Detecting Massive Scalar Particles at Proton Colliders

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Outline

- Motivation for scalar particles in particle theories
  - The Higgs particle
  - Supersymmetry
- Hints of scalar particles
- The Tevatron collider and the CDF experiment
  - Review of Run 1 searches for Higgs and SUSY
  - Status of Run 2 and search prospects
- The Large Hadron Collider and the CMS experiment
  - Construction progress and search prospects

Why Not Scalars?

So far, all known matter is composed of spin-½ fermions

- ➔ electrons, protons, neutrons, …

Thus, atomic and nuclear structure obeys the Pauli-Exclusion principle

Scalar objects do exist, but actually they are composites

- ➔ e.g. ^{4}He, π^+

In fact, all nuclear particles are composed of spin-½ quarks

- ➔ p = u u d
- ➔ n = u d d
- ➔ π^+ = u $\bar{d}$

Additionally, three of the fundamental forces are propagated by spin-1 bosons

- ➔ Electromagnetism: Photons (γ)
- ➔ Weak nuclear force: W^+, W^-, Z bosons
- ➔ Strong nuclear force: gluons (g)

} unified into one electro-weak theory

Quantum gravity would be propagated by a spin-2 boson

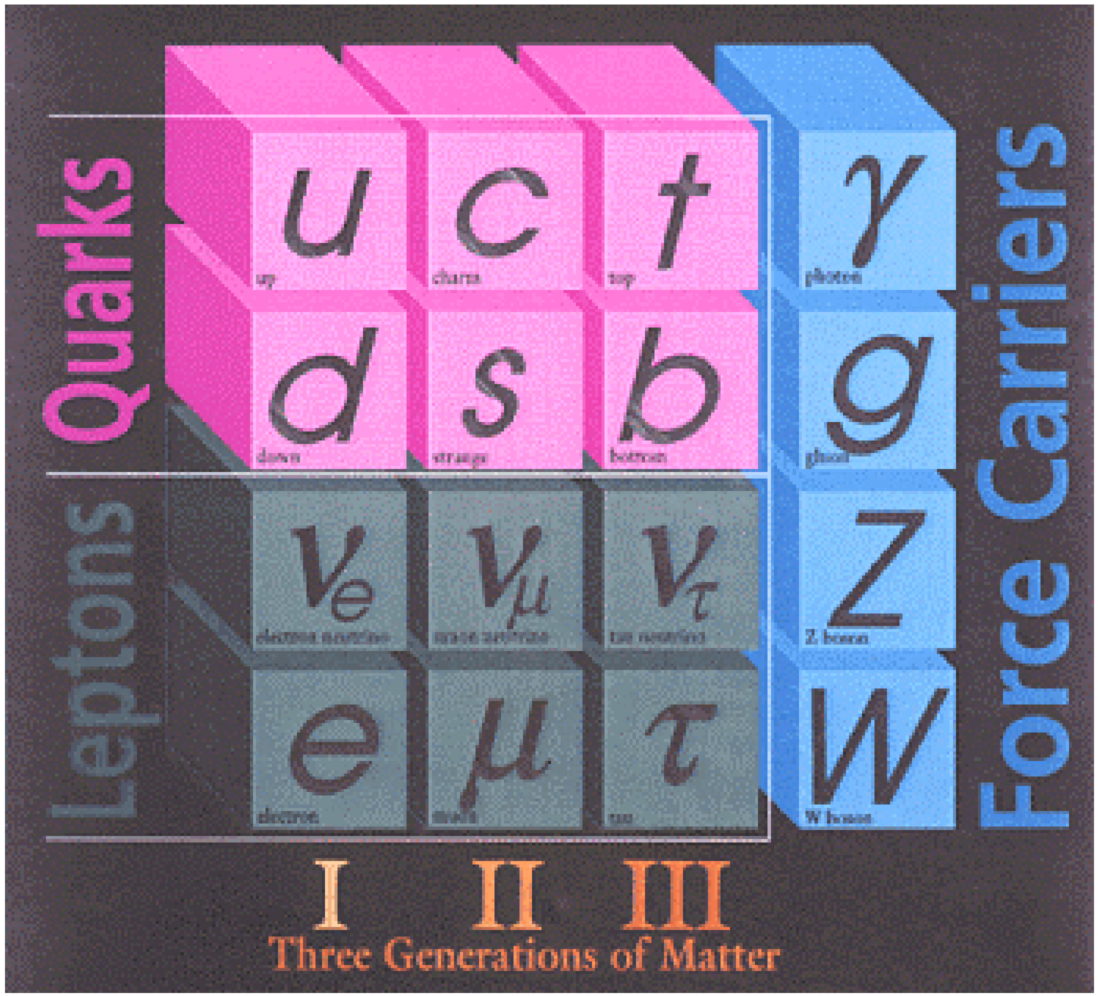
Elementary Particles

$m_{u,d} \sim 5$ MeV

$m_t = 174$ GeV

$m_\nu \neq 0$?

$m_e = 0.511$ MeV



$m_\gamma = 0$

$m_g = 0$

$m_Z = 91.188$ GeV

$m_W = 80.4$ GeV

1 eV = 1.6×10^{-19} J

The Higgs Mechanism

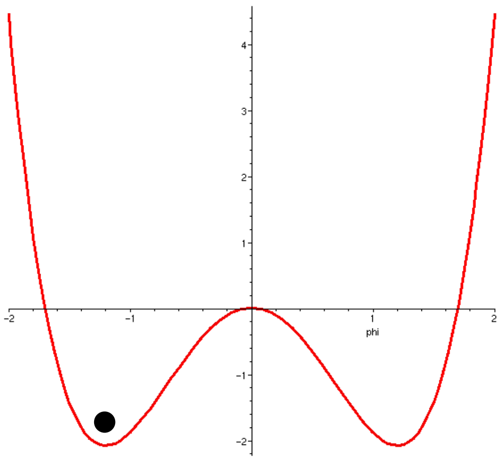
The electro-weak theory is described by the SU(2)×U(1) Weinberg-Salam Model

The quantum field theory of the strong force is described by Quantum Chromodynamics

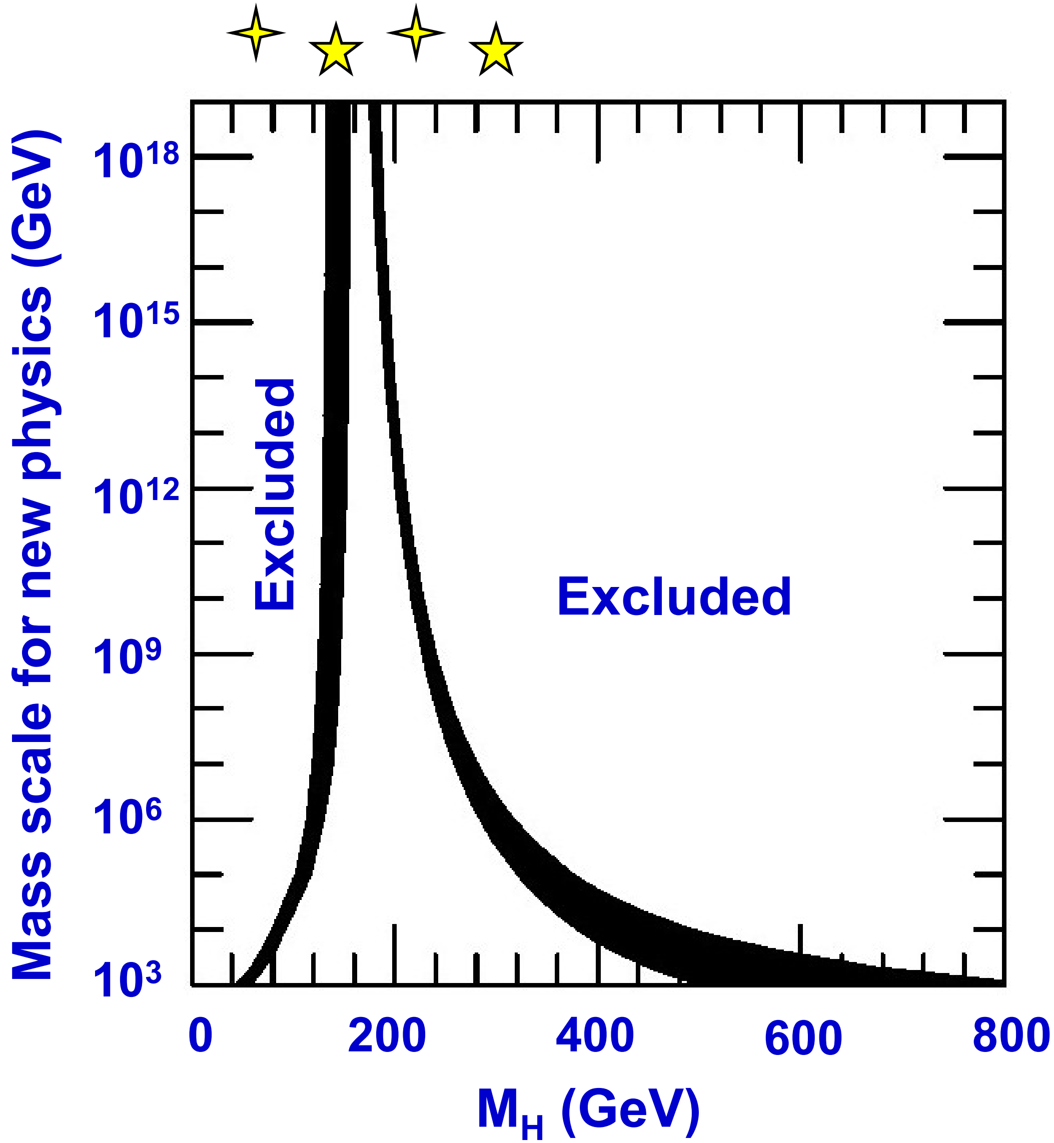
Collectively, they are referred to as the "Standard Model"

However, all masses are **zero** unless we introduce a scalar field, and this scalar field must obtain a non-zero vacuum expectation value through spontaneous symmetry breaking

- ➔ Generates mass for the vector bosons
- ➔ Generates mass for the fermions
- ➔ Generates a massive neutral scalar



Theoretical Higgs Mass Constraints

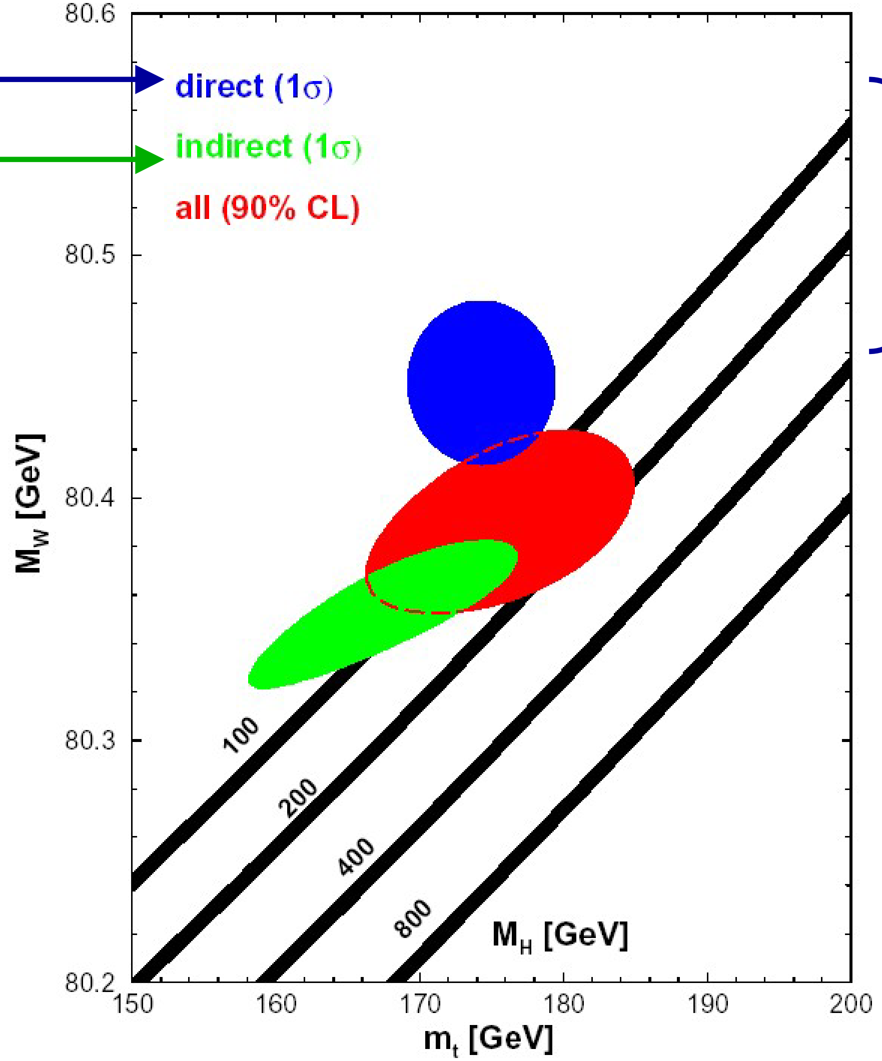


- Self consistency of the Standard Model places upper and lower bounds on the Higgs mass
- Wide mass range up to ~1 TeV allowed if new physics comes in at scale of 1 TeV
- Narrow mass range if new physics doesn't enter until Grand Unification scale

Indirect Experimental Constraints

Direct m_W, m_t measurements

Indirect from electro-weak parameters



SM predictions

PDG, 2002

Direct Higgs Search at e^+e^- Colliders

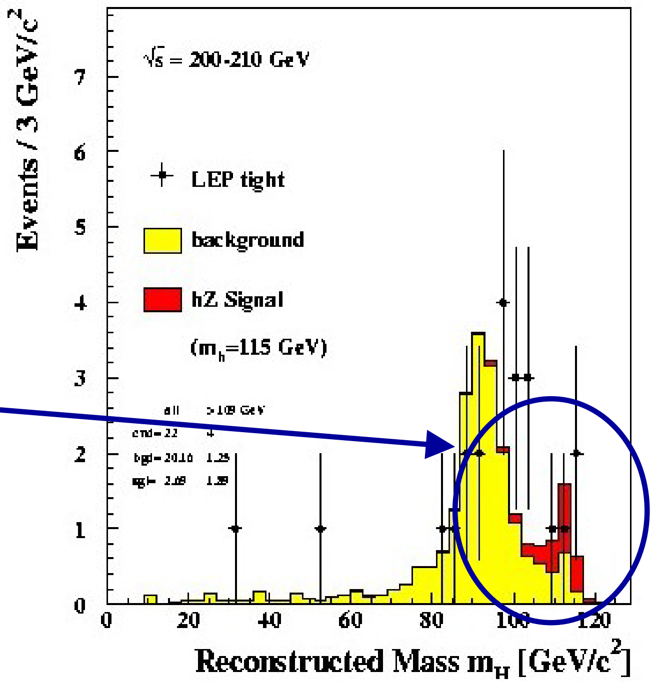
The Large Electron Positron (LEP) collider at CERN ran from 1989 until 2000

- ➔ In depth studies of the Z-boson resonance at 91 GeV
- ➔ Steadily increased energy to 209 GeV to study W production and to search for the Higgs
- ➔ Shut down to allow construction of the Large Hadron Collider

Possible hint of the Higgs ?

$N_{obs} = 4$
$N_{exp} = 1.25$

$\Rightarrow P = 3\%$



Lower bound on Higgs mass assuming no signal is 114 GeV at the 95% CL

Supersymmetry: another source of scalars

Why is all matter spin-½ ?

Antimatter is the charge conjugation of normal matter

- ➔ $C\,|e^-\rangle = |e^+\rangle$
- ➔ Predicted by P.A.M. Dirac in 1928, observed in 1932

Is there a spin conjugation as well?

