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Top physics with MC@NLO

LPSC, Grenoble, 10/10/2006

SF & B. Webber, JHEP 0206(2002)029 [hep-ph/0204244]
SF, P. Nason & B. Webber, JHEP 0308(2003)007 [hep-ph/0305252]
SF, E. Laenen, P. Motylinski & B. Webber, JHEP 0603(2006)092 [hep-ph/0512250]

Memo

- MC@NLO is a Parton Shower Monte Carlo which works just like any other PSMC: it outputs events

- The *defining feature*: partonic hard subprocesses are computed by including the full NLO QCD corrections

Basic facts

- Inclusive rates accurate to NLO (in α_s)
- More predictive than LO-based MC's (as usual when LO $\longrightarrow$ NLO) for shapes *and* rates
- The above true only for small numbers of extra jets – prefer CKKW-like procedures for many jets
- Tuning is the same as for the MC used for showering (presently only HERWIG) $\Longrightarrow$ smoother version upgrades

Why NLO corrections?

Among the many good reasons, let me mention those that are likely to have the largest impact on phenomenology

- *K factors*: the only way to compute them consistently (i.e., no bin-by-bin reweighting), and to use this information in detector simulations
- *Shapes* of observables do have NLO corrections $\Longrightarrow$ impact on acceptances and physics studies in general
- *Theoretical systematics*: scale dependence can be computed – this procedure is either meaningless or very difficult to perform with standard Monte Carlos

MC@NLO vs Matrix Element Corrections

MC@NLO is *not* another implementation of MEC (which is what you get by generating the hard process with `MadEvent`, `Alpgen`, and the like). MEC lack virtual corrections

This forces the use of an unphysical cutoff δ_{sep} in MEC, upon which physical observables depend $\longrightarrow$ matching systematics

MC@NLO is better than MEC since:

+ There is no δ_{sep} dependence (i.e., no merging systematics)
+ The computation of total rates is meaningful and reliable

MC@NLO is worse than MEC since:

− The number of hard legs is smaller

- The days of the universal tools are over. Choose the one that best suits your analysis. Typically: small/large number of *extra* legs $\Longrightarrow$ MC@NLO/MEC

MC@NLO 3.2 [hep-ph/0601192]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{\rm IL} l_{\rm IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{\rm IL} l_{\rm IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{\rm IL} l_{\rm IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{\rm IL} \nu_{\rm IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{\rm IL} \bar{\nu}_{\rm IL} + X$
–1396				×	$H_1H_2 \to \gamma^* (\to \sum_i f_i f_i) + X$
–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		×	$H_1H_2 \to H^0 W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0 (W^+ \to) l^+_i \nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0 W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0 (W^- \to) l^-_i \bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0 Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0 (Z \to) l_i l_i + X$
–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	×	$H_1H_2 \to Z^0 Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+ Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^- Z^0 + X$

Recent activities:

- Spin correlations in $t\bar{t}$ and single-top production
- Wt channel for single-top production
- Improvements to Higgs production
- Interface to HERWIG++ (ISR only)
- Dijet production

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

Running MC@NLO

- NLO code: integrates and unweights the matrix elements
- Event file: a list of hard events, i.e. the kinematics configurations emerging from hard subprocesses (typically, $2 \to 2$ and $2 \to 3$)
- MC code: HERWIG, which reads the hard events and showers them

The flowchart is the same as in MEC-based simulations. Features:

- Less than 1 hour for $1/2$ million $t\bar{t}$ hard events on my (2003) laptop
- Unweighting efficiency: 10-40%
- Events have weights ± 1

Negative weights

- Why are they around?

  Exact quantum mechanics computations feature interference phenomena, whose contributions don't have a definite sign. The presence of contributions of negative sign to the cross sections prevents us from having *only* $+1$ weights

- What's the difference wrt NLO?

  At the NLO, the negative-only weight distribution is divergent, while it is finite in MC@NLO. Unweighted event generation can only be achieved in MC@NLO

- Can I throw them away in MC@NLO?

  No, you can't: they are necessary in order to obtain the exact NLO results for total rates, and for differential distributions where relevant

- How do I have to use them?

