



LUND
UNIVERSITY

Monte Carlo Event Generators — III

Leif Lönnblad

Department of Physics
Lund University

32nd Vietnam School of Physics
ICISE, Quy Nhon Nam, 2026-07-22

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), hadronization, decays. ...
- ▶ Lecture III: Minimum bias, multi-parton interactions, pile-up, summary of general purpose event generators and tools, ...
- ▶ Lecture IV: Protons vs. heavy ions, Glauber calculations, initial/final-state interactions, ...

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145. See also arXiv:2605.16036.



Outline of Lecture III

Minimum Bias

Multiple Interactions

Interleaved showers

Colour connections

Underlying Events

General Purpose Event Generators

PYTHIA

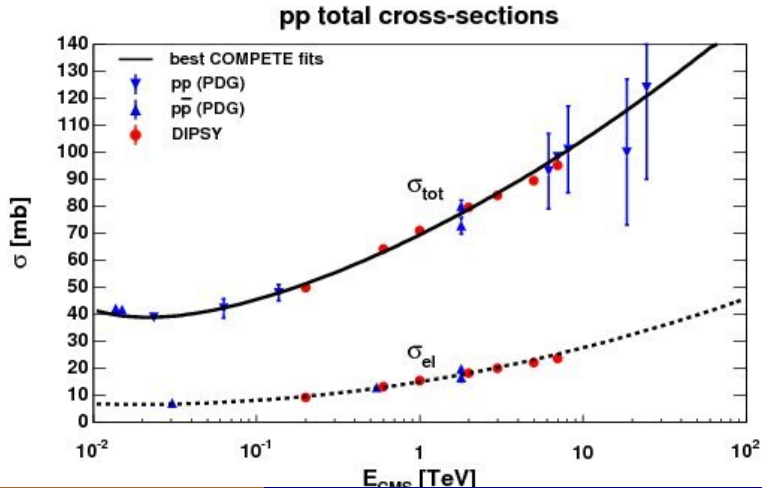
HERWIG

SHERPA

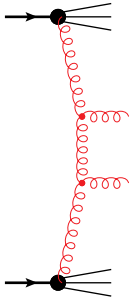
Related Tools



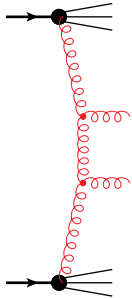
Inclusive cross sections.



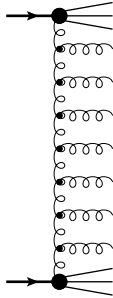
Minimum Bias: The typical pp collision



Minimum Bias: The typical pp collision



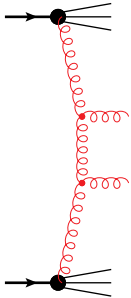
soft $gg \rightarrow gg$



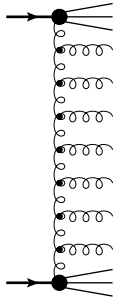
+ISR



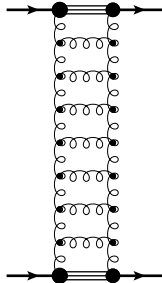
Minimum Bias: The typical pp collision



soft $gg \rightarrow gg$



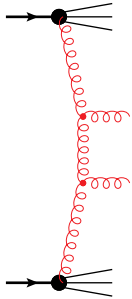
+ISR



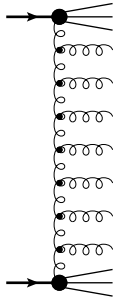
Related to elastic scattering
via optical theorem



