Fulvio Piccinini
INFN Sezione di Pavia

Generatori di eventi Monte Carlo per LHC

Contents

I apologize for forgetting some contributions. . .

IFAE, Torino, 15 April, 2004

Introduction

The last few years have seen a very intense activity in improving existing Monte Carlo tools and developing new ones.

Do we really need new generators for LHC?

After all LHC is an hadronic collider like Tevatron, which obtained very brilliant results already in the 90's, with the simulation software available at that time

Why not using the generators used in Tevatron analysis by simply changing the initial state ($p\bar{p} \to pp$) and $\sqrt{s} \simeq 2$ TeV $\to 14$ TeV?

Jump in luminosity of order 10^3 with respect to Tevatron Run I

Expected event rates at LHC ($\mathcal{L} = 10^{34}$ cm^{-2} s^{-1})

Process	Events/s	Events/year	Other machines (total statistics)
$W \to e\nu$	150	10^9	10^4 LEP / 10^7 Tevatron
$Z \to ee$	15	10^8	10^7 LEP
$t\bar{t}$	8	10^8	10^4 Tevatron
$b\bar{b}$	10^6	10^{13}	10^8 BaBar/Belle
QCD jets $p_t > 200$ GeV	10^3	10^{10}	10^7 Tevatron
QCD jets $p_t > 1$ TeV	0.15	10^6	

- $\Delta M_W \simeq 15$ MeV, $\Delta m_{top} \simeq 1$ GeV
- $\Delta m_H/m_H \simeq 10^{-3}$, determination of Higgs couplings

Uncertainty in theoretical predictions could be a limiting factor for benchmarking analysis strategies, detector simulations, luminosity monitors, tests of the SM, determination of properties of particles

- Large c.m. energy → production of new heavy particles (if any) giving rise to hard multiparton final states. Ex.: gluino pair production → final state with 8 jets plus missing energy
- Multi-jet final states originating from hard QCD radiation are serious backgrounds

$l\nu_l b\bar{b} + N$ jets	$N = 0$	$N = 1$	$N = 2$	$N = 3$	$N = 4$
LHC (pb)	2.222(4)	3.013(9)	1.83(1)	0.831(8)	0.307(5)
FNAL (fb)	332.2(7)	86.2(4)	18.3(2)	3.17(3)	0.44(3)

$Q\overline{Q}Q'\overline{Q}' + N$ jets	$N = 0$	$N = 1$	$N = 2$	$N = 3$	$N = 4$
$t\bar{t}t\bar{t}$, LHC (fb)	12.73(8)	17.4(2)	13.5(1)	7.55(6)	3.48(5)
$t\bar{t}b\bar{b}$, LHC (pb)	1.35(1)	1.47(2)	0.94(2)	0.457(8)	0.189(4)
$t\bar{t}b\bar{b}$, FNAL (fb)	3.44(3)	0.95(1)	0.154(1)	0.0187(2)	0.00187(5)
$b\bar{b}b\bar{b}$, LHC (pb)	477(2)	259(5)	95(1)	28.6(6)	25.0(3)
$b\bar{b}b\bar{b}$, FNAL (pb)	6.64(5)	2.25(3)	0.470(5)	0.076(1)	0.0025(5)

by `ALPGEN`: M.L. Mangano, M. Moretti, F. P., R. Pittau and A.D. Polosa, JHEP 0307 (2003) 001

In a hadronic environment like the LHC, QCD is the underlying theory for every physics aspect. Higher-order corrections are by far dominated by QCD radiation. However, for some precision observables also EW corrections sooner or later become important

see talks by C. Carloni Calame and E. Maina

- in Drell Yan, the precise W-mass determination with the foreseen accuracy requires the inclusion of $\mathcal{O}(\alpha)$ EW and higher-order photonic corrections. We have already now programs dealing with these problems
  - e.w. $\mathcal{O}(\alpha)$: `WGRAD`, `ZGRAD2` (U. Baur, S. Keller and D. Wackeroth)
  - h. o. QED: `HORACE` (C. Carloni Calame et al.), `WINHAC` (W. Placzek and S. Jadach)
- in the high mass tails of e.w. resonances electroweak or in events with $\mathcal{O}(\text{TeV})$ c.m. energies Sudakov enhanced double logarithmic corrections become relevant

see talk by P. Ciafaloni

- There are NNLO QCD calculations, but $\mathcal{O}(\alpha)$ corrections could become competitive $\alpha_s^2 \simeq \alpha_{e.m.}$

In the following I will concentrate on QCD Monte Carlos

Three main classes of MC programs

- MC integrators
- Parton Shower MC event generators
- Multi-parton MC event generators

Each of these classes has pros and cons

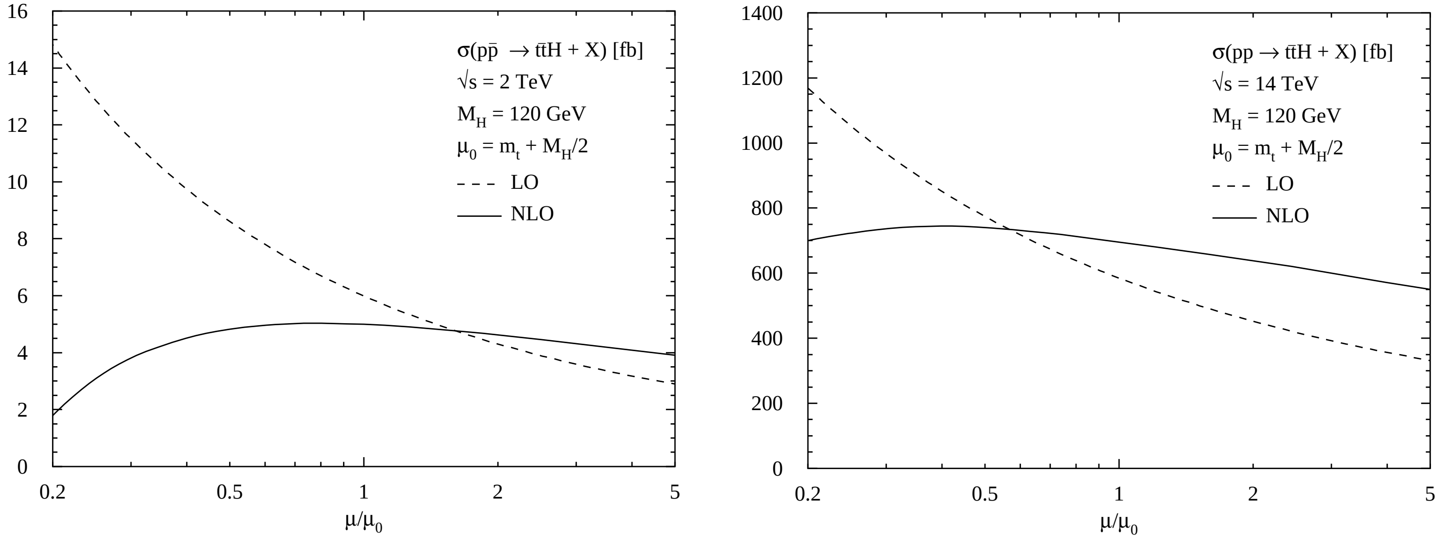
Can we combine good features from different classes?

