Electroweak Symmetry Breaking at the Tevatron, the LHC and the Linear Collider

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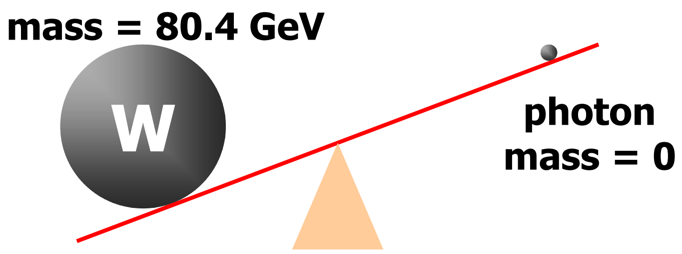
http://d0server1.fnal.gov/projects/d0_pictures/presentations/womersley/wineandcheese_mar2002.pdf

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

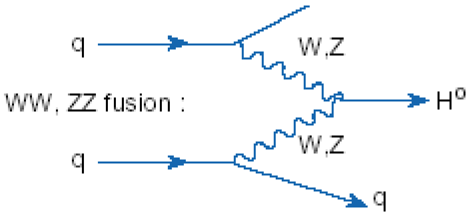


- **An appealing picture: is it correct?**
  - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field
  - All its properties (production and decay rates, couplings) are fixed except its own mass

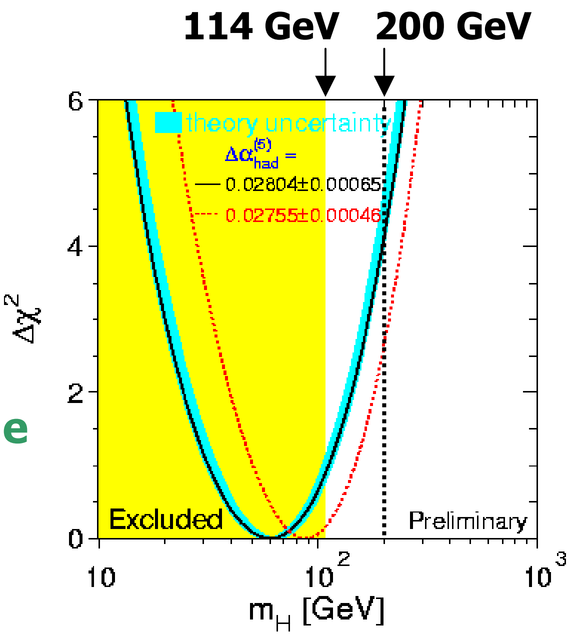
Highest priority of worldwide high energy physics program: find it!

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

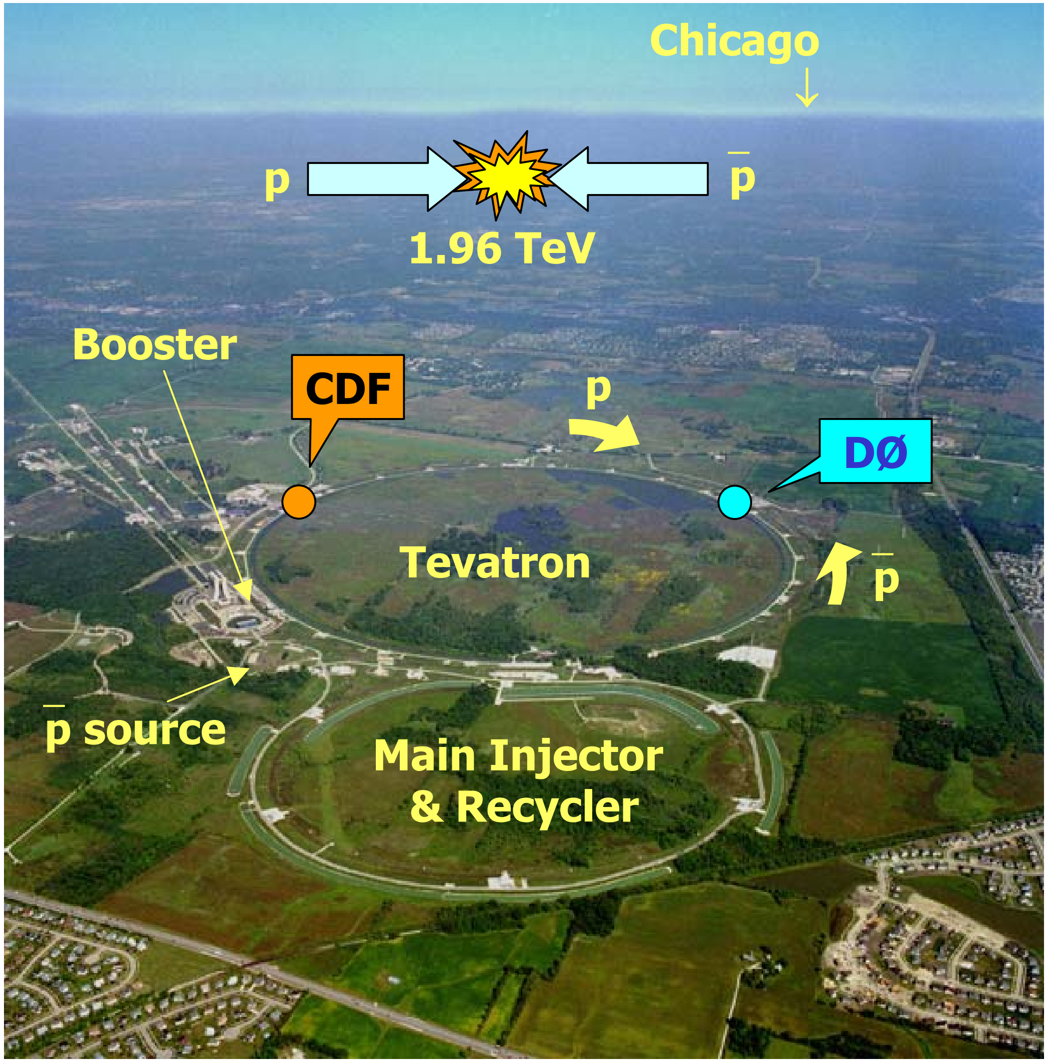


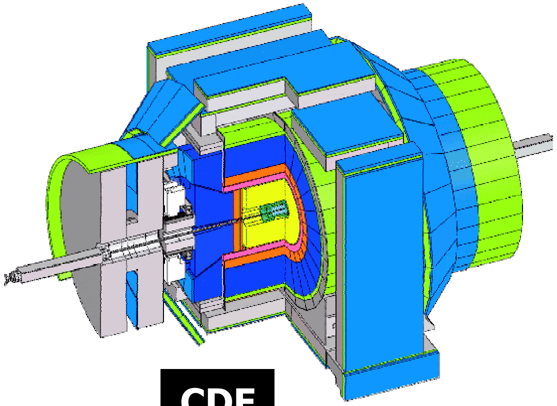
- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN**
  - **precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV**
  - **direct searches for Higgs production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

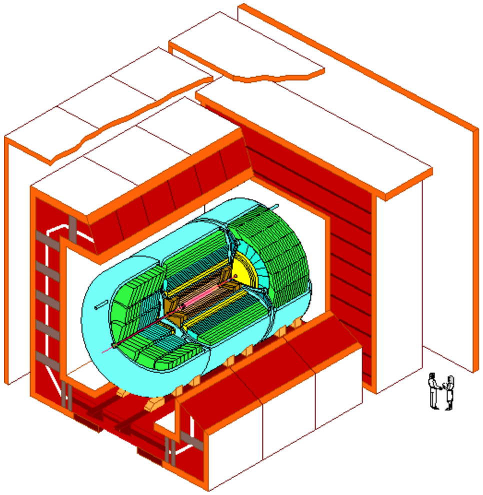
– Luciano Maiani

The Fermilab Tevatron Collider





CDF



DØ

Higgs at the Tevatron

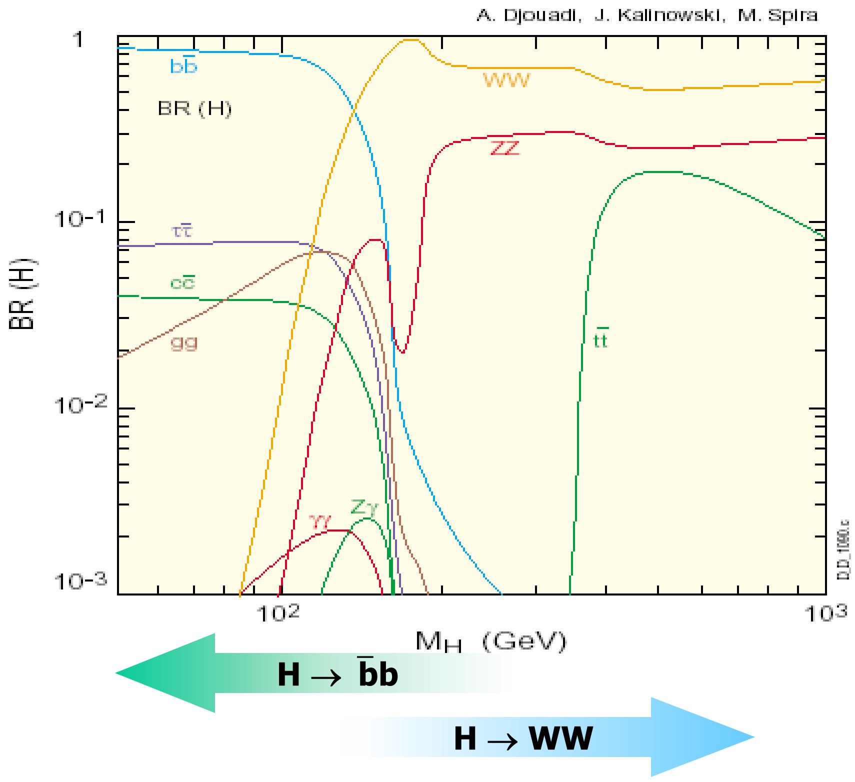
- The search for the mechanism of EWSB motivated the construction of supercolliders (SSC and LHC)

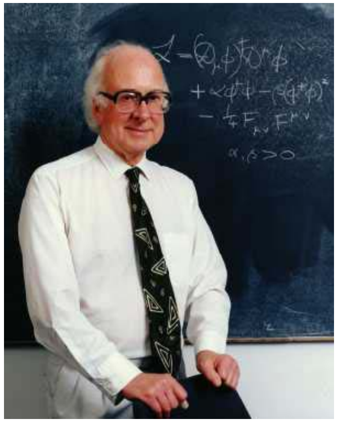
- After the demise of the SSC, there was a resurgence of interest in what was possible with a "mere" 2 TeV
  - Ideas from within accelerator community ("TeV33")
  - Stange, Marciano and Willenbrock paper 1994
  - TeV2000 Workshop November 1994
  - Snowmass 1996
  - TeV33 committee report to Fermilab 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 $2 fb^{-1}$

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**



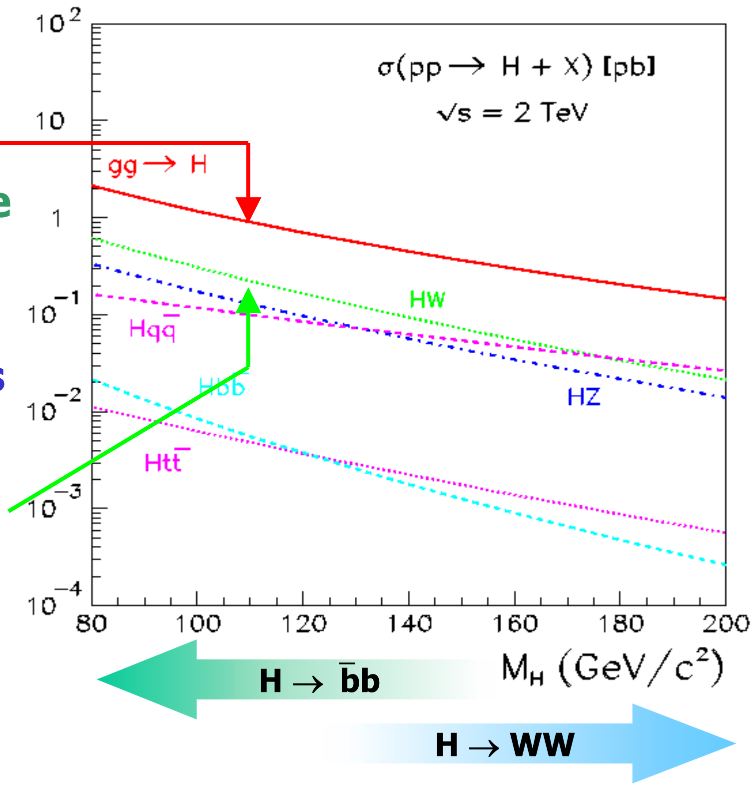


One Higgs

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**

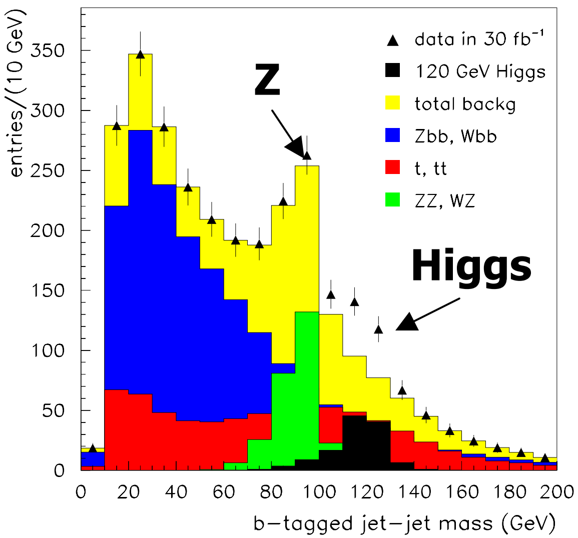


Dominant decay mode

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

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

m_H = 120 GeV

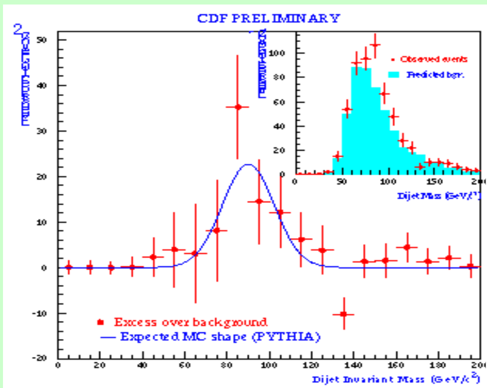


2 × 15fb⁻¹ (2 experiments)

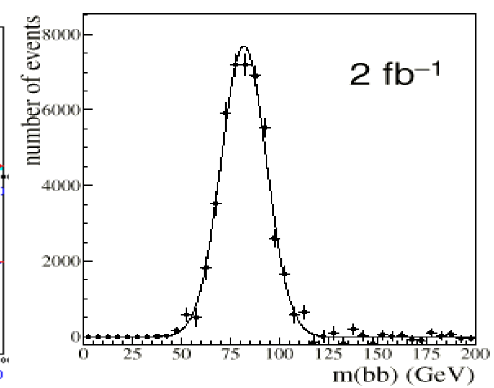
$\bar{b}b$ mass resolution

Directly influences signal significance

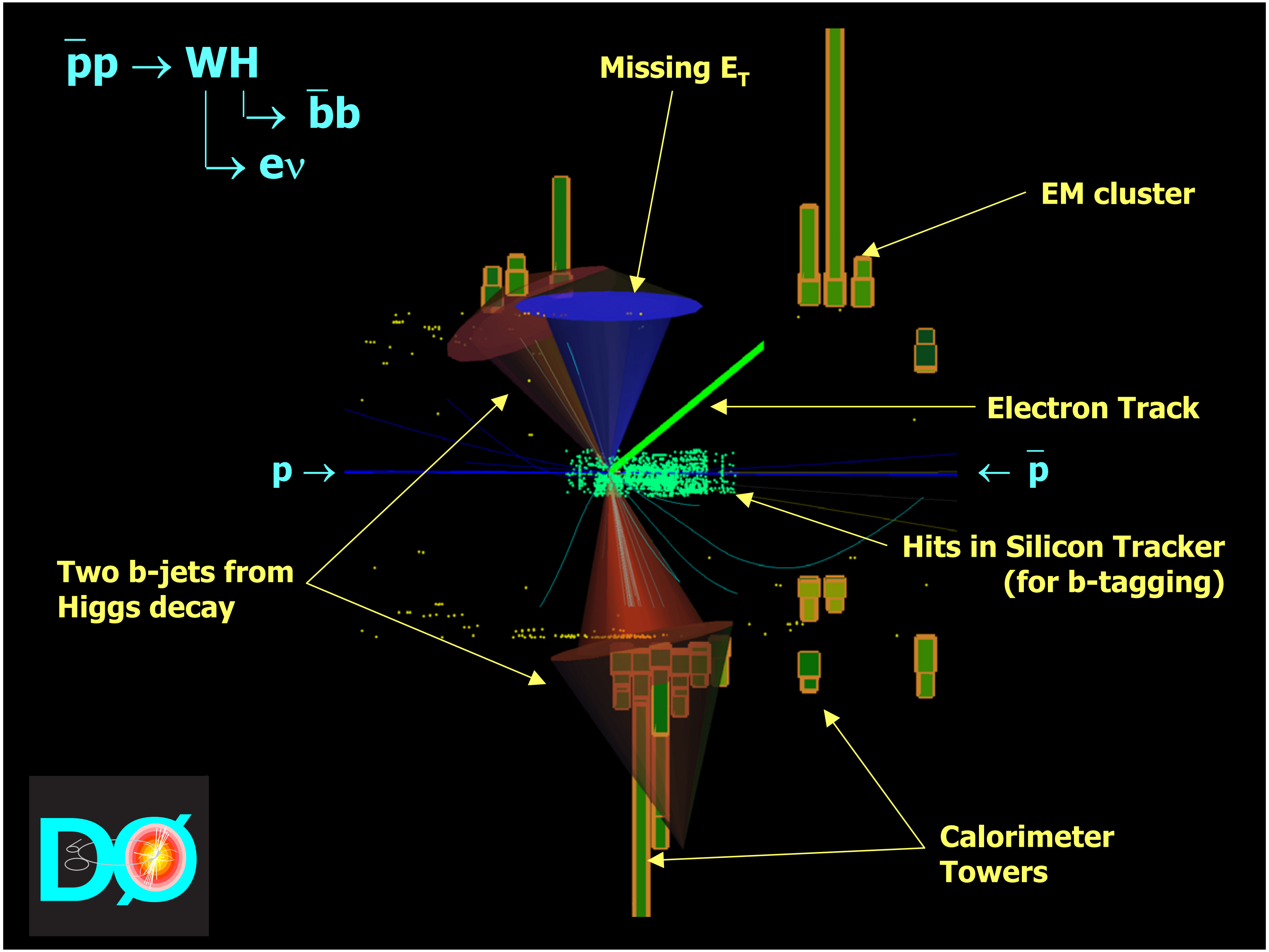
Z → $\bar{b}b$ will be a calibration



CDF Z → $\bar{b}b$ in Run I



DØ simulation for 2fb⁻¹


$\bar{p}p \rightarrow WH$
$\hookrightarrow \bar{b}b$
$\hookrightarrow e\nu$
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

