NNLOPS predictions for Higgs boson production

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GGI

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Outline

- brief motivation
- method used
- results
- conclusion, discussion, ...lunch!

NNLO Higgs production

NLO not always enough: NNLO needed when

1. large NLO/LO “K-factor”
   [as in Higgs Physics]
2. very high precision needed
   [e.g. Drell-Yan]

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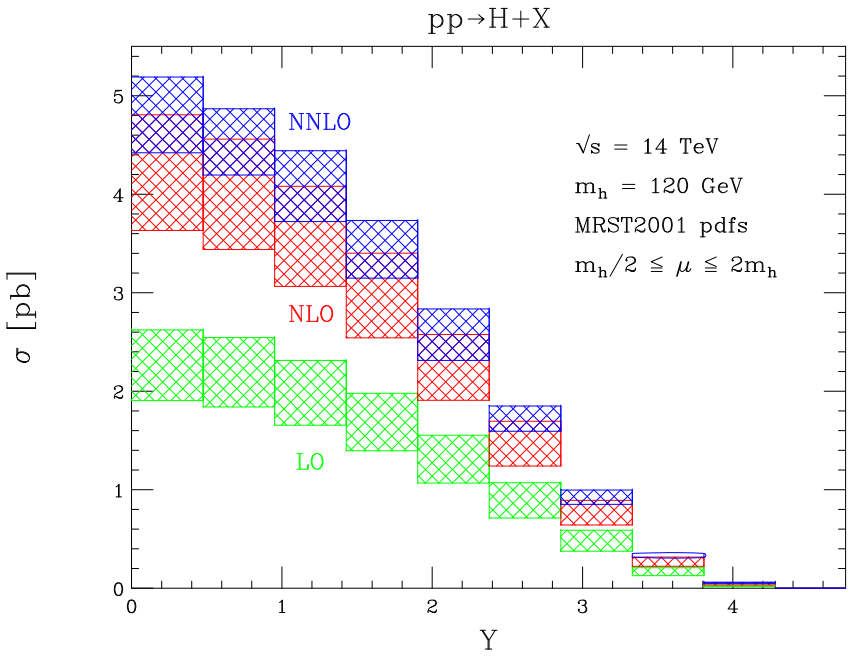
  huge progress in NNLO



[Anastasiou et al., ’04-’05]

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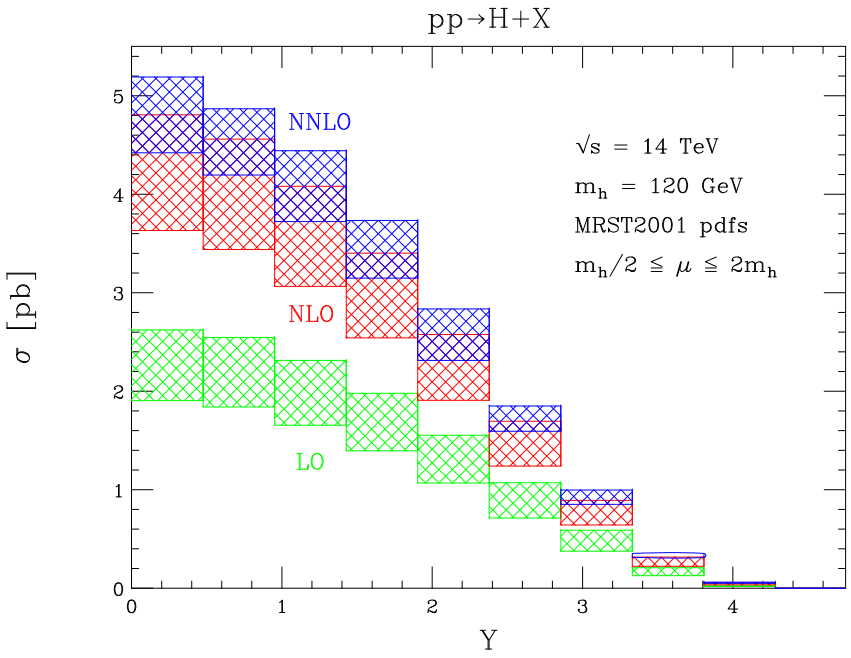


Q: can we merge NNLO and PS?

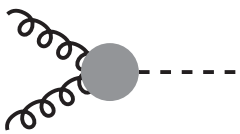
[Anastasiou et al., '04-'05]

☞ Realistic event generation with state-of-the-art perturbative accuracy !
☞ could be important for precision studies in Higgs physics

- 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]

Summary of the talk

Higgs at NNLO:



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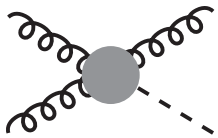

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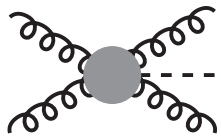

