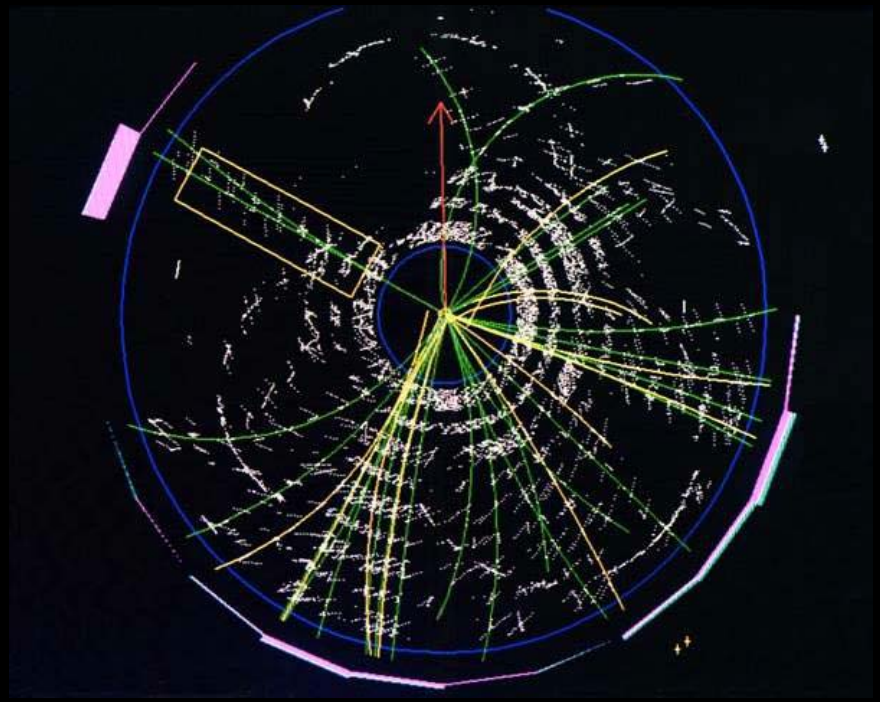
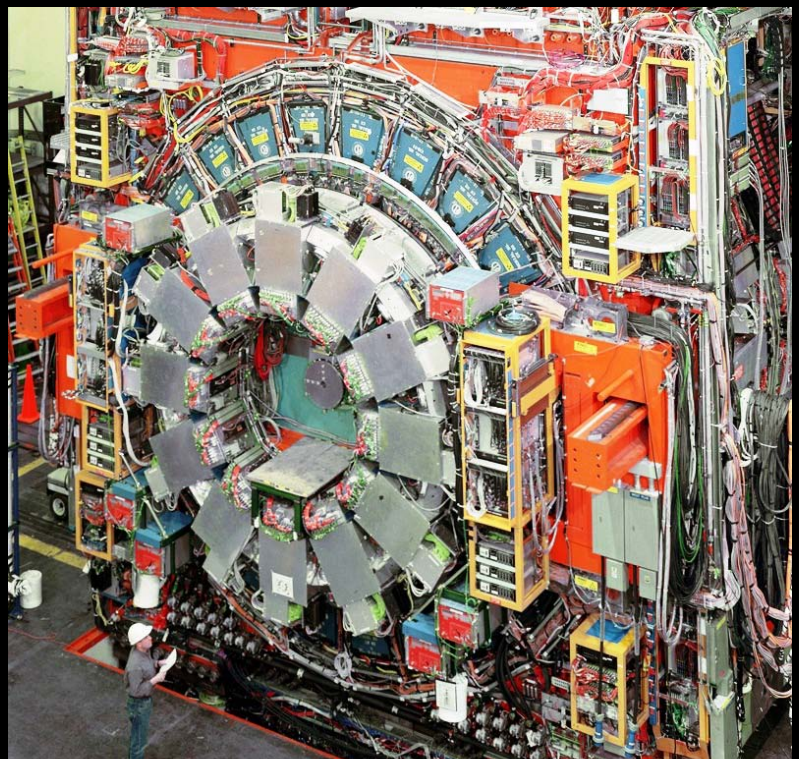
Life After the Top Quark

Dr. Robert Roser
Fermi National Accelerator Laboratory





Why Does One Do High Energy Physics?

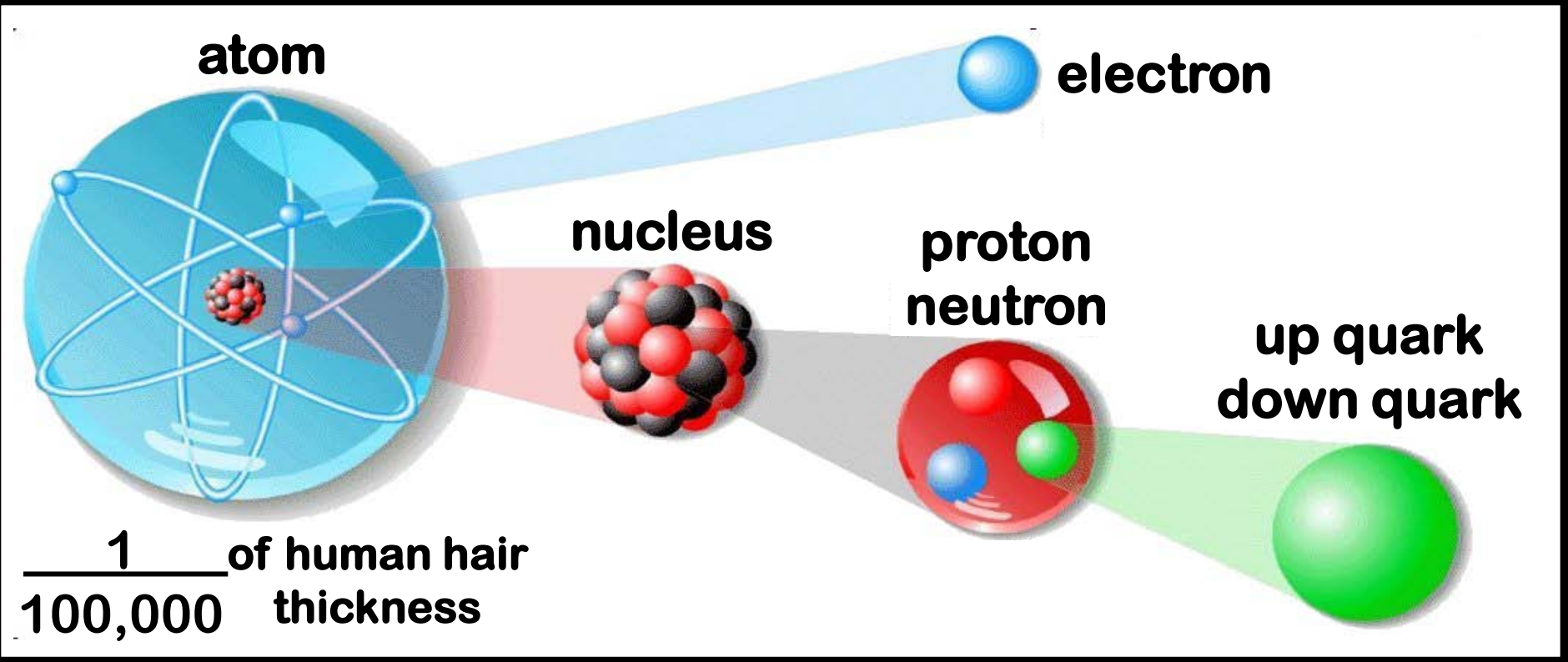
- The Experiments are large -- many operating experiments EACH have ~700 physicists. The LHC experiments will have many more (>2000/each)
- Author list might take more pages in a journal than the actual article
- Physicists have to travel great distances to get to their experiments
- Startup times for experiments are large; already working on experiments and accelerators that won't run till 2018 or beyond
- The apparatus is far from being table top in size
- A single experimenter does not have total control over his or her environment

One Person's Answer – My Answer

- We want to understand some of the most fundamental questions in nature
- We want to understand how the universe was created and the laws that govern it
- We, as physicists have an insatiable curiosity for the world we live in and how it works
- We enjoy working with a large group of smart people toward a common goal
- The variety of physics topics that these new experiments can address means life is never boring
- BECAUSE ITS FUN

The Past Century…

~90 years ago ~60 years ago ~40 years ago Present



$\frac{1}{10,000}$ $\frac{1}{10}$ $\frac{1}{100,000}$

An Introduction to Particle Physics

- The Standard Model of Particle Physics states:
  The world is comprised of Quarks and Leptons that interact by exchanging Bosons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Leptons

- There are three differet types of leptons
- Mass $Me < M\mu < M\tau$ $M\nu \cong 0$
- Each particle has an antiparticle
  (electrons $\rightarrow$ positrons)

The Standard Model: Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

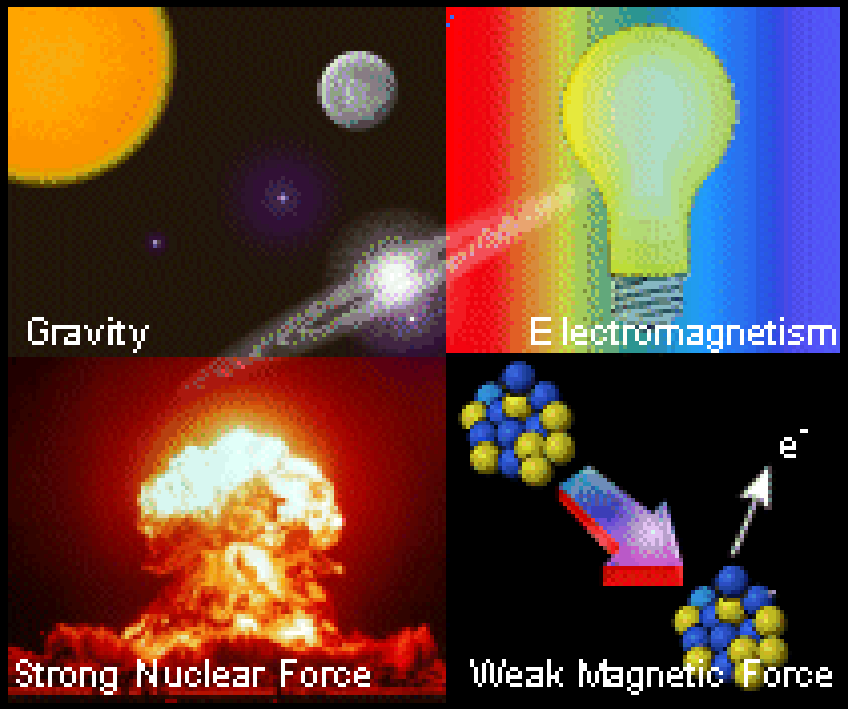
Quarks

- Quarks (u, d, s) were postulated by Gell Mann in 1964
- Quarks are unusual in that they have fractional charge
- Each Quark has its own antiparticle
- Mass Mu ~ Md < Ms < Mc < Mb << Mt
- The Charm Quark was discovered in 1974 at BNL & SLAC
- The Bottom and Top Quarks was discovered at Fermilab in 1977 and 1994 respectively

Four Fundamental Forces that tie it all together

graviton

gluon



Gamma ray,
Photon γ

W, Z

"Mediated" by particles called bosons!

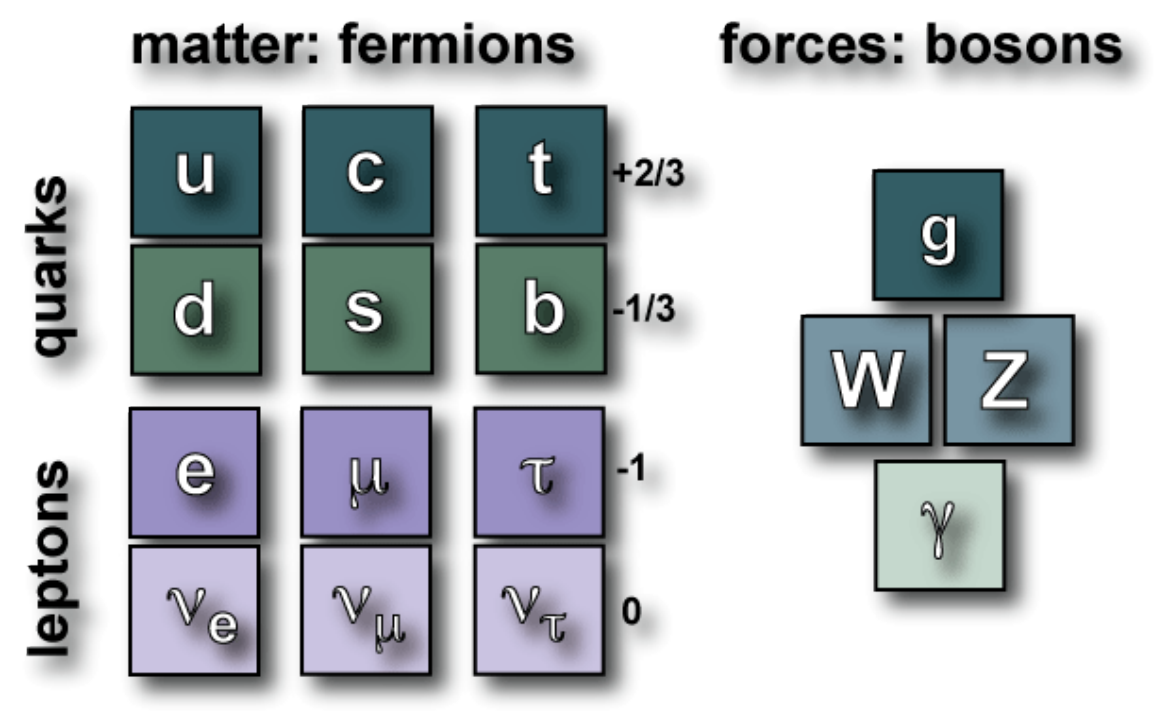
* *Graviton not discovered yet.*

Finally – the big picture!

The Standard Model of Particle Physics

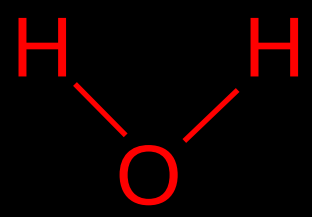
- Good description of particles and their interactions
- Extensively tested
- But… need explanation of masses
- This can't be the entire story…

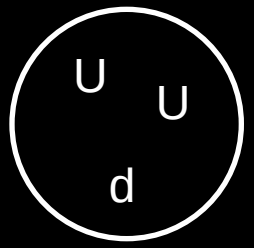
Periodic Table of the Particles



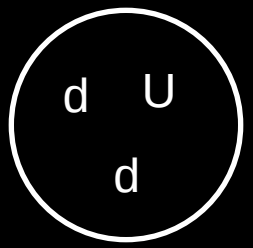
An example – Water!