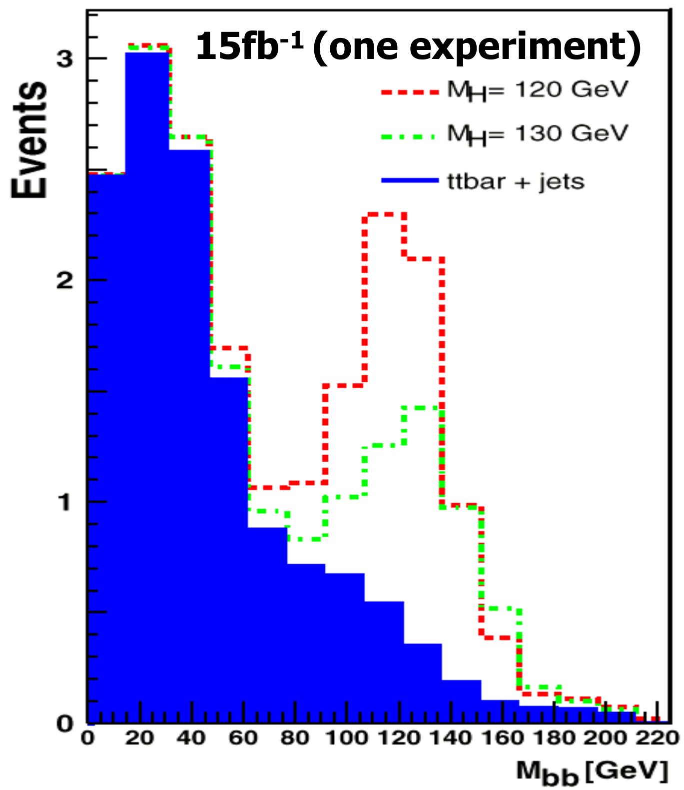
- Events in one experiment with 15 fb^{-1}:

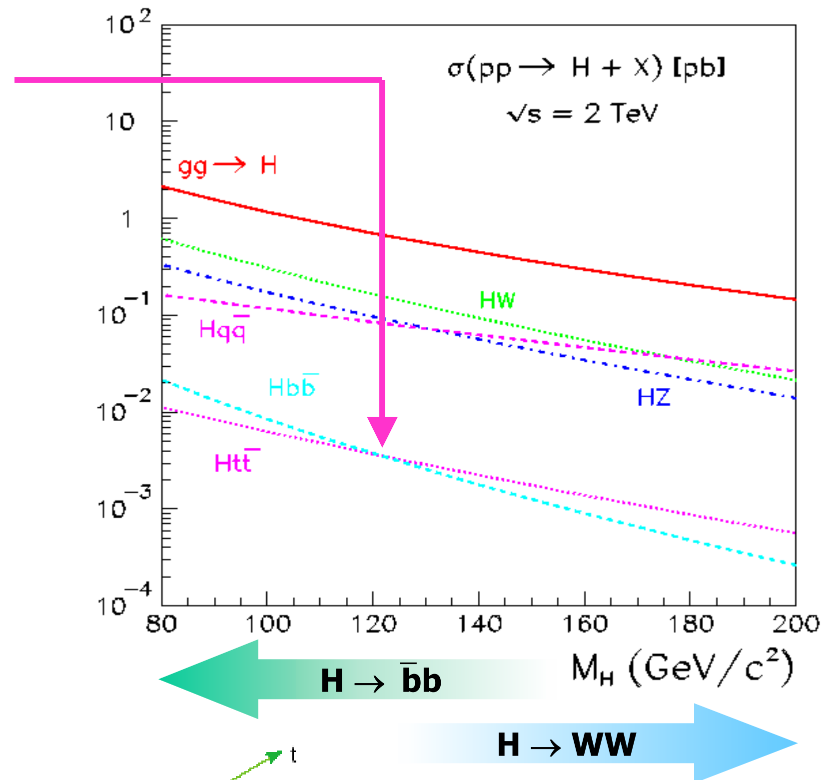
Mode	Signal	Background	S/$\sqrt{B}$
$l\nu bb$	92	450	4.3
$\nu\nu bb$	90	880	3.0
$llbb$	10	44	1.5

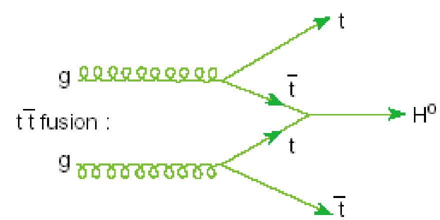
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - production cross section
  - Can we see H $\rightarrow$ WW? (Branching Ratio ~ 9% and rising w/ mass)
  - Can we see H $\rightarrow$ $\tau\tau$? (Branching Ratio ~ 8% and falling w/ mass)
  - Can we see H$\rightarrow$ $\gamma\gamma$? (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:**







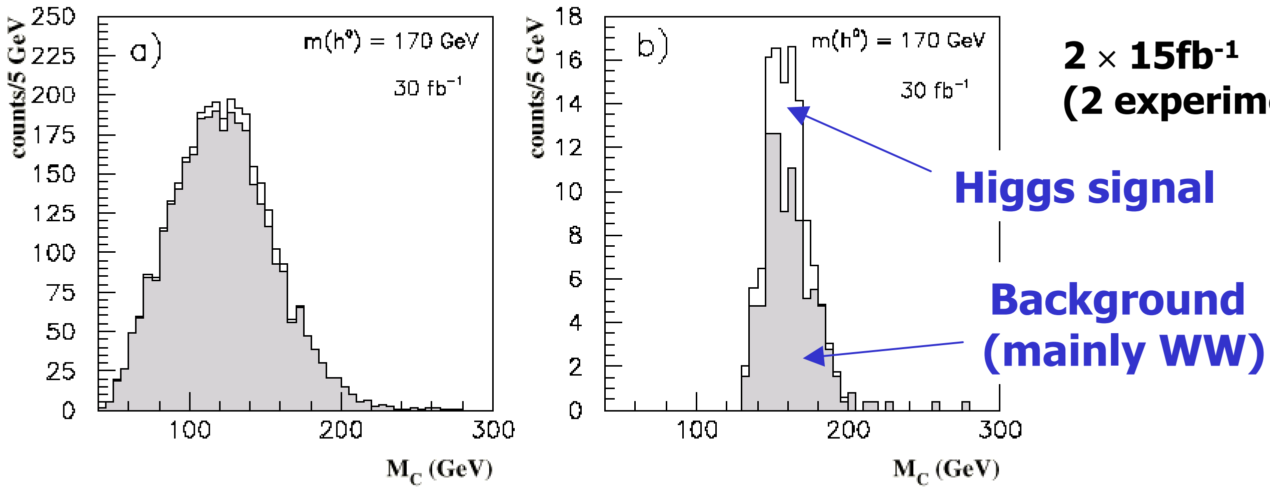
Tests top quark Yukawa coupling

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

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

  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



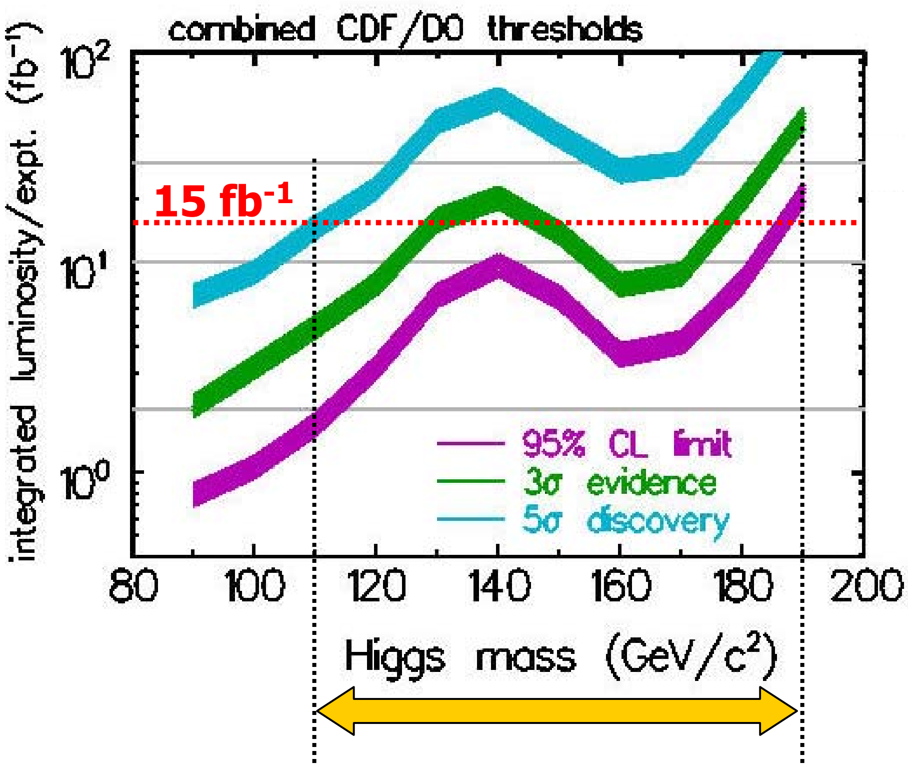
$2 \times 15\text{fb}^{-1}$
(2 experiments)

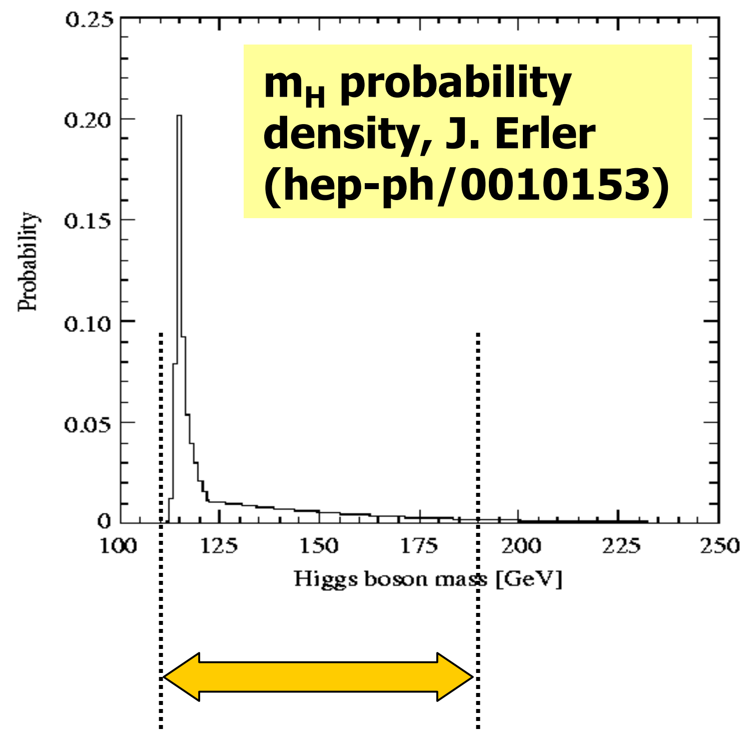
Before tight cuts:
verify WW modelling

After tight cuts

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

Tevatron Higgs mass reach





110-190 GeV

No guarantee of success, but certainly a most enticing possibility

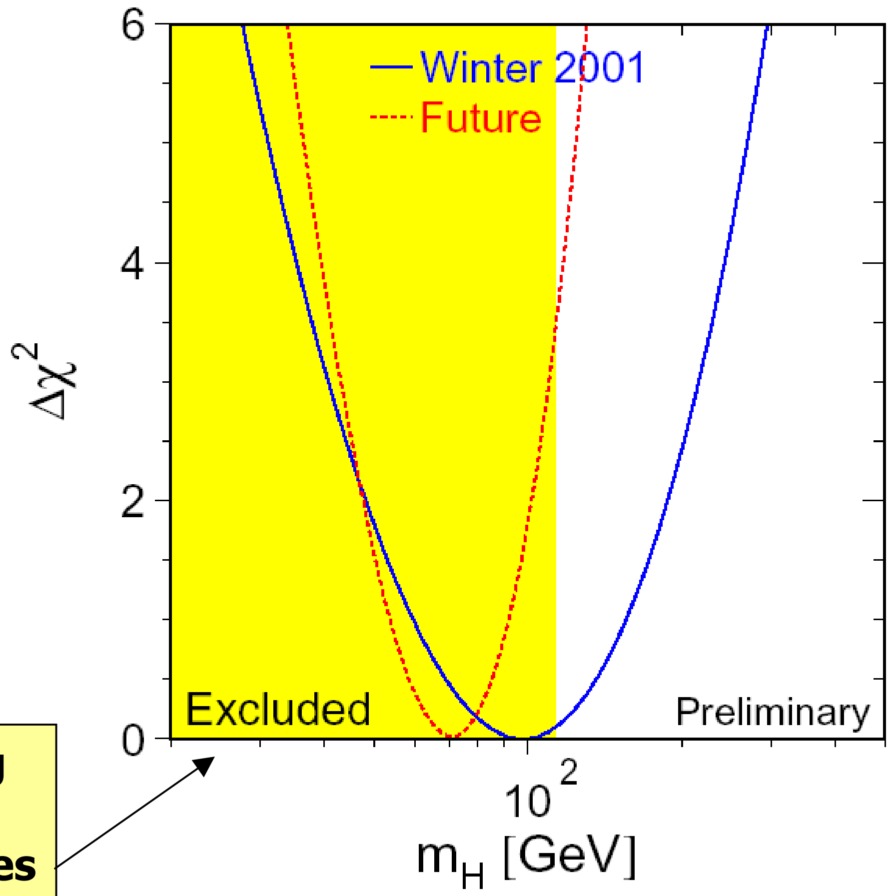
Indirect Constraints on Higgs Mass

- **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**

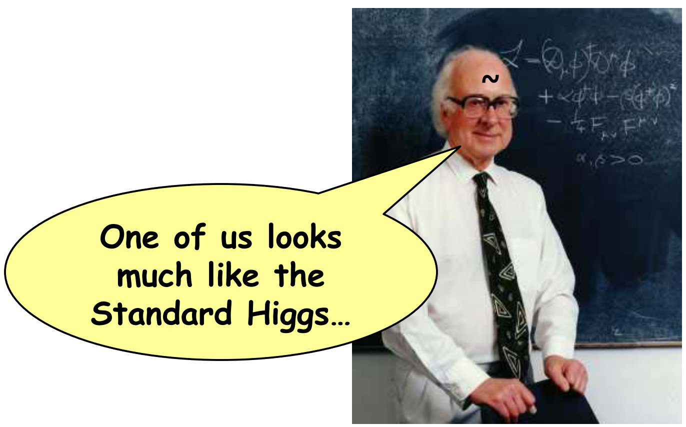
Impact on Higgs mass fit using Δm_W = 20 MeV, Δm_W = 1 GeV, $\Delta\alpha = 10^{-4}$, current central values
M. Grünewald et al., hep-ph/0111217



Supersymmetric Higgs sector

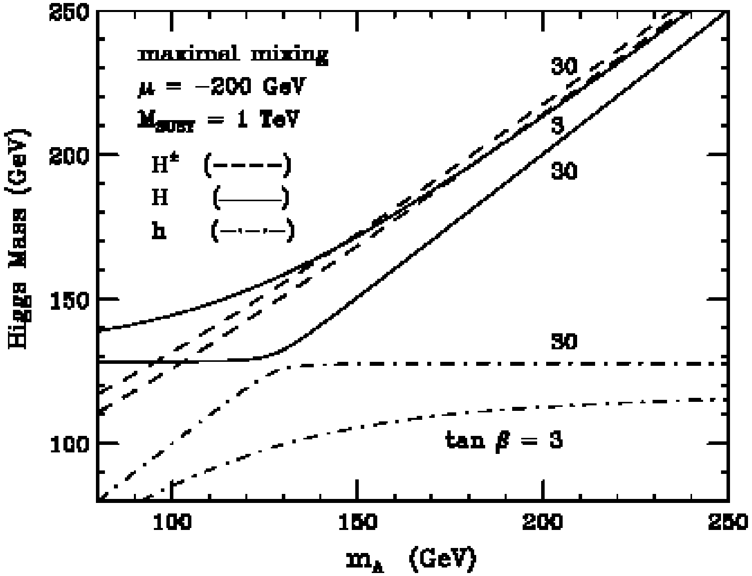
- **Expanded Higgs sector: h, H, A, $H^{\pm}$**
- **Properties depend on**
  - **At tree level, two free parameters (usually taken to be m_A, tan β)**
  - **Plus radiative corrections depending on sparticle masses and m_t**

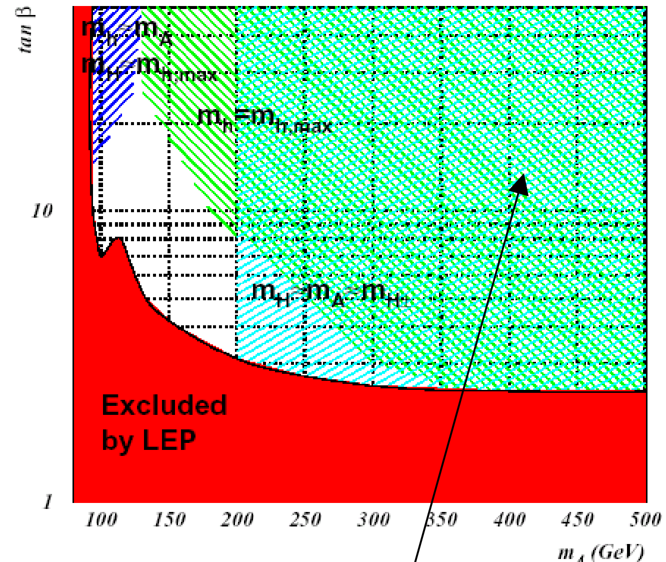
Multiple Higgses



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"

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

MSSM Higgs Decays

Very rich structure!

