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Considerations on NLO-MC matching

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- Extraction of parameters from data can be done at the parton level. This is less direct and sometimes requires ingenuity, but is cleaner, and can be pushed to NNLO

Before giving my answer to the question, let me mention that some of the typical motivations given by theorists, e.g.:

- better description of jet structure;
- extra contributions from initial-state partons (e.g., qg vs $q\bar{q}$);
- "NLO" effects on distributions (e.g., kinematics-dependent K factors);

are actually motivations for *tree-level* calculations (*beyond LO*) — that is, genuine NLO effects are not an issue

NLOwPS: why bother?

It is likely a very good idea to use NLOwPS's if at least one of the following conditions is fulfilled:

- Multivariate analyses (BDT, NN, likelihood) are essential, i.e. cut-based ones are not an option
- Lots of backgrounds, (some of which) difficult to tune to data
- Overstretching predictions is highly risky

In general: when experimental results may have a significant theory bias

This boils down to saying that the really crucial thing is:

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A couple of very non-trivial aspects:

- b-tagging: same as in experiments, for processes where the use of NLO results is desirable (note: b-tagging at parton level is very tricky)
- Behaviour of "extra" jet – perturbative or not. Typical application: jet-veto *systematics*

The case for the use of NLOwPS's in Higgs searches is serious, but not compelling

- The gain (wrt LO-based procedures) largely depends on the particular analysis and experimental setup – only experiments are qualified to assess it
- Discovery must be made regardless of NLOwPS's which, on the other hand, can be helpful to get there faster, and to give extra confidence

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Bottom line: do use NLOwPS's, but design analyses as if they were not available (which is what is being done)

NLOwPS will be relatively more important in the determination of Higgs properties (e.g., couplings from $t\bar{t}H$ and VBF processes)

Construction of standalone MC

The generating functional collects all "shower histories" (i.e. kinematic configurations weighted with their probabilities)

$$\mathcal{F}_{\text{MC}} \;=\; \mathcal{F}^{(2\to n)}\mathcal{M}^{(b)}(\phi_n)d\phi_n$$

The individual showers emerging from the $2+n$ partons obey:

$$\mathcal{F}(t_I) = \Delta(t_I, t_0) + \int_{t_0}^{t_I} \frac{dt}{t}\Delta(t_I, t)\int dz \frac{\alpha_S}{2\pi}P(z)\mathcal{F}((1-z)^2 t)\mathcal{F}(z^2 t)$$

with parton types understood. When $t = \theta^2 E^2$ one has angular ordering.

The Sudakov form factor is

$$\Delta(t_I, t_0) = \exp\left(-\int_{t_0}^{t_I}\frac{dt}{t}\int dz\frac{\alpha_S}{2\pi}P(z)\right)$$

MCs differ in the choice of shower variables (t and z)

Construction of MC@NLO

$$\mathcal{F}_{\mathsf{MC@NLO}} \quad = \quad \mathcal{F}^{(2\to n+1)}\, d\sigma^{(\mathbb{H})}_{\mathrm{MC@NLO}} + \mathcal{F}^{(2\to n)}\, d\sigma^{(\mathbb{S})}_{\mathrm{MC@NLO}}$$

with the two *finite* short-distance cross sections

$$d\sigma^{(\mathbb{H})}_{\mathrm{MC@NLO}} \quad = \quad d\phi_{n+1}\left(\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(\mathsf{MC})}(\phi_{n+1})\right)$$

$$d\sigma^{(\mathbb{S})}_{\mathrm{MC@NLO}} \quad = \quad \int_{+1} d\phi_{n+1}\left(\mathcal{M}^{(b+v+rem)}(\phi_n) - \mathcal{M}^{(c.t.)}(\phi_{n+1}) + \mathcal{M}^{(\mathsf{MC})}(\phi_{n+1})\right)$$

that feature the *MC subtraction terms*

$$\boxed{\mathcal{M}^{(\mathsf{MC})} = \mathcal{F}^{(2\to n)}\mathcal{M}^{(b)} + \mathcal{O}(\alpha_S^2\alpha_S^b)}$$

MC subtraction terms are process independent, by MC-dependent
(i.e., those for matching with Herwig and Pythia are different)

Construction of POWHEG

Use the exact phase-space factorization $d\phi_{n+1} = d\phi_n d\phi_r$, and construct

$$\overline{\mathcal{M}}^{(b)}(\phi_n) = \mathcal{M}^{(b+v+rem)}(\phi_n) + \int d\phi_r \left[\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(c.t.)}(\phi_{n+1})\right]$$

For a *given* p_T, define the (process-dependent) *vetoed* Sudakov

$$\Delta_R(t_I, t_0; p_T) = \exp\left[-\int_{t_0}^{t_I} d\phi_r' \frac{\mathcal{M}^{(r)}}{\mathcal{M}^{(b)}} \Theta(k_T(\phi_r') - p_T)\right]$$

The short-distance cross section is:

$$d\sigma_{\text{POWHEG}} = d\phi_n \overline{\mathcal{M}}^{(b)}(\phi_n) \left[\Delta_R(t_I, t_0; 0) + \Delta_R(t_I, t_0; k_T(\phi_r)) \frac{\mathcal{M}^{(r)}(\phi_{n+1})}{\mathcal{M}^{(b)}(\phi_n)} d\phi_r\right]$$

