NLO Monte Carlo Tools for Higgs Physics at the LHC

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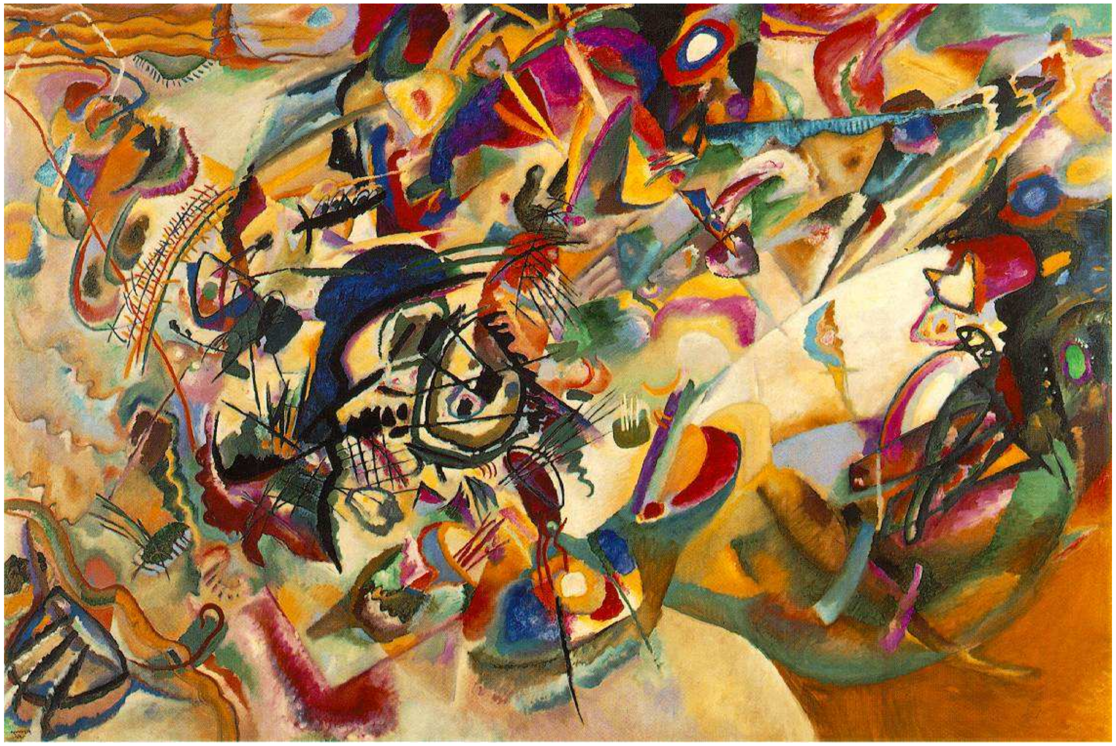
- Introduction to NLO Monte Carlo programs
- Higgs boson production in gluon fusion: H, Hj and Hjj
- H in VBF
- $t\bar{t}H$
- VH
- $tH^{\pm}$



Higgs boson production

- H in gluon fusion: MC@NLO, POWHEG BOX, POWHEG+SHERPA, POWHEG+HERWIG++, MC@NLO+SHERPA
- H+1jet: POWHEG+SHERPA, MC@NLO+SHERPA, POWHEG BOX
- H+2jet: POWHEG BOX
- H in VBF: POWHEG BOX, POWHEG+HERWIG++
- $t\bar{t}H$: POWHEG BOX + HELAS, aMC@NLO
- VH: POWHEG+HERWIG++, MC@NLO
- $tH^{\pm}$: MC@NLO, POWHEG BOX
- $H \to Q\overline{Q}$: POWHEG+HERWIG++

NLO vs Shower Monte Carlo

NLO

- ✓ accurate shapes at high p_T
- ✓ normalization accurate at NLO order
- ✓ reduced dependence on renormalization and factorization scales
- ✗ wrong shapes at small p_T
- ✗ description only at the parton level

SMC (LO + shower)

- ✗ bad description at high p_T
- ✗ normalization accurate only at LO
- ✓ correct Sudakov suppression at small p_T
- ✓ simulate events at the hadron level

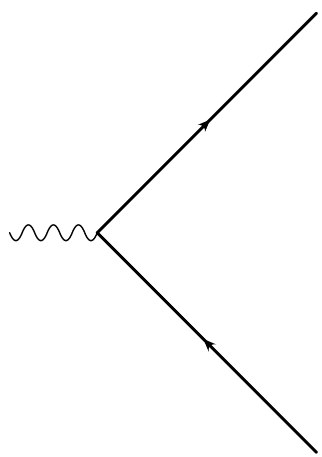
It is natural to try to merge the two approaches, keeping the good features of both

MC@NLO [Frixione and Webber, 2001] and POWHEG [Nason, 2004] do this in a consistent way

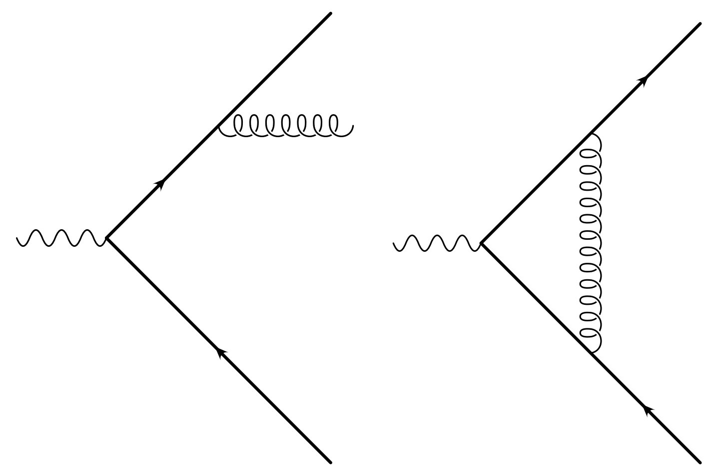
NLO + Parton Shower

The main problem in merging a NLO result and a Parton Shower is not to double-count radiation: the shower might produce some radiation already present at the NLO level (both at the virtual and at the real level).

LO:



NLO:



NLO differential cross section

The $(n+1)$-body phase space $d\mathbf{\Phi}_{n+1}$ can be factorized in term of the n-body phase space $\mathbf{\Phi}_n$ times the radiation phase space $d\Phi_r$: $d\mathbf{\Phi}_{n+1} = d\mathbf{\Phi}_n \times d\Phi_r$

$$d\sigma_{\text{NLO}} = d\mathbf{\Phi}_n \Big\{ B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \left[R(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r)\right] d\Phi_r \Big\}$$

$$d\mathbf{\Phi}_{n+1} = d\mathbf{\Phi}_n \times d\Phi_r \qquad\qquad d\Phi_r \div dt\, dz\, d\varphi$$

$$V(\mathbf{\Phi}_n) = V_b(\mathbf{\Phi}_n) + \int d\Phi_r\, C(\mathbf{\Phi}_n, \Phi_r) \qquad \Longleftarrow \text{ finite}$$

$$d\sigma_{\text{SMC}} = B(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta_{t_0} + \frac{\alpha_s}{2\pi} P(z) \frac{1}{t} \Delta_t\, d\Phi_r \right\}$$

$$\Delta_t = \exp\left[-\int d\Phi_r' \frac{\alpha_s}{2\pi} P(z') \frac{1}{t'} \theta(t' - t) \right] \qquad \text{SMC Sudakov form factor}$$

The POWHEG differential cross section

$R = R_s + R_f$ with $R_s > 0$, $R_f > 0$, R_s **s**ingular in the infrared regions, R_f **f**inite in collinear and soft limit. Define

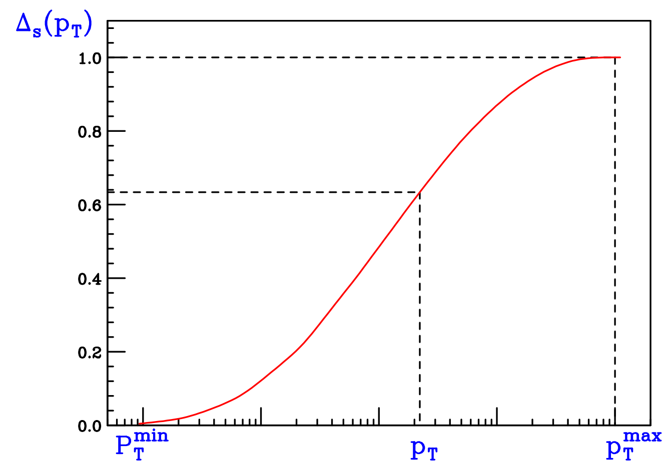
$$d\sigma = \overline{B}_s(\boldsymbol{\Phi}_n) \underbrace{\left\{ \Delta_s\left(p_T^{min}\right) + \Delta_s(p_T) \frac{R_s(\boldsymbol{\Phi}_{n+1})}{B(\boldsymbol{\Phi}_n)} \, d\Phi_r \right\}}_{\text{1 by unitarity}} d\boldsymbol{\Phi}_n + R_f(\boldsymbol{\Phi}_{n+1}) \, d\boldsymbol{\Phi}_{n+1}$$

$$\overline{B}_s(\boldsymbol{\Phi}_n) = B(\boldsymbol{\Phi}_n) + V(\boldsymbol{\Phi}_n) + \int d\Phi_r \left[R_s(\boldsymbol{\Phi}_n, \Phi_r) - C(\boldsymbol{\Phi}_n, \Phi_r) \right]$$

$$\Delta_s(p_T) = \exp\left[-\int d\Phi_r' \frac{R_s(\boldsymbol{\Phi}_n, \Phi_r')}{B(\boldsymbol{\Phi}_n)} \theta(p_T' - p_T) \right]$$

The expansion of $d\sigma$ up to the NLO level is exactly equal to $d\sigma_{\mathrm{NLO}}$.