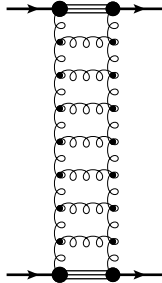
Minimum Bias: The typical pp collision



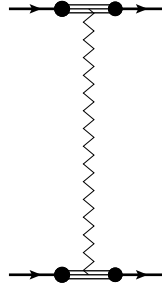
soft $gg \rightarrow gg$



+ISR



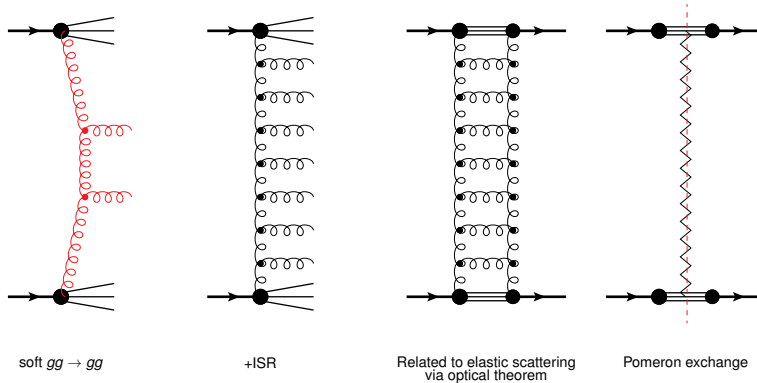
Related to elastic scattering
via optical theorem



Pomeron exchange



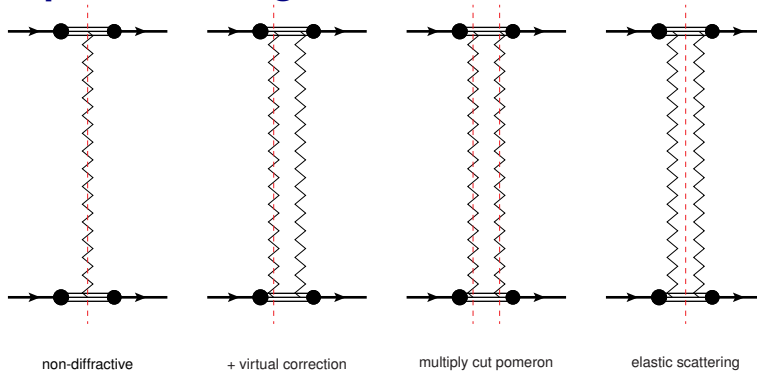
Minimum Bias: The typical pp collision



A **cut** pomeron in an elastic amplitude gives the non-diffractive cross section.
(From **Regge** theory [Regge, T, *Nuovo Cim.* **14** (1959) 951])



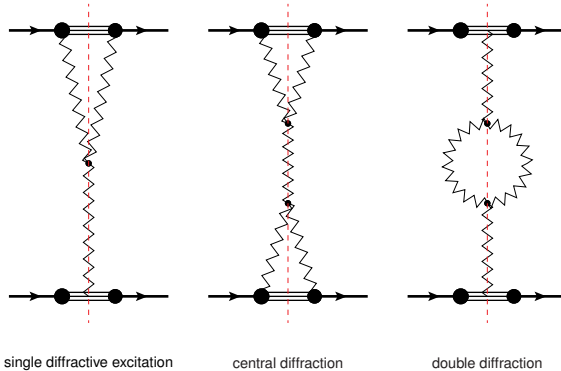
Multi-pomeron diagrams



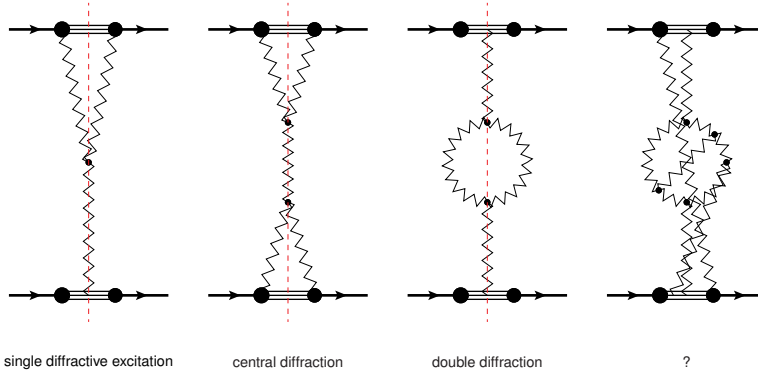
Each cut pomeron contributes with evenly distributed particle production in the corresponding rapidity interval.
Like two flat strings.



Diffraction and triple-pomeron vertices



Diffraction and triple-pomeron vertices



Soft multiple interactions

- ▶ PHOJET [Engel et al.]
- ▶ Shrimps (SHERPA) [Zapp et al.]
- ▶ EPOS-LHC (also Heavy ions) [Werner et al.]

Where are the (mini-) jets?



