Monte Carlo Event Generators at the LHC

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Outline

- Inner working of MC Event Generators
  (The perturbative part)
  - Hard matrix elements
  - Parton showers
  - Combination of ME & PS
- Selection of MC tools
  (Apologies for all unlisted programs ...)

How do Event Generators work ?

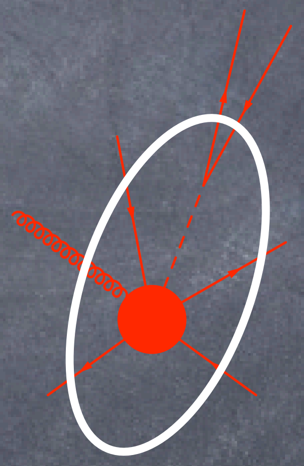
- Impose factorisation of perturbative/nonperturbative parts of an event → allows decomposition into different stages

e.g. hadronic collision

- Perturbative part

  Hard process

  (full matrix element
   fixed order in (running) coupling
   generates initial particle kinematics)



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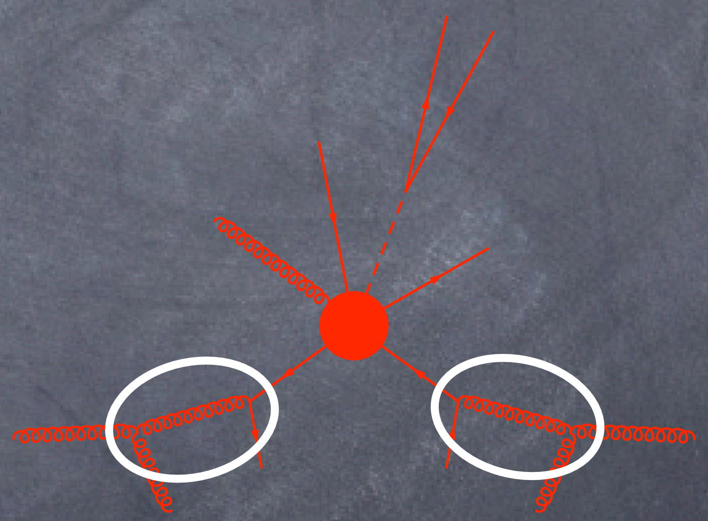
  Initial state parton shower

  (all orders (N)LL resummation
  mostly markovian approach)



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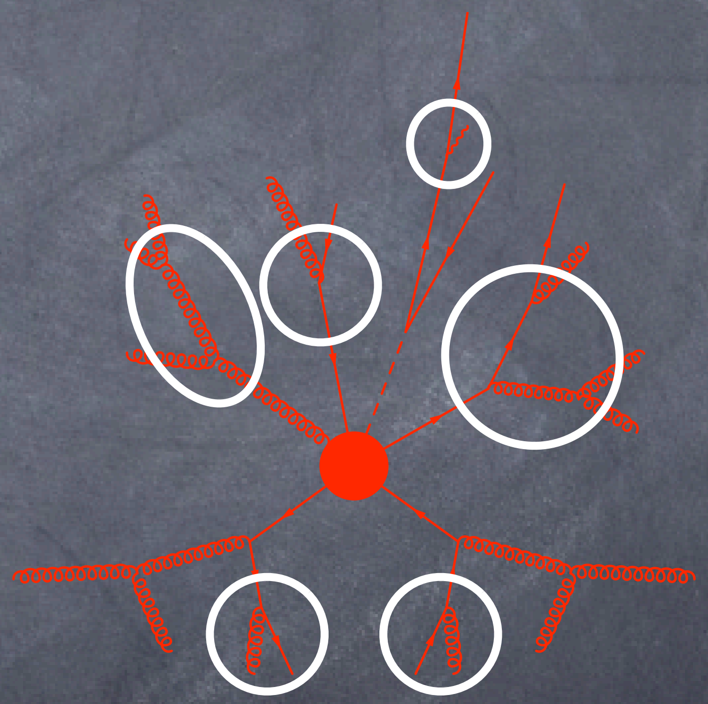
  Initial state parton shower

  Final state parton shower

  (all orders (N)LL resummation)



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- Impose factorisation of perturbative/nonperturbative parts of an event ➡ allows decomposition into different stages

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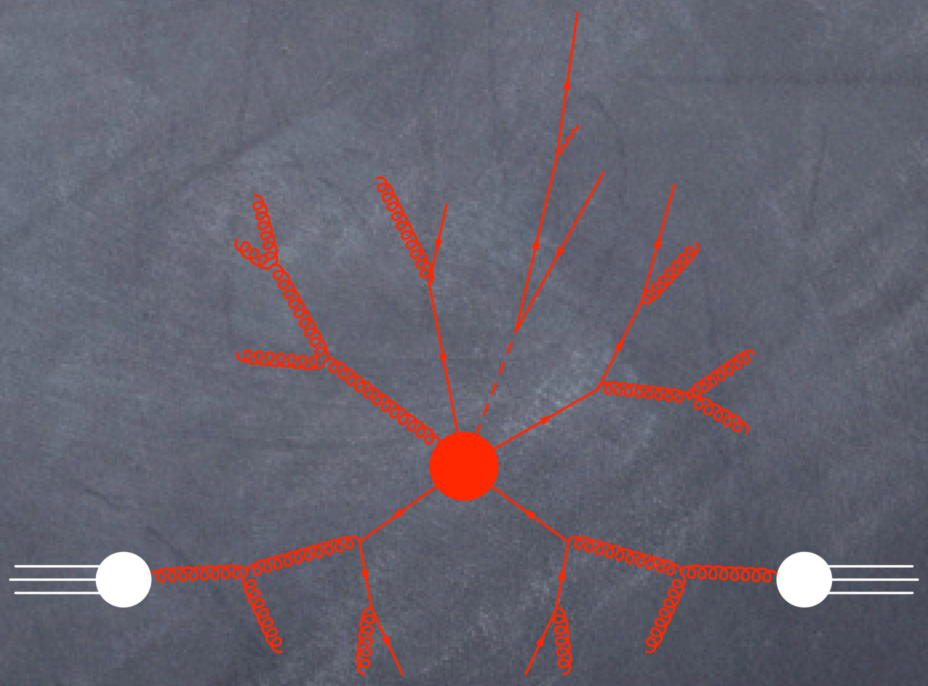
  Final state parton shower