The part of the real cross section that is treated with the shower technique can be varied.



MC@NLO in the POWHEG language

Write the MC@NLO hardest jet cross section in the POWHEG language. Hardest emission can be written as [Nason 2004]

$$d\sigma = \underbrace{\overline{B}_{\rm HW}\, d\mathbf{\Phi}_n}_{\mathbb{S}\ \text{event}} \underbrace{\left[\Delta_{\rm HW}(p_T^{min}) + \Delta_{\rm HW}(p_T)\frac{R_{\rm HW}(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)}\, d\Phi_r\right]}_{\text{HERWIG event}} + \underbrace{\left[R(\mathbf{\Phi}_{n+1}) - R_{\rm HW}(\mathbf{\Phi}_{n+1})\right] d\mathbf{\Phi}_{n+1}}_{\mathbb{H}\ \text{event}}$$

$$\overline{B}_{\rm HW}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int \left[R_{\rm HW}(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r)\right] d\Phi_r$$

$$\Delta_{\rm HW}(p_T) = \exp\left[-\int d\Phi_r' \frac{R_{\rm HW}(\mathbf{\Phi}_n, \Phi_r')}{B(\mathbf{\Phi}_n)}\,\theta(p_T' - p_T)\right]$$

Like POWHEG with
$$\begin{cases} R_s = R_{\rm HW} & \\ R_f = R - R_{\rm HW} & \Longleftarrow \ \text{can be negative} \end{cases}$$

This formula illustrates why MC@NLO and POWHEG are equivalent at NLO!
But differences can arise at NNLO.

The radiation cross section

$$\overline{B}_s(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r \left[R_s(\mathbf{\Phi}_n, \Phi_r) - C(\mathbf{\Phi}_n, \Phi_r)\right]$$

$$d\sigma = \overline{B}_s(\mathbf{\Phi}_n) \left\{ \Delta_s(p_T^{min}) + \Delta_s(p_T) \frac{R_s(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)} d\Phi_r \right\} d\mathbf{\Phi}_n + R_f(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$$

The differential cross section describing the hard radiation is given by

$$\begin{aligned} d\sigma_{\rm rad} &\approx \frac{\overline{B}_s(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} R_s(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} + R_f(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} \\ &= \left\{ R_s(\mathbf{\Phi}_{n+1}) + R_f(\mathbf{\Phi}_{n+1}) + \left[\frac{\overline{B}_s(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} - 1\right] R_s(\mathbf{\Phi}_{n+1}) \right\} d\mathbf{\Phi}_{n+1} \\ &= R(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} + \mathcal{O}(\alpha_s) R_s(\mathbf{\Phi}_{n+1}) \end{aligned}$$

- We expect differences at the NNLO level. While formally at NNLO, they may be large for particular processes (see i.e. Higgs boson production in gluon fusion).
- Notice that the $\overline{B}_s(\mathbf{\Phi}_n)/B(\mathbf{\Phi}_n)$ also depends on how the real contribution R has been split into R_s and R_f.

Sources of possible differences

$$d\sigma_{\rm rad} \approx \frac{\overline{B}_s(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} R_s(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1} + R_f(\mathbf{\Phi}_{n+1})\, d\mathbf{\Phi}_{n+1}$$

In an NLO+Parton Shower implementation, visible differences of the radiation cross section with respect to the fixed-order result will be present, due to

1. The $\Delta_s(p_T)$ factor, dropped in the NLO-accuracy derivation.
   The Sudakov factor yields resummation-improved results at NLO.
   It is less than 1: it always reduces the transverse-momentum spectrum of radiation with respect to the pure NLO result

2. The $\overline{B}_s(\mathbf{\Phi}_n)/B(\mathbf{\Phi}_n)$ factor, also dropped.
   This factor spreads the K factor over the finite p_T region. The spreading of the K factor depends upon the R_s and R_f separation.

3. The choice of scales used in the process.

In summary

Experience in comparing MC@NLO and POWHEG results (various papers from the POWHEG BOX and from the Herwig++ collaborations) has shown that

- all important differences between MC@NLO and POWHEG can be tracked back to the rôle of the $\overline{B}_s / B$ factor and to scale-choice issues.
- Exponentiation in $\Delta_s(p_T)$ does not seem to yield important differences. This is understood as due to the fact that the integral in

$$\Delta_s(p_T) = \exp\left[-\int d\Phi'_r \, \frac{R_s(\mathbf{\Phi}_n, \Phi'_r)}{B(\mathbf{\Phi}_n)} \, \theta(p'_T - p_T)\right]$$

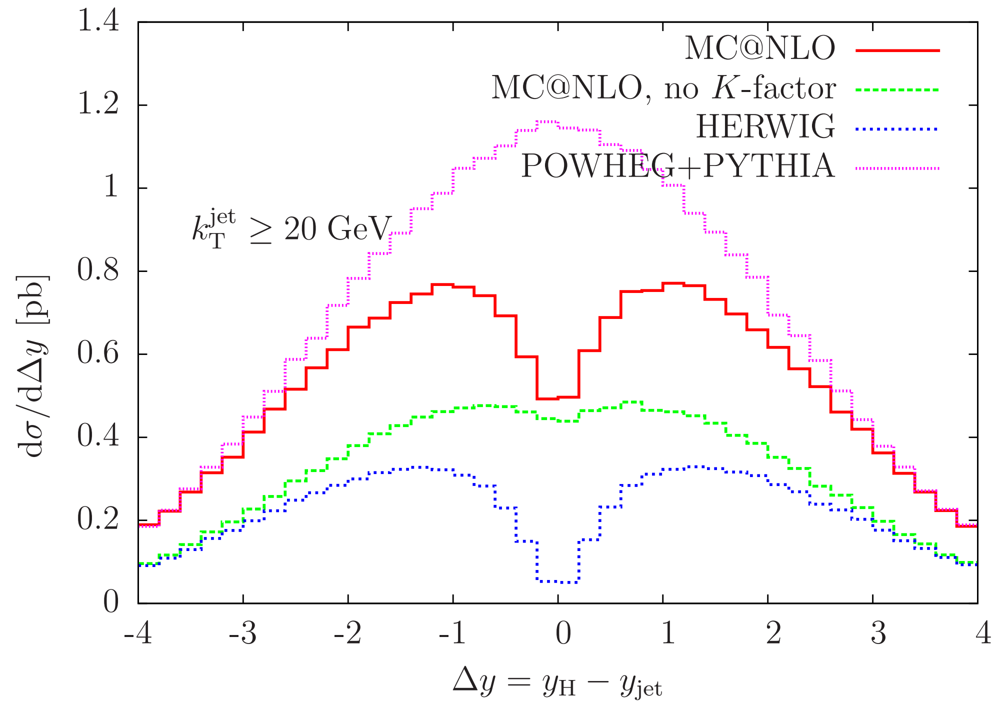
is dominated by the region of soft p_T, where all R_s agree.

