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# Combined Upper Limit on Standard Model Higgs Production at CDF

Y. Kusakabe, T. Masubuchi, J. Nielsen, A. Taffard, W. Yao

**Abstract**

This note describes a combination of several searches for Standard Model Higgs production at CDF using a data sample up to 695 $\mathrm{pb}^{-1}$ of integrated luminosity. The channels considered are $WH \to l\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, and $gg \to H \to W^+W^-$. We have calculated combined upper limits on the ratio of Higgs cross section times the branching ratio to its Standard Model prediction ($R_{95}$) for Higgs masses between 110 and 200 $\mathrm{GeV/c^2}$. The results are in a good agreement with the expectations obtained from pseudo-experiments. We have also recomputed upper limits for each individual channel using the same technique as a consistent check and are able to reproduce the blessed results over all the channels. The combined limit is still order of magnitude higher than the Standard Model prediction, but it will be greatly improved once the results are updated with 1 $\mathrm{fb}^{-1}$ data for summer 2006.

## 1 Changes from V1.0

We have made few changes since the previous version 1.0, which are summarized in following:

- Use more iterations for integration and finer steps in sampling.
- Fix to include the mass window cut efficiency in $ZH \to \nu\nu b\bar{b}$ channel, which was ignored previously.
- Some minor bug fixes in the code.

# 2 Introduction

CDF has made several searches for the Standard Model Higgs production using a data sample up to 695 pb$^{-1}$ of integrated luminosity [1] [2] [3] [4] [5]. The results are summarized in Figure 1, which show the ratio of the observed 95% CL upper limit on the production cross section times the branching ratio to the Standard Model prediction as function of Higgs masses. Since there is no single channel that is sensitive yet, it is necessary to combine the results of all the channels to maximize the search sensitivity. The most sensitive channels are $WH \to l\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$ in the low mass range [1] [2], and $g\bar{g} \to H \to W^+W^- \to l^+l^-\nu\bar{\nu}$ in the high mass range [3]. Recently, the $WH \to l\nu b\bar{b}$ result has been updated to 695 pb$^{-1}$. The remainingrest two are still based on a much smaller data sample of about 300 pb$^{-1}$. The purpose of the present note is to develop a strategy on how to combine the results properly based on what we currently have. More importantly in the future, it would help us to sort out and define the common systematic between different analyzes. We follow the same procedure that was used in the Run1 Higgs combination analysis [6], which is a Bayesian framework that would allow us to handle the systematic properly on the large number of background and efficiency parameters involved.

This note is organized as follows. In section 2, we will briefly describe the combination results including the method and systematic correlations. In section 3, we will discuss the expected limits. Finally, we will conclude in section 4.

# 3 Combination Results

The statistical method employed here is a Bayesian framework, that is the same technique used in the Run1 Higgs combination [6]. For a given Higgs Mass, the combined likelihood is a product of likelihood in the individual channels, each of which is a product over histogram bins of Poisson densities

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

where the prior densities for all the parameters in the likelihood are background normalization ($\vec{b}$), expected Standard Model signal ($\vec{s} = \sigma_{SM} \times B \times L \times \vec{\epsilon}$), luminosity (L), acceptance $\vec{\epsilon}$, and the ratio $R = \sigma \times B/(\sigma_{SM} \times B_{SM})$. The first product is over the number of channels ($N_C$), the second product is over histogram bins with observed data events ($n_{ij}$) in either dijet mass for $WH$ and $ZH$ or $\delta\phi$ of two leptons in $WW$. The parameters that contribute to the expected bin contents are $\mu_{ij} = R \times s_{ij} + b_{ij}$ for the channel i and the histogram bin j.

The Standard Model Higgs production cross sections at the Tevatron and the decay branching ratios are obtained from the Tev4LHC Higgs working group [7] and HDECAY [8], which are summarized in Table 1 as function of Higgs masses. The residual

