The Search for the SM Higgs Boson at DØ

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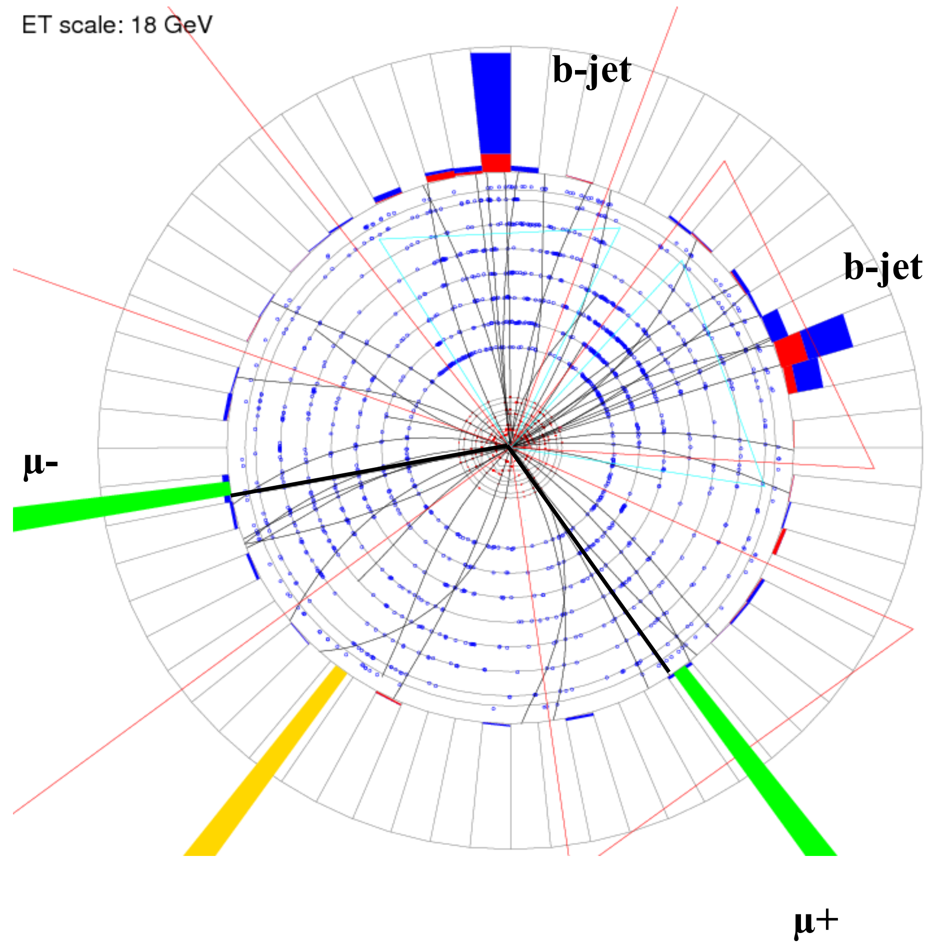
DØ / ATLAS

SLAC
Particle Physics Seminar
January 24, 2008



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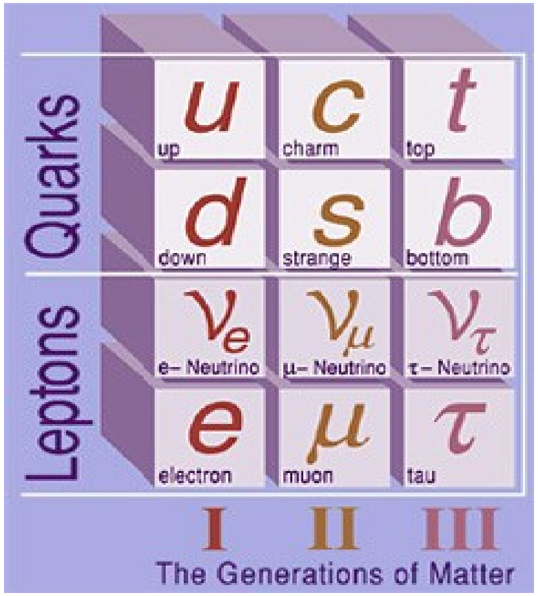
The Standard Model

3 families of matter

3 forces

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



Massive W,Z gauge bosons

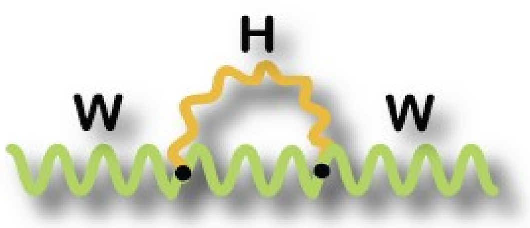
Scalar Higgs field, non-zero VEV

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

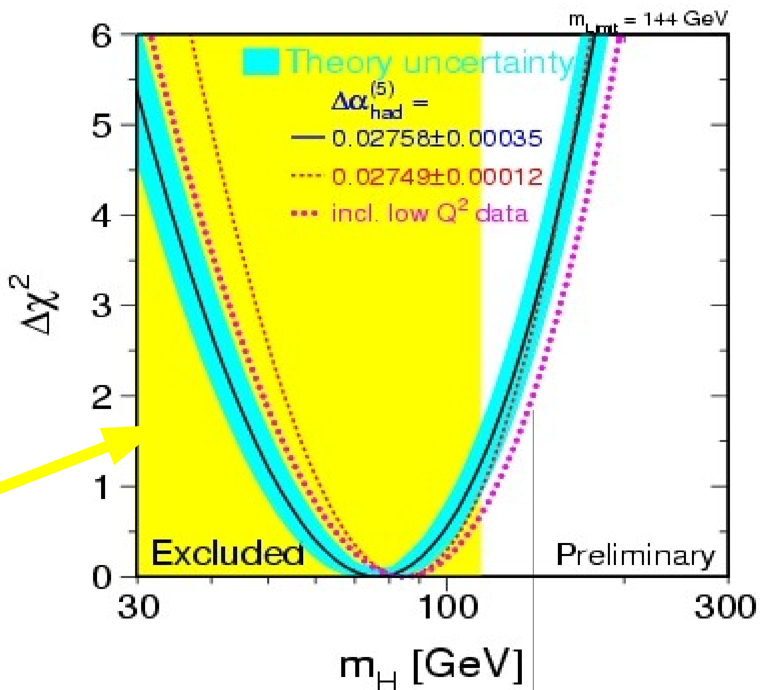
Higgs boson: excitation of the Higgs field - m_H

Higgs Mass Constraints

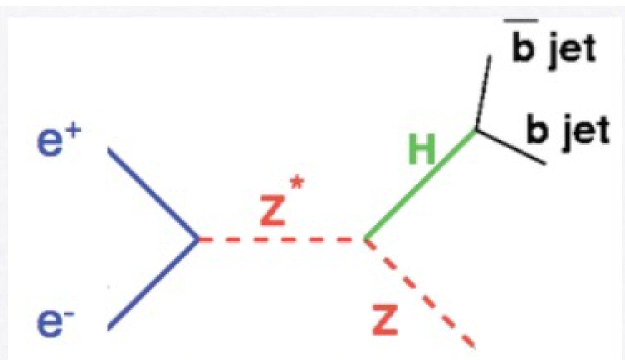
EW variables sensitive to m_H via radiative corrections:



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



LEP II direct: m_H>114.4 GeV

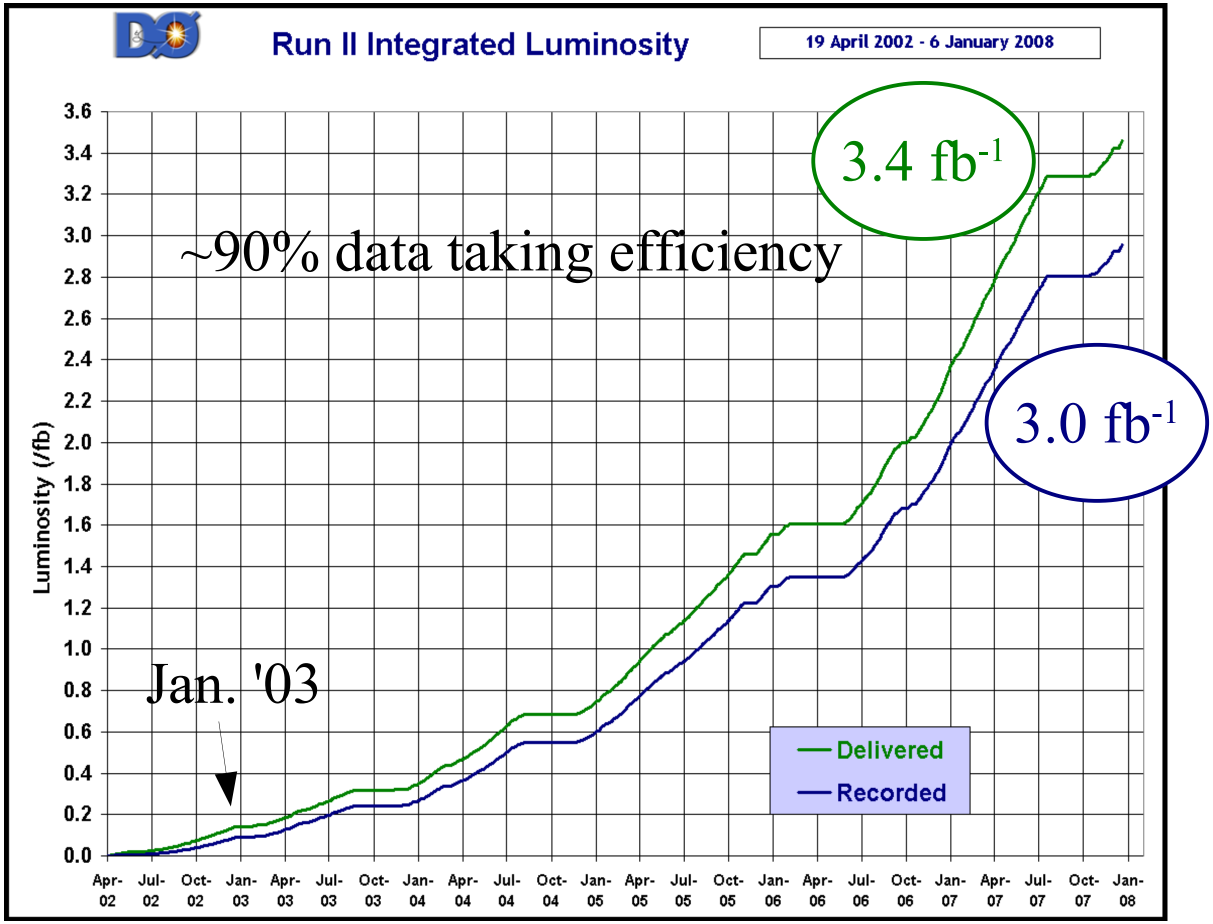


m_H<144 GeV (at 95% CL)

m_H<182 GeV (including direct limit)

The Tevatron at Fermilab

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



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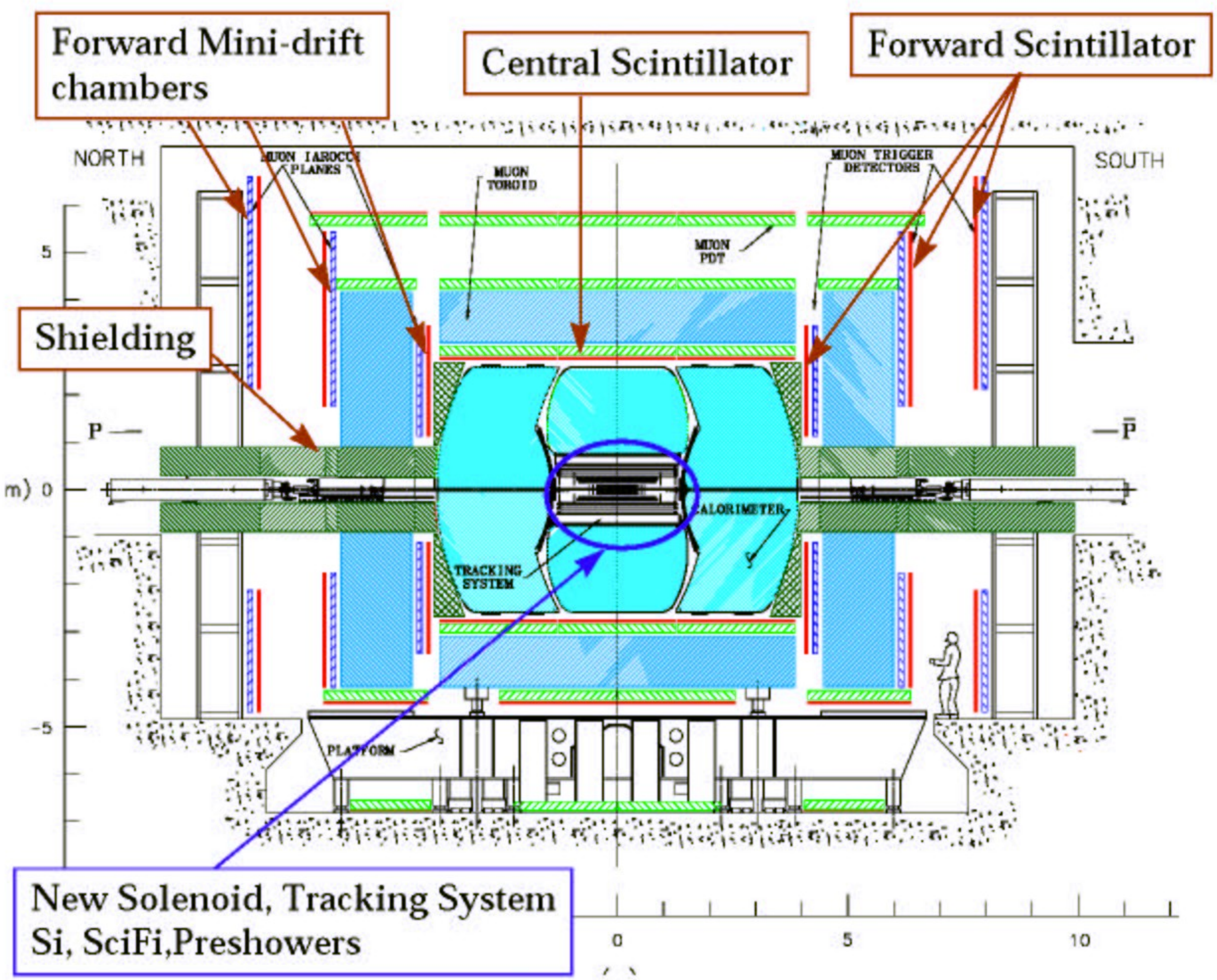
The DØ Detector



1000 Hz → Level 3 Trigger Farm → 100 Hz

<u>Retained from Run I</u>

LAr calorimeter
Central muon detector
Muon toroid

<u>New for Run II</u>

Magnetic tracker
- 2 T solenoid
- Silicon vertex tracker
- Scintillating fiber tracker

b-jet tagging

Preshower detectors
Forward muon detector
Front-end electronics
Trigger and DAQ

The DØ Collaboration

600 physicists from 18 nations

100 postdocs and 140 students

2005-2007
~20 people
~10 students

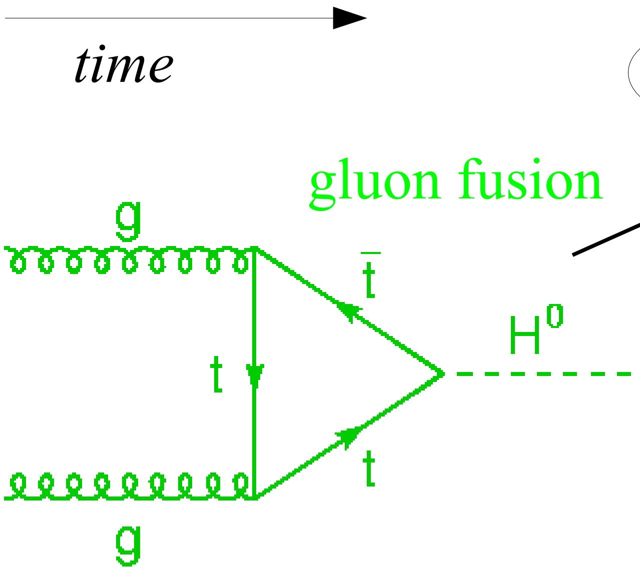
Track/Vertex **b-Tagging**
Muon Calorimetry

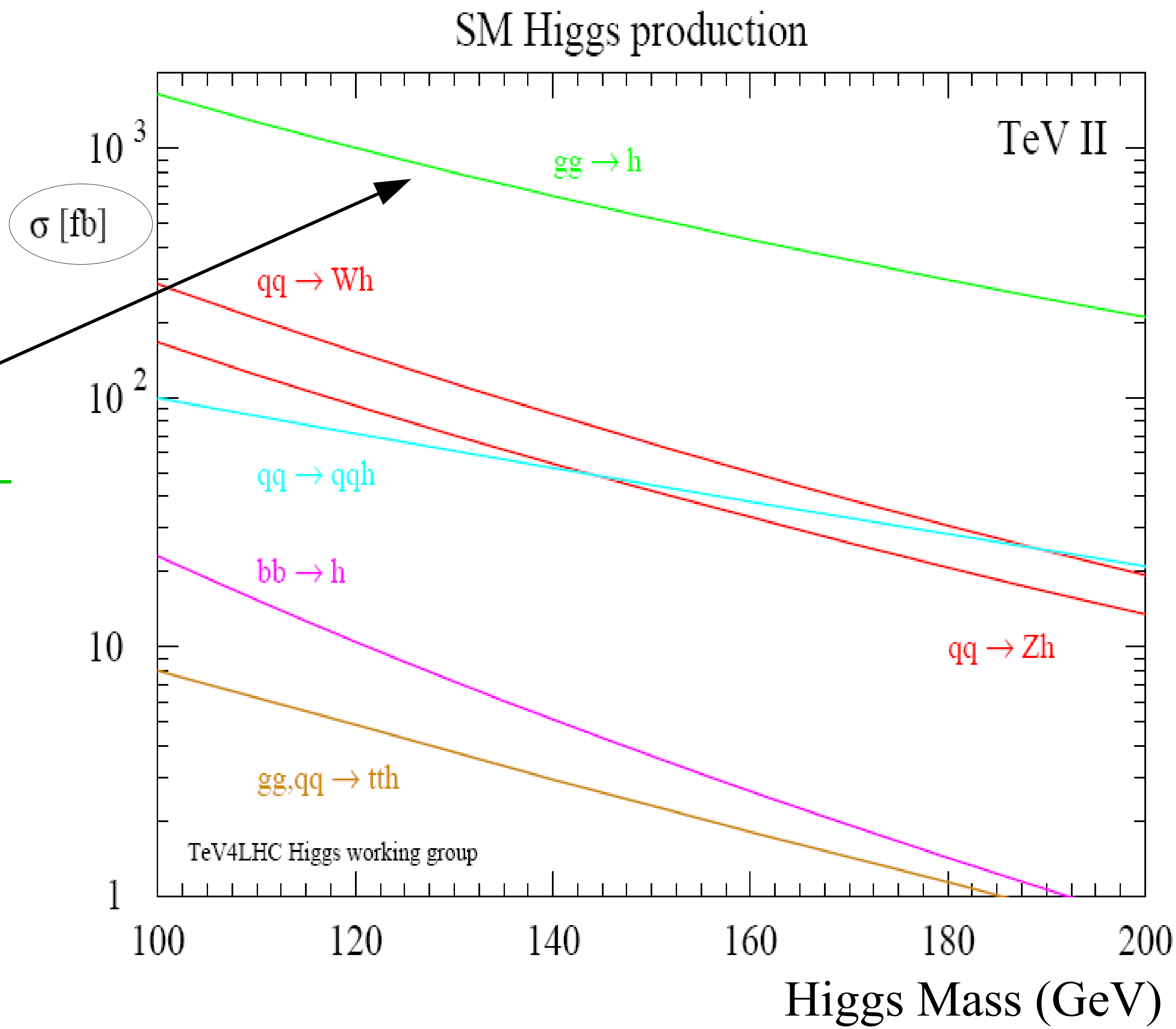
2007-
~200 people
~70 students

b-Physics Top **Higgs**
New Phenomena W/Z QCD

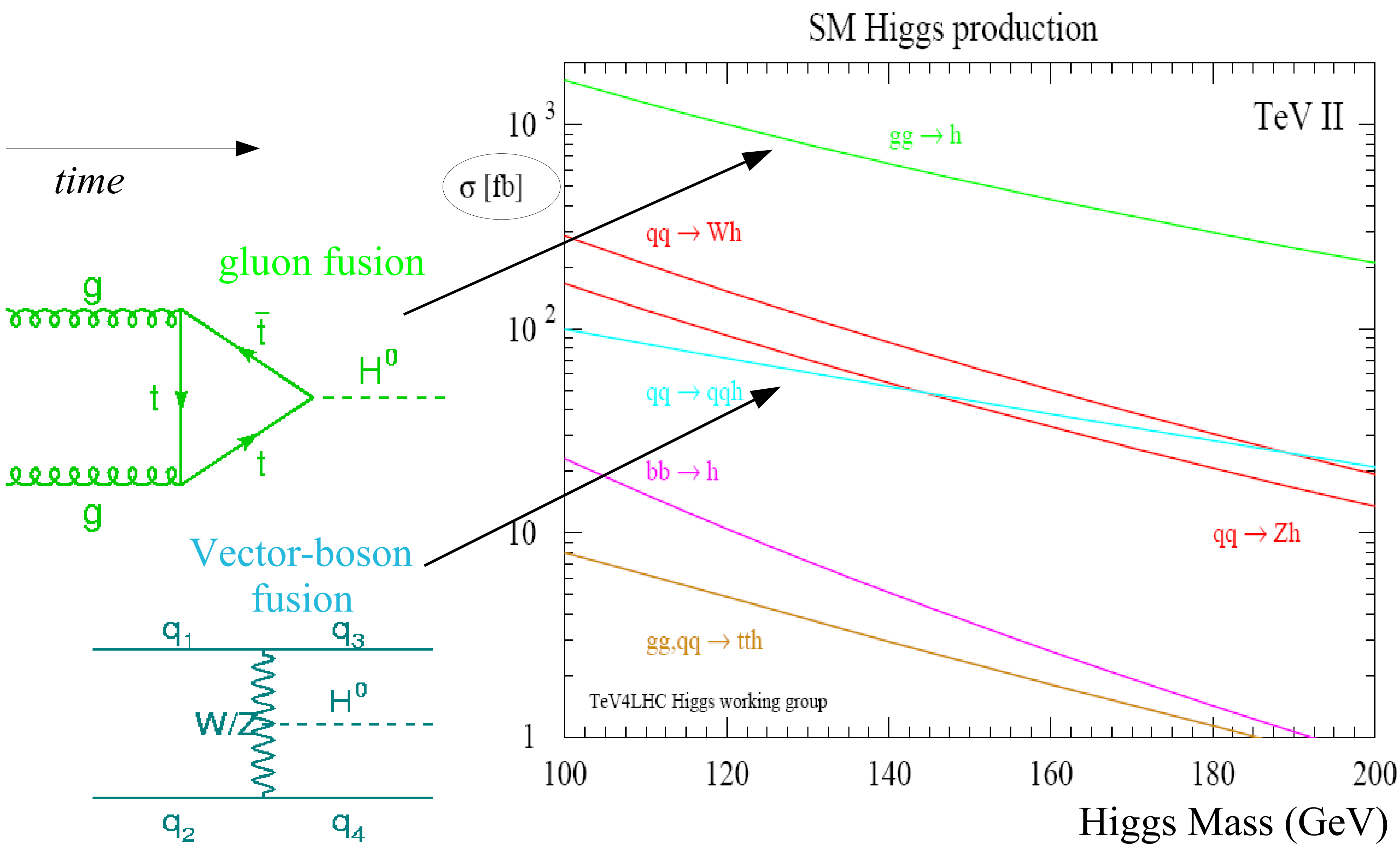
Finding the Higgs is now the main goal for DØ

Higgs Production at the Tevatron





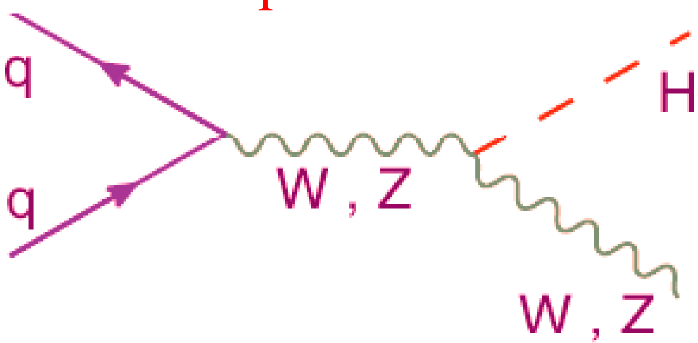
Higgs Production at the Tevatron

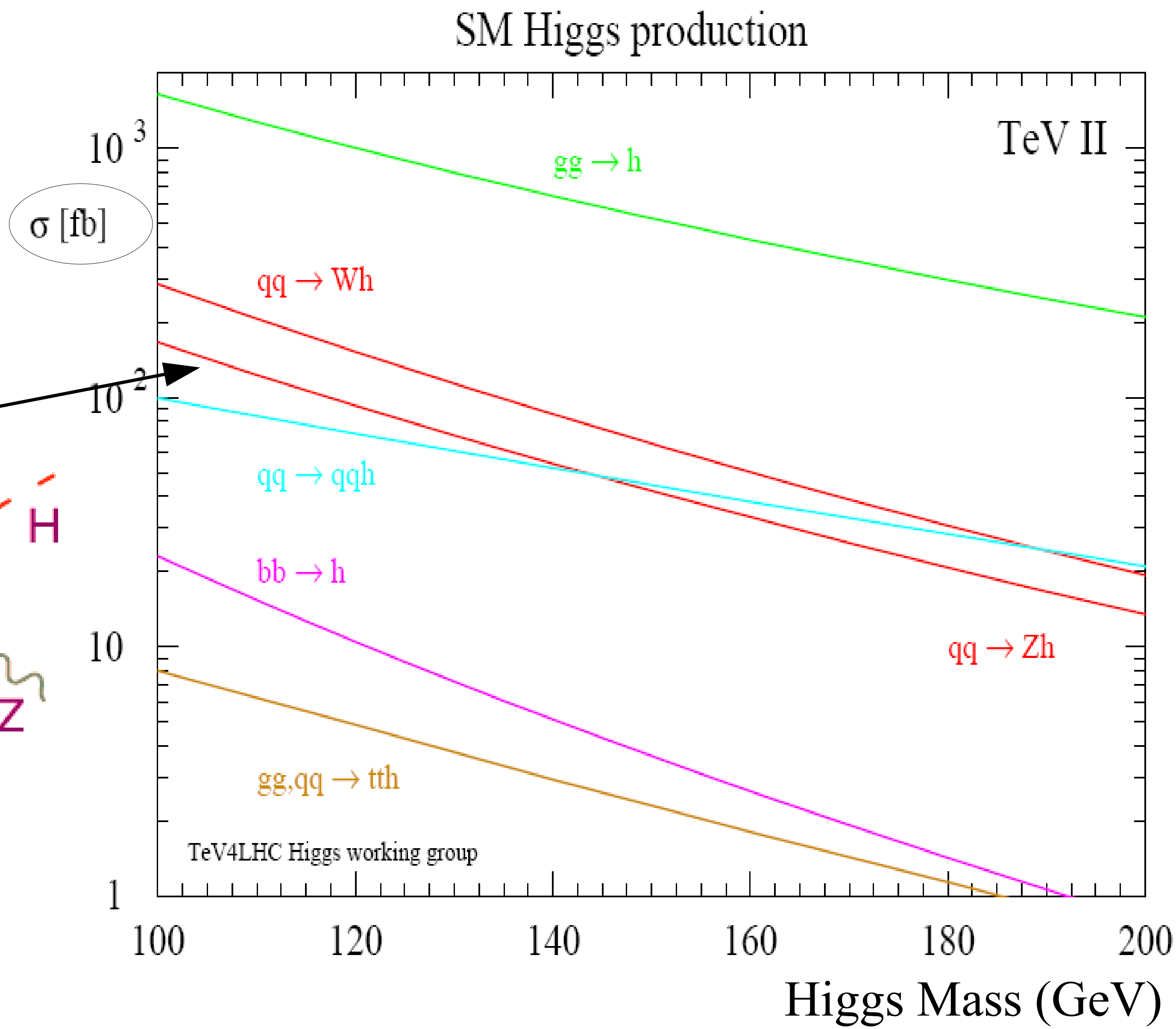


Higgs Production at the Tevatron

time

Associated production

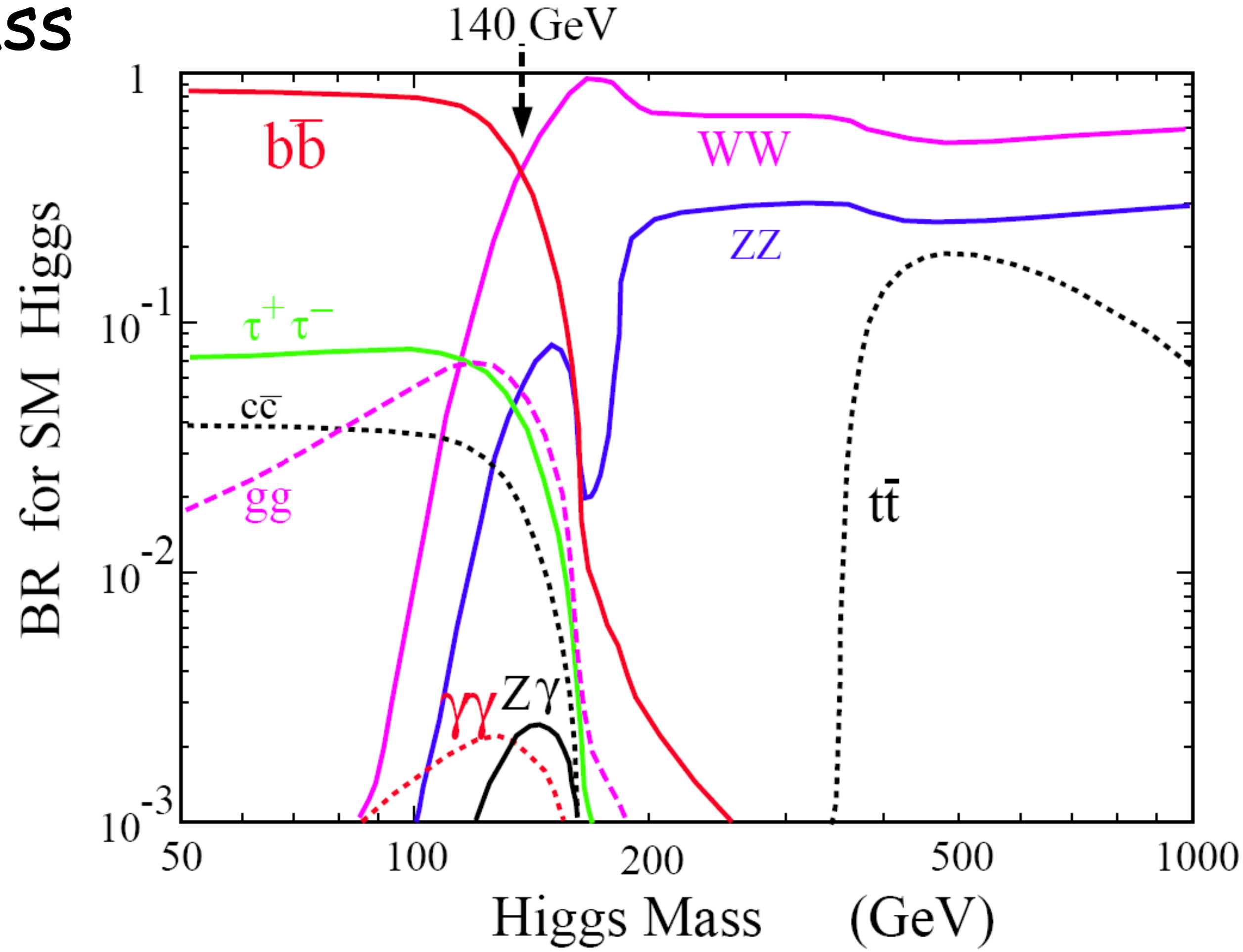




Higgs Decays

Coupling ∝ fermion mass

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



Main channels:

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

Need good b-jet tagging!

