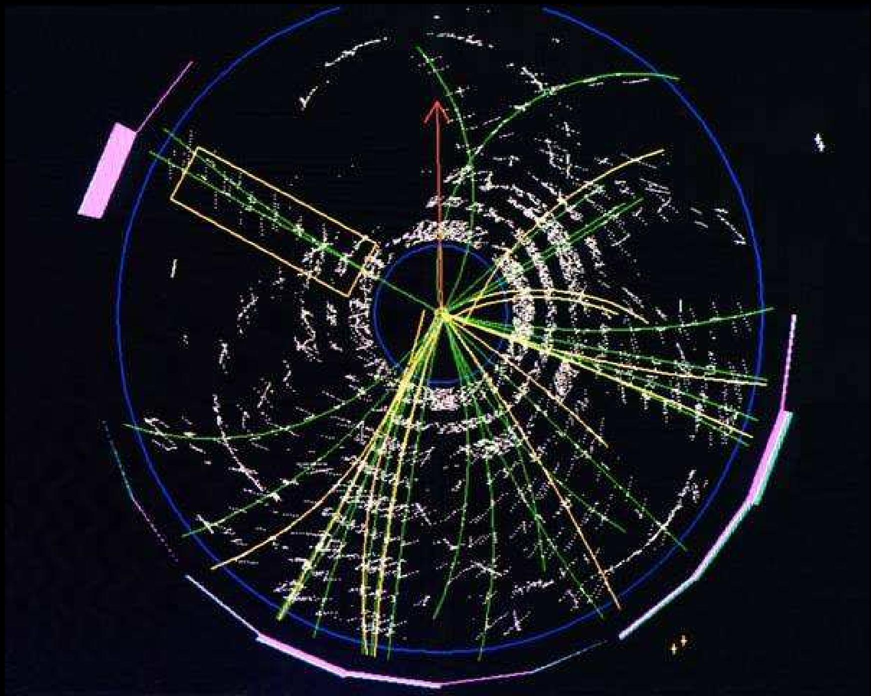
The Exciting Times at Fermilab

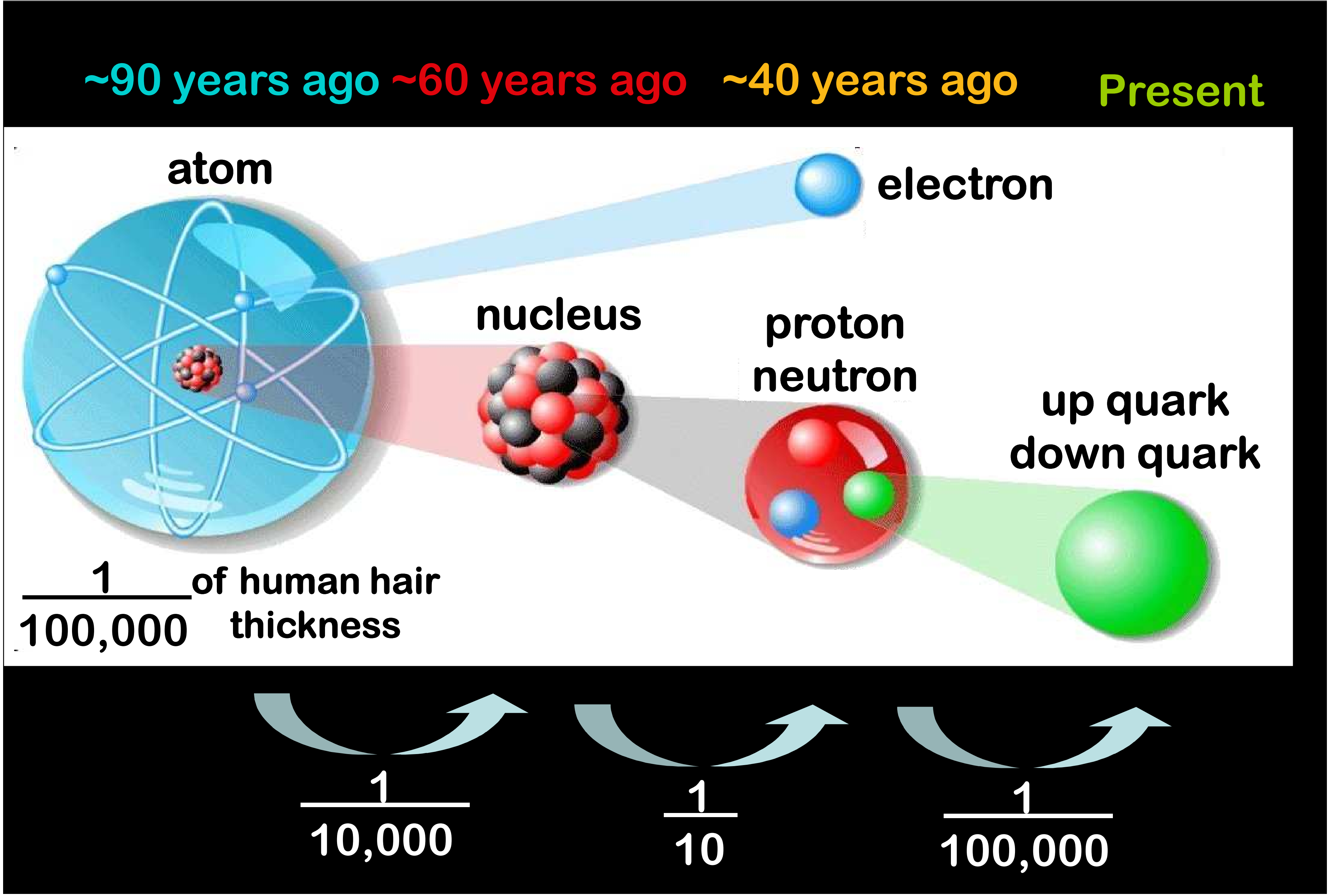
Robert Roser
Fermi National Accelerator Laboratory



Talk Outline

- Introduction to Particle Physics
- The Tools of the trade
- The Tevatron program and some recent exciting results
- The LHC – opening a new window
- The Intensity Frontier at Fermilab

The Past Century…

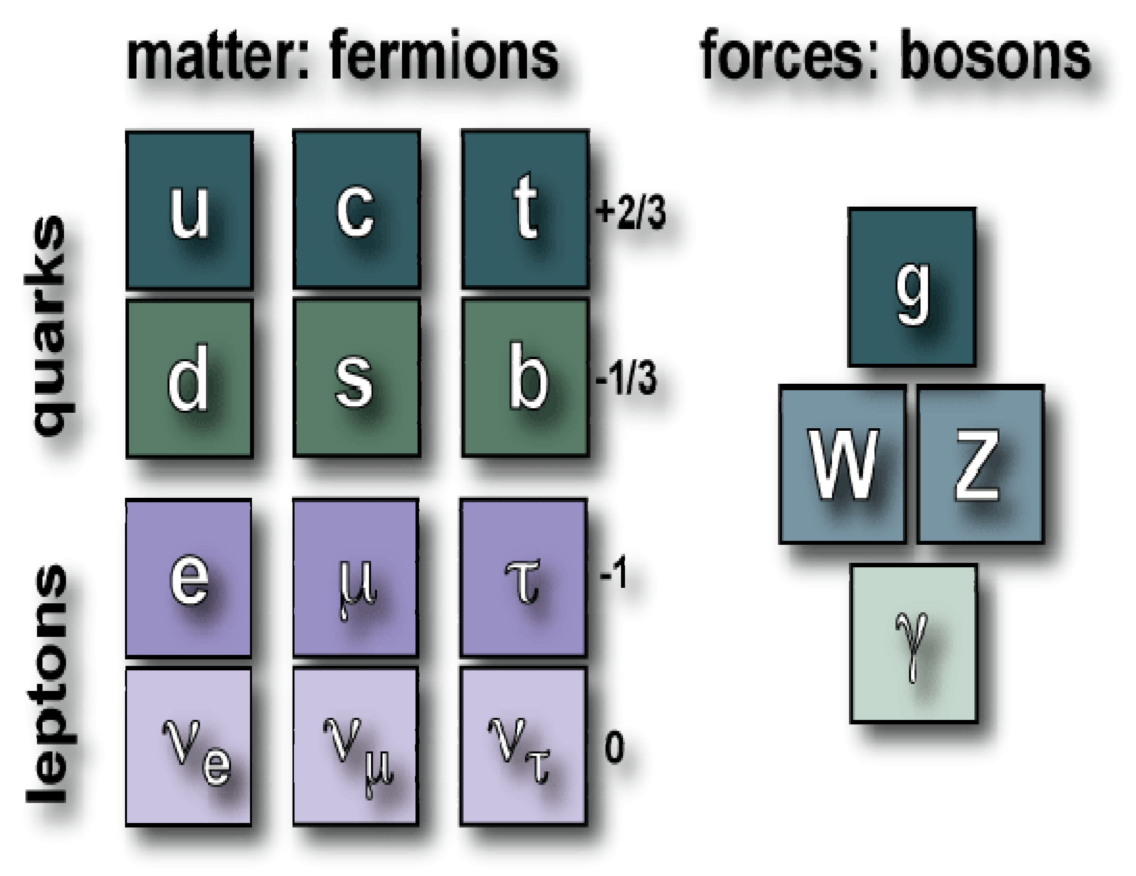


The Big Picture!

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

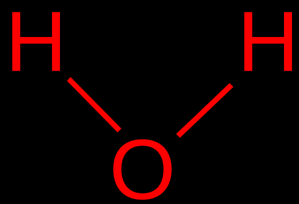
- World is comprised of quarks and leptons
- Each particle has its own anti particle
- Quarks have fractional charge!
- Good description of particles and their interactions
- Extensively tested

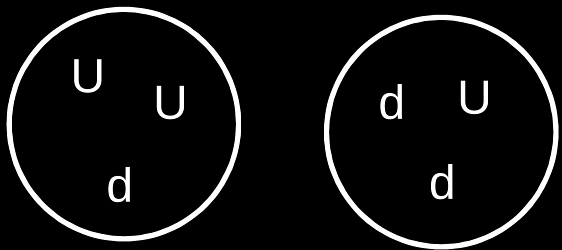
Periodic Table of the Particles



An example – Water!

- H_20





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

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

Hydrogen

Oxygen

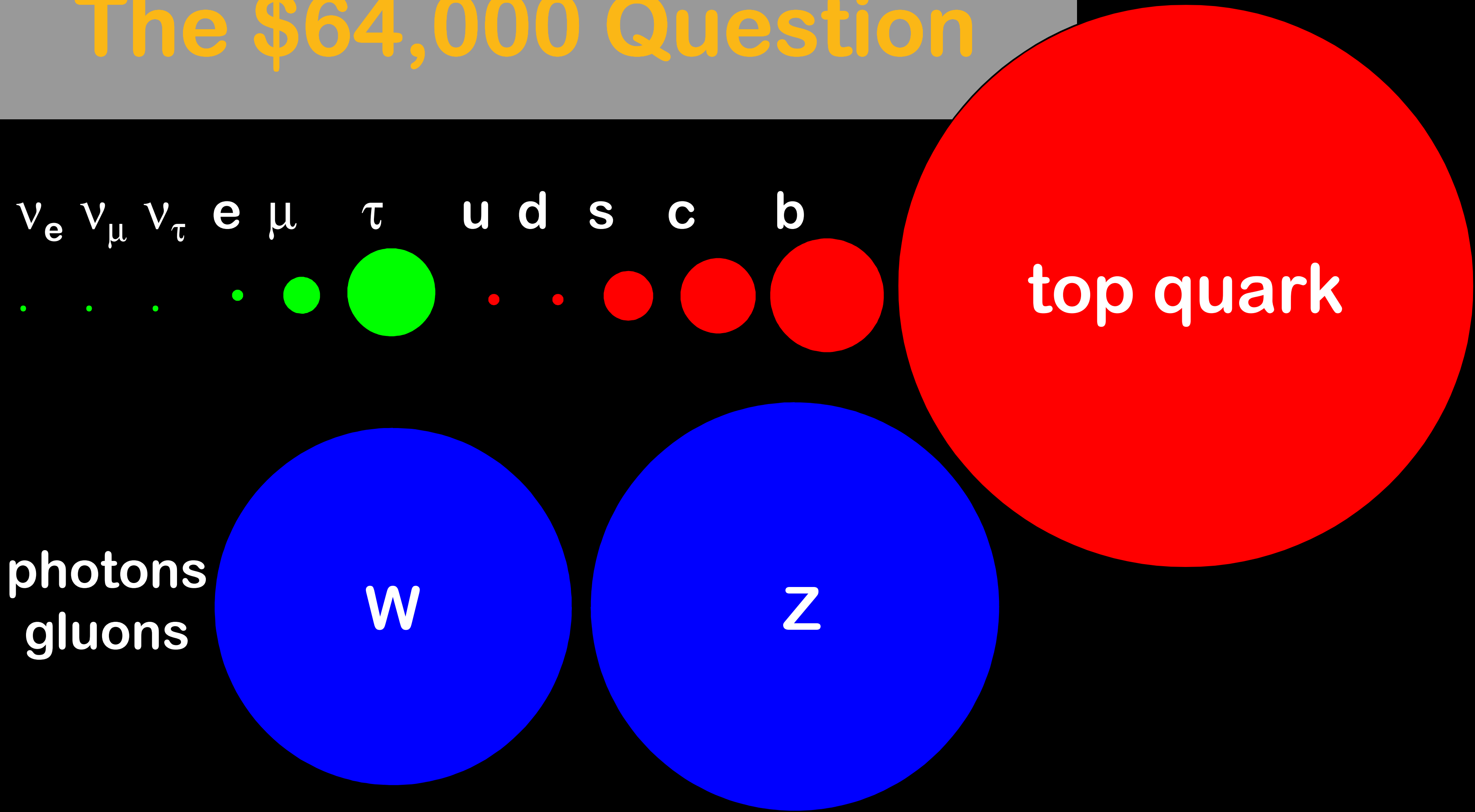
H_2O ➡ 28 Up Quarks

26 down quarks

10 electrons

BUILDING A UNIVERSE

The $64,000 Question



Why is top so heavy?

"Why are there so many particles?"

"Where does mass come from?"

Enter the Higgs Mechanism

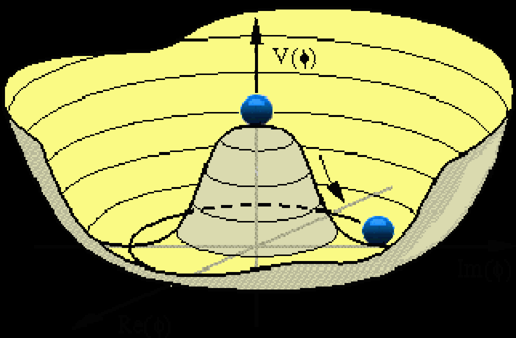
Popularity ∝ Mass

Analogy by Prof. David Miller
University College of London

Where Do Particles Get Their Mass?

The Solution: The Higgs Boson

- Add scalar field throughout the universe
  - Potential is symmetric
  - Ground state breaks symmetry

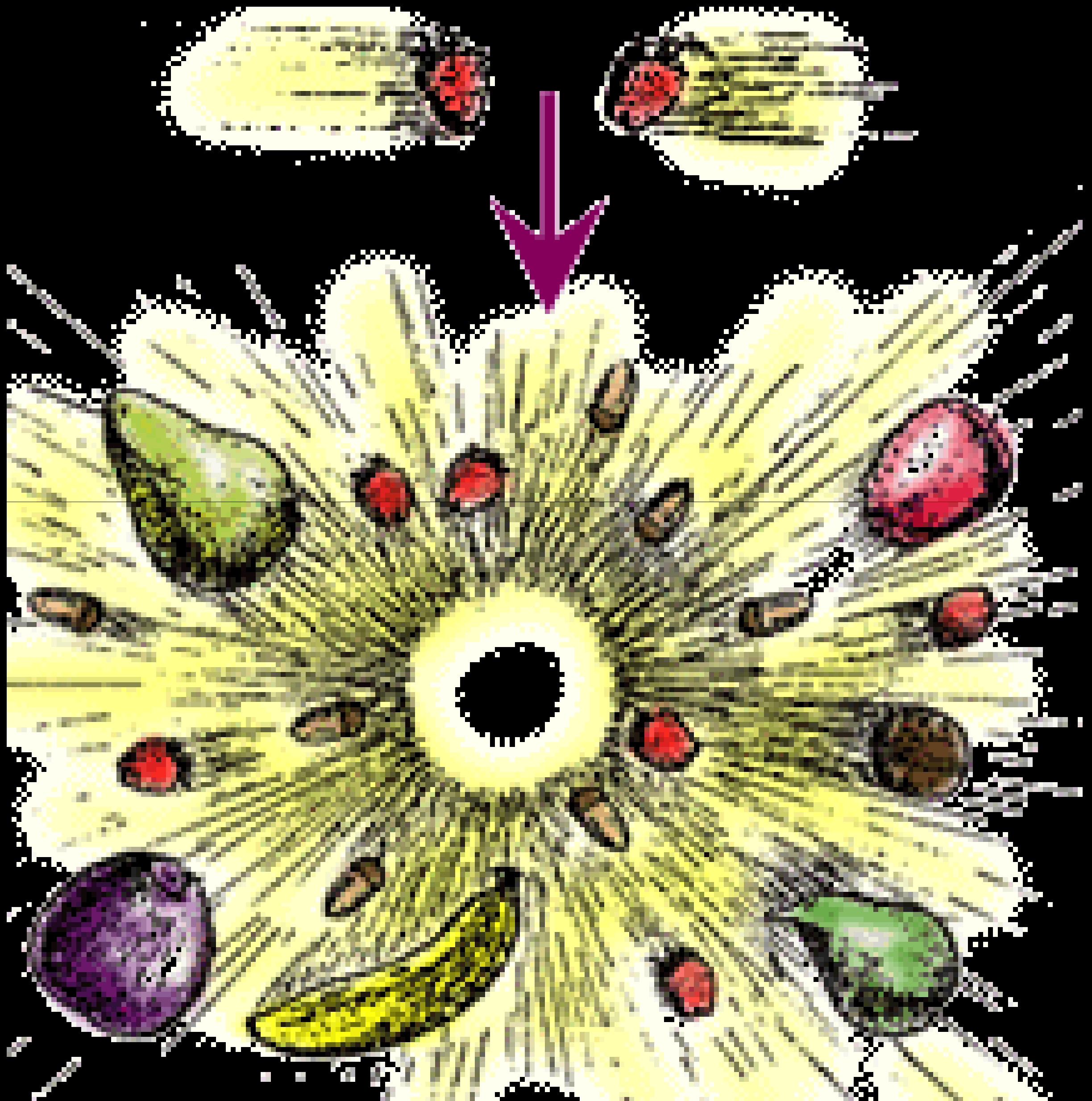


- Cleverly
  - Masses are generated for the fermions due to their interaction with this non-zero field
  - Theory preserves symmetry (gauge invariance)
  - Standard Model calculations no longer fail
  - A new particle is predicted: the Higgs boson

- Finding the Higgs boson
  - Means Higgs field exists
    - Means we confirm our theory for the origin of mass

How does one search for something new?

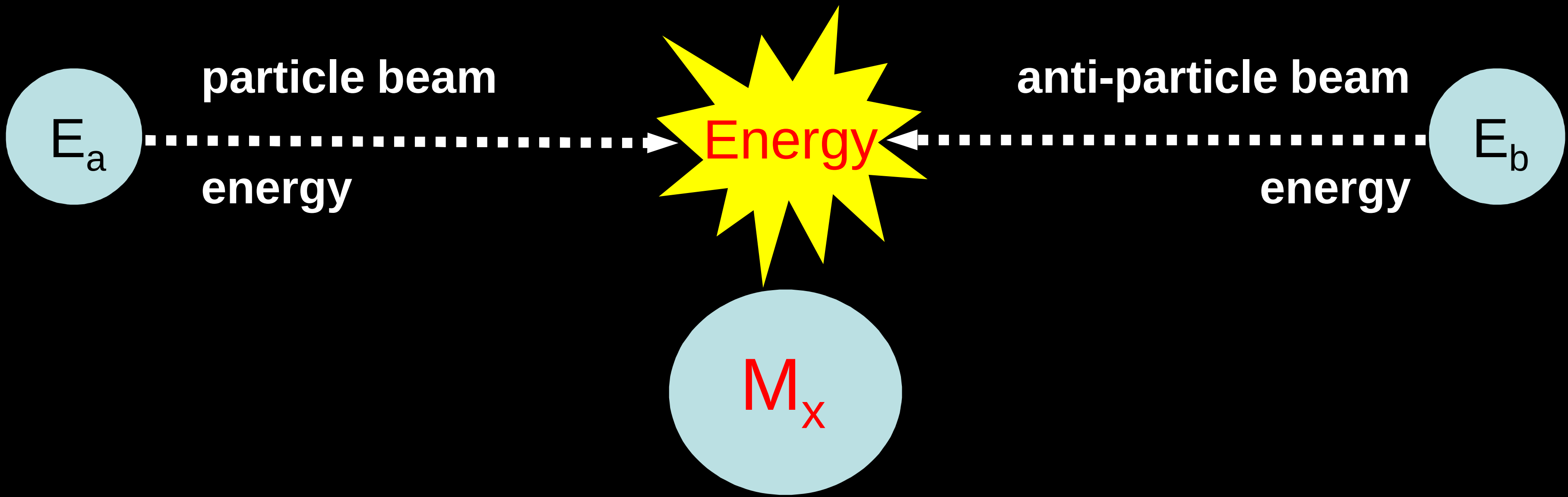
Fruit Salad?



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

$$E = mc^2$$



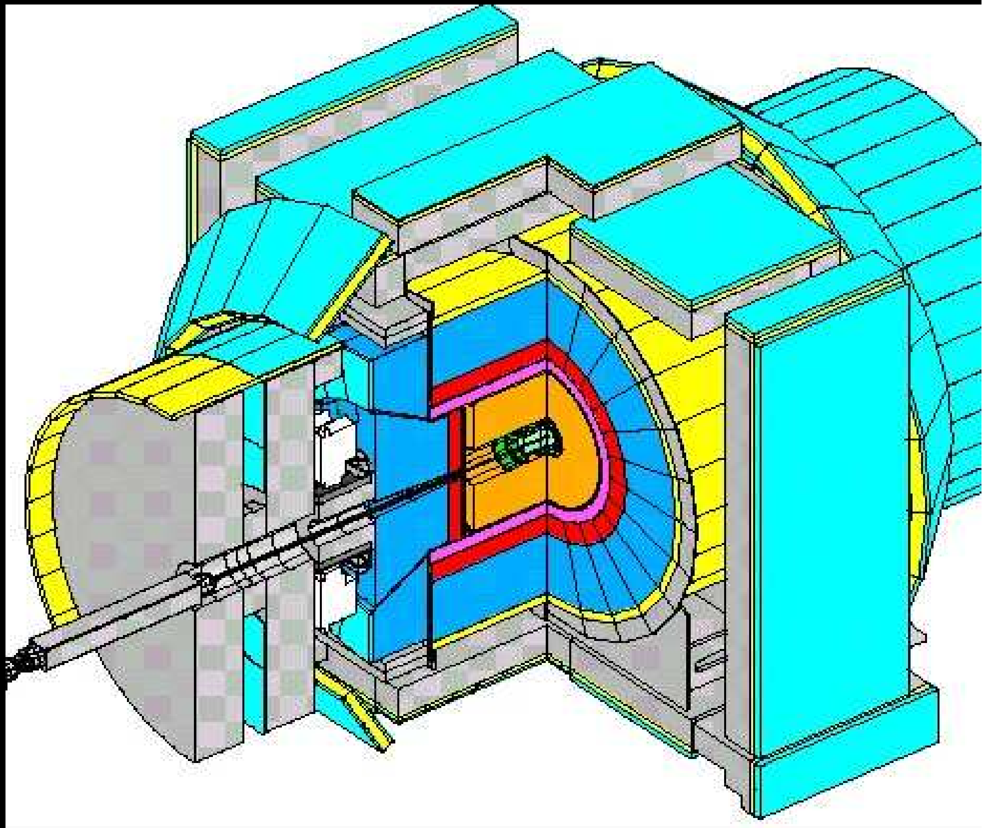
As long as $E_a + E_b >> M_x c^2$

America's Most Powerful Accelerator: Fermilab's Tevatron

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



Collecting the Data You Want!

