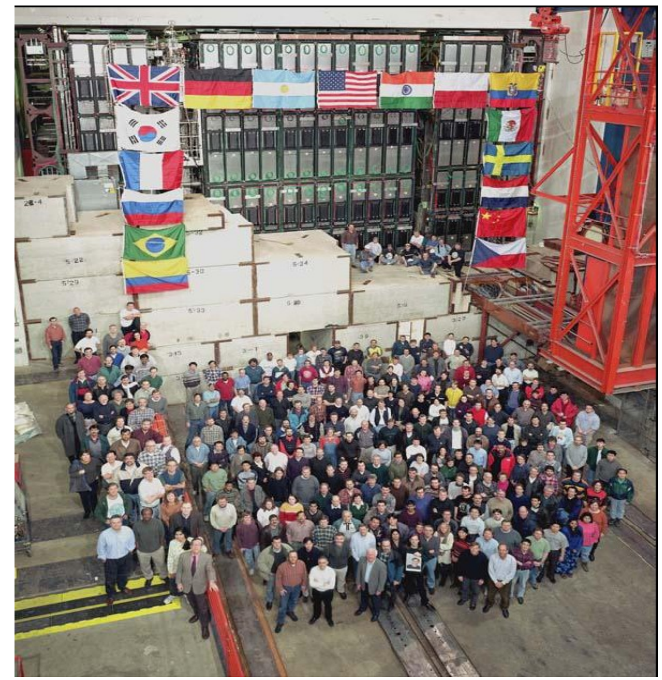
The Search for the SM Higgs Boson at DØ

Dr. Andy Haas
Columbia University
DØ / ATLAS

University of Chicago
Particle Physics Seminar
January 14, 2008



Columbia University
In the City of New York

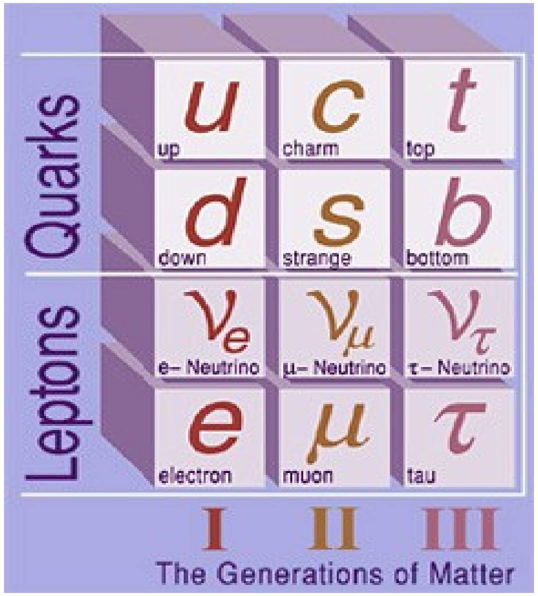
The Standard Model

3 families of matter

3 forces

- "gauge symmetries": $U(1)_Y \times SU(2)_L \times SU(3)_C$

Massive W,Z gauge bosons



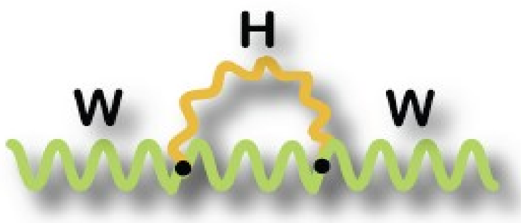
Scalar Higgs field, non-zero VEV

- W,Z get masses through "Higgs mechanism"
- Fermions can get Yukawa masses: $-\frac{1}{v} m_f \bar{\psi}_f \phi_h \psi_f$

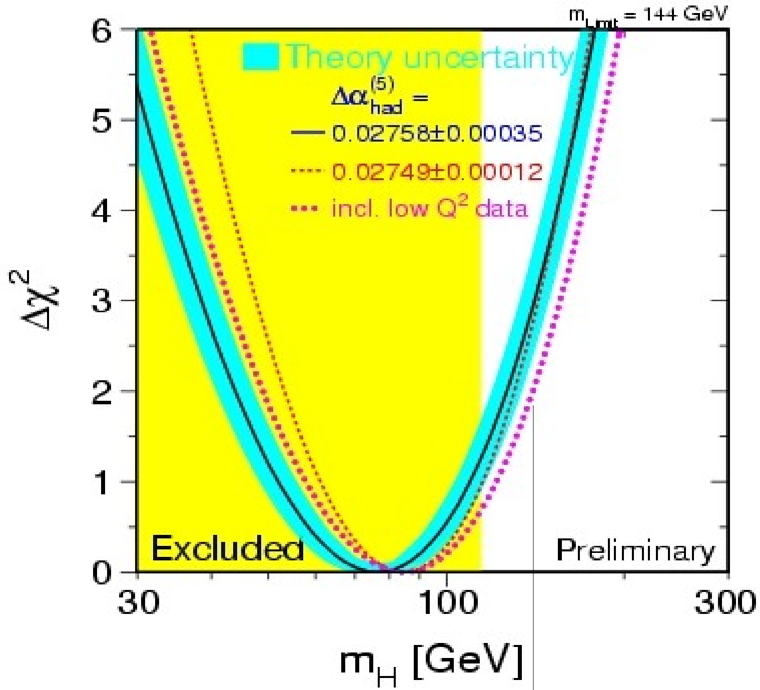
Higgs boson: excitation of the Higgs field - m_H

Precision EW Constraints

EW variables sensitive to m_H via radiative corrections:



$$\log \frac{m_H}{m_Z}$$



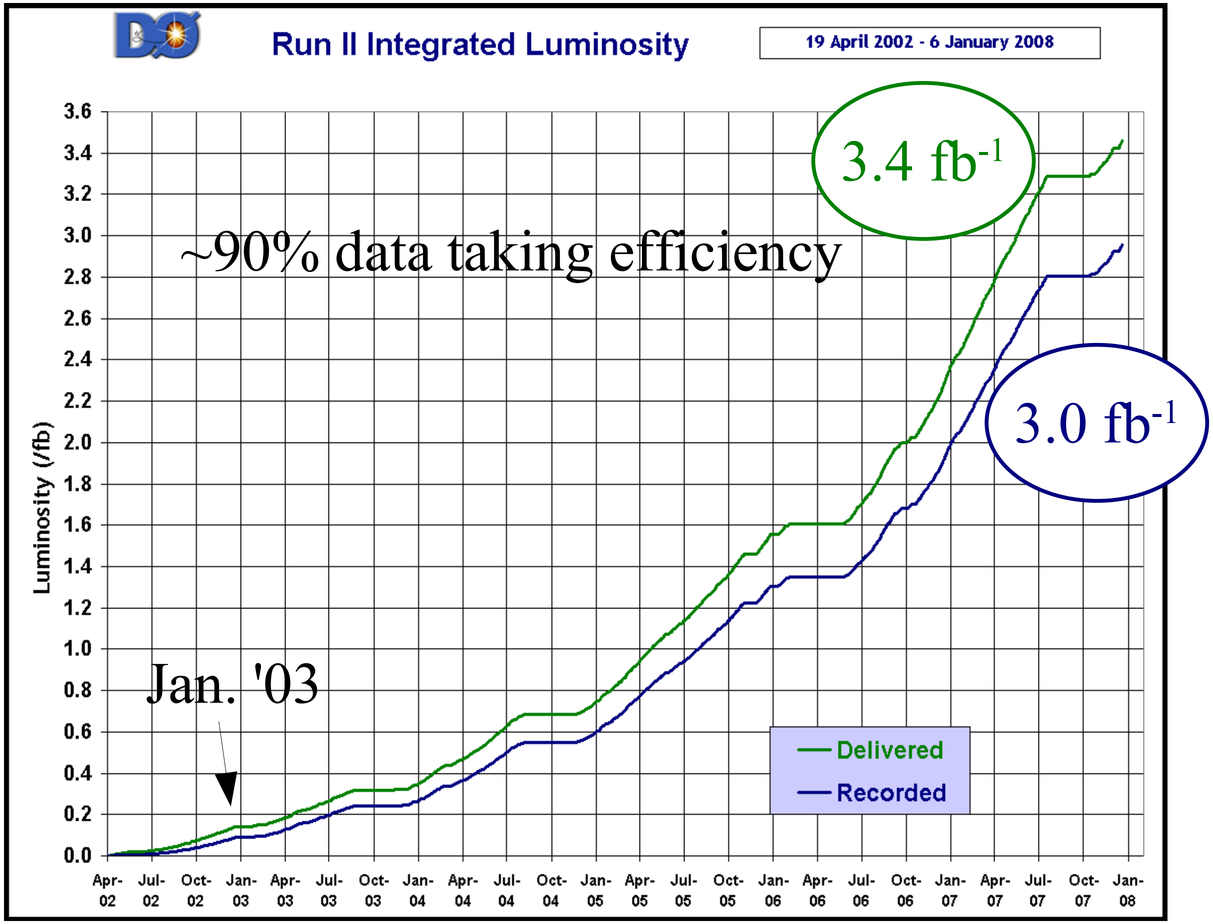
LEP II direct: m_H>114.4 GeV

m_H<182 GeV (including direct limit)

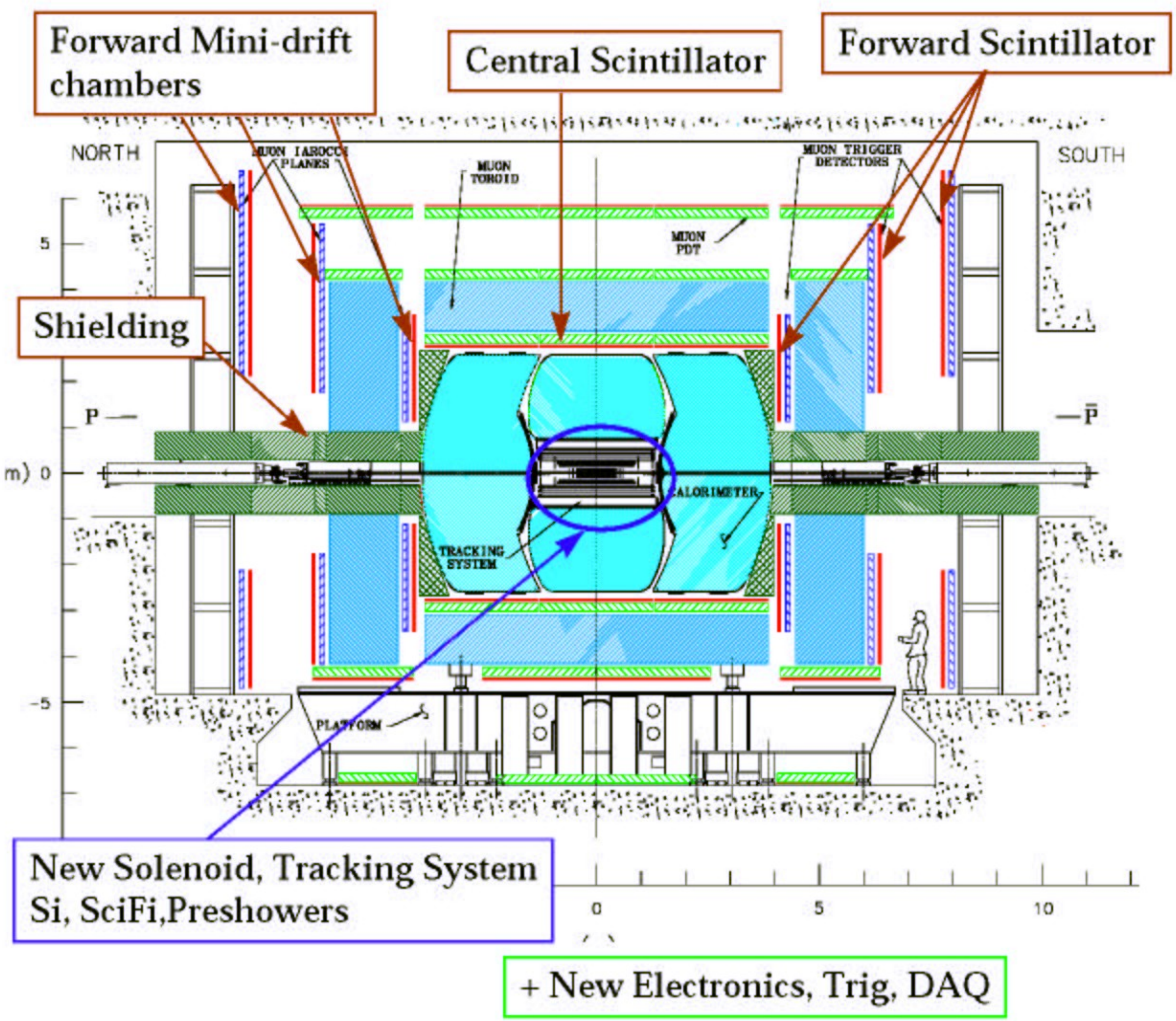
m_H<144 GeV (at 95% CL)

The Tevatron at Fermilab

Running (again) since ~2003
proton on anti-proton
sqrt(s)=1.96 TeV



The DØ Detector



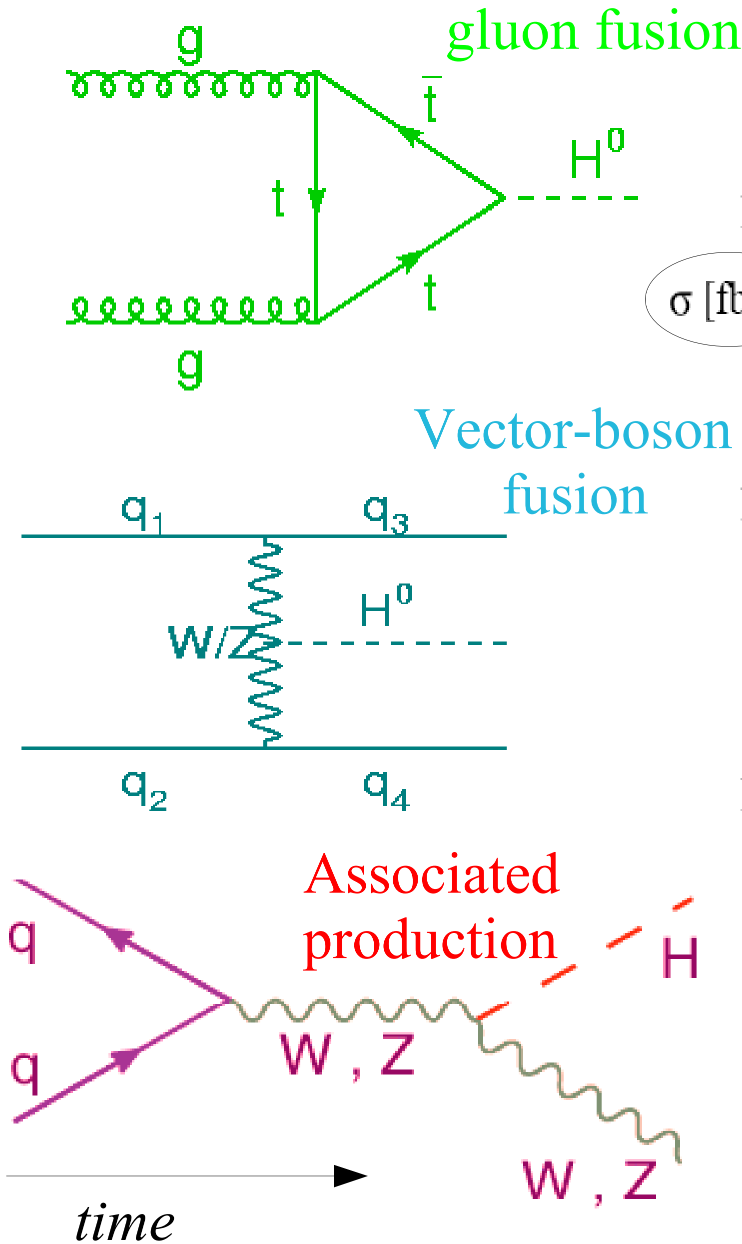
Retained from Run I

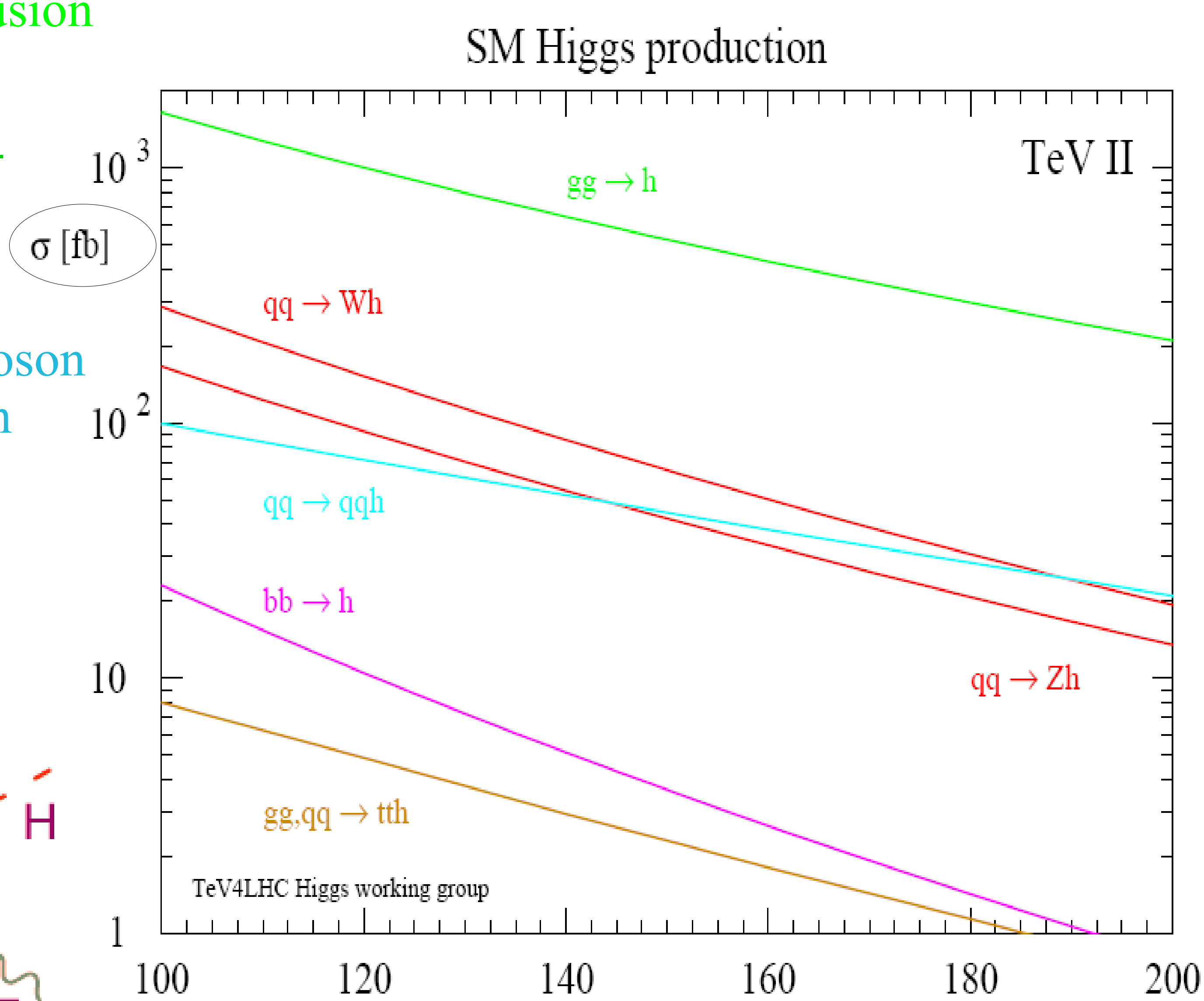
- LAr calorimeter
- Central muon detector
- Muon toroid

New for Run II

- Magnetic tracker
  - 2 T solenoid
  - Silicon vertex tracker
  - Scintillating fiber tracker
- Preshower detectors
- Forward muon detector
- Front-end electronics
- Trigger and DAQ

Higgs Production at the Tevatron





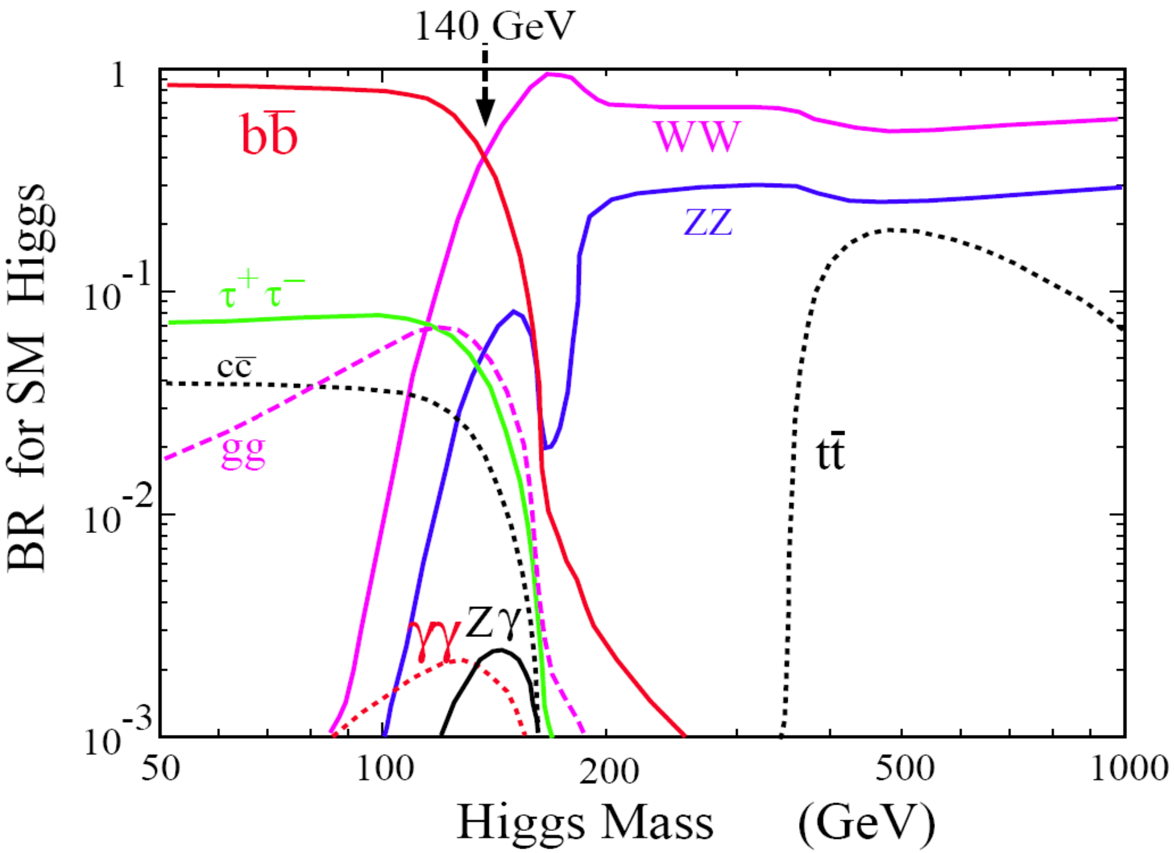
Higgs Decays

Coupling ∝ fermion mass

$$-\frac{1}{v} m_f \bar{\psi}_f \phi_h \psi_f$$

Main channels:

- bb (low mass)
- WW (high mass)



Main Higgs Analyses

	$H \rightarrow bb$	$H \rightarrow WW$
$p\bar{p} \rightarrow H$	~~$H \rightarrow bb$~~	**$H \rightarrow WW \rightarrow$ ee/eμ/μμ+MET**
$p\bar{p} \rightarrow WH$	**$WH \rightarrow Wbb \rightarrow$ e/μ+bb**	$W/Z+H \rightarrow W/Z+WW \rightarrow$ $l^+l^- l^+$ / l^+l^+jj + MET
$p\bar{p} \rightarrow ZH$	**$ZH \rightarrow Zbb \rightarrow$ ee/μμ+bb MET+bb**	

Main Higgs Analyses

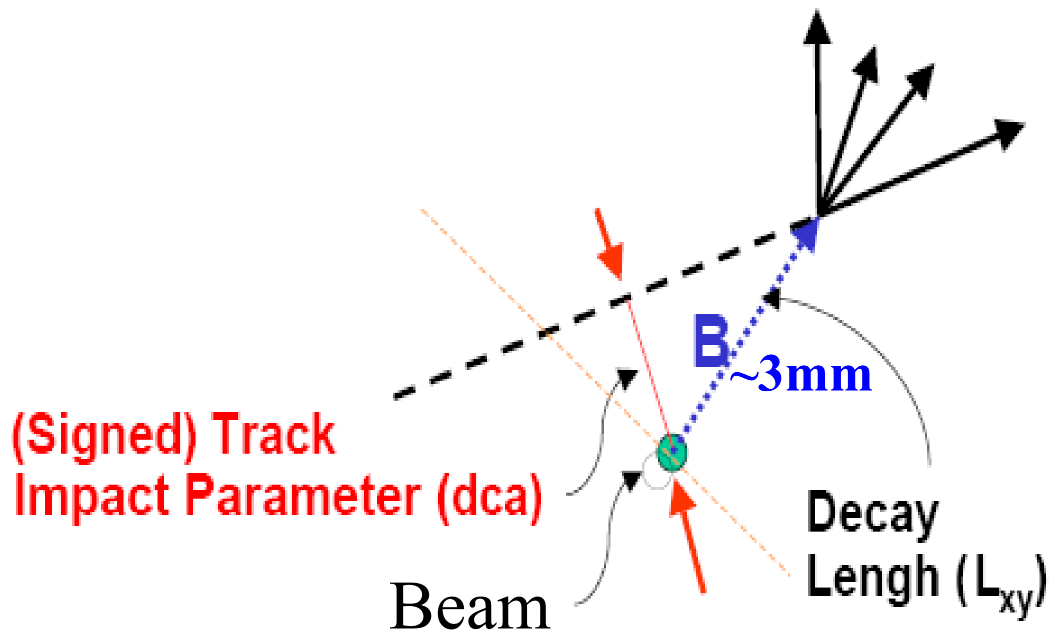
	$H\to b\bar b$	$H\to WW$
$p\bar p\to H$	$H\to b\bar b$	**$H\to WW\to$ ee/eμ/μμ+MET**
$p\bar p\to WH$	**$WH\to Wb\bar b\to$ e/μ+bb**	W/Z+H→W/Z+WW→ $l^+l^-l^+$ / l^+l^+jj + MET
$p\bar p\to ZH$	**$ZH\to Zb\bar b\to$ ee/μμ+bb MET+bb**	

b-Jet Tagging

B hadrons are "long"-lived

Reconstruct charged particles tracks

Reconstruct "vertices" where tracks overlap



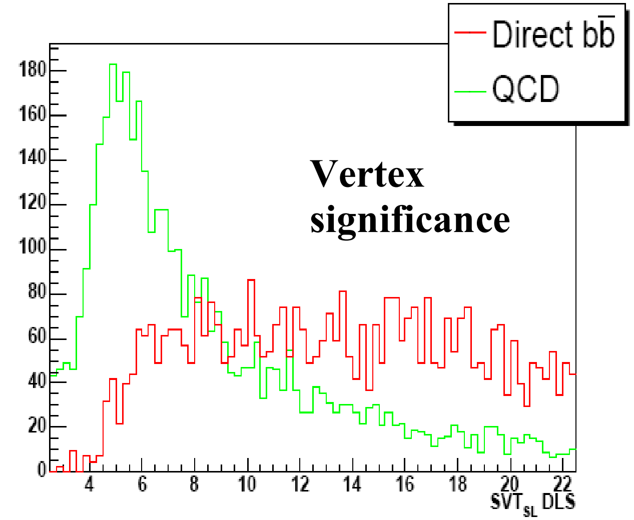
Identify jets with:

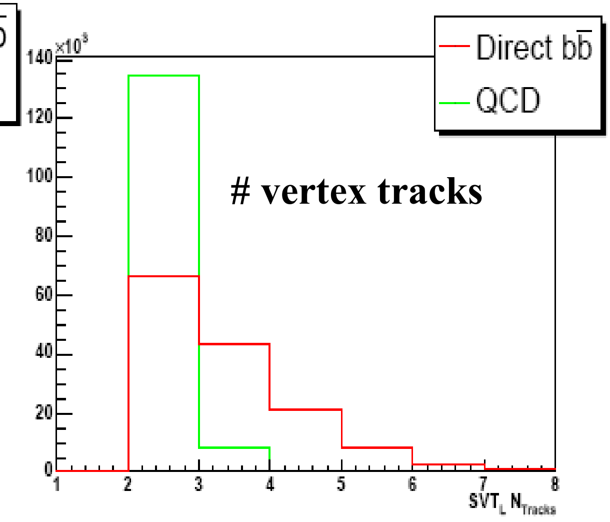
- large impact parameter significance tracks
- large decay length significance vertices

IP significance = $IP / \sigma(IP)$

b-Jet Tagging

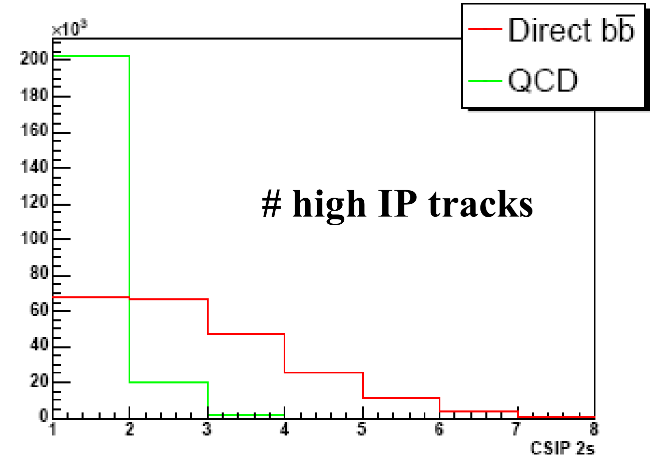
Look at jets with very loose b-tag





Many variables with separation power:

- Vertex: DLS, #tracks, #vertices, mass, chi2
- # high IP tracks, combined light-jet probability



