Physics at the Fermilab Tevatron Collider

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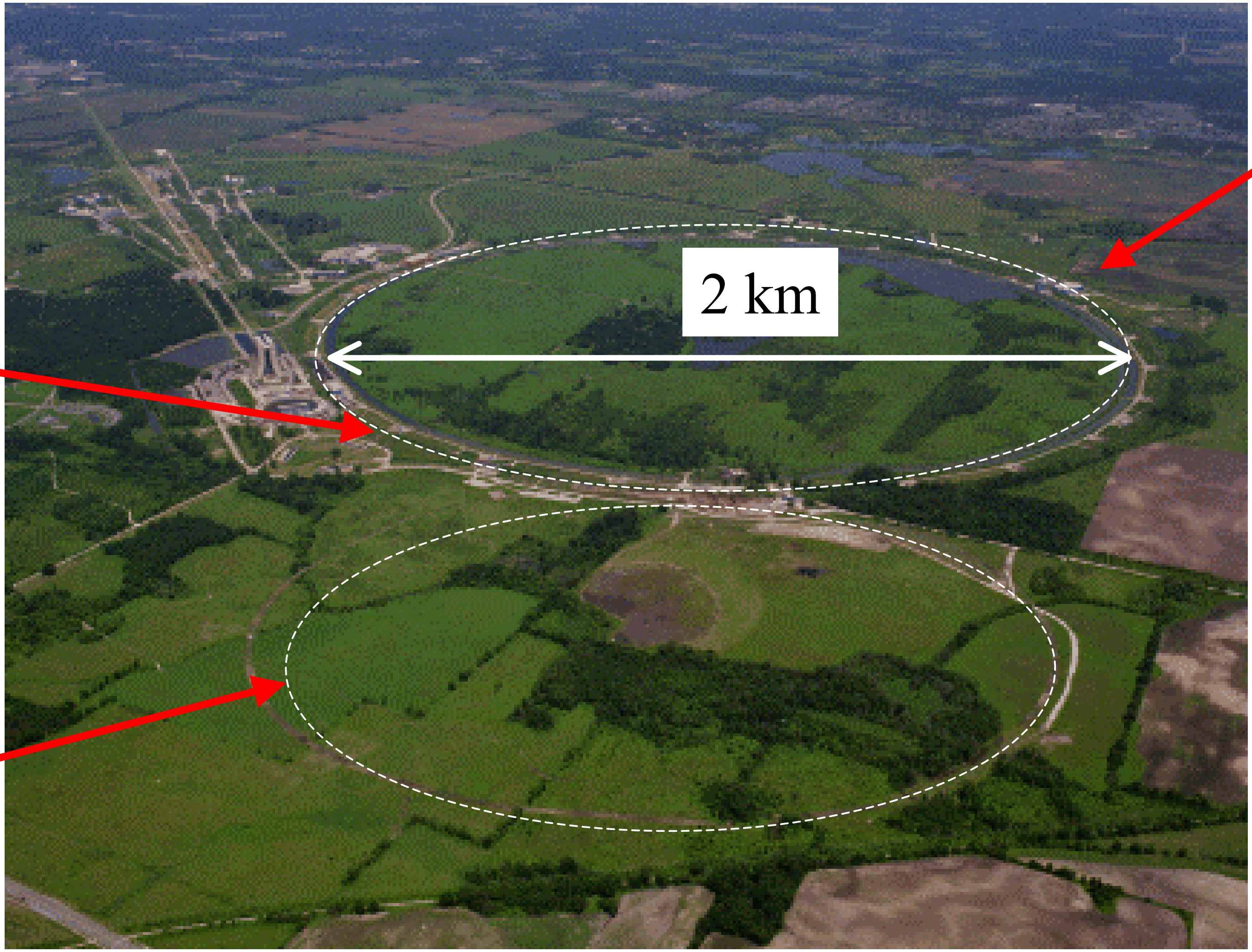
Outline

- Introduction: collider experiments
- The Tevatron complex (review)
- Examples of physics studies at the Tevatron
  - jet production – testing substructure
  - Search for extra space-time dimensions
  - Direct search for the Higgs boson
  - Precision measurements: W mass & top mass
  - Sleuth – is there anything new?
- What's next

Motivating Questions

- Do the laws of physics that we understand continue to work at the smallest scales that we can probe?
- Are the known "fundamental particles" (quarks, leptons, vector bosons)" truly fundamental, or are they made of something else?
- Is there a higher mass or energy scale at which new types of particles or interactions can be seen?

