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Monte Carlo event generators

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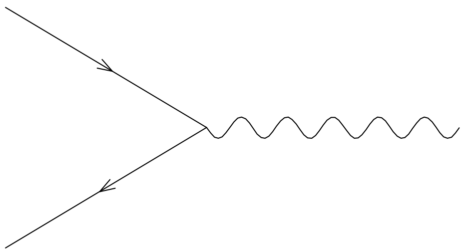
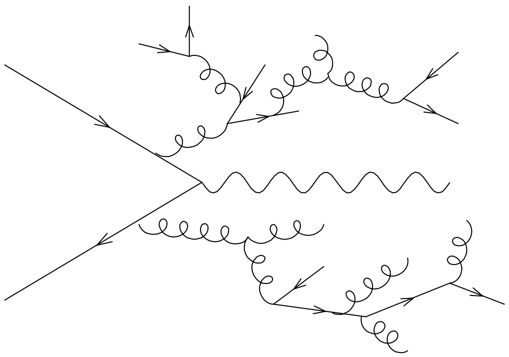
Physics processes with standard MC's

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
- Resum (at least) leading logarithmic contributions

Drawbacks

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

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

How to improve Monte Carlos?

We need to consider fixed-order computations* in perturbation theory, since they:

- Correctly account for hard emissions
- Estimate reliably total rates
- Reduce the impact of unphysical mass scales, and allow one to accurately determine the unknowns of the theory, such as α_S and PDFs

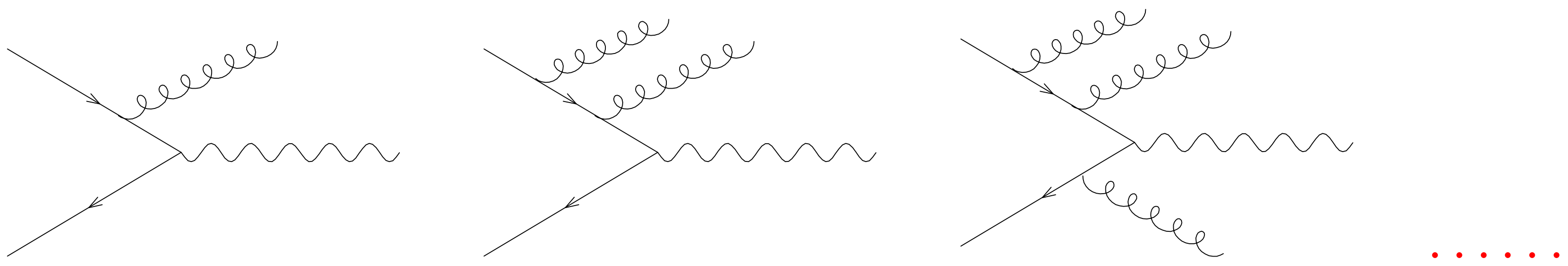
In other words, fixed-order computations perform well where MC's fail. The opposite is also true. The two approaches are thus complementary

To what extent can we combine the powerful features of perturbative computations and of Monte Carlo simulations in a single formalism?

* I won't discuss perspectives for Underlying Events – lot of work done (modelling and tuning), but still sort of plug & pray for LHC. Needs deeper theoretical understanding

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

Cut the divergences off by means of an arbitrary parameter δ_{sep}

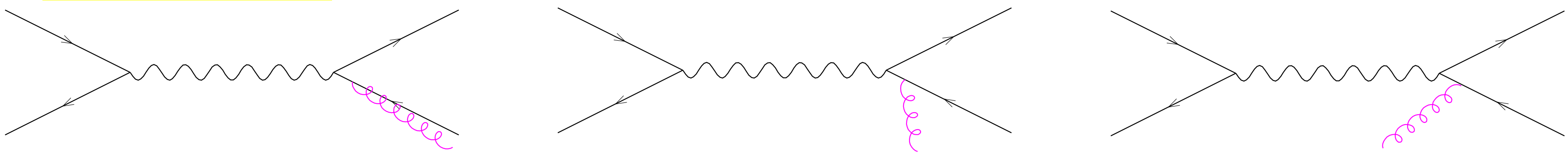
$\Longrightarrow$ physical observables will depend on the unphysical δ_{sep} cutoff

