Physics of CDF

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Lecture # 1 **Introduction**

1. Physics of proton-antiproton scattering
2. General cross section formula
3. Kinematics
4. The Tevatron Collider and the CDF Experiment

Lecture # 2 **W/Z Production and Decay**

1. Theory of production and decay
2. Detection of $W^{\pm}$'s and Z°'s
3. σ_W and WW/WZ production

Lecture # 3 **The W Mass**

1. Vector boson masses in SM
2. Measurement techniques
3. Latest CDF results

Lecture # 4 **Top Production and Decay**

1. Standard Model Top Production
2. Top Quark Decay Phenomenology
3. Dilepton and B-tagging

Lecture # 5 **More About Top**

1. Top Cross Section
2. Top Mass
3. V_{tb}
4. What Comes Next

TRIUMF Summer Institute
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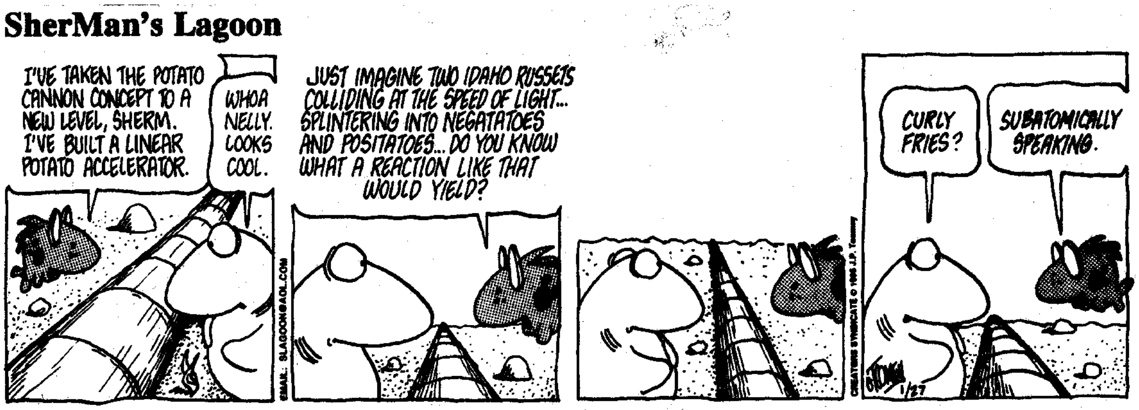
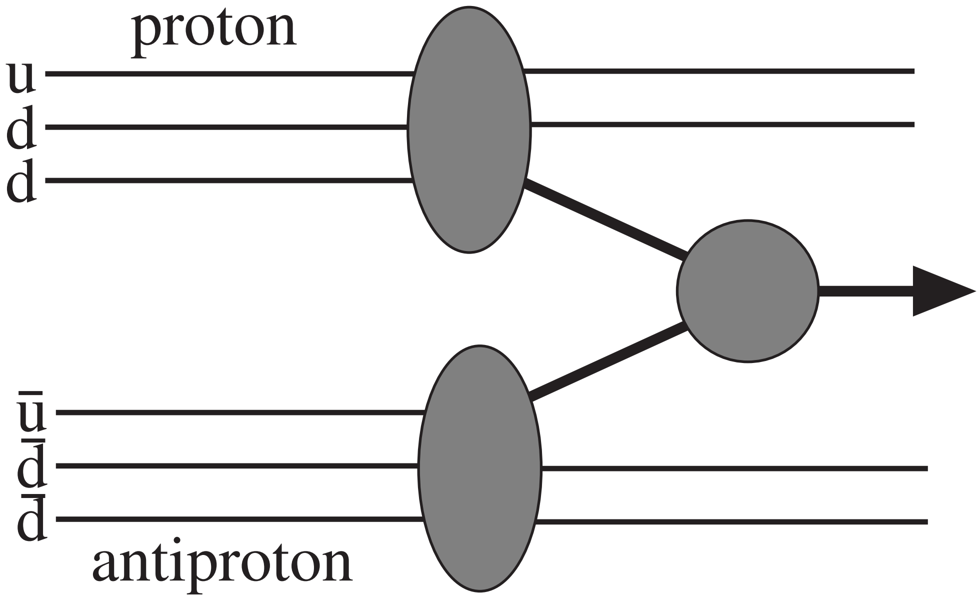


