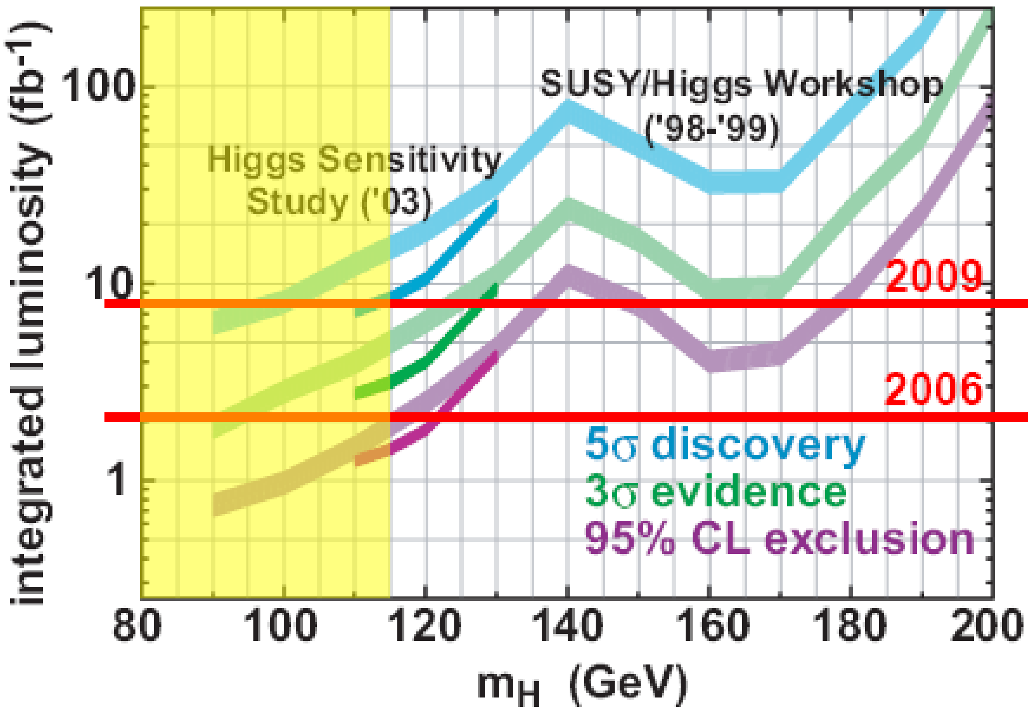
The Search for the Higgs Boson
- An Opening to New Physics

Dr. Andy Haas
Columbia University
DØ / ATLAS

NYU
Particle Physics Seminar
February 7, 2007



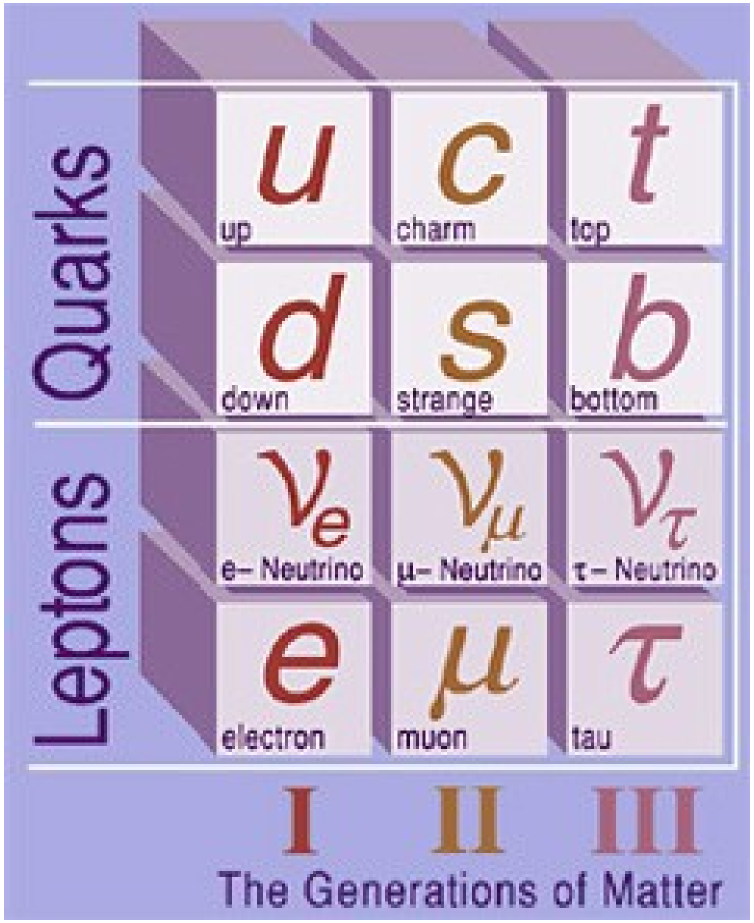
Columbia University
in the City of New York

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) x *SU(2)*$_L$ x SU(3)
- Mass terms mix left and right
  - would break SU(2)$_L$ symmetry



The Higgs Boson

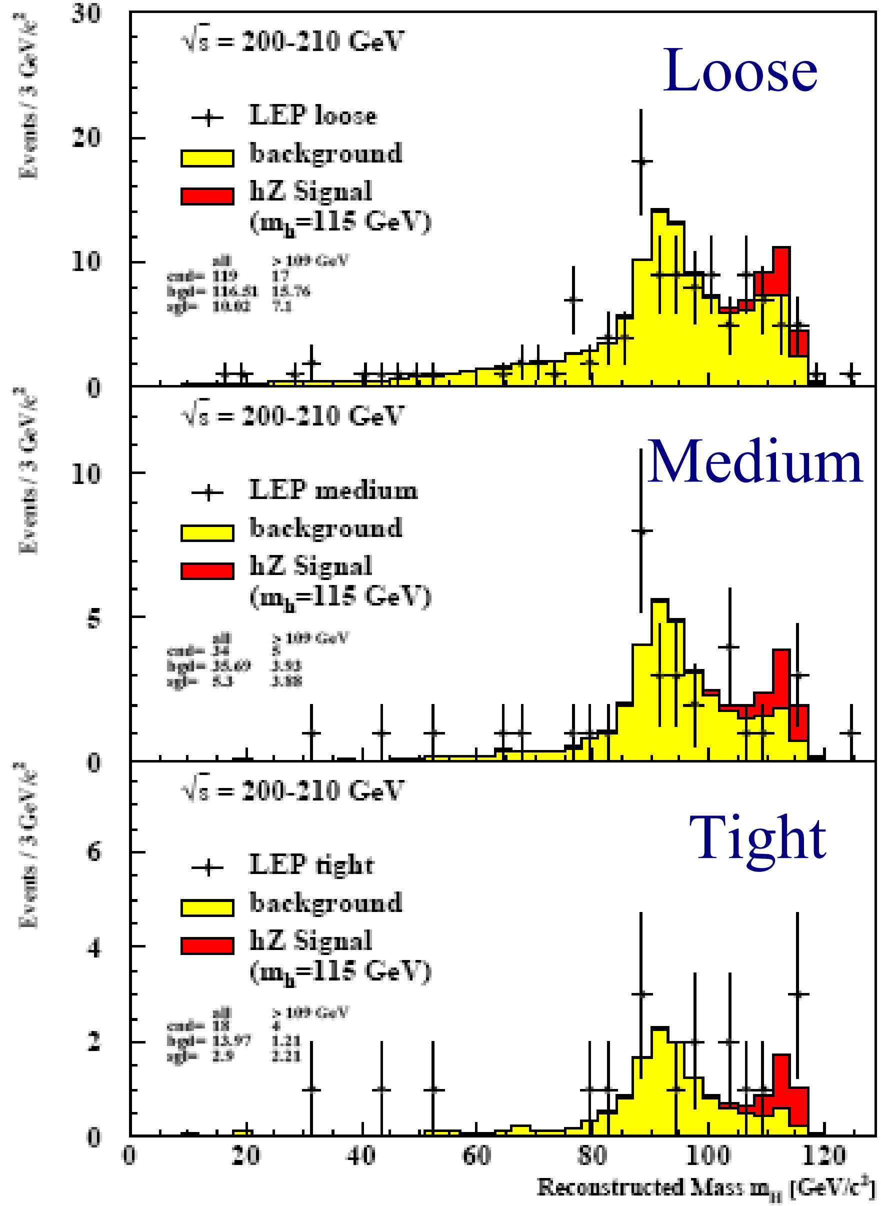
- The Higgs field costs *less than nothing* to have around
  - Empty space prefers a non-zero Higgs density

- Particles get *effective* mass by interacting with the Higgs field of empty space
- Gives masses to the quarks and leptons, and W/Z bosons
- Sounds good... let's make some Higgs *particles*

LEP @ CERN in 2000

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

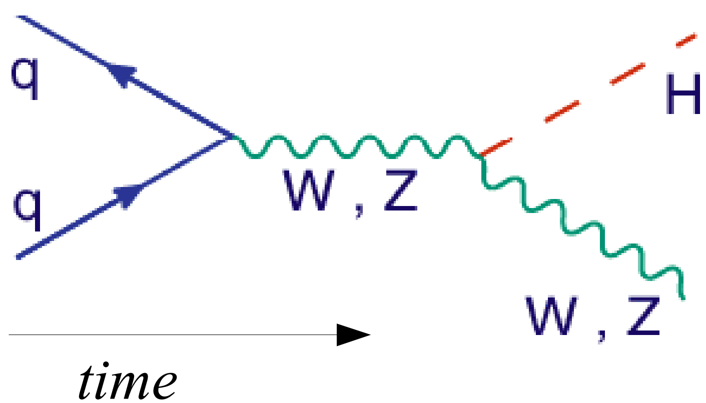
A good, but not the only variable...



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

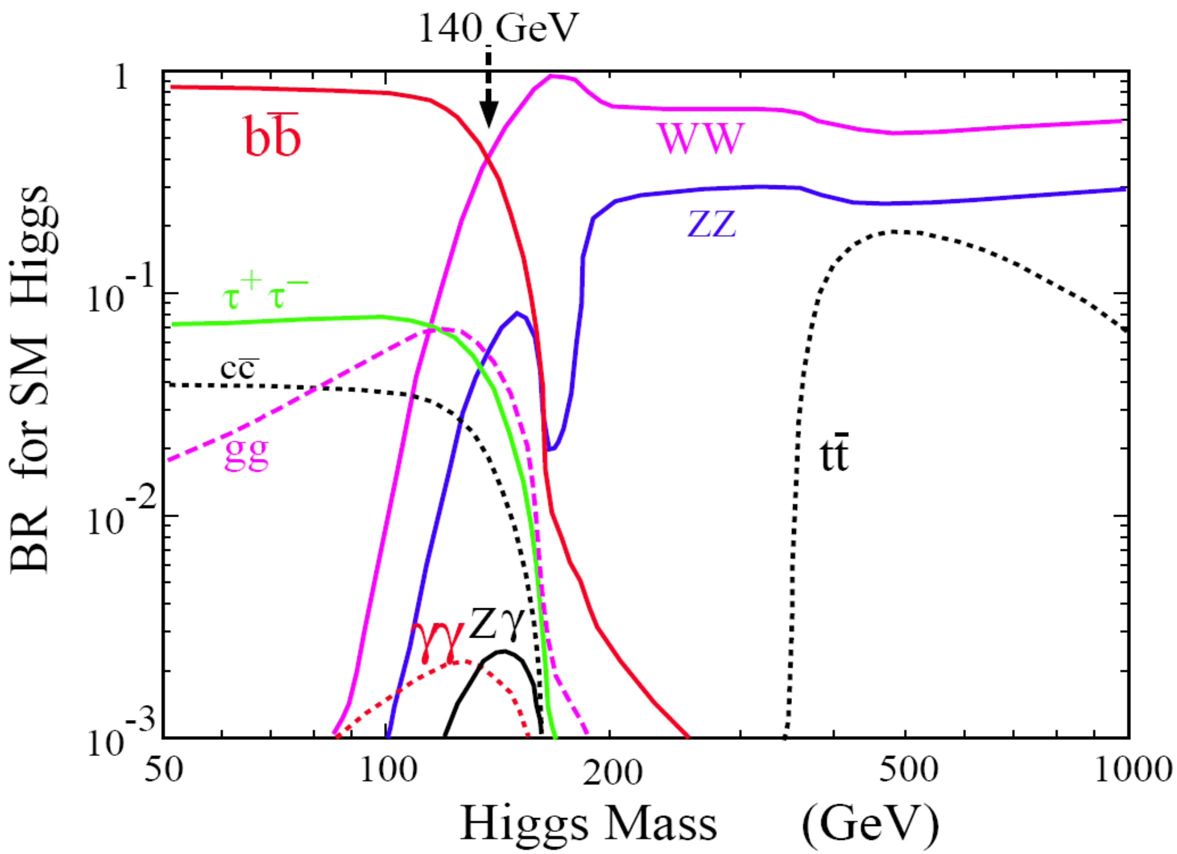
The Tevatron at Fermilab

- Running (again) since ~2003
- proton on anti-proton
- 1 km radius
- Each (anti)proton has E = 1 TeV
- 2.5 million collisions / sec.
  - Can look for very rare processes (like Higgs)



What the Higgs "Looks Like"

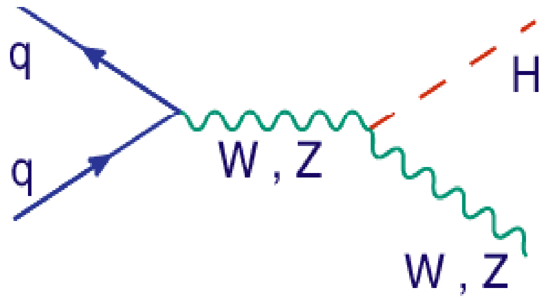
- The Higgs has a short life
- What it decays to depends on its mass
- Main focus at the Tevatron is:
  - bb (low mass)
  - WW (high mass)