(Semi-) Hard Multiple Interactions

Starting Point in PYTHIA:

$$\frac{d\sigma^H}{dk_{\perp}^2} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{ij}^H}{dk_{\perp}^2}$$

The QCD $2 \rightarrow 2$ cross section is divergent $\propto \alpha_S^2(k_{\perp}^2)/k_{\perp}^4$

$\int_{k_{\perp c}^2} d\sigma^H$ will exceed the total (non-diffractive) pp cross section at the LHC for $k_{\perp c} \lesssim 5$ GeV.

There are more than one partonic interaction per pp -collision

$$\langle N_H \rangle(k_{\perp c}) = \frac{\int_{k_{\perp c}^2} d\sigma^H}{\sigma^{\text{ND}}}$$



The trick in PYTHIA is to treat everything as if it is perturbative.

$$\frac{d\hat{\sigma}_{ij}^H}{dk_{\perp}^2} \rightarrow \frac{d\hat{\sigma}_{ij}^H}{dk_{\perp}^2} \times \left(\frac{\alpha_S(k_{\perp}^2 + k_{\perp 0}^2)}{\alpha_S(k_{\perp}^2)} \cdot \frac{k_{\perp}^2}{k_{\perp}^2 + k_{\perp 0}^2} \right)^2$$

Where $k_{\perp 0}^2$ is motivated by colour screening (saturation) and is dependent on collision energy.

$$k_{\perp 0}(E_{\text{CM}}) = k_{\perp 0}(E_{\text{CM}}^{\text{ref}}) \times \left(\frac{E_{\text{CM}}}{E_{\text{CM}}^{\text{ref}}} \right)^{\epsilon \sim 0.16}$$

(using handwaving about the the rise of the total cross section)



The total and non-diffractive cross section is put in by hand (or with a Donnachie—Landshoff parameterization).

- Pick a hardest scattering according to

$$\frac{1}{\sigma^{\text{ND}}} \frac{d\sigma^H}{dk_{\perp}^2} \times \exp \left(- \int_{k_{\perp}^2} dq_{\perp}^2 \frac{1}{\sigma^{\text{ND}}} \frac{d\sigma^H}{dq_{\perp}^2} \right)$$

- Pick an impact parameter, b , from the overlap function (high $k_{\perp}$ gives bias for small b).
- Generate additional scatterings with decreasing $k_{\perp}$ using $d\sigma^H(b)/\sigma^{\text{ND}}$



Hadronic matter distributions

We assume that we have factorization

$$\mathcal{L}_{ij}(x_1, x_2, b, \mu_F^2) = \mathcal{O}(b) f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)$$

$$\mathcal{O}(b) = \int dt \int dx dy dz \rho(x, y, z) \rho(x + b, y, z + t)$$

Where ρ is the matter distribution in the proton
(note: general width determined by σ^{ND})

- ▶ A simple Gaussian
- ▶ Double Gaussian
- ▶ x-dependent Gaussian



x-dependent overlap

Small-x partons are more spread out

$$\rho(r, x) \propto \exp\left(-\frac{r^2}{a^2(x)}\right)$$

with $a(x) = a_0(1 + a_1 \log 1/x)$

Note that high $k_{\perp}$ generally means higher x and more narrow overlap distribution.



A note on resummation

There are many scales in an event: $S, \hat{s}, -\hat{t} \sim k_{\perp}^2, \Lambda_{\text{QCD}}^2, m_W^2, \dots$

Every time we have two widely separated scales there may be large logarithms that need to be resummed:

- ▶ $k_{\perp}^2 \gg \Lambda_{\text{QCD}}^2$: DGLAP
- ▶ $S \gg k_{\perp}^2$: BFKL (CCFM)
- ▶ $\hat{s} \gg k_{\perp}^2$: FKL



A note on resummation

There are many scales in an event: $S, \hat{s}, -\hat{t} \sim k_{\perp}^2, \Lambda_{\text{QCD}}^2, m_W^2, \dots$

Every time we have two widely separated scales there may be large logarithms that need to be resummed:

- ▶ $k_{\perp}^2 \gg \Lambda_{\text{QCD}}^2$: DGLAP
- ▶ $S \gg k_{\perp}^2$: BFKL (CCFM)
- ▶ $\hat{s} \gg k_{\perp}^2$: FKL



