QCD for the LHC

• PDFs for the LHC
• Jets and Photons for the LHC
• Matrix Elements for the LHC
• …the week of Joey

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THE SM AND NLO MULTILEG WORKING GROUP:
Summary Report

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Fermilab
US National Science Foundation
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2010 CTEQ - MCnet Summer School on QCD Phenomenology and Monte Carlo Event Generators

Lauterbad (Black Forest) Germany
26 July - 4 August 2010

First LHC Results:
- High pt
- Minimum bias
- small x and fast
- Low pt and Particle ID

Physicslectures:

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Excitement about my visit

Joey Huston to visit LPC
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 backgrounds to BSM physics correctly taken into account
- and, in particular, that QCD at the LHC is properly understood
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 $x$ for the quarks and gluons 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
Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC.

- We will access pdf’s down to $10^{-6}$ (crucial for the underlying event) and $Q^2$ up to $100$ TeV$^2$.
- We can use the DGLAP equations to evolve to the relevant $x$ and $Q^2$ range, but...
  - we’re somewhat blind in extrapolating to lower $x$ values than present in the HERA data, so uncertainty may be larger than currently estimated.
  - we’re assuming that DGLAP is all there is; at low $x$ BFKL type of logarithms may become important (more later about DGLAP and BFKL).
Understanding cross sections at the LHC

...but to understand cross sections, we have to understand QCD (at the LHC)

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

underlying event and minimum bias events

jet algorithms and jet reconstruction

benchmark cross sections and pdf correlations

Sudakov form factors
Parton distribution functions and global fits

- 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
  - MRST2003->MRST2004
  - MSTW2008
  - CTEQ->CTEQ5->CTEQ6
  - CTEQ6.1->CTEQ6.5
  - CTEQ6.6->CT09->CT10
  - NNPDF1.0->NNPDF1.1->NNPDF1.2->NNPDF2.0

Figure 27. The CTEQ6.1 parton distribution functions evaluated at a $Q$ of 10 GeV.
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.
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
Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC

...but MSTW2008 also has increased W/Z cross sections at the LHC due at least partially to improvements in their heavy quark scheme

- now CTEQ6.6 and MSTW2008 in good 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.
Correlations with $Z$, $tT$

Define a correlation cosine between two quantities $Z$ and $tT$.

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

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

- $pp \rightarrow h^0X$ vs. $pp \rightarrow (Z^0 \rightarrow \ell\ell)X$ (left) and $pp \rightarrow t\bar{t}X$ (right)
  $\sqrt{s} = 14$ TeV, CTEQ6.6, NLO

$M_{h} = 120$ GeV
$M_{h} = 200$ GeV
$M_{h} = 500$ GeV
The shapes for the cross sections shown to the right are well-described by LO matrix elements using NLO PDFs, but there are distortions that are evident when LO PDFs are used.

Normalizations are not fully described using LO matrix elements (K-factor).
CTEQ modified LO PDFs (LO*)

- Mod LO $W^+$ rapidity distribution agrees better with NLO prediction in both magnitude and shape.
- Agreement at 7 and 10 TeV (not in fit) even better.
In the ATLAS Higgs group, we’ve just gone through an exercise of compilation of predictions for Higgs production at LO/NLO/NNLO at a number of LHC center-of-mass energies.

This has involved a comparison of competing programs for some processes, a standardization of inputs, and a calculation of uncertainties, including those from PDF’s/variation of $\alpha_s$:

- from eigenvectors in CTEQ/MSTW
- using the NNPDF approach

This is an exercise that other physics groups will be going through as well, both in ATLAS and in CMS.

