Matching of Matrix Elements and Parton Showers with MadEvent and Pythia

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Outline

Why Matching? – Matrix elements vs. parton showers

Matrix elements

1. Fixed order calculation
2. Limited number of particles
3. Valid when partons are hard and well separated
4. Quantum interference correct
5. Needed for multi-jet description

Parton showers

1. Resums large logs
2. No limit on particle multiplicity
3. Valid when partons are collinear and/or soft
4. Partial quantum interference through angular ordering
5. Needed for hadronization/ detector simulation

Matrix element and Parton showers complementary approaches

Both necessary in high-precision studies of multijet processes

Need to combine them without double-counting!

Parton showering

- QCD strahlung from soft/collinear emission approximation
- Evolves down from hard interaction scale to hadronization scale/initial state hadron scale
- Sudakov form factors gives non-branching probability between scales

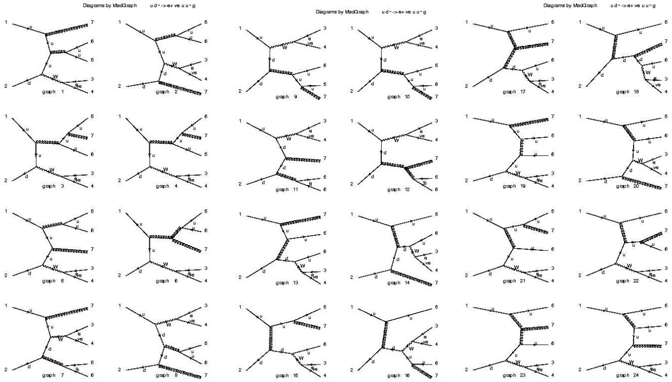
$$\Delta^{\mathrm{LL}}(t_1, t_2) = \exp\left\{ -\int_{t_2}^{t_1} \frac{dt'}{t'} \int_{\epsilon(t)}^{1-\epsilon(t)} dz \frac{\alpha_s(t)}{2\pi} \widehat{P}(z) \right\}$$

- t_2 distribution from $-\frac{d\Delta(t1,t2)}{dt_2}$
- z distribution from QCD splitting functions $P_{a\to bc}(z)$
- For initial state radiation (backward evolution), extra factor of $f(x, t_2)/f(x, t_1)$ at each splitting to account for parton content at different scales
- Different choice of evolution variable t in different generators

Pythia: Q^2 (old), p_T^2 (new) – Herwig $E^2\theta^2$ – Ariadne p_T^2 $(2 \to 3)$

Matrix element generators

Use complete matrix element



Diagrams for $u\bar{d} \to e^+\nu_e u\bar{u}g$ by MadGraph

- Get appropriate description for well separated jets (away from collinear region)
- Get interference effects/correlations correctly

Examples: MadGraph/MadEvent, Alpgen, HELAC, Sherpa

Matching schemes

The simple idea behind matching

- Use matrix element description for well separated jets, and parton showers for collinear jets
- Phase-space cutoff to separate regions

This allows to combine different jet multiplicities from matrix elements without double counting with parton shower emissions

Difficulties

- Get smooth transition between regions
- No/small dependence from precise cutoff
- No/small dependence from largest multiplicity sample

How to accomplish this

Two solutions so far:

- CKKW matching
- MLM matching

(Interesting newcomer: SCET M. Schwartz)

CKKW matching

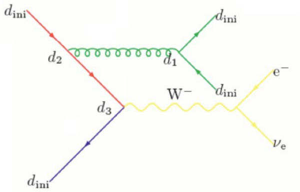
Catani, Krauss, Kuhn, Webber [hep-ph/0109231], Krauss [hep-ph/0205283]

Imitate parton shower procedure for matrix elements

1. Choose a cutoff (jet resolution) scale $d_{\rm ini}$
2. Generate multiparton event with $d_{\rm min} = d_{\rm ini}$ and factorization scale $d_{\rm ini}$
3. Cluster event with k_T algorithm to find "parton shower history"
4. Use $d_i \simeq k_T^2$ in each vertex as scale for α_s
5. Weight event with NLL Sudakov factor $\Delta(d_j, d_{\rm ini})/\Delta(d_i, d_{\rm ini})$ for each parton line between vertices i and j (d_j can be $d_{\rm ini}$)
6. Shower event, allowing only emissions with $k_T < d_{\rm ini}$ ("vetoed shower")
7. For highest multiplicity sample, use $\min(d_i)$ of event as $d_{\rm ini}$

