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On MC@NLO-Δ

Based on: 2002.12716 (Frederix, SF, Prestel, Torrielli)

HSF meeting, CERN, 20/11/2020

- MC@NLO-Δ is an MC@NLO-inspired matching formalism

- It aims to preserve the good features of MC@NLO, getting rid of the non-so-good ones

- Bar for minor details, the general considerations on advantages and drawbacks of MC@NLO vs POWHEG apply here as well

- Primary goal of MC@NLO-Δ: the reduction of negative weights

- Expected primary beneficial side effect: shower-scale assignments that are much more meaningful from a physics viewpoint

Negative weights: we talk about \$\$\$ (i.e. not physics)

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$$N_+ = (1 - f)N\,, \qquad N_- = fN\,, \qquad 0 \leq f < 0.5$$

The efficiency (of the simulation) is:

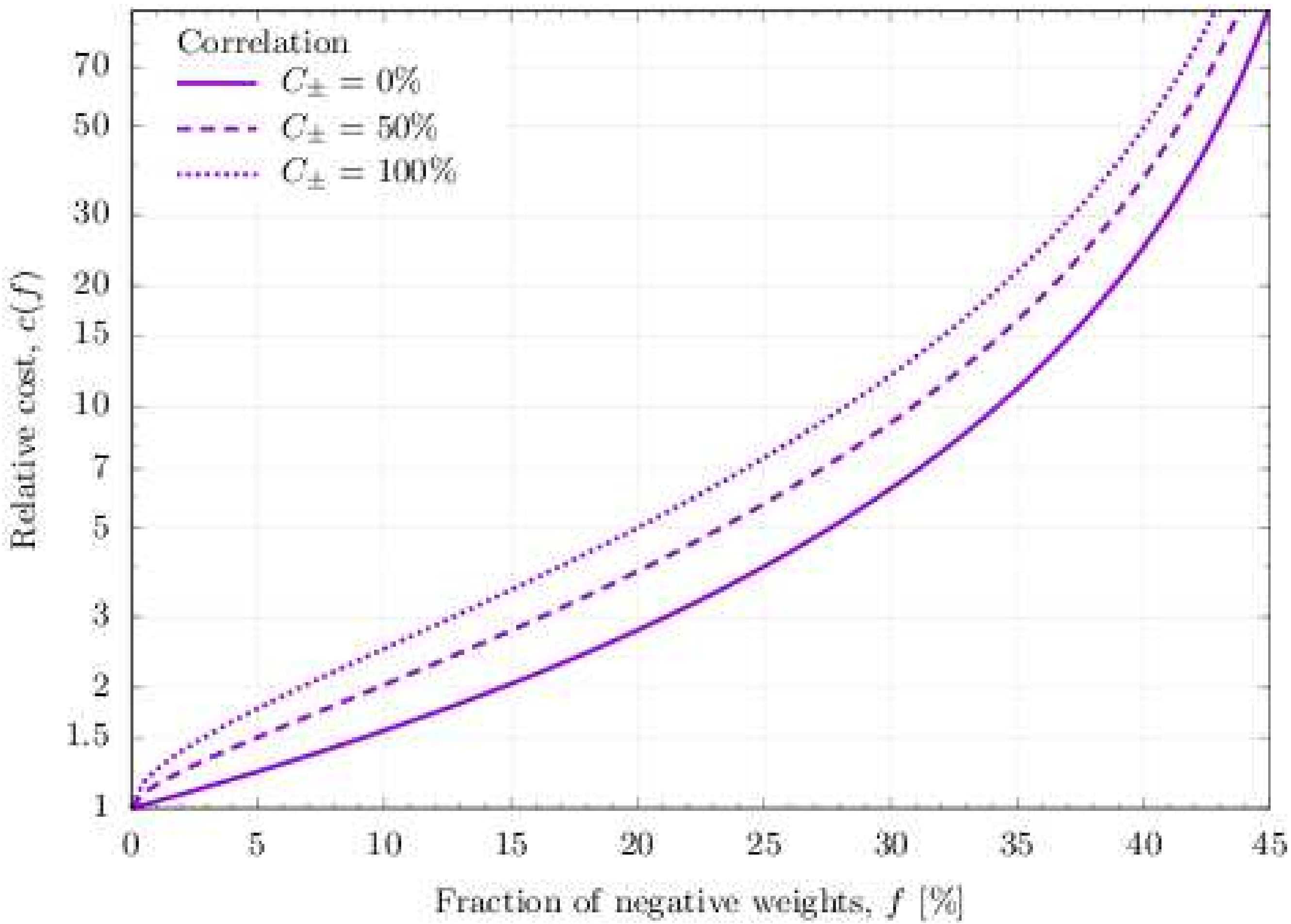
$$\varepsilon(f) = 1 - 2f\,, \qquad 0 < \varepsilon(f) \leq 1$$

In order to have the same statistical accuracy as an M-event positive-definite generation one needs to have:

$$N = c(f)\,M$$

with $c(f)$ the relative cost

$$c(f) = \frac{1 + C_\pm\sqrt{1 - \varepsilon(f)^2}}{\varepsilon(f)^2} \geq 1$$



With 10% (20%, 30%) negative weights one spends at least a factor
1.5 (3, 6) more than with positive weights only

Before moving on

Negative weights are unpleasant, but must not be used as an excuse to give up on accuracy

The consequences of watering down accuracy targets at a precision-physics machine will most likely be severe

(remember the discovery of SUSY right after the start of the LHC?)

