Lecture:

Standard Model of Particle Physics

Heidelberg SS 2016

Discovery of the Higgs

Contents

Statistics and Limit Setting

chi² fit:

$$\chi^2 = \sum_i \frac{(y_i - \mu_i)^2}{\sigma_i^2}$$

y_i measurement
μ_i model prediction (nuisance parameter)
σ_i uncertainty (statistical and systematical)

chi² fit with correlated errors:

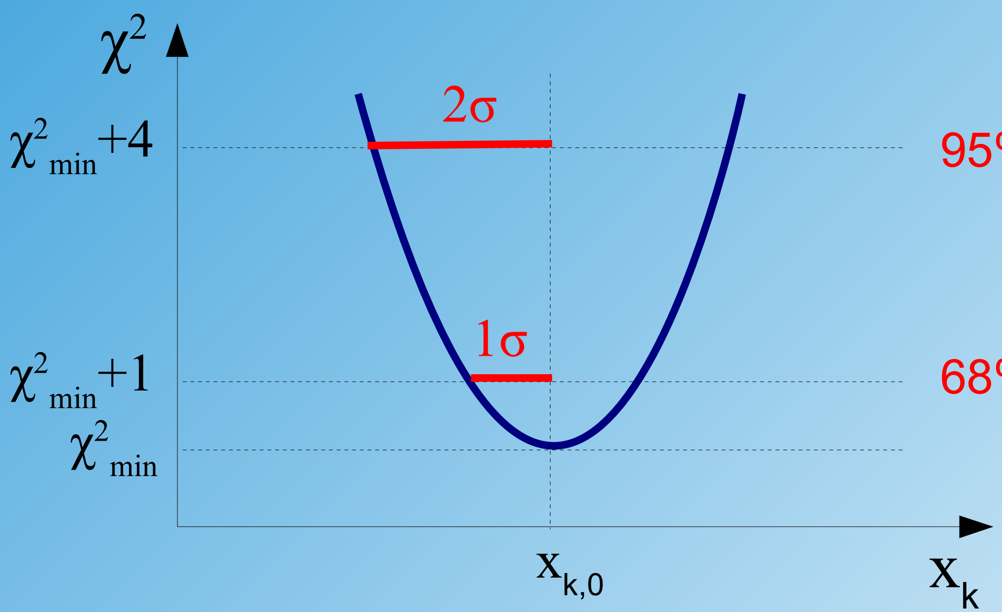
$$\chi^2 = \sum_i \sum_j (y_i - \mu_i) cov_{ij}^{-1} (y_j - \mu_j)$$

cov_{ij} covariance (error) matrix

Parameter Fit:

$$\mu_i = \mu_i(x_1, x_2, \ldots, x_n)$$

x_k model parameter, e.g. cross section



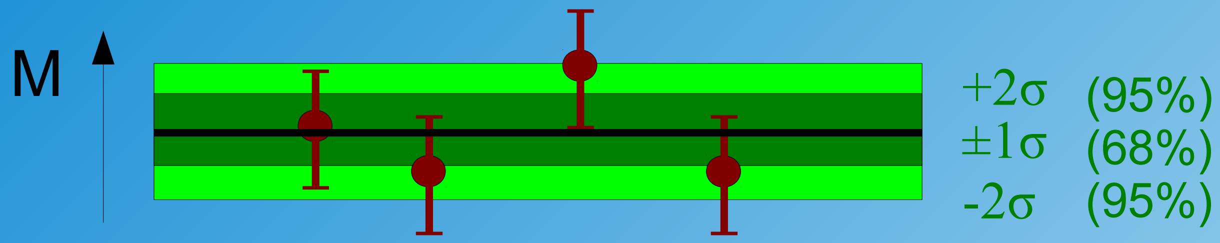
95% confidence level

68% confidence level

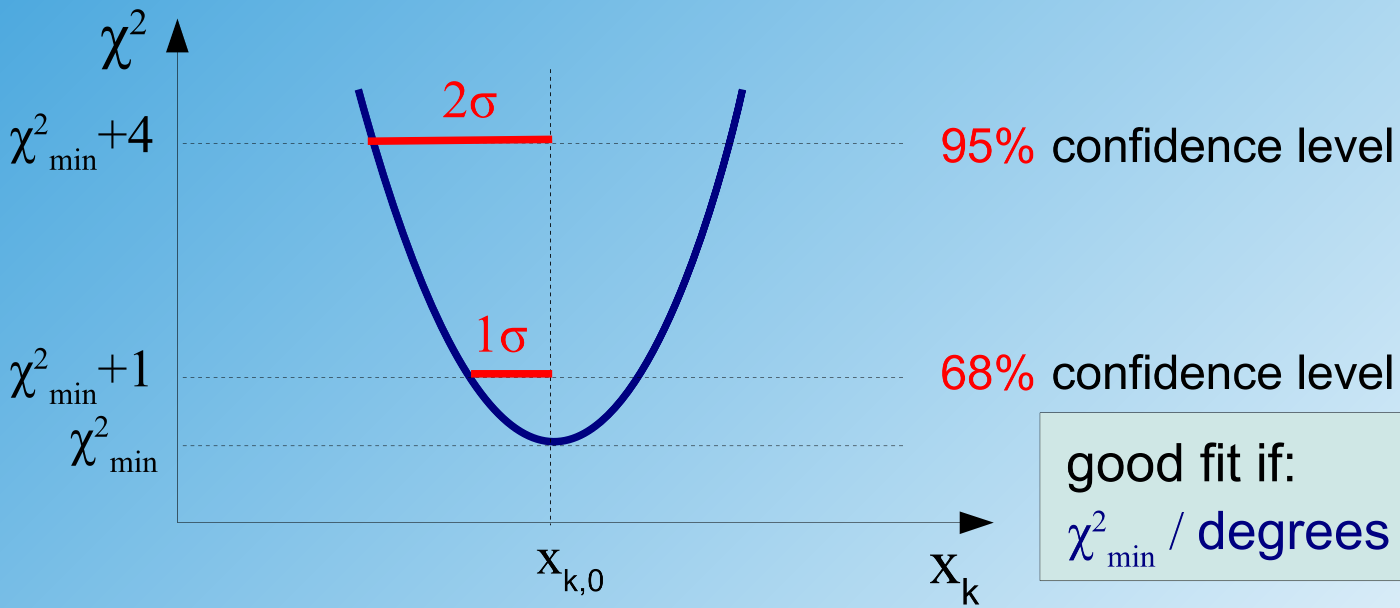
good fit if:
χ^2_{min} / degrees of freedom ~ 1

Example Fit

Measurement of some mass (1-Parameter fit) from 4 experiments:



confidence level bands



good fit if:

χ^2_{min} / degrees of freedom ~ 1

Probability Densities

Gaussian (normal) distribution:

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \rightarrow \quad P(a < x < b) = \int_a^b f(x)\, dx$$

- used for systematic uncertainties (symmetric)

Poissonian distribution:

$$P(N) = \frac{e^{-\mu}\,\mu^N}{N!}$$

- used for statistical uncertainties

Note, Poisson distribution approaches Gaussian distribution for large μ

Limit Setting Philosophies

Baysian Method:

- based on the **experiment posterior**, exclusion limits are calculated
- low probability models are excluded
- probabilities are assigned to models using a prior

"natural method" but choice of prior is arbitrary

Frequentist Method:

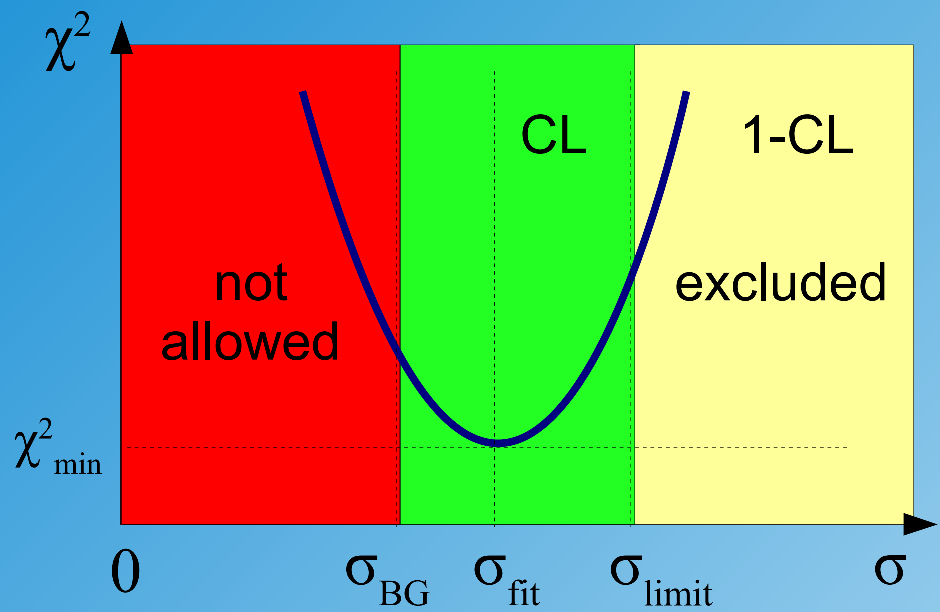
- based on **Monte Carlo** toy experiments probabilities are assigned to all possible experimental outcomes
- exclusion limit is set by that model which excludes this experimental outcome with certain confidence interval

computationally expensive and might give unphysical results
(e.g. negative cross sections)

Baysian Method

Model: $N = N_{BG} + N_{Sig}$ background + signal

$\sigma = \sigma_{BG} + \sigma_{Sig} = N/L$ choose cross section as “prior”



Probability:

$$P \propto e^{-\frac{1}{2}\left(\chi^2(\sigma)-\chi^2_{fit}\right)}$$

usually additional constraint:

$\sigma > \sigma_{BG}$ because $\sigma_{Sig} > 0$

$$CL = \frac{\int_{\sigma>\sigma_{BG}}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma>\sigma_{BG}}^{\infty} P(\sigma)\, d\sigma}$$

CL = confidence level

Choice of Prior

- Cross sections depend on couplings
- Alternatively we can choose coupling as prior

$$\sigma_{Sig} = \sigma_0 \, \alpha^2$$

$$\frac{d\sigma}{d\alpha} = \frac{d\sigma_{Sig}}{d\alpha} = 2\sigma_0 \, \alpha$$

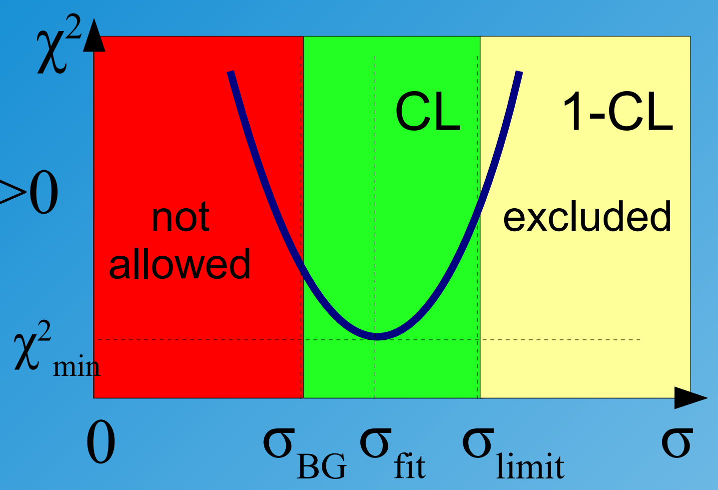
$$CL = \frac{\int_{\sigma_{Sig}>0}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma_{Sig}>0}^{\infty} P(\sigma)\, d\sigma} = \frac{\int_{\alpha>0}^{\sigma_{CL}} P(\alpha^2)\, \alpha \, d\alpha}{\int_{\alpha>0}^{\infty} P(\alpha^2)\, \alpha \, d\alpha} \neq \frac{\int_{\alpha>0}^{\alpha_{CL}} P(\alpha)\, d\alpha}{\int_{\alpha>0}^{\infty} P(\alpha)\, d\alpha}$$

Result depends on choice of prior!

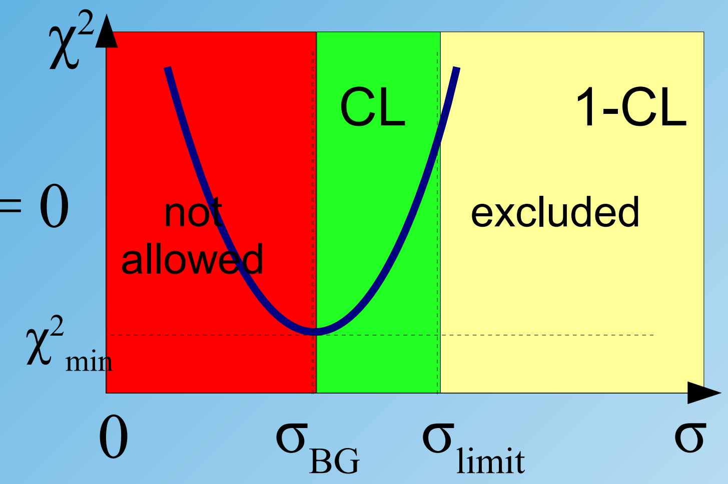
Negative Cross Section Limit Problem

possible outcomes::

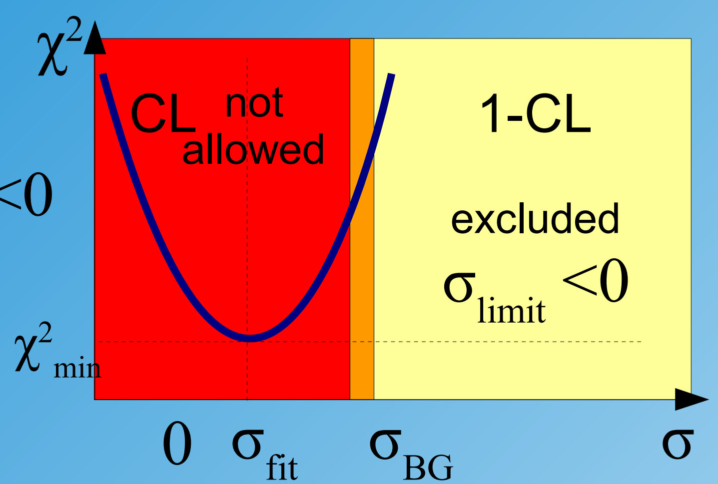
1. $\sigma_{fit} > 0$



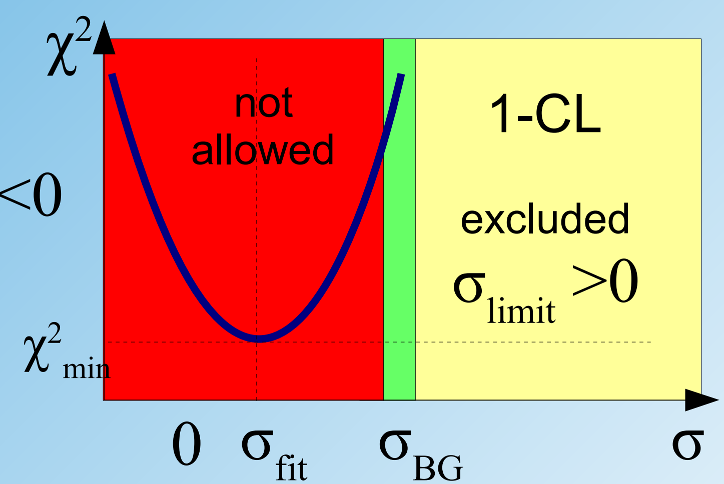
2. $\sigma_{fit} = 0$



3. $\sigma_{fit} < 0$



$\sigma_{fit} < 0$



$$CL = \frac{\int_{\sigma > -\infty}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma > -\infty}^{\infty} P(\sigma)\, d\sigma}$$

WRONG!

negative cross sections → unphysical

$$CL = \frac{\int_{\sigma_{Sig} > 0}^{\sigma_{CL}} P(\sigma)\, d\sigma}{\int_{\sigma_{Sig} > 0}^{\infty} P(\sigma)\, d\sigma}$$

only positive cross sections!

Frequentist Method

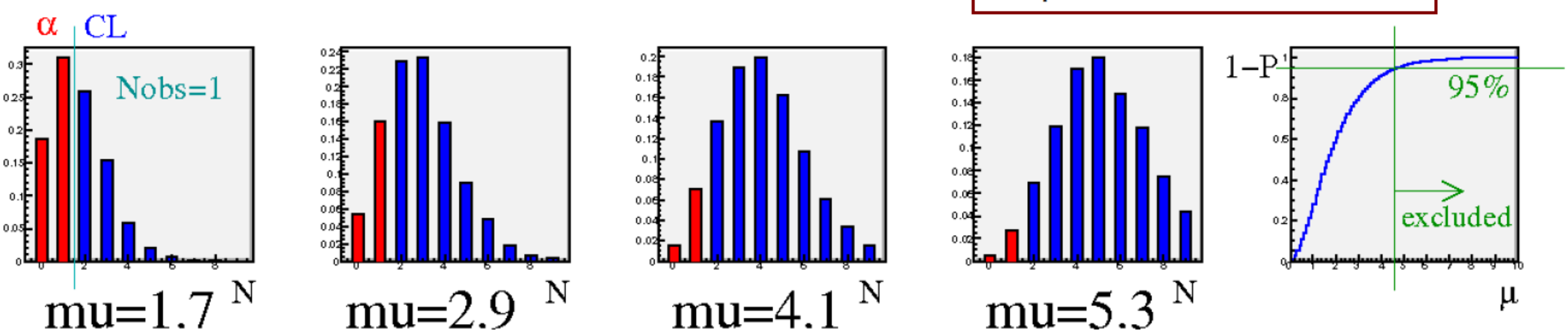
S.Schmitt

- Frequentist limit: exclude all theories which produce the data at small probability α less than 1-CL (typically: CL=0.95)

$$\alpha = P_{\mu}(N \le N_{obs}) < 1 - CL$$

α: also called p-value

Frequentist limit:
sum (integrate)
over observations
up to N_{obs}
Repeat for each model



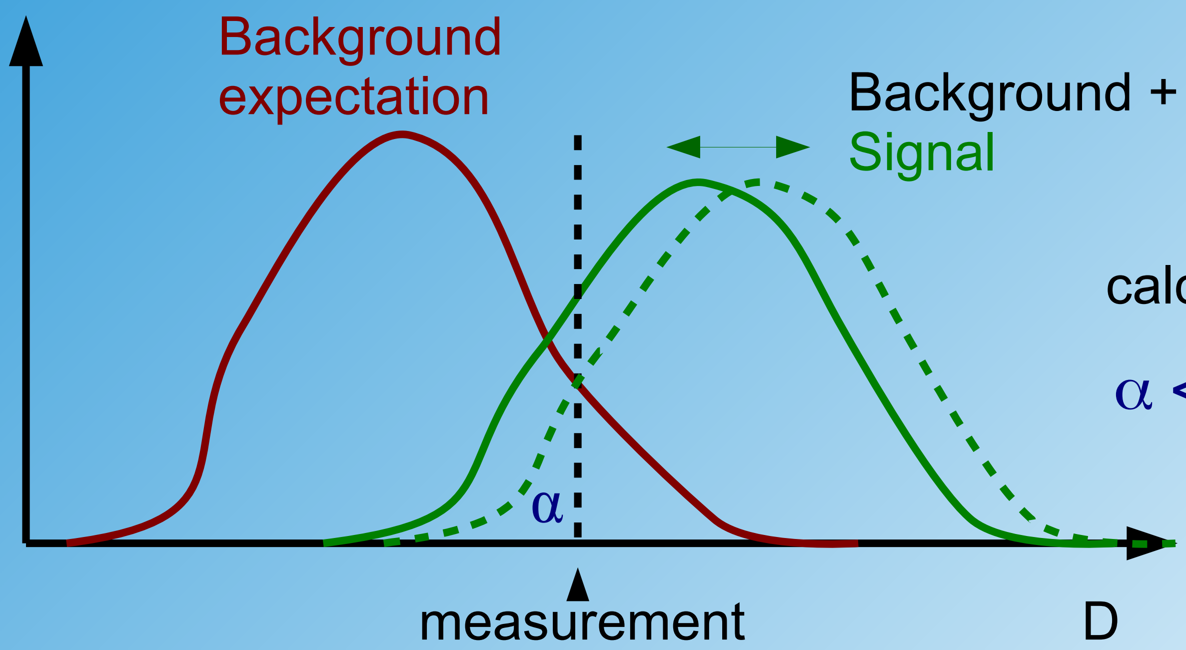
- mu = expectation value (BG+signal)
- set limit with 95% confidence level for mu=4.6
- experiment has a 5% probability to happen
- measurement uncertainty does not enter (in contrast to Baysian method)

