Combined SM Higgs Limits at the Tevatron

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On behalf of the CDF and DØ collaborations

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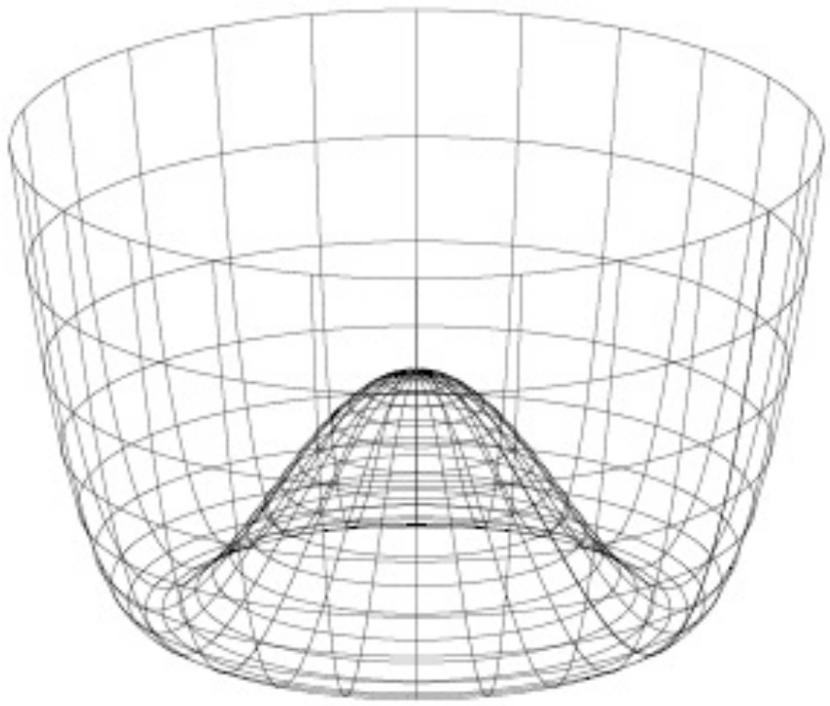
The Higgs Mechanism

- Simplest proposed mechanism to explain electroweak symmetry breaking
- Higgs Mechanism → adding potential V(φ) with non-vanishing vacuum expectation
- Broken electroweak symmetry
- → Spin 0 boson appears → Higgs boson