Monte Carlo integrators

- Only partonic final states, with arbitrary event selection
- Events with flat distribution on phase space and weighted by the matrix element. Events used to fill histograms for distributions
- Typically they are used to obtain accurate predictions in fixed order perturbation theory beyond Leading Order
- At present some NLO programs are available for a limited set of "simple" (but important) final states (difficulty in calculating virtual corrections)
- NLO calculations work well in describing hard radiation but fail in the region of soft/collinear singularities
- The accuracy can be increased in certain regions of phase space implementing resummed calculations (valid generally for one observable at a time)

$$\sigma = \sum_{a,b} \int dx_1\, dx_2 \int d\Phi\, f_{a/h_1}(x_1, \mu_F^2)\, f_{a/h_2}(x_2, \mu_F^2)\, \frac{d\hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)}{d\Phi}$$

- The NLO corrections give an handle to test the theoretical uncertainty of the calculation by studying the stability with respect to variations of the renormalisation and factorisation scales



W. Beenakker et al., *Phys. Rev. Lett 87 (2001) 201805*

- NLO programs can test the K-factors at the distribution level. Generally they are defined in an inclusive way as σ_{NLO}/σ_{LO} but different bins can receive different corrections

- NLO corrections consist of Real $\oplus$ Virtual contributions, which display strong cancellations. The Virtual part can become negative in the phase space $\Rightarrow$ difficulty in producing unweighted events

Available processes in NLO QCD MC integrators

- N jets $\quad N \leq 3$
- $VV' \quad V, V' = W, Z$
- Vj
- $\gamma + 1$ jet
- $\gamma\gamma$
- $V + N$ jets $\quad N \leq 2$
- $V + b\bar{b}$
- QCD production of $H + 2$ jets
- heavy flavour production

Other NLO calculations without a publicly released code

- Single top production ($qb \to bq'$ & $q\bar{q}' \to t\bar{b}$)
- $Q\bar{Q}H$

Some available NLO programs

- **`NLOJET++`** by Z. Nagy
- **`AYLEN/EMILIA`** by L. Dixon, Z. Kunszt, A. Signer and D. de Florian
- **`DIPHOX`** by P. Aurenche et al.
- **`MCFM`** by J. Campbell and R.K. Ellis

Multileg NLO calculations require new techniques. At present intensive work on seminumerical methods for virtual corrections

e.g. Passarino et al., Nagy and Soper, Giele and Glover

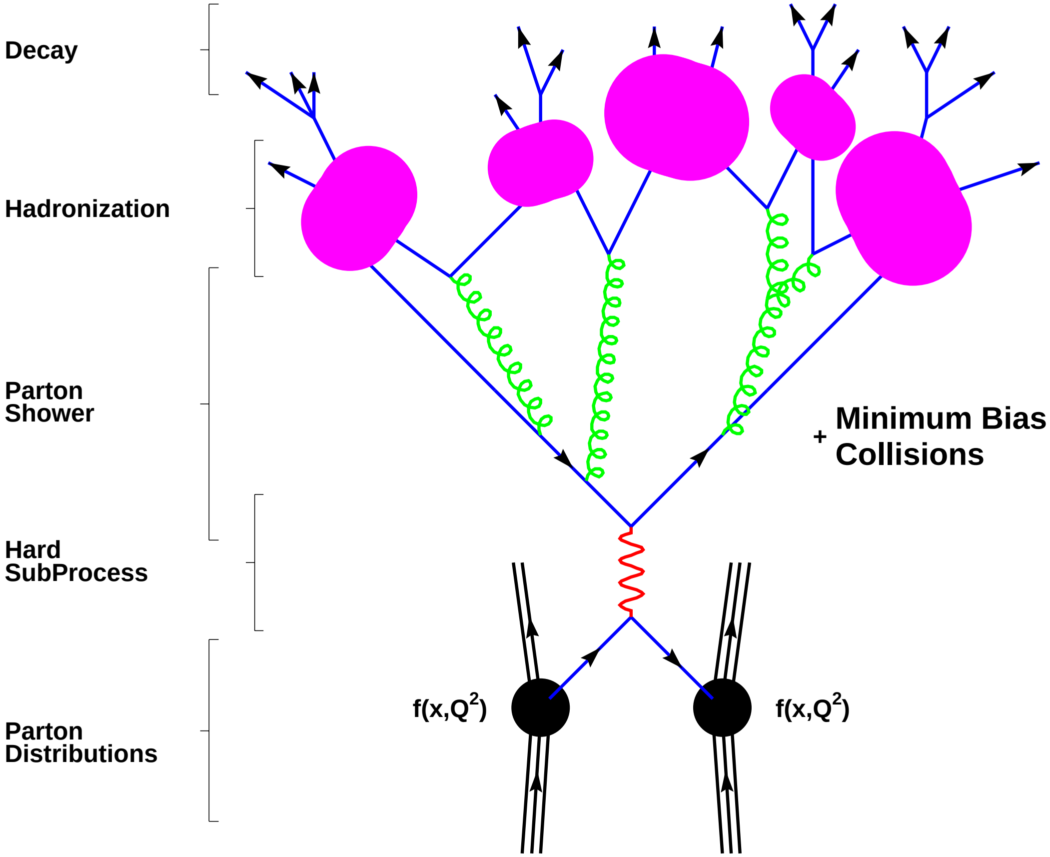
NNLO calculations

- Calculations available for DY ($q\bar{q} \to V$) and Higgs production ($gg \to H$)
- Progress in calculation of new topologies arising at NNLO and in isolating the universal structure of two-loop amplitudes for the infrared singularities subtraction
- No general recipe for NNLO fixed order MC available yet

see talk by C. Oleari

Parton Shower MC event generators

- General-purpose tools
- They describe the complete history of the hadron-hadron interaction, from ISR, hard scattering, showering, hadronization, to final state hadrons and leptons, including the underlying event (beam remnants, collisions between other partons in the hadrons and collisions between other hadrons in the colliding beams)
- Essentially only the hard subprocess is process dependent
- They provide an **exclusive** description of the events: complete information related to every particle is recorded
- Unweighted events are produced $\Rightarrow$ events are distributed in phase space as in the real experiment (provided the underlying theory is correct)
- PSMC's are invaluable tools for detector simulations
- For these reasons they are so widespreadly used by experimentalists
- Key theoretical ingredient: parton shower technique to generate higher order corrections starting from a simple ($2 \to 1$ or $2 \to 2$) hard scattering



from M. Dobbs and J.B. Hansen, Comput. Phys. Commun. **134**, (2001) 41

The parton-shower technique is a numeric Monte Carlo solution of the DGLAP evolution equations, which allows the calculation of QCD (and also QED) higher order radiative corrections in the region of collinear parton branching and/or soft gluon emission. Leading logarithms automatically resummed