Frequentist Method

In case of many observables x_k a combined discriminator variable is often defined: $D = D(x_1, x_2, x_3, \ldots X_k)$

- large discriminator means high probability
- small discriminator means low probability

Often, the output from artificial neural nets or other multivariate methods is used as discriminator variable



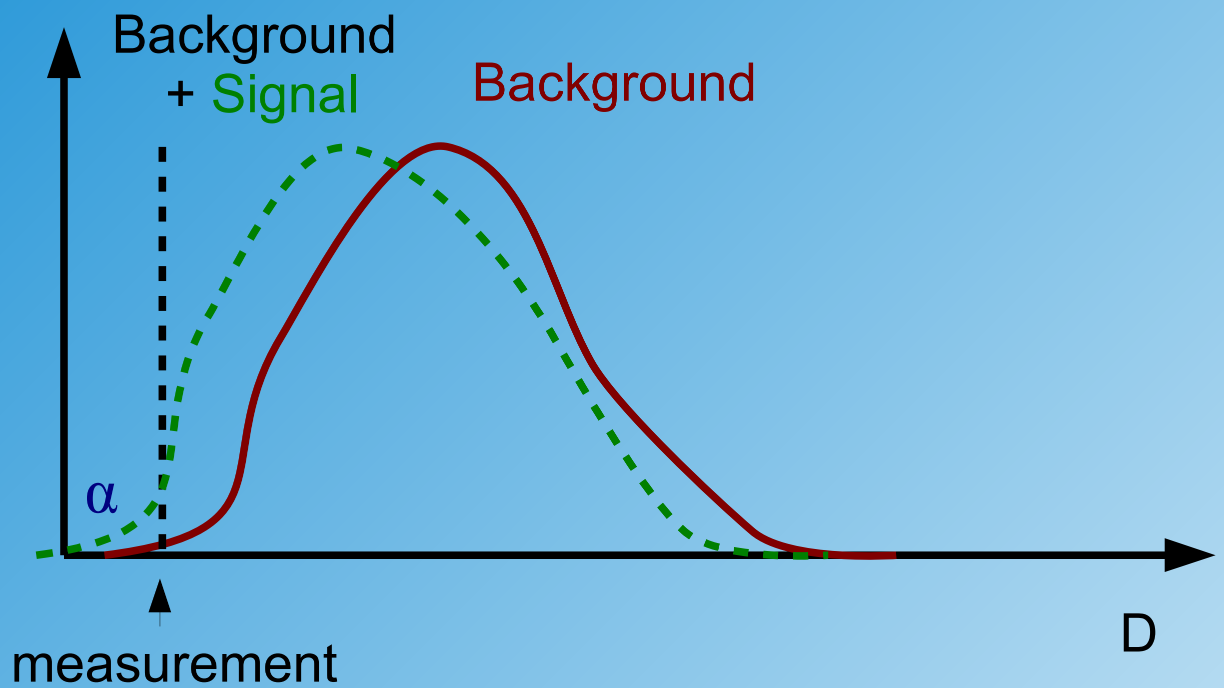
calculate smallest signal with:

$$\alpha < 1 - CL$$

Negative Limit Problem with Frequentist Method

Problem in case of a very small measurement value with P(BG)< (1-CL)

- would require a negative signal cross section:



negative signal → unphysical solution!

CL_S Method

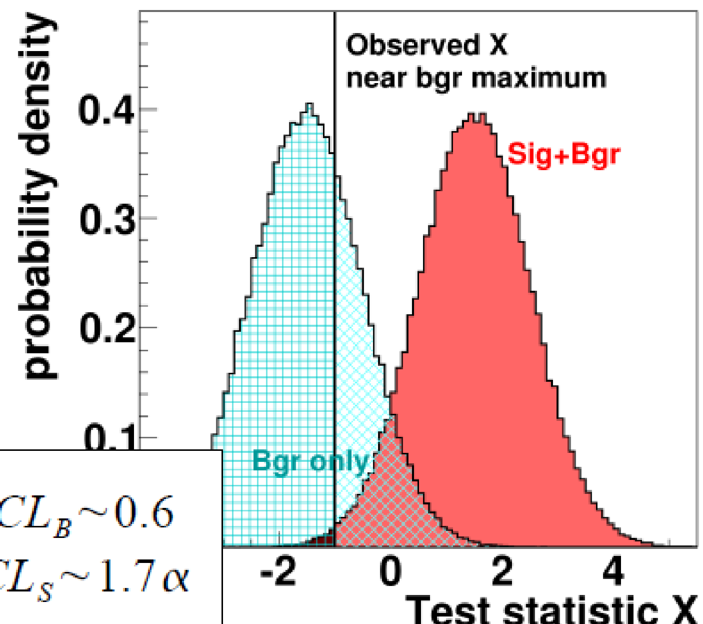
- Use ratio of two probabilities CL_S instead of α to test against CL

$$CL_{SB} = \alpha = \int_{X<X_{obs}} P(X|\text{signal}+\text{bgr})\, dX$$

$$CL_B = \int_{X<X_{obs}} P(X|\text{bgr})\, dX$$

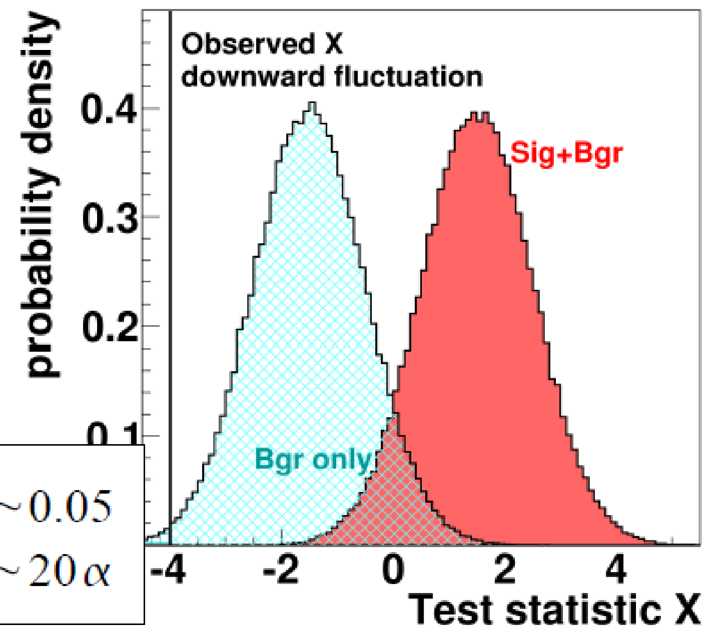
$$CL_S = \frac{CL_{SB}}{CL_B}$$

- Standard model has CL_S=1 and is never excluded



$CL_B \sim 0.6$

$CL_S \sim 1.7\alpha$



$CL_B \sim 0.05$

$CL_S \sim 20\alpha$

S.Schmitt

CL_S > CL_{SB} by definition!

Another Example CL_S Method

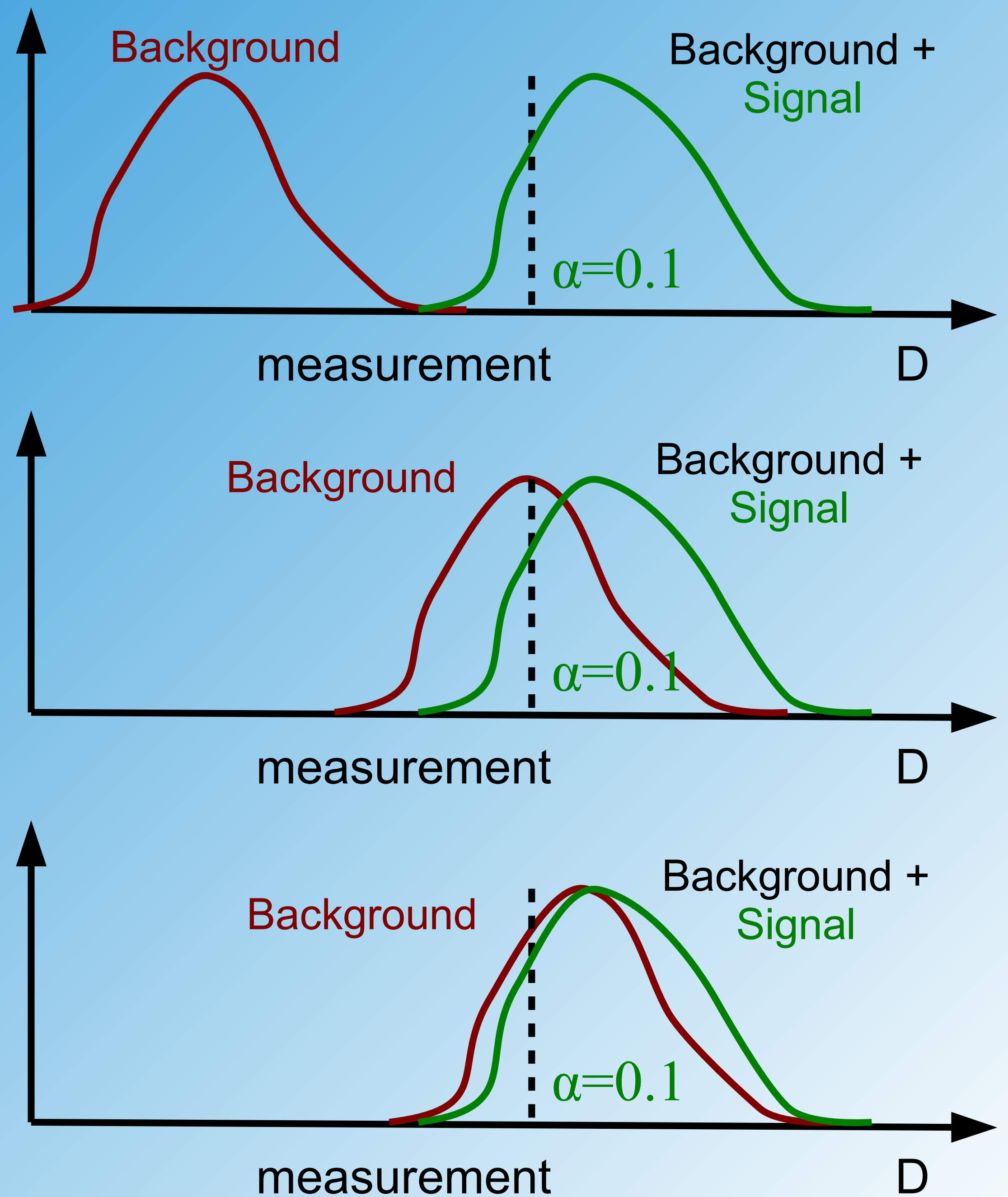
Definition:

$$CL_S = \frac{CL_{SB}}{CL_B}$$

$$0.1 = \frac{0.1}{1.0}$$

$$0.2 = \frac{0.1}{0.5}$$

$$0.5 = \frac{0.1}{0.2}$$



Another Example CL_S Method

Definition:

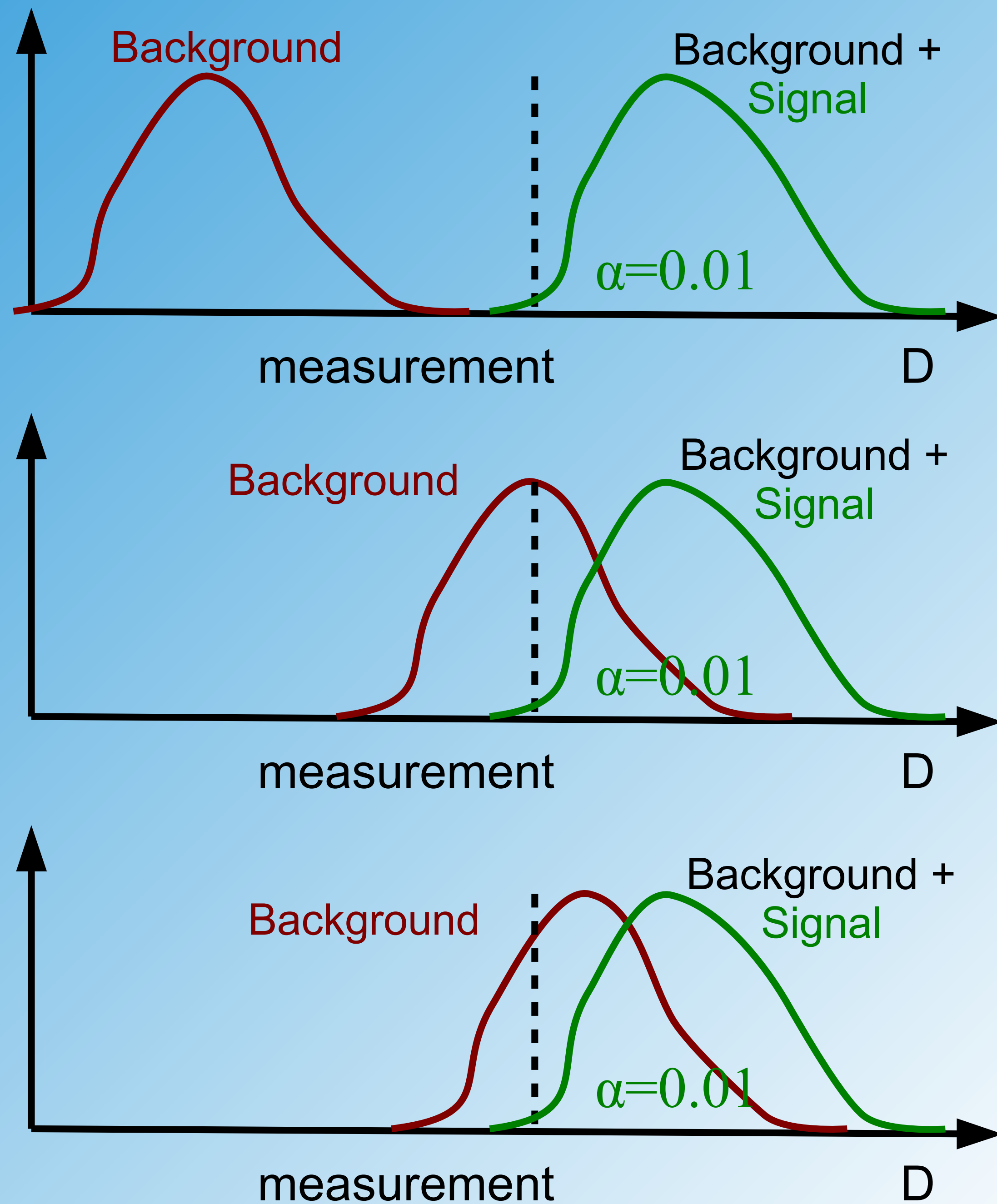
$$CL_S = \frac{CL_{SB}}{CL_B}$$

$$0.01 = \frac{0.01}{1.0}$$

$$0.02 = \frac{0.01}{0.5}$$

$$0.05 = \frac{0.01}{0.2}$$

excluded at 95% CL



Reminder:
Indirect Higgs Mass Constraints

Radiative Corrections and Indirect Higgs Constraints

$$\sin^2\theta_w = 1 - \frac{M_W^2}{M_Z^2} \qquad \sin\theta_w = \frac{e}{g}$$

Lowest order SM predictions

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\text{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

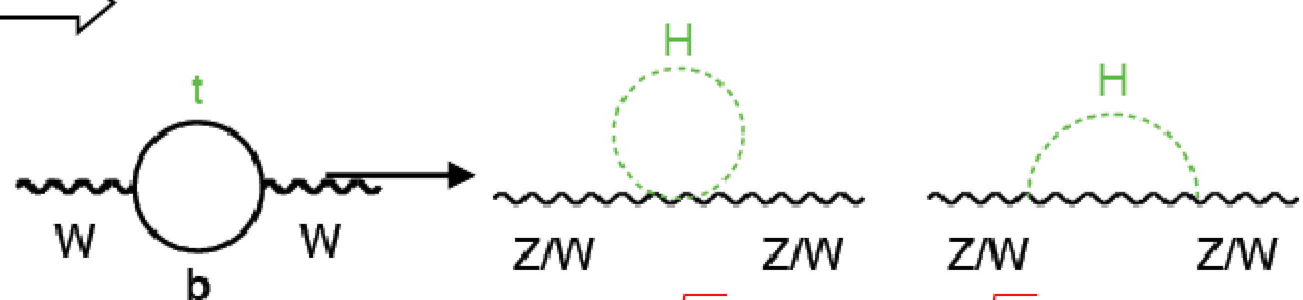
$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

Including radiative corrections

with : $\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{top}} + \Delta\alpha_{\text{had}}^{(5)}$

$\sin^2\theta_w$, g_A, g_V $\Longrightarrow$ $\sin^2\theta_{eff}$, $\bar{g}_A, \bar{g}_V$

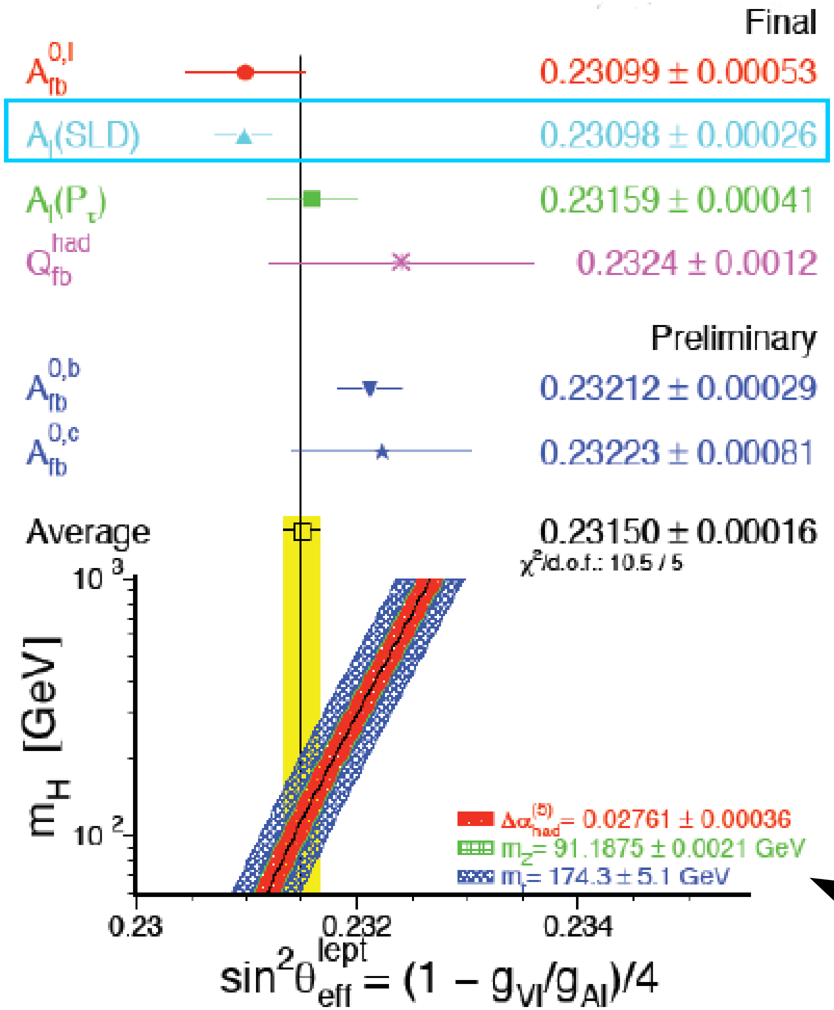
$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$



53

$$\bar{g}_A = \sqrt{\bar{\rho}}\,T^3 \qquad \bar{g}_V = \sqrt{\bar{\rho}}\,(T^3 - 2Q\sin^2\theta_{eff})$$

Indirect Higgs Mass Prediction



Take the top mass from direct measurements and use the radiative corrections to determine the Higgs mass.

