Stefano Frixione

Status of Monte Carlos

DIS09, Madrid, 26/4/2009

Plan

- Monte Carlos: scope and limitations
- What is available
- Recent progress (in the perturbative part)
- Outlook

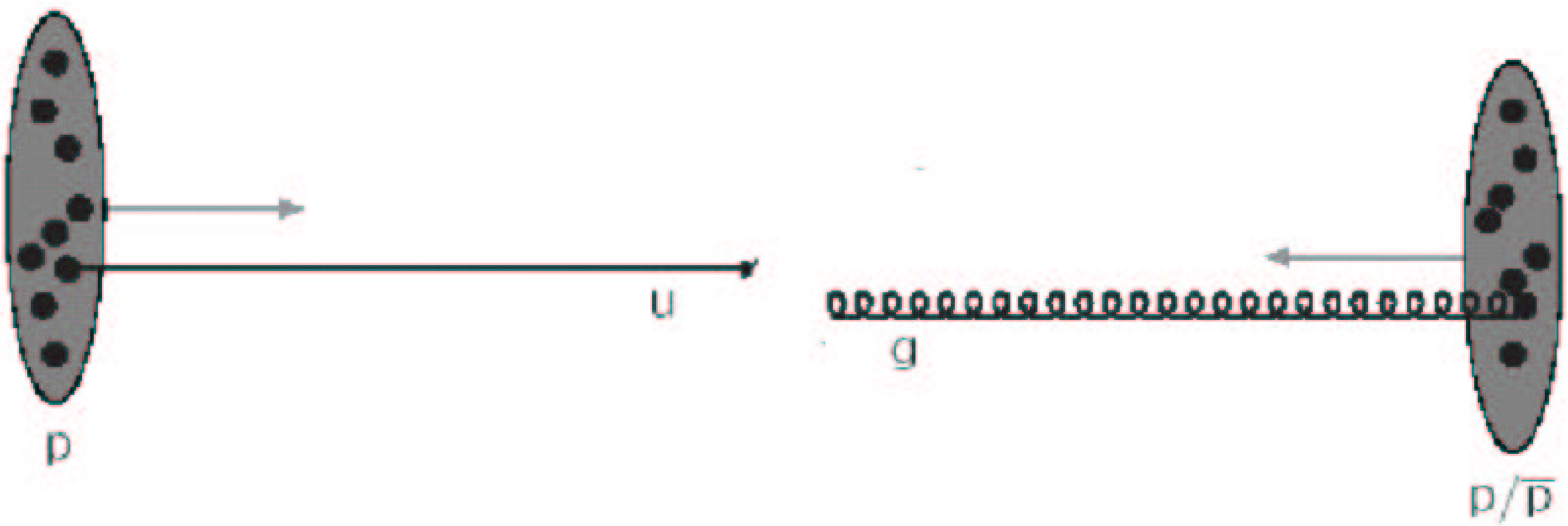
I shall limit technical details to a minimum

Parton Shower Monte Carlos

Why bother?

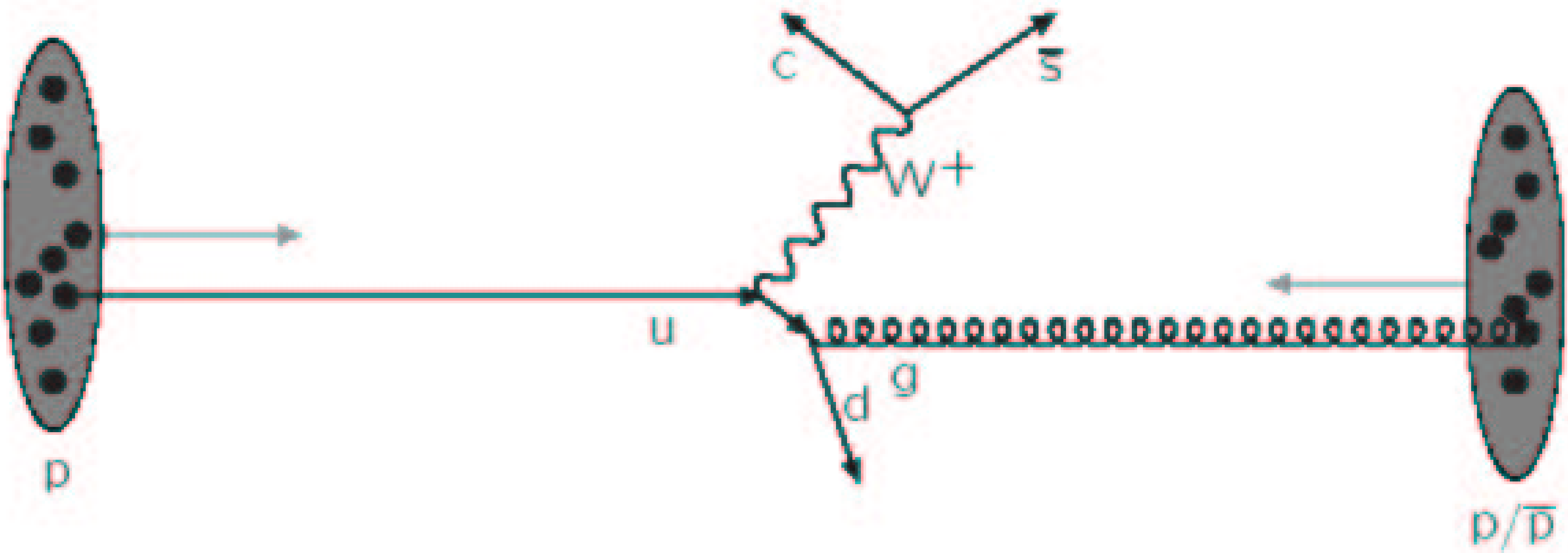
- Because they are designed so as to faithfully represent our ideas of what is going on in an actual collision process

Plot: T. Sjöstrand



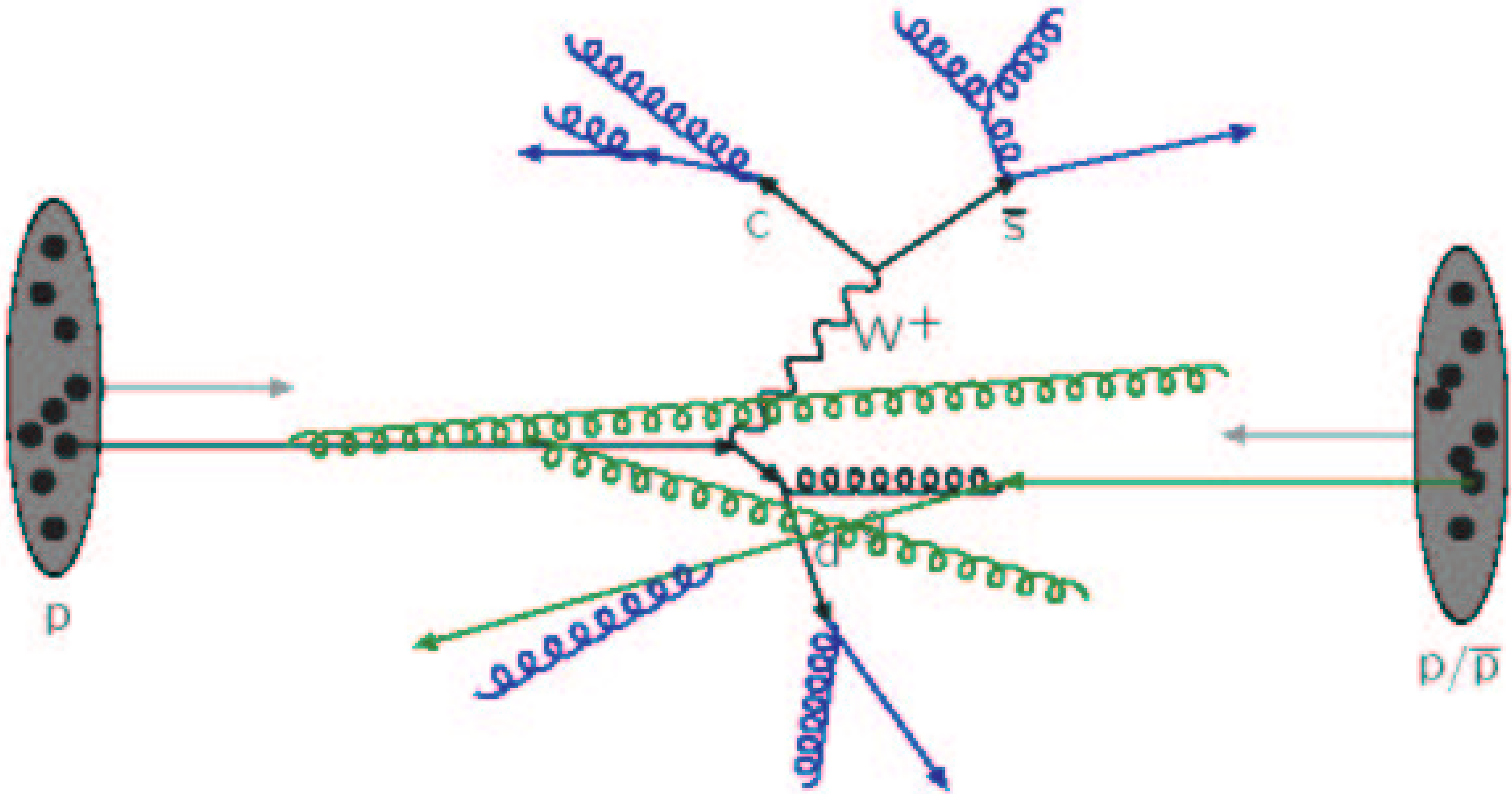
0. Pull out one parton from each of the incoming hadrons
(use PDFs to choose flavour and x)