The subsequent parton emission is a stochastic Markov process in which successive values of the evolution variable Q, the momentum fraction z and the azimuthal angle ϕ are generated (allowing for kinematics reconstruction)

Starting from the scale Q^2 of the hard process, the next value Q'^2 is selected by solving the equation

$$\Delta_i(Q^2, Q_0^2) = \xi \Delta_i(Q'^2, Q_0^2)$$

$$\Delta_i(Q^2, Q_0^2) = \exp\left[-\sum_j \int_{Q_0^2}^{Q^2} \frac{dQ'^2}{Q'^2} \int_0^1 dz\, \alpha_s \frac{P_{ji}(z)}{2\pi} \right]$$

Δ_i is the probability of no emission between the scales Q^2 and Q_0^2
$P_{ji}(z)$ is the splitting function for the parton branching $i \to j$
Q_0^2 is an infrared cutoff
z is extracted randomly according to $P(z)$

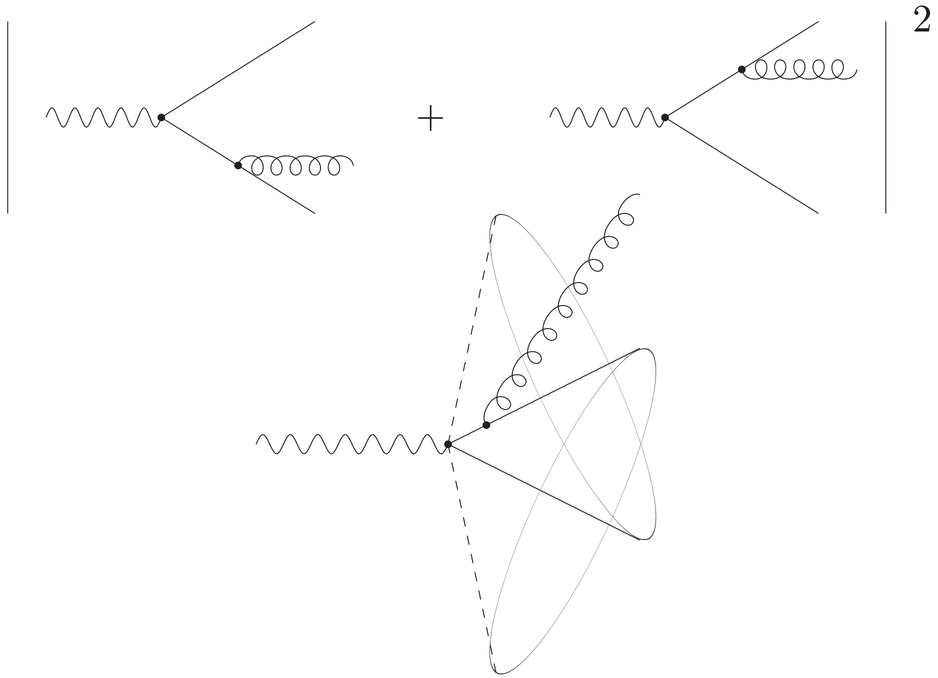
In case of branching repeat the procedure with $Q \to Q'$ and momentum fraction rescaled by z

Available PSMC Event Generators

- `HERWIG`, `PYTHIA`, `ISAJET`
- `SHERPA`, very recent (T. Gleisberg et al.)
- `HERWIG++`, `PYTHIA7`, for the future

They implement many hard processes (within and beyond SM), a realization of parton shower and a model of hadronization

Quantum coherence ⇒ angular ordering property

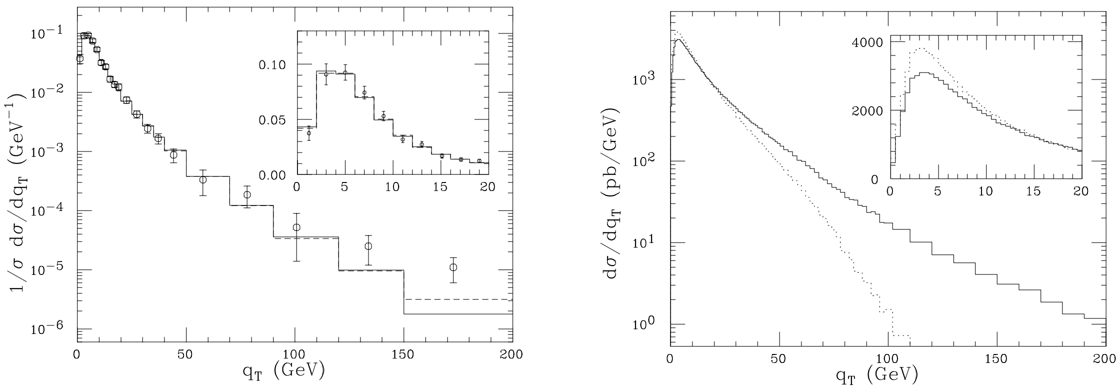


While PSMC event generators describe well radiation in the soft/collinear regions (resumming large logs), they fail to describe hard wide angle radiation and cross sections are correct at LO

First improvement: Matrix element corrections

HERWIG and **PYTHIA** have been corrected by means of the exact $\mathcal{O}(\alpha_s)$ real matrix element by filling the dead-zones of phase space (due to angular ordering) and by reweighting the PS weight of the hardest emission using the matrix element correction