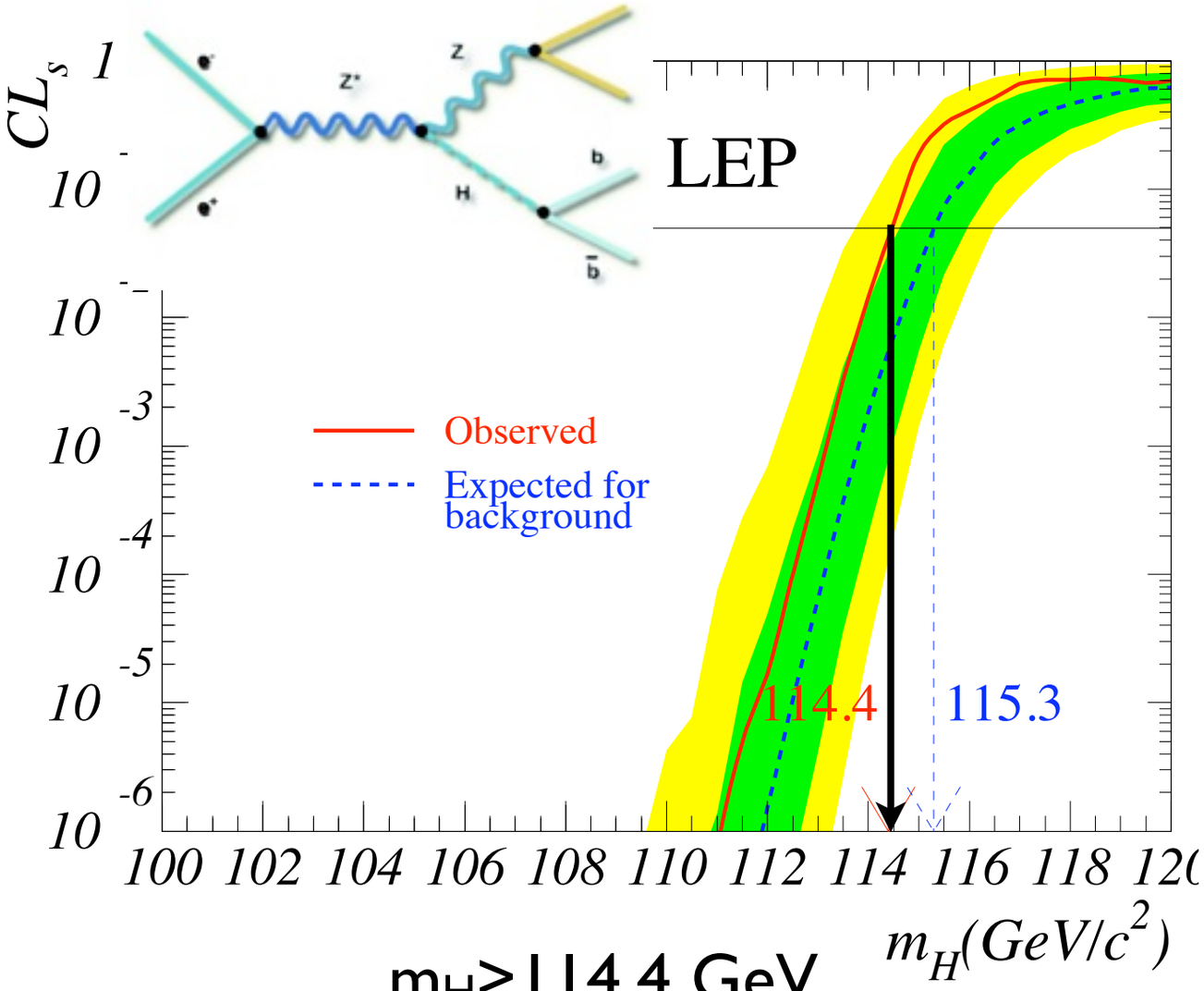
→ W±, Z boson acquire mass

→ Fermion masses can be generated

→ Higgs mass free parameter

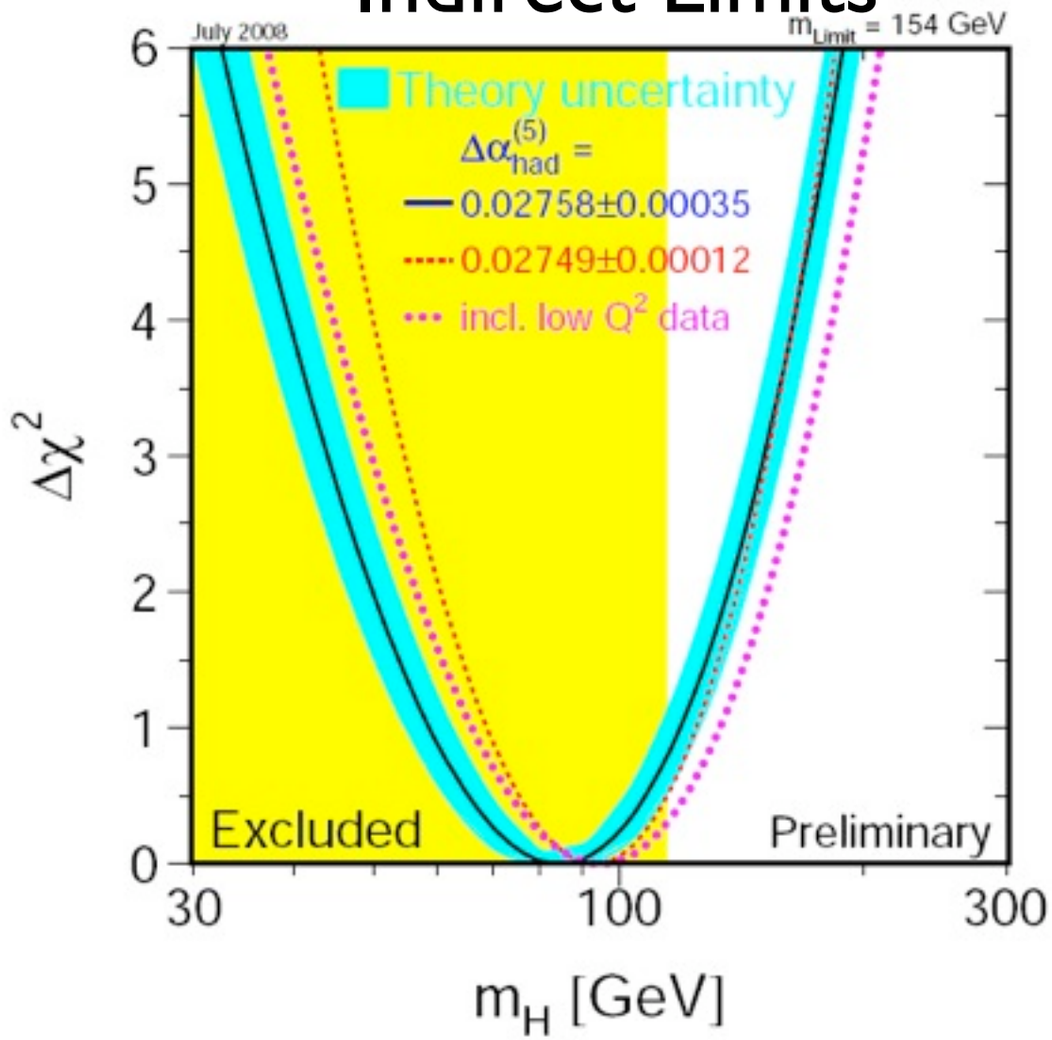
Experimental Limits

Direct Limits



m_H>114.4 GeV

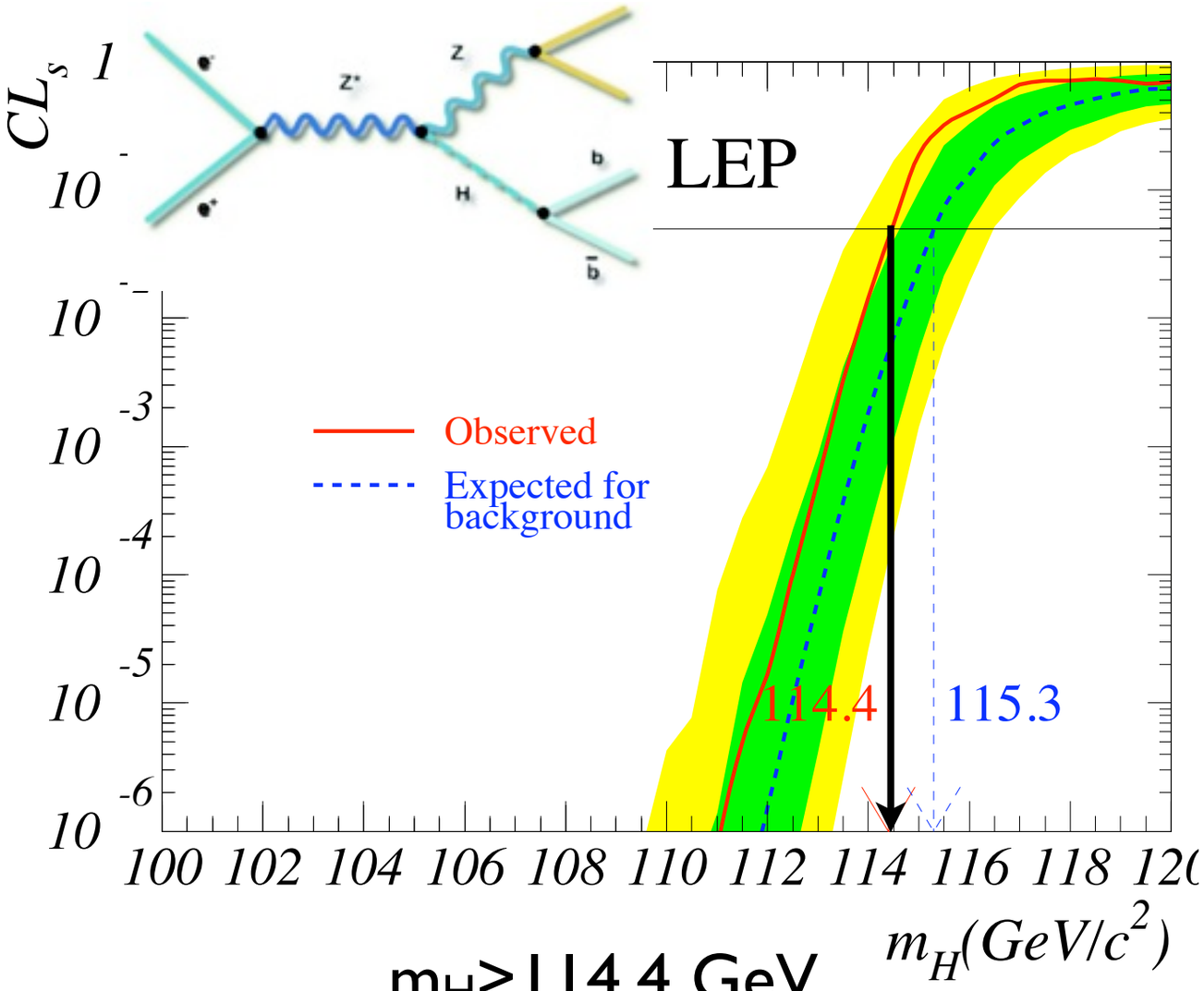
Indirect Limits



m_H<163 GeV

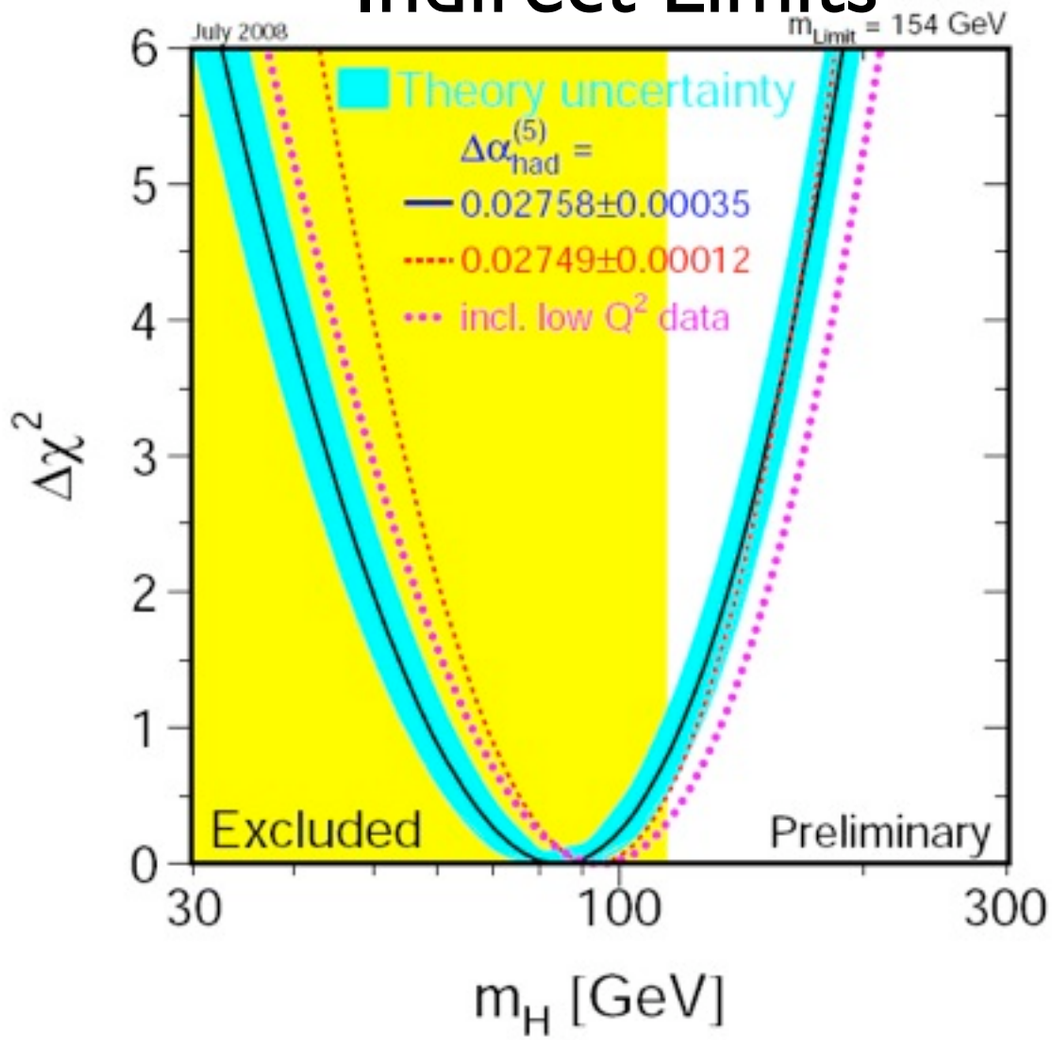
Experimental Limits

Direct Limits



m_H>114.4 GeV

Indirect Limits

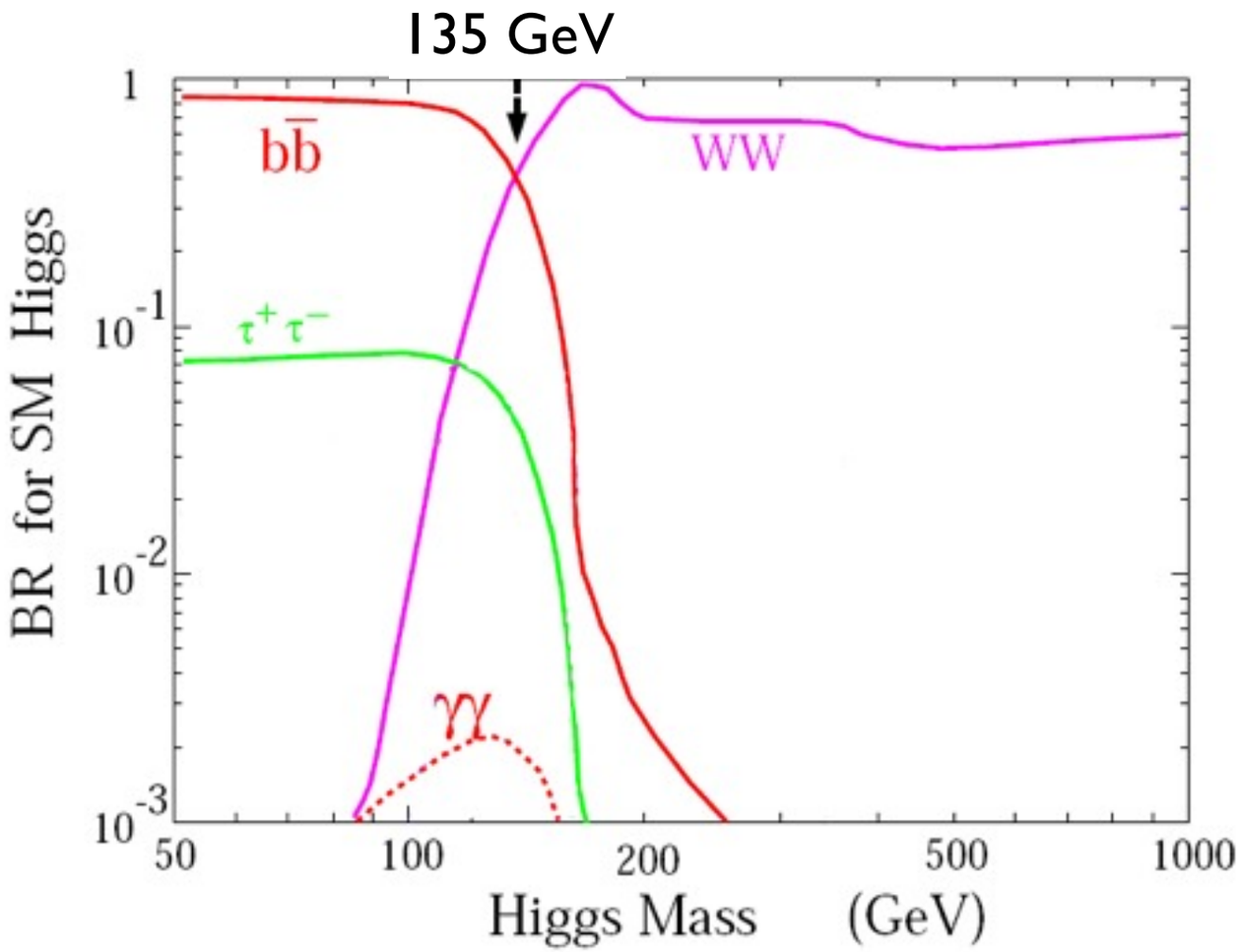


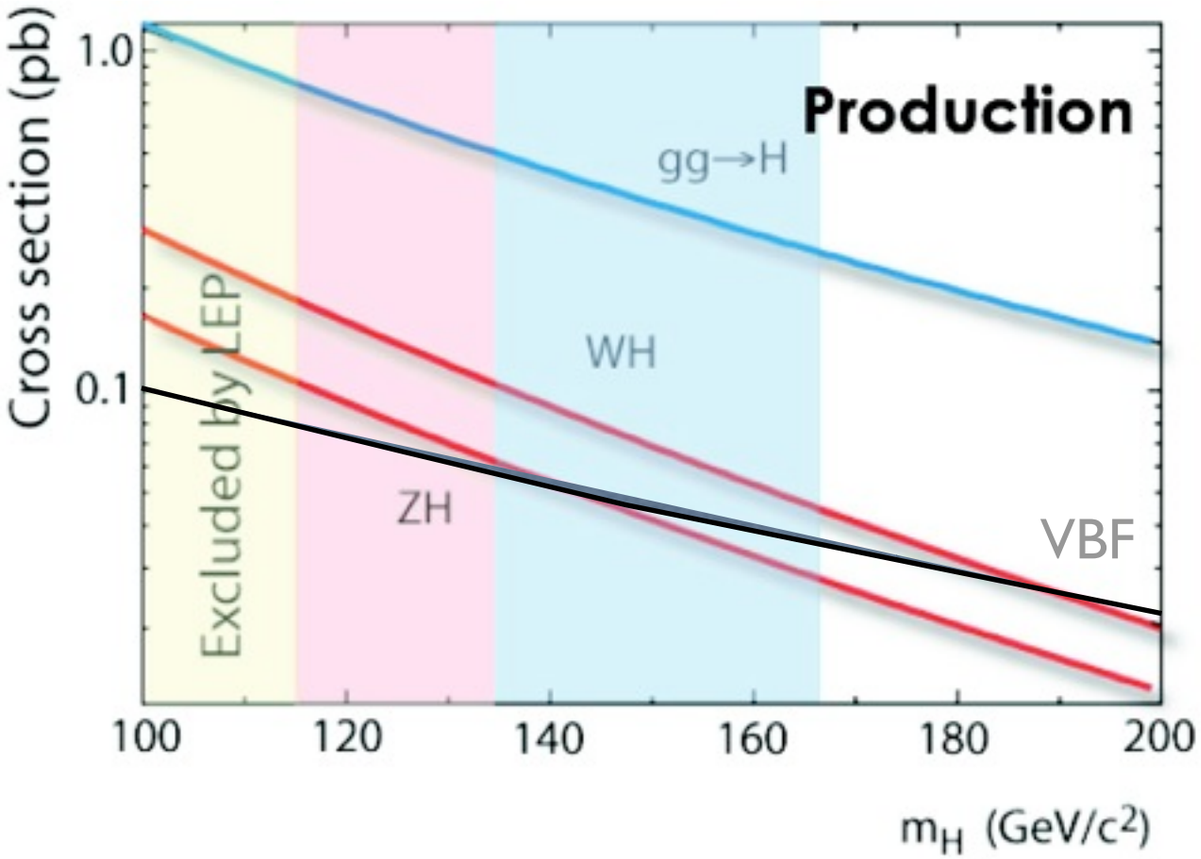
m_H<163 GeV

SM Higgs probably accessible at the Tevatron!

Higgs at the Tevatron

- Main production modes:
- $\sigma(gg \rightarrow H)$=2–0.1 pb
- $\sigma(gg \rightarrow WH)$=0.6–0.02 pb





- dominant decay modes:
- m_H<135 GeV: bb decay
- m_H>135 GeV: WW decay

Higgs Search Channels

DØ: 52 channels

Channel	Lumi. (fb^{-1})	Final Variable
WH → ℓν*bb*	2.7	NN / Dijet Mass
WH → τν*bb*	0.9	Dijet Mass
VH → ℓττ*bb*/*qq*ττ	1	NN
ZH → νν*bb*	2.1	DTree
ZH → ℓℓν*bb*	2.3	NN / DTree
WH → WWW	1.1	Likelihood
H → WW→ ℓℓ	4.2	NN
H → γγ	4.2	Di-photon mass
ttH → ttbb	2.1	Scaled H_T

- Most channels distinguish various lepton/jet multiplicity final states

→ 75 mutually exclusive final states

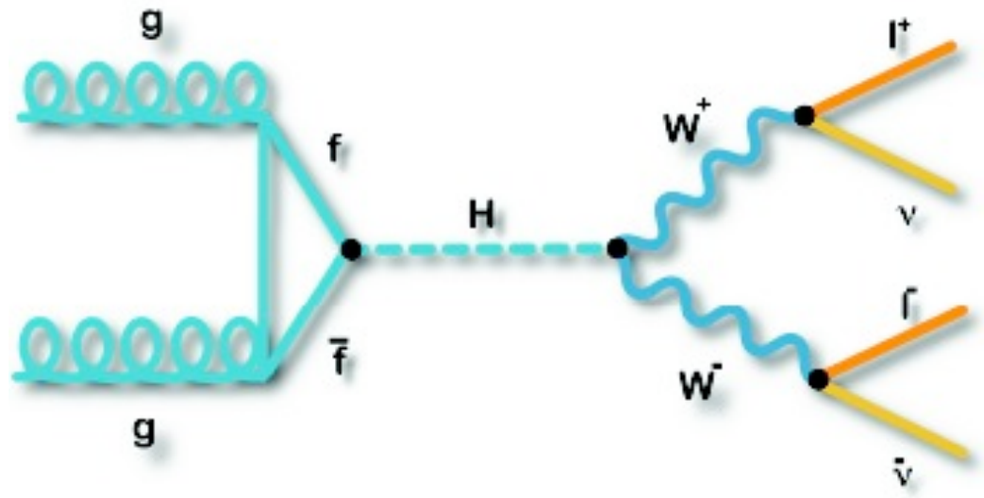
- Environment: High background, sizable systematics
- Most analyses use Multivariate Analysis Techniques:
  - Neural Network (NN)
  - Decision Tree (Dtree)
  - Matrix Elements (ME)
  - Likelihoods

