Combined Higgs Searches at DZero

W&C, December 7th 2007
Gregorio Bernardi, LPNHE-Paris
for the DØ Collaboration

- Standard Model Higgs Searches
- New results since Lepton-Photon (2007)
- Combination techniques

- Combination results:
  DØ and CDF & DØ (released today)

Special thanks to W. Fisher, T. Junk, W. Yao, TevNP-Higgs WG and all DØ and CDF colleagues

http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
### Experimental constraints on the Higgs Boson

#### Indirect Constraints:
- **Top, W-boson masses**

#### Direct searches at LEP II:
- \( m_H > 114.4 \text{ GeV} \) @ 95% CL

#### Precision EW fit:
- \( m_H < 144 \text{ GeV} \) (<182 GeV with LEPII Limit)

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**Graphical Representation:**
- **Leptos-electroweak fit:**
  - \( m_W \)
  - \( m_H \)
  - \( \chi^2 \) / dof = 9.2 / 10

**Top Quark Mass Measurement:**
- **CDF-I di-I:** \( 167.4 \pm 11.4 \) GeV/c²
- **DØ-I di-I:** \( 168.4 \pm 12.8 \) GeV/c²
- **CDF-II di-I:** \( 164.5 \pm 5.6 \) GeV/c²
- **DØ-II di-I:** \( 172.5 \pm 8.0 \) GeV/c²
- **CDF-I l+j:** \( 176.1 \pm 7.3 \) GeV/c²
- **DØ-I l+j:** \( 180.1 \pm 5.3 \) GeV/c²
- **CDF-II l+j:** \( 170.9 \pm 2.5 \) GeV/c²
- **DØ-II l+j:** \( 170.5 \pm 2.7 \) GeV/c²
- **CDF-I all-j:** \( 186.0 \pm 11.5 \) GeV/c²
- **CDF-II all-j:** \( 171.1 \pm 4.3 \) GeV/c²
- **CDF-II lxy:** \( 183.9 \pm 15.8 \) GeV/c²
- **Tevatron Run-I/II:** \( 170.9 \pm 1.8 \) GeV/c²

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Dataset

Run II Integrated Luminosity

19 April 2002 - 5 August 2007

Average data-taking efficiency: ~85%

Results presented here based on ~1.7 fb⁻¹ of analyzed luminosity

Run IIa

DØ Upgrade

Run IIb

2.81 fb⁻¹

3.29 fb⁻¹
The Upgraded DØ detector in Run IIb

- Trigger: L1 Calorimeter trigger
- Silicon vertex detector: Layer 0

Layer 0 now inserted and fully readout

Excellent noise performance S/N=18!!
SM Higgs boson production & decays

- **gg fusion**
  - Dominates at hadron machines
  - Usefulness depends on the Higgs decay channel

- **WH, ZH associated production**
  - Important at hadron colliders since can trigger on 0/1/2 high-p_T leptons and MET
SM Higgs Searches at the Tevatron

Low mass ($m_H \lesssim 135$ GeV):
dominant decay:

$H \to b\bar{b}$

Use associated production modes to get better signal/background

Intermediate mass:

High mass ($m_H \gtrsim 135$ GeV):
dominant decay:

$H \to WW$ (*)

$q\bar{q}' \to WH \to \ell v b\bar{b}$

$q\bar{q} \to ZH \to \ell^+\ell^- b\bar{b}$

$q\bar{q} \to ZH \to v\bar{v} b\bar{b}$

$gg \to H \to WW \to \ell v\ell' v'$
Comparison of expected limits/channel based on 0.3-0.4 fb\(^{-1}\) of data

DØ combination, 0.4 fb\(^{-1}\), arXiv:0712.0598, subm. to PLB
Combination with 0.4 fb\(^{-1}\) (→ PLB)

All limits in this talk are given as ratios to SM cross-sections

@ 115 GeV (0.4 fb\(^{-1}\))

