Lecture:

Standard Model of Particle Physics

Heidelberg SS 2013

Tests of the Standard Model II

Contents

- Intro: Statistics and limit setting
- Higgs Mass Predictions
- Higgs Searches at LEP
- Higgs Searches at Hadron Colliders
- WW-Scattering Amplitude

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:

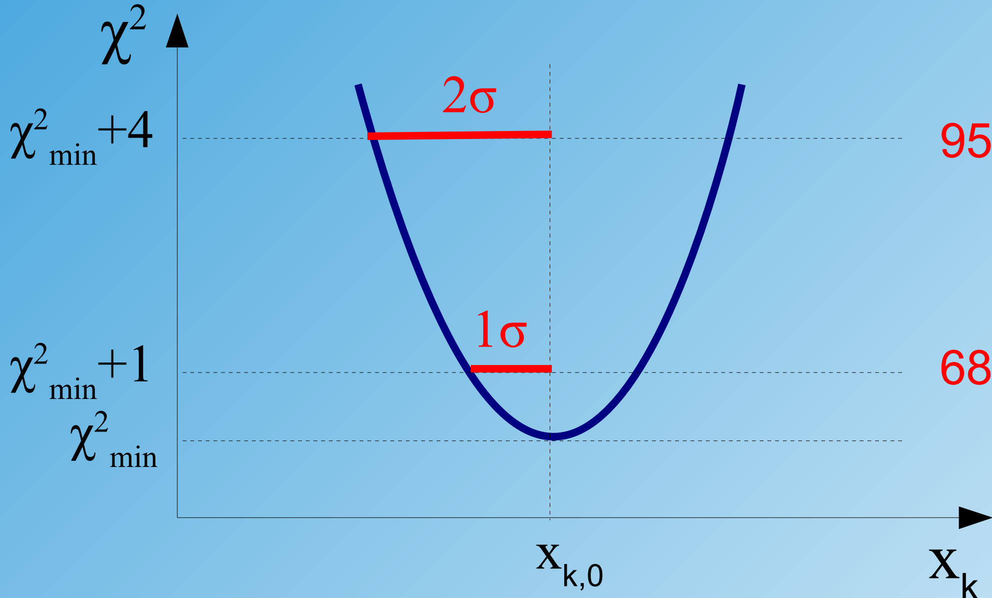
$$\chi^2 = \sum_i \sum_j (y_i - \mu_i) cov_{ij}^{-1} (y_j - \mu_j)$$

cov_{ij} covariance (error) matrix

Parameter Fit:

$$\mu_i = \mu_i(x_{1,} x_{2,} \ldots, x_n)$$

x_k model parameter



95% confidence level

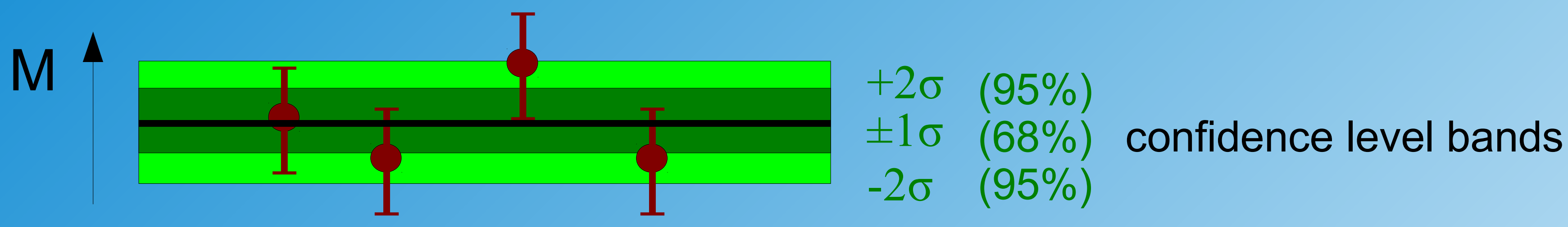
68% confidence level

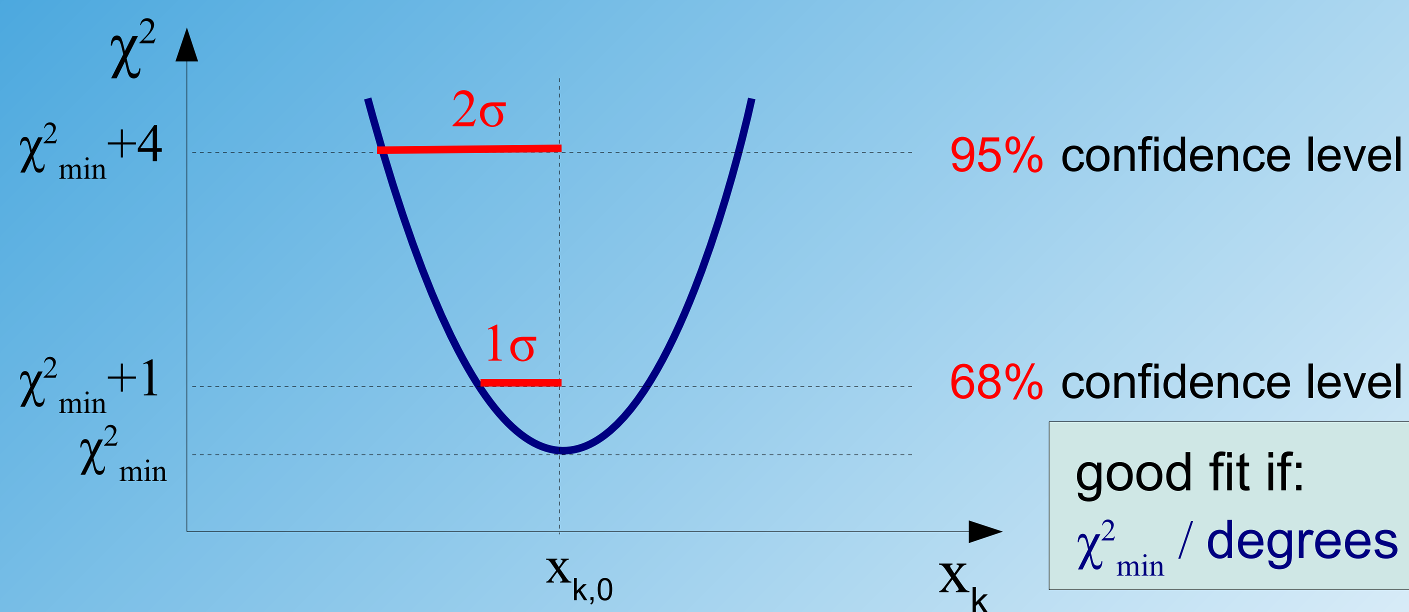
good fit if:

χ^2_{min} / degrees of freedom ~ 1

Example Fit

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





good fit if:

χ^2_{min} / degrees of freedom ~ 1

Probability Densities

for the above example a gaussian probability density was used

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)

Poissonan 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:

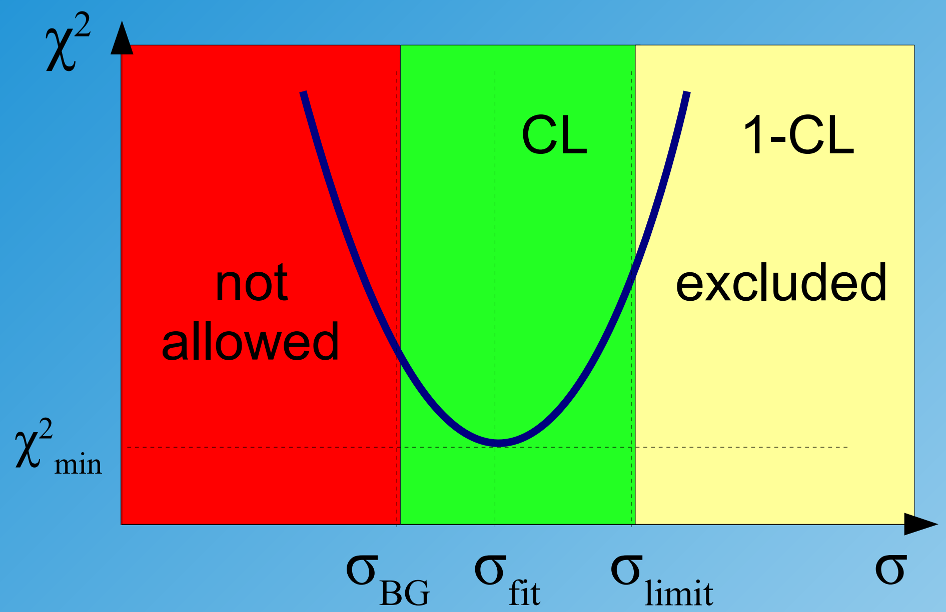
- based on Monte Carlo toy experiments probabilities are assigned to all possible experimental outcomes
- exclusion limit is set by that model which excludes this experimental outcome with certain confidence interval

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

Baysian Method

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

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



Probability:

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

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
- Choose alternatively coupling as prior

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

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

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

Result depends on choice of prior!

