

Searching for the Higgs Boson at the Tevatron

MLL Kolloquium, Garching

23rd October 2008

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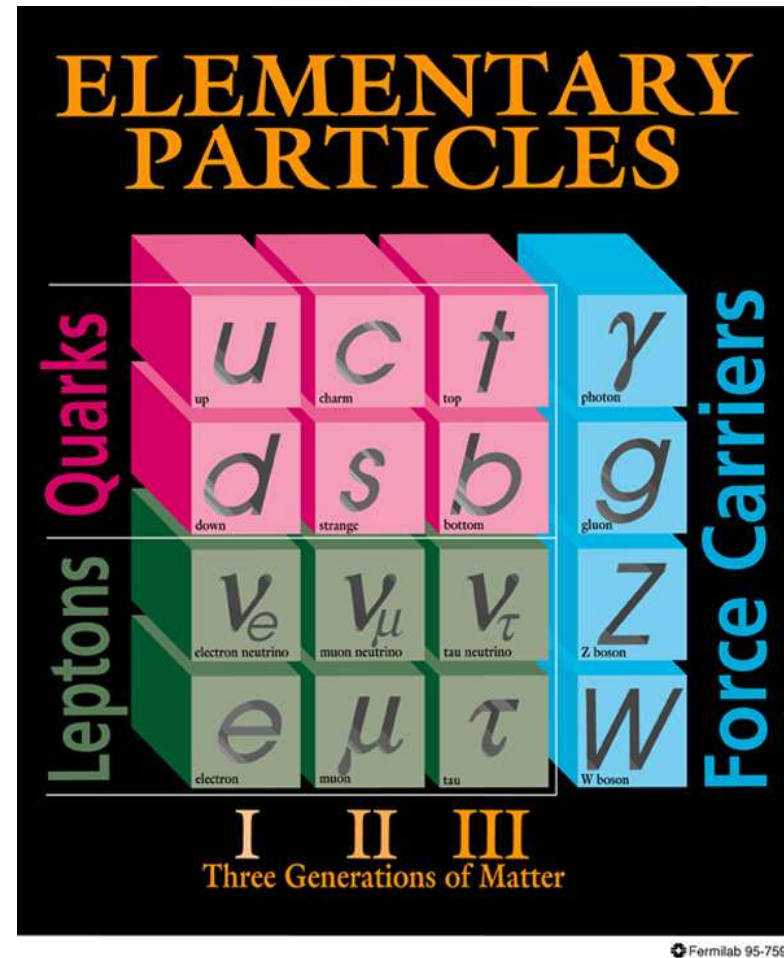
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Outline

- The Standard Model of particle physics
- Missing piece: Mass $\Rightarrow$ Higgs mechanism
- Higgs & Tevatron
- Low-mass Higgs searches
- High-mass Higgs searches
- Combination
- Conclusion & Outlook

The Standard Model

- Elementary particles: quarks, leptons
 - Basic forces: weak, strong, electromagnetic
 - Standard model describes all
 - * Based on (local) gauge symmetries
- ⇒ “Force” particles: $W^{\pm}$, Z, photon, gluon



⇒ Massless particles

Mass

- Proton/neutron mass: confinement energy, QCD
 - * Cf. mass of nucleus $\neq \sum$ mass of protons & neutrons
 - * Masses of light hadrons calculable by (lattice) QCD
 - $\Rightarrow$ Visible mass of the universe explained by QCD
- But: without massive quarks and W, no stable proton

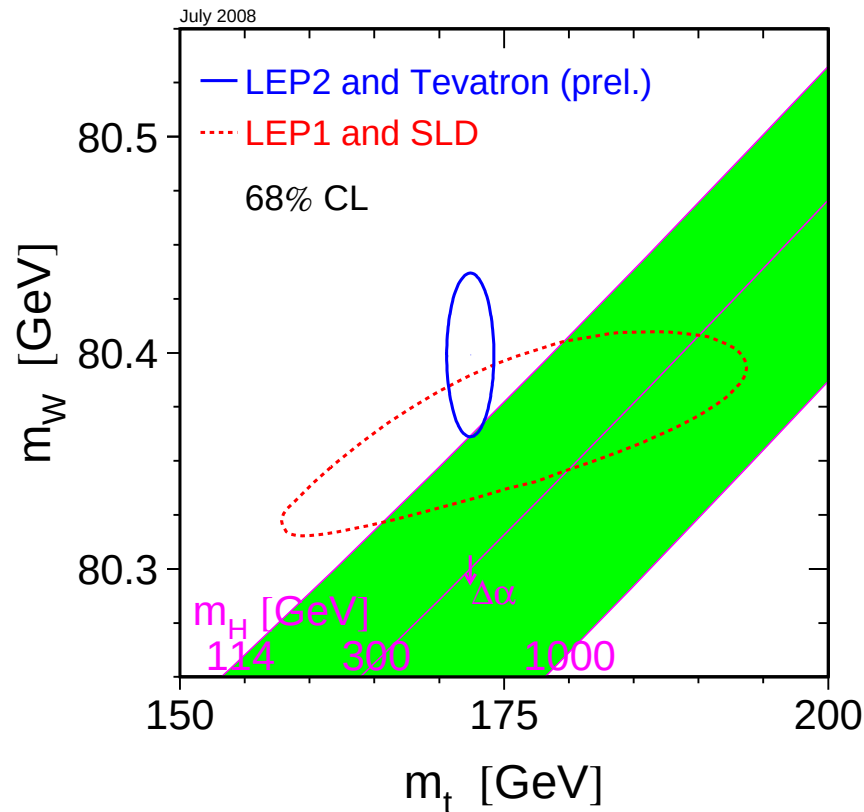
QCD = Quantum Chromodynamics = theory of strong force

Spontaneous Symmetry Breaking

- This year's Nobel prize for Nambu
 - Introduce another field, with a specific potential
- ⇒ Lowest energy state (vacuum) not invariant
- * Massive W and Z bosons, massless photon
 - * New massive particle: Higgs boson
 - * Massive quarks and leptons (BSM !)
 - * Cure some other problems
- ⇒ Where is the Higgs boson ?

What Do We Know?

Precision EW measurements at Tevatron, LEP and SLD



$$m_H = 84^{+34}_{-26} \text{ GeV}$$

$$m_H < 154 \text{ GeV at 95\% CL}$$

$$(m_t = 172.4 \pm 1.2 \text{ GeV})$$

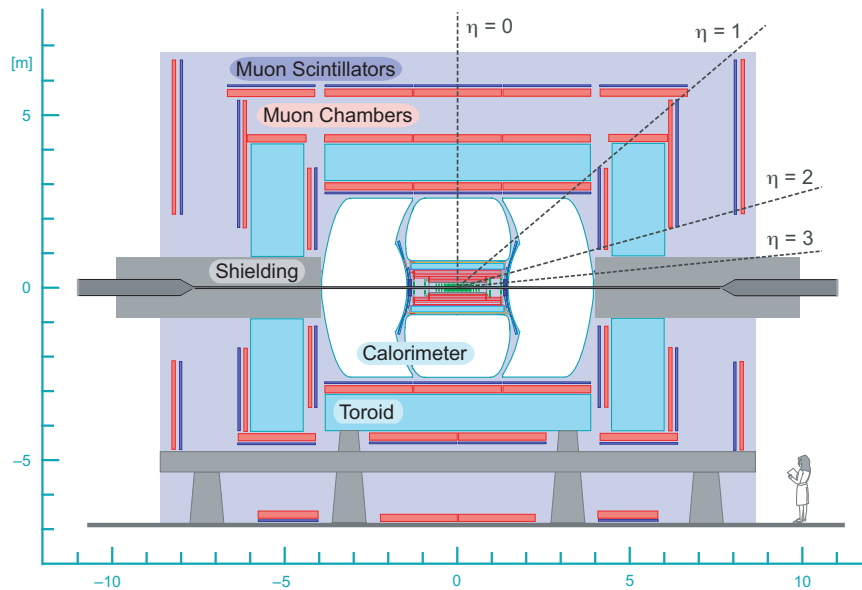
LEP2 direct search: $m_H > 114 \text{ GeV}$ ($m_H < 185 \text{ GeV}$)

$\Rightarrow$ Within reach of the Tevatron!

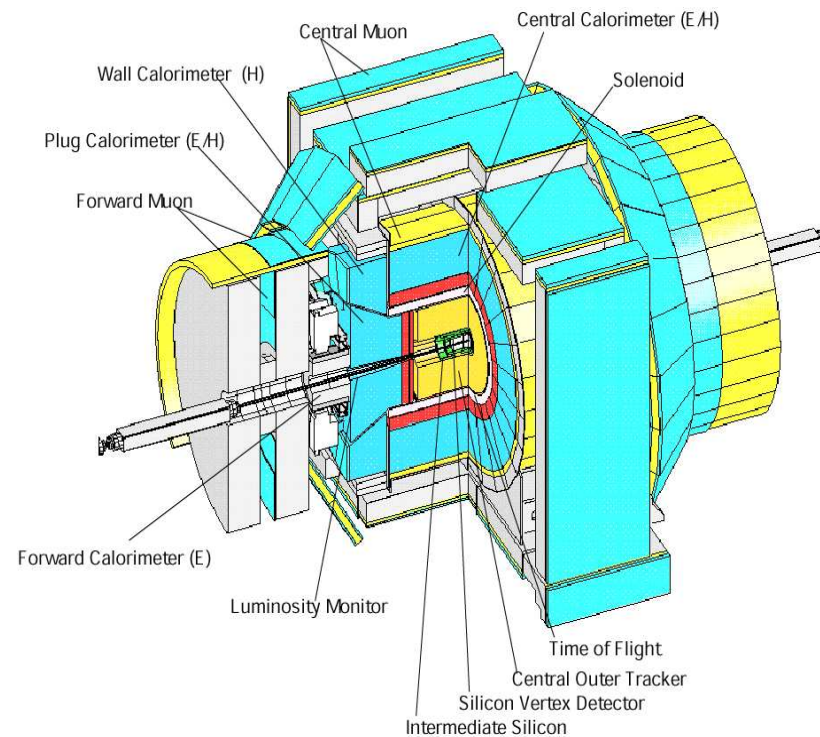
Tevatron

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Up to now: $\int \mathcal{L} dt \simeq 5.1 \text{ fb}^{-1}$ delivered / experiment
- Results shown in this talk: up to 3 fb^{-1}

