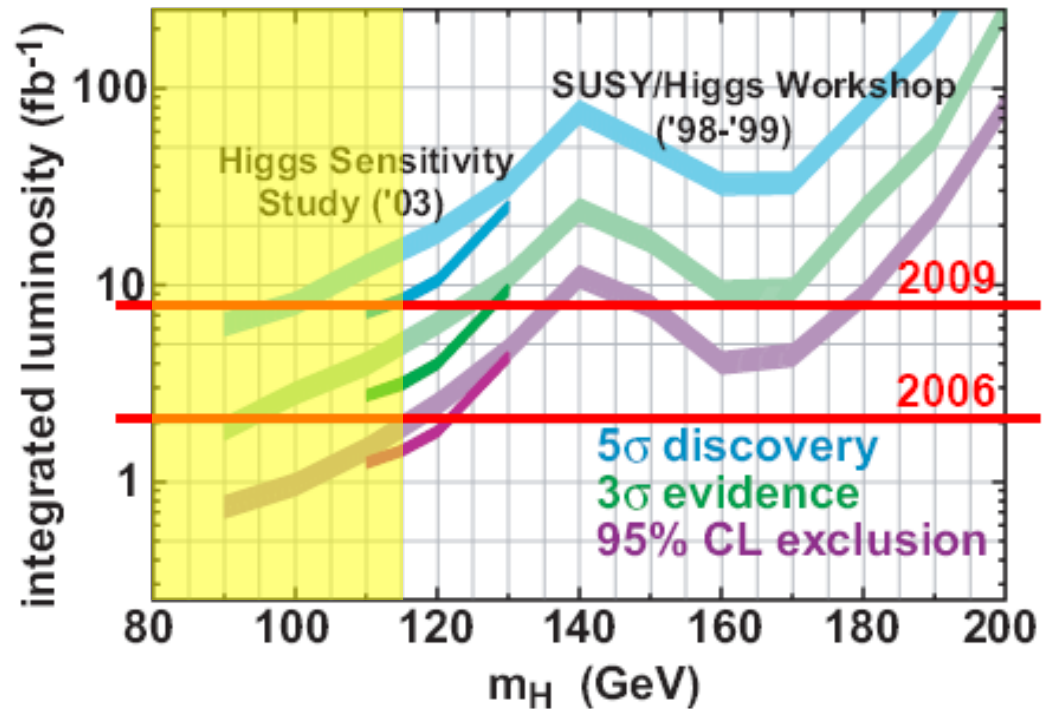


The Search for the Higgs Boson

- An Opening to New Physics

Dr. Andy Haas
Columbia University
DØ / ATLAS

University of Washington
Physics Colloquium
January 22, 2007

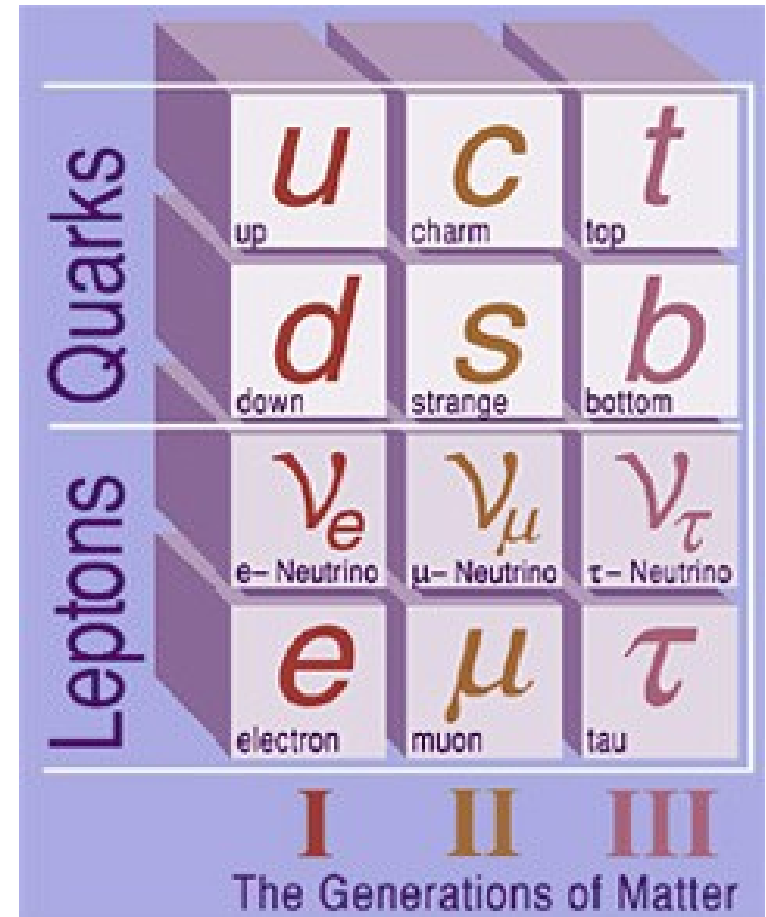


Outline

- What is the Higgs?
- Current searches for Higgs
 - Standard Higgs
 - Extra Higgses from supersymmetry
- Is something else going on?
 - Looking for some new things
- The big deal in Switzerland
 - A new way to see Higgses over there

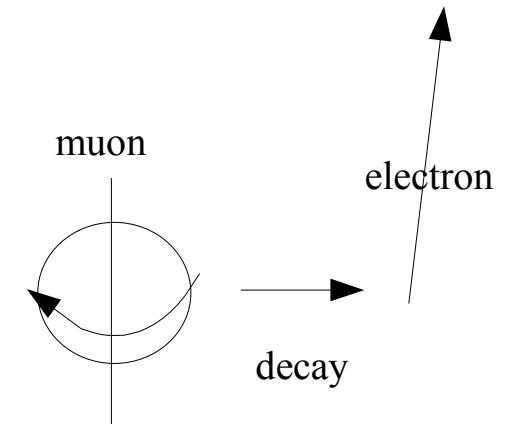
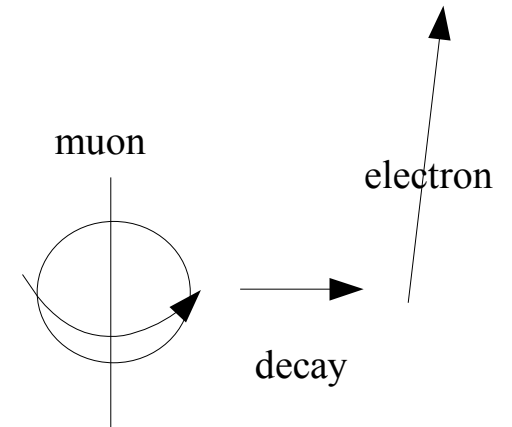
The Standard Model

- 3 families of matter
 - quarks, leptons
- 3 forces
 - EM, Weak, Strong forces
 - photon, W/Z, gluons
 - “gauge symmetries”:
 $U(1) \times SU(2)_L \times SU(3)$
- (oh, and there's gravity)



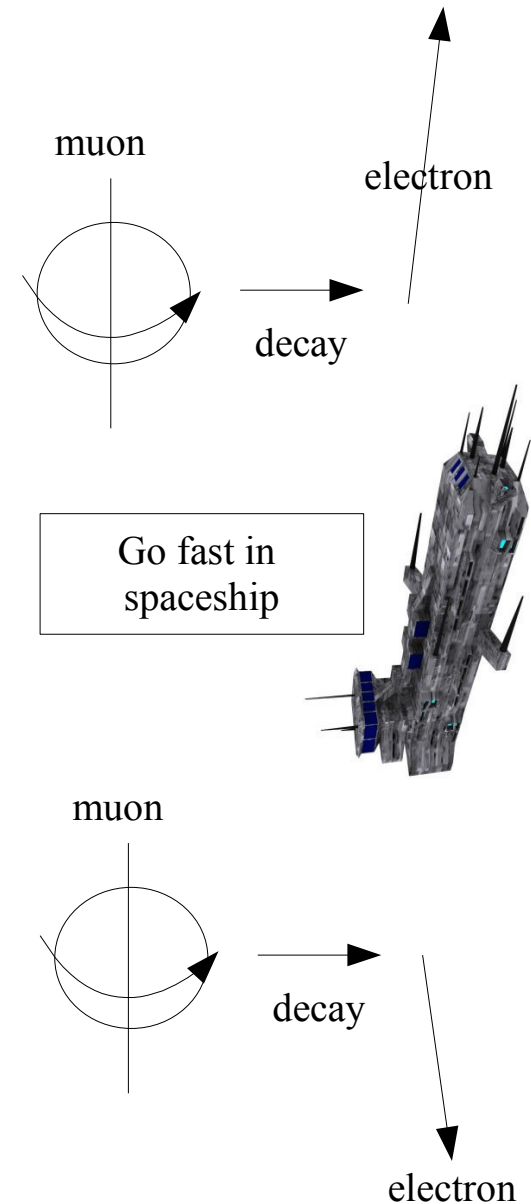
The Weak Force is Weird!

- Experiments in the 1950's showed that the Weak force is *left-handed*
 - particles go in a preferred direction based on the spin direction
- You can tell the real world from the world in a mirror!



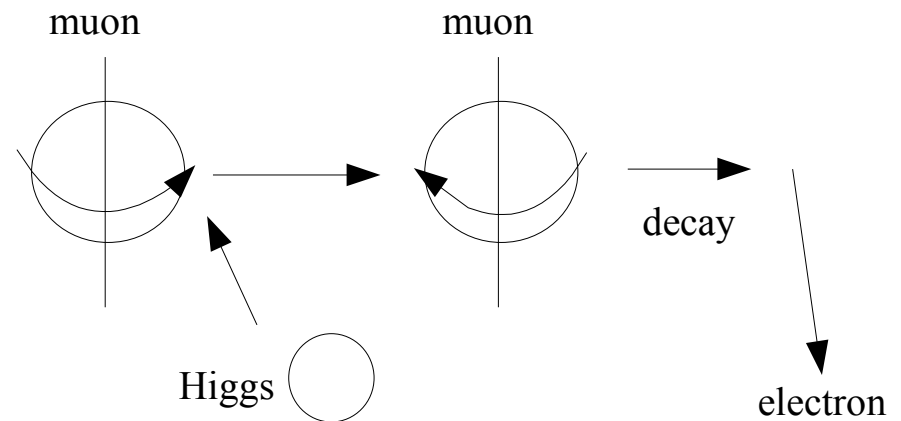
That "L" Makes a Big Difference

- Relativity: physics looks the same no matter how you are moving
- In a spaceship going faster than the electrons, you'd see them going *down*
- That violates our rule!
 - It must not be possible to go faster than an electron!
 - > The electron must be massless!
- $SU(2)_L$ gauge invariance
 - > All particles must be massless!
- How do we give particles mass?



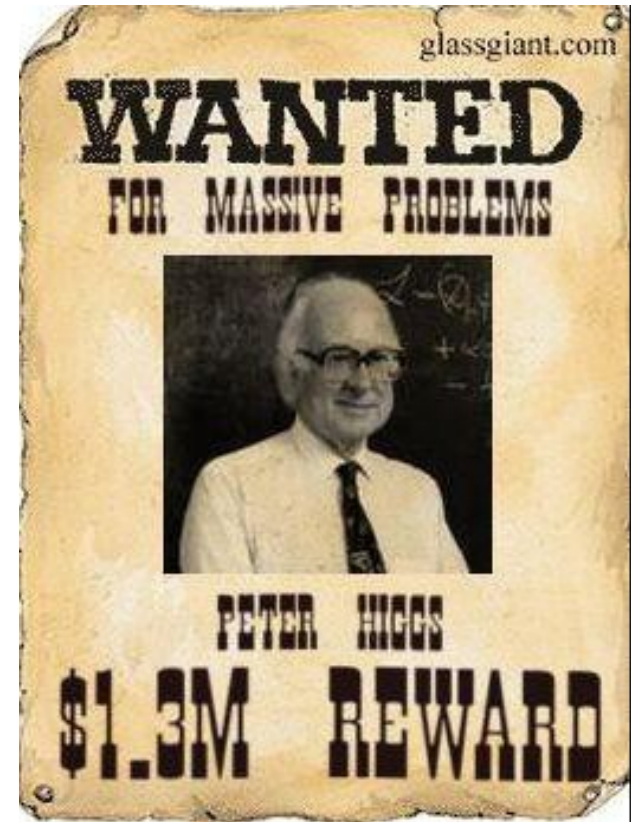
The Higgs Boson

- Gives masses to the quarks and leptons, and W/Z bosons
 - but leaves the photon alone (thankfully)
- The Higgs field costs *less than nothing* to have around - like a helpful friend!
 - Empty space prefers a non-zero Higgs density
- Particles get *effective* mass by interacting with the Higgs field of empty space



Searching for the Higgs

- Sounds good, but how do we know it's true?
- Excite the Higgs field
 - make Higgs *particles* !!!
- Need to collide particles with enough energy to create the mass of the Higgs
 - $E=mc^2$
- Indirect evidence, Higgs mass is about 10-1000 GeV
 - Build a big accelerator!



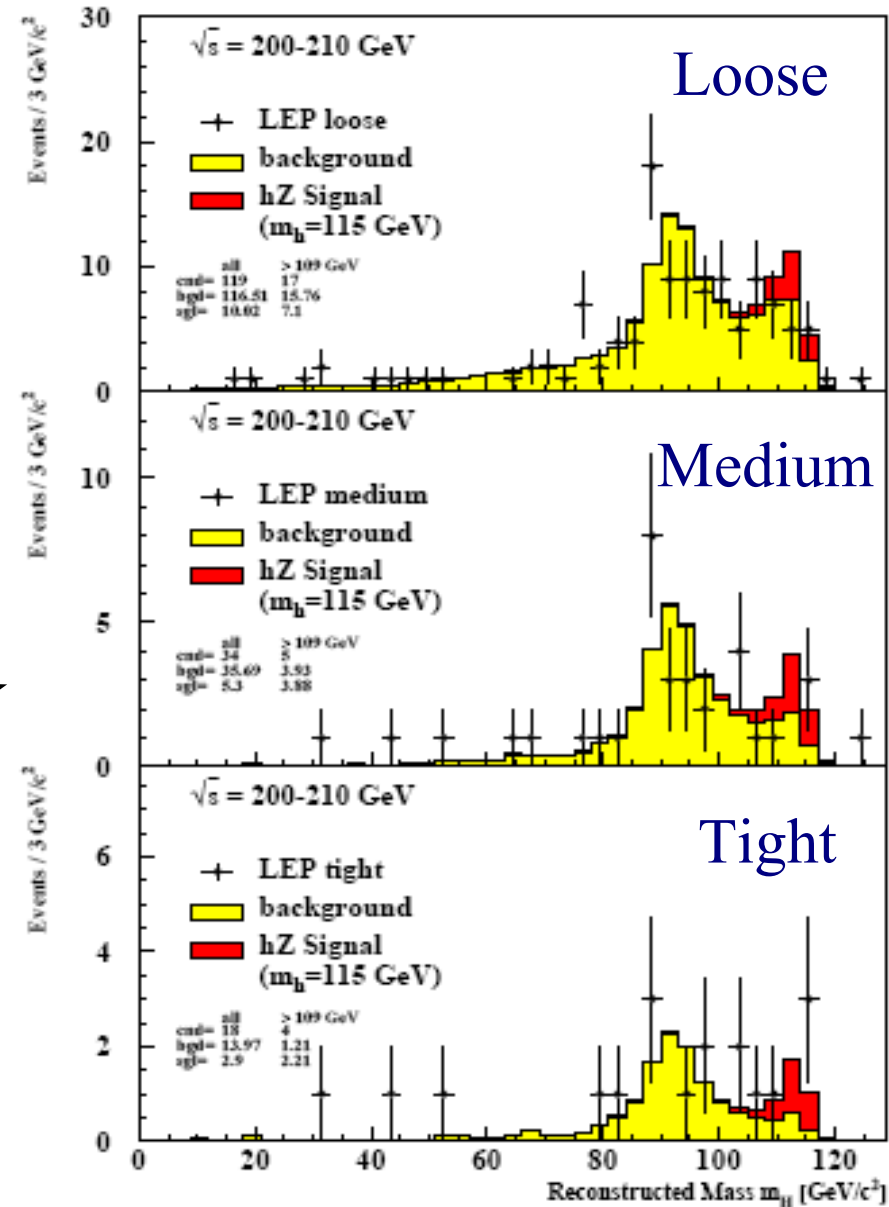
LEP @ CERN in 2000

- Circular $e^+ e^-$ collider
- Energy was 200-210 GeV



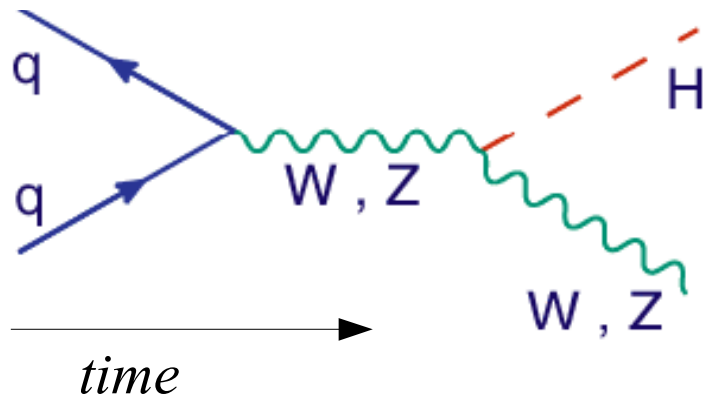
A good, but not the only variable...