Frequentist Method

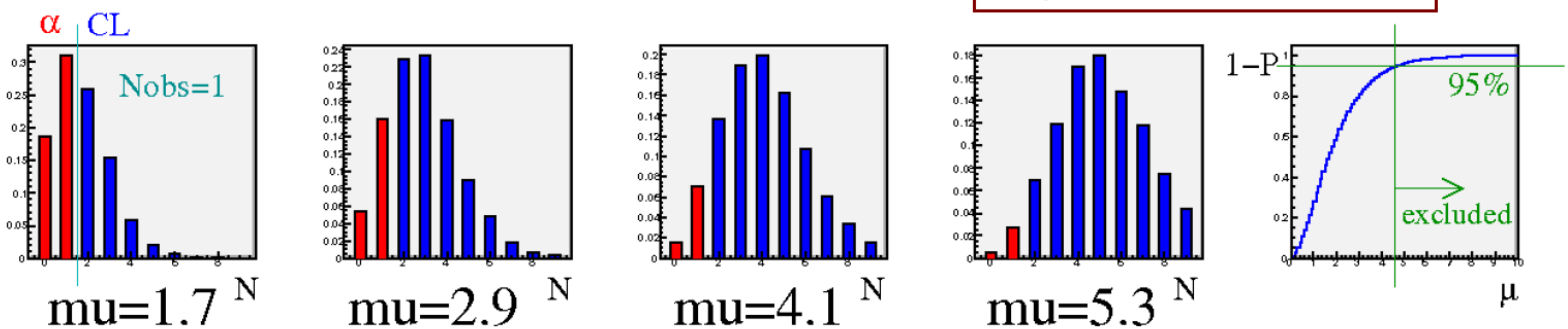
S.Schmitt

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

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

α: also called p-value

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



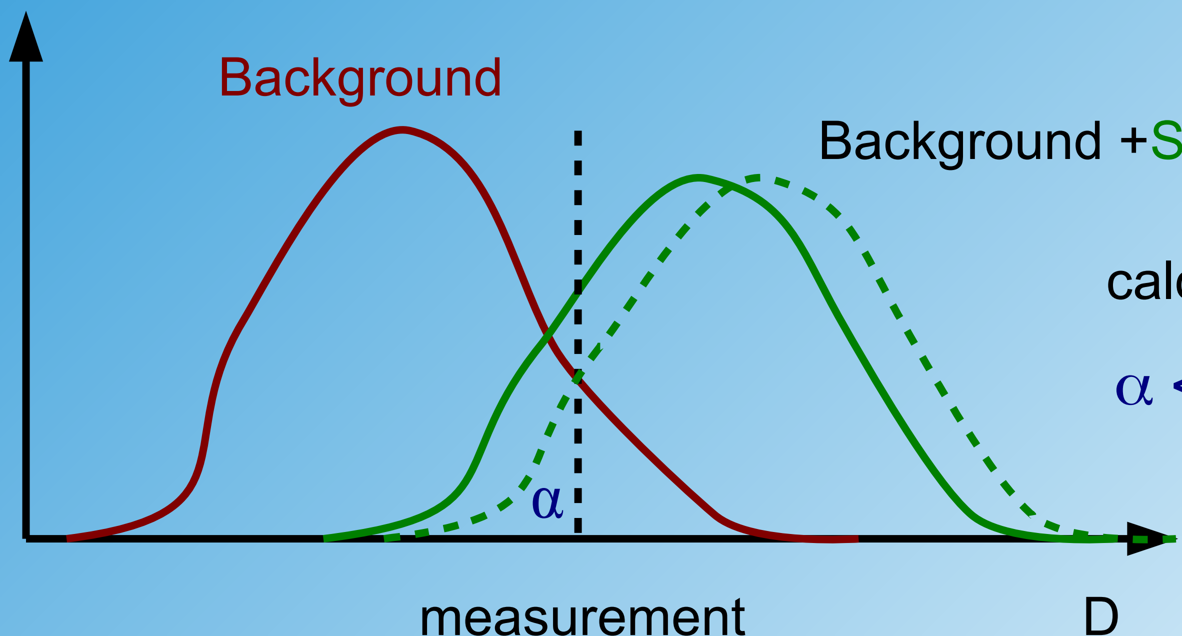
➜ set limit with 95% confidence level for mu=4.6
➜ experiment has a 5% probability to happen

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:

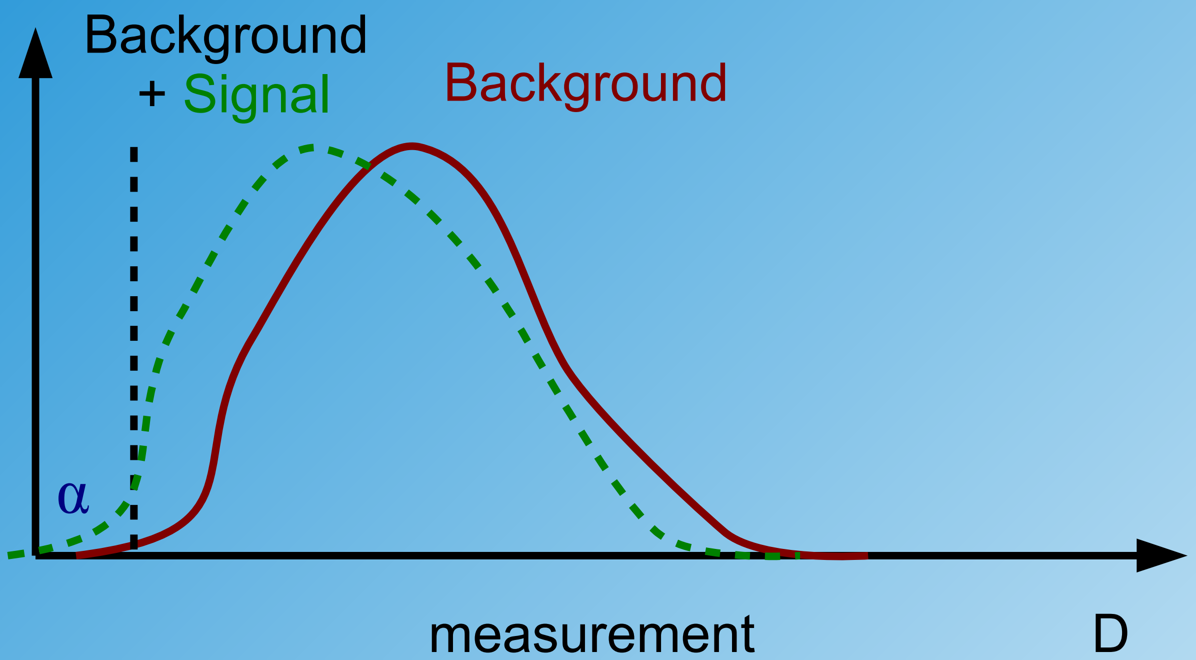
$\alpha < 1 - CL$

Problem with Frequentist Method

(same problem applies to Baysian Method as well)

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

- would require a negative signal cross section:



unphysical solution!

