Combined SM Higgs Limits at the Tevatron

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On behalf of the CDF and DØ collaborations

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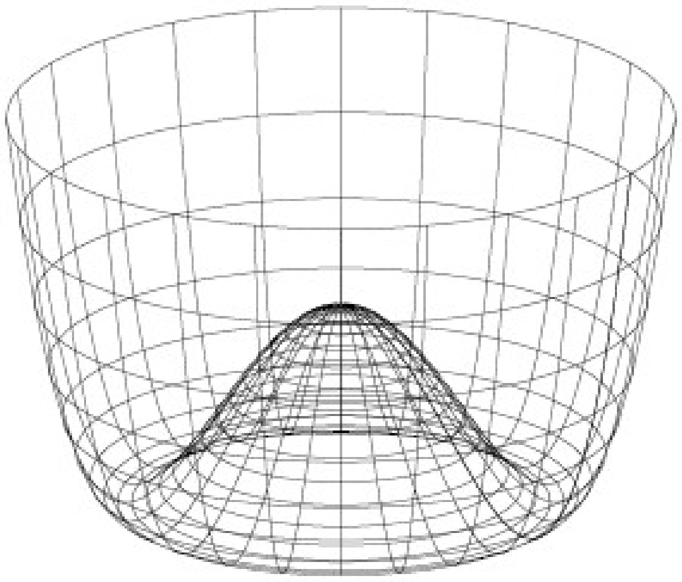
The Higgs Mechanism

- 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



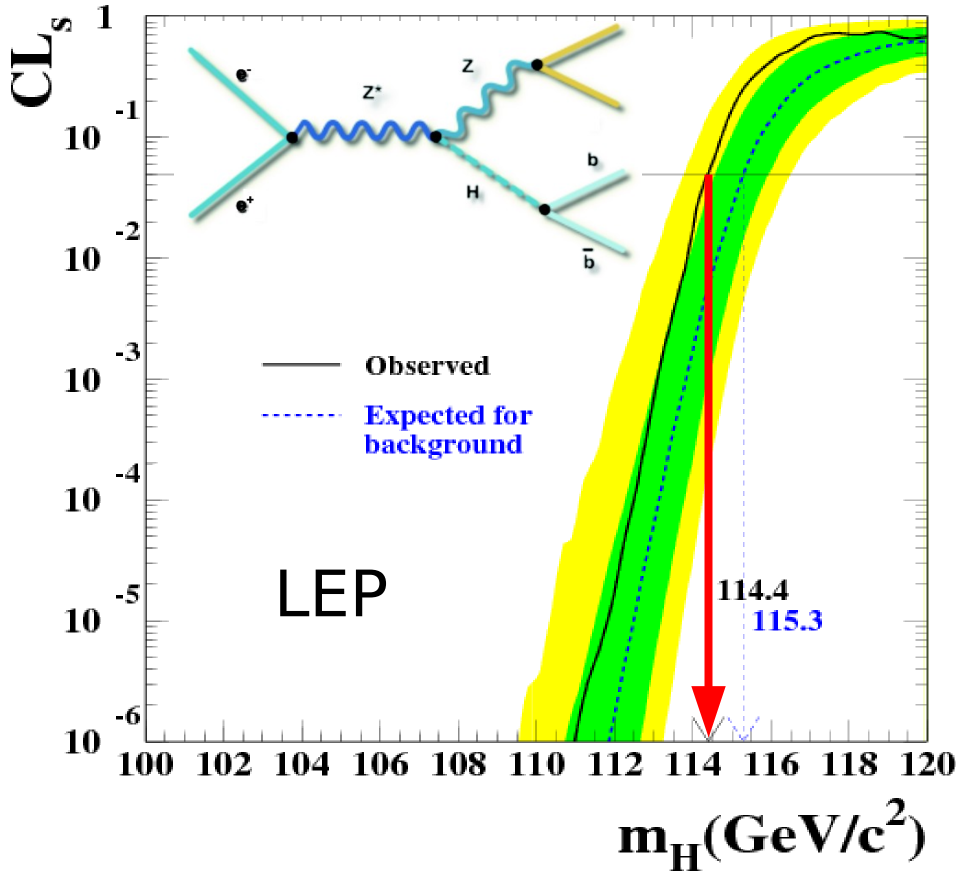
→ $W^{\pm}$, Z boson acquire mass

→ Fermion masses can be generated

→ Higgs mass free parameter

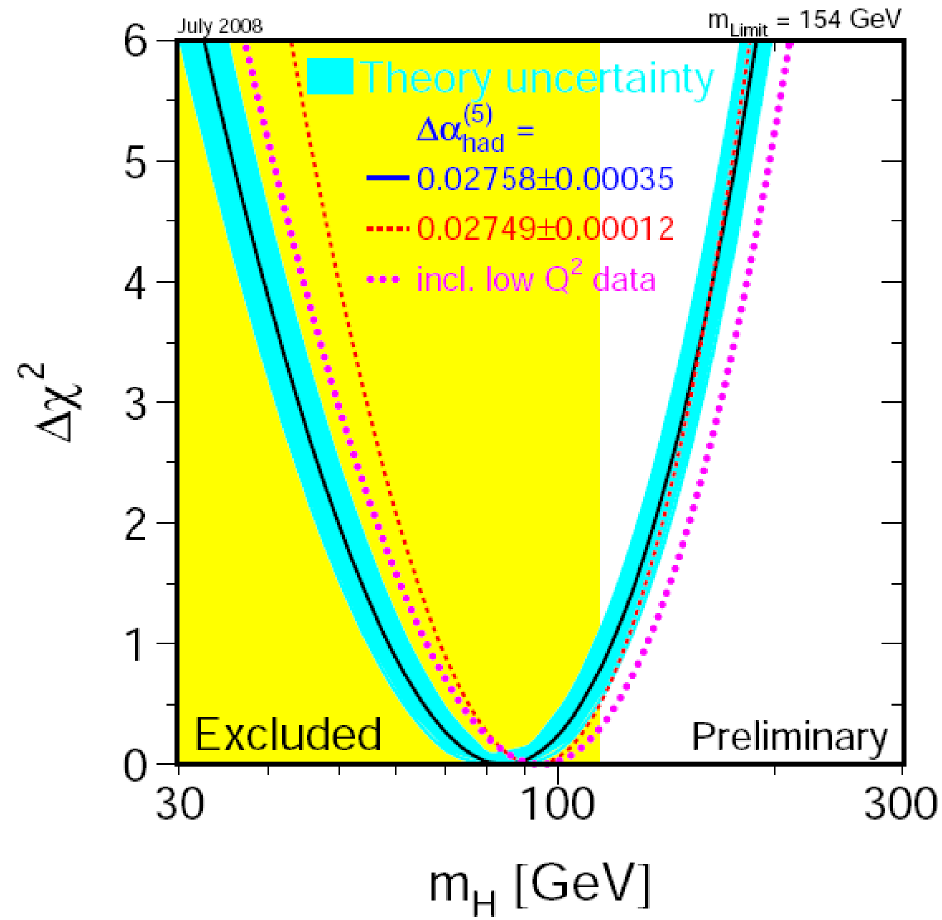
Existing Experimental Evidence

Direct Limits



$m_H > 114.4$ GeV

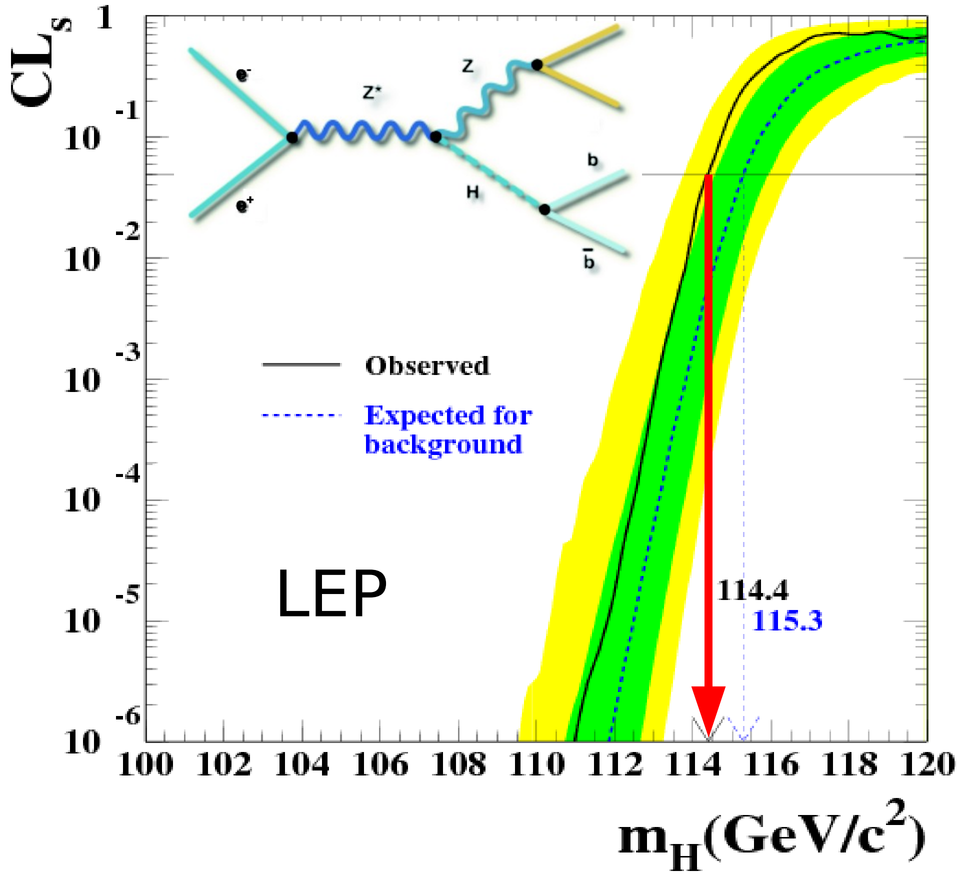
Electroweak Fits



$m_H < 163$ GeV@95 C.L.