  Just add -1 to *(i.e. subtract* $+1$ *from)* the histograms of physical observables. For geometric properties, treat them as you treat the positive weights

The only implication of negative weights is that you have to run a bit longer to obtain the same nominal accuracy – and in b physics you actually have to run *less*

A couple of things to remember

- The MC@NLO formalism is correct regardless of the parton shower code used. The implementation of the current version, however, is specifically designed to work with HERWIG. This information is hardwired in the code.
  If you use PYTHIA, you get wrong results

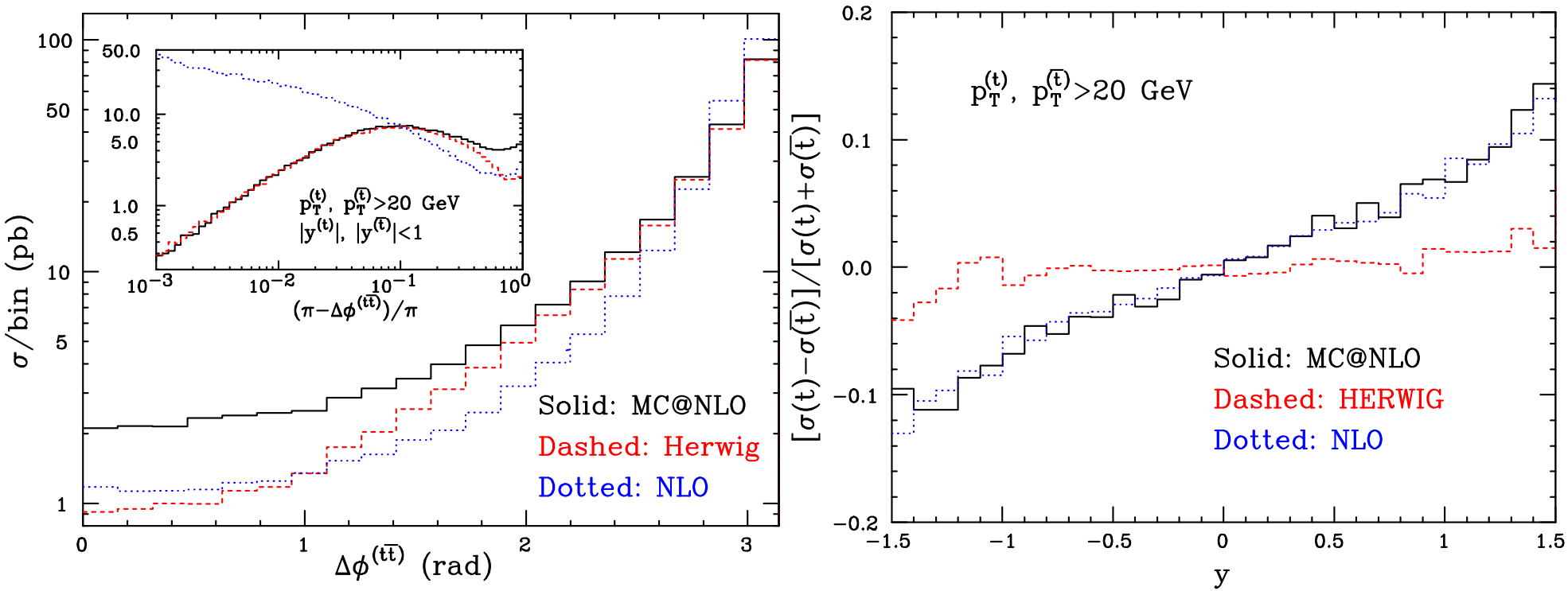
- The parton configurations corresponding to the hard subprocesses, stored in the event file, are non physical. They cannot be used in the same way as their analogues in the standard MC's codes

Top cross sections

	LO	NLO	NLO/LO
Tevatron			
$t+\bar{t}$	2.37 pb	2.81 pb	1.18
$t\bar{t}$	5.54 pb	6.87 pb	1.24
LHC			
$t+\bar{t}$	235.5 pb	253.2 pb	1.07
$t\bar{t}$	585.2 pb	879.7 pb	1.50

- Large corrections in $t\bar{t}$ production.Corrections are smaller for single top, dominated by t-channel mechanism
- Distributions are much more interesting (and relevant) than total rates

$t\bar{t}$ production: examples



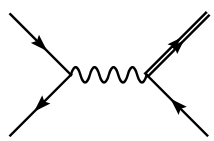
- $\Delta\phi$ an almost textbook example of the benefits of matched computations
- y asymmetry *(Tevatron)* is a pure-NLO feature. A definition at the LHC is more involved but still possible
- HERWIG results are rescaled here to match the NLO total rate

Single-top: production channels

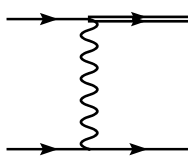
It is likely that single-top production will be observed for the first time at the LHC.
There is a lot of interesting physics to do