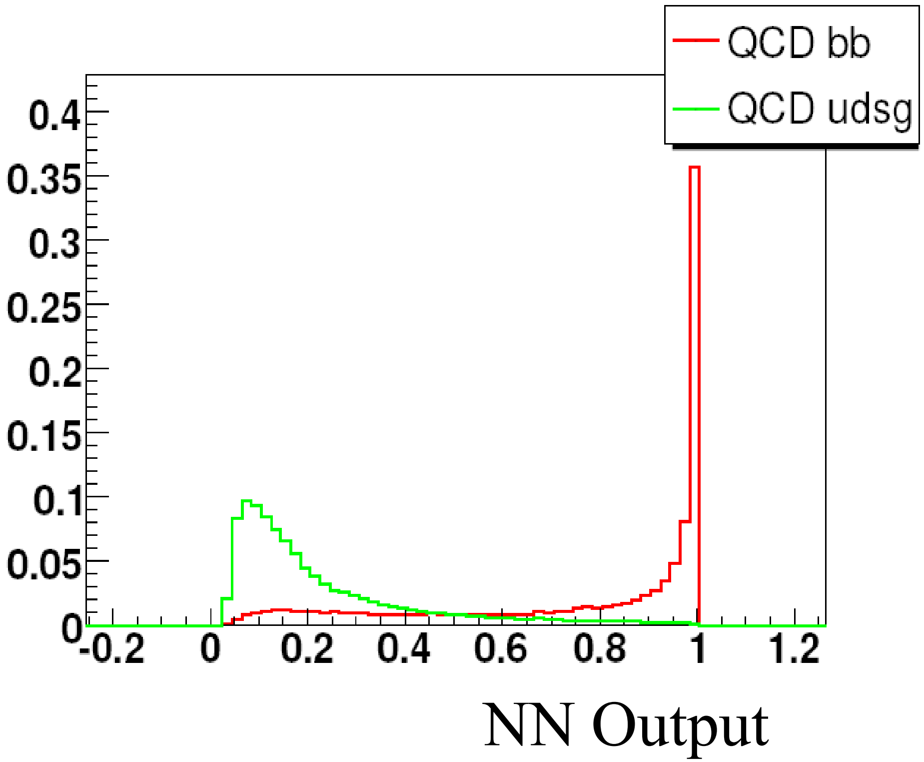
…

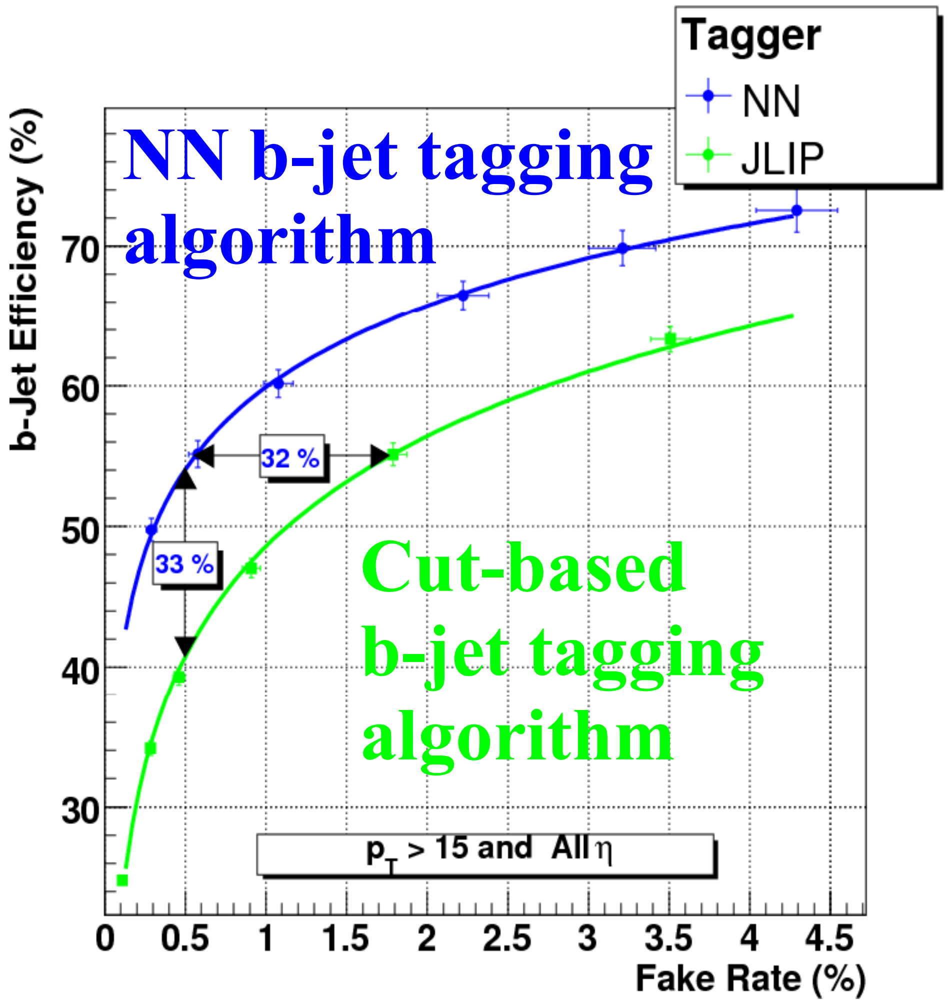
Neural Network b-Jet Tagging

Train NN on simulated events

- optimized inputs, training method, network topology

Test NN eff. and fake rate using data





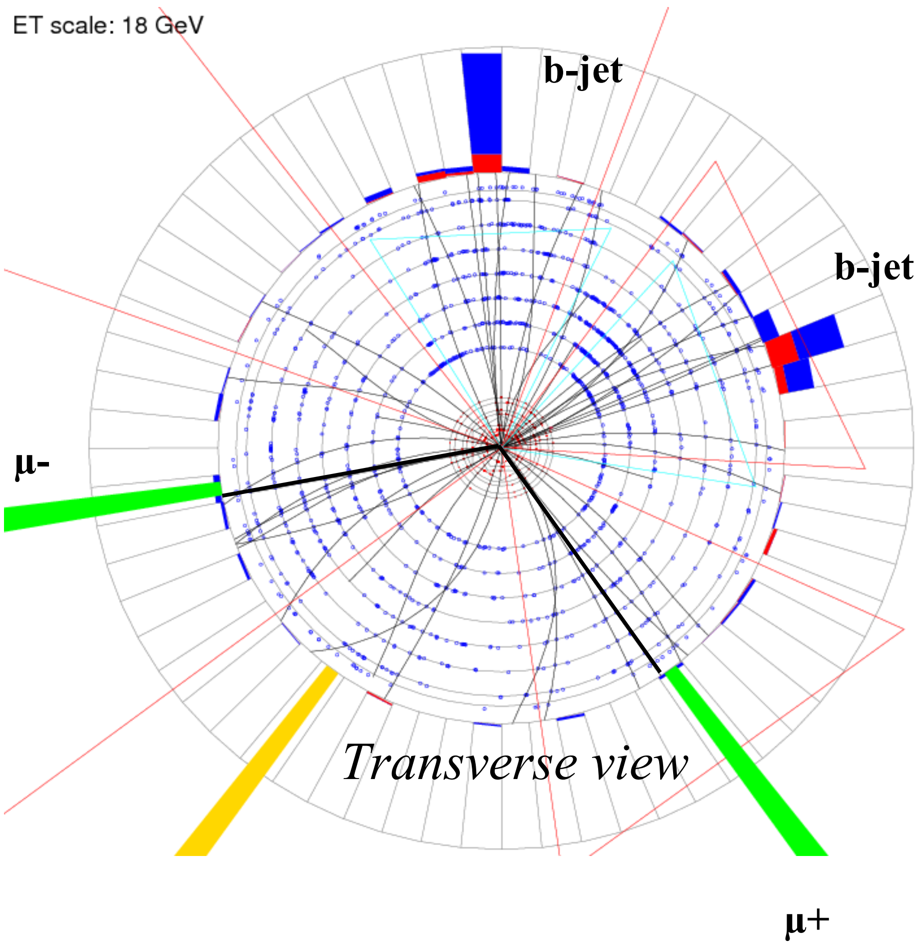
Equivalent to 2.5x as much data for double-tag analysis

ZH -> $\mu^+ \mu^-$ b b Search

Easy to observe Z decay
- reduces backgrounds
- provides trigger

Good b-tagging is essential

Reconstruct Higgs mass from two b-jets



Z + 2 jets

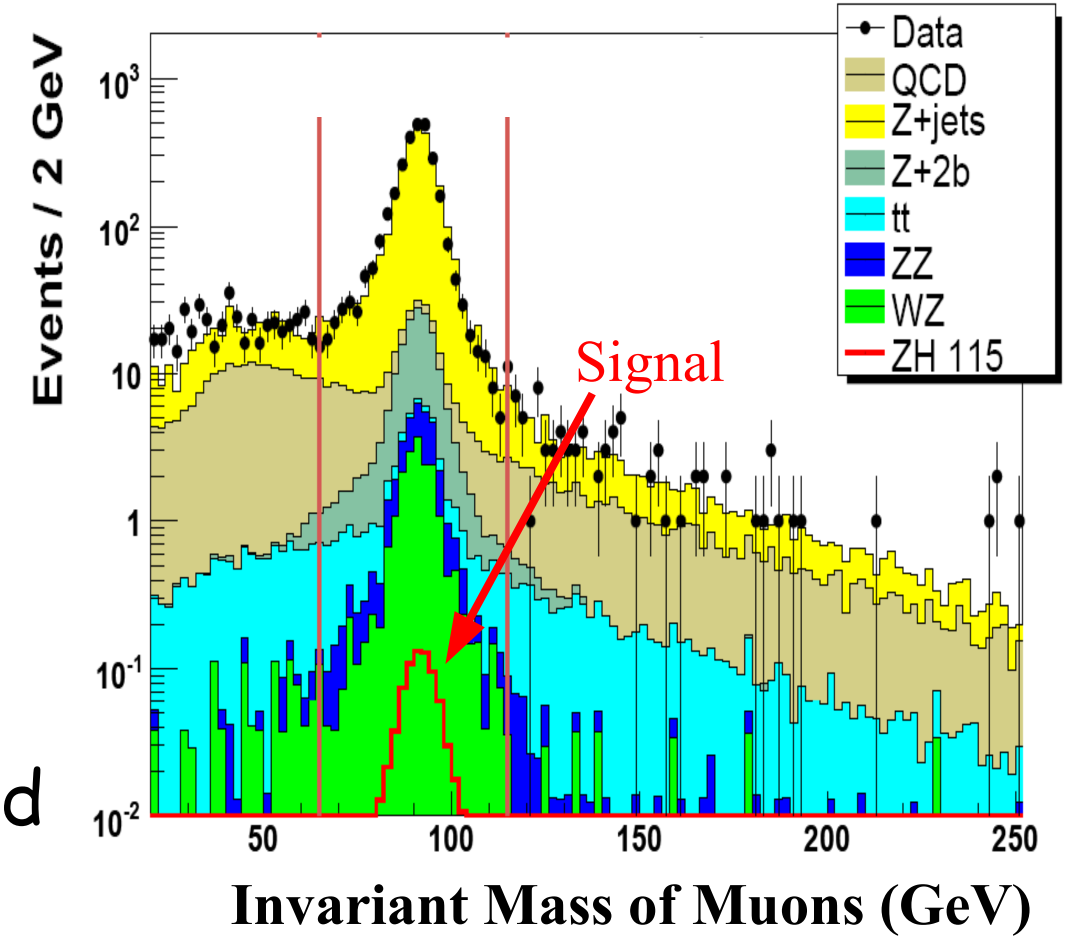
Select events:

- 2 μ, isolated*, p_T>10 GeV, |eta|<2
- >=2 jets, p_T>15 GeV
- 65<m_Z<115 GeV

Good agreement of data / simulation at Z peak

- Trigger eff. ~ 100%

QCD background determined from (less-isolated) data



Main background: Z+jets

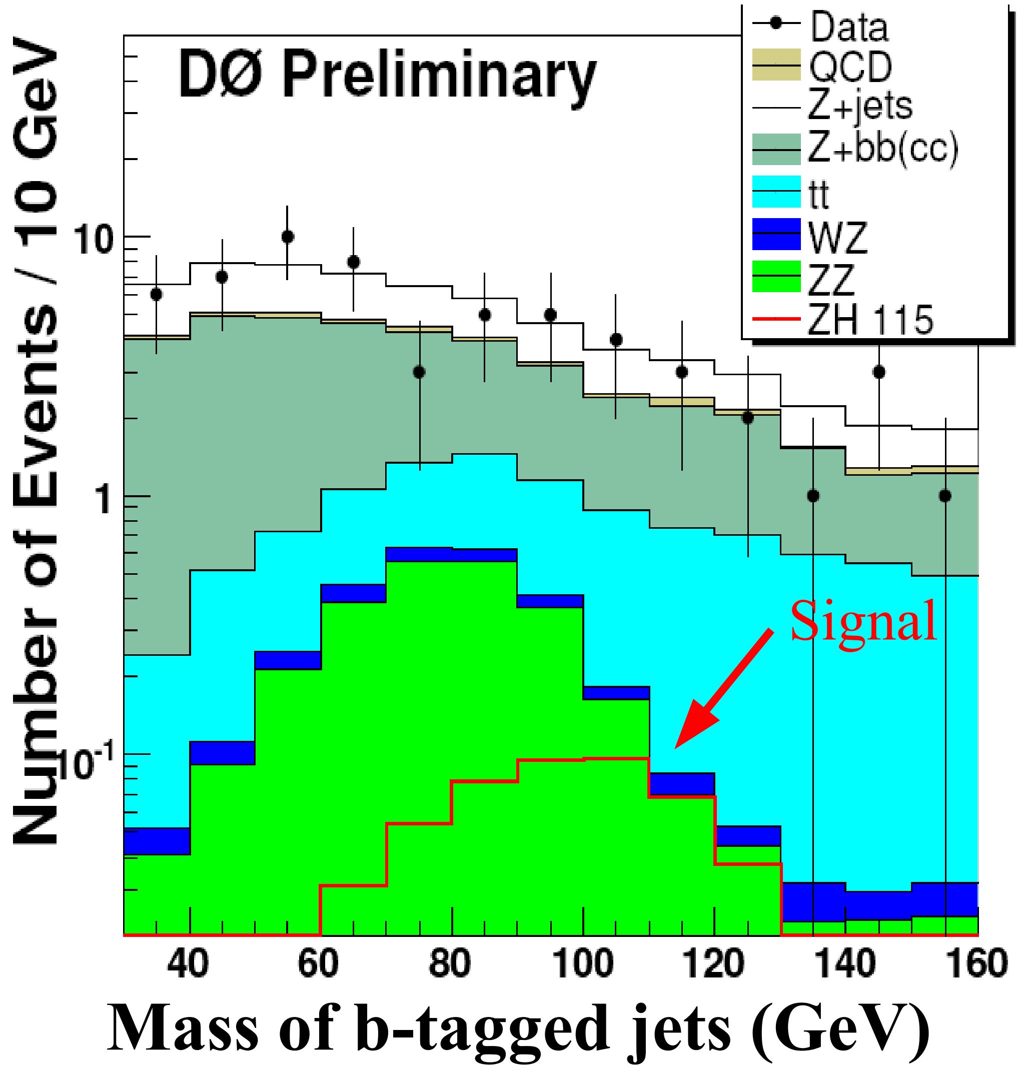
*scalediso = (cal iso + trk iso) / p_T
$scalediso_1$ x $scalediso_2$ < 0.1

Z + 2 b-jets

Require >=2 “NN b-tags”

NN tag cut for optimal expected limit:
~65% eff.
~2% fake

Higgs->bb forms bump in di-b-jet mass spectrum



Di-b-jet mass resolution is key!

Single b-tag

Also use events with a single "tight" NN b-tag:
~40% eff.
~0.5% fake

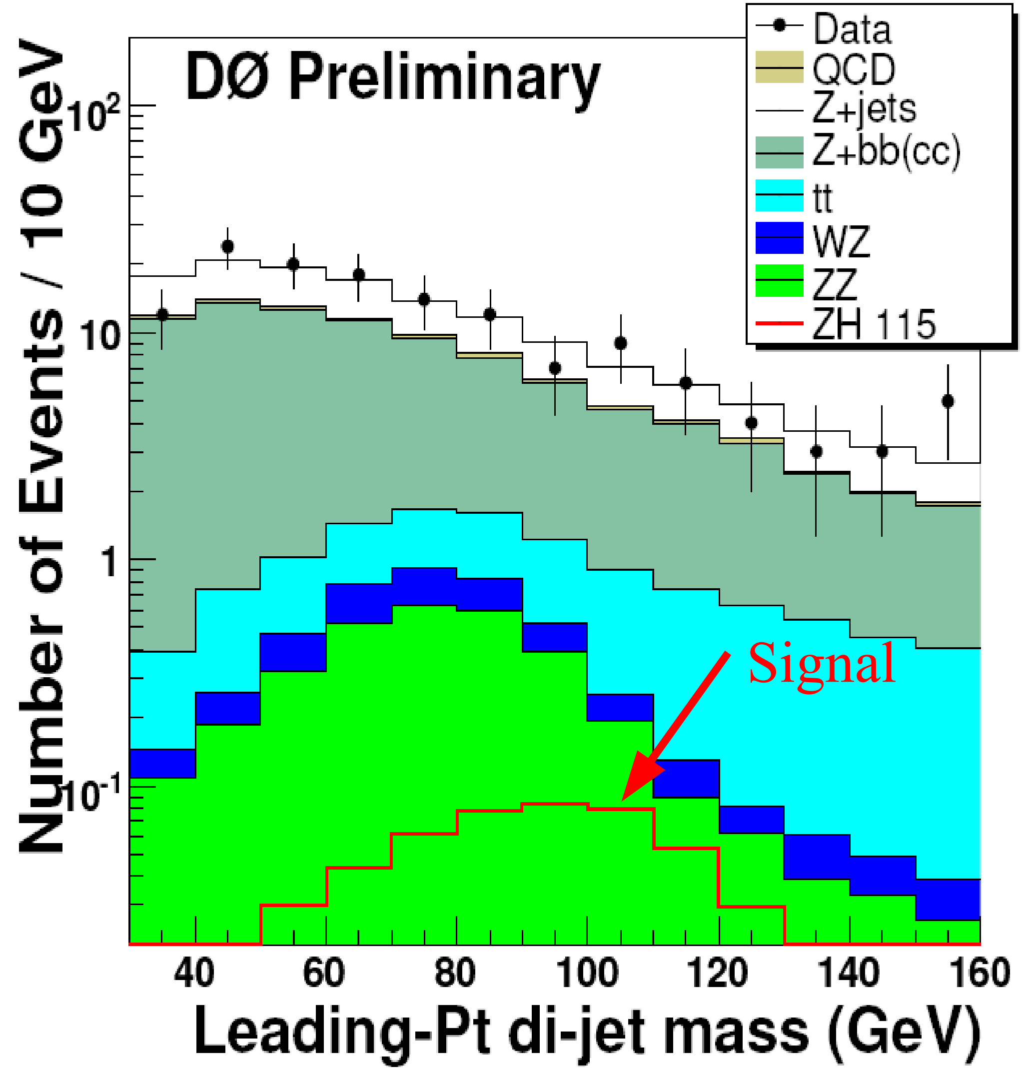
(AND NOT two "loose" tags)

Compared to double-b-tag:

- Similar amount of signal
- Double amount of background

Like having 25% more data

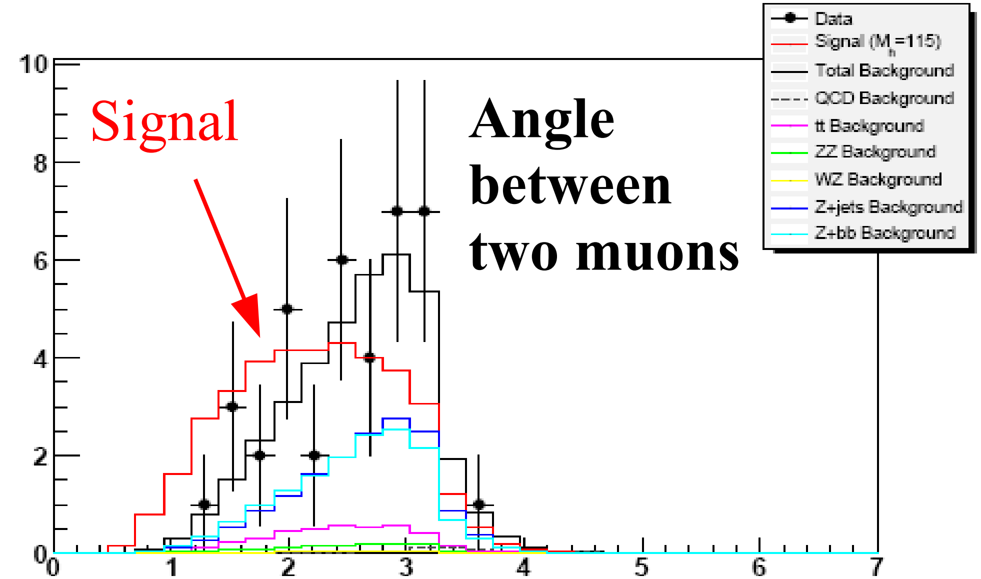
Combine during limit-setting

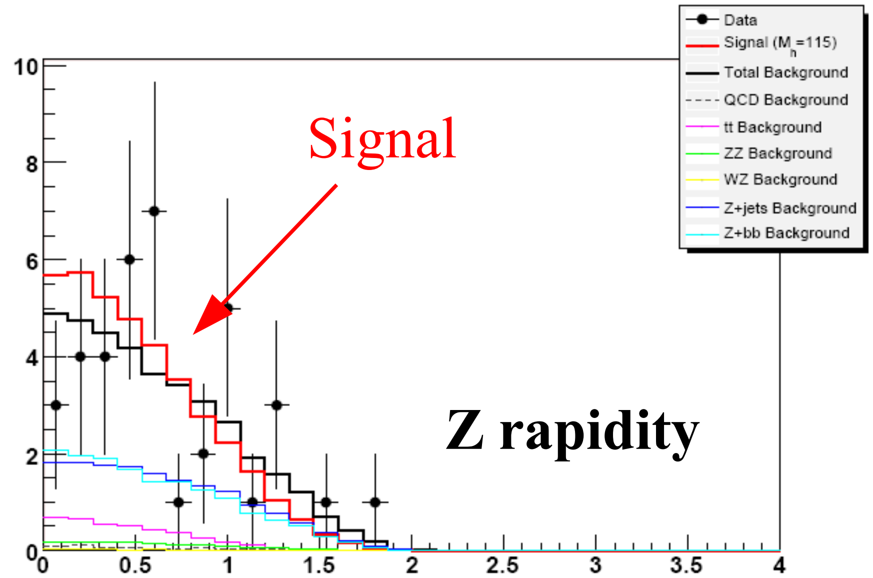


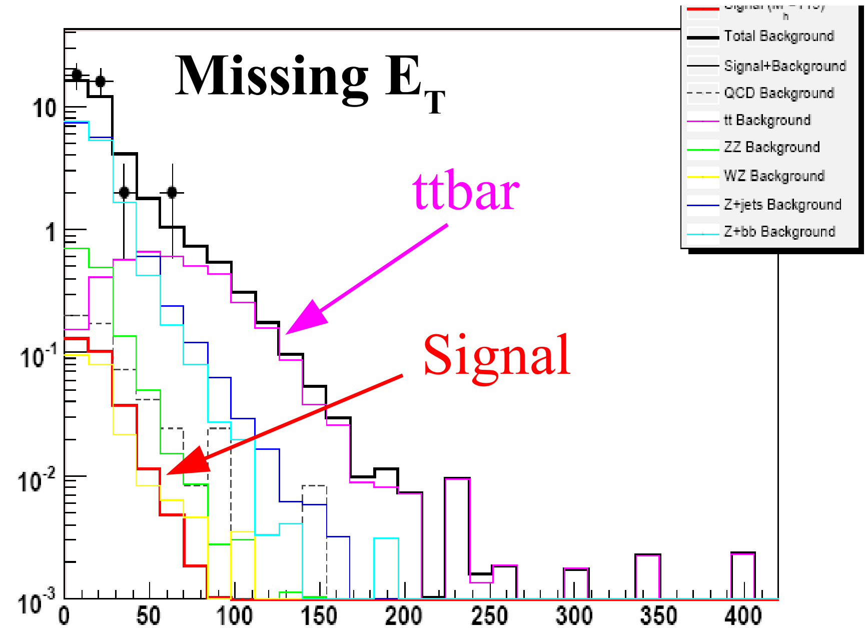
Additional Variables

Di-b-jet mass is the best variable

But other variables also have some separation power







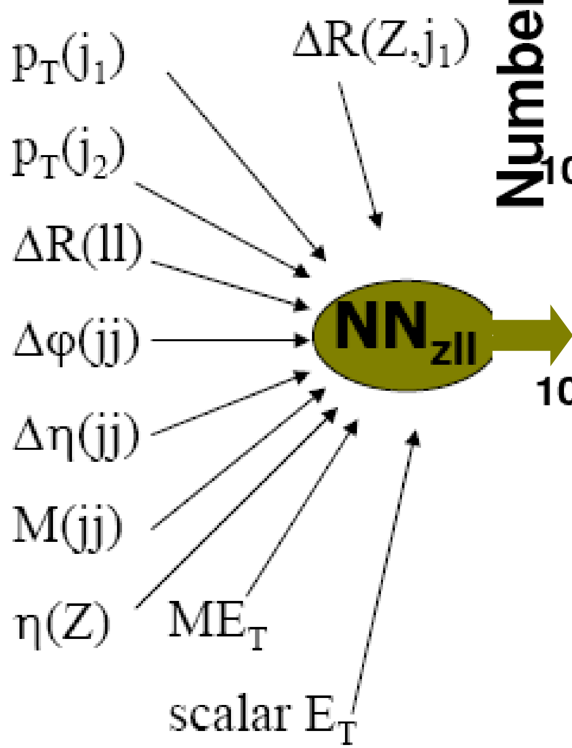
Neural Net Event Selection

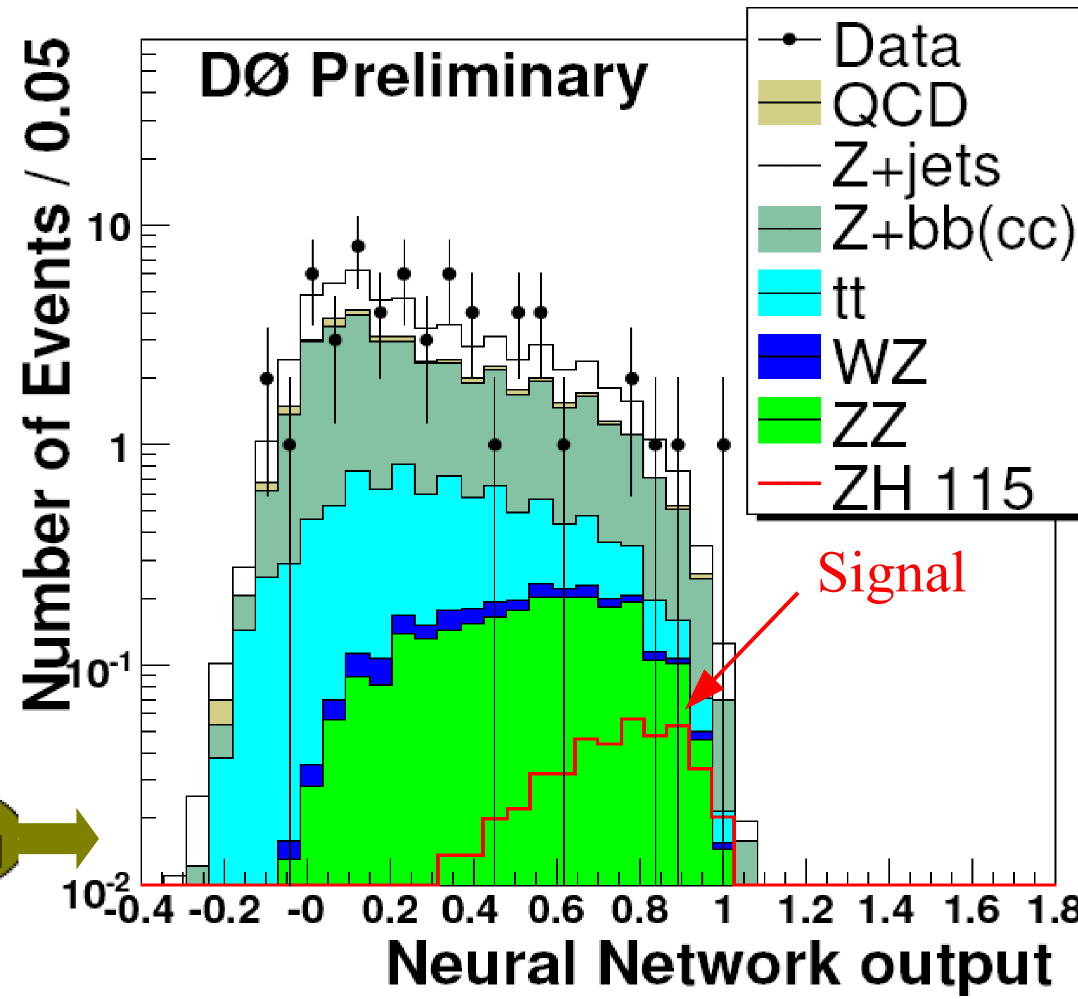
Loose kinematic cuts

Multivariate discriminant

Separate NN for
single/double b-tag

Train for
each m_H





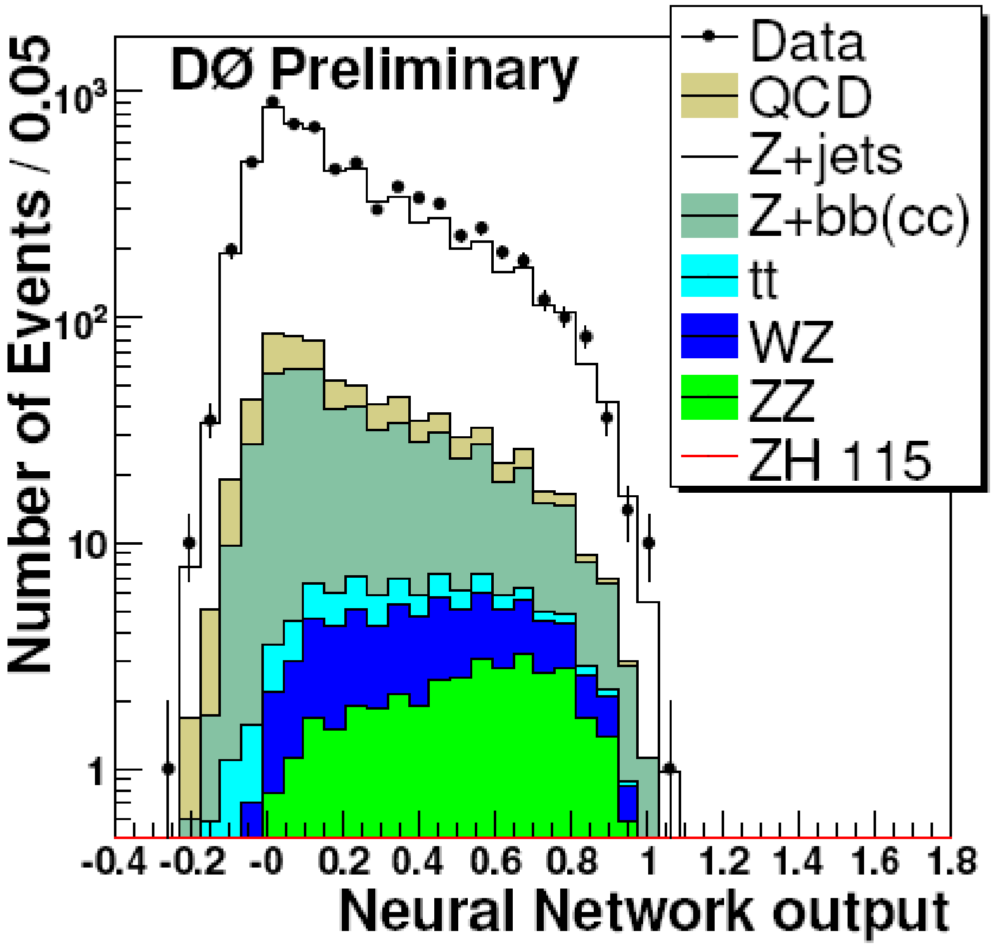
Sensitivity 37% greater than using M_{bb} alone!

