Standard Model Higgs Boson Search Combination at CDF

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On behalf of the
Collider Detector at Fermilab

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Outline

- **SM Higgs Boson Searches**
  - Motivation
  - Previous Higgs Exclusions
  - Low Mass Searches
  - High Mass Searches
- **SM Higgs Boson Combination at CDF**
  - Summary of Searches
  - Systematic Uncertainties
  - Statistical Inference
  - Expected and Observed Upper Limits

The Higgs Boson

- **Motivation**
  - The only elementary particle predicted by the Standard Model not yet observed or refuted
  - Predicted by the Higgs mechanism in 1964, which explains
    - the spontaneous symmetry breaking
    - the masses of the electroweak bosons, the masses of fermions
- **The Higgs boson characterized only by its mass**
  - LEP direct searches
    - exclude masses < 114.4 GeV/c^2 at 95% CL
  - Previous Tevatron direct searches
    - exclude masses in [158-173] GeV/c^2 at 95% CL
  - Indirect electroweak fits
    - exclude masses > 185 GeV/c^2 at 95% CL
- **Higgs production is a very rare process**

Divide, Conquer, Combine

- Divide in channels based on signature
- Optimize each channel individually
- Heavy use of multivariate techniques
  - Artificial Neural Networks
  - Boosted Decision Trees
  - Support Vector Machines
- Do not see an excess of signal, so set limits
  - Previous talks by Karolos Potamianos, Azzedine Kasmi, Antonio Limosani, Boris Tuchming
- Combine all channels and set combined CDF limits in the range [100-200] GeV/c^2
- We then combine with all D0 channels
  - Plenary talk by Eric James on Tevatron combination

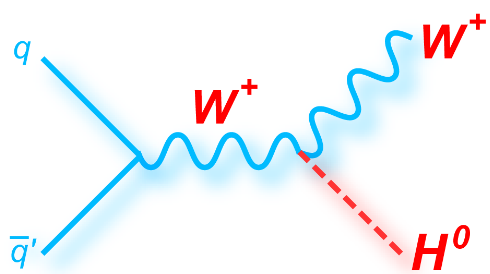
CDF Combination Channels

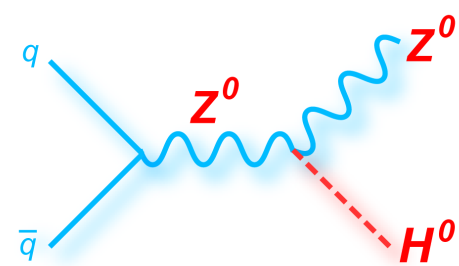
McGill

$WH \rightarrow l\nu b\bar{b}$ (2-jet, Neural Networks)	$L=7.5\ fb^{-1}$
$WH \rightarrow l\nu b\bar{b}$ (3-jet, Matrix Elements)	$L=5.6\ fb^{-1}$
$VH \rightarrow MET+b\bar{b}$	$L=7.8\ fb^{-1}$
$ZH \rightarrow ll\ b\bar{b}$	$L=7.5\ fb^{-1}$ (eebb) $L=7.9\ fb^{-1}$ ($\mu\mu bb$)
VH, VBF, ggH $\rightarrow$ 2jet+$H \rightarrow \tau\tau$	$L=6.0\ fb^{-1}$
VH,VBF $\rightarrow$ 2jet+$H \rightarrow bb$	$L=4.0\ fb^{-1}$
$H \rightarrow \gamma\gamma$	$L=7.0\ fb^{-1}$
$gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$	$L=8.2\ fb^{-1}$ ($W \rightarrow e,\mu+\nu$) $L=8.2\ fb^{-1}$ (taus)
ttH(l+MET+jets)	$L=7.5\ fb^{-1}$
ttH(No lepton)	$L=5.7\ fb^{-1}$
$H \rightarrow ZZ \rightarrow llll$	$L=8.2\ fb^{-1}$
$VH \rightarrow 2\tau$+lepton	$L=6.2\ fb^{-1}$

Low Mass Searches

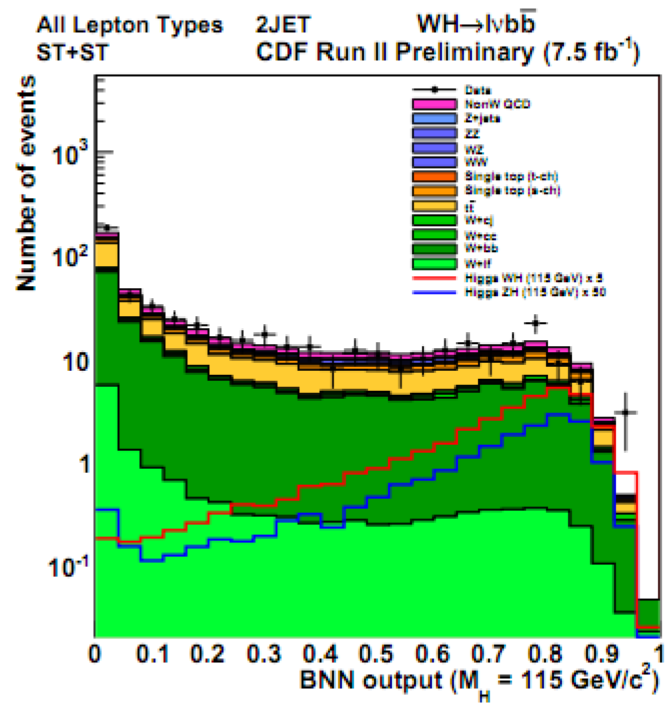
- Masses smaller than 135 GeV/c^2
- Higgs decays mostly to bottom quark pairs
- Single Higgs production (gluon fusion)
  - Largest cross section
  - Not feasible for bottom quark decay:10^9 more QCD background
  - Still, use it for Higgs decays to photon or tau lepton pairs
- Associated production (WH, ZH, ttH)
  - Take advantage of the leptonic decays of the W or Z bosons
  - Charged-lepton and missing-transverse-energy based triggers
  - Identify jets that originate from bottom quarks