Expected/Obs

12.1 / 8.5

@ 160 GeV (0.3 fb\(^{-1}\))

Expected/Obs

9.0 / 10.2

arXiv:0712.0598
SM Higgs Low mass searches: datasets/methods

Common to all analyses: b-tagging, Jet calibration & resolution, lepton-identification, Background cross-section

Differences: instrumental bckd, multivariate techniques
Neural Network b-tagger

All Higgs analyses uses Neural Network b-tagging algorithm

Asymmetric tagging:
Tight tagging for Single Tag
Loose tagging for Double Tag

→ Large improvement compared to the individual taggers:
  - Loose → 72% b-tagging eff. 6% mistag
  - Tight → 50% b-tagging eff. 0.3% mistag

Combine in Neural Network:
• vertex mass
• vertex number of tracks
• vertex decay length significance
• chi2/DOF of vertex
• number of vertices
• two methods of combined track impact parameter significances

Gain > 30% compared to our individual taggers (secondary vertex or impact parameter)
WH$\to l\nu$ bb ($l=e,\mu$): after b-tagging

Starting from a W+ 2 jet selection, apply NN_btagging $\rightarrow$ orthogonal samples

Backgrounds are measured one after the other (Wbb, Single Top), WZ with Z$\to$bb remains the golden benchmark on which we can tune our analysis tools.
WH → lν bb (l=e,μ): Neural Net and Limits

Use neural network to separate signal from background
Fit the NN output

- **Limit @ M_H=115 GeV:**
  \[ \sigma_{95}/\text{SM}, L=1.7 \, \text{fb}^{-1}= 9 \, \text{(exp)}/11 \, \text{(obs)} \]
  CDF \hspace{1cm} L=1.7 \, \text{fb}^{-1}=10 \, \text{(exp)}/10 \, \text{(obs)}

Future improvements (short term):
- include forward electrons and 3 jets sample
- Improve NN with more backgd rejection and use Matrix Element approach
ZH → ll bb (l=e,μ): setting limits

- Starting from a Z+ 1 or 2 b-jets selection
- Use neural network to separate signal from background
- Fit the NN output

Future improvements (short term):
- more efficient lepton-ID
- Improve NN and use Matrix element approach

**Limit @ M_H=115 GeV:**

\[ \sigma_{95}/\text{SM}, \; 1.1 \text{ fb}^{-1}=20(\text{exp})/18(\text{obs}) \]

CDF, \( L=1.0 \text{ fb}^{-1}=16(\text{exp})/16(\text{obs}) \)
ZH $\rightarrow \nu\nu \ bb$ / Update with Neural Net

Starting from a Missing $E_T$ (> 50 GeV) + jet selection

Distributions before b-tagging

Instrumental background and trigger are understood. Dominant physics background is W+jets with non reconstructed charged lepton
ZH $\gamma\gamma$ bb / Update with NN (0.9 fb$^{-1}$)

NN input variables, after double b-tag

$\Rightarrow$ Expected Limits improve by 20-30%
ZH → νν bb / Update with NN (0.9 fb⁻¹)

- Limit @ M_H = 115 GeV:
  \[ \sigma^{95}/SM, 0.9 \text{ fb}^{-1} = 12 \text{ (exp)}/ 13 \text{ (obs)} \]
  CDF, L = 1.7 fb⁻¹ = 10 (exp)/20 (obs)

Future improvements (short term):
  Improve QCD-multijet understanding. Improve Trigger efficiency (L1Cal RunIIb upgrade).
  Use single-tag as well.
High mass SM Higgs

Main mode: \( gg \rightarrow H \rightarrow WW^* \rightarrow l\nu \; l'\nu' \) (\( l, l' = e, \mu \))
- two high \( p_T \) isolated leptons, missing \( E_T \)
- three main channels (ee, e\( \mu \), \( \mu\mu \))
- start probing other channels (\( \mu\tau \))

Can’t reconstruct the Higgs mass (escaping \( \nu' \)’s)

\( H \rightarrow WW^* \) is low background mode

Dibosons: main background
- \( WW^* \) irreducible, separate from the signal based on angular correlation \( \Delta \phi(l,l') \) – Higgs is a scalar!