Neural Net Cross-Checks

All input variables are well-modeled

Also check shape of NN output *before b-tagging*

- High statistics
- Negligible signal



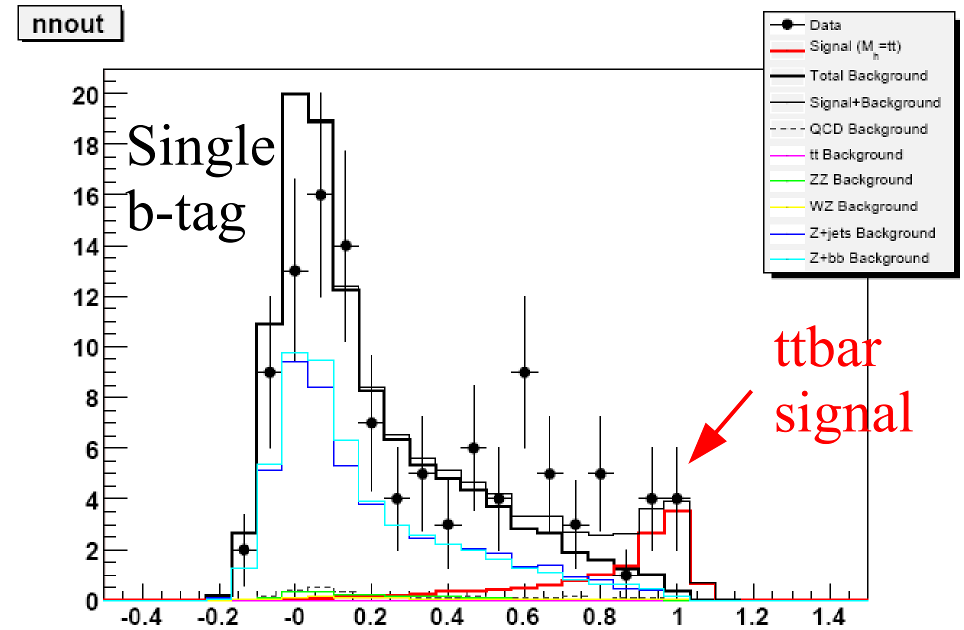
Variables / correlations are well-modeled in Z+jets

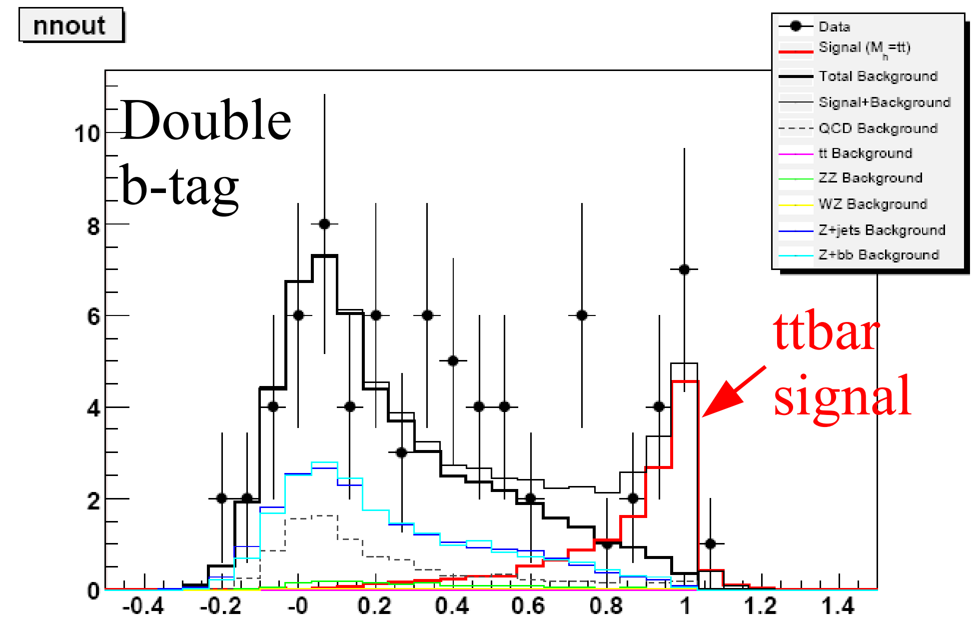
Neural Net Cross-Checks

Train NN on ttbar as *signal*

- A "standard candle"
- Cross-section well-known

Expected ttbar is observed in both single and double b-tag channels



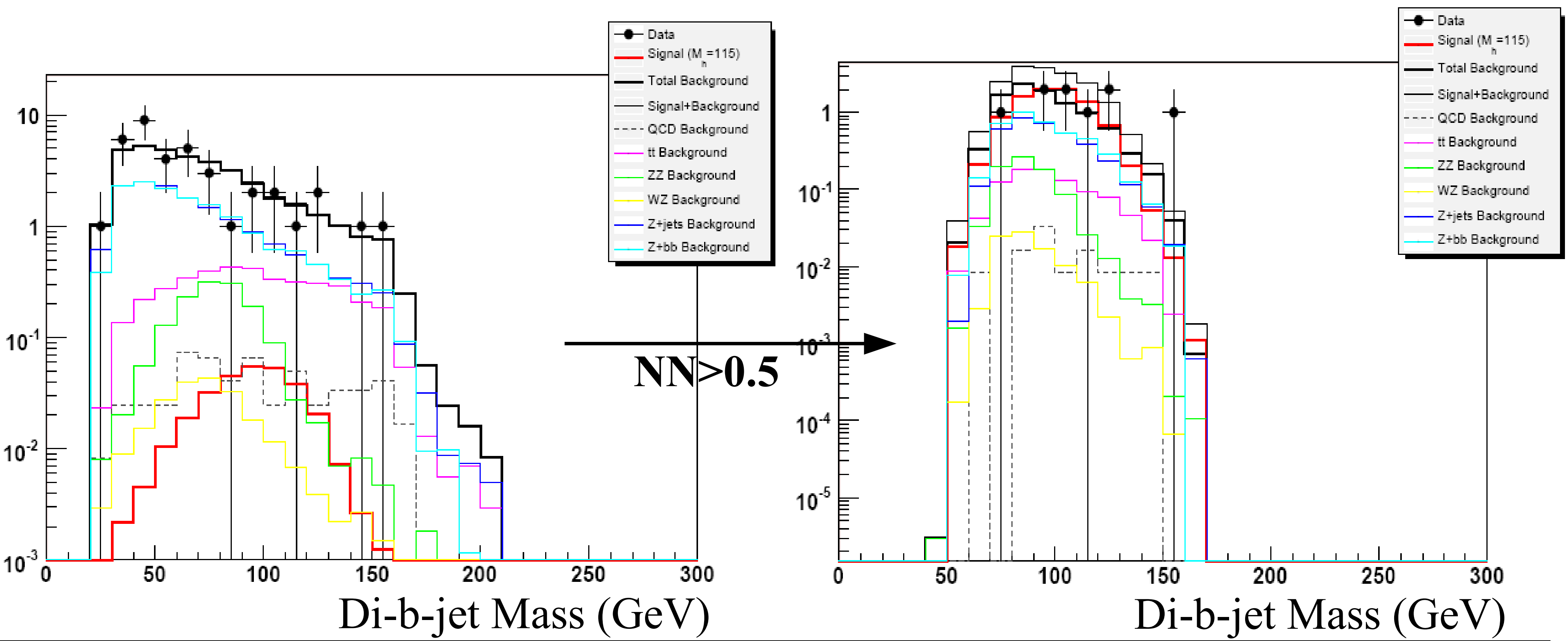


Neural Net Cross-Checks

Study variable shapes *after* cutting on NN output (>0.5)

NN is selecting signal-like region of phase-space

- No separation power remains



Systematic Uncertainties

Luminosity, 6.1%

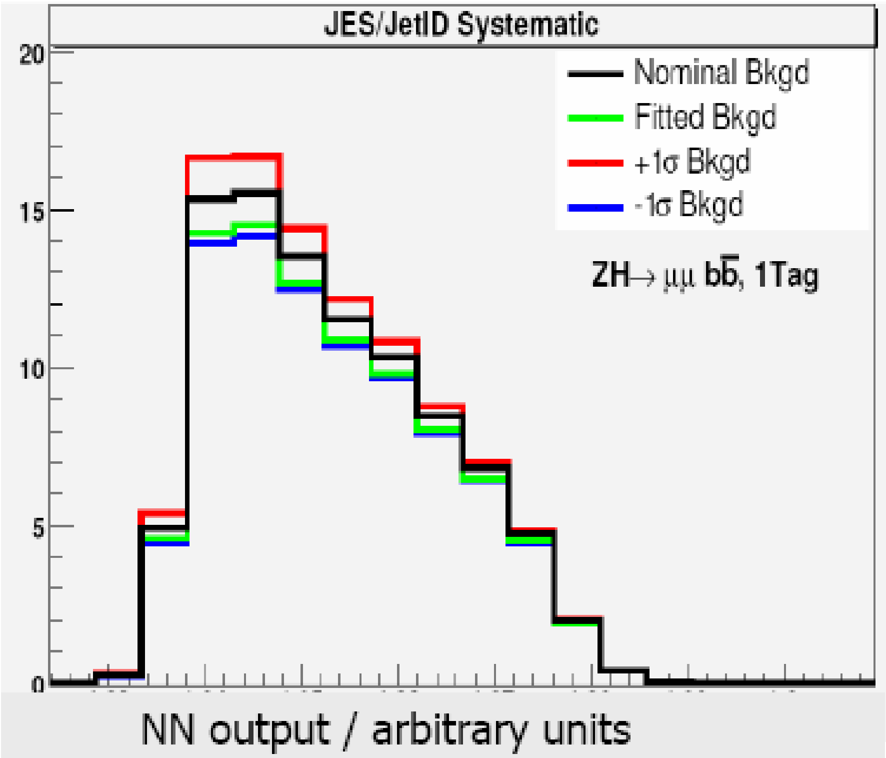
Lepton ID, 2%

Background cross-sections, 5-30%

QCD estimation, 20%

Jet-energy scale* →

b-tagging*

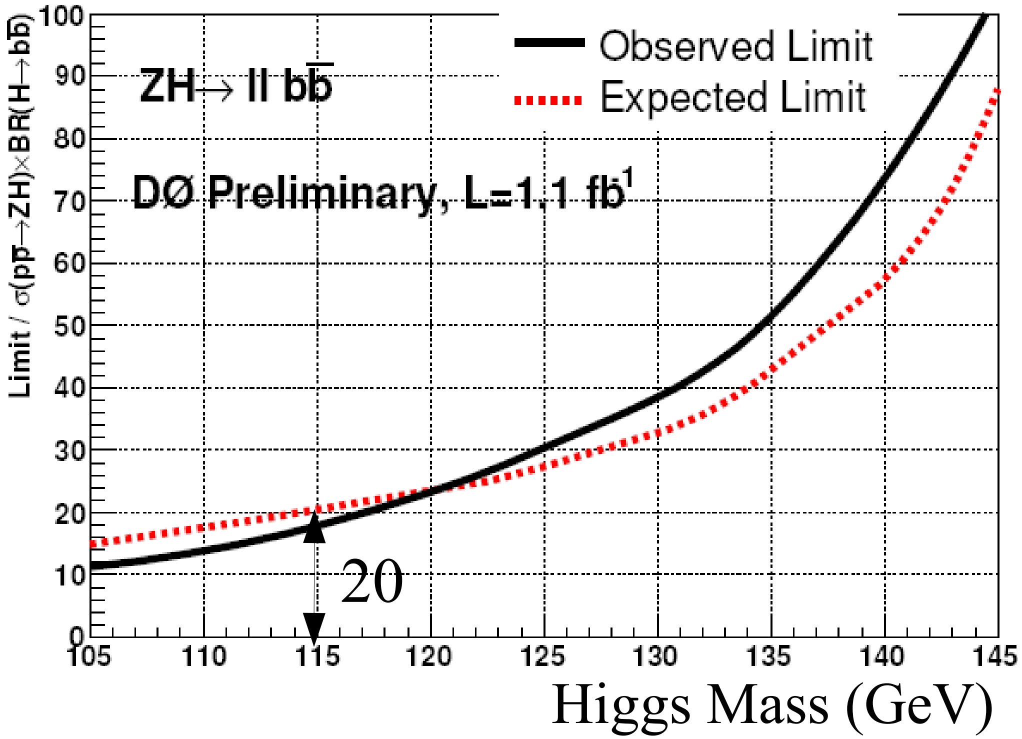


**Affects shape of NN output as well as normalization*

ZH -> l^+ l^- b b Limits

Use whole shape of NN outputs to set limits

Need ~20x more sensitivity to see the Higgs in this channel alone (at 115 GeV)



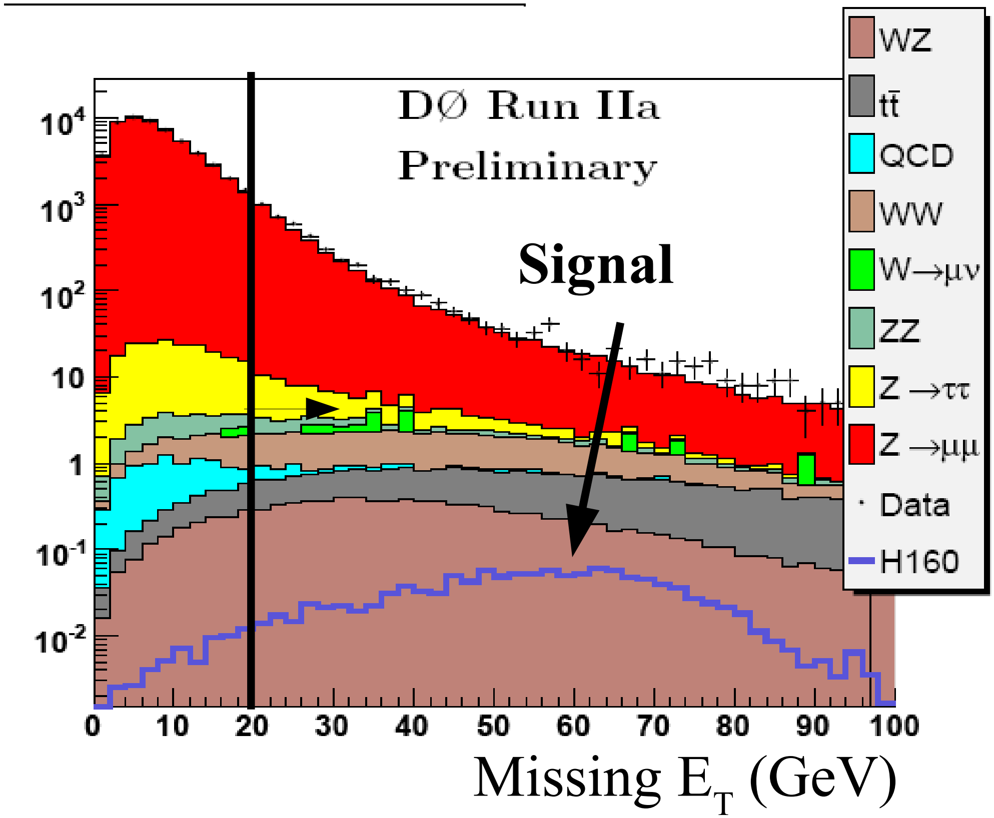
- Other channels
- Combine with CDF
- More data (2.4 fb^{-1} this winter)
- Reduced systematics
- Further improvements in analysis technique

H -> W^+W^- -> $\mu^+ \mu^-$ + MET

Select events:

- 2 μ, isolated, pT>10 GeV, |eta|<2
- ~~>=2 jets, pT > 15 GeV~~
- MET > 20 GeV*
- MET "scaled" > 5
- Min μ transverse mass > 20 *
- 15 < $m_{\mu\mu}$ < 70 *

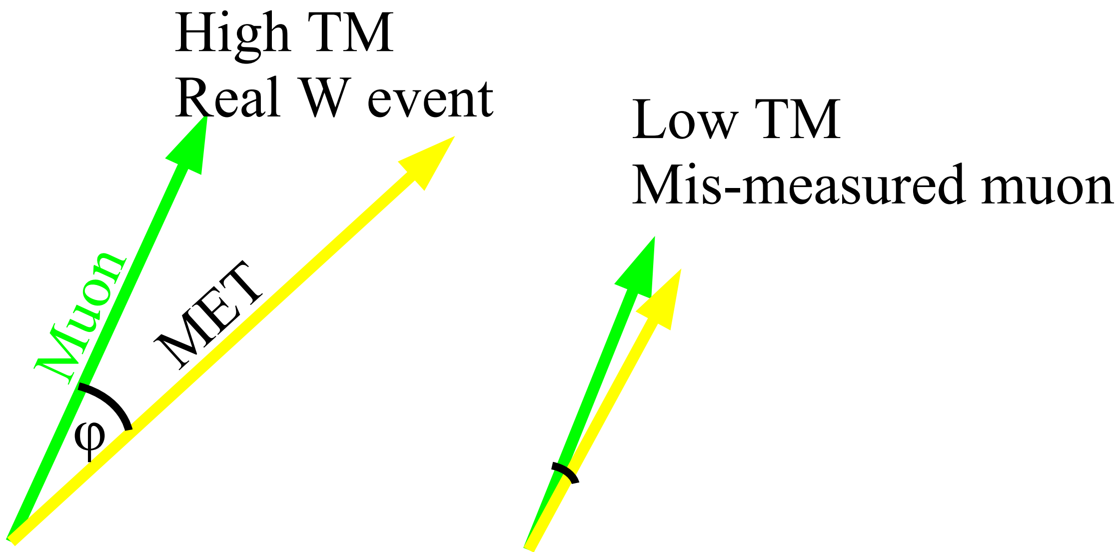
*(depending on m_H)

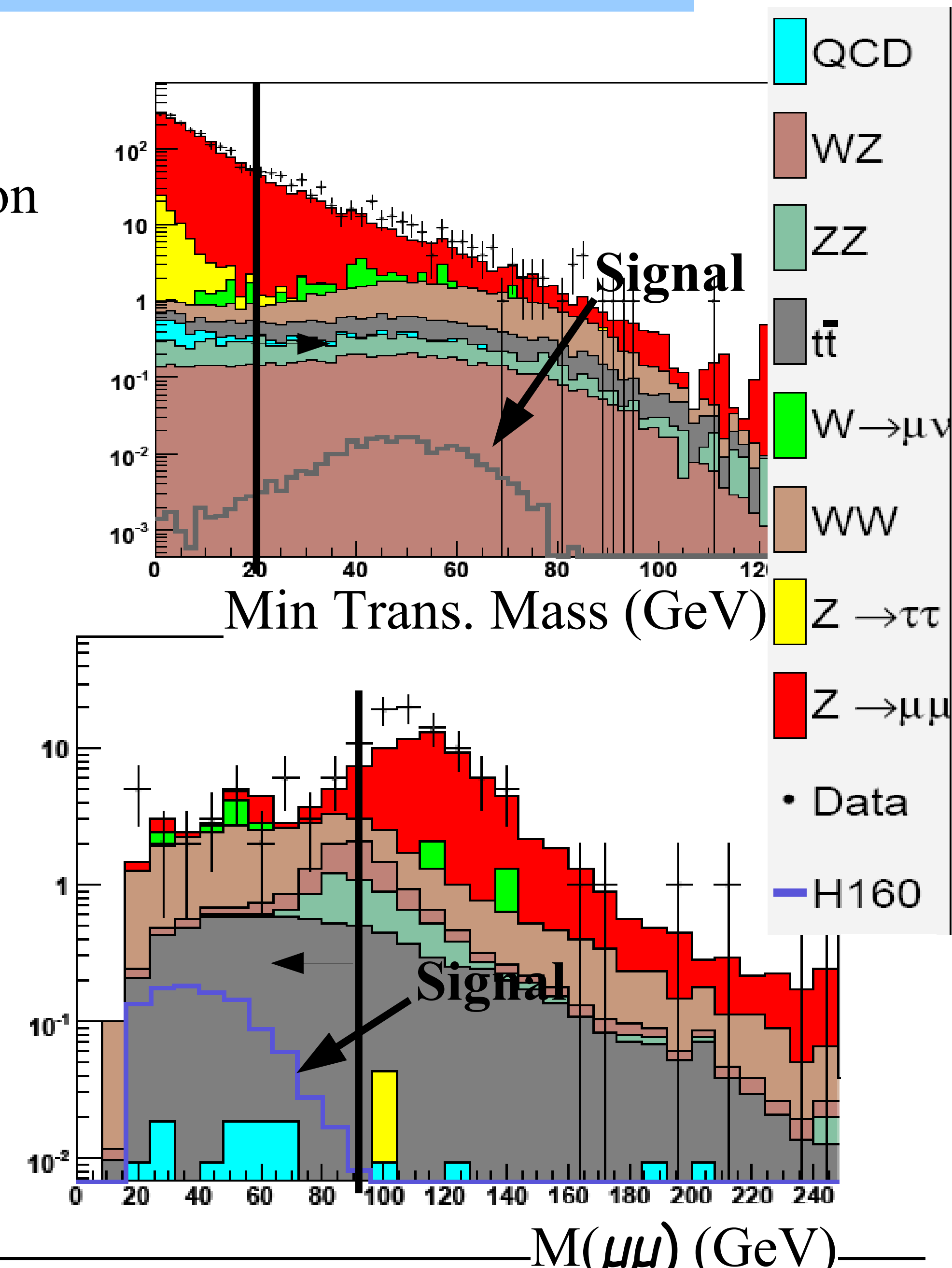


$$\not{E}_T^{\text{Scaled}} = \frac{\not{E}_T}{\sqrt{\sum_{\text{jets}} \left(\Delta E^{\text{jet}} \cdot \sin\theta^{\text{jet}} \cdot \cos\Delta\phi\,(\text{jet}, \not{E}_T)\right)^2}}$$

← *MET projected onto jet direction*

H -> W^+W^- -> $\mu^+ \mu^-$ + MET





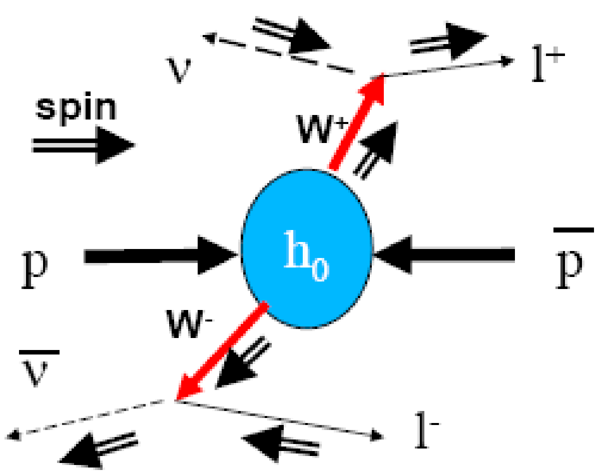
Main backgrounds after pre-selection:

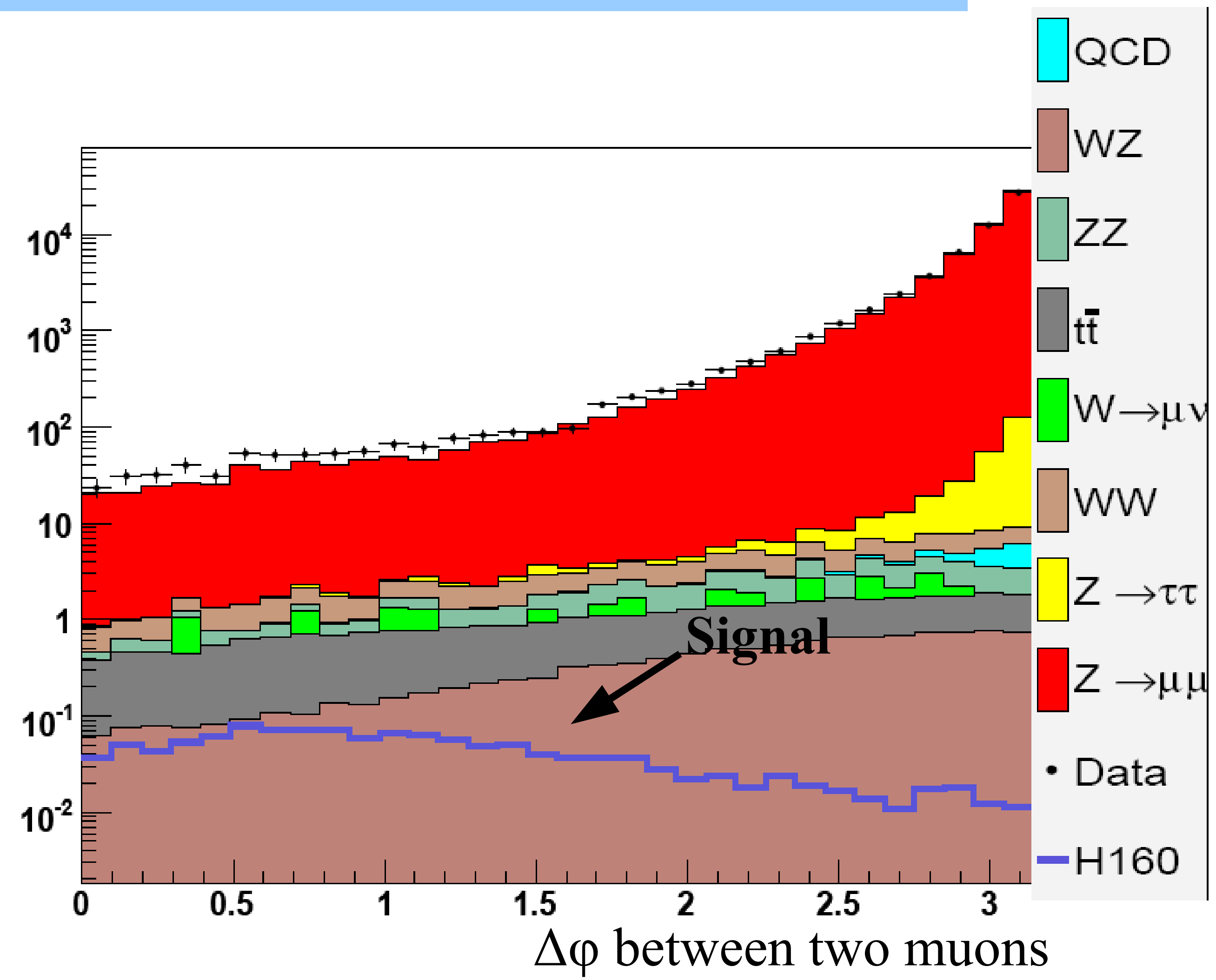
- Z+jets : Fake MET
- W+jets : Jet->Muon
- WW : Nearly irreducible
- tt : Two b-jets

H -> W^+W^- -> $\mu^+ \mu^-$ + MET

Higgs is a scalar

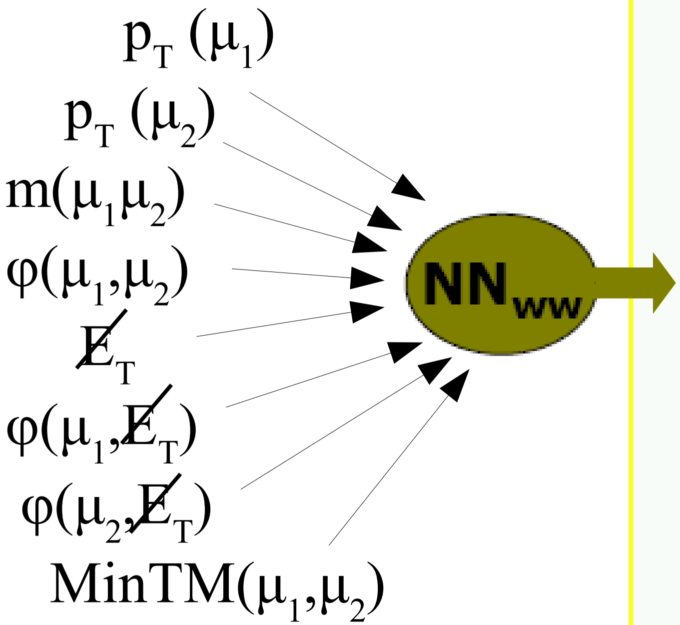
- Muons from W's tend to be more aligned