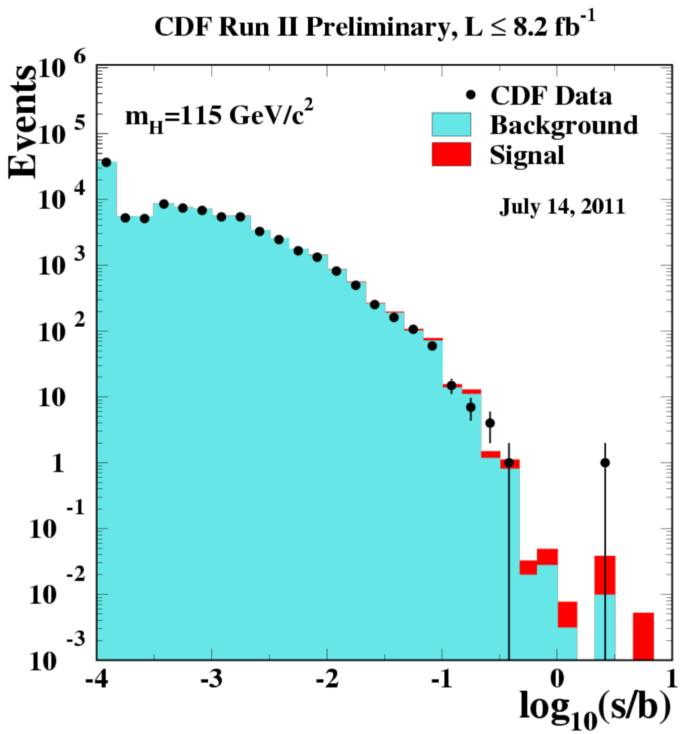
Example of Discriminant

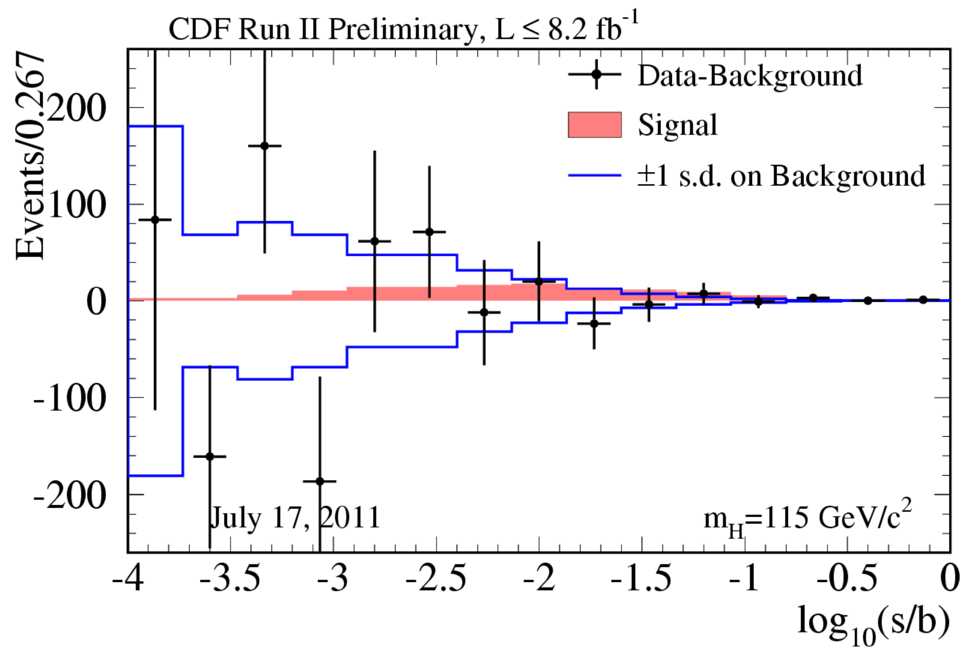
- WH → lνbb search 2jet b-tagging category with best s/b ratio; all charged leptons combined
- Artificial neural network as final discriminant trained for a Higgs boson mass of 115 GeV/c^2



S/B Ratio Plots for 115 GeV/c^2 McGill

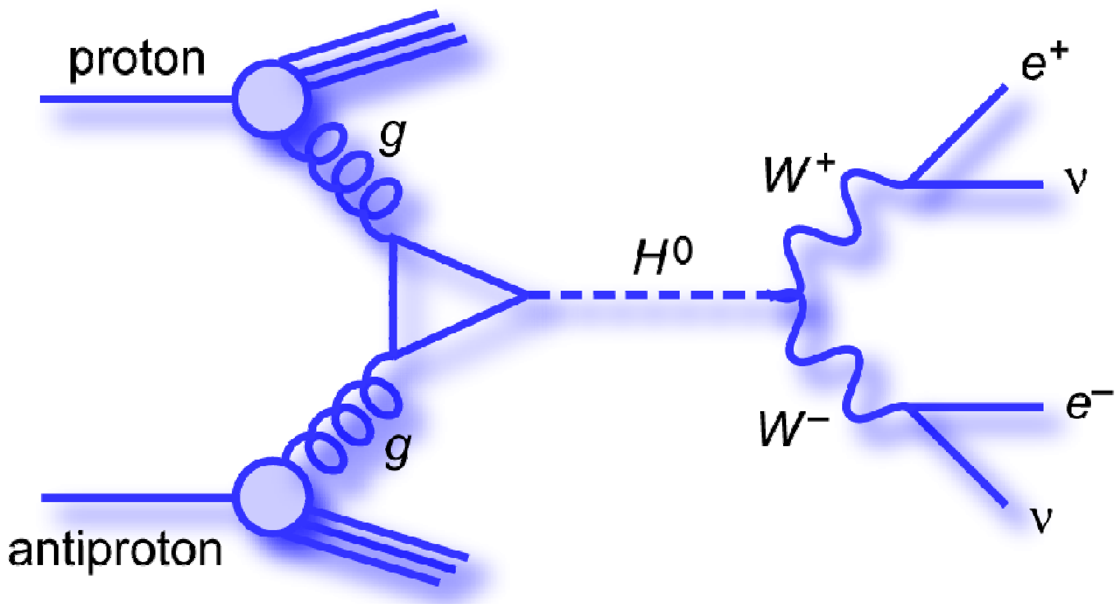
- Sum final discriminants after rebin in log(s/b)
  - Sum all independent channels
- Then subtract backgrounds from data
- No excess above backgrounds, so we set limits





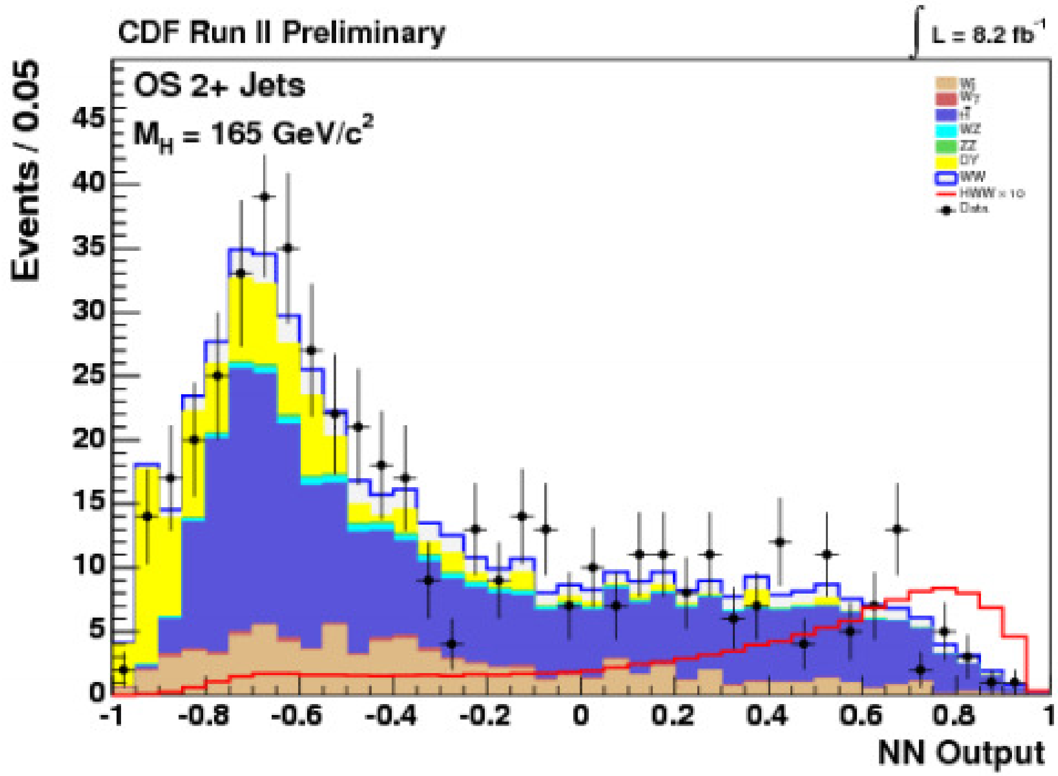
High Mass Searches

- ❑ Masses larger than 135 GeV/c^2
- ❑ Higgs decays mostly to W and Z boson pairs
- ❑ Single Higgs production (gluon fusion)
  - Most sensitive channel to the SM Higgs
  - 2 charged leptons; 0, 1 or 2 and more jets



