Showering at the LHC

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UCL HEP Seminar
17th March, 2015
Outline

Phenomenological Models

Tuning

Measure distributions sensitive to softQCD

Compare with model predictions

Application in jet substructure/top tagging
Soft-QCD

$$\sigma_{\text{total}} = \sigma_{\text{el}} + \sigma_{\text{sd}} + \sigma_{\text{dd}} + \sigma_{\text{nd}}$$
Soft-QCD

Underlying event = BBR+ MPI+ (ISR+FSR)

BBR: Beam-beam remnants
MPI: Multiple Parton interactions
ISR/FSR: Initial/Final state radiation
Glossary

• Minimum-bias (MB): Pretty much everything, exact definition trigger dependent.

• Underlying event (UE): background to events with an identified hard scatter (more like the actual interesting events we want to look at)

• Pileup (PU): (uncorrelated) separate collisions within the same/different bunch crossing we can’t differentiate because of our finite detector resolution (more like “isotropic” min-bias events).
Monte Carlo Models

• Leading order/Parton shower models: Trying to build up a complex 2->N final state by showers.

• Pieces of a Parton-Shower MC Generator: (2->2 hard scattering), ISR, FSR, MPI, Fragmentation, Hadronization.

• Examples: Pythia, Herwig family.

• Higher order/Multileg generators: Sherpa, Alpgen, aMC@NLO, Madgraph, Powheg ...

• Generators used mostly for a specific process: Phojet (diffraction), HIJING (heavy ion), AcerMC (top), JHU (spin and polarization information)...

Hard Process

Parton Shower

Hadronization

Decays

Multi Parton Interaction

From Frank Krauss
Parton Shower

- Probability that a branching happens at a given time is given by Sudakov Form Factor.

- Each branching governed by DGLAP equation.

- Branching continues until each parton finally undergoes transitions to hadrons that can be observed.
A Note on the Models

“The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory . . .”

– Richard Feynman and Rick Field, 1978
Why do we care?

- The “background” to the interesting physics signals are the SM processes.

- The hard scattering part can be calculated theoretically (in some order) by QCD matrix elements.

- The soft part is not calculable, so we use phenomenological models implemented in Monte Carlo event generators.
An Example

Signal: $ttH(bb)$

BG: $ttbb$

important for measuring Yukawa couplings
One of the hardest measurements now...

Signal: $ttH(bb)$
Tuning

• Ultimate goal: models need to describe real data.
• “Free” parameters control all these aspects of the models, which cannot be derived analytically.
• A bunch of correlated (or anti-correlated) parameters describe one aspect, so have to change them simultaneously.

Tune: A particular optimized parameter setting in a particular MC generator to match the simulation with available data. Differ according to which datasets are included.
A Brief History of Tuning

- Historically most effort has been devoted to tuning (Fortran) Pythia6, even at LEP/CDF.

- ATLAS did tune (Fortran) Herwig+Jimmy (which adds MPI), and now (C++) Pythia8.

- (C++) Herwig++, Sherpa has so far been tuned by authors.

- Hadronization and FSR: LEP

- ISR and MPI: Hadron colliders
Tuning Procedure

- **Tuning-by-eye:** the classical approach. Stare at a few distributions, think hard, change some parameters, hope those are better, nothing else is broken. Very intuition/experience dependent.

- **Automated tuning tool/Professor:** pioneered by ATLAS. Essentially generate lot of samples covering the parameter space. Interpolate the generator response, get the best fit by minimization. (and burn a lot of CPU)
Tune Jungle?

DW  4C  AU2

Z1  D6T  S0  AUET2B

A2  Z2*  4Cx

A14  AMBT  Perugia
Tevatron Era Tunes

- CDF/Rick Field tunes: Pythia6 tune A, AW, DW, DWT, D6, D6T.
- ATLAS: DC2, CSC/MC08, MC09, Mc09c.
- Perugia/Peter Skands tunes: S0, Perugia0, Perugia10 (soft, hard, no colour reconnection variants).
Measuring the Underlying Event
UE Measurements

- Many results from ATLAS and CMS.
- In busy LHC environments, how much of “UE” is UE?
- Sensitive to DPI contribution.
- Not just comparing with PS models, but with ME+PS setups too.
UE activity in Z-boson and jet events fairly similar in Tevatron.