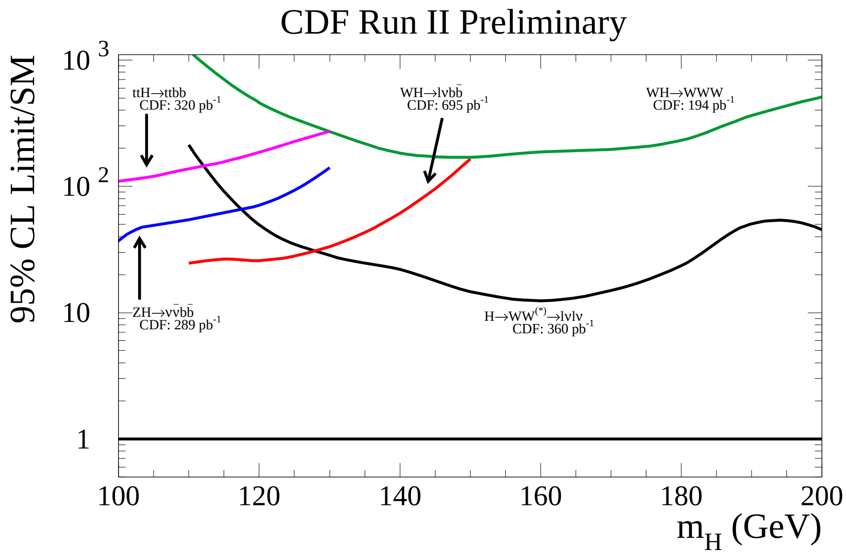


Figure 1: The summary of Higgs 95% CL upper limits on the ratio of the production cross section times the branching ratio to the Standard Model expectations as function of Higgs masses (Courtesy to Tom Junk).

| Mass (GeV/c$^2$) | $\sigma_{WH}$ (fb) | $\sigma_{ZH}$ (fb) | $\sigma_{WW}$ (fb) | $B(H \to bb)$ (%) | $B(H \to W^+W^-)$ (%) |
|---|---|---|---|---|---|
| 110 | 207.70 | 123.33 | 1281 | 77.02 | 4.41 |
| 120 | 152.89 | 92.70 | 1006 | 67.89 | 13.20 |
| 130 | 114.51 | 70.38 | 801 | 52.71 | 28.69 |
| 140 | 86.00 | 54.20 | 646 | 34.36 | 48.33 |
| 150 | 66.14 | 41.98 | 525 | 17.57 | 68.17 |
| 160 | 51.03 | 32.89 | 431 | 4.00 | 90.11 |
| 170 | 38.89 | 26.12 | 357 | 0.846 | 96.53 |
| 180 | 31.12 | 20.64 | 297 | 0.541 | 93.45 |
| 190 | 24.27 | 16.64 | 249 | 0.342 | 77.61 |
| 200 | 19.34 | 13.46 | 211 | 0.260 | 73.47 |

Table 1: The (N)NLO production cross sections and the decay branching ratios as function of Higgs masses.

theoretical uncertainties for $WH$ and $ZH$ production cross section are rather small, less than 5%. Also there is about 10% for gluon fusion $gg \to H$ process.

Systematic uncertainties in the various analyzes come from Monte Carlo model-

| Channels | $l\nu b\bar{b}$ Single | $l\nu b\bar{b}$ Double | $\nu\bar{\nu}b\bar{b}$ | $W^+W^-$ |
|---|---|---|---|---|
| Acceptance | | | | |
| Luminosity (%) | 6.0 | 6.0 | 6.0 | 6.0 |
| btag SF (%) | 5.3 | 16.0 | 6.3 | 0.0 |
| Lepton ID (%) | 2.0 | 2.0 | 2.0 | 3.0 |
| JES (%) | 3.0 | 3.0 | 8.0 | 1.0 |
| MC modeling (%) | 4.0 | 10.0 | 2.0 | 5.0 |
| Trigger (%) | 0.0 | 0.0 | 2.0 | 0.0 |
| Backgrounds | | | | |
| Heavy Flavor (%) | 33 | 34 | 0 | 0 |
| Mistag (%) | 22 | 15 | 16 | 0 |
| Top (%) | 13.5 | 20 | 18 | 0 |
| QCD (%) | 17 | 20 | -34 | 0 |
| Diboson (%) | 16 | 25 | 18 | 11 |
| Other (%) | 0 | 0 | 0 | -(12-18) |

Table 2: The breakdown of systematic uncertainties for each individual channel where the positive values mean correlated between the channels while the negative ones are uncorrelated with the rest of channels.

ing of the geometrical and kinematic acceptance, btag efficiency scale factor, lepton identification, the effect due to the jet energy scale, background uncertainties, and the uncertainty on the luminosity. We divide these systematics into several groups.

- Signal acceptance: luminosity, btag efficiency scale factor, lepton identification, the jet energy scale, MC modeling (ISR/FSR+PDF), and the rest of the uncertainties.

