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An overview of MC@NLO

ATLAS Tutorial, CERN, 22/6/2004

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 *any* production process 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.

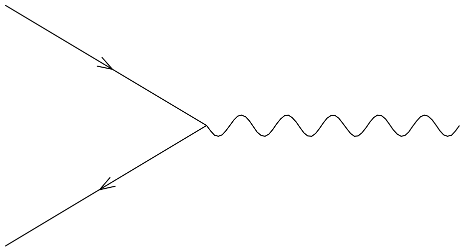
MC's haven't been proposed having in mind the very high-energy regimes of the Tevatron and the LHC

- 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, ...)

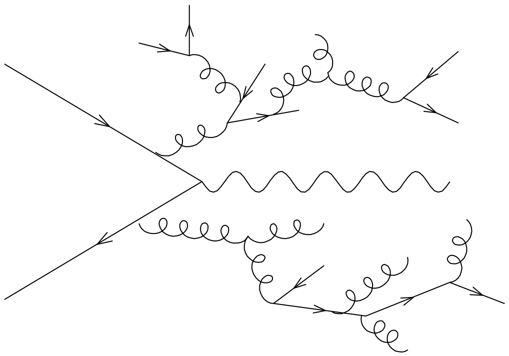
Standard MC's are not equal to the task of fully describing very high energy collisions in a sensible manner. They can't be replaced by standalone N^{k}LO results, which have unrealistic final states and can't be used in detector simulations

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

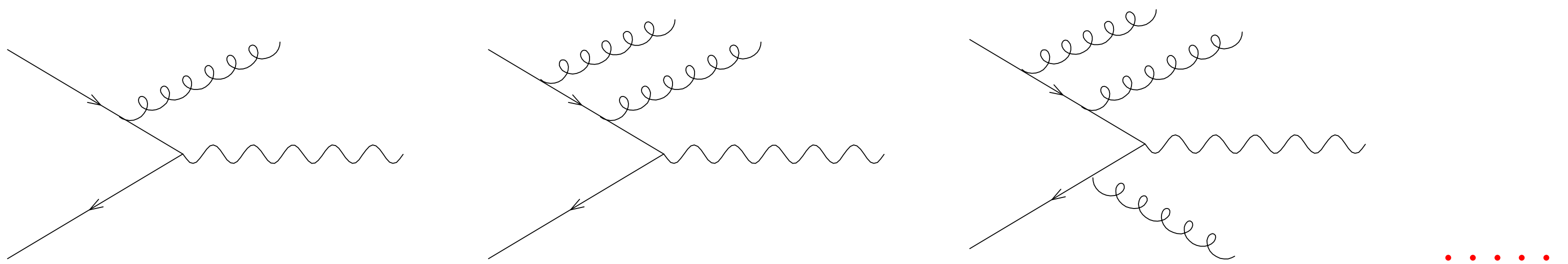
Drawbacks

- The high-p_T 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 <u>assuming that all emissions are collinear</u>

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

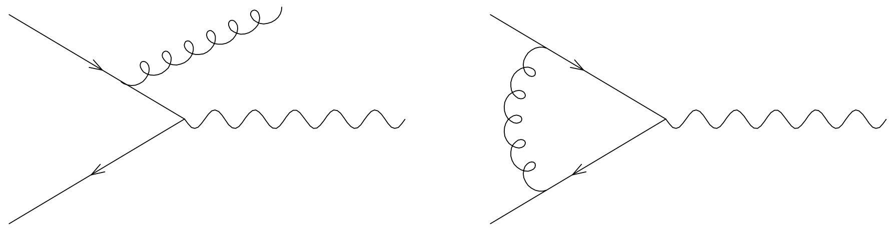
Solution (CKKW – see also MLM)

Cut the divergences off by means of an arbitrary parameter δ_{sep}, and modify the matrix elements and 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 HERWIG, PYTHIA, SHERPA). Although some of the diagrams above contribute to the N^{k}LO result, total rates are still computed to LO accuracy

Improvement: MC@NLO

Compute all NLO diagrams before starting the shower



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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 (yes, this is sufficient!)

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)

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 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

The MC counterterms have been computed by choosing HERWIG to perform the showers. If you use PYTHIA in the showering phase, you get wrong results

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 (weights: ± 1)
- Weighted event generation possible (currently not implemented)
- $\mathrm{MC@NLO}$ shape identical to HERWIG shape in soft/collinear regions
- $\mathrm{MC@NLO}$/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

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*

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

Adding new processes

In standard MC's, the implementation of a new process requires to:

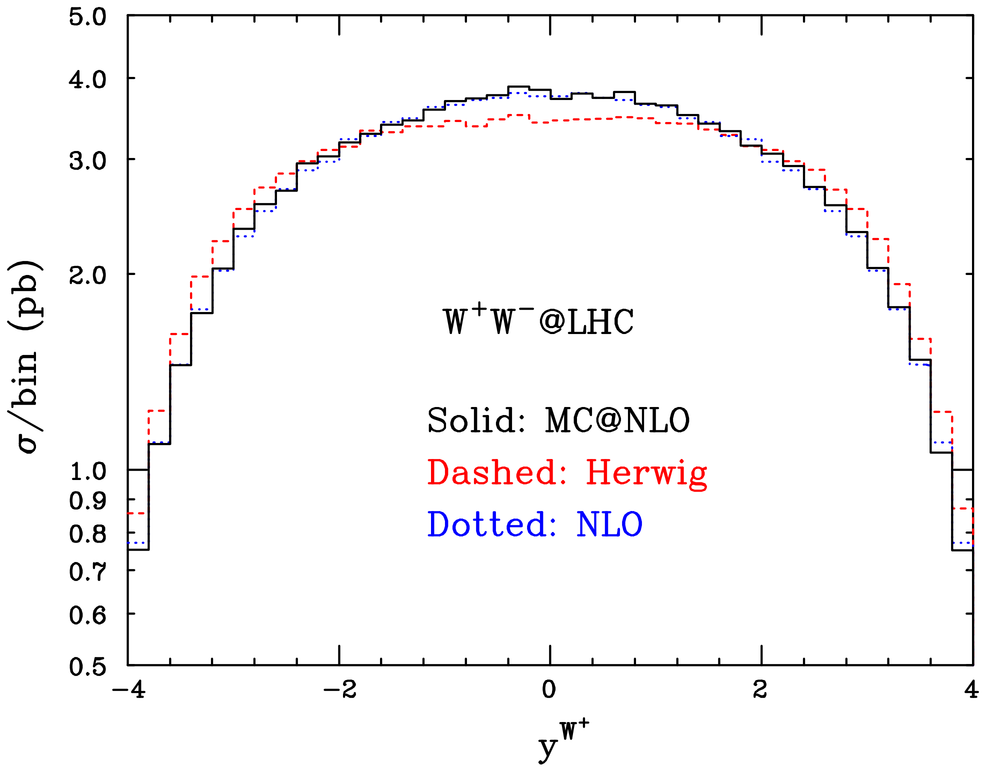
- Compute, or get from someone else, the matrix elements
- Code them in your MC, in the appropriate format. Alternatively, code them in a standalone package, and write a routine which reads the results into your MC
- Figure out the colour and mother-daughter connections for the partons entering the hard subprocess

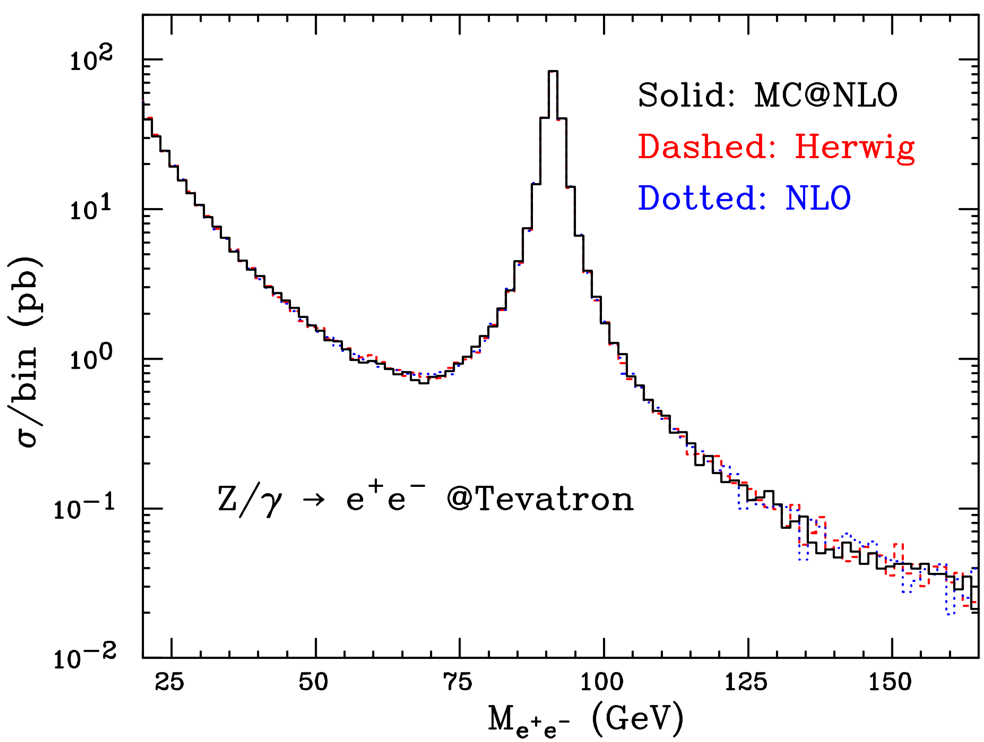
The very same things have to be done in MC@NLO. So the only difference between standard MC's and MC@NLO is:

- NLO matrix elements are more complicated than LO ones

This is why in general we first implement a process by neglecting the spin correlations of the decay products: spin correlations are equivalent to adding more legs to the final state, which take time to implement

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





NLO is OK for these observables

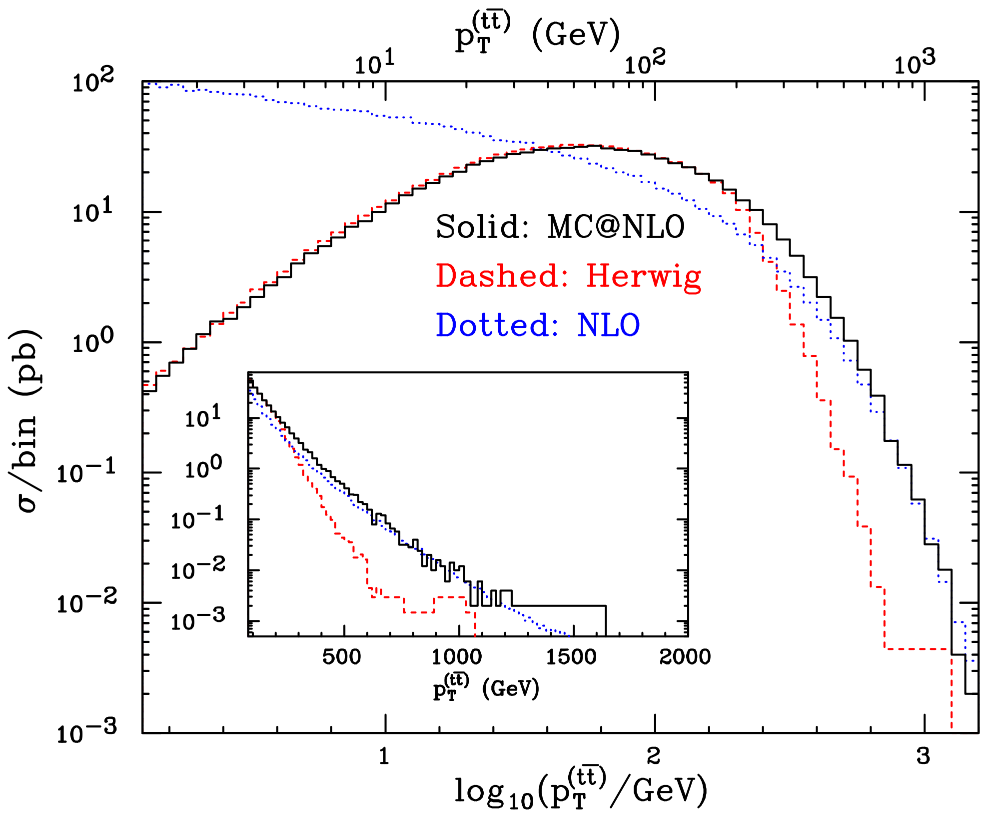
MC@NLO outputs a realistic final state, which matters when full detector simulation is included

