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An overview of MC@NLO

Fermilab, 11/6/2004

SF & Bryan Webber, JHEP 0206(2002)029 [hep-ph/0204244]
SF, Paolo Nason & Bryan Webber, JHEP 0308(2003)007 [hep-ph/0305252]

What is it?

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

However, at variance with standard PSMC's, the partonic hard subprocesses are computed by including the full NLO QCD corrections

This fact has non trivial implications on the dynamics of most of the production processes relevant to the Tevatron and LHC physics

Is MC@NLO a tool for precision physics?

It is a tool that improves the description of production processes wrt that of the standard event generators, and thus should be used also if precision is not an issue

- Provides the *only* way to sensibly compute the K factors event by event, and thus to use this information in detector simulation – this is impossible with NLO parton-level codes. **No more reweighting of MC results**
- The hardest p_T emission is computed *exactly*, and is in agreement with the NLO matrix element result – the correct NLO normalization is obtained upon integration over the visible spectrum
- The scale dependence of physical observables can be computed – this procedure is either meaningless or impossible to perform with standard Monte Carlos

MC@NLO includes dynamic features that cannot be present in standard MC's – heavy flavour physics is a major example

What's wrong with standard MC's?

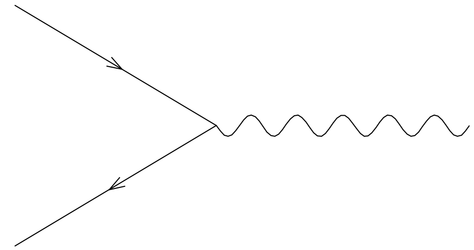
The theoretical ideas upon which MC's are based are more than 20 years old. They haven't been proposed having in mind the very high-energy regimes of the Tevatron and the LHC

- It is not unlikely that new physics signals will emerge from counting experiments, which require firm control on SM signal and background simulations
- The high-energy regime of the Tevatron and the LHC implies the relevance of multi-jet, multi-scale processes, with large K-factors
- Standard MC's don't perform well in predicting multi-jet observables, and the practice of multiplying the results by inclusive K-factors is just wrong. This may lead to major errors in the strategies for searches (kind of new in HEP!)
- There is also a loss of accuracy in the study of SM processes, and ultimately in the measurements of fundamental parameters (m_{top}, m_W, Γ_W, ...)

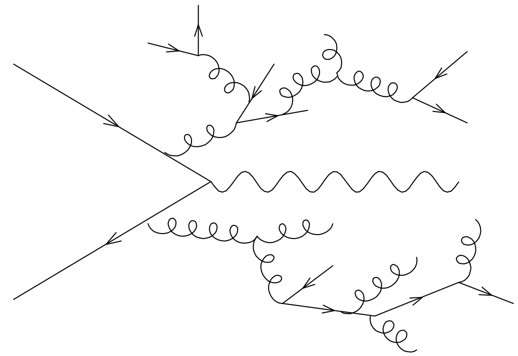
Standard MC's are not equal to the task of fully describing very high energy collisions in a sensible manner. They can't be replaced by standalone N^{k}LO results, which have unrealistic final states and can't be used in detector simulations

Physics processes with standard MC's

1) Compute the LO cross section in perturbation theory



2) Let the shower emit as many gluons and quarks as possible



Advantages

- The analytical computations are trivial
- Very flexible

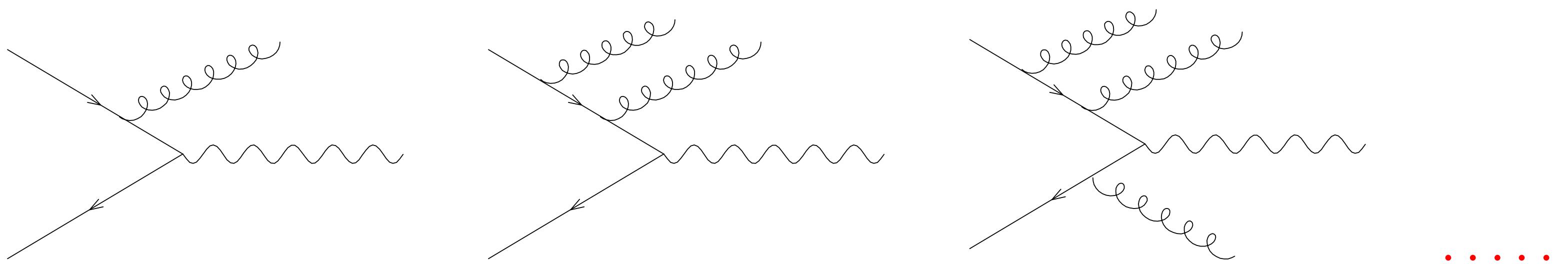
Drawbacks

- The high-p_T^W and multijet configurations are not properly described
- The total rate is computed to LO accuracy

The problems stem from the fact that the MC's perform the showers assuming that all emissions are collinear

Improvement: Matrix Element Corrections

Just compute (exactly) more real emission diagrams before starting the shower



Problems

- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

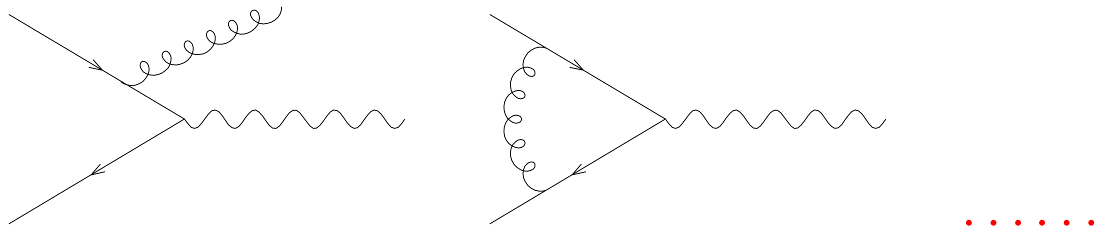
Solution (CKKW – see also MLM)

Cut the divergences off by means of an arbitrary parameter δ_{sep}, and modify the shower (through a veto) in such a way as to reduce as much as possible the δ_{sep} dependence on physical observables

Satisfactory results are in general obtained after tuning the parameters involved in the procedure (see Mrenna & Richardson, SHERPA). Although some of the diagrams above contribute to the N^{k}LO result, total rates are still computed to LO accuracy

Improvement: NLOwPS

Compute all NLO diagrams before starting the shower



Problems

- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

Solution (MC@NLO)

Remove the divergences locally by adding and subtracting the MC result that one would get after the first emission

Virtual diagrams cancel the divergences of the real diagrams, and therefore it is not necessary to introduce δ_{sep}; as a by-product, total rates are computed to NLO accuracy. No parameter tuning is involved in the procedure (there are no arbitrary parameters)

NLOwPS versus MEC

- Why is the definition of NLOwPS's much more difficult than MEC?