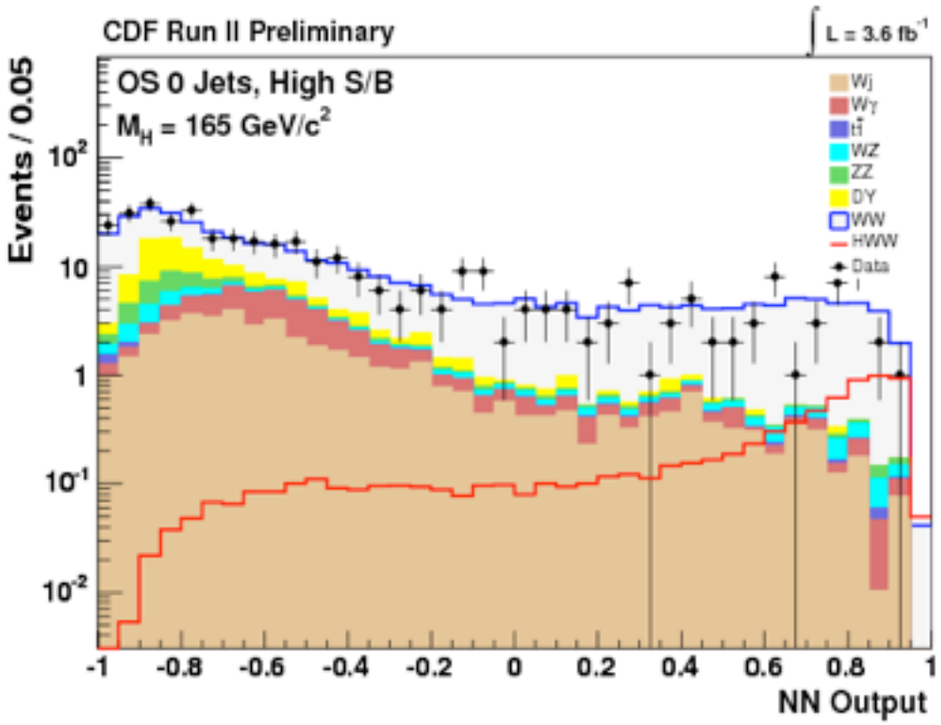
CDF: 23 channels

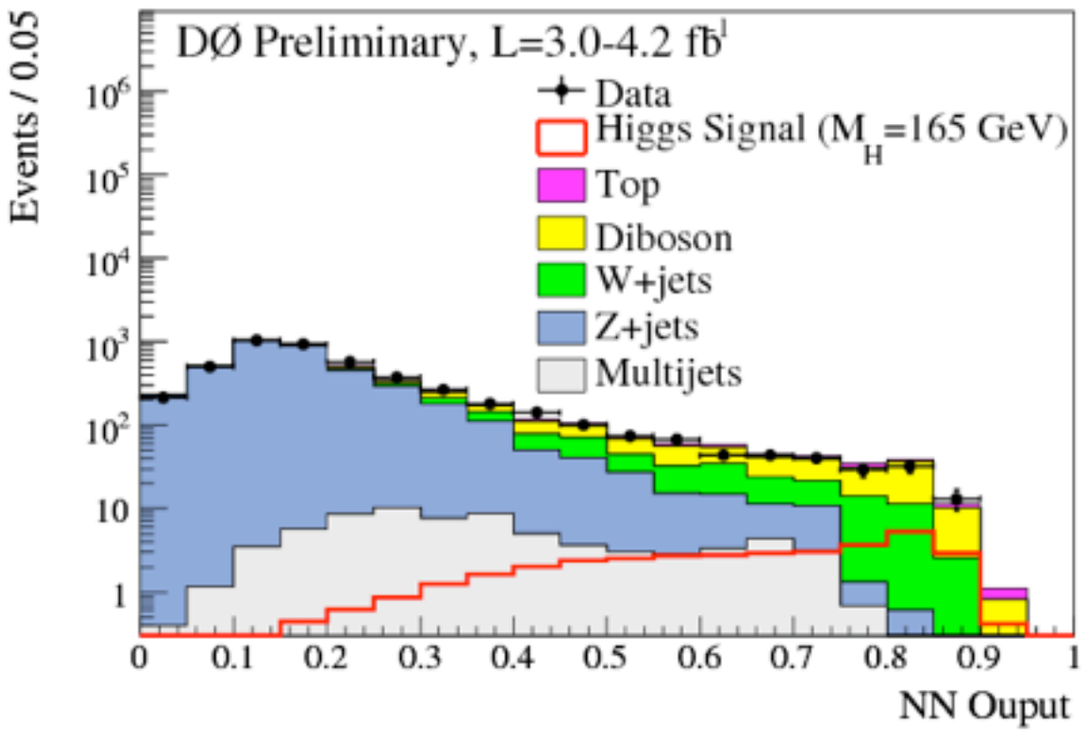
Channel	Lum. (fb^{-1})	Final Variable
WH → ℓν*bb*	2.7	NN / DTree
ZH → νν*bb*	2.1	NN
ZH → ℓℓ*bb*	2.7	NN/ME
WH+ZH → jj*bb*	2	ME
H →WW → ℓℓ	3.6	NN
WH→ WWW	3.6	NN
H+X → ττ+jj	2	NN

$H \rightarrow WW \rightarrow l\nu l\nu$

- main high mass channel
- most sensitive channel overall
- selects on two charged leptons and missing E_T
- accepts events from all production modes (mainly $gg \rightarrow H$)

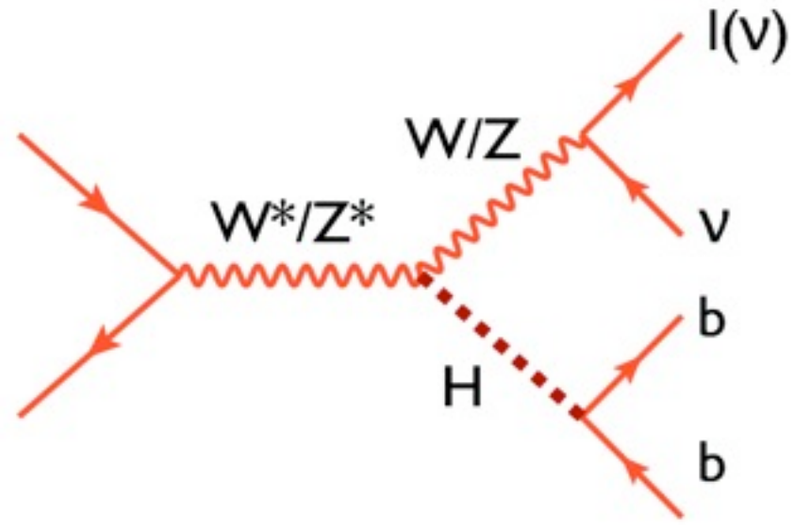




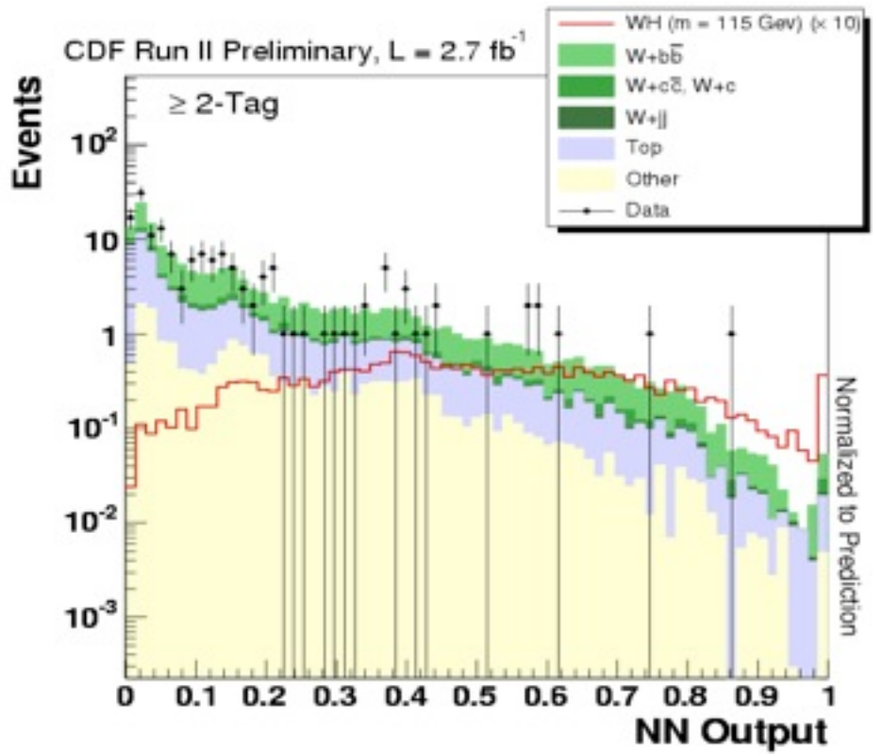


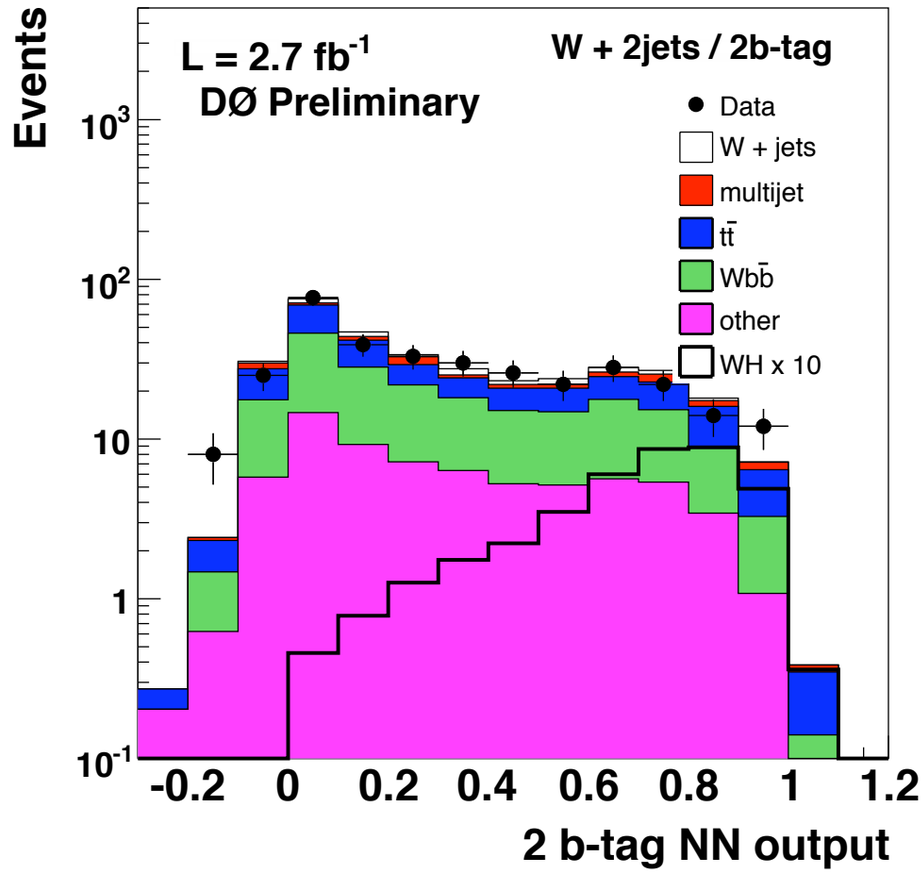
WH→lνbb

- main low mass search channel
- identify Higgs using two jets
- apply b-tags to reduce backgrounds
- gg→H mode unusable (high bkg)
  ⇒using associated production



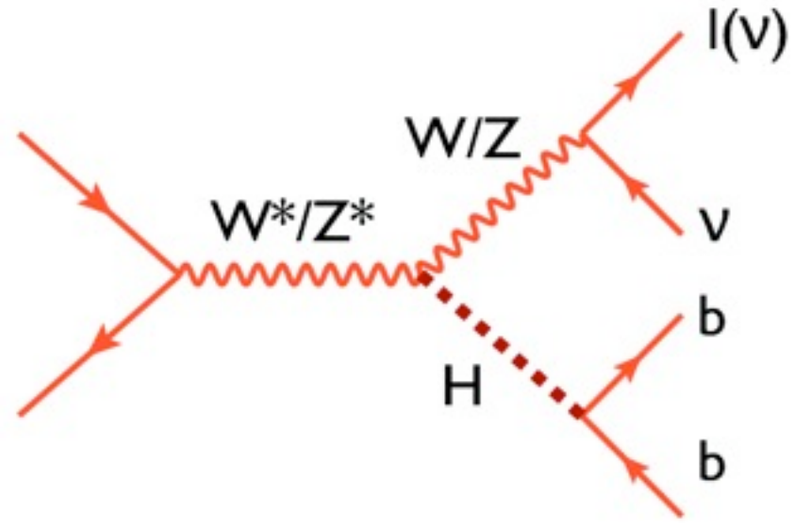
- W identified through charged lepton and missing E_T





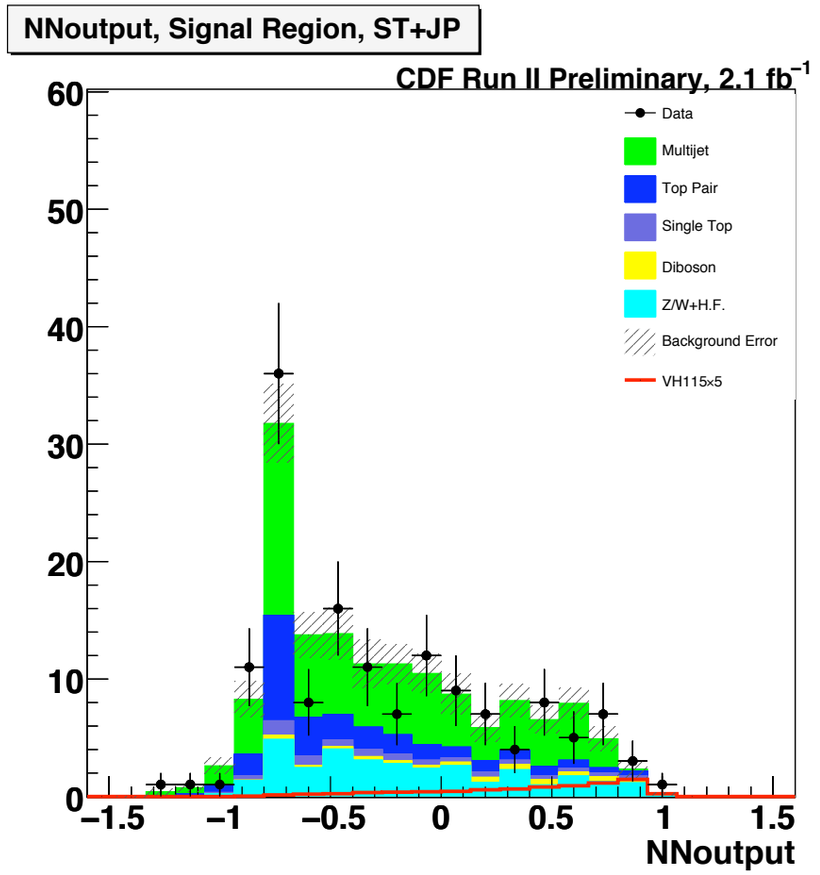
ZH→ννbb

- second main low mass search channel
- identify Higgs using two jets
- apply b-tags to reduce backgrounds