Main Higgs Analyses

	$H\to bb$ (low mass)	$H\to WW$ (high mass)
$p\bar{p}\to H$	~~$H\to bb$~~	**$H\to WW\to$ $ee/e\mu/\mu\mu$+MET**
$p\bar{p}\to WH$	**$WH\to Wbb\to$ $e/\mu+bb$**	$W/Z+H\to W/Z+WW\to$ $l^+l^-l^+$ / l^+l^+jj + MET
$p\bar{p}\to ZH$	**$ZH\to Zbb\to$ $ee/\mu\mu+bb$ MET+bb**	

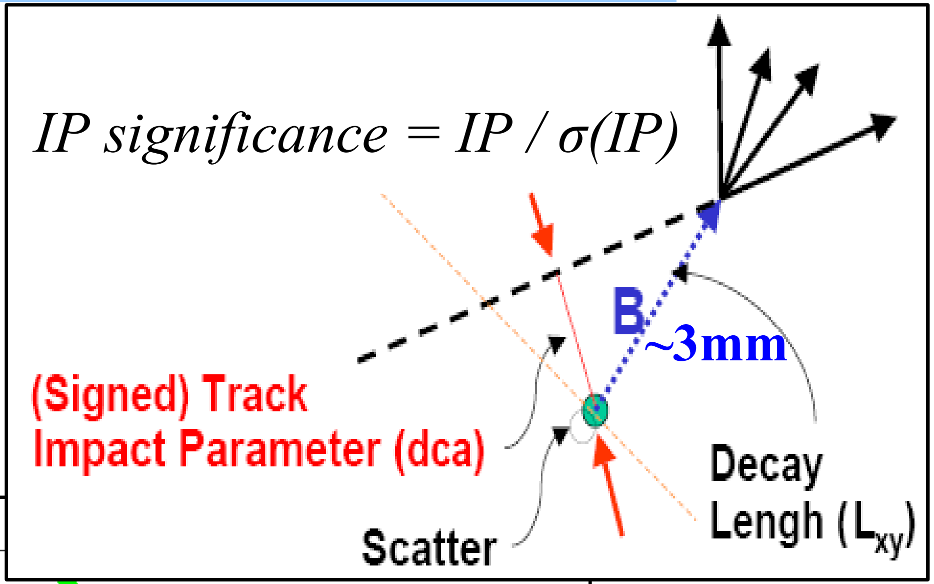
Main Higgs Analyses

	$H \rightarrow bb$ (low mass)	$H \rightarrow WW$ (high mass)
$p\bar{p} \rightarrow H$	~~$H \rightarrow bb$~~	**$H \rightarrow WW \rightarrow$ 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**	

b-Jet Tagging

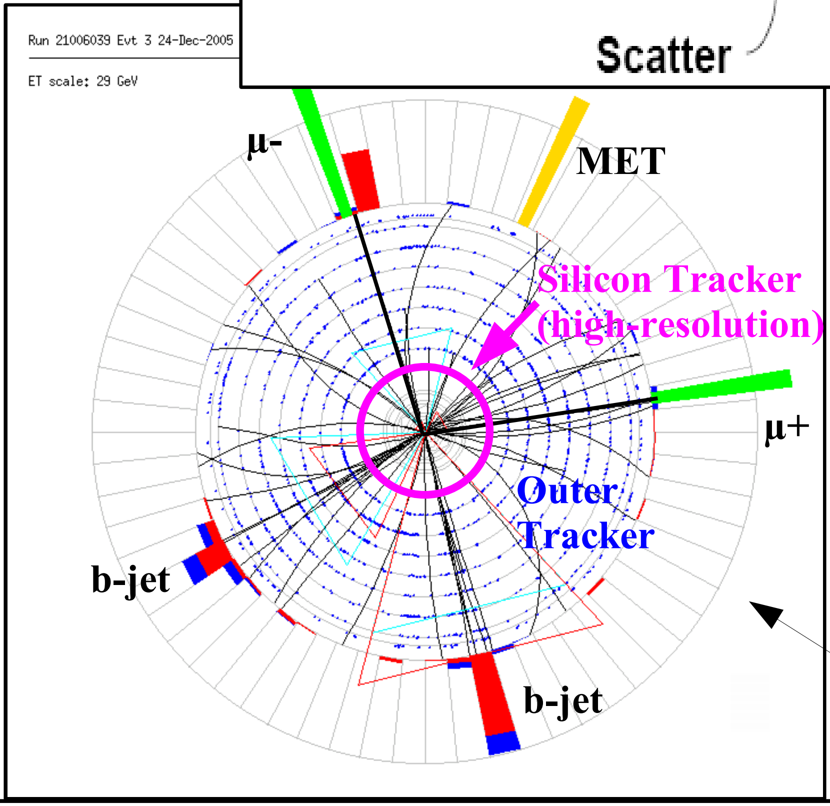
B hadrons are "long"-lived

- Reconstruct charged particles tracks
- Reconstruct "vertices" where tracks overlap

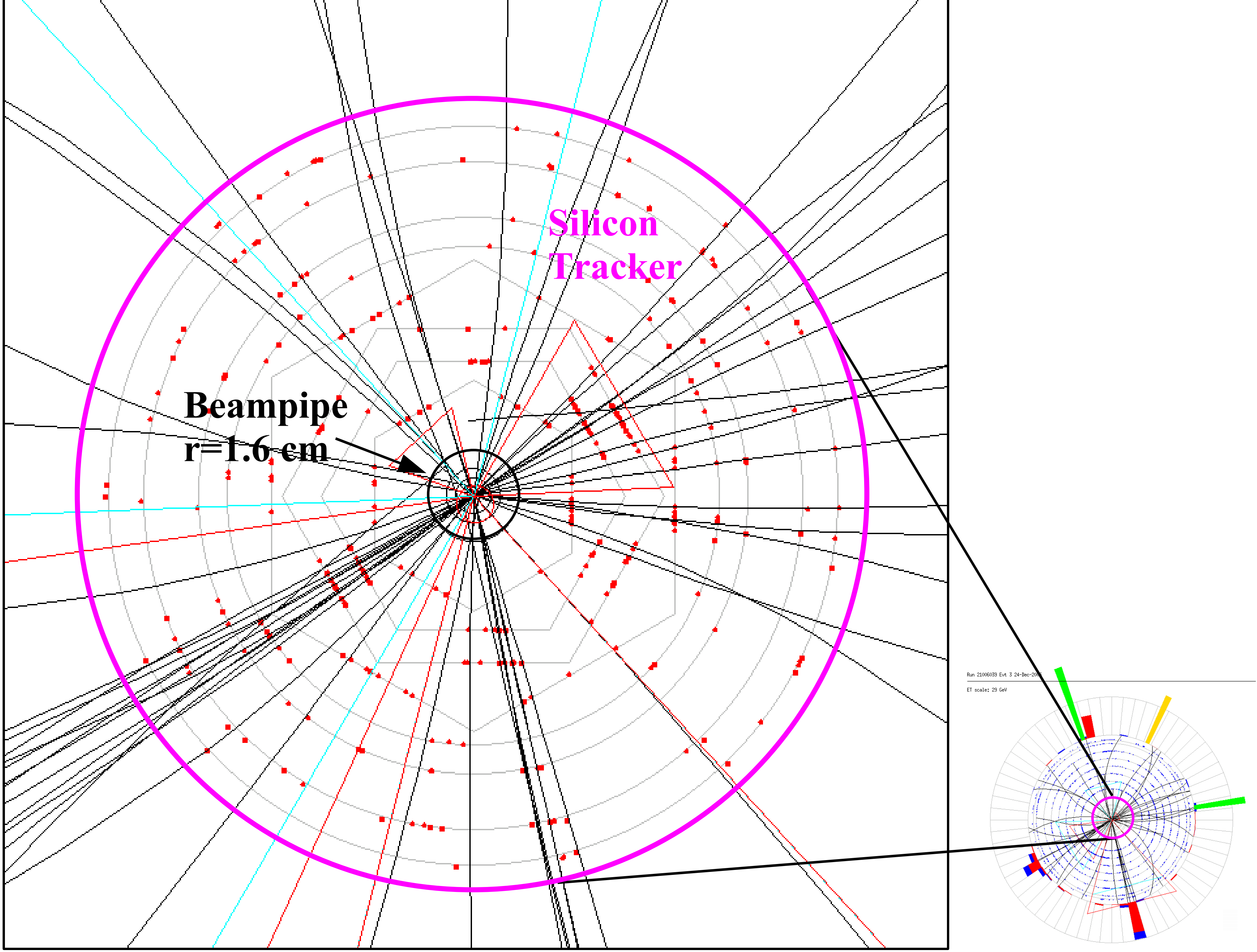


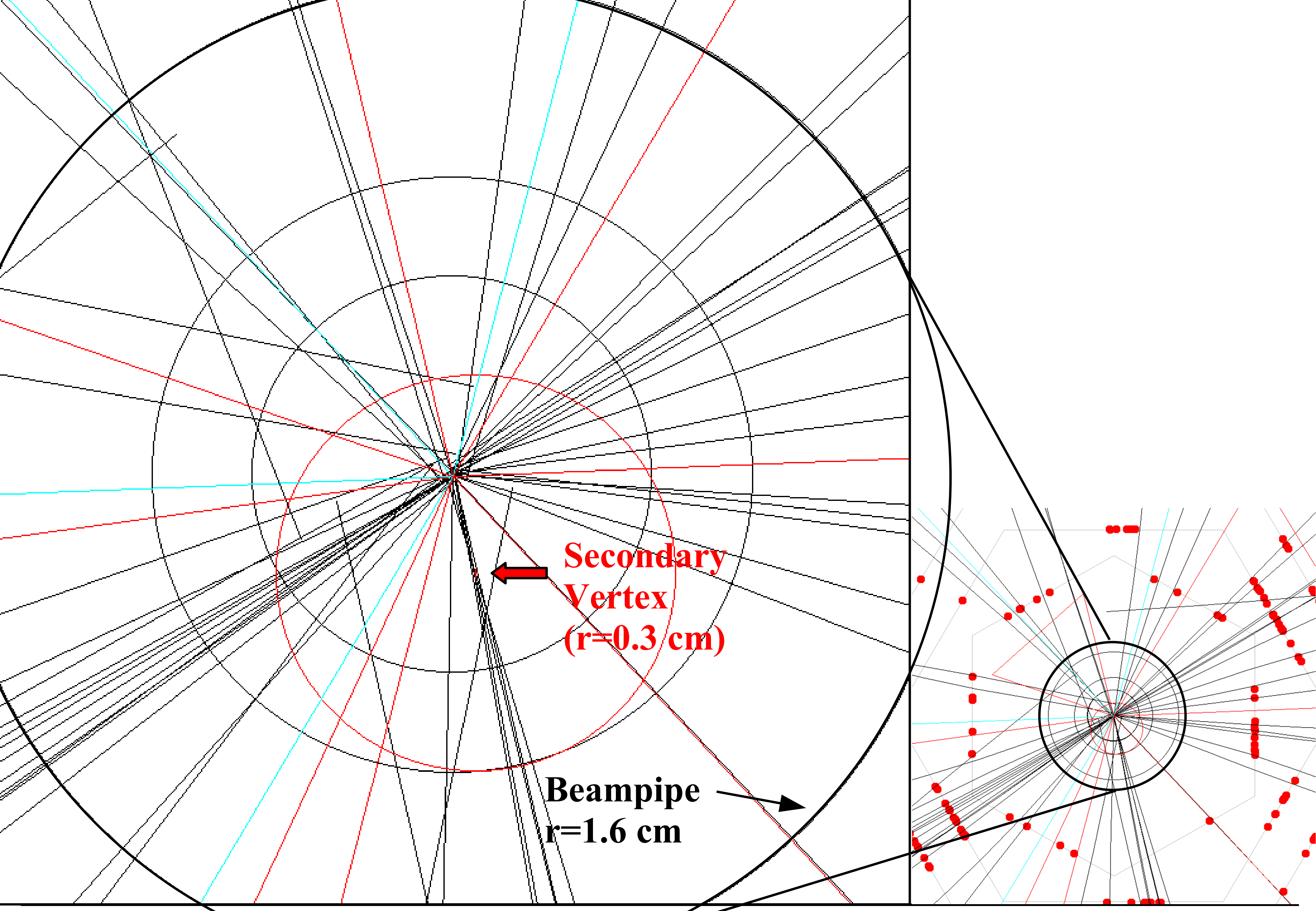
Identify jets with:

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



Simulated $ZH \rightarrow \mu\mu bb$ event

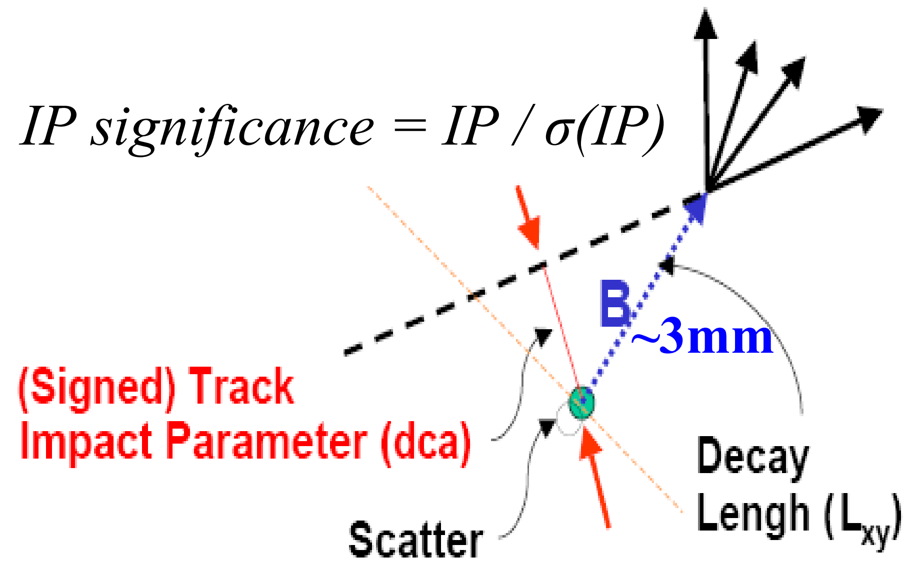

Silicon
Tracker
Beampipe
r=1.6 cm

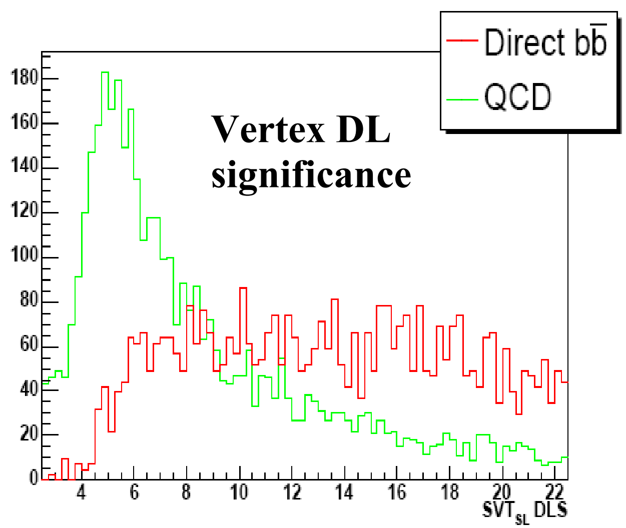

Secondary
Vertex
(r=0.3 cm)
Beampipe
r=1.6 cm

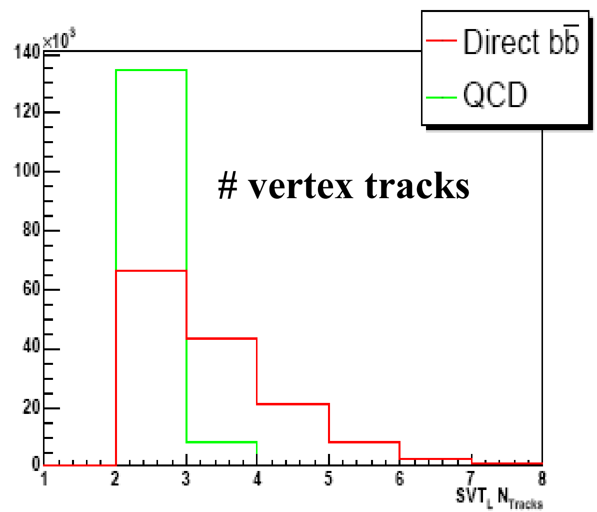
b-Jet Tagging

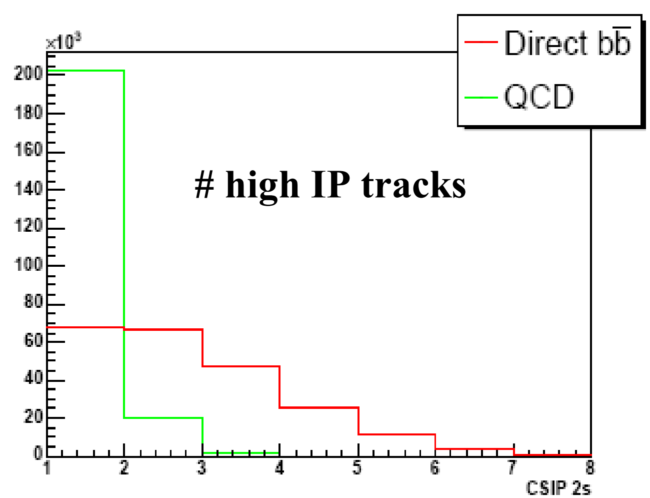
Many variables with separation power:

- Vertex: *DLS, #tracks,* #vertices, mass, chi2
- *#high IP sig. tracks,* combined light-jet prob.









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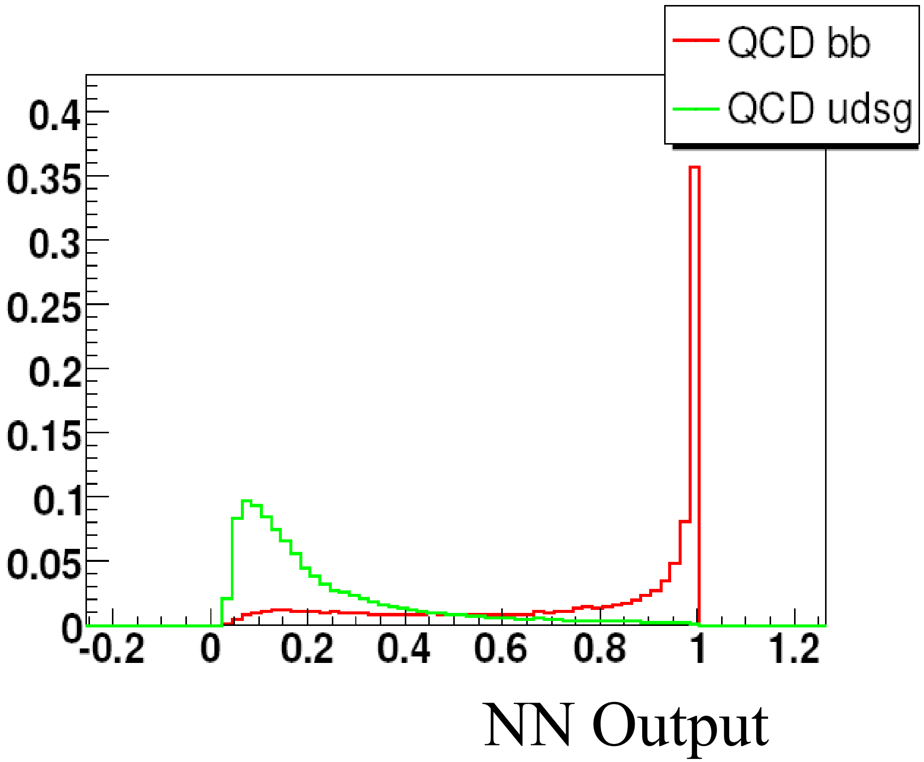
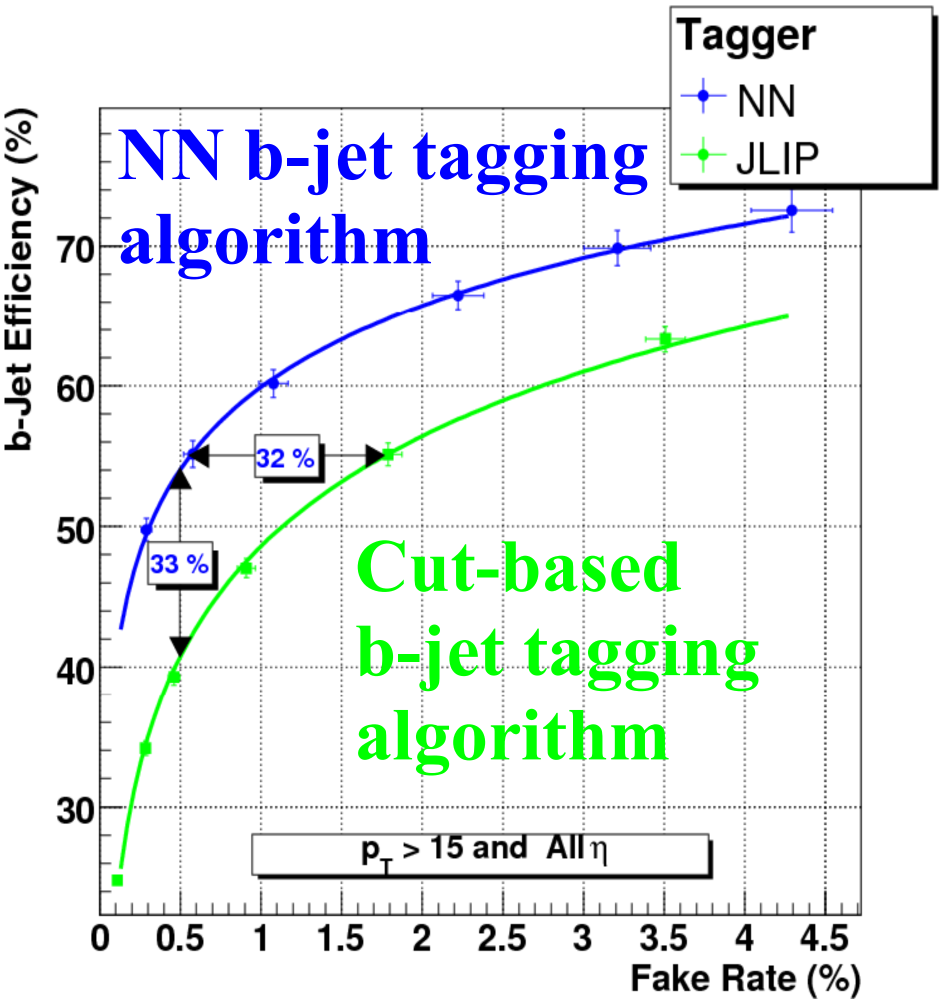
Neural Network b-Jet Tagging

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 a double-b-tag analysis!

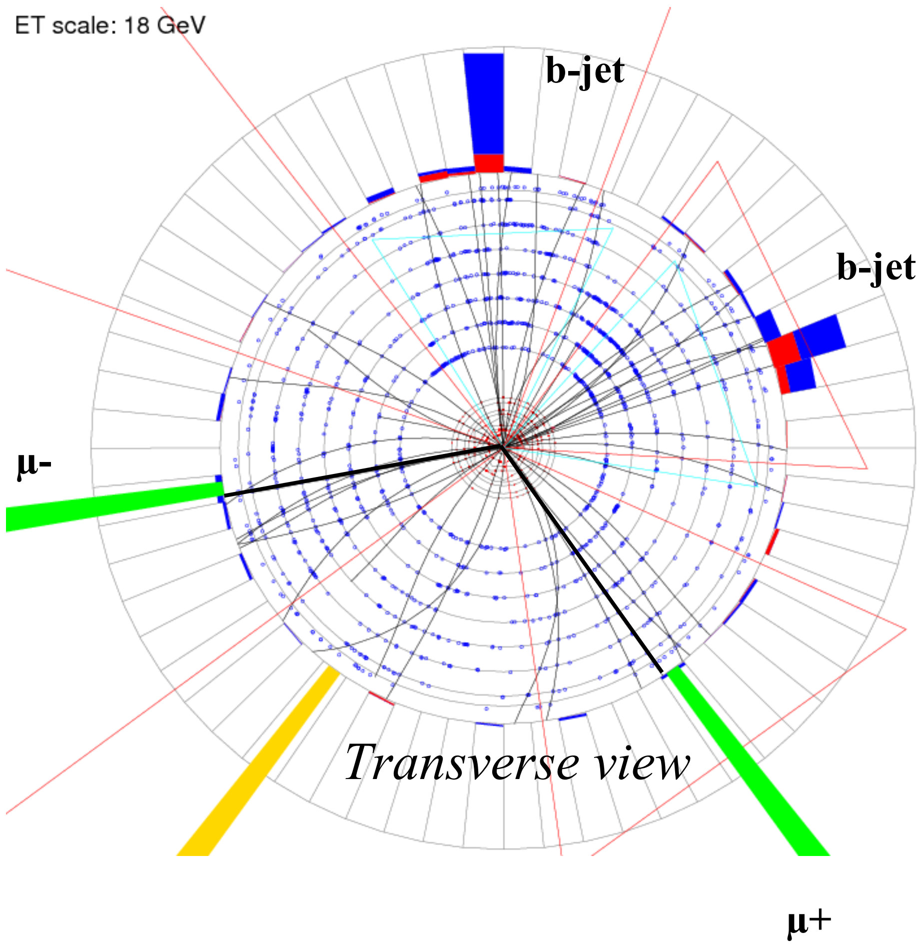
ZH -> $\mu^+ \mu^-$ b b Search

Easy to observe Z decay

- reduces backgrounds
- provides trigger

Good b-tagging is essential

Reconstruct Higgs mass from two b-jets



Z + 2 jets

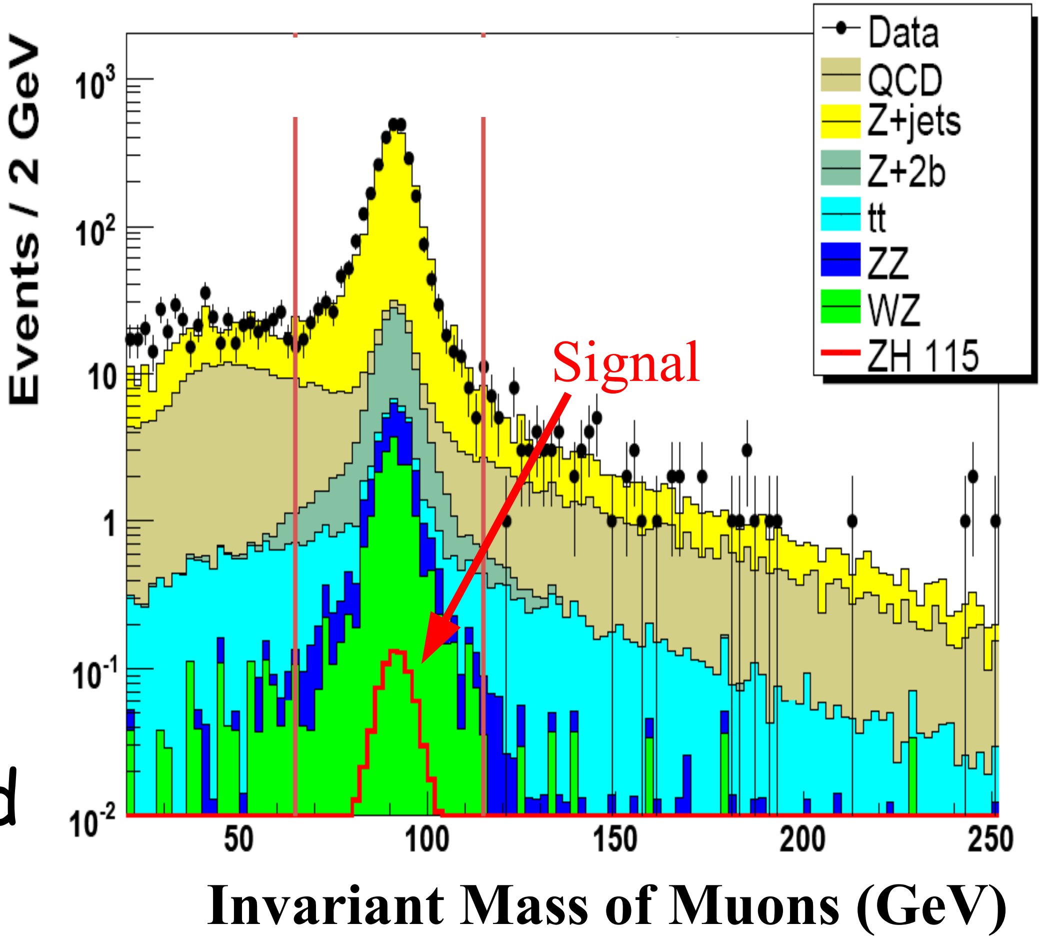
Select events:

- 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

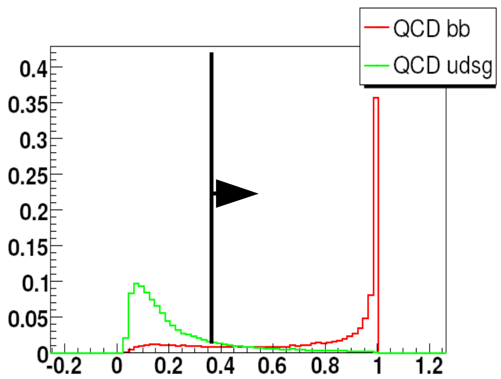
*$scalediso = (cal\ iso + trk\ iso) / p_T$