- ATLAS Standard Model group now, for example

There are a lot of tools/procedures out there now, and a lot of room for confusion.
...but compare on a consistent basis

- See A. Vicini’s talk in last PDF4LHC meeting
PDF errors

- So now, seemingly, we have more consistency in the size of PDF errors, at least for this particular example.
- The eigenvector sets represent the PDF uncertainty due to the experimental errors in the datasets used in the global fitting process.
- Another uncertainty is that due to the variation in the value of $\alpha_s$.
- It has been traditional in the past for the PDF groups to publish PDF sets for variant values of $\alpha_s$, typically over a fairly wide range.
  - Experiments always like to demonstrate that they can reject a value of $\alpha_s(m_Z)$ of 0.128.
- MSTW has recently tried to better quantify the uncertainty due to the variation of $\alpha_s$, by performing global fits over a finer range, taking into account any correlations between the values of $\alpha_s$ and the PDF errors.
- …more recent studies by CTEQ and NNPDF have shown that for their PDF’s the correlation between $\alpha_s$ errors and PDF errors is small enough that the two sources can be added in quadrature.
New CTEQ6.6 $\alpha_s$ series

- CTEQ6.6 central $\alpha_s(m_Z)$
  value=0.118
- Error PDFs with $\alpha_s$ values of
  - 0.116
  - 0.117
  - 0.118
  - 0.119
  - 0.120
  - available in next version of LHAPDF
- $\alpha_s$ error roughly half that of PDF error
\( \alpha_s(m_Z) \) and uncertainty

- But of course life is not that simple
- Different values of \( \alpha_s \) and of its uncertainty are used
- CTEQ and NNPDF use the world average (actually 0.118 for CTEQ and 0.119 for NNPDF), where MSTW2008 uses 0.120, as determined from their fit
- Latest world average (from Siggi Bethke->PDG)
  - \( \alpha_s(m_Z) = 0.1184 \pm 0.0007 \)
- What does the error represent?
  - Siggi said that only one of the results included in his world average was outside this range
  - Suppose we’re conservative and say that +/-0.002 is a 90% CL
- Could it be possible for all global PDF groups to use the world average value of \( \alpha_s \) in their fits, plus a prescribed range for its uncertainty (if not 0.002, then perhaps another acceptable value)?
- I told Albert that if he could persuade everyone of this, that I personally would nominate him for the Nobel Peace Prize
(My) interim recommendation for ATLAS
(and for the LHC community)

- Cross sections should be calculated with MSTW2008 and CTEQ6.6
- Upper range of prediction should be given by upper limit of error prediction using prescription for combining $\alpha_s$ uncertainty with error PDFs
  - in quadrature for CTEQ6.6
  - using $\alpha_s$ eigenvector sets for MSTW2008
- Ditto for lower limit
- So for a Higgs mass of 120 GeV at 14 TeV, the gg cross section limits would be 34.9 pb (defined by the CTEQ6.6 lower limit, $\alpha_s$=0.120) and 41.4 pb (defined by the MSTW2008 upper limit)
  - note that central predictions for CTEQ6.6 (35.74 pb) and MSTW2008 (38.45 pb) are different not because of the gluon distribution (which coincide very closely in the relevant x range), but because of the different values of $\alpha_s$ used
- Where possible, NNPDF predictions (and uncertainties) should be used as well in the comparisons
Benchmark processes, all to be calculated

(i) at NLO (in MSbar scheme)
(ii) in 5-flavour quark schemes (definition of scheme to be specified)
(iii) at 7 TeV [and 14 TeV] LHC
(iv) for central value predictions and ±68%cl [and ±90%cl] pdf uncertainties
(v) and with ±$\alpha_s$ uncertainties
(vi) repeat with $\alpha_s(m_Z)$=0.119

(prescription for combining with pdf errors to be specified)

Using (where processes available) MCFM 5.7

- gzipped version prepared by John Campbell using the specified parameters (and the new CTEQ6.6 $\alpha_s$ series)
- this was shipped out this week
Cross Sections

1. $W^+$, $W^-$, and $Z$ total cross sections and rapidity distributions total cross section ratios $W^+/W^-$ and $(W^+ + W^-)/Z$ rapidity distributions at $y = -4,-3,...,+4$ and also the $W$ asymmetry: $A_W(y) = (dW^+/dy - dW^-/dy)/(dW^+/dy + dW^-/dy)$ using the following parameters taken from PDG 2009