Introduction: Proton-Antiproton Scattering

The proton is a complex object

- Consists of valence quarks (uud), sea quarks and gluons
- each type of parton has momentum distribution function
- p beam is really "broad-band" beam of quarks and gluons
- $\bar{p}$ is primarily beam of anti-quarks and gluons

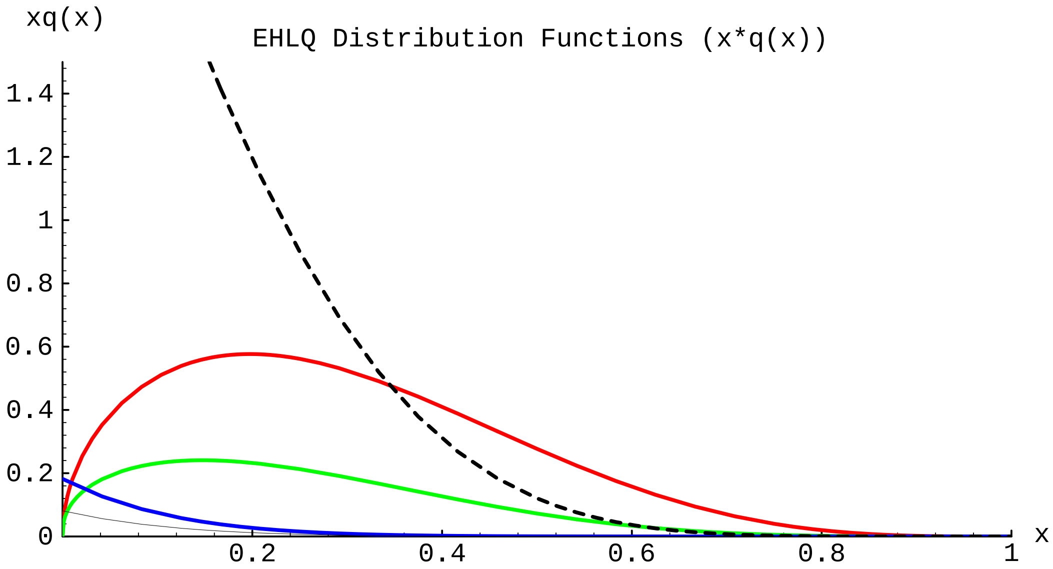


Interested mostly in "hard scattering"

- Characterised by high p_T of interaction

Parton Distribution Functions

Fraction of momentum carried by parton given by pdf's



- Example is EHLQ (Set I) at $Q^2 = 5$ GeV^2
- Derived from deep inelastic scattering
- Note large non-valence quark contribution
  - Largest uncertainty comes from gluon contribution

QCD predicts these PDF's to evolve with Q^2

- Get "softer" as $\hat{s}$ increases
- Best measurements come from neutrino and DIS
- Raison d'etres for several experiments