Reminder of MC@NLO:

$$\mathcal{F}_{\text{MC@NLO}} = \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{H})}\right) d\sigma^{(\mathbb{H})} + \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{S})}\right) d\sigma^{(\mathbb{S})}$$

with:

$$\mathbb{H} - \text{events} \qquad d\sigma^{(\mathbb{H})} = d\sigma^{(\text{NLO},E)} - d\sigma^{(\text{MC})}$$

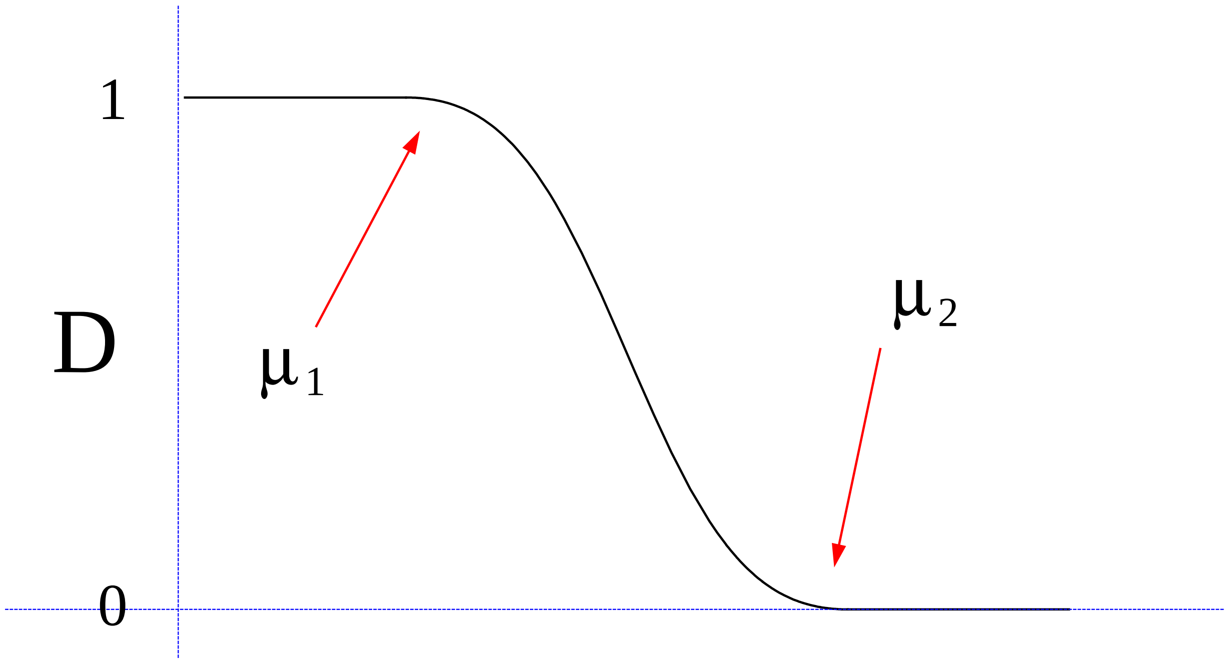
$$\mathbb{S} - \text{events} \qquad d\sigma^{(\mathbb{S})} = d\sigma^{(\text{MC})} + \sum_{\alpha=S,C,SC} d\sigma^{(\text{NLO},\alpha)}$$

This is the same cross section as for NLO computations, bar for the MC counterterms $\left(d\sigma^{(\text{MC})}\right)$, i.e. the MC cross section expanded at $\mathcal{O}(\alpha_S^{b+1})$

MC counterterms are determined by the MC up to user-controllable inputs, the most flexible of which is the shower scale

In MC@NLO, this flexibility is used to prevent MC hard radiation

$$d\sigma^{(\mathrm{MC})} = D\Big(q(\mathcal{K}^{(\mathbb{H})}), \mu_1, \mu_2\Big) \sum_c \sum_{\ell\in c} d\sigma_{c\ell}^{(\mathrm{MC})} \,,$$



Shower scale $\in \ (\mu_1, \mu_2)$

Classes of negative weights in MC@NLO

Call $P(\mathcal{K}^{(\mathbb{H})})$ (the pull) a measure of the "distance" from the Born kinematics (eg the recoil p_T in DY). Let M_H be the typical hard scale. Then:

N.1 $\mathbb{H}$ events with $P(\mathcal{K}^{(\mathbb{H})}) \ll M_H$

N.2 $\mathbb{H}$ events with $P(\mathcal{K}^{(\mathbb{H})}) \sim M_H$

N.3 $\mathbb{S}$ events

N.1 and **N.2** stem from the physics of MC@NLO, while **N.3** from a (otherwise convenient) *choice* in the generation of events

$\mathbf{N.3}$: $\mathbb{S}$-events

$$\begin{aligned}
\mathcal{F}_{\text{MC@NLO}} &= \ldots + \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{S})}\right) d\sigma^{(\mathbb{S})} \\
d\sigma^{(\mathbb{S})} &= d\sigma^{(\mathrm{MC})} + \sum_{\alpha=S,C,SC} d\sigma^{(\mathrm{NLO},\alpha)}
\end{aligned}$$

An n-body kinematics with an $(n+1)$-body support

$$\Longrightarrow \qquad \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{S})}\right) d\sigma^{(\mathbb{S})} \equiv \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{S})}\right) \int_{\phi_{n+1}\setminus\phi_n} d\sigma^{(\mathbb{S})}$$

This is folding (Nason, 2007). The idea is more general than MC@NLO $\mathbb{S}$-events (eg, it is used in POWHEGBOX)