DØ

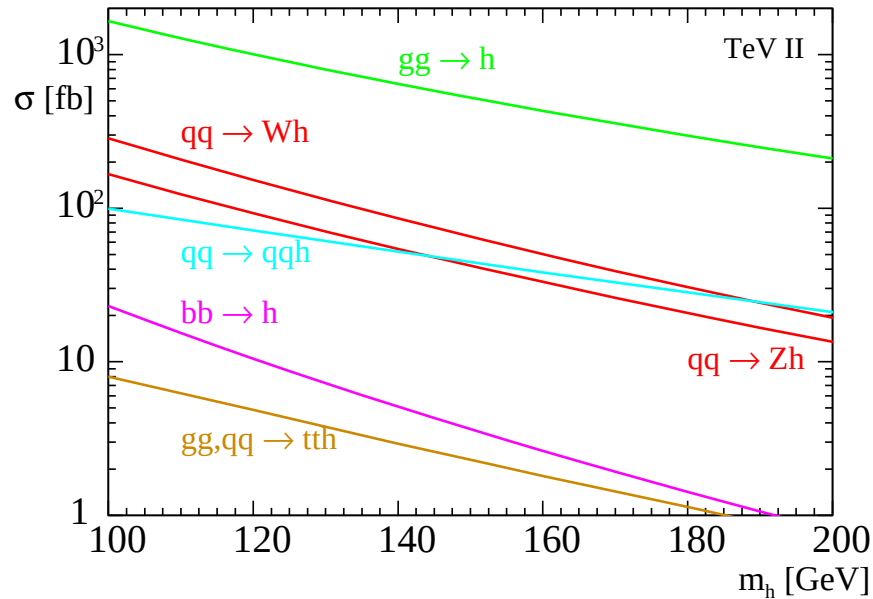


CDF



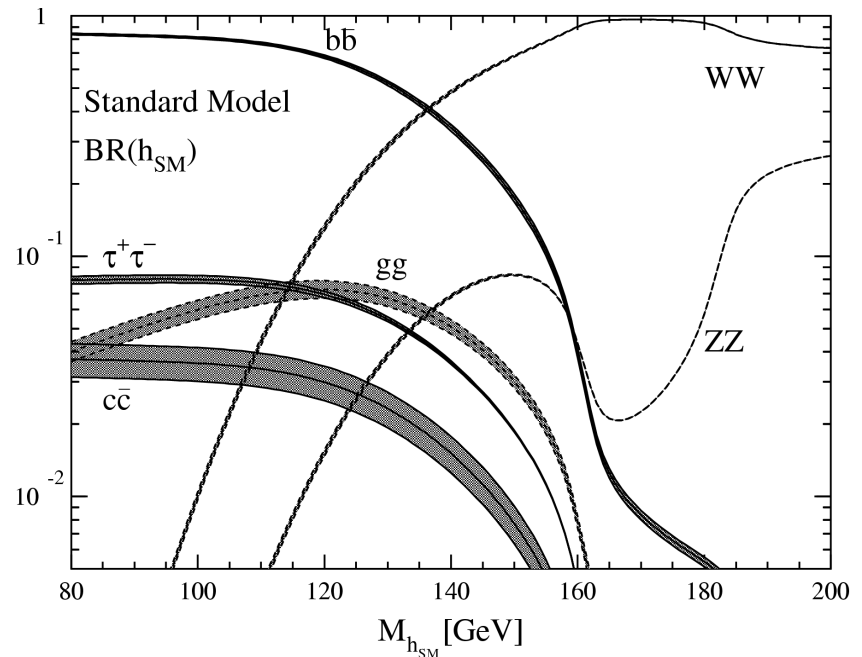
Higgs @ Tevatron

Production



- Gluon fusion
- Associated production

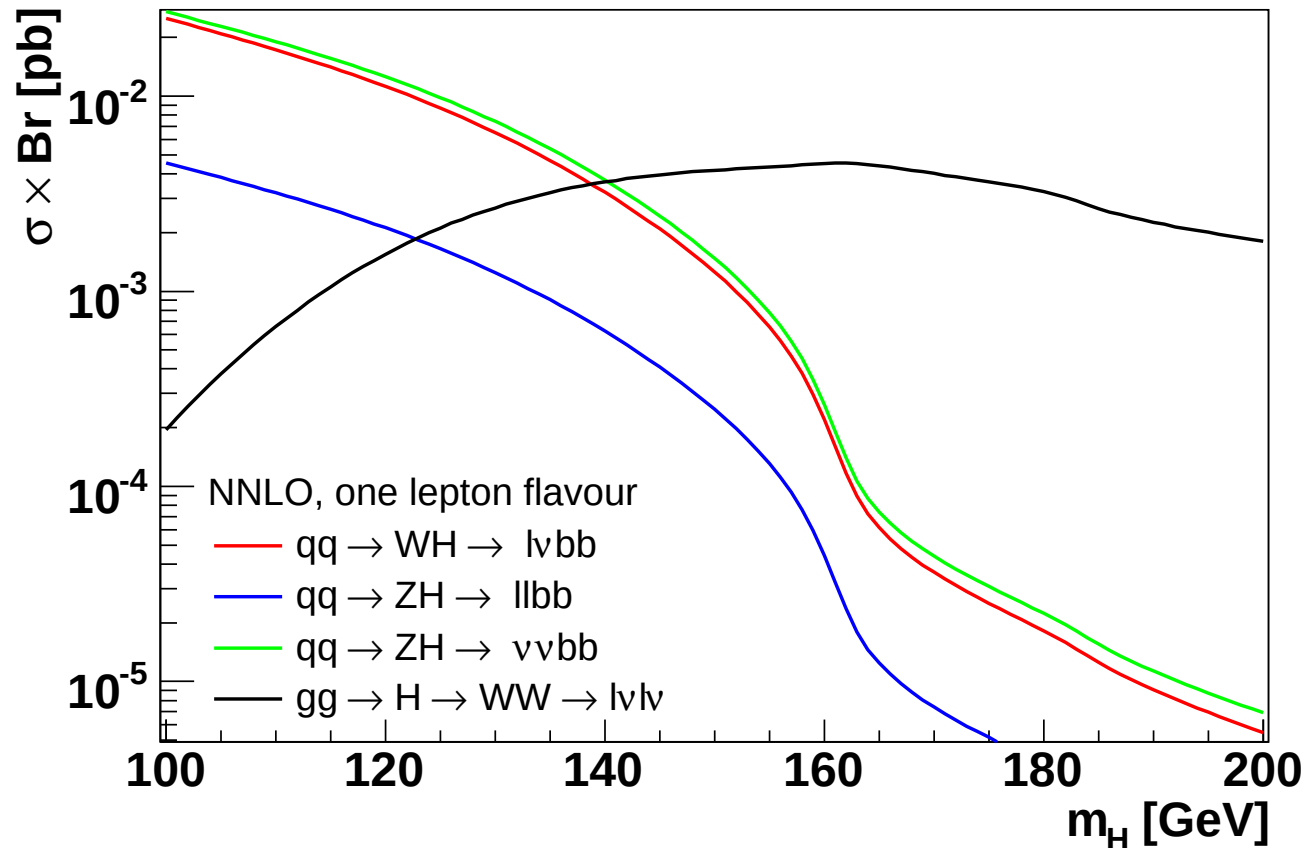
Decay



- $b\bar{b}$ at low m_H
- WW at high m_H

Higgs @ Tevatron

$\sigma \times \text{Br}$ for experimentally most accessible final states



WH, ZH with $H \rightarrow b\bar{b}$ at low m_H

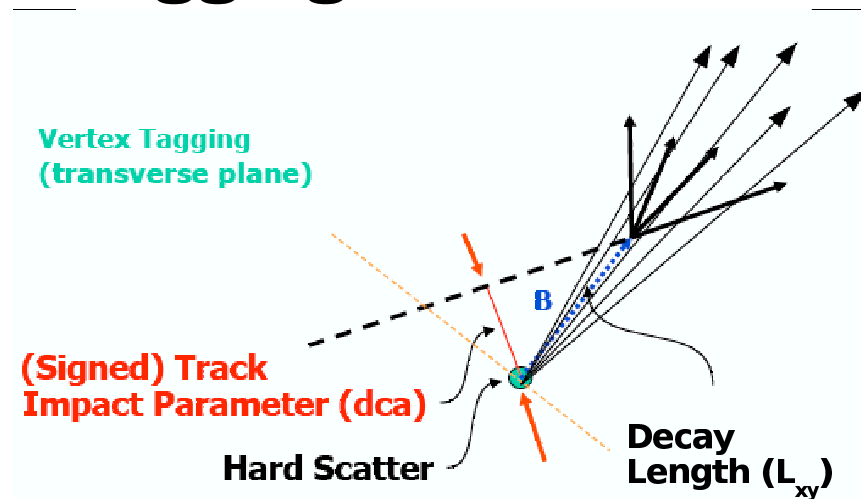
$gg \rightarrow H$ with $H \rightarrow WW$ at high m_H

Higgs at Low Mass: WH & ZH Searches

- Decays of W and Z: high p_T leptons and/or $\cancel{E}_T$
 - $H \rightarrow b\bar{b}$: at least two jets
 - Background sources:
 - * W/Z with additional jets (including $Wb\bar{b}$, $Zb\bar{b}$)
 - * $t\bar{t}$, single top
 - * Multi-jet production with mis-ID of lepton or $\cancel{E}_T$
 - * Di-boson (WW, WZ, ZZ)
- ⇒ Need to precisely model these !
- * Multi-jet directly from data
 - * Others from simulation of standard model processes

b-Tagging

Exploit b-lifetime:



– Combine lifetime variables in, e.g. a neural network:

- * Vertex mass, decay length, impact parameters, . . .

⇒ High b-tagging efficiency:

- * “Tight”: 50% at 0.5% fake rate (DØ neural net tagger)

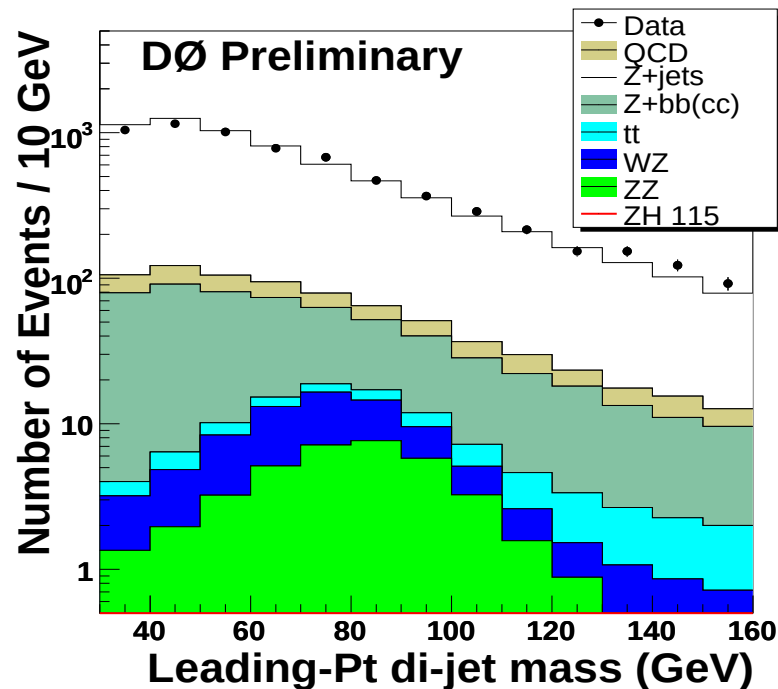
- * “Loose”: 74% at 5.0% fake rate (DØ neural net tagger)

– Typical analysis: two “Loose” tags or one “Tight” tag

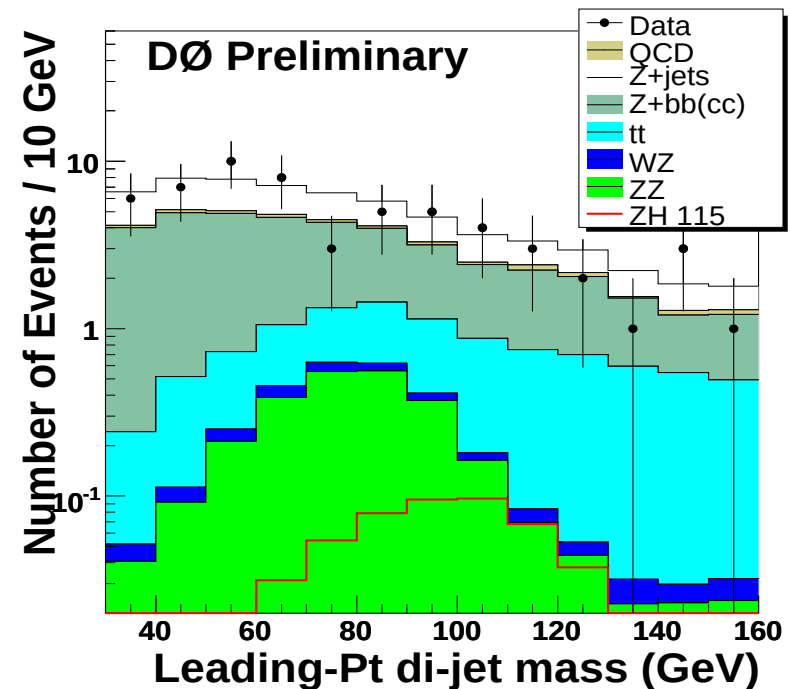
Two Charged Leptons: $ZH \rightarrow \ell\ell b\bar{b}$