Is it still the case at the LHC?
Pre-LHC tunes

The tunes do quite well ...

Did they work at the LHC?
Then Came the LHC

- Tevatron tunes did not agree with the early minbias and underlying event data.
- Not just at 7 TeV, but also at 900 GeV!
A slight detour: comparison between UE and MB

\[ \text{0.4} \rightarrow 2.5 \]
\[ \sim 1.3 \]
\[ \text{factor of 2!} \]

\[ \text{0.8} \rightarrow 5 \]
\[ \sim 2.4 \]
Post-LHC Tunes

- (Pythia 6) ATLAS Tunes: AMBT1, AMBT2, AMBT2B, AUET2, AUET2B. [First separate MB/UE Tunes. also for many PDFs.]
- (Pythia 6) CMS Tunes: Z1, Z2, Z2*.
- (Pythia 6) Perugia 2011 tunes.
- (Pythia 8) author tunes: 4C, 4Cx.
- (Pythia 8) ATLAS tunes: A2, AU2, A14.
How do they do?

How good is good?
How do they do?

Is not it amazing that the models are doing so well?
Back to (early)UE Results

shows UE activity can not be subtracted as an average "pedestal" from each event.

Sensitive to both charged and neutral component of UE.
LPCC UE&MB WG

Rick Field: WG meeting, 17th June 2011
Jet Radius Dependence

More UE activity for higher jet radius. Why?
Rise in inclusive, almost flat in when requiring exactly 2 jets. Models better describe exclusive profile.
Transmin independent of $Z\ p_T$ till about 10 GeV, profile best described by Pythia8 and Powheg+Pythia8

However full transverse (or trans-max) regions are described better by NLO or multileg generators than pure LO ones.
Z/Jet UE Comparison

Discrepancy due to selection bias, trans-min identical.
Isolating the UE

- Full transverse (or trans-max) regions are described better by NLO or multileg generators than pure LO ones.
- Trans-min (and towards region for Z-boson events) were thought to be populated by “pure” UE.
- But at LHC, even those are not flat.
Tuning Shower & MPI Together

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>SigmaProcess:alphaSvalue</td>
<td>The $\alpha_s$ value at scale $Q^2 = M_Z^2$</td>
</tr>
<tr>
<td>SpaceShower:pT0Ref</td>
<td>ISR $p_T$ cutoff</td>
</tr>
<tr>
<td>SpaceShower:pTmaxFudge</td>
<td>Mult. factor on max ISR evolution scale</td>
</tr>
<tr>
<td>SpaceShower:pTdampFudge</td>
<td>Factorisation/renorm scale damping</td>
</tr>
<tr>
<td>SpaceShower:alphaSvalue</td>
<td>ISR $\alpha_s$</td>
</tr>
<tr>
<td>TimeShower:alphaSvalue</td>
<td>FSR $\alpha_s$</td>
</tr>
<tr>
<td>BeamRemnants:primordialKThard</td>
<td>Hard interaction primordial $k_T$</td>
</tr>
<tr>
<td>MultipartonInteractions:pT0Ref</td>
<td>MPI $p_T$ cutoff</td>
</tr>
<tr>
<td>MultipartonInteractions:alphaSvalue</td>
<td>MPI $\alpha_s$</td>
</tr>
<tr>
<td>BeamRemnants:reconnectRange</td>
<td>CR strength</td>
</tr>
</tbody>
</table>

Used exponential matter overlap

Also:
MultipartonInteractions:ecmPow

$p_T(0(\text{ecmNow}) = p_T(0(\text{ecmNow})^{\text{ecmPow}})$

- 4C
- 4Cx
- AU2 (CTEQ6L1)
- A2 (CTEQ6L1)
Tuning Shower & MPI Together

New A14 tune! (with systematic variation tunes)

Extend to matched setups...
UE-sensitive Observables

Transverse energy flow: all models bad in forward region
UE-sensitive Observables