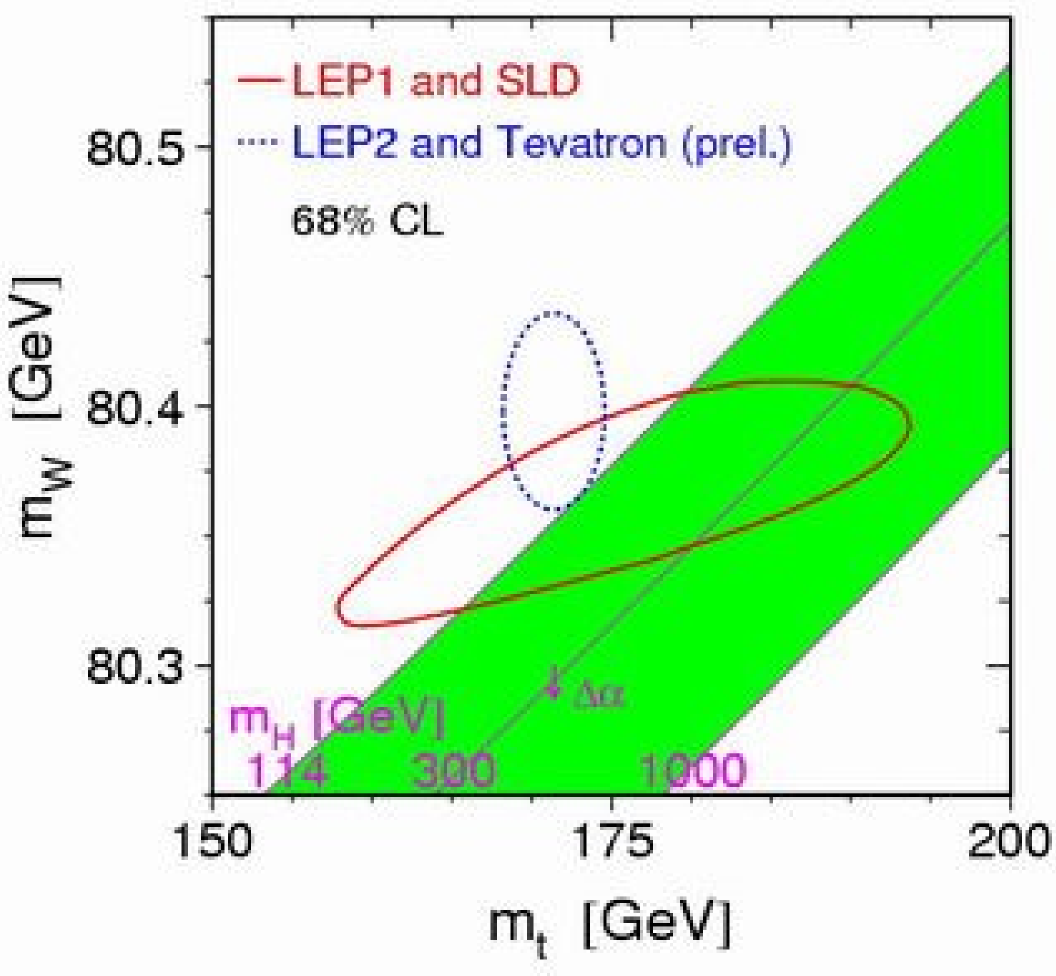
$$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \dots$$

outdated

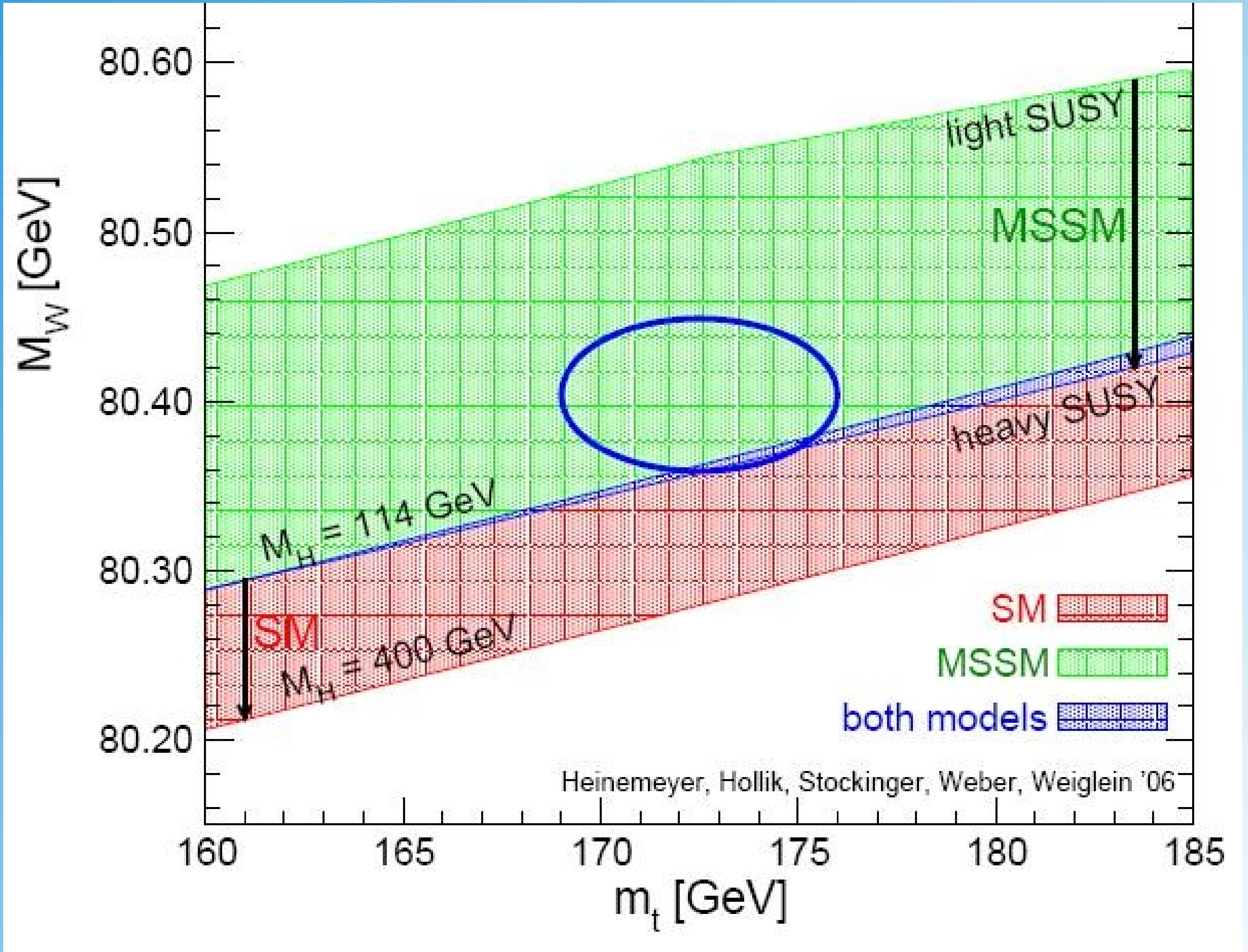
Theoretical prediction of $\sin^2\theta_{eff}$ as function of the Higgs mass.

SM Higgs Mass Predictions

Pre-LHC Plots



W-Top-Higgs Mass Relation and Supersymmetry (SUSY)



SUSY Higgs
is light!

Higgs Direct Searches at LEP

Higgs-Fermion Coupling to b- and t-quarks:

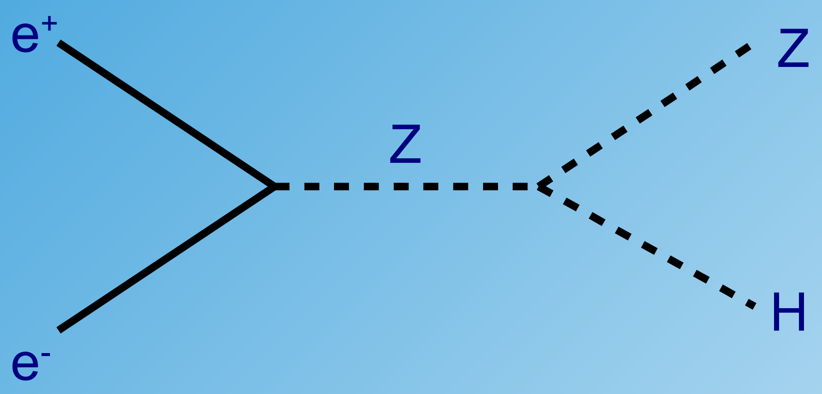
$$L_Y = -g_b \bar{L} \Phi b_R - g_t \bar{L} \tilde{\Phi} t_R \quad \text{with} \quad L = \begin{pmatrix} t \\ b \end{pmatrix}, \; \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \; \tilde{\Phi} = i \tau_2 \Phi^*$$

Higgs couples to masses:

$$m_{b,t} = \frac{g_{b,t} v}{\sqrt{2}}$$

Electron-Positron annihilation has tiny Higgs coupling!

LEP main production Process (Higgs-Strahlung): $e^+ e^- \rightarrow ZH$



ZZH coupling is large!

ZH Signature at LEP

Higgs decays dominantly into heaviest fermions:

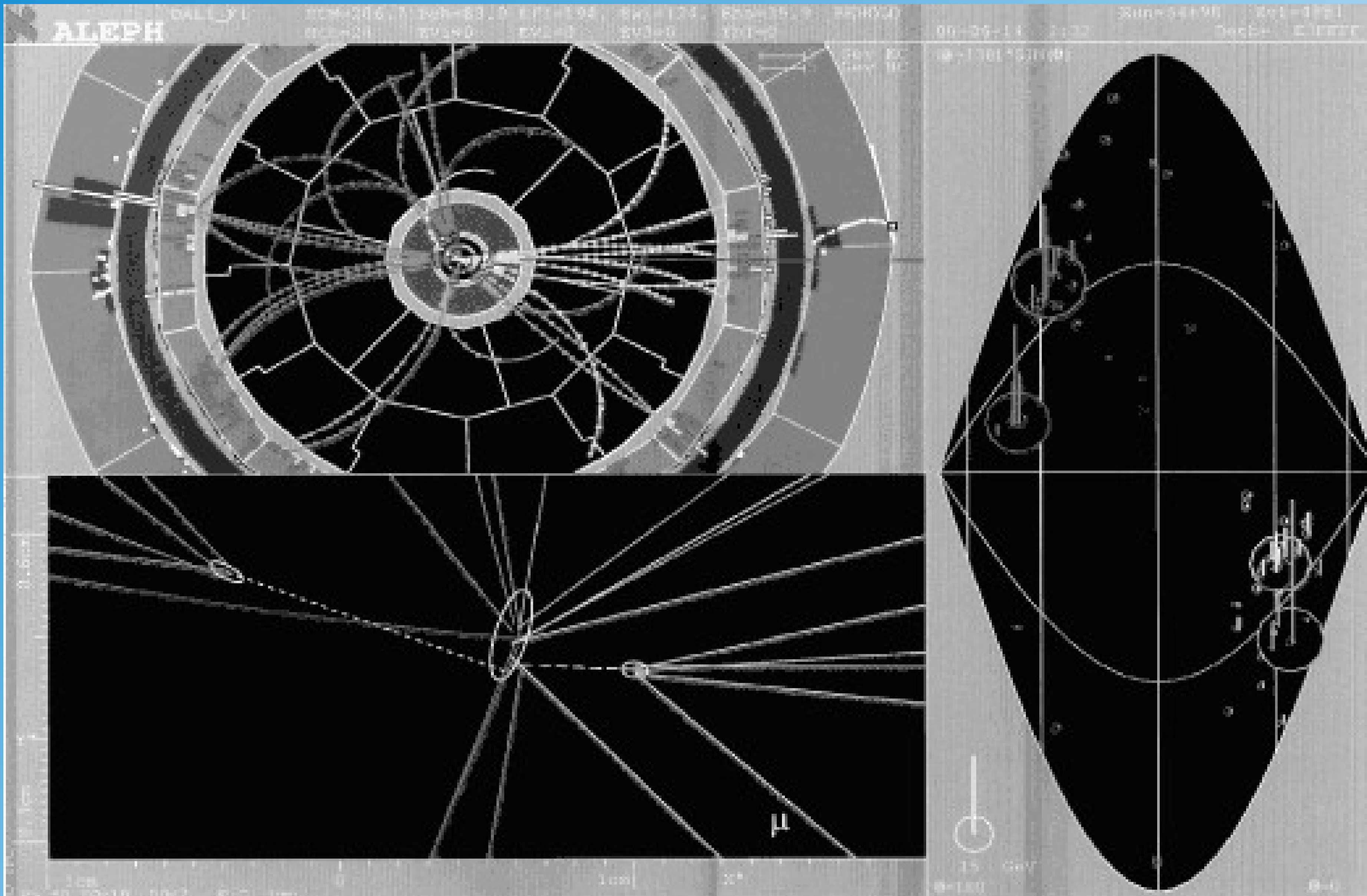
$ZH \to Z\,bb \to ll\,bb,\ jj\,bb,\ bbbb,\ \nu\nu\,bb$

All decay channels require (double) b-tag (lifetime)

LEP2 with E_{cms}=205 GeV:

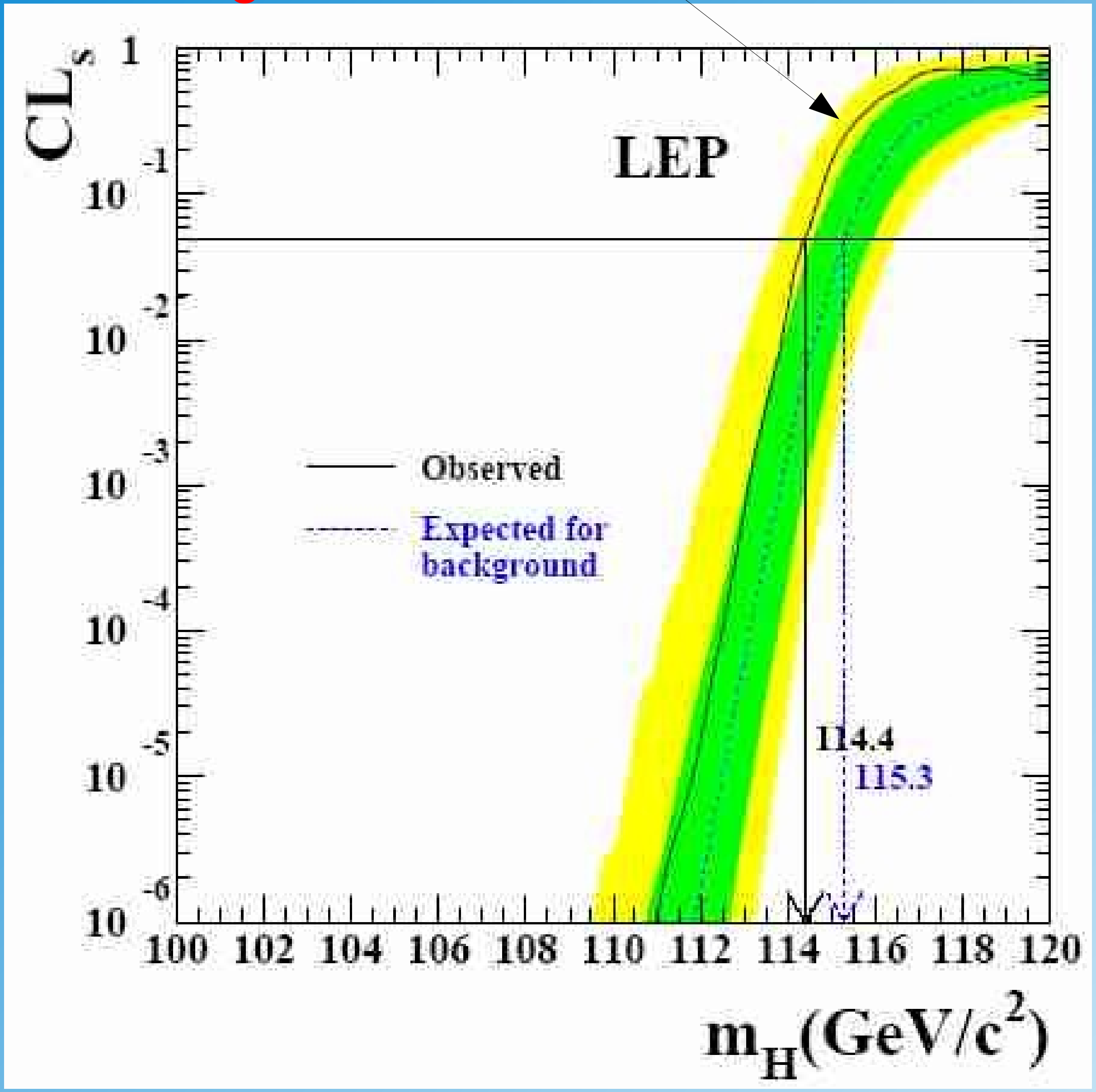
- installation of vertex detectors (high resolution silicon)
- sensitivity up to m_H=114 GeV   ($E_{cms} = m_H + m_Z$)

bbjj-candidate at ALEPH



Combined LEP2 Higgs Limit

no signficant excess



Higgs excluded with:

m_H < 114.4 GeV

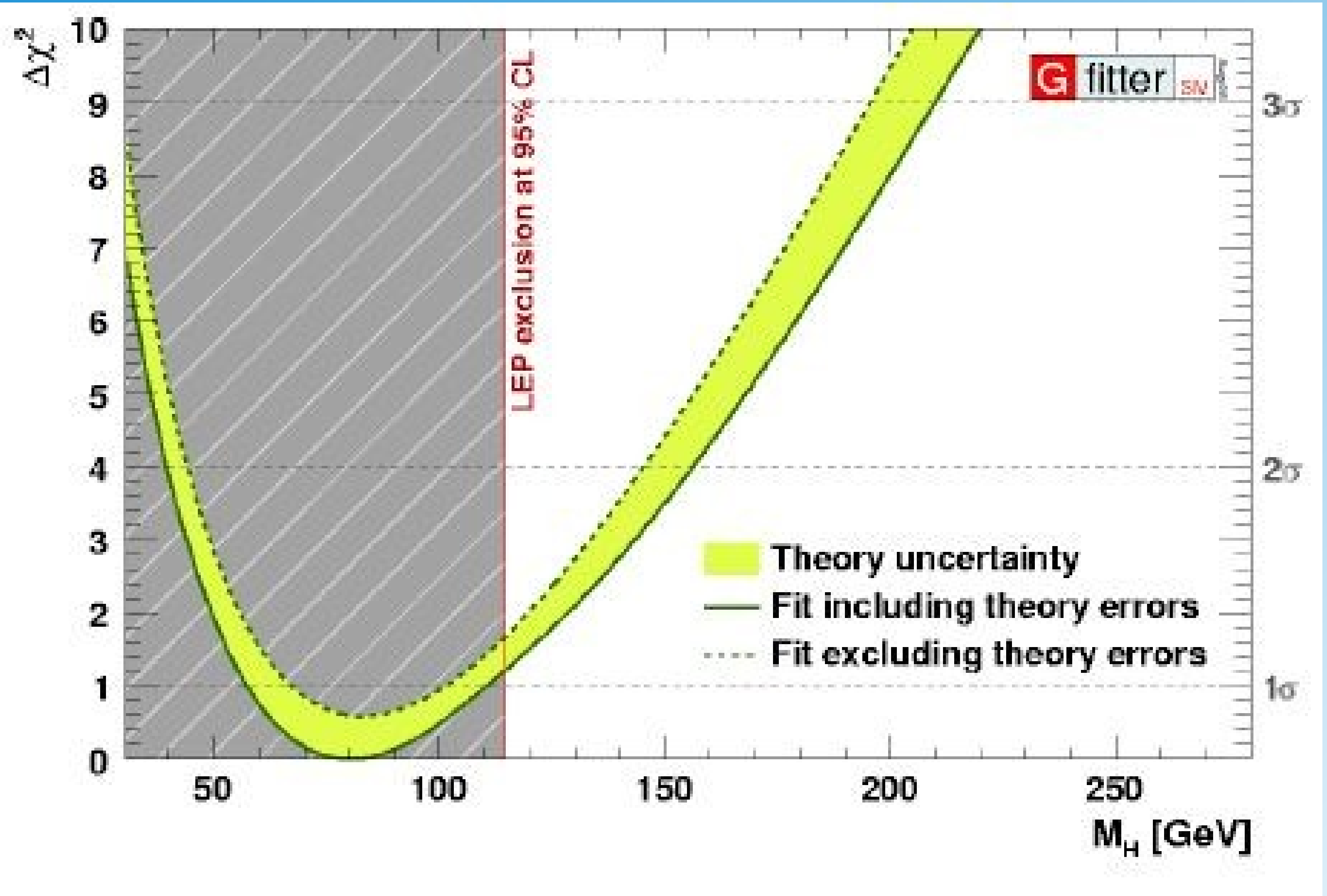
(expected 115.3)

at 95% CL

The bands shows the 1 sigma and 2 sigma contours of the expected limit

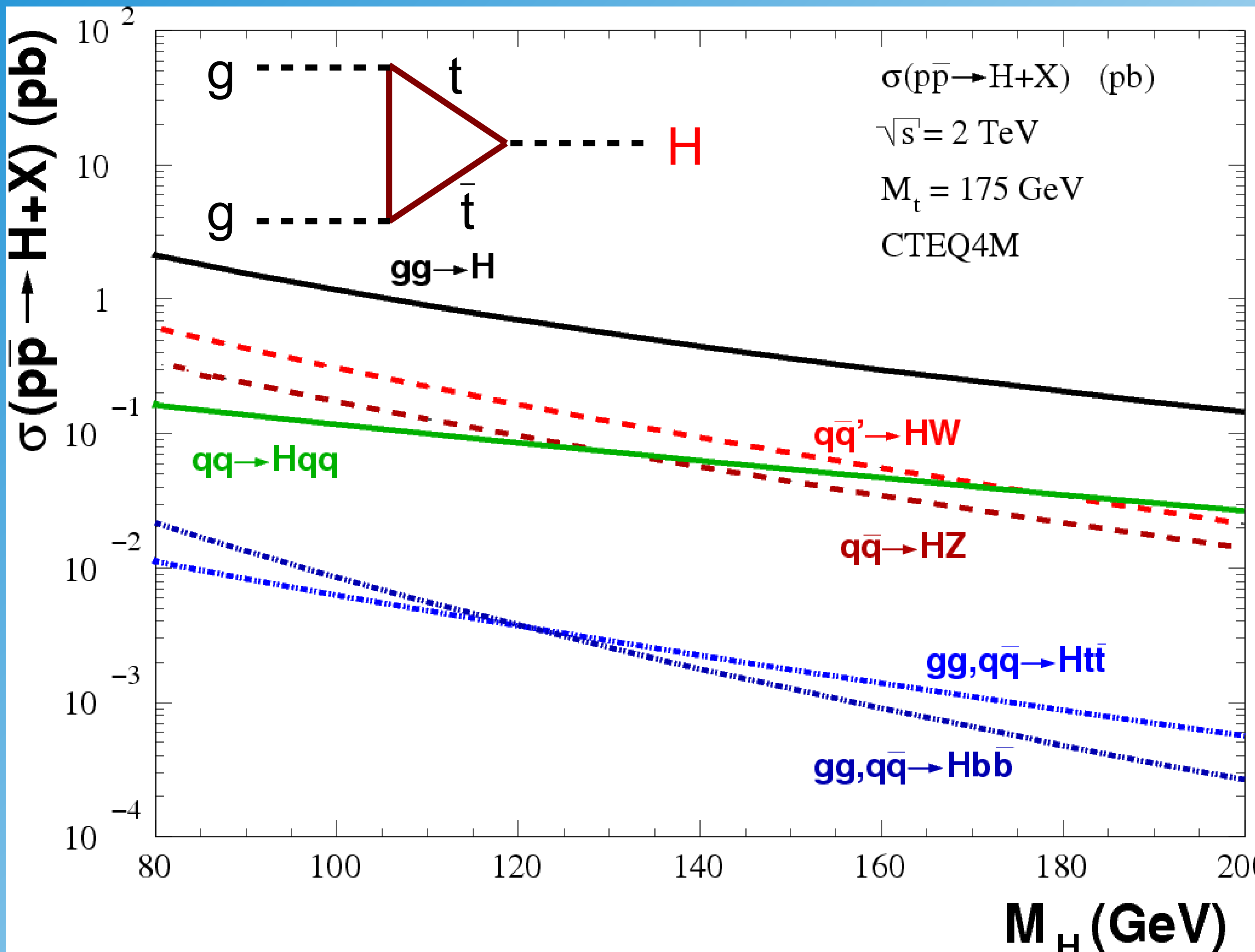
The black line shows the expected limit

Higgs LEP2 Direct Limits

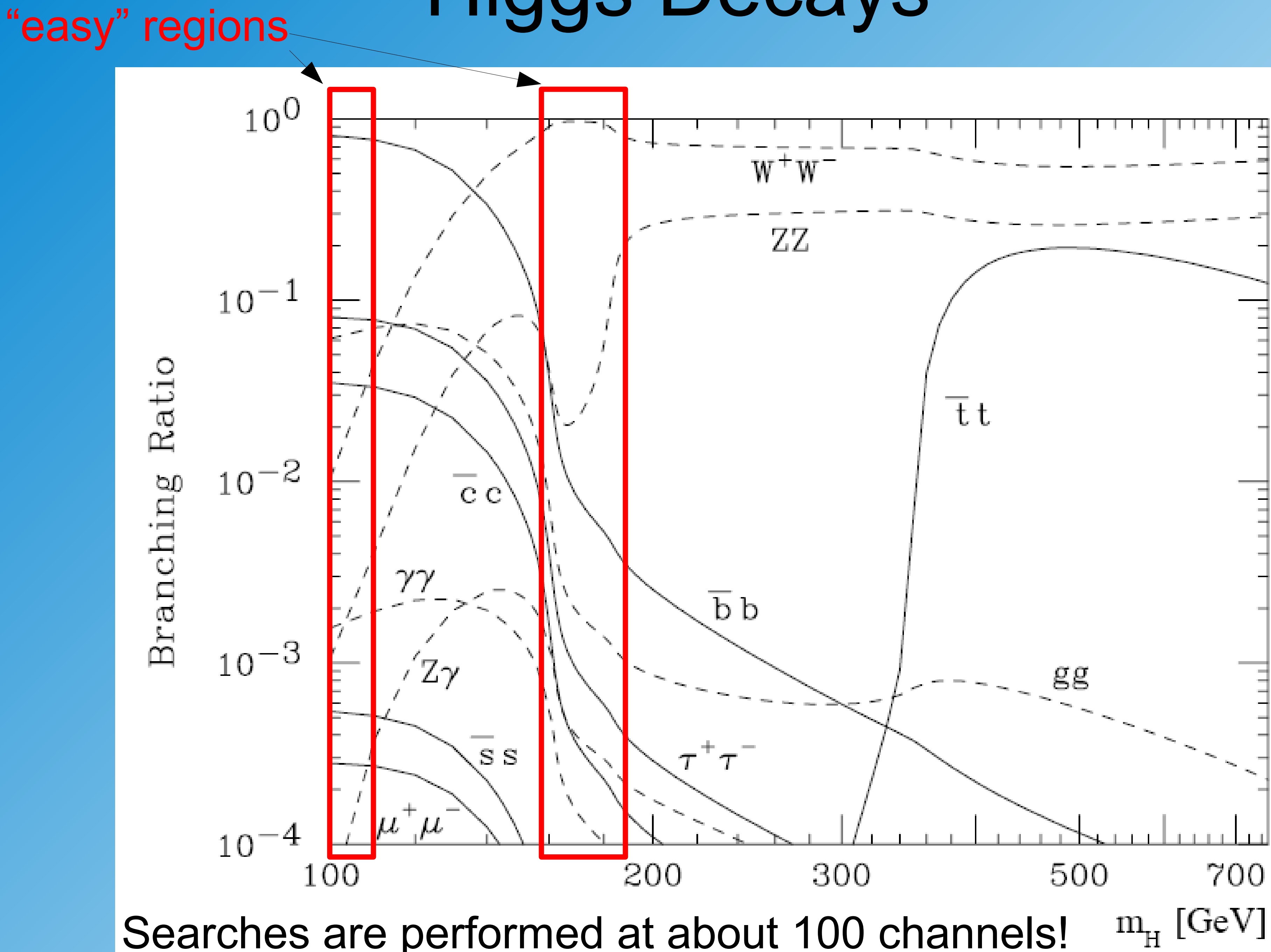


Gfitter perfroms a SM parameter fit.

Higgs Production at Tevatron

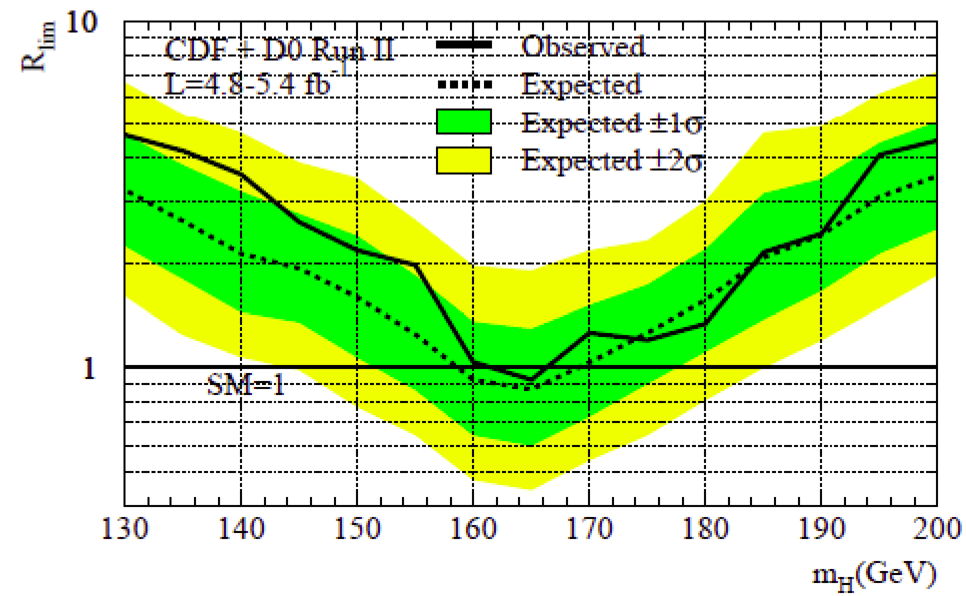


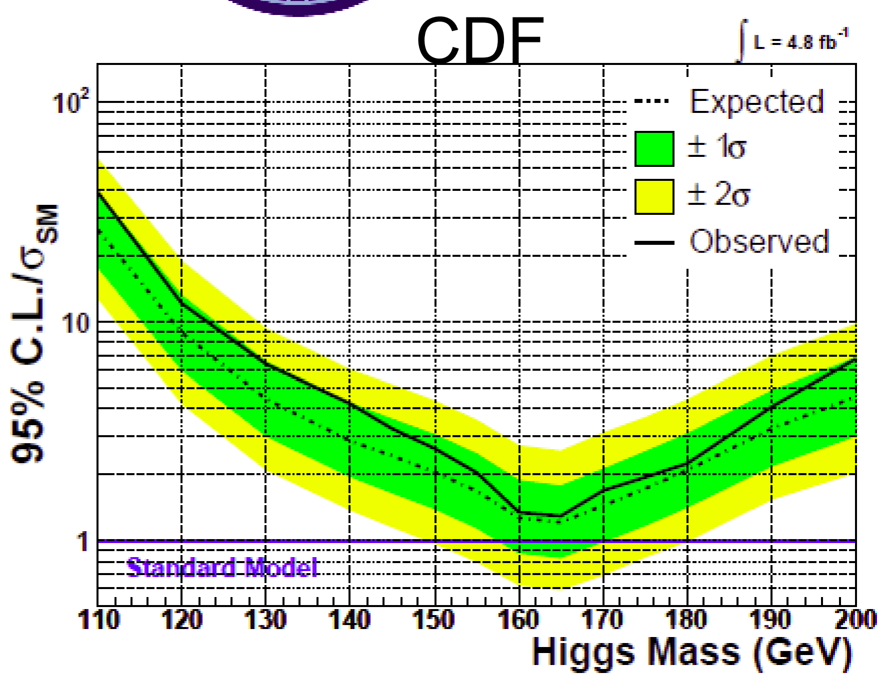
Higgs Decays

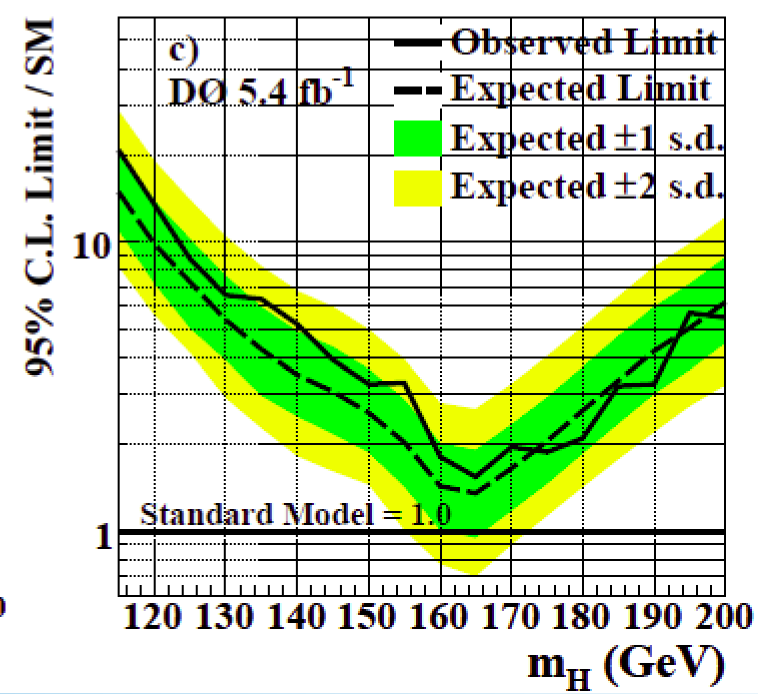


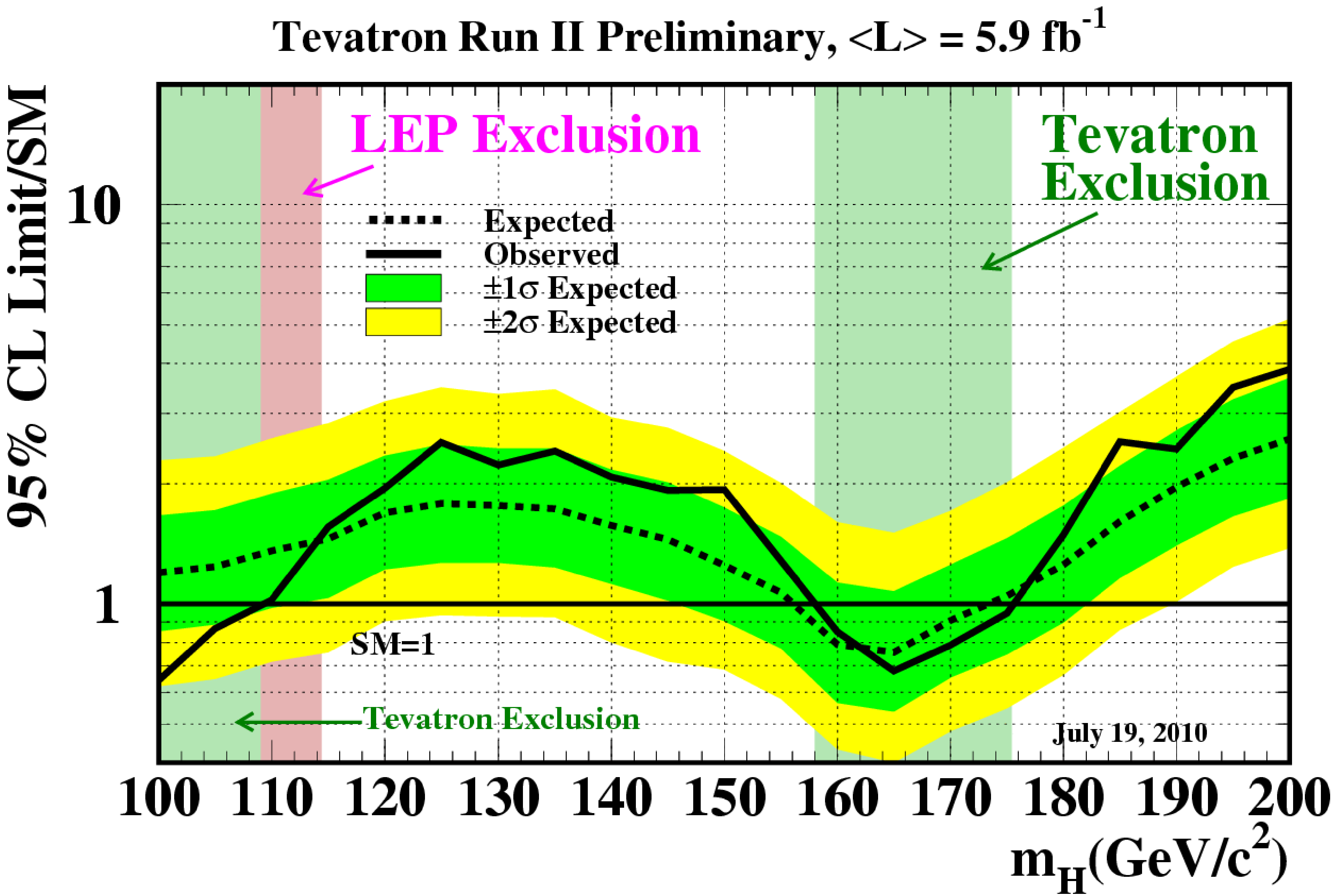
Searches are performed at about 100 channels!