- Clean signature: two isolated leptons, $m_{\text{inv}} \simeq m_Z$; no $\cancel{E}_T$
- Exclusive samples with one “Tight” or two “Loose” b-tags

$$\int \mathcal{L} dt \simeq 1.1 \text{ fb}^{-1} \text{ (Run IIa)}$$



Before b-tag: 1.45 ZH
7.6k background events

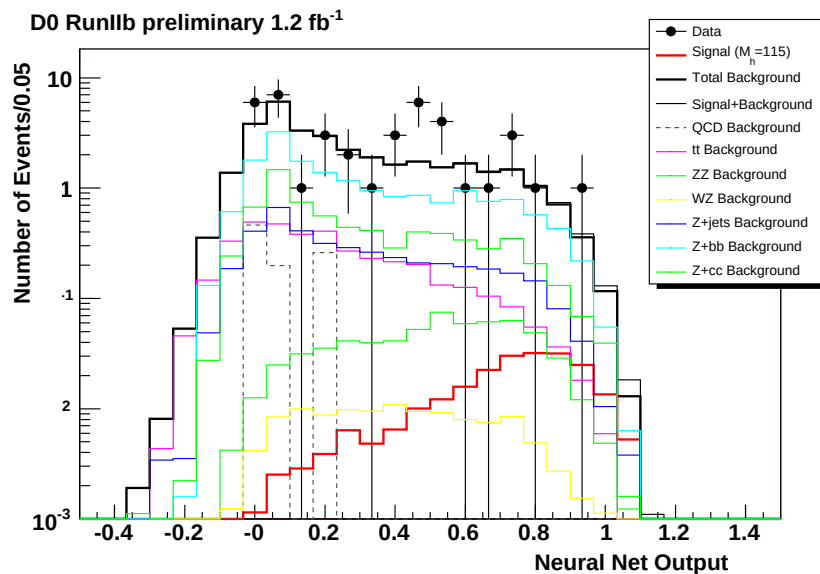


Double b-tag: 0.53 ZH
73.6 background events

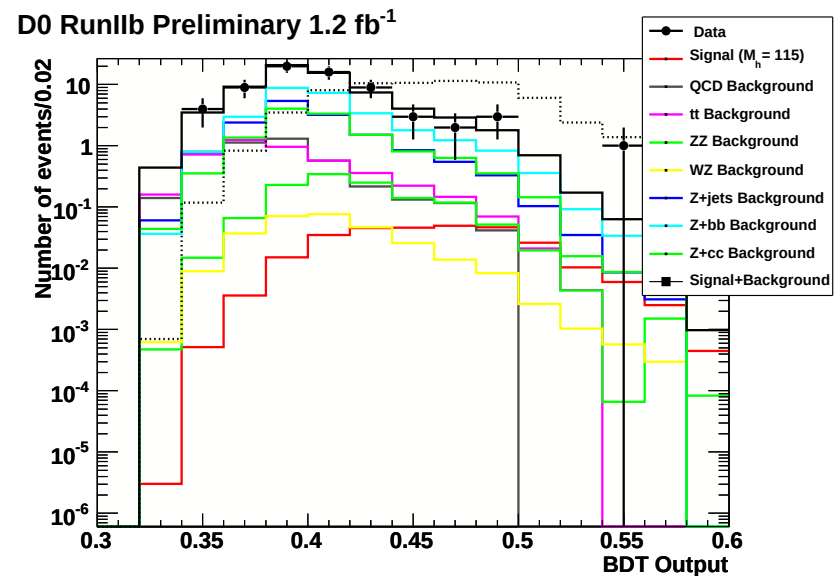
Two Charged Leptons: $ZH \rightarrow \ell\ell b\bar{b}$

- Improve sensitivity by using all event kinematics
- $\Rightarrow$ Neural network or (boosted) decision tree
 - * BDT recursively cuts on kinematic variables
 - * More discriminating than m_{jj}

$$\int \mathcal{L} dt \simeq 1.2 \text{ fb}^{-1} \text{ (Run IIb)}$$



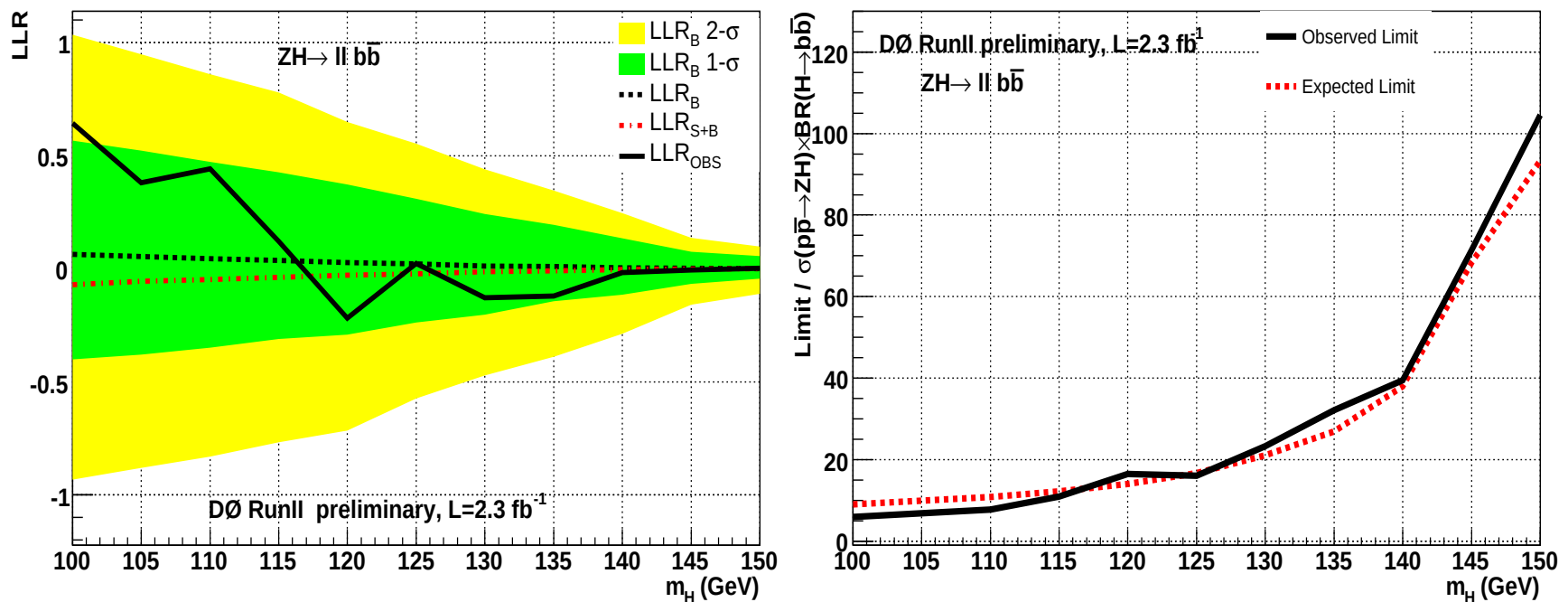
$ZH \rightarrow ee b\bar{b}$



$ZH \rightarrow \mu\mu b\bar{b}$

$ZH \rightarrow \ell\ell b\bar{b}$ Result

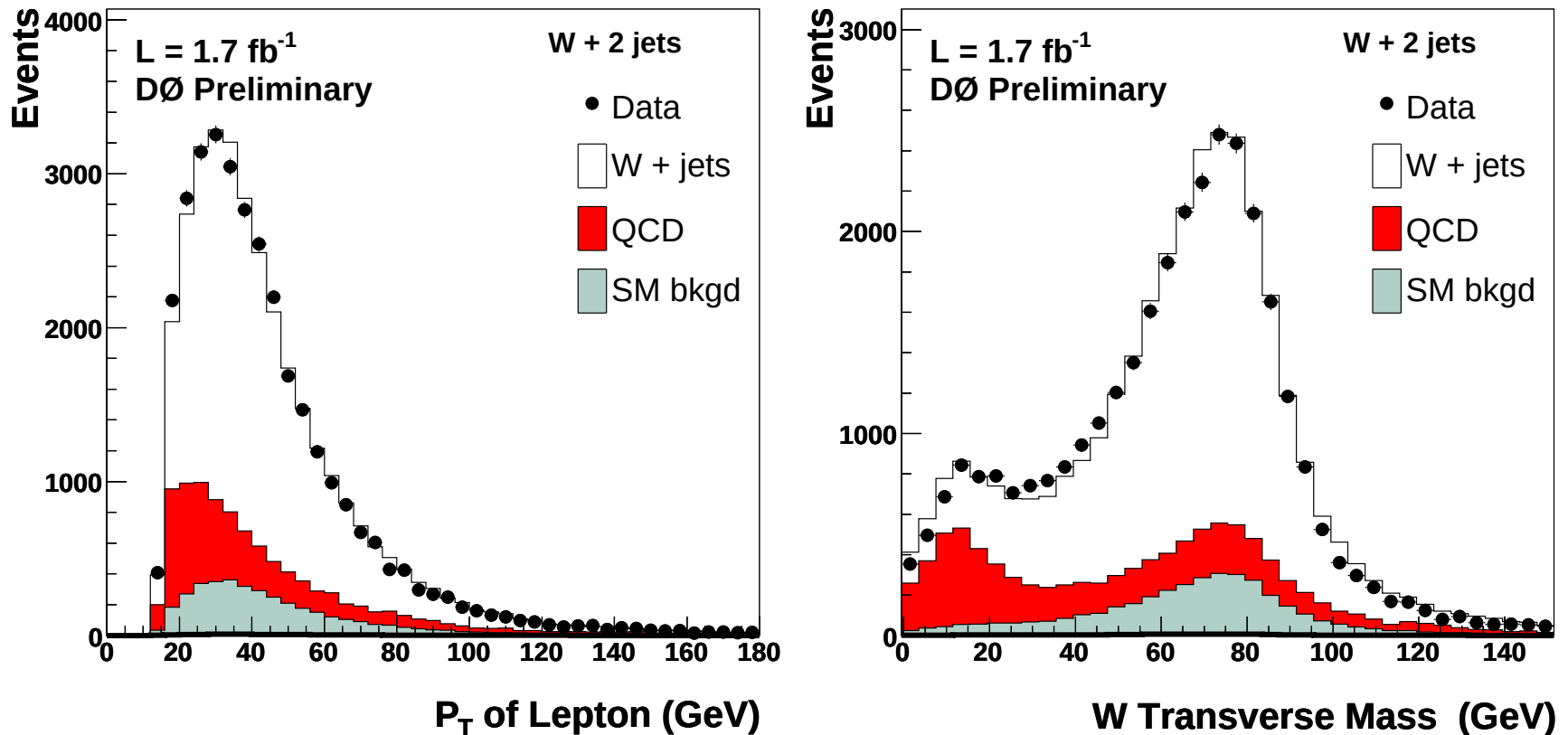
- No excess, data agree with background model
- Use neural network / decision tree output to derive limits



At $m_H = 115$ GeV: limit/SM 11 (12 expected)

One Charged Lepton: $WH \rightarrow \ell \nu b \bar{b}$

- Signature: one isolated lepton, large $\cancel{E}_T$
- Events with two or three jets, one or two jets b-tagged

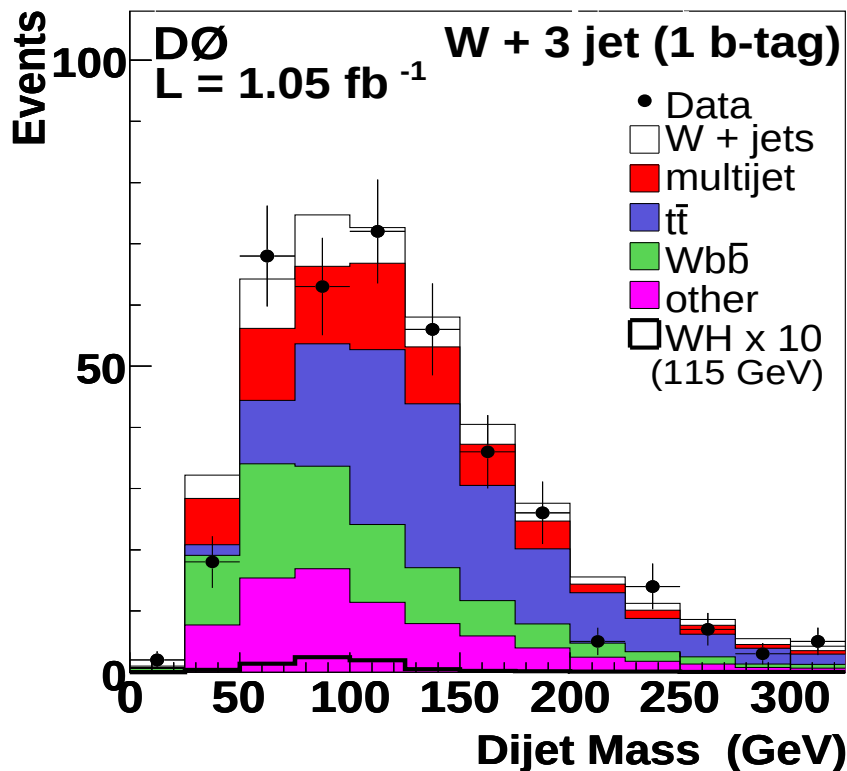


Before b-tag: 9.9 WH, 33.5k background events

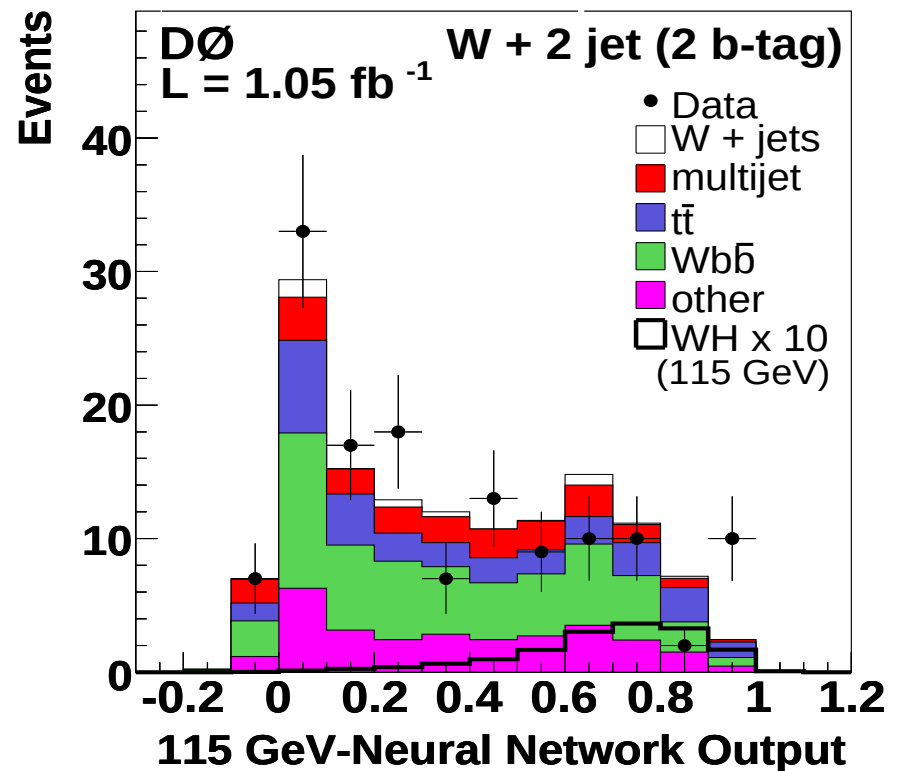
Double b-tag: 2.3 WH 204.1 background events