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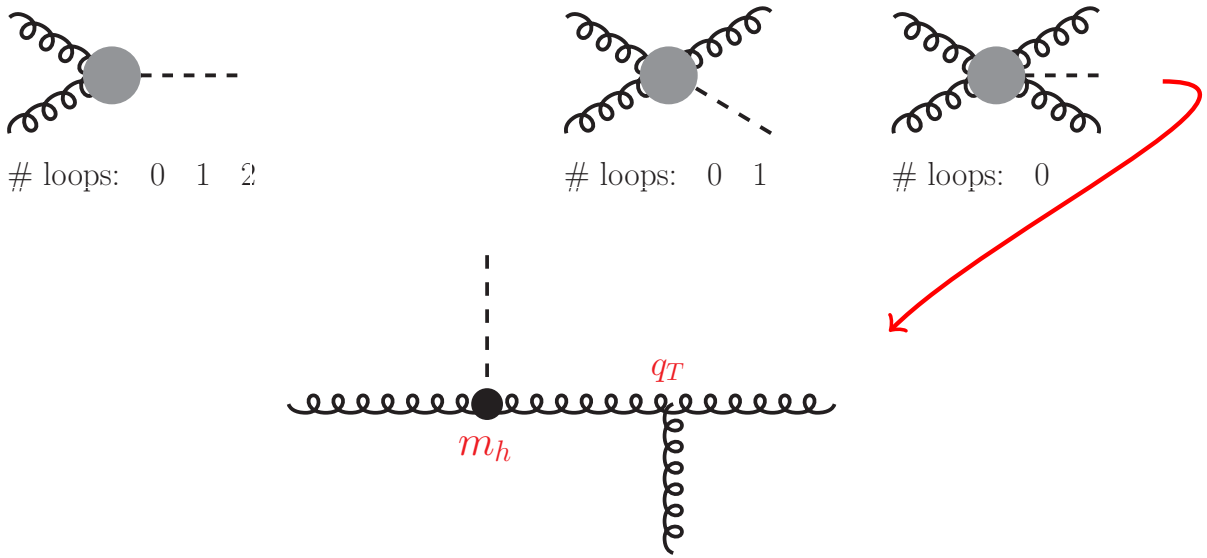

(a) 1 and 2 jets: POWHEG H+1j

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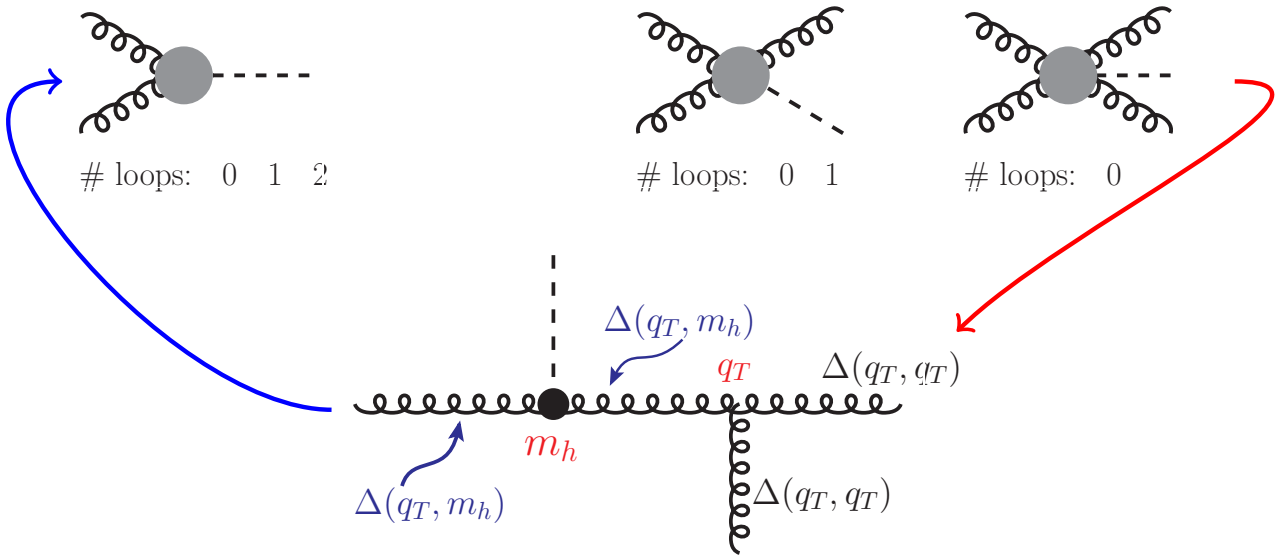

(b) - integrate down to $q_T = 0$ with MiNLO
- "Improved MiNLO" allows to build a H-HJ @ NLOPS generator

