Higgs Boson Searches at the Tevatron

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- Higgs production
- Search for heavy Higgs
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- Search for light Higgs
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  - $ZH \rightarrow \nu\nu b\bar{b}$
  - $ZH \rightarrow llb\bar{b}$
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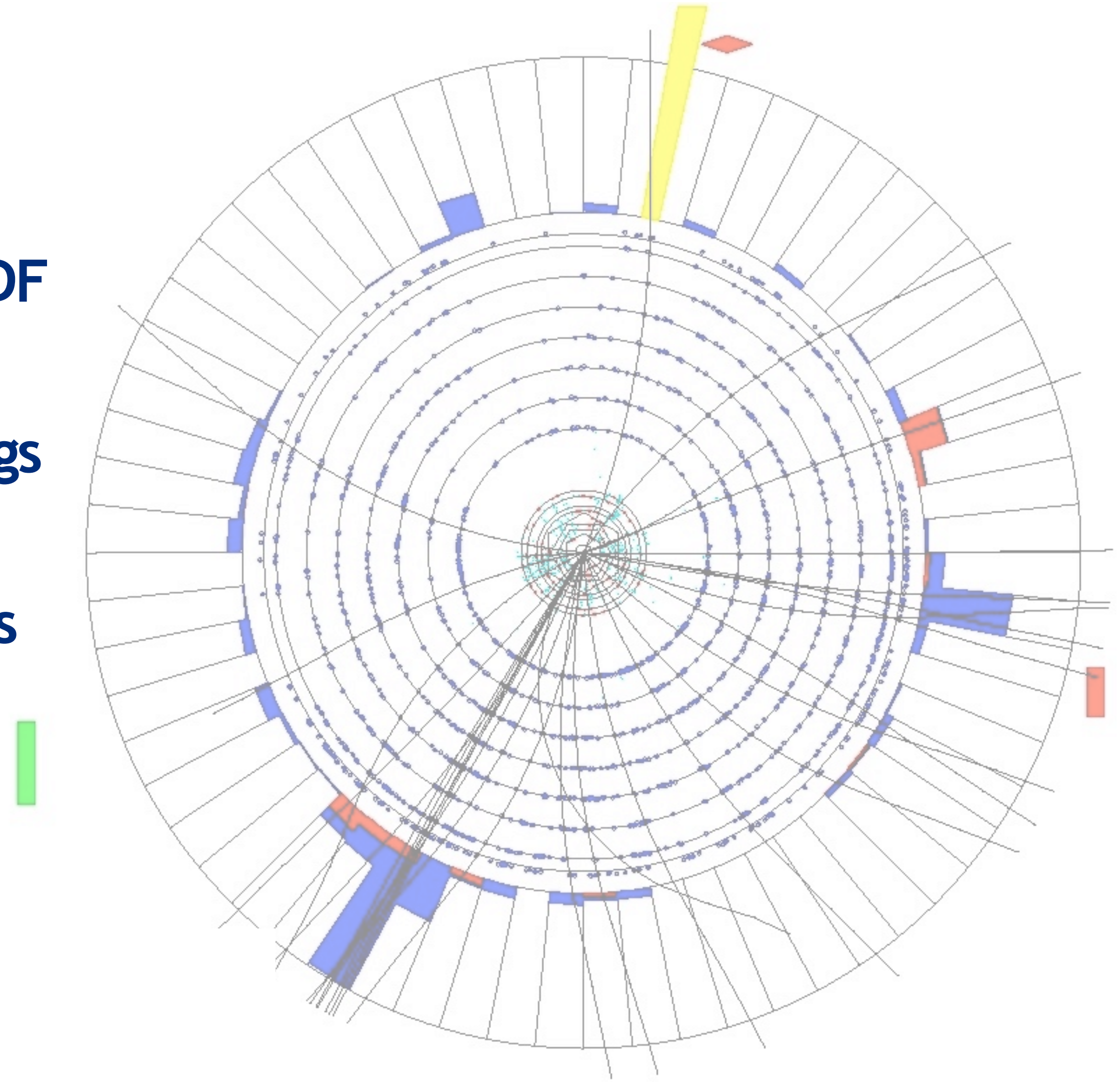
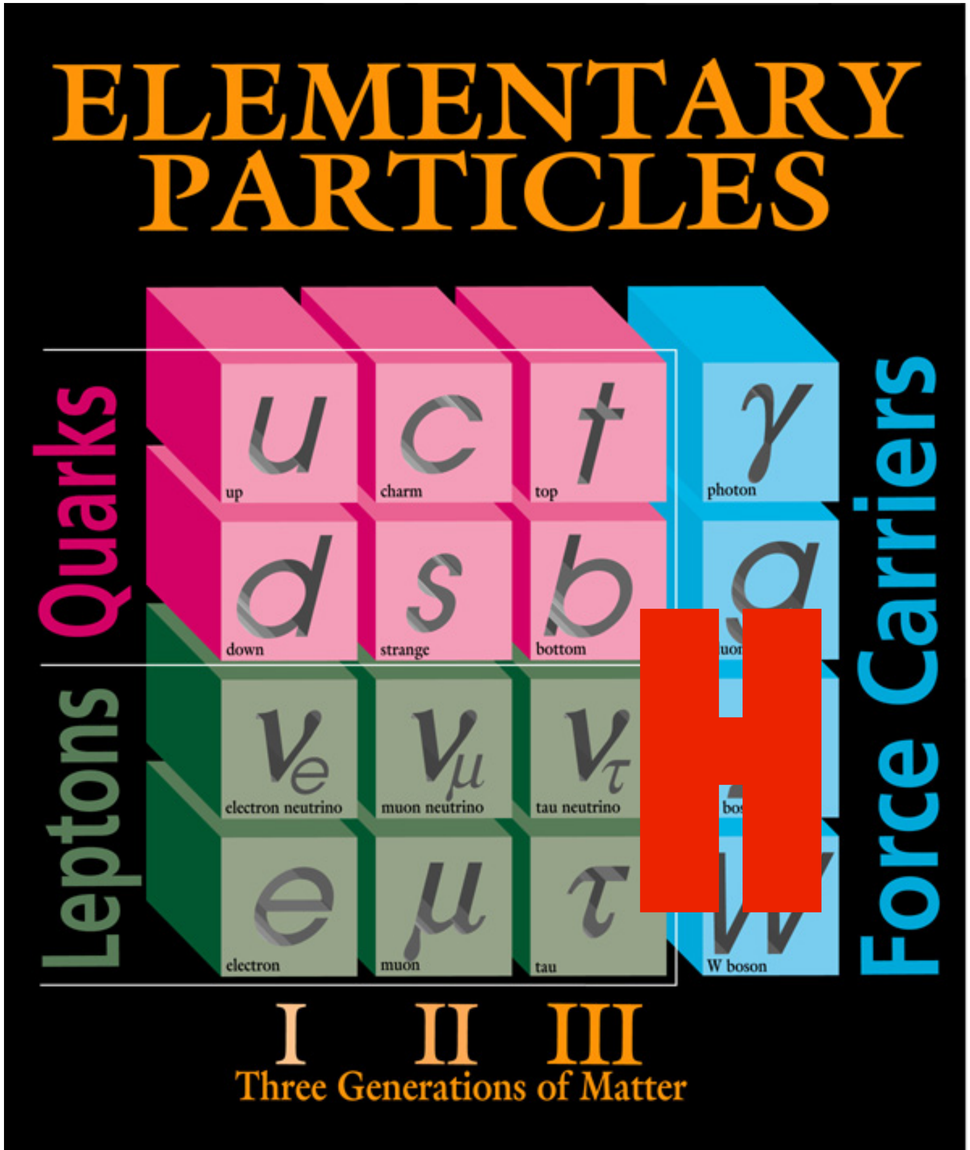
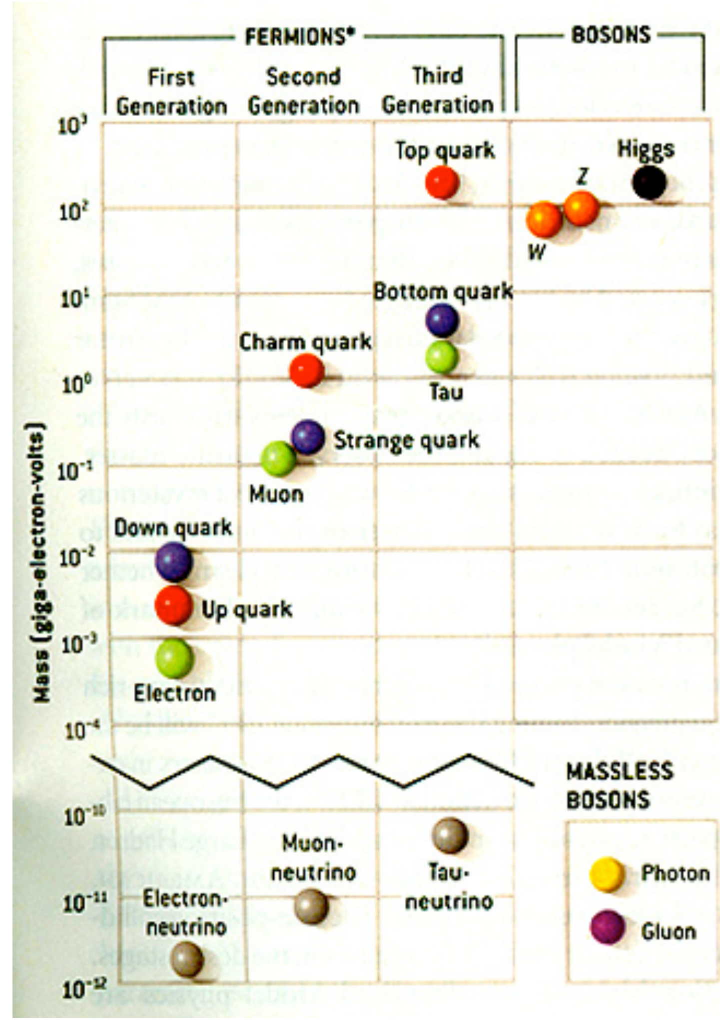
- Conclusion



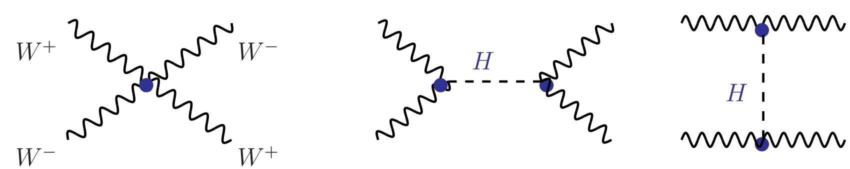
The Standard Model



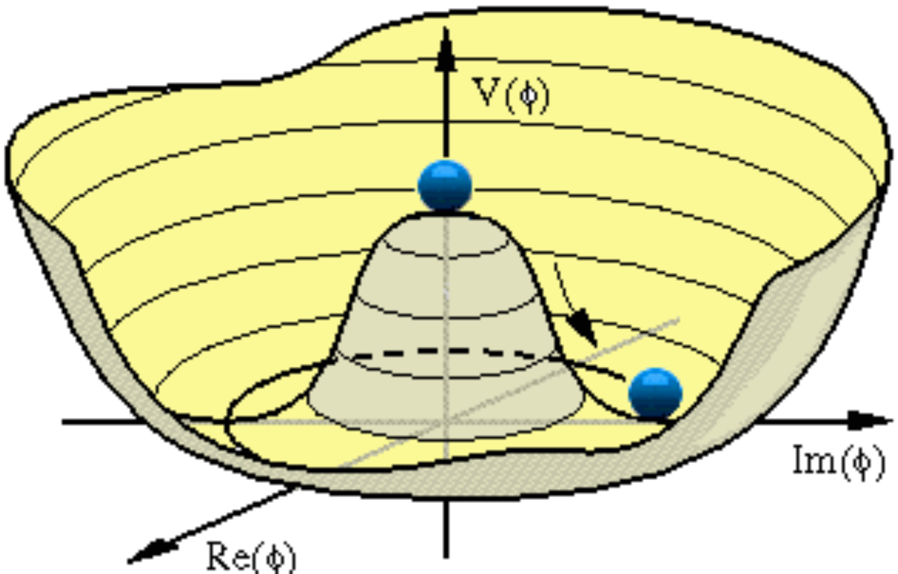
Fermilab 95-759



Kane, Scientific American, June 2003



The Higgs Mechanism



$V(\Phi)=\mu^2|\Phi|+\lambda(|\Phi|^2)^2$

- The Higgs field acquires a vacuum expectation value

$$v = \sqrt{\frac{-\mu^2}{2\lambda}} = 246\text{GeV}$$

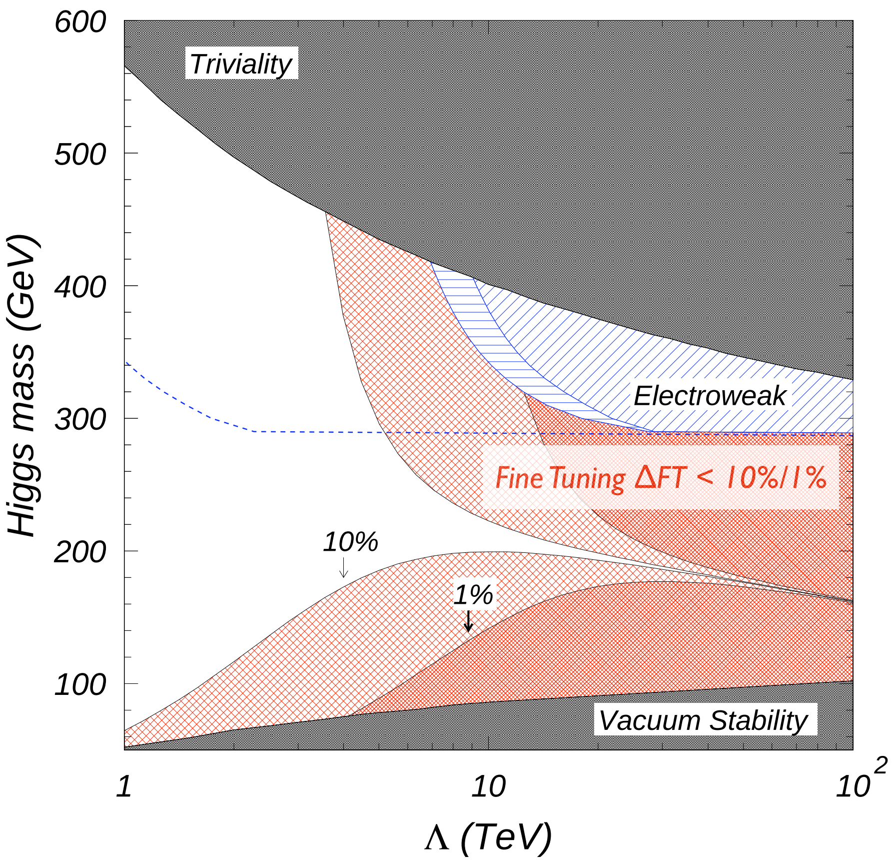
- Particles interact with the Higgs field and acquire an effective mass

$$\begin{aligned} m_\gamma &= 0 \\ m_W &= \frac{1}{2}vg \\ m_Z &= \frac{1}{2}vg\frac{1}{\cos\theta_W} \\ m_H &= \sqrt{2\lambda v^2} \\ m_f &= \frac{1}{\sqrt{2}}g_f v \end{aligned}$$

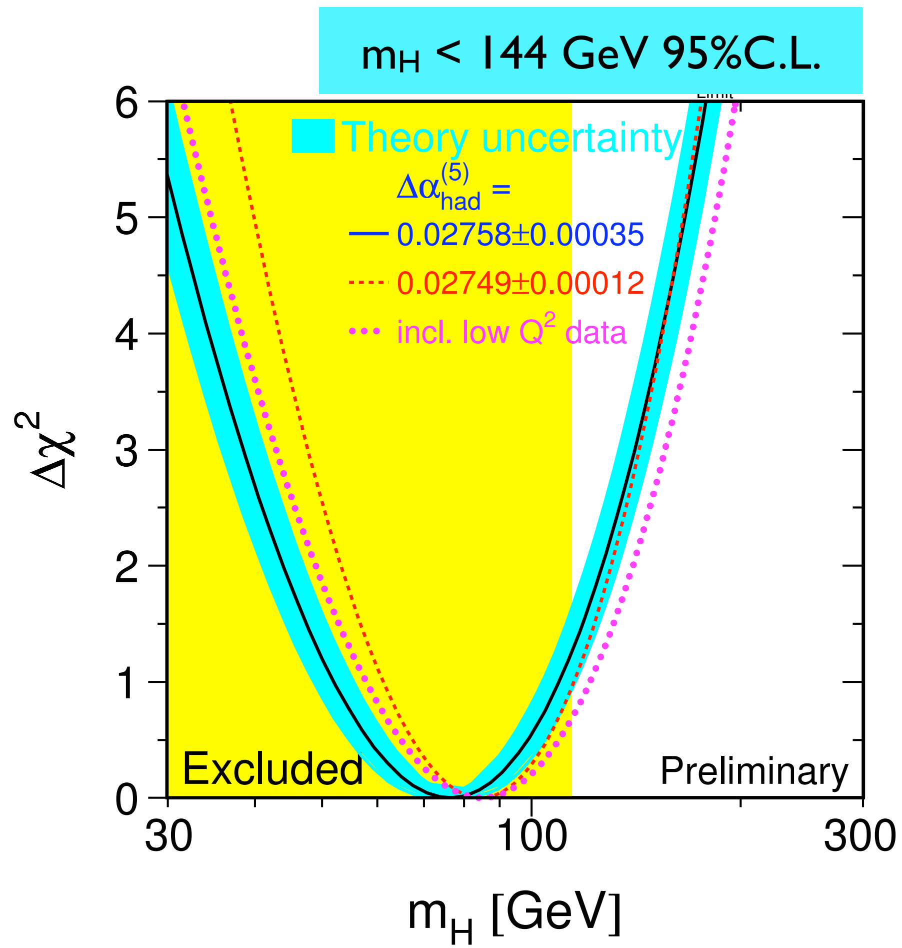
- The mass relation between γ, W and Z bosons is determined
- Couplings and branching ratios are determined.