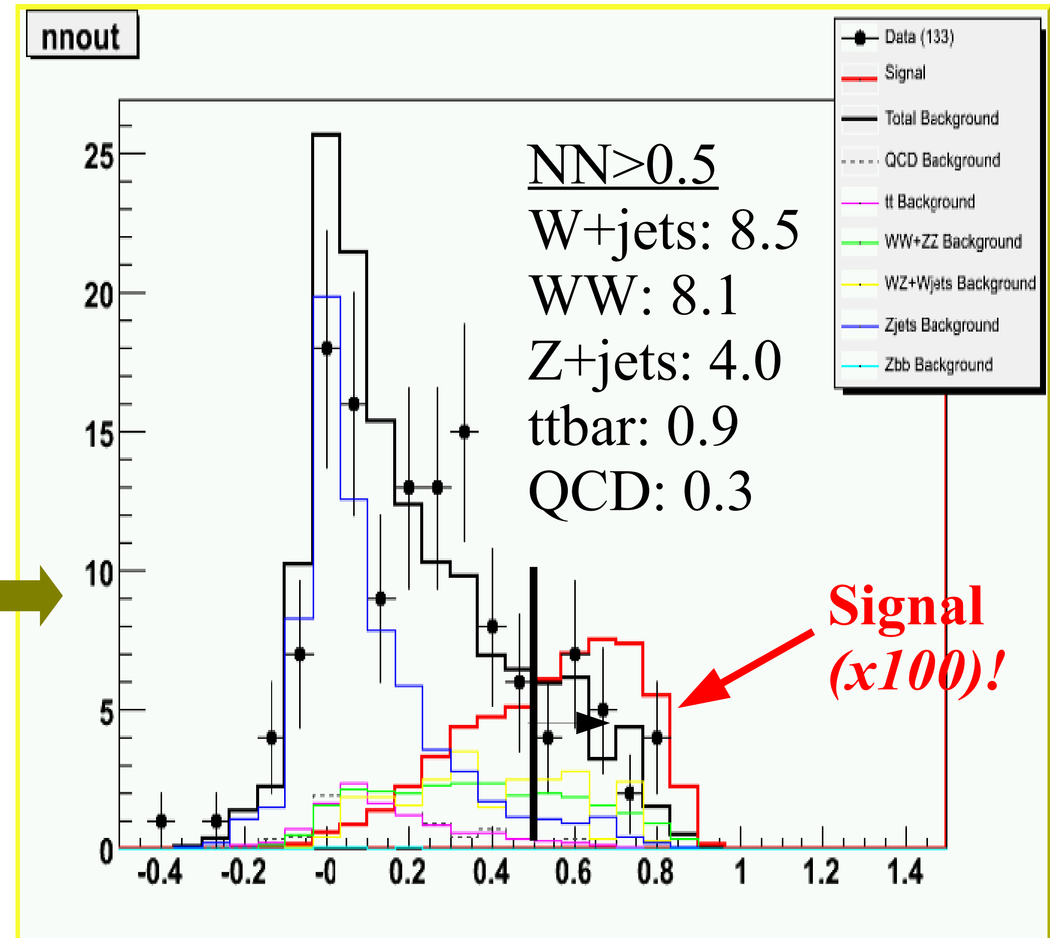




$H \rightarrow W^+W^- \rightarrow \mu^+ \mu^- + MET$

Train a NN for each simulated signal m_H

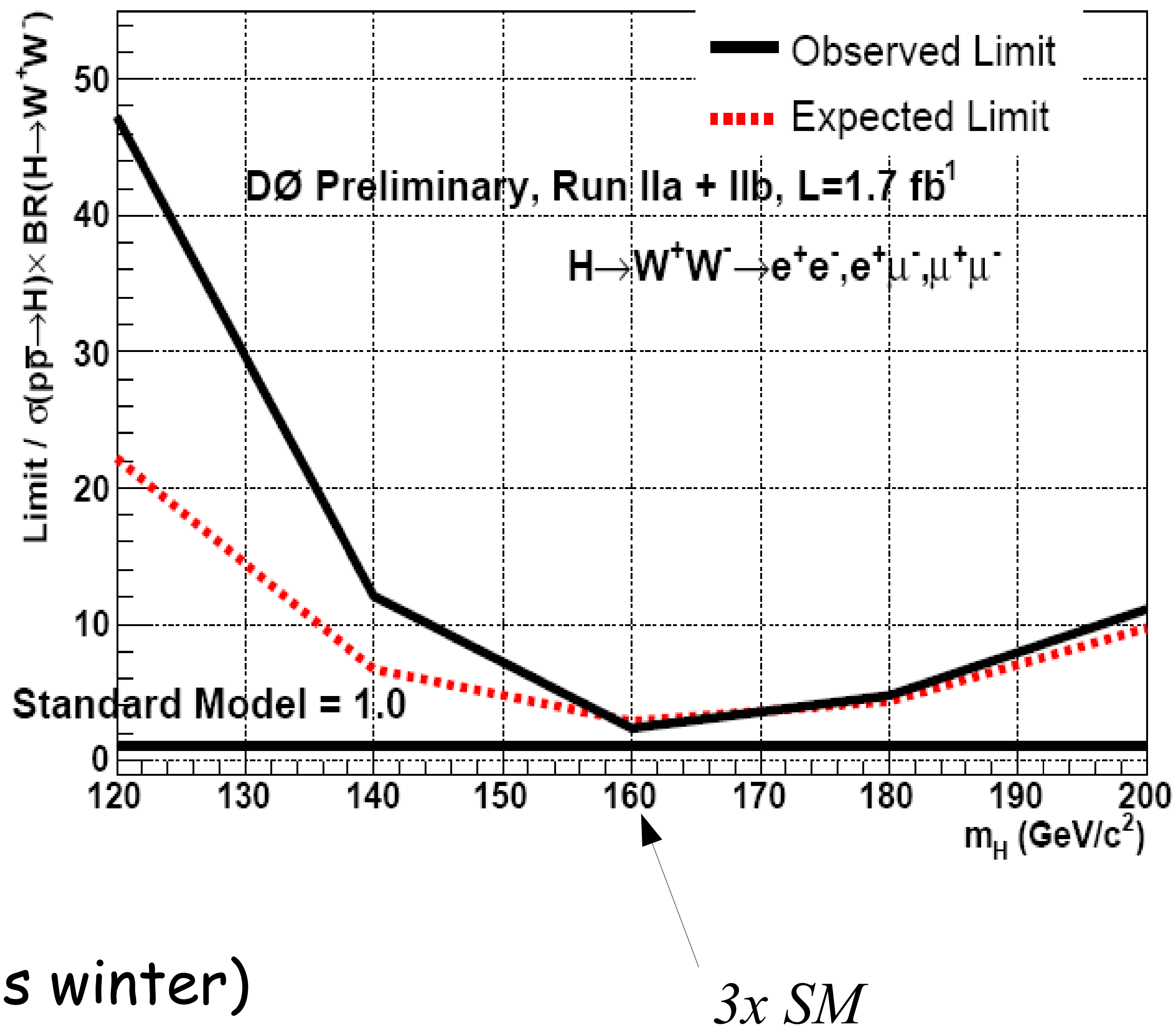




NN Output

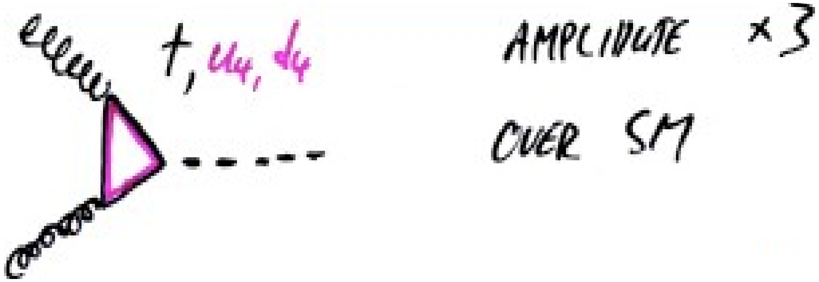
$H \to W^+W^- \to \mu^+ \mu^- + MET$

Combine with ee,
eμ channels



- Combine with CDF
- More data (2.4 fb^{-1} this winter)
- Further improvements in analysis technique

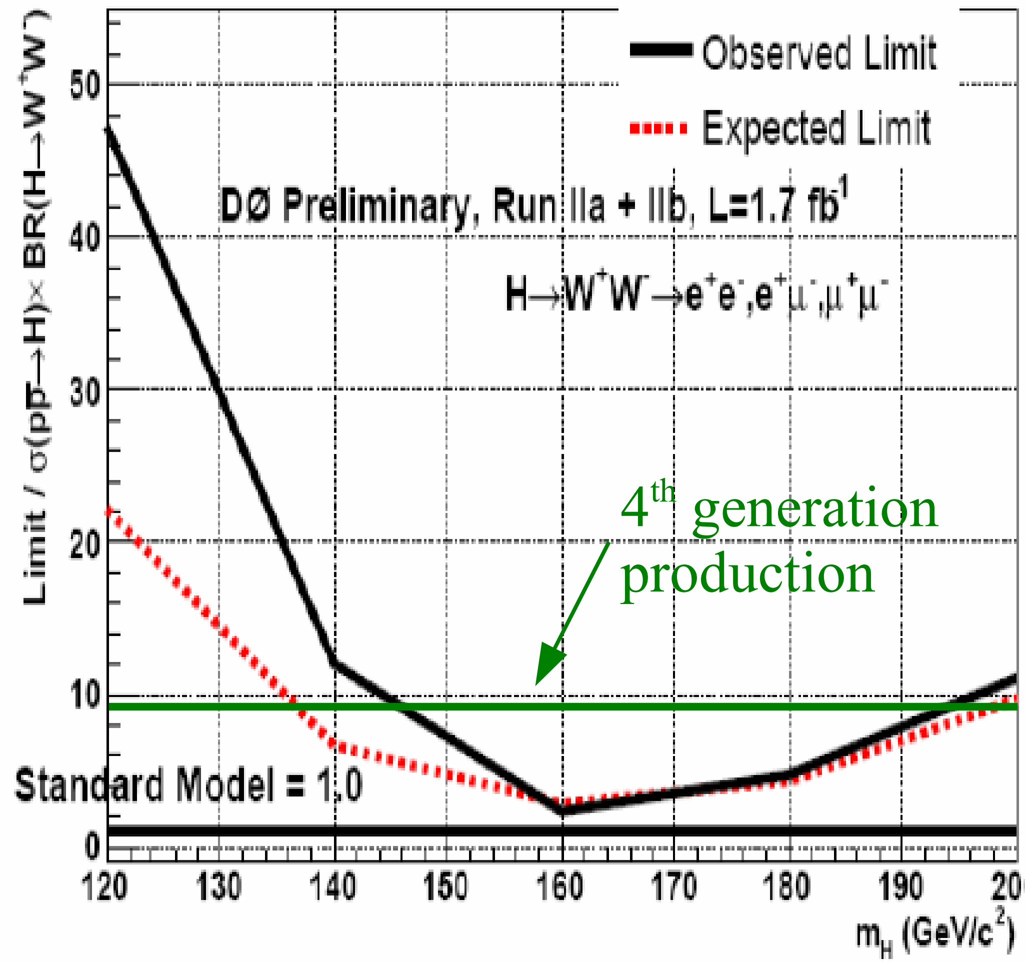
4^{th} Generation



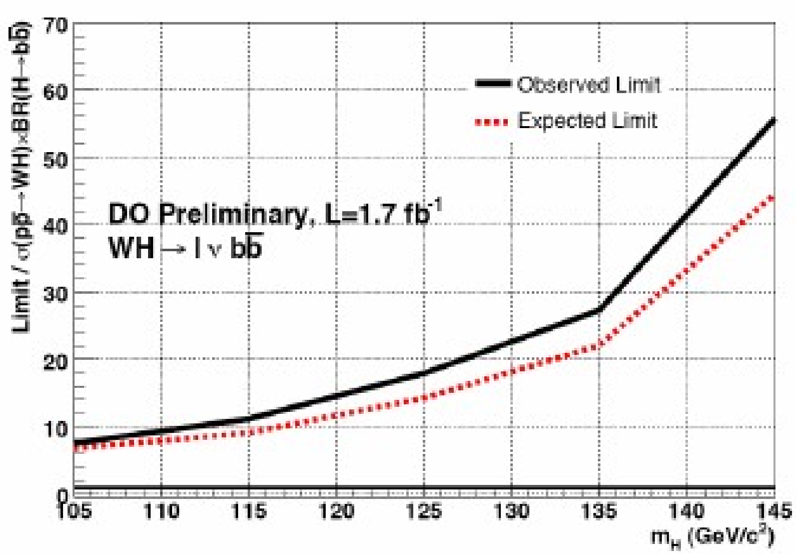
→ 9x more gg->H production!

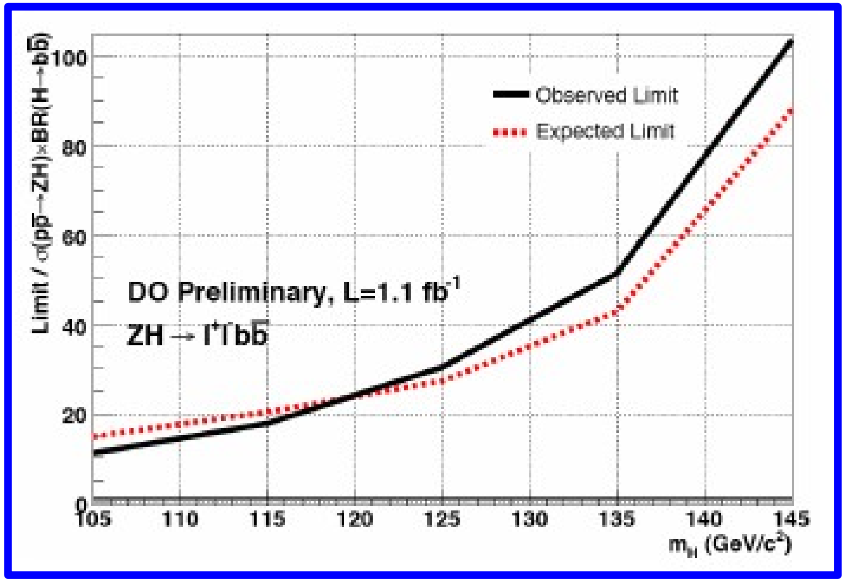
Already excluding from 145-195 GeV

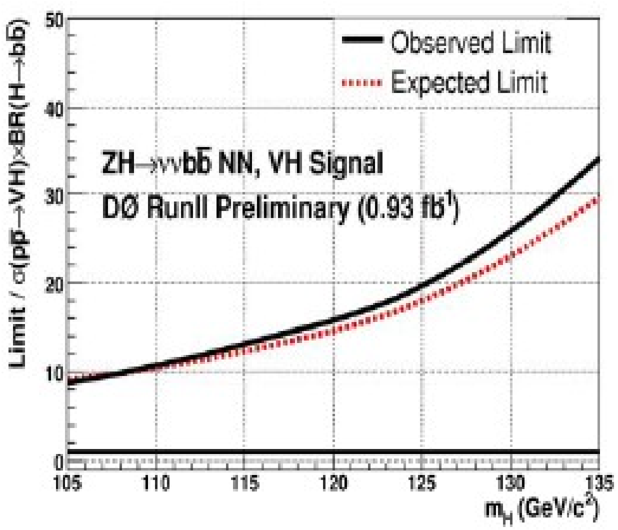
Sensitive up to 260 GeV by 2010

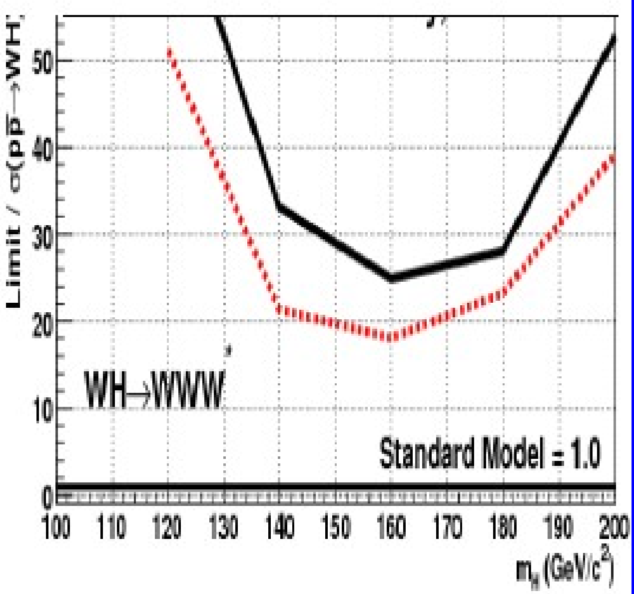


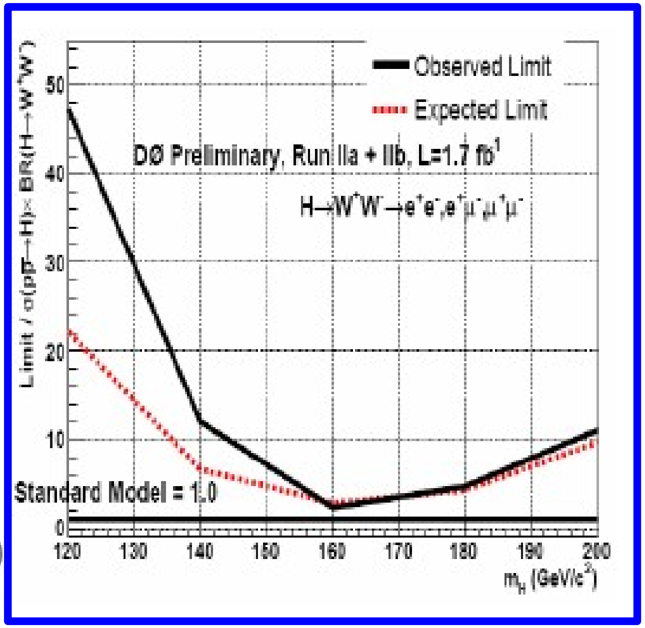
DØ Results in Main Higgs Channels



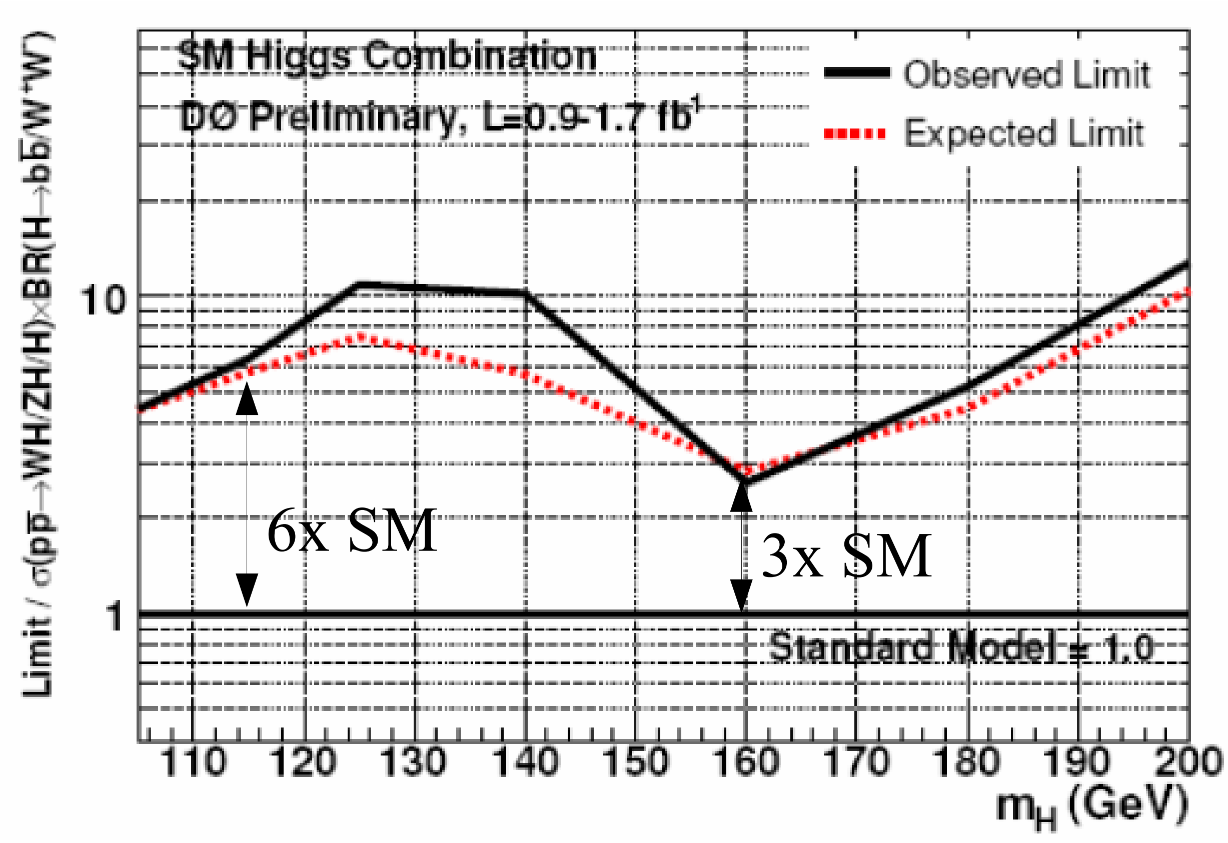




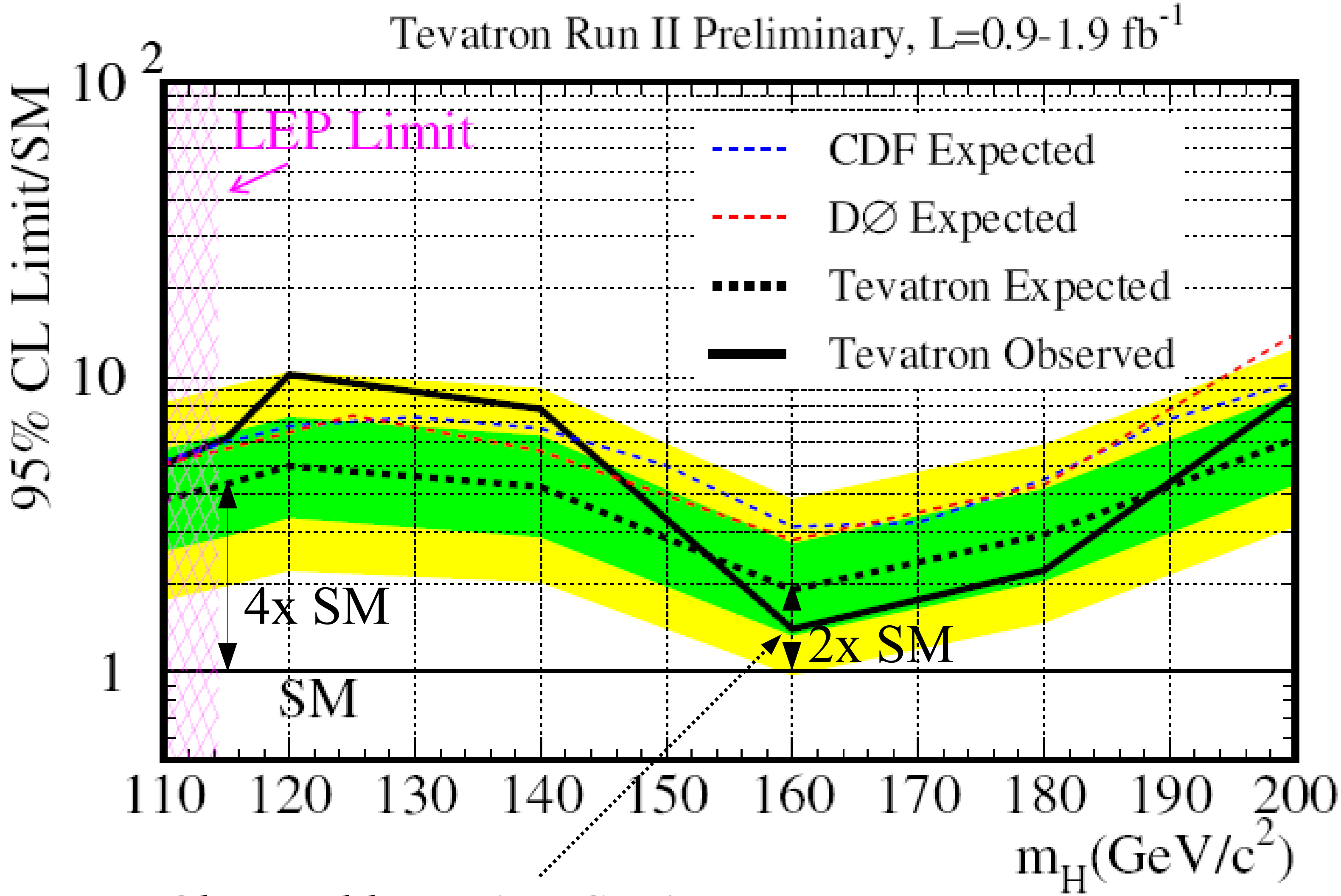




Combining the Channels



Combining the Experiments



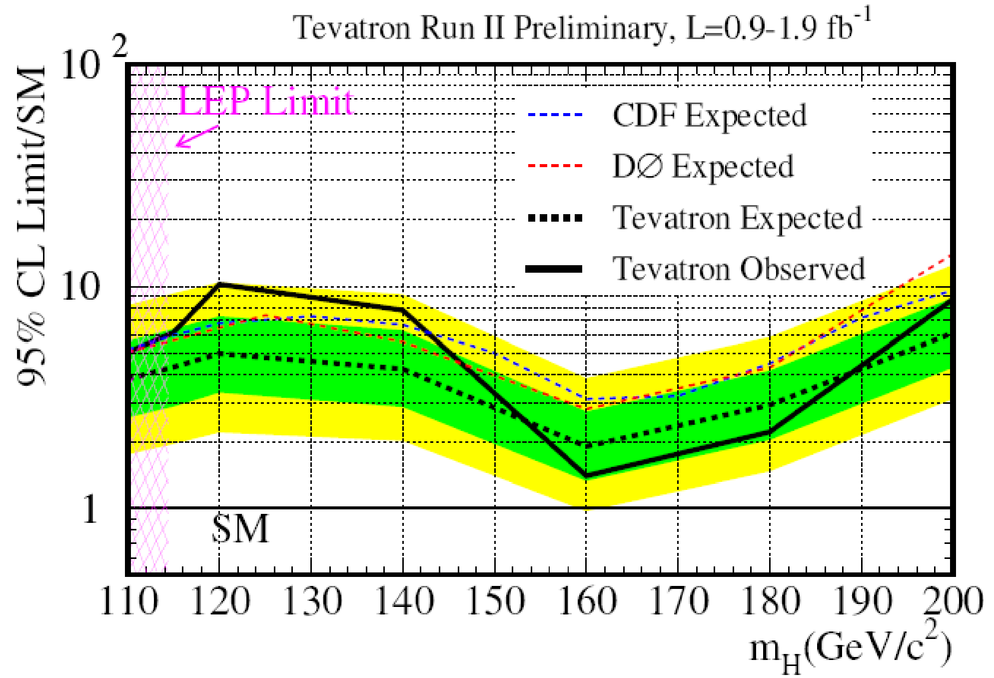
Observed limit: 1.4x SM !

Improving Sensitivity

With no improvements, would need much more luminosity to be sensitive:

- ~20 fb^{-1} at 115 GeV
- ~7 fb^{-1} at 160 GeV

Expect 6.8 fb^{-1} by 2010



Improvements underway:

- Better b-tagging
- Di-jet mass resolution
- Lepton efficiency
- Matrix Element techniques
- Further improvements in analysis technique...