Boost-invariant k_T measure:

$$\begin{cases} d_{iB} = p_{T,i}^2 \\ d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) F_{ij} \end{cases}$$
$$F_{ij} = \cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)$$

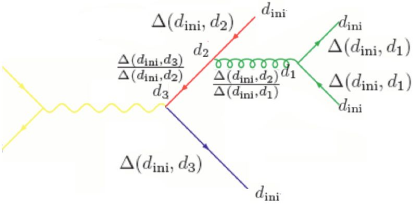


Sudakov reweighting

Telescopic product – in the example:

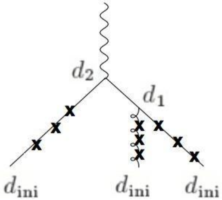
$$[\Delta_q(d_3, d_{ini})]^2 \frac{\Delta_g(d_2, d_{ini})}{\Delta_g(d_1, d_{ini})}$$

$$\times \Delta_q(d_1, d_{ini})\Delta_q(d_1, d_{ini})$$



Vetoed showers

- Start shower for parton at scale of mother node (*cf.* upper scale for Sudakov suppression)
- Veto (forbid) emissions with $d > d_{ini}$, but continue shower as if emission happened
- Allow emissions below d_{ini}

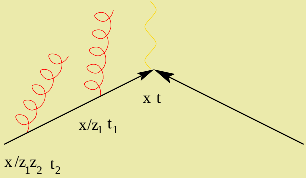


PDF factors in the Krauss algorithm

Want to account for probability of PS configuration in ME correction weight

For ISR process shown, get PS probability:

$$\Delta_q(t, t_{\rm ini})^2 \Delta_g(t1, t_{\rm ini}) \Delta_g(t2, t_{\rm ini}) \times \frac{q(x_2, t_{\rm ini})}{q(x_2, t)} \frac{q(x_1/z_1 z_2, t_{\rm ini})}{q(x_1/z_1 z_2, t_2)} \times \frac{q(x_1/z_1 z_2, t_2)}{q(x_1/z_1, t_1)} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{qq}(z_2)}{z_2} \times \frac{q(x_1/z_1, t_1)}{q(x_1, t)} \frac{\alpha_s(t_1)}{2\pi} \frac{P_{qq}(z_1)}{z_1}$$

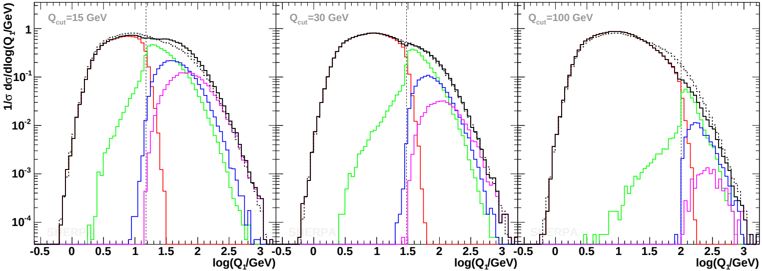


gives, combined with LO cross-section $q(x_1, t)\bar{q}(x_2, t) d\hat{\sigma}_{q\bar{q}\to ll}$:

$$d\sigma_{DY+gg} = \Delta_q(t, t_{\rm ini})^2 \Delta_g(t1, t_{\rm ini}) \Delta_g(t2, t_{\rm ini}) q(x_1', t_{\rm ini}) \bar{q}(x_2, t_{\rm ini}) \times \frac{\alpha_s(t_1)}{2\pi} \frac{\alpha_s(t_2)}{2\pi} \frac{P_{qq}(z_1)}{z_1} \frac{P_{qq}(z_2)}{z_2} d\hat{\sigma}_{q\bar{q}\to ll}(\hat{s}/z_1 z_2)$$

Red: Correction weight Blue: PDFs Green: $d\hat{\sigma}^{PS}_{q\bar{q}\to llgg}(x_1' = \frac{x_1}{z_1 z_2}, x_2)$