- Measurement of V_{tb}
- Constraints (measure?) on the b parton density
- An effective way to study new physics phenomena

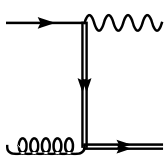
There are several production mechanisms

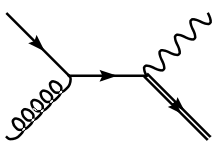


s channel



t channel



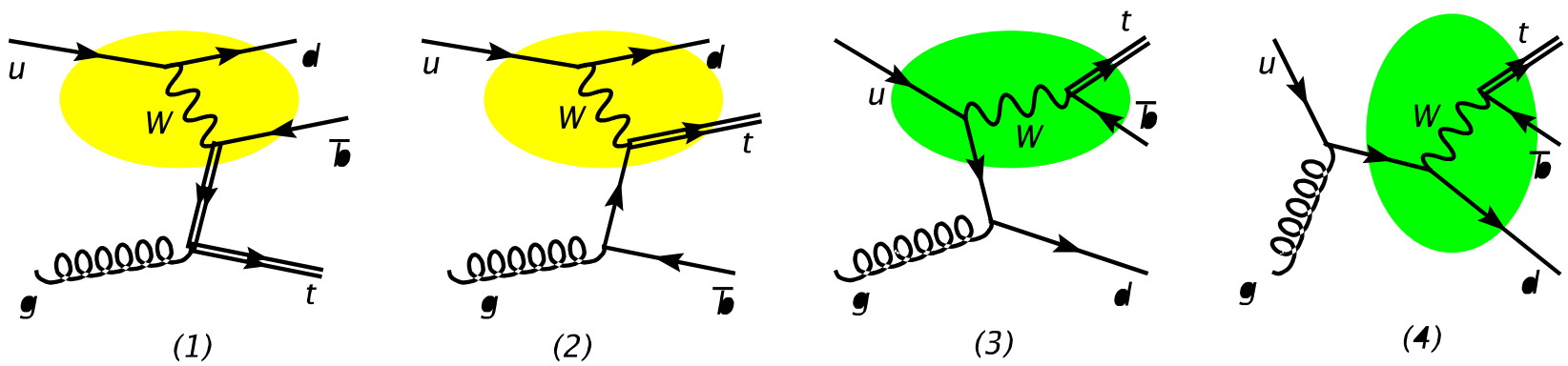


Wt mode

New features at the NLO

As for all other processes, the inclusion of the full NLO corrections puts MC-based predictions for rates *and* distributions on a firmer ground

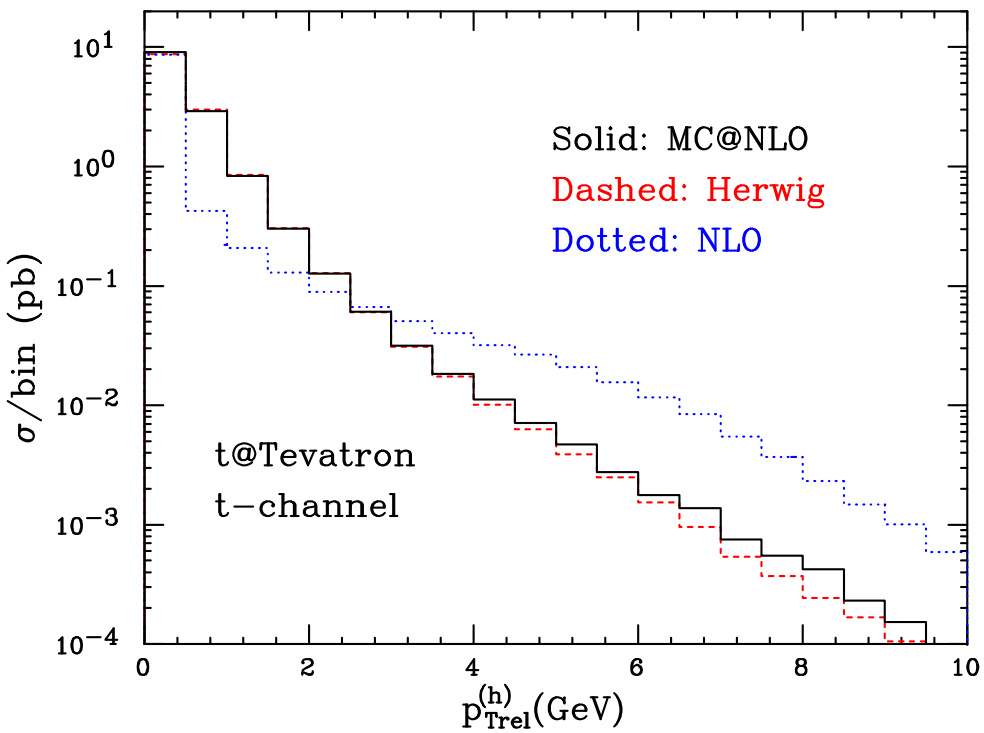
The separation into s- and t-channel production becomes a matter of convention