Today's highest energy beams: Fermilab

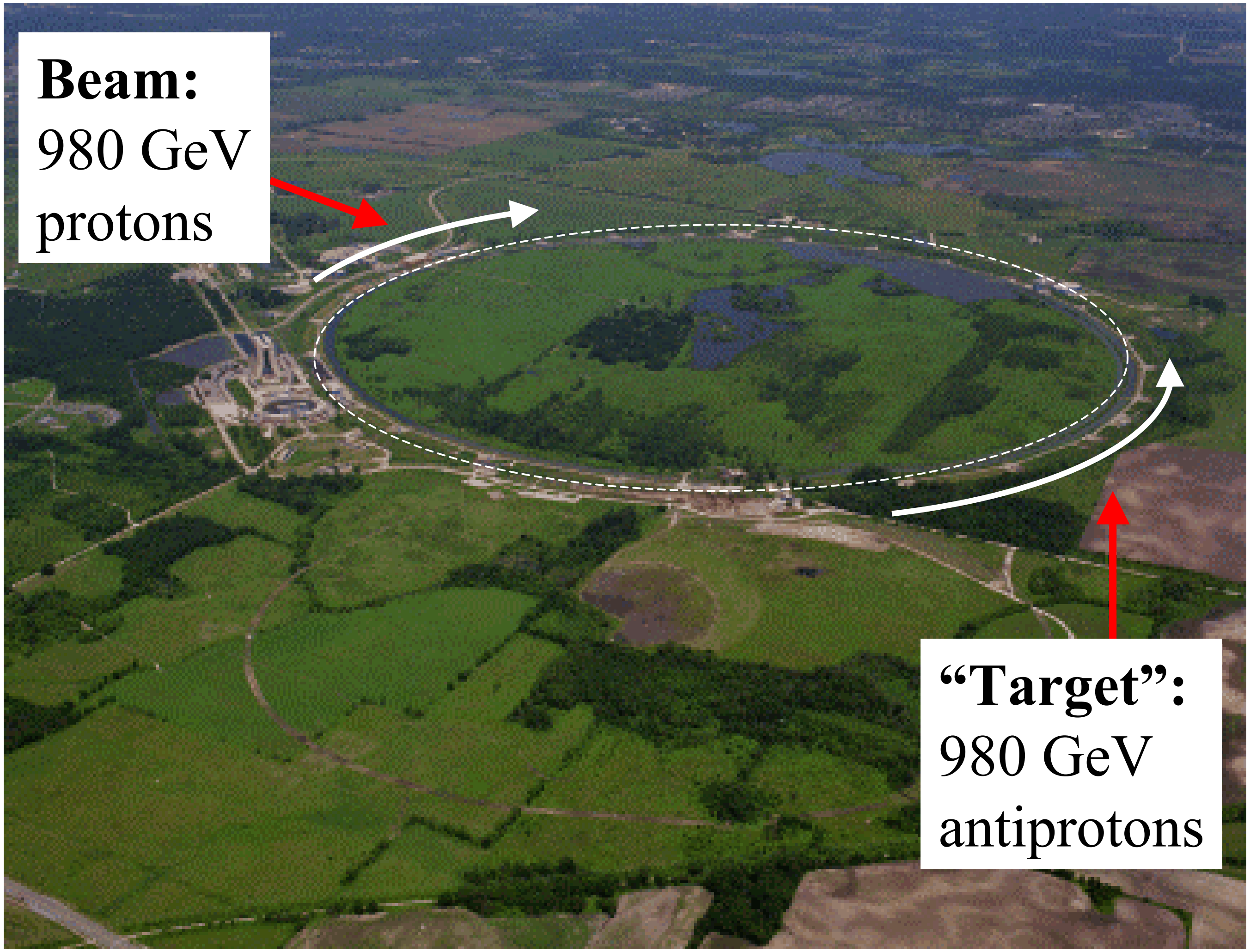


DØ

TeVatron

Main
Injector

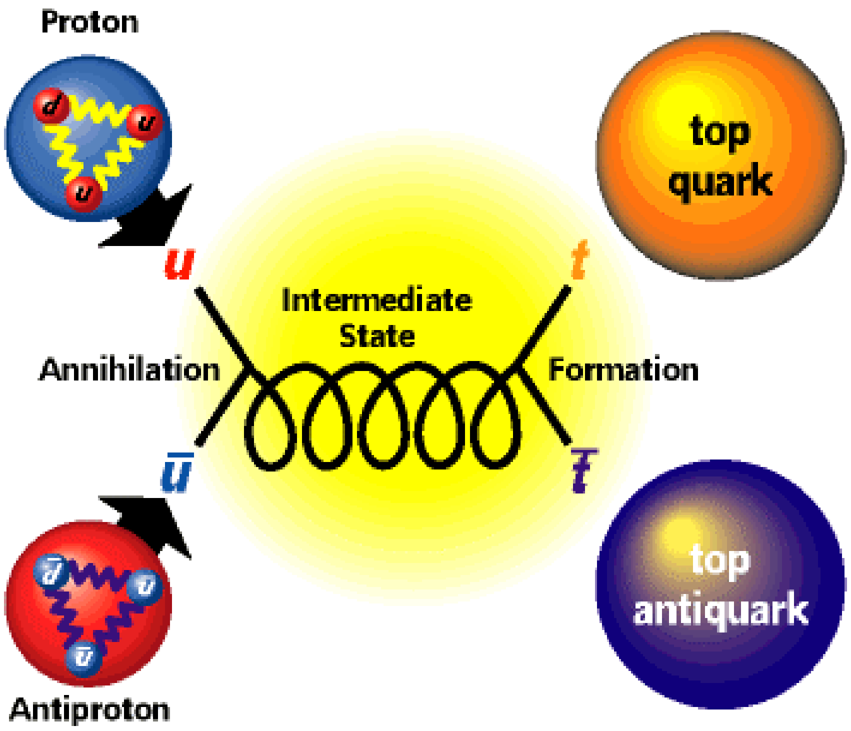
Tevatron Collider



Collision energy = 1.96 TeV

Why use antiprotons?

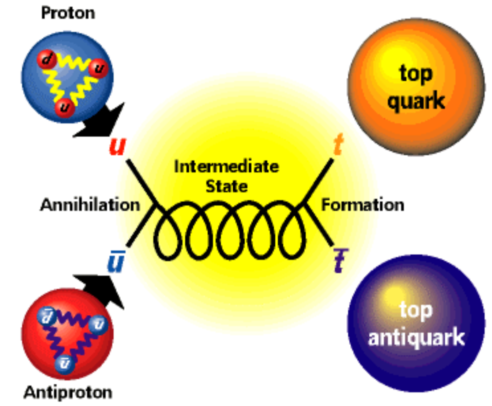
Efficient annihilation of particle and antiparticle



Also, protons & antiprotons automatically travel in opposite orbits in the accelerator

Collision statistics

- Each collision is a random event; many different kinds of new particles could be produced
- Theory does not predict what will happen on a given event, but it does predict the probability for certain things happening (like top quark production).
- Probability of producing a top and and anti-top is around 1 event in 10^{10}
- Some other processes are even more rar



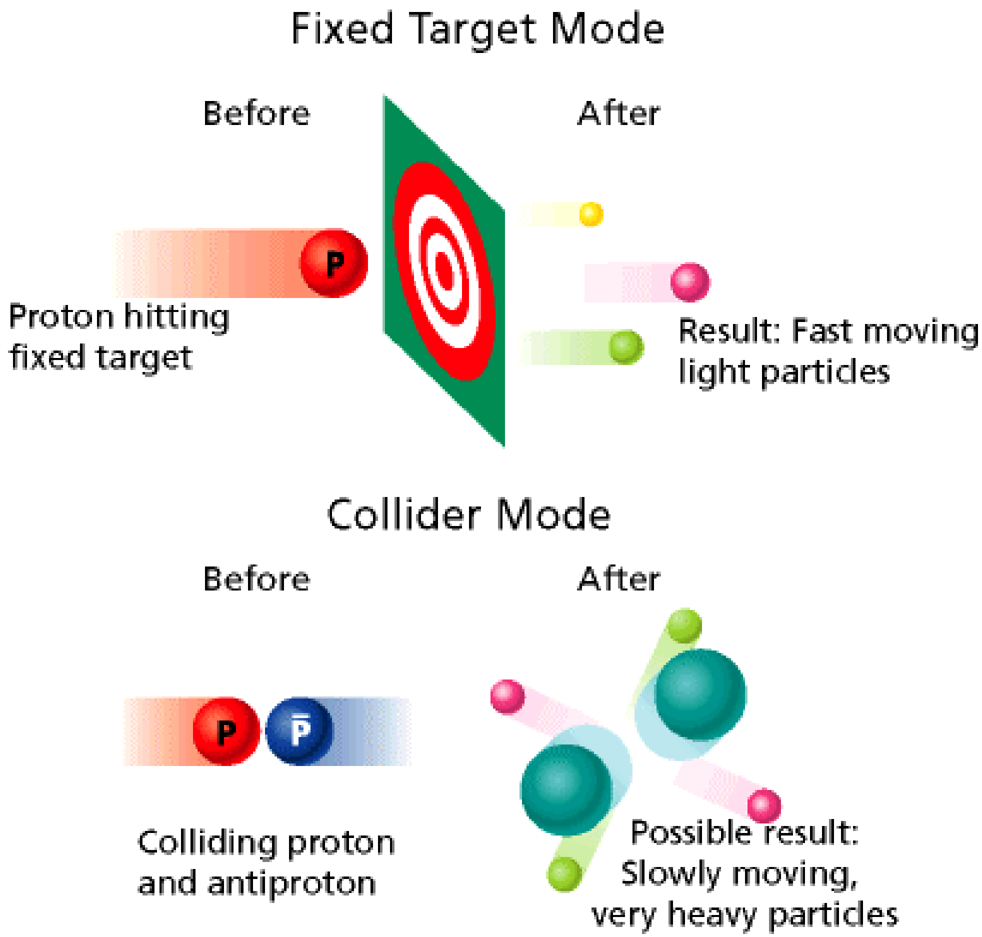
Why Colliding Beams?