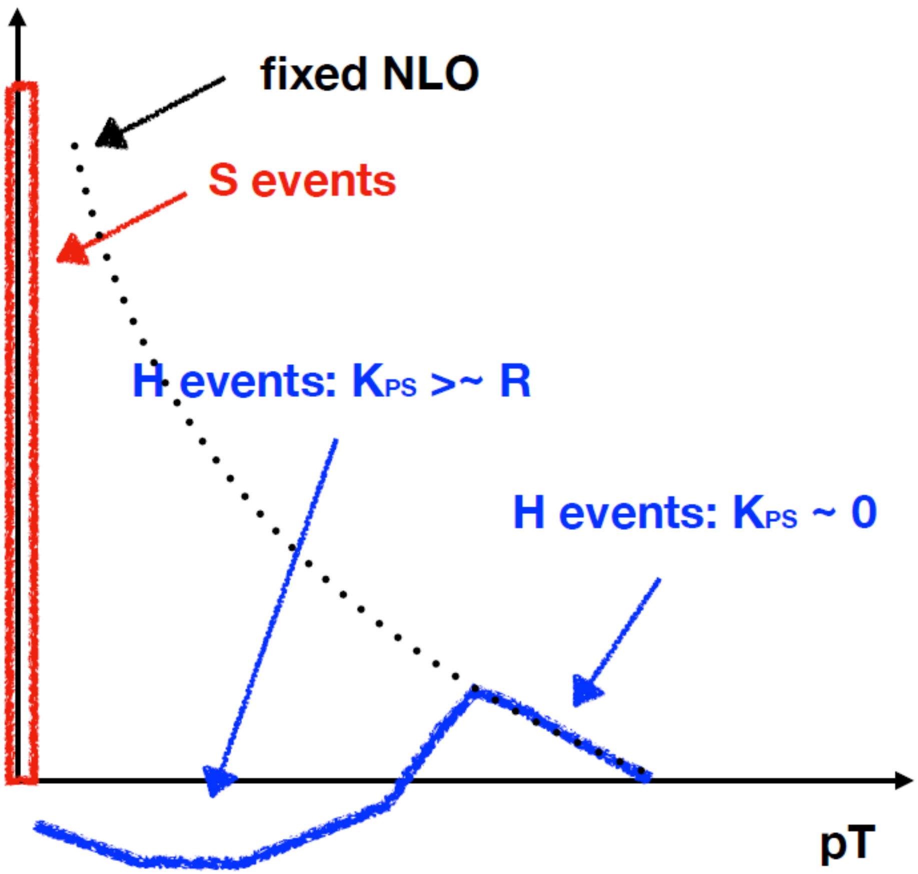
$\mathbf{N.1}$: $\mathbb{H}$-events

$$
\begin{aligned}
\mathcal{F}_{\text{MC@NLO}} &= \mathcal{F}_{\text{MC}}\left(\mathcal{K}^{(\mathbb{H})}\right) d\sigma^{(\mathbb{H})} + \ldots \\
d\sigma^{(\mathbb{H})} &= d\sigma^{(\mathrm{NLO},E)} - d\sigma^{(\mathrm{MC})}
\end{aligned}
$$

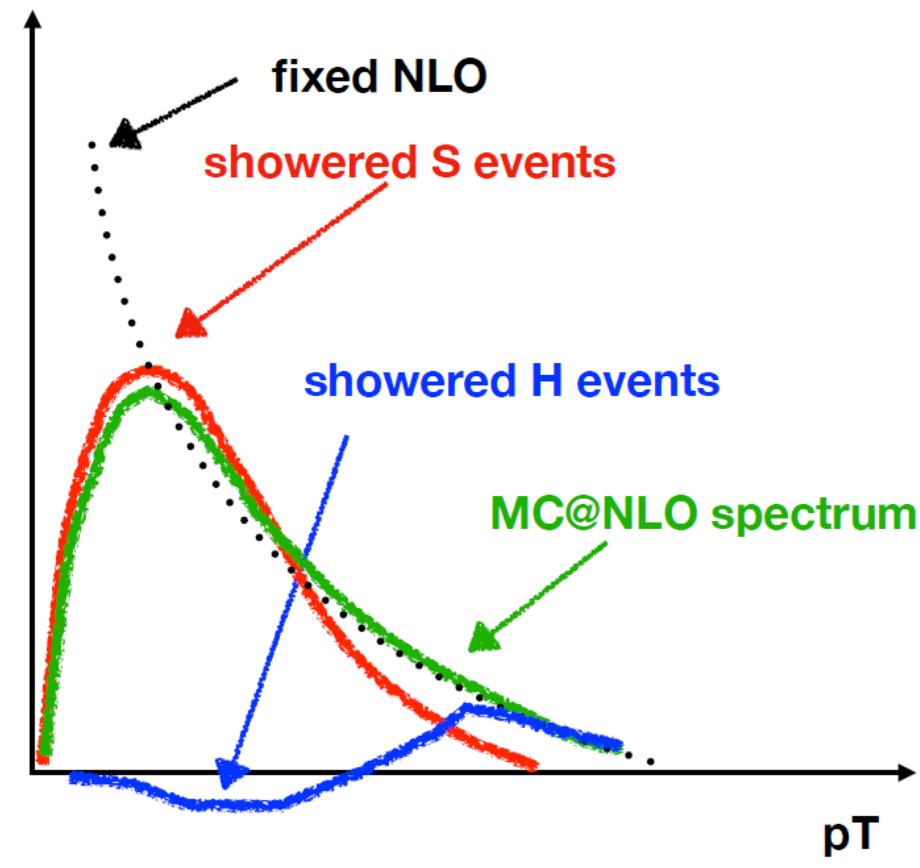
At small pulls, $P(\mathcal{K}^{(\mathbb{H})}) \rightarrow 0$, typically $d\sigma^{(\mathrm{MC})} > d\sigma^{(\mathrm{NLO},E)}$

This is unfortunate: that region is dominated by MC effects, and $\mathbb{H}$ events are essentially relevant only in an integrated sense (i.e. for rates)

$\longrightarrow$



Before showering (unphysical)



After showering (physical)

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The tiny negative contribution at intermediate p_T's: **N.2**

