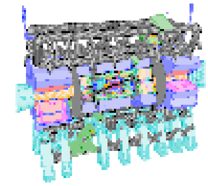


Re-discovering the Standard Model at the LHC

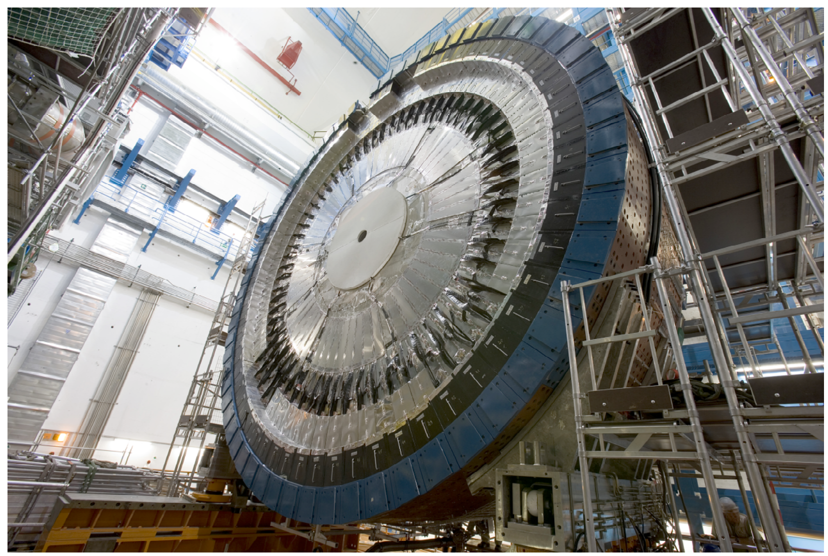
Roadmap for the first few fb^{-1}

(mostly pdf's and jets)

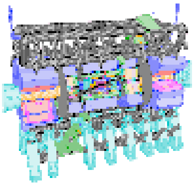
- End at **Stockholm**
- **Total Est. Time:** 18 hours, 50 minutes
- **Total Est. Distance:** 1264.67 miles

J. Huston

LHC New Physics Signatures Workshop



Some references



- Also online at ROP

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

arXiv:hep-ph/0611148 v1 10 Nov 2006

REVIEW ARTICLE

Hard Interactions of Quarks and Gluons: a Primer for LHC Physics

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Abstract. In this review article, we will develop the perturbative framework for the calculation of hard scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard scattering processes. We will include "rules of thumb" as well as "official recommendations", and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

Submitted to: *Rep. Prog. Phys.*

arXiv:0712.2447v1 [hep-ph] 14 Dec 2007

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 comparisons 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 (SpartyJet) for the convenient comparison of results using different jet algorithms.

Contents

For those with a short attention span

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-proton 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 end products, physicists can determine the properties of a jet, and thus the details of the collision that produced it. Scientists expect to see 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

"When you're a jet, you're a jet all the way, from your first gluon split to your last K decay..."

Symmetry
A joint Fermilab/SLAC publication
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USA

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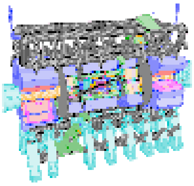
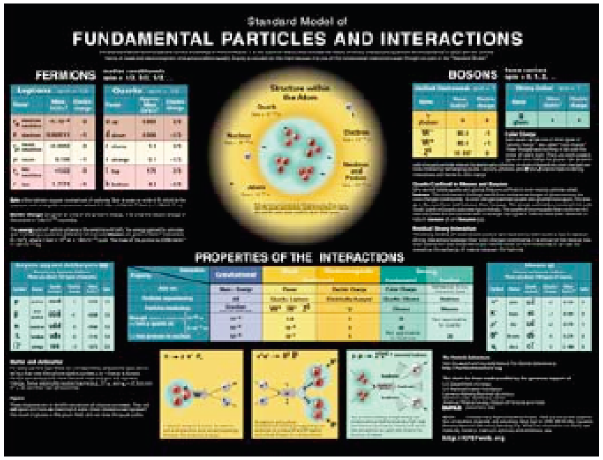
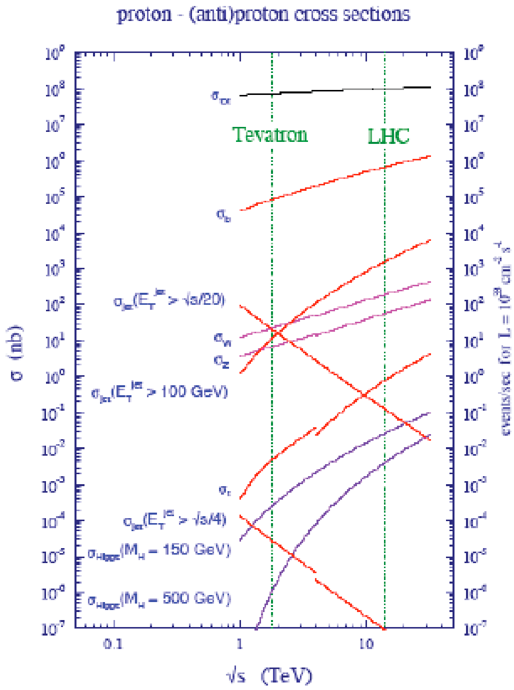
Discovering the SM at the LHC



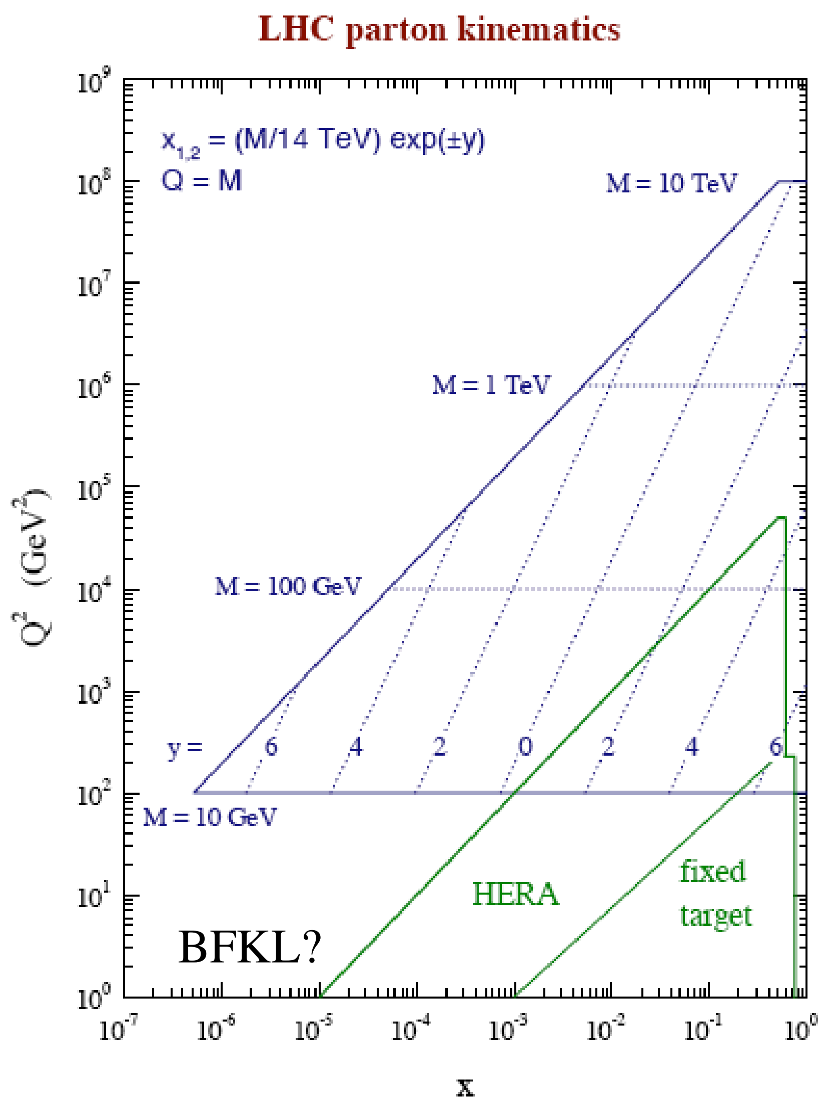
- We're all looking for BSM physics at the LHC
  - and SUSY of course
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
- ATLAS/CMS 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**



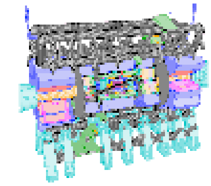


Cross sections at the LHC

- 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



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 ->MRST2003->MRST2004->MSTW
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5/6.6 *(->CTEQ7)*
- All global analyses use a generic form for the parametrization of both the quark and gluon distributions at some reference value Q_o, where Q_o is usually in the range of 1-2 GeV
- Pdf's are available at LO, NLO, NNLO
- NB: both CTEQ and MSTW currently working on *modified LO* pdf's for use with parton shower Monte Carlos

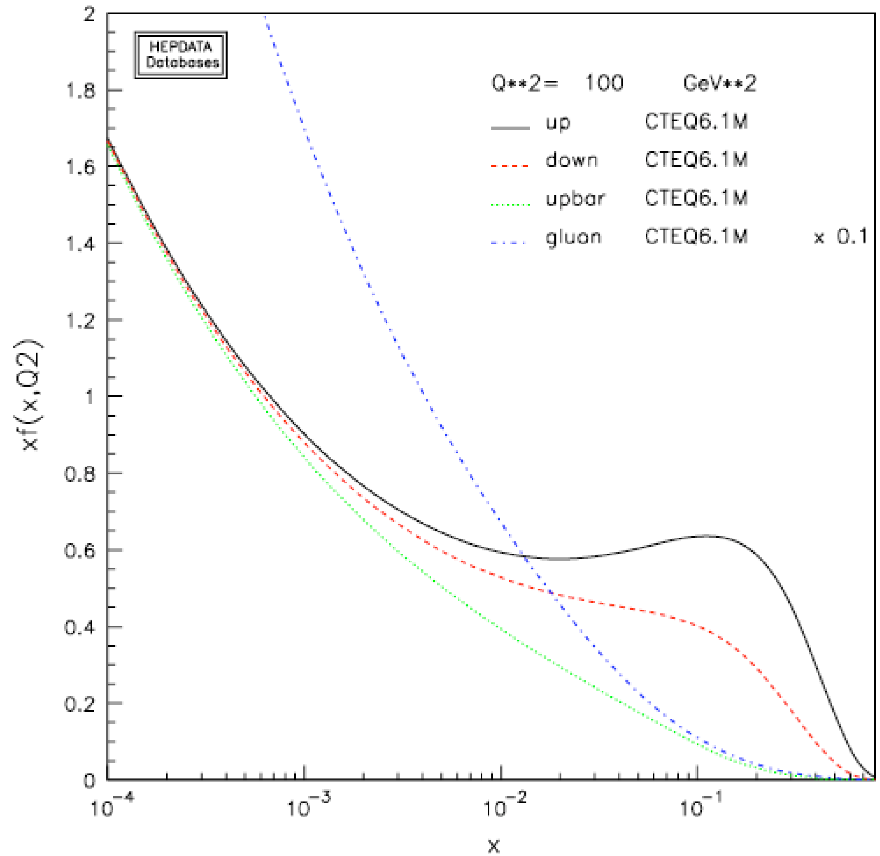
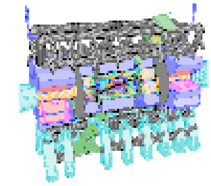