CL_S Method

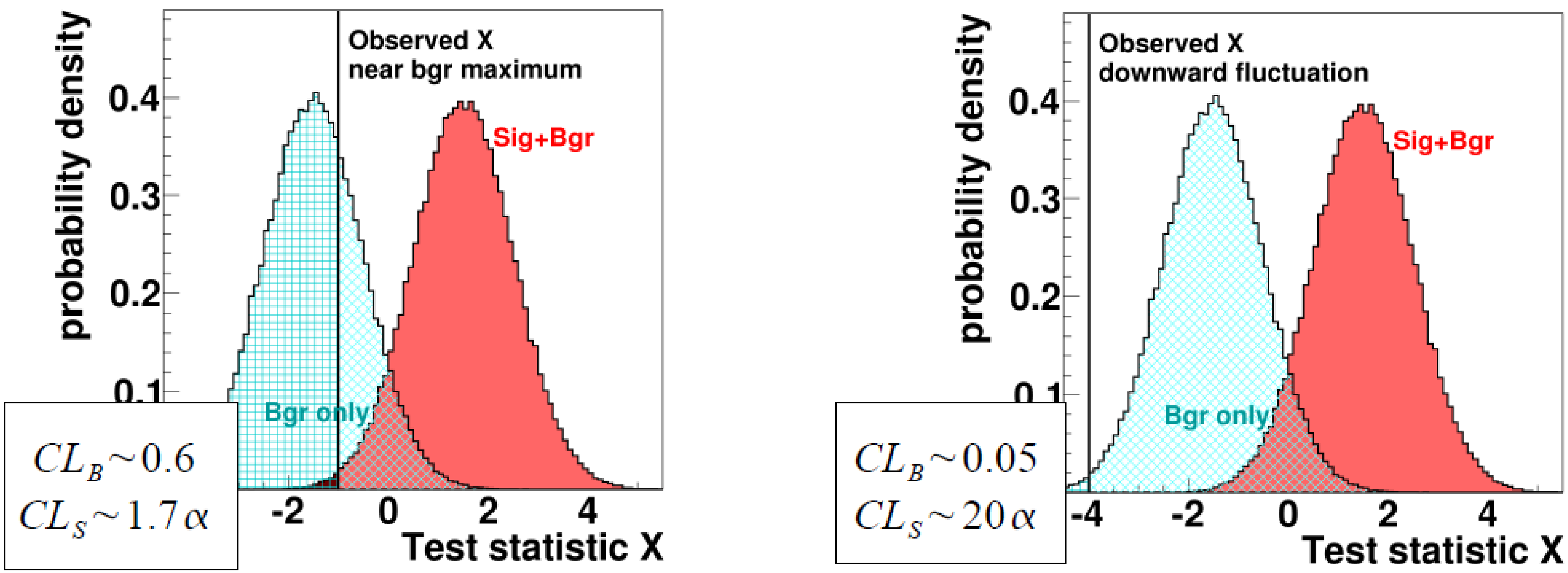
- Use ratio of two probabilities CL_S instead of α to test against CL

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

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

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

- Standard model has CL_S=1 and is never excluded



S.Schmitt

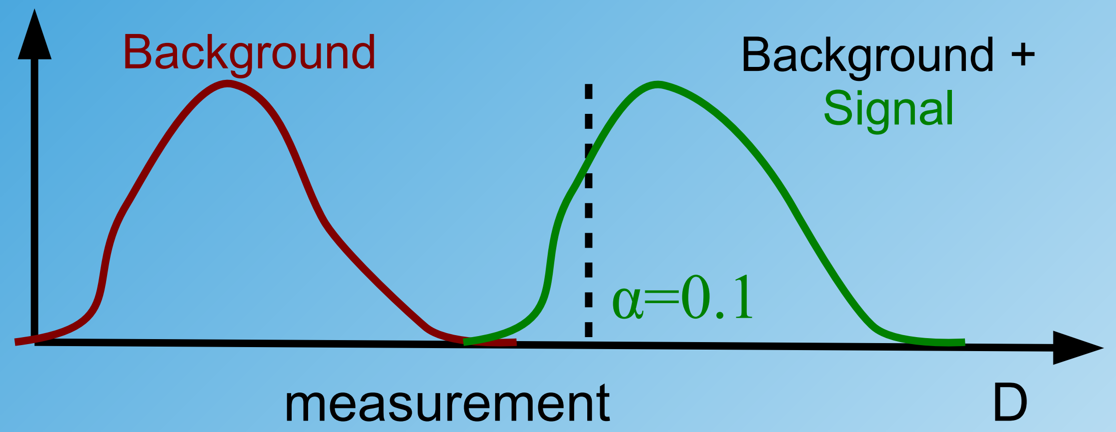
$CL_S > CL_{SB}$ by definition!