Plot: T. Sjöstrand



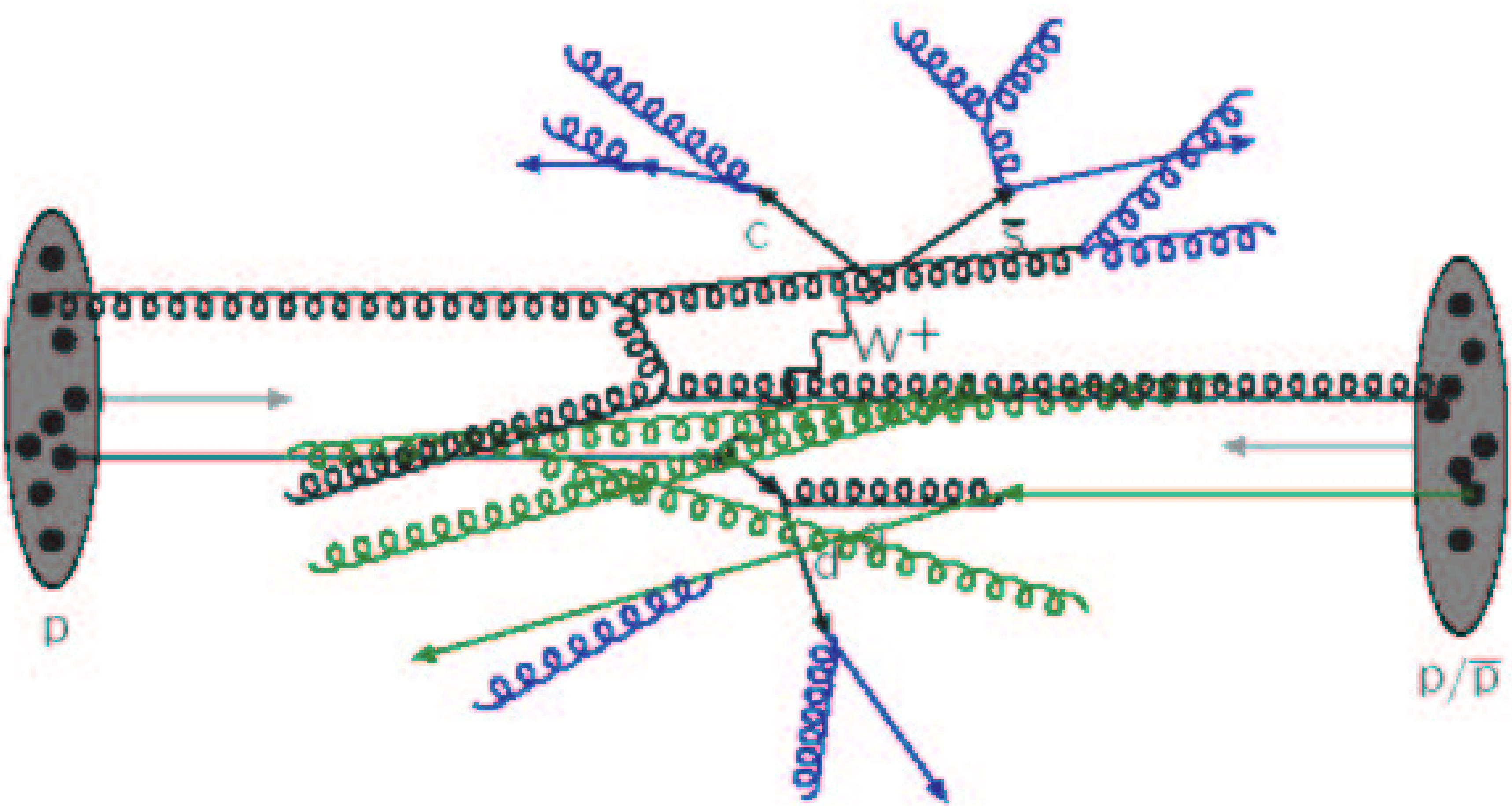
1. Make them collide and produce *large-*p_T *stuff*
   (Hard Subprocess)

Plot: T. Sjöstrand



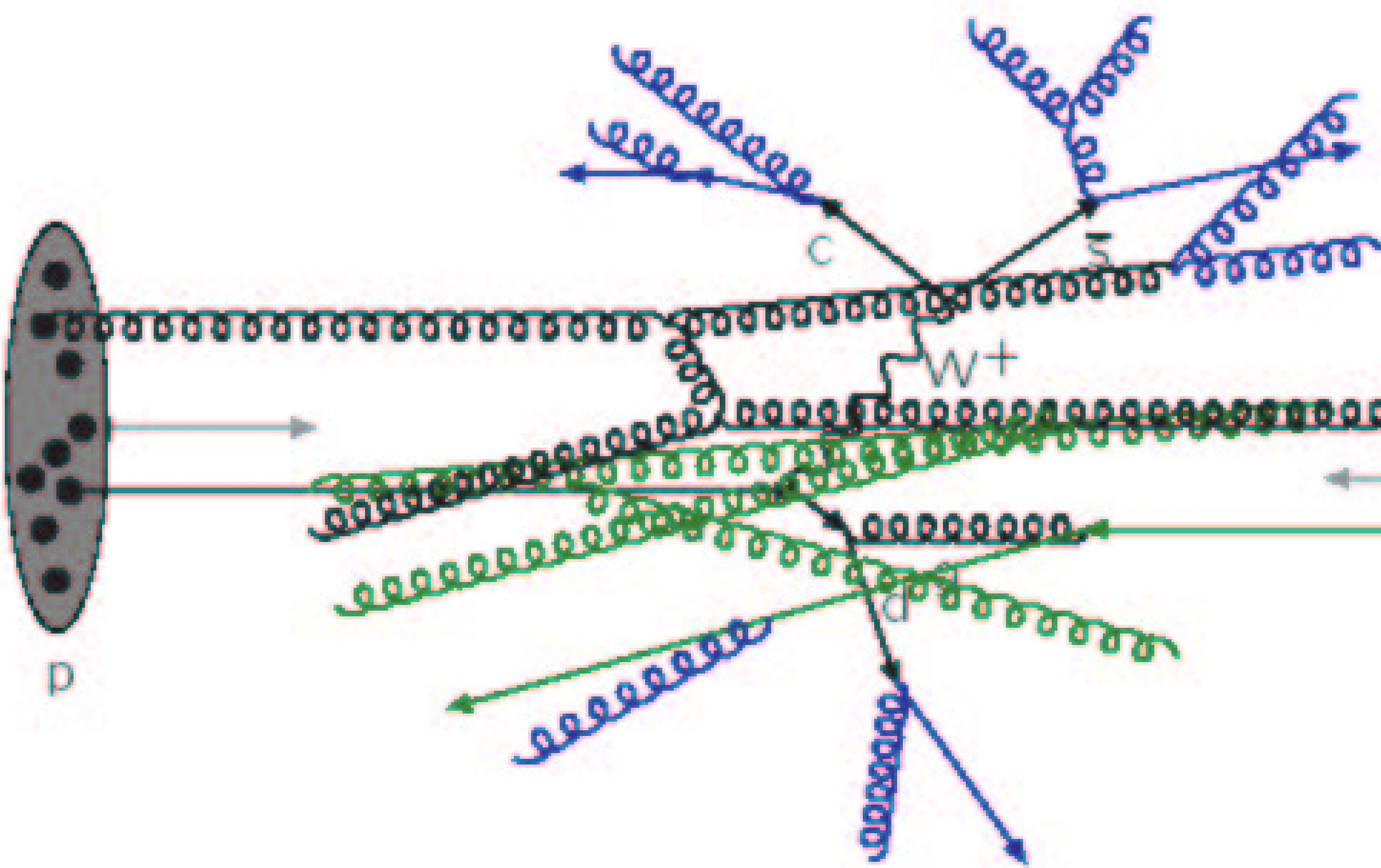
2. Let quarks and gluons emit other quarks and gluons
   (Parton Shower)

