Physics at Hadron Colliders
Selected Topics: Lecture 1

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http://d0server1.fnal.gov/users/klima/Vietnam/Hue/Lecture_1.pdf
Introduction

• These lectures are a personal survey of some selected topics in experimental high energy physics at hadron colliders
  – detectors
  – analysis issues
  – physics results (what’s new, what’s topical, and where there are problems)

• Hadron colliders = proton-antiproton / proton-proton
  – the next decade belongs to these machines:
    • Tevatron at Fermilab 2001-2007
    • LHC at CERN 2006 -

• Thanks to the many people whose work I have drawn on in putting these lectures together
  (M. Narain, N. Varelas, J. Ellison, H. Montgomery, J. Womersley,...)
Colliders

**Hadron-Hadron**

- **Past**
  - ISR at CERN
  - SPS at CERN

- **Present**
  - Tevatron at Fermilab

- **Future**
  - LHC at CERN

- **Emphasis on maximum energy**
  = maximum physics reach for new discoveries

**Electron-Positron**

- **Past**
  - SPEAR at SLAC
  - PETRA at DESY
  - . . .

- **“Present” (recently ended)**
  - LEP at CERN

- **Future**
  - Linear Collider

- **Emphasis on precision measurements**

**Both approaches are complementary**
Hadron Colliders

• **Advantages**
  – Protons can easily be accelerated to very high energies and stored in circular rings

• **Disadvantages**
  – Antiprotons must be collected from the results of lower energy collisions and stored
    • problem is avoided by using proton-proton collisions at the cost of a second ring
  – Protons are made of quarks and gluons
    • the whole of the beam energy is not concentrated in a single point-like collision
  – Quarks and gluons are strongly interacting particles
    • collisions are messy

• **Despite these problems, hadron colliders are the best way to explore the highest mass scales for new physics**
Outline

• Lecture 1: QCD
  – Brief introduction to QCD
  – Detectors: Calorimetry
  – Jets — experimental issues
    • jet algorithms
    • jet energy scale
  – Jet cross sections

• Lecture 3: The top quark
  – mass
  – cross section
  – decay properties

• Lecture 2: QCD
  – Other Jet measurements
  – Vector bosons
  – Photons
  – Heavy flavour production
  – $\alpha_s$
  – Hard diffraction
  – Concluding remarks on QCD

• Lecture 4: Higgs and Supersymmetry
  – what is mass?
  – Tracking detectors and b-tagging
  – Higgs search in Run 2
  – Supersymmetry searches
Before we can try to search for new physics at hadron colliders, we have to understand Quantum Chromo Dynamics (QCD)

The interactions between quarks and gluons
Hadron-hadron collisions are messy

- Energy flow:

  A collision in 3D

  project the energy flow on to the \((\eta, \phi)\) plane

  The same collision in 2D

  "Lego plot"
But become simple at high energies

- Jets are unmistakable:

  A collision in 3D

  The same collision in 2D

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Quantum Chromo Dynamics

- Gauge theory (like electromagnetism) describing fermions (quarks) which carry an SU(3) charge (color) and interact through the exchange of vector bosons (gluons)

- Interesting features:
  - gluons are themselves colored
  - interactions are strong
  - coupling constant runs rapidly
  - becomes weak at momentum transfers above a few GeV

\[ \alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f) \ln q^2 / \Lambda^2} \]
• These features lead to a picture where quarks and gluons are bound inside hadrons if left to themselves, but behave like “free” particles if probed at high momentum transfer

  – this is exactly what was seen in deep inelastic scattering experiments at SLAC in the late 1960’s which led to the genesis of QCD

  – electron beam scattered off nucleons in a target
    • electron scattered from pointlike constituents inside the nucleon
    • $\sim 1/\sin^4(\theta/2)$ behavior like Rutherford scattering
    • other (spectator) quarks do not participate
So what happens to this quark that was knocked out of the proton?