One Charged Lepton: $WH \rightarrow \ell \nu b \bar{b}$

- Train a neural network against $Wb\bar{b}$, kinematics as input:
 $\Delta R(\text{jets}), p_T(\text{di-jet system}), \Delta\phi(\text{jets}), p_T((\text{sub-})\text{leading jet}),$
 $p_T(\mu - \cancel{E}_T \text{ system}), m_{jj} \Rightarrow \simeq 15\%$ improvement in sensitivity



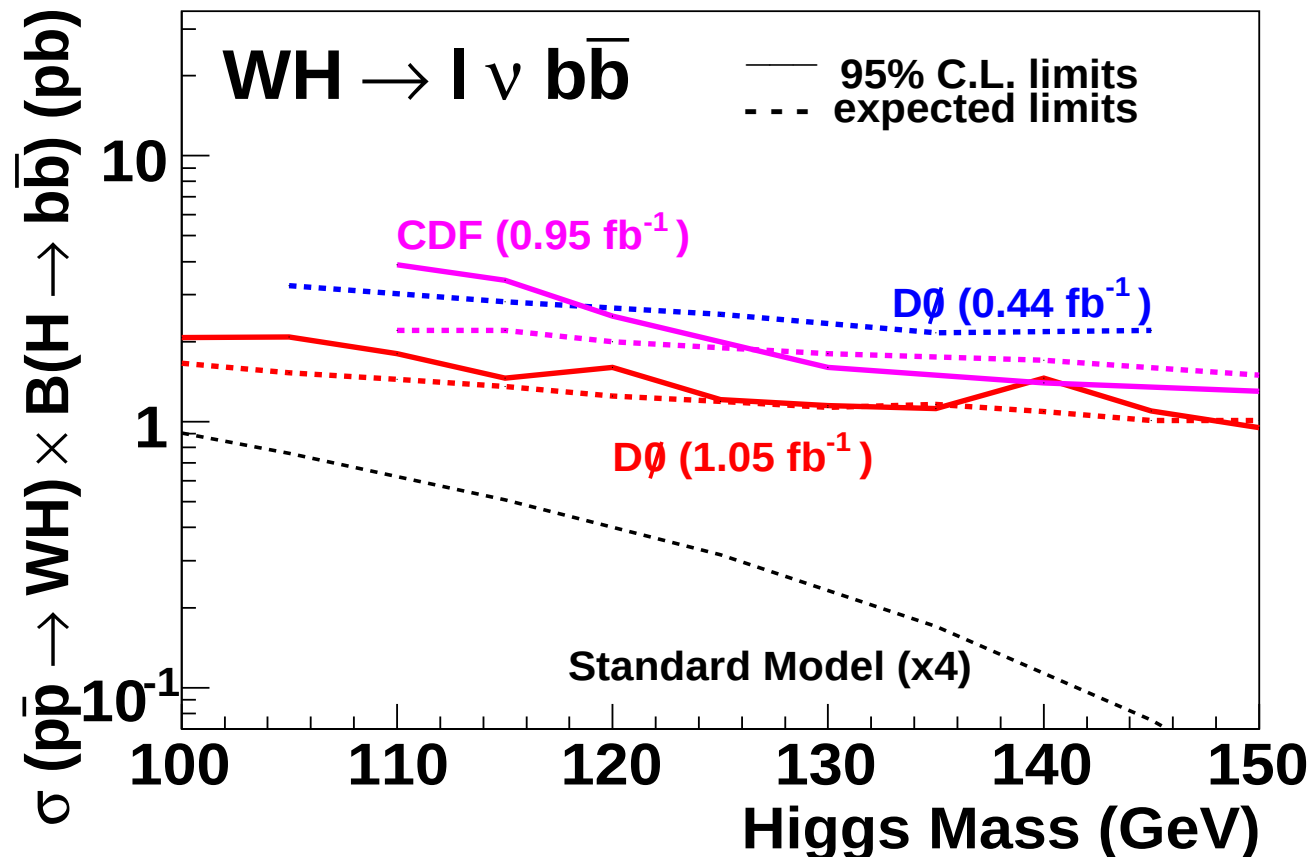
0.7 WH, 418 non-WH events



1.5 WH, 132 non-WH events

$WH \rightarrow \ell \nu b \bar{b}$ Result

- No excess, data agree with background model
- Use neural network output, dijet mass to derive limits



DØ at $m_H = 115 \text{ GeV}$: limit/SM 11.4 (10.7 expected)

Advanced Technique: Matrix Element

- For each event, estimate compatibility with signal or background hypothesis

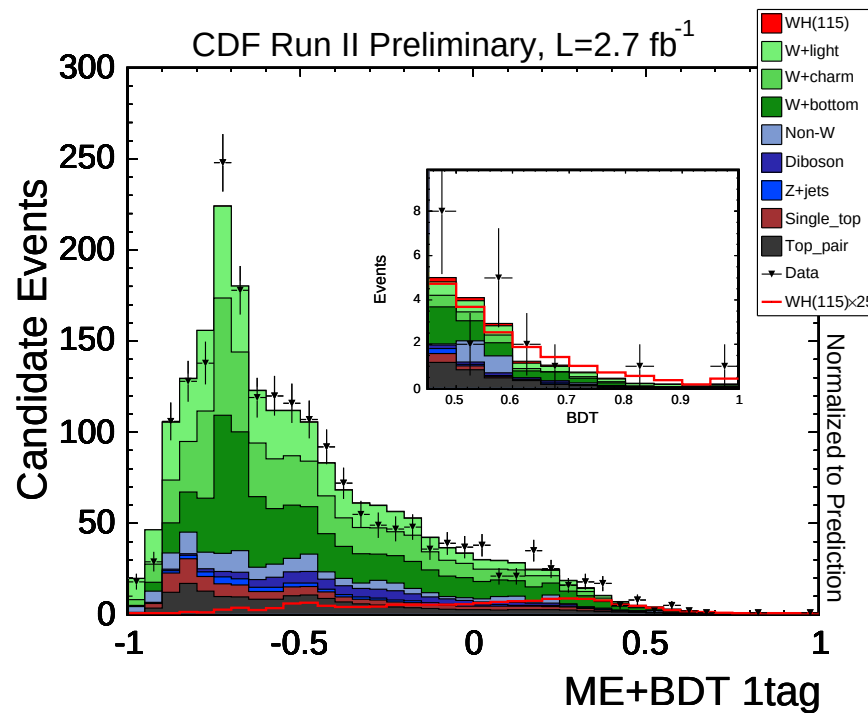
$$P(\vec{x}_{\text{obs}}) = \frac{1}{\sigma} \int \frac{d\sigma_{\text{theory}}}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{\text{obs}}, \vec{y}) d\vec{y}$$

$$\text{MEdisc}(\vec{x}_{\text{obs}}) = \frac{P_{\text{signal}}}{P_{\text{signal}} + P_{\text{background}}}$$

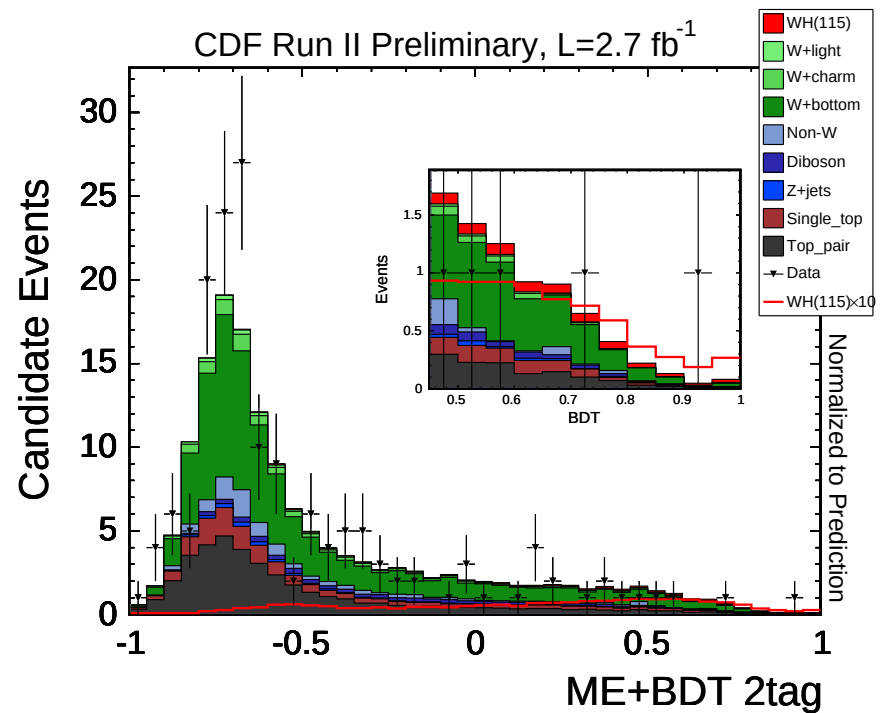
- $\vec{x}, \vec{y}$: event kinematics ϵ : acceptance $\times$ efficiency
 G : resolution function
- Use as input to a neural network or decision tree

One Charged Lepton: $WH \rightarrow \ell \nu b \bar{b}$

- CDF, $\int \mathcal{L} dt \simeq 2.7 \text{ fb}^{-1}$
- Matrix element probabilities as input to decision tree



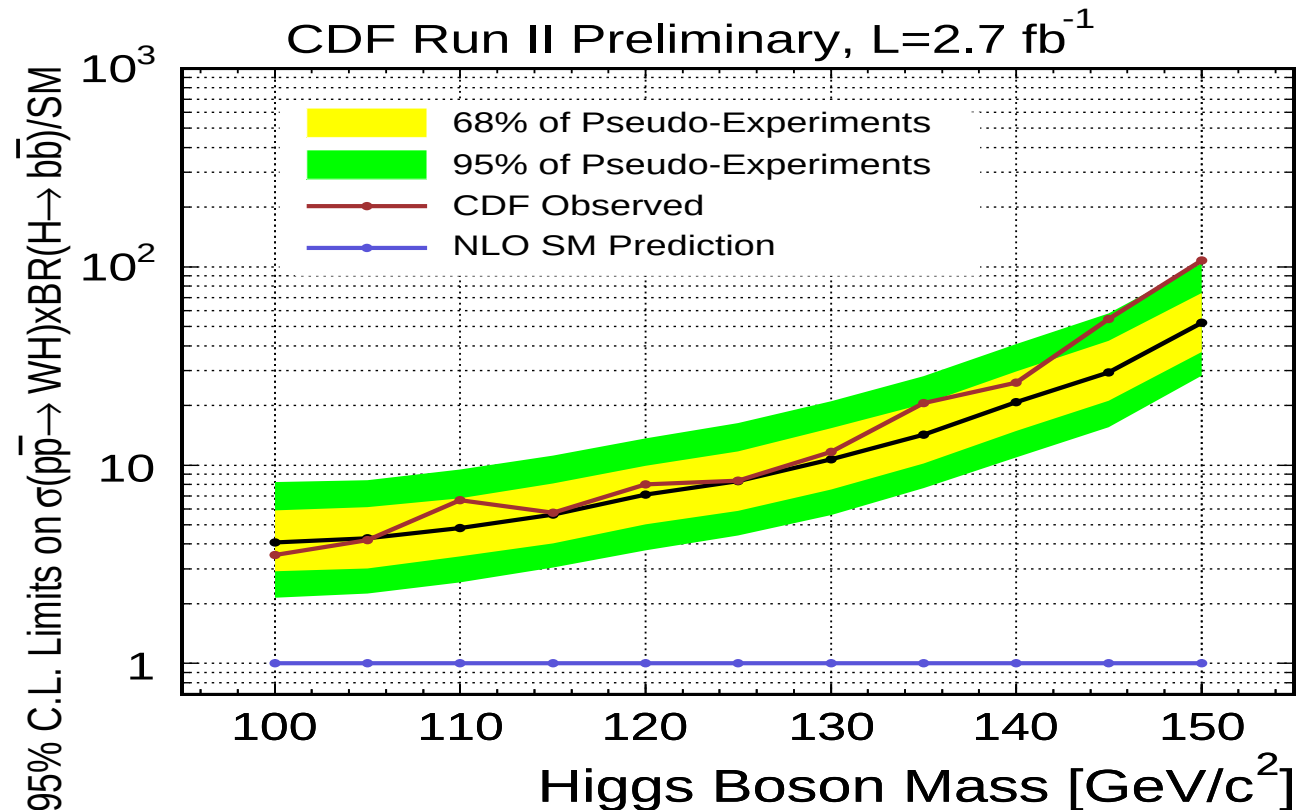
Single b-tag: 6.3 WH
2013 background events