Plot: T. Sjöstrand



3. Other partons may undergo the same fate *at smaller* p_T*'s* (MPI + beam remnants ≡ Underlying Event)

Plot: T. Sjöstrand



4. Convert quarks and gluons into physical hadrons (Hadronization)

1. Hard process. Very well understood, fully perturbative with no approximations (but typically at the LO only)

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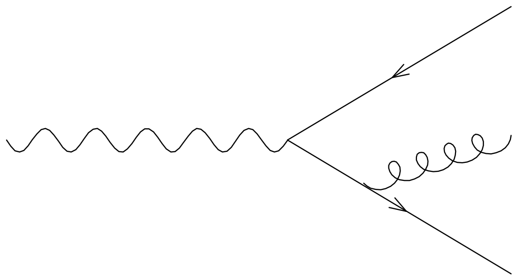
3. Underlying Event. Poorly understood. Models are not well constrained by data, and extrapolations are affected by very large uncertainties

Parton Showers

- Each emission in a shower is based on a collinear approximation; collinear emissions factorize and can be easily iterated



Master equation:

$$d\sigma_{q\bar{q}g} \xrightarrow{t\to 0} d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

- As long as $E_q \simeq E_g \gg \Lambda_{\rm QCD}$

$$t = Q^2, \qquad t = \theta^2, \qquad t = p_T^2$$

are equivalent

- Choices of shower variables are *not equivalent* in the soft region ($E_g \ll E_q$). Perturbative QCD theorems (Mueller) prescribe to use angles. In practice, pQCD deficiencies may be compensated by the non-perturbative part (mostly hadronization)

Different choices of variables led to:

HERWIG(++)	PYTHIA/SHERPA	ARIADNE
$t \simeq angle$	$t = virtuality$	$t = p_T^2$
hardest not first	hardest first	hardest first
coherent	coherence forced	coherent
dead zones	no dead zones	no dead zones
ISR easy	ISR easy	ISR difficult
kinematics: difficult	kinematics: easy	kinematics: easy
cluster hadr	string/cluster hadr	string hadr

- Since 2006 PYTHIA has also p_T-ordered evolution (PYTHIA8 is only p_T-ordered). SHERPA will also abandon virtuality order

"Historical" MCs PYTHIA and HERWIG are being re-written in C++ $\longrightarrow$ PYTHIA8 and HERWIG++. This is an opportunity to include new physics features, such as:

- ♦ PYTHIA8 (Status report: 0809.0303)
  - Interleaved p_T-ordered MI+ISR+FSR evolution
  - Improved UE model (more processes)
  - Two hard interactions in the same event

- ♦ HERWIG++ (v2.3 Release Note: 0812.0529)
  - New (angular-ordered) shower (better treatment of masses)
  - MPI model for UE
  - Spin correlations in all decays owing to use of spin unaveraged MEs

SHERPA (v1.1 Release Note: 0811.4622) is now fully independent of PYTHIA. Moving towards new p_T-ordered showers based on CS dipole formulae. Matching with MEs (see later) fully integrated

Further recent progress

An immense amount of activity on modelling & fitting UE physics. From the theoretical point of view, it is now established that

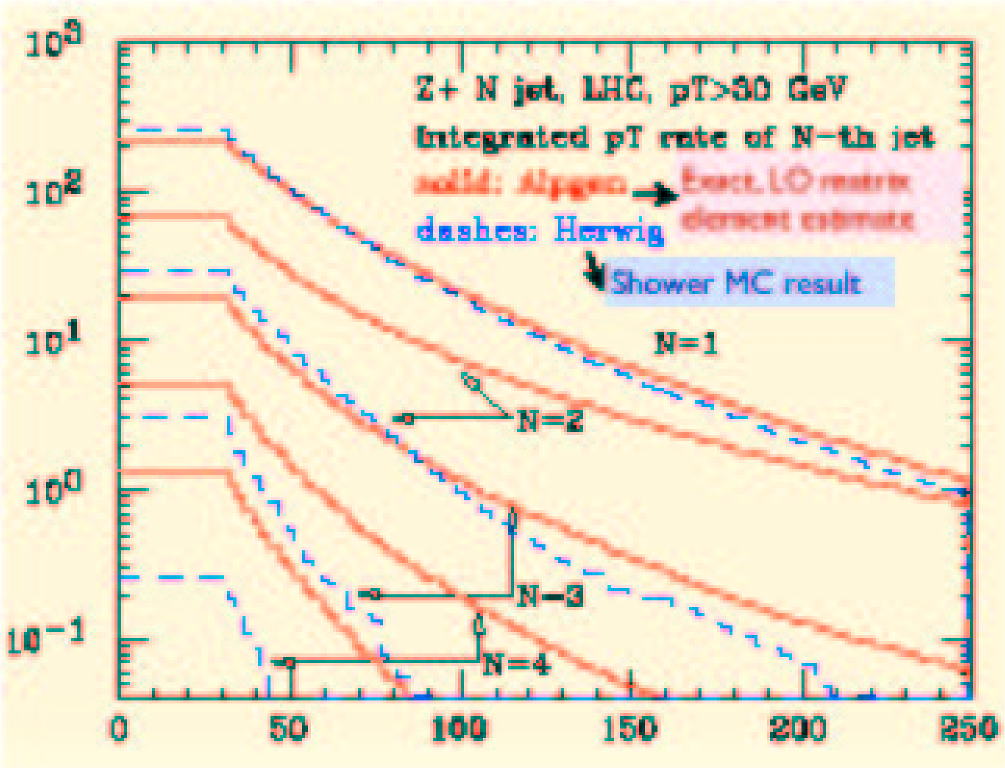
- MPI are necessary to describe well UE

A better understanding from first principles would improve extrapolations to LHC energies. For recent results see e.g. http://www.pg.infn.it/mpi08

The most significant theoretical progress lately has been made on the best-understood component of MCs: the perturbative part

There are compelling phenomenological motivations $\longrightarrow$

Plot: M. Mangano



LHC physics is a multi-jet physics

New-physics signal may easily have 5-10 jets (e.g. fully hadronic SUSY Higgs, $T \to tW$, heavy sparticle pair production, little Higgs, ...)

- MCs are simply unable to reliably simulate these multi-jet events
- The reason behind this failure is obvious. The parton shower is inherently collinear. The probability associated with well-separated final-state particles is largely underestimated

How to improve (perturbatively) Monte Carlos?

The key issue is to go beyond the collinear approximation

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

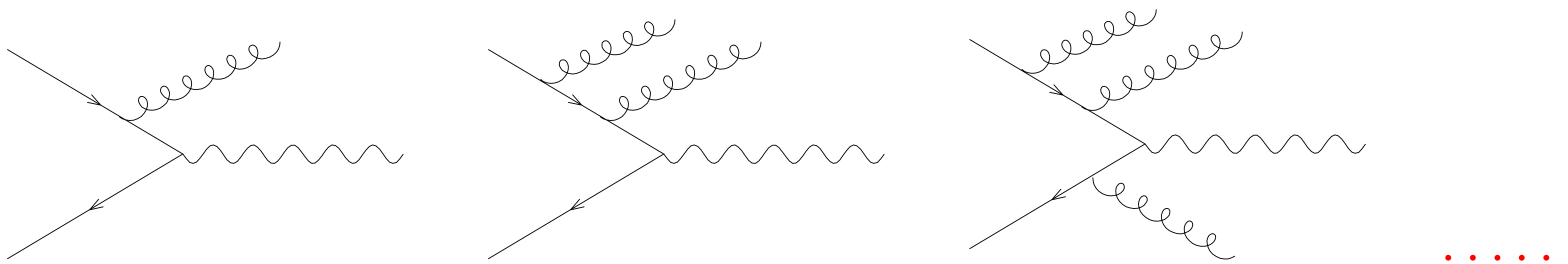
Which ones?

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

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

Matrix Element Corrections

Compute (exactly) as many as possible real emission diagrams before starting the shower. Example: W production



Problems

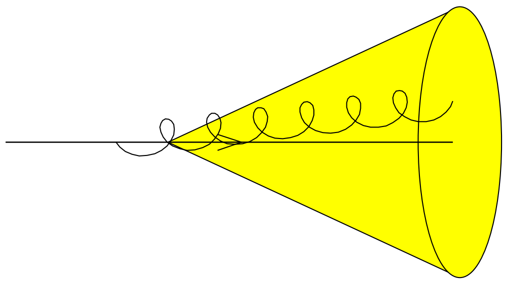
- Double counting (the shower can generate the same diagrams)
- The diagrams are divergent

Solutions

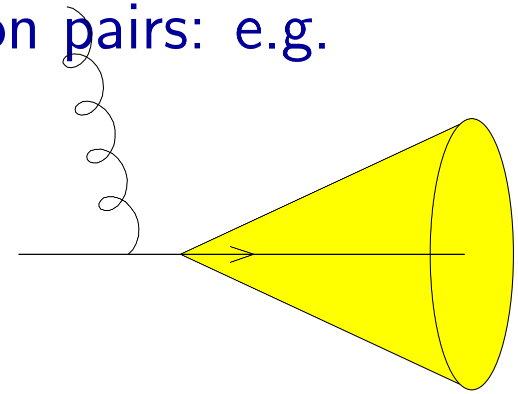
$\longrightarrow$ Catani, Krauss, Kuhn, Webber (2001), Lönnblad (2002), Mangano (2005) (CKKW, SMPR, CKKW-L, MLM)

What all solutions have in common

- Separate PS- from ME-dominated kinematics regions. This is done by "measuring" the hardness of each parton pairs: e.g.