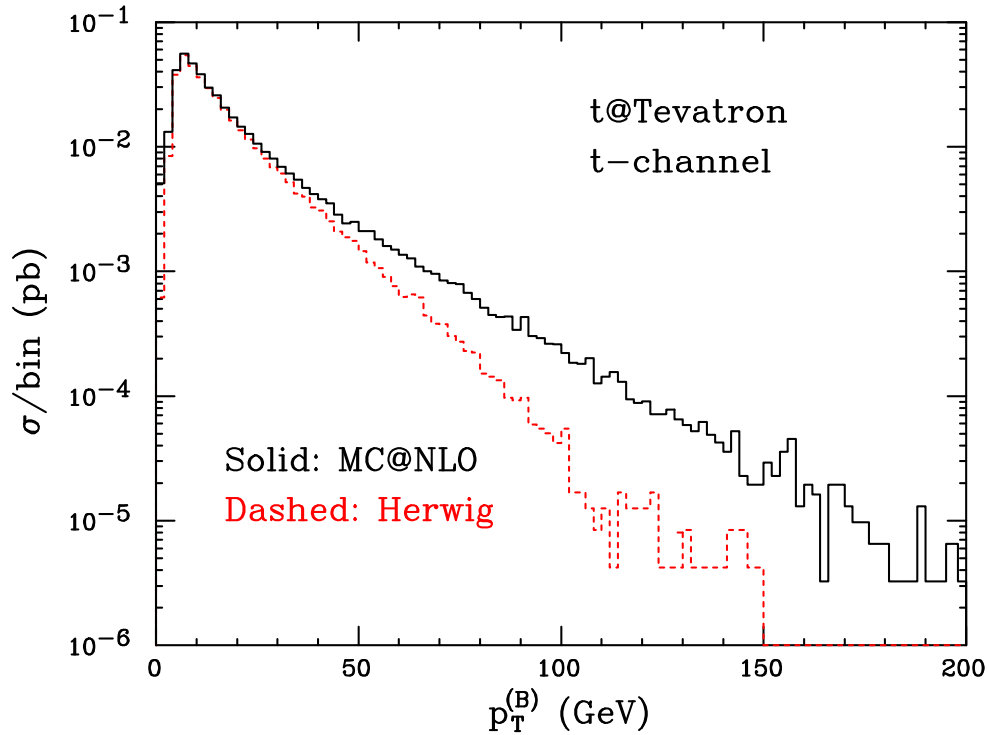


$$ug \longrightarrow t\bar{b}d$$

- (1) & (2) $\longrightarrow$ t channel, (3) & (4) $\longrightarrow$ s channel: this separation is unphysical. An observable-based definition must be adopted
- (1) & (4) cannot be generated by standard MC's
- The contribution of these diagrams to the total rate is missing in standard MC's

Single-top production: examples (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

