Basics of Event Generators IV

Leif Lönnblad

Department of Astronomy
and Theoretical Physics
Lund University

MCnet School on Event Generators
São Paulo 2015.04.29

Outline of Lectures

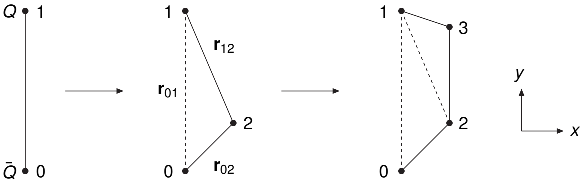
- Lecture I: Basics of Monte Carlo methods, the event generator strategy, matrix elements, LO/NLO, . . .
- Lecture II: Parton showers, initial/final state, matching/merging, . . .
- Lecture III: Matching/merging (cntd.), underlying events, multiple interactions, minimum bias, pile-up, hadronization, decays, . . .
- Lecture IV: Protons vs. heavy ions, summary, . . .

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145.

Outline

DIPSY (with E. Avsar, C. Bierlich, C. Flensburg, G. Gustafson)

The virtual cascade



- Mueller's formulation of BFKL
- $\frac{\mathrm{d}P}{\mathrm{d}y} = \frac{\bar{\alpha}}{2\pi}\mathrm{d}^2 r_2 \frac{r_{01}^2}{r_{02}^2 r_{12}^2}$
- Dipoles in impact parameter space, evolved in rapidity
- Builds up virtual Fock-states of the proton

Non-leading effects

- Running α_s
- Introduce $k_\perp \sim 1/r$ to get energy–momentum conservation.
  (Ordering in p_+ and p_- gives a dynamic cutoff)
- Non-perturbative regularization with small gluon mass (confinement effects)

The interaction

- Dipole–dipole interaction:
  $F = \sum_{ij} f_{ij} \qquad f_{(12)(34)} \propto \alpha_s^2 \ln^2\left(\frac{r_{13}r_{24}}{r_{14}r_{23}}\right)$
- Unitarize to get saturation effects (pomeron loops):
  $F \to 1 - e^{-F}$
- Without energy conservation we get exponential growth of small dipoles which do not interact
- Non-perturbative regularization with small gluon mass
- Rederive Mueller's expression above in transverse momentum space for final states.

The Swing

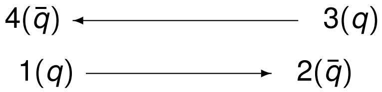
- The unitarized interaction probability gives pomeron loops only in the interaction frame.
- To be Lorentz invariant we want them also in the evolution
- Accomplished by the *Swing* (colour reconnection)
- Two dipoles with the same colour may reconnect.
- Does not reduce the number of dipoles, but smaller dipoles are favoured, and these have weaker interactions.
- In the end we get saturation in both evolution and interaction

Get into the swing

$$1(q) \longrightarrow 2(\bar{q})$$

Swing probability $\propto \frac{r_{12}^2 r_{34}^2}{r_{14}^2 r_{32}^2}$

Get into the swing

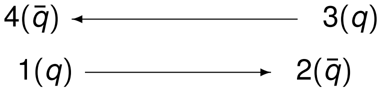


Swing probability $\propto \frac{r_{12}^2 r_{34}^2}{r_{14}^2 r_{32}^2}$

Get into the swing

$$\text{Swing probability} \propto \frac{r_{12}^2 r_{34}^2}{r_{14}^2 r_{32}^2}$$

Get into the swing



$$\text{Swing probability} \propto \frac{r_{12}^2 r_{34}^2}{r_{14}^2 r_{32}^2}$$

We now have a model for inclusive and semi-exclusive observables, which includes explicit modeling of fluctuations in the initial state

- pp and ep-DIS total cross section OK
- pp and ep-DIS (quasi) elastic cross section OK including t-dependence
- pp and ep-DIS diffraction OK
- Double parton scattering at the LHC — interesting predictions
  (σ_{eff} depends more on jet $p_\perp$ than on x and rapidity, arXiv:1103.4320 [hep-ph])

Going further to produce fully exclusive final states is quite complicated.