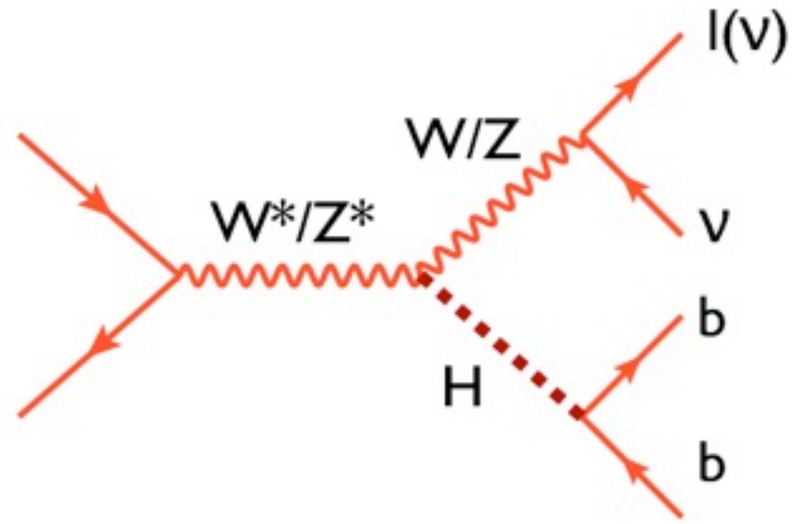
- associated production with Z
- identifies Z→νν as missing E_T (largest branching ratio)

- main background are multi-jet events
- no real missing energy, but obtained from jet missmeasurement
- cleaned up by comparing tracking and calorimeter missing energy
  - correlated for true missing energy

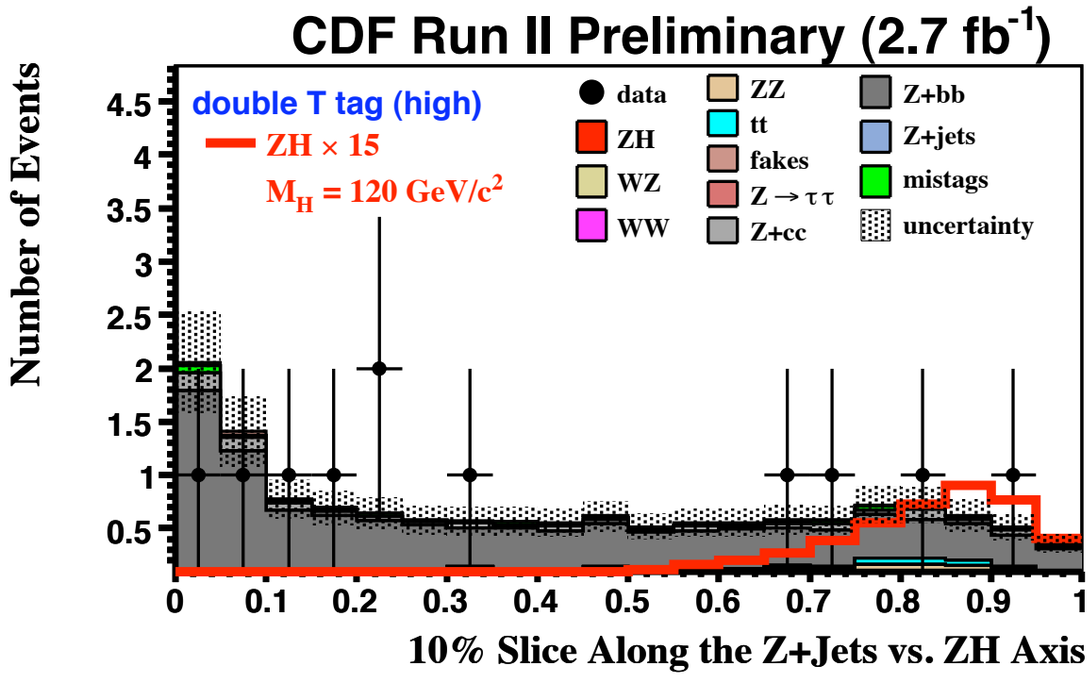


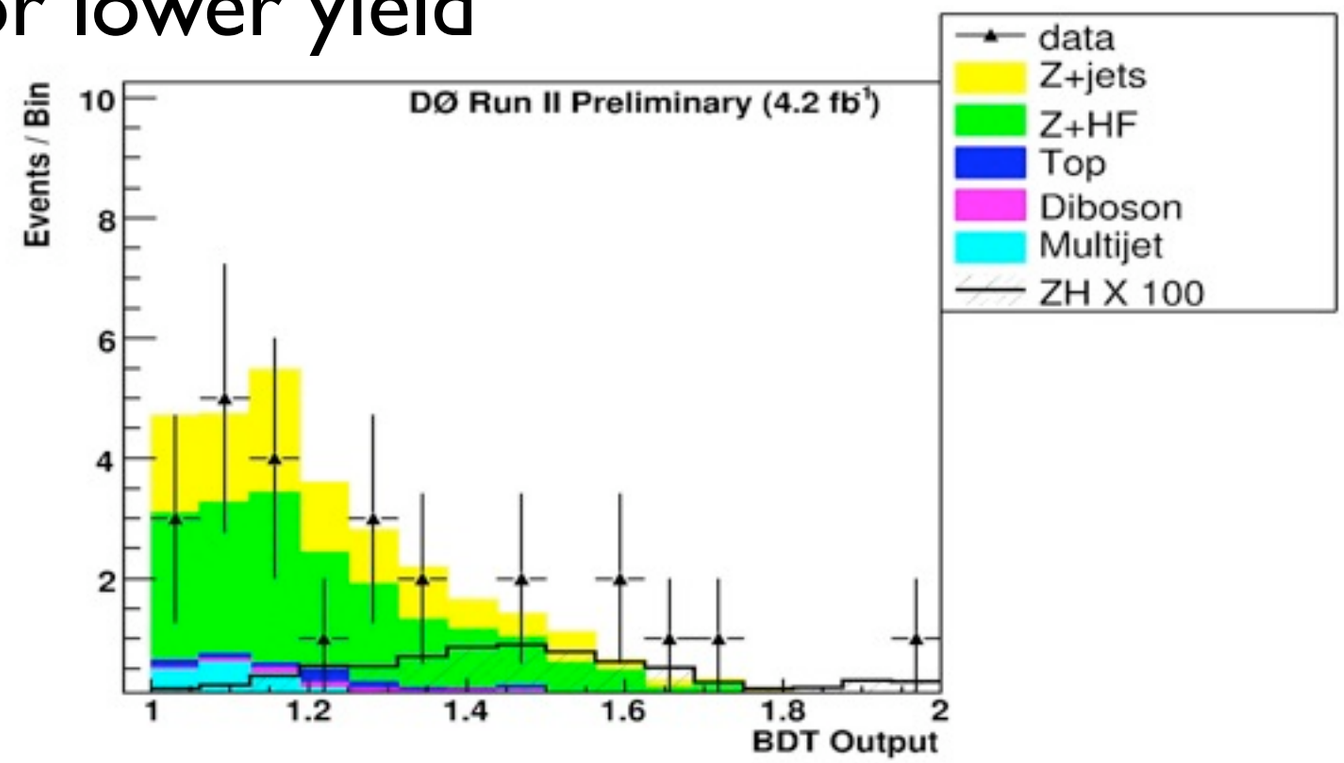
ZH→llbb

- third main low mass search channel
- identify Higgs using two jets
- apply b-tags to reduce backgrounds



- associated production with Z
- identifies Z→ll through two charged leptons consistent with Z decay
- fairly clean, compensates for lower yield

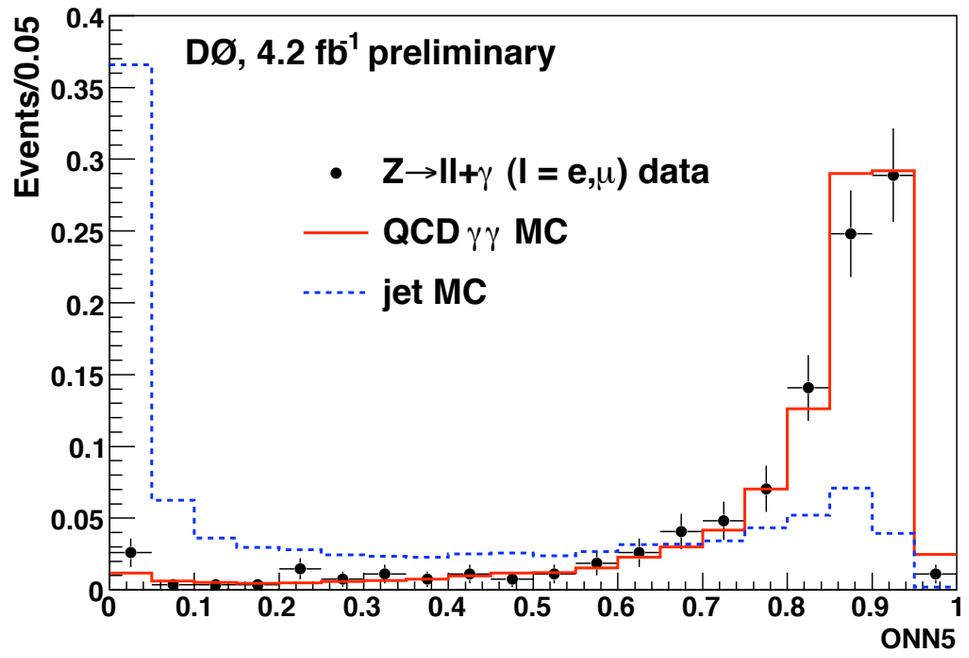




$H \rightarrow \gamma\gamma$

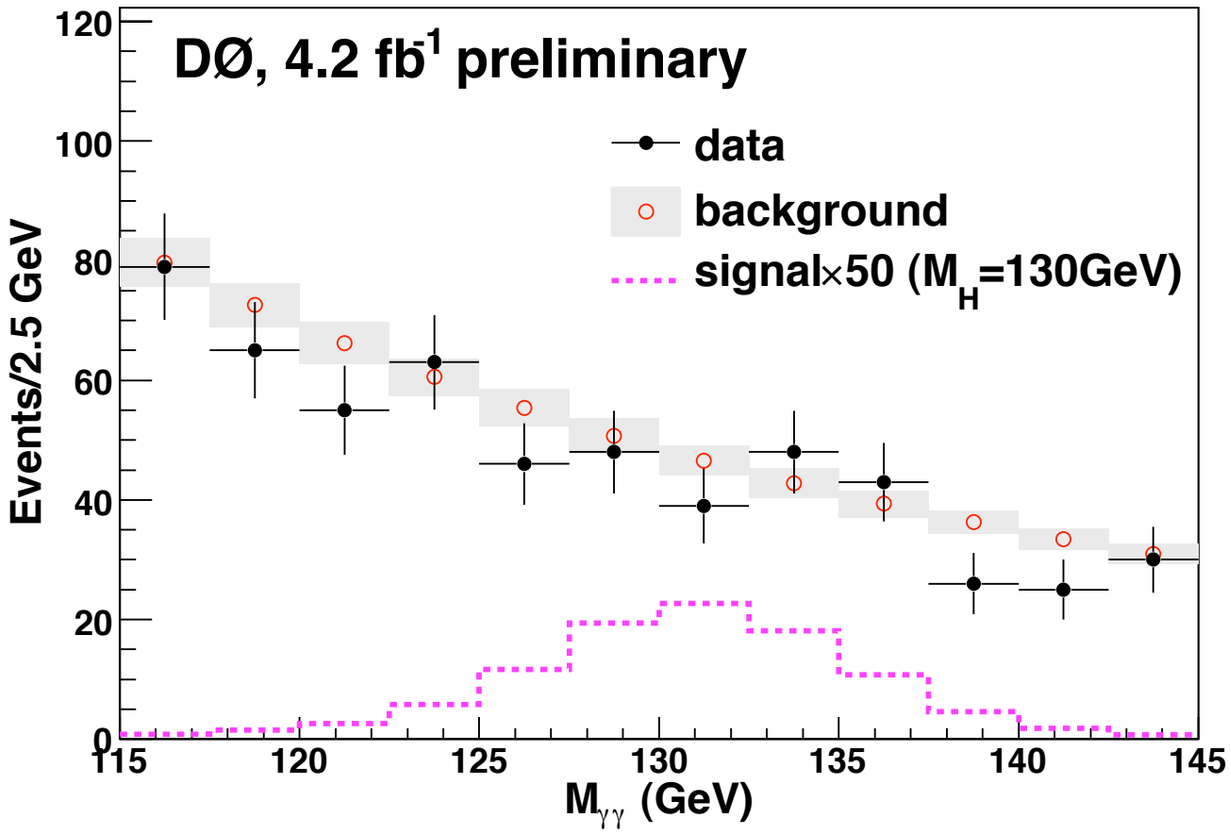
- minor low mass mode
- identifies Higgs as 2 photons
- branching ratio less than 1%

- however backgrounds are low
- can use all production modes



- employs a neural network for photon-jet separation

- limits a factor 3-4 worse than main channel
- still contributes to final limit
- helps at intermediate mass



Method of Combination

- using differential distributions (shapes), not just event yields
- using Poisson statistics for all bins
- two limit setting methods used and in good agreement

- Bayesian Method (CDF), integrating over likelihoods
- based on credibility, uses a prior
- "How likely is the real value below limit?"

