Higgs Searches at the Tevatron and LHC

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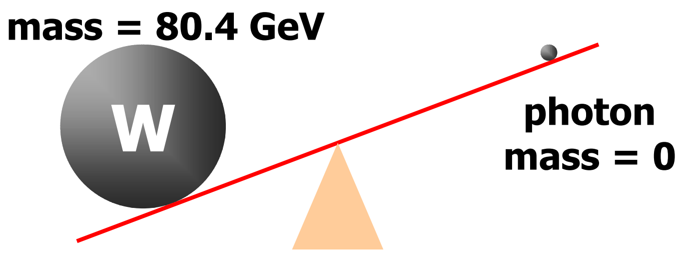
http://d0server1.fnal.gov/projects/presentations/womersley/win02/win02.pdf

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

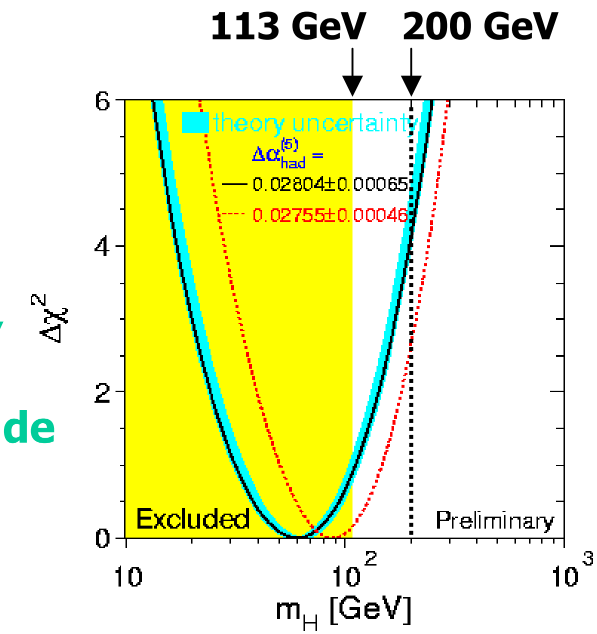


- An appealing picture: is it correct?
  - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field
  - All its properties (production and decay rates, couplings) are fixed except its own mass

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

Searching for the Higgs

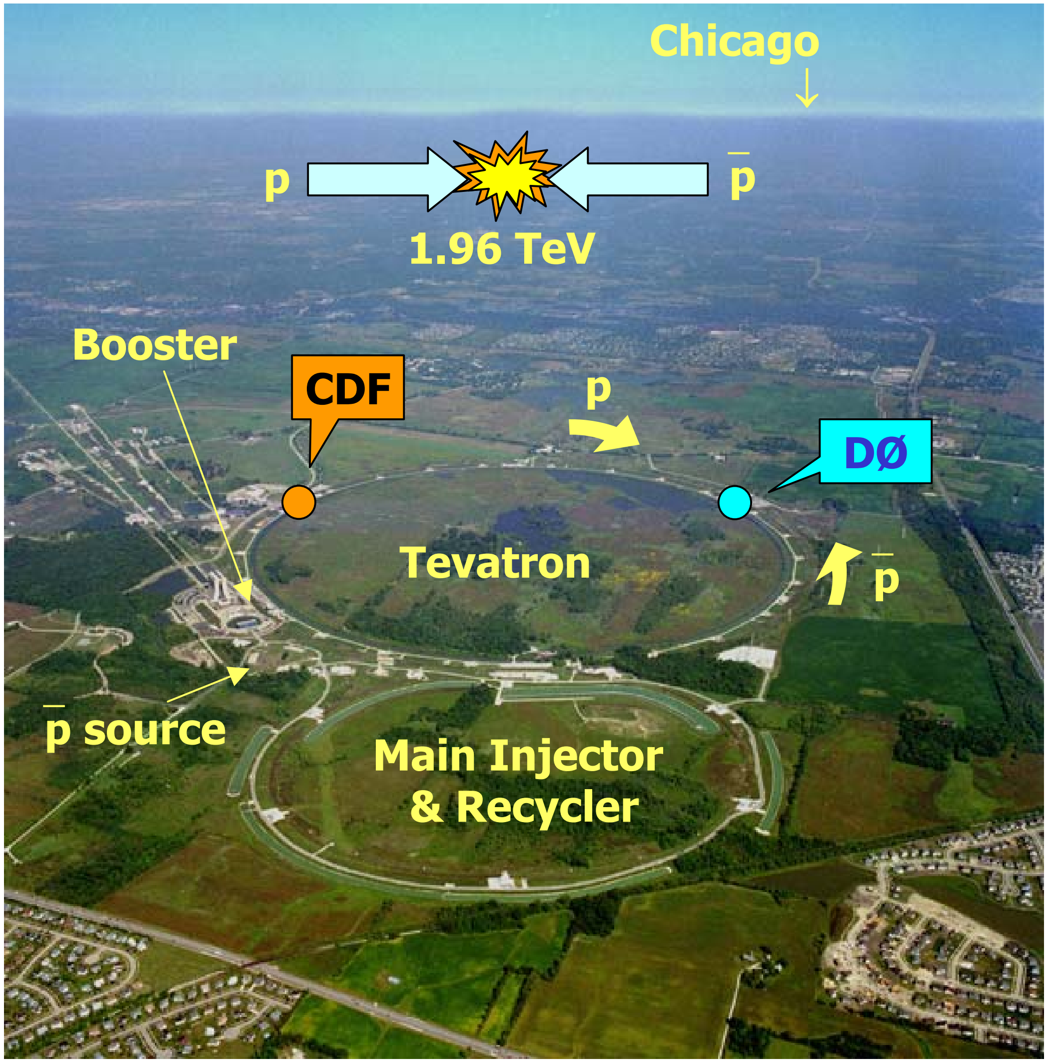
- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN**
  - precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV
  - direct searches for Higgs production exclude $m_H < 113$ GeV

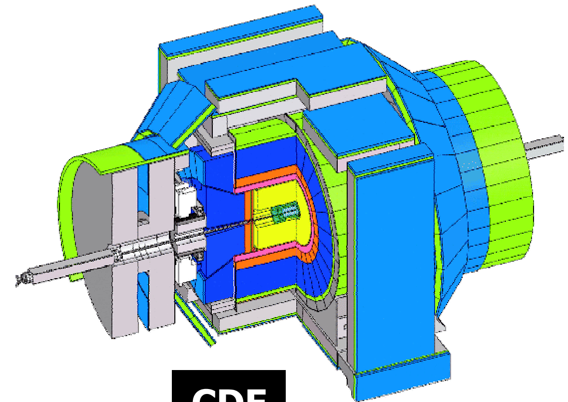


- **Summer and Autumn 2000: Hints of a Higgs?**
  - the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)
  - despite these hints, CERN management decided to shut off LEP operations in order to expedite construction of the LHC

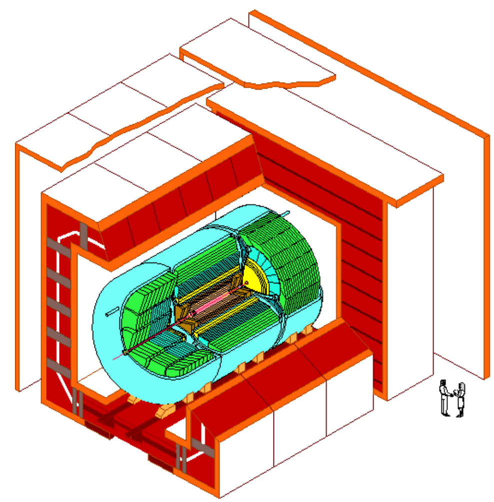
> *"The resolution of this puzzle is now left to Fermilab's Tevatron and the LHC."*
>
> – Luciano Maiani

The Fermilab Tevatron Collider

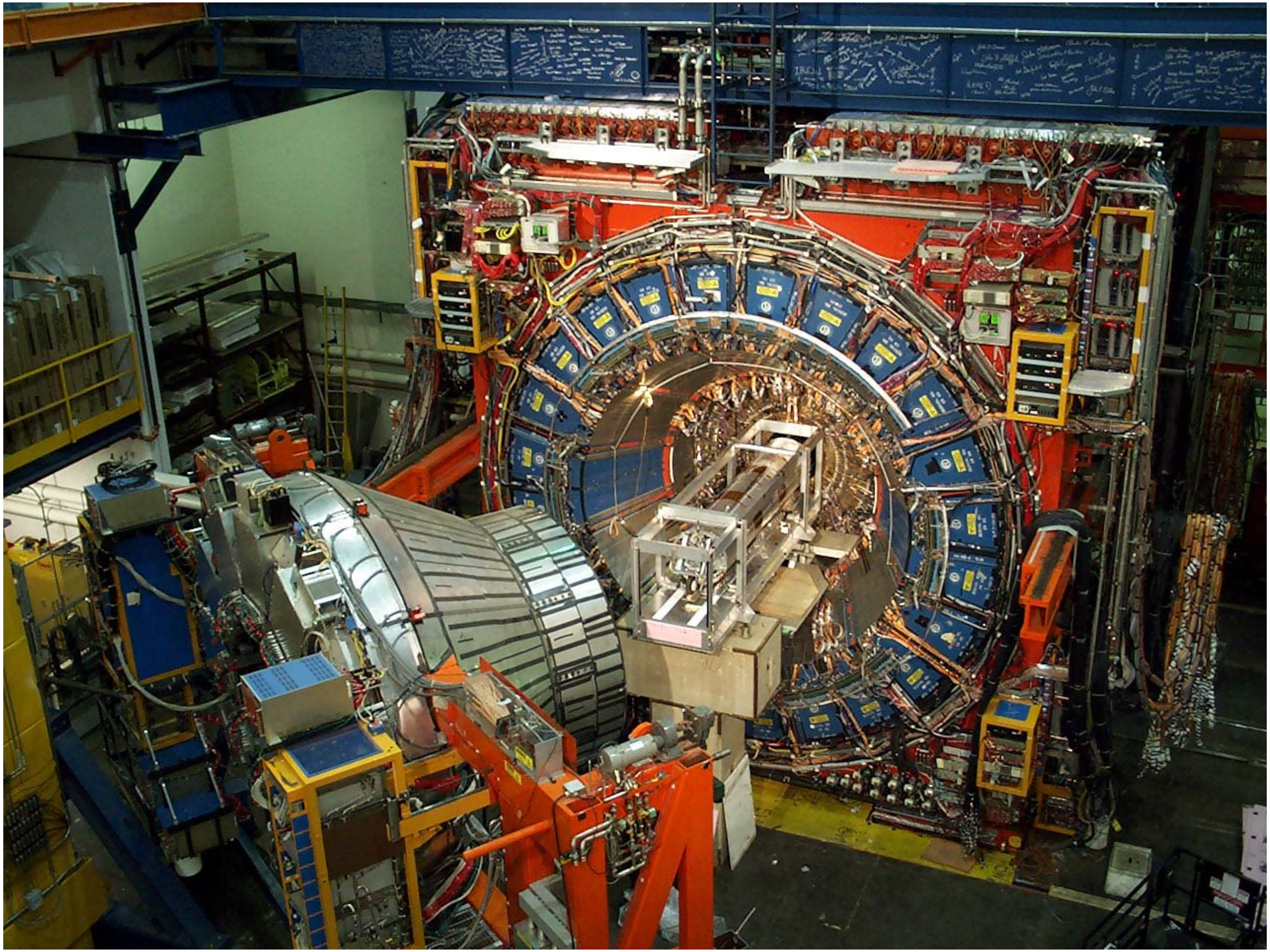




CDF



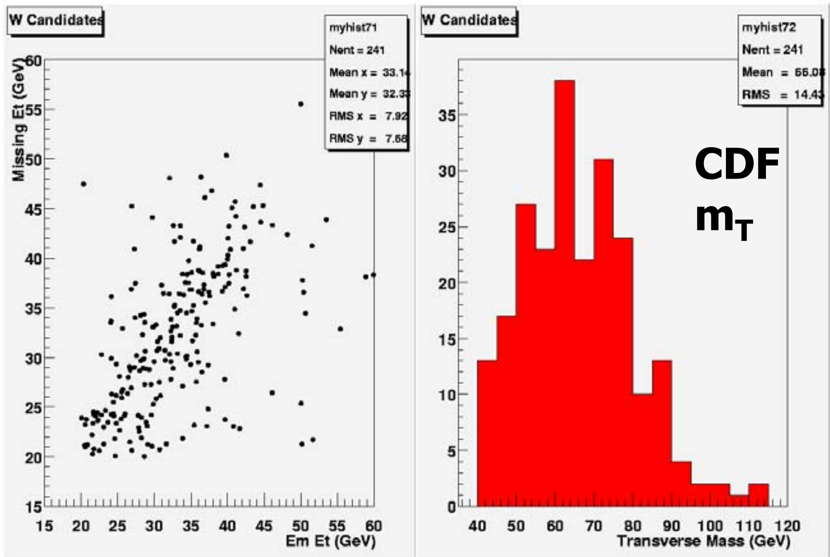
DØ

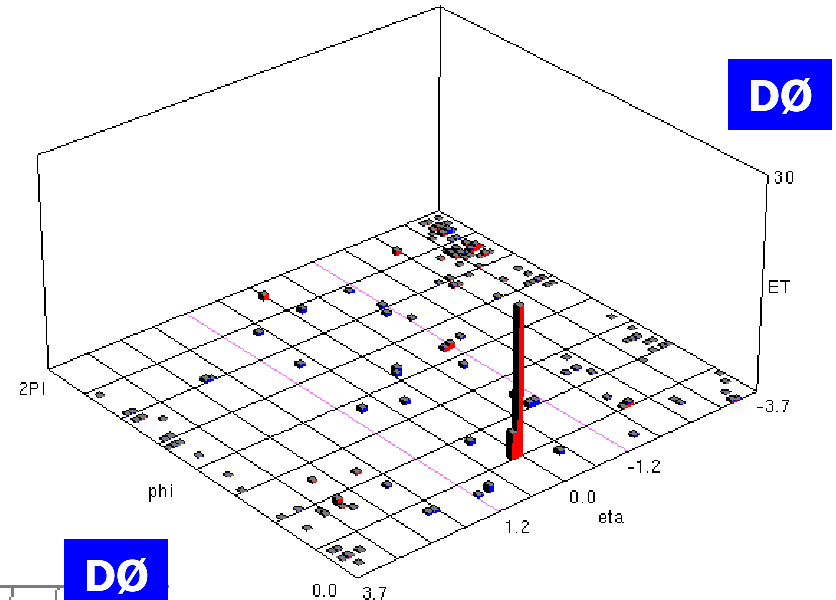


CDF installing silicon tracker, prior to detector roll-in

DØ detector installed in the Collision Hall, January 2001

W→ eν candidates





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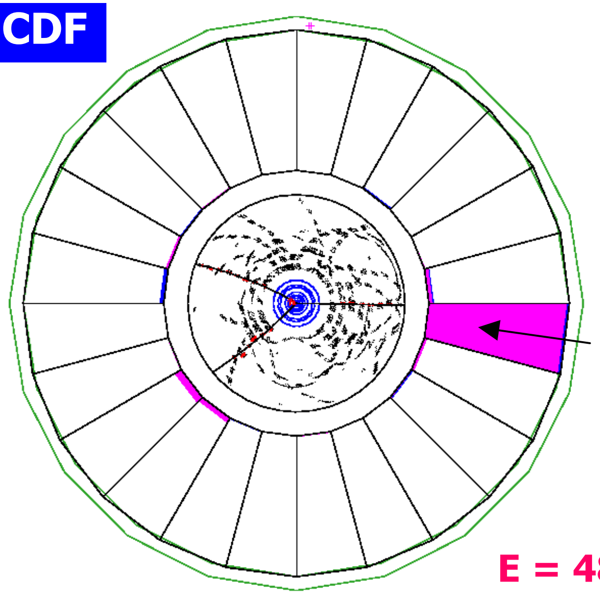
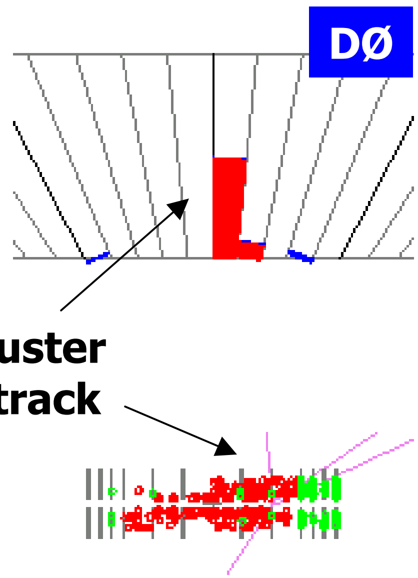
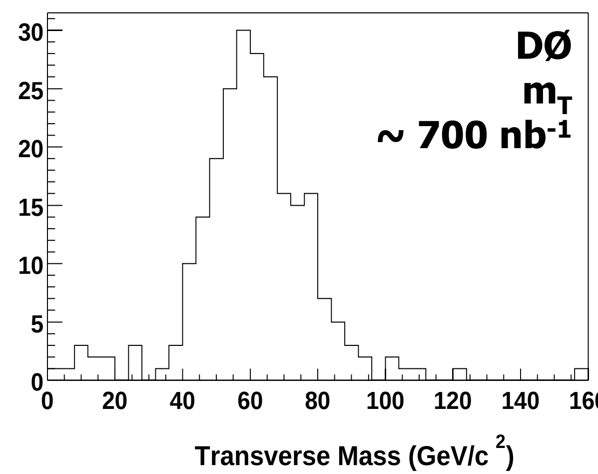


