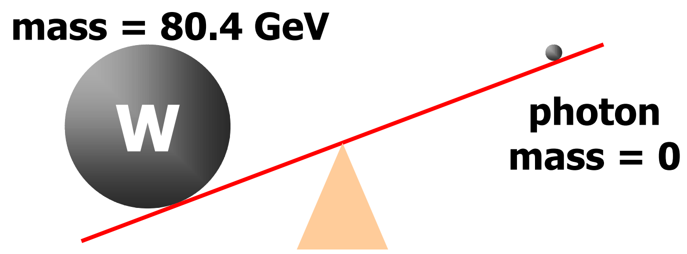
The Higgs search at the Tevatron

University of the Tevatron
March 27, 2002

John Womersley
Fermilab

The Higgs Mechanism



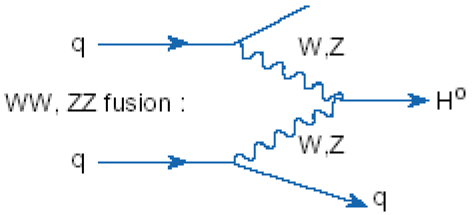
- In the Standard Model
  - Electroweak symmetry breaking occurs through introduction of a scalar field $\phi \rightarrow$ masses of W and Z
  - Higgs field permeates space with a finite vacuum expectation value = 246 GeV
  - If ϕ also couples to fermions $\rightarrow$ generates fermion masses

- An appealing picture: is it correct?
  - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field
  - All its properties (production and decay rates, couplings) are fixed except its own mass

Highest priority of worldwide high energy physics program: find it!

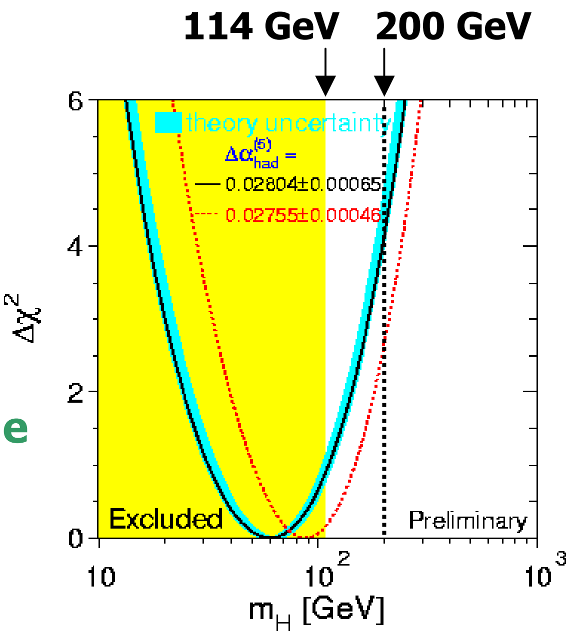
God particle disappears down £6billion drain

- This field need not result from a single, elementary, scalar boson
  - There can be more than one particle
    - e.g. SUSY
  - Composite particles can play the role of the Higgs
    - e.g. technicolor, topcolor
- We do know that
  - EW symmetry breaking occurs, so something is coupling to the W and Z
  - Precision EW measurements imply that this thing looks very much like a Standard Model Higgs
    - though its fermion couplings are less constrained
  - WW cross sections violate unitarity at ~ 1 TeV without H
    - A real LHC experiment:



Searching for the Higgs

- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN**
  - **precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV**
  - **direct searches for Higgs production exclude $m_H < 114$ GeV**

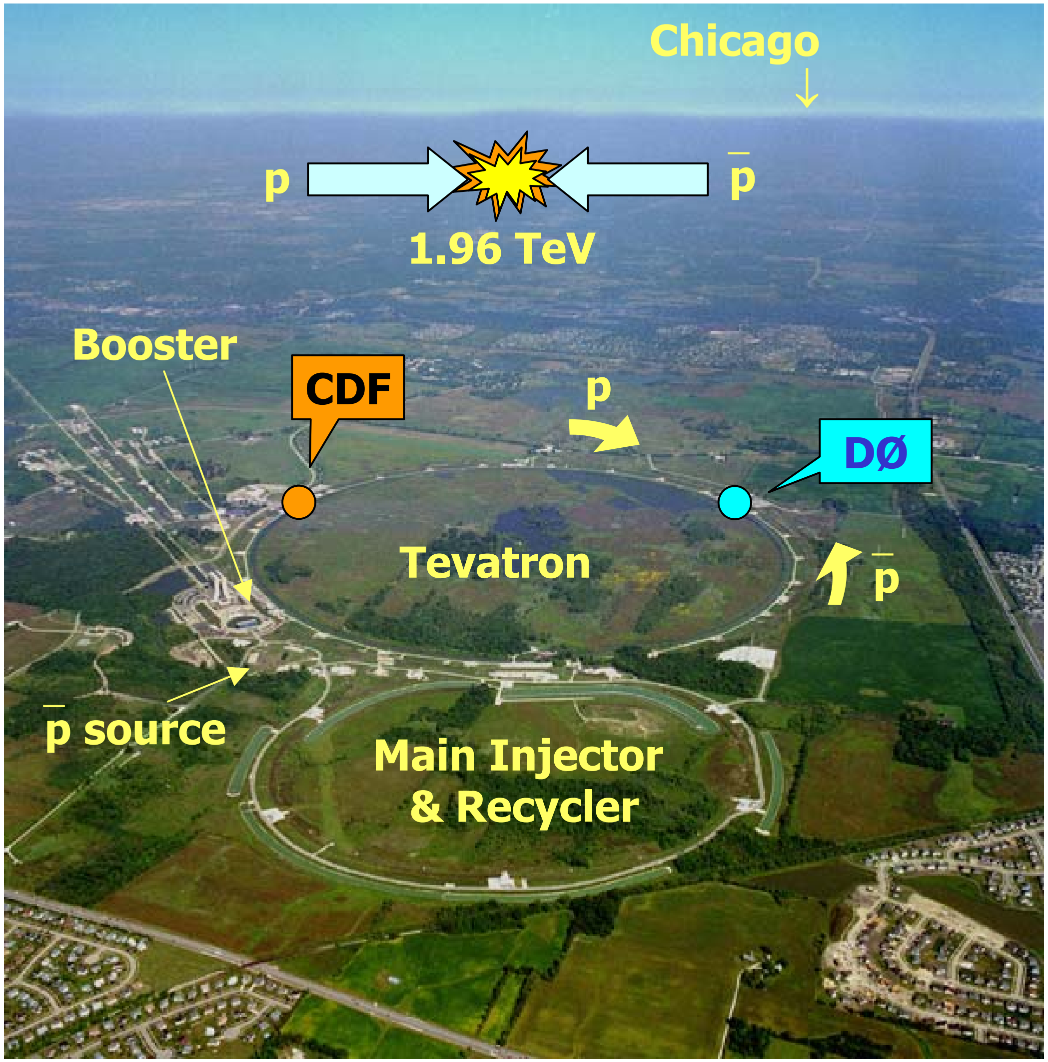


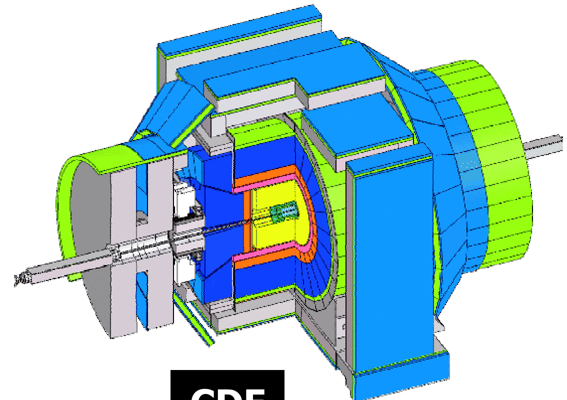
- **Summer and Autumn 2000: Hints of a Higgs?**
  - **the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)**
  - **despite these hints, CERN management decided to shut off LEP operations in order to expedite construction of the LHC**

"The resolution of this puzzle is now left to Fermilab's Tevatron and the LHC."

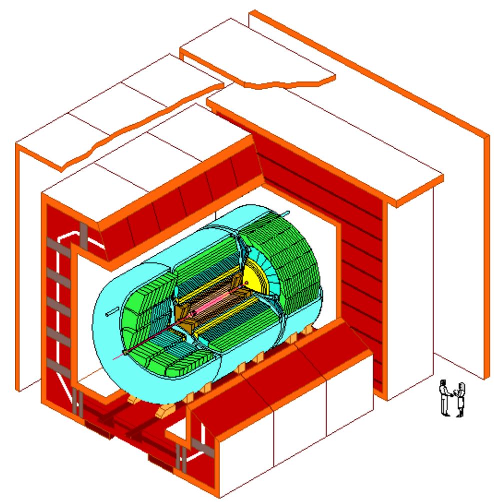
– Luciano Maiani

The Fermilab Tevatron Collider





CDF



DØ

Higgs at the Tevatron

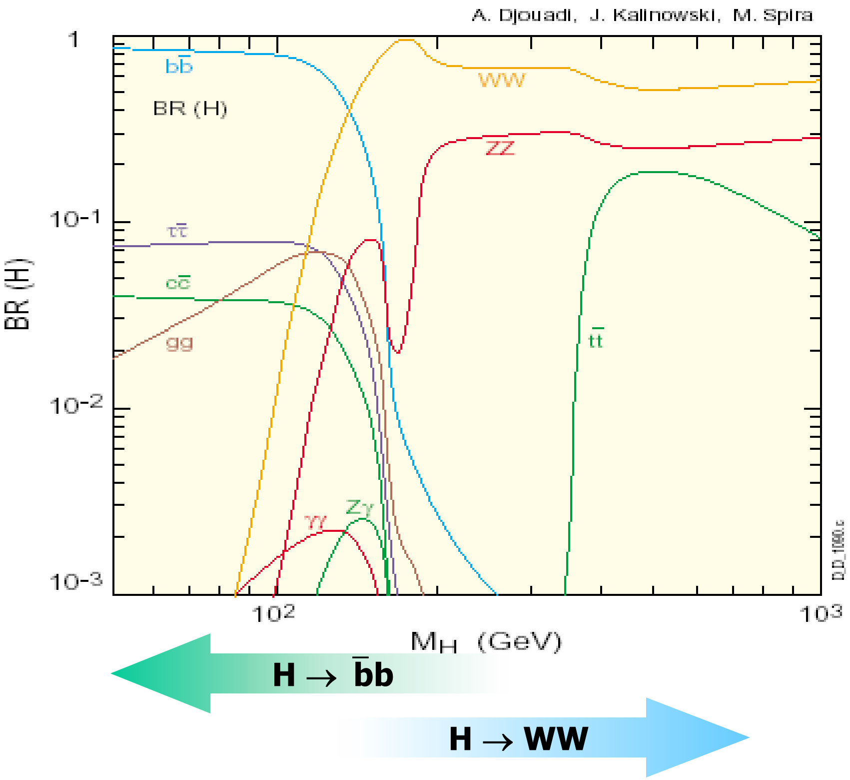
- The search for the mechanism of EWSB motivated the construction of supercolliders (SSC and LHC)