More energy in dijet events!
From Central to Forward

low $\eta$                 high $\eta$

UE tunes do better overall

JHEP11 (2012) 033
Event Shapes

Low lead $p_T$

High lead $p_T$

ATLAS

$\sqrt{s} = 7$ TeV

$p_T^{lead} > 0.5$ GeV

$\sqrt{s} = 7$ TeV

$p_T^{lead} > 7.5$ GeV

MC/Data

ATLAS

$\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{dS}$

$\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{dS}$


UE starts taking over....
Event Shape Profile

$\sqrt{s} = 7$ TeV

ATLAS

Data 2010

PYTHIA 6 Z1

PYTHIA 6 AMBT2B

PYTHIA 6 DW

Herwig++ UE7-2

Emergence of jets?

Jet Substructure in Brief
Large radius jets

With increasing c.m. energy: collimated decay products from boosted heavy particles result in a single massive jet.

The angular resolution of the decay products:
\[ \Delta R \approx \frac{2m}{p_T} \]

So for a top quark (of mass 173 GeV) with \( p_T > 350 \text{ GeV} \), we have \( \Delta R \sim 1 \).
So when you take apart a jet, what does it look like?
So when you take apart a jet, what does it look like?
So when you take apart a jet, what does it look like?

We want to exploit the “substructure” of the large-radius jet to identify original particles.
Substructure Techniques

- Jets need to be “groomed”.

The large-radius jets not only include particles coming from the interesting decays, but also from pileup, underlying event ....

- Need observables which would be sensitive to signal-like or background-like nature of these jets.
Filtering

Initial jet

\[ R_{\text{filt}} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}] \]

Filtered jet

Prunning

Initial jet

\[ p_T^{j_2}/p_T^{j_1+j_2} > z_{\text{cut}} \text{ or } \Delta R_{j_1,j_2} < R_{\text{cut}} \]

Pruned jet

Trimming

Initial jet

\[ p_T^i/p_T^{\text{jet}} < f_{\text{cut}} \]

Trimmed jet
• Target is to identify jets resulting from the decay of top quark or Higgs against jets coming from light quark/gluons.
Playing with the Shower
Recall

Top quark decay:

Parton Shower!
Shower Deconstruction

Top quark jet shower history

vs.

Light quark jet shower history
Shower Deconstruction

- Decompose the large-radius jet into small radius sub/microjets.
- Build all possible shower histories with the microjets.
- Assign probability whether signal-like or background-like.
- A single analytic function:

\[
\chi\left(\{p\}_N\right) = \frac{P\left(\{p\}_N | S\right)}{P\left(\{p\}_N | B\right)}
\]
Looking at our Data

LogChi modelled well by MC

LogChi robust against pileup
Signal and BG Discrimination

ATLAS Preliminary Simulation
\( \sqrt{s} = 8 \text{ TeV} \)

- \( \chi_{SD} \) (pass)
  - Red: \( Z' \) (m=1.75 TeV)
  - Blue: Dijet

Fraction of events vs. \( \log(\chi_{SD}) \)
Top-Tagging Comparison

Better top quark finding efficiency at the same rejection of multijets when compared to the HEPTopTagger.
Summary

• Soft QCD is fun (and useful).

• Tuning is fun too, but hard to get everything right.

• Generators contain a lot under their hood, and it is good to have some understanding of it.

• The improved modelling of low $p_T$ processes is feded back to full event generation, where it affects high $p_T$ part of the event, especially for precision measurements.

• Jet substructure techniques utilise the knowledge and modelling of shower, so direct application in searches as well.
Supporting Material
Powheg+Pythia8 Matching
(ongoing Les Houches Study)

- PoWHEG provides a scale (SCALUP) that is an indication of where the shower should take over from the perturbative calculation.

- What should be this scale?