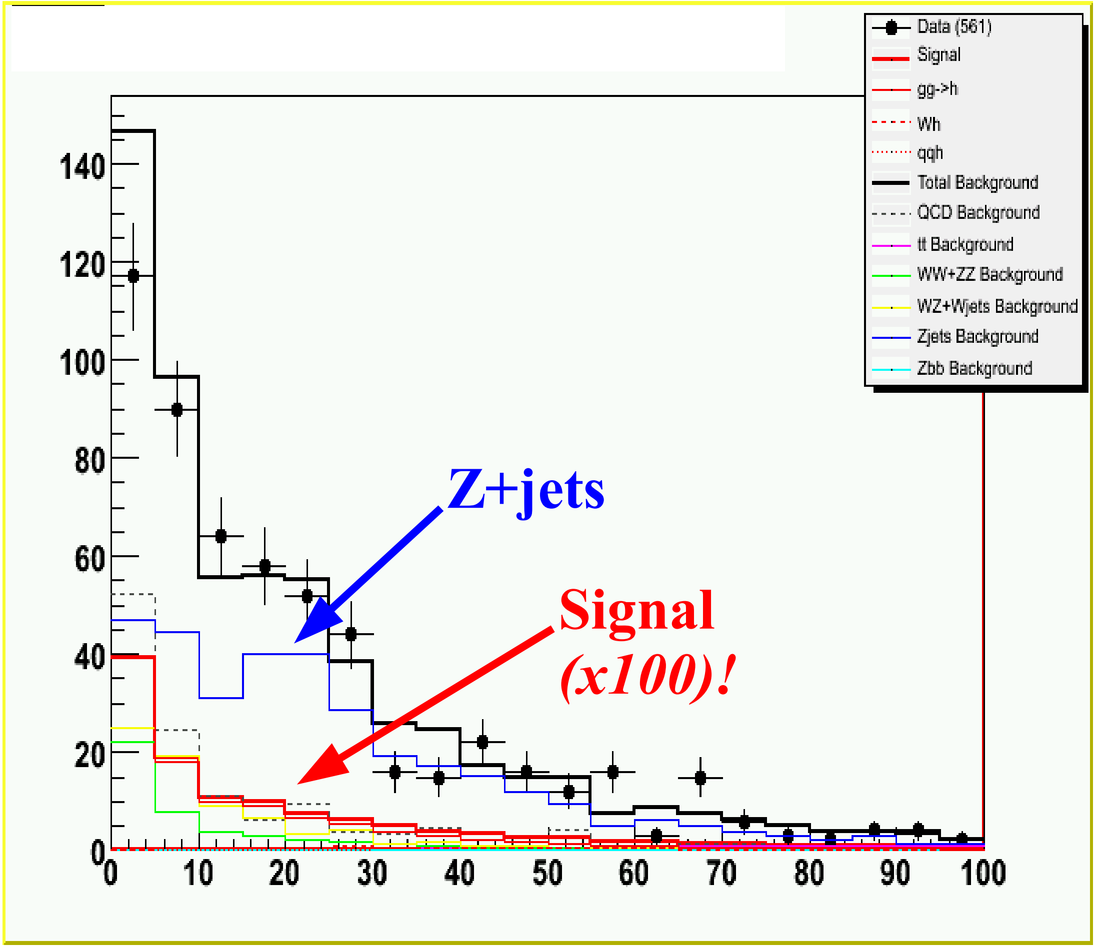
Reducing Backgrounds to H->WW

Z+jets:

MET likely comes from mis-measured jet(s)

- Look at H_T, the scalar sum of the jets' p_T

Useful as an additional NN variable to reduce Z+jets background



Sum p_T of all jets (H_T) (GeV)

Reducing Backgrounds to H->WW

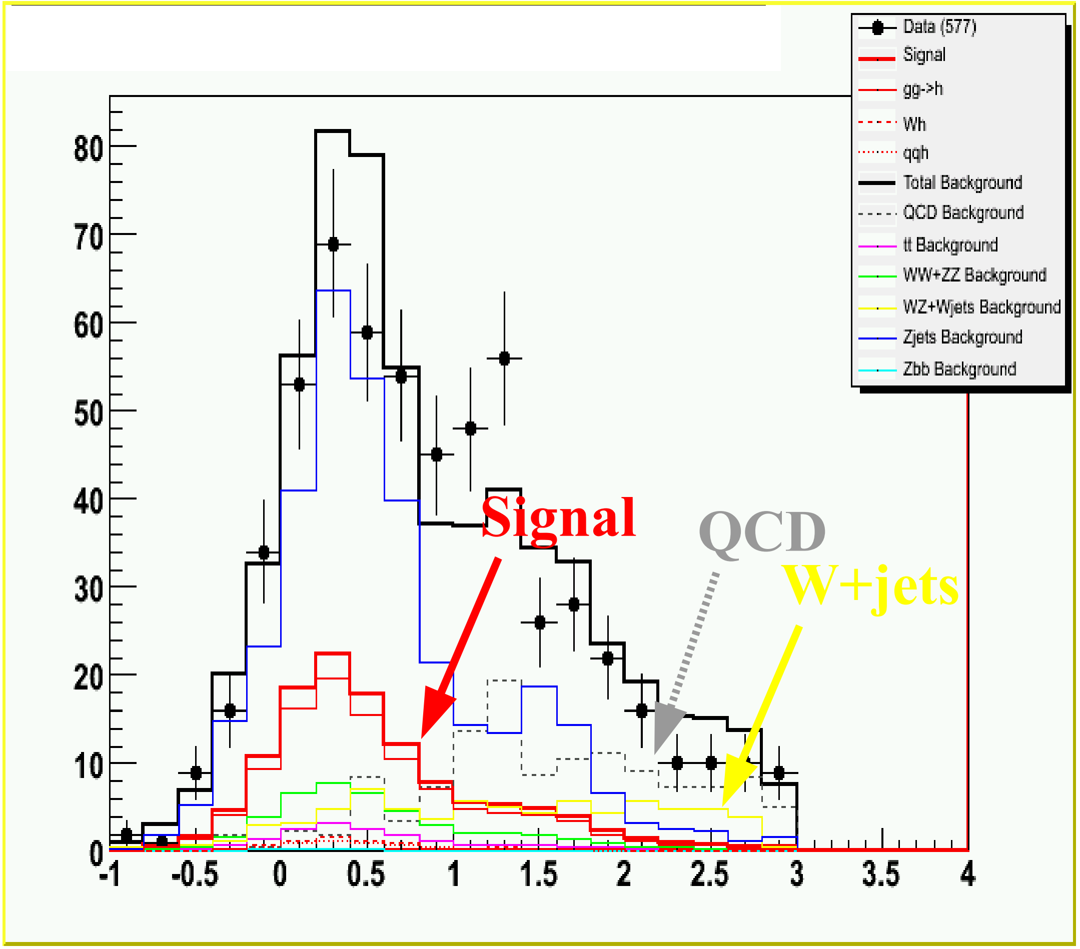
W+jets, QCD:

Muon(s) comes from a jet

Usually a low-p_T muon incorrectly matched to a high-p_T track

- Look at the worst χ^2 between track, muon

Useful as an additional NN variable to reduce QCD and W+jets

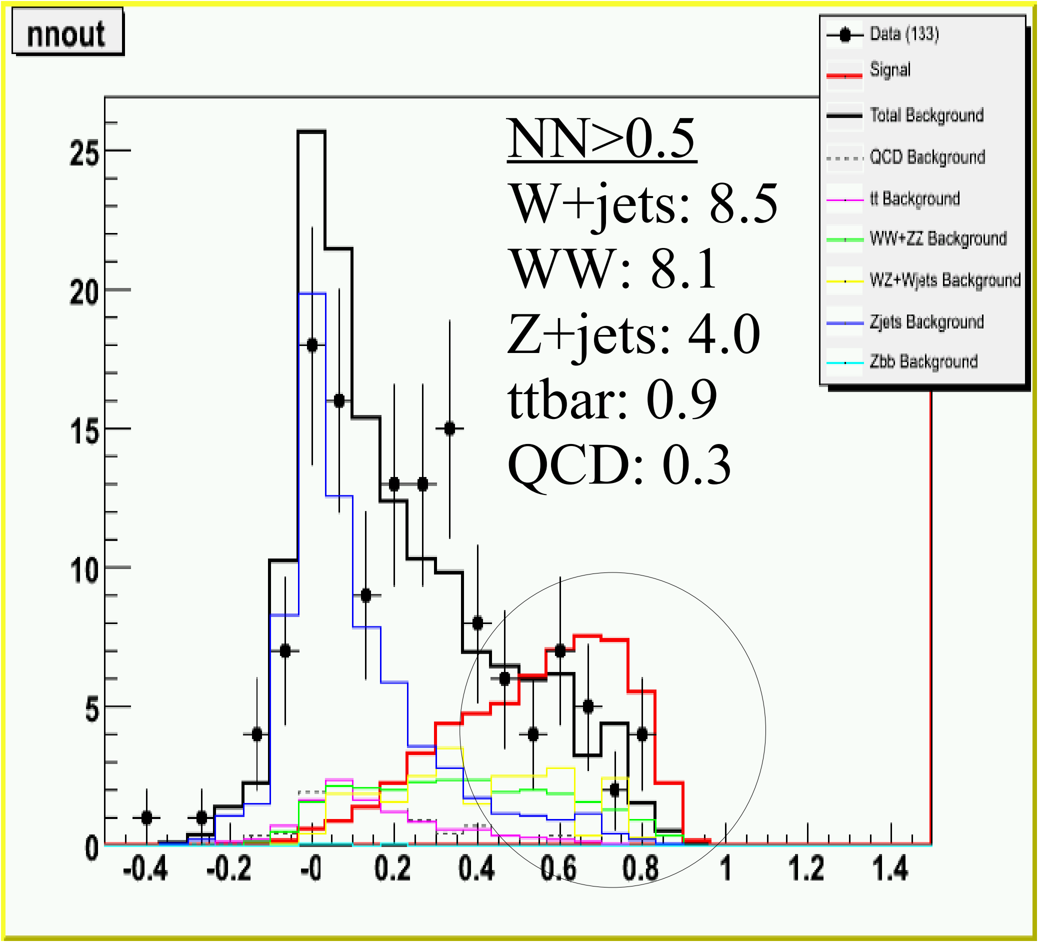


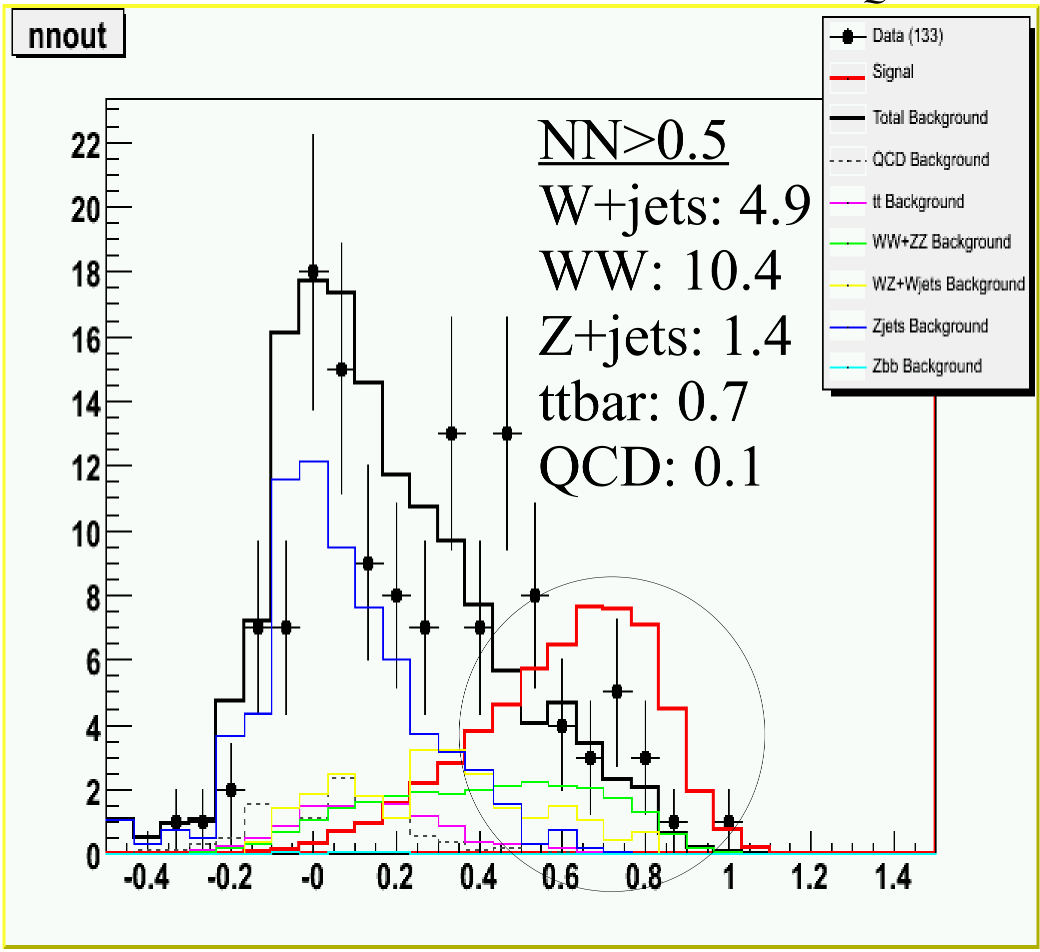
Log10(Max(Chi2 match of track to muon))

Reducing Backgrounds to H->WW

Original NN

Using additional variables: H_T, $p_T(\mu_1\mu_2)$, *UE*, *SET*, $\chi^2(track,\mu)$, $Min(\mu_Q)$



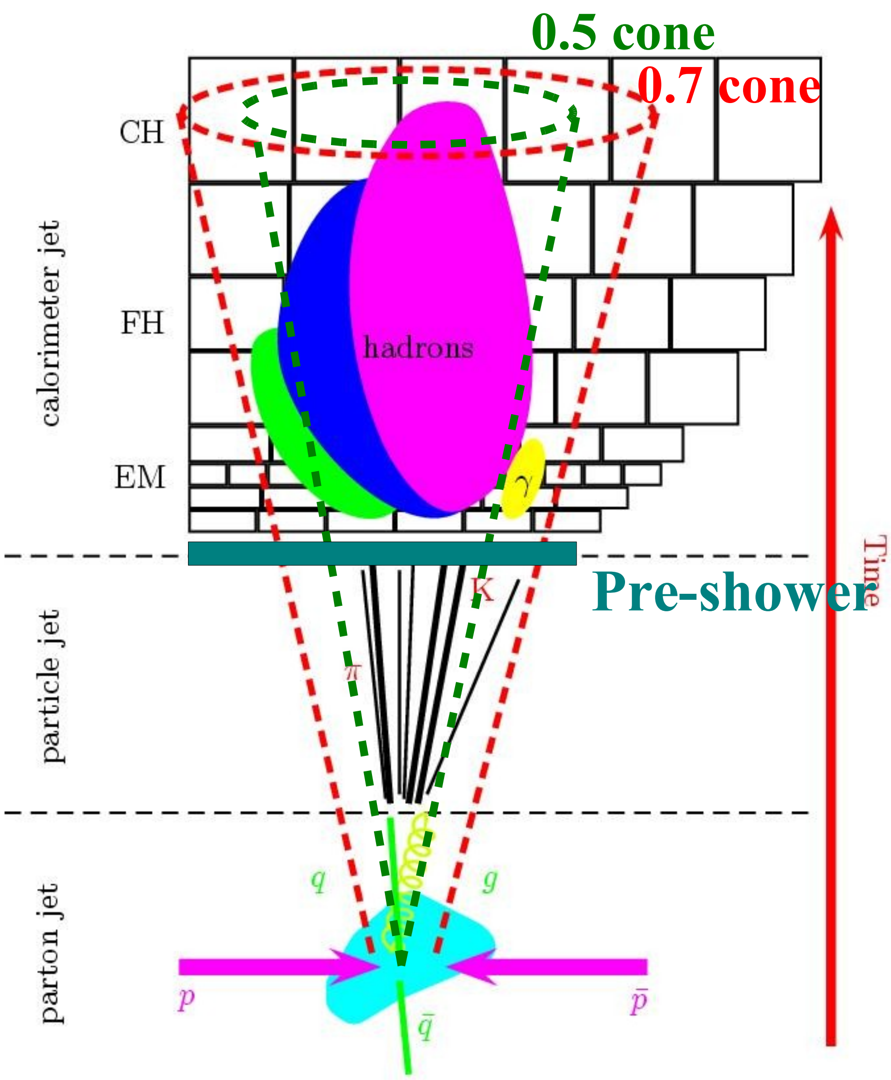


Sensitivity improved by 30%

Di-jet Mass Resolution

Undertaking a major effort to improve jet energy resolution

- Add "pre-shower" energy
- Correct for jet "width"
- Track-based corrections
- (H1-style) cell energy weighting



First a simple trick: measurements of 0.5 and 0.7 cone jets are different

- 0.5 less sensitive to noise, pileup, overlap
- 0.7 captures more jet energy

Average Cone Jets

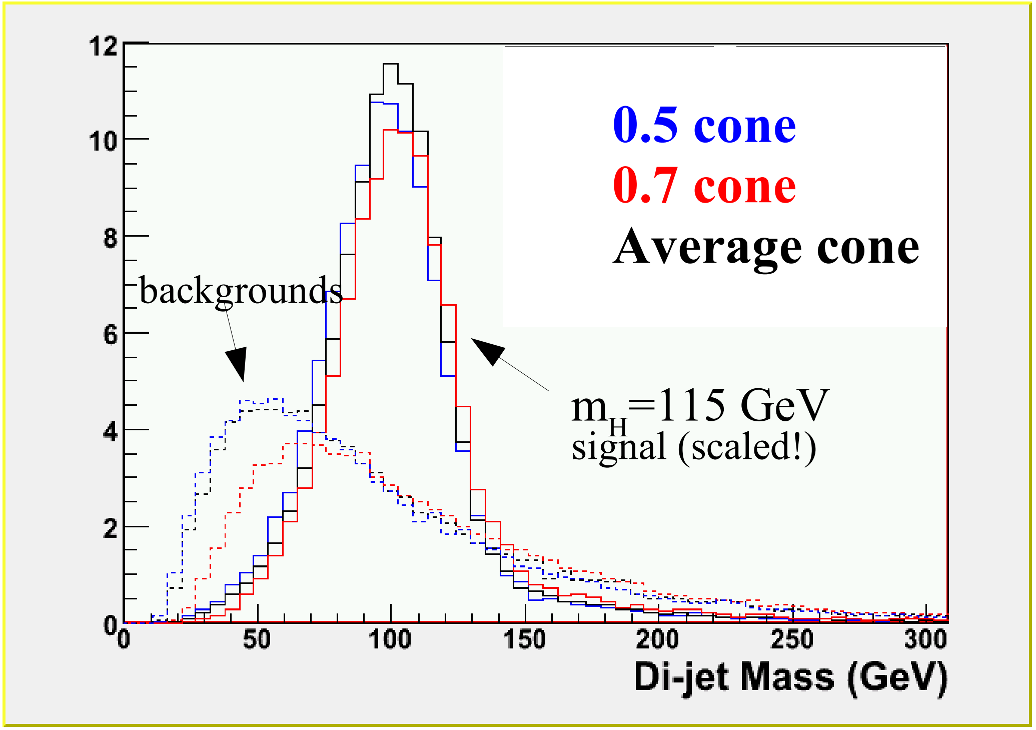
Use 0.5 cone jets for event selection and b-tagging

Match to 0.7 cone jet and average their 4-vectors

~8% di-jet mass resolution improvement

- angles are also measured better

~5% energy resolution improvement observed in γ+jet and di-jet data



Translates into 8% more sensitivity for low-mass Higgs searches

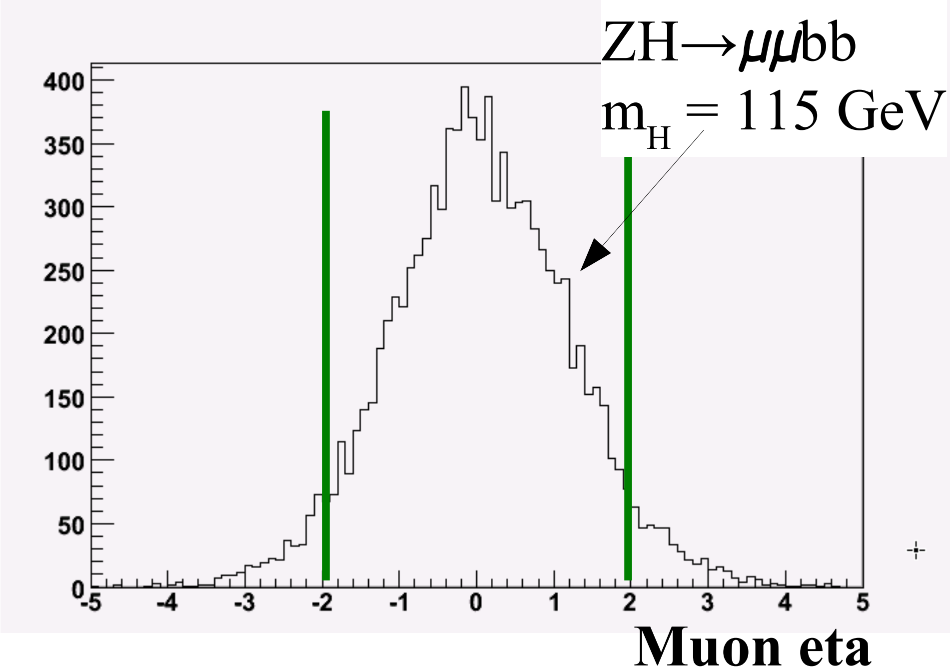
Muon Efficiency

Z->μμ efficiency is only ~60%

Limited muon acceptance

- 20% of Z's with muon |eta|>2

Use tracker, good acceptance to |eta|=~3.5

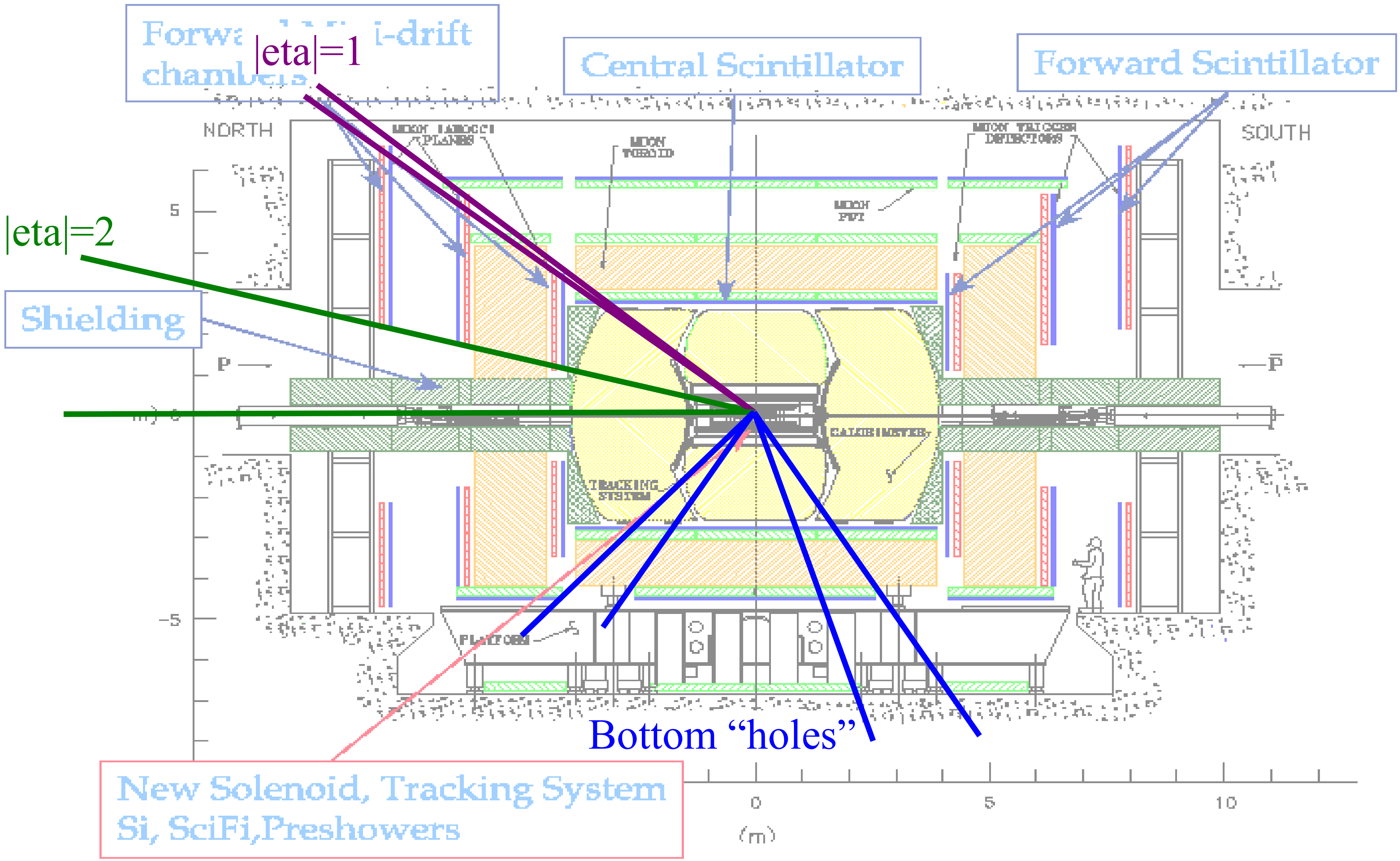


Require one standard muon, look for isolated track

- p_T > 10 GeV
- Tune track and isolation criteria

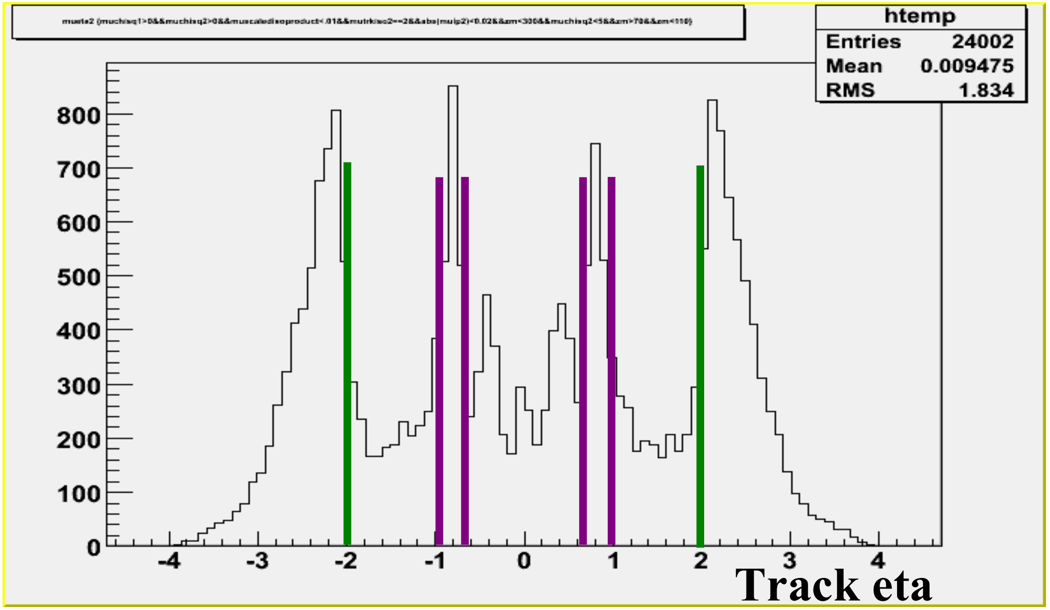
Similar methods also underway to improve electron ID

Muon Acceptance

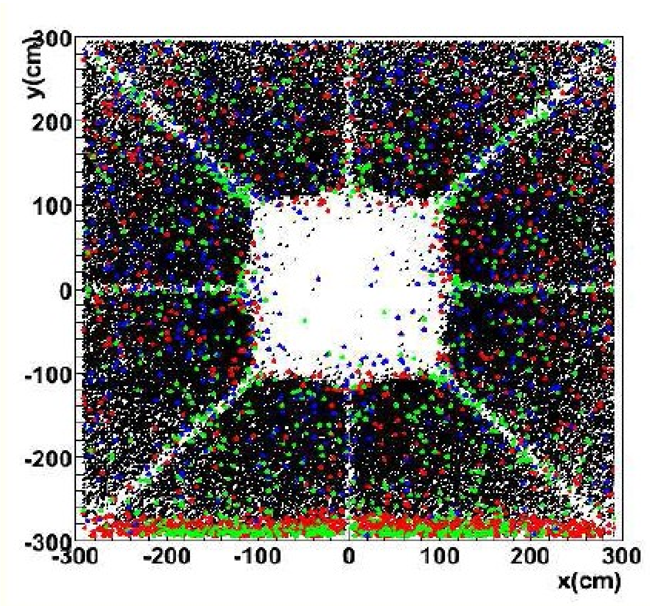


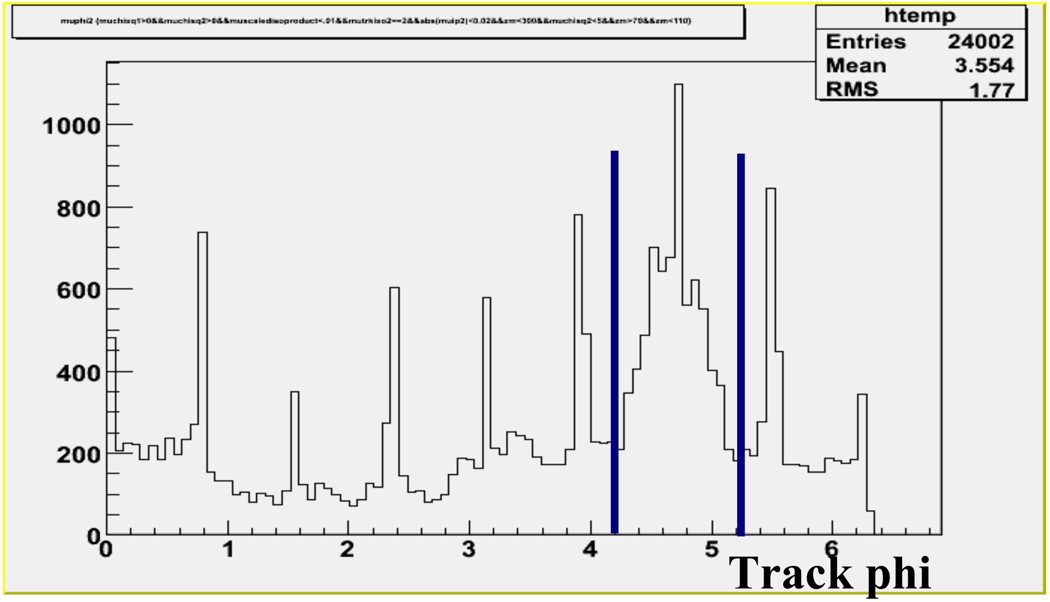
Muon Efficiency

Muons recovered in regions with poor muon acceptance



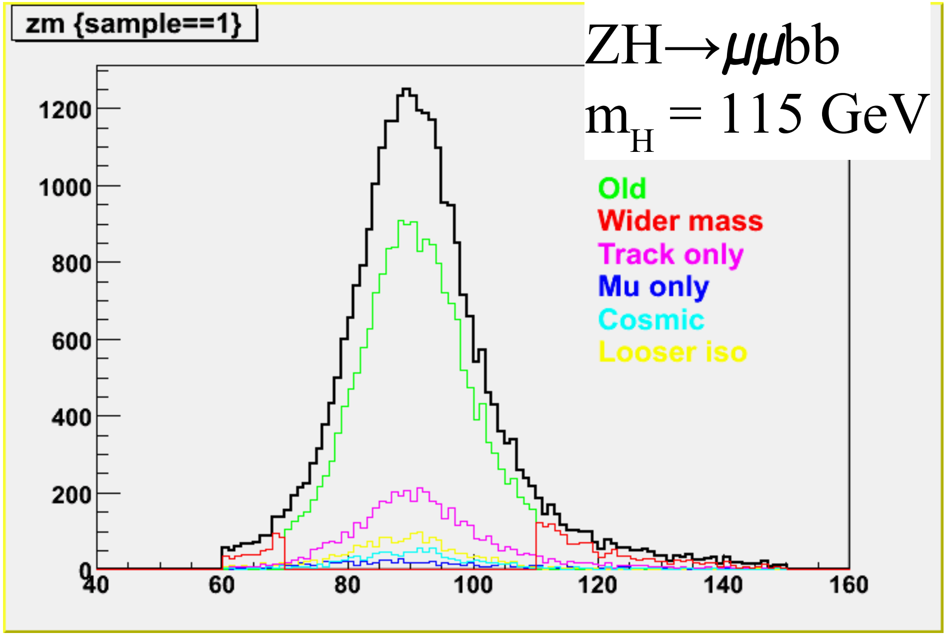
Forward-muon octants



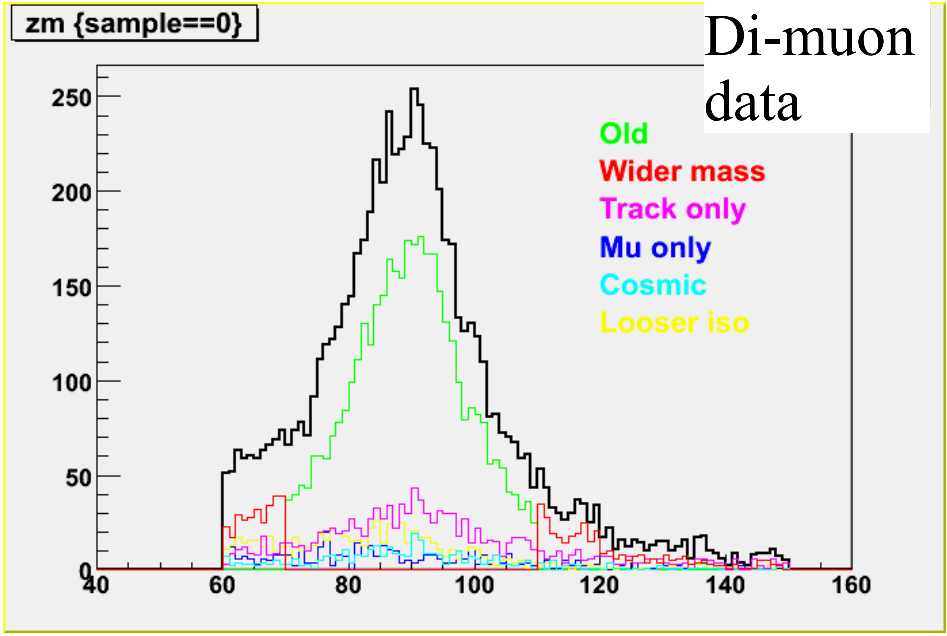


Muon Efficiency

Combine track-only muon with:
- wider Z mass window
- muons with no central track
- muons failing timing criteria
- looser muon isolation



