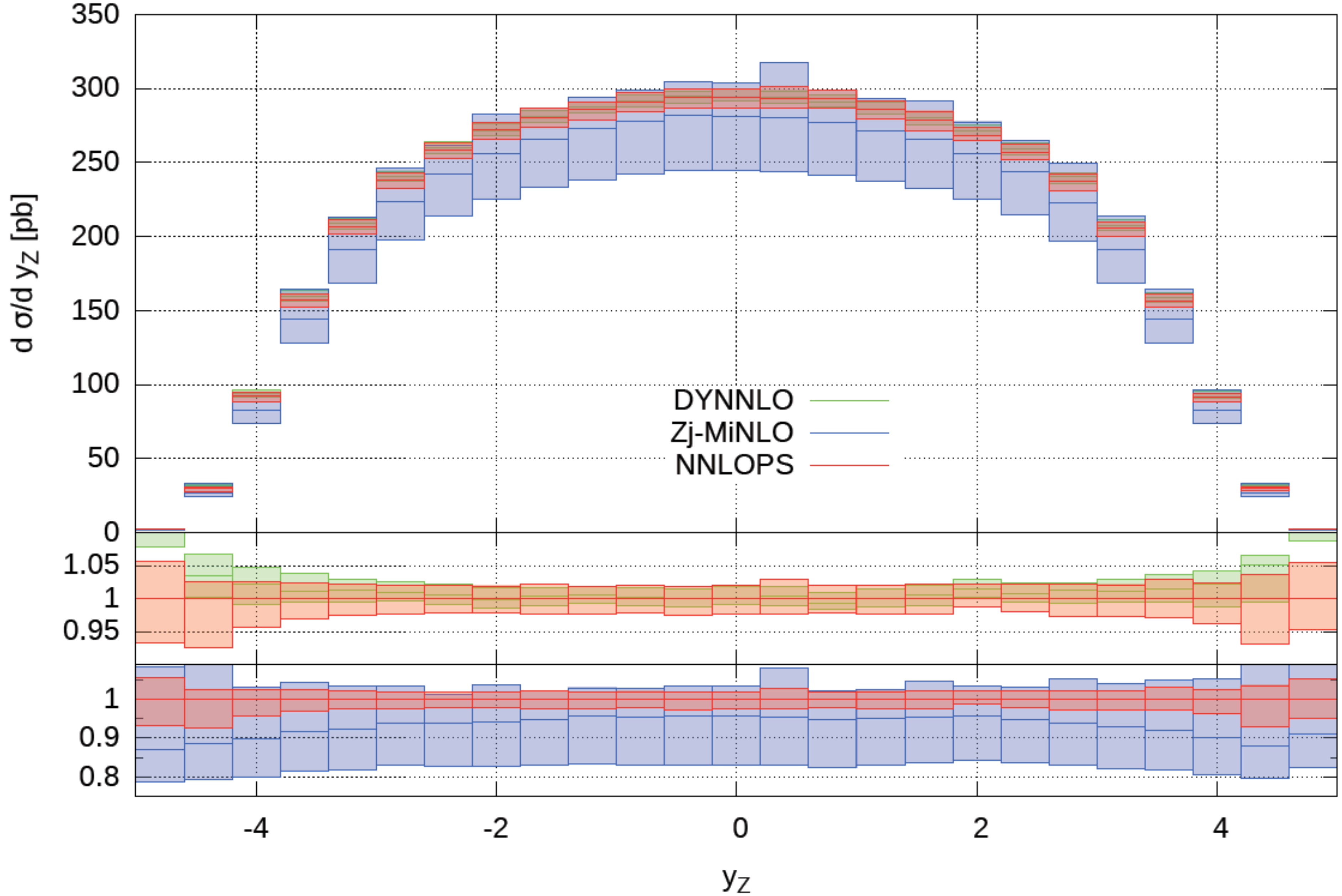
  ✓ angle between electron and beam in frame where $p_{l,Z}=0$

  ✓ variable related to dilepton-invariant mass $\mathrm{atan}((m_{ll}^2-M_Z^2)/\Gamma_Z M_Z)$