- Background normalization: heavy flavor fraction, mistags, top contributions, non-W, diboson and the rest of the backgrounds.

For each group, we assign each measurement to be 100% correlated or uncorrelated with other measurements. The breakdown of systematic for each channel are summarized in Table 2 where a positive value indicates 100% correlated systematic among the channels and a negative value indicates the systematic uncorrelated. The priors used are truncated Gaussian densities constraining a given parameter to its expected value with its uncertainty.

Since there is nothing known about the Higgs production cross section, we assign a flat prior to the total number of Higgs events $R \times s_{tot}$, instead of the cross section. The posterior density function becomes

$$p(R|\vec{n}) = \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot} / \int dR \int d\vec{s} \int d\vec{b} \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}) \times s_{tot},$$

where $s_{tot} = \Sigma_{i=0}^{Nc} \Sigma_{j=0}^{Nbins} s_{ij}$.

The corresponding 95% credibility upper limit $R_{95}$ is

$$\int_0^{R_{95}} p(R|\vec{n})dR = 0.95.$$

The posterior densities for all channels combined are shown in Figure 2 and Figure 3 for Higgs mass between 110 and 200 GeV/c$^2$ where the arrows indicate the 95% credibility upper limit $R_{95}$. Figure 4 summarizes the limits from each individual channel and all the channels combined as function of Higgs masses.

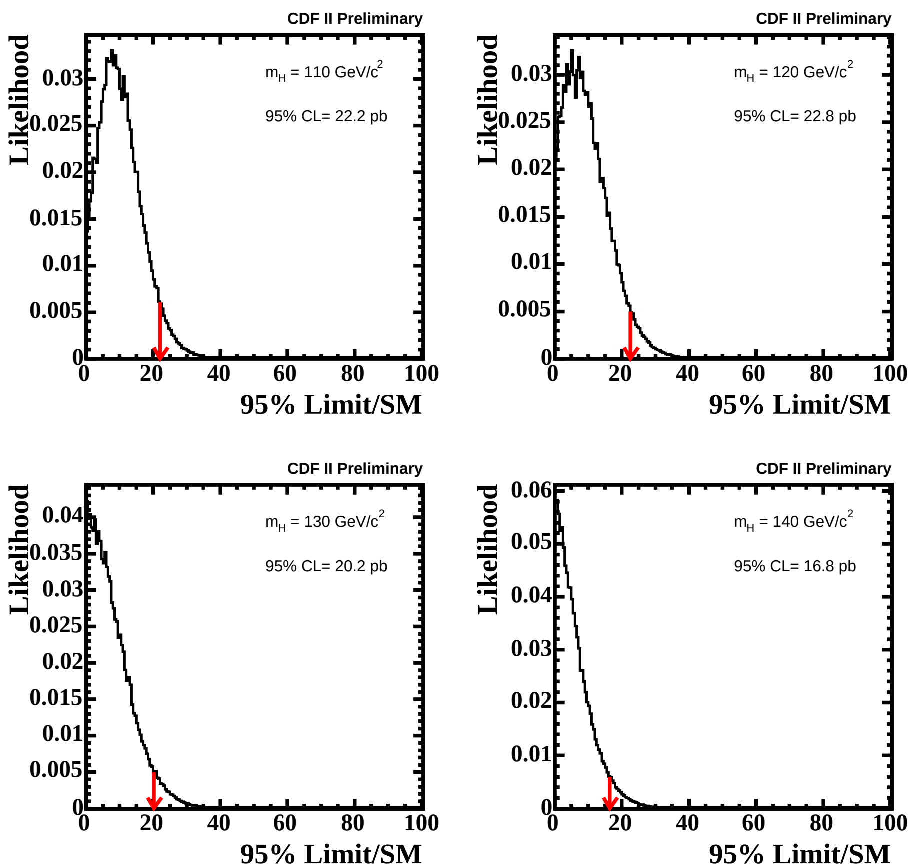


Figure 2: The posterior densities for all channels combined for Higgs mass between 110 and 140 GeV/c$^2$ where the arrows indicate the 95% credibility upper limit $R_{95}$.

As a check of the robustness of our calculation, we repeated the calculation by treating most systematics uncorrelated, except the luminosity and btag efficiency scale factor. This results in almost identical combined upper limits, shown in Table 3 as "uncorrelated", which indicates that the impact of correlations are small at the present time.