Hard subprocesses are typically generated with a standalone package (`AcerMC`, `ALPGEN`, `AMEGIC++`, `CompHEP`, `Grace`, `MadEvent`), which must be efficient in:
a) computing the matrix elements; *b)* sampling the phase space for unweighting

Getting rid of δ_{sep} dependence

In the context of e^+e^- physics, Catani, Krauss, Kuhn & Webber show that the problem cannot be solved at fixed number of hard legs. Extended to colour dipoles by Lönnblad; extended to hadronic collisions by Krauss; alternative (simpler) strategy by Mangano

- **The problem:** δ_{sep} dependence $\Leftrightarrow$ double counting



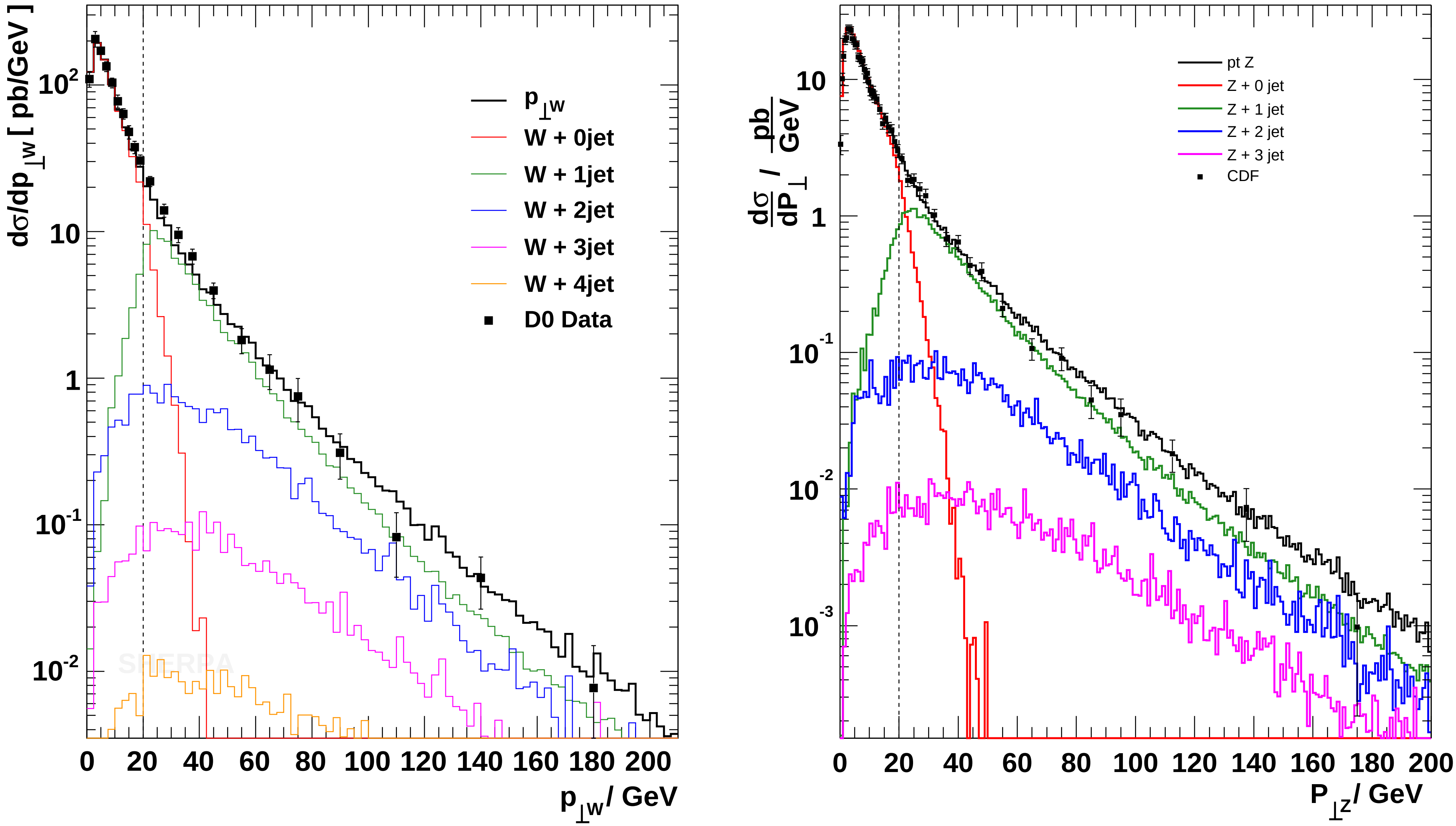
PS-dominated ? *ME-dominated*

- **The solution:** separate the PS- and ME-dominated regions in an arbitrary manner; to compensate for the arbitrariness, the shower and ME's must be modified accordingly

- **The aim:** compute the observable at $\mathcal{O}(\alpha_S^{n-2})$, for any n, and resum to NLL accuracy (downstairs) where needed. By-product: the δ_{sep} dependence is reduced

$$\sigma_n \sim \alpha_S^{n-2} \sum_k a_k \alpha_S^k \log^{2k} \delta_{sep} \quad \longrightarrow \quad \alpha_S^{n-2} \left(\delta_{sep}^a + \sum_k b_k \alpha_S^k \log^{2k-2} \delta_{sep} \right)$$