- First term ($\mathbb{S}$-type events) strongly suppressed
- $k_T(\phi_r)$ will play the role of hardest emission so far ($\mathbb{H}$-type events)

Attaching (angular-ordered) showers

- One wants the matrix-element-generated p_T to be the hardest
  $\Longrightarrow$ veto emissions harder than p_T during shower

- But this screws up colour coherence

Colour coherence can be restored at the price of a more involved structure

$$\mathcal{F}_{\text{POWHEG}}[t_I; p_T] = \Delta(t_I, t_0) + \int_{t_0}^{t_I} \frac{dt}{t} \int dz \Delta_R(t_I, t; p_T) \frac{\alpha_S}{2\pi} P(z)$$
$$\times \mathcal{F}_{\text{V}}((1-z)^2 t; p_T)\, \mathcal{F}_{\text{V}}(z^2 t; p_T)\, \mathcal{F}_{\text{VT}}(t_I, t; p_T)$$

- $\mathcal{F}_{\text{V}}(t; p_T)$ are *vetoed* showers. Evolve down to t_0, with all emissions constrained to have a transverse momentum smaller than p_T

- $\mathcal{F}_{\text{VT}}(t_I, t; p_T)$ are *vetoed-truncated* showers. Evolve from t_I down to t (i.e., *not* t_0) along the hardest line. On top of that, they are vetoed

To reduce the impact of the exponentiation of the full real matrix element, one introduces the following variant

$$d\sigma^{(\mathrm{damp})}_{\mathrm{POWHEG}} = d\phi_n \overline{\mathcal{M}}^{(b)}_S \left\{ \Delta^S_R \frac{\mathcal{M}^{(r)}_S}{\mathcal{M}^{(b)}} + \mathcal{M}^{(r)}_F \right\} d\phi_r$$

with:

$$\mathcal{M}^{(r)} = \mathcal{M}^{(r)}_S + \mathcal{M}^{(r)}_F = F(p_T)\mathcal{M}^{(r)} + (1 - F(p_T))\mathcal{M}^{(r)}$$

$$(1 - F(p_T))\mathcal{M}^{(r)} \longrightarrow \text{finite} \qquad p_T \longrightarrow 0$$

To maintain the NLO accuracy, one must define:

$$\overline{\mathcal{M}}^{(b)}_S = \overline{\mathcal{M}}^{(b)} \left(\mathcal{M}^{(r)} \longrightarrow \mathcal{M}^{(r)}_S \right) \qquad \Delta^S_R = \Delta_R \left(\mathcal{M}^{(r)} \longrightarrow \mathcal{M}^{(r)}_S \right)$$

Features

$\mathrm{MC@NLO} = \mathrm{POWHEG} + \mathcal{O}(\alpha_S^2 \alpha_S^b) + \mathrm{logs}$ (with or without damp)

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- The differences of matrix-element origin are due to
  - Exponentiation of real matrix elements
  - Use of $\overline{\mathcal{M}}^{(b)}$, which "moves" the $p_T = 0$ K factor to $p_T > 0$ *before* showering

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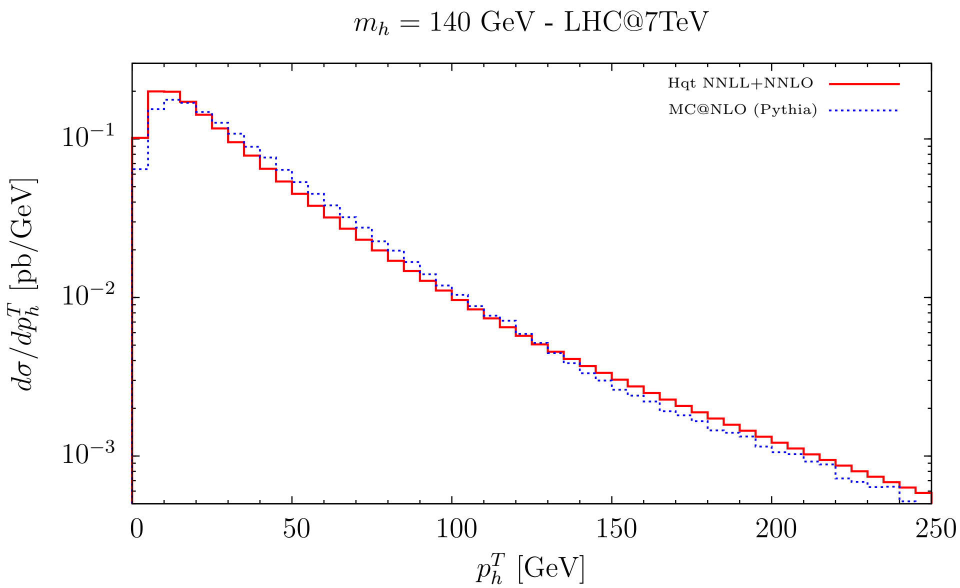
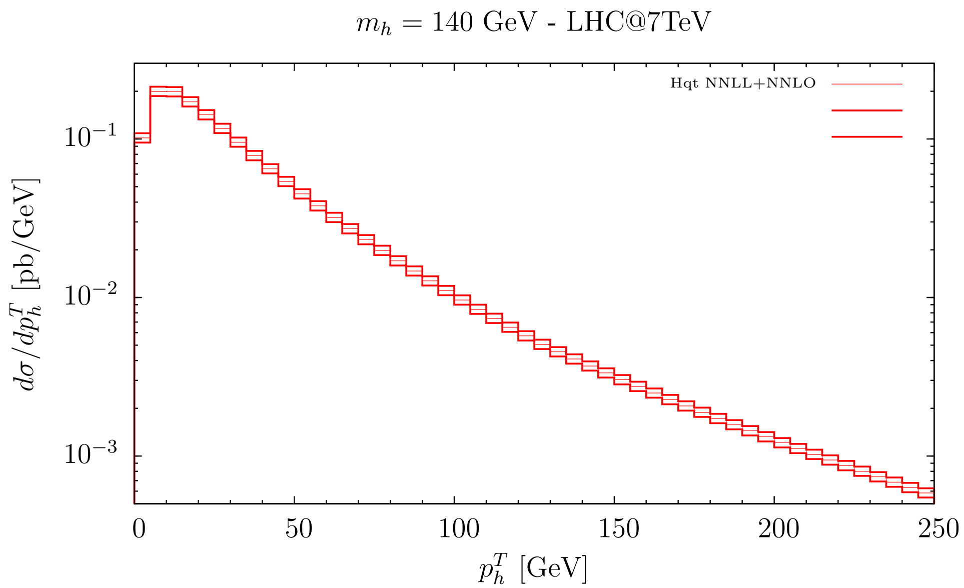
These differences are generally small (for inclusive variables at least).
$gg \to H$ is a spectacular counterexample