- Nonperturbative part

  Parton Distributions (PDF)



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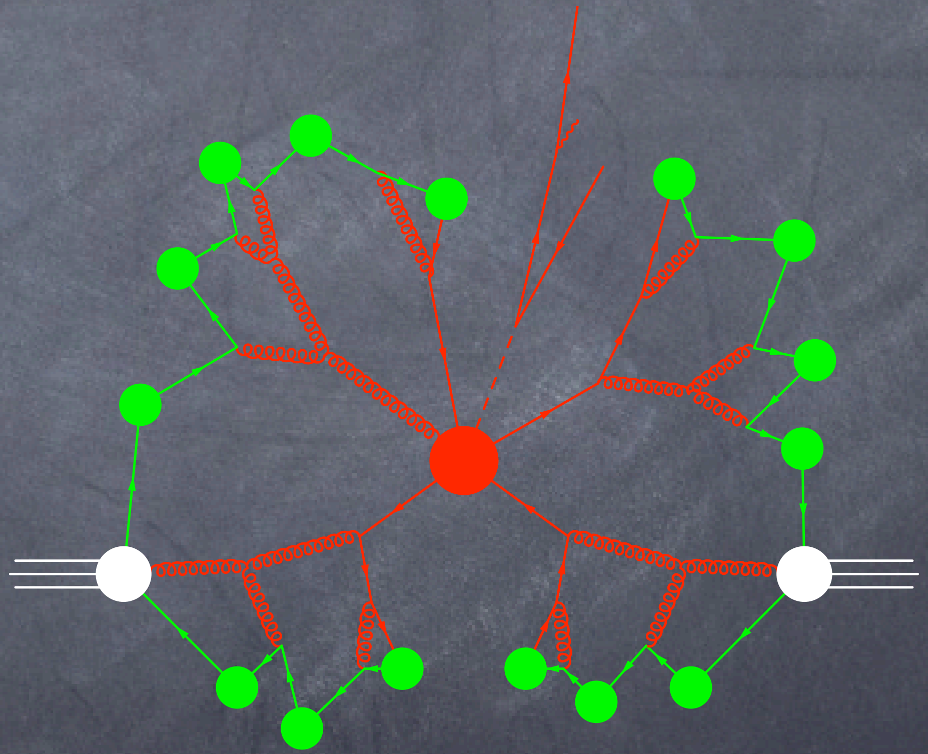
  - Hard process
  - Initial state parton shower
  - Final state parton shower
- Nonperturbative part
  - Parton Distributions (PDF)
  - Cluster/String formation
  - (modelling of nonperturbative dynamics of parton system)



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- Perturbative part
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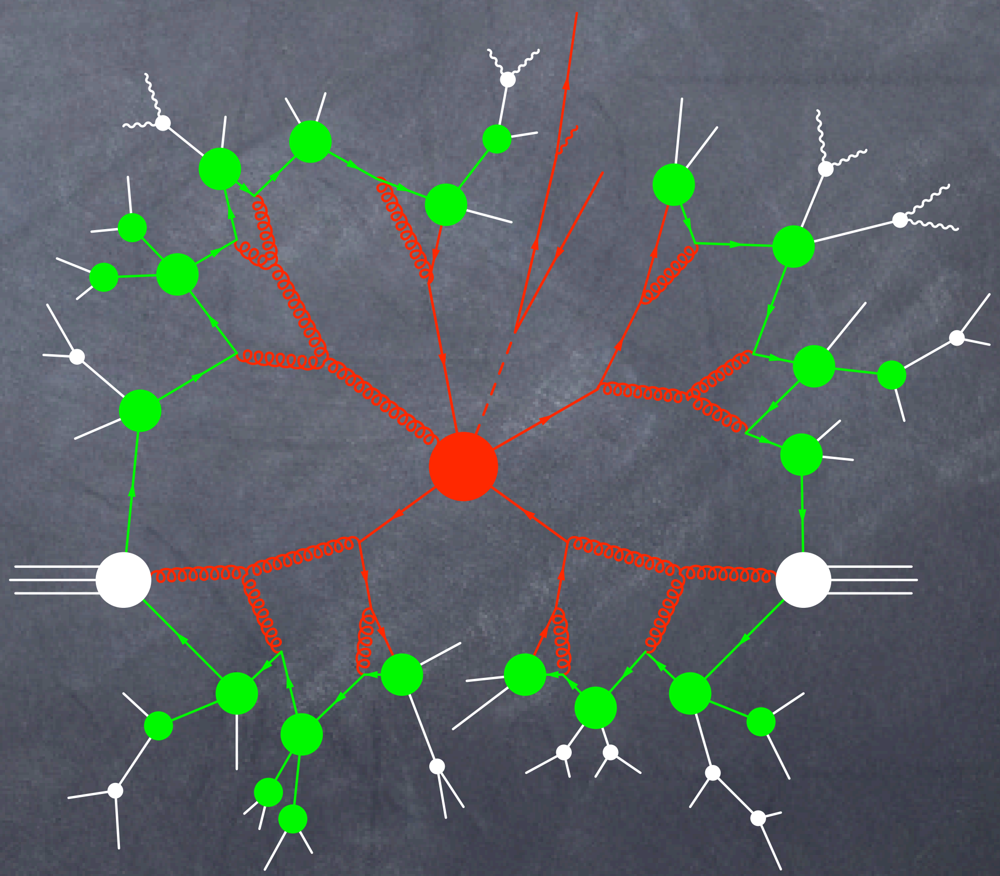
  - Parton Distributions (PDF)
  - Cluster/String formation
  - Cluster decays
  - Hadron Decays



Simulating the Hard Process

- General task: generate events (unweighted or weighted) according to the differential cross section

$$\mathbf{d}\sigma = \frac{\mathbf{1}}{\mathbf{F}} \mathrm{d}\mathbf{\Phi} \, |\mathcal{M}|^{\mathbf{2}}$$