Constraints on the Higgs Mass

Kolda, Murayama: JHEP 0007 (2000) 035

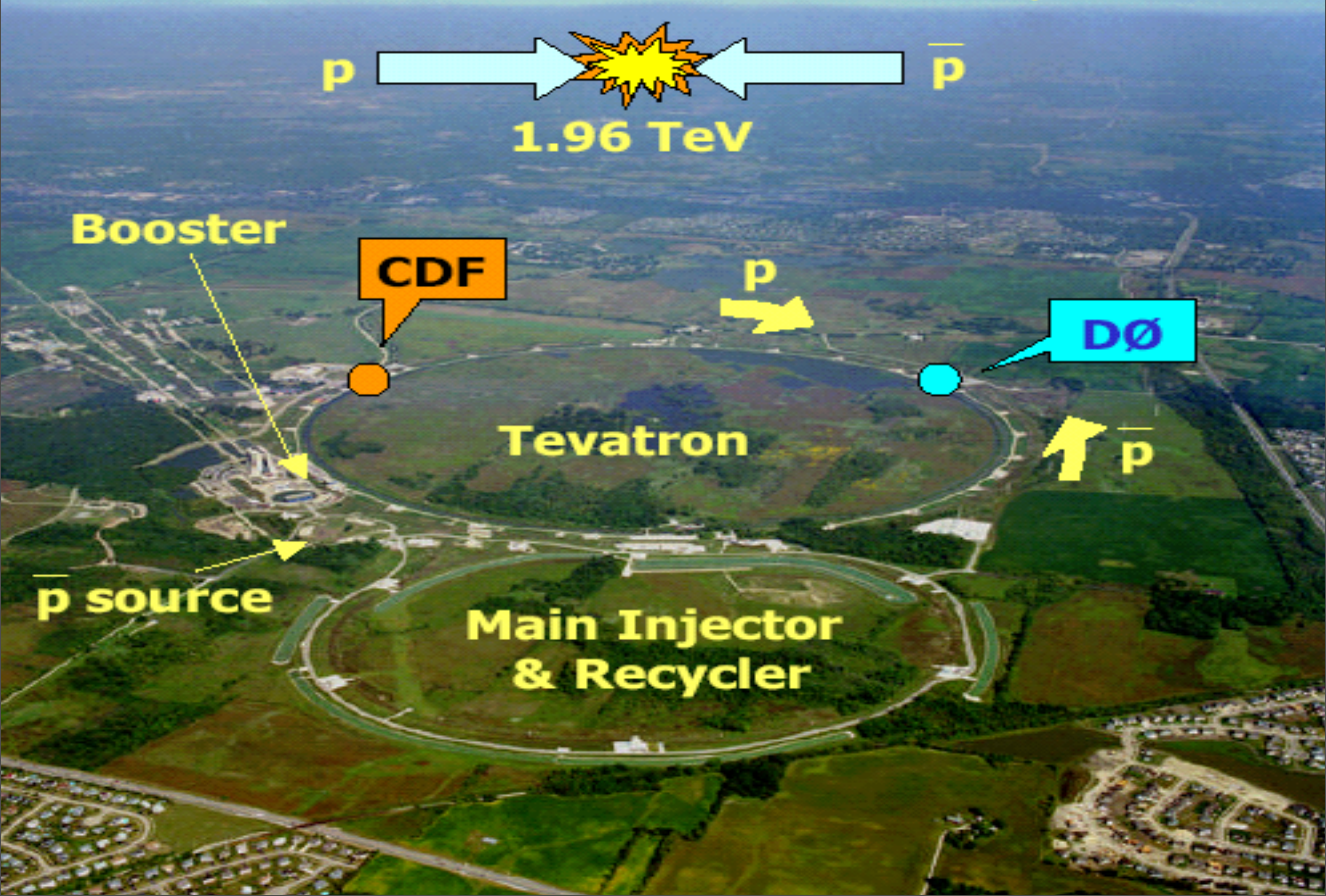


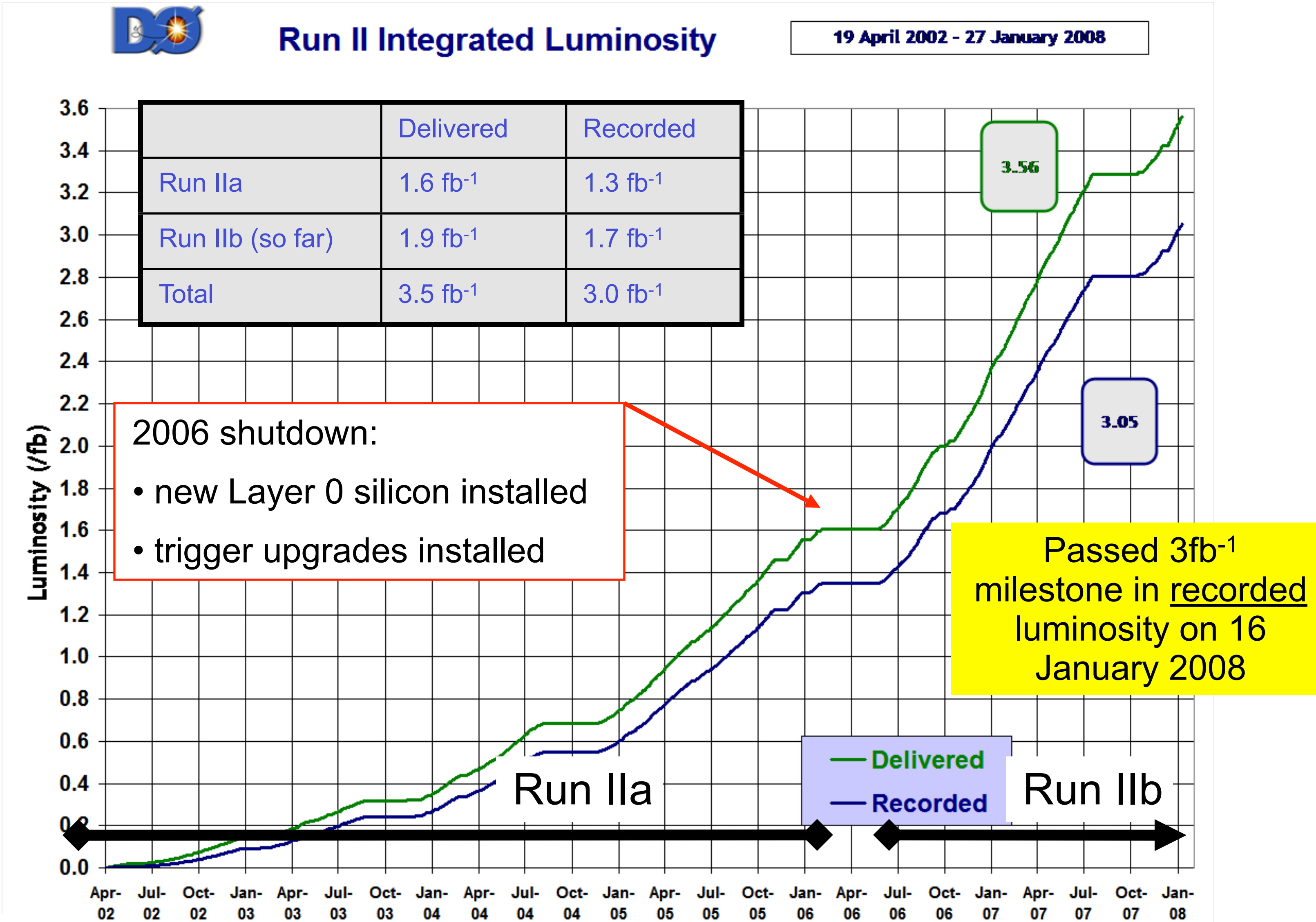
- Excluded by LEP



LEP EWWG

Tevatron


Chicago
p
$\bar{p}$
1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler

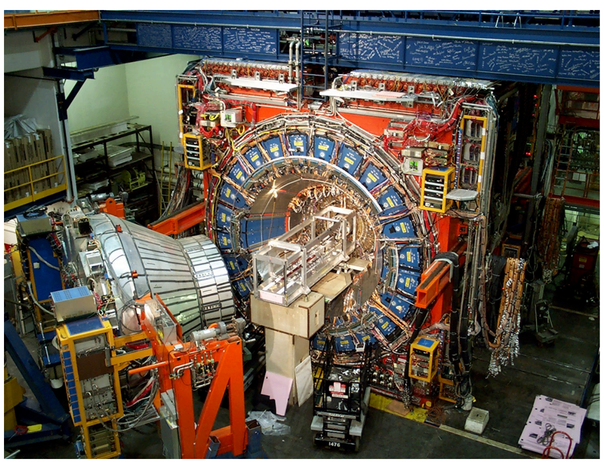


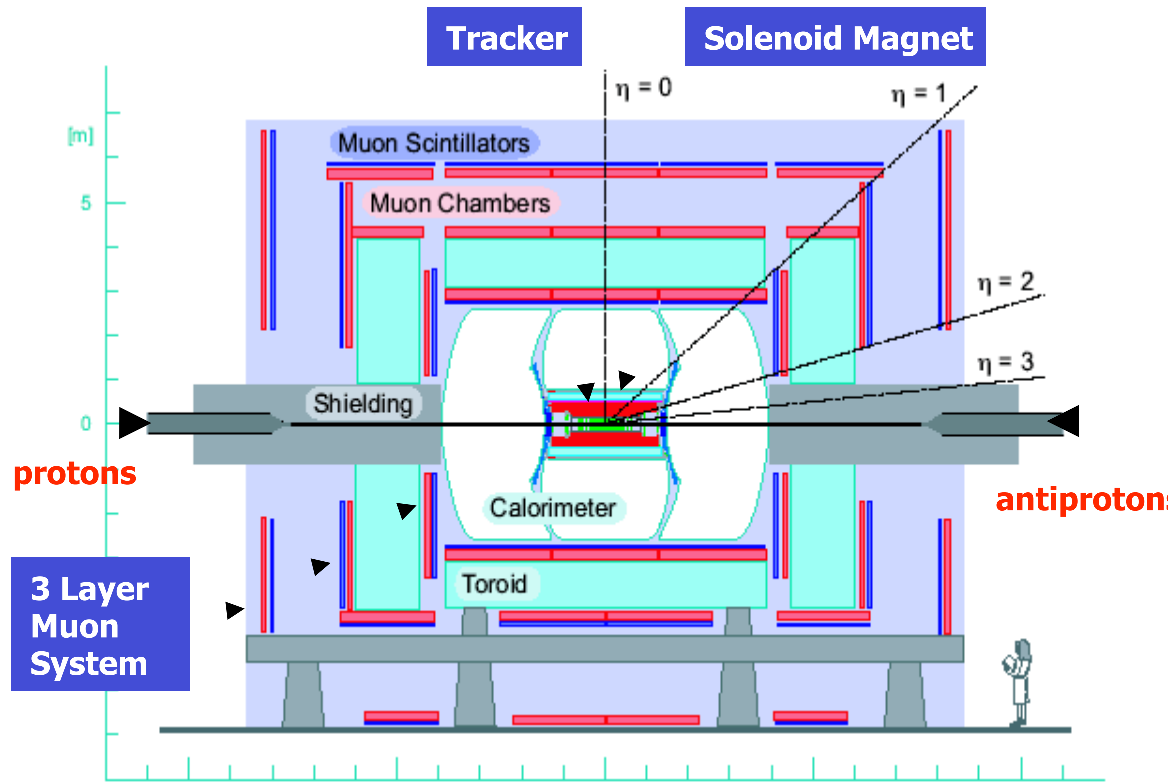
April 02

Jan 08

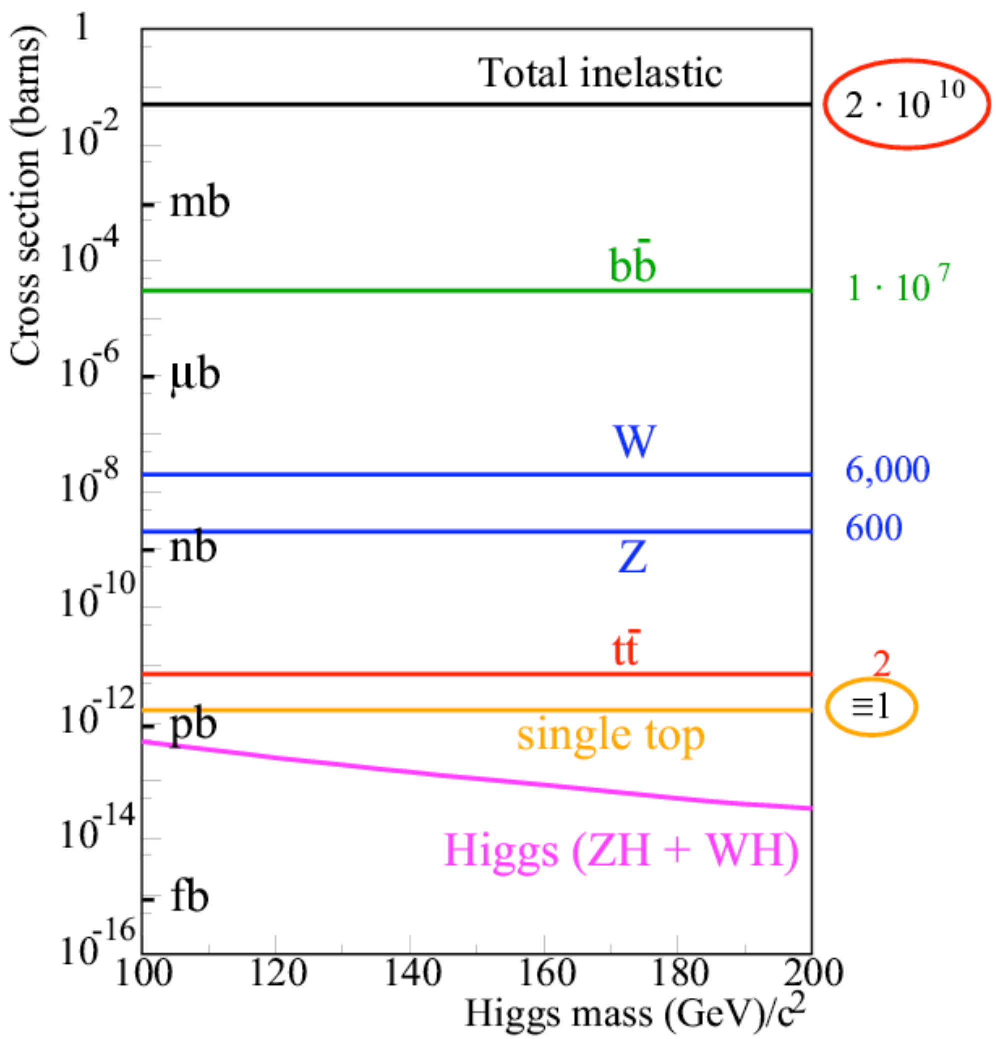
Two General Purpose Detectors:	CDF	DØ
Electron acceptance	$\lvert\eta\rvert<2.0$	$\lvert\eta\rvert<3.0$
Muon acceptance	$\lvert\eta\rvert<1.5$	$\lvert\eta\rvert<2.0$
Silicon Precision tracking	$\lvert\eta\rvert<2.0$	$\lvert\eta\rvert<3.0$
Hermetic Calorimeter	$\lvert\eta\rvert<3.6$	$\lvert\eta\rvert<4.2$

Powerful trigger systems (2.5MHz $\rightarrow$50Hz)
Dilepton triggers with p_T>4GeV





Tevatron Cross Sections



Total inelastic cross section.

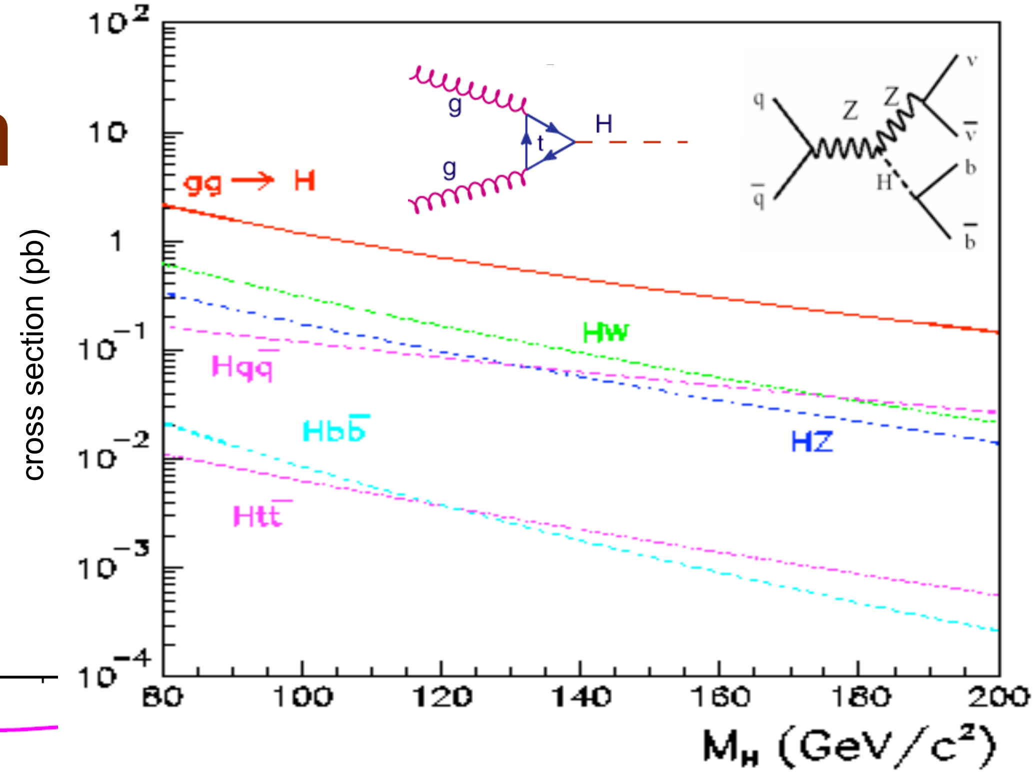
Light quarks are ubiquitous.

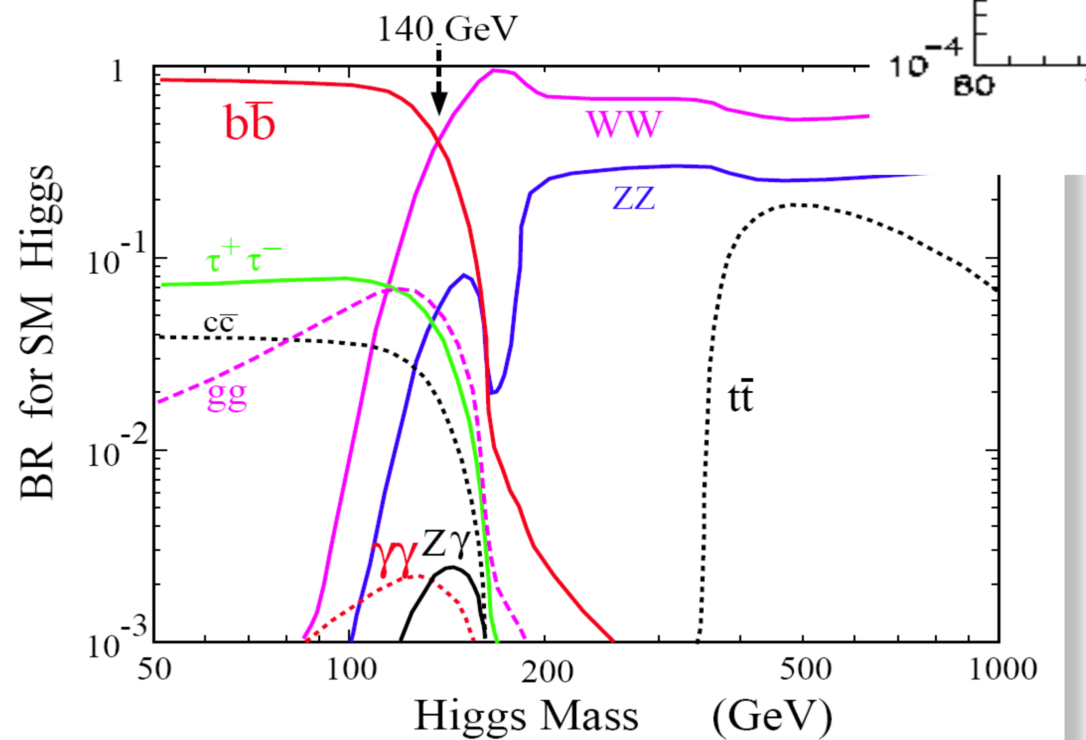
Plenty of W and Z bosons → calibration.