Double b-tag: 2.0 WH
148 background events

$WH \rightarrow \ell \nu b \bar{b}$ Result

- No excess, data agree with background model
- Use decision tree output to derive limits

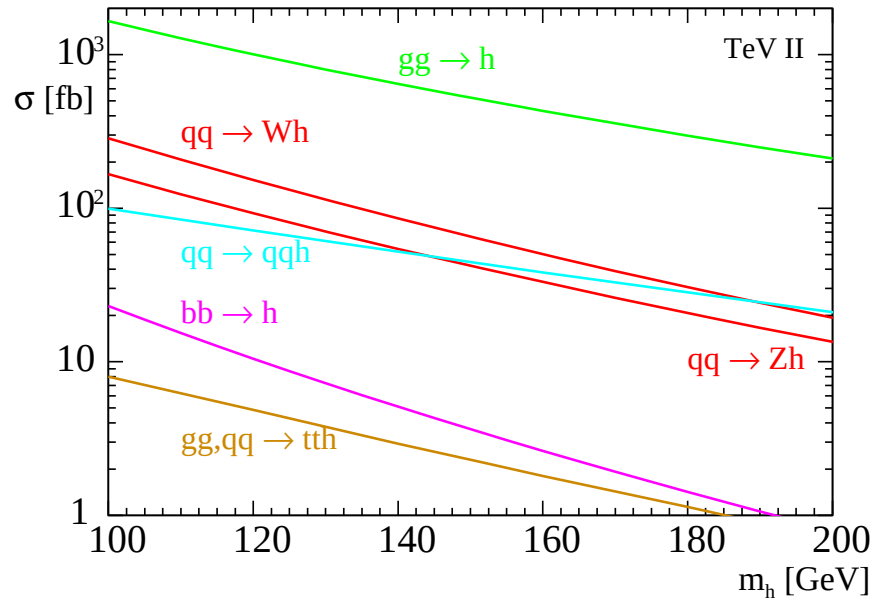


CDF, 2.7 fb^{-1} at $m_H = 115 \text{ GeV}$: limit/SM 5.8 (5.6 exp.)

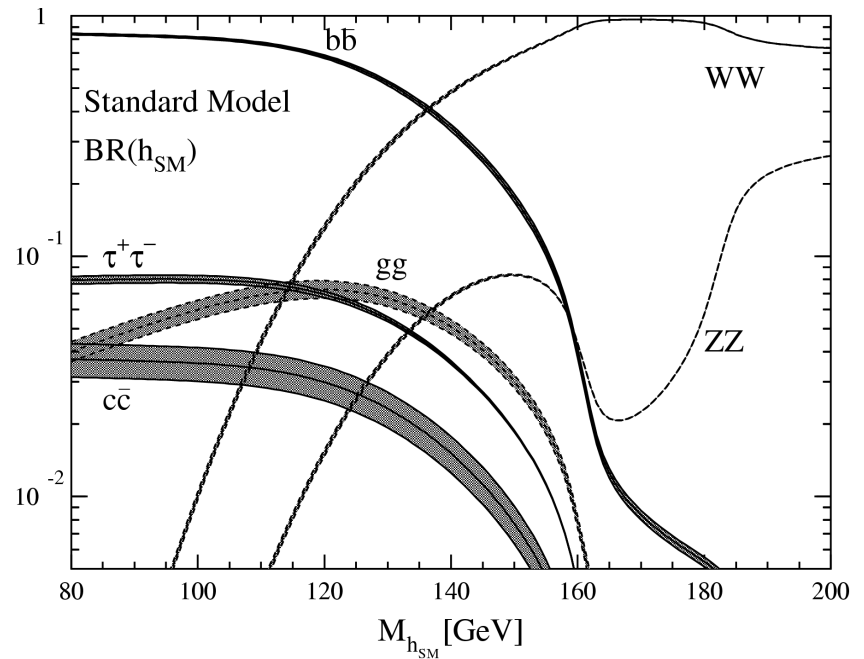
DØ, 1.0 fb^{-1} at $m_H = 115 \text{ GeV}$: limit/SM 11.4 (10.7 exp.)

Higgs $\rightarrow \tau\tau$

Production



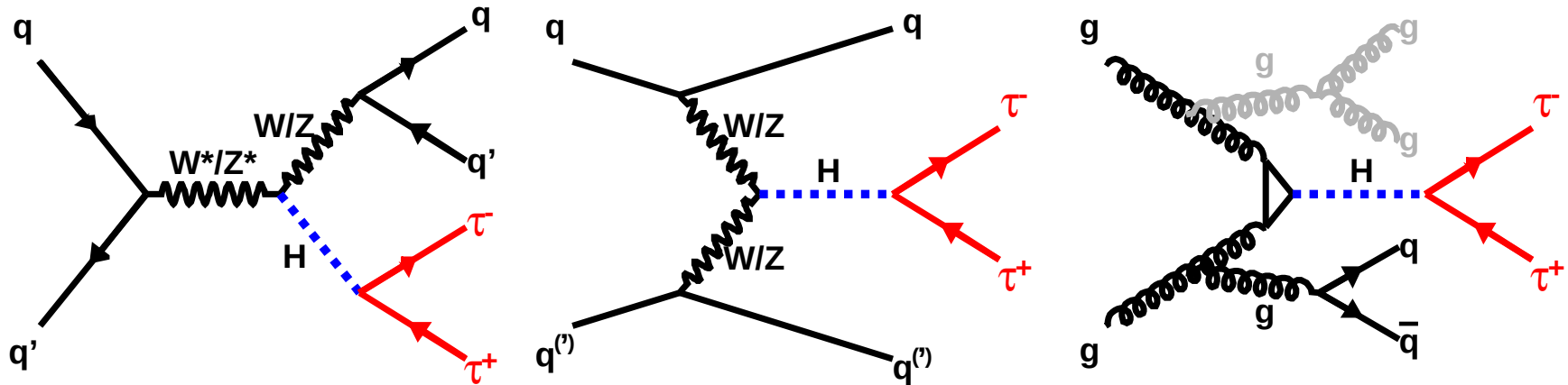
Decay



$$H \rightarrow \tau\tau \simeq 10\% \text{ of } H \rightarrow b\bar{b}$$

WBF $H \rightarrow \tau\tau$ important at LHC !

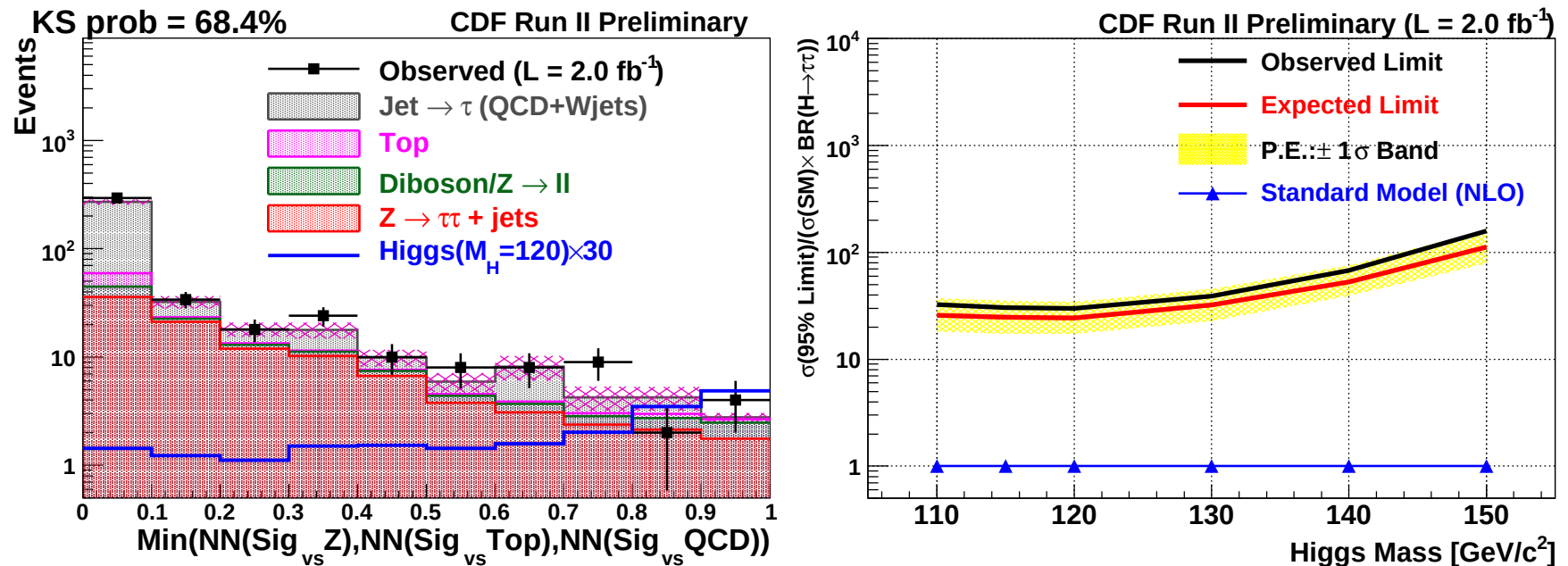
Higgs $\rightarrow \tau\tau$



- CDF, $\int \mathcal{L} dt \simeq 2 \text{ fb}^{-1}$
- Final state: $\tau(\rightarrow \ell X) \tau(\rightarrow \text{hadrons}) + 2 \text{ jets}$
- Sensitive to WH, ZH, WBF, gluon fusion
- Background from Z/W+jets, $t\bar{t}$, di-boson, multi-jet
- Neural networks trained against main backgrounds

Higgs $\rightarrow \tau\tau$

- At $m_H = 115$ GeV: 0.76 Higgs, 373.8 background events
- No excess, data agree with background model



At $m_H = 115$ GeV: limit/SM 30.5 (24.8 expected)

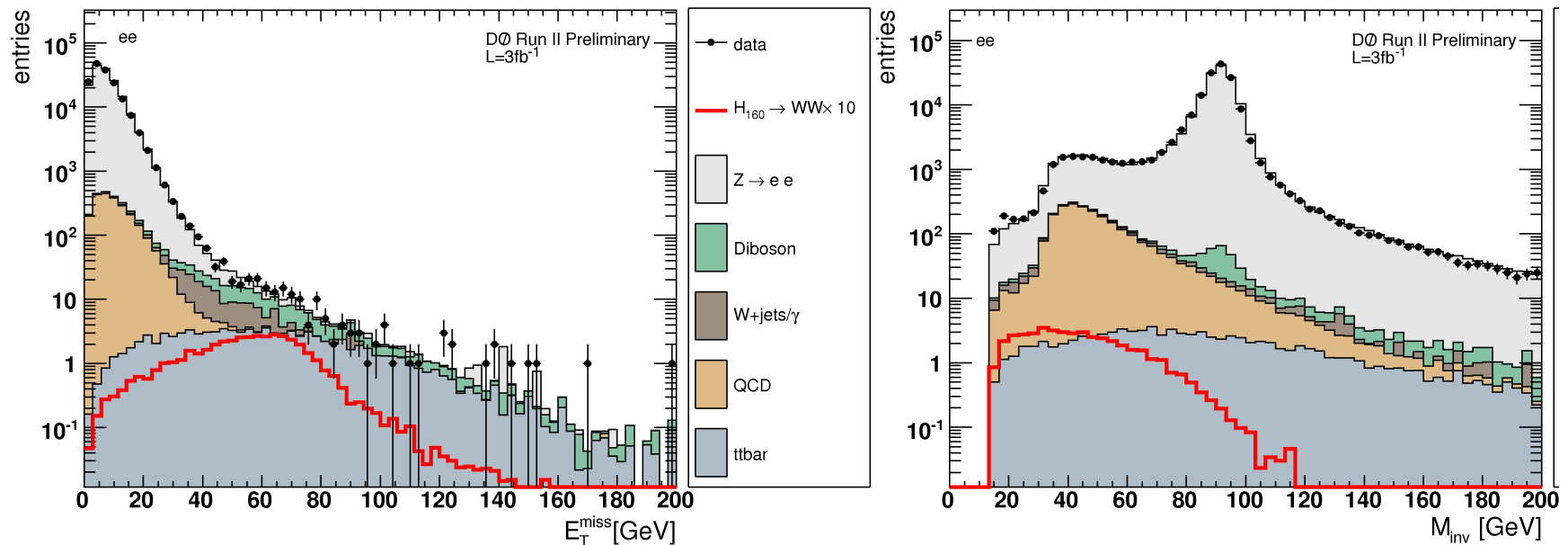
$\Rightarrow$ Another step in sensitivity!