- The Collider Challenge
  - 1.7 Million Collisions/second inside our detectors
- Detectors
  - Very complicated with lots of information available on each collision
- The problem
  - You can't write out each collision to tape!
  - Don't worry – not every collision is interesting and warrants saving…
- The Solution
  - A Device called a "trigger"
  - Examines every event in real time and identifies the most "interesting"
  - Reject 99.991% of events and collect data at ~50-100 hz

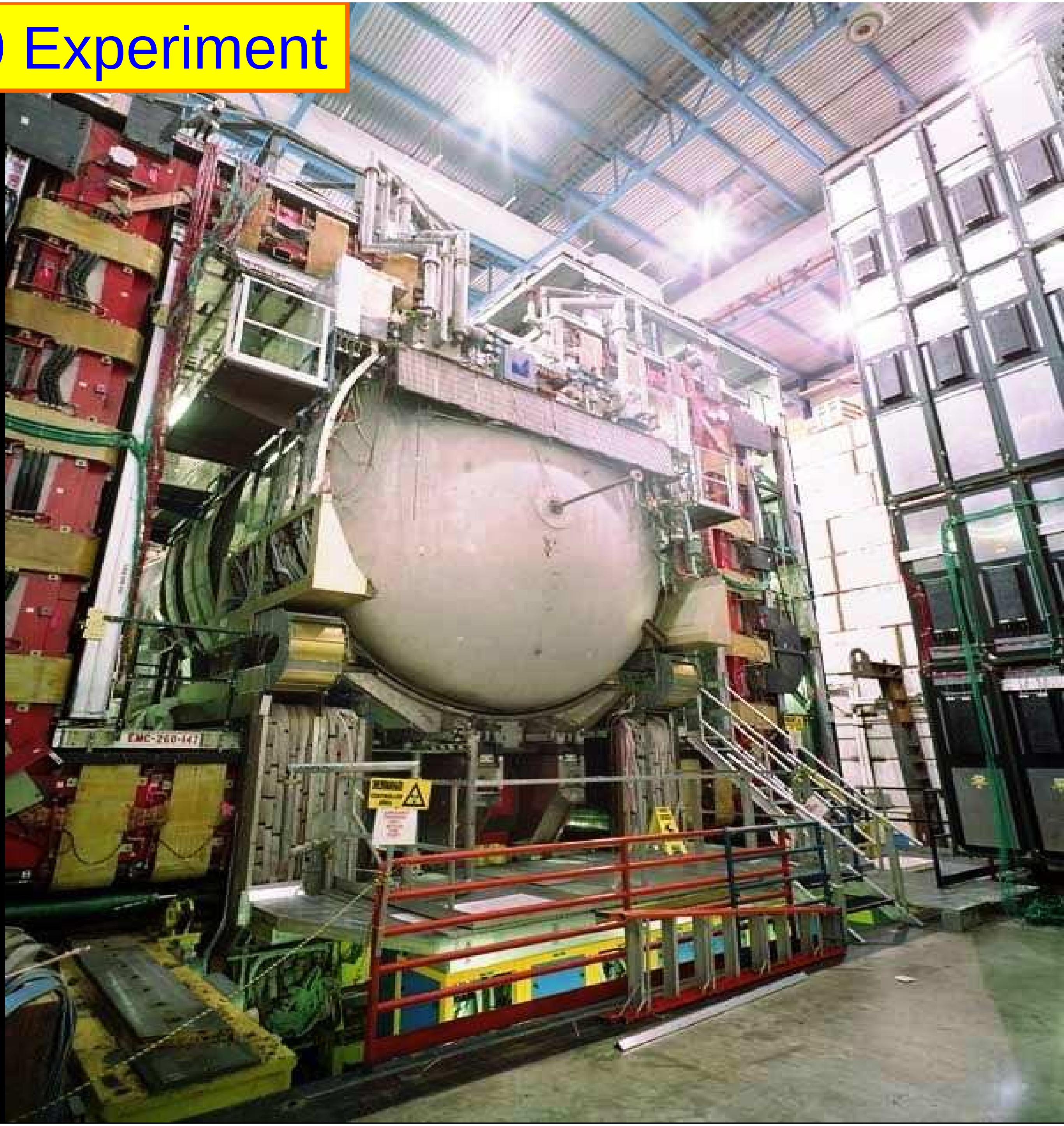
The Life of an Experimentalist…

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

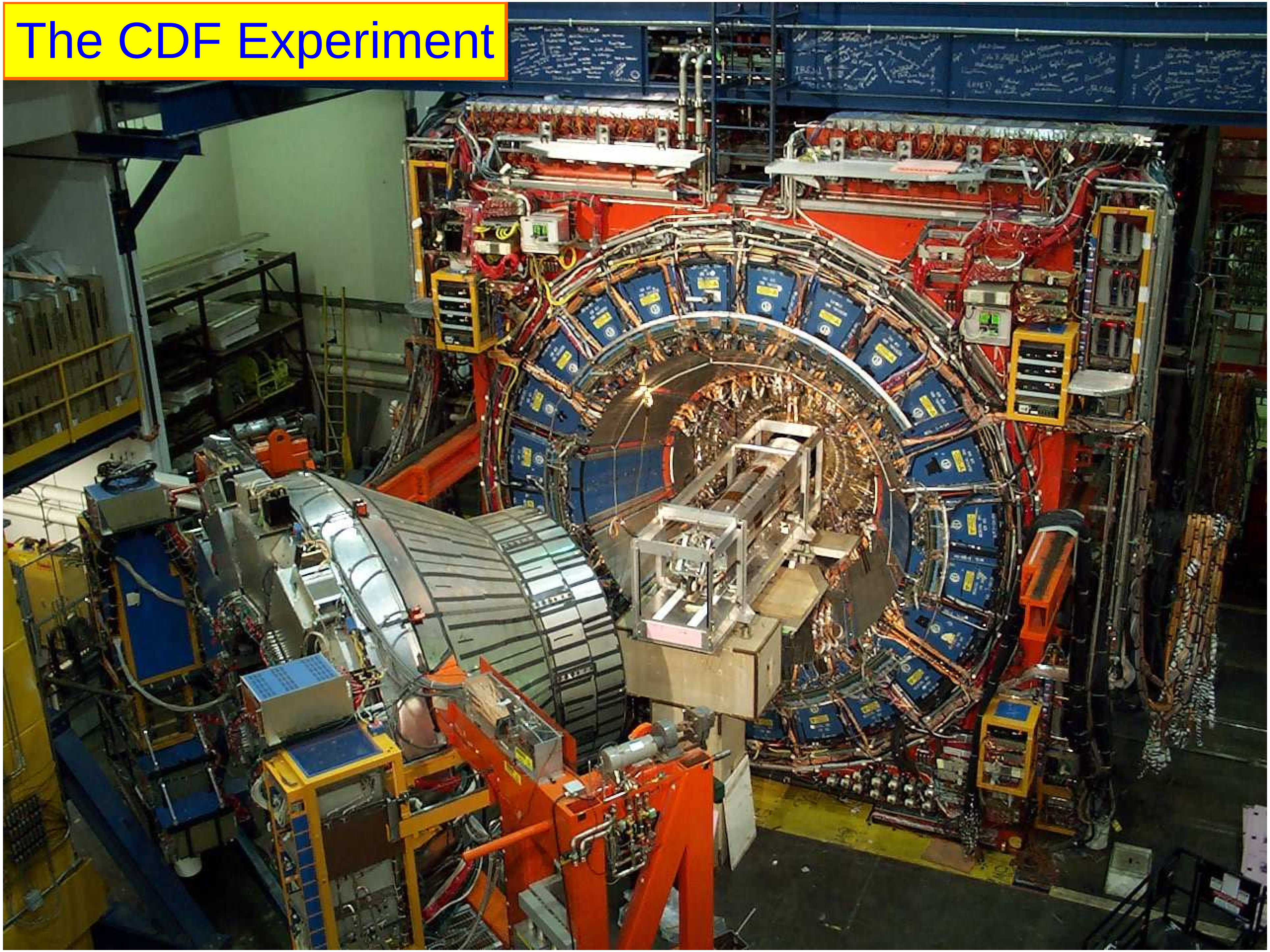
- What do we know?
  - Conservation of Energy
  - Conservation of Momentum
  - $E=mc^2$
- What do we want to identify?
  - Electrons
  - Muons
  - Quarks
  - Neutrinos
  - b quarks

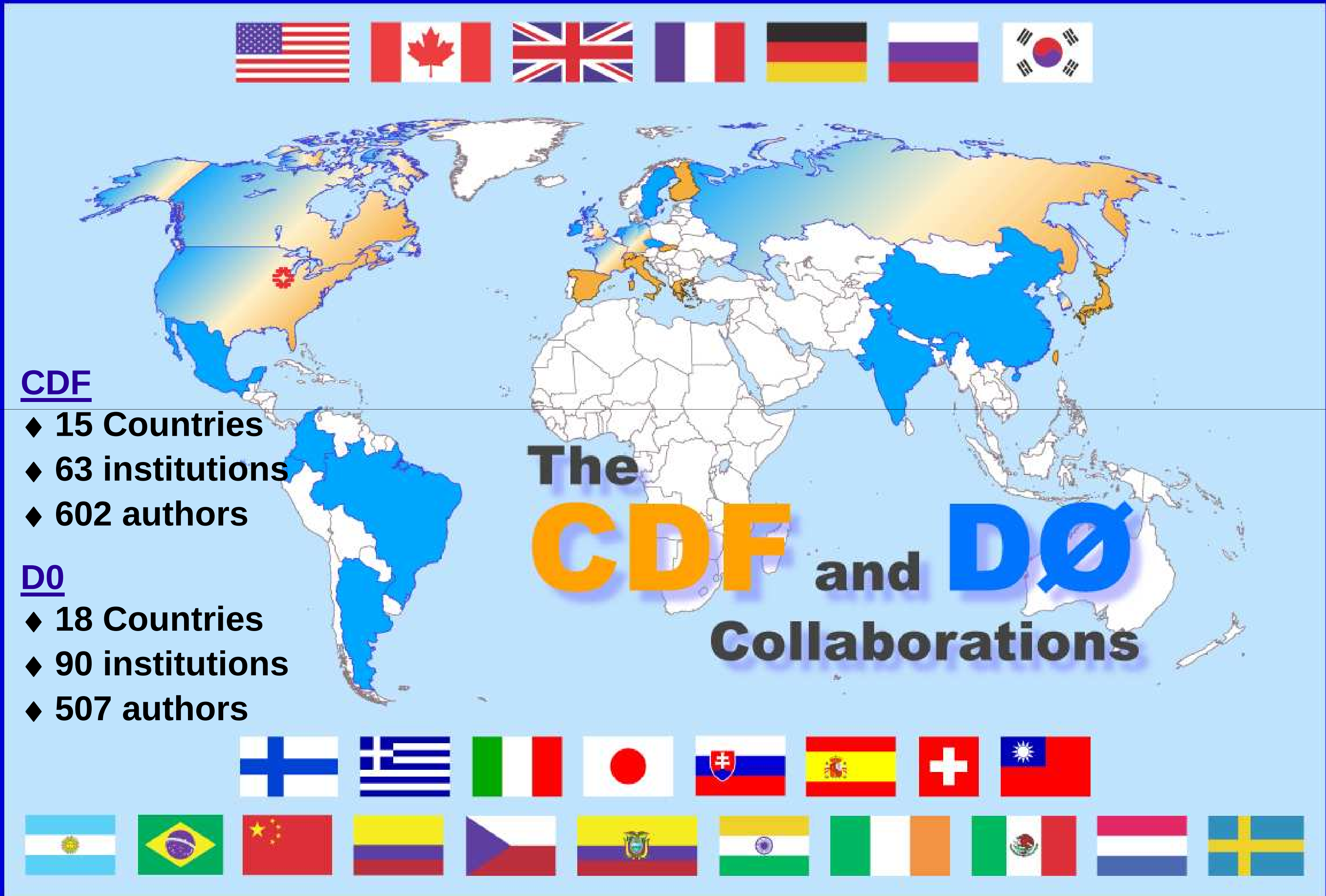
(Helps!)

The D0 Experiment

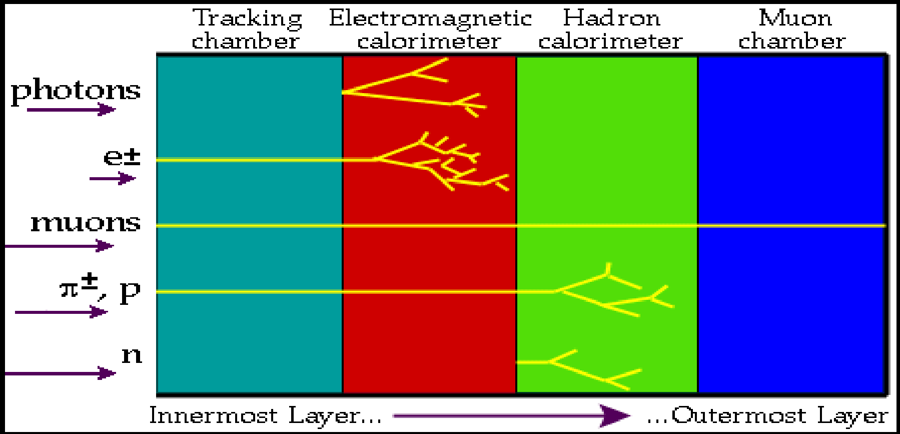


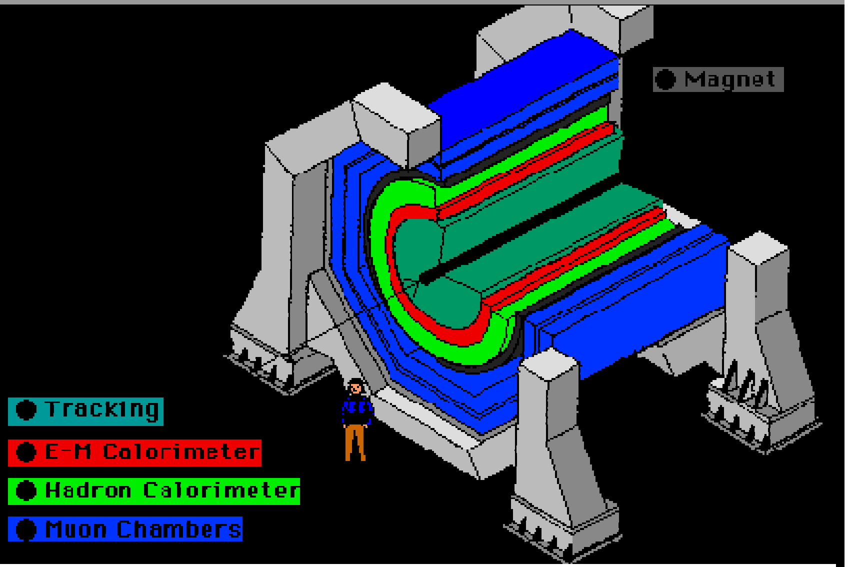
The CDF Experiment




The CDF and DØ Collaborations
CDF
♦ 15 Countries
♦ 63 institutions
♦ 602 authors
D0
♦ 18 Countries
♦ 90 institutions
♦ 507 authors

Principle of a Collider Detector

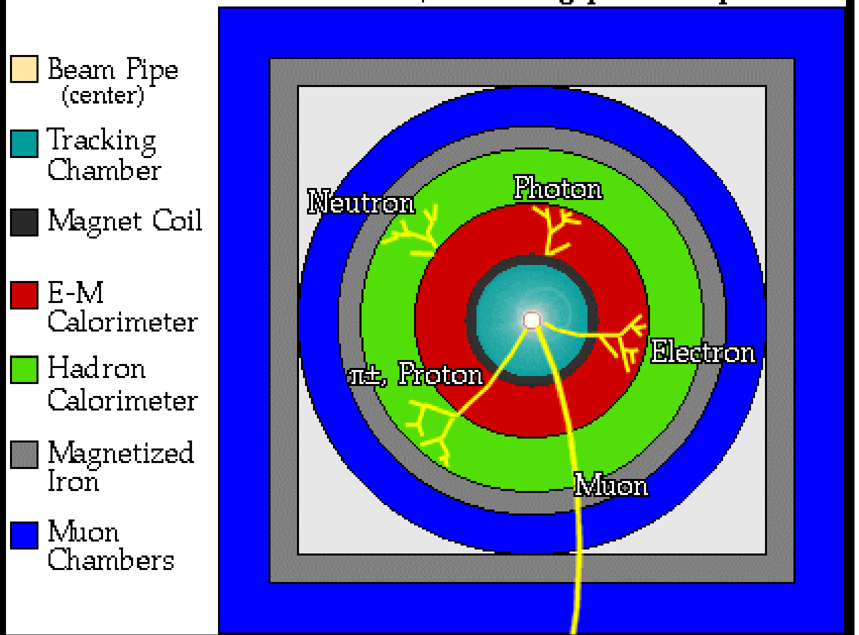


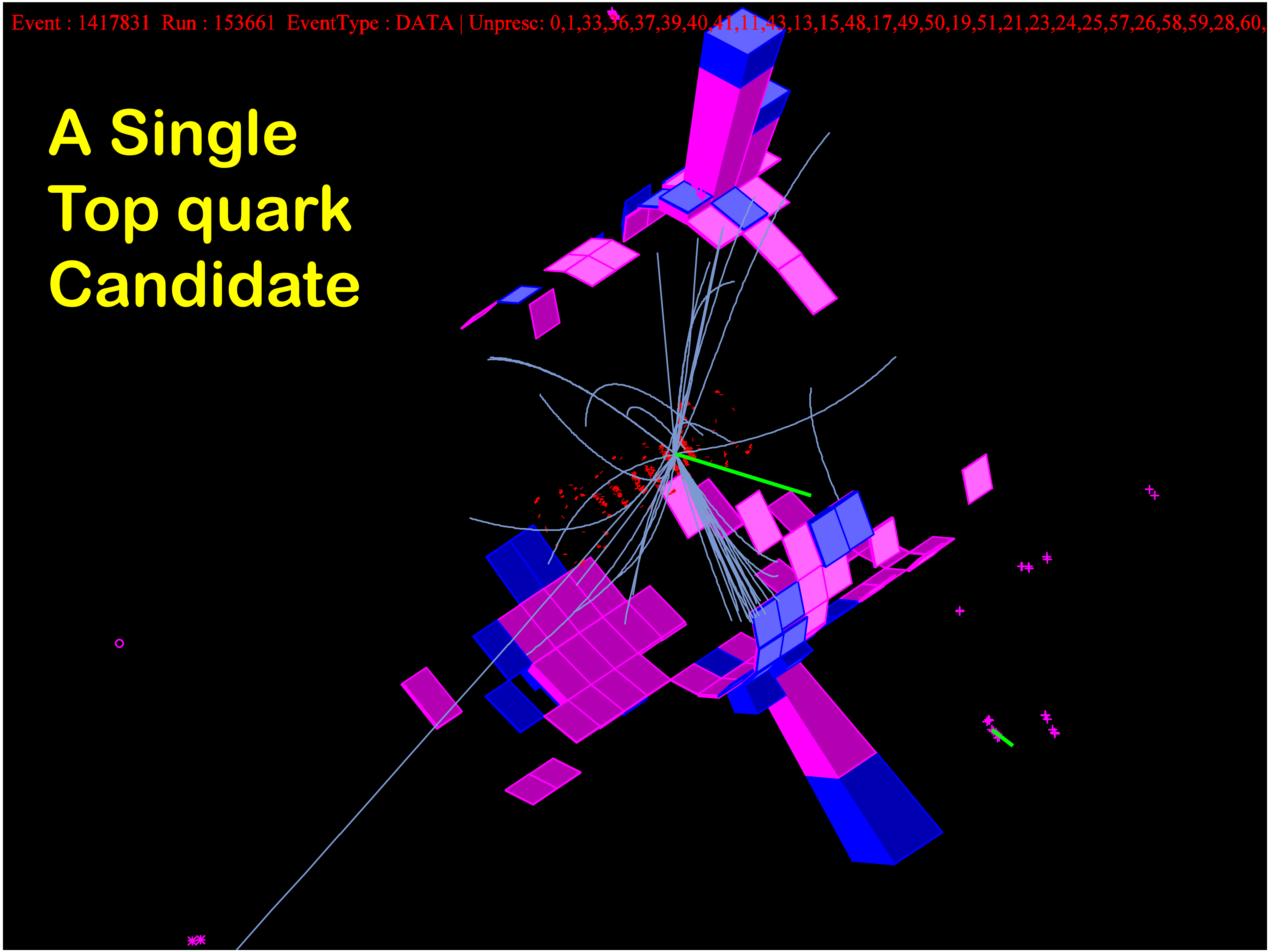


Basic principle is the interaction of particles with matter

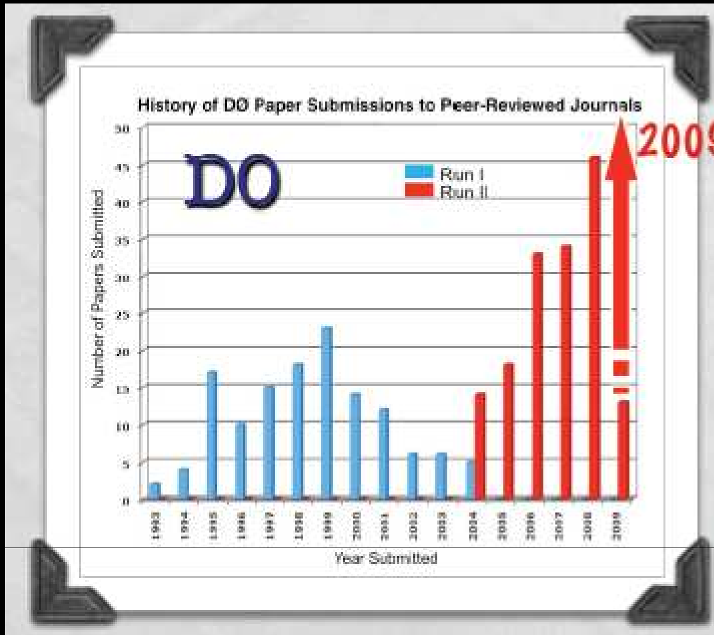
- **Momentum/Charge Measurement:**
  - need to affect particle as little as possible
  - use dilute/thin absorber medium (gas, thin silicon wafers): Tracker
- **Energy Measurement:**
  - want to fully absorb particle
  - use thick absorber medium (lead, steel, uranium): Calorimeter

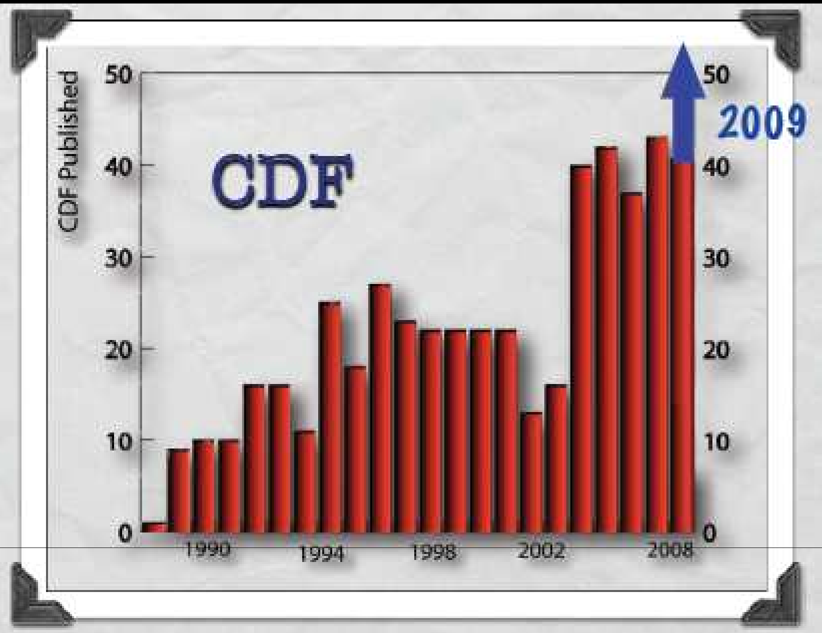
A detector cross-section, showing particle paths