980 GeV proton
Hits proton at rest:

$$\sqrt{s} \approx 30 GeV$$

980 GeV proton
Hits 980 GeV
antiproton:

$$\sqrt{s} \approx 1960 GeV$$



(see http://www-ed.fnal.gov/projects/exhibits/searching/)

Major particle colliders (past, present & future)

Lepton Colliders

- ~1974-1985, SPEAR
  - SLAC (Stanford, CA)
  - e+e-, ~3 GeV
- 1979-present, CESR
  - Cornell (Ithaca, NY)
  - e+e-, ~10 GeV
- ~1980-1990 PETRA,
  - DESY (Hamburg)
  - e+e-, ~35 GeV
- 1989-1998, SLC
  - SLAC (Stanford, CA)
  - e+e-, ~90 GeV
- 1989-2000, LEP
  - CERN (Geneva)
  - e+e-, ~200 GeV
- ~2020, NLC/TESLA
  - (CA, IL, Hamburg?)
  - e+e+, 500 GeV

Hadron Colliders

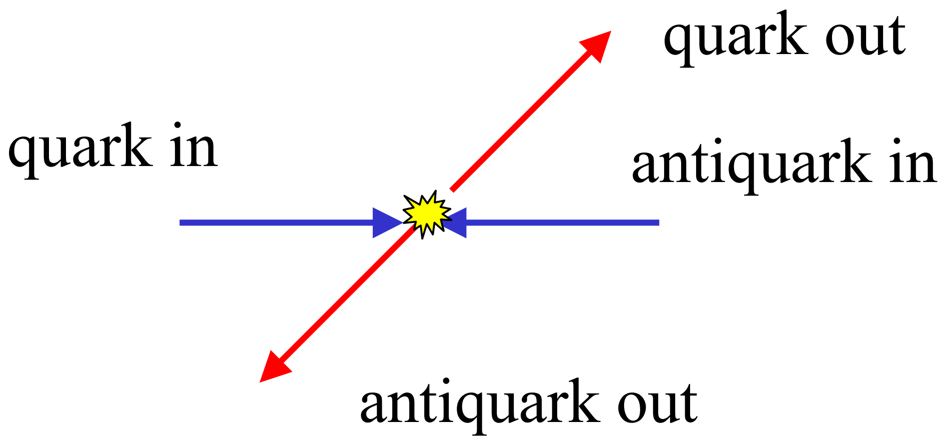
- 1981-1990, SppbarS,
  - CERN (Geneva)
  - p-pbar, ~630 GeV
- 1987-present, Tevatron
  - Fermilab (Batavia, IL)
  - p-pbar, ~2 TeV
- 2006?, LHC
  - CERN (Geneva)
  - 14 TeV pp

Mixed Colliders

- 1992-present, HERA
  - DESY (Hamburg)
  - ep, 30+280 GeV

Experiment example #1: quark scattering

- Repeating Rutherfoord's experiment, essentially



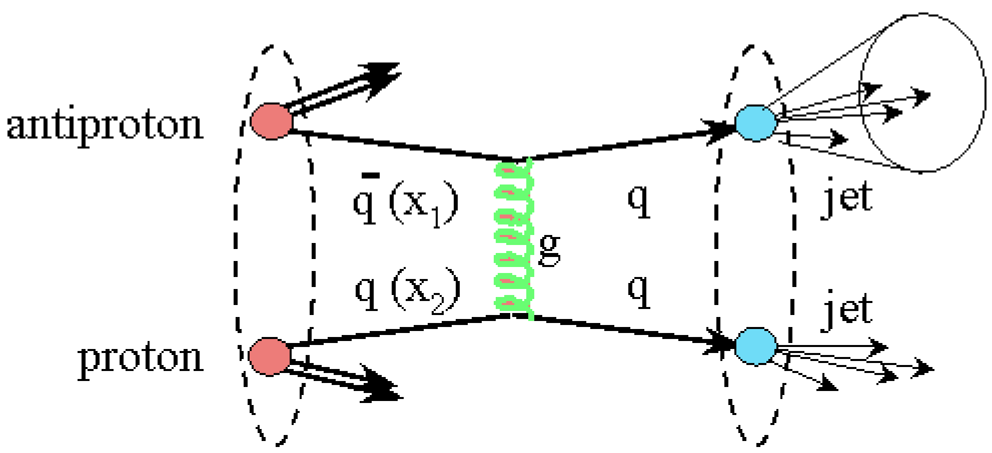
- Detect energy & angle of outgoing quarks
- Note: quarks could be replaced with gluons – very hard to distinguish
- At what distance scale is physics tested?

A closer look

(Too) simple minded calculation:

$$\lambda = \frac{hc}{pc} = \frac{1.2\text{GeV}\cdot\text{fm}}{900\text{GeV}} \approx 10^{-18}\text{m}$$

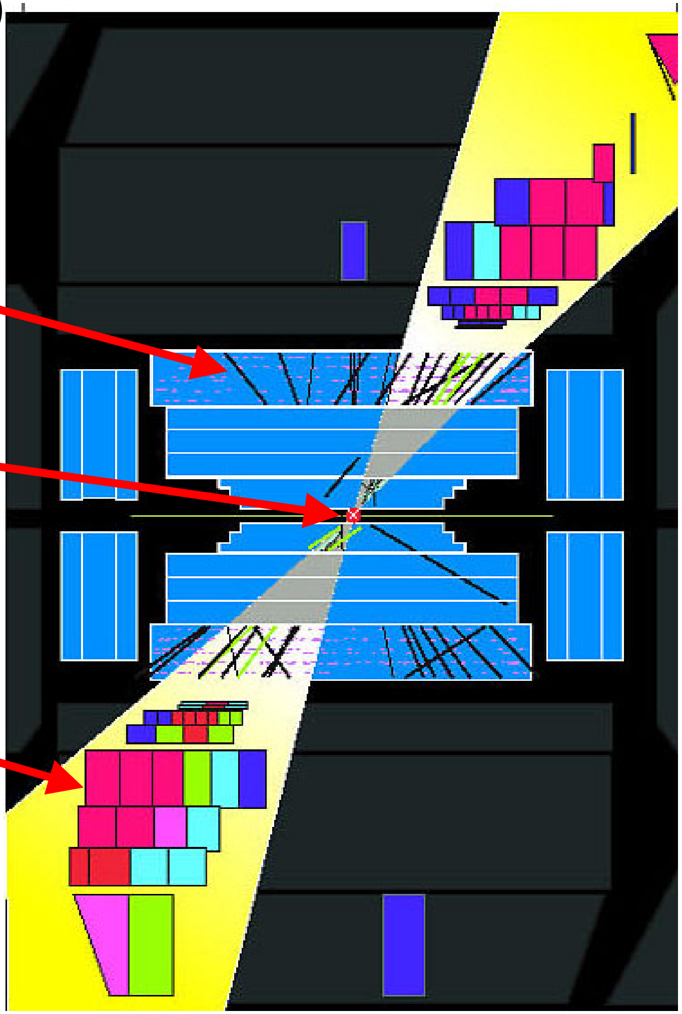
But this is a swindle, because typically, only a small fraction of the proton energy goes into the hard collision:



