Monte Carlo Methods in Particle Physics

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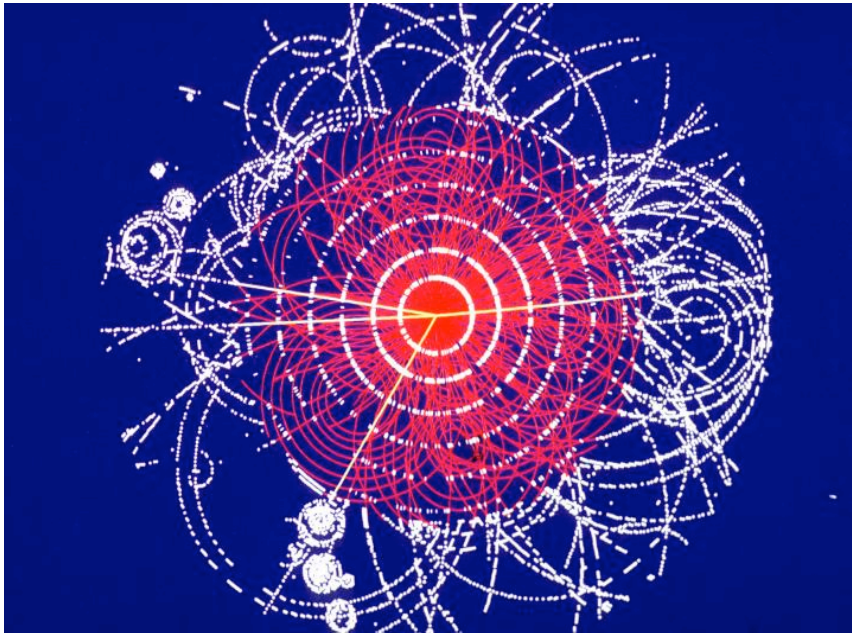
Monte Carlo Event Generation

- Basic Principles
- Event Generation
- Parton Showers
- Hadronization
- Underlying Event
- Event Generator Survey
- Matching to Fixed Order
- Beyond Standard Model



Event Generators

- **HERWIG**
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++
- **PYTHIA**
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran; v8 C++
- **SHERPA**
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

HERWIG 6

- Current status:
- Version 6.510 released on October 31st 2005
  - http://projects.hepforge.org/fherwig/
  - ~ 64,000 lines of FORTRAN, 11 authors (5 currently active)
- 6.51* will be the last FORTRAN version
- Some features:
  - Many built-in SM and MSSM processes
  - Les Houches Accord interface for arbitrary hard processes
  - Spin correlation algorithm → see later
  - Interface to MC@NLO program (Frixione & Webber) → see later
  - Interface to JIMMY multiple interaction underlying event model
  - Angular cutoff $\theta > m/E \Rightarrow$ "dead cone" for heavy quarks

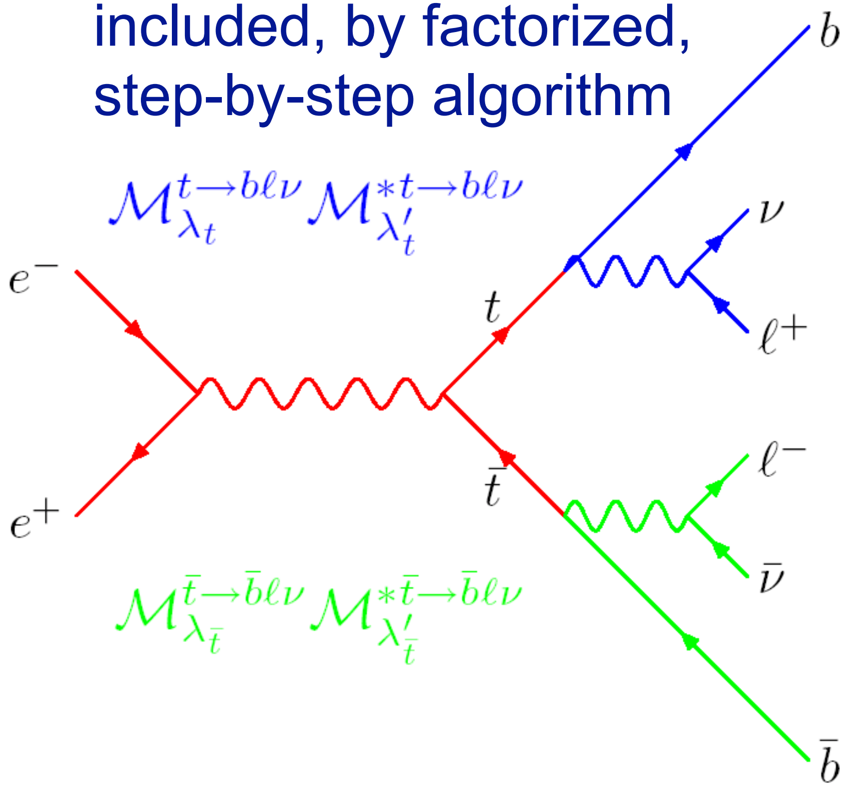
Production/Decay Spin Correlations

- Example: top quark pairs in e+e- annihilation:

Full spin correlations included, by factorized, step-by-step algorithm

$$\rho_{\rm prod}^{\lambda_c\lambda_c'\lambda_d\lambda_d'} = \mathcal{M}_{ab\to cd}^{\lambda_c\lambda_d}\mathcal{M}_{ab\to cd}^{*\lambda_c'\lambda_d'},$$

$$D_c^{\lambda_c\lambda_c'} = \mathcal{M}_{c\ {\rm decay}}^{\lambda_c}\mathcal{M}_{c\ {\rm decay}}^{*\lambda_c'},$$



$$|\mathcal{M}|^2 = \rho_{\rm prod}^{\lambda_c\lambda_c'\lambda_d\lambda_d'} D_c^{\lambda_c\lambda_c'} D_d^{\lambda_d\lambda_d'}$$

$$= \rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda_c'\lambda_d\lambda_d} D_c^{\lambda_c\lambda_c'}}{\rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}}\right)$$

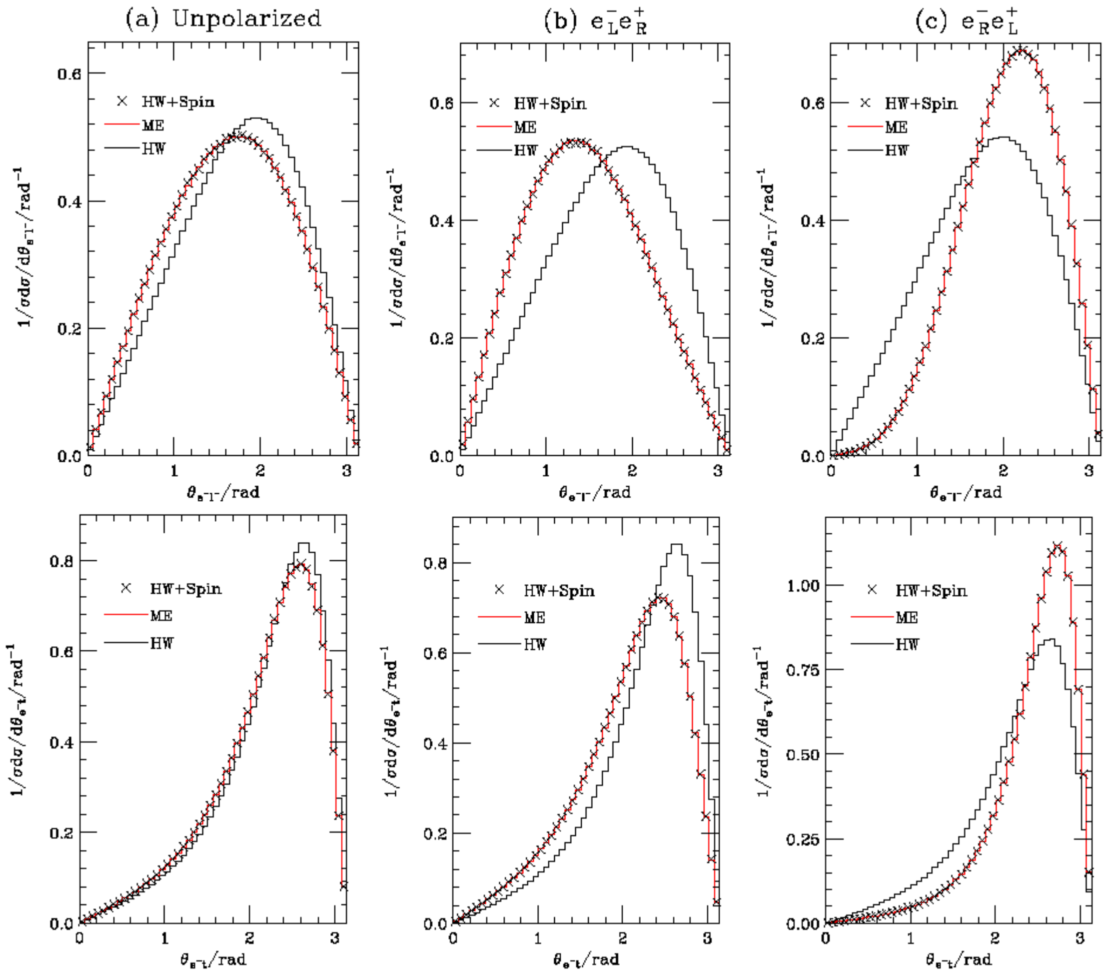
$$\times\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda_c'\lambda_d\lambda_d'} D_c^{\lambda_c\lambda_c'} D_d^{\lambda_d\lambda_d'}}{\rho_{\rm prod}^{\lambda_c\lambda_c'\lambda_d\lambda_d} D_c^{\lambda_c\lambda_c'}}\right)$$

Production/Decay Spin Correlations

- Top quark pairs in e+e- annihilation:

Correlation between lepton and beam

Correlation between lepton and top



PYTHIA 6

- Current status:
- Version 6.413 released September 2007
  - http://projects.hepforge.org/pythia6/
  - ~ 75,000 lines of FORTRAN
- Some features:
  - Many built-in SM and BSM processes
  - Les Houches accord interface for arbitrary hard processes
  - Mass effects in gluon emission (“no dead cone”) → see later
  - Option of virtuality- or k_T-ordered shower
  - Multiple interaction models for min bias and underlying events