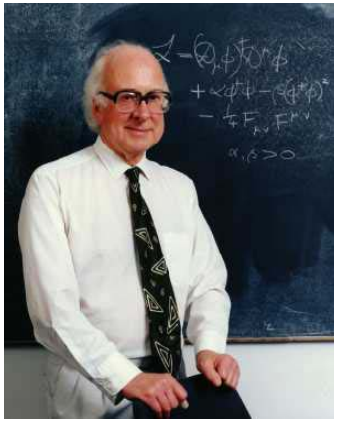
- After the demise of the SSC, there was a resurgence of interest in what was possible with a “mere” 2 TeV
  - Ideas from within accelerator community (“TeV33”)
  - Stange, Marciano and Willenbrock paper 1994
  - TeV2000 Workshop November 1994
  - Snowmass 1996
  - TeV33 committee report to Fermilab director
  - Run II Higgs and Supersymmetry Workshop, November 1998

- A convergence of
  - technical ideas about possible accelerator improvements
  - clear physics motivation
    - Plan for integrated luminosities, before LHC turn-on, much larger than the (then) approved $2fb^{-1}$

Higgs decay modes

- The only unknown parameter of the SM Higgs sector is the mass
- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model



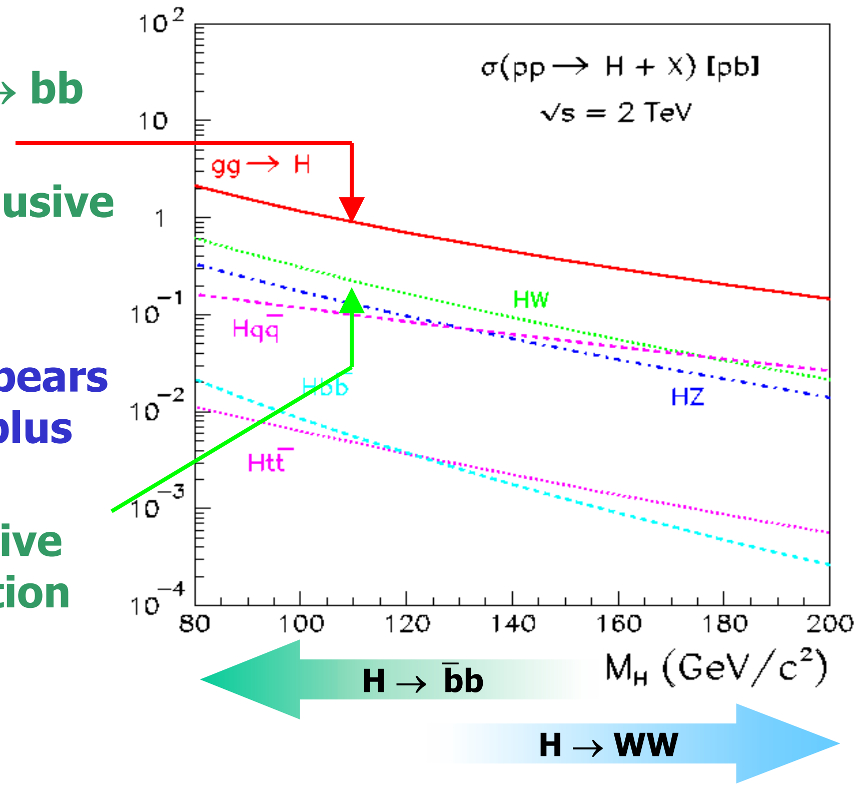


One Higgs

Higgs Production at the Tevatron

- **Inclusive Higgs cross section is quite high: ~ 1pb**
  - **for masses below ~ 140 GeV, the dominant decay mode H → bb is swamped by background**
  - **at higher masses, can use inclusive production plus WW decays**

- **The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z**
  - **leptonic decays of W/Z help give the needed background rejection**
  - **cross section ~ 0.2 pb**

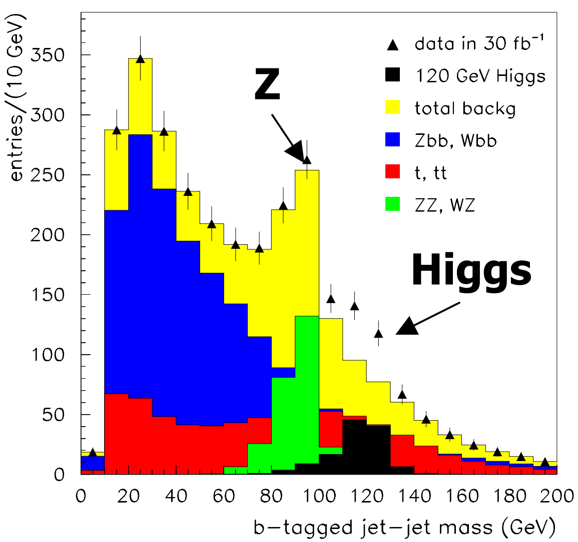


Dominant decay mode

$m_H \lesssim 140$ GeV: $H \to b\bar{b}$

- $WH \to q\bar{q}' b\bar{b}$ is the dominant decay mode but is overwhelmed by QCD background
- $WH \to l^{\pm}\nu\, b\bar{b}$ backgrounds $Wb\bar{b}$, WZ, $t\bar{t}$, single top
- $ZH \to l^{+}l^{-}\, b\bar{b}$ backgrounds $Zb\bar{b}$, ZZ, $t\bar{t}$
- $ZH \to \nu\nu\, b\bar{b}$ backgrounds QCD, $Zb\bar{b}$, ZZ, $t\bar{t}$
  - powerful but requires relatively soft missing E_T trigger (~ 35 GeV)

m_H = 120 GeV

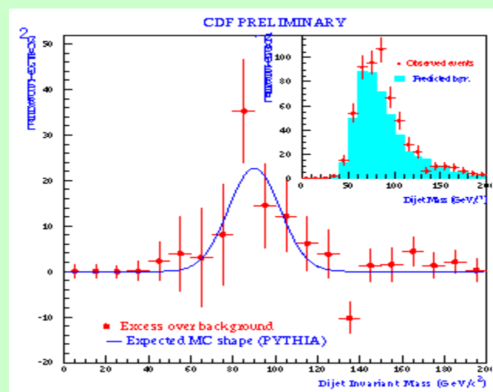


$2 \times 15\text{fb}^{-1}$ (2 experiments)