Evidence of single top production is an important milestone towards the Higgs boson.

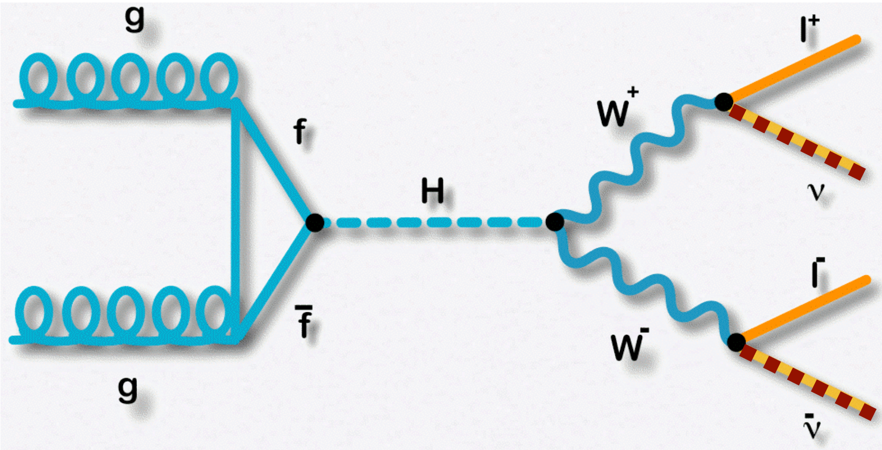
The Higgs cross section is 10-11 orders of magnitudes lower than the total inelastic cross section.

Higgs Production and Decay

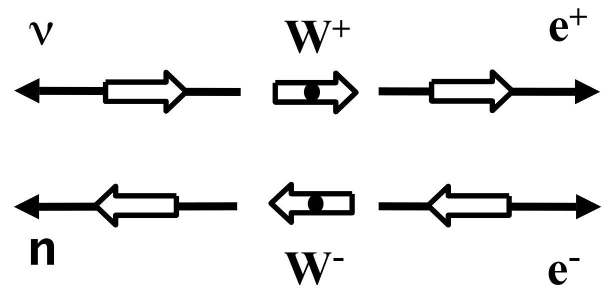




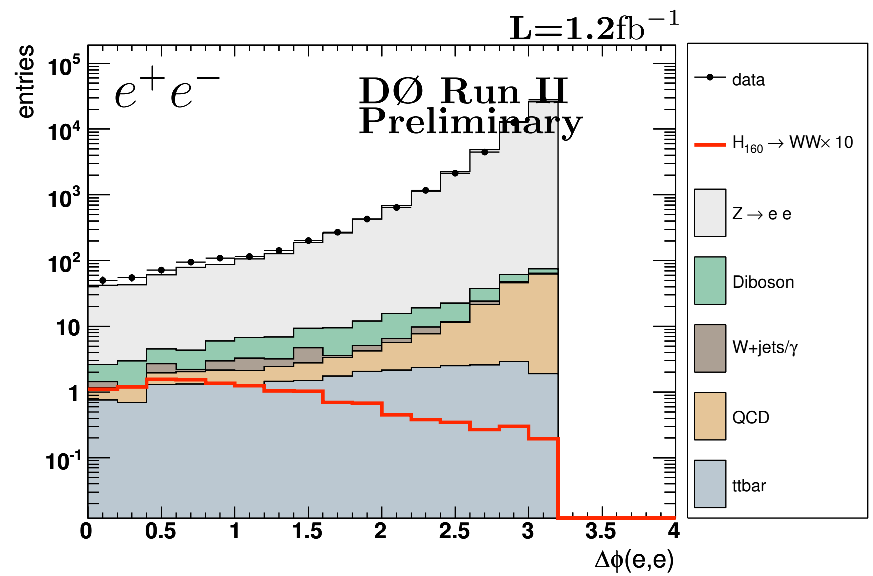
High Mass Higgs Channels



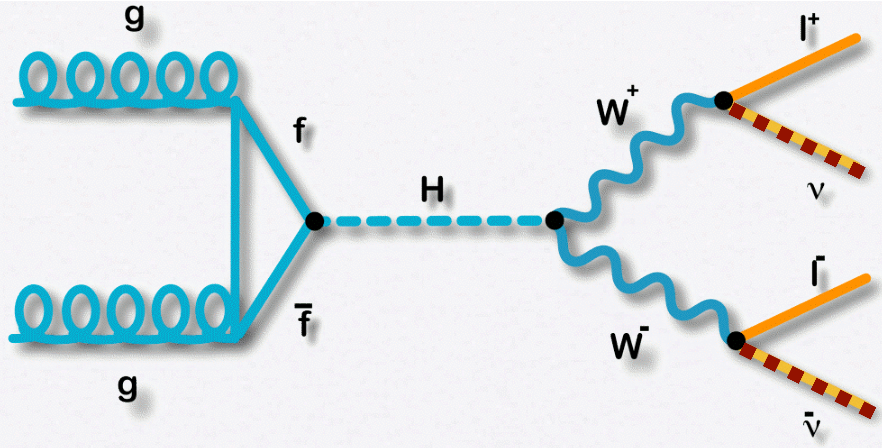
Angular correlation of leptons due to V–A as H is a spin 0 particle:

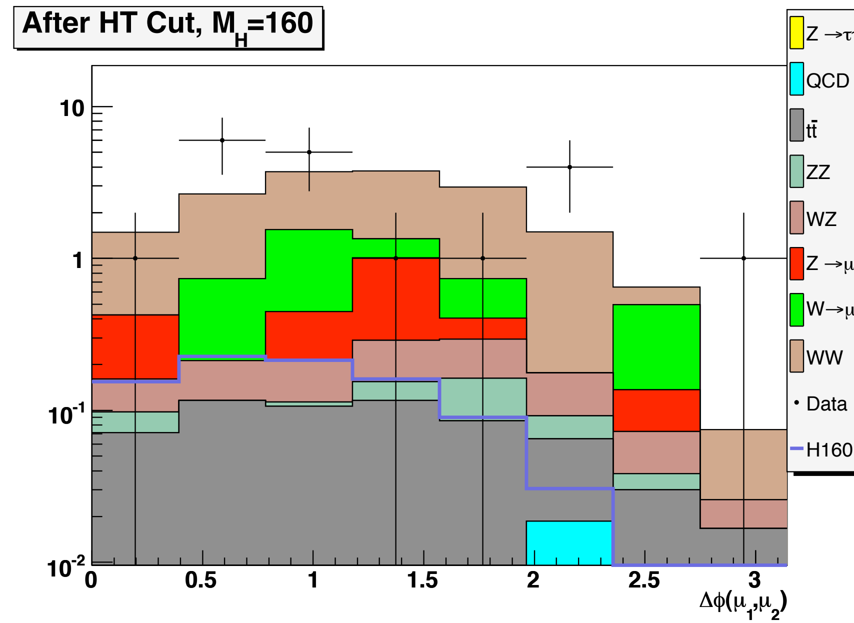


- final states with charged leptons:
  - $e^{\pm}e^{\mp}$
  - $e^{\pm}\mu^{\mp}$ ← counts twice
  - $\mu^{\pm}\mu^{\mp}$
  - $l^{\pm}\tau^{\mp}_{h}$ ← difficult
- hadronic final state:
  - very difficult



High Mass Higgs Channels





- 2 leptons with high p_T
- Isolation of e/μ against QCD and b-je
- $\not{E}_T$ due to 2 neutrinos
- $\not{E}_T$ significance:
  - not from mis-measured lepton p_T
  - not from mis-measured jet p_T
- $m_{ll} < m_Z$
- $\Sigma_{jets}\, p_T < 100$ against $t\bar{t}$ background

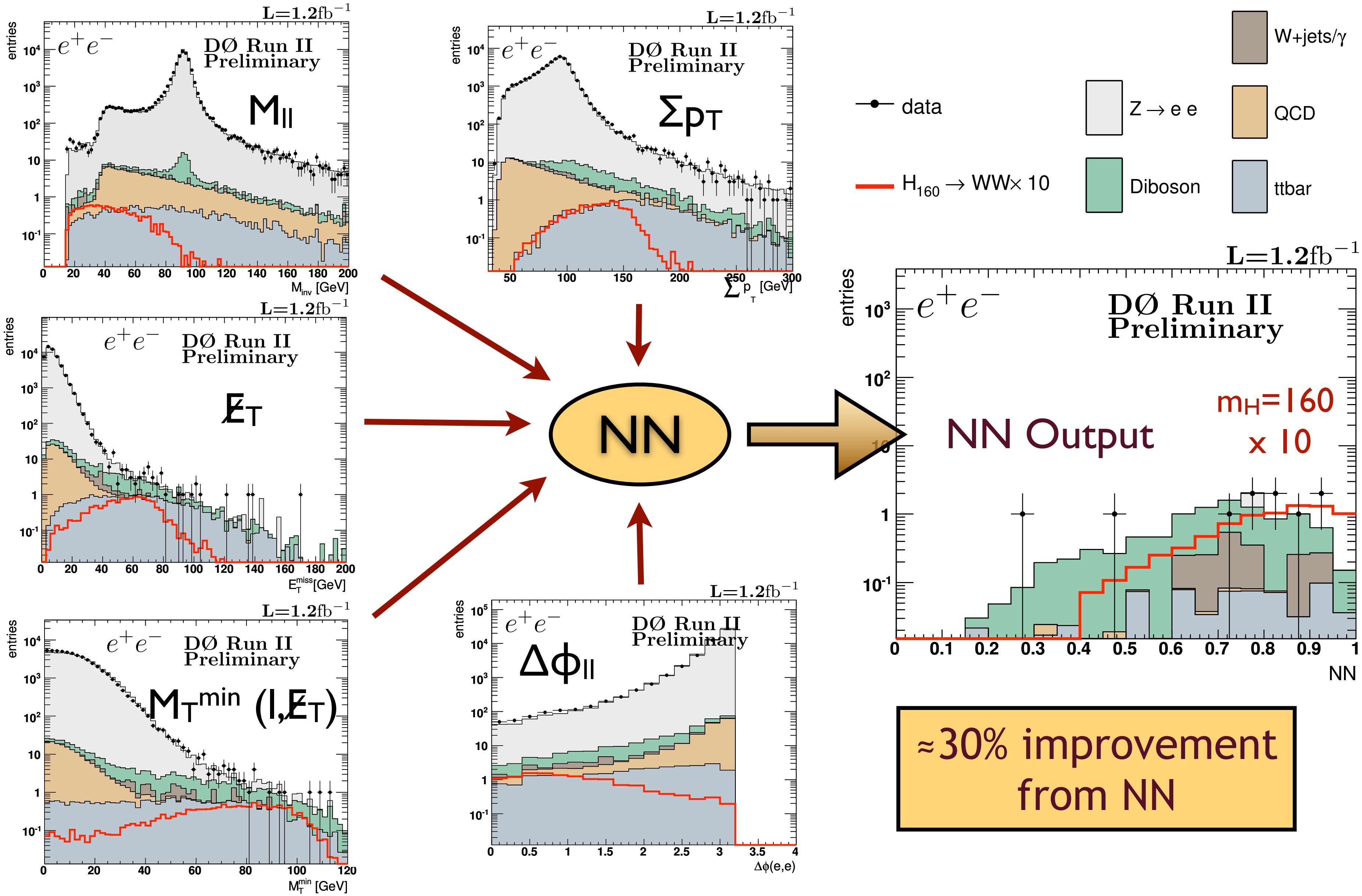
S/B ≈ 15/300k

S/B ≈ 5/50

Cuts Optimised for $m_H = 120 - 200$

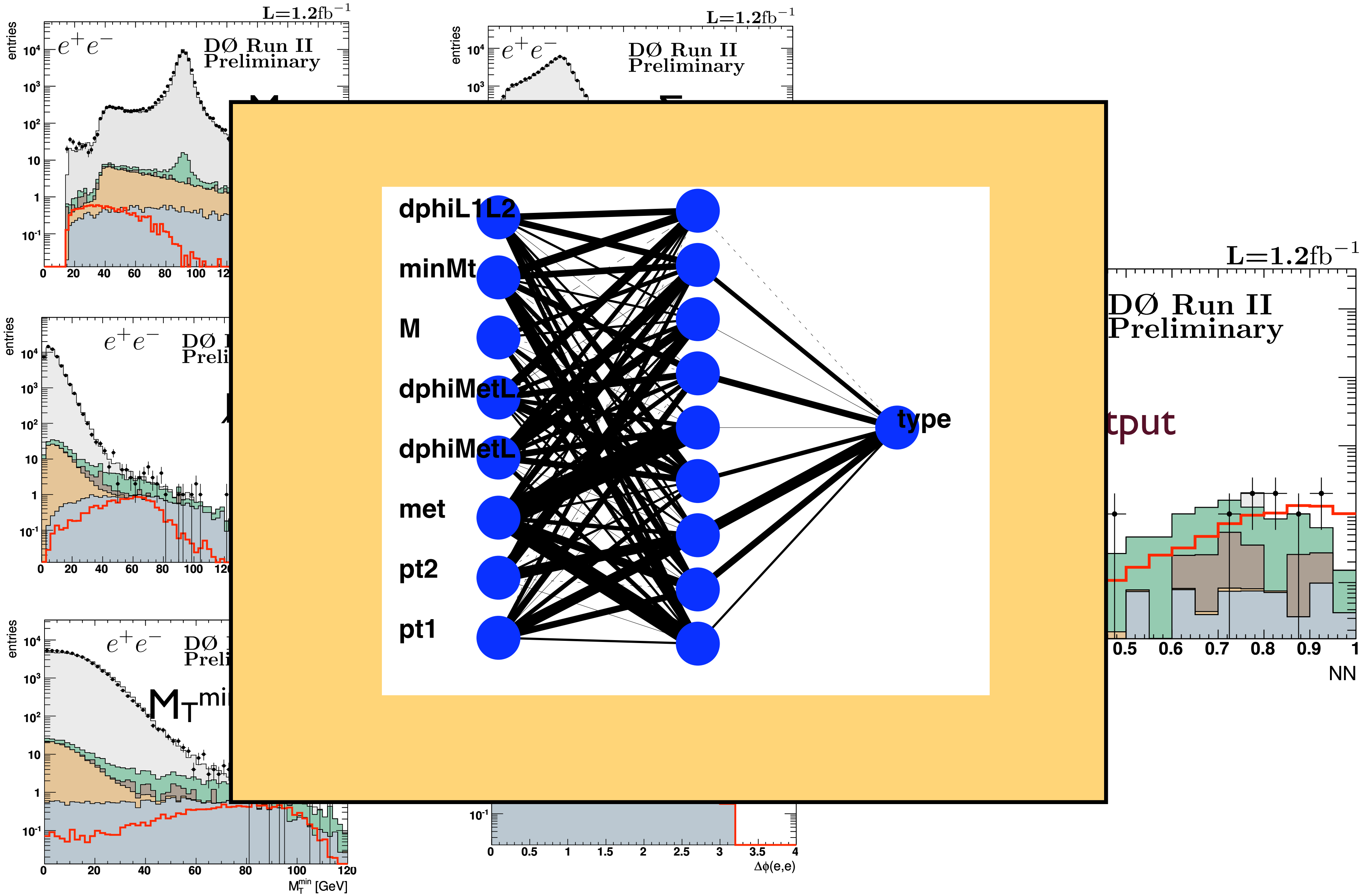
Selection criterion		$m_H = 120$	$m_H = 140$	$m_H = 160$	$m_H = 180$	$m_H = 200$
Cut 1	Preselection	Trigger, ID, leptons with opposite charge, $z_{VTX} < 60$ cm, $M_{\mu\mu} > 17$ GeV				
		$p_T > 20/10$GeV	20/15	25/15	25/15	25/15
Cut 2	Missing transverse energy $\not{E}_T$	$25 < \not{E}_T < 70$	$25 < \not{E}_T < 80$	$30 < \not{E}_T < 90$	$35 < \not{E}_T < 100$	$35 < \not{E}_T < 110$
Cut 3	$Sig(\not{E}_T)$	$Sig(\not{E}_T) > 5$ (for $N_{Jet} > 0$)				
Cut 4	$M^T_{min}\ (l, \not{E}_T)$	$M^T_{min} > 30$	$M^T_{min} > 30$	$M^T_{min} > 40$	$M^T_{min} > 45$	$M^T_{min} > 45$
Cut 5	Invariant mass $M_{\mu\mu}$	$17 < M_{\mu\mu} < 60$	$17 < M_{\mu\mu} < 70$	$17 < M_{\mu\mu} < 75$	$17 < M_{\mu\mu} < 85$	$17 < M_{\mu\mu} < 95$
Cut 6	$\Sigma p_T = p_T^l + p_T^{l'} + \not{E}_T$	$60 < \Sigma p_T < 135$	$70 < \Sigma p_T < 160$	$80 < \Sigma p_T < 170$	$90 < \Sigma p_T < 180$	$90 < \Sigma p_T < 200$
Cut 7	H_T (scalar sum of p_T^{Jet})	$H_T < 60$	$H_T < 60$	$H_T < 60$	$H_T < 60$	$H_T < 50$
Info	Neural Net	NN > 0.5				

Neural Net



≈30% improvement from NN

Neural Net



L=1.2fb^{-1}
entries
e^+e^-
DØ Run II
Preliminary
dphiL1L2
minMt
M
dphiMetL
dphiMetL
met
pt2
pt1
type
tput
M_T^{mi}
M_T^{min} [GeV]
$\Delta\phi(e,e)$
NN