A note on resummation

There are many scales in an event: $S, \hat{s}, -\hat{t} \sim k_{\perp}^2, \Lambda_{\text{QCD}}^2, m_W^2, \dots$

Every time we have two widely separated scales there may be large logarithms that need to be resummed:

- ▶ $k_{\perp}^2 \gg \Lambda_{\text{QCD}}^2$: DGLAP
- ▶ $S \gg k_{\perp}^2$: BFKL (CCFM)
- ▶ $\hat{s} \gg k_{\perp}^2$: FKL



A note on resummation

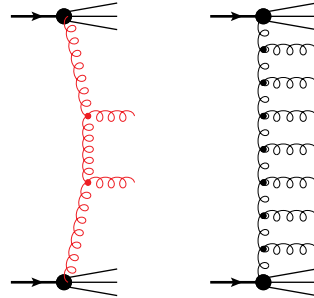
There are many scales in an event: $S, \hat{s}, -\hat{t} \sim k_{\perp}^2, \Lambda_{\text{QCD}}^2, m_W^2, \dots$

Every time we have two widely separated scales there may be large logarithms that need to be resummed:

- ▶ $k_{\perp}^2 \gg \Lambda_{\text{QCD}}^2$: DGLAP
- ▶ $S \gg k_{\perp}^2$: BFKL (CCFM)
- ▶ $\hat{s} \gg k_{\perp}^2$: FKL



Is it reasonable to use collinear factorization even for very small $k_{\perp}$?
Soft interactions means very small x ,
should we not be using $k_{\perp}$ -factorization and BFKL?



For very small x and small $k_{\perp}$ we also have *saturation*:
not only splittings, but also recombinations of gluons.



Energy–momentum conservation

Each scattering consumes momentum from the proton, and eventually we will run out of energy.

- ▶ Continue generating MI's with decreasing $k_{\perp}$, until we run out of energy.
- ▶ Or rescale the PDF's after each additional MI.
(Taking into account flavour conservation).

Note that also initial-state showers take away momentum from the proton.



Interleaved showers

When do we shower?

- ▶ First generate all MI's, then shower each?
- ▶ Generate shower after each MI?

Is it reasonable that a low- $k_{\perp}$ MI prevents a high- $k_{\perp}$ shower emission? Or vice versa?

- ▶ Include MI's in the shower evolution



Interleaved showers

When do we shower?

- ▶ First generate all MI's, then shower each?
- ▶ Generate shower after each MI?

Is it reasonable that a low- $k_{\perp}$ MI prevents a high- $k_{\perp}$ shower emission? Or vice versa?

- ▶ Include MI's in the shower evolution



After the primary scattering we can have

- ▶ Initial-state shower splitting, P_{ISR}
- ▶ Final-state shower splitting, P_{FSR}
- ▶ Additional scattering, P_{MI}
- ▶ Rescattering of final-state partons, P_{RS}

Let them compete

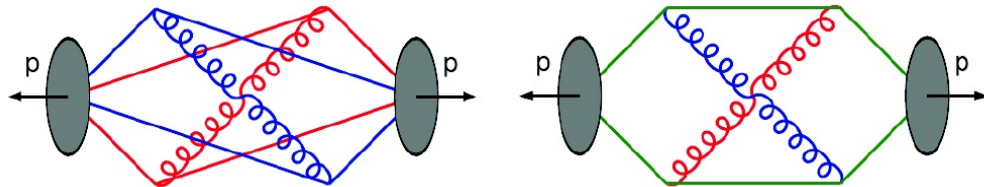
$$\frac{d\mathcal{P}_a}{dk_{\perp}^2} = \frac{dP_a}{dk_{\perp}^2} \times \exp - \left(\int_{k_{\perp}^2} (dP_{\text{ISR}} + dP_{\text{FSR}} + dP_{\text{MI}} + dP_{\text{RS}}) \right)$$