\( W+jets \) and multijets
- need good lepton identification

\( Z \rightarrow \tau\tau \) : specific for e\( \mu \) channel and channels involving taus
H → WW: ee, eμ in Run IIa; μμ in Run IIa & IIb

Run IIb
Similar detector performances
As Run IIa
$H \rightarrow WW$: Neural Net Output

- $p_T$ of the leading lepton,
- $p_T$ of the next-to-leading lepton,
- invariant di-lepton mass,
- angle between the two leptons,
- missing transverse energy $E_T$,
- angle between the leading lepton and $E_T$,
- angle between the next-to-leading lepton and $E_T$,
- minimum transverse mass of the leptons and $E_T$,
- sum of the lepton $p_T$ and $E_T$. 

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ee, $e\mu$, $\mu\mu$ Run IIa, Run IIb, NNs outputs
\( H \rightarrow WW^* \rightarrow l\nu l'\nu' \): NN input/output

Variables used depend on the mass/channel

Significant improvement compared to Delta-Phi (>30%), with NN_{WW}
Combining the results

For the searches and to set limits, Tevatron experiments use generalized CL$_s$ method (modified frequentist, DØ) and Bayesian methods (CDF), and cross-check each other.

Systematics, including correlations, are taken into account:

Main systematics (depending on channel):
- luminosity and normalisation
- QCD background estimates
- input background cross-sections
- jet energy scale and b-tagging
- lepton identification
- K-factors on W/Z+ Heavy Flavor

Limit setting approaches agree to within ~10%
## Systematics: ZH-llbb / CDF vs DØ

### CDF: Double Tag (DT) $ZH \rightarrow \ell\ell bb$ Analysis

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Fakes</th>
<th>Top</th>
<th>WZ</th>
<th>ZZ</th>
<th>$Z + bb$</th>
<th>$Z + c\bar{c}$</th>
<th>Z+mistag</th>
<th>ZH</th>
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<td>Jet Energy Scale (shape dep.)</td>
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<td>$\sigma(p\bar{p} \rightarrow Z + HF)$</td>
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### DØ: Double Tag (DT) $ZH \rightarrow \ell\ell bb$ Analysis

<table>
<thead>
<tr>
<th>Contribution</th>
<th>WZ/ZZ</th>
<th>Zbb/Zcc</th>
<th>Zjj</th>
<th>tt</th>
<th>QCD</th>
<th>ZH</th>
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<td>1.5</td>
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<td>7</td>
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<td>18</td>
<td>0</td>
<td>6</td>
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<td>Heavy-Flavor K-factor</td>
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<td>0</td>
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</table>
Limit Setting

LEP: low background, small systematics
Tevatron: high background, large systematics (at low mass)

But SMALL signals in both cases
> Background only (b) and signal plus background (s+b) hypotheses are compared to data using Poisson likelihoods.

Systematic uncertainties are included in the likelihood, via gaussian smearing of the expectation (‘profile likelihood’).

New compared to LEP:
Background is constrained by maximising profile likelihood (‘sideband fitting’), usefull in particular at low mass.
Constraining Systematics Uncertainties with Data

“Profiling” AKA side band fitting

Nuisance parameters introduced in the $\chi^2$ of the fit allow shifting of central value of the background estimation

Systematic uncertainty width gets also constrained

Shape of the systematic is also taken into account
More on $CL_S$

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:

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

$LLR = -2 \times \log Q$

$d_{ij}$ refers to “data” for model being tested:

- 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
**CLs**

- Model repeated outcomes of the experiment via Poisson distribution
  - Simulate Signal+Bkgd and Bkgd-Only outcomes based on predictions
  - Uncertainties on nuisance parameters folded in via Gaussian smearing
  - Define frequentist confidence levels based on these simulated outcomes