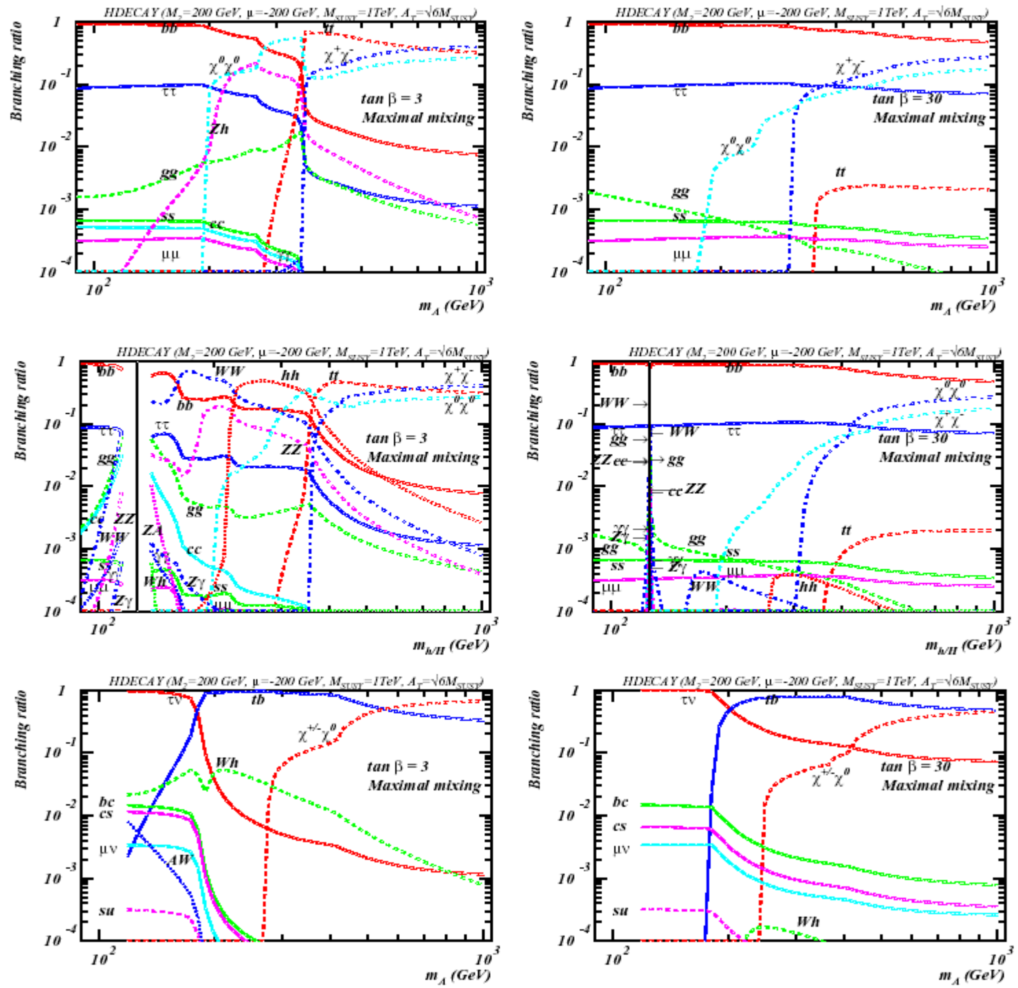
For most of allowed mass range h behaves very much like H_{SM}

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

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

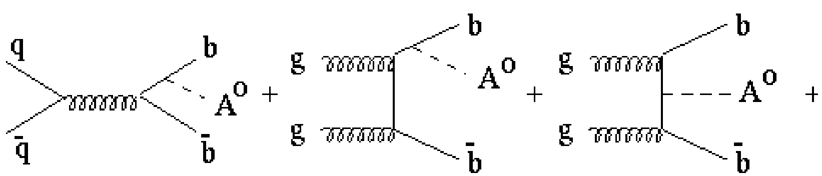
$H^{\pm} \rightarrow \tau\nu$ and $\bar{t}b$

	tan β = 3	tan β = 30
h, H		
A		
H±		



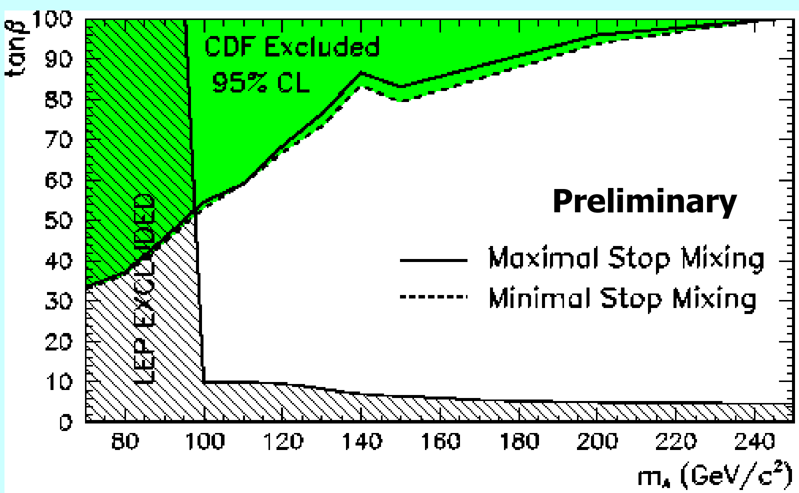
SUSY Higgs Production at the Tevatron

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

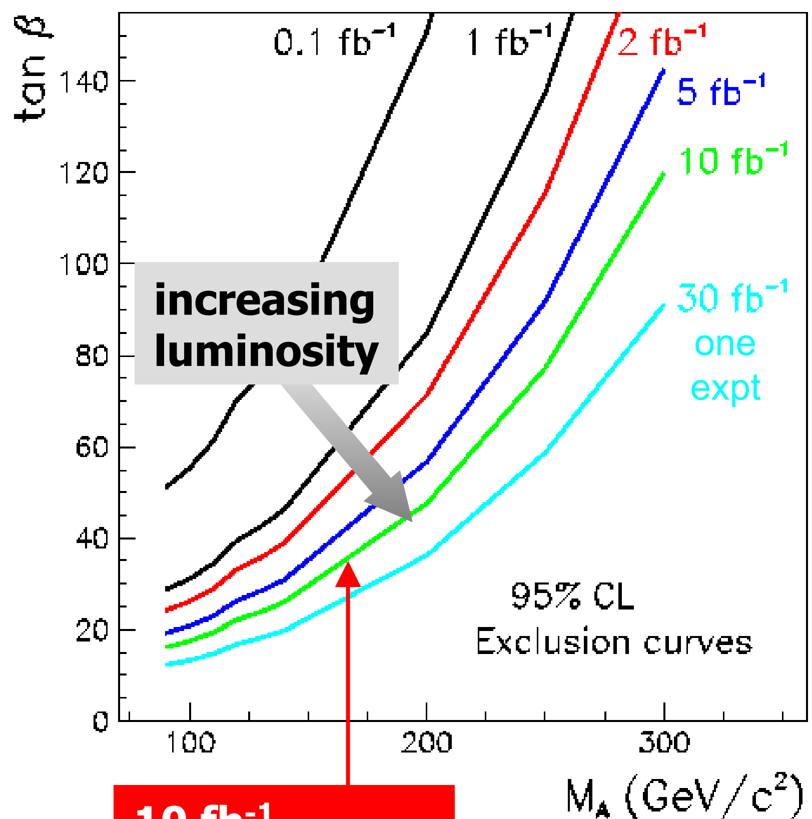


- **σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV**

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



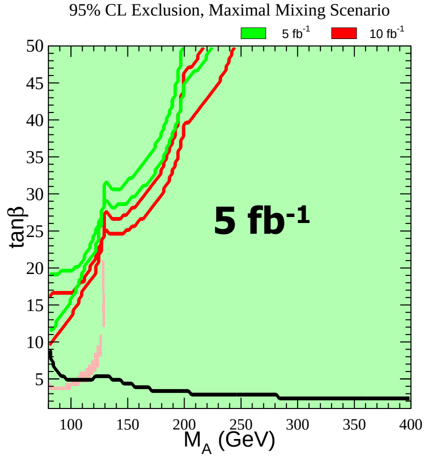
bb(h/A) → 4b



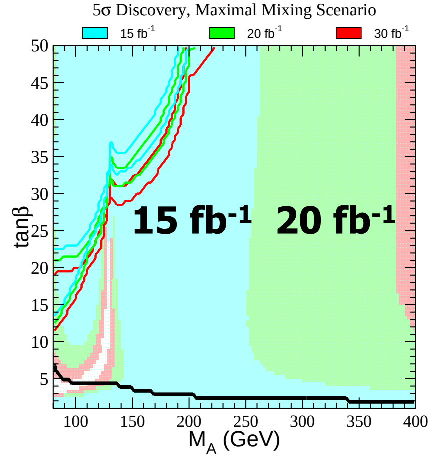
10 fb^{-1}
m_A =150 GeV,
tan β = 30

SUSY Higgs reach at the Tevatron

95% exclusion

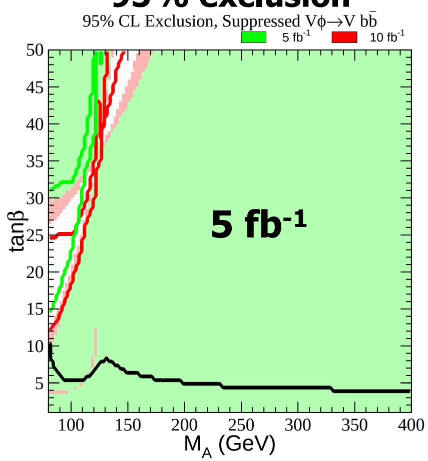


5σ discovery

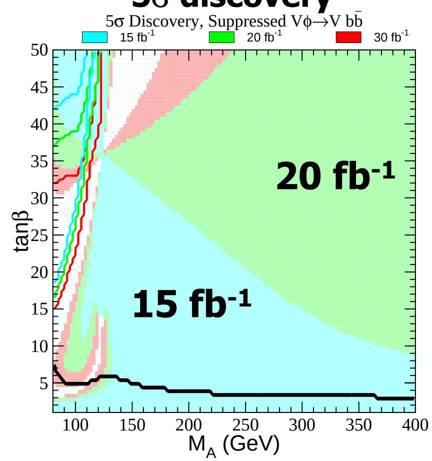


Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV

95% exclusion



5σ discovery



Most challenging scenario: suppressed couplings to bb

Enhances $h \to \gamma\gamma$?

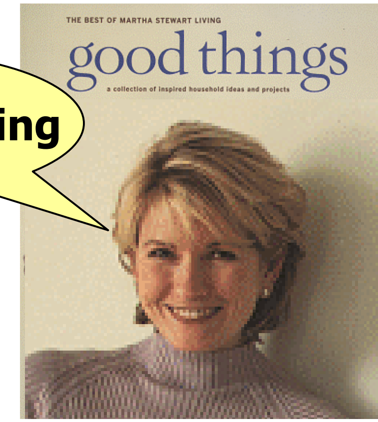
Luminosity per experiment, CDF + DØ combined

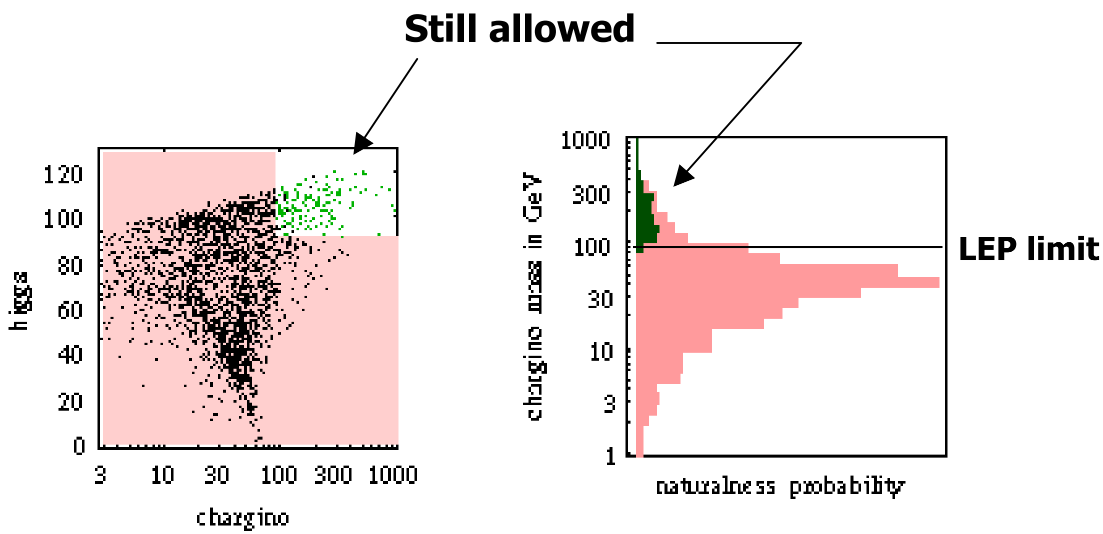
John Womersley

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 <u>all</u> the remaining mass range**
    - **A light Higgs is a very basic prediction of the supersymmetric SM**
    - **e.g. Strumia, hep-ph/9904247**

It's a good thing



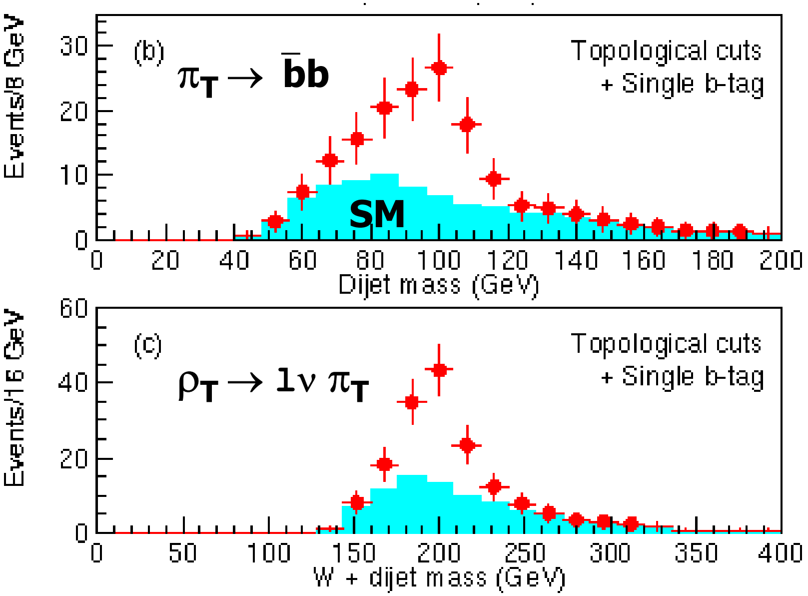


What if we see something else?

- **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.,)
$\rho_T \rightarrow W\pi_T$ Tevatron, 1fb^{-1}



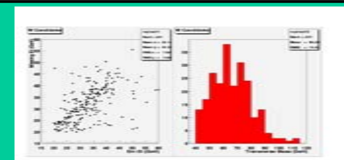
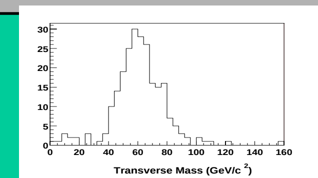
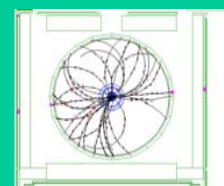
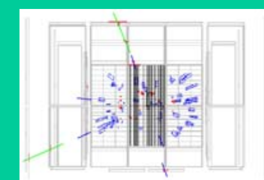
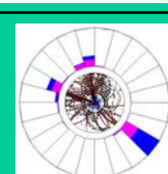
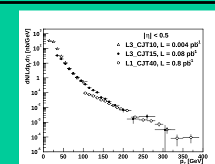
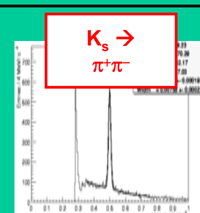
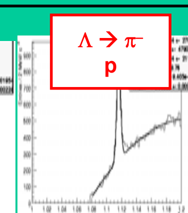
What will we know and when will we know it?

- **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**

A brief aside

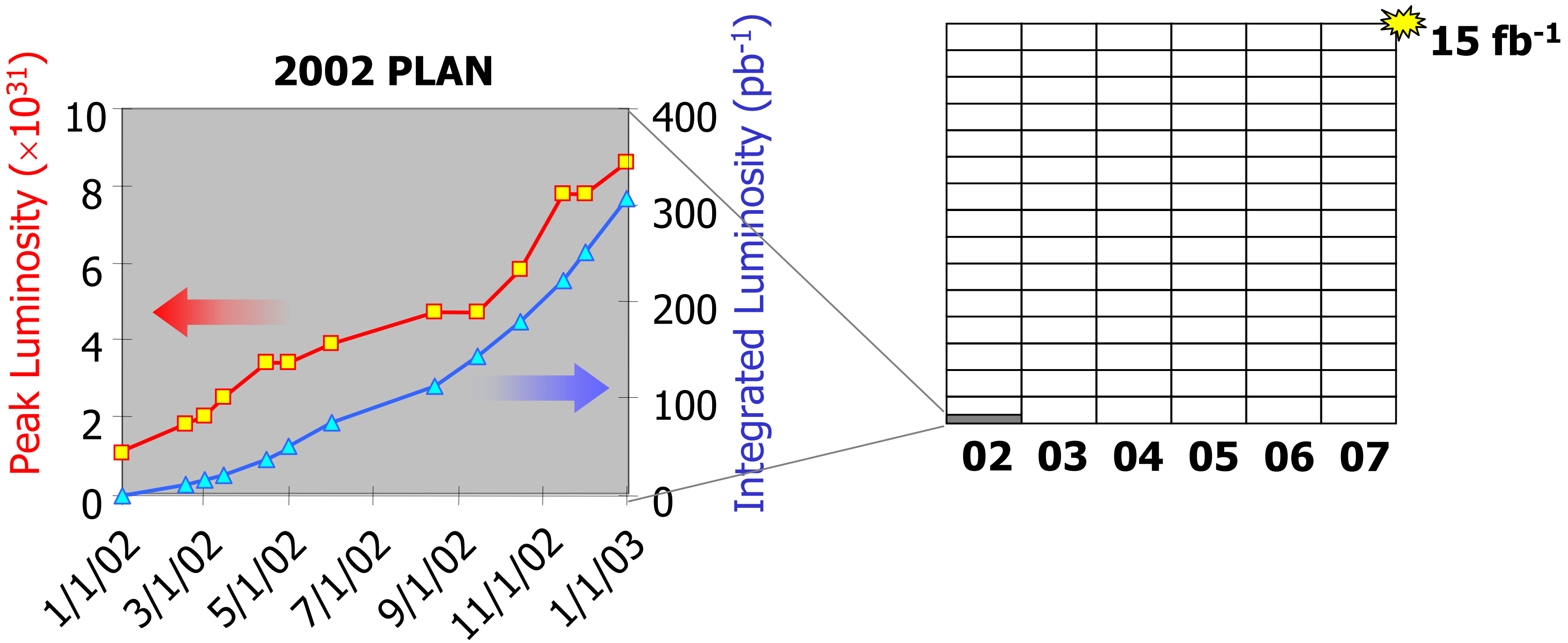
- So, how is the Run 2 physics program going so far?