- ➔ $Q\,|\text{fermion}\rangle = |\text{boson}\rangle$

Such "Supersymmetry" generalizes space-time symmetry

Predicts partners to all known particles with opposite spin statistics

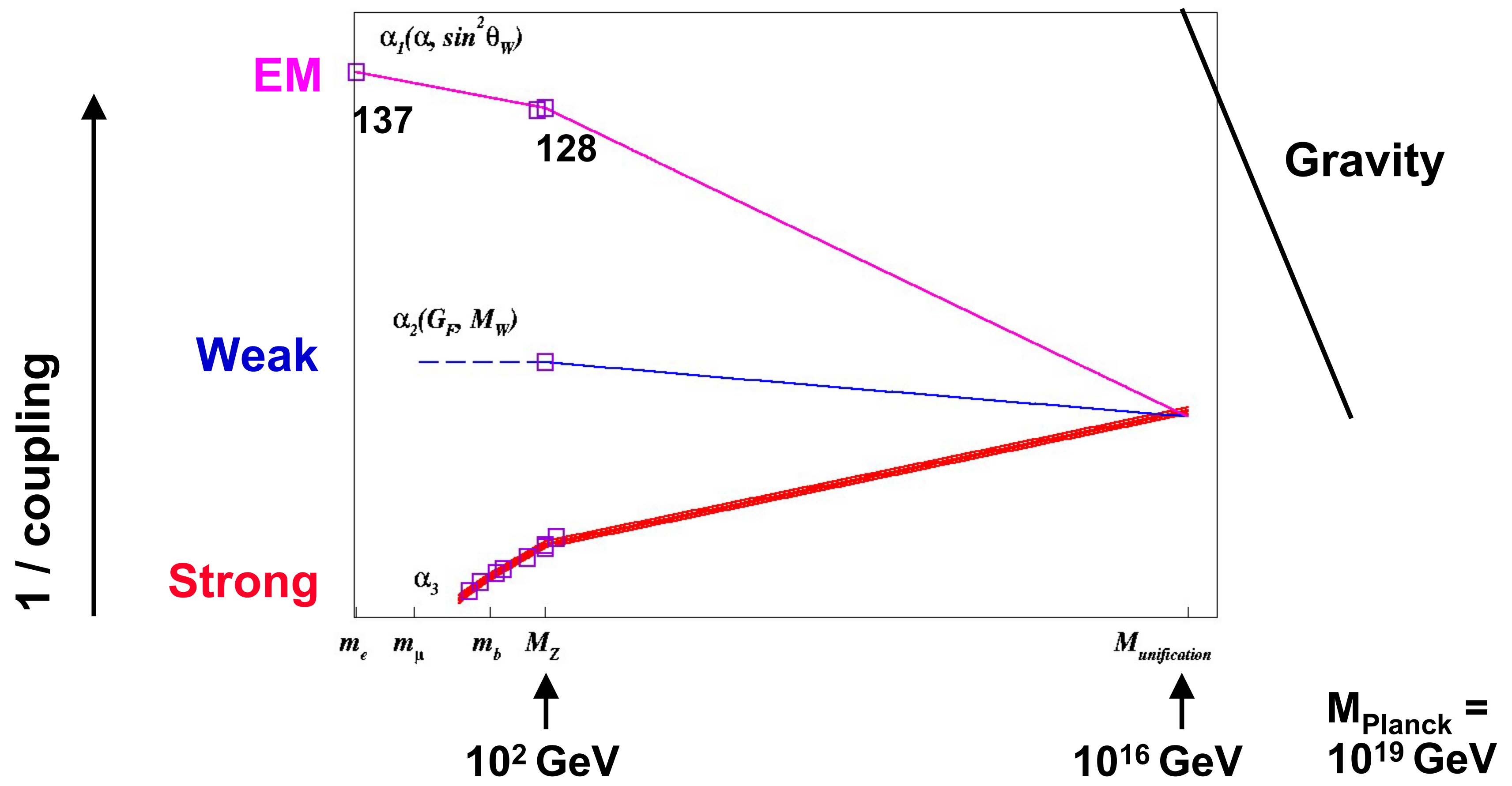
- ➔ Not so good for a theory, which ought to reduce the number of free parameters (28 for the Standard Model) !

Points the way to a larger theory

- ➔ When Supersymmetry is required to be a local symmetry, it can incorporate gravity (Supergravity)
- ➔ Supersymmetry is a prerequisite for string theories
- ➔ Allows for Grand Unification

Grand Unification

- Coupling "constants" vary with the energy scale
- Minimal Supersymmetric models allow for the unification of 3 forces at one energy scale (would miss otherwise)



Supersymmetry is Broken

- If Supersymmetry exists, there should be scalar partners to the fermions
  - ➔ e.g. scalar electrons, which would *not* obey the Pauli-Exclusion Principle in atoms
- So far, no such particles are observed at low energy
- Supersymmetry cannot be an exact symmetry, and must spontaneously break at some energy scale
- Particle masses should be less than about 1 TeV
- Lightest Higgs boson (there are at least 5 of them) must have mass < 135 GeV

Leptoquarks: also a source of scalars

There is no explanation in the Standard Model for why atoms are electrically neutral

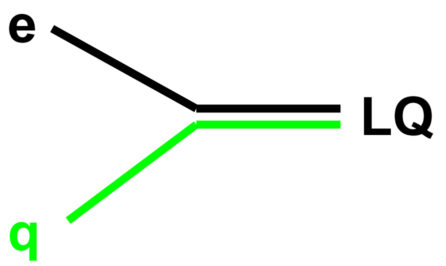
- ➔ Specifically, the relationships between quark and lepton electroweak charges exactly cancel triangle anomalies in the Standard Model
  - Makes the Standard Model a renormalizable theory

Leptoquarks arise in Grand Unification models, "technicolor", Supersymmetry, and compositeness

- ➔ Connects the lepton sector to the quark sector, which otherwise are just ad hoc ingredients to the SM

LQs are color triplet bosons (scalar or vector) with lepton number and fractional electric charge

Hint of leptoquarks in data taken by the HERA electron-proton collider in 1997, but no longer seems likely



Cosmological Implications of Scalars

In the Minimal Supersymmetric Standard Model the lightest supersymmetric particle is stable

- Generally a neutral, weakly interacting particle (neutralino)
- Good candidate for Cold Dark Matter

Scalar particles can obtain a non-zero vacuum expectation value (vacuum energy)

- May give rise to a cosmological constant

Current consensus among cosmologists from measurements of the cosmic microwave background, supernovae, Big Bang nucleosynthesis, clusters of galaxies,…

- $\Omega \approx 1$ (flat universe)
- $\Omega_\Lambda \approx 0.7$, $\Omega_m \approx 0.3$
- $\Omega_m = \Omega_b + \Omega_{CDM}$; $\Omega_b \approx 0.04$

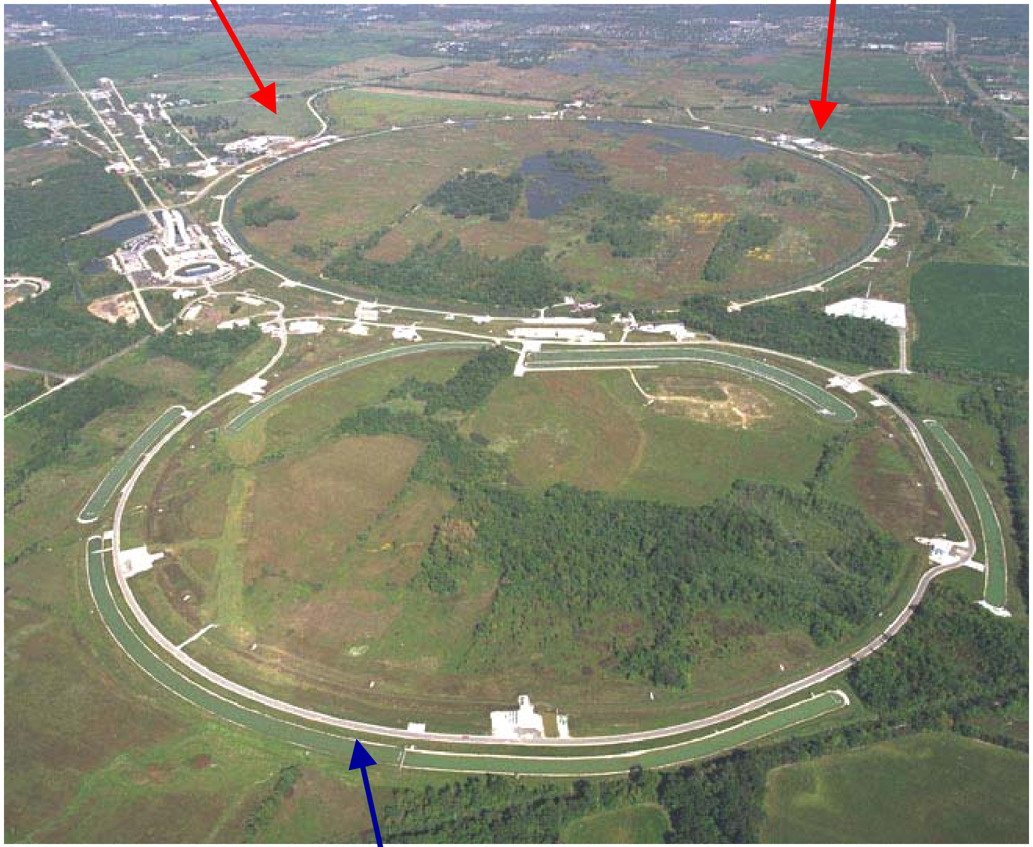
The Fermi National Accelerator Laboratory

Batavia, Illinois

The Tevatron

CDF

DØ



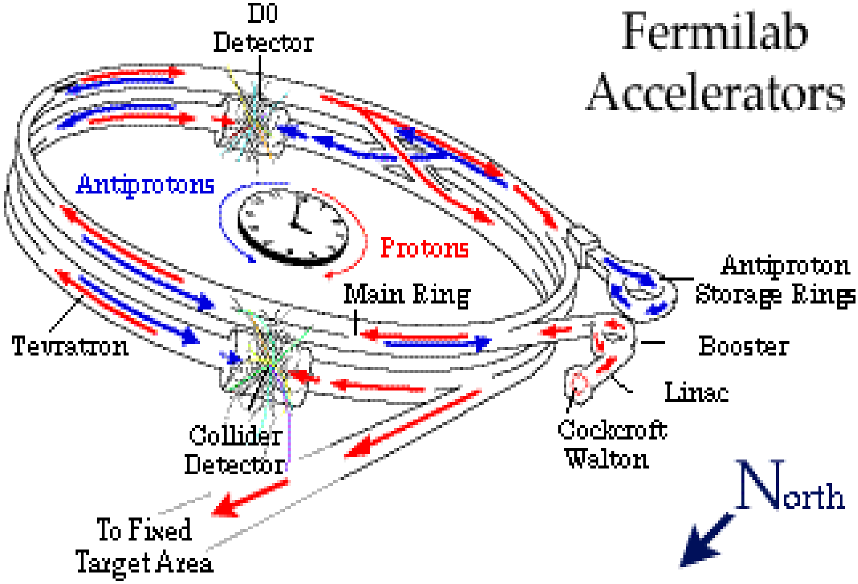
Main injector

Proton-Antiproton collider

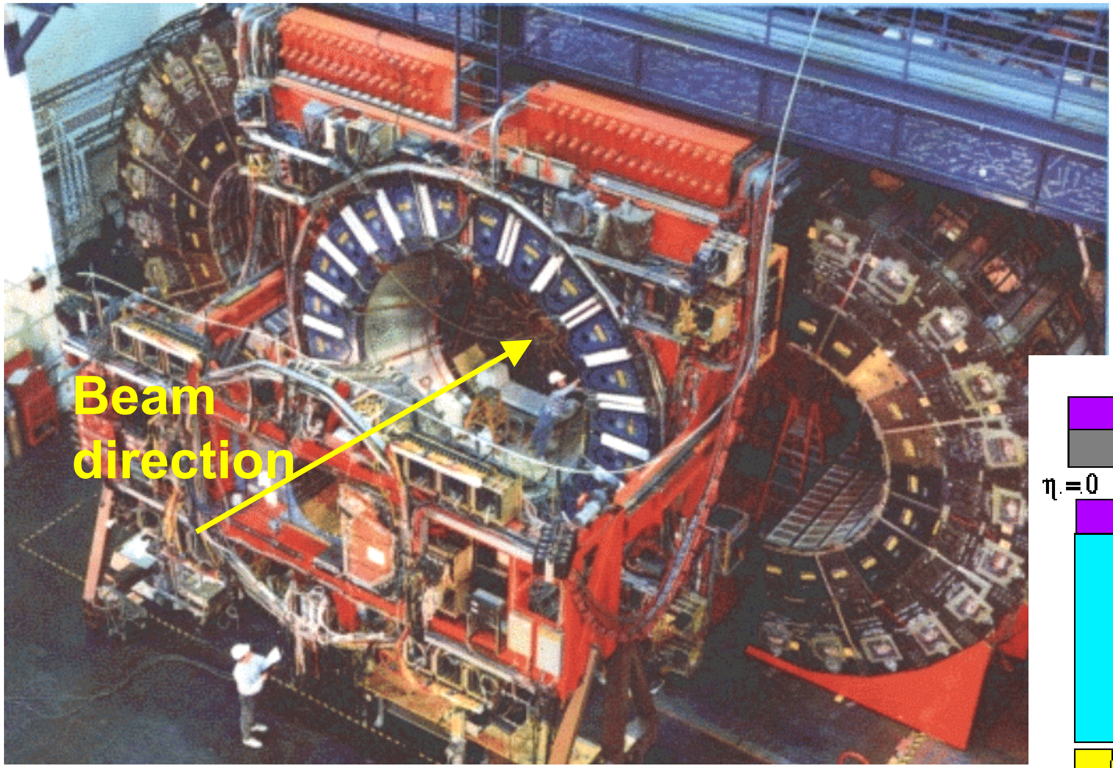
E_{beam} = 1 TeV

R = 1 km

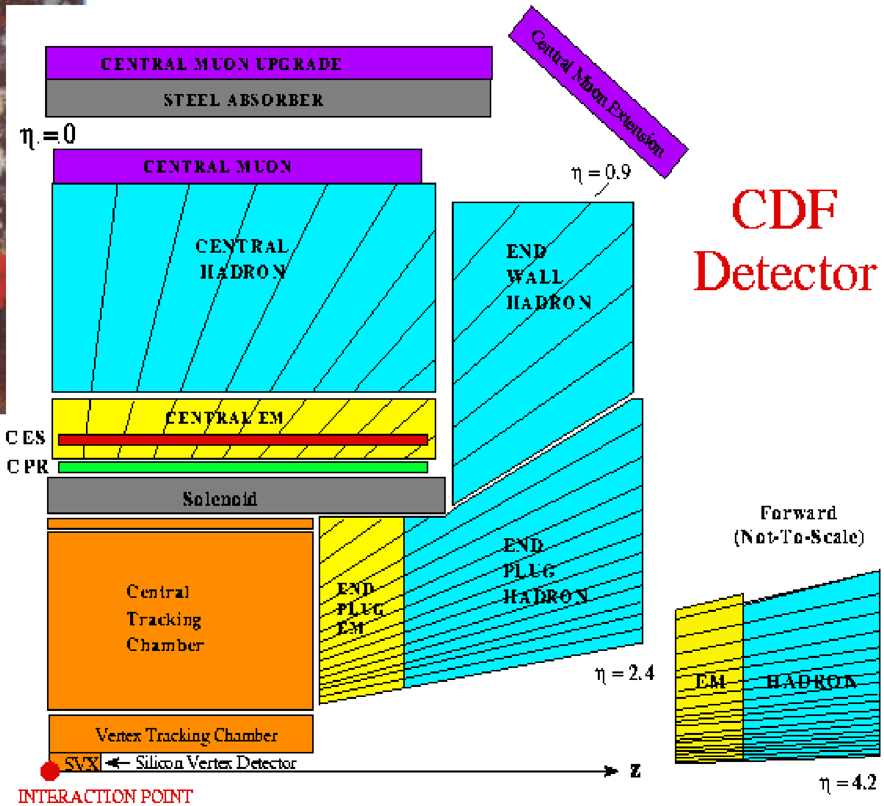
In operation since 1985
Major upgrade completed in 1999



The Collider Detector at Fermilab



Run 1: 1992 – 1996
L=120 pb^{-1}



CDF Detector

A very large, general purpose "microscope" to study the structure of matter

Hundreds of researchers participate

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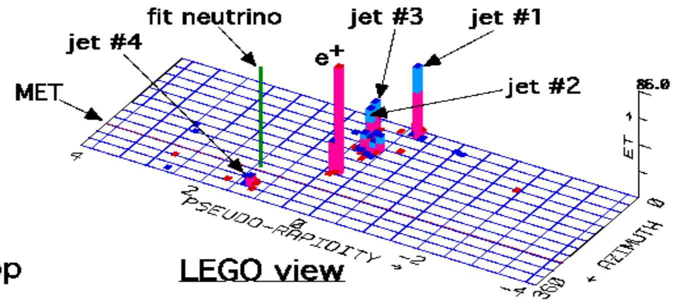
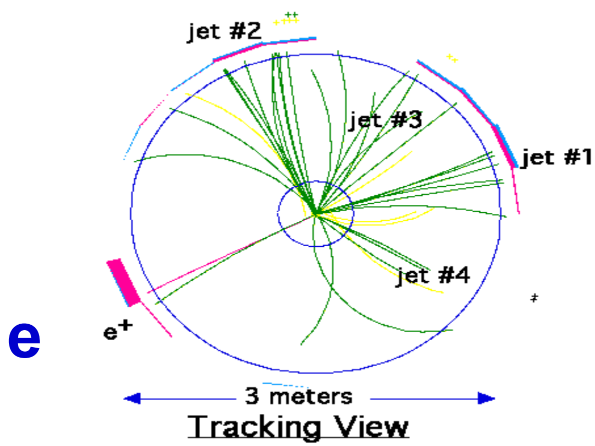
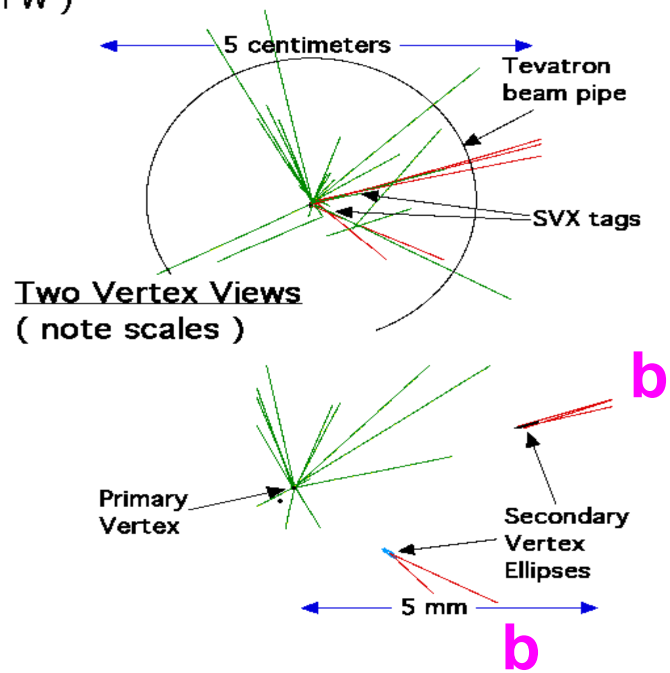
Discovery of the Top Quark in 1995

