QCD Backgrounds to New Physics II

J. Huston

...thanks to Weiming Yao, John Campbell, Bruce Knuteson, Nigel Glover for transparencies
but first some commercials
Run 2 Monte Carlo Workshop

- Transparencies, video links to individual talks and links to programs can all be found at http://www-theory.fnal.gov/runiimc/

- I’ll be referring to some of these programs in the course of my talk
Les Houches

- Two workshops on “Physics at TeV Colliders” have been held so far, in 1999 and 2001 (May 21-June 1)
- Working groups on QCD/SM, Higgs, Beyond Standard Model
- See web page: http://wwwlapp.in2p3.fr/conferences/LesHouches/Houches2001/
especially for links to writeups from 1999 and 2001
- QCD 1999 writeup (hep-ph/0005114) is an excellent pedagogical review for new students
- QCD 2001 writeup (hep-ph/0204316) is a good treatment of the state of the art for pdfs, NLO calculations, Monte Carlos
- Les Houches 2003 will have more of a concentration on EW/top physics
Les Houches 2001 Writeups

- The QCD/SM Working Group: Summary Report
  - hep-ph/0204316

  - hep-ph/0203056

- The Beyond the Standard Model Working Group: Summary Report
  - hep-ph/0204031
Les Houches 2001

- 200th bottle of wine consumed at the workshop

CTEQ SS02
J. Huston
Other useful references (for pdfs)

- LHC Guide to Parton Distributions and Cross Sections, J. Huston; http://www.pa.msu.edu/~huston/lhc/lhc_pdfnote.ps
- Parton Distributions Working Group, Tevatron Run 2 Workshop; hep-ph/0006300
- A QCD Analysis of HERA and fixed target structure function data, M. Botje; hep-ph/9912439
- Global fit to the charged leptons DIS data..., S. Alekhin; hep-ph/0011002
- Walter Giele’s presentation to the QCD group on Jan. 12; http://www-cdf.fnal.gov/internal/physics/qcd/qcd99_internal_meetings.html
- Error Estimates on Parton Density Distributions, M. Botje; hep-ph/0110123
- New Generation of Parton Distributions with Uncertainties from Global QCD Analysis (CTEQ6); hep-ph/0201195
Other references...

…to the ability to calculate QCD backgrounds

…to the need to do so

CTEQ SS02
J. Huston
Monojets in UA1

- UA1 monojets (1983-1984)
  - Possible signature of new physics (SUSY, etc)
  - A number of backgrounds were identified, but each was noted as being too small to account for the observed signal
    - pp -> Z + jets
      - νν
    - pp -> W + jets
      - τ + ν
      - hadrons + ν
    - pp -> W + jets
      - l + ν
  - "The sum of many small things is a big thing." G. Altarelli

- ...but the sum was not

- Can calculate from first principles or calibrate to observed cross sections for Z -> e⁺e⁻ and W -> ev

Signatures of New Physics

- $W$s, jets, $\gamma$s, $b$ quarks, $E_T$
- …pretty much the same as signatures for SM physics
- How do we find new physics? By showing that it’s not old physics.
  - can be modifications to the rate of production
  - …or modification to the kinematics, e.g. angular distributions
- Crucial to understand the QCD dynamics and normalization of both backgrounds to any new physics and to the new physics itself
- Some backgrounds can be measured in situ
  - …but may still want to predict in advance, e.g. QCD backgrounds to $H\rightarrow\gamma\gamma$
- For some backgrounds, need to rely on theoretical calculations, e.g. $ttbb$ backgrounds to $ttH$
Theoretical Predictions for New (Old) Physics

There are a variety of programs available for comparison of data to theory and/or predictions.

- **Tree level**
- **Leading log Monte Carlo**
- **$N^n$LO**
- **Resummed**

In general, agree quite well…but before you appeal to new physics, check the ME. (for example using Comphep) Can have ME corrections to MC or MC corrections to ME. (in CDF->HERPRT)

Perhaps biggest effort…include NLO ME corrections in Monte Carlo programs…correct normalizations. Correct shapes. $N^n$LO needed for precision physics.

Resummed description describes soft gluon effects (better than MC’s)…has correct normalization (but need HO to get it); resummed predictions include non-perturbative effects correctly…may have to be put in by hand in MC’s

Important to know strengths/weaknesses of each.

Where possible, normalize to existing data.

...in addition, worry about pdf, fragmentation uncertainties

CTEQ SS02
J. Huston
W + Jet(s) at the Tevatron

- Good testing ground for parton showers, matrix elements, NLO
- Background for new physics or old physics (top production)
- Reasonable agreement for the leading order comparisons using VECBOS (but large scale dependence)

- Good agreement with NLO (and smaller scale dependence) for W + >= 1 jet

CDF PRELIMINARY

CDF Data (108 pb⁻¹)
0.4 Jet Cones, |η| < 2.4
DYRAD NLO QCD Predictions with jet smearing
MRSA

Systematic uncertainties

CDF PRELIMINARY

CTEQ SS02
J. Huston
W + jets

- For $W + \geq n$ jet production, typically use Herwig (Herprt) for additional gluon radiation and for hadronization.

- Can also start off with $n-1$ jets and generate additional jets using Herwig.

---

---

---

---

---

---

---

---

---
More Comparisons (VECBOS and HERWIG)

- Start with $W + n$ jets from VECBOS

- Start with $W + (n-1)$ jets from VECBOS

CDF Preliminary Data $(108 \text{ pb}^{-1})$

$+$ VECBOS + HERWIG

$+$ Detector Simulation

CTEQ3M, $Q^2 = <p_T>^2$

(Normalized to data)

W + $\geq 2$ Jets Data

VECBOS W + 1 Jet

W + $\geq 3$ Jets Data

VECBOS W + 2 Jet

CTEQ SS02

J. Huston
More Comparisons

- Start with $W + n$ jets from VECBOS
- Start with $W + (n-1)$ jets from VECBOS

CDF Preliminary Data (108 pb$^{-1}$)
- VECBOS + HERWIG Fragmentation
+ Detector Simulation
CTEQ3M, $Q^2 = <p_T>^2$
(Normalized to data)

Events / (10 GeV/c$^2$)