  ➡ Two steps:
  - calculate the hard matrix element $|\mathcal{M}|^{\mathbf{2}}$
  - sample the phase space $\mathbf{\Phi}$

- Problems:
  - calculation of hard ME rather complex for large number of final state particles (factorial growth of Feynman diagrams) Example: W+5jets: about 7000 diagrams
  - high-dimensional phase space (3N-4) with probably sharply peaked integrand (e.g. QCD multi-parton matrix elements) and cuts on kinematic variables

Calculating the Hard ME

Methods to evaluate the hard ME:

- Pre-calculated matrix elements
  - in general very fast evaluation
  - limited set of processes, lacks generality
- Calculate total amplitude from Feynman rules (state of the art: helicity formalism (hep-ph/9403244))
  - can handle (in principle) arbitrary processes
  - limitations for large multiplicities due to factorial growth of diagrams
- ALPHA algorithm (Phys. Lett. B358 (1995) 332)
  - no Feynman rules needed at all (total amplitude directly from Lagrangian)
  - very fast evaluation, large multiplicities
  - so far formulated for tree level only

Sampling over Phase Space

General idea of MC integration: $\mathbf{I} = \int_\Omega \mathrm{d}x\, f(x) = \Omega \langle f \rangle_{\{x_i | i=1\dots n\}}$

- Problem: to be efficient, must sample such that each single weight is close to the average
- But: main peak structure of integrand known (in principle) and given by Feynman diagrams

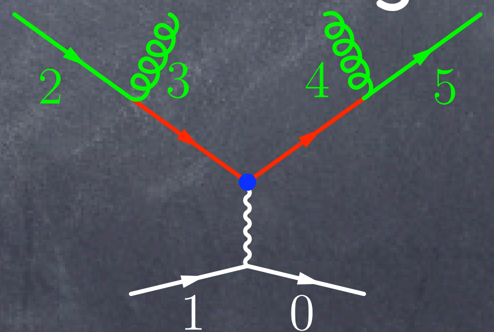
→ employ multi-channel method (e.g. hep-ph/9405257)

- $\mathbf{I} = \int_\Omega \mathrm{d}x\, g(x)\, w_g(x), \quad \mathbf{V} = \int_\Omega \mathrm{d}x\, g(x)\, w_g^2(x), \quad w_g(x) = \frac{f(x)}{g(x)}$

  where $g(x) = \sum \alpha_i\, g_i(x)$ with $\sum \alpha_i = 1$

  single channels g_i are constructed acc. to diagrams

  $D_{iso}(23,45) \otimes P_0(23) \otimes P_0(45) \otimes D_{iso}(2,3) \otimes D_{iso}(4,5)$ ↔



- channels can be improved further using adaptive algorithms like VEGAS (CLNS-80/447 (1980))

Calculating the Hard ME

- Comparison of ME Generators in context of MC4LHC (http://indico.cern.ch/categoryDisplay.py?categId=152)

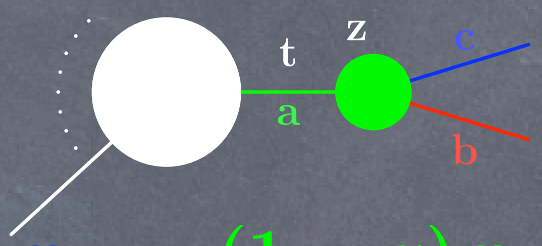
X-sects (pb)	$e^-\bar{\nu}_e + n$ QCD jets						
Number of jets	0	1	2	3	4	5	6
ALPGEN	3904(6)	1013(2)	364(2)	136(1)	53.6(6)	21.6(2)	8.7(1)
AMEGIC++	3908(3)	1011(2)	362.3(9)	137.5(5)	54(1)		
CompHEP	3947.4(3)	1022.4(5)	364.4(4)				
GR@PPA	3905(5)	1013(1)	361.0(7)	133.8(3)	53.8(1)		
JetI	3786(81)	1021(8)	361(4)	157(1)	46(1)		
MadEvent	3902(5)	1012(2)	361(1)	135.5(3)	53.6(2)		

X-sects (pb)	$e^+\nu_e + n$ QCD jets						
Number of jets	0	1	2	3	4	5	6
ALPGEN	5423(9)	1291(13)	465(2)	182.8(8)	75.7(8)	32.5(2)	13.9(2)
AMEGIC++	5432(5)	1277(2)	466(2)	184(1)	77.3(4)		
CompHEP	5485.8(6)	1287.5(7)	467.3(8)				
GR@PPA	5434(7)	1273 (2)	467.7(9)	181.8(5)	76.6(3)		
JetI	5349(143)	1275(12)	487(3)	212(2)			
MadEvent	5433(8)	1277(2)	464(1)	182(1)	75.9(3)		

Parton Shower Concept

- Multi-parton amplitudes exhibit soft & collinear singularities

  If b and c adjacent in color and collinear, they can be thought to originate from a common mother parton a with $p_b = z\, p_a$ and $p_c = (1-z)\, p_a$



  ➡ n+1 parton amplitude factorizes into n parton amplitude and invariant 1➔2 splitting acc. to