Quarks are not free, so what emerges is a collimated jet of hadrons along the original quark direction

An event observed in the detector:

(2-dimensional slice)



Charged tracks

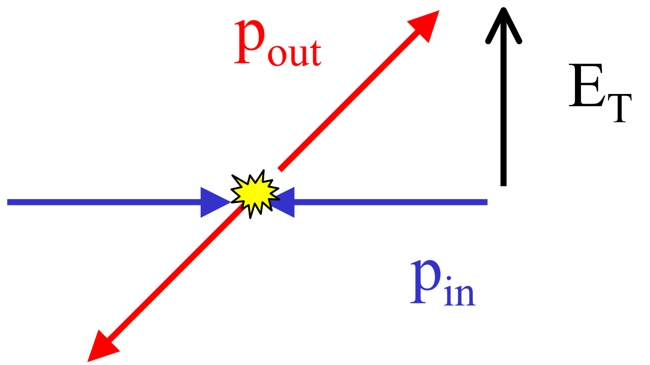
Point of collision

Colors correspond to energy deposited in a "cell" of the calorimeter

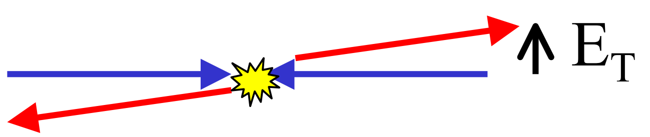
Note that energy is concentrated in two narrow cones, or jets.
Two-jet production is the most common hard scatter process

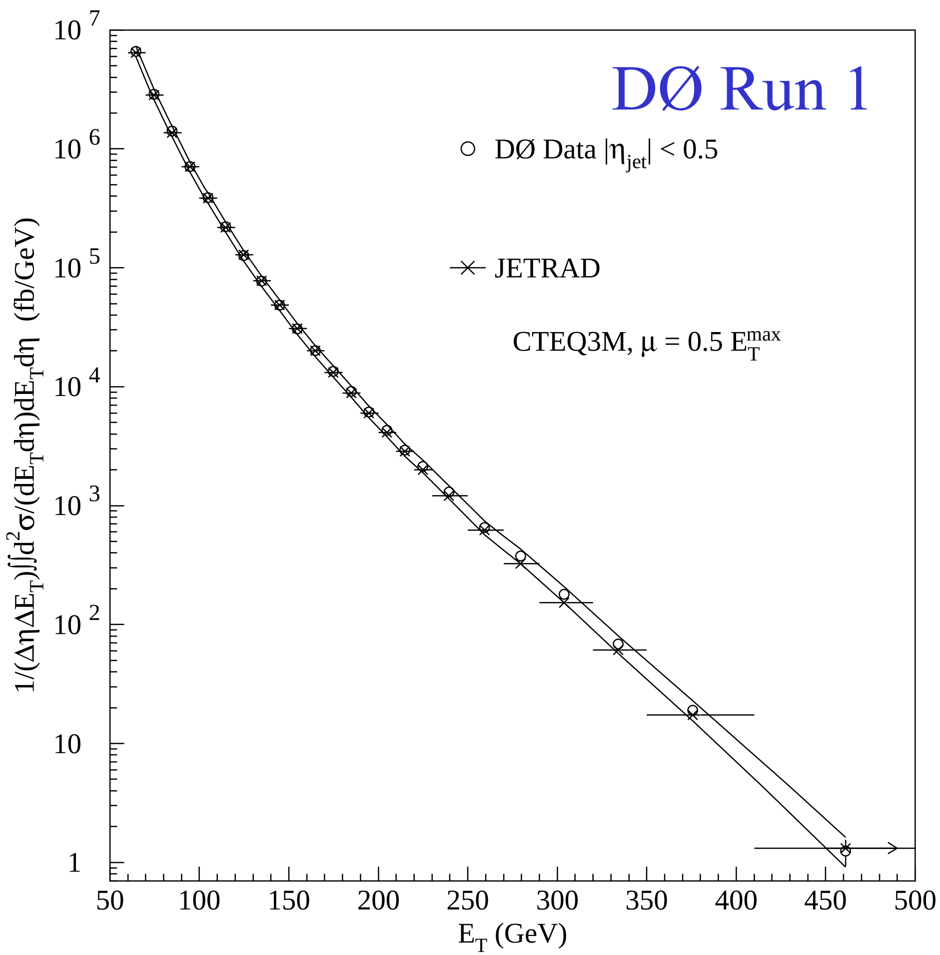
Spectrum of jet transverse energy

Hard collision:



soft collision:

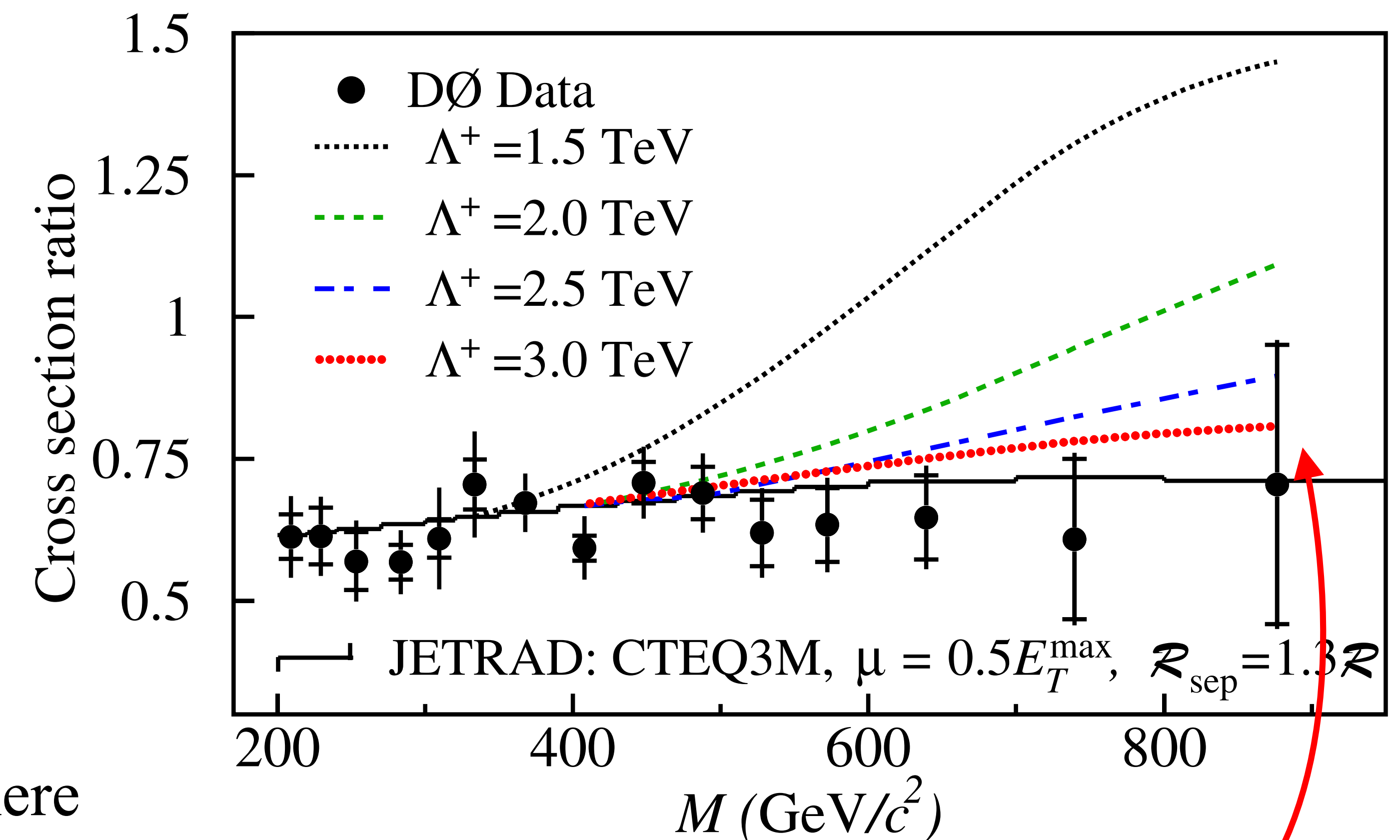




Angular distribution of two jet events

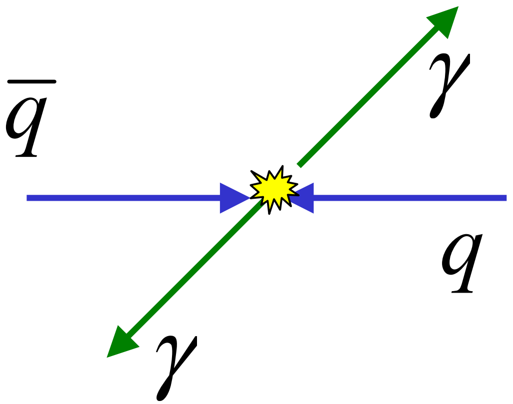
The ratio of (forward+backward)/(central) is plotted