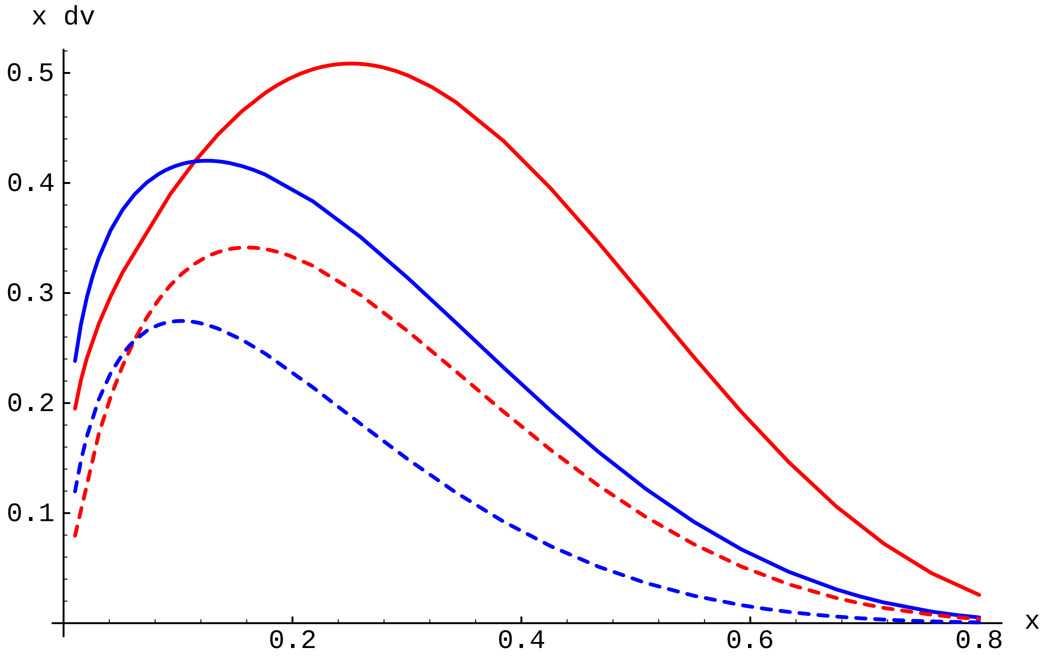
Evolution of PDF's

QCD predicts that $f_q(x, Q^2)$ will evolve as Q^2 increases

- Valence quark distributions become softer
- Sea quark and gluon distributions increase in size
- Evolution predicted by the Altarelli-Parisi equations

As example, Duke-Owens I evolution

- Red is $x\,u(x, Q^2)$ and blue is $x\,d(x, Q^2)$
- Plotted for $Q^2 = 4$ and $Q^2 = 5000$ GeV^2



Physics Processes

Rich physics accessible via $p\bar{p}$ interactions

1. $\log s$ interactions dominate cross section
   - soft non-perturbative hadronic interaction
   - results in large number of low p_T particles
2. jet production next largest cross section
   - dominated by two-jet final states
   - well described by perturbative QCD (α_s^2)
3. "light" heavy quark (c and b) production
   - next to leading order diagrams significant
   - Most copious source of b hadrons
4. Top Quark production
5. Electroweak IVB production
   - Drell-Yan scattering ($q\bar{q}$ annihilation)
   - WW and WZ production
6. Exotic particles
   - Allows one to reach very high centre-of-mass energy
   - Can search for new physics at 100 GeV mass scale
     - Has to couple to initial state though

Production Rates

Process	σ (nb)	Signature
Min-bias	5×10^7	Anything!
Jets ($p_T > 10$ GeV/c)	3×10^4	Jet with $p_T \gtrsim 10$ GeV/c
b ($p_T > 1$ GeV/c)	3×10^4	$b \to l\nu_l X$ or $b \to J/\psi X$
W, Z	18	$W \to l\nu_l$ or $Z \to e^+e^-, \mu^+\mu^-$
$t\bar{t}$	0.008	Lepton with jets or dileptons

Jet production "easy" to pick out

- Require at least one energetic calorimeter cluster
- Dominated by dijet final states

Heavy quark (b and c) production is copious

- Have to fight light quark backgrounds

Electroweak IVB production "harder"

- Easy to observe decay modes with $e^\pm$ or $\mu^\pm$
  - Fully hadronic decays $W, Z \to q\bar{q}'$ overwhelmed by
    * non-perturbative QCD background
    * perturbative QCD jet background

Parton Model Cross Section

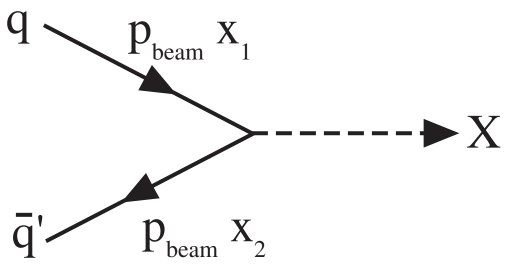
The Parton Model prediction for the cross section for

$$p\bar{p} \to X$$

given by

$$\sum_{q,q'} \int_0^1 dx_1 \int_0^1 dx_2 \; f_1(x_1, Q^2) f_2(x_2, Q^2) \hat{\sigma}(qq' \to X)(\hat{s}),$$