Multivariate Techniques :: TNG

Improved NN

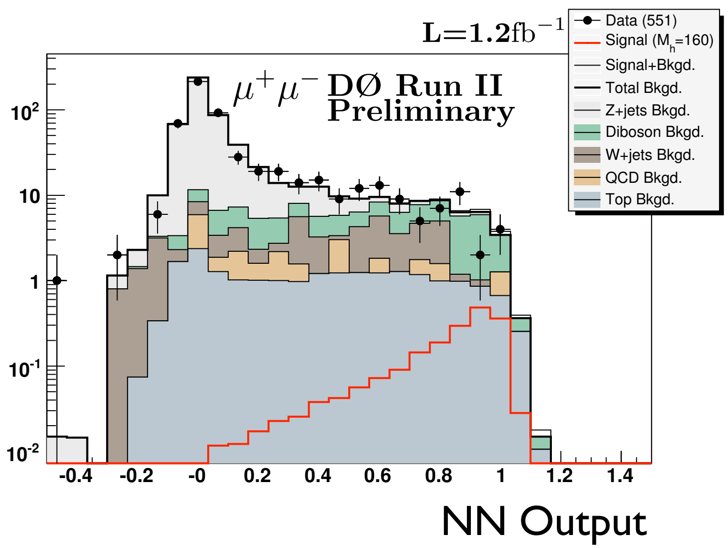
- Very loose selection
- More variables (~10 → ~20)
- Train against more backgrounds

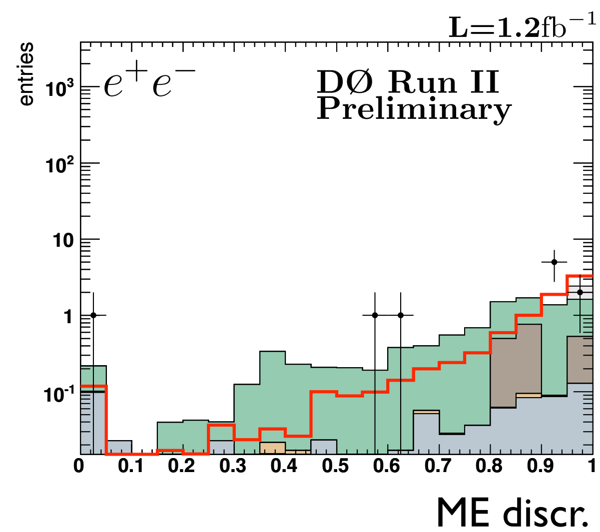
Matrix Element

$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

ME efficiency resolution

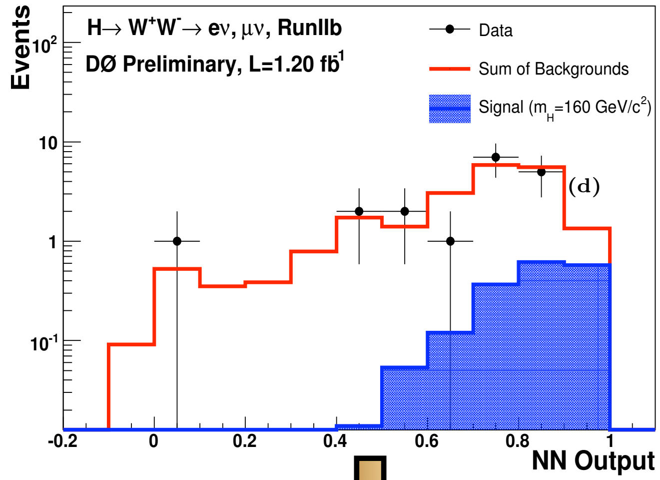
$$LR(x_{obs}) \equiv \frac{P_H(x_{obs})}{P_H(x_{obs}) + \sum_i k_i P_i(x_{obs})}$$

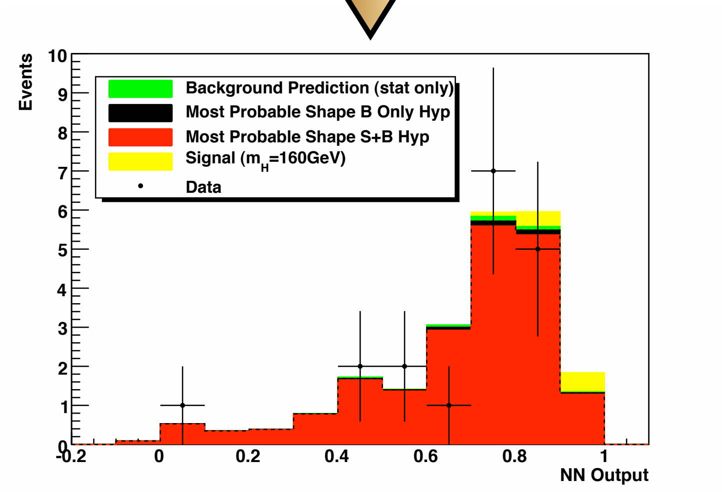




Additional input to NN

Combination of Channels





Combination of

- 3 final states
- 2 run periods

Uncertainties

- Statistical
- Correlated systematics
  - Bg cross sections (6-18%)
  - Normalisation (6%)
  - Jet energy scale
- Uncorrelated (some channels)
  - Lepton ID & resolution(3-10%)

LEP CL_s Method

Profile Likelihood

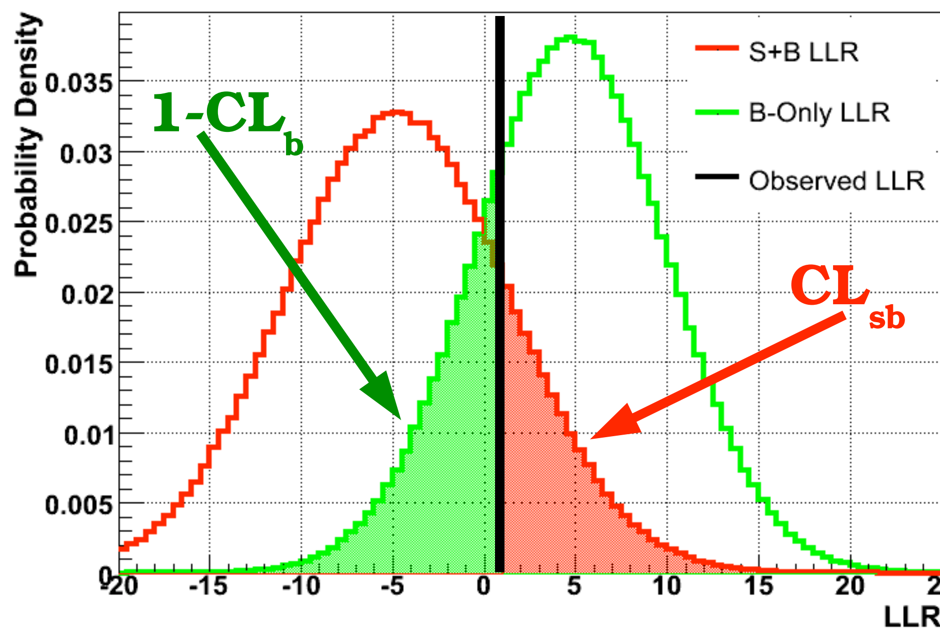
$$Q(\vec{s},\vec{b},\vec{d}) = \prod_{i=0}^{N_{\mathrm{Chan}}} \prod_{j=0}^{N_{\mathrm{bins}}} \frac{(s+b)_{ij}^{d_{ij}} \; e^{(s+b)_{ij}}}{d_{ij}!} \Big/ \frac{b_{ij}^{d} \; e^{b}}{d_{ij}!}$$

$$LLR = -2\ln Q$$

$$CL_s = 1 - \frac{CL_{s+b}}{CL_b}$$

Systematics taken into account via Gaussian marginalisation

Correlations taken into account



CLs Technique

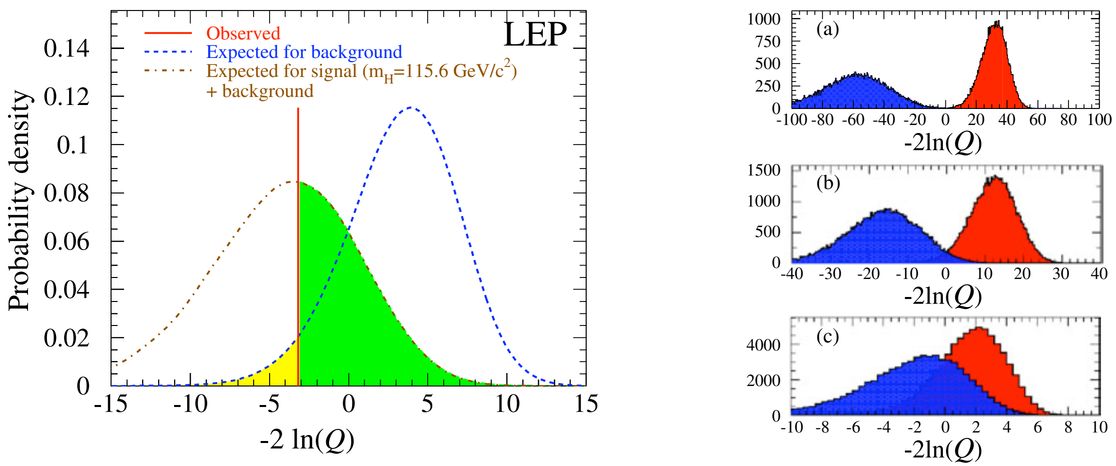
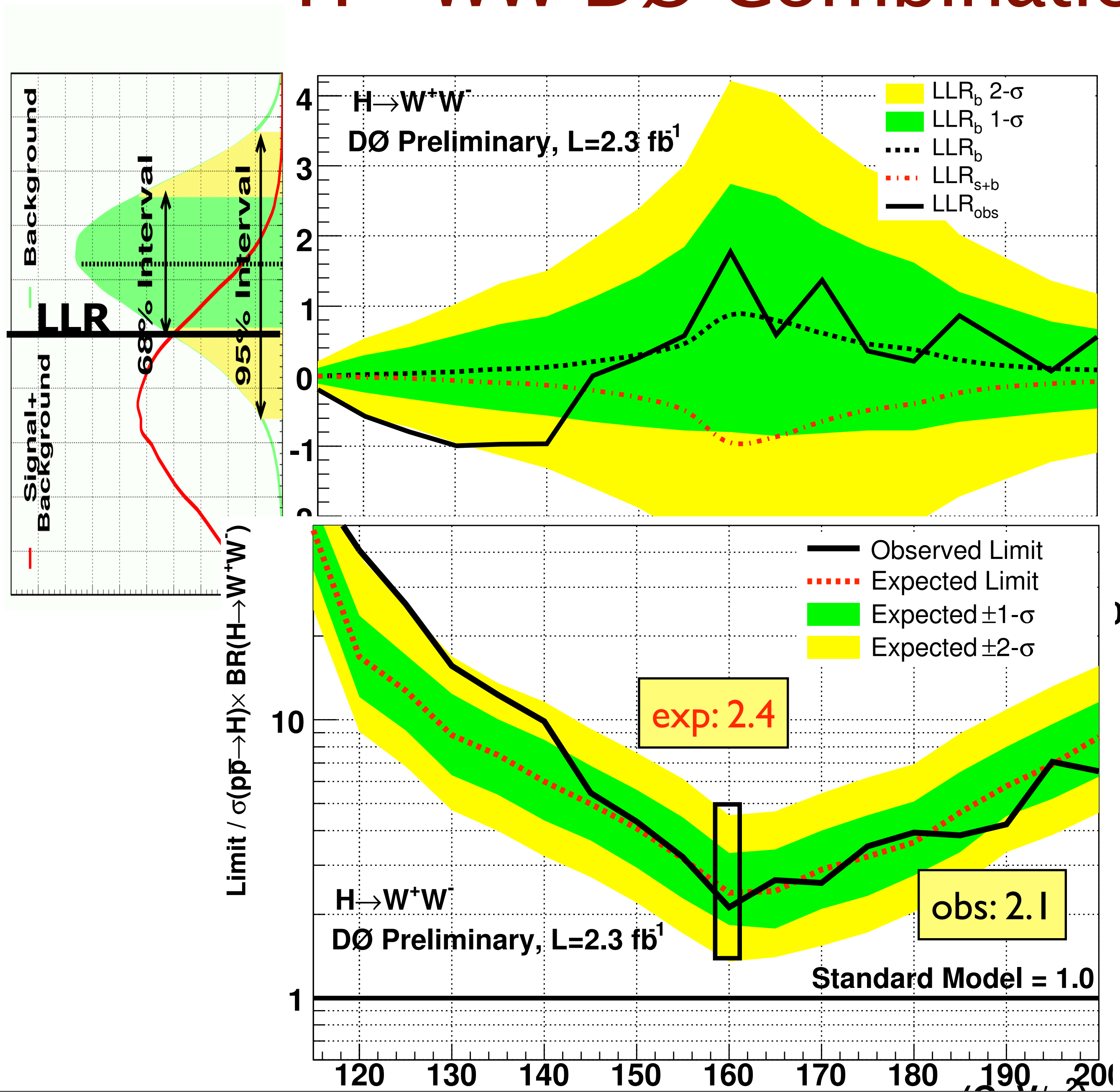


Figure 1. Left: The pdfs of the combined Higgs search at LEP for the background (right) and signal + background hypotheses (left) for $m_{\mathrm{H}} = 115.6\,\mathrm{GeV}/c^2$. The light grey region to the left of the observation is $1 - CL_b$ and the dark grey region to the right of the observation is CL_{s+b}. Right: Illustration of the evolution of the pdfs with falling search sensitivity from (a) to (c) as the Higgs mass hypothesis is increased and the production cross-section falls.

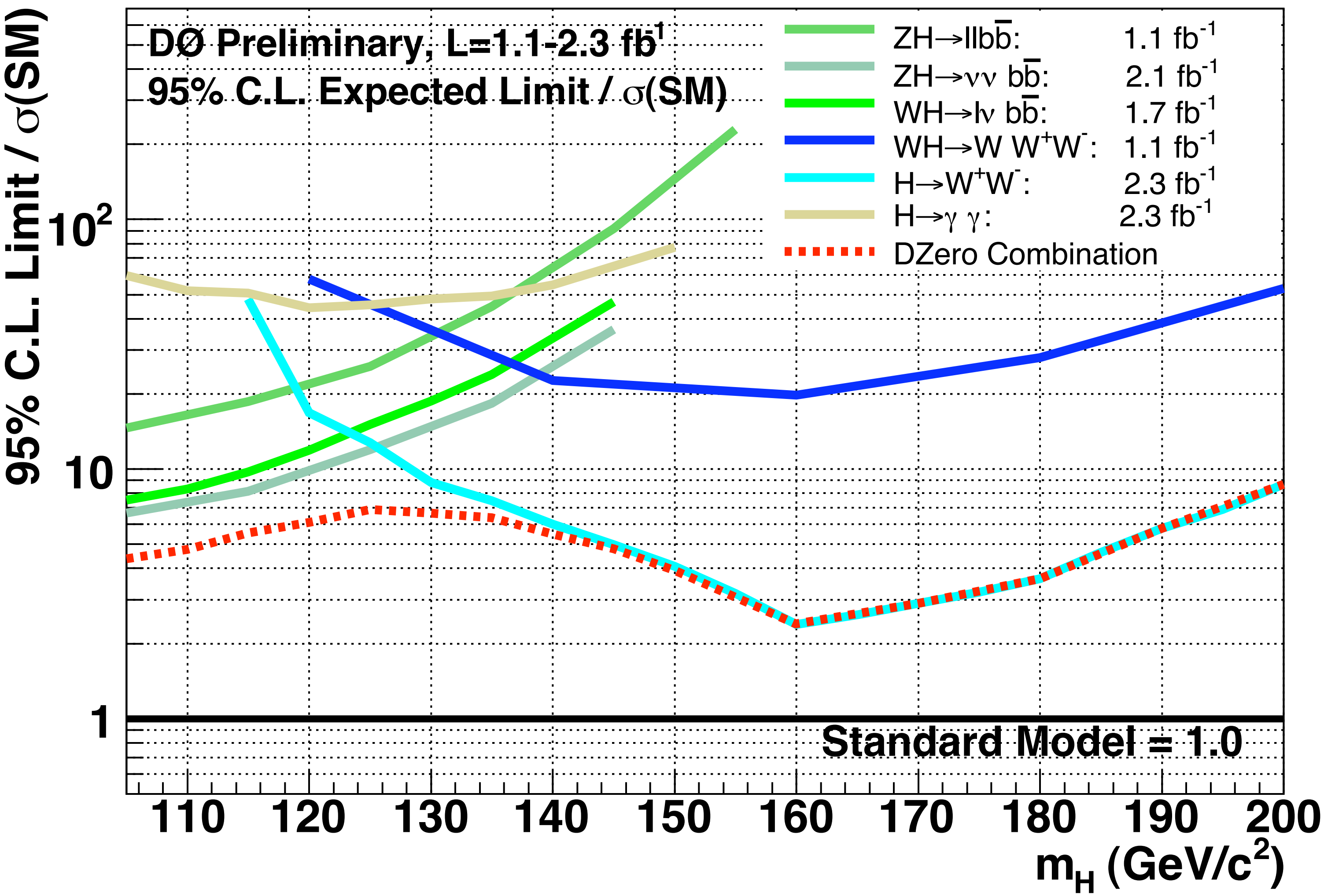
A. L. Read, J. Phys. G: Nucl. Part. Phys. **28** (2002) 2693-2704

H→WW DØ Combination

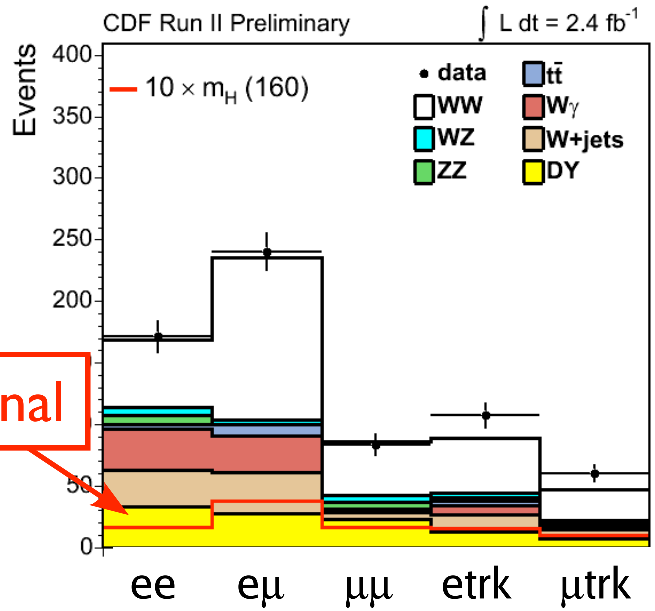


Limits relative to SM expectation!