Using MEC

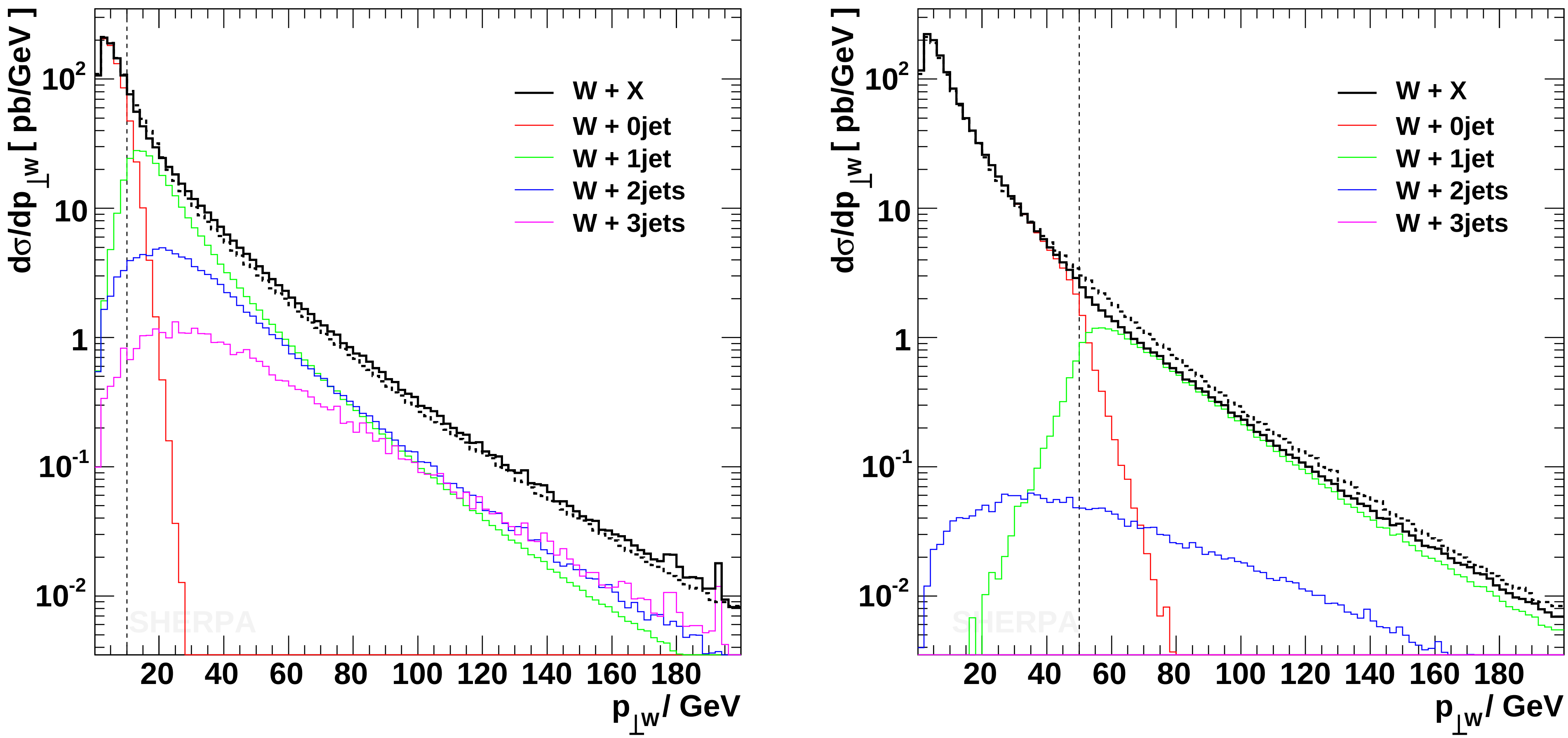


SHERPA (from hep-ph/0409122) – CKKW is built in

Different partonic subprocesses cooperate to give the physical result

- How about the δ_{sep} dependence?

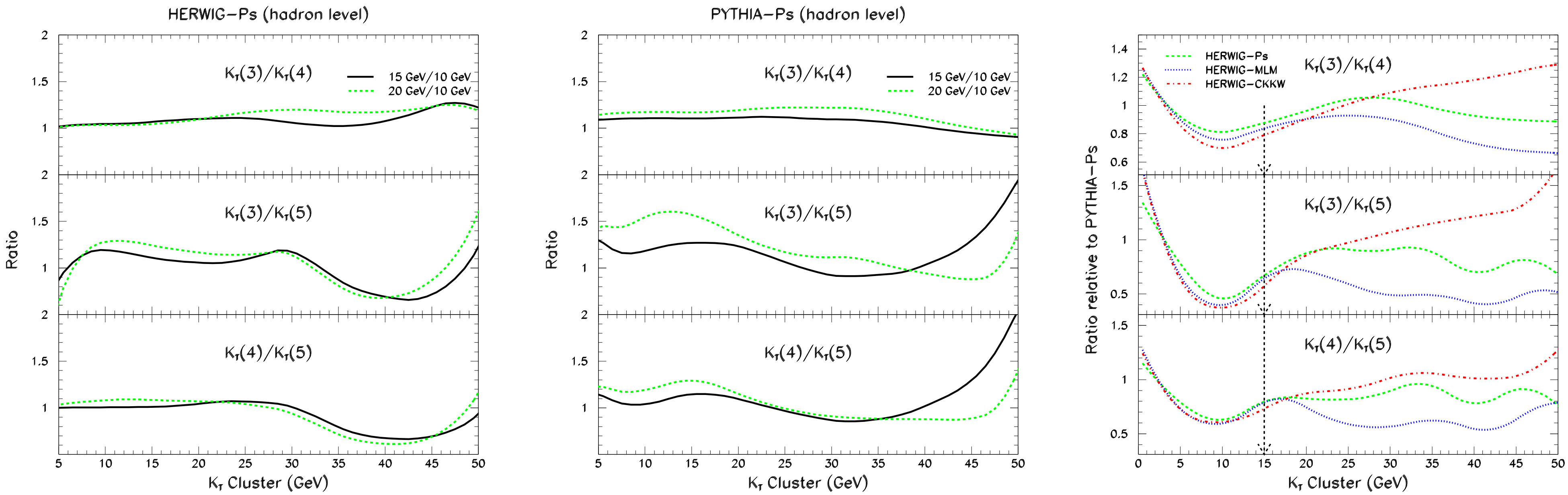
δ_{sep} effects on observables I



SHERPA (from hep-ph/0409122)

In hadronic collisions, δ_{sep} is dimensionful (Q_{cut}). It is reassuring that, in spite of the large dependence on Q_{cut} of the individual partonic subprocesses, the physical result is decently stable. The residual dependence may be used to tune the MC to data

δ_{sep} effects on observables II



HERWIG and PYTHIA (Richardson & Mrenna, hep-ph/0312274)

