NNLO+PS with POWHEG + MiNLO

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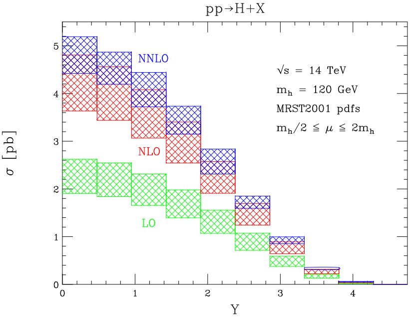
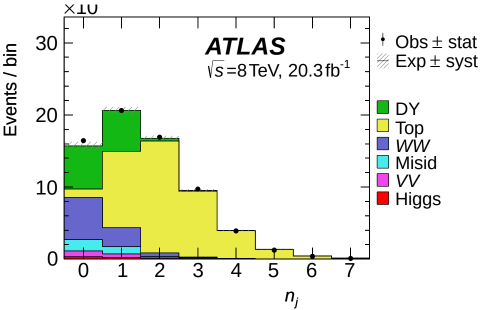
CERN & LAPTh Annecy

Future challenges for precision QCD
IPPP, Durham, 26 October 2016

Why NNLO? Why NNLO+PS?



[Anastasiou et al., '04-'05]



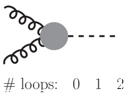
[ATLAS jet-binned cross section]

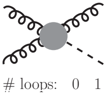
- NNLO when very-high precision required [DY] or large NLO/LO K-factor [Higgs].
- PS do a good job for differential distributions (limited formal accuracy wrt resummation, but "more flexible" and fully differential).

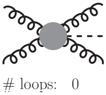
☞ aim: build an event generator that is NNLO accurate (NNLOPS)

Summary of the talk

Higgs at NNLO:







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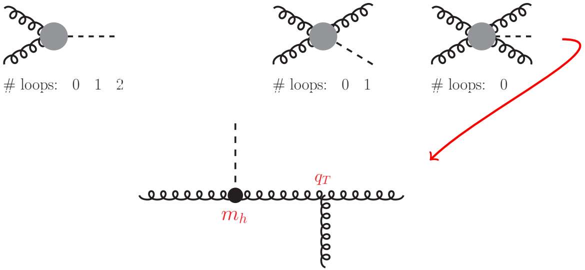

(a) 1 and 2 jets: POWHEG H+1j

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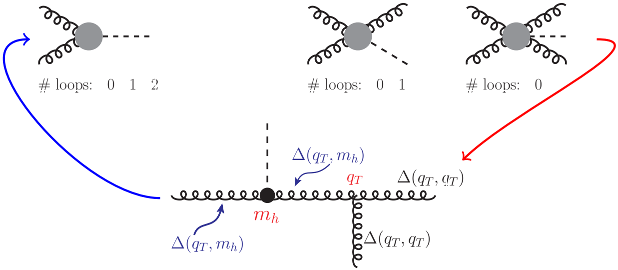

(b) - integrate down to $q_T = 0$ with MiNLO
- "Improved MiNLO" allows to build a H-HJ @ NLOPS generator

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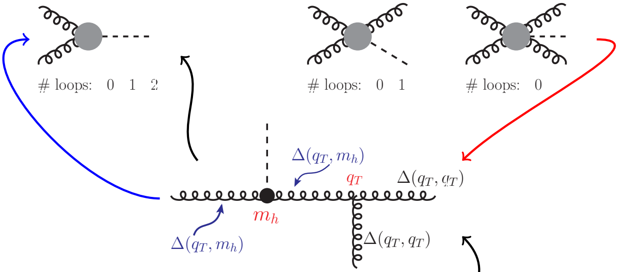

(c) 2 loops missing: from exact fixed-order NNLO

$$W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}}$$

(b) - integrate down to $q_T = 0$ with MiNLO
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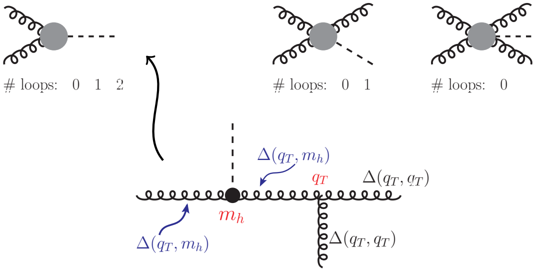

- method presented here was used so far for
  - Higgs production [Hamilton,Nason,ER,Zanderighi, 1309.0017]
  - neutral & charged Drell-Yan [Karlberg,ER,Zanderighi, 1407.2940]
  - associated WH production [Astill,Bizon,ER,Zanderighi, 1603.01620]
- as is, it can in principle be used for generic colour-singlet production

NNLO+PS

- what do we need and what do we already have?