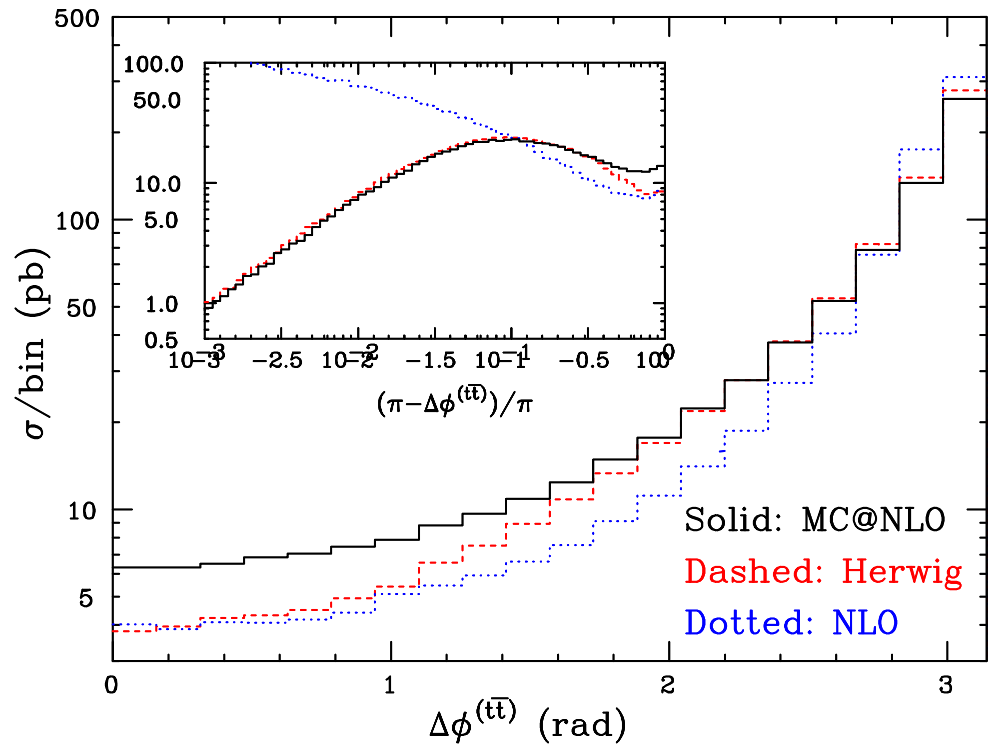
Solid: MC@NLO

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

Dotted: NLO

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





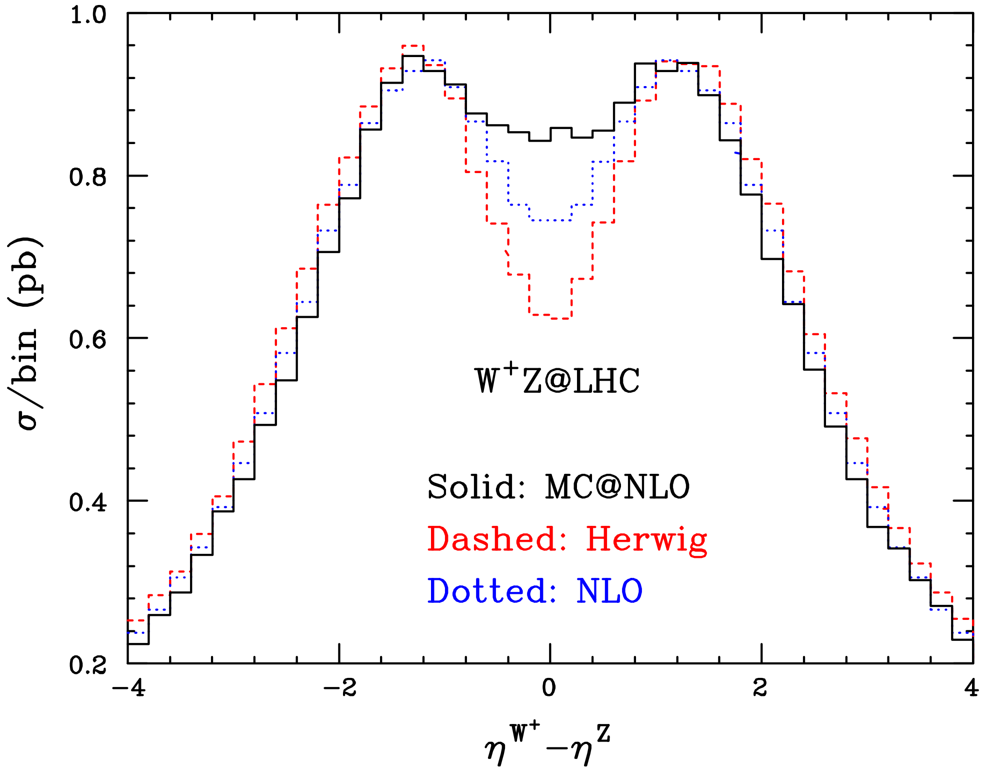
These correlations are problematic: soft and hard emissions are both relevant. MC@NLO does well, resumming large logarithms, and yet handling large-scale physics correctly