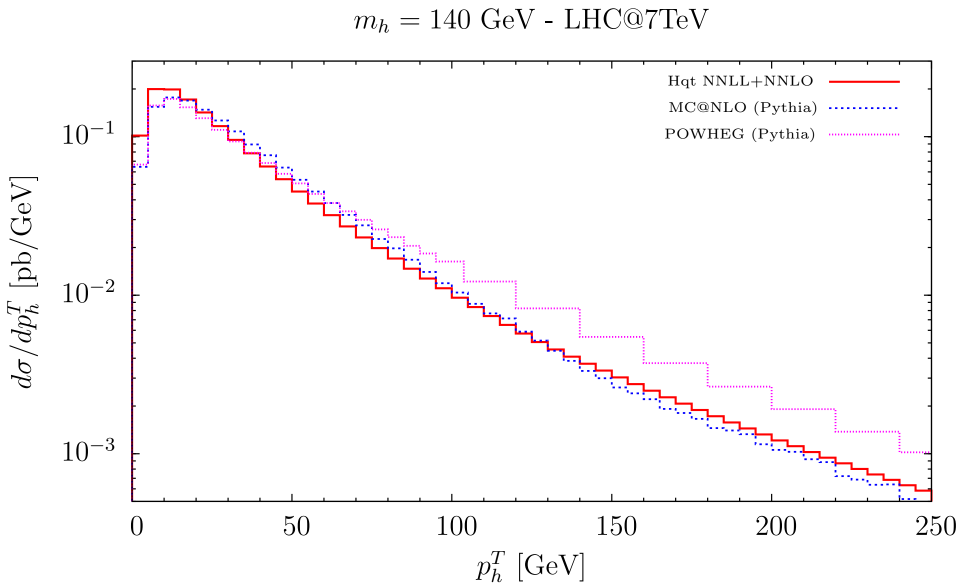
$p_T(H)$ in $gg \to H$

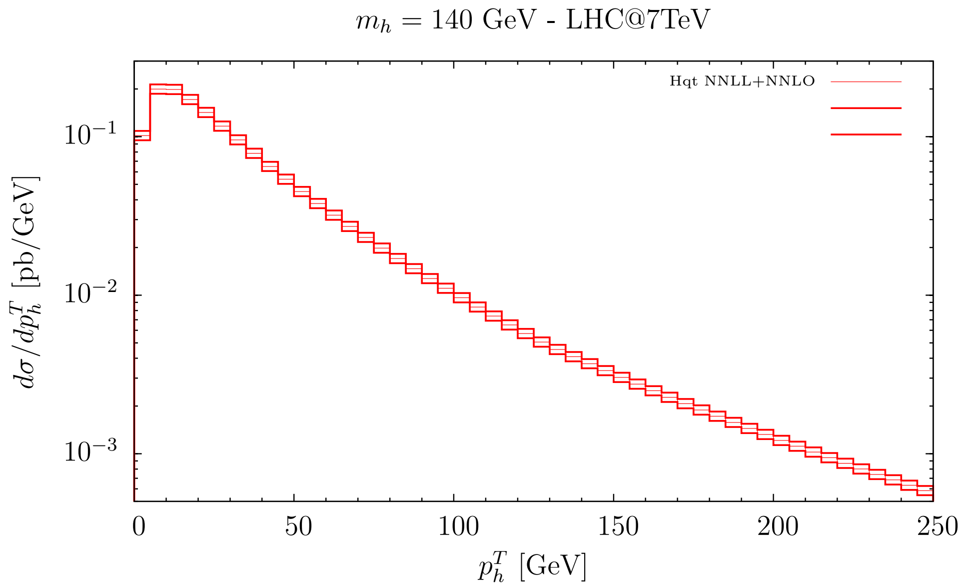




Note: matrix elements in MC@NLO (and POWHEG) are up to $\mathcal{O}(\alpha_S^3)$, in HqT up to $\mathcal{O}(\alpha_S^4)$. MC@NLO and HqT compatible within theory uncertainty