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
H @ NLOPS	NLO	LO	shower
HJ @ NLOPS	/	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

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- there are several multijet NLO+PS merging approaches; typically they combine 2 (or more) NLO+PS generators, often introducing a merging scale
- POWHEG + MiNLO: does not need a merging scale. It extends the validity of an NLO computation with jets in the final state in regions where jets become unresolved

MiNLO

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task: hierarchy among scales can spoil accuracy (large logs can appear, without being resummed)
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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  - for each point sampled, build the "more-likely" shower history that would have produced that kinematics (can be done by clustering kinematics with k_T-algo, then, by undoing the clustering, build "skeleton")
  - correct original NLO: α_{S} evaluated at nodal scales and Sudakov FFs
  - "without spoiling formal NLO accuracy":
    1. Scale dependence shows up at NNLO ["scale compensation"]:

       $$O(\mu') - O(\mu) = \mathcal{O}(\alpha_{\mathrm{S}}^{n+2}) \quad \text{if} \quad O \sim \alpha_{\mathrm{S}}^{n} \quad \text{at LO}$$

    2. Away from soft-collinear regions, exact NLO recovered:

       $$O_{\mathrm{MiNLO}} = O_{\mathrm{NLO}} + \mathcal{O}(\alpha_{\mathrm{S}}^{n+2}) \qquad [\; i.e.\; \alpha_{\mathrm{S}}^{n} \;\&\; \alpha_{\mathrm{S}}^{n+1} \text{ reproduce plain NLO} \;]$$

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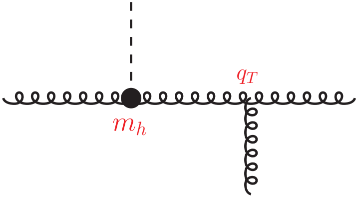
$$\bar{B}_{\rm NLO} = \alpha_{\rm S}^3(\mu_R)\Big[B + \alpha_{\rm S} V(\mu_R) + \alpha_{\rm S}\int d\Phi_{\rm r} R\Big]$$



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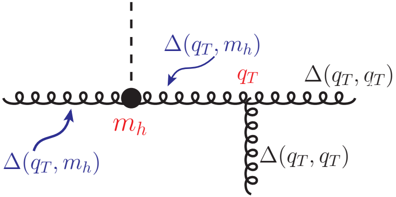
$$\bar{B}_{\mathrm{MiNLO}} = \alpha_{\mathrm{S}}^2(m_h)\alpha_{\mathrm{S}}(q_T)\Delta_g^2(q_T, m_h)\Big[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\mathrm{S}}\, V(\bar{\mu}_R) + \alpha_{\mathrm{S}} \int d\Phi_{\mathrm{r}} R\Big]$$



- $\bar{\mu}_R = (m_h^2 q_T)^{1/3}$
- $\log \Delta_{\mathrm{f}}(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\Big[A_f \log\frac{m_h^2}{q^2} + B_f\Big]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_h) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\Big[\frac{1}{2} A_{1,\mathrm{f}} \log^2\frac{m_h^2}{q_T^2} + B_{1,\mathrm{f}} \log\frac{m_h^2}{q_T^2}\Big]$
- $\mu_F = q_T$

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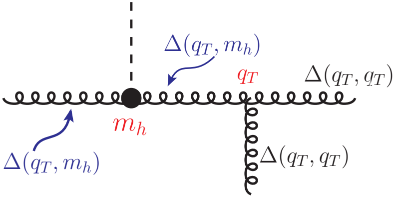

☞ Sudakov FF included on $H+j$ Born kinematics

- with MiNLO, finite results from HJ also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of HJ−POWHEG [called "HJ−MiNLO" hereafter]

“Improved” MiNLO & NLOPS merging

- formal accuracy of `HJ-MiNLO` for inclusive observables carefully investigated

  [Hamilton et al., 1212.4504]