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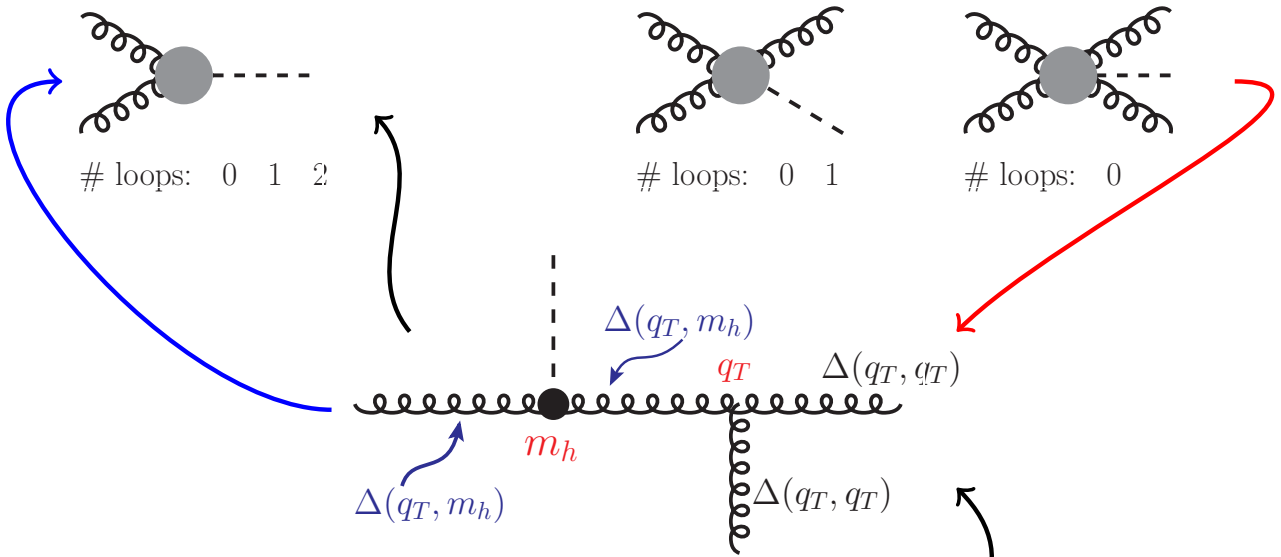

(c) 2 loops missing: from exact fixed-order NNLO

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

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

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

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-HJ @ NLOPS	NLO	NLO	LO
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☞ a merged H-HJ generator is almost OK

- many of the multijet NLO+PS merging approaches work by combining 2 (or more) NLO+PS generators, introducing a merging scale
- POWHEG + MiNLO: no need of 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
  - has been used in V/H + up to 2 jets and in VH + up to 1 jet

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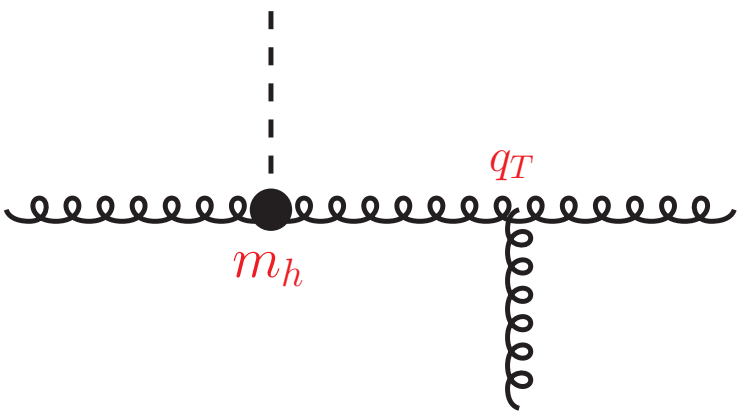

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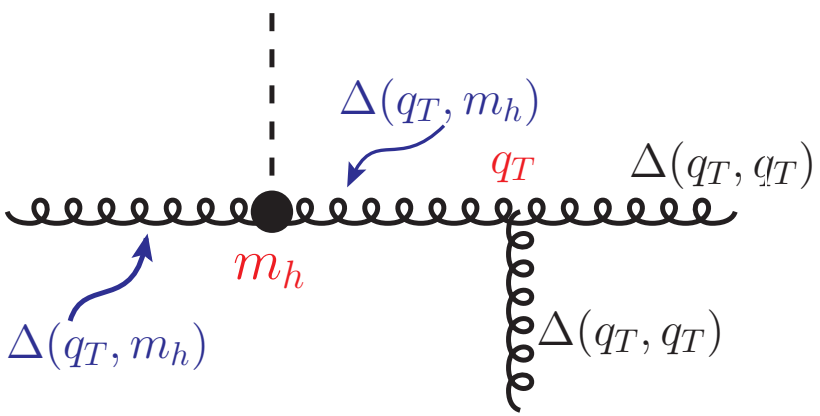

- $\bar{\mu}_R = (m_h^2 q_T)^{1/3}$
- $\log \Delta_{\rm f}(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_{\rm S}(q^2)}{2\pi} \left[A_f \log \frac{m_h^2}{q^2} + B_f\right]$
- $\Delta_{\rm f}^{(1)}(q_T, m_h) = -\frac{\alpha_{\rm S}^{(\rm NLO)}}{2\pi} \left[\frac{1}{2} A_{1,\rm f} \log^2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