Real gluons

We have generated the gluonic Fock-states of the colliding protons.

Most of the gluons in this state are simply virtual fluctuations, which will not make it to the final state.

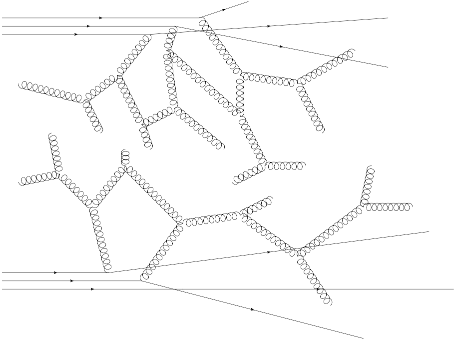
In the momentum picture all gluons in the proton with large p_+ will be off-shell with a negative p_- component.

Only those gluons which actually collides (or have children which collides) with gluons from the proton with large p_- will be able to come on-shell. All others must be reabsorbed.

Virtual vs Real gluons

Once the interactions are in place, it is easy to see the interacting gluon chains.

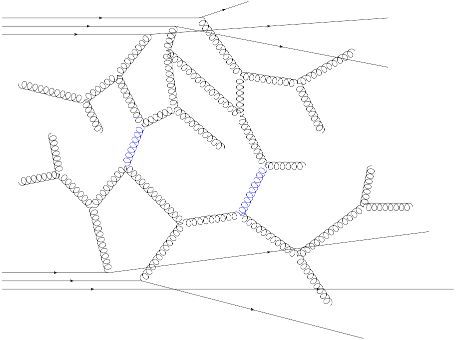
Emissions not on interacting chains are emitted as final state radiation by ARIADNE, removed in DIPSY to not double count.



Virtual vs Real gluons

Once the interactions are in place, it is easy to see the interacting gluon chains.

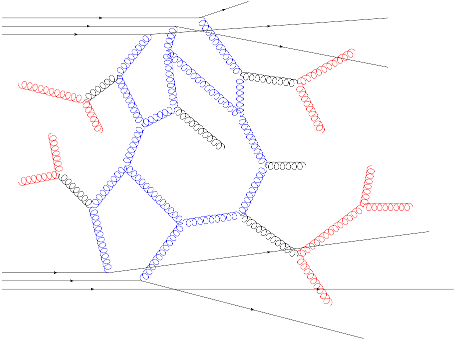
Emissions not on interacting chains are emitted as final state radiation by ARIADNE, removed in DIPSY to not double count.



Virtual vs Real gluons

Once the interactions are in place, it is easy to see the interacting gluon chains.

Emissions not on interacting chains are emitted as final state radiation by ARIADNE, removed in DIPSY to not double count.



But... energy–momentum conservation effects were taken into account assuming all gluons were real. When some are reabsorbed the kinematics will change.

Also some sequences of emissions in the evolution will correspond to local hard scatterings in some frame, and these will not get the proper $\sim 1/q_\perp^4$ behavior.

In the end we want to just have *primary* (a.k.a. backbone) gluons left, which are ordered in both q_+ and q_- (and hence also in rapidity).

These are the ones we know will completely dominate the cross section.

- Choose which dipoles interact: $1 - e^{-F_{ij}}$
- Take away non-interacting gluons
- Take away kinematically impossible interactions/gluons
- Take away wrongly distributed sub-scatterings
- Take away non-ordered gluons

Final state radiation and hadronization

The primary gluons are now sent to ARIADNE for final-state showering.

This is a unitary procedure and only emissions which are *unordered* in q_+ and q_- w.r.t. the primary gluons are allowed.

Then we send everything to PYTHIA8 for hadronization.

