Monte Carlo Issues

- Anatomy of an Event
- Fixed order perturbative QCD
- Showers & Resummations
- Non-Perturbative Physics
- Conclusions
Anatomy of a (collider) Event

- The experiment is a series of events defined by a resolution scale (imposed by analysis such as jet resolution or detector resolution).
- The MC generator is a series of events also defined by a resolution scale (cluster resolution or hadronization scale).
- For theory and experiment to agree both series of events should be statistically equivalent.
Anatomy of an Event

- For a high momentum transfer event the event looks like a $2 \rightarrow 2$ scattering event up to reasonably small resolution scales.
- A simple leading order description ($gg \rightarrow gg$, $gq \rightarrow gq, \ldots$) will do a good job simulating the di-jet correlations.
- Pushing towards a smaller and smaller resolution scale will reveal more structure (in the MC we will get “large logs” of the resolution scale).
- Next-to-leading order will describe the additional structure (average description)
- Reducing the resolution scale even further will require even higher orders and eventually we will need resummations (i.e. shower MC’s)
Anatomy of an Event

• At leading order the parton represents the average behavior of the hadronic clusters, provided the resolution scale is sufficiently large to encapsulate the cluster.

• Leading order cannot describe well the absolute probability (normalization) but will work reasonably well for event shapes (relative probability).

• Higher orders will be able to predict normalizations and depend on cluster shapes (i.e. defines its own resolution scale).

• To go to a calorimeter level scale resolution one would need resummed partonic showers.

• To go beyond hadronization scale one would need a hadronization model. Detector response will depend on hadronic correlations. This requires the MC to model the event all the way down to hadrons.
Anatomy of an Event

• The MC event goes through 3 steps:
  • Large resolution scale $Q$, such that $\alpha_s(Q) \ll 1$
    This results in a fixed order perturbative expansion (deterministic)
  • Small resolution scale $Q$ such that $\alpha_s(Q) \times \log(Q) \approx 1$
    This results in a resummed parton shower MC
      (some arbitrariness, but controllable)
  • Hadronization scale, controlled by non-perturbative physics. Only phenomenological models exist. Needs data to fit to…
• What are the issues in a chain of tools like MCFM → MC@NLO → HERWIG ?
• How do we improve on this set of tools…
pQCD

• This is the first step in any MC generator.
• Given the Feynman rules the answer to a given scattering process is unique.
• At leading order ("tree graphs") we can calculate all necessary scattering amplitudes. (started with VECBOS and evolved over the years to products like ALPHGEN, MADGRAF,...)
pQCD

- LO should describe the correlations between the average directions of the hadronic clusters well (provided appropriate large resolution)
- Difference between LO and NLO is small (except for normalization)
- NNLO and beyond, including partonic shower will/should not change anything
- Unfortunately the calometric detector response depends on the hadronic content of the clusters
- This makes the data comparison as shown here sensitive to hadronic effects and its interactions with the detector.
- Consequently the ability to add shower MC to fixed order is important.
Why is NLO (one-loop) so important?

- We become sensitive to the meaning of the resolution scale, i.e. the calculation becomes sensitive to the choice of scale.
- It gives the first reliable estimate of the normalization of the cross section.
- First sensitivity to the notion of dipoles (instead of the naïve jet). I.e. a hadron is part of a dipole, not a jet → new class of “jet algorithms” (which will be required as precision of measurement increases)
pQCD

- Progress in NLO calculations has been slow
  - All 2 to 2 NLO processes (including quark masses)
  - Some 2 to 3 NLO processes (no quark masses)
  - No 2 to 4 NLO processes
- Analytic calculations are running into complexity problems and progress daunting
- Alternatives seems to be needed giving a systematic calculational procedure: The Samper project (c++, f95, f77) (Semi-numerical AMPlitude EvaluatoR)
pQCD

• Development for semi-numerical evaluation of one-loop calculations.
  • Detailed algorithmic method has been developed.
  • Program has been checked and is ready for 2 to 3 processes (no internal masses yet)
• Will extend MCFM to:
  • Di-boson + 1 jet production
  • Tri-boson production + 0 jet production
  • H + 2 jets (with effective Hgg coupling)
pQCD