- Look for $e^+ e^- \rightarrow h(-\rightarrow bb)+Z$
- Slight excess around 115 GeV?
- Higgs mass > 114.4 GeV



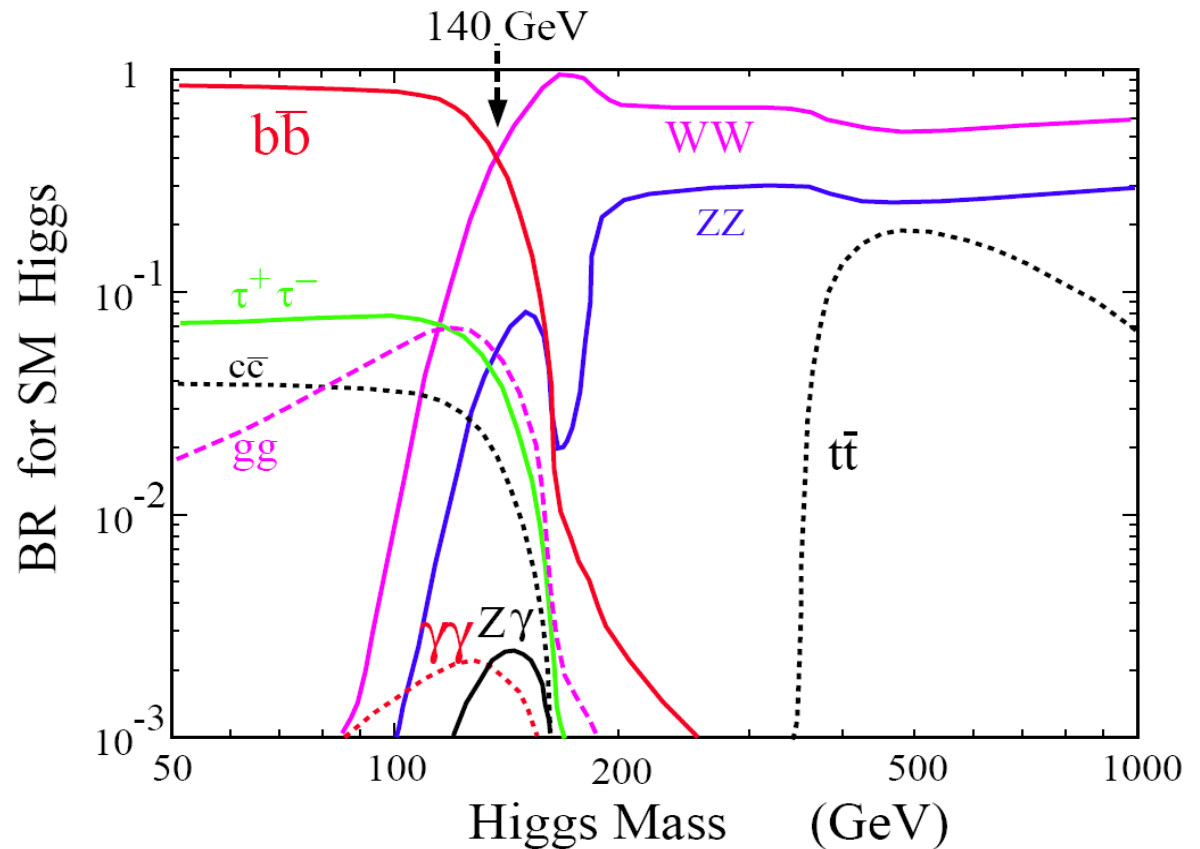
The Tevatron at Fermilab

- Running (again) since ~2003
- proton on anti-proton
- 1 km radius
- Each (anti)proton has $E = 1 \text{ TeV}$
 - 1000x the rest mass!
- 2.5 million collisions / sec.
 - Can look for very rare processes (like Higgs)



What the Higgs "Looks Like"

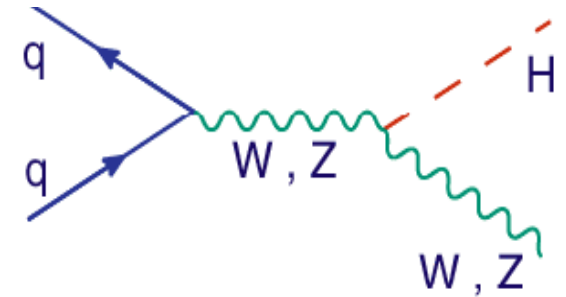
- The Higgs has a short life
- What it decays to depends on its mass
- Main focus at the Tevatron is:
 - $b\bar{b}$ (low mass)
 - WW (high mass)



Higgs Analyses at DØ

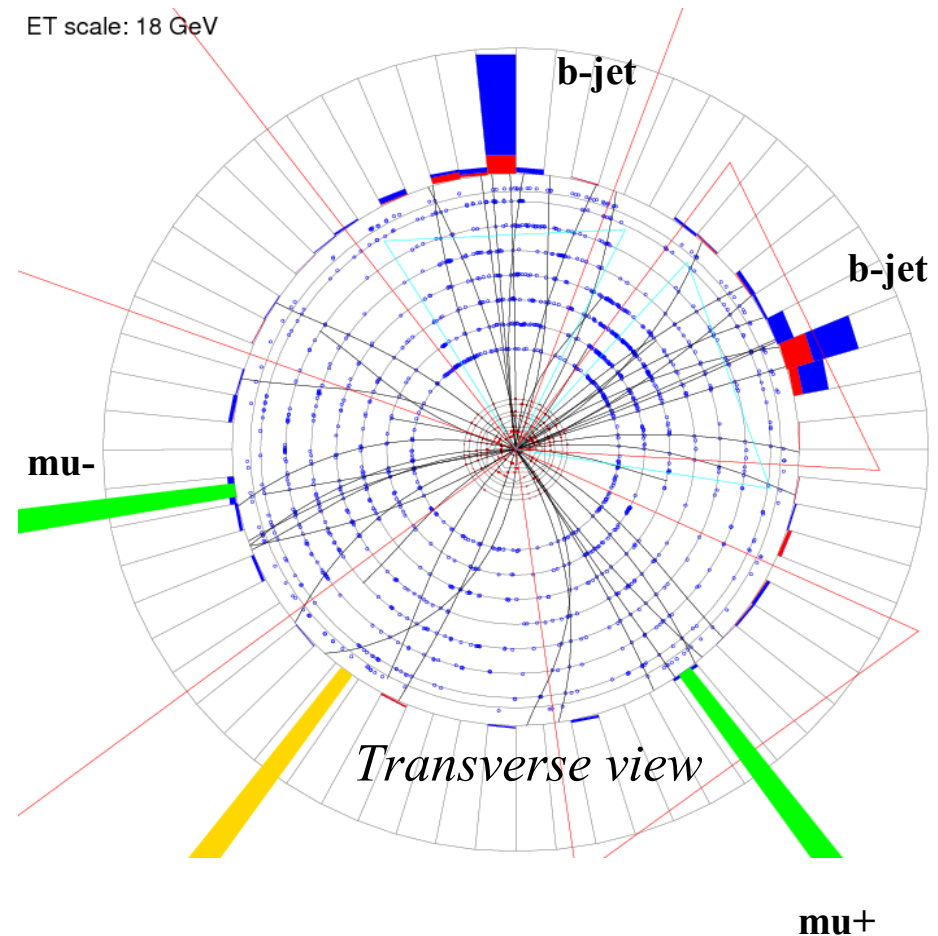
- $Wh \rightarrow e \nu b b$
- $Wh \rightarrow \mu \nu b b$
- $Wh \rightarrow \tau \nu b b$
- $Zh \rightarrow \nu \nu b b$
- $Zh \rightarrow e^+ e^- b b$
- **$Zh \rightarrow \mu^+ \mu^- b b$**

- $h \rightarrow WW \rightarrow e^+ \nu e^- \nu$
- $h \rightarrow WW \rightarrow \mu^+ \nu \mu^- \nu$
- $h \rightarrow WW \rightarrow e^+ \nu \mu^- \nu$
- $Wh \rightarrow WWW \rightarrow e^+ e^+ \nu \nu + X$
- $Wh \rightarrow WWW \rightarrow \mu^+ \mu^+ \nu \nu + X$

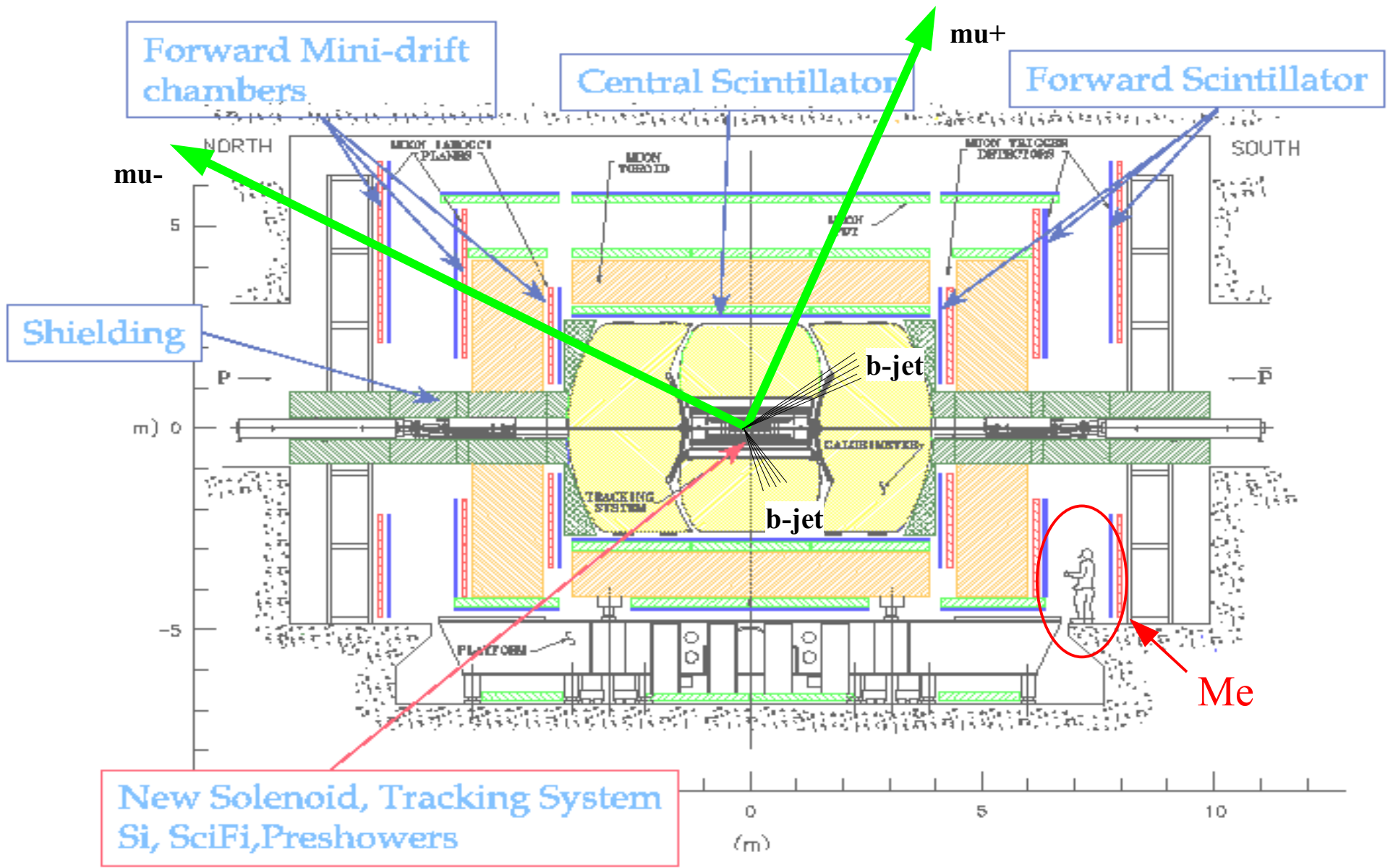


The $Zh \rightarrow \mu^+ \mu^- b b$ Search

- Look for $h+Z$ final state
 - Z decays to muons
 - Higgs decays to bb
- Easy to observe Z decay
 - reduces backgrounds
- b 's form b -jets
- can identify and separate from other jets (gluon, u,d,s)
 - reduces backgrounds

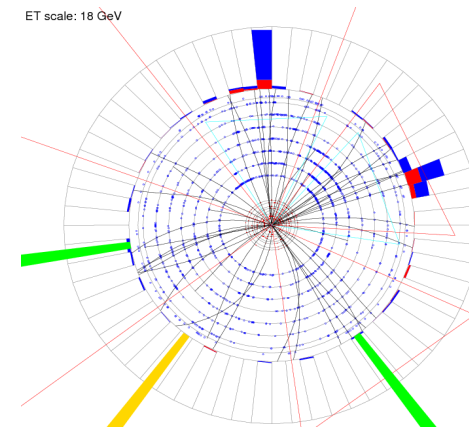
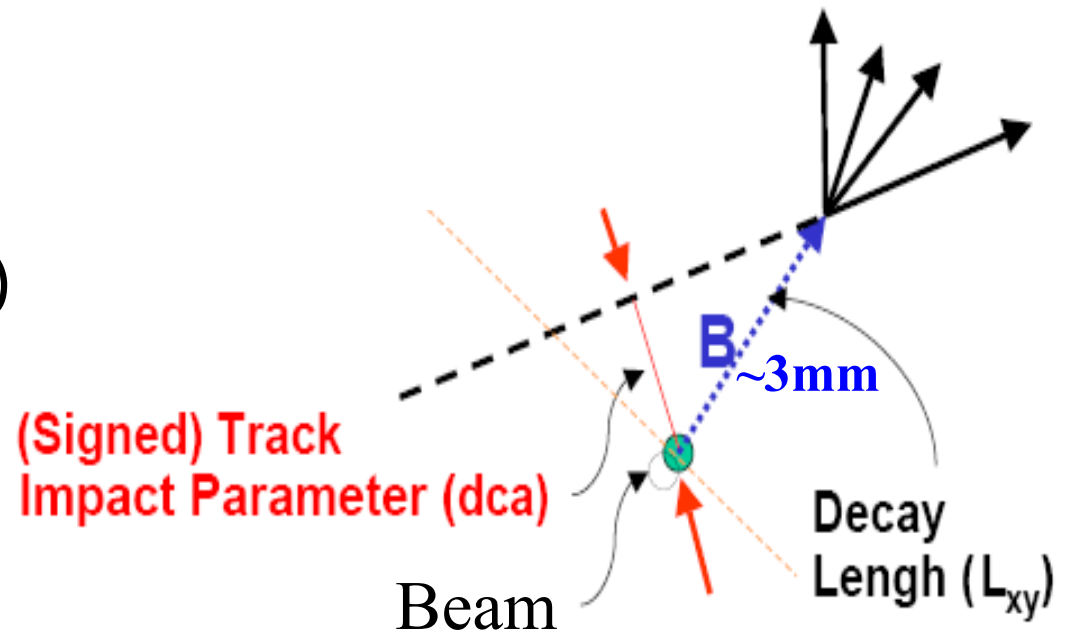