Higgs at High Mass

- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$
- Final states with e^+e^- , $\mu^+\mu^-$ or $e^\pm\mu^\mp$ and large $\cancel{E}_T$
- Background sources:
 - * Di-boson (WW, WZ, ZZ)
 - * $t\bar{t}$, DY di-lepton production
 - * $W +$ mis-identified jet/ γ
- Signal includes WBF, leptonic τ decays

Higgs at High Mass

$$D\bar{O}, \int \mathcal{L} dt \simeq 3 \text{ fb}^{-1}$$



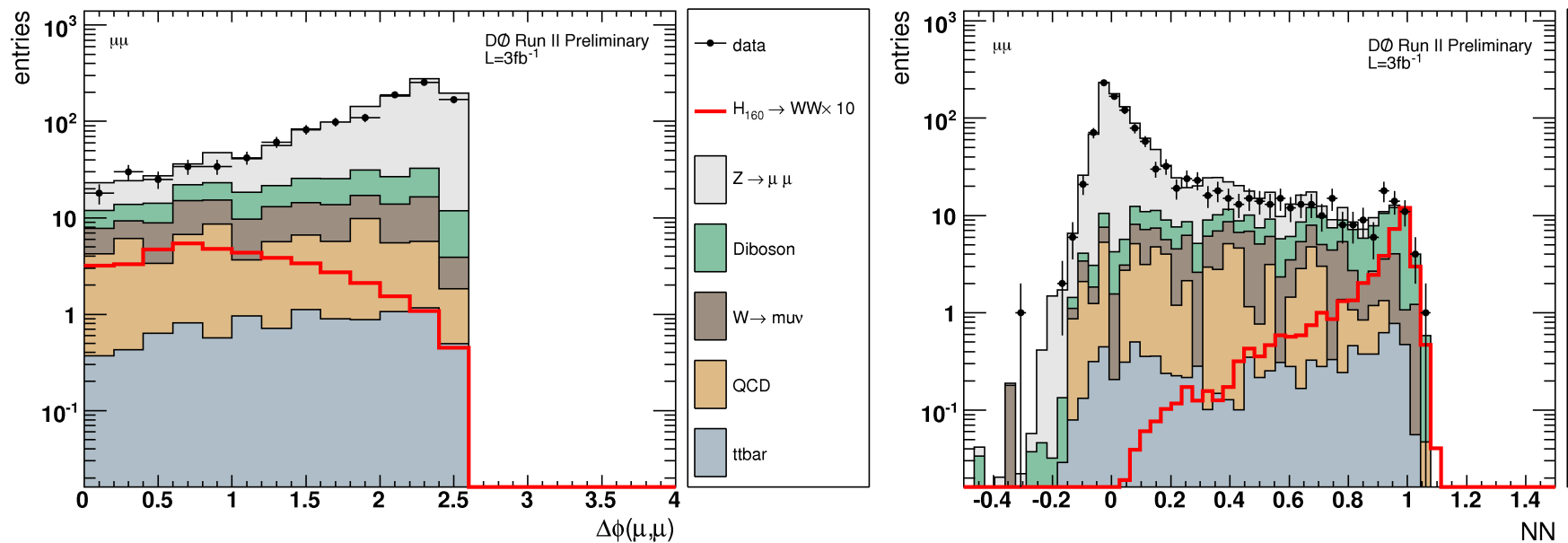
Good agreement at preselection level

- Cannot reconstruct m_H , but . . .
- Spin correlations: $\Delta\phi(\ell\ell)$ small for $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

$H \rightarrow WW$ Neural Net Discriminant

- Train a neural network against all background, using e.g.:

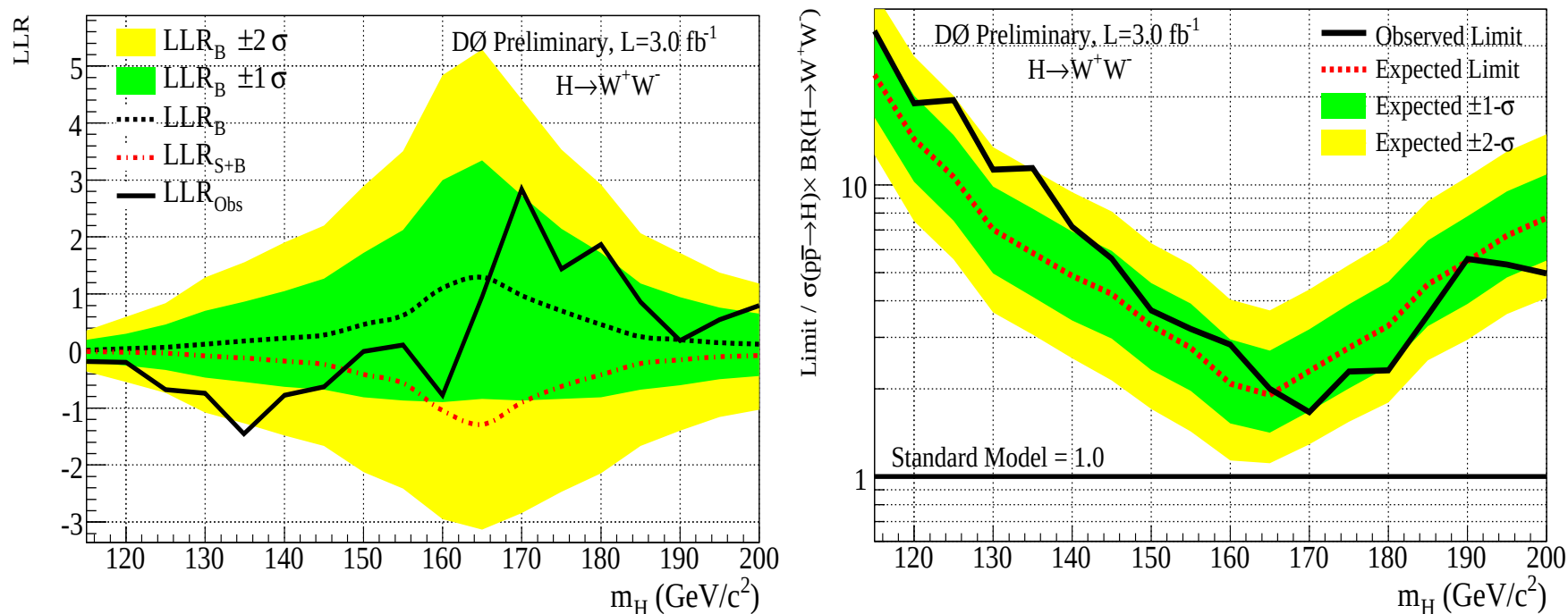
$$\Delta\phi(\ell_1\ell_2), p_T(\ell_1), p_T(\ell_2), \cancel{E}_T, M_T^{\min}, H_T, M_{\text{inv}}(\ell_1\ell_2)$$



⇒ Neural Net gives better separation than just $\Delta\phi$

Higgs at High Mass

- No excess, data agree with background model
- Use neural network output to derive limits



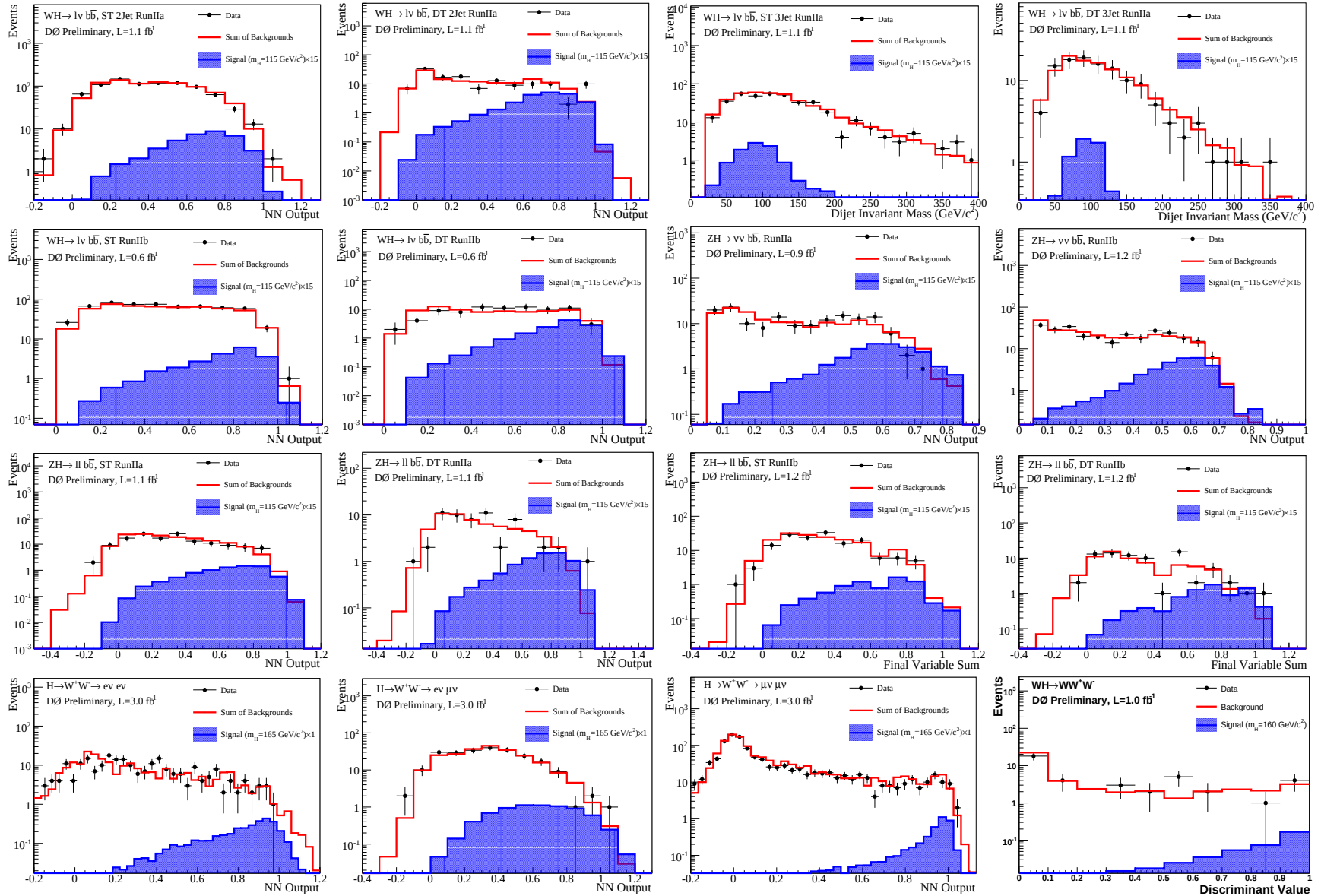
Just DØ at $m_H = 165$ GeV: limit/SM 2.0 (1.9 expected)