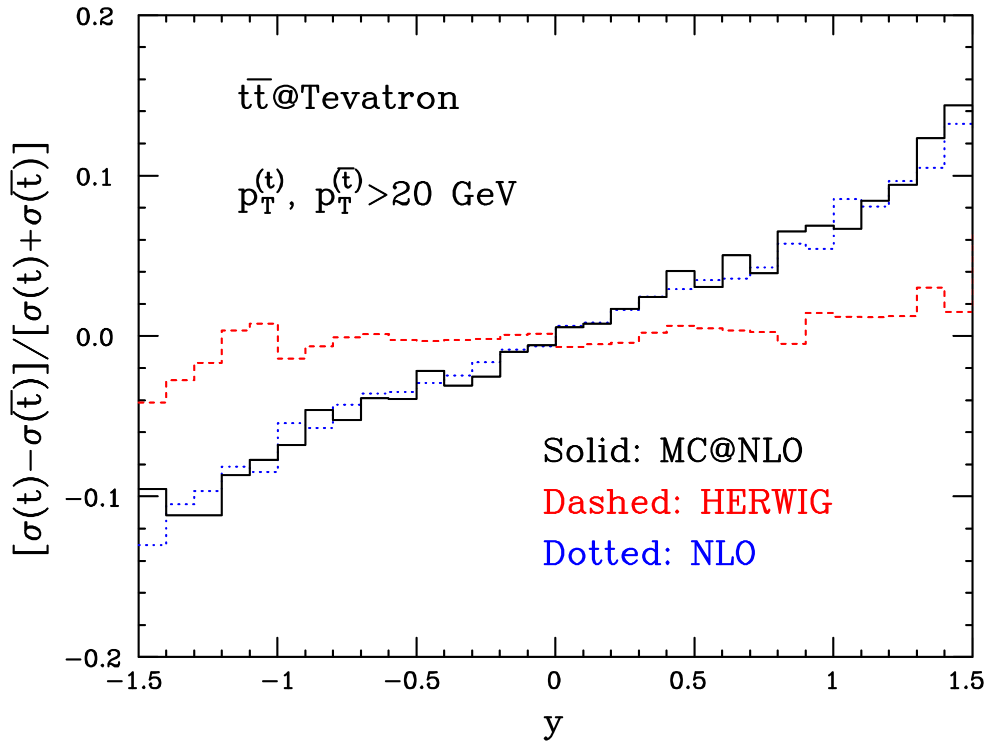
Solid: MC@NLO

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

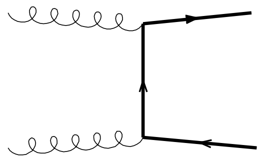
Solid: MC@NLO

Dashed: HERWIG

Dotted: NLO

Charm and bottom with standard MC's

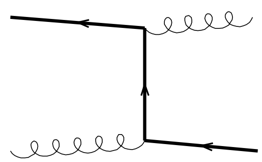
MC rule: if we aim to study any physical system, we start by producing it in the hard process $\Longrightarrow$