- Currently implementing $H + 2$ jets production (K. Ellis, W. Giele, G. Zanderighi)
- Excellent numerical stability
- We were able to get an analytic result for $H + 4$ quarks, not for the other two processes.
- Example: $H + qqb + rrb$:
  - analytic:
    \[-46.7813035247351/e^2+(111.948110122775+18.3709749348328 i)/e^+ (120.012242523826-335.917283834563 i)\]
  - numerical:
    \[-46.7813035247350/e^2+(111.948110122775+18.3709749348302 i)/e^+ (120.012242523817-335.917283834578 i)\]
- Other processes implemented numerically, checked on gauge invariance etc. (~1 part in $10^{11}$)
Next steps (programmatic approach):
• Implementing internal masses. This will give:
  • Q Qbar + jet
  • Q Qbar + V
• 2 to 4 processes. This will give access to a huge range of processes:
  • Q Qbar + Q Qbar (eg top-pair + bottom-pair)
  • 4 jets
  • 3 jets + V (including mass effects for quarks)
  • 2 jets + V V (including mass effects for quarks)
  • ....
Parton Showers

• The parton showers evolve from the resolutions of well separated clusters down to the hadronization scale.
• It is highly desirable to interface the pQCD calculations with the shower MC
• All current efforts are based on trying to interface with PHYTIA/HERWIG/…
• These shower MC in themselves correctly give the “leading log” behavior (i.e. resumming the most divergent resolutions scale logarithms)
• One runs in some issues when interfacing with pQCD calculations.
Parton Showers

- Suppose we know the unresolvable factorization behavior of the pQCD matrix elements:
  \[ A_n \approx T_{n-1 \to n} A_{n-1} \]
- This soft/collinear factor contains the large logarithms we need to resum.
- How do we get a shower description without double counting?
- Suppose we know \( A_2, A_3, \ldots, A_n \), then
  \[ \sum_{m=2}^{n} A_m = A_2 + A_3 + \cdots + A_{n-1} + S_n A_n \]
  \[ S_n = 1 + T_{n \to n+1} + T_{n \to n+1} T_{n+1 \to n+2} + \cdots \]
Parton Shower

\[ \sum_{m=2} A_m = A_2 + A_3 + \cdots + A_{n-1} + S_n A_n \]

\[ = A_2 + A_3 + \cdots + S_{n-1} A_{n-1} + S_n (A_n - T_{n-1 \rightarrow n} A_{n-1}) \]

\[ = A_2 + A_3 + \cdots + S_{n-1} A_{n-1} + S_n \tilde{A}_n \]

\[ = S_2 A_2 + S_3 \tilde{A}_3 + \cdots + S_n \tilde{A}_n \]

with

\[ S_m = 1 + T_{m \rightarrow m+1} S_{m+1} \]

\[ \tilde{A}_m = A_m - T_{m-1 \rightarrow m} A_{m-1} \]

Note that the subtracted matrix element goes to zero as the resolution scale goes to zero on an event by event basis.
Parton Shower

- This is all we need…
- We shower off the subtracted matrix elements..
- No double counting…
- The subtracted matrix elements are finite at any resolution scale (over the whole phase space)..
- The subtraction function is the same as the exponentiated function → strongly correlated
- The subtraction functions are well known
Parton Shower

• However, this is not the HERWIG/PYTHIA type shower:
  • The subtracted matrix element only goes to zero in the soft limit averaged over many events...
  • This is not really a problem as far as the shower MC go on themselves (collinear correct event by event)
  • However this is a problem for interfacing with multiple pQCD matrix elements (need to modify the subtraction function for matrix element, while leaving exponentiated function unchanged)
Parton Shower

• The “correct” shower is in fact based on $2 \rightarrow 3$ branching (dipole branching) instead of the splitting ($1 \rightarrow 2$ branching)

• An “engineering project” is underway to construct the desired shower MC: Higgs $\rightarrow$ gluons (Giele, Kosower, Skands)

• After completion this will be build up to a full shower MC (VIRCOL shower MC)
Hadronization Model

• Here the resolution scale is pushed below 1 GeV and individual hadrons are resolved
• This is a subject without much theoretical guidance
• To make systematic progress we need to understand the uncertainties in the pQCD and parton shower part well
• This is still in the future, for now both PYTHIA and HERWIG have QCD inspired phenomenological models
Conclusions

• We are busy addressing current issues:
  • Samper project: pushing the NLO calculations to 2→4 processes and beyond
  • VIRCOL project: improved parton shower MC with exact matching to LO/NLO/… matrix element
• Within the time span of run II we could complete:
  • All 2→3 processes at NLO (including quark masses… e.g. VVV, VV+jet, V+QQbar, jet+QQbar)
  • A VIRCOL shower which incorporates LO matrix elements (VIRTEV)