- H_20

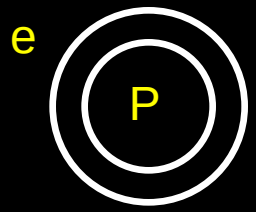




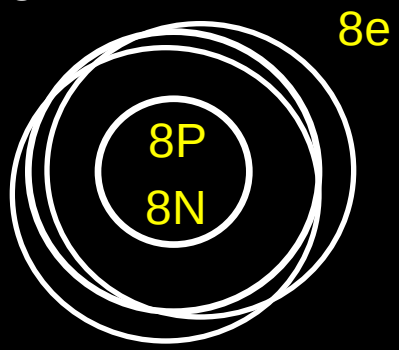
Proton
2/3+2/3-1/3



Neutron
2/3-1/3-1/3



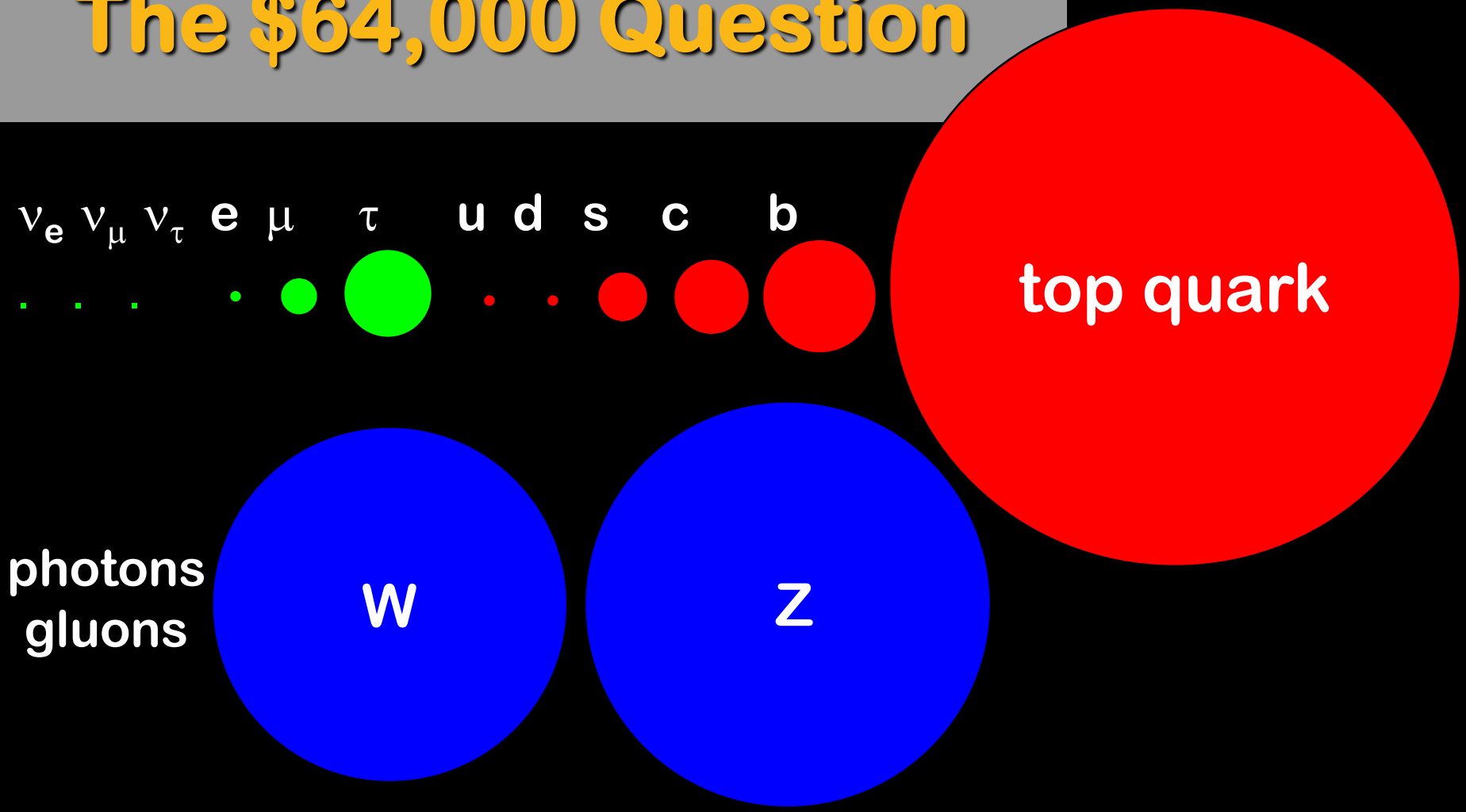
Hydrogen



Oxygen

H_2O ➡ 28 Up Quarks
26 down quarks
10 electrons

The $64,000 Question



Why is top so heavy?

"Why are there so many particles?"

"Where does mass come from?"

Enter the Higgs Mechanism

Popularity ∝ Mass

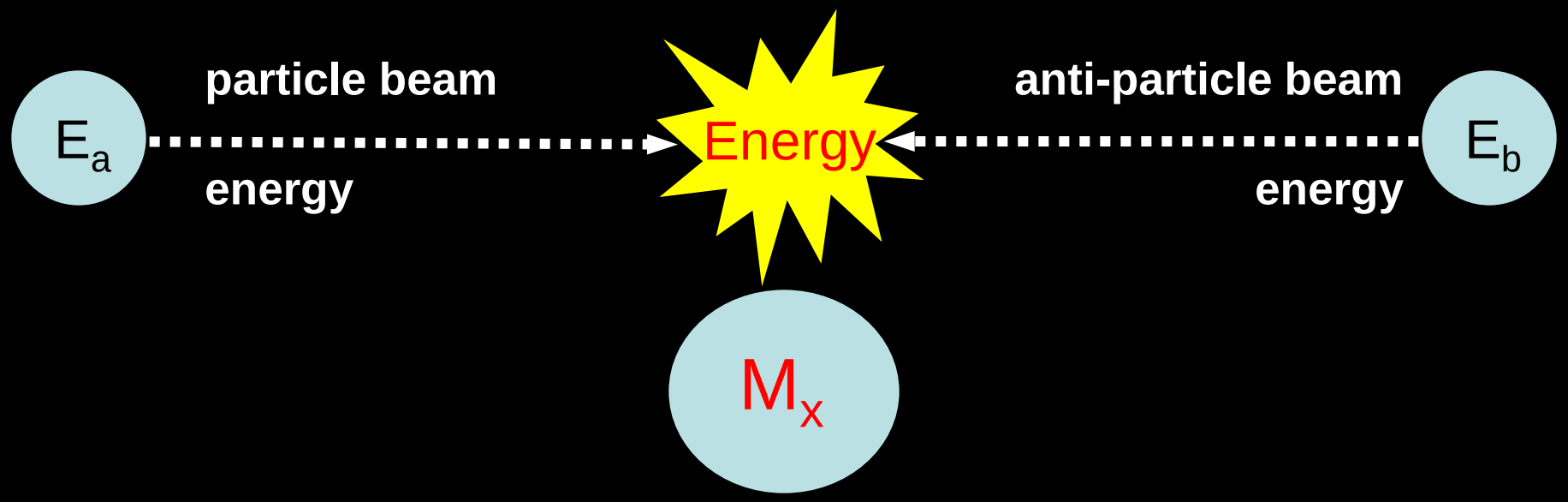
Analogy by Prof. David Miller
University College of London

How does one search for the top quark or the Higgs boson?
(or anything else for that matter)

Making Particle X

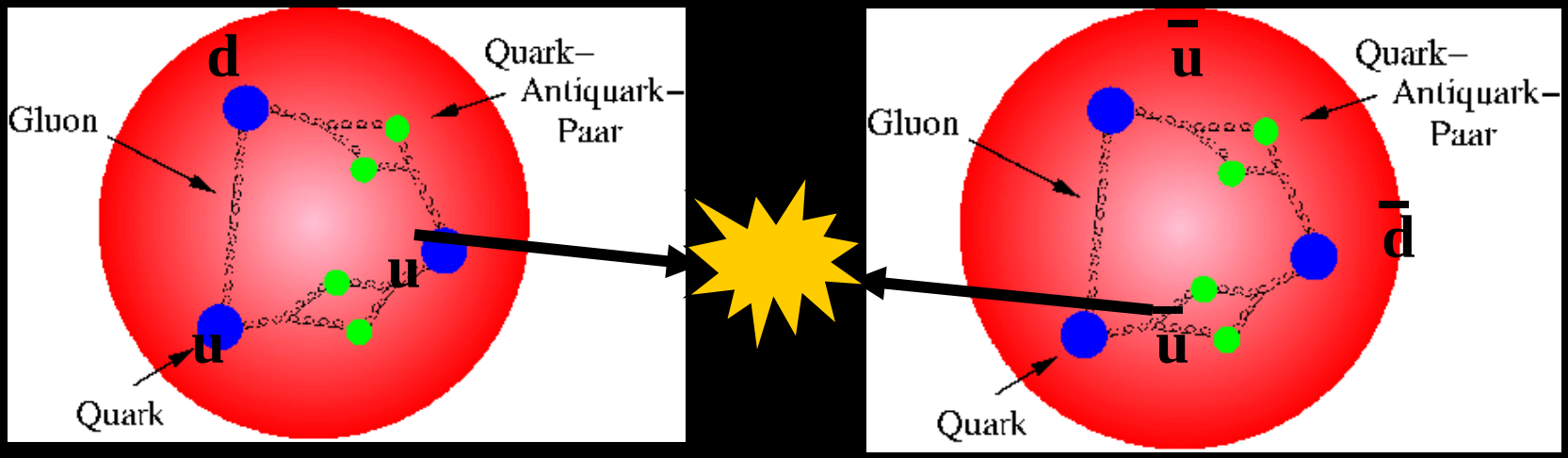
Thanks to Einstein we know that a high energy collision of particle A and B can result in the creation of particle X

$$E = mc^2$$



As long as $E_a + E_b >> M_x c^2$

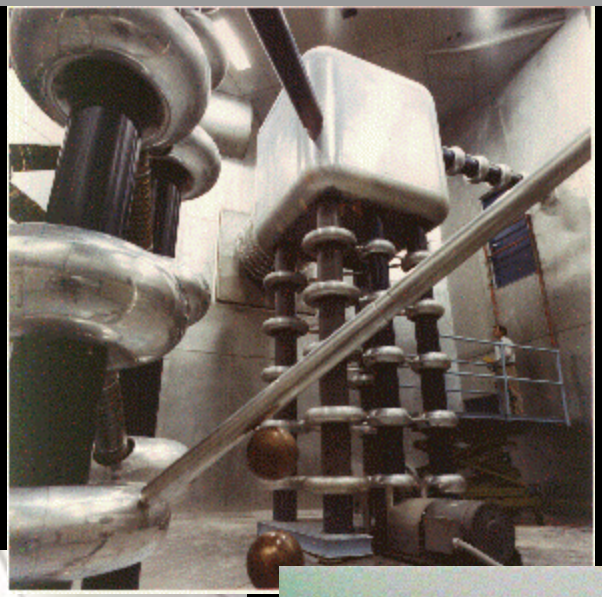
It's a bit more complicated...

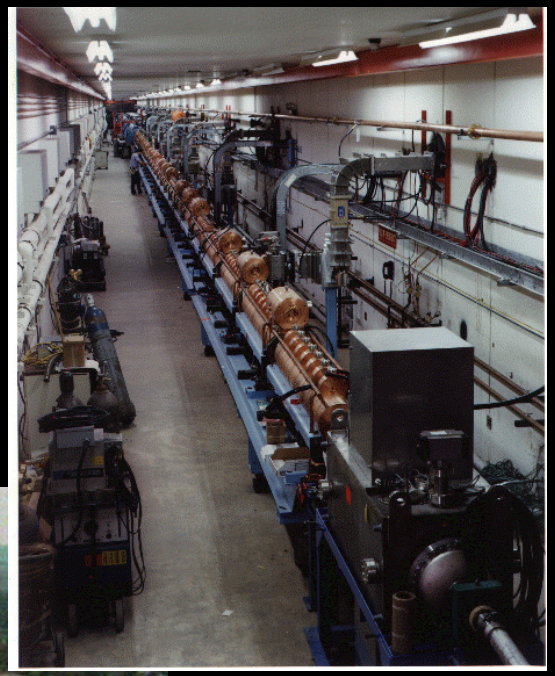


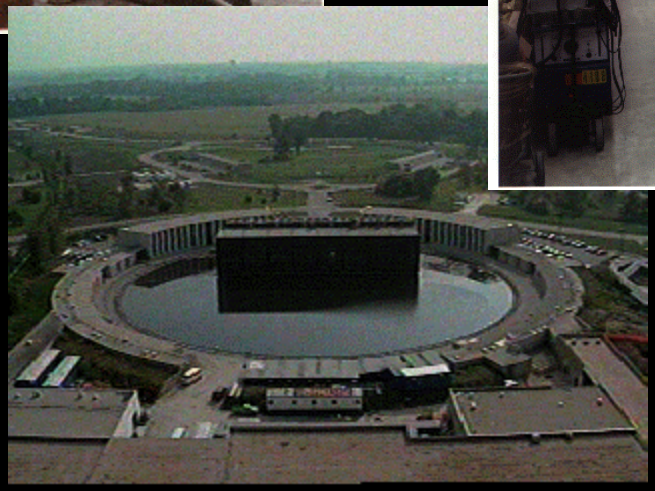
$$E_u + E_{\bar{u}} >> M_t + M_{\bar{t}}$$