- `HJ-MiNLO` describes inclusive observables at order α_S
- to reach genuine NLO when fully inclusive (NLO$^{(0)}$), “spurious” terms must be of relative order α_S^2, *i.e.*

$$O_{\mathrm{HJ-MiNLO}} = O_{\mathrm{H@NLO}} + \mathcal{O}(\alpha_S^{2+2}) \qquad \text{if } O \text{ is inclusive}$$

- “Original `MiNLO`” contains ambiguous “$\mathcal{O}(\alpha_S^{2+1.5})$” terms

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- Possible to improve `HJ-MiNLO` such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of $H+j$ (NLO$^{(1)}$).
- accurate control of subleading small-p_T logarithms is needed
  (scaling in low-p_T region is $\alpha_S L^2 \sim 1$, *i.e.* $L \sim 1/\sqrt{\alpha_S}$!)

Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

“Improved” MiNLO & NLOPS merging: details

- Resummation formula can be written as

$$\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2}\Big\{[C_{ga}\otimes f_a](x_A, q_T) \times [C_{gb}\otimes f_b](x_B, q_T) \times \exp S(q_T, Q)\Big\} + R_f$$

$$S(q_T, Q) = -2\int_{q_T^2}^{Q^2} \frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_f \log\frac{Q^2}{q^2} + B_f\right]$$

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- Take derivative, then compare with `MiNLO` :

$$\sim \sigma_0 \frac{1}{q_T^2}\left[\alpha_S, \boxed{\alpha_S^2}, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L\right] \exp S(q_T, Q) + R_f \qquad L = \log(Q^2/q_T^2)$$

- highlighted terms are needed to reach NLO$^{(0)}$:

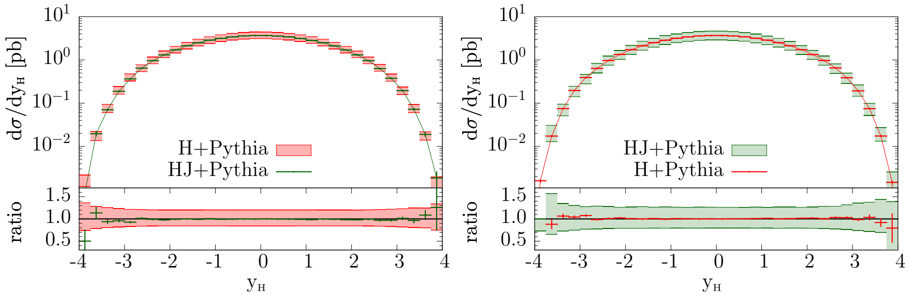
$$\int^{Q^2} \frac{dq_T^2}{q_T^2} L^m \alpha_S{}^n(q_T) \exp S \sim \left(\alpha_S(Q^2)\right)^{n-(m+1)/2}$$

(scaling in low-p_T region is $\alpha_S L^2 \sim 1$!)

- if I don't include B_2 in `MiNLO` Δ_g, I miss a term $(1/q_T^2)\ \boxed{\alpha_S^2}\ B_2 \exp S$
- upon integration, violate NLO$^{(0)}$ by a term of <u>relative</u> $\mathcal{O}(\alpha_S^{3/2})$

MiNLO merging: results

[Hamilton et al., 1212.4504]



- “H+Pythia”: standalone POWHEG $(gg \to H)$ + PYTHIA (PS level) [7pts band, $\mu = m_H$]
- “HJ+Pythia”: HJ-MiNLO* + PYTHIA (PS level) [7pts band, μ from MiNLO]

- very good agreement (both value and band) [✓]

☞ Notice: band is $\sim 20 - 30\%$

Higgs at NNLO+PS: details

- HJ−MiNLO+POWHEG generator gives H-HJ @ NLOPS

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
✓ H-HJ @ NLOPS	NLO	NLO	LO
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- reweighting (differential on Φ_B) of "MiNLO-generated" events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm HJ-MiNLO^*}}$$

  - by construction NNLO accuracy on fully inclusive observables $(\sigma_{\rm tot}, y_H; m_{\ell\ell}, \ldots)$ [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of HJ−MiNLO in 1-jet region [ ]

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  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{2+1.5})$ terms in H-HJ @ NLOPS

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  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{2+1.5})$ terms in H-HJ @ NLOPS
  - the more complicated Φ_B, the more computationally demanding the method will be