Frame-independence

We have quite a lot of parameters:

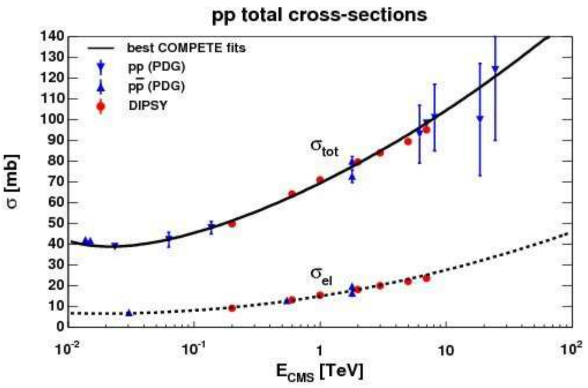
- $R_{\max}$: Non-perturbative regularization
- R_p: Proton size ($\approx R_{\max}$)
- w_p: Fluctuations in the initial proton size (small)
- Λ_{QCD}: in the running α_s
- λ_r: Swing parameter (saturated)

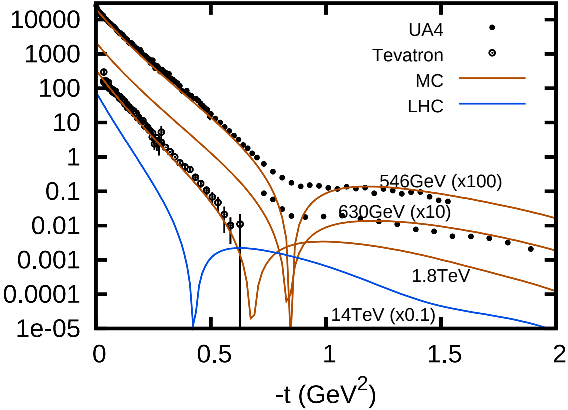
Most of these can be fit to the total and elastic cross sections.

But there are also a lot of choices made for which no guidance can be found in perturbative QCD, especially for the selection of the real gluons.

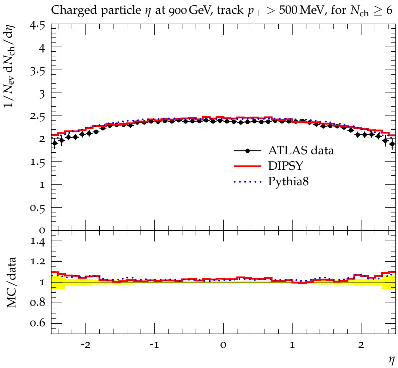
Most of these can be fixed by requiring frame-independence.

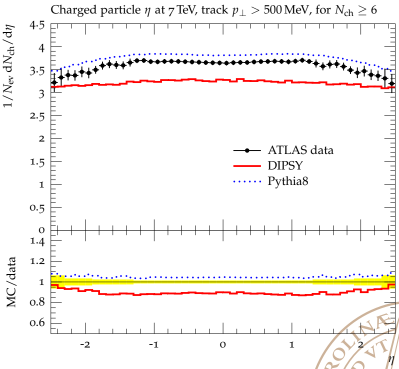
Inclusive cross sections.

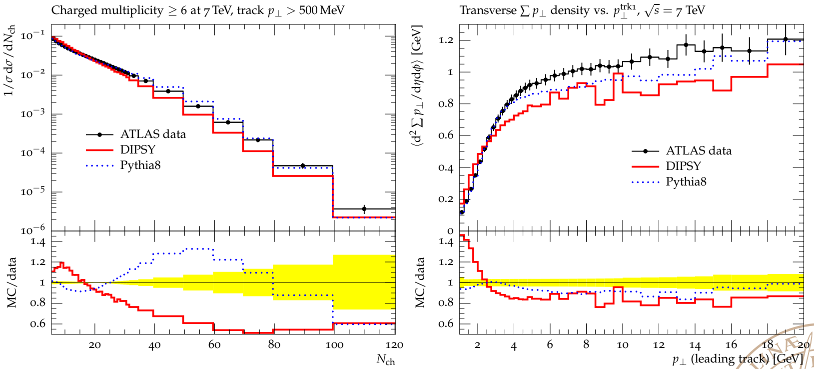



10000
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
0
0.5
1
1.5
2
-t (GeV^2)
UA4
Tevatron
MC
LHC
546GeV (x100)
630GeV (x10)
1.8TeV
14TeV (x0.1)