DY at NNLOPS: see also Hoche, Hi and Prestel 1405.3607

Drell Yan at NNLOPS

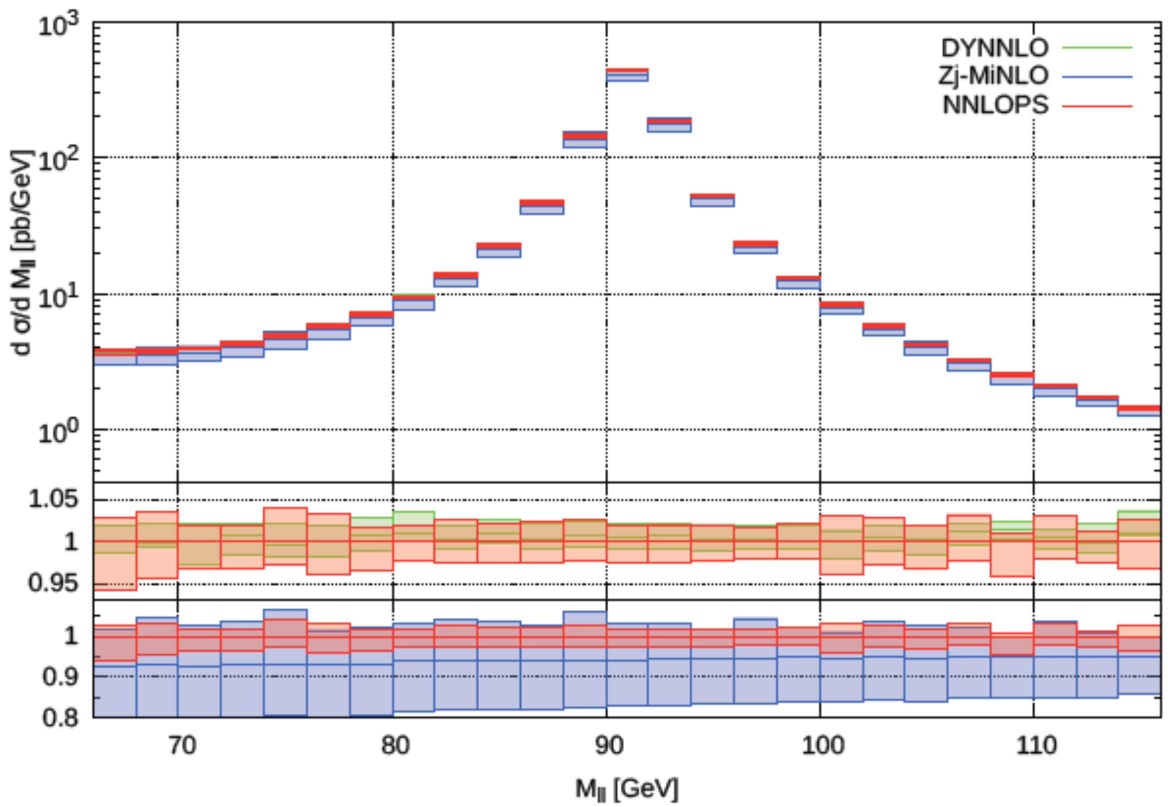
Karlberg, Re, Zanderighi preliminary

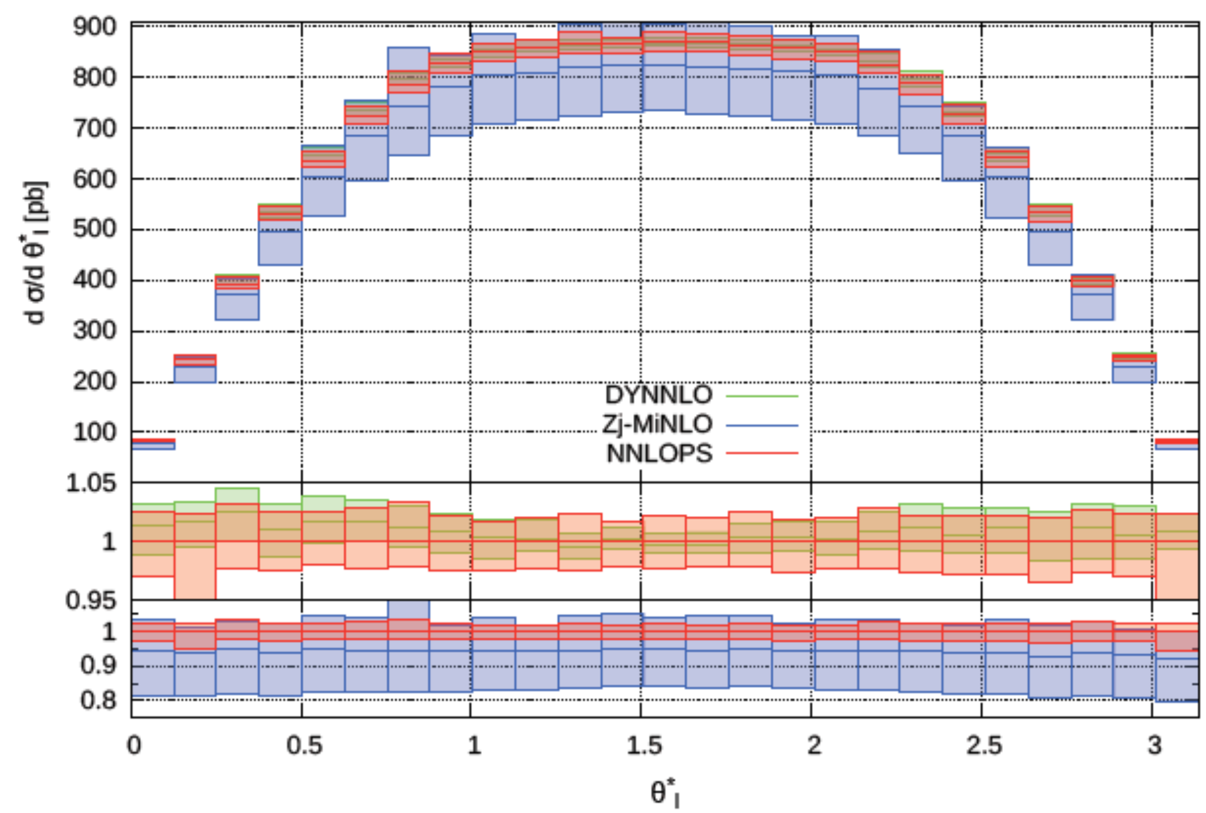