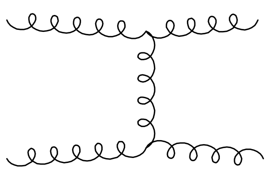
Flavour CReation

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



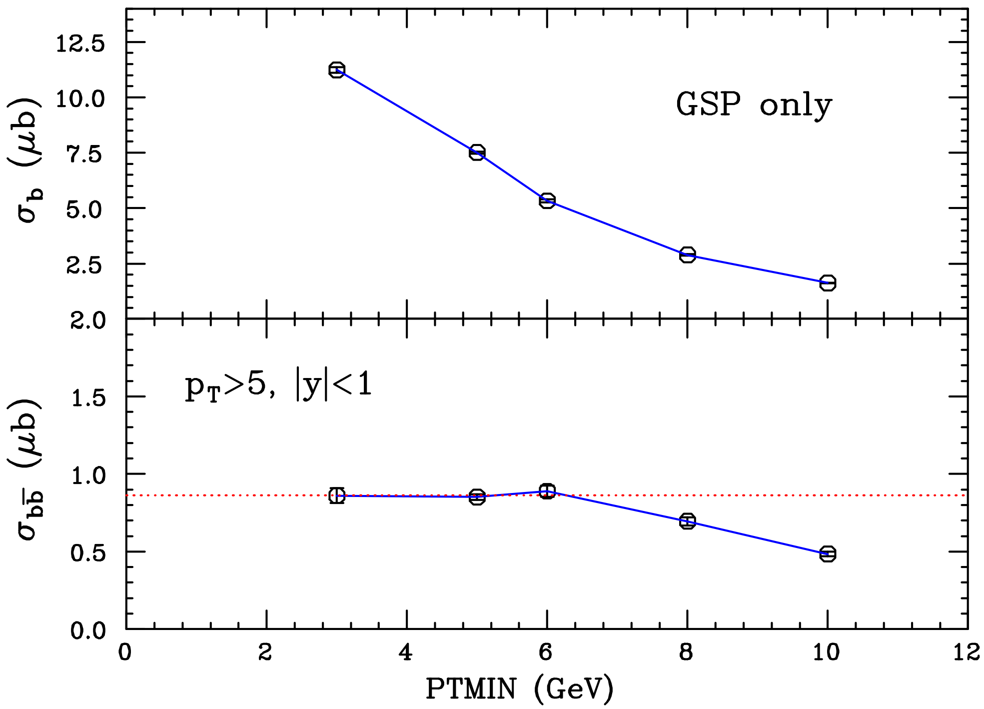
Flavour EXcitation

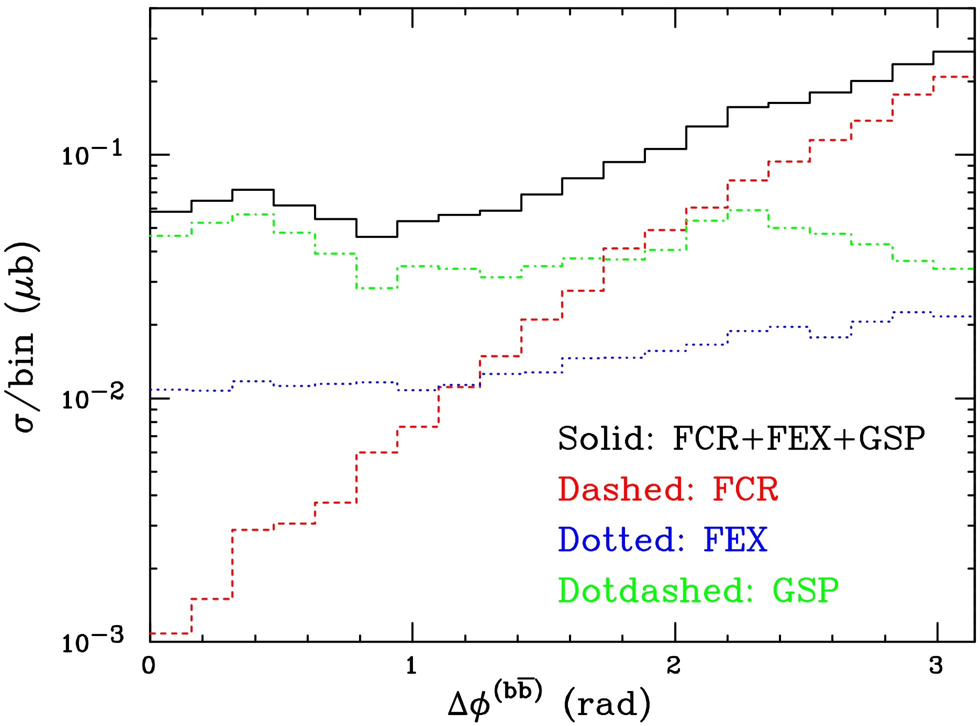


Gluon SPlitting

- 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



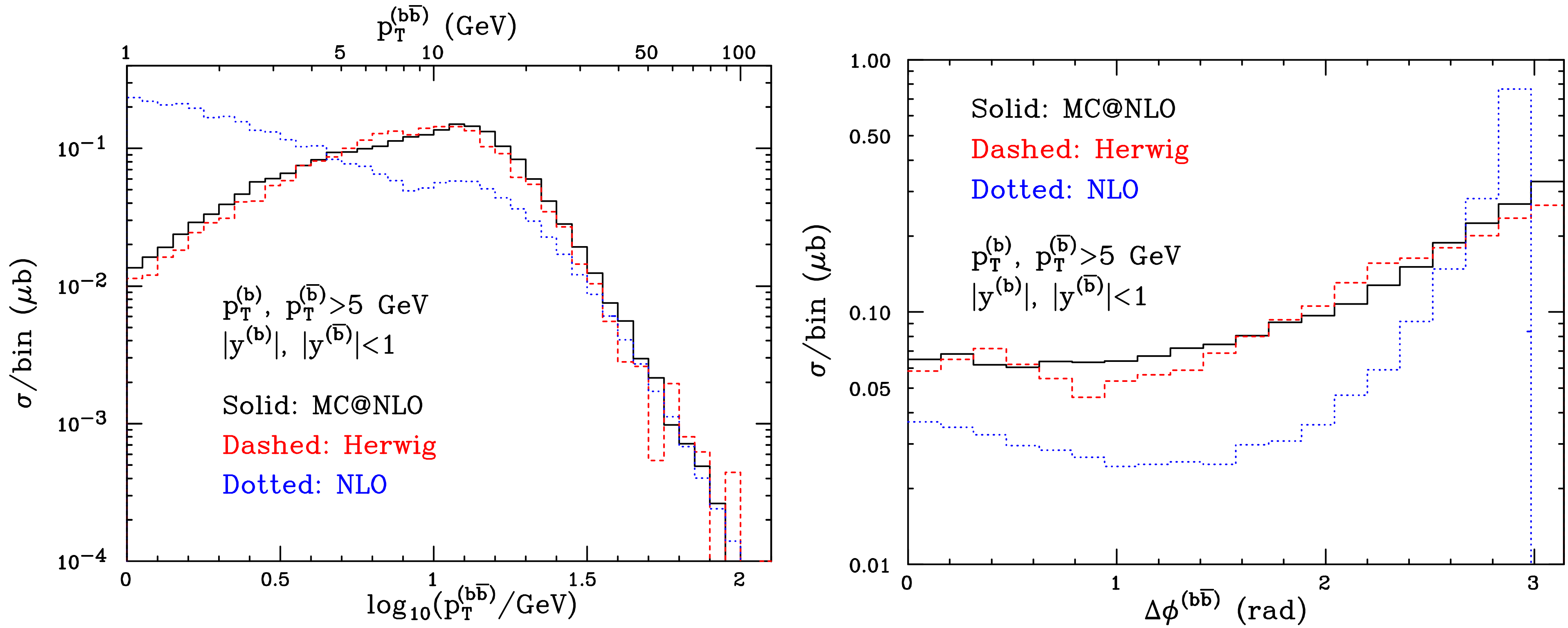


- The PTMIN dependence is worrisome in the case of single-inclusive observables
- FCR, FEX and GSP are complementary, and all must be generated
- GSP efficiency is extremely poor: 10^{-4} within cuts for correlations