<u>e + 4 jet event</u>
40758_44414
24-September, 1992

TWO jets tagged by SVX
fit top mass is 170 +- 10 GeV
e^+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)







Relatively long-lived

$t\,\bar{t} \rightarrow b\,\bar{b}\,W^+\,W^- \rightarrow b\,\bar{b}\,q\,q'\,e\,\nu$

$M_{top} = 174 \pm 5$ GeV

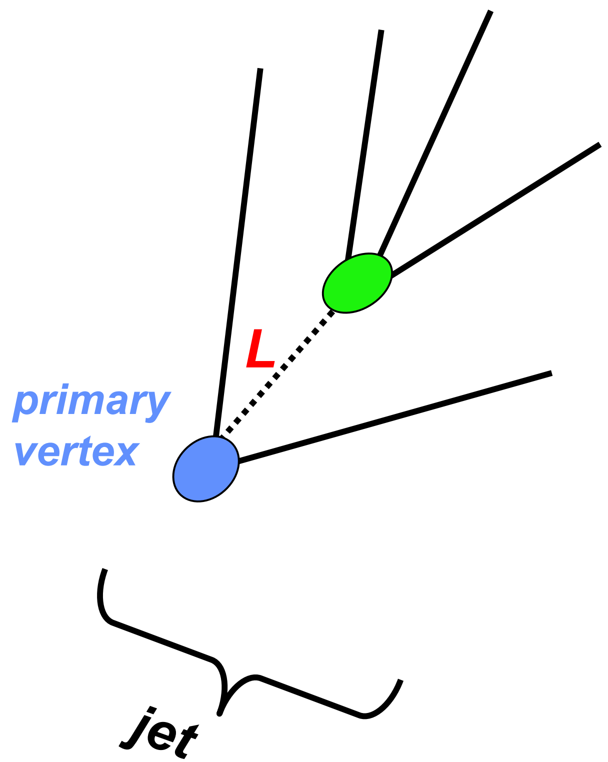
CDF Heavy Flavor Tagging

Bottom quarks and charm quarks have a lifetime of about 1 ps

Tag bottom and charm quarks by reconstructing the **secondary vertex** of their decay products

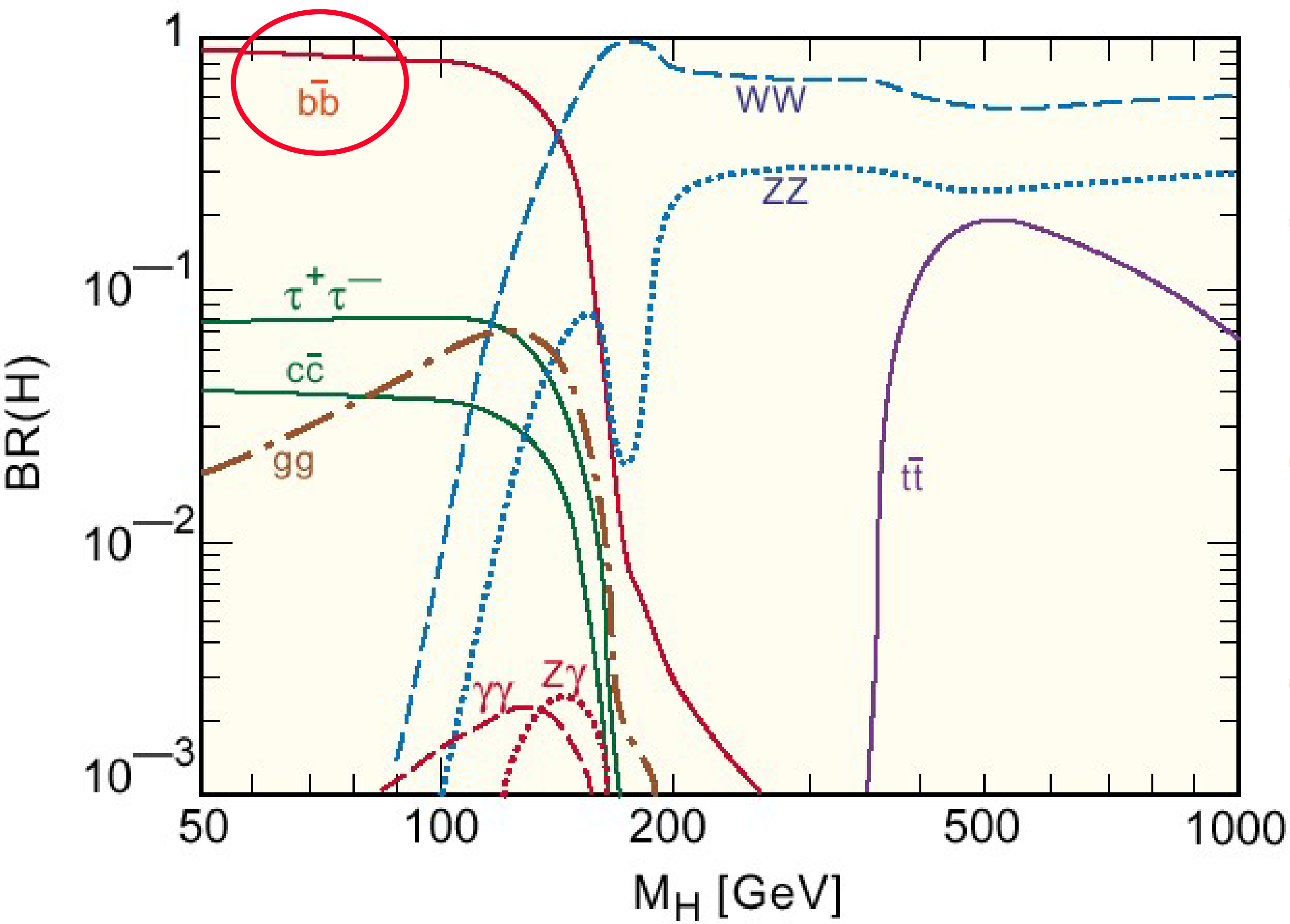
Measure the flight distance (*L*)

- ➔ Typically several hundred microns, extending up to a few mm
- ➔ This is still within the beam pipe, not in the detectors, so we must extrapolate a precisely measured track



An important signature of the decay of heavier particles…

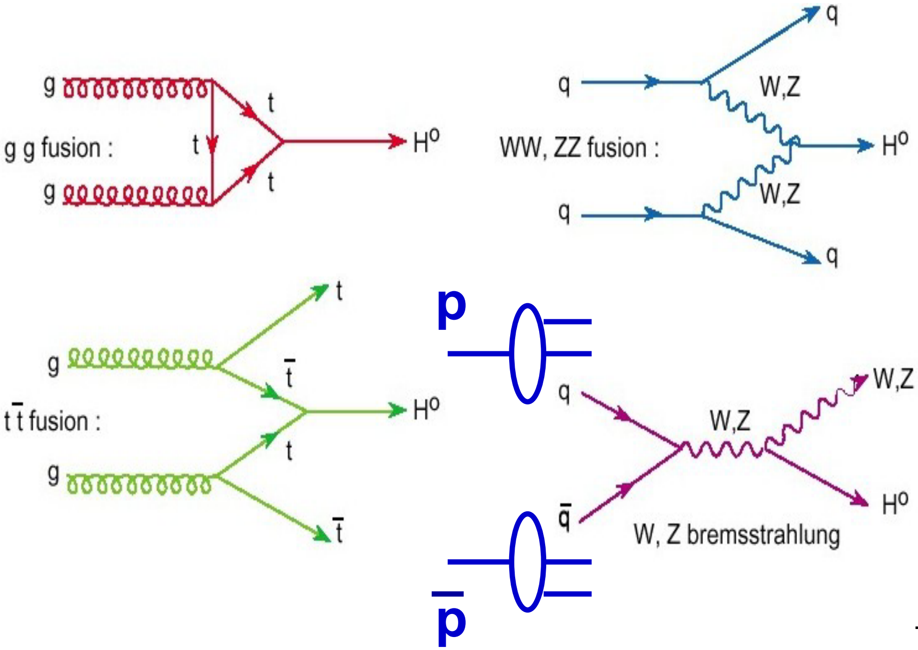
Branching Ratios for Higgs Decay

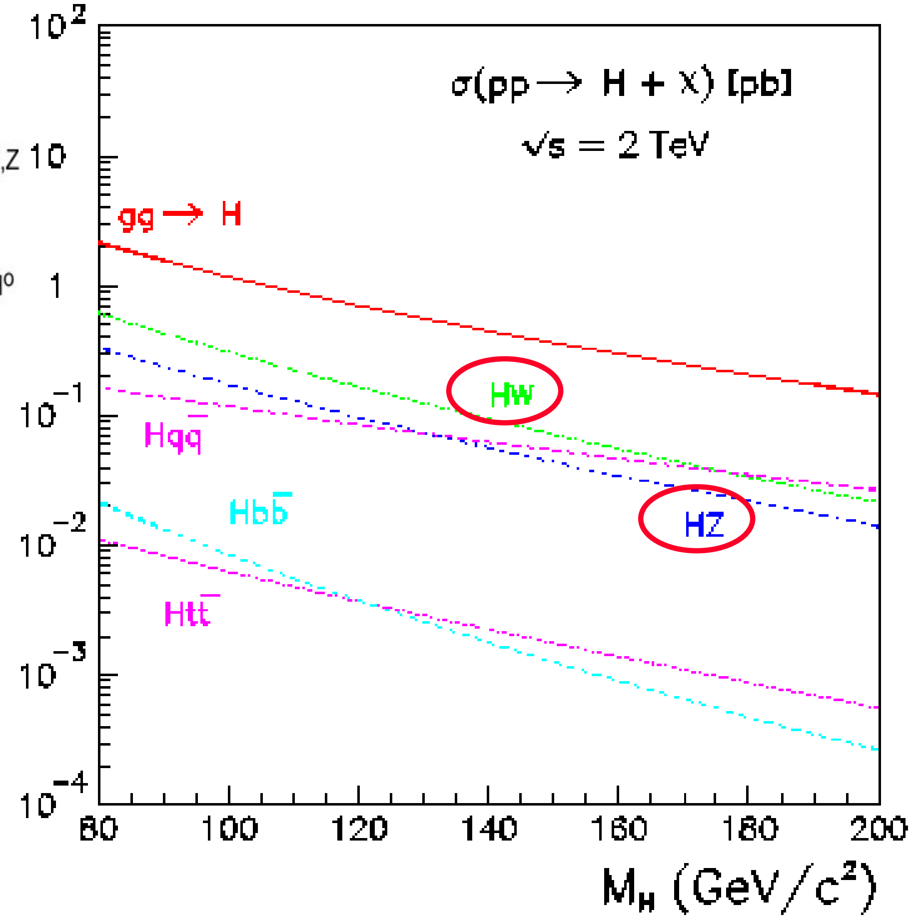


- BR ($H \to bb$) ~ 1
- BR ($H \to WW \to 2\mu$) ~ 0.01
- BR ($H \to ZZ \to 4\mu$) ~ 3×10^{-4}
- BR ($H \to \gamma\gamma$) ~ 10^{-3}

Tagging b quarks is important to discover a light Higgs

Higgs Production





Note:

σ = scattering cross section

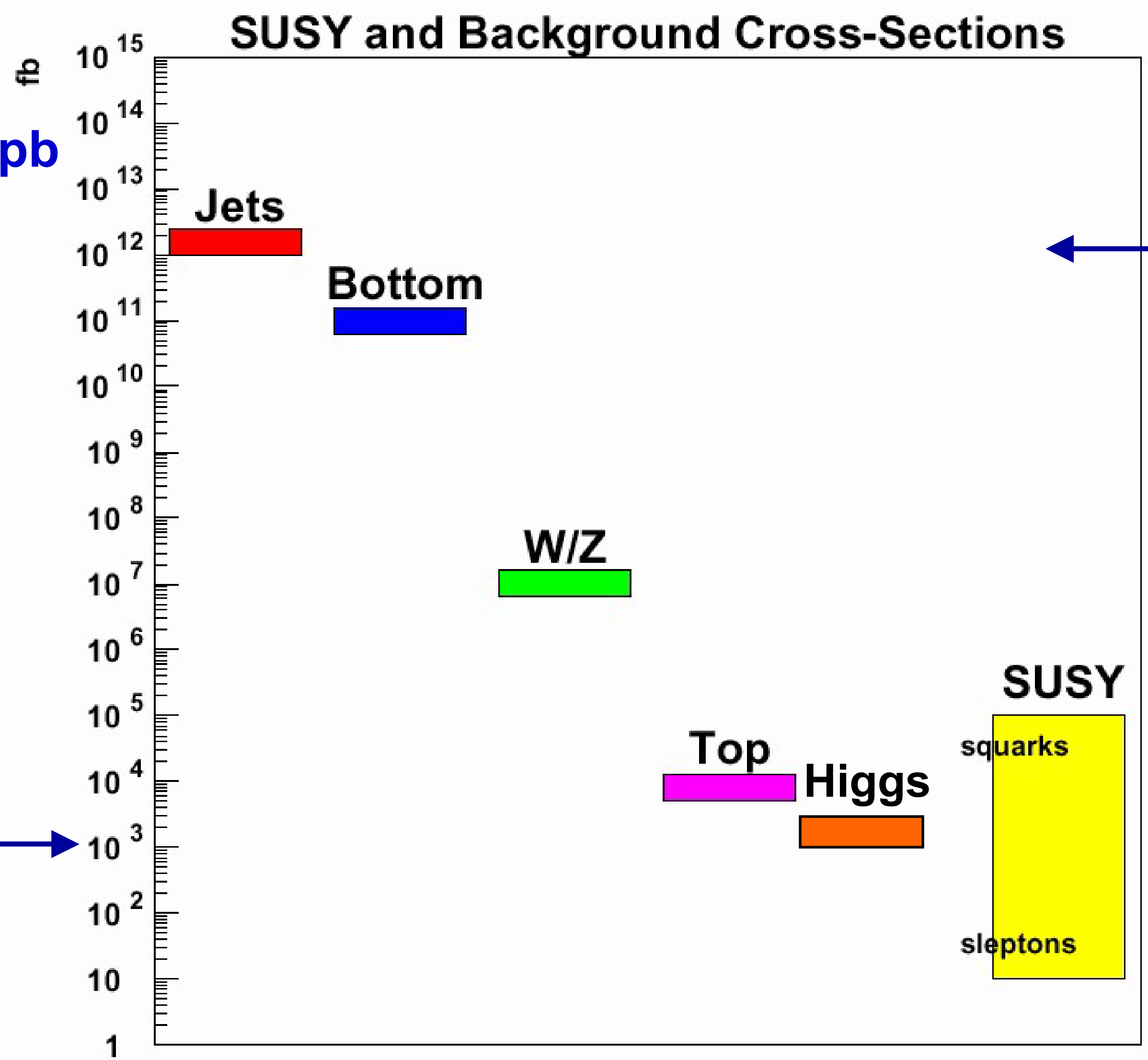
1 pb = 10^{-36} cm²

***L*·σ = *N* (number of events)**

***L* = 120 pb^{-1} for Run 1**

Relative Yields at the Tevatron

1 fb = 10^{-3} pb



Background

1 pb

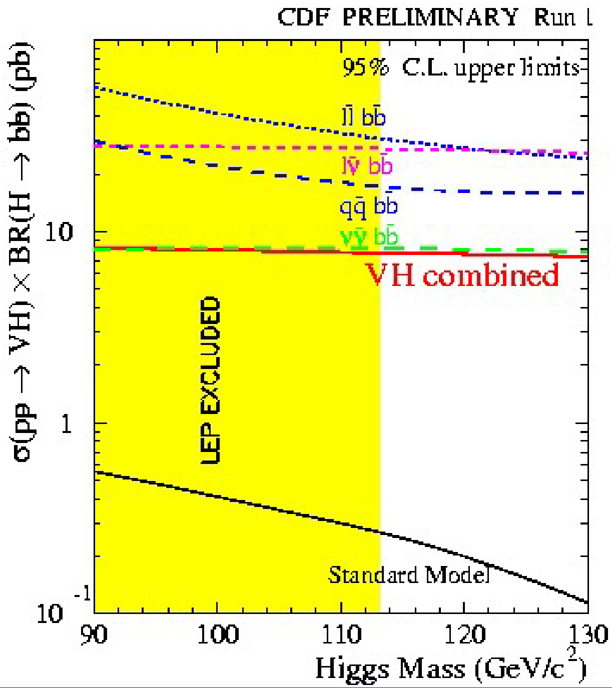
Signal

(one in a billion collisions!)

