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Recent progress in NLO Monte Carlos

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Motivation

- Fixed-order results: reliable predictions for total rates and large-p_T tails
- Resummations: reliable predictions for peak regions

The complementarity of the two approaches renders their merging into a single formalism particularly desirable and challenging

- Parton Shower Monte Carlos are the easiest and most flexible way to perform resummations

How to improve Monte Carlos?

The key issue is to go beyond the collinear approximation

$\Longrightarrow$ use exact matrix elements of order higher than leading

Which ones?

There are two possible choices, that lead to two vastly different strategies:

- Matrix Element Corrections $\longrightarrow$ tree level
- NLOwPS $\longrightarrow$ tree level and loop

NLOwPS is a field in its infancy

Although somewhat undermanned, there is a lot of ongoing activity

- First hadronic code: Φ-veto (Dobbs, 2001)
- First general solution: MC@NLO (SF, Webber, 2002)
- Automated computations of ME's: grcNLO (GRACE group, 2003)
- Absence of negative weights (Nason, 2004)
- Showers with high log accuracy in ϕ_6^3 (Collins, Zu, 2002–2004)
- Proposals for $e^+e^- \longrightarrow jets$ (Soper, Krämer, Nagy, 2003–2005)

I shall mainly deal with MC@NLO, the only approach formulated in a fully general and process-independent manner which has resulted into a public computer program

MC@NLO: formalism (SF, Webber (2002))

Double counting $\Longleftrightarrow$ MC evolution results in spurious NLO terms

$\longrightarrow$ *Eliminate the spurious NLO terms "by hand"*

- The generating functional is

$$
\begin{aligned}
\mathcal{F}_{\text{MC@NLO}} \quad = \quad & \sum_{ab} \int dx_1\, dx_2\, d\phi_{n+1}\, f_a(x_1) f_b(x_2) \times \\
& \left[\mathcal{F}_{\text{MC}}^{(2\to n+1)} \left(\mathcal{M}_{ab}^{(r)} - \mathcal{M}_{ab}^{(\text{MC})} \right) + \right. \\
& \left. \mathcal{F}_{\text{MC}}^{(2\to n)} \left(\mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} + \mathcal{M}_{ab}^{(\text{MC})} \right) \right]
\end{aligned}
$$

$$
\mathcal{M}_{\mathcal{F}(ab)}^{(\text{MC})} = \mathcal{F}_{\text{MC}}^{(2\to n)} \mathcal{M}_{ab}^{(b)} + \mathcal{O}(\alpha_S^2 \alpha_S^b)
$$

There are *two* MC-induced contributions: they eliminate the spurious NLO terms due to the branching of a final-state parton, and to the non-branching probability

MC@NLO 3.2 [hep-ph/0601192]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{\mathrm{IL}}\bar{l}_{\mathrm{IL}} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{\mathrm{IL}}\bar{l}_{\mathrm{IL}} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{\mathrm{IL}}\bar{l}_{\mathrm{IL}} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{\mathrm{IL}}\nu_{\mathrm{IL}} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{\mathrm{IL}}\bar{\nu}_{\mathrm{IL}} + X$
–1396				×	$H_1H_2 \to \gamma^* (\to \sum_i f_i \bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706				×	$H_1H_2 \to t\bar{t} + X$
–2000–IC				×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC				×	$H_1H_2 \to \bar{t} + X$
–2004–IC				×	$H_1H_2 \to t + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i (W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

- Works identically to HERWIG: the very same analysis routines can be used
- Reads shower initial conditions from an event file (as in ME corrections)
- Exploits Les Houches accord for process information and common blocks
- Features a self contained library of PDFs with old and new sets alike
- LHAPDF is now implemented

MC@NLO in a nutshell

1. Choose your favourite MC (HERWIG, PYTHIA), and compute analytically the "NLO cross section", i.e., the first emission. This is an observable-independent, process-independent procedure, which is done once and for all

2. Implement the NLO matrix elements of your favourite process according to the universal, observable-independent, subtraction-based formalism of SF, Kunszt, Signer (Nucl.Phys.B467(1996)399) for cancelling IR divergences

   This is the only non-trivial step necessary in order to add new processes

3. Add and subtract the MC counterterms, computed in step 1, to what computed in step 2. The resulting expression allows one to generate the hard kinematic configurations, which are eventually fed into the MC showers as initial conditions

