First we discover the Standard Model
Roadmap for the first few fb^{-1}
(more on tools than analysis strategies)

J. Huston
Michigan State University and
IPPP, University of Durham

- End at **Stockholm**
- **Total Est. Time:** 18 hours, 50 minutes
- **Total Est. Distance:** 1264.67 miles
Some references

- Also online at ROP

http://stacks.iop.org/0034-4885/70/89

Standard Model benchmarks
See www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html
More references

Jets in Hadron-Hadron Collisions

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December 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant compactness of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (3partyJet) for the convenient comparison of results using different jet algorithms.

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explain it in 60 seconds

Jets are sprays of particles that fly out from certain high-energy collisions—for instance, from violent collisions of protons and antiprotons at Fermilab’s Tevatron accelerator, or in the similar proton-antiproton collisions that will take place at CERN’s Large Hadron Collider.

These collisions create very energetic quarks and gluons as they travel away from the collision point, they emit more gluons, which can split into even more gluons. This results in a relatively narrow cascade, or jet, of particles.

In the last stage of jet creation, quarks and gluons combine to form particles such as protons, pions, and kaons. By measuring these final products, physicists can determine the properties of a jet, and thus the details of the collision that produced it. Scientists expect these jets in the signatures of almost every interesting collision at the Large Hadron Collider.

The most violent collisions will produce jets with the highest momentum, and these can be used to probe the smallest distances within the colliding protons, less than one-billionth of a billionth of a meter. Physicists hope they can use these most energetic jets to look inside the quarks that make up protons.

Joey Huston, Michigan State University

“Symmetry
A joint Fermilab/SLAC publication
PD 1503600
M3 2467
Batavia Illinois 60510
USA

When you’re a jet,
you’re a jet all the way,
from your first gluon split
to your last K decay...”
Some background: what to expect at the LHC

...according to a theorist, perhaps like many of you
What to expect at the LHC

...according to a theorist

- According to a current former Secretary of Defense
  - known knowns
  - known unknowns
  - unknown unknowns
What to expect at the LHC

...according to a theorist

- According to a former Secretary of Defense
  - known knowns
    - SM at the Tevatron
    - (most of) SM at the LHC
  - known unknowns
    - some aspects of SM at the LHC
  - unknown unknowns
    - ???
Discovering the SM at the LHC

- We’re all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
- ATLAS will have a program to measure production of SM processes: inclusive jets, W/Z + jets, heavy flavor during first inverse femtobarn
  - so experimenters need/have a program now of Monte Carlo production and studies to make sure that we understand what issues are important
  - and we also need tool and algorithm and theoretical prediction developments
Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron.
- Small typical momentum fractions $x$ in many key searches:
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony
Looking back in 15 years

LHC vs time: a wild guess ...

$L = 10^{35}$
...but before looking back

Understanding SM predictions at the LHC

- PDF’s, PDF luminosities and PDF uncertainties
- LO, NLO and NNLO calculations
- K-factors
- “Hard” Scattering
- benchmark cross sections and pdf correlations
- Sudakov form factors
- underlying event and minimum bias events
- jet algorithms and jet reconstruction
Parton distribution functions

- Calculation of production cross sections at the LHC relies upon knowledge of pdf’s in the relevant kinematic region
- Pdf’s are determined by global analyses of data from DIS, DY and jet production
- Two major groups that provide semi-regular updates to parton distributions when new data/theory becomes available
  - MRS->MRST98->MRST99
    ->MRST2001->MRST2002
  - CTEQ->CTEQ5->CTEQ6
    ->CTEQ6.1->CTEQ6.5/6
  - All global analyses use a generic form for the parametrization of both the quark and gluon distributions at some reference value $Q_0$, where $Q_0$ is usually in the range of 1-2 GeV
- Pdf’s are available at LO, NLO and NNLO
- NB: currently working on modified LO pdf’s for use with parton shower Monte Carlos

\[ F(x, Q_0) = A_0 x^{A_1} (1 - x)^{A_2} P(x; A_3, \ldots). \]
Parton distribution functions

- All of the above groups provide ways to estimate the error on the central pdf
  - Hessian methodology enables full characterization of parton parametrization space in neighborhood of global minimum
  - CTEQ6.1 has 20 free parameters so 20 directions in eigenvector space

Inclusive jets at the Tevatron

- theory uncertainties
  - higher twist/non-perturbative effects
  - choose Q^2 and W cuts to avoid higher order effects (NNLO)
  - heavy quark mass effects (see later)
Parton kinematics

- To serve as a handy “look-up” table, it’s useful to define a parton-parton luminosity
  - this is from the review paper (CHS) and the Les Houches 2005 writeup

- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element

\[
\frac{dL_{ij}}{d\hat{s} \, dy} = \frac{1}{s} \frac{1}{1 + \delta_{ij}} \left[ f_i(x_1, \mu) f_j(x_2, \mu) + (1 \leftrightarrow 2) \right]. \quad (1)
\]