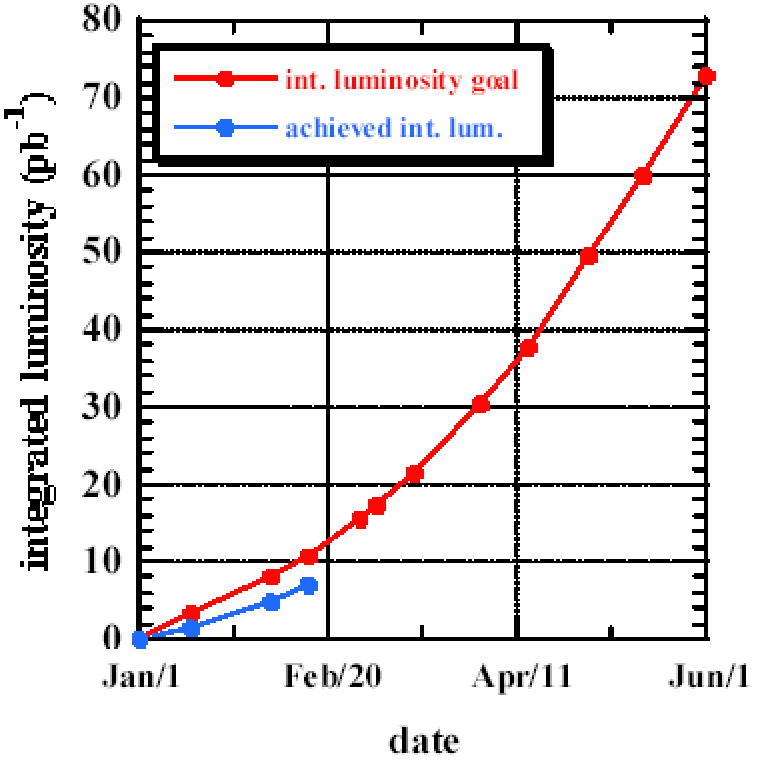
What do we need for the Higgs search?

	CDF 	DØ 
W/Z → e		
W/Z → μ		
Jets		
Tracks	 	
b-tagging		**not yet**

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**

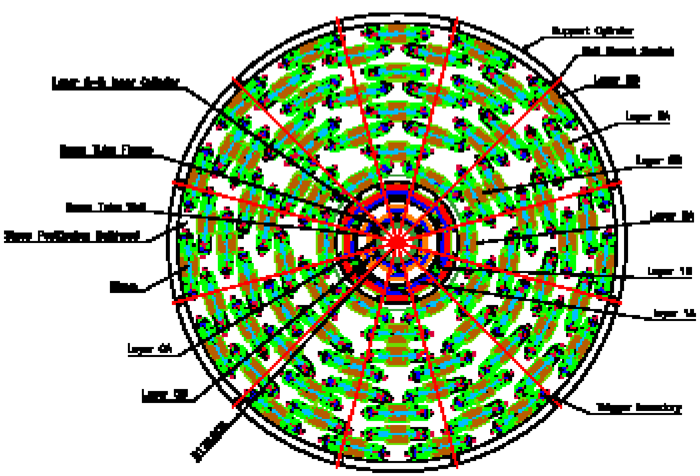




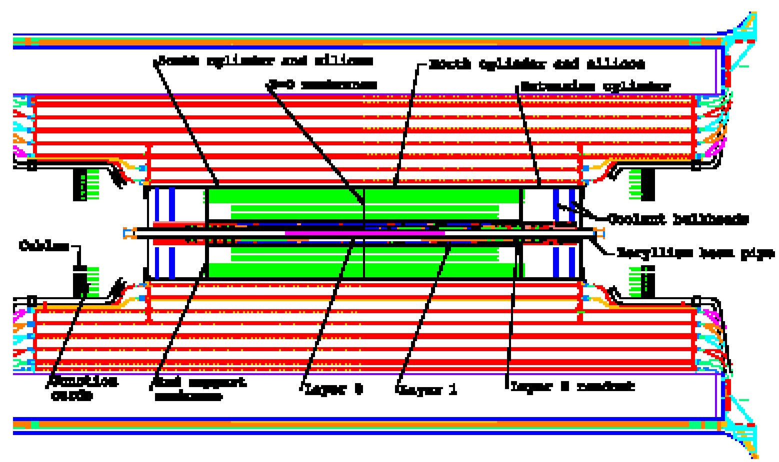
80
70
60
50
40
30
20
10
0
integrated luminosity (pb^{-1})
int. luminosity goal
achieved int. lum.
Jan/1
Feb/20
Apr/11
Jun/1
date

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**

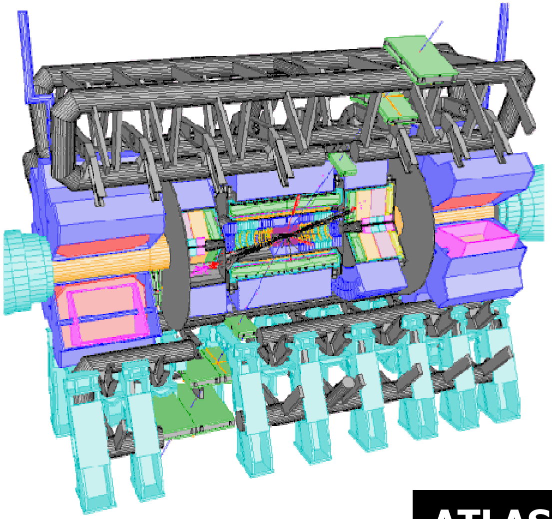


Proposed DØ Run 2B silicon detector

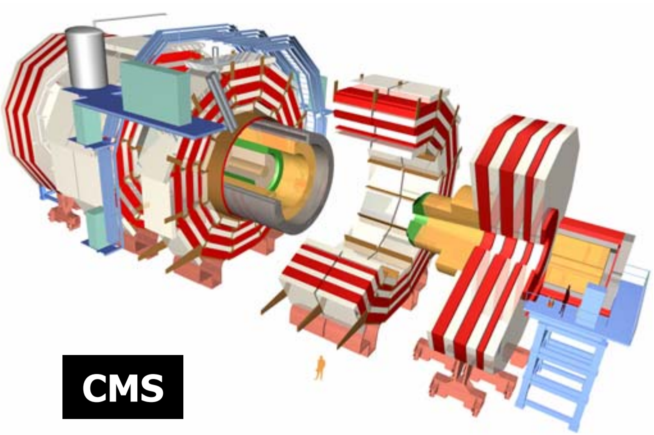


Run 2B silicon installed

The Large Hadron Collider

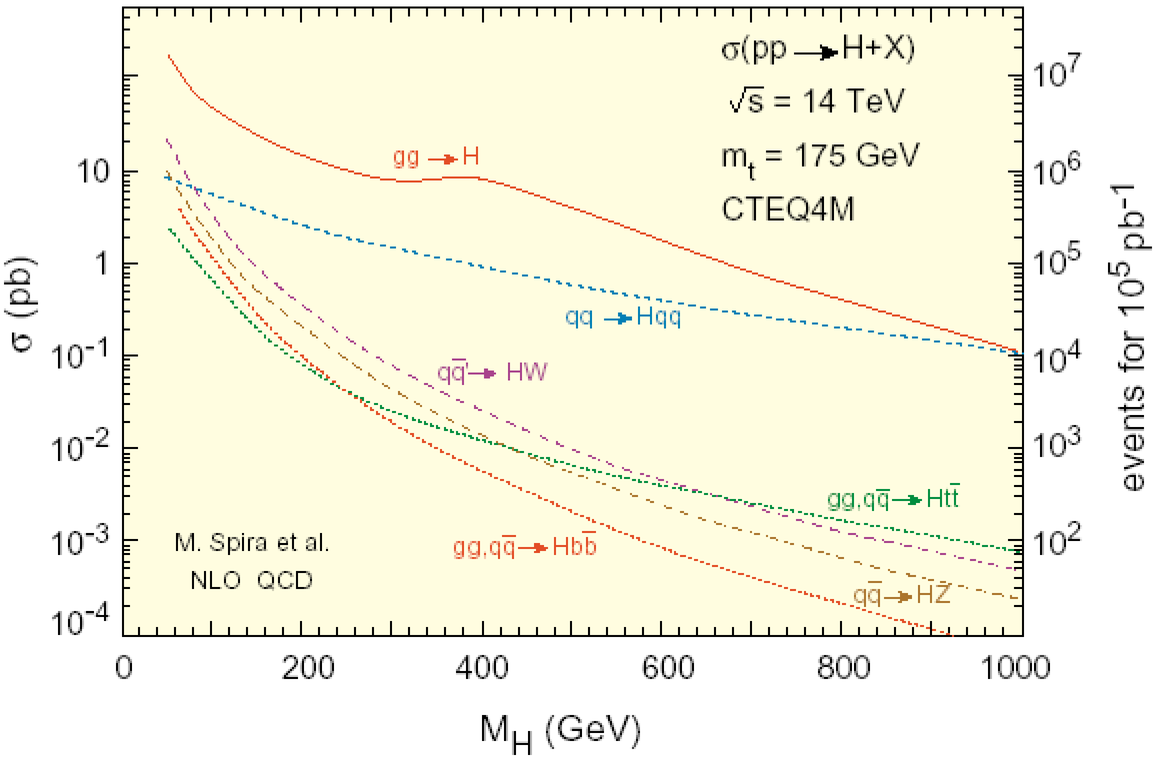


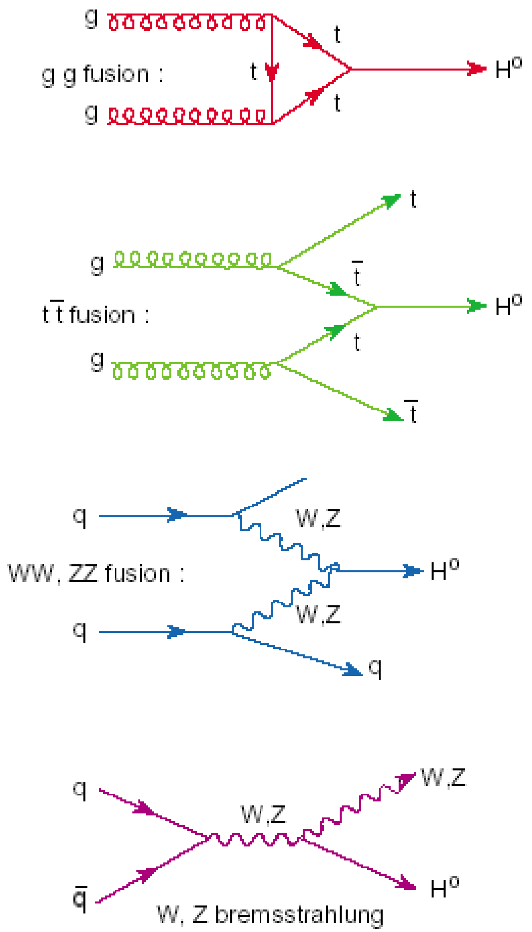
ATLAS



CMS

Higgs at LHC

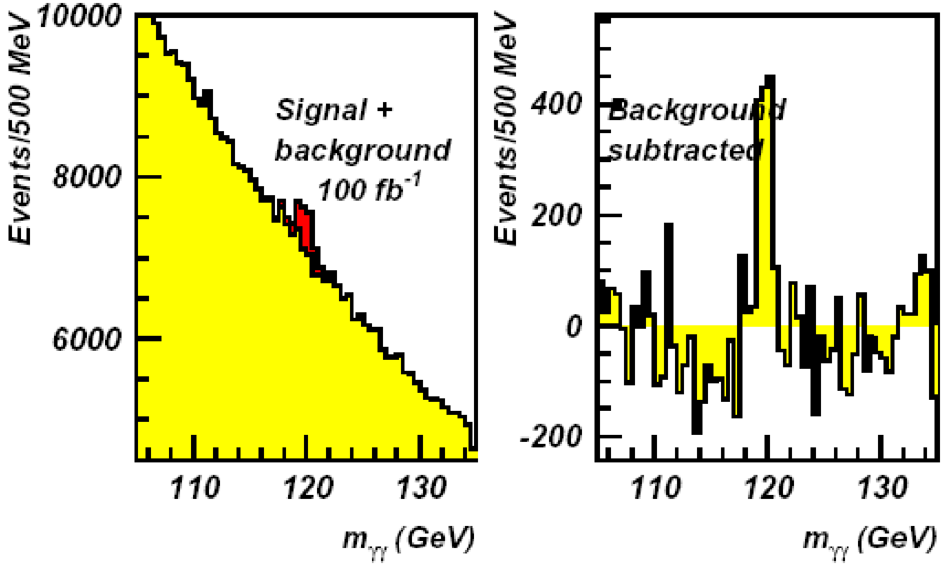




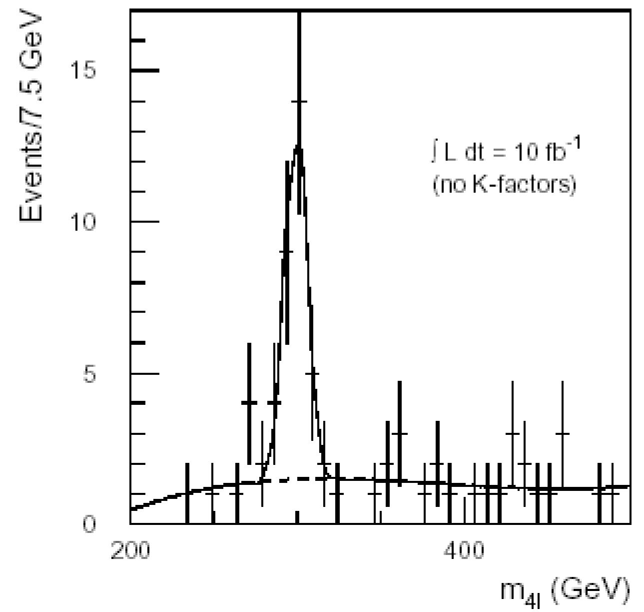
- **Production cross section and luminosity both ~ 10 times higher at LHC than at Tevatron**
  - **Can use rarer decay modes of Higgs**

"Precision Channels"

$H \to \gamma\gamma$
for m_H = 120 GeV, 100fb^{-1}, CMS



$H \to ZZ^{(*)} \to 4l$
for m_H = 300 GeV, 10fb^{-1}, ATLAS

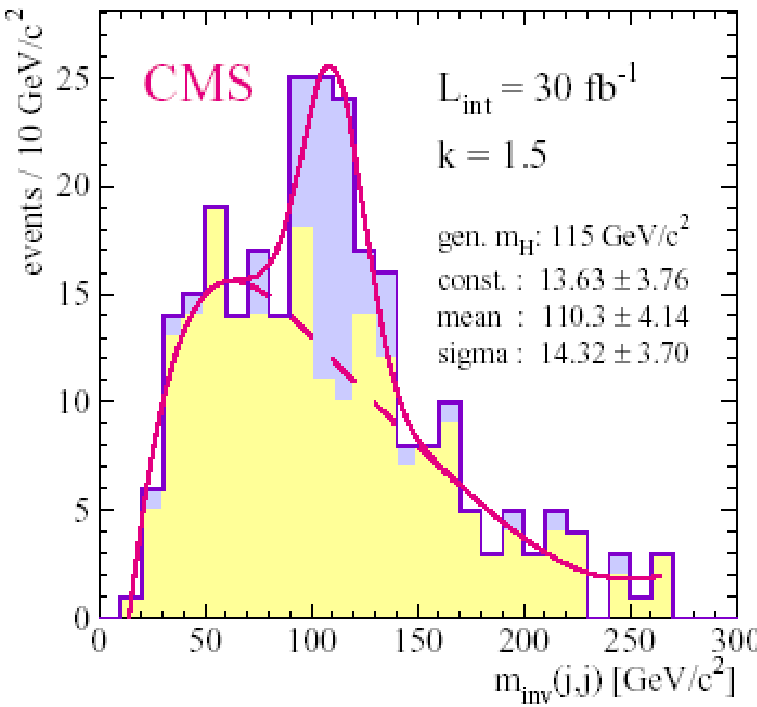


- **Both LHC detectors have invested heavily in precision EM calorimetry and muon systems in order to exploit these channels**

Associated production $t\bar{t}H$ at LHC

$$t\bar{t}H^0_{SM} \to l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$$

$$m_{H^0} = 115\ GeV/c^2$$



◇ $90 < m < 130\ GeV/c^2$:

N_{H115}	=	38
$N_{t\bar{t}Z^0}$	=	3
$N_{t\bar{t}b\bar{b}}$	=	23
$N_{t\bar{t}jj}$	=	26
N_{BG}	=	52

⇒ results (stat.):

$S/B = 73\%$

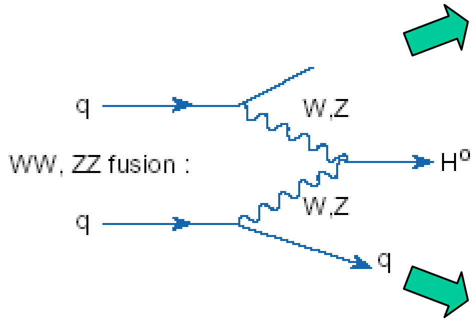
$S/\sqrt{B} = 5.3$

$\Delta y_t/y_t = 13\%$

$\Delta m/m = 3.8\%$

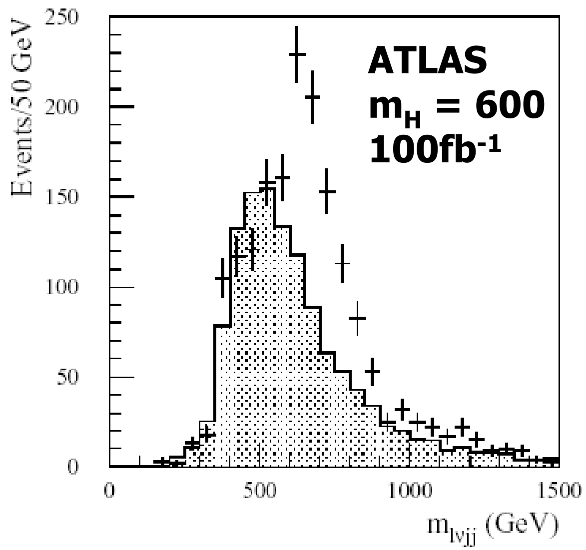
Vector boson fusion channels

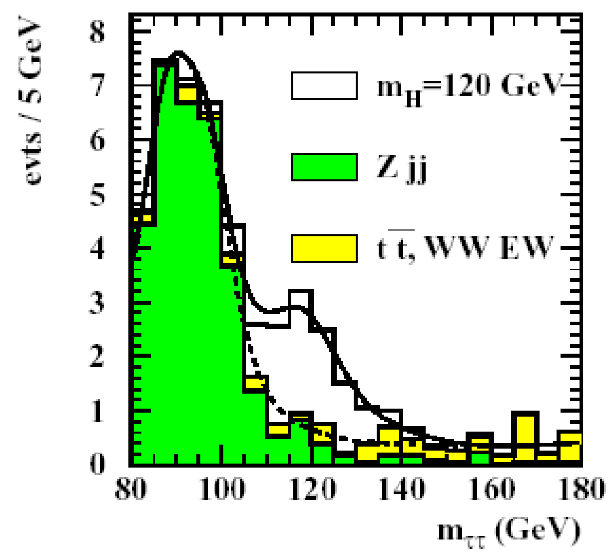
- Use two forward jets to "tag" the VB fusion process
  - Improves the S/B for large Higgs masses