On step 1: MC counterterms

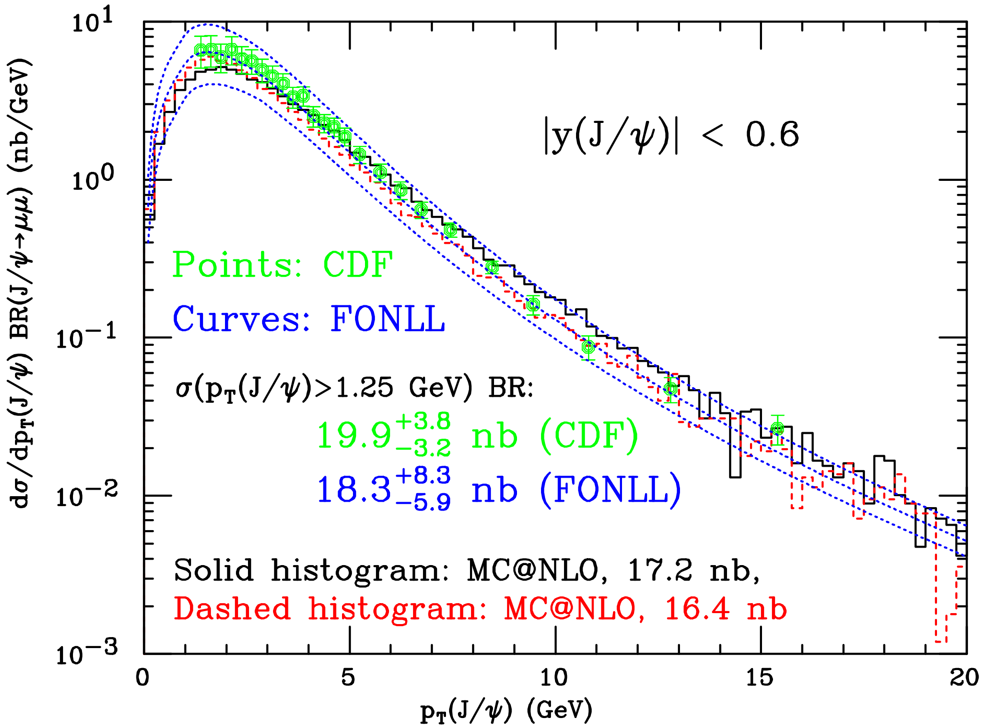
- An analytic computation is needed for each type of MC branching from a massless leg: there are only two cases!

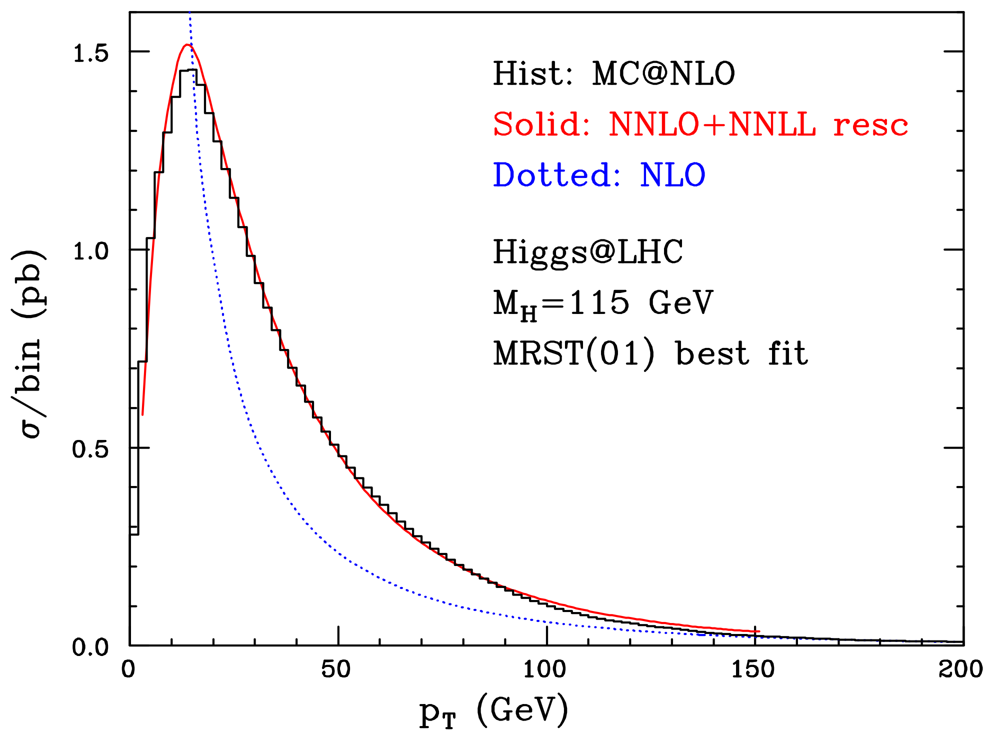
- Initial-state branchings have been studied in JHEP0206(2002)029 (SF, Webber) and JHEP0308(2003)007 (SF, Nason, Webber)

- Final-state branchings have been studied in JHEP0603(2006)092 (SF, Laenen, Motylinski, Webber)

For each new process, just assemble these pieces into a computer code. No new computation is required

