NNLO+PS with MiNLO and POWHEG

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PSR15

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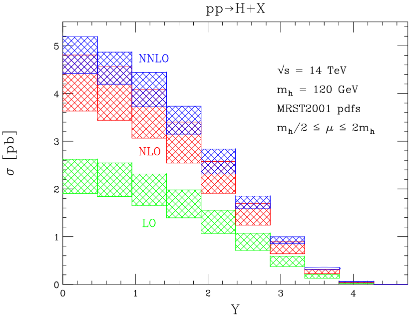
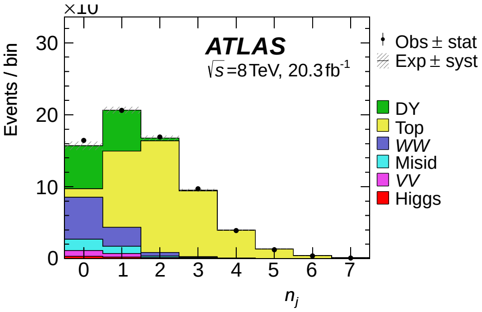
Why NNLO? Why NNLO+PS?



[Anastasiou et al., ’04-’05]



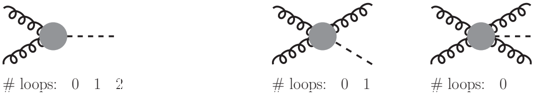
[ATLAS jet-binned cross section]

- 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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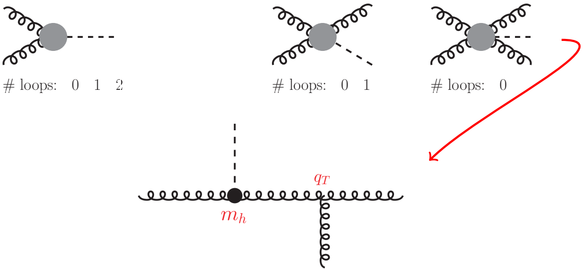

(a) 1 and 2 jets: POWHEG H+1j

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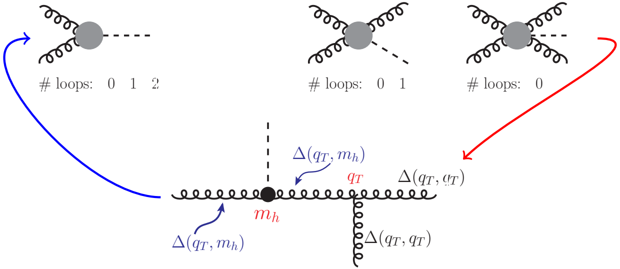

(b) - integrate down to $q_T = 0$ with MiNLO
- "Improved MiNLO" allows to build a H-HJ @ NLOPS generator

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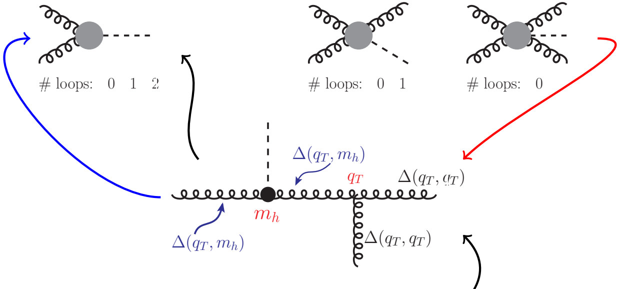

(c) 2 loops missing: from exact fixed-order NNLO

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

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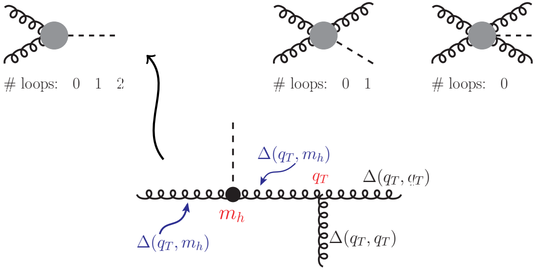

- method presented here was used so far for
  - Higgs production [Hamilton,Nason,ER,Zanderighi, 1309.0017]
  - neutral & charged Drell-Yan [Karlberg,ER,Zanderighi, 1407.2940]
- as is, it can in principle be used for generic colour-singlet production