As seen before, at high p_T, the MC@NLO radiation cross section goes as

$$d\sigma \approx \underbrace{R(\mathbf{\Phi}_{n+1})}_{\text{no dip}} d\mathbf{\Phi}_{n+1} + \underbrace{\left(\frac{\overline{B}_{\mathrm{HW}}(\mathbf{\Phi}_n)}{B(\mathbf{\Phi}_n)} - 1\right)}_{\mathcal{O}(\alpha_s)\text{ but large for Higgs}} \underbrace{R_{\mathrm{HW}}(\mathbf{\Phi}_{n+1})}_{\text{pure HERWIG dip}} d\mathbf{\Phi}_{n+1}$$

So: a contribution with a dip is added to the exact NLO result.
The contribution is $\mathcal{O}(\alpha_s R)$, i.e. NNLO

If we replace $\overline{B}_{\mathrm{HW}} \to B$ in MC@NLO, the dip disappears



[Alioli, Nason, Re and C.O., 2008; Hamilton, Richardson and Tully, 2009; Nason and Webber, 2012]

Scale dependence

$$d\sigma = \overline{B}_s(\mathbf{\Phi}_n, \mu_R)\, d\mathbf{\Phi}_n \left\{ \Delta_s(\mathbf{\Phi}_n, p_T^{min}) + \Delta_s(\mathbf{\Phi}_n, p_T)\, \frac{R_s(\mathbf{\Phi}_n, \Phi_r, \alpha_s(k_T))}{B(\mathbf{\Phi}_n)}\, d\Phi_r \right\}$$

$$+ R_f(\mathbf{\Phi}_{n+1}, \alpha_s(\mu_R))\, d\mathbf{\Phi}_{n+1}$$

$$\overline{B}_s(\mathbf{\Phi}_n, \mu_R) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n, \alpha_s(\mu_R)) + \int d\Phi_r \left[R_s(\mathbf{\Phi}_n, \Phi_r, \alpha_s(\mu_R)) - C(\mathbf{\Phi}_n, \Phi_r, \alpha_s(\mu_R)) \right]$$

$$\Delta_s(\mathbf{\Phi}_n, p_T) = \exp\left[- \int d\Phi_r' \, \frac{R_s(\mathbf{\Phi}_n, \Phi_r', \alpha_s(k_T))}{B(\mathbf{\Phi}_n)}\, \theta(k_T(\mathbf{\Phi}_n, \Phi_r') - p_T) \right]$$

- A scale variation in the curly braces {} is in practice never performed (in order not to spoil the NLL accuracy of the Sudakov form factor). The scale in the Sudakov has to go exactly to the transverse momentum of the radiation in the collinear and soft region.

- Scale dependence affects $\overline{B}_s$ and R_f differently: $\overline{B}_s$ is a quantity integrated over the radiation kinematics $\Longrightarrow$ milder scale dependence

Similar conclusions for the factorization scale μ_F

Scale dependence in $gg \to H$

$$d\sigma = \overline{B}_s(\mathbf{\Phi}_n, \mu_R)\, d\mathbf{\Phi}_n \left\{ \Delta_s\left(\mathbf{\Phi}_n, p_T^{min}\right) + \Delta_s(\mathbf{\Phi}_n, p_T)\, \frac{R_s(\mathbf{\Phi}_n, \Phi_r, \alpha_s(k_T))}{B(\mathbf{\Phi}_n)}\, d\Phi_r \right\}$$

$$+ R_f(\mathbf{\Phi}_{n+1}, \alpha_s(\mu_R))\; d\mathbf{\Phi}_{n+1}$$

$$\overline{B}_s(\mathbf{\Phi}_n, \mu_R) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n, \alpha_s(\mu_R)) + \int d\Phi_r \left[R_s(\mathbf{\Phi}_n, \Phi_r, \alpha_s(\mu_R)) - C(\mathbf{\Phi}_n, \Phi_r, \alpha_s(\mu_R))\right]$$

- The $\overline{B}$ prefactor is of order α_s^2 at the Born level, and it includes NLO corrections of order α_s^3. Its scale variation must therefore be of order α_s^4.
  Therefore the relative scale variation $\delta\overline{B}/\overline{B}$ is of order α_s^2.
- On the other hand, the R_f term ($\mathbb{H}$ in MC@NLO) is of order α_s^3, and its scale variation is of order $\alpha_s^4 \Longrightarrow$ its relative scale variation is of order α_s.

Thus, the larger the contribution to the transverse momentum distribution coming from R_s (or $\mathbb{S}$ in MC@NLO) events, the smaller its relative scale dependence will be.

Scale dependence in $gg \to H$

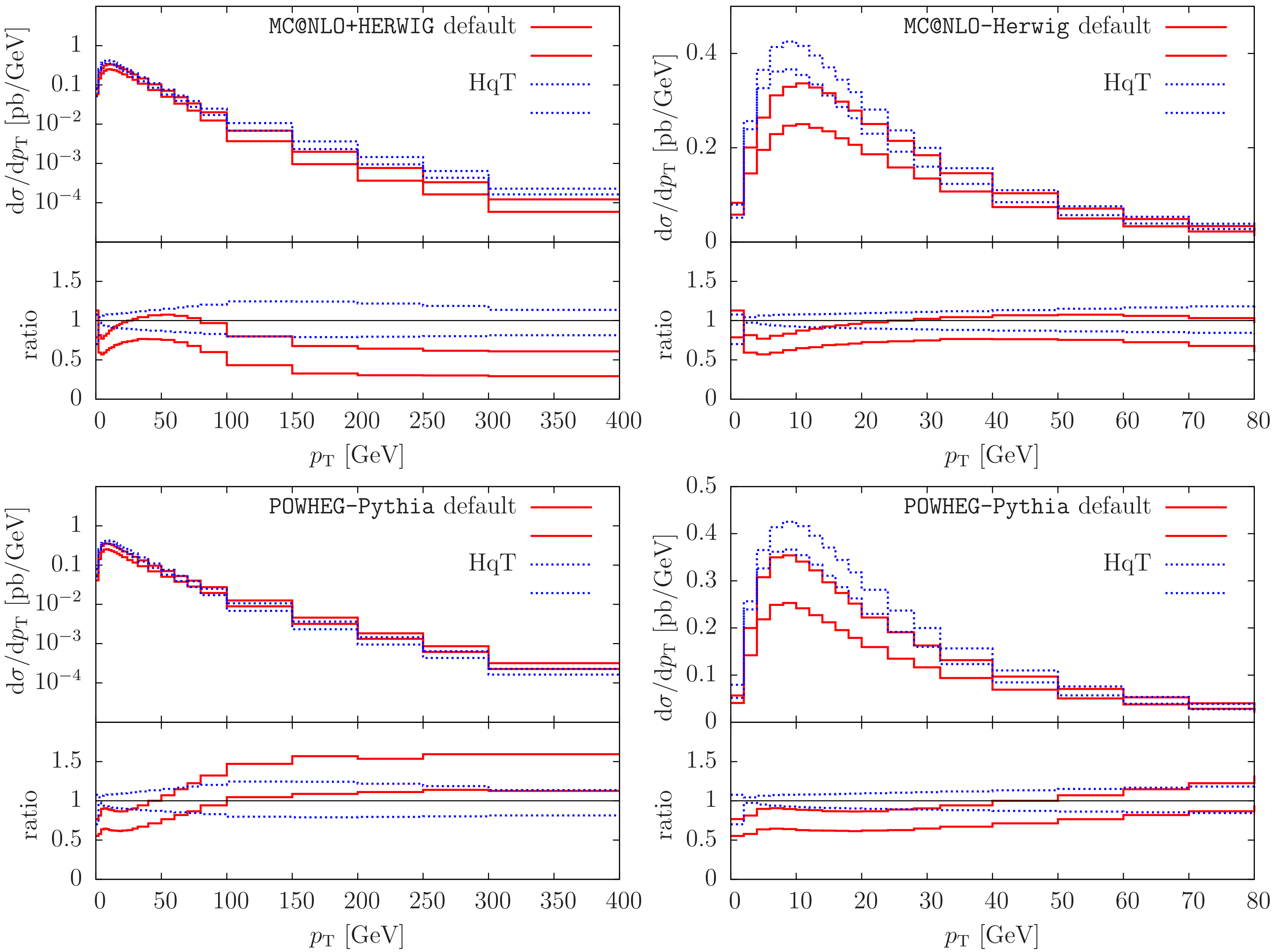
- $gg \to H$ at NLO+PS
- $m_{\mathrm{H}} = 120$ GeV
- $0.5 < \mu_{\mathrm{R}}/\mu_{\mathrm{F}} < 2$ around central reference scale μ
- Comparison with HqT [Catani, Grazzini et al.]: NNLL + NNLO. "Switched" result, with resummation scale $Q = m_{\mathrm{H}}/2$ and reference factorization and renormalization scale $\mu = m_{\mathrm{H}}$, as recommended by the authors
- MSTW2008NNLO central pdf for all the curves. This pdf set is needed by HqT. Used for all the other programs, since we want to focus on the differences that have to do with the calculation, rather than the pdf

The R_s and R_f terms are chosen such that

$$R_s = \frac{h^2}{p_T^2 + h^2} R, \qquad R_f = \frac{p_T^2}{p_T^2 + h^2} R, \qquad R = R_s + R_f$$

If $h \longrightarrow 0$, the NLO prediction is recovered, but the Sudakov region is dangerously squeezed and distorted.