At pre-selection:
- ~60% more ZH->μμbb signal
- ~90% more background



Equivalent to ~30% more data after training NN

Sensitivity Estimates

Better b-tagging

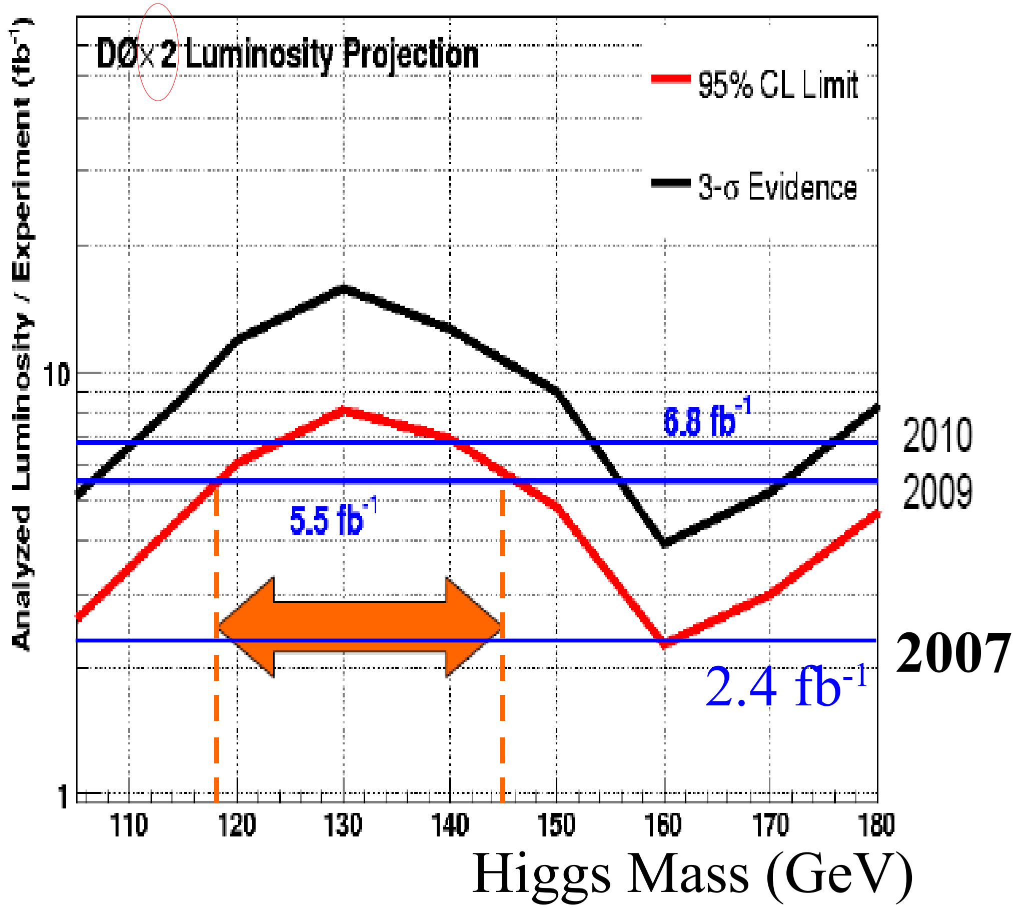
- Semi-leptonic tagging (5%)
- Silicon Layer-0 (8%)

Di-jet mass resolution (20%)

Lepton efficiency (10%)

Matrix Element (20%)

Sensitive to m_H=160 GeV with data already on tape



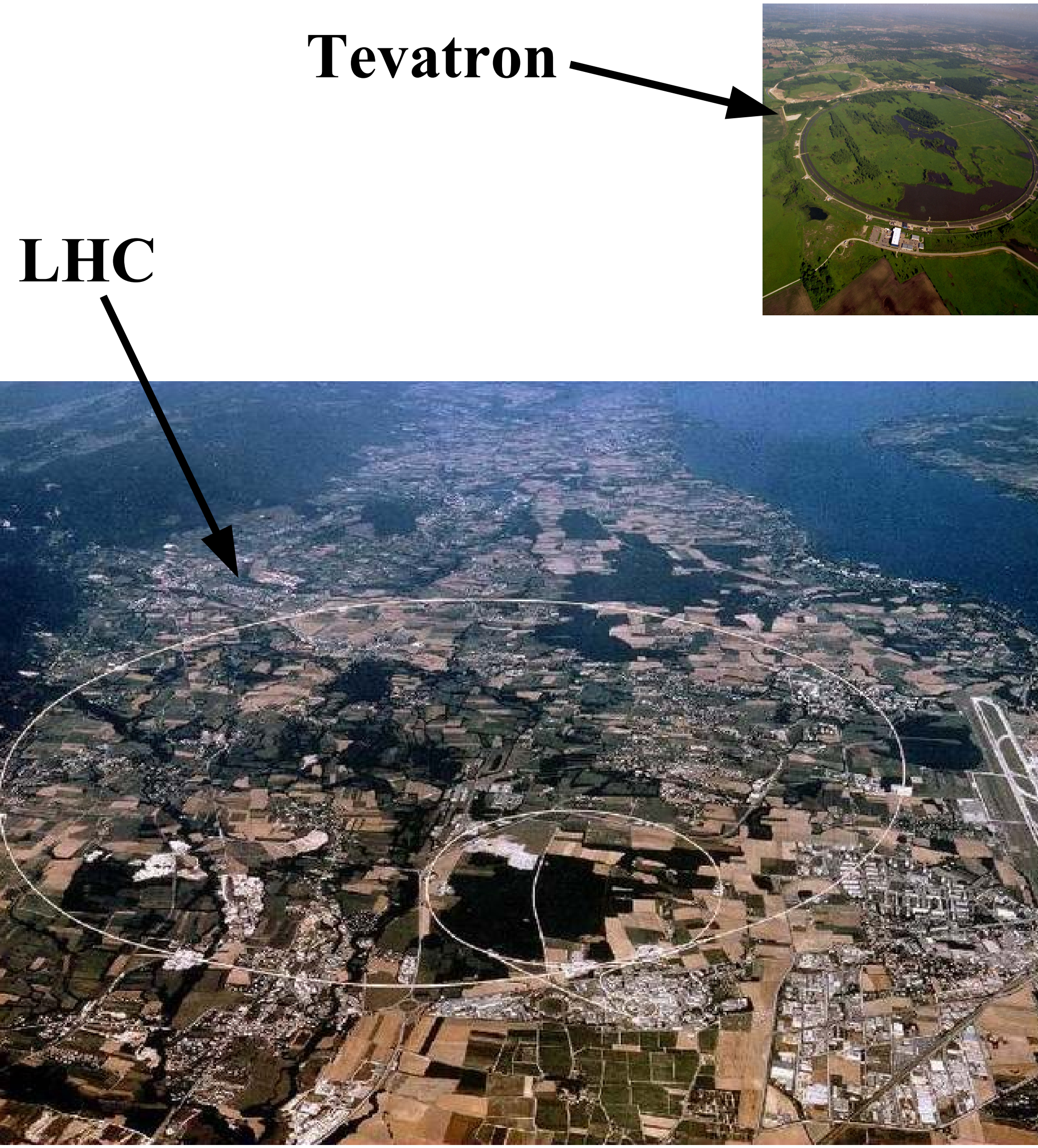
May be sensitive up to 200 GeV by 2010

LHC

proton on *proton*

7x Tevatron energy
~100x the luminosity

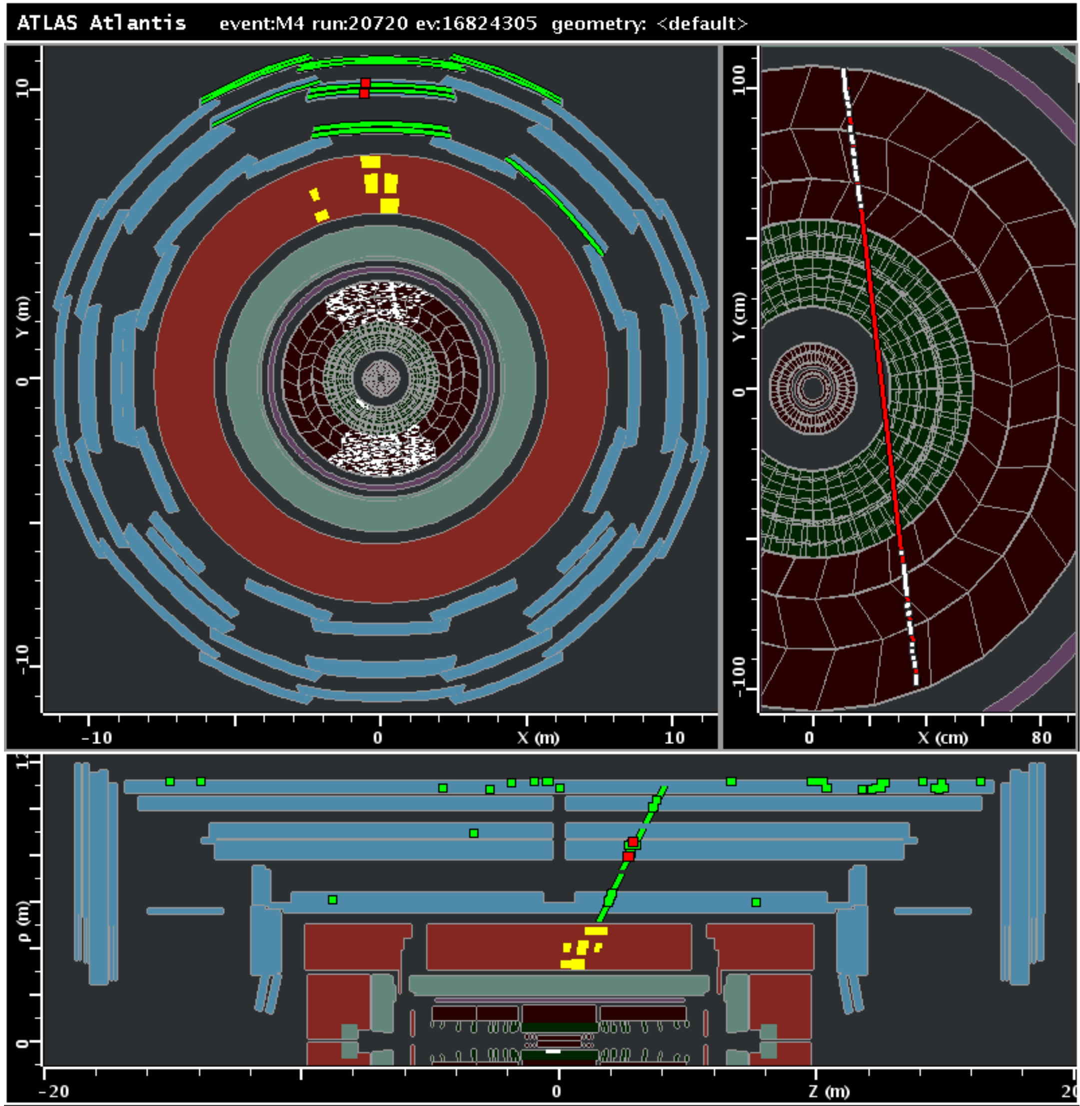
Collisions this summer?



ATLAS

Taking cosmic data with all detector subsystems

Barrel LAr / Tile calorimeter



Higgs at the LHC

Discovery possible in whole mass range after 30/fb (~2011)

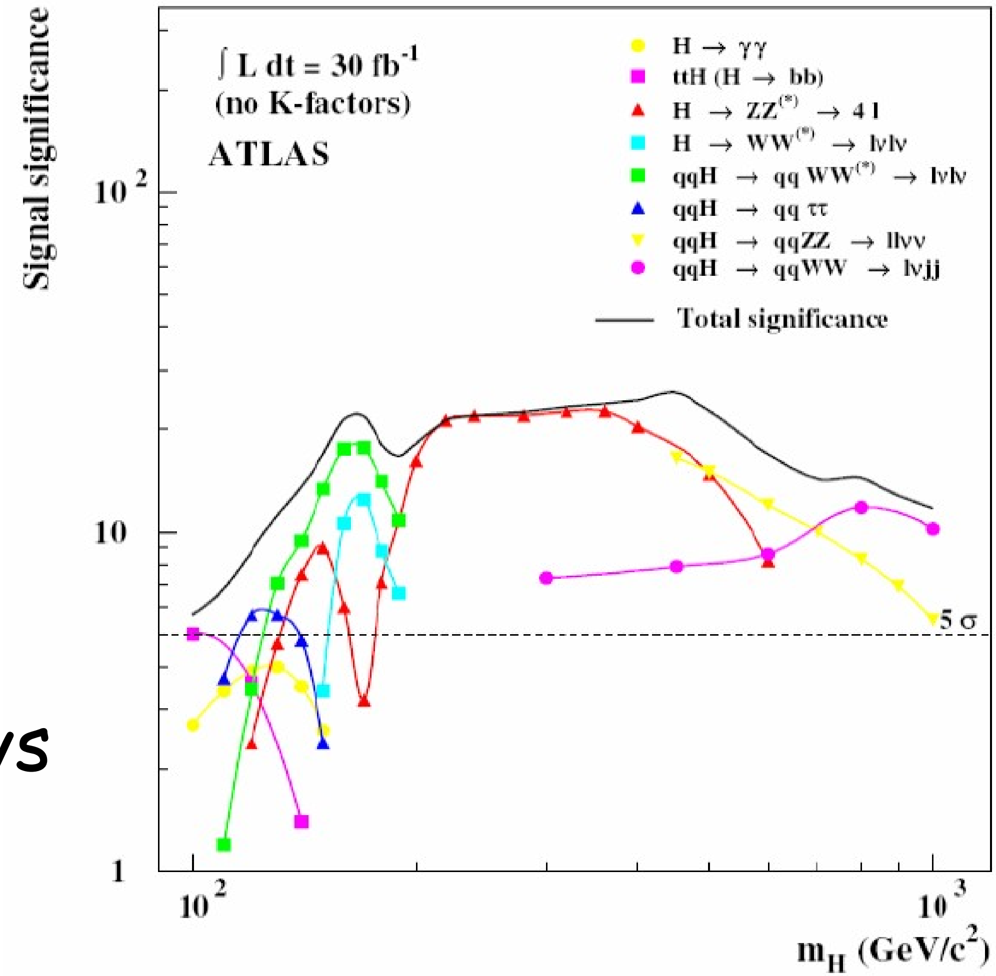
m_H<~130 GeV difficult

TeV: W/Z+H, H->bb decays

LHC: H, qqH, H->ττ/γγ decays

- ttH(->bb) is very hard

Important to measure many channels, to test SM



Conclusions

The Higgs Boson would complete verification of the SM

- Will also lead to new puzzles – and perhaps to new physics

DØ is hunting the Higgs, using advanced techniques

- NN b-tagging, single/double b-tag, NN event selection
- Combined with CDF: 4.3x SM @115 GeV, 1.9 @160 GeV exp.
  1.4 observed!

Finding the Higgs will take further innovations

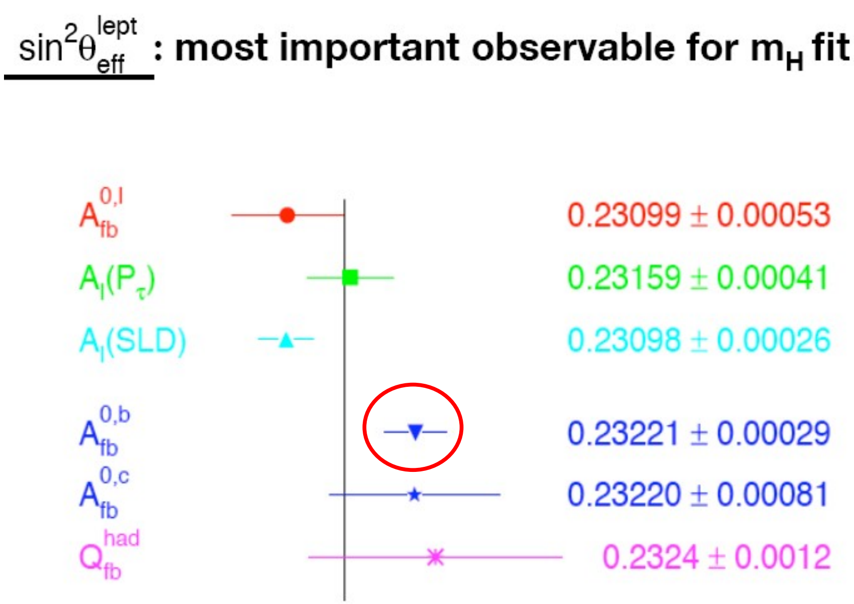
- Better b-tagging, di-b-jet mass resolution, lepton ID, ME's...
- May be sensitive to SM Higgs @160 GeV *this winter*
- Possible to be sensitive up to 200 GeV by 2010
- *And we're always ready for surprises!*

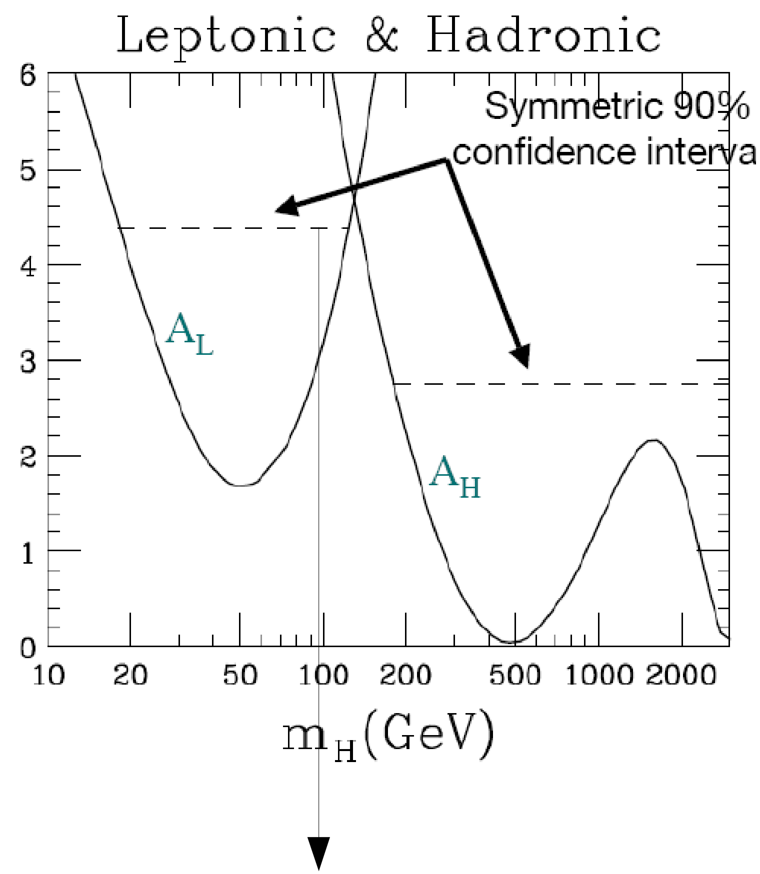
Backup

Precision EW Constraints

EW variables sensitive to m_H via radiative corrections: $\log \frac{m_H}{m_Z}$

LEP II: m_H>114.4 GeV



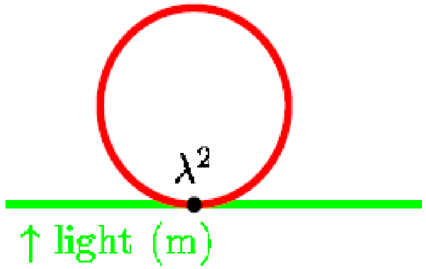


m_H<97 GeV
(at 95% CL)
(leptonic only)

Why is the Higgs so Light?

The Higgs mass is *unstable*

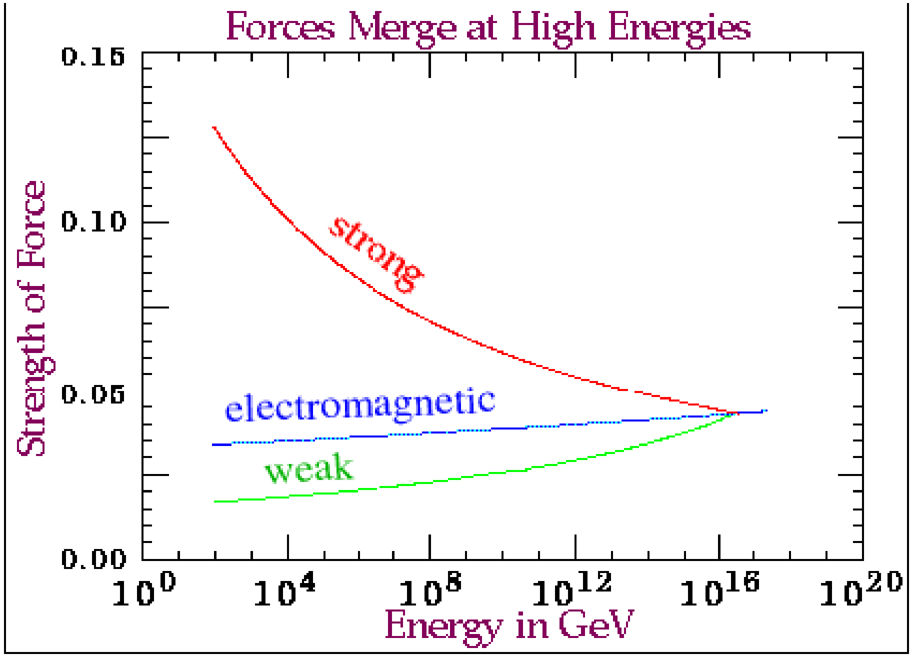
- Large radiative corrections (it's a scalar)



$$\Longrightarrow \delta m^2 \sim \lambda^2 \cdot M^2$$
$$10^2 \quad 10^{-1} \quad 10^{16}$$

Hierarchy problem:

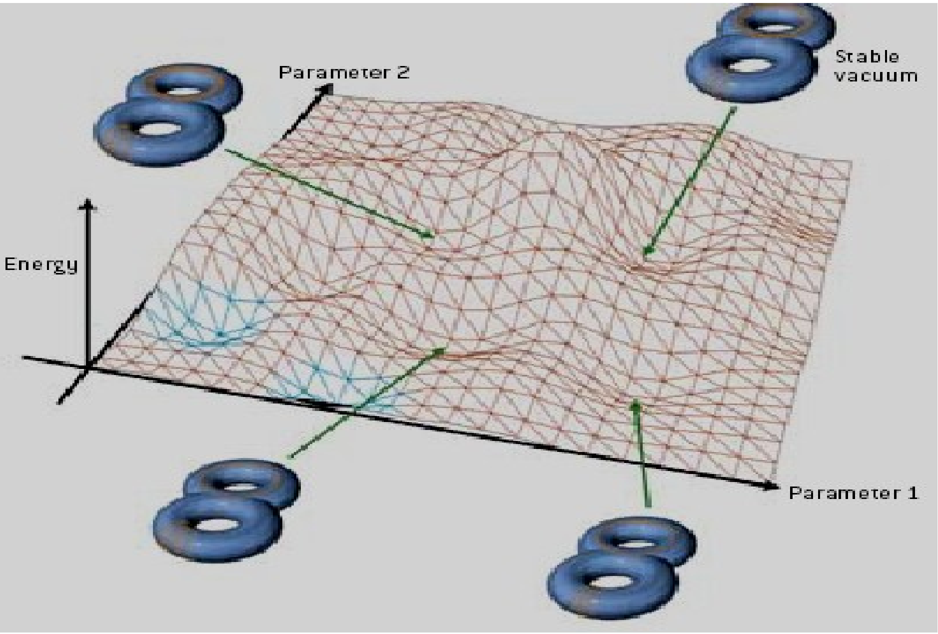
$m_H \ll m_{GUT}$



Why is the Higgs so Light?

We wouldn't be here if it wasn't

- A small Higgs VEV seems necessary for life

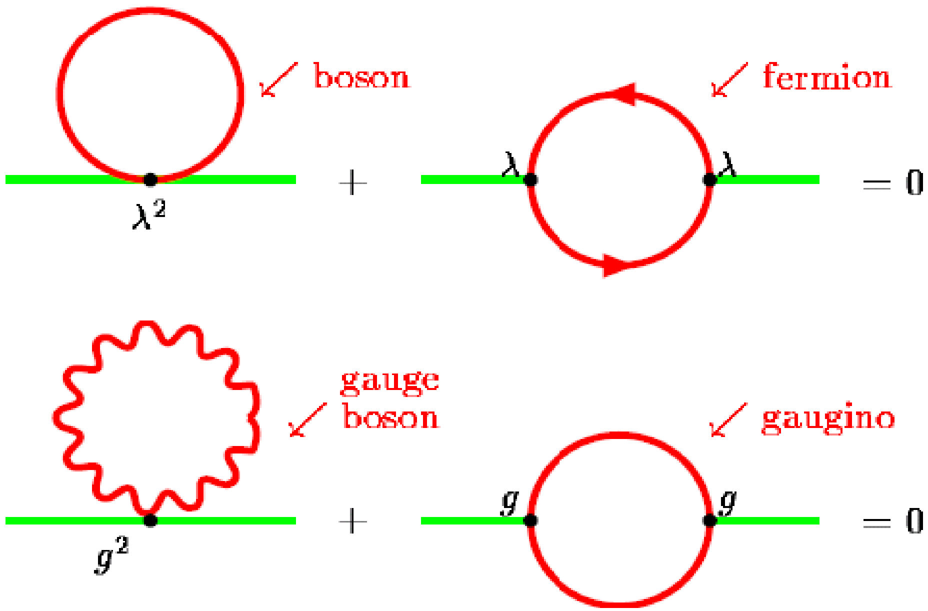


Same reason for a small cosmological constant?

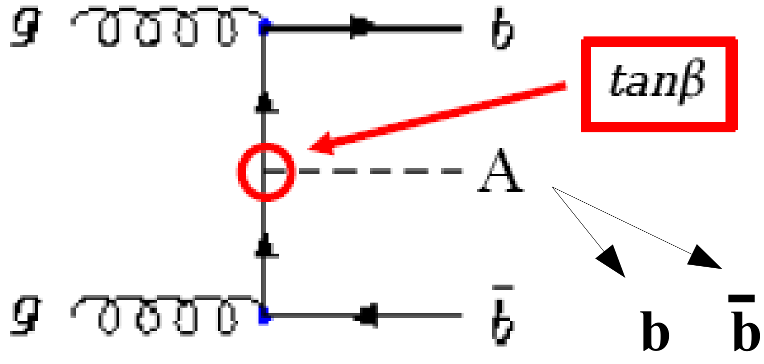
Why is the Higgs so Light?

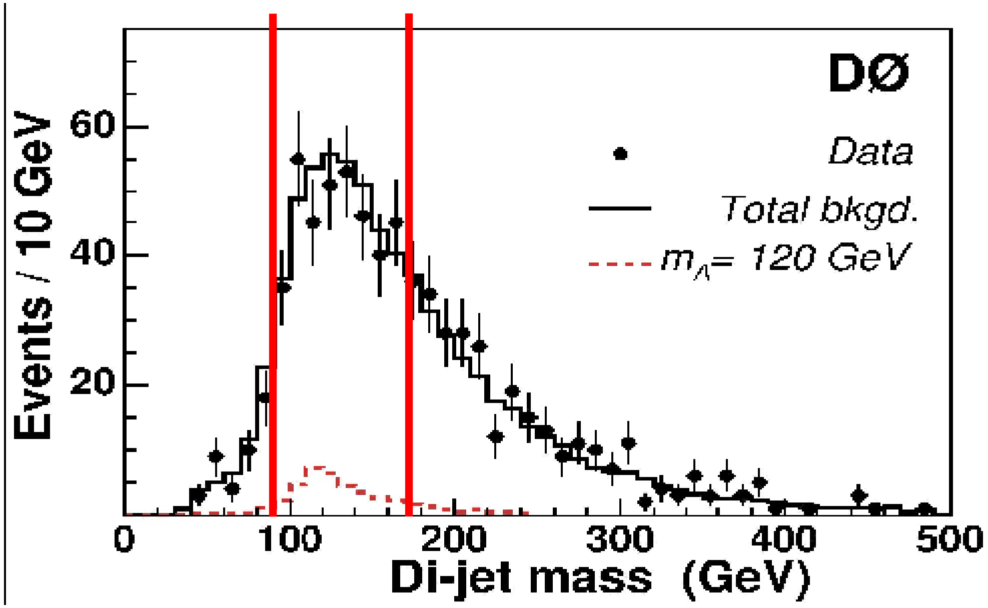
New physics: Supersymmetry

- Particles come in fermion-boson pairs
- Corrections to Higgs mass nearly cancel, if boson and fermion masses are similar

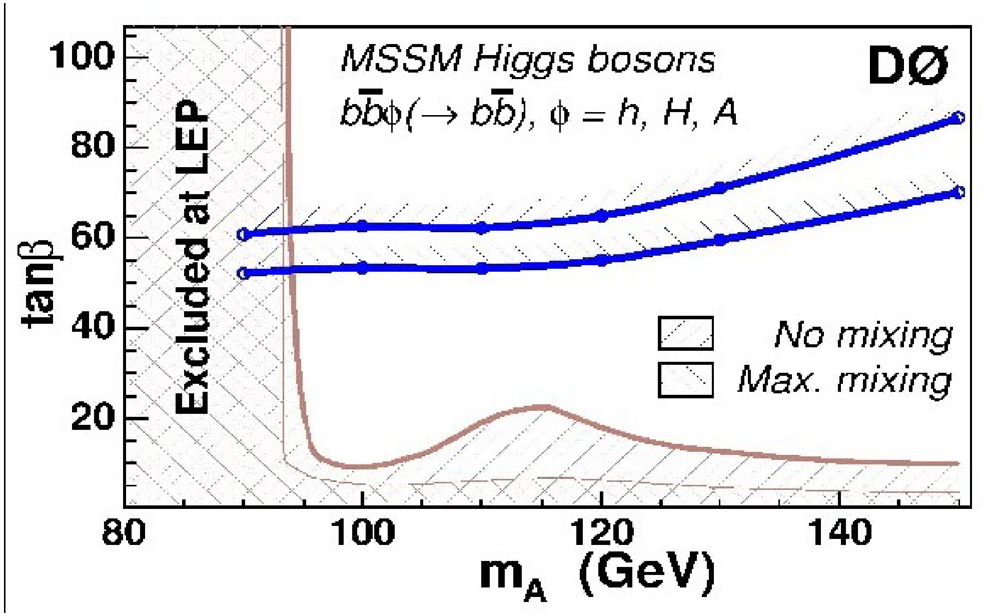


DØ SUSY Higgs Search





Search for bbb bump on bbb background



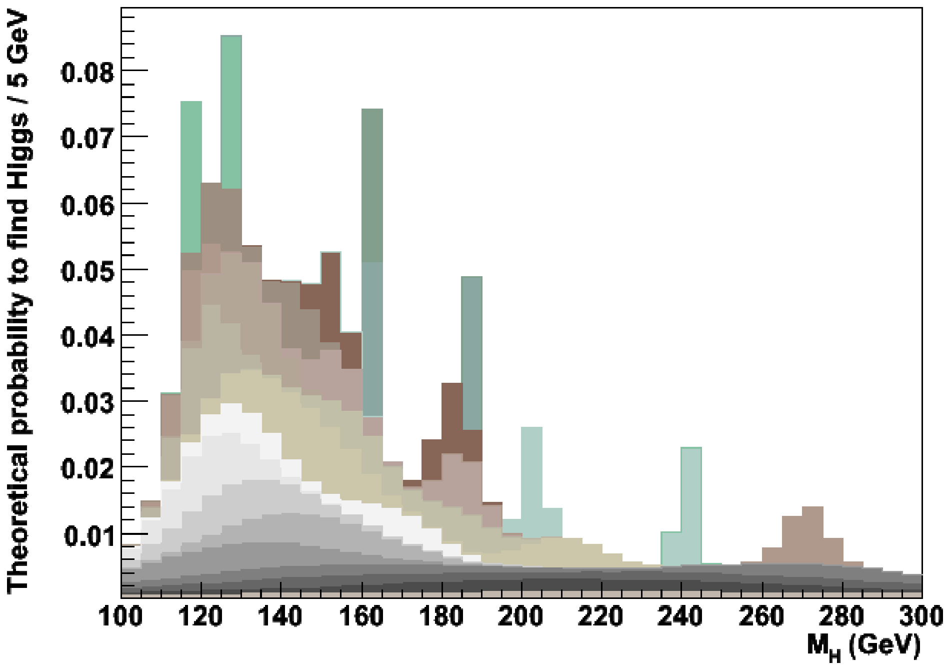
Interpret as limits in m_A / tanB plane

PRL 95, 151801 (2005)

Why is the Higgs so Light?