Higgs Analyses at DØ

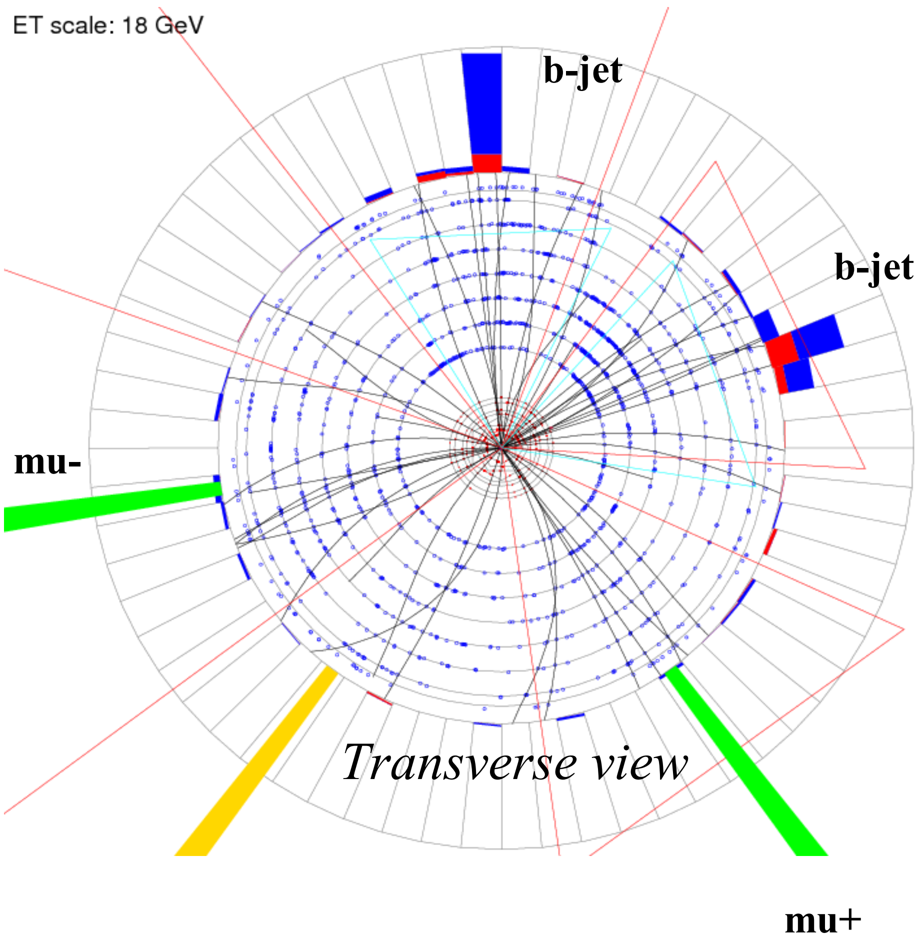
- Wh -> e nu b b
- Wh -> mu nu b b
- Zh -> nu nu b b
- Zh -> e+ e- b b
- **Zh -> mu+ mu- b b**

- h -> WW -> e+ nu e- nu
- h -> WW -> mu+ nu mu- nu
- h -> WW -> e+- nu mu-+ nu
- Wh -> WWW -> e+- e+- +nu's + X
- Wh -> WWW -> mu+- mu+- +nu's + X

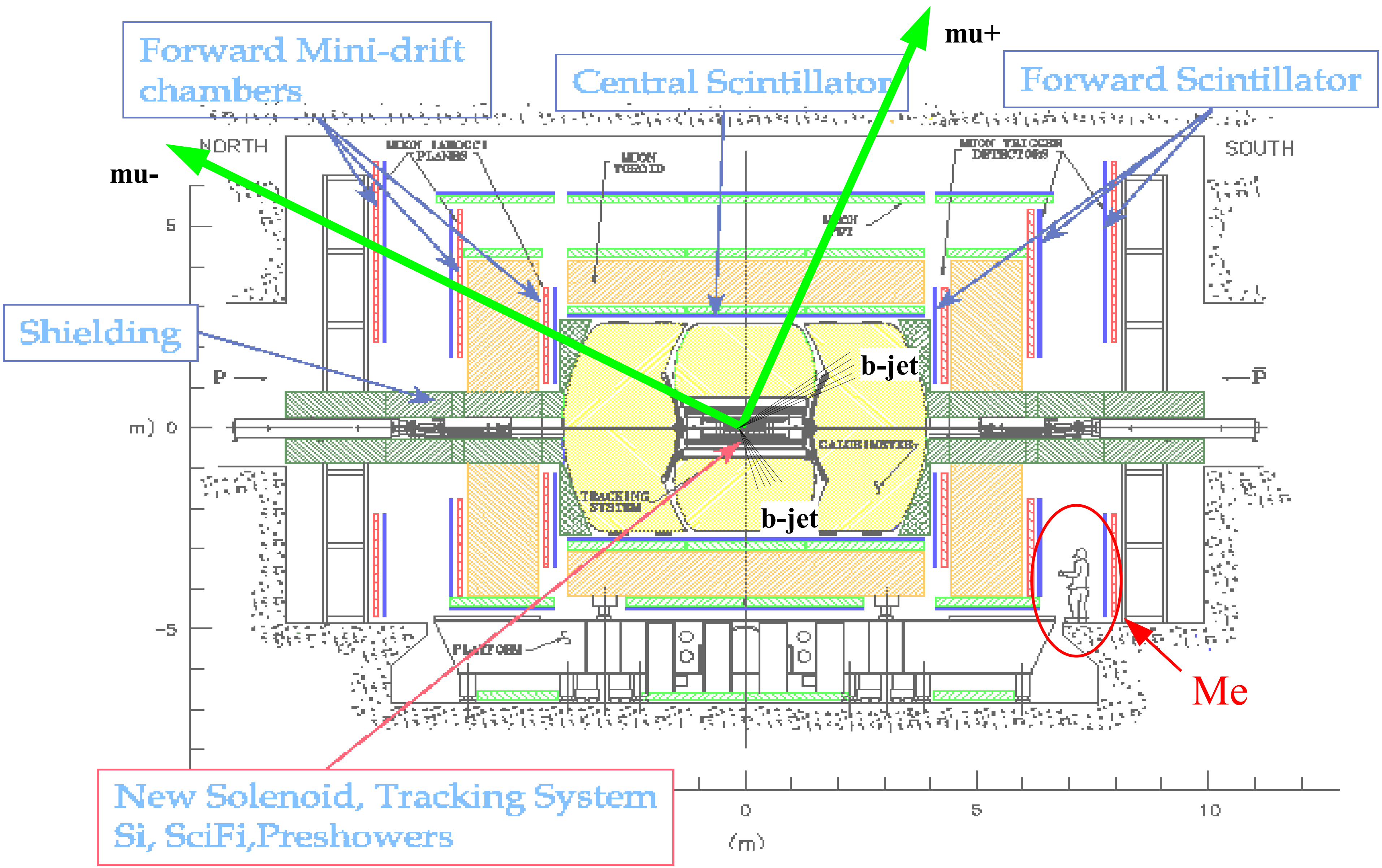


The Zh -> mu$^+$ mu$^-$ b b Search

- 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

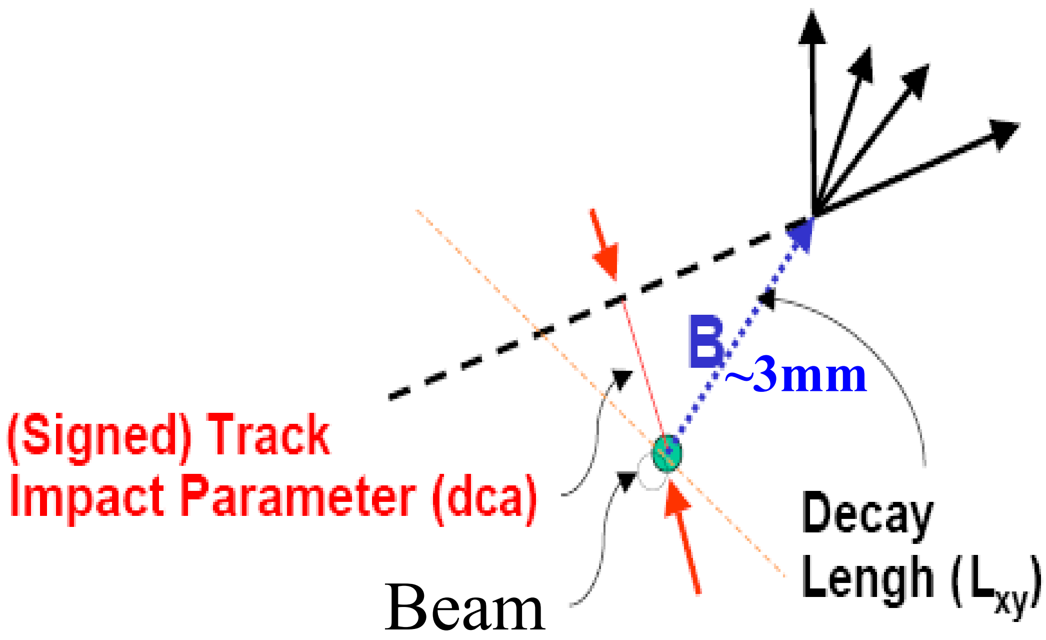


The DØ Detector



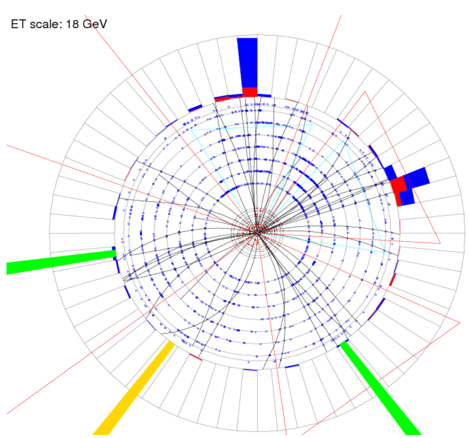
b-Jet Tagging

- How do we know when a jet is a b-jet?
  - B hadrons are “long”-lived (a picosecond is forever...)

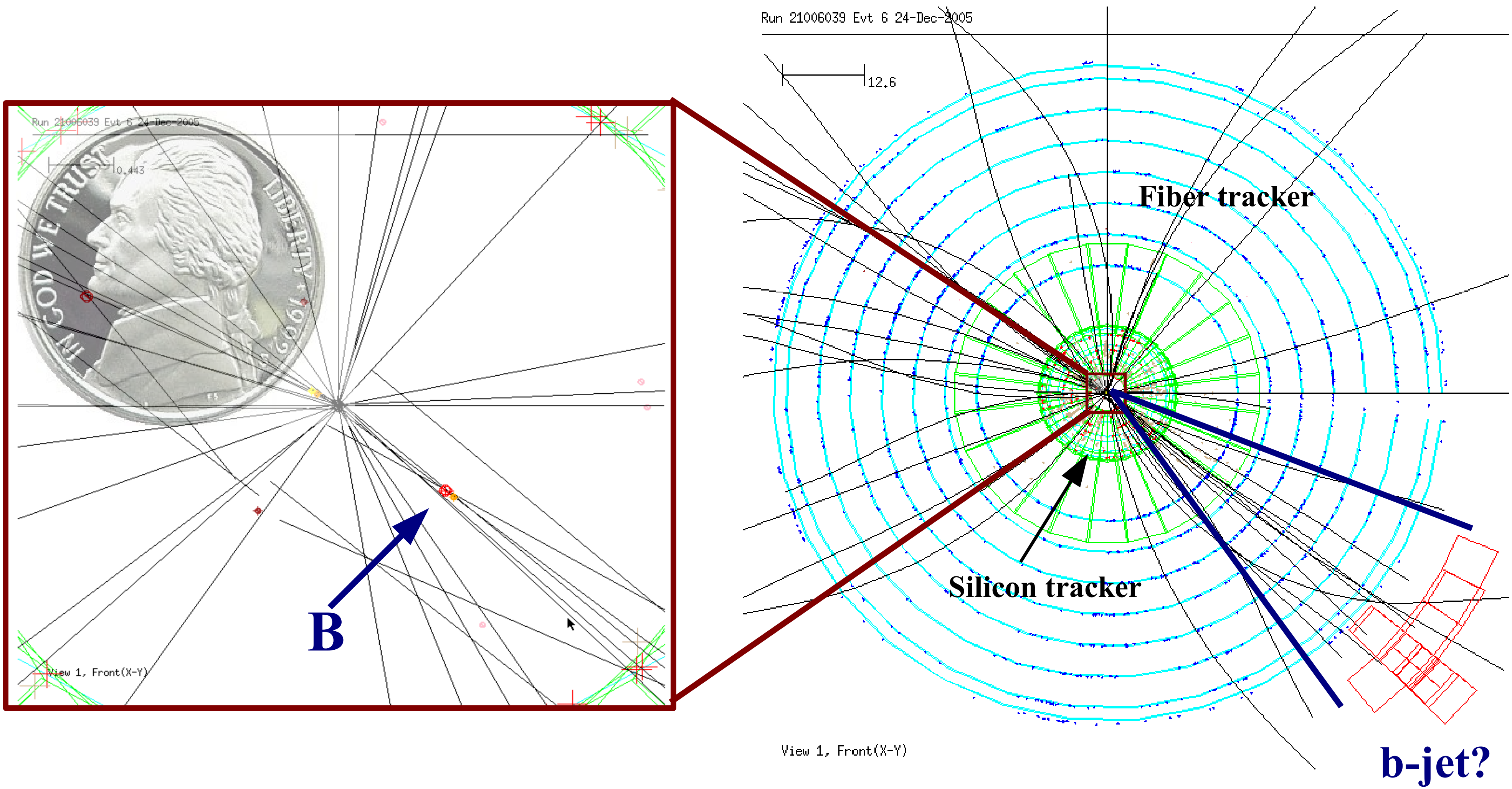


- Reconstruct charged particles tracks

- Identify jets with
  - large impact parameter significance tracks
  - large decay length significance vertices