Black line: Observed LLR value

Determined by data measurment

Green: Bkgd-only hypothesis

CL<sub>b</sub> is region to right of LLR<sub>obs</sub>

Equals ~50% for good bkgd/data agreement

Red: Signal+Bkgd hypothesis

CL<sub>s+b</sub> is region to right of LLR<sub>obs</sub>

“Data excess” scenario
CLs

- Model repeated outcomes of the experiment via Poisson distribution
  - Simulate Signal+Bkgd and Bkgd-Only outcomes based on predictions
  - Uncertainties on nuisance parameters folded in via Gaussian smearing
  - Define frequentist confidence levels based on these simulated outcomes

Black line: Observed LLR value
Determined by data measurement

Green: Bkgd-only hypothesis
CL$_b$ is region to right of LLR$_{obs}$
Equals $\sim$50% for good bkgd/data agreement

Red: Signal+Bkgd hypothesis
CL$_{s+b}$ is region to right of LLR$_{obs}$
CL$_b$ and CL$_{s+b}$ projections vs Mass

D0 combination, 0.4 fb$^{-1}$

arXiv:0712.0598
CL$_b$ and CL$_{s+b}$ projections vs Mass

CDF+DØ combination, 0.9-1.9 fb$^{-1}$

More details later
Profile Likelihood

× To counteract the degrading effects of systematic uncertainties, we actually integrate over the Profile Likelihood distributions

× Obtained by fitting MC expectations to “data” for each outcome

× Capitalizes on shape and statistics of data to constrain background fluctuations

× Must define the best fit of our MC model to data

× Assume: \[ B_i \rightarrow B_i \prod_k (1 + \sigma_i^k \rho_k) \]

Where \( \rho_k \) has a mean of 0 and width of 1

Minimize Poisson estimator by varying nuisance parameters \( \rho_k \)

\[
\chi^2 = 2 \sum_i \left( B_i - D_i \right) - D_i \ln \left( \frac{B_i}{D_i} \right) + \sum_k \rho_k^2
\]
Different approaches for $\text{CL}_S$ Profiling

Starting from the basics distributions (no systematics), how to proceed to optimize our sensitivity?

Simples approach: include systematics as a smearing effect on the background and signal $\Rightarrow$ large impact on the sensitivity since systematics are sometimes overestimated, full info of the data not used.

To reduce the impact of systematics two possibilities were investigated

A) Constrain the systematics by doing two fits on each data or pseudo-data sets: one assumes $S+B$ hypothesis, the other Background-only. (called Double-Fitting)

B) do only one fit assuming B-only, only on the bins with a small signal contamination ($\log(1+s/b) < 0.015$, i.e. less than $\sim 4\%$ of signal. (called Single-Fit/growing-window , $\Rightarrow$ window grows when scaling up the signal to check how much more signal we need to be sensitive to a SM Higgs).

Method B is slightly more performant than A, still maintaining appropriate coverage, so we use method B in the following
Frequentist Coverage of $\mathrm{CL}_S$

As obtained on full D0 combination (Lepton-photon 07) $\mathrm{CL}_S$ with growing window.

- Adequate coverage. (Double-Fitting is a bit more conservative: coverage 1-2\% higher, limits obtained 5-10\% less sensitive)
Effects of Profiling ($CL_s$)

Toy example: Data is set to expected background, signal scaled up to 95% exclusion, differently for these 3 cases:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>95% CL Limit</th>
<th>Coverage Probability</th>
<th>$CL_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Systematics</td>
<td>a</td>
<td>0.978</td>
<td>0.981</td>
</tr>
<tr>
<td>Standard Systematics</td>
<td>b</td>
<td>0.982</td>
<td>0.987</td>
</tr>
<tr>
<td>Double-Fitting</td>
<td></td>
<td>0.955</td>
<td>0.976</td>
</tr>
<tr>
<td>Single-Fit, Fixed Window</td>
<td>c</td>
<td>0.925</td>
<td>Bad!</td>
</tr>
<tr>
<td>Single-Fit, Growing Window</td>
<td></td>
<td>0.948</td>
<td>0.976</td>
</tr>
</tbody>
</table>
Effects of Systematics Profiling