Combination Tevatron Searches









Tevatron Run II Preliminary, <L> = 5.9 fb-1
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 19, 2010
100
110
120
130
140
150
160
170
180
190
200
mH(GeV/c2)

Situation before LHC

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

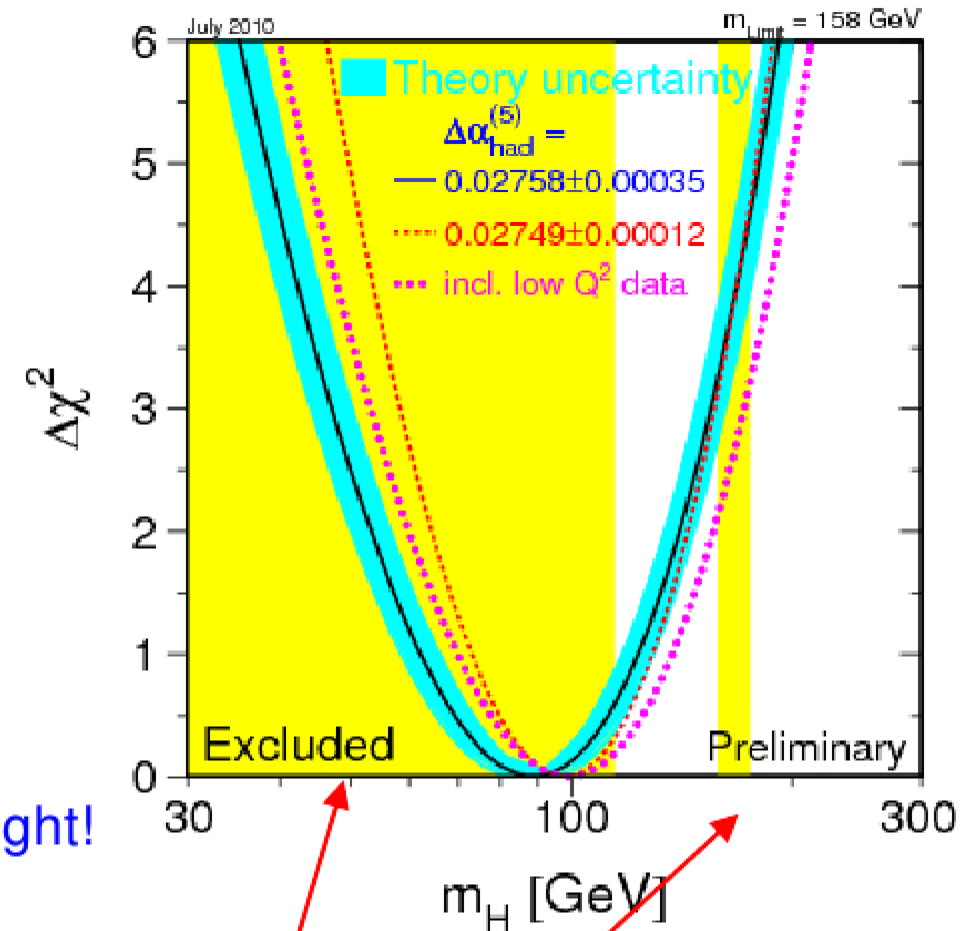
Fits to electro-weak data:

$m_H = 89^{+35}_{-26}$ GeV

$m_H < 158$ GeV (95% CL)

Assumption for fit:

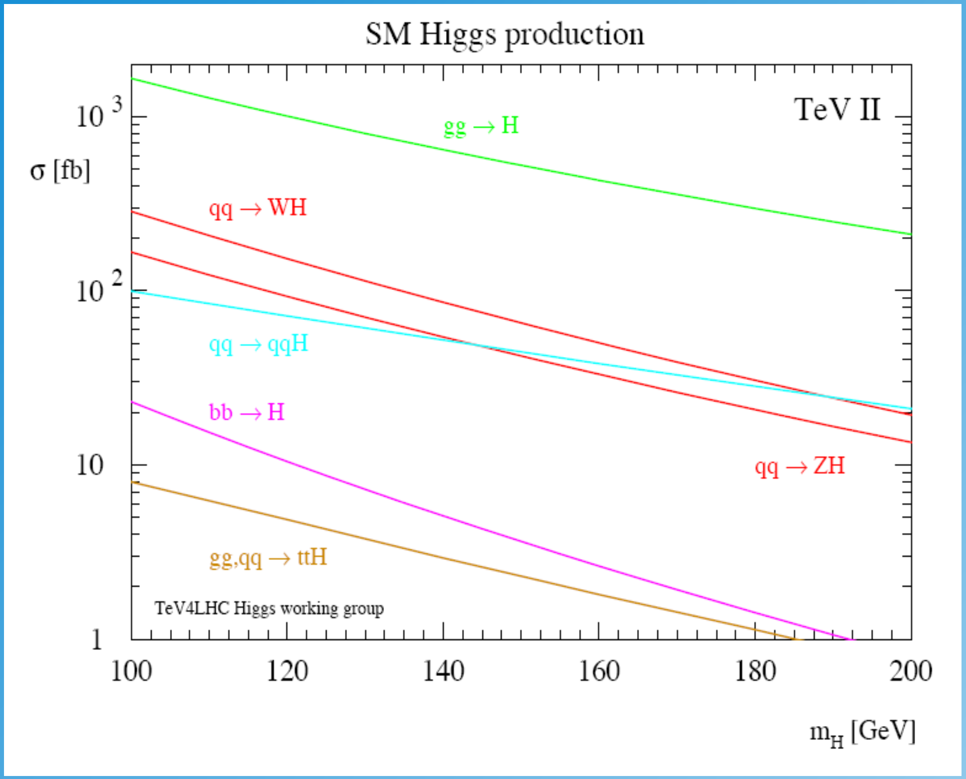
- SM including Higgs



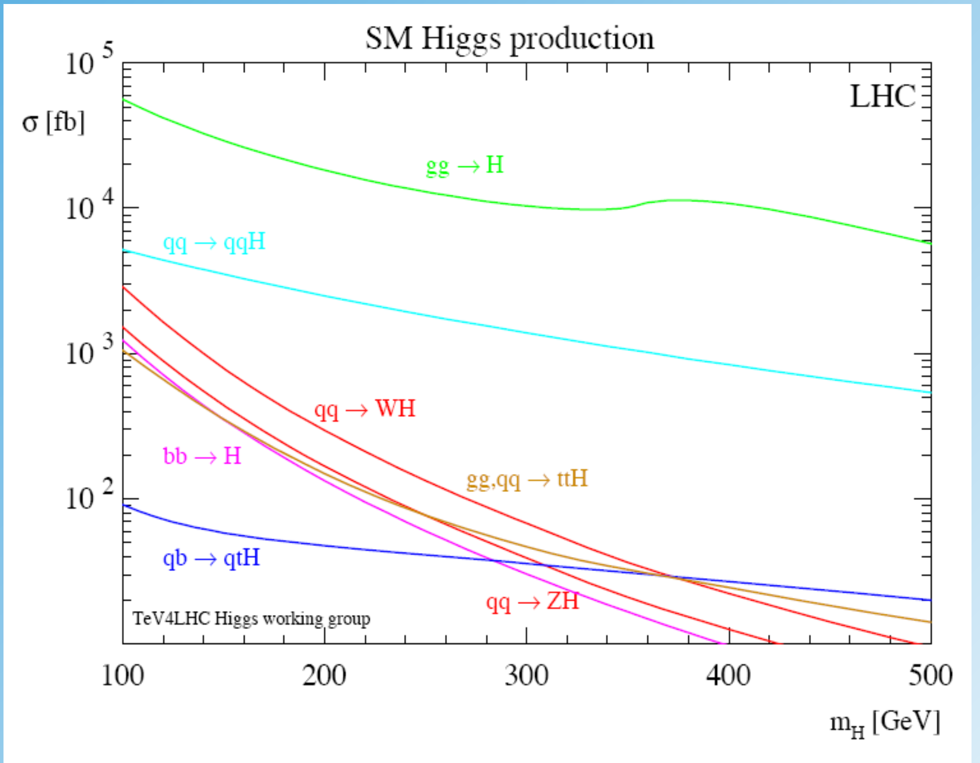
If existing, Higgs seems to be light!

- Direct searches at LEP: $m_H > 114.4$ GeV @ 95 % CL
- Direct searches at Tevatron

Higgs Production at LHC



proton-antiproton at Tevatron $s^{1/2}$=2 TeV

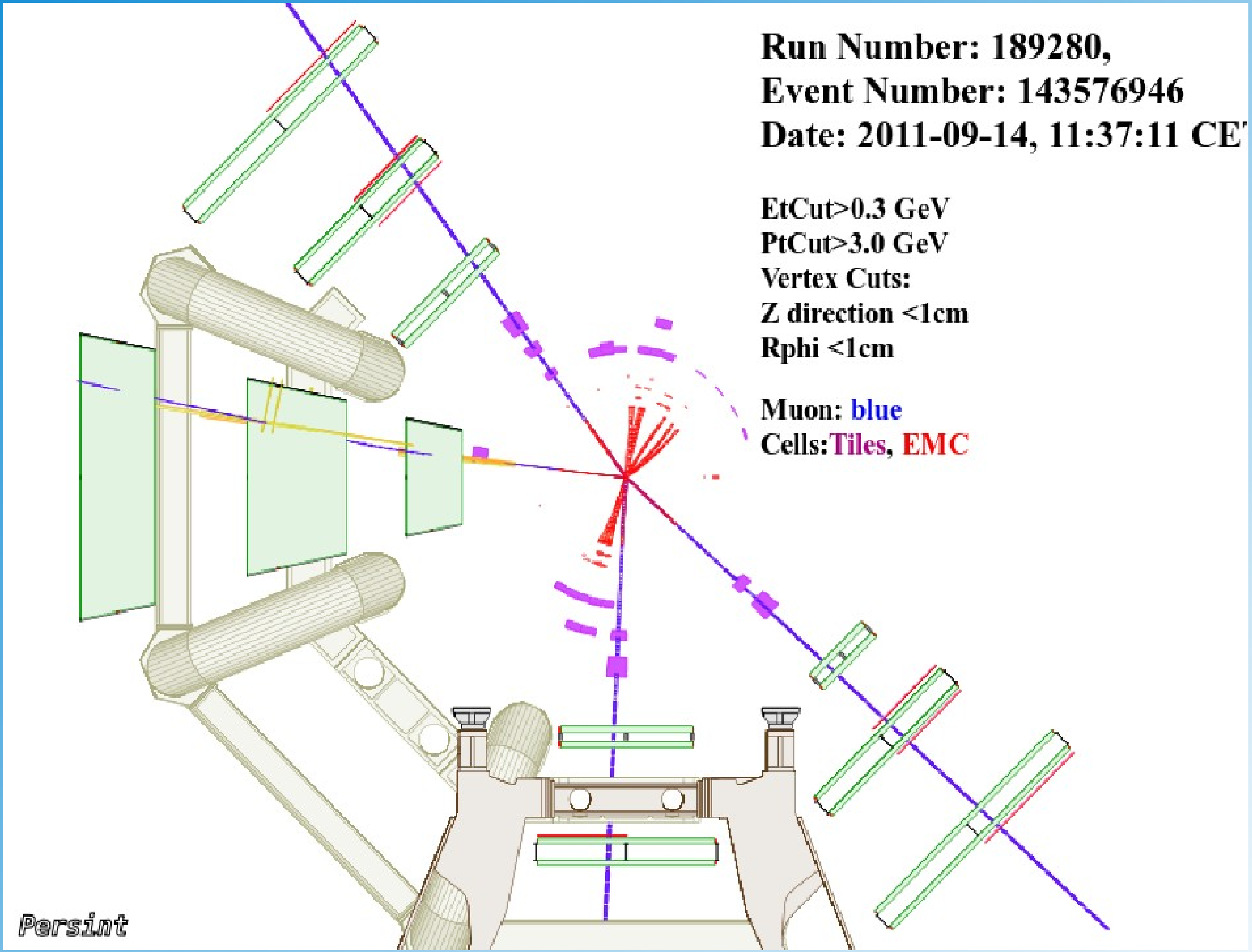


proton-proton at LHC $s^{1/2}$=14 TeV

much larger cross sections!

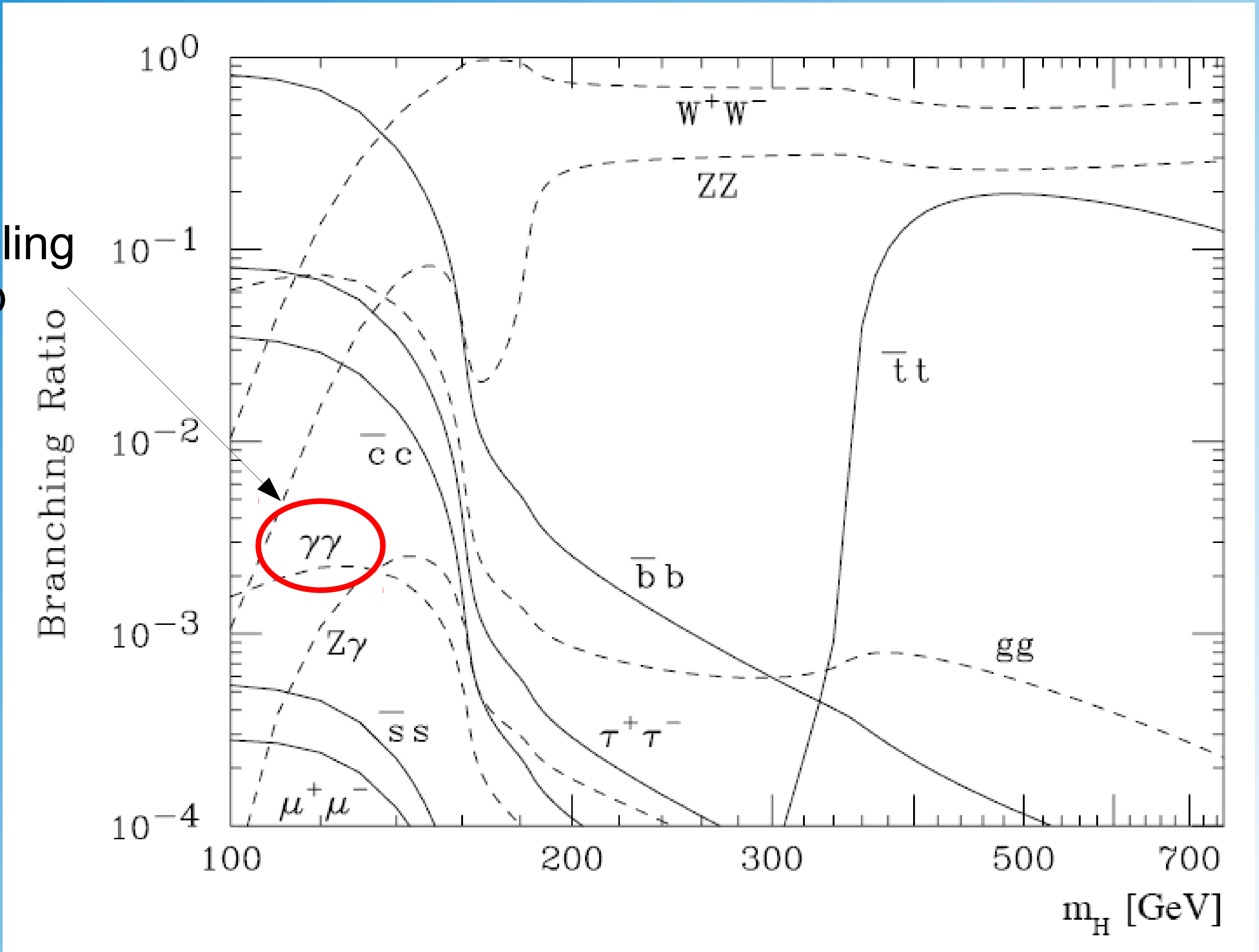
also higher luminosity!

Candidate H → ZZ → μμμμ

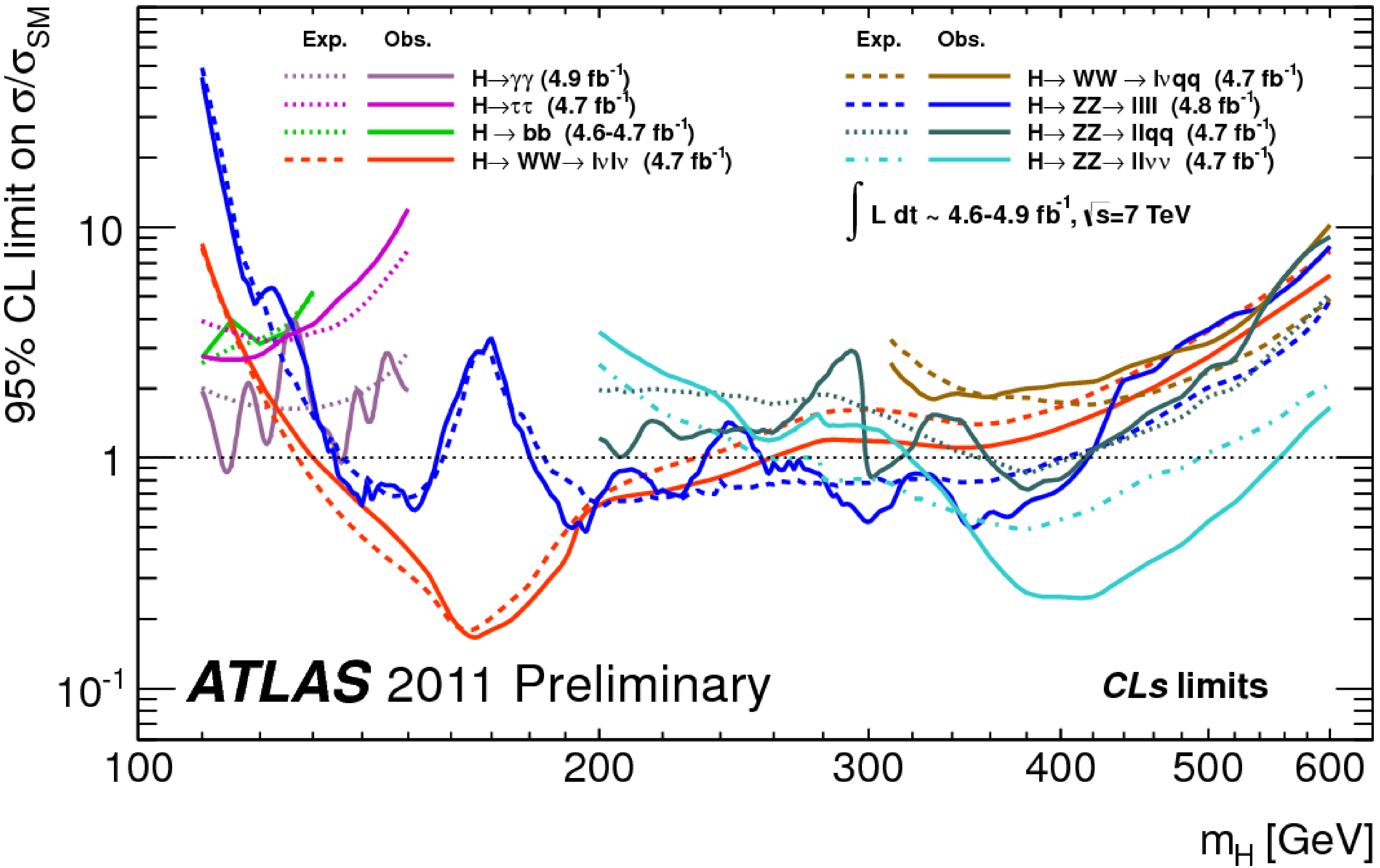


Special Channel $H \to \gamma\gamma$ (high inv. mass resolution)