- $M_Z = 91.188$ GeV
- $M_W = 80.398$ GeV
- zero width approximation
- $G_F = 0.116637 \times 10^{-5}$ GeV$^{-2}$
- other EW couplings derived using tree level relations
- $BR(Z\rightarrow\ell\ell) = 0.03366$
- $BR(W\rightarrow\ell\nu) = 0.1080$
- CKM mixing parameters from eq.(11.27) of PDG2009 CKM review
  \[
  V_{\text{CKM}} = \begin{pmatrix}
  0.97419 & 0.2257 & 0.00359 \\
  0.2256 & 0.97334 & 0.0415 \\
  0.00874 & 0.0407 & 0.999133
  \end{pmatrix}
  \]
- scales: $\mu_R = \mu_F = M_Z$ or $M_W$
2. gg->H total cross sections at NLO
   - $M_H = 120, 180$ and $240$ GeV
   - zero Higgs width approximation, no BR
   - top loop only, with $m_{\text{top}} = 171.3$ GeV in $\sigma_0$
   - scales: $\mu_R = \mu_F = M_H$

3. ttbar total cross section at NLO
   - $m_{\text{top}} = 171.3$ GeV
   - zero top width approximation, no BR
   - scales: $\mu_R = \mu_F = m_{\text{top}}$
The “Future”

- How well do we know PDFs going into the start of LHC running?
- For much of the kinematic region, the uncertainty is pretty small
- Primarily because of the precision data that came from HERA
- And the precision will improve as the final HERA data sets are released to the public
The Future, continued

- Of course, as the LHC data comes in, we will use it in future PDF fits.
- But in order to be useful, the precision has to be high, and most early data will not fulfill that requirement.
- The global fits are dominated not by statistical errors but by systematic errors… and the correlations.

*Figure 104.* Inclusive jet cross section predictions for the LHC using the CTEQ6.1 central pdf and

*Figure 105.* The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.
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 $W^+\geq 1, 2, 3$ 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.

**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.

- indication that can expect interesting events at LHC to be very jetty (especially from gg initial states)
- jet cuts are higher at LHC than at Tevatron

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**Figure 100.** 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.
Dynamic range

- Interested in jets from 20-30 GeV/c to several TeV/c
- There is a tendency to think of jets as static objects such as electrons, muons or photons
- Jets (and QCD) have a rich dynamic structure that is not fully probed with a single jet algorithm or a single jet size
  - for example, at the LHC, we will be more interested in jet masses and jet substructure
- We need to have a different mindset at the LHC than at the Tevatron

Figure 104. Inclusive jet cross section predictions for the LHC using the CTEQ6.1 central the 40 error pdfs.
For some events, the jet structure is very clear and there’s little ambiguity about the assignment of towers to the jet.

But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements.

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.
Comparison of $k_T$ and cone results

- Remember
  - 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
- Let's check this out with CDF results after applying hadronization corrections
- Nice confirmation of the perturbative picture
Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner, not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/parameters/jet substructure on every data set.

Blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level rather than jet itself being corrected.

Similar to running at hadron level in Monte Carlos.
Jet areas

Note that the $k_T$ algorithm has the largest jet areas, SISConE the smallest and anti-$k_T$ the most regular determined by clustering ghost particles of vanishing energy; see jet references.
Jet areas in presence of pileup

- Single W+4jets event, all matched to partons.
- SISCones and kT show decreased area in presence of pileup.

pileup nibbles away at perimeter of jet
Area-based correction

1) Find low $p_T$ jets in event. ($< 10\text{GeV}$) We use kT5jet.
2) From these, find average/median $p_T$ density of event $\rho$
3) Determine area $A$ of signal jets
4) Subtract “pileup/UE” estimate
   \[ p_{T_{corr}} = p_T - \rho A \]

W+5j event with kT5Jets
Gray jets = Signal Jets
Colored jets = Low $p_T$ jets

- Black points used to find $p_T$ density
- Red points are then corrected according to Jet area

See presentations of Brian Martin in ATLAS jet meetings.
From a theoretical perspective, it’s best to apply a Frixione-style isolation criterion, in which the amount of energy allowed depends on the distance from the photon; this has the advantage of removing the fragmentation contribution for photon production, as well as discriminating against backgrounds from jet fragmentation.