- agreement with DYNNLO (validation)
- reduction of uncertainty wrt to ZJ+MiNLO

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary





- agreement with DYNNLO (validation)
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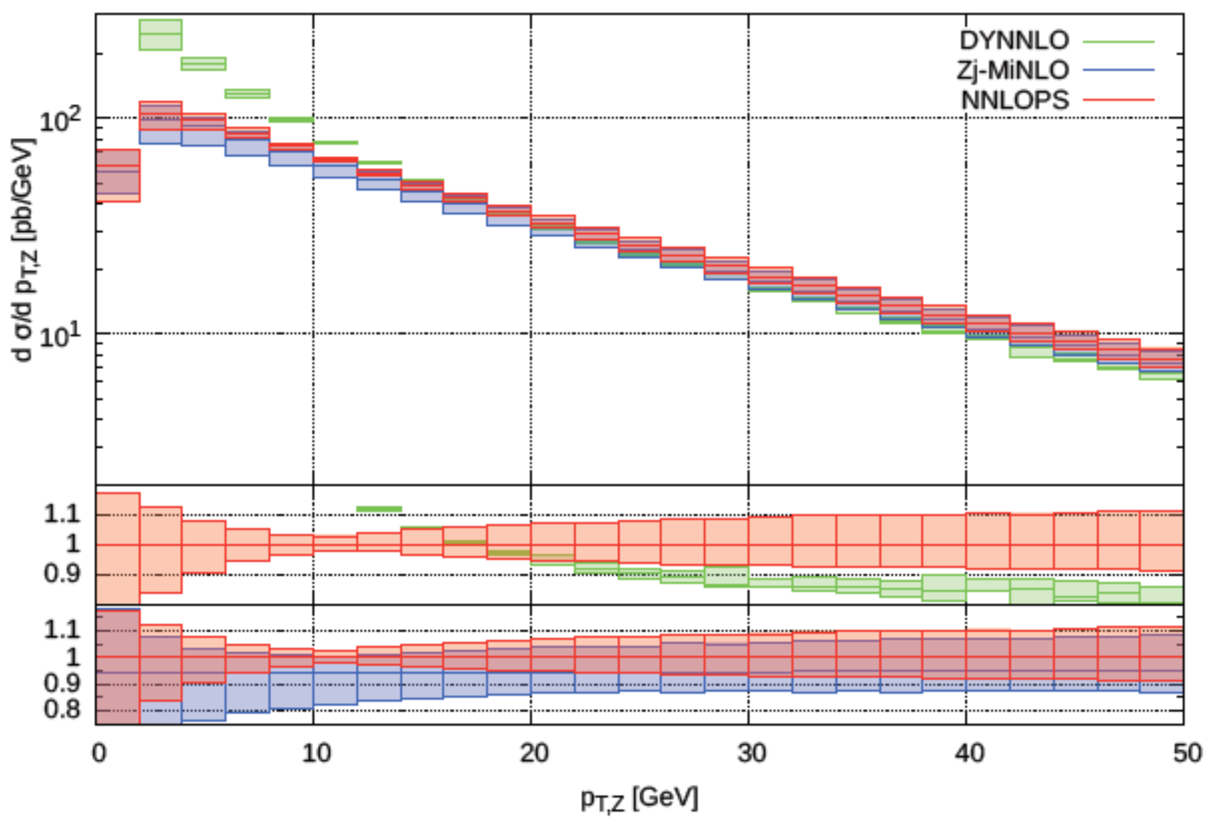
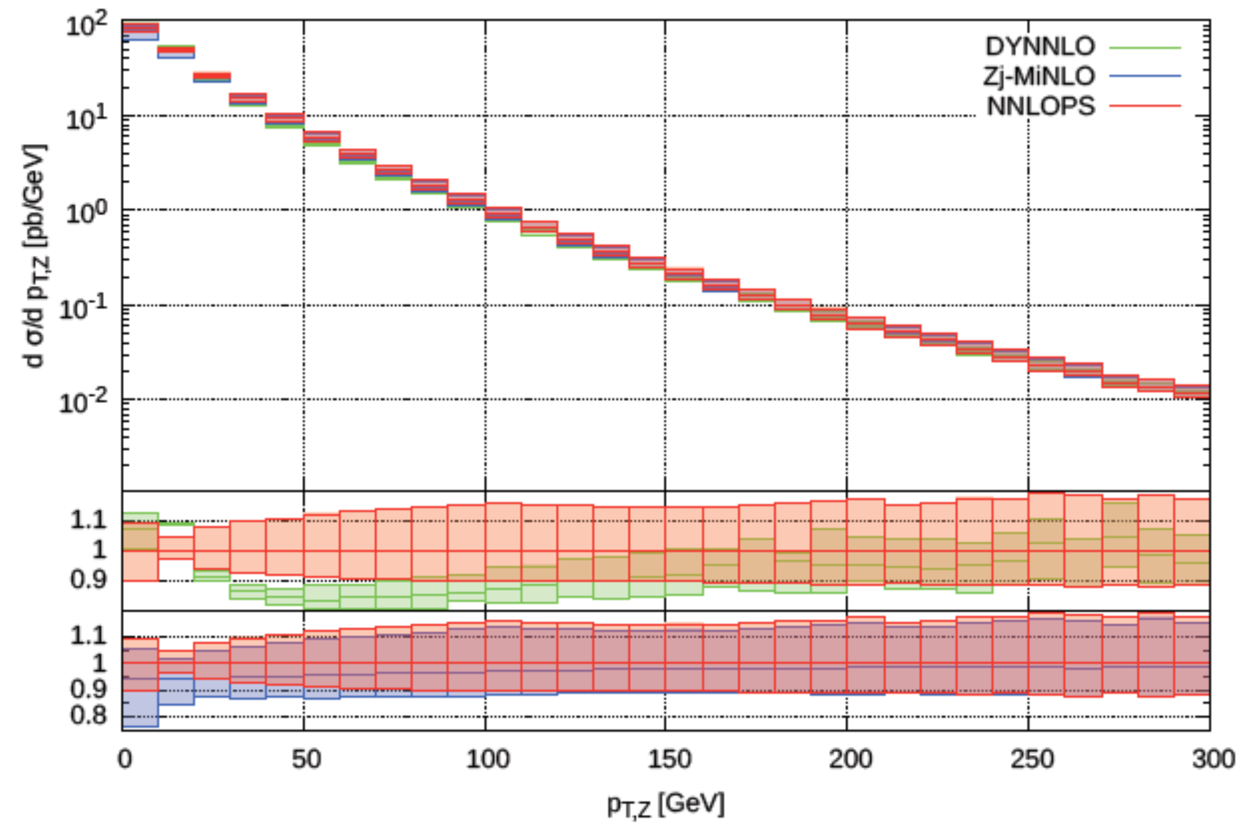
Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary



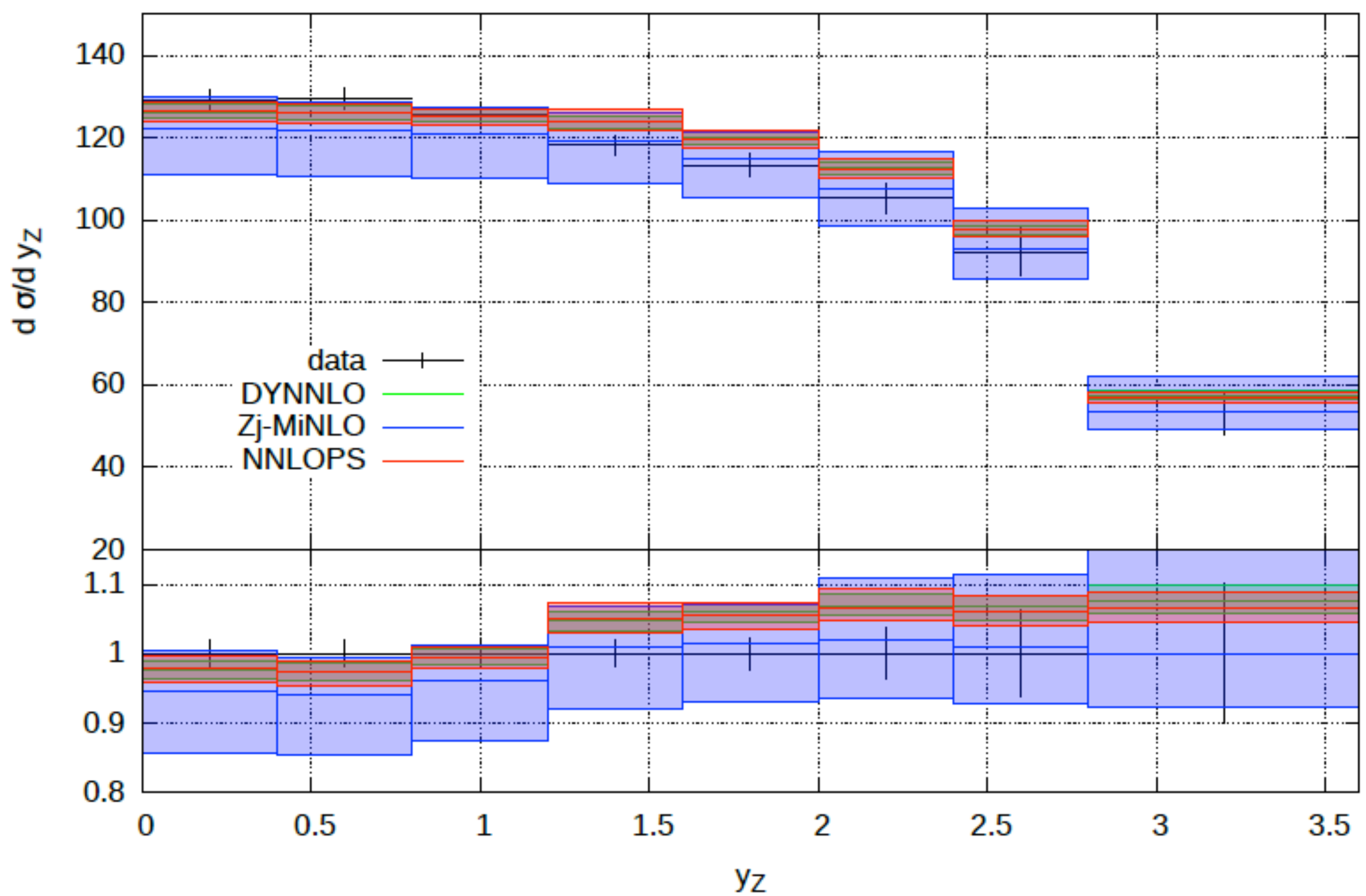


- NNLOPS smooth behavior where DYNNLO diverges
- DYNNLO uncertainty too small at low p_t
- at high p_t all calculations comparable

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

Comparison to data [ATLAS 1109.5141]

