Major upgrades of the Tevatron for Run II will result in:

- A large increase in the expected delivered luminosity for both CDF and D0:
  - Run I: 110 pb$^{-1}$
  - Run IIa: 2 fb$^{-1}$
  - Run IIb: 15 fb$^{-1}$

- An increase in the center-of-mass energy from 1.8 to 1.96 TeV
  - Big deal for high $E_T$ jets

- Main injector leads to increase in luminosity of factor of 5 (initial goal is $10^{32}$ cm$^{-2}$ s$^{-1}$)
- Recycler leads to additional factor of 2 (re-cool antiprotons from Tevatron)
- Initially 36X36 bunches at 396 ns spacing
- Ultimately 141X121 at 132 ns
Run 2 Luminosity Goals

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CDF in Run 2

- Detector underwent a major upgrade between Run 1 and Run 2 (~$120M)
- Brand new systems include:
  - Silicon
  - Central Open-cell Tracker
  - End-plug and mini-plug calorimeters (coverage up to $\eta$ of 5.5)
  - Time-of-flight
  - Forward muon
  - Luminosity monitor
  - DAQ, trigger etc
- Detector commissioning is complete
- Now taking physics quality data
Installation of silicon into CDF
Rolling in for collisions
The Tevatron Collider serves as arena for precision tests of QCD with photons, W/Z’s, jets

- Highest $Q^2$ scales currently achievable (searches for new physics at small distance scales)
- Sensitivity to parton distributions over wide kinematic range
- 2 scale problems: test effects of soft gluon resummation
- Diffractive production of W/Z, jets, heavy flavor

Dynamics of any new physics will be from QCD; backgrounds to any new physics will be from QCD processes

Data compared to NLO, resummed, leading log Monte Carlo, fixed order calculations
Overall, the data from CDF and D0 agree well with NLO QCD

Some puzzles resolved:
- $W + \text{jet(s)}$: $R_{10}$

Some puzzles remain:
- Jet excess at high $E_T$/mass??
  - Gluon distribution at large $x$?
- 630 GeV jet cross section and $x_T$ scaling
- Comparison of $k_T$ inclusive jet cross section and NLO theory
- Heavy flavor cross sections

Some theory work needs to be done:
- Inclusive photon cross section

Some searches still continue:
- BFKL effects

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Example: Jets at the Tevatron

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

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

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Similar excess observed in Run 1B

CDF Preliminary

NLO QCD prediction (EKS)
cteq4m $\mu=E_t/2$ $R_{sep}=1.3$

Statistical Errors Only

(CDF Preliminary)
Run 1B (87 pb$^{-1}$)
with run 1A results overlayed
NLO QCD CTEQ3M scale $E_t/2$

Statistical errors only

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**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
  - → increased cross section for high $E_T$ jets

- **$\alpha_s$ stops running**: possible conspiracy between new particles Susy (hep-ph9512325, hep-ph9601279), 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
- …but this is not the central fit; extra weight given to high E_T data points; need a more powerful sample
DØ jet cross section as function of rapidity

DØ Preliminary
Run 1B
- Nominal cross sections & statistical errors only
- JETRAD \( \mu = E_T^{\text{max}}/2 \)
- CTEQ4HJ provides best description of data

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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>
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<tr>
<td>CTEQ3M</td>
<td>121.56</td>
<td>1.35</td>
<td>0.01</td>
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<tr>
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<td>92.46</td>
<td>1.03</td>
<td>0.41</td>
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<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>
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<tr>
<td>MRSTgD</td>
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<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.
So is this the end of the story?

- You need to be careful that you are not mistaking old physics for new physics
- …but you also have to be careful that you are not labelling potential new physics as old physics
- Consider the remaining uncertainty on the parton distribution functions

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PDF Uncertainties

- Use Hessian technique (T=10) with the CTEQ6 pdf formalism

\[ u \text{ at } Q = 3.16 \text{ GeV} \]

\[ d \text{ at } Q = 3.16 \text{ GeV} \]
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
- But a great deal of uncertainty remains for the high x gluon, and thus for the predictions for the high $E_T$ jet cross section

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Luminosity function uncertainties at the Tevatron

![Graphs showing luminosity function at TeV RunII for different processes: Q-G → Z, Q-G → W^+, Q-G → W^−, Q-Q → W^+ (W^−), Q-̅Q → γ^* (Z). The graphs illustrate the fractional uncertainty as a function of √s (GeV).]
Luminosity Function Uncertainties at the LHC
MRST2001/CTEQ6M comparison for D0 jets

MRST 2001 and D0 jet data, $\alpha_s(M_Z)=0.119$, $\chi^2=106/82$ pts.

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

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Fit to the jet data gives a \( \chi^2 \) of 118 (for 113 points) compared to 170

\( \alpha_s = 0.121 \)

But gluon has a \textit{kink} at low Q, leading to a \textit{shoulder} at higher Q

Fit rejected

But an artifact of too strict a parametrization?

We get a kink in CTEQ6 gluon if we use MRST parametrization
MRST2001J: Comparison to CDF/D0 jets

\[ \alpha_s = 0.121 \]
\[ \chi^2 = 73/31 \]

Without systematic errors

With systematic errors

\[ \alpha_s(M_Z) = 0.121, \chi^2 = 45/82 \text{ pts} \]
Figure 19: Comparison between theory and the D0 jet data. The error bars are statistical and systematic errors combined.
Compare CTEQ6 to MRST

- Main difference is the gluon at high $x$
Jets at 630 GeV

- Jet measurements at 630 GeV don’t agree well with NLO QCD predictions
x_T scaling

- x_T scaling ratio of 1800 to 630 GeV jet cross sections also doesn’t agree with NLO QCD

CDF Preliminary Data 0.1 < |\eta_{jet}| < 0.7

D0 Data |\eta_{jet}| < 0.5

EKS NLO QCD, \mu = E_T/2 : CTEQ4M (1), CTEQ3M (2), MRSA (3)

Systematic Uncertainty ± 1σ
Jet Production in Run 2

The increase in the center-of-mass energy from 1.8 to 1.96 TeV has a large effect on the high $E_T$ jet rate.