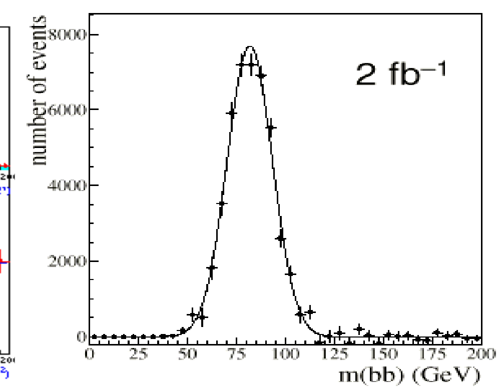
$b\bar{b}$ mass resolution

Directly influences signal significance

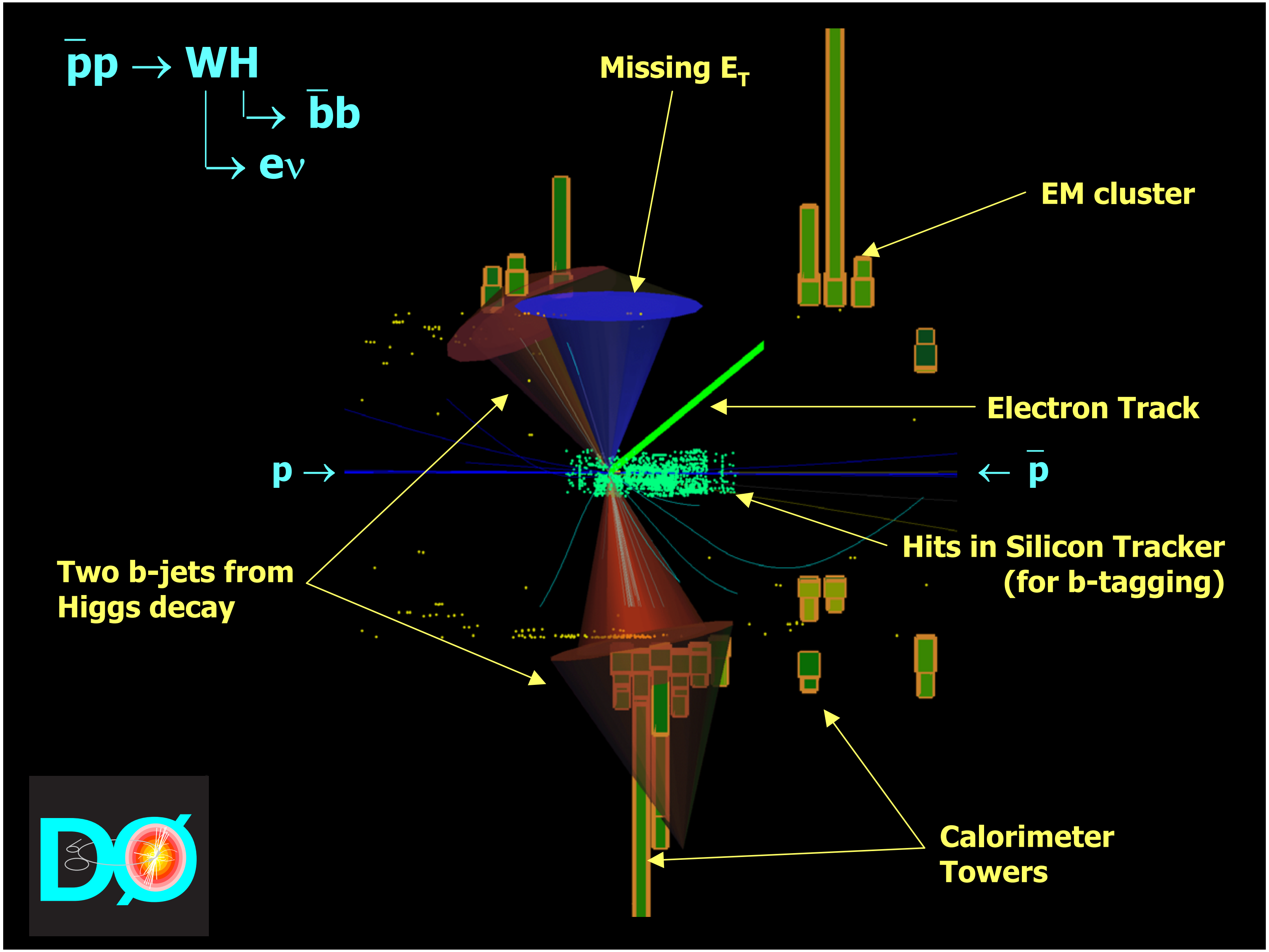
$Z \to b\bar{b}$ will be a calibration



CDF $Z \to b\bar{b}$ in Run I



DØ simulation for 2fb^{-1}



$\bar{p}p \rightarrow WH$
$\rightarrow \bar{b}b$
$\rightarrow e\nu$
Missing E_T
EM cluster
Electron Track
$p \rightarrow$
$\leftarrow \bar{p}$
Hits in Silicon Tracker (for b-tagging)
Two b-jets from Higgs decay
Calorimeter Towers
DØ

Example: m_H = 115 GeV

- ~ 2 fb^{-1}/expt (2003): exclude at 95% CL
- ~ 5 fb^{-1}/expt (2004-5): evidence at 3σ level
- ~ 15 fb^{-1}/expt (2007): expect a 5σ signal

Every factor of two in luminosity yields a lot more physics

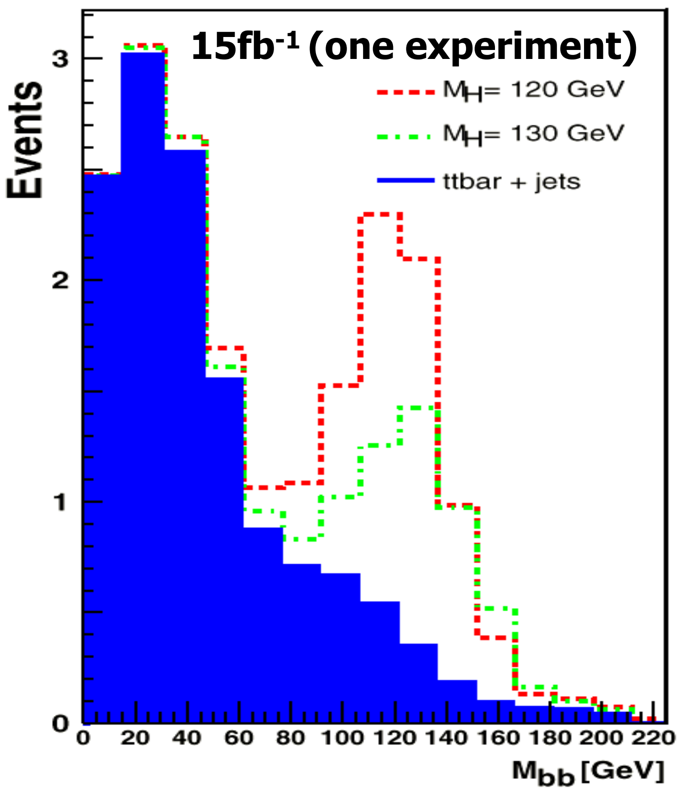
- Events in one experiment with 15 fb^{-1}:

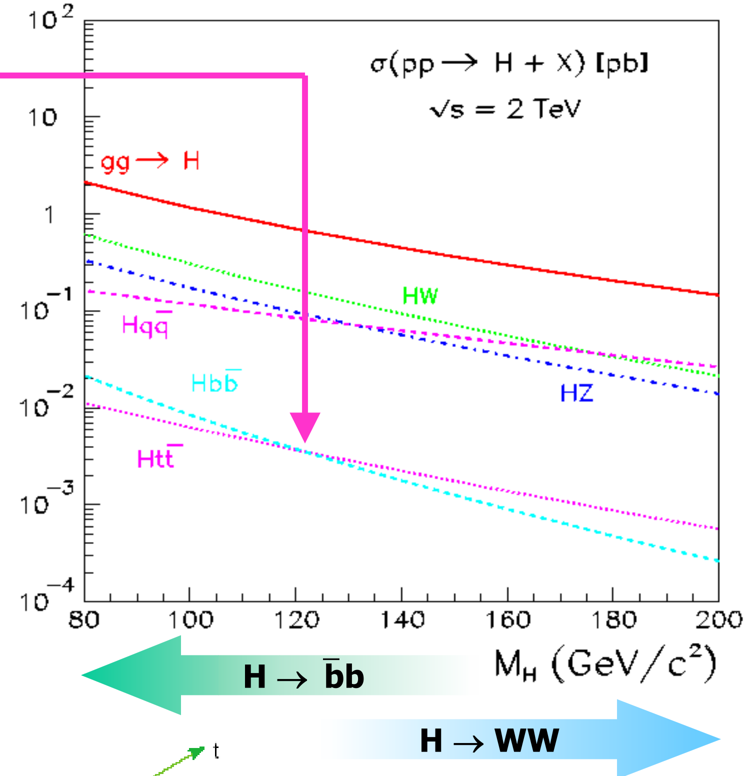
Mode	Signal	Background	S/√B
lνbb	92	450	4.3
ννbb	90	880	3.0
llbb	10	44	1.5

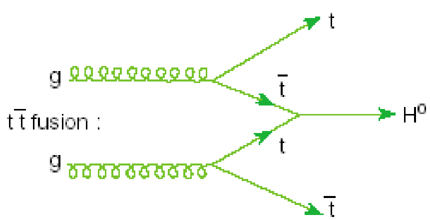
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - production cross section
  - Can we see H → WW? (Branching Ratio ~ 9% and rising w/ mass)
  - Can we see H → ττ? (Branching Ratio ~ 8% and falling w/ mass)
  - Can we see H→ γγ? (not detectable for SM Higgs at the Tevatron)

Associated production $t\bar{t}$ + Higgs

- Cross section very low (few fb) but signal:background good
- Major background is $t\bar{t}$ + jets
- Signal at the few event level:







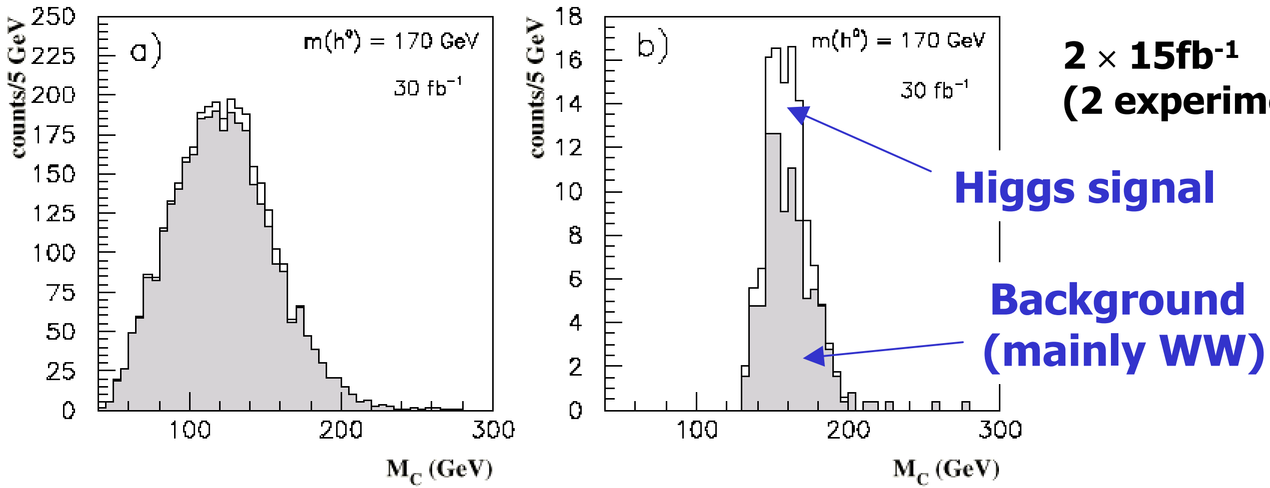
Tests top quark Yukawa coupling

$m_H \gtrsim 140$ GeV : $H \rightarrow WW^{(*)}$

- $gg \rightarrow H \rightarrow WW^{(*)} \rightarrow l^+ l^- \nu\nu$

Backgrounds Drell-Yan, WW, WZ, ZZ, tt, tW, $\tau\tau$
Initial signal:background ratio ~ 10^{-2}