Combination of Search Results

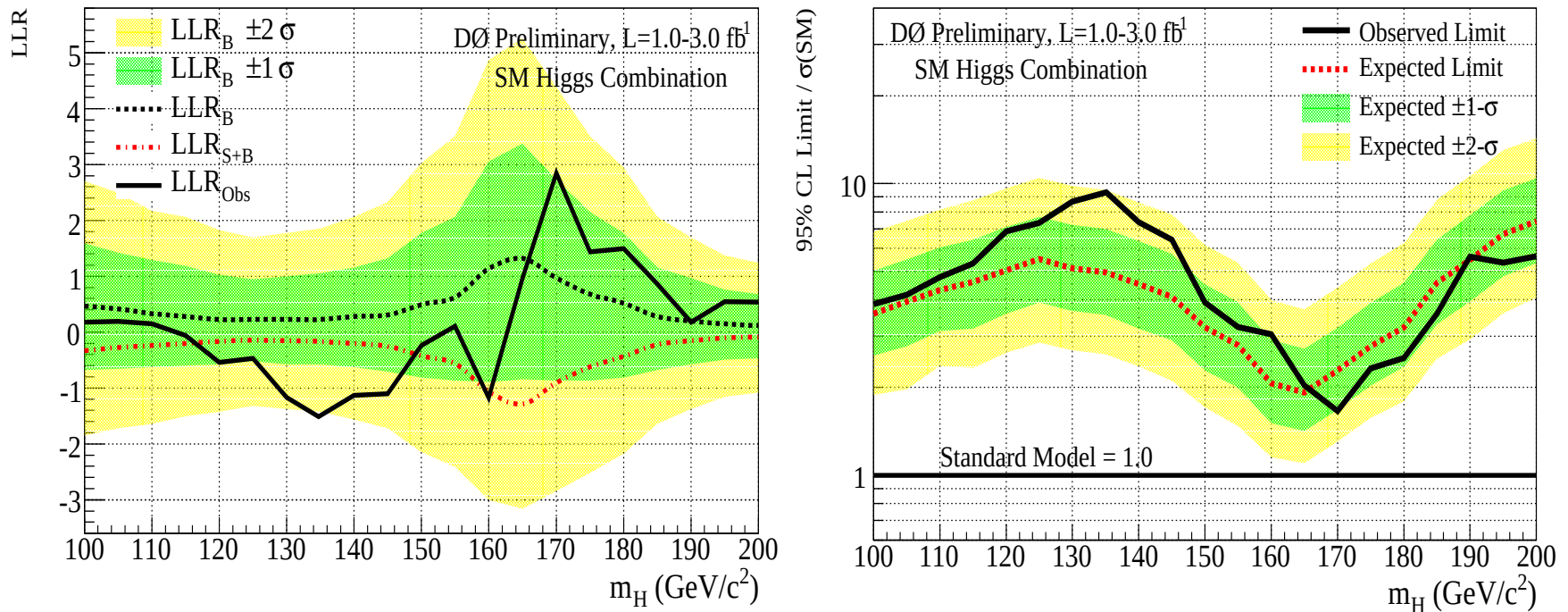
- Looking for SM Higgs $\rightarrow$ assume SM branching ratios $\rightarrow$ combine search channels
- $WH \rightarrow \ell \nu b \bar{b}$, $ZH \rightarrow \ell \ell b \bar{b}$, $H \rightarrow WW$,
 $ZH \rightarrow \nu \nu b \bar{b}$, $WH \rightarrow WWW$, $H \rightarrow \gamma \gamma$
- Per channel $\int \mathcal{L} dt = 1.1 \rightarrow 3.0 \text{ fb}^{-1}$
- Systematic uncertainties:
 - * $\int \mathcal{L} dt$, $\sigma(\text{background})$, lepton/jet-ID, physics-model, JES, b-tagging, . . .
 - * “Shape” or “flat” uncertainties
 - * Used to fit background to the data in the limit calculation
 - * Treated as (un-) correlated between channels

DØ Combination

31 Analyses



DØ Combination

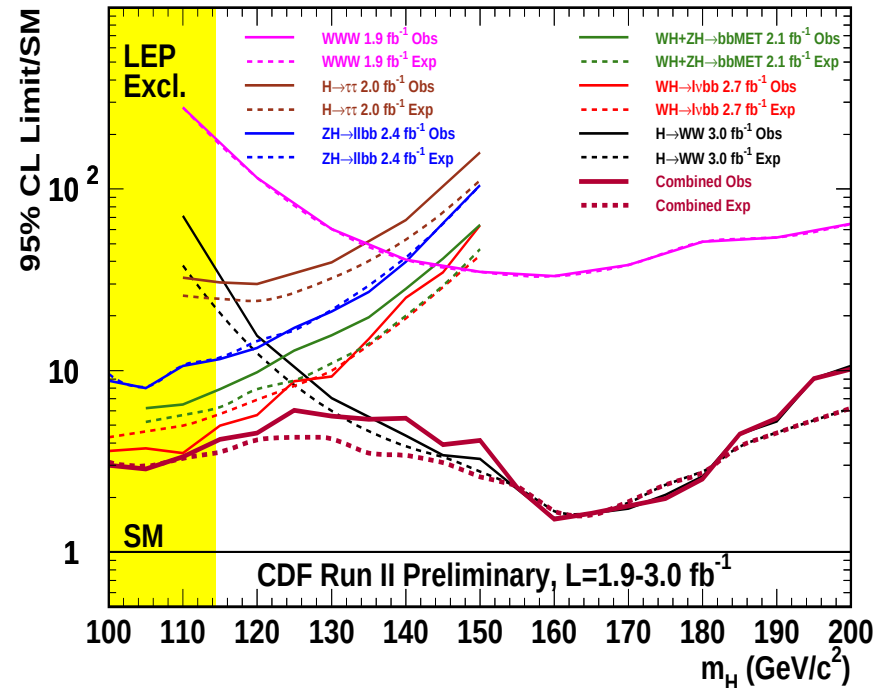
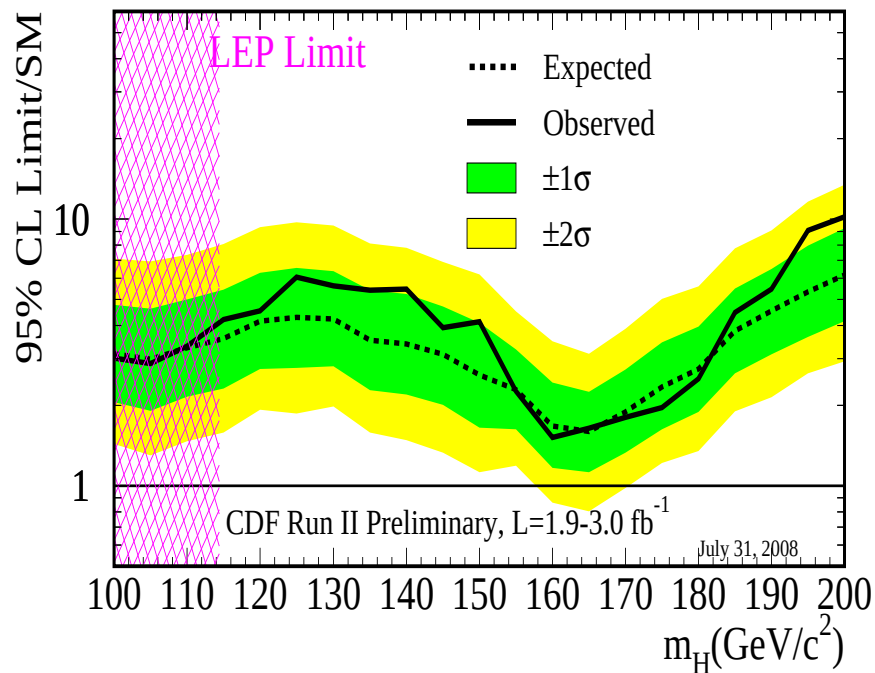


At $m_H = 115$ GeV: limit/SM 5.3 (4.6 expected)

At $m_H = 165$ GeV: limit/SM 2.0 (1.9 expected)

⇒ Getting close to the Standard Model expectation!

CDF Combination



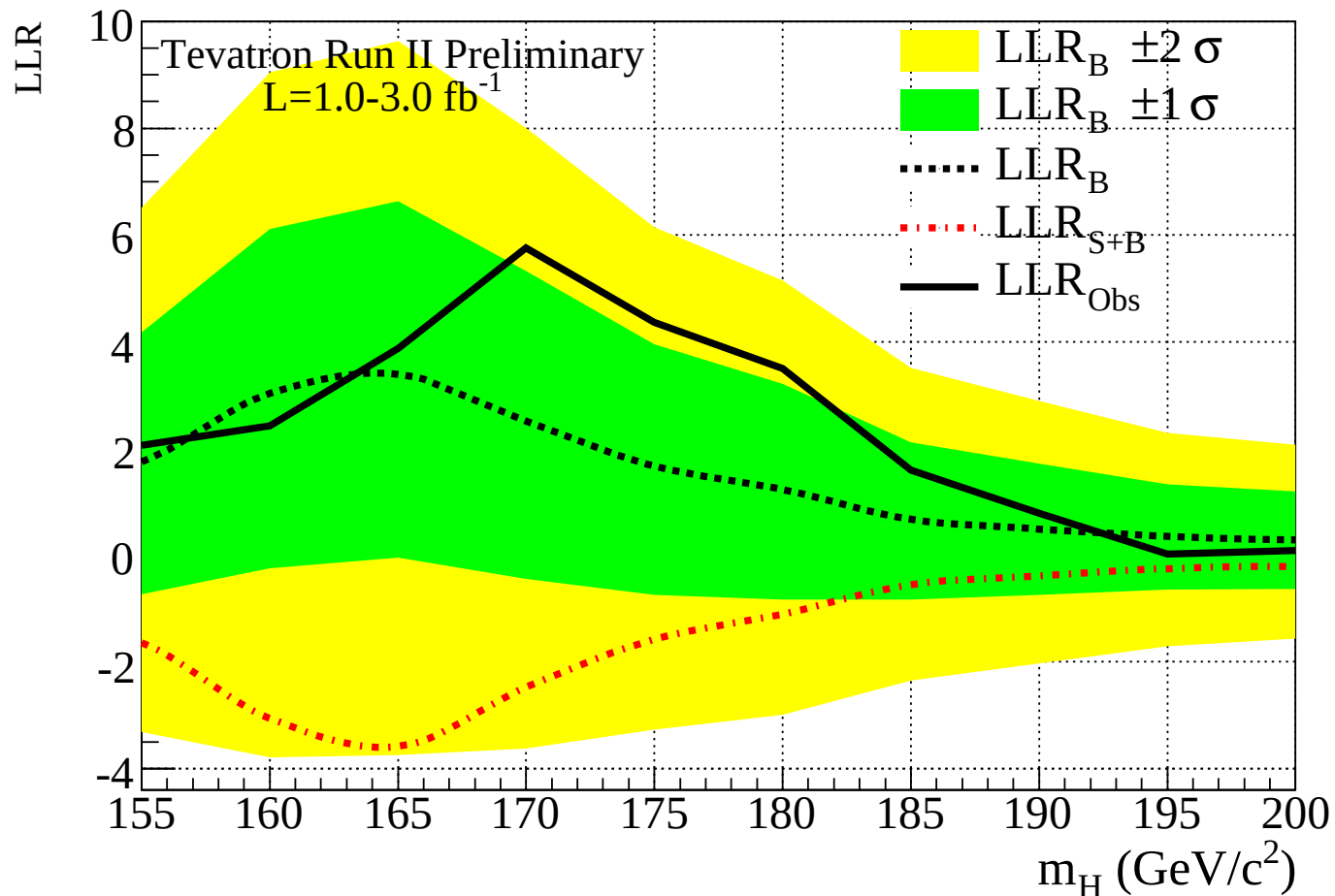
At $m_H = 115$ GeV: limit/SM 4.2 (3.6 expected)

At $m_H = 165$ GeV: limit/SM 1.6 (1.6 expected)

⇒ Getting close to the Standard Model expectation!