Corrected processes: top quark decay, DY, $gg \to H$



$W\ q_T$ distribution compared with D0 data and calculated for LHC

G. Corcella, M.H. Seymour, Nucl. Phys. B565 (2000) 227

Normalization still at LO: virtual corrections are missing

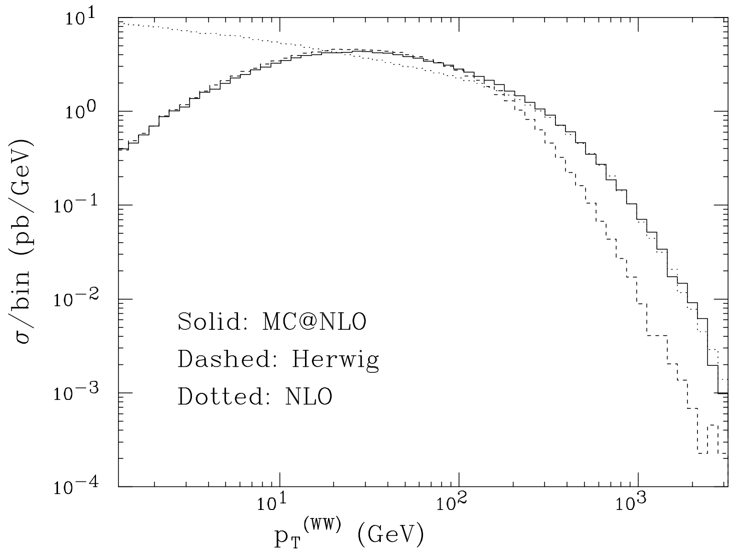
Combining NLO calculations with PS's

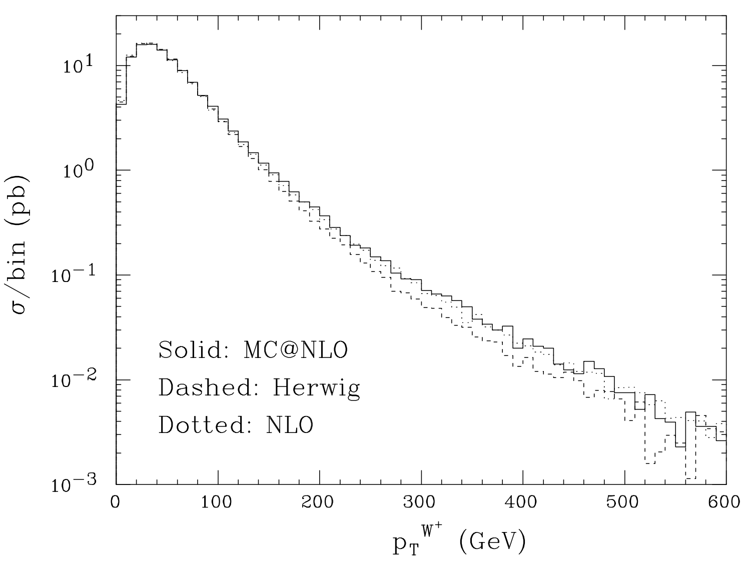
This would allow to have

- Normalizations accurate at NLO
- Hard tails of distributions as in NLO calculations
- Soft/Collinear emissions treated as with PS
- Smooth matching between soft/collinear and hard regions without double counting
- Generate unweighted exclusive events
- Negative weight events could be generated

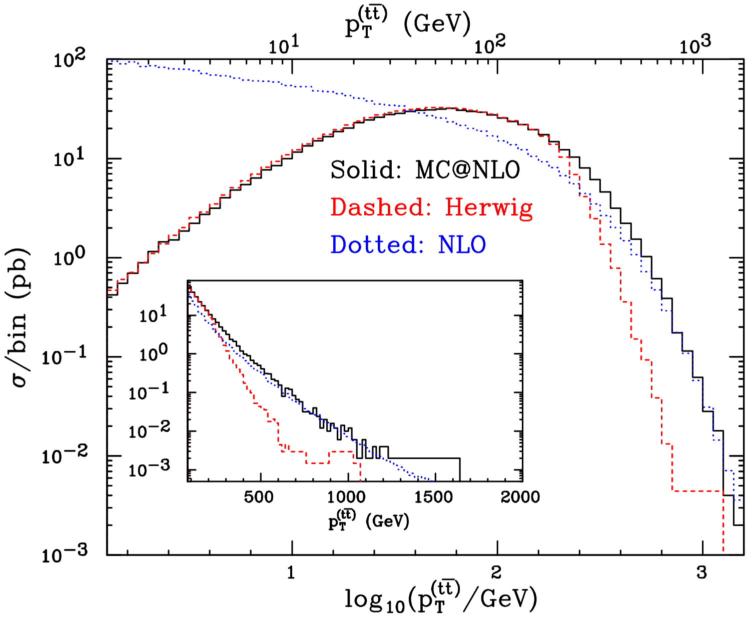
Methods and programs available up to now

- `MC@NLO` (Frixione, Webber and Nason)
  Based on NLO subtraction method. It is interfaced to **`HERWIG`** but the method is general. About 15% of the generated events have negative weight. Available final states:
  - W^+W^-, $W^\pm Z$, ZZ
  - $b\bar{b}$, $t\bar{t}$
  - H
  - $W^\pm$, Z, γ^*, $l_i\bar{l}_j$
- `grcNLO` (Y. Kurihara et al) program not yet public.
  Based on hybrid NLO slicing and subtraction method. Double counting avoided provided tuning of the MC, negative weights present
- `Phase Space Veto` (M. Dobbs) program not yet public.
  Based on NLO slicing method. No negative weight events but some double counting. Up to now the method has been applied to W and Z production





S. Frixione and B.R. Webber, hep-ph/0212216



S. Frixione, P. Nason, B.R. Webber, hep-ph/0305252

Multiparton MC Event Generators

The previous strategy of matching PSMC's with NLO calculations is not feasible now for arbitrary multiparton processes. We don't have NLO calculations for arbitrary external legs. But we do have techniques for computing exact LO matrix elements for multiparton hard scattering

Recenlty several matrix element event generators have been built up, thanks to helicity amplitudes algorithms or completely numerical algorithms (and of course computing power)

- `ACERMC`, `ALPGEN`, `CompHEP`, `GRACE`, `HELAC/PHEGAS/JETI`, `MADEVENT`, `SHERPA`, `VECBOS`, `NJETS`, . . .
- Matrix elements involving a very large number of Feynman diagrams
- Complex peaking structure in the phase space
- They can generate weighted (for cross sections and distributions) and unweighted events
- The strategy to describe real final states with hadrons is to pass the unweighted event samples (in LHA format) to the PSMC for further showering and hadronization ⇒ problems . . .