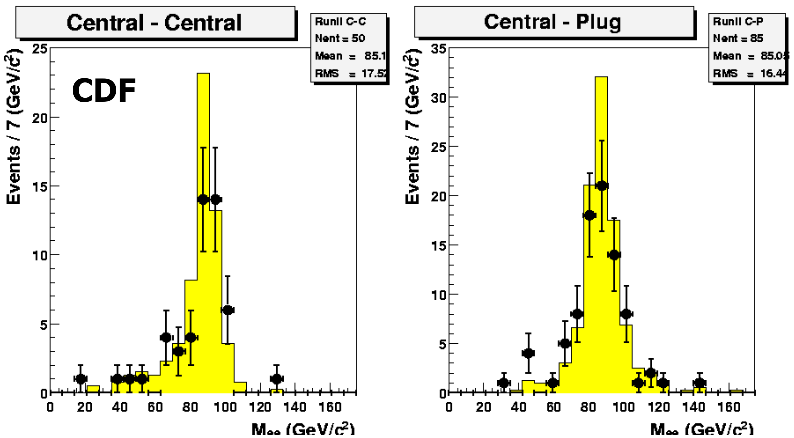


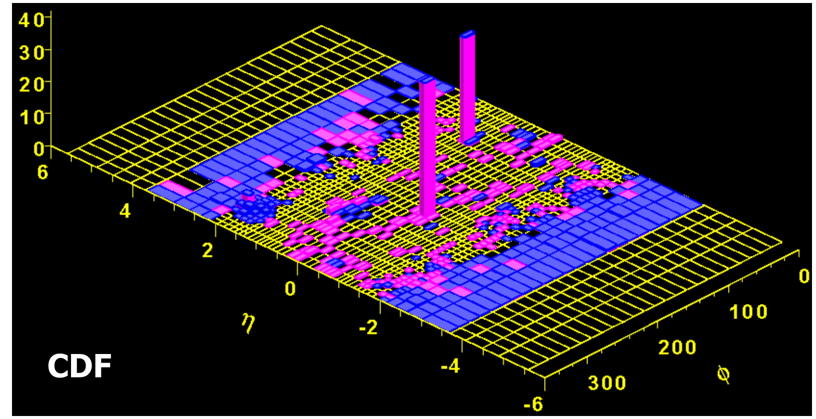
EM cluster with track

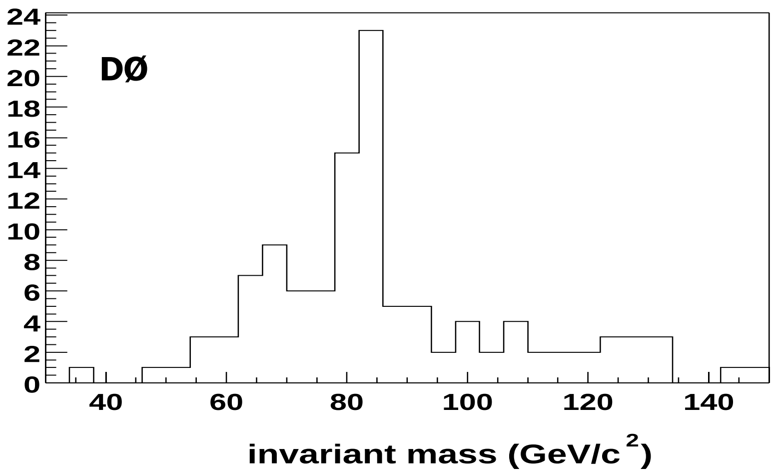
E = 48 GeV



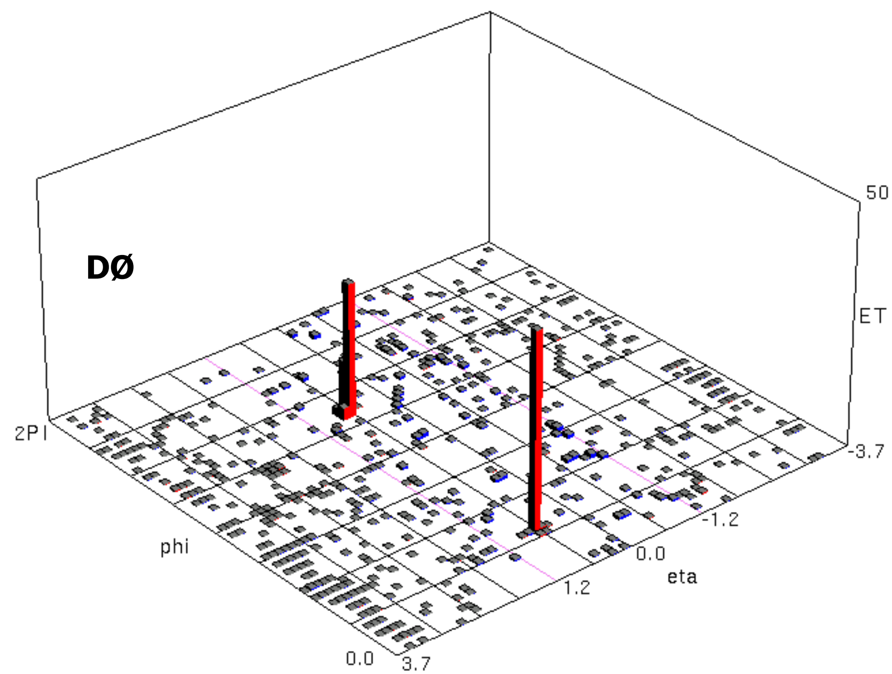
$Z \rightarrow e^+e^-$ candidates







(uncalibrated energy scale)



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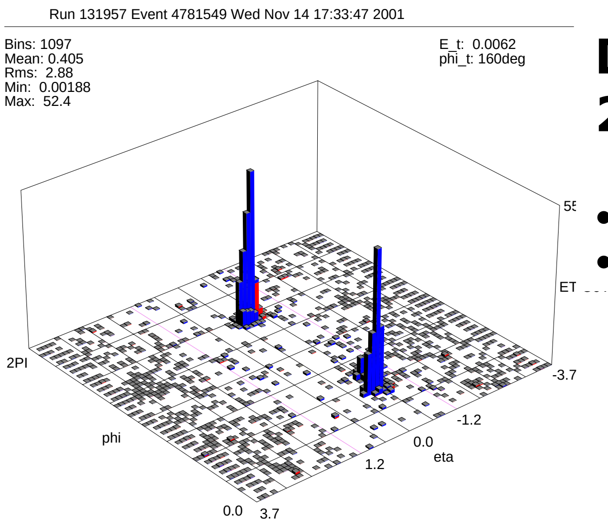
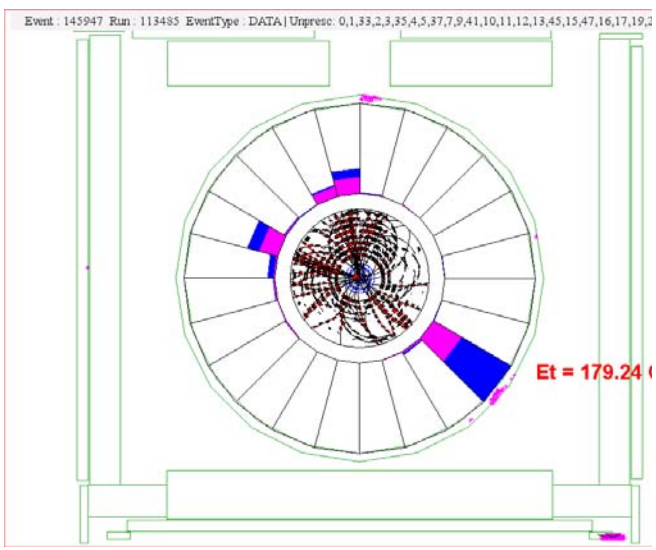
Jets



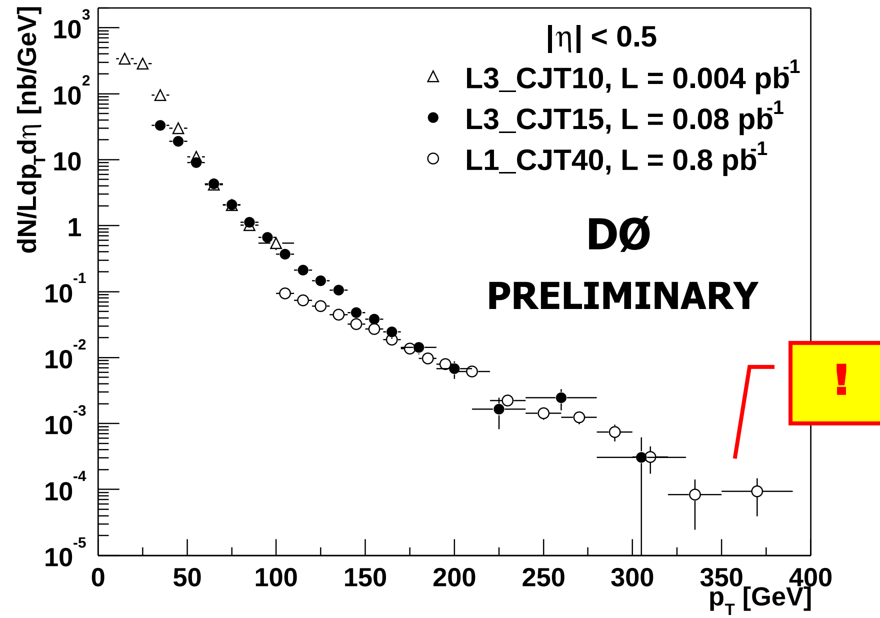
DØ 2-jet event

- E_T^{jet1} ~230 GeV
- E_T^{jet2} ~190 GeV



CDF 3-jet event

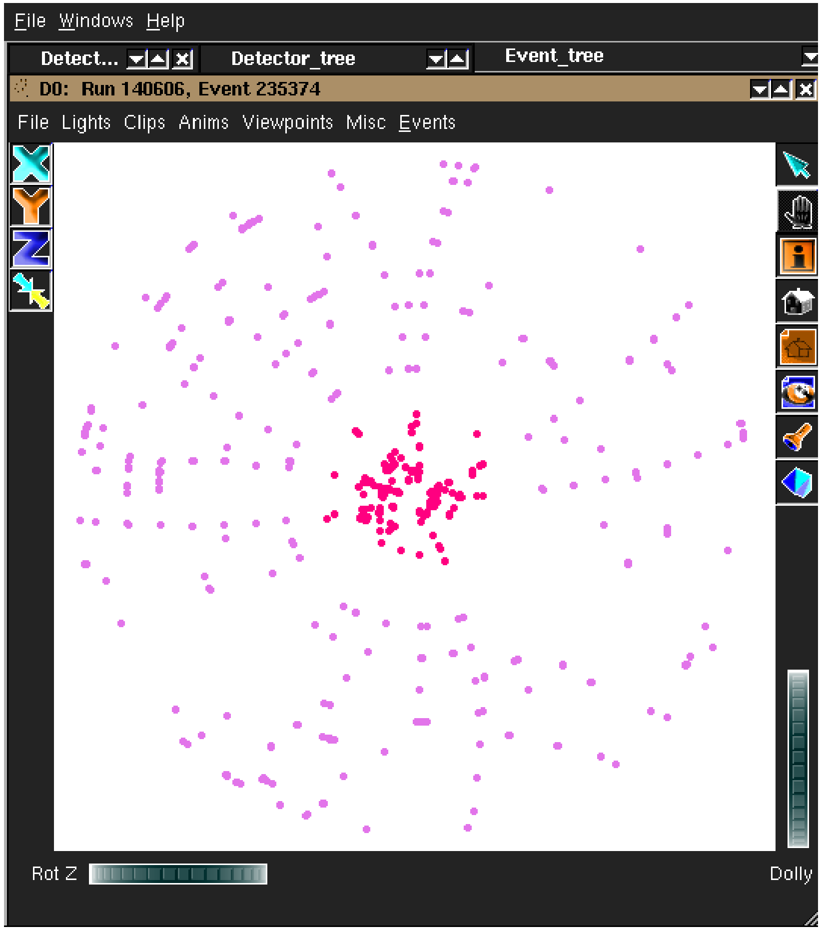
- E_T^{jet1}~180GeV



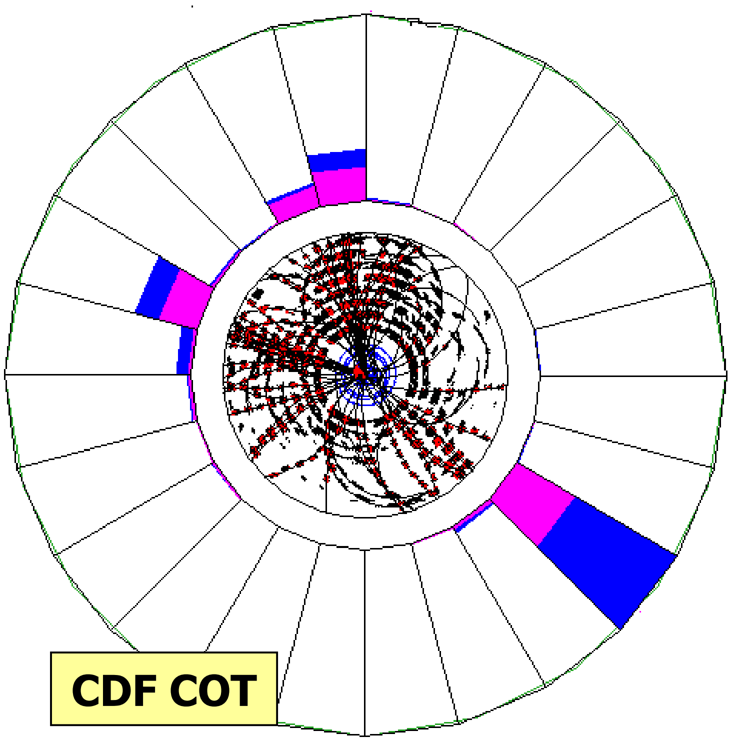
Jet cross section as a function of E_T, for $|\eta| < 0.5$

R=0.7 Cone Algorithm with Run 1 corrections

Tracking



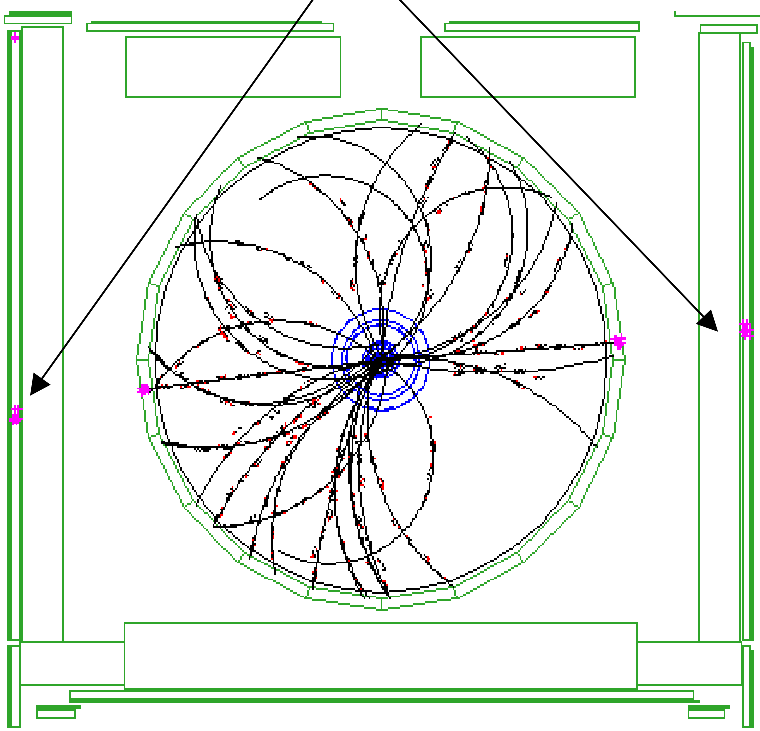
DØ Fiber Tracker

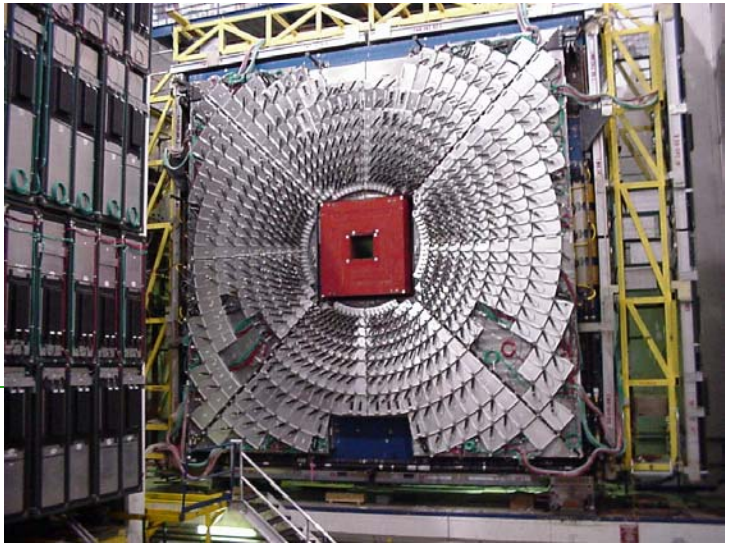


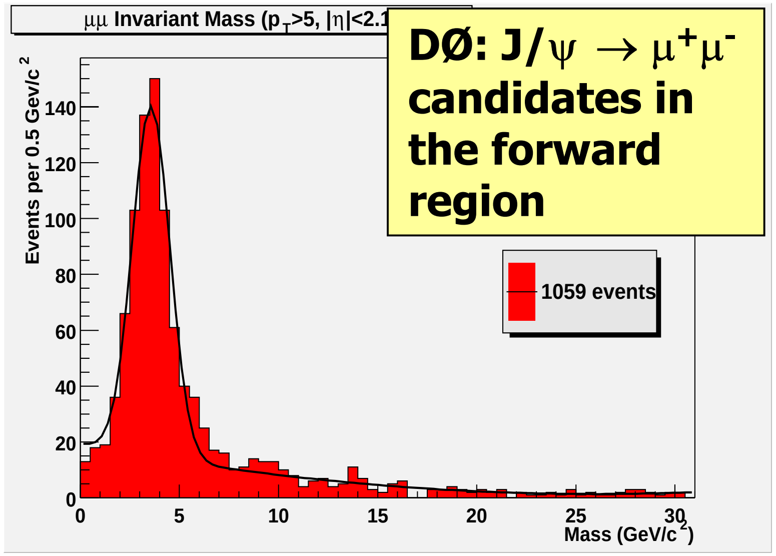
CDF COT

Muons

CDF:
$Z \rightarrow \mu^+\mu^-$ candidate
in muon system and COT
$M_{\mu\mu}$ = 88 GeV