616 papers on hep-ph in 2007 on "Higgs"

Lots of great ideas
Need experimental input

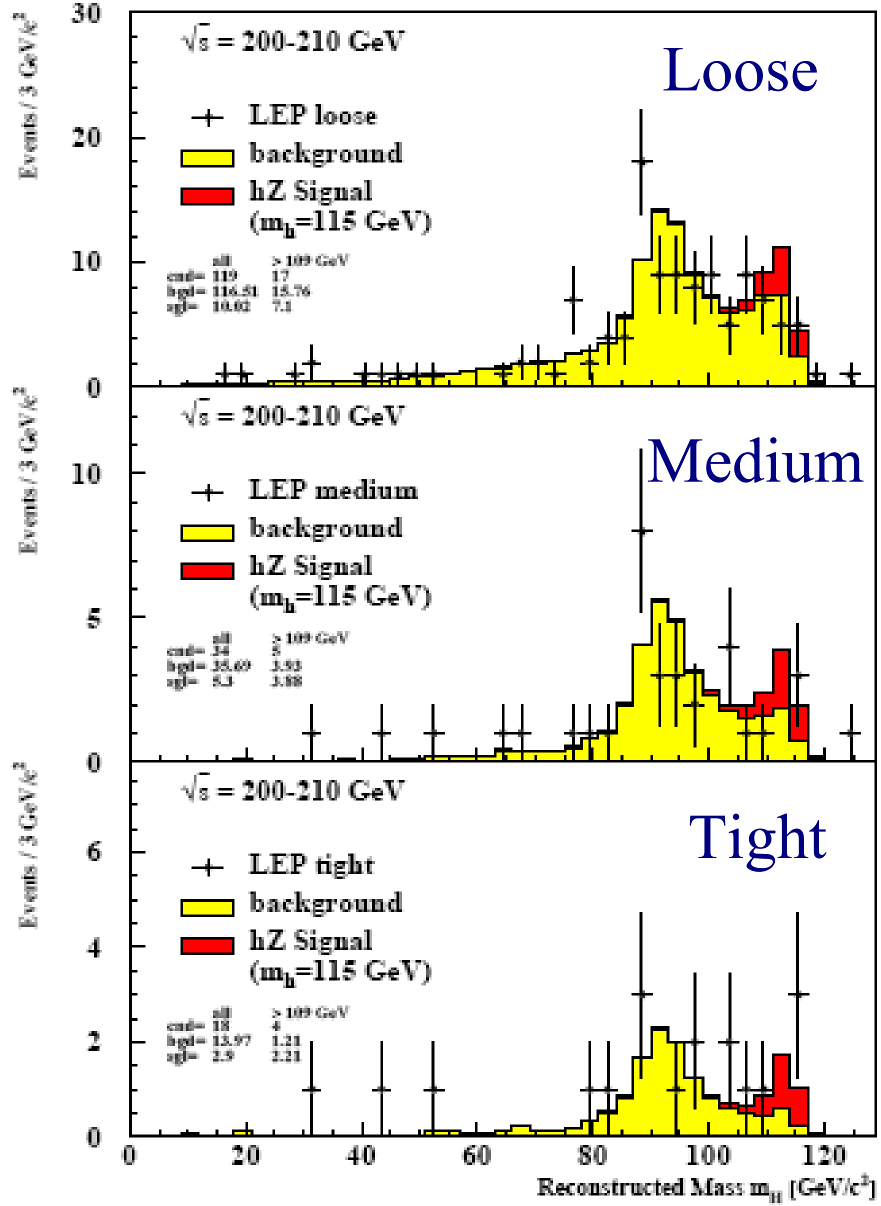


LEP @ CERN in 2000

Circular $e^+ e^-$ collider

Maximum E of 200-210 GeV

A good, but not the only variable...



Look for $e^+ e^-$ -> Z+H(->bb)

Slight excess around 115 GeV

Higgs mass > 114.4 GeV

Limit Setting

- In the absence of signal, we set limits on Standard Model Higgs boson production
  - We calculate limits via the CLs prescription:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

  - Using a Log-Likelihood Ratio test statistic:

$$Q(\vec{s},\vec{b},\vec{d}) = \prod_{i=0}^{N_{Chan}} \prod_{j=0}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{(s+b)_{ij}}}{d_{ij}!} \Big/ \frac{b_{ij}^{d_{ij}} e^{b_{ij}}}{d_{ij}!} \qquad LLR = -2 \times Log Q$$

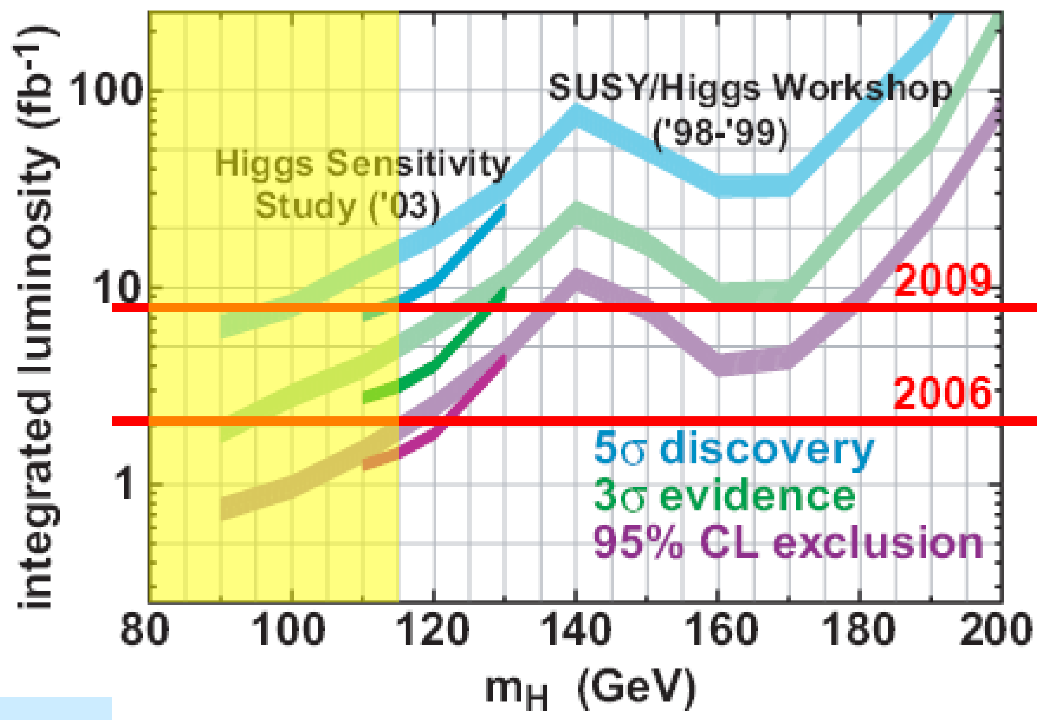
d_{ij} refers to "data" for model being tested: **Observed events, or expected Background or Signal+Background**

- Distributions of simulated outcomes are populated via Poisson trial with mean values given by B-only or S+B hypotheses
  - Systematics are folded in via Gaussian marginalization
  - Correlations held amongst signals and backgrounds

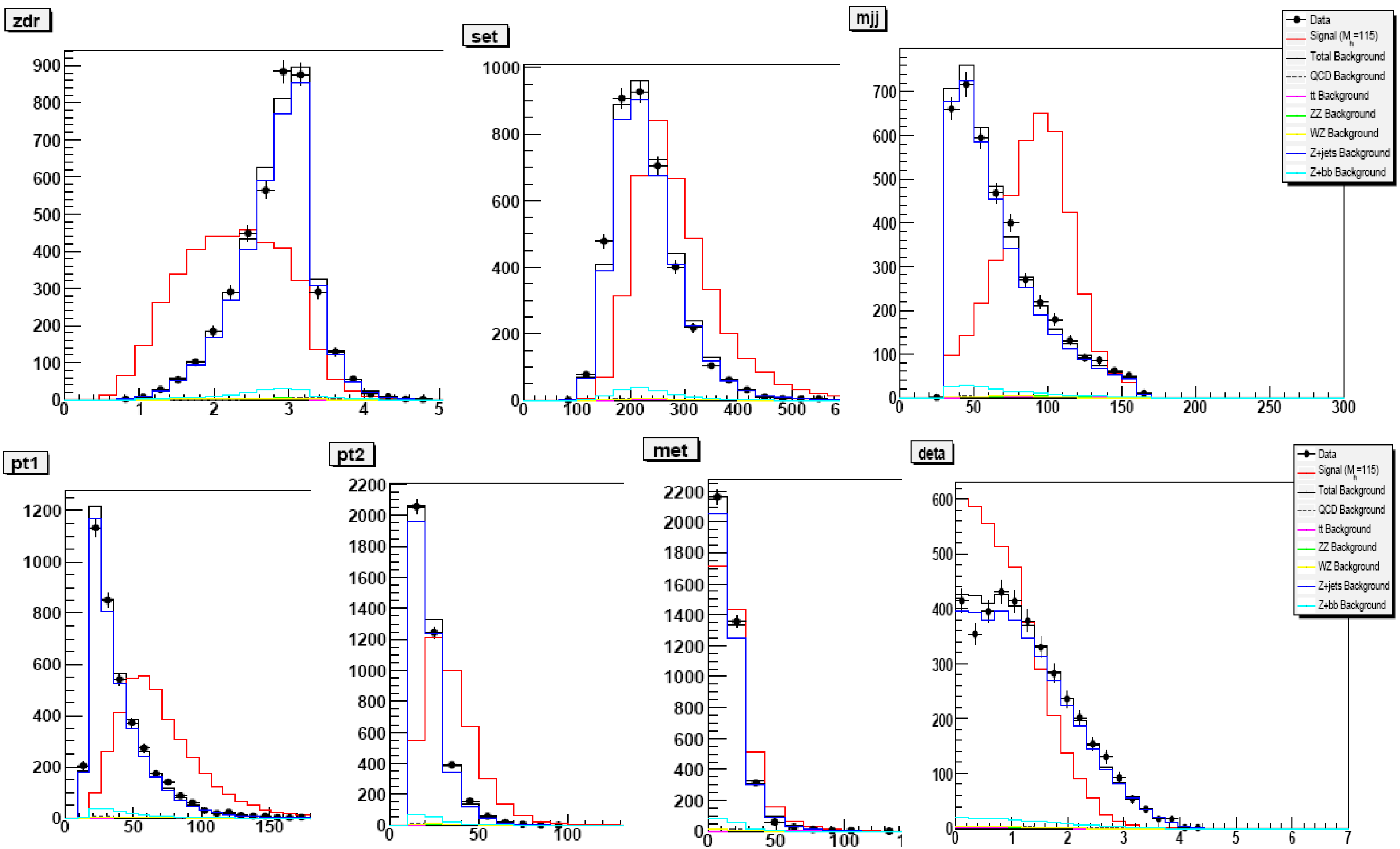
6

Sensitivity

2003 study



ZH->μμbb Pre-b-tagging



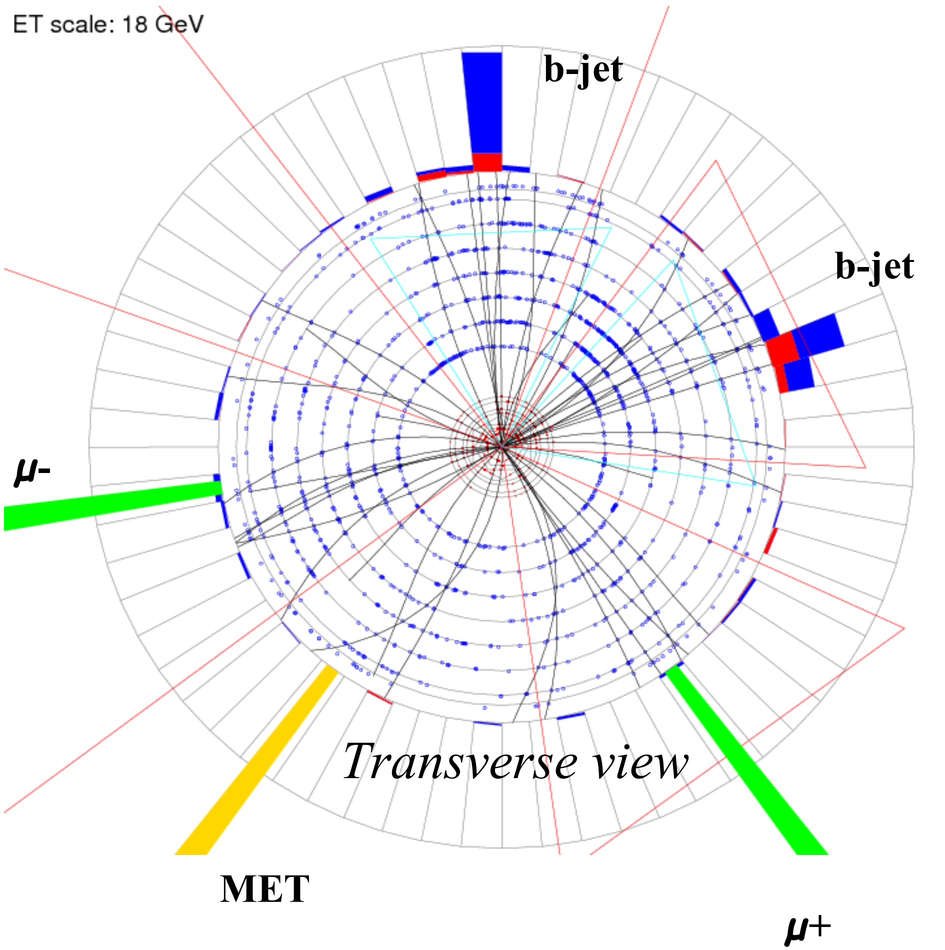
Event Kinematics

No true MET in $\mu\mu$bb events

Should assign observed MET to some combination of muons and jets – correct their pt's

Depends on:

- angles between MET, muons, and jets
- pt balance of Z and di-jets
- invariant mass constraint of Z and H->bb



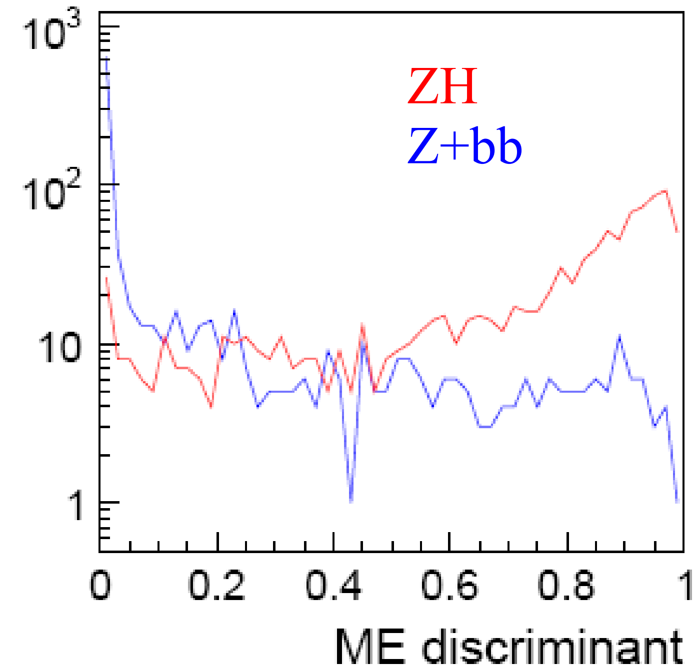
Too complicated for NN

Matrix Elements

Calculate "cross-section" for an observed event to be from Z+bb or Z+(H->bb)

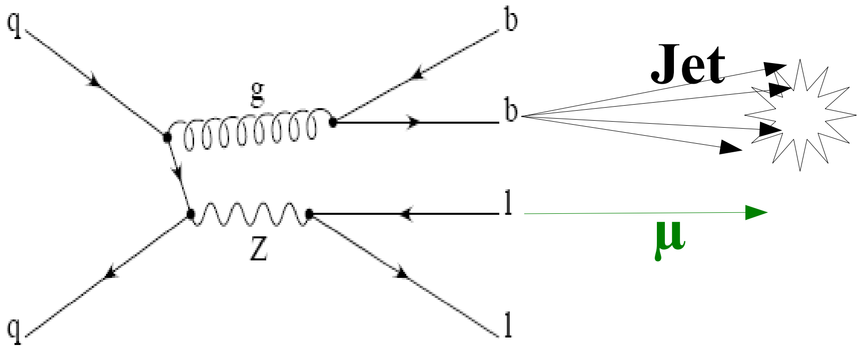
Use MC integration methods

Include as inputs to NN



$$p(m) = \int dx \; f_\Phi \cdot \sum_{a,b} f_a f_b \left|M_{ab}(k(m,x))\right|^2 \cdot T(k(m,x),m)$$

- m: detector measurement of event.
- x: integration parameters
- $k(x,m)$: parton solution given m and x.
- f_Φ: phase-space factors.
- $f_a f_b$: PDFs from MCFM.
- M_{ab}: matrix element from MCFM.
- T: transfer functions

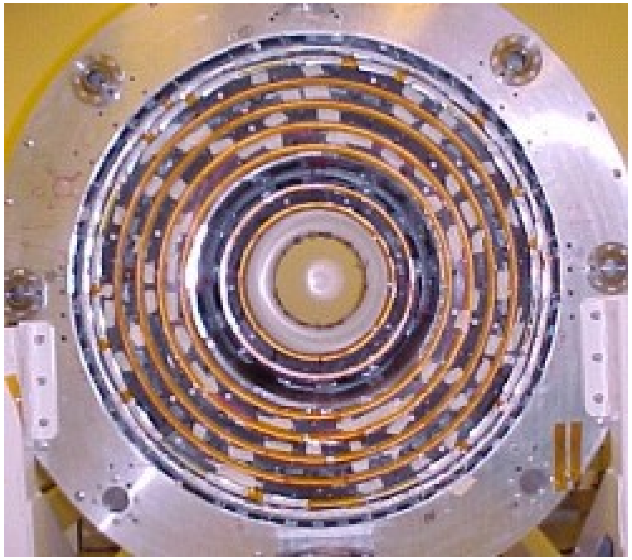


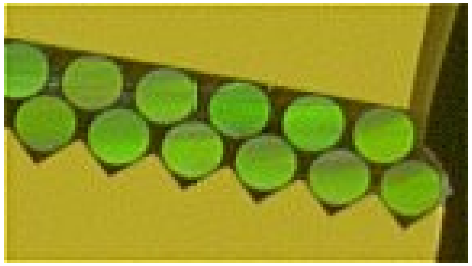
MET = μ1+μ2+j1+j2+σ(MET)

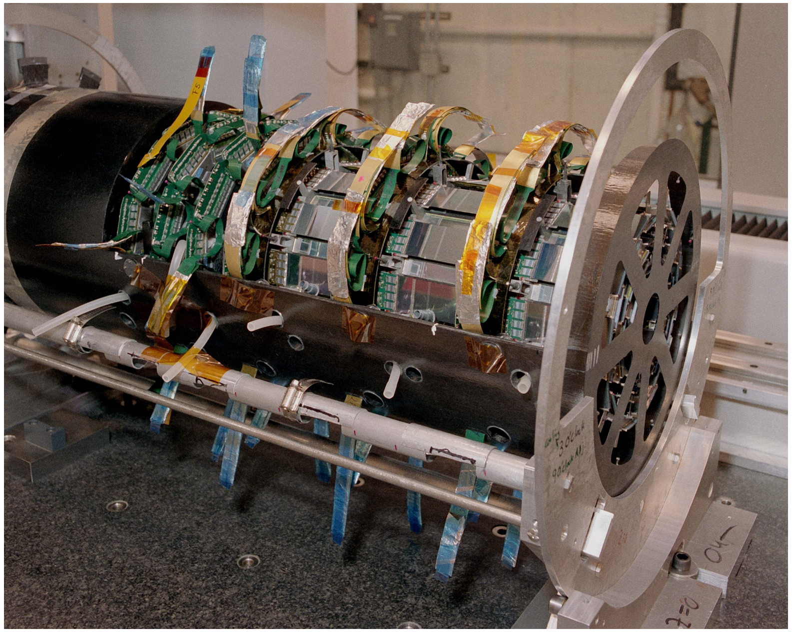
Tracking

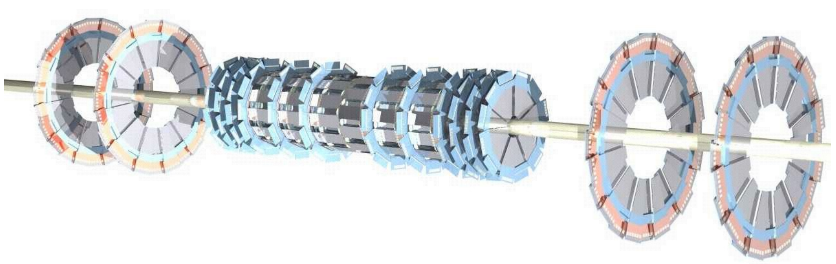
Central Fiber Tracker

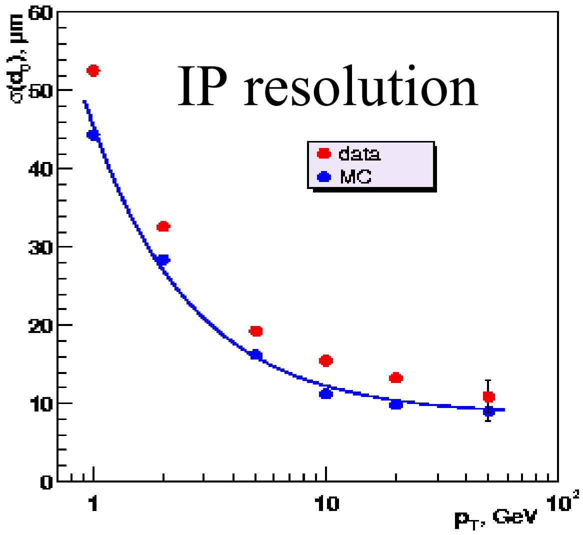
Silicon Microstrip Tracker

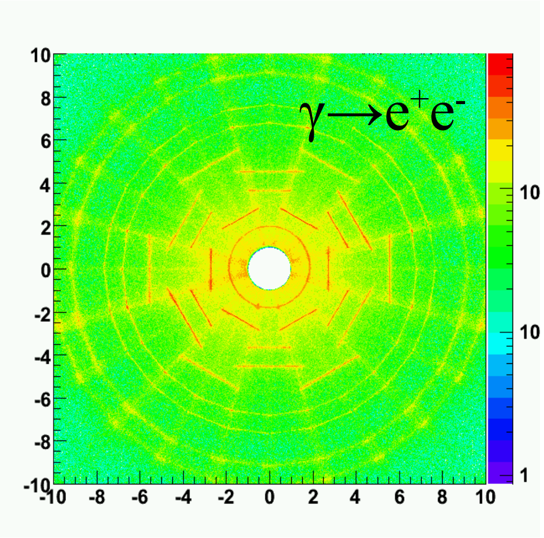






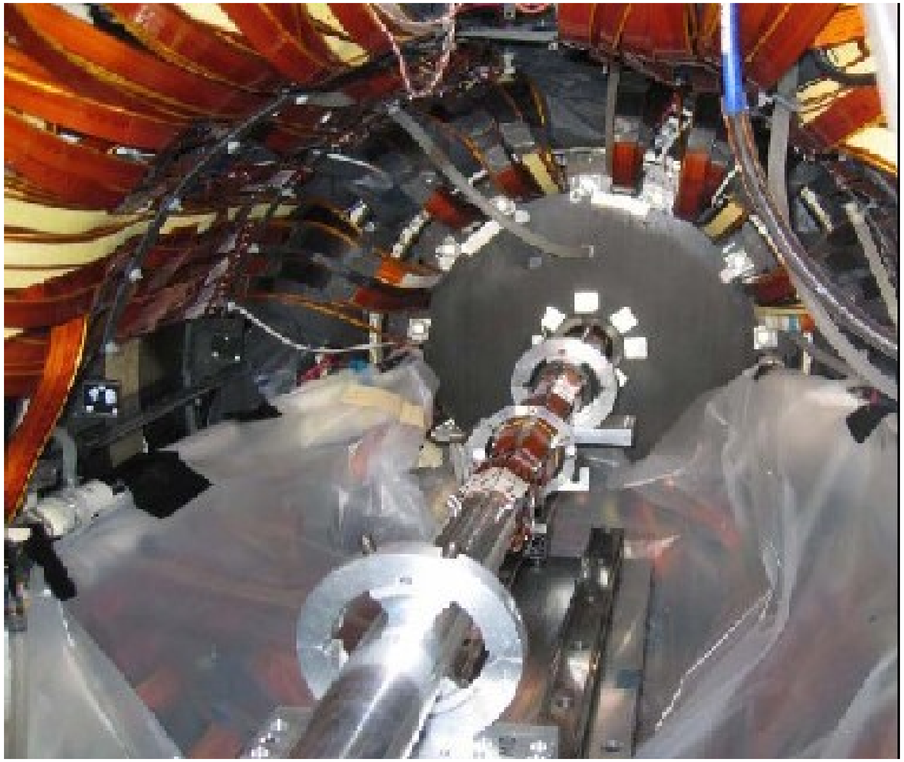




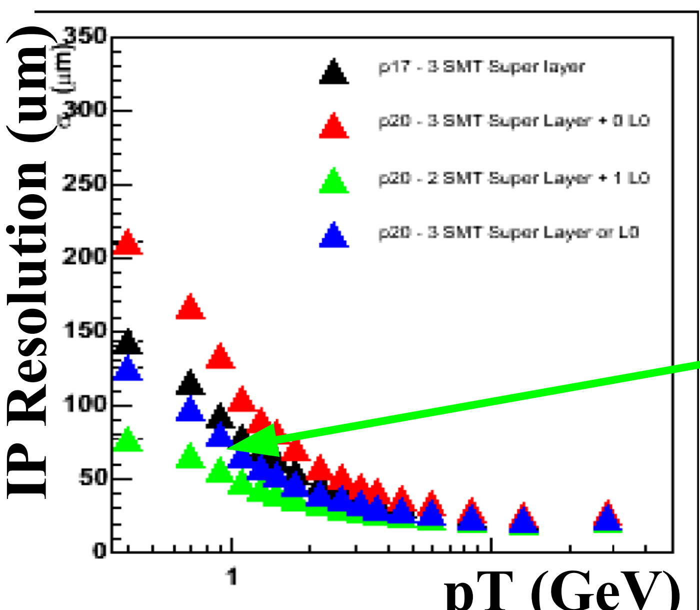


Layer 0 of Silicon Tracker

- Silicon detectors mounted just outside the beampipe
- Installed fall '06
- Better track impact-parameter resolution -> Better b-jet tagging

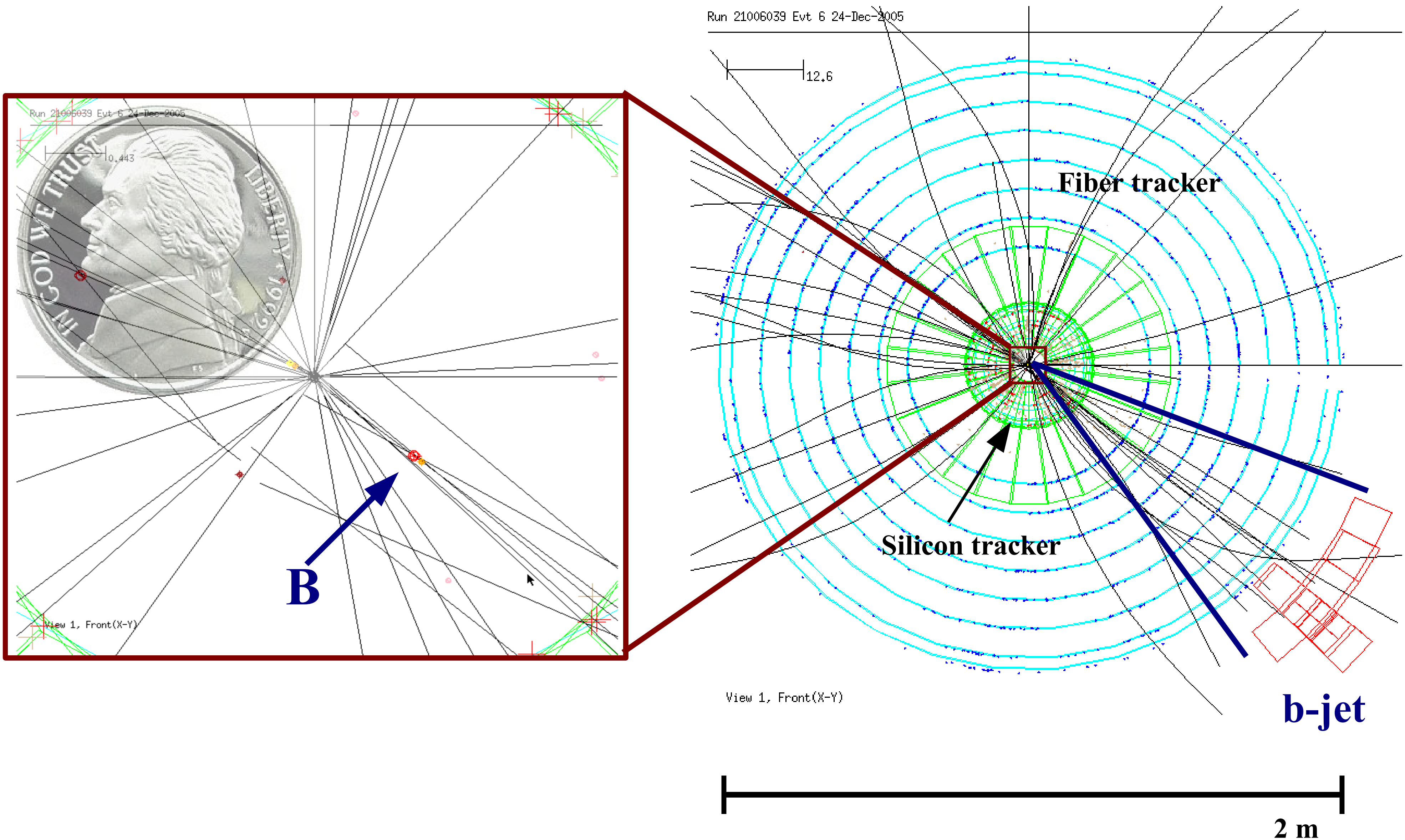


Layer 0 being inserted into the silicon tracker



Effect of Layer 0 in recent data

b-Jet Tagging Reality



b-Tagging Measurement

System 8 method:

$$
\begin{aligned}
n &= n_b + n_{udsgc} \\
p &= p_b + p_{udsgc} \\
n^{SLT} &= \varepsilon_b^{SLT} n_b + \varepsilon_{udsgc}^{SLT} n_{udsgc} \\
p^{SLT} &= \varepsilon_b^{SLT} p_b + \varepsilon_{udsgc}^{SLT} p_{udsgc} \\
n^{NN} &= \varepsilon_b^{NN} n_b + \varepsilon_{udsgc}^{NN} n_{udsgc} \\
p^{NN} &= \beta\varepsilon_b^{NN} p_b + \alpha\varepsilon_{udsgc}^{NN} p_{udsgc} \\
n^{SLT,NN} &= \kappa_b \varepsilon_b^{SLT} \varepsilon_b^{NN} n_b + \kappa_{udsgc} \varepsilon_{udsgc}^{SLT} \varepsilon_{udsgc}^{NN} n_{udsgc} \\
p^{SLT,NN} &= \kappa_b \beta \varepsilon_b^{SLT} \varepsilon_b^{NN} p_b + \kappa_{udsgc} \alpha \varepsilon_{udsgc}^{SLT} \varepsilon_{udsgc}^{NN} p_{udsgc}
\end{aligned}
$$

- Correlation coefficients, measured in MC:

α - Ratio of the *udsc*-tagging efficiencies in the two samples.