Another Example CL_S Method

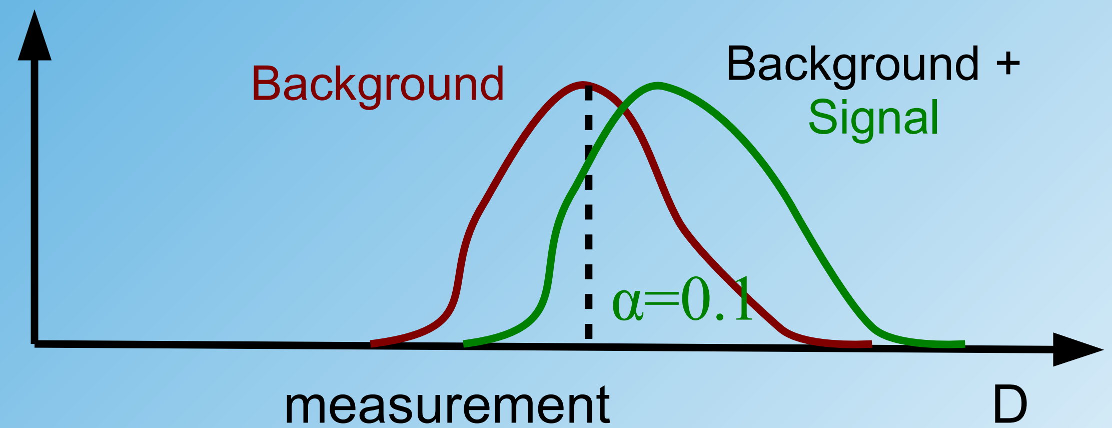
Definition:

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

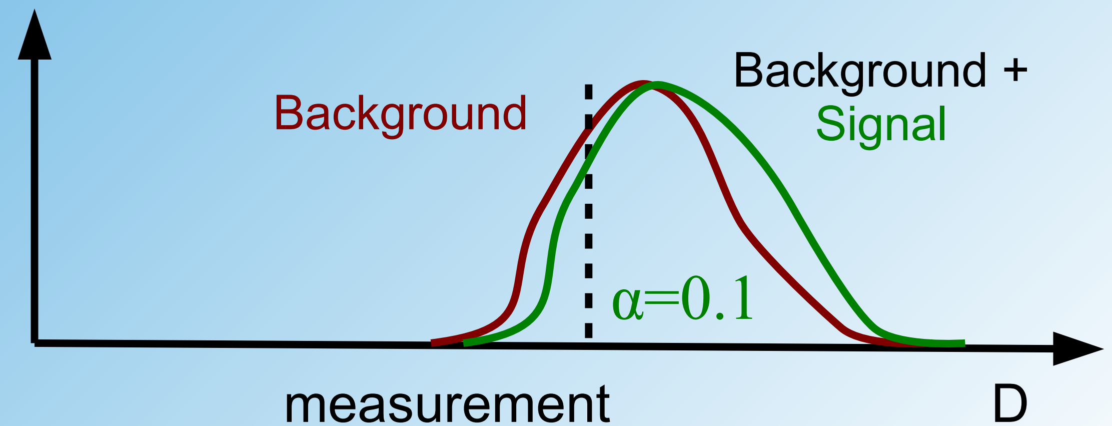
$$0.1 = \frac{0.1}{1.0}$$



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



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

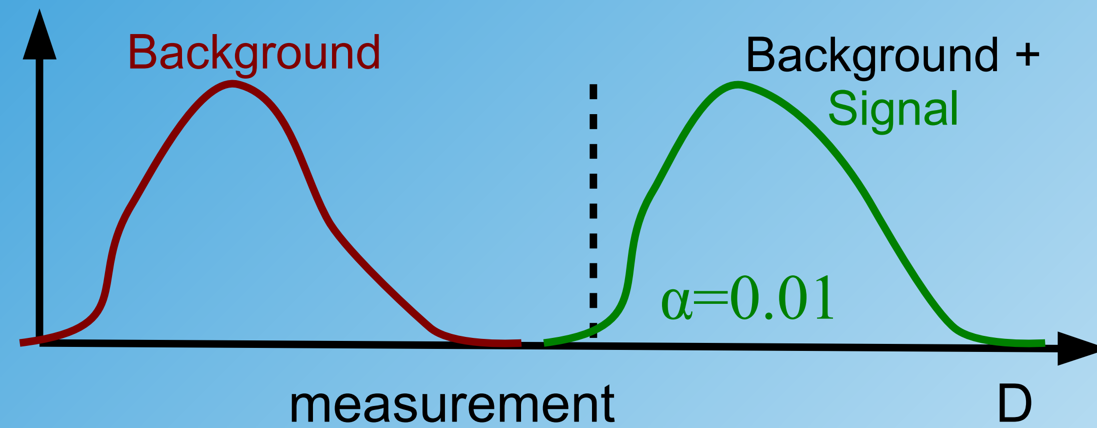


Another Example CL_S Method

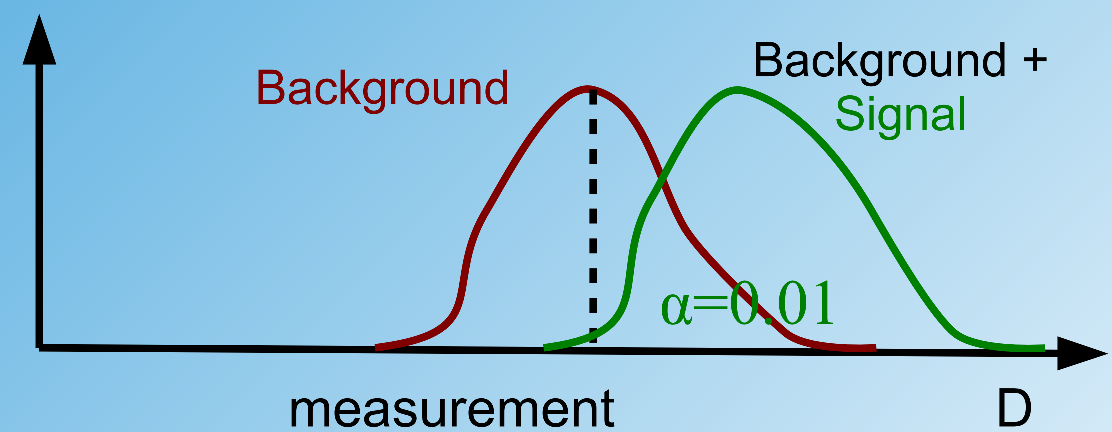
Definition:

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

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

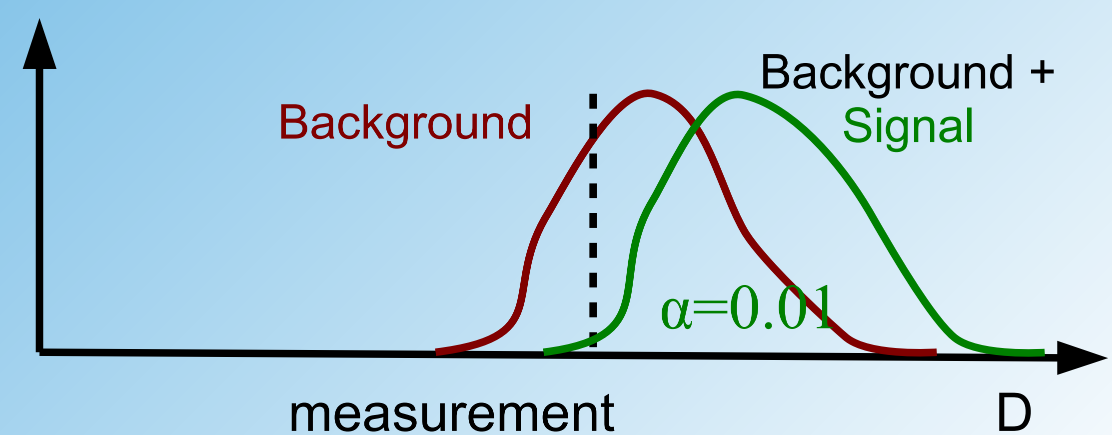


$$0.02 = \frac{0.01}{0.5}$$



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

excluded at 95% CL



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

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

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

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

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