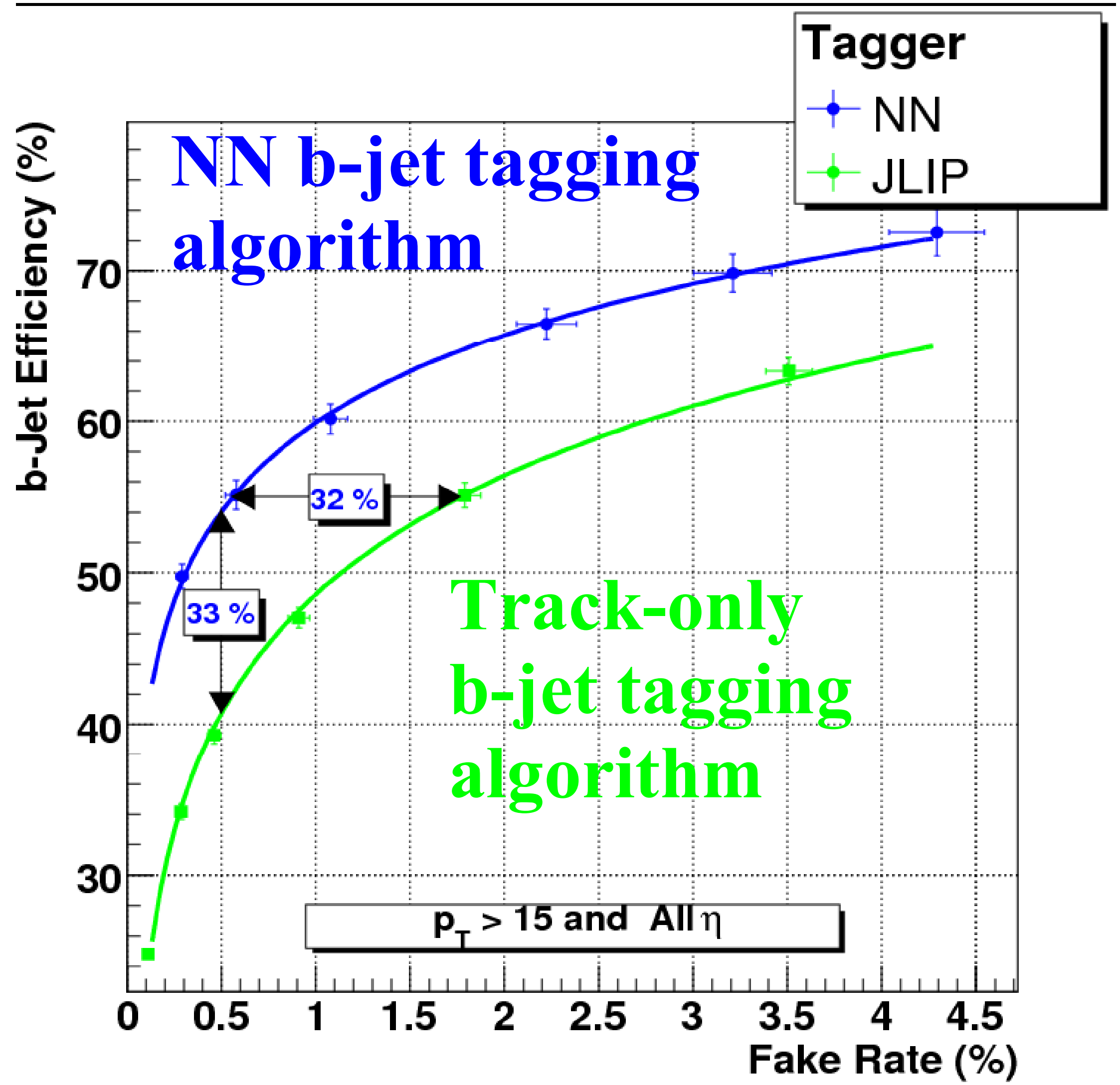


b-Jet Tagging Reality



NN b-Jet Tagging

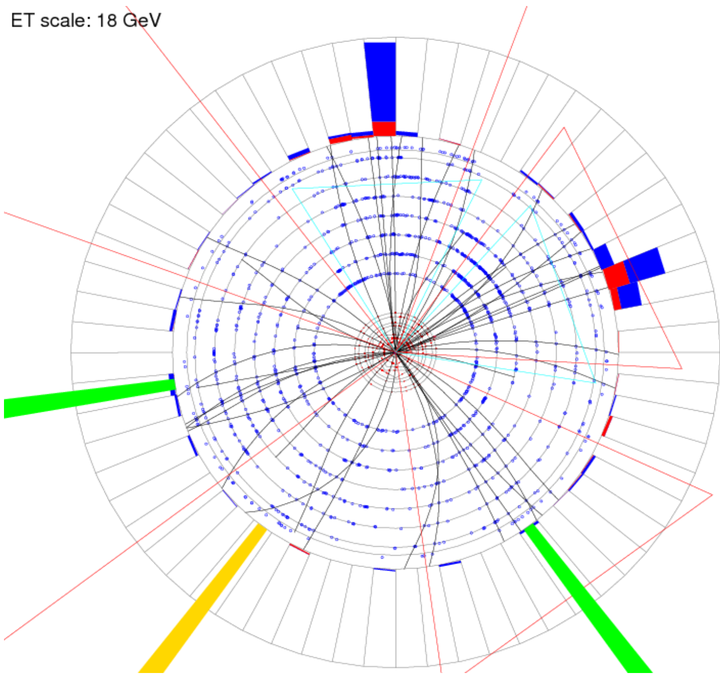
- Combine properties of the reconstructed vertices and tracks using an artificial Neural Network
  - Vertex: DLS, #tracks, N, mass, chi2
  - Combined track IP significances



- Increases S/sqrt(B) by ~30% per b-jet
- Like having 2.5x as much data!

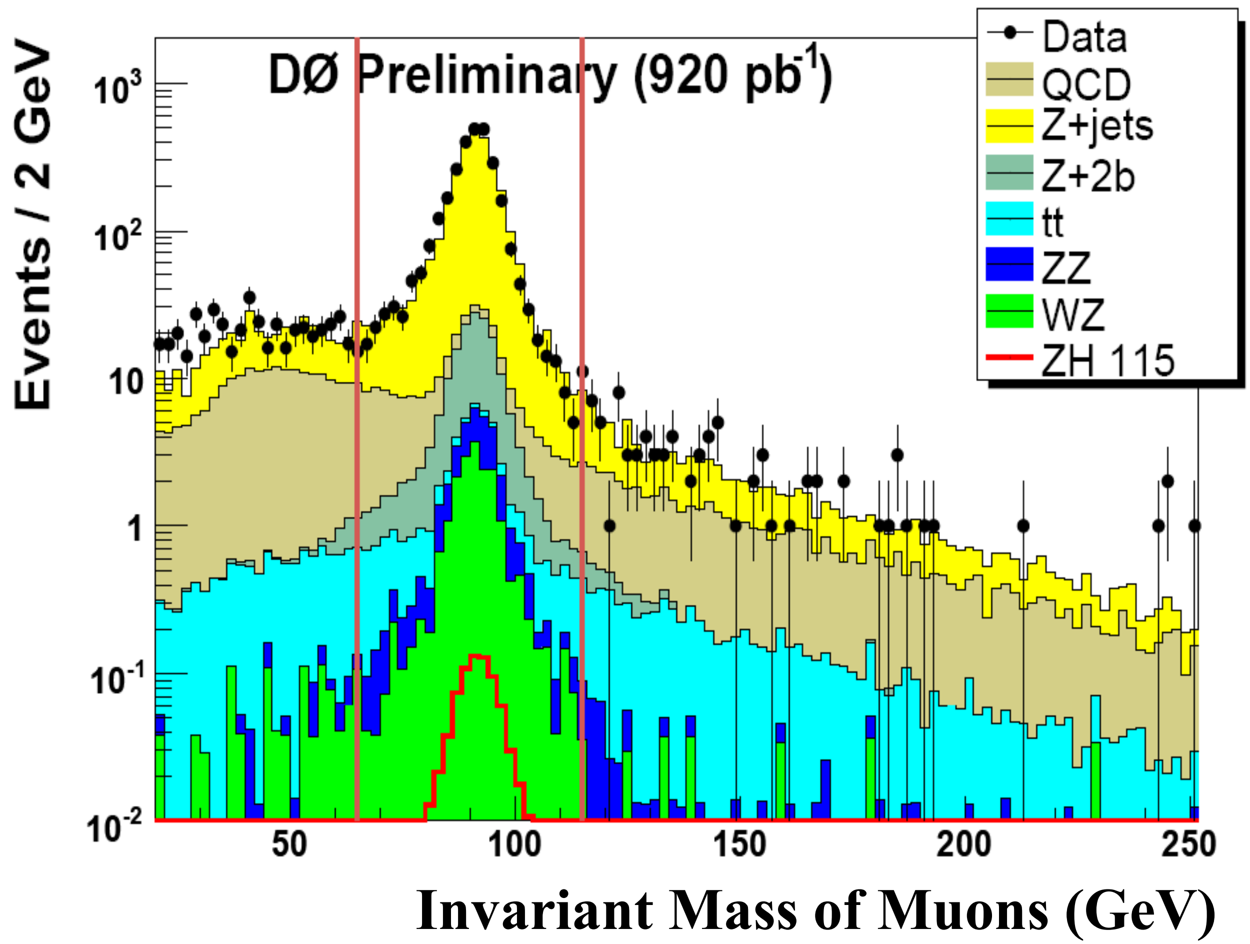
The Zh -> mu^+ mu^- b b Search

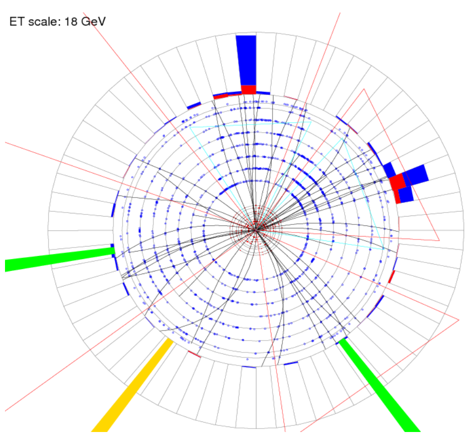
- Let's look at the data!
- And apply the b-tagging technique



Z + 2 jets Data

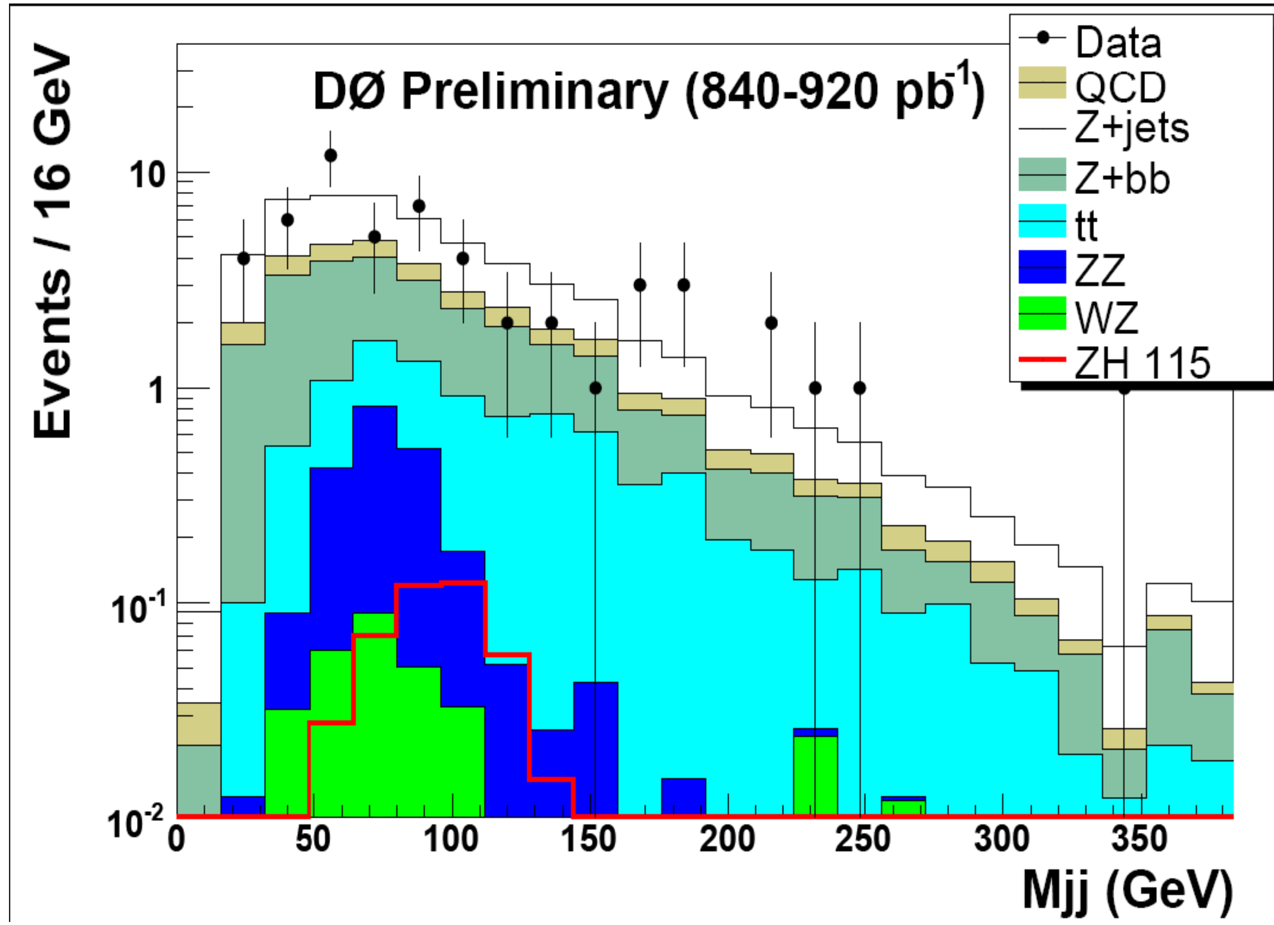
- Select events:
  - 2 jets, pT > 15 GeV
  - mu pT > 15 GeV
  - 65 < mZ < 115
- Main background is Z+(non-b-)jets
  - b-jet tagging will help reduce this