Spin correlations: definitions

In the production process

$$a + b \longrightarrow P(\longrightarrow d_1 + \cdots + d_n) + X$$

there are

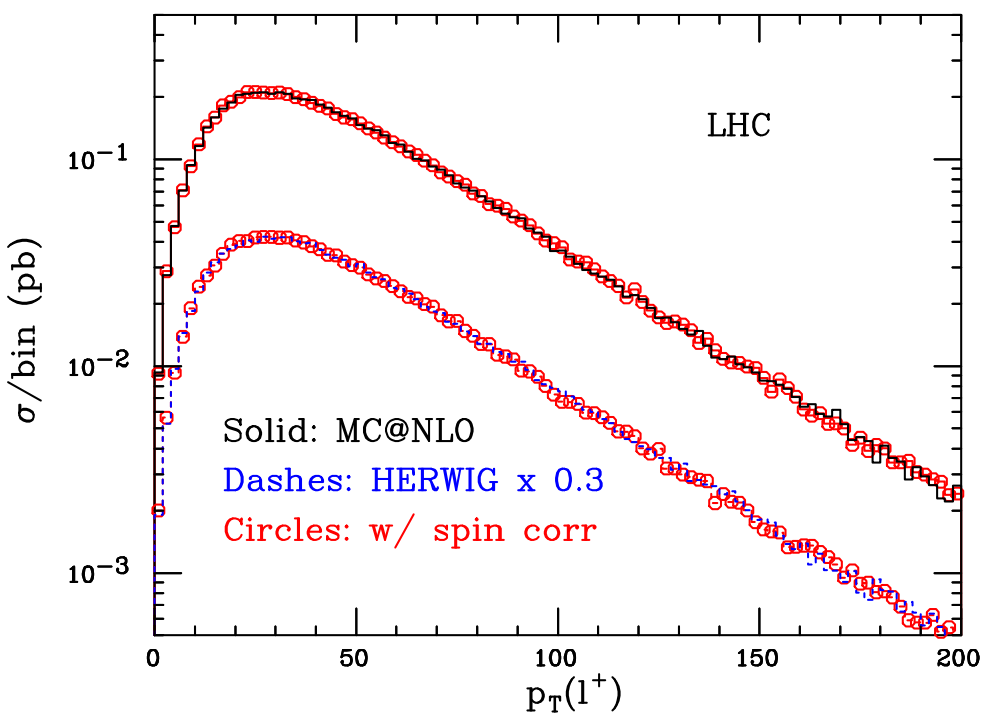
- *Decay* s.c.: if there is a non-trivial dependence on $(d_i \cdot d_j)$
- *Production* s.c.: if there is a non-trivial dependence on $(d_i \cdot a)$, $(d_i \cdot b)$, $(d_i \cdot X)$

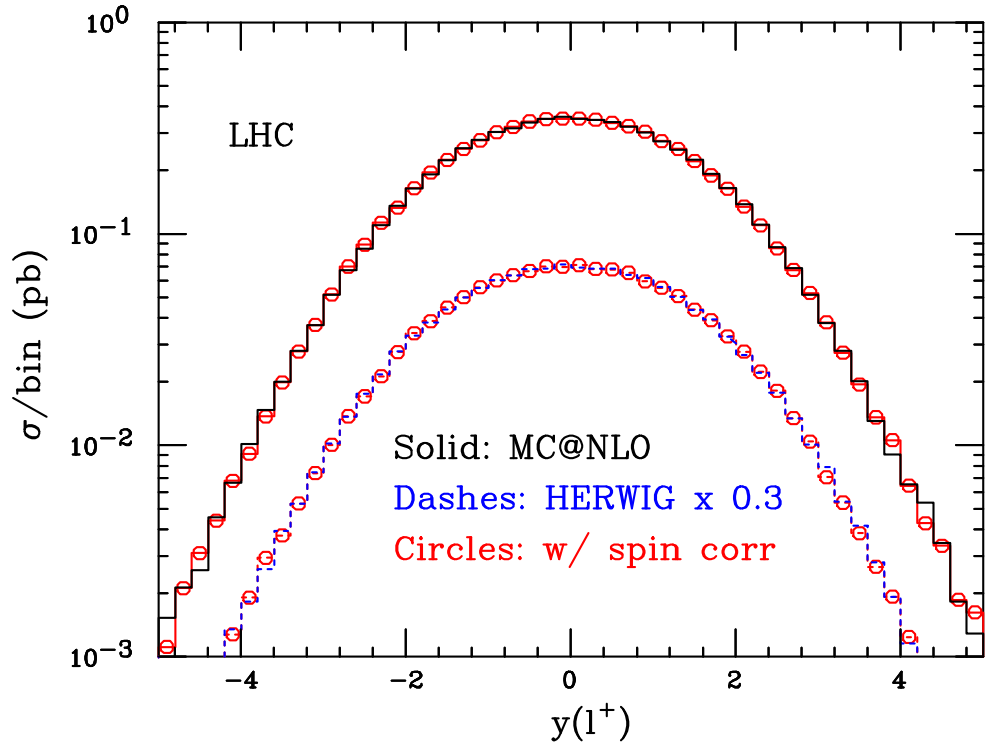
MC@NLO always implements decay s.c. through HERWIG