Up to now available processes (in `ALPGEN`)

- $(W \to f\bar{f}') + N$ jets, $N \leq 6$, $f = l, q$
- $(Z/\gamma^* \to f\bar{f}) + N$ jets, $N \leq 6$, $f = l, \nu$
- $(W \to f\bar{f}')Q\bar{Q} + N$ jets, $(Q = b, t)$, $N \leq 4$, $f = l, q$
- $(Z/\gamma^* \to f\bar{f})Q\bar{Q} + N$ jets, $(Q = b, t)$, $N \leq 4$, $f = l, \nu$
- $(W \to f\bar{f}') + c + N$ jets, $N \leq 5$, $f = l, q$
- $n\ W + m\ Z + l\ H + N$ jets, $n + m + l \leq 8$, $N \leq 3$
- $Q\bar{Q} + N$ jets, $(Q = b, t)$, $N \leq 6$
- $Q\bar{Q}Q'\bar{Q}' + N$ jets, $(Q, Q' = b, t)$, $N \leq 4$
- $Q\bar{Q}H + N$ jets, $(Q = b, t)$, $N \leq 4$
- N jets, $N \leq 6$
- $N\ \gamma + N$ jets, $N \geq 1$, $N + M \leq 8$, $M \leq 6$
- $gg \to H + N$ jets $(m_t \to \infty)$
- single top

Tuned comparisons during the 2003 CERN MC4LHC Workshop. Examples:

X-sects (pb)	Number of jets						
$e^- \bar{\nu}_e + n$ QCD jets	0	1	2	3	4	5	6
`ALPGEN`	3904(6)	1013(2)	364(2)	136(1)	53.6(6)	21.6(2)	8.7(1)
`SHERPA`	3905(4)	1014(3)	370(2)				
`CompHEP`	3947.4(3)	1022.4(5)	364.4(4)				
`GR@PPA`	3906.37 (4)	1046.85 (5)					
`JetI`	3786(81)	1021(8)	361(4)	157(1)	46(1)		
`MadEvent`	3902(5)	1012(2)	361(1)	135.5(3)	53.6(2)		

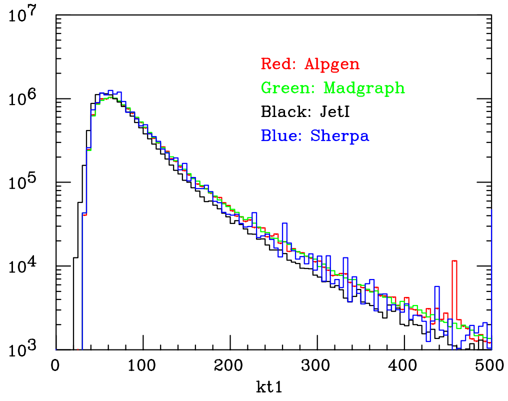
X-sects (pb)	Number of jets						
$t\bar{t} + n$ QCD jets	0	1	2	3	4	5	6
`ALPGEN`	755.4(8)	748(2)	518(2)	310.9(8)	170.9(5)	87.6(3)	45.0(5)
`SHERPA`	754.2(7)	747(2)					
`CompHEP`	757.8(8)	752(1)	519(1)				
`JetI`	745(5)	711(7)	515(5)	24.2(5)			
`MadEvent`	754(2)	749(2)	516(1)	306(1)			

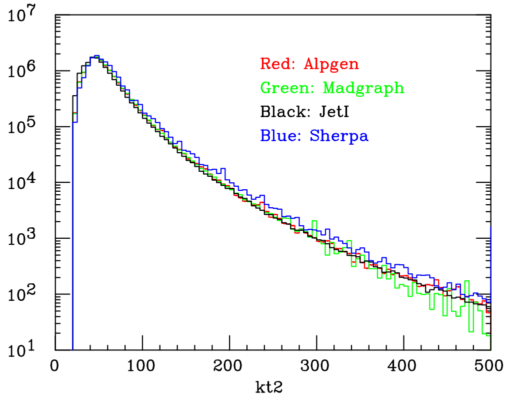
More results available on `http://agenda.cern.ch/fullAgenda.php?ida=a031457`

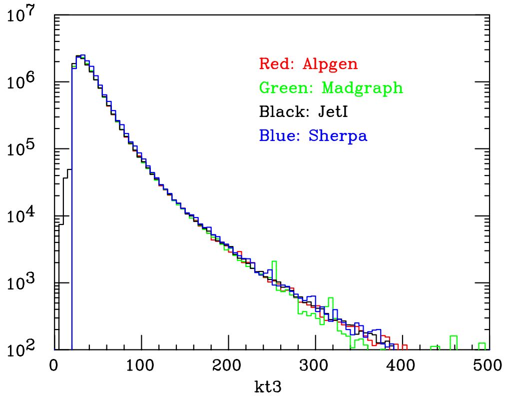
Comparison of color flows in different codes by analysing the $k_\perp$ distributions. For each pair of color-connected partons

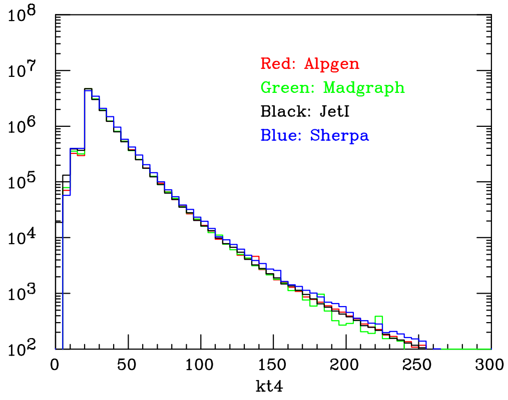
$$\begin{aligned} k_{ij}^2 &= p_{T,i}^2 \text{ if } i \text{ final state and } j \text{ incoming parton} \\ k_{ij}^2 &= \min(p_{T,i}^2, p_{T,j}^2)\Delta R_{ij} \text{ if } i,j \text{ outgoing} \end{aligned}$$