  The problem is a serious one: KLN cancellation is achieved in standard MC's through unitarity, and embedded in Sudakovs. This is no longer possible: IR singularities do appear in hard ME's

IR singularities are avoided in MEC by cutting them off with δ_{sep}. This must be so, since only loop diagrams can cut off the divergences of real matrix elements

NLOwPS's are better than MEC since:

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

NLOwPS's are worse than MEC since:

− The number of hard legs is smaller

− There are negative weights

At present, NLOwPS's and MEC are basically complementary (when this is not the case, NLOwPS's must be considered superior). A near-future realistic goal: CKKW in NLOwPS's (i.e. multi-leg, NLO generators)

The actual NLOwPS's

- MC@NLO (Webber & SF; Nason, Webber & SF)
  Based on NLO subtraction method
  Formulated in general, uses HERWIG for parton showers
  Processes implemented: $H_1 H_2 \longrightarrow$ W^+W^-, $W^\pm Z$, ZZ, $b\bar{b}$, $t\bar{t}$, H^0, $W^\pm$, Z/γ
- Φ-veto (Dobbs & Lefebvre)
  Based on NLO slicing method
  Avoids negative weights, at the price of double counting
  Processes implemented: $H_1 H_2 \longrightarrow$ Z
- grcNLO (Kurihara *et al* – GRACE)
  Based on NLO hybrid slicing method, computes ME's numerically
  Double counts, if the parton shower is not built *ad hoc*
  Process implemented: $H_1 H_2 \longrightarrow$ Z

A proposal by Collins aims at including NLL effects in showers, but lacks gluon emission so far. Φ-veto is based on an old proposal by Baer&Reno; jets in DIS have been considered by Pötter&Schörner using a similar method. Soper&Krämer implemented $e^+e^- \to 3$ jets (but without a realistic MC)

From the user's point of view

Almost nothing changes. MC@NLO works identically to Herwig (the same analysis routines can be used), except for the fact that hard partonic processes are generated by a companion piece of code, at the beginning of the run rather than on an event-by-event basis (generally speaking, the same happens in CKKW implementations)

- Unweighted event generation achieved
- Weighted event generation possible (currently not implemented)
- MC@NLO shape identical to MC shape in soft/collinear regions
- MC@NLO/NLO=1 in hard regions
- There are negative-weight events

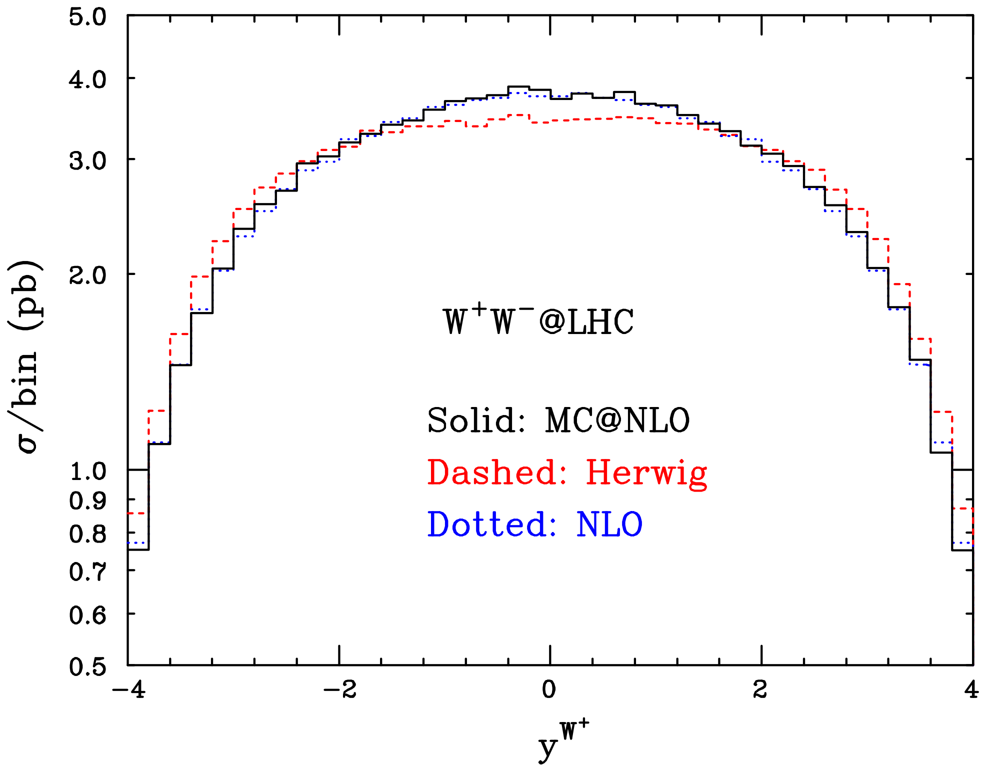
Negative weights don't mean negative cross sections. They arise from a different mechanism wrt those at the NLO, and their number is fairly limited

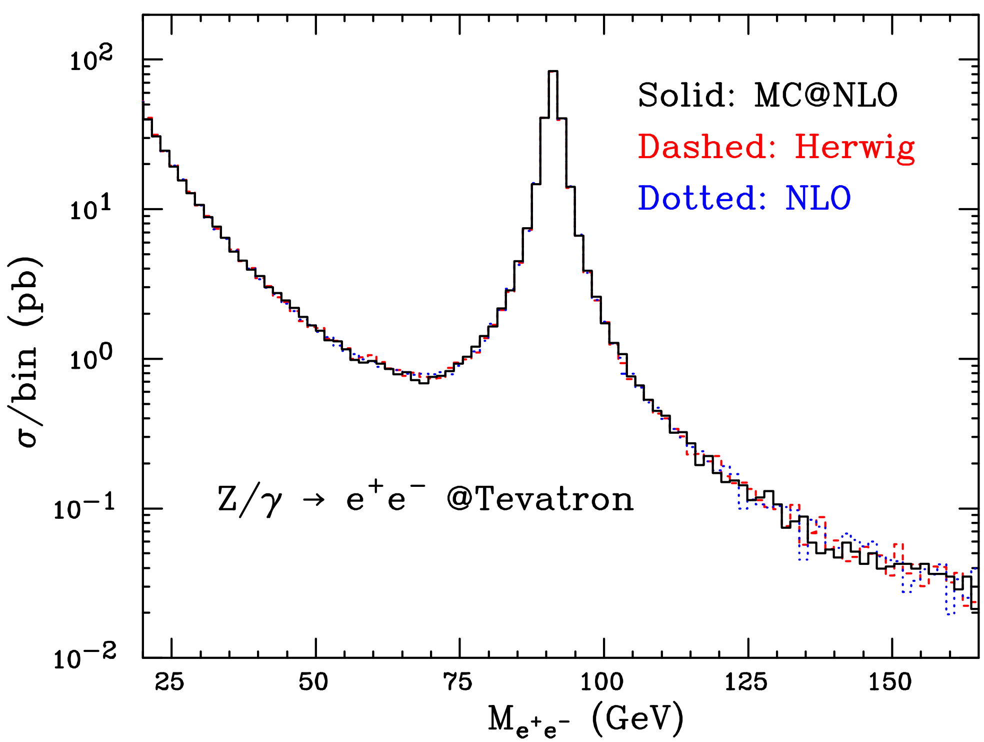
MC@NLO 2.31 [hep-ph/0402116]