Event : 1417831 Run : 153661 EventType : DATA | Unpresc: 0,1,33,36,37,39,40,41,11,43,13,15,48,17,49,50,19,51,21,23,24,25,57,26,58,59,28,60,
A Single
Top quark
Candidate

Tevatron Physics Output





Tevatron Experiments publishing >100 papers/year

Over the last few years, ~60 PhD’s/year

Present >200 talks at conferences each year

The Tevatron Research Program

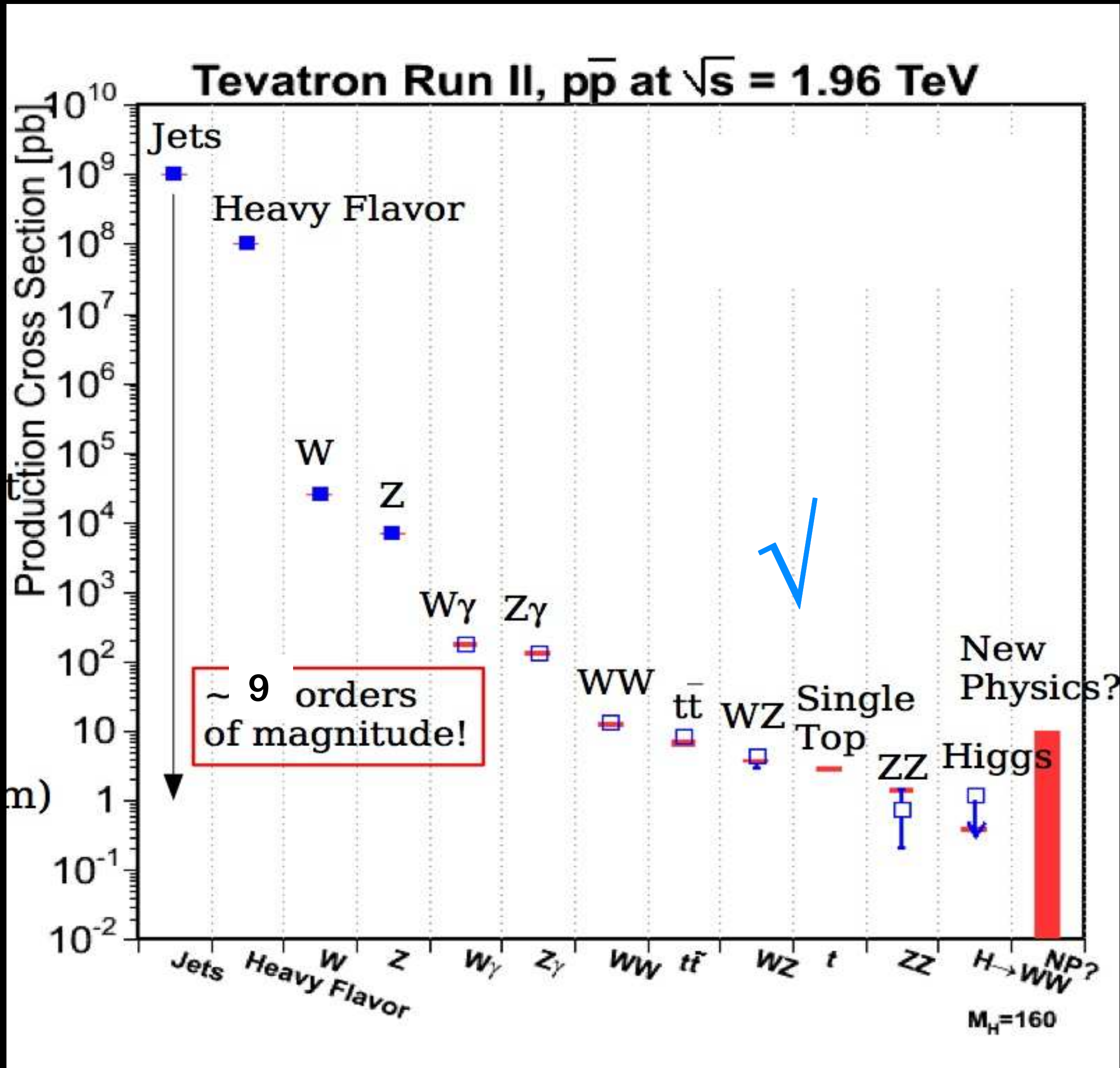
Precision, New Research Discoveries

- Mixing, CKM Constraints and CP Violation
- Heavy Flavor Spectroscopy
- New Heavy Baryon States
- Tests of Quantum Chromodynamics
- Precise measurement of Top-quark and W-boson Masses
- Top Quark Properties
- Di-Boson production and SM Gauge Couplings
- New Exclusive/Diffractive Processes

Unique Window into the unknown

- Searches for Supersymmetry, Extra Dimensions, Exotica
- Still at the Energy Frontier
  - Proobing the Terascale as the luminosity increases
- The Standard Model BEHHGK (Higgs) Boson is within reach!

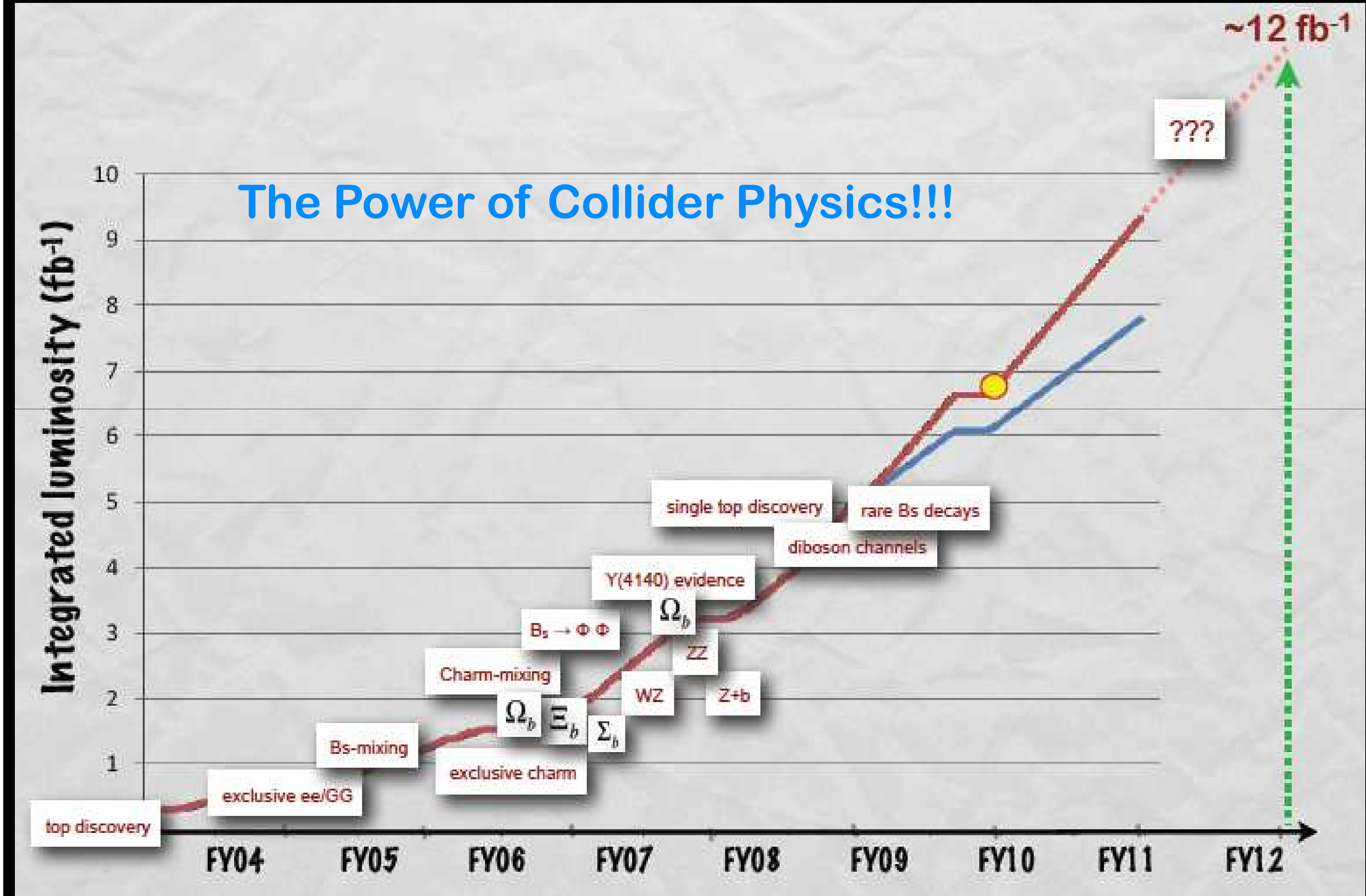
A Roadmap to discovery…



Harder to Produce

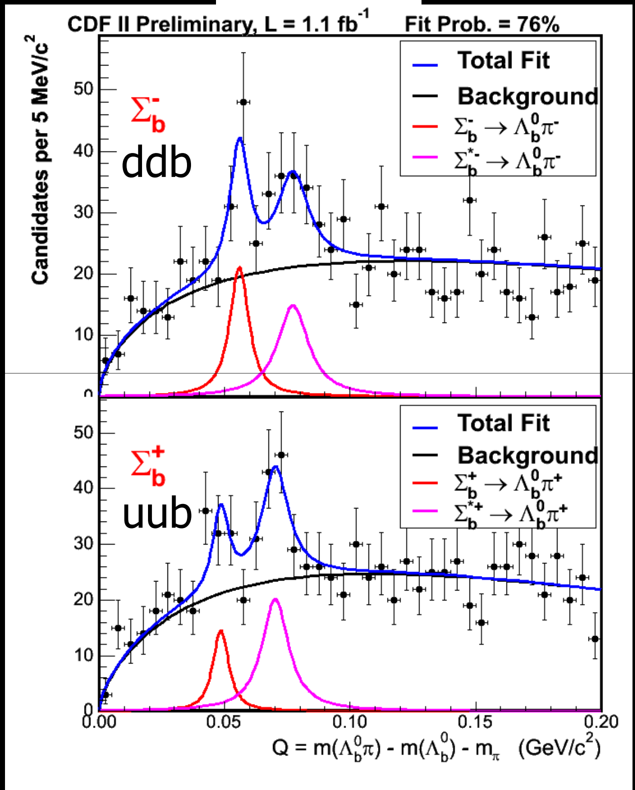
Harder to Observe

New Physics Shows Up Throughout

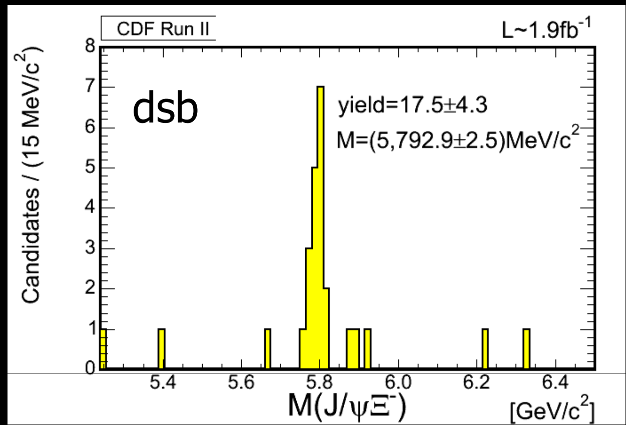


Observation of new heavy baryons

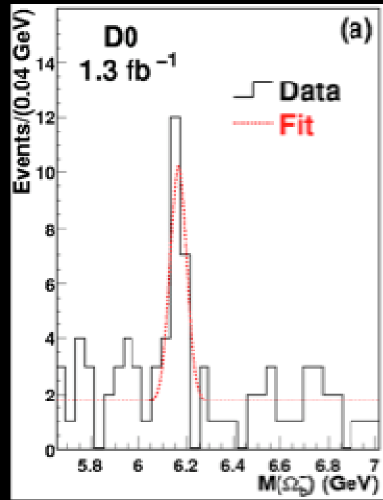
Σ_b

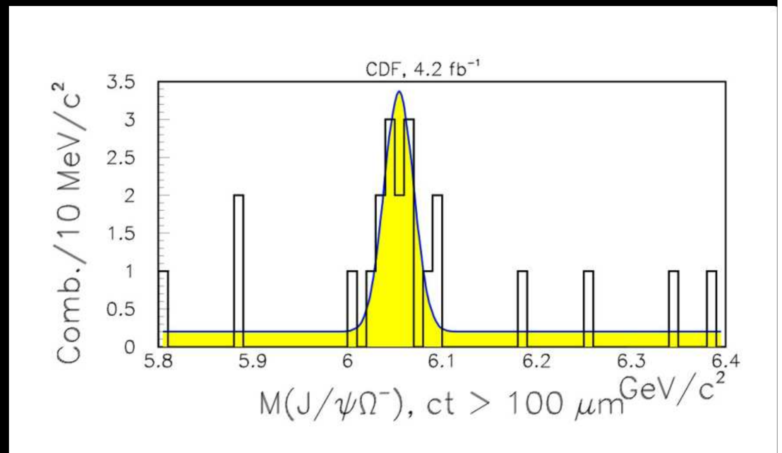


Ξ_b



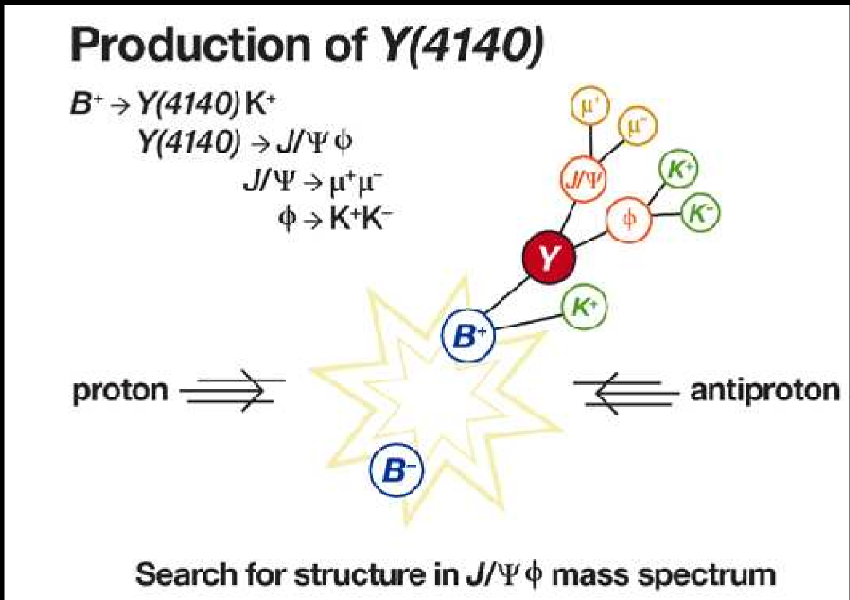
Ω_b

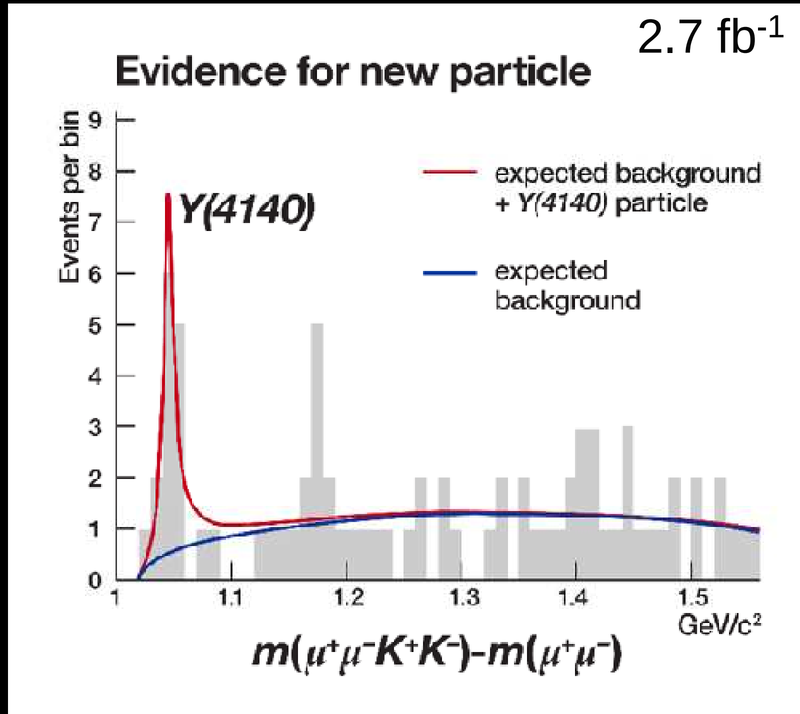




With more data : emergence of a new particle

Y(4140) unknown composition

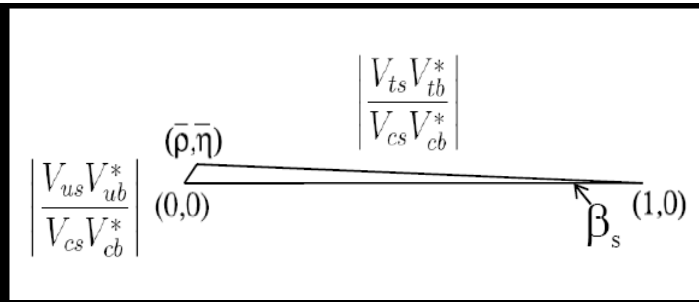


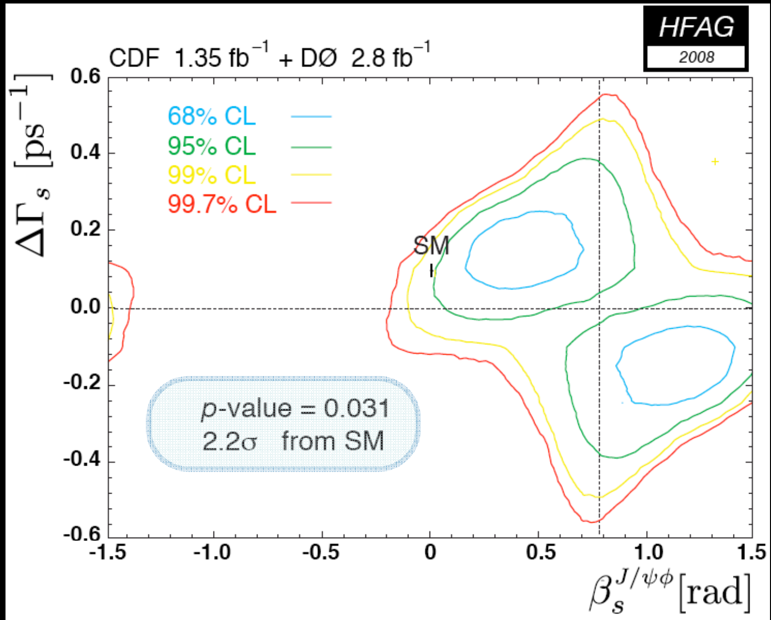


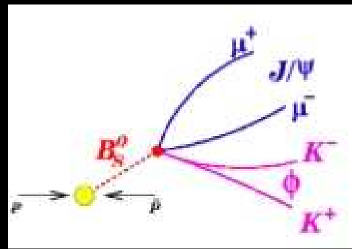
2009

These new discoveries yield a few events/fb^{-1} ==> new areas of research @ 10 fb^{-1}

Precision: CPV phase Sin(2β_s)



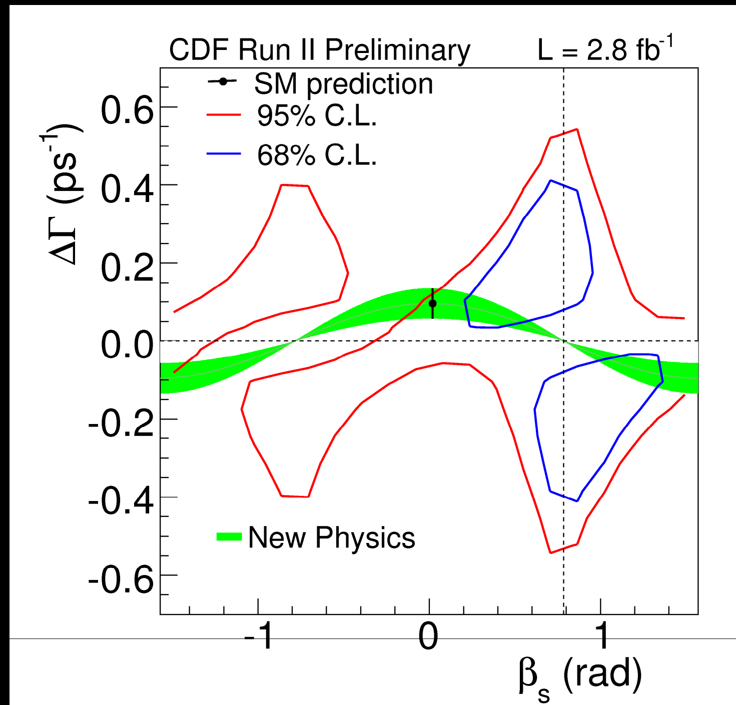




Combination of CDF and D0 results is incompatible with the SM at the 2.2-sigma level

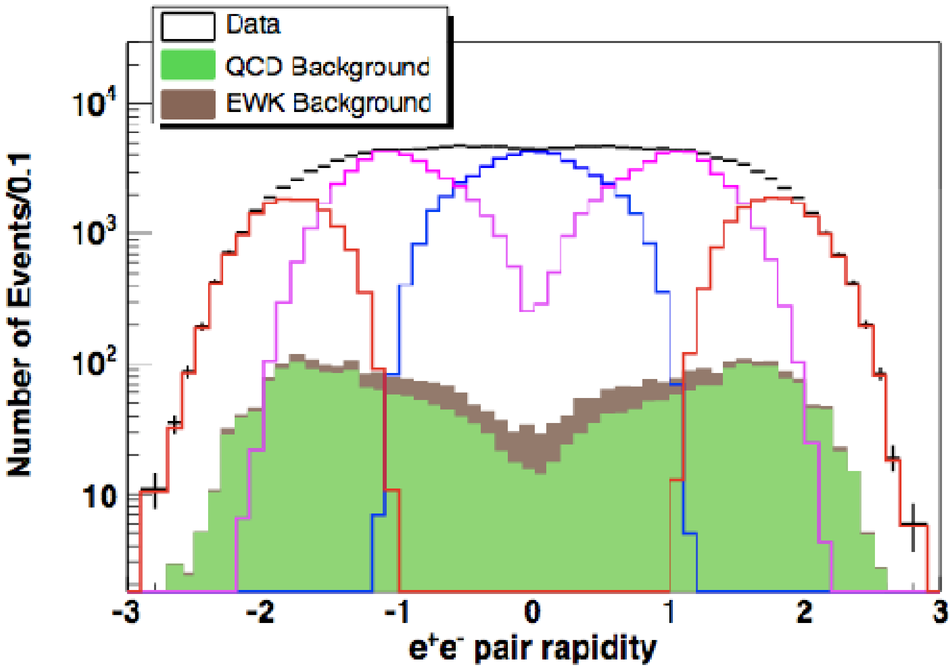
CDF: updated result with 2.8 fb^{-1}
Inconsistency with SM increased
(p-value from 0.15 to 0.08, corresponding to 1.8 standard deviations)

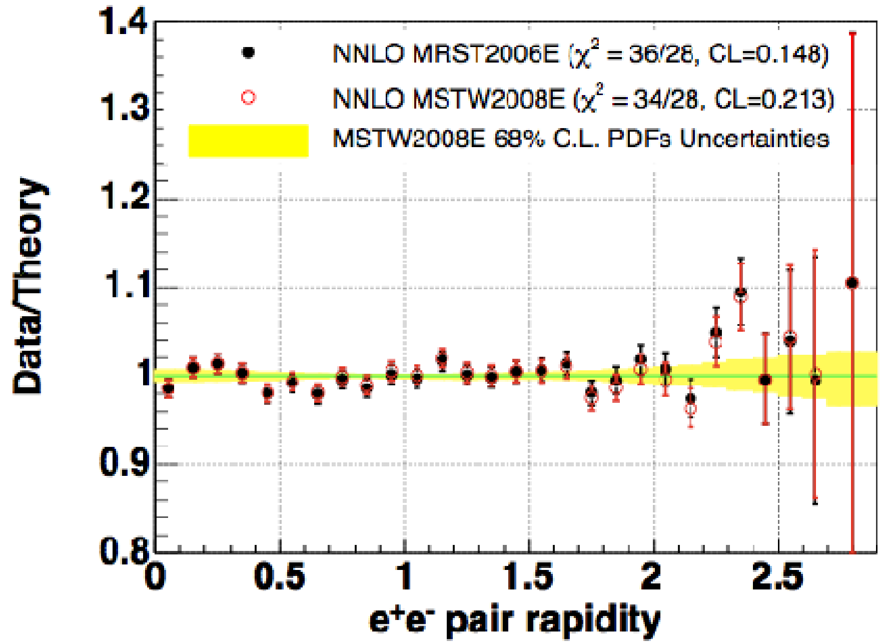
More data to come, look also in other channels (asymmetry in semileptonic decays)