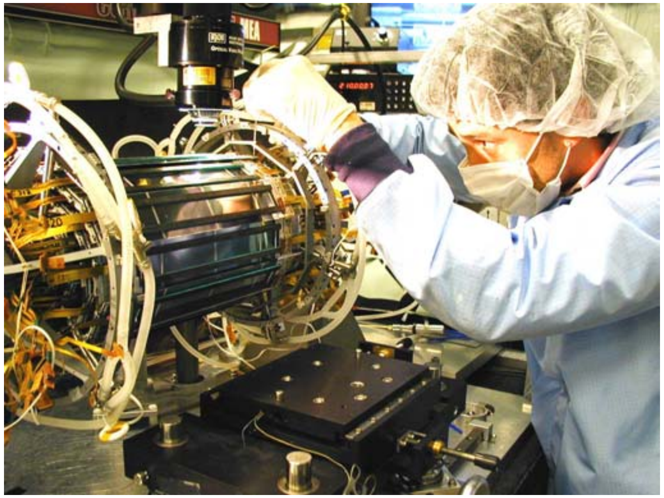


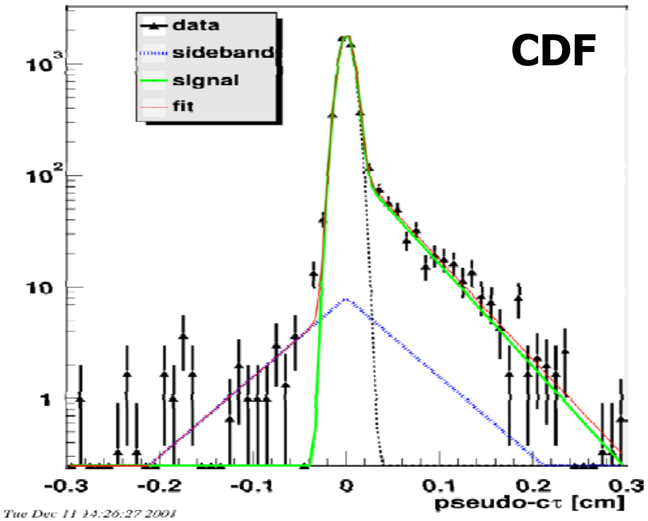




DØ: $J/\psi \rightarrow \mu^+\mu^-$ candidates in the forward region

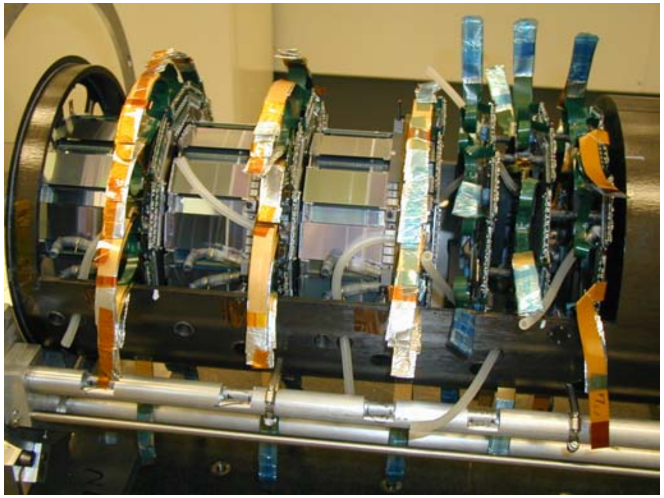
Silicon Detectors and b-tagging

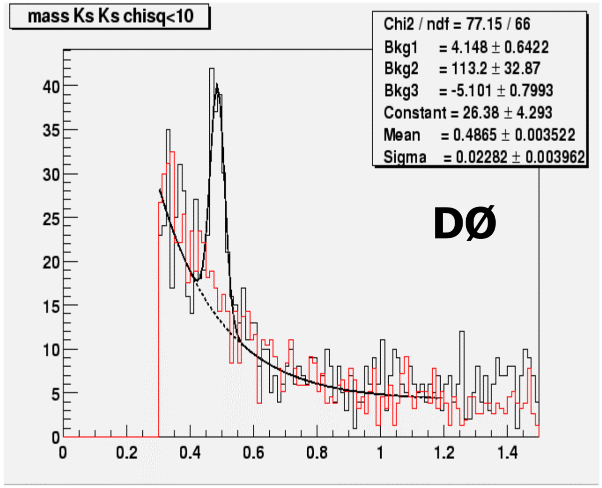




B-lifetime from $B \rightarrow J/\psi$ events

Consistent with world average





K^0 signal

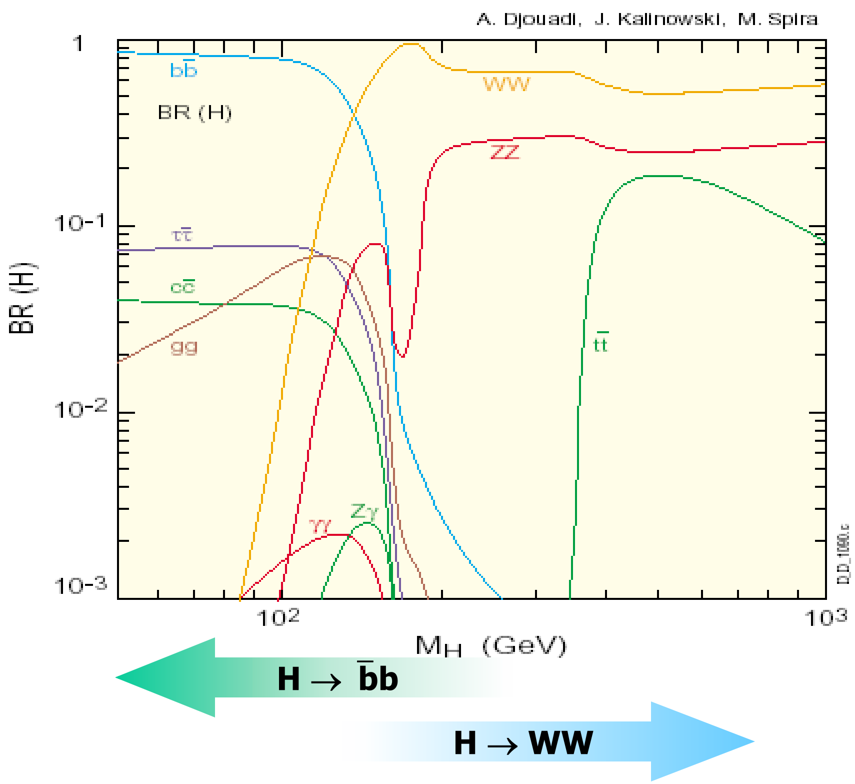
Silicon Stand-alone tracking

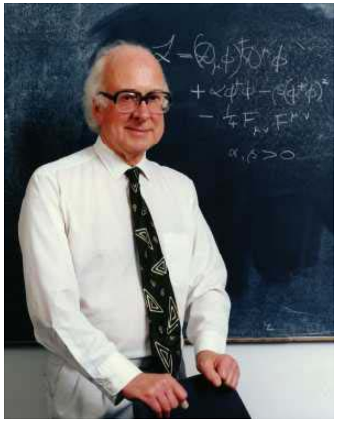
Higgs at the Tevatron

- The search for the mechanism of EWSB motivated the 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
- Consensus resulted from a convergence of
  - technical ideas about possible accelerator improvements
  - clear physics motivation 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



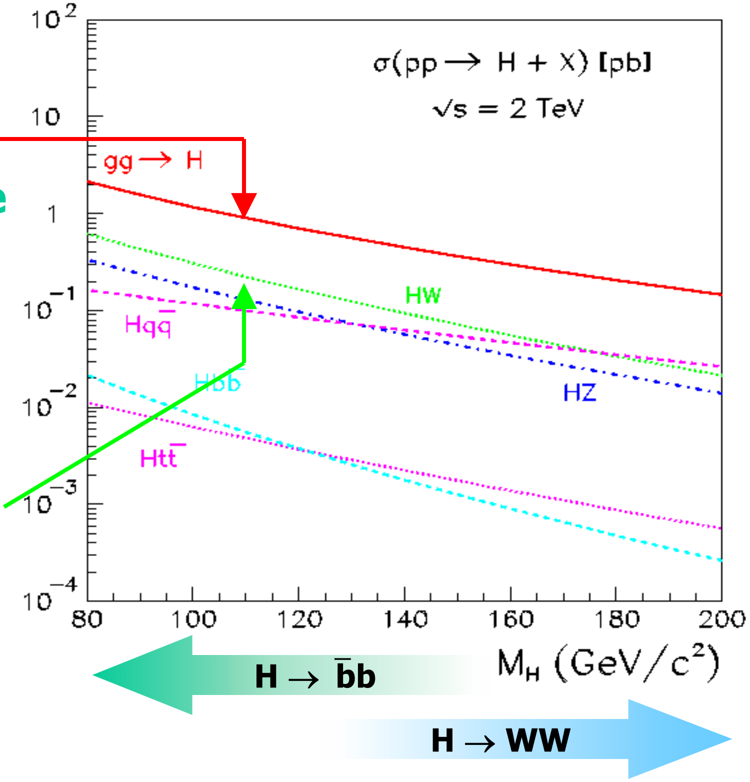


One Higgs

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**

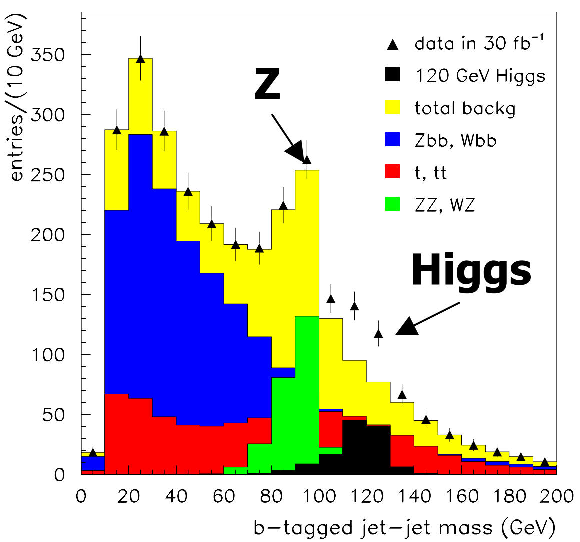


Dominant decay mode

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

- **WH → $q\bar{q}'$ $b\bar{b}$ 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

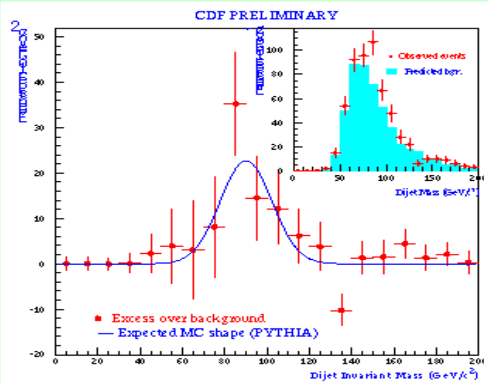


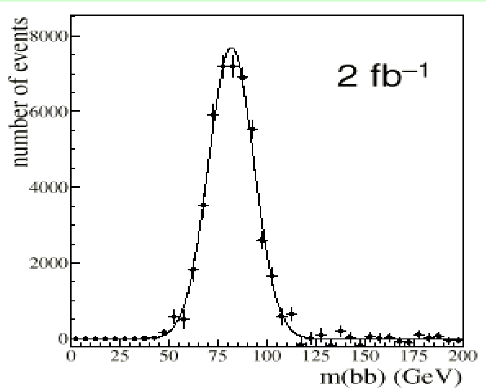
2 × 15fb⁻¹ (2 experiments)

$b\bar{b}$ mass resolution

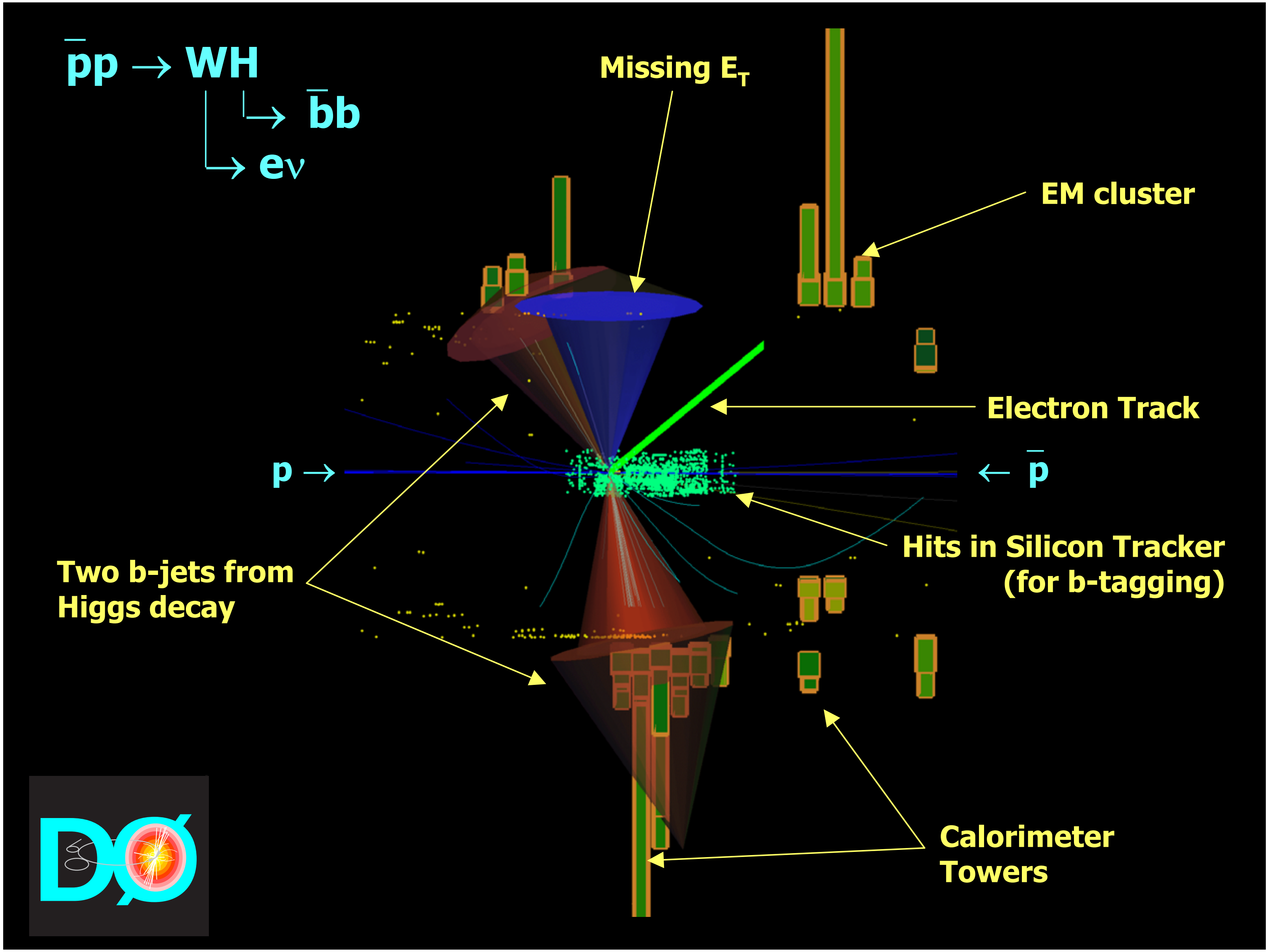
Directly influences signal significance

Z → $b\bar{b}$ will be a calibration





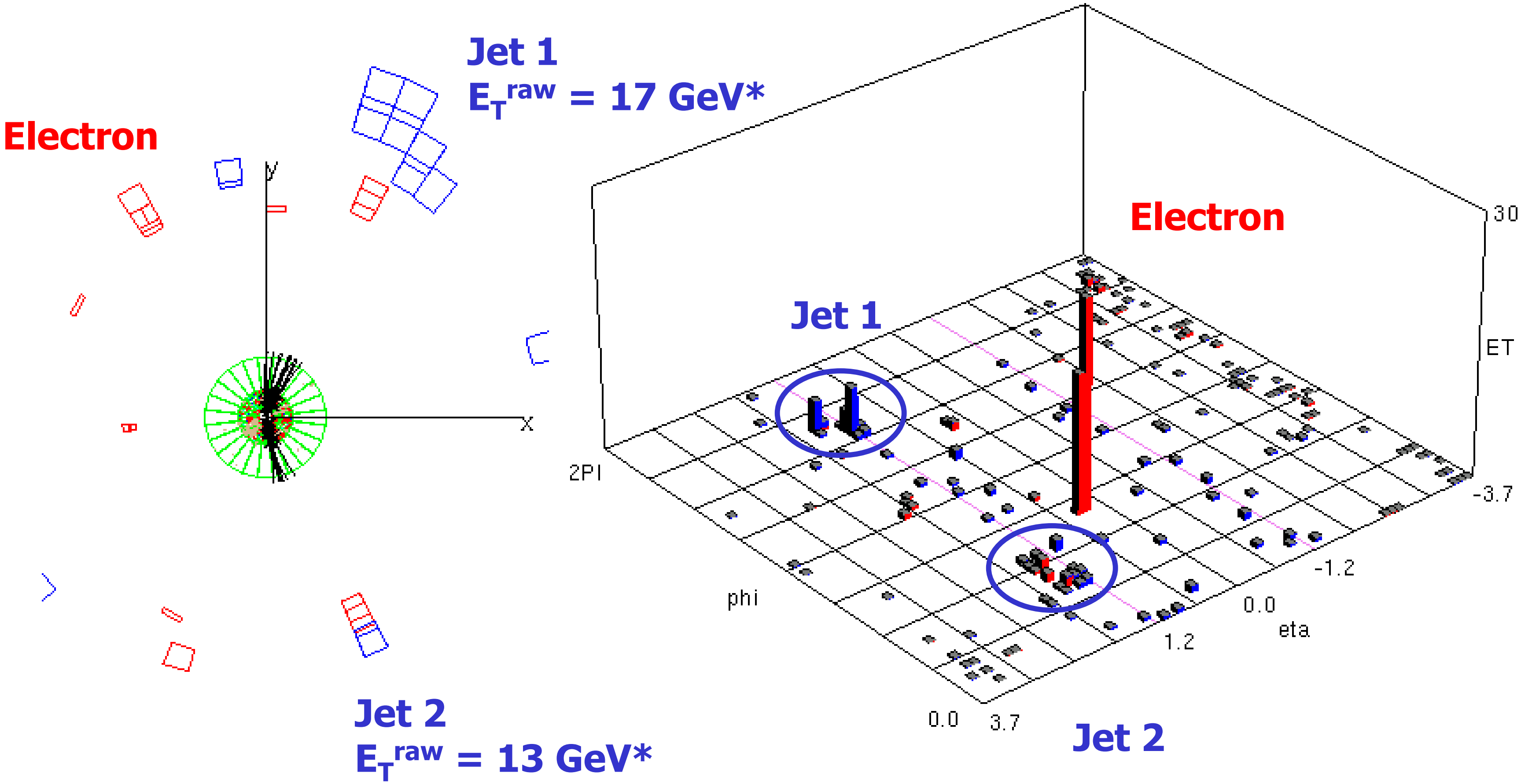
CDF Z → $b\bar{b}$ in Run I **DØ simulation for 2fb⁻¹**



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

Just for fun . . .