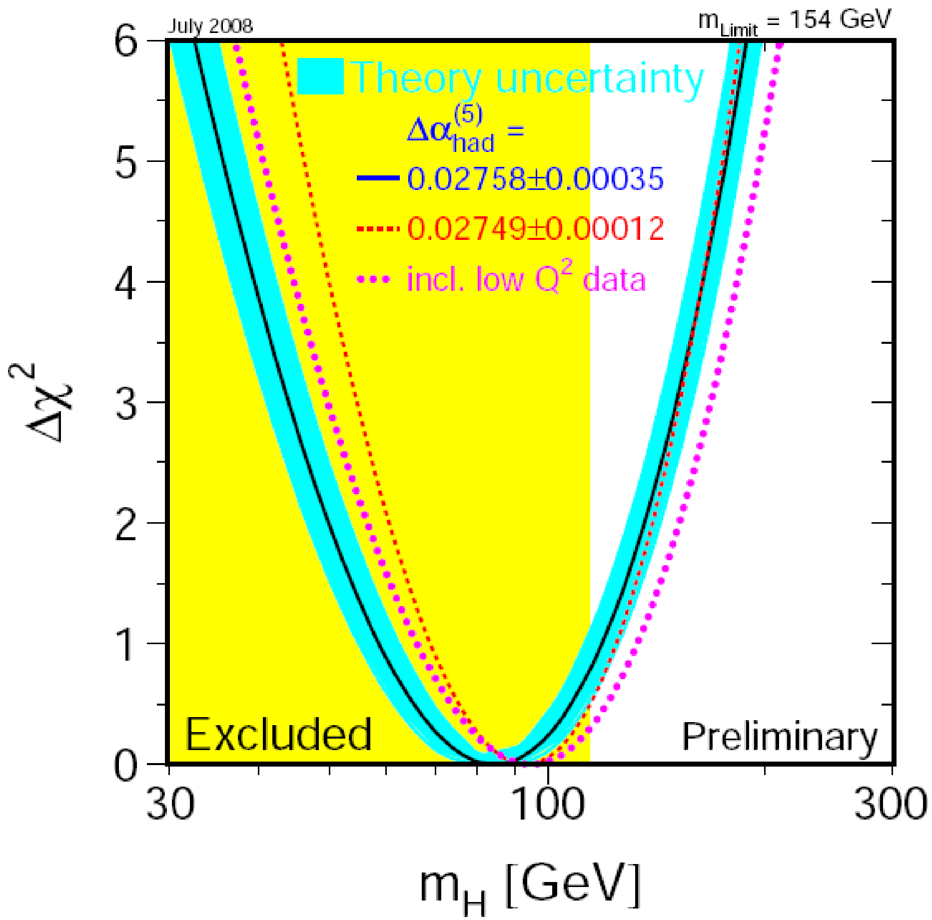
Existing Experimental Evidence

Direct Limits



m_H>114.4 GeV

Electroweak Fits

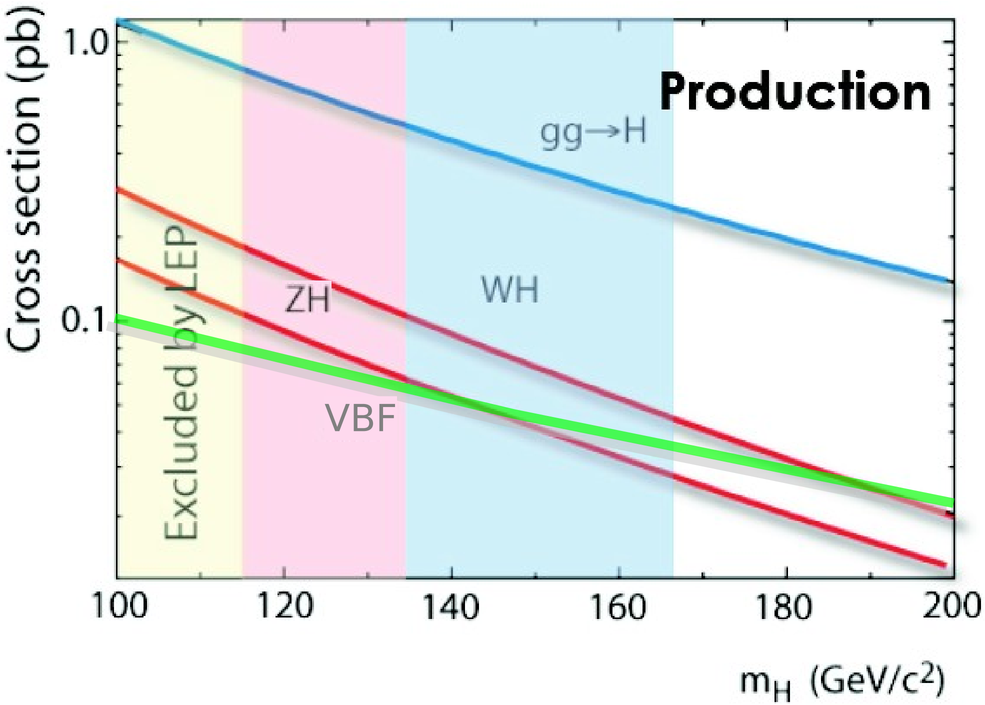


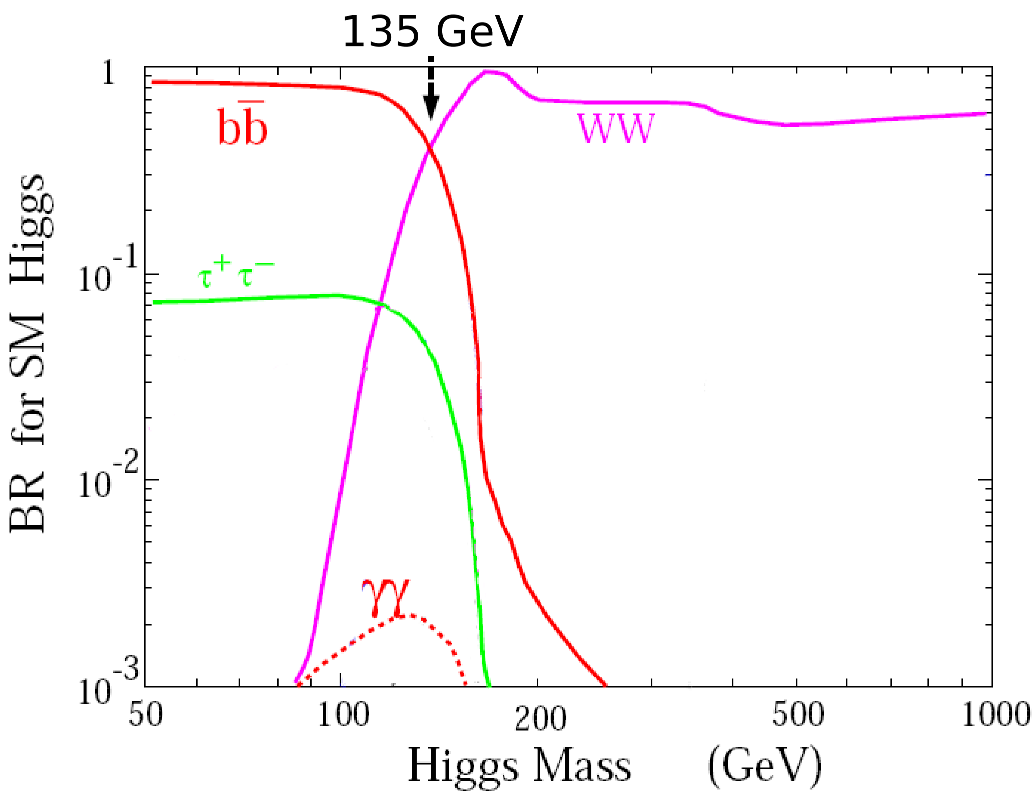
m_H<160 GeV@95 C.L.

SM Higgs probably accessible at the Tevatron!

- Cross Section Higgs production:
  - $\sigma(g\,g \rightarrow H) \approx 2 - 0.1\, pb$
  - $\sigma(q\,\bar{q} \rightarrow HW) \approx 0.6 - 0.02\, pb$