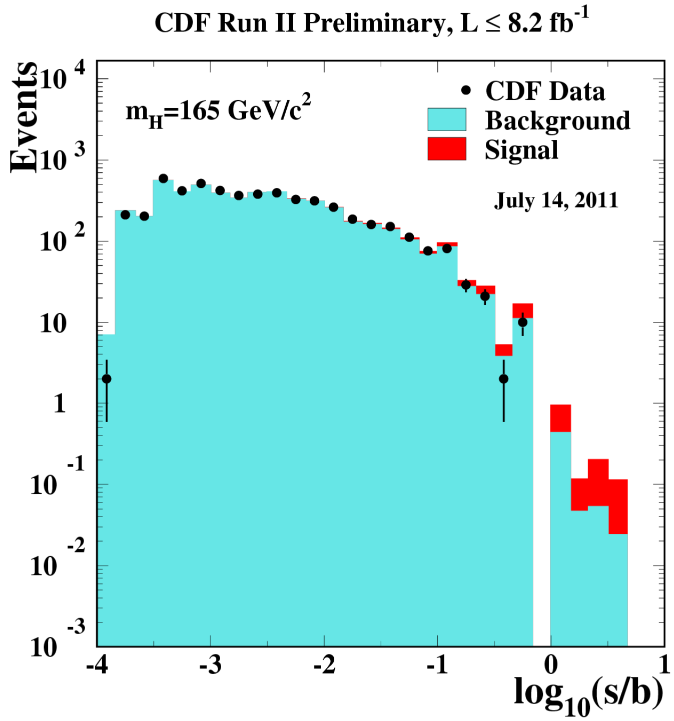
Example of Discriminant

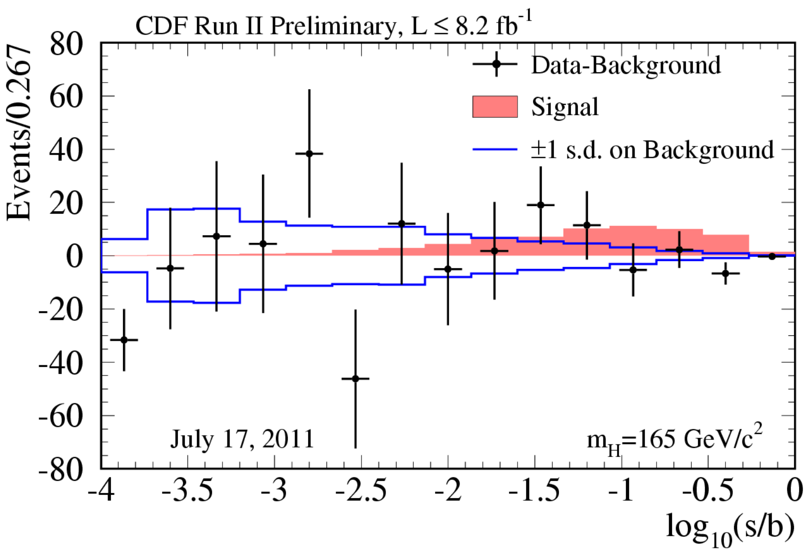
- H→ WW : 2 oppositely-charged leptons, at least 2 jets
- Artificial neural network as final discriminant trained for a Higgs boson mass of 165 GeV/c^2



S/B Ratio Plots for 165 GeV/c^2

- Sum final discriminants after rebin in log(s/b)
  - Sum all independent channels
- Then subtract backgrounds from data
- No excess above backgrounds, so we set limits



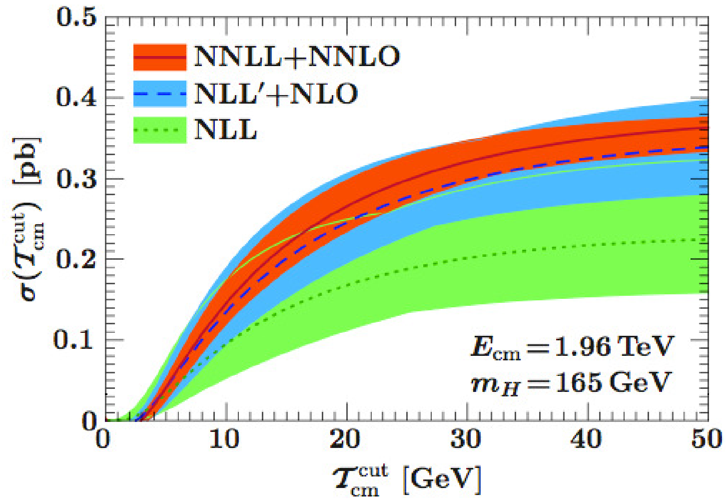


Limit Setting & Systematic Uncertainties

- **Bayesian** approach with **Poisson** statistics
- Rate and shape systematic uncertainties are introduced as **nuisance parameters**
- **Rate**: uncertainty on the total normalizations
- **Shape**: uncertainty on bin-by-bin normalizations
  - Use full discriminant shapes to extract the most information
- **Correlated** among various analyses
  - Charged lepton, trigger, b-tagging efficiencies
  - Luminosity, background & signal cross sections
- Uncorrelated among various analyses
  - Fake object identification (ex: jets faking electrons and MET)
  - Data-driven background modelling