The DØ Detector

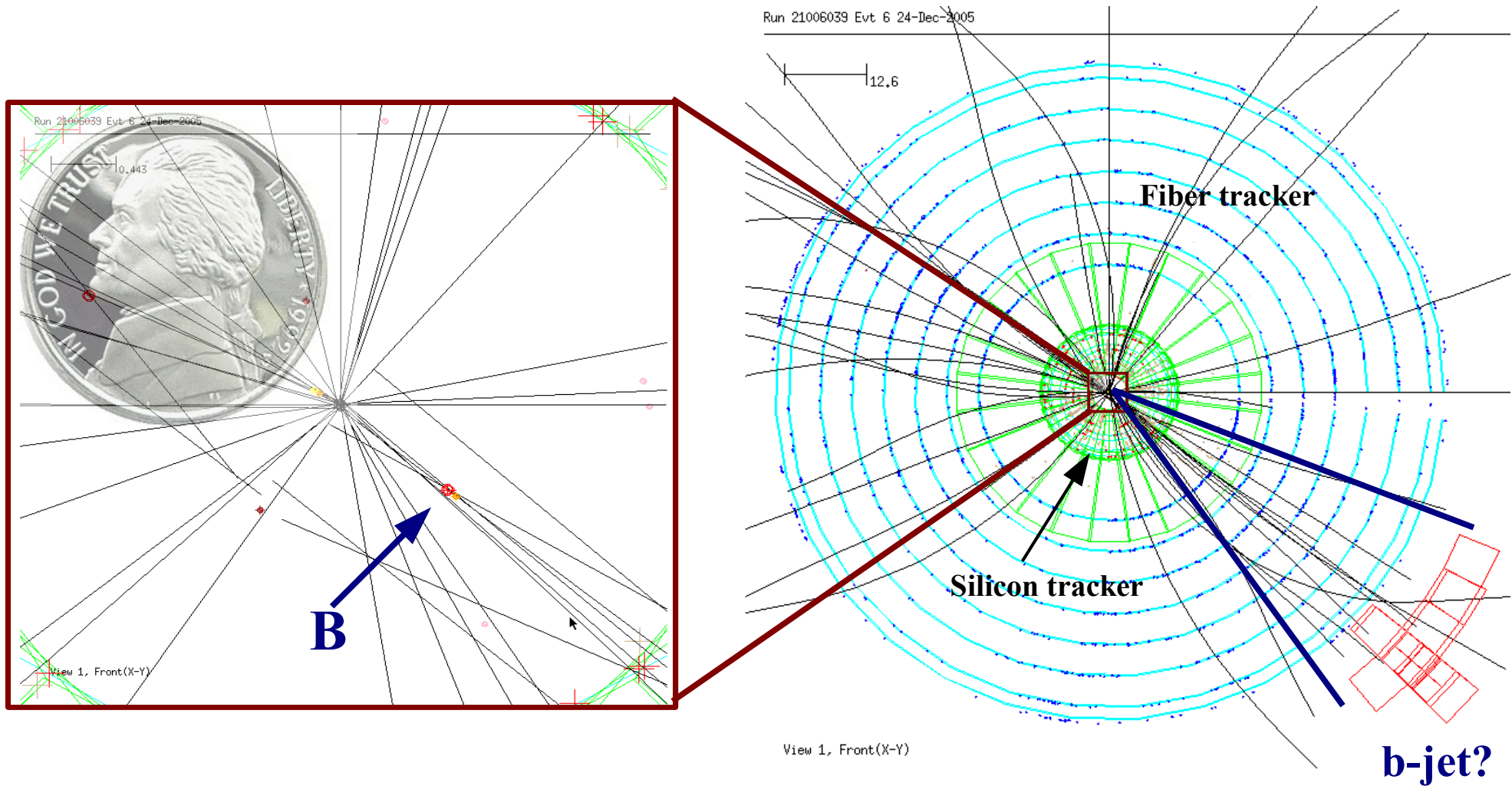


b-Jet Tagging

- How do we know when a jet is a b-jet?
 - B hadrons are "long"-lived (a picosecond is forever...)
- Reconstruct charged particles tracks
- Identify jets with
 - large impact parameter significance tracks
 - large decay length significance vertices

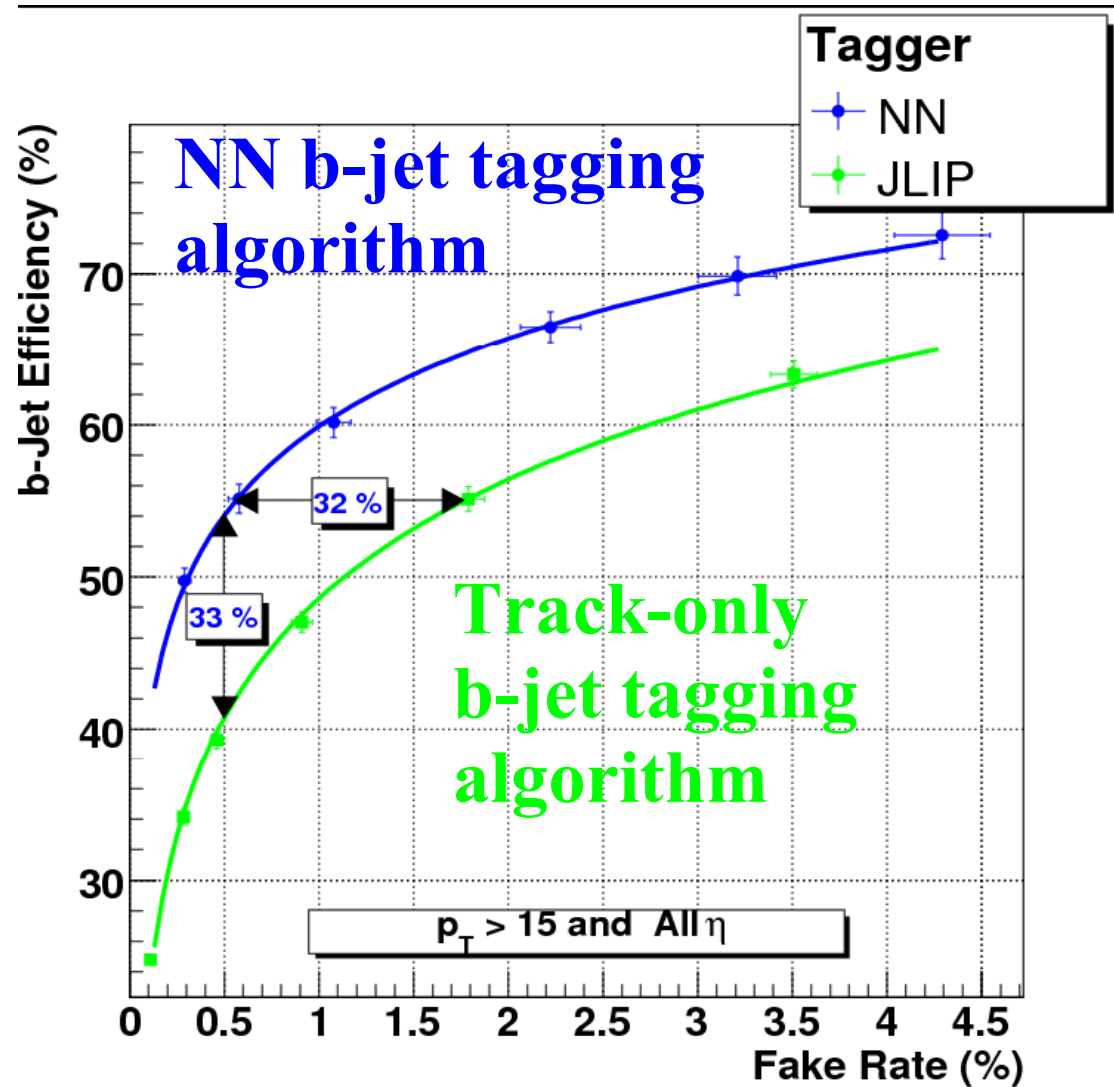


b-Jet Tagging Reality



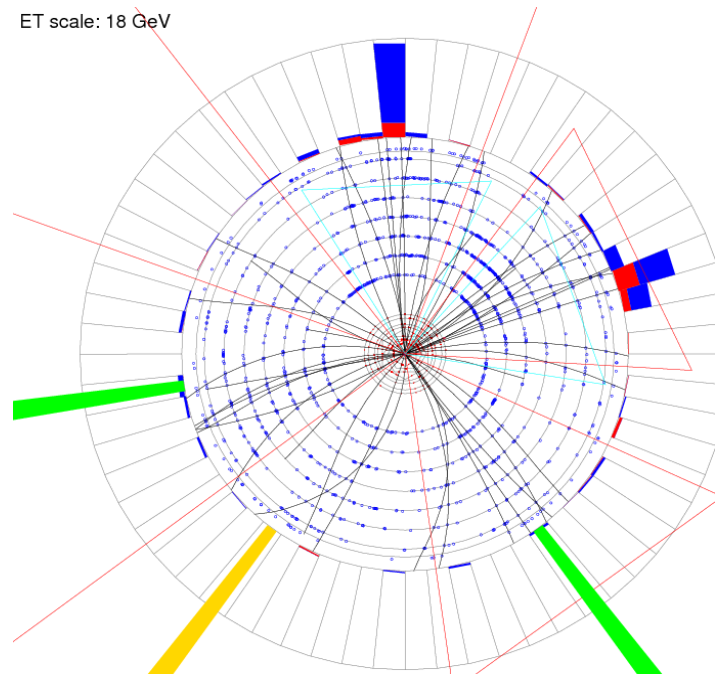
NN b-Jet Tagging

- Combine properties of the reconstructed vertex and tracks using an artificial Neural Network
- Increases S/\sqrt{B} by $\sim 30\%$ per b-jet
- Like having 2.5x as much data!



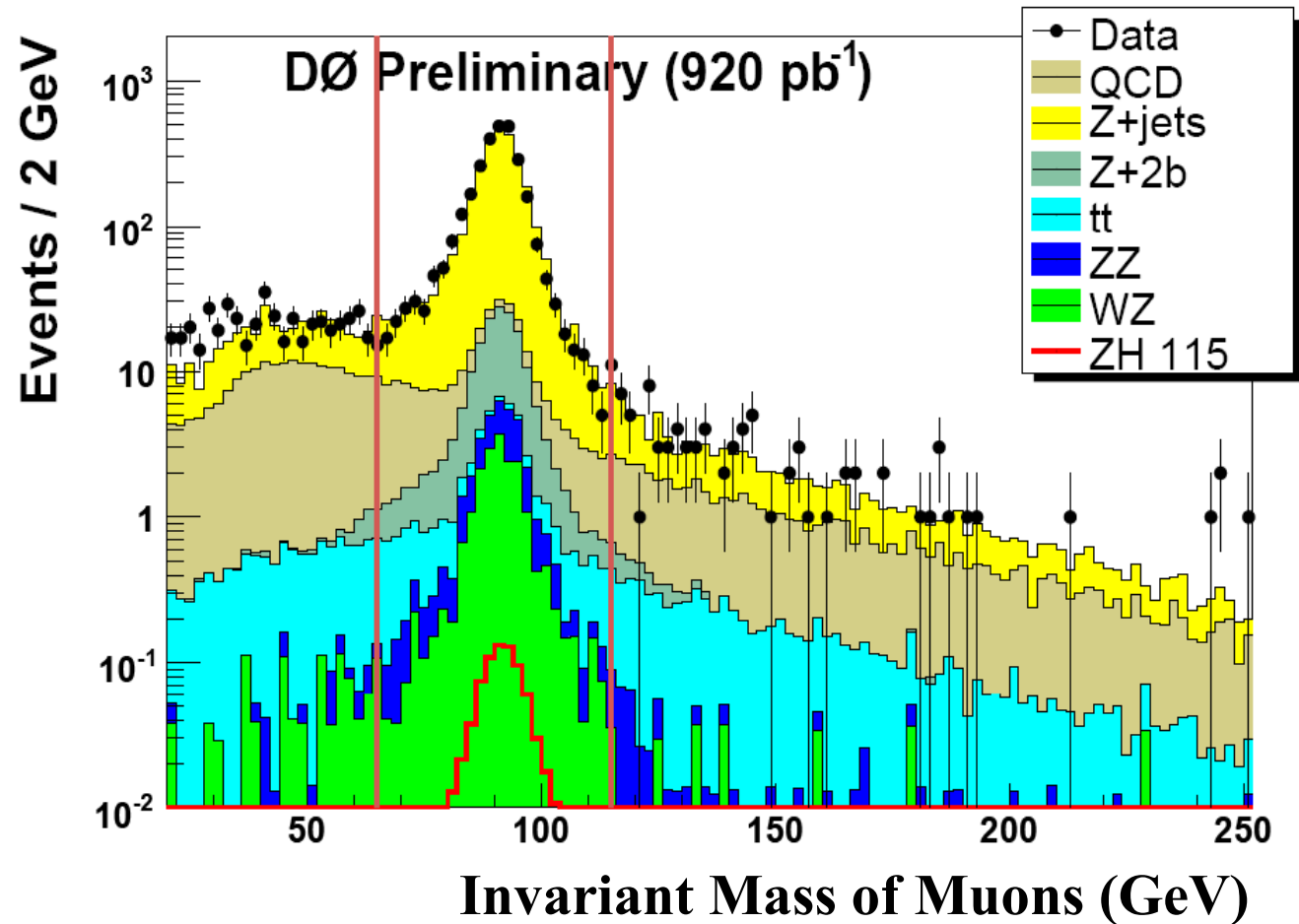
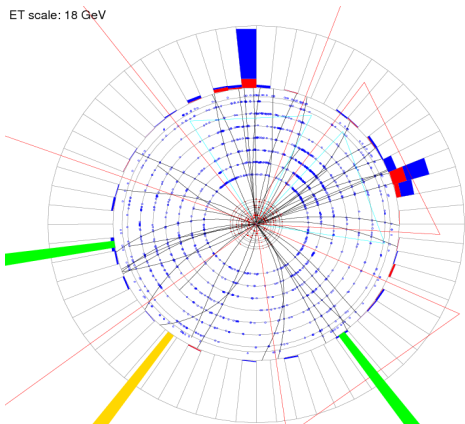
The $Z_h \rightarrow \mu^+ \mu^- b \bar{b}$ Search

- Let's look at the data!
- And apply the b-tagging technique



Z + 2 jets Data

- First, select events with a Z
- Main background is Z+(non-b-)jets
- b-jet tagging will help reduce this