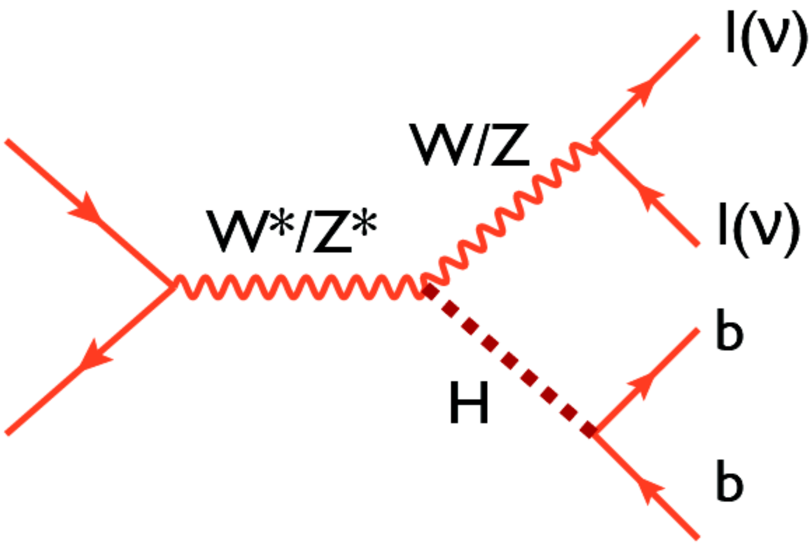
- Production Channels





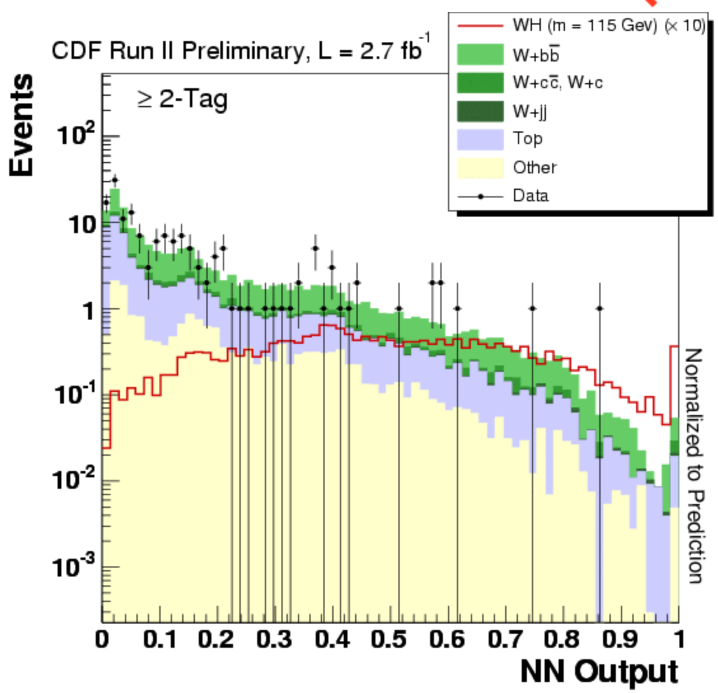
Main production via Gluon Fusion and Associated Production, dominant decay:

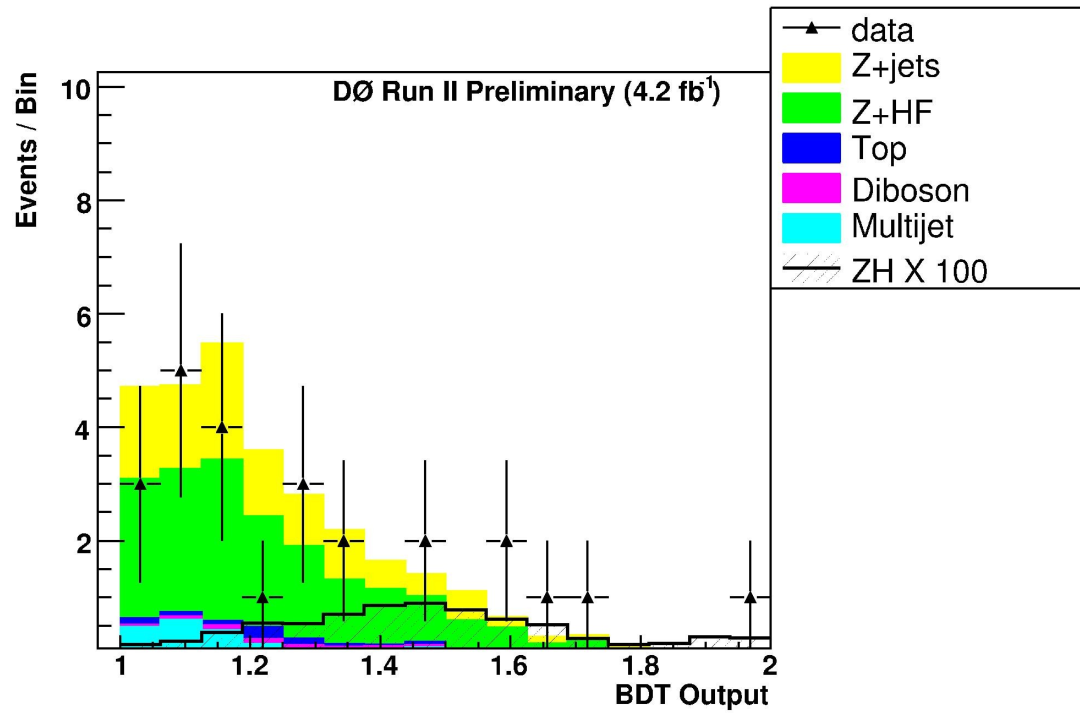
- m_H<135 GeV: $b\bar{b}$
- m_H>135 GeV: *WW* decay



W/ZH → ℓ(ℓ/ν)νbb

Lepton and missing Missing E_T consistent with an W decay, 2 b-tagged jets

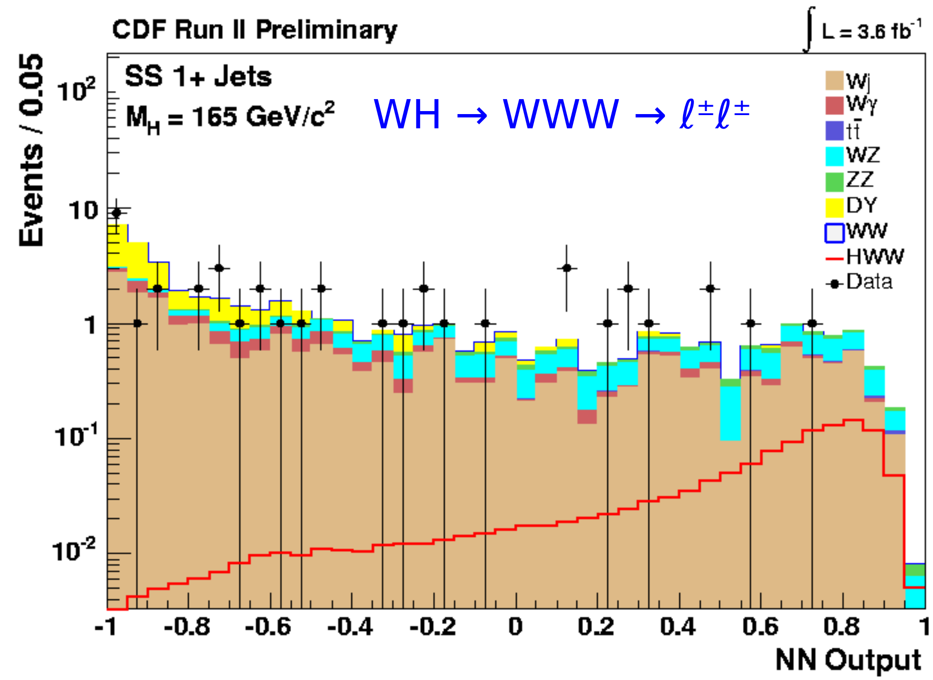


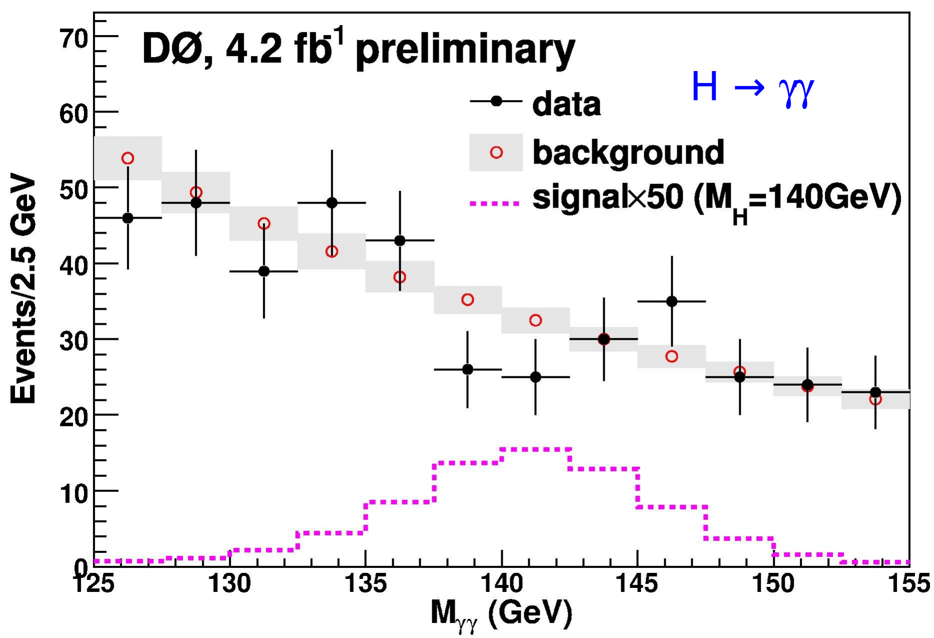


Filling the Gaps

$WH \to WWW \to \ell^\pm\ell^\pm + X$

- Important channel for intermediate mass range
- Select like-sign final states → difficult instrumental background