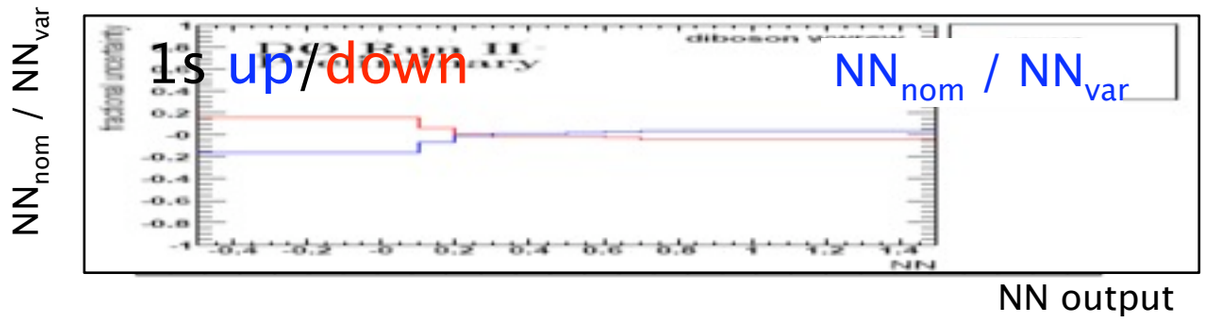
- Modified Frequentist Method (DØ), CL_s test statistics
- comparing 'background' & 'signal+background' hypotheses
- based on coverage, using pseudo-experiments
- "How likely is the limit above the real value?"

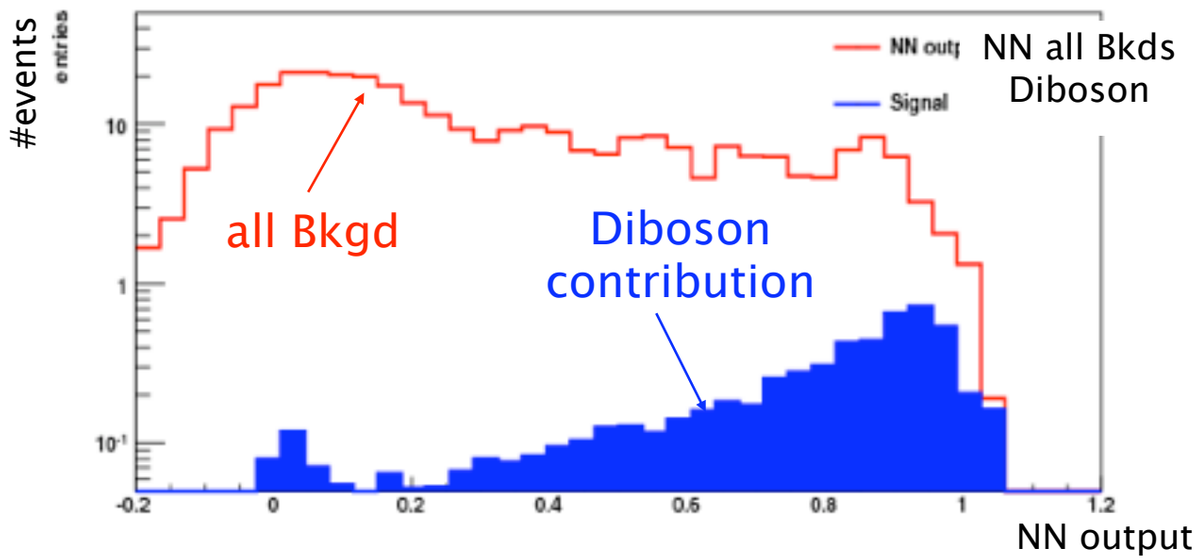
Shape Uncertainties

- Two types of systematics:
- Rate Systematics: only affect overall normalization, not the differential distribution (shape)
- Shape Systematics: change differential distribution, i.e. changes the multivariate variable for each event

- Shape uncertainty considered in limit setting process

Examples of Shape Systematics
- Jet energy scale
- b-tagging
- ISR, FSR
- Trigger
- Di-boson p_T
- W+jets modeling





Main Systematics

Low Mass Systematics

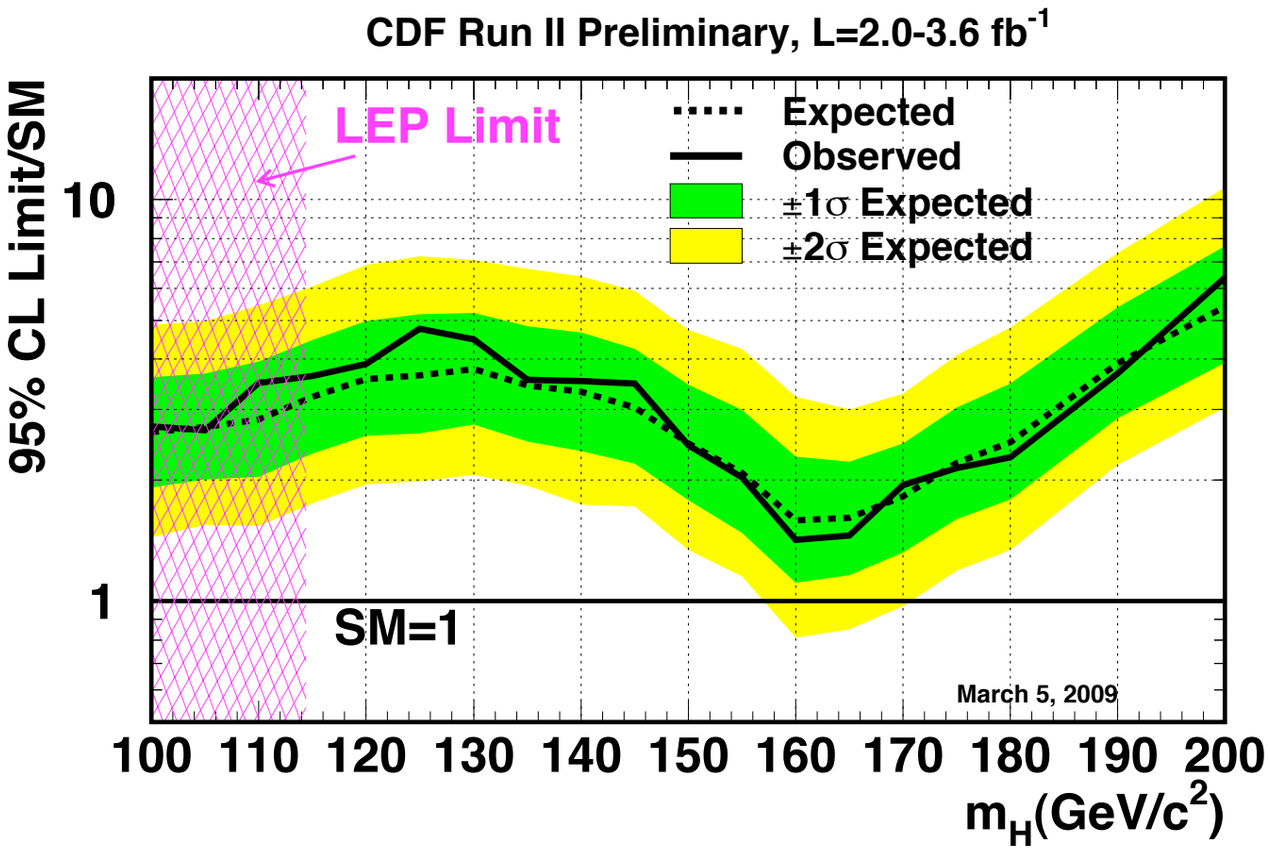
- b-tagging (4-15%)
- JES (3-10%)
- Luminosity (6%)
- Cross sections (6-30%)

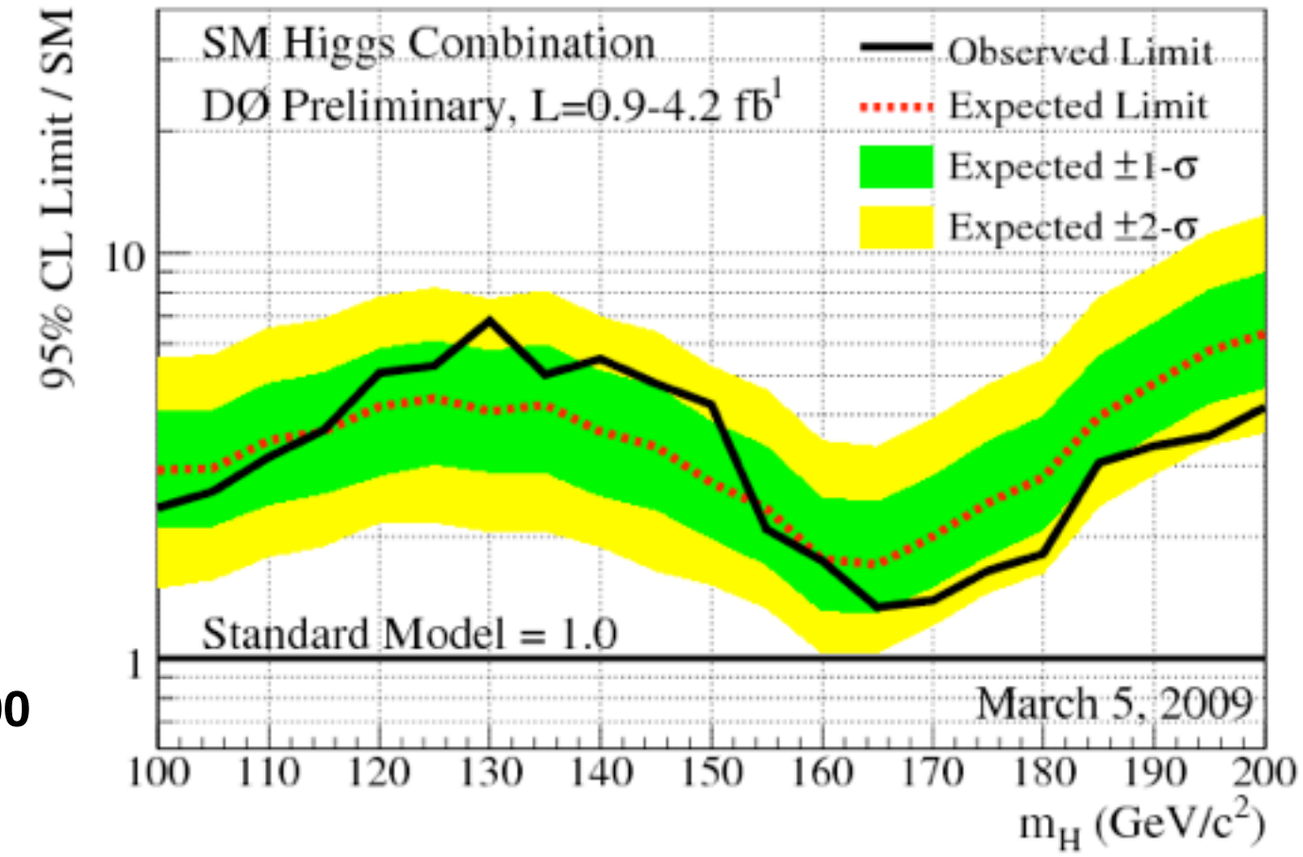
High Mass Systematics

- Jet-ID (8-20%)
- Theoretical Modeling
- Luminosity (6%)
- JES (5%)

- **Correlated uncertainties in CDF**
  - b-tagging, JES, ISR/FSR
- **Correlated uncertainties in DØ:**
  - b-tagging, JES, Jet-ID/Resolution, W+jets shape
- **Systematics correlated across experiments:**
  - Luminosity
  - Cross-sections: Higgs, top, single top, diboson