Two jets with E ~ 300 GeV and $2 < |\eta| < 4$

- Example: $H \rightarrow WW \rightarrow l\nu jj$

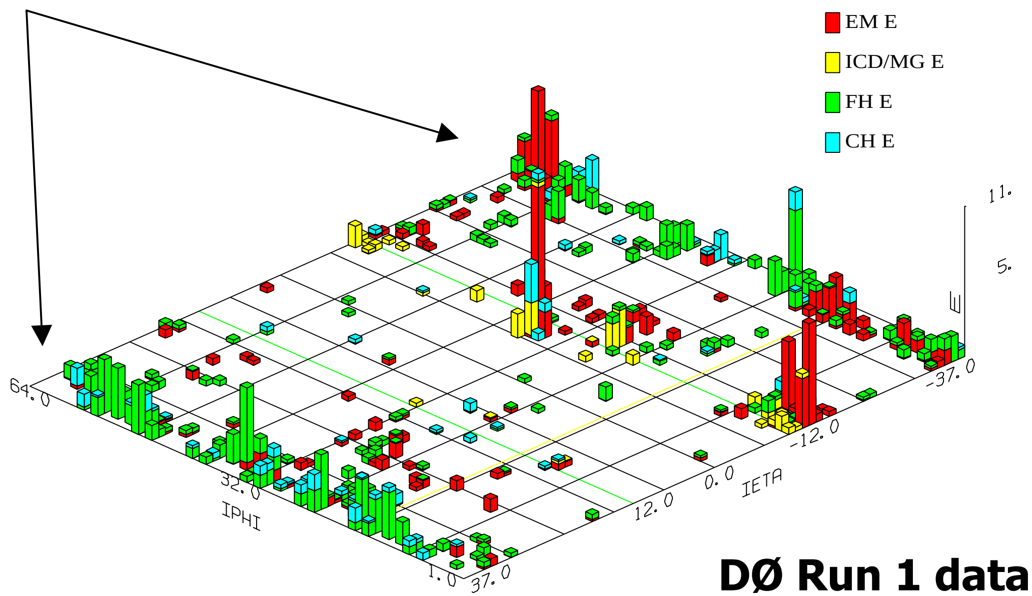




Also useful for lower Higgs masses (~10% of total cross section)

$H \rightarrow \tau\tau$
m_H = 120 GeV
ATLAS

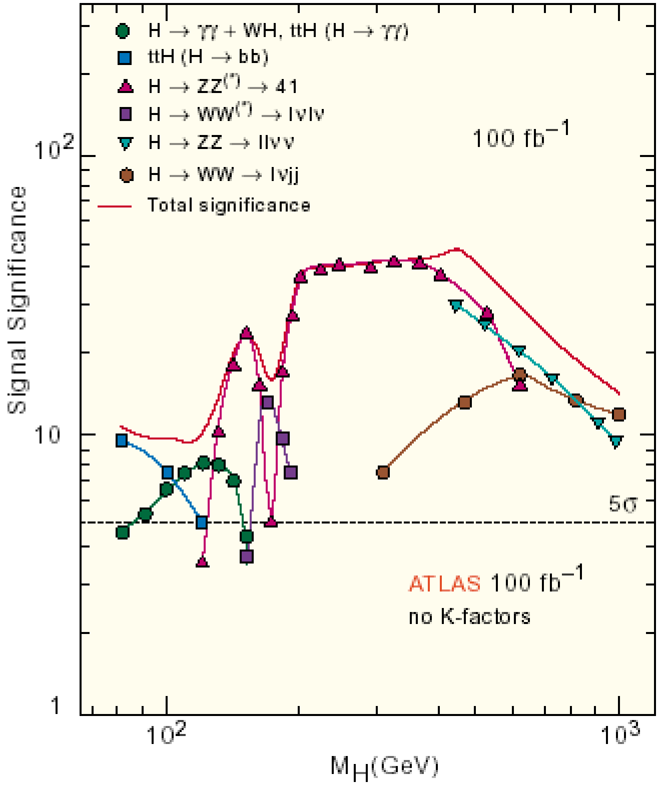
- **Tagging jets work well in GEANT simulation**
  - **But life at $\eta = \pm 4$ is always going to be hard**



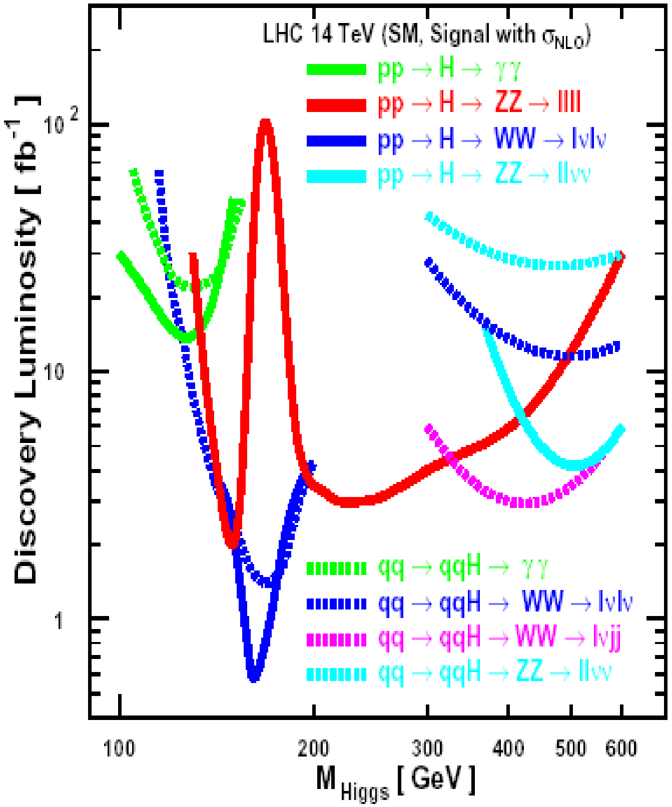
DØ Run 1 data

LHC Discovery Potential

- **Significance for 100 fb^{-1}**



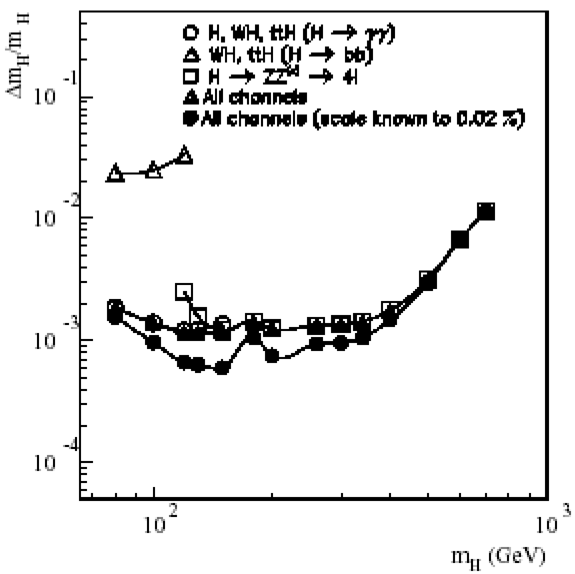
- **Luminosity required for 5σ**



The whole range of SM Higgs masses is covered

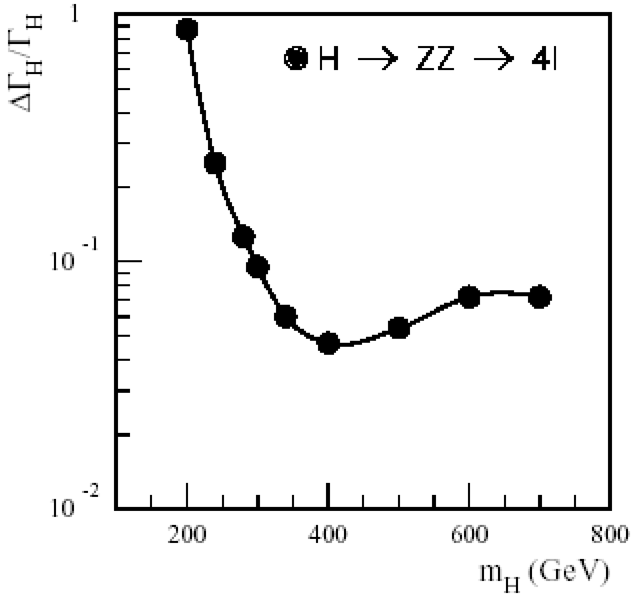
SM Higgs parameter determination at LHC

Mass



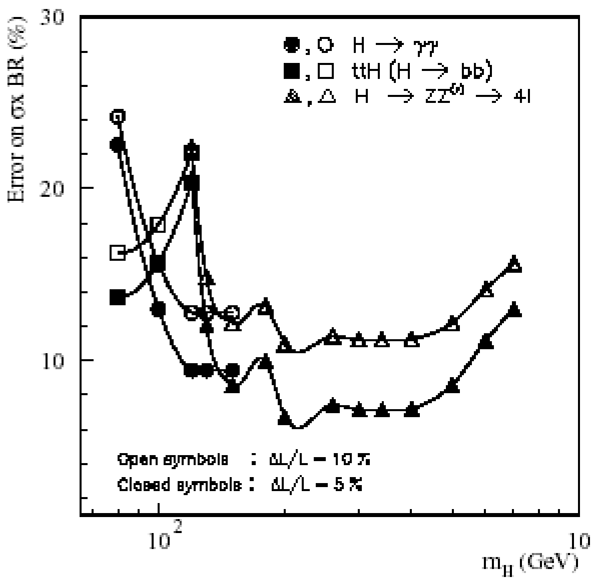
0.1% to 1% accuracy in measurement of m_H

Width



5 to 10% measurement of the width for m_H > 300 GeV

σ·B



σ·B measured to the level of the luminosity uncertainty (~5%?)

ATLAS TDR

Higgs coupling measurements

Can we verify that the Higgs actually provides a) vector bosons and b) fermions With their masses?

- **Can measure various ratios of Higgs couplings and branching fractions by comparing rates in different processes**
- **CMS estimates of uncertainties with 300 fb^{-1}**

Luminosity uncertainties largely cancel in ratios

Errors are dominated by statistics of the rarer process

$$\frac{\sigma \cdot B\,(WH \to \gamma\gamma)}{\sigma \cdot B\,(WH \to b\bar{b})} \Rightarrow \frac{BR\,(H \to \gamma\gamma)}{BR\,(H \to b\bar{b})}$$

known to ~ 30% stat. limited

only for: $80 \lesssim m_H \lesssim 120$ GeV

$$\frac{\sigma \cdot B\,(H \to \gamma\gamma)}{\sigma \cdot B\,(H \to ZZ^*)} \Rightarrow \frac{BR\,(H \to \gamma\gamma)}{BR\,(H \to ZZ^*)}$$

known to ~ 15% stat. limited

only for: $125 \lesssim m_H \lesssim 155$ GeV

$$\frac{\sigma \cdot B\,(t\bar{t}H \to \gamma\gamma/b\bar{b})}{\sigma \cdot B\,(WH \to \gamma\gamma/b\bar{b})} \Rightarrow \frac{g^2_{H\,tt}}{g^2_{H\,WW}}$$

known to ~ 25% stat. limited

only for: $80 \lesssim m_H \lesssim 130$ GeV

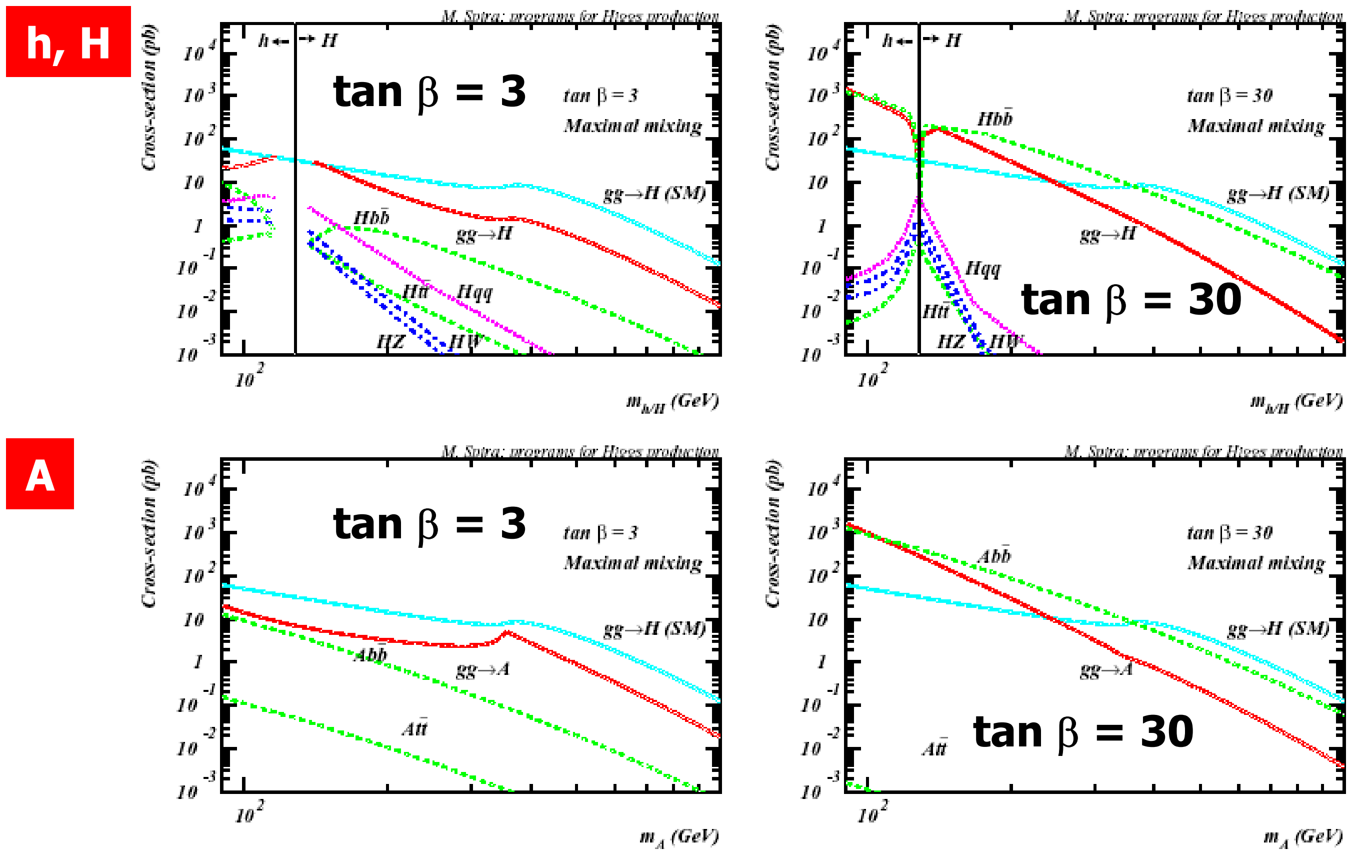
$$\frac{\sigma \cdot B\,(H \to WW^*/W)}{\sigma \cdot B\,(H \to ZZ^*/Z)} \Rightarrow \frac{g^2_{H\,WW}}{g^2_{H\,ZZ}}$$

known to ~ 30% stat. (ZZ*) limited

only for: $160 \lesssim m_H \lesssim 180$ GeV

$qq \to qqH$ process very important here

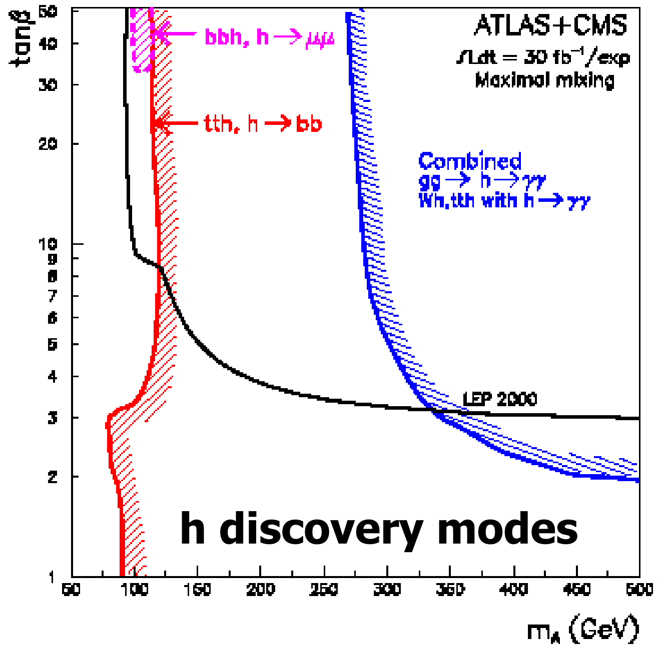
SUSY Higgs production at the LHC



- Cross sections at the 10 pb level and ↑ as tan β ↑
- (H/A) $\bar{b}b$ enhanced as tan β ↑ but VB fusion suppressed

SUSY Higgs discovery channels

- The best SM channel ($H \to ZZ^{(*)} \to 4l$) is suppressed
- Good bets:
  - $h \to \gamma\gamma$
  - $h \to \bar{b}b$
  - $H/A \to \tau\tau$
  - $H^{\pm} \to \tau\nu$
- In certain regions of parameter space:
  - $H/A \to \mu\mu$
  - $H \to hh$
  - $A \to Zh$
  - $H^{\pm} \to tb$
- SUSY masses permitting
  - $H/A \to$ neutralino pairs
  - h production in SUSY cascades $\chi^0_2 \to \chi^0_1 h$

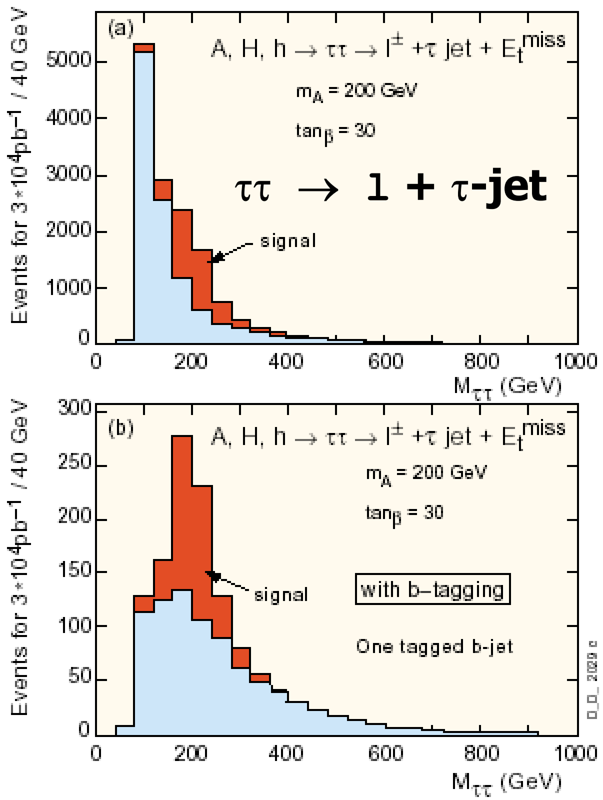


John Womersley

Importance of tau modes

- **A/H → ττ**

  $p_T^{jet} > 40$ GeV, $p_T^{\ell} > 15$ GeV,
  $\Delta\phi(j\ell) < 175°$, $E_T^{miss} > 20$ GeV