- For final-state showers (e^+e^- *collision*):
  Combination of NLL Sudakov factors and vetoed NLL showers guarantees independence of $q_{\rm ini}$ to NLL order
- For initial-state showers: No proof but seems to work ok (Sherpa)
- Problem in practice: No NLL shower implementation!
  (Sherpa uses Pythia-like showers and adapted Sudakovs)



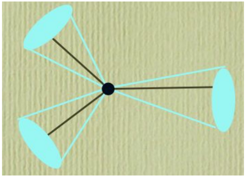
Differential $0 \to 1$ jet rate by Sherpa in $pp \to Z +$ jets for three different cutoffs $d_{\rm ini}$, compared to averaged reference curve [hep-ph/0503280]

MLM matching

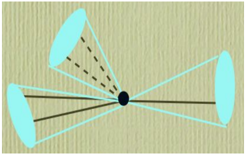
M.L. Mangano [2002, Alpgen home page, hep-ph/0602031]

Use parton shower to choose events

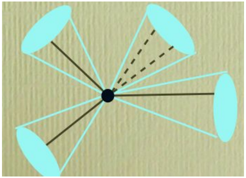
1. Generate multiparton event with cut on jet $p_{T\mathrm{min}}$, η_{max} and ΔR_{min}, and factorizations scale = "central scale" (e.g. transverse mass)
2. Cluster event (according to color) and use k_T^2 for α_s scale
3. Shower event (using Pythia or Herwig) starting from fact. scale
4. Collect showered partons in cone jets with same ΔR_{min} and $p_{T\mathrm{cut}} > p_{T\mathrm{min}}$
5. Keep event only if each jet matched to one parton ($\Delta R(\mathrm{jet}, \mathrm{parton} < 1.5\Delta R$)
6. For highest multiplicity sample, allow extra jets with $p_T < p_{T min}^{\mathrm{parton}}$



Keep



Discard



Keep only if highest multiplicity

Differences between CKKW and MLM

- CKKW scheme: Assumes intimate knowledge of and modifications to parton shower. Needs analytical form for parton shower Sudakovs.
- MLM scheme: Effective Sudakov suppression directly from parton shower
- However: MLM not sensitive to parton types of internal lines (remedied by pseudoshower approach, see below)
- Factorization scale: In CKKW jet resolution scale, in MLM central scale. Not clear (?) which is better.
- Highest multiplicity treatment – less obvious in MLM than in CKKW

CKKW with pseudoshowers

Lönnblad [hep-ph/0112284] (ARIADNE)
Mrenna, Richardsson [hep-ph/0312274]

- Apply parton shower stepwize to clustered event, reject event if too hard emission
- Apply vetoed parton shower as in the CKKW approach

Matching schemes in MadEvent

J.A. et al. [*in preparation*] (*cf.* Mrenna, Richardsson [hep-ph/0312274])

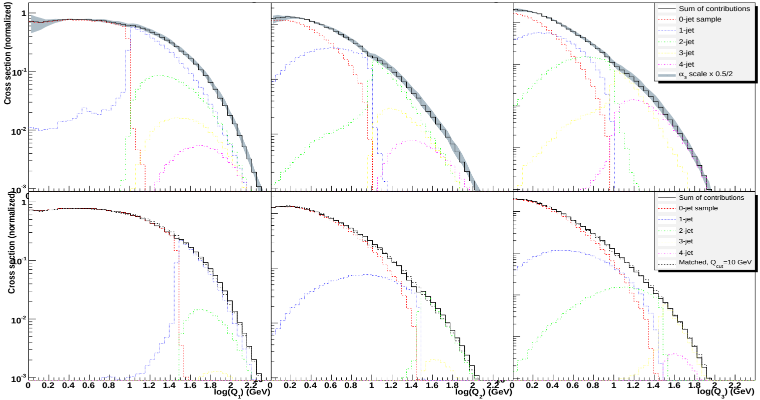
- CKKW scheme (for Sherpa showers) (with S. Höche)
- MLM scheme (Pythia showers)
- MLM scheme with k_T jet clustering (Pythia showers)
- Event rejection at parton shower level (*work in progress*)