Colour Connections

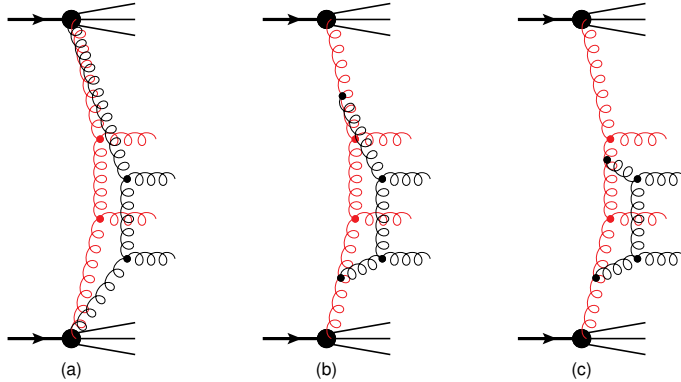
Every MI will stretch out new colour-strings.

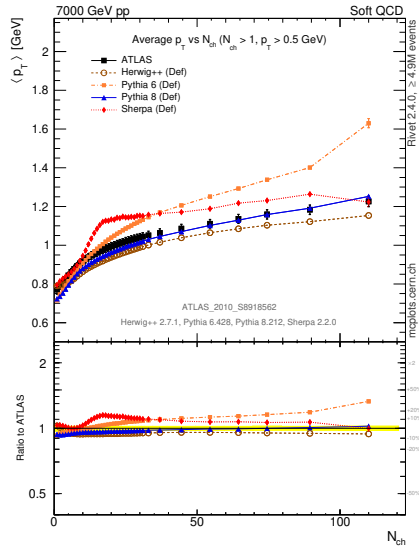
Evidently not all of them can stretch all the way back to the proton remnants.



To be able to describe observables such as $\langle p_{\perp} \rangle (n_{\text{ch}})$ we need (a lot of) colour (re-)connections.







Beyond simple strings

What if we kick out two valens quarks from the same proton?

Normally it is assumed that the proton remnant has a di-quark, giving rise to a leading baryon in the target fragmentation.

PYTHIA8 has can hadronize **string junctions**
(also used for baryon-number violating BSM models)

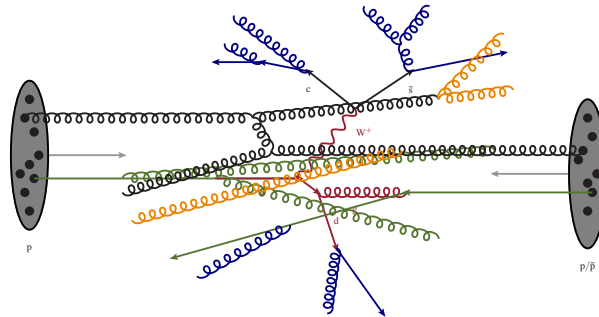
Non-trivial baryon number distribution in rapidity.



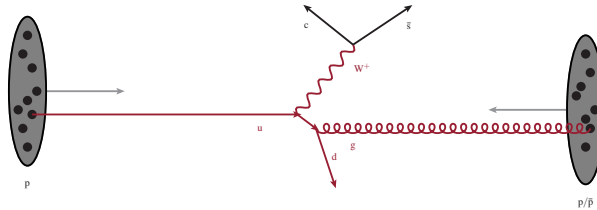
Questions!



What is the Underlying Event?



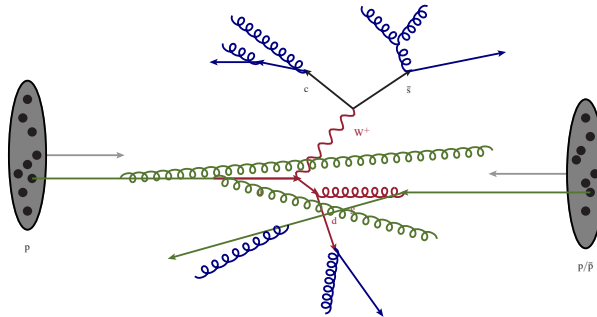
What is the Underlying Event?



Everything except the **hard sub-process**?



What is the Underlying Event?



Everything except the **hard sub-process** and **initial-** and **final-**state showers?



Subtracting underlying events from jets.

- ▶ ISR adds energy
- ▶ FSR removes energy
- ▶ UE adds energy
- ▶ Hadronization removes energy

Some of these can be made to cancel each other by adjusting the size of the jet cone.