Z Rapidity

- HERA F_2 / jet & Tevatron jet & W/Z data necessary for accurate PDFs for robust LHC predictions
- Z rapidity in 2.1 fb^{-1} using $Z \rightarrow ee$



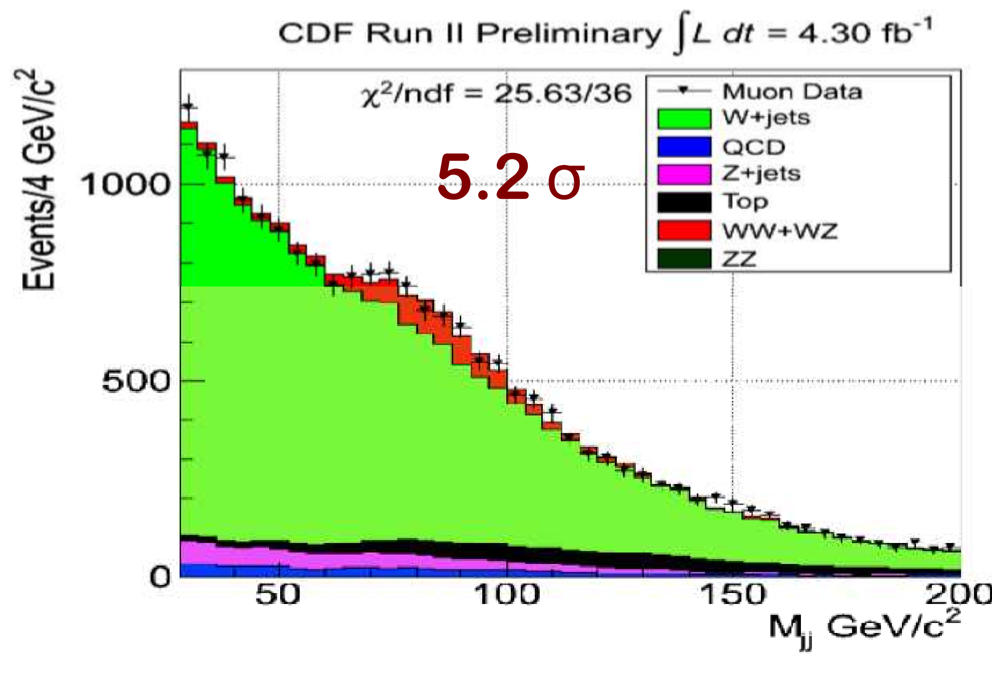


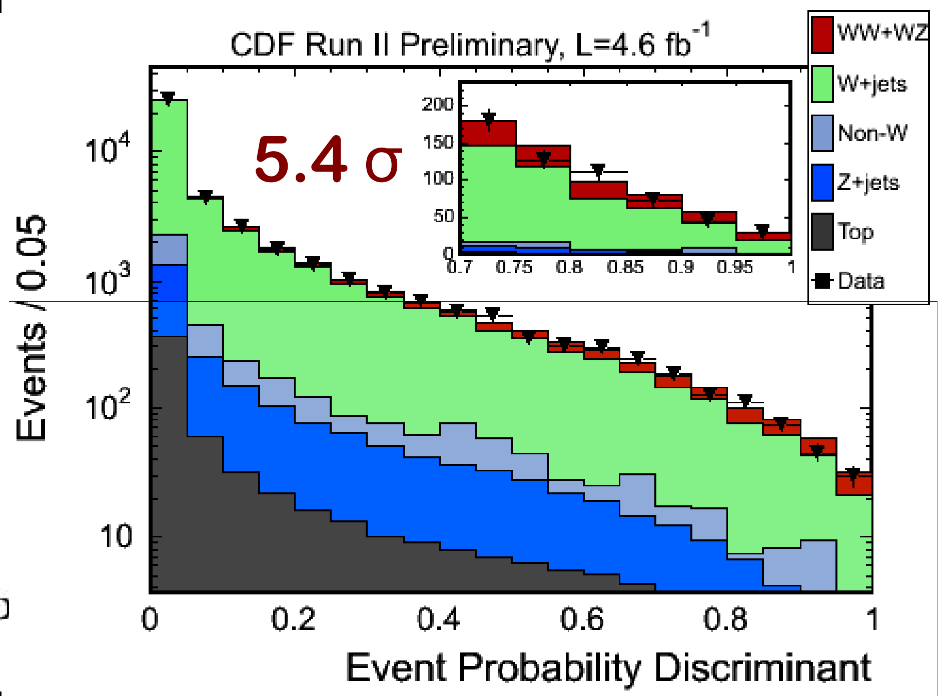
$\sigma = 256.6 \pm 0.7_{stat} \pm 2.0_{sys}$

$\sigma(y>0) = 256.4 \pm 1.0_{stat}$
$\sigma(y<0) = 256.9 \pm 0.9_{stat}$

Di-bosons

- WW/WZ lepton + Jets observations
- Using m_{jj} and matrix element techniques with 4.3-4.6fb^{-1}

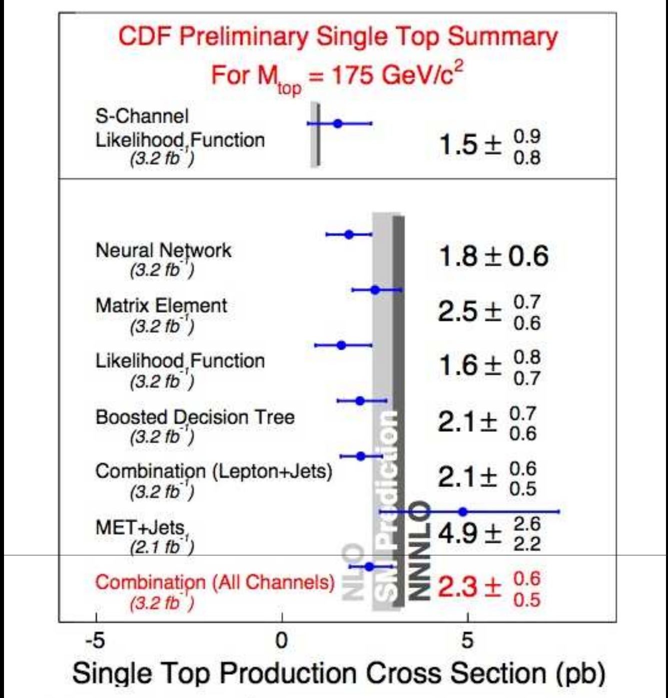


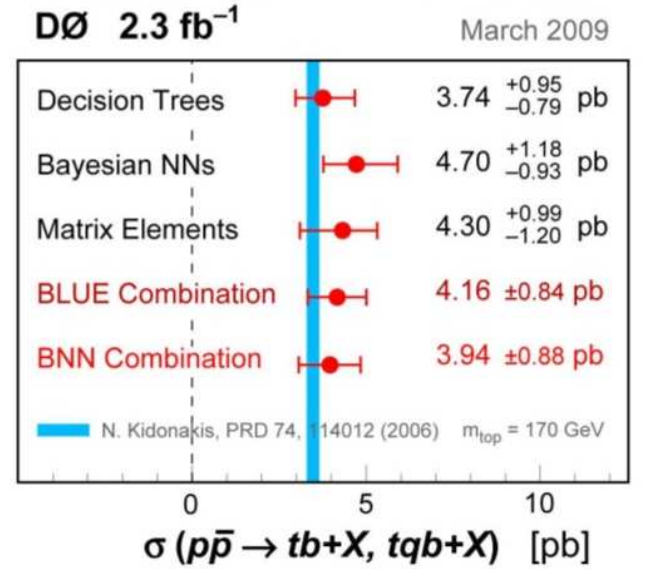


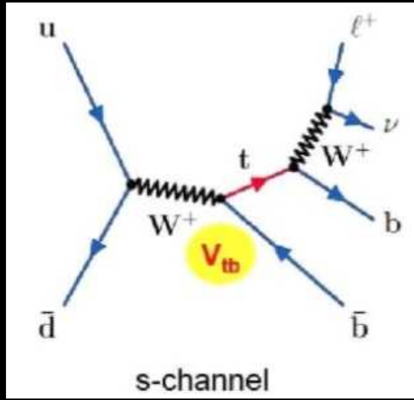
$\sigma = 18.1 \pm 3.3_{stat} \pm 2.5_{sys}$

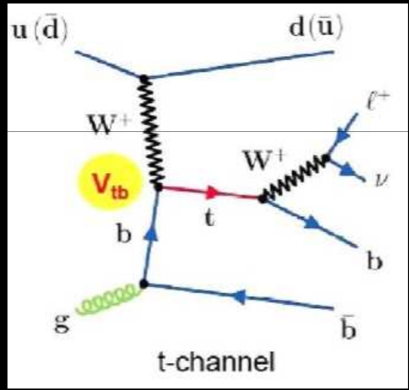
$\sigma = 16.5 +3.3-3.0 \pm 3.5_{sys}$

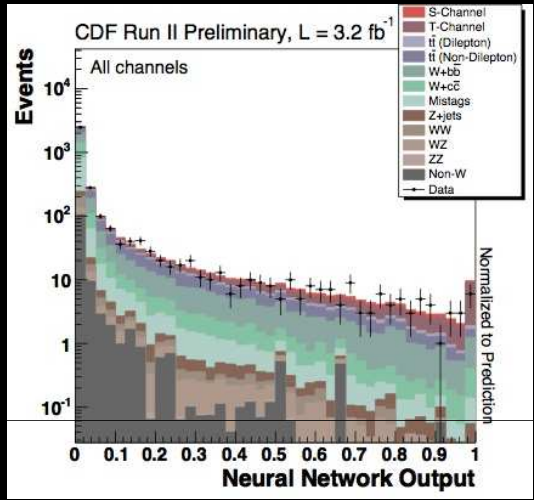
Recent discovery: single top







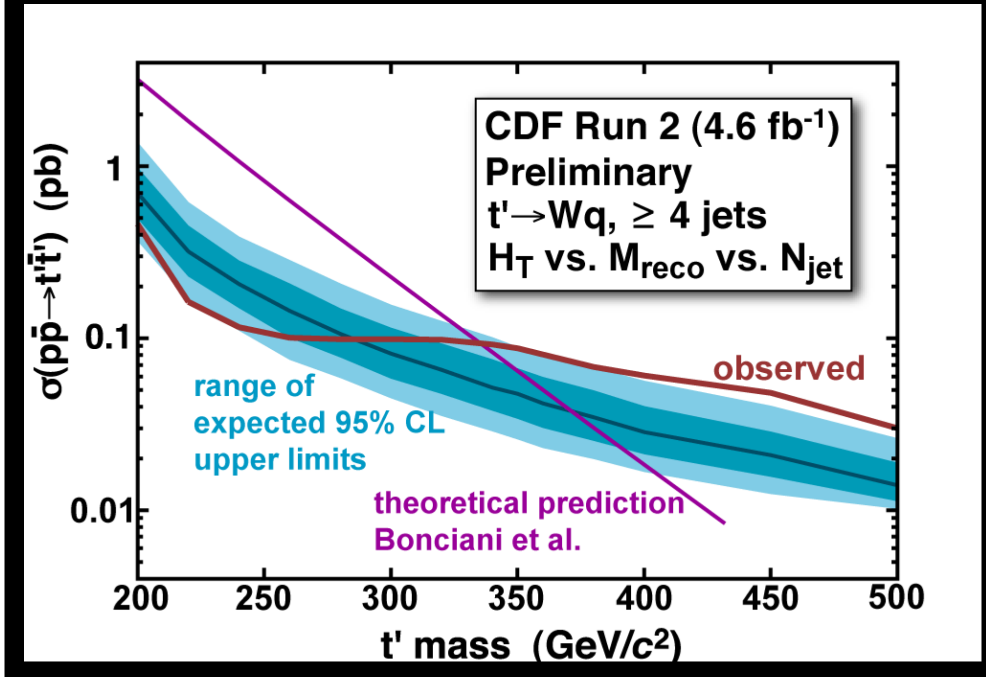


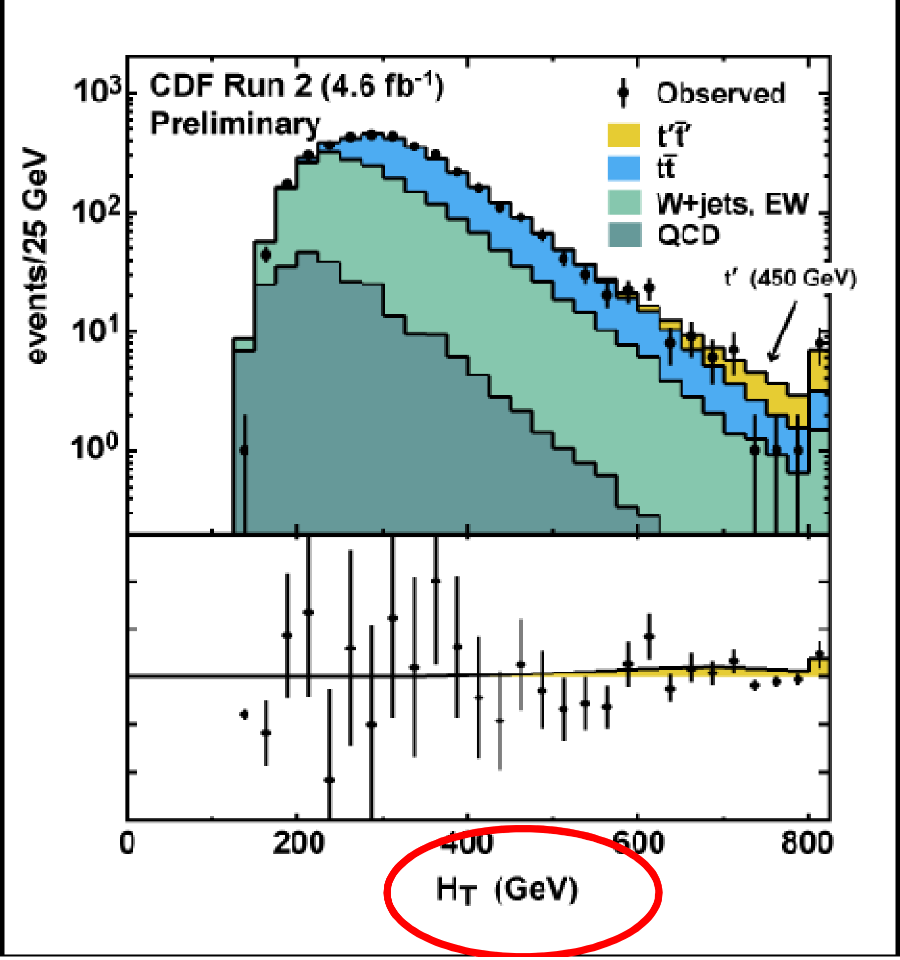


- **Single Top Physics Program**
  - Test s vs t [new physics]
  - Vtb [precision]
  - Lifetime [new physics]

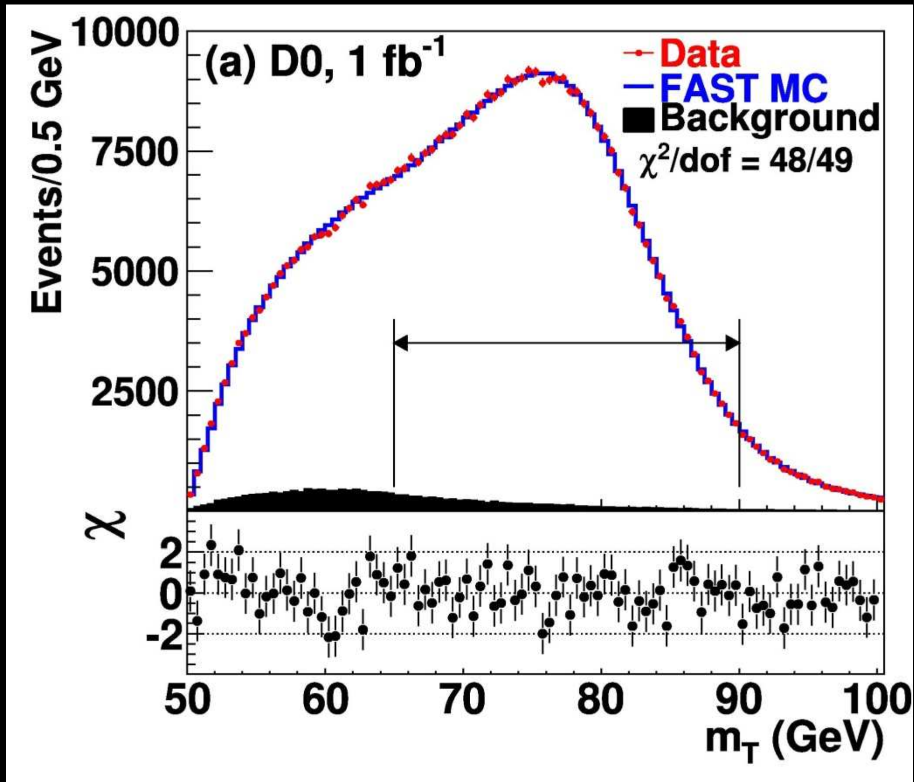
t’ Search

- Search for heavy top $t' \rightarrow Wq$
  - Leptons +Jets events with 4.6/fb
  - Reconstruct mass of t’ and search in H_T and $m_{t'}$
  - May occur in little Higgs, forth generation, …