– Angular cuts to separate signal from "irreducible" WW background



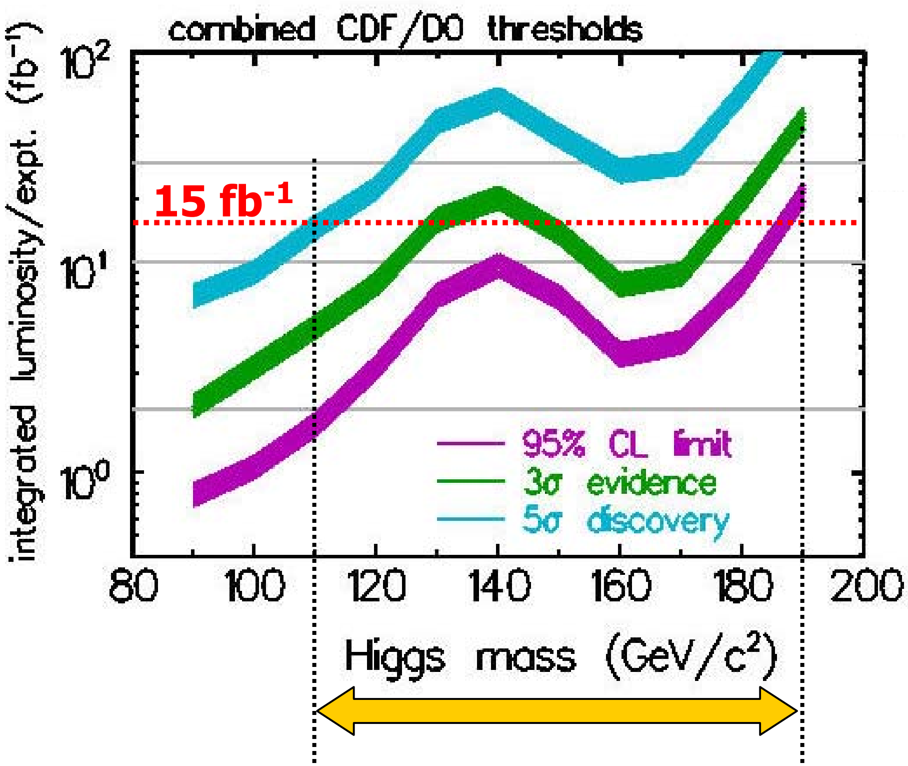
$2 \times 15\text{fb}^{-1}$
(2 experiments)

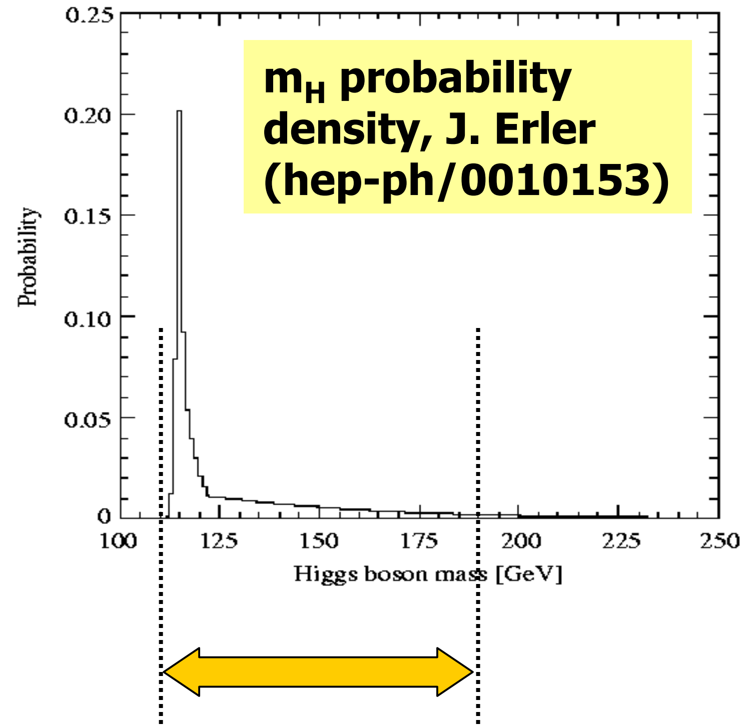
Before tight cuts:
verify WW modelling

After tight cuts

M_C = *cluster transverse mass* $= \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$

Tevatron Higgs mass reach





110-190 GeV

No guarantee of success, but certainly a most enticing possibility

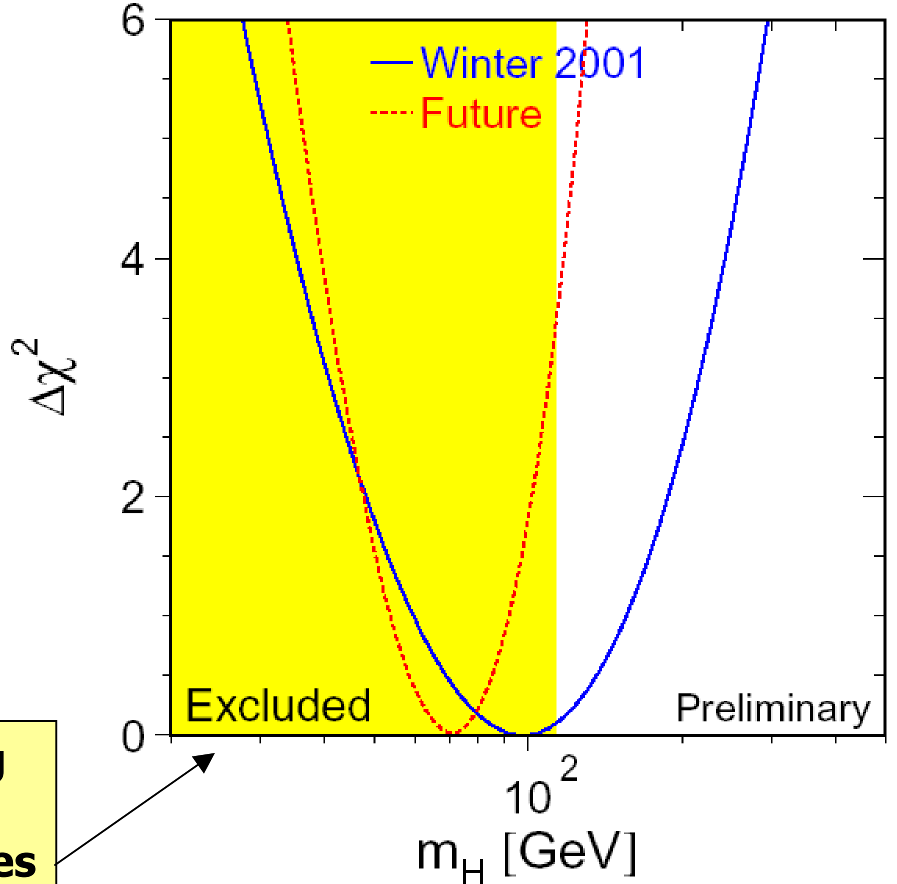
Indirect Constraints on Higgs Mass

- **Future Tevatron W and top mass measurements, per experiment**

	Δm_W
2 fb^{-1}	±27 MeV
15 fb^{-1}	±15 MeV

	Δm_t
2 fb^{-1}	±2.7 GeV
15 fb^{-1}	±1.3 MeV

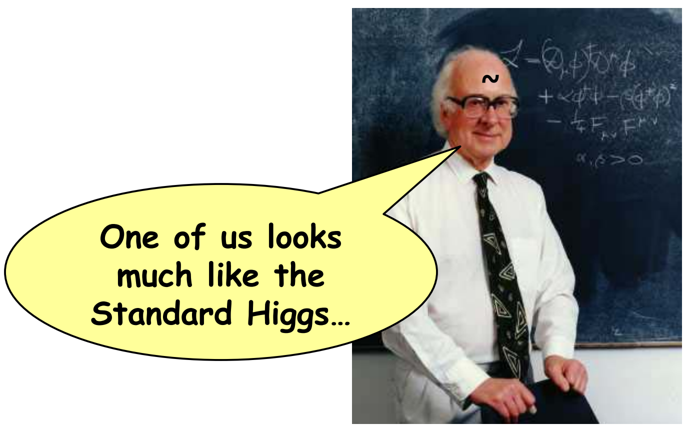
Impact on Higgs mass fit using Δm_W = 20 MeV, Δm_W = 1 GeV, $\Delta\alpha = 10^{-4}$, current central values
M. Grünewald et al., hep-ph/0111217



Supersymmetric Higgs sector

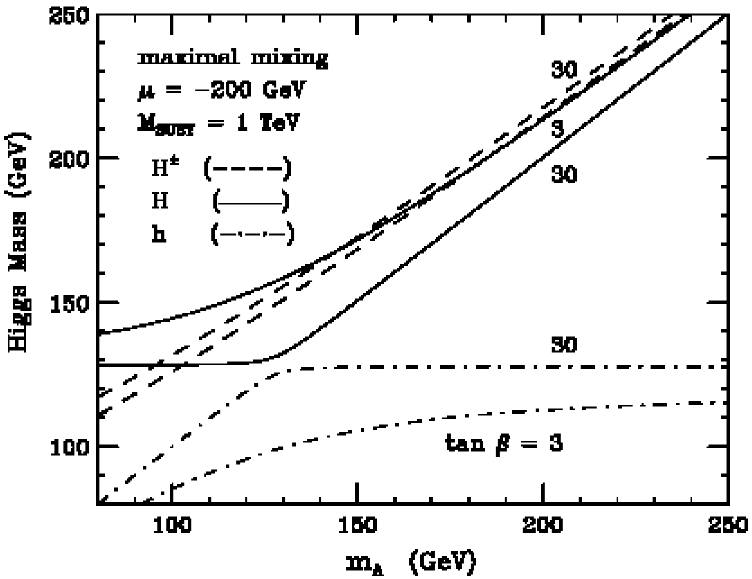
- Expanded Higgs sector: h, H, A, $H^{\pm}$
- Properties depend on
  - At tree level, two free parameters (usually taken to be m_A, tan β)
  - Plus radiative corrections depending on sparticle masses and m_t

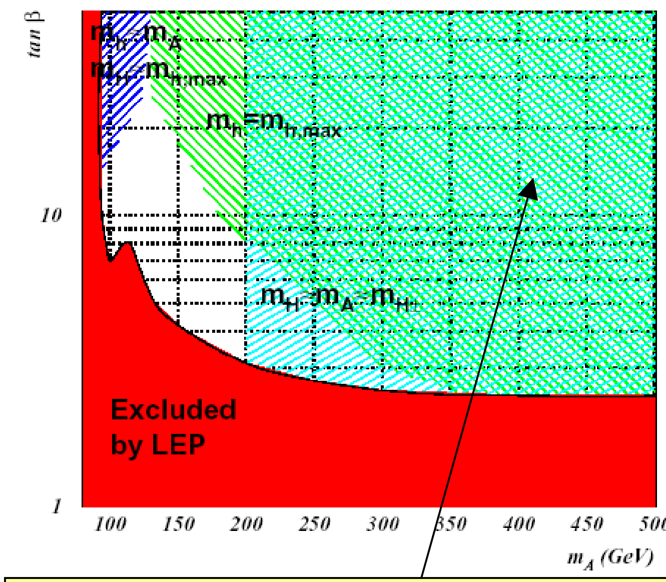
Multiple Higgses



Supersymmetric Higgs Masses

hep-ph/0010338





Over much of the remaining allowed parameter space,
$m_h \sim 130$ GeV,
$m_A \sim m_H \sim m_{H\pm}$ = "large"

From LEP:
$m_h > 91$ GeV, $m_A > 92$ GeV, $m_{H\pm} > 79$ GeV, $\tan\beta > 2.4$

MSSM Higgs Decays

Very rich structure!