The δ_{sep} dependence appears here to be larger than for $p_T^{(W)}$; furthermore, there are differences between implementations of different matching procedures in the same MC, and of the same matching procedure in different MC's

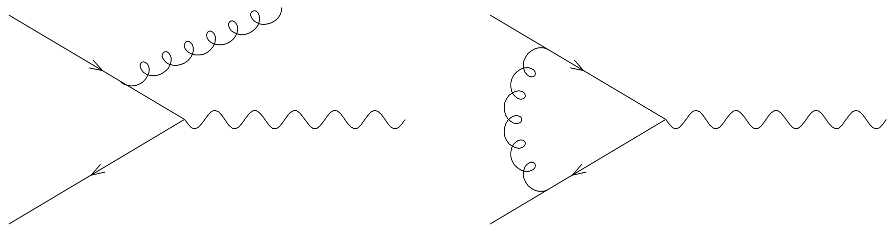
- Matching systematics must be carefully assessed for each observable studied, using at least two different MC's

A short summary on MEC

- MEC have come a long way since the mid-90's works of Sjöstrand and Seymour
- Old-fashioned MEC are basically impossible to apply to anything but processes whose radiation and colour patterns are simple
- New MEC are formally established in e^+e^- collisions; similar formal proofs are lacking in hadronic collisions, but implementations appear robust
- Although no principle problems have to be expected, it is mandatory to check that these techniques work with processes more involved than $W+n$ jets (e.g. preliminary D0 2-jet studies – perhaps 2 is not a large number)
- The dependence upon the unphysical δ_{sep} is a mixed blessing. The substantial amount of work done for $W+n$ jets *may need* be done again for other processes. On the other hand, the residual δ_{sep} dependence gives an extra lever arm for tuning on data
- The dependence upon δ_{sep} seems much smaller in ARIADNE (Lavesson, Lönnblad, hep-ph/0503293)

Adding virtual corrections: NLOwPS

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

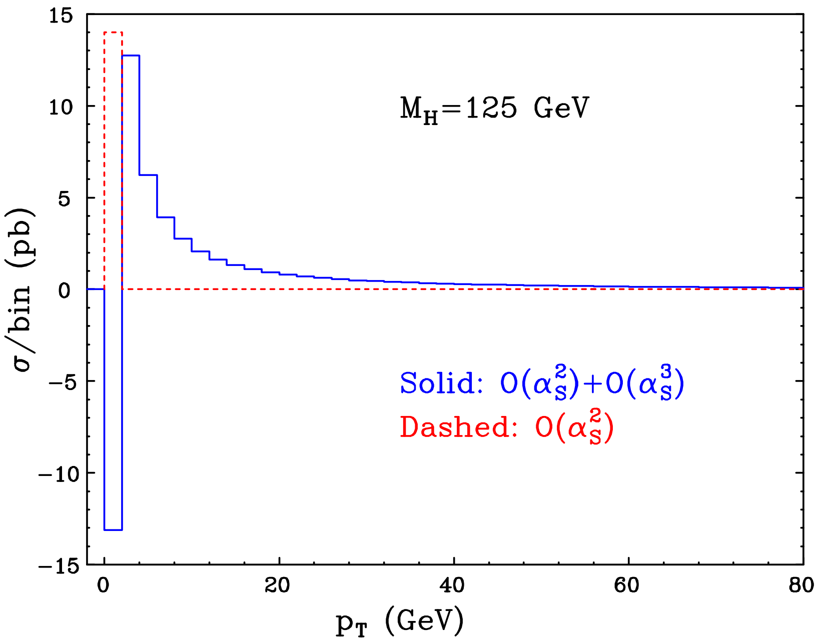
Solution (MC@NLO here – others have been proposed, see later)

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)

What does NLO mean?