But we still need to understand the underlying event.



Subtracting underlying events from jets.

- ▶ ISR adds energy
- ▶ FSR removes energy
- ▶ UE adds energy
- ▶ Hadronization removes energy

Some of these can be made to cancel each other by adjusting the size of the jet cone.

But we still need to understand the underlying event.



UE is not MB

- ▶ Harder processes gives a bias towards larger overlap (smaller b) giving more UE.
- ▶ The UE fluctuates — we can't just subtract a number
- ▶ Beware of jet cuts in a steeply falling spectrum



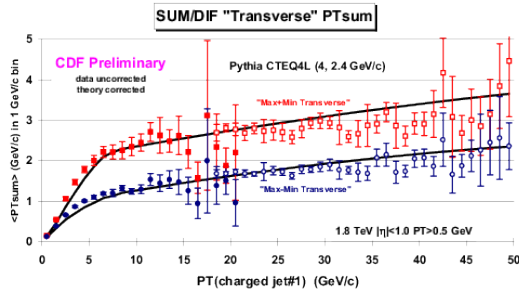
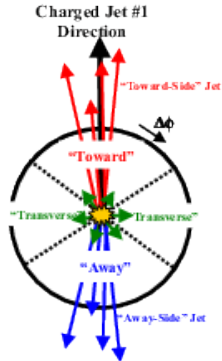
UE is not MB

- ▶ Harder processes gives a bias towards larger overlap (smaller b) giving more UE.
- ▶ The UE fluctuates — we can't just subtract a number
- ▶ Beware of jet cuts in a steeply falling spectrum

Also relevant for pile-up



How to measure the underlying event



A note on Tuning

The Min-bias and UE machineries contains a fair number of parameters that need to be tuned to data. In PYTHIA we have:

- ▶ Soft regularisation parameters
- ▶ Overlap function parameters
- ▶ Cross section parameterisations
- ▶ Colour reconnection parameters
- ▶ Intrinsic transverse momenta
- ▶ PDF choices
- ▶ ...



Global Tuning

General purpose event generators should describe everything. They should not be tuned to a single observable.

- ▶ Hadronization parameters and final-state showers can be tuned to e^+e^- data (LEP).
- ▶ Initial-state showers and UE/MPI can be tuned to MB data.
- ▶ Anythings else should be fixed by measured Standard Model parameters.
- ▶ ... in principle



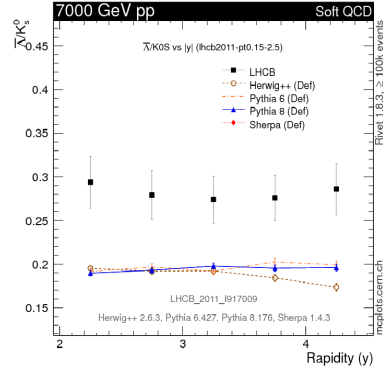
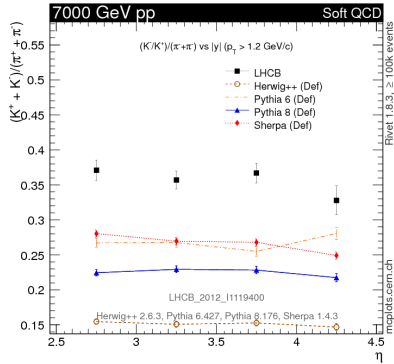
Global Tuning

General purpose event generators should describe everything. They should not be tuned to a single observable.

- ▶ Hadronization parameters and final-state showers can be tuned to e^+e^- data (LEP).
- ▶ Initial-state showers and UE/MPI can be tuned to MB data.
- ▶ Anythings else should be fixed by measured Standard Model parameters.
- ▶ ... in principle



Jet universality



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, Vincia, DIRE, ... need to be integrated with a specific general purpose generator
- ▶ Multiple interactions: JIMMY (HERWIG) Shrimps (SHERPA)
- ▶ Hadronization (?)
- ▶ 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 (not automatic)
- ▶ Multiple interactions interleaved with shower
- ▶ Lund String Fragmentation
- ▶ Particle decays

<https://pythia.org>



HERWIG

- ▶ Construction of arbitrary MEs using helicity amplitudes
- ▶ Angular ordered and dipole shower
- ▶ Different matching schemes via MatchBox
- ▶ Soft+hard multiple interactions
- ▶ Cluster hadronization
- ▶ Particle decays with correlations

<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 (also Shrimps)
- ▶ Cluster hadronization (string fragmentation via old PYTHIA).
- ▶ Standard particle decays.