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

\[
\sigma = \sum_{i,j} \int_0^1 dx_1 \, dx_2 \, f_i(x_1, \mu) \, f_j(x_2, \mu) \, \hat{\sigma}_{ij} \quad (2)
\]

can then be written as

\[
\sigma = \sum_{i,j} \int \left( \frac{d\hat{s}}{\hat{s} \, dy} \right) \left( \frac{dL_{ij}}{d\hat{s} \, dy} \right) \left( \hat{s} \, \hat{\sigma}_{ij} \right). \quad (3)
\]
Cross section estimates

\[ \sigma = \frac{\Delta \hat{s}}{\hat{s}} \left( \frac{dL_{ij}}{d\hat{s}} \right) (\hat{s} \hat{\sigma}_{ij}) \]

@500 GeV tT mass, gg factor of 10 larger than qQ; \(\sigma_{xs}\) factors ~ same; ~1 * 4E4 pb * 0.012 = order of 500 pb (LO)

Fig. 2: Left: luminosity \(\frac{1}{\hat{s}} \frac{dL_{ij}}{d\tau}\) in pb integrated over \(\tau\). Green=gg, Blue=\(g(d + u + s + c + b) + g(d + u + s + c + b)\), Red=\(d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + \bar{b}b\), Green=\(g(d + u + s + c + b) + g(d + u + s + c + b)\), Red=\(d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + \bar{b}b\). Right: parton level cross sections \([\hat{s} \hat{\sigma}_{ij}]\) for various processes.
PDF uncertainties at the LHC

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small.

Need similar level of precision in theory calculations.

It will be a while, i.e. not in the first $\text{fb}^{-1}$, before the LHC data starts to constrain pdf's.

NB I: the errors are determined using the Hessian method for a $\Delta \chi^2$ of 100 using only experimental uncertainties, i.e. no theory uncertainties.

NB II: the pdf uncertainties for W/Z cross sections are not the smallest.

NB III: tT uncertainty is of the same order as W/Z production.
Ratios: LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. chargino pair production) have small enhancements.
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC.
- W+4 jets is a background to tT production both at the Tevatron and at the LHC.
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10.
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100:
  - but increased W + jets background means that a higher jet cut is necessary at the LHC.
  - known known: jet cuts have to be higher at LHC than at Tevatron.
The LHC Environment
Known unknowns: total cross section at LHC (14 TeV)

- Fair amount of uncertainty on extrapolation to LHC
  - $\ln(s)$ or $\ln^2(s)$ behavior
  - rely on Roman pot measurements
    - need 90 m optics run; sometime in 2009?
  - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)
  - we'll need benchmark cross sections for normalization
- Also uncertainty on $dN_{\text{charged}}/d\eta$ and $dN_{\text{charged}}/dp_T$
  - role of semi-hard multiple parton interactions
  - reasonable expectation is 7-8 particles per unit rapidity and $<p_T> \sim 0.65$ GeV/c
  - 10K events should be enough
Early triggering in ATLAS

- Beam pickups will indicate which bunches are filled
- Need a fast signal from detector that an interaction has occurred
- This is the role of the MBTS counters
  - mounted on LAr cryostats and cover an $\eta$ region from ~2 to 3.8
  - 8 segments in $\phi$ on each side; 2 segments in $\eta$
  - good signal to noise offline
  - signal to noise online is being improved by mods to drawers

- trigger logic still being determined
- forward/backward coincidence, multiplicity at L1
- more info at L2, if needed
- will be first detector in ATLAS to die (but ok for year)
There’s also a great deal of uncertainty regarding the level of underlying event at 14 TeV, but it’s clear that the UE is larger at the LHC than at the Tevatron.

Should be able to establish reasonably well with the first collisions in 2008:

- ~20M MB events will allow overlap with hard scatter regime (~30 GeV/c)
Known known: the LHC will be a very jetty place

- Total cross sections for \( t\bar{t} \) and Higgs production saturated by \( t\bar{t} \) (Higgs) + jet production for jet \( p_T \) values of order 10-20 GeV/c
- \( \sigma_{W+3 \text{ jets}} > \sigma_{W+2 \text{ jets}} \)

**Figure 91.** Predictions for the production of \( W^+ \| 1, 2, 3 \) jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- Indication that can expect interesting events at LHC to be very jetty (especially from gg initial states)
- Also can be understood from point-of-view of Sudakov form factors

**Figure 95.** The dependence of the LO \( t\bar{t}+\text{jet} \) cross section on the jet-defining parameter \( p_{T,\text{min}} \), together with the top pair production cross sections at LO and NLO.

**Figure 100.** The dependence of the LO \( t\bar{t}+\text{jet} \) cross section on the jet-defining parameter \( p_{T,\text{min}} \), together with the top pair production cross sections at LO and NLO.
Sudakov form factors

- Sudakov form factor gives the probability for a gluon not to be emitted; basis of parton shower Monte Carlos
- Consider $t\bar{t}$ production
- In going from the Tevatron to the LHC, you are moving from primarily $qQ$ initial states to $gg$ initial states
- ...and to smaller values of parton $x$
  - so there's more phase space for gluon emission
- So significantly more extra jets associated with the $t\bar{t}$ final state

![Figure 95. The dependence of the LO $t\bar{t}$-jet cross section on the jet-defining parameter $p_T_{\text{min}}$ together with the top pair production cross sections at LO and NLO.](image)

![Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton $x$ values of 0.3 (crosses) and 0.03 (open circles).](image)
NLO corrections

- NLO is the first order for which the normalization, and sometimes the shape, is believable.
- NLO is necessary for precision comparisons of data to theory.
- Sometimes backgrounds to new physics can be extrapolated from non-signal regions, but this is difficult to do for low cross section final states and/or final states where a clear separation of a signal and background region is difficult.

Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$. 
NLO corrections

Sometimes it is useful to define a K-factor (NLO/LO). Note the value of the K-factor depends critically on its definition. K-factors at LHC (mostly) similar to those at Tevatron.

<table>
<thead>
<tr>
<th>Process</th>
<th>Typical scales</th>
<th>Tevatron K-factor</th>
<th>LHC K-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_0$</td>
<td>$\mu_1$</td>
<td>$K(\mu_0)$</td>
</tr>
<tr>
<td>$W$</td>
<td>$m_W$</td>
<td>$2m_W$</td>
<td>1.33</td>
</tr>
<tr>
<td>$W + 1$ jet</td>
<td>$m_W$</td>
<td>$\langle p_T^{jet} \rangle$</td>
<td>1.42</td>
</tr>
<tr>
<td>$W + 2$ jets</td>
<td>$m_W$</td>
<td>$\langle p_T^{jet} \rangle$</td>
<td>1.16</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$m_t$</td>
<td>$2m_t$</td>
<td>1.08</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$m_b$</td>
<td>$2m_b$</td>
<td>1.20</td>
</tr>
<tr>
<td>Higgs via WBF</td>
<td>$m_H$</td>
<td>$\langle p_T^{jet} \rangle$</td>
<td>1.07</td>
</tr>
</tbody>
</table>

K-factors may differ from unity because of new subprocesses/contributions at higher order and/or differences between LO and NLO pdf's.
Now we come to the “maligned” experimenter’s NLO wishlist

7 years later and yet not a single calculation finished! Shame

### An experimenter’s wishlist

<table>
<thead>
<tr>
<th>Single boson</th>
<th>Diboson</th>
<th>Triboson</th>
<th>Heavy flavour</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + \leq 5j$</td>
<td>$WW + \leq 5j$</td>
<td>$WWW + \leq 3j$</td>
<td>$t\bar{t} + \leq 3j$</td>
</tr>
<tr>
<td>$W + \bar{b}\bar{b} + \leq 3j$</td>
<td>$WW + \bar{b}\bar{b} + \leq 3j$</td>
<td>$WWW + \bar{b}\bar{b} + \leq 3j$</td>
<td>$t\bar{t} + \gamma + \leq 2j$</td>
</tr>
<tr>
<td>$W + c\bar{c} + \leq 3j$</td>
<td>$WW + c\bar{c} + \leq 3j$</td>
<td>$WWW + \gamma\gamma + \leq 3j$</td>
<td>$t\bar{t} + W + \leq 2j$</td>
</tr>
<tr>
<td>$Z + \leq 5j$</td>
<td>$ZZ + \leq 5j$</td>
<td>$Z\gamma\gamma + \leq 3j$</td>
<td>$t\bar{t} + Z + \leq 2j$</td>
</tr>
<tr>
<td>$Z + \bar{b}\bar{b} + \leq 3j$</td>
<td>$ZZ + \bar{b}\bar{b} + \leq 3j$</td>
<td>$WZZ + \leq 3j$</td>
<td>$t\bar{t} + H + \leq 2j$</td>
</tr>
<tr>
<td>$Z + c\bar{c} + \leq 3j$</td>
<td>$ZZ + c\bar{c} + \leq 3j$</td>
<td>$ZZZ + \leq 3j$</td>
<td>$t\bar{b} + \leq 2j$</td>
</tr>
<tr>
<td>$\gamma + \leq 5j$</td>
<td>$\gamma\gamma + \leq 5j$</td>
<td></td>
<td>$b\bar{b} + \leq 3j$</td>
</tr>
<tr>
<td>$\gamma + \bar{b}\bar{b} + \leq 3j$</td>
<td>$\gamma\gamma + \bar{b}\bar{b} + \leq 3j$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma + c\bar{c} + \leq 3j$</td>
<td>$\gamma\gamma + c\bar{c} + \leq 3j$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ + \leq 5j$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ + \bar{b}\bar{b} + \leq 3j$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ + c\bar{c} + \leq 3j$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W\gamma + \leq 3j$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$Z\gamma + \leq 3j$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NLO calculation priority list from Les Houches 2005: theory benchmarks