The $\mathrm{MC@NLO}\text{-}\Delta$ approach:

$$\mathcal{F}_{\textsf{MC@NLO-}\Delta} = \mathcal{F}_{\textsf{MC}}\left(\mathcal{K}^{(\mathbb{H})}\right) d\sigma^{(\Delta,\mathbb{H})} + \mathcal{F}_{\textsf{MC}}\left(\mathcal{K}^{(\mathbb{S})}\right) d\sigma^{(\Delta,\mathbb{S})} \,,$$

with:

$$\begin{aligned}
&\mathbb{H}-\text{events} \qquad && d\sigma^{(\Delta,\mathbb{H})} = \left(d\sigma^{(\mathrm{NLO},E)} - d\sigma^{(\mathrm{MC})}\right)\Delta \\
&\mathbb{S}-\text{events} \qquad && d\sigma^{(\Delta,\mathbb{S})} = d\sigma^{(\mathrm{MC})}\Delta \\
& && \qquad + \sum_{\alpha=S,C,SC} d\sigma^{(\mathrm{NLO},\alpha)} + d\sigma^{(\mathrm{NLO},E)}(1-\Delta)
\end{aligned}$$

and:

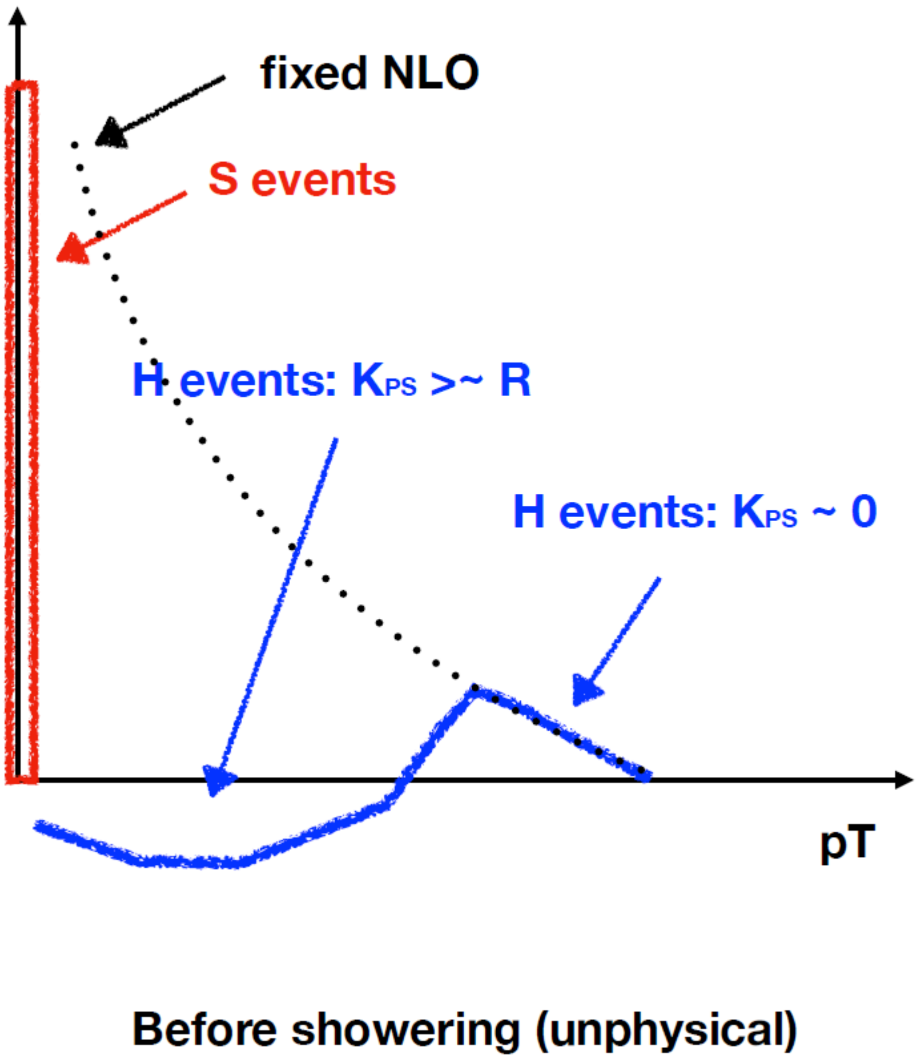
$$\begin{aligned}
&0 \le \Delta \le 1 \\
&\Delta = 1 + \mathcal{O}(\alpha_S) \\
&\Delta \longrightarrow 0 \qquad && \text{soft and collinear limits} \\
&\Delta \longrightarrow 1 \qquad && \text{hard regions}
\end{aligned}$$