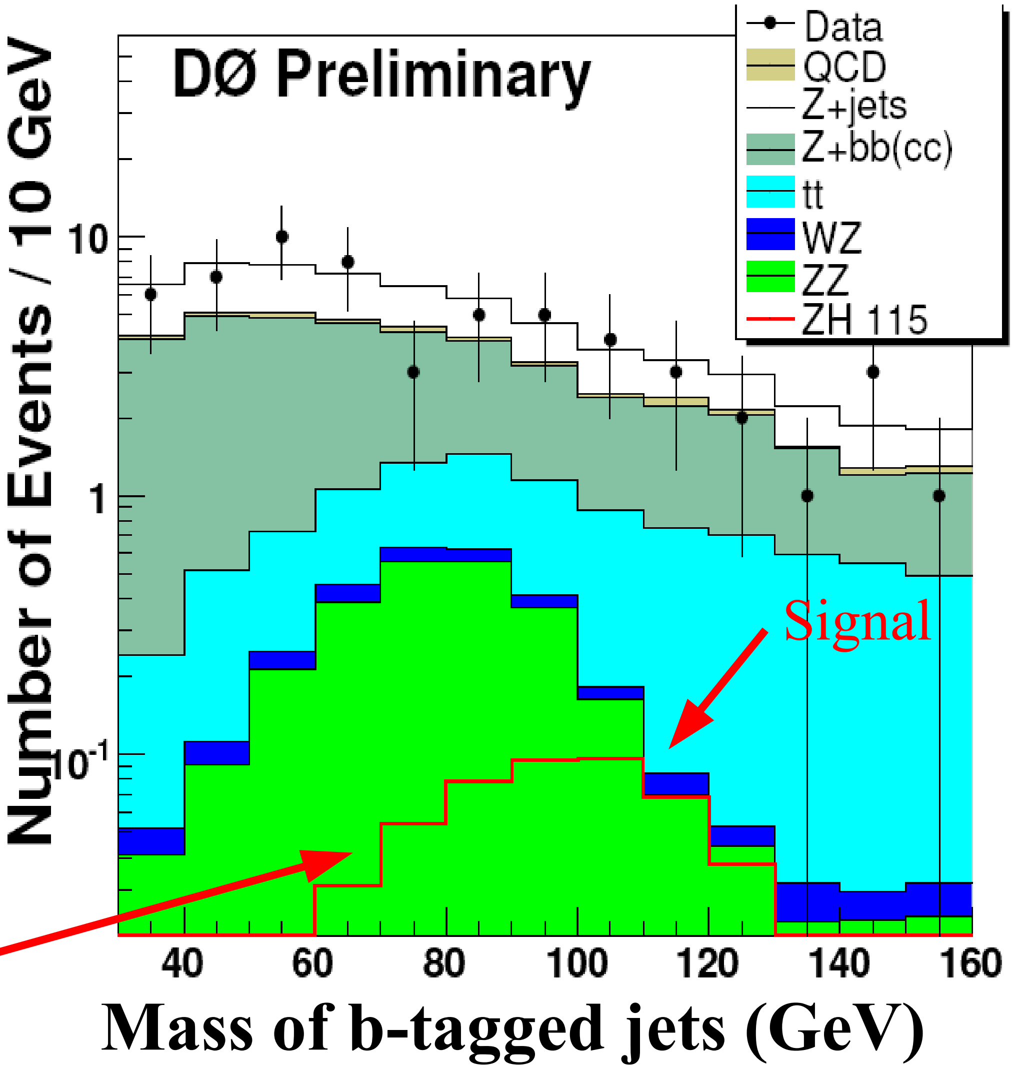
$scalediso_1 \times scalediso_2 < 0.1$

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)

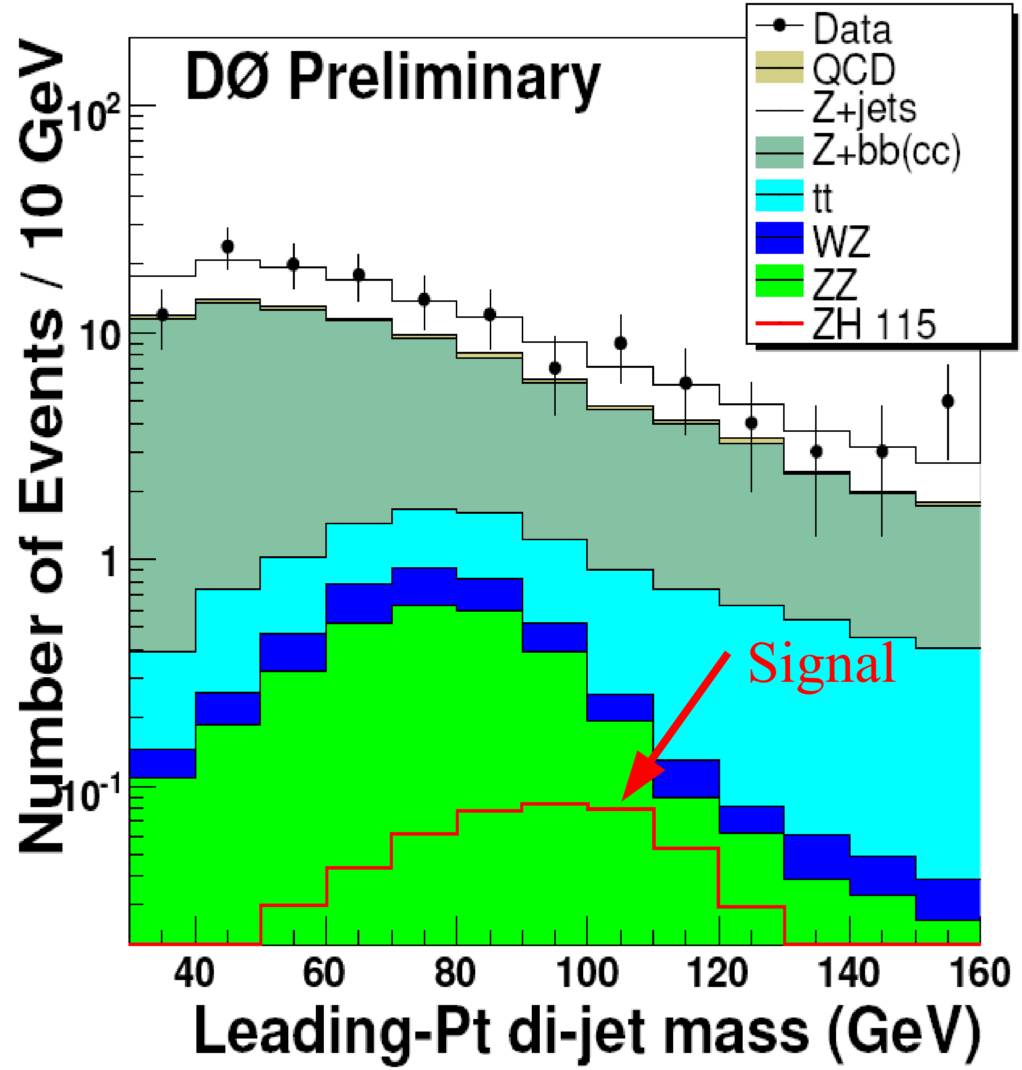
- Orthogonal event sample!

Compared to double-b-tag:

- Similar amount of signal
- Double amount of background

Like having 25% more data

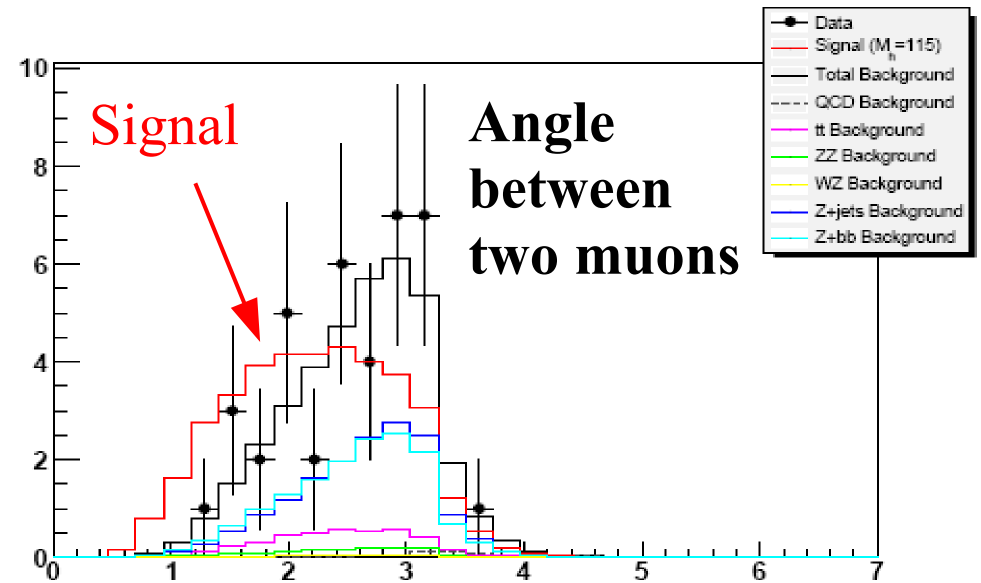
Combine during limit-setting

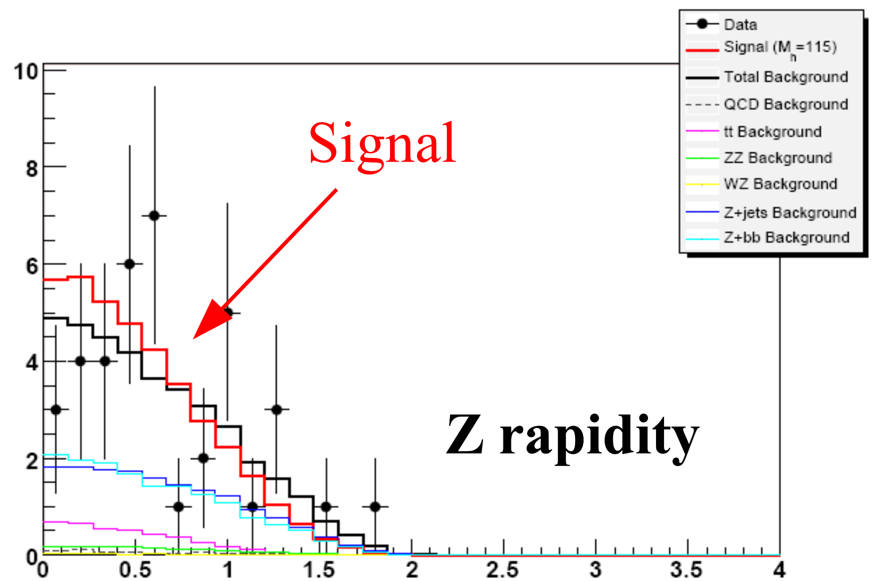


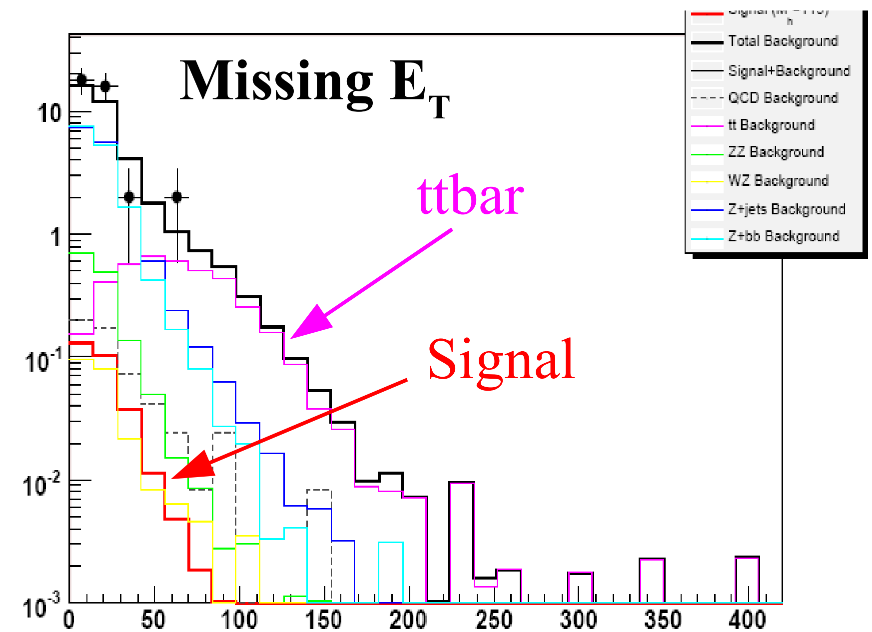
Additional Variables

Di-b-jet mass is the best variable

Other variables also have some separation power





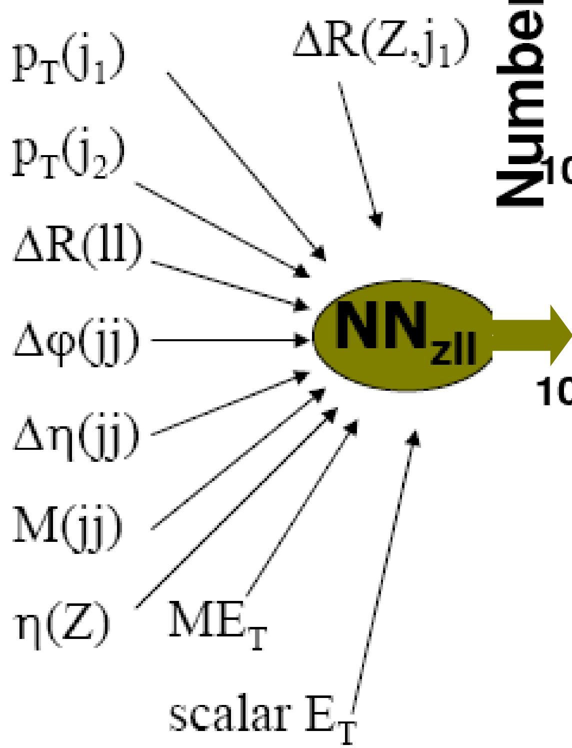


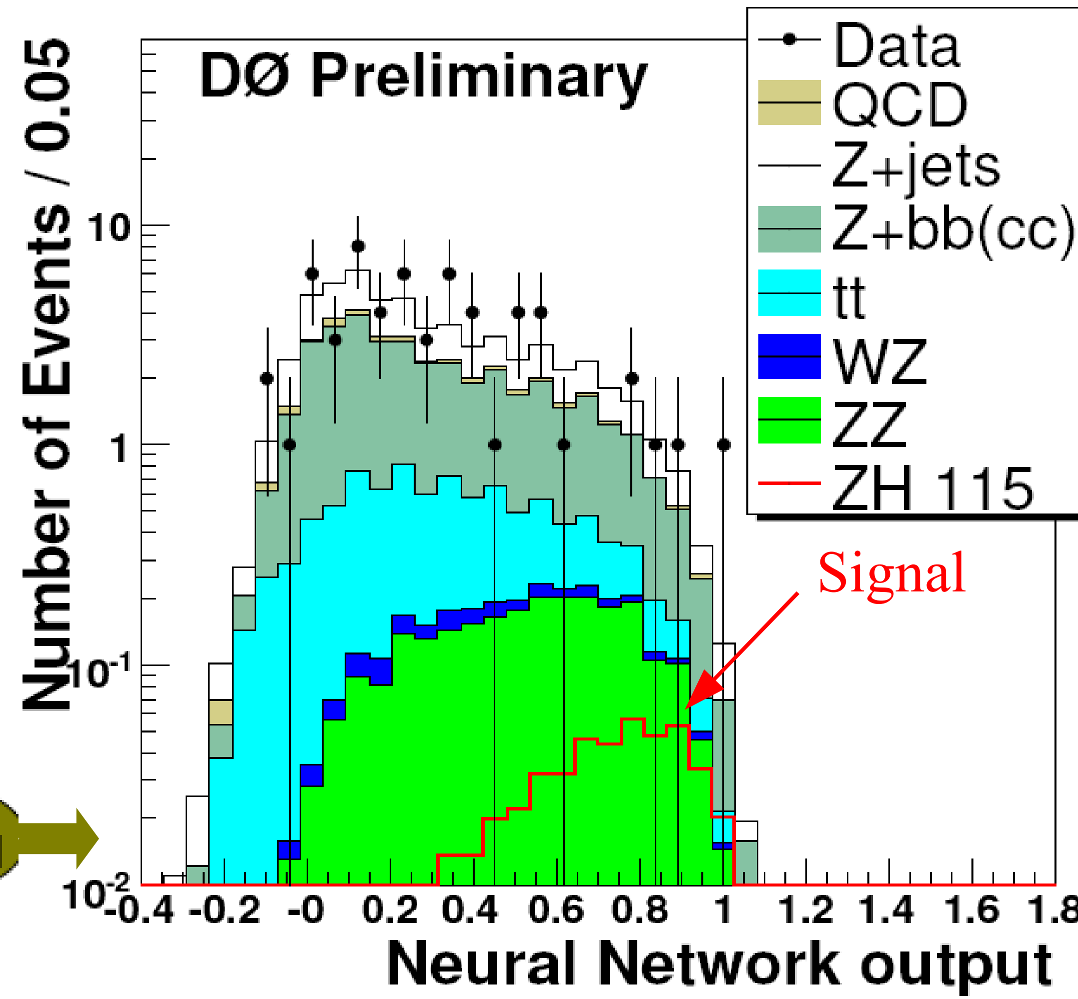
Neural Net Event Selection

Combine variables with NN

Separate NN for single/double b-tag

Train for each m_H





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

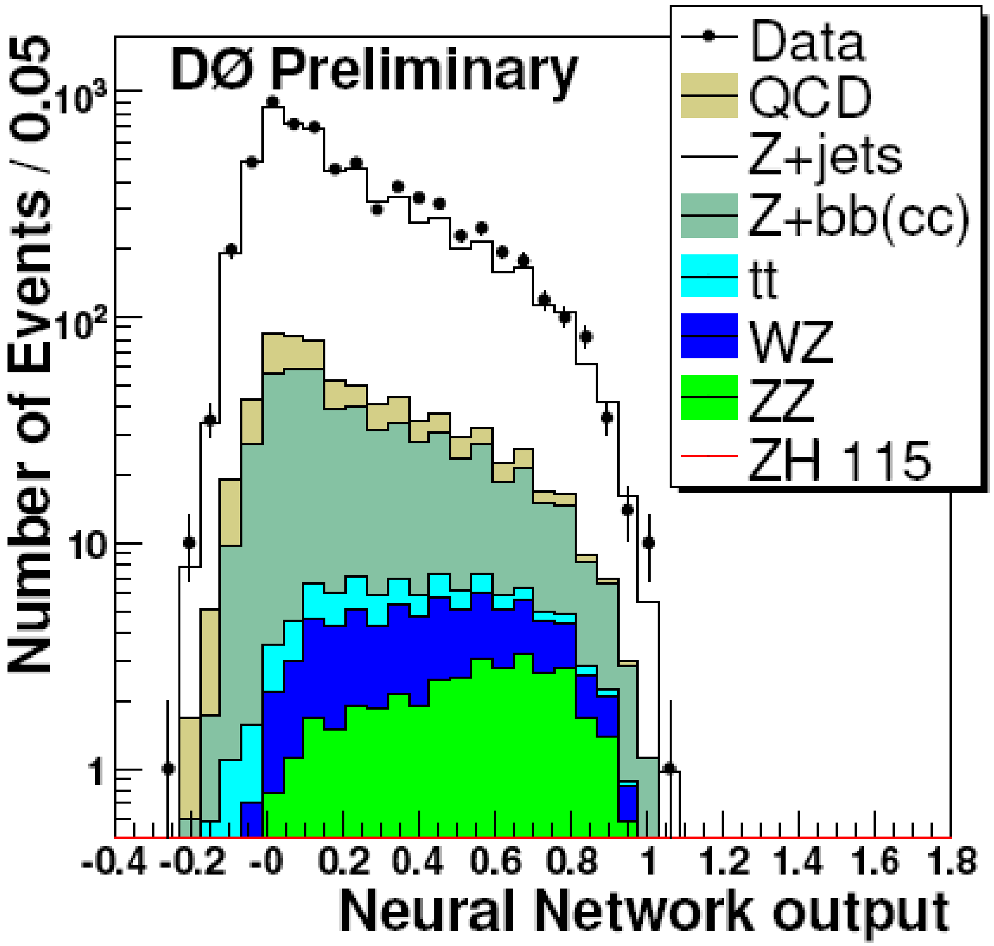
Neural Net Cross-Checks

All input variables are well-modeled

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

- High statistics
- Negligible signal

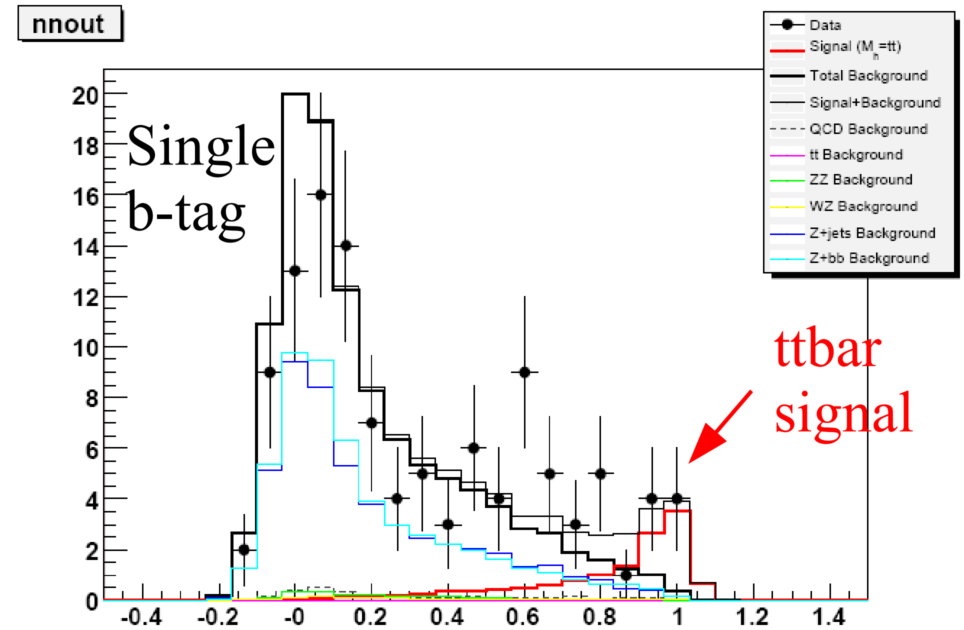
Variables / correlations are well-modeled in Z+jets



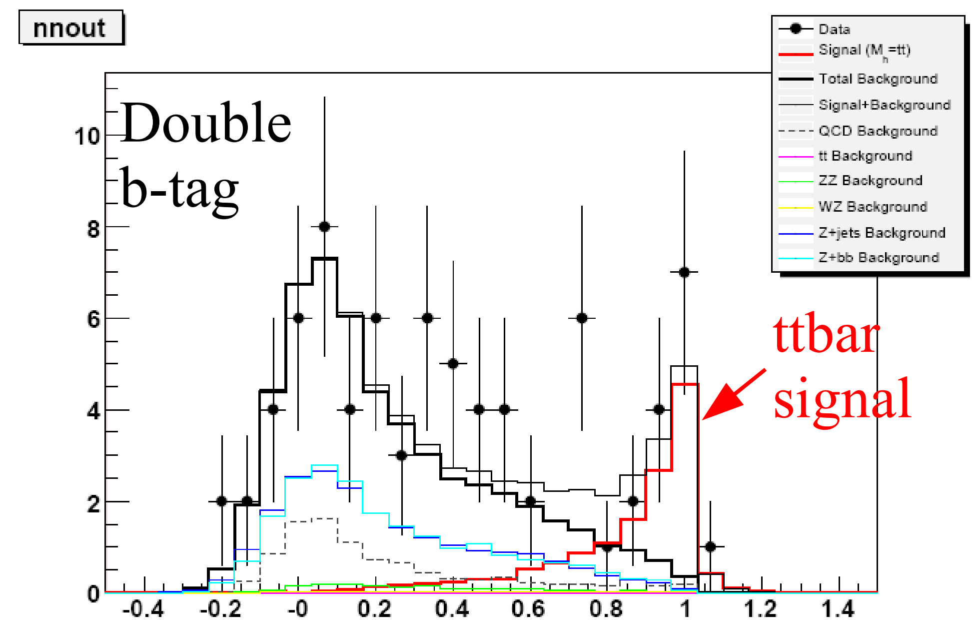
Neural Net Cross-Checks

Train NN on ttbar as *signal*

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



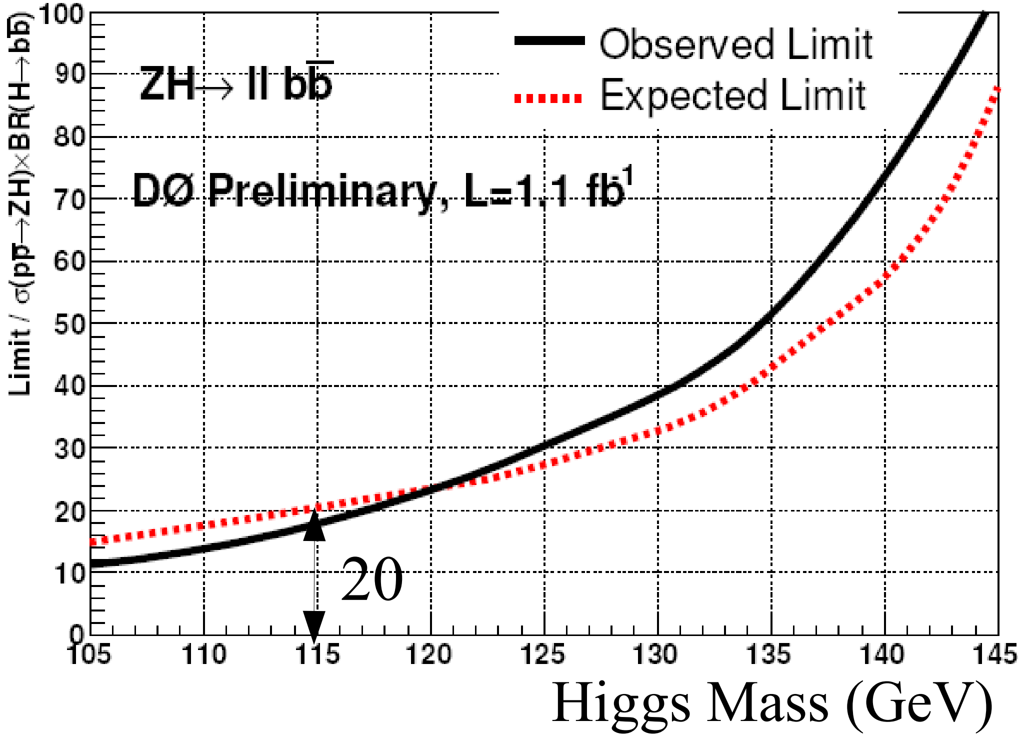
Expected ttbar is observed in both single and double b-tag channels



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)



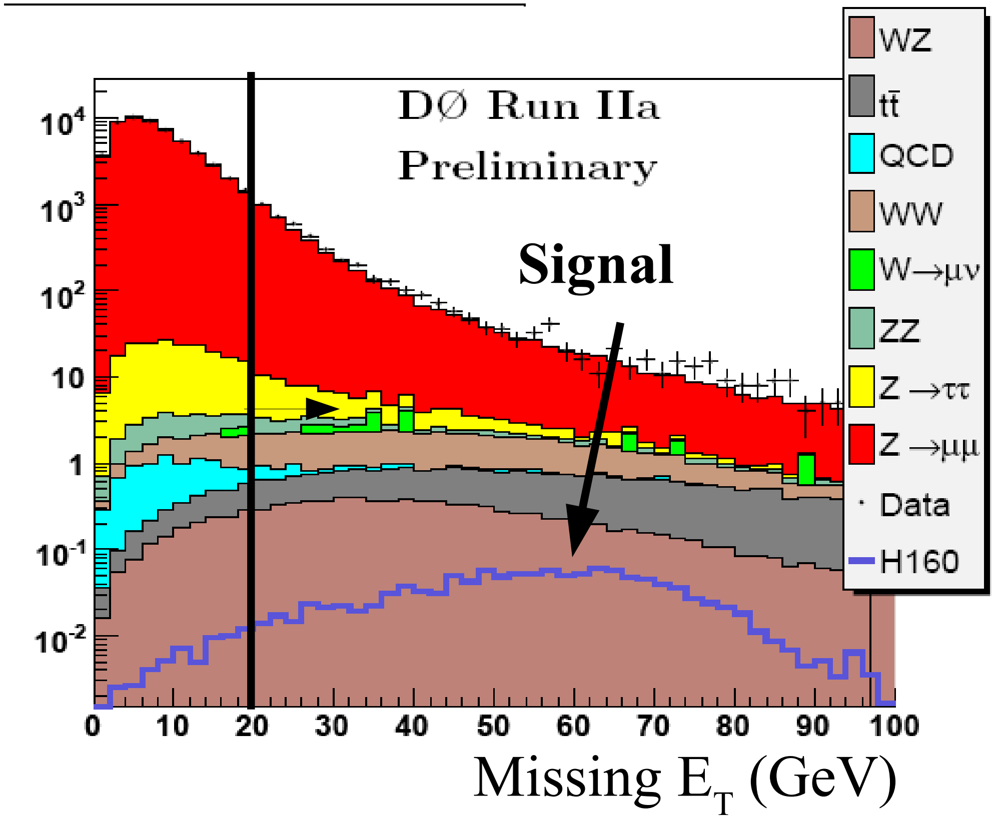
- Other channels
- Combine with CDF
- More data (2.4 fb^{-1} this winter)
- Reduced systematics
- Further improvements in analysis technique

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)



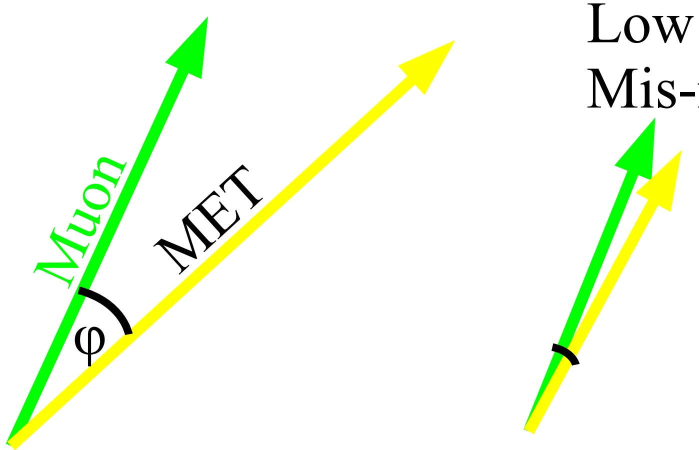
$$\not{E}_T^{\text{Scaled}} = \frac{\not{E}_T}{\sqrt{\sum_{\text{jets}} \left(\Delta E^{\text{jet}} \cdot \sin\theta^{\text{jet}} \cdot \cos\Delta\phi\left(\text{jet}, \not{E}_T\right)\right)^2}}$$