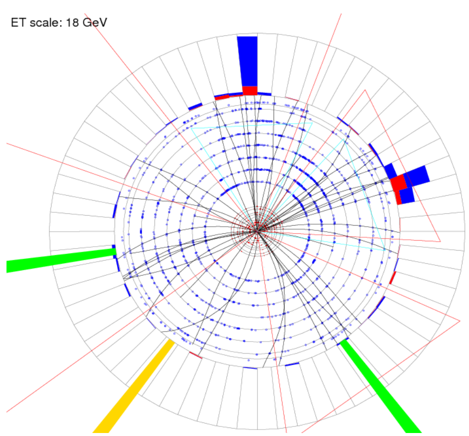




Z + 2 b-jets Data

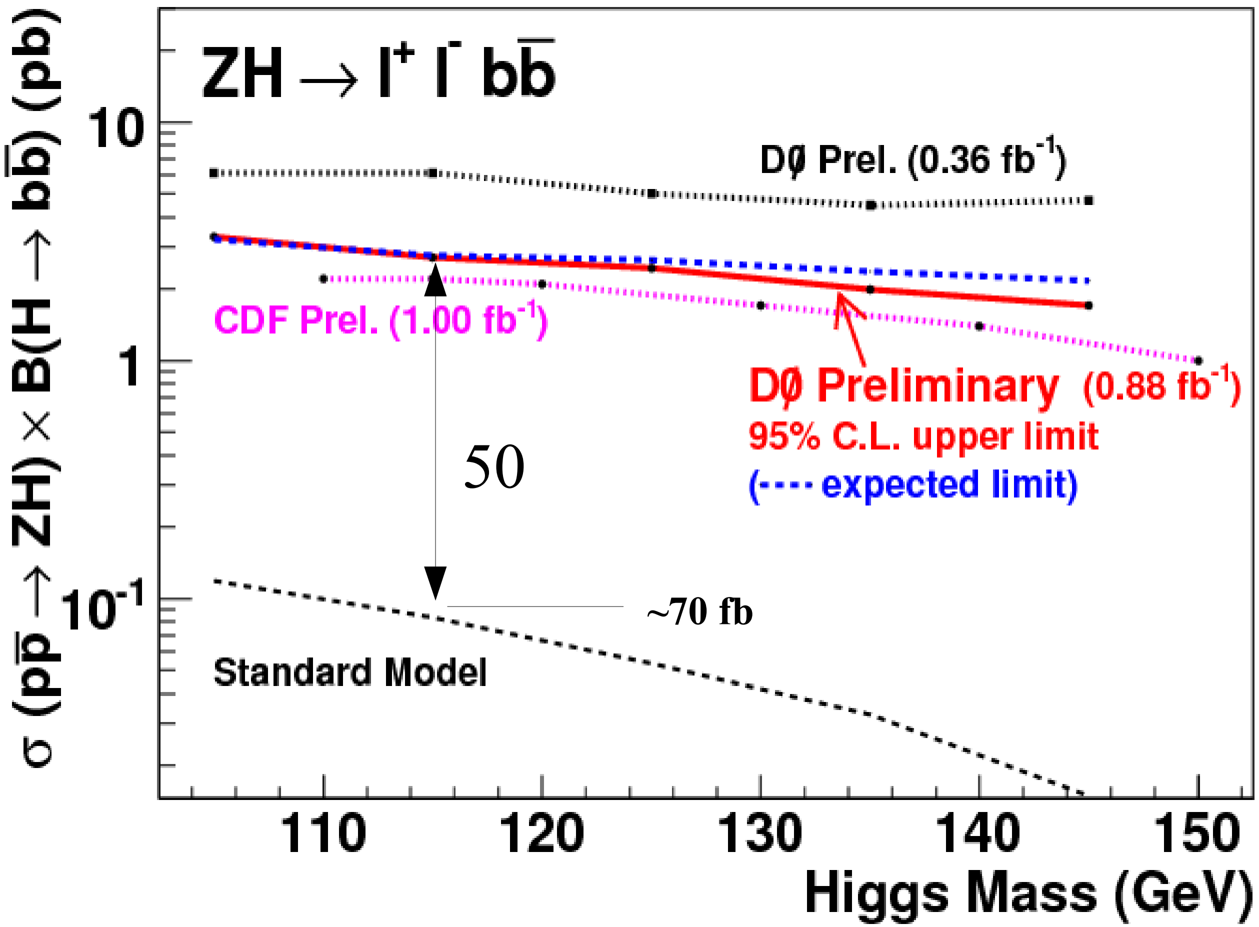
- Require at least 2 of the jets to have NN b-tags
  - Z+(non-b-)jets background greatly reduced
- Look for bump from Higgs->bb





Zh -> $l^+ l^-$ b b Limits

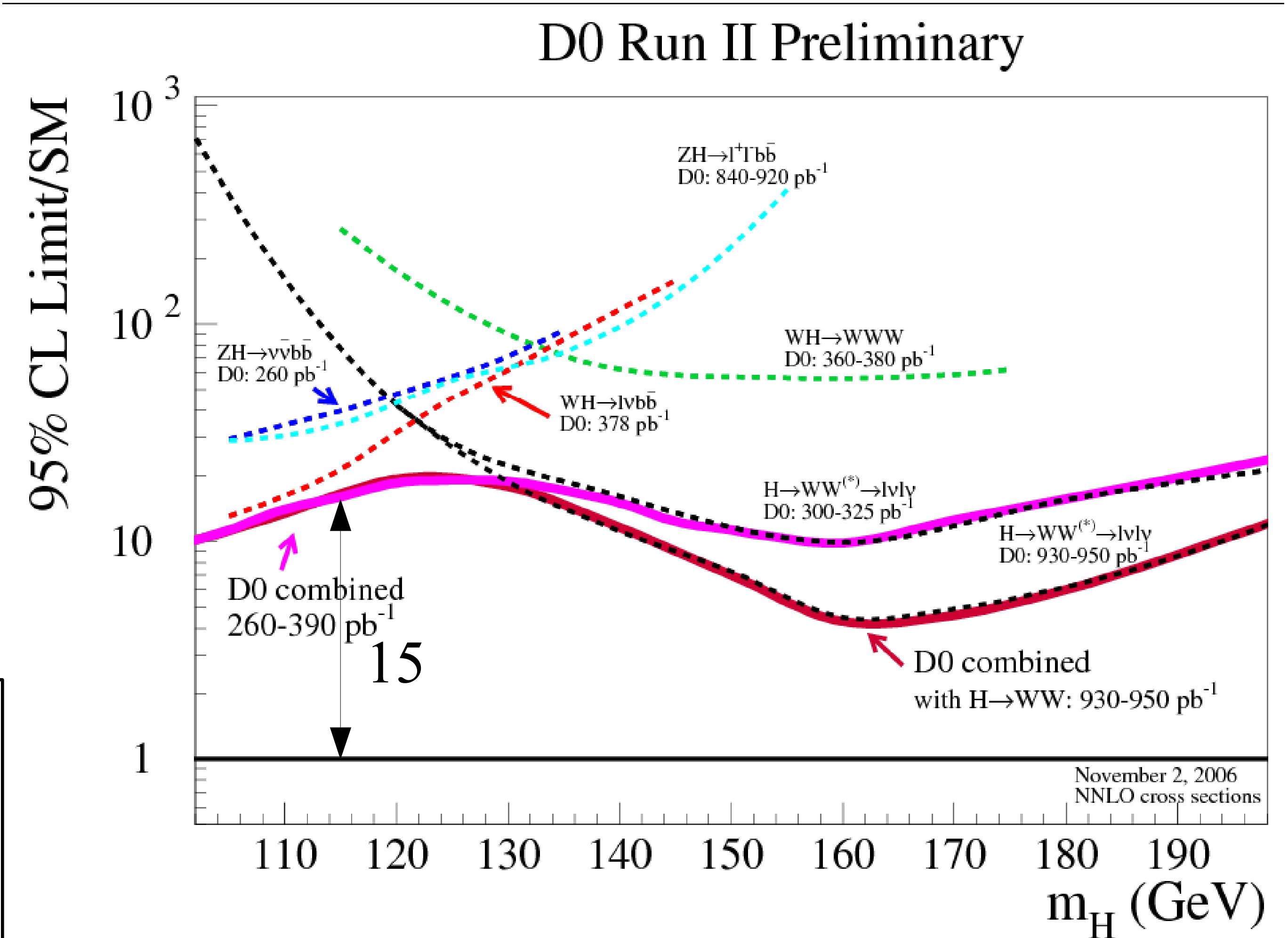
- Combine with Zh-> $e^+ e^-$ b b channel
- Set an upper limit on the rate of Zh production
- We need a factor of ~50x more sensitivity to see the Higgs in this channel alone (at 115 GeV)



Combining the Channels

- Fortunately, there are many channels

- *A factor of ~15 away from the Higgs (115 GeV)*



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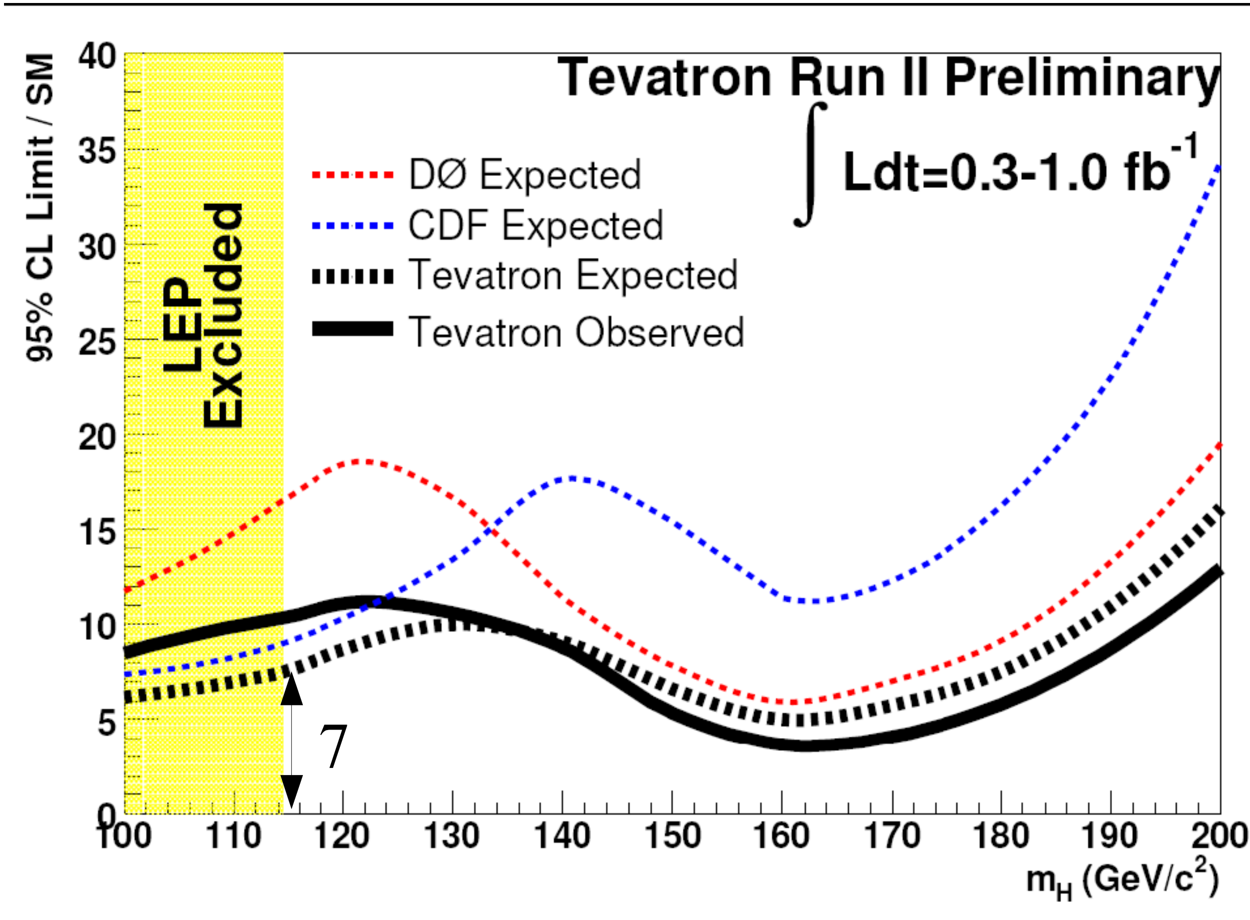
- h -> WW -> e+ nu e- nu
- h -> WW -> mu+ nu mu- nu
- h -> WW -> e+- nu mu-+ nu
- Wh -> WWW -> e+- e+- +nu's + X
- Wh -> WWW -> mu+- mu+- +nu's + X

Combining the Experiments

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

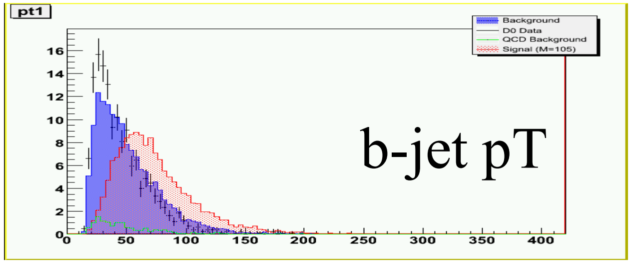


Improving Sensitivity

- 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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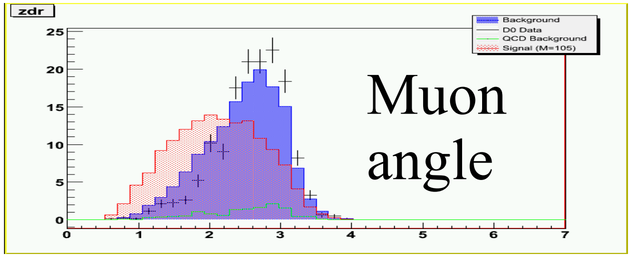

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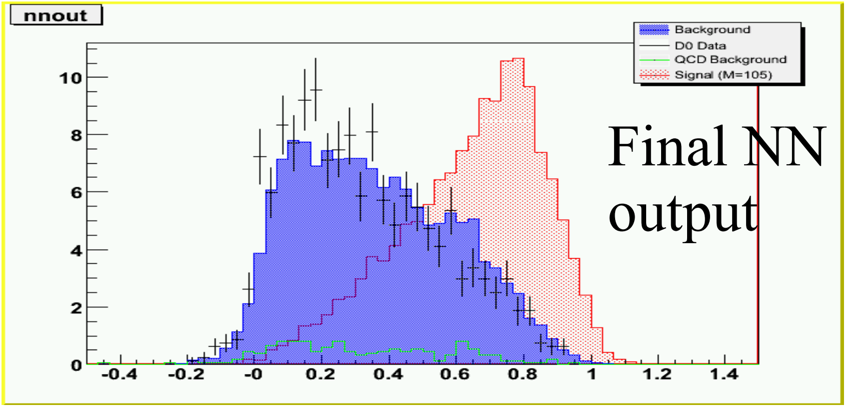