<https://sherpa-team.gitlab.io>



Related Tools

Matrix Element Generators

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

PDF parametrizations

- ▶ LHAPDF

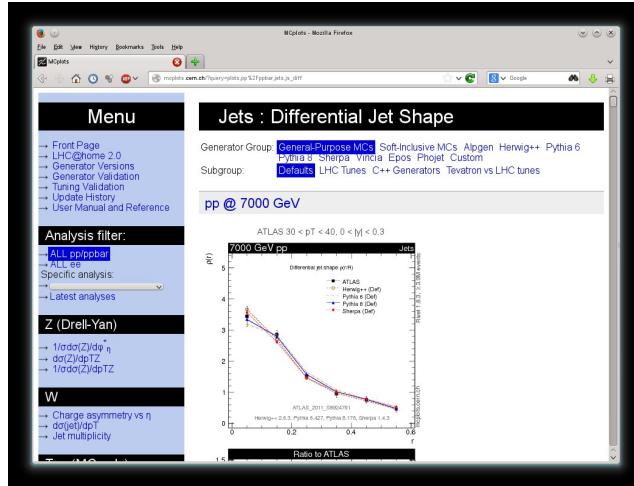
Jet algorithms

- ▶ Fastjet



MCplots.cern.ch

(Skands et al.)



Rivet.hepforge.org

(Buckley et al.)

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

1200+ 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



Summary III

There are effects which are beyond the formal perturbative precision. We can choose observables that are more or less insensitive to these effects, but they will always be there. We need to understand them better.

General Purpose Event Generators have different solutions to this. The most advanced treatment is found in Pythia8.



Summary III

There are effects which are beyond the formal perturbative precision. We can choose observables that are more or less insensitive to these effects, but they will always be there. We need to understand them better.

General Purpose Event Generators have different solutions to this. The most advanced treatment is found in Pythia8.

And only Pythia8 handles collisions involving Heavy Ions



Assignment 3 — RIVET

What is a *measurement*?

- ▶ Experimental apparatus (collider + detector)
- ▶ Data collection and corrections
- ▶ Analysis (selection, combination)
- ▶ Interpretation



Assignment 3 — RIVET

What is a *measurement*?

- ▶ Experimental apparatus (collider + detector)
- ▶ Data collection and corrections
- ▶ *Analysis* (selection, combination)
- ▶ Interpretation



Assignment 3 — RIVET

What is a *measurement*?

- ▶ Experimental apparatus (collider + detector)
- ▶ Data collection and corrections
- ▶ *Analysis* (selection, combination)
- ▶ (Interpretation)



How to make your analysis useful for others

- ▶ It should not depend on your detector
- ▶ It should not use extrapolation outside of detector acceptance
- ▶ It must be very clear exactly which cuts are used



How to make your analysis useful for others

- ▶ It should not depend on your detector
Correct data to *particle level*
- ▶ It should not use extrapolation outside of detector acceptance
- ▶ It must be very clear exactly which cuts are used



How to make your analysis useful for others

- ▶ It should not depend on your detector
Correct data to *particle level*
- ▶ It should not use extrapolation outside of detector acceptance
Always use *fiducial* cross sections
- ▶ It must be very clear exactly which cuts are used



How to make your analysis useful for others

- ▶ It should not depend on your detector
Correct data to *particle level*
- ▶ It should not use extrapolation outside of detector acceptance
Always use *fiducial* cross sections
- ▶ It must be very clear exactly which cuts are used
It should be implemented in RIVET



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), hadronization, decays. ...
- ▶ Lecture III: Minimum bias, multi-parton interactions, pile-up, summary of general purpose event generators and tools, ...
- ▶ Lecture IV: Protons vs. heavy ions, Glauber calculations, initial/final-state interactions, ...

Buckley et al. (MCnet collaboration), *Phys. Rep.* **504** (2011) 145. See also arXiv:2605.16036.