$W + \geq 2$ Jets Data
VECBOS $W + 2$ Jets

$W + \geq 3$ Jets Data
VECBOS $W + 3$ Jets

CTEQ SS02
J. Huston
When good Monte Carlos go bad

- Consider $W + \text{jet(s)}$ sample
- Compare data (Run 0 CDF) to VECBOS+HERPRT (Herwig radiation+hadronization interface to VECBOS) normalized to $W+X$ jets
- Starting with $W + 1$ jet rate in data, Herwig predicts 1 $W + >4$ jet events; in data observe 10
- …factor of ~2 every jet
  - very dependent on kinematic situation, though
    - jet $E_T$ cuts
    - center-of-mass energy
    - etc

<table>
<thead>
<tr>
<th>#events</th>
<th>&gt;1 jet</th>
<th>&gt;2 jets</th>
<th>&gt;3 jets</th>
<th>&gt;4 jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &gt; 10 \text{ GeV/c}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>920</td>
<td>213</td>
<td>42</td>
<td>10</td>
</tr>
<tr>
<td>VECBOS + HERPRT ($Q=\langle p_T \rangle$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + 1\text{jet}$</td>
<td>920</td>
<td>178</td>
<td>21</td>
<td>1</td>
</tr>
<tr>
<td>$W + 2\text{jet}$</td>
<td>-----</td>
<td>213</td>
<td>43</td>
<td>6</td>
</tr>
<tr>
<td>$W + 3\text{jet}$</td>
<td>-----</td>
<td>-----</td>
<td>42</td>
<td>10</td>
</tr>
<tr>
<td>VECBOS+HERPRT($Q=m_W$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + 1\text{jet}$</td>
<td>920</td>
<td>176</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>$W + 2\text{jet}$</td>
<td>-----</td>
<td>213</td>
<td>46</td>
<td>6</td>
</tr>
<tr>
<td>$W + 3\text{jet}$</td>
<td>-----</td>
<td>-----</td>
<td>42</td>
<td>7</td>
</tr>
</tbody>
</table>
Factors get worse at the LHC
Why?

- Some reasons given by the experts (Mangano, Yuan, Ilyin…)
  - Herwig (any Monte Carlo) only has collinear part of matrix element for gluon emission; underestimate for the wide angle emission that leads to widely separated jets
  - phase space: Herwig has ordering in virtualities for gluon emission while this is not present in exact matrix element calculations; more phase space for gluon emission in exact matrix element calculations
  - in case of exact matrix element, there are interferences among all of the different diagrams; these interferences become large when emissions take place at large angles (don’t know a priori whether interference is positive or negative)
  - unitarity of Herwig evolution: multijet events in Herwig will always be a fraction of the 2 jet rate, since multijet events all start from the 2-jet hard process
    ▲ all “K-factors” from higher order are missed.
Tree Level Calculations

- Leading order matrix element calculations describe multi-body configurations better than parton showers

- Many programs exist for calculation of multi-body final states at tree-level
  - References: see Dieters talk; see Run 2 MC workshop

- CompHep
  - includes SM Lagrangian and several other models, including MSSM
  - deals with matrix elements squared
  - calculates leading order 2->4-6 in the final state taking into account all of QCD and EW diagrams
  - color flow information; interface exits to Pythia
  - great user interface

- Grace
  - similar to CompHep

- Madgraph
  - SM + MSSM
  - deals with helicity amplitudes
  - “unlimited” external particles (12?)
  - color flow information
  - not much user interfacing yet

- Alpha + O’Mega
  - does not use Feynman diagrams
  - gg->10 g (5,348,843,500 diagrams)

CTEQ SS02
J. Huston
Monte Carlo Interfaces

- To obtain full predictability for a theoretical calculation, would like to interface to a Monte Carlo program (Herwig, Pythia, Isajet)
  - parton showering (additional jets)
  - hadronization
  - detector simulation
- Some interfaces already exist
  - VECBOS->Herwig (HERPRT)
  - CompHep->Pythia
- A general interface accord was reached at the 2001 Les Houches workshop
- All of the matrix element programs mentioned will output 4-vector and color flow information in such a way as to be universally readable by all Monte Carlo programs
- CompHep, Grace, Madgraph, Alpha, etc, etc
  ->Herwig, Pythia, Isajet
Les Houches accords

- Les Houches accord #1 (ME->MC)
  - accord implemented in Pythia 6.2
  - accord implemented in CompHEP
    ▲ CDF top dilepton group has been generating ttbar events with CompHEP/Madgraph + Pythia
  - accord implemented in Wbbgen (not yet released)
  - accord implemented in Madgraph
    ▲ MADCUP:http://pheno.physics.wisc.edu/Software/MadCUP/}
    ▲ MADGRAPH 2: within a few weeks
  - work proceeding on Herwig; in release 6.5 June 2002
  - work proceeding on Grace
  - In AcerMC:hep-ph/0201302

- Les Houches accord #2 (pdfs in ME/MC)
  - version of pdf interface has been developed
    ▲ writeup available now; website will be publically available next week (http://pdf.fnal.gov)
  - commitment for being implemented in MCFM
Les Houches accord #2

- Using the interface is as easy as using PDFLIB (and much easier to update)
- First version will have CTEQ6M, CTEQ6L, all of CTEQ6 error pdfs and MRST2001 pdfs
- See pdf.fnal.gov

- call InitPDFset(name)
  - called once at the beginning of the code; name is the file name of external PDF file that defines PDF set
- call InitPDF(mem)
  - mem specifies individual member of pdf set
- call evolvePDF(x,Q,f)
  - returns pdf momentum densities for flavor f at momentum fraction x and scale Q
 Reminder: the big idea:

- The Les Houches accords will be implemented in all ME/MC programs that experimentalists/theorists use.
- They will make it easy to generate the multi-parton final states crucial to much of the Run 2/HERA/LHC physics program and to compare the results from different programs.
- Experimentalists/theorists can all share common MC data sets.
- They will make it possible to generate the pdf uncertainties for any cross sections.
Les Houches accord

hep-ph/0109068

Generic User Process Interface for Event Generators


September 7, 2001

Abstract

Generic Fortran common blocks are presented for use by High Energy Physics event generators for the transfer of event configurations from parton level generators to showering and hadronization event generators.

Modularization of High Energy Particle Physics event generation is becoming increasingly useful as the complexity of Monte Carlo programs grows. To accommodate this trend, several authors of popular Monte Carlo and matrix element programs attending the *Physics at TeV Colliders Workshop* in Les Houches, 2001 have agreed on a generic format for the transfer of parton level event configurations from matrix element event generators (MEG) to showering and hadronization event generators (SHG).