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

$$F(x, Q_0) = A_0 x^{A_1} (1-x)^{A_2} P(x; A_3, \ldots).$$

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

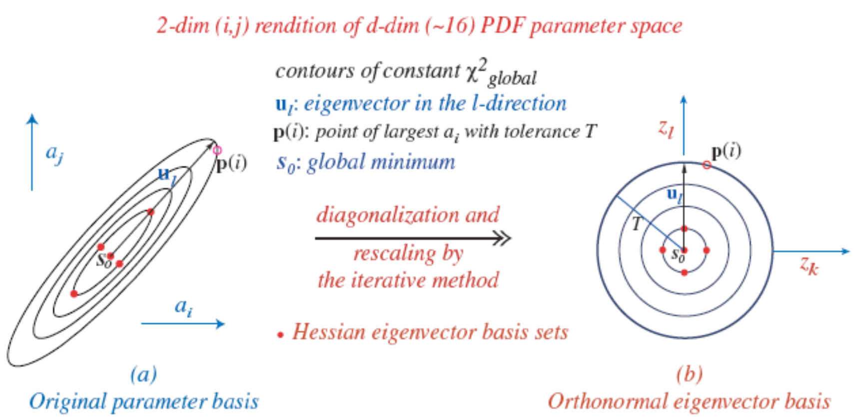


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

  - CTEQ6.1 has 20 free parameters so 20 directions in eigenvector space

40 error pdfs

$$\Delta X^{+}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X_i^+ - X_0, X_i^- - X_0, 0)]^2},$$

$$\Delta X^{-}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X_0 - X_i^+, X_0 - X_i^-, 0)]^2}.$$

Inclusive jets at the Tevatron

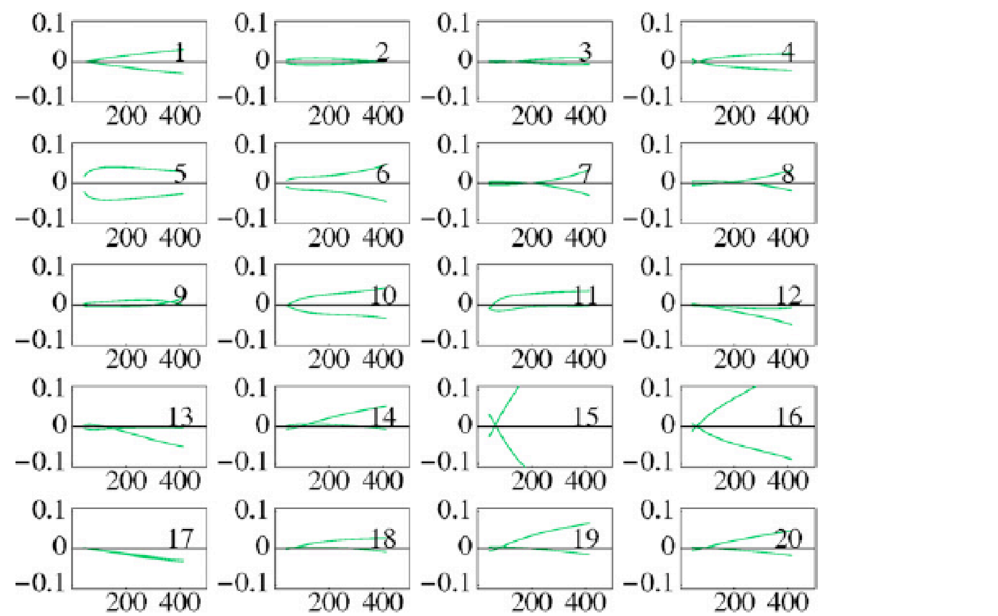


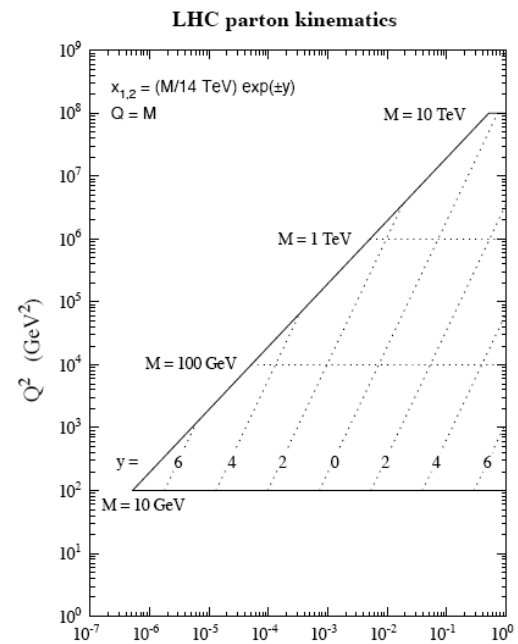
Figure 29. The pdf errors for the CDF inclusive jet cross section in Run 1 for the 20 different eigenvector directions. The vertical axes show the fractional deviation from the central prediction and the horizontal axes the jet transverse momentum in GeV.

▲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



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

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

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

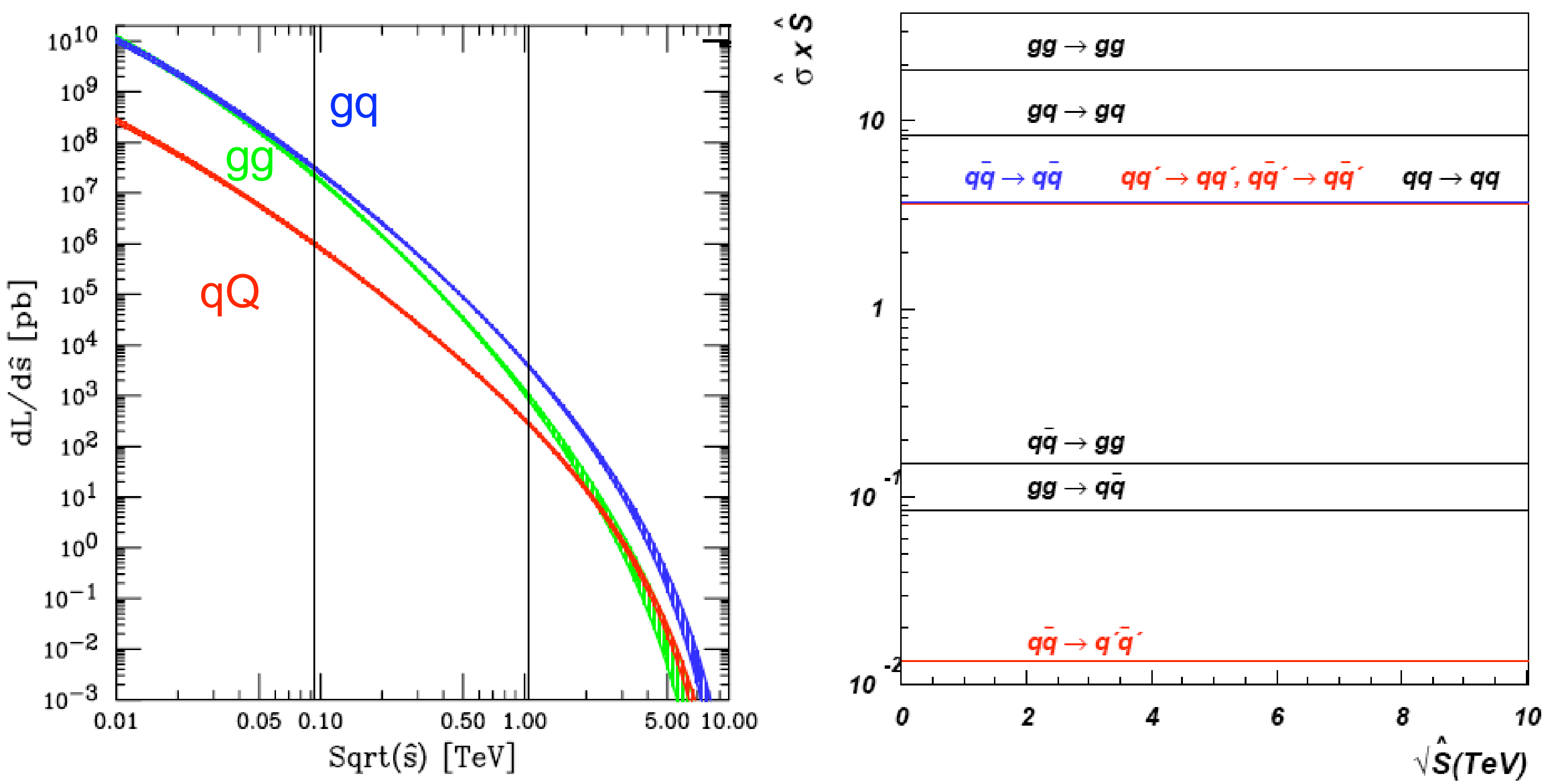
can then be written as

$$\sigma = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}\,dy\right)\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)\left(\hat{s}\,\hat{\sigma}_{ij}\right). \qquad (3)$$

Cross section estimates

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

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$, we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb



for p_T=0.1* sqrt(s-hat)

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

PDF luminosities as a function of y

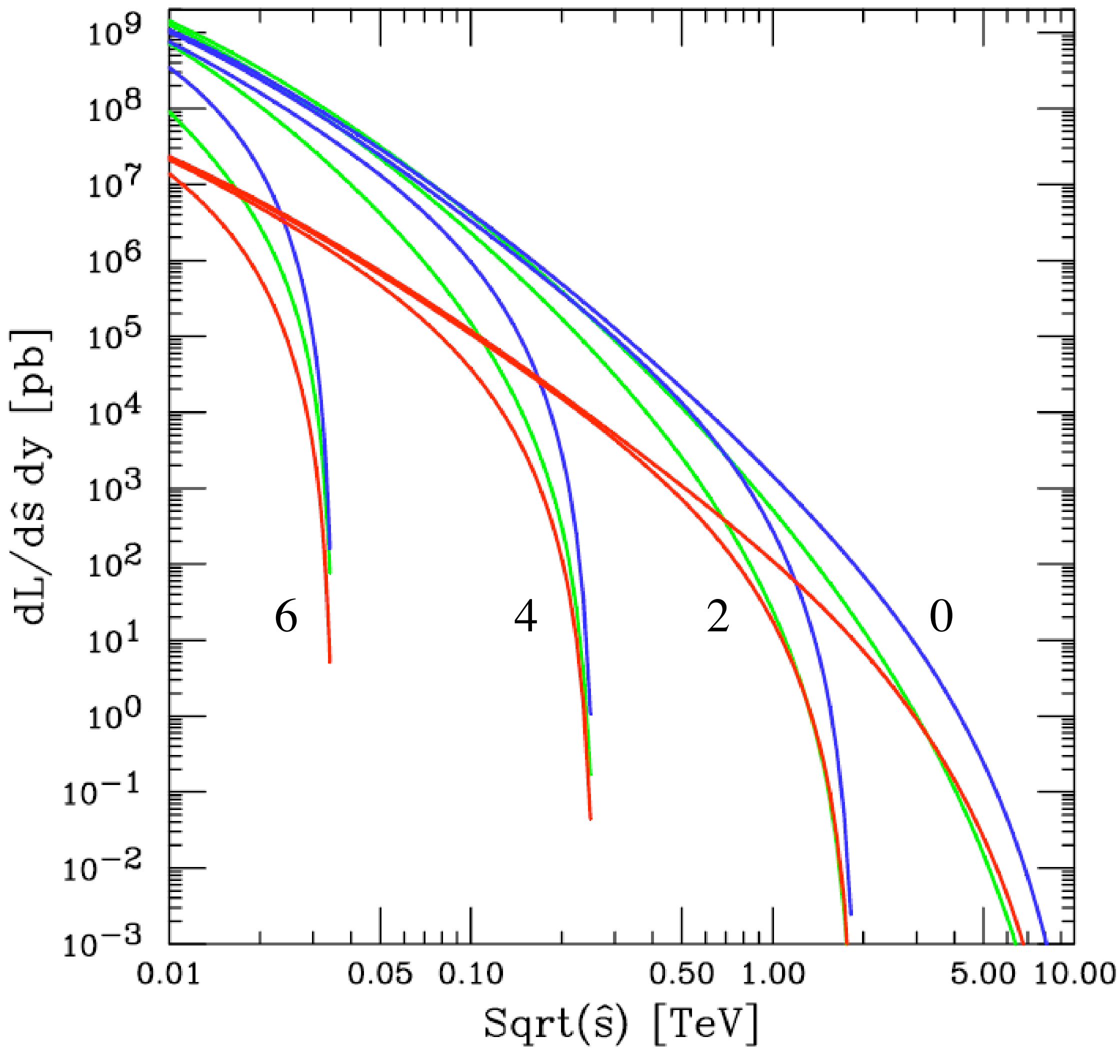
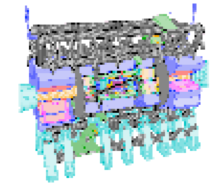