Minimum-Bias Observables






Charged multiplicity ≥ 6 at 7 TeV, track $p_\perp > 500$ MeV
$1/\sigma \, d\sigma / dN_{ch}$
MC/data
N_{ch}
ATLAS data
DIPSY
Pythia8
Transverse $\sum p_\perp$ density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
$\langle d^2 \sum p_\perp / d\eta d\phi \rangle$ [GeV]
$p_\perp$ (leading track) [GeV]

More final-state observables can be found on `http://home.thep.lu.se/~leif/DIPSY.html`

In general the description of data is worse than for e.g. PYTHIA8 (Tune 4c), but better than many other generators/tunes (c.f. `mcplots.cern.ch`).

One main problem is the naive valence configuration used: we may get very high energy gluons interacting and giving too hard jets in the forward region.

Other issues:

- Frame dependence
- Final state swing
- Hadronization of dense string configurations

The DIPSY model in unique in its treatment of correlations and fluctuations in the colliding protons, and even if it does not describe final states as well as PYTHIA8 it is still interesting.

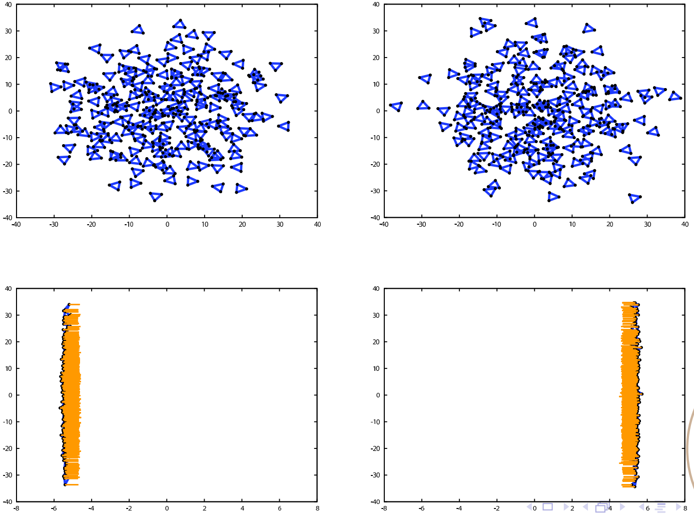
Especially for understanding multiple interactions and minimum bias.

And the extention to also model heavy-ion collisions is "trivial"