Soft $\Longrightarrow$ use PS



Hard $\Longrightarrow$ use ME's

- This removes double counting (and divergencies in ME's), but it introduces an unphysical bias, upon which physical predictions depend

- The bias is removed by *at least one* of the following operations

  Modify ME's (through reweighting)

  Choose suitable PS initial conditions (depend on kinematics)

  Forbid emissions/Reject events in the shower phase

CKKW

- Separation criterion: jet k_T clustering algorithm (merge if $d_{ij} < Q^2_{sep}$)
- Reweight ME's with Sudakovs, i.e. the probability that shower could not have generated softer branchings. Sudakovs are LL ones, e.g.

$$\Delta_q(Q_1, Q_2) = \exp\left[-\frac{2C_F}{\pi}\int_{Q_1}^{Q_2} dq \frac{\alpha_S(q)}{q}\left(\log\frac{Q_2}{q} - \frac{3}{4}\right)\right],$$

- Correct the (angular-ordered) shower by *vetoeing* certain emissions (those harder than Q^2_{sep})
- The latter two steps guarantee that Q^2_{sep} dependence is of NLL

Formal proof given for e^+e^-. Extented to hadronic collisions (without proof) by Krauss. More recent applications ⟶

CKKW-like

SMPR (S. Mrenna & P. Richardson)

Apply CKKW to hadronic collisions with Pythia and Herwig

Tests several choices of scales and initial conditions

Use (among others) the same Sudakovs as in the MC

SHERPA (pre-2009)

CKKW except for use of virtuality-order shower

SHERPA (2009 - not released yet)

Use (CS) dipole-type shower, p_T-ordered

Introduce a clustering algorithm that matches shower variables

Use the same Sudakovs as in MC

CKKW-L (Lönnblad)

Implemented in ARIADNE, thus uses dipole shower and p_T ordering

Clustering is done by inverting shower evolution. This implies that intermediate configurations are indistinguishable from shower-generated final states (in CKKW, this is true only up to power-suppressed effects)

Use the same Sudakovs as in the MC

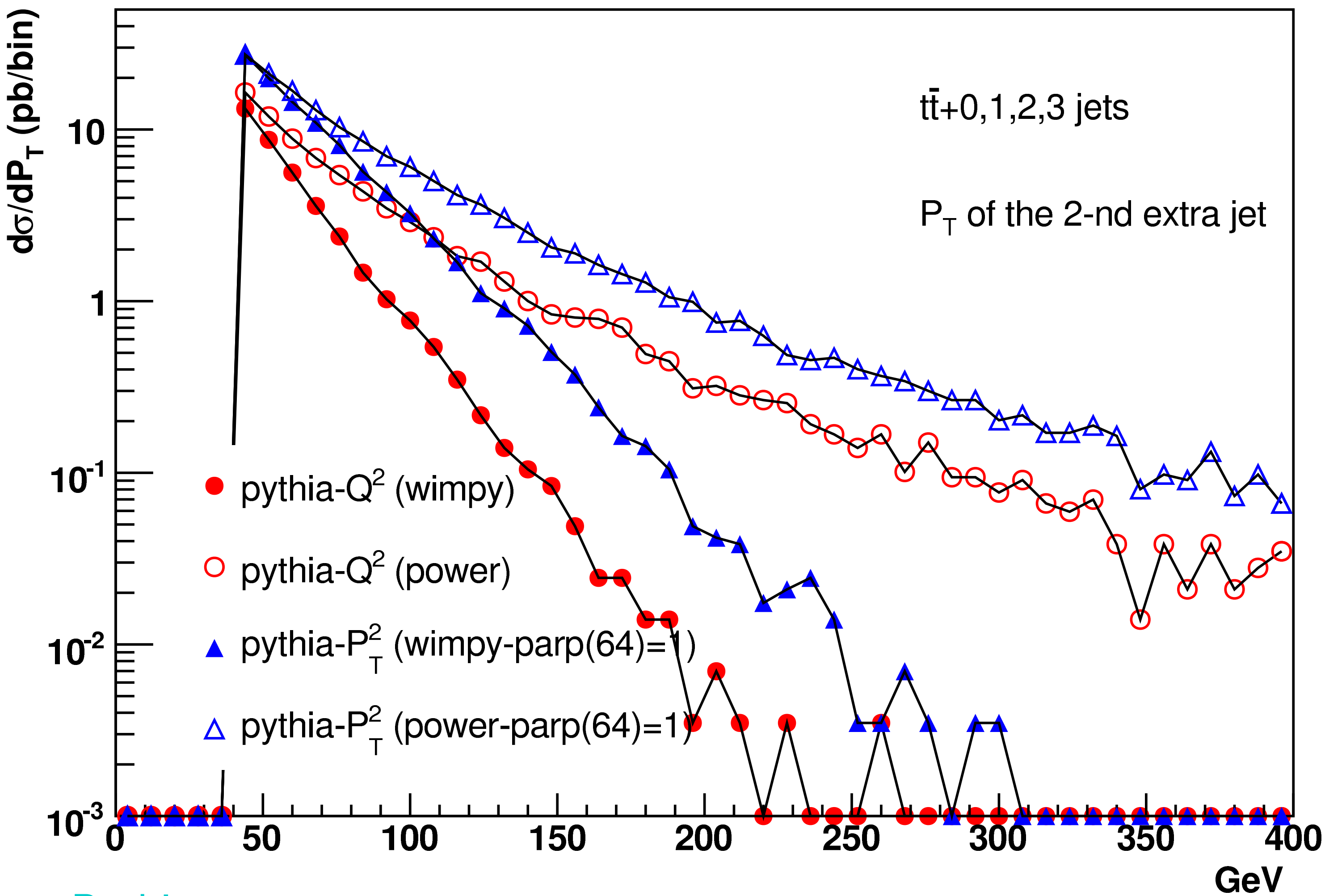
MLM (Mangano)

A cone algorithm is used for clustering

Shower the hard events without vetoeing. Matrix elements are not reweighted

Reconstruct jets after shower. If the number of jet is not equal to the number of original hard partons, throw the event away
(this corresponds to matrix element reweighting and vetoed showers)