IPROC	Process
–1350–IL	$H_1H_2 \to (Z/\gamma^* \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–1360–IL	$H_1H_2 \to (Z \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–1370–IL	$H_1H_2 \to (\gamma^* \to) l_{\rm IL}\bar{l}_{\rm IL} + X$
–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	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–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	$H_1H_2 \to t\bar{t} + X$
–2850	$H_1H_2 \to W^+W^- + X$
–2860	$H_1H_2 \to Z^0Z^0 + X$
–2870	$H_1H_2 \to W^+Z^0 + X$
–2880	$H_1H_2 \to W^-Z^0 + X$

- 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 will also be implemented

The first check: MC@NLO $\simeq$ NLO





NLO is OK for these observables

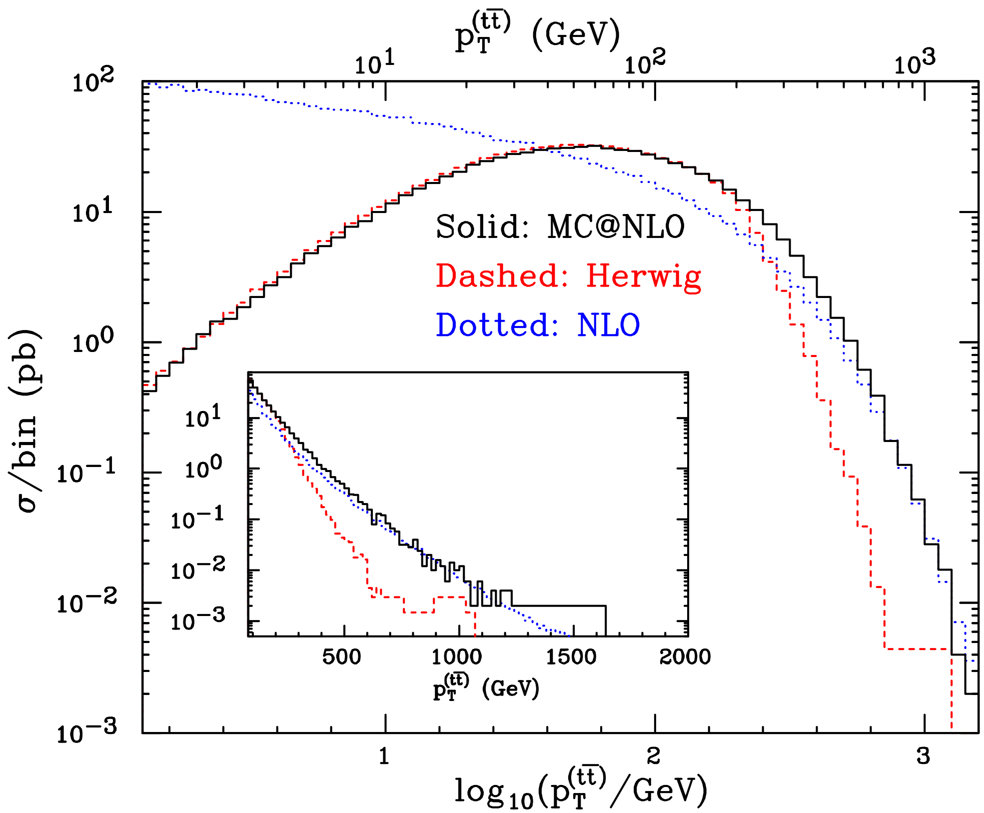
MC@NLO outputs a realistic final state, which matters when full detector simulation is included

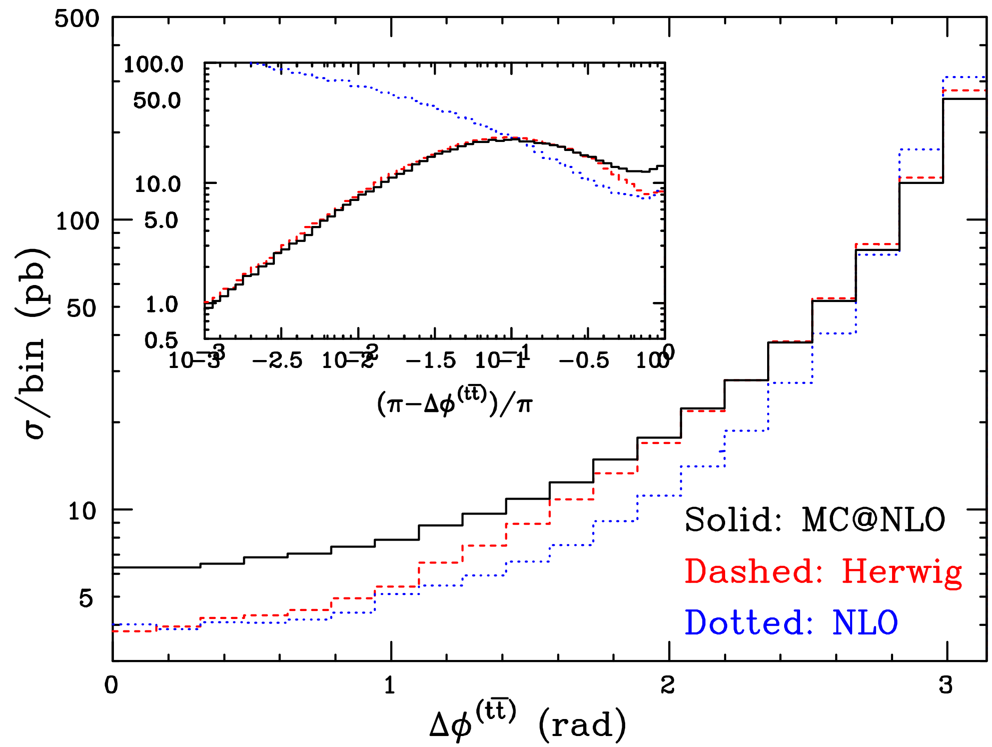
Solid: MC@NLO

Dashed: HERWIG$\times\frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

A highly non-trivial check: $t\bar{t}$ production





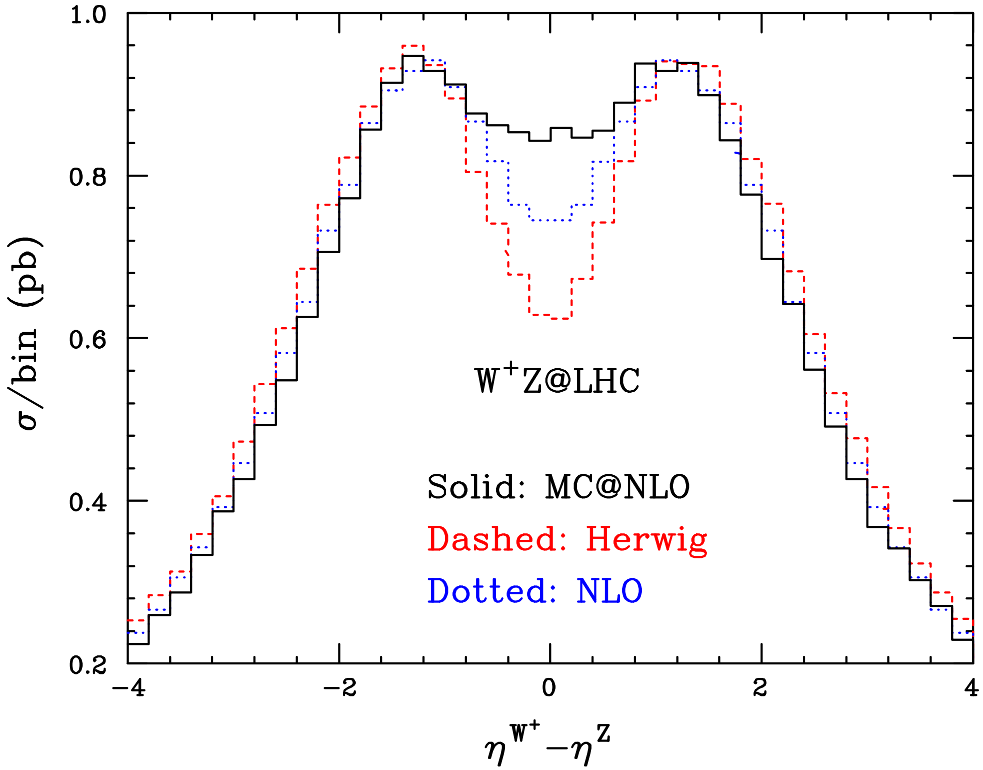
These correlations are problematic: soft and hard emissions are both relevant. MC@NLO does well, resumming large logarithms, and yet handling large-scale physics correctly