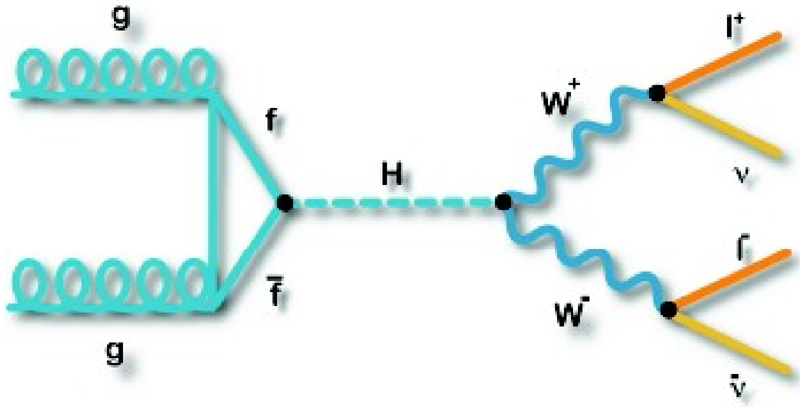


$H \to \gamma\gamma$

- Small branching ratio
- Cross section limit nearly constant for large masses

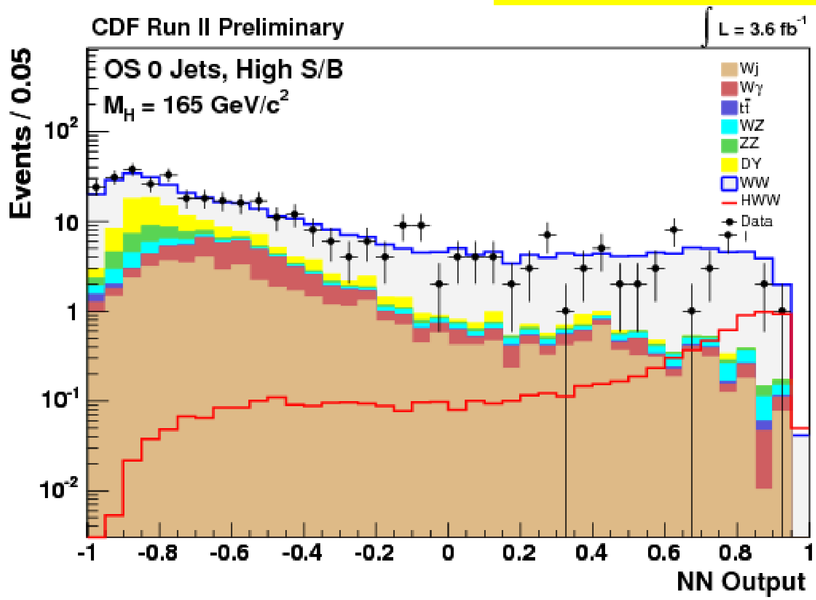
- Additional acceptance by $H + X \to \tau(\tau) + X$ searches

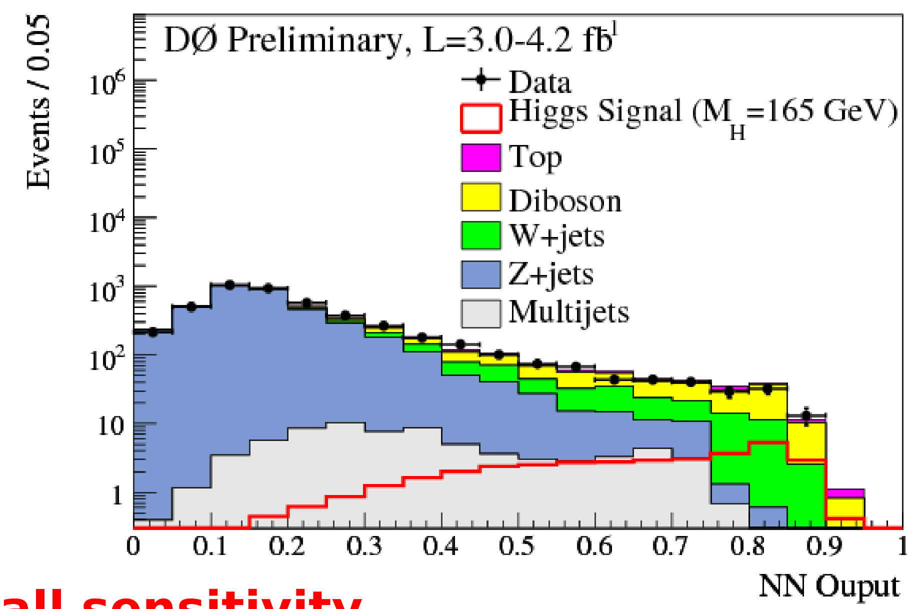
High Mass Higgs Searches



$WW \rightarrow \ell\nu\ell\nu$

2 high-p_T leptons, high Missing E_T





Best overall sensitivity

Channels entering the Combination

DØ: 52 channels

Channel	Lumi. (fb^{-1})	Final Variable
WH → $\ell\nu bb$	2.7	NN / Dijet Mass
WH → $\tau\nu bb$	0.9	Dijet Mass
VH → $\ell\tau\tau bb/qq\tau\tau$	1	NN
ZH → $\nu\nu bb$	2.1	DTree
ZH → $\ell\ell\nu bb$	2.3	NN / DTree
WH → WWW	1.1	Likelihood
H → WW→ $\ell\ell$	4.2	NN
H → $\gamma\gamma$	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

- All analyses use Multivariate Methods:
  - Neural Network (NN)
  - Decision Tree (Dtree)
  - Matrix Elemts (ME)
  - Likelihoods

CDF: 23 channels

Channel	Lum. (fb^{-1})	Final Variable
WH → $\ell\nu bb$	2.7	NN / DTree
ZH → $\nu\nu bb$	2.1	NN
ZH → $\ell\ell bb$	2.7	NN/ME
WH+ZH → $jjbb$	2	ME
H →WW → $\ell\ell$	3.6	NN
WH→ WWW	3.6	NN
H+X → $\tau\tau$+jj	2	NN

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%)

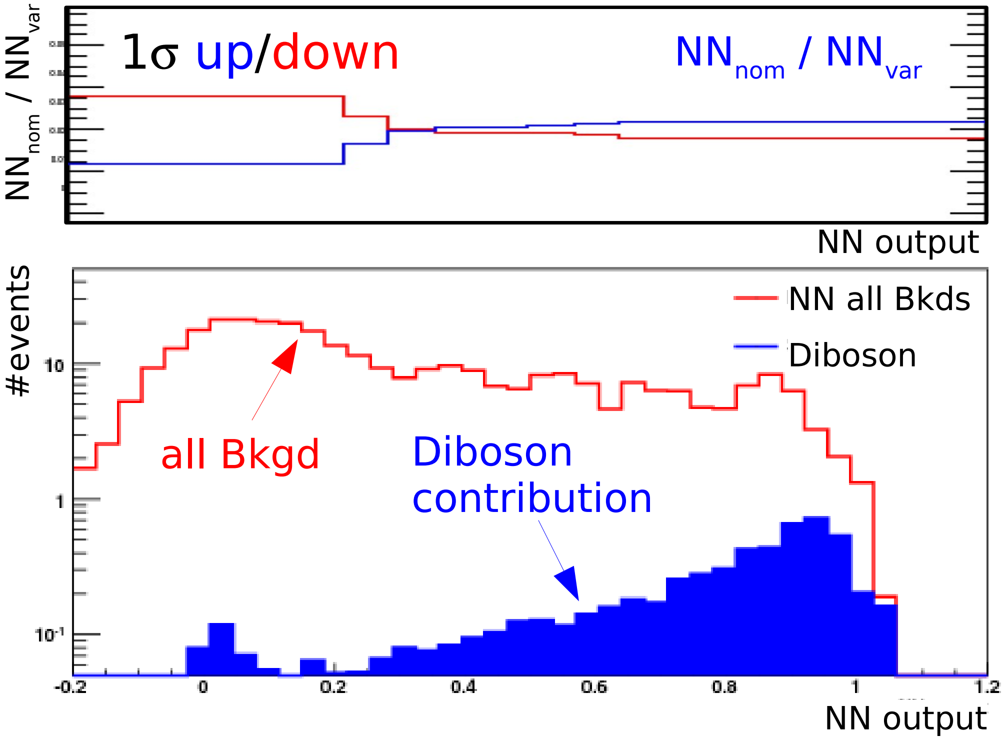
- **Correlated uncertainties in CDF**
  - b-tagging, JES, ISR/FSR
- **Correlated uncertainties in DØ:**
  - b-tagging, JES, Jet-ID/Resolution, W+jets shape
- **Systematics correlated across experiments:**
  - Luminosity
  - Cross-sections: Higgs, top, single top, diboson

Shape Uncertainties

- Two types of systematics:
  - *Rate Systematics:*
    related to overall normalization and selection efficiencies of the contributing physical processes.
  - *Shape Systematics*:
    uncertainties which impact the multivariate classification of events

- Shape of 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



Method of Combination

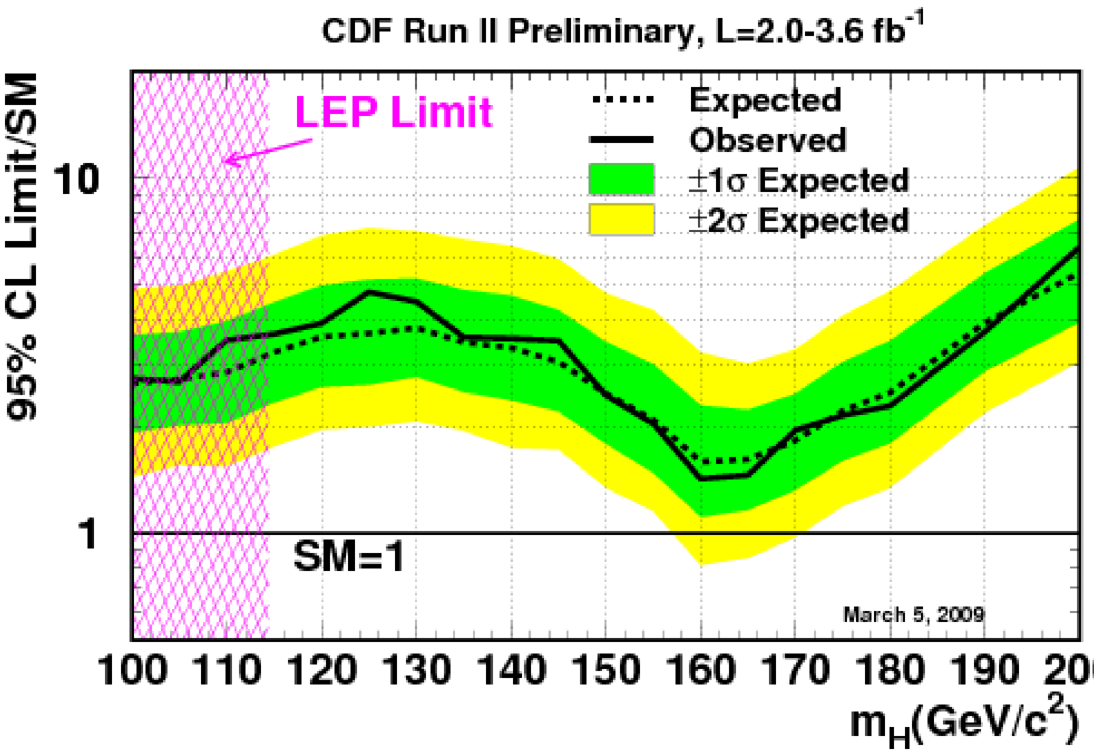
- Environment: High background (BG) and sizeable systematics
  → testing 'background only' and 'signal+background' hypotheses
  → using Poisson statistics for systematic uncertainties