Effective width of average systematic uncertainty of the background before and after

Effective width of average systematic uncertainty of the signal before and after

The per-bin fluctuations in the background model before fitting (black), after the S+B fitting (red), and after the B-Only fit (green). The values in the histogram represent the ratio to the nominal background prediction per bin.
Best fit for Jet energy scale, for K-Factor

Chi$^2$ for K-factor of W+jets, centered at 0 we got it right!

RMS$<<1 \Rightarrow$ systematic overestimated

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Check on Constraints on Cross Sections: WW vs ttbar

WW cross section is barely constrained. Shallow minimum. Rate too small to impact the fit.

Top-antiTop cross section can be constrained. Minimum found at ~+1 sigma(15%)

Understandable since we use cross-section computed for $m_{\text{top}} = 175$ GeV, i.e a bit too low.
Best fit for nuisance parameters

No smoking gun after all the checks, proceed to derive combined limit...

...and let’s also keep in mind that we will be able to test the “evidence potential” of the method with WZ/ZZ where $Z \rightarrow bb$, i.e. identical final state as WH and ZH
## Combining the Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lumi /Technique</th>
<th>Final state</th>
<th>#chan.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{WH} \rightarrow l \nu \ bb$</td>
<td>1.7 fb$^{-1}$ / NN</td>
<td>$e/\mu$, 1b/2b</td>
<td>2*(2+2)</td>
</tr>
<tr>
<td>$\text{ZH} \rightarrow ll \ bb$</td>
<td>1.1 fb$^{-1}$ / NN</td>
<td>$e/\mu$, 1b/2b</td>
<td>2+2</td>
</tr>
<tr>
<td>$\text{ZH} \rightarrow \nu \nu \ bb$</td>
<td>0.9 fb$^{-1}$ / NN</td>
<td>$Z \rightarrow \nu \nu$, $W \rightarrow l \nu$ (2b)</td>
<td>2</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>1.7 fb$^{-1}$ / NN</td>
<td>$ee$, $e\mu$, $\mu\mu$</td>
<td>2*3</td>
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<tr>
<td>$\text{WH} \rightarrow WWW^*$</td>
<td>1 fb$^{-1}$ / 2D LHood</td>
<td>$ee$, $e\mu$, $\mu\mu$</td>
<td>3</td>
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</tbody>
</table>

Total of 23 DØ channels combined (tau-channels not included yet)
Final variables used for the Combination
DØ Channels

DO Preliminary, $L=1.7$ fb$^{-1}$

$WH \rightarrow l \nu b\bar{b}$

Limit / $\alpha (p \rightarrow WH \rightarrow b\bar{b})$

$DO Preliminary, L=1.1$ fb$^{-1}$

$ZH \rightarrow l^+l^- b\bar{b}$

Limit / $\alpha (p \rightarrow ZH \rightarrow b\bar{b})$

$Z\rightarrow \nu \nu b\bar{b}$ NN, VH Signal

$DØ Run IIa Preliminary (0.93$ fb$^{-1})$

Limit / $\alpha (p \rightarrow VH)$

$WH \rightarrow WWW$

Standard Model = 1.0

$H \rightarrow WW \rightarrow e^+e^-, e^+\mu^-\mu^+$

$DØ Preliminary, Run IIa + IIb, L=1.7$ fb$^{-1}$

Limit / $\alpha (p \rightarrow H \rightarrow WW)$
New DØ SM Higgs Limits

• For $m_H = 115$, expected (observed) 95% CL relative to $\sigma_{SM} = 5.7$ (6.4)
• For $m_H = 160$, expected (observed) 95% CL relative to $\sigma_{SM} = 2.8$ (2.6)