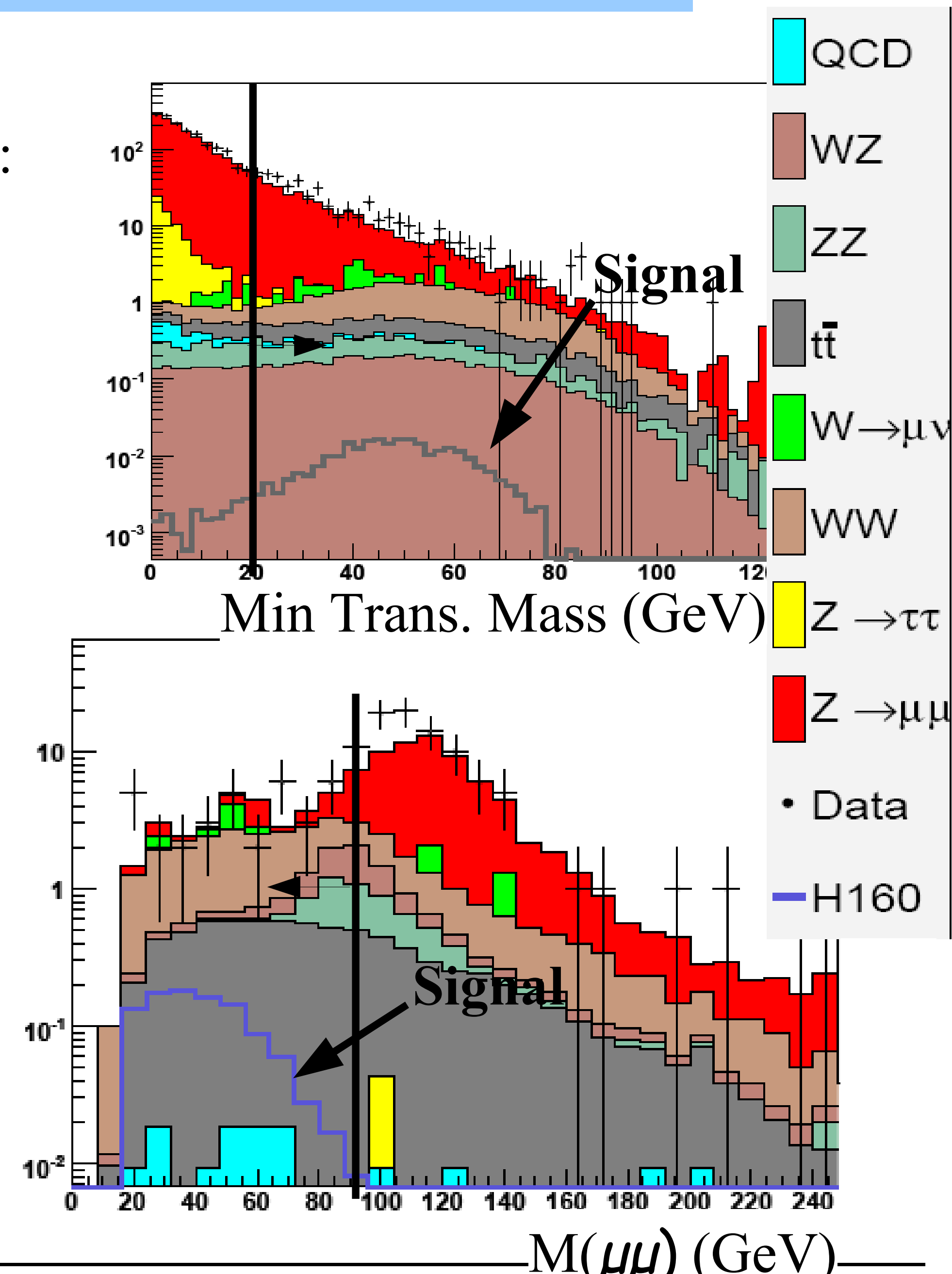
← *MET projected onto jet direction*

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

High transverse mass:
Real W event

Low transverse mass:
Mis-measured muon





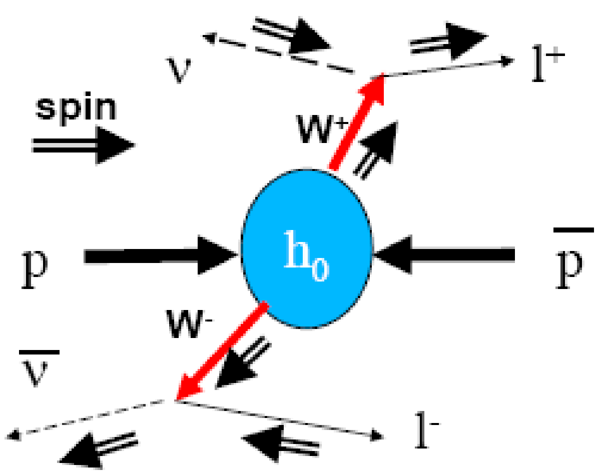
Main backgrounds after pre-selection:

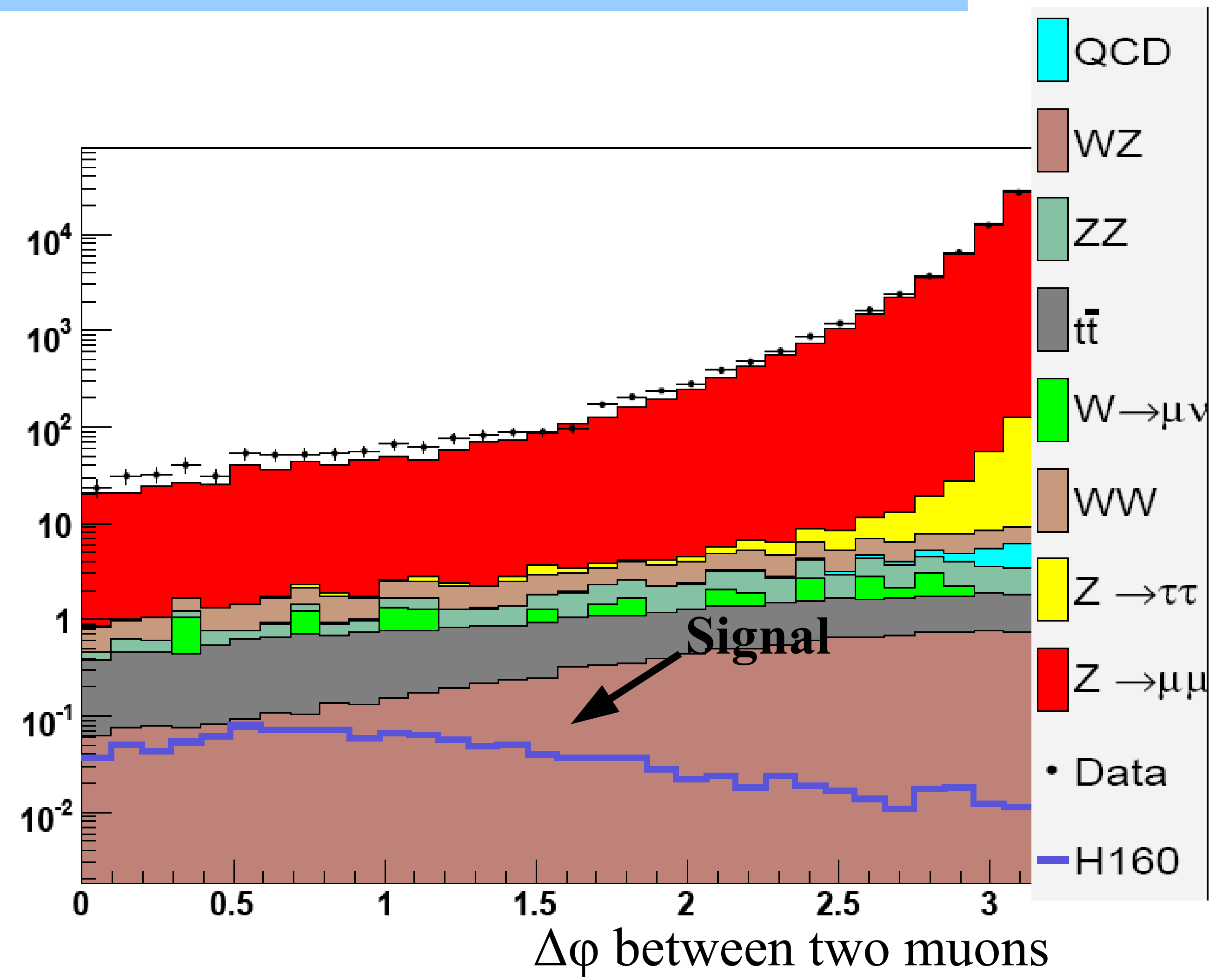
- Z+jets : Fake MET
- W+jets : Jet->Muon
- WW : Nearly irreducible
- tt : Two b-jets

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

Higgs is a scalar

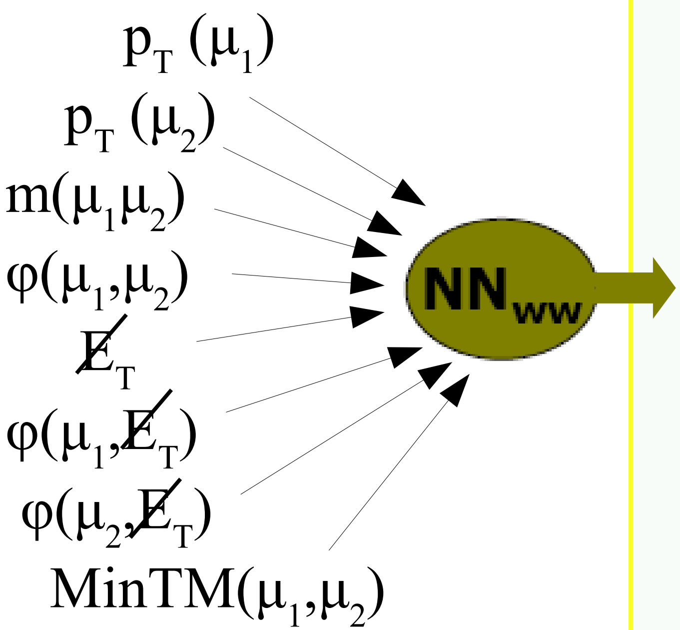
- Muons from W's tend to be more aligned

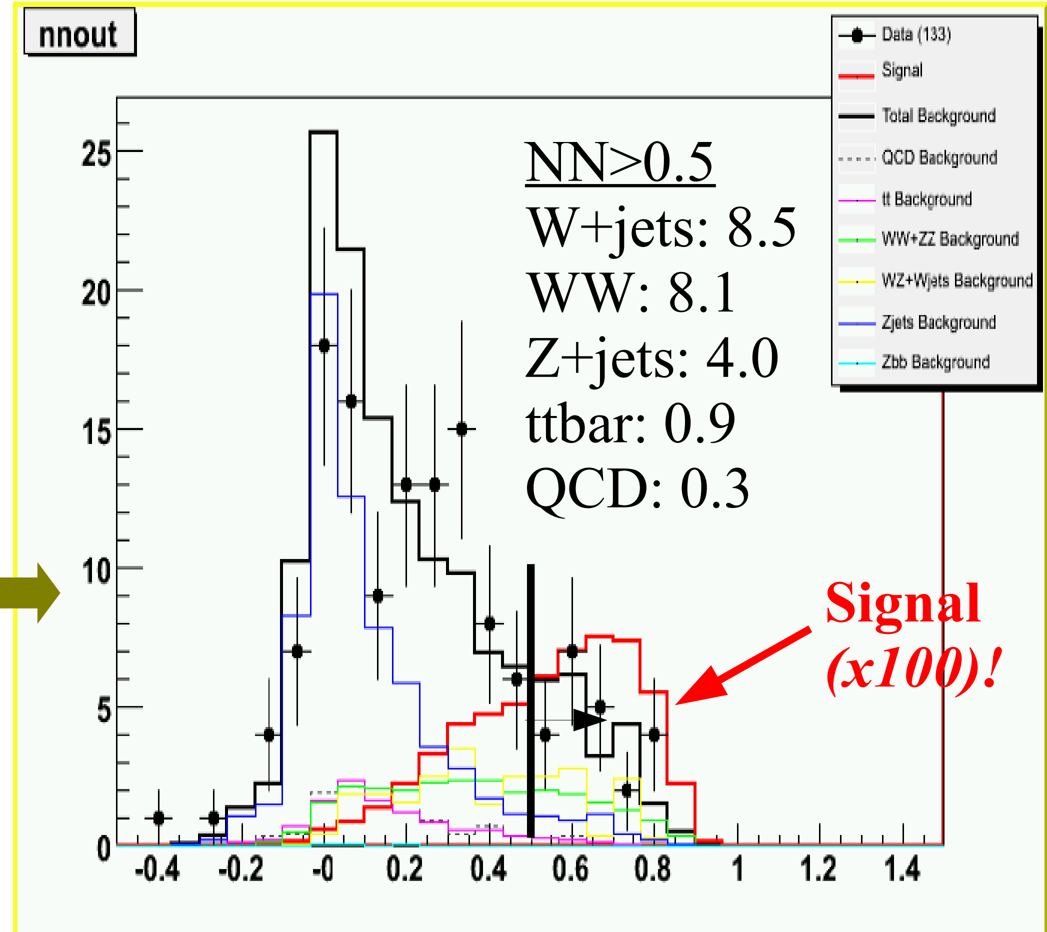




H -> W^+W^- -> $\mu^+ \mu^-$ + MET

Train a NN for each simulated signal m_H



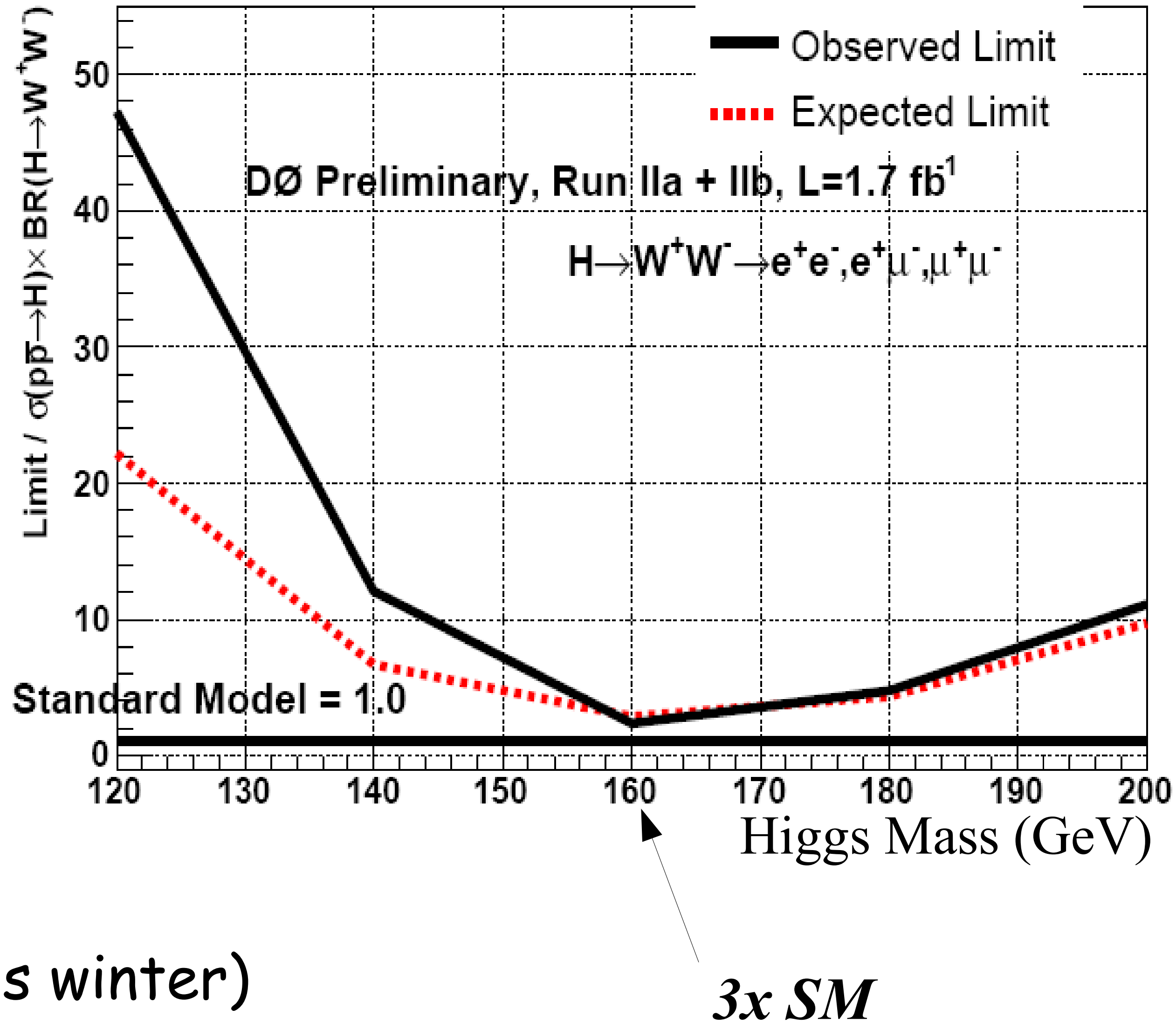


NN Output

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

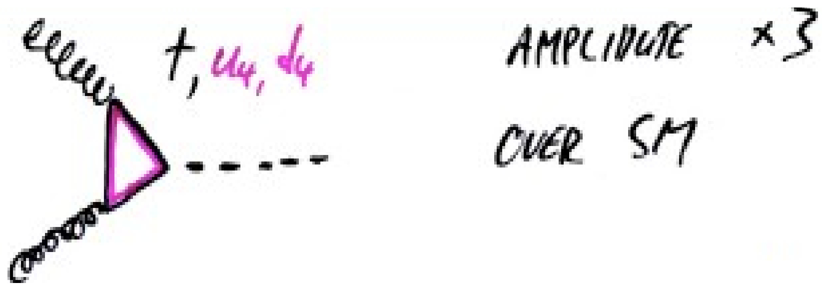
Combine with ee, $e\mu$ channels

Only 3x away from SM cross-section (at m_H=160 GeV)



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

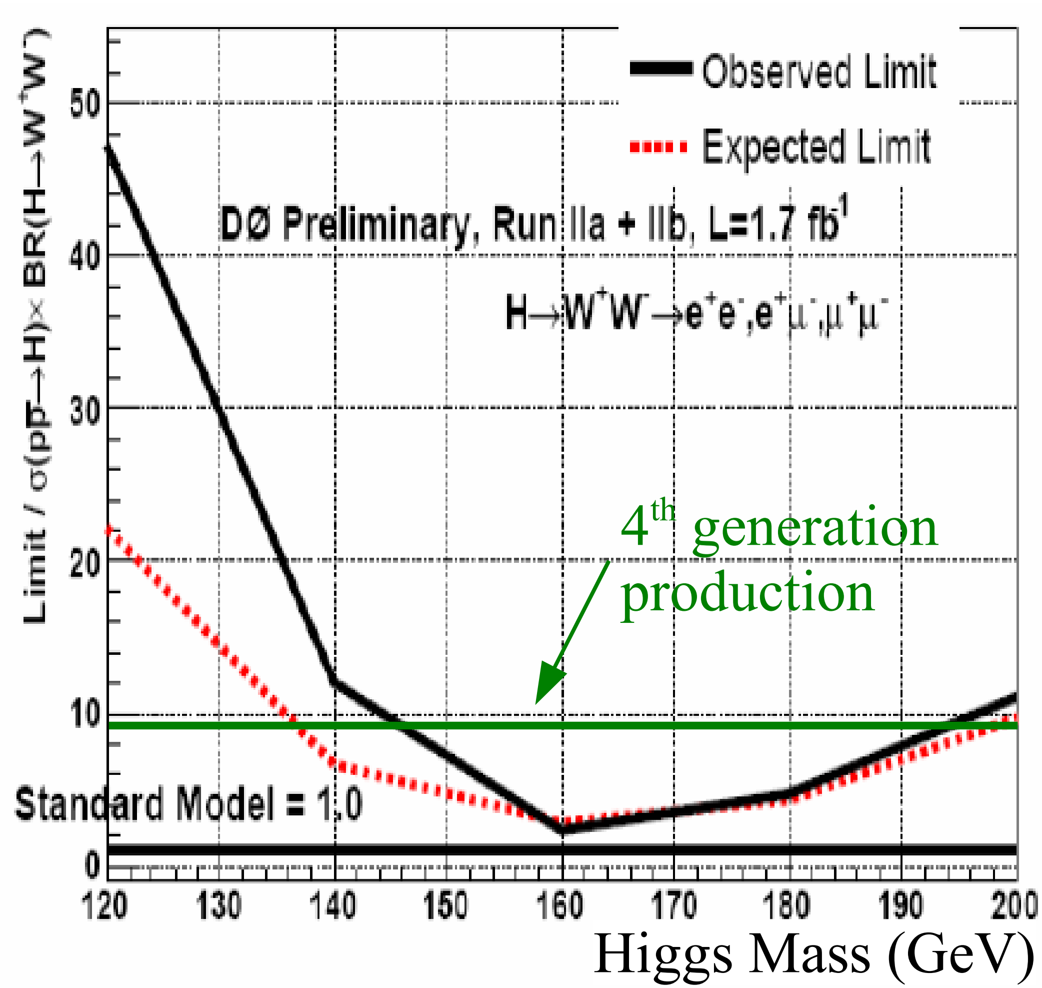
4th Generation



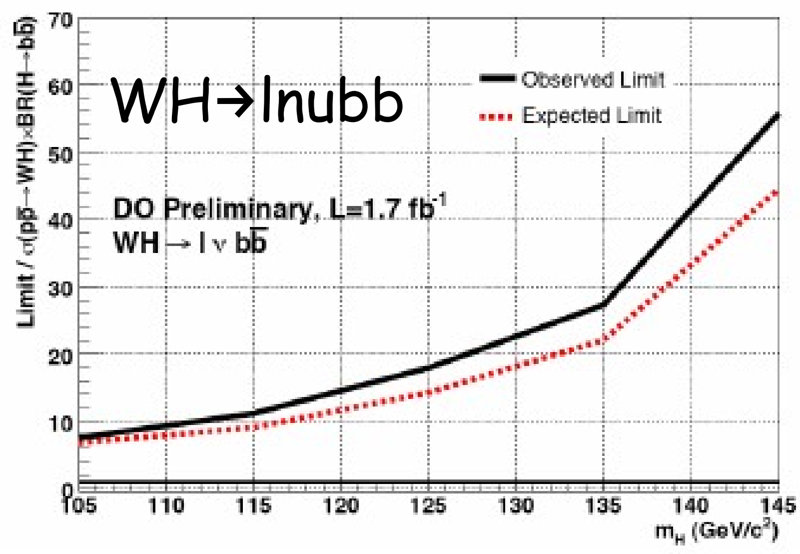
→ 9x more gg->H production!

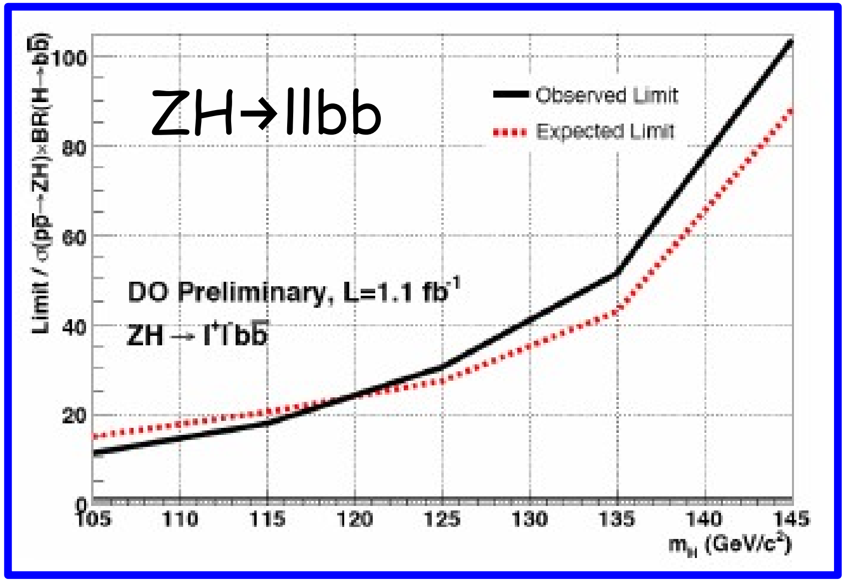
Already excluding from 145-195 GeV

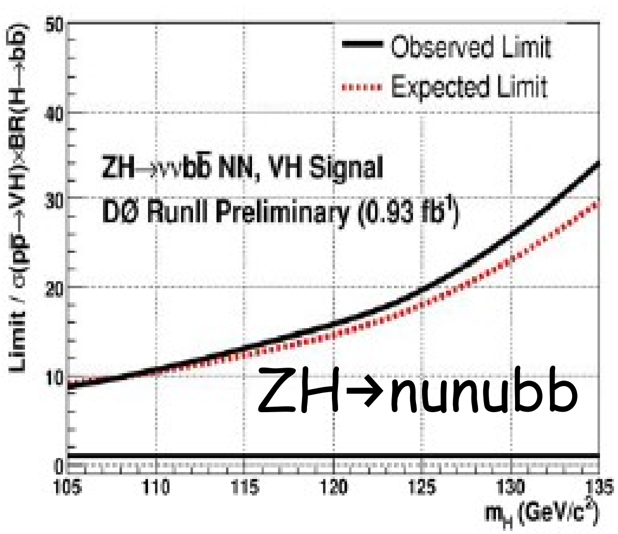
Sensitive up to 260 GeV by 2010

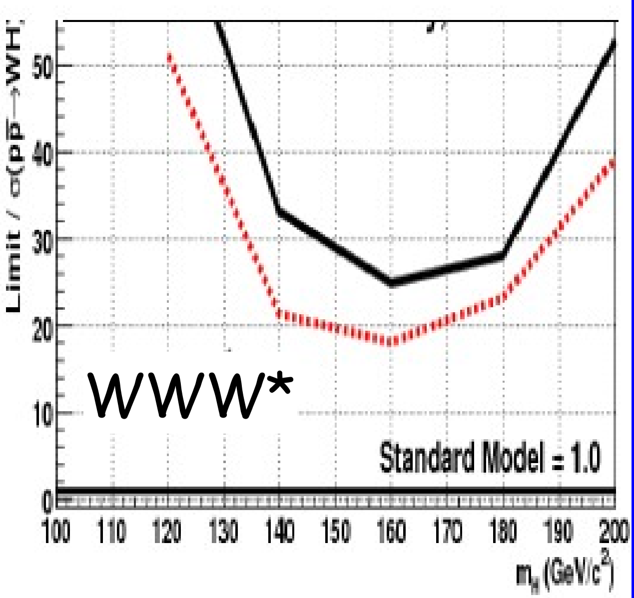


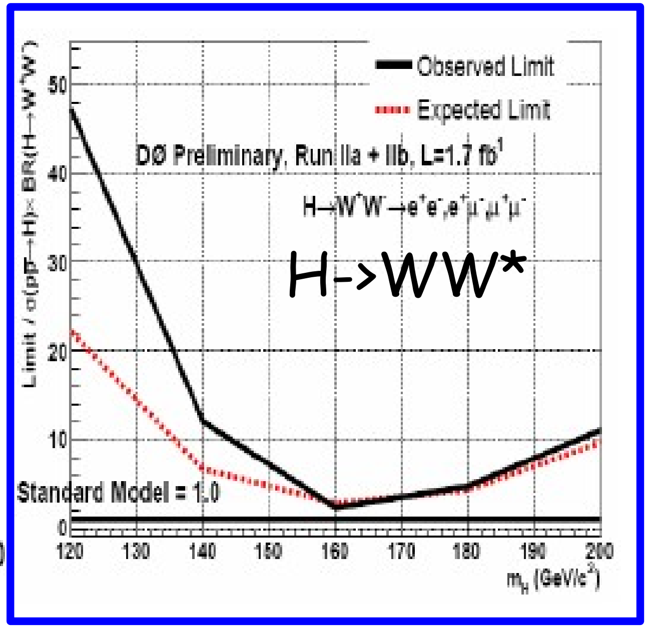
DØ Results in Main Higgs Channels



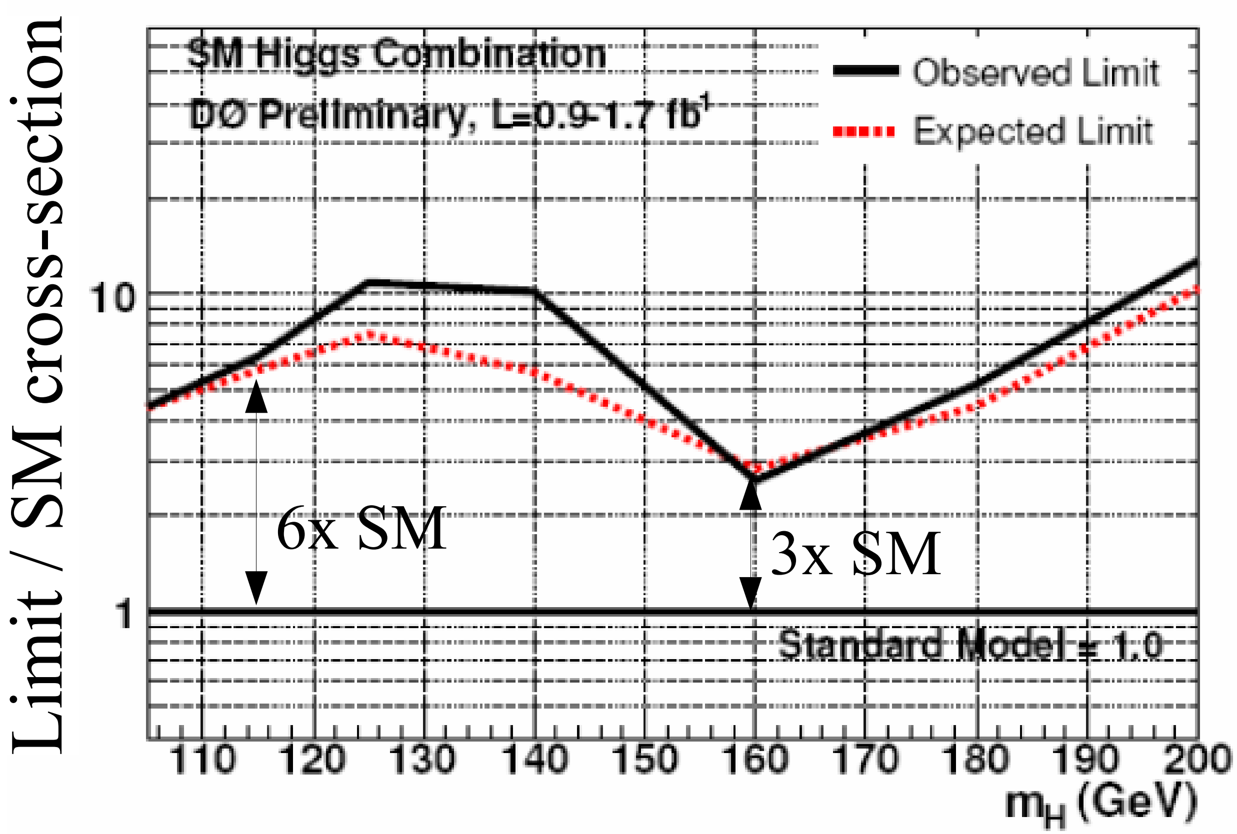








Combining the Channels



<u>Low mass (115 GeV)</u>

ZH→llbb 20x SM

WH→lnubb 10x SM

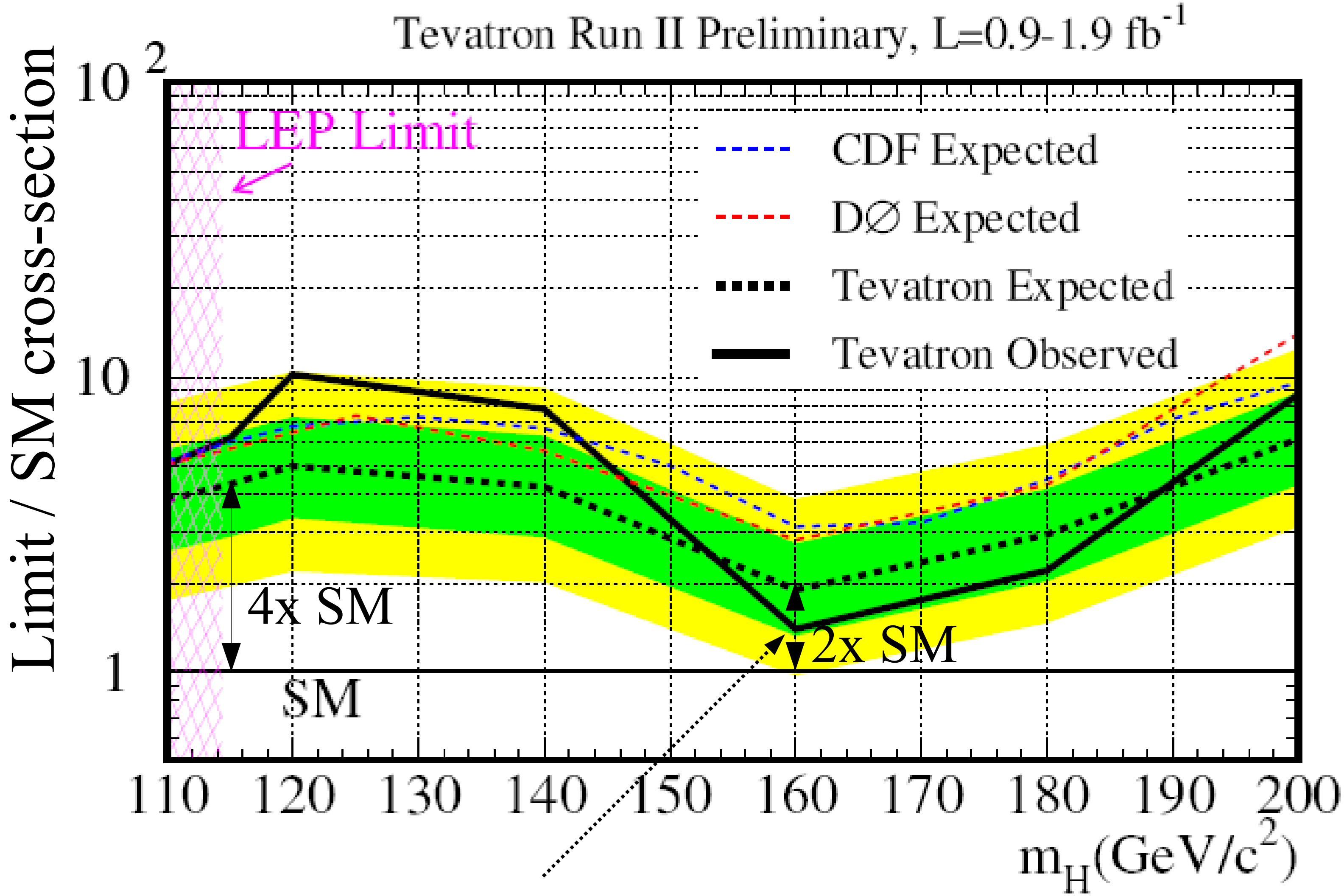
ZH→nunubb 12x SM

<u>High mass (160 GeV)</u>

H->WW*→ll 3.1x SM

WWW* 18x SM

Combining the Experiments



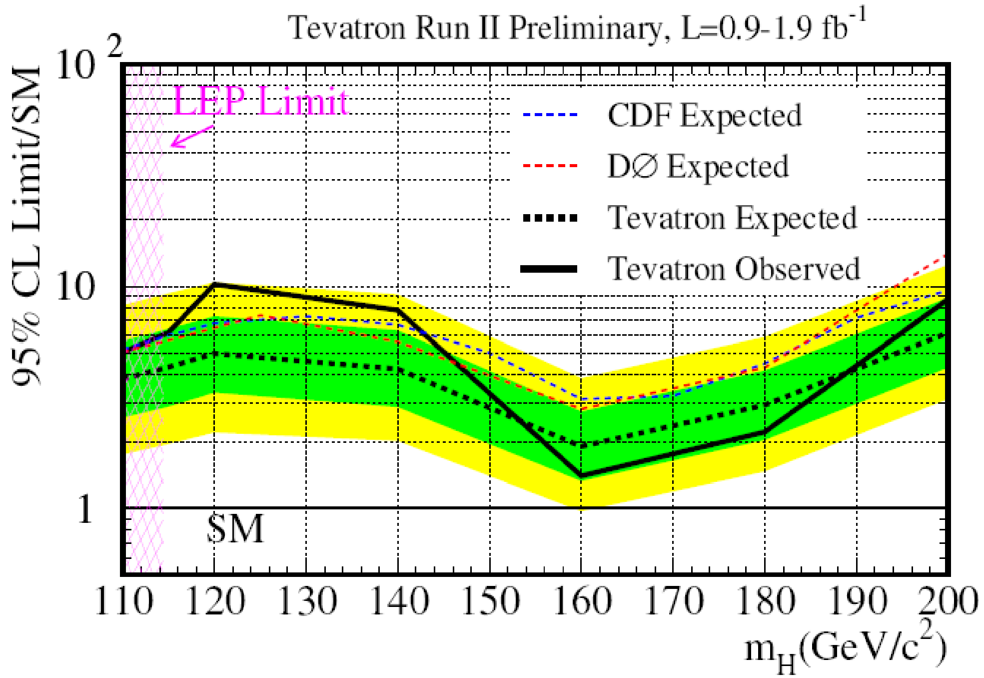
Observed limit: 1.4x SM !