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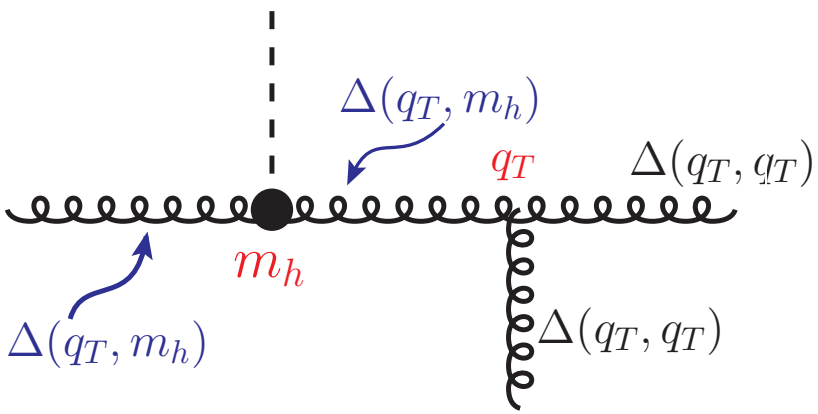

☞ Sudakov FF included on H+j Born kinematics

- 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 $\alpha_S^2 + \alpha_S^3$
- to reach genuine NLO when fully inclusive (NLO$^{(0)}$), “spurious” terms must be of relative order α_S^2, *i.e.*

$$O_{\mathrm{HJ-MiNLO}} = O_{\mathrm{H@NLO}} + \mathcal{O}(\alpha_S^4) \qquad \text{if } O \text{ is inclusive}$$

- “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$^{(1)}$) .

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- proof based on careful comparisons of MiNLO with general resummation formula

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

- need to include B_2 coefficient in MiNLO-Sudakovs:
  - 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 relative $\mathcal{O}(\alpha_S^{3/2})$
- need to evaluate ${\alpha_S}^{(\text{NLO})}$ in HJ-MiNLO at scale q_T, and $\mu_F = q_T$

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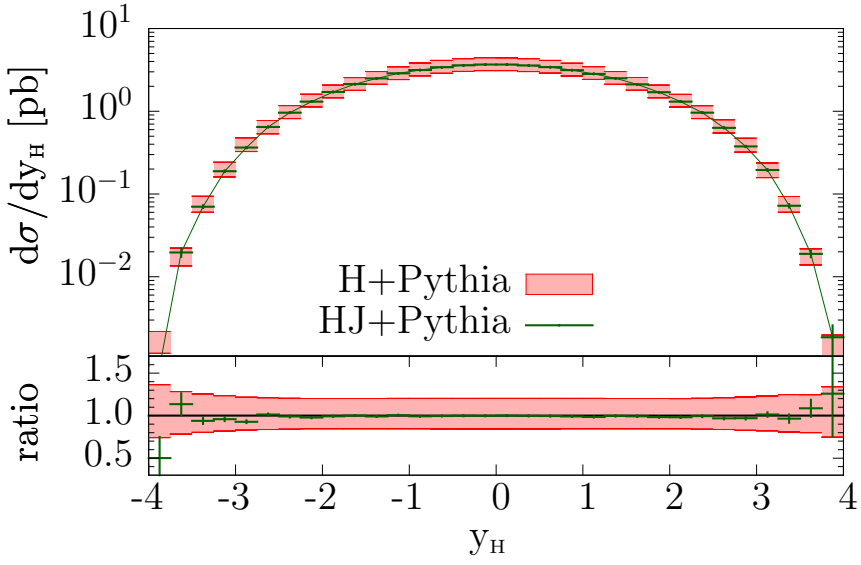
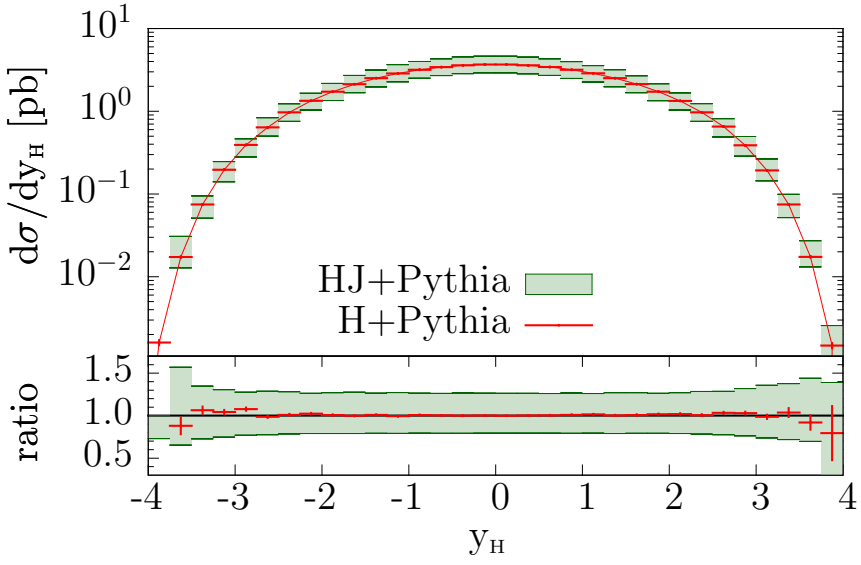
- Possible to improve `HJ-MiNLO` such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of H+j (NLO$^{(1)}$) .