G. Heinrich and J. Huston

<table>
<thead>
<tr>
<th>process</th>
<th>relevant for</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VV + \text{jet}$</td>
<td>$t\bar{t}H$, new physics</td>
</tr>
<tr>
<td>$H + 2 \text{jets}$</td>
<td>$t\bar{t}H$, production by vector boson fusion (VBF)</td>
</tr>
<tr>
<td>$tt\bar{b}b$</td>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td>$VVbb$</td>
<td>VBF $\rightarrow H \rightarrow VV$, $t\bar{t}H$, new physics</td>
</tr>
<tr>
<td>$VVV$</td>
<td>various new physics signatures</td>
</tr>
</tbody>
</table>

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

- **$pp \rightarrow VV + \text{jet}$**: One of the most promising channels for Higgs production in the low mass range is through the $H \rightarrow WW^*$ channel, with the W’s decaying semileptonically. It is useful to look both in the $H \rightarrow WW$ exclusive channel, along with the $H \rightarrow WW + \text{jet}$ channel. The calculation of $pp \rightarrow WW + \text{jet}$ will be especially important in understanding the background to the latter.

- **$pp \rightarrow H + 2 \text{jets}$**: A measurement of vector boson fusion (VBF) production of the Higgs boson will allow the determination of the Higgs coupling to vector bosons. One of the key signatures for this process is the presence of forward-backward tagging jets. Thus, QCD production of $H + 2 \text{jets}$ must be understood, especially as the rates for the two are comparable in the kinematic regions of interest.

- **$pp \rightarrow t\bar{t}b\bar{b}$ and $pp \rightarrow t\bar{t} + 2 \text{jets}$**: Both of these processes serve as background to $t\bar{t}H$, where the Higgs decays into a $b\bar{b}$ pair. The rate for $t\bar{t}jj$ is much greater than that for $t\bar{t}b\bar{b}$ and thus, even if 3 b-tags are required, there may be a significant chance for the heavy flavour mistag of a $t\bar{t}jj$ event to contribute to the background.

- **$pp \rightarrow VVb\bar{b}$**: Such a signature serves as non-resonant background to $t\bar{t}$ production as well as to possible new physics.

- **$pp \rightarrow VV + 2 \text{jets}$**: The process serves as a background to VBF production of Higgs.

- **$pp \rightarrow V + 3 \text{jets}$**: The process serves as background for $t\bar{t}$ production where one of the jets may not be reconstructed, as well as for various new physics signatures involving leptons, jets and missing transverse momentum.

- **$pp \rightarrow VVV$**: The process serves as a background for various new physics subprocesses such as SUSY tri-lepton production.

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available? See e.g. $H + 2 \text{jets}$. Other processes are going to be just as complex. What about other processes for which we are theoretist/time-limited?
Some rules-of-thumb

- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - \( gg \rightarrow \text{Higgs} \)
  - \( gg \rightarrow \gamma\gamma \)
  - \( K(gg \rightarrow t\bar{t}) > K(qQ \rightarrow t\bar{t}) \)

- NLO corrections decrease as more final-state legs are added
  - \( K(gg \rightarrow \text{Higgs} + 2 \text{jets}) < K(gg \rightarrow \text{Higgs} + 1 \text{jet}) < K(gg \rightarrow \text{Higgs}) \)
  - unless can access new initial state gluon channel

- Can we generalize for uncalculated HO processes?
  - so expect K factor for \( W + 3 \text{jets} \) or \( \text{Higgs} + 3 \text{jets} \) to be reasonably close to 1

---

**Table 1.** \( K \)-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. \( K \) uses the CTEQ6L1 set at leading order, whilst \( K' \) uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements \( p_T > 15 \text{ GeV} \) and \( |\eta| < 2.5 \) (5.0) at the Tevatron (LHC). In the \( W + 2 \text{ jet} \) process the jets are separated by \( \Delta R > 0.52 \), whilst the weak boson fusion (WBF) calculations are performed for a Higgs of mass 120 GeV.

<table>
<thead>
<tr>
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<th>Tevatron K-factor</th>
<th>LHC K-factor</th>
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<tbody>
<tr>
<td></td>
<td>( \mu_0 )</td>
<td>( \mu_1 )</td>
<td>( K(\mu_0) )</td>
</tr>
<tr>
<td>( W )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W + 1 \text{ jet} )</td>
<td>( m_W )</td>
<td>( 2m_W )</td>
<td>1.33</td>
</tr>
<tr>
<td>( W + 2 \text{jets} )</td>
<td>( m_W )</td>
<td>( m_W )</td>
<td>1.42</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>( m_t )</td>
<td>( 2m_t )</td>
<td>1.16</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>( m_b )</td>
<td>( 2m_b )</td>
<td>1.08</td>
</tr>
<tr>
<td>Higgs via WBF</td>
<td>( m_H )</td>
<td>( m_H )</td>
<td>1.07</td>
</tr>
</tbody>
</table>

### Notes
- Casimir for biggest color representation final state can be in
  - Simplistic rule \( C_{i1} + C_{i2} - C_{f,\text{max}} \)
  - Casimir color factors for initial state
Don’t forget

- NNLO: we need to know some processes (such as inclusive jet production) at NNLO
- Resummation effects: affect important physics signatures
  - mostly taken into account if NLO calculations can be linked with parton showering Monte Carlos

Figure 16. The single jet inclusive distribution at $E_T = 100$ GeV, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

Figure 102. The predictions for the transverse momentum distribution for a 125 GeV mass Higgs boson at the LHC from a number of theoretical predictions. The predictions have all been normalized to the same cross section for shape comparisons. This figure can also be viewed in colour on the benchmark website.
...and

- **BFKL logs:** will we finally see them at the LHC?
- **EW logs:** $\alpha_W \log^2(p_T^2/m_W^2)$ can be a big number at the LHC

**Figure 92.** The rate for production of a third (or more) jet in $W+\geq 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale, and using the BFKL formalism, requiring either that there be exactly 3 jets or 3 or more jets.