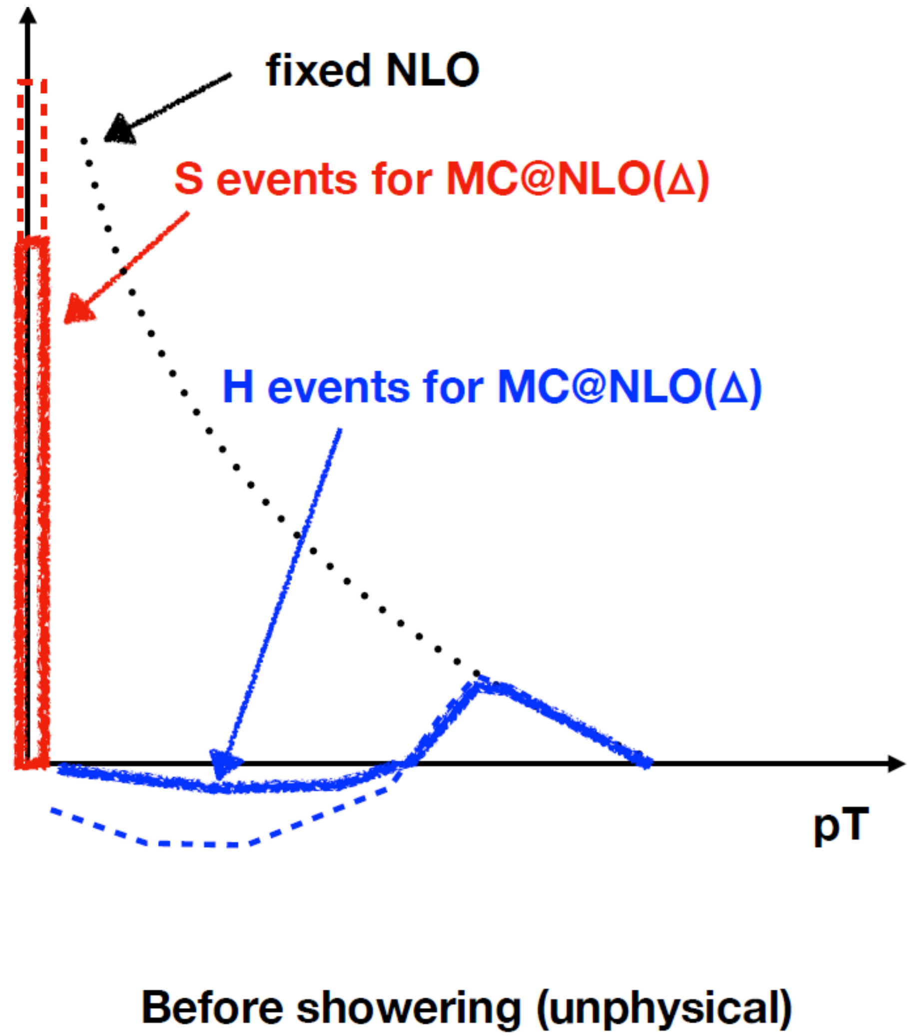
Rationale:

- Δ is small where the MC is most active (lots of emissions)
- Δ is large where the MC is less active (no/few emissions)
- Δ does not change the formal properties of $\mathrm{MC@NLO}$

It sounds like Δ is a no-emission probability

Because it is





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- Δ is constructed with the no-emission probabilities *provided by the MC*

$$\Delta = \prod_{k=1}^{n} \Pi_k \left(\mu_k, t_k \right)$$

- All Born-level legs contribute

- However, on average only one NEP is close to zero (collinear dominance)

- The starting scales (the μ's of D) are inputs; the stopping scales are provided by the MC. This is done leg by leg

- These scales are written onto the LHEF (μ's for $\mathbb{S}$ events; t's for $\mathbb{H}$ events); up to two scales per particle (one scale per dipole end)

Formal properties. Bear in mind that for any observable O:

$$\frac{d\sigma_\alpha}{dO} = \sum_{showers} \delta(O - O_n)\mathcal{F}_\alpha\,, \qquad \alpha = \mathrm{MC}, \mathrm{MC@NLO}, \mathrm{MC@NLO\text{-}\Delta}$$

- Unitarity

$$\int dO\, \frac{d\sigma_{\text{MC@NLO-}\Delta}}{dO} = \int dO\, \frac{d\sigma_{\text{MC@NLO}}}{dO} = \sigma_{\text{NLO}}$$

- Matrix-element dominance in hard regions ($\mathcal{O}(\alpha_S^{b+2})$ are terms of MC origin)

$$\frac{d\sigma_{\text{MC@NLO-}\Delta}}{dO} = \frac{d\sigma_{\text{MC@NLO}}}{dO} + \mathcal{O}(\alpha_S^{b+2}) = \frac{d\sigma_{\text{NLO}}}{dO} + \mathcal{O}(\alpha_S^{b+2})$$

- MC dominance in IR regions

$$\frac{d\sigma_{\text{MC@NLO-}\Delta}}{dO} \sim \frac{d\sigma_{\text{MC@NLO}}}{dO} \sim \frac{d\sigma_{\text{MC}}}{dO}$$

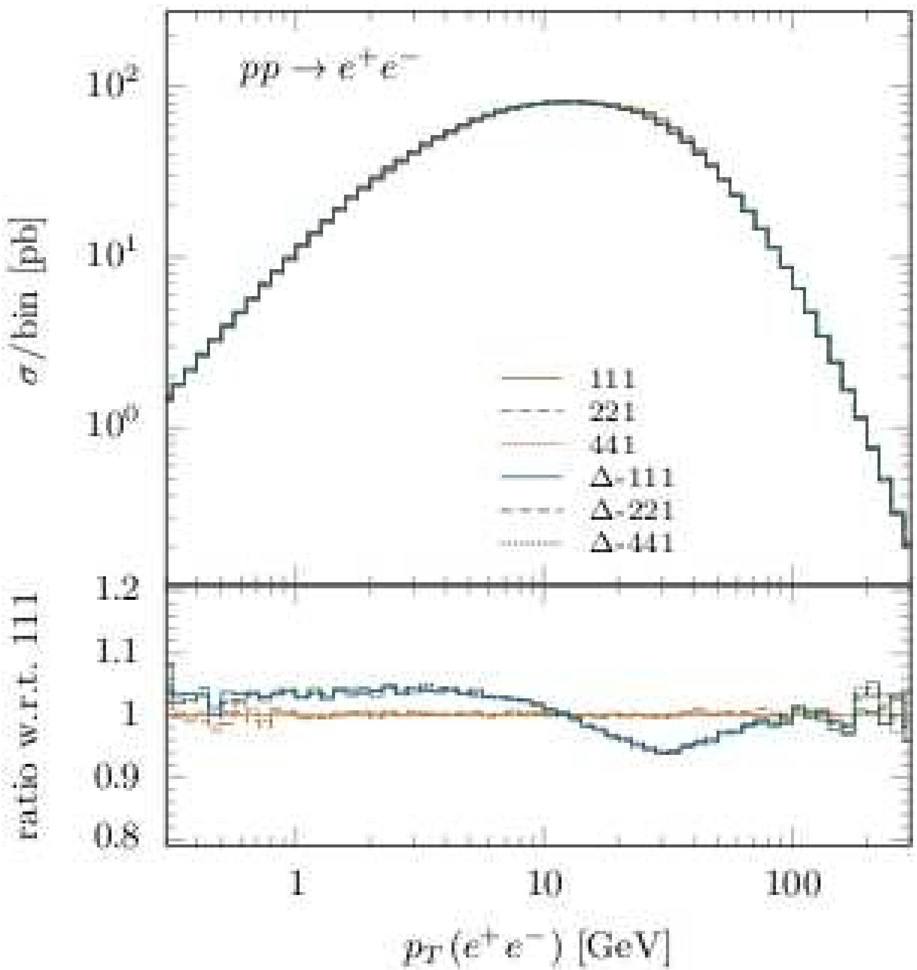
Structure:

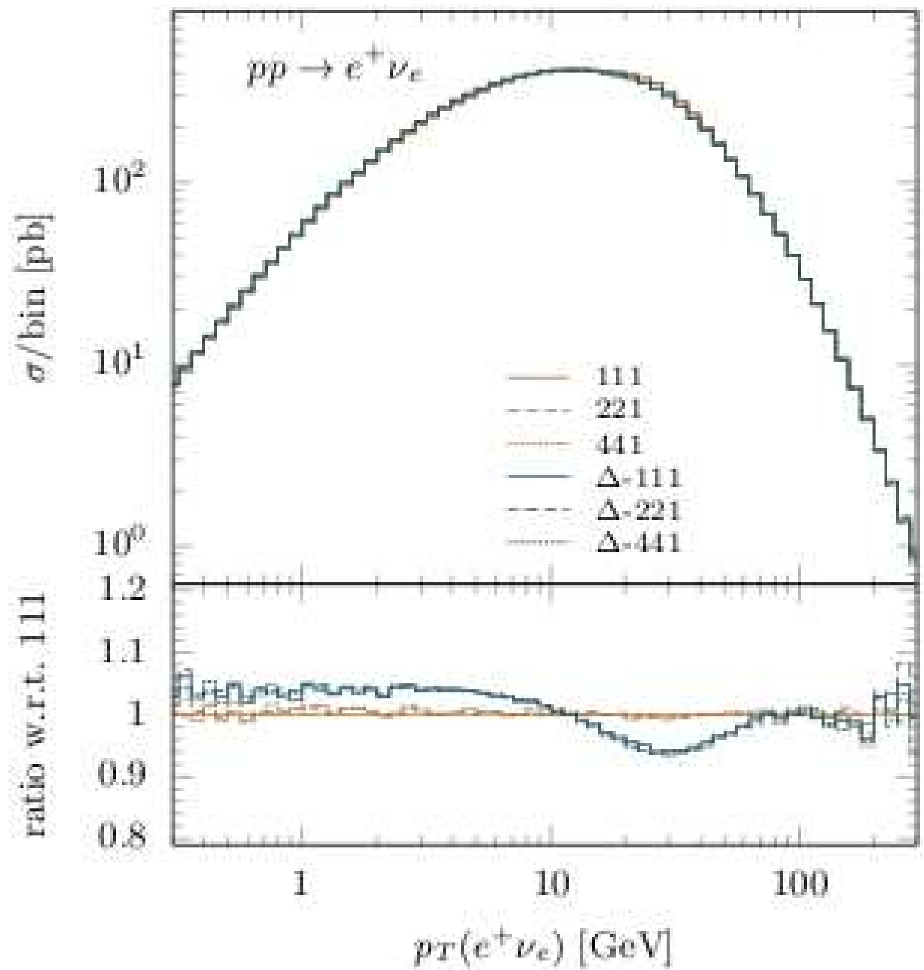
0. Use Pythia8 to pre-tabulate NEP's (increases runtime speed)
1. MG5_aMC scans phase space and generates kinematics
2. Pythia8 is given the kinematics, returns stopping scales and information on dead zones
3. Acting on Pythia8 input, MG5_aMC constructs Δ and integrates the cross section
4. Events are unweighted and written onto LHEF
5. Events are showered by Pythia8