If $h \longrightarrow \infty$, $R_s = R$ and $R_f \longrightarrow 0$ and the whole real contribution enters the Sudakov form factor. This is the default POWHEG BOX setting.
The NLO K factor, $\overline{B}/B$ multiplies uniformly the whole transverse-momentum distribution



DEFAULT VALUES

POWHEG

$\mu = m_H$

$h = \infty$

MC@NLO

$\mu = m_T = \sqrt{m_H^2 + p_T^2}$

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high p_T

$\frac{\text{POWHEG}}{\text{MC@NLO}} \approx 3 = 2 \times 1.6$

K fac ≈ 2

$(\alpha_s(m_T)/\alpha_s(m_H))^3 \approx 1.6$

in the last bin

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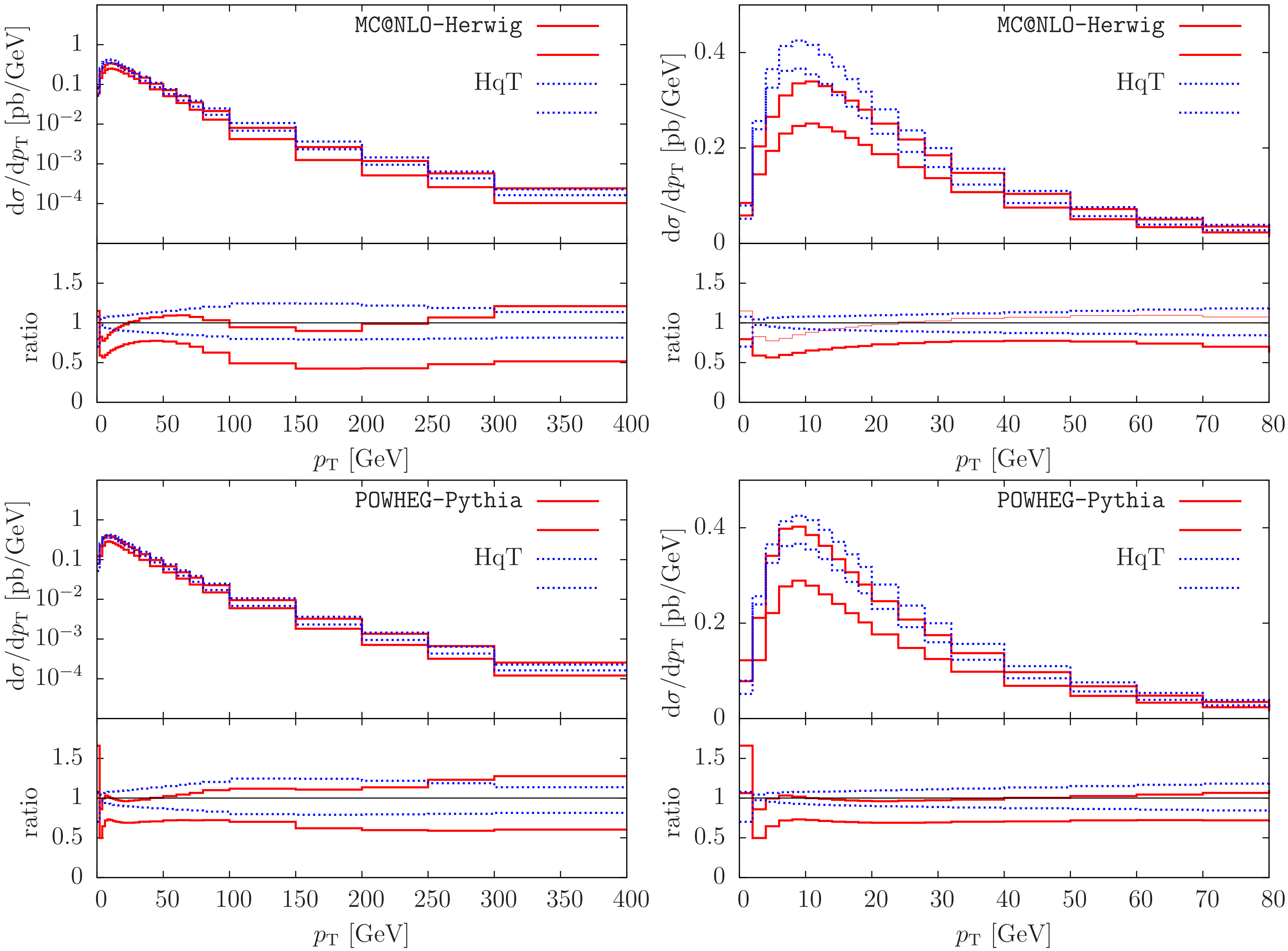
narrow band at small p_T

larger band at large p_T

[YRHXS2; Nason and Webber, 2012]



BEST VALUES

POWHEG

$\mu = m_H$

$h = \mu/1.2$

MC@NLO

$\mu = m_H$

$h = 100$ GeV, the large-p_T tail in POWHEG and MC@NLO are now very similar

---

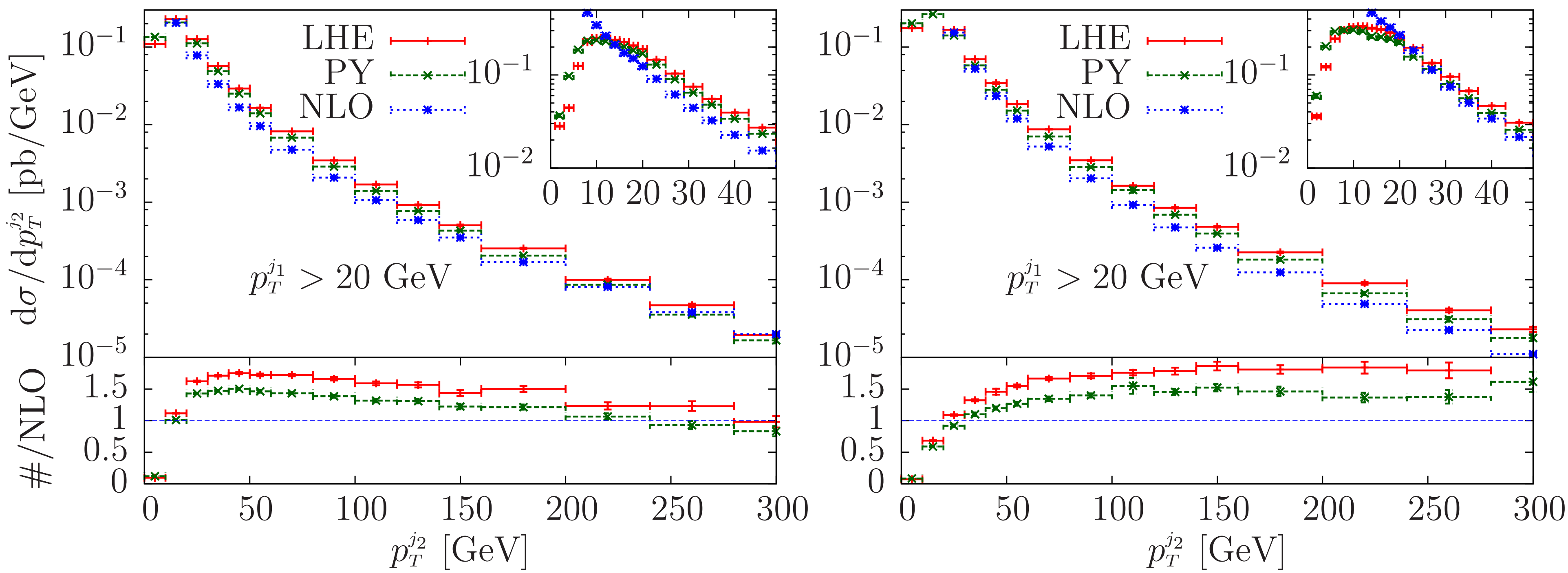
narrow band at small p_T

larger band at large p_T

Question: what is the most "appropriate" scale in the high-p_T region?

[YRHXS2; Nason and Webber, 2012]