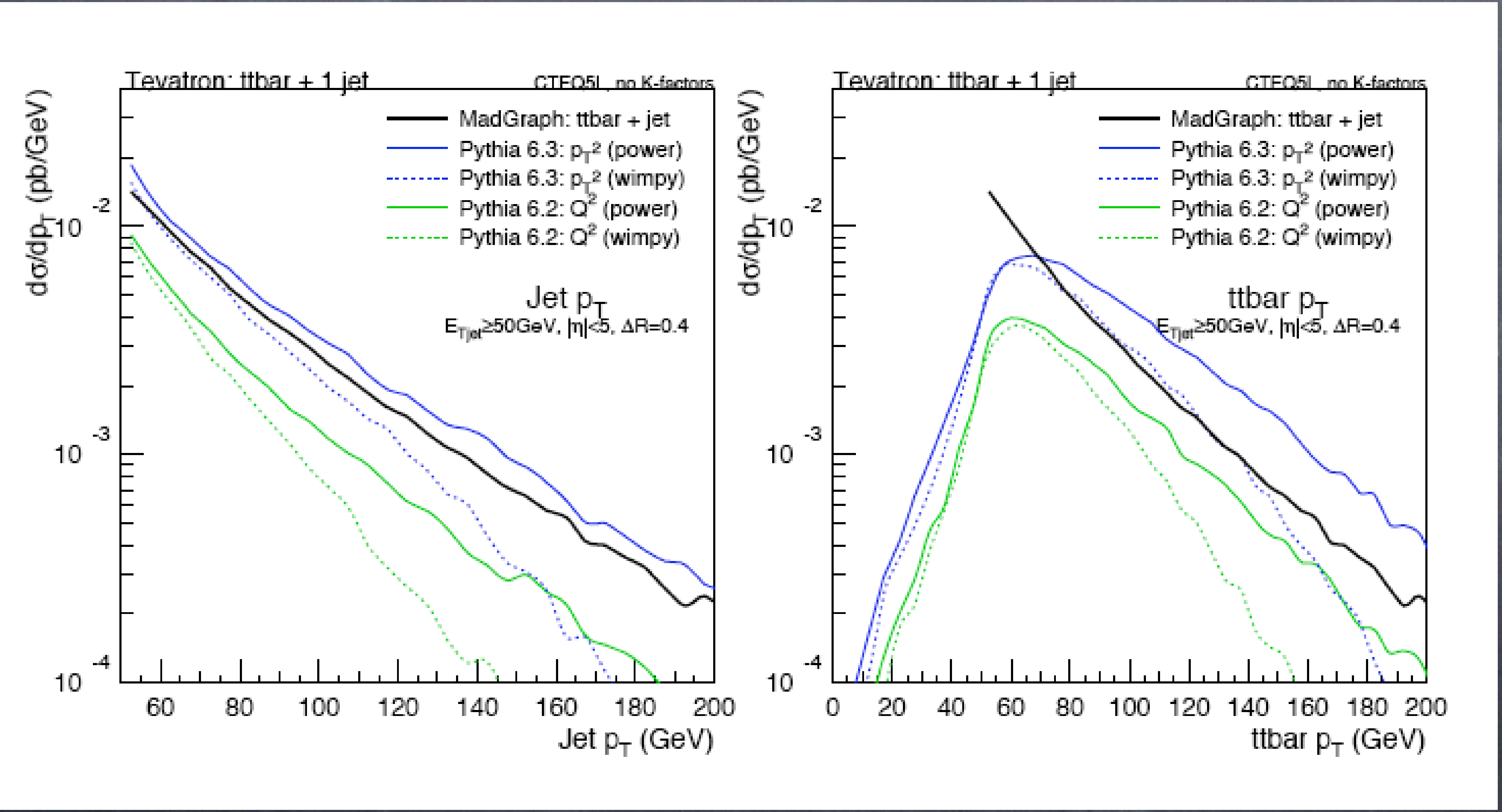
$$\mathrm{d}\sigma_{n+1} = \mathrm{d}\sigma_n \otimes \sum_{a\in q,g} \frac{\mathrm{d}t}{t}\mathrm{d}z \frac{\alpha_s(t,z)}{2\pi} P_{a\to bc}(z)$$

- No interference of daughter partons with remaining partons

  ➡ allows probabilistic interpretation ➔ Markov chain
- But: Must respect angular ordering (color coherence) !
- Ambiguities:
  - $z(1-z)\,t = k_t^2$; $t/z(1-z) \approx E^2\theta^2$ yield formally equivalent evolution
  - z ➔ light-cone momentum or energy fraction
  - Starting scale not fixed (process dependent)

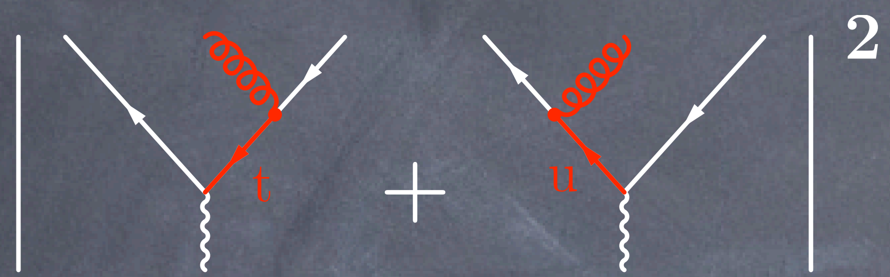
Parton Shower Issues

- Test of different PS prescriptions in PYTHIA
  (by P. Skands, T. Plehn, D. Rainwater
  presented at TeV4LHV, CERN, 29.4.2005)



Matrix Element vs. Parton Shower

Matrix Elements



- Exact to fixed order in running coupling α
- Include all quantum interferences
- Calculable only for low FS multiplicity (n≤6-8)

Parton Showers

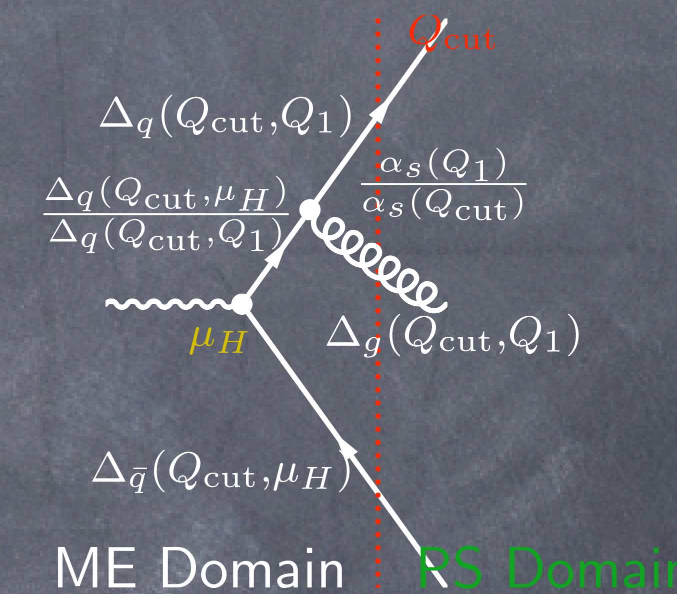
$$d\sigma_{n+1} = d\sigma_n \otimes \sum_{b\in q,g} \frac{dt}{t} dz \frac{\alpha_s(t,z)}{2\pi} P_{a\to b}(z)$$