Consider Higgs production:



$$\frac{d\sigma}{dp_T} = \left(A\alpha_S^2 + B\alpha_S^3\right)\delta(p_T) + C(p_T)\alpha_S^3$$

$$\int_{p_T^{min}}^{\infty} dp_T \frac{d\sigma}{dp_T} = \mathcal{C}_3\alpha_S^3, \qquad p_T^{min} > 0$$

$$= \mathcal{D}_2\alpha_S^2 + \mathcal{D}_3\alpha_S^3, \quad p_T^{min} = 0$$

$p_T^{min} > 0 \Rightarrow$ LO, $p_T^{min} = 0 \Rightarrow$ NLO

The answer depends on the observable, and even on the kinematic range considered. So this definition cannot be adopted in the context of event generators

- N^{k}LO accuracy in event generators is defined by the number k of extra gluons (either virtual or real) wrt the LO contribution (hopefully we all agree on LO definition)

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., no merging systematics)

+ 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 (i.e., more running time required)

The actual hadronic NLOwPS's

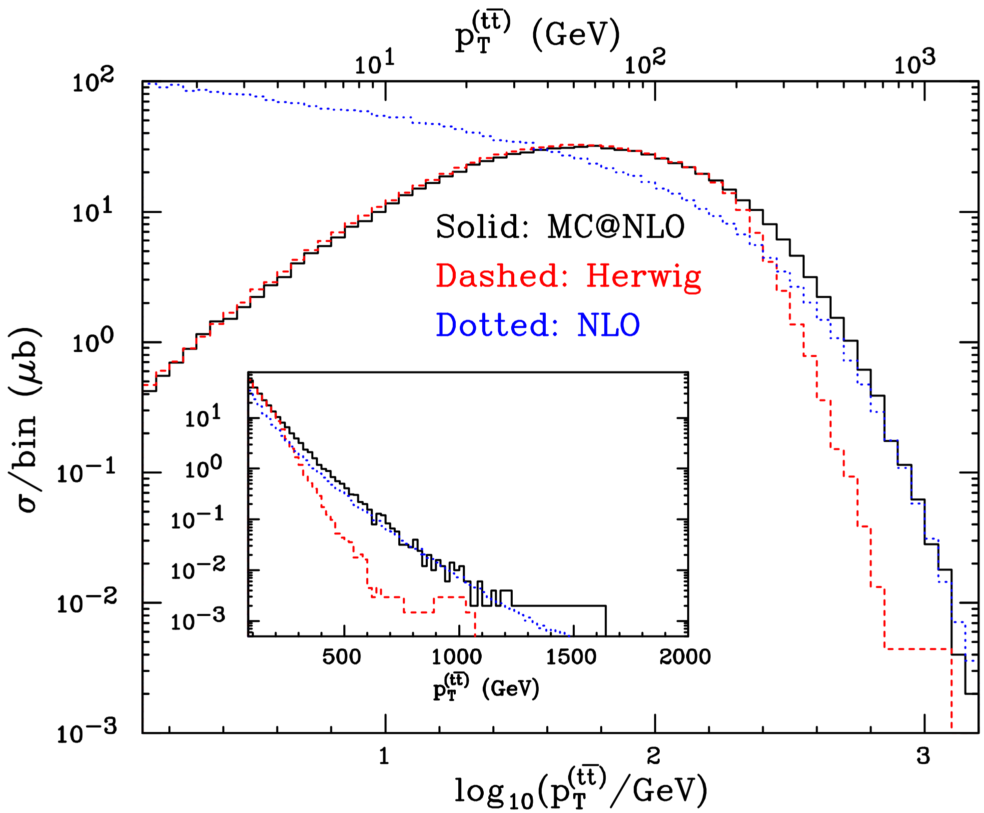
- MC@NLO (Webber & SF; Nason, Webber & SF)
  Based on NLO subtraction method
  Formulated in general, interfaced to HERWIG
  Processes implemented: $H_1 H_2 \longrightarrow$ W^+W^-, $W^\pm Z$, ZZ, $b\bar{b}$, $t\bar{t}$, H^0, $W^\pm$, Z/γ