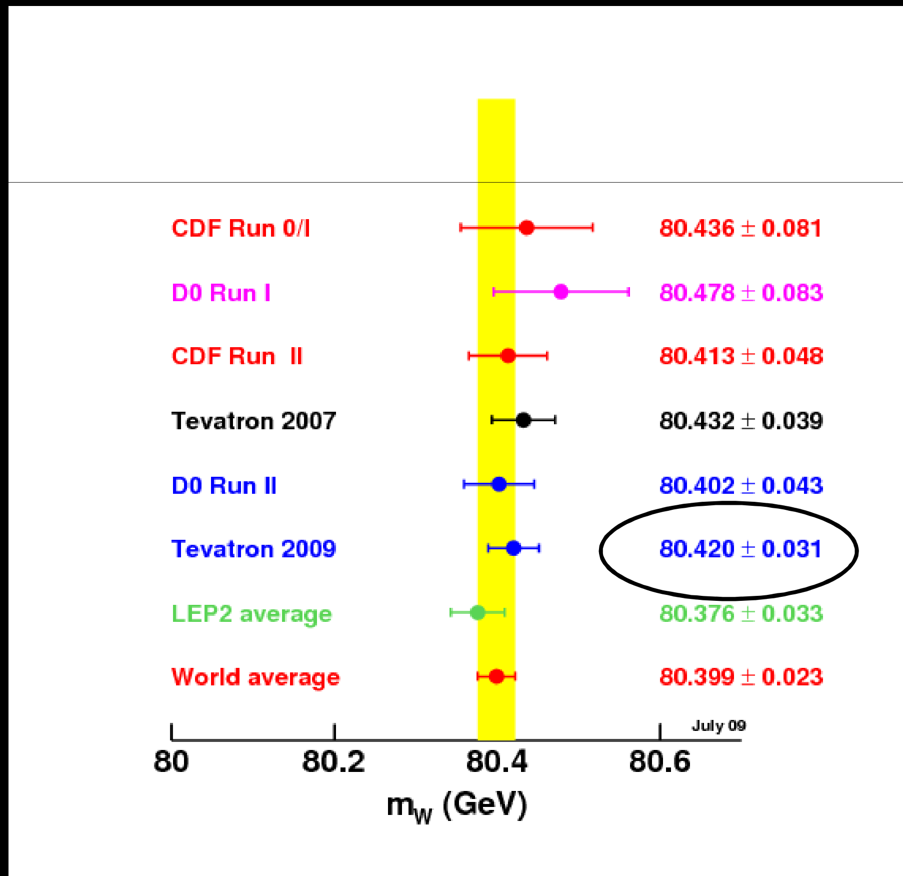




W Mass Summary

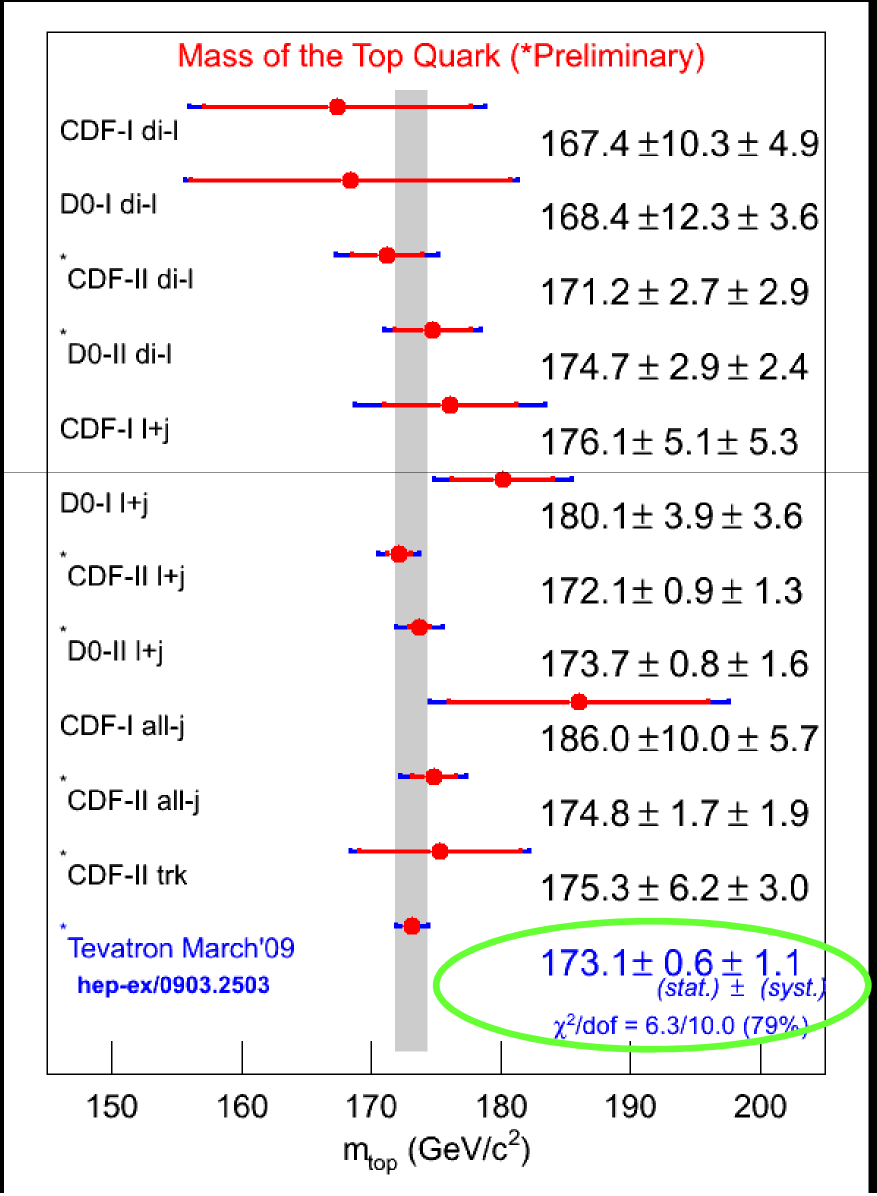


Tevatron has worlds best measurement



$M_W = 80.399 \pm 0.023$ GeV

Summary of Top Mass

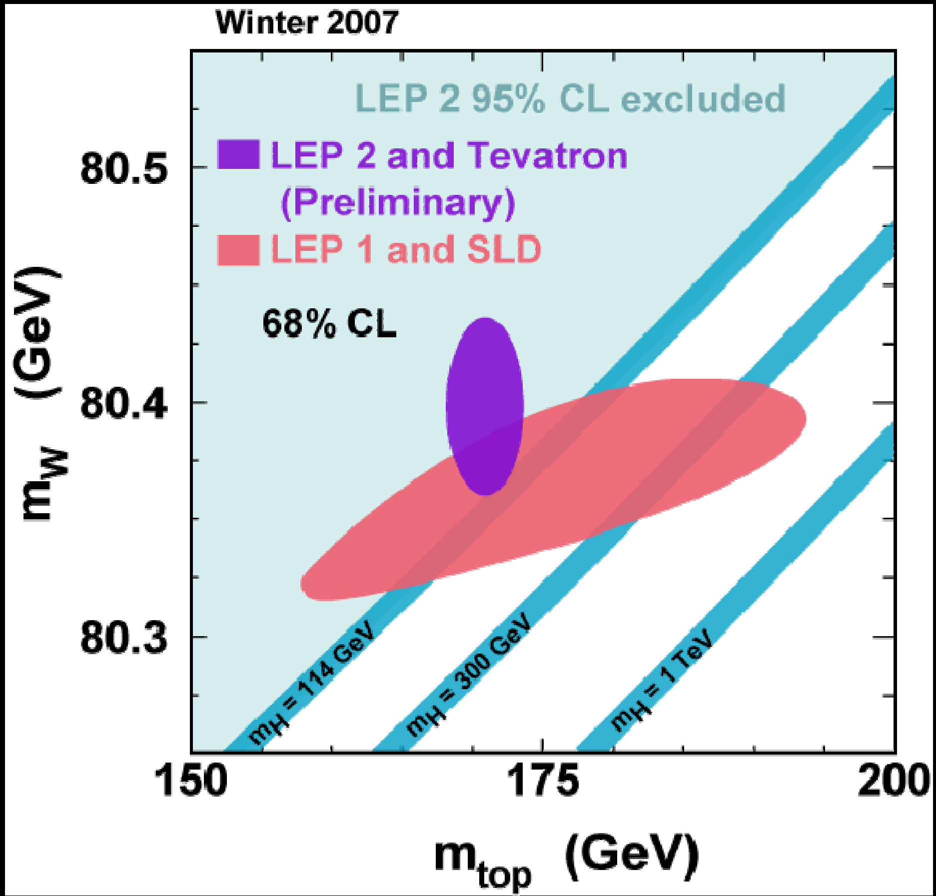


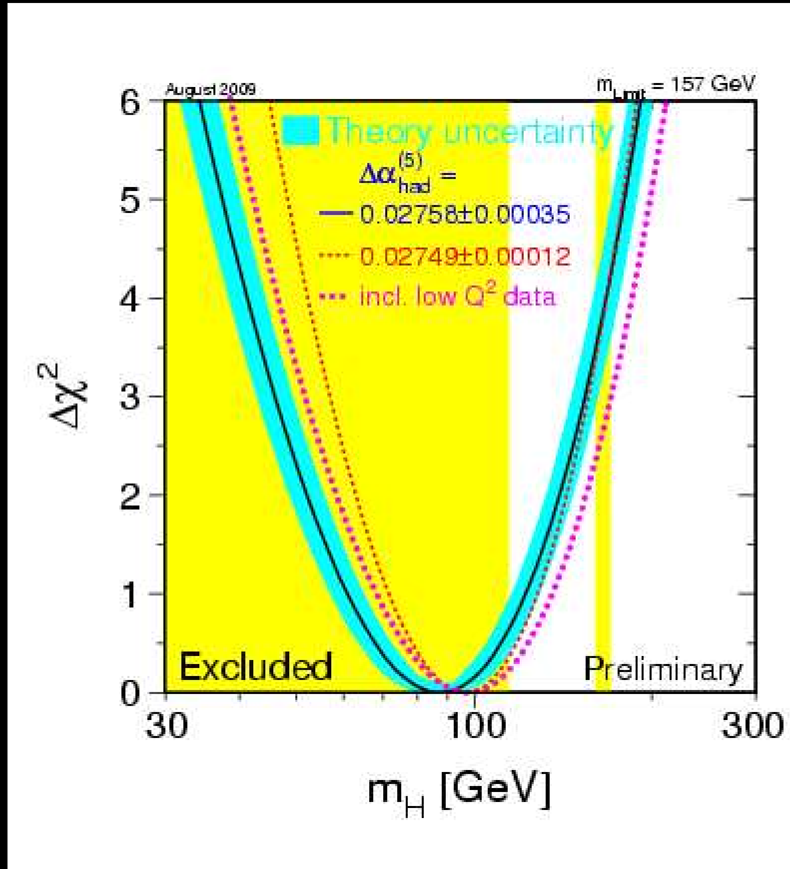
M_t = 173.1 ± 1.2 GeV
<1% Precision

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

15 short years from discovery to this….

Where is the Higgs Hiding?



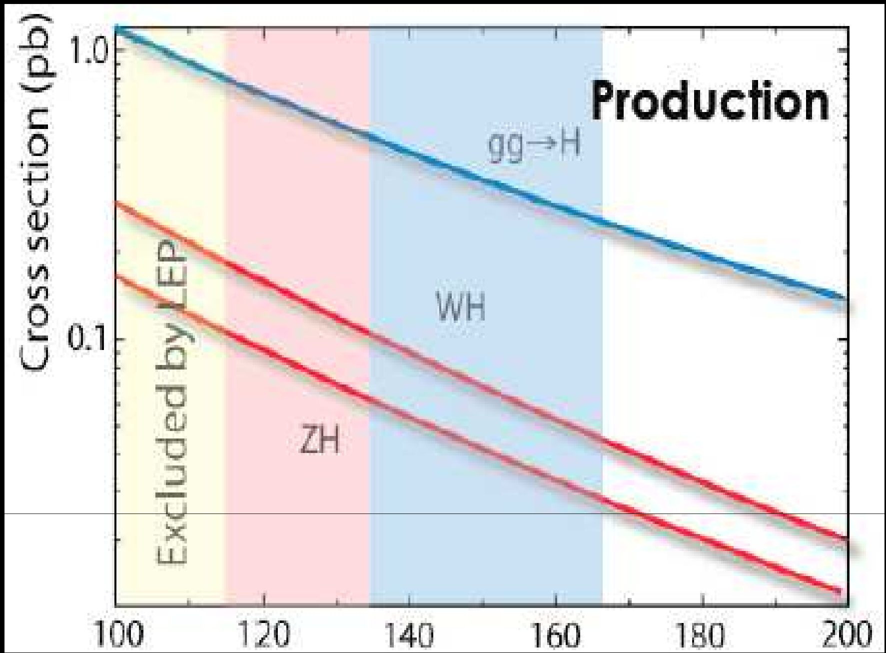


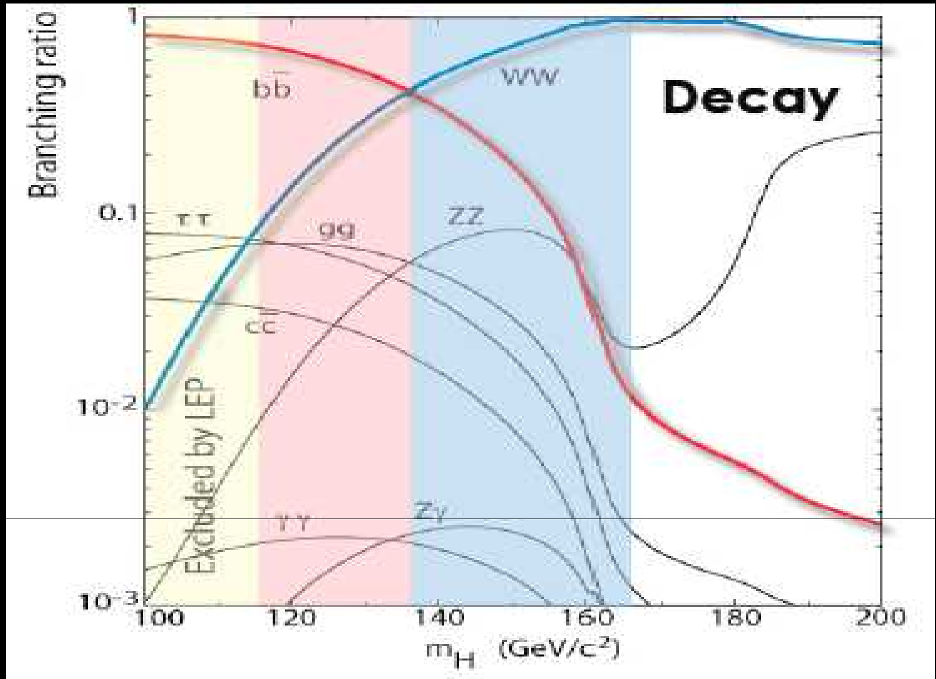
Mw vs Mtop

M_H < 157 GeV at 95% C.L.

Preferred M_H – 87^{+35}_{-26} GeV

Higgs Production and Decay



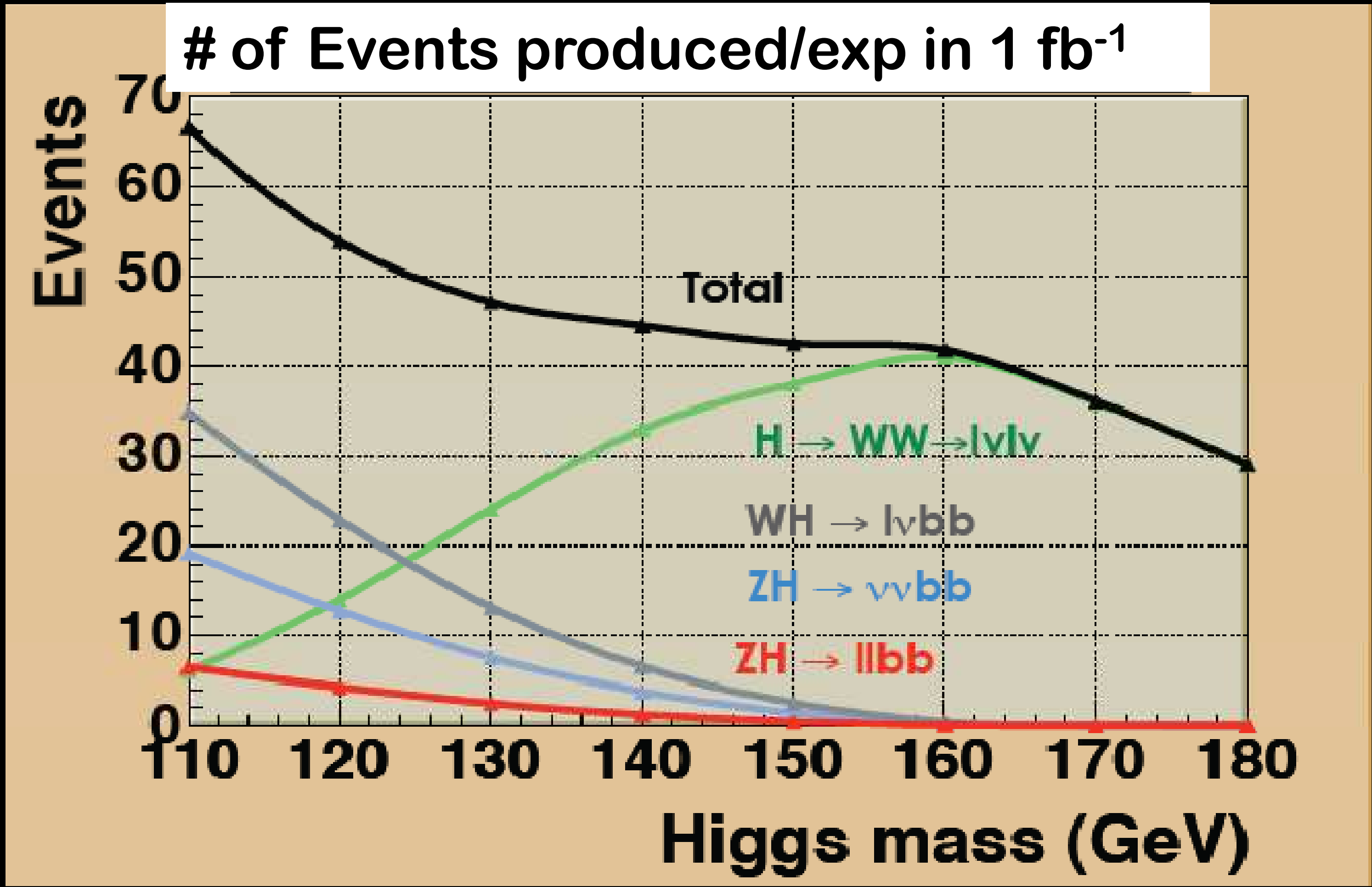


Higgs are produced in several diferent ways…

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

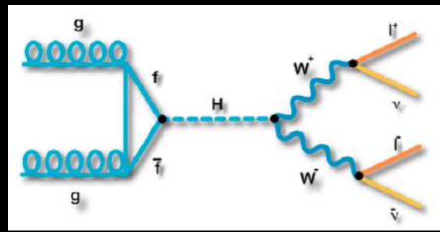
The Challenge

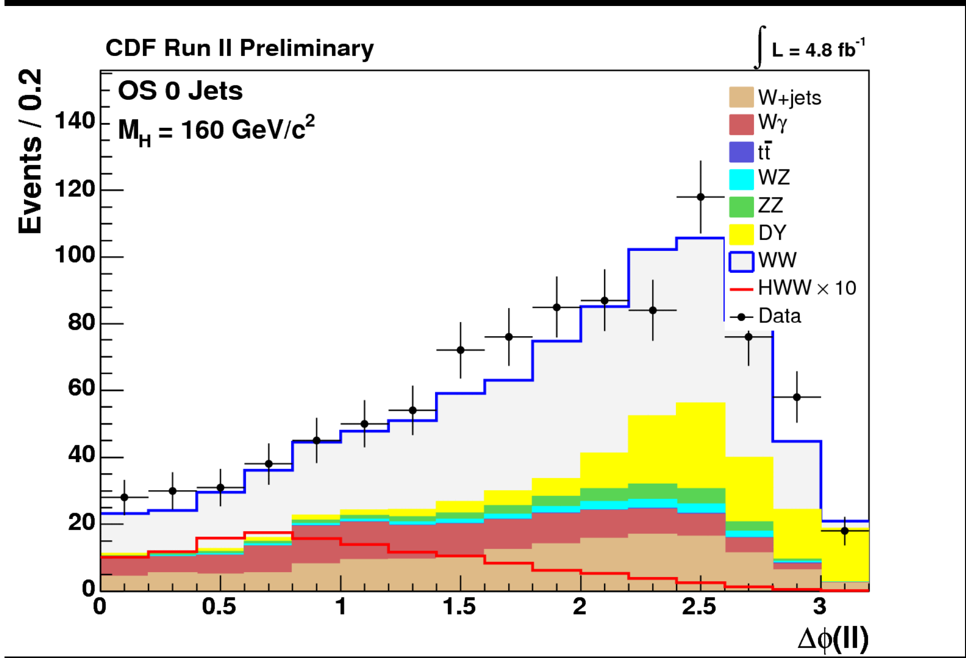


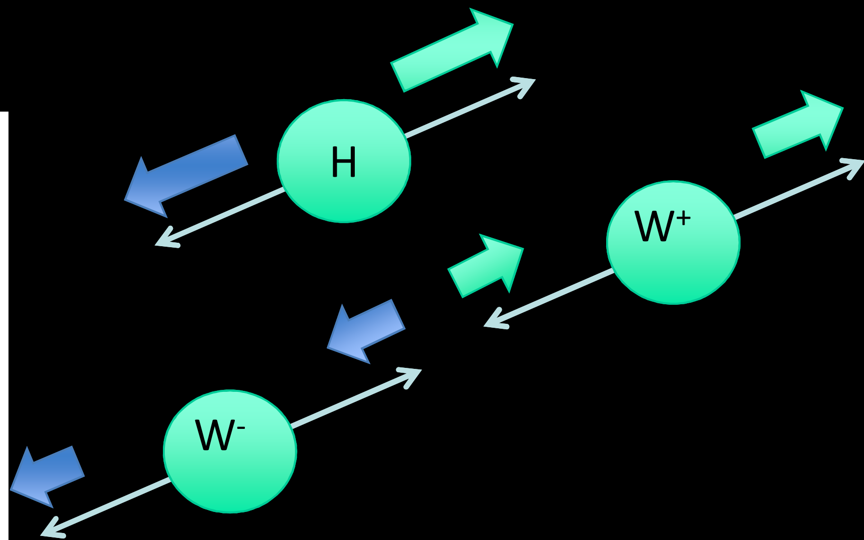
These are production numbers –
trigger, acceptance etc.not yet factored in…

SM Higgs: H→WW (High Mass Channel)

- $H \to WW \to l\nu l\nu$ - signature: Two high p_T leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay channel
  - Key issue: Maximizing signal acceptance
  - Excellent physics based discriminants
- Most sensitive Higgs search channel at the Tevatron

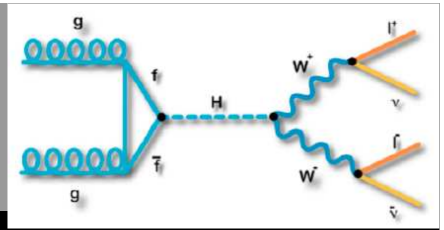






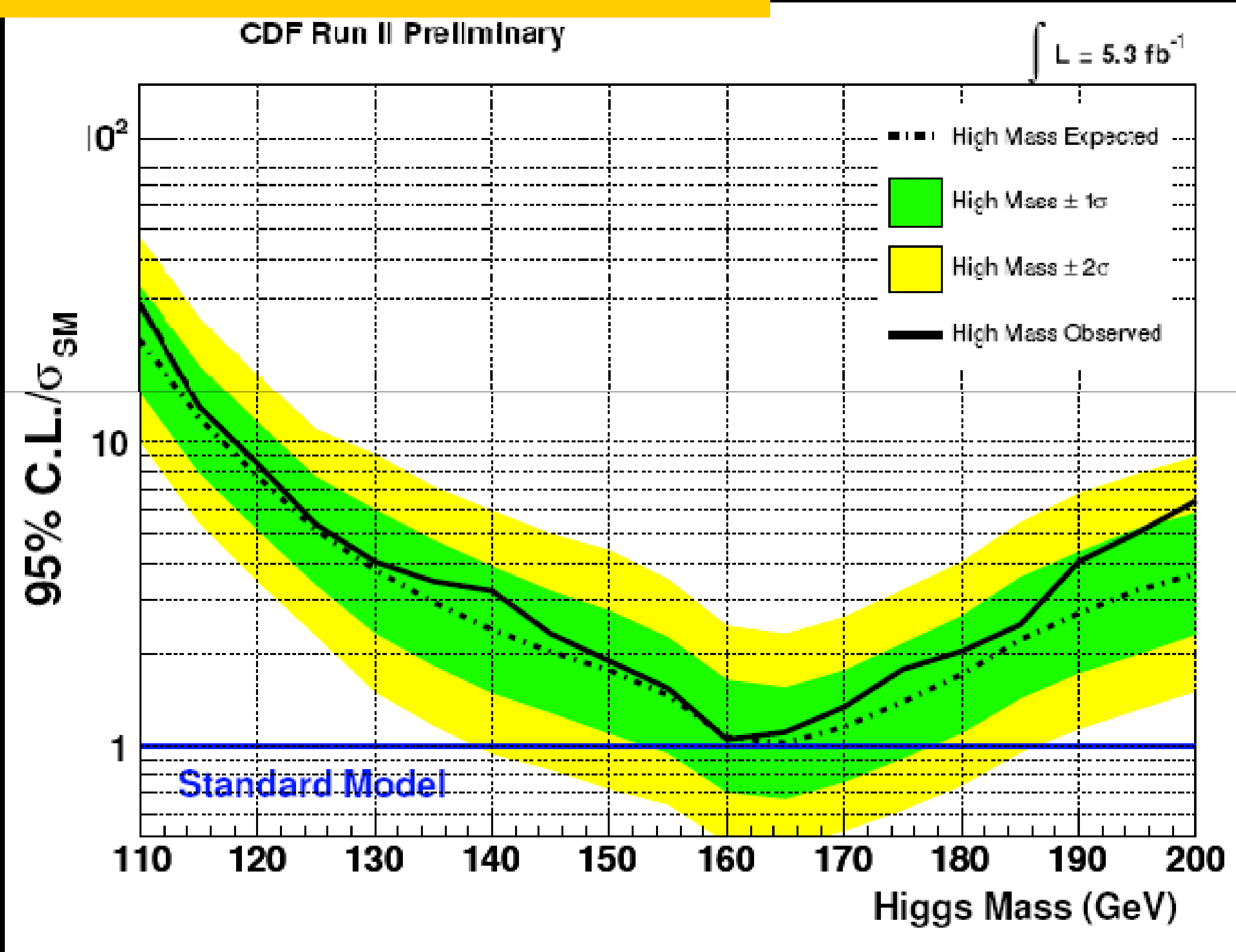
Spin correlation: Charged leptons go in the same direction