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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H-HJ @ NLOPS	NLO	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: $\alpha_{\rm S}$ evaluated at nodal scales and Sudakov FFs
  - has been used in V/H + up to 2 jets and in VH + up to 1 jet
  - "without spoiling formal NLO accuracy":
    1. Scale dependence shows up at NNLO ["scale compensation"]:
    $$O(\mu') - O(\mu) = \mathcal{O}(\alpha_{\rm S}^{n+2}) \quad \text{if} \quad O \sim \alpha_{\rm S}^n \quad \text{at LO}$$
    2. Away from soft-collinear regions, exact NLO recovered:
    $$O_{\rm MiNLO} = O_{\rm NLO} + \mathcal{O}(\alpha_{\rm S}^{n+2}) \qquad [\; i.e. \;\; \alpha_{\rm S}^n \;\; \& \;\; \alpha_{\rm S}^{n+1} \;\; \text{reproduce plain NLO} \;]$$

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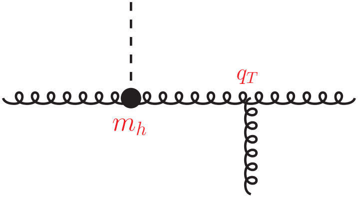
$$\bar{B}_{\mathrm{NLO}} = \alpha_{\mathrm{S}}^3(\mu_R)\Big[B + \alpha_{\mathrm{S}} V(\mu_R) + \alpha_{\mathrm{S}} \int d\Phi_{\mathrm{r}} R\Big]$$



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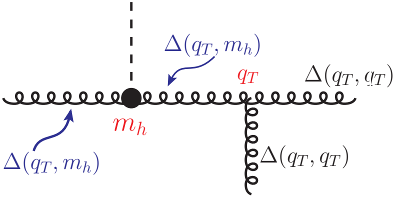
$$\bar{B}_{\rm MiNLO} = \alpha_{\rm S}^2(m_h)\alpha_{\rm S}(q_T)\Delta_g^2(q_T, m_h)\Big[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\rm S}\, V(\bar{\mu}_R) + \alpha_{\rm S}\int d\Phi_{\rm r} R\Big]$$



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

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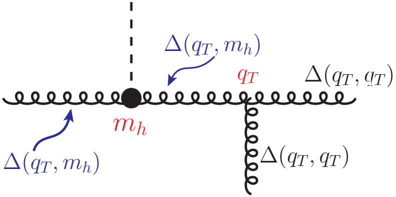

☞ Sudakov FF included on H+j Born kinematics

- 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

- Resumment formula can be written as

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

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

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

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

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

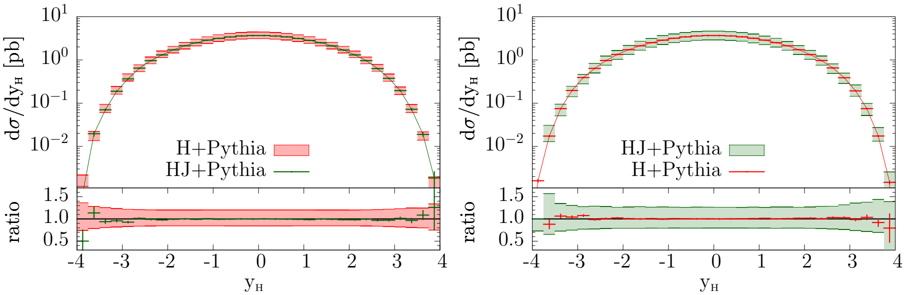
$$\int^{Q^2} \frac{dq_T^2}{q_T^2} L^m {\alpha_S}^n(q_T) \exp S \sim \big(\alpha_S(Q^2)\big)^{n-(m+1)/2}$$

(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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  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `HJ−MiNLO` in 1-jet region [✓]
  - 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)

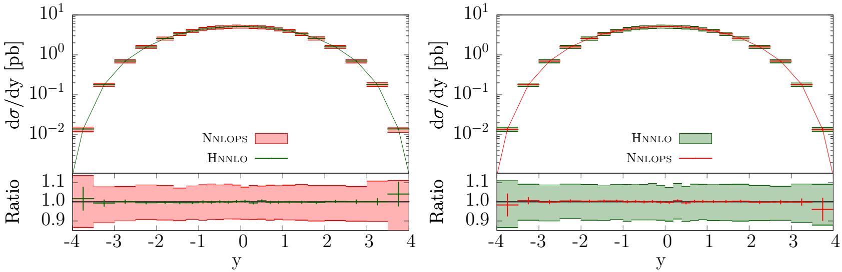
for V@NNLOPS plots:

- similar choices as above
- NNLO always from DYNNLO [Catani,Cieri,Ferrera,de Florian,Grazzini]
- used also Pythia8 at the PS level (and with full hadronization and MPI switched on in data comparison)

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]
- $(7_{\rm Mi} \times 3_{\rm NN})$ pts scale var. in NNLOPS, 7pts in NNLO

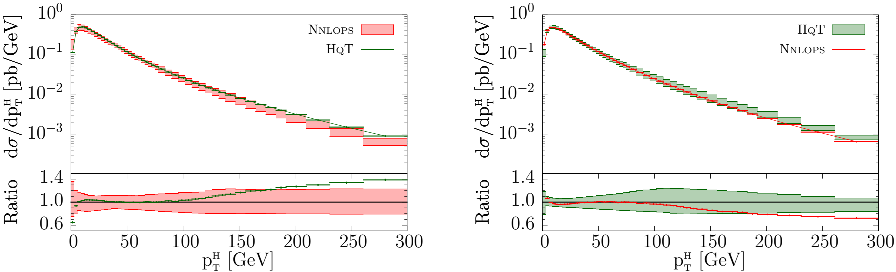


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%) [✓]

[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)

$\beta = 1/2$



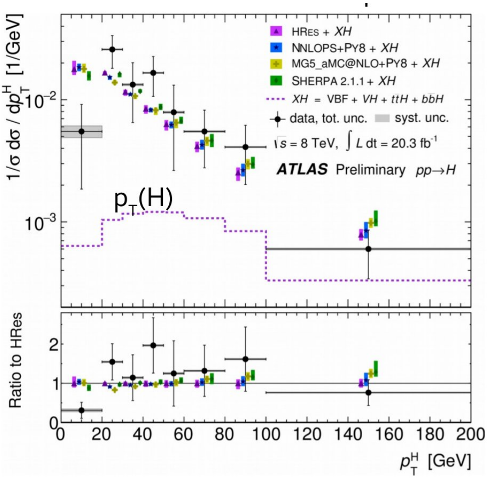
- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$ [HqT, Bozzi et al.]

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

- very good agreement with HqT resummation
  ["∼ expected", since $Q_{\rm res} \equiv m_H/2$, and $\beta = 1/2$]

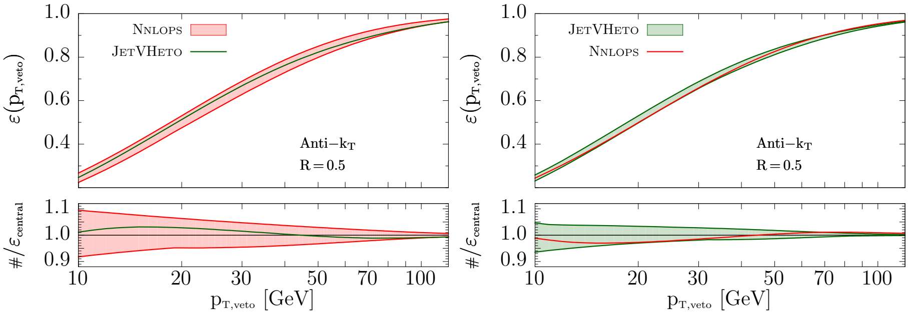
- HqT tail harder than NNLOPS tail ($\mu_{\rm HqT} <$ "$\mu_{\rm MiNLO}$")

data



... with Run II we will know more ...