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:

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

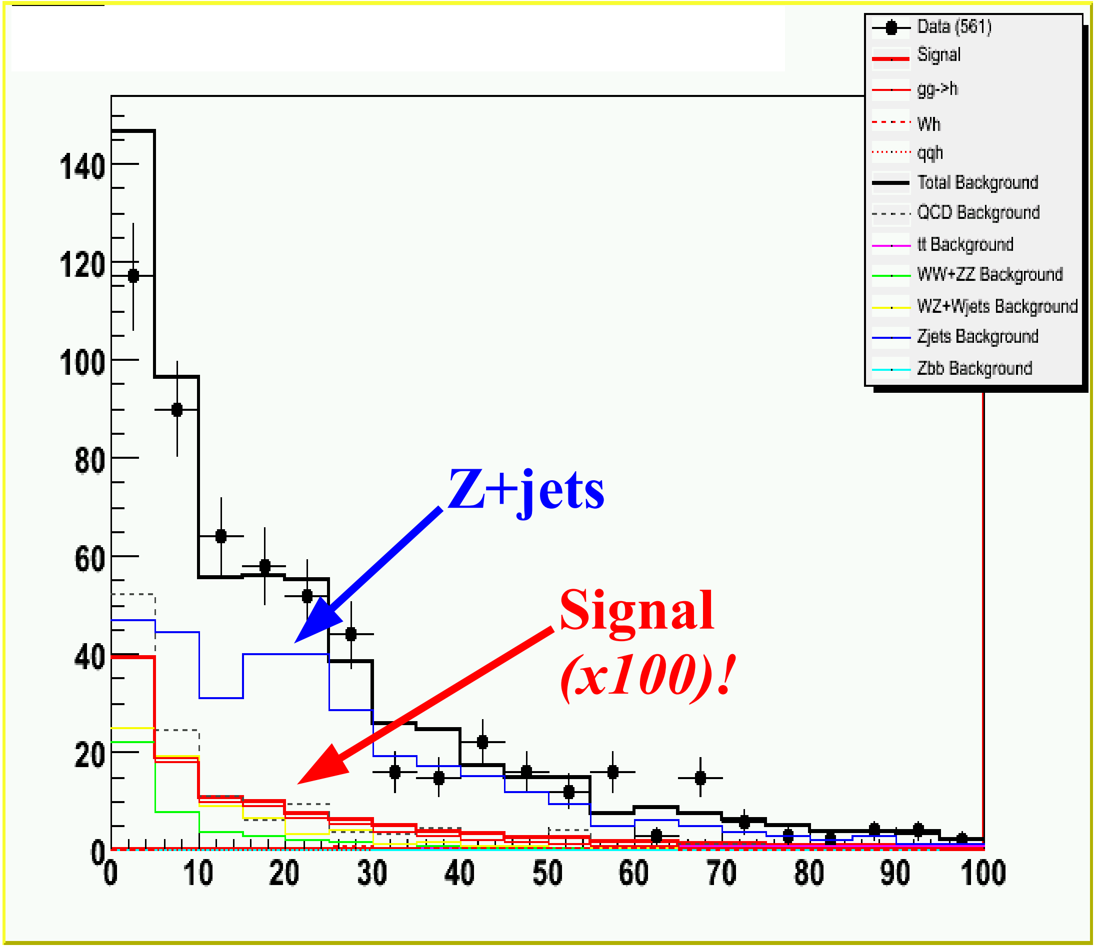
Reducing Backgrounds to H->WW

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



H_T: Sum p_T of all jets (GeV)

Reducing Backgrounds to H->WW

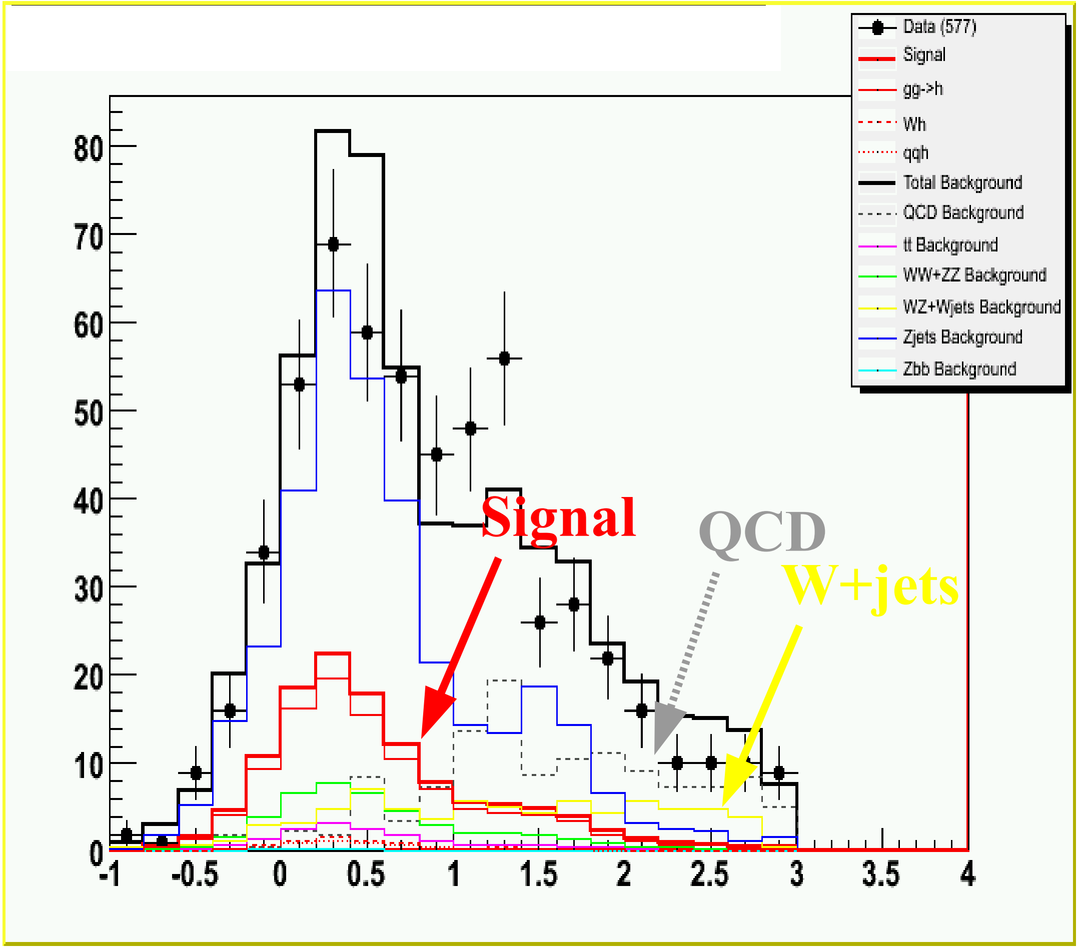
W+jets, QCD:

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

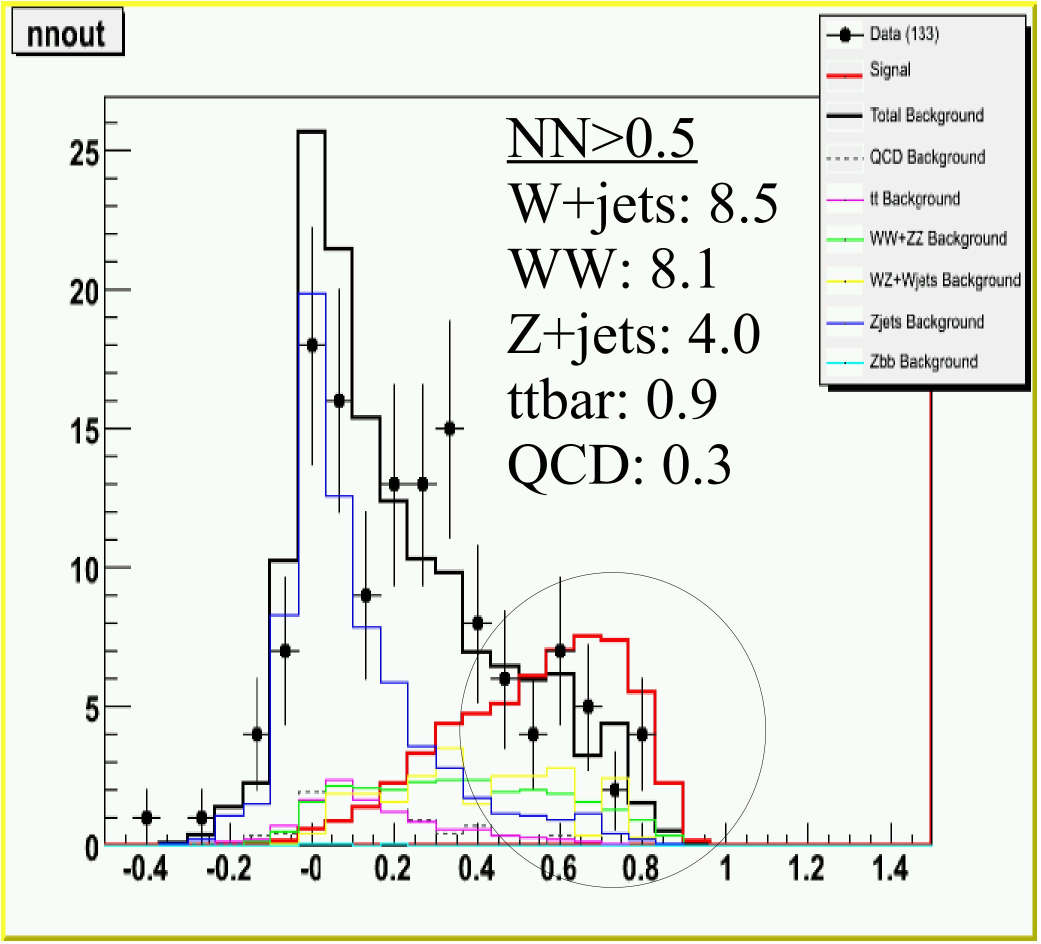


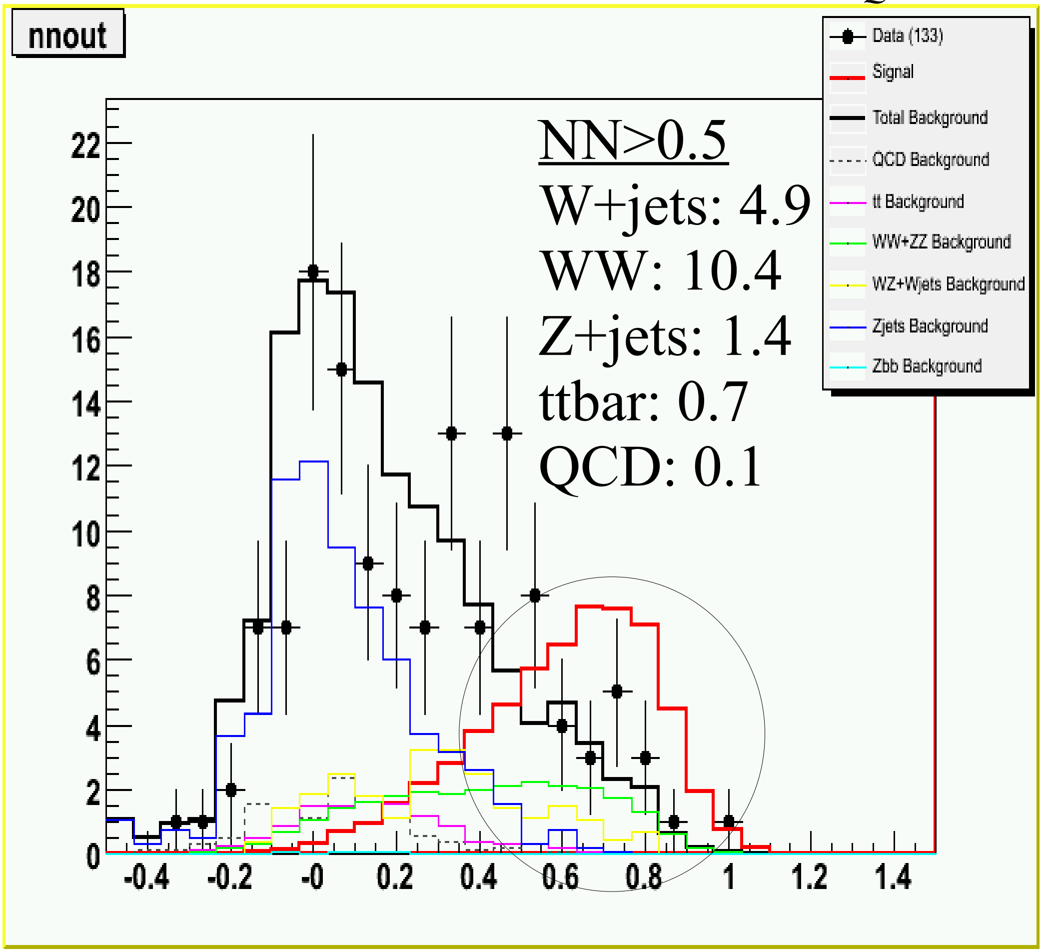
Log10(Max(Chi2 match of track to muon))

Reducing Backgrounds to H->WW

Original NN

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





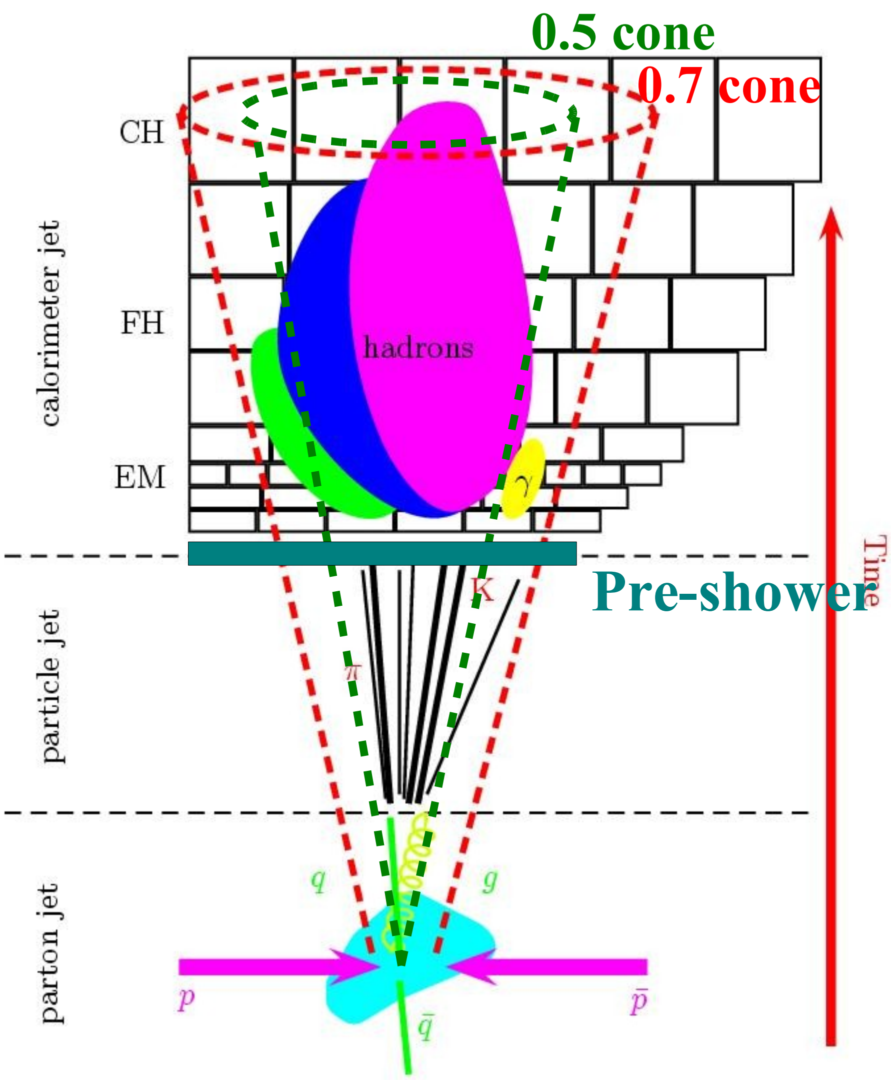
Sensitivity improved by 30%

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

- Multiple jet-cone sizes
  - 0.5 less sensitive to noise, pileup, overlap
  - 0.7 captures more jet energy
  - *Jet-by-jet showering / FSR correction*



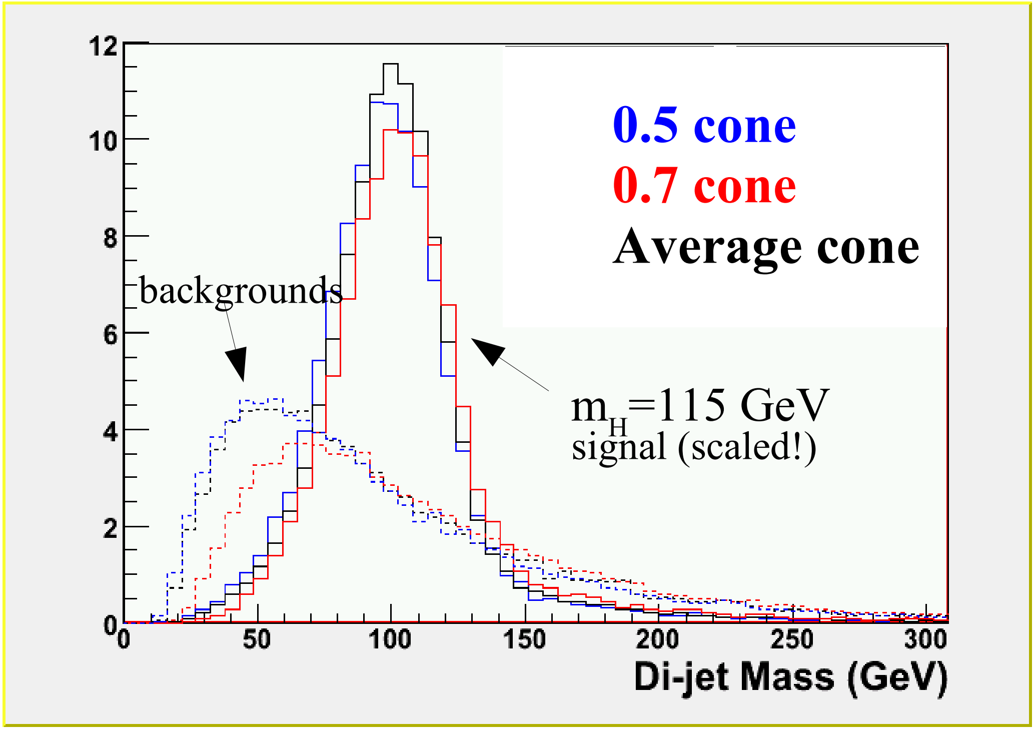
Average Cone Jets

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

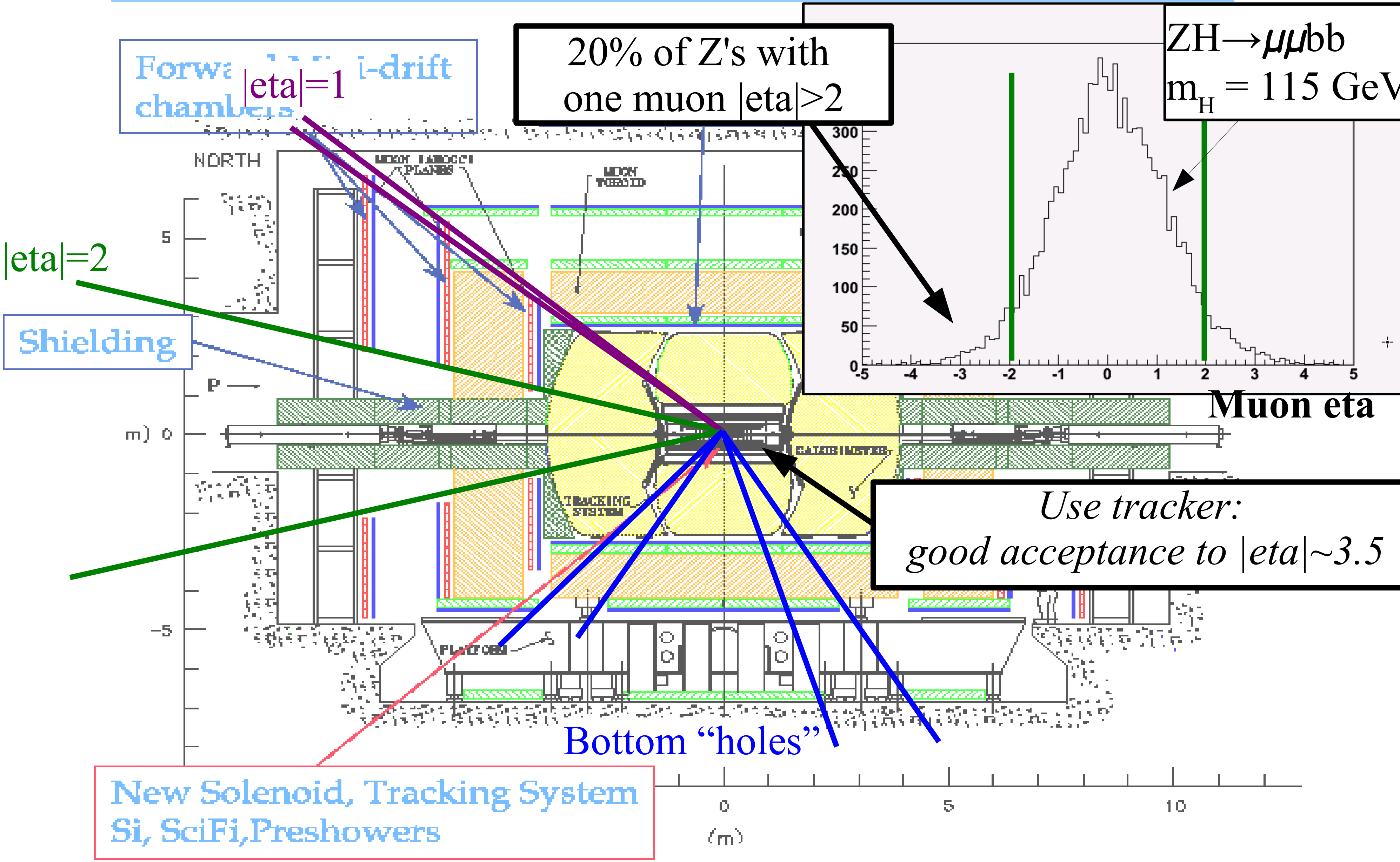
- angles are also measured better



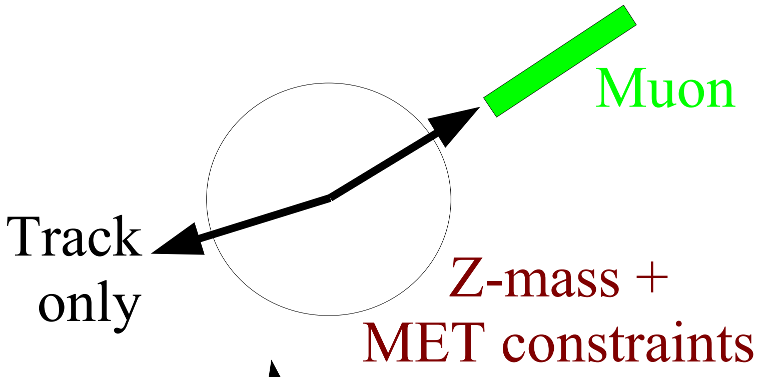
Translates into 8% more sensitivity for low-mass Higgs searches