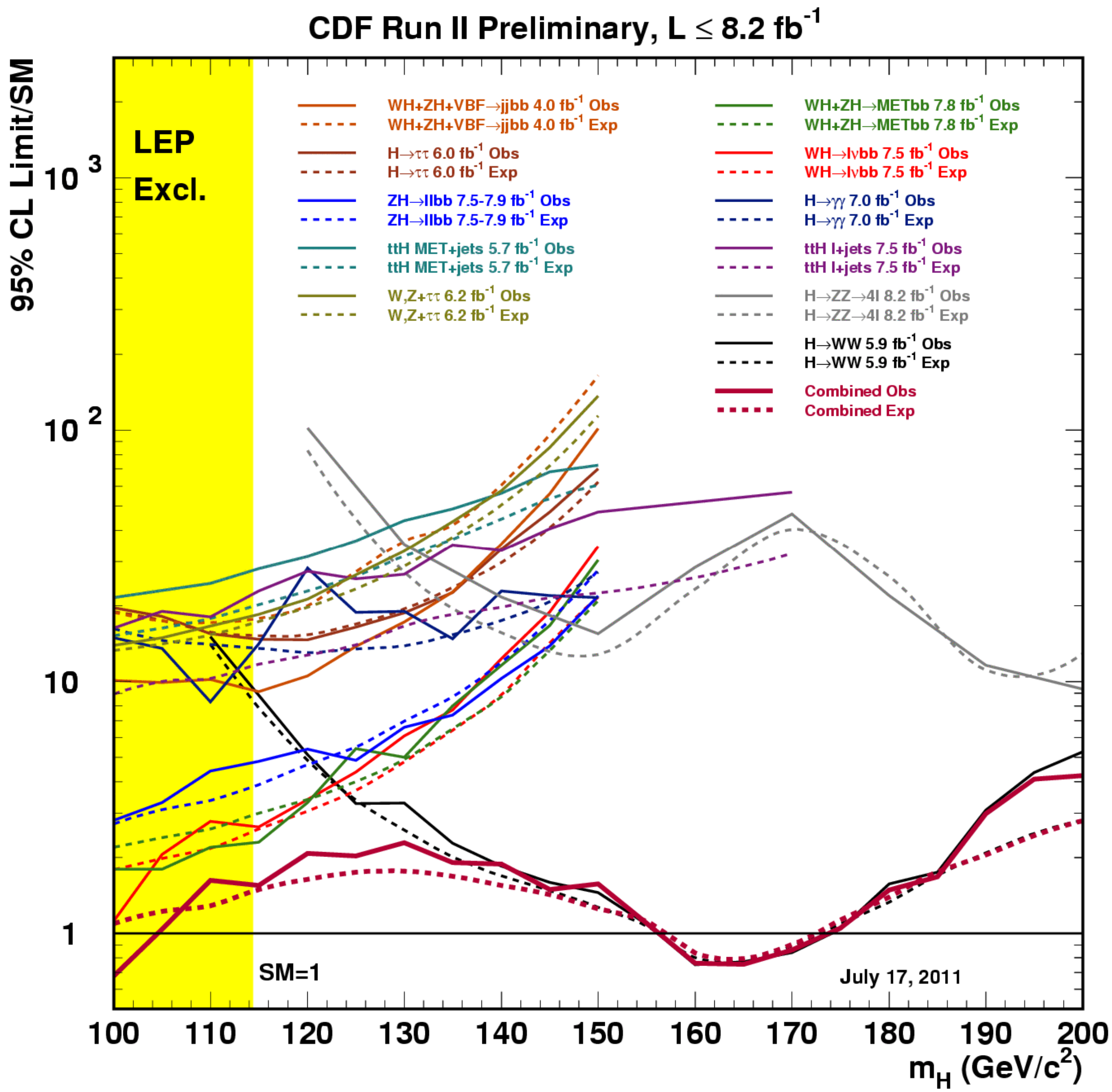
More on Uncertainties

- Most up-to-date cross sections, branching ratios, and their uncertainties
- Consider three independent scale variations for gluon fusion Higgs production
  - Beam, soft and hard
  - Berger, Marcantonini, Stewart,
  - Tackmann, Waaleweijn
  - http://arxiv.org/abs/arXiv:1012.4480
  - Stewart and Tackmann, arXiv:1107.2117
  - Current prescription - BNL accord



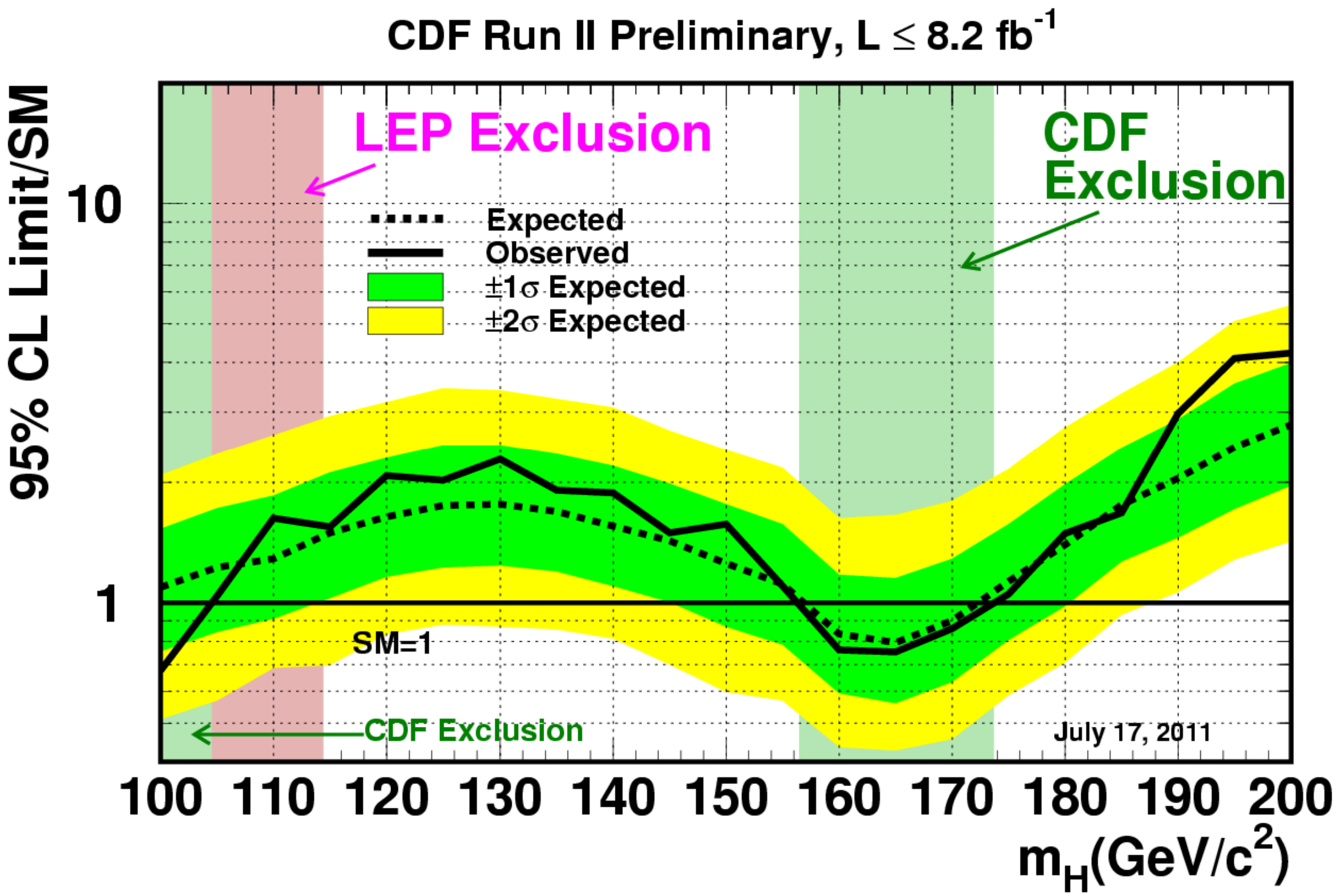
- Branching ratio uncertainties
  - From α_s, and masses of bottom and charm quarks
  - Baglio and Djouadi, JHEP 1103:055 (2011)