Individual Combinations



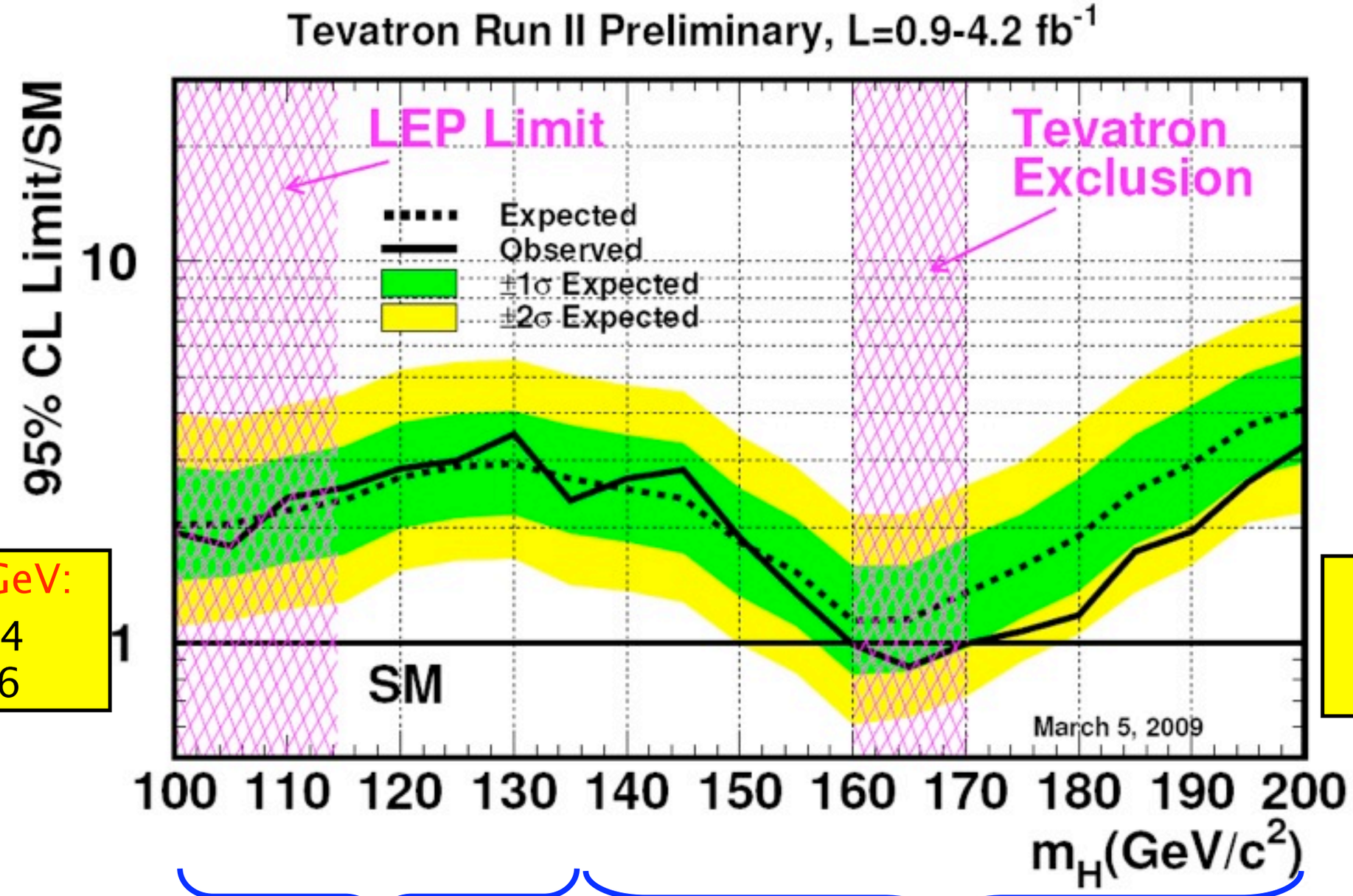


m_H=115 GeV		
	exp	obs
CDF	3.2	3.7
DØ	3.6	3.7

m_H=160 GeV		
	exp	obs
CDF	1.6	1.5
DØ	1.7	1.3

Tevatron Combination

combining CDF and D0 for maximum sensitivity



m_H=115 GeV:
Exp: 2.4
Obs. 2.6

m_H=165 GeV:
Exp: 1.1
Obs. 0.81

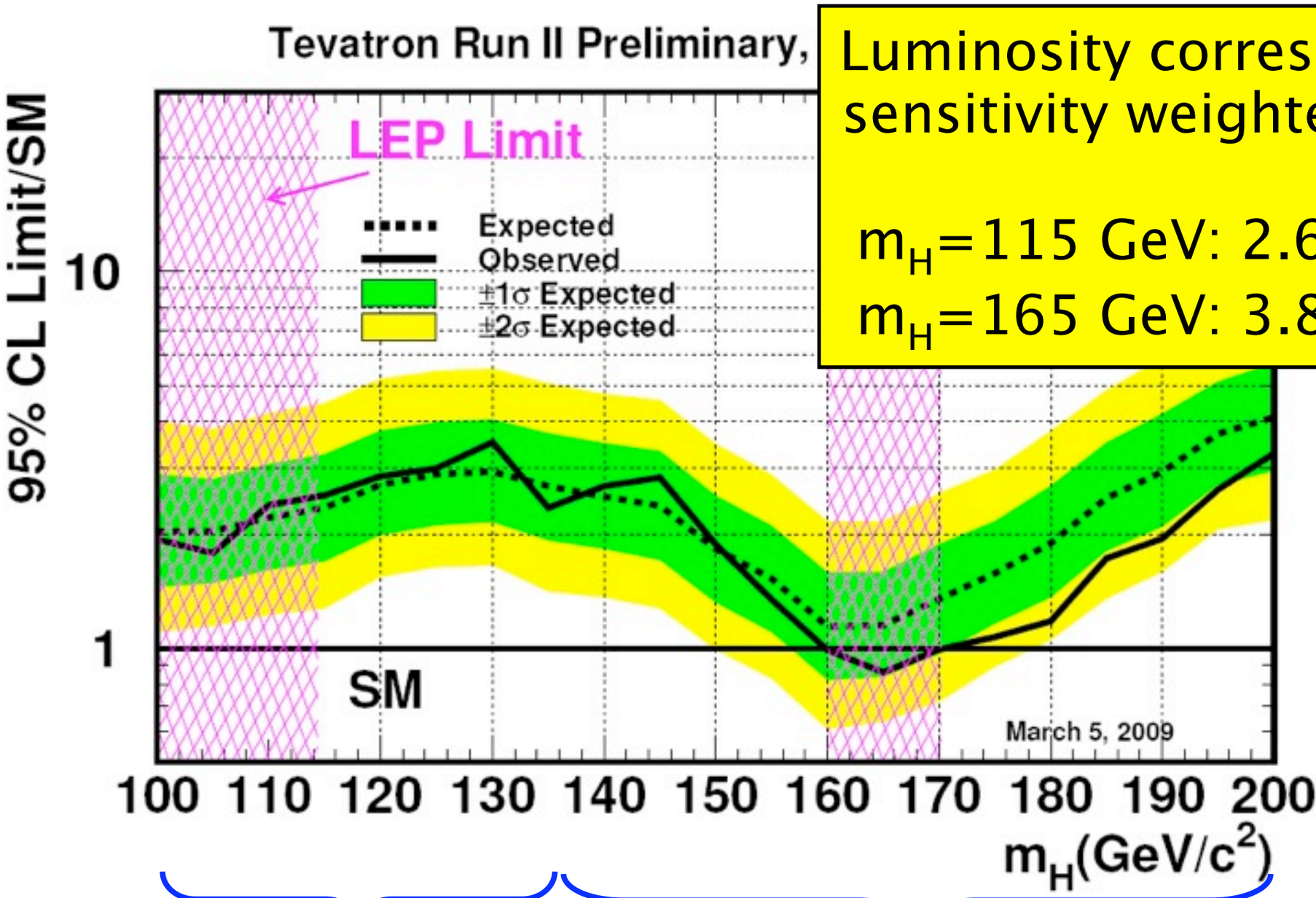
Dominated by

WH/ZH analyses

H→WW analyses

Tevatron Combination

combining CDF and D0 for maximum sensitivity



Luminosity corresponds sensitivity weighted to:

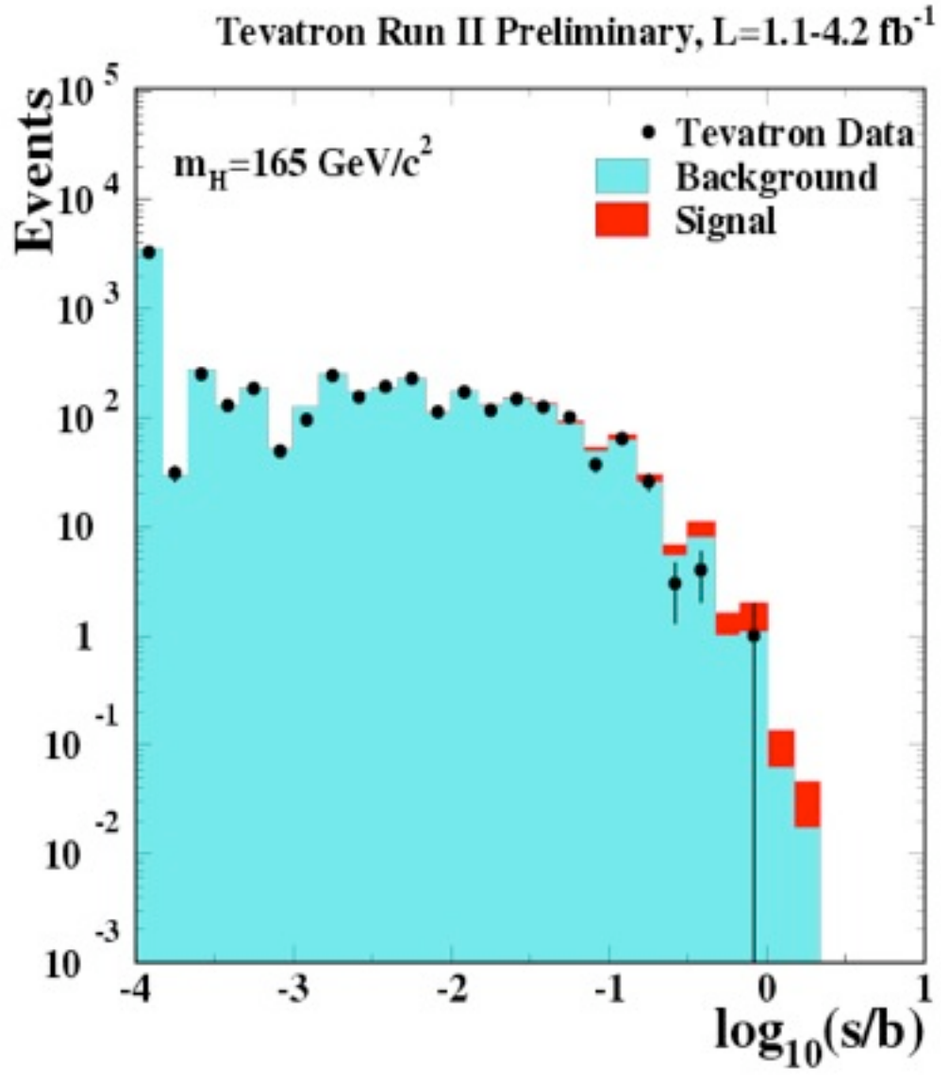
m_H=115 GeV: 2.6 fb^{-1}

m_H=165 GeV: 3.8 fb^{-1}

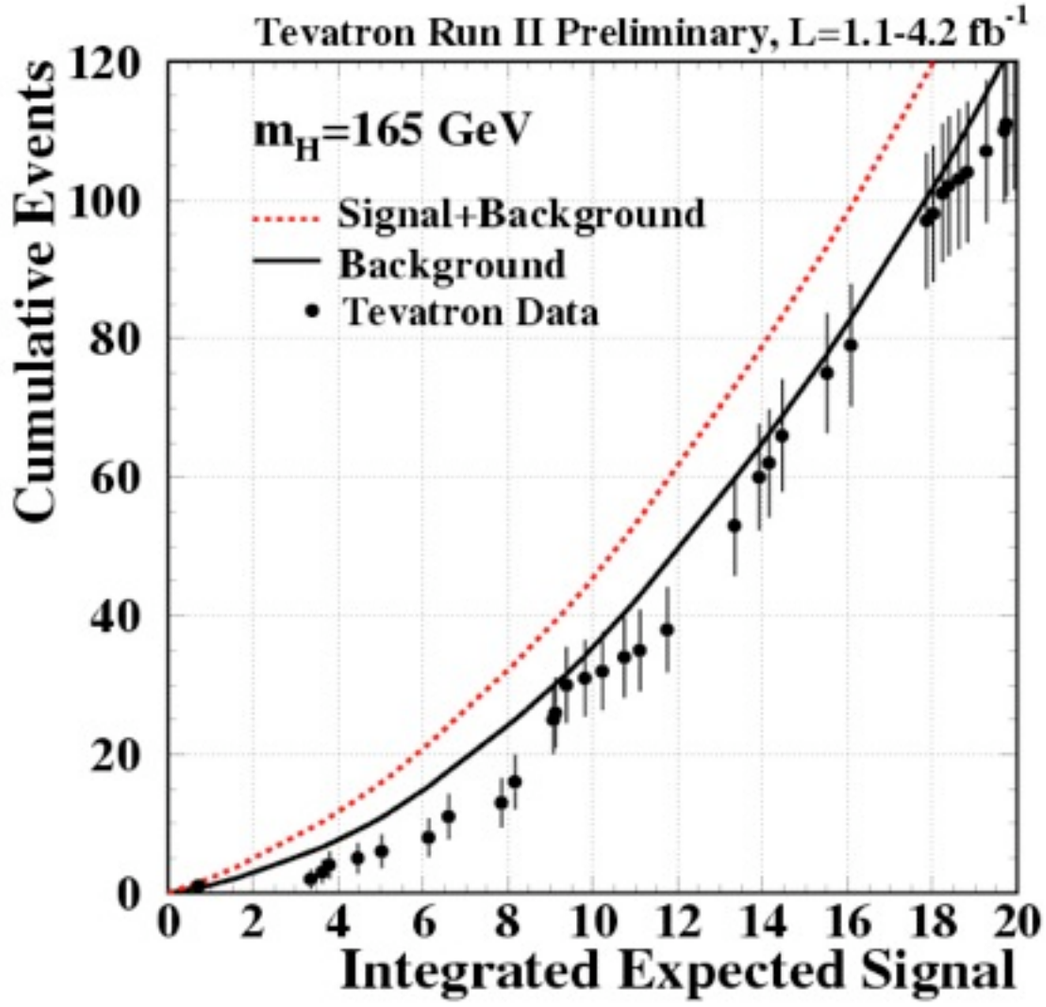
Dominated by WH/ZH analyses H→WW analyses

High Mass Exclusion

- all events sorted in "S/B" bins
- events up to S/B=1
- deficit at high S/B



- Cumulative distributions of bkg only & sig+bkd hypothesis and comparison with data
- vertical slices correspond to counting experiments



