Combination of Standard Model Higgs searches at CDF

Karolos Potamianos

Purdue University

CDF Collaboration

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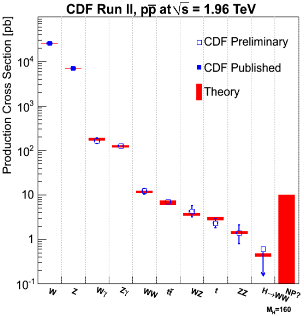
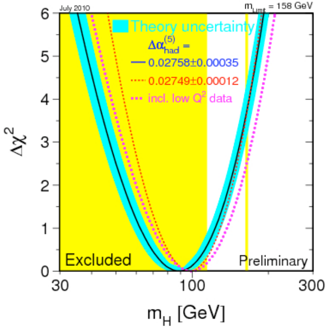
Outline

- Motivation for Higgs searches
- Quick Overview of SM Higgs Searches at CDF
- Combination Method
- Results using 2.3-5.9 fb^{-1} of CDF data
- Details were covered in talks by Y. Nagai, D. Lucchesi, K. Peters and P. Totaro.
- More details on every analysis and the combination at `http://www-cdf.fnal.gov/physics/new/hdg/Results.html`

Search for the SM Higgs: motivation

- The Higgs boson is THE missing piece of the SM.
  - Search for SM Higgs is a central part of the Tevatron Program.
  - Observations of single top and diboson production have brought us closer to the Higgs.
- EW fits and direct searches: $114 < m_H < 185\ \mathrm{GeV}/c^2$ at 95% C.L.
- SM Higgs is (if it exists) within Tevatron's reach !!!

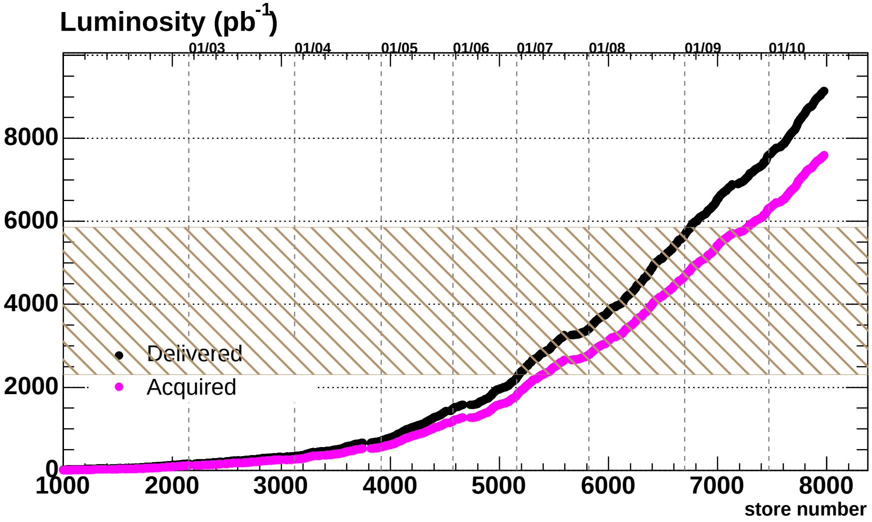




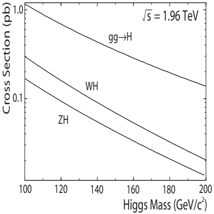
See: `http://lepewwg.web.cern.ch/LEPEWWG/`

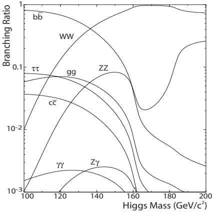
CDF Luminosity

- Tevatron doing great in providing collisions to experiments.
- Today's talk: 2.3-5.9 fb^{-1}



Higgs Searches at CDF

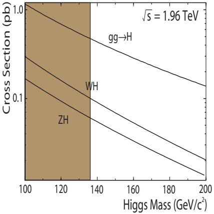


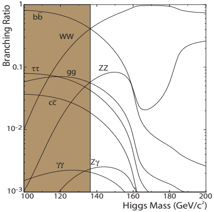


About the Higgs at the Tevatron:

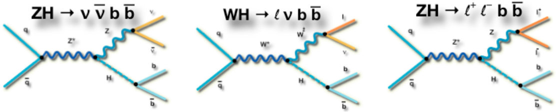
- **Direct production** dominates for all Higgs masses.
- **Associated production** $\sim$ 5 times smaller.
- Two decay modes dominate: low / high mass
  - $m_H < 135$ GeV$/c^2$: $H \rightarrow b\bar{b}$
  - $m_H > 135$ GeV$/c^2$: $H \rightarrow WW$
- No single channel with sufficient sensitivity. **Must divide and conquer.**
- Analyzing all decay channels for best sensitivity.
  - Numerous dedicated triggers for collecting as many Higgs events as possible.
  - Details discussed during other talks in this track.
- **Need** to **combine all** CDF Higgs searches (this talk) and also combine with DZero (see plenary talk of B. Kilminster).

Low Mass Searches – $m_H < 135\ \mathrm{GeV}/c^2$



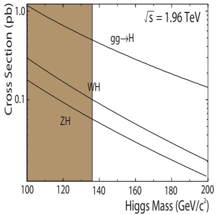


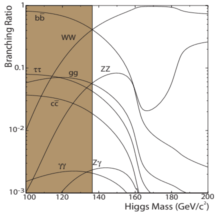
- $\sigma(H) \times B(H \to b\bar{b}) \approx 0.5$ pb
  - Final state overwhelmed by QCD multi-jet background.
  - Accessible for other rarer decay modes.
- $\sigma(VH) \times B(H \to b\bar{b}) \approx 0.1$ pb
  - Extra vector boson helps to reduce backgrounds.
- **Associated production**: main low mass channels
  - $VH \to \not{E}_T b\bar{b}$, $WH \to l\nu b\bar{b}$, $ZH \to llb\bar{b}$, $VH \to qqb\bar{b}$



- **Direct production**: using other decay modes
  - $H \to \tau\tau$, $H \to \gamma\gamma$, $H \to WW$

Low Mass Searches – $m_H < 135$ GeV$/c^2$



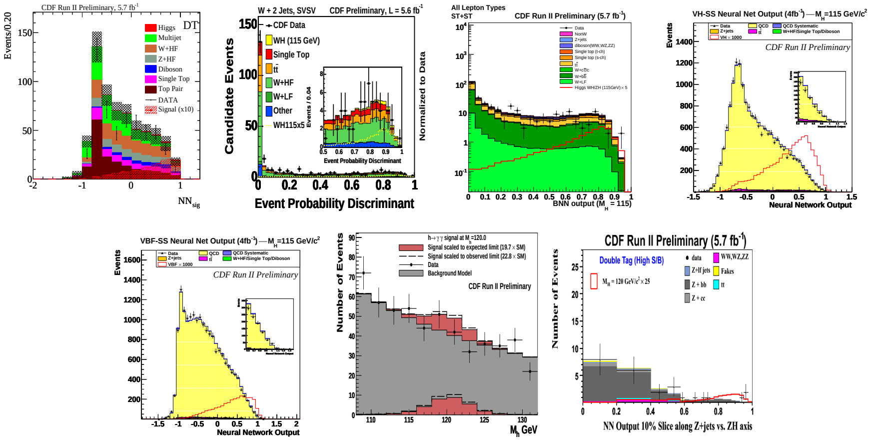


- **Associated production**: $W/ZH \rightarrow ll/l\nu/\nu\nu\ b\bar{b}$
  - $H \rightarrow b\bar{b}$ identified with 1 or 2 "b-tags".
  - W/Z typically identified from leptonic decay.

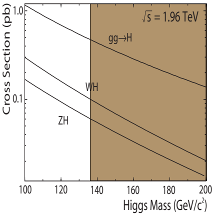
- **Direct production**: $H \rightarrow \tau\tau$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW$
  - Decay mode reduces background
  - H identified as pair of τ or γ (important for LHC)
  - $H \rightarrow WW$ from leptonic decays of the W bosons
- Many variables (di-jet invariant mass, angular, background-specific, etc.) and advanced analysis tools (NN,BDT, ME) deployed to separate signal from background and maximize sensitivity in each channel.