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

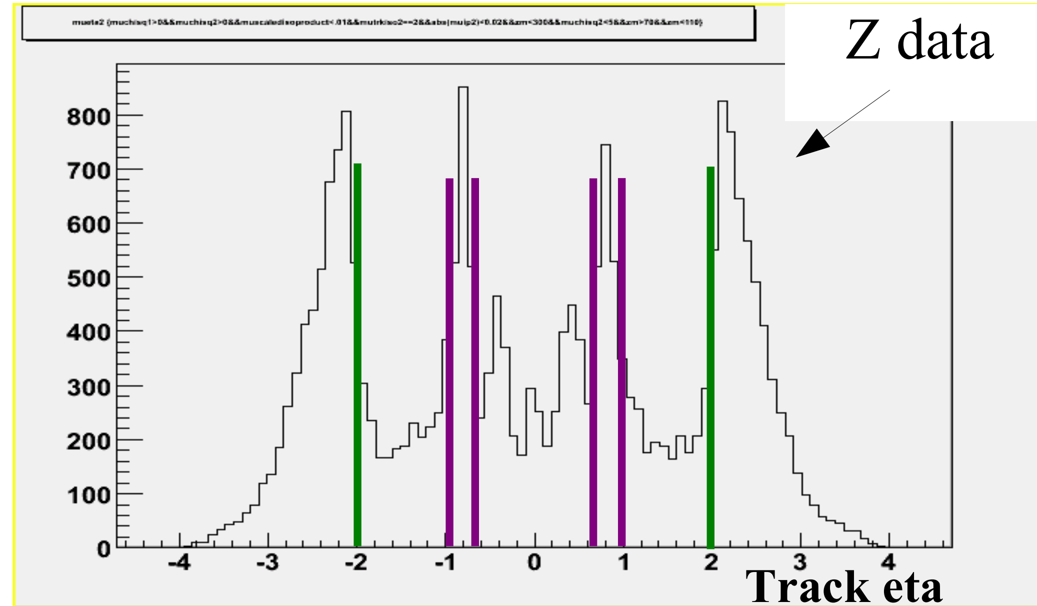
Muon Acceptance



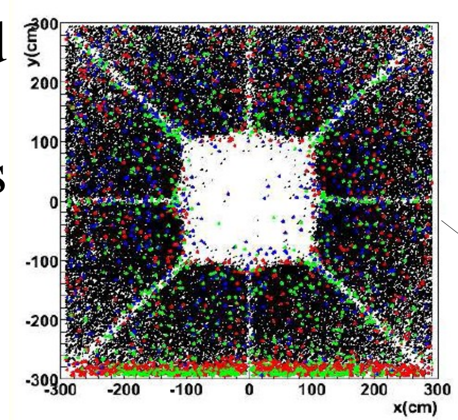
Muon Efficiency

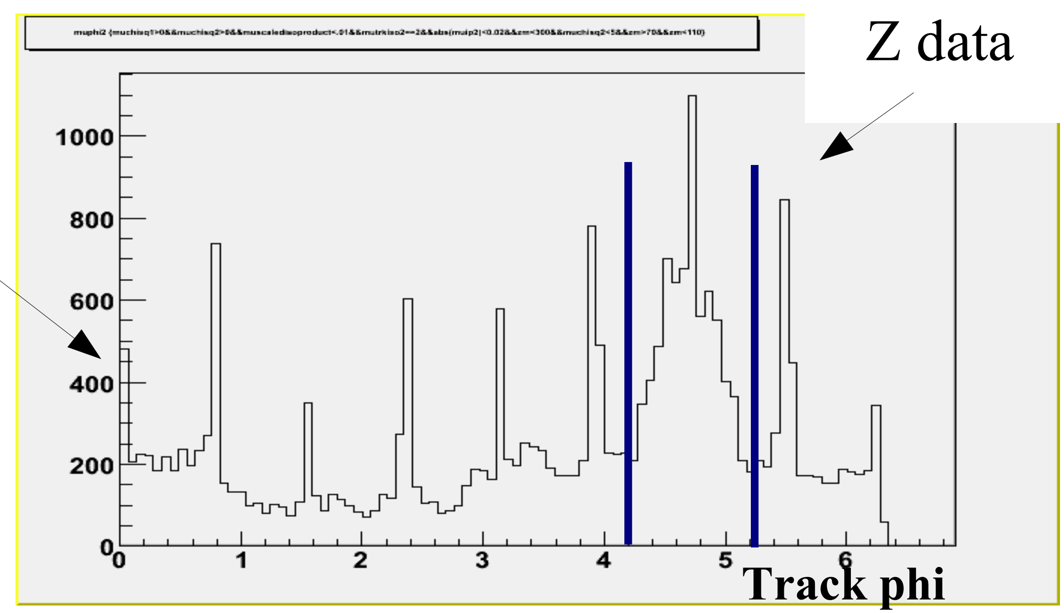


Tune the track quality selections



Forward muon octants



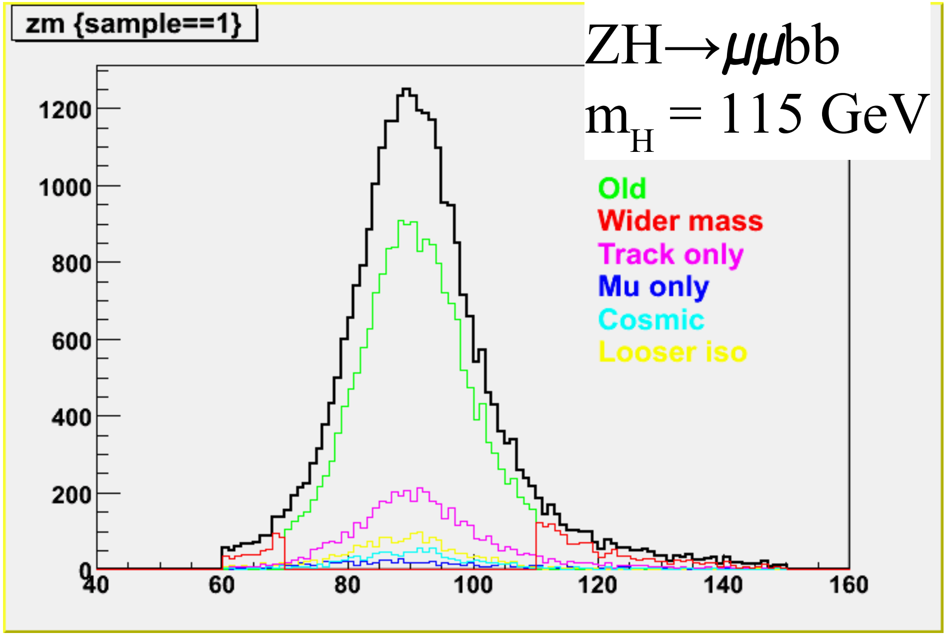


Muons recovered in regions with poor muon acceptance

Muon Efficiency

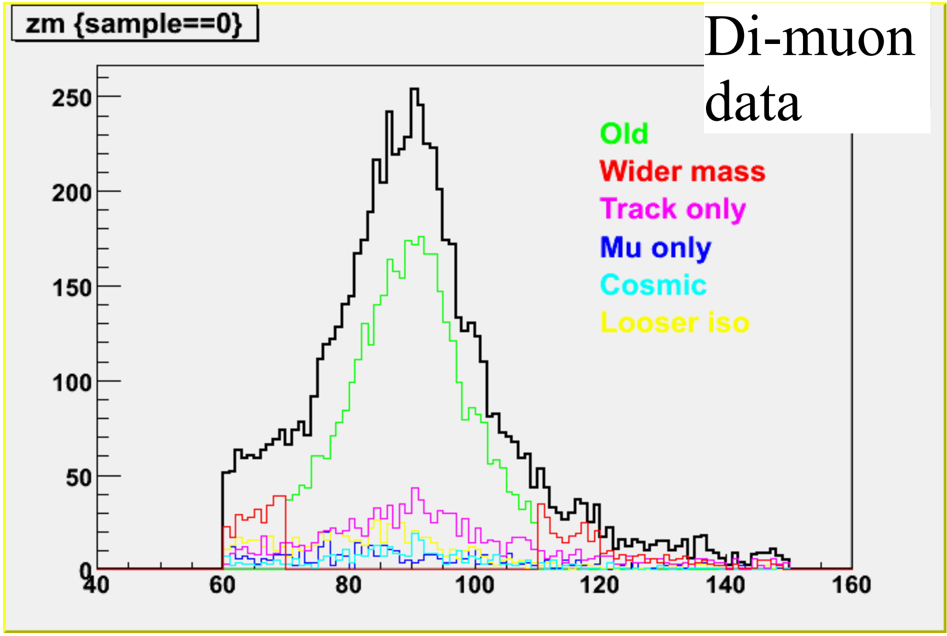
Combine track-only muon with:

- 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

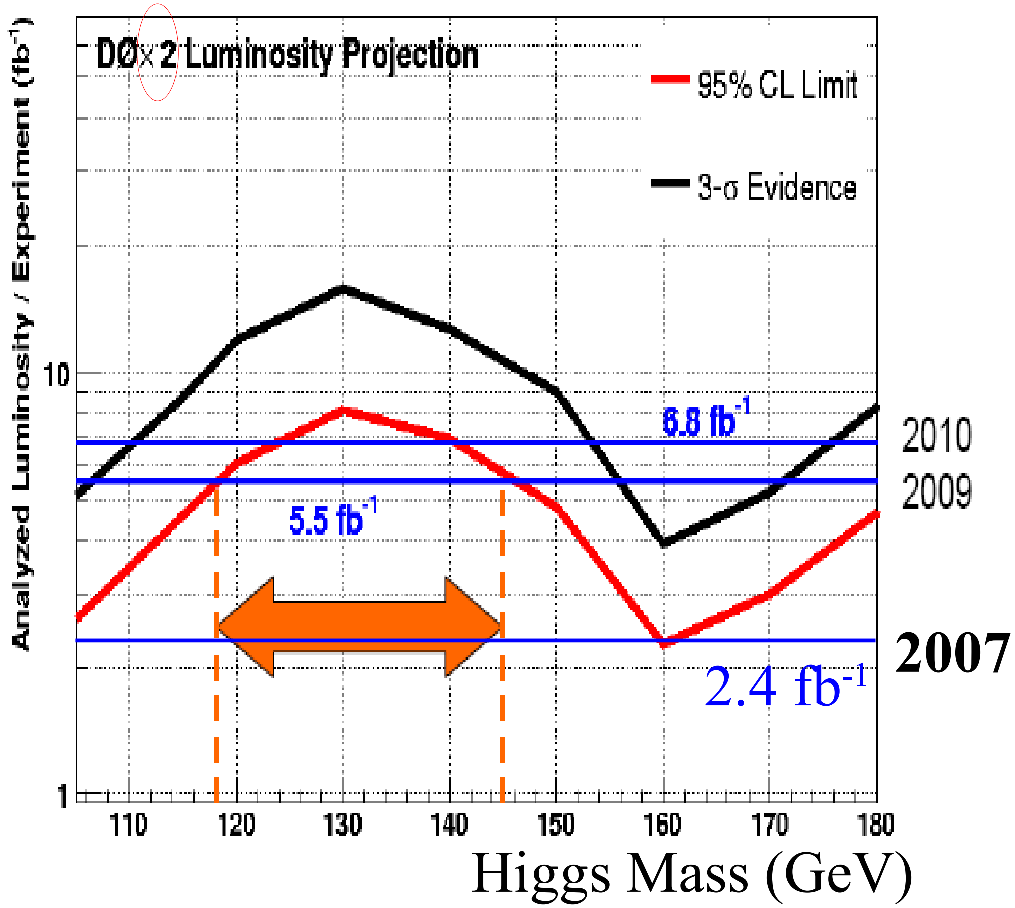


Equivalent to 30% more data after training NN

Sensitivity Estimates

Di-jet mass resolution (20%)
Lepton efficiency (10%)
Improved analyses (?%)
Matrix Element (20%)
Better b-tagging

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



Should be sensitive to m_H=160 GeV ~now

May be sensitive up to 200 GeV by 2010

LHC

Tevatron

LHC

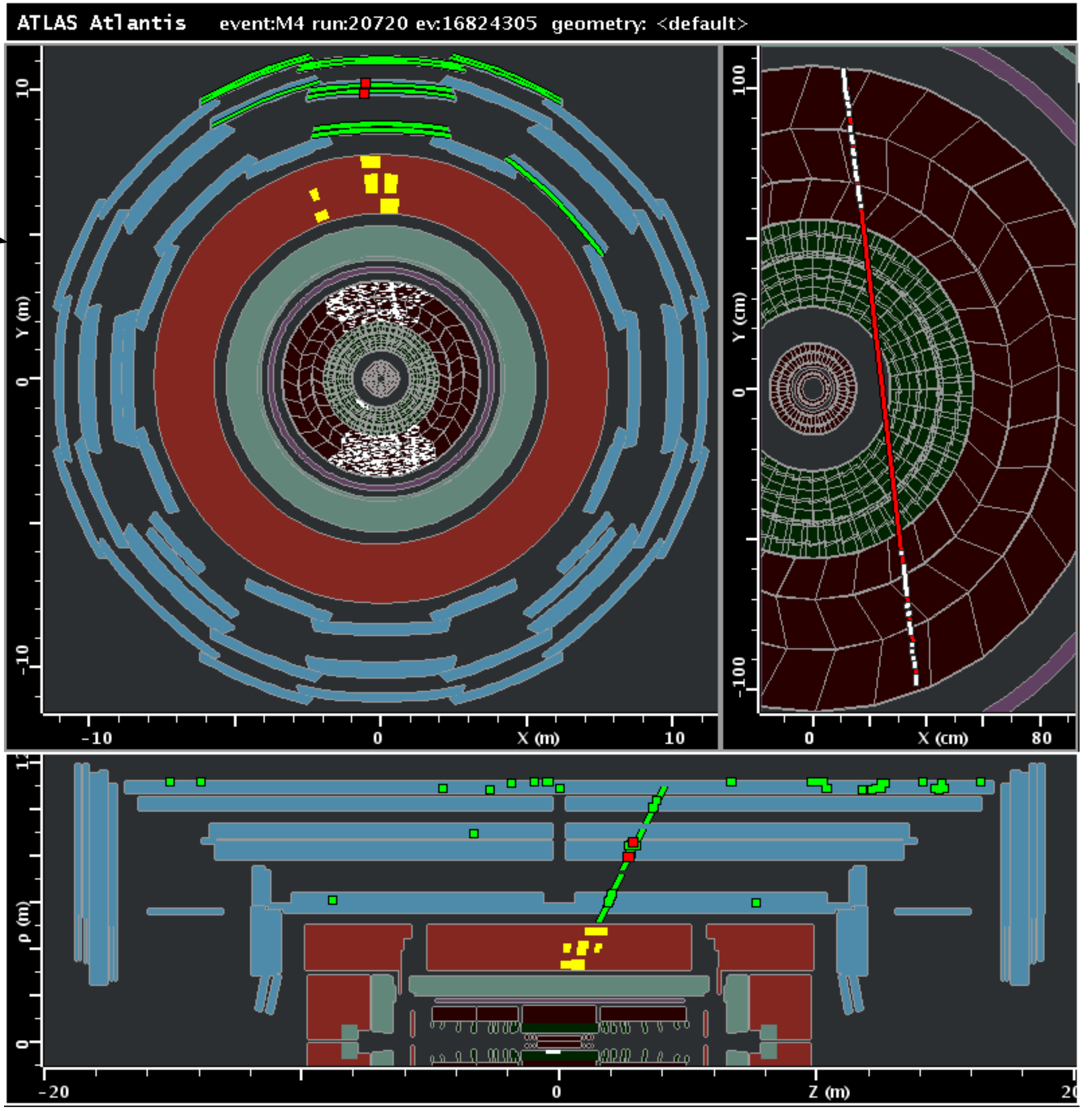
proton on *proton*

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)

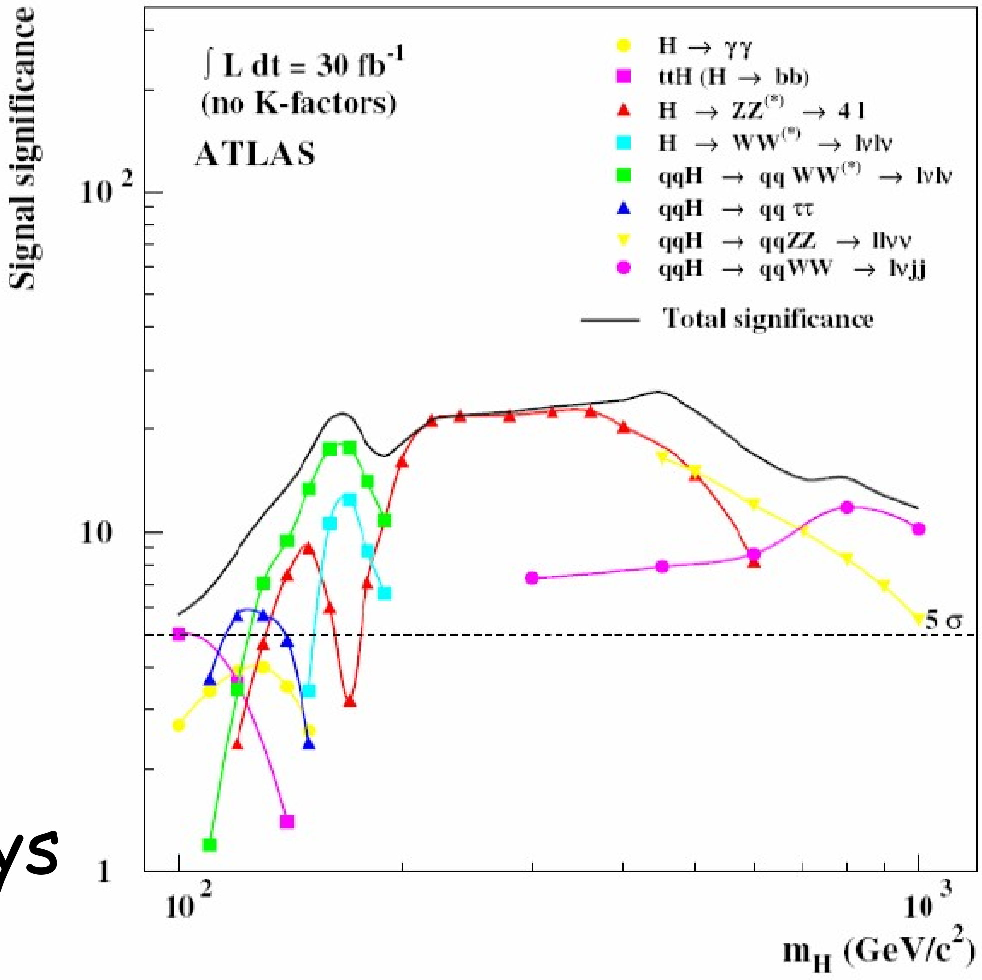
m_H<~130 GeV difficult

Complimentary:

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

LHC: H, qqH : H->ττ/γγ decays

- ttH(->bb) is very hard



Experience and methods from the Tevatron are vital to LHC analyses!

Conclusions

A Higgs Boson, consistent with EW constraints, would be fantastic verification of the SM

DØ has a large and dedicated Higgs group, covering many analyses, 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 takes further innovations, underway

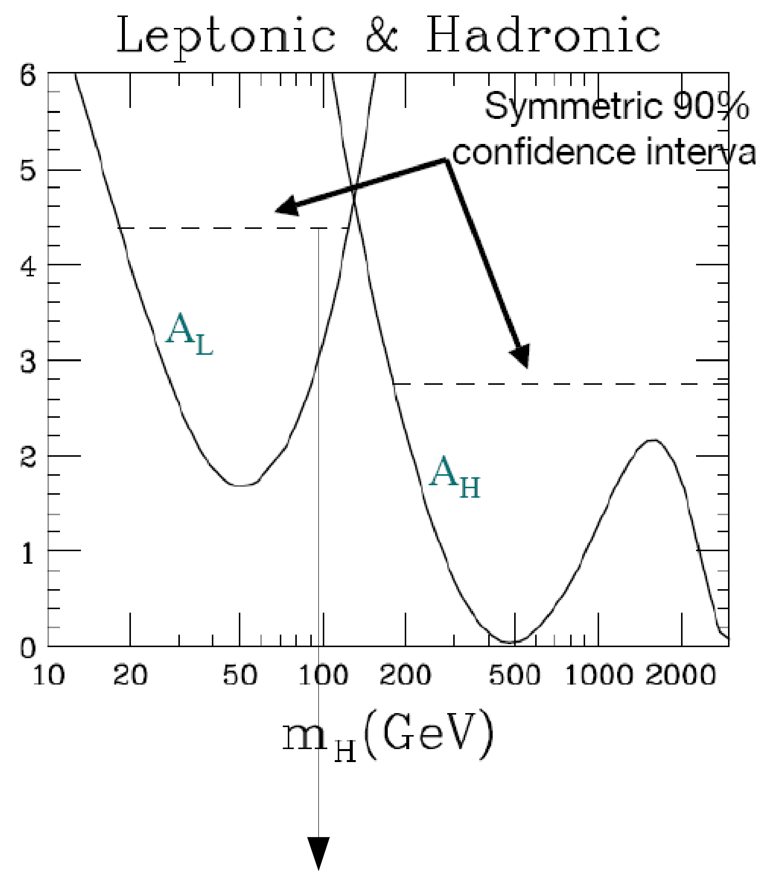
- Better di-b-jet mass res., lepton ID, analysis methods, ...
- May be sensitive to SM Higgs @160 GeV *this winter*
- **Possible to be sensitive up to 200 GeV by 2010**

Backup

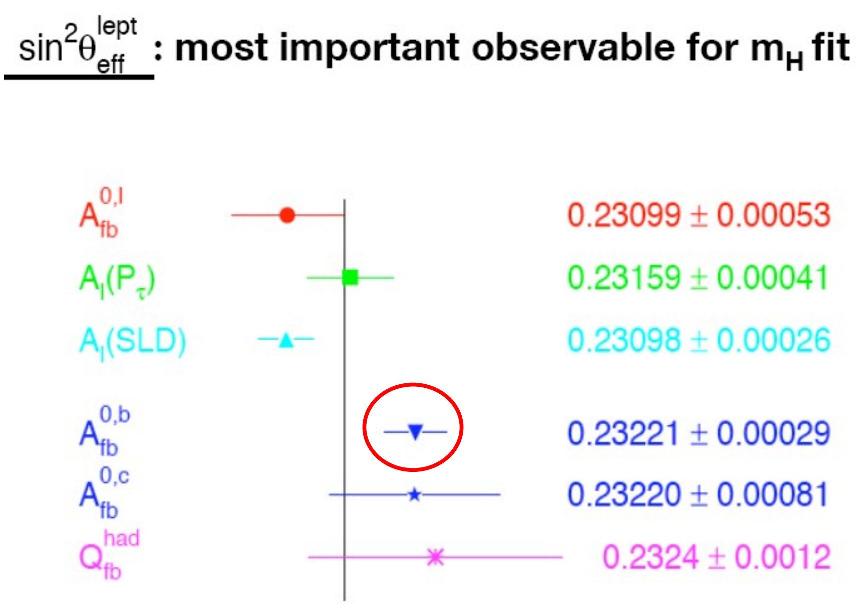
Precision EW Constraints

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

LEP II: m_H>114.4 GeV



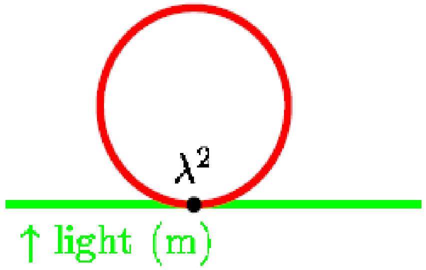
m_H<97 GeV (at 95% CL) (leptonic only)



Why is the Higgs so Light?

The Higgs mass is *unstable*

- Large radiative corrections (it's a scalar)

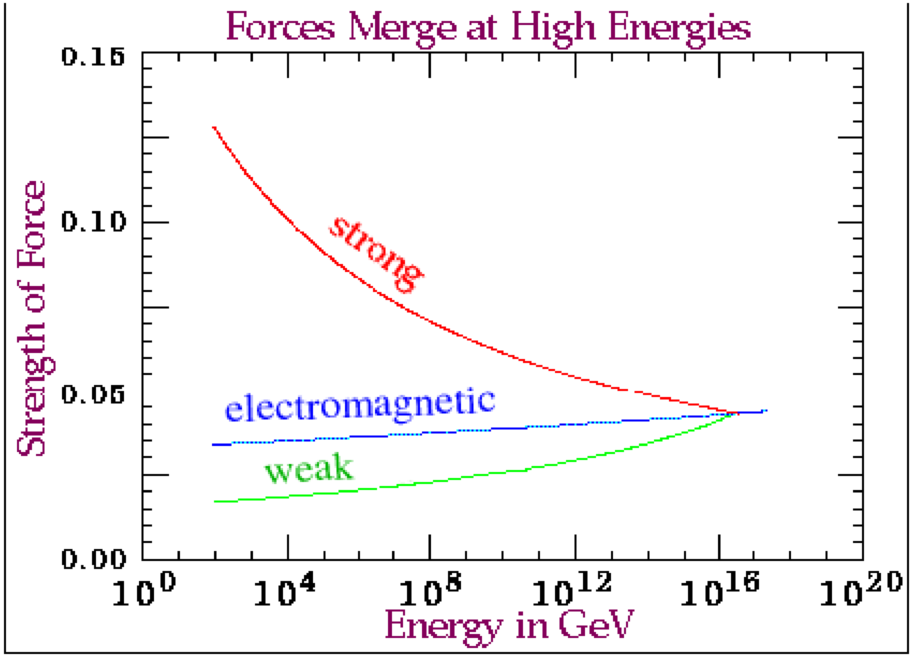


$$\Longrightarrow \quad \delta m^2 \sim \lambda^2 \cdot M^2$$

$10^2 \quad 10^{-1} \quad 10^{16}$

Hierarchy problem:

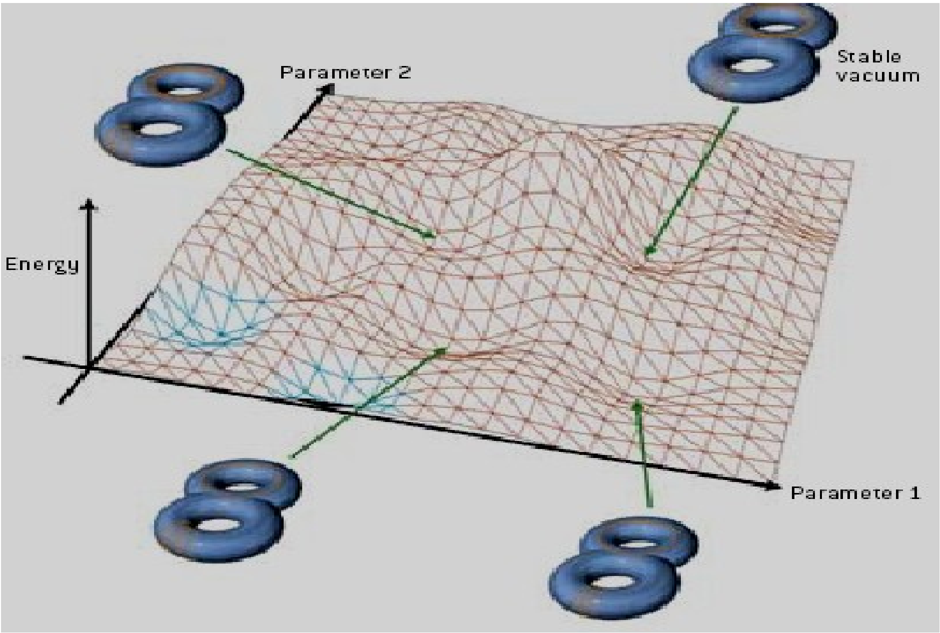
$m_H \ll m_{GUT}$



Why is the Higgs so Light?

We wouldn't be here if it wasn't

- A small Higgs VEV seems necessary for life

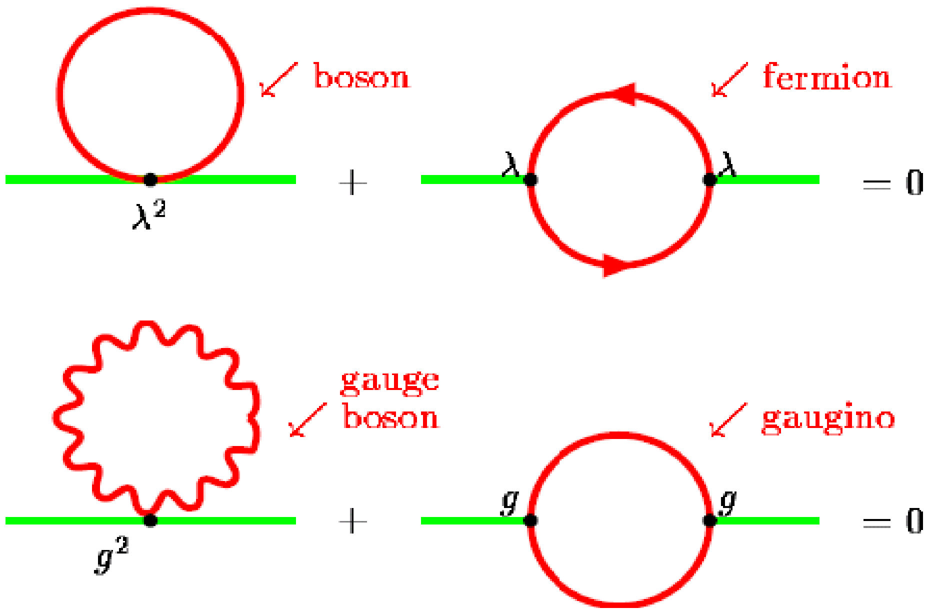


Same reason for a small cosmological constant?

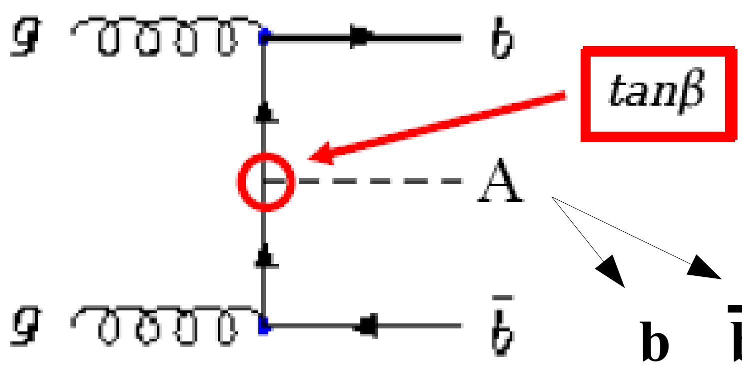
Why is the Higgs so Light?

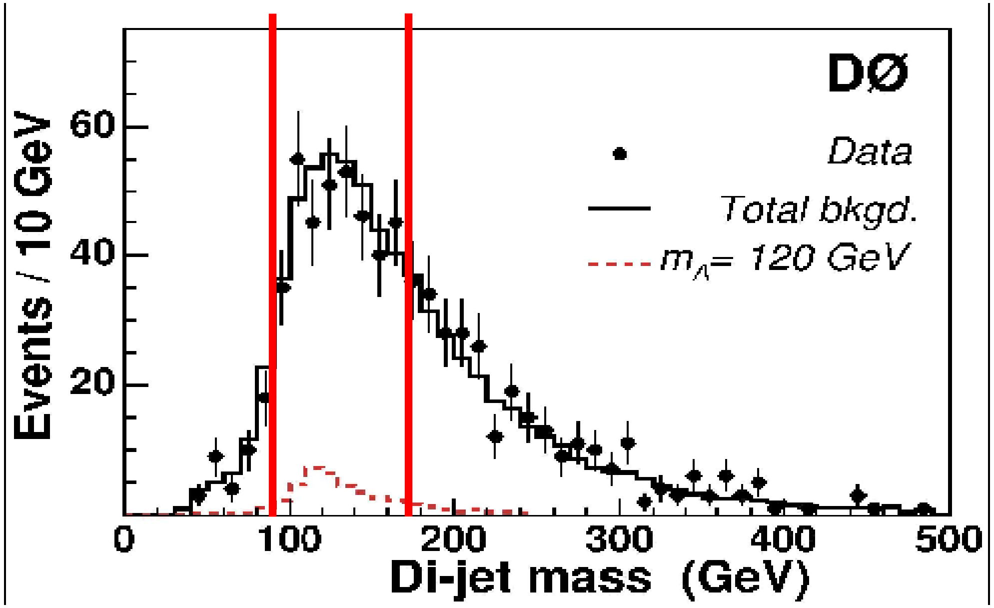
New physics: Supersymmetry

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



DØ SUSY Higgs Search

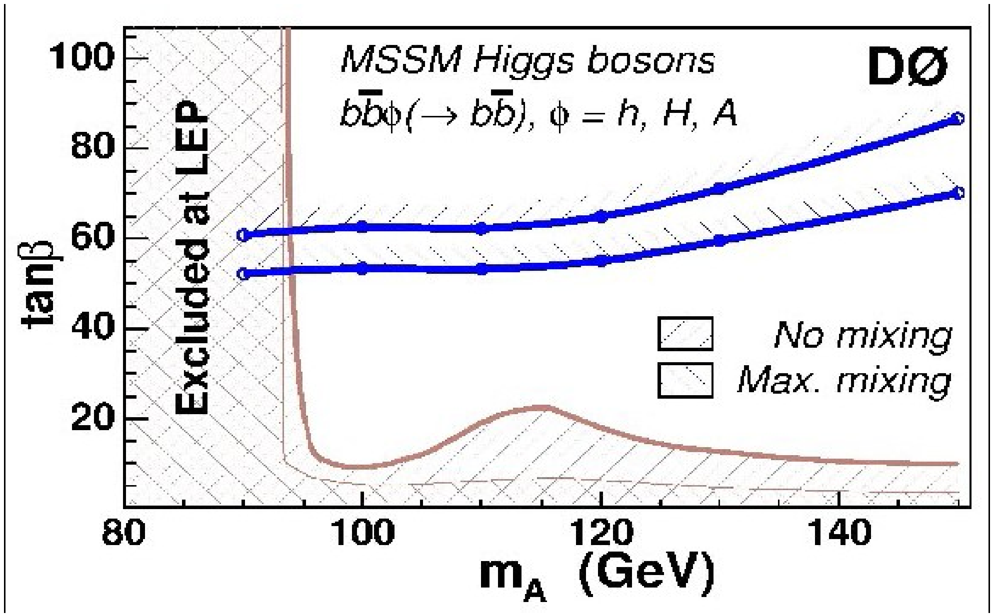




Search for bbb bump on bbb background

Interpret as limits in m_A / tanB plane

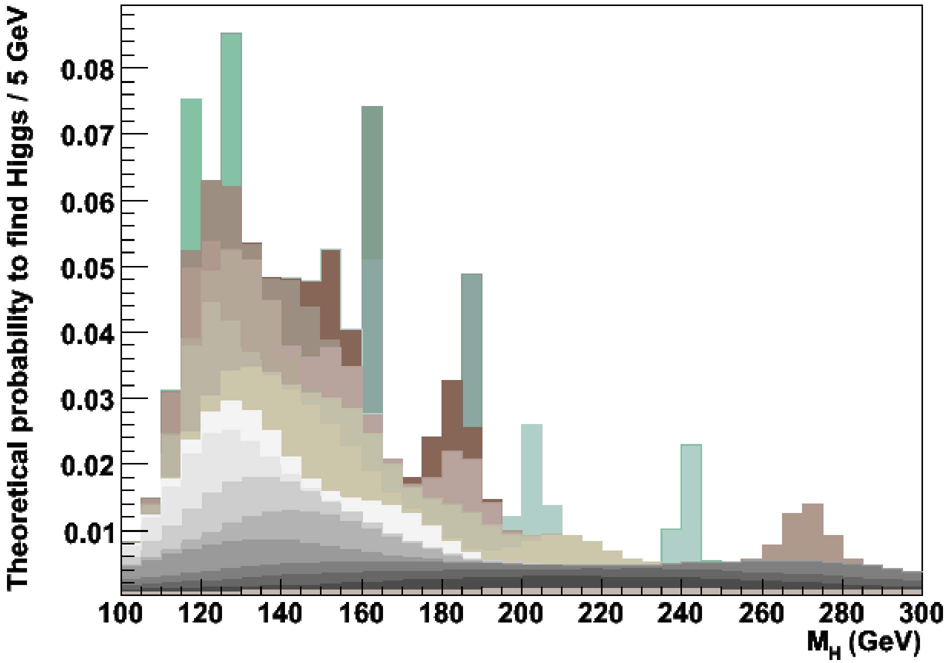
PRL 95, 151801 (2005)



Why is the Higgs so Light?