SM Higgs Boson Limits - 1



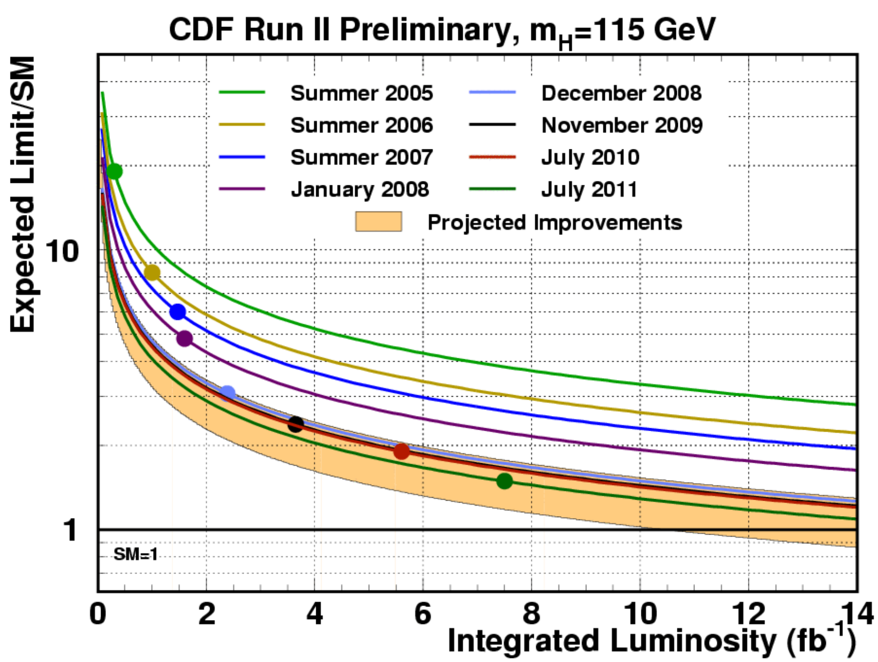
SM Higgs Boson Limits - 2

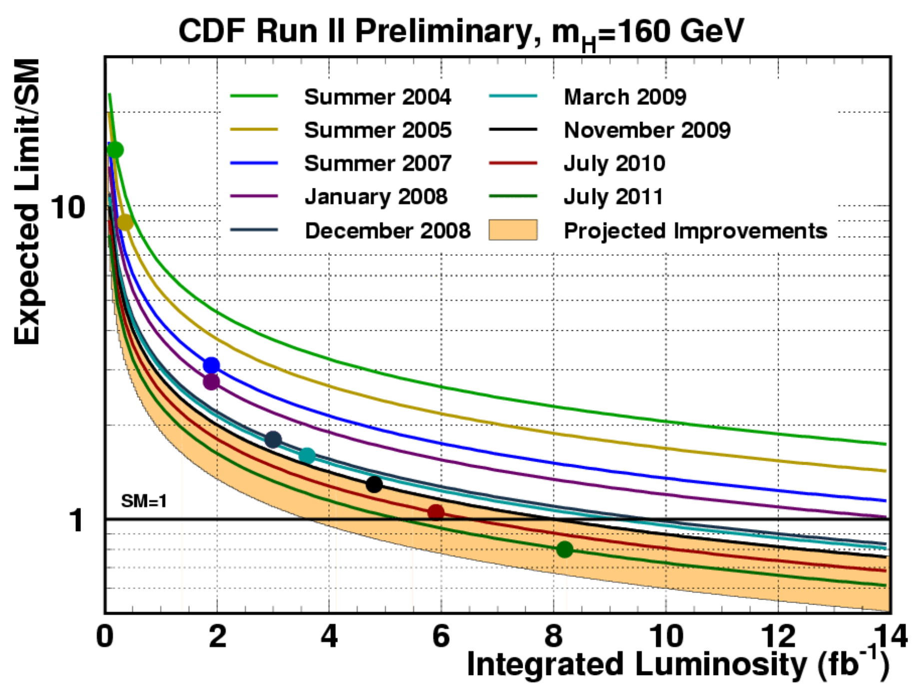
- Exclude at 95% CL: [100.0 -104.5] & [156.7-173.8] GeV/c^2
- Expect to exclude at 95% CL: [156.5-173.7] GeV/c^2



Trajectory of Sensitivity

- Sensitivity improved continuously more than just by increasing the integrated luminosity; showing 115 and 160 GeV/c^2





Conclusions

- CDF Collaboration, up to 8.2 fb^{-1}
- Search for the Standard Model Higgs Boson
- Very many channels
- None sees an excess of signal over backgrounds
- We combine all channels and use a Bayesian statistical approach to compute 95% CL upper limits on the cross section of the Higgs boson
- We expect to exclude at 95% CL Higgs masses in the range : [157.0-172.2] GeV/c^2
- We exclude at 95% CL Higgs masses in the ranges [100.0 -104.5] & [156.5-173.7] GeV/c^2
- Stay tuned for the Tevatron combination result!

Backup Slides

Statistical Approach

Bayesian Posterior Probability

$$p(R|\vec{n}) = \frac{\int\int d\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})}{\int\int\int dRd\vec{s}d\vec{b}L(R,\vec{s},\vec{b}|\vec{n})\pi(R,\vec{s},\vec{b})} \Rightarrow \int_0^{R_{0.95}} p(R|\vec{n})dR = 0.95$$

$R = (\sigma \times BR)/(\sigma_{SM} \times BR_{SM}),\ R_{0.95}$: 95% Credible Level Upper Limit

$\vec{s},\vec{b},\vec{n} = s_{ij}, b_{ij}, n_{ij}$ (# of signal, background and observed events in j-th bin for i-th channel)

π : Bayes' prior density

Combined Binned Poisson Likelihood

$$L(R,\vec{s},\vec{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

Principle of ignorance

- for the number of higgs events (instead of higgs Xsec)

$$\pi(R,\vec{s},\vec{b}) = \pi(R)\pi(\vec{s})\pi(\vec{b}) = s_{tot}\theta(Rs_{tot})\pi(\vec{s})\pi(\vec{b})$$

$s_{tot} = \Sigma_{i,j} s_{ij}$: Total number of signal prediction

$\pi(x) = G(x|\hat{x},\sigma_x) \quad (x = s, b)$ $\quad \hat{x}$: expected mean, σ_x: total uncertainty

Very Many Channels

cdf15 <> CDF VH->MET bb 1S 7.8 fb-1
cdf16 <> CDF VH->MET bb SS 7.8 fb-1
cdf17 <> CDF VH->MET bb SJ 7.8 fb-1
cdf28 <> CDF HWW 8.2fb HighSB0J
cdf29 <> CDF HWW 8.2fb LowSB0J
cdf30 <> CDF HWW 8.2fb HighSB1J
cdf31 <> CDF HWW 8.2fb LowSB1J
cdf32 <> CDF HWW 8.2fb 2JOS
cdf56 <> CDF WH WWW 8.2 fb-1 like-sign
cdf57 <> CDF H->WW 8.2 fb-1 low-mll
cdf64 <> CDF WH ME 5.6 fb-1 3J SVJP
cdf65 <> CDF WH ME 5.6 fb-1 3J SVJP loose
cdf66 <> CDF WH ME 5.6 fb-1 3J SVnoJP
cdf67 <> CDF WH ME 5.6 fb-1 3J SVnoJP loose
cdf68 <> CDF WH ME 5.6 fb-1 3J SVSV
cdf69 <> CDF WH ME 5.6 fb-1 3J SVSV loose
cdf84 <> CDF H->WW Trilepton NoZ 8.2 fb-1
cdf85 <> CDF H->WW Trilepton InZ 1jet 8.2 fb-1
cdf86 <> CDF H->WW etau 8.2 fb-1
cdf87 <> CDF H->WW mutau 8.2 fb-1
cdf88 <> CDF H->WW Trilepton InZ 2jet 8.2 fb-1
cdf101 <> CDF Htautau 2jets 6.0 fb-1
cdf102 <> CDF Htautau 1jet 6.0 fb-1
cdf103 <> CDF jjbb SS 4fb-1
cdf104 <> CDF jjbb SJ 4fb-1
cdf105 <> CDF jjbb VBF SS 4fb-1
cdf106 <> CDF jjbb VBF SJ 4fb-1
cdf112 <> CDF H->gammagamma 7.0 fb-1 CC
cdf113 <> CDF H->gammagamma 7.0 fb-1 CP
cdf114 <> CDF H->gammagamma 7.0 fb-1 CC Conv
cdf115 <> CDF H->gammagamma 7.0 fb-1 CP Conv
~~cdf116 <> CDF Vtautau lll 6.2 fb-1~~
cdf117 <> CDF Vtautau lltau 6.2 fb-1
cdf118 <> CDF Vtautau emutau 6.2 fb-1
~~cdf119 <> CDF Vtautau ltautau 6.2 fb-1~~
cdf120 <> CDF Vtautau llll 6.2 fb-1
cdf121 <> CDF ttH MET+jets 2btag 5.7 fb-1
cdf122 <> CDF ttH MET+jets 3btag 5.7 fb-1
cdf123 <> CDF ttH All 2btag 5.7 fb-1
cdf124 <> CDF ttH All 3btag 5.7 fb-1