$p_T(H)$ in $gg \to H$





The POWHEG tail is more than a factor of two higher than the MC@NLO one

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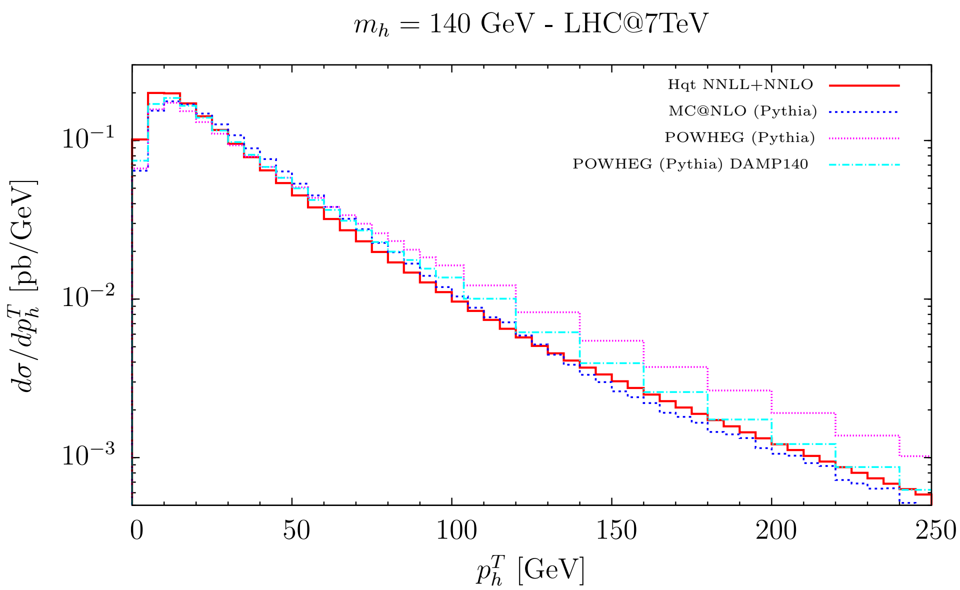
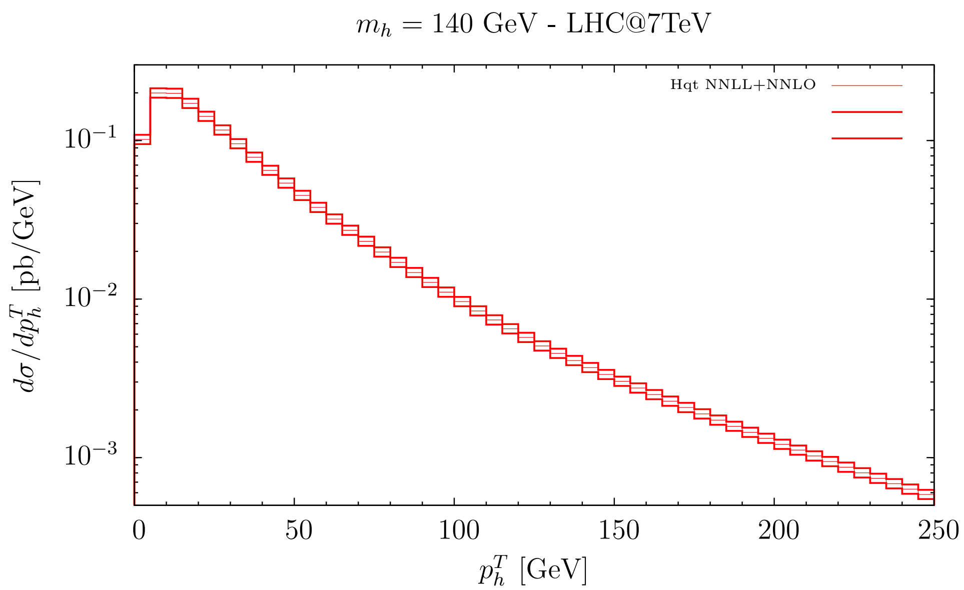
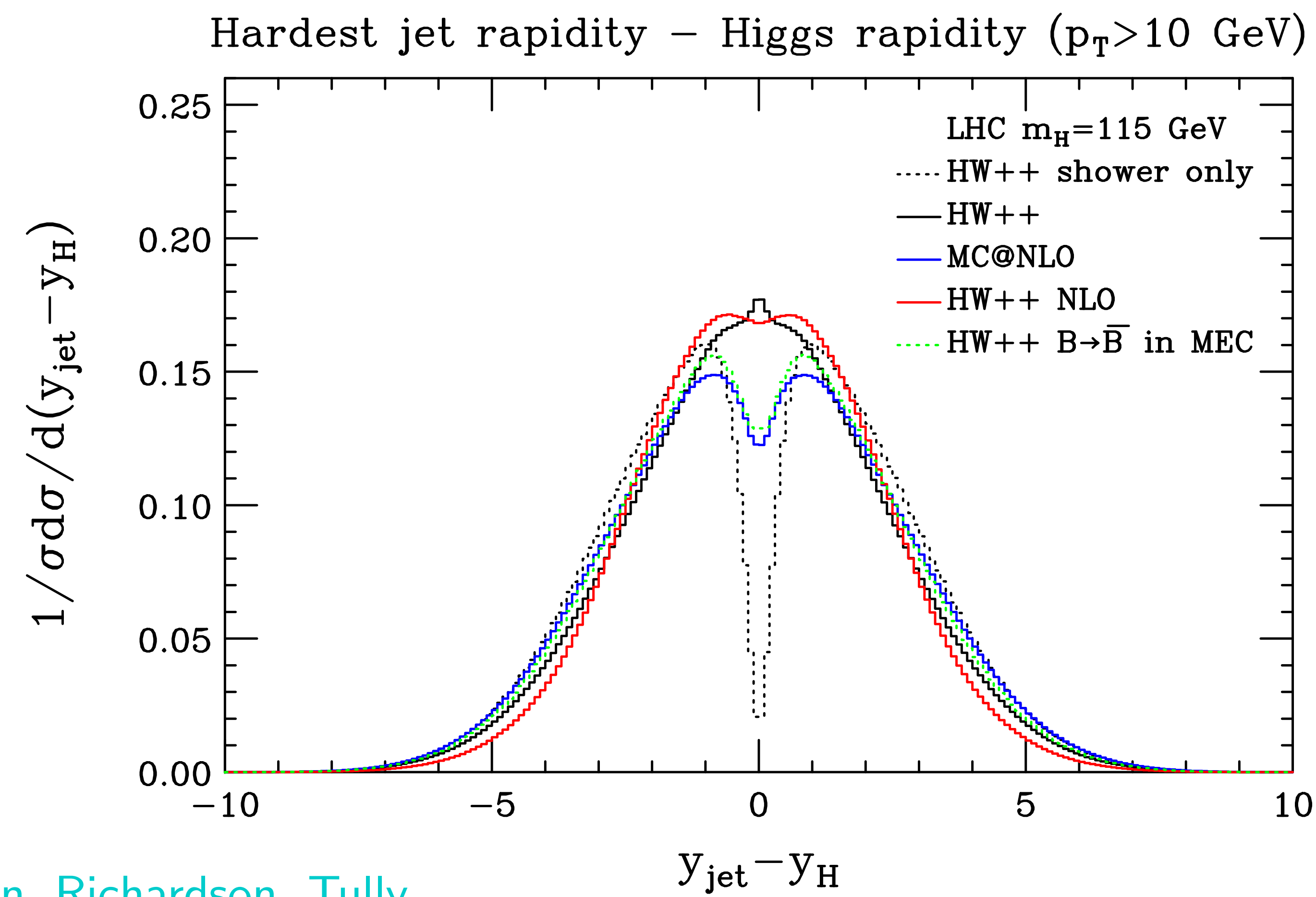