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

PDF uncertainties at the LHC



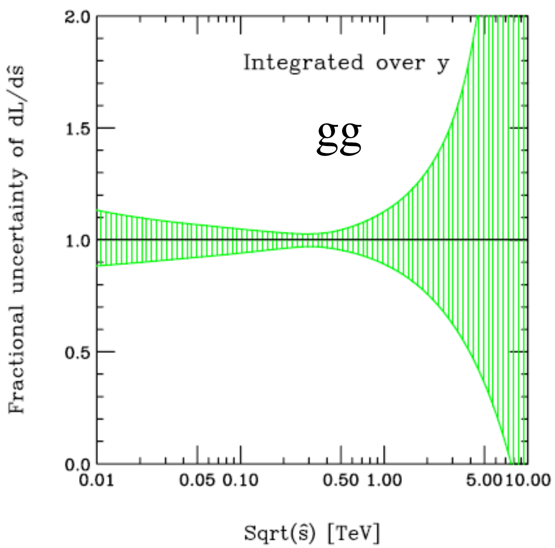


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

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 fb^{-1}, before the LHC data starts to constrain pdf's

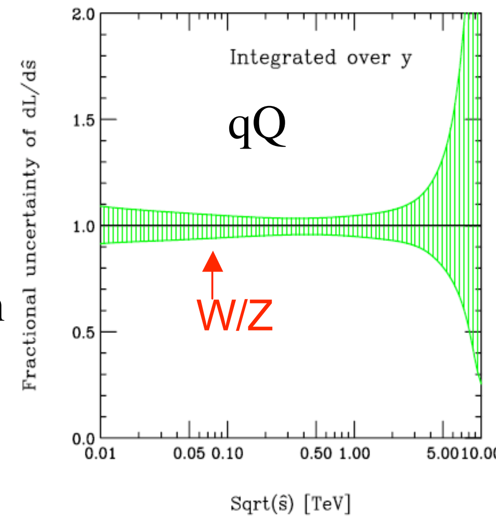


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

great deal of recent work in ATLAS on storing error pdf information when generating MC events with central pdf; by now, standard practice in CDF/D0

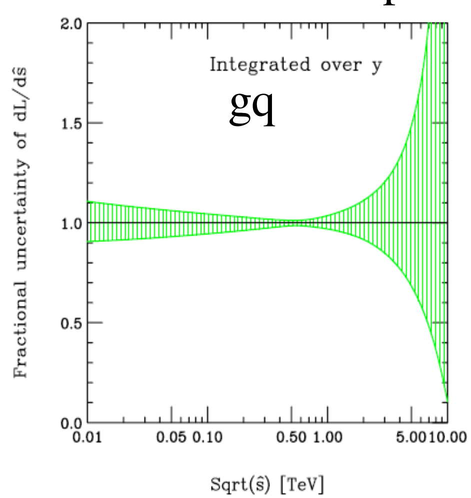
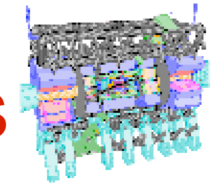


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

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

Ratios:LHC to Tevatron pdf luminosities



- Processes that depend on qQ initial states (e.g. chargino pair production) have small enchancements
- 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 in general that a higher jet cut is necessary at the LHC
  - known known: jet cuts have to be higher at LHC than at Tevatron

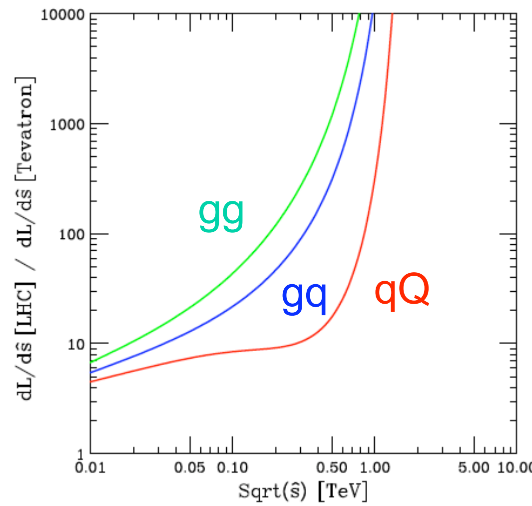


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

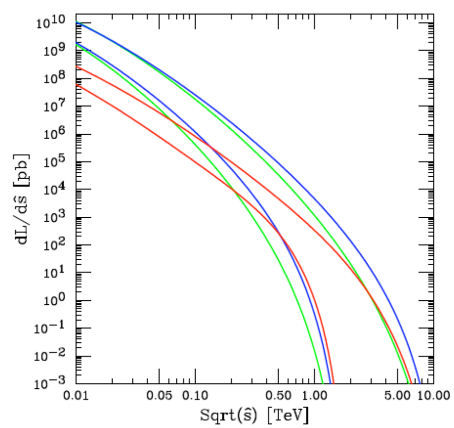


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

Precision benchmarks: W/Z cross sections at the LHC

- CTEQ6.1 and MRST2004 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
- W/Z cross sections could serve as a useful luminosity normalization benchmark
  - especially since we will not know the luminosity to an accuracy better than 15-20% for some time
- But just wait…

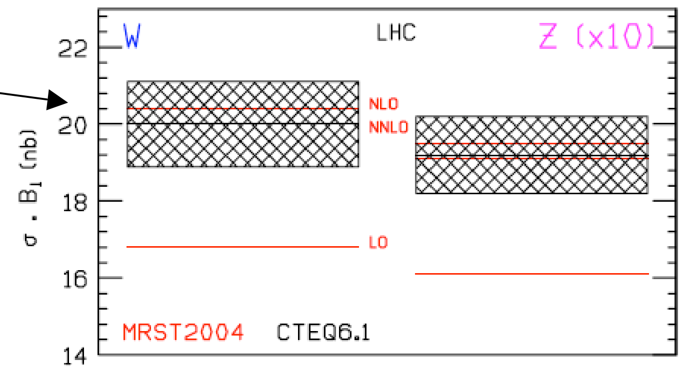


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

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

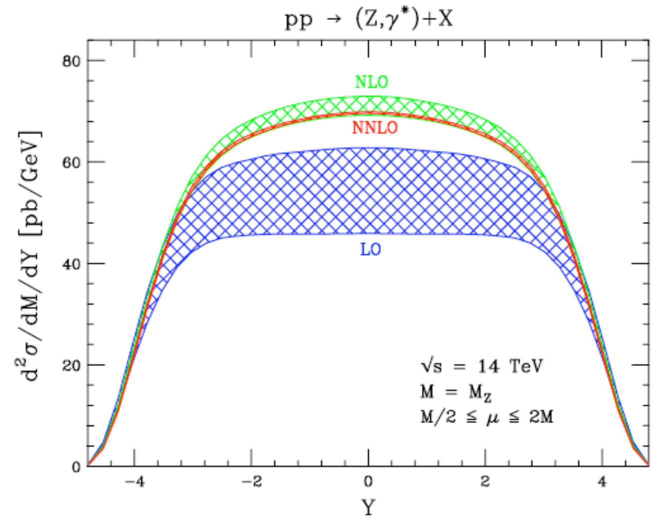


Figure 87. The rapidity distributions for *Z* production at the LHC at LO, NLO and NNLO.

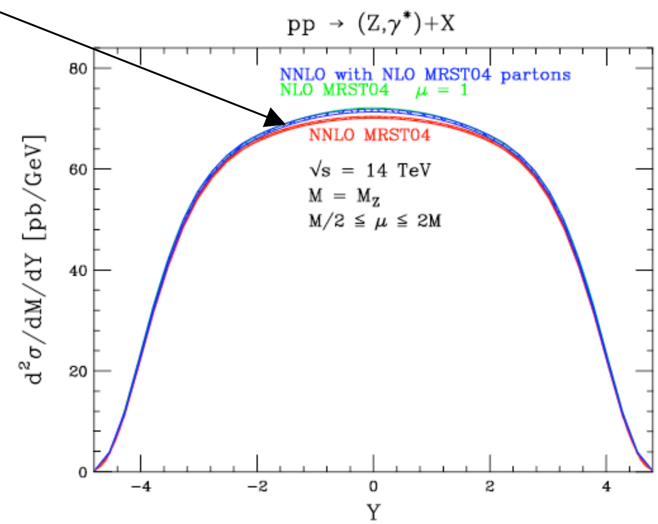


Figure 88. The rapidity distributions for *Z* production at the LHC at NNLO calculated with NNLO and with NLO pdfs.

W/Z p_T distributions

- p_T distributions will be shifted (slightly) upwards due to larger phase space for gluon emission
- 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}**

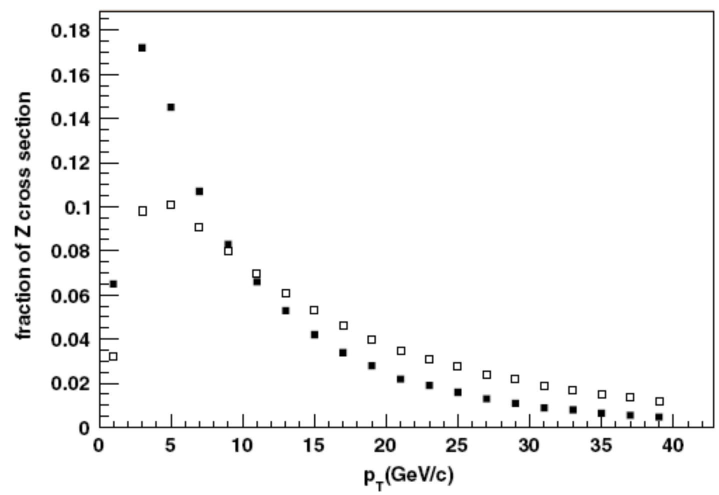


Figure 89. Predictions for the transverse momentum distributions for *Z* production at the Tevatron (solid squares) and LHC (open squares).