Events generated this way are customarily called user (or user-defined) processes, to distinguish them from the internal processes that come with the SHG. Specific solutions are already in use, including an interface of WbbGen with Herwig [9] and an interface of CompHEP with Pythia [10]—that experience is exploited here.

An implementation of the user process interface has been included in Pythia 6.2, described (with an example) in Ref. [11].

The user process interface discussed here is not intended as a replacement for HEPEVT [12], which is the standard Fortran common block for interface between generators and analysis/detector simulation. The user process common blocks address the communication between two event generators only, a MEG one and a SHG one, and not the communication of event generators with the outside world.

In the course of a normal event generation run, this communication occurs at two stages:

1. At initialization, to establish the basic parameters of the run as a whole. (2) For each new event that is to be transferred from the MEG to the SHG. Each of these two stages

Example: hadronic $t\bar{t}$ production

$I$ ISTUP($I$) IDUP($I$) MOTHUP($1,I$) MOTHUP($2,I$) ICOLUP($1,I$) ICOLUP($2,I$)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>-1</th>
<th>21 (g)</th>
<th></th>
<th>501</th>
<th>502</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-1</td>
<td>21 (g)</td>
<td></td>
<td>503</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+2</td>
<td>21 (g)</td>
<td></td>
<td>503</td>
<td>502</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+2</td>
<td>-6 (t)</td>
<td></td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>+2</td>
<td>6 (t)</td>
<td></td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-5 (b)</td>
<td></td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>+1</td>
<td>-24 (W$^-$)</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>5 (b)</td>
<td></td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>+1</td>
<td>24 (W$^+$)</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The $Z^0, t, \bar{t}$ are given ISTUP=-2, which informs the showering and hadronization generator to preserve their invariant masses when showering and hadronizing the event.

The definition of a line as ‘color’ or ‘anti-color’ depends on the orientation of the graph. This ambiguity is resolved by defining color and anti-color according to the physical time order. A quark will always have its color tag ICOLUP($1,I$) filled, but never its anti-color tag ICOLUP($2,I$); the reverse is true for an anti-quark, and a gluon will always have information in both ICOLUP($1,I$) and ICOLUP($2,I$) tags.

Events generated this way are customarily called user (or user-defined) processes, to distinguish them from the internal processes that come with the SHG. Specific solutions are already in use, including an interface of WbbGen with Herwig [9] and an interface of CompHEP with Pythia [10]—that experience is exploited here.

An implementation of the user process interface has been included in Pythia 6.2, described (with an example) in Ref. [11].

The user process interface discussed here is not intended as a replacement for HEPEVT [12], which is the standard Fortran common block for interface between generators and analysis/detector simulation. The user process common blocks address the communication between two event generators only, a MEG one and a SHG one, and not the communication of event generators with the outside world.

In the course of a normal event generation run, this communication occurs at two stages:

1. At initialization, to establish the basic parameters of the run as a whole. (2) For each new event that is to be transferred from the MEG to the SHG. Each of these two stages

Example: hadronic $t\bar{t}$ production

$I$ ISTUP($I$) IDUP($I$) MOTHUP($1,I$) MOTHUP($2,I$) ICOLUP($1,I$) ICOLUP($2,I$)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>-1</th>
<th>21 (g)</th>
<th>501</th>
<th>502</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-1</td>
<td>21 (g)</td>
<td>503</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+2</td>
<td>21 (g)</td>
<td>503</td>
<td>502</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+2</td>
<td>-6 (t)</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>+2</td>
<td>6 (t)</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-5 (b)</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>+1</td>
<td>-24 (W$^-$)</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>5 (b)</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>+1</td>
<td>24 (W$^+$)</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

The $Z^0, t, \bar{t}$ are given ISTUP=-2, which informs the showering and hadronization generator to preserve their invariant masses when showering and hadronizing the event.

The definition of a line as ‘color’ or ‘anti-color’ depends on the orientation of the graph. This ambiguity is resolved by defining color and anti-color according to the physical time order. A quark will always have its color tag ICOLUP($1,I$) filled, but never its anti-color tag ICOLUP($2,I$); the reverse is true for an anti-quark, and a gluon will always have information in both ICOLUP($1,I$) and ICOLUP($2,I$) tags.

Note the difference in the treatment by the parton shower of the above example, and an identical final state, where the intermediate particles are not specified:

$I$ ISTUP($I$) IDUP($I$) MOTHUP($1,I$) MOTHUP($2,I$) ICOLUP($1,I$) ICOLUP($2,I$)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>-1</th>
<th>21 (g)</th>
<th>501</th>
<th>502</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-1</td>
<td>21 (g)</td>
<td>503</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>-5 (b)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>-24 (W$^-$)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>5 (b)</td>
<td>1</td>
<td>2</td>
<td>503</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>24 (W$^+$)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Note the difference in the treatment by the parton shower of the above example, and an identical final state, where the intermediate particles are not specified:

$I$ ISTUP($I$) IDUP($I$) MOTHUP($1,I$) MOTHUP($2,I$) ICOLUP($1,I$) ICOLUP($2,I$)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>-1</th>
<th>21 (g)</th>
<th>501</th>
<th>502</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-1</td>
<td>21 (g)</td>
<td>503</td>
<td>504</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>-5 (b)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>-24 (W$^-$)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>5 (b)</td>
<td>1</td>
<td>2</td>
<td>503</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>24 (W$^+$)</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
Parton Showering

- Determination of the Higgs signal requires an understanding of the Higgs $p_T$ distribution at both LHC and Tevatron
  - For example, for $gg\rightarrow HX\rightarrow \gamma\gamma X$, the shape of the signal $p_T$ distribution is harder than that of the $\gamma\gamma$ background; this can be used to advantage

- To reliably predict the Higgs $p_T$ distribution, especially for low to medium $p_T$ region, have to include effects of soft gluon radiation
  - Can either use parton showering a la Herwig, Pythia, ISAJET or $k_T$ resummation a la ResBos
  - Parton showering resums primarily the (universal) leading logs while an analytic $k_T$ resummation can resum all logs with $Q^2/p_T^2$ in their arguments; but expect predictions to be similar and Monte Carlos offer a more useful format