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

H-HJ @ NLOPS





- "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 I

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

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
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H @ NNLOPS	NNLO	NLO	LO

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- reweighting (differential on y_H) of "MiNLO-generated" events:

$$W(y_H) = \frac{\left(\frac{d\sigma}{dy_H}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy_H}\right)_{\mathrm{HJ-MiNLO}}}$$

  - by construction NNLO accuracy on fully inclusive observables ($\sigma_{\mathrm{tot}}, y_H$) [✓]
  - 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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  - 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 $\mathcal{O}(\alpha_{\rm S}^{2+1.5})$ terms in H-HJ @ NLOPS

Higgs at NNLO+PS II

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

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

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

. $h(p_T)$ 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 Higgs (and for Drell-Yan) we used

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

. one gets exactly $(d\sigma/dy)_{\rm NNLOPS} = (d\sigma/dy)_{\rm NNLO}$ (no $\alpha_{\rm S}^5$ terms)

. we used $h(p_T^{j_1})$

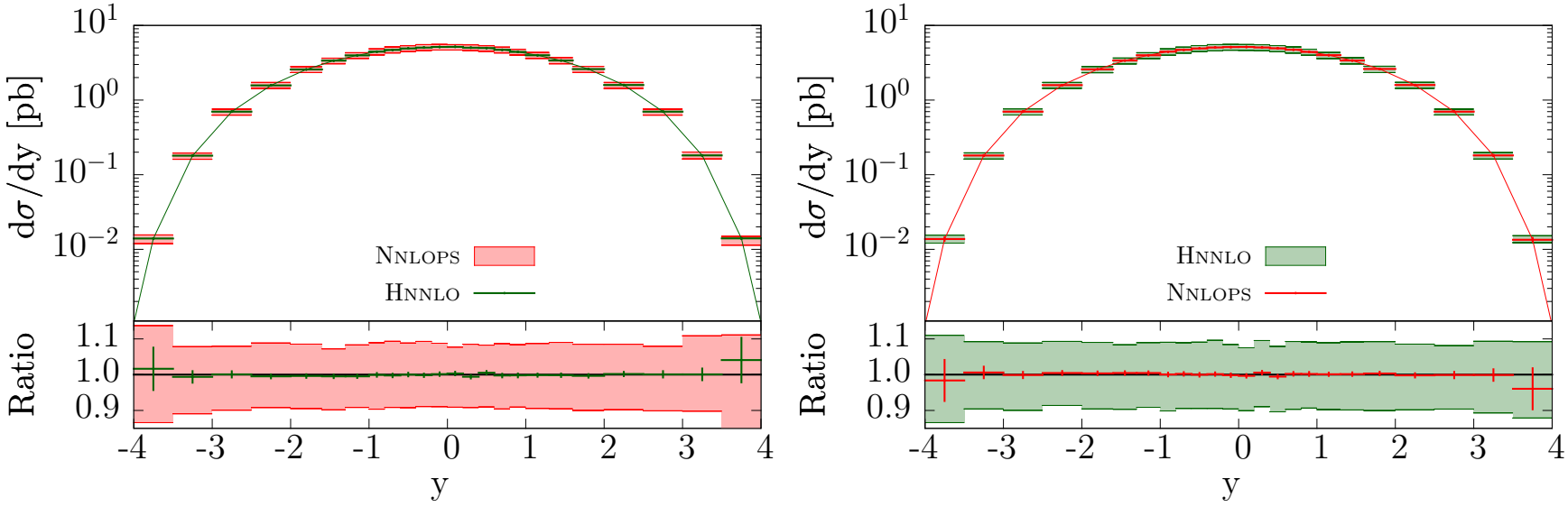
Settings

inputs for following 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`
- 6M events reweighted at the LH level
- plots after k_{T}-ordered `PYTHIA 6` at the PS level (hadronization and MPI switched off)

NNLO+PS (fully incl.)

- 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

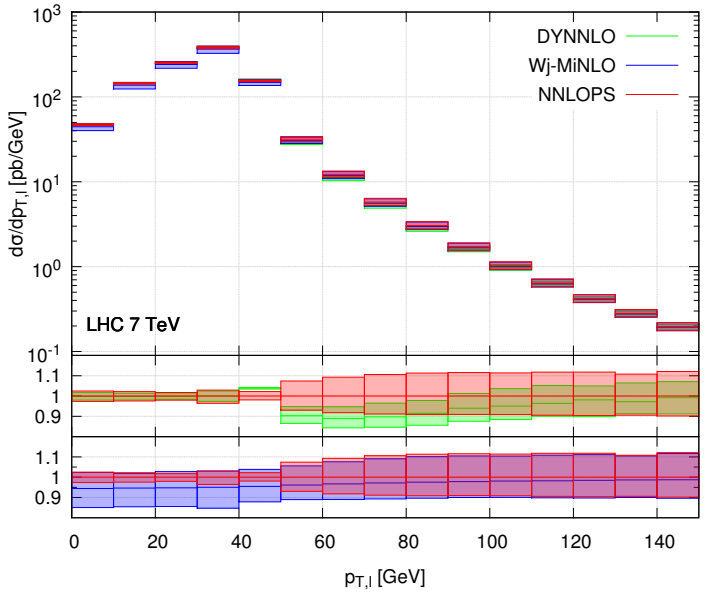


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%)

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

NNLO+PS: multi-dim reweighting

- for Higgs: 1-dim NNLOPS reweighting ($W(y; p_T)$), so y_H will be obviously OK
- does it work if Φ_B is multi-dim (as in Drell-Yan)?