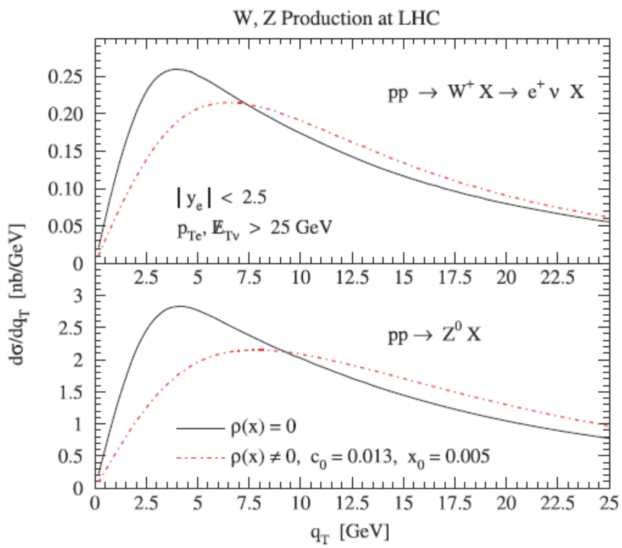


Figure 90. The predictions for the transverse momentum distributions for *W* and *Z* production with and without the p_T-broadening effects.

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

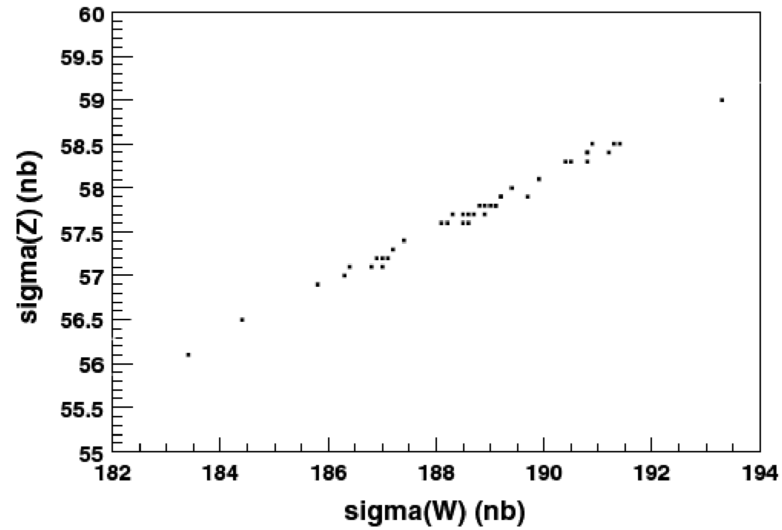


Figure 85. The cross section predictions for Z production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

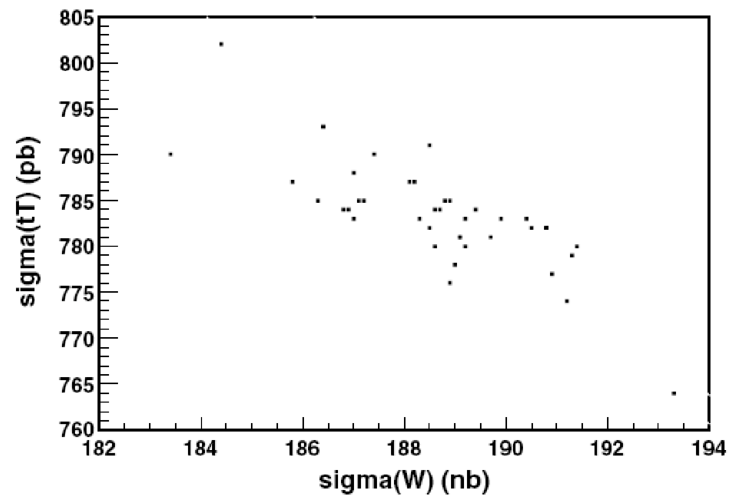


Figure 93. The cross section predictions for $t\bar{t}$ production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

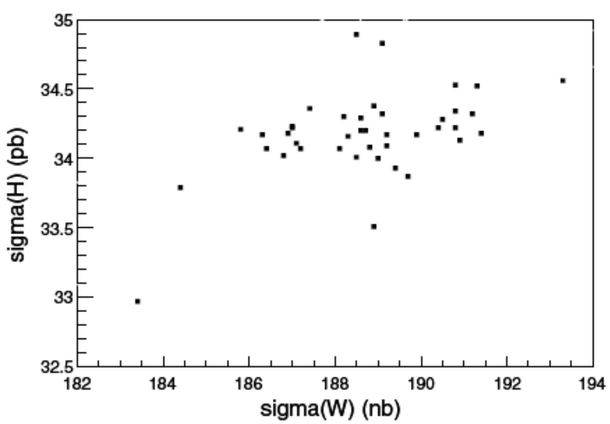
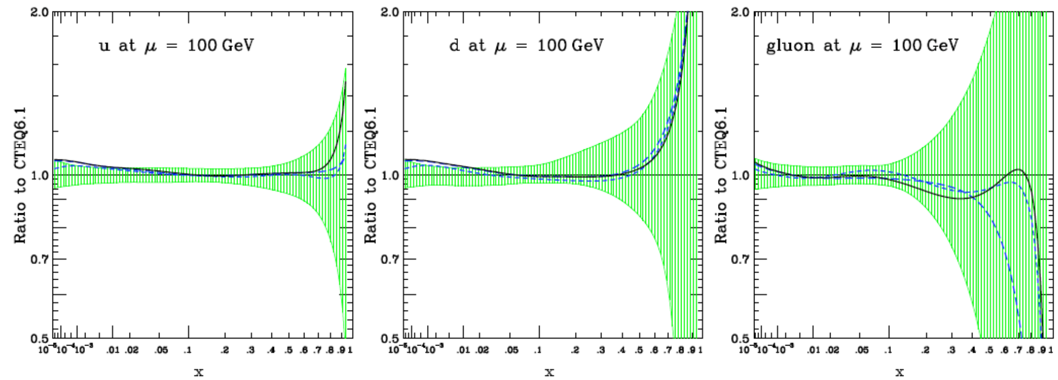


Figure 99. The cross section predictions for Higgs production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

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



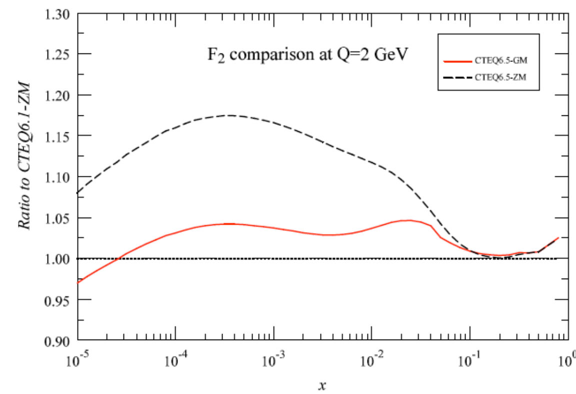
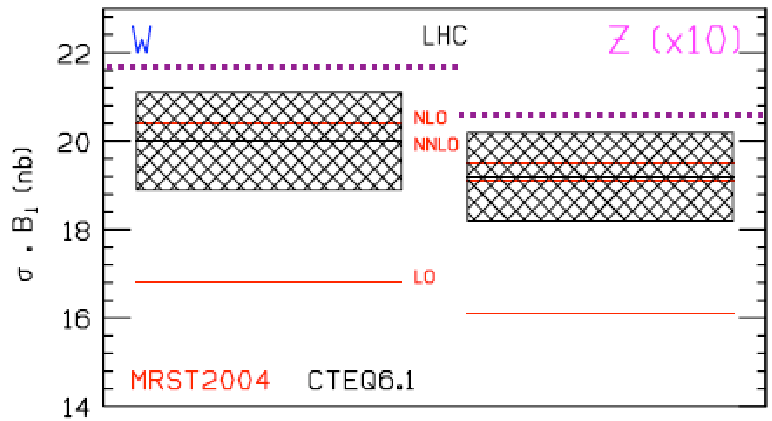


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

→ implications for LHC phenomenology

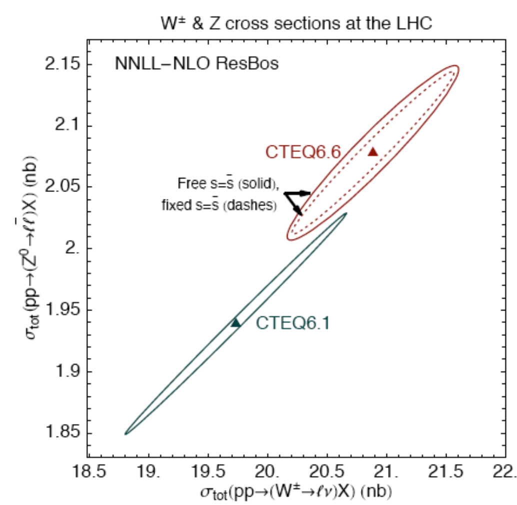
CTEQ6.5(6)

- 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
- Joe now has to use 45 pdf’s to keep me happy



CTEQ6.5(6)

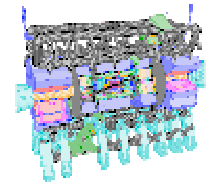
Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.