Matching at work: before matching

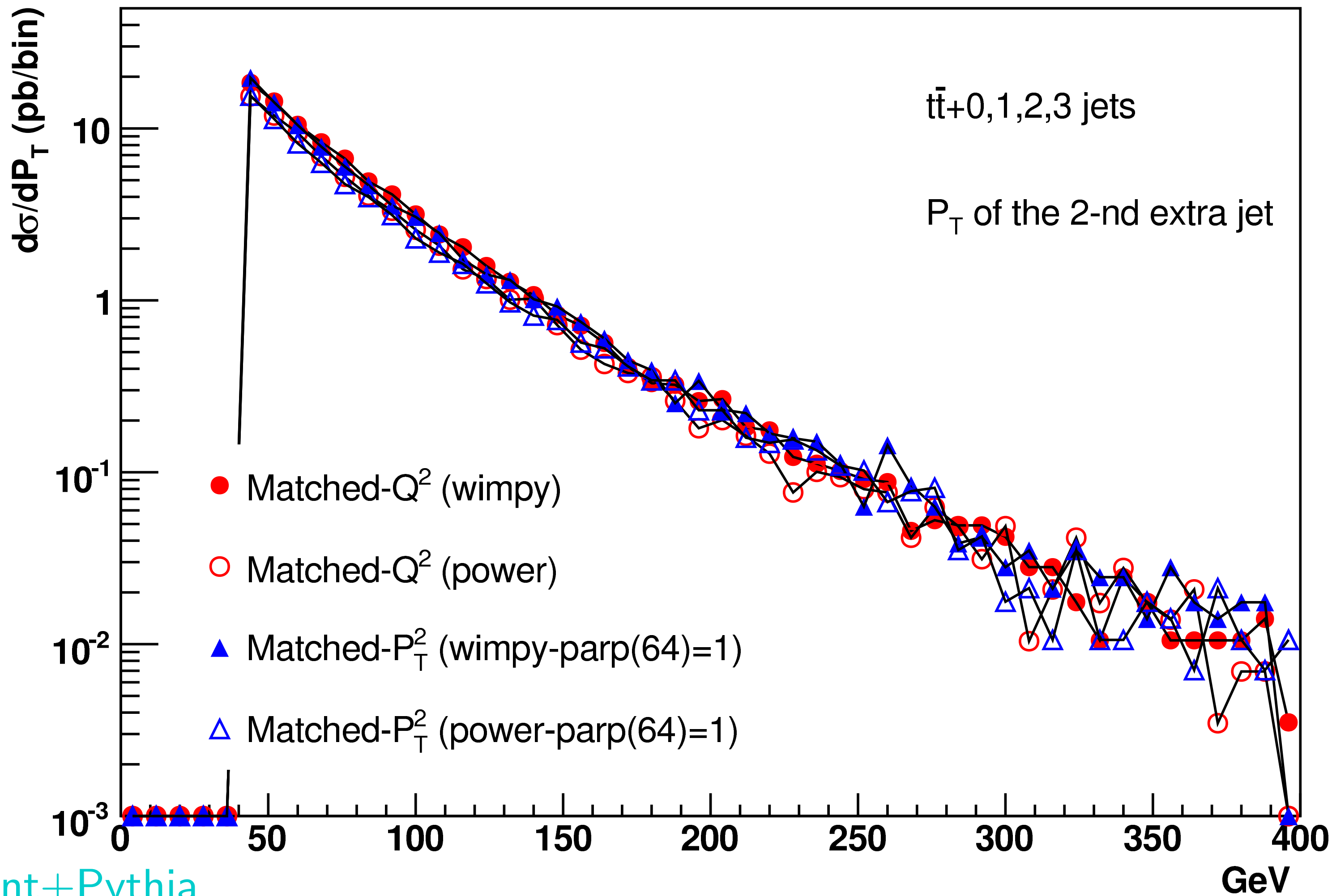


MadEvent+Pythia

OK if you want to fit data, useless to have an idea of how data *will* look like

In other words, good at postdictions, but no predictive power

Matching at work: after matching

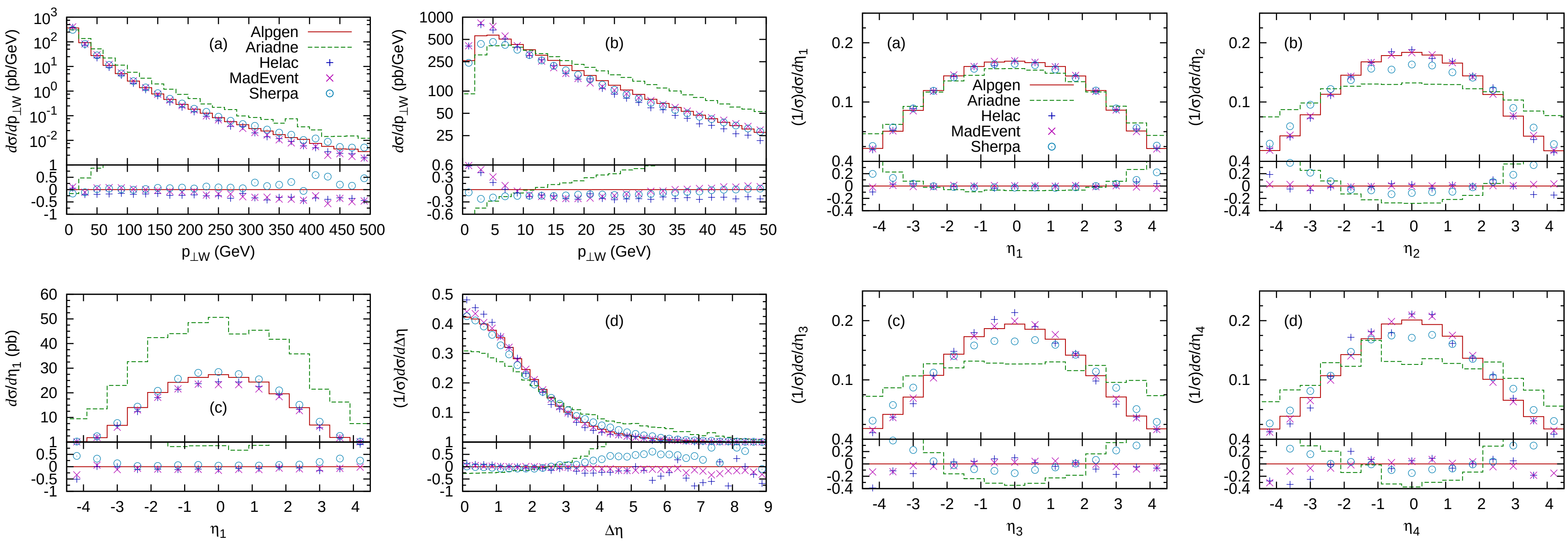


MadEvent+Pythia

A simple reason for this: the physics is right (no collinear approximation used outside the collinear regions)

Is this prediction reliable?

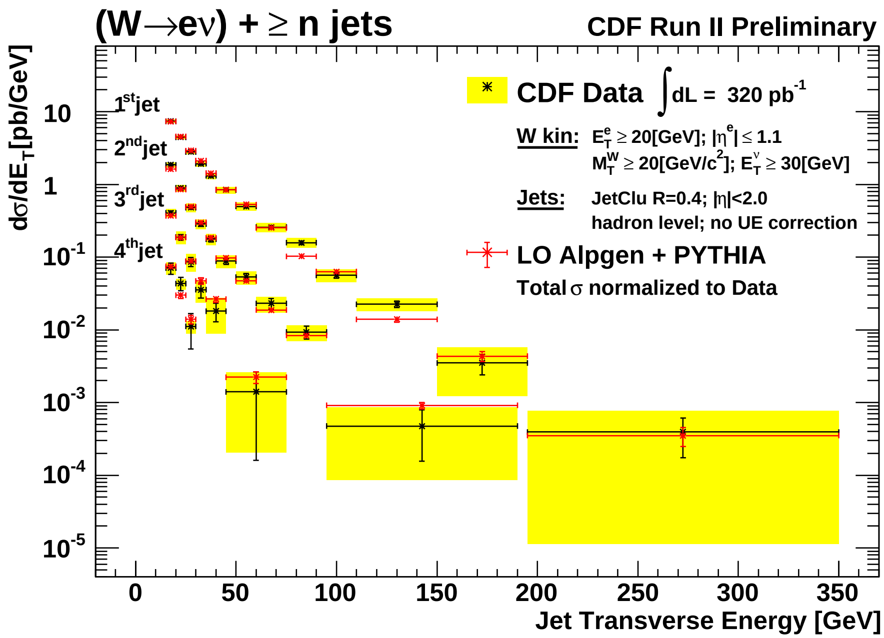
Different matching schemes result in...

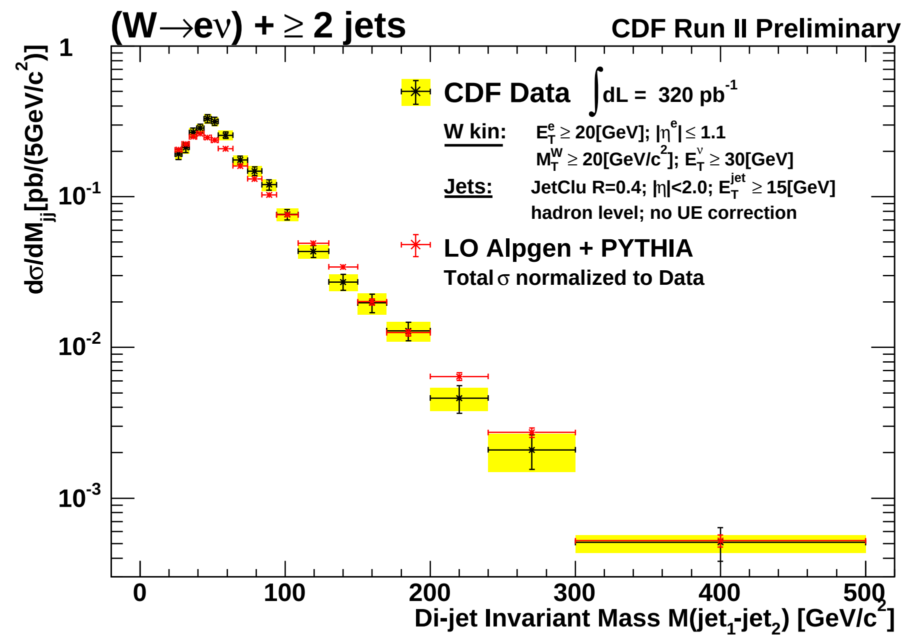


(Alwall *et al.*, 0706.2569)

...reasonably good agreement (10-50%). ARIADNE has the largest differences, but this is more a consequence of lack of proper ISR description than of matching

Comparisons to data





http://www-cdf.fnal.gov/physics/new/qcd/wjets_07/wjets.html

Once the overall normalization is fixed (i.e., one parameter) one obtains a very satisfactory description (which improves that of standard MCs by *orders of magnitude*)

Several other successful comparisons exist (typically, for Z/W+jets) using different codes (SHERPA, MadEvent+MCs,...)