cdf125 <> CDF mumubb ST 7.9 fb-1
cdf126 <> CDF mumubb LJP 7.9 fb-1
cdf127 <> CDF mumubb DT 7.9 fb-1
cdf128 <> CDF eebb ST 7.5 fb-1
cdf129 <> CDF eebb LJP 7.5 fb-1
cdf130 <> CDF eebb DT 7.5 fb-1
cdf131 <> CDF WHAM NN 7.5 fb-1 SVTSVT TIGHT with BNN
cdf132 <> CDF WHAM NN 7.5 fb-1 SVTJP05 TIGHT with BNN
cdf133 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05Roma TIGHT with BNN
cdf134 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05noRoma TIGHT with BNN
cdf135 <> CDF WHAM NN 7.5 fb-1 SVTSVT PHX with BNN
cdf136 <> CDF WHAM NN 7.5 fb-1 SVTJP05 PHX with BNN
cdf137 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05Roma PHX with BNN
cdf138 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05noRoma PHX with BNN
cdf139 <> CDF WHAM NN 7.5 fb-1 SVTSVT ISOTRK with BNN
cdf140 <> CDF WHAM NN 7.5 fb-1 SVTJP05 ISOTRK with BNN
cdf141 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05Roma ISOTRK with BNN
cdf142 <> CDF WHAM NN 7.5 fb-1 SVTnoJP05noRoma ISOTRK with BNN
cdf155 <> CDF WH NN 7.5 fb-1 2JET SVTSVT LOOSE ISOTRK
cdf156 <> CDF WH NN 7.5 fb-1 2JET SVTJP05 LOOSE ISOTRK
cdf157 <> CDF WH NN 7.5 fb-1 2JET SVTnoJP05Roma LOOSE ISOTRK
cdf158 <> CDF WH NN 7.5 fb-1 2JET SVTnoJP05noRoma LOOSE ISOTRK
cdf159 <> CDF HZZ mLLLL 8.2 fb-1
cdf160 <> CDF ttH l+5J STSTST 6.3 fb-1
cdf161 <> CDF ttH l+5J STSTJP 6.3 fb-1
cdf162 <> CDF ttH l+5J STST 6.3 fb-1
cdf163 <> CDF ttH l+5J STJPJP 6.3 fb-1
cdf164 <> CDF ttH l+5J STJP 6.3 fb-1
cdf165 <> CDF ttH l+5J STSTST 6.3 fb-1
cdf166 <> CDF ttH l+5J STSTJP 6.3 fb-1
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cdf168 <> CDF ttH l+5J STJPJP 6.3 fb-1
cdf169 <> CDF ttH l+5J STJP 6.3 fb-1

Results - numbers

CDF Run II Preliminary SM Higgs Combination, $L \leq 8.2$ fb^{-1}

m_H (GeV/c^2)	obs (Limit/SM)	-2σ exp (Limit/SM)	-1σ exp (Limit/SM)	Median exp (Limit/SM)	$+1\sigma$exp (Limit/SM)	$+2\sigma$exp (Limit/SM)
100	0.68	0.51	0.76	1.09	1.53	2.08
105	1.04	0.57	0.84	1.22	1.72	2.36
110	1.62	0.69	0.91	1.29	1.85	2.63
115	1.55	0.70	1.03	1.49	2.12	2.93
120	2.08	0.83	1.16	1.64	2.30	3.18
125	2.02	0.88	1.23	1.75	2.48	3.45
130	2.29	0.87	1.24	1.77	2.48	3.40
135	1.91	0.86	1.20	1.69	2.36	3.24
140	1.88	0.81	1.10	1.55	2.20	3.08
145	1.49	0.70	1.00	1.42	1.98	2.70
150	1.57	0.60	0.87	1.25	1.76	2.42
155	1.10	0.57	0.79	1.11	1.57	2.17
160	0.76	0.44	0.59	0.84	1.17	1.62
165	0.75	0.43	0.56	0.79	1.15	1.66
170	0.86	0.46	0.63	0.90	1.28	1.80
175	1.05	0.59	0.81	1.13	1.57	2.16
180	1.49	0.71	0.98	1.39	1.97	2.75
185	1.68	0.93	1.27	1.76	2.44	3.34
190	2.98	1.06	1.45	2.05	2.88	3.99
195	4.09	1.28	1.72	2.45	3.54	5.07
200	4.23	1.42	1.96	2.80	3.98	5.57

Scale Uncertainty Prescription

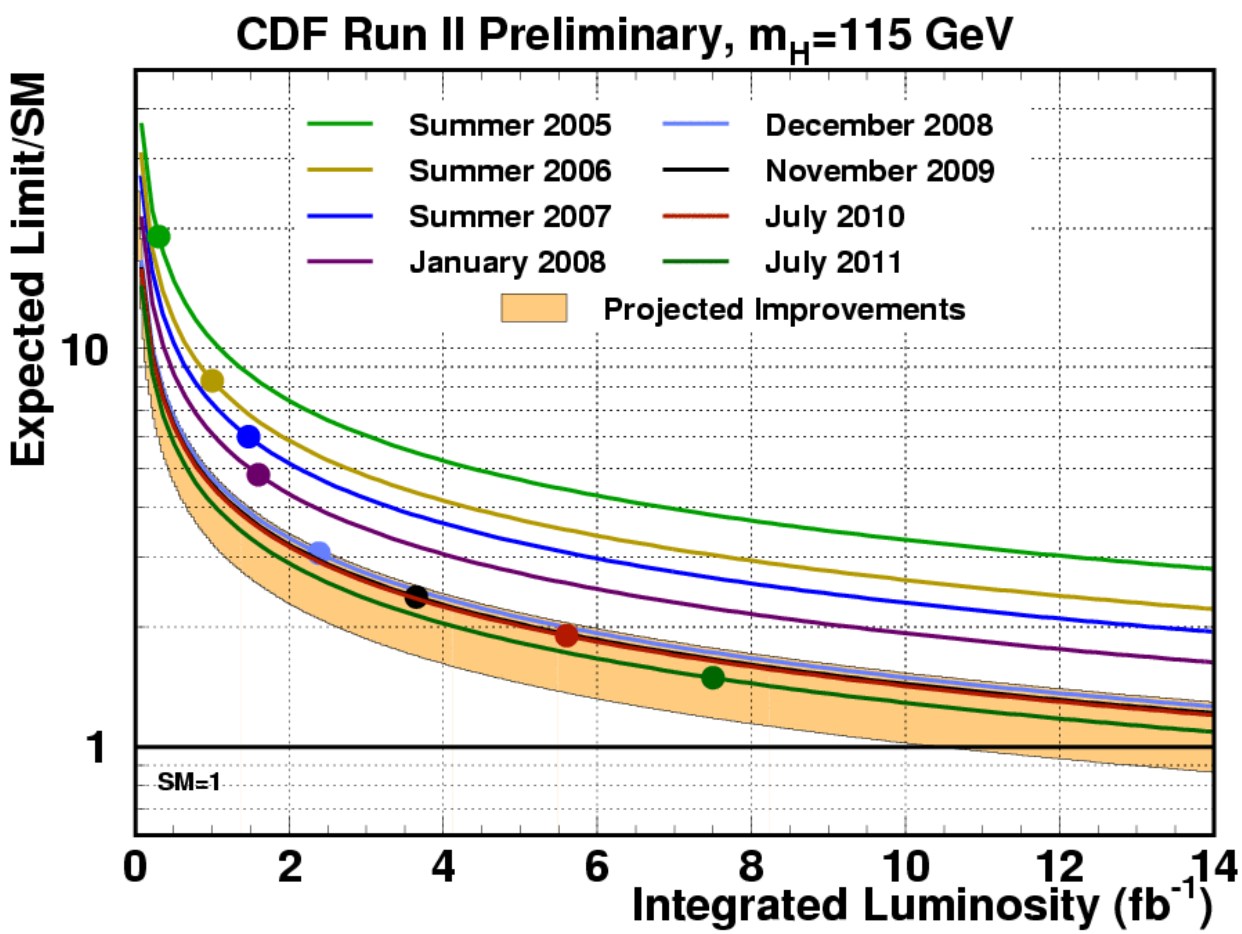
- **Theory gives cross section uncertainties**
  - Higgs + >= 0 jets: 7.05% (Grazzini, de Florian)
  - Higgs + >= 1 jets: 25.5% (MCFM)
  - Higgs + >= 2 jets: 33% (Campbell, Ellis, Williams)
- **We use: 0 jet, 1 jet, >=2 jets**