Higgs boson plus 1 jet production

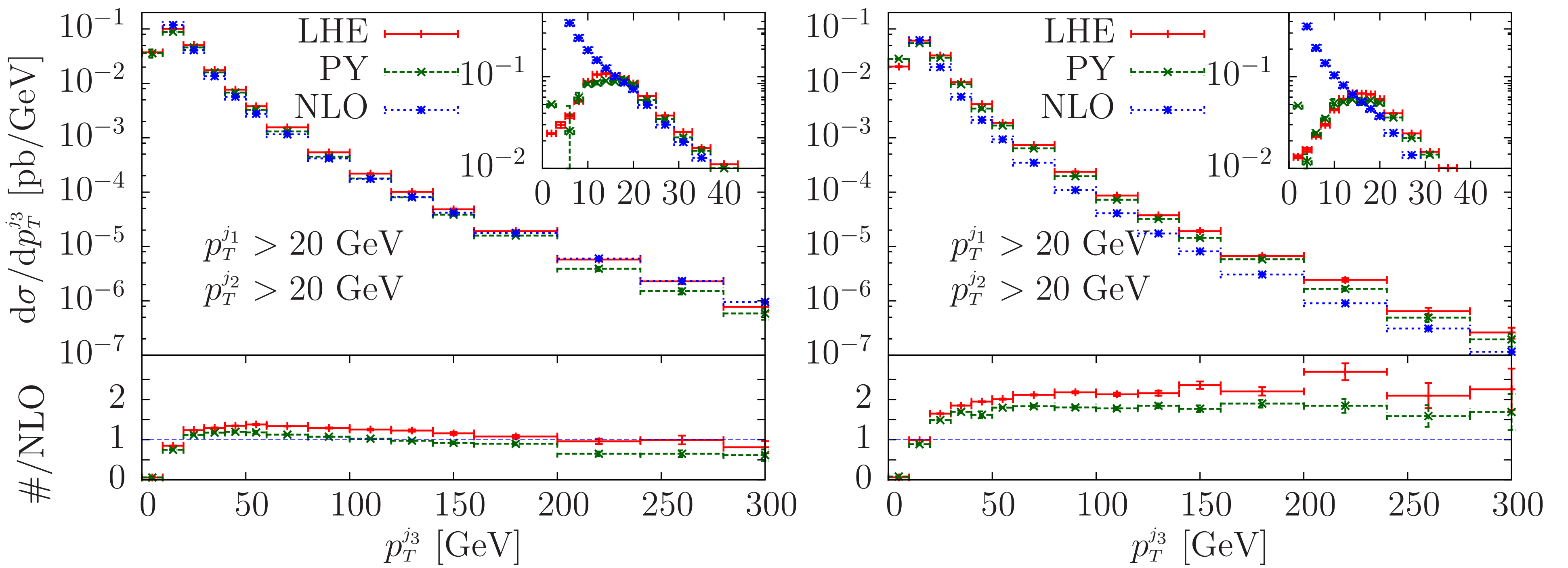


Left: $\mu_F = \mu_R = m_H$. Right: $\mu_F = \mu_R = p_T^{UB}$ = p_T of the underlying Born configuration

- Diverging NLO, Sudakov suppression in LHE
- The trend of the $\overline{B}_s/B$ factor very evident
- In LHE results, one power of α_s is evaluated at the p_T of the radiation

[Campbell, Ellis, Frederix, Nason, Williams, C.O., 2012]

Higgs boson plus 2 jet production

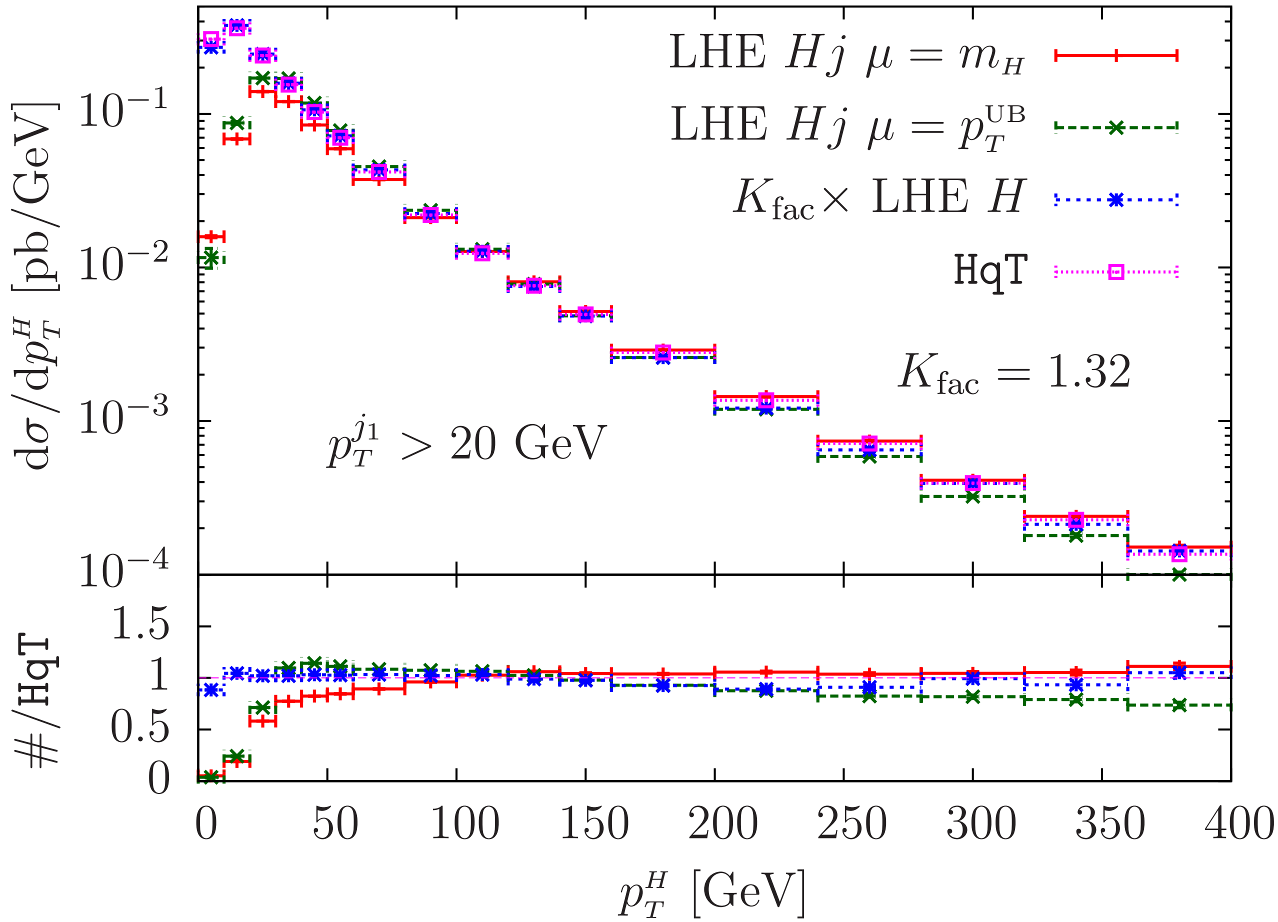


Left: $\mu_F = \mu_R = m_{\rm H}$. Right: $\mu_F = \mu_R = \hat{H}_T = m_T^H + \sum_i p_{T\,i}$ where $m_T^H = \sqrt{m_{\rm H}^2 + (p_T^H)^2}$ and $p_{T\,i}$ are the final-state parton transverse momenta in the underlying-Born kinematics.

- The trend of the $\overline{B}_s/B$ factor very evident
- K factor close to 1 for fixed scales
- These are two "extreme" scales. $\hat{H}_T$ too big at large p_T

[Campbell, Ellis, Frederix, Nason, Williams, C.O., 2012]

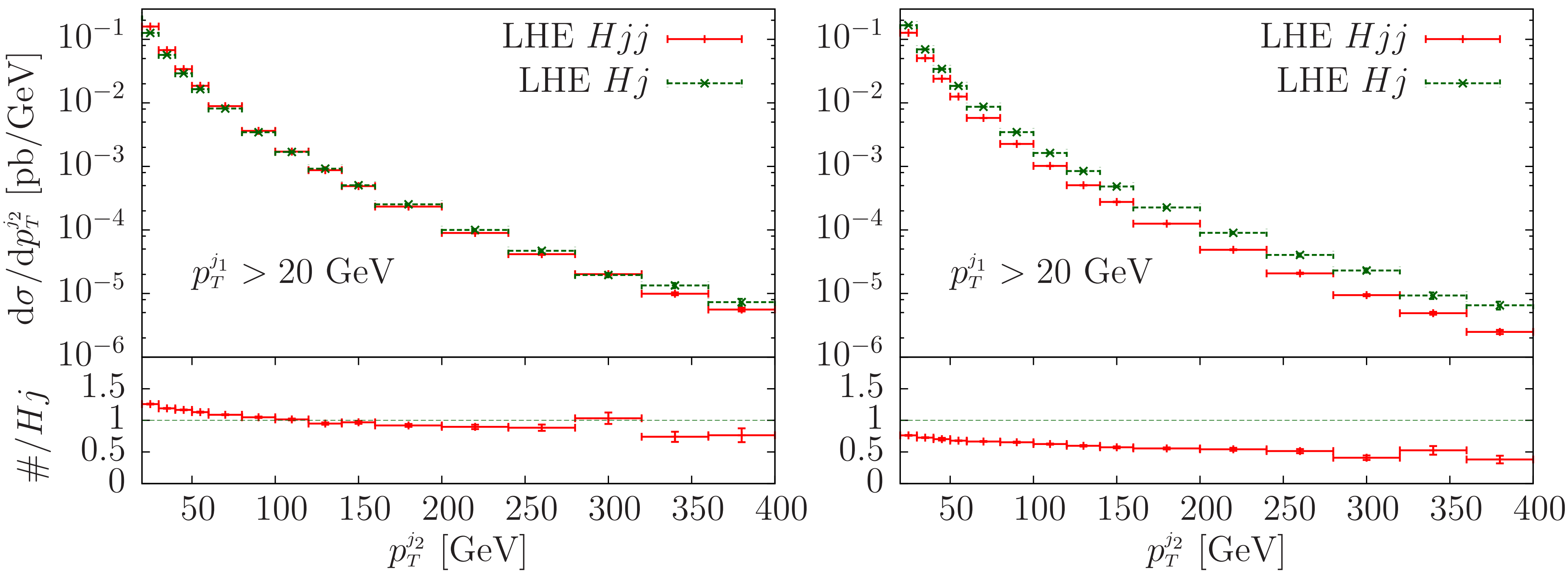
H and Hj comparison



- $\sigma_H^{\rm NLO} = 10.85$ pb, $\sigma_H^{\rm NNLO} = 14.35$ pb $\Longrightarrow K = 1.32$
- H generator: NLL accuracy in the low p_T region but only LO at high p_T
- Hj generator: NLO accuracy only in the high p_T region. No Sudakov resummation.