MEC: what to take home

Substantial progress made in the past few years. Main consequence: multi-jet backgrounds not a matter of science fiction any longer

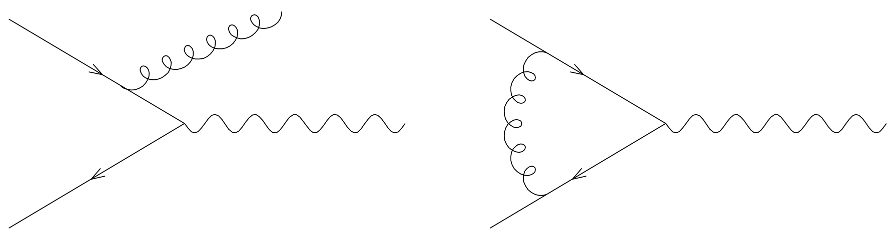
- Never forget to check the merging systematics (*at least* a 20% effect)
- Tuning to data is strongly recommended, and anyhow necessary to figure out the correct normalization: these are LO QCD computation!
- These procedures have been thoroughly tested for $W/Z+$jets. For other processes, or peculiar observables, systematics can be (much?) larger. Compare predictions from different codes

The use of standalone PYTHIA/HERWIG for multi-jet physics cannot be excused any longer. That's the stone age

NLOwPS

Compute all the NLO diagrams (and only those) before starting the shower.

Example: W production



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Problems

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Solution

$\longrightarrow$

Proposals for NLOwPS's

- First working hadronic code (Z): Φ-veto (Dobbs, 2001)
- First correct general solution: MC@NLO (Frixione, Webber, 2002)
- Automated computations of ME's: grcNLO (GRACE group, 2003)
- Absence of negative weights (Nason, 2004; Frixione, Nason, Oleari, 2007) – POWHEG
- Showers with high log accuracy in ϕ_6^3 (Collins, Zu, 2002–2004)
- Proposals for $e^+e^- \to jets$ (Soper, Krämer, Nagy, 2003–2006)
- Within Soft Collinear Effective Theory (Bauer, Schwartz, 2006)
- Shower and matching with QCD antennae (Giele, Kosower, Skands 2007) – VINCIA
- With analytic showers (Bauer, Tackmann, Thaler, 2008) – GenEvA
- Together with MEC in e^+e^- (Lavesson, Lönnblad, 2008)

Some of these ideas have passed the crucial test of implementation. However, only two codes (MC@NLO and POWHEG) can be used to fully simulate a variety of hadronic processes

MC@NLO

- Compute what the MC does at the first non trivial order, and subtract it from the matrix elements. The resulting short-distance cross sections can be unweighted, and the hard events thus obtained are used as initial conditions for parton showers

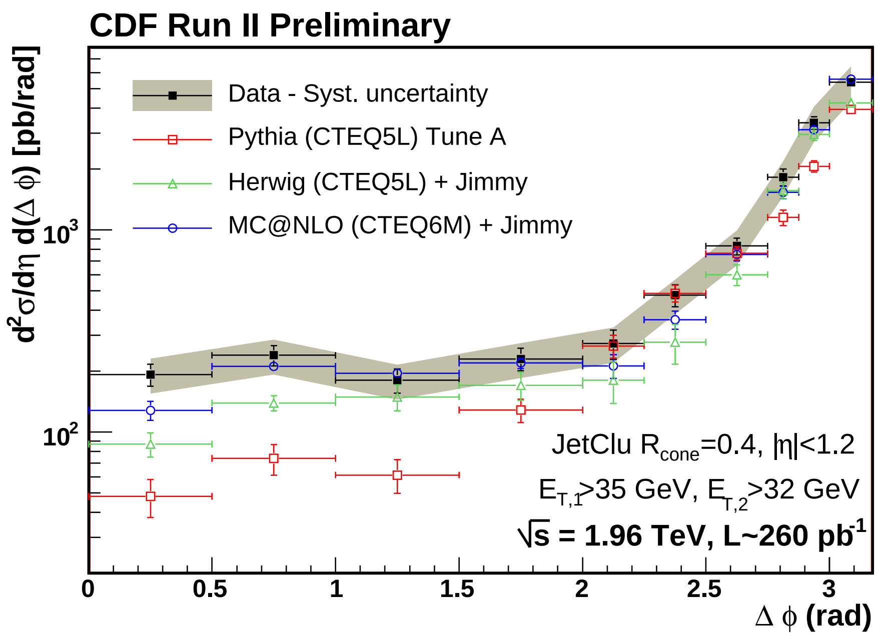
- One set of analytical computations per MC (presently, HW and HW++)
- Negative weights
- Strictly identical to MC in soft/collinear regions
- Strictly identical to NLO in hard emission regions;
  all $\mathcal{O}(\alpha_S^{2+b})$ terms not logarithmically enhanced are zero
- Inclusive cross sections identical to total cross section @NLO

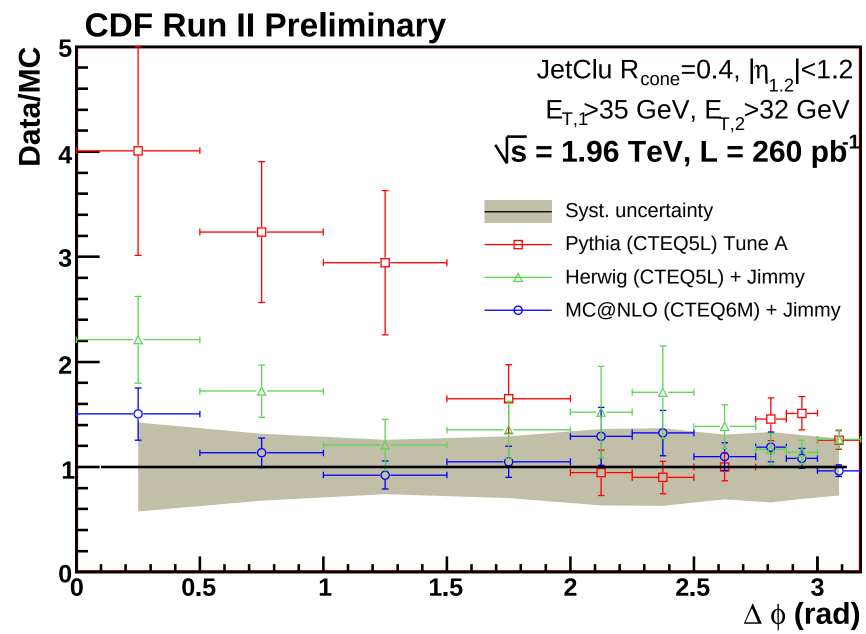
POWHEG

- Replace the first MC emission with one generated with a p_T-ordered Sudakov, constructed by exponentiating the *full real matrix element*. Requires a truncated shower to restore the correct pattern of soft emissions

- Short-distance computations independent of MCs
- No negative weights
- LL (NLL) differences wrt MC in the soft/collinear regions without (with) truncated shower. Likely relevant only to angular-ordered MCs (the other MCs already wrong there). Trunc shower only in HW++ so far
- Differs from NLO in hard emission regions by $\mathcal{O}(\alpha_S^{2+b})$ terms (may be very large as e.g. in Higgs production). Tuning?
- Inclusive cross sections not identical to total cross section @NLO