- Where possible it’s best to compare $p_T$ predictions to a similar data set to insure correctness of formalism; if data is not available, compare MC’s to a resummed calculation or at least to another Monte Carlo
  - All parton showers are not equal

Note the large difference between PYTHIA versions 5.7 and 6.1. Which one is correct?

\[
\frac{d\sigma}{dp_T} \text{ (pb/GeV)}
\]

- $gg\rightarrow H + X$ at LHC
  - $m_H = 150$ GeV, CTEQ4M, $\sqrt{s} = 14$ TeV

- PYTHIA 5.7 default
- PYTHIA 6.122 default
- PYTHIA 6.122 $Q^2_{\text{max}}=s$
Change in PYTHIA

- Older version of PYTHIA has more events at moderate $p_T$
- Two changes from 5.7 to 6.1
  - A cut has been placed on the combination of $z$ and $Q^2$ values in a branching: $u=Q^2-s(1-z)<0$ where $s$ refers to the subsystem of hard scattering plus shower partons
    - corner of emissions that do not respect this requirement occurs when $Q^2$ value of space-like emitting parton is little changed and $z$ value of branching is close to unity
    - necessary if matrix element corrections are to be made to process
    - net result is substantial reduction in amount of gluon radiation
    - In principle affects all processes; in practice only gg initial states
  - Parameter for minimum gluon energy emitted in space-like showers is modified by extra factor corresponding to $1/\gamma$ factor for boost to hard subprocess frame
    - result is increase in gluon radiation
- The above are choices, not bugs; which version is more correct?
- ->Compare to ResBos

S. Mrenna
80 GeV Higgs generated at the Tevatron with Pythia
Comparison of PYTHIA and ResBos for Higgs Production at LHC

- **ResBos agrees much better with the more recent version of PYTHIA**
  - Suppression of gluon radiation leading to a decrease in the average $p_T$ of the produced Higgs
  - Affects the ability of CMS to choose to the correct vertex to associate with the diphoton pair

- **Note that PYTHIA does not describe the high $p_T$ end well unless $Q_{\text{max}}^2$ is set to $s$ (14 TeV)**
  - Again, ResBos has the correct matrix element matching at high $p_T$; setting $Q_{\text{max}}^2=s$ allows enough additional gluon radiation to mimic the matrix element
Comparisons with Herwig at the LHC

- HERWIG (v5.6) similar in shape in PYTHIA 6.1 (and perhaps even more similar in shape to ResBos)
- Is there something similar to the u-hat cut that regulates the HERWIG behavior?
  - Herwig treatment of color coherence?
Logs that we know and love

\textit{Res\sum\textsuperscript{TM} a la C.S.S. "Cogito ergo resum!"}

\textbf{Problem}

\begin{itemize}
  \item QCD corrections to the $Q_T$ dist'n contain logs:
  \[ \frac{d\sigma_{gg\to H}}{dQ_T^2} \rightarrow \sum_{n,m=0}^{\infty} \frac{1}{\alpha_s^n} \frac{1}{\alpha_s^m} L^n m + \mathcal{O}(\frac{1}{\alpha_s}) = \]
  \begin{align*}
    \text{Singular + Regular}
  \end{align*}
  \item Each ‘Big Bad Log’ (D.Soper) $L = \ln(\frac{Q_T}{Q})$ factor due to emission of a soft/collinear gluon
  \item The coeffs of $\alpha_s$ carry potentially large logs $\rightarrow$ no convergence
\end{itemize}

\textbf{Solution}

\begin{itemize}
  \item Reorganize the perturbative sum in terms of $\alpha_s^n L^m$
  \[ \frac{d\sigma_{gg\to H}}{dQ_T^2} \sim \alpha_s^i \frac{L^{i+1}}{\alpha_s^j} \]
  \[ \left( \alpha_s^2 + \alpha_s^3 L^2 + \alpha_s^4 L^4 + \alpha_s^5 L^6 + \ldots \right) \left( \alpha_s^2 + \alpha_s^3 L^2 + \alpha_s^4 L^4 + \ldots \right) \left( \alpha_s^3 + \alpha_s^4 L^2 + \ldots \right) \]
  \begin{itemize}
    \item $A_1, B_1, C_0$ control the NLO normalization
    \item $A_2, A_2, B_2, C_1$ which control the NLO normalization
  \end{itemize}
  \item The $B_2$ term has recently been calculated for gg-$\rightarrow$H
\end{itemize}

C. Balazs, Higgs production with soft-gluon effects, les Houches ’99
Study of $gg\rightarrow$Higgs for different masses and different energies

- Outgrowth of previous Les Houches work

- Probe Higgs production for different kinematic regions
  - most difficult case for parton showering ($gg$)
  - important process

- Try to understand whether improvement in Pythia is universal and what the underlying
$m_H=125$ GeV at 14 and 40 TeV

CTEQ SS02

J. Huston
Rescale to make up for *lost* high $p_T$ cross section

• Herwig agrees almost exactly with ResBos LL
Absolutely normalized

$gg \rightarrow H + X$ at Tevatron
$m_H = 125$ GeV, CTEQ5M, $\sqrt{s} = 1.96$ TeV
curves: ResBos
- NLL: $B(1,2)$, $A(1,2)$, $C(0,1)$
- LL: $B(1)$, $A(1)$, $C(0)$
histograms:
- PYTHIA 5.7
- PYTHIA 6.136
- PYTHIA 6.203
- HERWIG 6.3

$gg \rightarrow H + X$ at LHC
$m_H = 125$ GeV, CTEQ5M, $\sqrt{s} = 14$ TeV
curves: ResBos
- NLL: $B(1,2)$, $A(1,2)$, $C(0,1)$
- LL: $B(1)$, $A(1)$, $C(0)$
histograms:
- PYTHIA 5.7
- PYTHIA 6.136
- PYTHIA 6.203
- HERWIG 6.3
$m_H = 500$ GeV
The need for higher order...

OVERVIEW OF NNLO QCD CORRECTIONS
E.W.N. GLOVER
Department of Physics, University of Durham, South Road,
Durham DH1 3LE, England

We discuss the motivation for making predictions for jet cross sections at next-to-next-to-leading order. I describe the theoretical ingredients needed for such a calculation and kindly review the progress in the field.