DØ W + 2 jet (Higgs!) candidate, October 2001



* Jet E_T corrections will be large

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

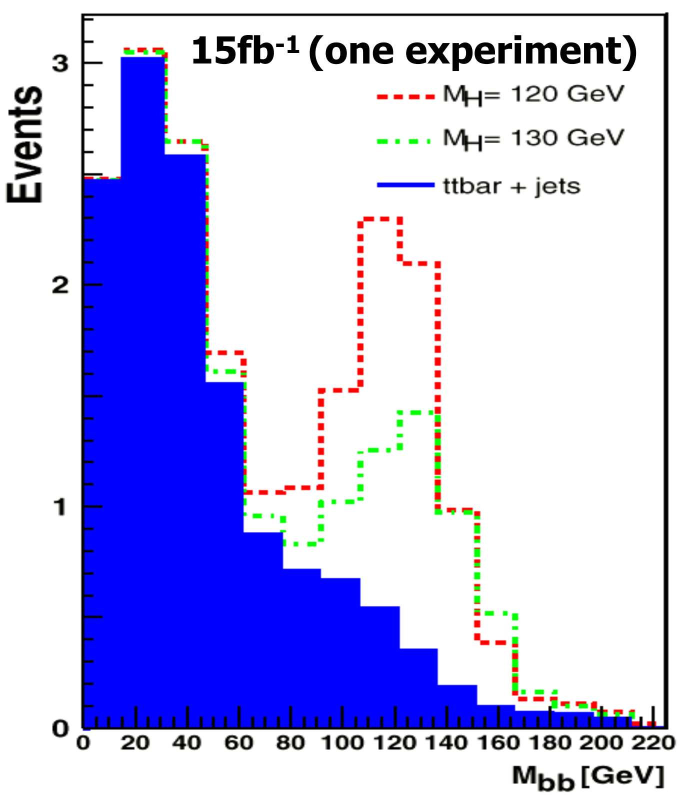
- Events in one experiment with 15 fb^{-1}:

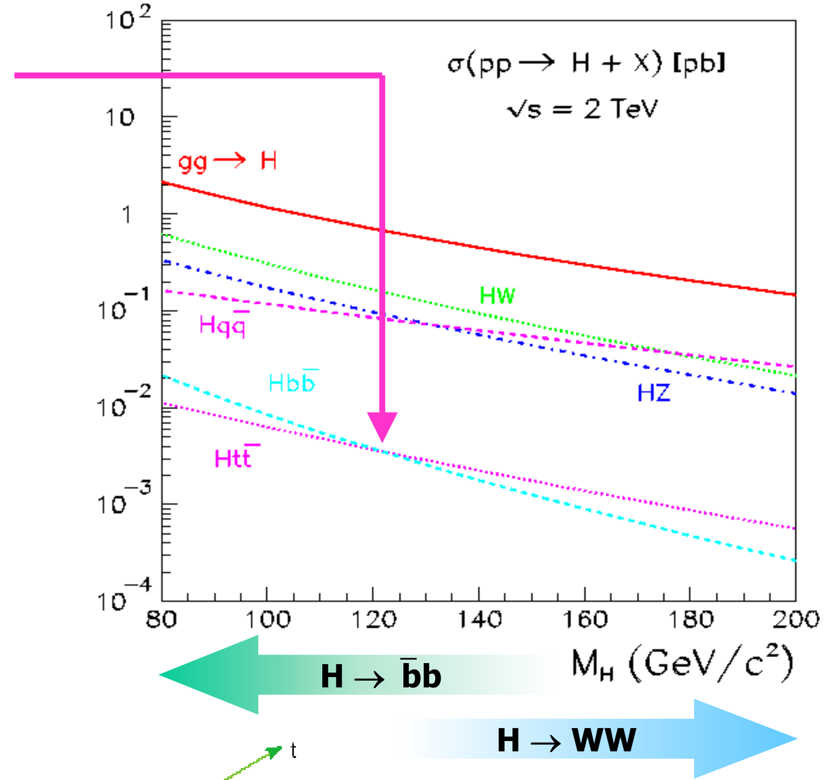
Mode	Signal	Background	S/√B
lνbb	92	450	4.3
ννbb	90	880	3.0
llbb	10	44	1.5

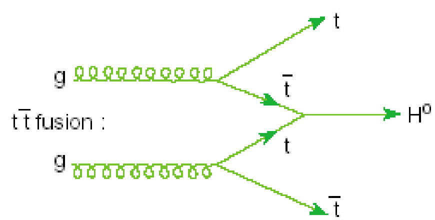
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - production cross section
  - Can we see H → WW? (Branching Ratio ~ 9% and rising w/ mass)
  - Can we see H → ττ? (Branching Ratio ~ 8% and falling w/ mass)
  - Can we see H→ γγ? (not detectable for SM Higgs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







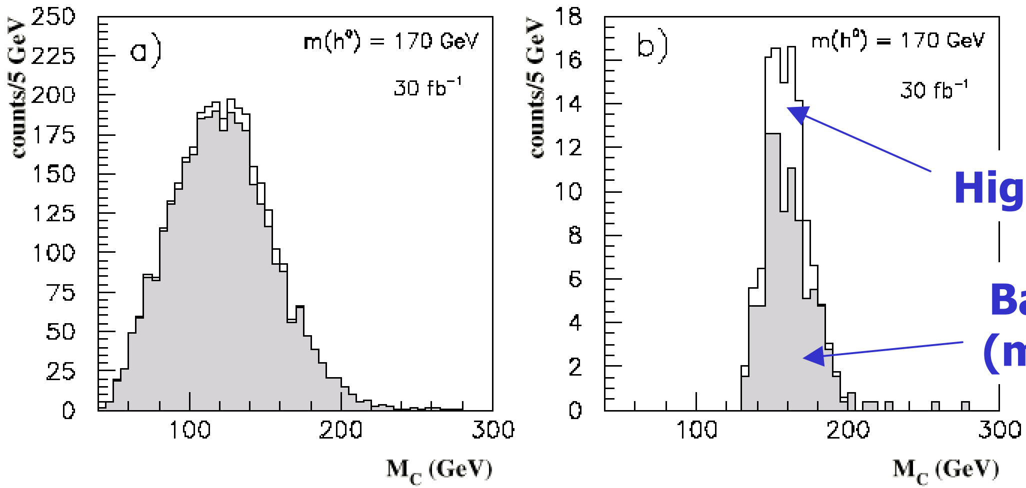
Tests top quark Yukawa coupling

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

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

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 × 15fb^{-1} (2 experiments)

Higgs signal

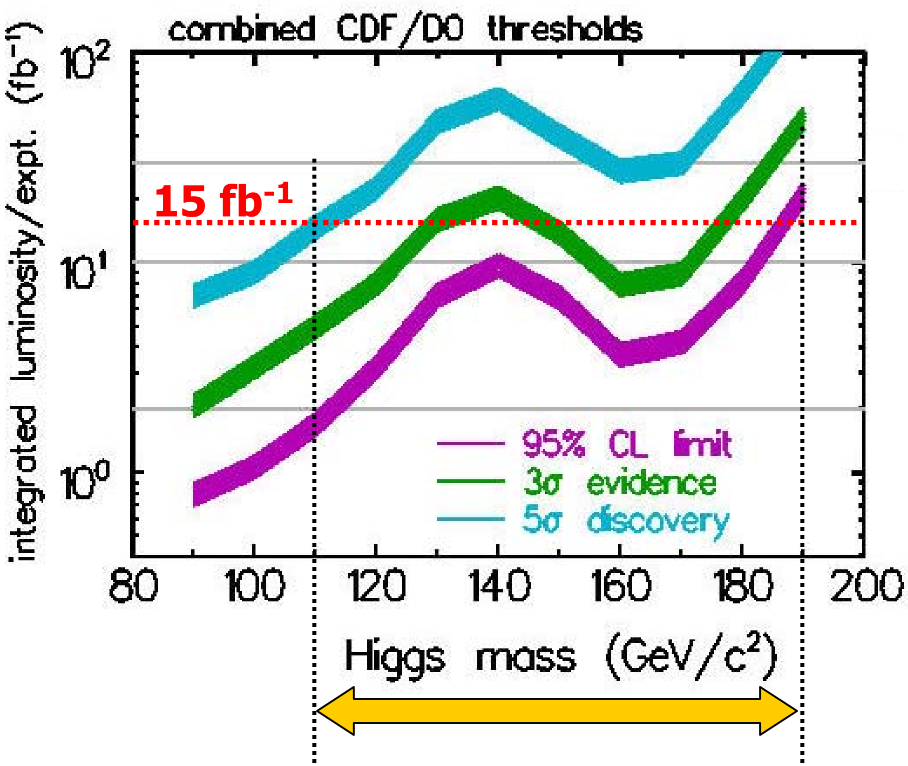
Background (mainly WW)

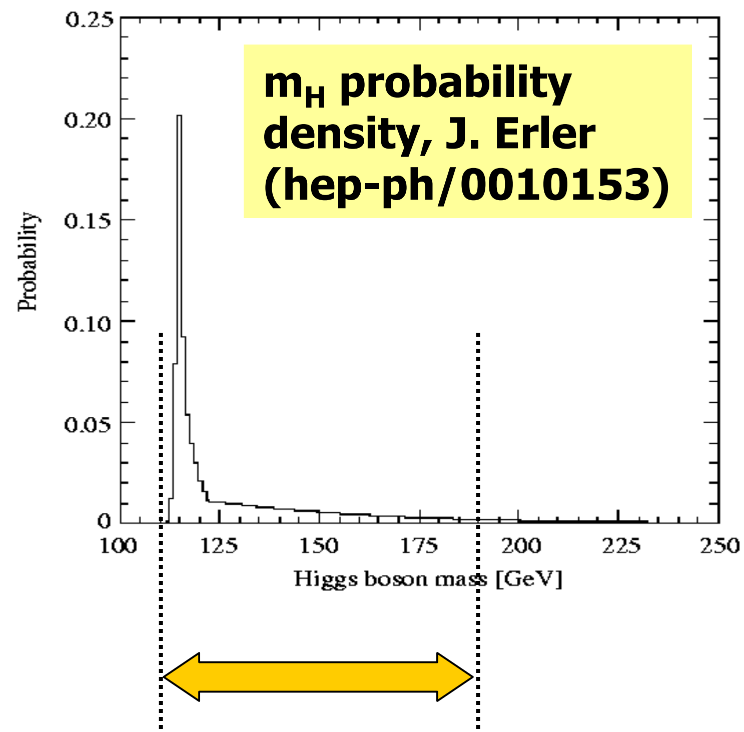
Before tight cuts: verify WW modelling

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

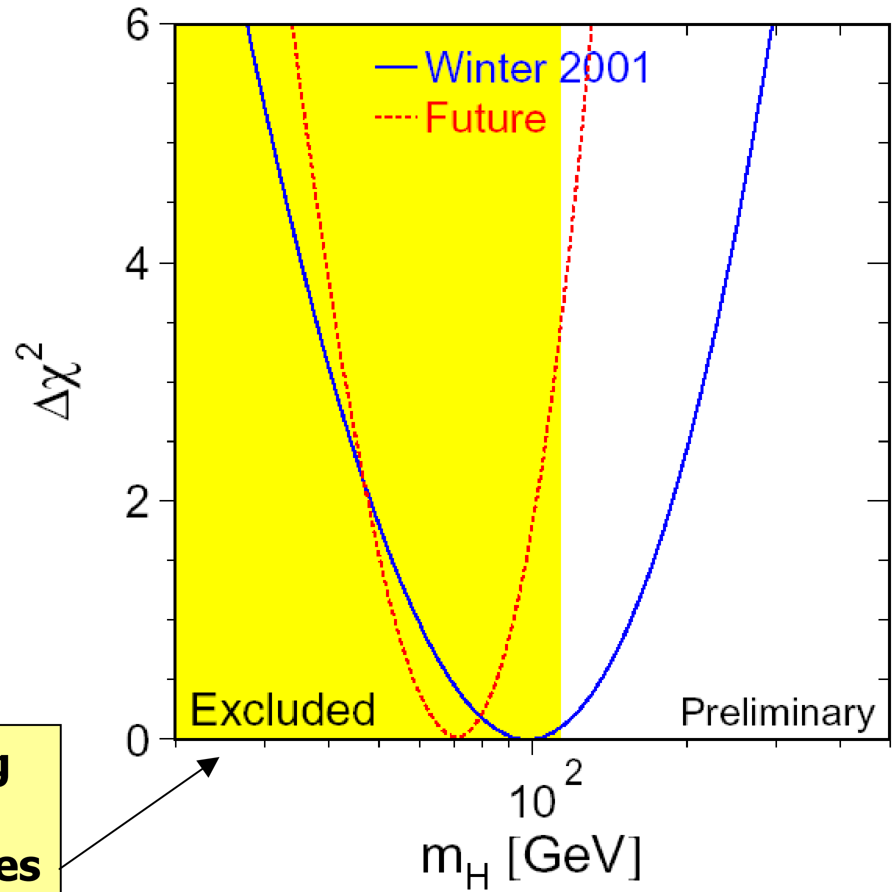
Indirect Constraints on Higgs Mass

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

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

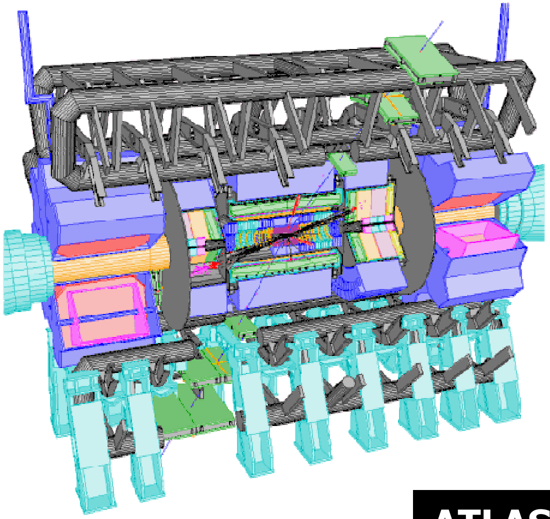
	Δm_t
2 fb^{-1}	**±2.7 GeV**
15 fb^{-1}	**±1.3 MeV**