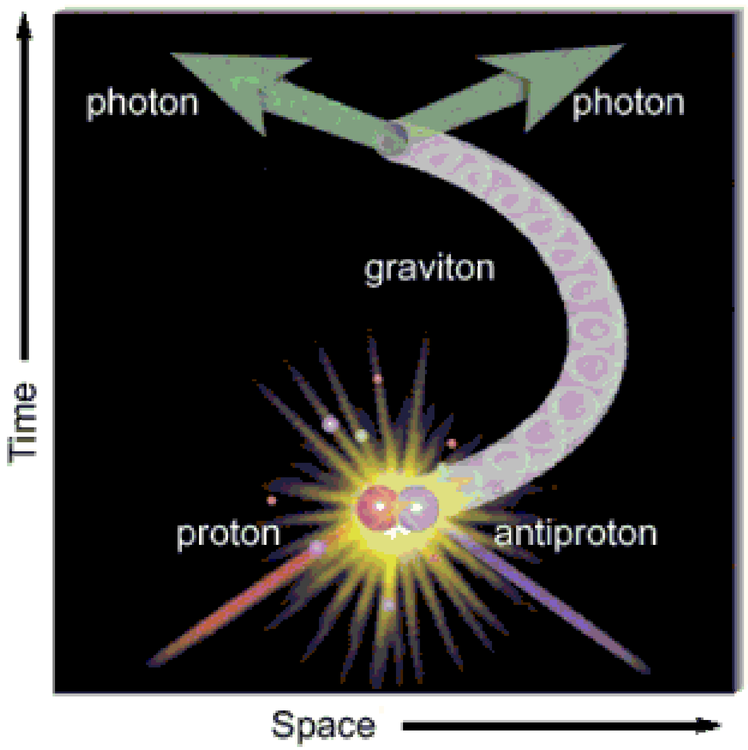
Λ is the compositeness mass scale

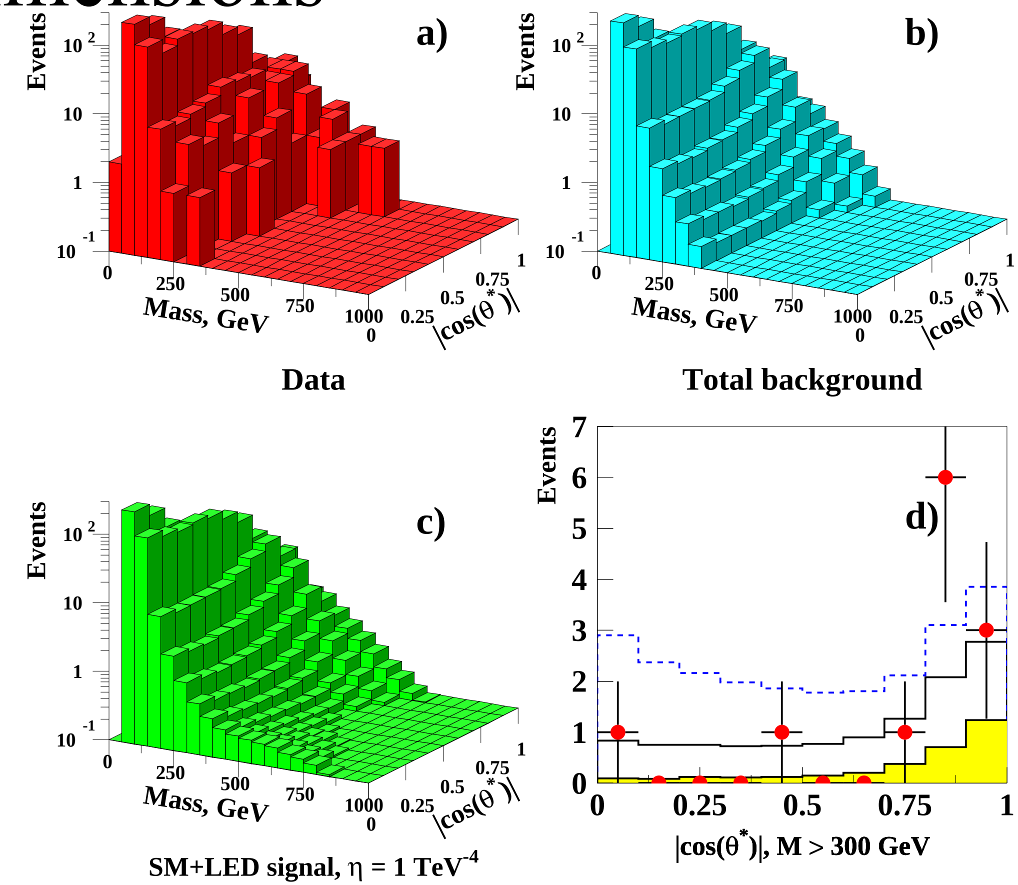


This is where you would expect to see evidence of quark substrucure

Example 2: Looking for Extra Space-time Dimensions





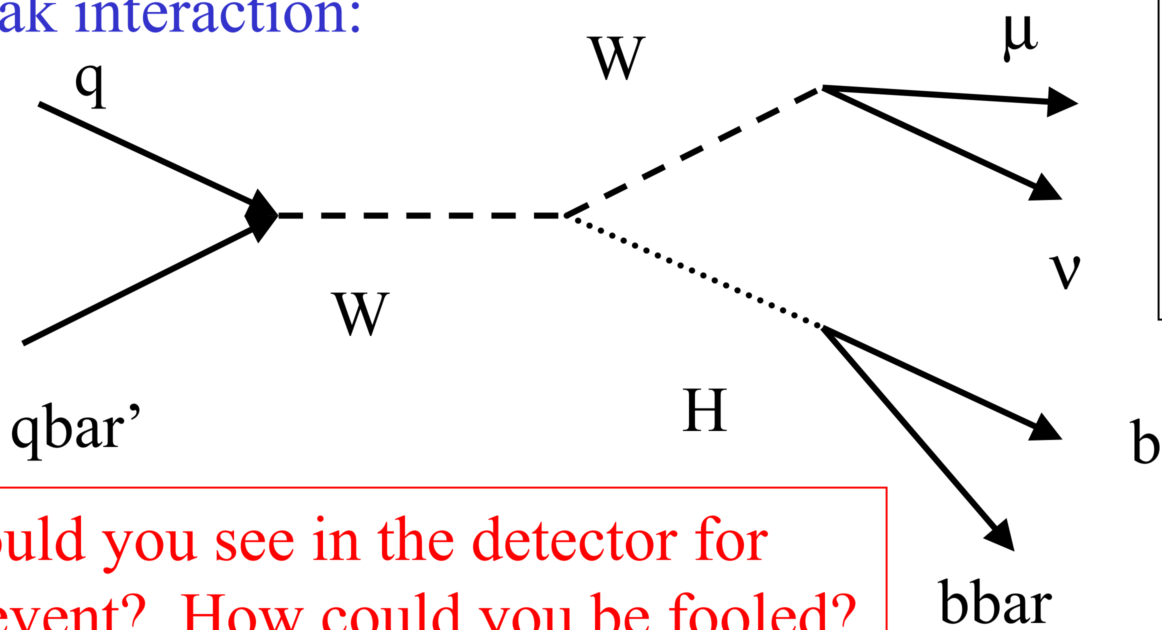


R<3x10^{-4}m (n=2)

R<2x10^{-15}m (n=7)

Example 3: Direct Search for Higgs Boson

- The most important missing piece of the "Standard Model"
- Responsible for giving mass to all particles with mass
- Mass of Higgs itself is unknown, >115 GeV
- Likes to be produced with W's and Z's, the carriers of the weak interaction:

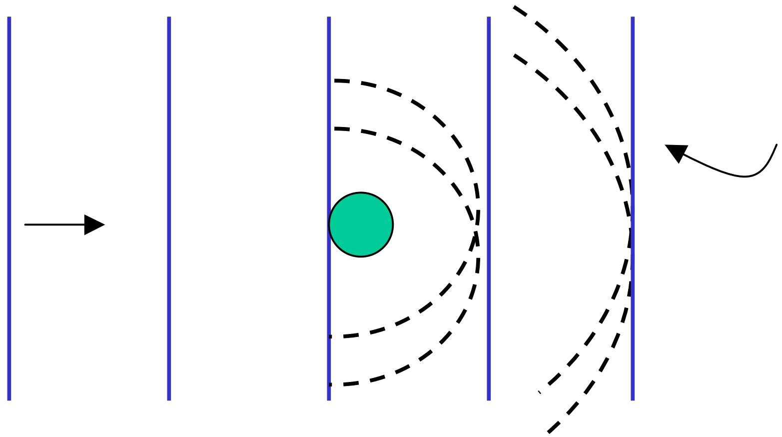


Predicted frequency: ~1 in 2×10^{12} collisions

What would you see in the detector for such an event? How could you be fooled?

Example 4: precision measurements

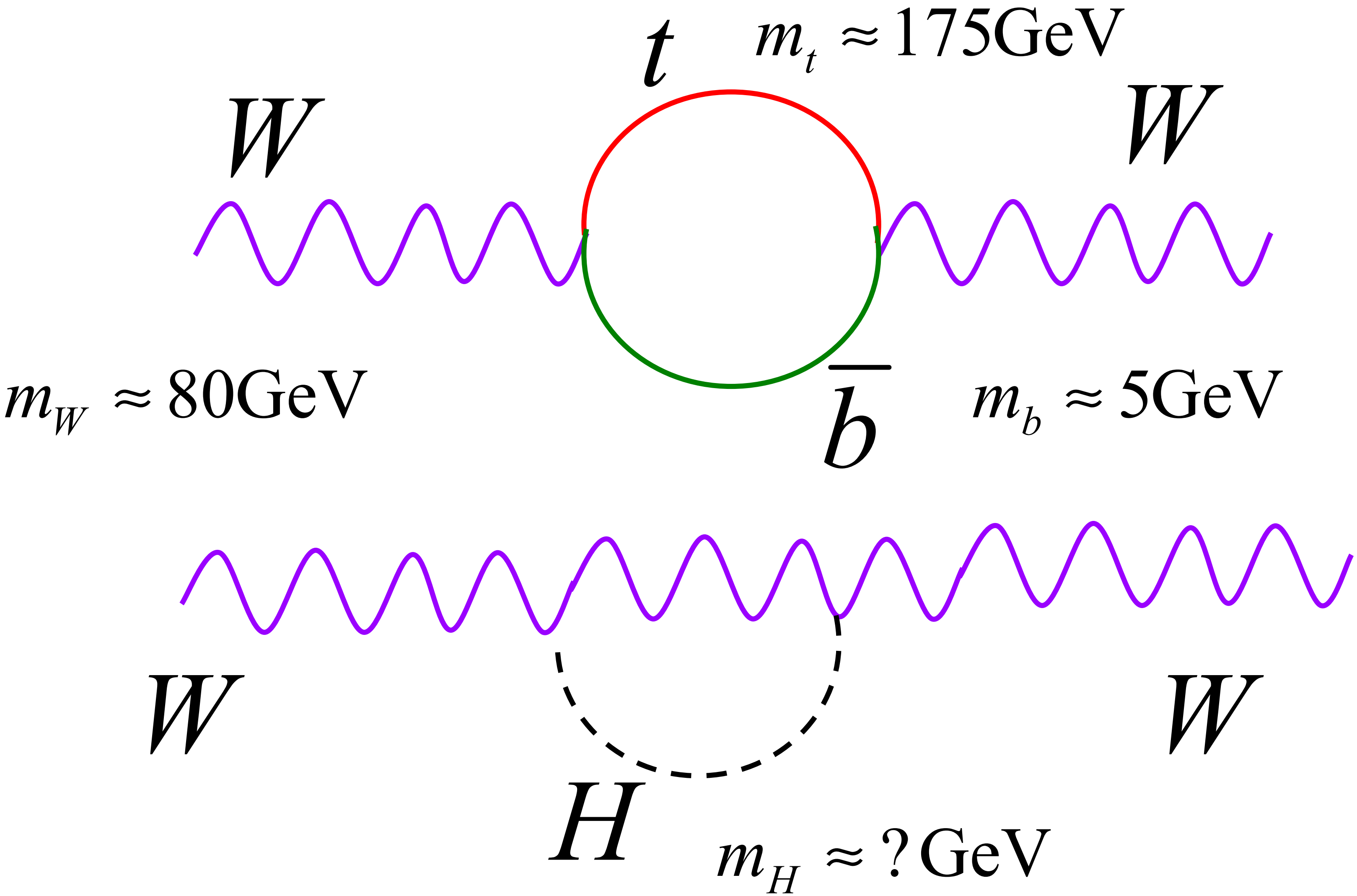
- With enough measurement precision and statistics, it is possible to “see” objects smaller than the wavelength:



Wavefront distorted by interference effects

- Similarly, the properties of lower mass particles can be distorted by the effects of “virtual” higher mass particles

“Self-interference” of W boson

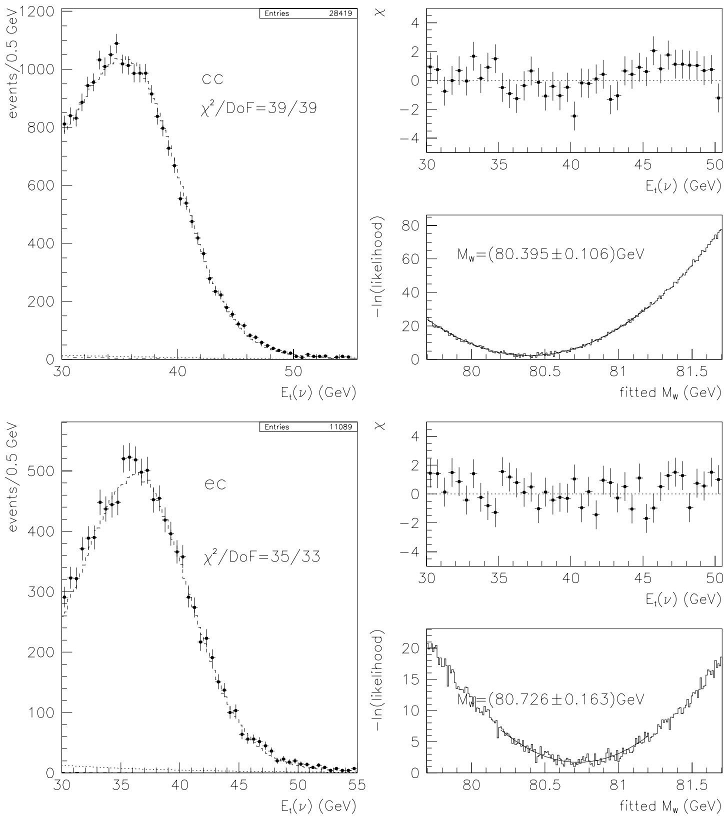


W Boson

- Discovered at CERN in 1982
- Now produced at both the Tevatron and LEP
- At DØ, its mass is measured precisely using the decay mode

$$W \rightarrow e\nu$$

- Approximately 60,000 W events used in the mass measurement.
- Fit transverse mass (formed using quantities perpendicular to the beam direction)
- mass measured to less that 100 MeV (about 0.1%)