Improving Sensitivity

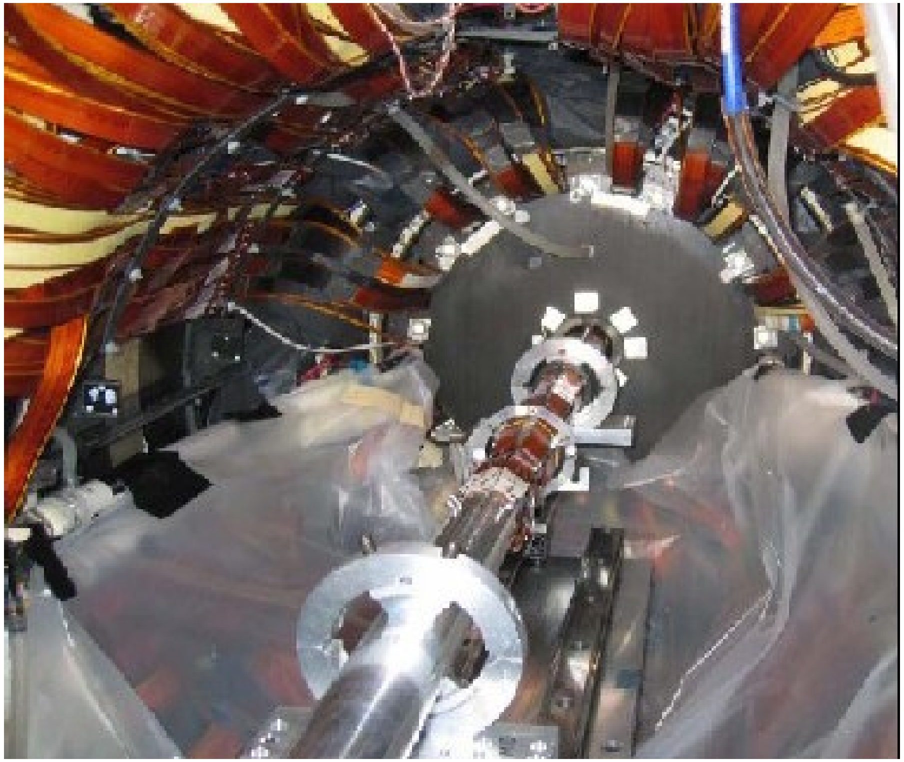
- Now: 7.0
- More data (2/fb per exp. by this year) : 5.0
- NN b-tagging for all analyses: 3.2
- **NN event weighting: 2.0**

Small, difficult improvements

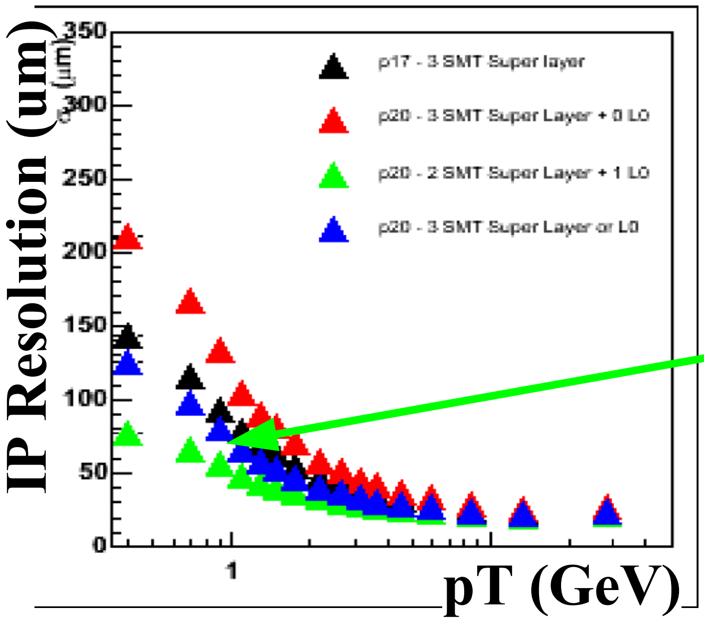
- Better Higgs mass resolution: 1.6
- Use forward electrons in WH: 1.45
- Add tau channels: 1.32
- Better calibrations, reduced systematics: 1.2

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

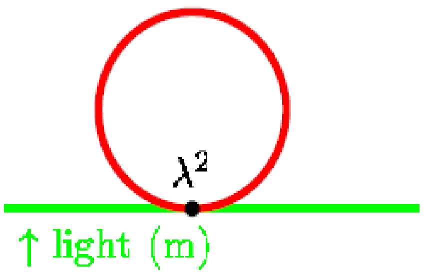
Small, difficult improvements

- 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**

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

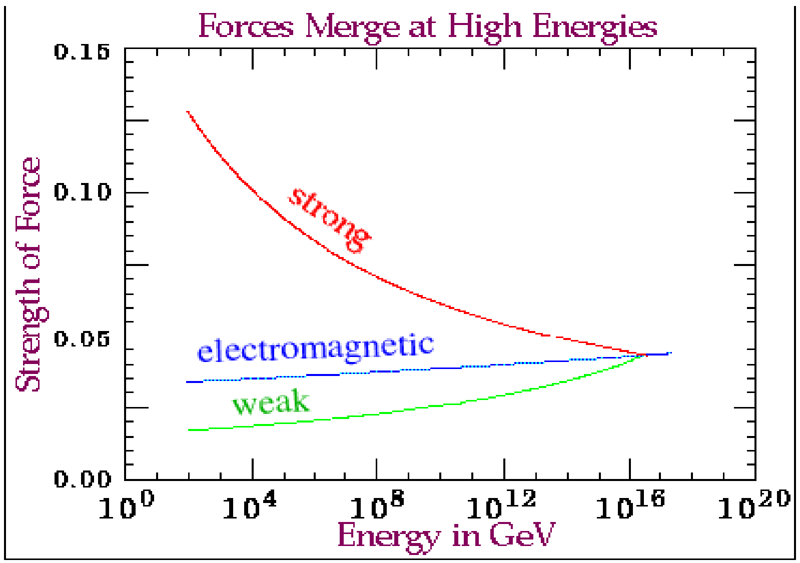
Why is the Higgs so Light?

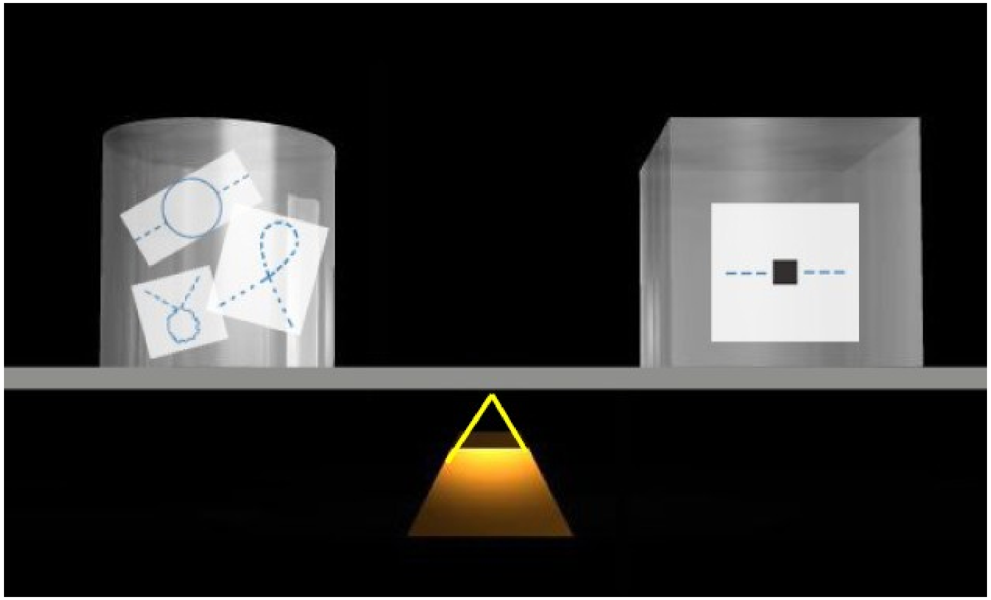
- Where does the Higgs get its mass from?
- The Higgs mass is *unstable*
  - Large radiative corrections (it's a scalar – spin 0)



$$\Longrightarrow \begin{array}{ccc} \delta m^2 \sim & \lambda^2 & \cdot M^2 \\ \wr & \wr & \wr \\ 10^2 & 10^{-1} & 10^{16} \end{array}$$

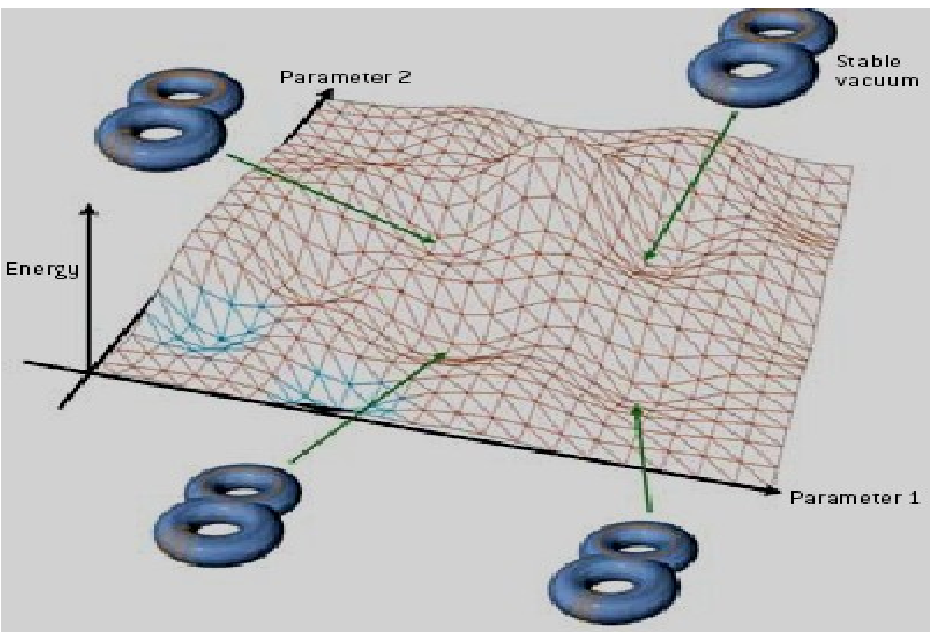
- A delicate *balance* between many large forces
- Hierarchy problem

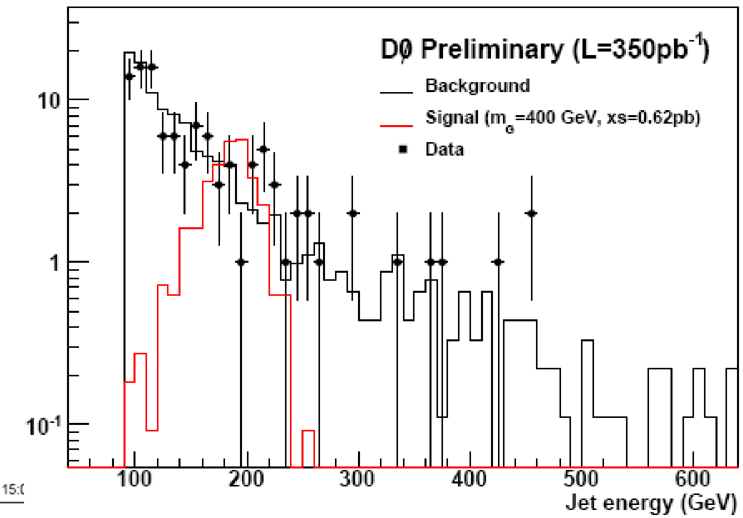


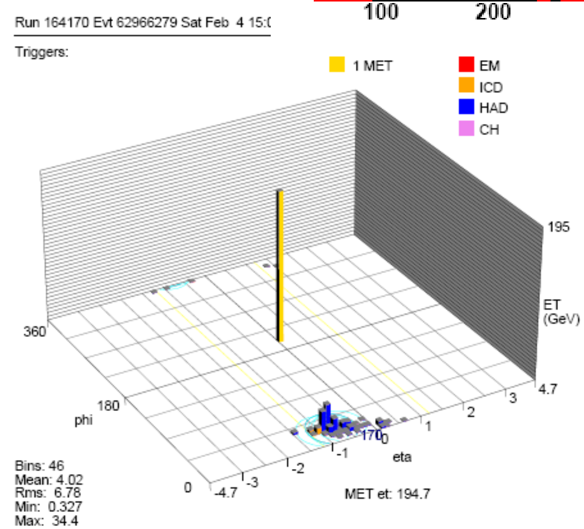


Why is the Higgs so Light?

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







D0 search for "stopping gluinos"

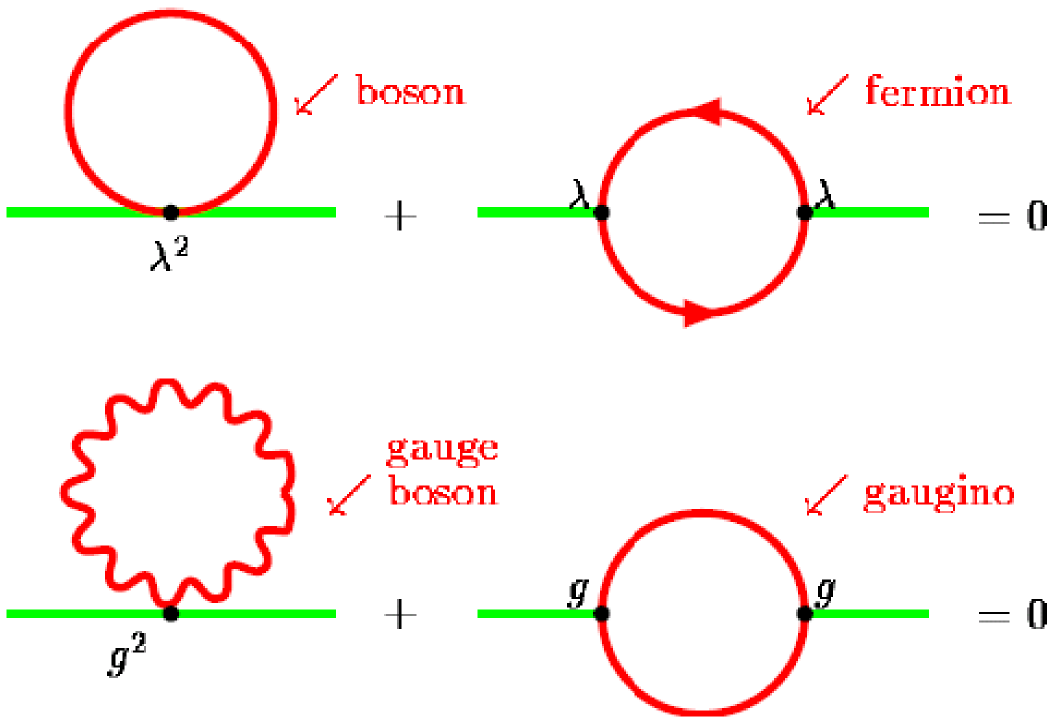
- Same reason for a small cosmological constant?