World's Most Powerful Accelerator: Fermilab's Tevatron

Chain of Accelerators



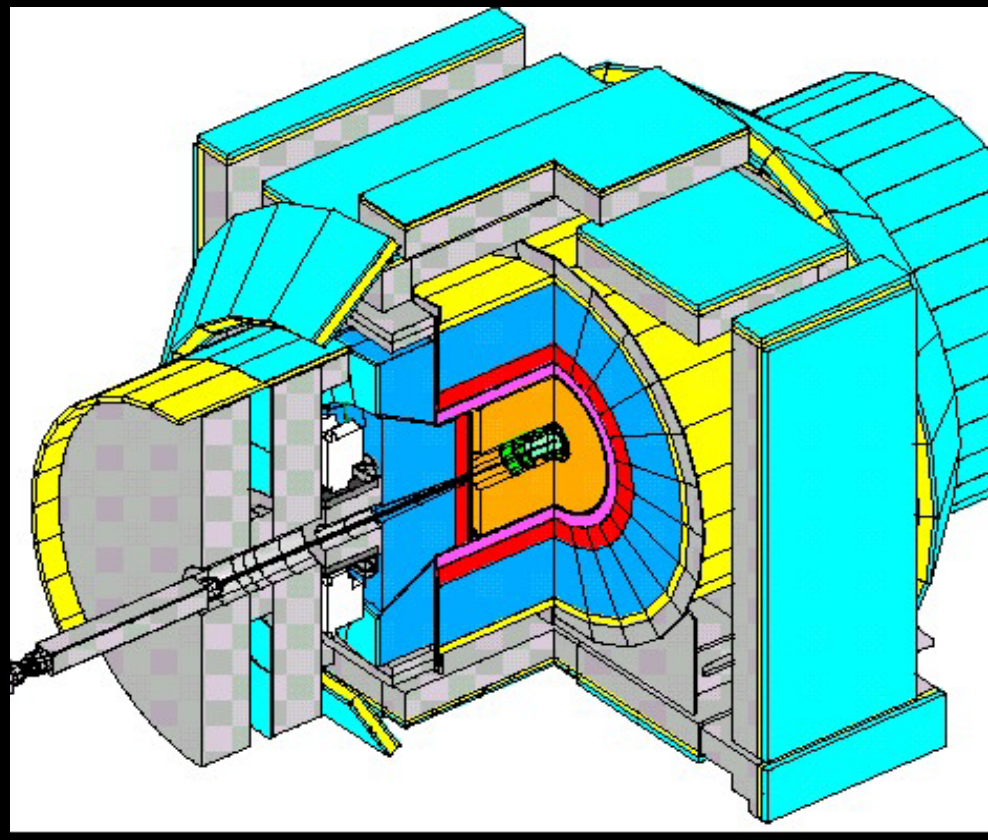




Colliding Beam Detectors

- Detector design is always a compromise
  - $$$
  - available space
  - technological risk
  - readout time and construction time
- Goal is to completely surround collision with detectors
- Arrange detectors in layers based on functionality
  - Measure particle's position, momentum and charge first
  - Type and kinetic energy second

CDF II Detector cross section



The Life of an Experimentalist…

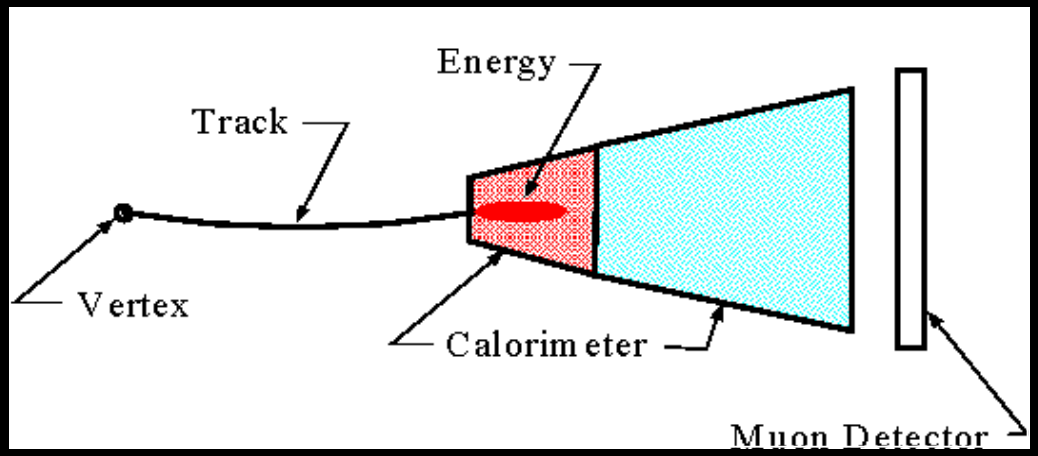
- Our "camera" is not fast enough to take a picture of say a top quark! We have to infer based on the information provided!!!!

- What do we know?
  - Conservation of Energy
  - Conservation of Momentum
  - $E=mc^2$
- What do we want to identify?
  - Electrons
  - Muons
  - Quarks
  - Neutrinos
  - b quarks

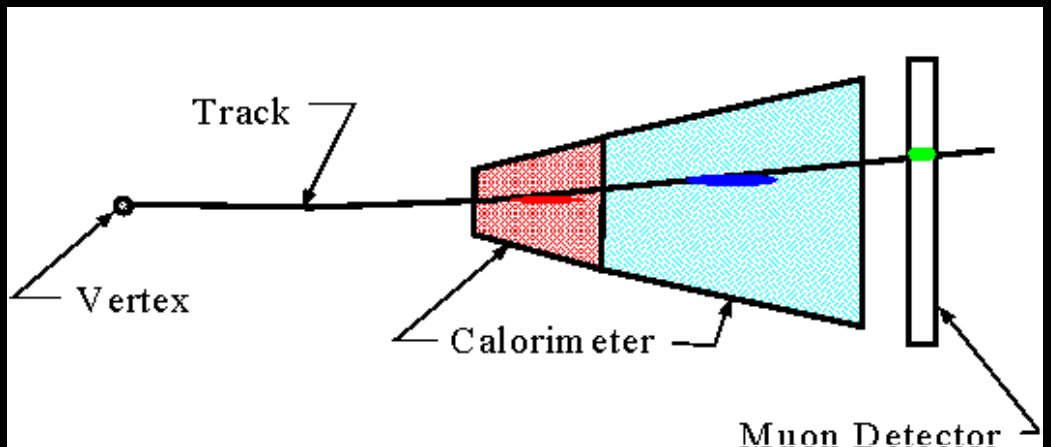
(Helps!)

Particle Signatures

- Electrons - deposit all their energy in electromagnetic calorimeter which can be matched to a track
- Photons - no track

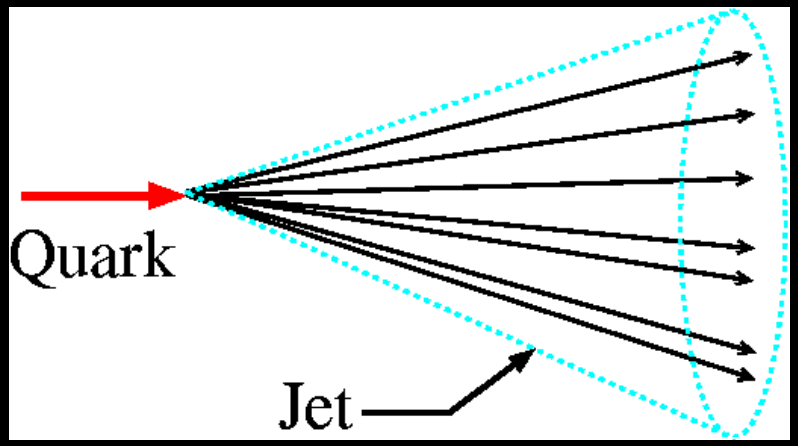


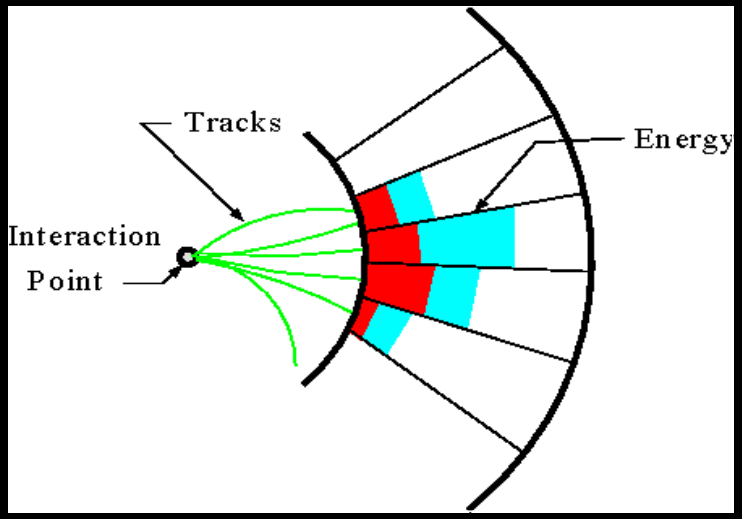
- Muons: Match signal in muon chambers to track



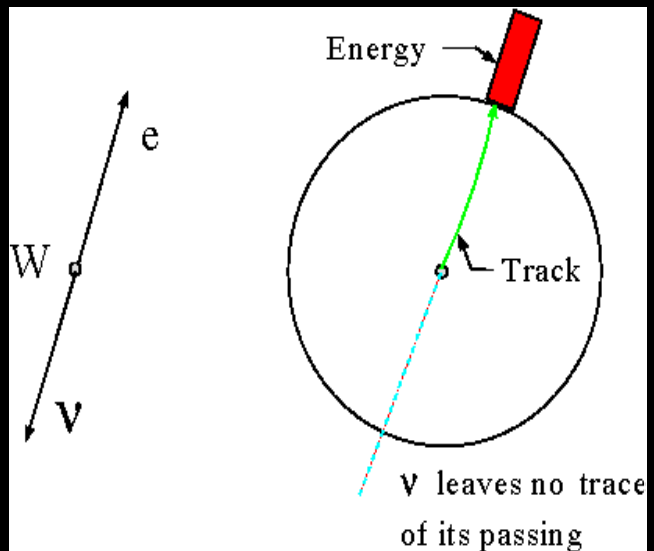
Particle Signatures (2)

- **Quarks - fragment into many particles to form a jet**
  - Leave energy in both calorimeters



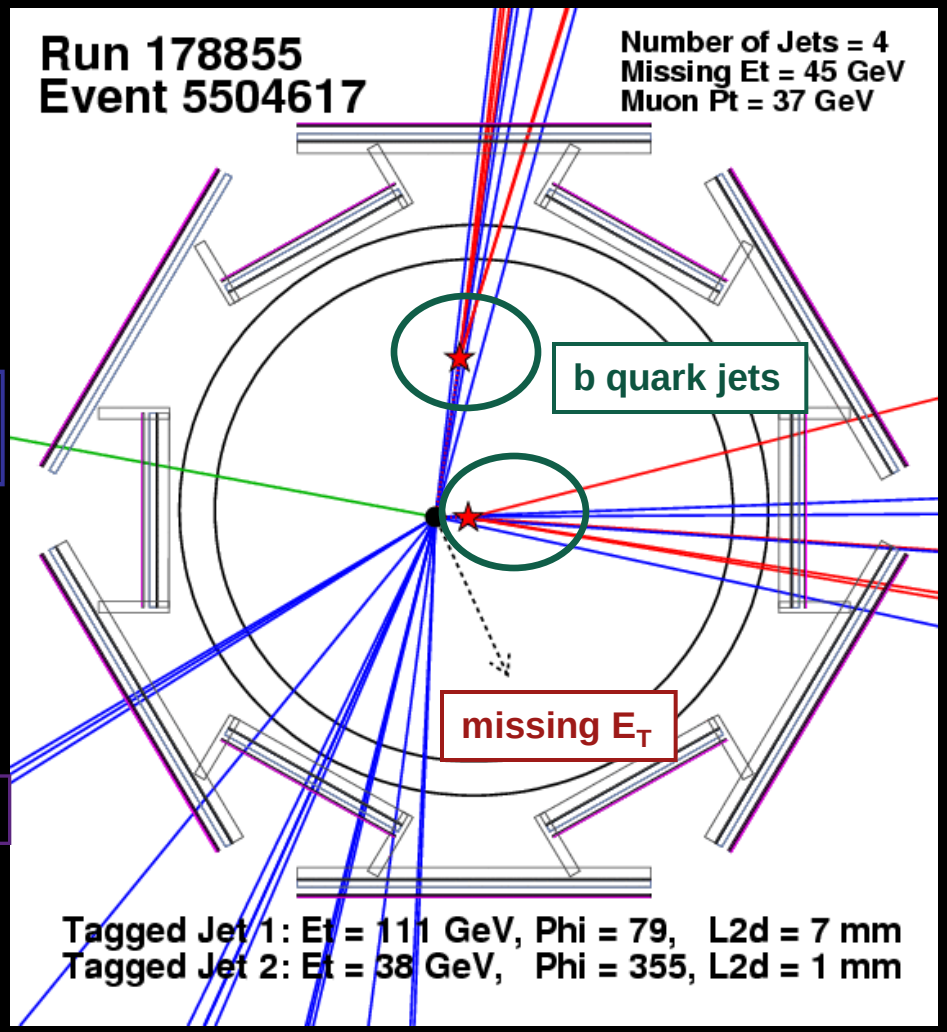


- **Neutrinos - pass through material**
  - Measured indirectly by imbalance of transverse energy in calorimeters



Identifying b quarks…

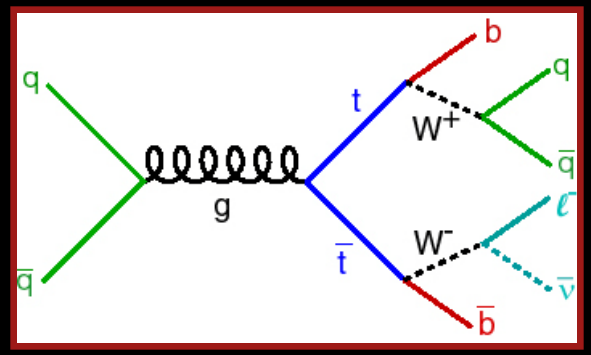
A Top Quark Event

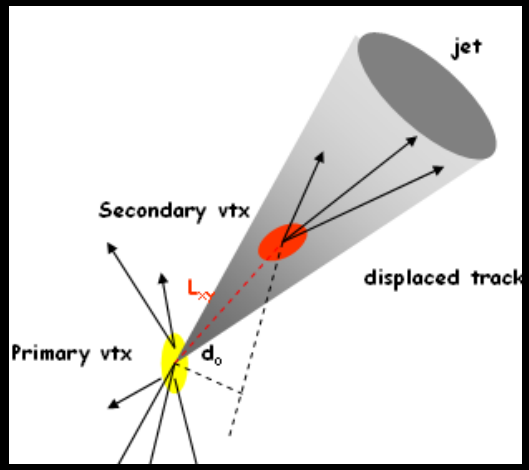


high p_T muon

q jet 1

q jet 2





b-quark lifetime:

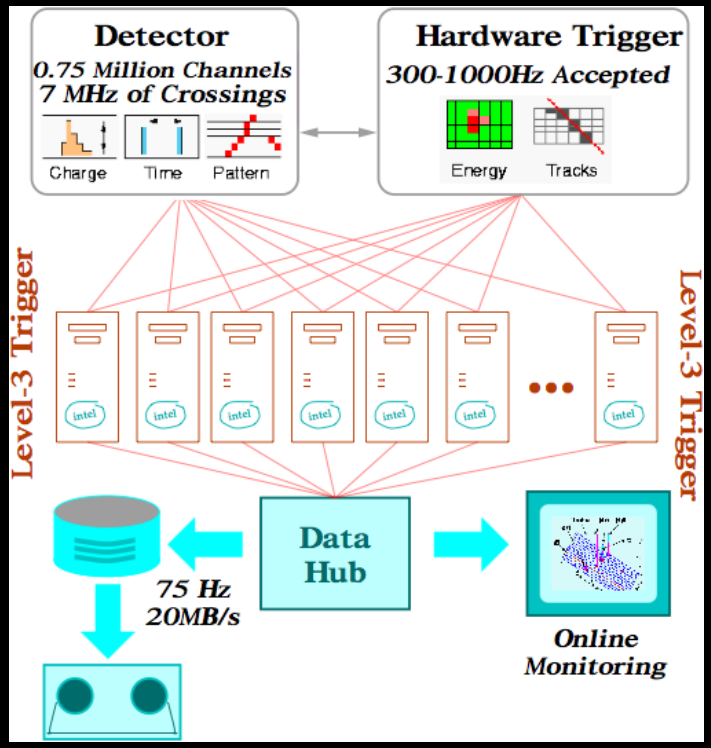
$c\tau \sim 450\mu m$

→ b quarks travel ~3 mm before decay

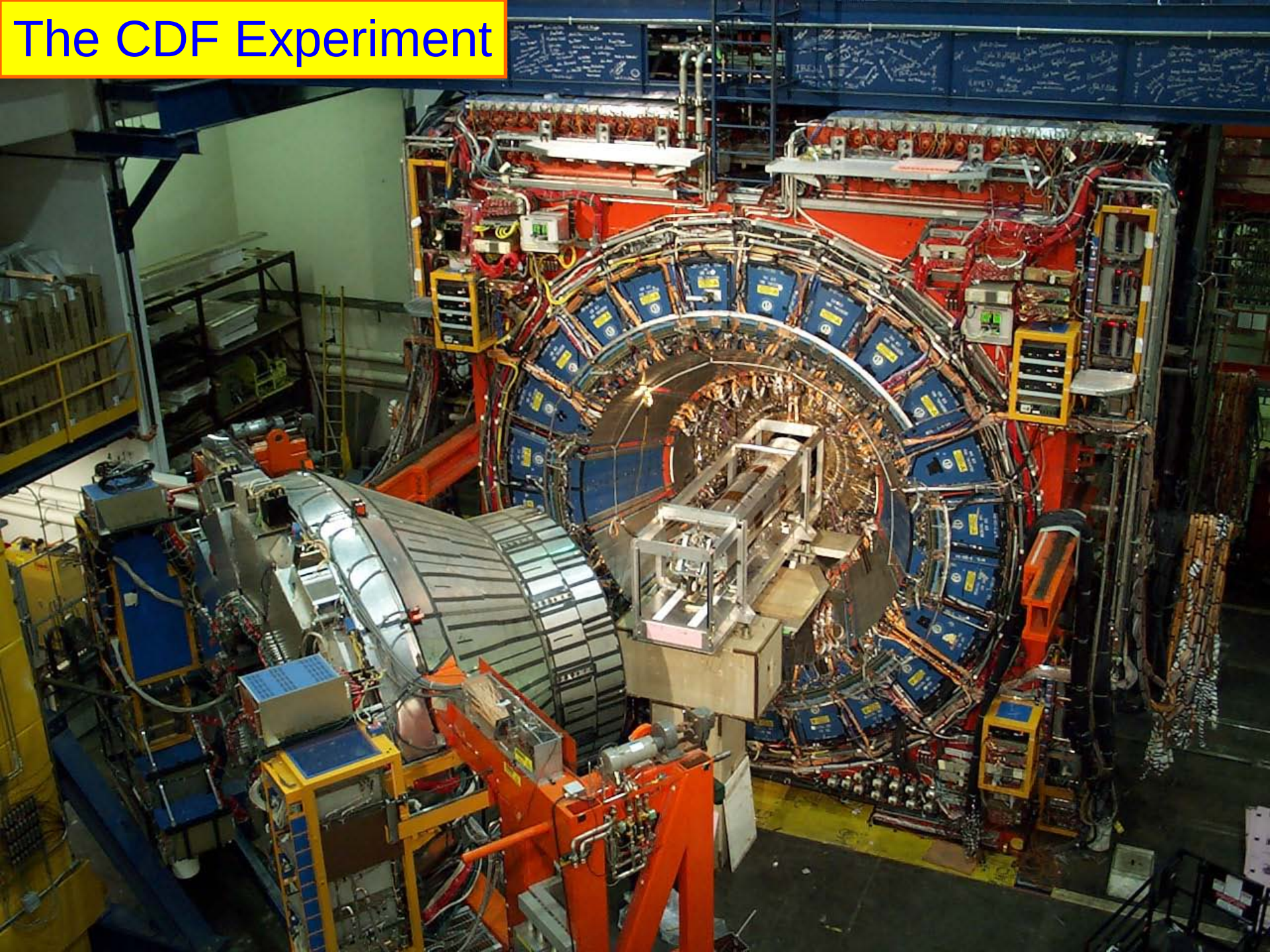
Collecting the Data You Want!

- Tevatron:
  - 36 p x 36 p bunches
  - collisions every 396 ns
  - 1.7 MHz of crossings
- CDF Detector
  - Very complicated with lots of information available on each collision
- The problem
  - You can't write out each collision to tape!
- The Solution
  - A Device called a "trigger"
  - Examines every event in real time and identifies the most "interesting"

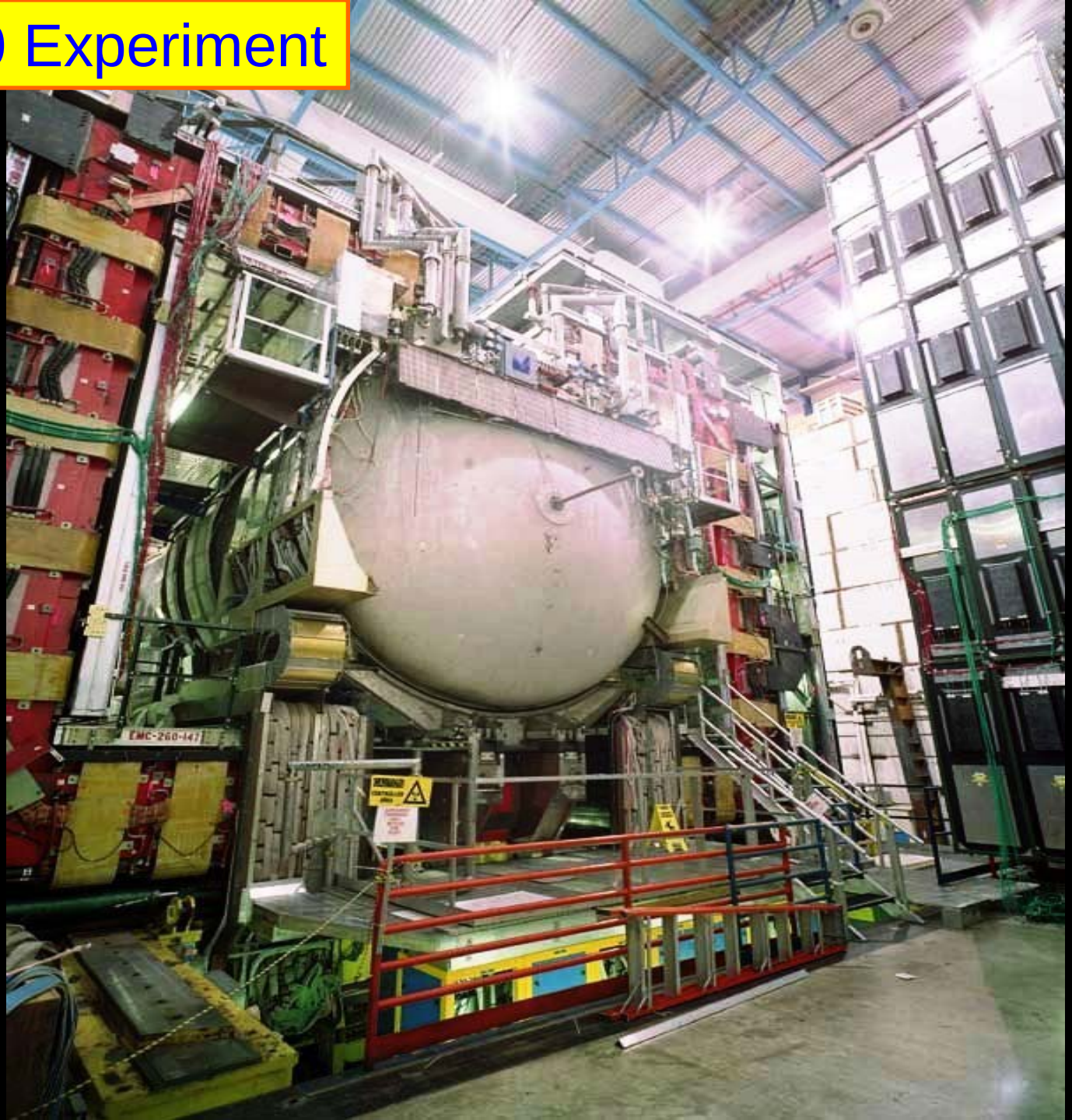
- CDF 3-tiered trigger:
  - L1 accepts ~25 kHz
  - L2 accepts ~800 Hz
  - L3 accepts ~150 Hz
    (event size is ~250 kb)
- Accept rate ~1:12,000
- Reject 99.991% of the events



The CDF Experiment



The D0 Experiment



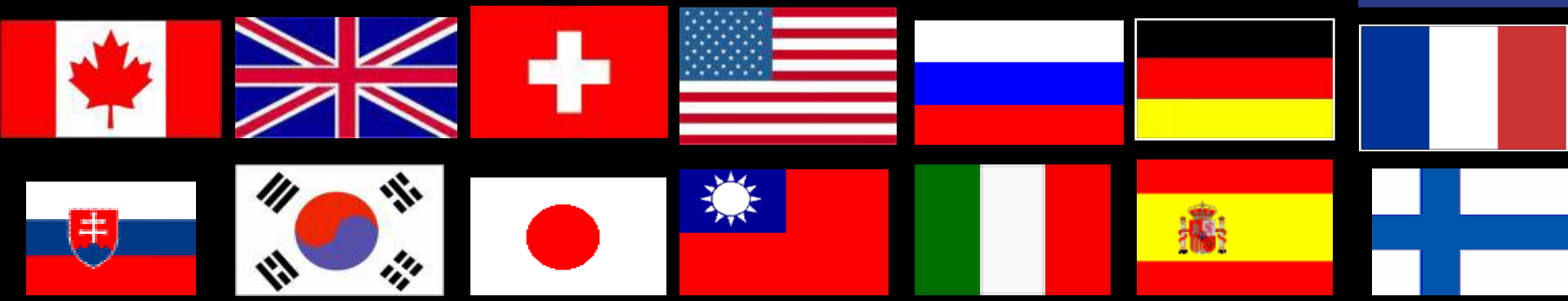
The CDF Collaboration

Europe
- 21 institutions

North America
- 34 institutions

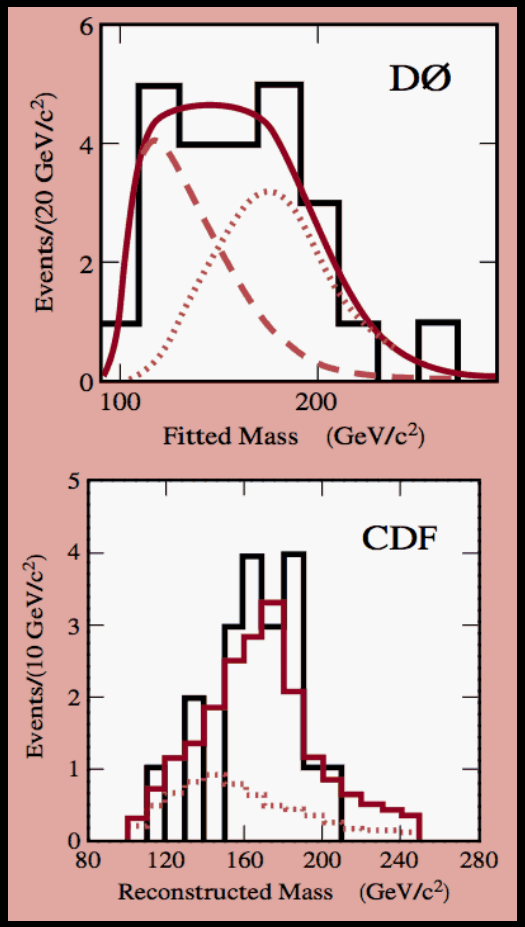
Asia
- 8 institutions

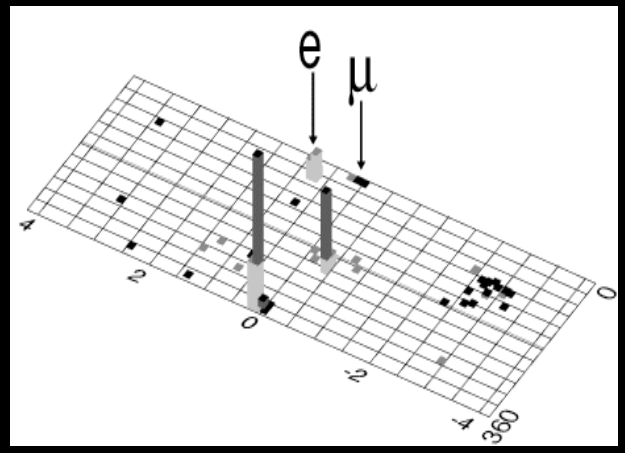
The CDF Collaboration
- 15 Countries
- 63 institutions
- 635 authors

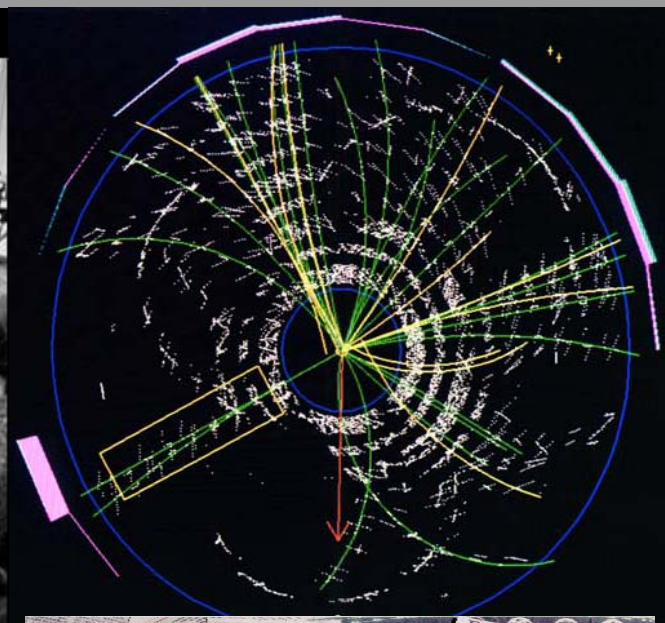


Top Quark Discovered!