SM Higgs Search in Run 1

Channel	b-tags	Experiment	$\int \mathcal{L}$ (pb^{-1})	BR × Accept.(%) for M_H (GeV/c^2) 90	110	130	Expected background	Observed events
$\ell\nu b\bar{b}$	1	CDF[3]	106	$.55 \pm .14$	$.74 \pm .18$	$.89 \pm .22$	30 ± 5	36
$\ell\nu b\bar{b}$	2	CDF[3]	106	$.23 \pm .06$	$.29 \pm .07$	$.34 \pm .09$	3.0 ± 0.6	6
$\ell\nu b\bar{b}$	1	DØ[4]	106	$.30 \pm .02$	$.36 \pm .02$	$.44 \pm .03$	25.5 ± 3.3	27
$\nu\nu b\bar{b}$	1	CDF	88	$.59 \pm .12$	$.69 \pm .14$	$.86 \pm .17$	39.2 ± 4.4	40
$\nu\nu b\bar{b}$	2	CDF	88	$.37 \pm .08$	$.44 \pm .11$	$.53 \pm .11$	3.9 ± 0.6	4
$\ell\ell b\bar{b}$	1	CDF	106	$.14 \pm .03$	$.20 \pm .04$	$.19 \pm .04$	3.2 ± 0.7	5
$q\bar{q}b\bar{b}$	2	CDF[5]	91	$1.3 \pm .4$	$2.2 \pm .6$	$3.1 \pm .8$	594 ± 30	589

WH, ZH **production**



Observed events agree well with background expectations

Require 10–100X more data to be sensitive to SM Higgs production

No anomalous production

Signatures of Supersymmetry

Larger cross sections for the production of scalar quarks and gluons rather than leptons at a proton collider because of the strong force couplings

Examples:

$$\left.\begin{array}{l} p\bar{p} \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \\ p\bar{p} \to \tilde{G}\tilde{G}g, \tilde{G}\tilde{G}q \\ p\bar{p} \to \tilde{t}_1\bar{\tilde{t}}_1, \tilde{b}_1\bar{\tilde{b}}_1 \end{array}\right\} \begin{array}{l} \tilde{q}, \tilde{g}, \tilde{G} \Rightarrow \not{E}_T + jets \\ \tilde{t}, \tilde{b} \Rightarrow \not{E}_T + HF\ jets \end{array}$$

Signatures:

- Jets (from the hadronization of quarks and gluons)
- Missing energy (from undetected lightest SUSY particle)

Backgrounds:

- QCD jets
- W/Z production
- top quarks

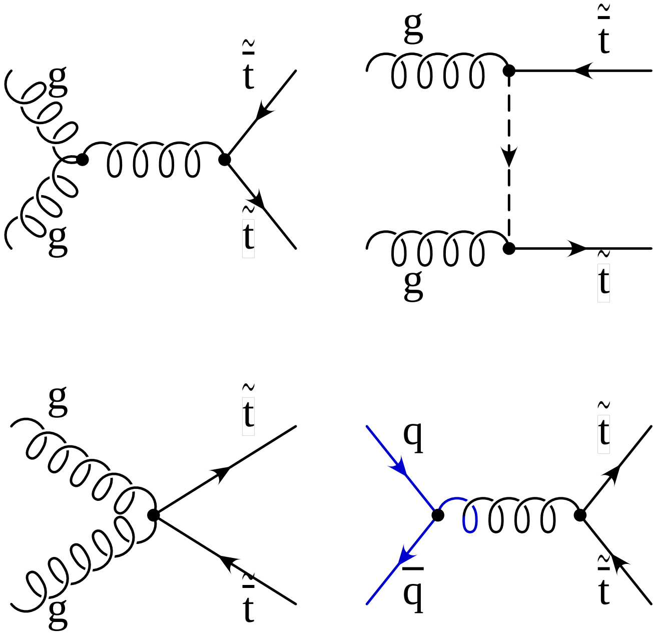
(QCD jets and W/Z production: Orders of magnitude larger)

Review just one search of many here →

Scalar Top Quark Search

- The heavy top quark mass gives rise to a large mixing between the left- and right-handed scalar top eigenstates
  - ➔ Results in a large mass splitting between the two mass eignenstates
- Thus, the "stop" could be the lightest scalar quark

- Search for the pair production of stop quarks



- Look for the decays:
  - ➔ $\tilde{t} \rightarrow b\chi_1^{\pm}$
  - ➔ $\tilde{t} \rightarrow c\,\tilde{\chi}_1^0$ (if first closed)

Scalar Top Quark Search (Jets + MET)

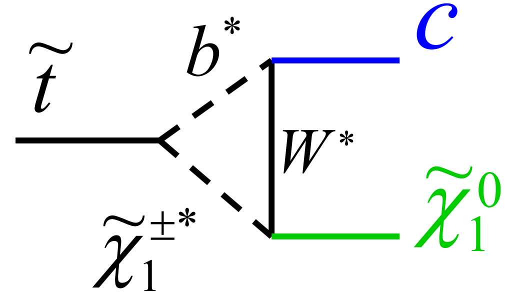
- Use Missing transverse energy data sample

  2 or 3 jets, $E_T \geq 15$ GeV and $|\eta| \leq 2$
  No jets with $7 \leq E_T \leq 15$ GeV and $|\eta| \geq 3.6$

- Cuts on jet-*MET*, jet-jet angles
- No l with $P_T > 10$ GeV
- *MET* > 40 GeV

⇨ Require ≥ 1 charm quark tag

$M(\tilde{\chi}_1^{\pm}) > M(\tilde{\nu}) > M(\tilde{t})$



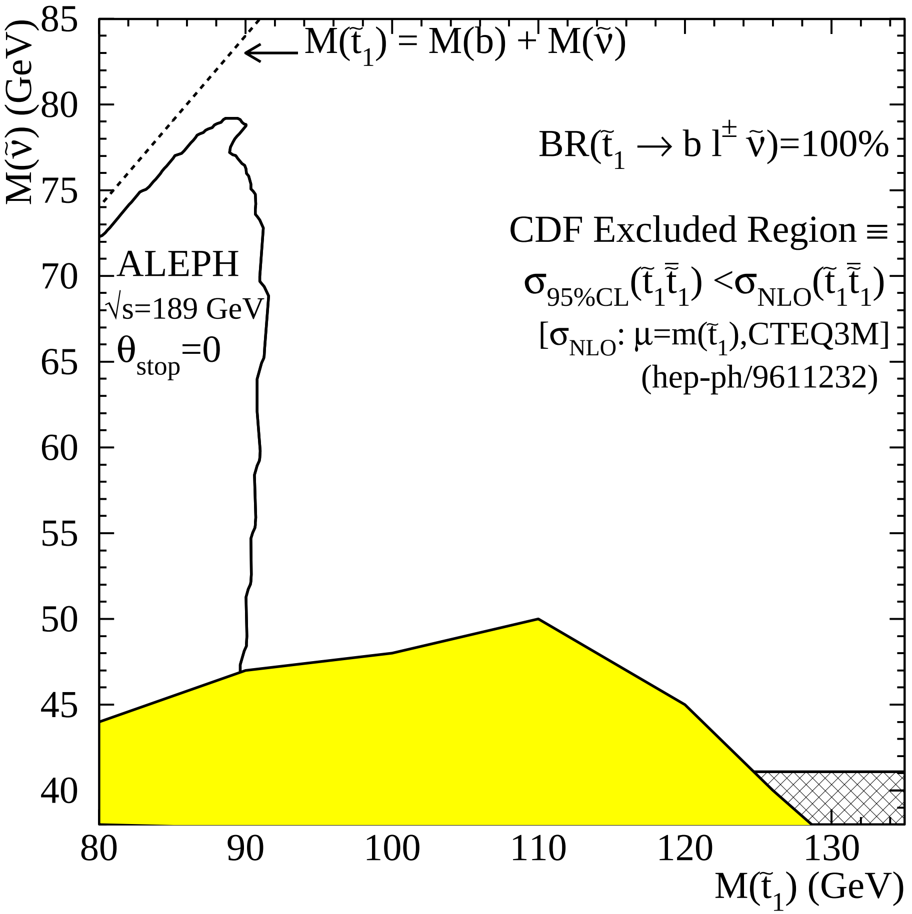
Main Backgrounds:

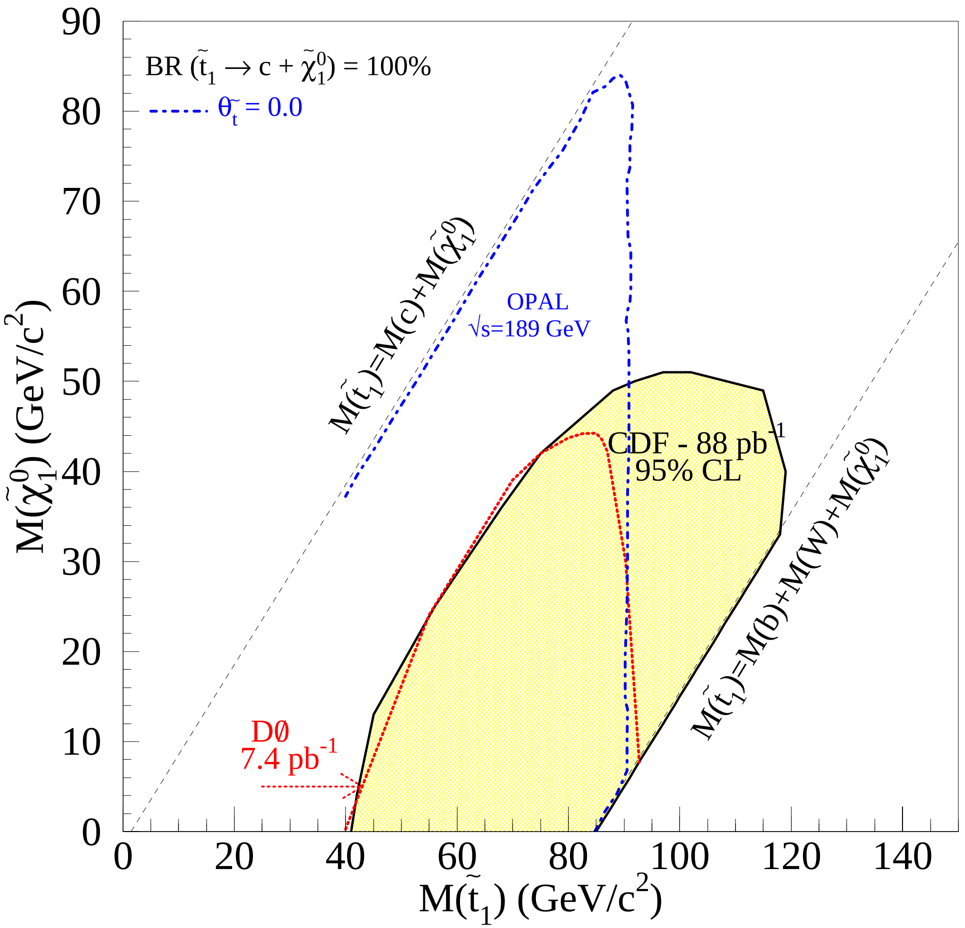
$W \rightarrow \tau\nu + 1(2,3,\ldots)$ jet
$Z \rightarrow \nu\tilde{\nu}$ +2(3,4,...) jet
QCD

Expect 14.5 ± 4.2 events
Observe 11

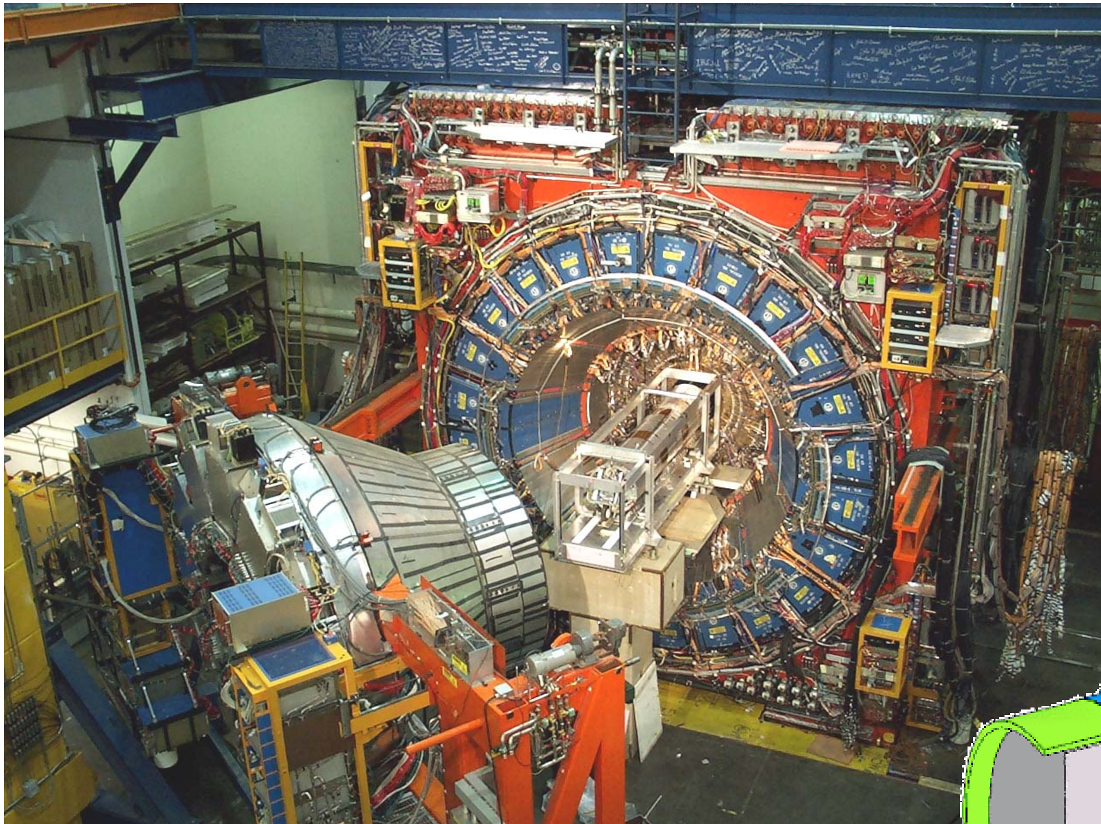
Published: PRL, 84,5704(2000)

Scalar Top Quark Limits



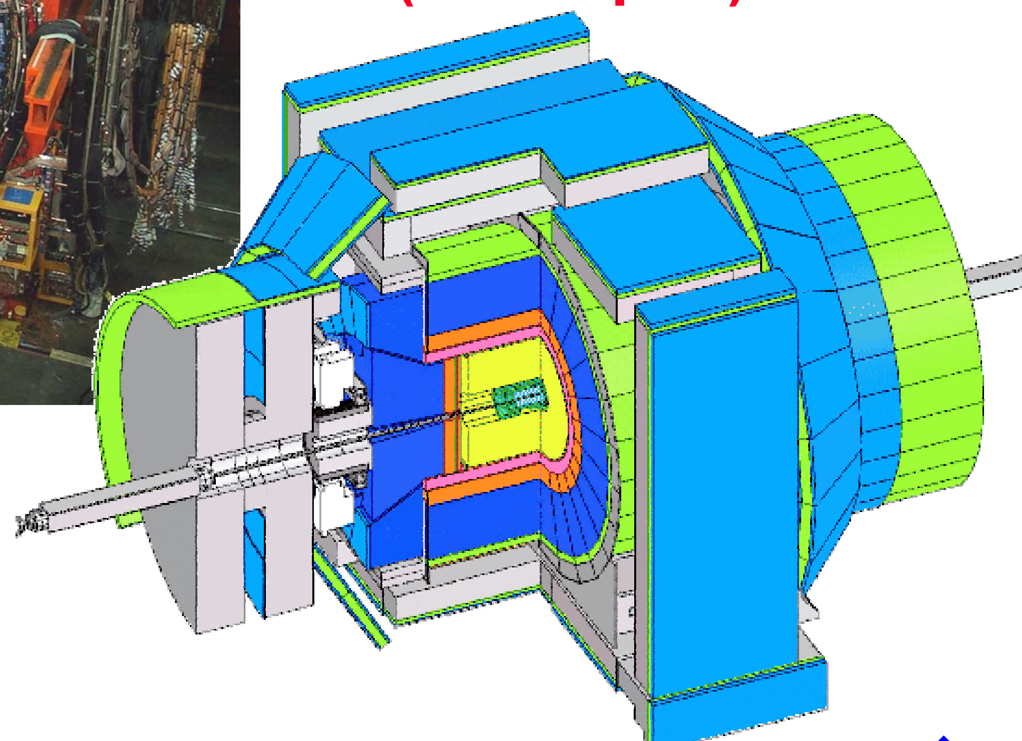


CDF II Detector



Goal:

Run 2a: 2001 – 2004
(2000 – 4000 pb^{-1})
Run 2b: 2004 – 2007+
(15000 pb^{-1})



Completely new electronics
New plug calorimeter
New muon chambers
New central tracker
New silicon vertex detector

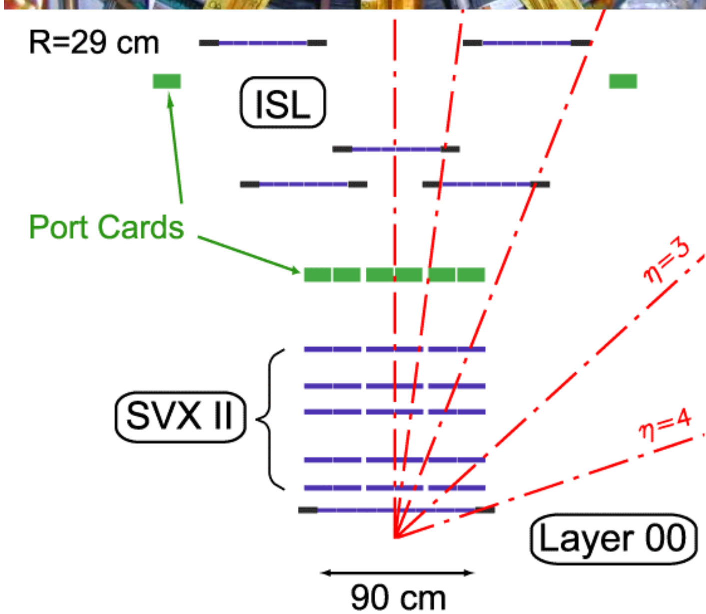
Silicon Vertex Detector

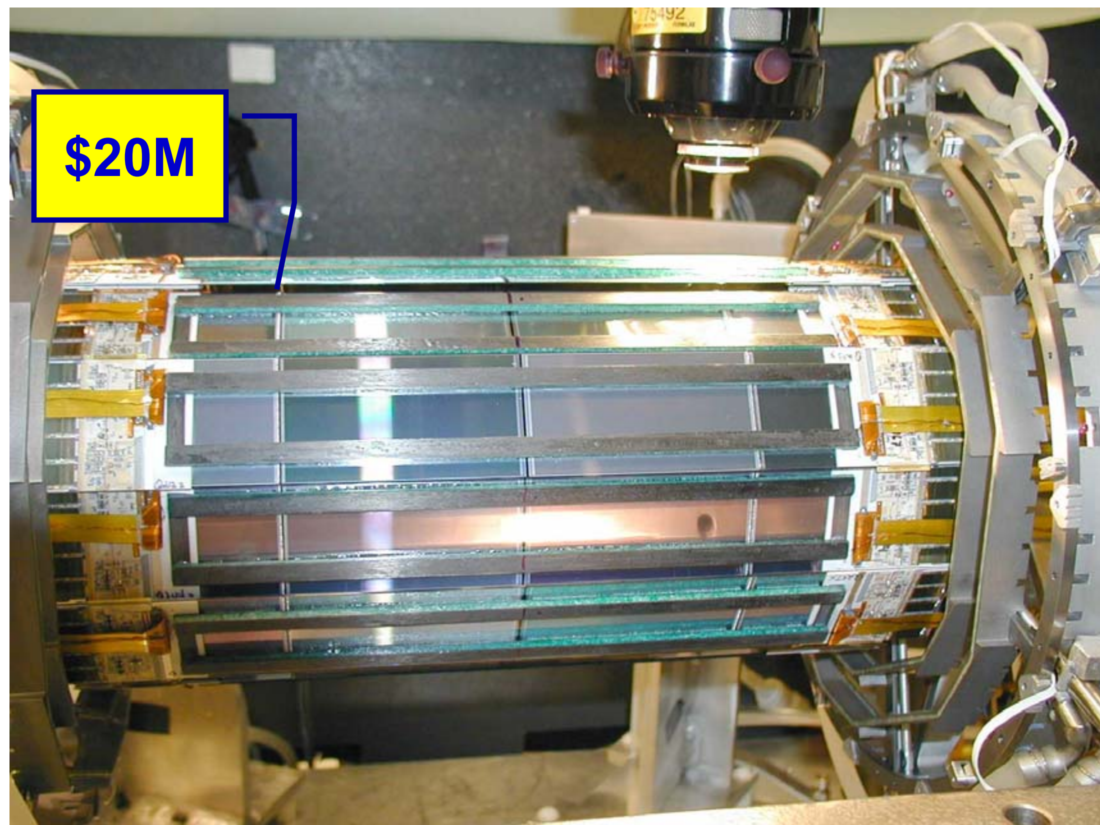
Radius: inner = 1.35 cm, outer = 29 cm

Length: 90 cm

strip pitch: 60μm

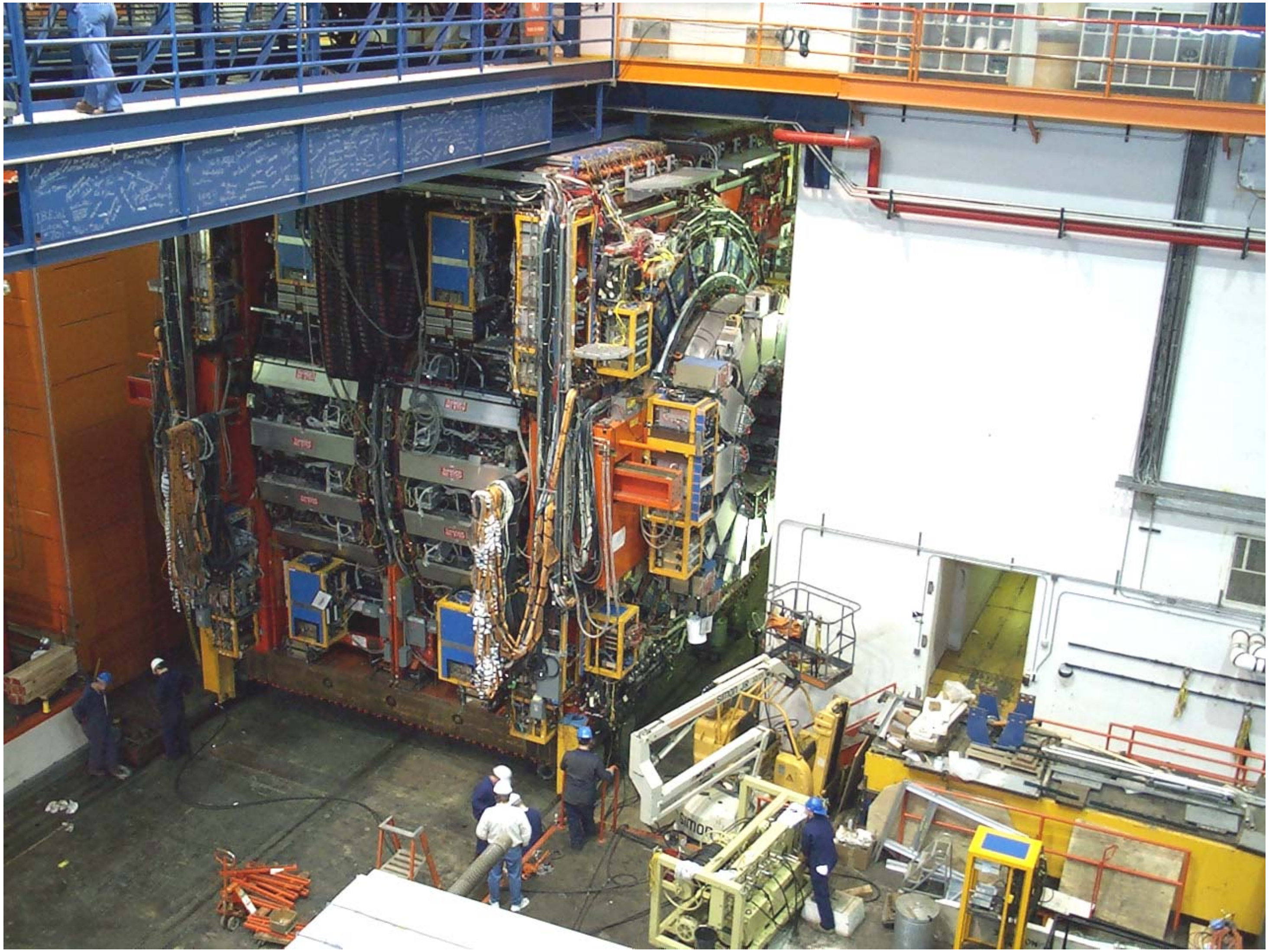
Double-sided layers for r–ϕ, stereo r–ϕ, r–z ← **New**



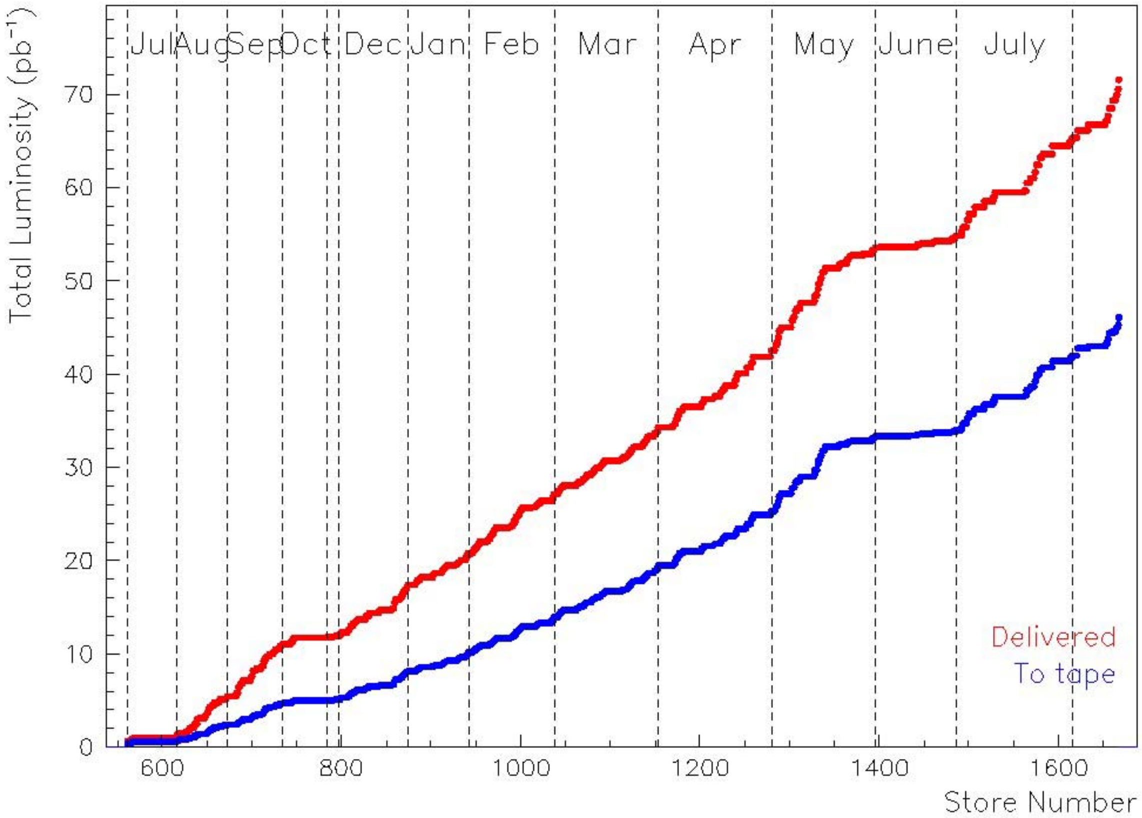


CDF-II Rolling into the Collision Hall

March 2001



Run 2 Integrated Luminosity (CDF)



≈70 pb^{-1} delivered

≈50 pb^{-1} recorded

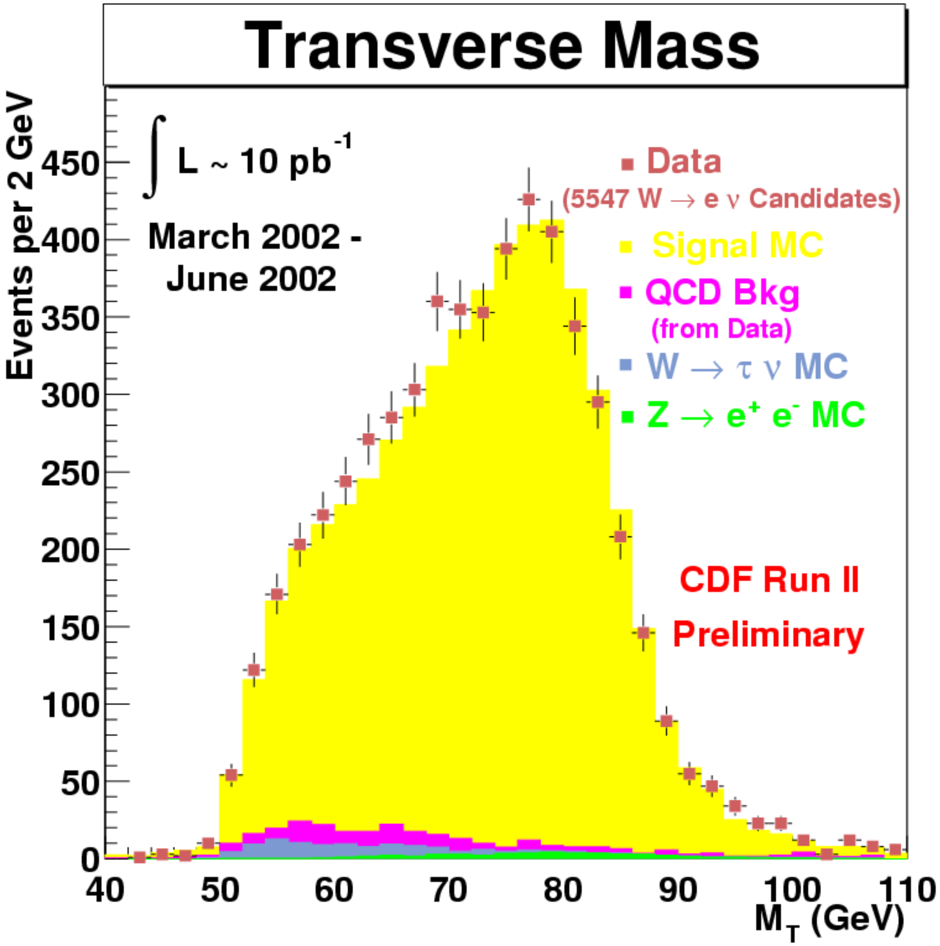
Best instantaneous luminosity: 2.8×10^{31} cm^{-2} s^{-1}
Design goal: 8.6×10^{31} cm^{-2} s^{-1}

Expect 100–200 pb^{-1} delivered by end of year

W Boson Measurement from Electrons

W cross section measurement from $W \rightarrow e\,\nu$

- ➔ $\sigma(W)*BR(W\rightarrow e\nu)$ (nb) = $2.60 \pm 0.07_{stat} \pm 0.11_{syst} \pm 0.26_{lum}$
- ➔ Consistent with Run 1 results rescaled for higher collision energy: $2.72 \pm 0.02_{stat} \pm 0.08_{syst} \pm 0.09_{lum}$