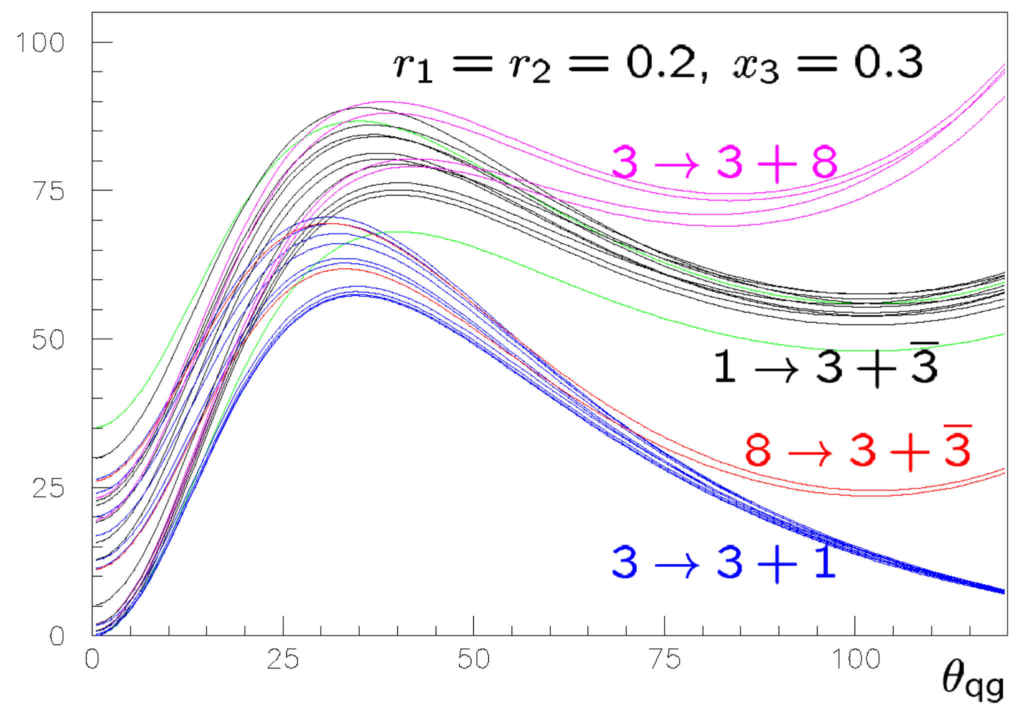
Mass Effects in PYTHIA

- Dead cone only exact for
  - emission from spin-0 particle, or
  - infinitely soft emitted gluon

- In general, depends on
  - energy of gluon
  - colours and spins of emitting particle and colour partner

→ process-dependent mass corrections

colour	spin	γ_5	example
$1 \to 3+\bar{3}$	—	—	(eikonal)
$1 \to 3+\bar{3}$	$1 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3+1$	$\frac{1}{2} \to \frac{1}{2}+1$	$1, \gamma_5, 1\pm\gamma_5$	$t \to bW^+$
$1 \to 3+\bar{3}$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$H^0 \to q\bar{q}$
$3 \to 3+1$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1\pm\gamma_5$	$t \to bH^+$
$1 \to 3+\bar{3}$	$1 \to 0+0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to 0+1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3+\bar{3}$	$0 \to 0+0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to 0+0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1\pm\gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3+1$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1\pm\gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3+8$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3+8$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1\pm\gamma_5$	$t \to \tilde{t}\tilde{g}$



PYTHIA Underlying Event Models

Parameter	Value	Description
MSTP(81)	0,10,20	Multiple-Parton Scattering off, for old, intermediate & new models
	1,11,21	Multiple-Parton Scattering on, for old, intermediate & new models
MSTP(82)	1 2	Multiple interactions with fixed probability & abrupt cut-off PTmin=PARP(81) or smooth turn-off at PARP(82)
MSTP(82)	3	Multiple interactions with varying impact parameter & hadronic matter overlap with single Gaussian matter distribution, with smooth turn-off at PARP(82)
MSTP(82)	4 5	Multiple interactions with varying impact parameter and a hadronic matter overlap with double Gaussian matter distribution (governed by PARP(83) and PARP(84)), or distribution $\Delta\phi^{(\mathrm{WW})} \simeq 0$ PARP(83), both with smooth turn-off at PARP(82)

Object Oriented Event Generators

- ThePEG: Toolkit for High Energy Physics Event Generation, used by Herwig++ (and ARIADNE++?)
- Herwig++: Physics improvements from HERWIG 6
- PYTHIA 8: Implementation of physics of PYTHIA 6 plus some improvements: see http://www.thep.lu.se/~torbjorn
- SHERPA: Completely new event generator