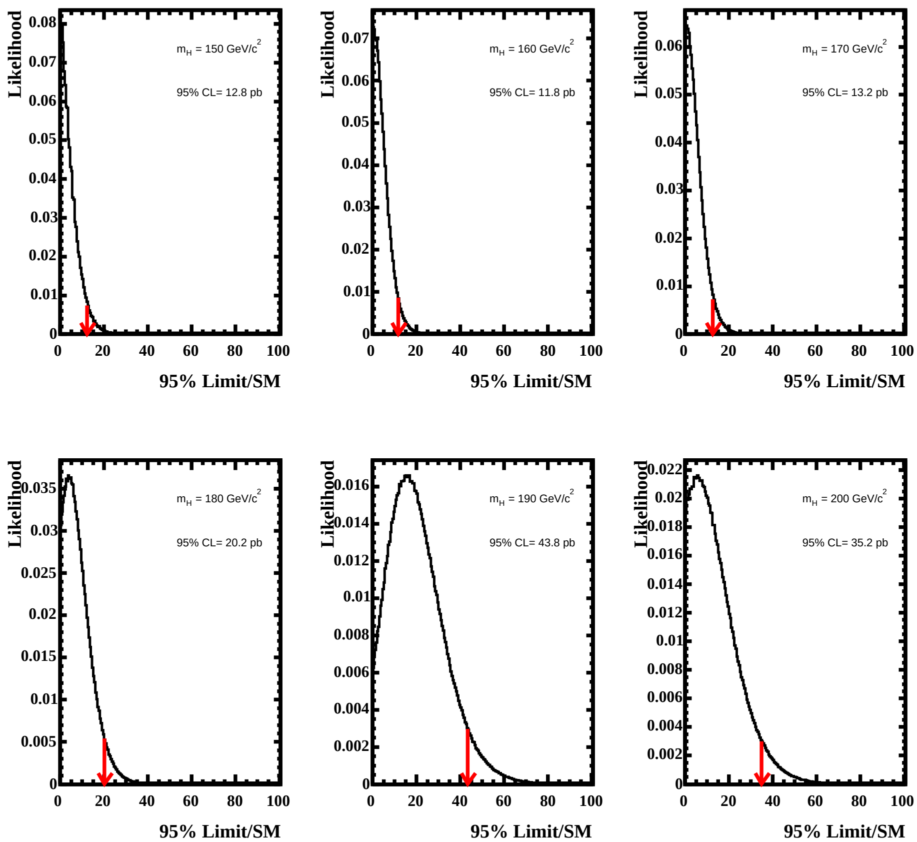


Figure 3: The posterior densities for all channels combined for Higgs mass between 150 and 200 GeV/c$^2$ where the arrows indicate the 95% credibility upper limit $R_{95}$.

# 4 Expected Upper Limit

To check the sensitivity of different channels, we calculate the mean upper limits one would obtain from a large ensemble of experiments. In the absence of Higgs signal, the pseudo-experiment is generated by fluctuating the expected backgrounds with their uncertainties. Figure 5 and Figure 6 show the distributions of upper limits from the pseudo-experiments for various Higgs masses. The observed upper limits from data are also shown by the red arrows, which are consistent with the expectation of pseudo-experiments.

The final combined limit and its expectation are listed in Table 3.