- $\hat{\sigma}(qq' \to X)(\hat{s})$ is parton level cross section
  - Contains all non-trivial physics – can calculate in SM
- Q^2 is 4-momentum of process ($\sim M_X^2$ is typical)
- integration over all values of x_1 and x_2



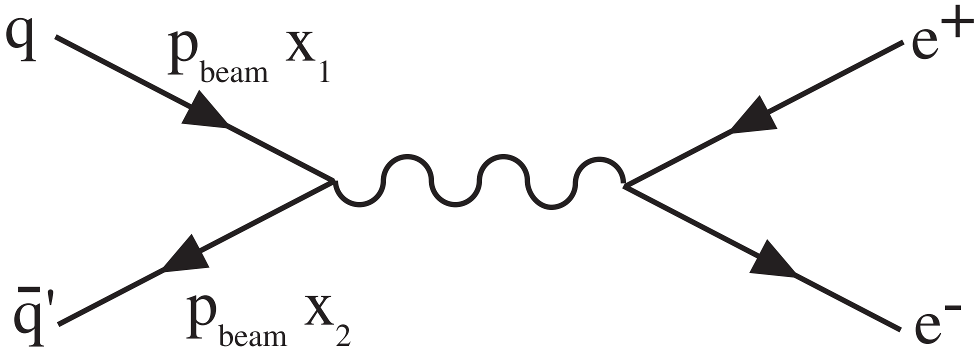
This is not complete story

- doesn't include "shattering" of incoming hadrons
  - generates soft "underlying event" (30-40 particles)
  - similar to non-perturbative log(s) interactions
- No good fundamental theoretical description
- Modelled by parametrisations of data

Parton Level Scattering

Parton level cross section $\hat{\sigma}(qq' \to X)(\hat{s})$ is the physics

- Can use SM to calculate for EWK and perturbative QCD
- Worry about large QCD corrections in initial state



Consider Drell-Yan scattering $p\bar{p} \to e^+e^-$

$$\hat{\sigma}(\hat{s}) = 3e_q^2\left(\frac{4\pi\alpha^2}{3\hat{s}}\right)$$

$$\Rightarrow \sigma_{DY} = \sum_{q,q'}\int_0^1 dx_1 \int_0^1 dx_2\ f_1(x_1,Q^2)f_2(x_2,Q^2)\left[3e_q^2\left(\frac{4\pi\alpha^2}{3x_1x_2s}\right)\right]$$