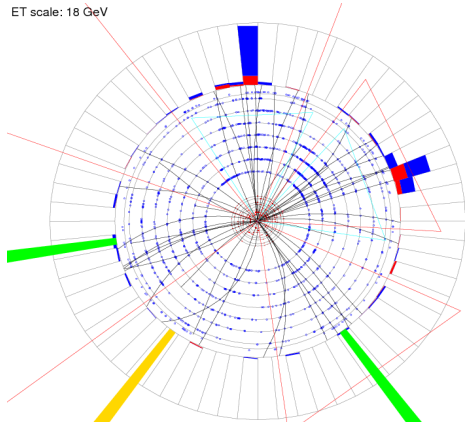


Z + 2 b-jets Data

- Require at least 2 of the jets to have NN b-tags
 - Z+(non-b-)jets background greatly reduced
- Look for bump from Higgs→bb

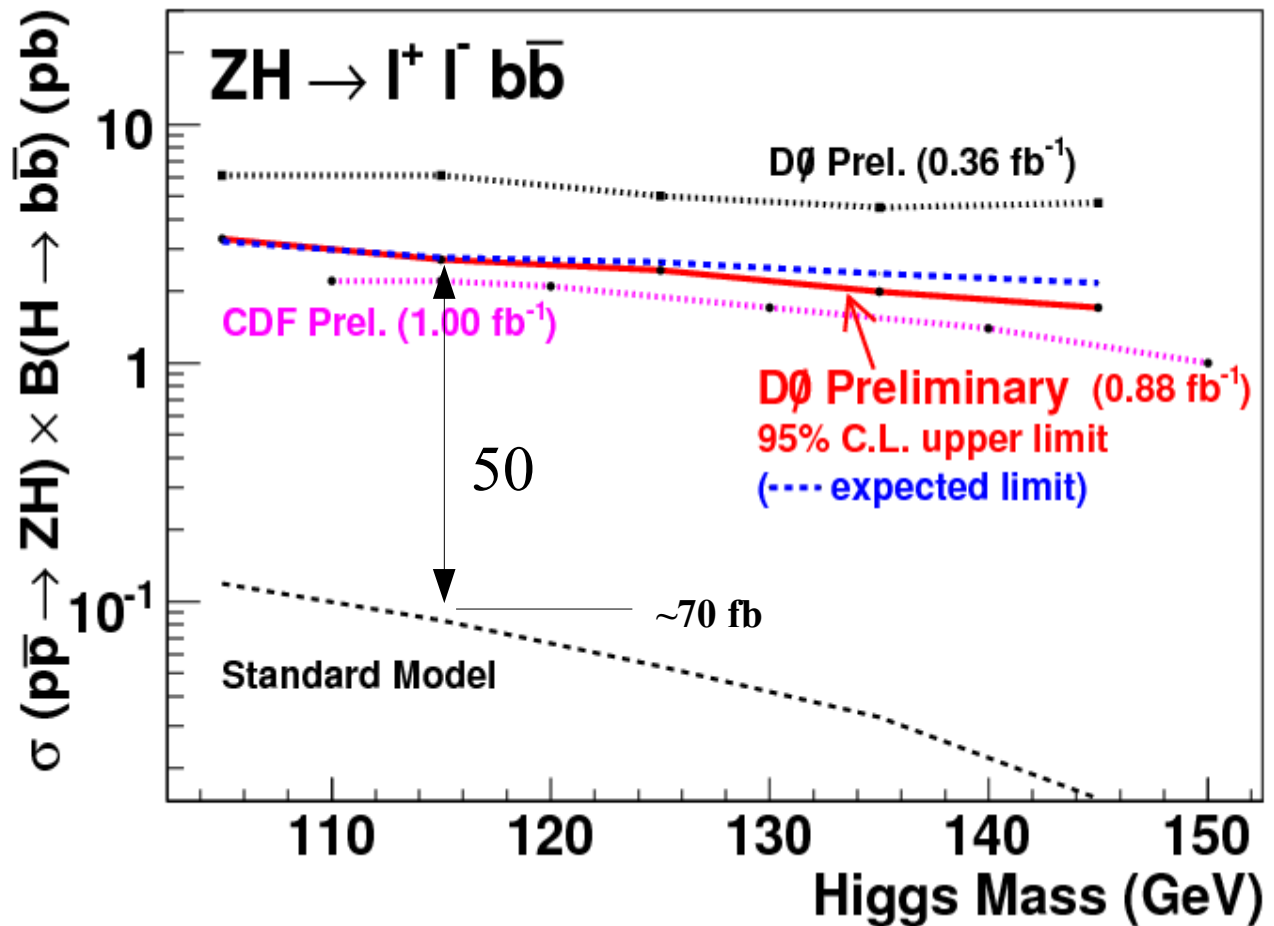


ET scale: 18 GeV



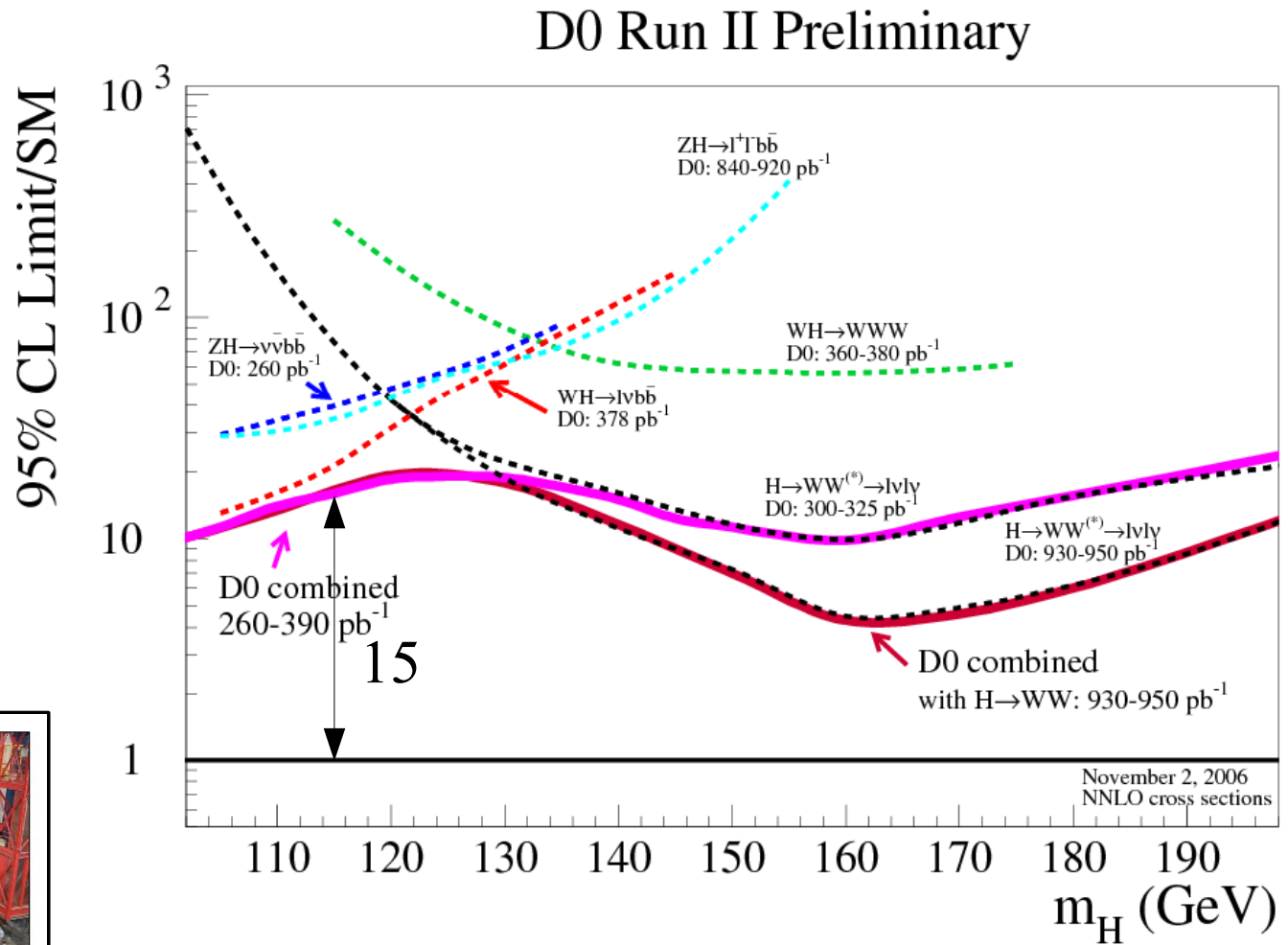
Zh \rightarrow $l^+ l^- b \bar{b}$ Limits

- Combine with Zh \rightarrow $e^+ e^- b \bar{b}$ channel
- Set an upper limit on the rate of Zh production
- We need a factor of $\sim 50\times$ more sensitivity to see the Higgs in this channel alone (at 115 GeV)



Combining the Channels

- Fortunately, there are many channels
- A factor of ~ 15 away from the Higgs (115 GeV)



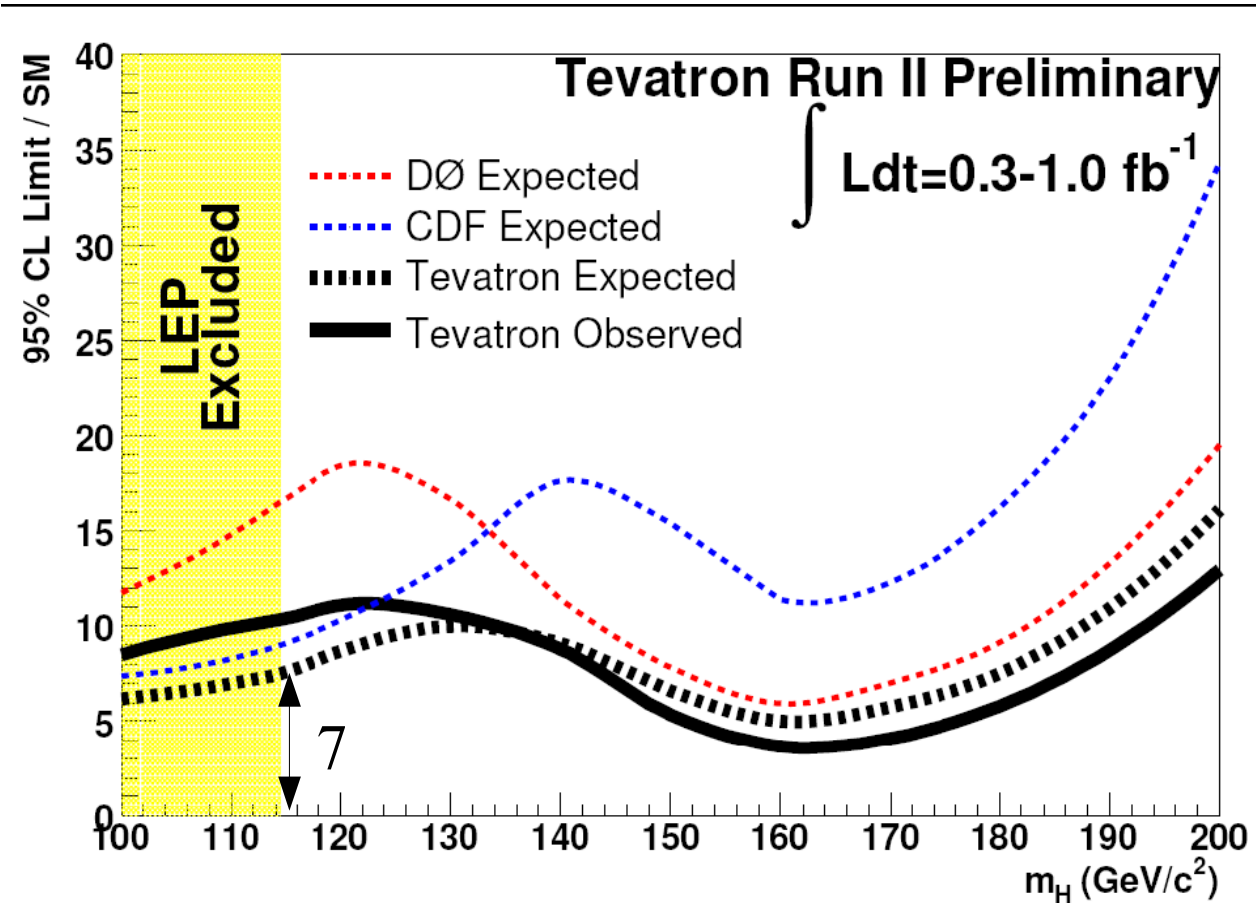
- $Wh \rightarrow e \nu b \bar{b}$
- $Wh \rightarrow \mu \nu b \bar{b}$
- $Wh \rightarrow \tau \nu b \bar{b}$
- $Zh \rightarrow \nu \nu b \bar{b}$
- $Zh \rightarrow e^+ e^- b \bar{b}$
- **$Zh \rightarrow \mu^+ \mu^- b \bar{b}$**



- $h \rightarrow WW \rightarrow e^+ \nu e^- \nu$
- $h \rightarrow WW \rightarrow \mu^+ \nu \mu^- \nu$
- $h \rightarrow WW \rightarrow e^+ \nu \mu^- \nu$
- $Wh \rightarrow WWW \rightarrow e^+ e^- + \nu$'s + X
- $Wh \rightarrow WWW \rightarrow \mu^+ \mu^- + \nu$'s + X

Combining the Experiments

- And there's another experiment at the Tevatron (CDF)
- *Only a factor of ~ 7 away from seeing the Higgs (115 GeV)*

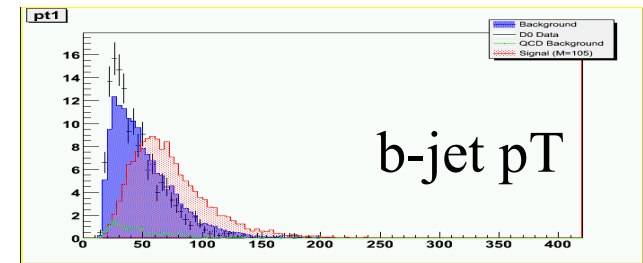


Improving Sensitivity

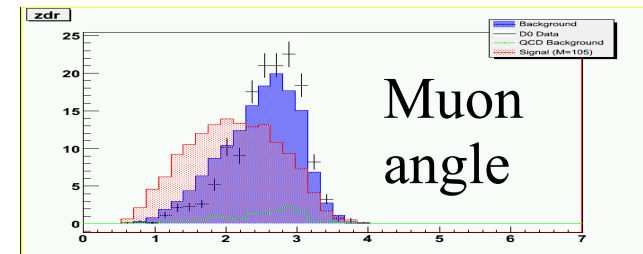
- Now: 7.0
- More data (2/fb per exp. by this year) : 5.0
- NN b-tagging for all analyses: 3.2

Neural Net Event Weighting

- Train an artificial Neural Net to discriminate between Higgs-like and background-like event kinematics
- Variables:
 - bb invariant mass
 - $\mu^+ \mu^-$ invariant mass
 - pT's of b-jets
 - Angle between muons
 - Angle between jets
 - Boost between jets
 - Missing ET