0.9-1.7 fb$^{-1}$ analyzed,

Equivalent

To 1.3 fb$^{-1}$
@ low mass,

To 1.7 fb$^{-1}$
@ high mass

New results added since Lepton-Photon 07
CDF+ DØ @ Lepton-Photon 2007

Tevatron Run II Preliminary

L=0.9-1.9 fb⁻¹

Excluded by LEP

D0 Expected
CDF Expected
Tevatron Expected
Tevatron Observed

95% C.L. limit \( \sigma(Higgs) / SM \)

110 120 130 140 150 160 170 180 190 200

\( m_H (\text{GeV/c}^2) \)

Observed limit at \( m_H = 160 \text{ GeV} \): 1.4 x SM

→ Downward fluctuation compared to the expected
With latest updates of DØ (ZH→nunubb with NN, H→WW, more statistics and NN), CDF and DØ expected limits are the same at high mass. (Situation essentially unchanged at low mass)
Combined CDF and DØ Upper Limits on Standard Model Higgs-Boson Production

Version 4.9 as of December 7, 2007

The TEVNPH Working Group*

for the CDF and DØ Collaborations

We combine results from CDF and DØ searches for a standard model Higgs boson ($H$) in $pp$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.96$ TeV. With 1.0-1.9 fb$^{-1}$ of data collected at CDF, and 0.9-1.7 fb$^{-1}$ at DØ, the 95% C.L. upper limits on Higgs production are a factor of 6.2 (1.4) higher than the SM cross section for a Higgs mass of $m_H = 115$ (160) GeV/c$^2$. Based on simulation, the expected upper limit should be 4.3 (1.9). These results extend significantly the individual limits of each experiment.
Several Approaches used

CDF uses a Bayesian approach

- Use Bayesian posterior probability
- Assume flat prior density for the number of Higgs events

- **Combined Binned Poisson Likelihood:**

  \[ L(R, s, b | \bar{n}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{bins}} \frac{n_{i,j}^{n_{i,j}} e^{-\mu_{i,j}}}{n_{i,j}!} \]

- **Combined Posterior Density Function:**

  \[ p(R | \bar{n}) = \int d\bar{s} \int d\bar{b} L(R, \bar{s}, \bar{b} | \bar{n}) \times s_{tot} / \int dR \int d\bar{s} \int d\bar{b} L(R, \bar{s}, \bar{b} | \bar{n}) \times s_{tot} \]

DØ uses the CLs Method

the CLs confidence interval is a normalization of CL_{S+B}

CL_{S+B} = signal + bkgd hypothesis, \quad CL_B = bkgd only hypothesis

CL_S = CL_{S+B} / CL_B: \quad CL_{S+B} & CL_B are defined using a “test statistic”

Test statistic used is the Log-Likelihood Ratio (LLR=-2 ln Q)

generated via Poisson statistics \( Q = e^{-(s+b)(s+b)^d/e^{-b}b^d} \) s,b,d=signal,bkgd,data

**Tevatron Higgs combination is done with both methods**

⇒ they give results compatible within ~10%.
Observed limit at $m_H = 160$ GeV: 1.4 x SM

⇒ SM Higgs could be excluded @ 160 GeV in 2008
Projection assumptions: High mass Higgs

- Since 2005, our high Higgs mass experimental sensitivity has improved by a factor of 1.7 (i.e. taking out gain due to luminosity)
  - NN discriminants
  - Lepton acceptance

- For 2010, we estimate an additional improvement in analysis sensitivity by a factor of 1.4
  - increased lepton efficiency (10% per lepton)
  - multivariate analyses (~30% in sensitivity)

- Potential improvements not included in estimate
  - add $\tau$ channels
  - ...
• Since 2005, our analysis sensitivity has improved by a factor of 1.7 beyond improvement expected from $\sqrt{\text{luminosity}}$
  - Acceptance/kin. phase space/Trigger efficiency
  - Asymmetric tagging for double b-tags
  - b-tagging improvements (NN b-tagging)
  - improved statistical techniques/event NN discriminant
  $\rightarrow$ for channel with largest effort applied (WH) factor was 2.1