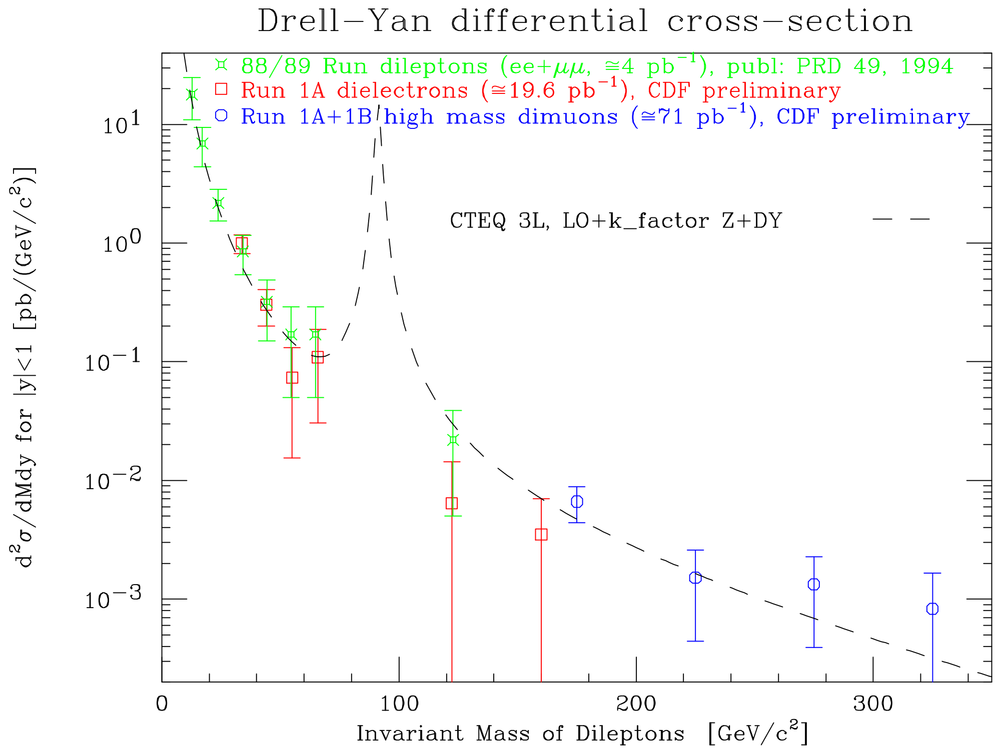
$$= 3\left(\frac{4\pi\alpha^2}{3s}\right)\sum_{q=u,d,s} e_q^2 \int_0^1 dx_1 \int_0^1 dx_2\ \frac{1}{x_1x_2}f_1(x_1)f_2(x_2)$$

- Should scale as $1/s$
- Will fall rapidly with dilepton mass
- Much larger in $p\bar{p}$ than pp

Drell-Yan Cross Section

Observed Drell-Yan mass distribution from CDF

- dominated by γ coupling at low mass
- Shows clear Z^o pole



Demonstrates high mass dominated by physics

- Makes collider good place for new heavy particle searches

Transverse Physics is It

Conventional to describe kinematics using

- $p_T = p \sin\theta$ and $E_T = E \sin\theta$
- pseudorapidity $\eta \equiv -\ln\tan(\theta/2)$

$$\eta \simeq y \equiv \frac{E + p_z}{E - p_z} \text{ when } m \ll E$$

- Low p_T particle production uniform in η

On collision-to-collision basis

- p_z of initial state ($q\bar{q}$, gg, gq, etc.) is $P_{beam}(x_1 - x_2)$
  - Only known statistically
- Final state particles "close" to beam not detectable
  - Detectors instrumented to $\eta \sim \pm 4 \rightarrow \theta \sim 1.7^\circ$
  - Some fraction of "underlying event" escapes detection

Emphasis is on E_T

- Detectors are designed to have uniform response in E_T
- Triggers and data selection based on E_T