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



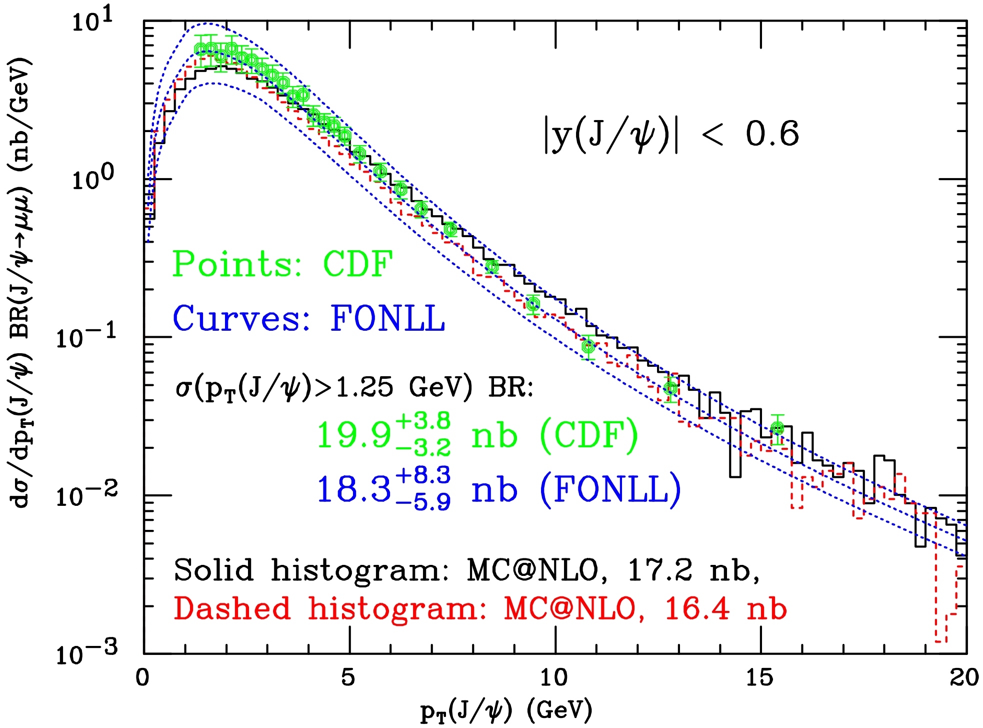
HERWIG does surprisingly well, but needs quite a lot of CPU (14 millions events – 1 million for MC@NLO). The hard emission effects are huge for b production, and cannot be neglected