Jet bin	s0	s1	s2
0 jet	13.4%	-23.0%	0
1 jet	0	35%	-12.7%
>= 2 jets	0	0	33%

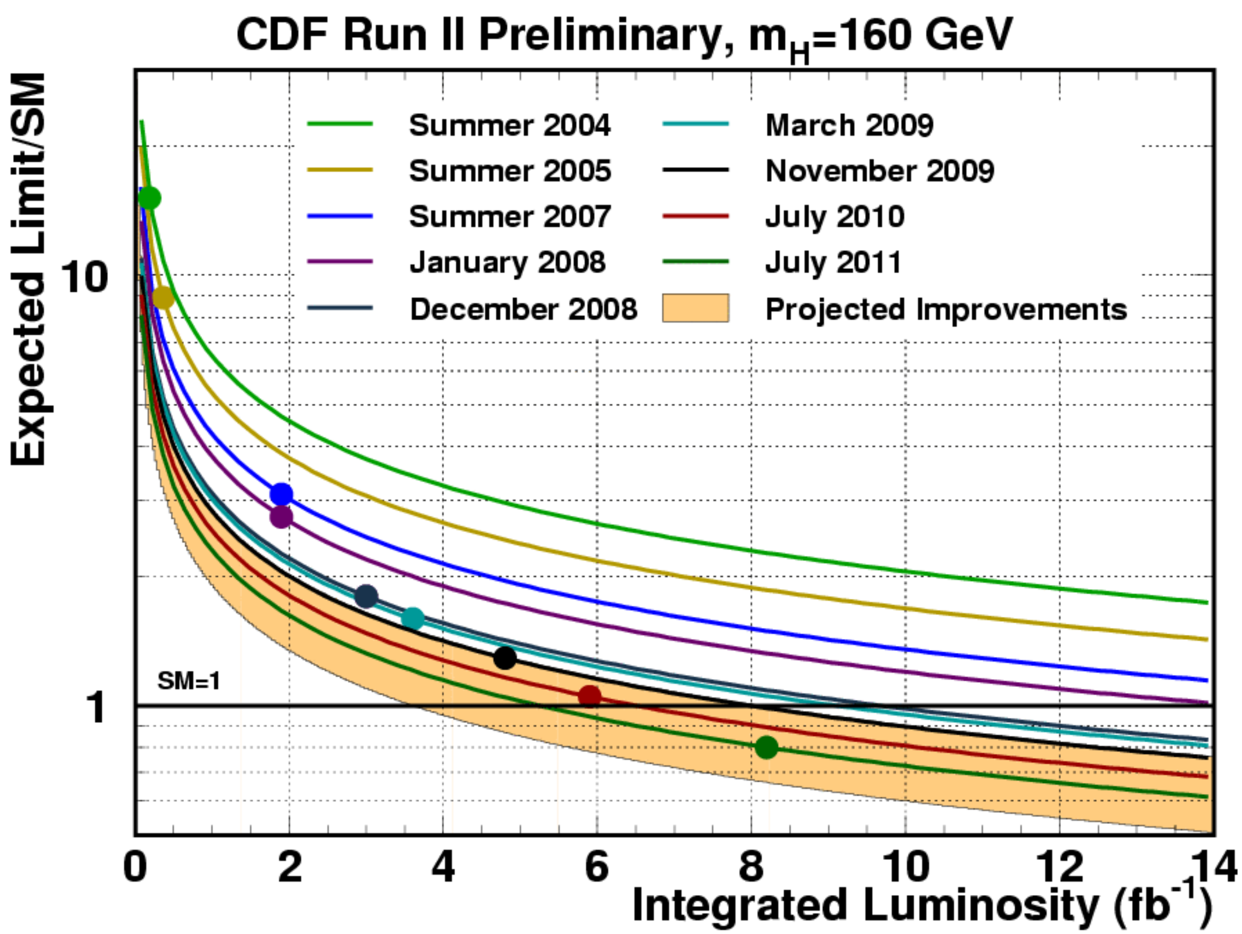
Cross Sect. & Branch. Ratios

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1821.8	291.90	169.8	97.2	8.000	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	248.40	145.9	89.7	7.062	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	212.00	125.7	82.7	6.233	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.50	103.9	76.4	5.502	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.10	90.2	70.7	4.857	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.50	78.5	65.3	4.279	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.00	68.5	60.4	3.769	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.20	60.0	55.9	3.320	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.60	52.7	51.8	2.925	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.70	46.3	48.1	2.593	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.40	40.8	44.6	2.298	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.20	35.9	41.2	2.037	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.50	31.4	38.2	1.806	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.60	28.4	36.0	1.607	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.50	25.3	33.4	1.430	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.00	22.5	31.0	1.272	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.10	20.0	28.8	1.132	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.90	17.9	26.9	1.004	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.00	16.1	25.0	0.890	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.40	14.4	23.3	0.789	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.10	13.0	21.6	0.700	0.238	0.0110	0.0287	74.1	25.6	0.00526