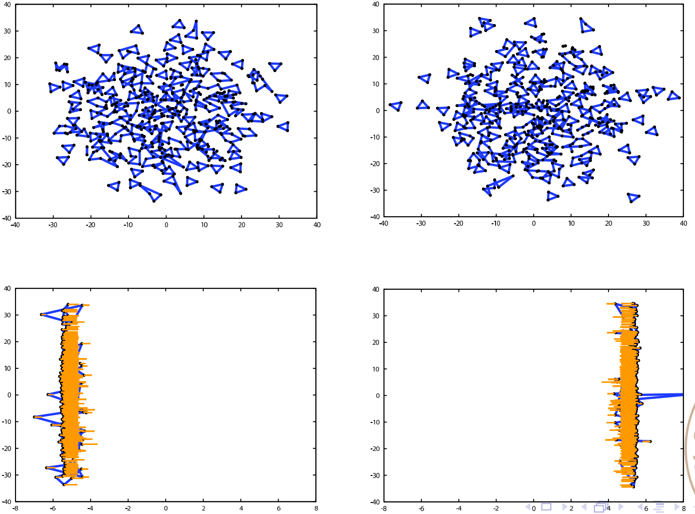
Heavy Ions

- An ion starts as *A* nucleons (dipole triangles) distributed in transverse space.
  - Wood-Saxon with hard core.
- The swings, within and between nucleons, describe the saturation in the evolution.
- Get a full partonic picture with both momentum and transverse position.
- Dynamically describes all fluctuations and correlations.
- No new model dependence! (only nucleon distribution) Everything tuned from *pp* and $\gamma^* p$.
- (DIPSY is a bit too slow right now, ∼30 min for a PbPb-event at LHC)