Note importance of strange quark uncertainty for ratio

Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

Re-visit correlations with Z, tT



Define a correlation cosine between two quantities

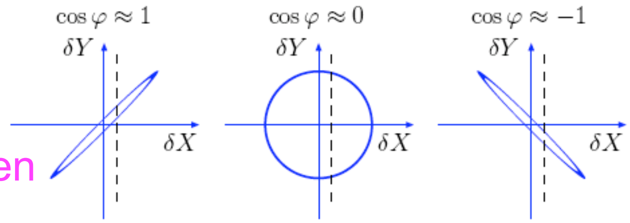
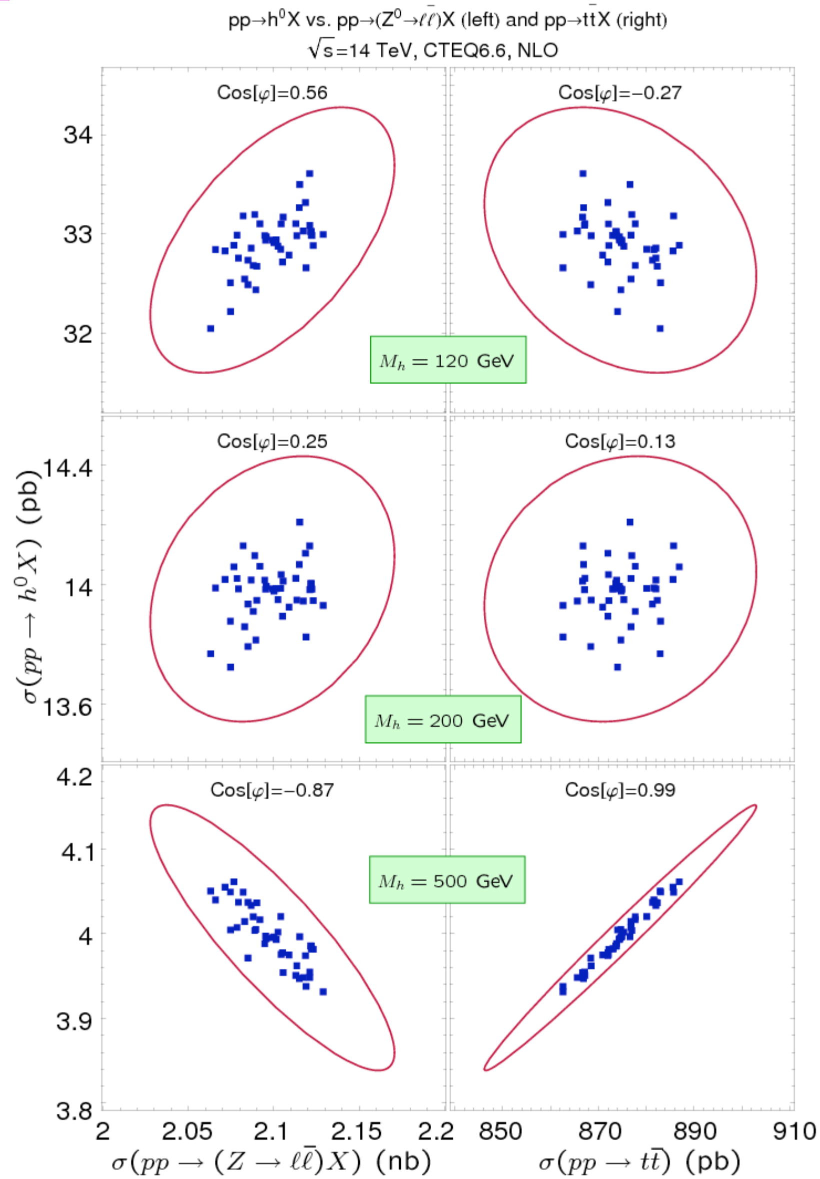


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.



- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1

Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

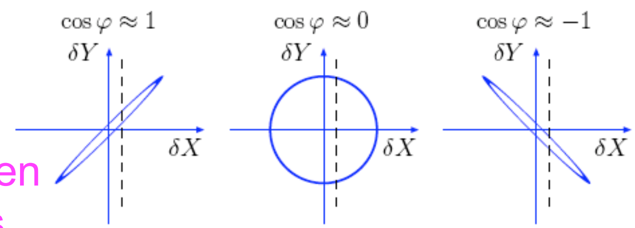


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
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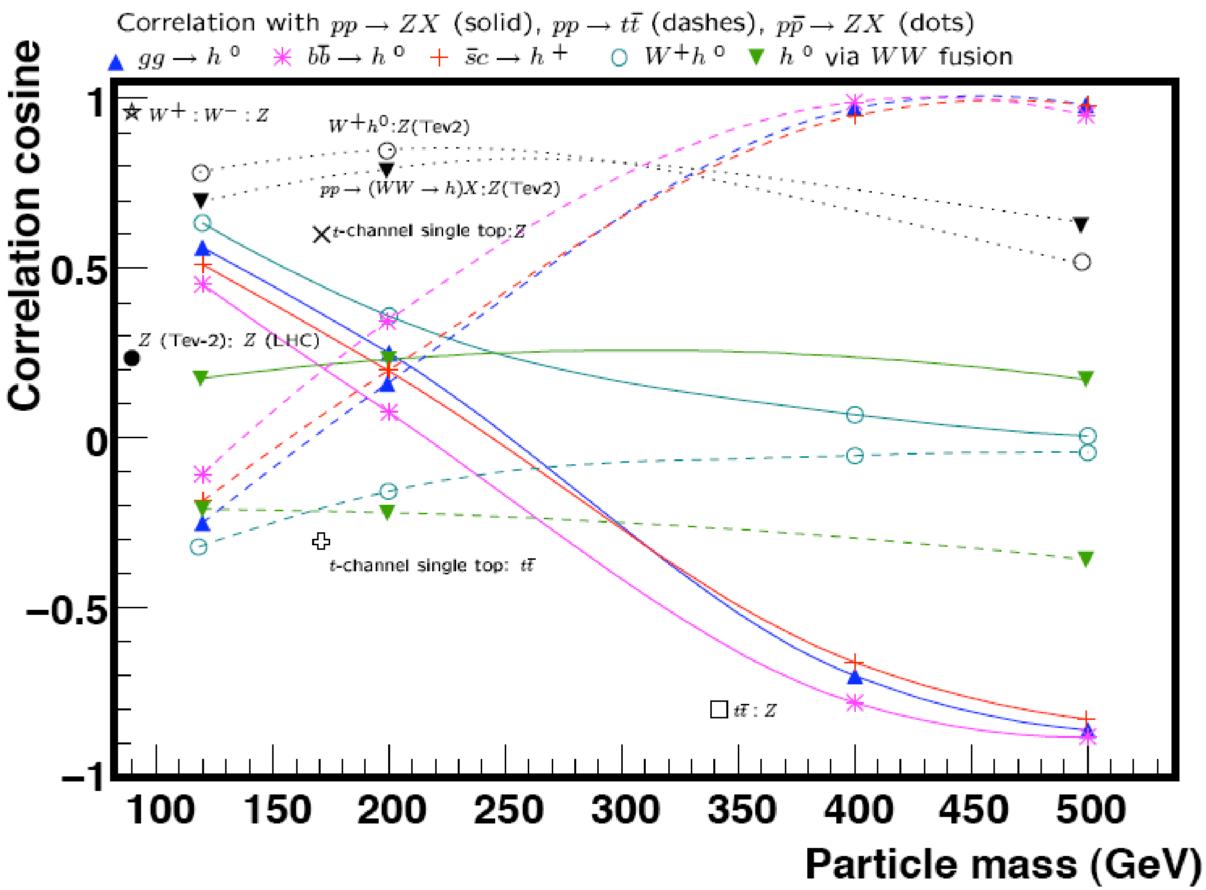
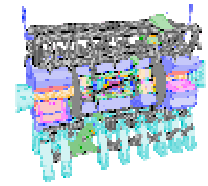


- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W^+}/\sigma_Z)$~1%
- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 5%; $\Delta(\sigma_H/\sigma_Z)$~10%

Known known: the LHC will be a very *jetty* place



- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{W+3\ jets} > \sigma_{W+2\ jets}$ if p_T of lead jet>100 Gev/c (cut of 20 GeV/c on other jets)

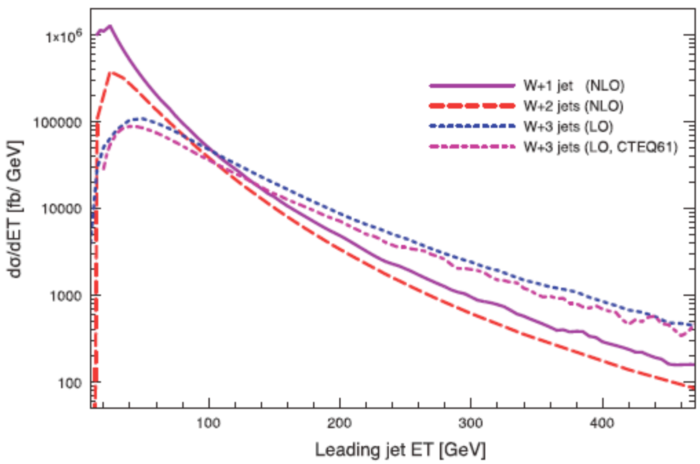


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

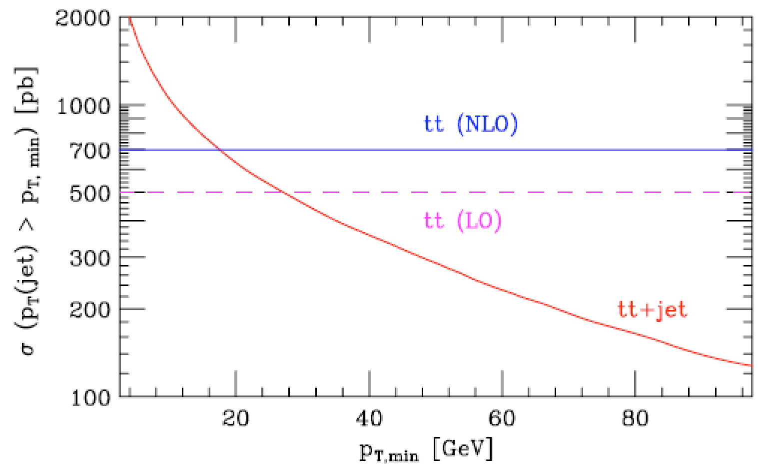


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

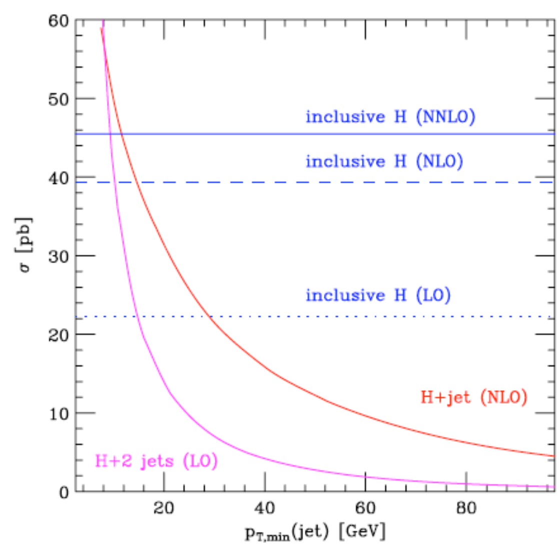


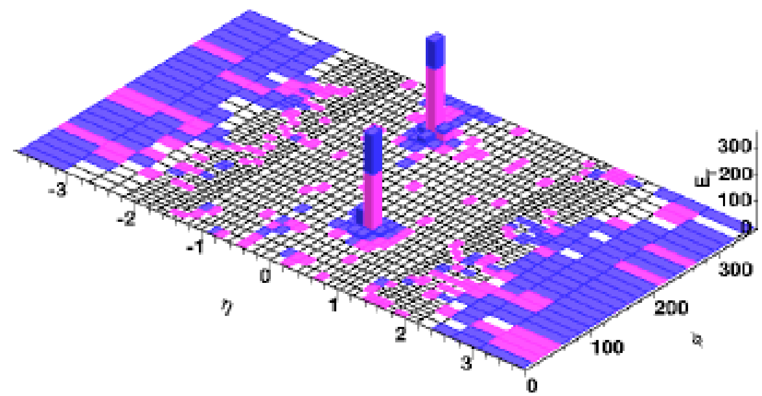
Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