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



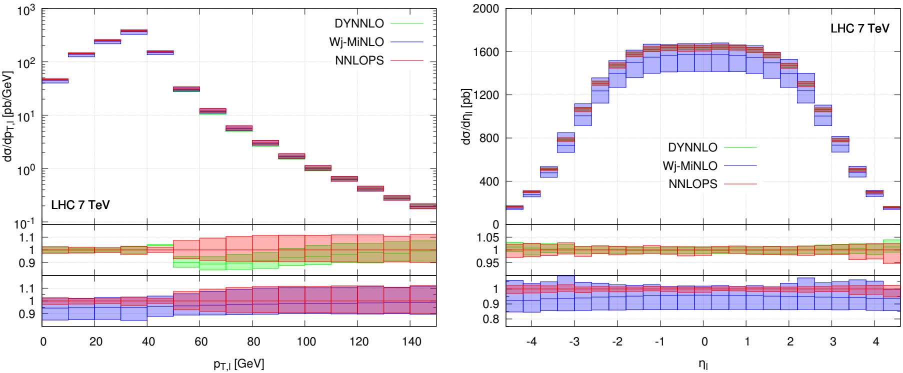
$$\varepsilon\left(p_{\mathrm{T,veto}}\right) = \frac{\Sigma(p_{\mathrm{T,veto}})}{\sigma^{\mathrm{tot}}} = \frac{1}{\sigma^{\mathrm{tot}}}\int d\sigma\,\theta\left(p_{\mathrm{T,veto}} - p_{\mathrm{T}}^{\mathrm{j}_1}\right)$$

- `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

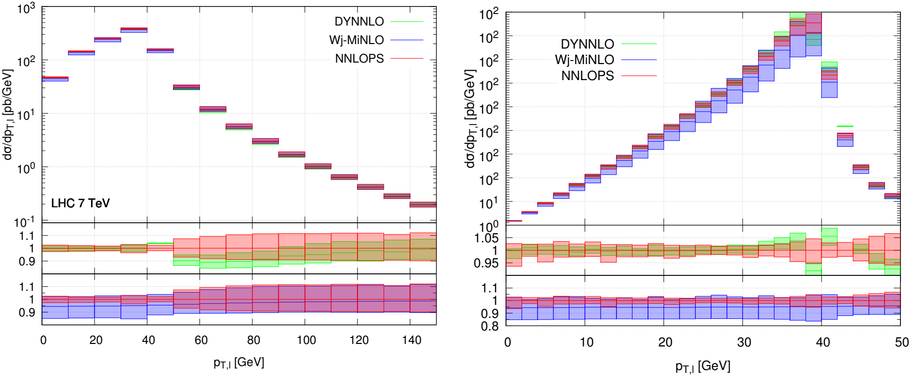
To reweight, use $(y_{\ell\ell}, m_{\ell\ell}, \cos\theta_\ell)$



- **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

W@NNLOPS, PS level

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



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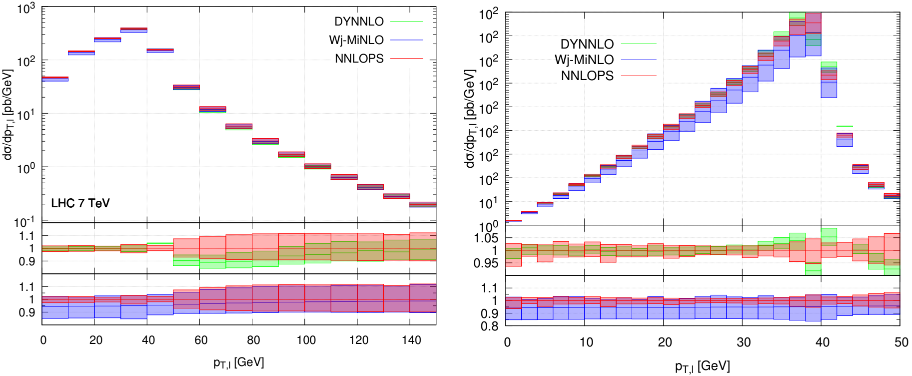

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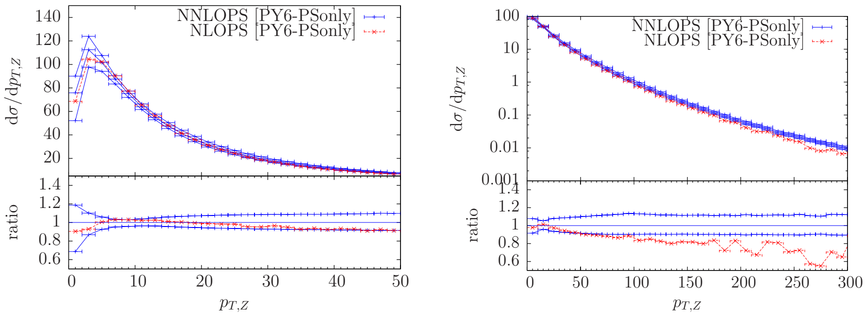
    (due to resummation of logs at small $p_{T,V}$)
- ▶ just above peak, DYNNLO uses $\mu = M_W$, WJ−MiNLO uses $\mu = p_{T,W}$
  - here $0 \lesssim p_{T,W} \lesssim M_W$ (so resummation region does contribute)

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

conclusions

- MiNLO-improved POWHEG generator allows to reach NNLOPS accuracy for simple processes
- shown results for Higgs and Drell-Yan at NNLOPS
- 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

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What next?