**Figure 107.** The effect of electroweak logarithms on jet cross sections at the LHC.
Precision benchmarks:
W/Z cross sections at the LHC

- CTEQ6.1 and MRST NLO predictions in good agreement with each other
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

Figure 81. Predicted total cross section of W^+ + W^- production at the LHC for the fits obtained in the CTEQ stability study, compared with the MRST results. The overall pdf uncertainty of the prediction is ~5%, as observed in figure 77.

removing low x data from global fits increases uncertainty but does not significantly move central answer

MRST found a tension between low x and high x data; not present in CTEQ analysis

Figure 82. Lagrange multiplier results for the W cross section (in nb) at the LHC using a positive-definite gluon. The three curves, in order of decreasing steepness, correspond to three sets of kinematic cuts, standard/intermediate/strong.
Rapidity distributions and NNLO

- Effect of NNLO just a small normalization factor over the full rapidity range
- NNLO predictions using NLO pdf’s are close to full NNLO results, but outside of (very small) NNLO error band
W/Z $p_T$ distributions

- $p_T$ distributions will be shifted (slightly) upwards due to larger phase space for gluon emission
- I’ve generated a million $W\rightarrow e\nu$ and $Z\rightarrow e^+e^-$ events for each of the CTEQ6.1 error pdf’s using ResBos
  - currently ROOT ntuples on CASTOR at CERN for use by ATLAS (castor/cern.ch/atlas/project/smgroup/ResBos)
- BFKL logs may become important and have a noticeable effect
  - one of the first steps at the LHC will be to understand the dynamics of $W/Z$ production
  - can be done with first 100 pb$^{-1}$

Figure 89. Predictions for the transverse momentum distributions for $Z$ production at the Tevatron (solid squares) and LHC (open squares).

Figure 90. The predictions for the transverse momentum distributions for $W$ and $Z$ production with and without the $p_T$-broadening effects.
Correlations using CTEQ6.1 error pdf’s

- As expected, W and Z cross sections are highly correlated
- Anti-correlation between tT and W cross sections
  - more glue for tT production (at higher x) means fewer anti-quarks (at lower x) for W production
  - mostly no correlation for (low mass) H and W cross sections
  - see more later

Figure 85. The cross section predictions for Z production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

Figure 93. The cross section predictions for tt production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.
Heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With new sets of pdf’s (CTEQ6.5/6.6), heavy quark mass effects consistently taken into account in global fitting cross sections and in pdf evolution
- In most cases, resulting pdf’s are within CTEQ6.1 pdf error bands
- But not at low x (in range of W and Z production at LHC)
- Heavy quark mass effects only appreciable near threshold
  - ex: prediction for $F_2$ at low $x,Q$ at HERA smaller if mass of $c,b$ quarks taken into account
  - thus, quark pdf’s have to be bigger in this region to have an equivalent fit to the HERA data

Figure 6: Comparison of theoretical calculations of $F_2$ using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

implications for LHC phenomenology
Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC.

Cross sections for W/Z increase by 7-8%

- now CTEQ and MRST2004 in disagreement
- and relative uncertainties of W/Z increase
- although individual uncertainties of W and Z decrease

Two new free parameters in fit dealing with strangeness degrees of freedom so now have 44 error pdf's rather than 40
Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC.

...but MSTW2008 has also lead to increased W/Z cross sections at the LHC.

Now CTEQ6.6 and MSTW2008 in agreement.

Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.
Now some technical stuff

- Consider a cross section \( X(a) \)
- \( i^{th} \) component of gradient of \( X \) is
  \[
  \frac{\partial X}{\partial a_i} = \partial_i X = \frac{1}{2}(X_i^+ - X_i^-)
  \]
- Now take 2 cross sections \( X \) and \( Y \) ◆ or one or both can be pdf's
- Consider the projection of gradients of \( X \) and \( Y \) onto a circle of radius 1 in the plane of the gradients in the parton parameter space
- The circle maps onto an ellipse in the \( XY \) plane
- The angle \( \phi \) between the gradients of \( X \) and \( Y \) is given by
  \[
  \cos \phi = \frac{\nabla X \cdot \nabla Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^{N} \left( X_i^+ - X_i^- \right) \left( Y_i^+ - Y_i^- \right)
  \]
- The ellipse itself is given by
  \[
  \left( \frac{\delta X}{\Delta X} \right)^2 + \left( \frac{\delta Y}{\Delta Y} \right)^2 - 2 \left( \frac{\delta X}{\Delta X} \right) \left( \frac{\delta Y}{\Delta Y} \right) \cos \phi = \sin^2 \phi
  \]