Including radiative corrections

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

$\sin^2\theta_w$

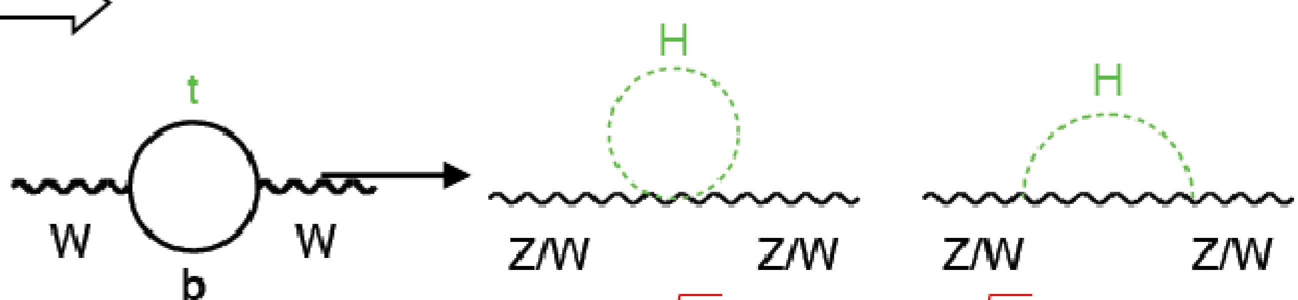
g_A, g_V

$\Rightarrow$

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

$\sin^2\theta_{eff}$

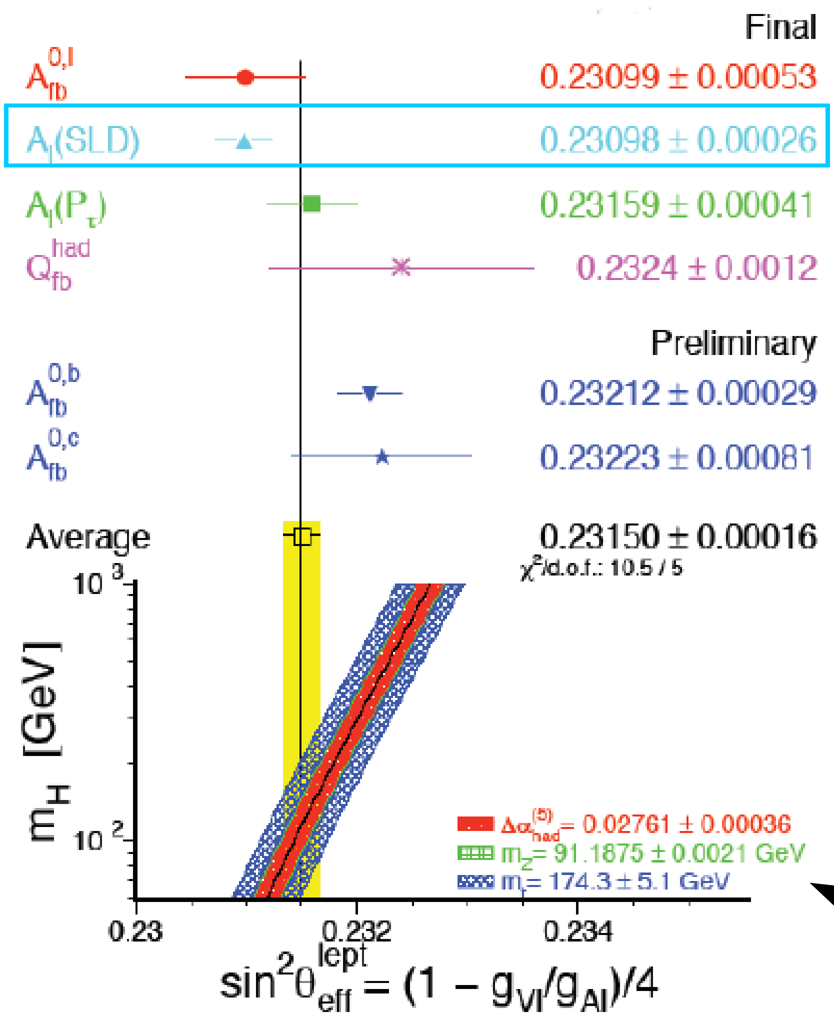
$\bar{g}_A, \bar{g}_V$



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



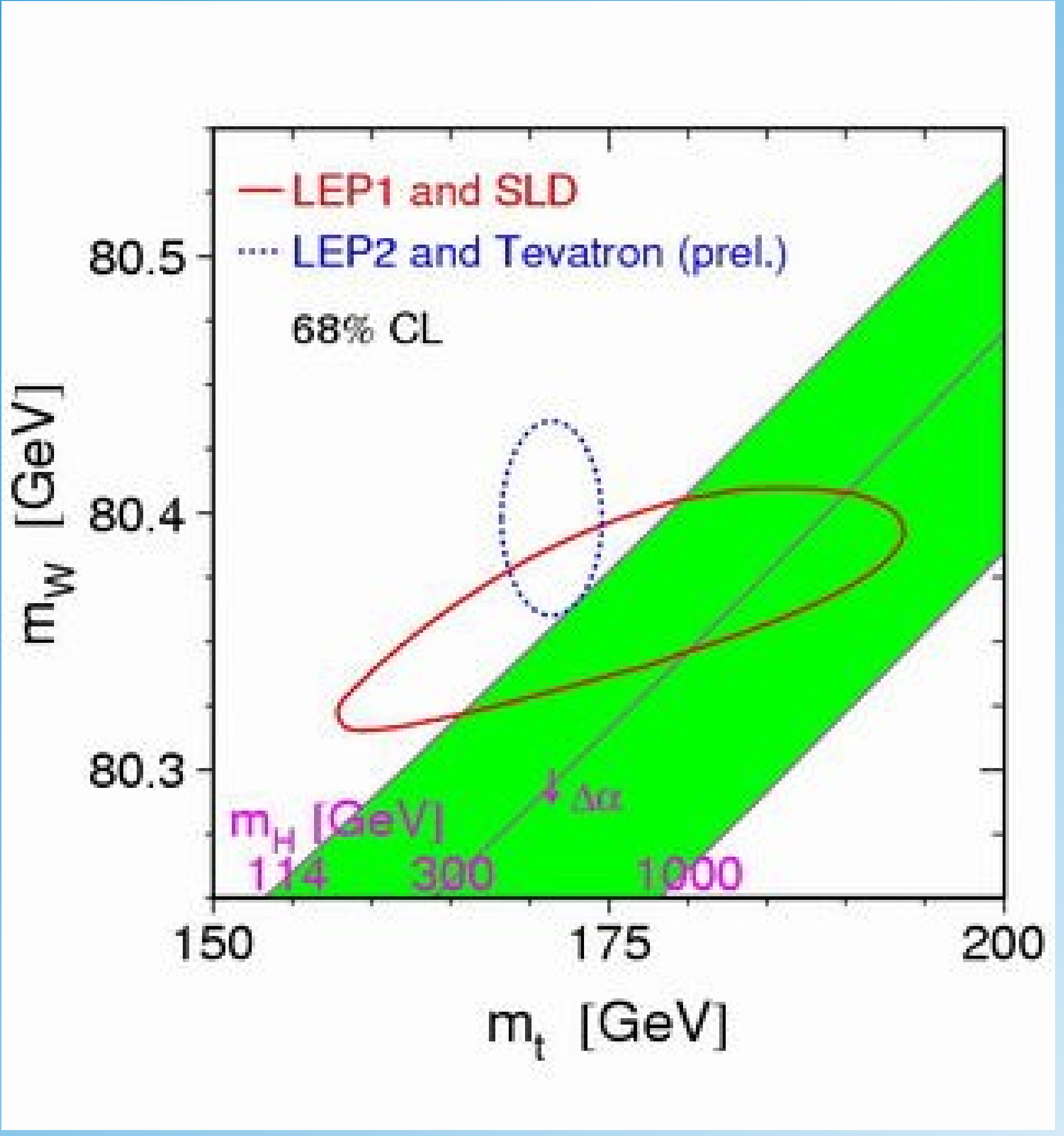
Take the top mass from direct measurements and use the radiative corrections to determine the Higgs mass.