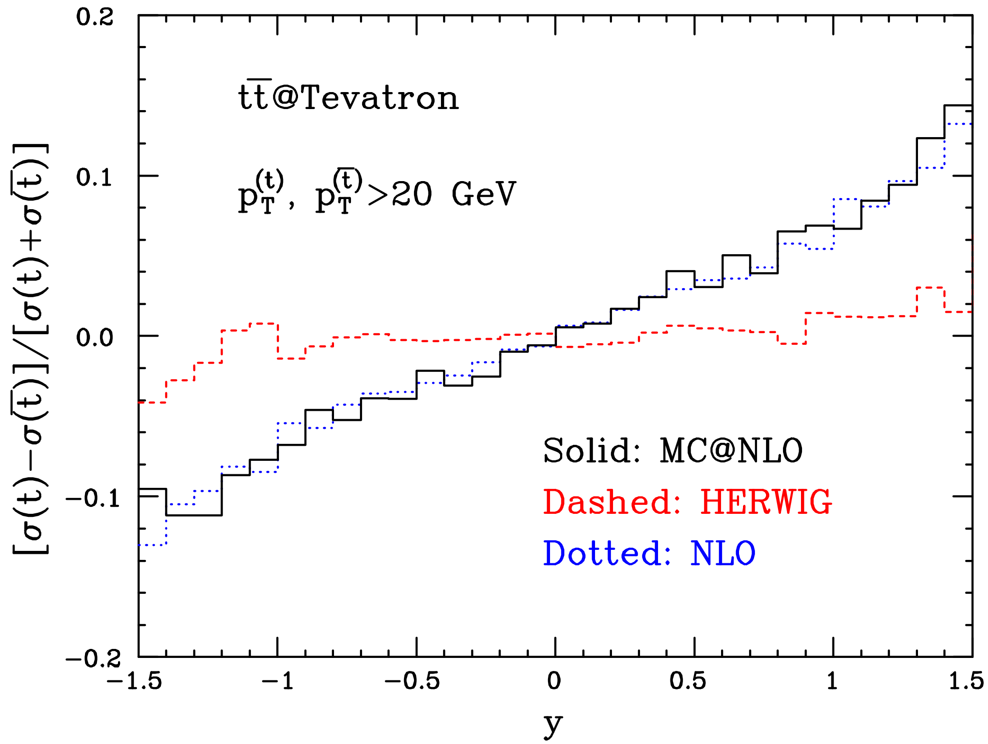
Solid: MC@NLO

Dashed: HERWIG$\times \frac{\sigma_{NLO}}{\sigma_{LO}}$

Dotted: NLO

New features in MC's





Radiation zero is further filled by MC@NLO

$t\bar{t}$ asymmetry is absent at the Born level, and thus also in standard MC's

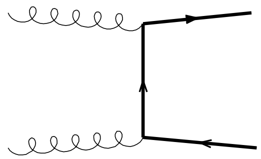
Solid: MC@NLO

Dashed: HERWIG

Dotted: NLO

Charm and bottom with standard MC's

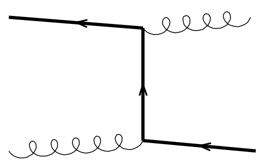
MC rule: if we aim to study any physical system, we start by producing it in the hard process $\Longrightarrow$



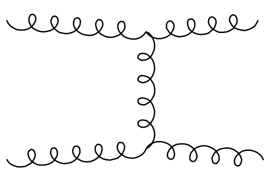
Flavour CReation

This is going to underestimate the rate by a factor of 4 (which is not so important), and to miss key kinematic features (which is crucial – see R. Field)

So break the rule and add other hard processes



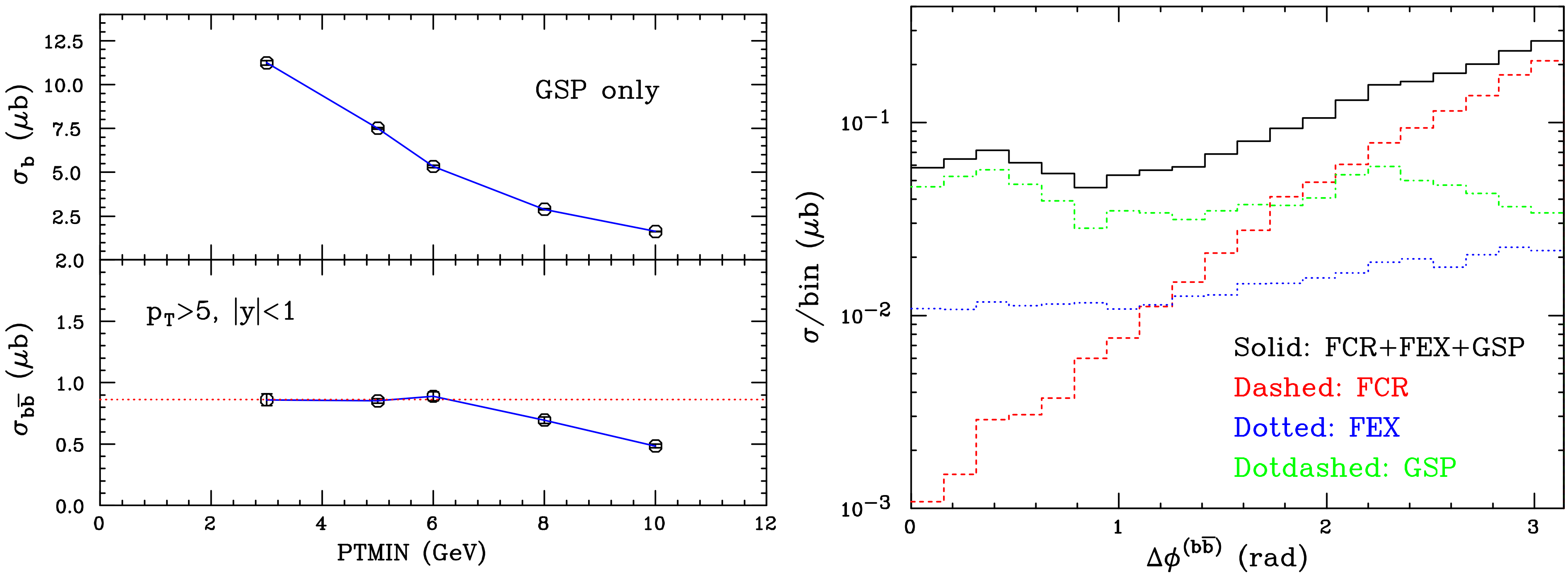
Flavour EXcitation



Gluon SPlitting

- In FEX, the missing Q or $\overline{Q}$ results from initial-state radiation. A cutoff PTMIN avoids divergences in the matrix element
- In GSP, the Q and $\overline{Q}$ result from final-state gluon splitting. PTMIN is again necessary to obtain finite results