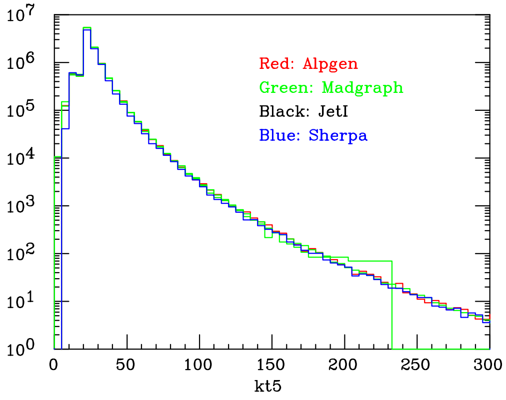
For $gg \to ggg$ 5 possible pairings











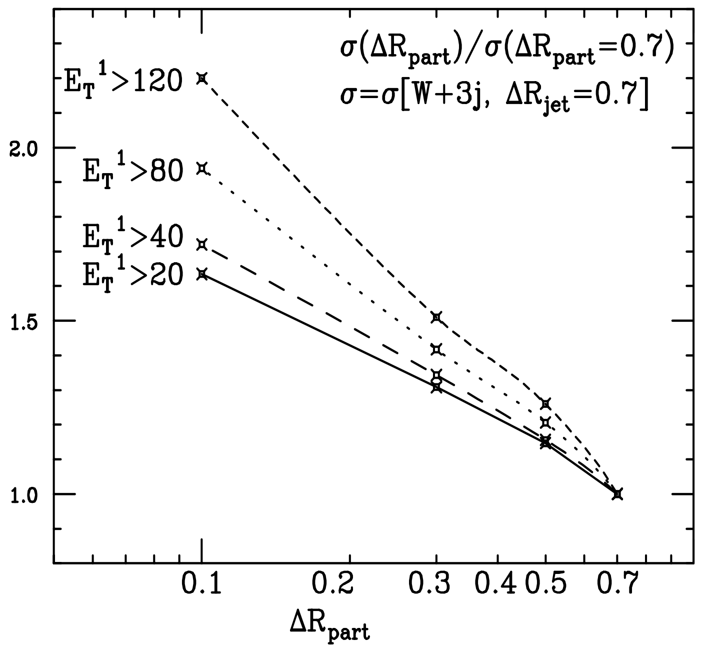
From partons to jets

To obtain realistic results the generated partonic events need to be given as initial condition to the PSMC. However, two problems arise

- Double counting: configurations with n final state partons can be obtained starting from $(n-m)$ partonic configurations, with m partons provided by the PSMC. The same n-jet configuration can be generated starting with different $(n-m)$ configurations

- Results depend on the unphysical partonic set of cuts, while they should not

Example: $W + 3$ jets at Tevatron



Two different sources for the increasing ratio when decreasing ΔR_{part}:

- collinear divergence of the matrix element
- increasing double counting for smaller ΔR_{part}

Towards matching of ME & PS

For e^+e^- physics a solution has been proposed

S. Catani et al., JHEP 0111 (2001) 063

L. Lönnblad, JHEP 0205 (2002) 046

which avoids double counting and shifts the dependence on the resolution parameter beyon NLL accuracy

The method consists in separating arbitrarily the phase-space regions covered by ME and PS, and use vetoed parton showers together with reweighted tree-level matrix elements for all parton multiplicities

Proposal to extend the procedure to hadronic collisions but the proof is still missing

F. Krauss, JHEP 0208 (2002) 015

Necessary steps for CKKW procedure

- select the jet multiplicity n according to the jet rates obtained with matrix elements with resolution $y_{ij} > y_{cut}$, defined according to the k_T-algorithm
- generate n parton momenta according to the matrix element with fixed $\alpha_s(y_{cut})$ and reweight the event with the probability of no further branching by means of Sudakov form factors
- build a “PS history” by clustering the partons to determine the values at which 1,2,...n jets are resolved. In so doing a tree of branchings is constructed and the nodal scales characteristic of each branching are used to reweight the event with running α_s
- apply a coupling constant reweighting factor $\alpha_s(y_1)\ \alpha_s(y_2)\ \ldots\ \alpha_s(y_n)\ /\ \alpha_s(y_{cut})^n \leq 1$, where y_i are the nodal scales
- after successful unweighting, use the n-parton kinematics as initial condition for the shower, vetoing all branchings such that $y_{ij} > y_{cut}$

The CKKW procedure has been successfully tested on LEP data

e.g. S. Catani et al., JHEP 0111 (2001) 063

R. Kuhn et al., hep-ph/0012025

F. Krauss, R. Kuhn and G. Soff, J. Phys. G26 (2000) L11

Preliminary work for hadronic collisions

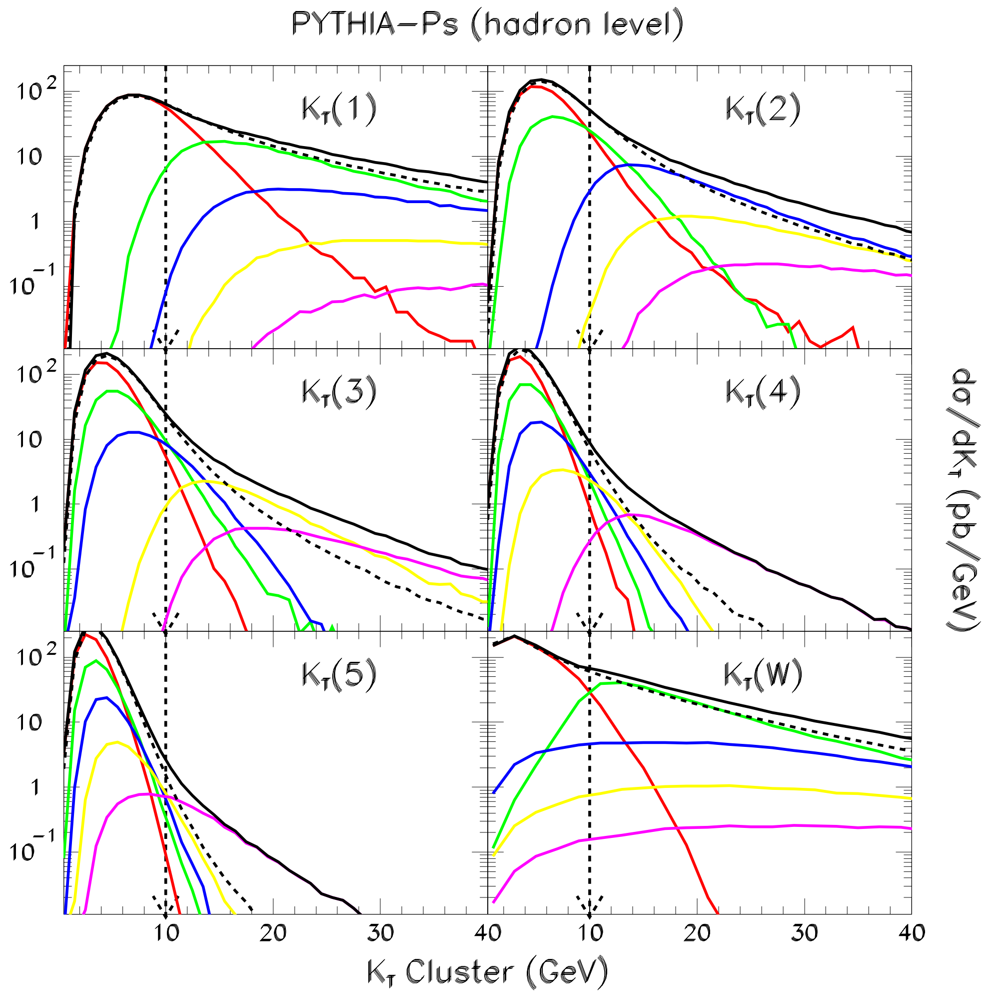
- `HERWIG` (P. Richardson), `PYTHIA` (S. Mrenna)

