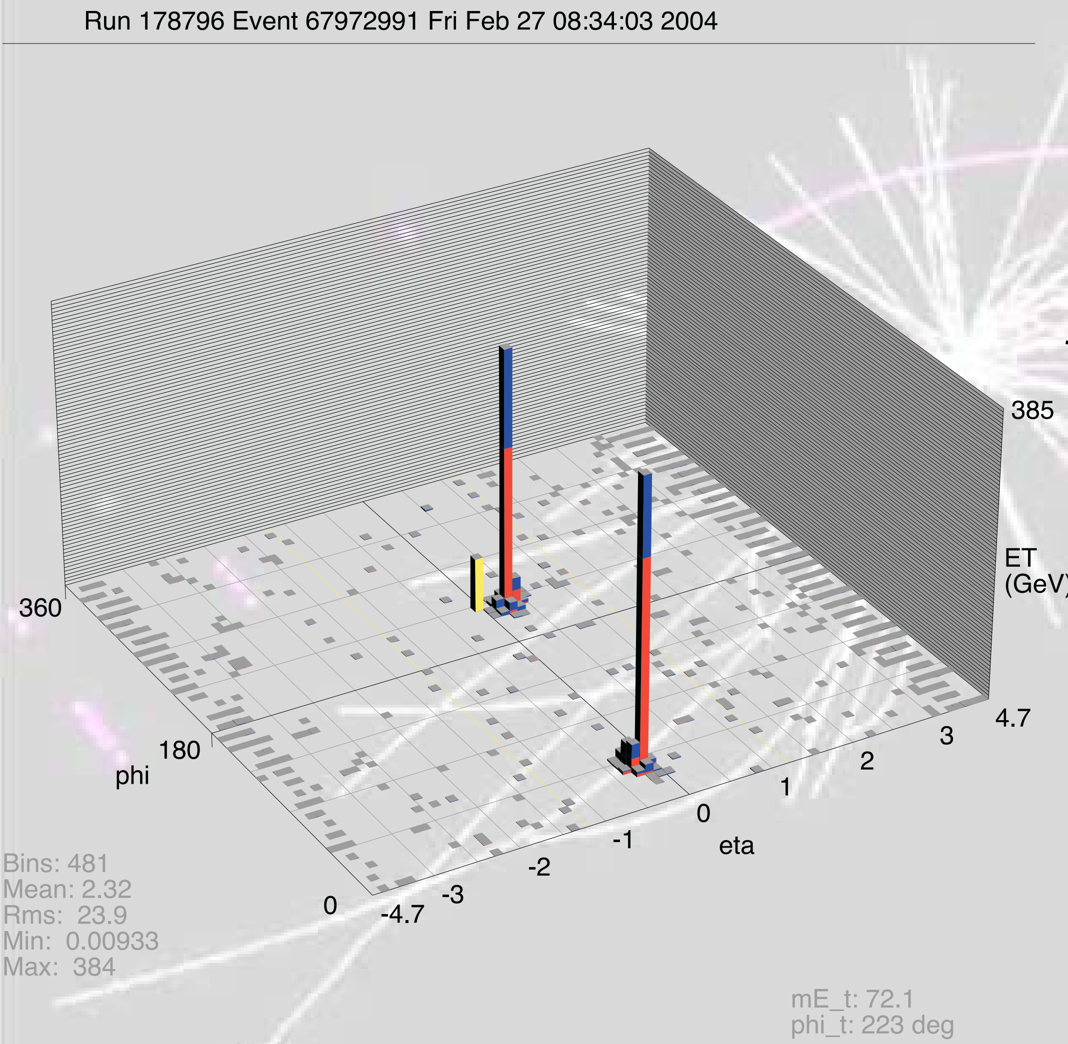
Monte Carlo Issues

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

Anatomy of a (collider) Event

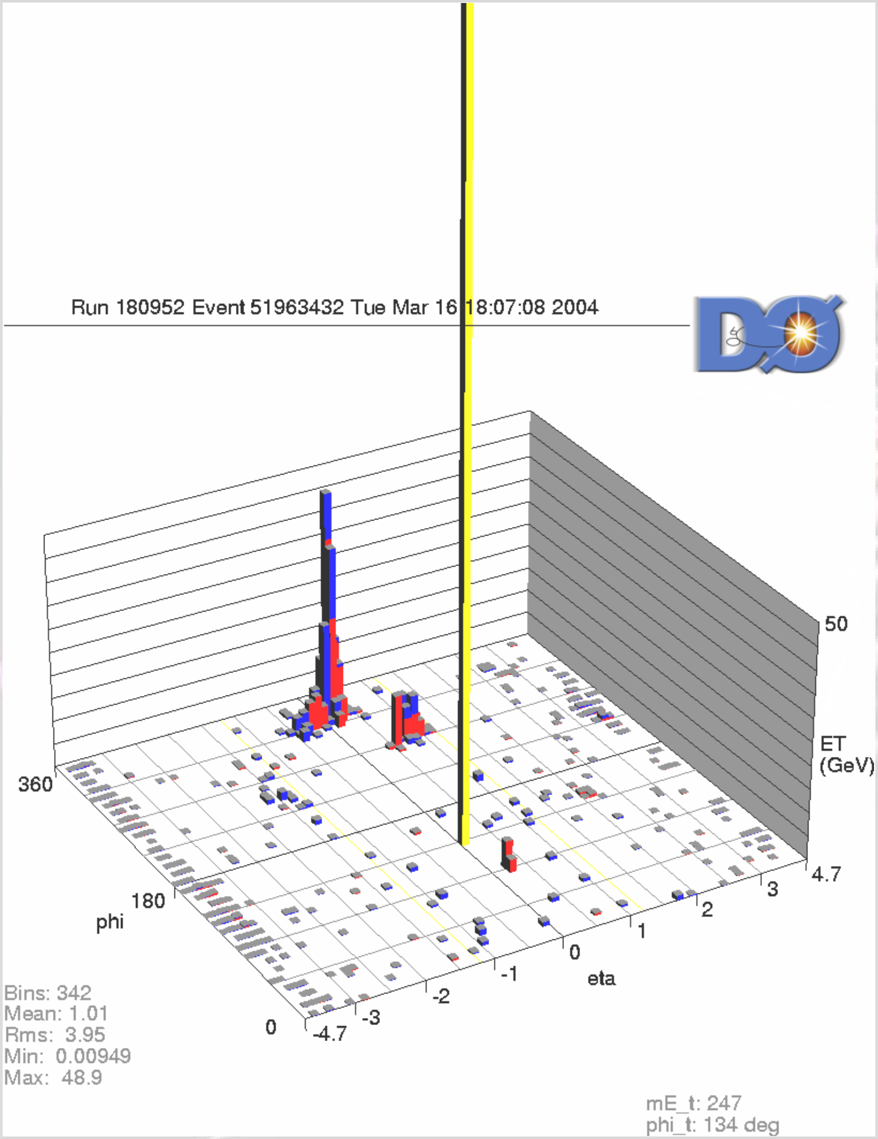
- The experiment is a series of events defined by a resolution scale (imposed by analysis such as jet resolution or detector resolution).
- The MC generator is a series of events also defined by a resolution scale (cluster resolution or hadronization scale).
- For theory and experiment to agree both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

Anatomy of an Event



- For a high momentum transfer event the event looks like a 2 → 2 scattering event up to reasonably small resolution scales.
- A simple leading order description (gg→gg, gq→gq,…) 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 it 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.

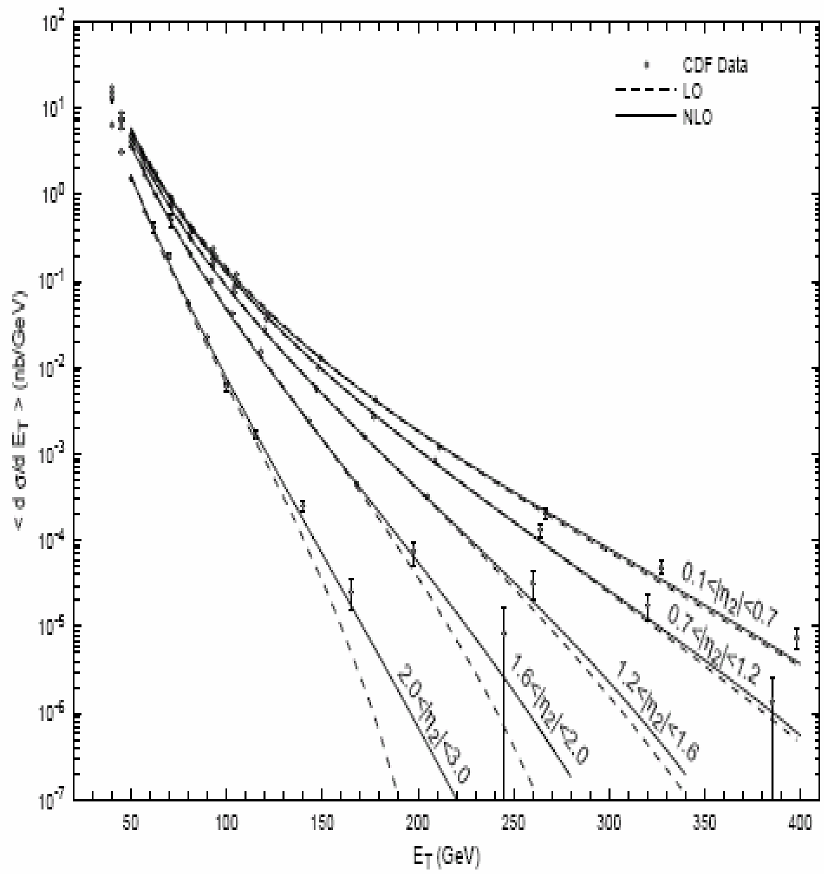
Anatomy of an Event

- 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.

pQCD

- 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)

pQCD

- Next steps (programmatc 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: $A_n \simeq T_{n-1\to n} A_{n-1}$
- 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

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

$$S_n = 1 + T_{n\to n+1} + T_{n\to n+1} T_{n+1\to n+2} + \cdots$$

Parton Shower

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

$$= A_2 + A_3 + \cdots + S_{n-1} A_{n-1} + S_n (A_n - T_{n-1\to n} A_{n-1})$$

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

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

with

$$S_m = 1 + T_{m\to m+1} S_{m+1}$$

$$\tilde{A}_m = A_m - T_{m-1\to m} A_{m-1}$$

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→3 branching (dipole branching) instead of the splitting (1→2 branching)
- An "engineering project" is underway to construct the desired shower MC: Higgs→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 phenomelogical 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)