But most of the energy in an isolation cone is from underlying event/pileup.

At Les Houches, we developed:

1. An implementation of the Frixione isolation appropriate for segmented calorimeters.
2. A hybrid technique that separates the UE/pileup energy from fragmentation contributions using the jet density approach.

**Action Items:**

- Susan, Joey, Kajari, Jean-Philippe

**Exp:**

Look again in detail at the Frixione criterion, what is the impact at LHC of UE/PU of fragmentation; see if some “hybrid” (simple cone vs Frixione) can be found, suitable for exp. application.

**Theory:**

Use existing (and possibly upgraded) codes to study difference in x-sections obtained with Frixione-criterion and some “pedestal” allowed in the central cone.

Look also at “democratic” approach.
SpartyJet

J. Huston, K. Geerlings, Brian Martin
Michigan State University

P-A. Delsart, Grenoble

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

If interested for ATLAS, please contact
Brian.thomas.martin@cern.ch
Parton level Monte Carlo generators

- Programs that do NLO calculations, such as MCFM, are parton-level Monte Carlo generators in which (weighted) events and counter-events are generated
  - for complicated processes, such as $W + 2$ jets, there can be many counter-events (24), corresponding to the Catani-Seymour subtraction terms, for each event
  - only the sum of all events (events + counter-events) is meaningful, since many positive and negative weights need to cancel against each other; if too few events are generated, or if the binning is too small, can have negative results
  - in general, cannot connect these complex NLO matrix elements to parton showering…although that’s the dream/plan
    ▲ processes such as $W, Z, WW, ZZ, Higgs, \text{ttbar}, \text{single top}, \ldots$ have been included in NLO parton shower Monte Carlo programs like MC@NLO, Powheg
    ▲ state of the art now is $Z + 1$ jet (I believe)
MCFM

- Many processes available at LO and NLO
  - note these are partonic level only
- Option for ROOT output (see later)
- mcfm.fnal.gov

\[
\begin{align*}
p\bar{p} & \rightarrow W^\pm / Z \\
p\bar{p} & \rightarrow W^\pm + Z \\
p\bar{p} & \rightarrow W^\pm + \gamma \\
p\bar{p} & \rightarrow W^\pm + g^* (\rightarrow b\bar{b}) \\
p\bar{p} & \rightarrow W^\pm / Z + 1 \text{ jet} \\
p\bar{p}(gg) & \rightarrow H \\
p\bar{p}(VV) & \rightarrow H + 2 \text{ jets} \\
p\bar{p} & \rightarrow t + W \\
p\bar{p} & \rightarrow W^+ + W^- \\
p\bar{p} & \rightarrow Z + Z \\
p\bar{p} & \rightarrow W^\pm / Z + H \\
p\bar{p} & \rightarrow Zb\bar{b} \\
p\bar{p} & \rightarrow W^\pm / Z + 2 \text{ jets} \\
p\bar{p}(gg) & \rightarrow H + 1 \text{ jet} \\
p\bar{p} & \rightarrow t + X
\end{align*}
\]
State of the art

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- **LO**: well under control, even for multiparticle final states
- **NLO**: well understood for 2->1, 2->2 and 2->3; first calculations of 2->4 (W +3 jets, ttbb)
- **NNLO**: known for inclusive and exclusive 2->1 (i.e. Higgs, Drell-Yan); work on 2->2 (Higgs + 1 jet)
Some issues/questions

- Once we have the calculations, how do we (experimentalists) use them?
- Best is to have NLO partonic level calculation interfaced to parton shower/hadronization
  - but that has been done only for relatively simple processes and is very (theorist) labor intensive
    - still waiting for inclusive jets in MC@NLO, for example

- Even with partonic level calculations, need public code and/or ability to write out ROOT ntuples of parton level events
  - so that can generate once with loose cuts and distributions can be re-made without the need for the lengthy re-running of the predictions
  - what is done for example with MCFM for CTEQ4LHC
    - but 10’s of Gbytes for file sizes
MCFM has ROOT output built in; standard Les Houches format has been developed.