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

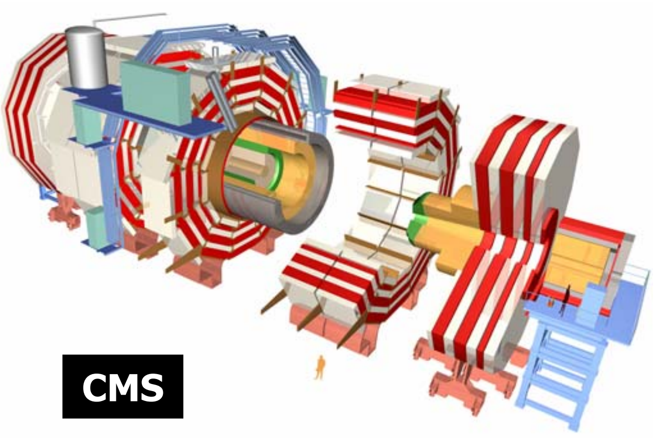


M. Schmitt's talk in the parallel session

The Large Hadron Collider

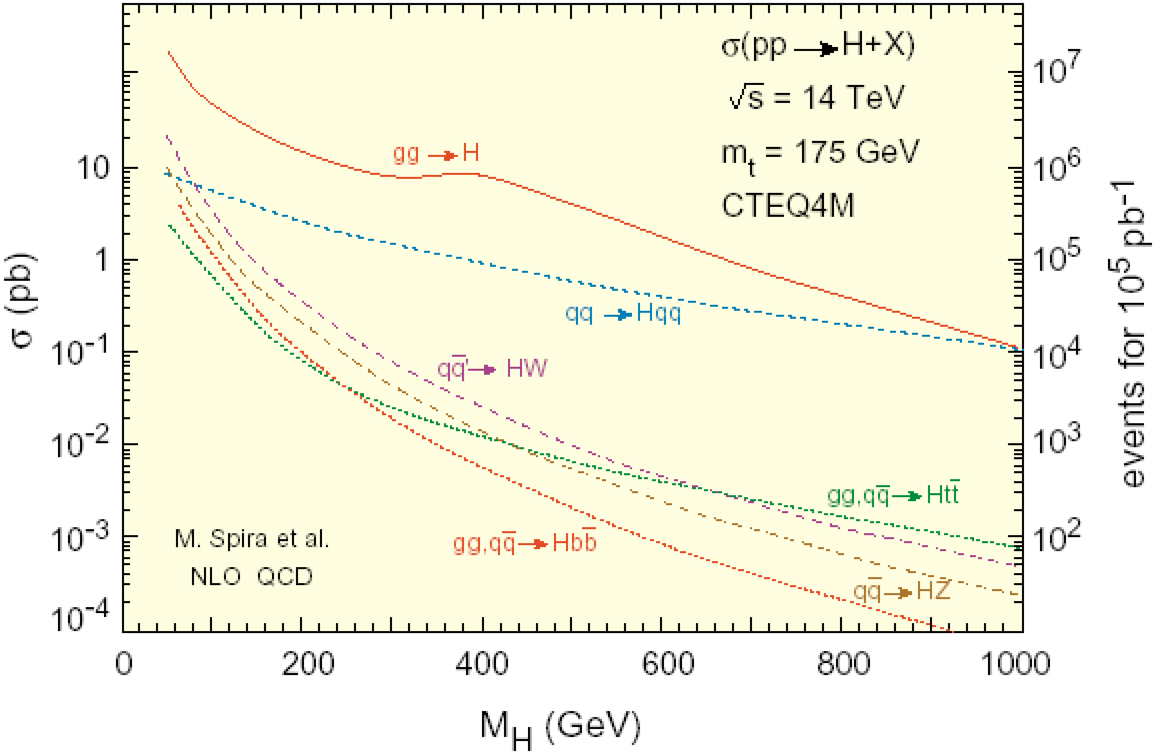


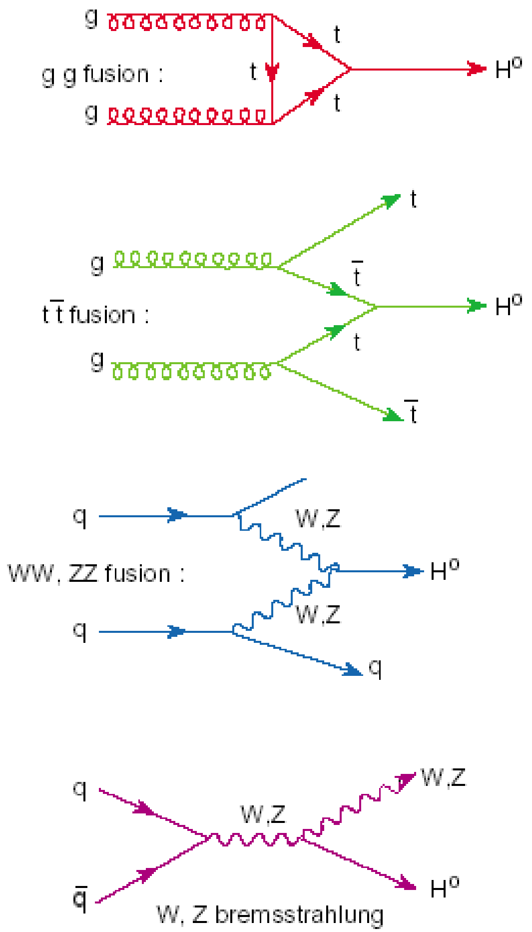
ATLAS



CMS

Higgs at LHC

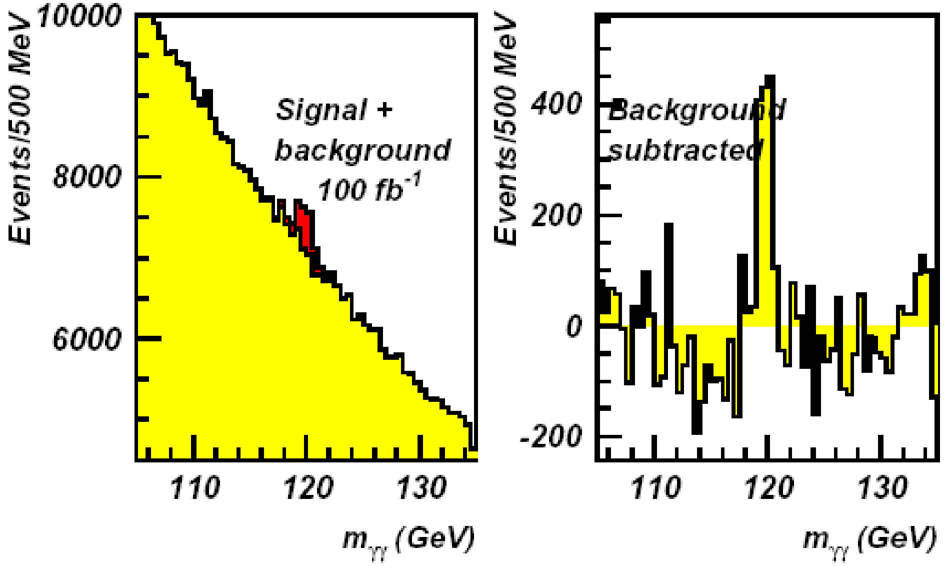




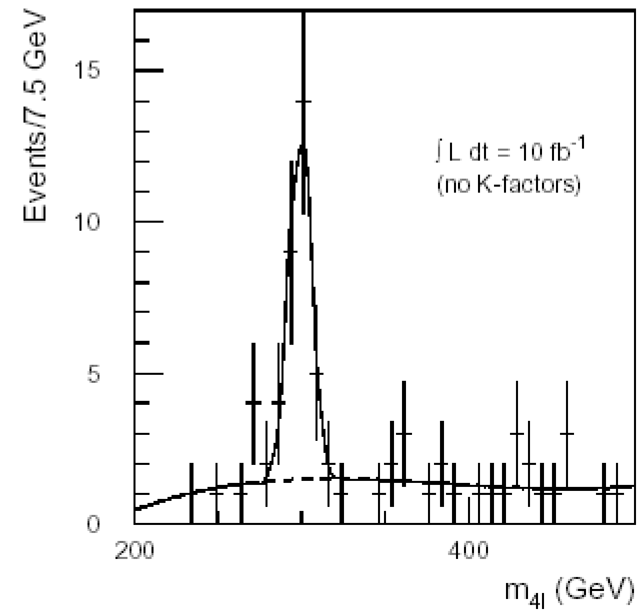
- **Production cross section and luminosity both ~ 10 times higher at LHC than at Tevatron**
  - **Can use rarer decay modes of Higgs**

“Precision Channels”

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



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

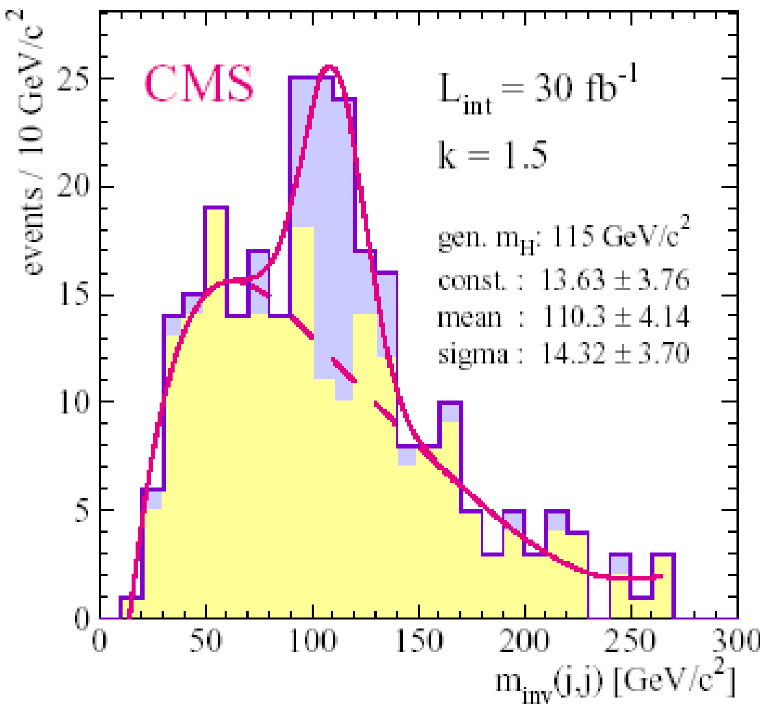


- **Both LHC detectors have invested heavily in precision EM calorimetry and muon systems in order to exploit these channels**

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

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

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



◇ $90 < m < 130\ GeV/c^2$:

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.):

$S/B = 73\%$

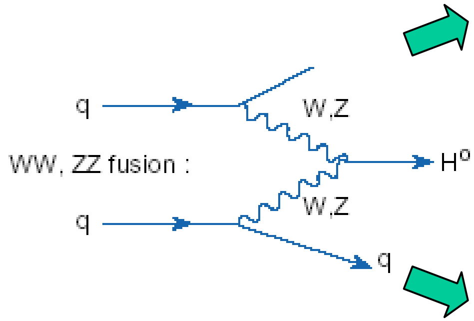
$S/\sqrt{B} = 5.3$

$\Delta y_t/y_t = 13\%$

$\Delta m/m = 3.8\%$

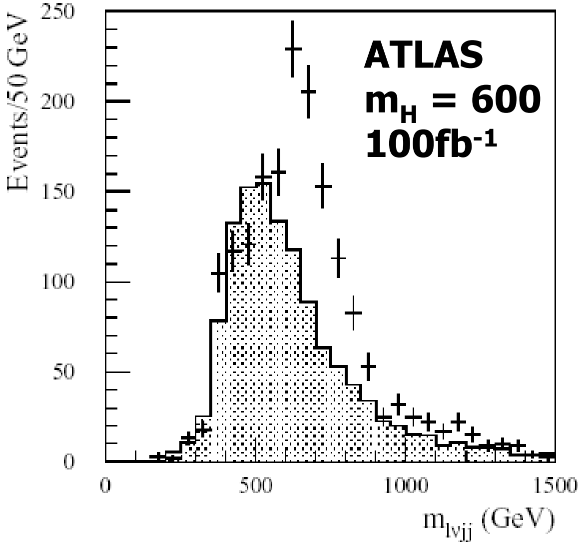
Vector boson fusion channels

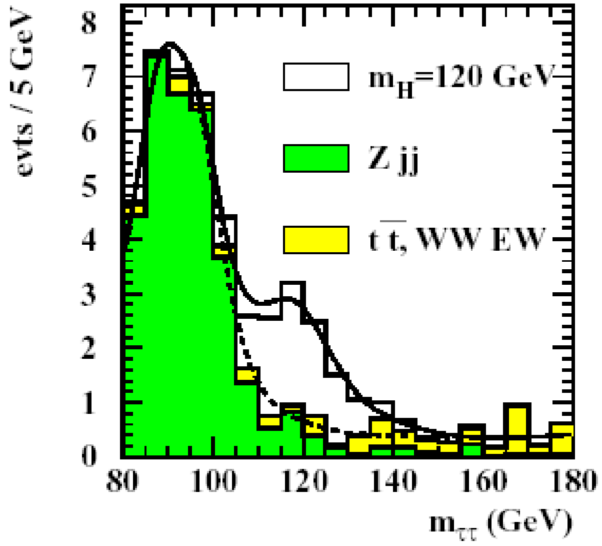
- Use two forward jets to "tag" the VB fusion process
  - Improves the S/B for large Higgs masses



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

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



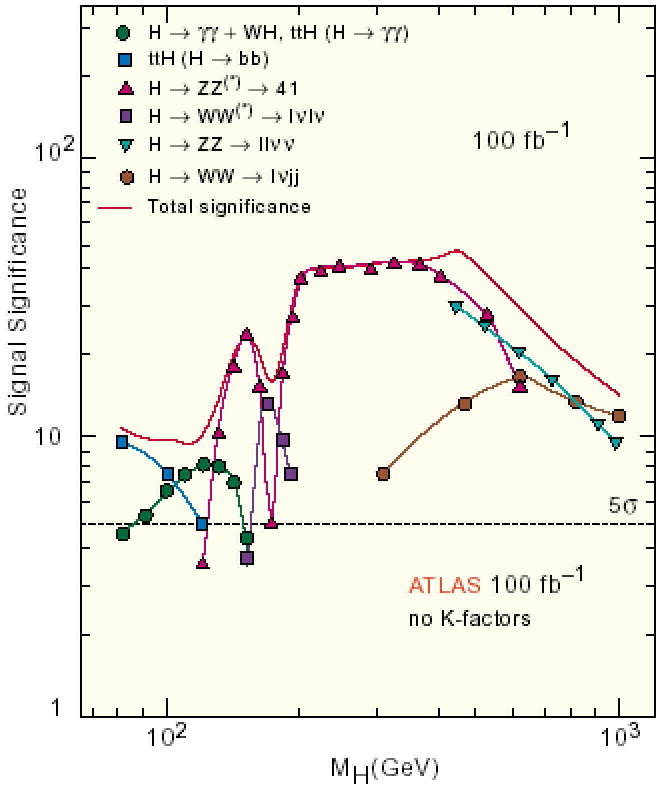


Also useful for lower Higgs masses:

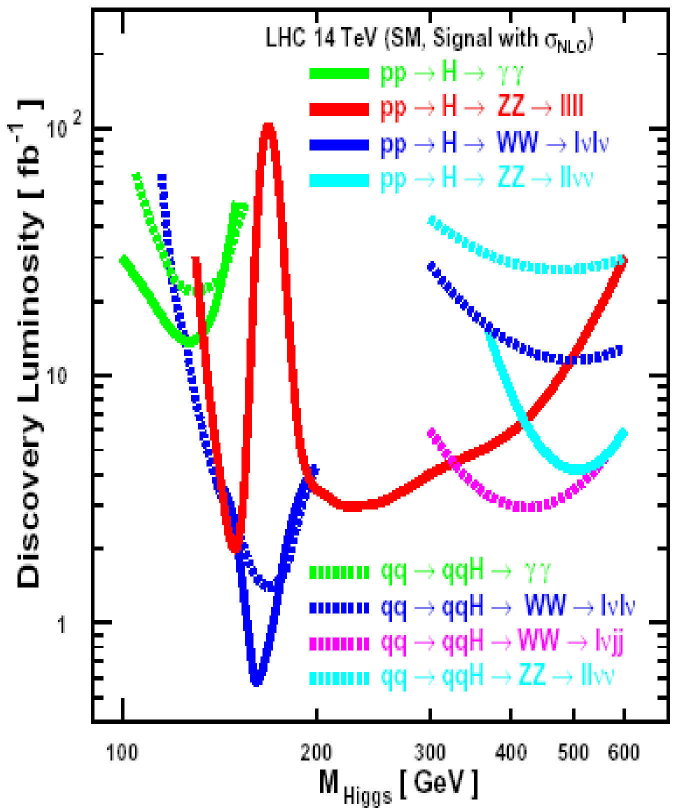
$H \rightarrow \tau\tau$
m_H = 120 GeV
ATLAS

LHC Discovery Potential

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



- **Luminosity required for 5σ**

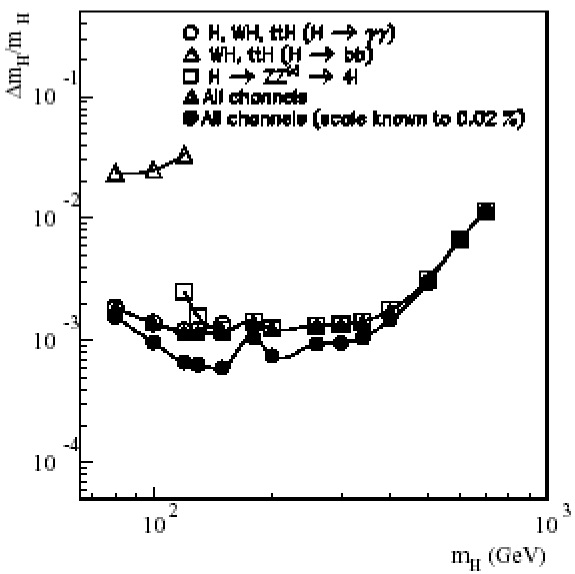


The whole range of SM Higgs masses is covered

John Womersley

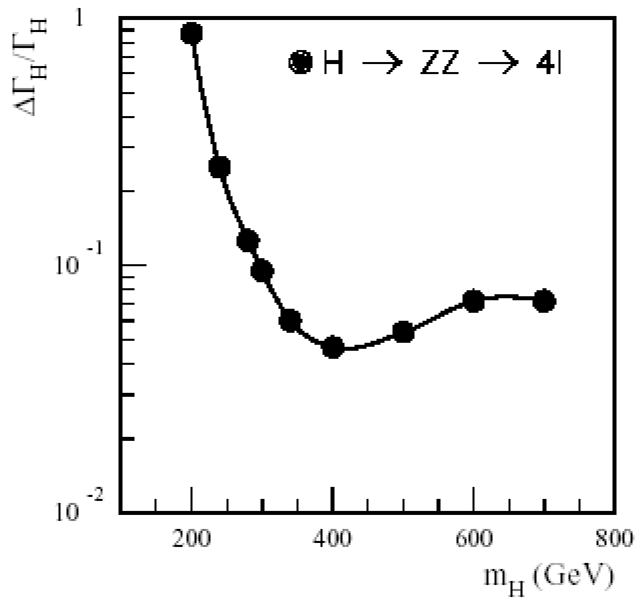
SM Higgs parameter determination at LHC

Mass



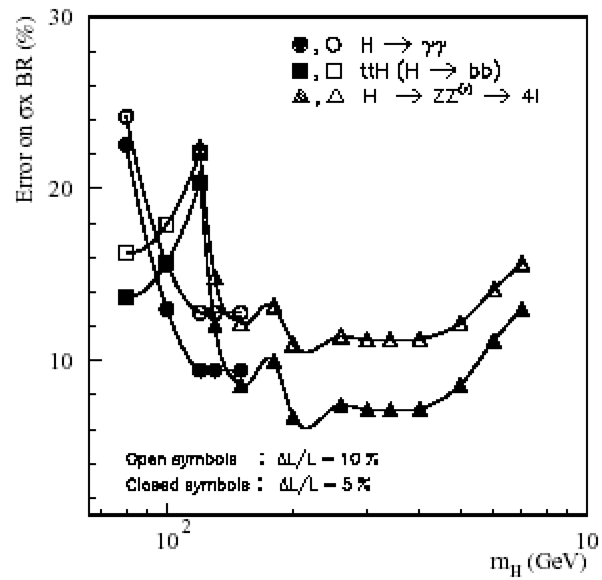
0.1% to 1% accuracy in measurement of m_H