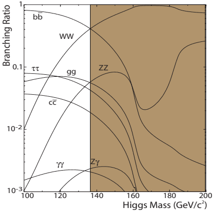
Low Mass – Final discriminants ($m_H = 115$ GeV$/c^2$)

Some of the distributions (many more actually used)

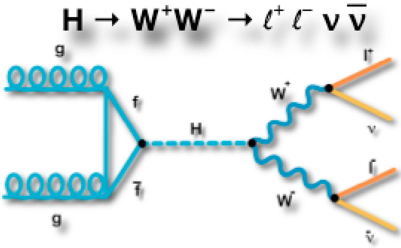


High Mass Searches – $m_H > 135$ GeV$/c^2$





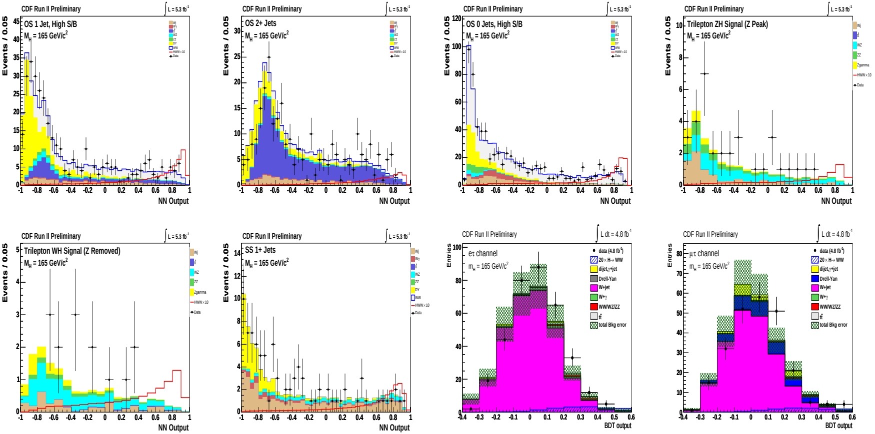
- $\sigma(H) \times B(H \to WW) \approx 0.2$ pb
  - Identification of two e,μ (and $\not{E}_T$) from W bosons.
  - Incorporate additional contributions from WH/ZH VBF production.



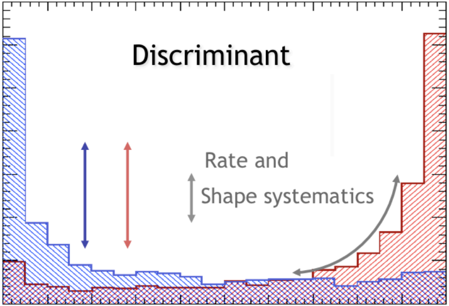
- Separate events by number of reconstructed jets to maximize sensitivity.
- Also analyze same-sign dilepton and tri-lepton data samples which contain potential signal contributions.

High Mass – Final discriminants ($m_H = 165$ GeV$/c^2$)

Some of the distributions (many more actually used)



Systematic Uncertainties



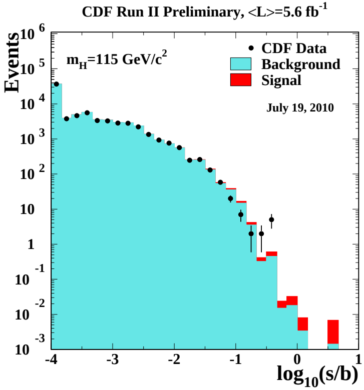
Systematic uncertainties can affect rate and template shape

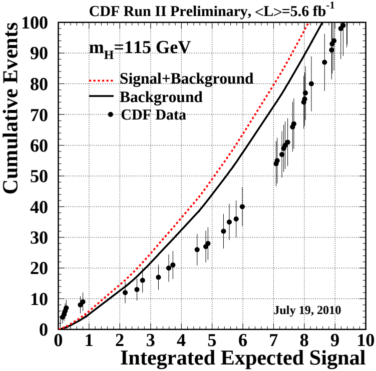
- Rate systematics only affect normalization.
- Shape systematics allow template variations bin by bin.