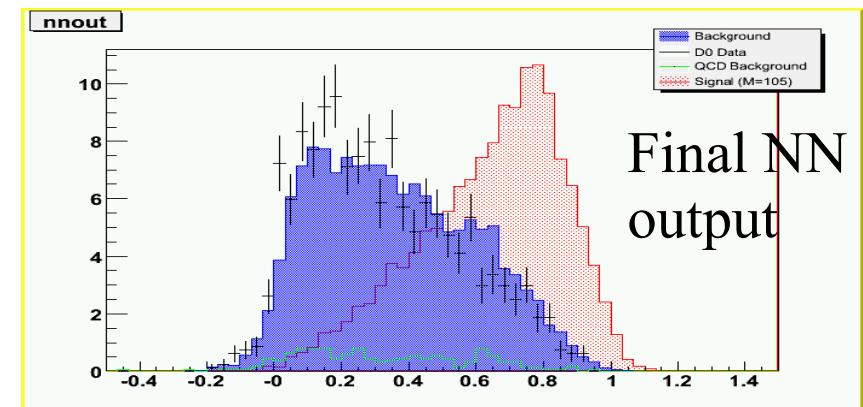


+



+

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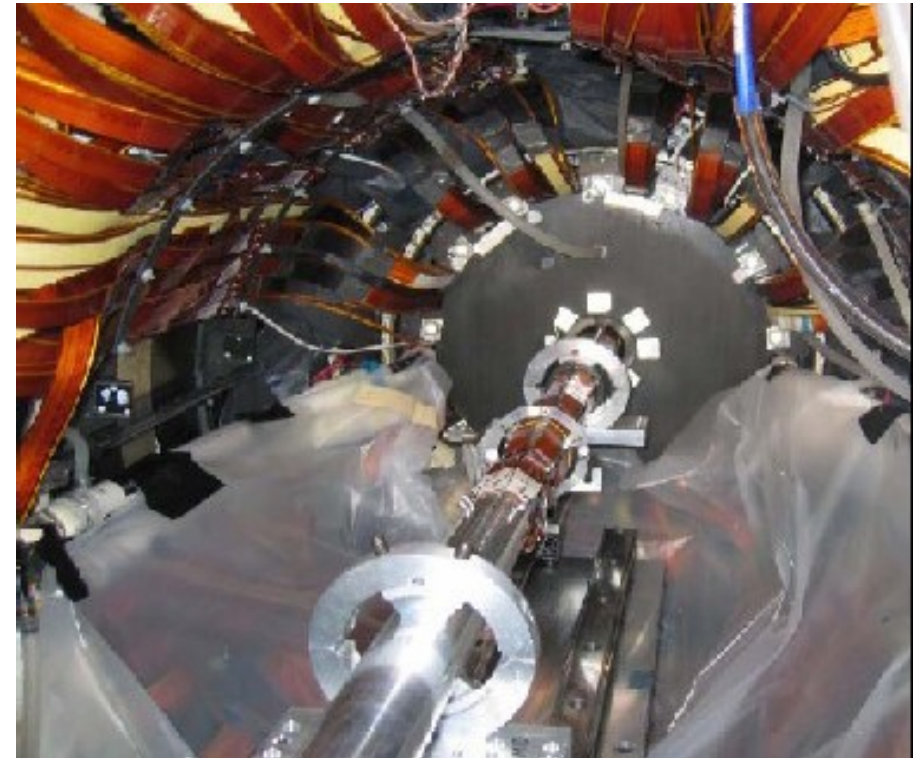
Improving Sensitivity

- Now: 7.0
- More data (2/fb per exp. by this year) : 5.0
- NN b-tagging for all analyses: 3.2
- **NN event weighting: 2.0**
- Better Higgs mass resolution: 1.6
- Use forward electrons in WH: 1.45
- Add tau channels: 1.32
- Better calibrations, reduced systematics: 1.2

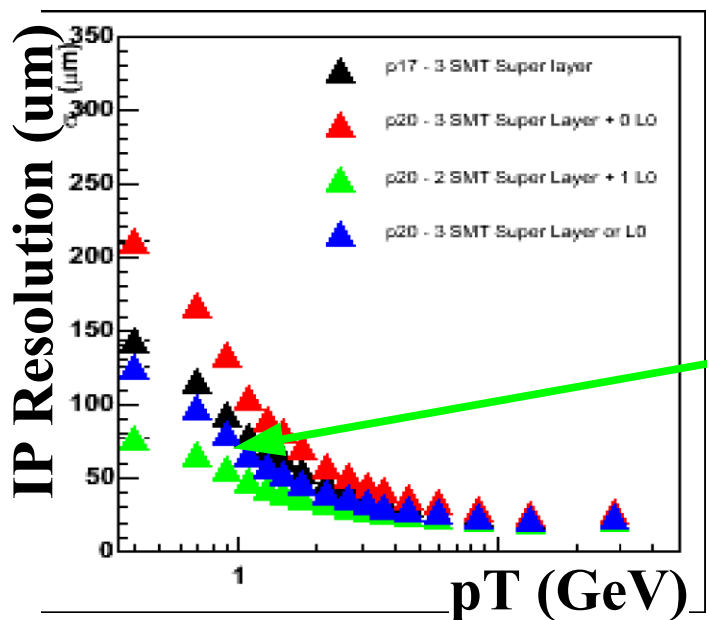
← Small, difficult improvements

Layer 0 of Silicon Tracker

- Silicon detectors mounted just outside the beampipe
- Installed last Fall
- Better track impact-parameter resolution
-> Better b-jet tagging



Layer 0 being inserted into the silicon tracker



**Effect of Layer 0
in recent data**

Improving Sensitivity

- Now: 7.0
- More data (2/fb per exp. by this year) : 5.0
- NN b-tagging for all analyses: 3.2
- NN event weighting: 2.0

- Better Higgs mass resolution: 1.6
- Use forward electrons in WH: 1.45
- Add tau channels: 1.32
- Better calibrations, reduced systematics: 1.2
- **Added Layer 0 silicon: 1.0**

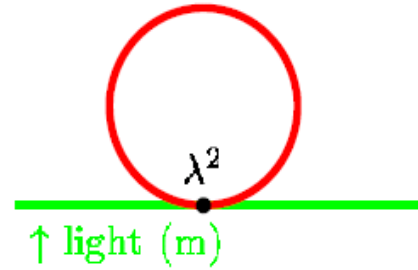
Small, difficult improvements



We'll get there! But it's a lot of hard work.

Why is the Higgs so Light?

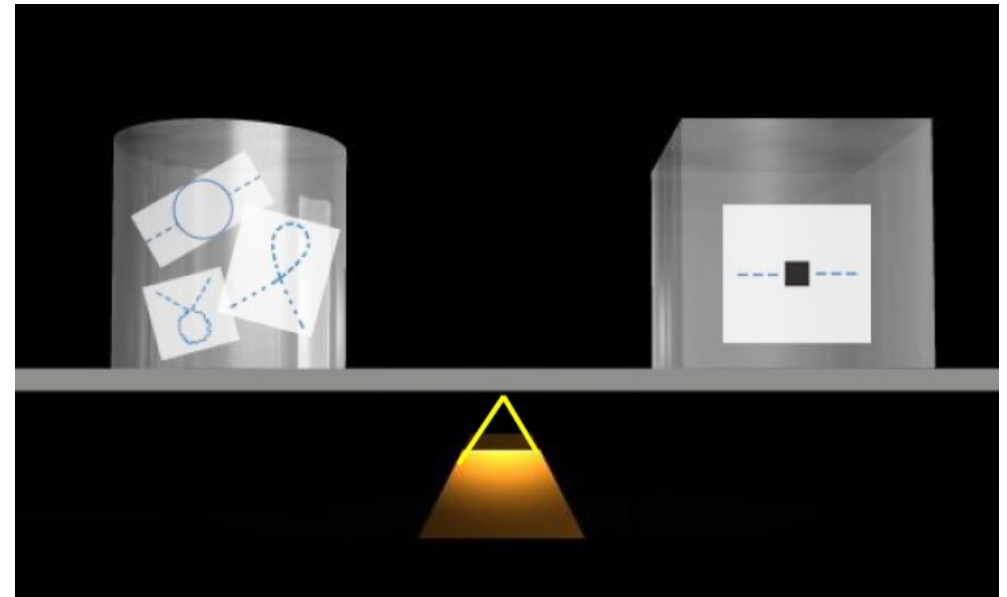
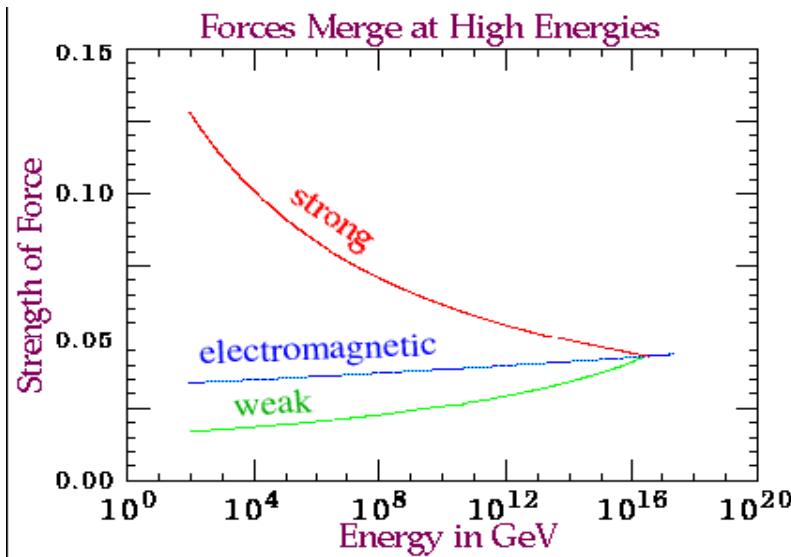
- Where does the Higgs get its mass from?
- The Higgs mass is *unstable*
 - Large radiative corrections (it's a scalar - spin 0)



$$\Rightarrow \delta m^2 \sim \lambda^2 \cdot M^2$$

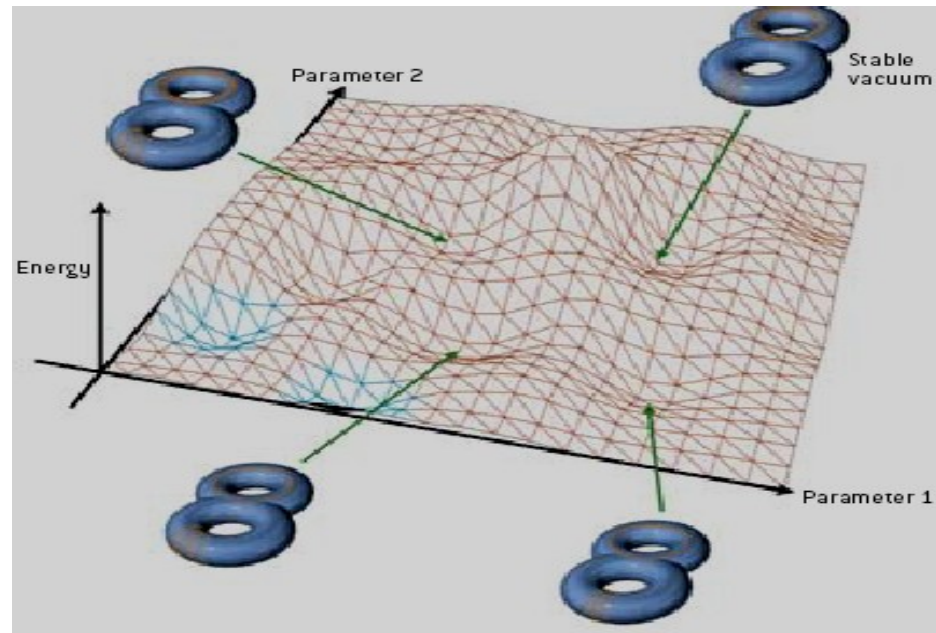
$$\begin{matrix} \lambda & \lambda & \lambda \\ 10^2 & 10^{-1} & 10^{16} \end{matrix}$$

- A delicate *balance* between many large forces
- Hierarchy problem



Why is the Higgs so Light?

- We wouldn't be here if it wasn't?
 - A small Higgs mass seems necessary for life!



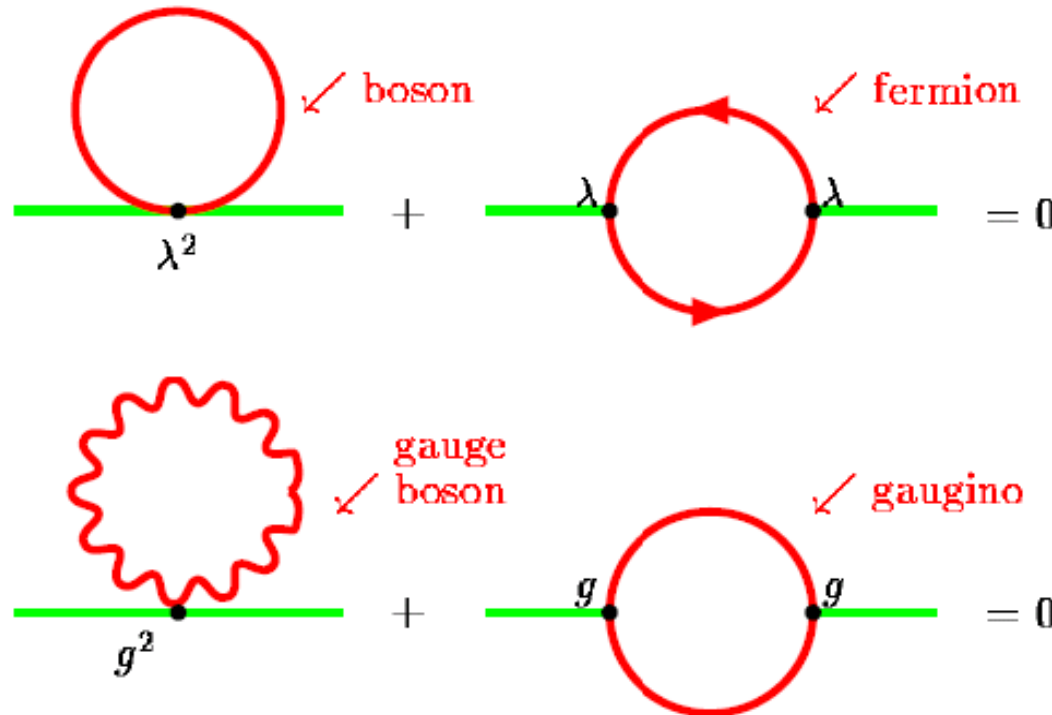
- Same reason for a small cosmological constant?

Why is the Higgs so Light?