- Imperfection in transition region
14 TeV UE Predictions

![Graph 1: Leading track $p_T$ density](image1)

![Graph 2: Leading track $p_T$ density](image2)

![Graph 3: Ratio vs. $p_T$](image3)
Effect of Grooming on Pileup

[Graphs showing data on jet m_{jet} versus m_{miss} with different grooming options and pileup corrections.]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013HighMuSubstructure
Jet Mass

Clear peak visible after grooming
$\sqrt{d_{ij}} = \min(p_{Ti}, p_{Tj}) \times \Delta R_{ij}$

When combining two subjets with $k_t$ algorithm:

Symmetric for heavy particle two body decay

arXiv:1203.4606

arXiv:1302.1415

arXiv:1302.1416
N-Subjettiness

Quantify the degree to which jet radiation is aligned along specific subjet axes.

\[ \tau_N \equiv \frac{1}{d_0} \sum_{k=1}^{M} \left( p_{T,k} \times \frac{\Delta R_{\text{min},k}}{\text{distance to nearest subjet}} \right) \]

\[ d_0 = R \times \text{sum of } p_T \text{ of all constituents} \]

Smaller values: N or less energy deposits

Larger values: more than N energy deposits

No of Subjets: \( \leq N \) \( \tau_N = 0 \)

\( > N \) \( \tau_N = 1 \)

Calculated by \( k_t \) clustering the constituents, and requiring exactly N subjets
N-Subjettiness

The ratio $\tau_N/\tau_{N-1}$ is used as discriminant

More like 2 subjets than 1

More like 3 subjets than 2

arXiv:1203.4606

W-like  QCD-like

arXiv:1203.4606
N-Subjettiness

The ratio of $\tau_N/\tau_{N-1}$ is used as discriminant

More like 2 subjets than 1

More like 3 subjets than 2

arXiv:1203.4606

W-like ↔ QCD-like
Angular Correlation Function (or jet substructure without trees)

\[ G(R) \equiv \sum_{i \neq j} p_{\perp i} p_{\perp j} \Delta R_{ij}^2 \Theta[R - \Delta R_{ij}] \]

\[ \Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]
Angular Structure Function

\[ \Delta G(R) \equiv \frac{d \log G(R)}{d \log R} \]

- Location of the peaks
- Height of the peaks
- Number of peaks
Where it all started:

**Butterworth-Davison-Rubin-Salam**

Higgs to bb tagger (2008)

- Start with fat (C-A 1.2) boosted ($p_T > 200$) b-tagged jet.
- De-cluster the jet. At each stage, mass drop and symmetric splitting requirement.
- Continue till an interesting splitting has been found.
- Higgs candidate from two hardest b-tagged subjets among the three hardest.
HEPTopTagger

Browsing through all the branches of jet recombination history

Figure by Xiaoxiao Wang
HEPTopTagger Performance

Before and after tagging by HepTopTagger

Pileup resilience
Detour: Jet Clustering

• Find the smallest of all \( \{ d_{ij}, d_{iB} \} \)

• If this is one of the \( d_{ij} \) values, inputs i and j are merged.

• If it is one of the \( d_{iB} \) values, \( i^{th} \) input is considered a jet.

• Continue till all inputs are merged into jets.
## Milestones and Prospects

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Commissioning the tools</th>
</tr>
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<tbody>
<tr>
<td>Run 2: 100 fb(^{-1})</td>
<td>and... Improve precision of top/W/Higgs mass measurements. Exclude/severely constraint many of the new physics models with the higher energy reach</td>
</tr>
<tr>
<td>Run 3: 300 fb(^{-1})</td>
<td>and... Directly test the coupling of the Higgs boson to fermions</td>
</tr>
<tr>
<td>HL-LHC: 3000 fb(^{-1})</td>
<td>and... Measure Higgs self coupling Measure vector boson scattering Observe rare Higgs decays</td>
</tr>
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</table>
PDF Dependence of Tunes

- Changing PDFs change gluon density, so re-tuning is needed.

- ATLAS systematically explored the effect of NLO and modified LO PDFs on the tunes.

- Many matrix element generators use NLO/mLO PDFs, so it is important to understand the effect on matched parton-shower generators.

- LO PDFs generally give the best description, with mLO ones the worst.

- NLO PDFs require less MPI cross-section screening and stronger color reconnection.
PDF Dependence

![Graph showing PDF dependence with data points for different tunes.]