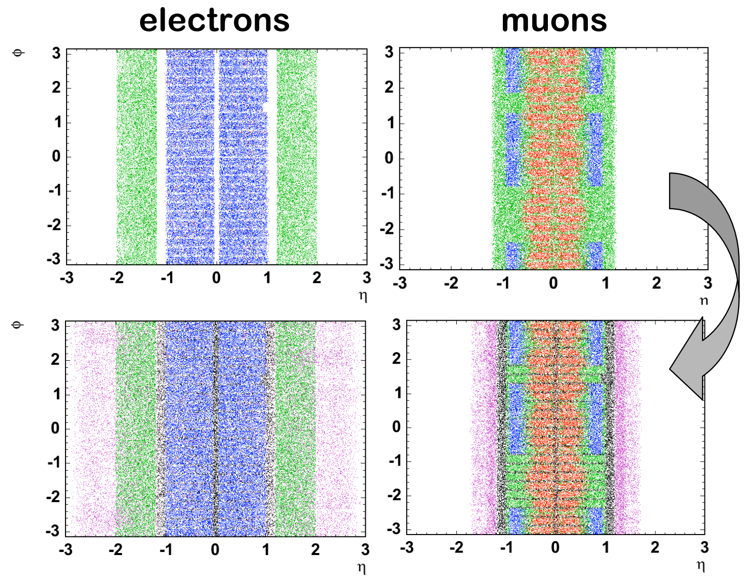
DØ Final States



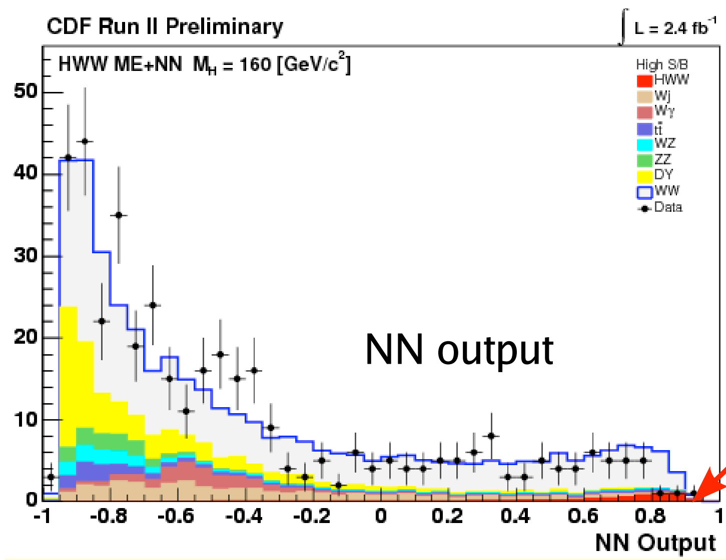
H → WW @ CDF



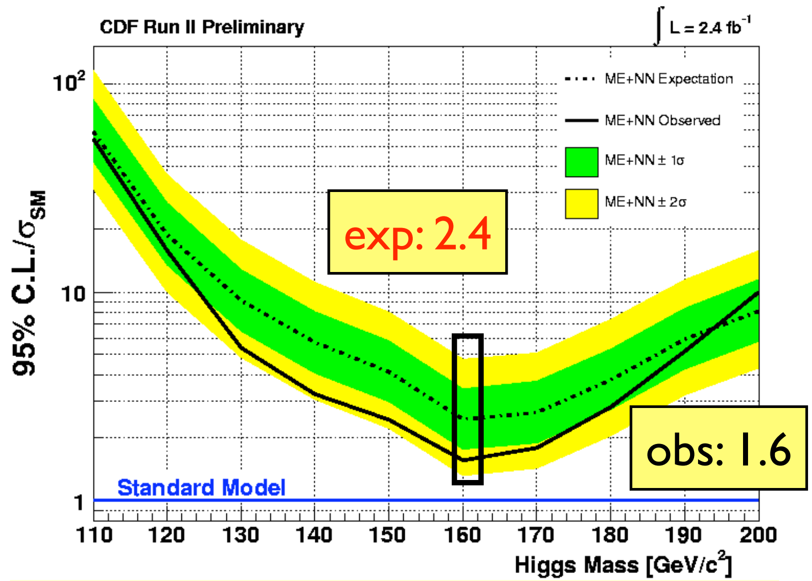
CDF Run II Preliminary
∫ L dt = 2.4 fb⁻¹
Events
10 × mH (160)
data
WW
WZ
ZZ
tt̄
Wγ
W+jets
DY
signal
ee
eμ
μμ
etrk
μtrk



electrons
muons
φ
η



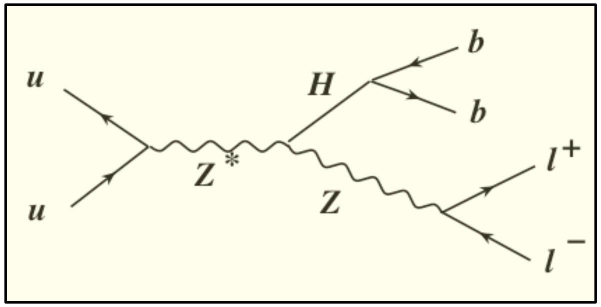
CDF Run II Preliminary
∫ L = 2.4 fb⁻¹
HWW ME+NN MH = 160 [GeV/c²]
High S/B
HWW
Wj
Wγ
tt̄
WZ
ZZ
DY
WW
Data
NN output
signal
NN Output



CDF Run II Preliminary
∫ L = 2.4 fb⁻¹
ME+NN Expectation
ME+NN Observed
ME+NN ± 1σ
ME+NN ± 2σ
exp: 2.4
obs: 1.6
Standard Model
95% C.L./σSM
Higgs Mass [GeV/c²]

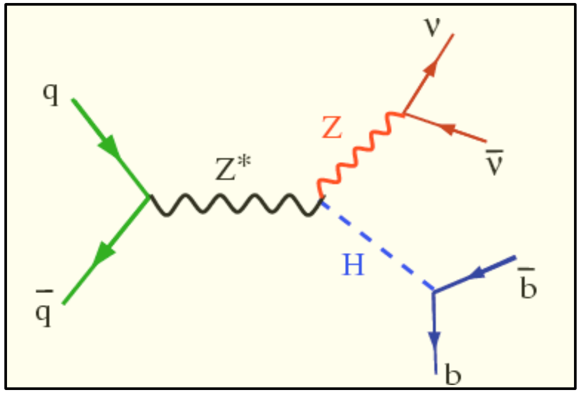
Low Mass Higgs Channels

ZH → l^+l^- bb



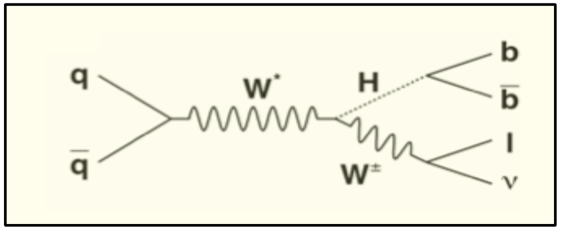
2 b jets ~ 1/2 M_H each
2 leptons ~ 45 GeV each
Z mass constraint
Cleanest signal

ZH → νν bb



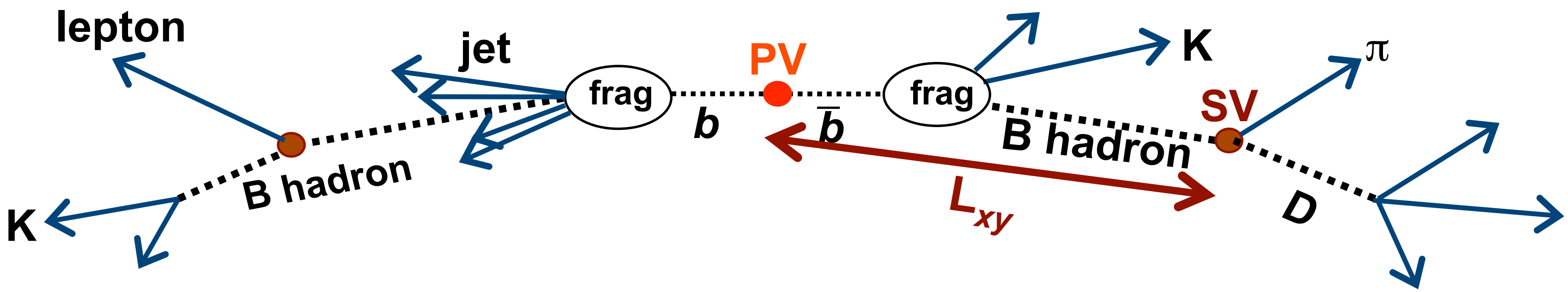
2 b jets ~ 1/2 M_H each
0 leptons
Missing E_T ~ 100 GeV
Largest expected signal

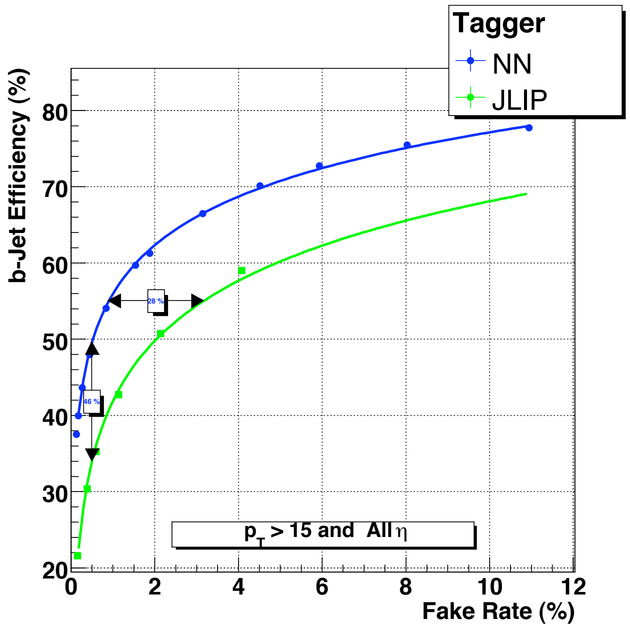
WH → lνbb

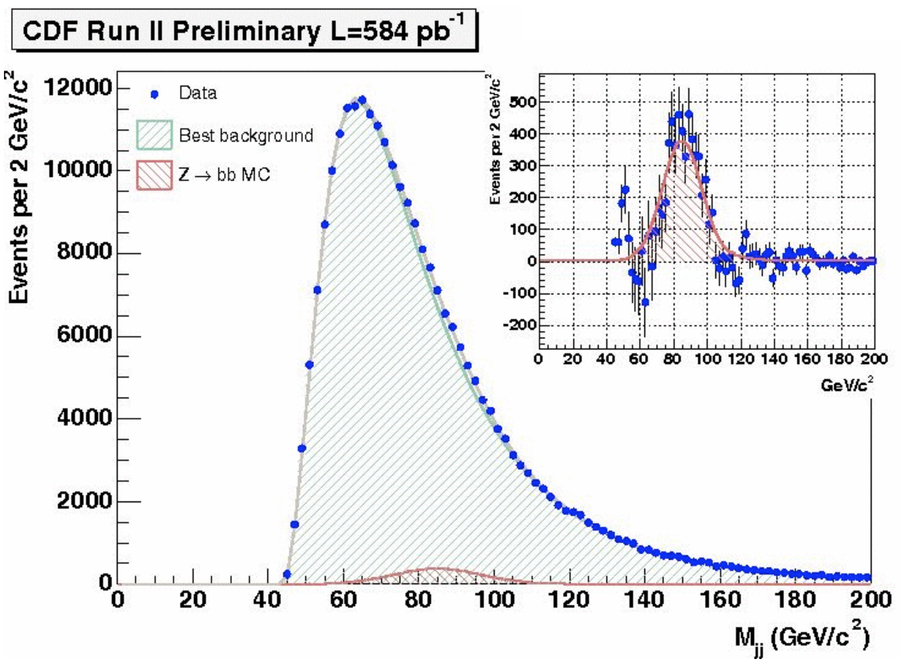


2 b jets ~ 1/2 M_H each
1 lepton ~ 50 GeV each
Missing E_T ~ 50 GeV
Highest production X-sec

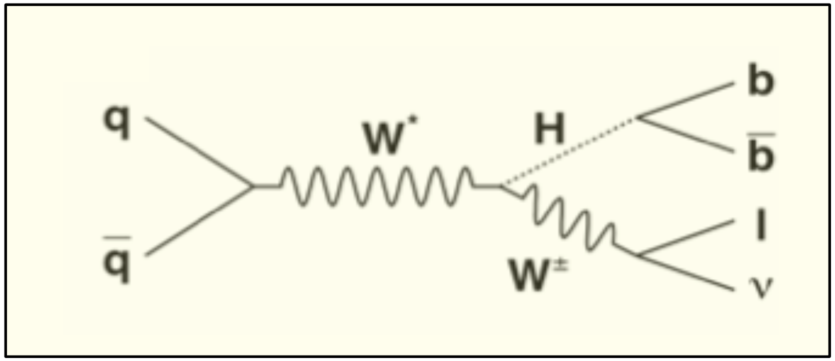
Tools: b-tagging

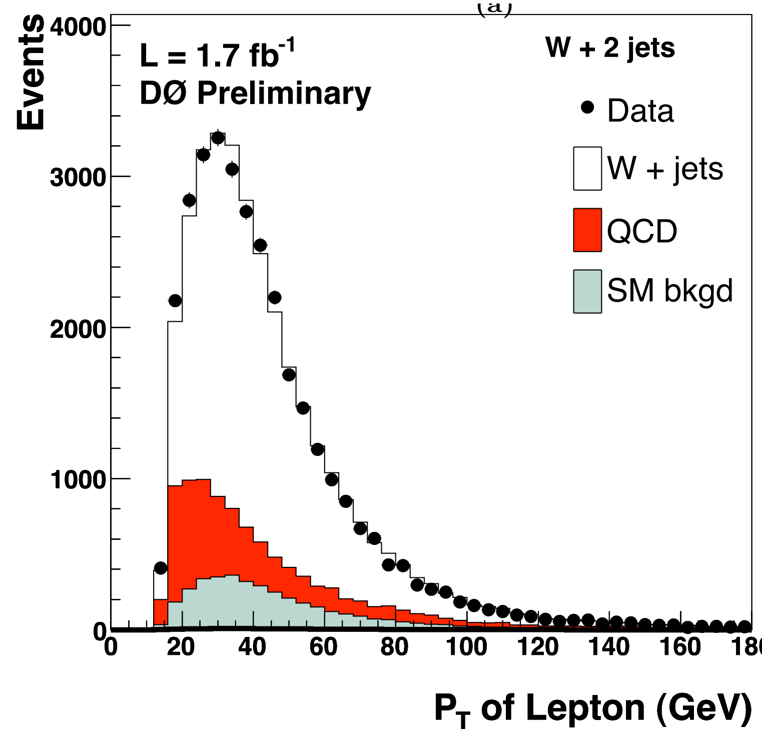


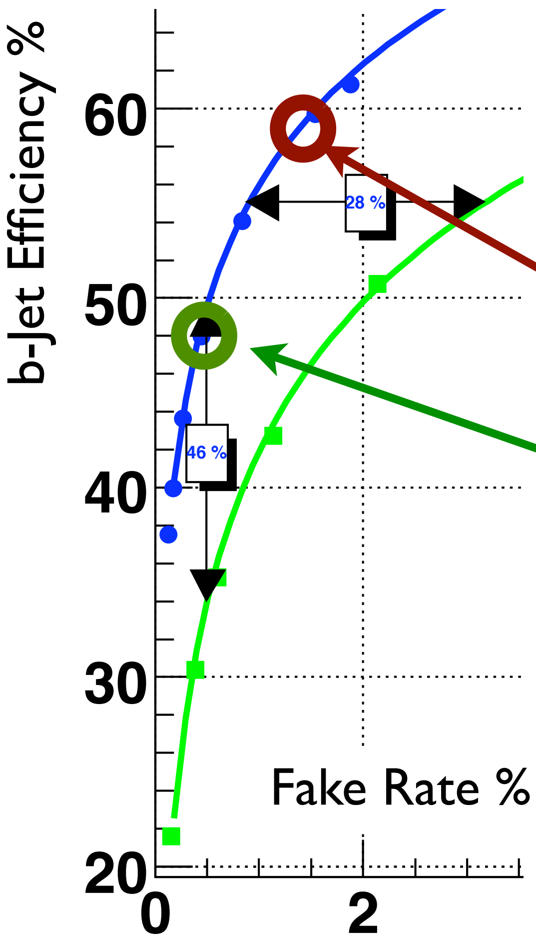




WH → lνbb



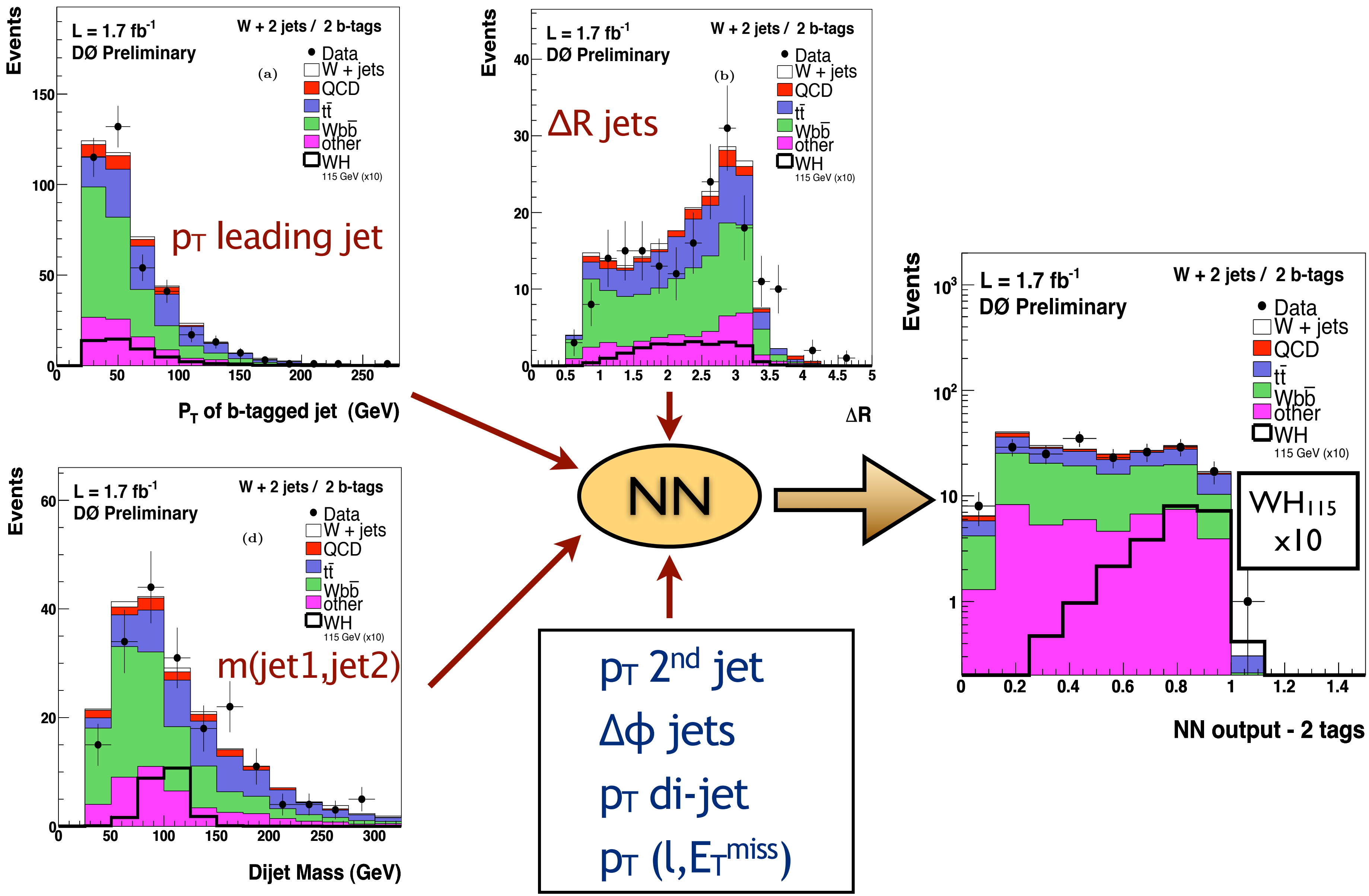




4 different analyses:

- Double b–tag (S/B ~ 2.3/204)
- Single b–tag (S/B ~ 4/1400)
- W → eν
- W → μν

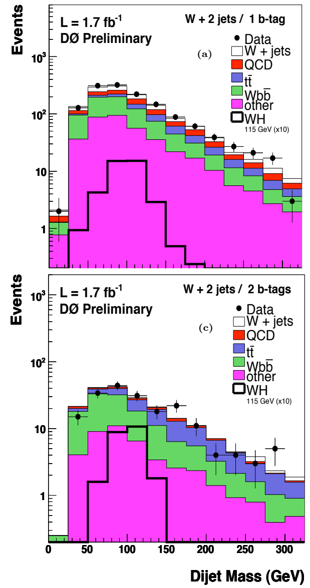
WH → lνbb̄: Neural Net

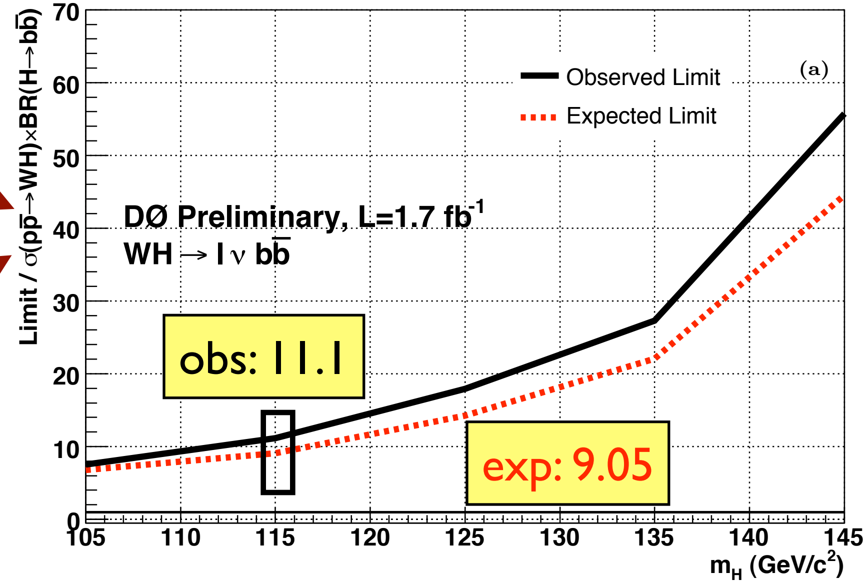


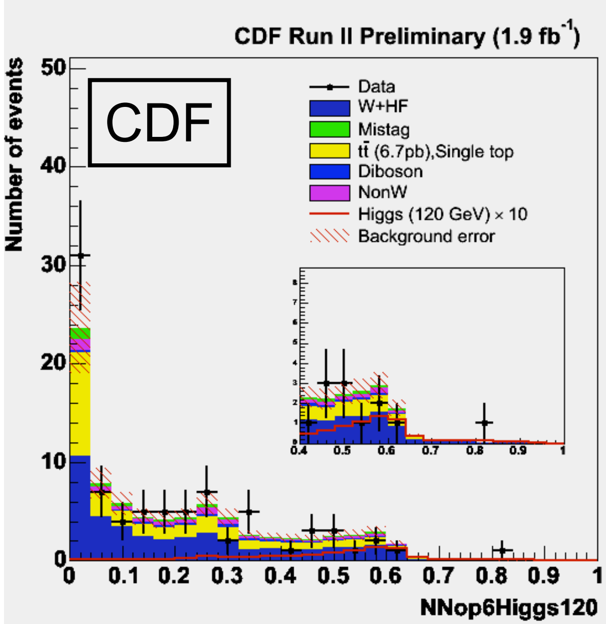
Combining WH Results

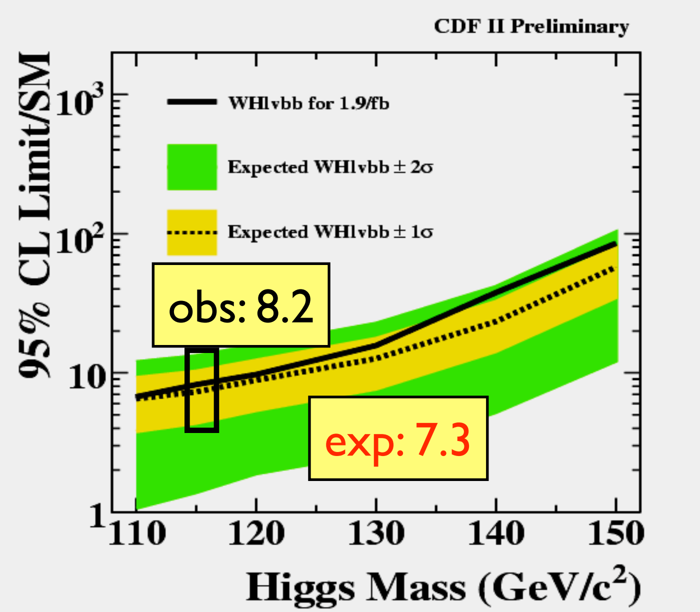
single b-tag

double b-tag



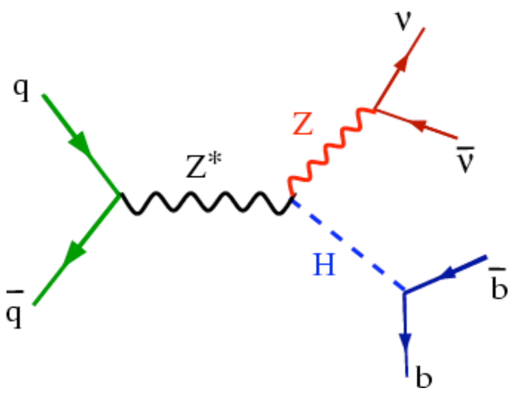


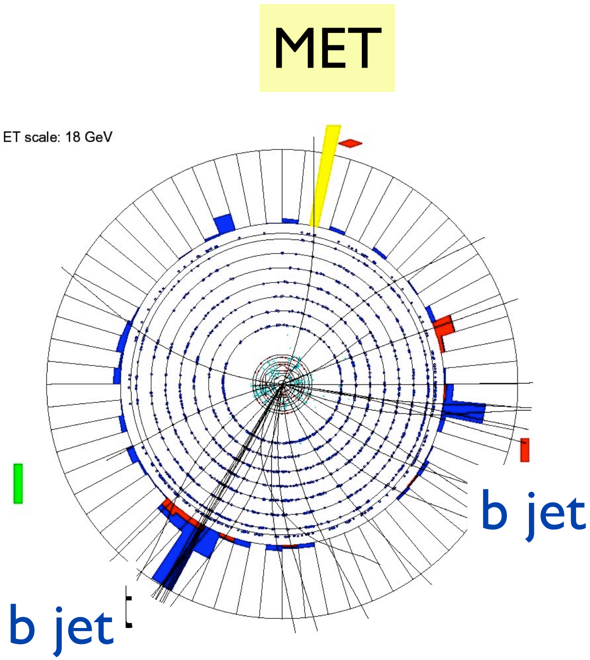




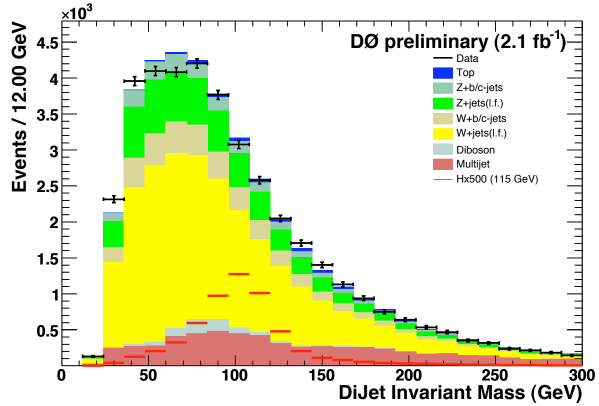
Limits relative to SM expectation

$ZH \rightarrow \nu\nu b\bar{b}$ $(+\ WH \rightarrow \not{\ell}\nu b\bar{b})$

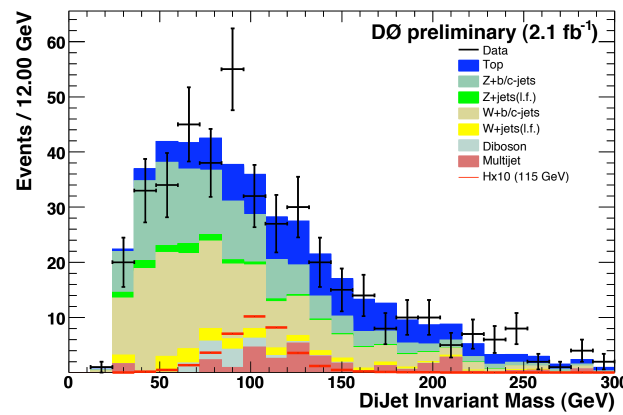




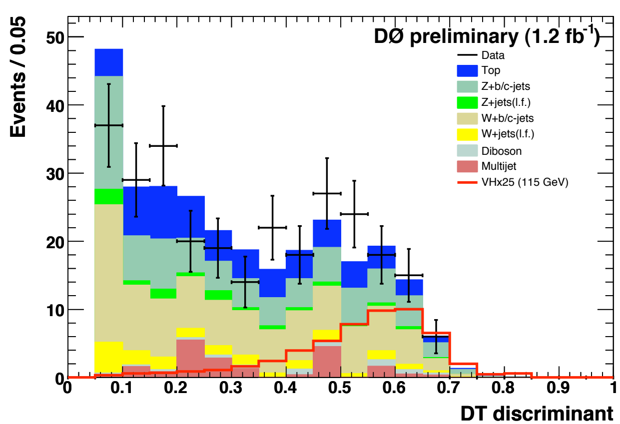
E_T^{miss} + 2 jets



1 tight b–tag + 1 loose b–tag



Decision Tree (Run IIb)

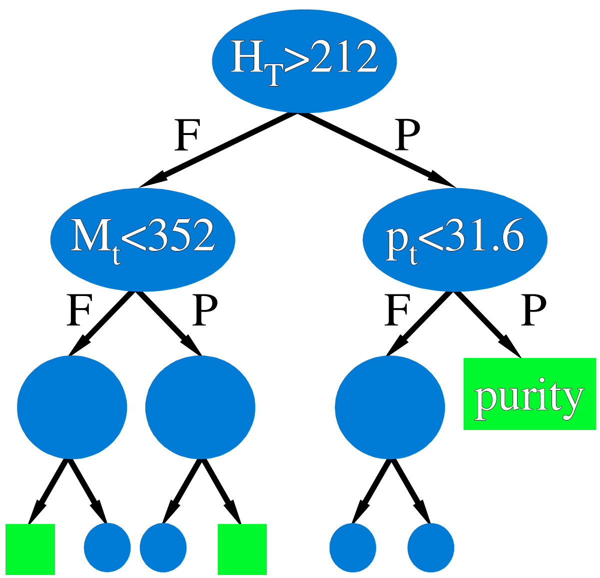


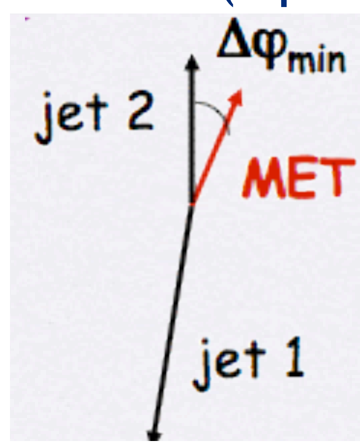
S/B ~ 3.7/443

Decision Tree

$\not{E}_T$	$\sum p_T{}^{\text{jets}}$
scalar E_T	$p_T{}^{\text{jet}_1}$
$\not{H}_T$	$p_T{}^{\text{jet}_2}$
H_T	η_{jet_1}
$A(\not{E}_T,\not{H}_T) \doteq (\not{E}_T - \not{H}_T)/(\not{E}_T + \not{H}_T)$	η_{jet_2}
$\not{H}_T/H_T$	dijet invariant mass
$\min \Delta\phi(\not{E}_T, \text{jets})$	dijet transverse mass
$\Delta\phi(\not{E}_T, \text{jet}_1)$	$(\not{E}_T - \sum p_T{}^{\text{tracks}})/(\not{E}_T + \sum p_T{}^{\text{tracks}}))$
$\Delta\phi(\not{E}_T, \text{jet}_2)$	$max(\Delta\phi(\not{E}_T, \text{jets})) - min(\Delta\phi(\not{E}_T, \text{jets}))$
$\Delta\phi(\not{E}_T, p_T{}^{\text{jet}_1} + p_T{}^{\text{jet}_2})$	$max(\Delta\phi(\not{E}_T, \text{jets})) + min(\Delta\phi(\not{E}_T, \text{jets}))$
$\Delta\phi(\text{jet}_1, \text{jet}_2)$	$\sum p_T{}^{\text{tracks}}$
$\Delta R(\text{jet}_1, \text{jet}_2)$	$p_T{}^{\text{tracks}}$ from dijets
	$(\sum p_T{}^{\text{tracks}} - \sum^{\text{dijets}} p_T{}^{\text{tracks}})/\sum p_T{}^{\text{tracks}}$

Table 15: Variables used as input to the Decision Tree





Boosting:

as single top (adaptive boosting, AdaBoost)

give mis-classified events a higher weight before re-training to make the tree work harder.

Asymmetric b-tagging:

ϵ=73%/48%; f=5%/0.5% (@pT>30, η<0.8)

$ZH \rightarrow \nu\nu b\bar{b}$ @ CDF

2 b-tagging requirements:

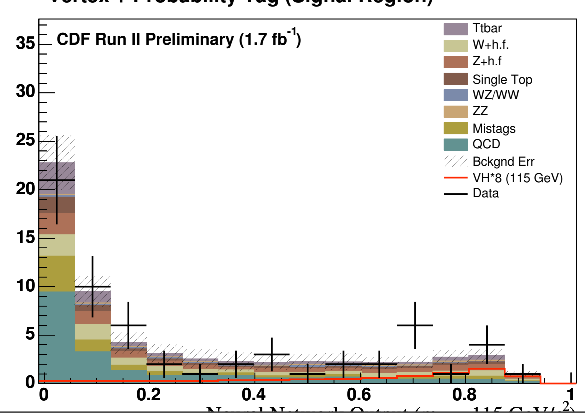
both jets with secondary vertex tag

1 jet with SVT, 1 jet with low probability that all tracks originate from the primary vertex

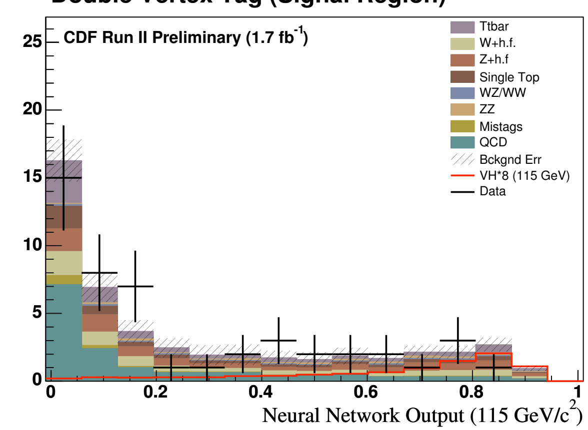
2 separate NN:

- against fake $\not{E}_T$ in QCD multi-jet like events: $\not{E}_T$ is related to jets and un-correlated to tracks; track based quantities enter the NN
- ZH discriminating NN for limit setting: NN$\not{E}_T$, m(jj), $\not{E}_T$(cal), met-dot-product: $\not{E}_T$(cal) · $\not{E}_T$(trk), dR(jj)

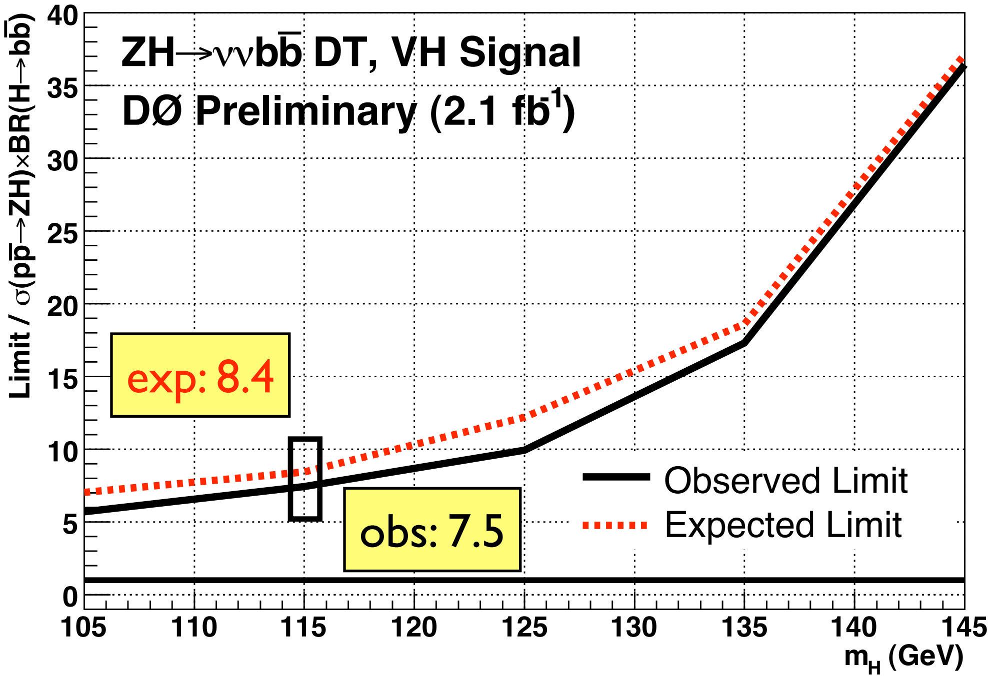
Vertex + Probability Tag (Signal Region)