CDF H→WW Result



Exp. 1.07 @ 160 GeV, 1.02 @ 165 GeV

36 Higgs Events!

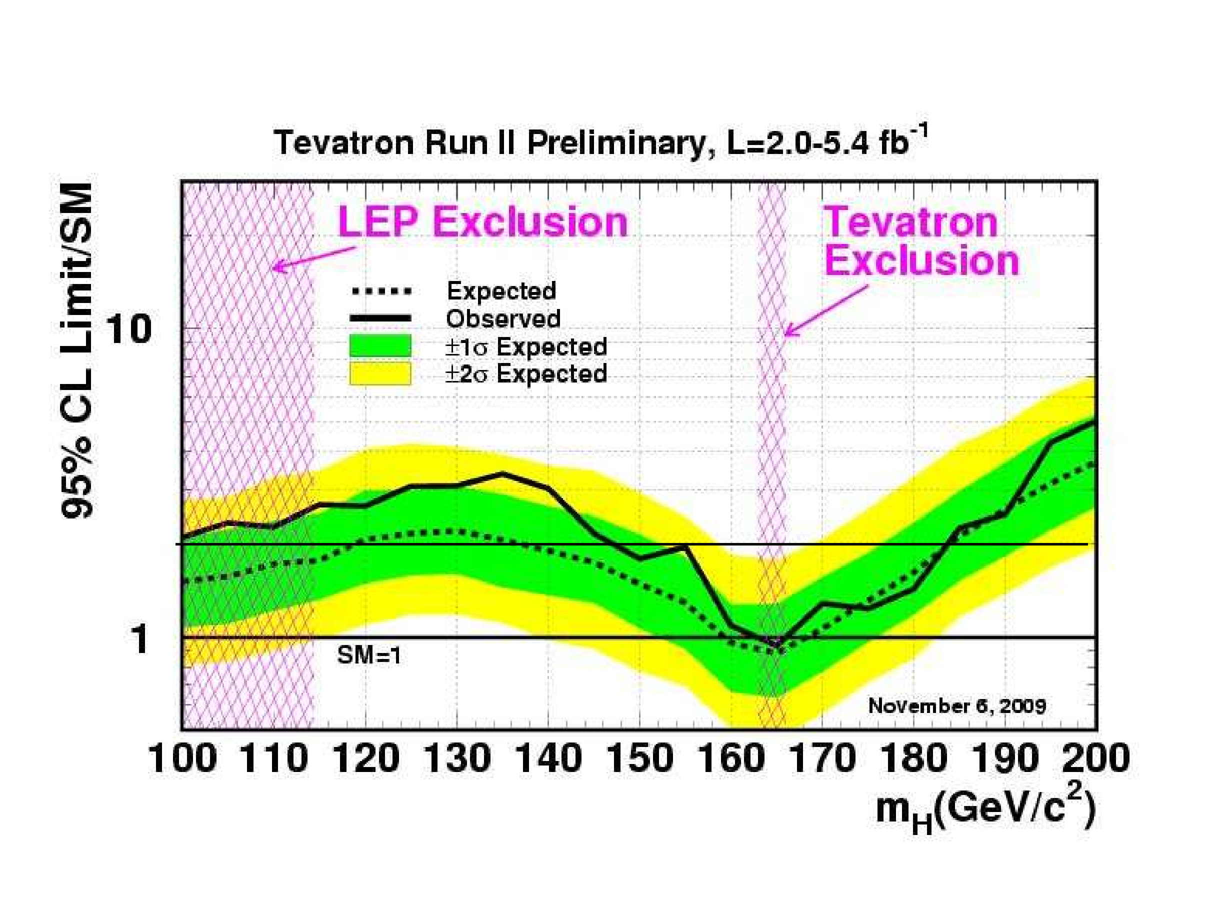


Obs. 1.05 @ 160 GeV, 1.11 @ 165 GeV

Combine Experiments

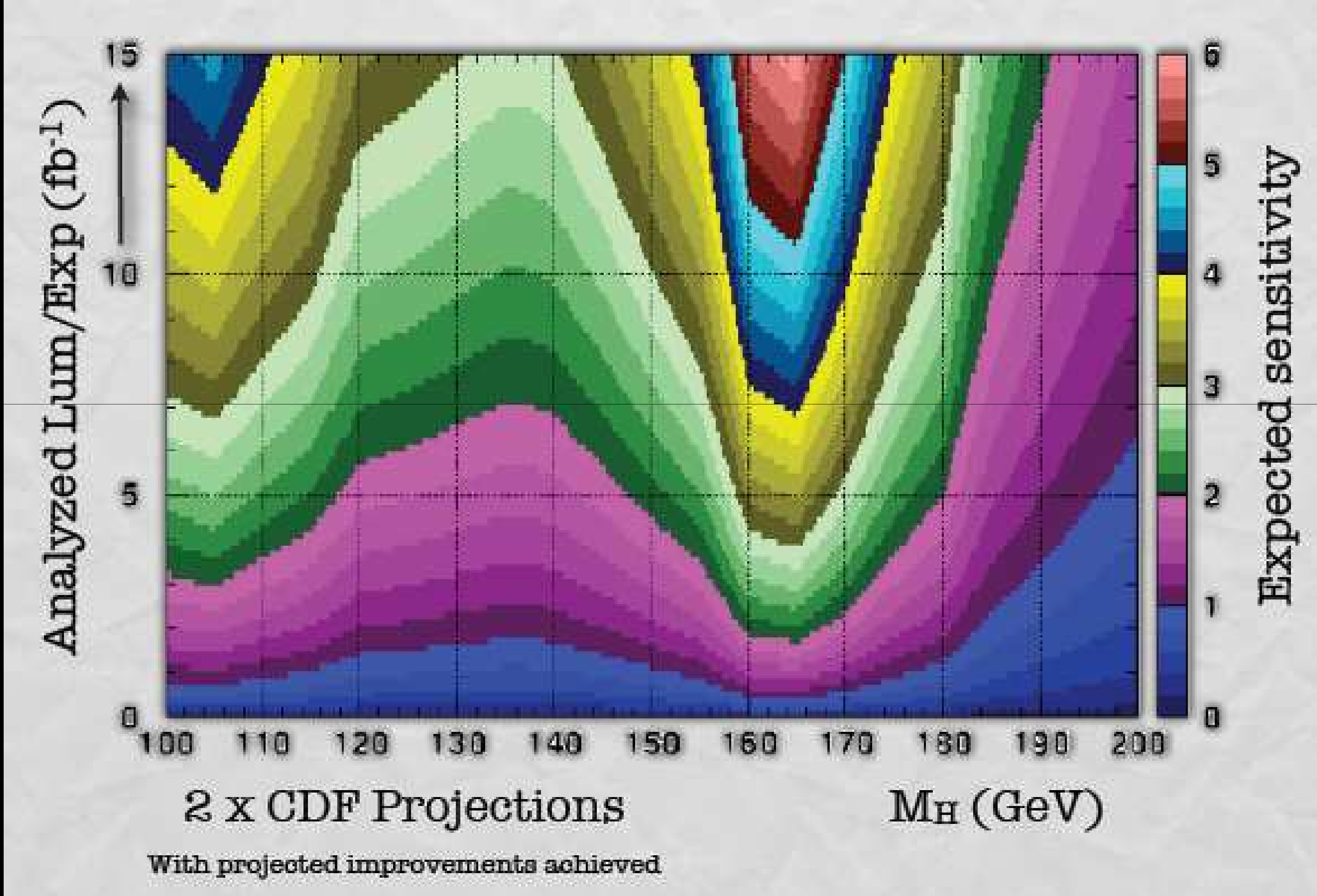
Neither experiment has sufficient power to span the entire mass range using the luminosity we expect to acquire in Run II

Factor away in sensitivity from SM

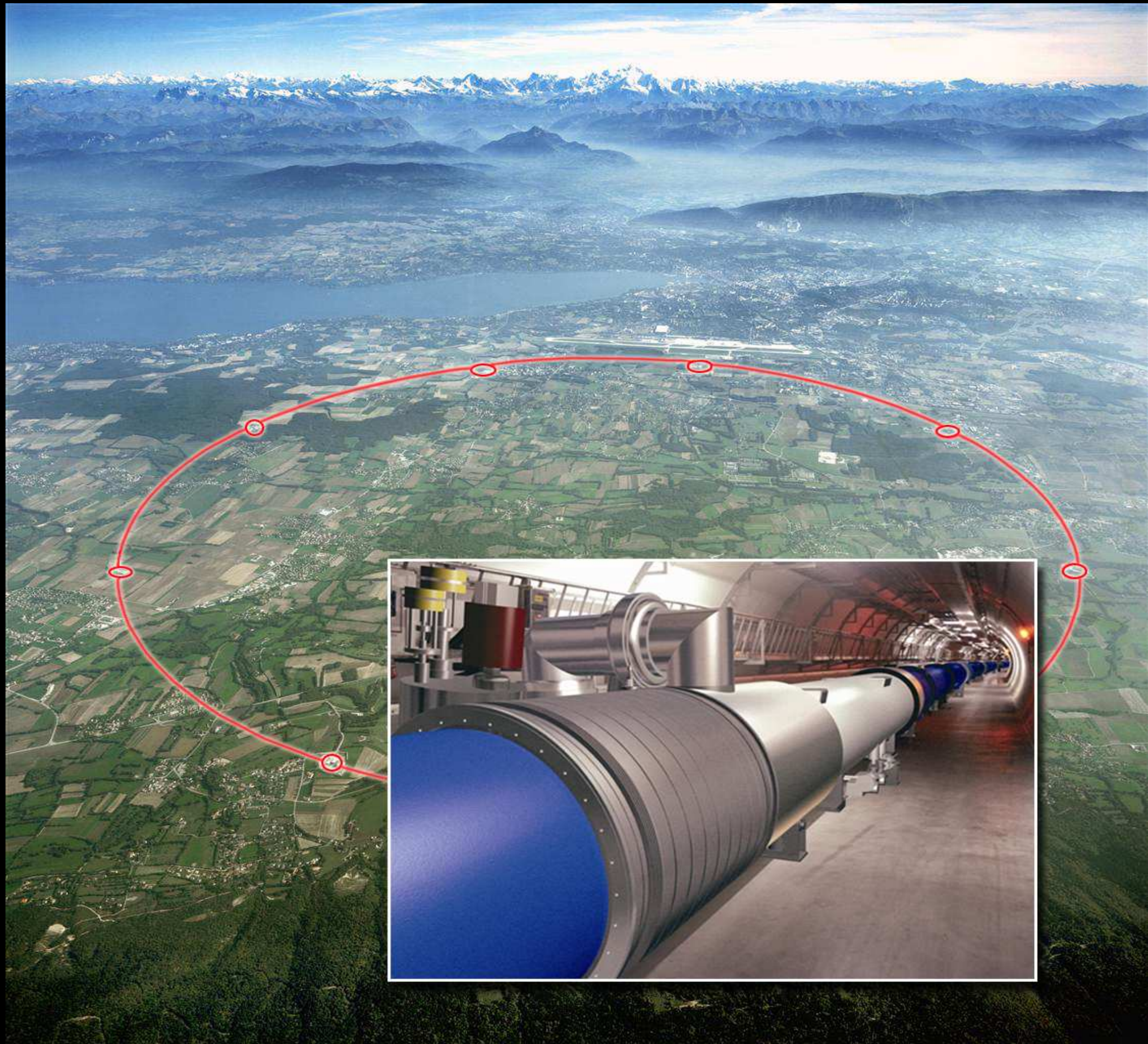


SM Higgs Excluded: m_H = 163-166 GeV

How Well Can We Do?



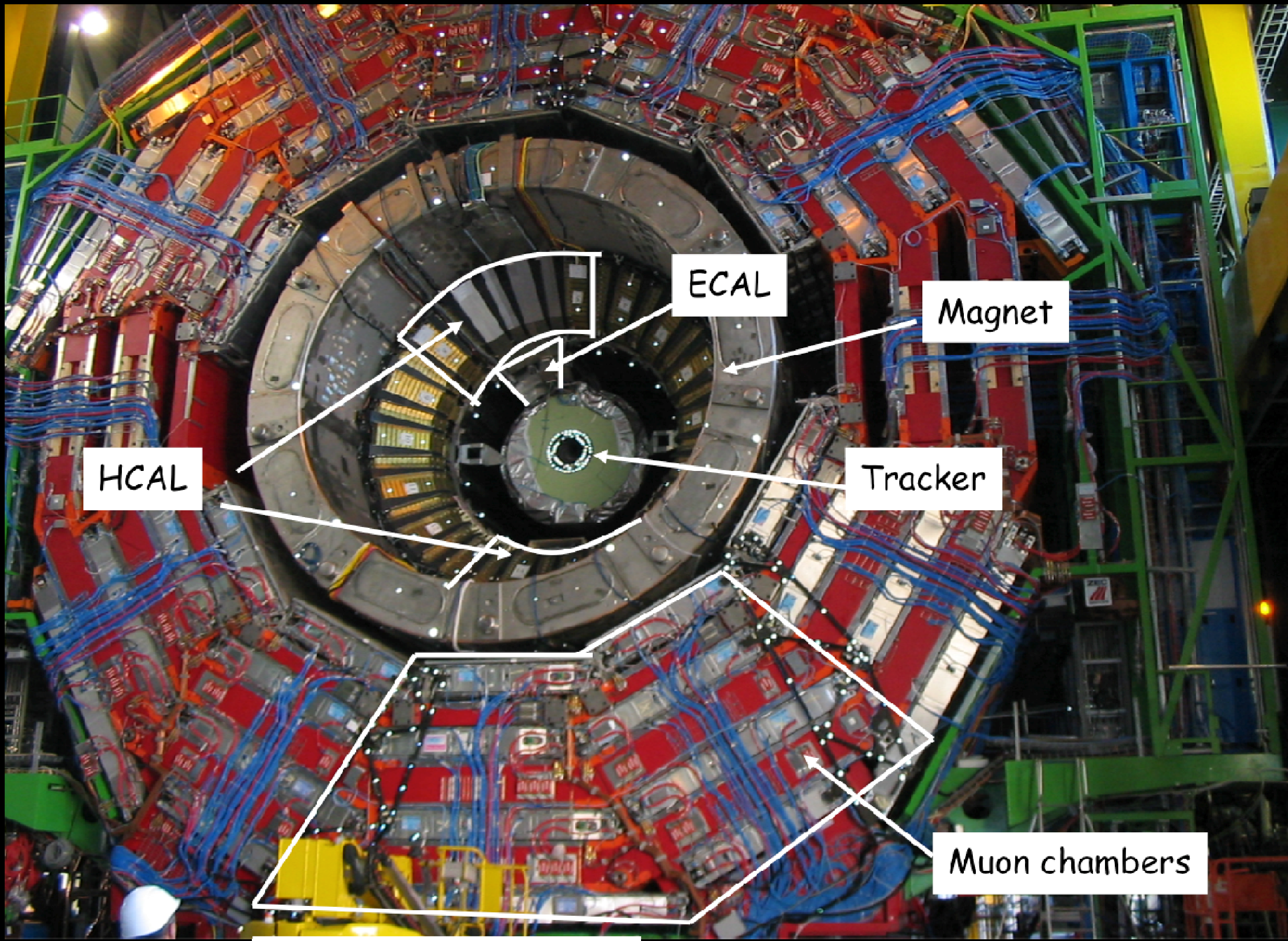
The LHC at CERN



Transition to CERN

- LHC is strategic to US High Energy Physics and to Fermilab!
  - US has made a substantial investment both in $$$ and people on the LHC experiments and accelerator
- At Fermilab – it's a cornerstone of the physics program
  - LPC – LHC Physics Center – to bring US community together to do analysis
  - ROC – Remote Operations Center – US Scientists can participate in detector commissioning here in the US
  - Tier 1 site for computing

The CMS Experiment



The Immediate Plan

- The LHC is starting up again after a short but successful early commissioning run last fall
- Plan is to re-establish stable operations and then work their way up in energy to 3.5 TeV on 3.5 TeV
  - Half of the design energy
  - Deemed a safe operating point and sufficiently advanced in energy to have discovery potential
  - Collect data for the next 18 months with the goal of 1 fb-1 / experiment delivered
- In 2012/13 Shut down for 12-18 months repair all magnet connections so that we can get to full energy ~7x7 TeV
- Begin a 2 year data run

In Terms of Physics Plans

- Re-commission detectors – and commission for the first time the trigger, high rate daq.
- Perform a slew of Standard Model measurements
  - Demonstrates an understanding of data
    - No one will believe a discovery until these SM measurements have been performed
  - With 1 fb of data – CMS and Atlas are competitive for many Tevatron results
- Search for New Physics
  - The high mass searches will be the domain of the LHC essentially immediately

What to expect???

Or.....

Low Hanging Fruit

Or…..

We Just Don't Know….

- What We Do Know….
- Every time we have made a leap in energy, we have had un-expected surprises
- Never before has HEP turned on a machine with such a dramatic increase in capability from its predecessors
- The Detectors are amazing instruments
- Expertise from the Tevatron has been captured so things will progress quite rapidly

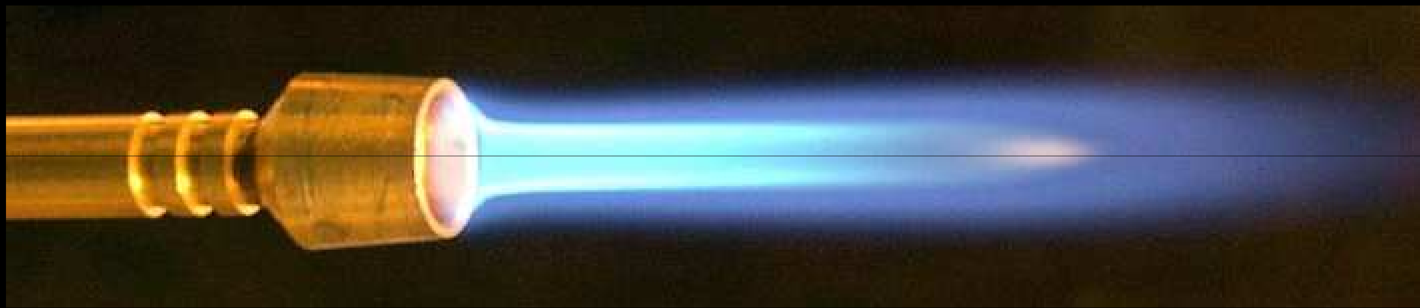
The Intensity Frontier…

Fermilab's Ambition

- **It aims to be the best laboratory in the world for the study of neutrino physics and the ultra-rare behavior of particles**

Intensity Frontier Tools

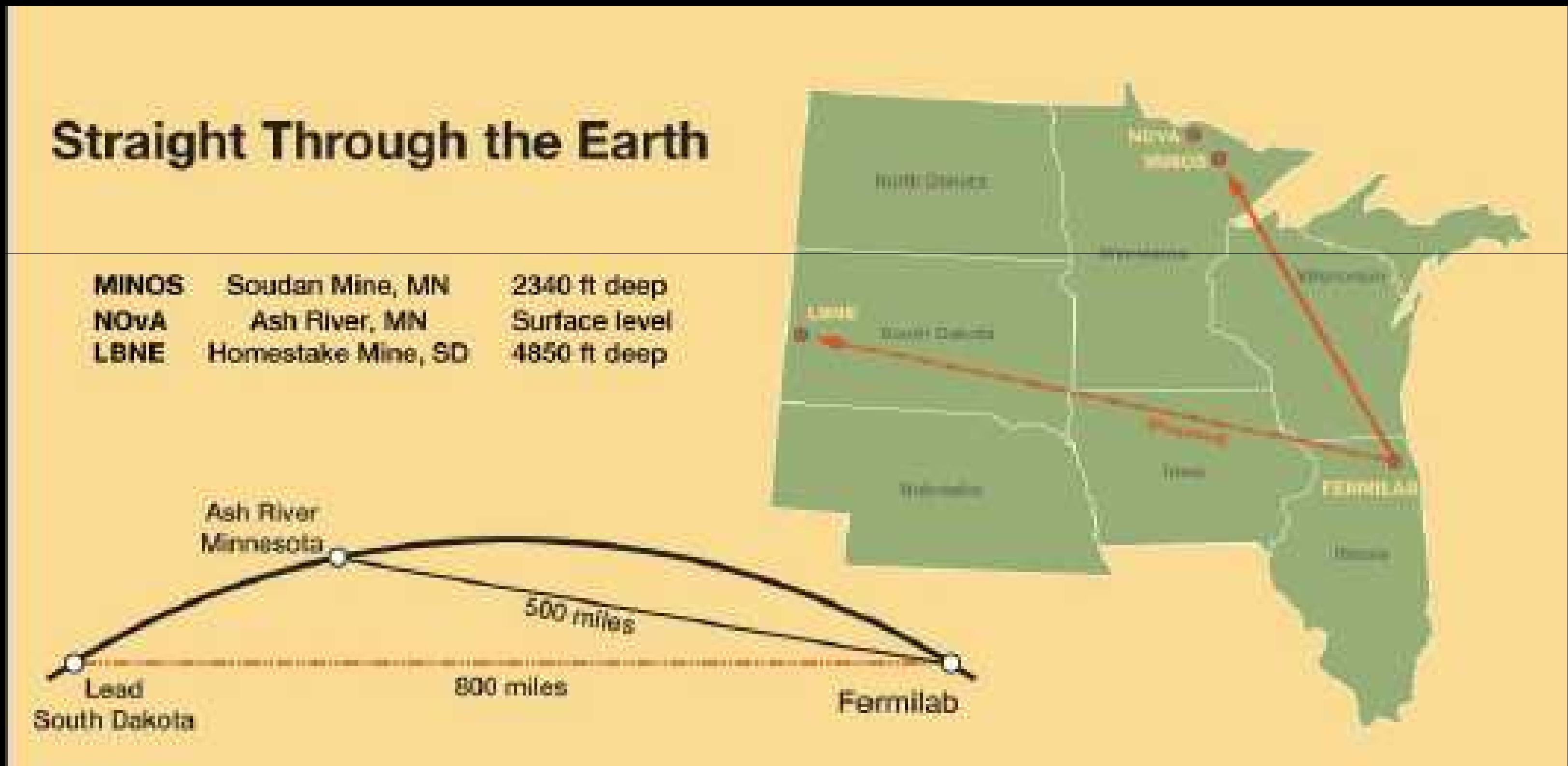
- The accelerator needs to be able to produce lots of particles – a “blow torch” if you will



The more particles accelerators produce the better chances the scientists have in seeing something rare

Intensity Frontier

- **Shining Neutrino's through 500 miles of rock to study their family behavior…**



Long Baseline Neutrino Experiments

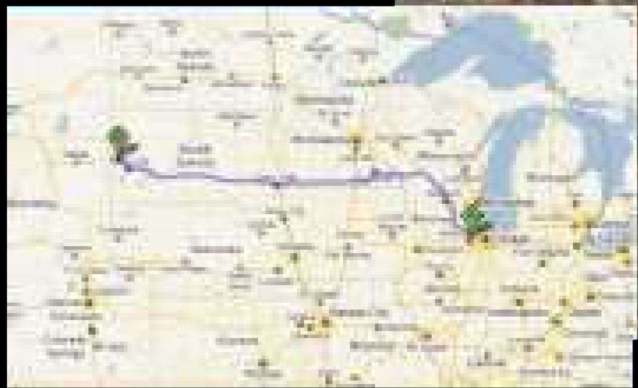
MINOS

Soudan
Minnesota

Ash River
Minnesota

Next Step…

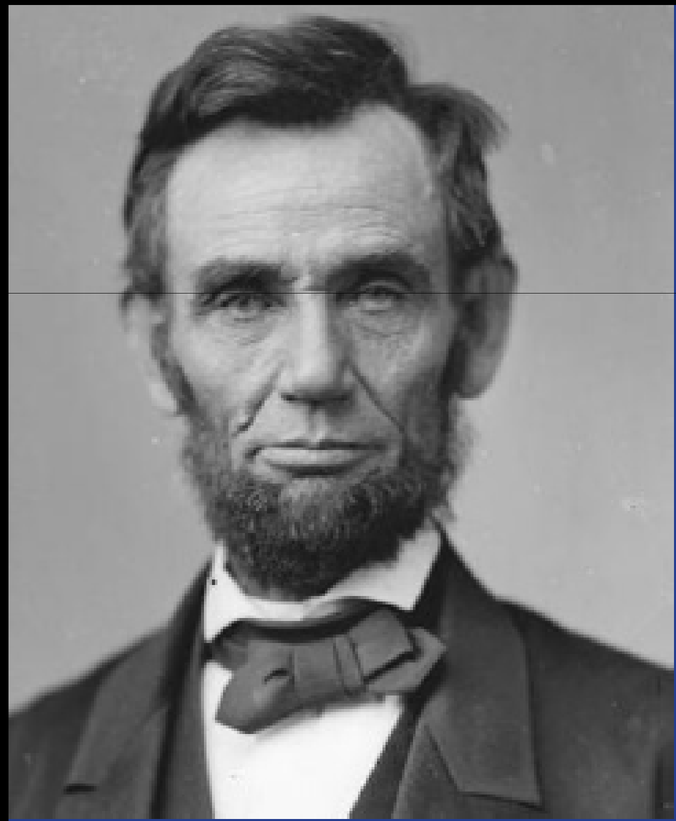
Referred to as LBNE or DUSEL



Why are scientists interested in rare events?

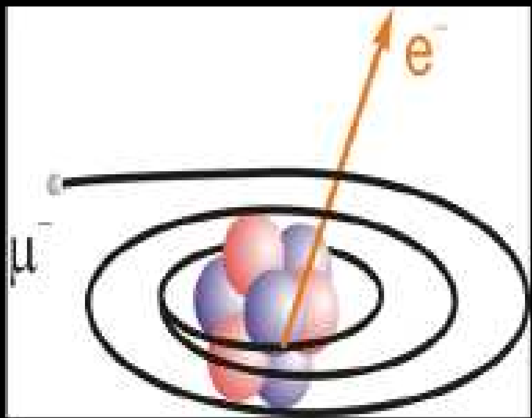
We as a species are fascinated by rare events

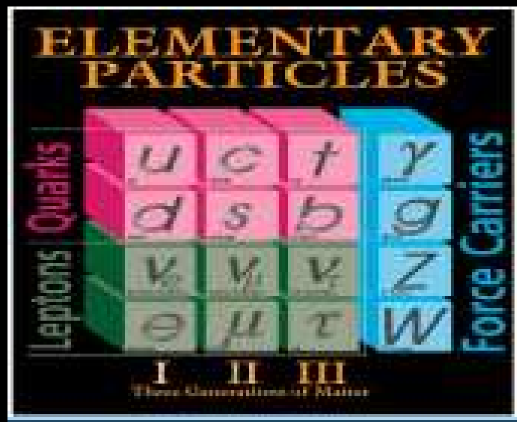
Rare Events can change the course of History



- **Fermilab is aiming to lead the frontier of ultra-rare event experiments in particle physics**

- **Searching for family jumping in the charged cousins of neutrino's – muons to electrons!**





Fermilab will study 1,000,000,000,000,000,000 muons searching for this… a number equal to all the grains of sands on all the world's beaches

Project X

- **A unique and flexible facility with intense beams for many intensity frontier experiments**

From "The Quantum Universe"

The most pressing problems in our field!