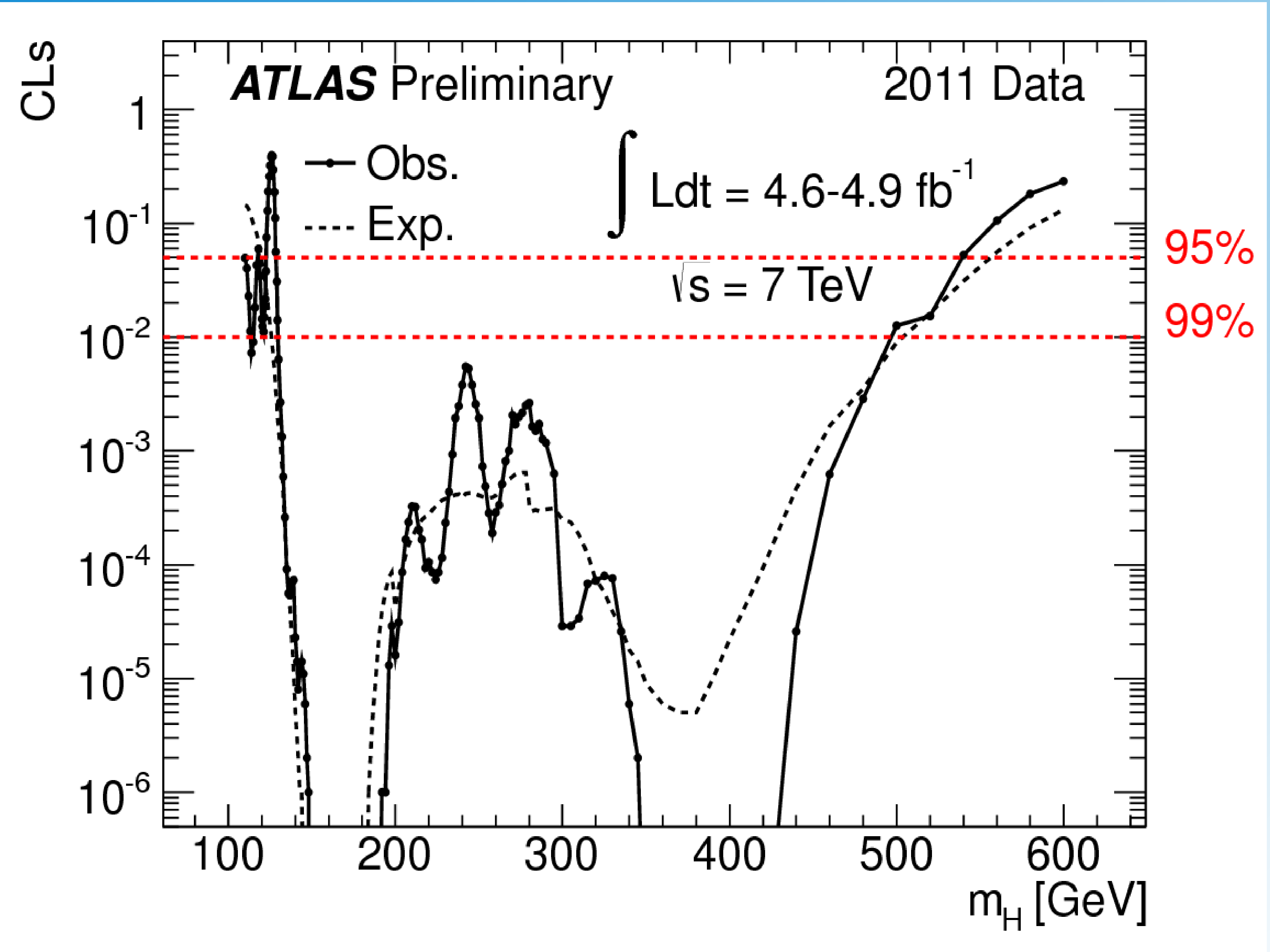
Higgs coupling via top loop



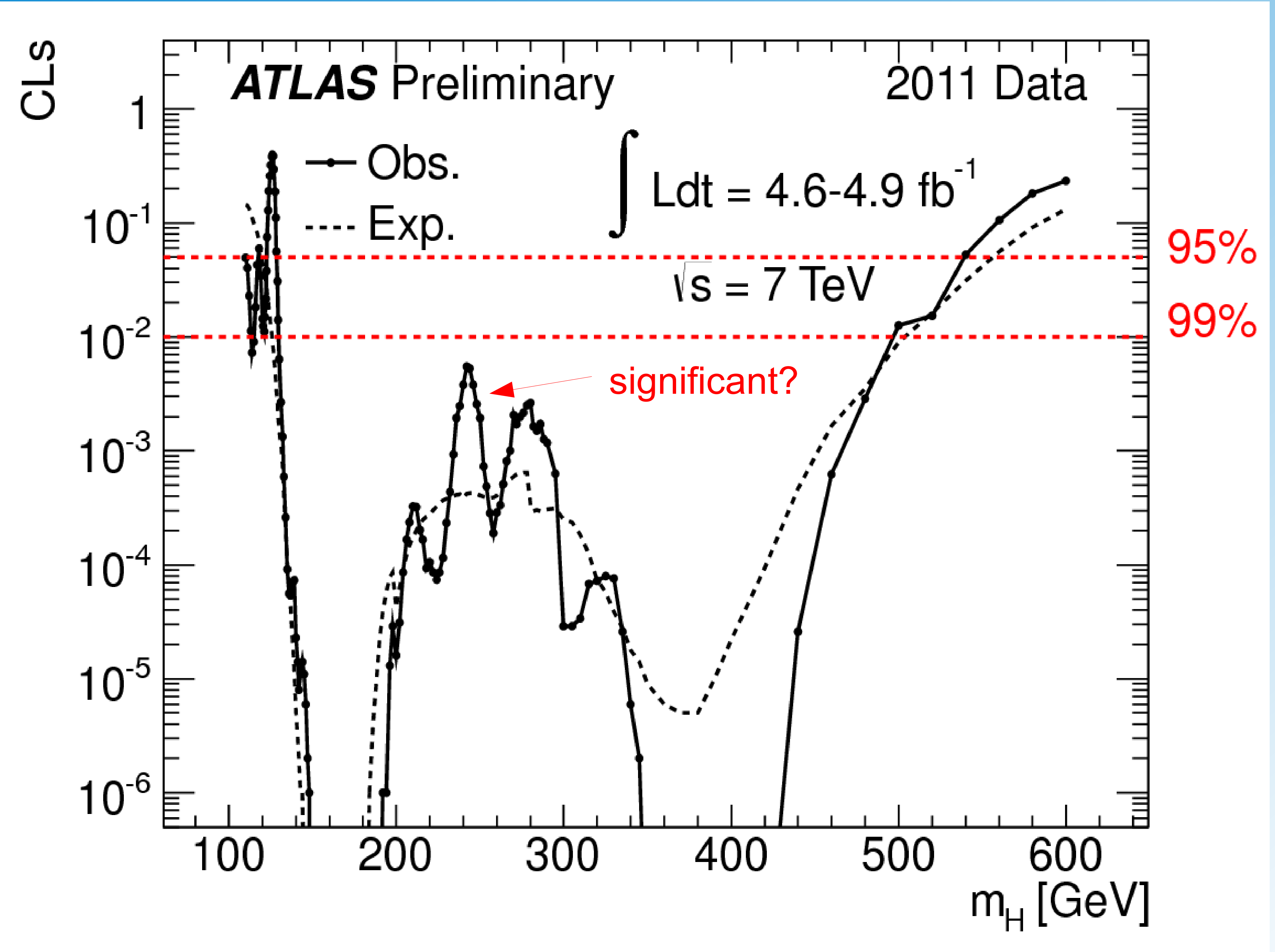
Summary ATLAS Searches



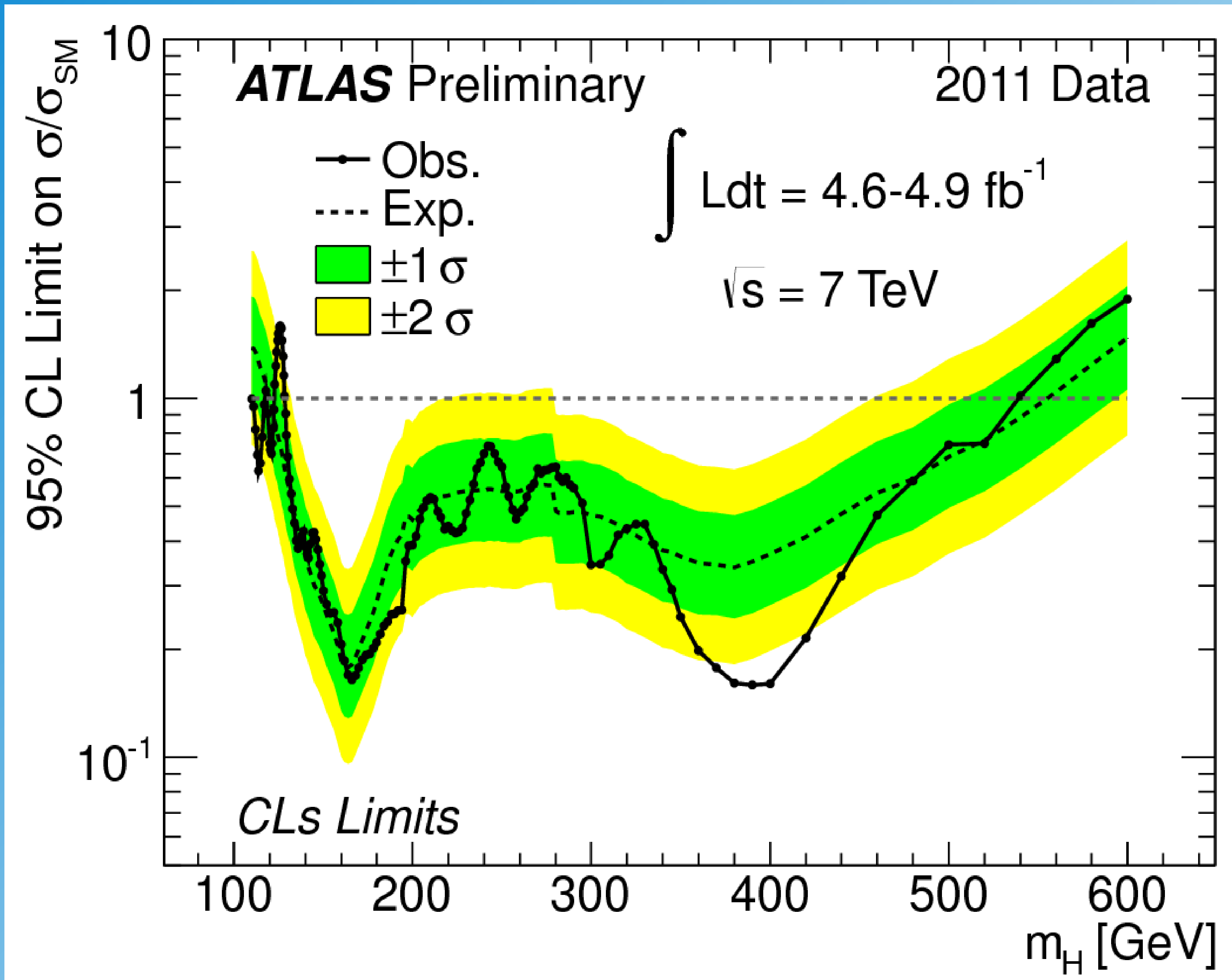
ATLAS Combined Result



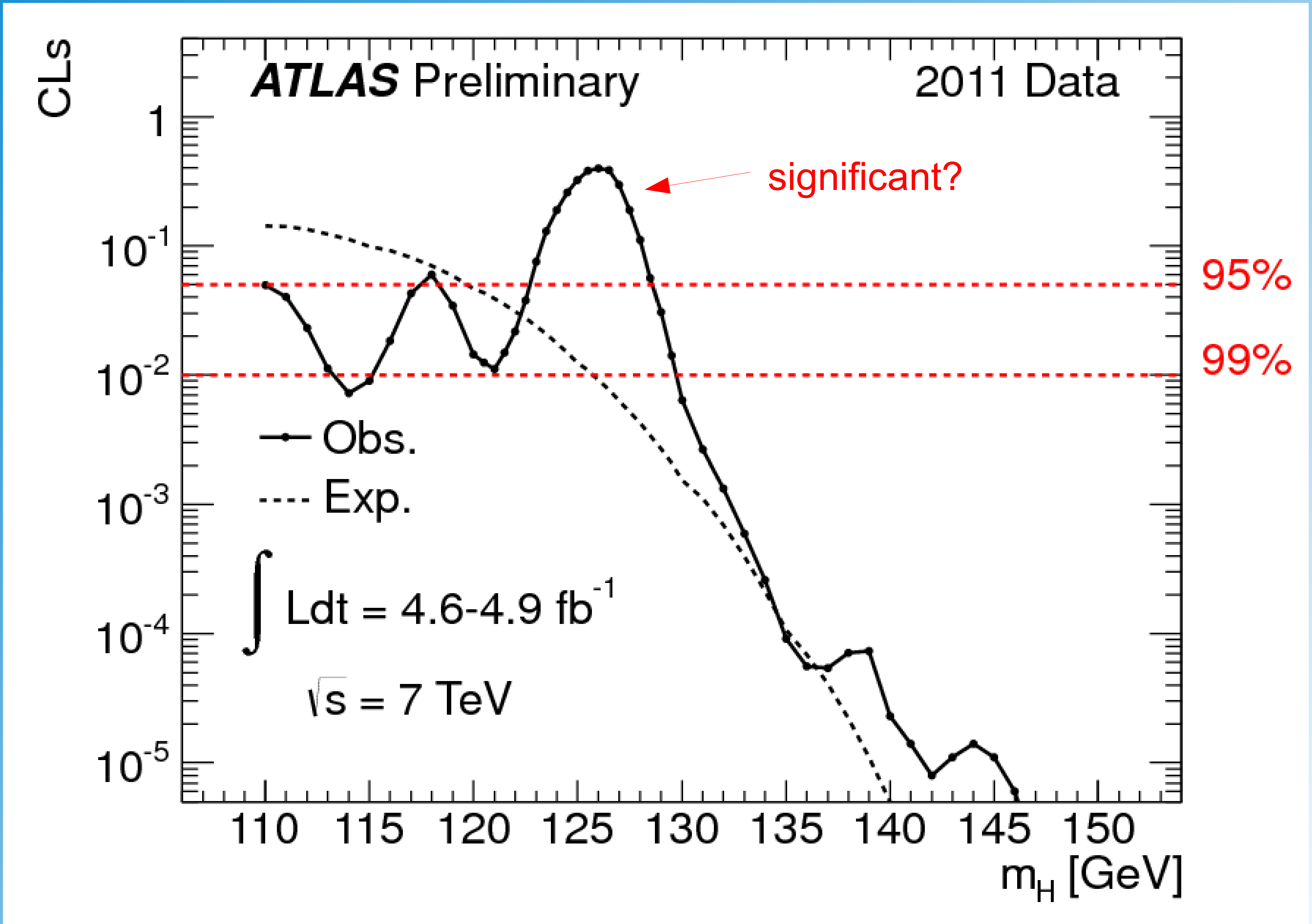
ATLAS Combined Result



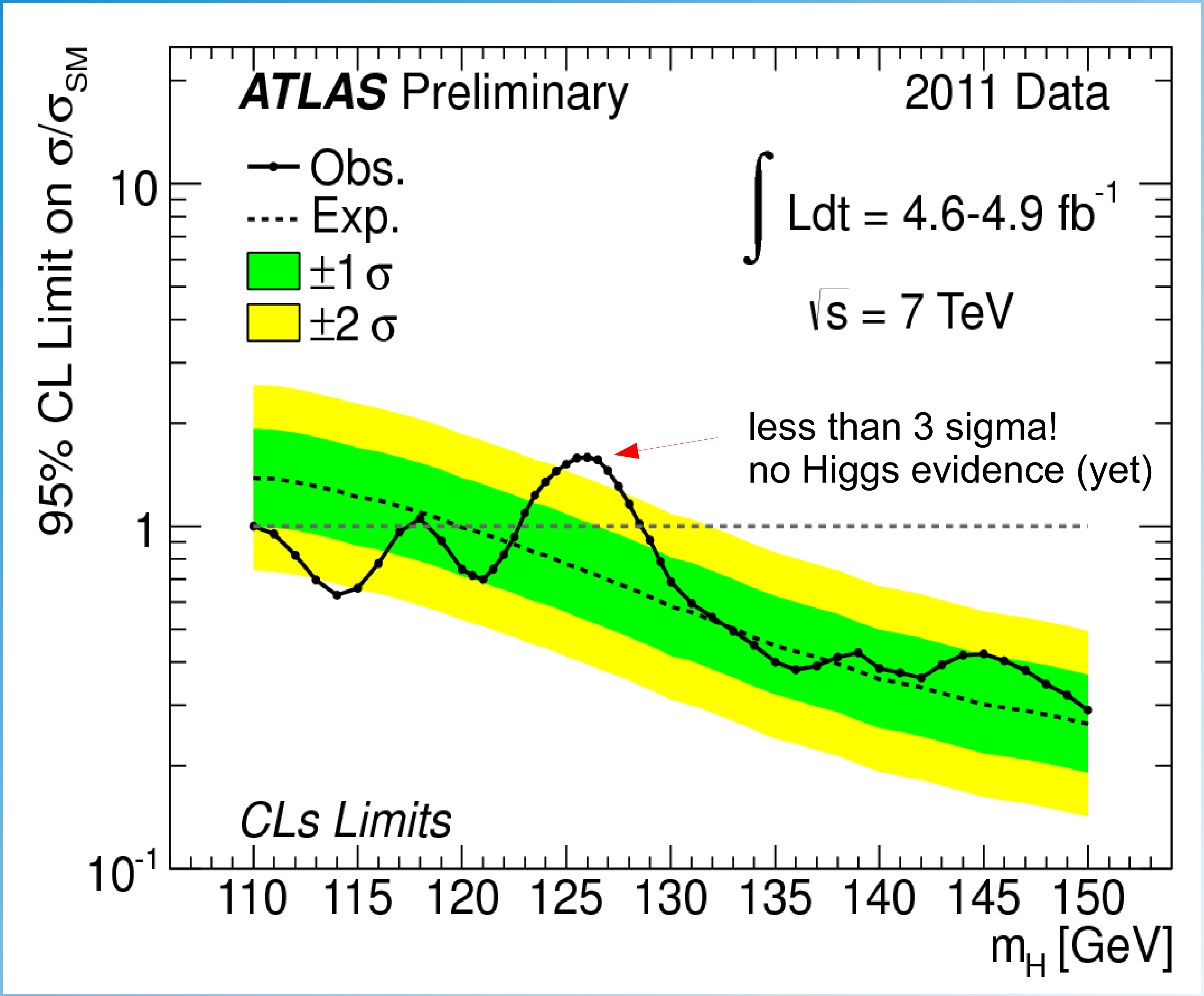
ATLAS Combined Result



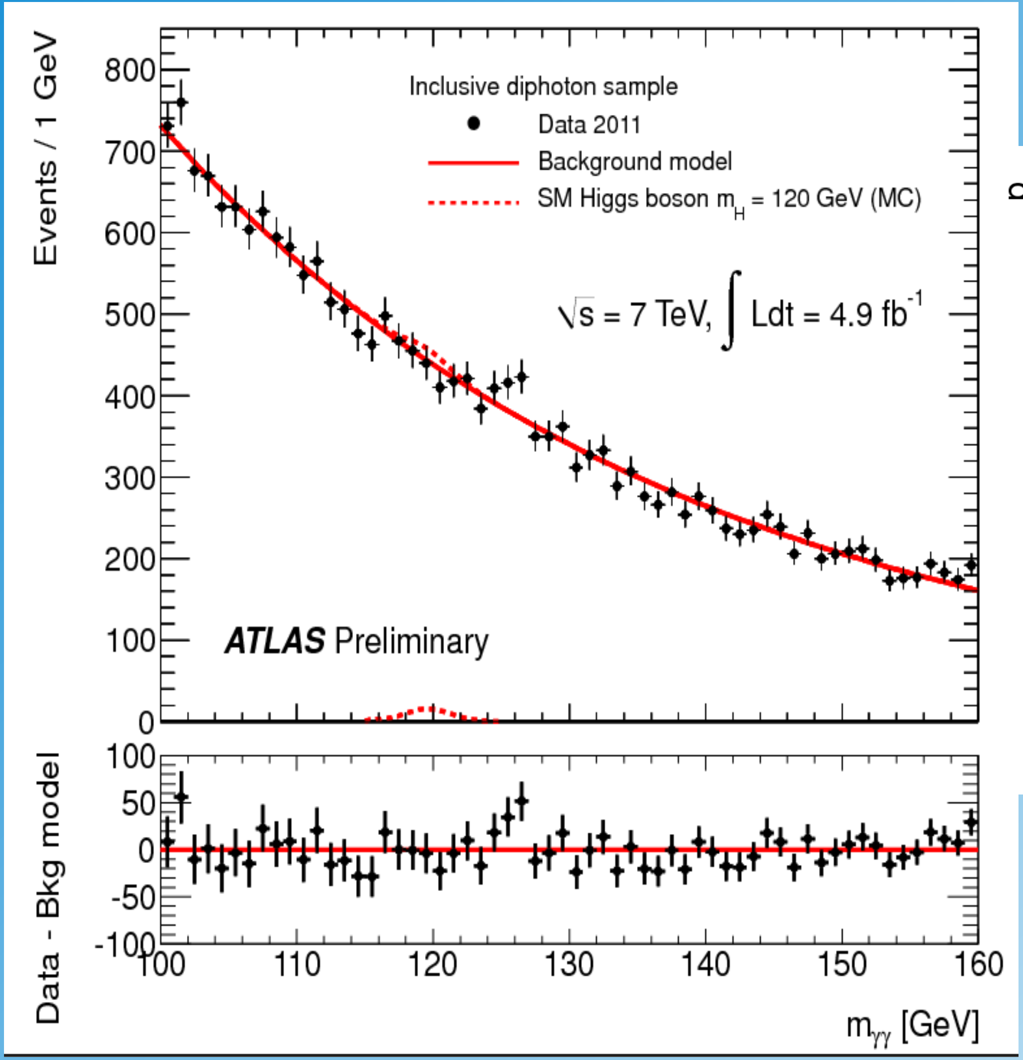
ATLAS Combined Result

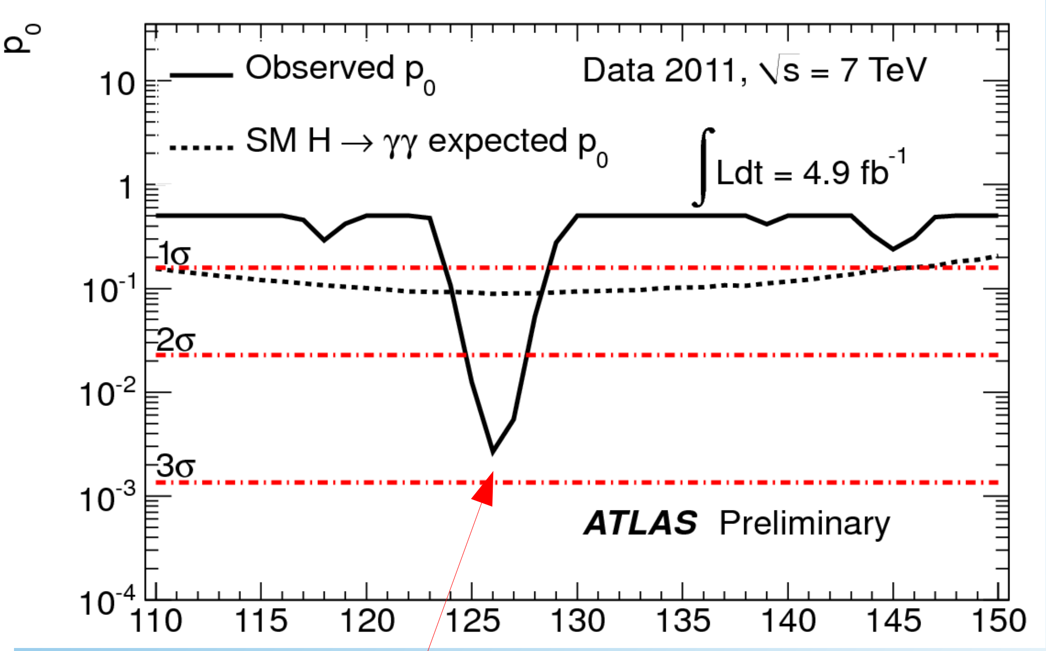


ATLAS Combined Result



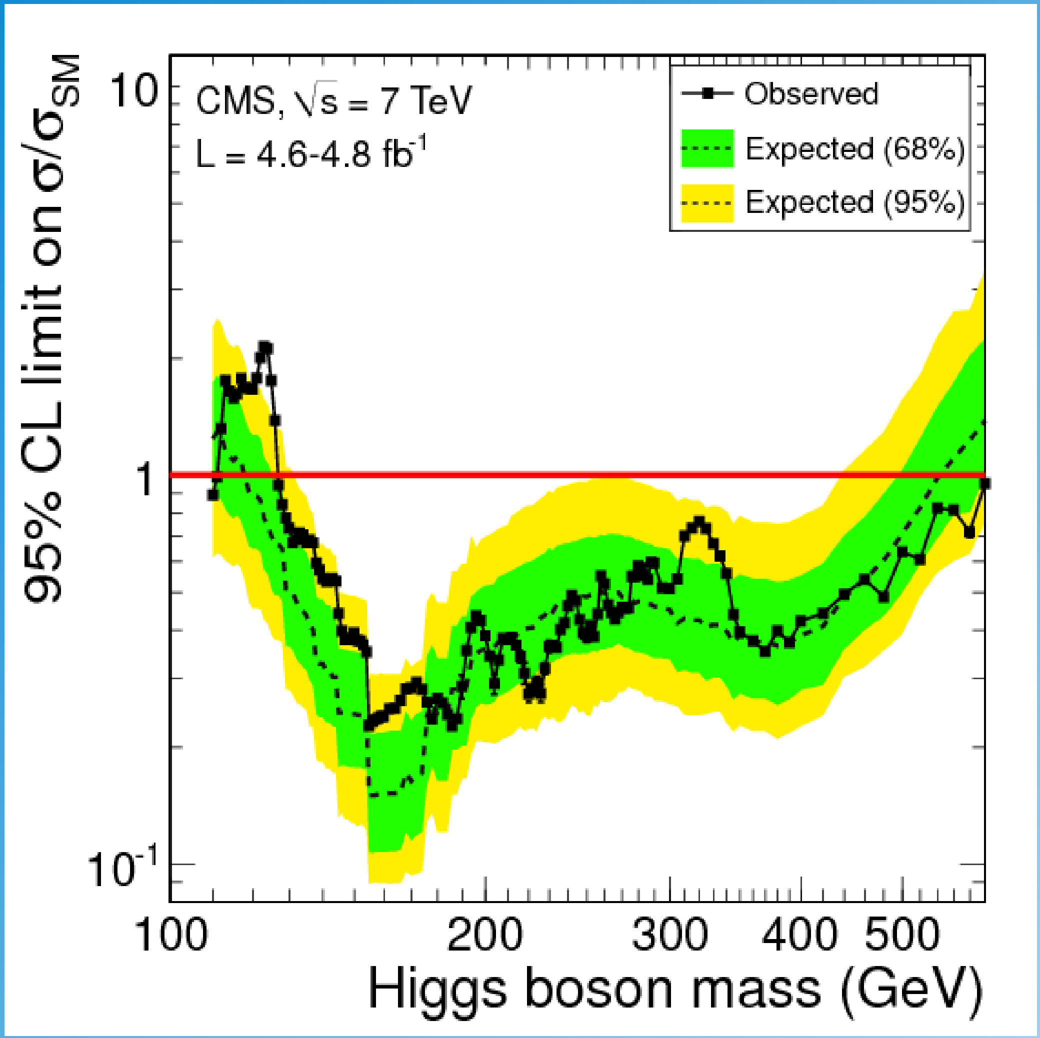