- store 4-vectors for final state particles
- + event weights; use analysis script to construct any observables and their pdf uncertainties; in future will put scale uncertainties and pdf correlation info as well.
K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections
Some rules-of-thumb

- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - $gg\rightarrow$Higgs
  - $gg\rightarrow\gamma\gamma$
  - $K(gg\rightarrow t\bar{t}) > K(qQ\rightarrow t\bar{t})$
  - these gg initial states want to radiate like crazy (see Sudakovs)

- 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?
- What about effect of jet vetoes on K-factors? Signal processes compared to background. Of current interest.

Table 2: $K$-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6 PDF set is used at NLO. $K$ uses the CTEQ6L1 set at leading order, whilst $K'$ uses the same set, CTEQ6M, as at NLO. For most of the processes listed, jets satisfy the requirements $p_T > 15 \text{ GeV/c}$ and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). For Higgs+$1,2$ jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{j,i} > 20 \text{ GeV/c}$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{j,i} > 50 \text{ GeV/c}$ for $WW$+jet. In the $W$ (Higgs)+2 jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass $120 \text{ GeV}$. In each case the value of the $K$-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

$$C_{i1} + C_{i2} - C_{f,\text{max}}$$

L. Dixon

Casimir color factors for initial state

Casimir for biggest color representation final state can be in

Simplistic rule

$$\sum_i C_i$$
Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. 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 and K'' uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and |η| < 4.5 has been applied. A cut of p_T^jet > 20 GeV/c has been applied for the t\bar{t}+jet process, and a cut of p_T^jet > 50 GeV/c for WW+jet. In the W(Higgs)+2jets process the jets are separated by ΔR > 0.52, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

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<td>m_b</td>
<td>2m_b</td>
<td>1.20</td>
</tr>
<tr>
<td>Higgs</td>
<td>m_H</td>
<td>p_T^jet</td>
<td>2.33</td>
</tr>
<tr>
<td>Higgs via VBF</td>
<td>m_H</td>
<td>p_T^jet</td>
<td>1.07</td>
</tr>
<tr>
<td>Higgs+1jet</td>
<td>m_H</td>
<td>p_T^jet</td>
<td>2.02</td>
</tr>
<tr>
<td>Higgs+2jets</td>
<td>m_H</td>
<td>p_T^jet</td>
<td>–</td>
</tr>
</tbody>
</table>
Realistic NLO wishlist

- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time

<table>
<thead>
<tr>
<th>Process ($V \in { Z, W, \gamma }$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calculations completed since Les Houches 2005</strong></td>
<td></td>
</tr>
<tr>
<td>1. $pp \rightarrow VV$ jet</td>
<td>$WW$ jet completed by Dittmaier/Klutei/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]; $ZZ$ jet completed by Binoth/Gleisberg/Kang/Karan/Sangmuinetti [7]; NLO QCD to the $gg$ channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciecolini/Denner/Dittmaier [9, 10]</td>
</tr>
<tr>
<td>2. $pp \rightarrow Hgg+2jets$</td>
<td>$ZZ$ completed by Larcangio/Melnikov/Petriello [11] and $WWZ$ by Hanhele/Zupperfeld [12] (see also Binoth/Osola/Papadopoulos/Pittau [13])</td>
</tr>
<tr>
<td>3. $pp \rightarrow VVV$</td>
<td>relevant for $t\bar{t}H$ computed by Breidenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16] calculated by the Blackbat/Shepa [17] and Rocker [18] collaborations</td>
</tr>
<tr>
<td>4. $pp \rightarrow b\bar{b}b$</td>
<td></td>
</tr>
<tr>
<td>5. $pp \rightarrow V+3jets$</td>
<td></td>
</tr>
<tr>
<td><strong>Calculations remaining from Les Houches 2005</strong></td>
<td></td>
</tr>
<tr>
<td>6. $pp \rightarrow t\bar{t}+2jets$</td>
<td>relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]</td>
</tr>
<tr>
<td>7. $pp \rightarrow VVb$</td>
<td>relevant for VBF $\rightarrow H \rightarrow VV$, $t\bar{t}H$</td>
</tr>
<tr>
<td>8. $pp \rightarrow VVV+2jets$</td>
<td>relevant for VBF $\rightarrow H \rightarrow VV$ VBF contributions calculated by (Bozzi)/Bl[01m]z/Oleari/Zeppenfeld [20–22]</td>
</tr>
<tr>
<td><strong>NLO calculations added to list in 2007</strong></td>
<td></td>
</tr>
<tr>
<td>9. $pp \rightarrow b\bar{b}b$</td>
<td>$q\bar{q}$ channel calculated by Golemb collaboration [23]</td>
</tr>
<tr>
<td><strong>NLO calculations added to list in 2008</strong></td>
<td></td>
</tr>
<tr>
<td>10. $pp \rightarrow V+4$ jets</td>
<td>top pair production, various new physics signatures</td>
</tr>
<tr>
<td>11. $pp \rightarrow W(b\bar{b})$</td>
<td>top, new physics signatures</td>
</tr>
<tr>
<td>12. $pp \rightarrow t\bar{t}H$</td>
<td>various new physics signatures</td>
</tr>
<tr>
<td><strong>Calculations beyond NLO added in 2007</strong></td>
<td></td>
</tr>
<tr>
<td>13. $gg \rightarrow W^{*+} W \cdot O(\alpha^2\alpha_s^2)$</td>
<td>backgrounds to Higgs</td>
</tr>
<tr>
<td>14. NNLO $pp \rightarrow t\bar{t}$</td>
<td>normalization of a benchmark process</td>
</tr>
<tr>
<td>15. NNLO to VBF and $Z/\gamma$+jet</td>
<td>Higgs couplings and SM benchmark</td>
</tr>
<tr>
<td><strong>Calculations including electroweak effects</strong></td>
<td></td>
</tr>
<tr>
<td>16. NNLO QCD+NLO EW for $W/Z$</td>
<td>precision calculation of a SM benchmark</td>
</tr>
</tbody>
</table>

Table 1: The updated experimenter’s wishlist for LHC processes
Loops and legs

2->4 is very impressive

but just compare to the complexity of the sentences that Sarah Palin uses.
Choosing jet size

● Experimentally
  ♦ in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  ♦ this can also reduce the impact of pileup/underlying event

● Theoretically
  ♦ hadronization effects become larger as R decreases
  ♦ for small R, the ln R perturbative terms referred to previously can become noticeable
  ♦ this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,
  ♦ …under investigation

Another motivation for the use of multiple jet algorithms/parameters (i.e. SpartyJet) in LHC analyses.
Proposed common ntuple output

- A generalization of the FROOT format used in MCFM
- Writeup in NLM proceedings

Table 4: Variables stored in the proposed common ROOT ntuple output.