• For 2010, we estimate that we will gain an additional factor of 2.0 beyond improvement expected from $\sqrt{\text{luminosity}}$
  - add single-b-tag channel to $ZH \rightarrow \nu \nu b b$
  - include forward electrons, and 3-jet sample in WH
  - b-tagging improvements
    • Layer 0 ($\sim$8% per tag efficiency increase)
    • add semileptonic b-tags ($\sim$5% per tag efficiency increase)
  - Di-jet mass resolution (18% to 15% in $\sigma(m)/m$)
  - increased lepton efficiency (10% per lepton)
  - improved/additional multivariate techniques ($\sim$20% in sensitivity)
By the time LHC produces Physics (end 2009) Precision EW measurements + Tevatron could allow SM Higgs only with mass between 118 and 145 GeV definitely only a light Higgs boson, which will take several years to be found at LHC (needs 5 fb^{-1}) \(\rightarrow\) LHC/Tevatron complementarity \(H \rightarrow \gamma\gamma\) vs \(H \rightarrow bb\)
With data accumulated by the end of 2010, we will be able to explore much of the SM Higgs mass region allowed by the constraints from precision measurements and LEP direct exclusion

- Expected 95% CL exclusion over whole allowed range, (except possibly around 130 GeV) - assuming the Higgs does not exist at these masses
- Three-sigma evidence for a Higgs possible over almost entire range, and probable for the low end and high end.
Conclusion

New Higgs analysis became available and keep coming in, large common effort in both collaborations

Combining our many SM Higgs channels is becoming mature, inside DØ and CDF and between the two collaborations. Different methods allow to optimize sensitivity and spot mistakes.

Further improvements in front of us:
   CDF – DØ unification of systematic uncertainties treatment.
   Finer $m_H$ binning for next iteration.

2008 should allow us to go beyond LEP w.r.t SM Higgs, in particular at 160 GeV

2008 will also teach us how well we perform at low mass, with the golden WZ/ZZ ($Z \rightarrow bb$) benchmark

2009-2010 will also be most exciting years.
SM Higgs boson production

- **gg fusion**
  - Dominates at hadron machines
  - Usefulness depends on the Higgs decay channel

- **WH, ZH associated production**
  - Important at hadron colliders since can trigger on 0/1/2 high-\(p_T\) leptons and MET

- **ttH and bbH associated production**
  - High-\(p_T\) lepton, top reconstruction, b-tag
  - Low rate at the Tevatron

- **Vector Boson Fusion**
  - Two high-\(p_T\) forward jets help to “tag” event
  - Important at LHC, being studied at DØ
**SM Higgs Production and Decays**

**Production**

- gg → H
- WH
- ZH

**Decays**

- Dominant Decays:
  - bb for $M_H < 135$ GeV
  - WW* for $M_H > 135$ GeV

**Production cross section ($m_H$ 115-180)**

- in the 0.8-0.2 pb range for gg → H
- in the 0.2-0.03 pb range for WH associated vector boson production

**Search strategy:**

- $M_H < 135$ GeV: associated production WH and ZH with H → bb decay
  - Backgrounds: top, Wbb, Zbb...
- $M_H > 135$ GeV: gg → H production with decay to WW* or WH → WWW*
  - Backgrounds: WW, DY, WZ, ZZ, tt, tW, ττ
In earlier studies, the Tevatron sensitivity in the mass region above LEP limit (114 GeV) was estimated to start at \( \sim 2 \text{ fb}^{-1} \) with 8 fb\(^{-1} \): exclusion would be 115-135 GeV & 145-180 GeV, Now, we are:

- optimizing analysis techniques, understanding detectors better
- measuring SM backgrounds (ttbar, Zbb, Wbb, WW, single top!)
- Placing first Combined Higgs limits and compare to the prospects