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

Lots of great ideas
Need experimental input

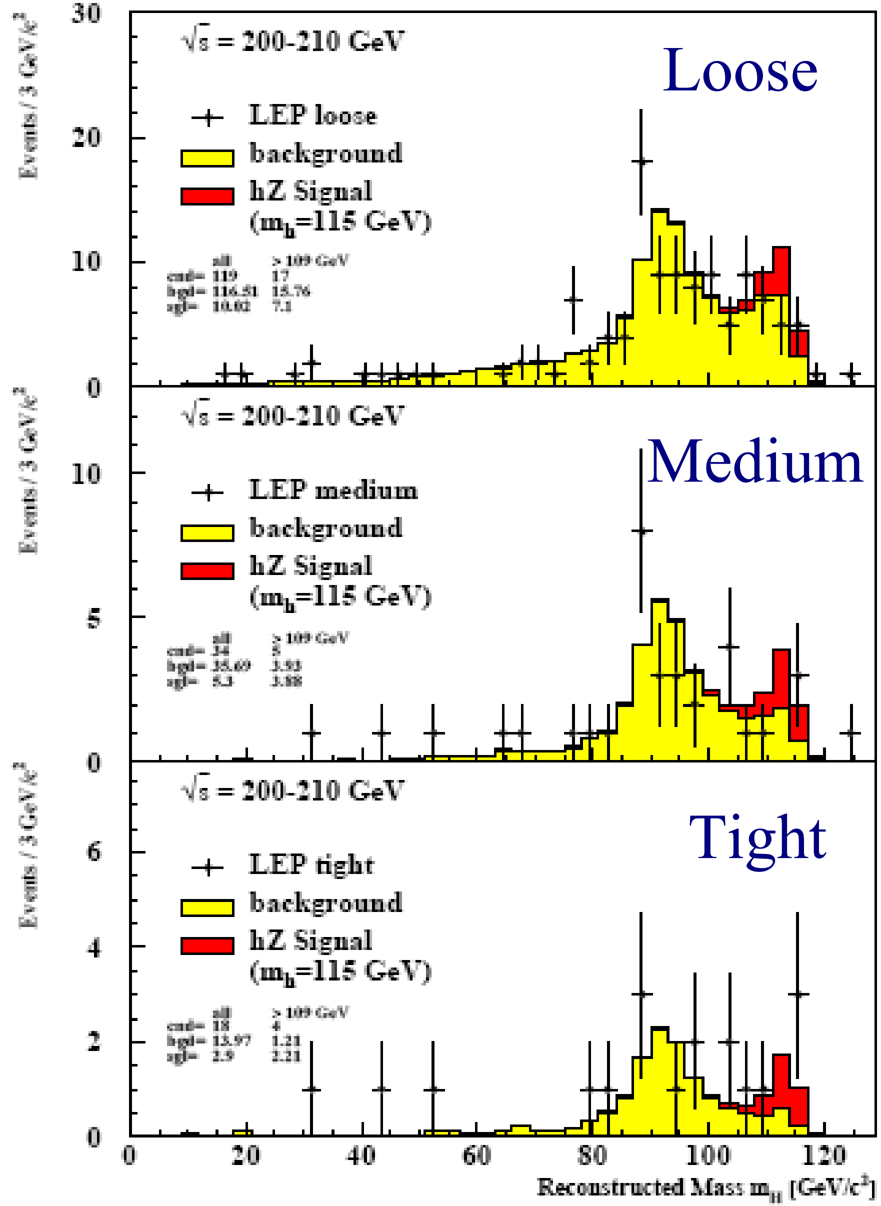


LEP @ CERN in 2000

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:

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

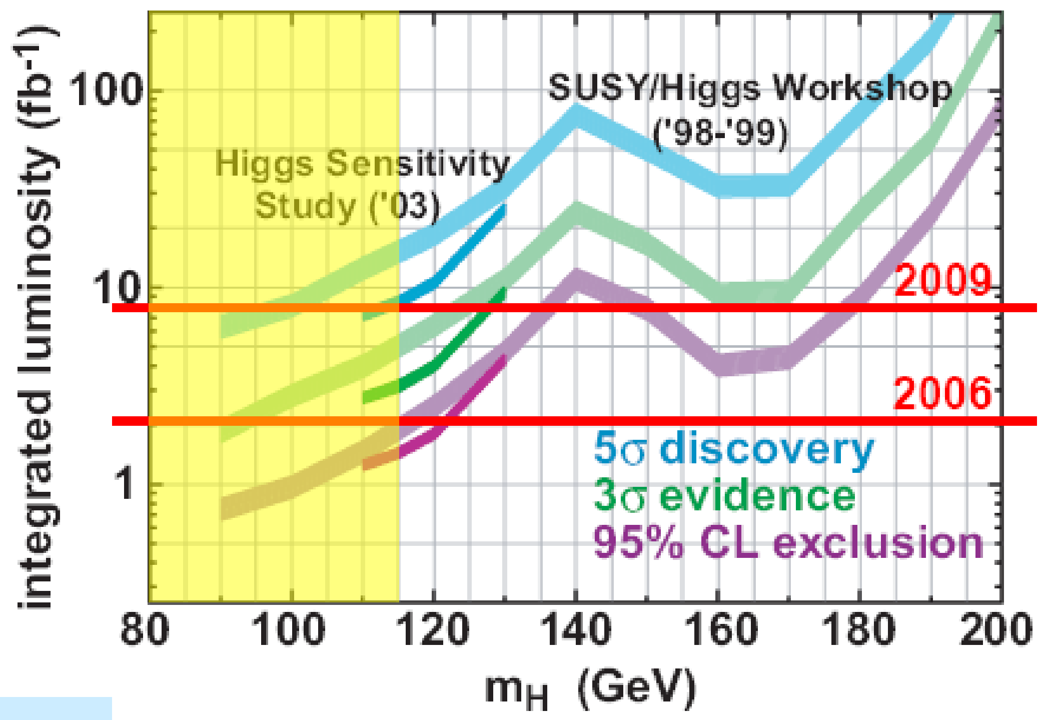
d_{ij} refers to "data" for model being tested: Observed events, or expected Background or Signal+Background

- 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

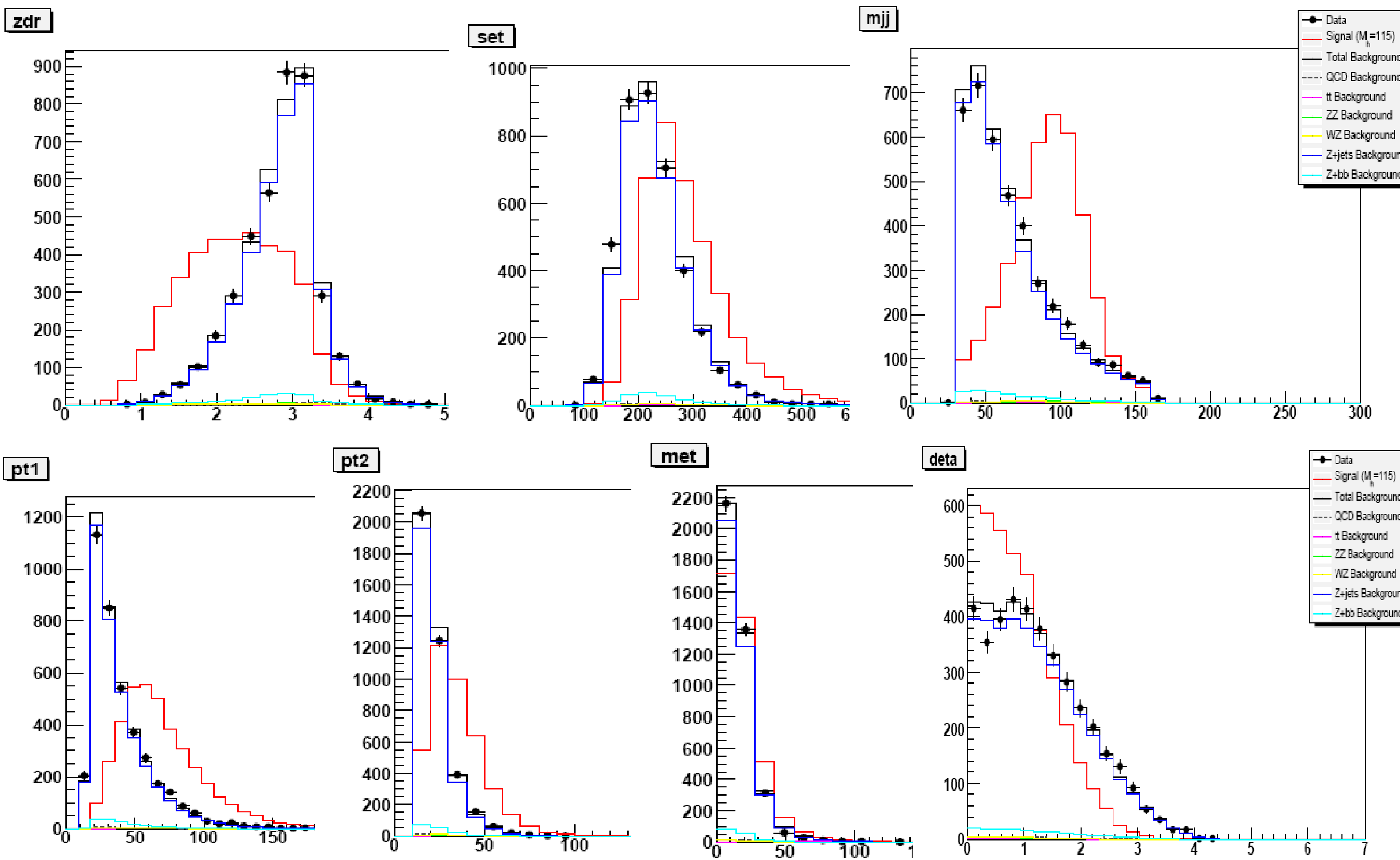
6

Sensitivity

2003 study



ZH->μμbb Pre-b-tagging

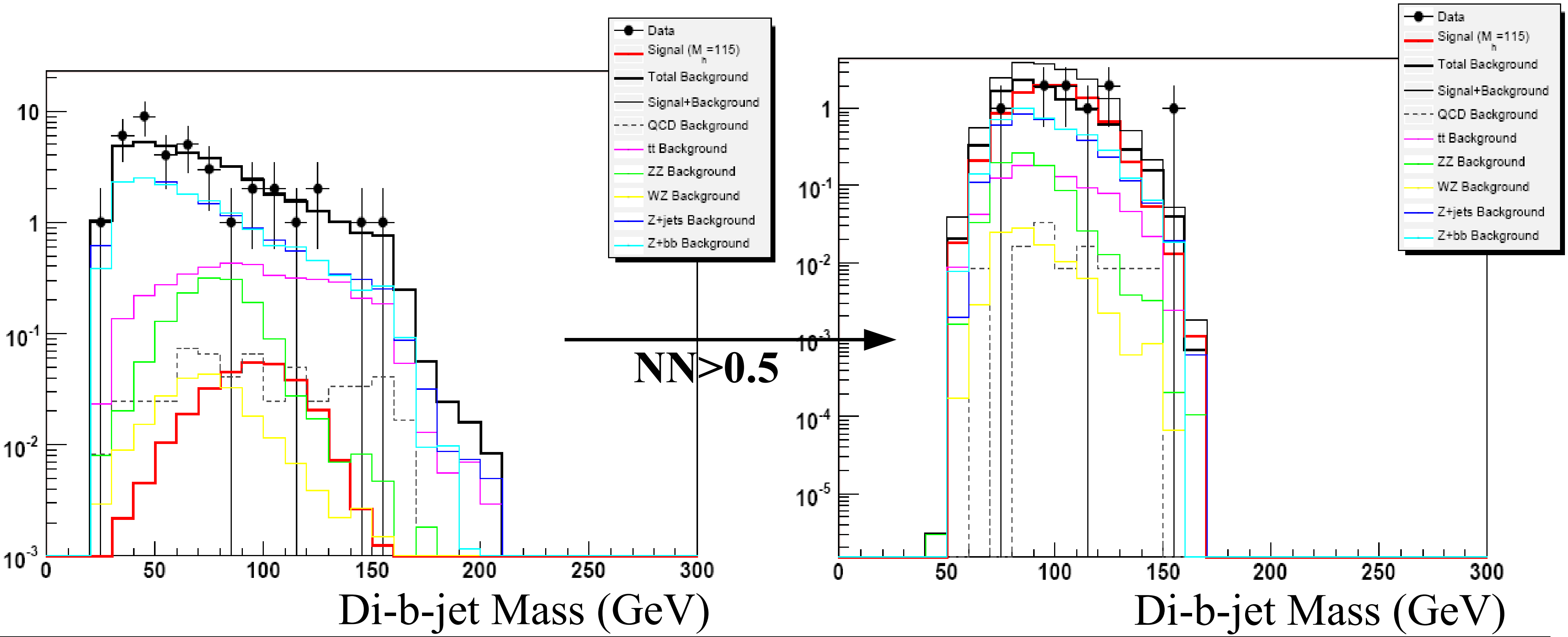


Neural Net Cross-Checks

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%

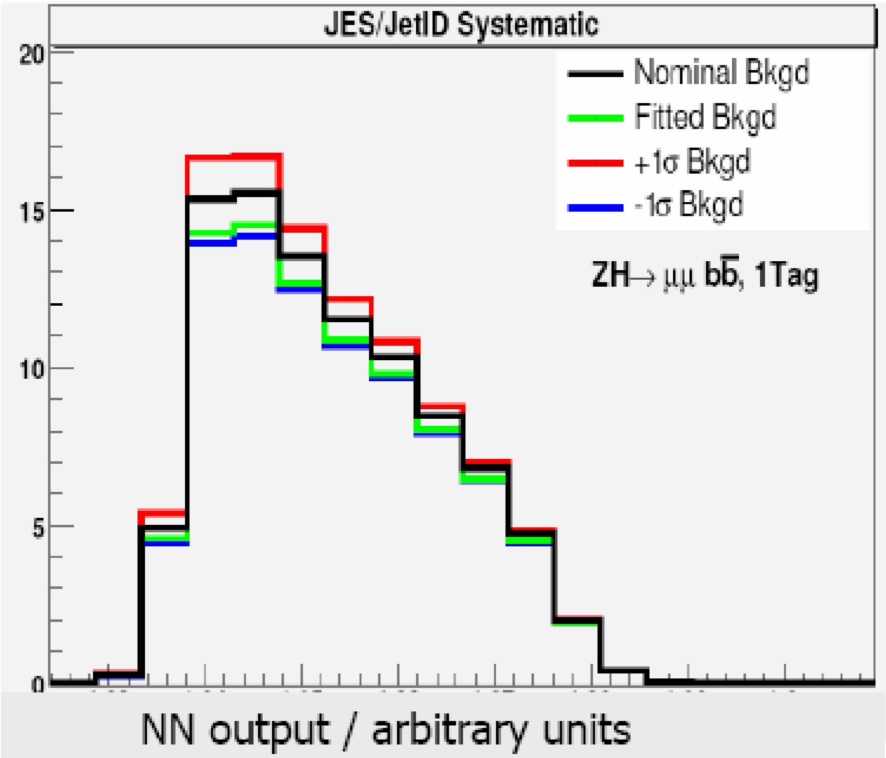
Lepton ID, 2%

Background cross-sections, 5-30%

QCD estimation, 20%

Jet-energy scale* →

b-tagging*



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

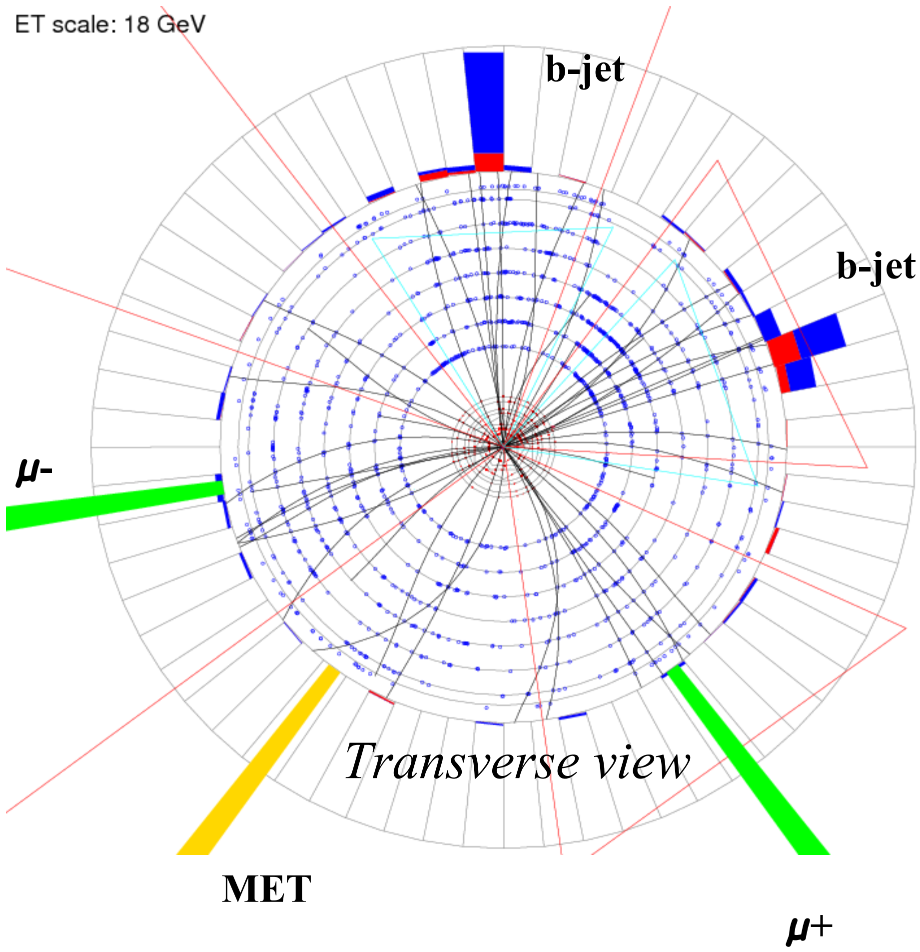
Event Kinematics

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



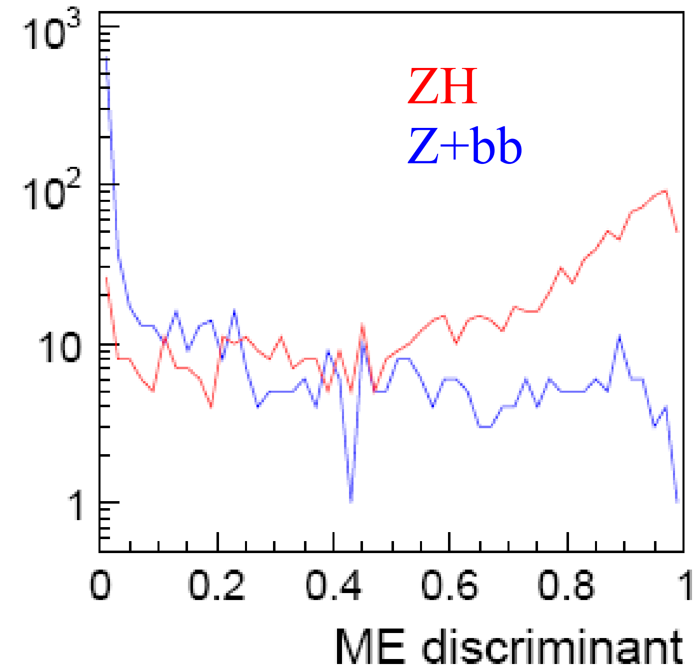
Too complicated for NN

Matrix Elements

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

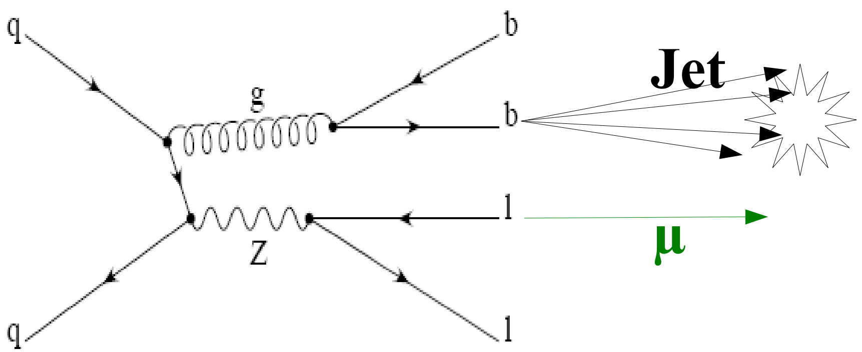
Use MC integration methods

Include as inputs to NN



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

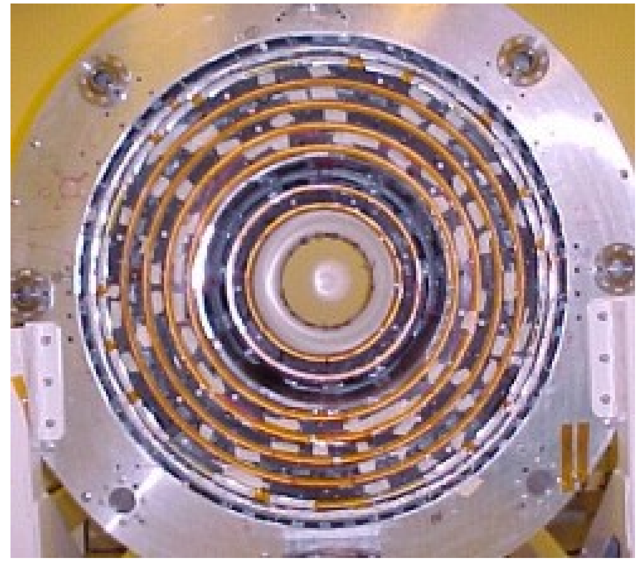
- m: detector measurement of event.
- x: integration parameters
- $k(x,m)$: parton solution given m and x.
- f_Φ: phase-space factors.
- $f_a f_b$: PDFs from MCFM.
- M_{ab}: matrix element from MCFM.
- T: transfer functions

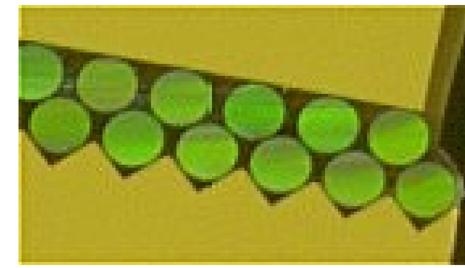


MET = μ1+μ2+j1+j2+σ(MET)