Details of MadEvent k_T MLM scheme

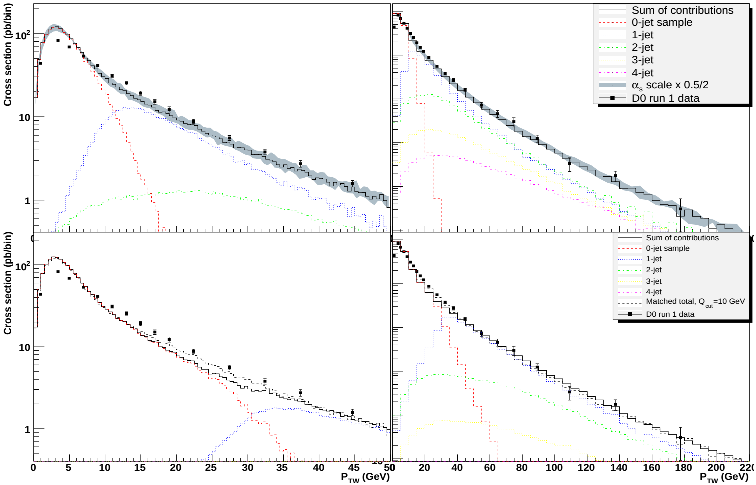
1. Generate multiparton event with jet measure cutoff $d_{\rm min}$
2. Cluster event (according to diagrams) and use k_T for α_s scale
3. Shower event with Pythia starting from highest clustering scale (= factorization scale)
4. Perform jet clustering with k_T algorithm with $d_{\rm cut} > d_{\rm min}$
5. Match clustered jets to partons ($d(\rm jet, parton) < d_{\rm cut}$)
6. Discard events where jets not matched
7. For highest multiplicity sample, jets matched if $d(\rm jet, parton) < d_{\rm min}(\rm parton, parton)$

Results 1: $W^{\pm}$ + jets

- Important background (especially at the Tevatron)
- Only one hard scale
- Mainly initial state radiation
- Implemented by all matching softwares



Differential $0 \to 1$, $1 \to 2$, $2 \to 3$ jet rates at parton level by MadEvent + Pythia in $p\bar{p} \to W +$ jets at the Tevatron, $d_{\text{cut}} = 10$ GeV (top), 30 GeV (bottom).



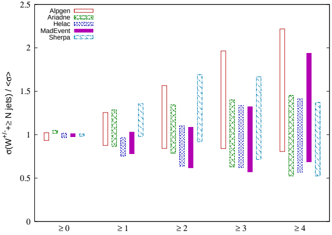
p_T of $W^{\pm}$ by MadEvent + Pythia in $p\bar{p} \to W$ + jets at the Tevatron, $d_{\text{cut}} = 10$ GeV (top), 30 GeV (bottom).

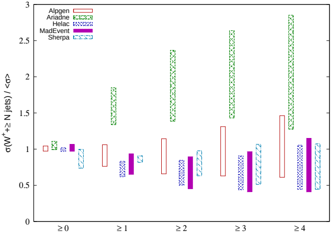
Note:
Pure Pythia shower (without matrix element corrections) below cut.

Comparison between codes

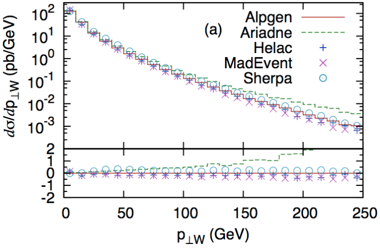
J.A. et al. [hep-ph/soon]

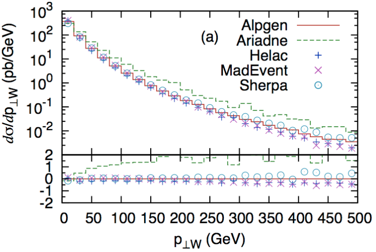
Alpgen+Herwig, Ariadne, Helac+Pythia, MadEvent+Pythia, Sherpa