[Campbell, Ellis, Frederix, Nason, Williams, C.O., 2012]

Hj and Hjj comparison



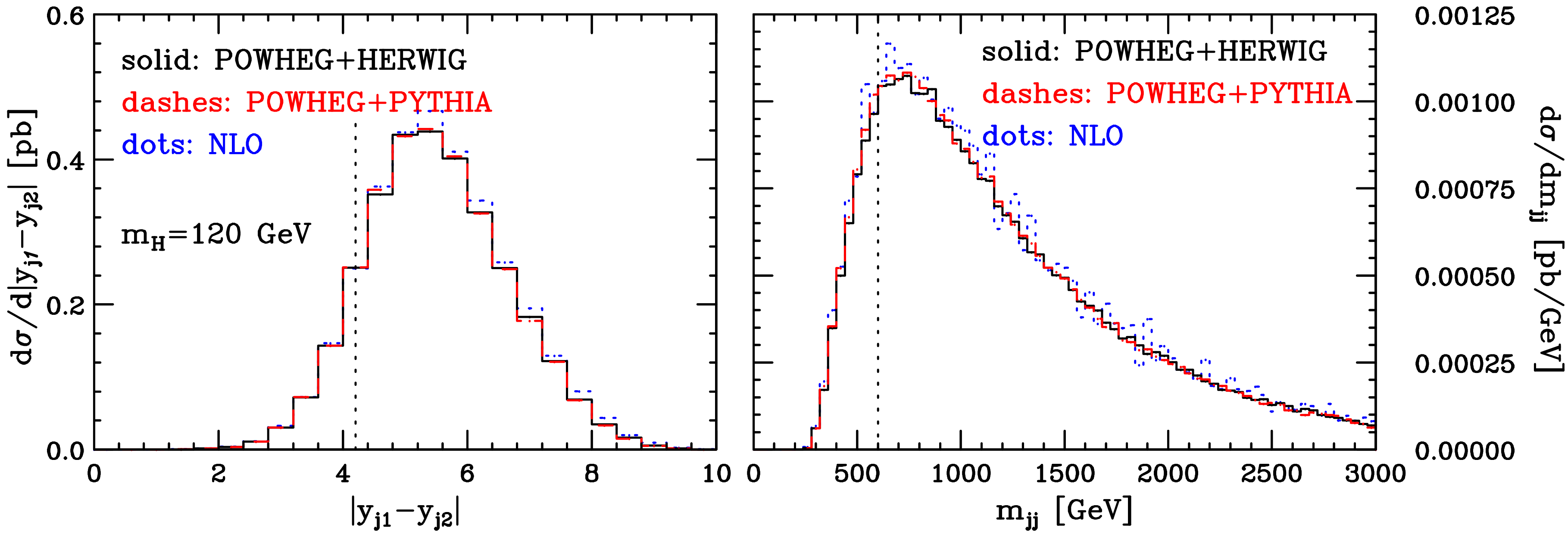
Left: $\mu_F = \mu_R = m_{\rm H}$. Right: $\mu_F = \mu_R = p_T^{\rm UB}$ for Hj and $\mu_F = \mu_R = \hat{H}_T$ for Hjj

- Hj generator: NLL accuracy in the low p_T region but only LO at high p_T
- Hjj generator: NLO accuracy only in the high p_T region. No Sudakov resummation.

Work in progress to merge the H, Hj and Hjj samples

[Campbell, Ellis, Frederix, Nason, Williams, C.O., 2012]

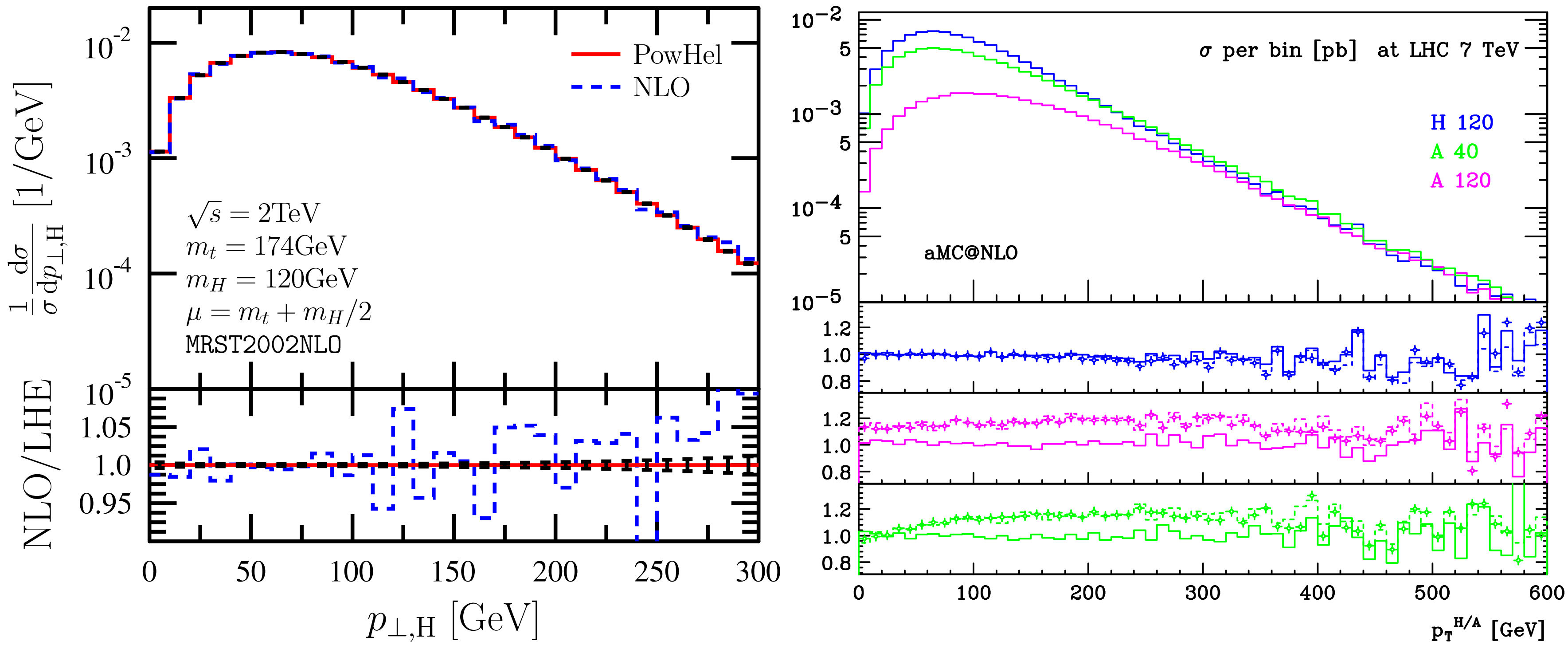
Higgs in vector-boson fusion



- Only *t*-channel vector-boson exchange diagrams: built having in mind VBF cuts [Nason and C.O, 2010].
- Nevertheless, the cross section is finite even with no cuts.

This is what has been used in the Yellow Report Higgs Cross Section 1 and 2.

$t\bar{t}H$

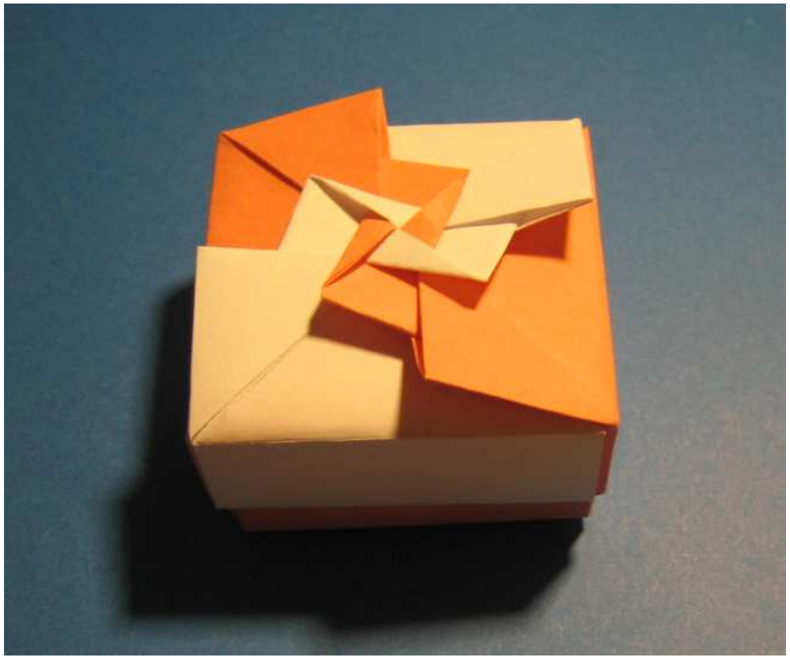


- POWHEG+HELAC [Garzelli, Kardos, Papadopoulos and Trocsanyi, 2011]
- aMC@NLO: scalar and pseudoscalar Higgs boson
  [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, 2011]