In the last decade there has been enormous progress in using perturbative QCD to predict and describe events containing jets. At the simplest lowest-order (LO) level, each jet is the footprint of a hard, well separated parton produced in the event. Although the predicted rate is sensitive to the choice of renormalisation and factorisation scales, qualitative comparisons of data and theory are generally very good. A more quantitative description is achieved by improving the theoretical prediction to next-to-leading order (NLO). This has the effect of reducing the dependence on the unphysical renormalisation and factorisation scales so that the normalisation is more certain. Furthermore, the sensitivity to the details of the jet finding algorithm and the size of the jet is increased since now two partons may be combined to form the jet. However, for the most basic jet production processes such as \( p\bar{p} \rightarrow j + X \), \( p\bar{p} \rightarrow V + j + X \), \( e^+e^- \rightarrow 3 \text{ jets} \) or \( e+p \rightarrow e-(2+1) \text{ jets} \), the experimental accuracy is such that even more precise theoretical predictions are required. In this talk, we review the recent progress made towards predicting jet cross sections at next-to-next-to-leading order (NNLO).

The addition of NNLO effects gives significant improvements over an NLO estimate. First, the dependence on the unphysical scales is significantly reduced. At NLO we find a reliable estimate of the cross section, while NNLO calculations yield a reliable estimate of the uncertainty in the cross section. For example, if we consider the single jet inclusive cross section for jets with \( E_T = 100 \text{ GeV} \) and \( 0.1 < |\eta| < 0.7 \) at \( \sqrt{s} = 1800 \text{ GeV} \), the renormalisation scale dependence due to variations of a factor of two about \( \mu_R = E_T \) is reduced from 20% to 9% to 1% as we move from...

Figure 1: Jet cross section \( d\sigma/dE_T \) for \( E_T = 100 \text{ GeV} \) versus renormalisation scale \( \mu/E_T \). NNLO is the renormalisation group predictable part. We see that for renormalisation scales within a factor of two of the jet energy, the renormalisation scale uncertainty is reduced from 20% to 9% to 1%.

CTEQ SS02
J. Huston
What would we like?

Bruce Knuteson’s wishlist from the Run 2 Monte Carlo workshop

<table>
<thead>
<tr>
<th>Single boson</th>
<th>Diboson</th>
<th>Triboson</th>
<th>Heavy flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+ ≤5j</td>
<td>WW+ ≤5j</td>
<td>WWW+ ≤3j</td>
<td>tt+ ≤3j</td>
</tr>
<tr>
<td>W + bb+ ≤3j</td>
<td>WW + bb+ ≤3j</td>
<td>WWZ+ ≤3j</td>
<td>tt + γ+ ≤2j</td>
</tr>
<tr>
<td>W + c̄c+ ≤3j</td>
<td>WW + c̄c+ ≤3j</td>
<td>Wγγ+ ≤3j</td>
<td>tt + W+ ≤2j</td>
</tr>
<tr>
<td>Z+ ≤5j</td>
<td>ZZ+ ≤5j</td>
<td>Zγγ+ ≤3j</td>
<td>tt + Z+ ≤2j</td>
</tr>
<tr>
<td>Z + bb+ ≤3j</td>
<td>ZZ + bb+ ≤3j</td>
<td>WZZ+ ≤3j</td>
<td>tt + H+ ≤2j</td>
</tr>
<tr>
<td>Z + c̄c+ ≤3j</td>
<td>ZZ + c̄c+ ≤3j</td>
<td>ZZZ+ ≤3j</td>
<td>tb+ ≤2j</td>
</tr>
<tr>
<td>γ+ ≤5j</td>
<td>γγ+ ≤5j</td>
<td></td>
<td>bb+ ≤3j</td>
</tr>
<tr>
<td>γ + bb+ ≤3j</td>
<td>γγ + bb+ ≤3j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γ + c̄c+ ≤3j</td>
<td>γγ + c̄c+ ≤3j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ+ ≤5j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ + bb+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ + c̄c+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wγγ+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wγ+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zγ+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zγ+ ≤3j</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

…all at NLO

CTEQ SS02
J. Huston
What are we likely to get?

- **Single top production**
  - Fully differential final states - see Z. Sullivan’s talk
    Harrie, Laenen, Phaf, Sullivan and Weinzierl, 2000

- **Diboson production**, e.g. $p\bar{p} \rightarrow W^+W^- \rightarrow$ leptons.
  - Baur et al. - lepton correlations only partially included
    Ohnemus, 1994
    Baur, Han and Ohnemus, 1995, 1996
  - Dixon et al. - full correlations, anomalous couplings
    Dixon, Kunszt and Signer, 1999
  - MCFM - full correlations, singly-resonant contributions
    JC and Ellis, 1999

- **Inclusive jets**
  - JETRAD - 1 and 2 jets only
    Giele, Glover and Kosower, 1993
  - Giele, Kilgore - 3 jet production
    Giele, Kilgore, 2000

**Drell-Yan + heavy flavours**
- MCFM - $W^{\pm}g^* (\rightarrow b\bar{b})$
  Ellis and Vessell, 1998
- MCFM - $Zg^* (\rightarrow b\bar{b})$
  JC and Ellis, 2000

**Drell-Yan + jets**
- DYRAD - handles vector boson + 0 or 1 jets
  Giele, Glover and Kosower, 1993
- VECBOS - handles vector boson + up to 3 ($Z$) or 4 ($W$) jets at leading order only
  Berends, Kuijf, Tanik and Giele, 1991
MCFM (Monte Carlo for Femtobarn Processes) J. Campbell and K. Ellis

- Goal is to provide a unified description of processes involving heavy quarks, leptons and missing energy at NLO accuracy.

- There have so far been three main applications of this Monte Carlo, each associated with a different paper:
  - Calculation of the Wbb background to a WH signal at the Tevatron.
  - Vector boson pair production at the Tevatron, including all spin correlations of the boson decay products.
  - Calculation of the Zbb and other backgrounds to a ZH signal at the Tevatron.

The last of these references contains the most details of our method.

- Various leptonic and/or hadronic decays of the bosons are included as further sub-processes.

  No NLO prediction for $W/Z + 2$ jets is available, but this is under construction in MCFM.