b-jet CDF data vs MC@NLO



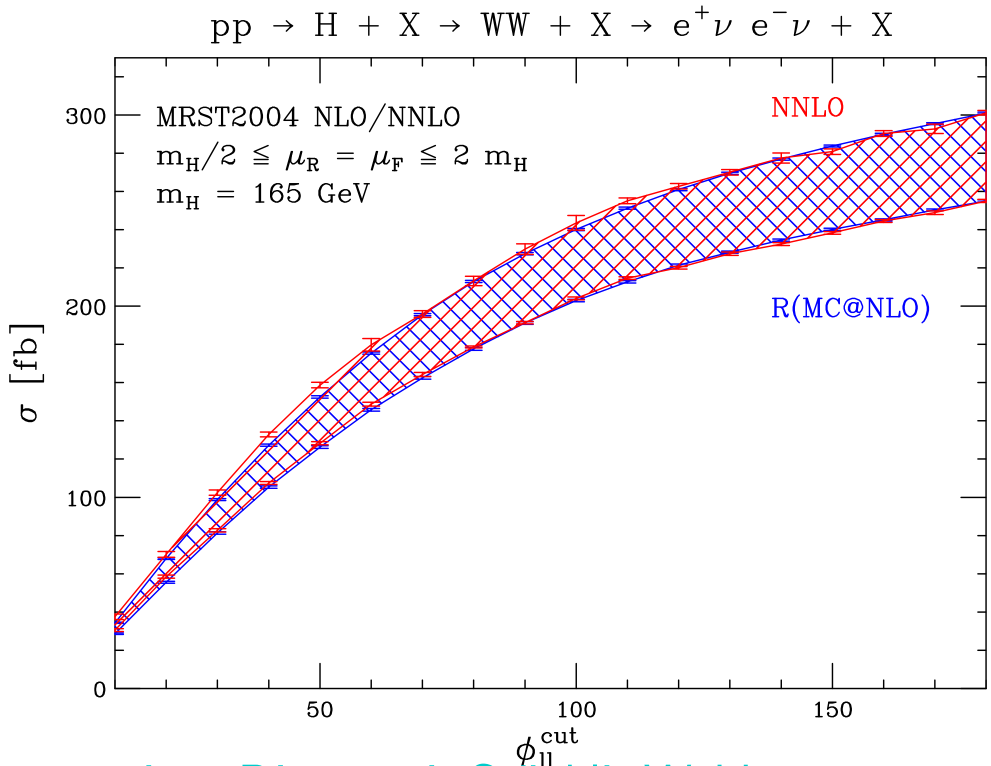


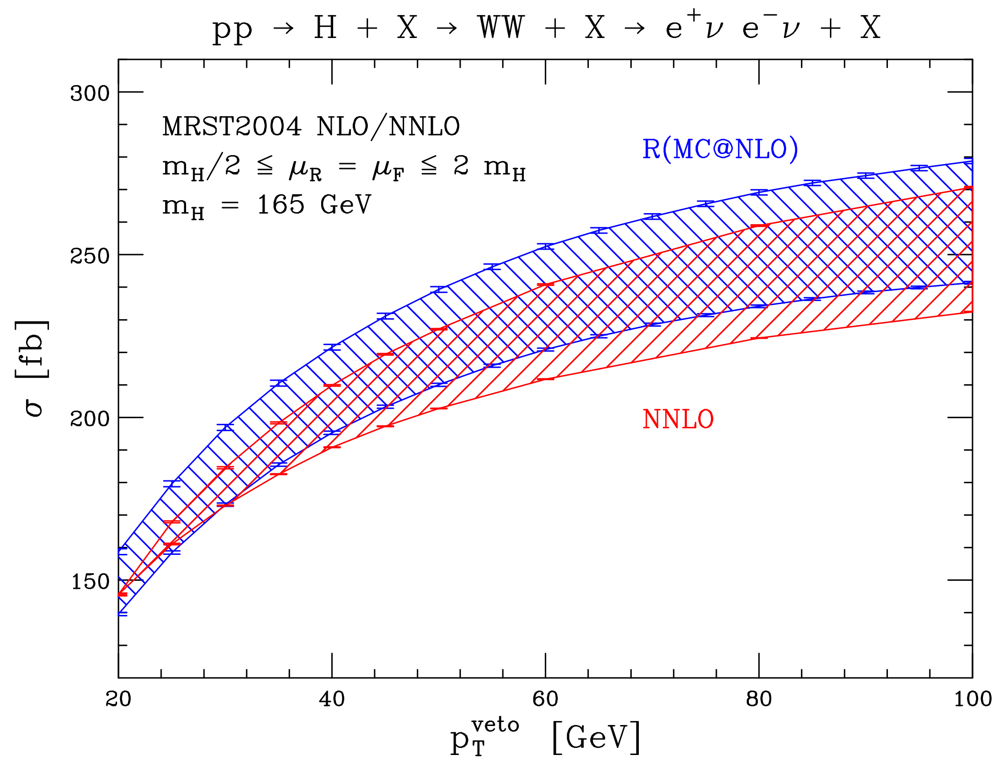
Agreement with data significantly improves when including NLO corrections

Jimmy does significantly better than Herwig default

$\Longrightarrow$ Quite a powerful test of the whole NLO+shower machinery

MC@NLO vs NNLO



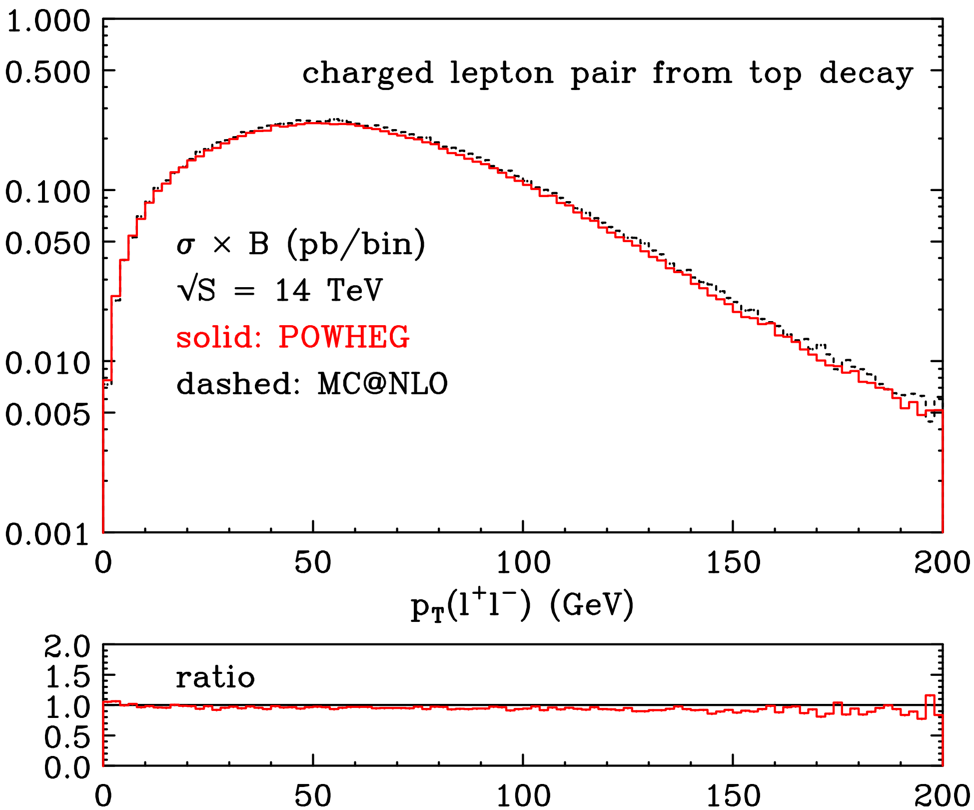


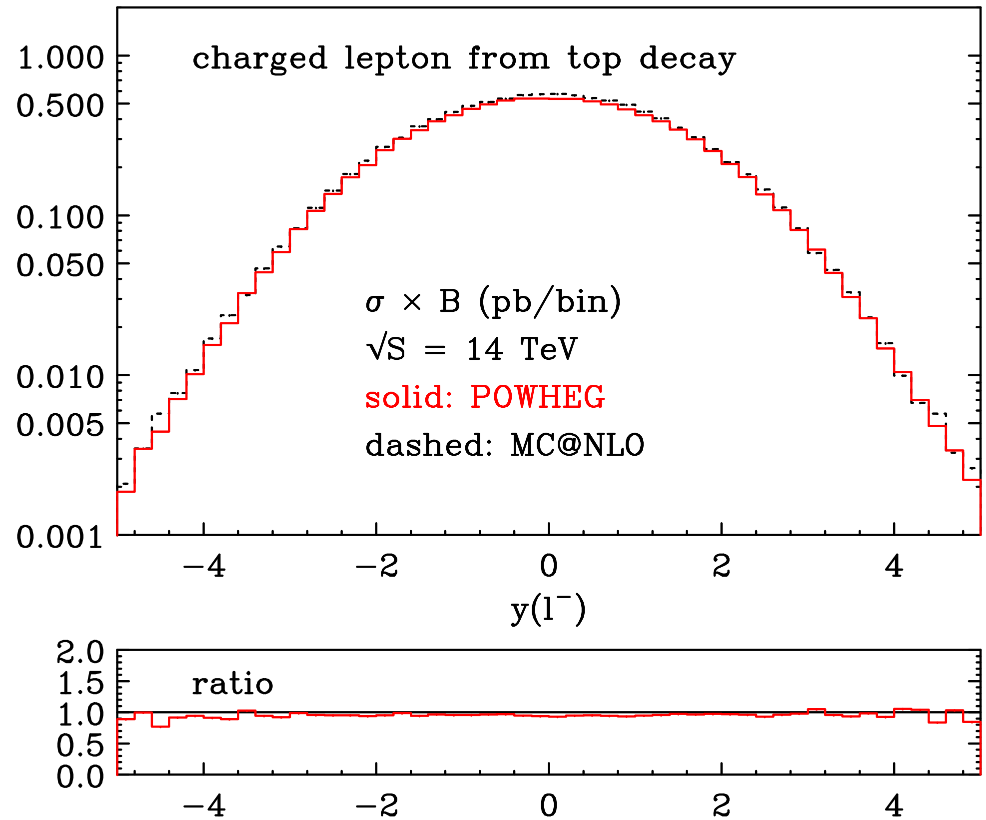
Anastasiou, Dissertori, Stöckli, Webber

After *overall* rescaling NNLO/NLO, most observables are in perfect agreement

Similar findings by M. Grazzini. For certain observables, NNLO must be matched to (analytical) resummation results for full agreement. Very powerful test of MC@NLO