β - Ratio of the *b*-tagging efficiencies in the two samples.

κ_b - Correlations between the NN tagger and the SLT tagger on *b*-jets.

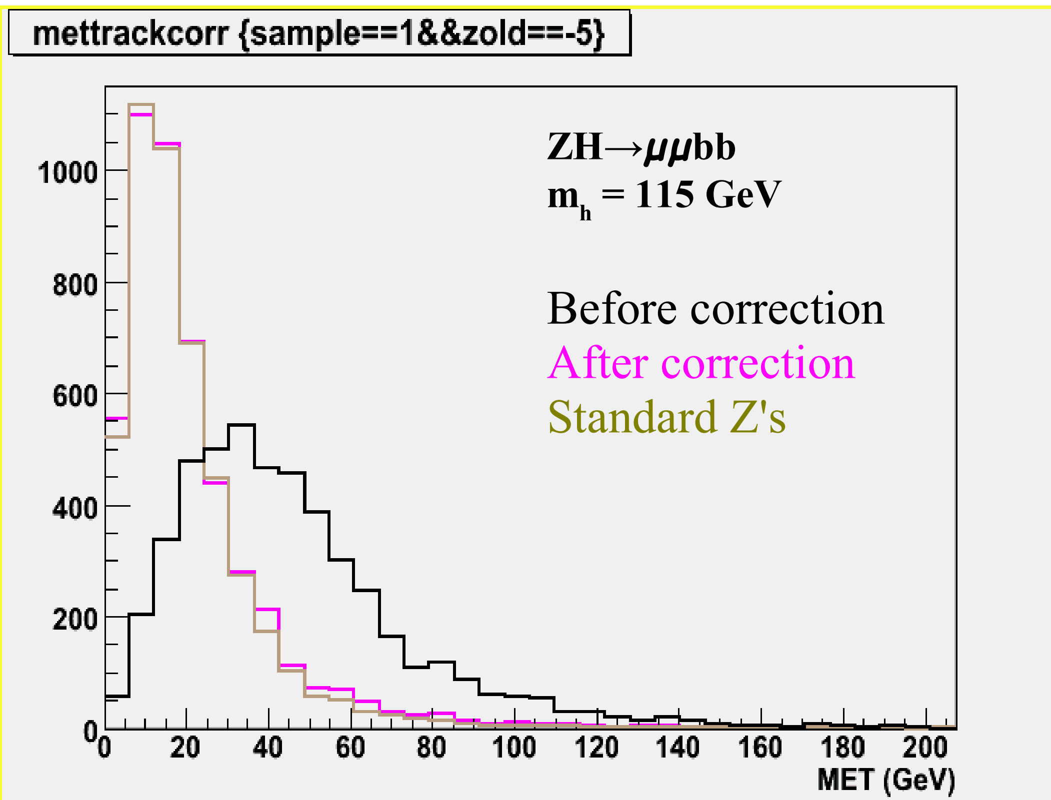
κ_{udsc} - Correlations between the NN tagger and the SLT tagger on *udsc*-jets.

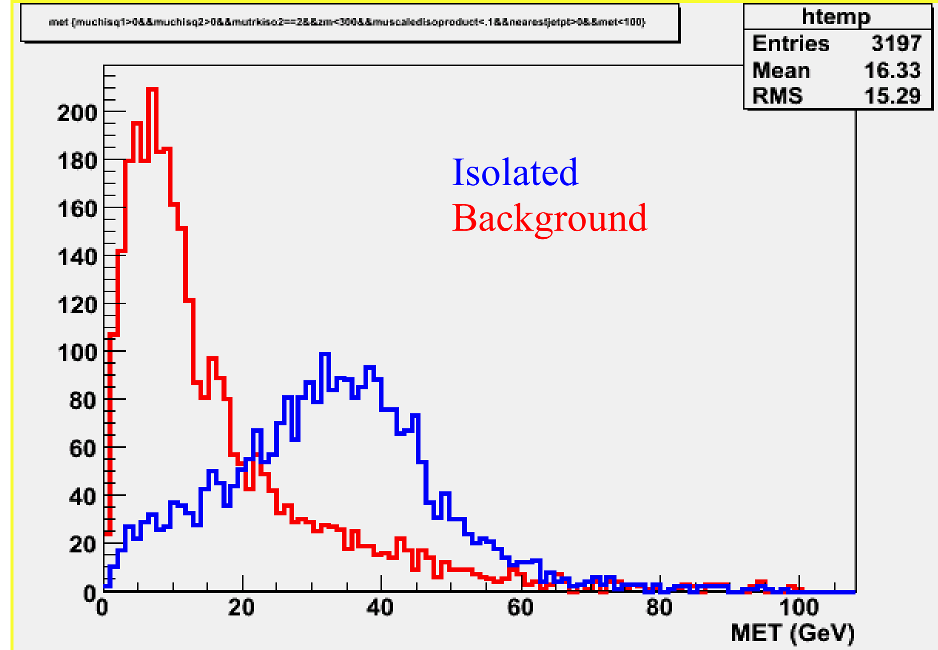
$p_{T\,Rel}$ - Ratio of the SLT tagging efficiencies on *c* and *uds*-jets.

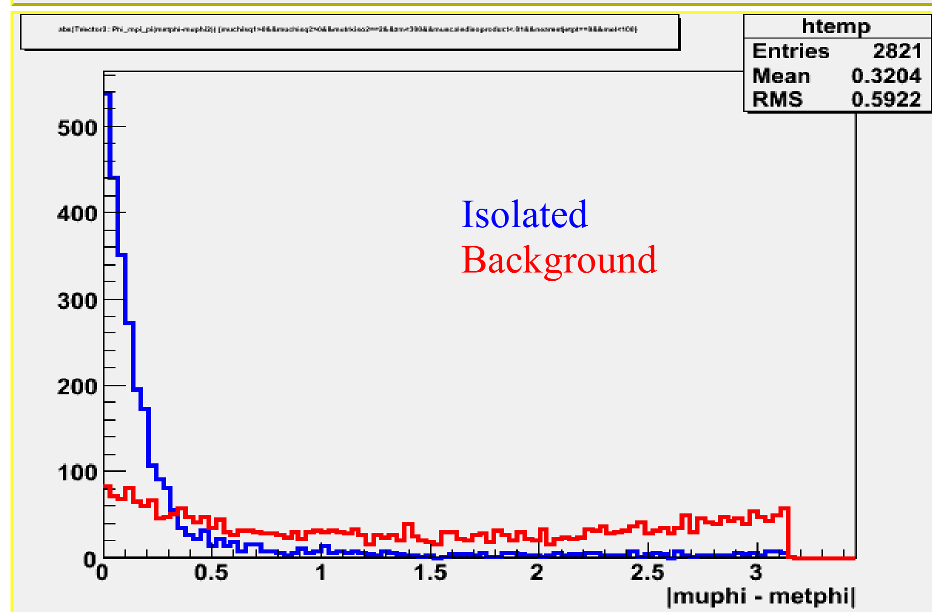
Lepton Efficiency

MET from non-reconstructed muon is present

And points in the direction of the isolated track





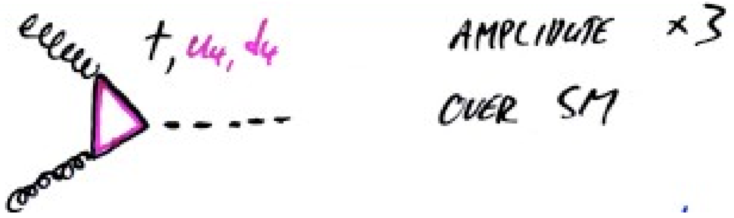


4^{th} Generation

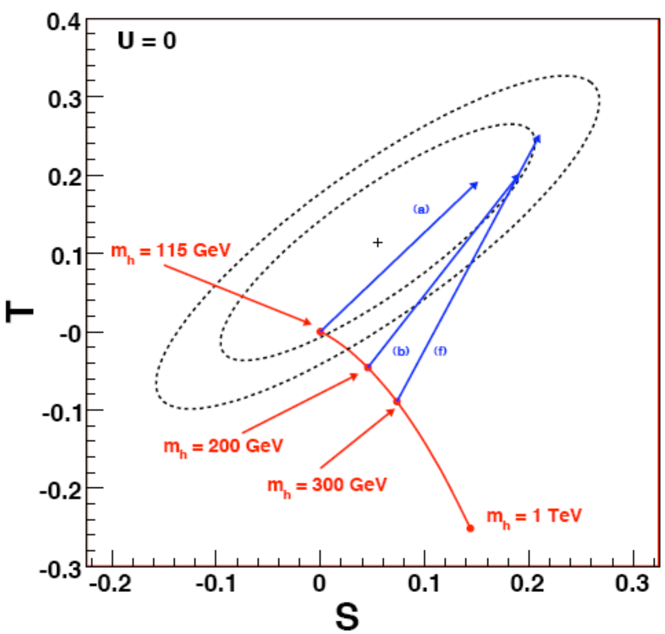
9x more gg->H production!

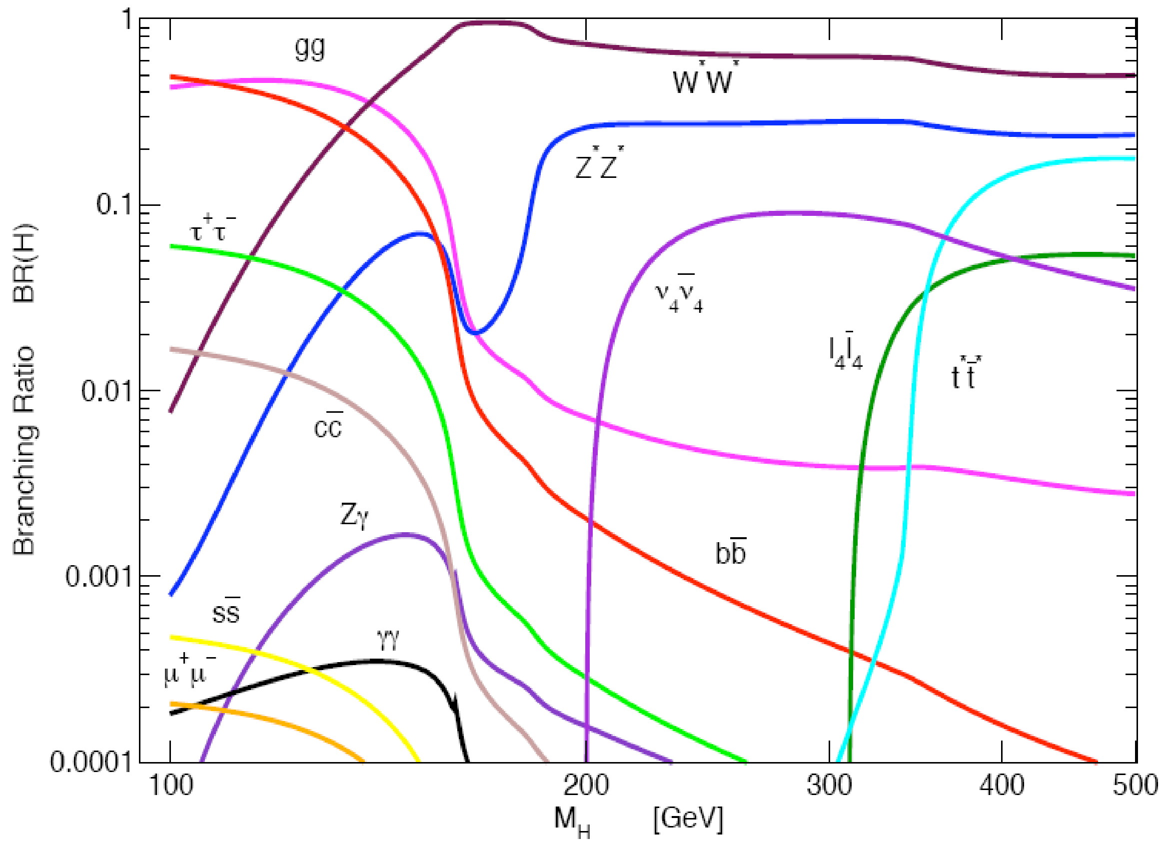
Reduced H->bb,tautau

Enhanced H->gg



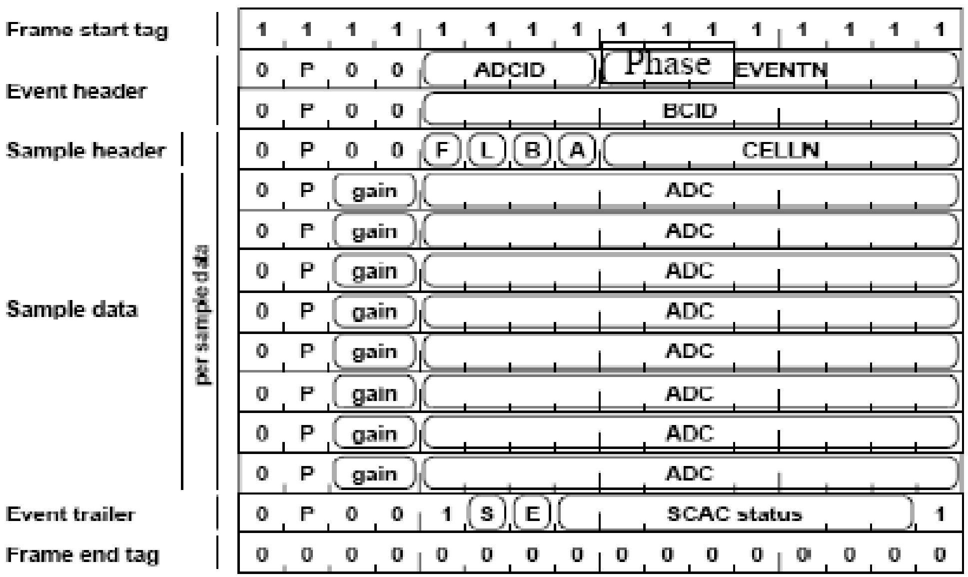
Relieves m_H EW tension





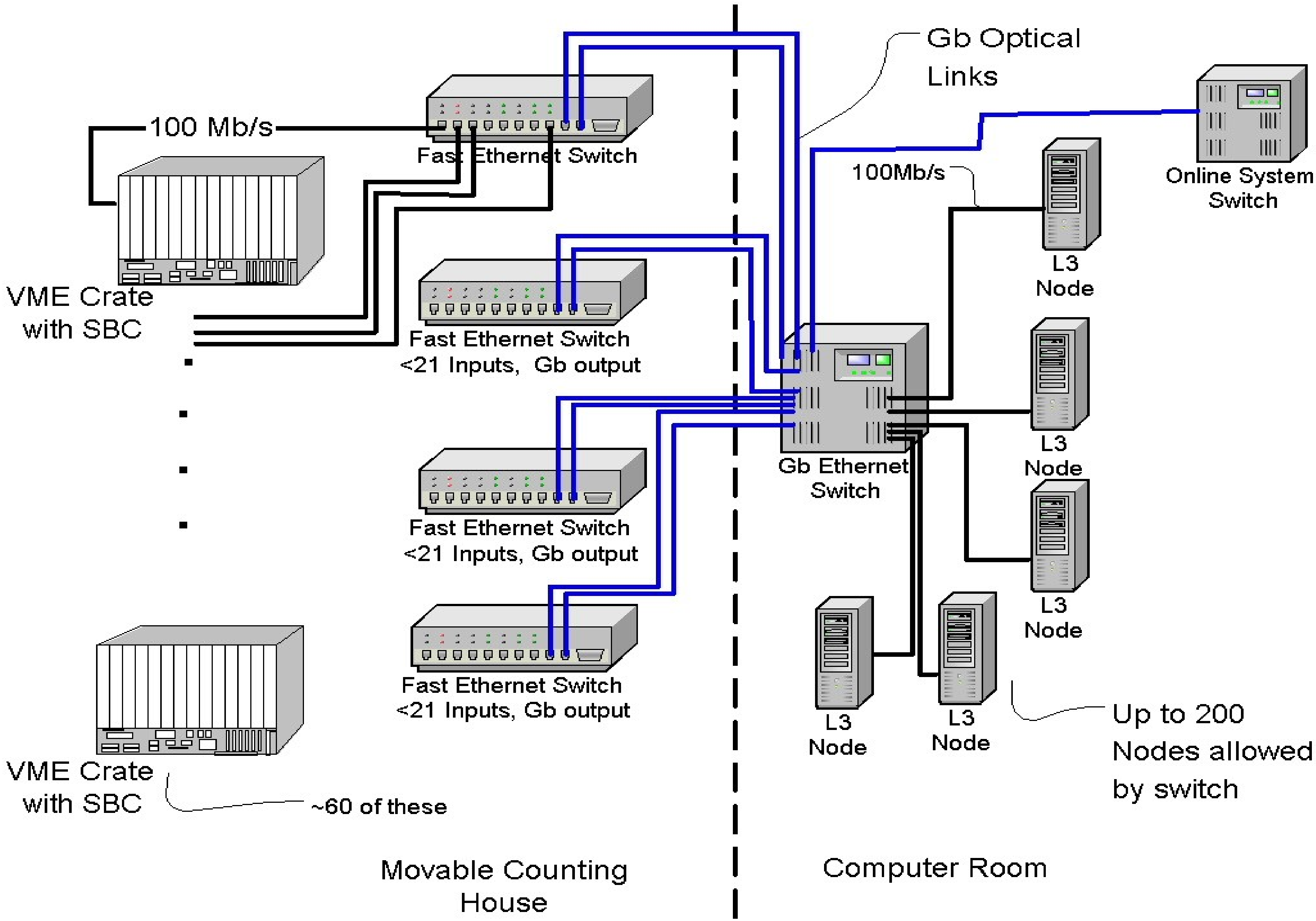
FEB Header Monitor (FEBMon)

- **In the data sent from each FEB is information on data quality**
  - transmission errors (parity)
  - radiation-induced logic errors (SEU)
  - synchronization between FEBs (same event)
  - synchronization of GSELs within a FEB
  - various other checks that each FEB is behaving as expected
- This information is unpacked by the ByteStreamConverter and available in Athena (after some more interpretation / bitshifting)
- Was run during the full expert-week
  - Found some unexpected behavior (explained on next slide)
- Also run in real-online mode!
  - Tested by Haleh, and Henric



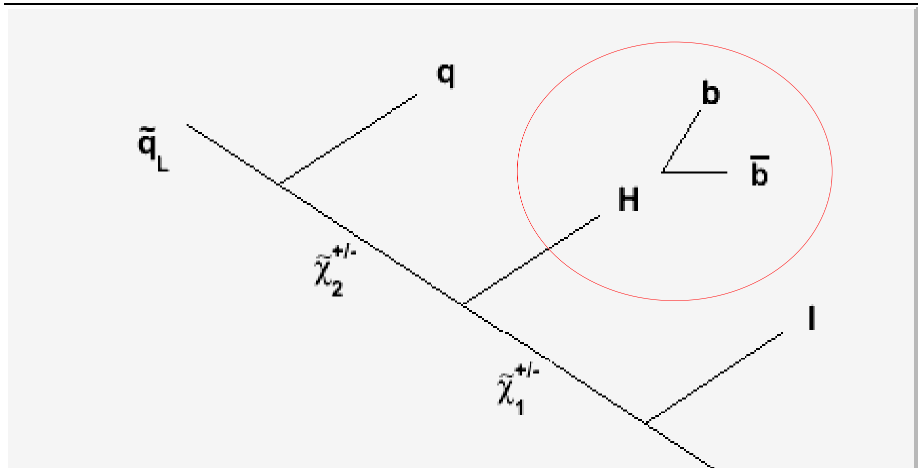

```
// ROD-Header, always present (is part of the FEB-Header)
uint32_t FormatVersion;
uint32_t SourceId;
uint32_t RunNumber;
uint32_t ELVL1Id;
uint32_t BCId;
uint32_t LVL1TigType;
uint32_t DetEventType;

// DSP-Header (most of it is actually in the DSP-Trailer)
uint32_t CodeVersion; // DSP code version
uint32_t EventCounter; // DSP event counter
std::vector<uint16_t> m_SCA; // SCA number for each samples
uint32_t m_ELVL1Id; // FEB EventId
uint32_t m_BCId // FEB BCId
uint32_t ctlr1, ctlr2, ctlr3; // RodStatus / SCAC / etc.;
```

DAQ System


Gb Optical
Links
100 Mb/s
Fast Ethernet Switch
Online System
Switch
100Mb/s
L3
Node
VME Crate
with SBC
Fast Ethernet Switch
<21 Inputs, Gb output
Gb Ethernet
Switch
L3
Node
Fast Ethernet Switch
<21 Inputs, Gb output
L3
Node
Fast Ethernet Switch
<21 Inputs, Gb output
L3
Node
L3
Node
Up to 200
Nodes allowed
by switch
VME Crate
with SBC
~60 of these
Movable Counting
House
Computer Room

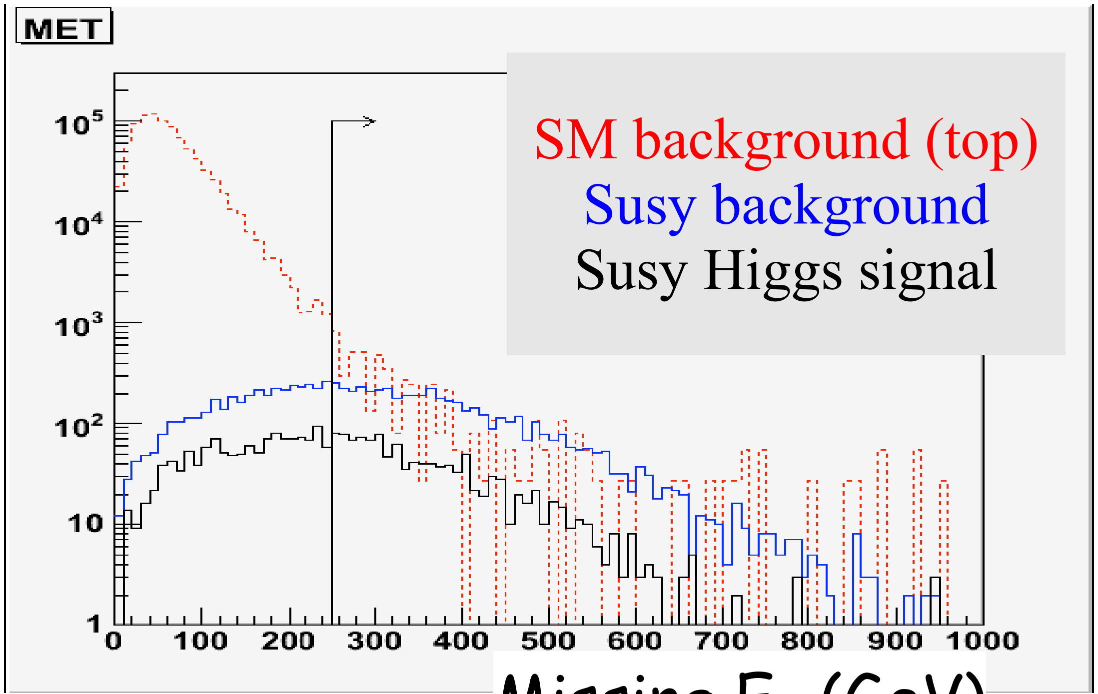
The Higgs in Supersymmetry Decays

Look for Higgs bosons in the *decays* of supersymmetric particles



BR X_2->X_1H = 19%

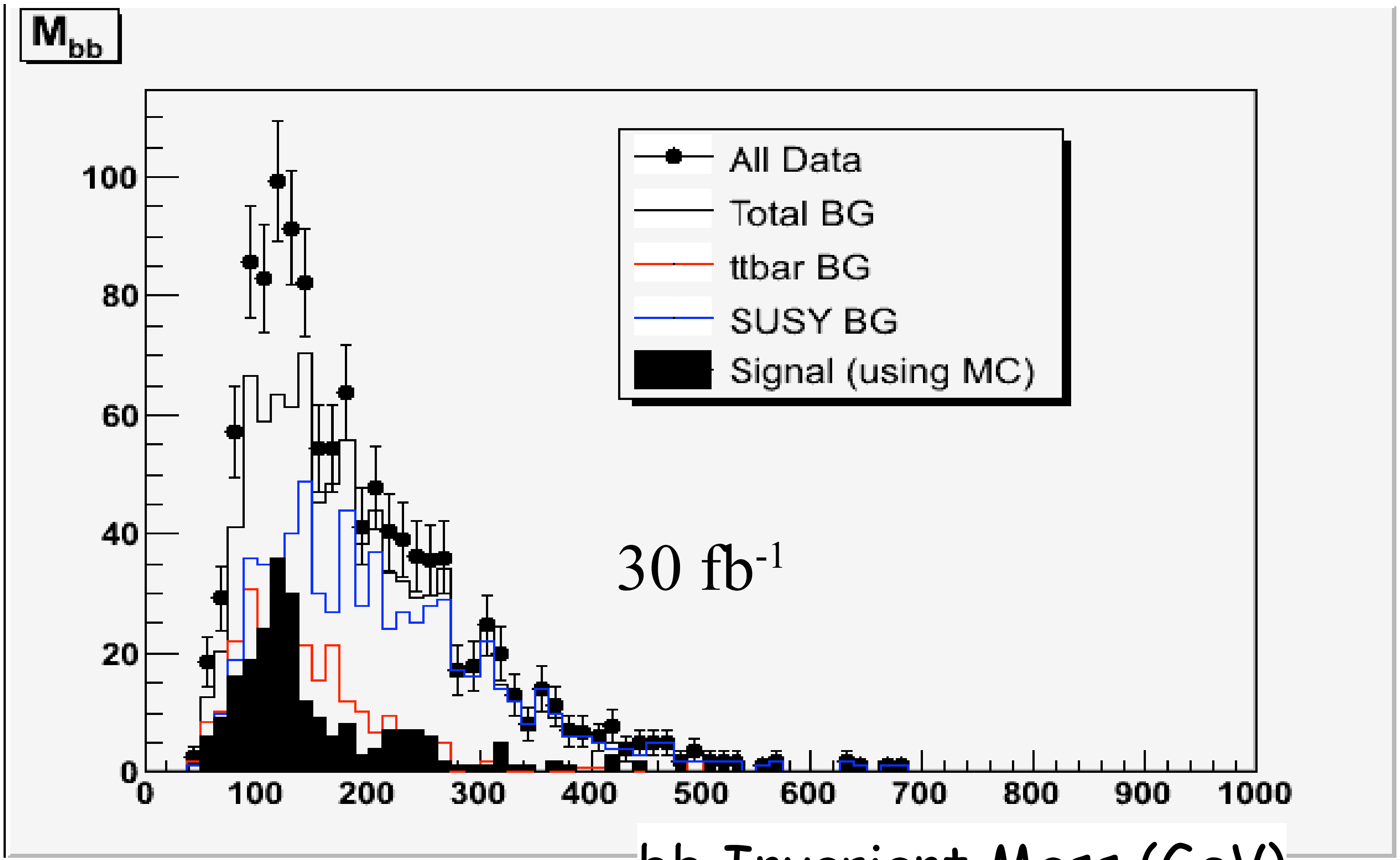
Require MET>250 GeV to reduce SM background



Missing E_T (GeV)

The Higgs in Supersymmetry Decays

Look for bump from H->bb decays



bb Invariant Mass (GeV)