Higgs → γγ Search

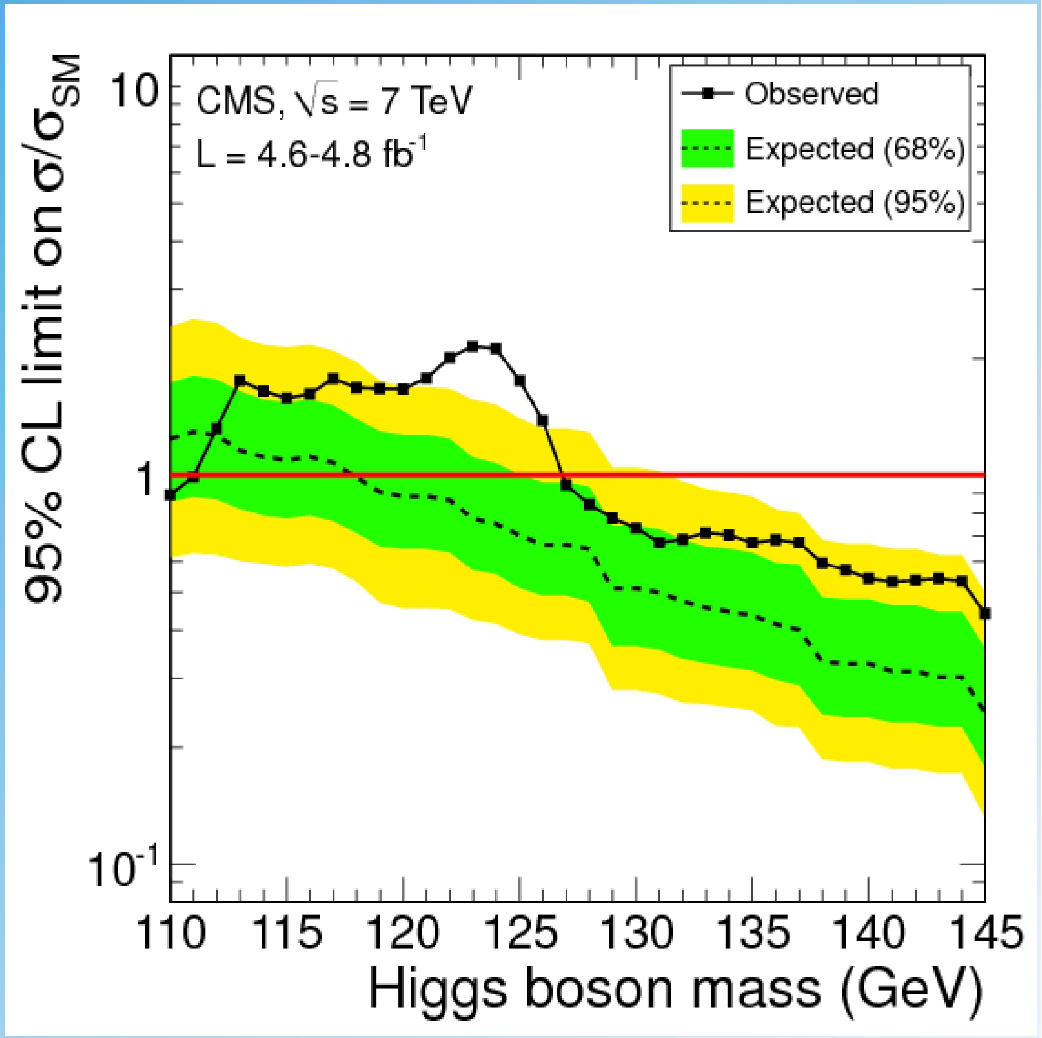




note, signal too strong for Higgs!

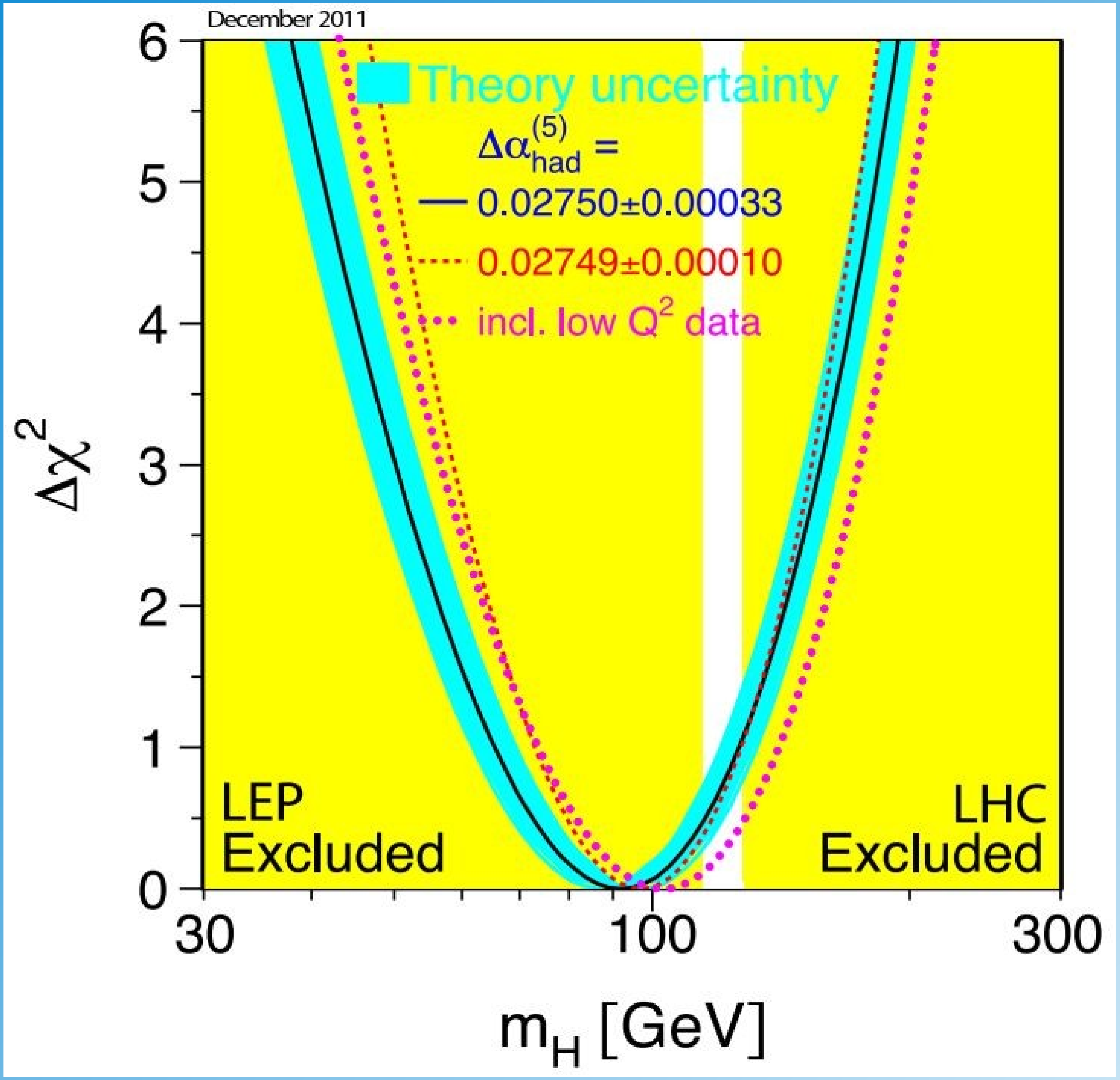
CMS Higgs Search (2011 data)





very consistent with ATLAS results, Higgs?

Situation in June 2012
(before summer conferences)

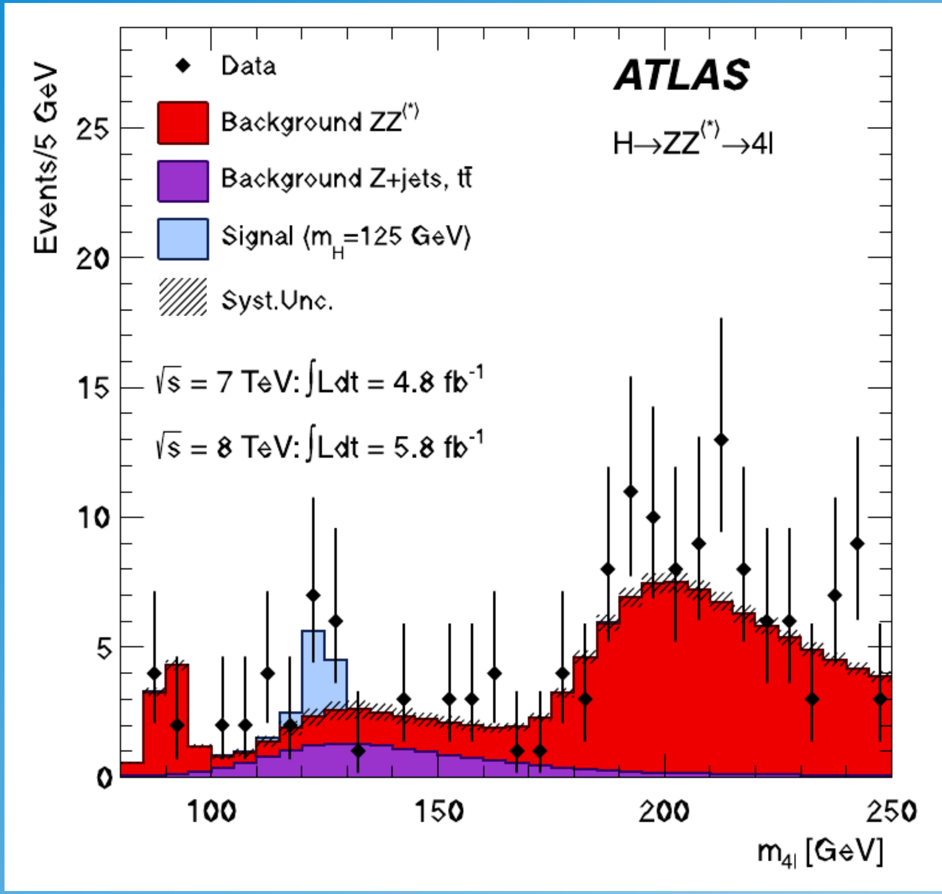


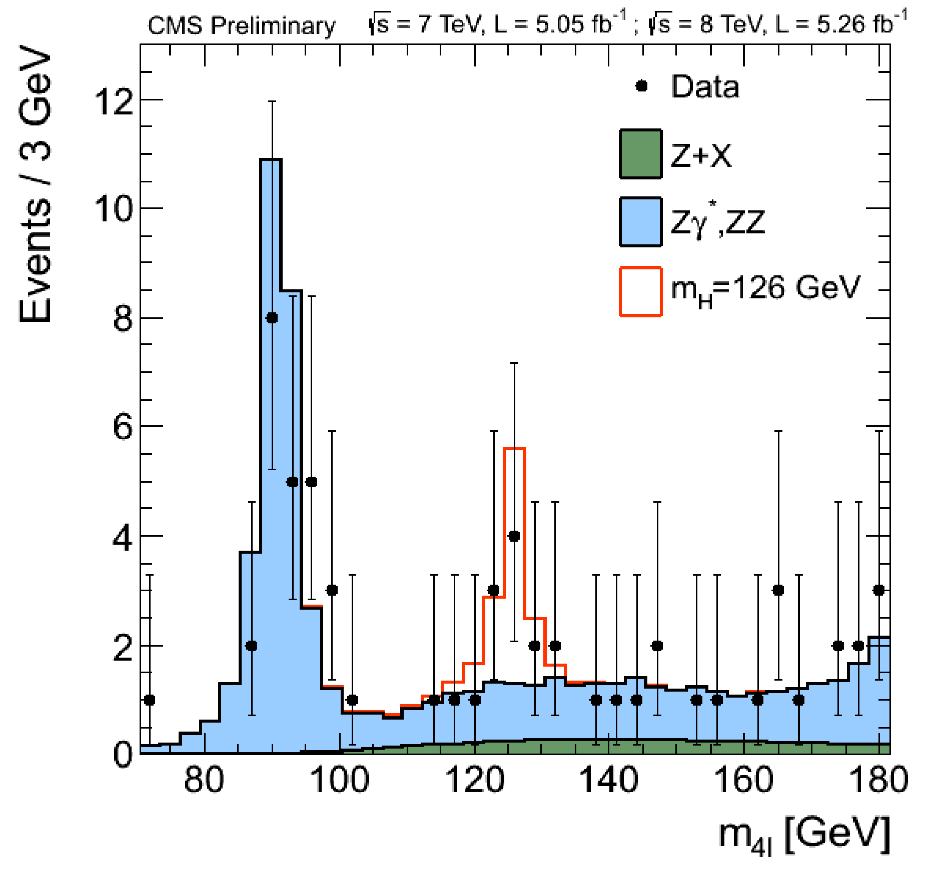
Non-excluded region is the most difficult!

small window around 125 GeV not excluded at 95% CL

→ Updates July 4th 2012!