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

John Womersley

Higgs coupling measurements

- **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

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

known to ~ 30% stat. limited

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

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

known to ~ 15% stat. limited

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

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

known to ~ 25% stat. limited

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

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

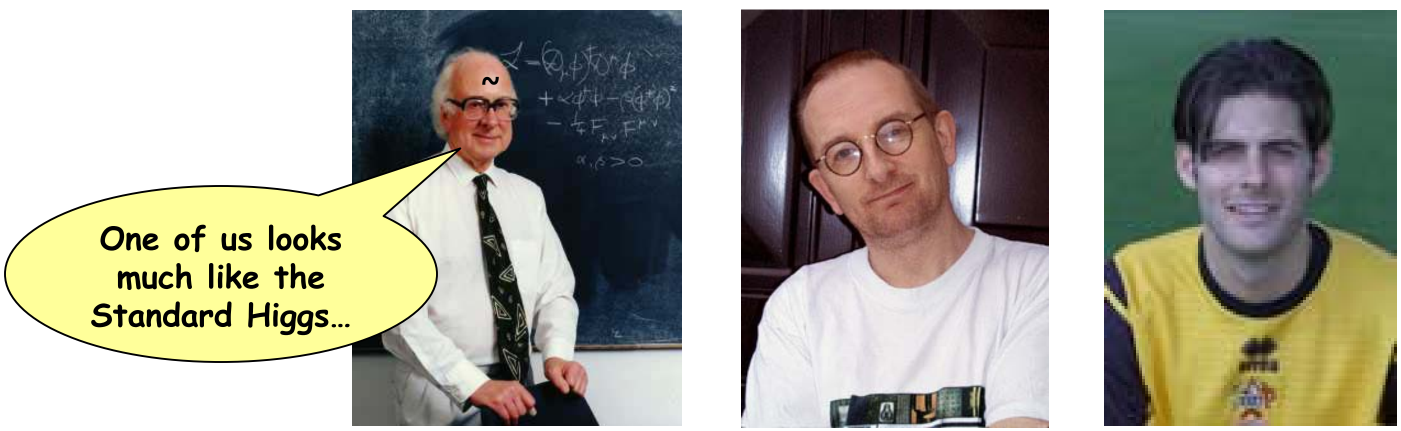
known to ~ 30% stat. (ZZ*) limited

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

Supersymmetric Higgs sector

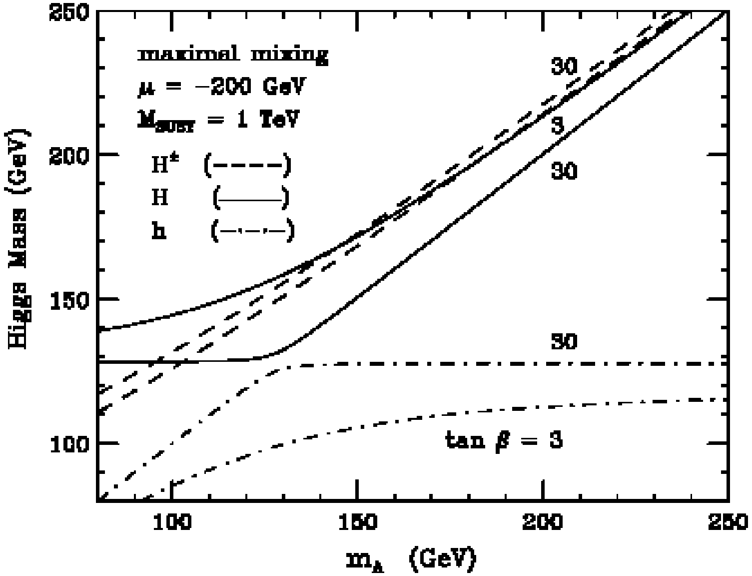
- **Expanded Higgs sector: h, H, A, $H^{\pm}$**
- **Properties depend on**
  - At tree level, two free parameters (usually taken to be m_A, tan β)
  - Plus radiative corrections depending on sparticle masses and m_t

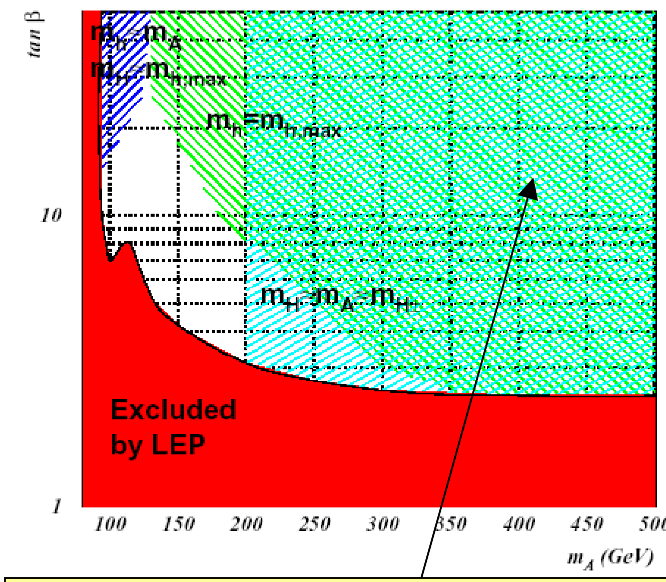
Multiple Higgses



Supersymmetric Higgs Masses

hep-ph/0010338



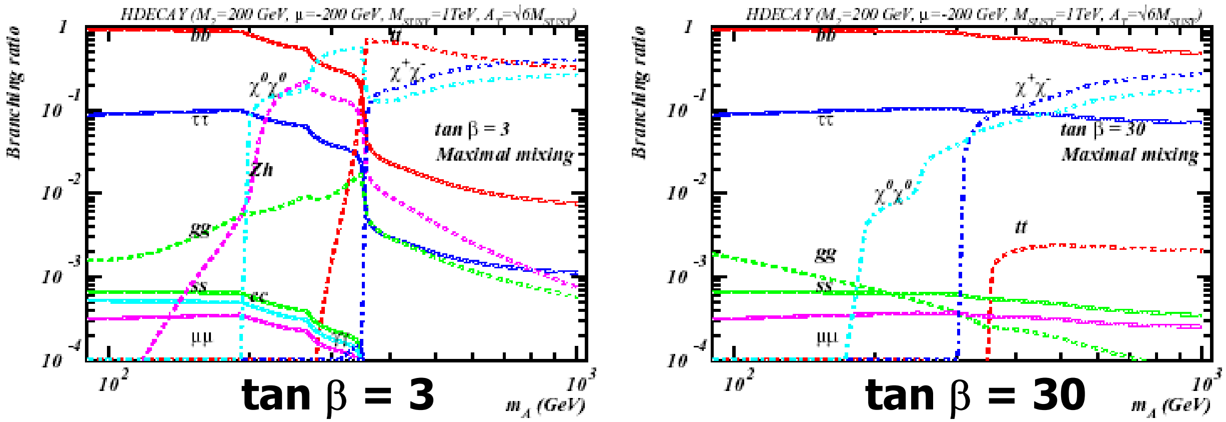


Over much of the remaining allowed parameter space,
$m_h \sim 130$ GeV,
$m_A \sim m_H \sim m_{H\pm}$ = "large"

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

MSSM Higgs Decays

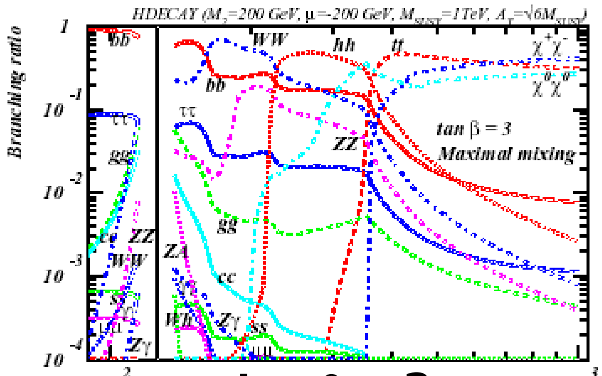
h, H



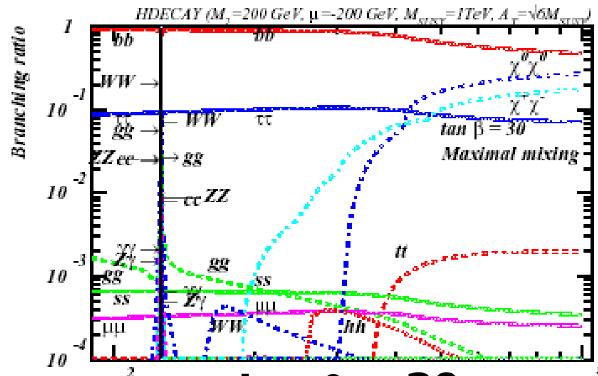
- **Very rich structure!**
  - **For most of allowed mass range h behaves very much like H_{SM}**
  - **WW and ZZ modes suppressed compared to SM**
  - **bb and ττ modes enhanced**

MSSM Higgs Decays

A

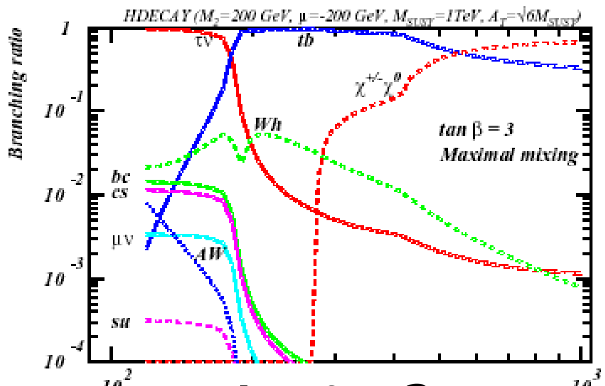


tan β = 3

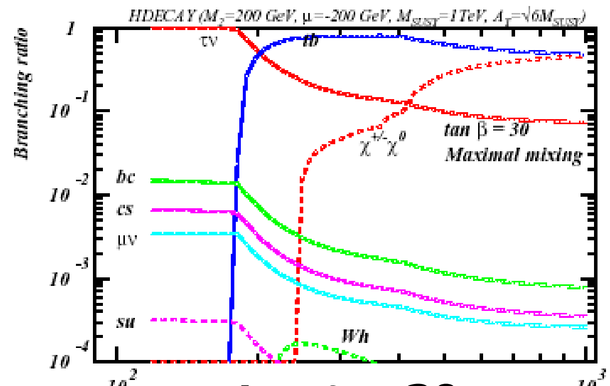


tan β = 30

H±



tan β = 3

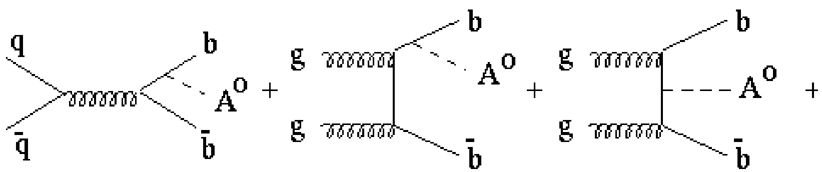


tan β = 30

- **A → $\bar{b}b$ and ττ**
- **$H^{\pm} \to \tau\nu$ and $\bar{t}b$**

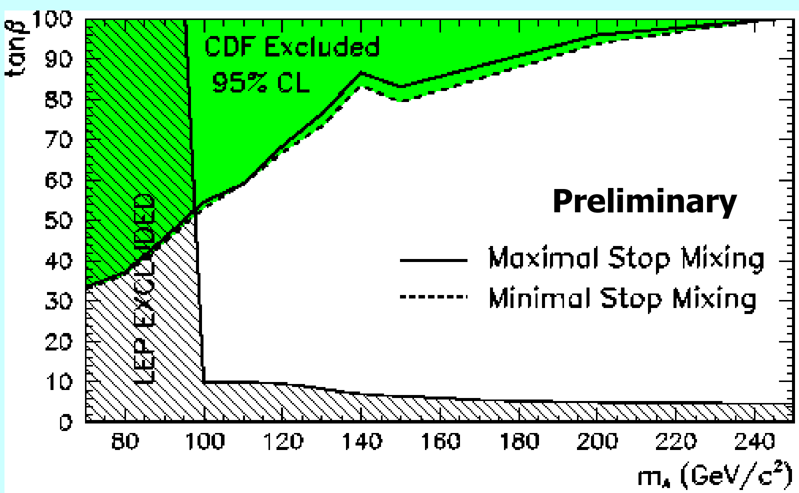
SUSY Higgs Production at the Tevatron

- bb(h/H/A) enhanced at large tan β:

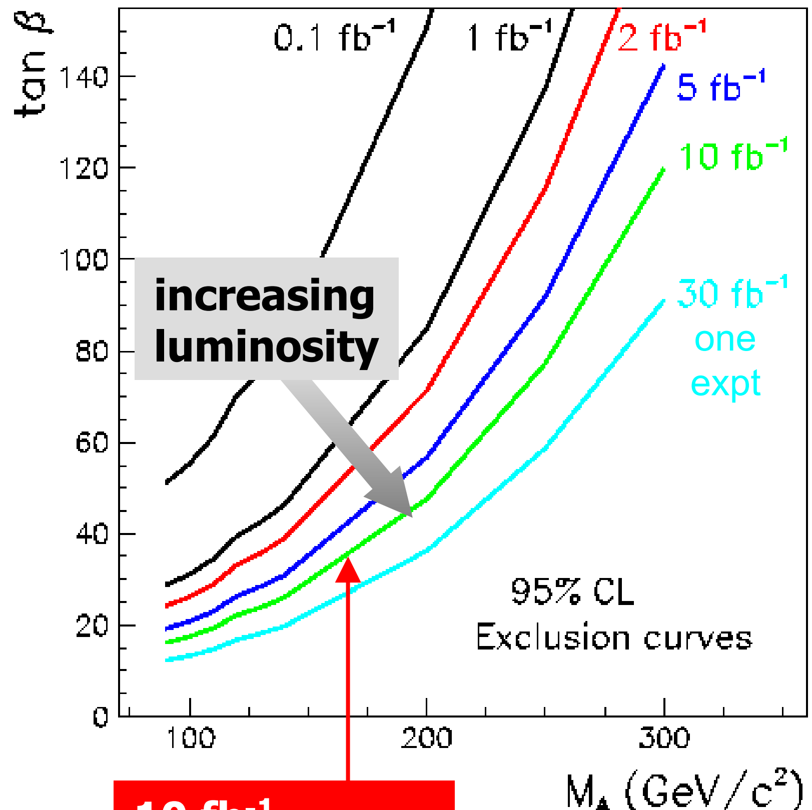


- σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV

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



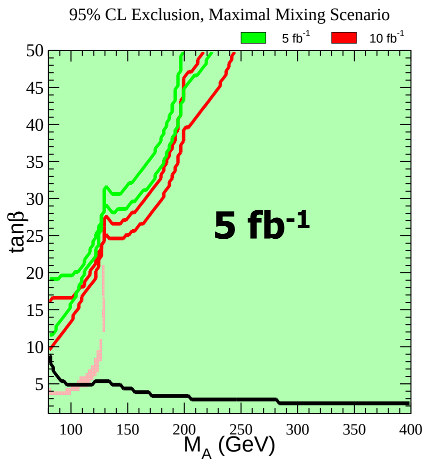
bb(h/A) $\rightarrow$ 4b



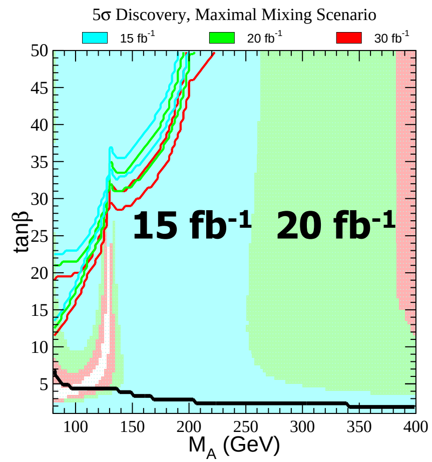
10 fb^{-1}
m_A =150 GeV,
tan β = 30

SUSY Higgs reach at the Tevatron

95% exclusion

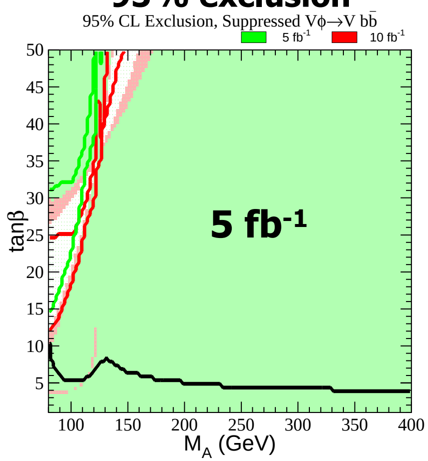


5σ discovery

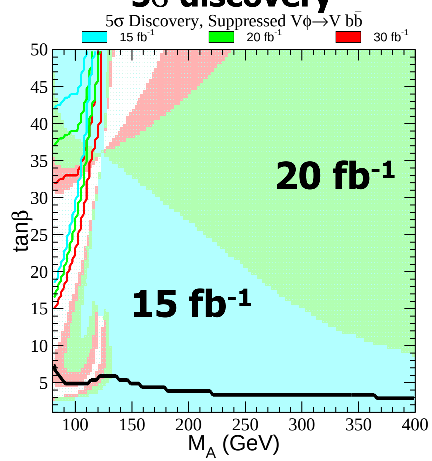


Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV

95% exclusion



5σ discovery

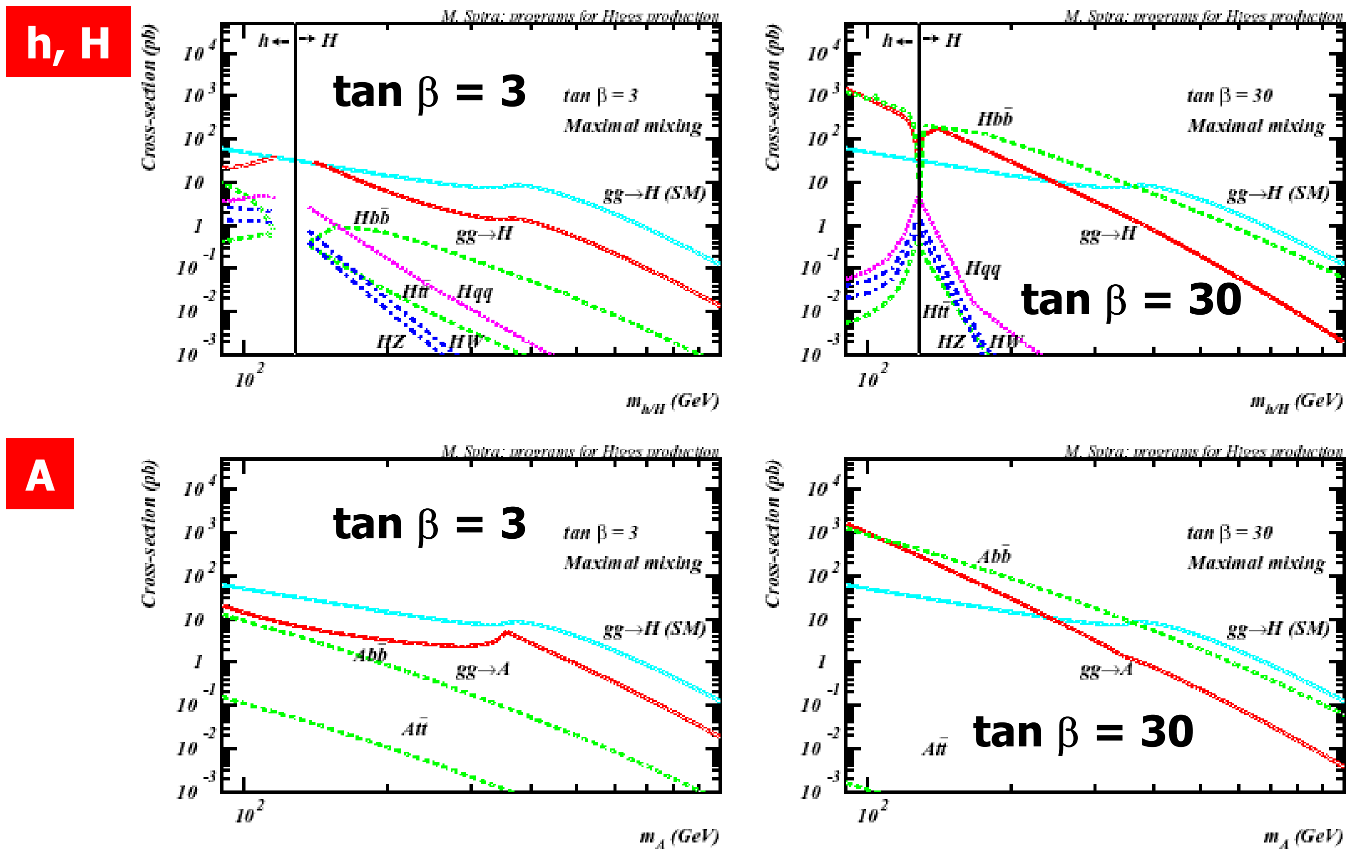


Most challenging scenario: suppressed couplings to bb

Enhances h $\rightarrow \gamma\gamma$?

Luminosity per experiment, CDF + DØ combined

SUSY Higgs production at the LHC

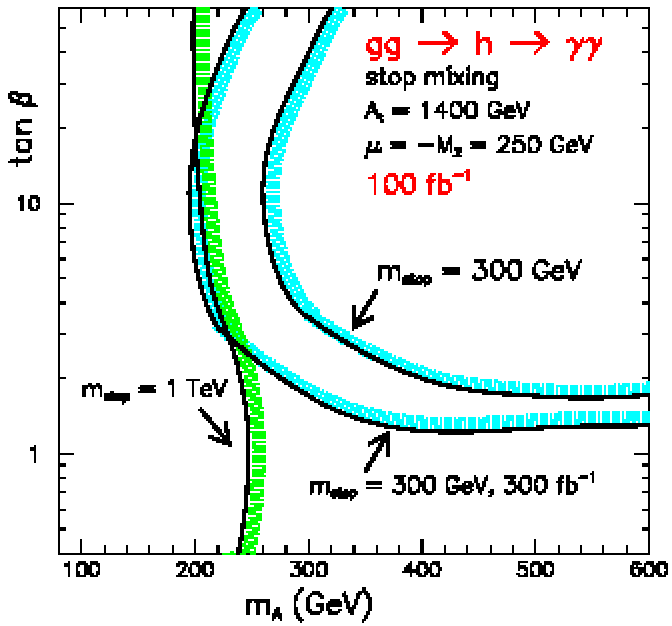


- Cross sections at the 10 pb level and ↑ as tan β ↑
- (H/A) $b\bar{b}$ especially enhanced at large tan β
- VB fusion suppressed

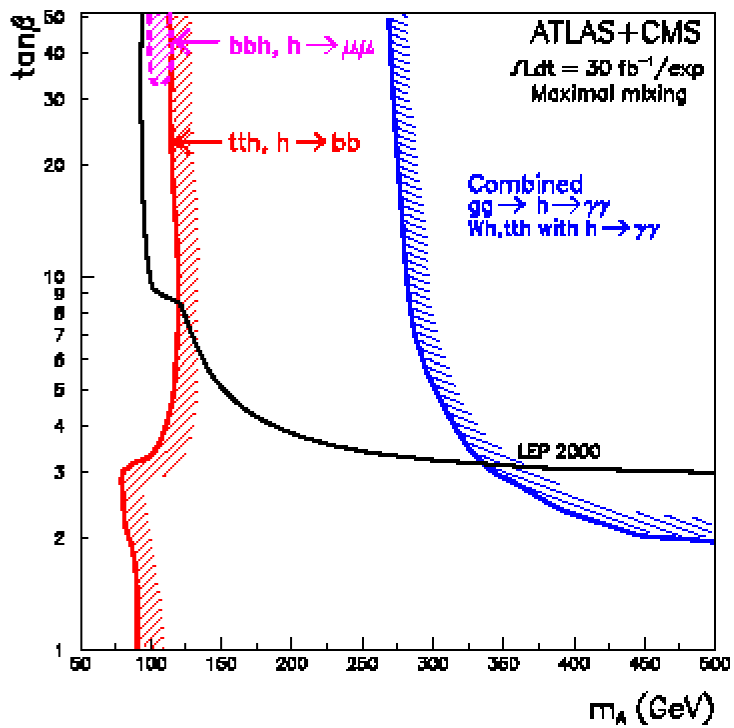
SUSY Higgs discovery channels

- 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 $\chi^0_2 \to \chi^0_1 h$

h discovery modes



$h \to \gamma\gamma$
Suppressed at lower m_h:
sensitive at larger m_A and tan β

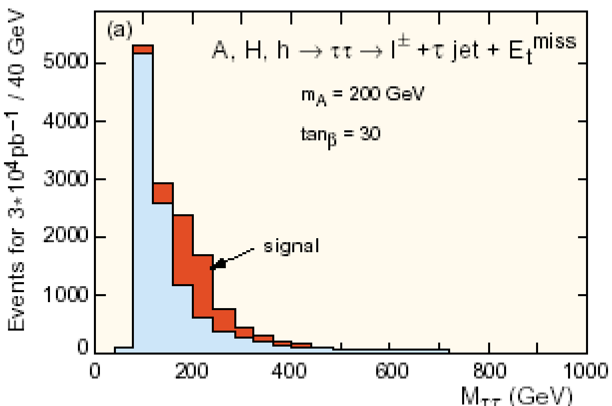


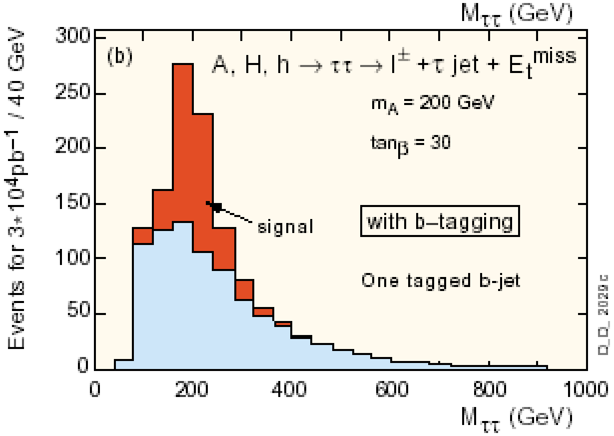
$h \to \bar{b}b$
Using $\bar{t}th$ (and $\bar{b}bh$ at large tan β)

H/A → ττ

$H/A \to \tau\tau \to \ell\tau\text{-jet} + X$

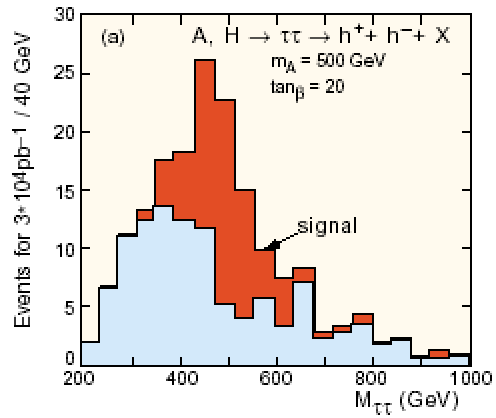
$p_T^{jet} > 40$ GeV, $p_T^{\ell} > 15$ GeV,
$\Delta\phi(j\ell) < 175°$, $E_T^{miss} > 20$ GeV

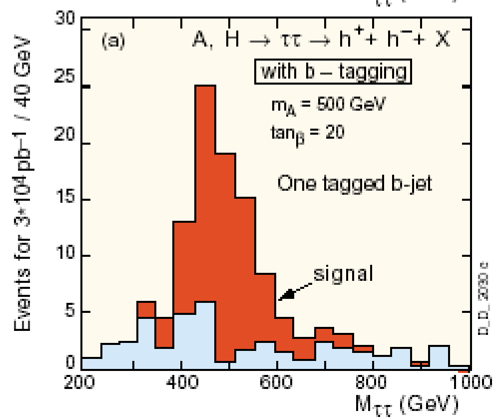




$H/A \to \tau\tau \to 2\tau\text{-jets} + X$

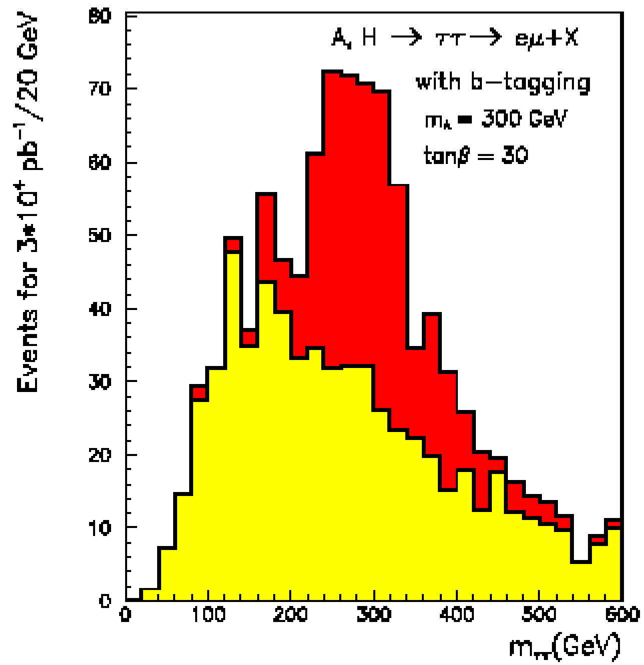
$p_T^{jet} > 60$ GeV, $p_T^{h} > 40$ GeV,
$\Delta\phi(jj) < 175°$, $E_T^{miss} > 40$ GeV





$H/A \to \tau\tau \to 2\ell + X$

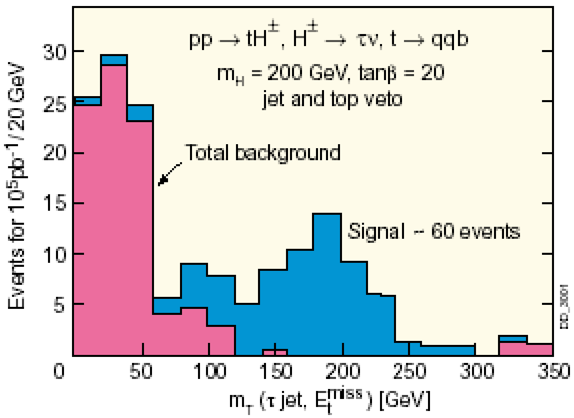
$p_T^{\ell} > 20$ GeV, cut on imp. param.,
$\Delta\phi(e\mu) < 175°$, 1 jet $p_T^{jet} > 20$ GeV

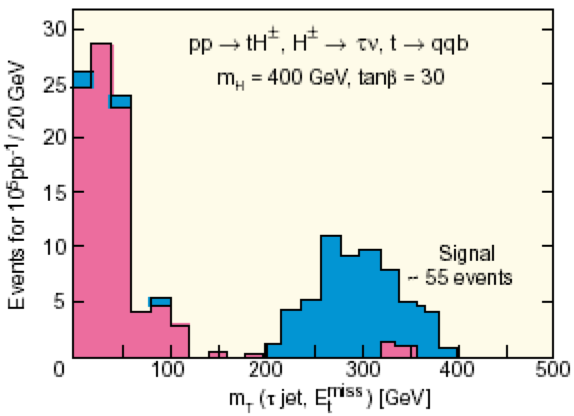


- **b-tagging associated jets is a powerful way to pull out the signal**

$H^{\pm} \to \tau\nu$

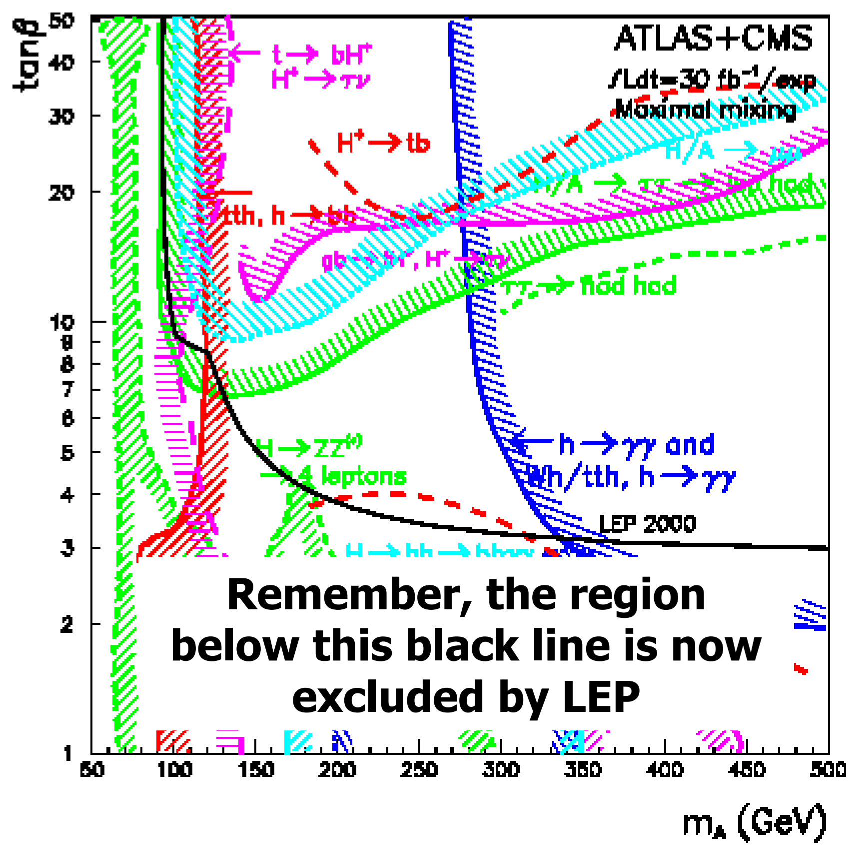
- **For lower masses, search in top decays ($t \to \tau$ rate enhanced)**
- **For higher masses, associated production with top:**
  - **$pp \to tH^{\pm} \to t\tau\nu$**
    - **Signal is a peak in transverse mass of τ jet and E_T^{miss}**
    - **tt background suppressed by jet veto and cut on mass of τ, E_t^{miss} and jet (= m_t for $t \to bW^{\pm} \to b\tau\nu$)**