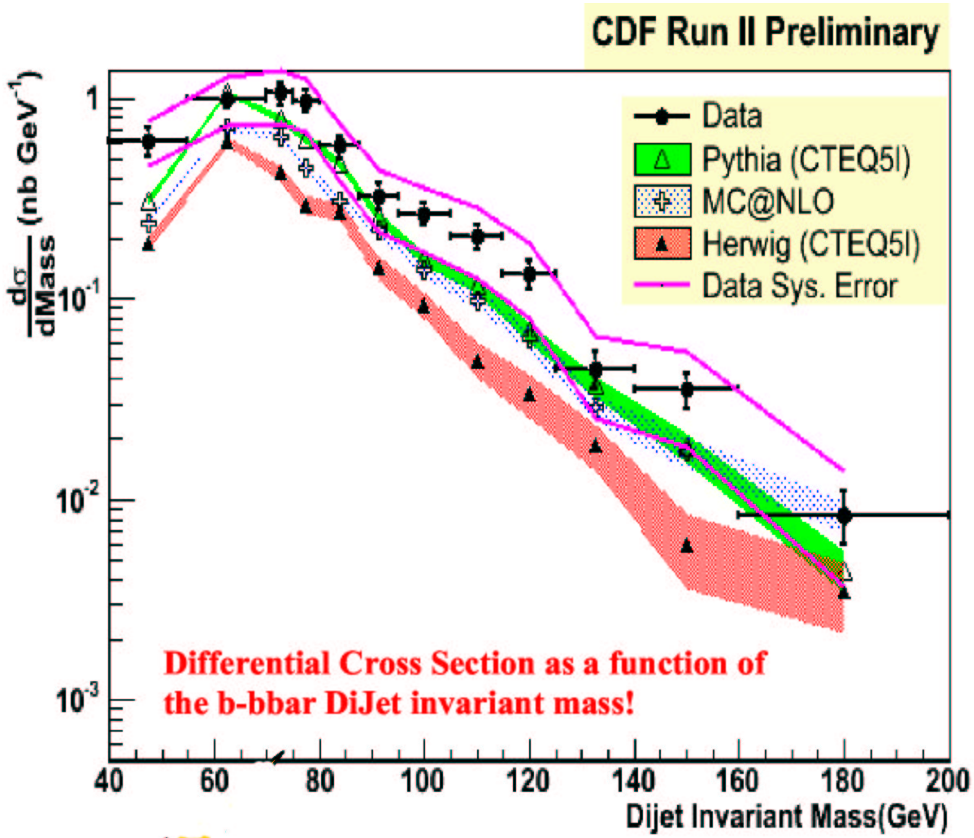
MC@NLO vs analytical results

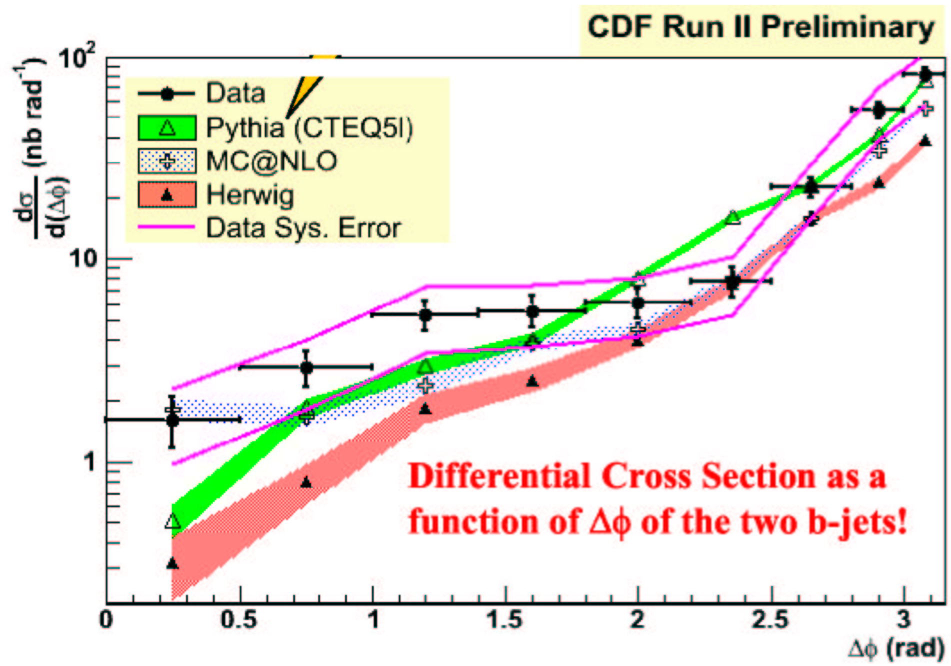




- Note: analytical resummations are *formally* more accurate: Cacciari, Nason (single-inclusive b), Bozzi, Catani, de Florian, Grazzini (Higgs)
- Not accidental: HERWIG does an excellent job (for perturbative physics in particular), the matching with NLO improves it further
- MC@NLO thus effectively allows one to perform high-accuracy computations in a realistic environment (as complicated as detector simulations)