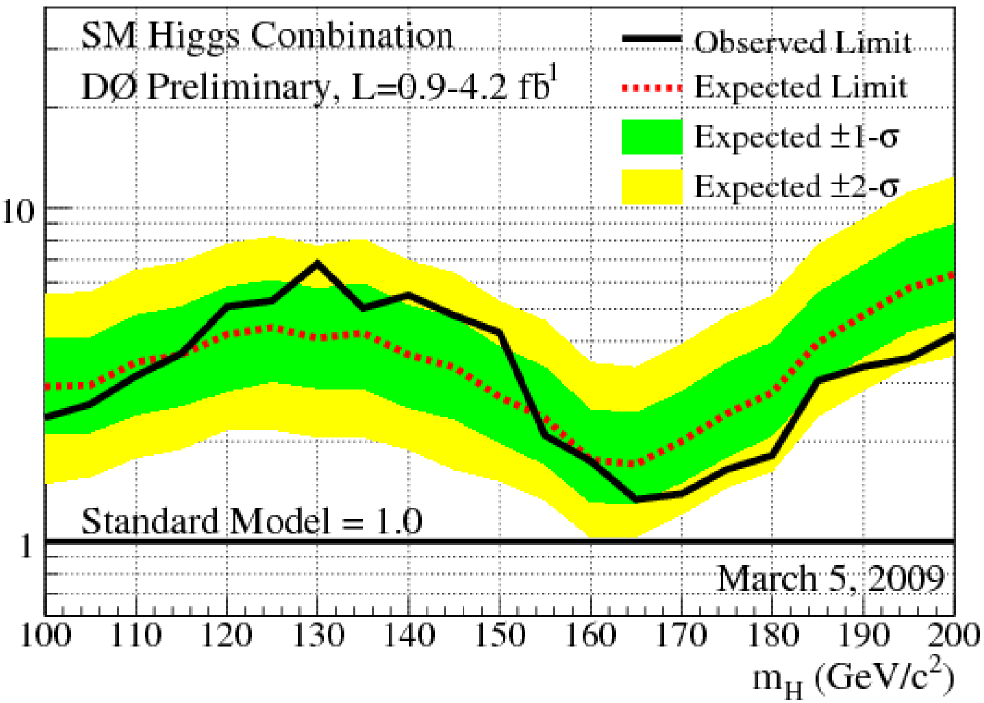
- Two methods used:
  - CDF: Bayesian Method, integration over likelihood
    - Probability based approach, uses a prior:
      "Is number of head/tails consistent with 50%?"
  - DØ: Modified Frequentist Method, CLs test statistics:
    - Essentially testing difference between `Test` and `NULL` hypothesis
      "How often do we observe head, how often tail?"

- Both methods use differential distributions (shapes), not only yields

- **Systematic uncertainties**
  Systematics are included via Gaussian smearing of expected number of events
  → CLs method fits uncertainties for each systematics uncertainty
  → Bayesian method integrates over systematic uncertainties

Individual Combinations





m_H=115 GeV:

CDF	exp. 3.2	obs. 3.7
DØ	exp. 3.6	obs. 3.7

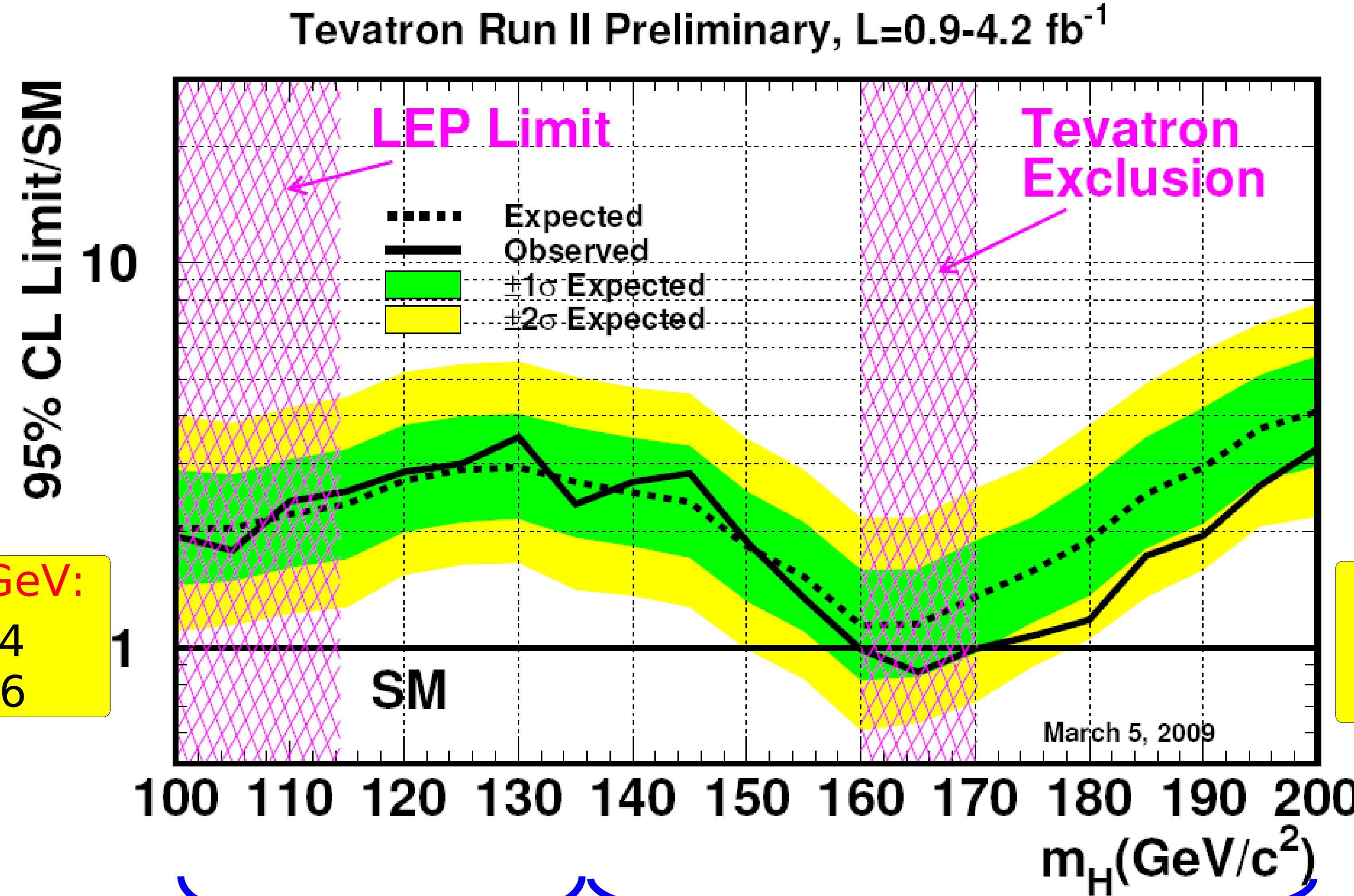
m_H=165 GeV:

CDF	exp. 1.6	obs. 1.5
DØ	exp. 1.7	obs. 1.3

comparable sensitivity

Combination & Exclusion

- In order two achieve maximal sensitivity CDF and DØ combined



m_H=115 GeV:
Exp: 2.4
Obs. 2.6

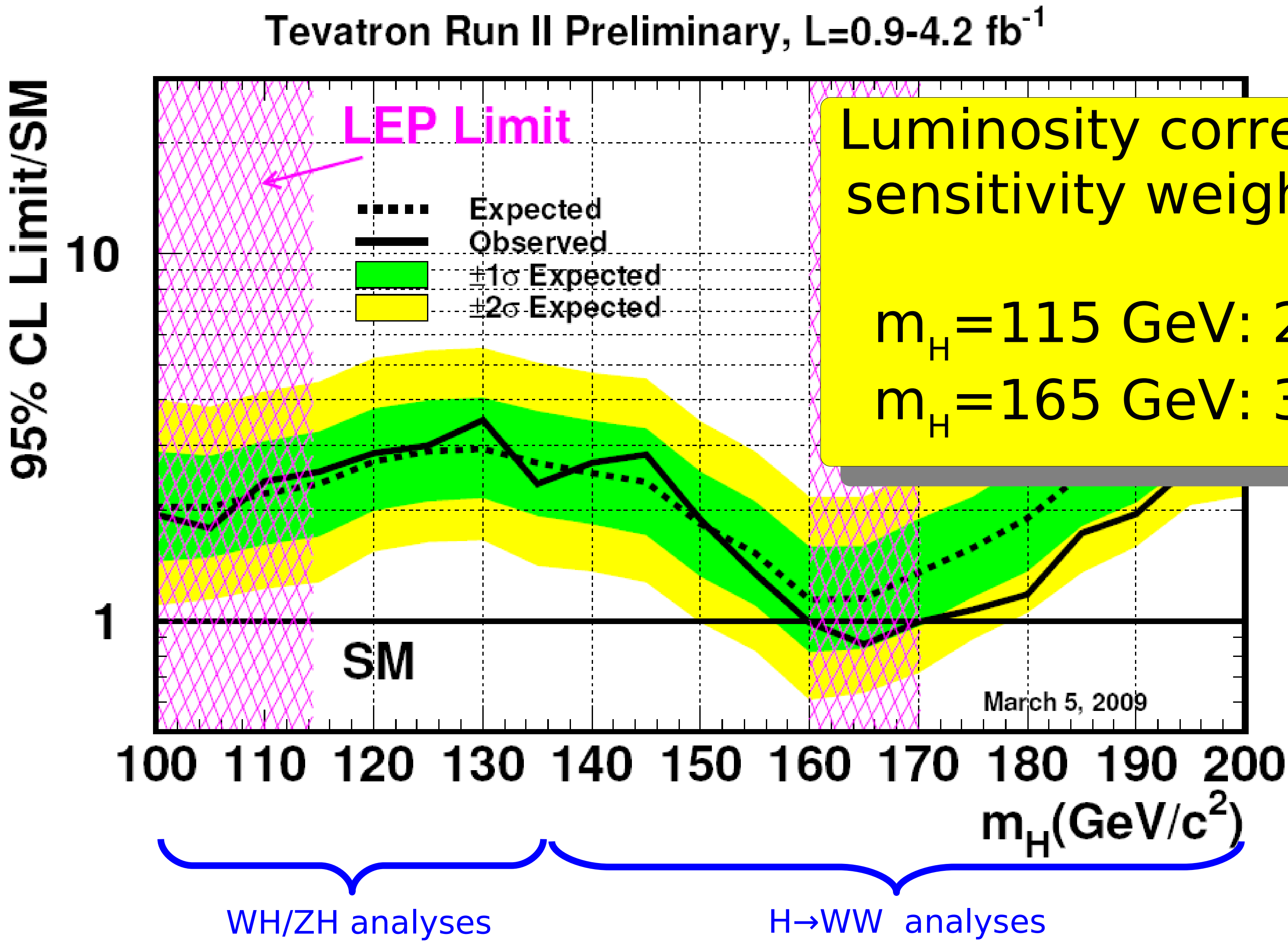
m_H=165 GeV:
Exp: 1.1
Obs. 0.81

Dominated by WH/ZH analyses H→WW analyses

- Excluding significant region, rapidly adding more Data

Combination & Exclusion

- In order two achieve maximal sensitivity CDF and DØ combined



- Excluding significant region, rapidly adding more Data

Summary

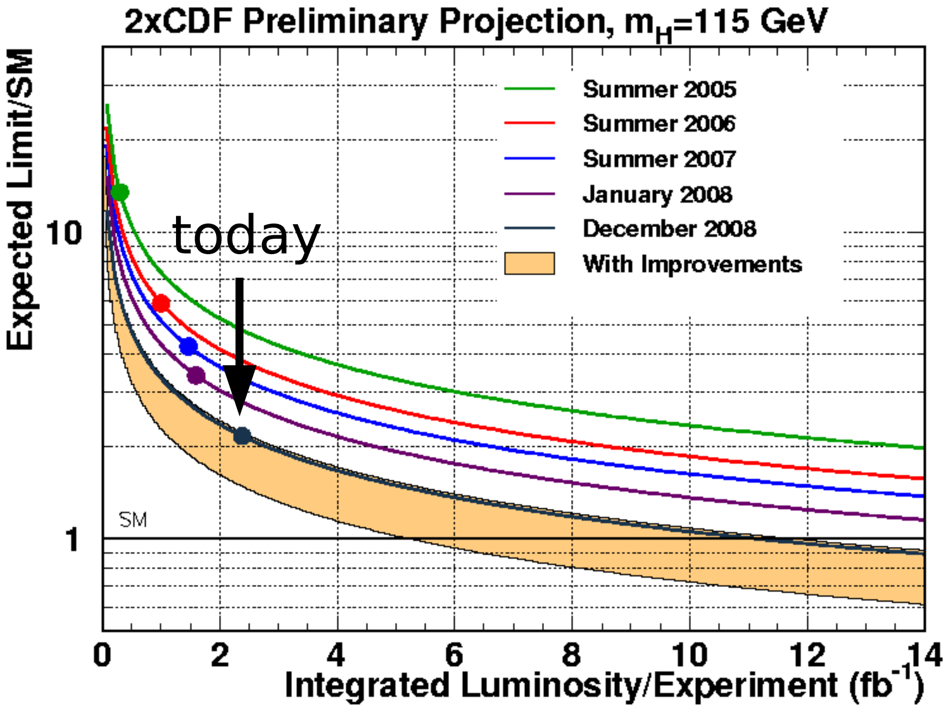
- Today sensitivity of each experiment comparable to Tevatron combination Spring 08.

- Moriond08: 1.6 x SM
  → ICHEP08: excluded m_H=170GeV
  → Moriond09: excluded m_H=160-170GeV

More sensitivity gained by:

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

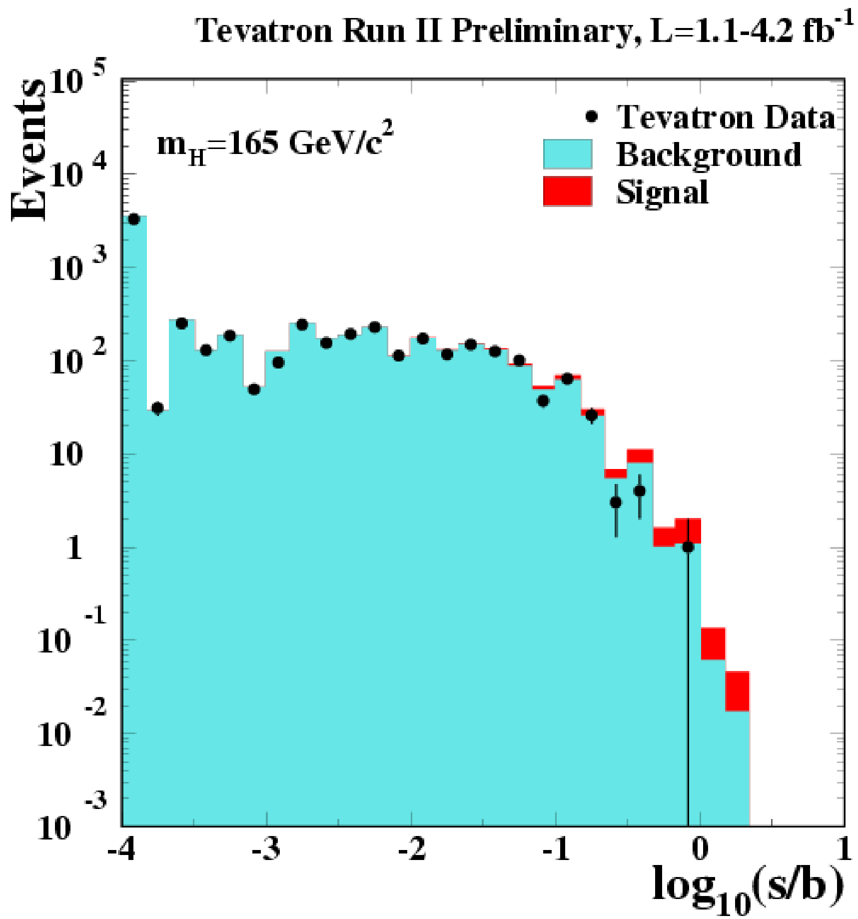
→ **Exciting times at the Tevatron**



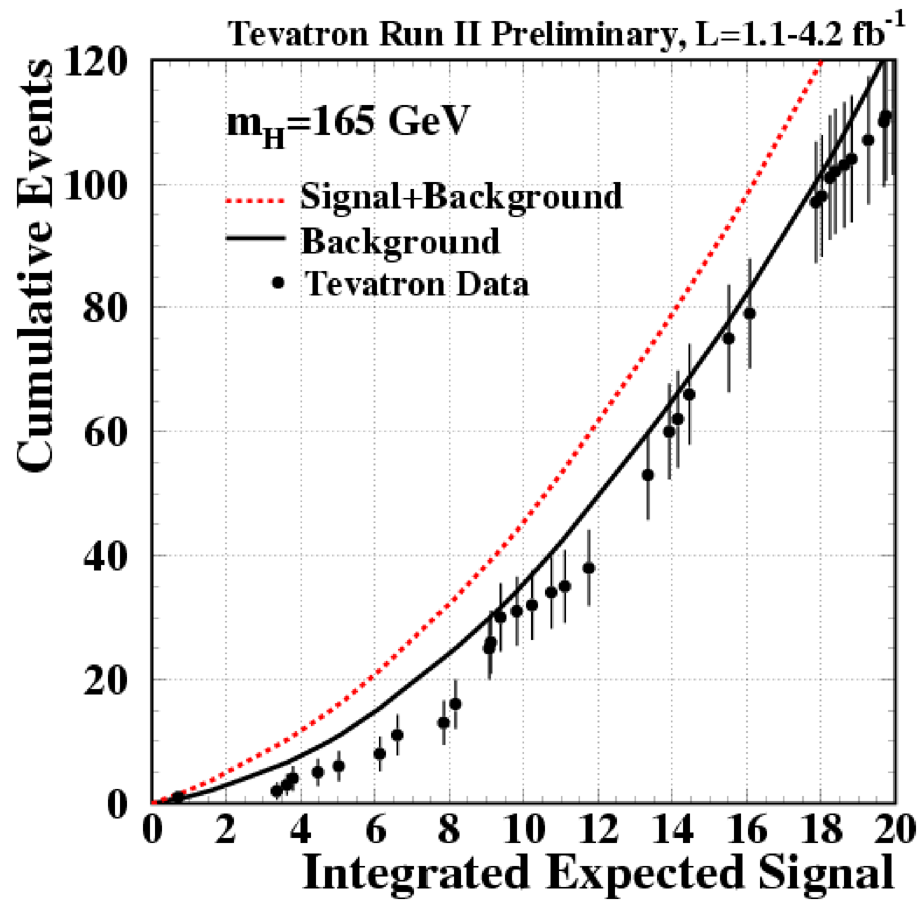
low mass Higgs projection

Backup Slides

Combination & Exclusion



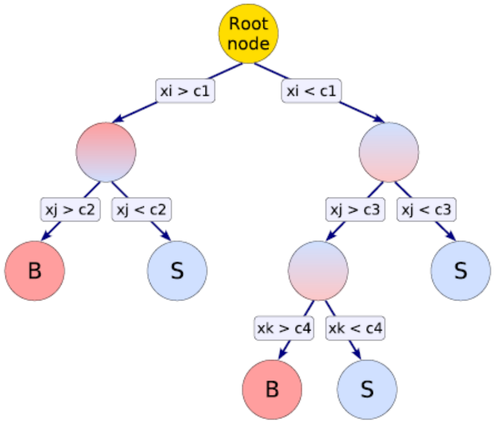
- All Events sorted in “S/B” bins



- Cumulative distributions. of bkgd only & sig+bkd hypothesis and comparison with data