Conclusions

- There are several NLO+PS programs that describe the production of a Higgs boson in different channels
- Although they formally all agree at NLO, NNLO terms can be large for processes with large K factors.
- Differences among each other are well understood and have been studied in the past few years
- For processes in the POWHEG BOX, please visit the web page

http://powhegbox.mib.infn.it



Backup slides

Squeezing R_s

$$d\sigma = \overline{B}_s(\mathbf{\Phi}_n)\left\{\Delta_s(p_T^{min}) + \Delta_s(p_T)\,\frac{R_s(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)}\,d\Phi_r\right\} d\mathbf{\Phi}_n + R_f(\mathbf{\Phi}_{n+1})\,d\mathbf{\Phi}_{n+1}$$

$$\overline{B}_s(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \int d\Phi_r\left[R_s(\mathbf{\Phi}_n,\Phi_r) - C(\mathbf{\Phi}_n,\Phi_r)\right]$$

$$\Delta_s(p_T) = \exp\left[-\int d\Phi'_r\,\frac{R_s(\mathbf{\Phi}_n,\Phi'_r)}{B(\mathbf{\Phi}_n)}\,\theta(p'_T - p_T)\right]$$

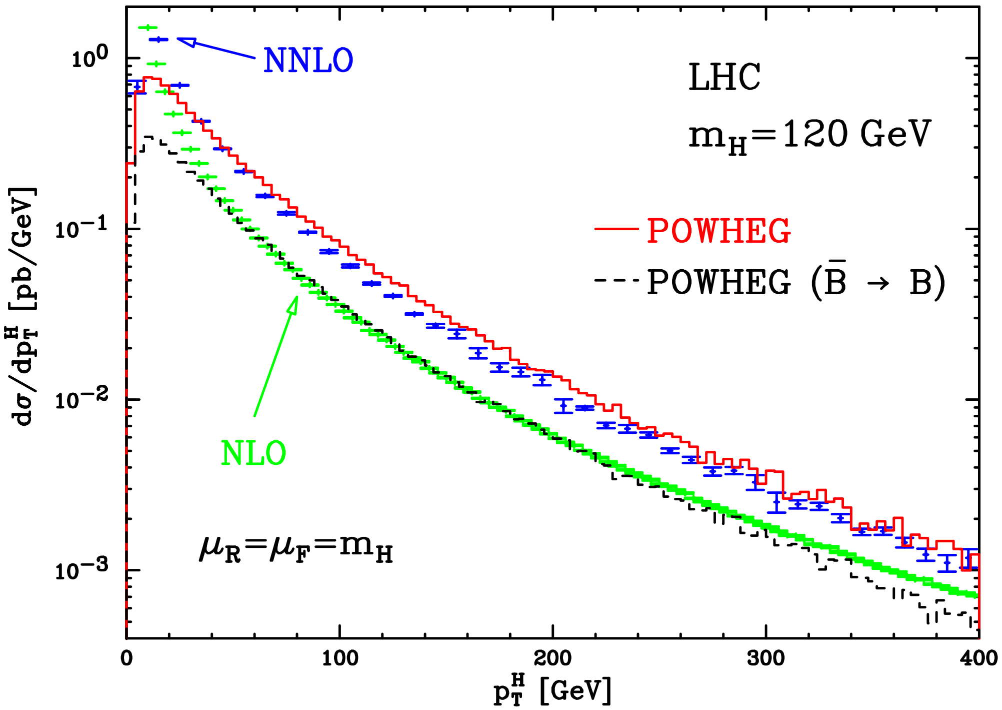
Notice: by restricting R_s more and more we recover exactly the NLO result, with no further higher order effects.

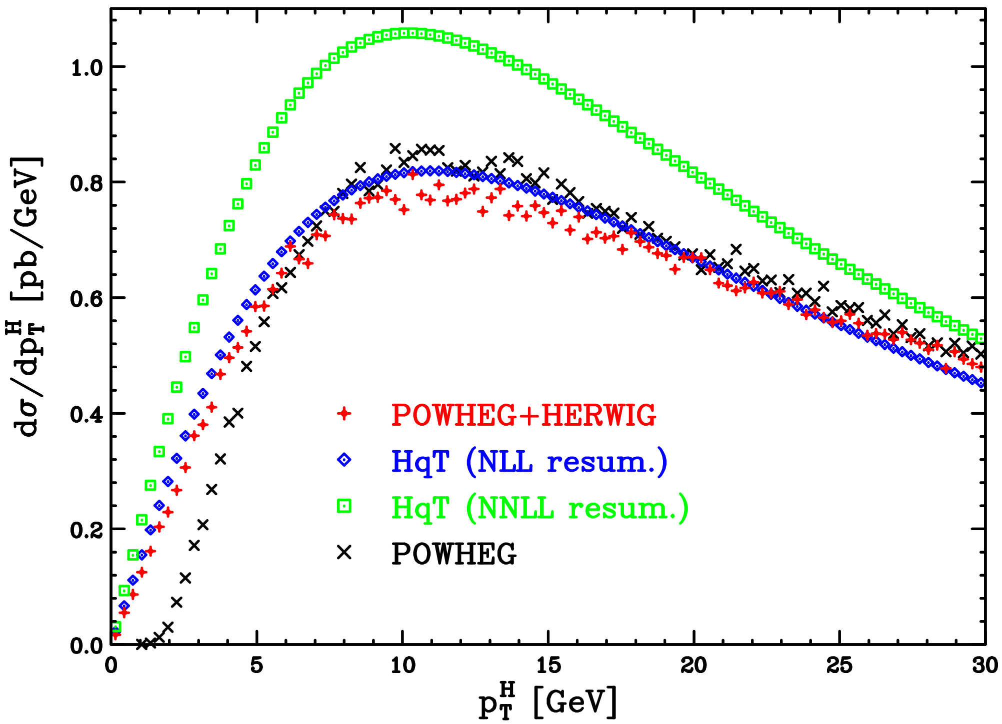
For example

$$R_s = \theta(k_{\rm cut} - k_T)R \qquad\qquad k_{\rm cut} \longrightarrow 0$$

But we cannot do this if we want an NLO+PS result: as $k_{\rm cut} \rightarrow 0$ the Sudakov region becomes squeezed and distorted, even to a point when positivity is lost.

NNLO contributions: Higgs boson production





$$\overline{B}_s(\boldsymbol{\Phi}_n) = B(\boldsymbol{\Phi}_n) + V(\boldsymbol{\Phi}_n) + \int d\Phi_r \left[R_s(\boldsymbol{\Phi}_n, \Phi_r) - C(\boldsymbol{\Phi}_n, \Phi_r)\right]$$

$$d\sigma = \overline{B}_s(\boldsymbol{\Phi}_n) \left\{ \Delta_s(\boldsymbol{\Phi}_n, p_T^{min}) + \Delta_s(\boldsymbol{\Phi}_n, p_T) \frac{R_s(\boldsymbol{\Phi}_{n+1})}{B(\boldsymbol{\Phi}_n)} \, d\Phi_r \right\} d\boldsymbol{\Phi}_n + R_f(\boldsymbol{\Phi}_{n+1}) \, d\boldsymbol{\Phi}_{n+1}$$

$$d\sigma_{\rm rad} \approx \frac{\overline{B}_s(\boldsymbol{\Phi}_n)}{B(\boldsymbol{\Phi}_n)} R_s(\boldsymbol{\Phi}_{n+1}) \, d\boldsymbol{\Phi}_{n+1} + R_f(\boldsymbol{\Phi}_{n+1}) \, d\boldsymbol{\Phi}_{n+1}$$