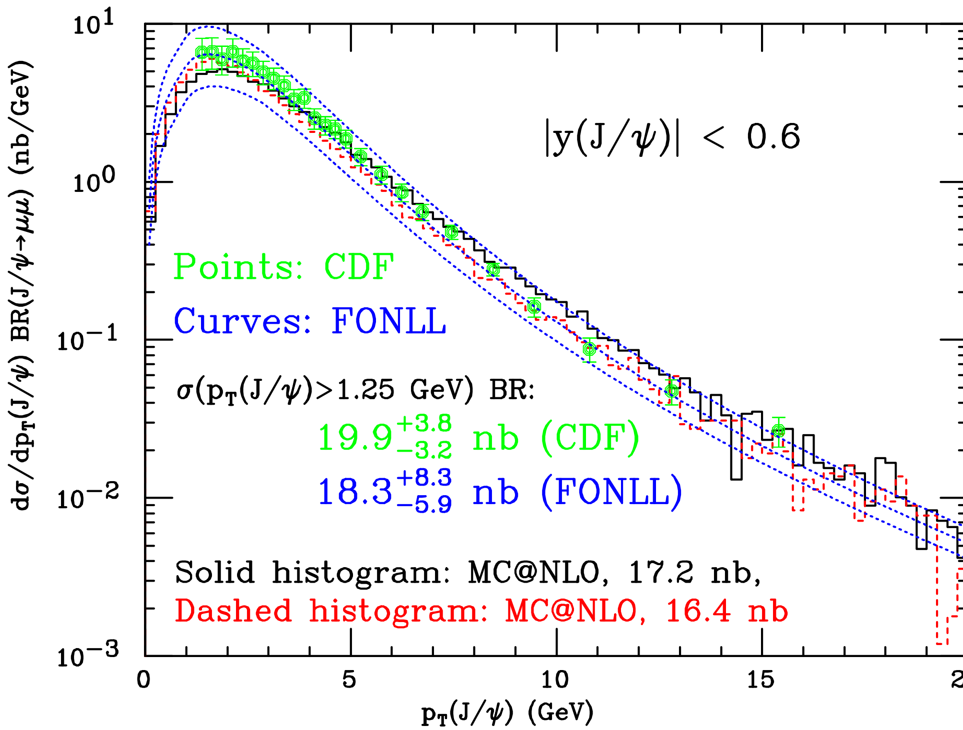
- Φ-veto (Dobbs; Dobbs & Lefebvre)
  Based on NLO slicing method
  Avoids negative weights, at the price of double counting
  Processes implemented: $H_1 H_2 \longrightarrow$ Z

- 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

. . . and a lot of ongoing theoretical activity

What to expect from an NLOwPS (here MC@NLO)





- MC@NLO rate $=$ NLO rate $\Longrightarrow$ K-factors are included consistently
- MC@NLO- and MC-predicted shapes are identical where MC does a good job
- $\mathcal{S}$+0 jet and $\mathcal{S}$+1 jet treated exactly, $\mathcal{S}+n$ jets $(n > 1)$ better than in MC's
- No dependence on δ_{sep} $\Longrightarrow$ tuning is the same as in ordinary MC's
- Some negative-weight events, to be subtracted (rather than added) from histograms

The field is hot

- NLOwPS without negative weights (Nason)
  - Move hardest emission up the shower, exponentiate full real corrections
  - Potentially large beyond-NLO spurious contributions – need to check
- Showers beyond leading order (Collins & Zu)
  - Introduce new factorization theorem
  - Soft emissions so far untreated
- CKKW in NLOwPS (Nagy & Soper)
  - Forced to re-introduce a δ_{sep}-dependence into NLOwPS
  - Not implemented, and thus can't quantify the δ_{sep} bias
- Progress in MC@NLO (Webber, Laenen, Motylinski, Oleari, del Duca, SF)
  - New processes (single-t, WH, ZH)
  - Spin correlations being added
  - Kinematic cuts at the matrix element level understood

Conclusions

There has been substantial theoretical progress in MC's in the past three years or so. The timing is just right, since it's the Tevatron and the LHC that demand the construction of improved MC tools

MEC for multileg processes are firmly established

- Expect CKKW to become part of HERWIG, PYTHIA, and SHERPA releases
- Reliable estimates for many backgrounds to new physics

NLOwPS's improve NLO computations and MC simulations in several respects

- NLOwPS's are the only way in which K-factors can be embedded into MC's
- Hard radiation is incorporated in MC's, without any kinematical distortion and unphysical parameters

Theorists are working hard – the increasing awareness by experimenters of the flaws of standard MC's will provide them with crucial feedback