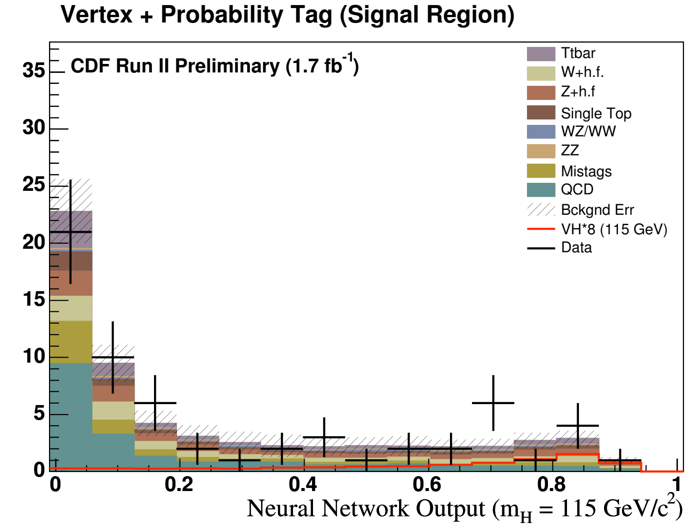


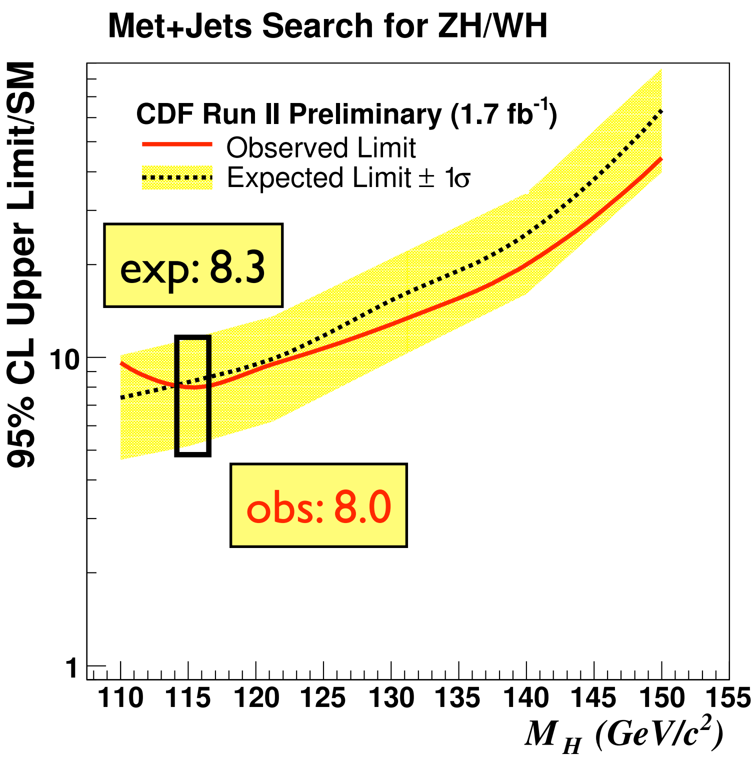
Double Vertex Tag (Signal Region)



ZH → ννbb̄



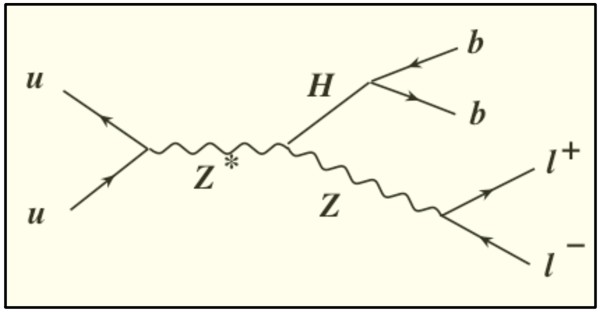




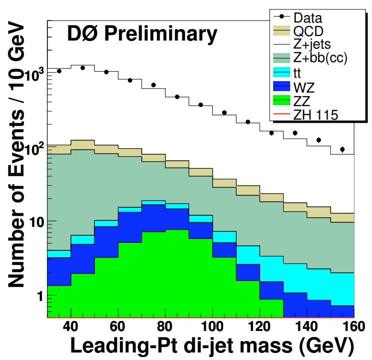
Upcoming improvements:

- QCD-multijet understanding.
- Run IIb Level 1 CAL trigger upgrade.
- Include single-tag.

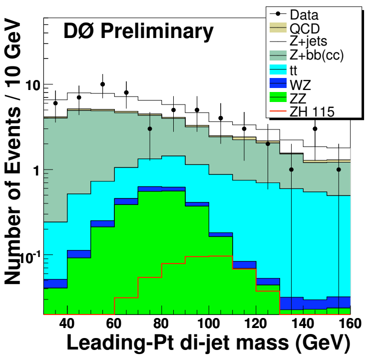
ZH → llb$\bar{b}$: DØ



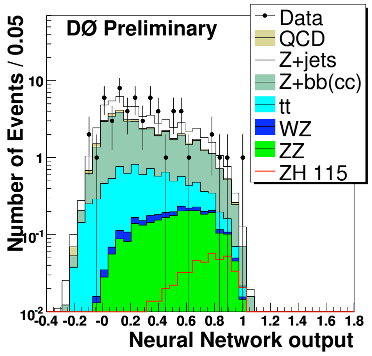
No b-tag



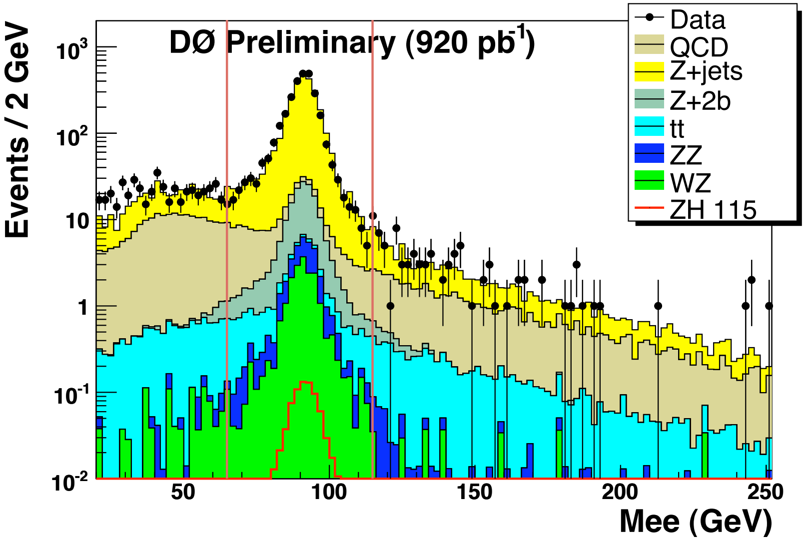
Double b-tag

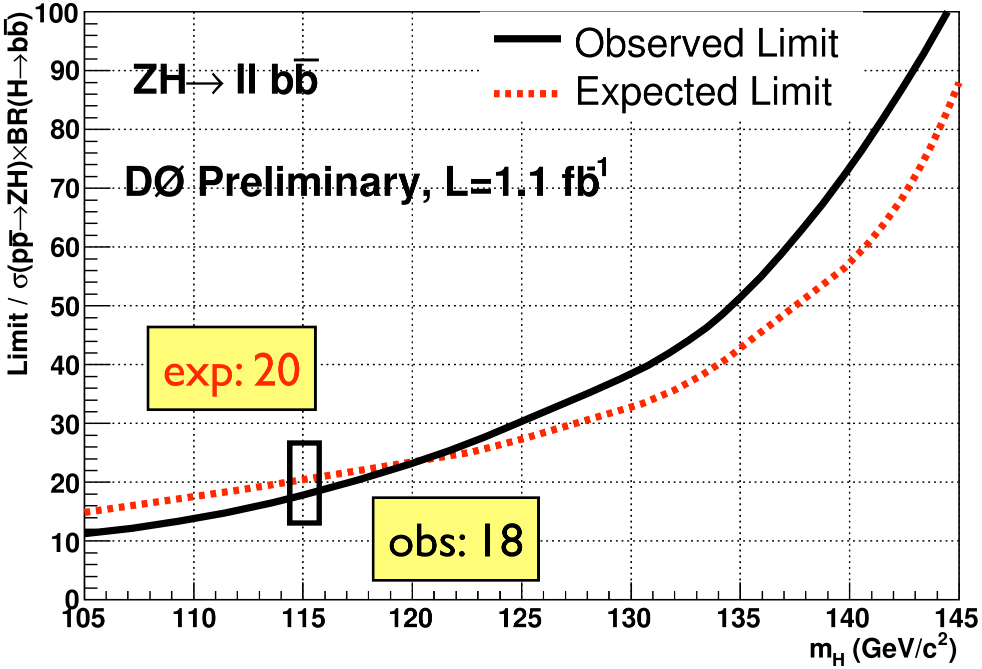


Neural Net



S/B ~ 0.53/74 before NN

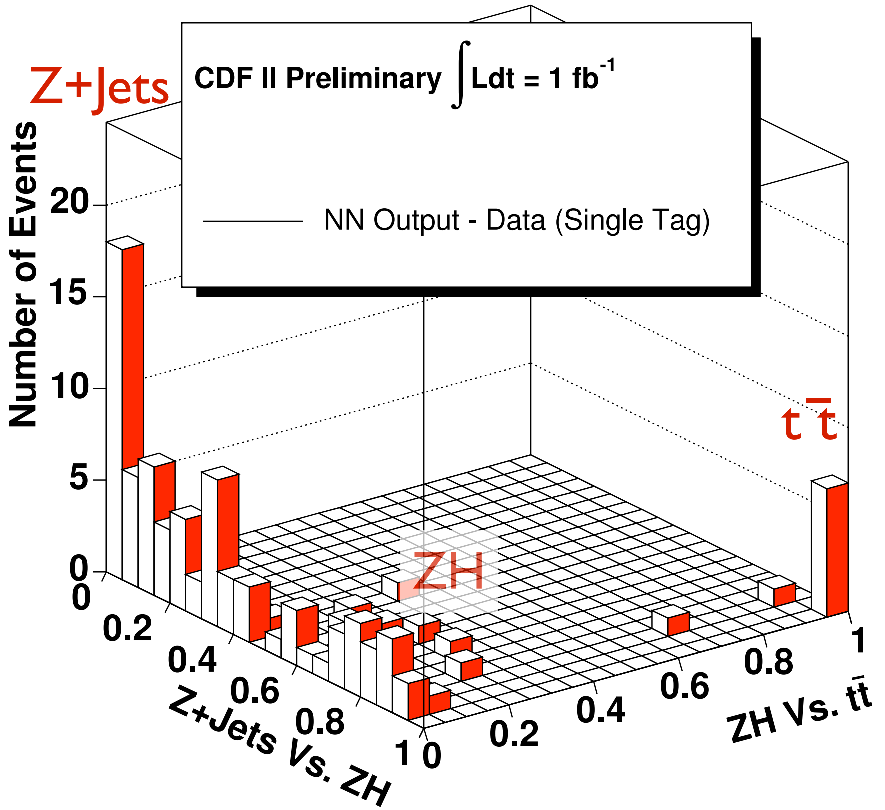


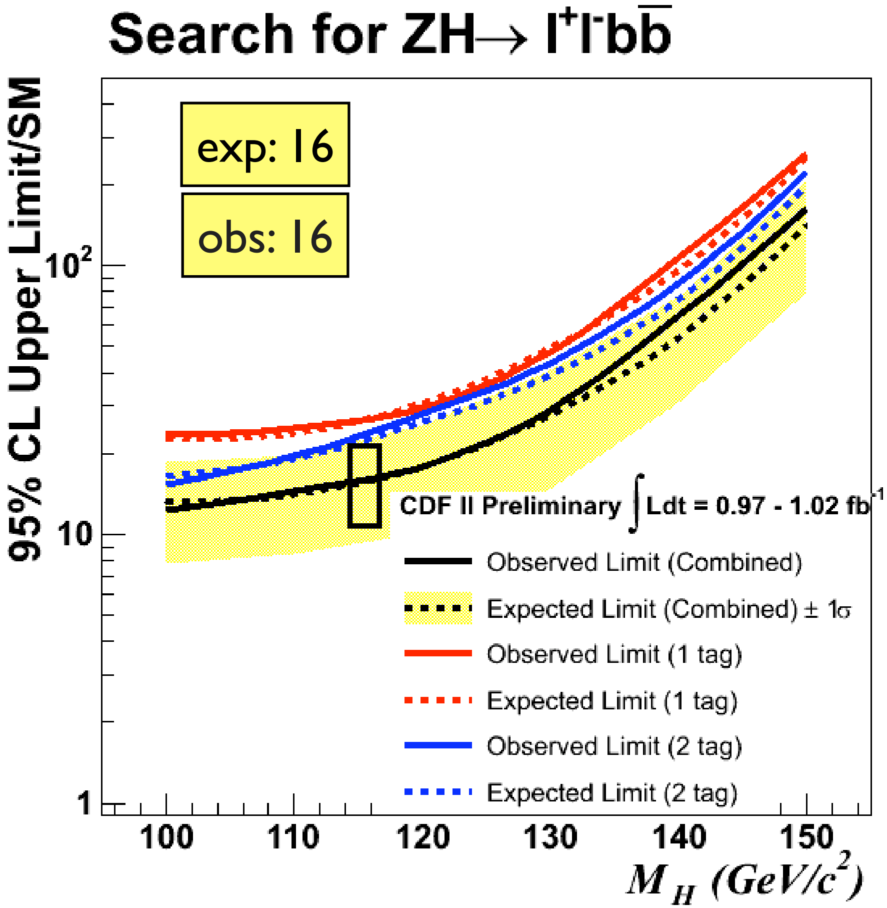


ZH → llb$\bar{b}$: CDF

Two independent neural nets are trained to separate ZH from

- t$\bar{t}$ background
- Z+jet background





CDF: H → ττ

Use $\tau_{lep}\tau_{had}$ mode.

- Lepton p_T > 10 GeV
- Hadronic τ p_T > 15 GeV

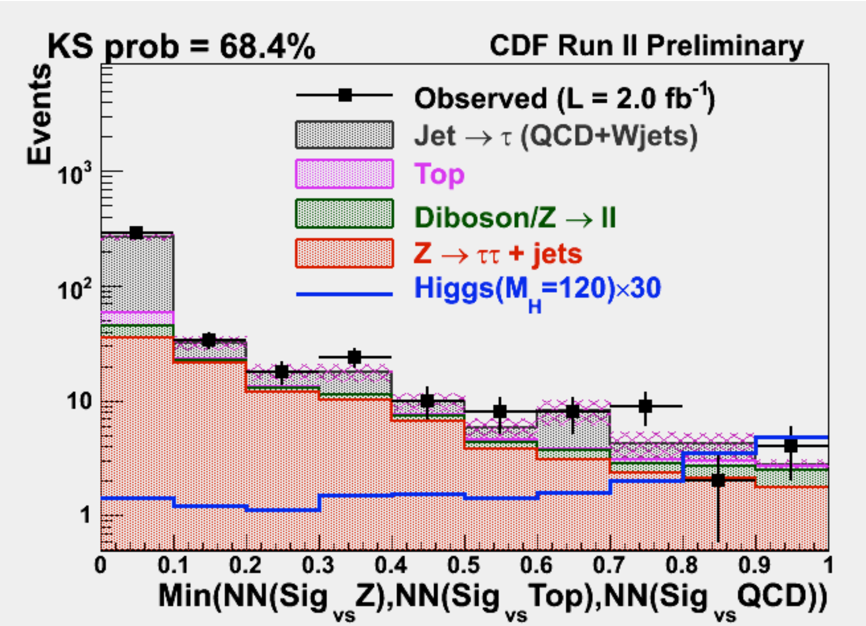
3 Neural Nets are trained:

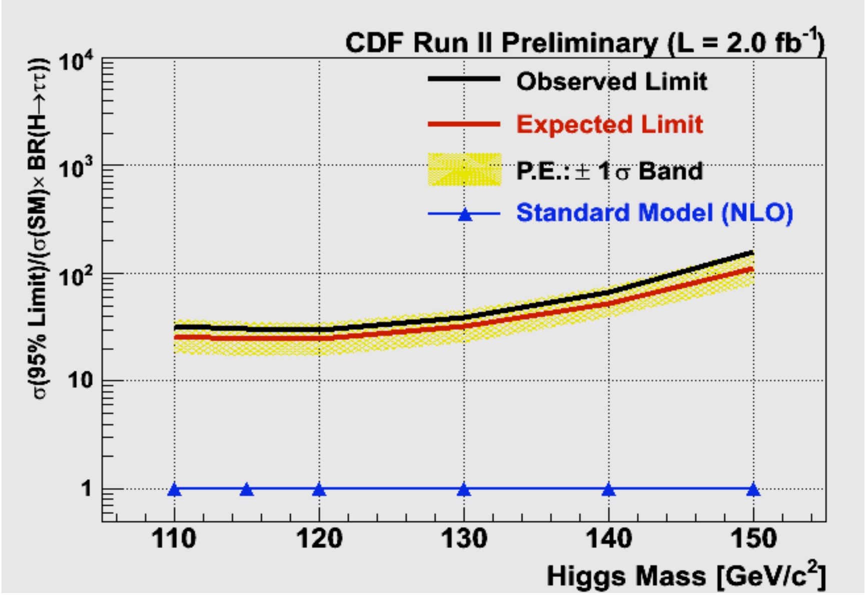
Signal vs Z-> ττ + jets

Signal vs ttbar

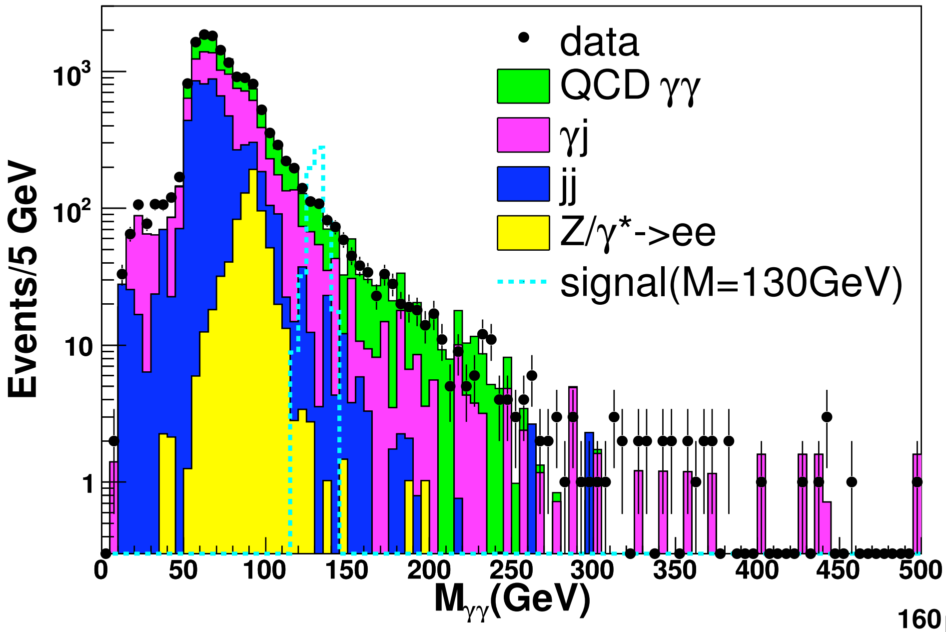
Signal vs QCD

Select Minimum of 3 NN to fit data.