Higgs at NNLO+PS: details II

- Variants for reweighting ($W(y_H)$, $W(\Phi_B)$) are also possible:

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

$$d\sigma_A = d\sigma\, h(p_T), \qquad d\sigma_B = d\sigma\,(1-h(p_T)), \qquad h = \frac{(\beta m_H)^2}{(\beta m_H)^2 + p_T^2}$$

- freedom to distribute "NNLO/NLO K-factor" only over medium-small p_T region
  - $h(p_T)$ controls where the NNLO/NLO K-factor is distributed
    (in the high-p_T region, there is no improvement in including it)
  - β cannot be too small, otherwise resummation spoiled:
    for Higgs, chosen $\beta = 1/2$; for DY, $\beta = 1$

- in practice, we used

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

  - one gets exactly $(d\sigma/dy)_{\rm NNLOPS} = (d\sigma/dy)_{\rm NNLO}$ (no α_S^5 terms)
  - chosen $h(p_T^{j_1})$

Settings

inputs for H@NNLOPS plots:

- results are for 8 TeV LHC
- scale choices: NNLO input with $\mu = m_H/2$, HJ-MiNLO "core scale" m_H (other powers are at q_T)
- PDF: everywhere MSTW2008 NNLO
- NNLO always from HNNLO [Catani,Grazzini]
- 6M events reweighted at the LH level
- plots after k_{T}-ordered Pythia6 at the PS level (hadronization and MPI switched off)

for V@NNLOPS plots:

- similar choices as above
- NNLO always from DYNNLO [Catani,Cieri,Ferrera,de Florian,Grazzini]
- used also Pythia8 at the PS level

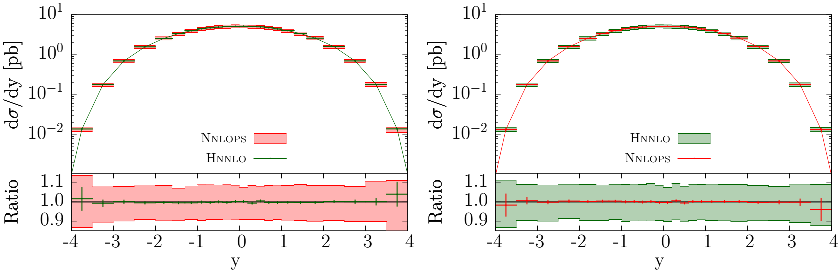
for WH@NNLOPS plots:

- similar choices as above
- NNLO always from HVNNLO [Ferrera,Grazzini,Tramontano]
- PDF: MMHT2014nnlo

H@NNLOPS (fully incl.)

To reweight, use y_H

- NNLO with $\mu = m_H/2$, HJ-MiNLO "core scale" m_H [NNLO from HNNLO, Catani,Grazzini]
- $(7_{\text{Mi}} \times 3_{\text{NN}})$ pts scale var. in NNLOPS, 7pts in NNLO

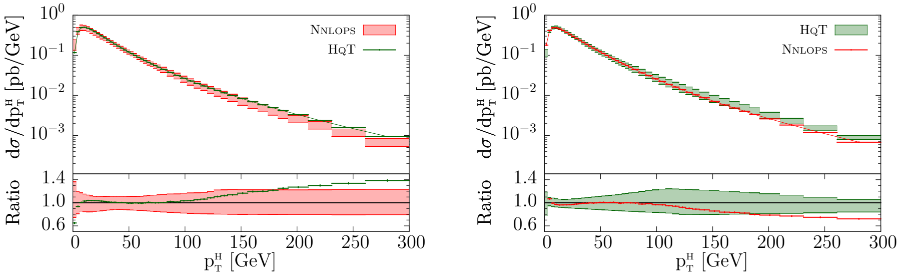


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%) [✓]

[Until and including $\mathcal{O}(\alpha_S^4)$, PS effects don't affect y_H (first 2 emissions controlled properly at $\mathcal{O}(\alpha_S^4)$ by MiNLO+POWHEG)]

H@NNLOPS (p_T^H)