Production s.c. are available in v3.2 for dilepton, H, WH, ZH, W^+W^- processes

Production s.c. are now also included in $t\bar{t}$ and single-top processes

Spin correlations in $t\bar{t}$ I

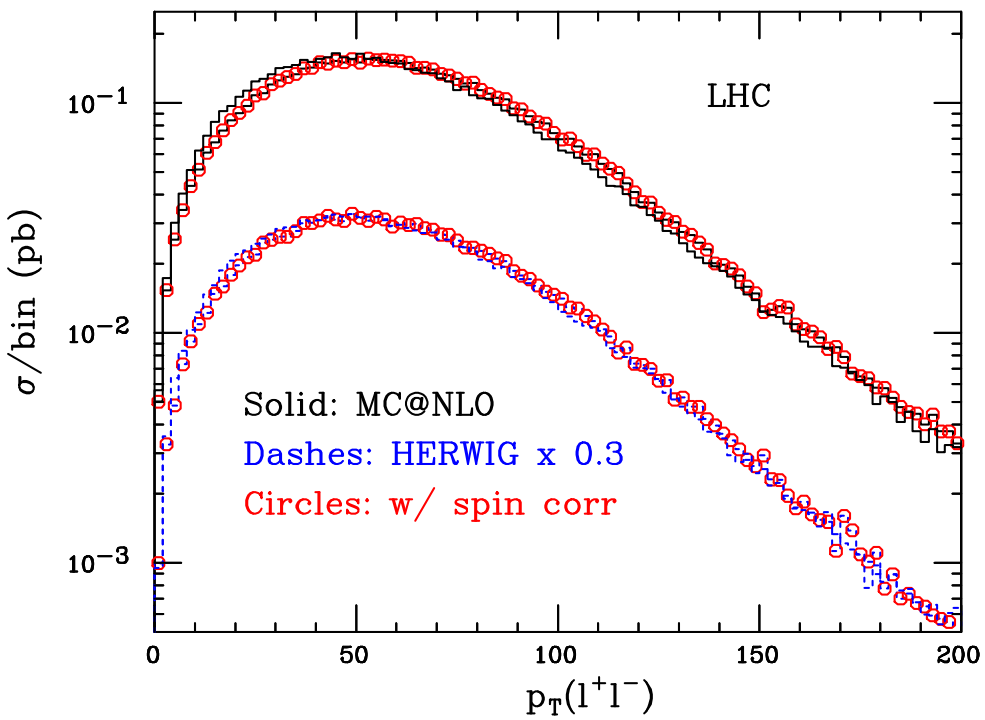


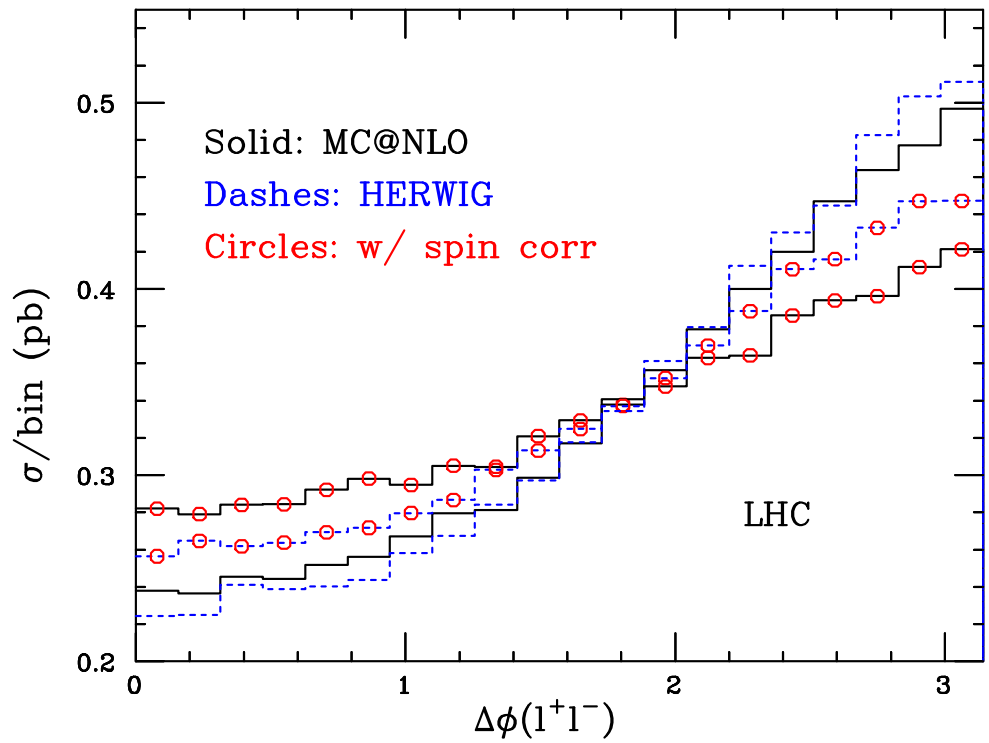


- All single-inclusive distributions have this pattern
- Almost all correlations display a similar behaviour

"Large" is here confortably small. Will this stay true after acceptance cuts?