More good news on b physics

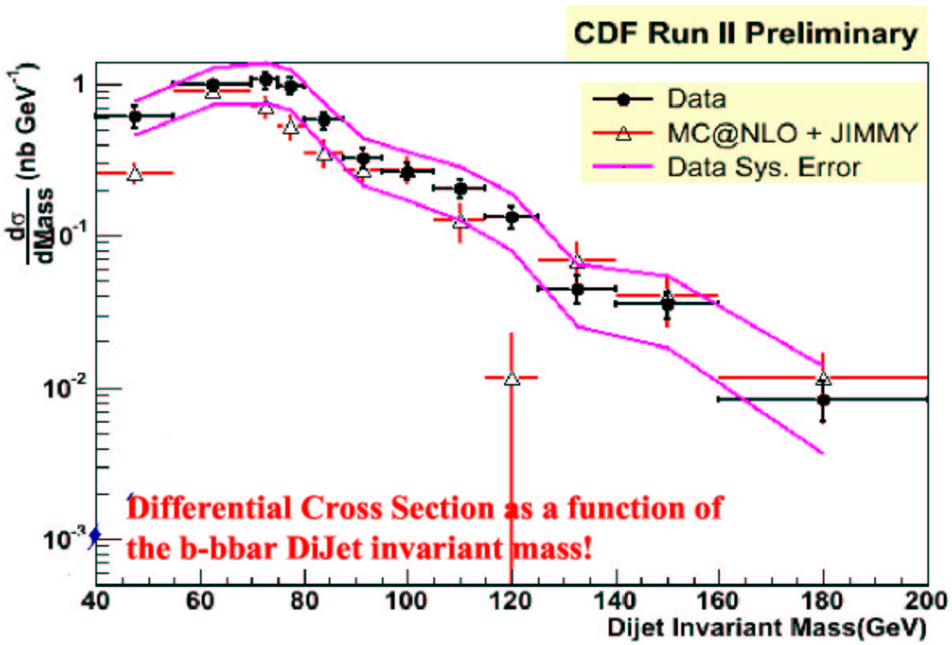


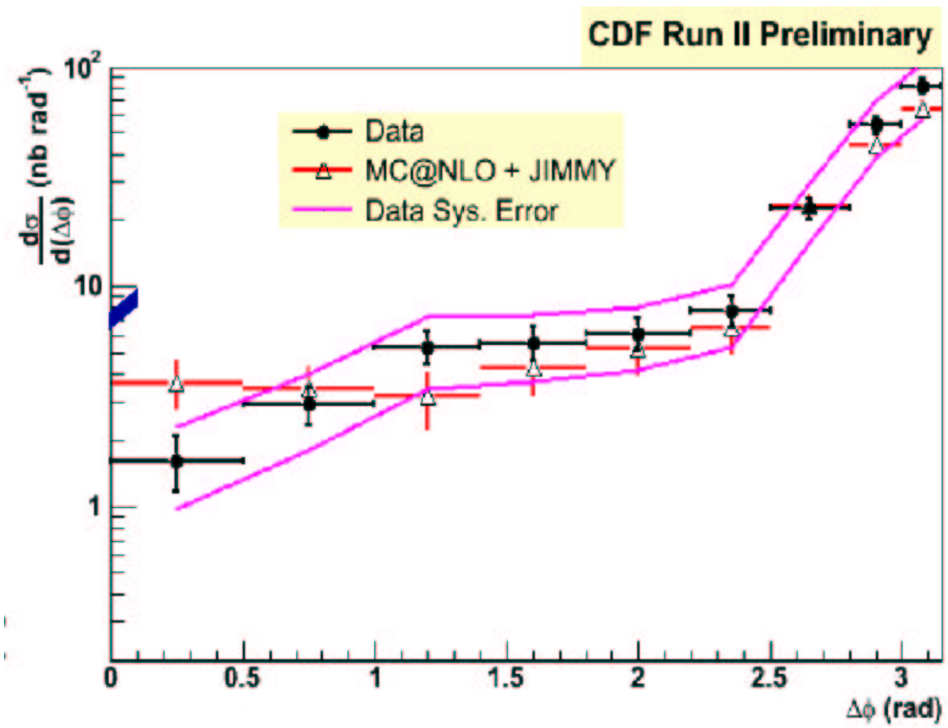


- These observables are very involved (b-jets at hadron level), and cannot be computed with analytic techniques
- The underlying event in Pythia is fitted to data; that of Herwig (used in MC@NLO) does not fit the data well (lack of MPI)

It's actually even better

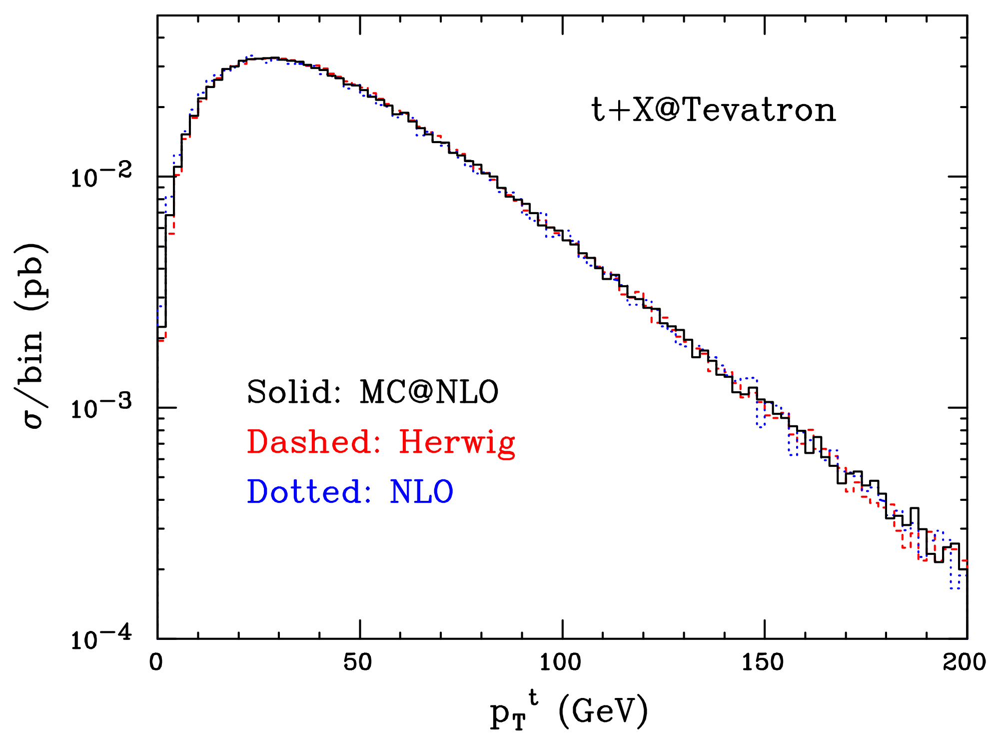
The treatment of the UE in Herwig recently improved: Jimmy