http://projects.hepforge.org/

Hard Processes in Herwig++

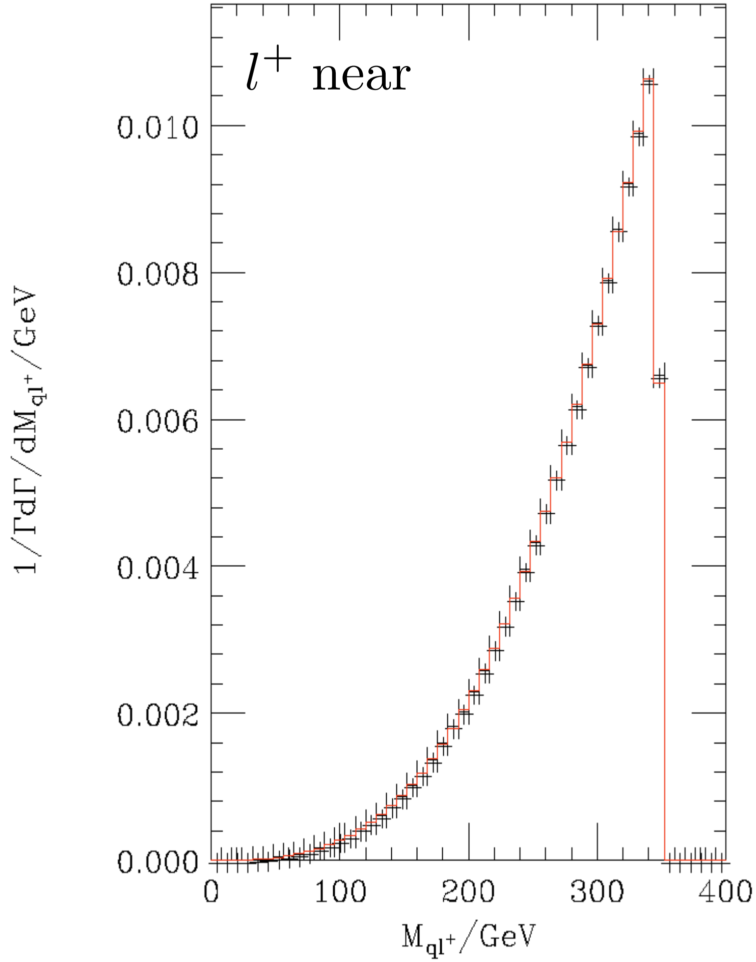
- In FORTRAN HERWIG each hard process and decay matrix element was typed in by hand.
  - Isn't a good use of time.
  - Meant that models of new physics were very hard to include.
- Herwig++ uses an entirely different philosophy.
  - A C++ helicity library based on the HELAS formalism is used for all matrix element and decay calculations.
  - Code the hard 2→2 matrix elements based on the spin structures.
  - Code the 1→2 decays in the same way and use phase space for the 1→3 decays to start with.
  - Easy to include spin correlations as we have access to the spin unaveraged matrix elements.

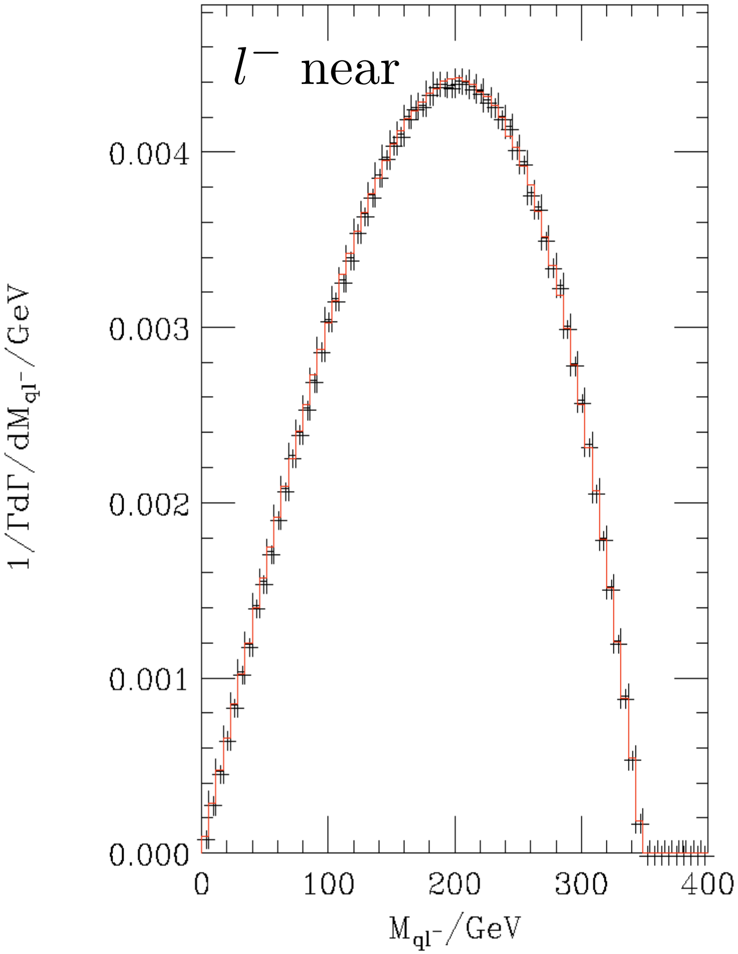
M Gigg and P Richardson hep-ph/0703199

M Bähr et al. arXiv:0711.3137 (today!)