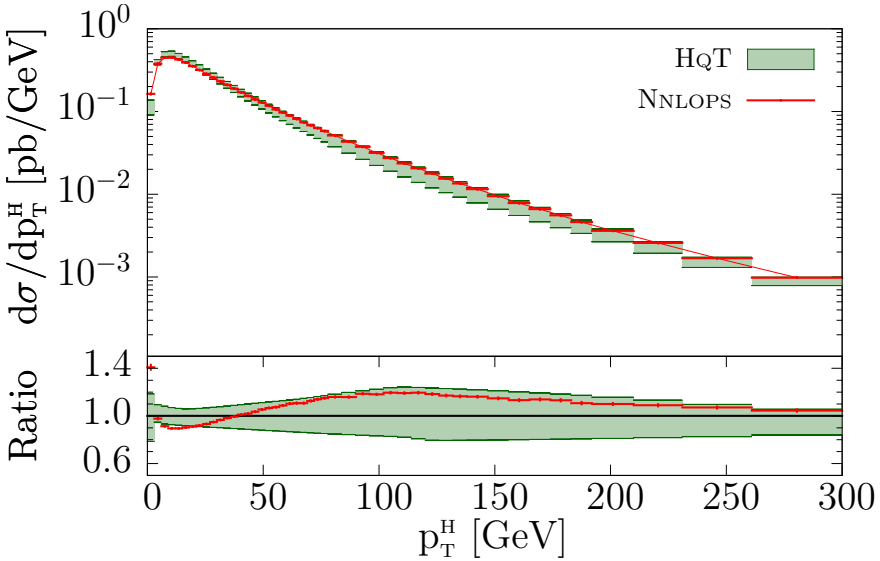
- $p_{T,\ell}$ is not the observable we are using to do the NNLO reweighting

✓ we see exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_{T,\ell} < M_W/2$, and NLO if $p_{T,\ell} > M_W/2$

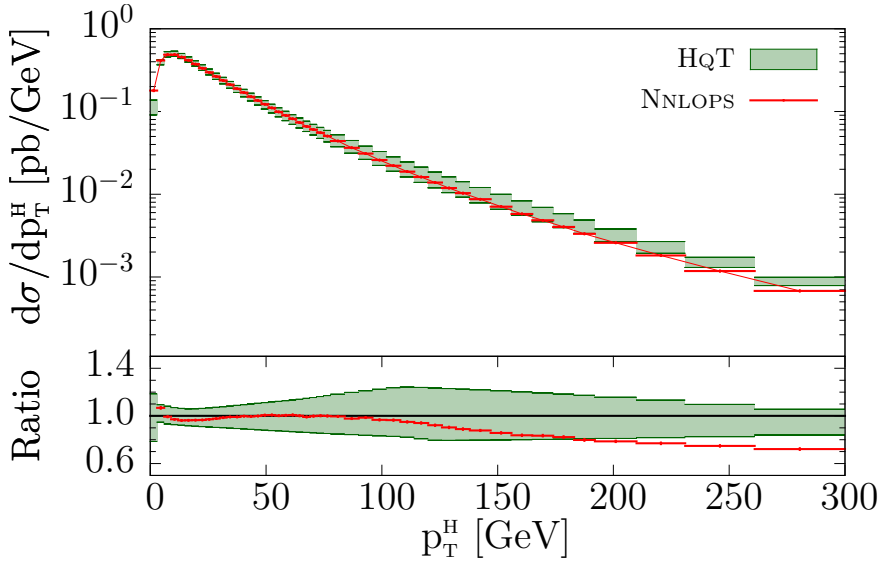
- [just above peak, `DYNNLO` uses M_W, `WJ-MiNLO` uses $p_{T,W}$ and here $0 \lesssim p_{T,W} \lesssim M_W$]

NNLO+PS (p_T^H)

$\beta = \infty$ (W indep. of p_T)