$\beta = 1/2$

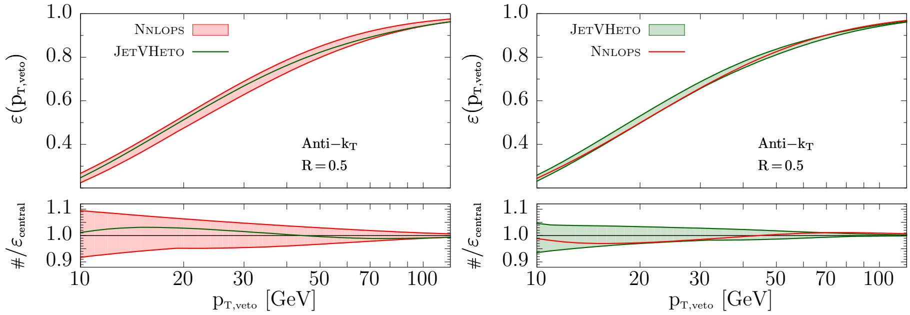


- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\mathrm{res}} \equiv m_H/2$ [HqT, Bozzi et al.]

✓ uncertainty bands of HqT contain NNLOPS at low-/moderate p_T

- very good agreement with HqT resummation
  ["∼ expected", since $Q_{\mathrm{res}} \equiv m_H/2$, and $\beta = 1/2$]
- HqT tail harder than NNLOPS tail ($\mu_{\mathrm{HqT}} <$ "μ_{MiNLO}")

NNLO+PS ($p_T^{j_1}$)



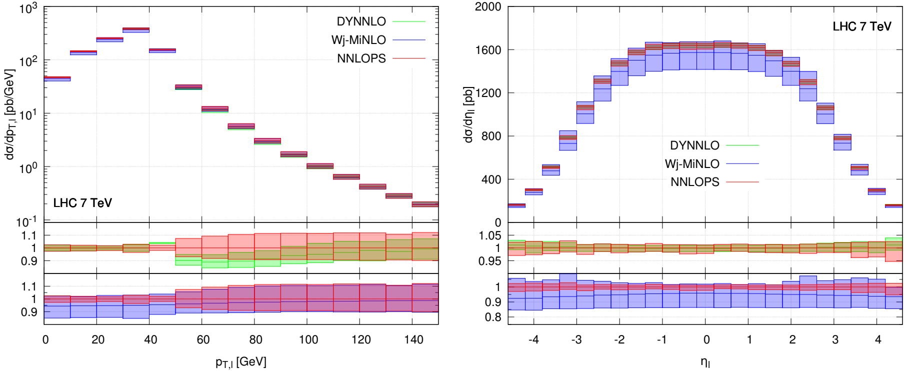
$$\varepsilon\left(p_{\mathrm{T,veto}}\right) = \frac{\Sigma(p_{\mathrm{T,veto}})}{\sigma^{\mathrm{tot}}} = \frac{1}{\sigma^{\mathrm{tot}}} \int d\sigma\, \theta\left(p_{\mathrm{T,veto}} - p_{\mathrm{T}}^{\mathrm{j_1}}\right)$$

- `JetVHeto`: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\mathrm{res}} \equiv m_H/2$, (a)-scheme only
  [`JetVHeto`, Banfi et al.]
- nice agreement, differences never more than 5-6 %

☞ Separation of $H \to WW$ from $t\bar{t}$ bkg: x-sec binned in N_{jet}
0-jet bin ⇔ jet-veto accurate predictions needed !

W@NNLOPS, PS level

To reweight, use $(y_{\ell\ell}, m_{\ell\ell}, \cos\theta_\ell)$



- not the observables we are using to do the NNLO reweighting
  - observe exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
  - η_ℓ is NNLO everywhere

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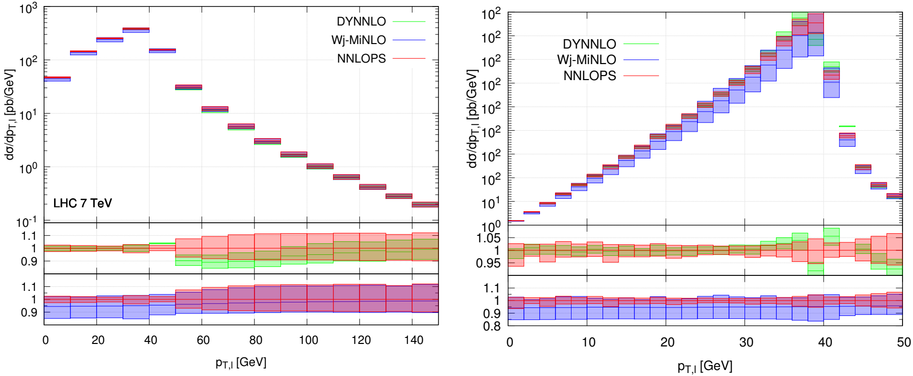