<table>
<thead>
<tr>
<th>Included at NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow W^\pm/Z$</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow W^\pm + Z$</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow W^\pm/Z + H$</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow W^\pm/Z + g^* (\rightarrow b\bar{b})$</td>
</tr>
</tbody>
</table>

CTEQ SS02
J. Huston
Higgs backgrounds using MCFM

- Studies using LO Monte Carlos and other event generators show that for a Higgs in the mass range of 100-130 GeV, the most promising channels for discovery at Run II are associated Higgs production.

  \[ p\bar{p} \rightarrow W(e\nu)H(\rightarrow b\bar{b}) \]
  \[ p\bar{p} \rightarrow Z(\nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b}) \]

- Particularly interesting in the light of hints from LEP2.

- Backgrounds for the WH signal:

  \[ p\bar{p} \rightarrow Wg^*(\rightarrow b\bar{b}) \]
  \[ p\bar{p} \rightarrow t(\rightarrow bW^+)\bar{t}(\rightarrow bW^-) \]
  \[ p\bar{p} \rightarrow W^{\pm*}(\rightarrow bW^+)\bar{b} \]
  \[ p\bar{p} \rightarrow Z(\rightarrow \ell\bar{\ell})H(\rightarrow b\bar{b}) \]
  \[ qg \rightarrow q't(\rightarrow bW^+)\bar{b} \]

- Double $b$-tagging efficiency of $\epsilon_{b\bar{b}} = 0.45$

- Extraction of the signal requires detailed knowledge of the normalization and the kinematics of the backgrounds.
Wbbar and Zbbar

**Results for Wbbar**

- Use a set of “standard” cuts from the literature, appropriate for the WH study and MRS98 parton distribution functions.
- $m_{b\bar{b}}$ distribution at LO and NLO, scale of 100 GeV.

![Graph showing $m_{b\bar{b}}$ distribution](image)

- The shape changes very little and the $K$-factor $\approx 1.5$

**$m_{b\bar{b}}$ mass distribution for Zbbar**

- For a ‘conventional’ scale of 100 GeV, there is a large $K$-factor in the region of interest, around 1.8.

![Graph showing mass distribution](image)

- The entire distribution is changed both in shape and normalization - perhaps suggesting that this scale choice is no longer appropriate ($\rightarrow$ new $gg$ processes).
Recent example of data vs Monte Carlo

- There is a discovery potential at the Tevatron during Run 2 for a relatively light Higgs (especially if Higgs mass is 115 GeV)
- ...but small signal to background ratio makes understanding of backgrounds very important
- CDF and ATLAS recently went through similar exercises regarding this background
  - CDF using Run 1 data
  - ATLAS using Monte Carlo predictions

CDF SEARCH FOR $p\bar{p} \rightarrow ZH^0 \rightarrow \nu\bar{\nu} b\bar{b}$

- Use $p_T$ trigger data set (88.6 $pb^{-1}$)
  - $p_T > 40$, $2-3$ jets ($E_T > 45, |\eta| < 2$), no other jets ($E_T > 7, |\eta| < 3.6$)
  - $\Delta\phi_{min}(p_T,i) > 45^0, \Delta\phi(p_T,i) < 165^0$, $45^0 < \Delta\phi(j_1,j_2) < 165^0$
- 1 or 2 SVX/JTPB tags
- Backgrounds: QCD, $t\bar{t}, W/Z + jets$
- For $m_H = 70-140$ GeV, Acceptances are $\approx 2.7-7.8\%$.
Data vs Monte Carlo

Double Tagging

<table>
<thead>
<tr>
<th>$M_H$ (GeV/c²)</th>
<th>90</th>
<th>110</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ZH}/\sigma_{WH}$ (pb)</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>$\varepsilon_{VH}$ (%)</td>
<td>0.28 ± 0.06</td>
<td>0.33 ± 0.07</td>
<td>0.40 ± 0.08</td>
</tr>
<tr>
<td>(a) QCD</td>
<td>1.9 ± 0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) $W/Z^0 + h.f.$</td>
<td>1.0 ± 0.2</td>
<td>(0.79 ± 0.46)†</td>
<td></td>
</tr>
<tr>
<td>(c) $top(t\bar{t})$</td>
<td>0.81 ± 0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) WZ + ZZ</td>
<td>0.17 ± 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Bkg(B)</td>
<td>3.9 ± 0.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data 4

Single Tagging

<table>
<thead>
<tr>
<th>$M_H$ (GeV/c²)</th>
<th>90</th>
<th>110</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{VH}$ (%)</td>
<td>0.51 ± 0.10</td>
<td>0.60 ± 0.12</td>
<td>0.75 ± 0.15</td>
</tr>
<tr>
<td>(a) QCD</td>
<td>26.2 ± 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) $W/Z^0 + h.f.$</td>
<td>10.1 ± 2.5</td>
<td>(9.2 ± 1.7)†</td>
<td></td>
</tr>
<tr>
<td>(c) $top(t\bar{t})$</td>
<td>2.4 ± 0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) WZ + ZZ</td>
<td>0.45 ± 0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Bkg(B)</td>
<td>39.2 ± 4.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data 40

† stop-like calculation

- Find 40 Events with one Tagged Jets (39.2 ± 4.4 Expected)
- Find 4 Events with Two Tagged Jets (3.9 ± 0.6 Expected)
  - 2 events are due to QCD
  - Atlas estimated CDF should see 15 QCD events
Sleuth strategy

Transparencies from Bruce Knuteson talk at Moriond 2001

- Consider recent major discoveries in hep
  - W,Z bosons CERN 1983
  - top quark Fermilab 1995
  - tau neutrino Fermilab 2000
  - Higgs Boson? CERN 2000

- In all cases, predictions were definite, aside from mass

- Plethora of models that appear daily on hep-ph

- Is it possible to perform a “generic” search?
We consider exclusive final states

We assume the existence of standard object definitions

These define $e$, $\tau$, $\gamma$, $j$, $b$, $E_T$, $W$, and $Z$

All events that contain the same numbers of each of these objects belong to the same final state
Results

Search for regions of excess (more data events than expected from background) within that variable space