- other approaches appeared (UNNLOPS, Geneva): will be interesting to compare
- NLOPS merging for higher multiplicity
- 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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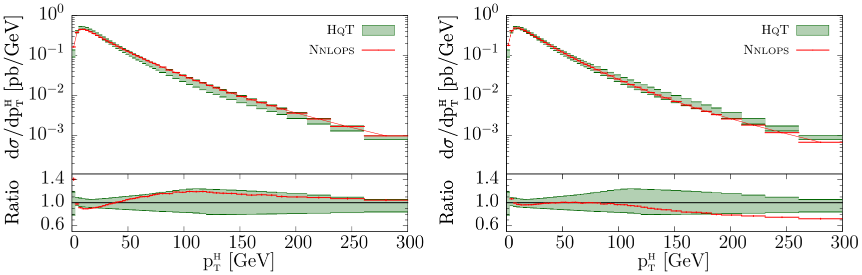
Thank you for your attention!

NNLO+PS (p_T^H)

$\beta = \infty$ (W indep. of p_T) $\qquad\qquad$ $\beta = 1/2$



- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$ [HqT, Bozzi et al.]
- ✓ $\beta = 1/2$ & ∞: uncertainty bands of HqT contain NNLOPS at low-/moderate p_T
- $\beta = 1/2$: HqT tail harder than NNLOPS tail ($\mu_{\rm HqT} <$ "$\mu_{\rm MiNLO}$")
  HJ @ NNLO will allow to say more for large $p_{T,H}$
- $\beta = 1/2$: very good agreement with HqT resummation
  ["$\sim$ expected", since $Q_{\rm res} \equiv m_H/2$]

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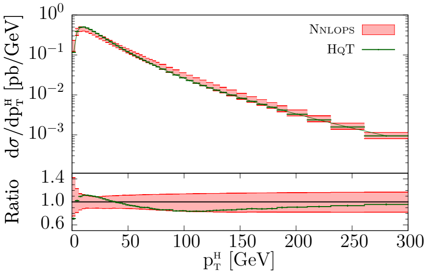

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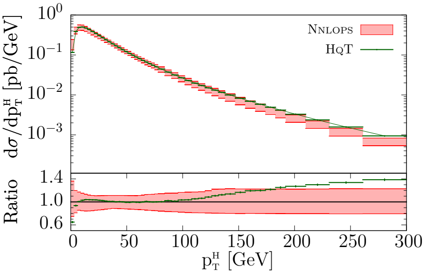
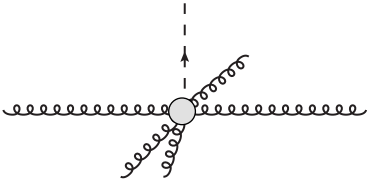


- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$
- $\beta = 1/2$: NNLOPS tail $\rightarrow$ NLOPS tail [$W(y, p_T \gg m_H) \rightarrow 1$]
  larger band (affected just marginally by NNLO, so it's $\sim$ genuine NLO band)

From CKKW to MiNLO

- Find "most-likely" shower history (via k_T-algo): $Q > q_3 > q_2 > q_1 \equiv Q_0$



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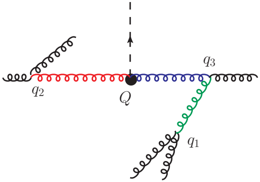

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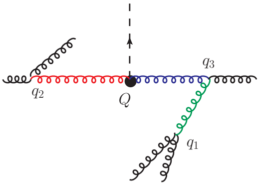

- Evaluate α_S at nodal scales

$$\alpha_S^n(\mu_R)B(\mathbf{\Phi}_n) \Rightarrow \alpha_S(q_1)\alpha_S(q_2)...\alpha_S(q_n)B(\mathbf{\Phi}_n)$$

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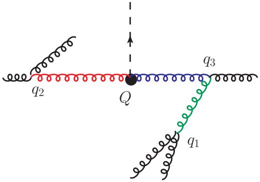