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    (due to resummation of logs at small $p_{T,V}$)

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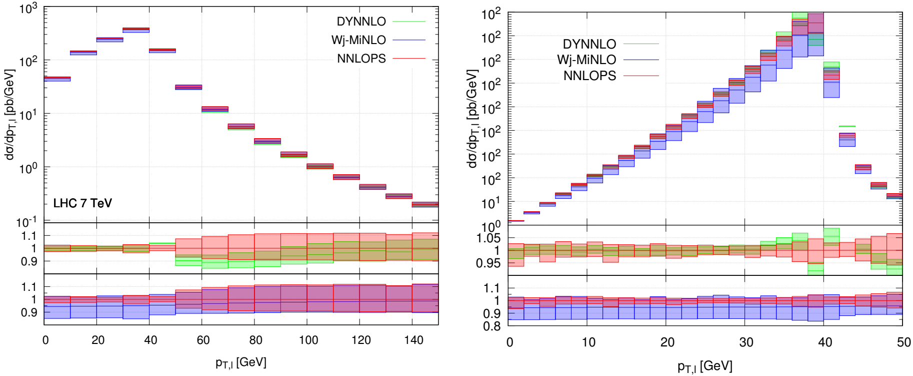

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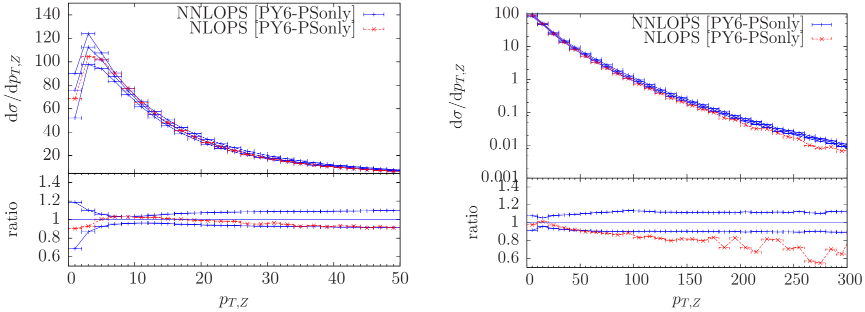
  - smooth behaviour when close to Jacobian peak (also with small bins) (due to resummation of logs at small $p_{T,V}$)
- just above peak, DYNNLO uses $\mu = M_W$, WJ-MiNLO uses $\mu = p_{T,W}$
  - here $0 \lesssim p_{T,W} \lesssim M_W$ (so resummation region does contribute)

NNLOPS vs. NLOPS



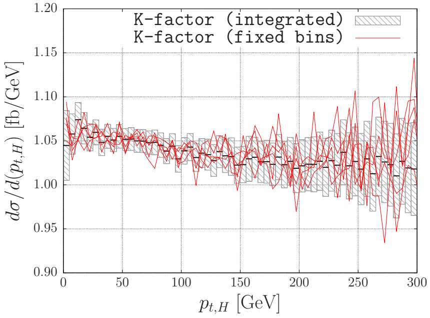
- different terms in Sudakov, although both contain NLL terms in momentum space
  - in NLOPS: α_S in radiation scheme; in NNLOPS: MiNLO Sudakov
- formally they have the same logarithmic accuracy (as supported by above plot)
- at large p_T, difference as expected

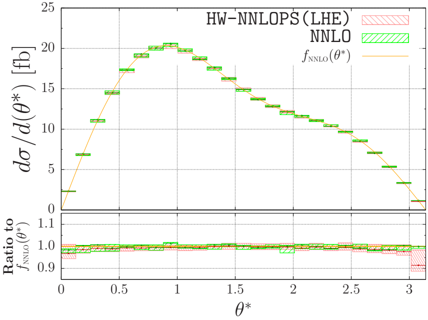
WH@NNLOPS

To reweight, use $(y_{\rm HW}, \Delta y_{\rm HW}, p_{t,\rm H})$ + Collins-Soper angles (assuming, and validating, that dependence upon $m_{\ell\nu}$ is negligible)

$$\frac{d\sigma}{d\Phi_B} = \frac{d\sigma}{dy_{\rm HW}\, d\Delta y_{\rm HW}\, dp_{t,\rm H}\, d\cos\theta^* d\phi^*}$$