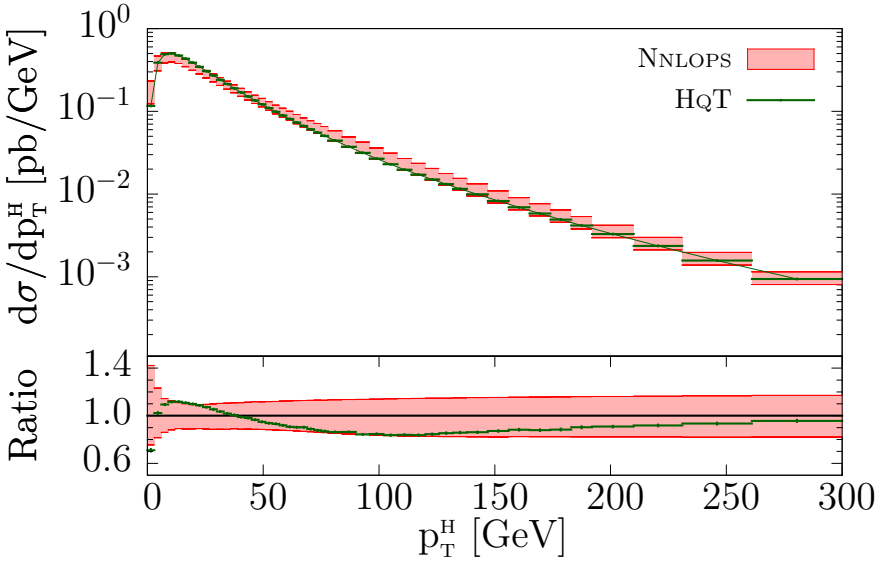
$\beta = 1/2$



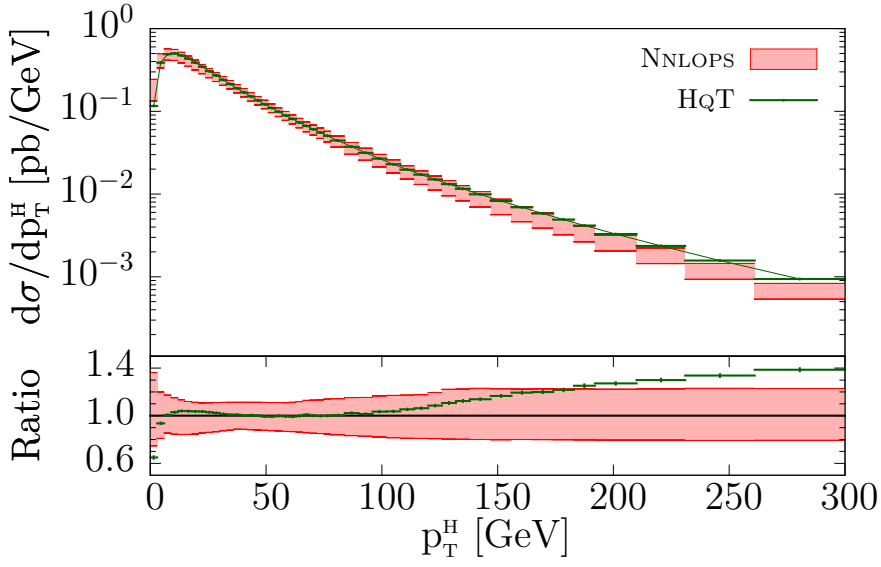
- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$ [HqT, Bozzi et al.]
- ✓ $\beta = 1/2$ & ∞: uncertainty bands of HqT contain NNLOPS at low-/moderate p_T
- $\beta = 1/2$: HqT tail harder than NNLOPS tail ($\mu_{\rm HqT} <$ "$\mu_{\rm MiNLO}$")
  HJ @ NNLO will allow to say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

NNLO+PS (p_T^H)

$\beta = \infty$ (W indep. of p_T)

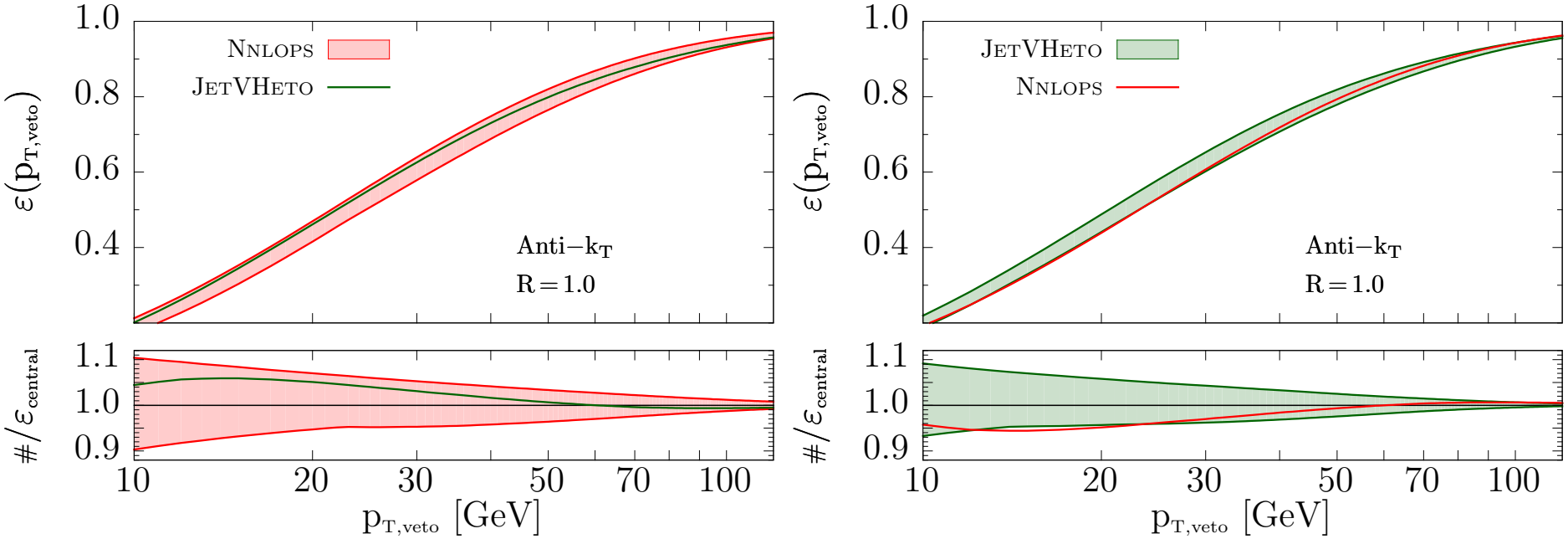


$\beta = 1/2$



- `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)