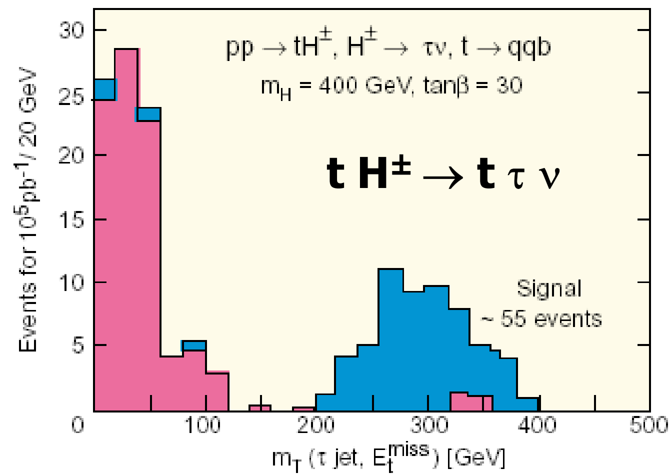
b-tagging associated jets is a powerful way to enhance the signal

- **H± → τν**

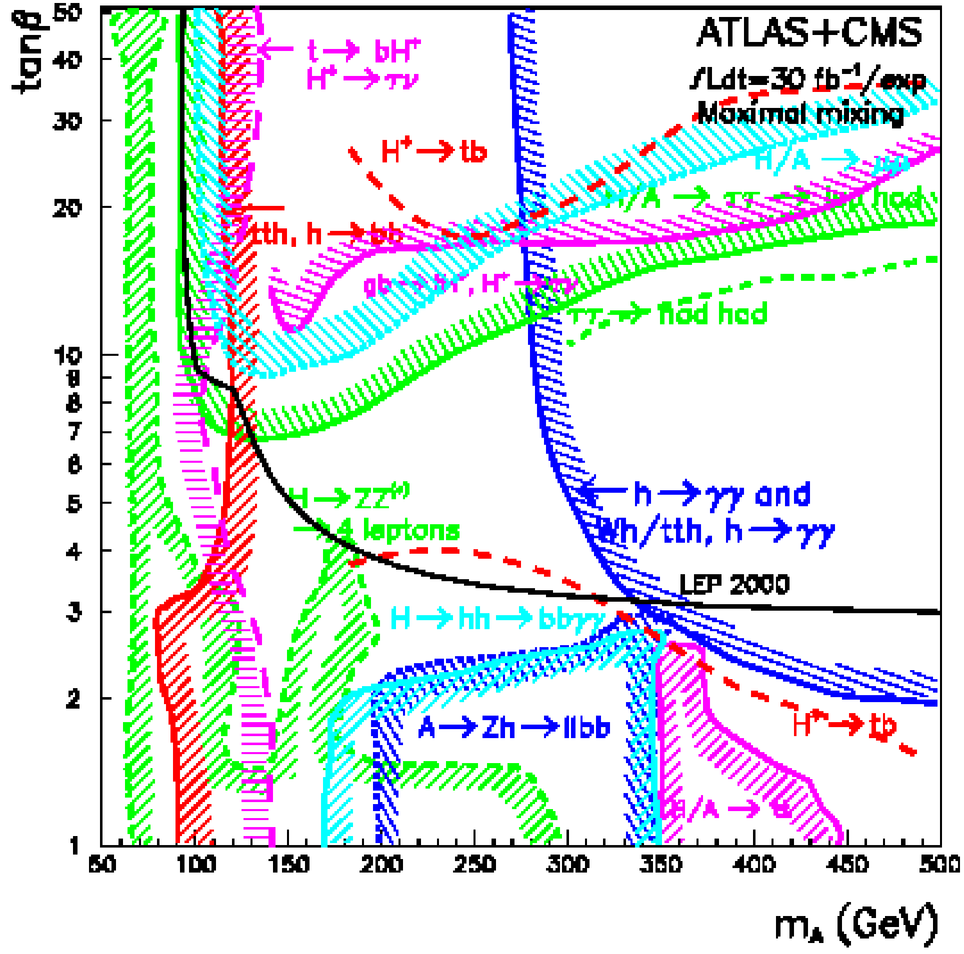
  For lower masses, search in top decays (t → τ rate enhanced)

  For higher masses, associated production pp → tH±→ tτν

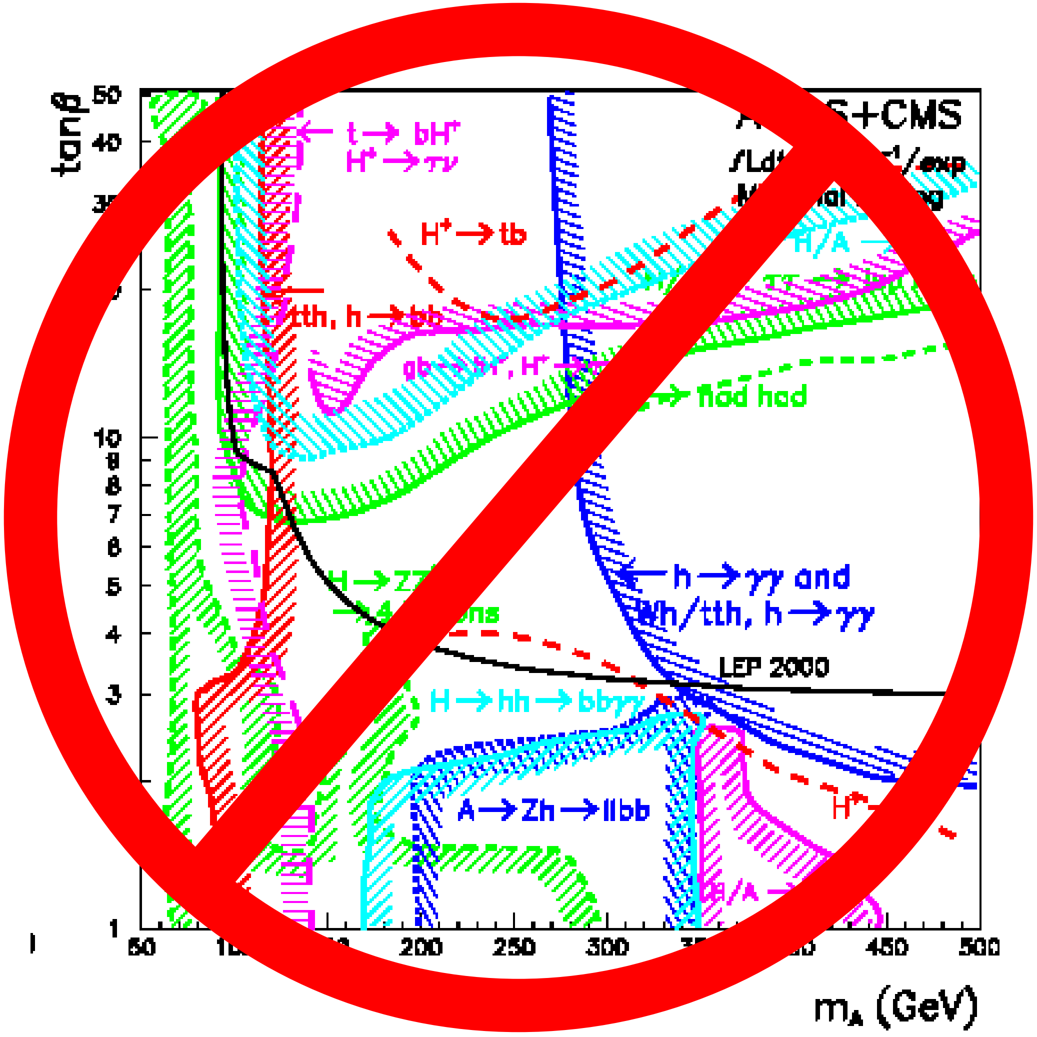
  - **Signal is a peak in transverse mass of τ jet and E_T^{miss}**
  - **tt background suppressed by jet veto and cut on mass of τ, E_t^{miss} and jet (= m_t for t → bW± → bτν)**



Combined Coverage



Combined Coverage



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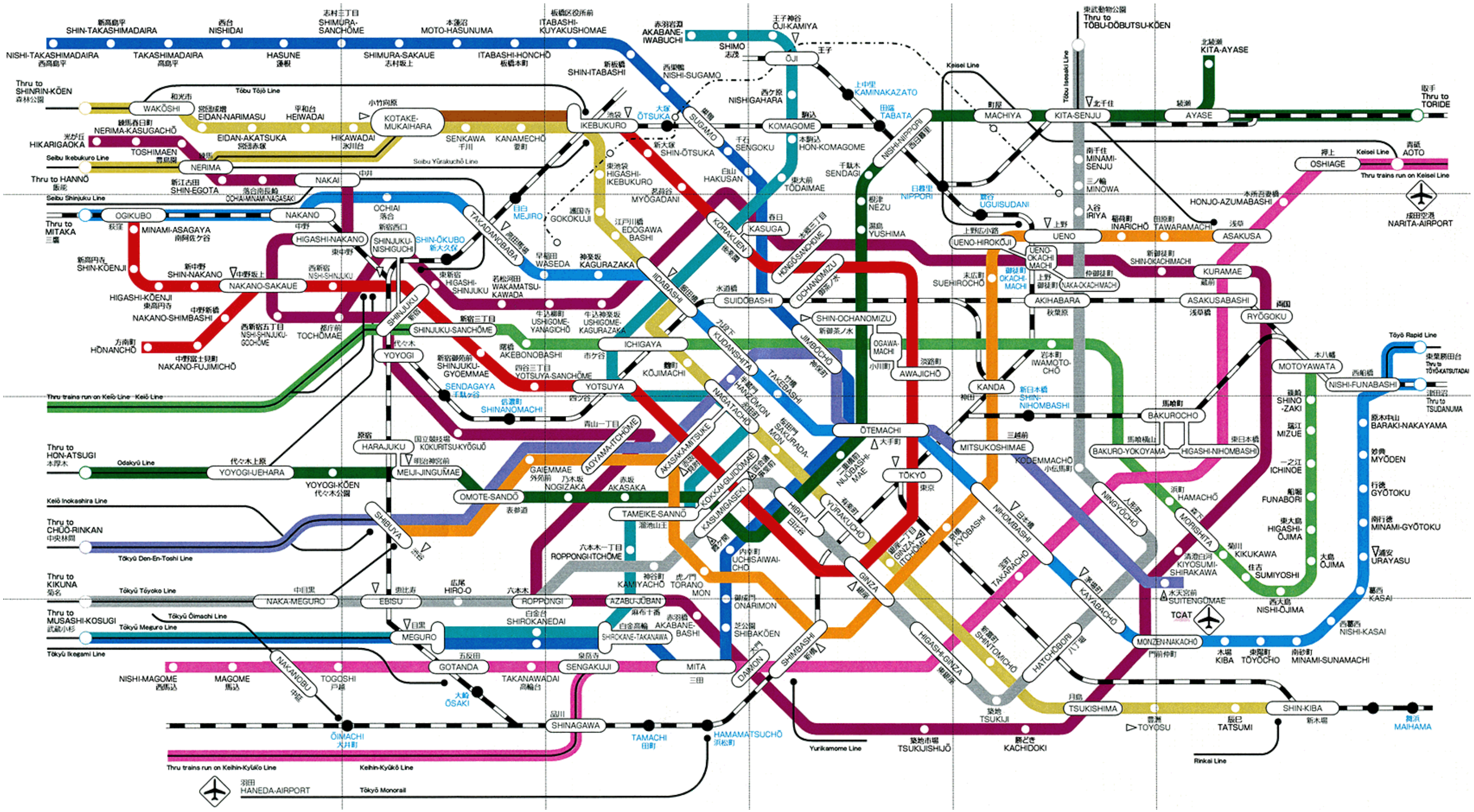
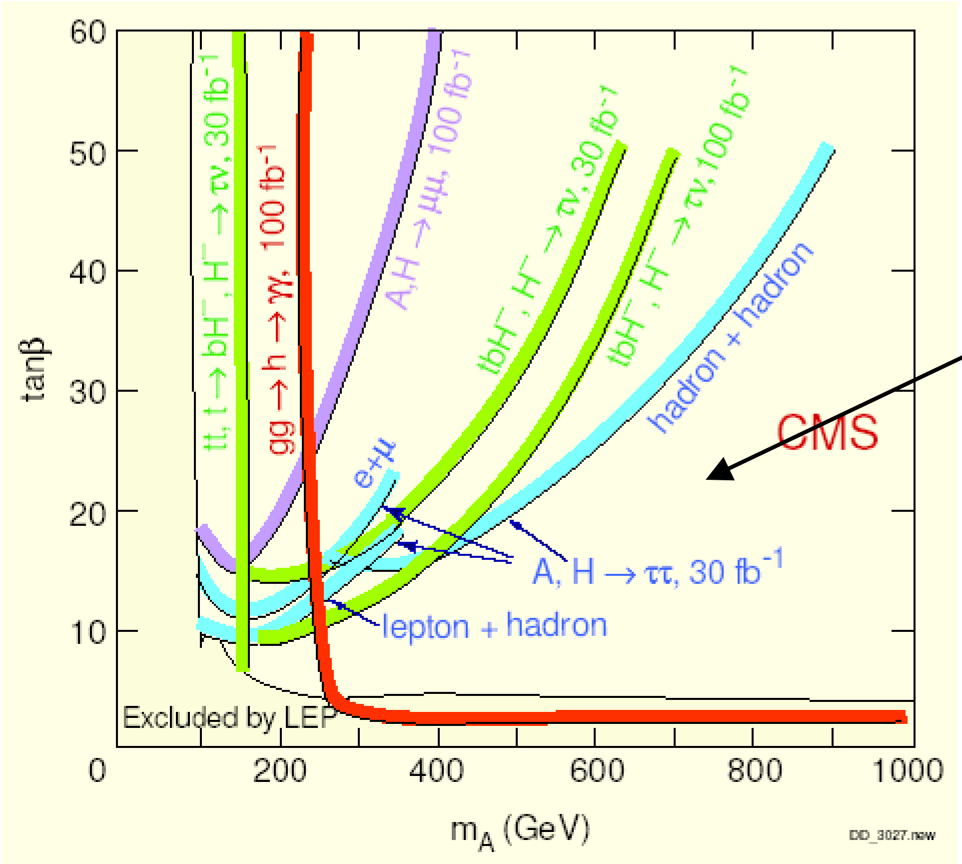
Combined Coverage

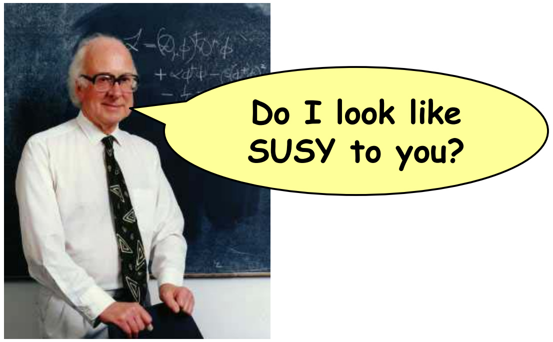


Combined Coverage

Discovery Regions



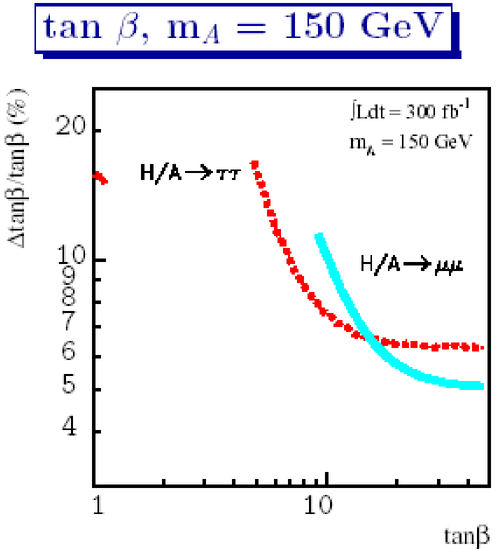
Problematic region:
Only h visible, looks like SM Higgs
Need to observe SUSY particles

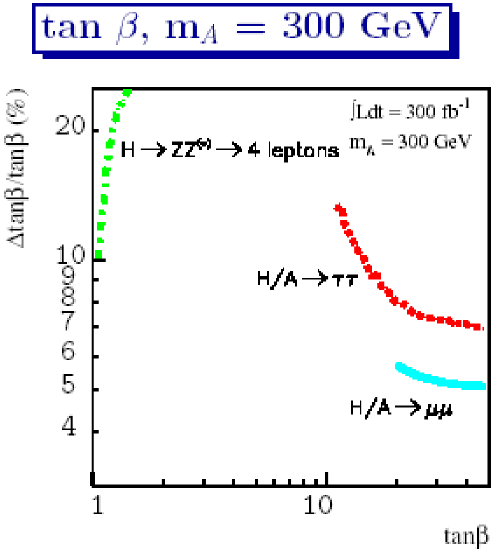


Note that 95% exclusion is more forgiving:
m_A = 450, tan β=10 can be ruled out by A $\to \tau\tau$

Determination of parameters

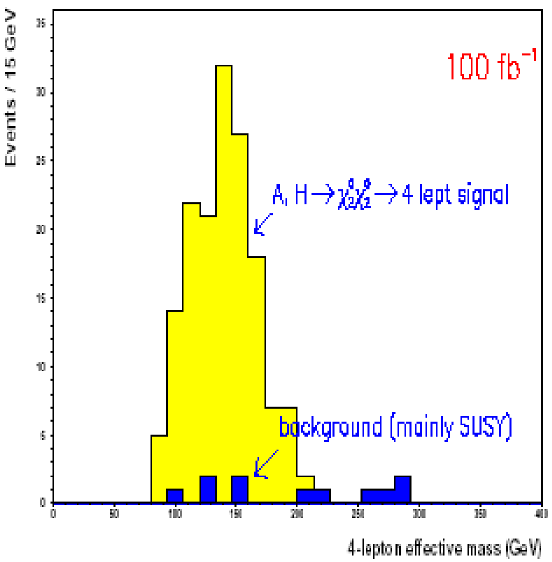
- **First question: do we have a SM H or a SUSY h?**
  - **Note: often this will be moot at the LHC because squarks and gluons will have been observed before any Higgs – but there is always the possibility of more complicated Higgs sectors**
- **Second question: where are we in SUSY parameter space (or 2HDM space?)**
  - **Use masses, widths and branching ratios**
  - **If more than one Higgs is observed, more straightforward**
  - **Example of tan β determination from ATLAS TDR:**