Herwig++ New Physics: MSSM

$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to ql^\pm\tilde{l}^\mp \to ql^\pm l^\mp\tilde{\chi}_1^0$$





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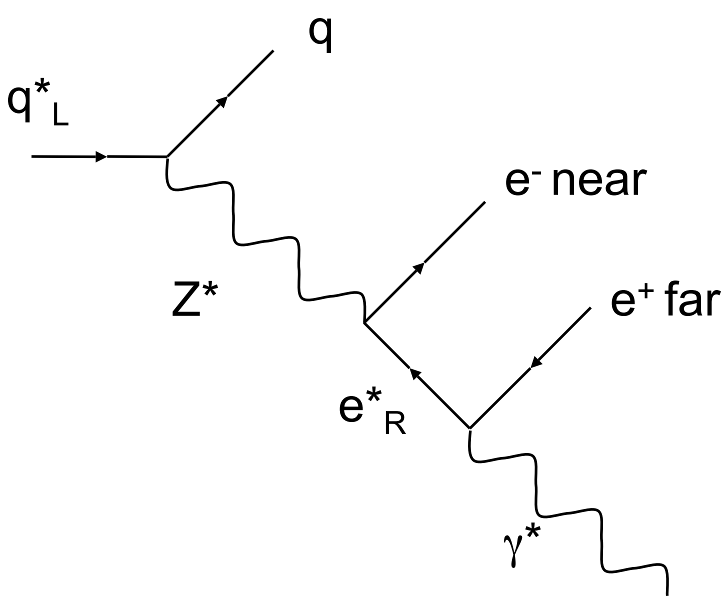
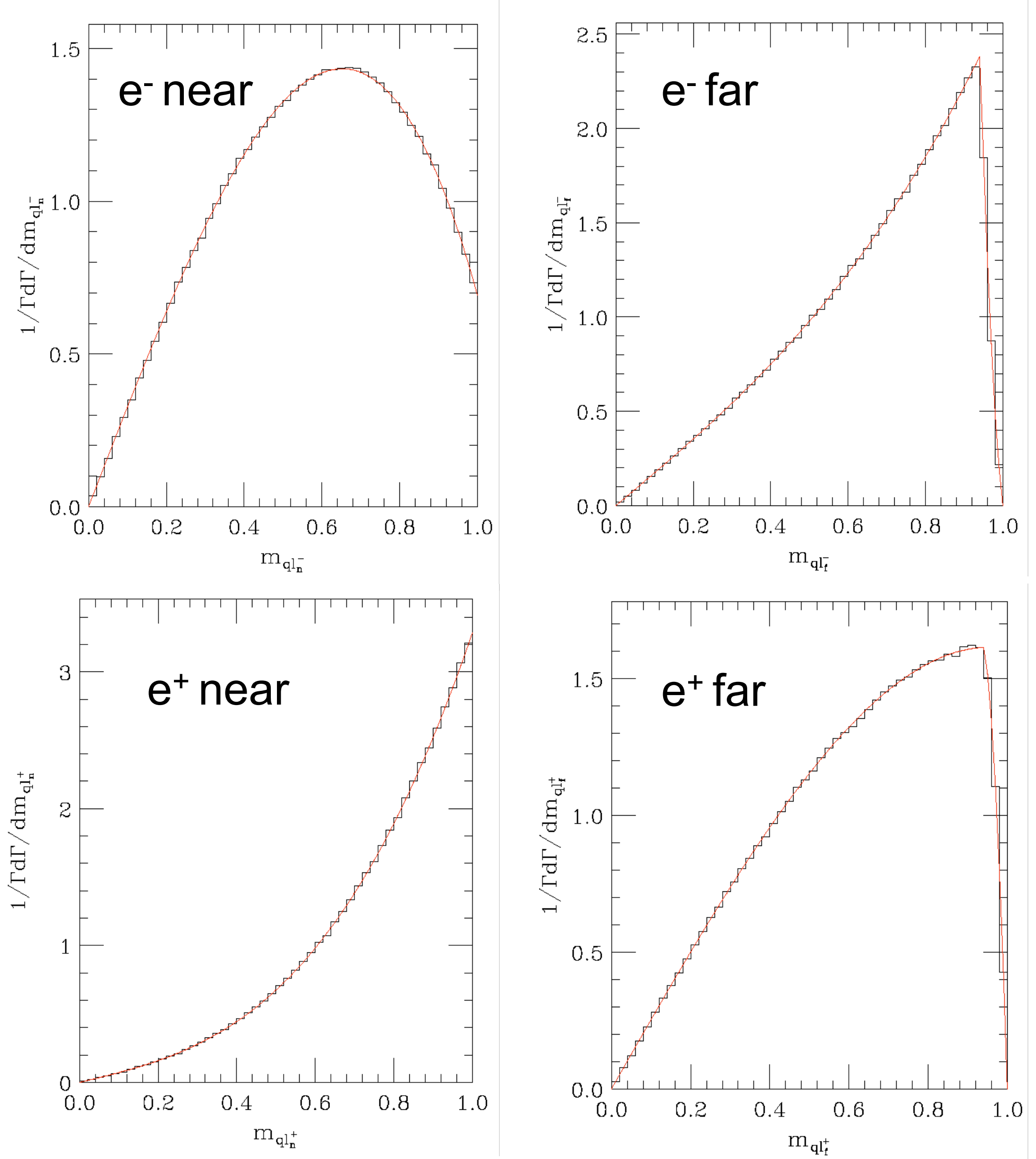
Herwig++ New Physics: UED

Analogous decay:





J Smillie, BW JHEP10 (2005), hep-ph/0507170

PYTHIA history

- 1978: work begun on JETSET: string fragmentation in e^+e^-
- 1982: work begun on PYTHIA: hadron collisions on top of JETSET
- 1997: the two program combined under PYTHIA label
- today: PYTHIA 6.410, 75 000 lines of code, 580 pp manual (JHEP), author team: Torbjörn Sjöstrand, Stephen Mrenna, Peter Skands
- intensely used for LEP, Tevatron, LHC (since 1990!), . . .