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

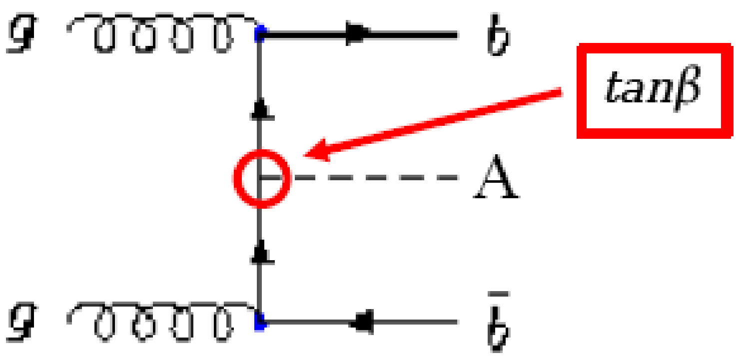
fermion = *spin 1/2, 3/2, …*

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

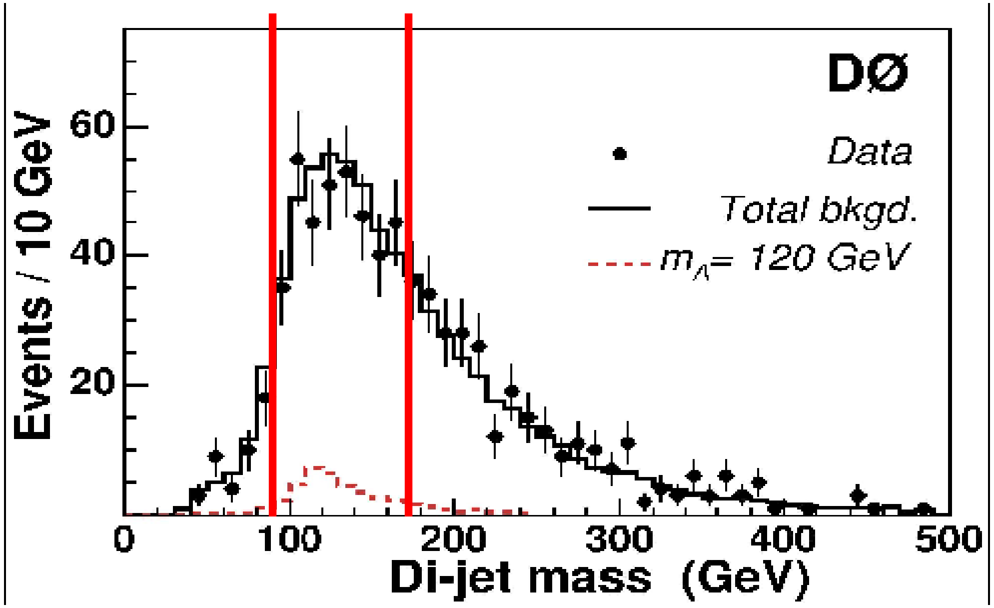


- *tanB* -> ratio of Higgs fields' VEVs
- H/A +bb production proportional to $\tan^2 B$

- Should be able to see H/A + bb at high tanB...
- H/A decays to bb 90% of the time (the rest to tau's)
  - Look for: H/A + bb -> bb bb

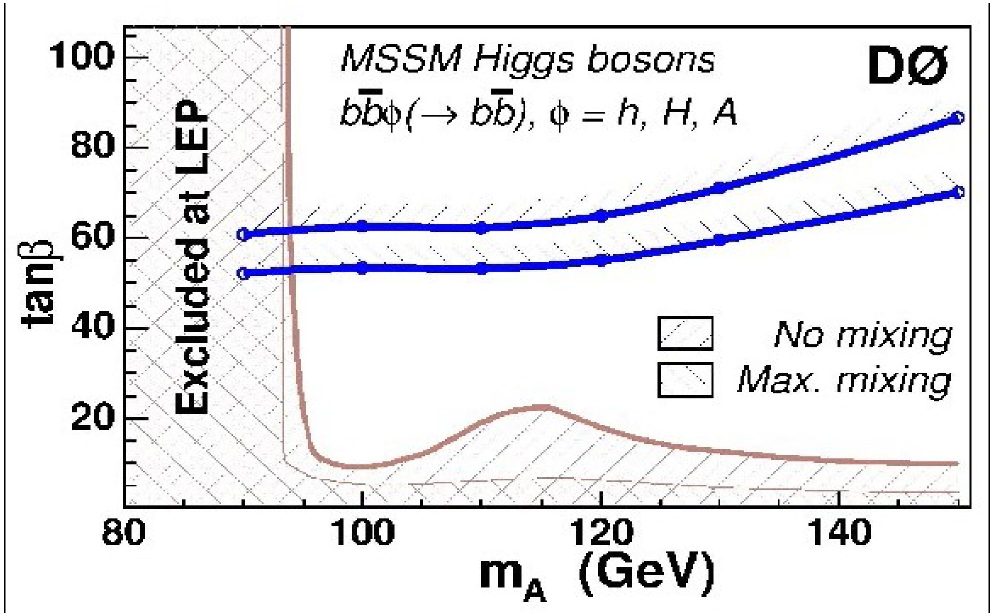
DØ Search for H/A + bb -> bb bb

- Look for bump in bb invariant mass spectrum in events with at least 3 b-jets
  - Background determined from 2 b-jet data



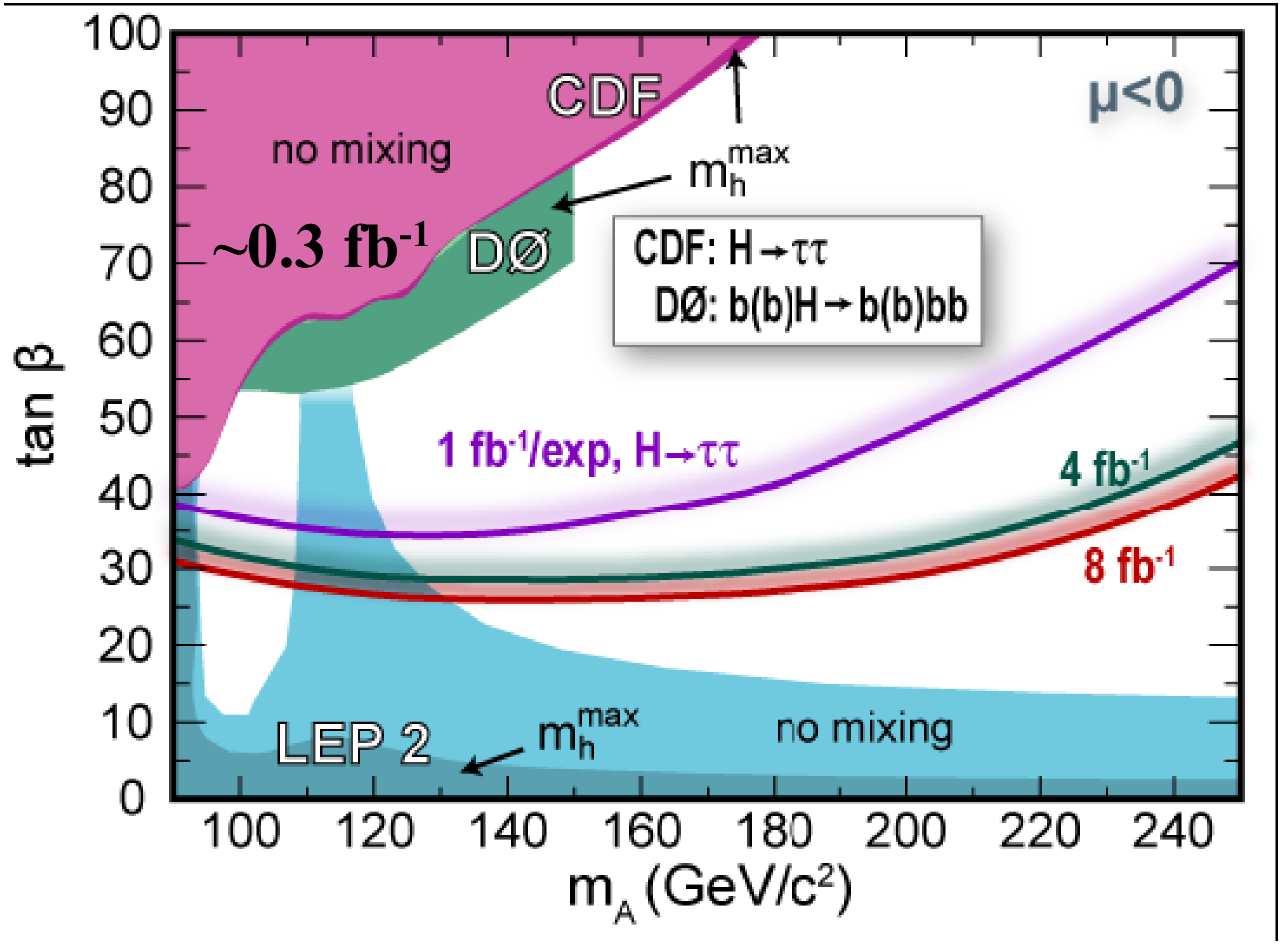
- No excess observed for any H/A mass

- Interpret as limits in the Higgs mass vs. tanB plane
- PRL 95, 151801 (2005)



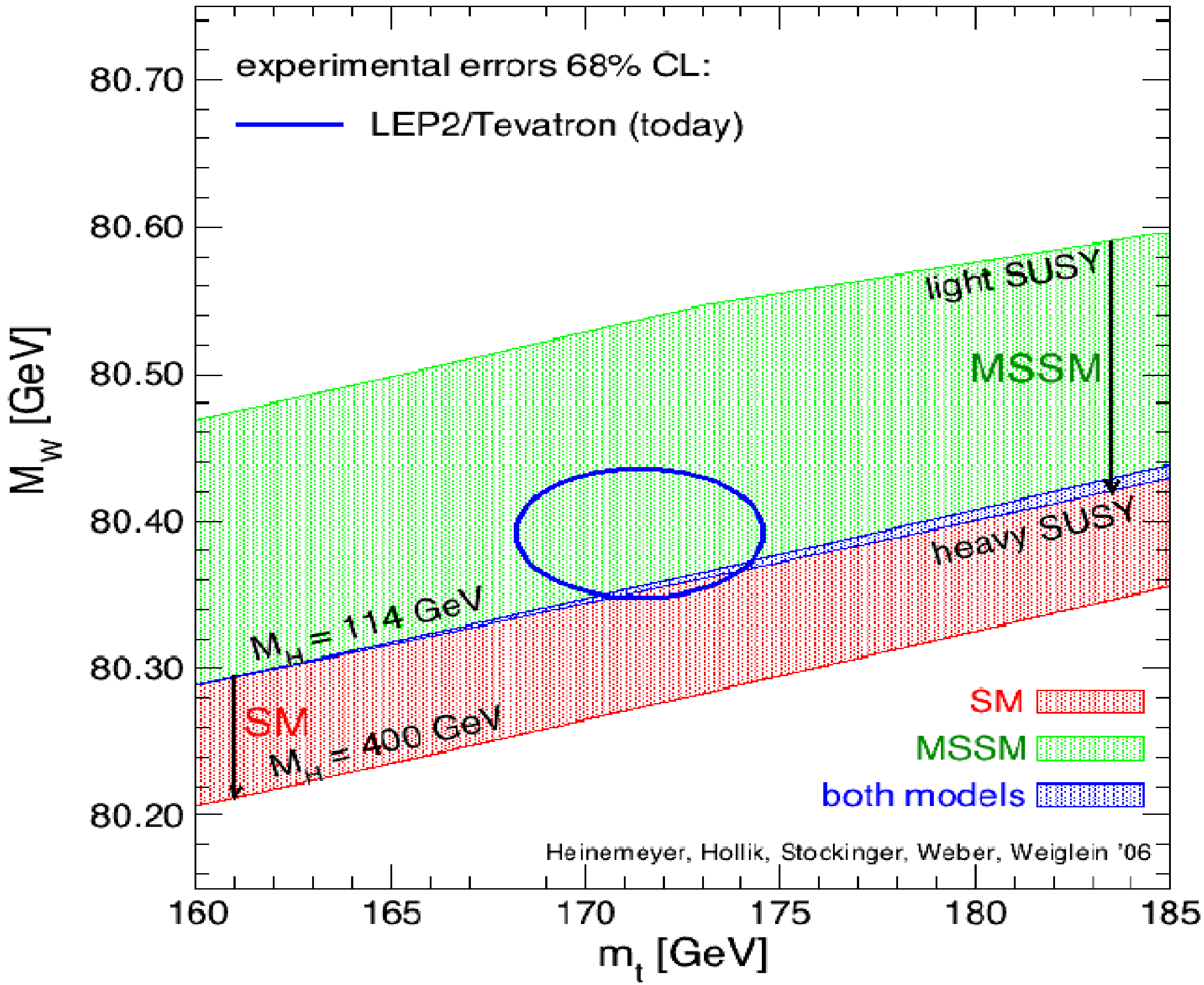
H/A Sensitivity at the Tevatron

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



Trouble with *Minimal* Supersymmetry?