- $\alpha_s$ is large
  - lots of gluon radiation and pair production of quarks in the color field between the outgoing quark and the colored remnant of the nucleon
- these quarks and gluons produced in the “wake” of the outgoing quark recombine to form a “spray” of roughly collinear, colorless hadrons: a jet
  - “fragmentation” or “hadronization”
What are jets?

- The hadrons in a jet have small transverse momentum relative to the parent parton’s direction and the sum of their longitudinal momenta is roughly the parent parton momentum.

- Jets are the experimental signatures of quarks and gluons and manifest themselves as localized clusters of energy.
**Timeline**

**Introduction of Color and the Quark Model**

**SLAC**
- Experimental evidence of quarks in DIS scattering, Bjorken scaling

**ISR**
- Birth of QCD: Renormalizability, Asymptotic Freedom, Confinement
- Discovery of the charm quark (SLAC, BNL)
- Observation of jets in $e^+e^-$ as manifestation of quarks (SLAC, 1975) and gluons (DESY, 1979)

**PETRA**
- Discovery of the bottom quark (FNAL)

**SppS**
- Violation of Bjorken scaling, Evolution of Parton Distribution and Fragmentation Functions
- QCD calculations start to become available for many processes
- Discovery of W and Z (CERN)

**LEP**
- Next to Leading Order predictions for jet production

**HERA**
- Discovery of the top quark (FNAL)

**Tevatron Run I**
- Discovery of the top quark (FNAL)

**Tevatron Run II**
- Next to Next to Leading Order predictions for jet production
**e^+e^- annihilation**

- **Fixed order QCD calculation of** $e^+e^- \rightarrow (Z^0/\gamma)^* \rightarrow \text{hadrons}:

  \[
  \alpha(\alpha_s^0) \quad \alpha(\alpha_s^1) \quad \alpha(\alpha_s^2)
  \]

- **Monte Carlo approach (PYTHIA, HERWIG, etc.)**

\[
\begin{align*}
e^- & \rightarrow Z^0/\gamma \rightarrow q \rightarrow e^+ \\
\alpha(\alpha_s^0) & \\

\text{Perturbative phase} & \\
\alpha_s < 1 \text{ (Parton Level)}
\end{align*}
\]

\[
\begin{align*}
e^- & \rightarrow Z^0/\gamma \rightarrow \bar{q} \rightarrow e^+ \\
\alpha(\alpha_s^1) & \\

\text{Non-perturbative phase} & \\
\alpha_s \geq 1
\end{align*}
\]
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The Fermilab Tevatron collider

- Run I (1992-96) \(\sim 100 \text{ pb}^{-1}\)
- Run IIa (2001-05) \(\sim 2 \text{ fb}^{-1}\)

Several months shutdown to install new silicon detectors +...

- Run IIb (2006-09?) \(\sim 10-15 \text{ fb}^{-1}\)

Until LHC produces physics
Hadron-hadron collisions

- **Complicated by**
  - parton distributions — a hadron collider is really a broad-band quark and gluon collider
  - both the initial and final states can be colored and can radiate gluons
  - underlying event from proton remnants
\[ \sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij} \left( \alpha_s^m(\mu_R^2), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2} \right) \]
Hadron Collider variables

- The incoming parton momenta $x_1$ and $x_2$ are unknown, and usually the beam particle remnants escape down the beam pipe
  - longitudinal motion of the centre of mass cannot be reconstructed

- Focus on transverse variables
  - Transverse Energy $E_T = E \sin \theta$ (= $p_T$ if mass = 0)

- and longitudinally boost-invariant quantities
  - Pseudorapidity $\eta = -\log(\tan \theta/2)$ (= rapidity $y$ if mass = 0)
  - particle production typically scales per unit rapidity
Simplifying things . . .

- It is a general feature of particle physics that many interactions become simpler to understand at high energies.

- In the case of QCD:
  - Coupling constant becomes smaller at high momentum transfer.
  - Jet structure becomes more obvious (jets become narrower, stand out more clearly from underlying energy flow).
  - Many measurement related systematic effects get smaller.

- We tend to start with high $E_T$ or high momentum transfer ($Q^2$) processes and try to use them to help us understand lower energy scales, rather than the reverse.