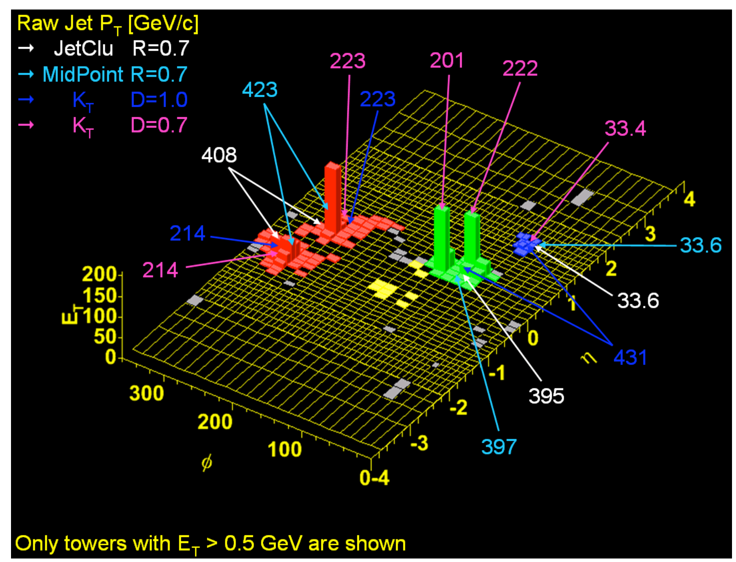
- Indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- Also can be understood from point-of-view of Sudakov form factors (see paper)

Jet reconstruction will be important

- 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, 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

CDF Run II events





Entrez Le SpartyJet

SpartyJet

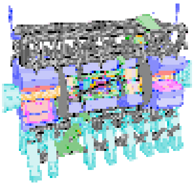
Kurtis Geerlings
Michigan State University

Pierre-Antoine Delsart
~~Université de Montréal~~ LAPP

Joey Huston
Michigan State University

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

SpartyJet



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

Available Algorithms

CDF - JetClu
- MidPoint (with optional second pass)

D0 - D0RunIICone
(from Lars Sonnenschein)

ATLAS - Cone
- FastKt

FastJet (from Gavin Salam and Matteo Cacciari)
- FastKt
- Seedless Infrared Safe Cone (SISCone)

Pythia 8 - CellJet

all algorithms are fully parameterizable

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

with JetBuilder

```
gSystem->Load("libTree.so") ;
gSystem->Load("libs/libJetCore.so");
gSystem->Load("libs/libCDFJet.

StdTextInput textinput("data/J1_Clusters.dat");

JetBuilder builder;
builder.configure_input((InputMaker*)&textinput);

builder.add_default_alg( new cdf::JetClustFinder("myJetClu"));
builder.set_default_cut(0,1*textinput.getGeV);

builder.configure_output
("SpartyJet_Tree","data/output/simple.root");
```

without JetBuilder

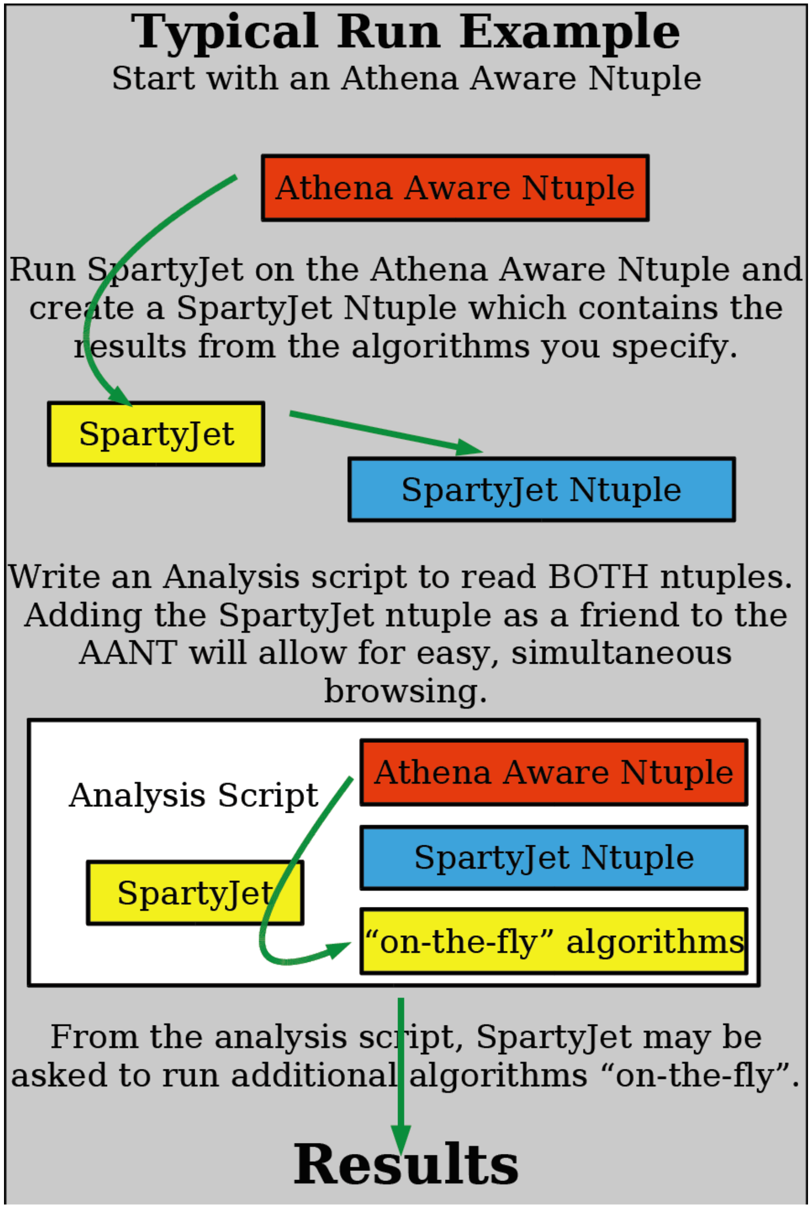
```
TFile f("/home/delsart/SpartyJet_vwithSISCone/example/data/small.root");
TTree * tree = (TTree*) f.Get("CollectionTree");

atlas::CBNTInput input;
input.init(tree);

JetAlgorithm * alg = new JetAlgorithm("MidPointJets");

JetPtSelectorTool *selec = new JetPtSelectorTool(1*GeV);
MidPoint * midpoint = new MidPoint("TOTO");

alg->addTool((JetTool*)midpoint);
alg->addTool((JetTool*)selec);

alg->init();

NtupleMaker ntp;
ntp.addJetVar("MidPointJets");
ntp.init("JetTree","out.root");

Jet::jet_list_t injets;
Jet::jet_list_t outjets;

input->fillInput(2,injets);
alg->execute(injets, outjets);

ntp.set_data("MidPointJets", outjets);
ntp.fillJets() ;

clear_jetlist(injets);
clear_jetlist(outjets);

 input->fillInput(5,injets);
alg->execute(injets, outjets);

ntp.set_data("MidPointJets", outjets);
ntp.fillJets() ;

ntp.finalize();
```

“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:

Jet::jet_list_t&	SpartyJet::getjets(JetTool* tool, Jet::jet_list_t& inputJets);
std::vector<TLorentzVector>&	SpartyJet::getjets(JetTool* tool, std::vector<TLorentzVector>& input);
std::vector<TLorentzVector>&	SpartyJet::getjets(JetTool* tool, std::vector<TLorentzVector>& input, std::vector<std::vector<int> >& constituents);
std::vector<SpartyJet::simplejet>	SpartyJet::getjets(JetTool* tool, std::vector<simplejet>& input);

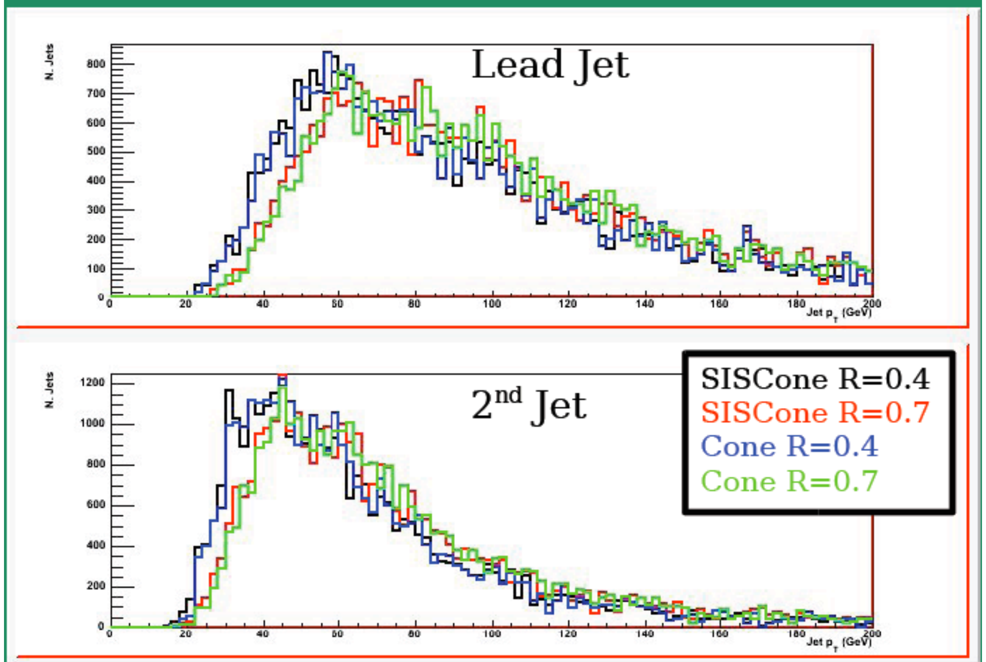
SpartyJet ntuples in ATLAS



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

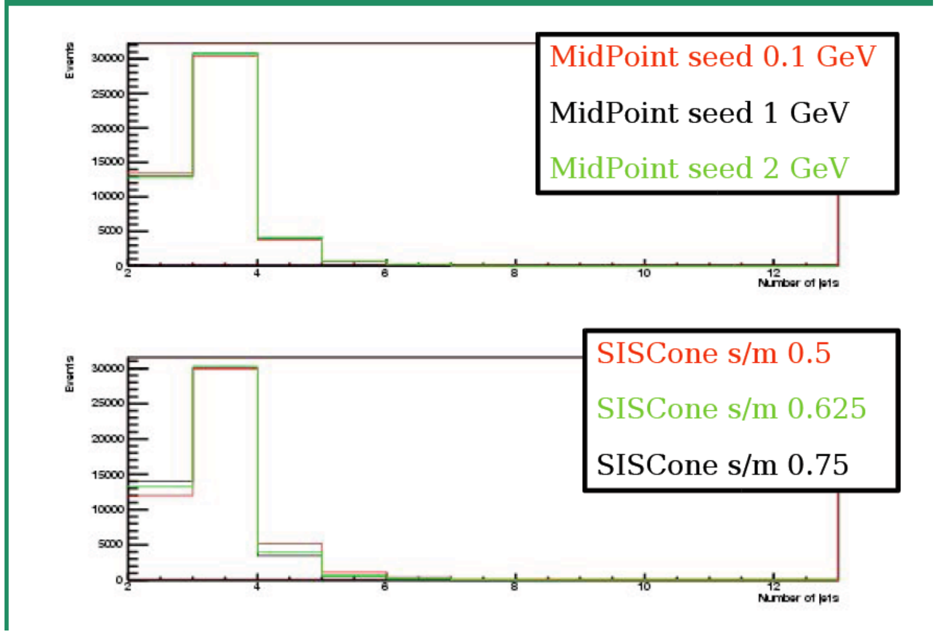
SpartyJet

W + 4parton
Jet pT distributions



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

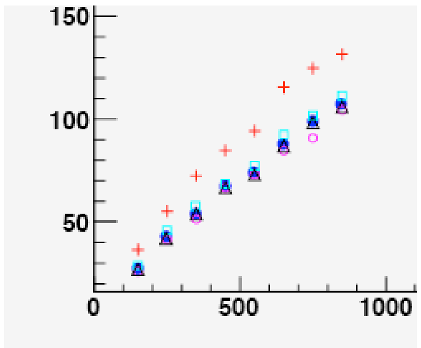
Changing jet parameters: Number of jets



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

jet mass vs jet p_T for R=D=0.7



blue squares = midpoint
red crosses = jetclu
purple circles = celljet
turqoise squares = fastjet
black triangles = siscone

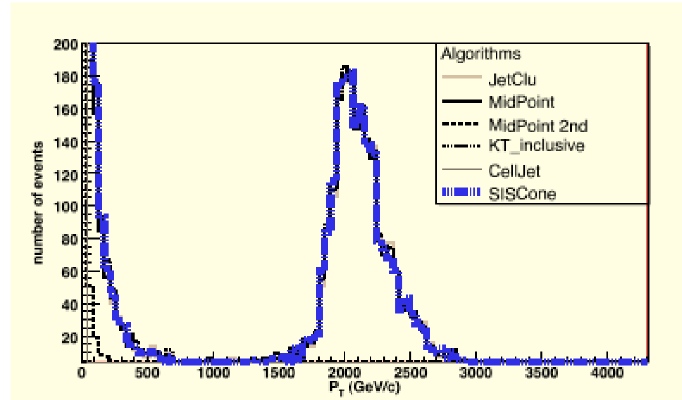


Figure 43: The inclusive jet cross section for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{cone}$) of 0.7. The first bin has been suppressed.