b production with HERWIG

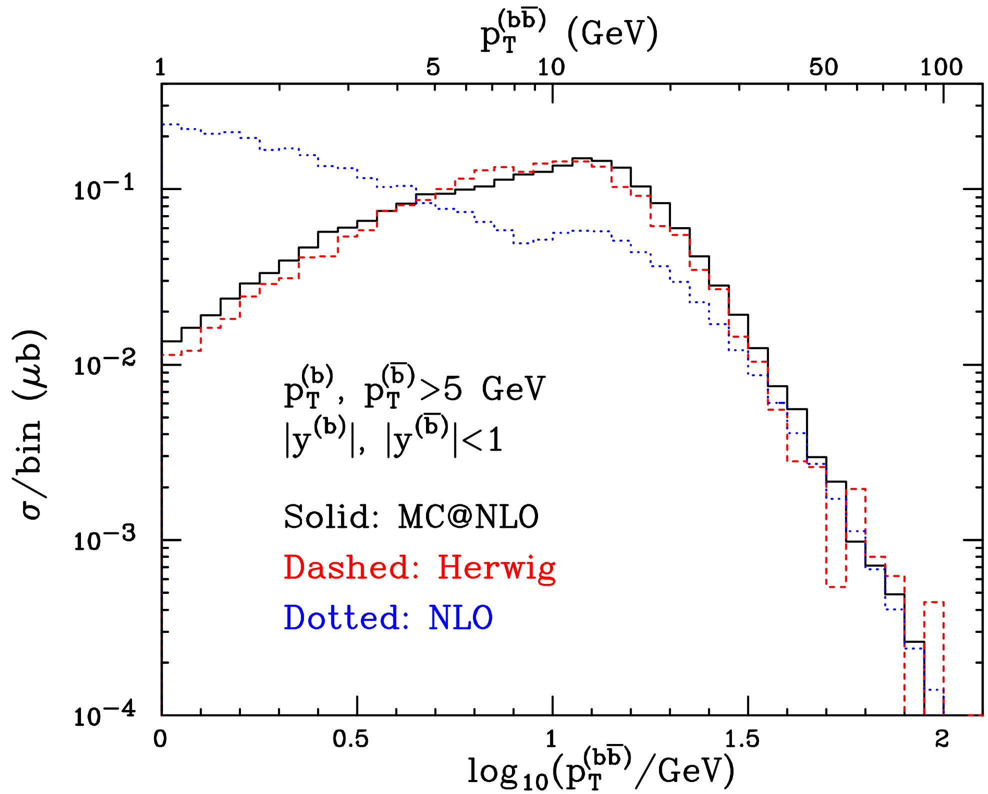


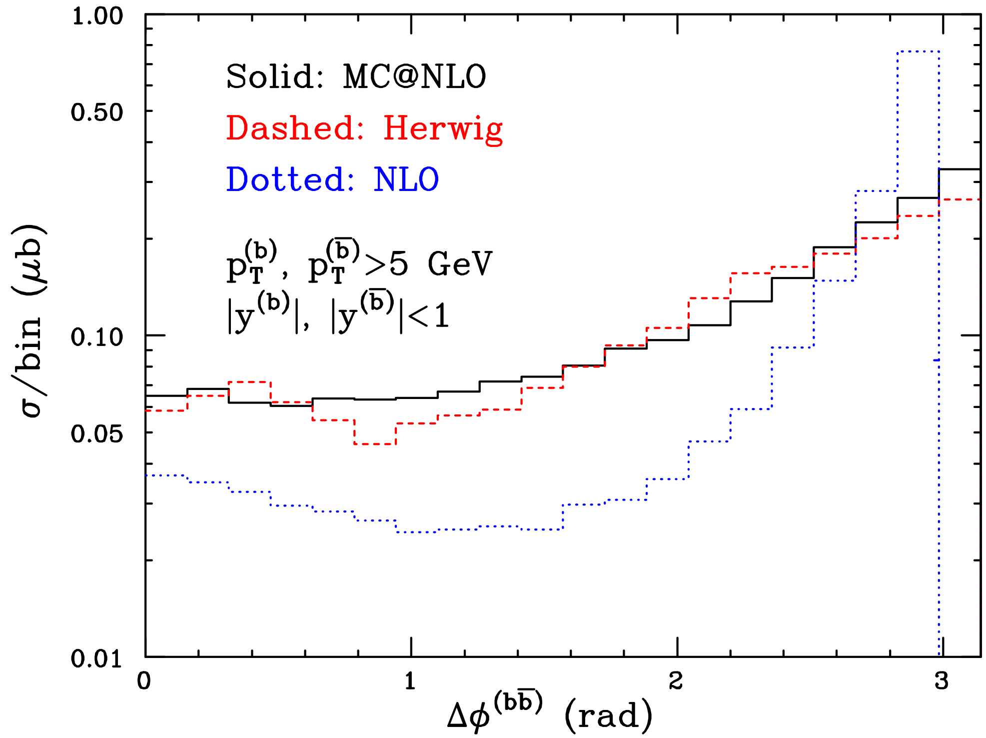
- The PTMIN dependence is worrisome in the case of single-inclusive observables
- FCR, FEX and GSP are complementary, and all must be generated
- GSP efficiency is extremely poor: 10^{-4} within cuts for correlations

Reliability and efficiency rapidly degrade for smaller p_T cuts. In FEX, the dependence on bottom PDF is problematic. No standard MC can work for $p_T \simeq 0$