Sources of systematic uncertainties: jet energy scale, PDF model, luminosity, background/signal cross-sections, b-jet identification efficiency, initial/final state radiation, background modeling

Events Ranked by S/B – $m_H = 115$ GeV/c^2

- Re-binning all final discriminants in log(S/B)
- Second plot obtained by integrating over bin contents in first plot moving from right to left.
- Observe upward fluctuation in highest S/B bins in conjunction with downward fluctuation in next most sensitive S/B bins.



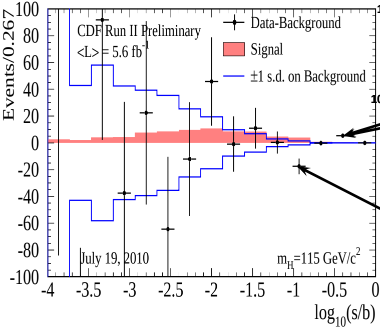


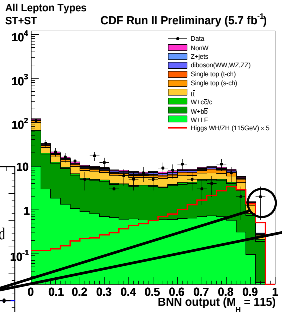
With Background Subtracted

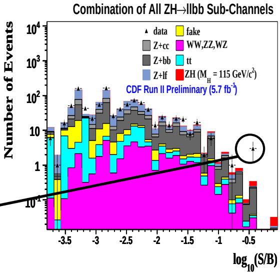
Some bins with deficit

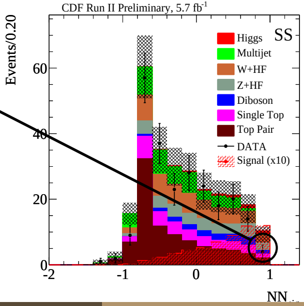
Some with excess.

Effect cancels out.



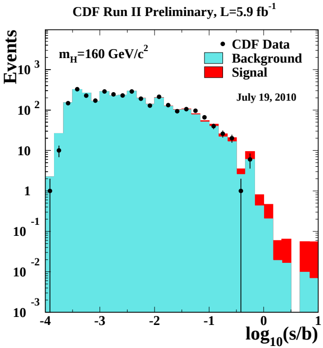


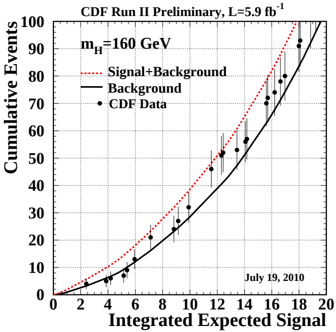


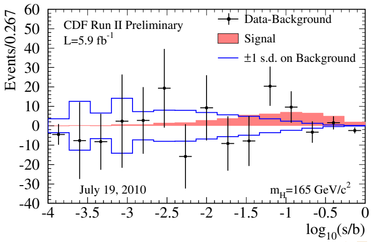


Final limits in good agreement with background-only expectation.

Events Ranked by S/B – $m_H = 160$ GeV$/c^2$







Combination

- Using Bayesian approach:
  - "How likely is the real x-section below the limit?"
- Cross-check analyzer's individual results before combining
- Using all 56 distributions (not just yields)

Channel	Lumi. (fb^{-1})	m_H (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TDT,LDT,ST,LDTX)	5.7	100-150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	5.6	100-150
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	5.7	100-150
$ZH \to \ell^+\ell^- b\bar{b}$ 4×(TDT,LDT,ST)	5.7	100-150
$H \to W^+W^-$ 2×(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	5.9	110-200
$WH \to WW^+W^-$ (same-sign leptons 1+ jets)+(tri-leptons)	5.9	110-200
$ZH \to ZW^+W^-$ (tri-leptons 1 jet)+(tri-leptons 2+ jets)	5.9	110-200
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	2.3	100-150
$WH + ZH \to jjb\bar{b}$ 2×(TDT,LDT)	4.0	100-150
$H \to \gamma\gamma$	5.4	100-150