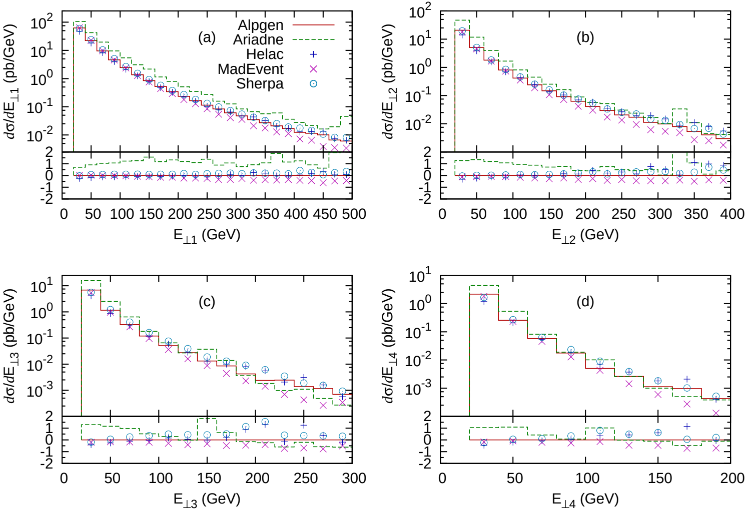
Jet rates at the Tevatron (top) and LHC (bottom)



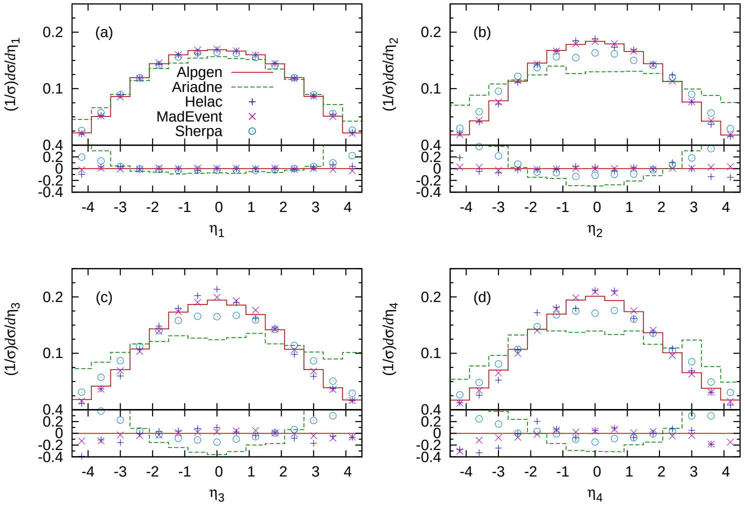


p_T of the $W^{\pm}$ at the Tevatron (top) and LHC (bottom)

$W^{\pm}$ + jets comparison plots: Jet E_T for LHC



$W^{\pm}$ + jets comparison plots: Jet η for LHC

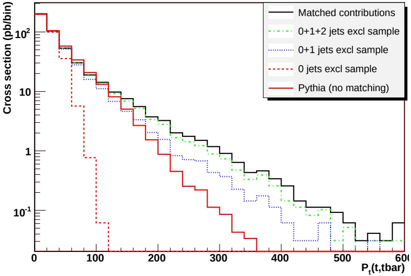


Results 2: Top pairs + jets at LHC

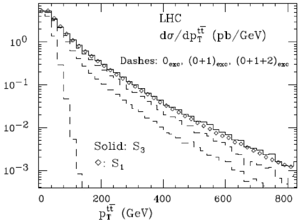
J.A., S. de Visscher et al. [*in preparation*]

One of the most important backgrounds to new physics at the LHC

p_T of the $t\bar{t}$ pair – indicator of jet activity/hardness

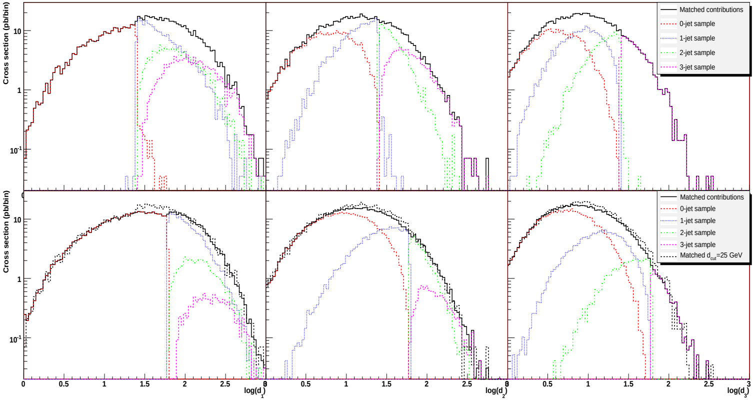


Matched MadEvent+Pythia $t\bar{t}$ + jets compared to only $t\bar{t}$ + Pythia parton showers