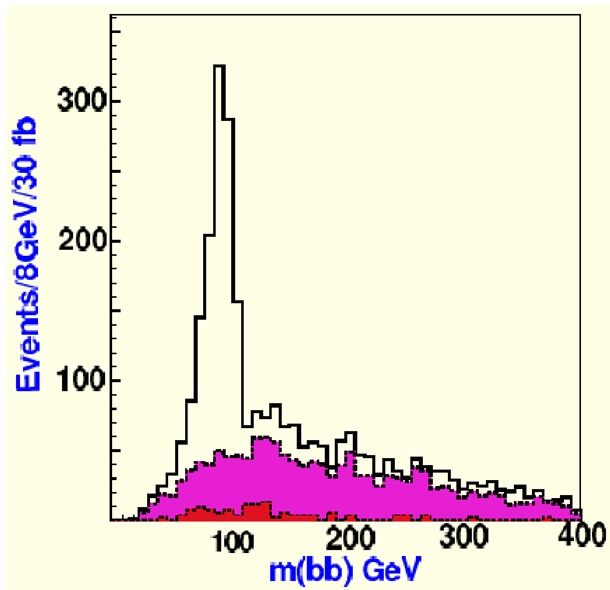


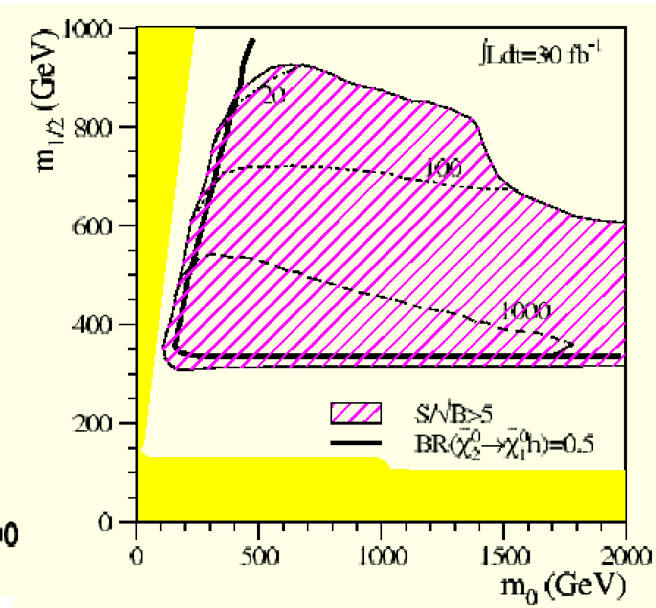


Additional SUSY decay modes

- **If we are lucky, beautiful signals may be observable**
  - **Higgs → sparticles or sparticles → Higgs**







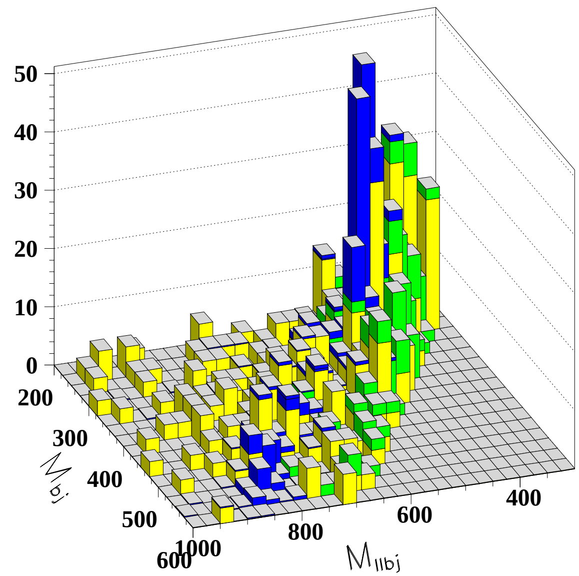
(H/A) → $\chi^0_2\chi^0_2$ → 4l

H → $\bar{b}b$ in cascade decays of squarks and gluinos → **Region of observability**

John Womersley

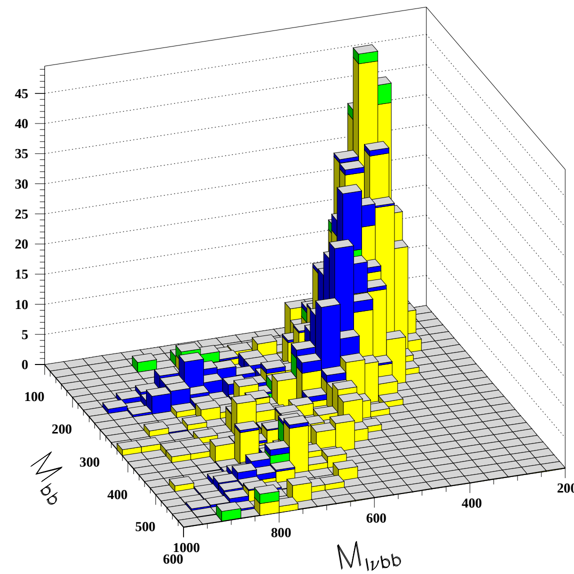
Technicolor

$\rho_T \to \pi_T Z \to \mathbf{bq}\ l^+l^-$



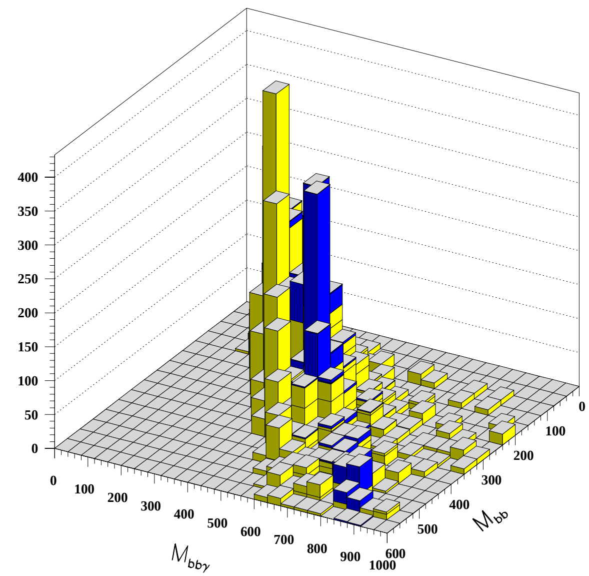
Yellow = Z+jets
Green = $t\bar{t}$
Blue = technicolor signal
(m_ρ, m_π) = (500, 300) GeV
(m_ρ, m_π) = (800, 500) GeV

$\rho_T \to \pi_T W \to \mathbf{bq}\ l\nu$



Yellow = Z+jets
Green = $t\bar{t}$
Blue = technicolor signal
(m_ρ, m_π) = (500, 300) GeV
(m_ρ, m_π) = (800, 250) GeV
(m_ρ, m_π) = (800, 500) GeV

$\omega_T \to \pi_T \gamma \to \gamma\ \mathbf{b\bar{b}}$

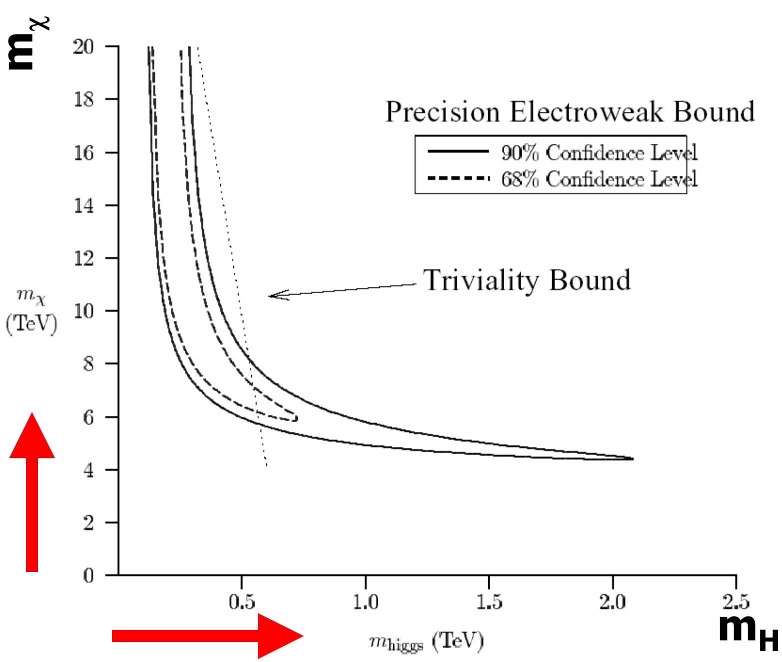


Yellow = γ+jets
Blue = technicolor signal
(m_ω, m_π) = (500, 300) GeV
(m_ω, m_π) = (800, 500) GeV

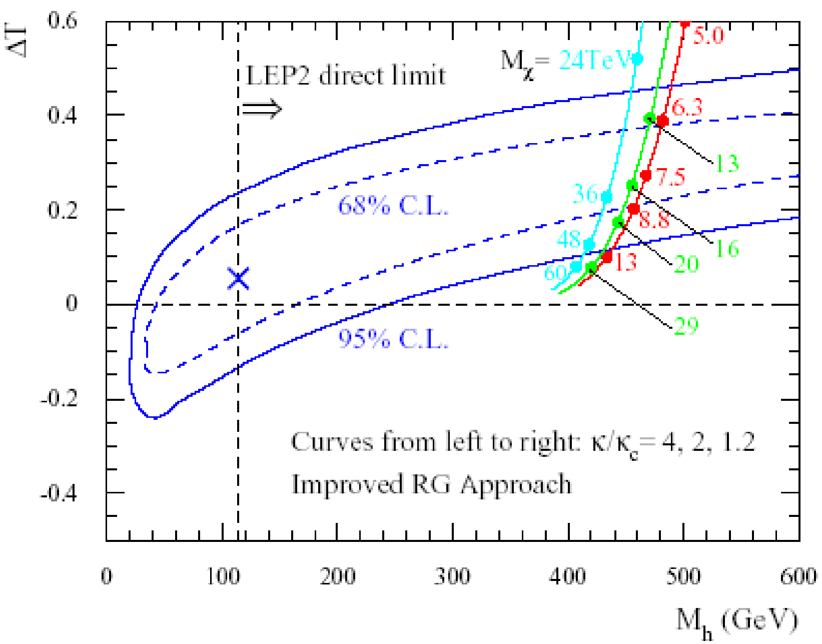
Topcolor

- Composite Higgs (top plus new isosinglet quark χ)
  - Can be significantly more massive than in SM as long as other new physics exists (ΔT)
    - topgluons, Z'

LHC probably won't see the χ (> 6 TeV)



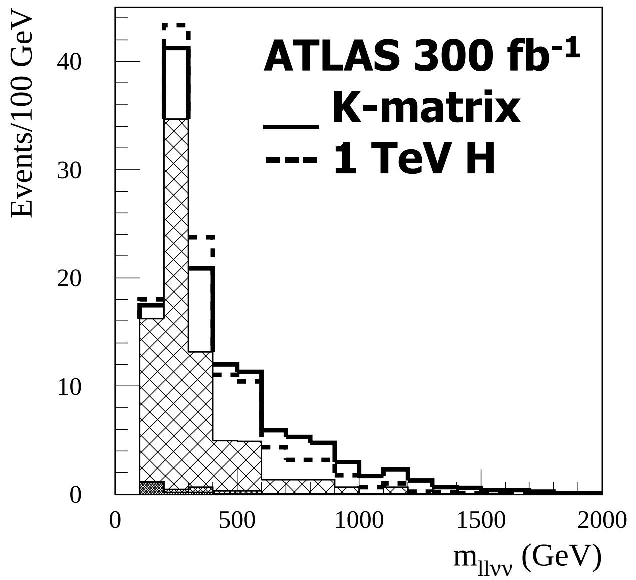
LHC will see the Higgs (400 - 500 GeV)



Chivukula, He, Hoelbling

Strong WW scattering

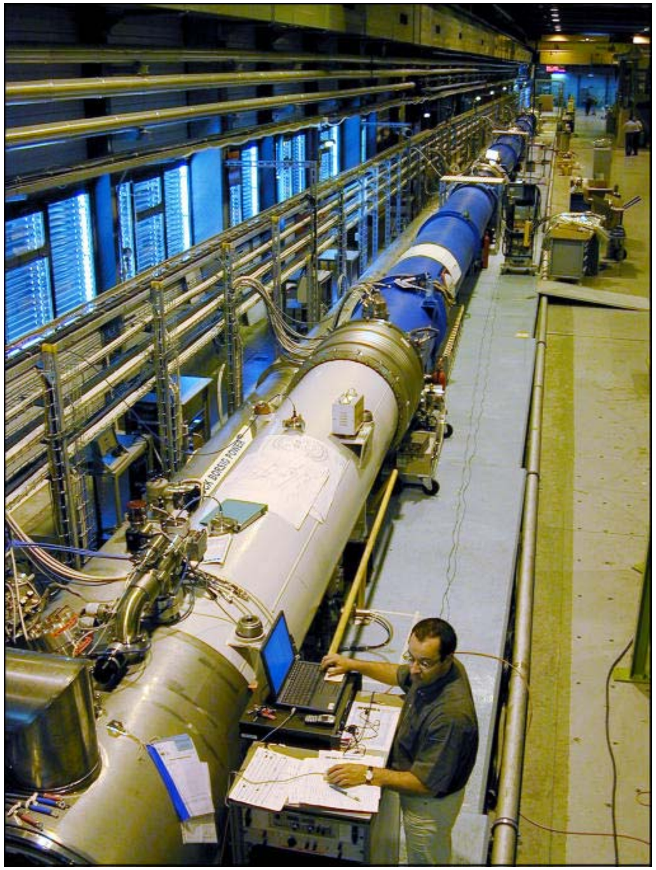
- **Strong WW scattering**
  - **Will be possible to establish a signal as an excess of W^+W^+ events, but measurements will be hard**



What will we know and when will we know it?

- **By 201x at the LHC, if all goes well**
  - **We will observe at least one and maybe several Higgses**
    - **Test their properties at the 20% level**
    - **Not always able to differentiate SM from MSSM Higgs**
      - But almost always expect to discover SUSY directly in other ways
  - **Or we will observe some other signal of EWSB**
    - **Technicolor**
    - **Strong WW scattering**
  - **And we will know a lot more about physics at the TeV scale**
    - **SUSY?**
    - **Extra dimensions?**