Use of $F(p_T) \neq 1$ brings the POWHEG curve significantly down.

Note that this is formally an $\mathcal{O}(\alpha_S^4)$ effect

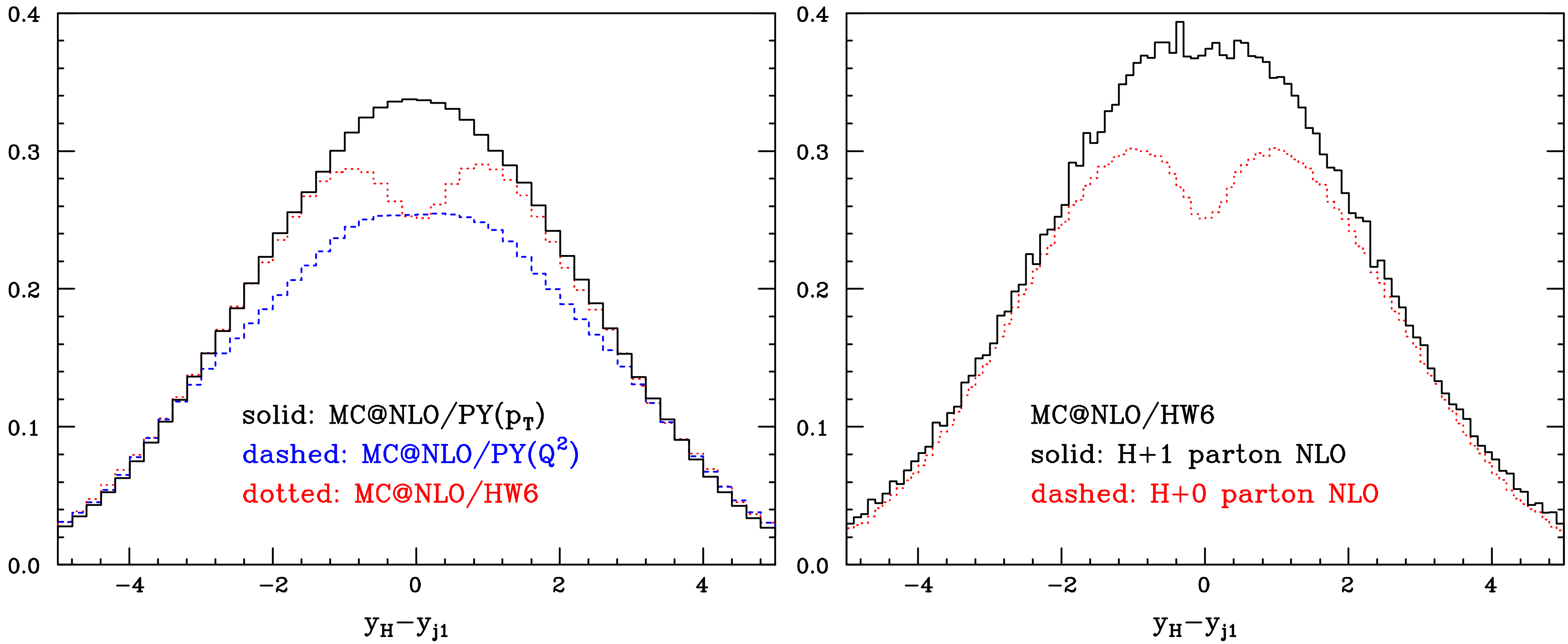
$y(H) - y(j_1)$ in $gg \to H$



Hamilton, Richardson, Tully

When showering POWHEG events with HW6, there is basically no dip at $\Delta y = 0$. An effect of the missing truncated-vetoed shower in HW6?

$y(H) - y(j_1)$ in $gg \to H$



plots: P. Torrielli, R. Frederix

Left: very large dependence on MC used

Right: very sensitive to short-distance production mechanism

Some final considerations on $y(H) - y(j_1)$

- The dip is not an MC@NLO feature, but an MC one.
- MC@NLO "fills" the original MC dip via $\mathbb{H}$ events, whose effect is largely MC-independent. Hence, the pattern of the dips in the original MCs will be loosely respected by MC@NLO
- One may argue that this has to be expected, since $y(H) - y(j_1)$ is effectively LO, and the use of $H + 1$ parton NLO calculation is necessary here