- Resum (next-to) leading logarithms to all orders
- Interference effects e.g. through angular ordering

- Desirable to combine both approaches to have
  - Good description of hard/wide-angle emissions (ME)
  - Correct intrajet evolution (PS)
- Must prevent double counting e.g. through CKKW

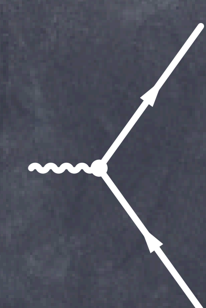
Combining ME & PS à la CKKW

- Define jet resolution parameter Q_{cut} (Q-jet measure)
  ➡ divide phase space into regions of
  jet production (n-jet ME) & jet evolution (PS)
- Select jet multiplicity and kinematics according to σ 'above' Q_{cut}
- K_T cluster backwards (construct PS tree) and identify core process
- Reweight ME to get exclusive samples at resolution scale Q_{cut}
- Start PS at scale μ_{hard}, reject all emissions above Q_{cut}



➡ Yields correct jet rates,
e.g. 2-jet rate in 2-jet event at scale q

$$R_2(q^2) = \left(\Delta(Q_{\rm cut},\mu_{\rm hard})\,\frac{\Delta(q,\mu_{\rm hard})}{\Delta(Q_{\rm cut},\mu_{\rm hard})}\right)^2$$



Combining ME & PS

There exist several variants of the above algorithm ...

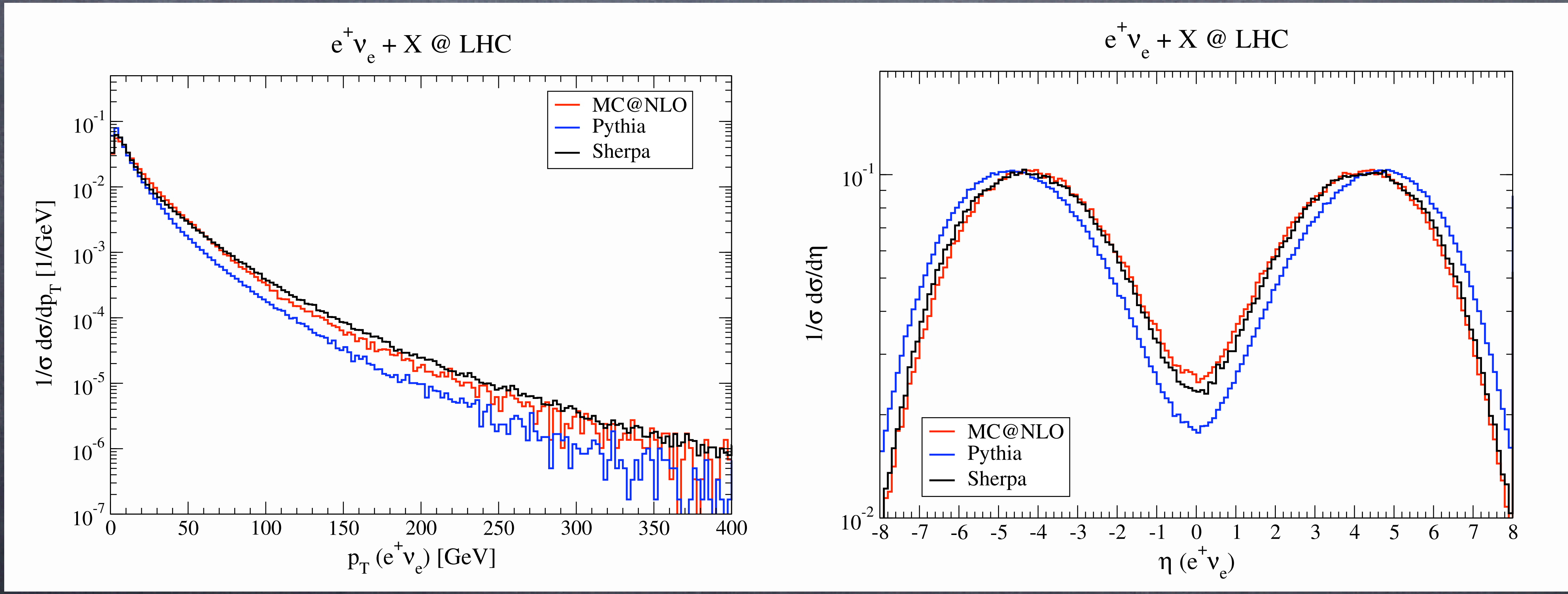
- The MLM prescription (Nucl. Phys. B632 343 (2002))
  - Employ cone algorithm to define jets after PS
  - Match N+M reconstructed jets to N ME partons
  - Different samples can be added w/o need for analytic Sudakovs
- The Lönnblad prescription (JHEP 0205 046 (2002))
  - Employs dipole cascade instead of PS
  - Sudakov weights are calculated using the cascade itself

Similar systematics for all algorithms

- Residual dependence on the phase space separation cut
- Variations with the number of hard ME partons
- Dependencies on the internal jet algorithm