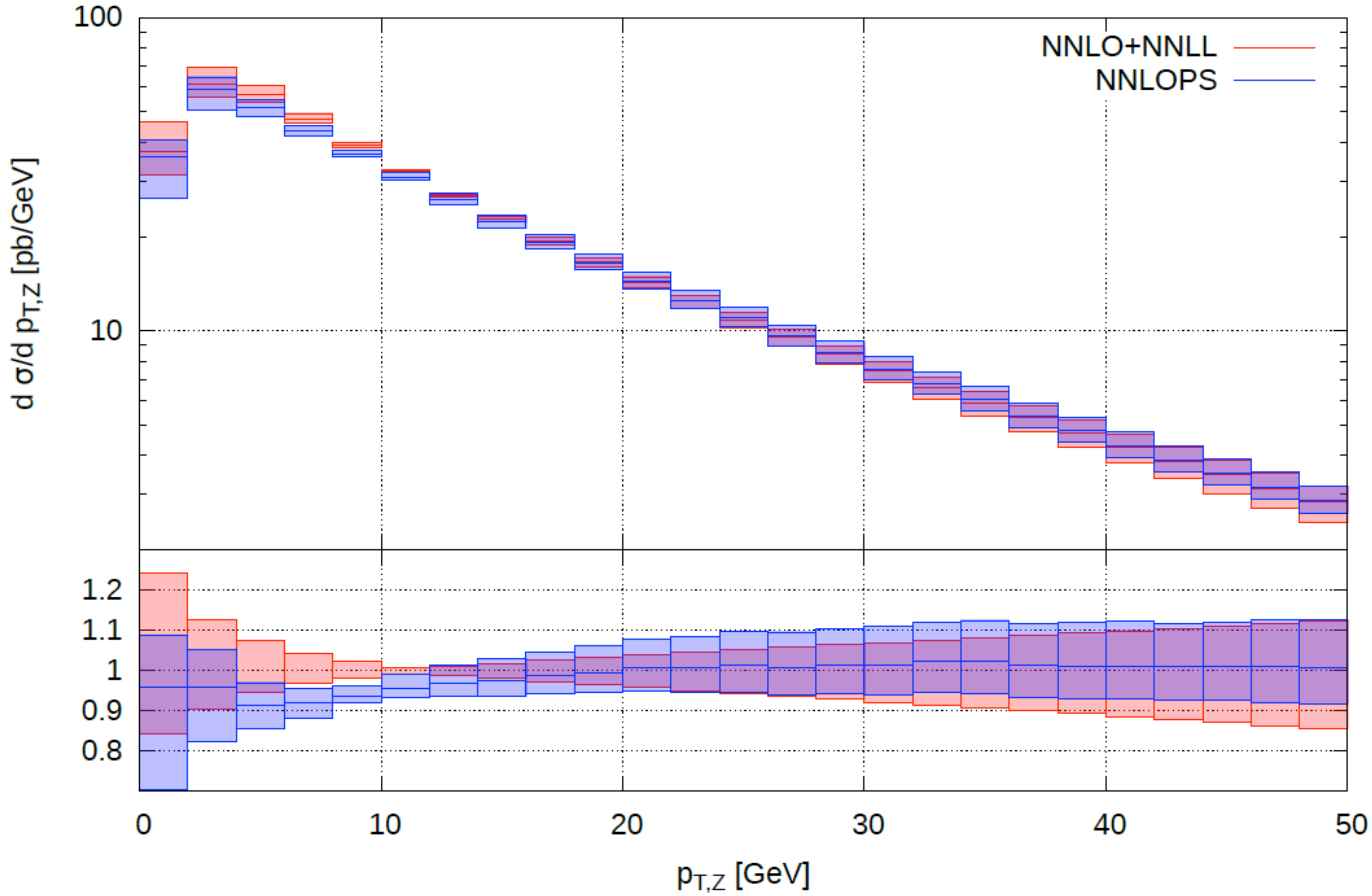


More comparisons to data available soon [Karlberg et al. 1406.xxxx]