$\Longrightarrow$ the executable links Pythia8 and MG5_aMC

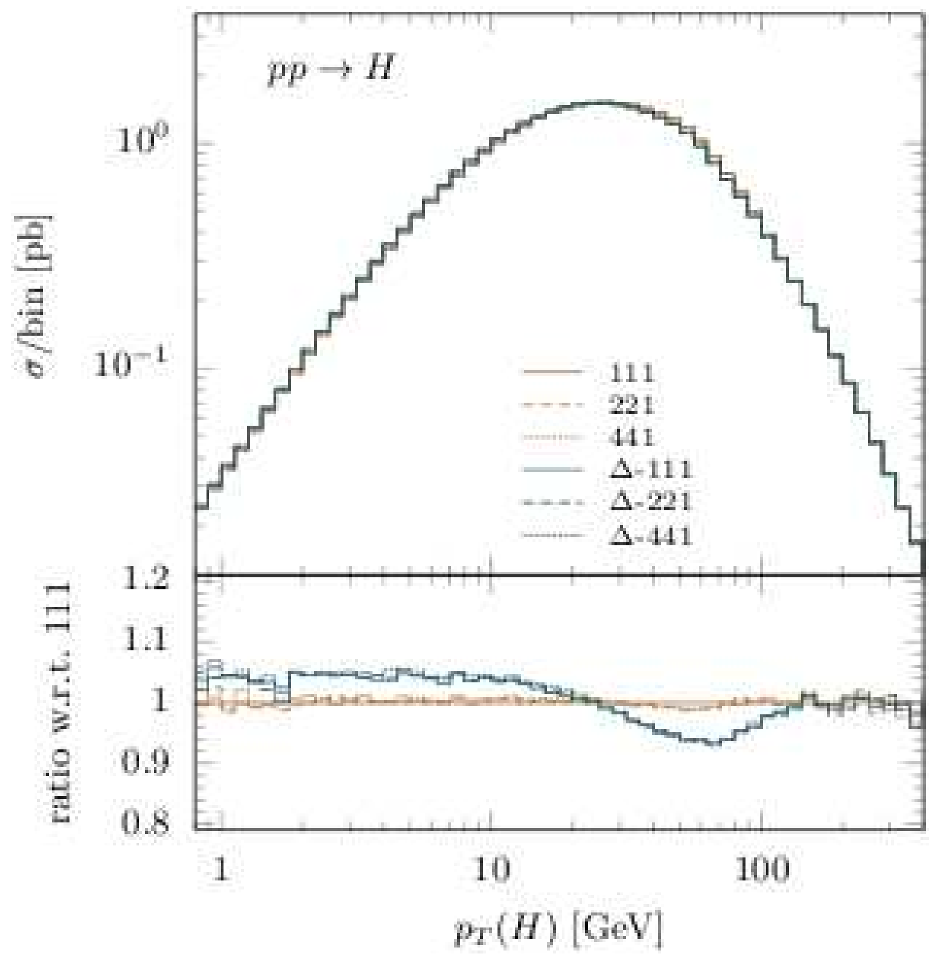
	MC@NLO			MC@NLO-Δ		
	111	221	441	Δ-111	Δ-221	Δ-441
$pp \to e^+e^-$	6.9% (1.3)	3.5% (1.2)	3.2% (1.1)	5.7% (1.3)	2.4% (1.1)	2.0% (1.1)
$pp \to e^+\nu_e$	7.2% (1.4)	3.8% (1.2)	3.4% (1.2)	5.9% (1.3)	2.5% (1.1)	2.3% (1.1)
$pp \to H$	10.4% (1.6)	4.9% (1.2)	3.4% (1.2)	7.5% (1.4)	2.0% (1.1)	0.5% (1.0)
$pp \to Hb\bar{b}$	40.3% (27)	38.4% (19)	38.0% (17)	36.6% (14)	32.6% (8.2)	31.3% (7.2)
$pp \to W^+j$	21.7% (3.1)	16.5% (2.2)	15.7% (2.1)	14.2% (2.0)	7.9% (1.4)	7.4% (1.4)
$pp \to W^+t\bar{t}$	16.2% (2.2)	15.2% (2.1)	15.1% (2.1)	13.2% (1.8)	11.9% (1.7)	11.5% (1.7)
$pp \to t\bar{t}$	23.0% (3.4)	20.2% (2.8)	19.6% (2.7)	13.6% (1.9)	9.3% (1.5)	7.7% (1.4)

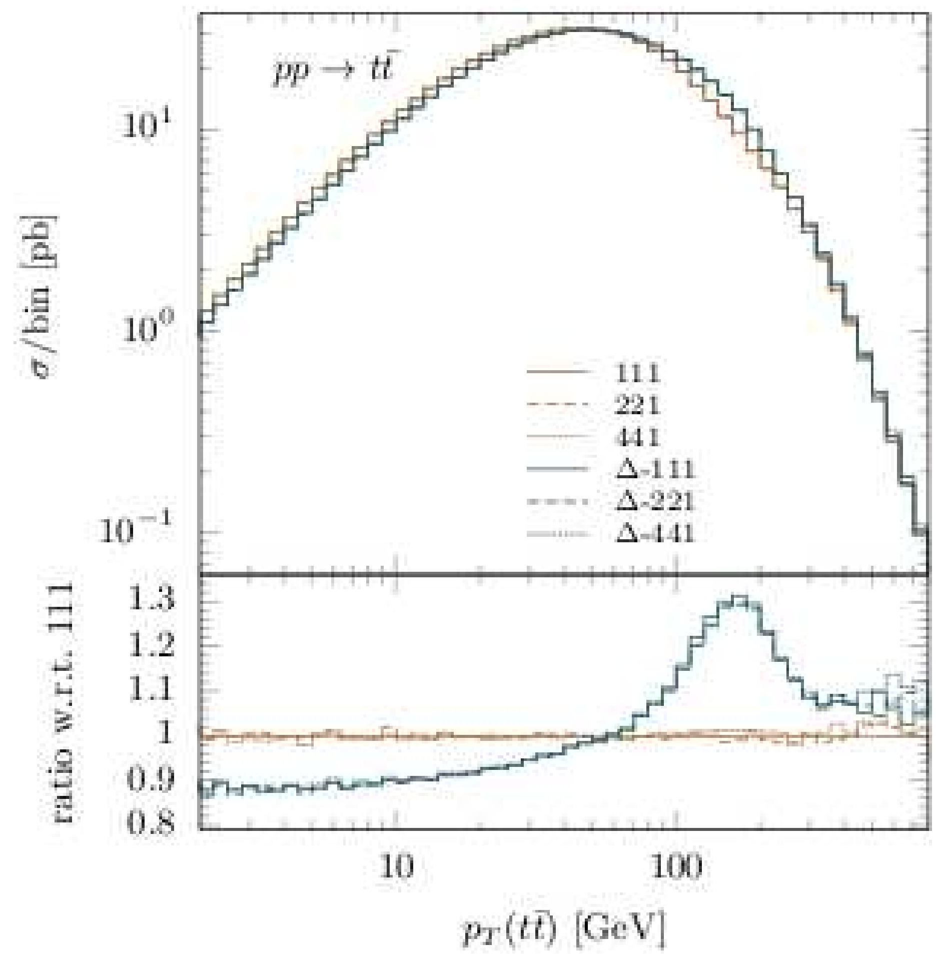
- 111, 221, 441 refer to folding (larger numbers $\longrightarrow$ more folding)
- The relative cost is reported in round brackets
- $Hb\bar{b}$ the only one whose cost is still significant, although its reduction (wrt MC@NLO) is large as well. Room for improvement?