Combining ME & PS

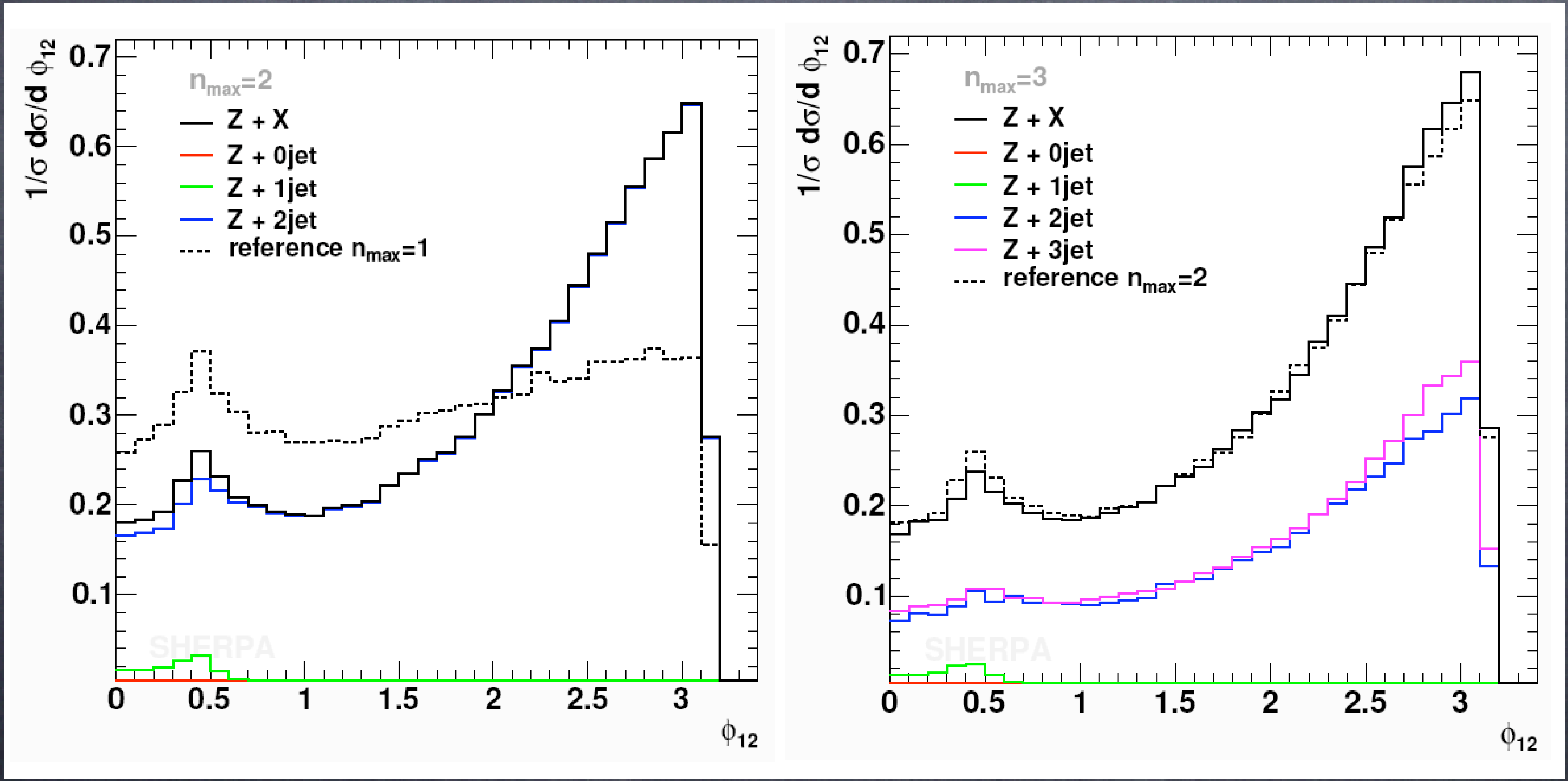
- Comparison of CKKW as implemented in Sherpa with PYTHIA and MC@NLO in W+jets at LHC (hep-ph/0503280)
  - Sherpa uses Q_{cut}=20 GeV and $N_{max\ jet}$= 1
  - MC@NLO in default mode (NLO)
  - PYTHIA with PS starting scale $(14TeV)^2$



- Rates in CKKW are still LO !