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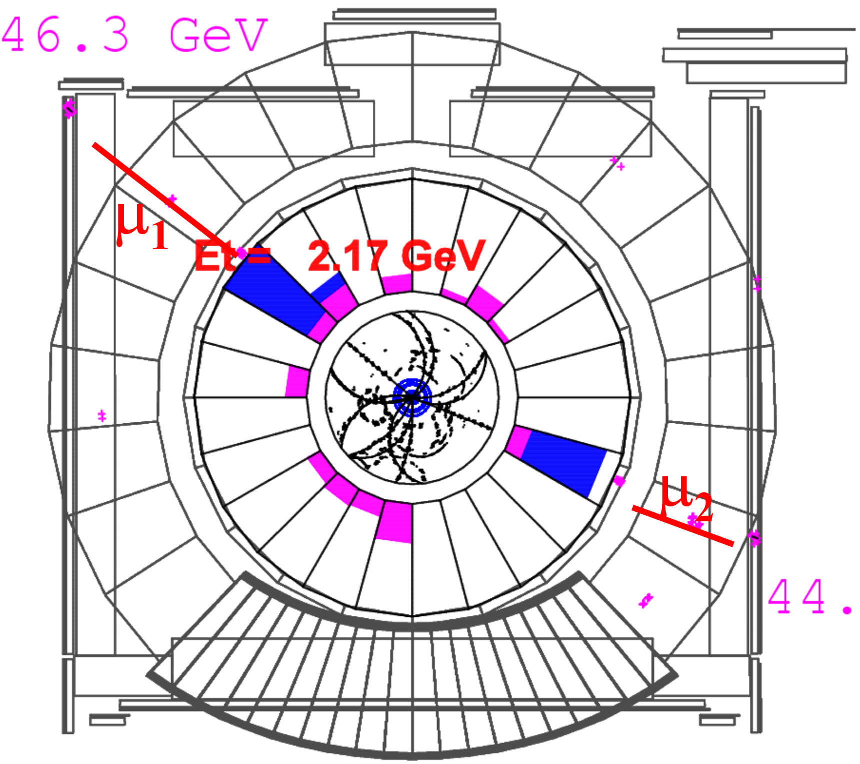
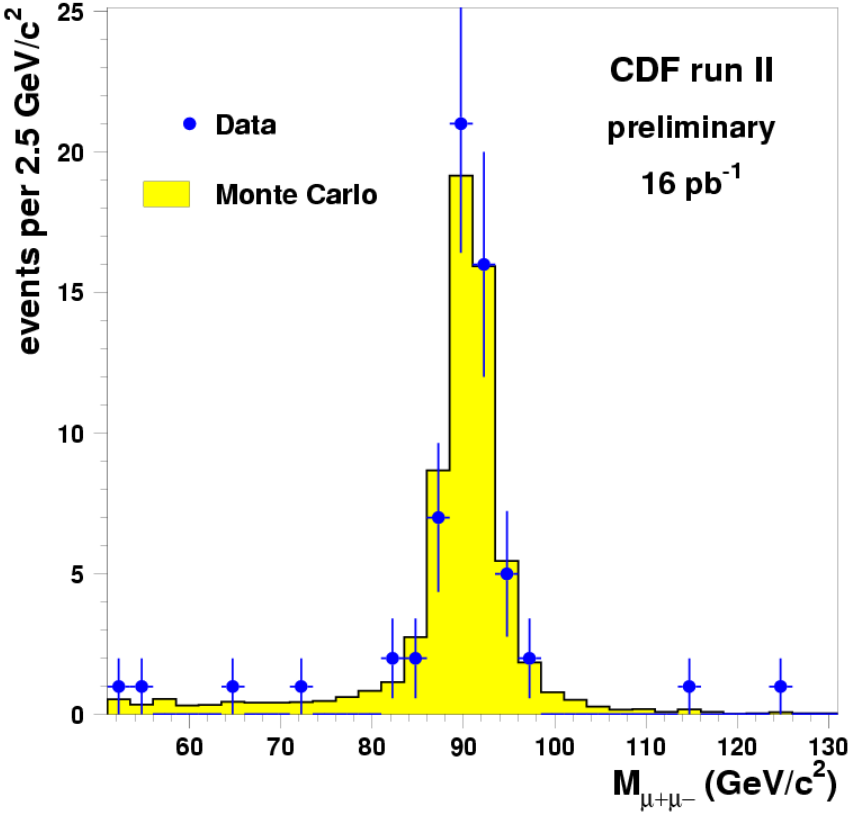
Observation of Z Bosons

Clear evidence of Z→ $\mu^+\mu^-$

- ➔ Signal shown for opposite sign muons detected in both inner and outer muon chambers

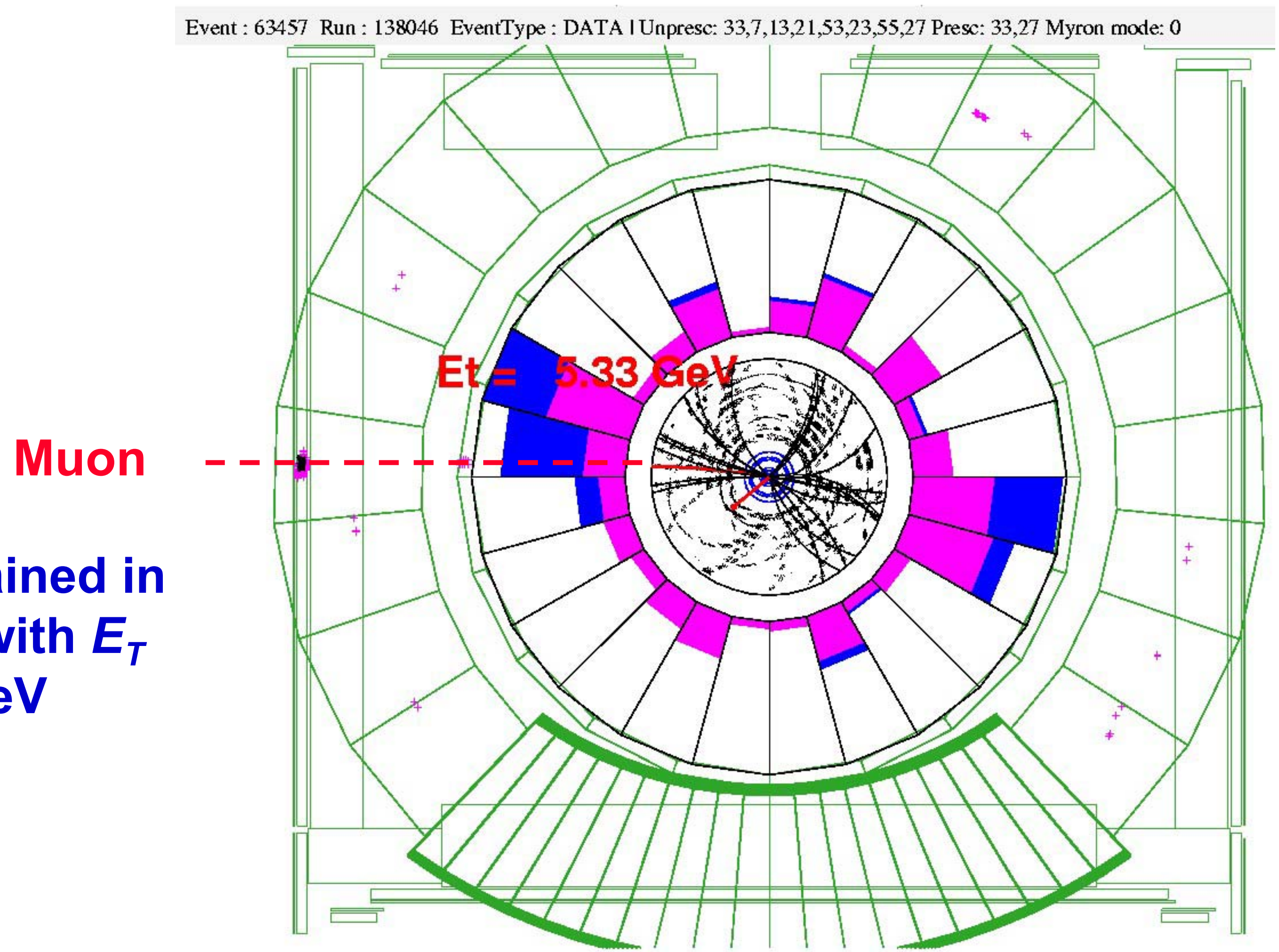




-57 candidate events in $66<M_{inv}<116$ range

University of Florida

Tagged Muon in CDF

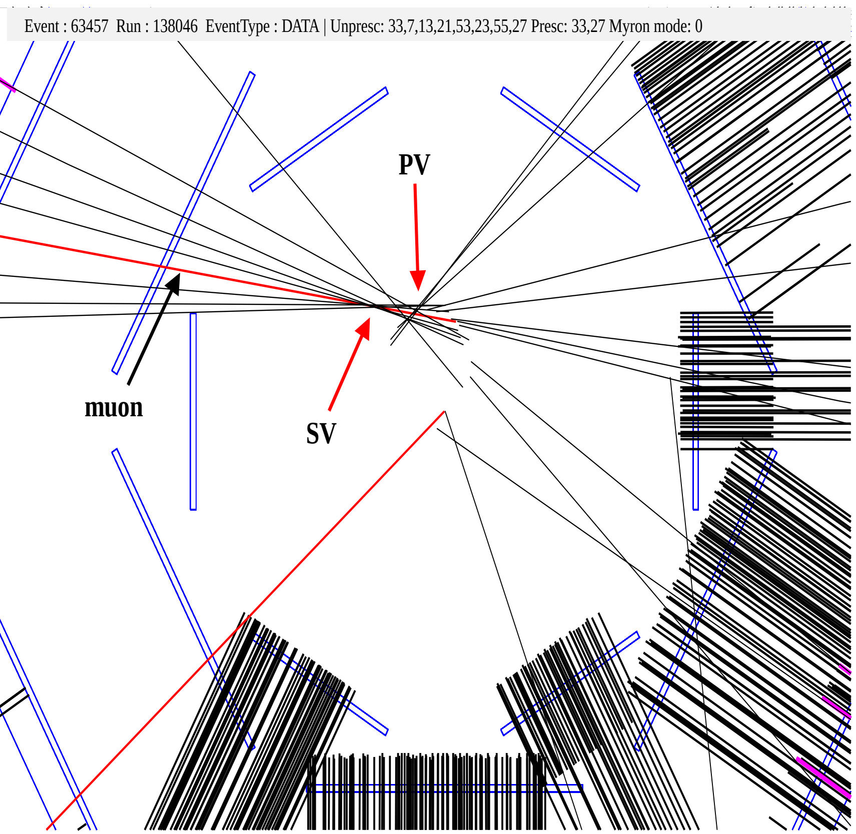


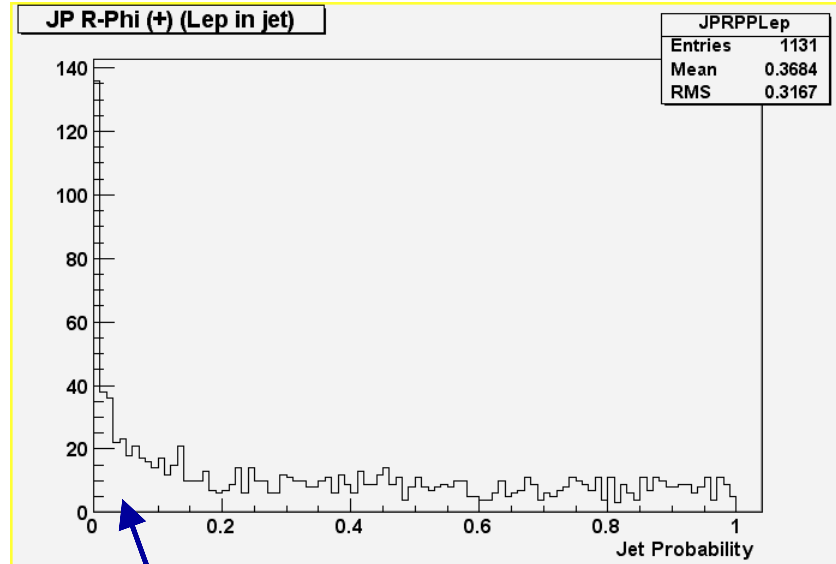
Contained in a jet with E_T = 9 GeV

Note: B mesons decay into soft leptons about 10% of the time

Secondary Vertices in CDF II

Zoom-in of previous event:

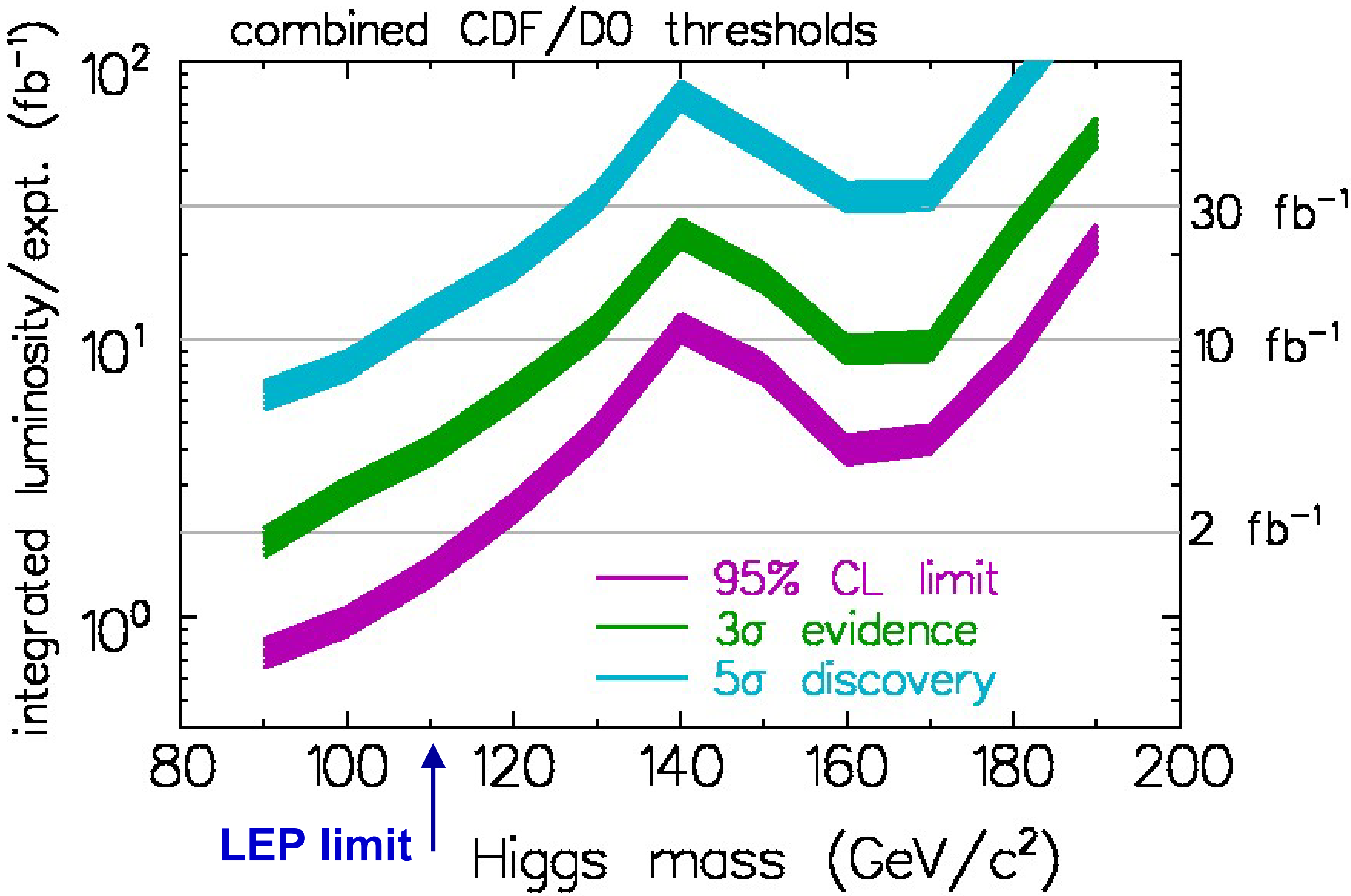




Jets containing soft muons exhibit low probability of coming from the primary vertex

Event was tagged by the "Jet Probability" algorithm we are developing at UF for tagging bottom and charm jets