- The most basic high momentum transfer process to understand is the hard scattering of the colored constituents of the hadrons to produce high $E_T$ jets.
A high-$E_T$ event at CDF

Cluster Et_min 0.0 GeV

Clusters: ETHAT CLUSTERING
$CLP$: Cone-size=?, Min Tower Et=?

EM HA Nr Et Phi Eta DEta #Tow EM/Et Trks Mass

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<th>Phi</th>
<th>Eta</th>
<th>DEta</th>
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Detectors
Typical detector

- Interaction point
- Magnetized volume Tracking system
- Calorimeter Induces shower in dense material
- Absorber material

Common detector layers:
- EM layers with fine sampling
- Hadronic layers
- Innermost tracking layers use silicon
- Muon detector

Electron
Jet
Muon

Experimental signature of a quark or gluon

"Missing transverse energy"
Signature of a non-interacting (or weakly interacting) particle like a neutrino

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protons \hspace{1cm} \textbf{Calorimeters} \hspace{1cm} \textbf{Tracker} \hspace{1cm} \textbf{Muon System} \hspace{1cm} \textbf{Electronics} \\
\hspace{1cm} \textbf{Beamline Shielding} \\
\hspace{1cm} 20 \text{m} \\
\hspace{1cm} \textbf{antiprotons}
Jet detection

Jet structure = energy flow

- Therefore the basic tool for jet detection and measurement is a segmented calorimeter surrounding the interaction point

- Basic idea: induce a shower of interactions between the incident particle and dense material; measure the energy deposited
Sampling calorimeters

- For reasons of cost and compactness, typically measure only a fixed fraction of the ionization (the "sampling fraction")

- Alternate dense absorber with sensitive medium
- Absorber can be
  - lead, uranium (for maximum density), steel, copper, iron (for magnetic field), tungsten (costly)
- Sensitive layers can be
  - scintillator, wire chambers, liquid argon, silicon (cost, specialized applications only)
Energy Resolution

- Usually dominated by statistical fluctuations in the number of shower particles
  - \( N \propto E_0 \)
  - \( \frac{\delta N}{N} \propto \frac{1}{\sqrt{E_0}} \)
- Often quoted as “\( X\% / \sqrt{E} \)” (E in GeV)
- Typical real-life values:
  - 15\% / \( \sqrt{E} \) (GeV) for electrons
  - 50\% / \( \sqrt{E} \) (GeV) for single hadrons
  - 80\% / \( \sqrt{E} \) (GeV) for jets

- Other terms contribute in quadrature
  - “noise term” (independent of E; dominant at low E)
    - electronic noise
  - “constant term” (constant fraction of E, dominant at high E)
    - calibration uncertainties, nonlinear response, unequal response to hadrons and electrons
Scintillator calorimeters

- Cheap, straightforward to build, but suffer from radiation damage

“Classic” design
Wavelength-shifter readout bars

CDF, ZEUS

Wavelength-shifting fibres
More compact, more flexible

ATLAS, CMS

ATLAS

CMS
Liquid Argon

- Stable, linear, radiation hard
- BUT operates at 80K: cryostat and LN$_2$ cooling required
e.g. H1, SLD, DØ, ATLAS

- Absorber plates
- Readout boards

DØ North endcap liquid argon cryostat vessel

ATLAS “accordion” EM calorimeter
Typical calorimeter arrangement

- Tracking system
- Hadronic layers
- EM layers (fine sampling)
- “Tail catcher”

CDF

- CDF
- EM
- Forward
- CMS

D0

- D0
- EM
- Fine Hadronic
- Coarse Hadronic (Tail catcher)