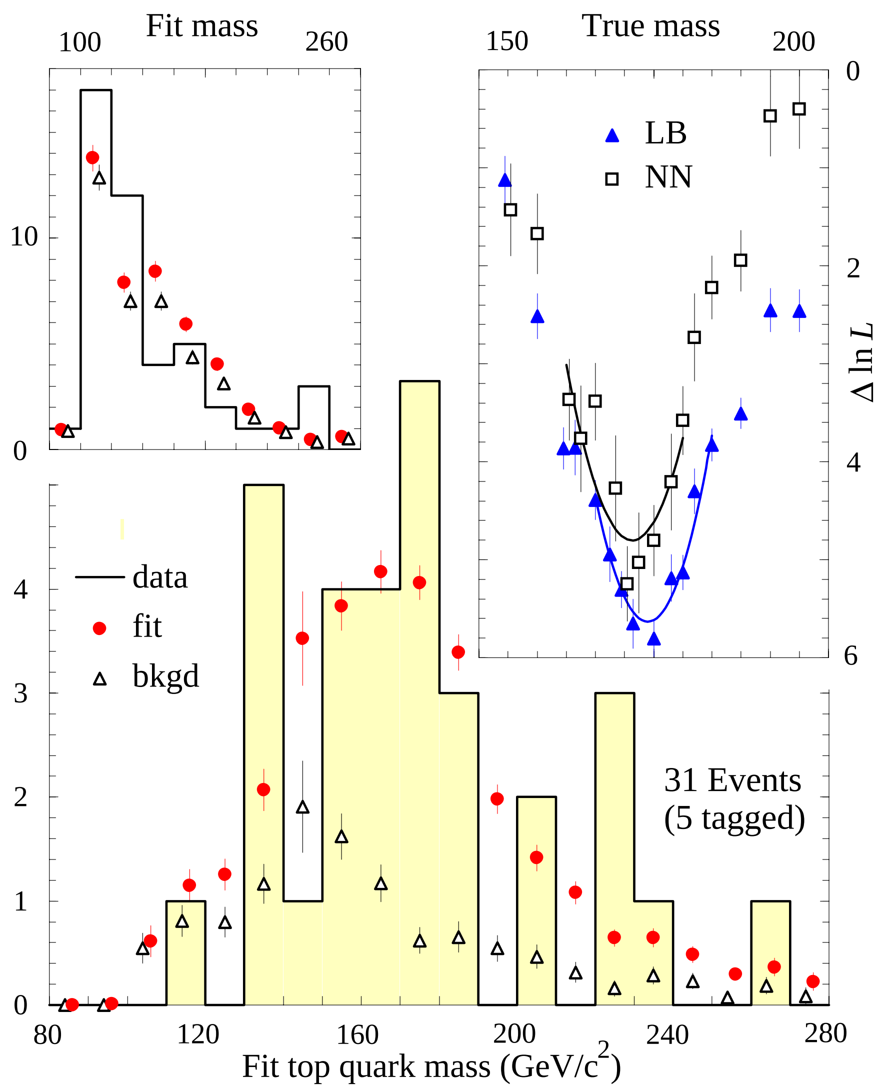


The top quark

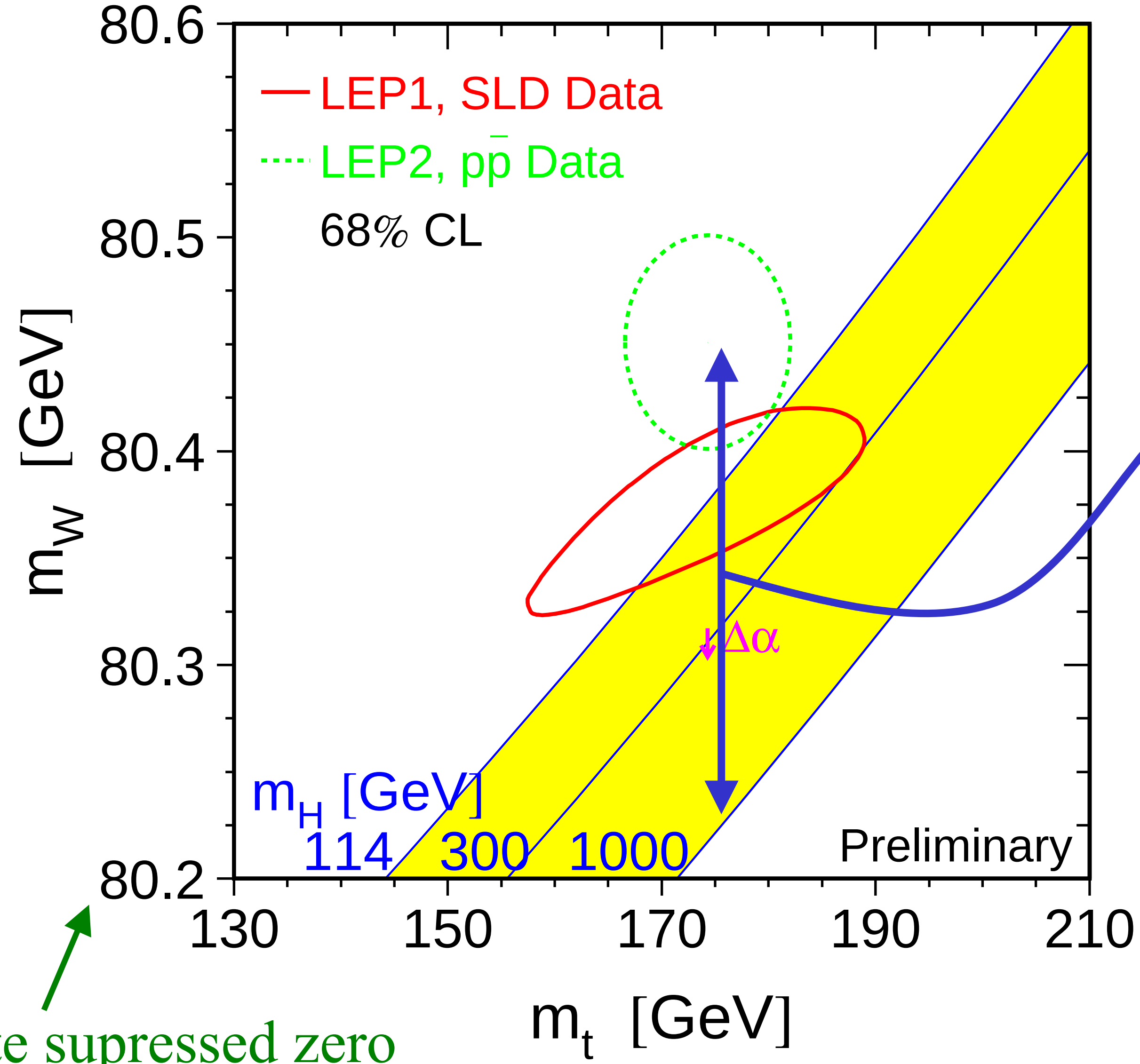
- Discovered at the Tevatron in 1995
- Produced mostly in pairs

$$p\bar{p} \rightarrow t\bar{t} + X$$

- almost every possible decay mode is used in its discovery and mass measurement
- about 90 events used in mass measurement.
- Mass measured to better than 5% by DØ



W mass precision



Mass shift from virtual Higgs effects (?)

Note supressed zero

Question: Is it possible to perform a *data*-driven search for new phenomena?

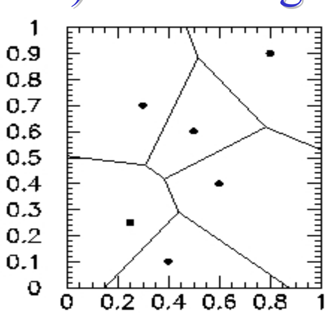
1) Define final states

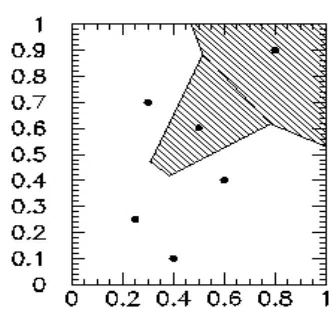
2) Define variables

$\sum p_T^{\gamma WZ}$ $\sum p_T^{j}$

$\sum p_T^{\ell}$ $\not{p}_T$

3) Define regions



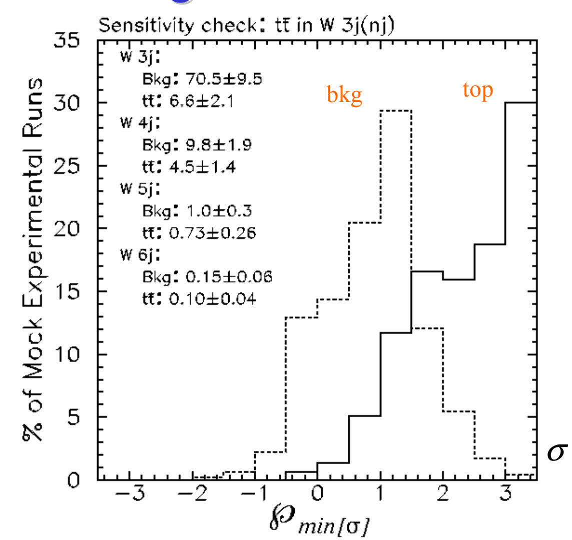


4) Define "interestingness"

$$\sum_{i=0}^{N} \frac{e^{-b} b^i}{i!}$$

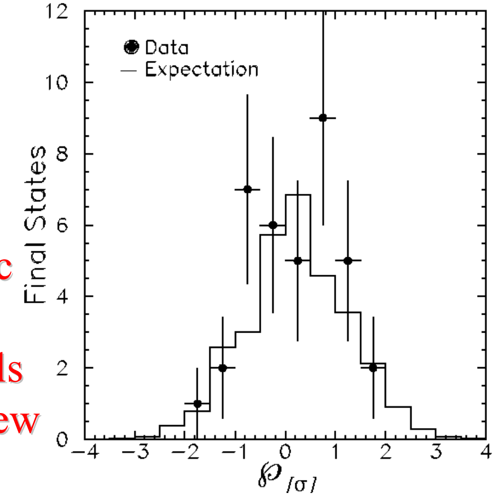
5) Run *hypothetical similar experiments*

6) Can Sleuth find something interesting? (yes!)



7) Does Sleuth find anything interesting in Run I data?

No. A systematic search of many final states reveals no evidence of new high p_T physics.



8) Apply to Run II

Sleuth

A quasi-model-independent new physics search strategy

Main points

- Creating collisions with lots of kinetic energy (in the center of mass system) makes it possible to create many different new particles
- Creation of massive particles requires more energy
- The average result of collisions can be predicted by theory (if the theory is correct) but each individual collision has a random outcome, so
  - Many different processes can be studied with the same experiment (with different analysis procedures)
  - Detecting rare processes requires the accumulation and examinatio of trillions of collisions.