1994 - 1995

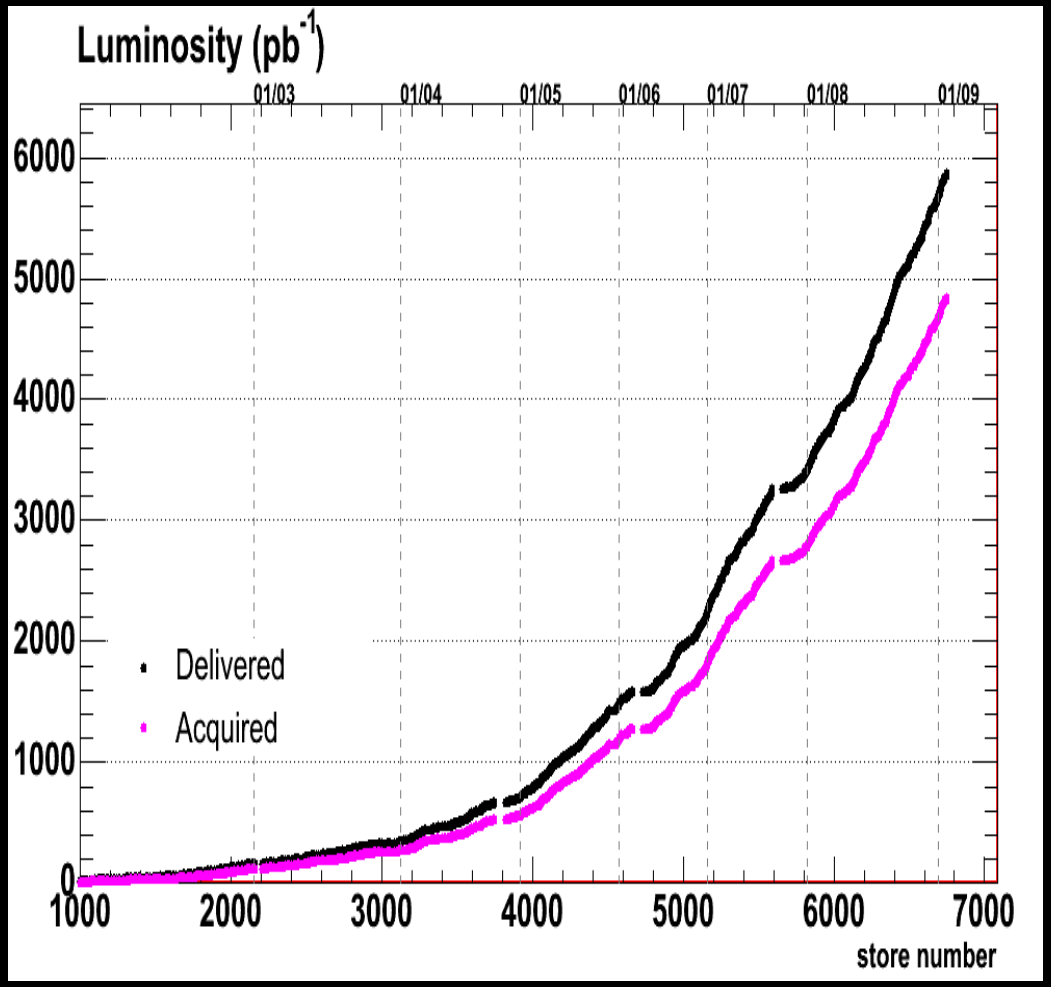






You Can Not make a Discovery with one Collision

It is a Statistical Process!

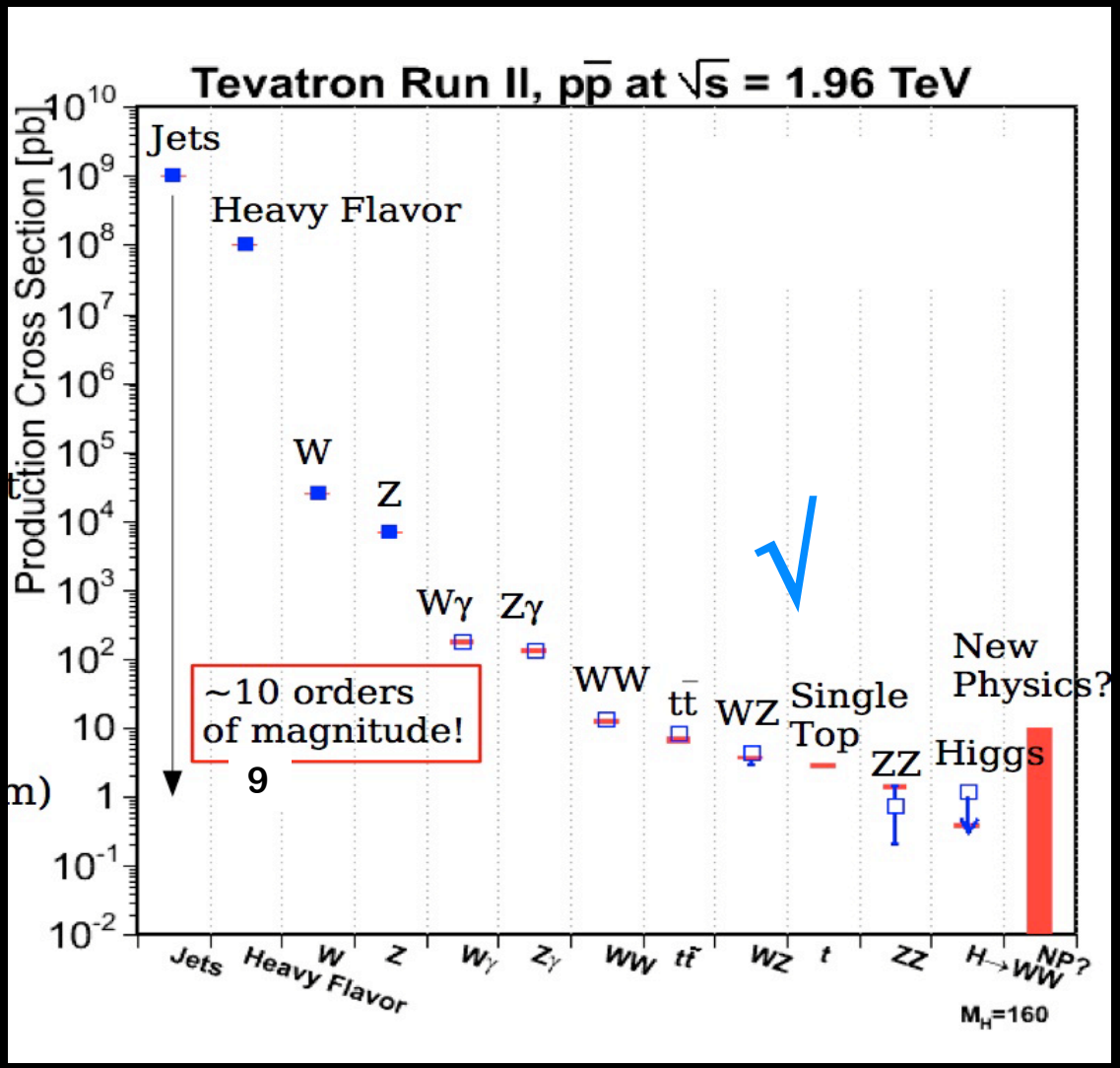


Today we have 50 times more data collected than we used to discover the top quark

The road to the (SM) Higgs

A Roadmap to discovery…

Harder to Produce



Harder to Observe

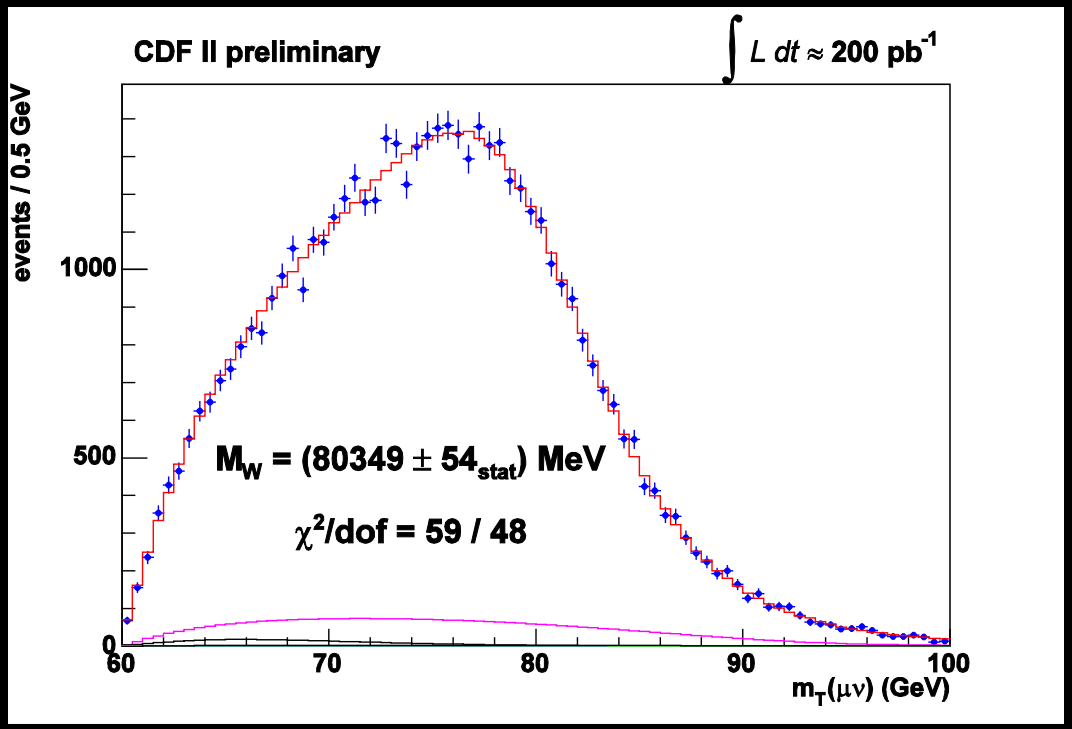
Colliders Produce Lots of Physics!!!
Some Recent Physics Highlights

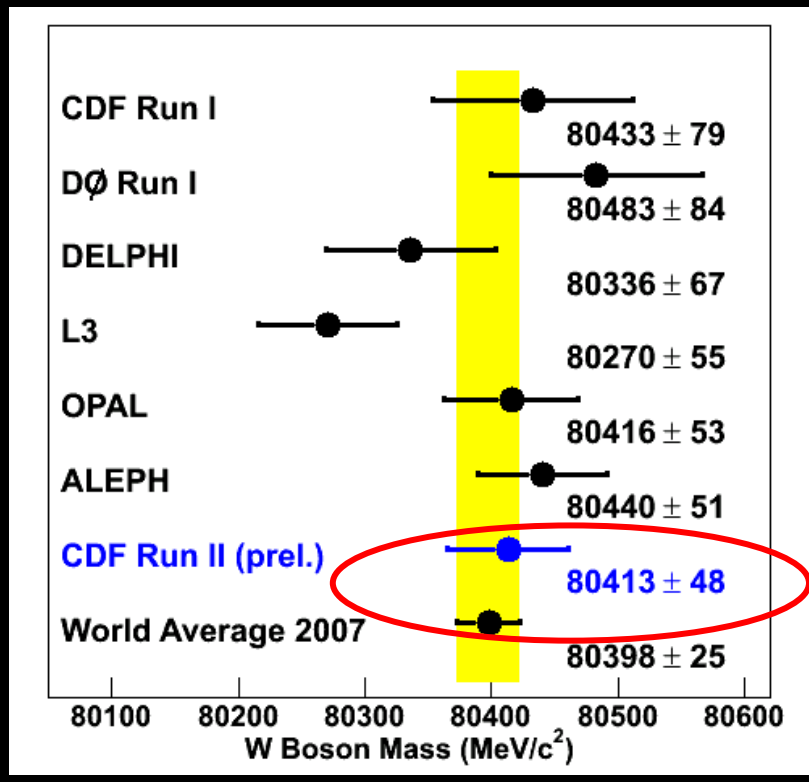
- ✓ Observation of Bs-mixing
  - Δm_s = 17.77 +- 0.10 (stat) +- 0.07(sys)
- ✓ Observation of new baryon states
  - Σ_b and Ξ_b
- ✓ WZ discovery (6-sigma)
  - Measured cross section 5.0 (1.7) pb
- ✓ ZZ observation
  - 4.4-sigma
- ✓ Single top evidence (5-sigma sens./2.2 fb^{-1})
  - cross section = 2.2 (0.7) pb
  - $|V_{tb}|$= 0.88 ± 0.14 (exp.) ± 0.07 (th.)
- ✓ Observation of new charmless B==>hh states
- ✓ Observation of exclusive/diffractive production
  - Di-jets, W/Z, charmonium, etc
- ✓ Observation of D^o-D^obar mixing
- ✓ Measurement of Sin(2β_s)
- ✓ …

Most are world's best results

- Precision W mass measurement
  - Mw_cdf = 80.413 GeV (48 MeV)
- Precision Top mass measurement
  - Mtop_cdf = 172.4 (1.6) GeV
- W-width measurement
  - 2.032 (.071) GeV
- Extended exclusions on BSM
- Continued improvement in Higgs Sensitivity
  - Exclusion of 170 GeV Higgs