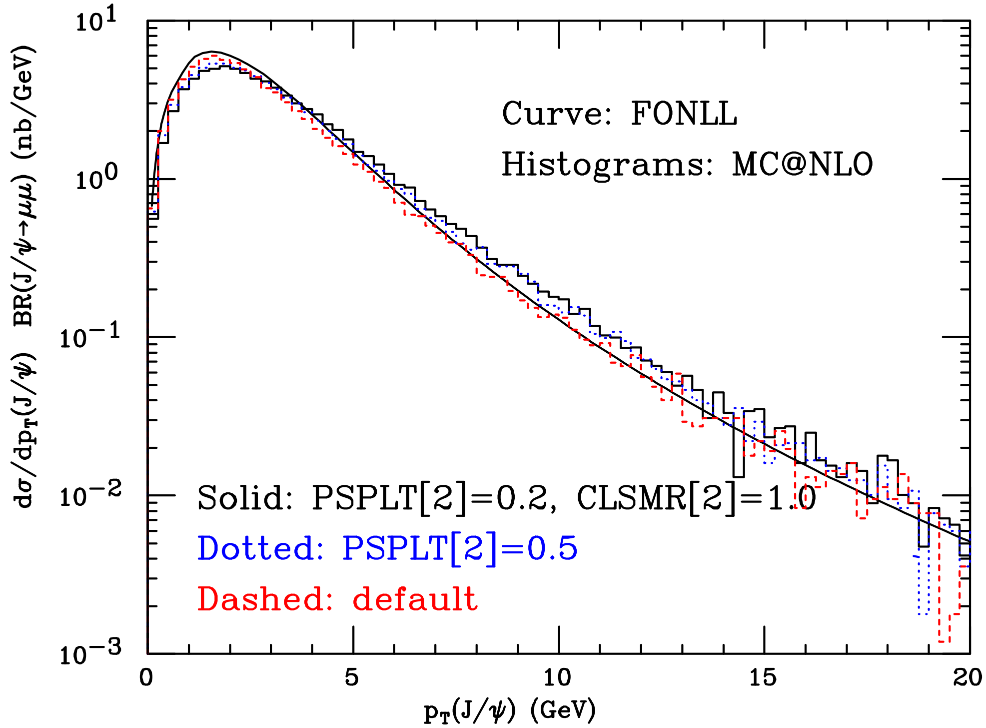
Solid: MC@NLO

Dashed: HERWIG

Dotted: NLO

Single-inclusive b at the Tevatron

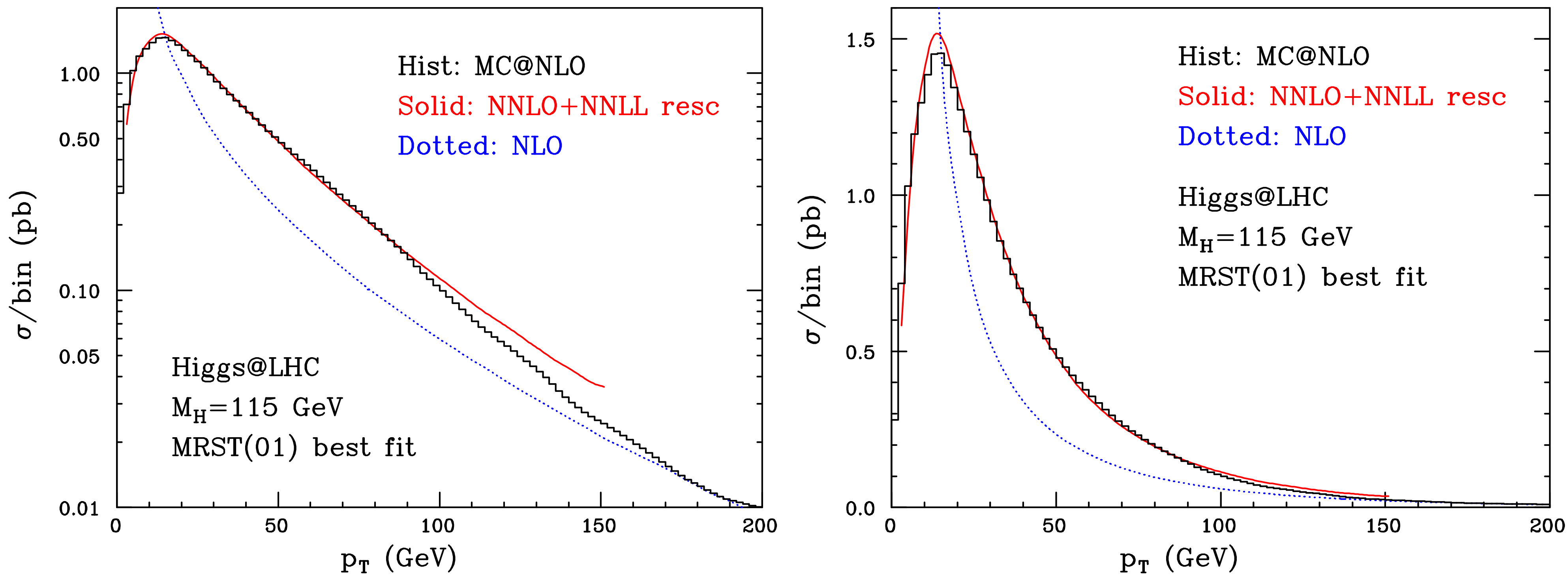




No significant discrepancy with data

- 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

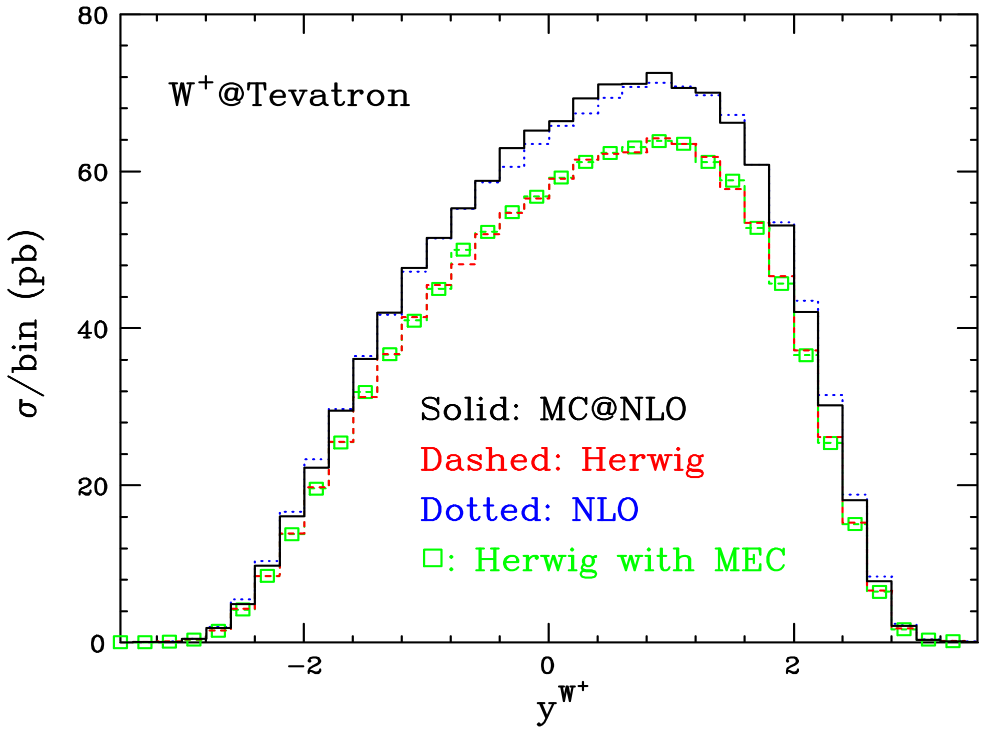
Is the agreement with the resummed result accidental?