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

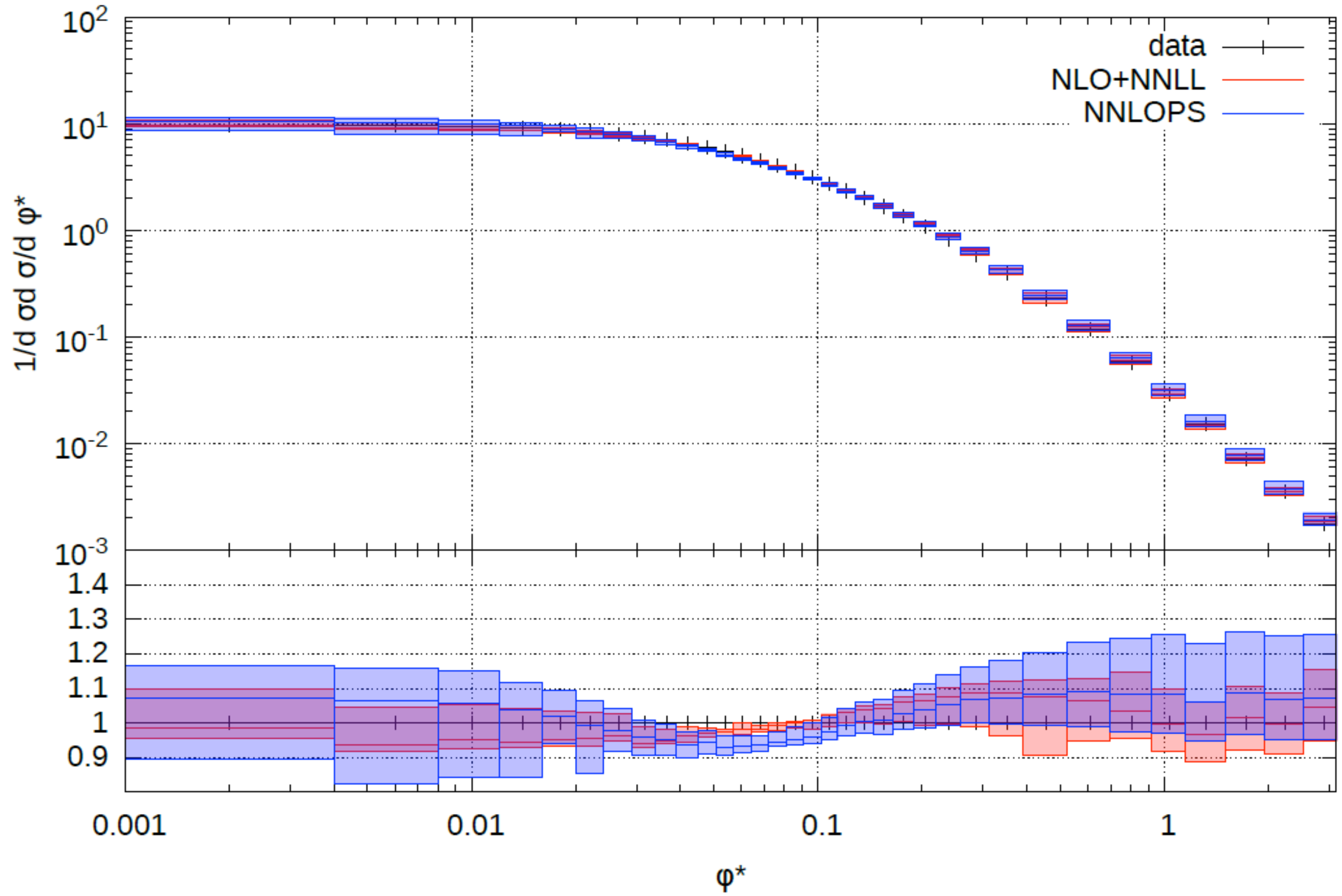
Comparison to NNLL+NNLO resummation for $p_{t,Z}$ [Bozzi et al. 1007/2351]



Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

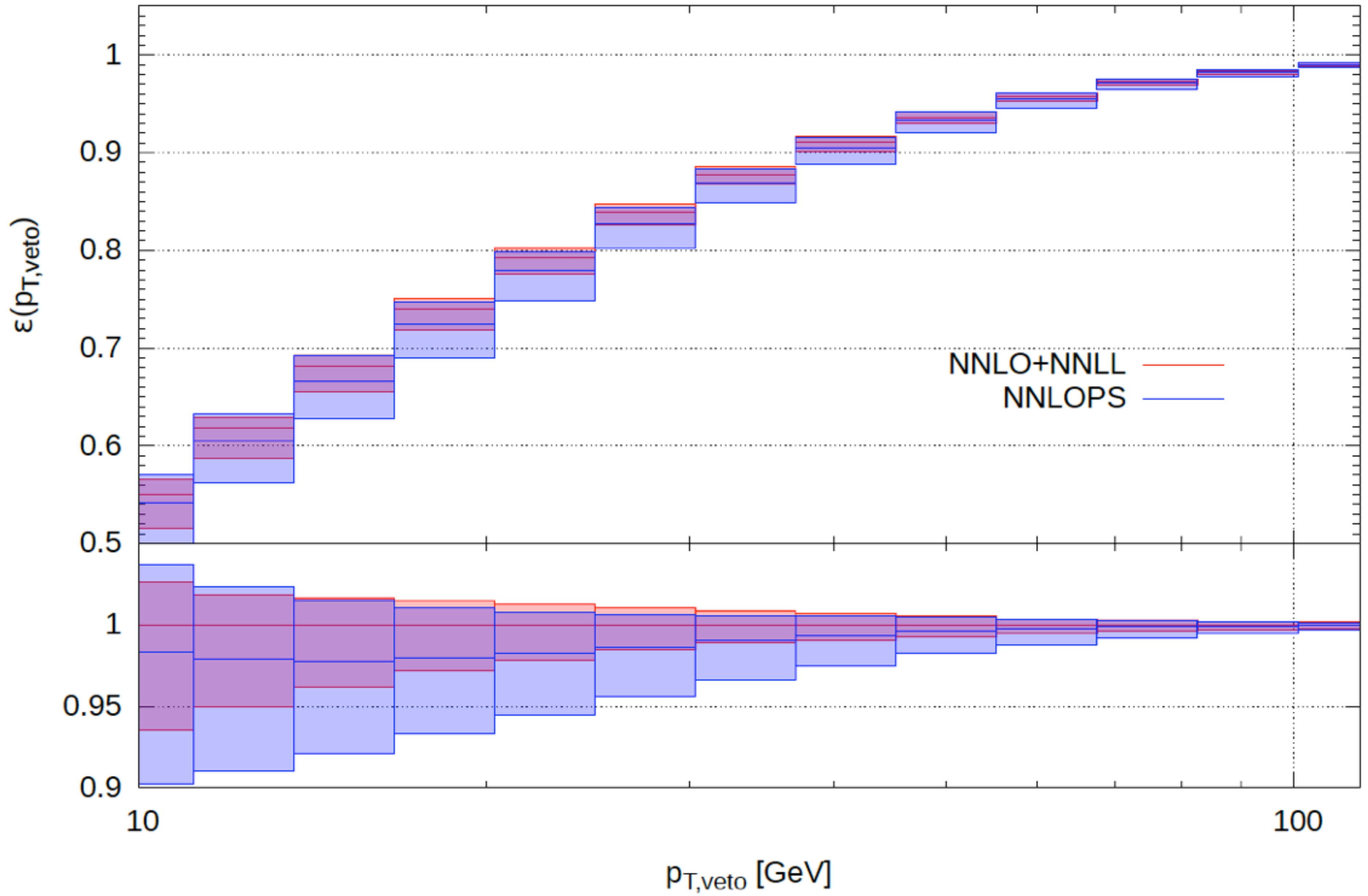
Comparison to NNLL+NNLO resummation [Banfi et al. 1205.4760] and data [ATLAS 1211.6899] for φ*



Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

Comparison to NNLL+NNLO resummation [Banfi et al. 1206.4998] for the jet veto



Conclusions

- MiNLO born as a scale-setting procedure à-la CKKW
- inclusion of Sudakov form factor turn 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)
- first NNLOPS generator for Higgs and Drell-Yan processes
- more to come from MiNLO

Extra Slides

A useful integral

$$I(m,n) \equiv \int_{\Lambda^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2} \left(\log \frac{Q^2}{q^2}\right)^m \alpha_s^n\,(q^2)\,\exp\left\{-\int_{q^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} A\,\alpha_s(\mu^2) \log \frac{Q^2}{\mu^2}\right\}$$

$$\approx \left[\alpha_s(Q^2)\right]^{n-\frac{m+1}{2}}$$

i.e. each log "counts" as a square-root of $1/\alpha_s$ after integration over the transverse momentum when the Sudakov weight is present