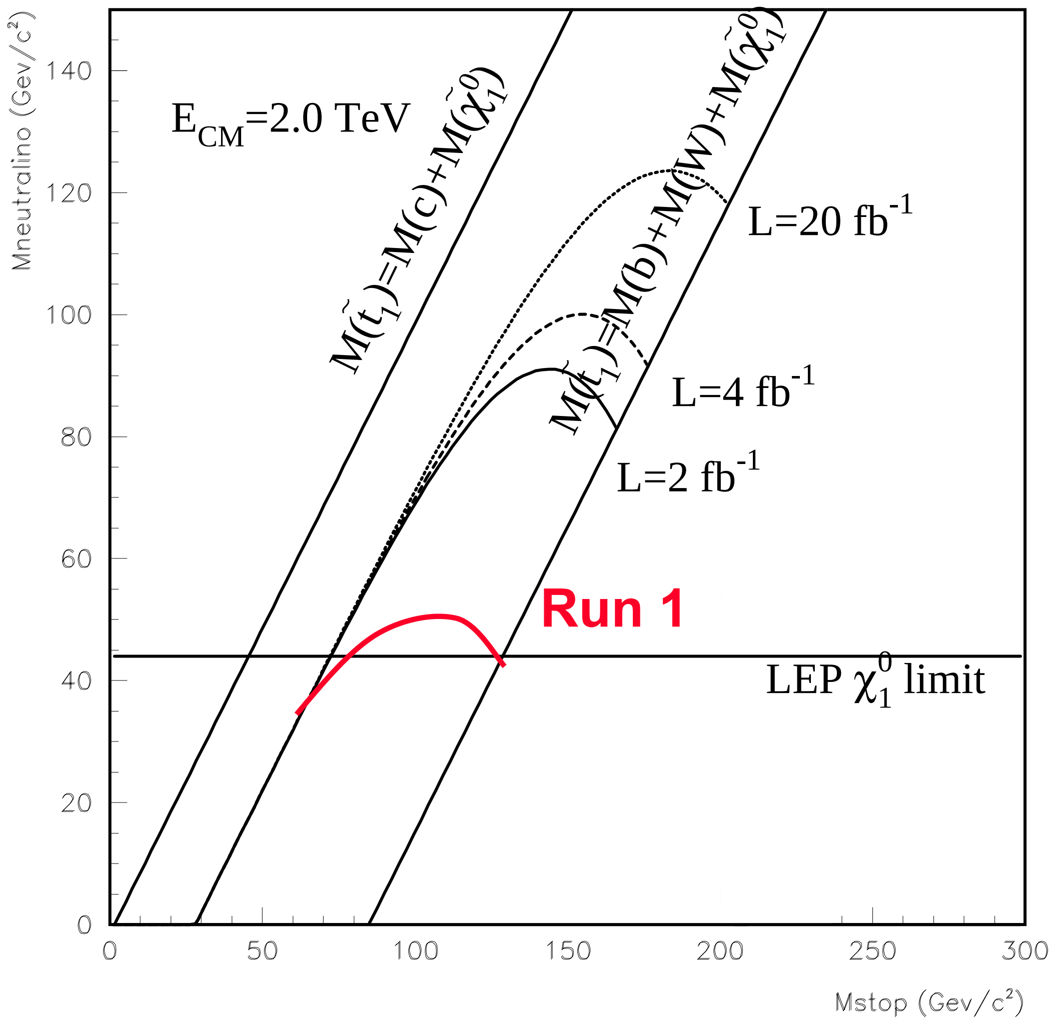
SM Higgs Search in Run II



Run II Higgs WG

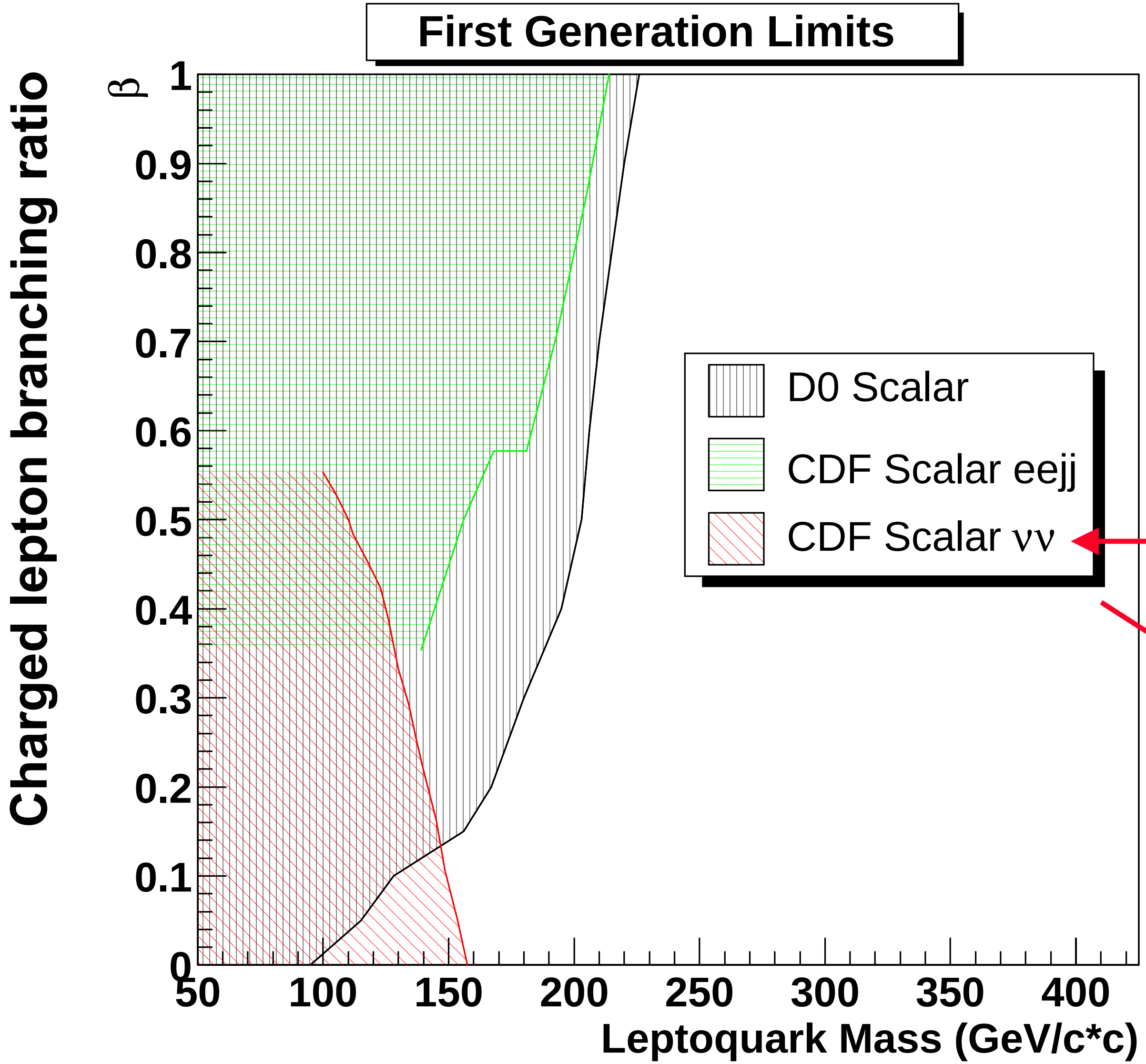
Scalar Top Quark Search in Run II

$\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$



D.Tsybychev's thesis topic

Scalar Leptoquark Prospects



A.Moorhead, 2002 REU project

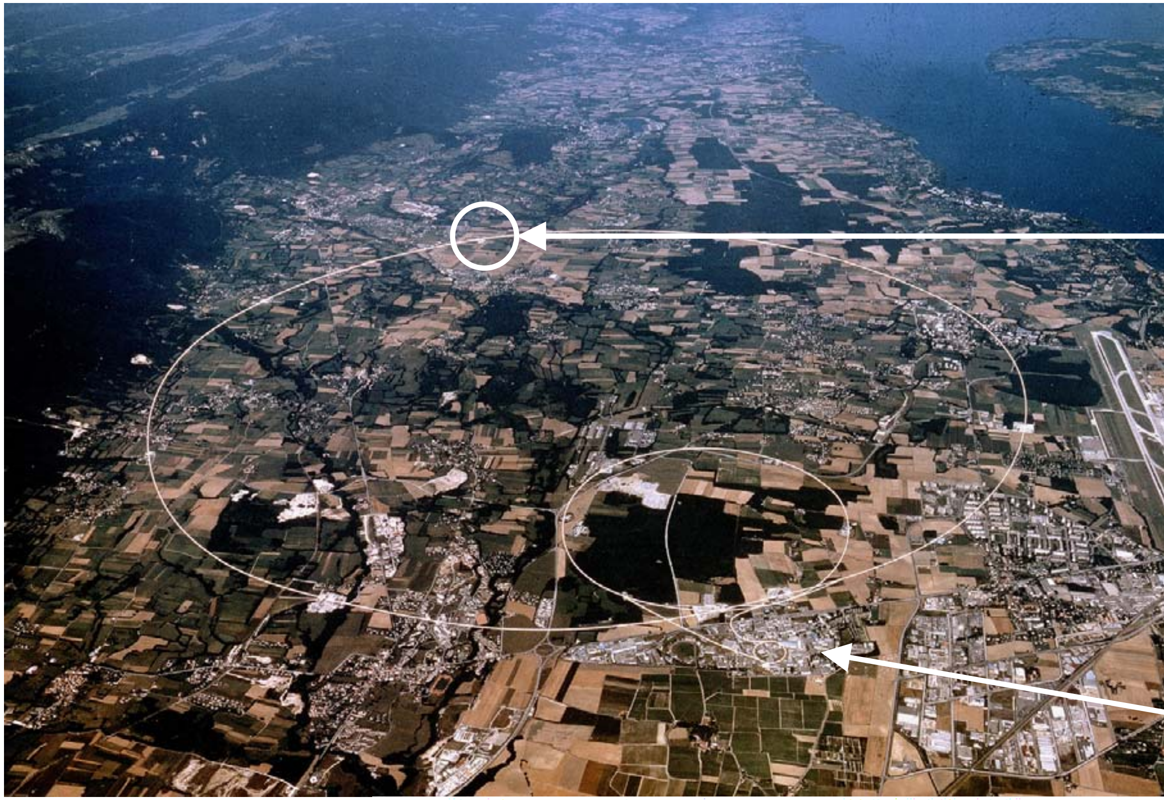
Existing Run 1 limits

Projected limit for 2 fb^{-1}

Same topology as for scalar top quark search

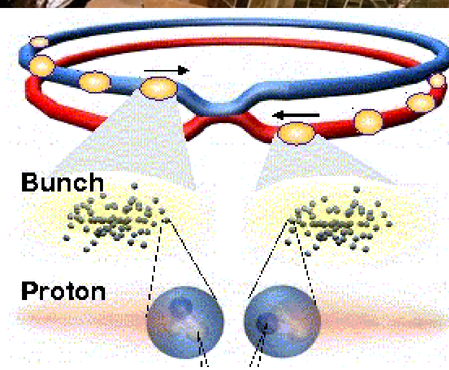

The CERN Laboratory
Geneva, Switzerland

The Large Hadron Collider



Point 5 – CMS

R = 4.5 km
E = 7 TeV
L=100 fb^{-1}/year



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

2 proton rings housed in same tunnel as LEP

Completion: mid 2007

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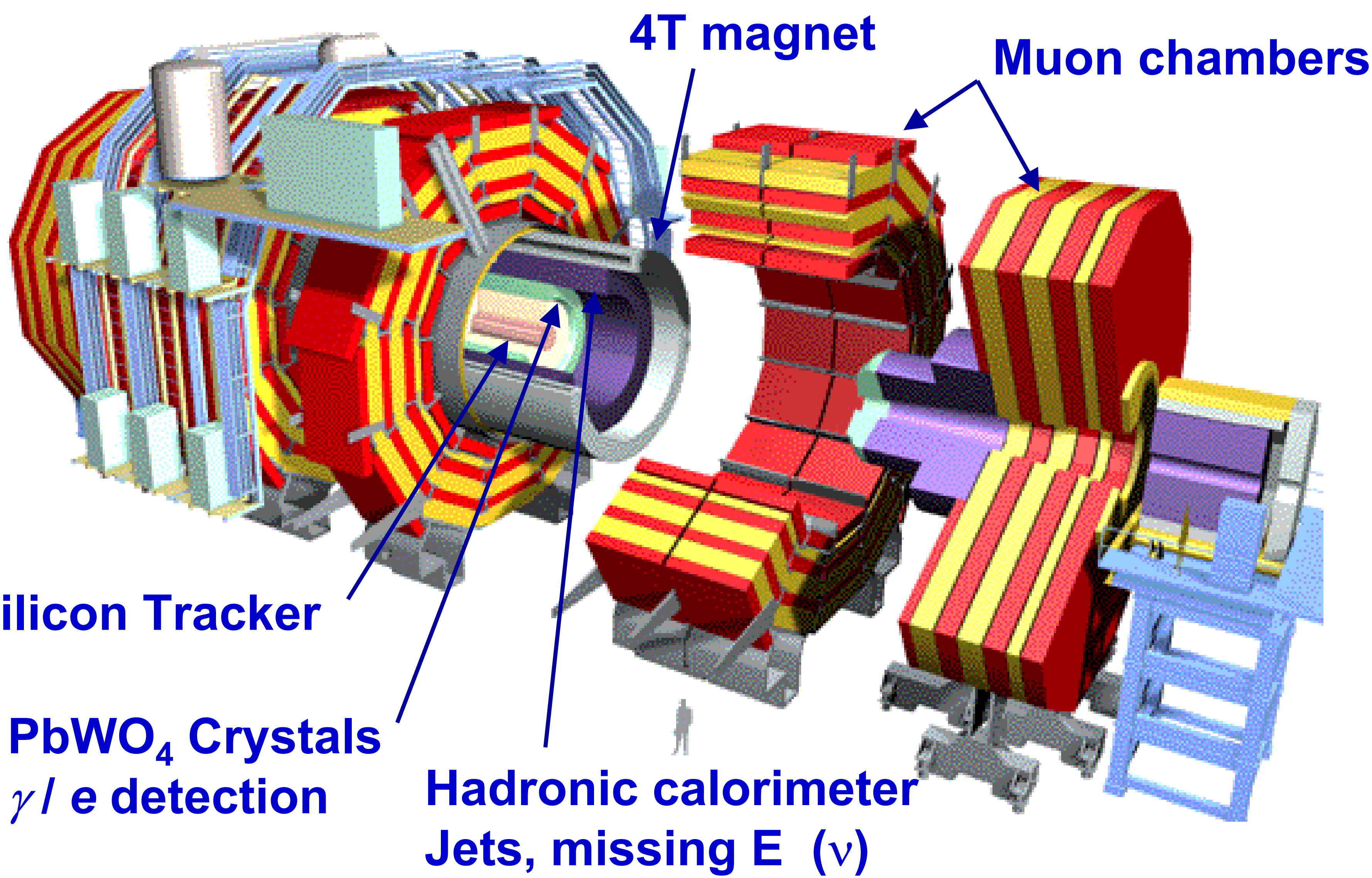
The Compact Muon Solenoid Expt.



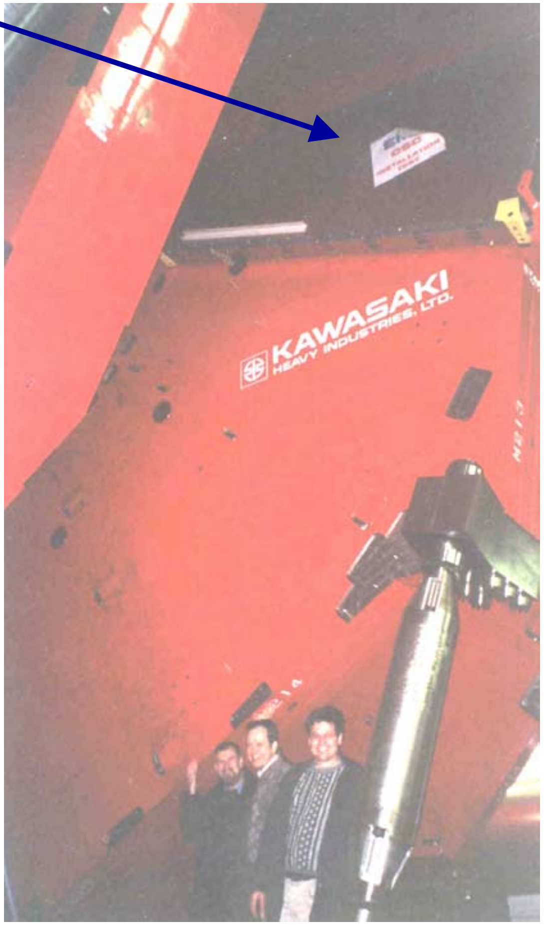
"There's no scale"

The inner vacuum tank of the magnet cryostat

Endcap Muon System

Iron disk of endcap muon system

One of 540 chambers to be mounted



System will have 0.5 million electronic channels

CMS DAQ Architecture

CMS has a multi-tiered trigger system:

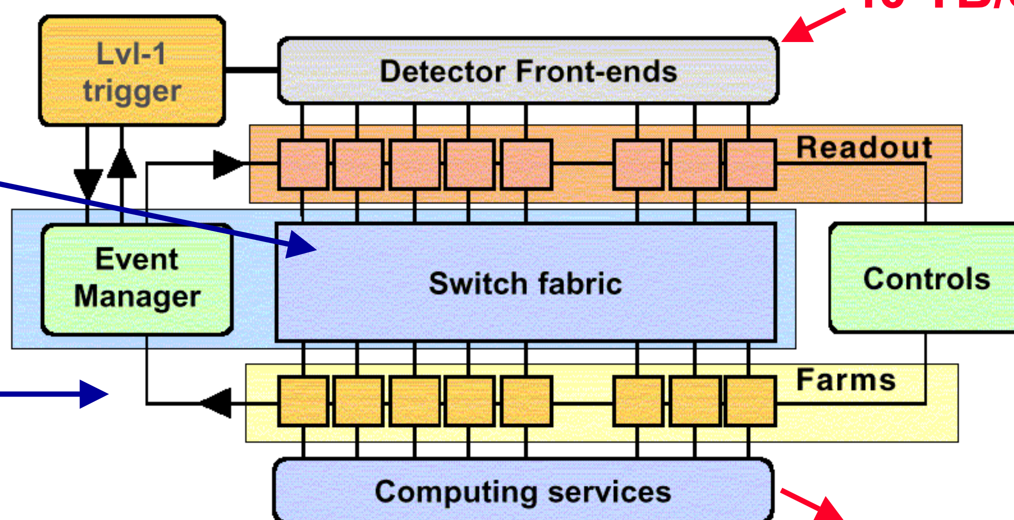
40 MHz BX rate ⇒ 1 GHz of collisions

- L1 reduces rate from 40 MHz to 75 kHz
  - Custom hardware processes calorimeter and muon data to select *electrons, photons, jets, muons,* $\not{E}_T$ above threshold
- L2, L3,… (HLT) reduces rate from 75 kHz to 100 Hz
  - Commercial CPU farm runs online programs to select *physics channels*