- New Physics! Supersymmetry?
 - Particles come in fermion-boson pairs
 - Corrections to Higgs mass nearly cancel, if boson and fermion masses are similar

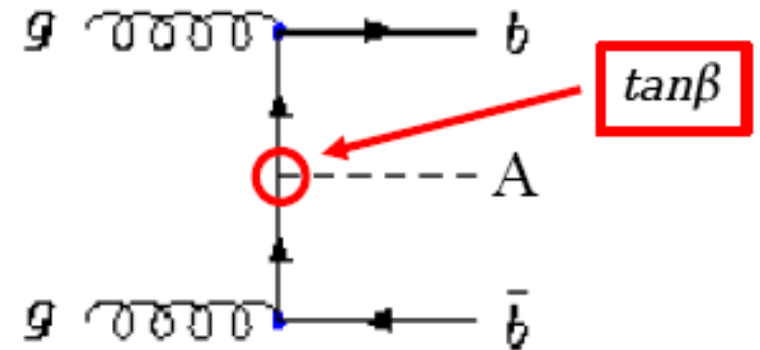
*fermion =
spin 1/2, 3/2, ...*

*boson =
spin 0, 1, ...*



Higgses in Supersymmetry

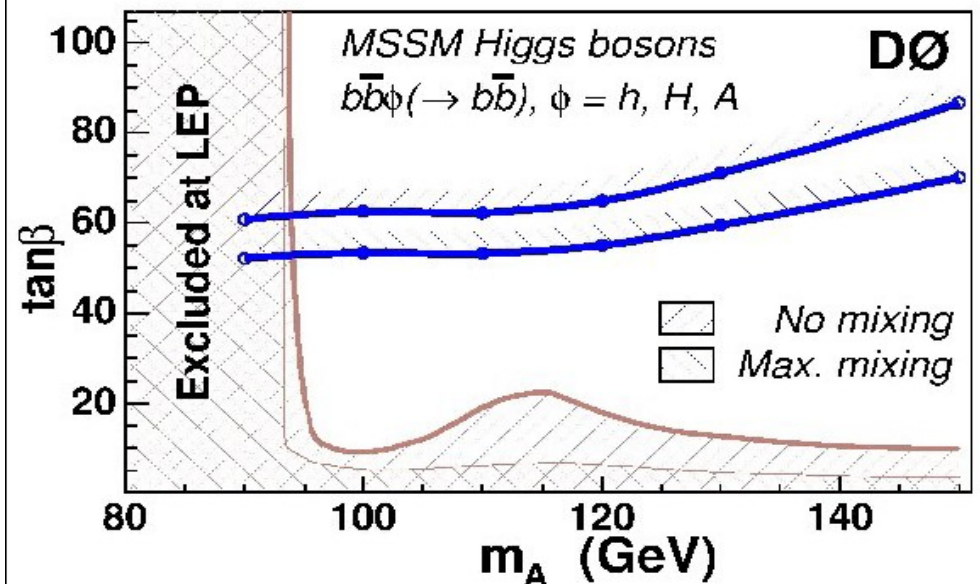
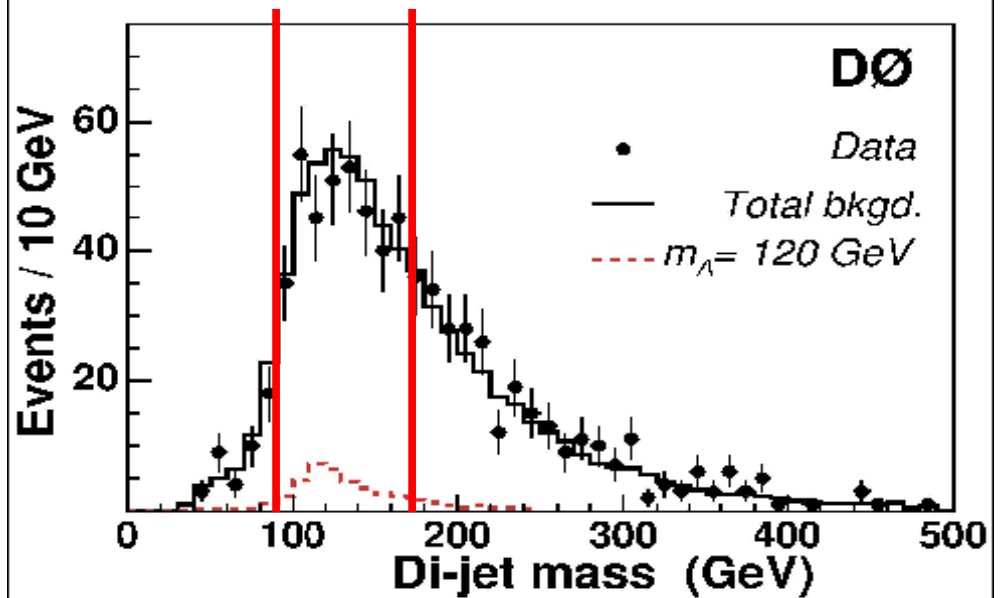
- Requires **two** Higgs (doublet) fields, **5** Higgs bosons:
 - h -> like the standard Higgs boson
 - H, A -> heavier, neutral also
 - H^+, H^- -> heavier, charged



- $\tan\beta$ -> ratio of Higgs fields' VEVs
- $H/A + bb$ production proportional to $\tan^2\beta$
- Should be able to see $H/A + bb$ at high $\tan\beta$...
- H/A decays to bb 90% of the time (the rest to tau's)
 - Look for: $H/A + bb \rightarrow bb\ bb$

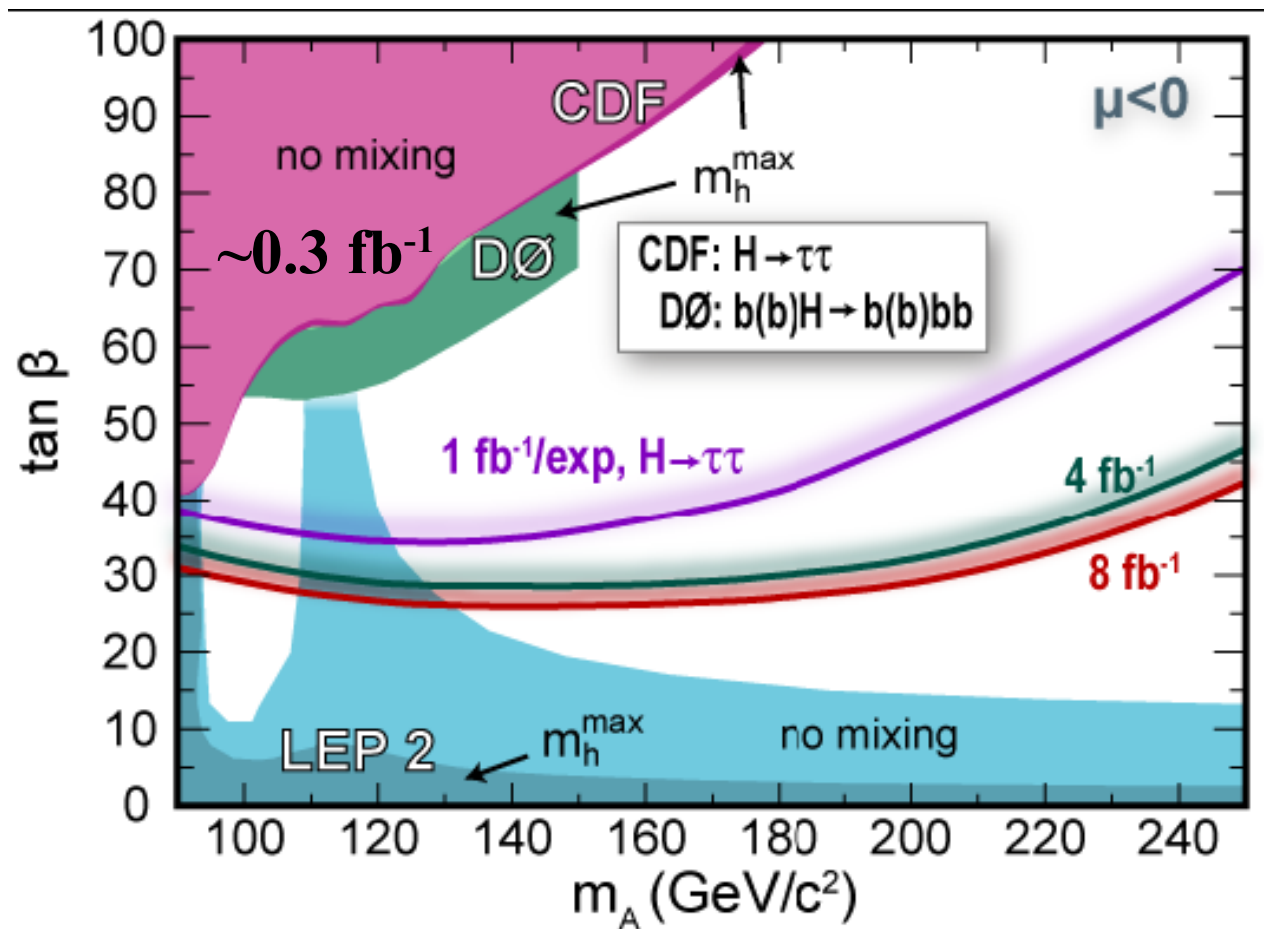
DØ Search for $H/A + bb \rightarrow bb bb$

- Look for bump in bb invariant mass spectrum in events with at least 3 b-jets
 - Background determined from 2 b-jet data
- No excess observed for any H/A mass
- Interpret as limits in the Higgs mass vs. $\tan\beta$ plane
- PRL 95, 151801 (2005)



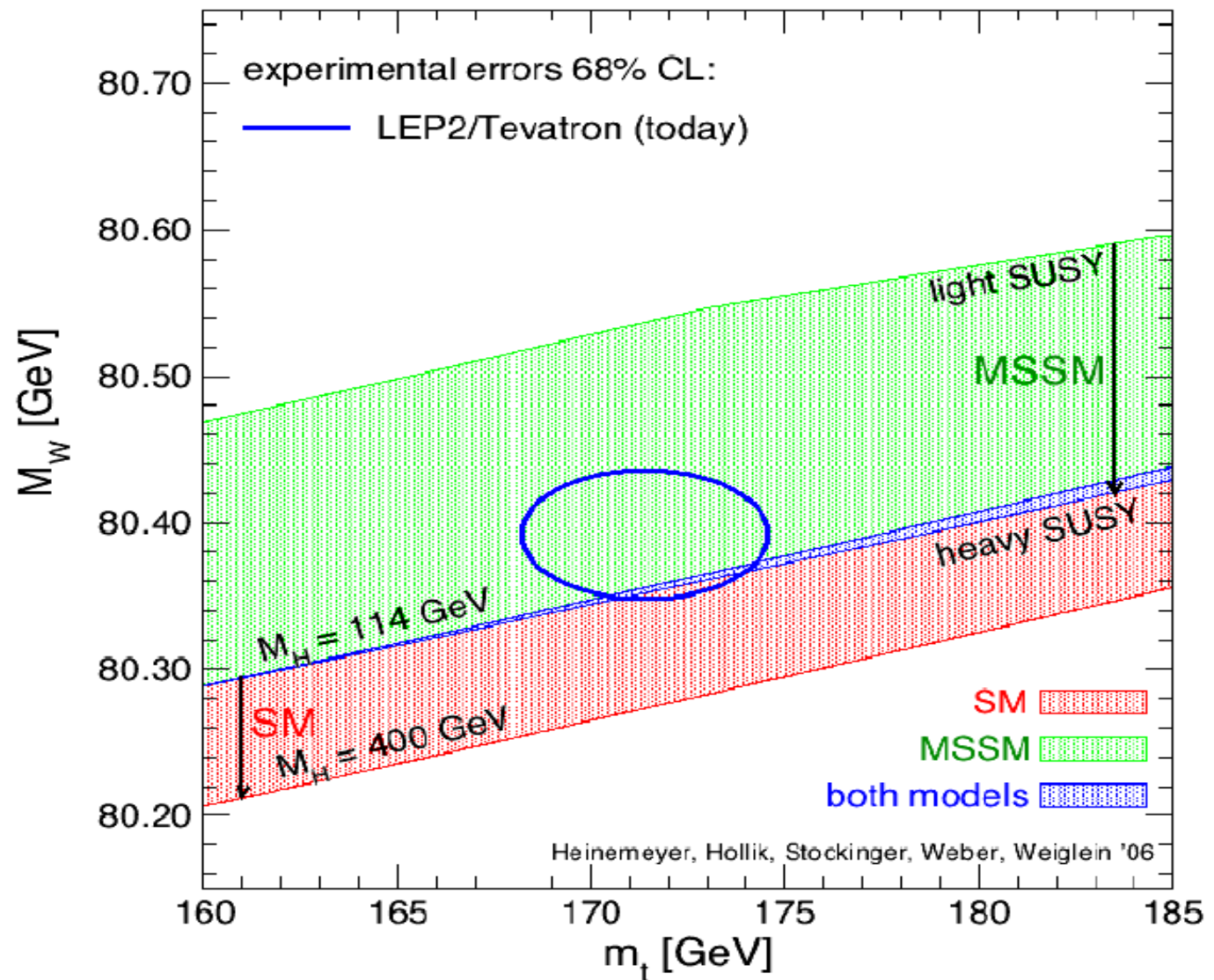
H/A Sensitivity at the Tevatron

- Combine with the H/A \rightarrow tau tau decay channel
- Combine with CDF
- Sensitive down to $\tan\beta=40$ soon for H/A masses up to ~ 200 GeV
 - A nice explanation for the t/b mass ratio?



Trouble with *Minimal Supersymmetry*?

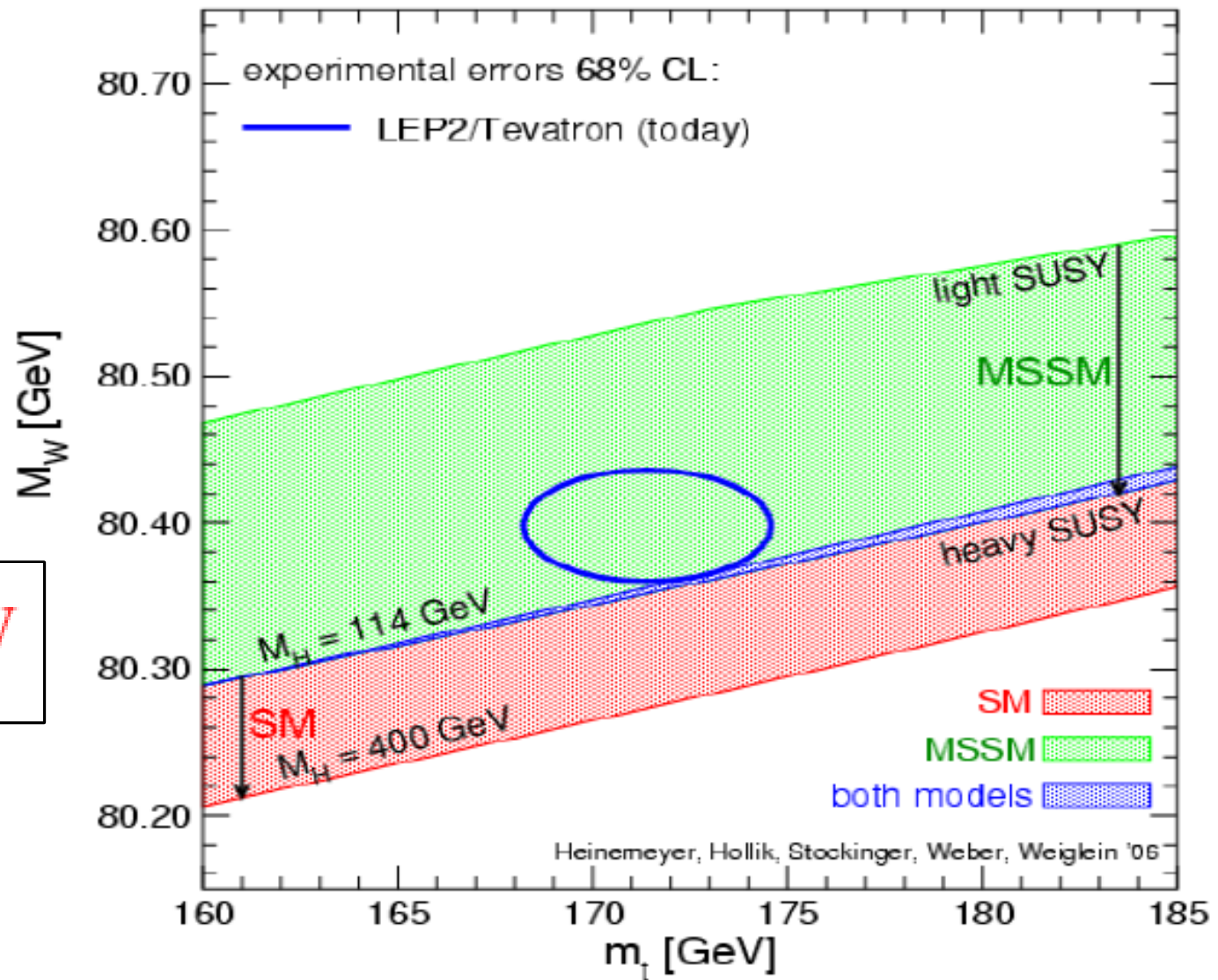
- We should have found the Higgs already?!
 - Supersymmetry predicts a light Higgs
 - Comparisons of the W and top masses point to a light Higgs
- But searches at LEP exclude a light Higgs!