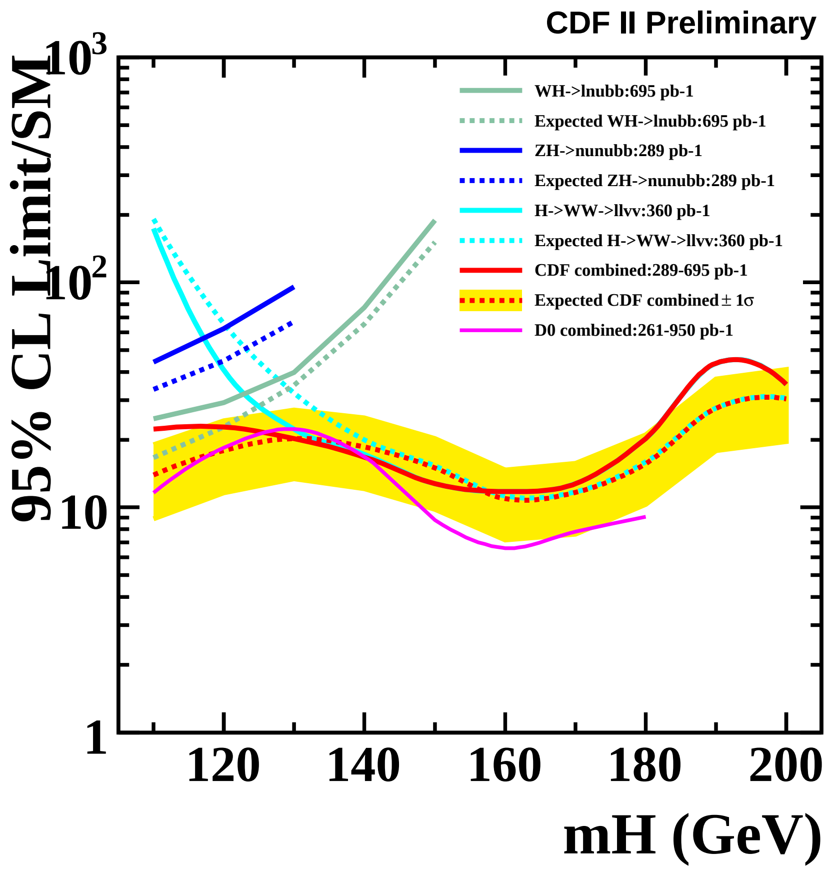


Figure 4: The combined upper limit as function of Higgs masses between 110 and 200 GeV/c$^2$ as well as the individual limits from individual channels.

## 5 Conclusions

We have described a combination of several searches for Standard Model Higgs production at CDF using a data sample up to 695 pb$^{-1}$ of integrated luminosity. The channels considered are $WH \to l\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, and $gg \to H \to W^+W^-$. We have calculated combined upper limits on the ratio of Higgs cross section times the branching ratio to its Standard Model prediction ($R_{95}$) for Higgs masses between 110 and 200 GeV/c$^2$. The results are in a good agreement with the expectations obtained from pseudo-experiments. We have also recomputed upper limits for each individual channel using the same technique as a consistent check and are able to reproduce the blessed results over all the channels. The combined limit is still order of magnitude higher than the Standard Model prediction, but it will be greatly improved once the results are updated with 1 fb$^{-1}$ data for summer 2006.

| Mass (GeV/c$^2$) | Combined Limits (pb) | | Expected Limits (pb) | |
|---|---|---|---|---|
| | Correlated | Uncorrelated | Mean | RMS |
| 110 | 22.2 | 21.8 | 14.0 | 5.0 |
| 120 | 22.8 | 22.8 | 18.0 | 6.3 |
| 130 | 20.2 | 20.8 | 20.3 | 6.9 |
| 140 | 16.8 | 17.2 | 18.6 | 6.4 |
| 150 | 12.8 | 12.8 | 15.0 | 5.2 |
| 160 | 11.8 | 11.8 | 10.9 | 3.8 |
| 170 | 12.8 | 12.8 | 11.6 | 4.0 |
| 180 | 20.2 | 20.2 | 15.6 | 5.4 |
| 190 | 43.8 | 43.8 | 27.6 | 9.7 |
| 200 | 35.2 | 35.2 | 30.3 | 10.8 |

Table 3: The summary of observed, expected limits for various Higgs masses.

# 6 Acknowledgements

We thank Tom Junk for his contributions that give us an independent cross checks on the final results.