- I find that this argument is based on the prejudice that the dip should not be there. However, the large MC-dependence may suggest that a matrix-element-based description is not suited
- A more solid solution will be available when $H + 0$ and $H + 1$ parton results will be consistently merged (*a la* CKKW or MLM)

Higgs phenomenology: status

- SM Higgs signals (gg, VBF, VH, $t\bar{t}H$) are available in both MC@NLO and POWHEG (VBF in MC@NLO not public yet). BSM scenarios have been considered (e.g., $tH^{\pm}$), but not systematically

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- Background implementations are not as complete. Some exist (e.g., dibosons), some others don't (e.g., Zjj, $t\bar{t}jj$)

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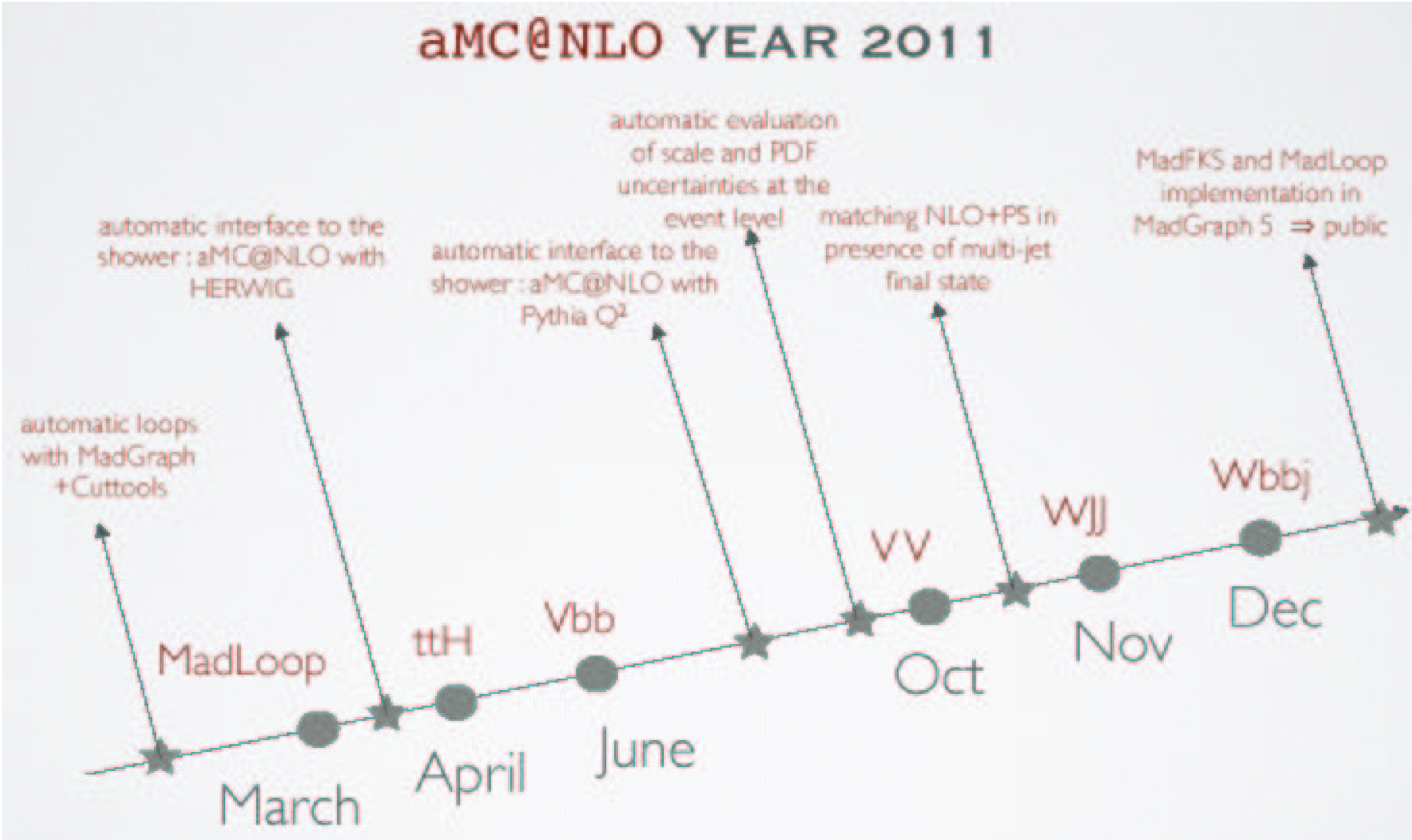
The situation will rapidly improve, thanks to a very recent, and extremely significant, achievement: *automation*