Inclusive jet cross section at 1.8 and 2.0 TeV (CTEQ4HJ)

For Run 2b potential, see www.pa.msu.edu/~huston/run2btdr/tdr.ps

Jet Yields Bin 1 - 0.1 < $|y|$ < 0.7

For the full Run IIa sample the number of jets above 400 GeV will increase from 11 to ~500.

~ 18 events by June
~ 75 events by end of year

Jets will be measured with the $k_T$ clustering algorithm as well as with improved cone clustering models.

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Measurements will extend to forward regions

- Measurements in the forward region are crucial; a pdf explanation covers both regions; presumably new physics is central

Jet Yields Bin 3 - 1.4 < |y| < 2.1

Jet Yields Bin 4 - 2.1 < |y| < 3.0

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CDF Photons in Run 1B

- Deviations from predictions of NLO QCD observed at both 1800 and 630 GeV
  - steeper slope at low p_T
  - normalization problem at high p_T at 1800 GeV
Results consistent with those from D0 and UA2
What’s the cause?

- PDFs don’t appear to be the answer

Can cause shape change by suitable choice of factorization and renormalization scales.
What’s the cause?

One possibility is the effect of soft gluon initial state radiation (see $k_T$ Effects in Direct-Photon Production, PRD59 (1999) 074007)
Can direct photon production be used to probe the high $x$ gluon and look for $hj$-like behavior?
\[ \bar{p}p \rightarrow \gamma + X \]

\[ s^{1/2} = 2 \text{ TeV} \quad \text{CTEQ5} \quad -0.9 < y < 0.9 \quad Q = p_T/2 \]

- > 10 events per 10 GeV/c \( p_T \) bin for 2 fb\(^{-1} \)
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

- $Q^2 = (0.5 M_W)^2$
- $Q^2 = M_W^2$
- $Q^2 = (2.0 M_W)^2$

Leading Jet $E_T$ (GeV)

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

- Good description over full \( E_T \) range.
- In Run 2, the jet \( E_T \) range will be extended out to 400 GeV/c, with up to 8 jets in the final state.
- In 2 fb\(^{-1}\), will have >1000 \( Wb-b\overline{b} \) events, 300 of them with 1 or more additional jets.
Ok, what have we done in Run 2 so far?

Leading Jet ET in CDF Jet Events
CDF Run 2 Preliminary (12/14/2001 - 2/18/2002) 4.4 pb-1

Raw \( E_T \) values!
A nice dijet event

$E_T^{jet1} = 403\text{ GeV/c}$
$E_T^{jet2} = 322\text{ GeV/c}$

Raw $E_T$ values!!

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Another nice dijet event

$E_{\text{jet}1} = 154$ GeV/c
$E_{\text{jet}2} = 147$ GeV/c

Raw jet $E_T$!!

both jets in plug

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Run 2 diphoton production

- Diphoton production is an interesting QCD measurement but is also a great place to look for new physics.
Diphoton mass reach in Run 2

- Dominant mechanism at low mass is gg scattering; qqbar at higher masses
Plans/actuality for 2002

2002 Integrated Luminosity

you are here

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Luminosity

- Peak bests and weekly averages are improving
  - approaching 4 pb\(^{-1}\)/week
  - with cooling tank installation (June), should have a further factor of 2 improvement

- Peak luminosity and accumulation per store have both bested Run 1 records

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Les Houches update

- 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/ALPGEN
  - 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 July 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 and available website publically available now (http://pdf.fnal.gov)
  - commitment for being implemented in MCFM

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Les Houches update

- Reminder: the big idea:
  - The Les Houches accords will be implemented in all ME/MC programs that CDF/D0 use
  - They will make it easy to generate the multi-parton final states crucial to much of the Run 2 physics program and to compare the results from different programs
  - CDF/D0/theorists can all share common MC data sets
  - They will make it possible to generate the pdf uncertainties for any cross sections measurable at the Tevatron
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

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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 \( (q + \overline{q}) \) is well-determined over wide range of \( x \) and \( Q^2 \)
  - Quark distributions primarily determined from DIS and DY datasets which have large statistics and systematic errors in few percent range (\( \pm 3\% \) 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 dbar and ubar comes at small \( x \) from HERA and at medium \( x \) from fixed target DY production on \( H_2 \) and \( D_2 \) targets
  - Note dbar\( \neq \)ubar

- 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

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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

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Run 2 prospects

- **2-4 fb\(^{-1}\) of data**
  - ~2-4 X 10\(^6\) W events
  - ~6-12 X 10\(^3\) jets events with \(E_T > 300\) GeV/c; jet \(\sigma\) measured precisely to 500 GeV/c
  - ~1.4-2.8 X 10\(^4\) \(\gamma\gamma\) events (\(p_T > 12\) GeV/c)

- **New improved theory tools for comparisons to data**
  - Resummed predictions in both \(q_T\) and \(b\) space; combined threshold/\(k_T\) resummation
  - NLO Monte Carlo calculations
  - NNLO cross section, NNLO pdf’s

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