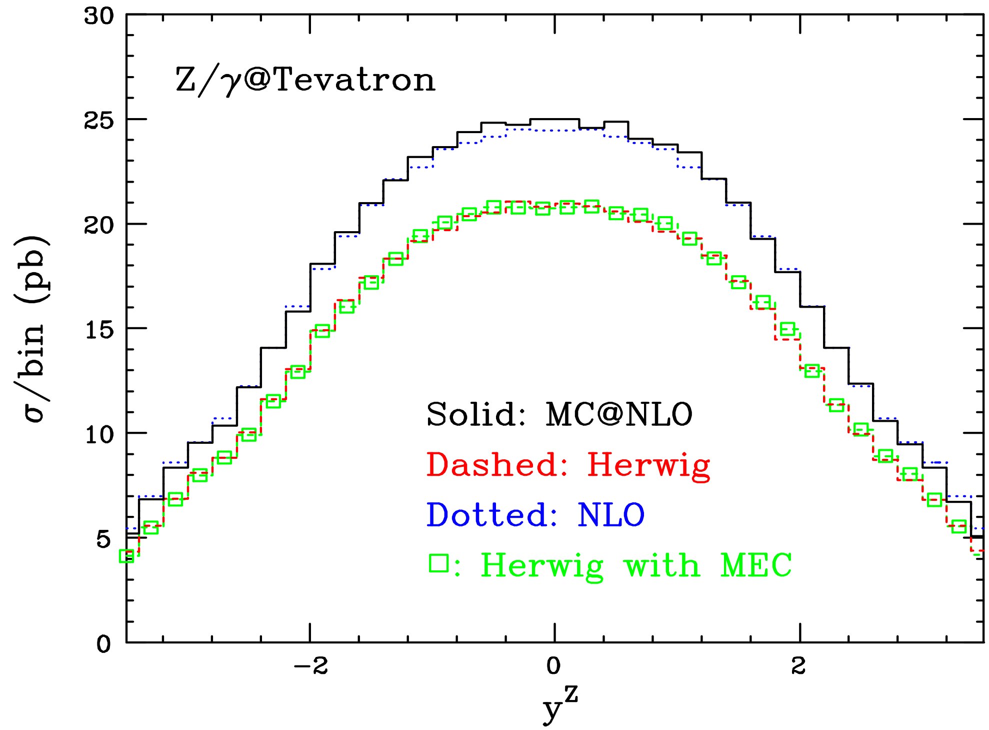


The same happens with Higgs. The result of Bozzi, Catani, de Florian, Grazzini has a matching condition similar to MC@NLO, in that it conserves the total rate

- The agreement with the analytically-resummed result improves when the logarithmic accuracy of the latter is increased $\longrightarrow$ 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

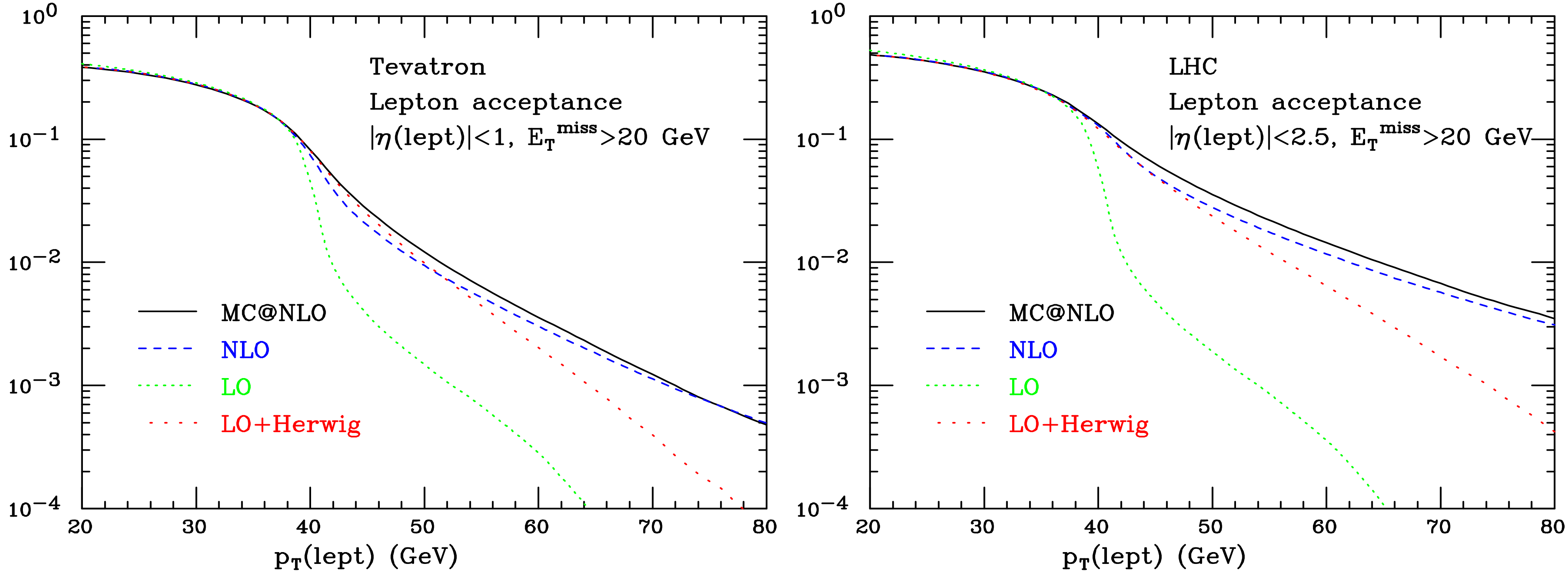
	LO		LO+HW	NLO		MC@NLO
Cuts A	0.5249	$\xrightarrow{-7.7\%}$	0.4843	0.4771	$\xrightarrow{+1.5\%}$	0.4845
	$\downarrow$5.4%			$\downarrow$7.0%		$\downarrow$6.3%
Cuts A, no spin	0.5535			0.5104		0.5151
Cuts B	0.0585	$\xrightarrow{+208\%}$	0.1218	0.1292	$\xrightarrow{+2.9\%}$	0.1329
	$\downarrow$29%			$\downarrow$16%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

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), $WW \to H$ (VBF) 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 negative weights (P. Nason)

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