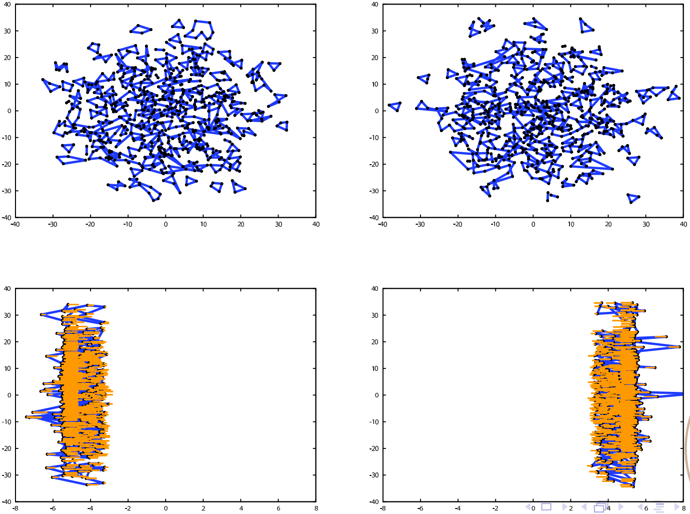
Sample Au-Au event



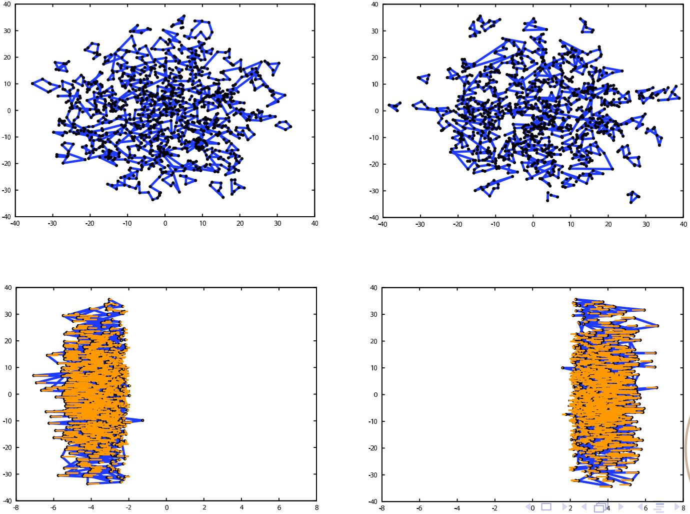
Sample Au-Au event



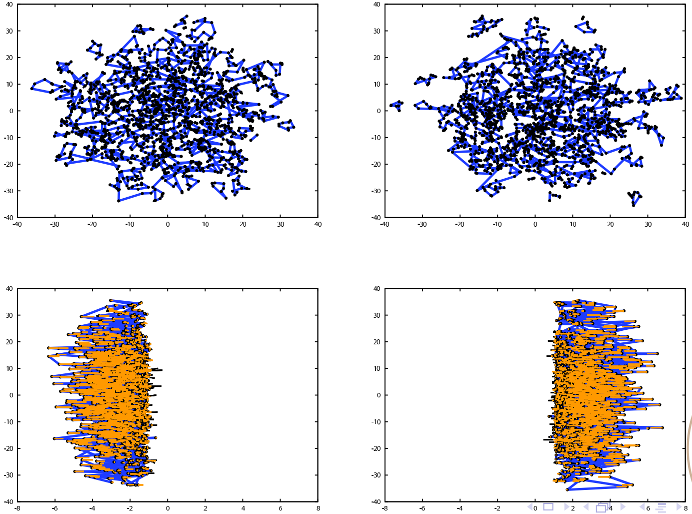
Sample Au-Au event



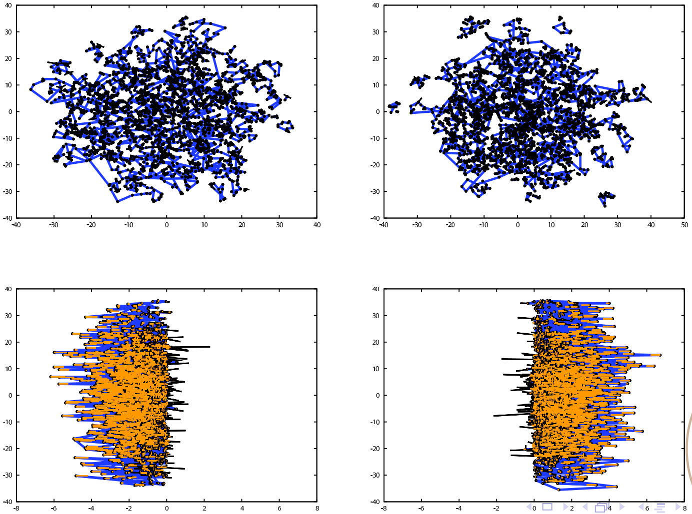
Sample Au-Au event



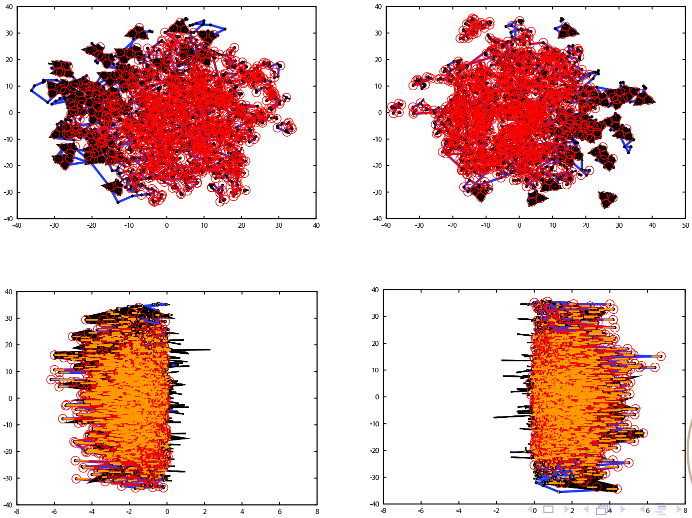
Sample Au-Au event



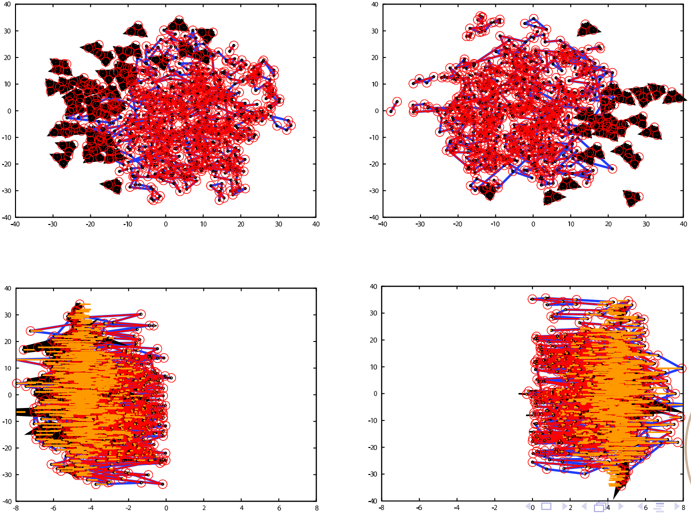
Sample Au-Au event



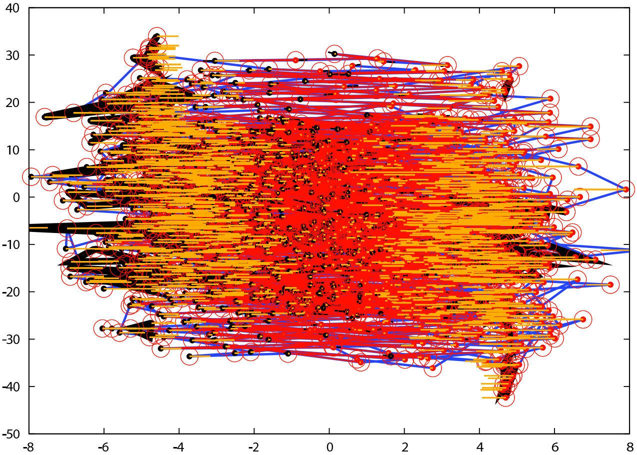
Sample Au-Au event



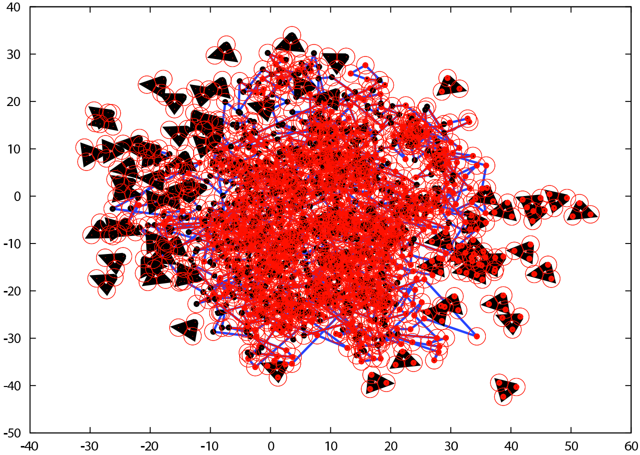
Sample Au-Au event



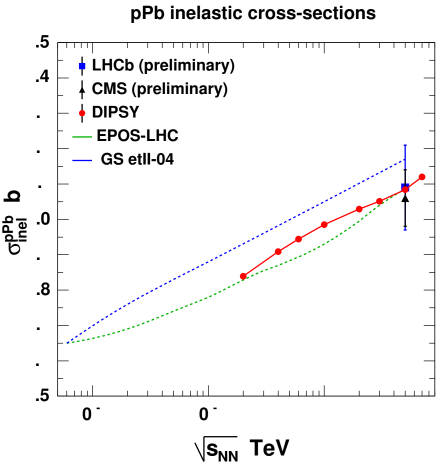
Sample Au-Au event



Sample Au-Au event



p-A collisions



General Purpose Event Generators

There are only a few programs which deals with the whole picture of the event generation

- Hard sub-processes
- Parton showers
- Multiple interactions
- Hadronization
- Decays

Many more programs deal with a specific part of the event generation

- Hard subprocess: AlpGen, MadEvent, ... can be used with other generators using the Les Houches interface (but be sure to do proper merging)
- Parton Shower: ARIADNE, CASCADE, ... need to integrated with a specific general purpose generator
- Multiple interactions: JIMMY (now integrated with HERWIG)
- Hadroniziation (?)
- Decays: Tauola, EvtGen, typically called from within other generators.