Matched Alpgen+Herwig – agrees well within statistics

Differential jet rates (once again) to check smoothness over transition + independence of cut

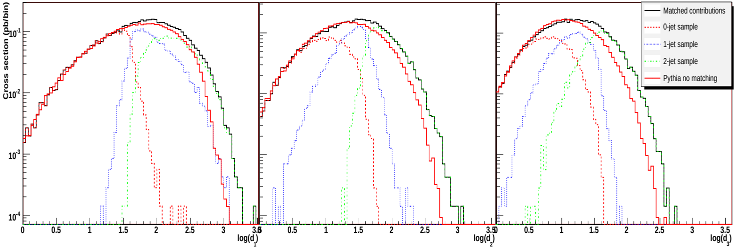


Differential $0 \to 1$, $1 \to 2$, $2 \to 3$ jet rates at parton level by MadEvent + Pythia in $p\bar{p} \to t\bar{t}$ + jets at the LHC,
$d_{\rm cut} = 25$ GeV (top), 60 GeV (bottom). No top decays.

Results 3: Gluino pairs at LHC

Work in progress using new scheme

600 GeV mass gluino pair production (SPS1a) at LHC

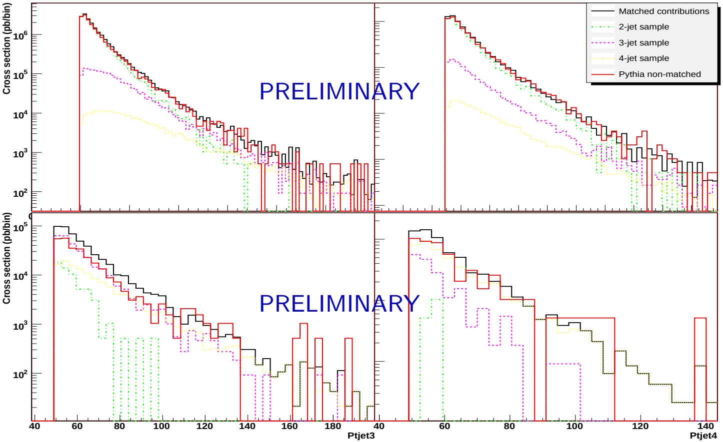


Differential $0 \to 1$, $1 \to 2$, $2 \to 3$ jet rates at parton level by MadEvent + Pythia in $p\bar{p} \to \tilde{g}\tilde{g}$ + jets at the LHC, $d_{\rm cut} = 40$ GeV, compared to default Pythia showers (red curve). No gluino decays.

Results 4: QCD jets at LHC

Work in progress using new scheme

Pure QCD jets – difficult since no fixed hard scale



Steeply falling p_T spectra – Pythia showers (red curve) seems to give OK shape description with the correct starting scale (p_T^2 of jets)

Conclusions

- Matrix elements and parton showers - complementary descriptions of parton production:
  - ME needed to describe hard and widely separated jets
  - PS needed for very high multiplicities / substructure of jets / evolution to hadronization scale
- For realistic description of multijet backgrounds – necessary to combine descriptions: Matching!
- Important backgrounds: $Z/W^{\pm} + \mathrm{jets}$, $t\bar{t} + \mathrm{jets}$, $W^+W^-/ZZ/W^{\pm}Z + \mathrm{jets}$, pure QCD
- Also interesting to study jet structure of signal, e.g. WBF
- Comparison with other codes done!
- Validation with Tevatron data underway
- MadGraph/MadEvent can do it – more studies underway!