40 TB/s

Large telecomm switch (500 Gbit/s)

~1000 node PC cluster



100 MB/s

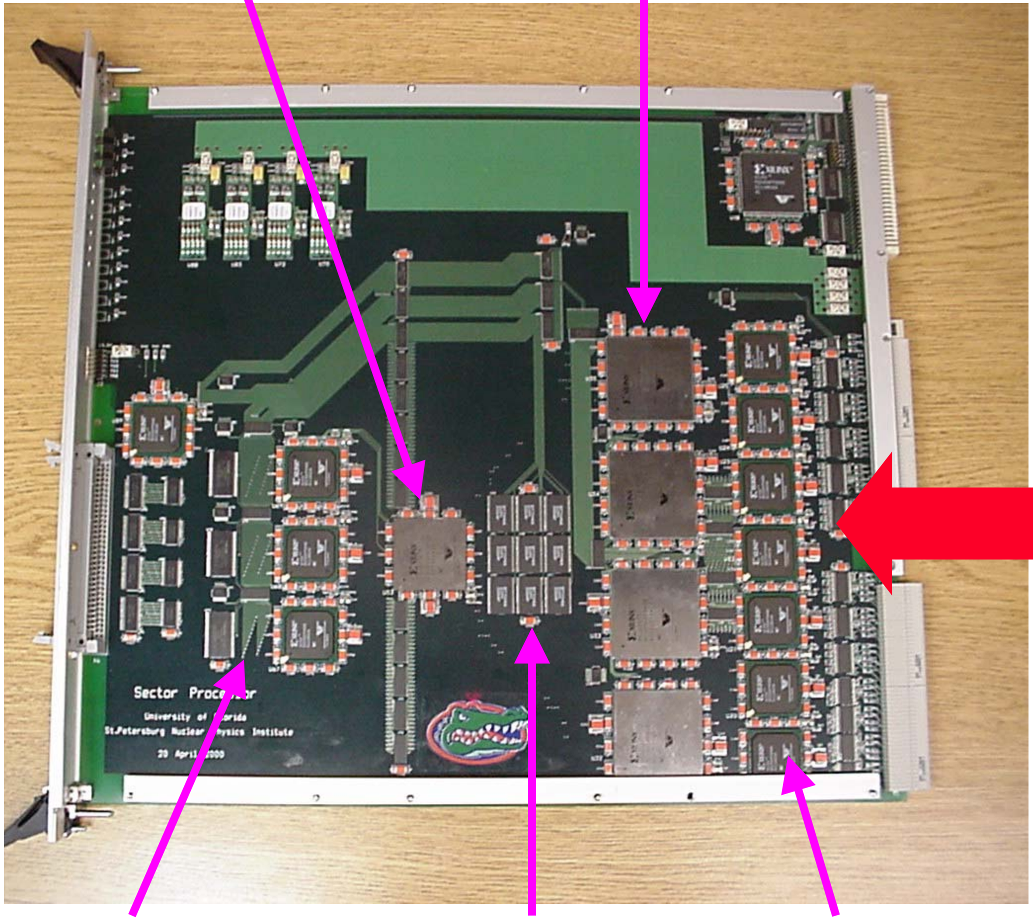
UF Muon Trigger Prototype

Final Selection Unit
XCV150BG352

Extrapolation Units
XCV400BG560

Successfully tested in 2000

Programmable logic performs massively parallel computation to reconstruct muons in real-time



3 GB/s input

100 billion operations per second

Assignment Units
XCV50BG256 &
2M x 8 SRAM

Track Assemblers
256k x 16 SRAM

Bunch Crossing Analyzer
XCV50BG256

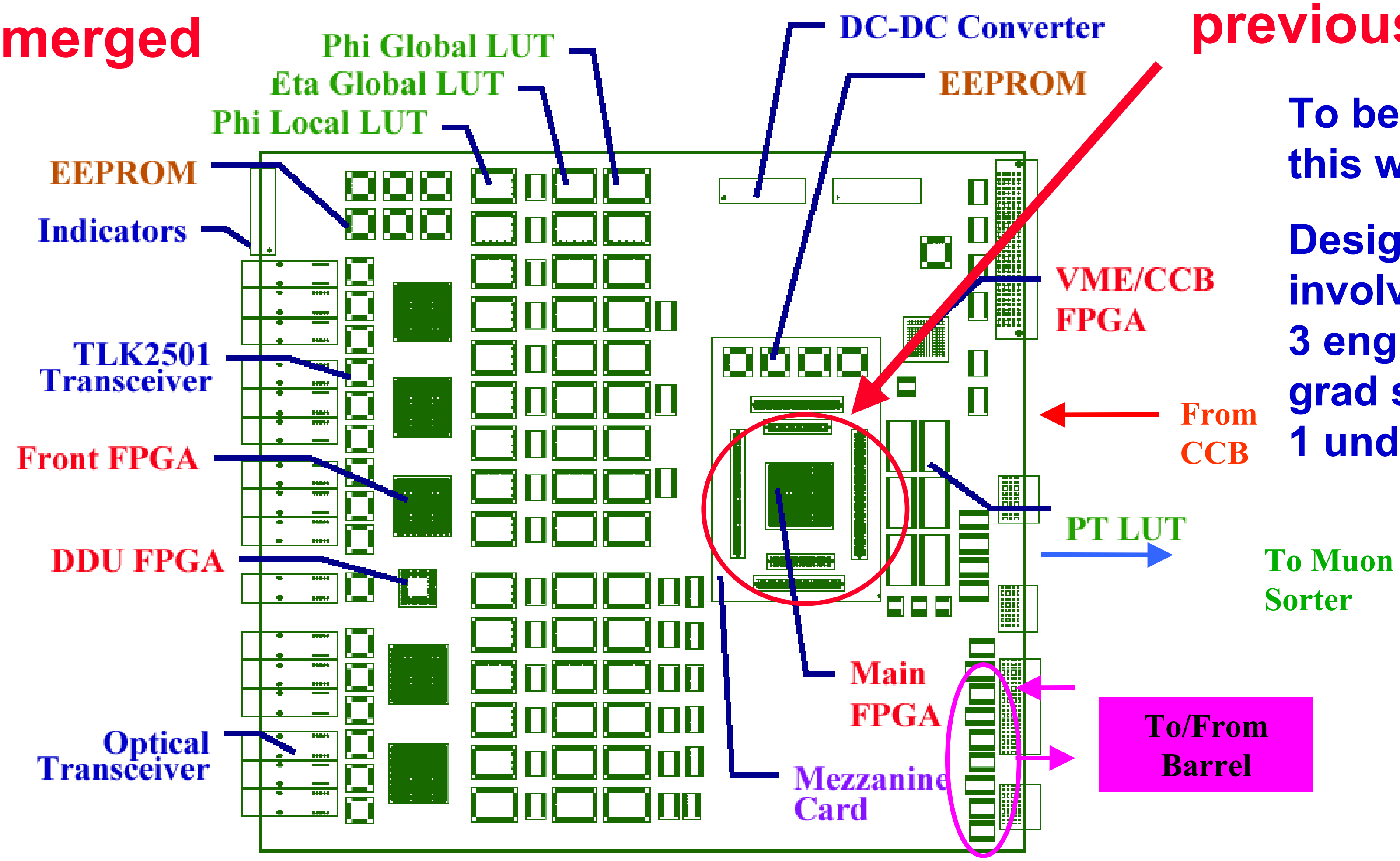
The Next Generation

3 other boards merged

1 chip contains all logic of previous board!

To be tested this winter –

Design/test involves 3 engineers, 1 grad student, 1 undergrad



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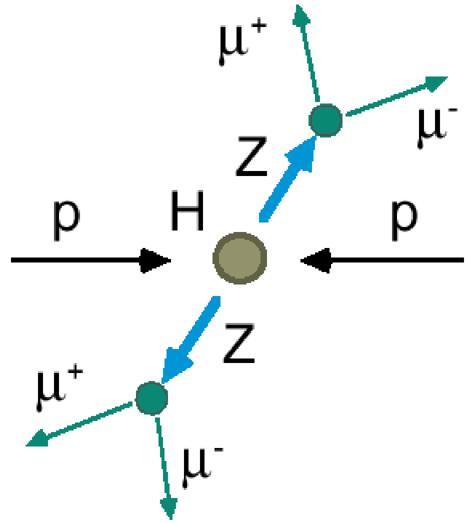
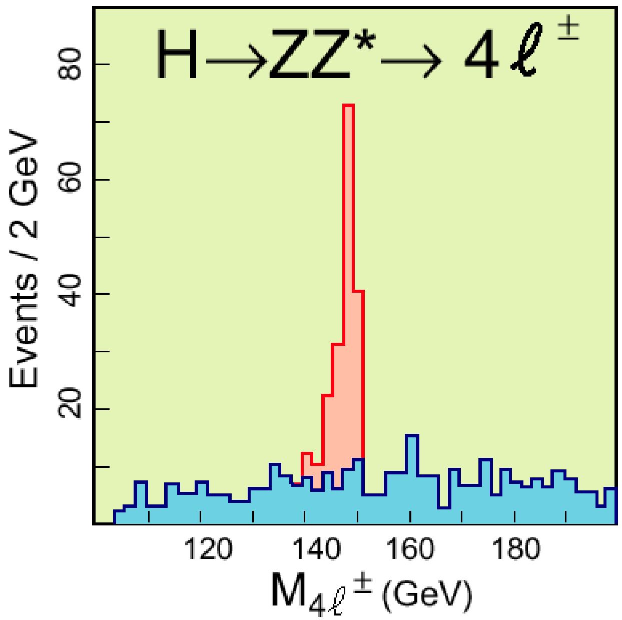
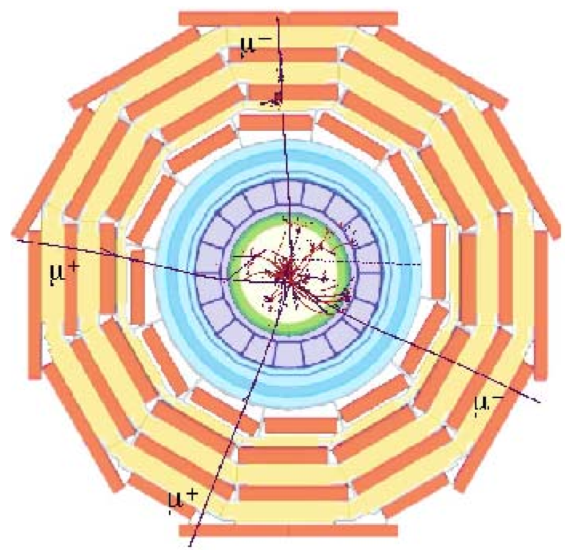
SM Higgs – Intermediate Mass

$H \to ZZ \to \ell^+\ell^- \ell^+\ell^-$ (ℓ = e, μ)

- ➔ Very clean
  - Resolution: ~ 1 GeV
- ➔ Works for the mass range $130 < M_H < 500$ GeV/c^2







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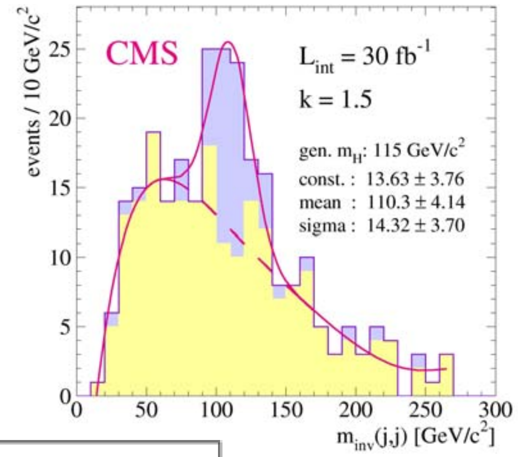
SM Higgs – Low Mass

$H \to bb$ via

$ttH \to ttbb \to l\nu b + bjj + bb$

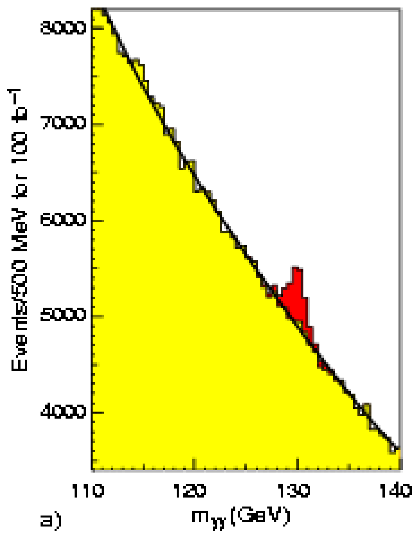
- ➔ Use likelihood for top quark decays & event kinematics
  - □ $S/B \approx 0.8$

CMS $30 fb^{-1}$
S=38 B=52



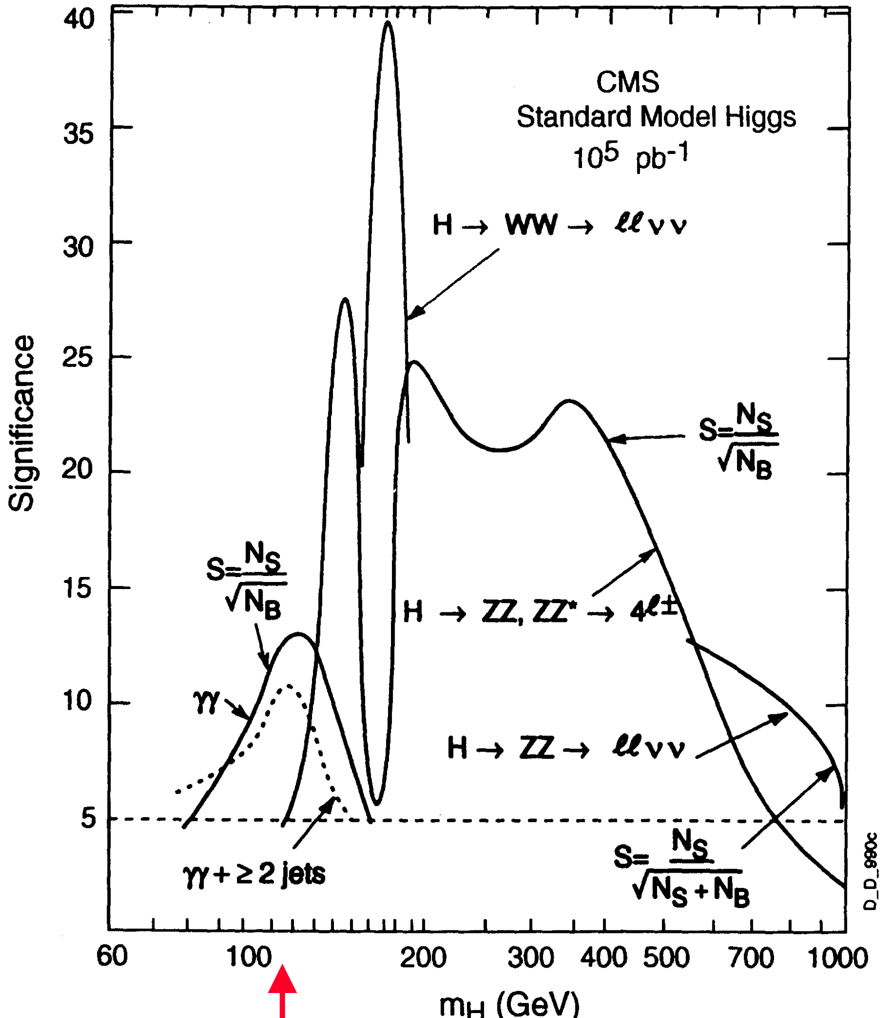
$H \to \gamma\gamma$: decay is rare ($B \sim 10^{-3}$)

- ➔ good resolution essential
- ➔ reason for $PbWO_4$ crystals
- ➔ at 100 GeV, $\sigma \approx 1 GeV$
  - □ $S/B \approx 1:20$



CMS
$100 fb^{-1}$
K=1.6, S/B ~4%

SM Higgs Prospects at CMS



LEP limit

$H \rightarrow ZZ \rightarrow 4l$ covers widest mass range

- ➔ Good muon coverage

$H \rightarrow \gamma\gamma$ important at low mass

- ➔ Good calorimetry

Greater than 5σ discovery potential over full mass range from LEP limit to 1 TeV in 1 year at design luminosity

Conclusion

Scalar particles are the key to understanding the nature of the fundamental forces and space-time

- Higgs
  - Strong indirect evidence of its existence, though no direct measurement yet. Last particle to be discovered in SM
- Supersymmetry
  - Compelling theoretical framework, but no experimental evidence
- Leptoquarks
  - Stranger things could happen…

CDF II is operating well, but data coming slowly

- Expect 100–200 pb^{-1} delivered by end of year (≈ Run 1)
- Goal is to collect ~15000 pb^{-1} of data by 2007
- Good heavy-flavor tagging (*b*,*c* quarks) is essential

If not discovered at the Tevatron, the LHC will be capable of discovering the Higgs and ruling in/out Supersymmetry, starting in 2007