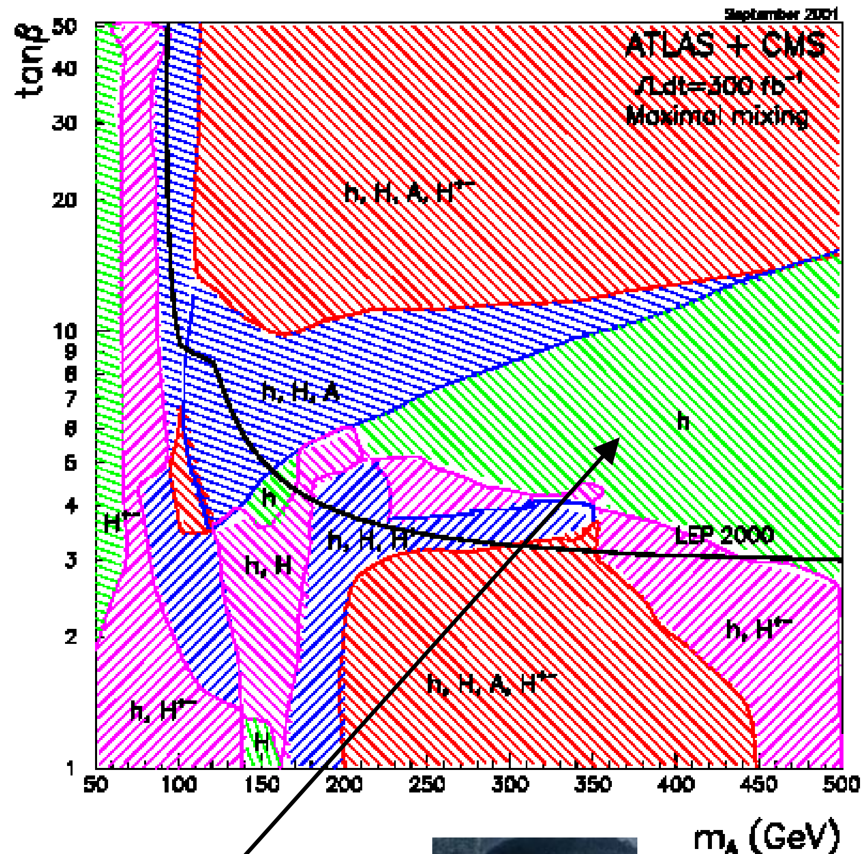
Combined coverage

Discovery Channels

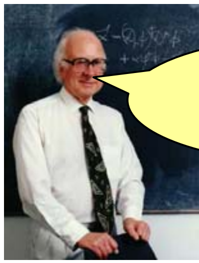


Remember, the region below this black line is now excluded by LEP

Number of Higgses visible



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



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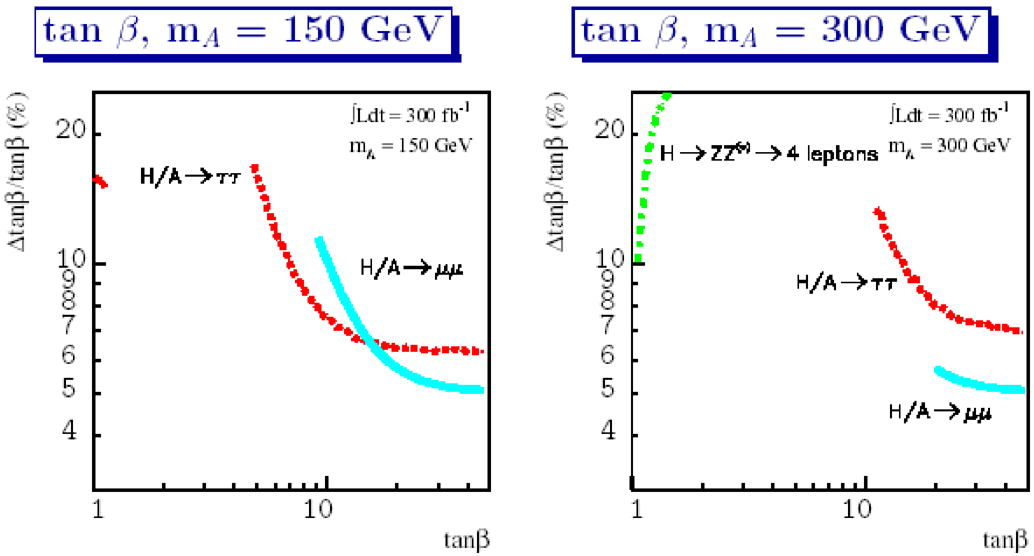
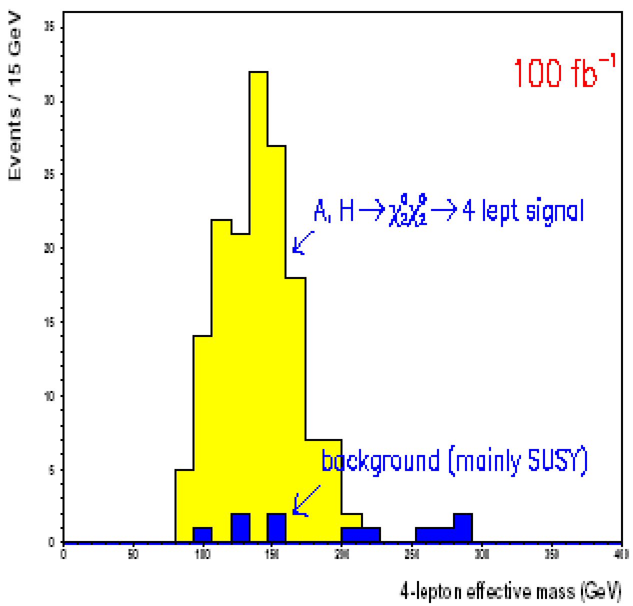
Determination of parameters

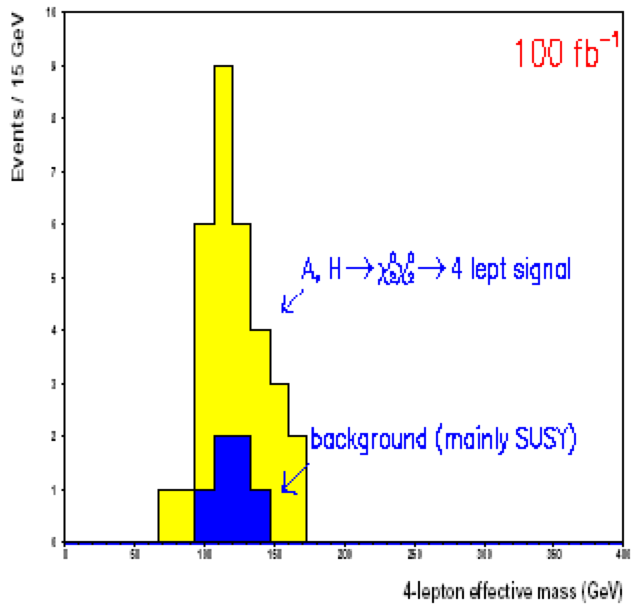
- **First question: do we have a SM H or a SUSY h?**
  - **Note: often this will be moot at the LHC because squarks and gluons will have been observed before any Higgs – but there is always the possibility of more complicated Higgs sectors**
- **Second question: where are we in SUSY parameter space (or 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:**



SUSY decay modes

- **If we are lucky, beautiful signals may be observable**
  - **e.g. (H/A) $\rightarrow \chi^0_2\chi^0_2 \rightarrow 4l$**





  - **h $\rightarrow$ $\bar{b}$b in cascade decays from squark and gluon production**

Complementarity of the Tevatron and LHC

- The Physics goals of the Tevatron and the LHC are not very different, but the discovery reach of the LHC is hugely greater
  - SM Higgs:
    - Tevatron < 180 GeV LHC < 1 TeV
  - SUSY (squark/gluino masses)
    - Tevatron < 400-500 GeV LHC < 2 TeV
- For Standard Model physics, systematics may dominate:
  - Top mass precision
    - Tevatron ~ 2 GeV LHC ~ 1 GeV?
  - m_W precision
    - Tevatron ~ 20 MeV? LHC ~ 20 MeV?

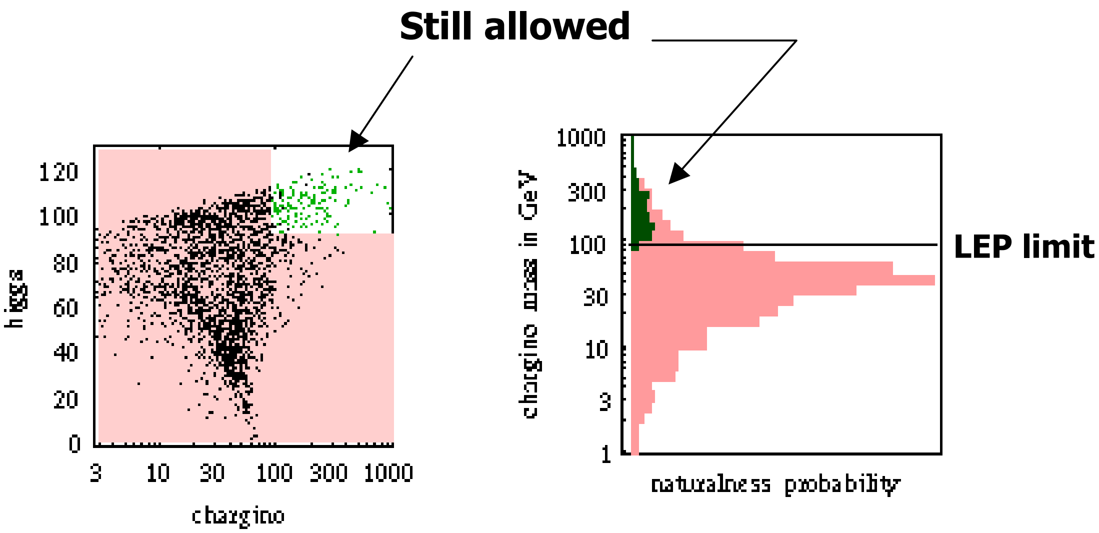
Despite its limited reach, the Tevatron is interesting because both Higgs and SUSY "ought to be" light and within reach — and because of the timing

If the Tevatron and LHC are in a race, it is a relay race

Where is SUSY?

Direct searches at LEP and the Tevatron all negative so far

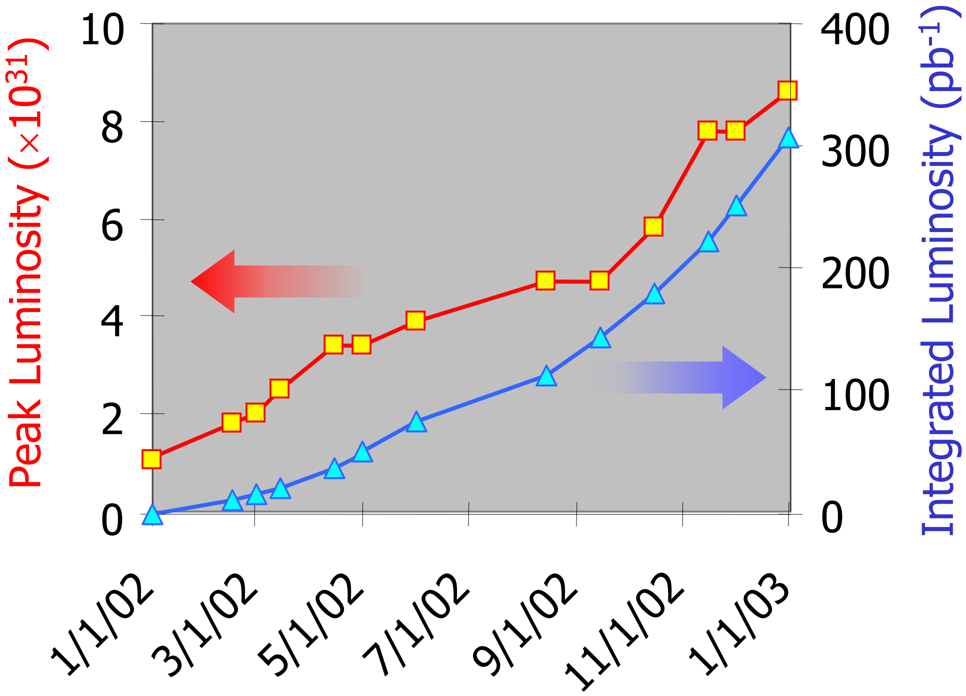
- Typical minimal supergravity-inspired SUSY models are already excluded at the 95% level
  (e.g. Strumia, hep-ph/9904247)



- Either we should expect to see something soon, or we (HEP) are on the wrong track . . .

Tevatron plans 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
- Laboratory plan for luminosity:

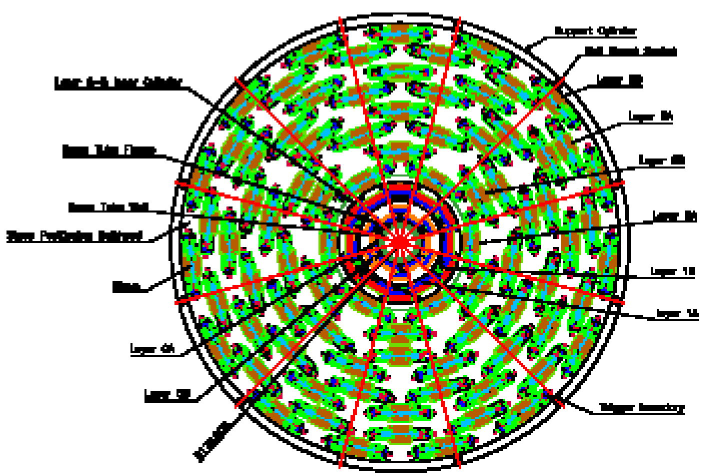


We anticipate first physics results in Summer* 2002

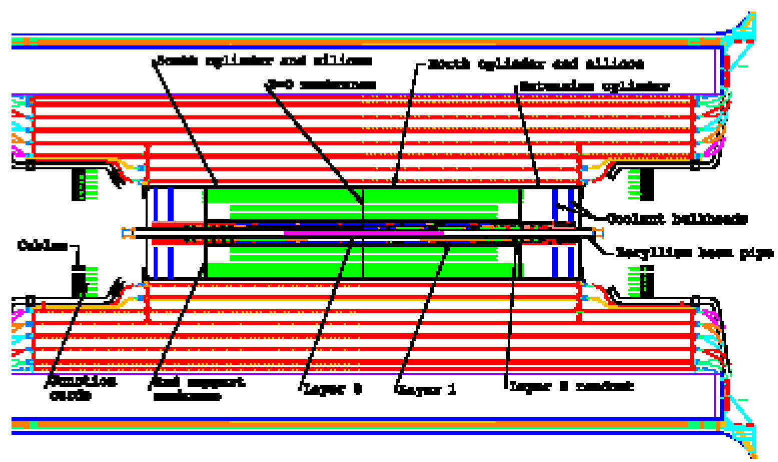
*(*northern hemisphere)*

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**

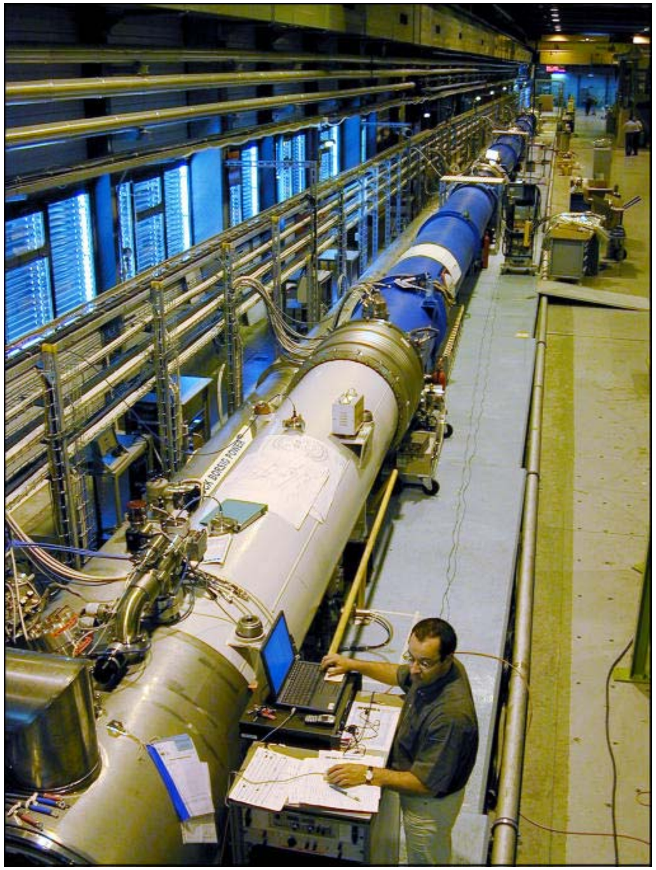


Proposed DØ Run 2B silicon detector



Run 2B silicon installed

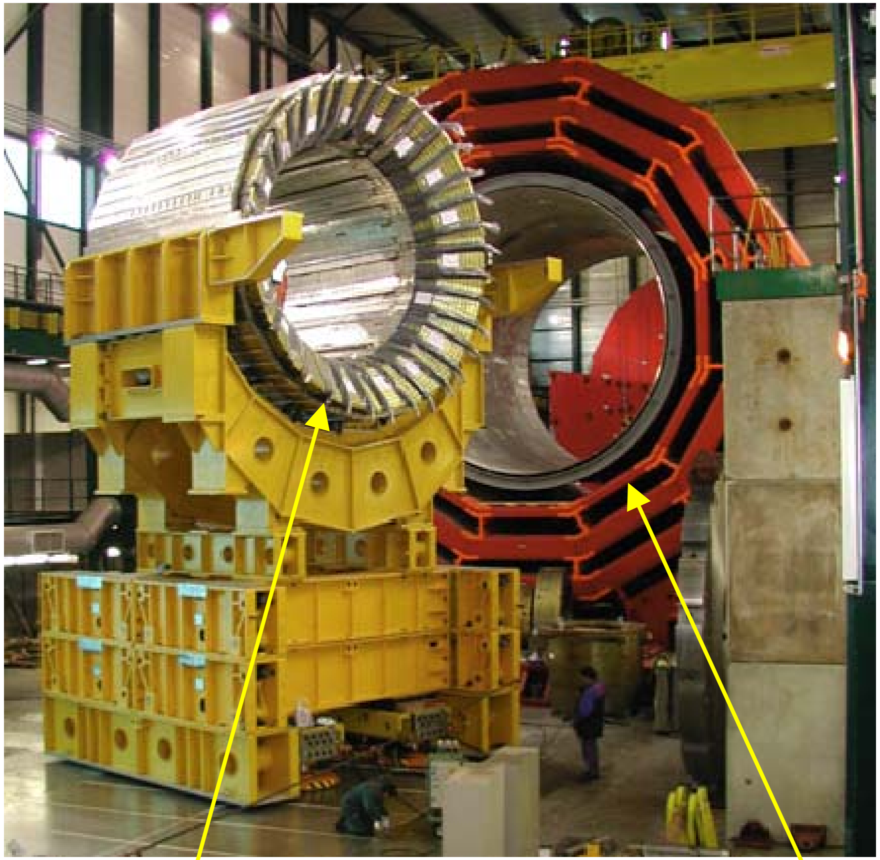
LHC construction



Magnet String Test (dipole procurement now approved)

Underground construction at the ATLAS cavern

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 already 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

Conclusions

- In the current run at the Tevatron (2001–200x)
  - We will discover the Higgs, if we are fortunate and clever
  - If not, we will exclude a very interesting region
    - including exclusion of much of SUSY space
- at the LHC (200x—)
  - We will discover the Higgs, pretty much no matter what
  - We will measure it more precisely, in more decay modes
  - We will explore more SUSY Higgs states
    - and we will learn lots about SUSY from other searches

- 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, we hope, the first window on to a new domain of physics at the EW scale