Introduction to Event Generators IV
Minimum bias and underlying events

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MCnet School
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Outline

- The (semi-) inclusive pp cross section(s)
- Minimum bias and Regge theory
- Multiple interactions
- Underlying events
- Summary: General Purpose Event Generators
What happens at LHC? (13 TeV)

- Total 100 mb
- Non-diffractive 56 mb
- Elastic 22 mb
- Diffractive 22 mb
- Jets $p_\perp > 150$ GeV 220 nb
- W+Z 200 nb
- Top 600 pb
- Higgs 30 pb
What happens at LHC? (13 TeV)

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Event Generators IV
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What happens at LHC? (13 TeV)

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BSM $\sim 0$ fb

Almost everything at LHC is pure QCD
Inclusive cross sections.
Minimum Bias: The typical $pp$ collision

soft $gg \to gg$
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

- Single diffractive excitation
- Central diffraction
- Double diffraction
Diffraction and triple-pomeron vertices

single diffractive excitation

central diffraction

double diffraction

?
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:

\[
\frac{d\sigma^H}{dk^2_{\perp}} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu^2_F) f_j(x_2, \mu^2_F) \frac{d\hat{\sigma}_{ij}^H}{dk^2_{\perp}}
\]

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

\[
\int_{k^2_{\perp}} \sigma^H \text{ will exceed the total (non-diffractive) } pp \text{ cross section}
\]

at the LHC for $k_{\perp c} \lesssim 5 \text{ GeV}$.

There are more than one partonic interaction per $pp$-collision

\[
\langle N_H \rangle (k_{\perp c}) = \frac{\int_{k^2_{\perp}} d\sigma^H}{\sigma^{\text{ND}}}
\]
The trick in PYTHIA is to treat everything as if it is perturbative.

\[
\frac{d\hat{\sigma}^H_{ij}}{dk^2_\perp} \rightarrow \frac{d\hat{\sigma}^H_{ij}}{dk^2_\perp} \times \left( \frac{\alpha_s(k^2_\perp + k^2_{\perp0})}{\alpha_s(k^2_\perp)} \cdot \frac{k^2_\perp}{k^2_\perp + k^2_{\perp0}} \right)^2
\]

Where \( k^2_{\perp0} \) is motivated by colour screening (saturation) and is dependent on collision energy.

\[
k_{\perp0}(E_{CM}) = k_{\perp0}(E_{CM}^{\text{ref}}) \times \left( \frac{E_{CM}}{E_{CM}^{\text{ref}}} \right)^{\epsilon \sim 0.16}
\]

(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 \( \rho \) is the matter distribution in the proton

(note: general width determined by \( \sigma^{\text{ND}} \))

- A simple Gaussian (too flat)
- Double Gaussian (hot-spot)
- \( x \)-dependent Gaussian
Hadronic matter distributions

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**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.
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?
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

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After the primary scattering we can have

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

Let them compete

\[
\frac{dP_a}{dk^2_{\perp}} = \frac{dP_a}{dk^2_{\perp}} \times \exp \left( - \int k^2_{\perp} (dP_{\text{ISR}} + dP_{\text{FSR}} + dP_{\text{MI}} + dP_{\text{RS}}) \right)
\]
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.
Minimum Bias
Multiple Interactions
Underlying Events
Interleaved showers
Colour connections

(a)

(b)

(c)
Minimum Bias
Multiple Interactions
Underlying Events
Interleaved showers
Colour connections

**7000 GeV pp**

Average $p_T$ vs $N_{ch}$ ($N_{ch} > 1, p_T > 0.5$ GeV)

- **ATLAS**
- **Herwig++ (Def)**
- **Pythia 6 (Def)**
- **Pythia 8 (Def)**
- **Sherpa (Def)**

**Rivet 2.4.0, ≥ 4.9M events**

**Average $p_{ch}$**

$N_{ch}$

**Ratio to ATLAS**

0 50 100

+20% -20% +10% -10% +50% -50%

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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.
What is the Underlying Event?
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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
- Hadronization removes energy
- UE adds 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.

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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
Multiple Interactions
Underlying Events
General Purpose Event Generators

UE is not MB

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Also relevant for pile-up
Multiple Interactions
Underlying Events
General Purpose Event Generators

![Diagram of charged jet interactions](image)

**SUM/DIF "Transverse" PTsum**

- **CDF Preliminary**
  - data uncorrected
  - theory corrected
- **Pythia CTEQ4L (4, 2.4 GeV/c)**
- **"Max+Min Transverse"**
- **"Max-Min Transverse"**

1.8 TeV | | PT>0.5 GeV

**<PTsum> (GeV/c) in 1 GeV/c bin**

**PT(charged jet#1) (GeV/c)**

0 5 10 15 20 25 30 35 40 45 50

0 1 2 3 4 5

Event Generators IV
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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
- Intrisic 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

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- ... in principle
Jet universality

There may be problems with flavour and meson/baryon issues. Also at LEP there were mainly quark jets, gluon jets are softer and not very well measured. At LHC there will be very hard gluon jets. We need to check that jet universality works.
Multiple Interactions
Underlying Events
General Purpose Event Generators

**7000 GeV pp**

**Soft QCD**

- $\bar{\Lambda}/K^0$ vs $|y|$ (lhcb2011-pt0.15-2.5)
  - LHCb
  - Herwig++ (Def)
  - Pythia 6 (Def)
  - Pythia 8 (Def)
  - Sherpa (Def)

- $(K^+/K')/(\pi^+ + \pi^-)$ vs $|y|$ ($p_T > 1.2$ GeV/c)
  - LHCb
  - Herwig++ (Def)
  - Pythia 6 (Def)
  - Pythia 8 (Def)
  - Sherpa (Def)

LHCb_2011_l917009
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3

LHCb_2012_l1119400
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
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.
Pythia 8

- 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

http://home.thep.lu.se/~torbjorn/Pythia.html
**HERWIG++**

- Construction of arbitrary MEs using helicity amplitudes
- Angular ordered and dipole shower
- Different matching schemes via MatchBox
- JIMMY-based 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 (∼ old PYTHIA) with some CKKW features (also Shrimps)
- 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
(Buckley et al.)

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

400+ 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.)

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**Jets: Differential Jet Shape**

- **Generator Group:** General-Purpose MCs
- **Subgroup:** Defaults, LHC Tunes, C++ Generators, Tevatron vs LHC tunes

**pp @ 7000 GeV**

**ATLAS** 

- 80 < pT < 40, 0 < |y| < 0.3

**Ratio to ATLAS**
Monte Carlo training studentships

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use! Application rounds every 3 months.

MCnet projects
Pythia+Vincia
Herwig
Sherpa
MadGraph
“Plugin” – Ariadne+HEJ
CEDAR – Rivet+Professor +Contur+hepforge+…

for details go to: www.montecarlonet.org