- If two cross sections are very correlated, then \( \cos \phi \sim 1 \)
  • ...uncorrelated, then \( \cos \phi \sim 0 \)
  • ...anti-correlated, then \( \cos \phi \sim -1 \)
Correlations: W/Z and pdf’s

• At the Tevatron, W and Z cross sections most correlated with u,U,d,D pdf’s

• At the LHC, W and Z cross sections most correlated with charm, bottom and gluon distributions

• A large correlation with the gluon for x values ~0.005 is accompanied by a large anti-correlation with the gluon at larger x

• This implies a strong anti-correlation of W and Z with heavy states produced by gg

Figure 10: (a,b) Correlation between the total cross sections for $Z^0$ and $W^\pm$ production at the Tevatron and PDF’s of various flavors, plotted as a function of x for $Q = 85$ GeV; (c,d) the same for the LHC
Correlations: Z to W ratio

- The ratio of the Z to W cross section is most strongly correlated with the strange quark distribution.

Figure 11: Correlation between the ratio $\sigma_Z/\sigma_W$ of LHC total cross sections for $Z^0$ and $W^\pm$ production at PDF's of various flavors, plotted as a function of $x$ for $Q = 85$ GeV.
Re-visit correlations with $Z, tT$

Define a correlation cosine between two quantities

- If two cross sections are very correlated, then $\cos \phi \approx 1$
- ...uncorrelated, then $\cos \phi \approx 0$
- ...anti-correlated, then $\cos \phi \approx -1$

Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos \phi$. 

The graph shows different correlation ellipses for varying values of $\cos \phi$, with $\cos \phi = 0.56$, $\cos \phi = -0.27$, $\cos \phi = 0.25$, $\cos \phi = 0.13$, $\cos \phi = -0.87$, and $\cos \phi = 0.99$. The ellipses are labeled with their corresponding correlation values and masses $M_0$.
Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

- If two cross sections are very correlated, then $\cos \phi \approx 1$
- ...uncorrelated, then $\cos \phi \approx 0$
- ...anti-correlated, then $\cos \phi \approx -1$

- Note that correlation curves to Z and to tT are mirror images of each other

- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section iff $\cos \phi > 0$; e.g. $\Delta (\sigma_W/\sigma_Z) \approx 1\%$

- If $\cos \phi < 0$, pdf uncertainty for one cross section normalized to a benchmark cross section is larger

- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta (\sigma_H/\sigma_Z) \approx 8\%$
• We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
  - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
• The pdf uncertainty for the ratio of a cross section that proceeds with a qQ initial state to the W/Z cross section is significantly reduced
• The pdf uncertainty for the ratio of a cross section that proceeds with a gg initial state to the W/Z cross section is significantly increased
• Would it be reasonable to use tT production as an additional normalization tool?
Theory uncertainties for tT at LHC

- Note that at NLO with CTEQ6.6 pdf’s the central prediction for the tT cross section for $\mu = m_t$ is ~850 pb (not 800 pb, which it would be if the top mass were 175 GeV); ~880 pb if use effect of threshold resummation
- The scale dependence is around +/-11% and mass dependence is around +/-6%
- Tevatron plans to measure top mass to 1 GeV
  - mass dependence goes to ~+/-3%
- NNLO tT cross section will be finished this year (Czakon et al)
  - scale dependence will drop (how far?)
  - threshold resummation reduces scale dependence to <6%; may hope for 3% with full NNLO
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller
New tool from John Campbell: MCFM with pdf errors

- Error pdf parton luminosities stored along with other event information; tremendous time-saving for MCFM
- Example output below from tT at LHC with CTEQ6.1 (virtual diagrams only)

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* Summary

Minimum value: 899134.509 fb
Central value: 922503.705 fb
Maximum value: 944892.019 fb
Err estimate +/-: 31131.272 fb
+ve direction: 31383.680 fb
-ve direction: 32098.504 fb

real diagrams contribute -70000 fb, so central NLO is ~850 pb; threshold resum->880 pb
What about experimental uncertainties?

- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value

- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?

- Tevatron now does 8% (non-lum)
Last but not least: Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers/particles to the jet.
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements.
- There is the tendency to treat jet algorithms as one would electron or photon algorithms.
- There's a much more dynamic structure in jet formation that is affected by the decisions made by the jet algorithms and which we can tap in ATLAS.
- ATLAS, with its fine segmentation and the ability to make topoclusters, has perhaps the most powerful jet capabilities in any hadron collider experiment to date...if we take full advantage of what the experiment offers.
Entrez Le SpartyJet

SpartyJet

Kurtis Geerlings
Michigan State University

Pierre-Antoine Delsart
Université de Montréal

Joey Huston
Michigan State University

http://www.pa.msu.edu/~huston/SpartyJet/SpartyJet.html
What is SpartyJet?