1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter ? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Fermilab (and Uva) is addressing most of these

Conclusions

- Fermilab is and will remain the center for HEP in the United States
- While operating the Tevatron, it is working to re-invent itself
- Tevatron will run through 2011
- The LHC is starting up and Fermilab through the LPC and ROC will be a focal point of this community
- Fermilab's shift to the intensity frontier will open up a new set of challenges and exciting physics opportunities

Backup

Mu 2 e Experiment

- **Mu 2 e** experiment is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu N \rightarrow e^- N$

- Strictly speaking, forbidden in Standard Model

- In wide array of New Physics models CLFV processes occur at rates we can observe with next generation experiments

- “Phase-I” experiment uses current proton source at Fermilab to achieve world’s best sensitivity
  - Further improvements possible in “Phase-II” using Project-X

Mu 2 e Physics Case

- Discovery sensitivity over a very broad range of New Physics Models
  - SuperSymmetry, Little Higgs, Leptoquarks, Extended Technicolor, Extra Dimensions
- Complimentary sensitivity to rest of the world HEP program
  - LHC, $\mu \rightarrow e\gamma$, ν mixing
- Factor of 10^4 improvement over world's previous best results
  - C.Dohmen et al (Sindrum II), Phys Lett B 317 (1993) 631
  - W.Honecker et al (Sindrum II), Phys Rev Lett 76 (1996) 200

Mu2e Concept

- Generate a beam of low momentum muons (μ-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- Stopped muons are trapped in a nuclear orbit
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^{N} important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$
- Use a delayed timing window to suppress bgd

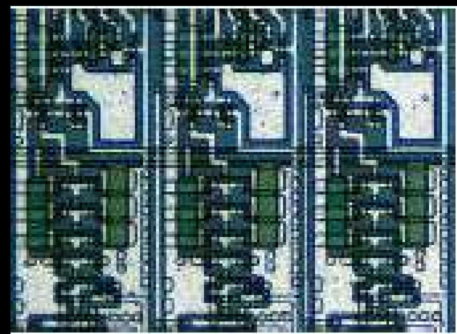
Particle Physics Spinoffs

Medical Imaging

Bright X Ray Source
Materials/Chemistry/Biology

GRID Computing
and the WWW

Education



Silicon Technology

MISSING PARTICLE:

Name: *Higgs boson*

Age: *13.7 billion years*

Missing: *45 years*

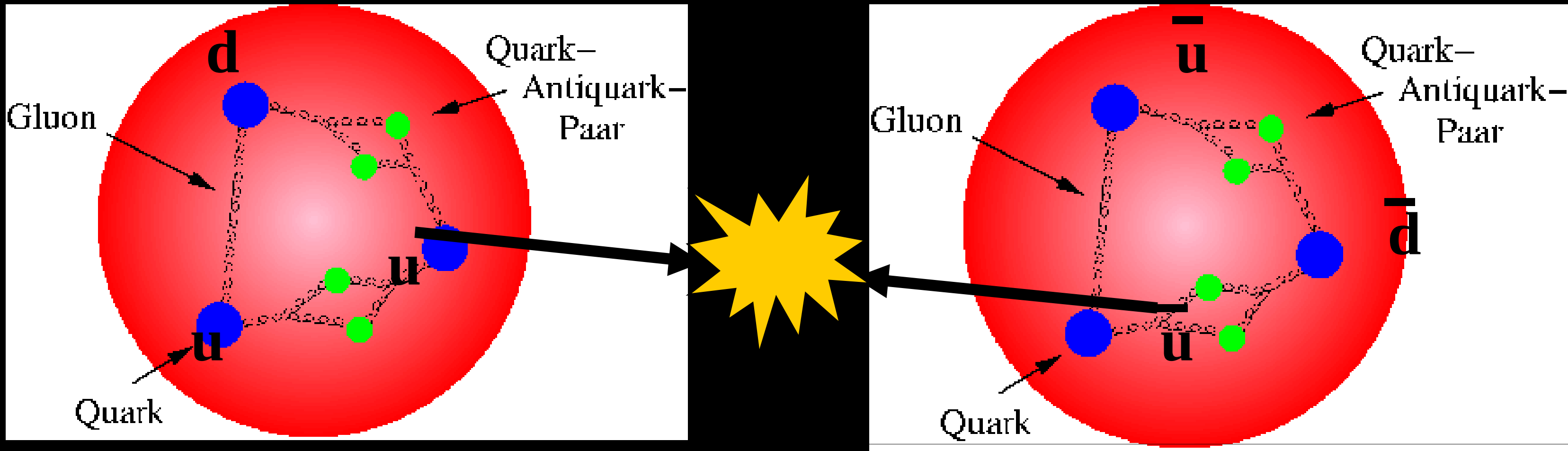
Birthday: *Every few days at Fermilab*

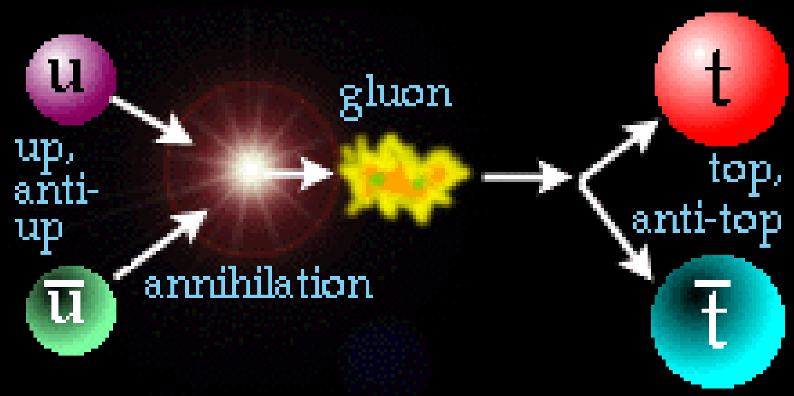
Favorite trait: *Mass*

Favorite particle: *top quark*

Favorite Hangout: *Tevatron*

It's a bit more complicated…

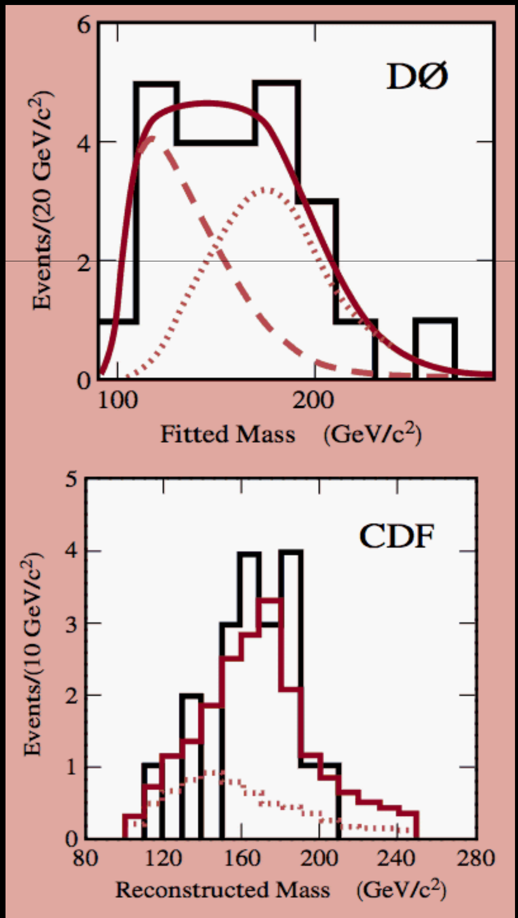


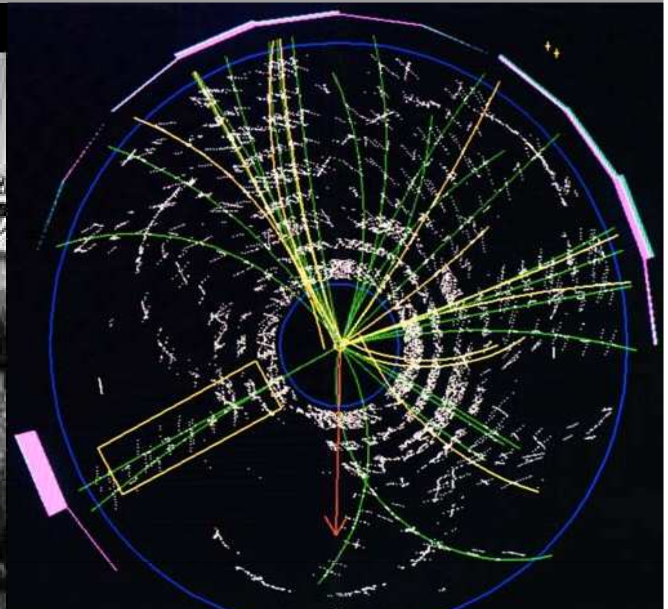


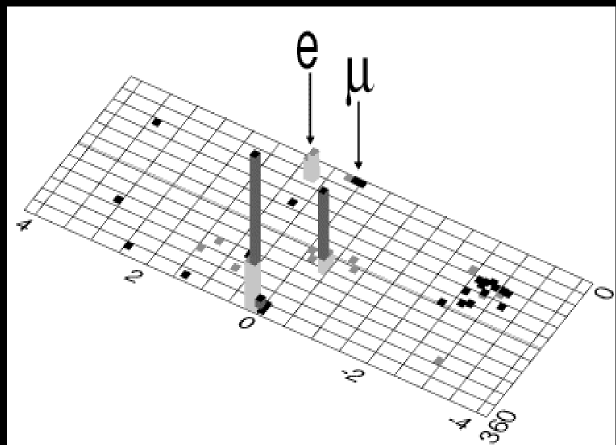
$$E_u + E_{\bar{u}} >> M_t + M_{\bar{t}}$$

Top Quark Discovered!

1995

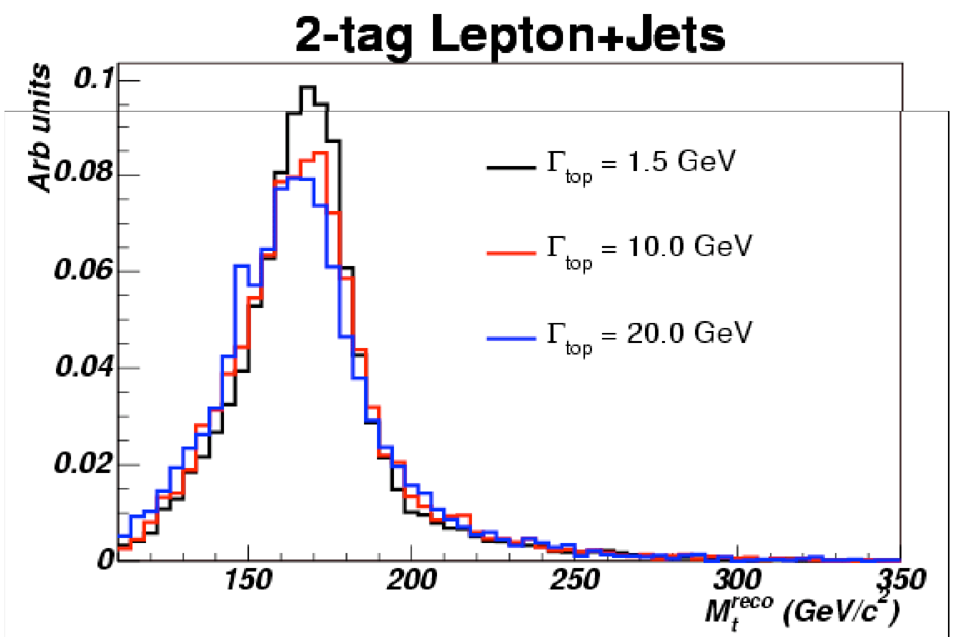


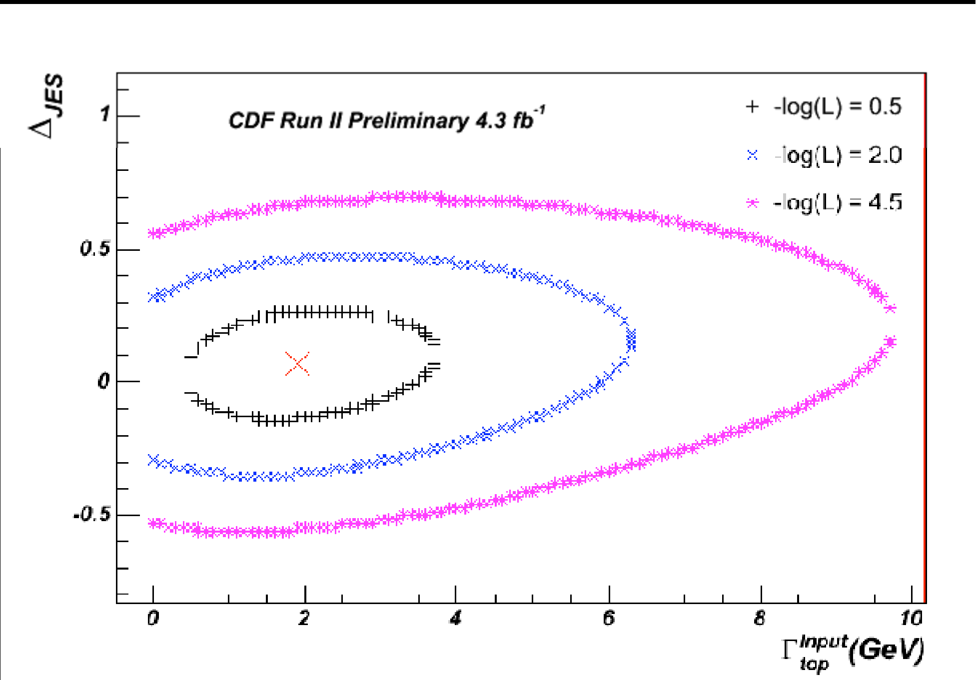




Top Width

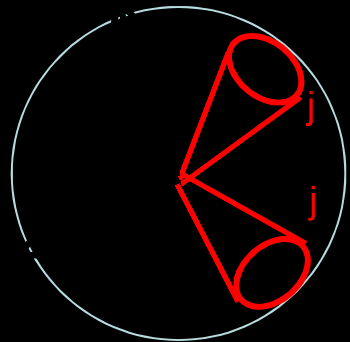
- Template based top width measurement
  - Lepton+Jets with 4.3fb^{-1}
    - Simultaneous constraint of jet energy scale using W jets
    - Upper limit placed on top width





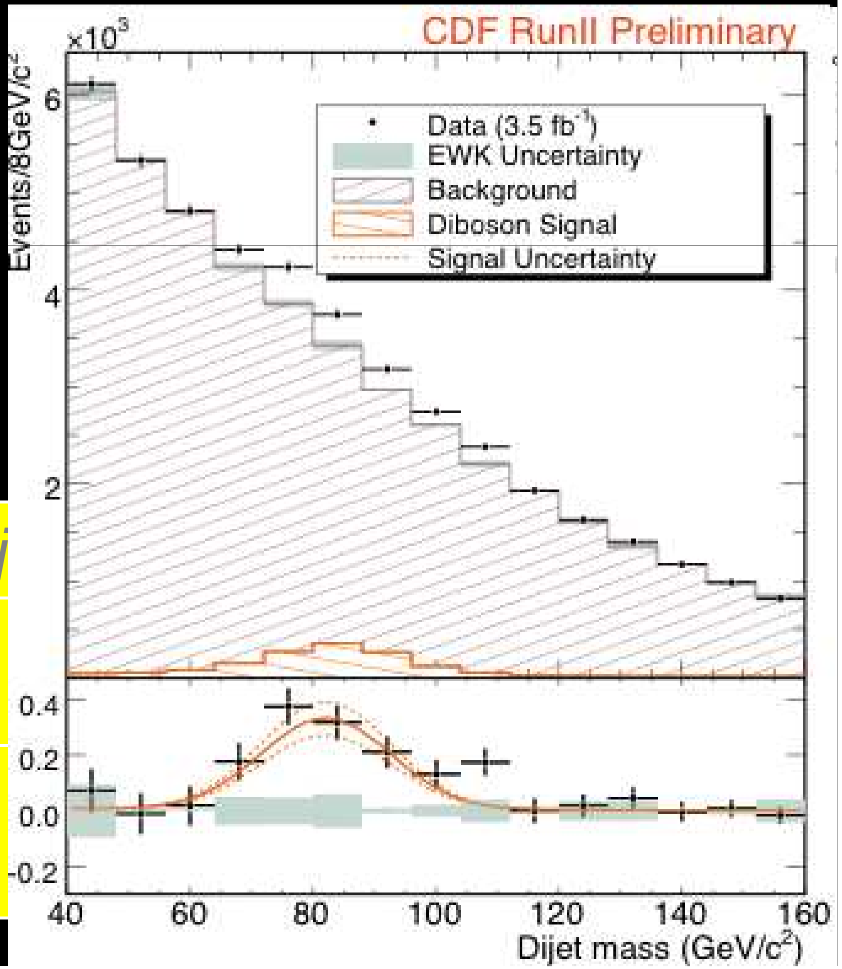
95% CL: Γ_{top} < 7.5 GeV   68% CL: 0.4 GeV < Γ_{top} < 4.4 GeV

Observation of Diboson Production in E_T+jj

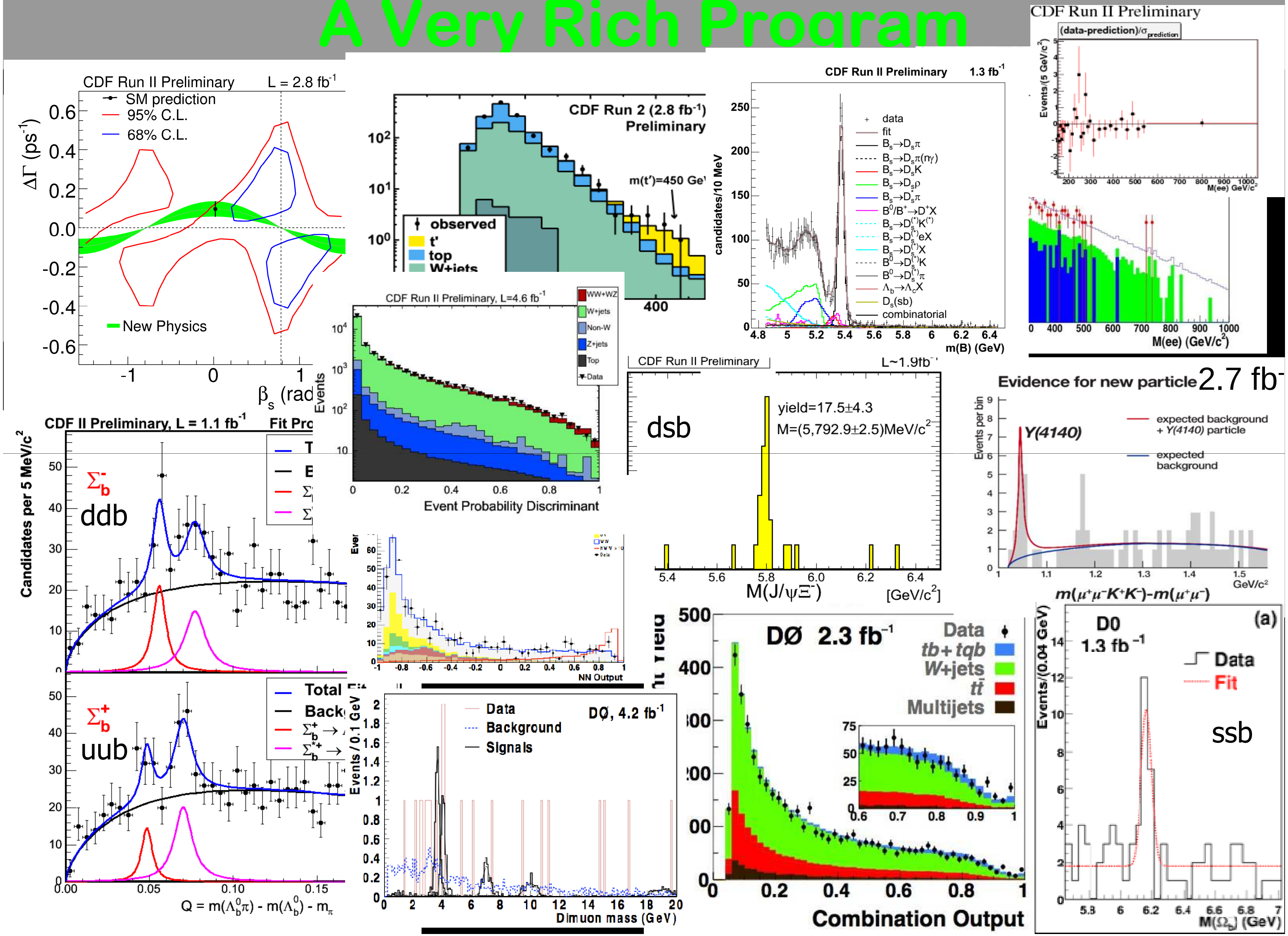


- Search for $\nu\nu jj$ and $l\nu jj$ final states
- Sensitive to WW, WZ and ZZ
- Signal Significance 5.3σ
- Technical benchmark for
  ZH $\rightarrow \nu\nu$ bbar and WH $\rightarrow l\nu$ bbar
- Challenging due to large W/Z+jets and huge QCD background

$\sigma(pp \rightarrow VV)$, V=W,Z , with one $V \rightarrow jj$	
Data	*18.0 ± 2.8 (stat.) ± 2.4 (syst.) 1.1 (lumi.)*
NLO prediction	*16.8 ± 0.5*

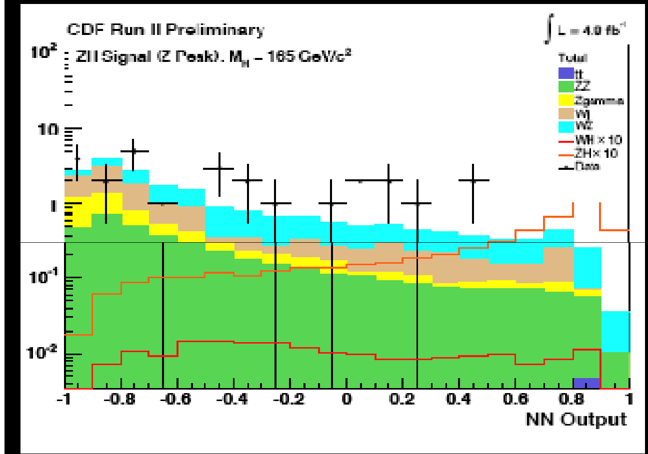


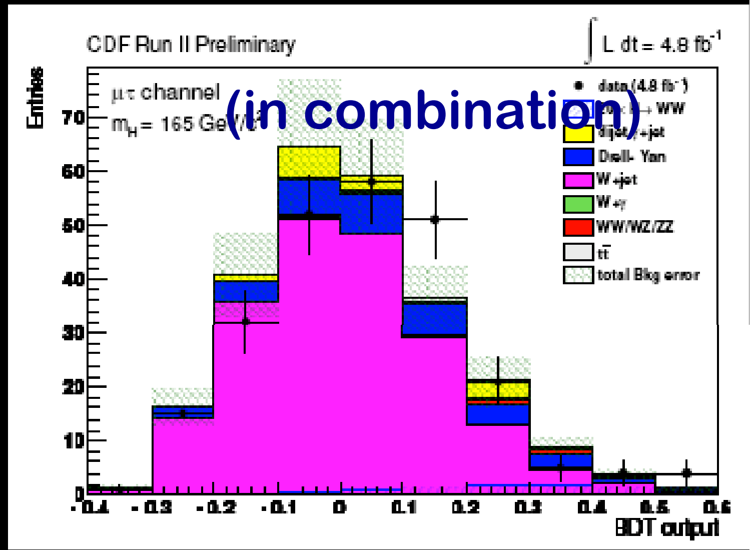
A Very Rich Program



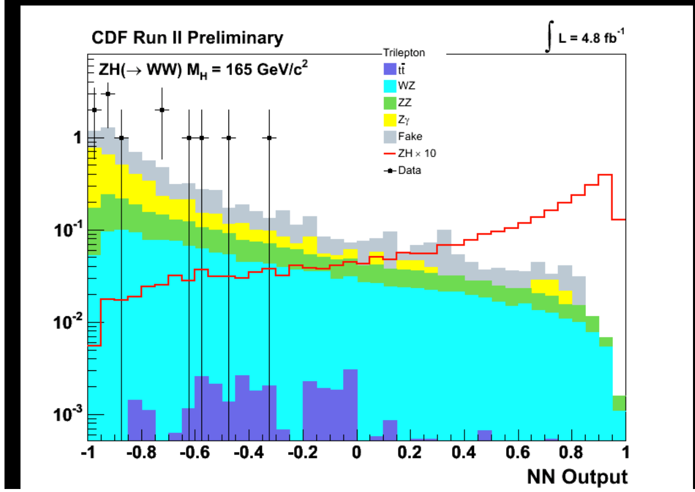
New High Mass Contributions

- VH $\rightarrow$ VWW $\rightarrow$ lll +MET
  - WH and ZH search (in combination). Also ZH search in 2 jets only
- H $\rightarrow$ WW $\rightarrow$ lτ + MET, hadronic tau