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

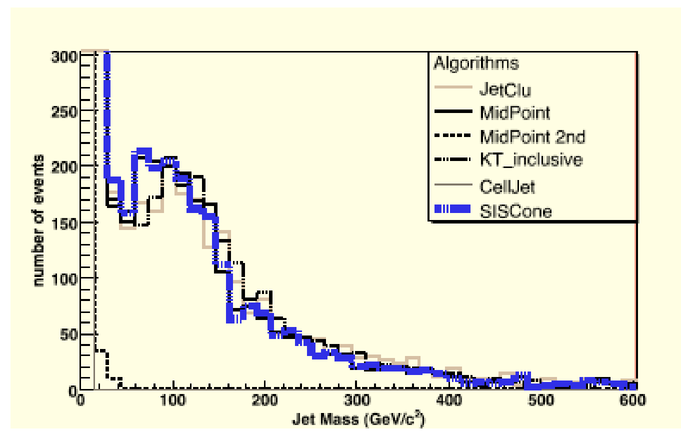
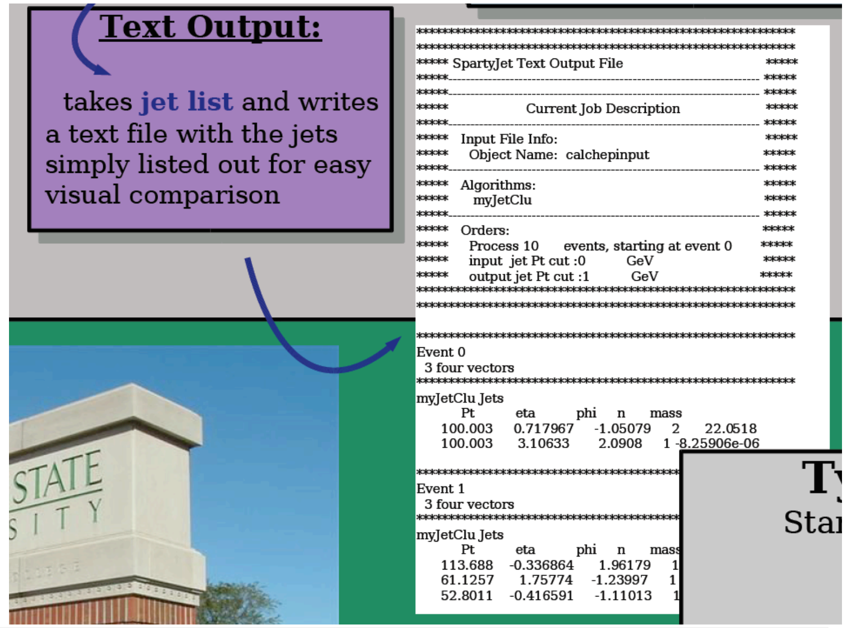
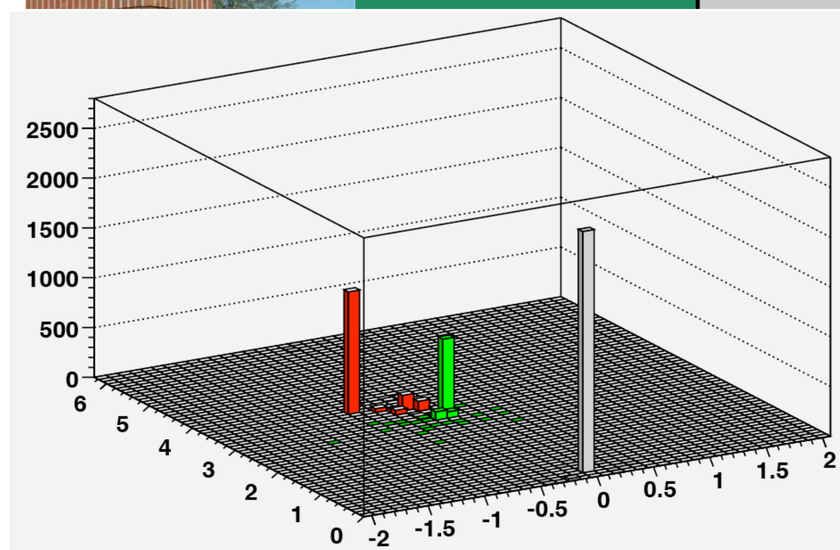


Figure 44: The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale (D=R) of 0.7. The first bin has been suppressed.

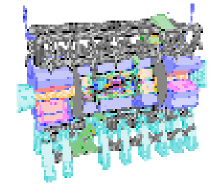
Other features

- Access to jet constituents
- Y-splitter, to determine scale at which jet can be resolved into n sub-jets
- Ability to add n min bias events
- Event visualization
- SpartyJet gui coming in near future





Some recommendations from jet paper



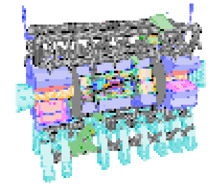
- 4-vector kinematics (p_T,y and not E_T,η) should be used to specify jets
- Where possible, analyses should be performed with multiple jet algorithms
- For cone algorithms, split/merge of 0.75 preferred to 0.50

Summary

- Physics will come flying hot and heavy when LHC turns on at full energy in 2008
- 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
- Also important that US have a strong effort in this early physics

- The detector is going to be "as is" and constantly changing
  - "We take data with the detector we have, not with the detector we want."

New CTEQ project

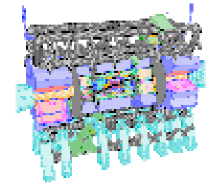


- Collate/create cross section predictions for LHC
  - processes such as W/Z/Higgs(both SM and BSM)/diboson/tT/single top/photons/jets…
    - relative subprocess fractions
  - at LO, NLO, NNLO (where available)
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- Using programs such as:
  - MCFM
  - ResBos
  - EKS
  - Pythia/Herwig/Sherpa
  - …numerous private codes with CTEQ
- First on webpage and later as a report
- Feedback on utility of project would be helpful

- Pdf-related workshop to be held at CERN (and Fermilab) on use of NLO, modified LO, error pdf's
  - in conjunction with MSTW, PDF4LHC

Extra slides

New tool:MCFM with pdf errors

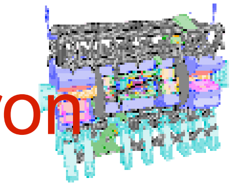


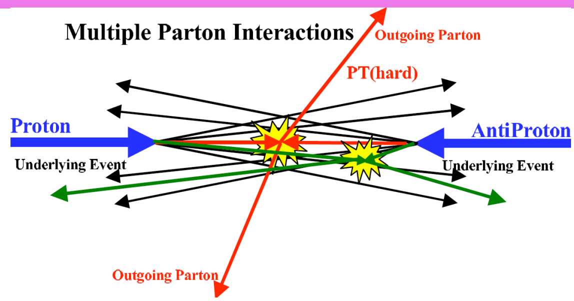
- Error pdf parton luminosities stored along with other event information; tremendous time-saving for MCFM
- Example output below from tT at LHC (virtual diagrams only)