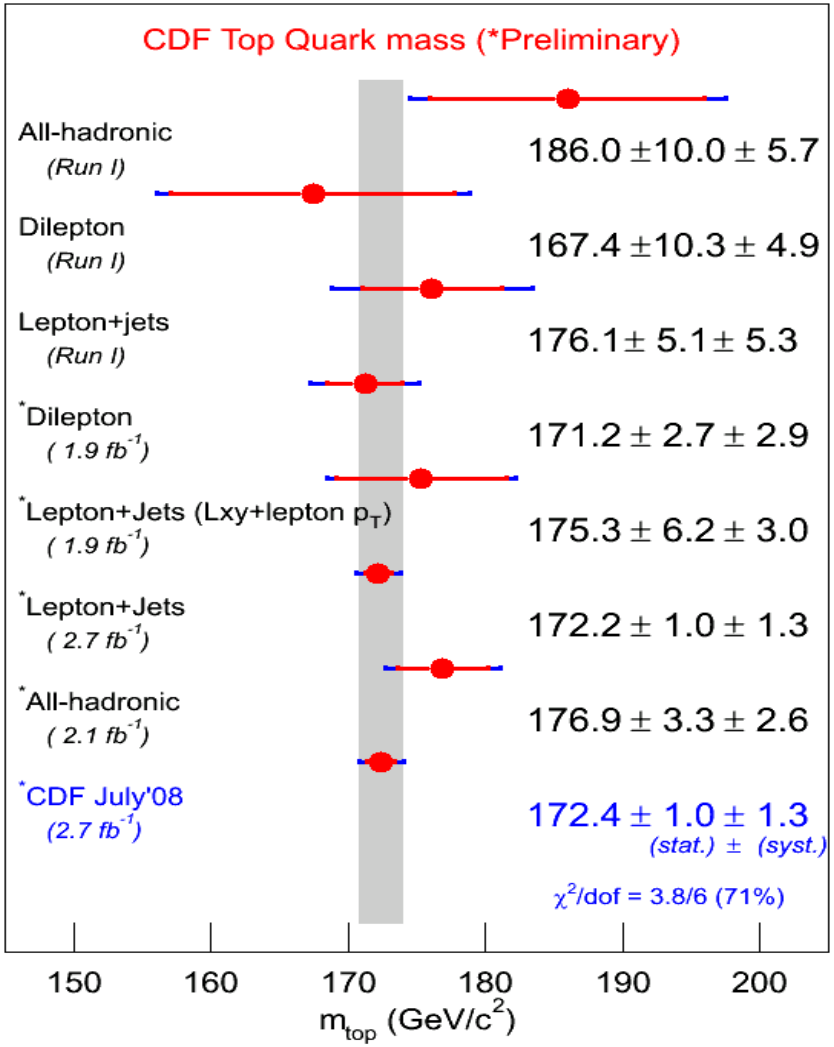
Tevatron's Latest W Mass Result





$$M_W = 80.413 \pm 0.048\ \text{GeV}$$

Summary of Top Mass



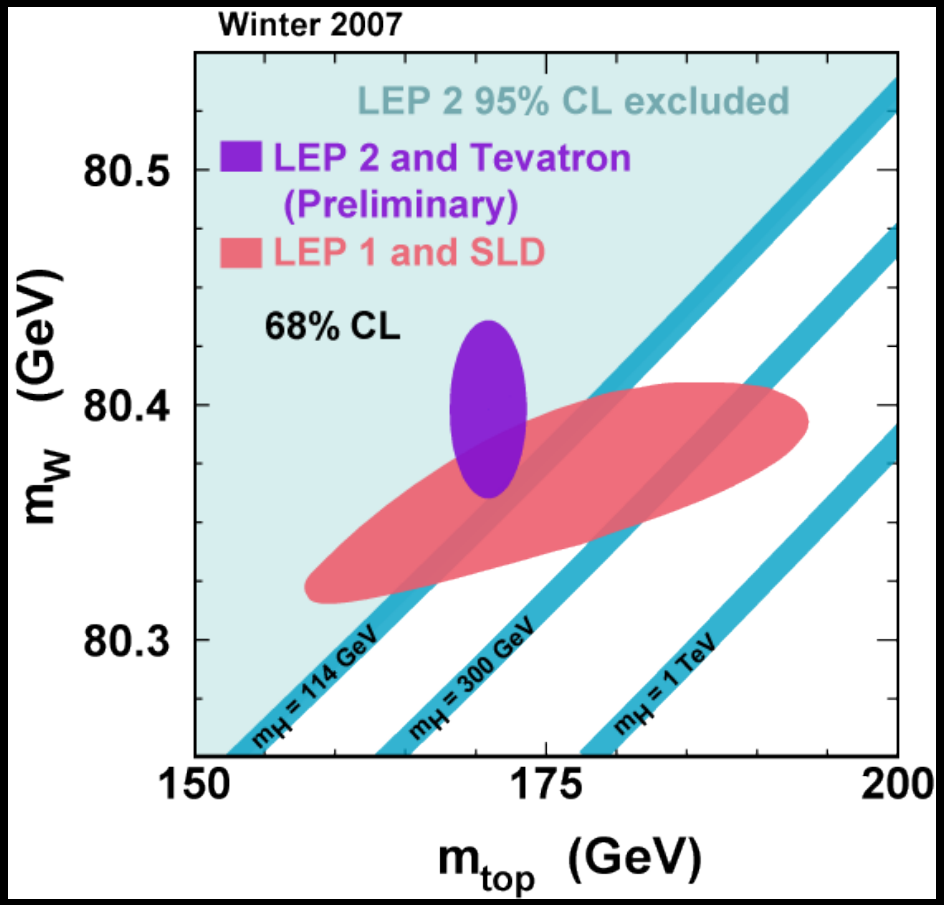
$M_t = 172.4 \pm 1.6$ GeV

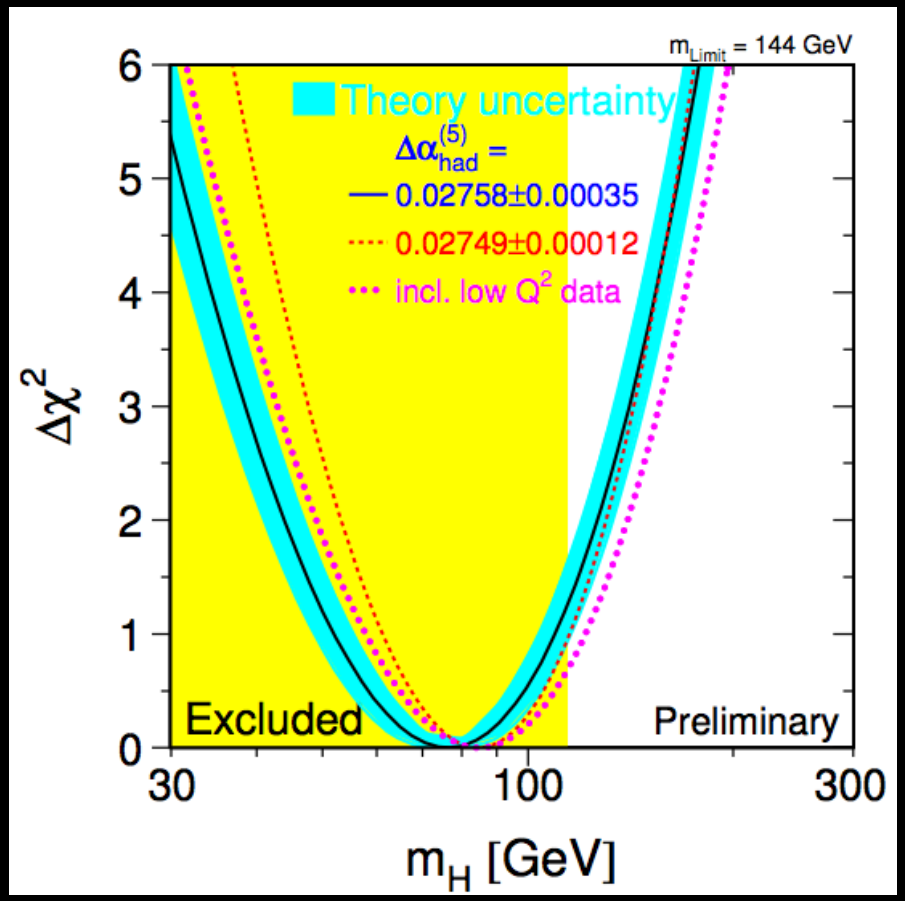
<1% Precision

We now know the mass of the top quark with better precision than any other quark!!!

14 short years from discovery to this….

Where is the Higgs Hiding?



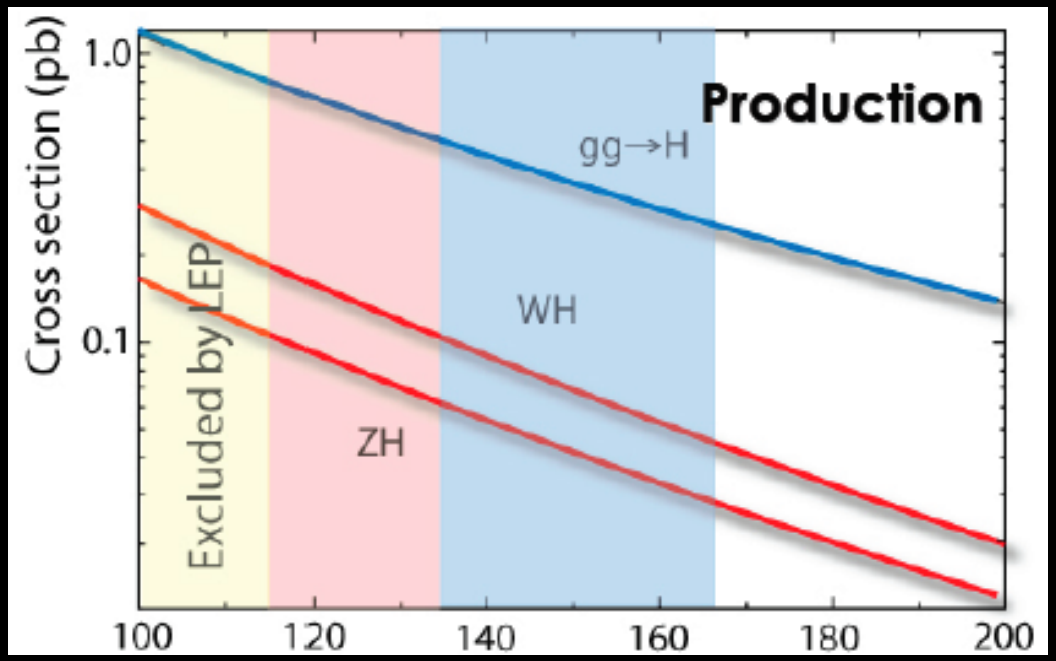


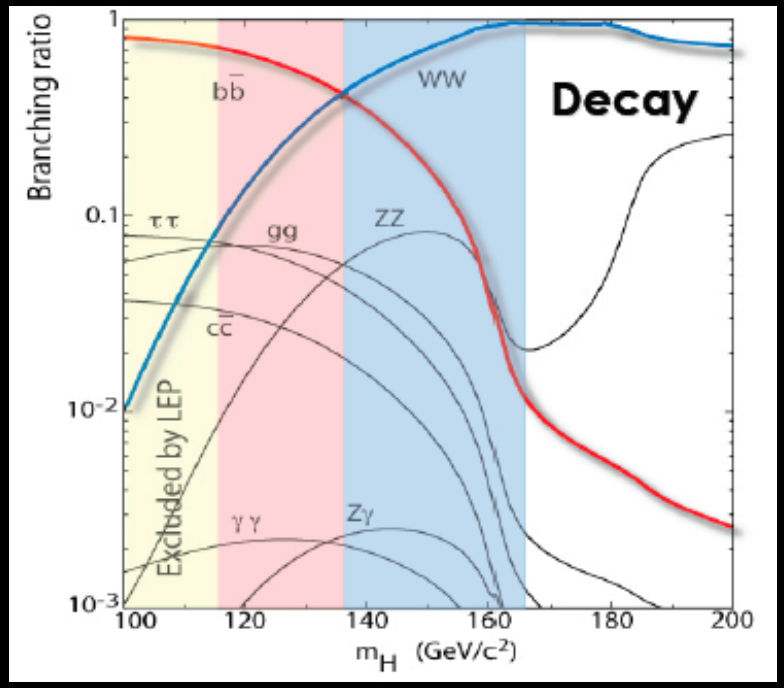
Mw vs Mtop

$M_H < 154$ GeV at 95% C.L.

Preferred $M_H - 87^{+36}_{-27}$ GeV

Higgs Production and Decay



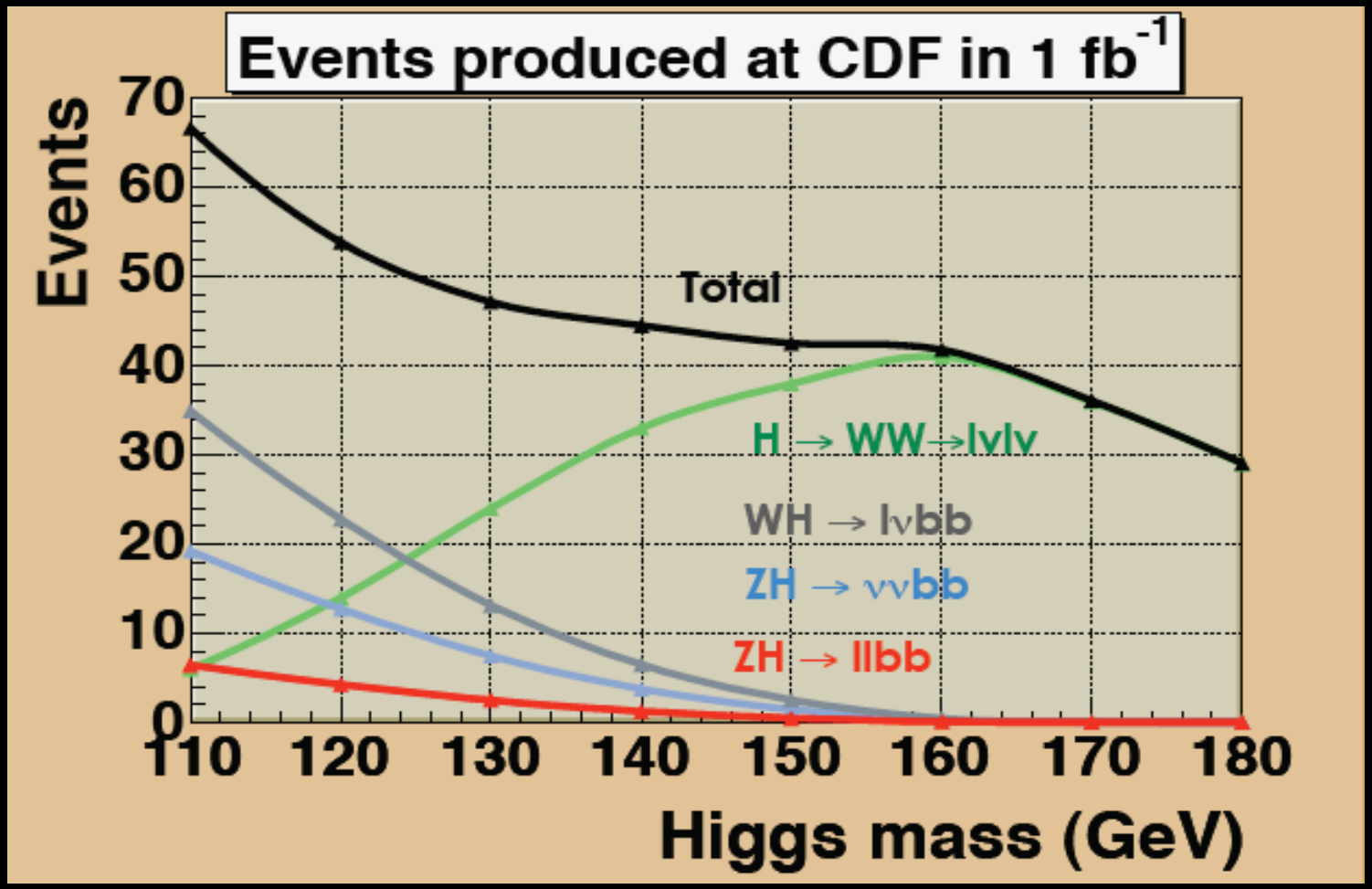


Higgs are produced in several diferent ways…

Higgs decay into different "final states" depending on the mass of the Higgs

To find it, we need to look at all these final decay states and combine the results

The Challenge



These are production numbers –
trigger, acceptance etc not yet factored in…

Can we use the strategy for the top quark to find the Higgs?