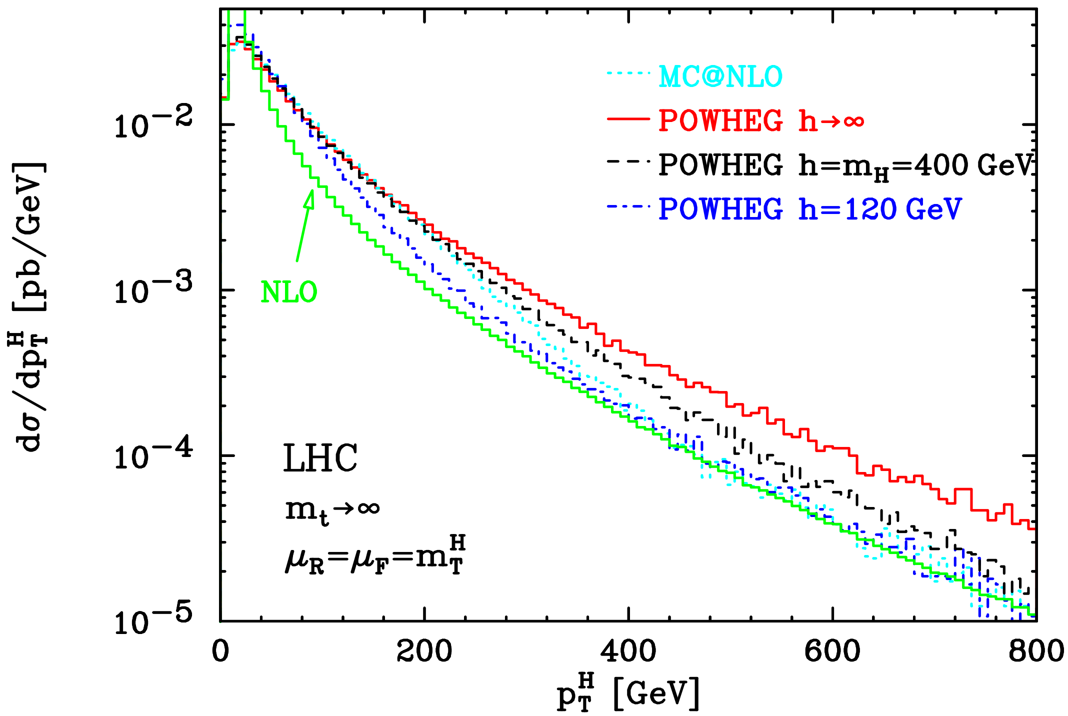
$$= \left\{ \left[1 + \mathcal{O}(\alpha_s)\right] R_s(\boldsymbol{\Phi}_{n+1}) + R_f(\boldsymbol{\Phi}_{n+1}) \right\} d\boldsymbol{\Phi}_{n+1} = R(\boldsymbol{\Phi}_{n+1}) \, d\boldsymbol{\Phi}_{n+1} + \mathcal{O}(\alpha_s) R_s(\boldsymbol{\Phi}_{n+1})$$

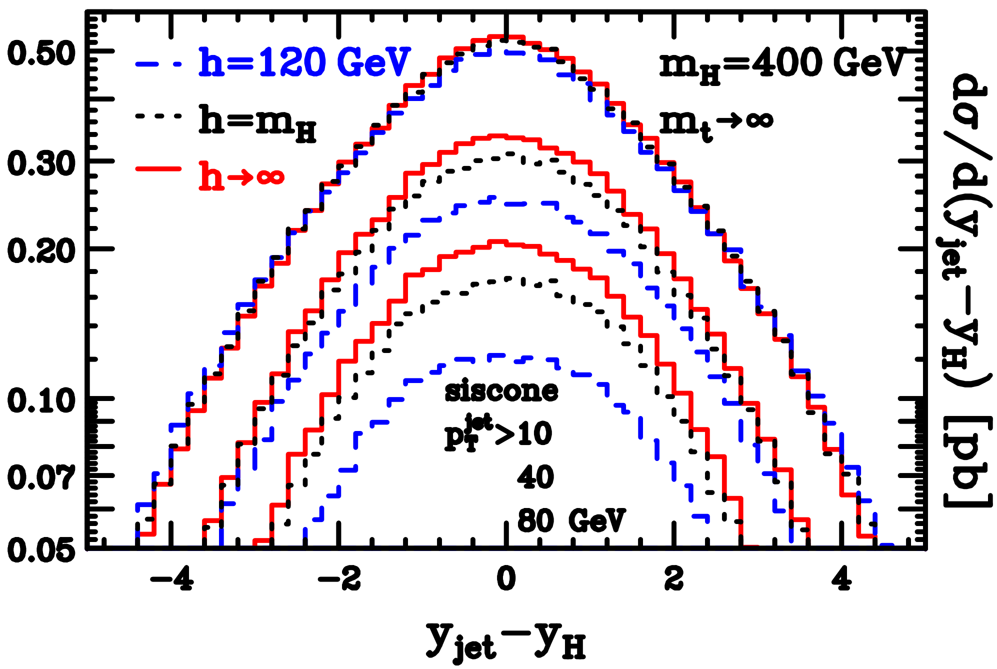
$$R_s = \frac{h^2}{p_T^2 + h^2} R$$

$$R_f = \frac{p_T^2}{p_T^2 + h^2} R$$

$$R = R_s + R_f$$

agrees with NLO at high p_T

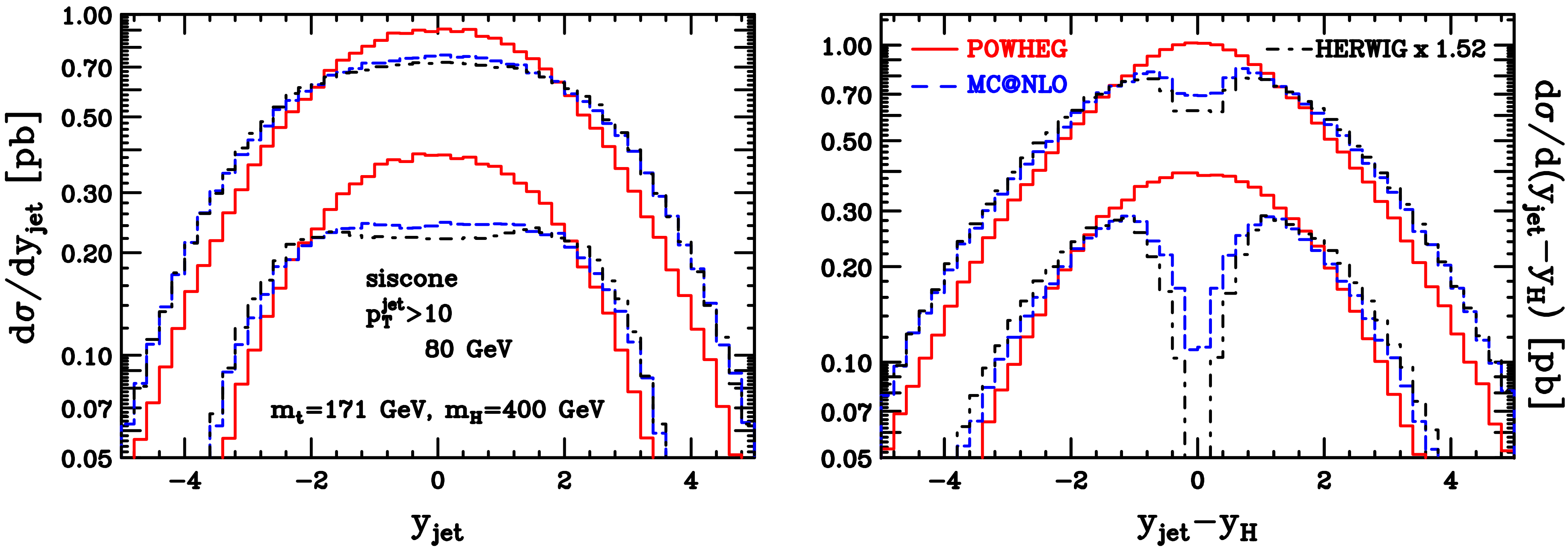




No new features appear in all the other distributions

When $h \to 0$, we recover the pure NLO cross section

NNLO contributions: the dip in MC@NLO



- Why MC@NLO has a dip in the hardest jet rapidity?
  ANSWER: because it is very sensitive to the dead zone in the HERWIG phase space
- Why POWHEG has no dip? Is that because of the hardest p_T spectrum?
  ANSWER: NO, it does not depend on the hardest p_T spectrum. POWHEG generate by itself the hardest radiation.

Processes implemented in the POWHEG BOX

- heavy-quark pair production (Frixione, Nason, Ridolfi, 2007)
- Z/W (with decay) (Alioli, Nason, Re, C.O., 2008)
- Higgs boson in gluon fusion (Alioli, Nason, Re, C.O., 2008)
- single top (Alioli, Nason, Re, C.O., 2009) and tW (Re, 2010)
- Higgs boson in VBF (Nason,C.O., 2010)
- Z/W (with decay) + 1 jet (Alioli, Nason, Re, C.O., 2010)
- dijet (Alioli, Hamilton Nason, Re, C.O., 2010)
- $t\bar{t}$ + 1 jet (Kardos, Papadopoulos, Trocsanyi, 2011) also (Alioli, Moch, Uwer, 2011)
- $t\bar{t}H$, $t\bar{t}Z/\gamma$ (Garzelli, Kardos, Papadopoulos, Trocsanyi, 2011)
- W^+W^+ plus two jets (Melia, Nason, Rontsch, Zanderighi, 2011)
- W^+W^+ plus two jets via VBF (Jäger, Zanderighi, 2011)
- $Wb\bar{b}$ (with approximated decay) (Reina, C.O., 2011)
- diboson production (with decay), (Melia, Nason, Rontsch, Zanderighi, 2011)
- tH^- (Klasen, Kovaric, Nason, Weydert, in preparation)