Note that there are two levels of automation involved: that of the NLO matrix element computation, and that of the NLO-MC matching

Automation

- aMC@NLO (Frederix, Frixione, Hirschi, Pittau, Maltoni, Torrielli): automation of matrix elements and MC@NLO matching in the same framework
- SHERPA (Krauss, Höche, Siegert, Schönherr): automation of matrix elements (except virtuals) and matching (both MC@NLO and POWHEG) in the same framework
- POWHEL (Papadopoulos, Garzelli, Kardos, Trocsanyi; $+\cdots$): automation of matrix elements, POWHEG matching via POWHEG-box (Alioli, Nason, Oleari, Re)

No systematic comparison among these codes has been performed yet, and thus I'm unable to comment on the extent of automation/flexibility of the packages I'm not involved in. I suppose the dust will settle soon



plot: F. Maltoni

Each of the processes listed here would have cost *years* of work with traditional methods

Theory uncertainties: (a)MC@NLO

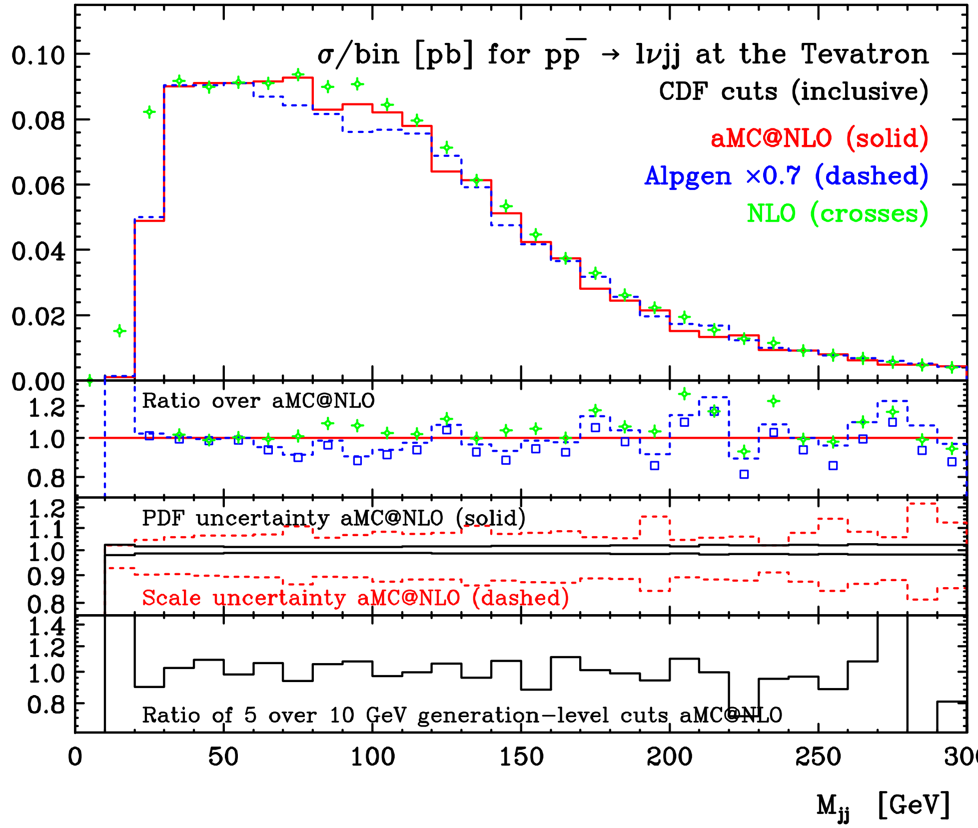
Key point: the dependences on coupling constants, logarithms of scales, and PDFs is linear in the short-distance MC@NLO cross section