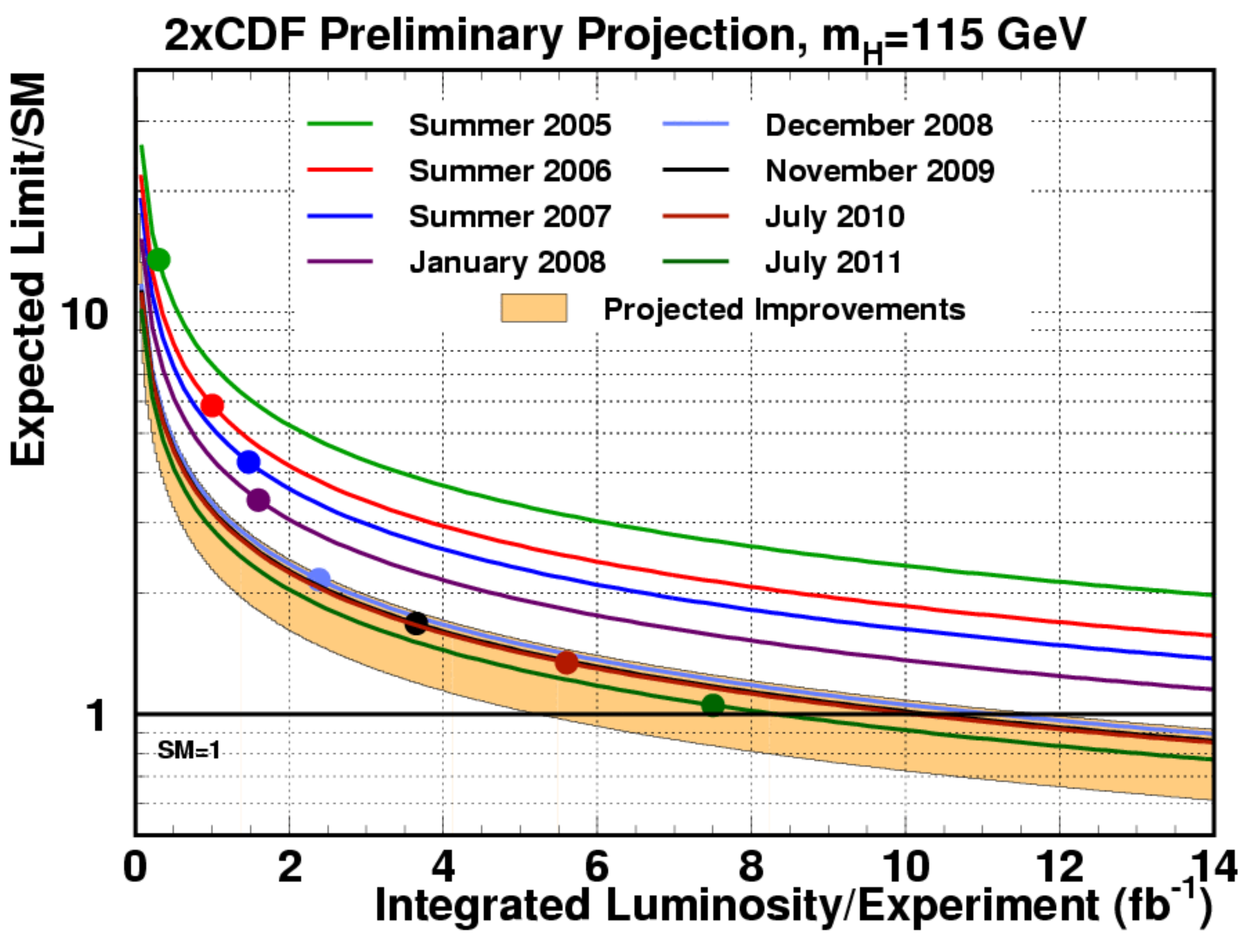
CDF Projection for 115 GeV/c^2



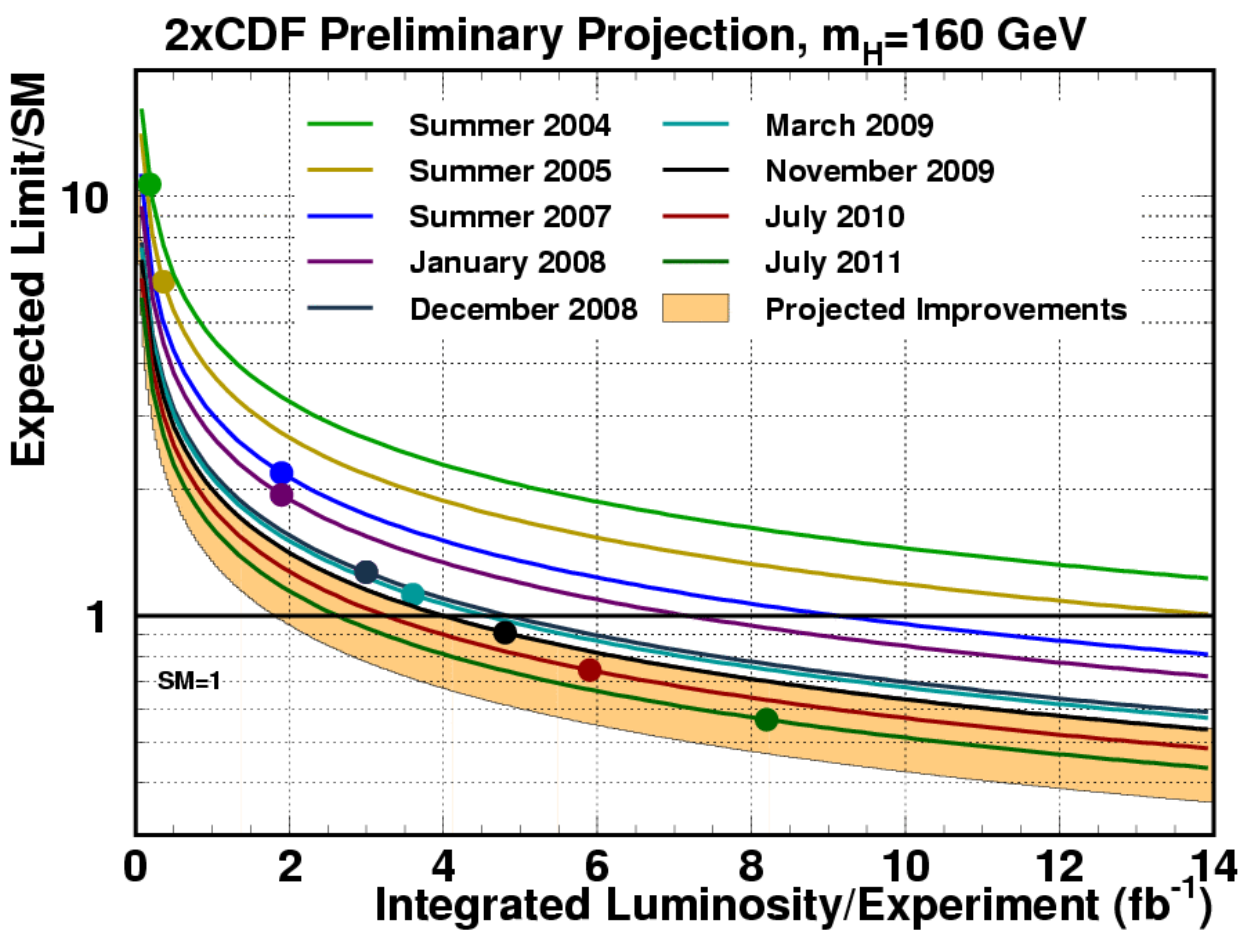
CDF Projection for 160 GeV/c^2



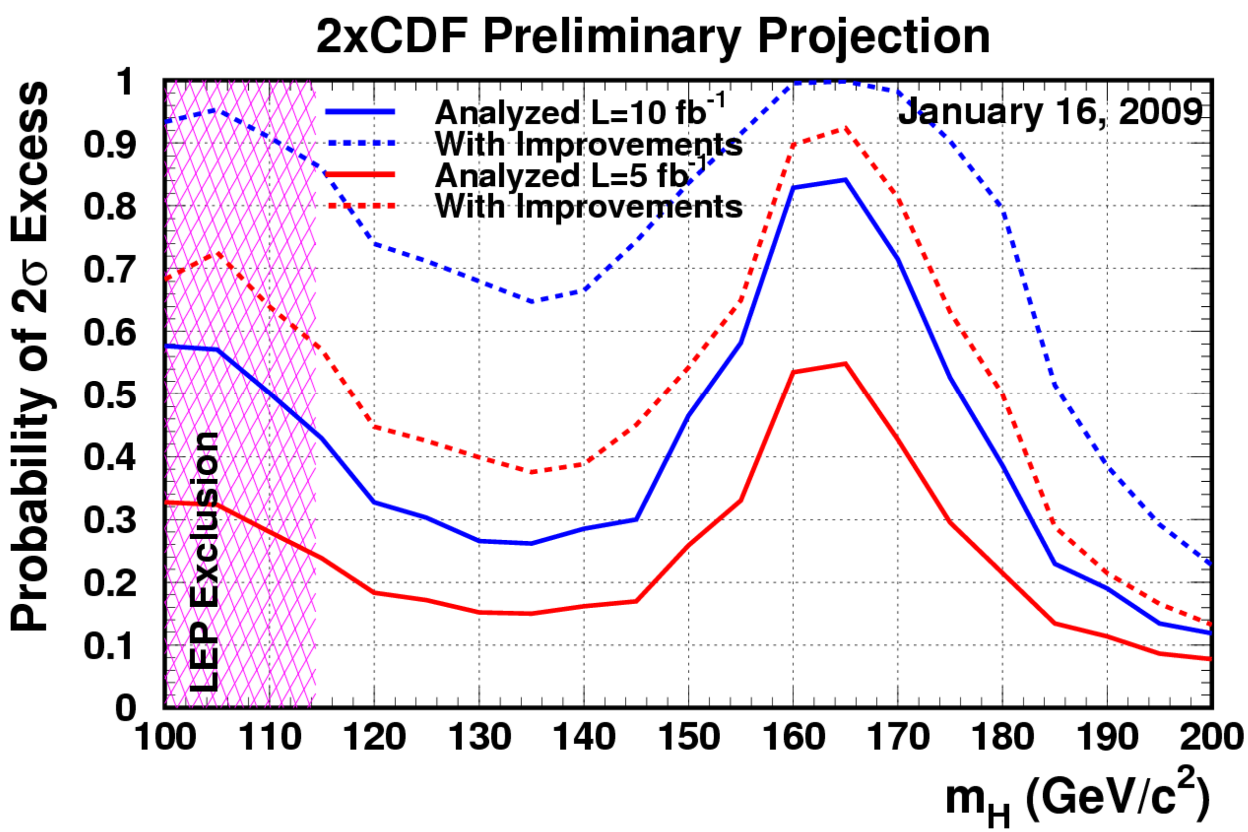
2xCDF Projection for 115 GeV/c^2



2xCDF Projection for 160 GeV/c^2



2 sigma Projection for 2xCDF



3 sigma Projection for 2xCDF