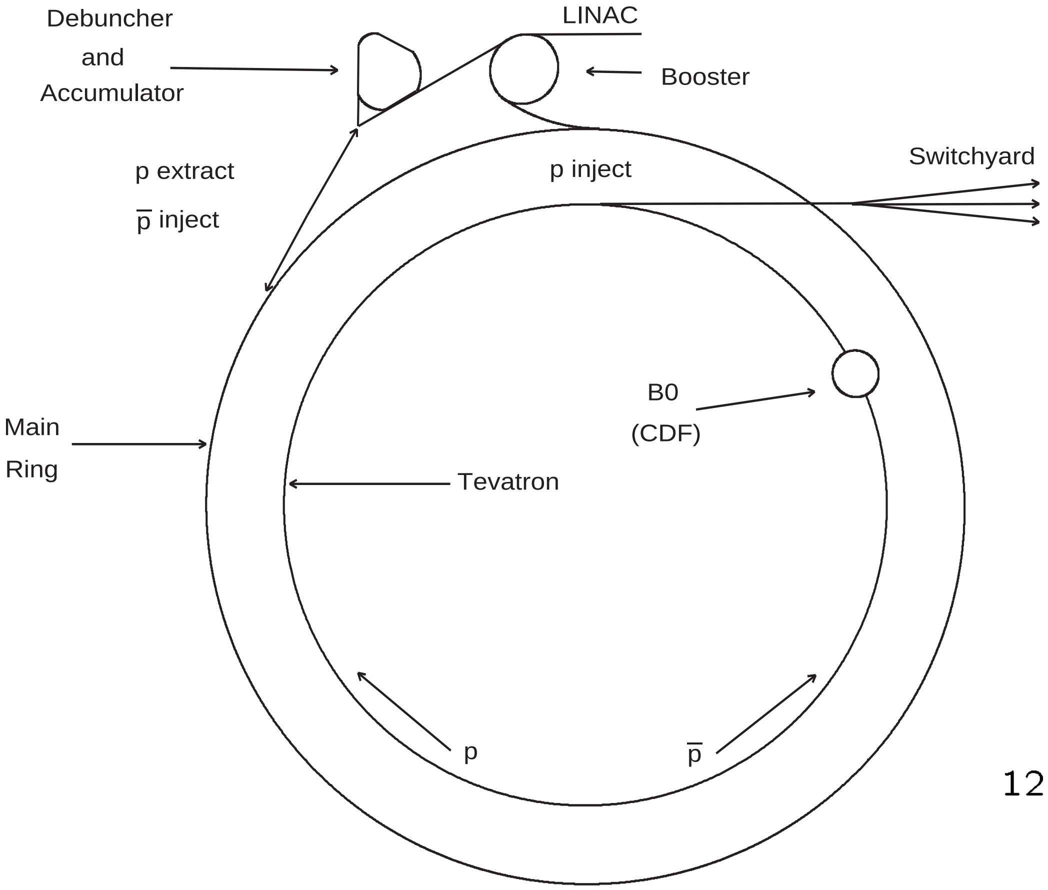
Tevatron Collider

Tevatron collides 6×6 bunchs of p's and $\bar{p}$'s

- Antiprotons stored and cooled in accumulator
- Bunchs injected into Main Ring for boost to 120 GeV
- Injected into Tevatron, ramped to 900 GeV

Luminosity about $2\times$ design

- Routinely $> 2 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Beam lifetime $12 - 15$ hr
- Delivers $3 - 5\ \mathrm{pb}^{-1}$/week



Goals of CDF Experiment

CDF experiment designed to study all high p_T physics

- Use $\overline{p}\,p$ interactions at $\sqrt{s} = 1.8$ TeV
- General purpose 5000 ton detector equipped to
  - Reconstruct charged tracks
  - Reconstruct jets using calorimeter
  - Detect neutrinos using missing transverse energy
  - Identify $e^{\pm}$ and $\mu^{\pm}$ efficiently

Collaboration of $\sim$ 450 Ph.D.'s taken data since 1987

- 30 nb^{-1} in 1987
- 4 pb^{-1} in 1988-89
- 100 pb^{-1} in 1992-95

Interest is to study all the physics of $p\bar{p}$ collisions

- Trigger is primarily on large transverse energy events
- Take advantage of large $\sqrt{s}$ and $\mathcal{L}$
- Evolving to study b and c physics as well

The Fermilab Collider Detectors

Two detectors, CDF and DØ, study Tevatron collisions

- Spectrometer designs are complementary
- Work somewhat in competition

Main detector features:

- Hermetic Calorimetry
  - CDF has traditional Pb and Fe calorimeter
    - Scintillator readout for central region $|\eta| < 1.1$
    - Gas proportional chamber readout for plug/forward
  - Coverage over $|\eta| \lesssim 4.2$
  - Good hermiticity for $\not{E}_T$ measurement
  - Provides electron ID and jet detection

Resolutions	DØ	CDF
EM	$0.15\sqrt{E} \oplus 0.004E$	$0.13\sqrt{E} \oplus 0.02E$
$\pi^{\pm}, K^{\pm}$	$0.50\sqrt{E}$	$0.80\sqrt{E}$
$\not{E}_{T}x,y$	$1.08 + 0.019\sum E_T$	$-0.58 + 0.74\sqrt{\sum E_T}$

Detectors (continued)