For most of allowed mass range h behaves very much like H_{SM}

- $H \to$ WW and ZZ modes suppressed compared to SM
- bb and $\tau\tau$ modes enhanced

$A \to \bar{b}b$ and $\tau\tau$

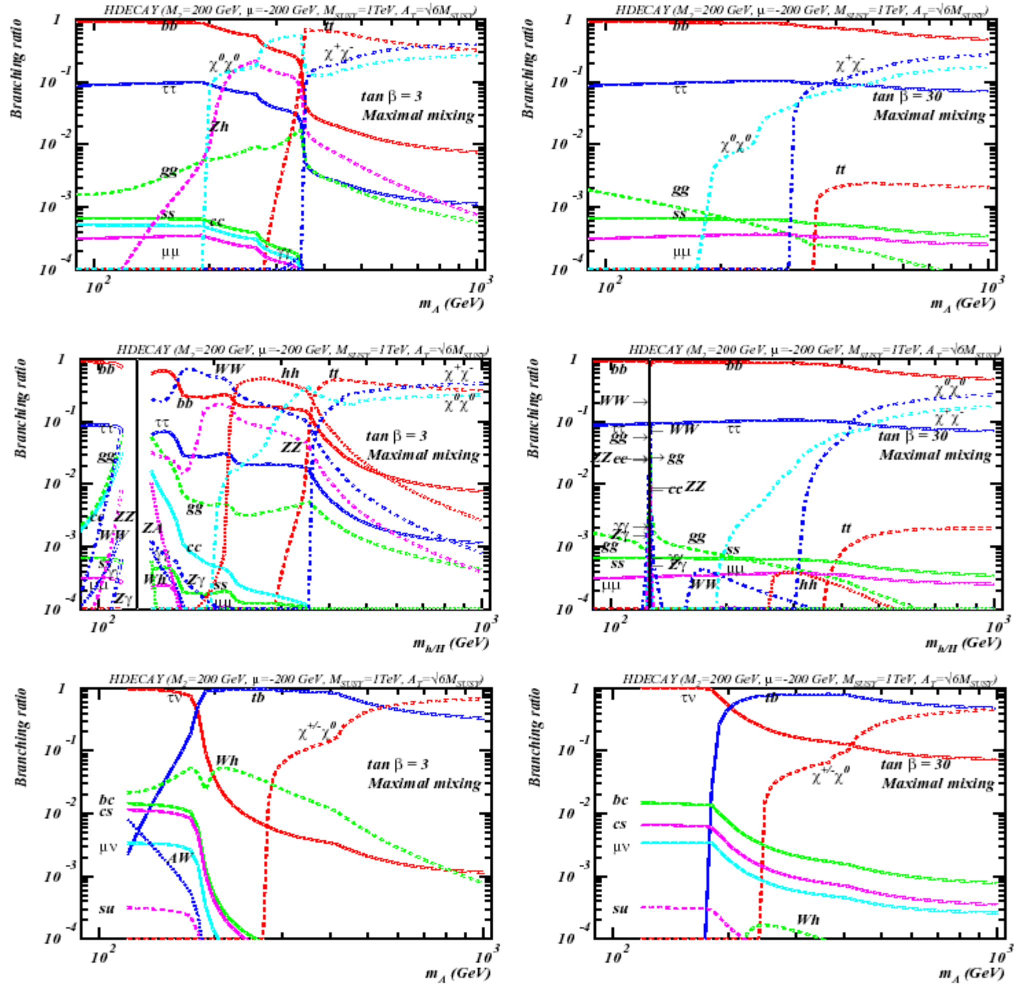
$H^{\pm} \to \tau\nu$ and $\bar{t}b$

tan β = 3 | tan β = 30

h, H

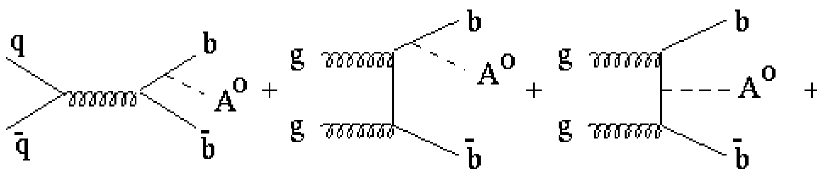
A

H±



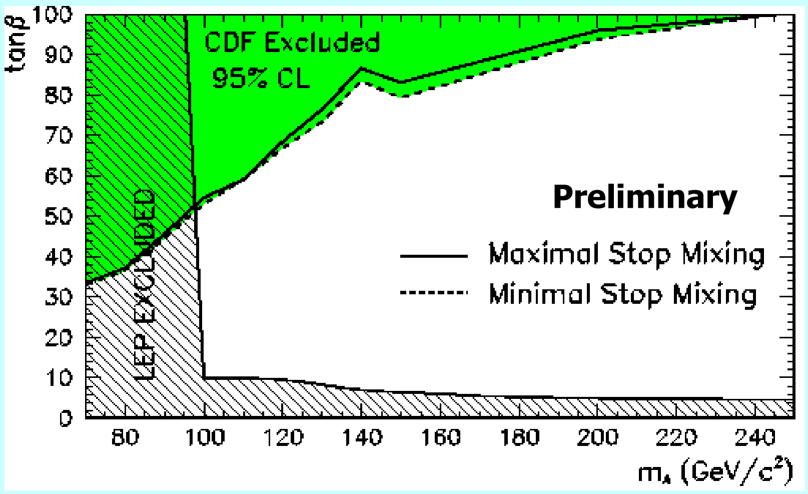
SUSY Higgs Production at the Tevatron

- **bb(h/H/A) enhanced at large tan β:**

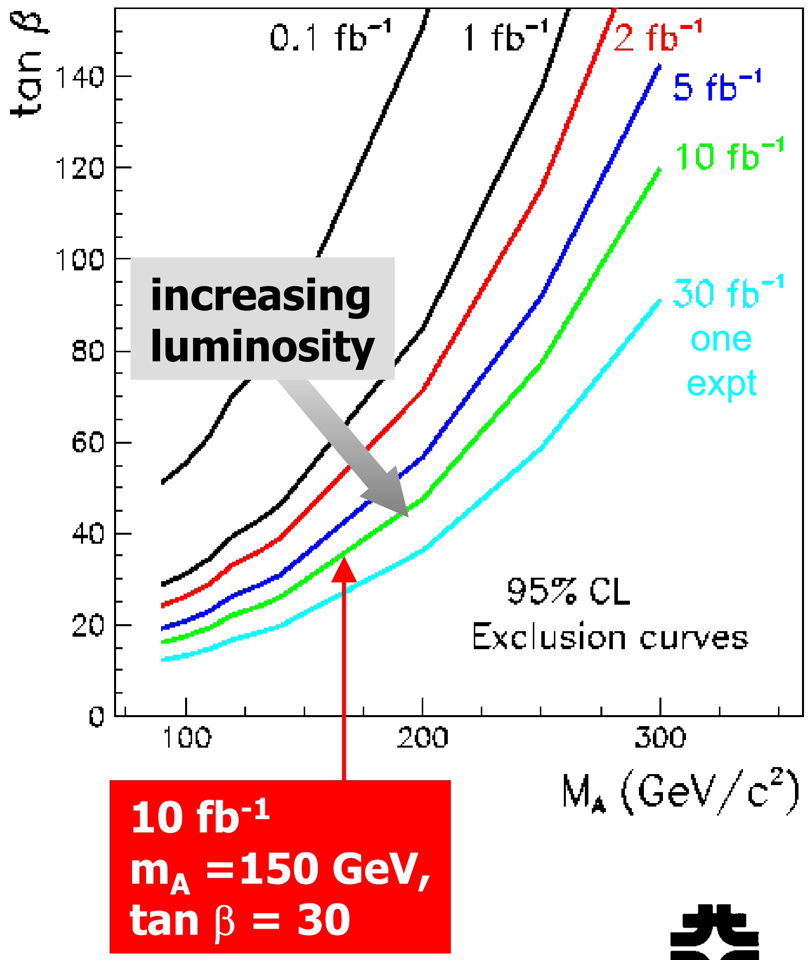


- **σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV**

CDF Run 1 analysis (4 jets, 3 b tags) sensitive to tan β > 60



bb(h/A) → 4b



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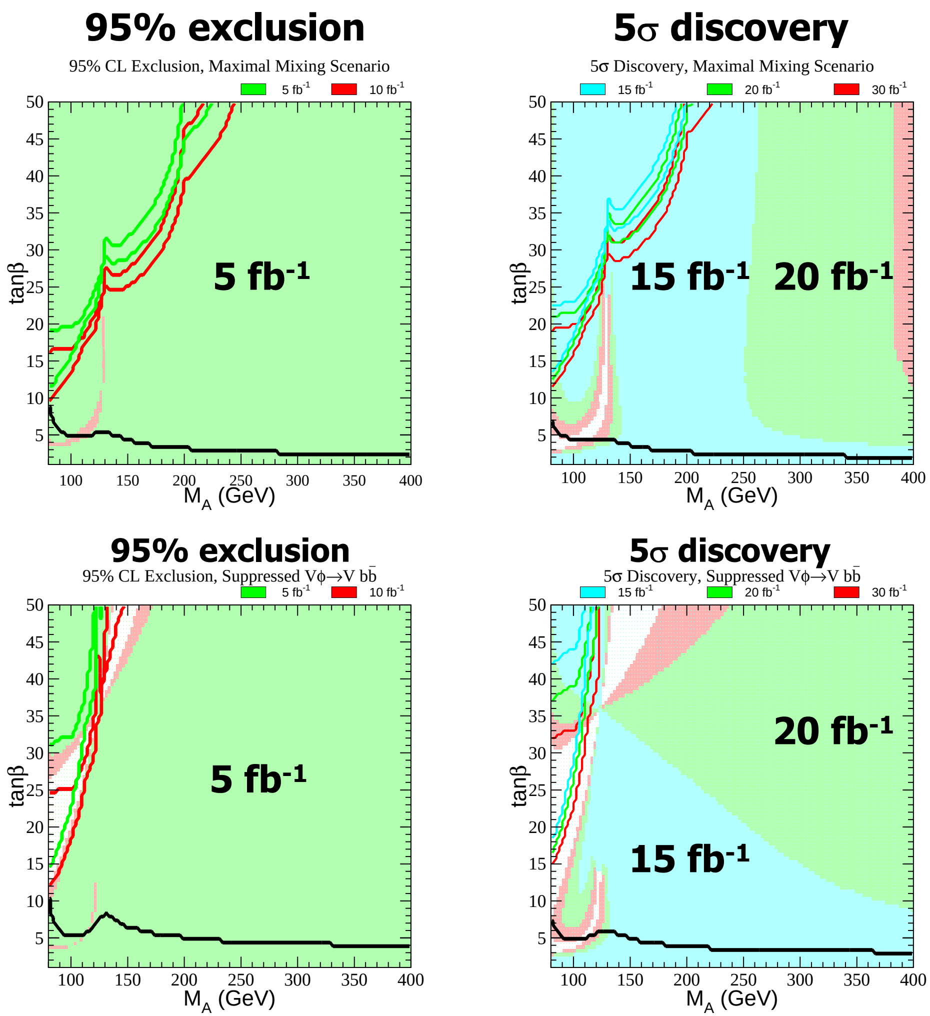
SUSY Higgs reach at the Tevatron



Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV

Most challenging scenario: suppressed couplings to bb

Enhances h $\rightarrow \gamma\gamma$?

Luminosity per experiment, CDF + DØ combined

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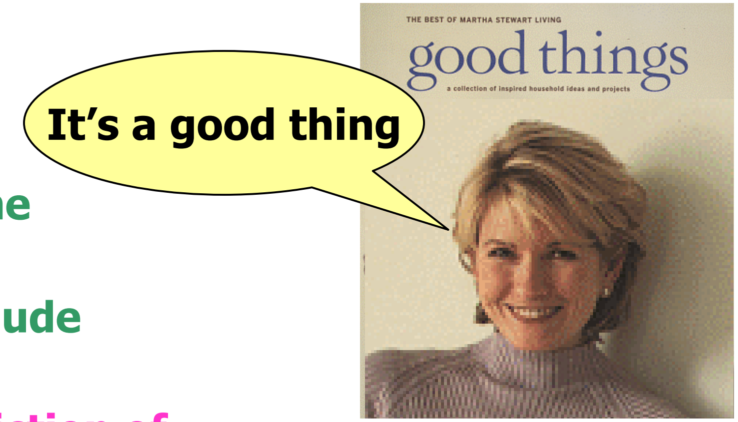
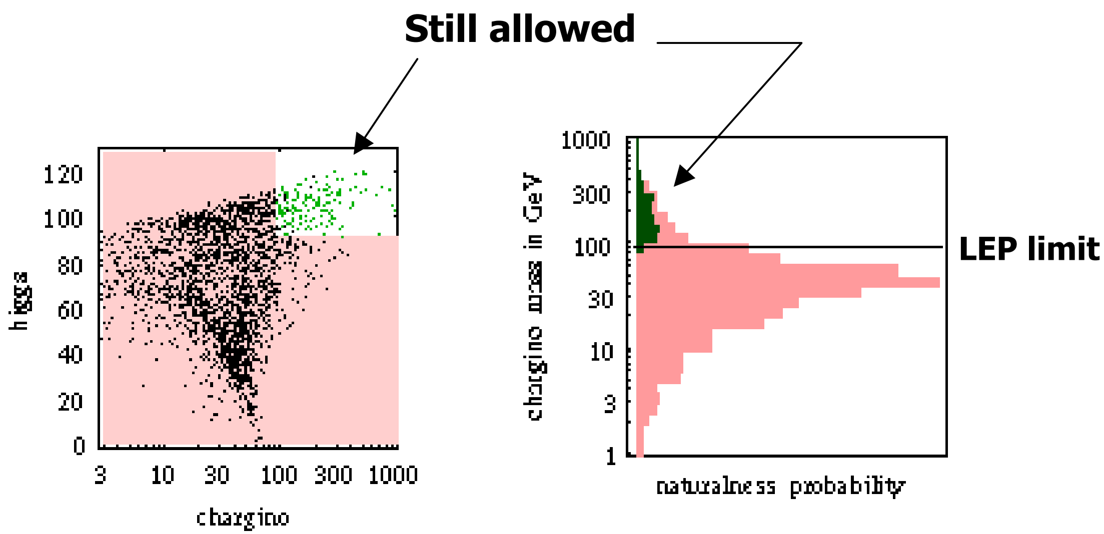
What if we see nothing?



- As long as we have adequate sensitivity, exclusion of a Higgs is still a very important discovery for the Tevatron