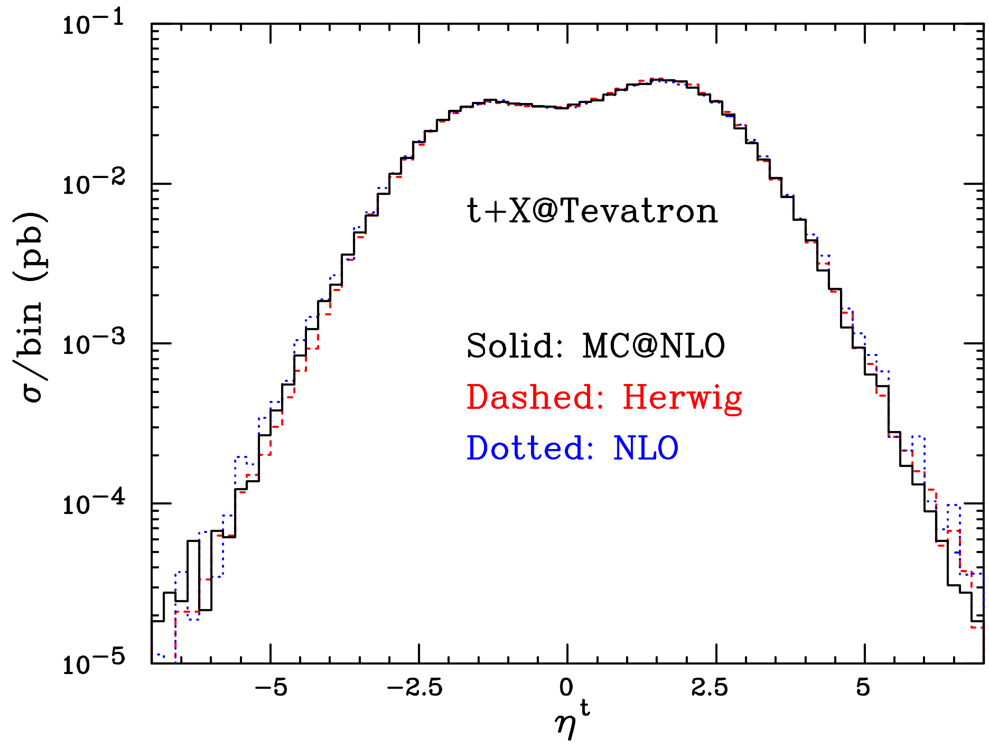




- The importance of the underlying event stresses the necessity of embedding a *precise* computation into a Monte Carlo framework, as done in MC@NLO

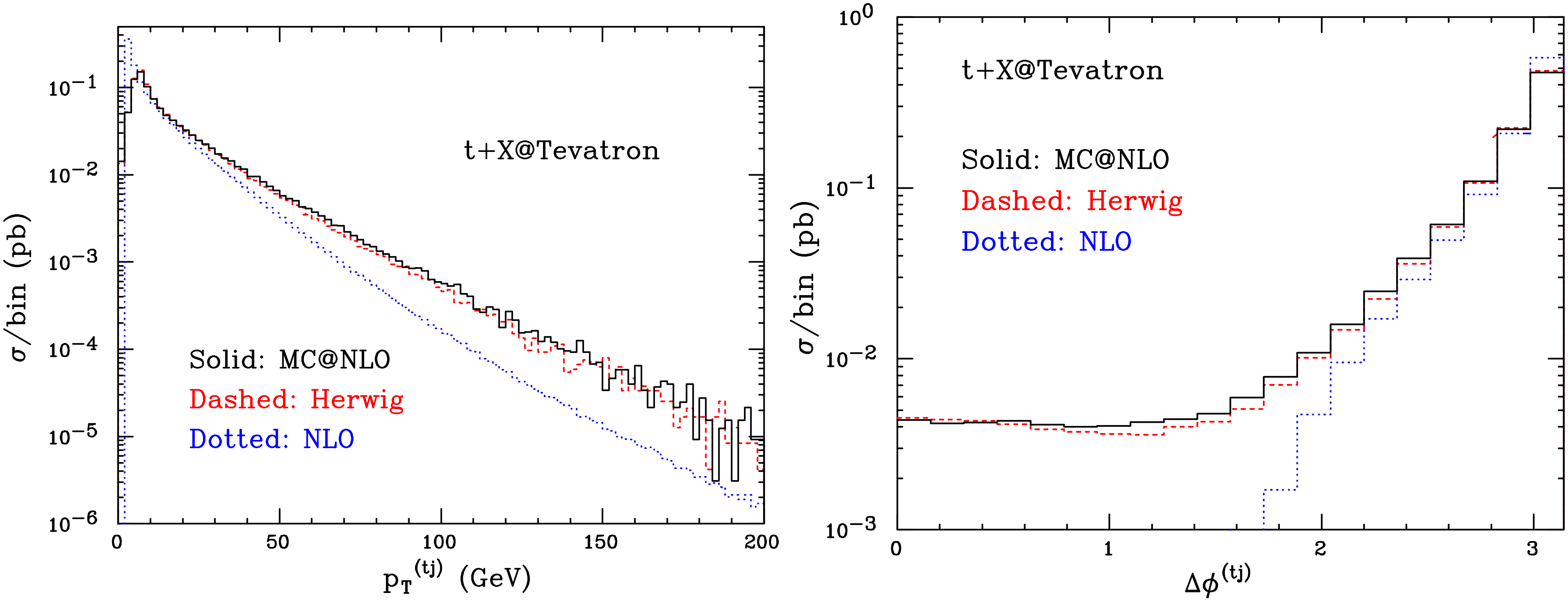
The ultimate test: single-top





- Single-t production features *all possible IR singularities* and *unequal masses* in the final state $\Longrightarrow$ the ultimate test for the formalism
- The previously untreated case of final-state collinear singularities required some analytical computations which are *process independent*
- The code performs similarly as for simpler processes (speed, efficiency,...)