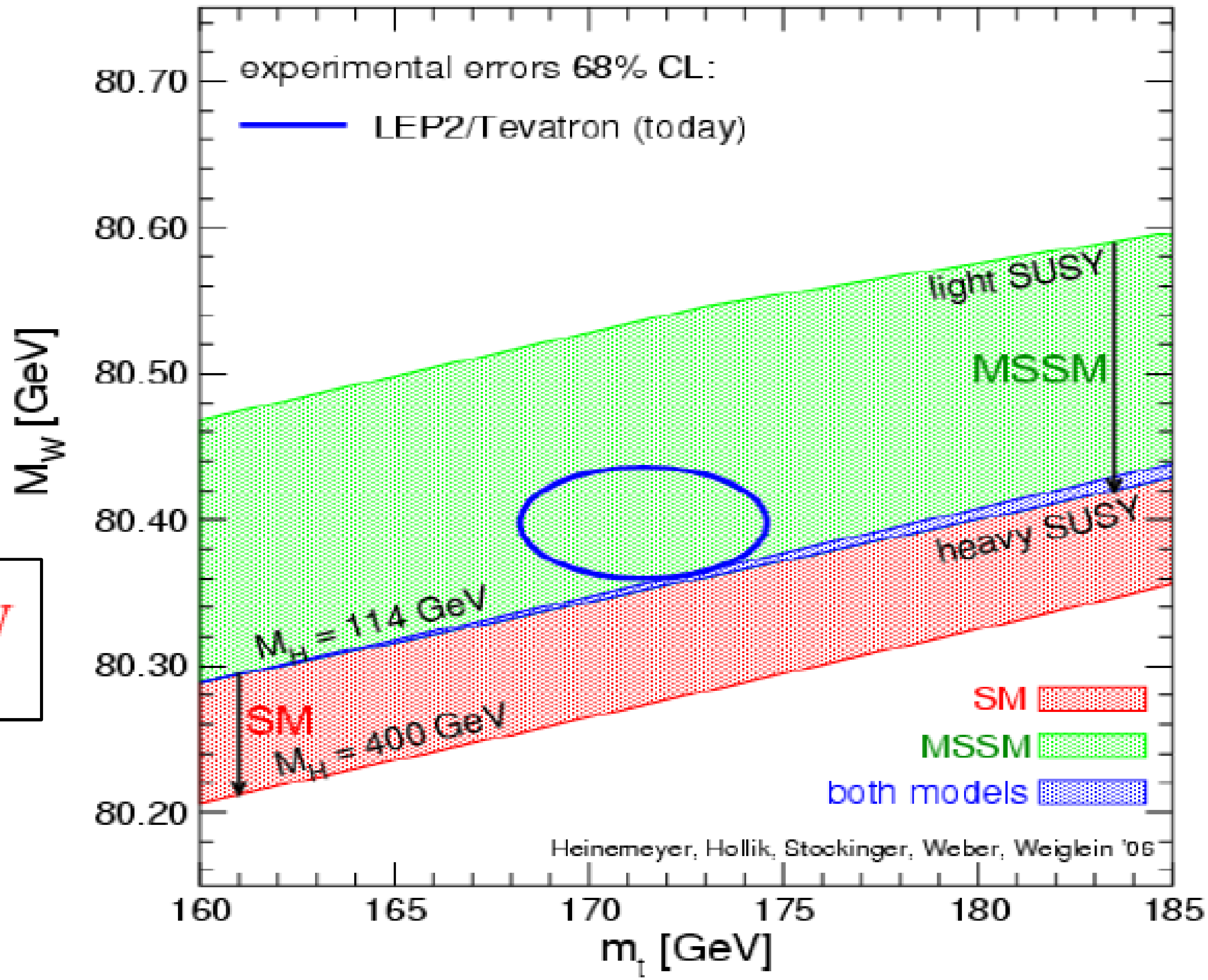
- We should have found the Higgs already?!
  - Supersymmetry predicts a light Higgs
  - Comparisons of the W and top masses point to a light Higgs
- But searches at LEP exclude a light Higgs!



Trouble with *Minimal* Supersymmetry?

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

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



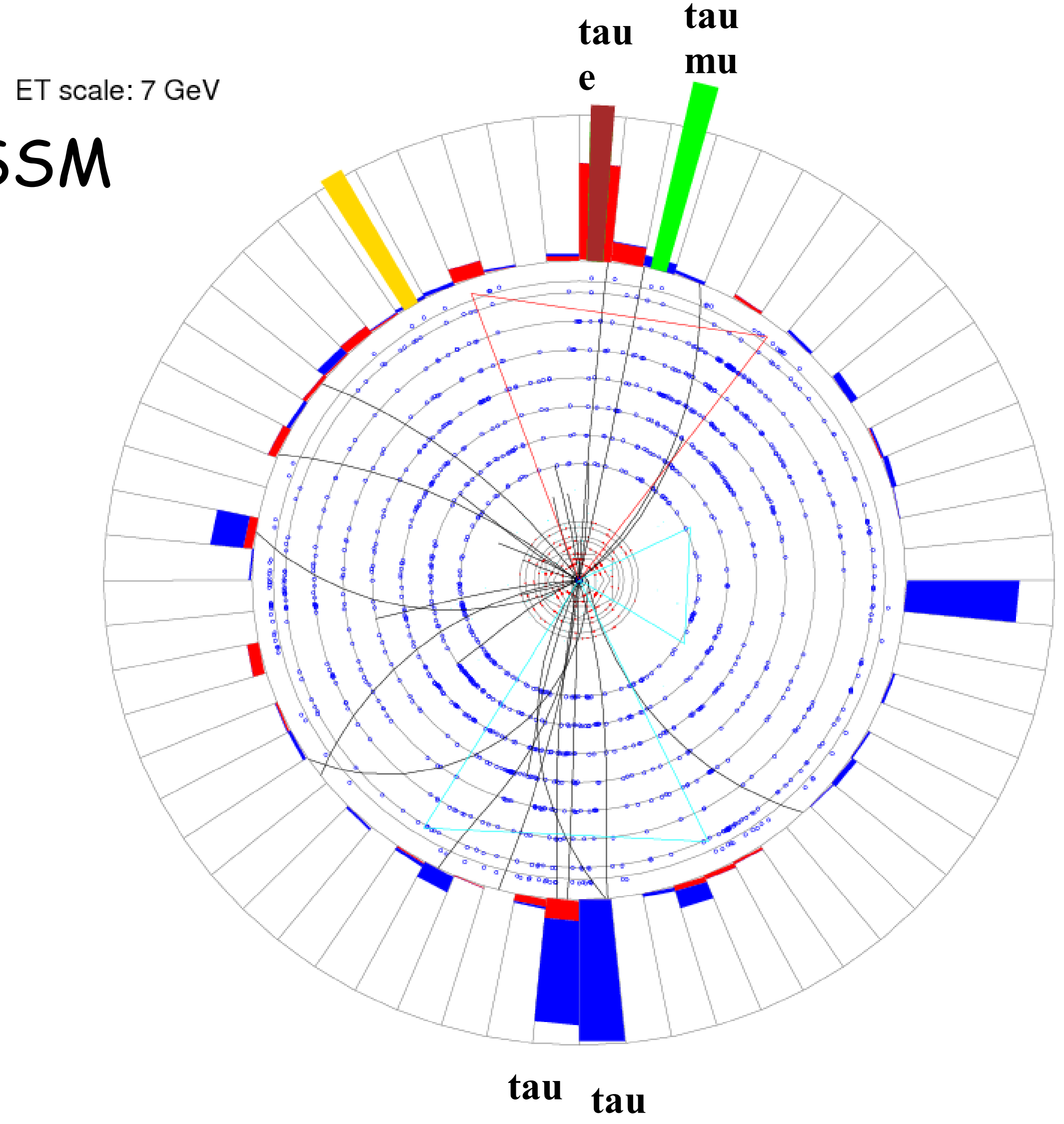
A Hint of Something New?

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

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

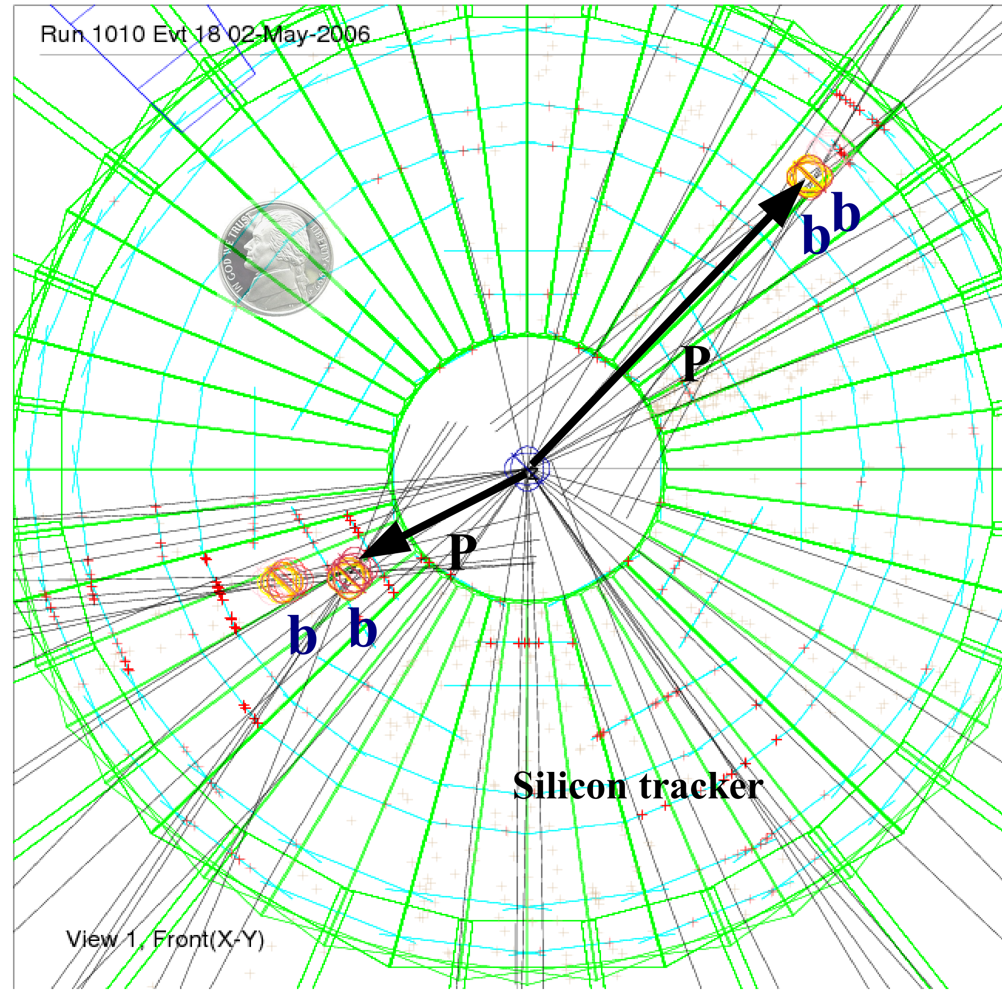
Higgs Decays to Intermediate Particles

- New light scalar particle: "a"
  - NMSSM, additional singlet
  - Solves "mu" problem of MSSM
- a decays to 2 taus
- h -> a a -> tau tau tau tau
  - BR can be *large!*
- a is light, so tau's are close to each other
  - Hard to identify!
  - Not excluded by LEP data for $m_h > 85$ GeV
- Analysis in progress...



Higgs Decays to Long-lived Particles

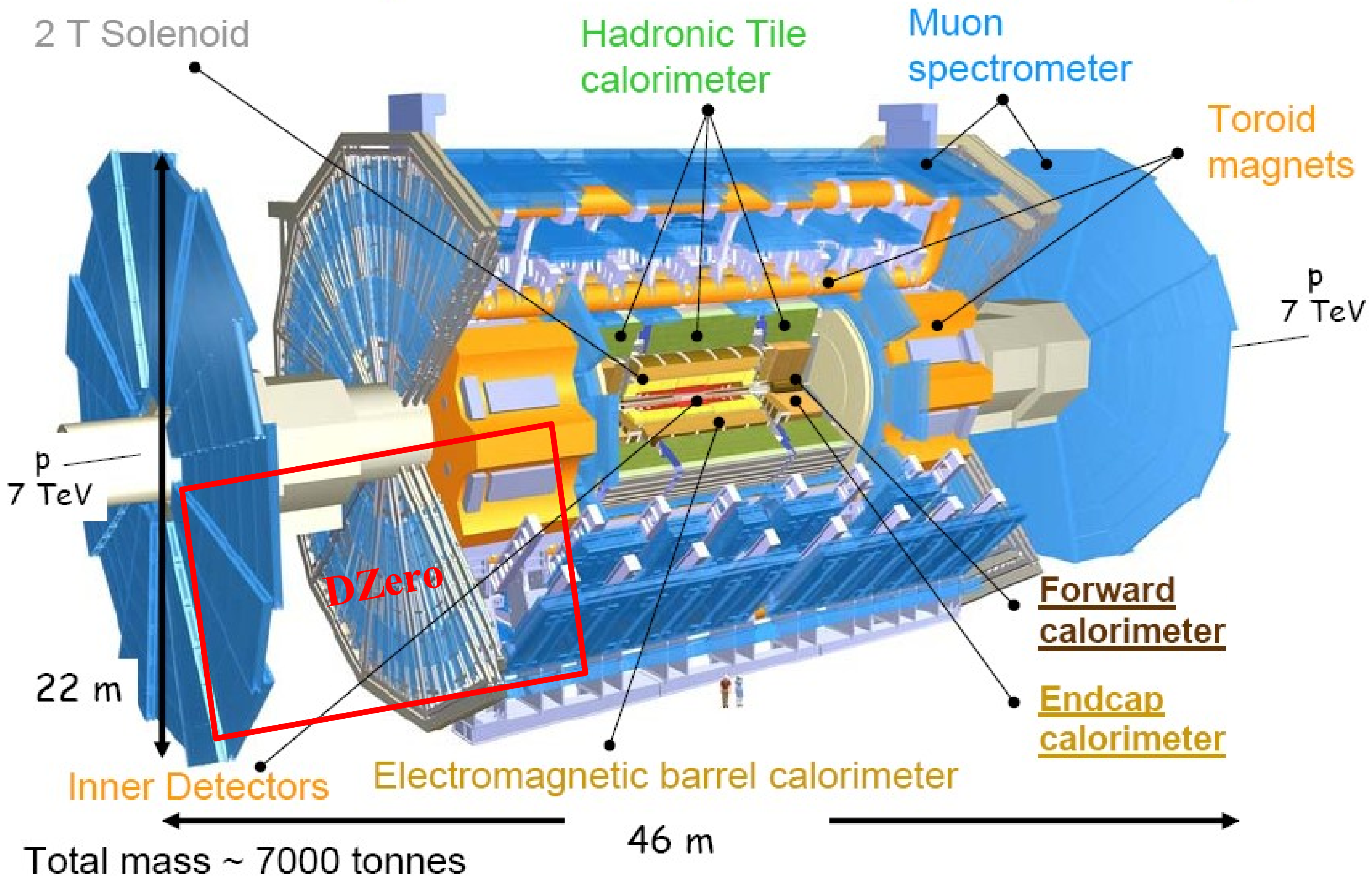
- New strongly-coupled gauge group, uncharged under SM, mix with Higgs
  - "Hidden Valley"
- New long-lived particle: "P"
  - P decays to 2 b-jets
- h -> P P -> b b b b
  - BR can be *large!*
- No one's ever looked for long-lived particles decaying to b-jets
  - Weak LEP, $m_h > 82$ GeV
- Analysis in progress...