  - In the SM, we can exclude most of the allowed mass range
  - In the MSSM, we can potentially exclude all the remaining mass range
    - A light Higgs is a very basic prediction of the supersymmetric SM
    - e.g. Strumia, hep-ph/9904247

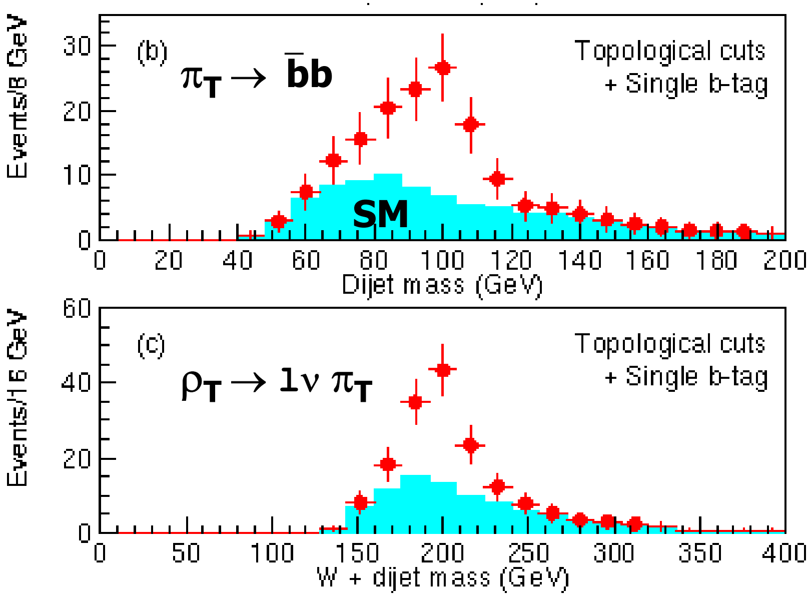


What if we see something else?

- Alternatives to SUSY: dynamical models like technicolor and topcolor
  - the Higgs is a composite particle: no elementary scalars
  - many other new particles in the mass range 100 GeV - 1 TeV
  - with strong couplings and large cross sections
  - decaying to vector bosons and (third generation?) fermions

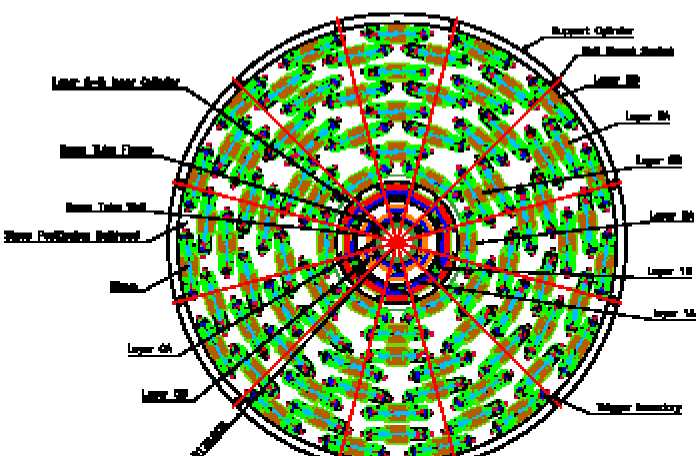
At the Tevatron, you have to be lucky, but if you are, you can win big:

"MTSM" Technicolor (Lane et al.,)
$\rho_T \to W\pi_T$ Tevatron, 1fb^{-1}

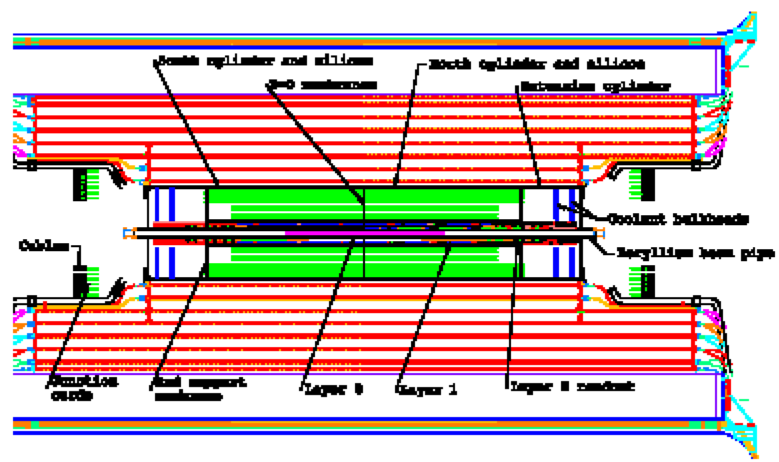


Run 2B

- **Planning has started on the additional detector enhancements that will be needed to meet the goal of accumulating 15 fb^{-1} by end 2007**
  - **major components are two new silicon detectors to replace the present CDF and DØ devices which can not survive the radiation dose**
  - **Technical design reports submitted to the laboratory Oct 2001**
  - **goal: installed and running by early 2005**