Bayesian method: integrating over likelihoods

- Systematics as nuisance parameters (truncated Gaussian)

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)

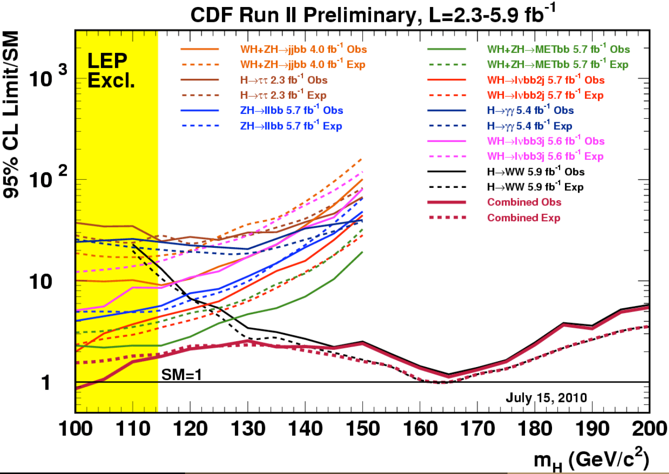
$$\pi(R,\vec{s},\vec{b}) = \pi(R)\pi(\vec{s})\pi(\vec{b}) = s_{tot}\theta(Rs_{tot})\pi(\vec{s})\pi(\vec{b})$$

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

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

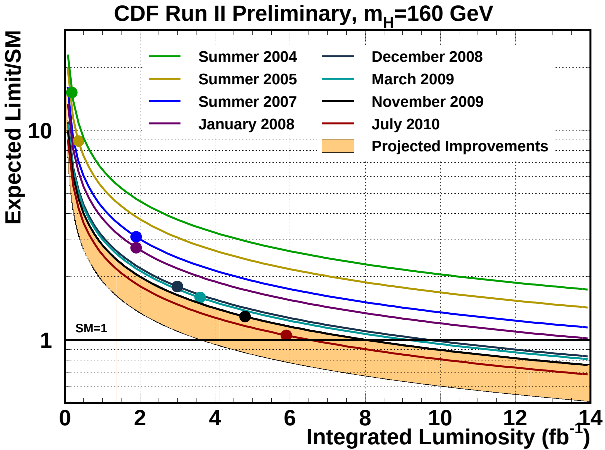
Expected and Observed Limits By Channel

- Expected (median) limit $< 2.3\times$ SM prediction below 185 GeV/c^2
- At SM sensitivity at 165 GeV/c^2
- Exp. (obs.) limits: 1.90 (1.79) @ 115 and 1.00 (1.13) @ 165 GeV/c^2

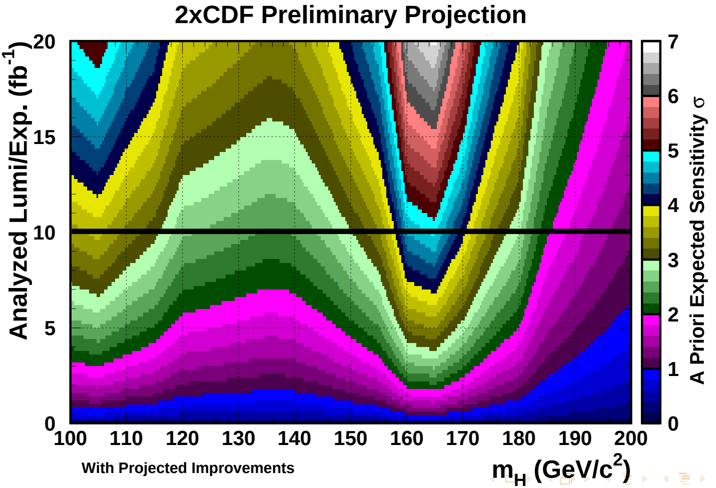


Projections

- Analysis improvements measured against two stages of projected 50% improvements relative to 2007 limits (top and bottom of shaded band).
- Current SM sensitivity is a direct consequence of past and current efforts to add analysis improvements.



- With 10 fb-1 of data for both experiments, Tevatron expects to have better than 2σ SM Higgs sensitivity for the entire mass range below 185 GeV$/c^2$.