The LHC at CERN

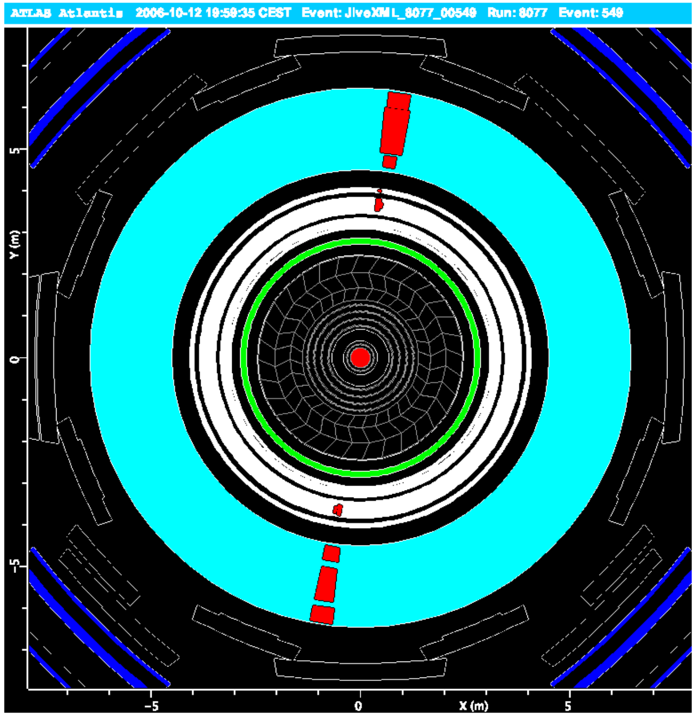
- proton on *proton*
- 4.3 km radius
- Each proton has 7x the Tevatron energy
- 100x as many collisions/sec. as the Tevatron
- Starts in 2008! (low-energy test run this year)

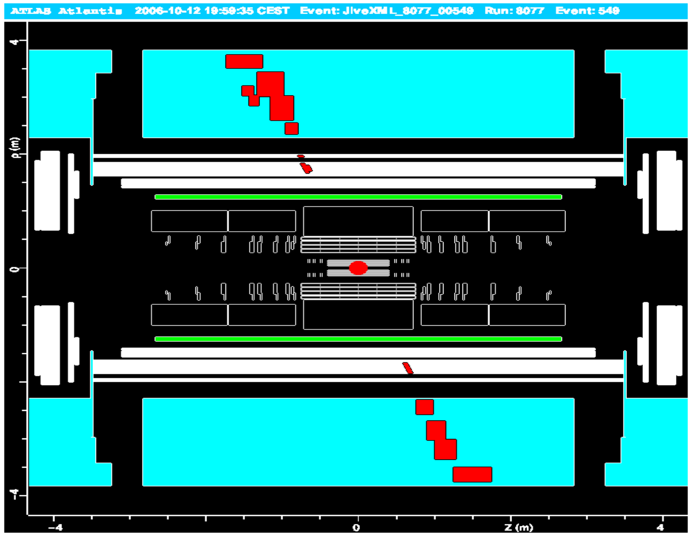
The ATLAS Detector



ATLAS is Real

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

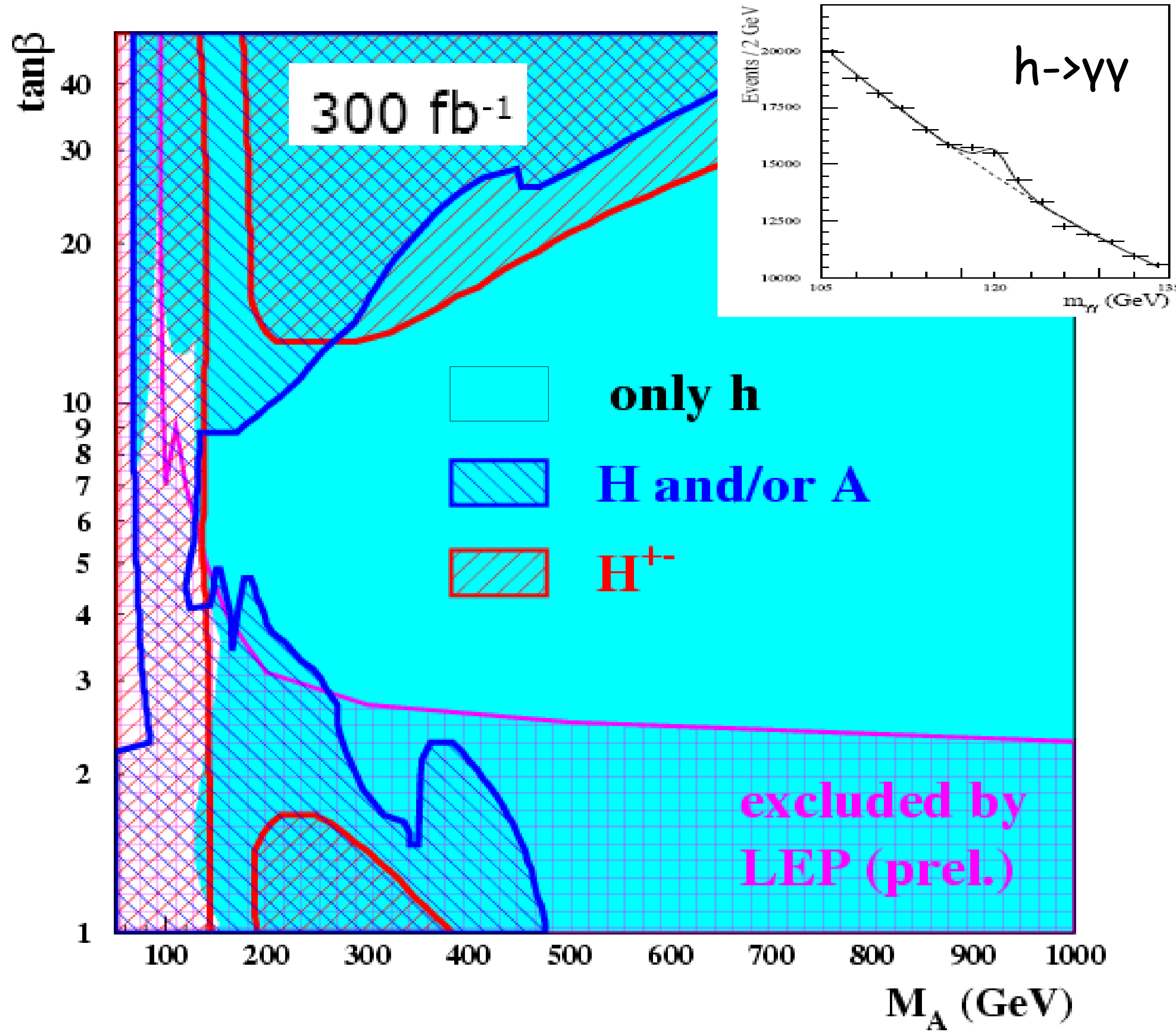




The ATLAS Control Room

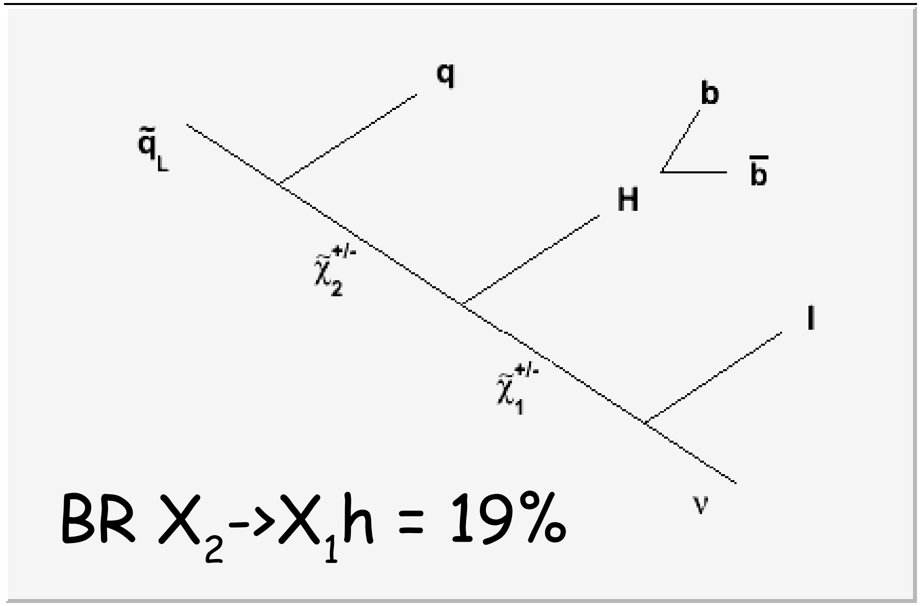
Higgs Searches at ATLAS

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

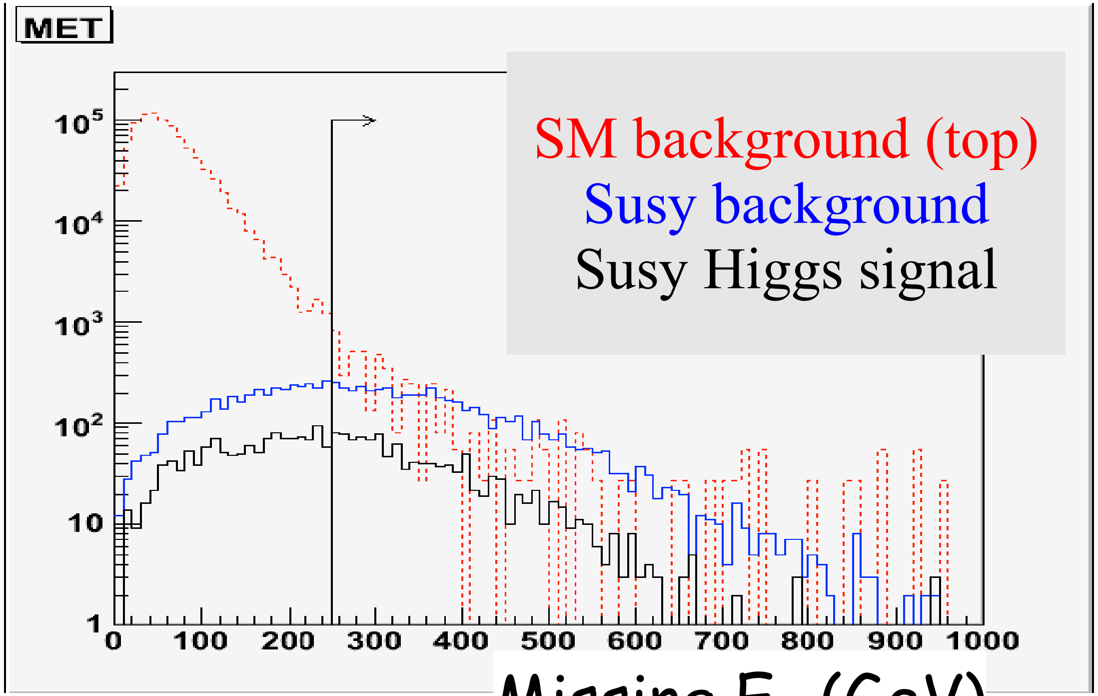


The Higgs in Supersymmetry Decays

- 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...



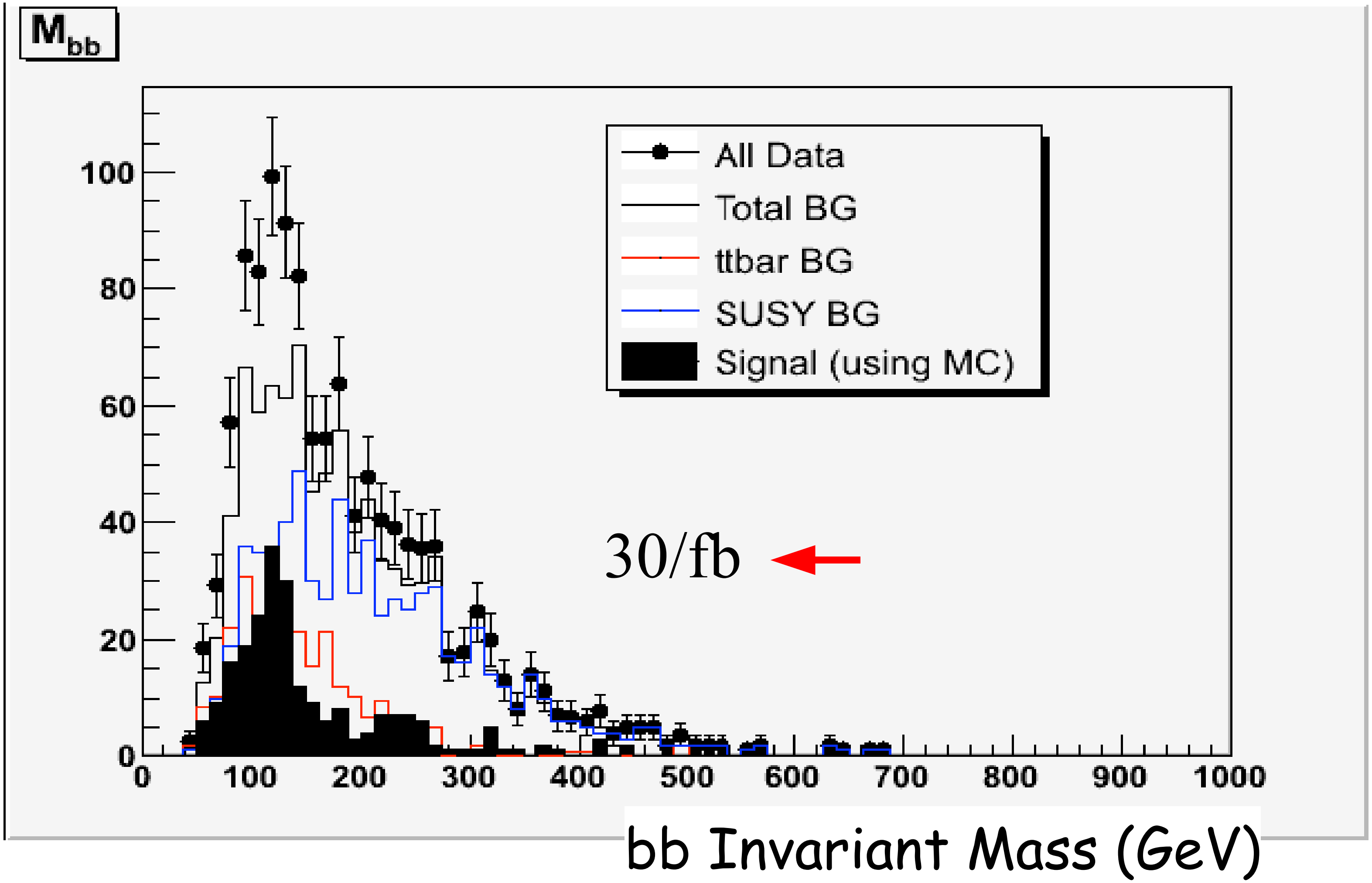
BR X_2->X_1h = 19%



Missing E_T (GeV)

The Higgs in Supersymmetry Decays

- Remaining background is mostly supersymmetric!
- Look for bump from H->bb 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!