$\Longrightarrow$ Define scale- and PDF-independent coefficients, and use them to compute scale and PDF uncertainties by *reweighting*

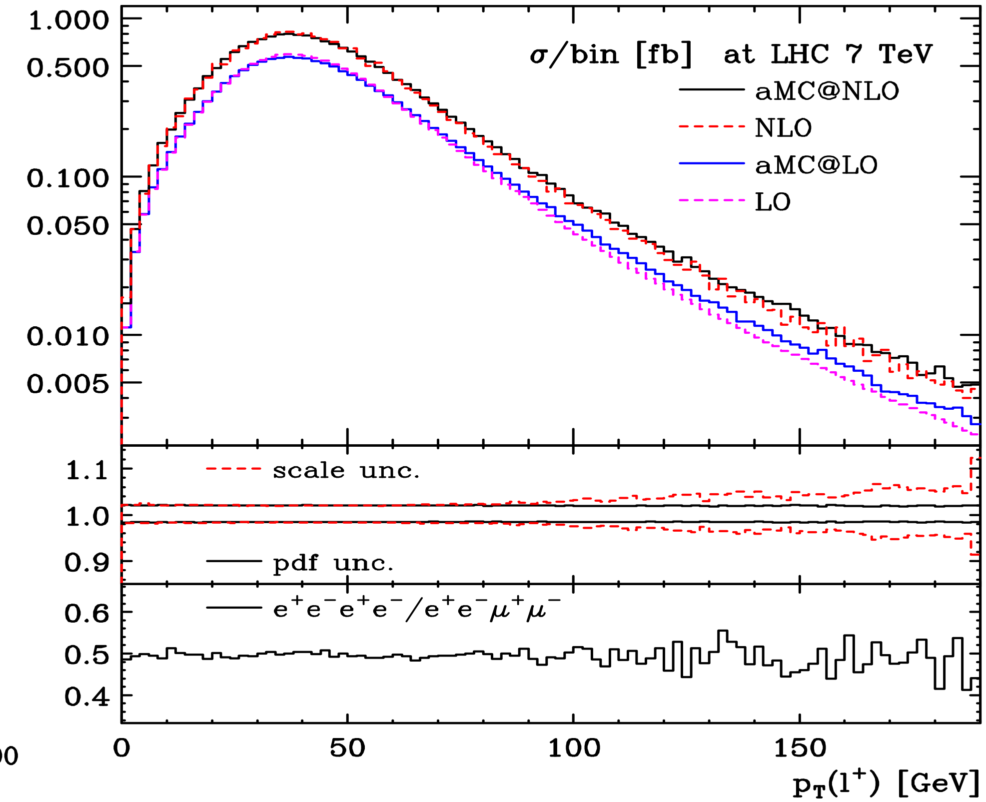
This has zero CPU cost! All aMC@NLO event samples include by default these reweighting coefficients (see 1110.4738)

- Note: this is at the short-distance cross section level. The interplay with choices made in the MC is an open issue, which is being studied (Webber, SF)

Examples



$$pp \longrightarrow (W \rightarrow)\ell\nu_\ell jj$$



$$pp \longrightarrow (Z/\gamma^* \rightarrow)\ell^+\ell^- b\bar{b} \Big/ (W \rightarrow)\ell\nu_\ell b\bar{b}$$

Thanks to reweighting, events for central predictions and their variations are correlated. One thus gets a fairly smooth uncertainty band

Theory uncertainties: POWHEG

- Cannot change scales in Δ_R without spoiling logarithmic accuracy
- Scale dependence of $\overline{\mathcal{M}}^{(b)}$ is standard. However, its role in the POWHEG formula implies that the shape of the first emission is independent of scales (i.e., $d\sigma/dp_T(H)$ for any $p_T(H) > 0$ has the same scale uncertainty as the total rate)
- The above is not correct if one uses the damp version (owing to $\mathcal{M}_F^{(r)}$). However, this exposes the fact that it is also necessary to study the systematics due to the choice of $F(p_T)$ (see $p_T(H)$ in $gg \to H$)

All this is being considered (Hamilton, Nason)

I don't know whether reweighting techniques are viable, and am not aware of general approaches to PDF systematics

Outlook

Automation is allowing one to extend the scope of NLOwPS's much further than previously thought possible

Topics of particular interest for Higgs physics (but not limited to it) include:

- NLO in the extra jet (e.g., VBF$+1j$, $Wb\bar{b}j$)
- Inclusion of exact corrections to top decays (e.g. for $t\bar{t}H$ and $t\bar{t}b\bar{b}$)
- Comparison between NLOwPS's and NNLO results
  (vast expertise in the ZH area...)
- Extension of merging techniques (CKKW, MLM) to NLOwPS's