Tevatron Combination (July 2008)

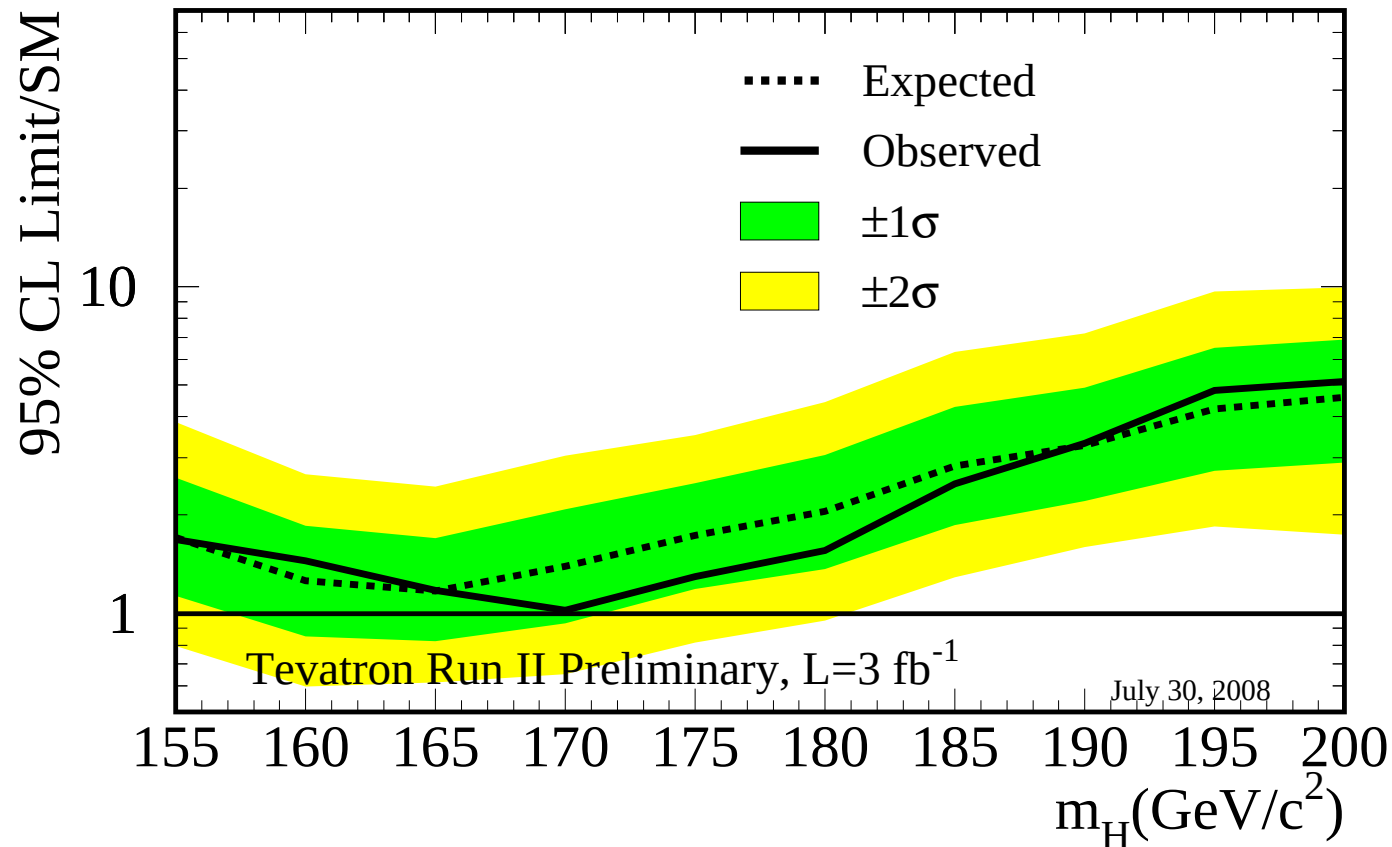
$$H \rightarrow WW, WH \rightarrow WWW$$



Largest sensitivity at $m_H = 165 \text{ GeV}$

Tevatron Combination (July 2008)

$$H \rightarrow WW, WH \rightarrow WWW$$

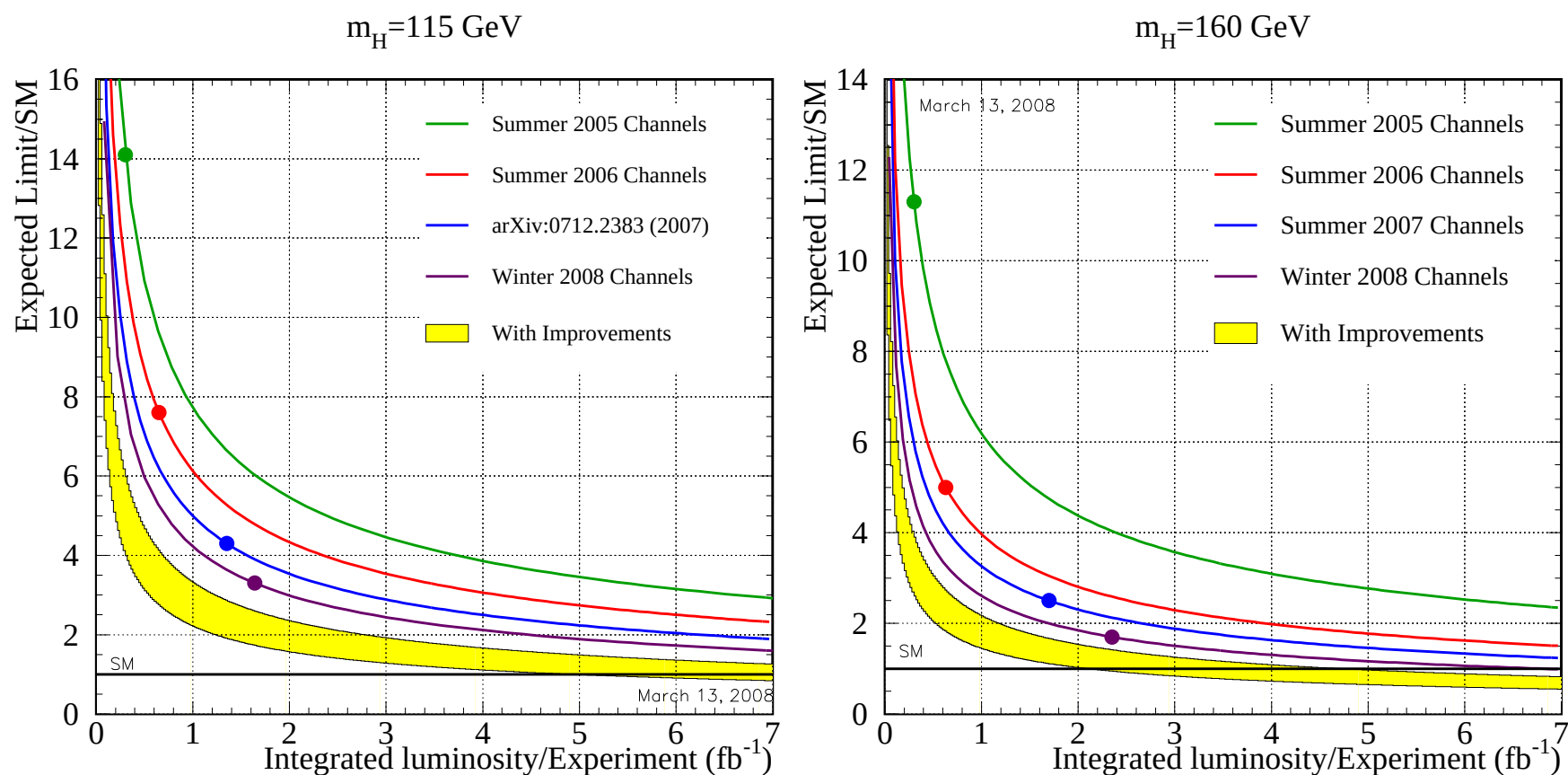


$\Rightarrow$ Exclude $m_H = 170$ GeV at 95% CL !

New combination including low-mass results soon

Conclusion & Outlook

- Higgs not found yet, but becoming sensitive . . .
- Improvement in sensitivity $\sim \int \mathcal{L} dt$



Conclusion & Outlook

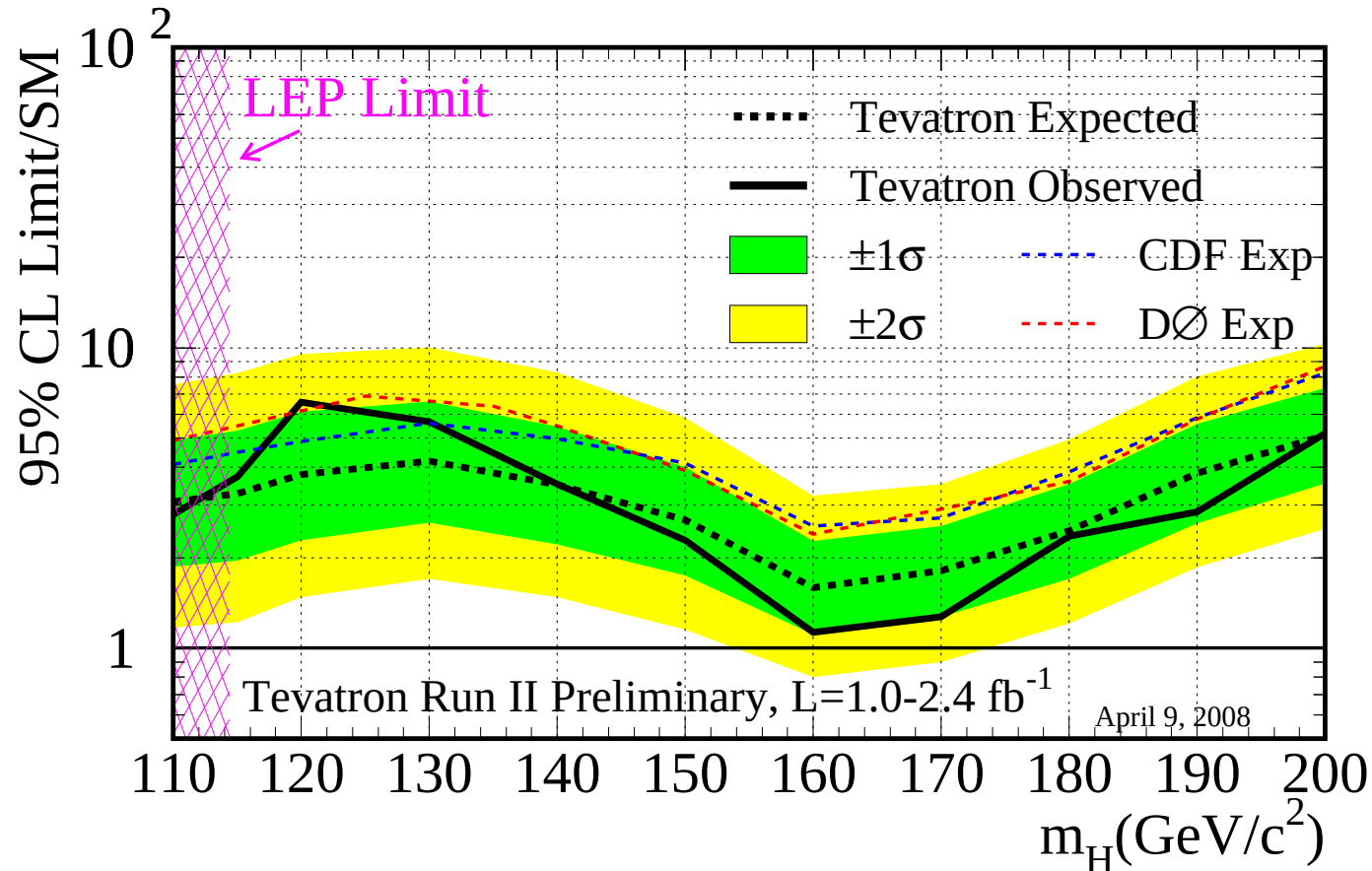
- Many small steps to follow:
 - * $\int \mathcal{L} dt = 7 \text{ to } 9 \text{ fb}^{-1}$ by 2010
 - * Improvements to b-tagging, jet energy, mass resolution
 - * Improved multivariate techniques
 - * Increased efficiency for leptons
 - * Add more production/decay channels
 - * Better understanding of systematics
 - * Observe di-boson production in hadronic ($b\bar{b}$) decays
 - DØ already observed $WW/WZ \rightarrow \ell\nu q\bar{q}$
 - * Indirect constraints from m_{top} and m_W
- Further exclusion or observation possible soon !

Future Beyond Tevatron

- Find the Higgs, or something else
- Understand what we found
- Measure and understand the Higgs potential
- (S)LHC, ILC, . . .

Tevatron Combination (April 2008)

$WH \rightarrow \ell \nu b \bar{b}$, $ZH \rightarrow \ell \ell / \nu \nu b \bar{b}$, $H \rightarrow WW$, $WH \rightarrow WWW$, $H \rightarrow \gamma \gamma$, $H \rightarrow \tau \tau + 2 \text{ jets}$



At $m_H = 115 \text{ GeV}$: limit/SM 3.7 (3.3 expected)

At $m_H = 160 \text{ GeV}$: limit/SM 1.1 (1.6 expected)

⇒ Getting really close to the Standard Model expectation!