# References

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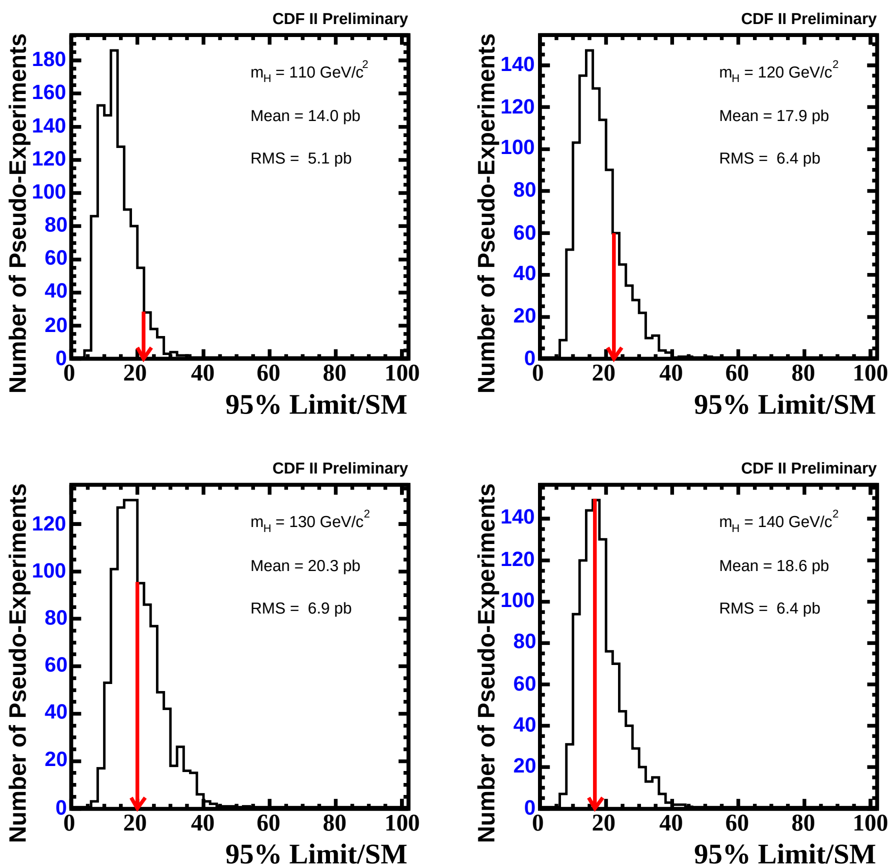


Figure 5: The distributions of upper limits from the pseudo-experiments for Higgs mass between 110 and 140 GeV/$c^2$ where the arrows indicate the observed 95% upper limit from data.

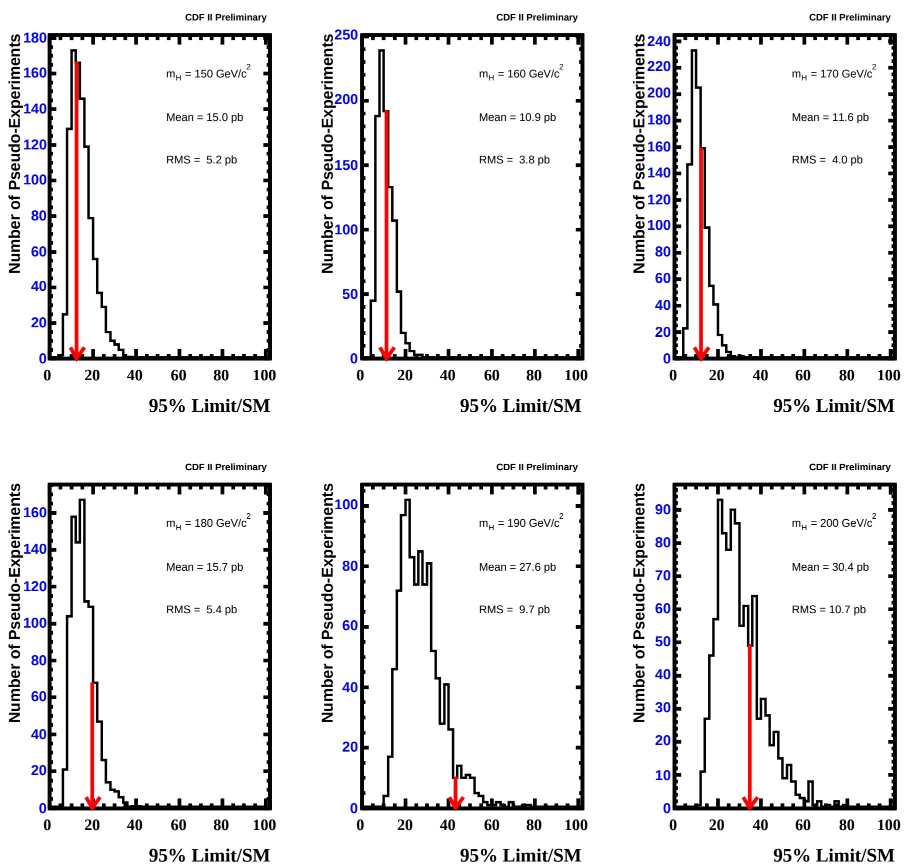


Figure 6: The distributions of upper limits from the pseudo-experiments for Higgs mass between 150 and 200 GeV/$c^2$ where the arrows indicate the observed 95% upper limit from data.