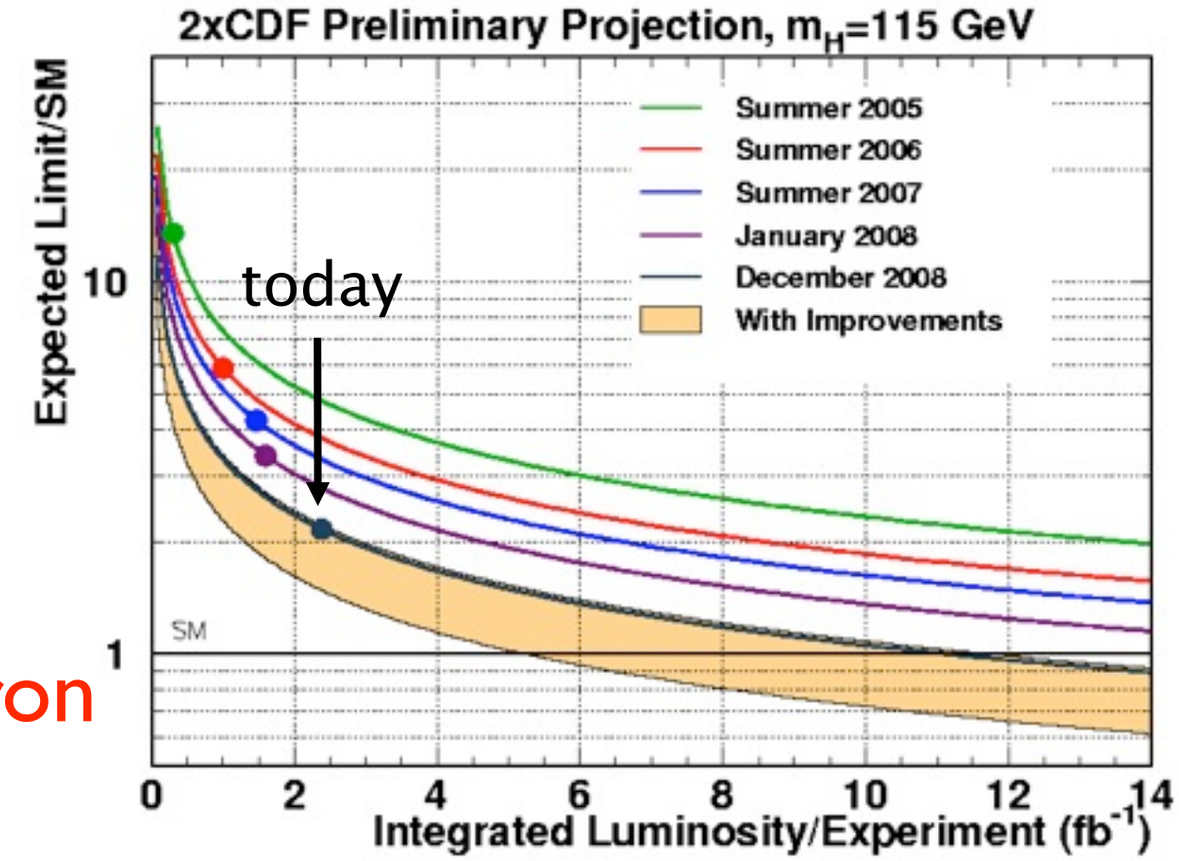
Summary & Outlook

- Higgs sensitivity quickly improving:
  Moriond08: 1.6 x SM @ m_H=160 GeV
  → ICHEP08: excluded m_H=170 GeV
  → Moriond09: excluded m_H=160-170 GeV

Sensitivity gained by:

- Improving multivariate analysis techniques
- Adding more data
- Adding more channels

⇒ Exciting times at the Tevatron



low mass Higgs projection

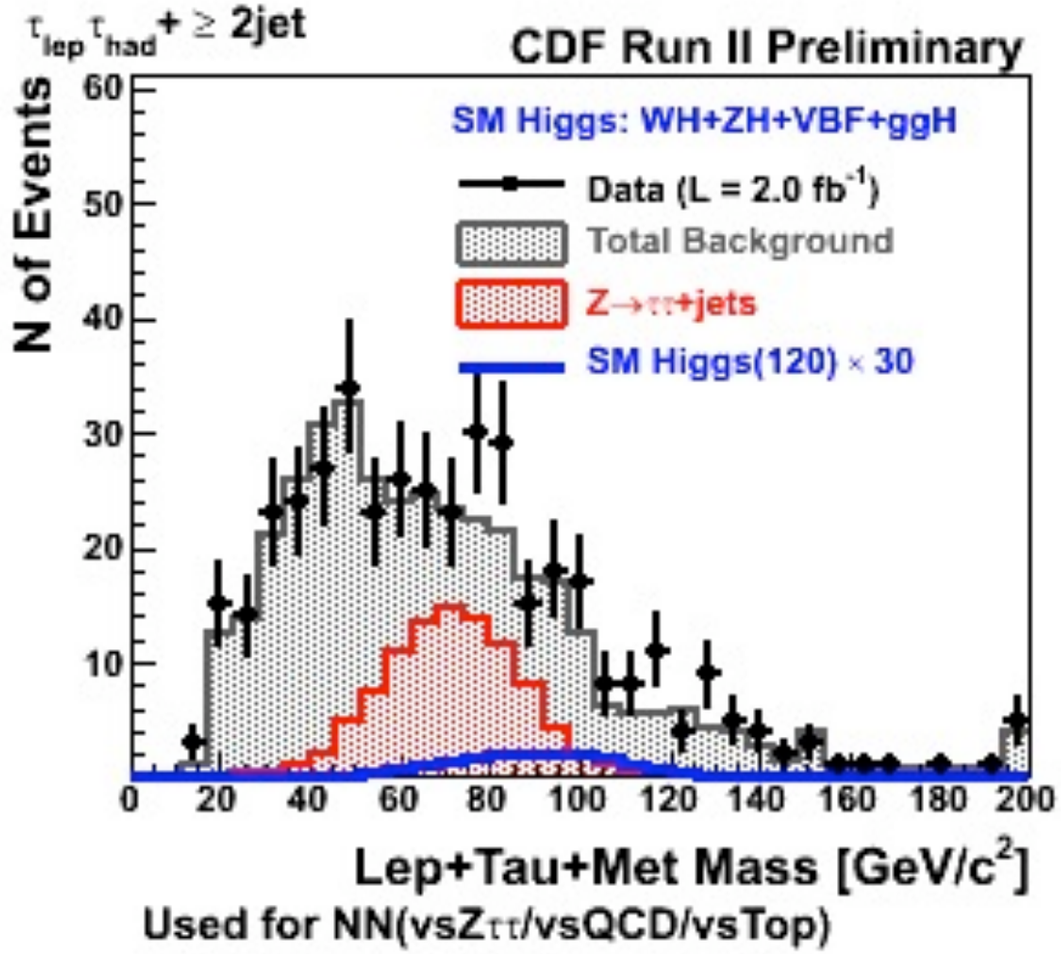
Backup Slides

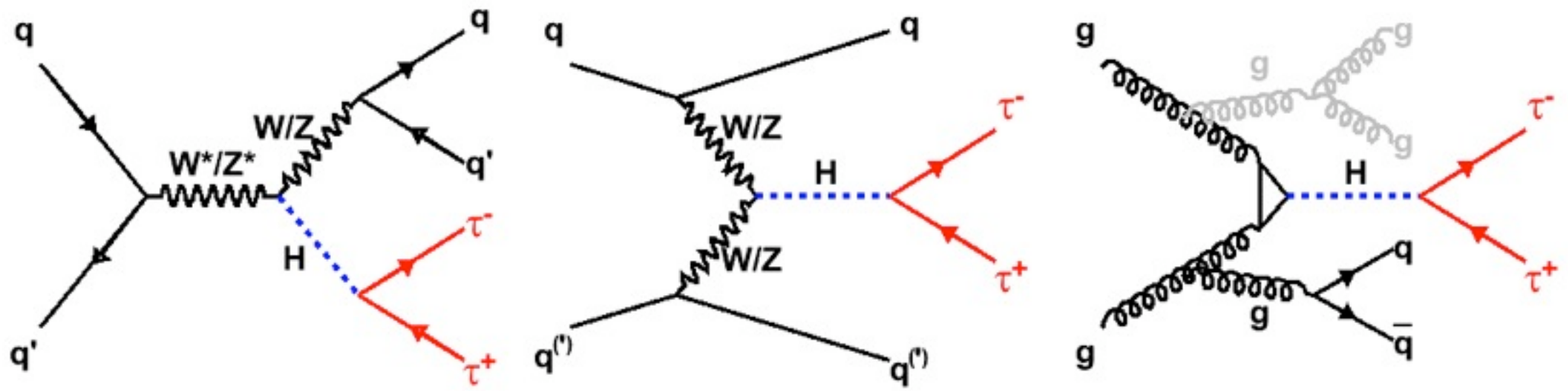
VH→ττjj

- minor low mass mode
- identifies Higgs through one hadronic and one leptonic tau
- branching ratio less than 10%
- lower backgrounds than for b-jets

- identifies W/Z as two jets
- picks up gg→H & VBF events too

- noticeable contribution to final limit

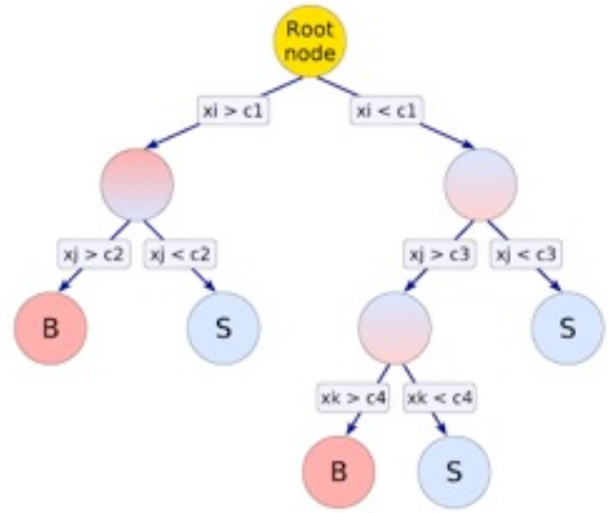




Multivariate Methods

- Both experiments use Multivariate Methods to further suppress backgrounds.

- Boosted Decision Tree (BDT):
  - Binary tree structured classifier
  - Insensitive to poorly discriminating variables

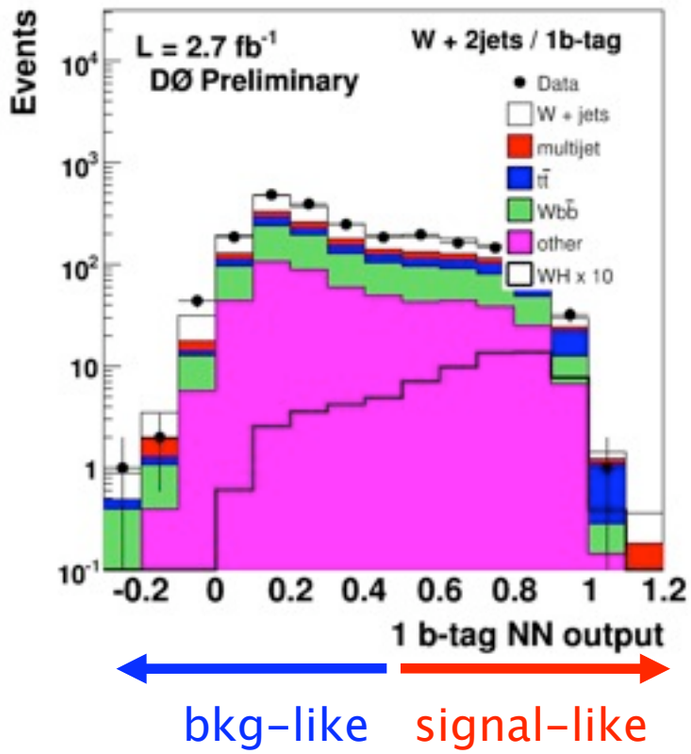


- Neural Network (NN):

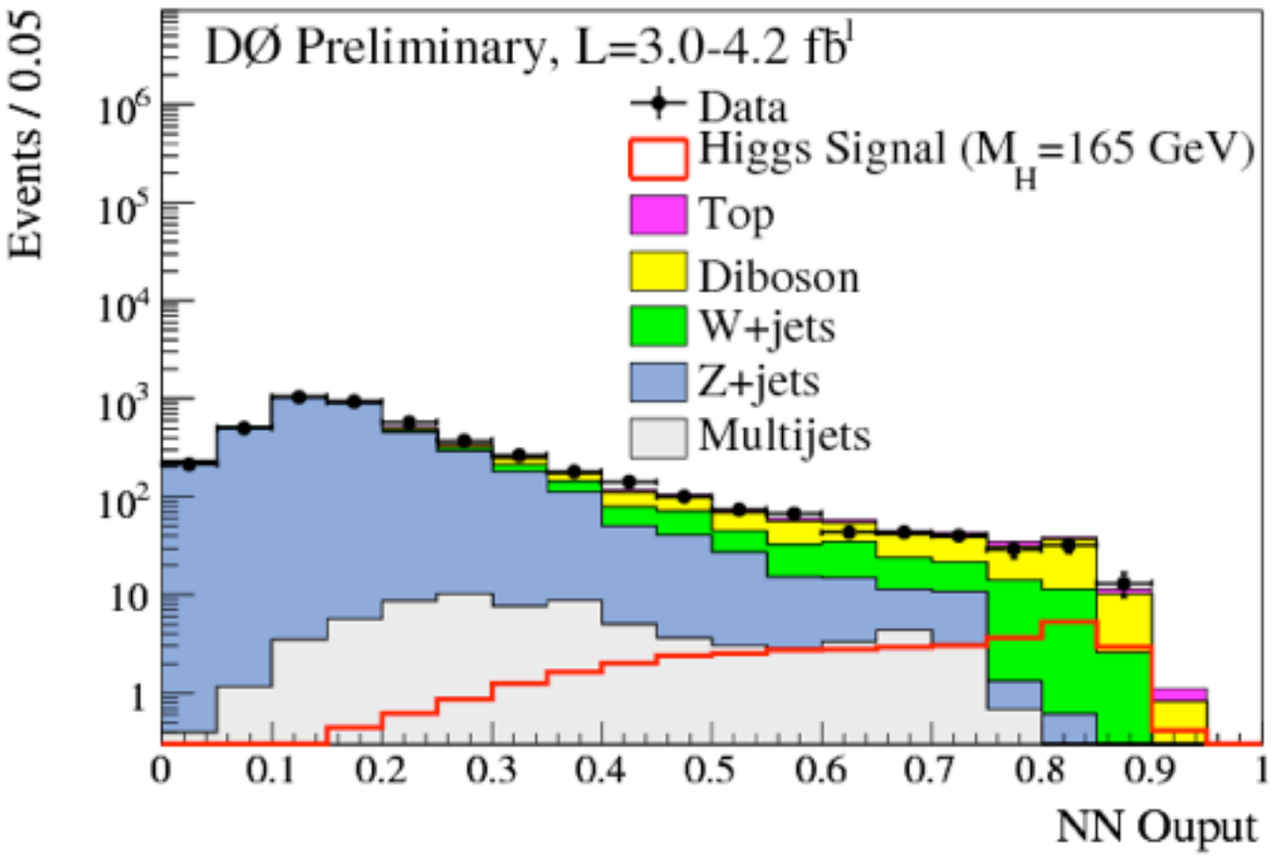
- Matrix Elements:
  - Event probability based on leading-order matrix elements