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



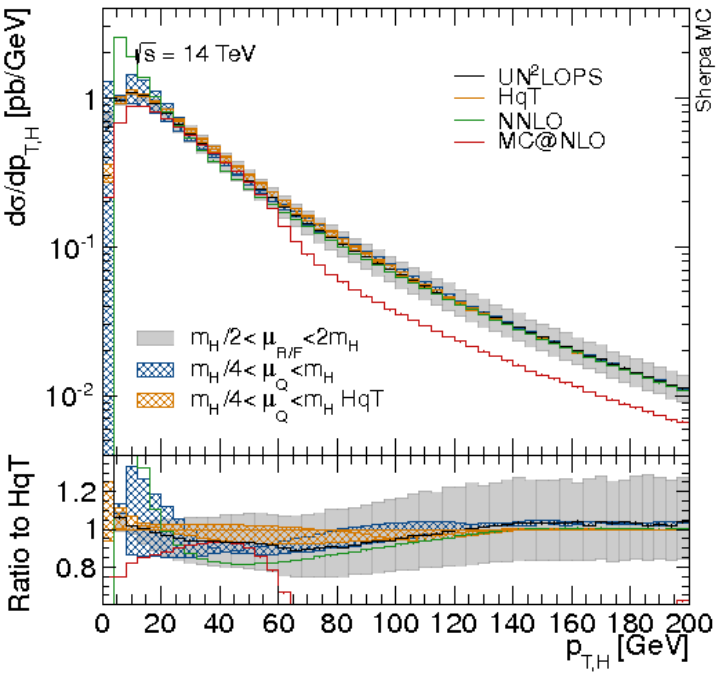
$$\varepsilon\left(p_{\mathrm{T,veto}}\right) = \frac{\Sigma(p_{\mathrm{T,veto}})}{\sigma^{\mathrm{tot}}} = \frac{1}{\sigma^{\mathrm{tot}}} \int d\sigma\ \theta\left(p_{\mathrm{T,veto}} - p_{\mathrm{T}}^{\mathrm{j1}}\right)$$

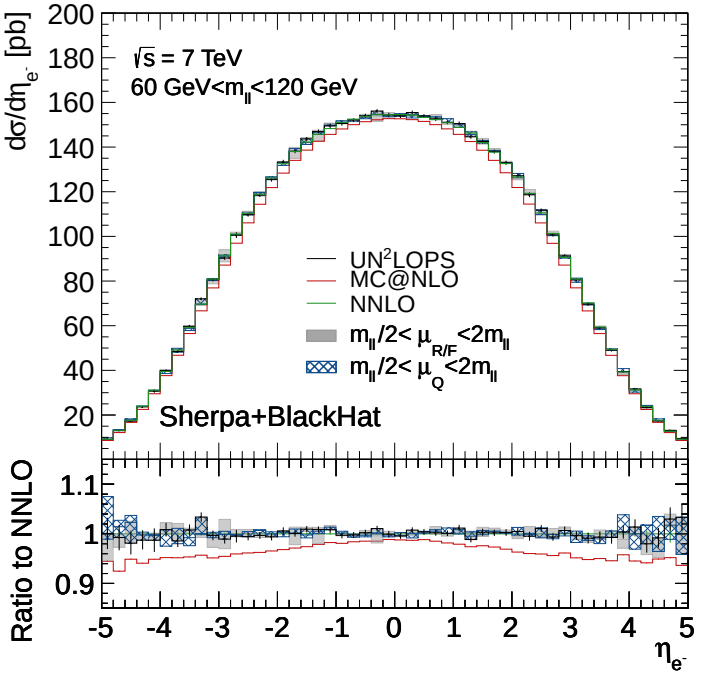
- `JetVHeto`: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\mathrm{res}} \equiv m_H/2$, (a)-scheme only
  [`JetVHeto`, Banfi et al.]
- nice agreement, differences never more than 5-6 %

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

other NNLOPS results this year

- UNNLOPS [Hoeche,Li,Prestel '14]





- formalism worked out also within the `Geneva` framework: [Alioli,Bauer, et al, '13]
  - work in progress, preliminary results for DY shown at "PSR2014"

conclusions

- MiNLO-improved POWHEG generator allows to reach NNLOPS accuracy for simple processes
- shown results for Higgs at NNLOPS
- predictions and theoretical uncertainties match NNLO where they have to
- typically, quite good agreement with analytic resummation (but for Drell-Yan slightly worse...)
  - good news, but not yet really studied/understood formally
- other approaches appeared: will be interesting to compare
- mass effects in Higgs @ NNLOPS
- ... phenomenology ...

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Thank you for your attention!