hep-ph/0312274

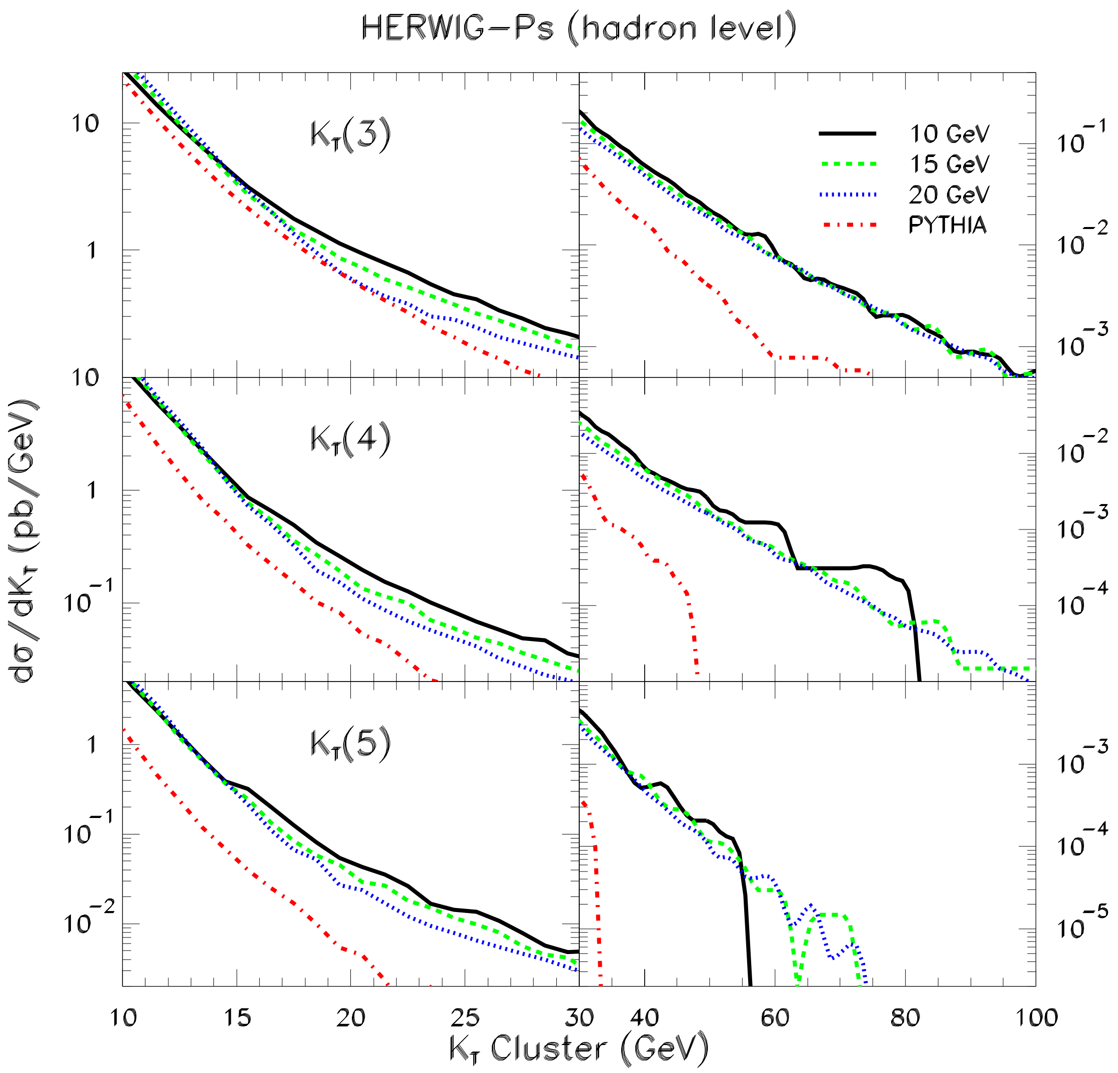
- `SHERPA with APACIC++/AMEGIC++` (F. Krauss and A. Schälicke)
- `ALPGEN`, simpler proposal by M.L. Mangano (see later)

Several parameters need to be tuned to the data in order to have smooth interpolation between ther regions below and above the resolution. Missing virtual corrections ⇒ still a residual cutoff dependence

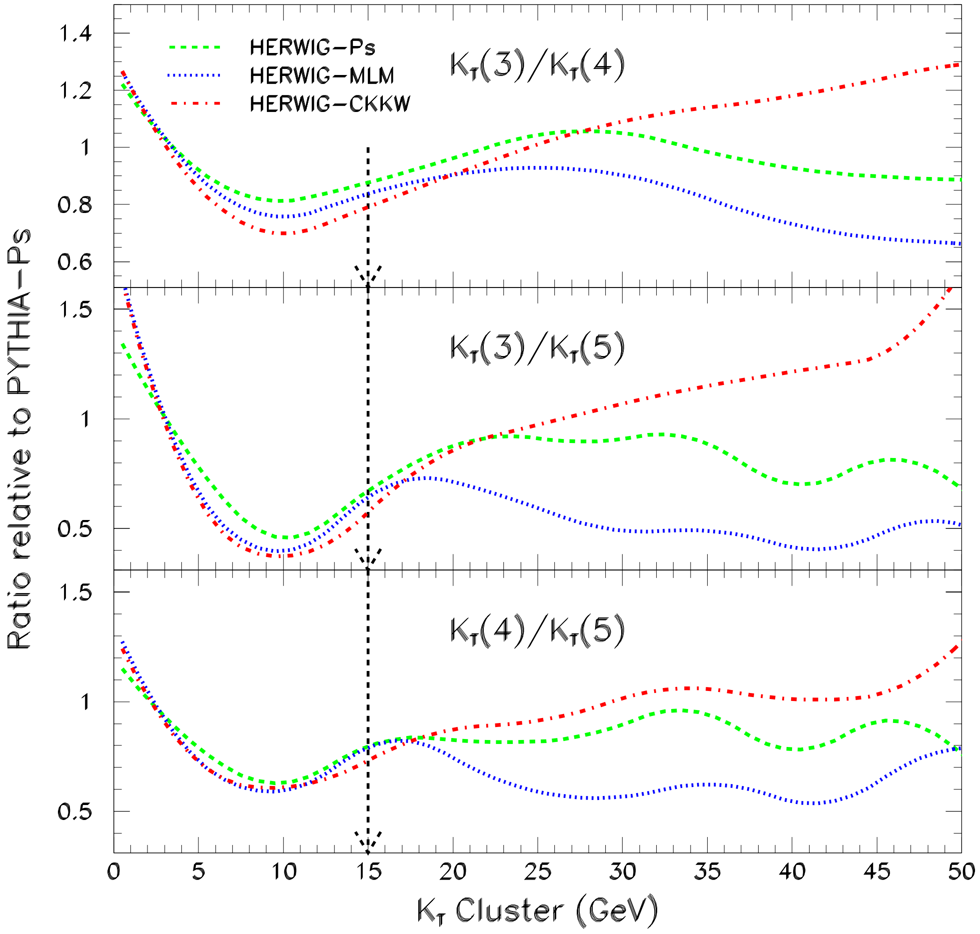
Some results for $W+$ jets at Tevatron



S. Mrenna and P. Richardson, hep-ph/0312274



S. Mrenna and P. Richardson, hep-ph/0312274



S. Mrenna and P. Richardson, hep-ph/0312274

Systematic of $\mathcal{O}(30\%)$ for cross sections

Why not use a simpler recipe (always at LL order)?