Visit us – generate processes – generate events on

http://madgraph.phys.ucl.ac.be

http://madgraph.roma2.infn.it

http://madgraph.hep.uiuc.edu

BACKUP SLIDES

MadGraph/MadEvent

A user-driven matrix element generator and event generator

Madgraph (T.Stelzer and W.F.Long - 1994)

- Matrix element generation
- Identifies all Feynman diagrams and creates Fortran code for the matrix element squared (calls HELAS routines)
- Handles tree-level processes with many particles in the final state
- Keeps full spin correlations / interference

MadEvent (F.Maltoni and T.Stelzer - 2003)

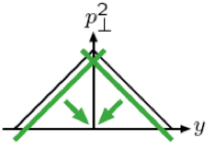
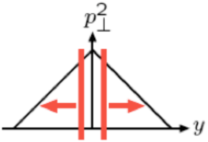
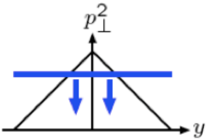
- Phase space integration and event generation
- Uses the MadGraph output and diagram information
- Efficient phase space integration using the technique Single-Diagram-Enhanced multichannel integration

$$f_i = \frac{|A_{\text{tot}}|^2}{\sum_i |A_i|^2} |A_i|^2$$

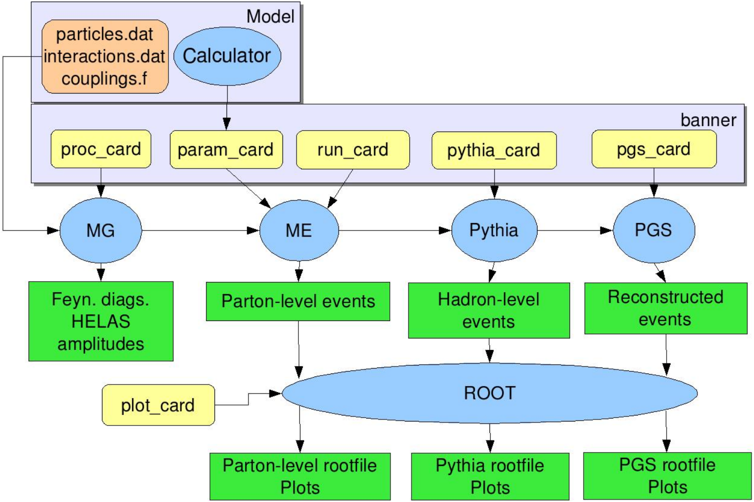
- Algorithm parallell in nature - optimal for clusters!

More about MadGraph/MadEvent

- Models
  - Implemented by default: SM, SUSY, 2HDM, Higgs EFT
  - Framework for easy implementation of new models
  - Soon to come: MadRules (MG files from Lagrangian)
- Tools
  - Pythia and PGS interface for shower/hadronization and detector simulation
  - MadAnalysis, ExRootAnalysis
  - BRIDGE (Reece, Meade): Decay of particles in any MadGraph model
- Complete simulation chain available: from hard scale physics to detector simulation! (MadGraph/MadEvent – Pythia – PGS)
- Web-based generation or download code
- Three public clusters:
  - Belgium (http://madgraph.phys.ucl.ac.be)
  - Italy (http://madgraph.roma2.infn.it)
  - US (http://madgraph.hep.uiuc.edu)

PYTHIA: $Q^2 = m^2$	HERWIG: $Q^2 \sim E^2\theta^2$	ARIADNE: $Q^2 = p_\perp^2$
		
large mass first	large angle first	large $p_\perp$ first
$\Rightarrow$ "hardness" ordered	$\Rightarrow$ **hardness not ordered**	$\Rightarrow$ "hardness" ordered
coherence brute force	coherence inherent	coherence inherent
covers phase space	**gaps in coverage**	covers phase space
ME merging simple	**ME merging messy**	ME merging simple
g $\rightarrow$ q$\overline{\text{q}}$ simple	g $\rightarrow$ q$\overline{\text{q}}$ simple	g $\rightarrow$ q$\overline{\text{q}}$ **messy**
not Lorentz invariant	**not Lorentz invariant**	Lorentz invariant
ISR: $m^2 \rightarrow -m^2$	ISR: $\theta \rightarrow \theta$	**ISR: more messy**

Sherpa like Pythia – New Pythia shower similar to Ariadne


Model
particles.dat
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couplings.f
Calculator
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amplitudes
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Reconstructed
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Plots
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