<table>
<thead>
<tr>
<th>ROOT Tree Branch</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Npart/I</td>
<td>number of partons (incoming and outgoing)</td>
</tr>
<tr>
<td>Px[Npart]/D</td>
<td>Px of partons</td>
</tr>
<tr>
<td>Py[Npart]/D</td>
<td>Py of partons</td>
</tr>
<tr>
<td>Pz[Npart]/D</td>
<td>Pz of partons</td>
</tr>
<tr>
<td>E[Npart]/D</td>
<td>E of partons</td>
</tr>
<tr>
<td>x1/D</td>
<td>Bjorken-x of incoming parton 1</td>
</tr>
<tr>
<td>x2/D</td>
<td>Bjorken-x of incoming parton 2</td>
</tr>
<tr>
<td>id1/I</td>
<td>PDG particle ID of incoming parton 1</td>
</tr>
<tr>
<td>id2/I</td>
<td>PDG particle ID of incoming parton 2</td>
</tr>
<tr>
<td>fac_scale/D</td>
<td>factorization scale</td>
</tr>
<tr>
<td>ren_scale/D</td>
<td>renormalization scale</td>
</tr>
<tr>
<td>weight/D</td>
<td>global event weight</td>
</tr>
<tr>
<td>Nuwtg/I</td>
<td>number of user weights</td>
</tr>
<tr>
<td>user_wgts[Nuwtg]/D</td>
<td>user event weights</td>
</tr>
<tr>
<td>evt_no/L</td>
<td>unique event number (identifier)</td>
</tr>
<tr>
<td>Nptr/I</td>
<td>number of event pointers</td>
</tr>
<tr>
<td>evt_pointers[Nptr]/L</td>
<td>event pointers (identifiers of related events)</td>
</tr>
<tr>
<td>Npdfs/I</td>
<td>number of PDF weights</td>
</tr>
<tr>
<td>pdf_wgts[Npdfs]/D</td>
<td>PDF weights</td>
</tr>
</tbody>
</table>

LhaNLOEvent* evt = new LhaNLOEvent();
evt->addParticle(px1,py1,pz1,E1);
evt->setProcInfo(x1,id1,x2,id2);
evt->setRenScale(scale);
...

Another class LhaNLOTreeIO is responsible for writing the events into the ROOT tree and outputting the tree to disk. In addition to the event-wise information global data such as comments, cross sections etc can be written as well. An example is shown below:

LhaNLOTreeIO* writer = new LhaNLOTreeIO(); // create tree writer
writer->initWrite("'test.root'");
...
writer->writeComment("'W+4 jets at NNLO'"); // write global comments
writer->writeComment("'total cross section: XYZ+/IJK fb'");...
writer->writeEvent(*evt); // write event to tree (in event loop)
...
writer->writeTree(); // write tree to disk

Similarly, a tree can be read back from disk:

LhaNLOTreeIO* reader = new LhaNLOTreeIO(); // init reader
ier=reader->initRead("test.root");
if (!ier) {
    for (int i=0; i<reader->getNumberOfEvents(); i++) {
        event->reset();
        ier=reader->readEvent(i,*event);
        ...
    }
}
A proposal for a standard interface between Monte Carlo tools and one-loop programs

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ABSTRACT: Many highly developed Monte Carlo tools for the evaluation of cross sections based on tree matrix elements exist and are used by experimental collaborations in high energy physics. As the evaluation of one-loop matrix elements has recently been undergoing enormous progress, the combination of one-loop matrix elements with existing Monte Carlo tools is on the horizon. This would lead to phenomenological predictions at the next-to-leading order level. This note summarizes the discussion of the next-to-leading order multileg (NLM) working group on this issue which has been taking place during the workshop on Physics at TeV colliders at Les Houches, France, in June 2009. The result is a proposal for a standard interface between Monte Carlo tools and one-loop matrix element programs.

Dedicated to the memory of, and in tribute to, Thomas Binoth, who led the effort to develop this proposal for Les Houches 2009. Thomas led the discussions, set up the subgroups, collected the contributions, and wrote and edited this paper. He made a promise that the paper would be on the arXiv the first week of January, and we are faithfully fulfilling his promise. In his honor, we would like to call this the Binoth Les Houches Accord. The body of the paper is unchanged from the last version that can be found on his webpage http://www.ph.ed.ac.uk/~binoth/NLOHACURRENT_VERSION.pdf
…and finally

http://www.youtube.com/watch?v=ADcf3cOpiT8