All these problems are avoided with MC@NLO

$b\bar{b}$ correlations with MC@NLO





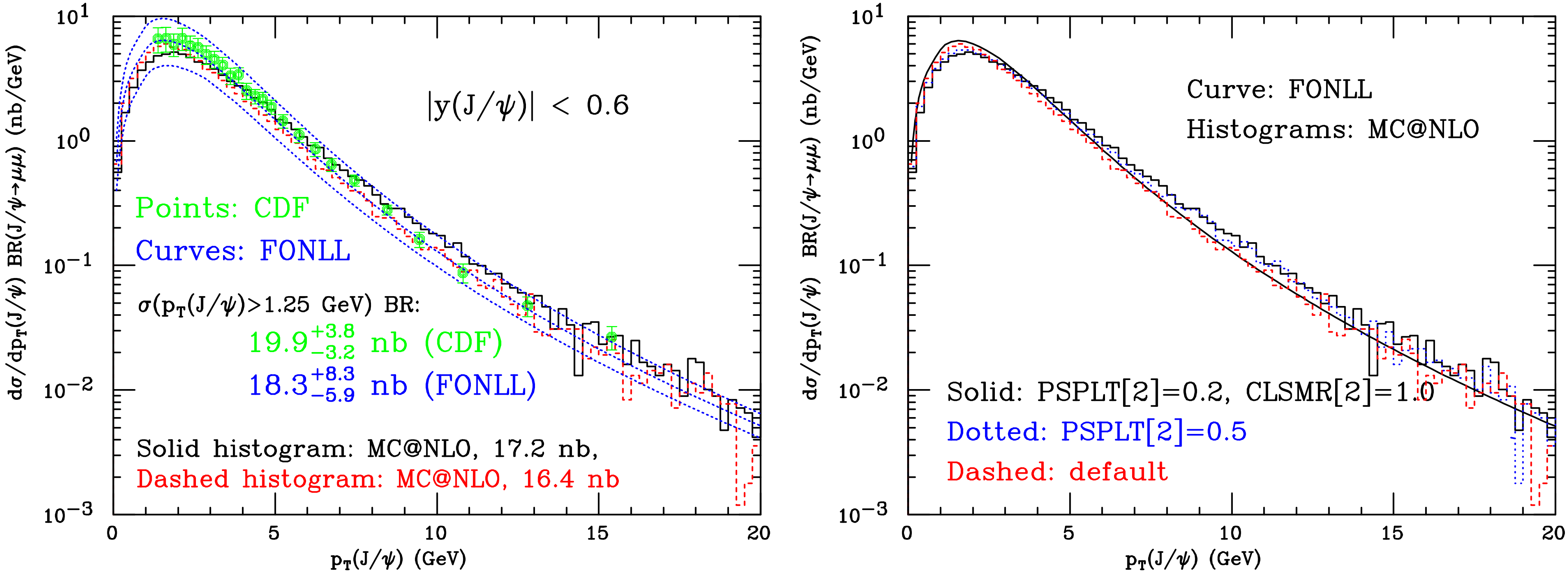
HERWIG does surprisingly well, but needs quite a lot of CPU (14 millions events – 1 million for MC@NLO). The hard emission effects are huge for b production, and cannot be neglected

Solid: MC@NLO

Dashed: HERWIG

Dotted: NLO

Single-inclusive b at the Tevatron



No significant discrepancy with data

- No PTMIN dependence in MC@NLO $\Longrightarrow$ solid predictions down to $p_T = 0$, no "perturbative-parameter tuning" (more work on b hadronization parameters needed)
- Full agreement with NLL+NLO computation (FONLL, Cacciari&Nason), if the large dependence (at small p_T) on the hadronization scheme of the latter is taken into account

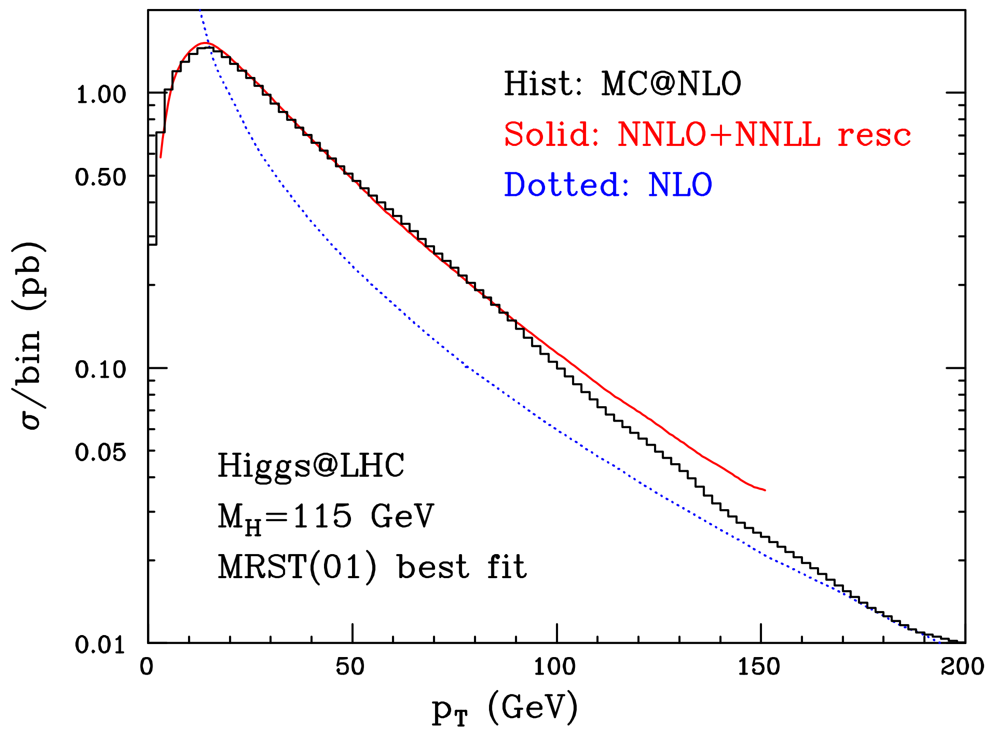
Why does MC@NLO work better?

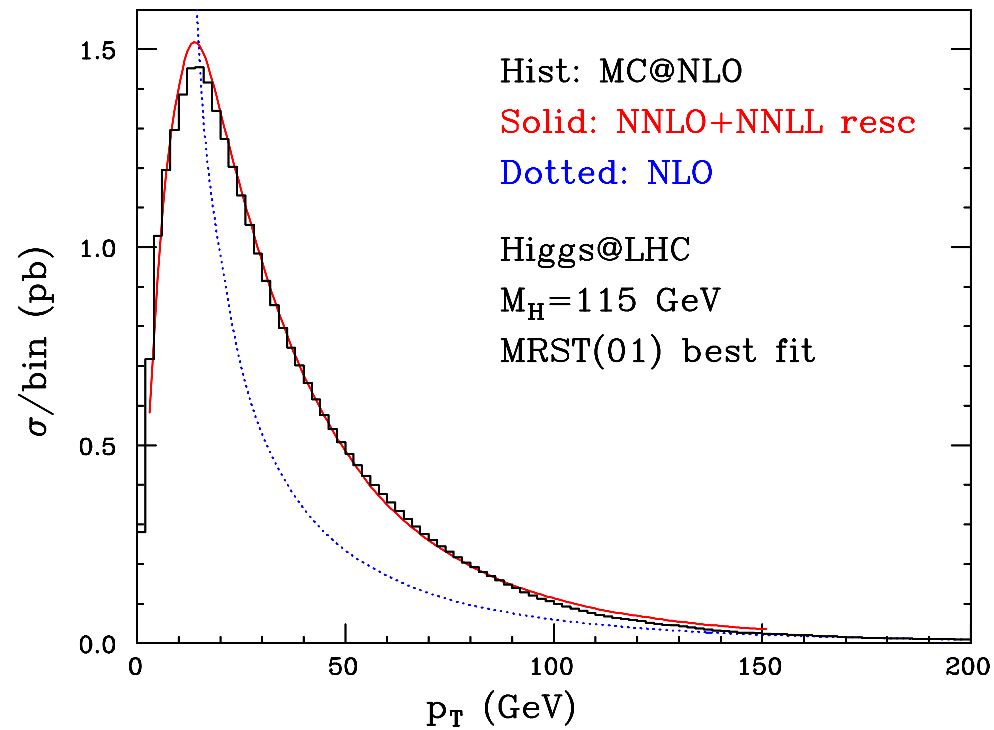
MC@NLO is by definition a formalism that matches fixed-order and resummed results (in this sense, is analogous to FONLL), the latter obtained by means of the shower

- MC@NLO vs FONLL
  - \+ Fully realistic final state, hadronization, and decay
  - \+ Works for any observable
  - − Formally less accurate in terms of logs
- MC@NLO vs standard MC's
  - \+ No PTMIN dependence, no separate generation of FCR, FEX, and GSP
  - \+ Reliable prediction of hard emission
  - − Misses some of the higher logs in GSP

MC@NLO can be used to obtain state-of-the-art theoretical predictions, and/or to treat raw data

Is the agreement with the resummed result accidental?