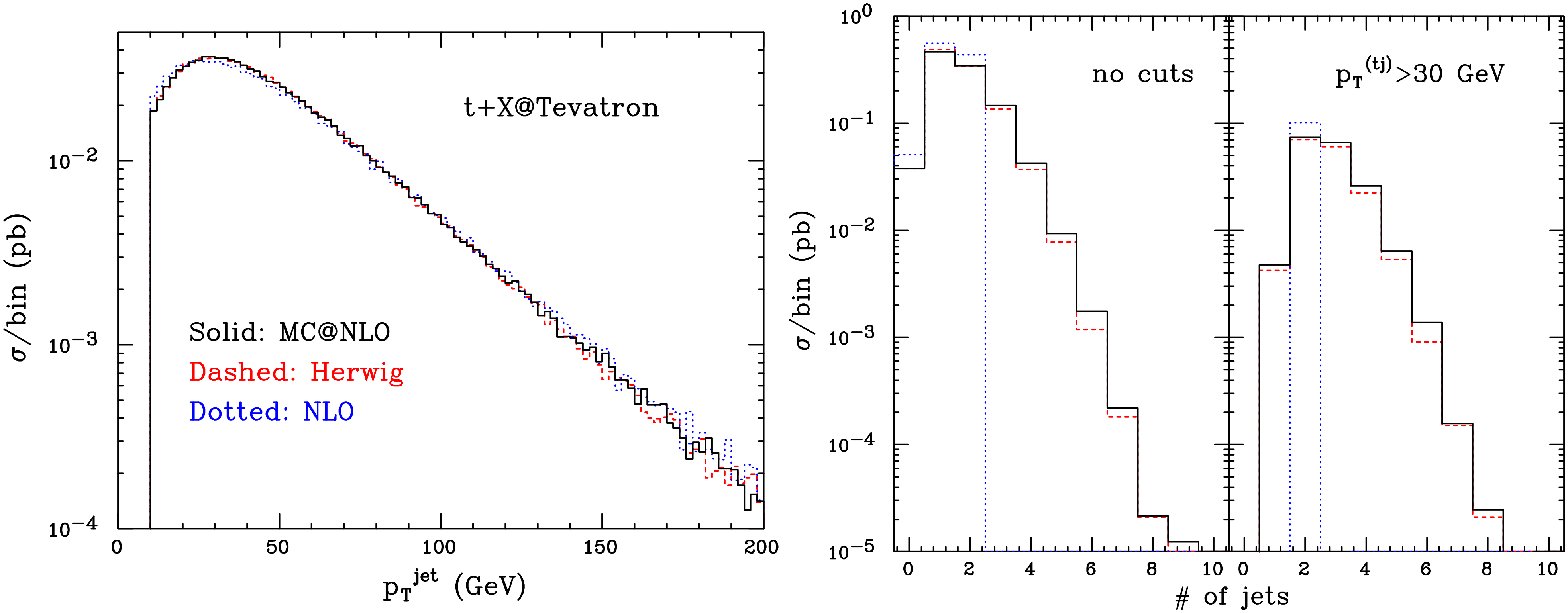
Single-top + jets at the Tevatron I



- These are fairly "exclusive" variables. The complicated structure emerging from the showers is very different wrt the two- or three-parton NLO final states
- NLO corrections visible, but very small (accurate ME-PS matching)
- Effects are enhanced: transverse observables in "longitudinal" events