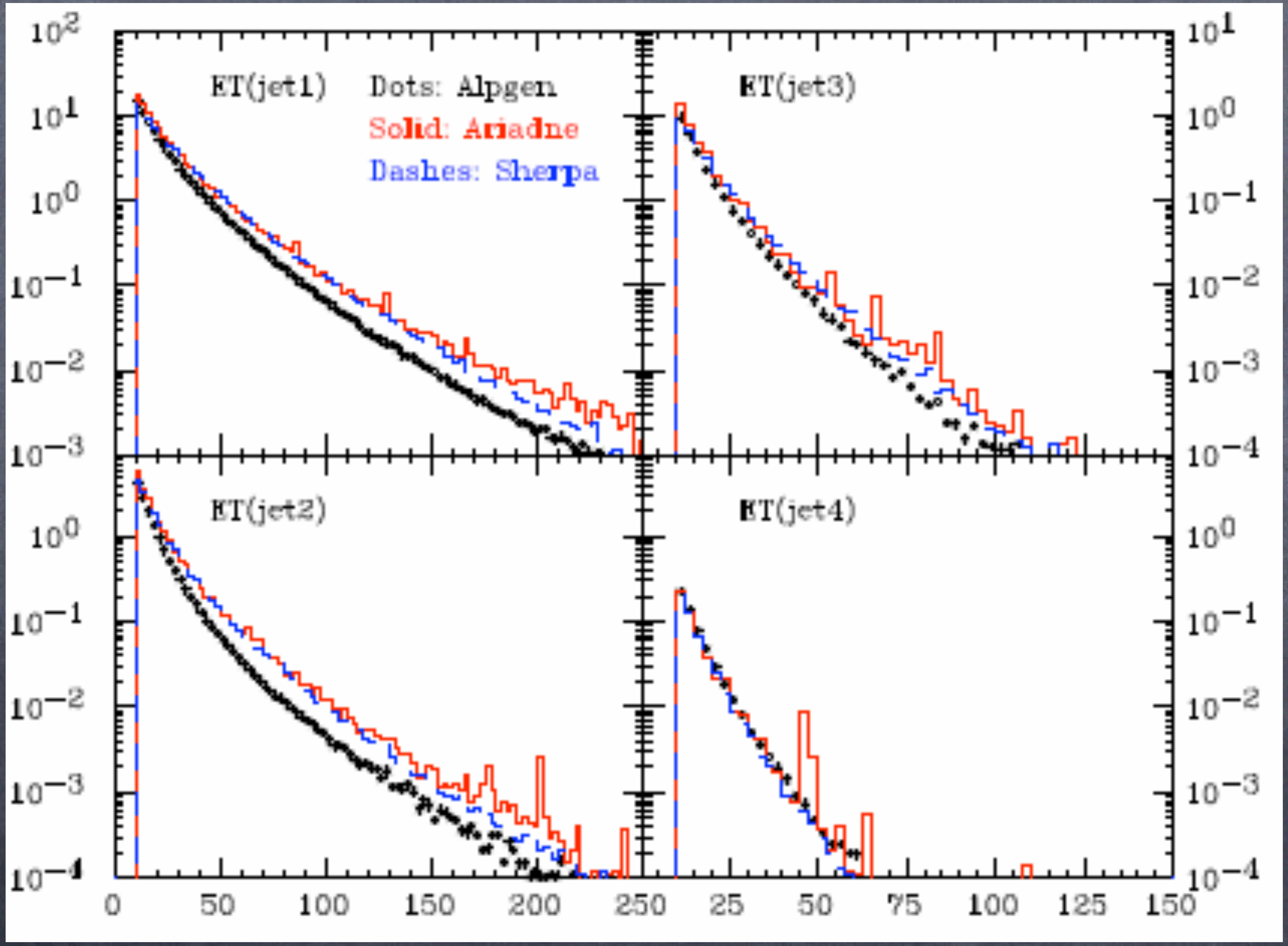
Combining ME & PS

- $\Delta\phi$ of two hardest jets in Z+jets at LHC from Sherpa (hep-ph/0503280)



Combining ME & PS

- Detailed comparison of merging approaches started ALPGEN, ARIADNE, Sherpa (hep-ph/0601012, hep-ph/0601013)
  - E_T spectra of jets in $pp \to e^+ \bar{\nu}_e + X$



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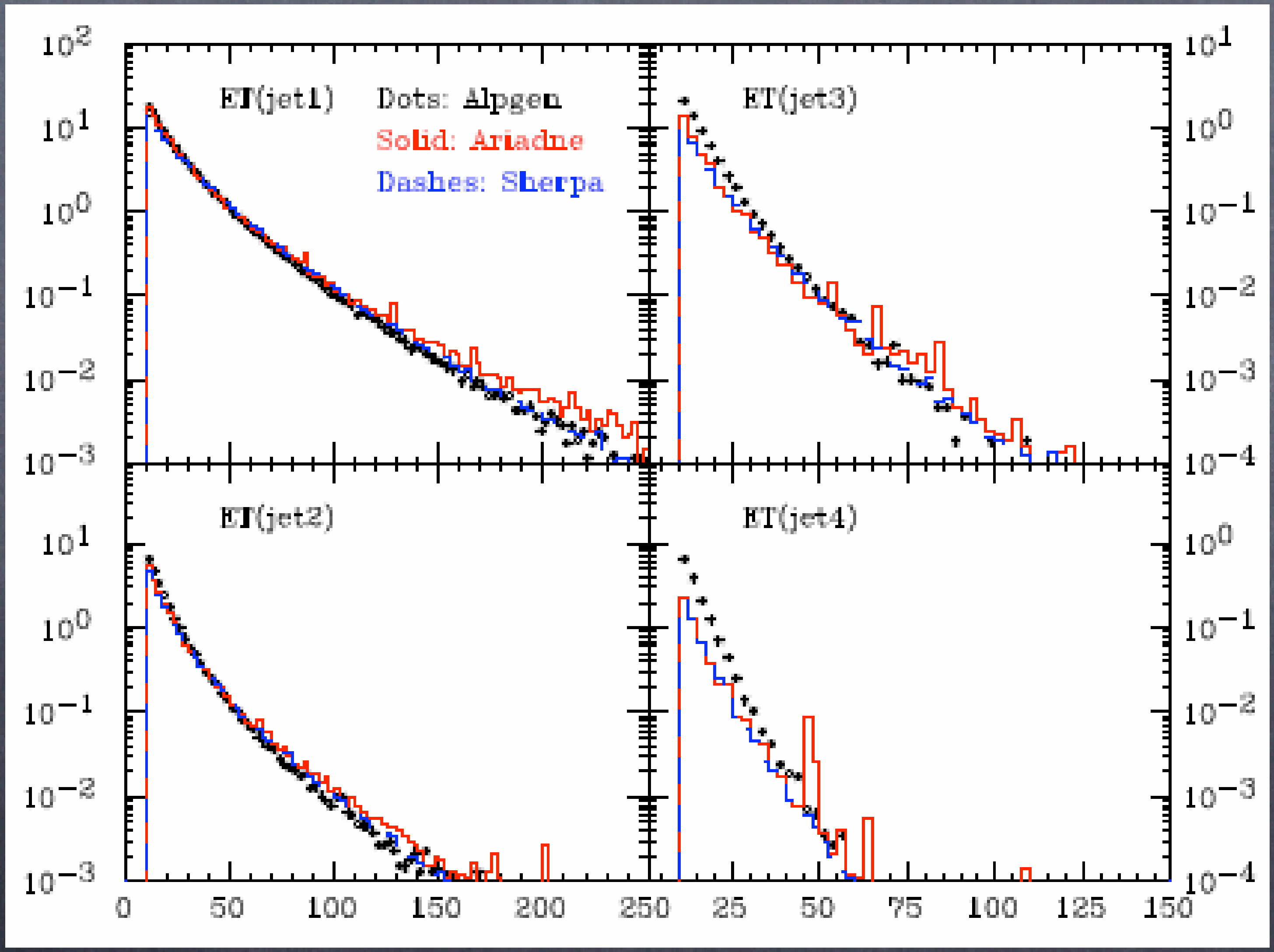
    ALPGEN μ_R rescaled by 0.5 (hint on scale uncertainty)



Now the MCs ...