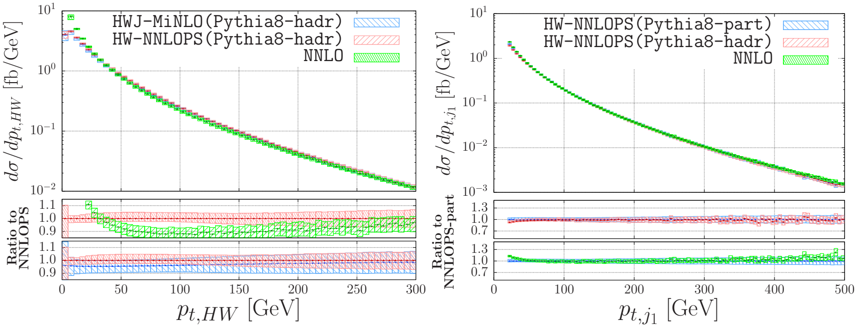
$$= \frac{3}{16\pi}\left(\frac{d\sigma}{d\Phi_{\rm HW^*}}(1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(\Phi_{\rm HW^*}) f_i(\theta^*,\phi^*)\right)$$





- left plot: K-factor for $p_{T,H}$, in different slices of $m_{\ell\nu}$
- right plot: angular dependence in slice of $y_{\rm HW}$

WH@NNLOPS



- left plot: standard behaviour
  - resummation effects at small $p_{T,WH}$
  - at high p_T: NNLOPS → MiNLO
- right plot: hardest-jet spectrum

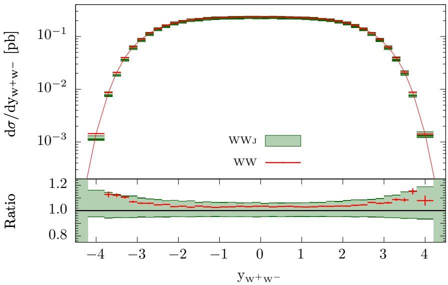
“Improved” MiNLO: from Drell-Yan to WW

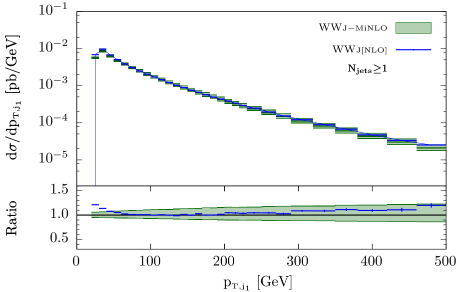
[Hamilton,Melia,Monni,ER,Zanderighi ’16]

In 1606.07062 we presented a `MiNLO′` generator for WW and WW + 1 jet:

- `POWHEG` WWJ generator obtained using interfaces to `Madgraph` and `Gosam`
- starting from the Drell-Yan case, we extracted the B_2 term from the virtual (V) and Born (B) contributions of $pp \to WW$
- for Drell-Yan, V and B are proportional, hence B_2 is just a number
- in $pp \to WW$, this is no longer true: $B_2 = B_2(\Phi_{WW})$
- process-dependent part of B_2 extracted on an event-by-event basis

“Improved” MiNLO: from Drell-Yan to WW





- left: total cross-section agrees at the level of 4% (although MiNLO uncertainty bands are wider than the WW ones)
- right: plot shows that MiNLO mantains the formal NLO accuracy in the “1-jet” region
  - small differences can be explained by Sudakov effects, and use of different scale choices

conclusions

- MiNLO-improved POWHEG generator allows to reach NNLOPS accuracy for simple processes
- the (improved) MiNLO idea is central
- shown results for Higgs, Drell-Yan and associated WH production
- predictions and theoretical uncertainties match NNLO where they have to
- typically, quite good agreement with analytic resummation
  - good news, but more work need to be done here

What next?

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What next?

- other approaches appeared (UNNLOPS, Geneva): will be interesting to compare
- NLOPS merging for higher multiplicity [Frederix,Hamilton '15]
- NNLOPS for more complicated processes (color-singlet in principle doable, in practice a more analytic-based approach might be needed)
- Real phenomenology in experimental analyses

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Thank you for your attention!