- "a framework intended to allow for the easy use of multiple jet algorithms in collider analyses"
- **Fast** to run, no need for heavy framework
- **Easy** to use, basic operation is very simple
- **Flexible**
  - ROOT-script or standalone execution
  - "on-the-fly" execution for event-by-event results
  - many different input types
  - different algorithms
  - output format

JetBuilder

- basically a frontend to handle most of the details of running SpartyJet
- not necessary, but makes running SpartyJet much simpler
- Allows options that are not otherwise accessible
  - text output
  - add minimum bias events

Available Algorithms

- **CDF**
  - JetClu
  - MidPoint (with optional second pass)
- **D0**
  - DORunIIConCone
    - (from Lars Sonnenschein)
- **ATLAS**
  - Cone
  - FastKt
  - FastJet (from Gavin Salam and Matteo Cacciari)
    - FastKt
    - Seedless Infrared Safe Cone (SISConCone)
- **Pythia 8**
  - CellJet
  - **all algorithms are fully parameterizable**

"on-the-fly" method

- no input data file, no output data file
- from other C++ programs, call a variant of
  `jets = SpartyJet::getjets(JetTool*, data)`
- Currently supported data types:
  ```cpp
  jet = jet & SpartyJet::getjets(JetTool* tool, JetTool* tool
  jet = jet & input jets);
  std::vector<TLorentzVector>& SpartyJet::getjets(JetTool* tool
  std::vector<TLorentzVector>& input);
  std::vector<TLorentzVector>& SpartyJet::getjets(JetTool* tool
  std::vector<TLorentzVector>& input);
  std::vector<SpartyJet::simplejet>& SpartyJet::getjets(JetTool* tool
  std::vector<simplejet>& input);
  ```

reconstruct individual jets with new parameters in context of analysis
SpartyJet ntuples for ATLAS

- SpartyJet ntuples produced for W/Z + jets analysis for 0,1,2,3,4,5 parton samples
- VBF Higgs production
- tT
SpartyJet

W + 4parton
Jet pT distributions

Lead Jet

2nd Jet

SISCone R=0.4
SISCone R=0.7
Cone R=0.4
Cone R=0.7

Cone uses split/merge = 0.5
SISCone uses split/merge = 0.75

Changing jet parameters: Number of jets

MidPoint seed 0.1 GeV
MidPoint seed 1 GeV
MidPoint seed 2 GeV

SISCone s/m 0.5
SISCone s/m 0.625
SISCone s/m 0.75
Jet masses

- It’s often useful to examine jet masses, especially if the jet might be some composite object, say a W/Z or even a top quark

- For 2 TeV jets (J8 sample), peak mass (from dynamical sources) is on order of 125 GeV/c², but with long tail
  - Sudakov suppression for low jet masses
  - fall-off as 1/m² due to hard gluon emission
  - algorithm suppression at high masses
    ▲ jet algorithms tend to split high mass jets in two

Figure 50: The inclusive jet cross section for the LHC with a $p_T_{\text{min}}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale $(D = R_{\text{cone}})$ of 0.7. The first bin has been suppressed.

Figure 51: The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_T_{\text{min}}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale $(D = R_{\text{cone}})$ of 0.7. The first bin has been suppressed.
Other features

- Access to jet constituents
- Y-splitter, to determine scale at which jet can be resolved into n sub-jets (pending)
- Ability to add n min bias events
- Event visualization
- gui interface (coming soon)
Some recommendations from jet paper

- 4-vector kinematics ($p_T, y$ and not $E_T, \eta$) should be used to specify jets
- Where possible, analyses should be performed with multiple jet algorithms
- For cone algorithms, split/merge of 0.75 preferred to 0.50
Summary

- Physics will come flying hot and heavy when LHC turns on in 2008
  - most likely 10-11 TeV, in August, with a running period of 2-3 months
- Important to establish both the SM benchmarks and the tools we will need to properly understand this flood of data
- So we can have confidence that any BSM signals that we see are really BSM

“We have to live with the Standard Model we have, not the Standard Model we want.”
New CTEQ project: CTEQ4LHC

- Collate/create cross section predictions for LHC
  - processes such as W/Z/Higgs (both SM and BSM)/diboson/tT/single top/photons/jets...
  - at LO, NLO, NNLO (where available)
    ▲ new: W/Z production to NNLO QCD and NLO EW
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation ($q_T$ and threshold)
- As prelude towards comparison with actual data
- Using programs such as:
  - MCFM
  - ResBos
  - EKS
  - Pythia/Herwig/Sherpa
  - …numerous private codes with CTEQ
- First on webpage and later as a report
2008 CTEQ summer school

...in conjunction with MCNET

A combination of broad lectures on QCD theory, phenomenology and analysis and a practical approach to event generator physics and techniques, with hands-on sessions and talks on using them in real analyses

Debrecen, Hungary
Aug 8-16

http://cteq-mcnet.org/
Extra slides
**Known known:** underlying event at the Tevatron

- Define regions transverse to the leading jet in the event
- Label the one with the most transverse momentum the MAX region and that with the least the MIN region
- The transverse momentum in the MAX region grows as the momentum of the lead jet increases
  - receives contribution from higher order perturbative contributions
- The transverse momentum in the MIN region stays basically flat, at a level consistent with minimum bias events
  - no substantial higher order contributions
- Monte Carlos can be tuned to provide a reasonably good universal description of the data for inclusive jet production and for other types of events as well
  - multiple interactions among low x gluons
Aside: Why K-factors < 1 for inclusive jet production?