M.L. Mangano

- Generate partonic events for different jet multiplicities $(p_T > p_T^{\mathrm{min}}, \Delta R_{jj} > R_{\mathrm{min}})$
- Shower the events with default PSMC
- Before hadronization, process the showered events with a cone jet algorithm
- Require partons-jets matching
  - require for each hard parton a jet within $\Delta R_{\mathrm{match}} \simeq R_{\mathrm{jet}}$
  - reject the event if two partons match to the same jet or if one parton has no match
  - keep the event if all partons are matched
- The above procedure defines the **inclusive** sample
- For **exclusive** samples rejects events where there is an extra jet not matched to any ME parton. Cross section $= \sigma$ partonic $\cdot$ matching efficiency
- **Inclusive sample containing events with all multiplicities** obtained combining exclusive samples
- Physics analysis with inclusive samples should be as much as possible **independent** of generation cuts

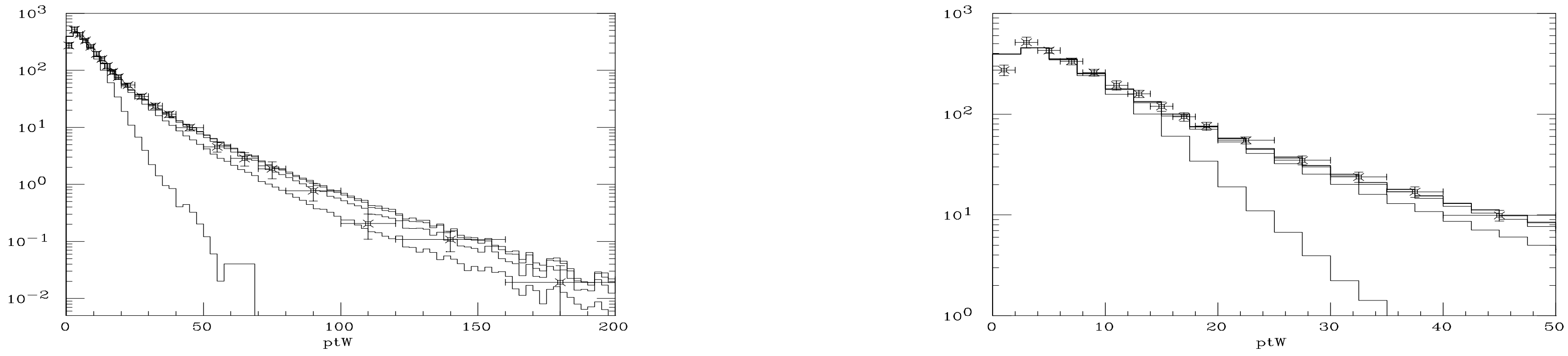


Figure 1: p_T^W spectrum. The points represent run I CDF data. The curves correspond to the subsequent inclusion of samples with higher multiplicity, form the $W + 0$ jet, up to the $W + 4$ jets case. The right plot is the same as the left one, with an enhanced low-p_T scale.

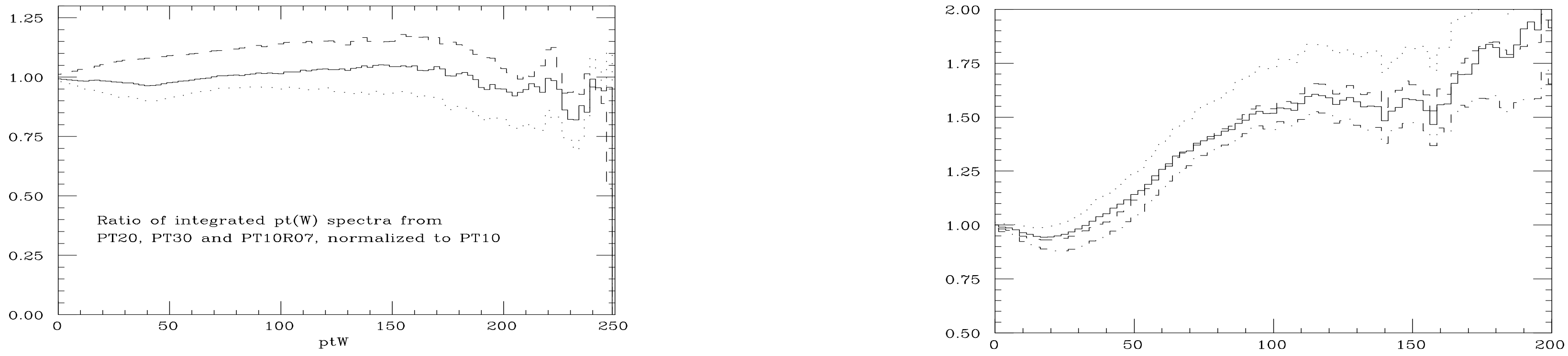


Figure 2: Effect of different generation cuts on the integrated p_T^W spectrum. Uncertainty of the order of ± 15%. The right panel shows the ratios of the samples generated with PT20, PT30 and PT10R07, divided by PT10. The right panel shows all four samples divided by a plain HERWIG W sample.

Conclusions

- Impressive progress in recent years in developing new MC tools
- Standards have been fixed to allow for use of different MC outputs without problems of compatiblity (Les Houches Accords)
- It is worth emphasizing the development of techniques aimed at exploiting good features from different Monte Carlos in different phase space regions (e.g. NLO with Parton Shower, CKKW, . . .)
- Waiting for LHC, we can test/tune these MC tools on data from Tevatron run II and HERA
- Most of the available programs are still written in the "old" `FORTRAN`. Shall we convert to `C++`?
- Let's see next talk to have a flavour of how Monte Carlos can help in performing physics measurements at the LHC