Proposed DØ Run 2B silicon detector

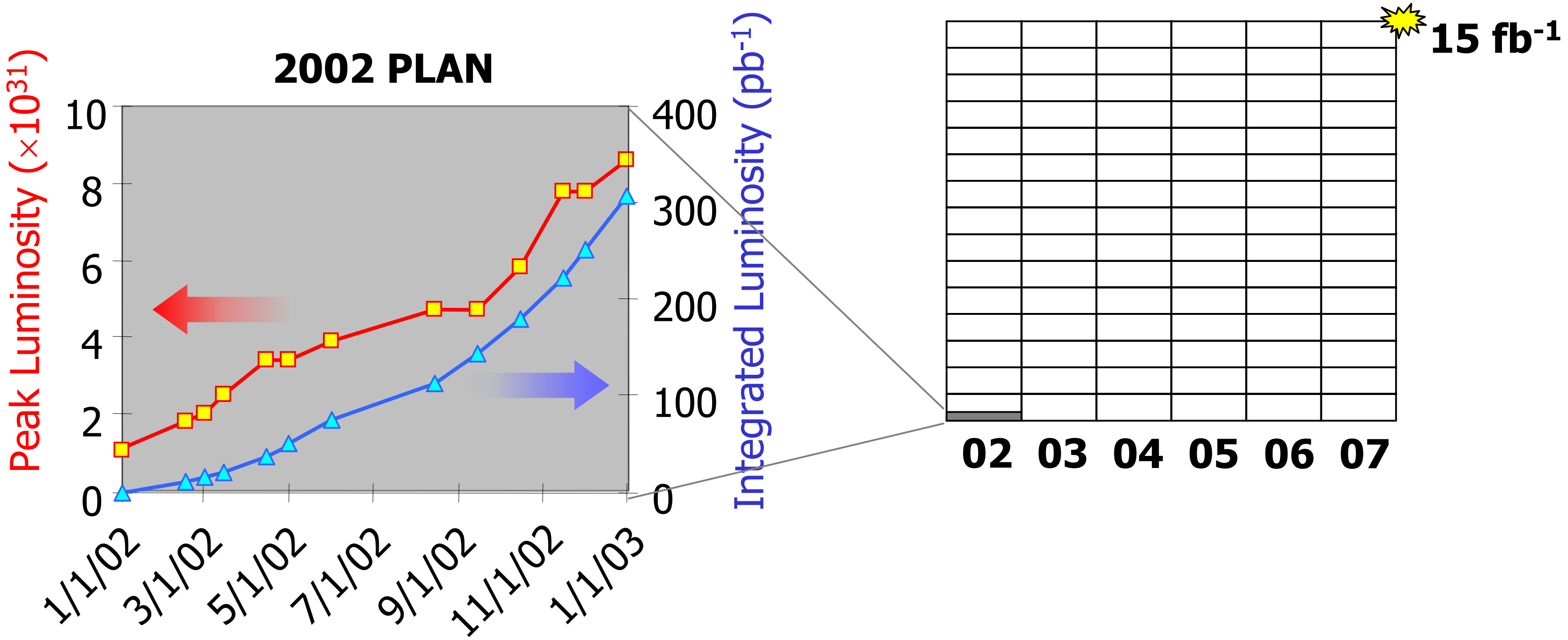


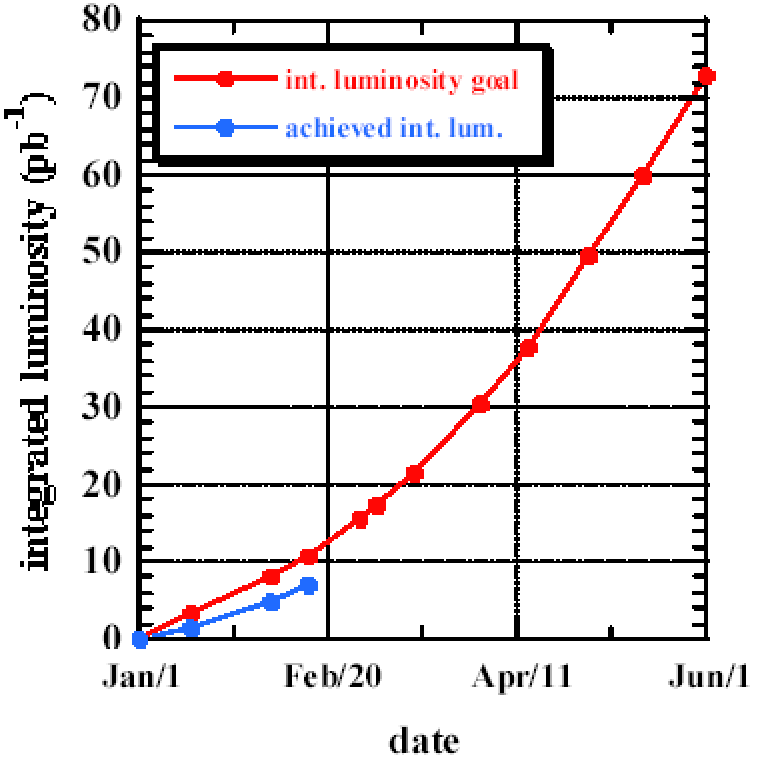
Run 2B silicon installed

Tevatron plan for 2002

- Only ~ 20pb^{-1} delivered so far, which CDF and DØ have used to commission their detectors

- 2002 will be the year that serious physics running starts

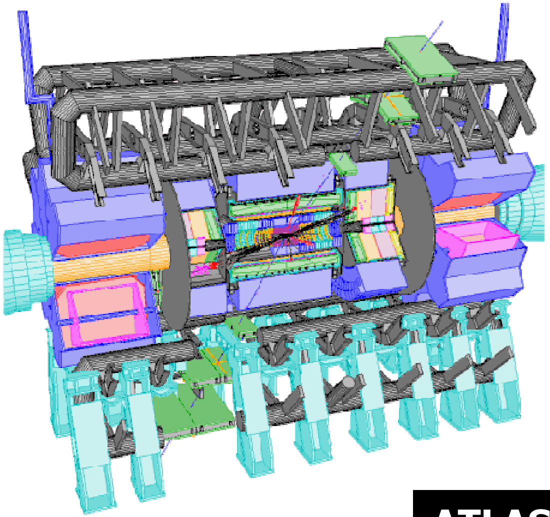



int. luminosity goal
achieved int. lum.
integrated luminosity (pb^{-1})
0
10
20
30
40
50
60
70
80
Jan/1
Feb/20
Apr/11
Jun/1
date

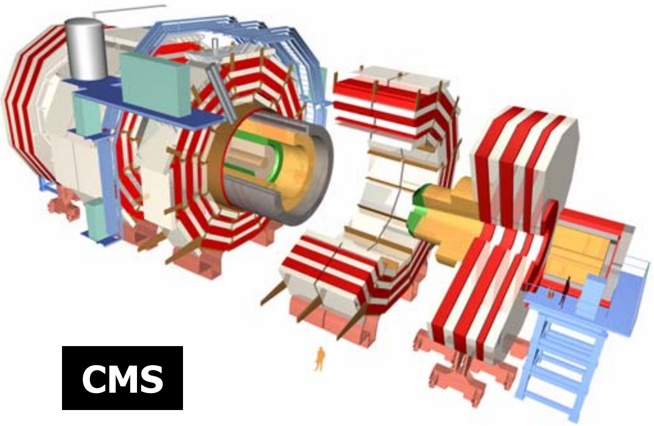
What will we know and when will we know it?

- **By 200x at the Tevatron, if all goes well**
  - **We will observe a light Higgs**
    - **Test its properties at the gross level**
    - **but not able to differentiate SM from MSSM**
  - **<u>Or</u> we will exclude a light Higgs**
    - **Interesting impact on SUSY**
  - **We will tighten exclusion regions for MSSM charged Higgs and multi-b jet signals at high tan β**
  - **We may even be lucky enough to find something else**
    - **e.g. low scale technicolor**