PYTHIA8

- A few simple MEs, the rest from Les Houches
- $k_\perp$-ordered initial-/final-state DGLAP-based shower
- (N)LO multi-leg matching with UNLOPS
- Multiple interactions interleaved with shower
- Lund String Fragmentation
- Particle decays

`http://home.thep.lu.se/~torbjorn/Pythia.html`

HERWIG++

- Construction of arbitrary MEs using helicity amplitudes, but not automized.
- Angular ordered, DGLAP-based shower (with spin correlations)
- Different matching schemes via MatchBox
- JIMMY-based multiple interactions
- Cluster hadronization
- Particle decays with correlations
- Open structure based on THEPEG

`http://projects.hepforge.org/herwig`

SHERPA

- Built-in automated ME generator
- Dipole-based shower
- Semi-automatic (N)LO multi-leg matching
- Multiple interactions ($\sim$ old PYTHIA) with some CKKW features
- Cluster hadronization (string fragmentation via old PYTHIA).
- Standard particle decays.

`http://projects.hepforge.org/sherpa`

Related Tools

Matrix Element Generators

- MadGraph5(aMC@NLO)
- POWHEG
- ALPGEN
- HELAC
- CompHEP
- ...

PDF parametrizations

- LHAPDF

Rivet.hepforge.org

(Buckley et al.)

Analyze Event Generator output and compare with published experimental data, using exactly the same cuts, triggers, etc.

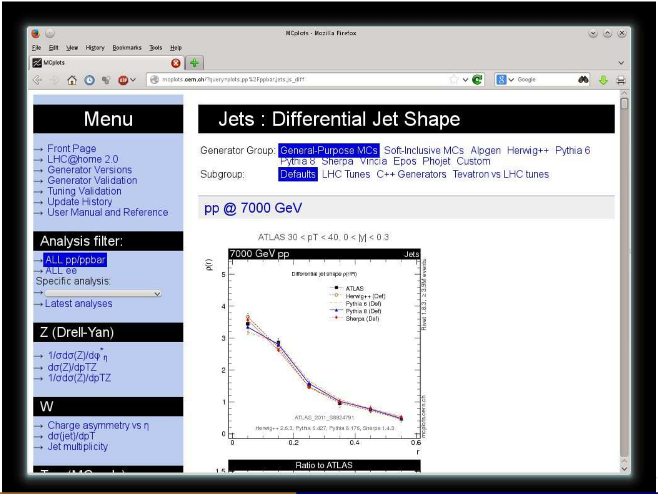
250+ analyses are already in there.

If you want to make your analyses useful for others —
Publish them in Rivet!

Connected to *Professor* for tuning of parameters

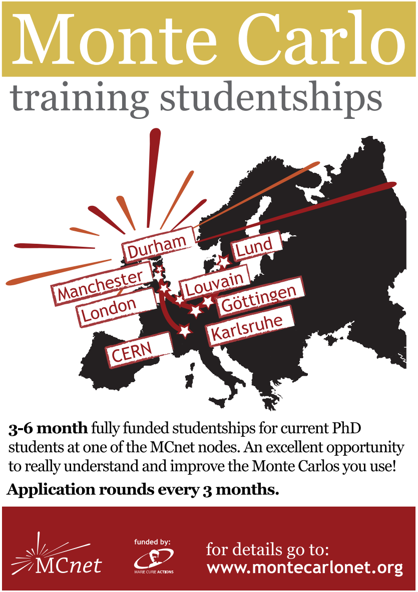
MCplots.cern.ch

(Skands et al.)



All authors of HERWIG, PYTHIA, SHERPA, as well as, THEPEG, ARIADNE, MADGRAPH and RIVET are members of MCnet.

EU-funded research training network with teams in CERN, Durham, Göttingen, Karlsruhe, Manchester, Louvain, Lund and UCL.



MC*net* projects
Pythia
Herwig
Sherpa
MadGraph
Ariadne
CEDAR

The Tenth Commandment of Event Generation