Results from ATLAS+CMS

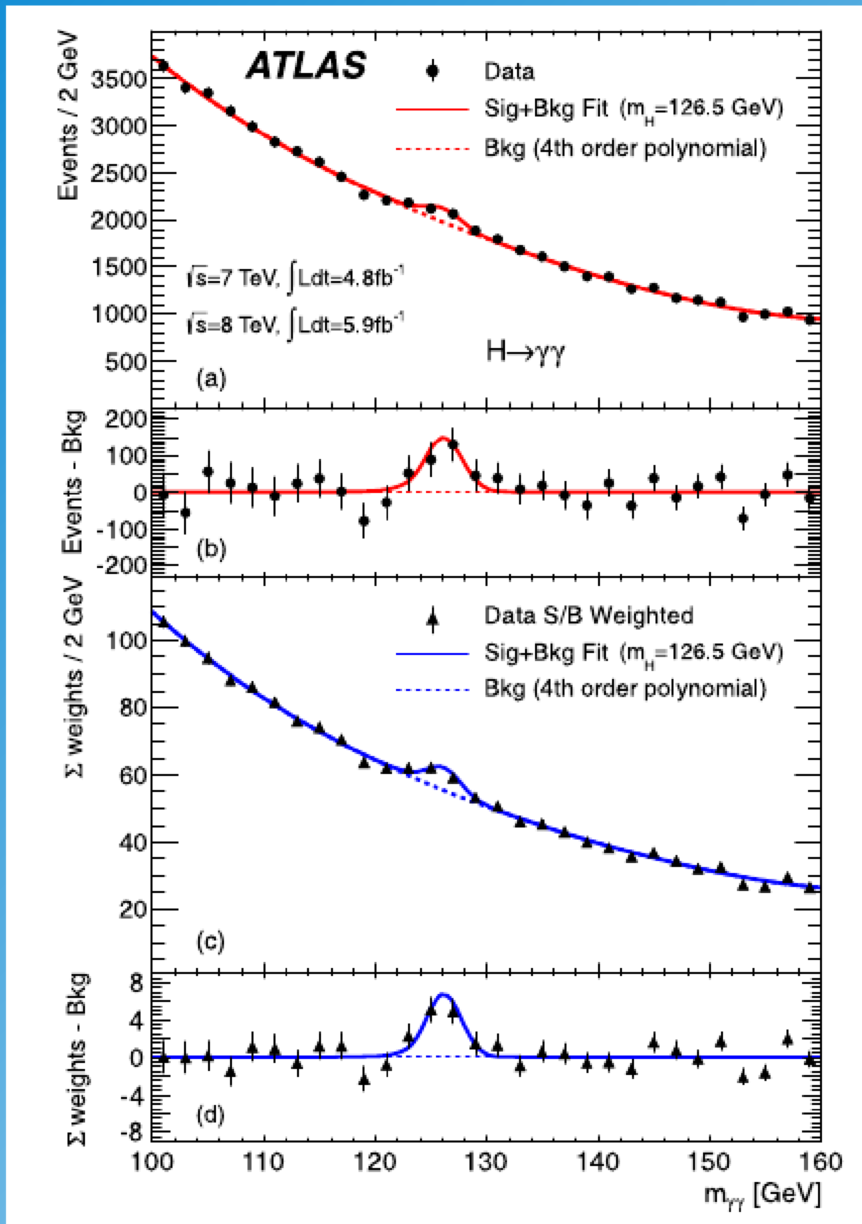




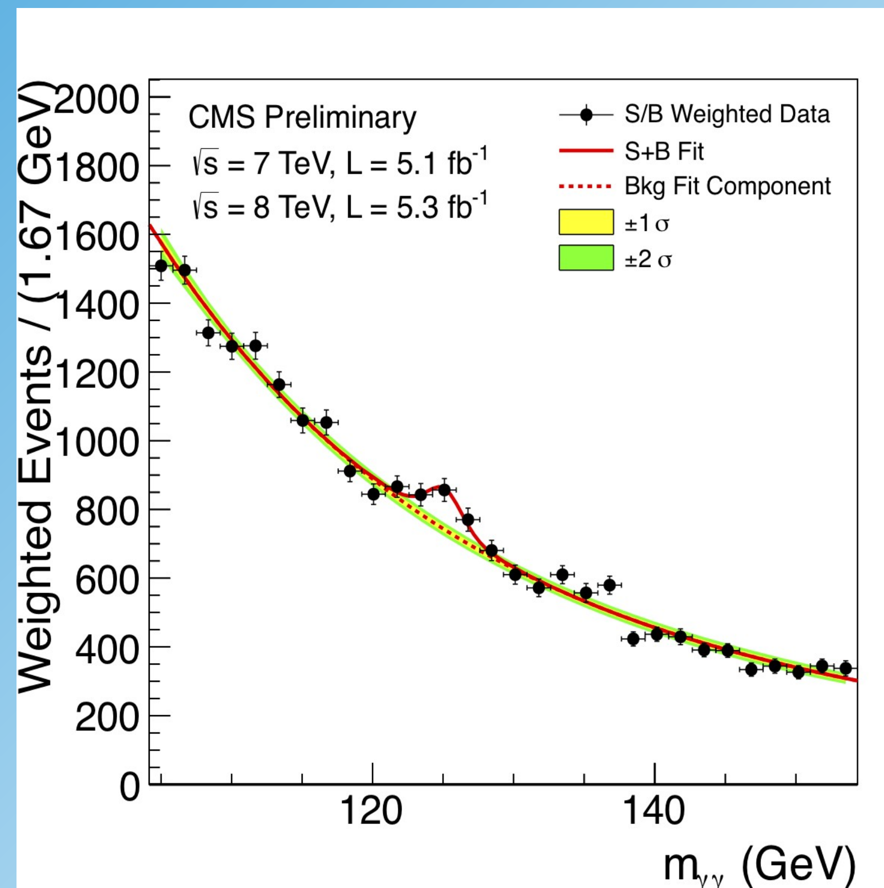
$H \to ZZ \to$ leptons

Growing Signal $H \rightarrow ZZ$

Results from ATLAS+CMS

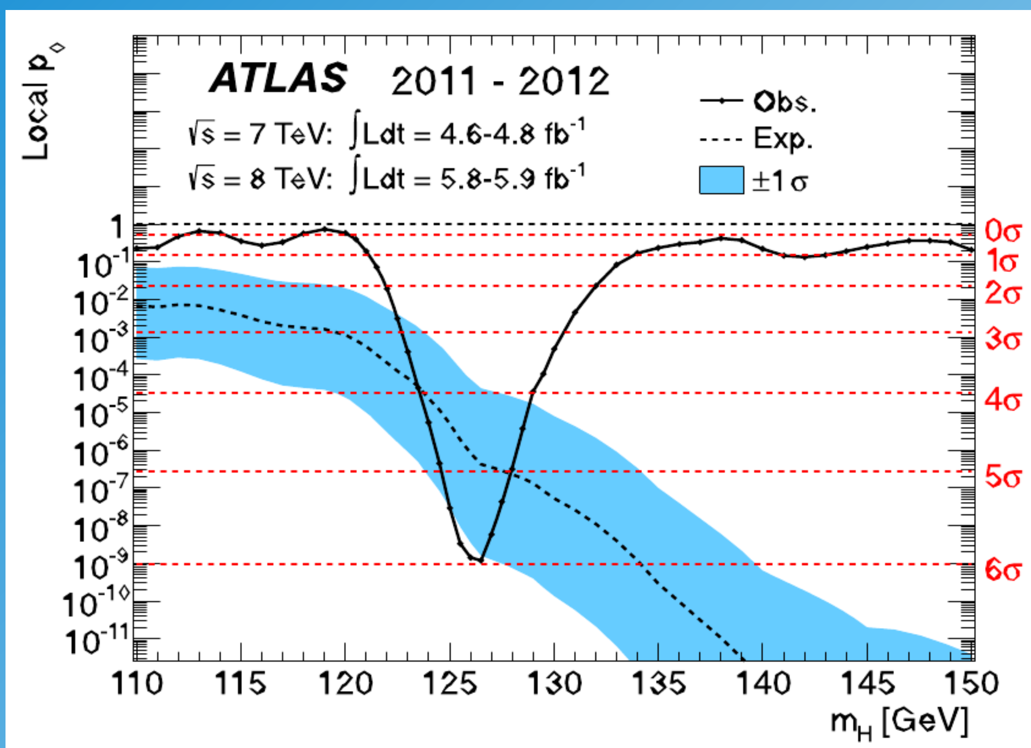


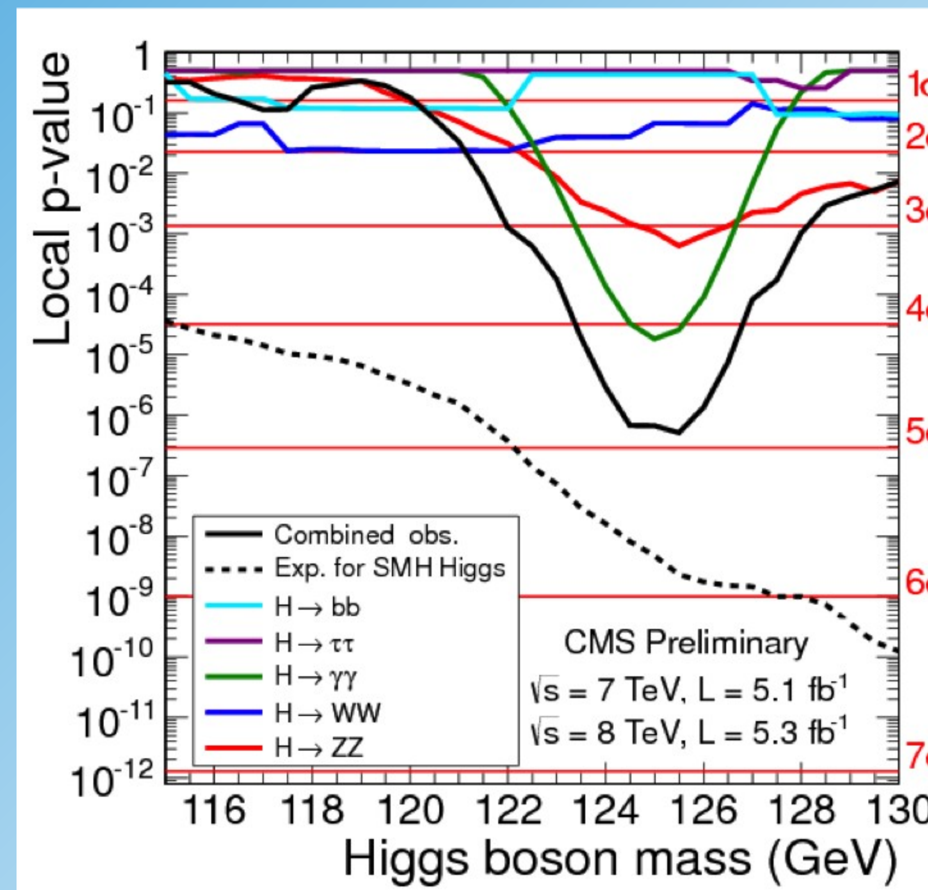
H → gamma gamma



Results from ATLAS+CMS

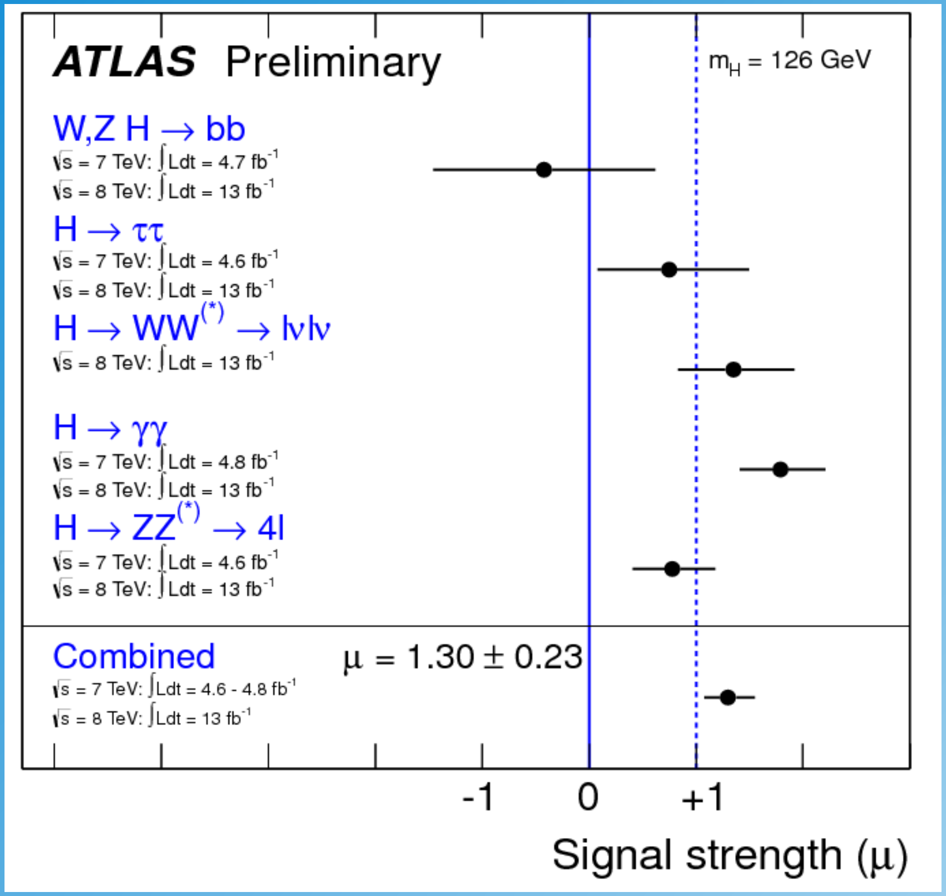
Combined local probabilities

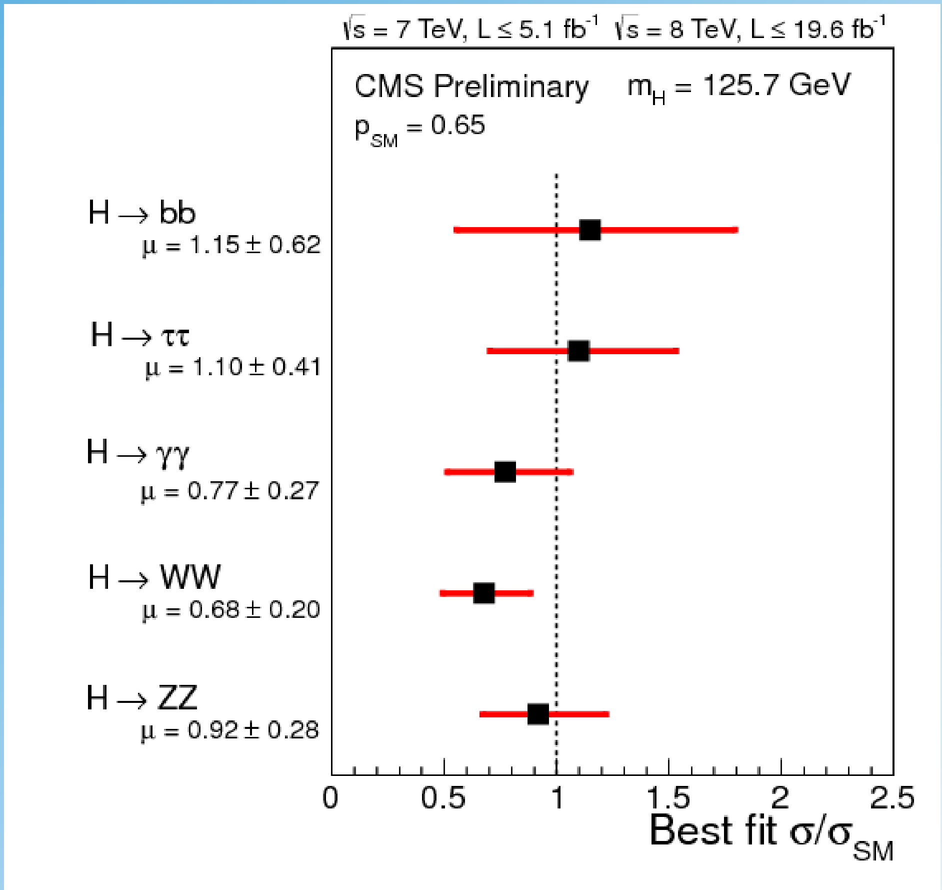




Note: difference between local and global probabilities!

Some First Higgs Decay Results from ATLAS+CMS





Couplings strengths consistent with SM expectation

Summary

- Indirect constraints predict a light Higgs in the Standard Model
- Experimentally a Higgs with m_H~ 125 GeV is most difficult too find
- Direct searches exclude (June 2012) Higgs except for a small region around m_H~125 GeV
- Excess of Higgs candidate events at m_H~125 by ATLAS and CMS. More events are seen than expected by SM Higgs model.
- Interestingly, m_H~125-130 GeV is theoretically also favored by vacuum stability and triviality reasons.
  No new physics required up to very high mass scales!
- At m_H~125 GeV Higgs almost all decay channels can be measured

→ allows for many experimental tests
→ nature is very kind to particle physicists!