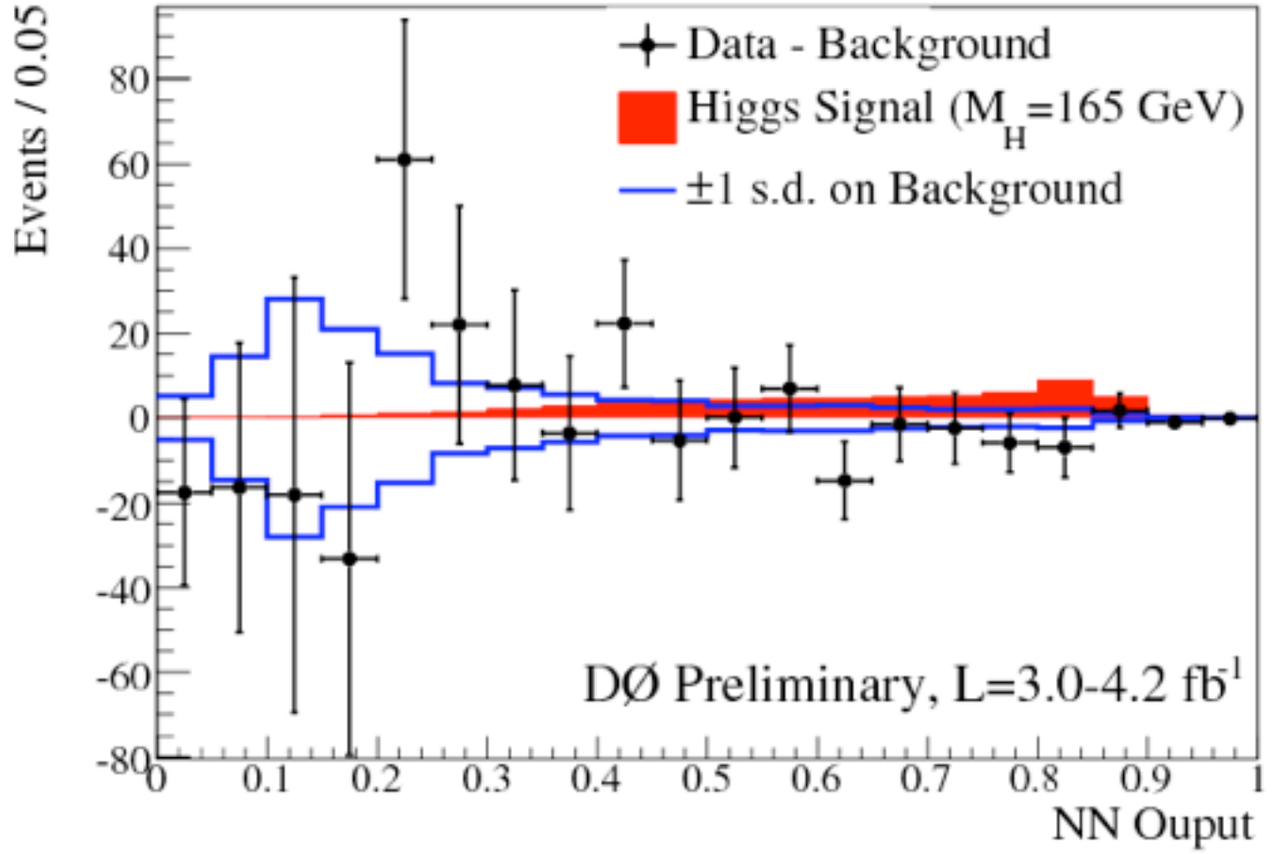
$$P_{\mathrm{WH}}(x) = \frac{1}{\sigma} \underbrace{\sum_{i,j}}_{\text{Flavor}} \int_y \underbrace{f_i(q_1) f_j(q_2)}_{\text{PDF}} \times \underbrace{\frac{d\sigma_{\mathrm{WH}}}{dy}}_{\text{ME}} \times \underbrace{W(x,y)}_{\text{Detector Responce}}$$

- Multivariate Methods separately trained for 1,2 b-tag samples



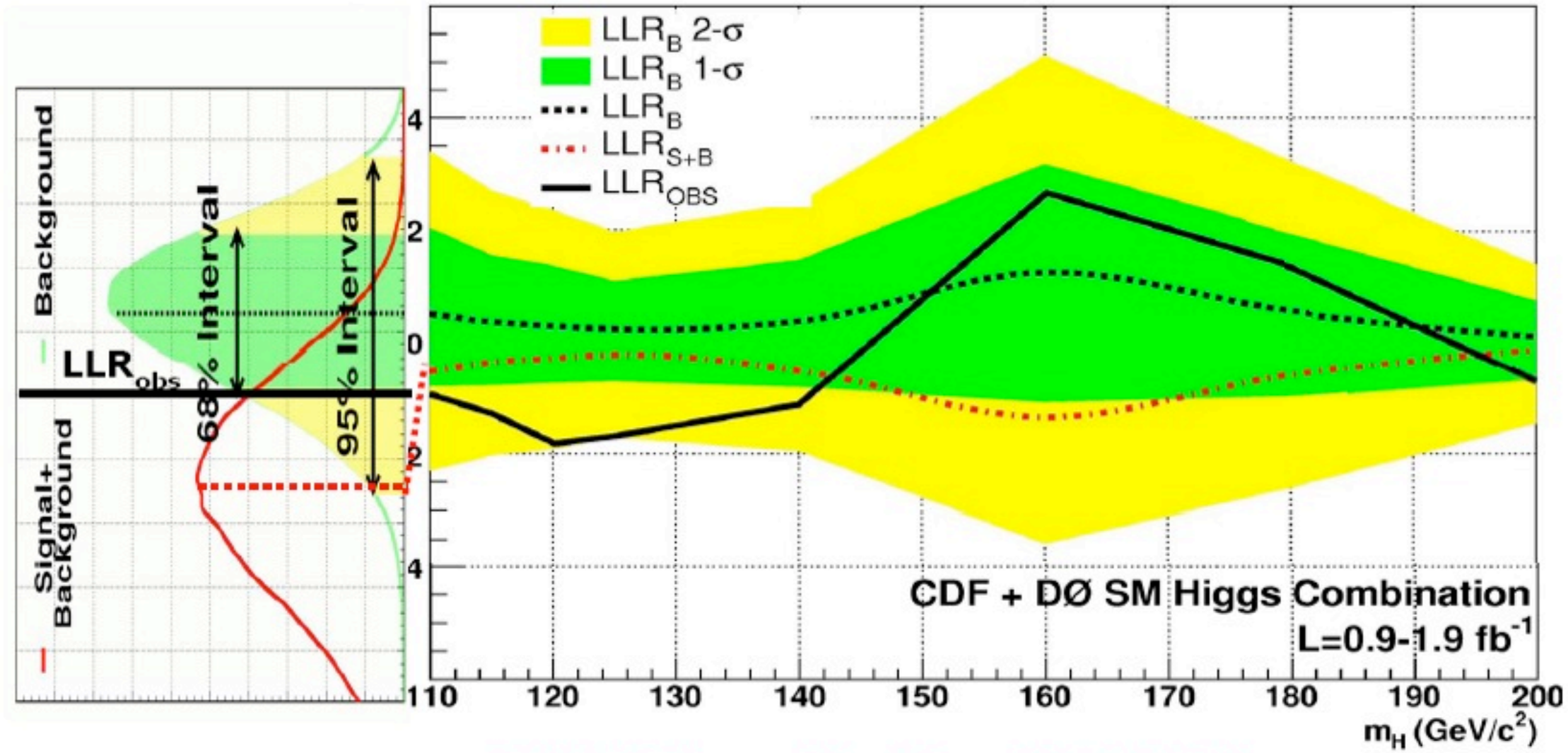
DØ NN output classifier for full dataset and all channels





Large backgrounds, but under control

LLR Explanation



CDF+DØ combination, 0.9-1.9 fb^{-1}

Method of Combination

- Environment: High background (BG) and sizeable systematics

→ testing 'background only' and 'signal+background' hypotheses

→ using Poison statistics for systematic uncertainties

- Two methods are used:
  - CDF: Bayesian Method, integration over likelihoods:

$$\mathcal{L}(R,\vec{s},\vec{b}|\vec{n},\vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2}$$

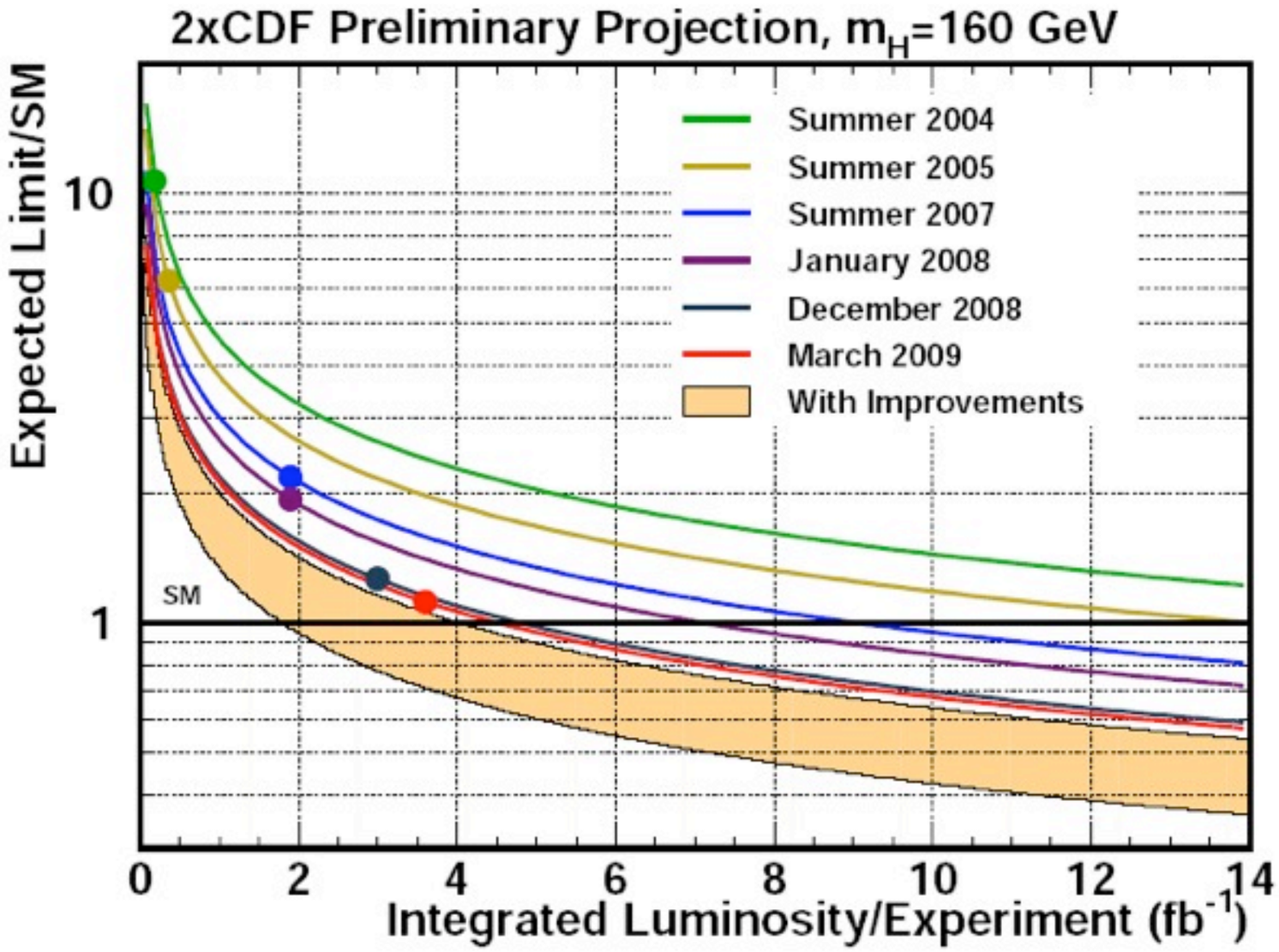
  - D

$$LLR = -2 \ln \frac{p(\text{data}|H_1)}{p(\text{data}|H_0)}. \qquad \begin{aligned} CL_b &= p(LLR \geq LLR_{obs}|H_0) \\ CL_{s+b} &= p(LLR \geq LLR_{obs}|H_1) \end{aligned} \qquad CL_s = \frac{CL_{s+b}}{CL_b}$$

- Both

- Same results using both methods → very good crosscheck

Summary



high mass Higgs projection

Tau Final States:

- Both experiments have inclusive H+ X→ t(t)+X searches
- Bringing additional acceptance