. . . but

- only add, never subtract

$\Rightarrow$ has become bloated and unmanageable

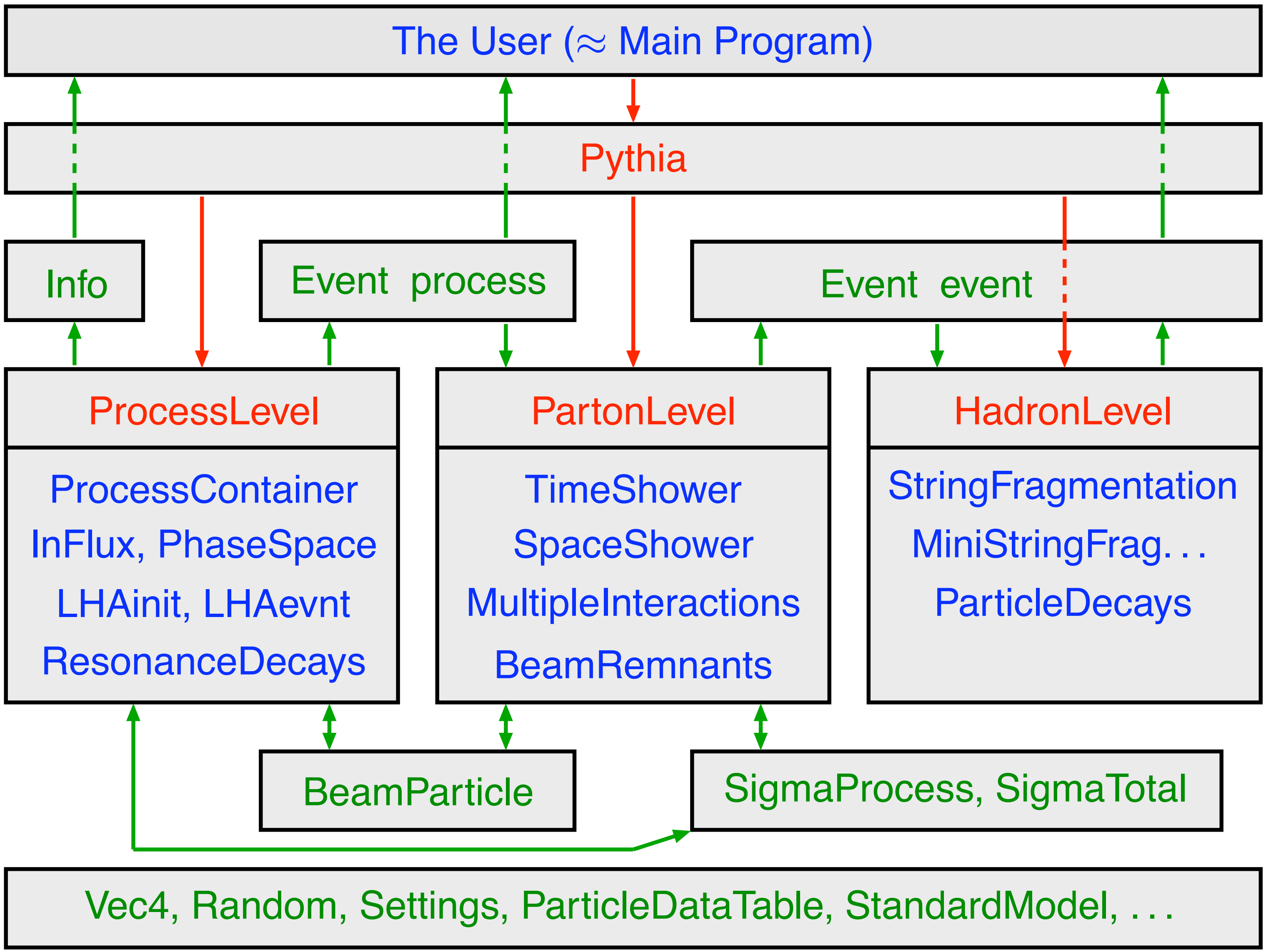
- is in Fortran 77, so not understood by young people

- 1998: C++ PYTHIA 7 begun $\Longrightarrow$ THEPEG, physics stalled
- Sep 2004: C++ PYTHIA 8 begun
- $\sim$1 sub-subversion per working week (T. Sjöstrand on “sabbatical”)
- March 2007: PYTHIA 8.080
- October 2007: PYTHIA 8.100; overtakes PYTHIA 6 as “current”

PYTHIA 8 status

task	status
administative structure	operational; extensions planned
hard processes, internal	Standard Model $2 \to 1/2$; more needed
resonance decays	Standard Model; more needed
hard processes, external	interfaces to LHA F77, LHEF, PYTHIA 6
SUSY(+more) parameters	primitive SLHA2; more needed
initial-state showers	operational
final-state showers	operational
matching ME's to showers	some exists; much more needed
multiple interactions	operational; extensions planned
beam remnants & colour flow	operational; alternatives to come
parton densities	only 2 internal, but interface to LHAPDF
string fragmentation	operational; improvements planned
decays & particle data	operational; may need updates
Bose-Einstein	operational; off by default (tuning)
analysis	some simple tools; may be enough
graphical user interface	operational; could be extended
tuning	major task for MCnet postdocs!