1. Namely just count events that look like top
2. Estimate a top signal the number of events that might "mimic"
3. The <u>difference</u> between the two is the signal

<u>NO!</u>

From the previos page…. we expect to make 40-60 Higgs events inside our detector for each 1/fb of data

We now have 5 /fb of data – so we expect to have made 200-300 Higgs candidates

If our efficiency for finding them is a few percent, we are trying locate a handful of events out of billions of collisons!

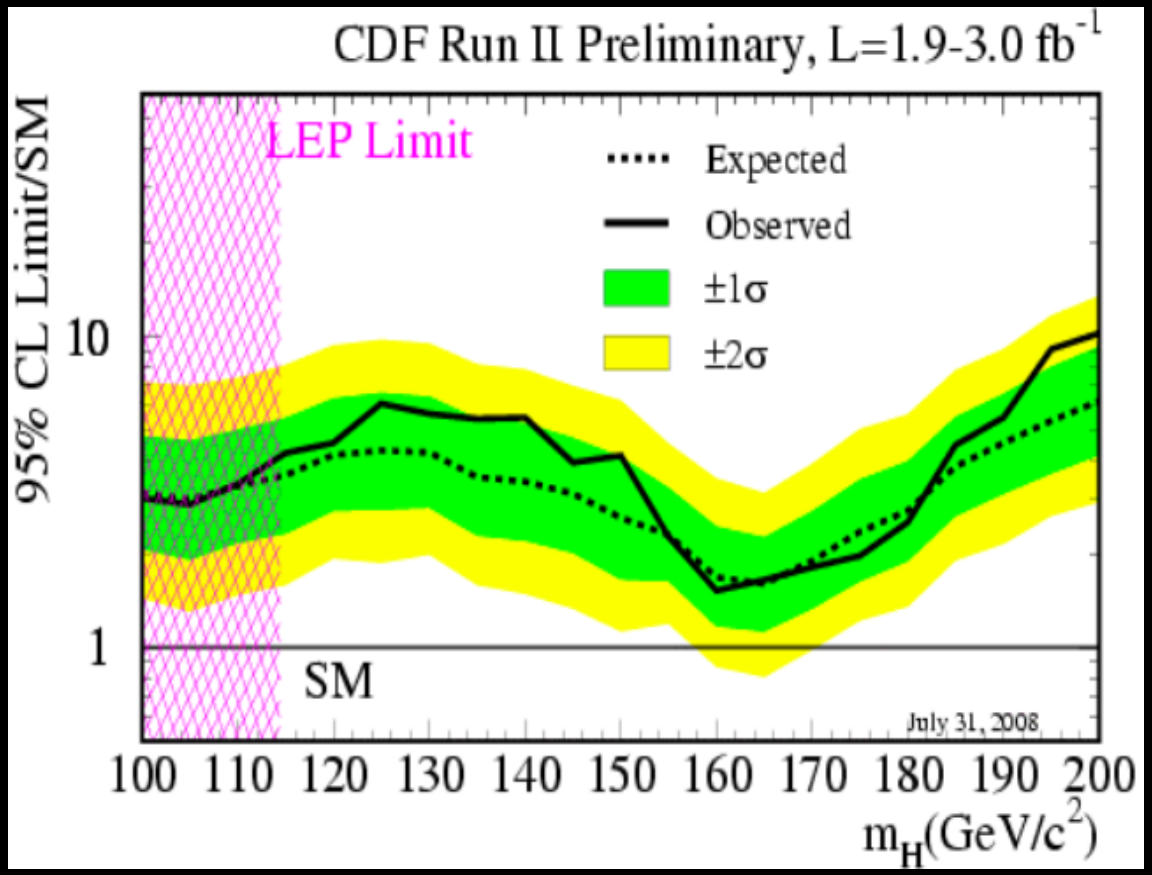
This is Hard!!!

The Multistep Process

- Step 1 – select events using simple kinematic cuts (high pt lepton, missing energy, b jets in the event
- Step 2 – Make use of other distinguishing features
  - Fits to kinematic distributions
  - Multivariate techniques (neural nets) to make optimal use of the information in each event
- Step 3 -- Optimize
  - Improve triggering
  - Improve lepton acceptance
  - Improve background rejection
  - All of this is very hard pain staking work
- Step 4 – Combine efforts
  - Combine all the different decay channels together
  - Combine results from both experiments

One Experiment's Channel Combination

Factor away in sensitivity from SM

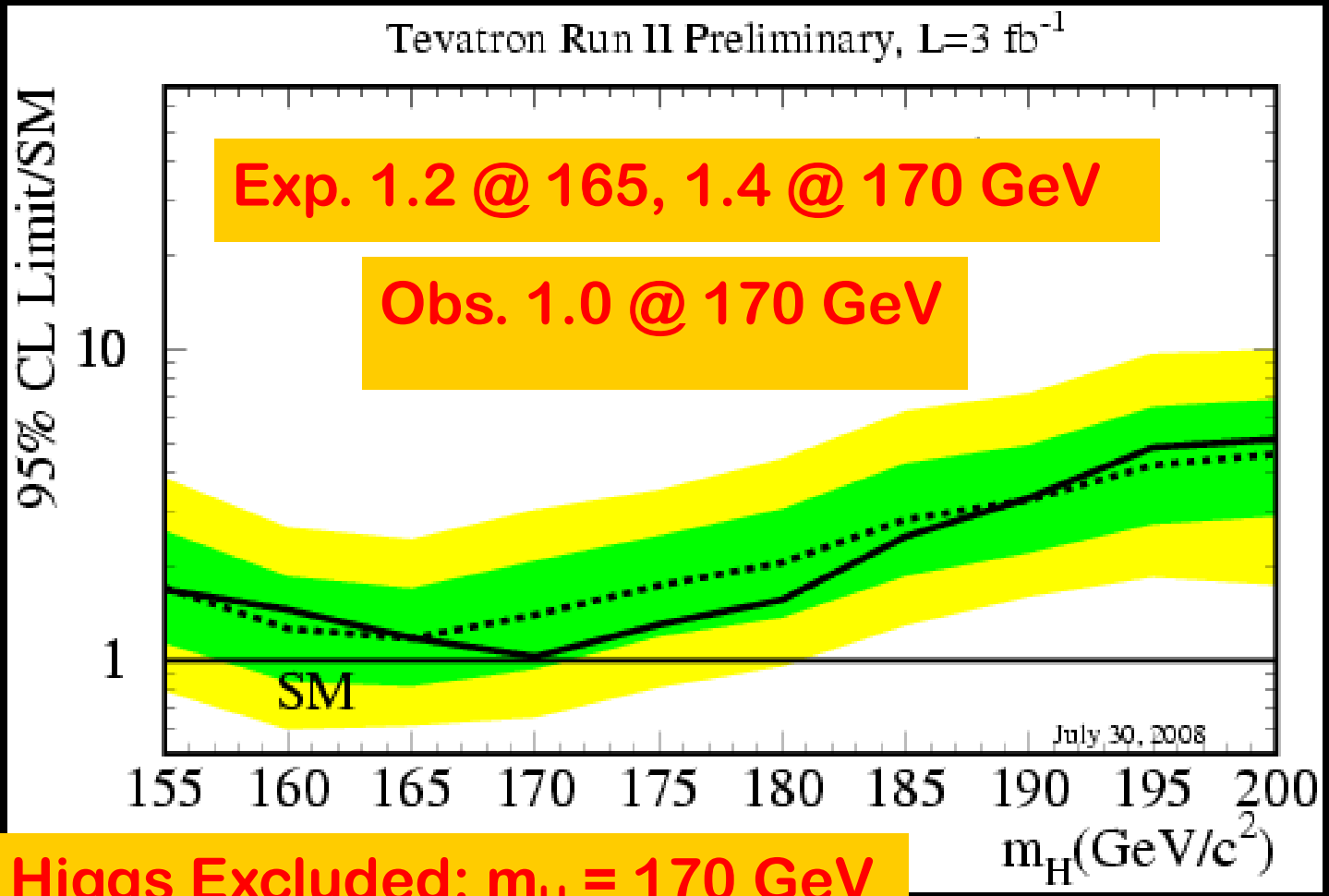


- Statistically combine channels
- Use a procedure to account for correlated uncertainties

Step 5 – Combine Experiments

Neither experiment has sufficient power to span the entire mass range using the luminosity we expect to acquire in Run II

Factor away in sensitivity from SM

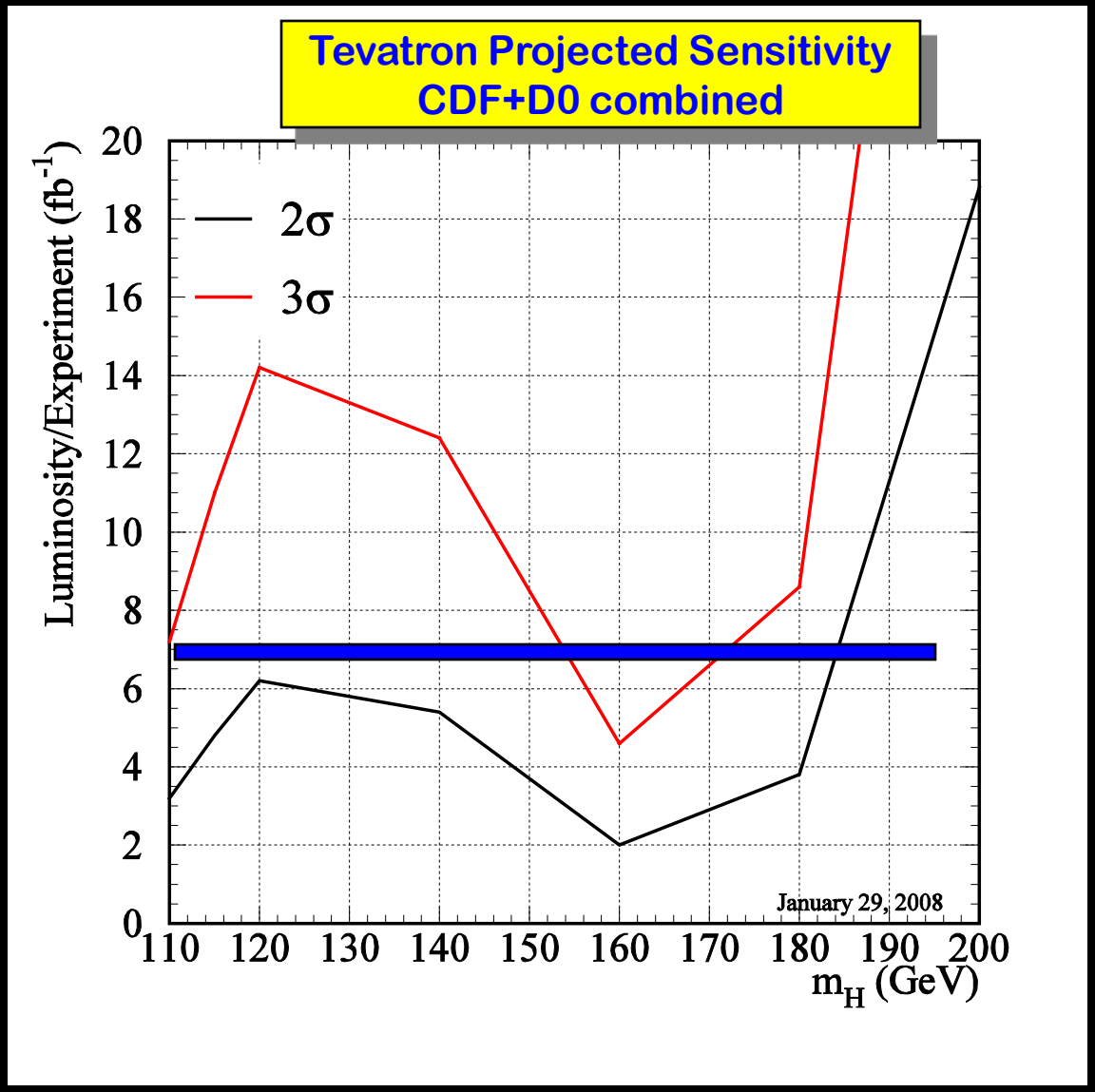


Exp. 1.2 @ 165, 1.4 @ 170 GeV

Obs. 1.0 @ 170 GeV

SM Higgs Excluded: m_H = 170 GeV

Tevatron Higgs reach with FY10 run



With 7 fb^{-1} analyzed

- exclude all masses !!! [except real mass]
- 3-sigma sensitivity 155:170 LHC's sweet spot

We find this very compelling

We are Getting Serious!