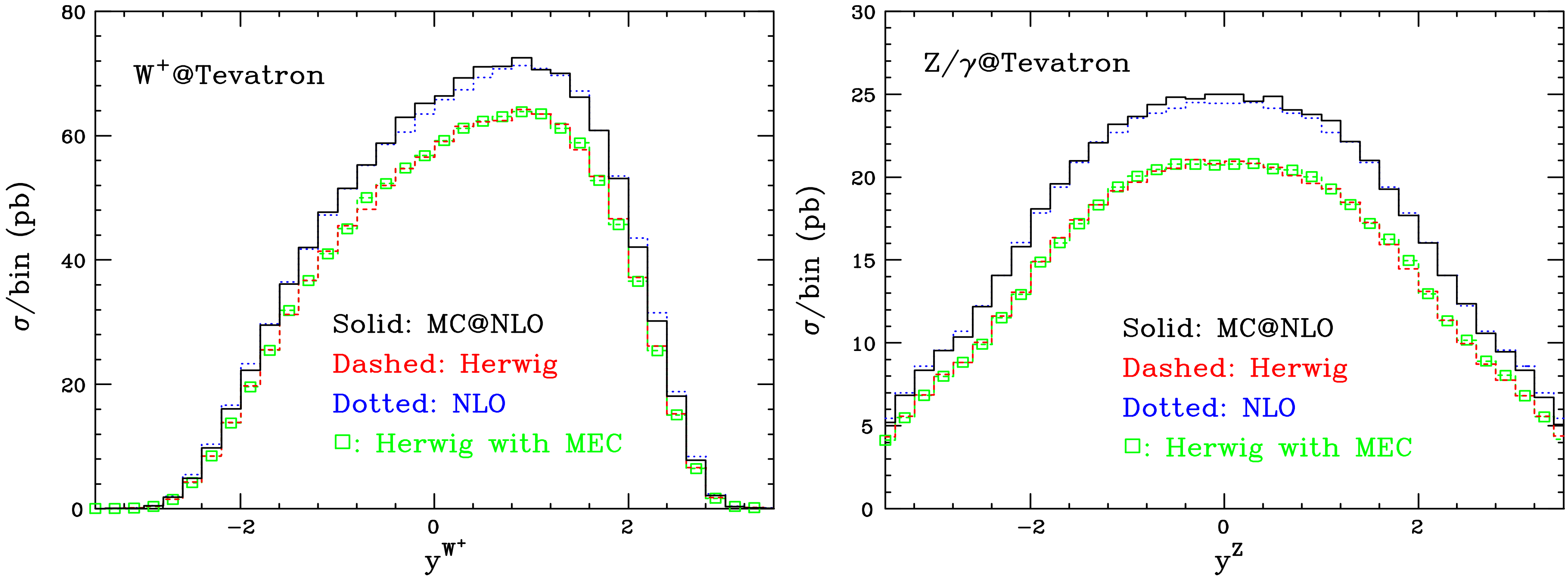




The same happens with Higgs. The result of Bozzi, Catani, de Florian, Grazzini has a matching condition similar to MC@NLO, in that it conserves the total rate

- The agreement with the analytically-resummed result improves when the logarithmic accuracy of the latter is increased ⟶ HERWIG has more logs than you expect
- We can now apply any cuts we like (decay products, recoiling system) – a fully realistic jet-veto analysis is doable
- Beware: vastly different from Pythia!

Luminosity monitors (with MLM, hep-ph/0405130)



There is a good agreement between MC@NLO and NLO. NNLO contributions could perhaps be included by following the procedure advocated by Anastasiou, Dixon, Melnikov, Petriello, of multiplying by $K^{(2)} = \sigma_{\rm NNLO}/\sigma_{\rm NLO}$

- However, $|{\rm MC@NLO} - {\rm NLO}| = \mathcal{O}(1-2\%)$
- A careful analysis, including realistic experimental cuts, is therefore necessary to decide whether Z and W production can be used as parton luminosity monitors in an analisys aimed at the 1% precision

W production acceptances I

For a *precise* determination of the acceptances we must consider

- Fixed order $\longleftrightarrow$ parton shower interplay
- NNLO results do not have lepton spin correlations

	LO		LO+HW	NLO		MC@NLO
Cuts A	0.4093	$\xrightarrow{-5.7\%}$	0.3858	0.3848	$\xrightarrow{-0.4\%}$	0.3833
	$\downarrow$0.9%			$\downarrow$2.5%		$\downarrow$2.8%
Cuts A, no spin	0.4129			0.3944		0.3940
Cuts B	0.3564	$\xrightarrow{-6.7\%}$	0.3326	0.3401	$\xrightarrow{-1.2\%}$	0.3359
	$\downarrow$9.0%			$\downarrow$9.9%		$\downarrow$10%
Cuts B, no spin	0.3887			0.3738		0.3697

@Tevatron: Cuts A $\longrightarrow \left|\eta^{(e)}\right| < 1$, $p_T^{(e)} > 20$ GeV, $p_T^{(\nu)} > 20$ GeV

Cuts B $\longrightarrow 1 < \left|\eta^{(e)}\right| < 2.5$, $p_T^{(e)} > 20$ GeV, $p_T^{(\nu)} > 20$ GeV