Results agree well with expectation
No evidence of new physics is observed

<table>
<thead>
<tr>
<th>Data set</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu \Psi_T$</td>
<td>0.14 (+1.08σ)</td>
</tr>
<tr>
<td>$e\mu \Psi_T j$</td>
<td>0.45 (+0.13σ)</td>
</tr>
<tr>
<td>$e\mu \Psi_T 2j$</td>
<td>0.31 (+0.50σ)</td>
</tr>
<tr>
<td>$e\mu \Psi_T 3j$</td>
<td>0.71 (-0.55σ)</td>
</tr>
<tr>
<td>$W/2j$</td>
<td>0.29 (+0.55σ)</td>
</tr>
<tr>
<td>$W/3j$</td>
<td>0.23 (+0.74σ)</td>
</tr>
<tr>
<td>$W/4j$</td>
<td>0.53 (-0.08σ)</td>
</tr>
<tr>
<td>$W/5j$</td>
<td>0.81 (-0.88σ)</td>
</tr>
<tr>
<td>$W/6j$</td>
<td>0.22 (+0.77σ)</td>
</tr>
<tr>
<td>$e\Psi_T 2j$</td>
<td>0.76 (-0.71σ)</td>
</tr>
<tr>
<td>$e\Psi_T 3j$</td>
<td>0.17 (+0.95σ)</td>
</tr>
<tr>
<td>$e\Psi_T 4j$</td>
<td>0.13 (+1.13σ)</td>
</tr>
<tr>
<td>$Z/2j$</td>
<td>0.52 (-0.05σ)</td>
</tr>
<tr>
<td>$Z/3j$</td>
<td>0.71 (-0.55σ)</td>
</tr>
<tr>
<td>$Z/4j$</td>
<td>0.83 (-0.95σ)</td>
</tr>
<tr>
<td>$e\gamma 2j$</td>
<td>0.61 (-0.28σ)</td>
</tr>
<tr>
<td>$e\gamma 3j$</td>
<td>0.72 (-0.58σ)</td>
</tr>
<tr>
<td>$e\gamma 4j$</td>
<td>0.04 (+1.75σ)</td>
</tr>
<tr>
<td>$e\gamma \Psi_T 2j$</td>
<td>0.68 (-0.47σ)</td>
</tr>
<tr>
<td>$e\gamma \Psi_T 3j$</td>
<td>0.04 (-0.95σ)</td>
</tr>
<tr>
<td>$e\gamma \Psi_T 4j$</td>
<td>0.06 (+1.41σ)</td>
</tr>
<tr>
<td>$e\gamma \gamma 2j$</td>
<td>0.30 (+0.52σ)</td>
</tr>
<tr>
<td>$W/\gamma \gamma$</td>
<td>0.18 (+0.92σ)</td>
</tr>
<tr>
<td>$\gamma \gamma$</td>
<td>0.41 (+0.23σ)</td>
</tr>
<tr>
<td>$\gamma \gamma \gamma$</td>
<td>0.89 (-1.23σ)</td>
</tr>
</tbody>
</table>

probability to be SM
Fragmentation Uncertainties: Higgs-$\gamma\gamma$ and Backgrounds

- One of the most useful search modes for the discovery of the Higgs in the 100-150 GeV mass range at the LHC is in the two photon mode.

- Higgs-$\gamma\gamma$ has very large backgrounds from QCD sources:
  - Diphoton production
  - $\gamma\pi^0$ and $\pi^0\pi^0$ production; jets fragmenting into very high $z\, \pi^0$'s

- With excellent diphoton mass resolution, can try to resolve Higgs “bump”

- Still important to understand level of background
Diphoton Backgrounds in ATLAS

Again, for a $H\rightarrow\gamma\gamma$ search at the LHC, face irreducible backgrounds from QCD $\gamma\gamma$ and reducible backgrounds from $\gamma\pi^0$ and $\pi^0\pi^0$

- in range from 70 to 170 GeV jet-jet cross section is estimated to be a factor of $2\times10^7$ times the $\gamma\gamma$ cross section and $\gamma$-jet a factor of $8\times10^2$ larger
- Need rejection factors of $2\times10^7$ and $8\times10^3$ respectively
- PYTHIA results seem to indicate that reducible backgrounds are comfortably less than reducible ones
- ...but how to normalize PYTHIA predictions for very high $z$ fragmentation of jets; fragmentation not known well at high $z$ and certainly not for gluon jets

These rejection factors have been realistically evaluated by using large samples of fully simulated two-jet events, as described in Section 7.6. The rejection factors were then applied to estimate the cross-sections for the reducible jet-jet and $\gamma$-jet backgrounds relative to the irreducible $\gamma\gamma$-background. The results are shown in Figure 19-2 as a function of the two-photon invariant mass $m_{\gamma\gamma}$. After applying the full photon identification cuts from the calorimeter and the Inner Detector, the residual jet-jet and $\gamma$-jet backgrounds are found to be at the level of approximately 15% and 20%, respectively, of the irreducible $\gamma\gamma$ background over the mass range relevant to the $H\rightarrow\gamma\gamma$ search.

Figure 19-2 Expected ratios of the residual reducible jet-jet and $\gamma$-jet backgrounds to the irreducible $\gamma\gamma$-continuum background as a function of the invariant mass of the pair of photon candidates at high luminosity.
Different models predict different high $z$ fragmentation

- Backgrounds to $\gamma\gamma$ production in Higgs mass region arise from fragmentation of jets to high $z$ $\pi^0$'s
  - Pythia and Herwig predict very different rates for high $z$
  - all fragmentation is not equal
- Example of a background that can be measured in situ, but nice to be able to predict the environment beforehand
- DIPHOX (see Run 2 MC workshop) program can calculate $\gamma\gamma$, $\gamma\pi^0$, and $\pi^0\pi^0$ cross sections to NLO
  - comparisons underway to Tevatron data
- $gg\rightarrow\gamma\gamma$ and $qqbar\rightarrow\gamma\gamma$ at NNLO may be available soon

Figure 12: Charged particle spectra in quark and gluon
PDF Uncertainties

What’s unknown about PDF’s

- the gluon distribution
- strange and anti-strange quarks
- details in the \{u,d\} quark sector; up/down differences and ratios
- heavy quark distributions

\[ \Sigma \] of quark distributions \((q + q\overline{q})\) is well-determined over wide range of \(x\) and \(Q^2\)

- Quark distributions primarily determined from DIS and DY data sets which have large statistics and systematic errors in few percent range \((\pm 3\% \text{ for } 10^{-4} < x < 0.75)\)
- Individual quark flavors, though may have uncertainties larger than that on the sum; important, for example, for W asymmetry

Information on \(d\overline{q}\) and \(u\overline{q}\) comes at small \(x\) from HERA and at medium \(x\) from fixed target DY production on \(H_2\) and \(D_2\) targets

- Note \(d\overline{q} \neq u\overline{q}\)

Strange quark sea determined from dimuon production in \(\nu\) DIS (CCFR)

\(d/u\) at large \(x\) comes from FT DY production on \(H_2\) and \(D_2\) and lepton asymmetry in W production
Example: Jets at the Tevatron

- Both experiments compare to NLO QCD calculations
  - D0: JETRAD, modified Snowmass clustering ($R_{sep}=1.3$, $\mu_F=\mu_R=E_{Tmax}/2$)
  - CDF: EKS, Snowmass clustering ($R_{sep}=1.3$ (2.0 in some previous comparisons), $\mu_F=\mu_R=E_{Tjet}/2$)

In Run 1a, CDF observed an excess in the jet cross section at high $E_T$, outside the range of the theoretical uncertainties shown.