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DØ Calorimeter Performance

Electrons

Jets

Inclusive jet cross section

$$m_W = 80.483 \pm 0.084 \text{ GeV}$$

DØ electrons

Missing $E_T$ resolution

$\gamma \gamma + X$ events

CDF

DØ
Using Additional Information

- It is possible to augment the calorimetric measurements using charged track information in various ways:
  - \[ E(\text{jet}) = \sum E(\text{towers without tracks}) + \sum p(\text{tracks}) \]
  - \[ E(\text{jet}) = a_{EM} \sum E(\text{towers without tracks}) + a_{\text{had}} \sum E(\text{towers with tracks}) \]
  - \[ E(\text{jet}) = a_{EM} \sum E(\text{identified } \pi^0 \text{ clusters}) + a_{\text{had}} \sum E(\text{other cells}) \]

- Usually in $e^+e^-$ colliders, $E(\text{jet})$ is defined from a constrained fit to the overall event kinematics including the requirement that $\sum E = \sqrt{s}$
Jet Cross Sections
Triggering

- Accelerator luminosity is driven by physics goals
  - e.g. to find the Higgs we will need $\sim 10 \text{ fb}^{-1}$ of data
  - requires collision rate $\sim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

- But low-$E_T$ inelastic cross sections are much much higher than the processes we are interested in saving
  - even with beam bunches crossing in the detector every 132 ns, get $>1$ inelastic collision per crossing

- Triggering challenge
  - Real-time selection of perhaps 50 events per second (maximum that can be written to a tape) from a collision rate of 10,000,000 events per second
  - usually based on rapid identification of
    - high energy particles
    - comparatively rare objects (electrons, muons...)

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Typical trigger scheme

- **Detector**
  - 10MHz collisions
- **Level 1 trigger**
  - hardware based, looks at fast outputs from specialized detectors
  - accepts 10kHz
- **Level 2 trigger**
  - microprocessors, fast calculations on a small subset of the data
  - accepts 1 kHz
- **Level 3 trigger**
  - computers, fast calculations, all the data is available
  - accepts 50 Hz
- **Offline processing**
  - computer farm to process all the data within a few days of recording
  - streaming and data classification
  - Reprocessing with newer versions of the reconstruction program
Jet Triggering

- Unlike most physics at hadron colliders, the principal background for jets is other jets
  - because the cross section falls steeply with $E_T$, lower energy jets mismeasured in $E_T$ often have a much higher rate than true high $E_T$ jets (“smearing”)

- Multi-level trigger system with increasingly refined estimates of jet $E_T$

- Large dynamic range of cross section demands that many trigger thresholds be used e.g.
  - 15 GeV prescaled 1/1000
  - 30 GeV prescaled 1/100
  - 60 GeV prescaled 1/10
  - 100 GeV no prescale

![DØ L3 simulation diagram]

- Factor of ~ 30 rate reduction
Jet Algorithms

- The goal is to be able to apply the “same” jet clustering algorithm to data and theoretical calculations without ambiguities.

- Jets at the “Parton Level”
  - i.e., before hadronization
  - Fixed order QCD or (Next-to-) leading logarithmic summations to all orders
• Jets at the particle (hadron) level

The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects

• Jets at the “detector level”
Jet Algorithms

- Traditional Choice at hadron colliders: cone algorithms
  - Jet = sum of energy within $\Delta R^2 = \Delta \eta^2 + \Delta \phi^2$

- Traditional choice in $e^+e^-$: successive recombination algorithms
  - Jet = sum of particles or cells close in relative $\kappa_T$

Sum contents of cone
Recombine
Theoretical requirements

- **Infrared safety**
  - insensitive to “soft” radiation

- **Collinear safety**

- **Low sensitivity to hadronization**
- **Invariance under boosts**
  - Same jets solutions independent of boost
- **Boundary stability**
  - maximum $E_T = \sqrt{s}/2$
- **Order independence**
  - Same jets at parton/particle/detector levels
- **Straightforward implementation**
Experimental requirements

- Detector independence
  - can everybody implement this?
- Best resolution and smallest biases in jet energy and direction
- Stability
  - as luminosity increases
  - insensitive to noise, pileup and small negative energies
- Computational efficiency
- Maximal reconstruction efficiency
- Ease of calibration
- ...