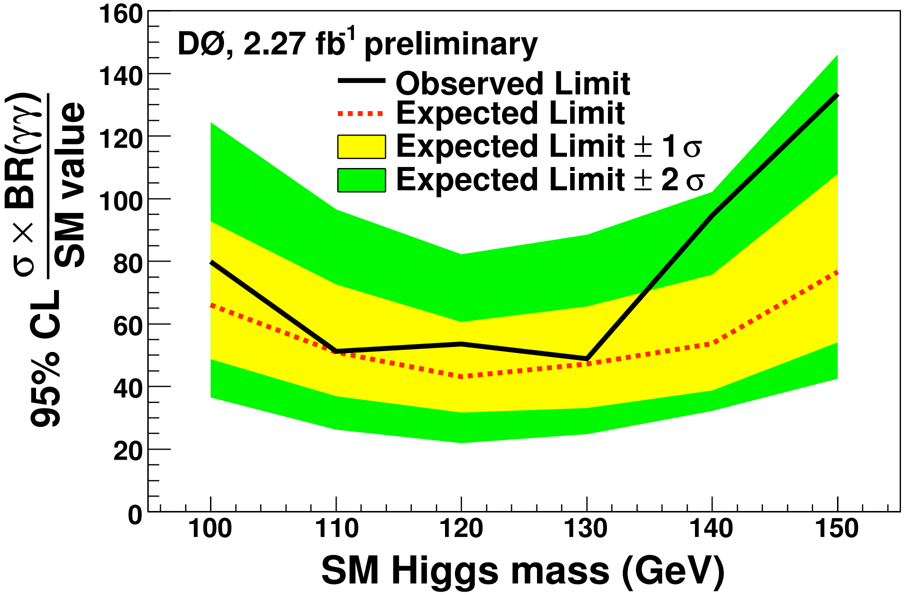




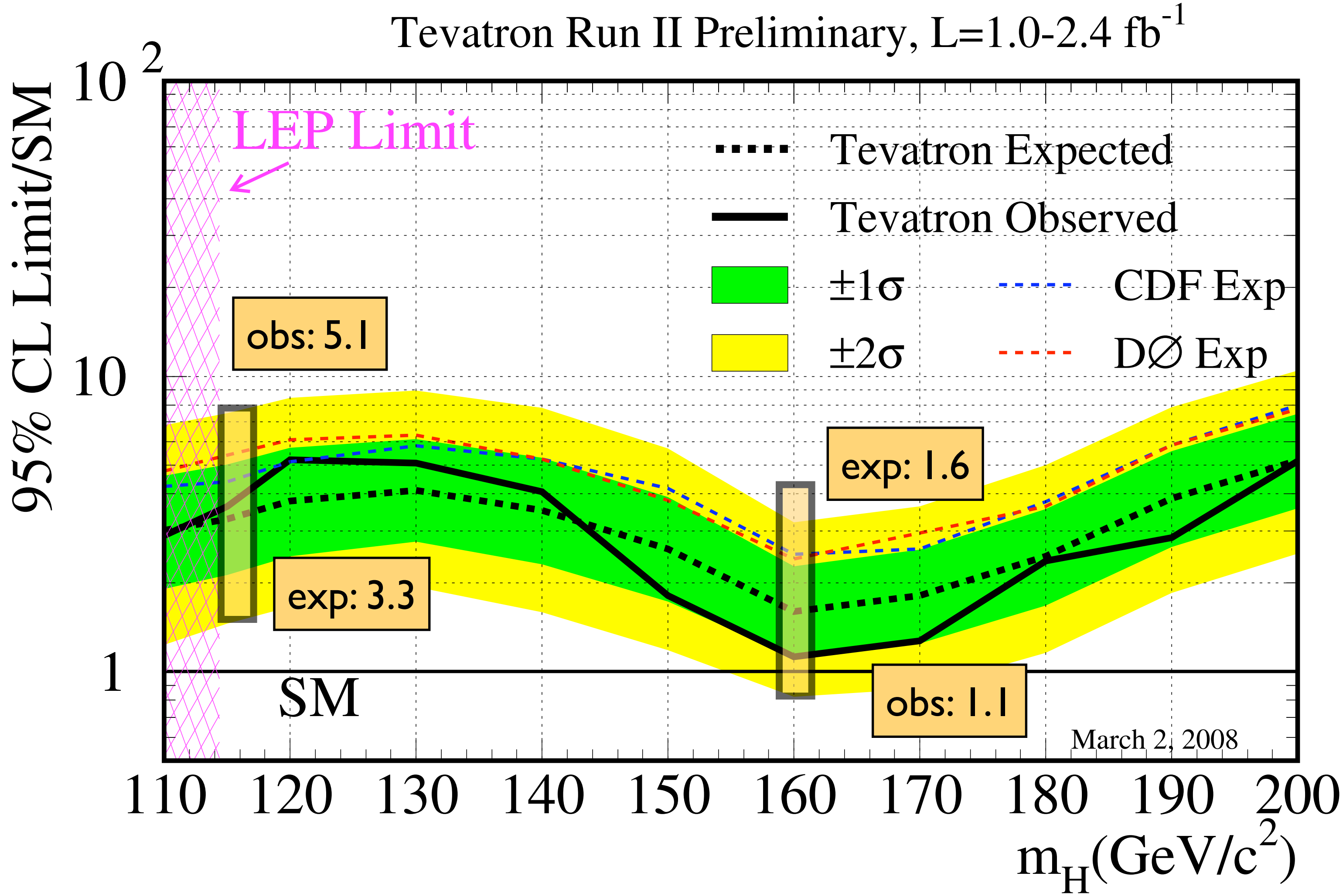
DØ: H → γγ



2 isolated em clusters
QCD and γj background estimated from data



Tevatron Combination



Projecting Higgs Reach to 2010

Improvements assumed in projections

- b-tagging
  - b-tagging with Layer 0 (~8% per tag efficiency increase, DØ)
  - add semileptonic b-tags (~5% per tag efficiency increase, DØ)
  - improved usage of existing taggers (~25%, CDF)
  - add single-b-tag channel to ZH→ννbb (DØ)
- Acceptance
  - include forward electrons in WH (DØ)
  - include 3-jet sample in WH (DØ)
  - 25% trigger acceptance (CDF)
- Analysis techniques
  - improved multivariate analyses (~20% in sensitivity)
  - better usage of E_T^{miss}
  - di-jet mass resolution (from 18% to 15% in σ(m)/m, DØ)
- scaling of systematic uncertainties as a function of luminosity

Additional improvements not yet included in projection

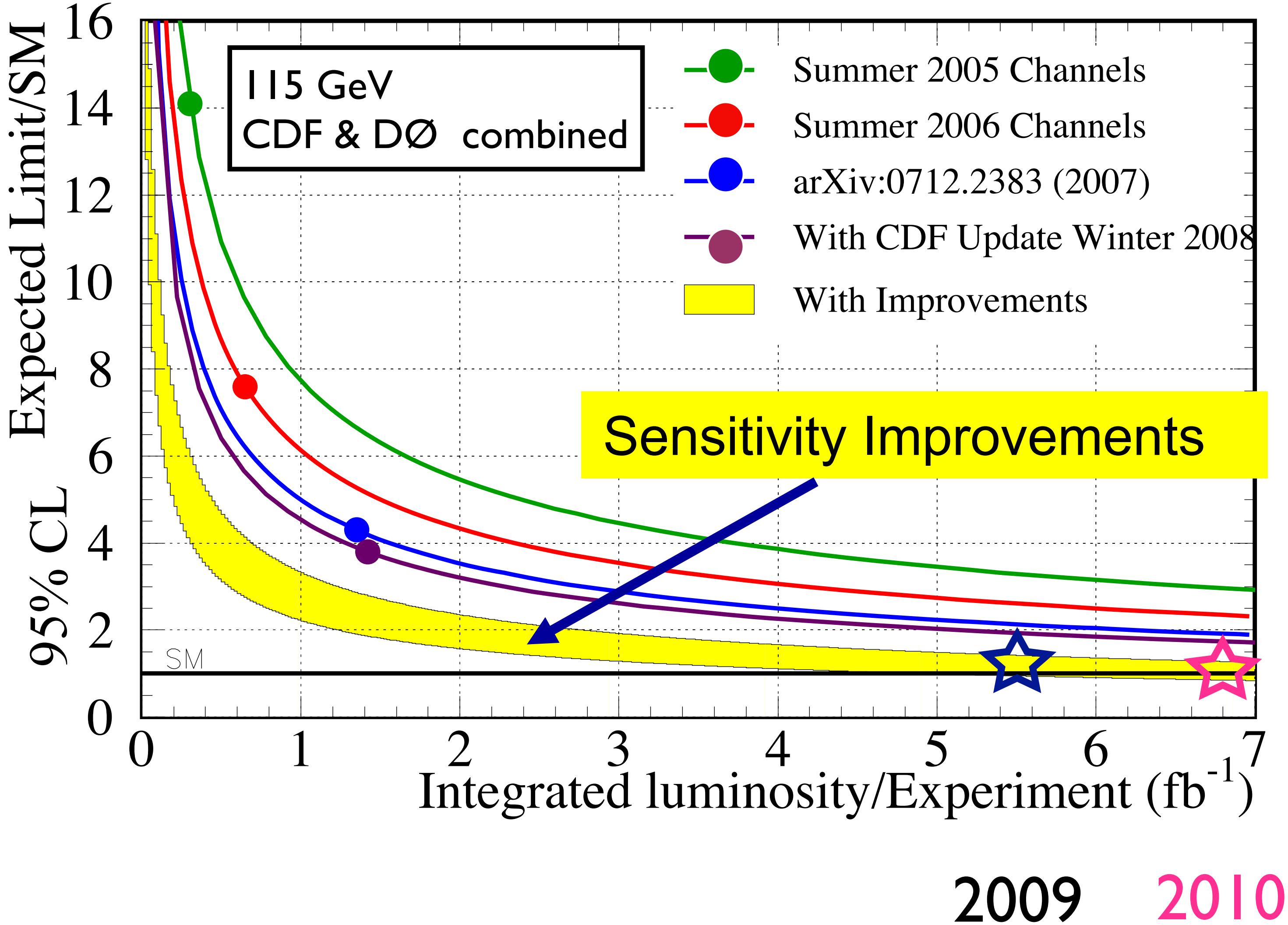
inclusion of tau channels

charm rejection in single b-tag analyses

optimizing H→WW at low mass

...

Higgs Projections 115GeV

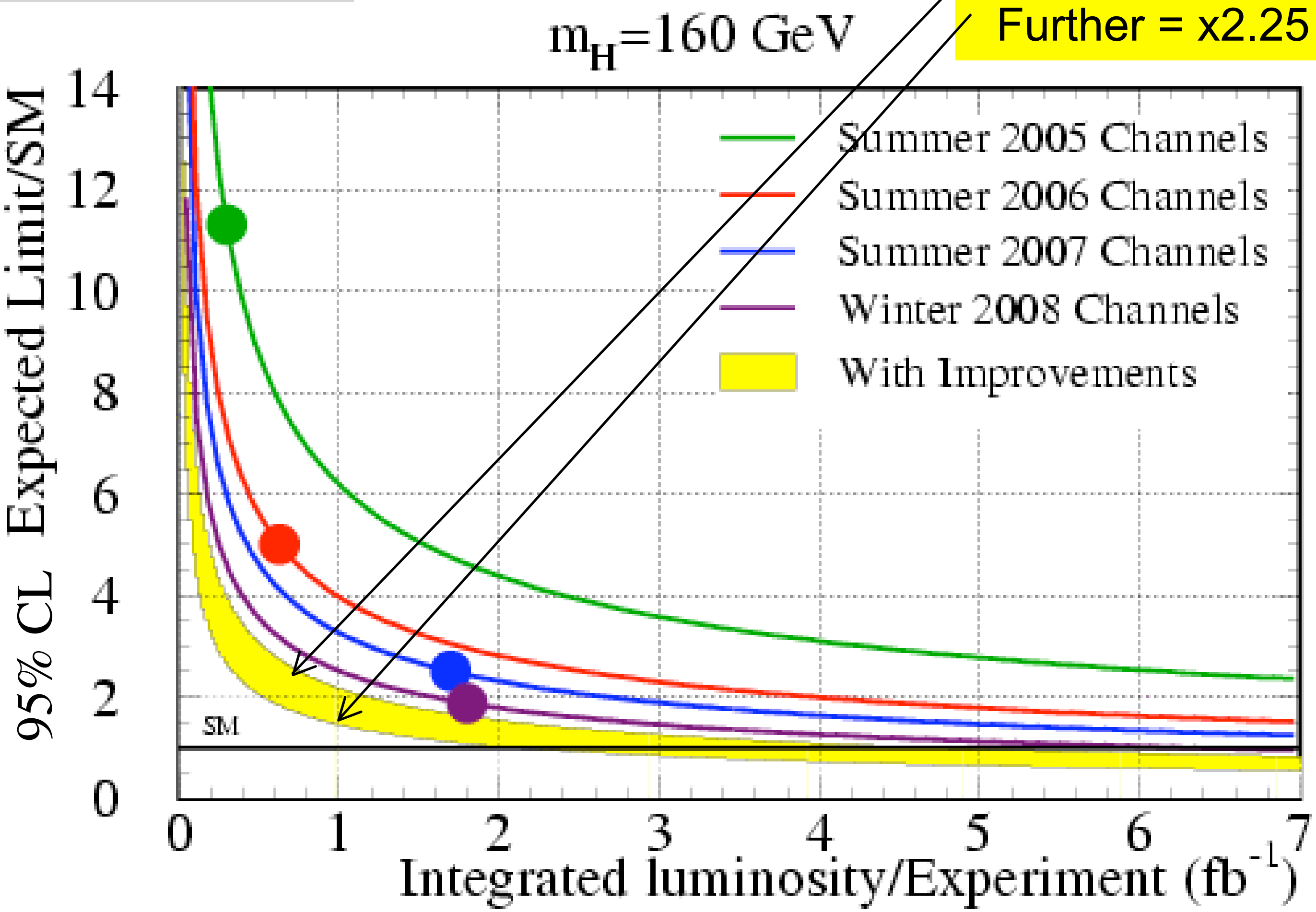


Rob Roser, P5 Meeting, 01/02/08

Higgs Projection 160 GeV

<u>CDF+D0 combined</u>
- curves are sqrt(*L*)

Sensitivity factors
Minimum = x1.5
Further = x2.25



Conclusion

The

rise

or

setting

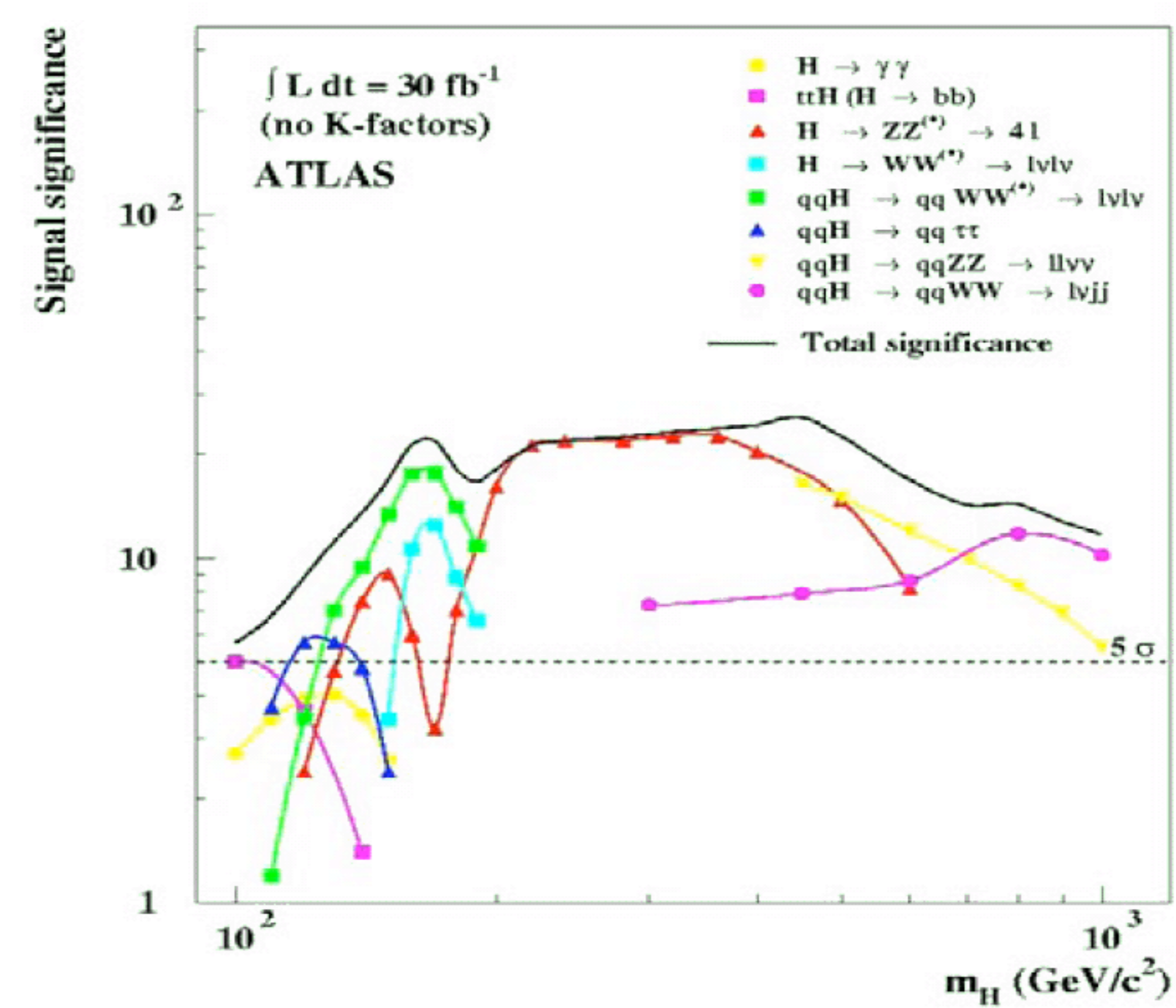
of the

Higgs

is close

Backup Slides

Higgs @ATLAS



Signal significance
∫ L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4l
H → WW(*) → lνlν
qqH → qq WW(*) → lνlν
qqH → qq ττ
qqH → qqZZ → llνν
qqH → qqWW → lνjj
Total significance
5 σ
10 2
10
1
10 2
10 3
mH (GeV/c2)