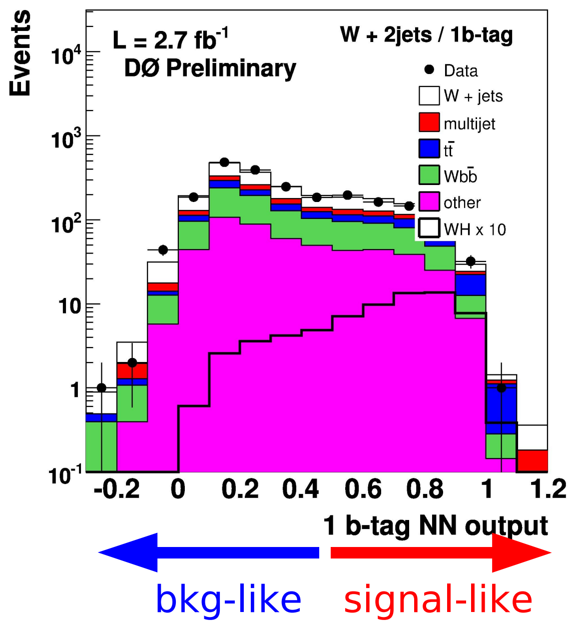
Multivariate Methods

- Both experiments use Multivariate Methods to further suppress backgrounds.



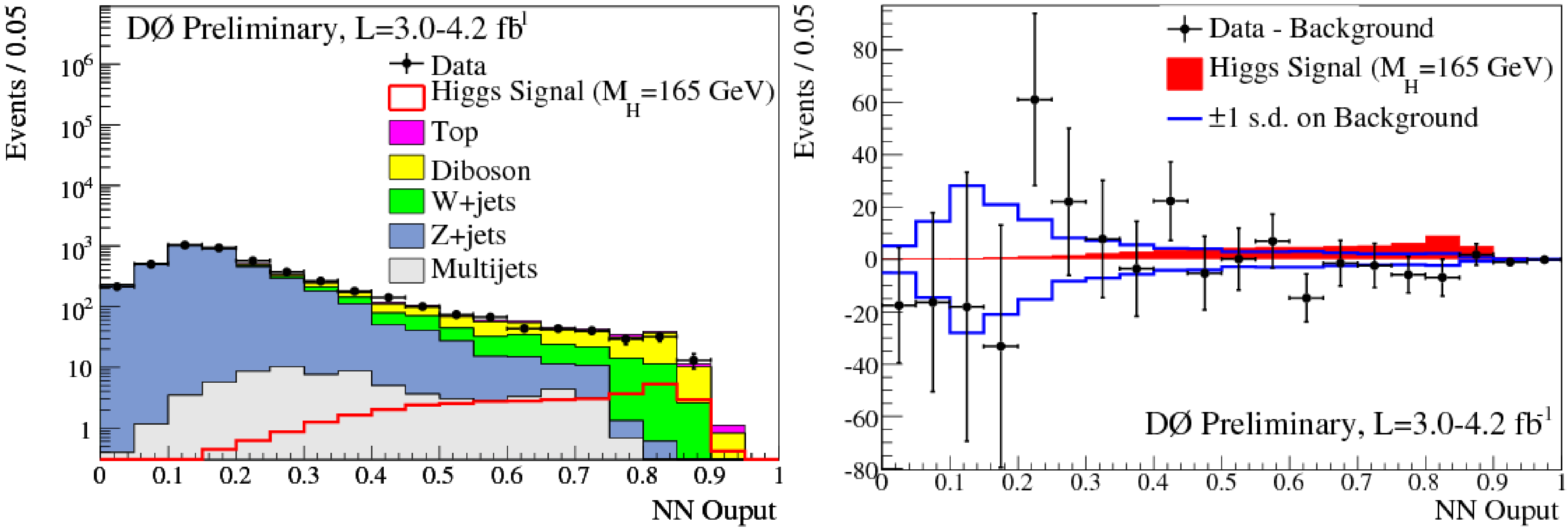
- Boosted Decision Tree (BDT):
  - Binary tree structured classifier
  - Insensitive to poorly discriminating variables
- Neural Network (NN):
- Matrix Elements:
  - Event probability based on leading-order matrix elements

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



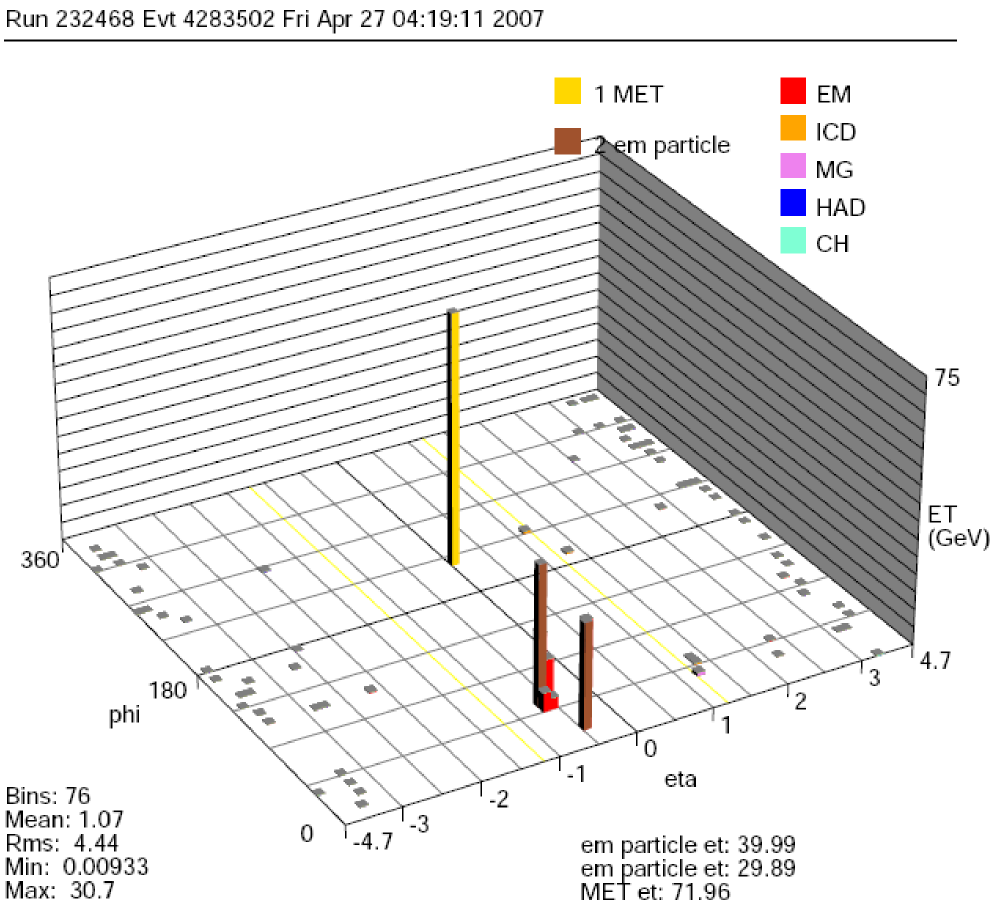
- Multivariate Methods separately trained for 1,2 *b*-tag samples

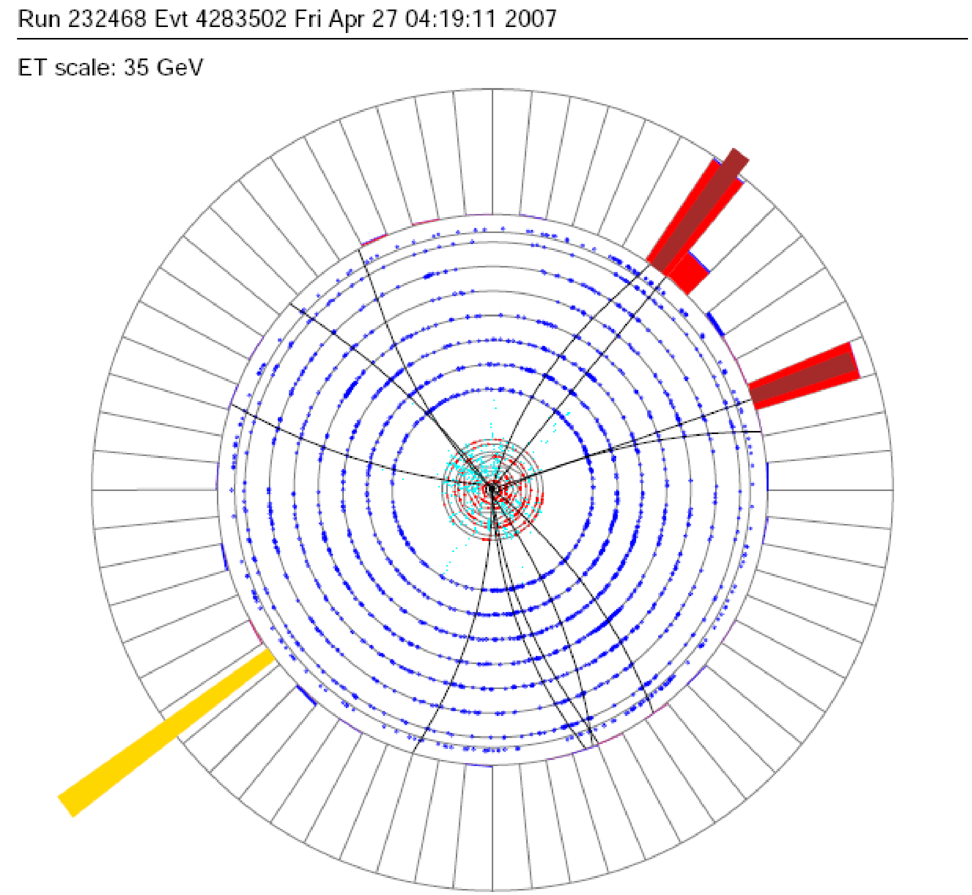
DØ NN output classifier for full dataset and all channels