Effect of pileup on Thrust $k_T$ algorithm jets, $E_T > 30$ GeV

**DØ MC**

- MC overlayed $L=5$, cal. level
- MC, cal. level no overlayed
- MC, ptcl level
  - $|\eta|<1$, jets 1 & 2
  - $|\eta|<3$, jets 3, ...
  - $30 < E_T < 50$
Cone Jets

- **Use DØ as an example:**

Cone jets are defined by a number of algorithm parameters:

- Cone Size (i.e., radius, $R = 0.3, 0.5, 0.7$ in $\eta \times \phi$ space)
- Seed or starting point for iterations (DØ uses 1 GeV $E_T$ towers)

- Calorimeter $E_T$
- Jet Seeds

- Minimum $E_T$ requirement $= 8$ GeV
• Clustering begins w/ seed tower > 1 GeV

• Preclusters are formed by combining seed towers w/ their neighbors (reduces # of jet computations)

• Draw cone around seed/precluster, find ET weighted centroid, recalculate jet centroid, repeat until stable

Standard Snowmass definitions

\[ \eta_{\text{jet}} = \frac{\sum_i E_T^i \eta^i}{\sum_i E_T^i} \]

\[ \phi_{\text{jet}} = \frac{\sum_i E_T^i \phi^i}{\sum_i E_T^i} \]

\[ E_T = \sum_i E_T^i = \sum_i E_i \sin(\theta_i) \]

Lost jets

Seed tower energy distribution for 18-20 GeV jets

Inefficiency
Jet Energy Calibration

1. Establish calorimeter stability and uniformity
   - pulsers, light sources
   - azimuthal symmetry of energy flow in collisions
   - muons

2. Establish the overall energy scale of the calorimeter
   - Testbeam data
   - Set $E/p = 1$ for isolated tracks
     - momentum measured using central tracker
     - EM resonances ($\pi^0 \rightarrow \gamma \gamma$, $J/\psi$, $\Upsilon$ and $Z \rightarrow e^+e^-$)
       - adjust calibration to obtain the known mass

3. Relate EM energy scale to jet energy scale
   - Monte Carlo modelling of jet fragmentation + testbeam hadrons
     - CDF
   - $E_T$ balance in jet + photon events
     - DØ

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Overall Correction Factor

<table>
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<th>$E_T$ (GeV)</th>
<th>CorrFac</th>
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<tr>
<td>20</td>
<td>1.08 ± 0.030</td>
</tr>
<tr>
<td>100</td>
<td>1.15 ± 0.017</td>
</tr>
<tr>
<td>450</td>
<td>1.12 ± 0.025</td>
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Uncertainty reduced by 50% in 1996-1998

... thanks to a lot of hard work
Jet Resolutions

- Determined from collider data using dijet $E_T$ balance

$$ A = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} $$

$$ \frac{\sigma_{ET}}{E_T} = \sqrt{2\sigma_A} $$

In the limit of no soft radiation

$\approx \frac{75\%}{\sqrt{E(GeV)}}$

$\sigma_A$ vs. $\frac{(E_T - E_{T2})}{(E_T + E_{T2})}$

$\sigma_{ET}/E_T: 0.105 \quad 0.075 \quad 0.035$

$E_T: 50 \text{ GeV} \quad 100 \text{ GeV} \quad 450 \text{ GeV}$
Simulation tools

- A “Monte Carlo” is a Fortran or C++ program that generates events
- Events vary from one to the next (random numbers) — expect to reproduce both the average behavior and fluctuations of real data
- Event Generators may be
  - parton level:
    - Parton Distribution functions
    - Hard interaction matrix element
  - and may also handle:
    - Initial state radiation
    - Final state radiation
    - Underlying event
    - Hadronization and decays
- Separate programs for Detector Simulation
  - GEANT is by far the most commonly used
Jet cross sections at $\sqrt{s} = 1.8$ TeV

- Cross section falls by seven orders of magnitude from 50 to 450 GeV
- Pretty good agreement with NLO QCD over the whole range
Highest $E_T$ jet event in DØ

Quotes from Postcards sold at Fermilab with this event’s displays:

1. These two jets of particles recorded by the DØ experiment at Fermilab probe distances a billion times smaller than an atom

2. Two jets of particles observed in the DØ experiment at Fermilab probe the smallest distances ever examined by humans

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$E_{T1} = 475$ GeV, $\eta_1 = -0.69, x_1=0.66$

$E_{T2} = 472$ GeV, $\eta_2 = 0.69, x_2=0.66$

$M_{JJ} = 1.2$ TeV

$Q^2 = 2.2 \times 10^5$ GeV$^2$
What’s happening at high \( E_T \)?