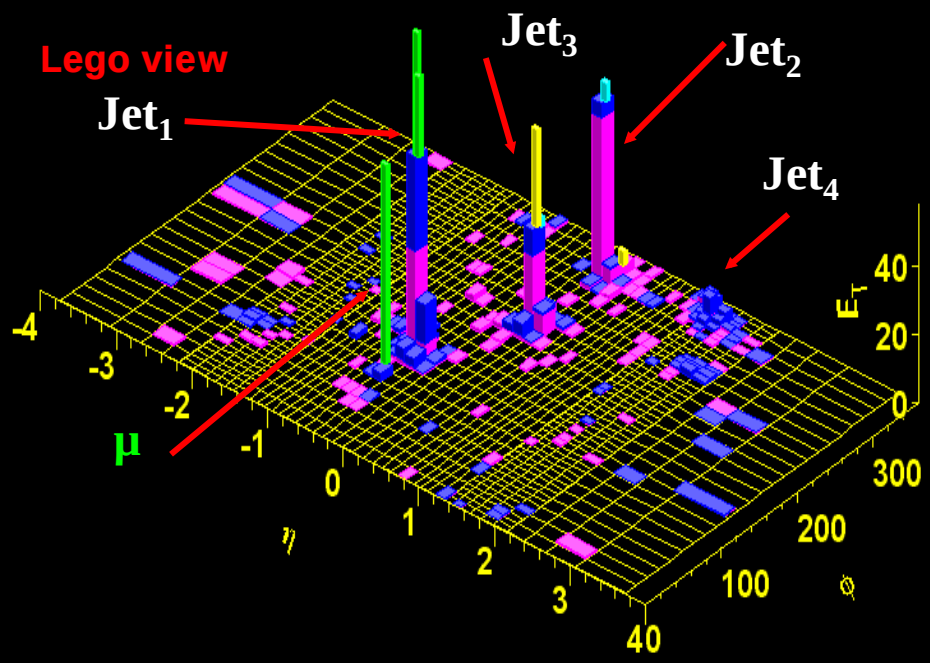
Reaching for the Higgs Horizon

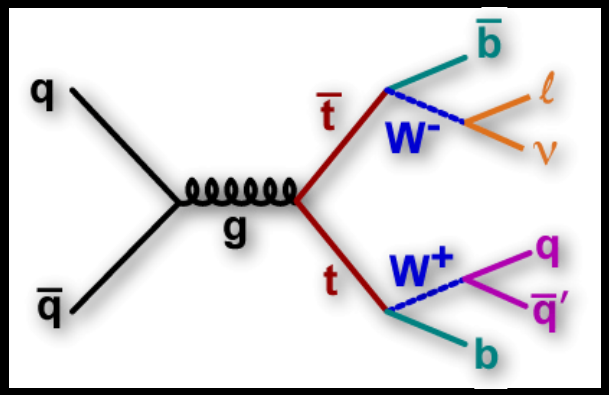
Conclusions

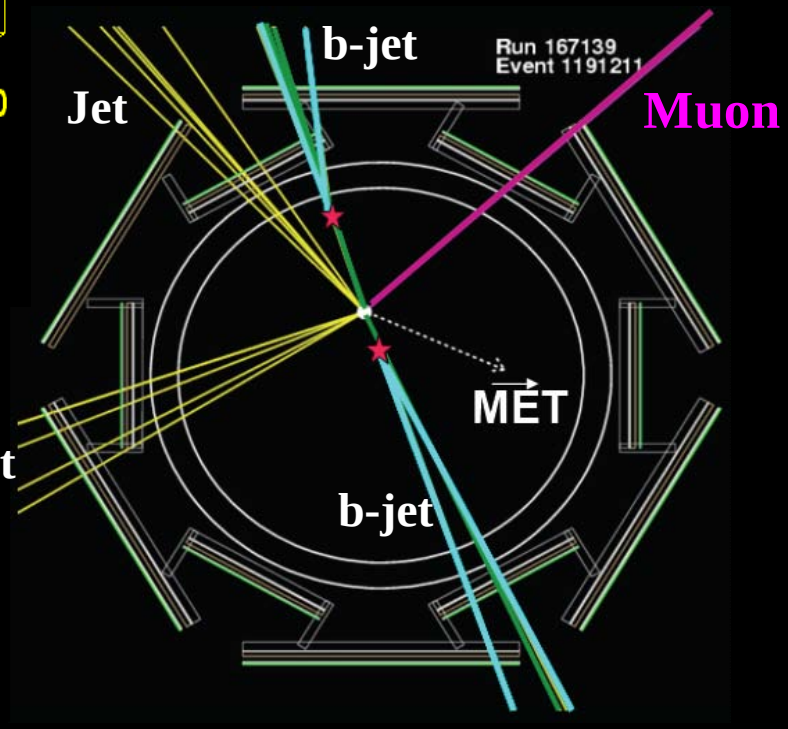
- We are making great strides in the search for the Higgs
- The accelerator WILL provide data sets of sufficient size to give us a chance!
- We know what to do in terms of analysis
- If the Higgs is there, we have a chance to find it!
- These next two years will be a very exciting time as we conclude our search and the LHC starts theirs.

Backup

Top Quarks at CDF





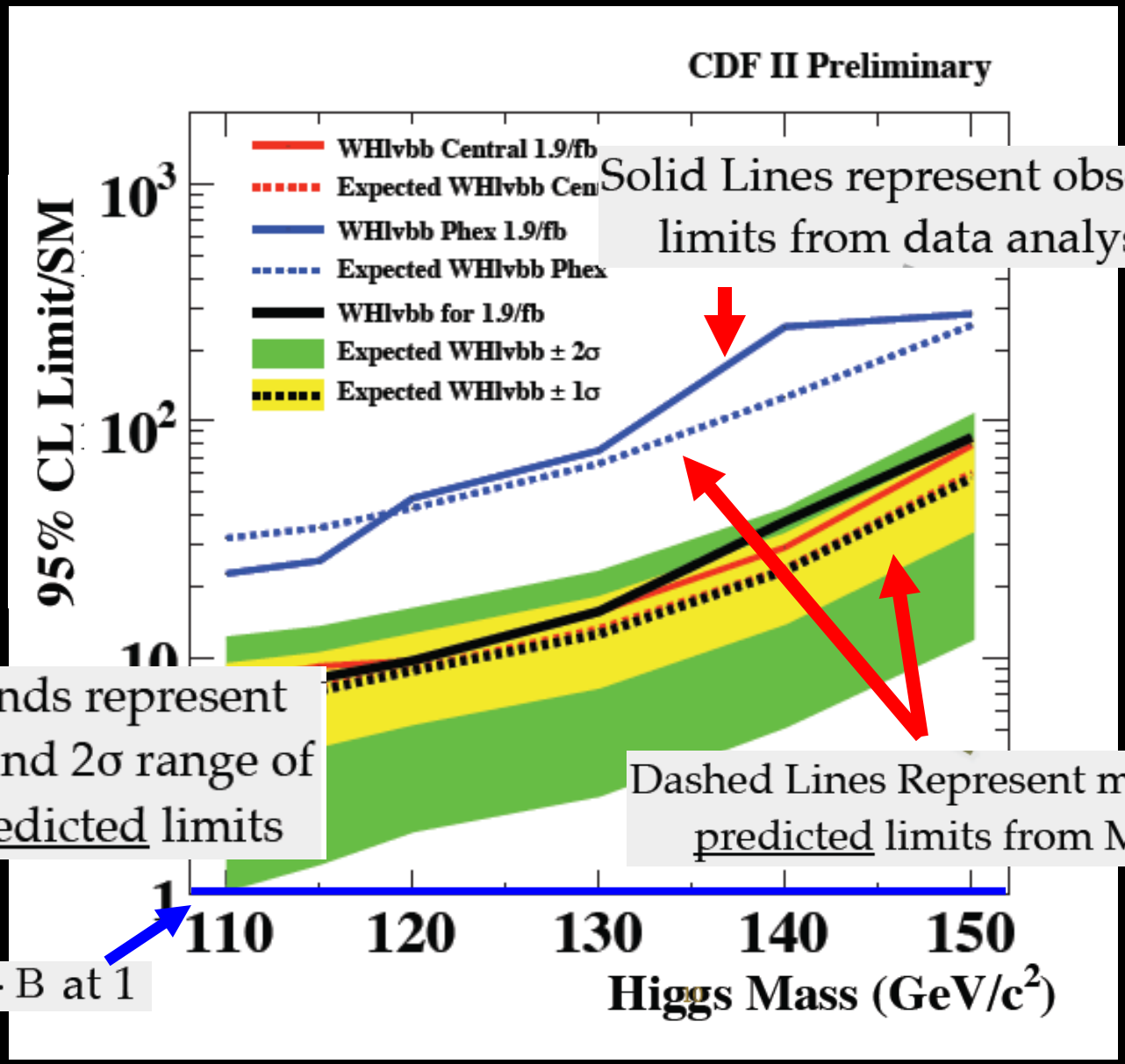


Top quarks are one of the more sexy things to study at the Tevatron

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.

Decoding Limit Plots 101

Factor away in sensitivity from SM



Solid Lines represent observed limits from data analysis.

Bands represent 1σ and 2σ range of <u>predicted</u> limits

Dashed Lines Represent median <u>predicted</u> limits from MC

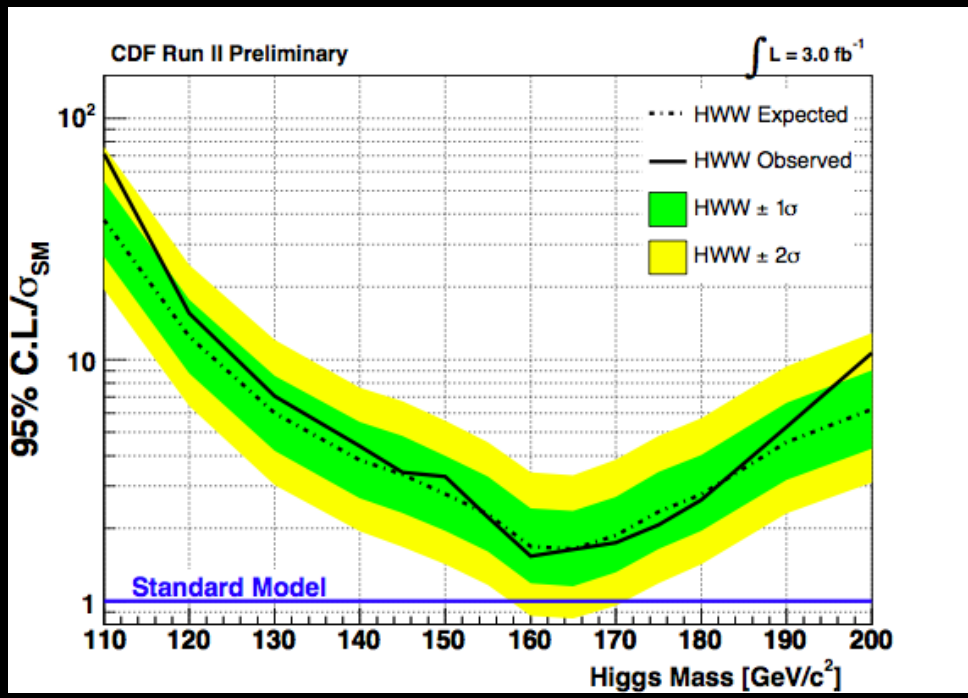
SM $\sigma \cdot B$ at 1

An Example -- Higgs →WW

- H→WW→lνlν - signature: Two high pT leptons and Missing Energy
  - Primary backgrounds: WW and top in di-lepton decay channel
  - Key issue: Maximizing lepton acceptance
- Most sensitive Higgs search channel at the Tevatron

σ x BR (H→WW*) expected limit 1.66 times SM for a Higgs mass of 165 GeV;

Observed 1.63



Step 4 – Combine Channels

No single channel has the power to reach SM prediction for M_H < ~ 160 GeV/c^2

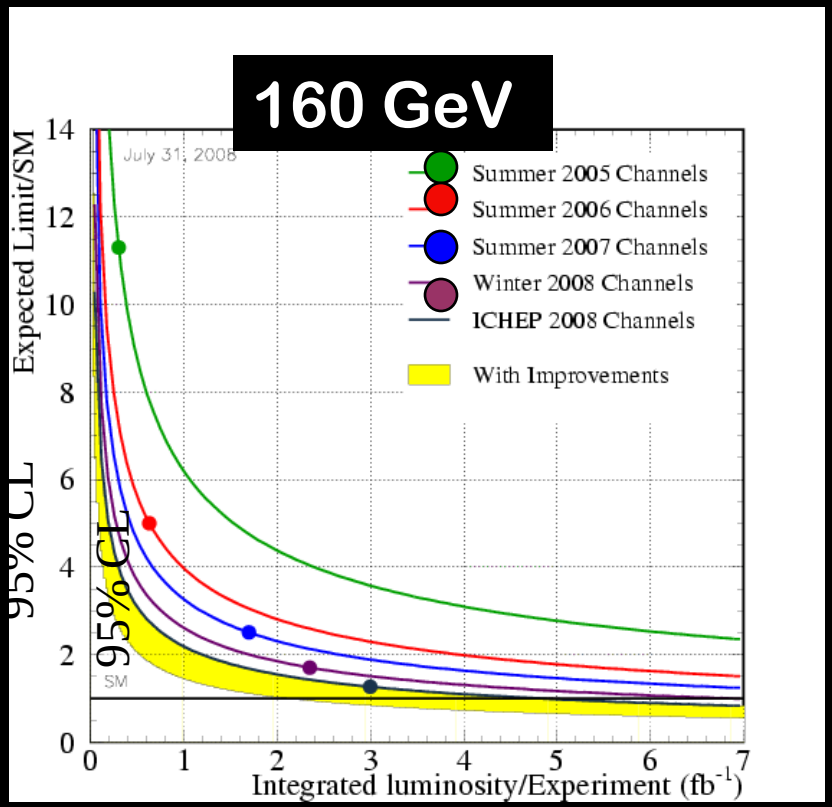
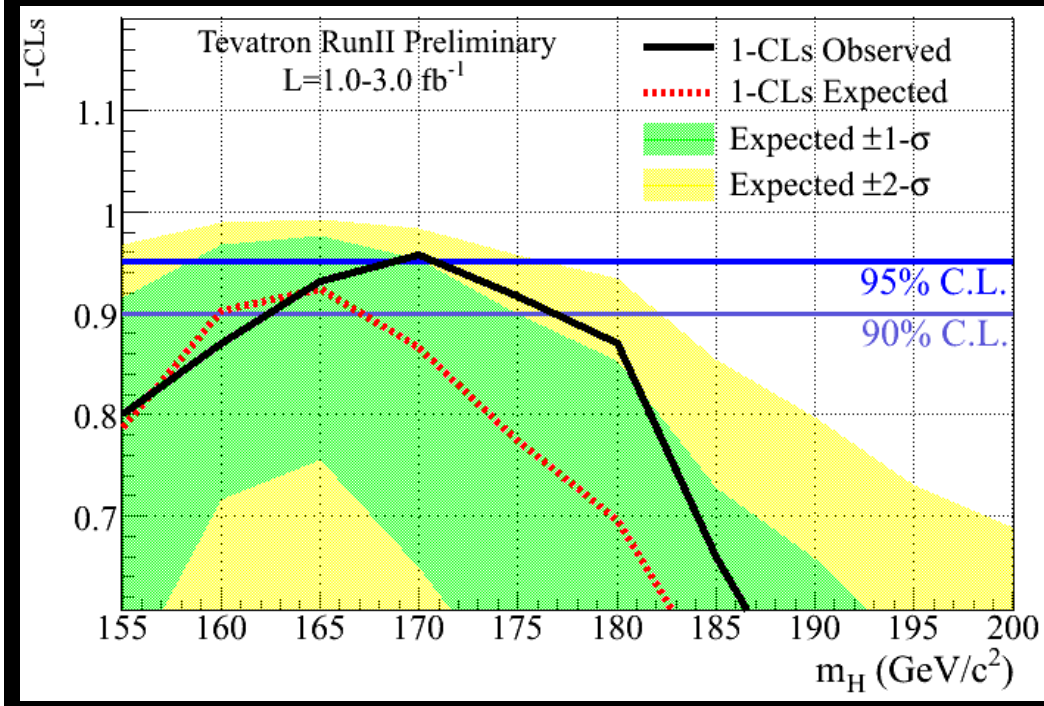
With 3/fb

M_H = 115 GeV/c^2

Channel	CDF Limits (expected)
WH $\rightarrow l\nu bb$	5.6 (5.7)
ZH $\rightarrow \nu\nu bb$	6.3(7.9)
ZH $\rightarrow llbb$	11.8 (11.6)
H $\rightarrow \tau\tau$	30.5 (24.8)
Combined	3.8 (3.6)
Tevatron Combined	In progress
H $\rightarrow WW^*$	1.6 (1.6)
Tevatron Combined	1.2 (1.0)

170 GeV/c^2

Future Prospects

We can extrapolate into the future…

1. With current analysis and just add more data
2. Extend the sensitivity for anticipated improvements