- Write cross section indicating explicit scale-dependent terms
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases
- Second term is negative for \( \mu < p_T \), positive for \( \mu > p_T \)
- Third term is negative for factorization scale \( M < p_T \)
- Fourth term has same dependence as lowest order term
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to \( p_T \), and are positive for larger scales
- At NLO, result is a roughly parabolic behavior

Consider a large transverse momentum process such as the single jet inclusive cross section involving only massless partons. Furthermore, in order to simplify the notation, suppose that the transverse momentum is sufficiently large that only the quark distributions need be considered. In the following, a sum over quark flavors is implied. Schematically, one can write the lowest order cross section as

\[
E \frac{d^3\sigma}{dp^3} = \sigma = a^2(\mu) \tilde{\sigma}_B \otimes q(M) \otimes q(M) \tag{1}
\]

where \( a(\mu) = \alpha_s(\mu)/2\pi \) and the lowest order parton-parton scattering cross section is denoted by \( \tilde{\sigma}_B \). The renormalization and factorization scales are denoted by \( \mu \) and \( M \), respectively. In addition, various overall factors have been absorbed into the definition of \( \tilde{\sigma}_B \). The symbol \( \otimes \) denotes a convolution defined as

\[
f \otimes g = \int_\pi^1 \frac{dy}{y} f\left(\frac{y}{\bar{y}}\right) g(y). \tag{2}
\]

When one calculates the \( \mathcal{O}(a_s^3) \) contributions to the inclusive cross section, the result can be written as

\[
\begin{align*}
(1) \quad \sigma &= a^2(\mu) \tilde{\sigma}_B \otimes q(M) \otimes q(M) \\
(2) \quad &+ 2a^3(\mu) b \ln(\mu/p_T) \tilde{\sigma}_B \otimes q(M) \otimes q(M) \\
(3) \quad &+ 2a^3(\mu) \ln(p_T/M) P_{ss} \otimes \tilde{\sigma}_B \otimes q(M) \otimes q(M) \\
(4) \quad &+ a^3(\mu) K \otimes q(M) \otimes q(M). \tag{3}
\end{align*}
\]

In writing Eq. (3), specific logarithms associated with the running coupling and the scale dependence of the parton distributions have been explicitly displayed; the remaining higher order corrections have been collected in the function \( K \) in the last line of Eq. (3). The \( \mu \)
Why K-factors < 1?

- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases.
- Second term is negative for $\mu < p_T$, positive for $\mu > p_T$.
- Third term is negative for factorization scale $M < p_T$.
- Fourth term has same dependence as lowest order term.
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to $p_T$, and are positive for larger scales.
- NLO parabola moves out towards higher scales for forward region.
- Scale of $E_T/2$ results in a K-factor of ~1 for low $E_T$, <<1 for high $E_T$ for forward rapidities at Tevatron.
Aside: Jet algorithms at NLO

- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood.
  - More difficulty when comparing to parton level calculations.

- Remember at LO, 1 parton = 1 jet.

- At NLO, there can be two (or more) partons in a jet and life becomes more interesting.

- Let's set the $p_T$ of the second parton $= z$ that of the first parton and let them be separated by a distance $d (= \Delta R)$.

- Then in regions I and II (on the left), the two partons will be within $R_{cone}$ of the jet centroid and so will be contained in the same jet.
  - ~10% of the jet cross section is in Region II; this will decrease as the jet $p_T$ increases (and $\alpha_s$ decreases).
  - At NLO the $k_T$ algorithm corresponds to Region I (for $D=R$); thus at parton level, the cone algorithm is always larger than the $k_T$ algorithm.

---

Image 1: Diagram illustrating the cone algorithm with $z = p_{T2}/p_{T1}$.

Image 2: Plots showing the parameter space $(d, Z)$ for which two partons will be merged into a single jet. The plots indicate that at $R = 0.7$, the merging becomes more significant.
W + jets at the Tevatron

- Interesting for tests of perturbative QCD formalisms
  - matrix element calculations
  - parton showers
  - ...or both
- Backgrounds to tT production and other potential new physics
- Observe up to 7 jets at the Tevatron
- Results from Tevatron to the right are in a form that can be easily compared to theoretical predictions (at hadron level)
  - see www-cdf.fnal.gov QCD webpages
  - in process of comparing to MCFM and CKKW predictions
  - remember for a cone of 0.4, hadron level ~ parton level

Note emission of each jet suppressed by a factor of $\alpha_s$

Agreement with MCFM for low jet multiplicity
High $p_T$ tops

- At the LHC, there are many interesting physics signatures for BSM that involve highly boosted top pairs
- This will be an interesting/challenging environment for trying to optimize jet algorithms
  - each top will be a single jet
- Even at the Tevatron have tops with up to 300 GeV/c of transverse momentum