MC@NLO vs POWHEG



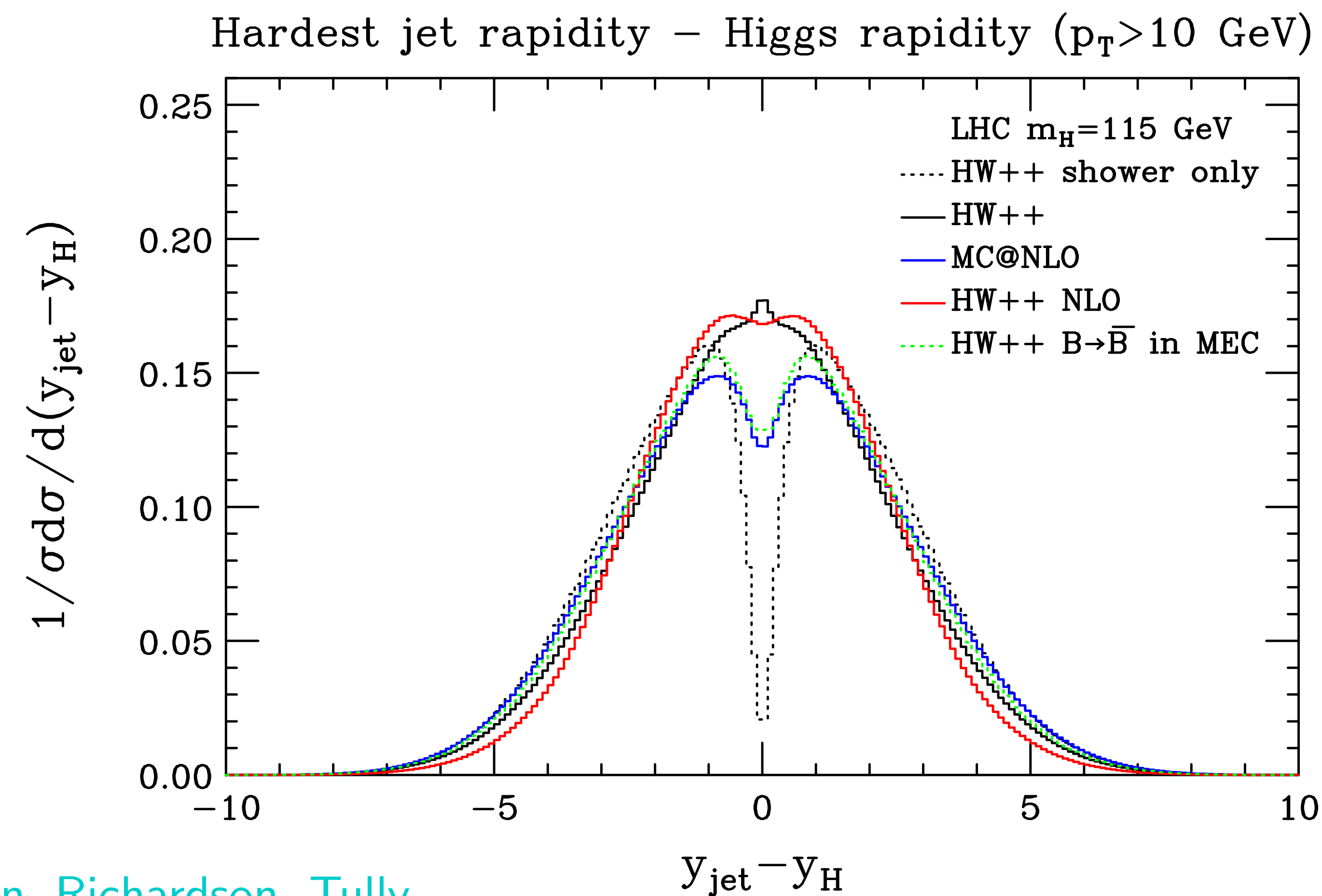


Shown here for lepton observables arising from top decays at the LHC

In the vast majority of cases, extremely good agreement is found

There are a few interesting cases where large differences are found

MC@NLO vs POWHEG: discrepancies



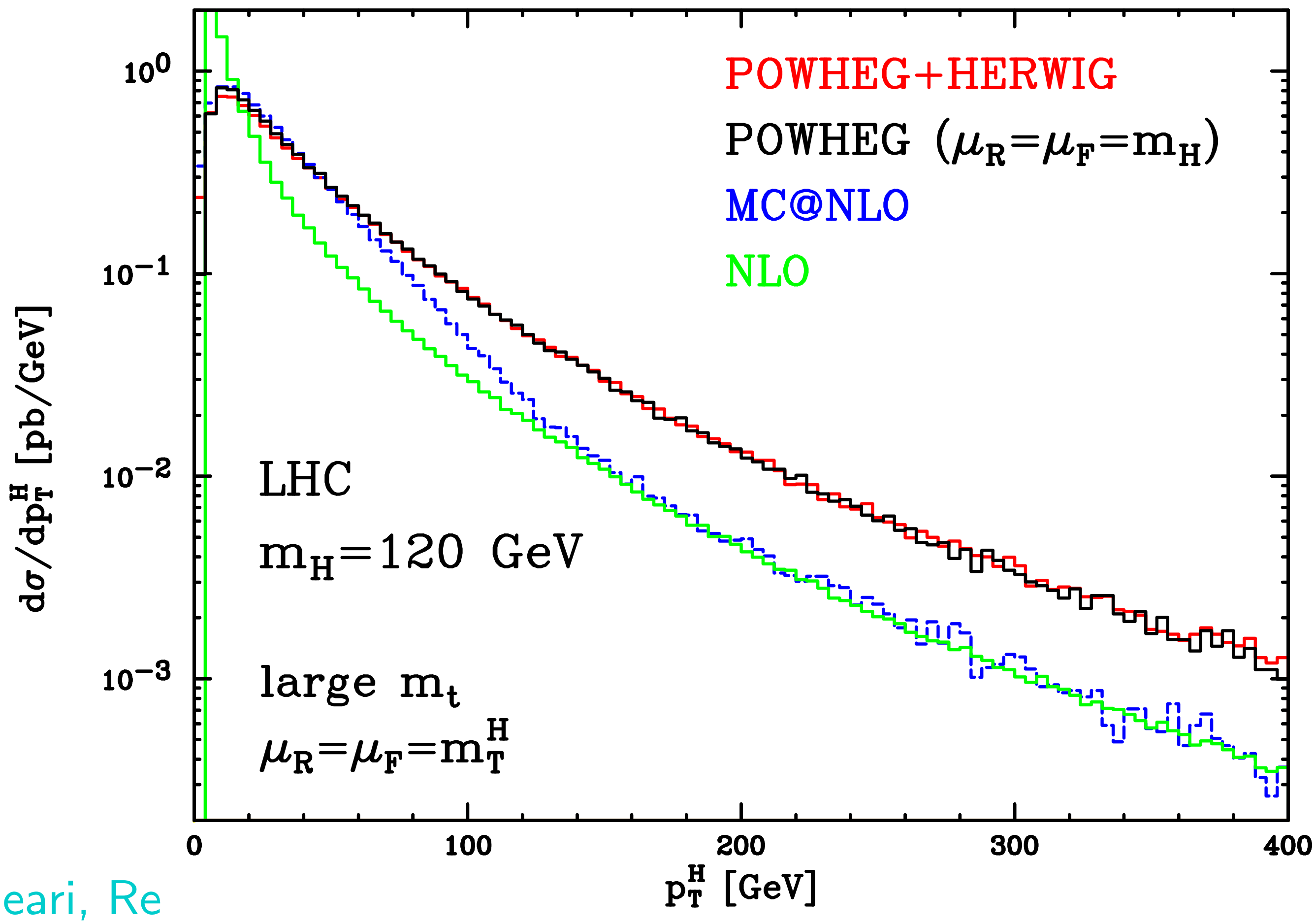
Hamilton, Richardson, Tully

HW/HW++ have dips at $\Delta y = 0$. Likely an artifact of dead zones

MC@NLO fills that dip, via hard radiation

POWHEG fills it much more, owing to extra (spurious) $\mathcal{O}(\alpha_S^4)$ terms

MC@NLO vs POWHEG: discrepancies



Alioli, Nason, Oleari, Re

POWHEG a factor ~ 3 larger than MC@NLO$\equiv$ NLO in the tail (Hamilton *et al* find ~ 2.3)

These are the same terms that fill the dip in Δy

Note: MC@NLO and POWHEG use the *same matrix elements*

Outlook

- New versions of PYTHIA, SHERPA, and HERWIG++ released in 2008/2009
- Non-perturbative models systematically studied and fitted. Substantial theoretical progress in the perturbative part
- NLOwPS and MEC have complementary advantages

Future prospects

- NLOwPS (low mult)+MEC (high mult): soon
- MEC $\longrightarrow$ NLOwPS (high mult): require automated 1-loop computations
- NNLOwPS?