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$$B(\mathbf{\Phi}_n) \Rightarrow B(\mathbf{\Phi}_n) \times \{\Delta(Q_0, Q)\Delta(Q_0, q_i)...\}$$

* Upon expansion, $\mathcal{O}(\alpha_S^{n+1})$ (log) terms are introduced, and need to be removed

$$B(\mathbf{\Phi}_n) \Rightarrow B(\mathbf{\Phi}_n)\Big(1 - \Delta^{(1)}(Q_0, Q) - \Delta^{(1)}(Q_0, q_i) + ...\Big)$$

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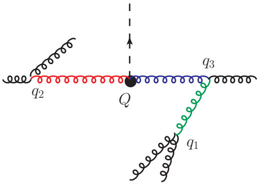

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✓ $X+$ jets cross-section finite without generation cuts
$\Rightarrow \bar{B}$ with `MiNLO` prescription: ideal starting point for NLOPS (POWHEG) for $X+$ jets

MiNLO details

MiNLO: All α_S in Born term are chosen with CKKW (local) scales $q_1, ..., q_n$

$$\alpha_S^n(\mu_R)B \Rightarrow \alpha_S(q_1)\alpha_S(q_2)...\alpha_S(q_n)B$$

- Normal NLO structure ($\mu = \mu_R$):

$$\sigma(\mu) = \underbrace{\alpha_S^n(\mu)B}_{\text{Born}} + \underbrace{\alpha_S^{n+1}(\mu)\Big(C + nb_0 \log(\mu^2/Q^2)B\Big)}_{\text{Virtual}} + \underbrace{\alpha_S^{n+1}(\mu)R}_{\text{Real}}$$

- Explicit μ dependence of virtual term as required by RG invariance:

$$\alpha_S^n(\mu')B = \Big[\alpha_S(\mu) - nb_0\alpha_S^{n+1}(\mu)\log(\mu'^2/\mu^2)\Big]B + \mathcal{O}(\alpha_S^{n+2})$$

$$\text{Virtual}(\mu') = \text{Virtual}(\mu) + \alpha_S^{n+1}(\mu)nb_0\log(\mu'^2/\mu^2)\, B + \mathcal{O}(\alpha_S^{n+2})$$

$\Rightarrow \sigma(\mu') - \sigma(\mu) = \mathcal{O}(\alpha_S^{n+2})$

- In MiNLO "scale compensation" kept if

$$\Big(C + nb_0 \log(\mu_R^2/Q^2)B\Big) \Rightarrow \Big(C + nb_0 \log(\bar{\mu}_R^2/Q^2)B\Big)$$

with $\bar{\mu}_R^2 = (q_1 q_2 ... q_n)^{2/n}$

MiNLO details

Few technicalities for original MiNLO:

- $\mu_F = Q_0$ (as in CKKW)
- Cluster with CKKW also V and R kinematics
  - Actual implementation uses FKS mapping for first cluster of $\mathbf{\Phi}_{n+1}$
  - Ignore CKKW Sudakov for 1^{st} clustering of $\mathbf{\Phi}_{n+1}$ (inclusive on extra radiation)
- Some freedom in choice of $\alpha_{\rm S}^{(\rm NLO)}$ (entering V, R and $\Delta^{(1)}$):
  * suggested average of LO $\alpha_{\rm S}$
  * not free for "improved" MiNLO
- Used full NLL-improved Sudakovs (A_1, B_1, A_2)

Improved MiNLO: where are terms coming from when differentiating resum. formula?

$1/q_T^2$, always from integration in Sudakov
$\alpha_{\rm S}$ from $C^{(0)} \times B_1$, ...
$\alpha_{\rm S}^2$ from $C^{(0)} \times B_2$, ...
...
$\alpha_{\rm S} L$ from A_1 term in exponent
$\alpha_{\rm S} L^2$ from A_2 term in exponent
...

NNLO+PS (p_T^H)

p_T^H spectrum:

- "$\mu_{\mathrm{HJ-MiNLO}} = m_H, m_H, p_T$"
- At high p_T, $\mu_{\mathrm{HJ-MiNLO}} = p_T$
- If $\beta = 1/2$, NNLOPS $\to$ HJ-MiNLO at high p_{T}
- NNLO/NLO ~ 1.5, because HNNLO with $\mu = m_H/2$, $\mu_{\mathrm{HJ-MiNLO,core}} = m_H$