Current PYTHIA 8 structure



Introducing SHERPA

Physics of SHERPA

T.Gleisberg, S.Höche, F.K., A.Schälicke, S.Schumann and J.C.Winter, JHEP **0402** (2004) 056

- New event generator, written from scratch in C++.
- Matrix elements from AMEGIC, combined with own parton shower implementation

  (F.K., A.Schälicke and G.Soff, arXiv:hep-ph/0503087; similar to shower in PYTHIA)
- Hadronization of Pythia interfaced, will be replaced by own cluster model

  (J.Winter, F.K. and G.Soff, Eur. Phys. J. C**36** (2004) 381)
- Tested in a number of processes (highlights see below).
- A few other implementations exist for specific channels.

Automatic cross section calculators

Example: AMEGIC++

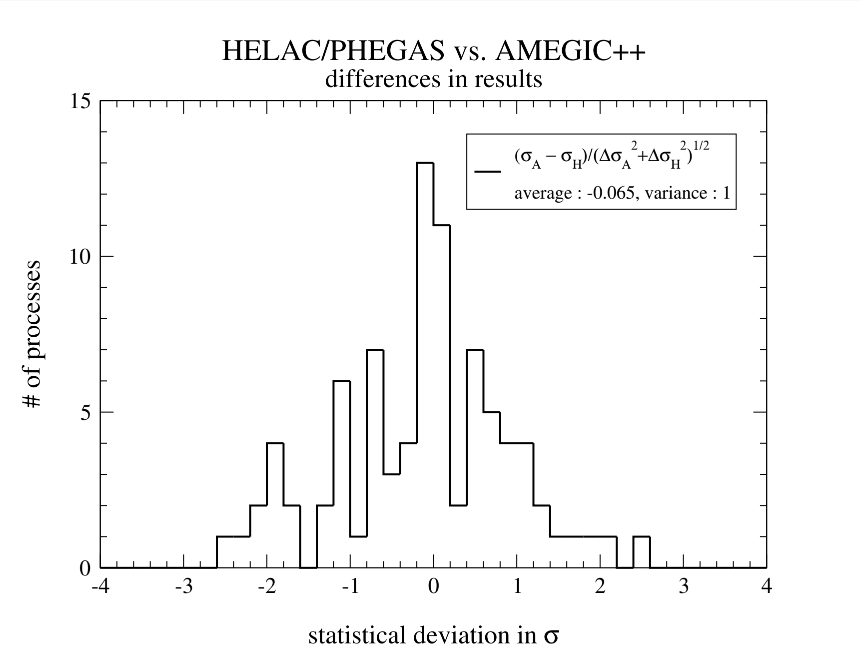
F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- Uses helicity method + multi-channeling.
  Operational mode: 2 runs.
  - Generation run:
    - Generate Feynman diagrams,
    - construct and simplify helicity amplitudes,
    - produce integration channels,
    - write out library files.
  - Compile & link libraries.
  - Production run:
    - cross section calculations,
    - parton level events.
- Implemented & tested models: SM, MSSM, ADD.

Standard Model @ Linear Collider

Consistency of HELAC/PHEGAS & AMEGIC++

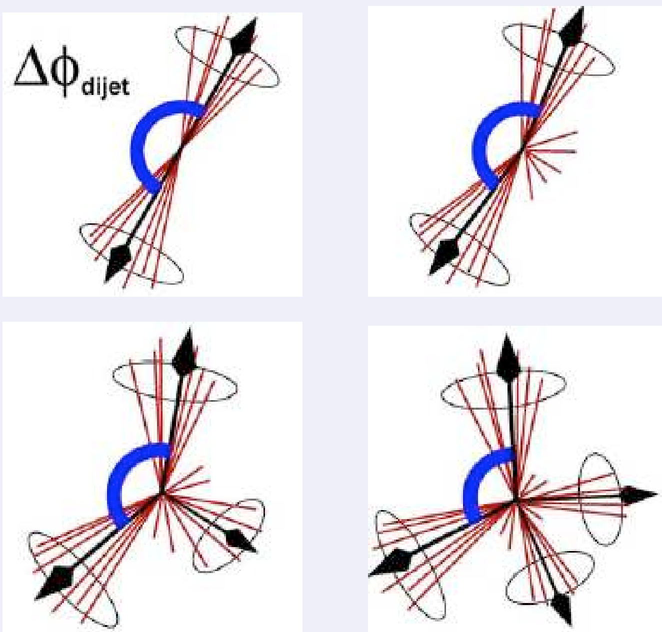
T.Gleisberg, F.K., C.Papadopoulos, A.Schälicke and S.Schumann, Eur. Phys. J. C **34** (2004) 173