The Large Hadron Collider

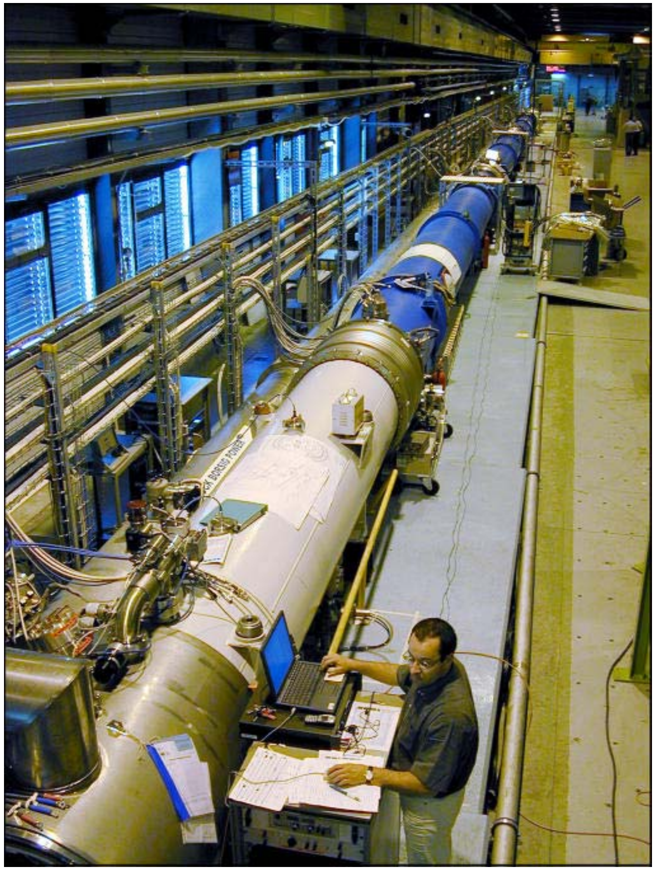


ATLAS



CMS

LHC construction

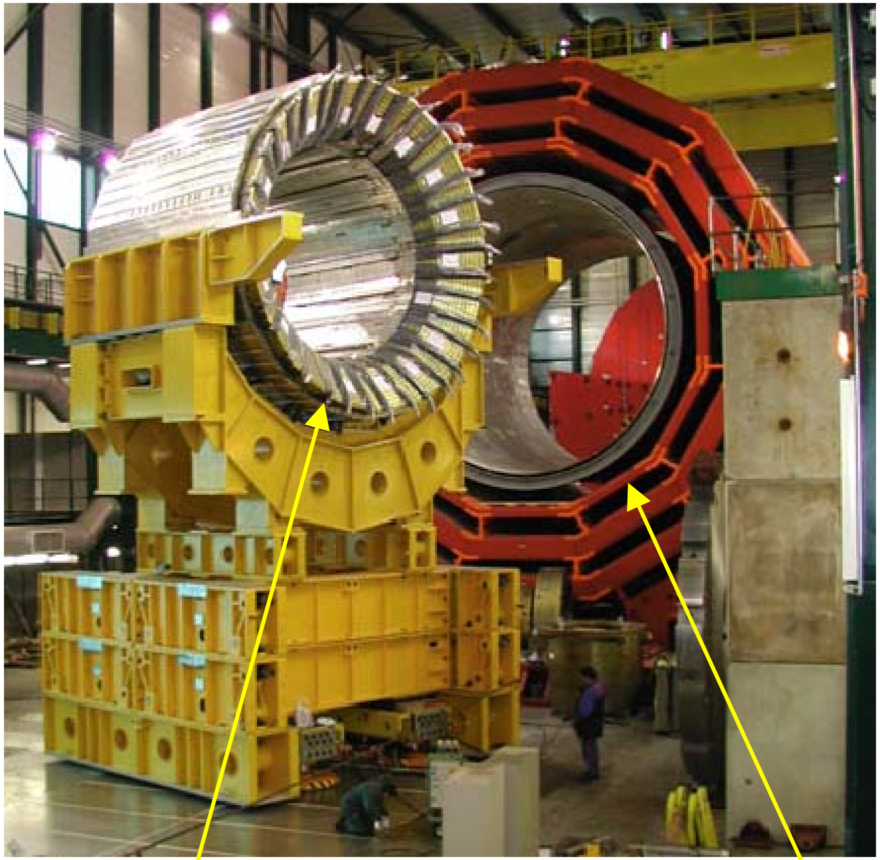


Underground construction at the ATLAS cavern

Magnet String Test

Dipole procurement now approved
<u>but</u> significant delays due to SC cable (~ 9 mos. late)
→ one year delay in official schedule

LHC detector construction



ATLAS tile calorimeter

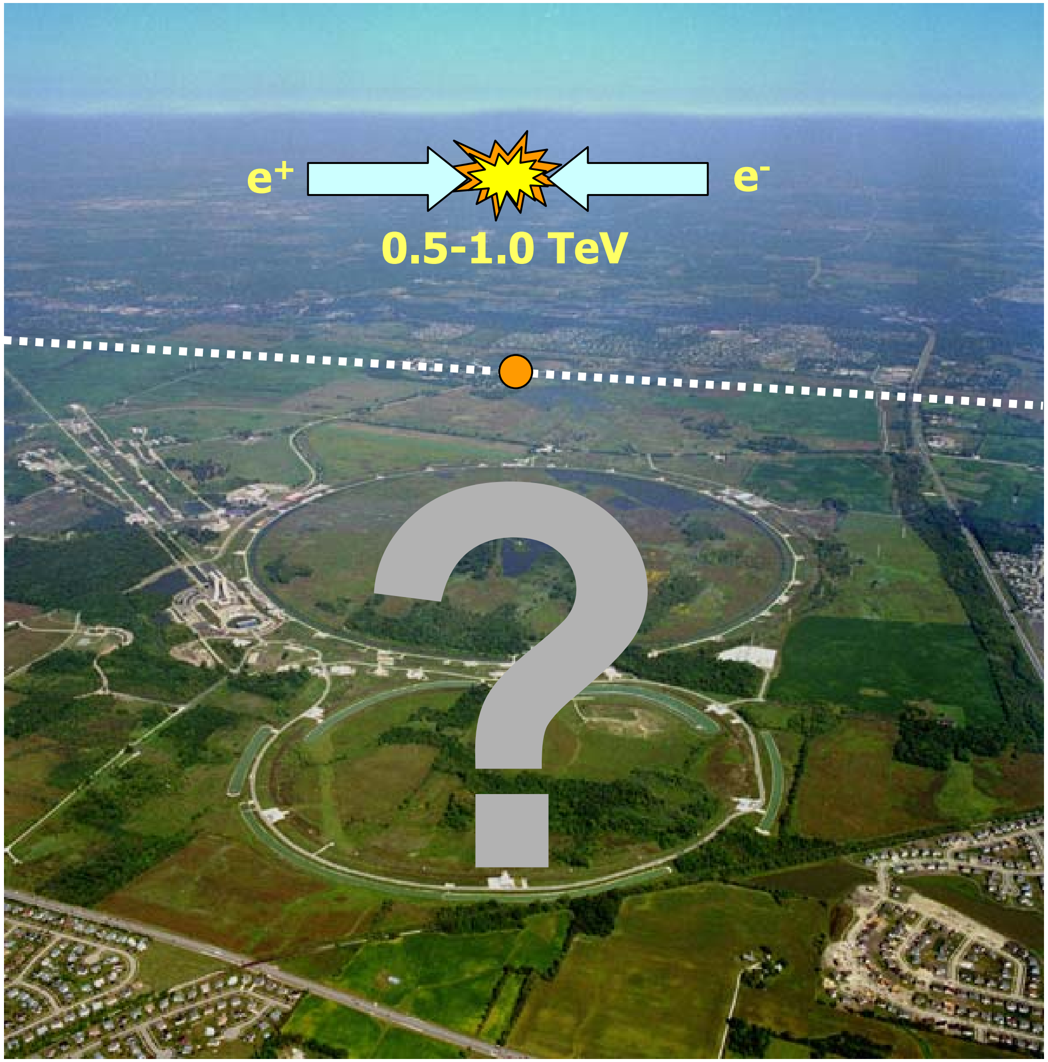
CMS hadron calorimeter

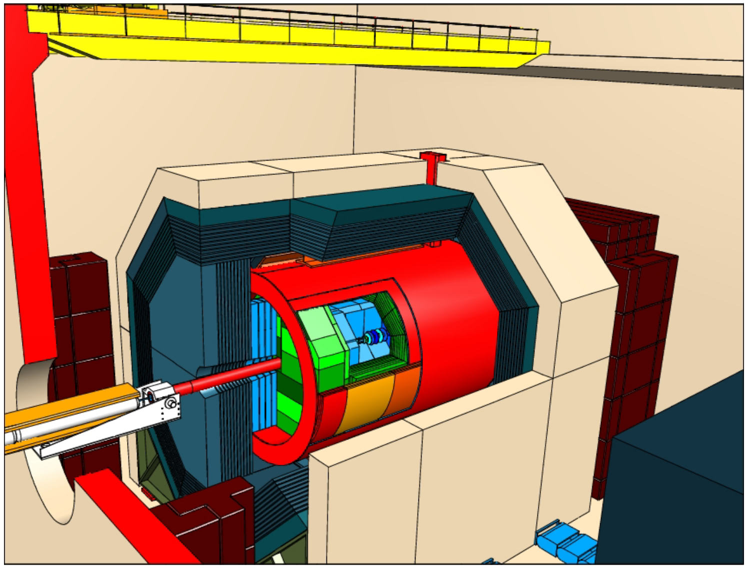
CMS 4T solenoid inside muon iron

LHC cost problems

- LHC cost review (9/01) concluded there is a 850M CHF cost overrun at CERN (machine cost plus significant extra costs for detectors, computing, etc.)
- Discussions in council
- Five internal task forces established, austerity measures being taken:
  - Cost cutting, reduction of scientific activity in 2002 (reduce accelerator operating time by 25%)
  - allow 33.5 MCHF to be reallocated to the LHC this year
- External review committee established, will examine:
  - LHC accelerator, experimental areas and CERN's share of detector construction
  - CERN's scientific program not directly related to the LHC
  - For the longer term, a series of internal Task Forces has been set up to examine CERN's functioning, thereby allowing for a meaningful analysis of savings.
- CERN's commitment to the LHC is not in any way in doubt, but the impact of all this on the start date for physics is not yet clear

The Linear Collider





A three-stage relay race

- Tevatron
  - Discovery if we're lucky
    - Fermilab's role is obvious
- LHC
  - Guaranteed discovery of one or more Higgs or some other signal of EWSB
  - Measure properties at the 20% level
  - Learn a lot more about physics at the TeV scale
    (SUSY? Extra dimensions?)
    - Fermilab's role is significant but needs to be consolidated for the physics analysis phase
- Linear Collider
  - Measure, measure, measure:
    Higgs couplings to W, Z, individual fermions, HHH coupling
    - What is Fermilab's role?

Top ten reasons to pursue the Higgs search at Fermilab

10. Window of opportunity before LHC startup is not getting shorter
9. The origin of EWSB has been unclear for way too long, and theorists can't figure the question out by themselves
8. Find it while Mr. Higgs is still alive and can win the Nobel Prize
7. Learn if there really are fundamental scalars (SUSY?)
6. Learn why the standard model seems to work so well
5. We might find something other than a Higgs
4. Excluding a light Higgs is almost as interesting as finding it
3. Huge potential payback for a (relatively) small investment
2. Excitement and discovery move the field forward
1. Because we can!

What the Higgs search will teach us

- What is the source of mass of the W and Z?
  - Why is the weak force weak?
- What is the source of mass of the fundamental fermions?
- Are there fundamental scalars?
- Is there SUSY?
  - if no light Higgs, no weak scale SUSY…
- Is there other new physics at the weak scale?
  - New forces like technicolor
  - Are m_W, m_t and m_H consistent with precision EW fits?
- What is the mass scale of new physics?
- What is the next machine we'll want to build after the linear collider?

What the Higgs search won't explain

- **Why fermion masses have the values they do**
  - **Why is the top quark so heavy?**
- **The origin of all mass in the universe**
  - **The universe is roughly**
    - **70% dark energy (???)**
    - **20% cold dark matter**
      - e.g. neutralinos with mass ~100 GeV
    - **5% neutrinos?**
    - **5% baryons**
      - whose mass is almost all due to QCD
- **Flavor**
  - **What distinguishes a top quark from an up quark?**

Conclusions

- For as long as I have done high energy physics, we have known that we needed something like a Higgs, and it has been the highest priority of the field to explore this question experimentally
- That is about to change dramatically: the next few years will see the Higgs become a discovery or set of discoveries to be understood and measured
  - and, we hope, the first window on to a new domain of physics at the TeV scale
- Personally, I can't wait to see what's behind the curtain