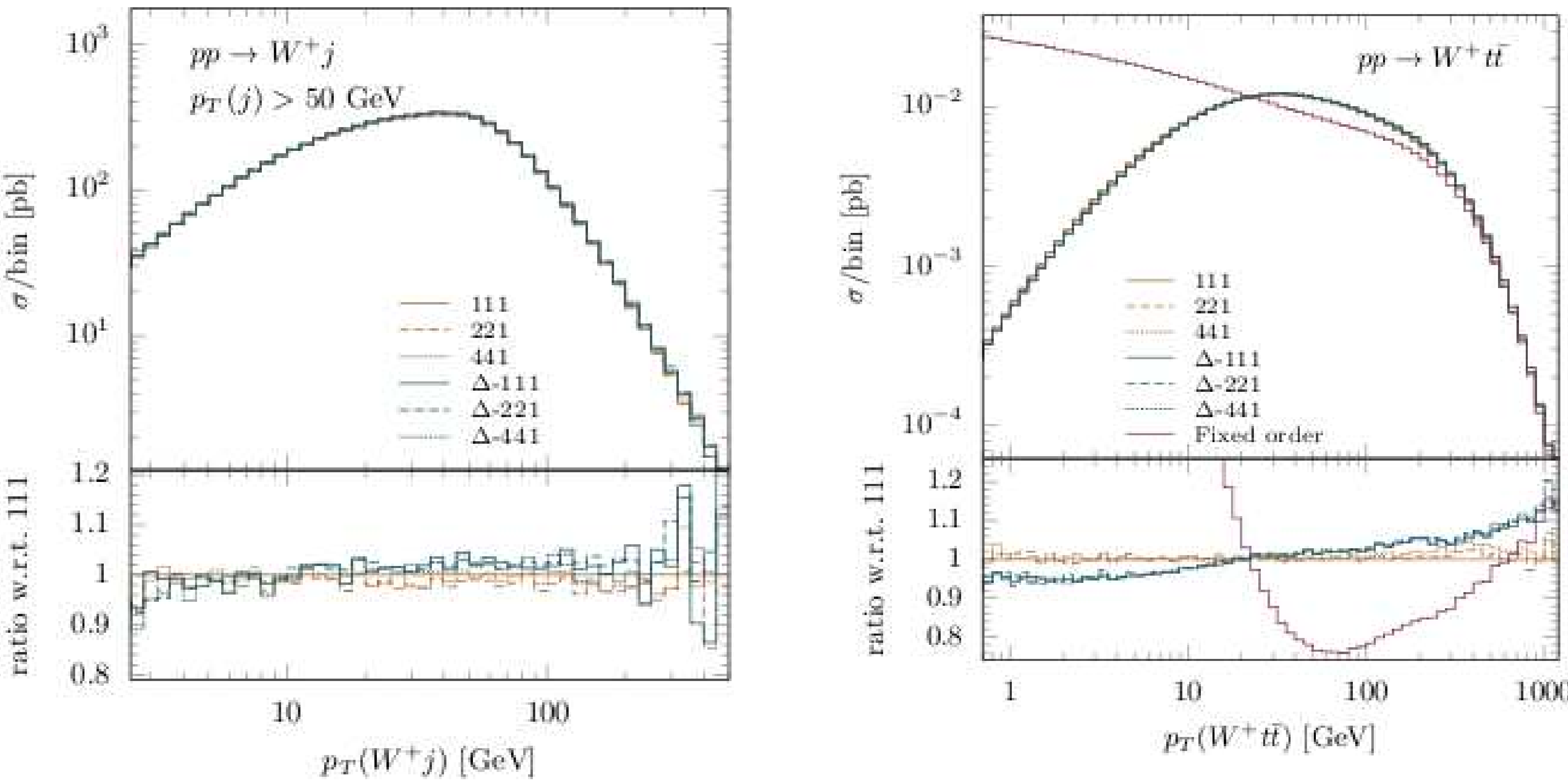


- Same shape at small p_T, same shape and normalisation at large p_T
- Differences in the matching region $\mathcal{O}(5\%)$, compatible with theo systematics
- Folding does not affect differential observables (only statistical effects)





- Same pattern in $gg \to H$ as in DY
- Qualitatively similar in $t\bar{t}$ production, but effects much larger
- Still compatible with theoretical systematics



- In $Wt\bar{t}$, large shower effects up to very large p_T's (very massive system)
- MC@NLO-Δ "converges" to NLO faster than MC@NLO
- Most likely, a benefit of the more sensible scale assignments in MC@NLO-Δ

Conclusions

- MC@NLO-Δ must be seen as a new matching formalism, which requires testing
- There are some clear advantages w.r.t. MC@NLO:
  - Reduction of negative weights and smaller event samples
  - More physical scale assignments
  - Reduced sensitivity to MC approximations in the soft limits
- ...and the disadvantage of longer running times (up to LHEF writing)
- In MG5_AMC, we have implemented folding for both MC@NLO and MC@NLO-Δ. LHEF is multi-scale for MC@NLO-Δ
- We are still considering alternative options (eg dynamical folding)