LHC construction

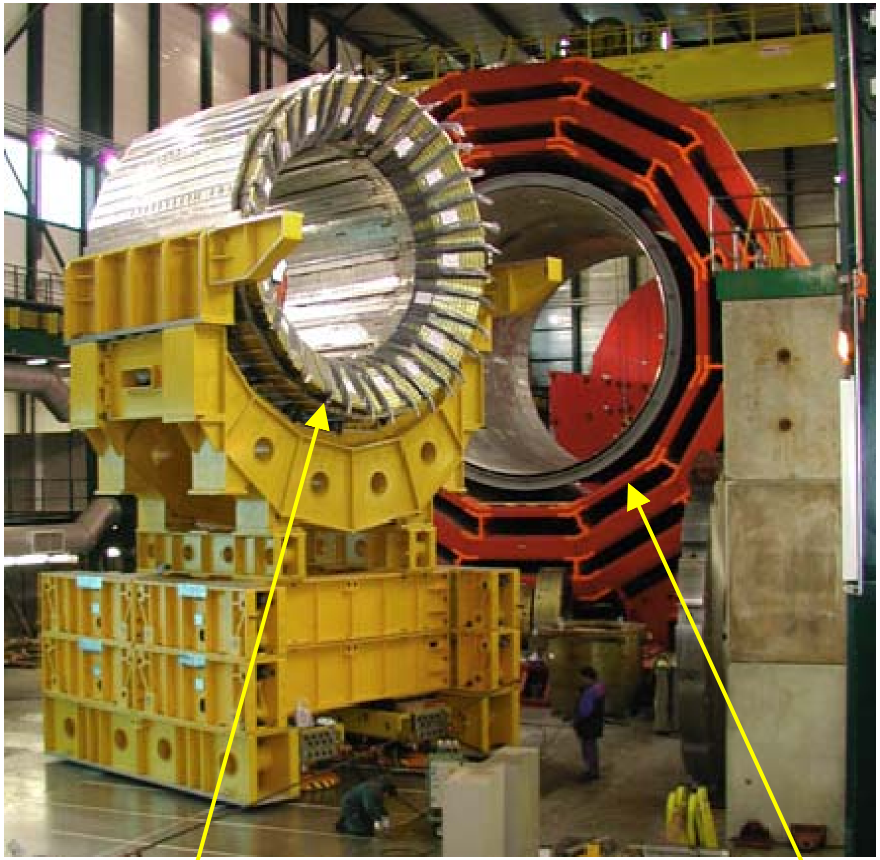


Underground construction at the ATLAS cavern

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

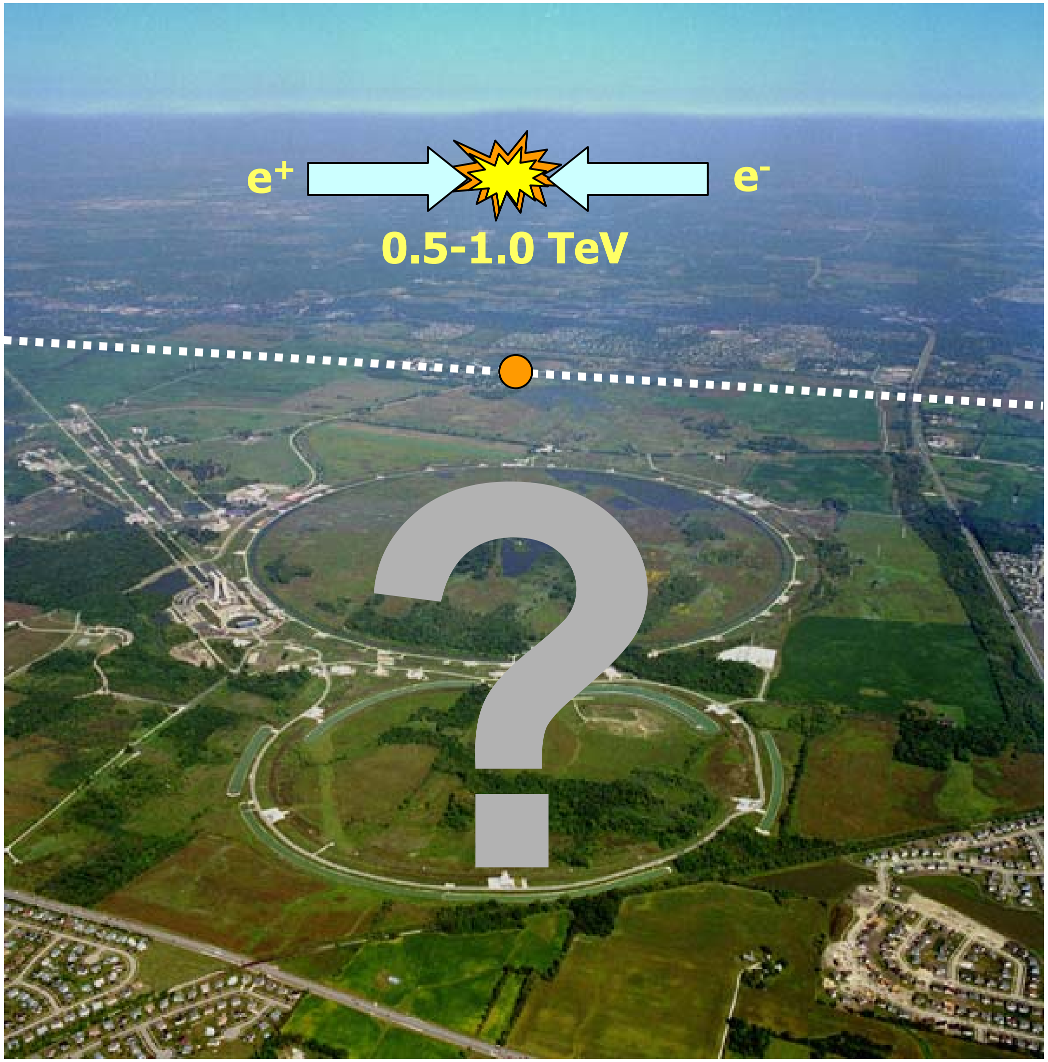
LHC detector construction

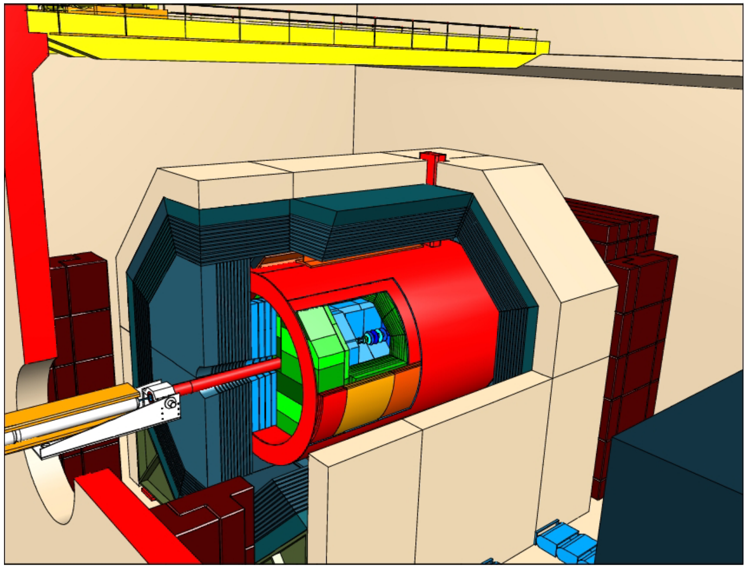


LHC cost problems

- 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

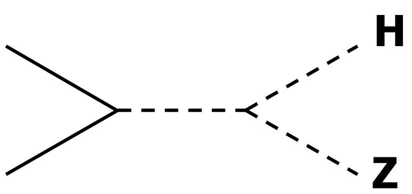


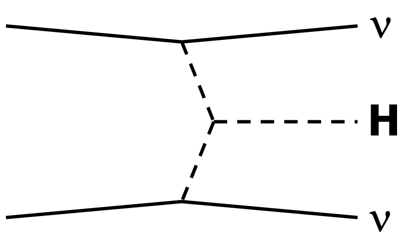


Higgs at a Linear Collider

- **No longer about discovery; about precision**
  - **Plays the role that LEP did to the SPS for W/Z**
  - **Psychology very different!**
- **Exploit**
  - **Aggressive detector technology (charm tagging, calorimetry)**
  - **Polarization**
- **Higgs production at a LC:**

Jim Brau at Snowmass:
"Just finding the Higgs is of limited value"





For $\sqrt{s}$ = 500 GeV (few×100fb^{-1} per year)

m_H = 120 GeV, σ ~ 80fb
m_H = 240 GeV, σ ~ 40fb
(cf. total $e^+e^- \rightarrow q\bar{q}$ cross section few pb)

HZ process allows H reconstruction in a model independent way (from Z)

For an 800 GeV machine, HZ is suppressed, $H\nu\nu$ dominant

Higgs couplings to W and Z

- **Use Z → l^+l^- together with known √s to reconstruct mass of Higgs (= whatever the Z recoils against)**
  - **Flavor blind, includes invisible decays (e.g. neutralinos)**

    → σ(HZ) (few %/500fb^{-1})
    → HZZ coupling determined to few %

Provides simple test of whether this is the only Higgs: does it account for all of the mass of the Z?

e.g. in the MSSM $g_{hZZ} = g_Z M_Z \sin(\beta-\alpha)$

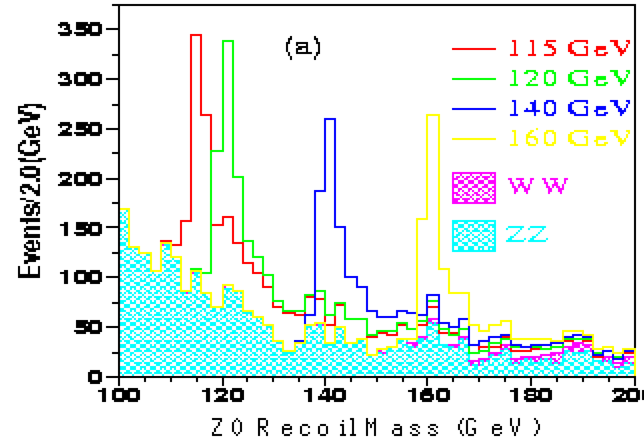
$$g_{HZZ} = g_Z M_Z \cos(\beta-\alpha)$$

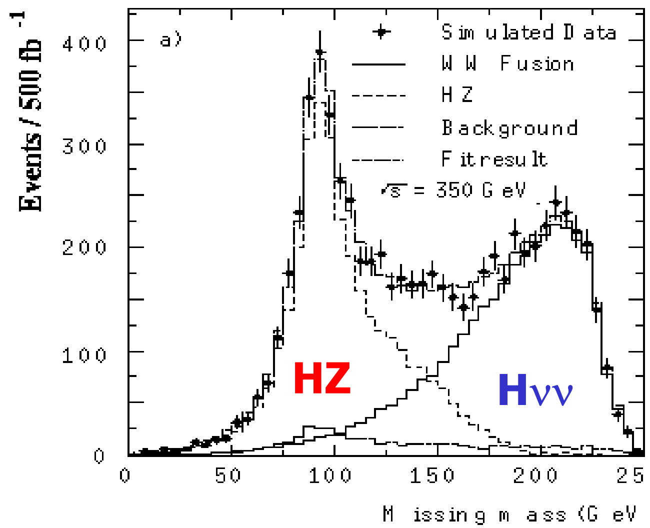
- **Use Hνν process with H→ $\bar{b}b$ and reconstruct missing mass**

    → σ(Hνν) (few %/500fb^{-1})
    → HWW coupling determined to few %

Also get total width to a few % from σ(Hνν) and BR(H→WW)

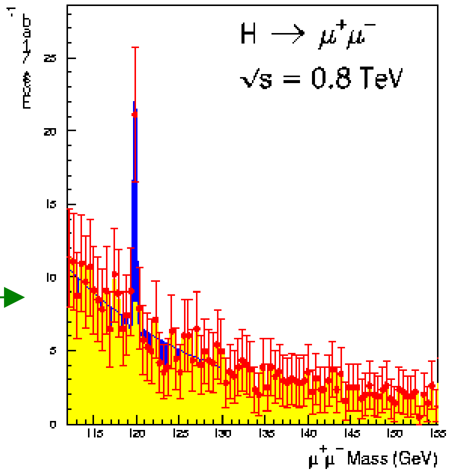
√s = 350 GeV





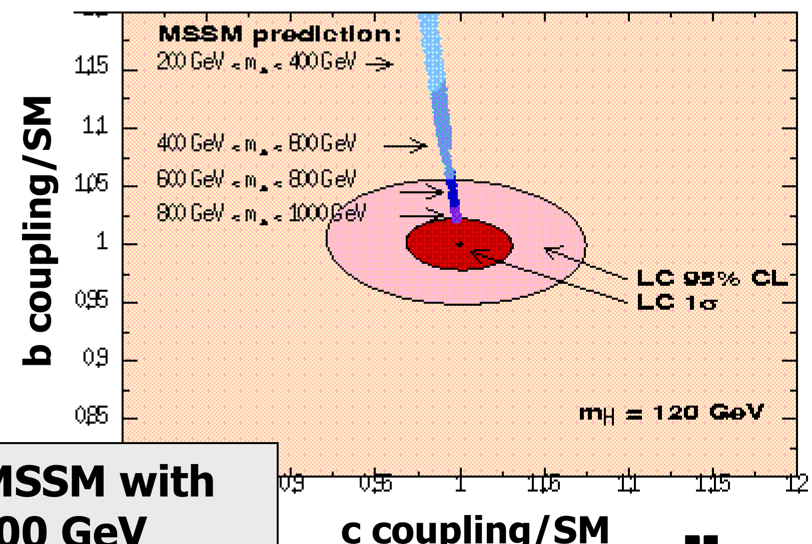
Higgs couplings to fermions

- **Requires b, c, tagging based on vertex**
- **Requires tau-ID based on hadronic jet multiplicity and kinematics**
- **H → μμ**
  - **BR ~ 10^{-4} but clean**
- **H → tt**
  - **indirectly (through H → gg)**
  - **through ttH if √s sufficient**



- **Bottom line for Δ(g^2) Snowmass**

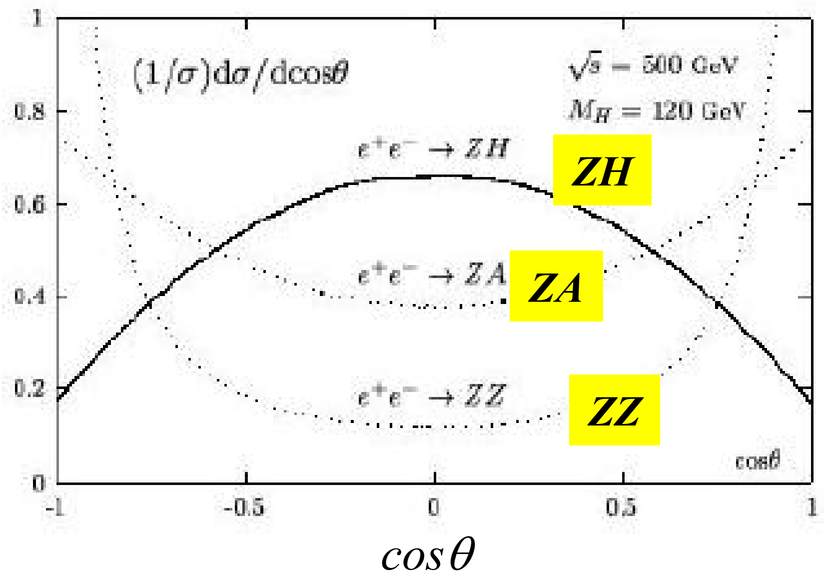
  m_H = 120 GeV, 500 fb^{-1} @ 500 GeV
  - **hbb ~ 4 %**
  - **htt ~ 10 % [@ 800GeV]**
    - **→ topcolor?**
  - **hττ ~ 7 %**
  - **hcc ~ 7 %**
  - **hμμ ~ 30 %**



Distinguish MSSM with m_A up to ~ 600 GeV

Quantum numbers of the Higgs

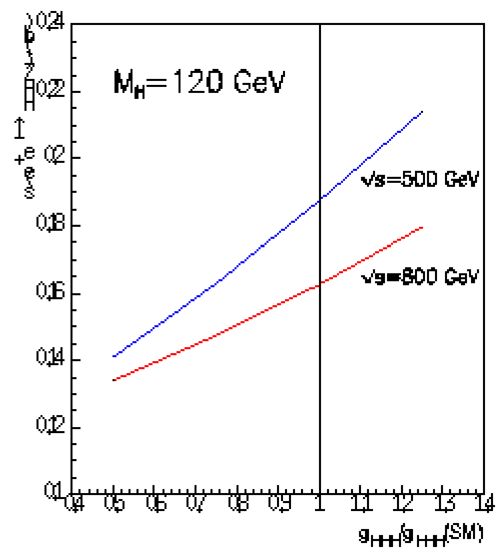
- $H \rightarrow \gamma\gamma$ at LHC already excludes J =1 and requires C even
- Angular dependence of $e^+e^- \rightarrow ZH$ and of the $Z \rightarrow \bar{f}f$ decay products can cleanly separate CP-even H and odd A
  - sensitive to a 3% admixture of CP-odd A in the "H" signal



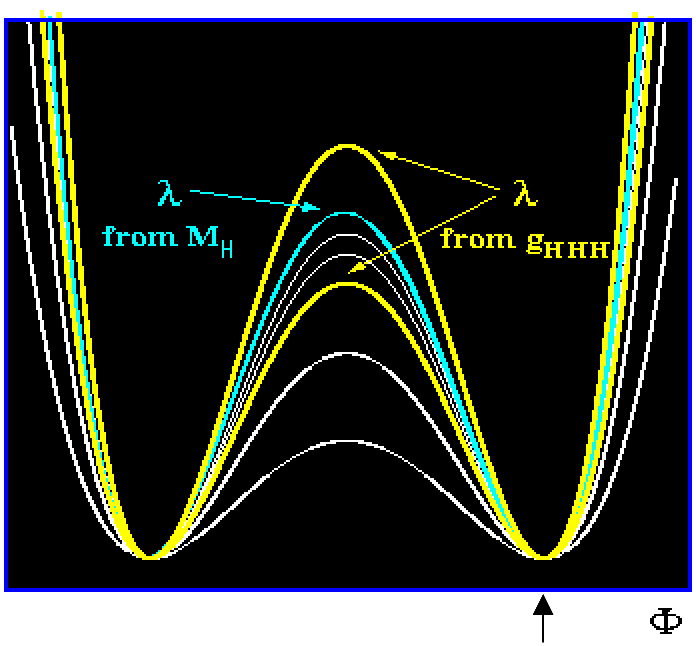
Higgs self-coupling

- **Shape of the Higgs potential can be tested if the HHH coupling is determined**
  - Extract from ZHH production ($\rightarrow$ 6 jets)
  - Cross section $_{\text{tiny}}$ ~ 0.2 fb
    $\Rightarrow$ requires O(1 ab^{-1})
  - g_{HHH} at the 20 - 30% level

$$e^+e^- \rightarrow HHZ$$

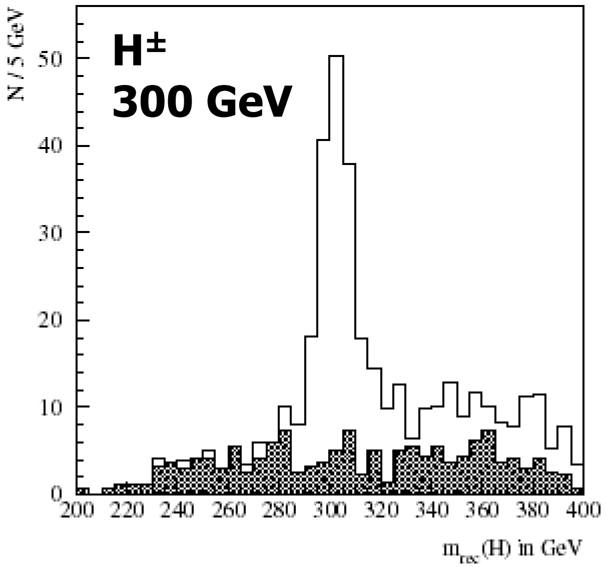


g/g(SM)



MSSM

- **How can the LC help in the moderate tan β "problem region" for the LHC?**
  - **Charged $H^{\pm}$ only visible in top decays (m_A < 150 GeV or so)**
  - **H and A not visible at all**
- **At the LC, direct observation**
  - **$e^+e^- \rightarrow H^+H^- \rightarrow$ tb tb**
  - **$e^+e^- \rightarrow HA \rightarrow 4b$**
    - **Both cover ~ all m_A < 350 GeV for $\sqrt{s}$ = 800 GeV**



- **Indirectly**
  - **Distinguish h from H_{SM} up to m_A ~ 600 GeV**

No Higgs

- An LC would be an excellent machine to explore the rich spectrum of technihadrons in low-scale technicolor

- If the LHC sees an excess in WW $\rightarrow$ WW scattering, the LC can measure the form factor of the resonance from $e^+e^- \rightarrow$ WW
  - LC can probe WW masses far beyond its $\sqrt{s}$, measure real and imaginary parts of form factor
  - LC can explore other final states hard to see at LHC
    - WW $\rightarrow$ tt, WW $\rightarrow$ ZZ

- Worst cases are just that — a bad outcome for all
  - The LC potentially makes a bad outcome less bad
  - Provides additional information needed in order to choose the next steps

A three-stage relay race

- Tevatron
  - Discovery if we're lucky
    - Fermilab's role is obvious

- LHC
  - Guaranteed discovery, start to measure
    - Fermilab's role is significant but needs to be consolidated for the physics analysis phase

- Linear Collider
  - Measure, measure, measure
    - What is Fermilab's role?

… leading to a VLHC?

- Phase 1 – complete our study of the TeV scale
  - heavy superpartners, isosinglet quarks, few TeV WW resonances . . .
    - Physics that can be simulated and described
- Phase 2 - Explore the next higher energy scale 10-100 TeV
  - SUSY breaking scale?
  - Deep inelastic WW scattering (see constituents?)
    - This physics is much harder to simulate or describe, but potentially much more interesting and important

In many cases (inverted heirarchy SUSY, topcolor…) there can be new particles at the few TeV scale that are not visible at the LHC

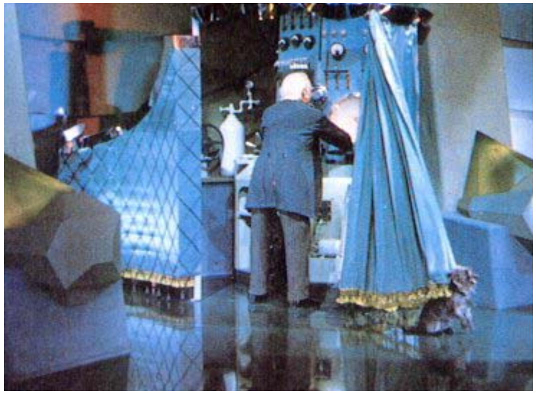
Often the only way to know whether a new collider has high enough energy to see them is from precision measurements of the Higgs, or whatever plays its role; this is the only thing that is guaranteed to be visible ($\sqrt{s}$!)

Without that knowledge, could we go to a funding agency to ask for a VLHC?

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





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