Is jet physics hopeless at NLO? Of course it is not $\longrightarrow$

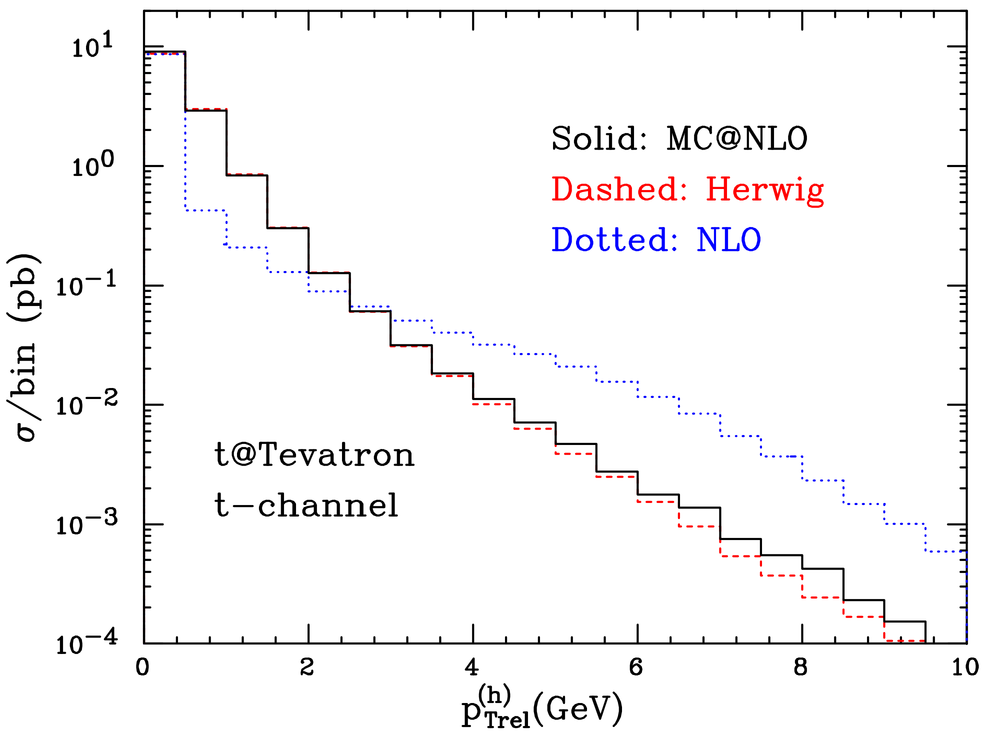
Single-top + jets at the Tevatron II

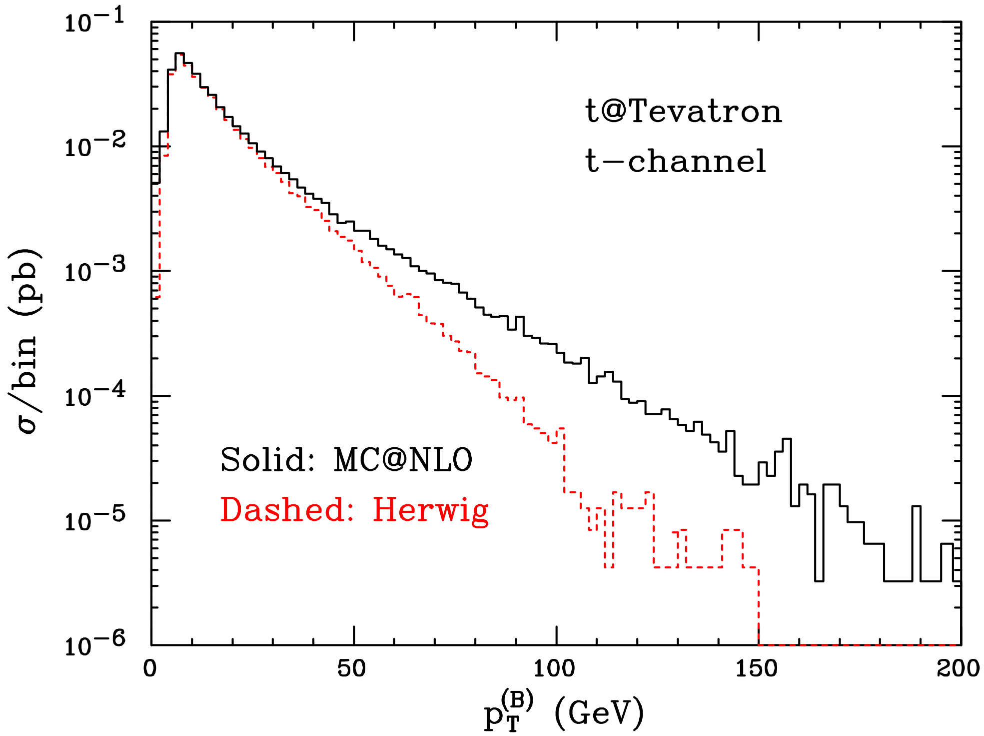


- The good agreement between (parton-level) NLO and (hadron-level) MC@NLO for a single-inclusive observable is reassuring
- For those phase-space regions dominated by jetty events, NLO doesn't work well

Single-t production in MC@NLO is the first process for which *hadronization corrections to jets* can be studied in a solid manner to NLO accuracy

Activity around single top (Tevatron)





- Hadron p_T relative to the jet axis: hard emissions show up
- B-hadron p_T: hard emission effects are striking
  (but cannot be predicted by pure NLO)

There is ample evidence of MC@NLO improving both NLO computations and standard MC simulations

Event generation in MC@NLO

- Compute the integrals

$$J_{\mathbb{H}} = \sum_{ab} \int dx_1\, dx_2\, d\phi_{n+1}\, f_a(x_1) f_b(x_2) \left| \mathcal{M}_{ab}^{(r)} - \mathcal{M}_{ab}^{(\mathrm{MC})} \right|$$

$$J_{\mathbb{S}} = \sum_{ab} \int dx_1\, dx_2\, d\phi_{n+1}\, f_a(x_1) f_b(x_2) \left| \mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} + \mathcal{M}_{ab}^{(\mathrm{MC})} \right|$$

- Get $N_{\mathbb{H}}$ $2 \to n+1$ events and $N_{\mathbb{S}}$ $2 \to n$ events, with

$$N_{\mathbb{H}} = N_{tot} \frac{J_{\mathbb{H}}}{J_{\mathbb{S}} + J_{\mathbb{H}}}\,, \qquad N_{\mathbb{S}} = N_{tot} \frac{J_{\mathbb{S}}}{J_{\mathbb{S}} + J_{\mathbb{H}}}$$

- For each phase-space point (x_1, x_2, ϕ_{n+1}), $\mathbb{H}$ and $\mathbb{S}$ kinematic configurations are unambiguously determined, and related by a map

$$\mathcal{P}_{\mathbb{H} \to \mathbb{S}}$$

An alternative event generation: βMC@NLO

- Compute the integral

$$J_{\mathbb{H}+\mathbb{S}} = \sum_{ab} \int dx_1\, dx_2\, d\phi_{n+1}\, f_a(x_1) f_b(x_2) \left| \mathcal{M}_{ab}^{(r)} + \mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} \right|$$