Spin correlations in $t\bar{t}$ II

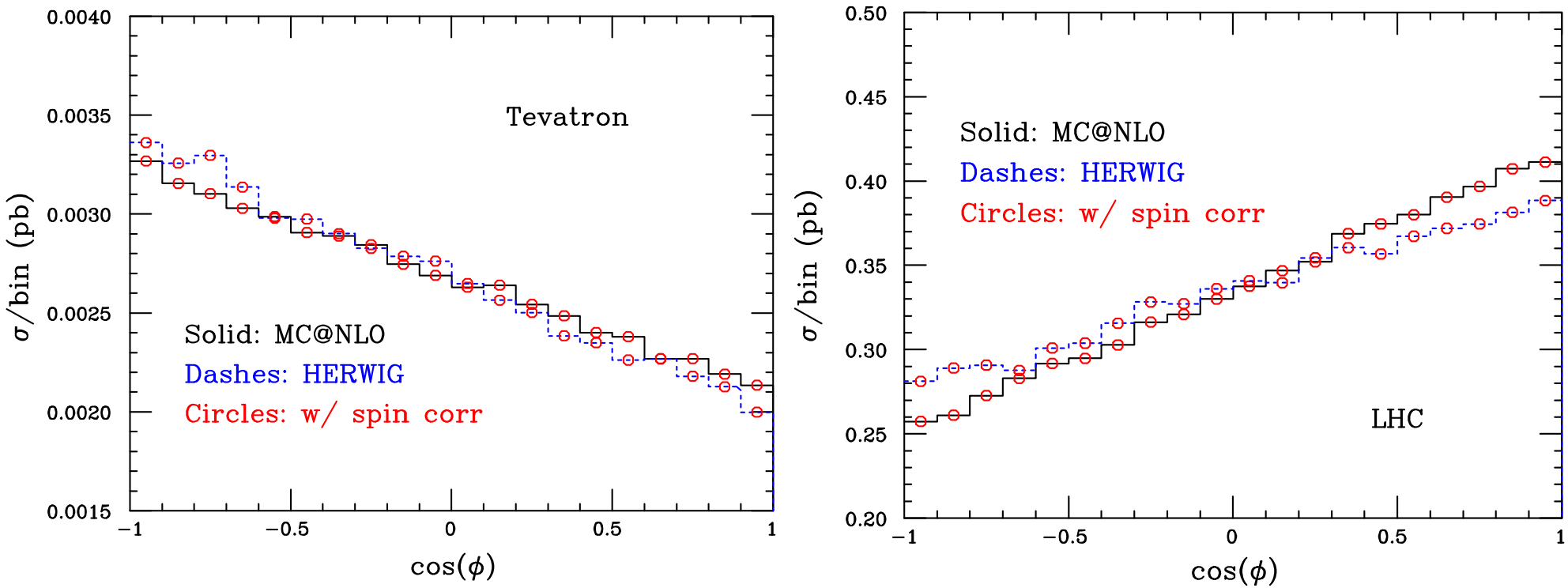




- These are the only cases in which I've found non-negligible effects
- Spin correlations are not the whole story: for $\Delta\phi$, NLO effects are clearly visible