Trouble with *Minimal Supersymmetry*?

- CDF just measured the W mass
- Include their measurement into the world average and...

$$M_H = 80^{+36}_{-26} \text{ GeV}$$



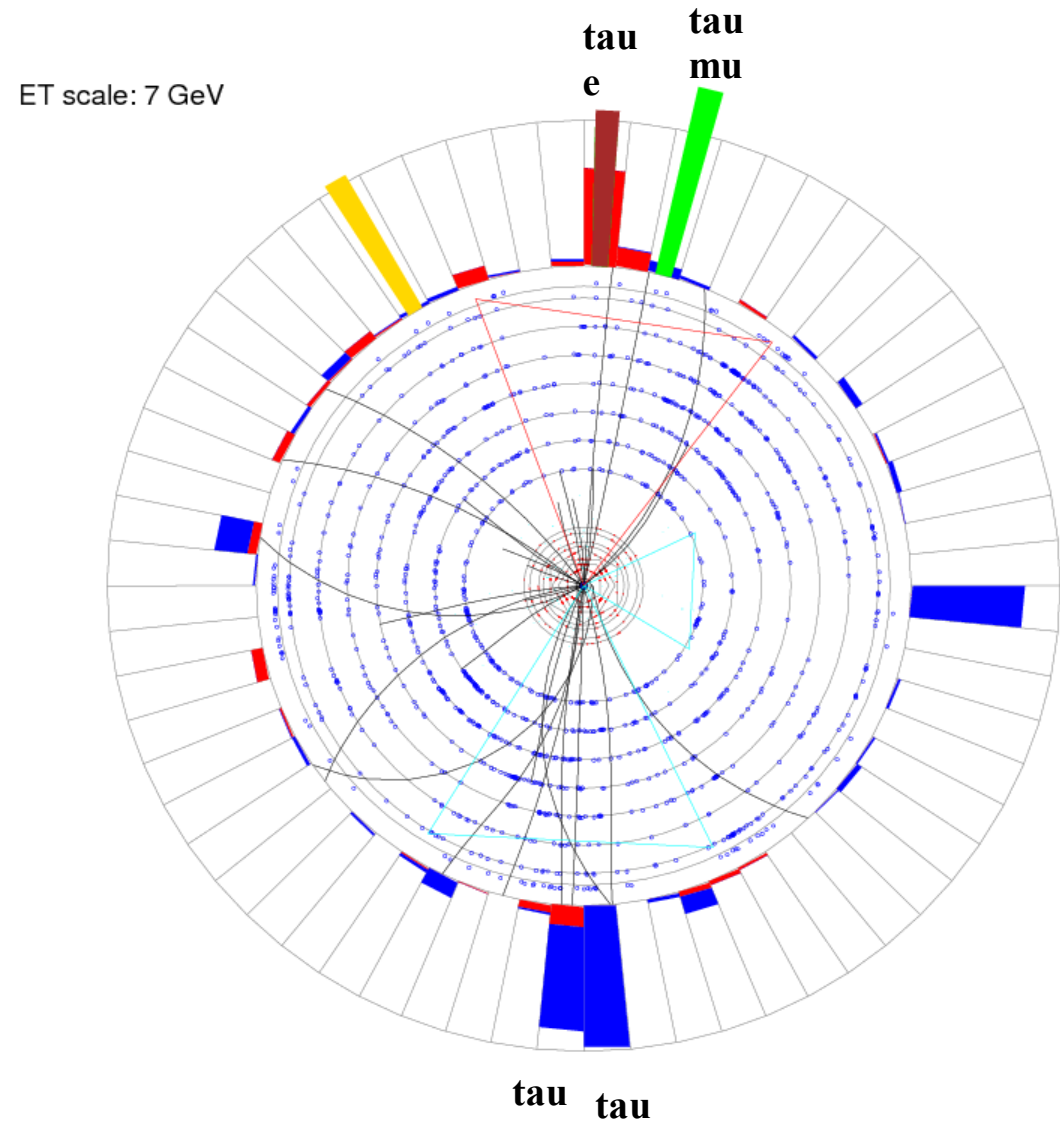
A Hint of Something New?

- LEP didn't really exclude a light Higgs
- They only excluded a *standard* light Higgs!

- What if it decays to some *new particles*?

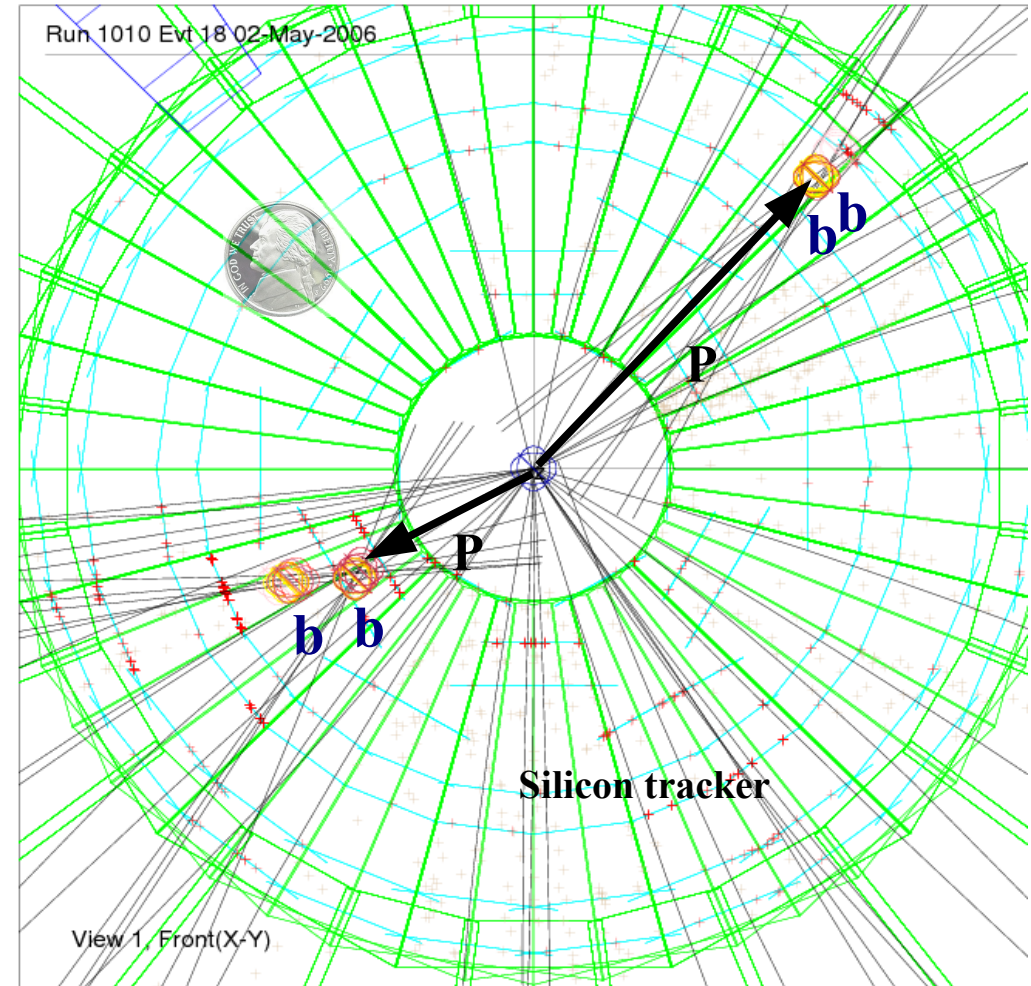
Higgs Decays to Intermediate Particles

- New light scalar particle: "a"
 - favored in many models
- a decays to 2 taus
- $h \rightarrow a a \rightarrow \text{tau tau tau tau}$
- a is light, so tau's are close to each other
 - Hard to identify!
 - Not excluded by LEP
- Analysis in progress...



Higgs Decays to Long-lived Particles

- New long-lived particle: "P"
- P decays to 2 b-jets
- $h \rightarrow P P \rightarrow b b b b$
- No one's ever looked for long-lived particles decaying to b-jets
 - Not excluded by LEP
- Analysis in progress...



The LHC at CERN

- proton on *proton*
- 4.3 km radius
- Each proton has 7x the Tevatron energy
- 100x as many collisions/sec. as the Tevatron
- **Starts in 2008!**
(low-energy test run this year)

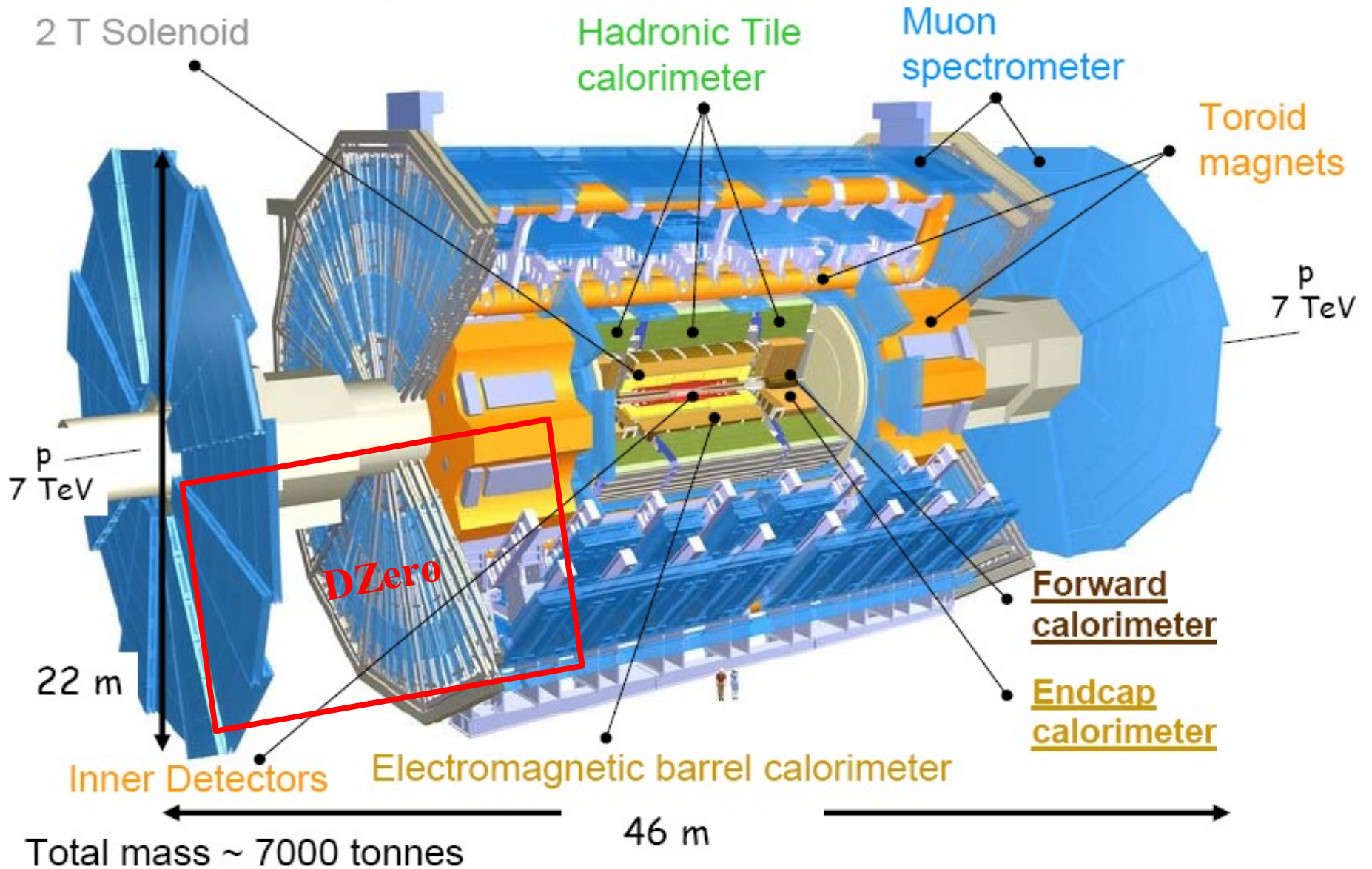
Tevatron



LHC

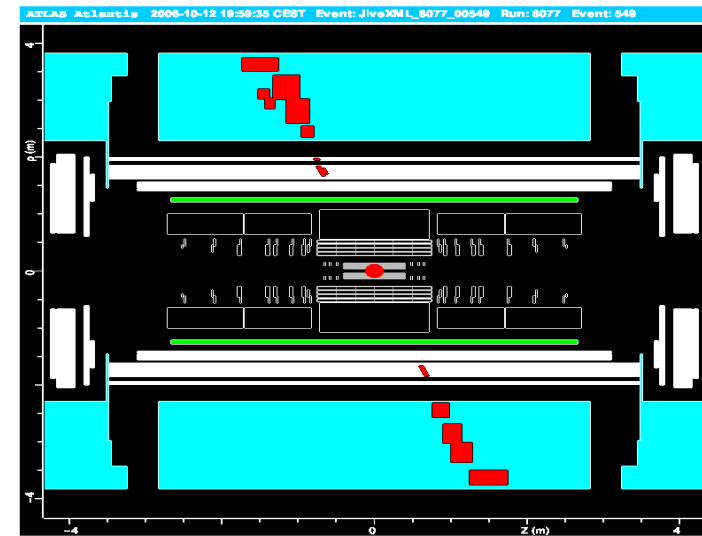
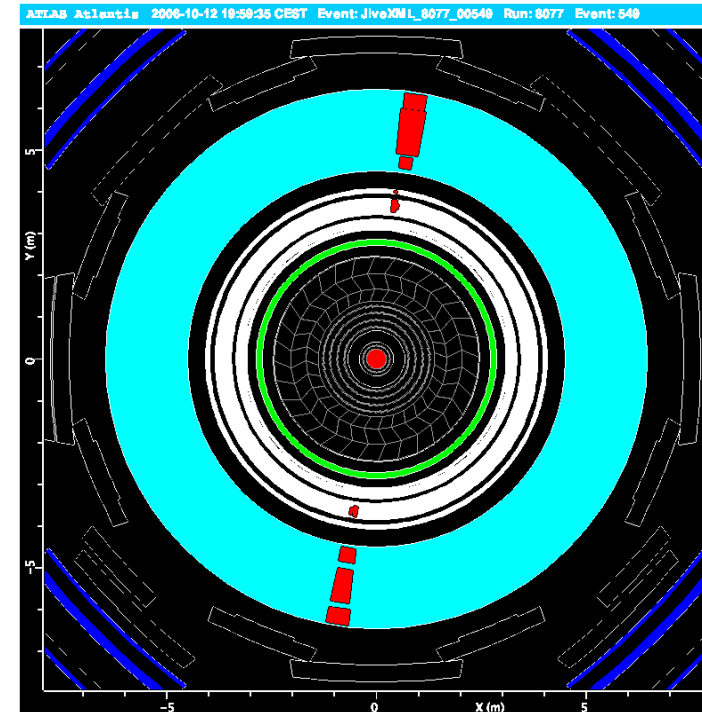
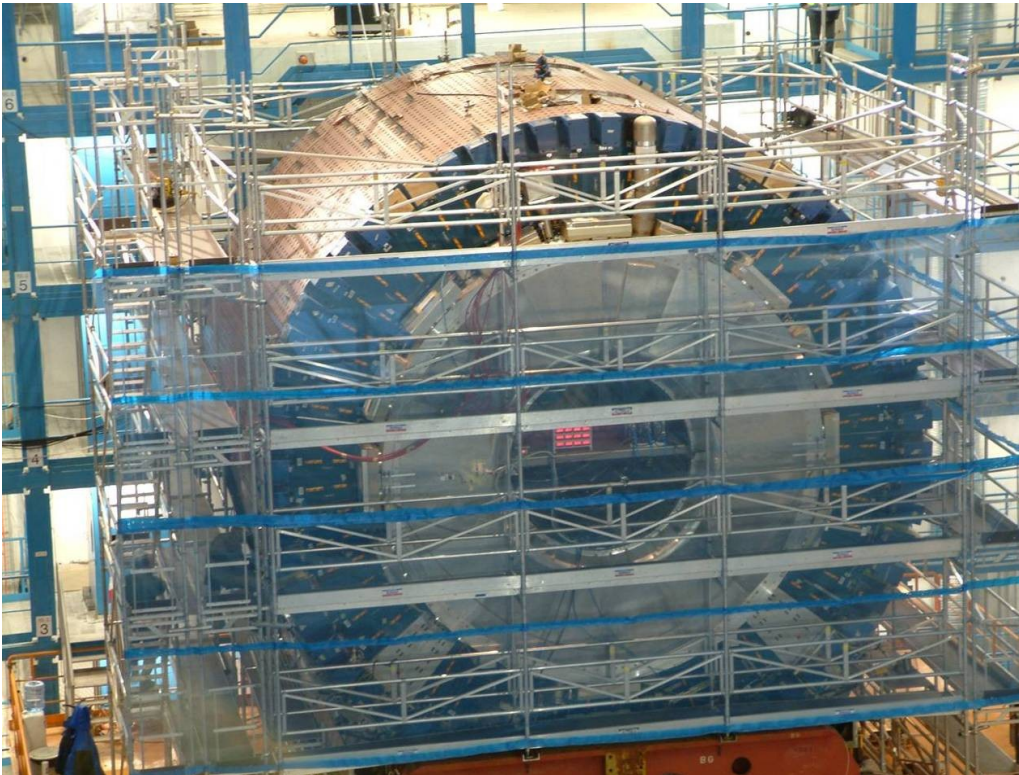