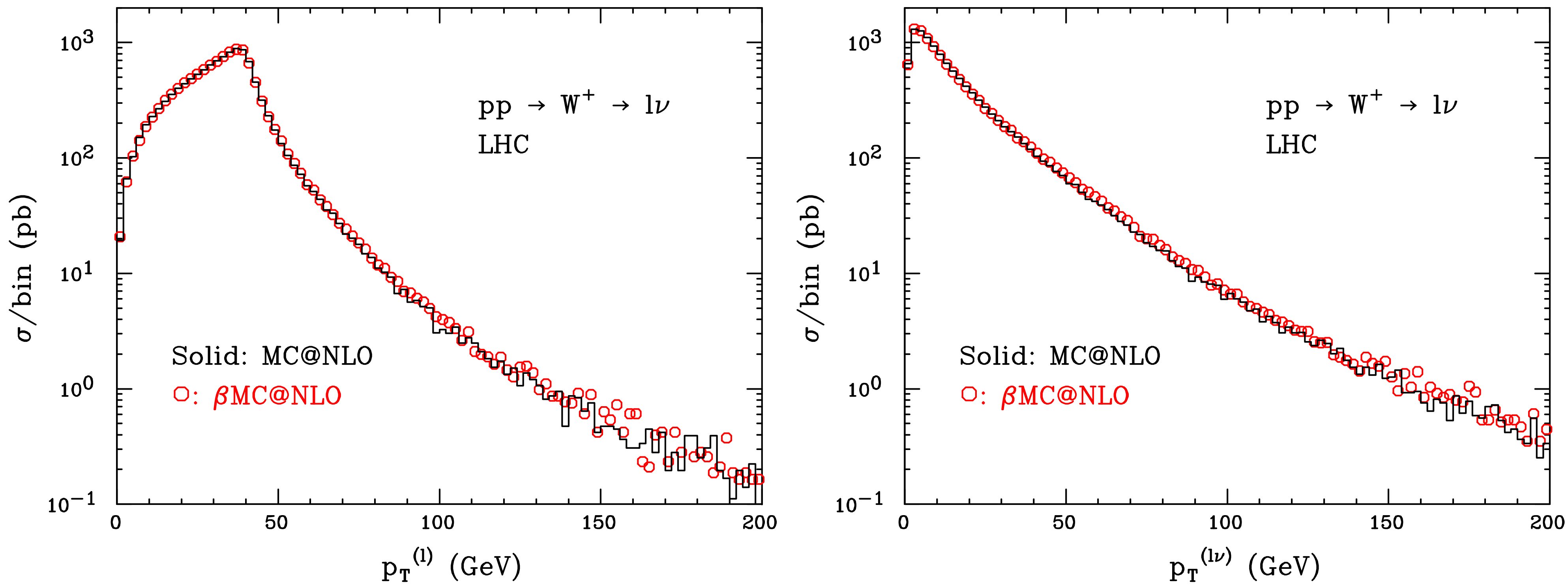
- For each phase-space point (x_1, x_2, ϕ_{n+1}), generate either $\mathbb{H}$ or $\mathbb{S}$ kinematics according to the ratio of weights

$$w_{\mathbb{H}} = \left| \mathcal{M}_{ab}^{(r)} - \mathcal{M}_{ab}^{(\mathrm{MC})} \right|, \qquad w_{\mathbb{S}} = \left| \mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} + \mathcal{M}_{ab}^{(\mathrm{MC})} \right|$$

- Tested in $e^+e^- \to$ 2 jets and $H_1 H_2 \to l\nu_l$: reduces the fraction of negative weights to less than 1%!

- But: expansion to $\mathcal{O}(\alpha_S \alpha_S^b)$ in the regions where the signs of $w_{\mathbb{H}}$ and $w_{\mathbb{S}}$ differ doesn't coincide with NLO $\longrightarrow$ double counting

$W^+ \longrightarrow l\nu_l$ with βMC@NLO



- No evidence of double counting in $e^+e^- \longrightarrow$ 2 jets and $H_1H_2 \longrightarrow l\nu_l$
- Fractions of negative weights: 7.5%$\longrightarrow$ 0.03% (2 jets), 9%$\longrightarrow$ 0.8% ($l\nu_l$)

$w_{\mathbb{H}}$ and $w_{\mathbb{S}}$ have opposite signs only where $\mathcal{M}_{ab}^{(\mathrm{MC})} \neq 0$
$\Longrightarrow$ NLO results are irrelevant there

βMC@NLO is a very interesting option, which is worth further studies

Towards positive-only weights: pMC@NLO

Nason's proposal (JHEP0411(2004)040) should render it easier the implementation of new processes for theorists able to perform NLO computations, but lacking MC expertise

We are currently working on:

- Writing down a process-independent formulation of the method, based on Frixione-Kunszt-Signer subtraction. This entails:
  - Find a general definition of radiation variables $\longleftarrow$ Nason's talk
  - Work out the corresponding projections $\mathbb{S} \longrightarrow \mathbb{H}$ (related to $\mathcal{P}_{\mathbb{H}\to\mathbb{S}}$ of MC@NLO)
- Formulating truncated & vetoed showers in a way independent of the particular MC the NLO computation is matched to

At the end of the day, we aim at giving explicit prescriptions, down to implementation details, for dealing with new processes

Outlook

NLOwPS's have received considerable theoretical attention recently

It is crucial that NLOwPS's be standard analysis tools for experiments. Fortunately, this appears to be the case: MC@NLO is being used by Tevatron and LHC collaborations

My present activity includes:

- Mainstream MC@NLO: implementation of new processes (dijets, Higgs through VBF, Wt-mode in single top, anomalous couplings in WZ, spin correlations in $t\bar{t}$ and single top (with V. Del Duca, C. Oleari, E. Laenen, P. Motylinski, A. Oh, B. Webber))
- pMC@NLO: general formulation (with P. Nason)
- βMC@NLO: can it be made rigorous?