W production acceptances II

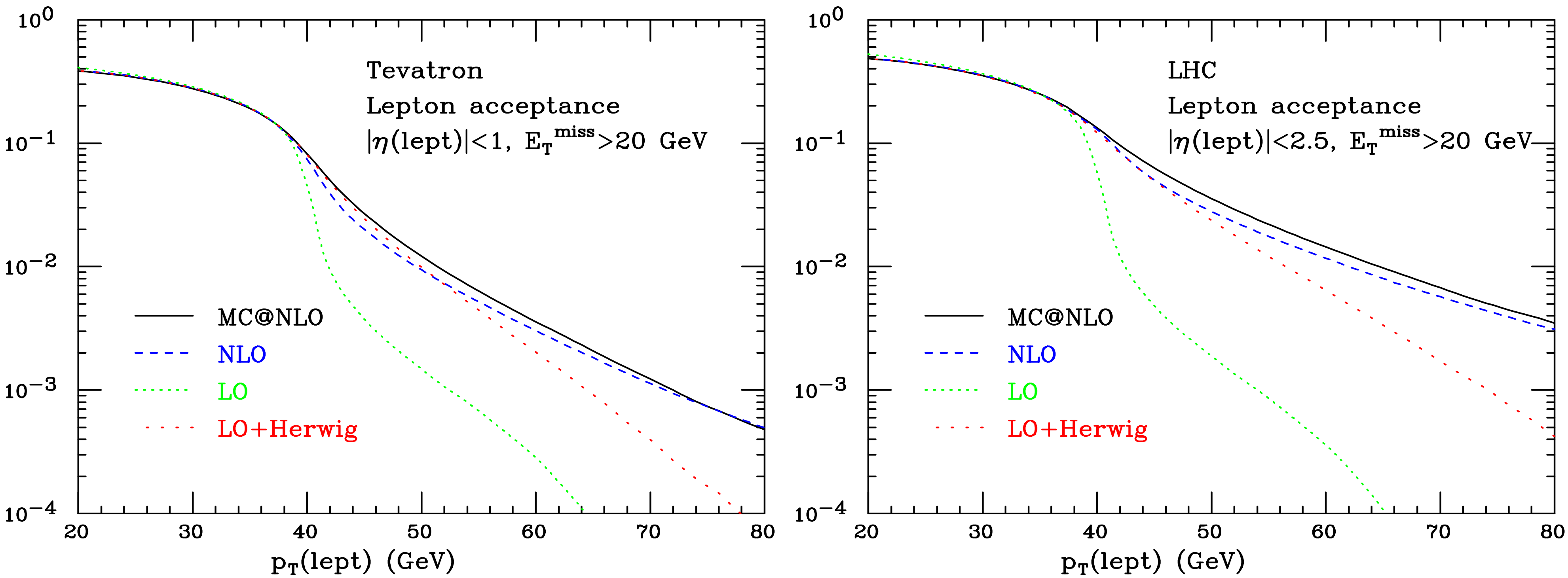
	LO		LO+HW	NLO		MC@NLO
Cuts A	0.5249	$\xrightarrow{-7.7\%}$	0.4843	0.4771	$\xrightarrow{+1.5\%}$	0.4845
	$\downarrow$5.4%			$\downarrow$7.0%		$\downarrow$6.3%
Cuts A, no spin	0.5535			0.5104		0.5151
Cuts B	0.0585	$\xrightarrow{+208\%}$	0.1218	0.1292	$\xrightarrow{+2.9\%}$	0.1329
	$\downarrow$29%			$\downarrow$16%		$\downarrow$18%
Cuts B, no spin	0.0752			0.1504		0.1570

@LHC: Cuts A $\longrightarrow$ $\left|\eta^{(e)}\right| < 2.5$, $p_T^{(e)} > 20$ GeV, $p_T^{(\nu)} > 20$ GeV

Cuts B $\longrightarrow$ $\left|\eta^{(e)}\right| < 2.5$, $p_T^{(e)} > 40$ GeV, $p_T^{(\nu)} > 20$ GeV

- Acceptances depend very weakly on the perturbative accuracy of the computation, provided that ISR is included, and cuts are tuned
- Can't really use NNLO results for acceptance computations, because of the lack of spin correlations. Inclusive distributions should be *very moderately* affected by ISR

W production acceptances III

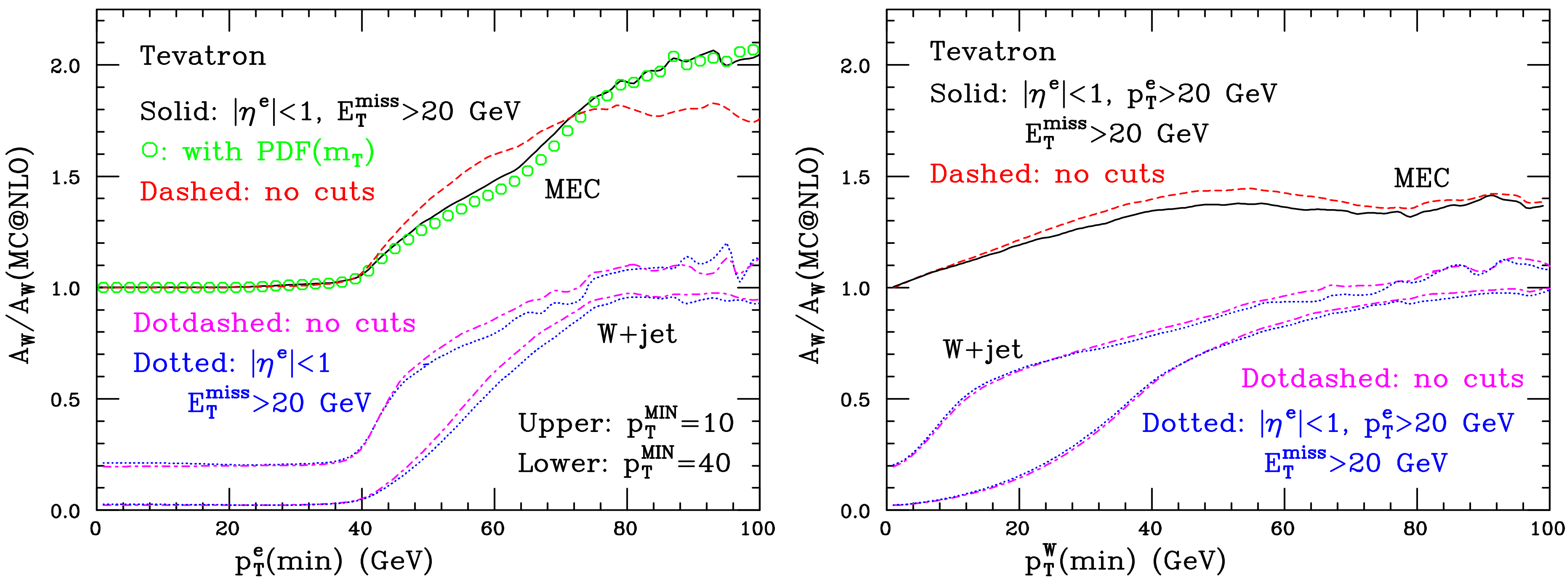


The agreement previously shown between MC@NLO and HERWIG degrades rapidly when moving towards phase-space regions dominated by hard emissions

$\Longrightarrow$ If these regions are relevant to your favourite analysis, you better use an NLOwPS such as MC@NLO

Why not Matrix Element Corrections?

MC@NLO vs MEC in acceptance computations



- MEC make use of *some of* the matrix elements which enter NLO computations, but the total rate is accurate to LO. What is the proper normalization in the computation of acceptances?
- MEC results don't seem to agree with W+jet predictions where they should agree, namely at large p_T

Outlook

MC@NLO (as any other NLOwPS that will appear on the market) must be considered superior to standard MC's, since it includes *all* the good features of the MC's, plus the complete information on NLO matrix elements

The implementation of new processes takes time. We are working/shall soon work on:

- Spin correlations for WW, WZ, ZZ; $t\bar{t}$ will come next
- HW and HZ (with V. del Duca and C. Oleari), $WW \to H$ next
- Single top (with E. Laenen)
- $W + n$ jets, $n = 1, 2$ (with J. Cambpell and K. Ellis), presumably from the fall
- Jet and dijet production
- MC@NLO++ $\Longrightarrow$ Less or zero negative weights (mainly P. Nason)

It is crucial that experimenters use these new MC tools – the only way to encourage us to keep on working on them