- Muon chambers outside calorimeter
  - identify charge tracks that pass through calorimeter
- Central Tracking Systems
  - CDF has three-tiered system in 1.4 T field
    * Central Track Chamber (CTC) for $28 < R < 130$ cm
    * Vertex Chambers (VTX) in $10 < R < 23$ cm
    * Silicon Vertex Detector (SVX) in $3 < R < 12$ cm
    * $\Rightarrow \sigma_p/p \sim 0.001p$ (in GeV/c)

By design, CDF and DØ are complementary detectors

- DØ emphasises calorimetery and muon ID
- CDF emphasises tracking and electron ID
- Reality is that both have strengths and weaknesses
  - CDF Muon system "thin" and fragmented
  - DØ lacks magnetic field – reduces redundancy

$\boxed{\textbf{Triggering Issues}}$

Use multi-level trigger to tag events in real-time

- Interaction rate of

  $$\left(50 \times 10^{-27}\ \text{cm}^2\right) \times \left(1.5 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}\right) = 7.5 \times 10^5\ \text{Hz}$$

  has to be reduced to of order 1-10 Hz

- Most challenging aspect of experiment
  - Depends critically on all subsystems
  - Need efficiency $> 75\%$ to be competitive

Triggering for high p_T physics is relatively easy

- For example, consider triggering for $t\bar{t}$
  - Tag high P_T ($> 15 - 20$ GeV/c) lepton(s)
  - Missing energy requirements ($\not\!\!E_T > 20 - 25$ GeV)
  - Multijet topologies
  - Trigger efficiencies $\geq 90 - 95\%$ in most cases

Bandwith Limitations

Total event rate to tape limited to ~ 5 Hz

- About 1 Mb/s of data
- Limited by offline processing/data handling
- Sets trigger cross section of < 350 nb

Bandwidth reduction achieved by 3-level trigger

1. look at calorimeter E_T and muon stubs
   - $E_T > 5$ GeV gets down to 1-2 kHz (100 μb)
   - Ask for a muon "stub" with $p_T > 2$ GeV/c
2. look at tracks, calorimeter clusters and correlations
   - $e^{\pm}$ candidate is charged track and cal cluster
   - $\mu^{\pm}$ candidate is charged track and μ stub
   - Correlated cuts gets down to 30 kHz (2 μb)
   - Lepton ID gets $S/N \sim 1/10$
3. perform most of full offline reconstruction
   - Identify lepton, jet and neutrino candidates
   - get down to ~ 5 Hz (350 nb)

$\boxed{\text{1992-95 Collider Run}}$

Tevatron Collider has been running since 1992

- Run 1A (1992-93) provided ~ 20 pb^{-1}
  - CDF scanned $\sim 1 \times 10^{12}$ collisions in 19.3 pb^{-1}
    * Collected 16×10^{6} events on tape
- Run 1B (1994-95) has produced another ~ 85 pb^{-1}
  - Run expected to continue till end of 1995

By far the largest and most sensitive dataset

- For example, a top quark with a mass of 160 GeV/c^2
  - $\sigma_{t\bar{t}} = 8.2$ pb $\Rightarrow$ 400 produced $t\bar{t}$ events
  - DØ and CDF would each expect to detect
    * ~ 6 dilepton events
    * ~ 20 lepton $+$ jet events

$\boxed{\text{CDF Physics Suite}}$

Have studied an enormous wealth of physics

1. QCD tests ($gg \to gg$ and $q\bar{q} \to X$)
   - inclusive jet production and multijet production
   - differential cross section measurements
2. EWK processes
   - Drell-Yan (γ, W, Z) production and decay
   - Divector Boson production
3. Heavy Quark production
   - Have produced 3×10^9 bottom quarks already
   - World's largest sample of $b \to J/\psi X$
   - Only place to study top
4. Exotic searches
   - Most sensitive SUSY searches
   - Frontier of large $\sqrt{s}$ physics
   - Pushing mass limits of new physics

Will focus on just a few studies

- Chosen for recent interest
- Illustrates techniques well