The ATLAS Detector



ATLAS is Real

- Full central calorimeter tested with cosmic rays, in final position
- All subsystems should be ready for beam in September!

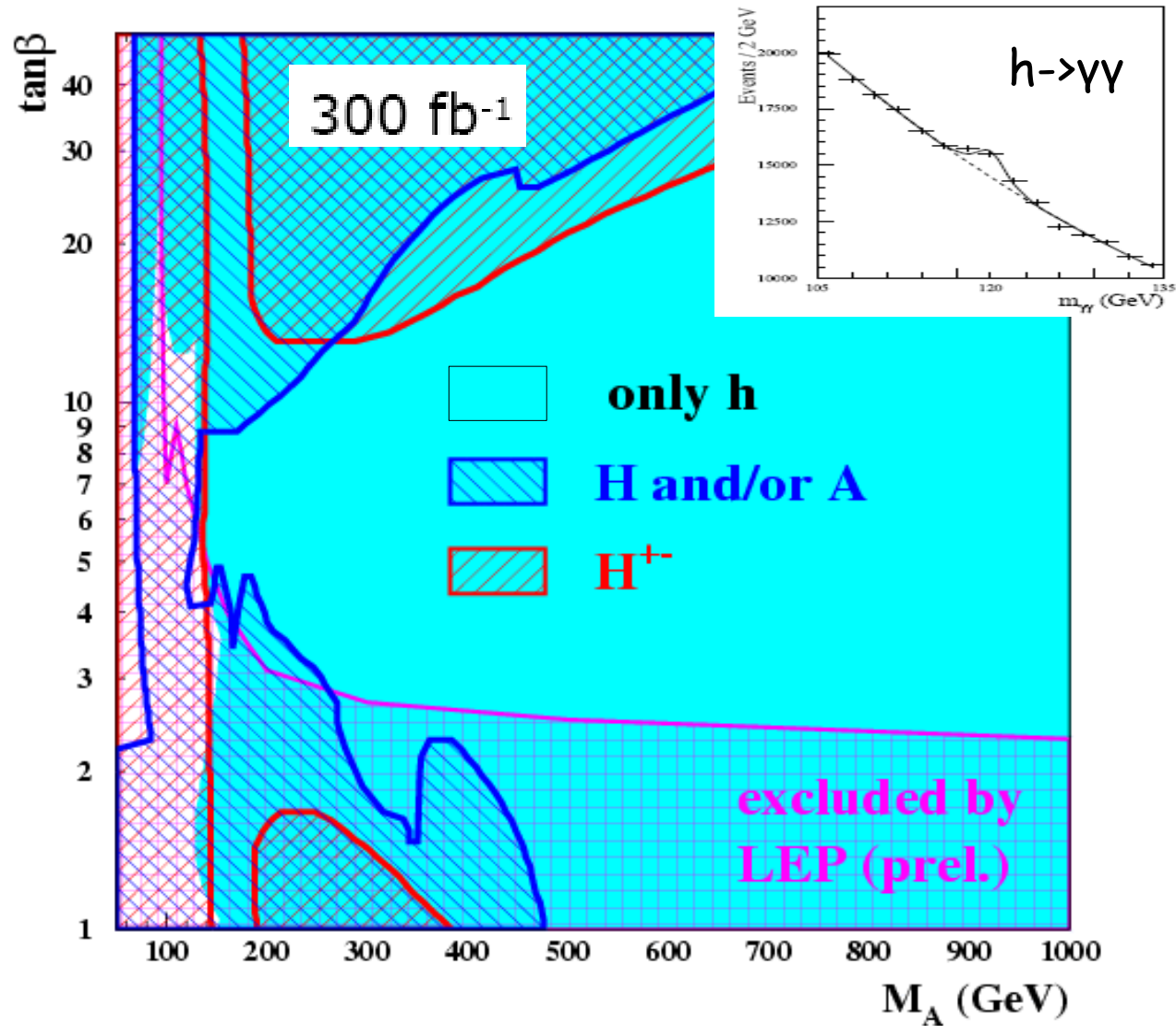


The ATLAS Control Room



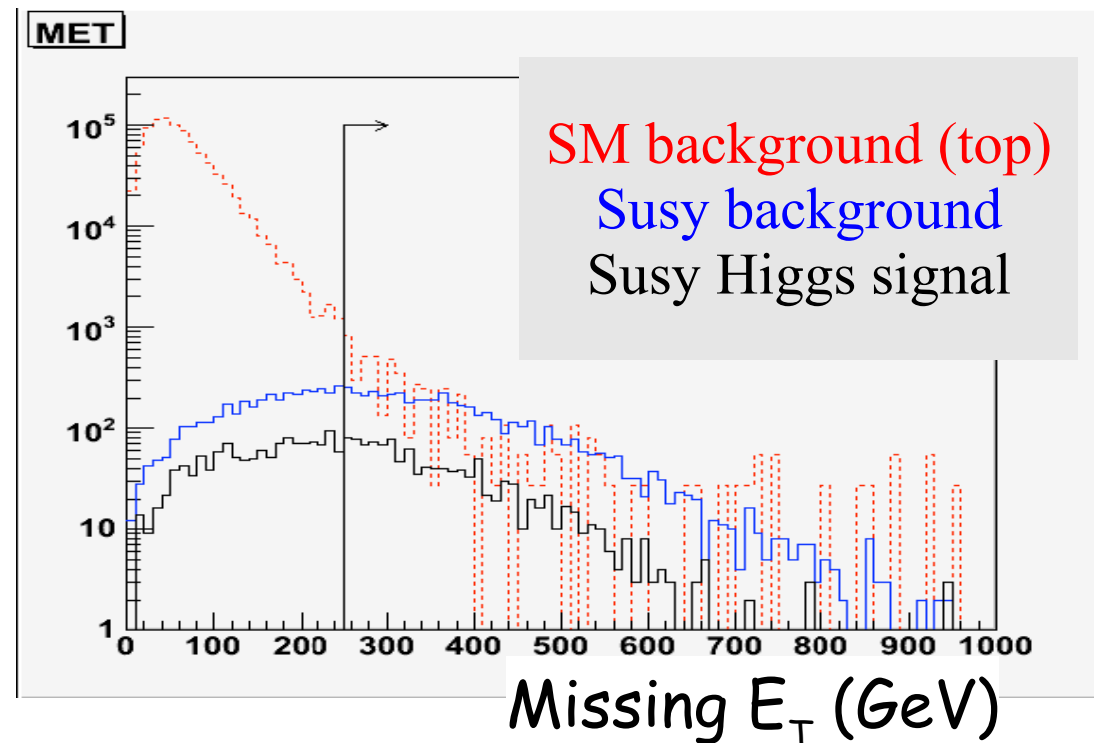
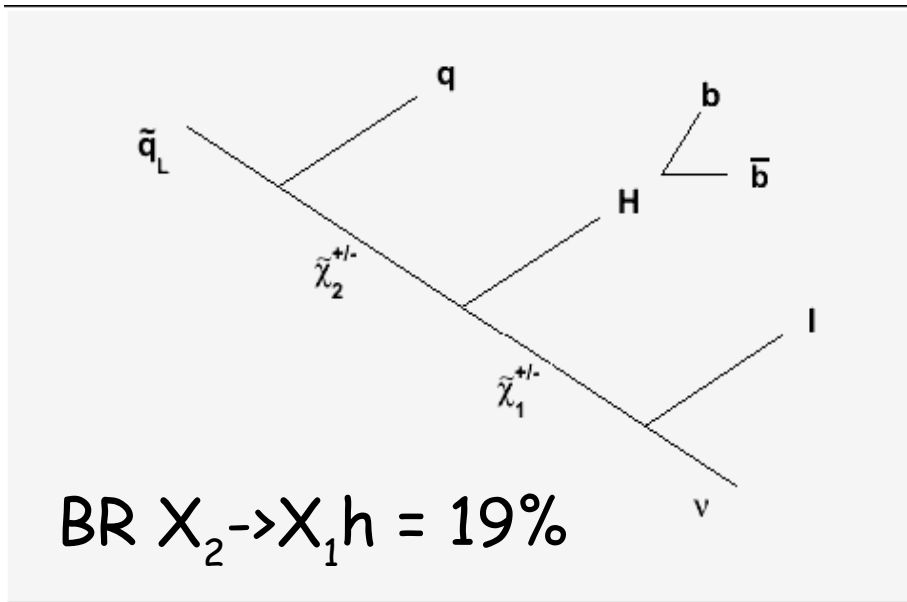
Higgs Searches at ATLAS

- The light Higgs will be found (if it exists)
- H/A and H^{\pm} may also be seen
- But these discoveries won't be easy or quick!
 - 3 years for 30/fb
 - 5 years for 300/fb



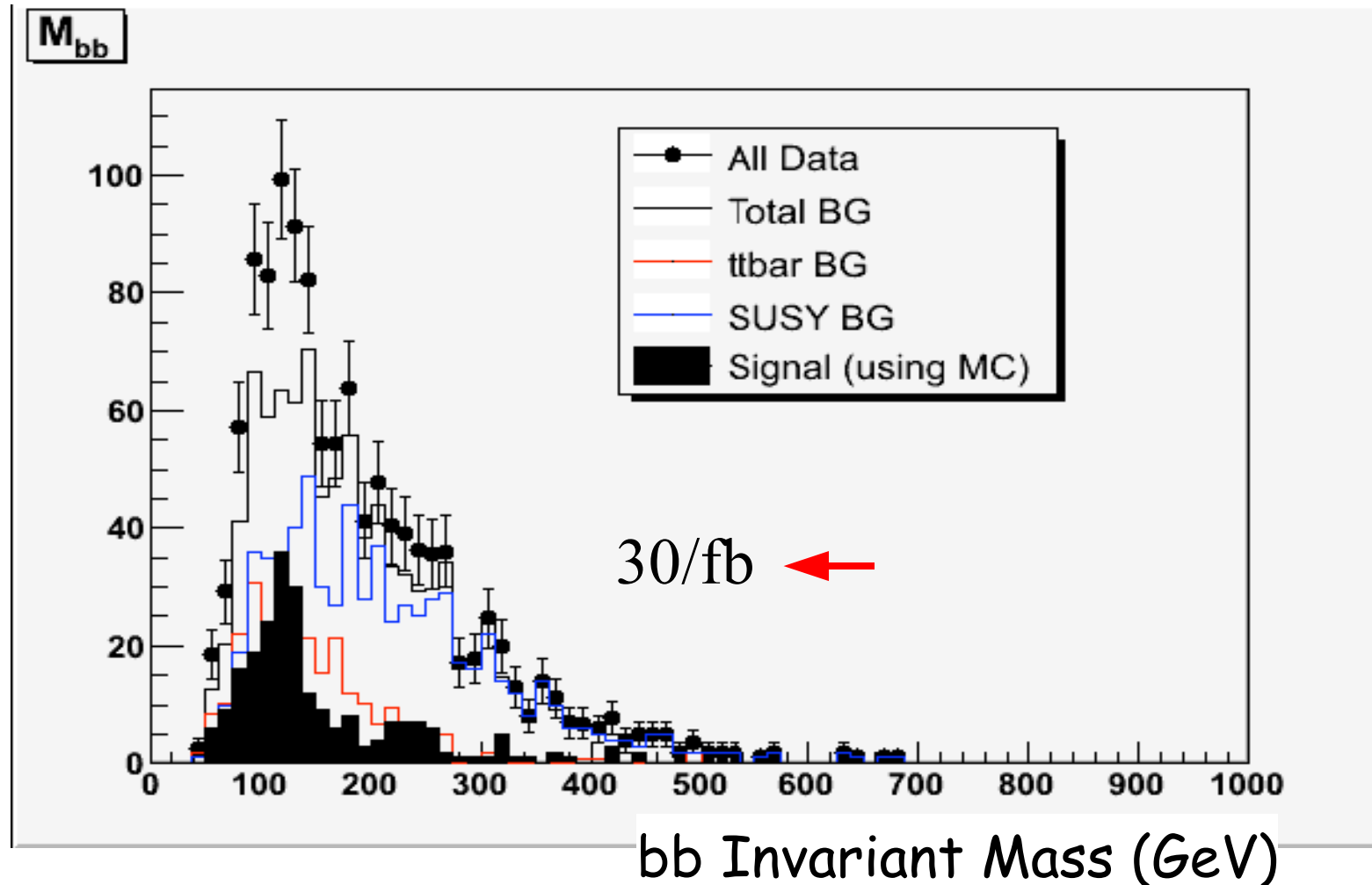
The Higgs in Supersymmetry Decays

- Look for Higgs bosons in the *decays* of supersymmetric particles
 - A possible shortcut to Higgs discovery
- Require lots of missing transverse energy
 - Backgrounds are greatly reduced...



The Higgs in Supersymmetry Decays

- Remaining background is mostly supersymmetric!
- Look for bump from $H \rightarrow b\bar{b}$ decays



Conclusions

- We'll soon find some kind of Higgs(es), *if they exist*
 - Possibly at the Tevatron, certainly at the LHC
- Maybe *just* a plain-old Higgs
 - Nothing to stabilize its mass?
- Maybe more interesting Higgs(es), with *new physics*
 - Supersymmetry?
- Maybe a Higgs connected to *stranger* new physics
 - Extended supersymmetry?, Long-lived particles?, ...
- Maybe we rule out the Higgs completely
 - Certainly new physics!

Conclusions

A very exciting time ahead!

We have little idea what's right around the corner...
Keep our minds open and look in all places!