General Purpose MCs: PYTHIA

T. Sjöstrand, L. Lönnblad, S. Mrenna, P. Skands, ... hep-ph/0308153

- THE standard event generator (FORTRAN version)
- Includes large collection of pre-calculated hard matrix elements ($2\to2$ and $2\to3$ processes)
- PS:
  - virtuality ordered w/ angular veto and $z \to$ energy fraction
  - k_T ordered with $z \to$ light cone momentum fraction (since version 6.3)
- Lund string fragmentation (and others)
- Models for hard and soft UE (Phys. Rev. D36 2019 (1987))
- No automatic ME Generator, no ME-PS merging

Currently being rewritten in C++
(PYTHIA 8, proposed to be useable by mid 2007)
Robust and fast general purpose MC (handles 'everything')

General Purpose MCs: HERWIG

G. Corcella, I. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M. Seymour, B. Webber hep-ph/0011363

- General purpose MC (FORTRAN version)
- Large collection of pre-calculated hard matrix elements (2➔2 and 2➔3 processes)
- angular ordered PS w/ full spin correlations
- Cluster fragmentation model
- Models for hard (JIMMY (hep-ph/9601371)) and soft UE
- No automatic ME Generator, no ME-PS merging

Currently being rewritten in C++ (HERWIG++, improved PS) (recently tested in pp->Z (S. Gieseke et al. hep-ph/0602069))

New hadron decay package w/ web-interface by P. Richardson

General purpose MC like PYTHIA but different models

General Purpose MCs: Sherpa

currently: T. Fischer, T. Gleisberg, S.H., F. Krauss, T. Laubrich, S. Schumann, F. Siegert, J. Winter; JHEP 0402 (2004) 056

- Automatic ME Generator AMEGIC++ (JHEP 0202 (2002) 044) (SM, MSSM (hep-ph/0512260), ADD (hep-ph/0306182))
- virtuality ordered PS similar to PYTHIA (hep-ph/0503087)
- currently relying on Lund string fragmentation (PYTHIA) but: Cluster fragmentation model ready (hep-ph/0311085)
- Model for hard UE (based on Sjöstrand/Zijl model) new model in preparation
- Special emphasis on ME-PS merging (hep-ph/0205283)
- New: Hadron decay package (tested in τ decays vs. Tauola)

Written in C++ from scratch
MSSM part tested against MadGraph & WHIZARD
Well tested ME Generator, general purpose MC, original CKKW

(S)MadGraph / MadEvent

K. Hagiwara, F. Maltoni, T. Plehn, D. Rainwater, T. Stelzer

- Automatic ME Generator MadGraph (hep-ph/9401258)
  based on HELAC (KEK-91-11)
  (SM, MSSM (SMadGraph) (hep-ph/0512260), Higgs EFT)
- Single diagram enhanced integration / event generation
  (suitable basis for multi-channel ➞
  independent weights (hep-ph/0208156))
- LHA interface ➞ full events from HERWIG/PYTHIA
- ME-PS merging à la CKKW / MLM in preparation

Parallel nature of integration perfect for PC cluster

Web interface: http://madgraph.hep.uiuc.edu

MSSM part tested against AMEGIC++ & WHIZARD

Very fast SM / MSSM ME Generator,
large multiplicities (6-7 FS particles e.g. in W+jets)

ALPGEN

M. Mangano, M. Moretti, F. Piccinini, R. Pittau, A. Polosa (hep-ph/0206293)

- Collection of processes calculated in the ALPHA algorithm
- full events from HERWIG/PYTHIA
- Phase space not "multi-channelled"; uses adaptive algorithm

Processes currently available in the package:

- W Q Qbar + up to 4 jets
- Z/gamma* Q Qbar + up to 4 jets
- W + up to 6 jets
- W + charm + up to 5 jets
- Z + up to 6 jets
- nW+mZ+kH + up to 3 jets
- Q Qbar plus up to 6 jets
- Q Qbar Q' Qbar' plus up to 4 jets
- Q Qbar Higgs plus up to 4 jets
- Inclusive N jets, with N up to 6
- N photons + M jets, with N larger than 0, N+M up to 8 and M up to 6
- NEW:Higgs + N jets, with N<5
- NEW:Single top: tq, tb, tW, tbW. No extra jets.

- ME-PS merging in the MLM prescription

ALPGEN provides full spin & color information to the PS MC

Currently largest multiplicities, original MLM

WHIZARD / O'Mega

WHIZARD:

W. Kilian (LC-TOOL-2001-39)

- General integration & event generation package
  for O'Mega, MadGraph, CompHep, ...
  (up to six particle final states)
- Interfaces PYTHIA to generate full events

O'Mega:

T. Ohl, M. Moretti, J. Reuter (hep-ph/0102195)

- Generator-generator based on ALPHA algorithm
  many new physics models (spin 2 particles, gravitinos, AGC)
  very flexible, easy to extend
  MSSM part tested against AMEGIC++ & MadGraph

MC@NLO

S. Frixione, B. Webber (JHEP 06 (2002) 029)

- Collection of processes calculated at NLO
- PS and hadronization from HERWIG 6.5
- NLO-MC merging according to the MC@NLO algorithm

NLO cross sections and shapes

Can be used to calculate any observable at hadron level

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–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				×	$H_1H_2 \to t\bar{t} + X$
–2000–IC				×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC				×	$H_1H_2 \to \bar{t} + X$
–2004–IC				×	$H_1H_2 \to t + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

Other Tools

ME Generators:

- GRACE / Gr@ppa
  J. Fujimoto et al. (hep-ph/0007053)
  SM / MSSM processes (tree level)
  BASES/SPRING for integration/ event generation
- CompHEP
  A. Pukhov et al. (hep-ph/9908288)
  SM / MSSM processes
  (tree level up to four FS particles)

NLO codes:

- MCFM
  J. Campbell, K. Ellis (hep-ph/0006304)
  various processes, see http://mcfm.fnal.gov
- NLOjet++
  J. Campbell, K. Ellis (hep-ph/0006304)
  pp: up to 3 jets at NLO / 4 jets at LO

Conclusions

- Many good tree level and NLO tools on the market
- So far only one approach for full NLO simulation
  But: To predict correct shapes ME-PS merging
  à la CKKW/MLM is often sufficient
  ← we get the shapes of real emissions right!
- Need more input from experimental community
  in order to fix systematics (e.g. CKKW/MLM)

Hot topics:

- Shower algorithms (still !)
- Tree-level ME's
  (new recursion relations for QCD)
- Underlying events
- ...