CTEQ SS02
J. Huston
Similar excess observed in Run 1B
Exotic explanations

Possible Explanations of High $E_T$ Excess

Until uncertainties within the realm of QCD are better understood any claim of NEW PHYSICS is INDEFENSIBLE!

However, the new physics possibilities include:

Composite quarks: Eichten, Lane and Peshkin, PRL 50 811 (1983)
a contact term is added to LO QCD Lagrangian
$\rightarrow$ increased cross section for high $E_T$ jets

$\alpha_s$ stops running: possible conspiracy between new particles Susy (hep-ph/9512325, hep-ph/9601279),
color sextet (Alan White ANL)

New Particle $Z'$: leptophobic $Z'$, this could also possibly explain the charm/bottom problem at LEP (hep-ph/9601324)
Non-exotic explanations

Modify the gluon distribution at high $x$
Tevatron Jets and the high x gluon

- Best fit to CDF and D0 central jet cross sections provided by CTEQ5HJ pdf’s

![Graph showing jet cross sections for CDF and D0 data compared to NLO QCD predictions using CTEQ5M and CTEQ5HJ pdfs. The graphs display the ratio of data to NLO QCD predictions for different ranges of p_T, with error bars and normalization factors provided. The CTEQ5HJ predictions are shown with a normalized factor of 1.04 for CDF and 1.08 for D0, while the CTEQ5M predictions have a factor of 1.00 for both datasets. The graphs also show the correlation systematics errors for both data and predictions, with CDF having errors between 14% and 27%, and D0 between 8% and 30%.]
D0 jet cross section as function of rapidity

Nominal cross sections & statistical errors only

$E_T$ (GeV)

CTEQ4HJ provides best description of data

How reliable is NLO theory in this region? K-factors?

JETRAD $\mu = E_T^{\text{max}}/2$
Chisquares for recent pdf’s

• For 90 data points, are the chisquares for CTEQ4M and MRSTgU “good”?
• Compared to CTEQ4HJ?

<table>
<thead>
<tr>
<th>PDF</th>
<th>$\chi^2$</th>
<th>$\chi^2$/dof</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTEQ3M</td>
<td>121.56</td>
<td>1.35</td>
<td>0.01</td>
</tr>
<tr>
<td>CTEQ4M</td>
<td>92.46</td>
<td>1.03</td>
<td>0.41</td>
</tr>
<tr>
<td>CTEQ4HJ</td>
<td>59.38</td>
<td>0.66</td>
<td>0.99</td>
</tr>
<tr>
<td>MRST</td>
<td>113.78</td>
<td>1.26</td>
<td>0.05</td>
</tr>
<tr>
<td>MRSTgD</td>
<td>155.52</td>
<td>1.73</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MRSTgU</td>
<td>85.09</td>
<td>0.95</td>
<td>0.63</td>
</tr>
</tbody>
</table>
D0 jet cross section

- CTEQ4 and CTEQ5 had CDF and D0 central jet cross sections in fit
- Statistical power not great enough to strongly influence high x gluon
  - CTEQ4HJ/5HJ required a special emphasis to be given to high E_T data points
- Central fit for CTEQ6 is naturally HJ-like
- $\chi^2$ for CDF+D0 jet data is 113 for 123 data points

Figure 19: Comparison between theory and the D0 jet data. The error bars are statistical and systematic errors combined.

CTEQ SS02
J. Huston
PDF Uncertainties: included in CTEQ6M sets in LHAPDF

- Use Hessian technique (T=10)
Gluon Uncertainty

- Gluon is fairly well-constrained up to an x-value of 0.3
- New gluon is stiffer than CTEQ5M; not quite as stiff as CTEQ5HJ
Luminosity function uncertainties at the Tevatron

CTEQ SS02
J. Huston
Luminosity Function Uncertainties at the LHC
Effective use of pdf uncertainties

PDF uncertainties are important both for precision measurements (W/Z cross sections) as well as for studies of potential new physics (a la jet cross sections at high $E_T$).

Most Monte Carlo/matrix element programs have “central” pdf’s built in, or can easily interface to PDFLIB.

Determining the pdf uncertainty for a particular cross section/distribution might require the use of many pdf’s:

- CTEQ Hessian pdf errors require using 33 pdf’s
- GKK on the order of 100

Too clumsy to attempt to includes grids for calculation of all of these pdf’s with the MC programs.

- Les Houches accord #2

  - Each pdf can be specified by a few lines of information, if MC programs can perform the evolution
  - Fast evolution routine will be included in new releases to construct grids for each pdf

NB: pdf uncertainties make most sense in the context of NLO calculations; current MC programs are basically leading order and LO pdfs should be used when available.

  - NNB: CTEQ6L is a leading order fit to the data but using the 2-loop $\alpha_s$, since some higher order corrections are in MC programs like Pythia, Herwig, etc.
Conclusions

- Great opportunity at Run 2 at the Tevatron for discovery of new physics; even better opportunity when the LHC turns on
- In order to be believable, we must understand the QCD backgrounds to any new physics
  - Don’t rely totally on Monte Carlos and certainly not on one Monte Carlo alone
  - In the words of Ronald Reagan, “Trust but Verify”, if possible, theoretical predictions/formalisms with data
    - existing Run 1 data/Run 2 data
    - background” data to be taken at the LHC
- If no data, then verify with more complete theoretical treatments
- Many new tools/links between old tools are now being developed to make this job easier for experimenters
- Hopefully, we’ll find many more of the type of the event on the right to try them