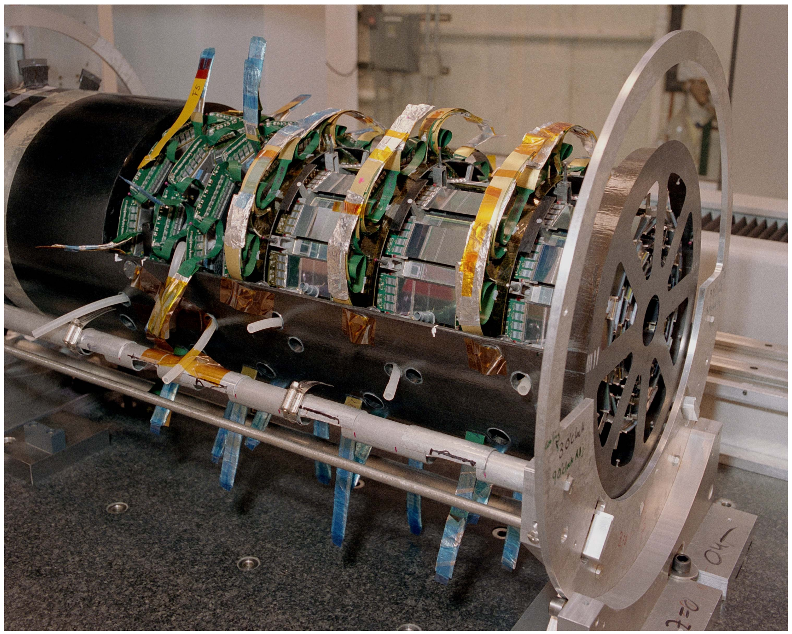
Tracking

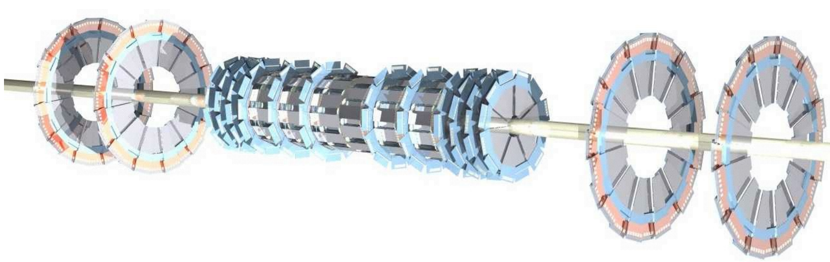
Central Fiber Tracker

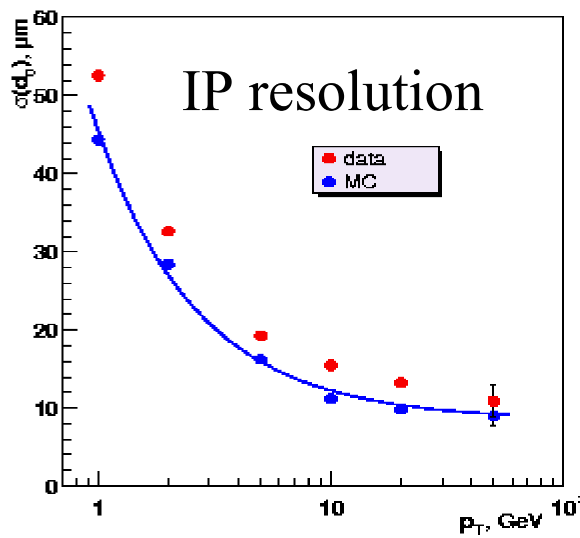


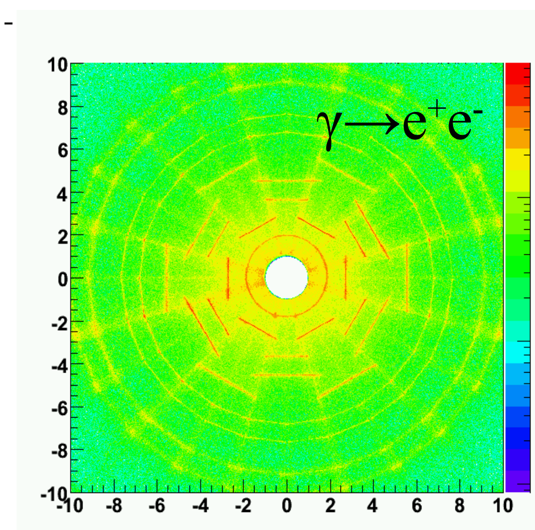


Silicon Microstrip Tracker



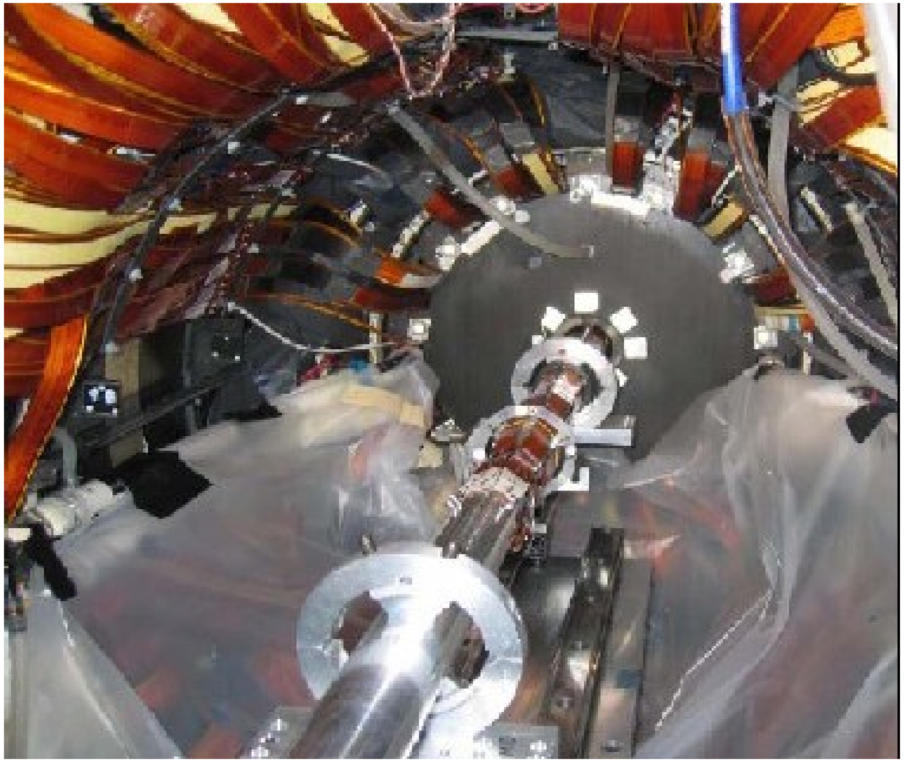




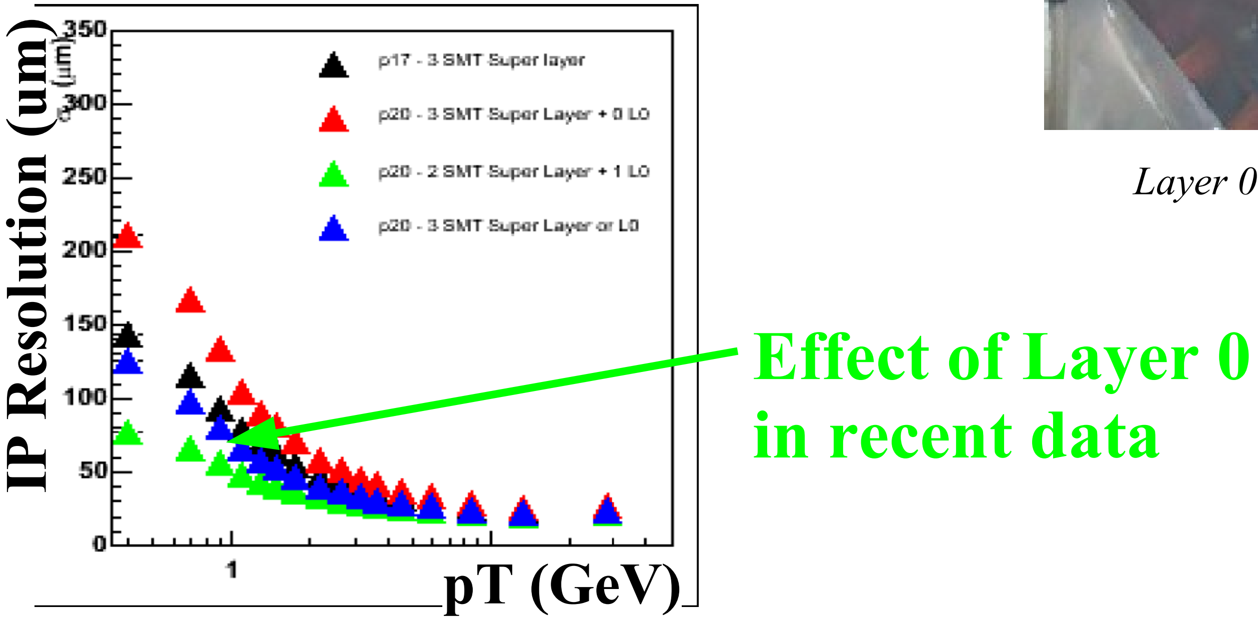


Layer 0 of Silicon Tracker

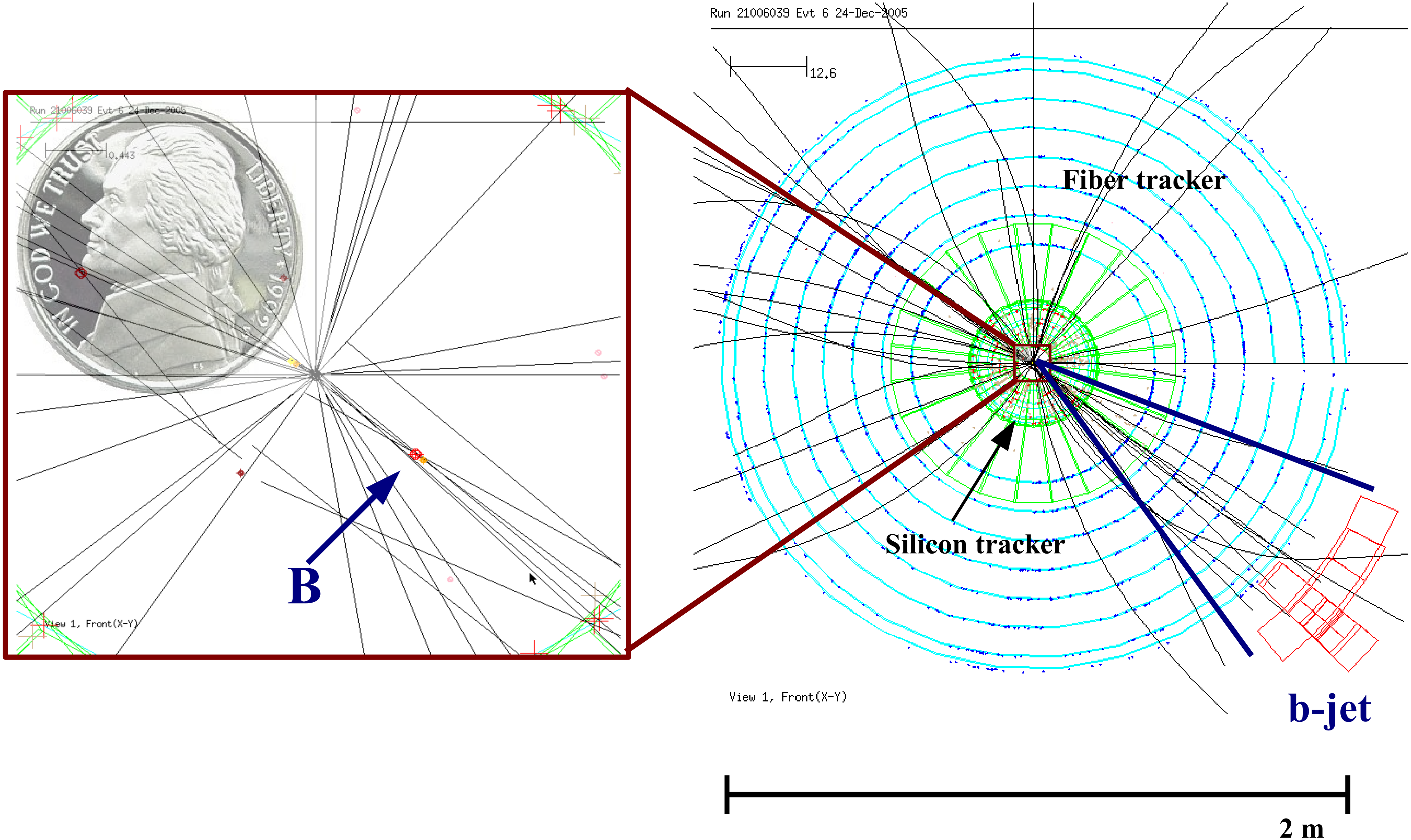
- Silicon detectors mounted just outside the beampipe
- Installed fall '06
- Better track impact-parameter resolution -> Better b-jet tagging



Layer 0 being inserted into the silicon tracker



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.

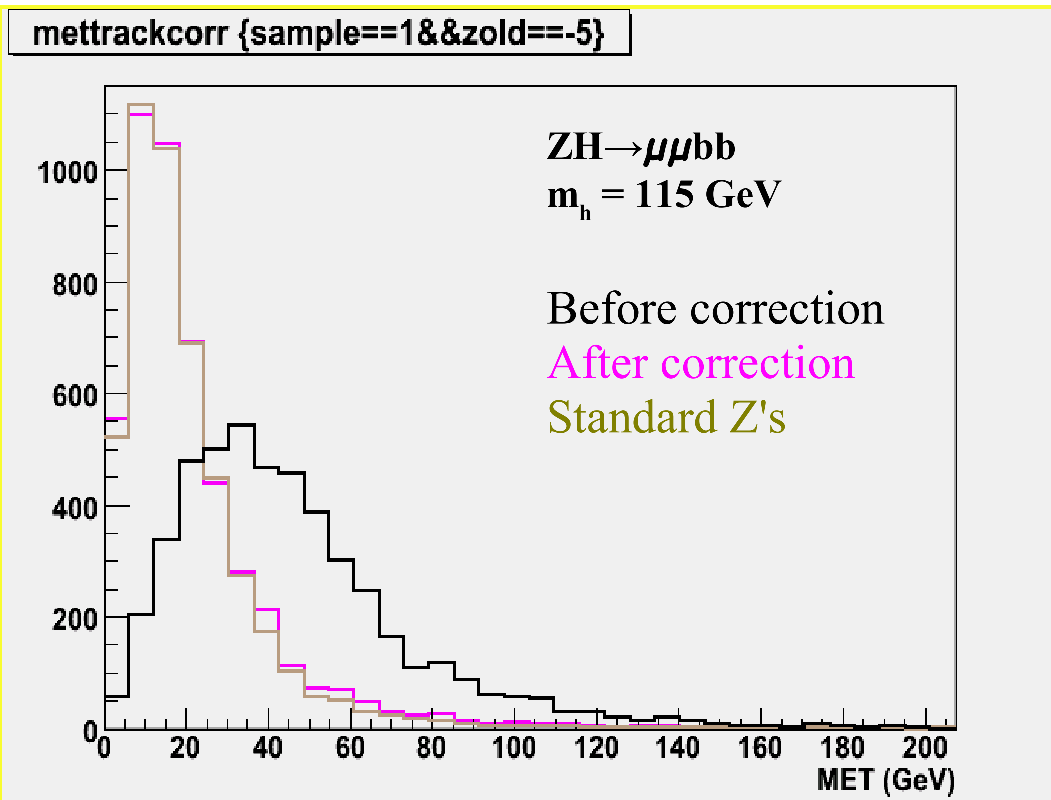
κ_{udsc} - Correlations between the NN tagger and the SLT tagger on *udsc*-jets.

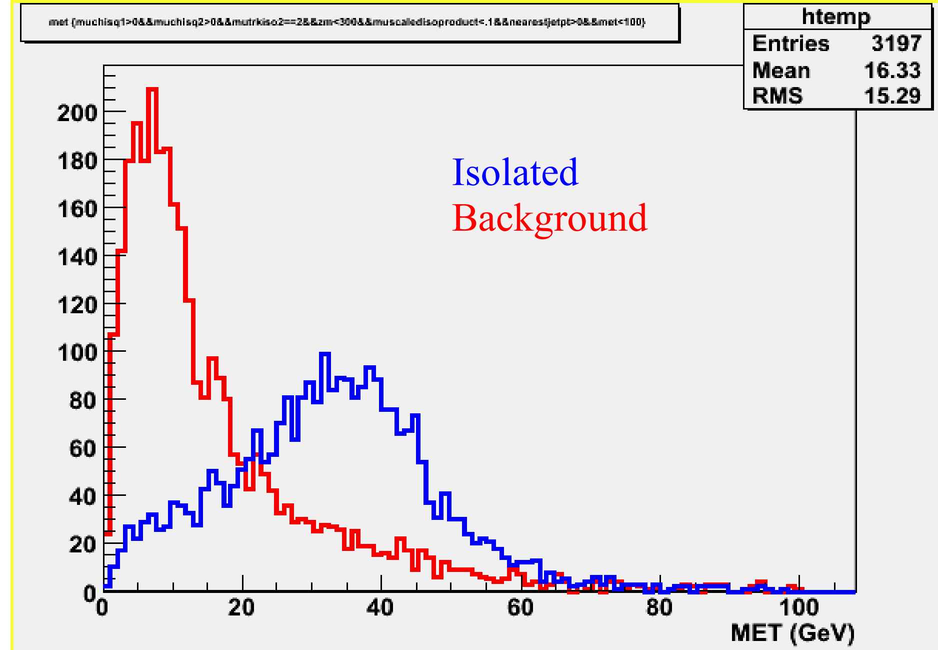
$p_{T\,Rel}$ - Ratio of the SLT tagging efficiencies on *c* and *uds*-jets.

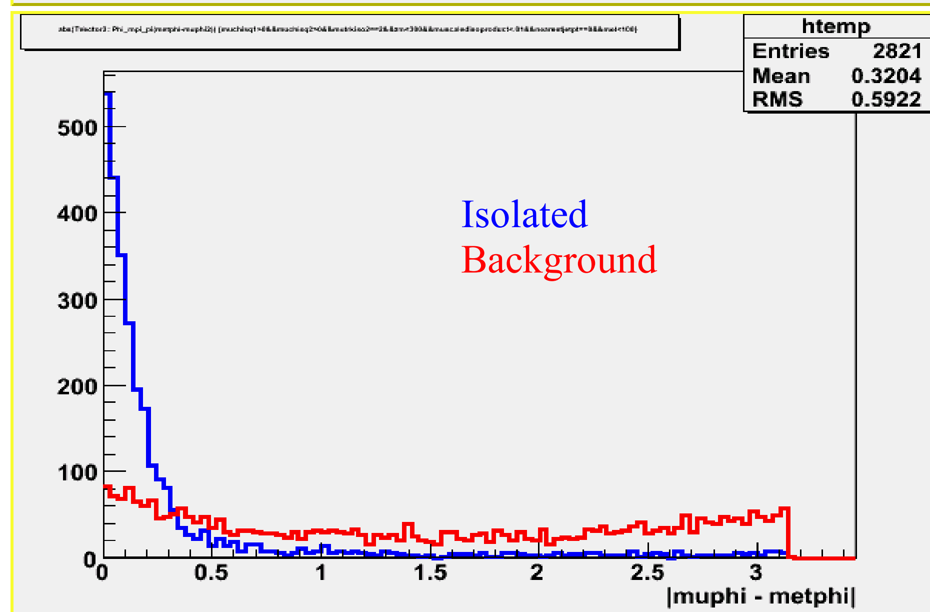
Lepton Efficiency

MET from non-reconstructed muon is present

And points in the direction of the isolated track

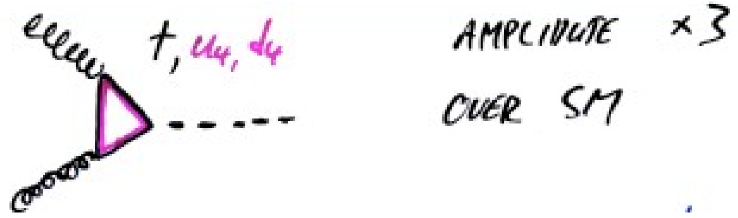




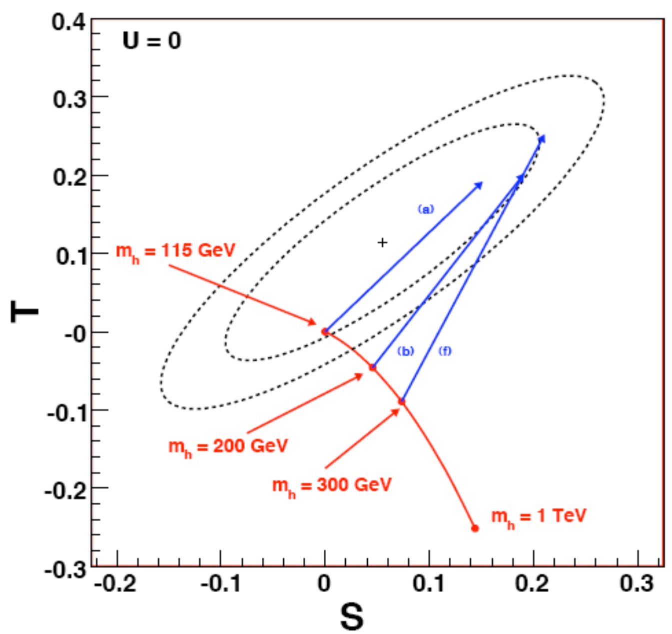


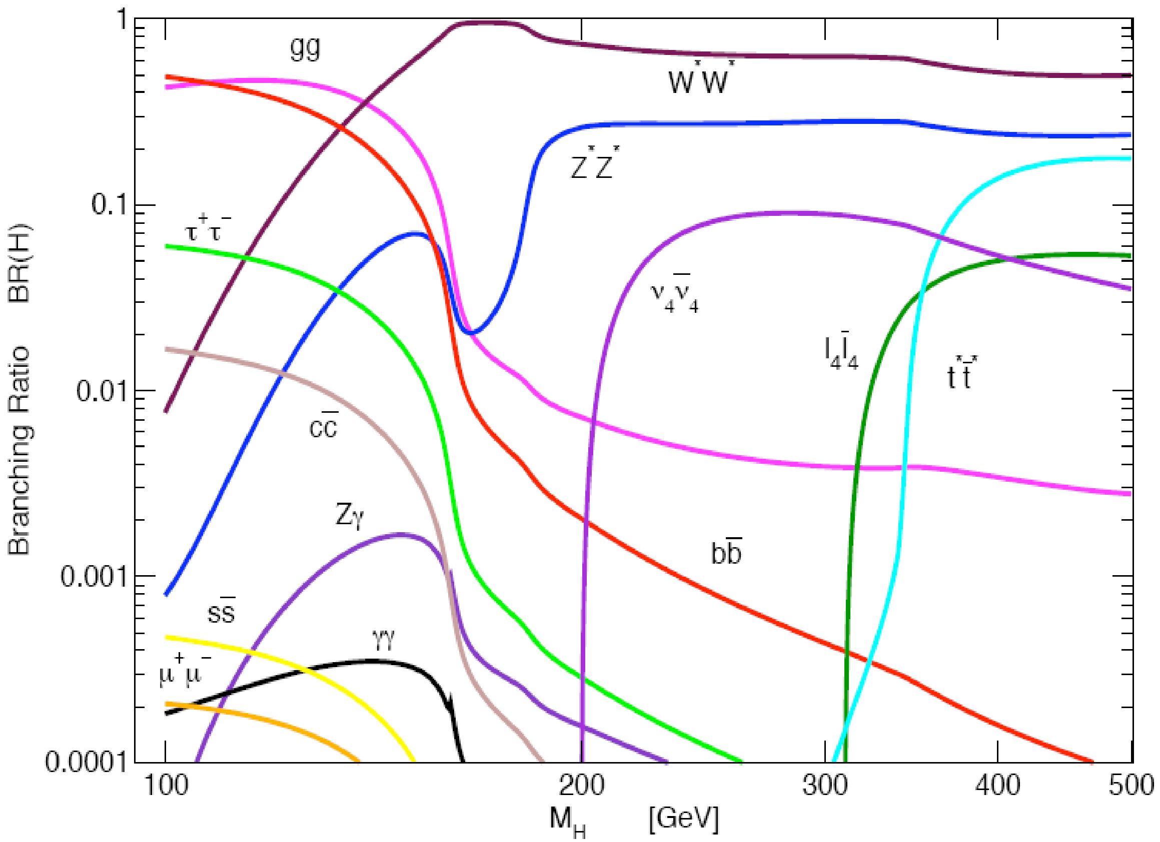
4^{th} Generation

9x more gg->H production!
Reduced H->bb,tautau
Enhanced H->gg



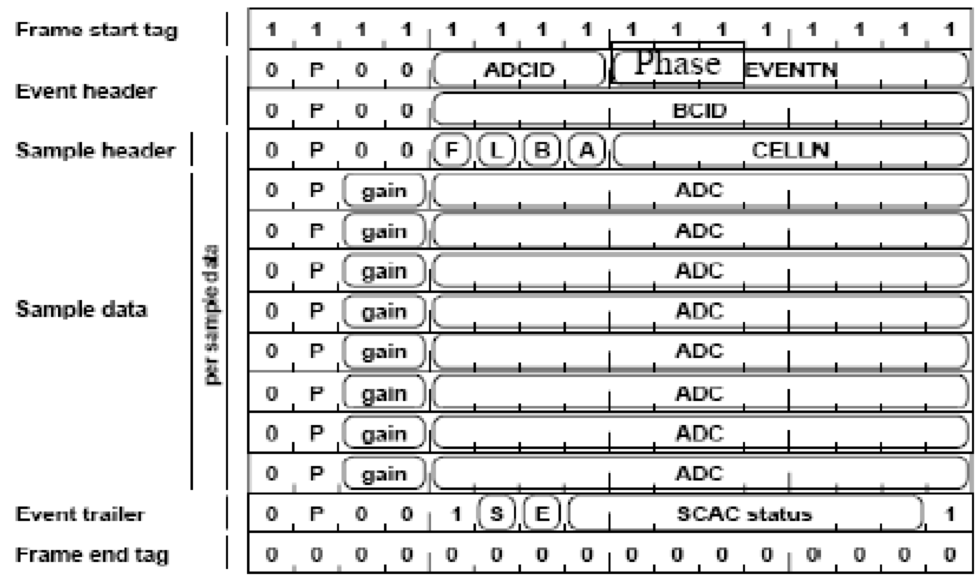
Relieves m_H EW tension





FEB Header Monitor (FEBMon)

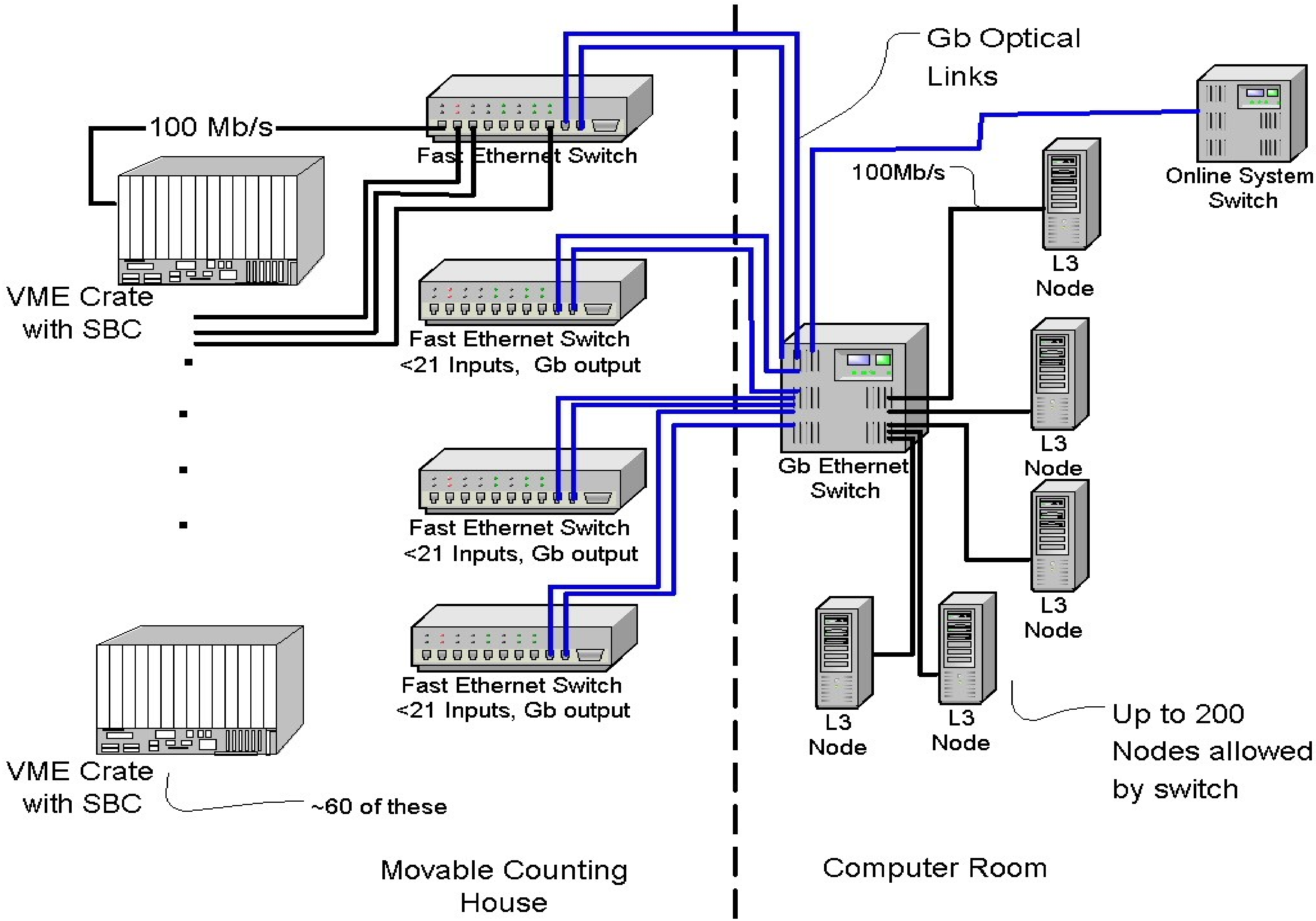
- **In the data sent from each FEB is information on data quality**
  - transmission errors (parity)
  - radiation-induced logic errors (SEU)
  - synchronization between FEBs (same event)
  - synchronization of GSELs within a FEB
  - various other checks that each FEB is behaving as expected
- This information 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.;
```

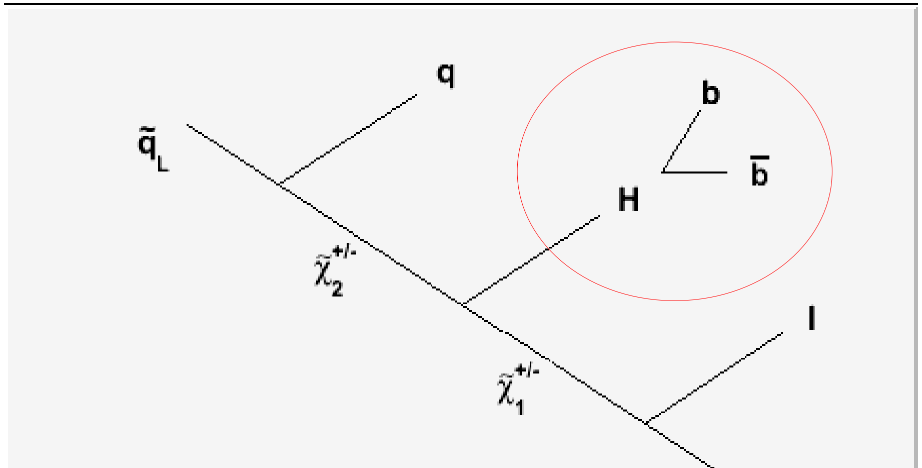
DAQ System



100 Mb/s
Fast Ethernet Switch
Gb Optical
Links
100Mb/s
Online System
Switch
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

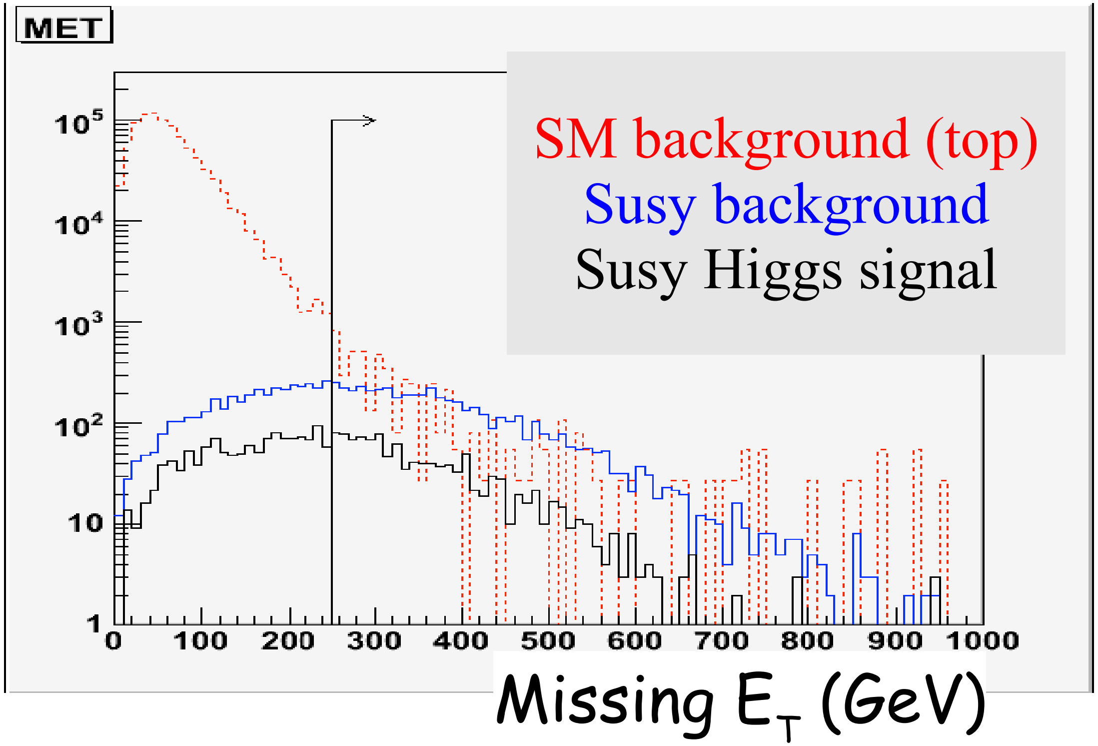
The Higgs in Supersymmetry Decays

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



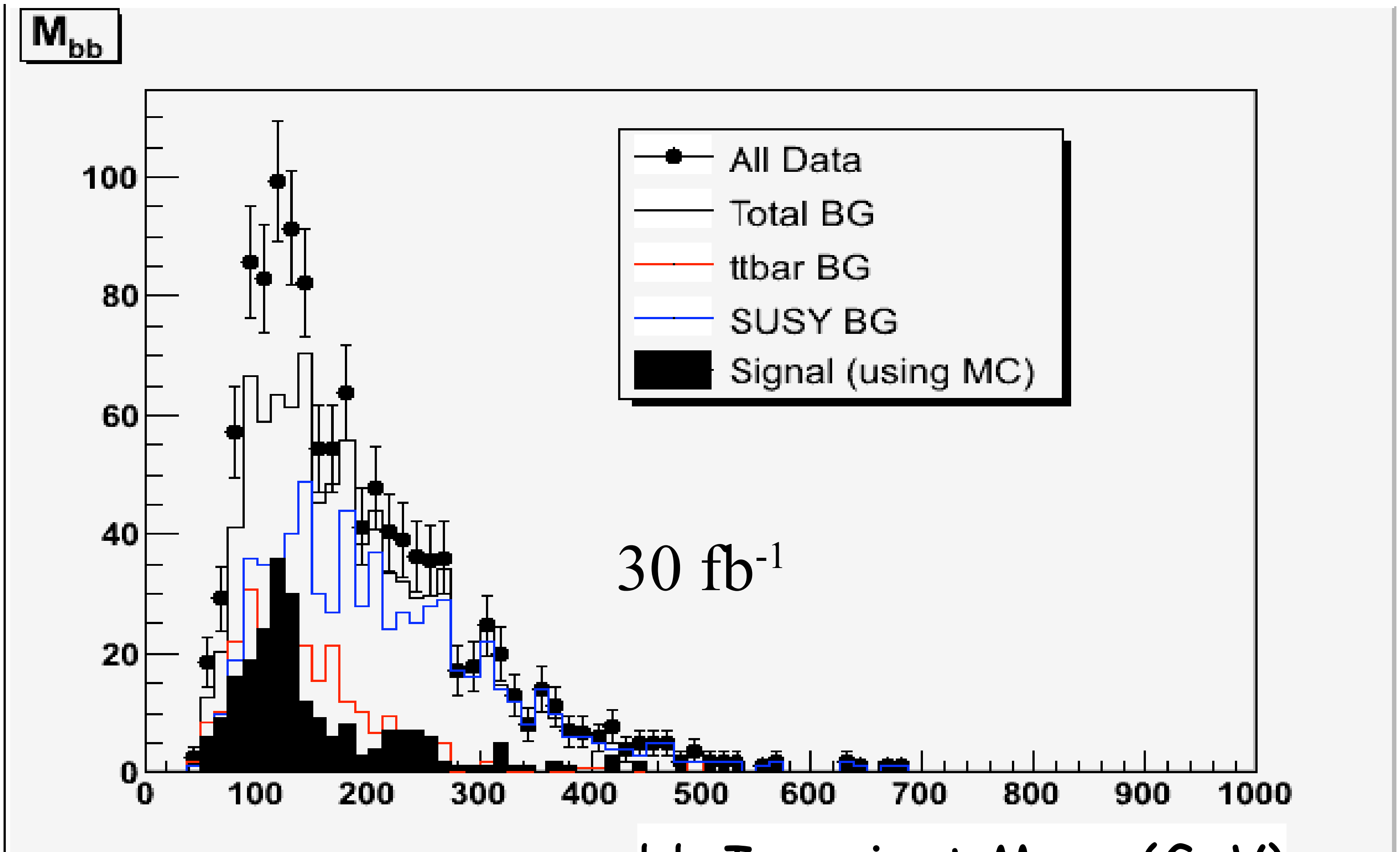
BR $X_2 \to X_1 H$ = 19%

Require MET>250 GeV to reduce SM background



The Higgs in Supersymmetry Decays

Look for bump from H->bb decays



bb Invariant Mass (GeV)