Large backgrounds, but under control

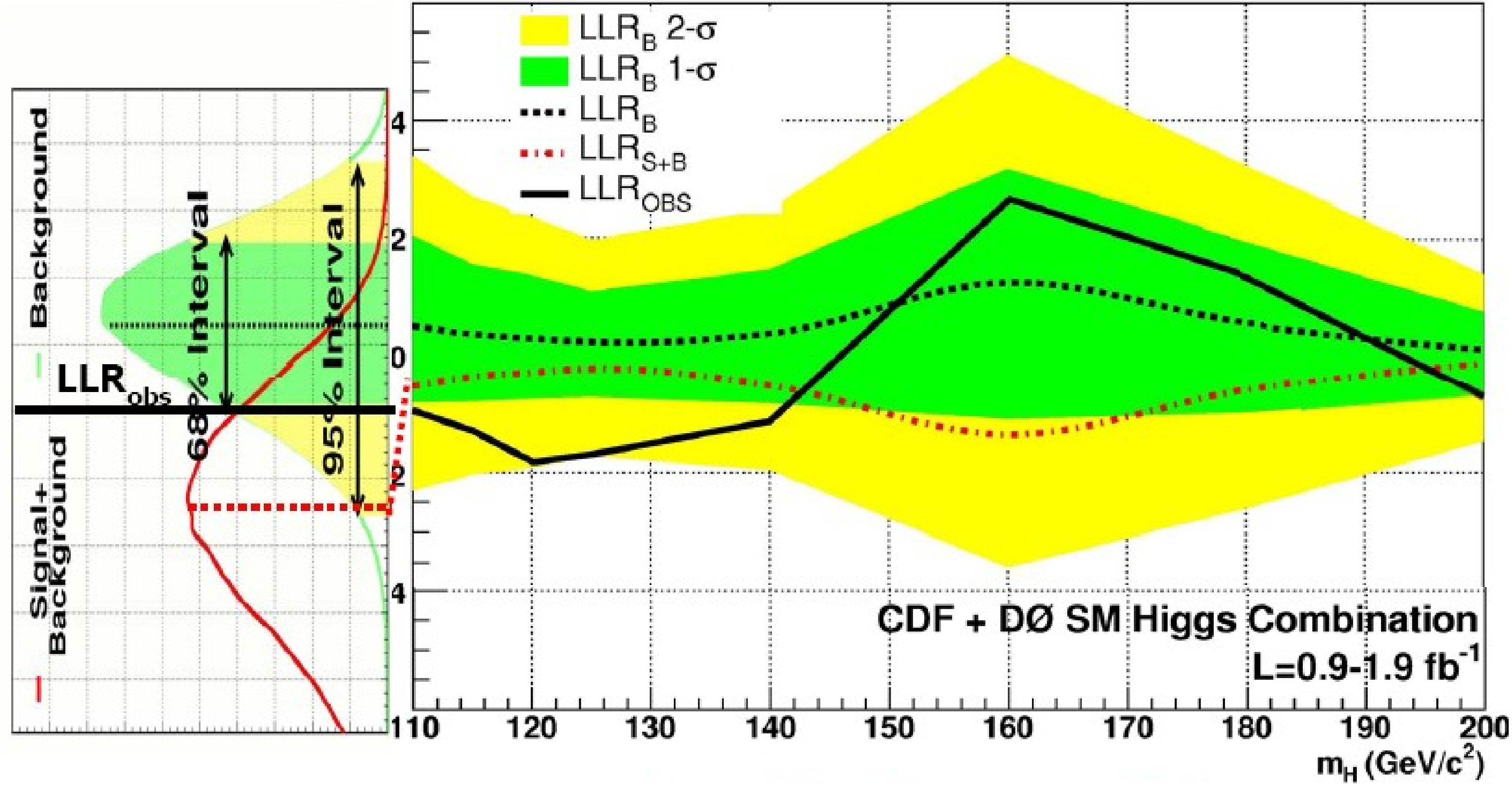
Higgs Candidate





- Higgs candiate:
  - NN: 1.0@165 GeV,
  - $p_T(e_1)$=40 GeV, $p_T(e_2)$=30 GeV
  - Missing E_T=72 GeV

LLR Explanation



Method of Combination

- Environment: High background (BG) and sizeable systematics
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  → using Poison statistics for systematic uncertainties

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

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

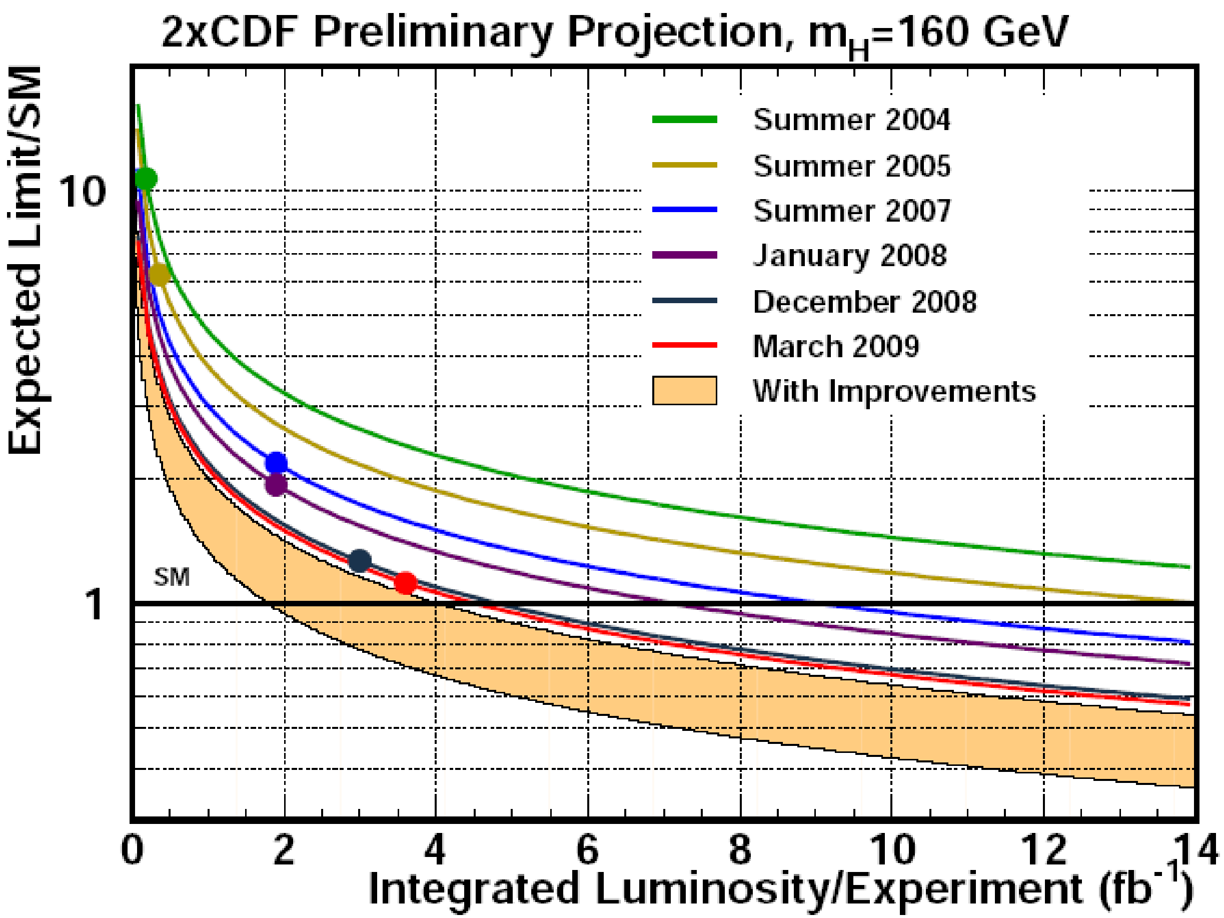
  - DØ: Modified Frequentist method, Cls:

$$LLR = -2\ln\frac{p(\mathrm{data}|H_1)}{p(\mathrm{data}|H_0)}; \quad CL_b = p(LLR \geq LLR_{obs}/H_0) \quad CL_{s+b} = p(LLR \geq LLR_{obs}/H_1) \quad CL_s = \frac{CL_{s+b}}{CL_b}$$

- Both methods use differential distribution (shapes), not only yields

- Same results using both methods → very good crosscheck

Summary



high mass Higgs projection

Tau Final States:

- Both experiments have inclusive H+ X→ τ(τ)+X searches

- Bringing additional acceptance