Conclusions

- CDF has obtained single-experiment sensitivity for a SM Higgs with a mass of 165 GeV/c^2
- Exp. (obs.) limits: 1.90 (1.79) @ 115 and 1.00 (1.13) @ 165 GeV/c^2.
- We can combine these Higgs search results with those from DZero to obtain another $\sim \sqrt{2}$ improvement in sensitivity (see B. Kilminster's talk in plenary session).
- The sensitivity of the individual search results has continued to increase at a significantly greater rate that obtained simply by incorporating additional luminosity.
- Combining all available results gives much greater sensitivity than what is available from any individual search. We divide, conquer, and combine!
- Exciting times for Higgs searches at Tevatron and LHC will soon be joining in the fun!!!

Backup Slides

Cross-sections and Branching Fractions

m_H (GeV/c^2)	$\sigma_{gg \to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$B(H \to b\bar{b})$ (%)	$B(H \to \tau^+\tau^-)$ (%)	$B(H \to W^+W^-)$ (%)
100	1861	286.1	166.7	99.5	81.21	7.924	1.009
105	1618	244.6	144.0	93.3	79.57	7.838	2.216
110	1413	209.2	124.3	87.1	77.02	7.656	4.411
115	1240	178.8	107.4	79.07	73.22	7.340	7.974
120	1093	152.9	92.7	71.65	67.89	6.861	13.20
125	967	132.4	81.1	67.37	60.97	6.210	20.18
130	858	114.7	70.9	62.5	52.71	5.408	28.69
135	764	99.3	62.0	57.65	43.62	4.507	38.28
140	682	86.0	54.2	52.59	34.36	3.574	48.33
145	611	75.3	48.0	49.15	25.56	2.676	58.33
150	548	66.0	42.5	45.67	17.57	1.851	68.17
155	492	57.8	37.6	42.19	10.49	1.112	78.23
160	439	50.7	33.3	38.59	4.00	0.426	90.11
165	389	44.4	29.5	36.09	1.265	0.136	96.10
170	349	38.9	26.1	33.58	0.846	0.091	96.53
175	314	34.6	23.3	31.11	0.663	0.072	95.94
180	283	30.7	20.8	28.57	0.541	0.059	93.45
185	255	27.3	18.6	26.81	0.420	0.046	83.79
190	231	24.3	16.6	24.88	0.342	0.038	77.61
195	210	21.7	15.0	23	0.295	0.033	74.95
200	192	19.3	13.5	21.19	0.260	0.029	73.47

Expected and Observed Limits

m_H (GeV/c^2)	Observed limit/SM	-2σ expected	-1σ expected	median expected	$+1\sigma$ expected	$+2\sigma$ expected
100	0.86	0.83	1.11	1.55	2.18	3.02
105	1.07	0.90	1.18	1.63	2.28	3.17
110	1.59	0.96	1.30	1.81	2.53	3.50
115	1.79	1.00	1.37	1.90	2.61	3.52
120	2.13	1.10	1.59	2.26	3.12	4.22
125	2.28	1.23	1.66	2.28	3.11	4.18
130	2.56	1.25	1.68	2.33	3.23	4.44
135	2.23	1.22	1.65	2.28	3.15	4.30
140	2.24	1.08	1.47	2.04	2.84	3.90
145	2.16	1.01	1.31	1.84	2.65	3.80
150	2.40	0.84	1.14	1.60	2.24	3.10
155	1.79	0.74	1.01	1.43	2.05	2.90
160	1.37	0.55	0.75	1.05	1.49	2.08
165	1.13	0.54	0.72	1.00	1.41	1.96
170	1.32	0.63	0.84	1.20	1.72	2.45
175	1.59	0.76	0.98	1.36	1.92	2.69
180	2.34	0.91	1.21	1.70	2.42	3.41
185	3.66	1.16	1.56	2.18	3.07	4.27
190	3.37	1.49	1.93	2.66	3.75	5.25
195	4.92	1.77	2.30	3.17	4.46	6.24
200	5.47	1.87	2.53	3.56	5.04	7.06

Expected and Observed Limits