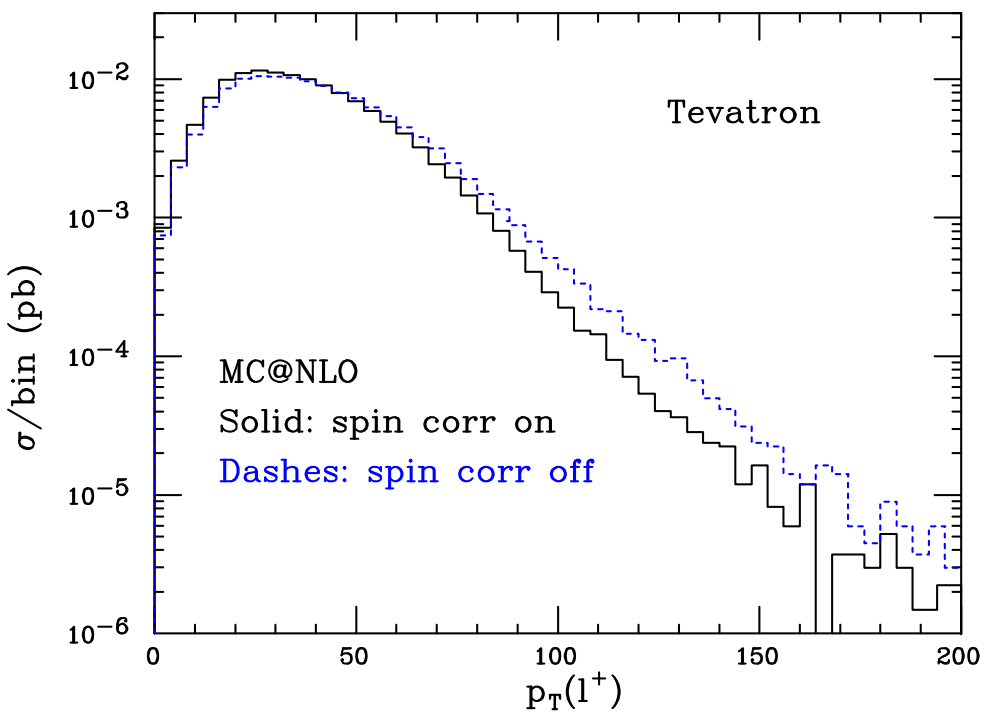
Observables can be designed to specifically target spin correlations $\longrightarrow$

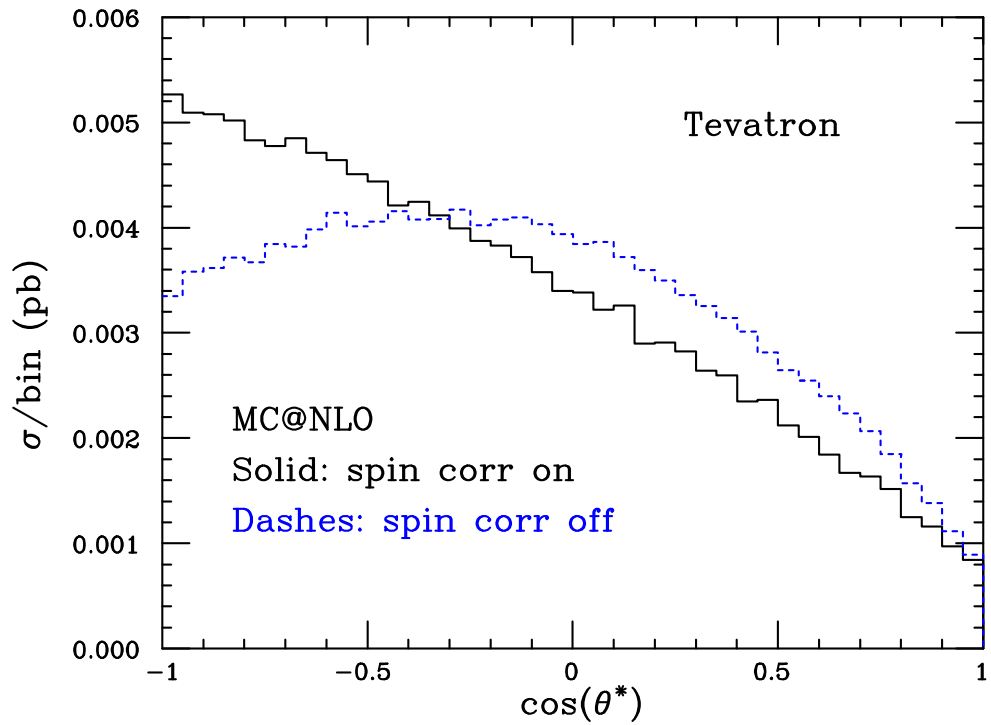
Spin correlations in $t\bar{t}$ III



- NLO corrections again visible and in agreement with parton-level fixed-order results
- These kinds of observables are difficult to define in practice: need to know the rest frames of the $t\bar{t}$ system, of the t and of the $\bar{t}$

Spin correlations in single top





- For single-top, "large" is large indeed: the production proceeds through W exchange which effectively polarizes the top
- The effects are visible in single-inclusive observables (at variance with $t\bar{t}$)

Conclusions

- MC@NLO implements by now several processes of interest for LHC and Tevatron physics, and top production features prominently among them

- The addition of spin correlations (to be officially released with the next version) adds interesting features – we are beginning to study phenomenology implications

- Important theoretical progress is being made (including reduction of negative weights) and will likely be implemented in a few months time

- I'll be happy to provide you with technical details. Tutorials can be organized at CERN if need be