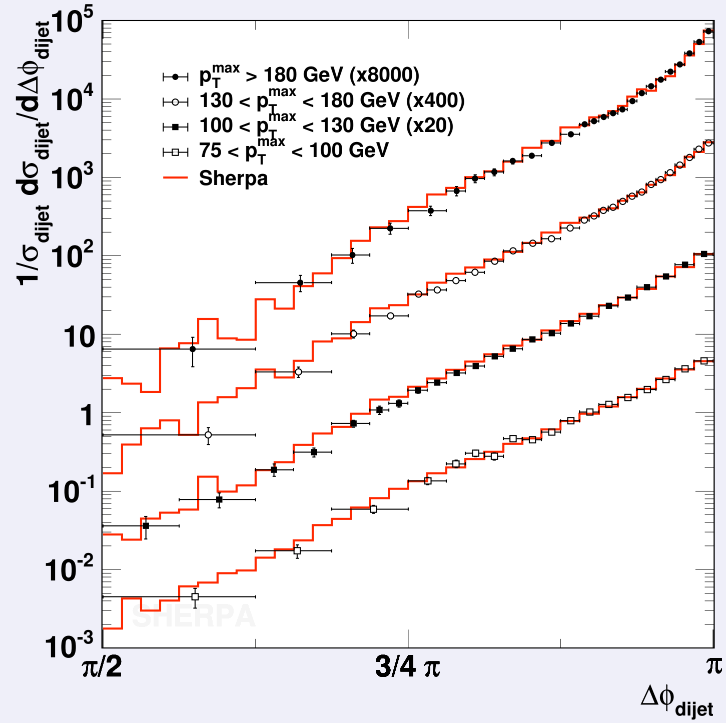
Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern



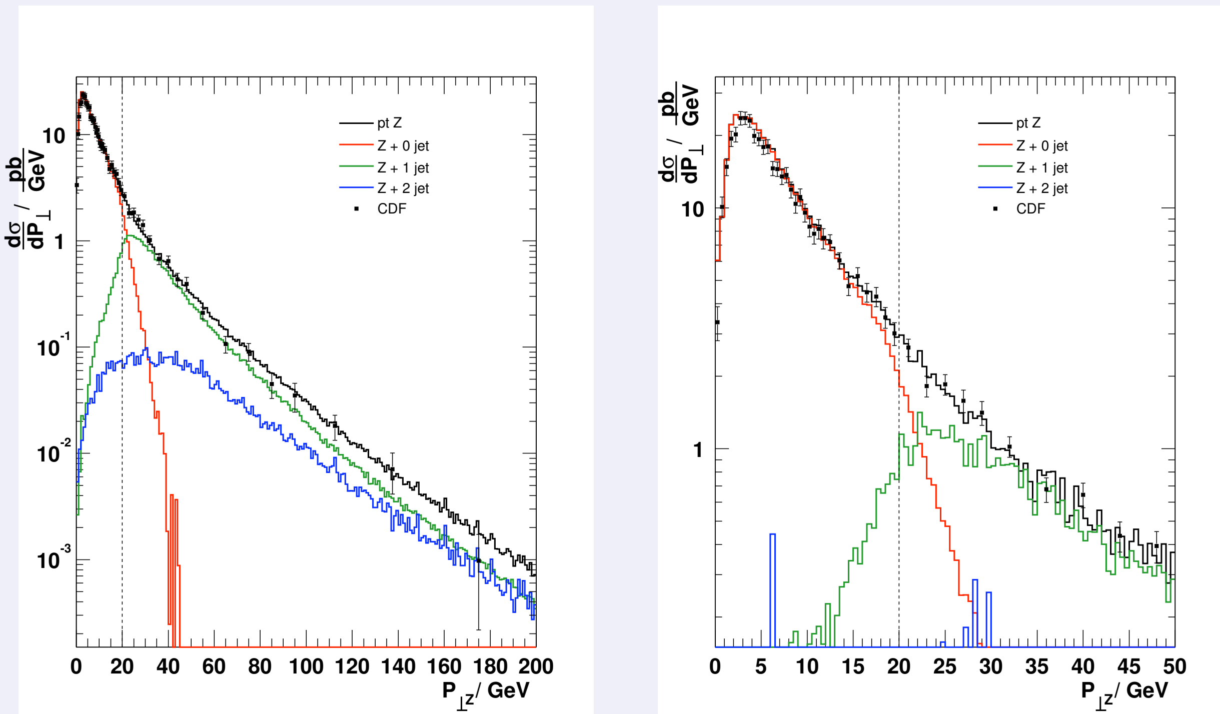
Distributions @ Run II



Comparison with data from Tevatron

$p_\perp$ of Z-bosons in $p\bar{p} \to Z + X$

Data from CDF, Phys. Rev. Lett. 84 (2000) 845



MSSM

Automated tools

K.Hagiwara *et al.*, arXiv:hep-ph/0512260;

- 3 validated tools for MSSM studies: (S)MadGraph, O'Mega/Whizard & Amegic;
- completely different approaches & notations;
- SUSY spectra through SLHA interface;
- checked roughly 500 pair-production processes;
- some simple studies for LHC and LC.

Summary on Event Generators

- Get to know your event generator!
- Remember what is fixed by LEP and HERA data
- Question what isn't
- Tevatron data crucial testing ground

- The next generation is here…
  - Software improvements
  - Physics improvements