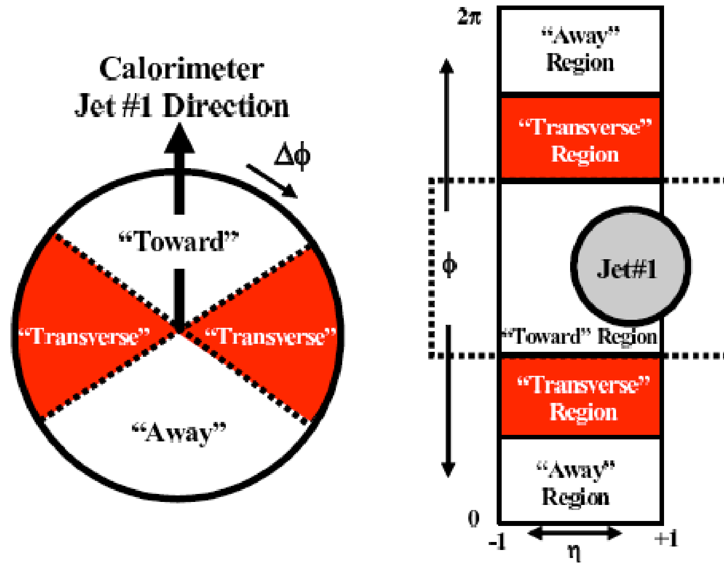
```
PDF error set  0  --->   922503.705 fb
PDF error set  1  --->   924901.729 fb
PDF error set  2  --->   920106.561 fb
PDF error set  3  --->   926873.142 fb
PDF error set  4  --->   918314.821 fb
PDF error set  5  --->   924319.039 fb
PDF error set  6  --->   920737.988 fb
PDF error set  7  --->   930912.022 fb
PDF error set  8  --->   914120.978 fb
PDF error set  9  --->   944892.019 fb
PDF error set 10  --->   899134.509 fb
PDF error set 11  --->   910661.311 fb
PDF error set 12  --->   933849.973 fb
PDF error set 13  --->   918037.641 fb
PDF error set 14  --->   926658.411 fb
PDF error set 15  --->   929544.061 fb
PDF error set 16  --->   916165.078 fb
PDF error set 17  --->   926807.189 fb
PDF error set 18  --->   918520.852 fb
PDF error set 19  --->   914185.317 fb
PDF error set 20  --->   928791.454 fb
PDF error set 21  --->   916124.098 fb
PDF error set 22  --->   919646.351 fb
PDF error set 23  --->   922102.562 fb
PDF error set 24  --->   920512.494 fb
PDF error set 25  --->   923791.211 fb
PDF error set 26  --->   919567.536 fb
PDF error set 27  --->   924333.235 fb
PDF error set 28  --->   922540.280 fb
PDF error set 29  --->   917348.784 fb
PDF error set 30  --->   933489.451 fb
PDF error set 31  --->   921711.144 fb
PDF error set 32  --->   920739.212 fb
PDF error set 33  --->   919592.767 fb
PDF error set 34  --->   923451.843 fb
PDF error set 35  --->   923859.904 fb
PDF error set 36  --->   923632.556 fb
PDF error set 37  --->   923740.945 fb
PDF error set 38  --->   921204.429 fb
PDF error set 39  --->   922465.341 fb
PDF error set 40  --->   922560.436 fb
* --------------- 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

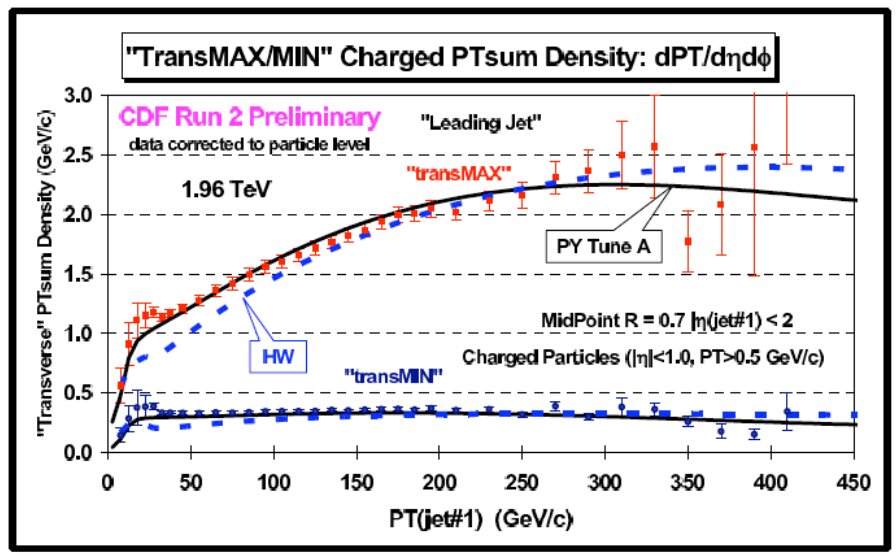
Known known: underlying event at the Tevatron



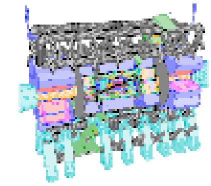




- Define regions transverse to the leading jet in the event
- Label the one with the most transverse momentum the MAX region and that with the least the MIN region
- The transverse momentum in the MAX region grows as the momentum of the lead jet increases
  - receives contribution from higher order perturbative 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 prodution?



- 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

$$E\frac{d^3\sigma}{dp^3} \equiv \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \qquad (1)$$

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

$$f \otimes g = \int_x^1 \frac{dy}{y}\, f(\frac{x}{y})\, g(y). \qquad (2)$$

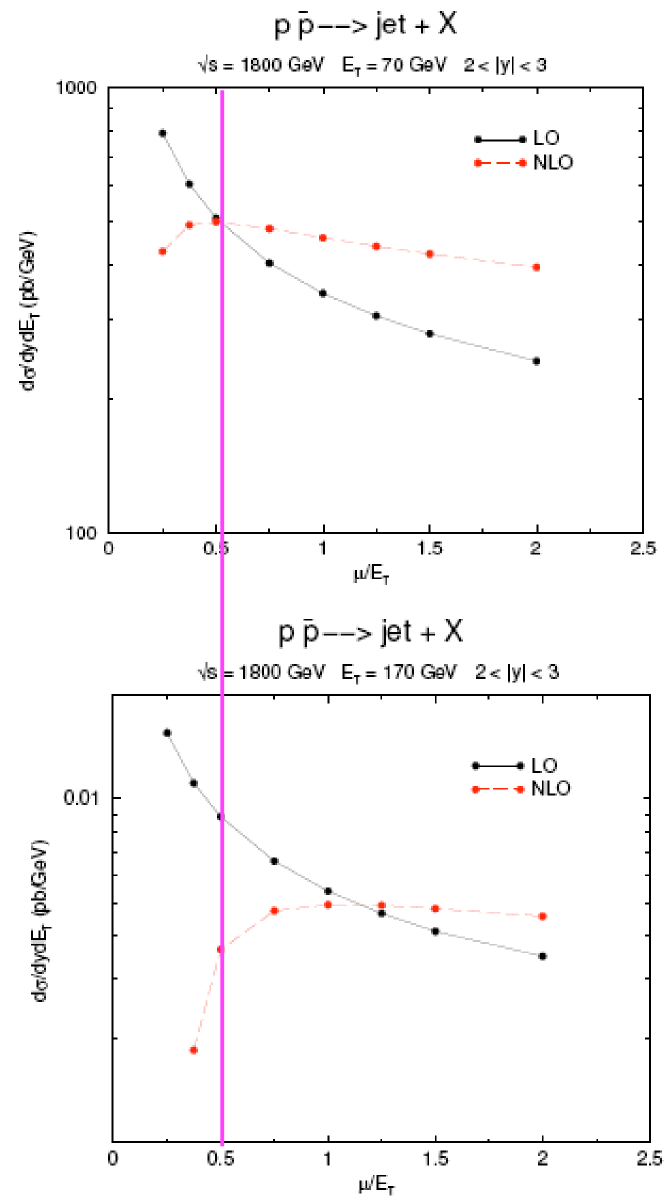
When one calculates the $\mathcal{O}(\alpha_s^3)$ contributions to the inclusive cross section, the result can be written as

$$\begin{aligned}
(1)\quad \sigma &= a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(2)\quad &+ 2a^3(\mu)\,b\ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(3)\quad &+ 2a^3(\mu)\,\ln(p_T/M)P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(4)\quad &+ a^3(\mu)\,K \otimes q(M) \otimes q(M). \qquad (3)
\end{aligned}$$

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 μ

Why K-factors < 1?

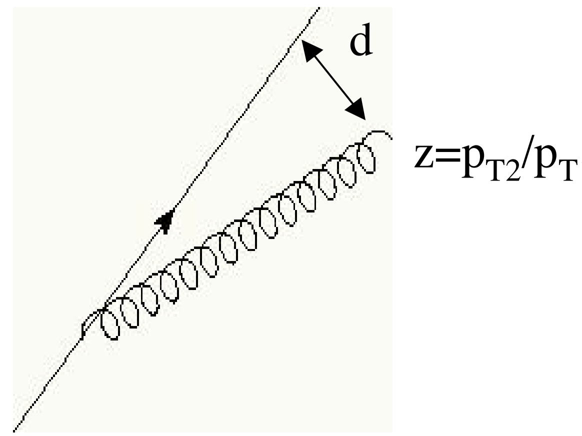
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases
- Second term is negative for $\mu < p_T$, positive for $\mu > p_T$
- Third term is negative for factorization scale $M < p_T$
- Fourth term has same dependence as lowest order term
- Thus, lines one and 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 (=ΔR)
- 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 α_s decreases)
  - at NLO the k_T algorithm corresponds to Region I (for D=R); <u>thus at parton level, the cone algorithm is always larger than the k_T algorithm</u>



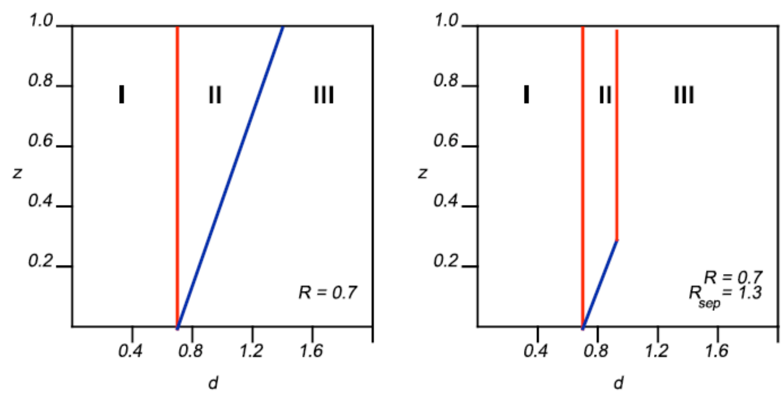
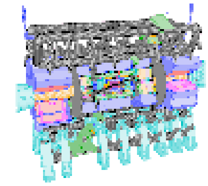


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

SM benchmarks for the LHC



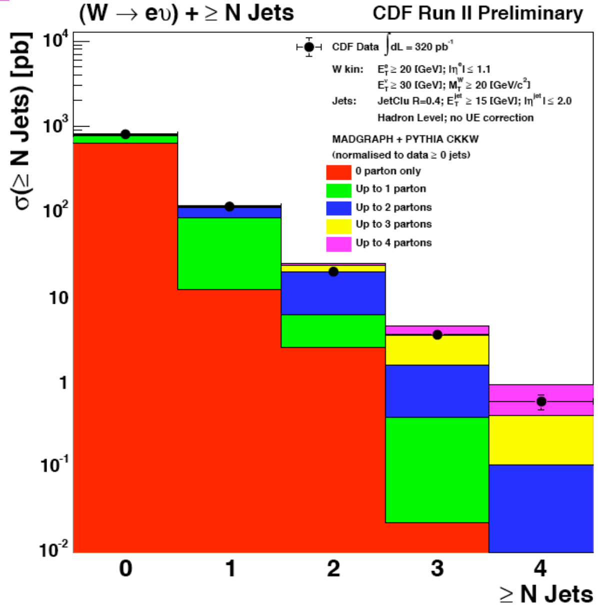
See www.pa.msu.edu/~huston/ Les_Houches_2005/Les_Houches_SM.html (includes CMS as well as ATLAS)

- pdf luminosities and uncertainties
- expected cross sections for useful processes
  - inclusive jet production
    - simulated jet events at the LHC
    - jet production at the Tevatron
      - a link to a CDF thesis on inclusive jet production in Run 2
      - CDF results from Run II using the kT algorithm
  - photon/diphoton
  - Drell-Yan cross sections
  - W/Z/Drell Yan rapidity distributions
  - W/Z as luminosity benchmarks
  - W/Z+jets, especially the *Zeppenfeld* plots
  - top pairs
    - ongoing work, list of topics (pdf file)

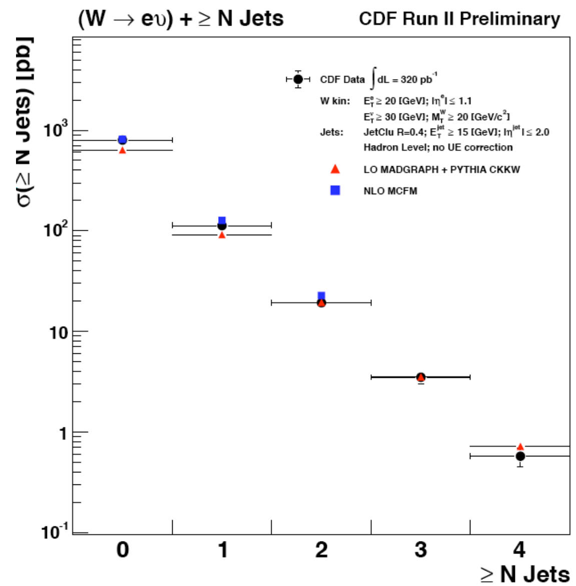
W + jets at the Tevatron

- 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 ~factor of α_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