(in combination)

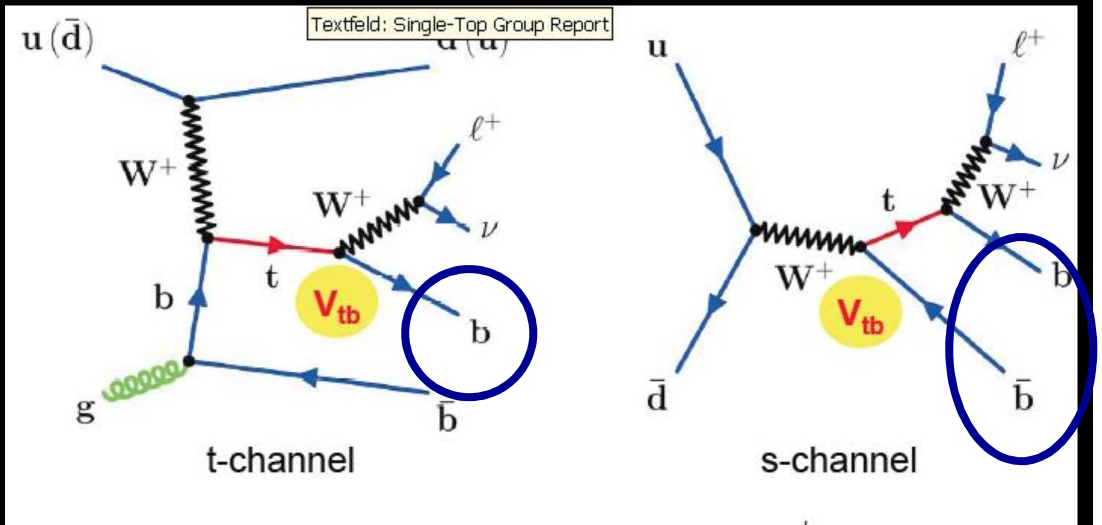


Results at mH = 165 GeV: 95%CL Limits/SM

Analysis	Lum (fb^{-1})	Exp. Limit	Obs. Limit
CDF VH, 3l	4.8	6.3	7.6
CDF ZH, 3l + 2jets	4.8	14.0	12.9
CDF H$\rightarrow$ WW $\rightarrow$ lτ	4.8	15.7	29.7

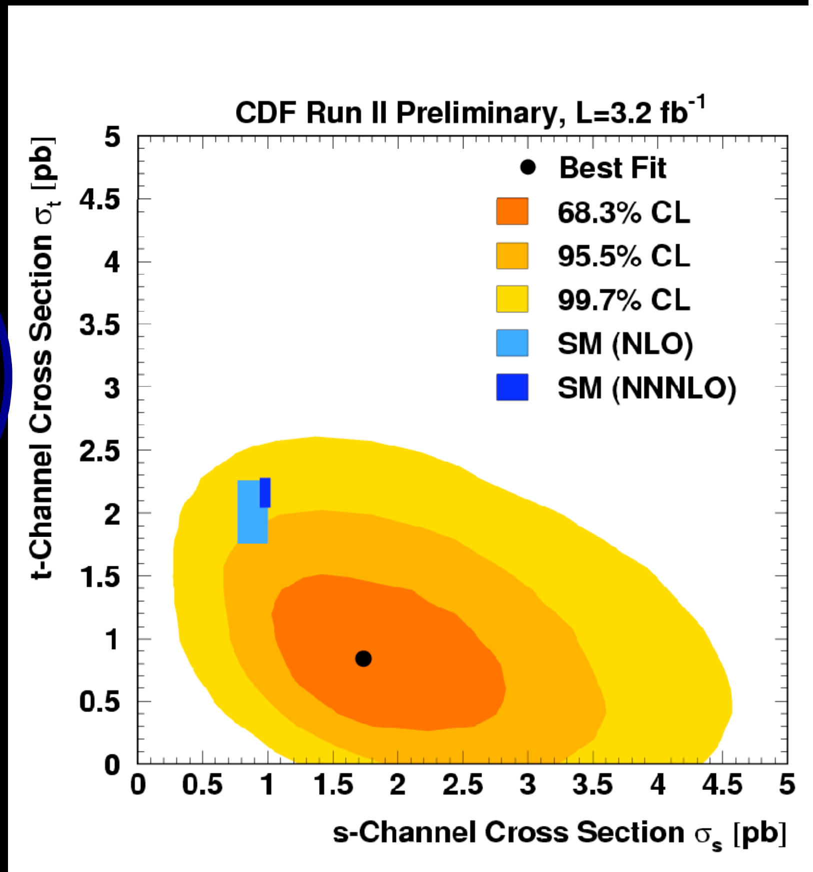
Single Top

- Separately measure s and t channel production.
  - Measurement driven by statistics of single and double tag events

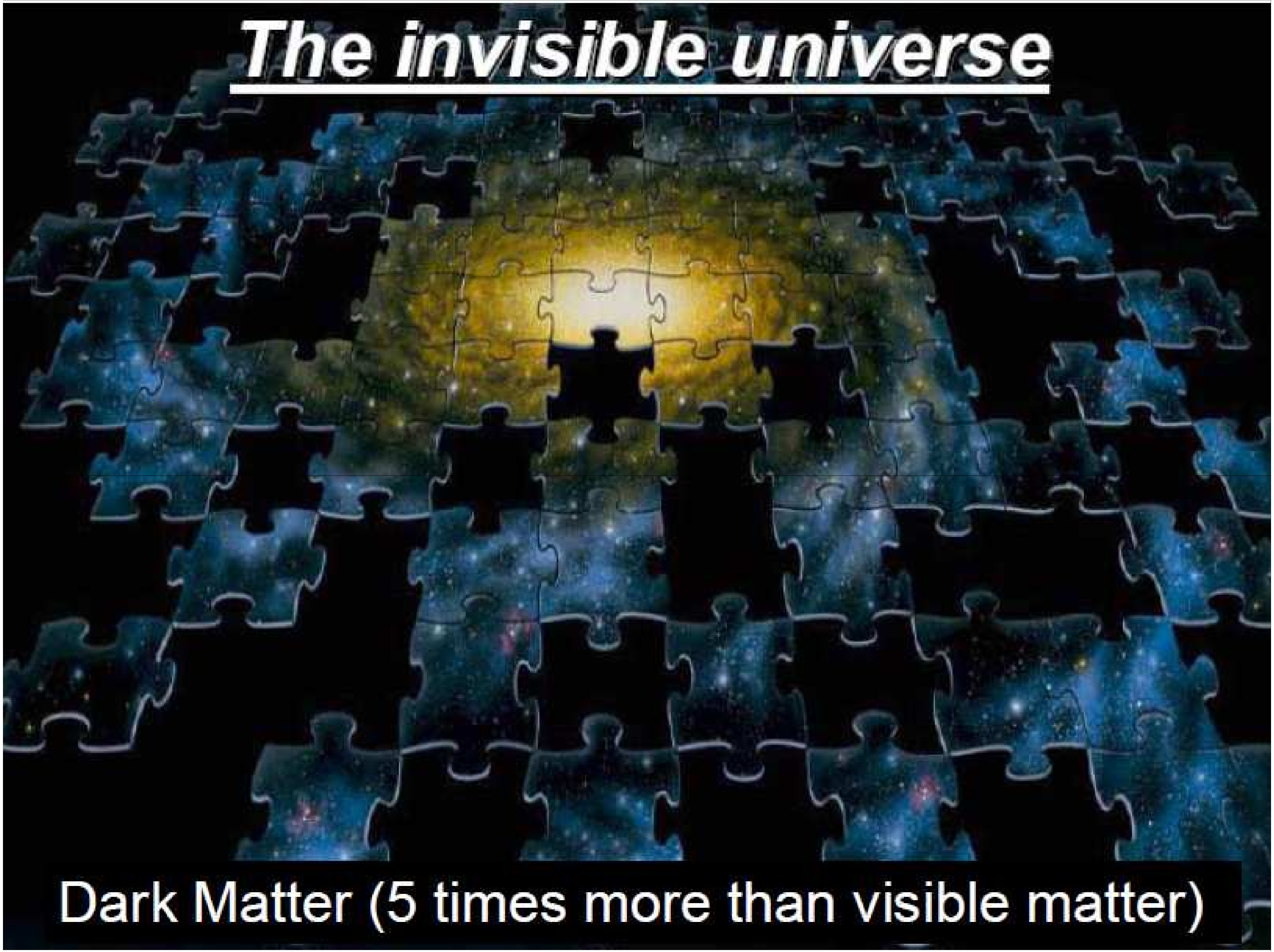


$\sigma_t = 0.8 \pm 0.4$ pb

$\sigma_s = 1.8 \pm^{0.7}_{-0.5}$ pb

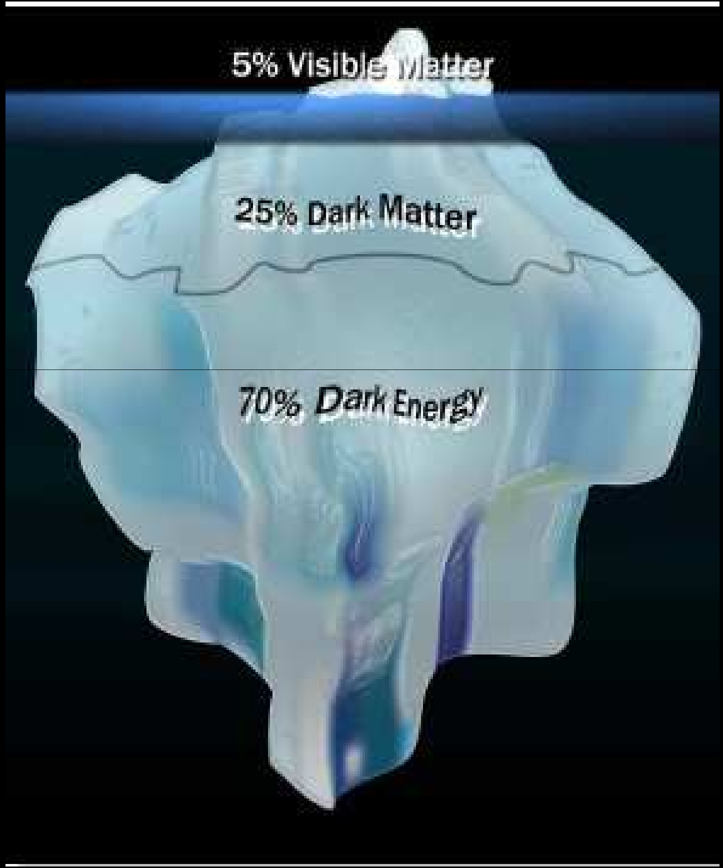



The visible universe
M63
Galaxies


The invisible universe
Dark Matter (5 times more than visible matter)

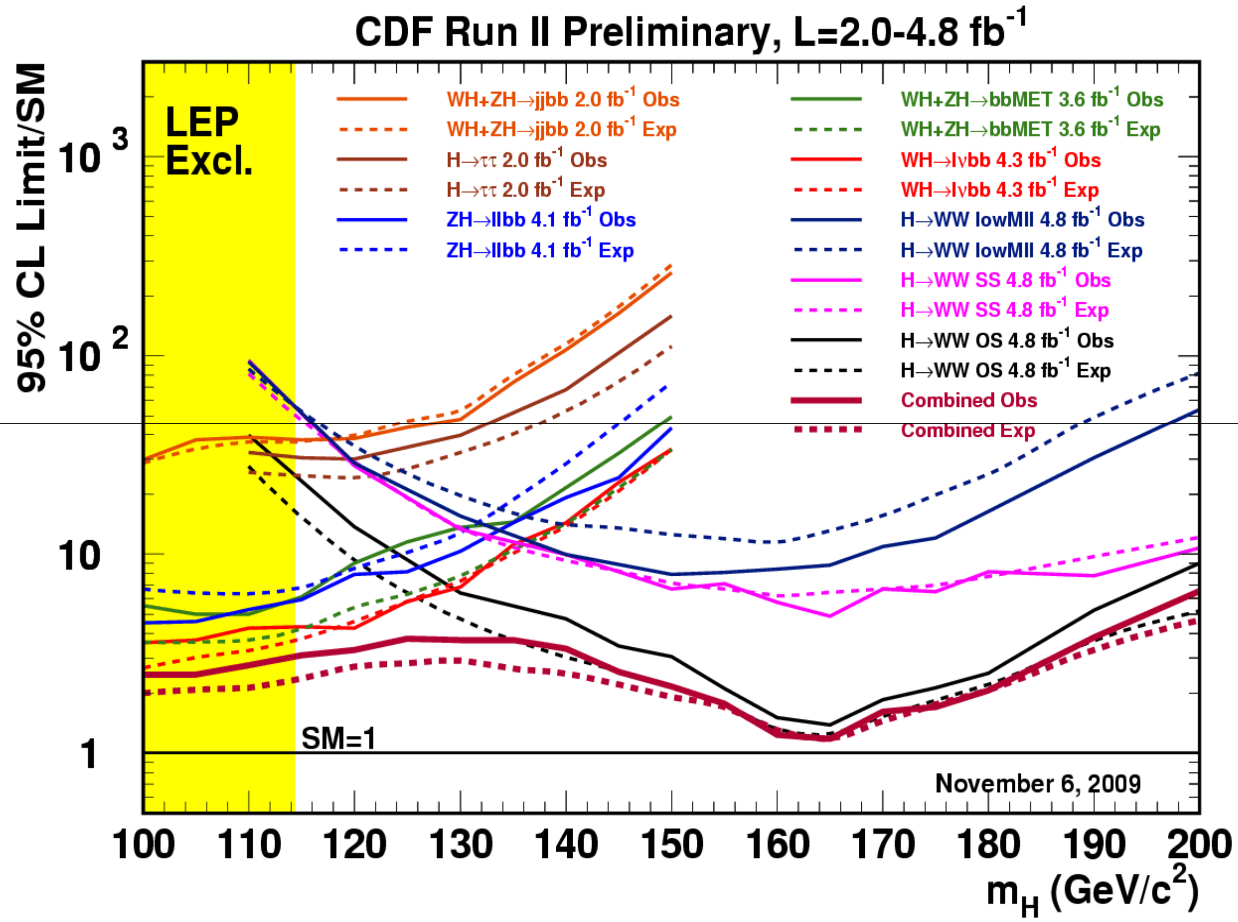
What is Dark Matter

- Normal Matter
  - Made from atoms (quarks and electrons
  - Includes stars, people, planets
- Dark Matter
  - Unknown Substance (not atoms)
- Dark Energy
  - Even more strange



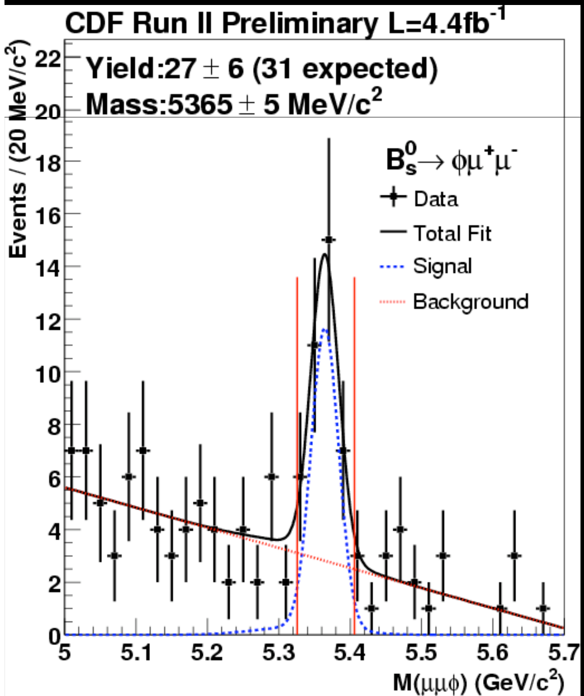
One Experiment's Channel Combination

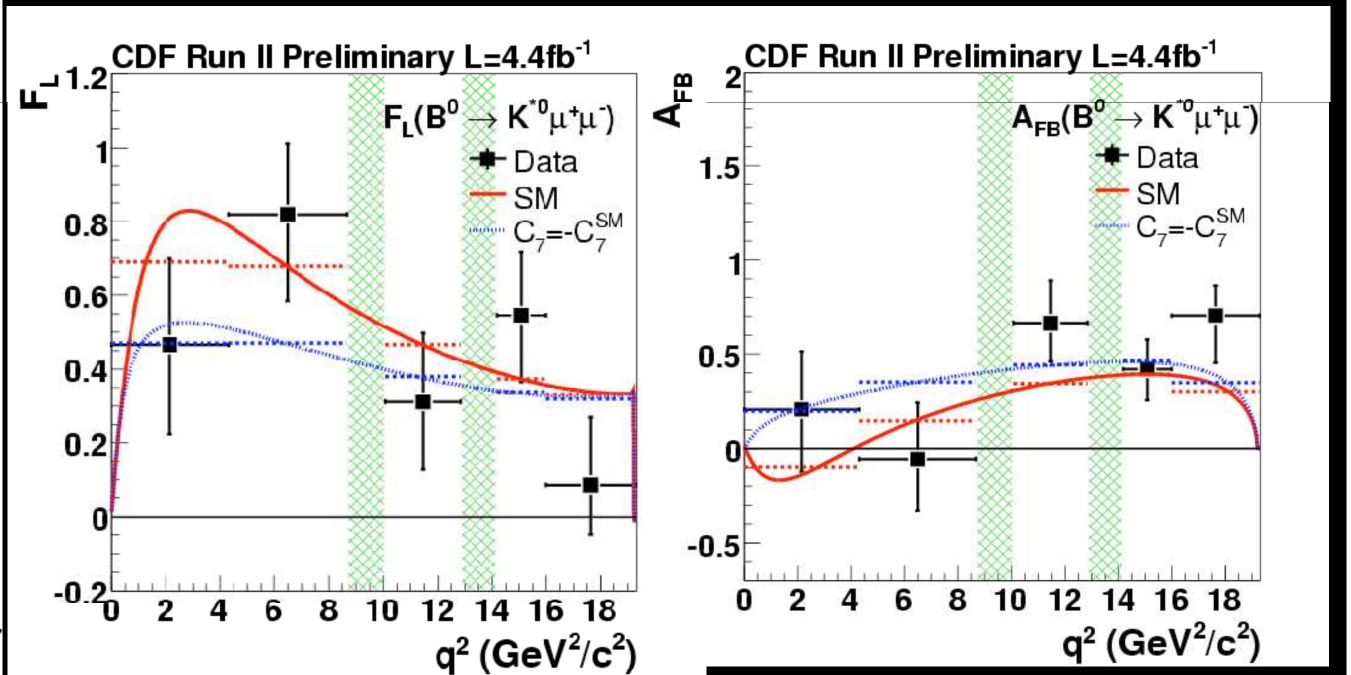
Factor away in sensitivity from SM



$B \rightarrow \mu\mu X_s$

- Rare decays $B \rightarrow \mu\mu X_s$: $B^+ \rightarrow \mu\mu K^+$, $B^0 \rightarrow \mu\mu K^{0*}$, $B_s \rightarrow \mu\mu\phi$
  - Decay to strange mesons and non resonant muons
  - FCNC process. NP could modify rate or decay distributions
  - Observation of $B_s \rightarrow \mu\mu\phi$! Measurement of A_{FB}(muons) and $F_L(K^{0*})$

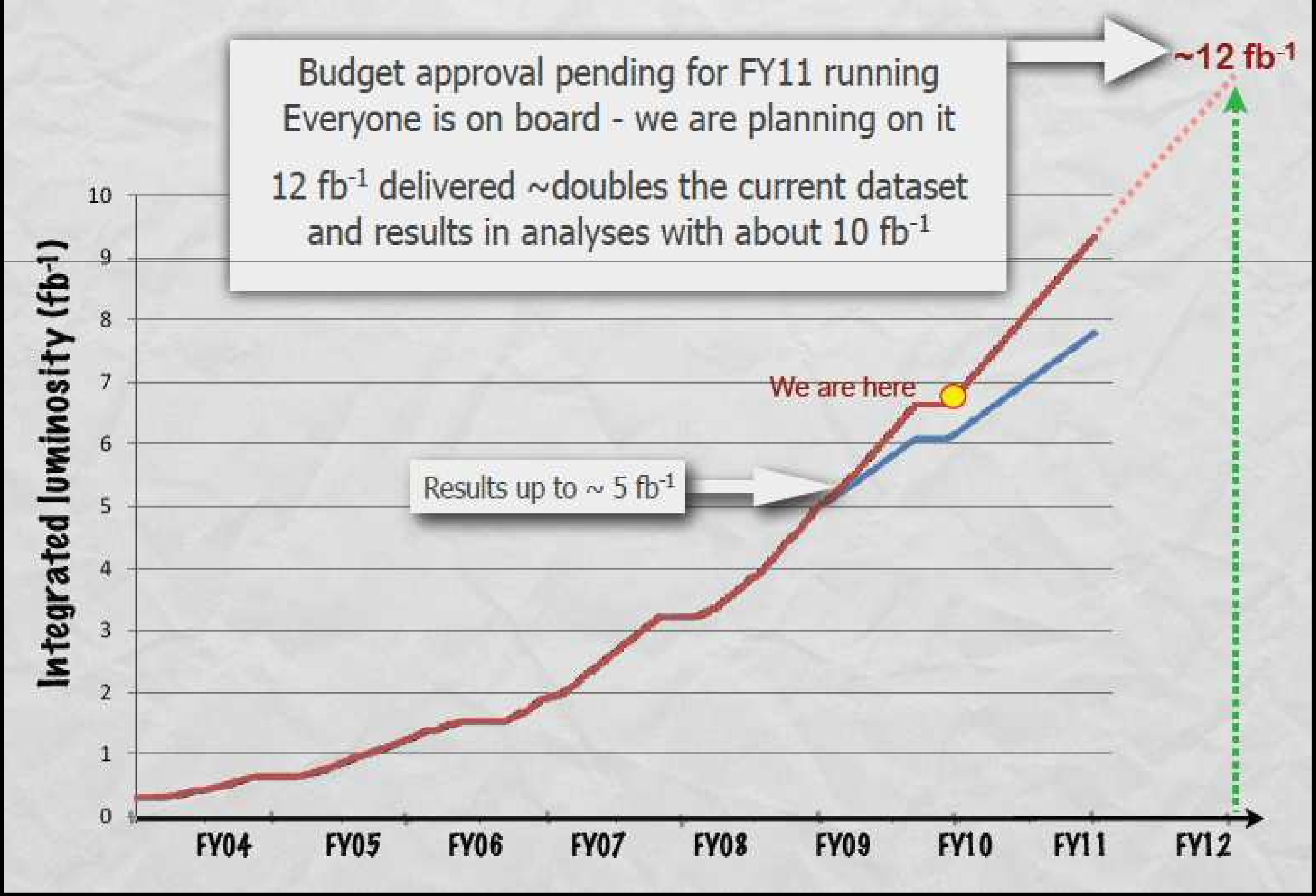




$BR(_{Bs}) = (1.44 \pm 0.33_{stat} \pm 0.46_{sys})\times10^{-6}$ **Competitive with B factories**

You Can Not make a Discovery with one Collision

It is a Statistical Process!



Today we have 70 times more data collected than we used to discover the top quark