CDF  \( 0.1 < |\eta| < 0.7 \)

\[ \text{(DATA-THEORY)/THEORY} \]

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

DØ  \( |\eta| < 0.5 \)

\[ \text{CTEQ3M, } \mu = 0.5 E_T^{\text{max}}, \ R_{\text{gen}}=1.3 \]

So much has been said about the high-\( E_T \) behaviour of the cross section that it is hard to know what can usefully be added

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The DØ and CDF data agree

- DØ analyzed $0.1 < |\eta| < 0.7$ to compare with CDF
  - Blazey and Flaugher, hep-ex/9903058 Ann. Rev. article

- Studies (e.g. CTEQ4HJ distributions shown above) show that one can boost the gluon distribution at high-$x$ without violating experimental constraints*; results are more compatible with CDF data points
  *except maybe fixed-target photons, which require big $k_T$ corrections before they can be made to agree with QCD (see later)
Jet data with latest CTEQ5 PDF's

- **CDF data**

  ![CDF Data Graph](image1)

  Ratio: Prel. data / NLO QCD (CTEQ5M | CTEQ5HJ)
  
  CTEQ5M: norm. facor: 1.00
  CTEQ5HJ: norm. facor: 1.04

  Incl. Jet: $p_T^7 \cdot d\sigma / dp_T$

  Error bars: statistical only
  
  14% < Corr. Sys. Err. < 27%

- **DØ data**

  ![DØ Data Graph](image2)

  Ratio: Data / NLO QCD (CTEQ5M | CTEQ5HJ)
  
  CTEQ5M: $\chi^2 = 24/24$, norm. factor: 1.04
  CTEQ5HJ: $\chi^2 = 25/24$, norm. factor: 1.08

  Incl. Jet: $p_T^7 \cdot d\sigma / dp_T$

  Error bars: statistical only
  
  8% < Corr. Sys. Err. < 30%
Forward Jets

- DØ inclusive cross sections up to $|\eta|=3.0$
- Comparison with JETRAD using CTEQ3M, $\mu = E_T^{\text{max}}/2$

Data - Theory / Theory

$\left\langle \frac{d^2\sigma}{dE_T d\eta} \right\rangle$ (fb/GeV)

$E_T$ (GeV)
Triple differential dijet cross section

\[ \frac{d^3 \sigma}{dE^T_1 d\eta_1 d\eta_2} \]

Can be used to extract or constrain PDF’s

At high \( E_T \), the same behaviour as the inclusive cross section, presumably because largely the same events
Tevatron jet data can constrain PDF’s

- For dijets:

\[ x_{1(2)} = \sum_{i=1}^{2} \left[ \frac{E_{T,i}}{\sqrt{s}} \exp(\eta_i) \right] \text{ and } Q^2 = E_{T,1}E_{T,2} \]
What have we learned from all this?

- Whether nature has actually exploited the “freedom” to enhance gluon distributions at large $x$ will only be clear with the addition of more data
  - with $2fb^{-1}$ at the Tevatron the reach in $E_T$ will increase by $\sim 70$ GeV and should make the asymptotic behaviour clearer
  - With higher $E_{cm}$ there will be a significant increase in the number of high $E_T$ jets

- whatever the Run II data show, this has been a useful lesson:
  - parton distributions have uncertainties, whether made explicit or not
  - we should aim for a full understanding of experimental systematics and their correlations

- We can then use the jet data to reduce these uncertainties on the parton distributions