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

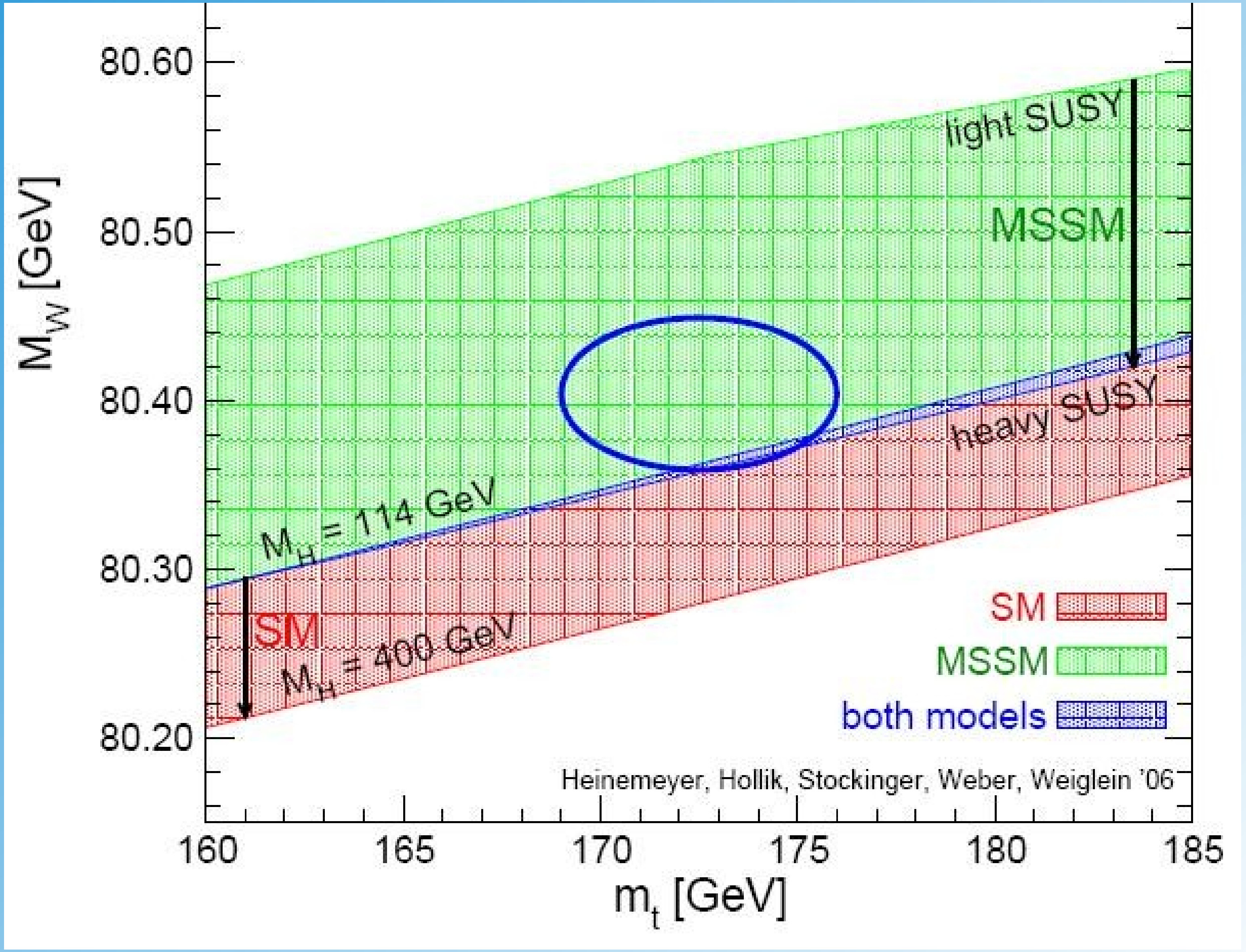
outdated

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

SM Higgs Mass Predictions



W-Top-Higgs Mass Relation and SUSY



SUSY Higgs is light!

Higgs Direct Searches at LEP

Higgs-Fermion Coupling:

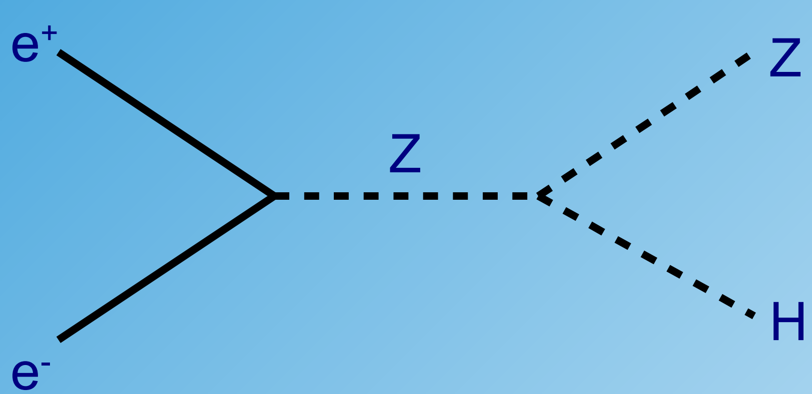
$$L_Y = -g_b \bar{L}\Phi b_R - g_t \bar{L}\tilde{\Phi} t_R \quad \text{with} \quad L = \begin{pmatrix} t \\ b \end{pmatrix}, \ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \ \tilde{\Phi} = i\tau_2 \Phi^*$$

Higgs couples to masses:

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

Electron-Positron annihilation has tiny Higgs coupling!

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



ZZH coupling is large!

ZH Signature at LEP

Higgs decays dominantly into heaviest fermions:

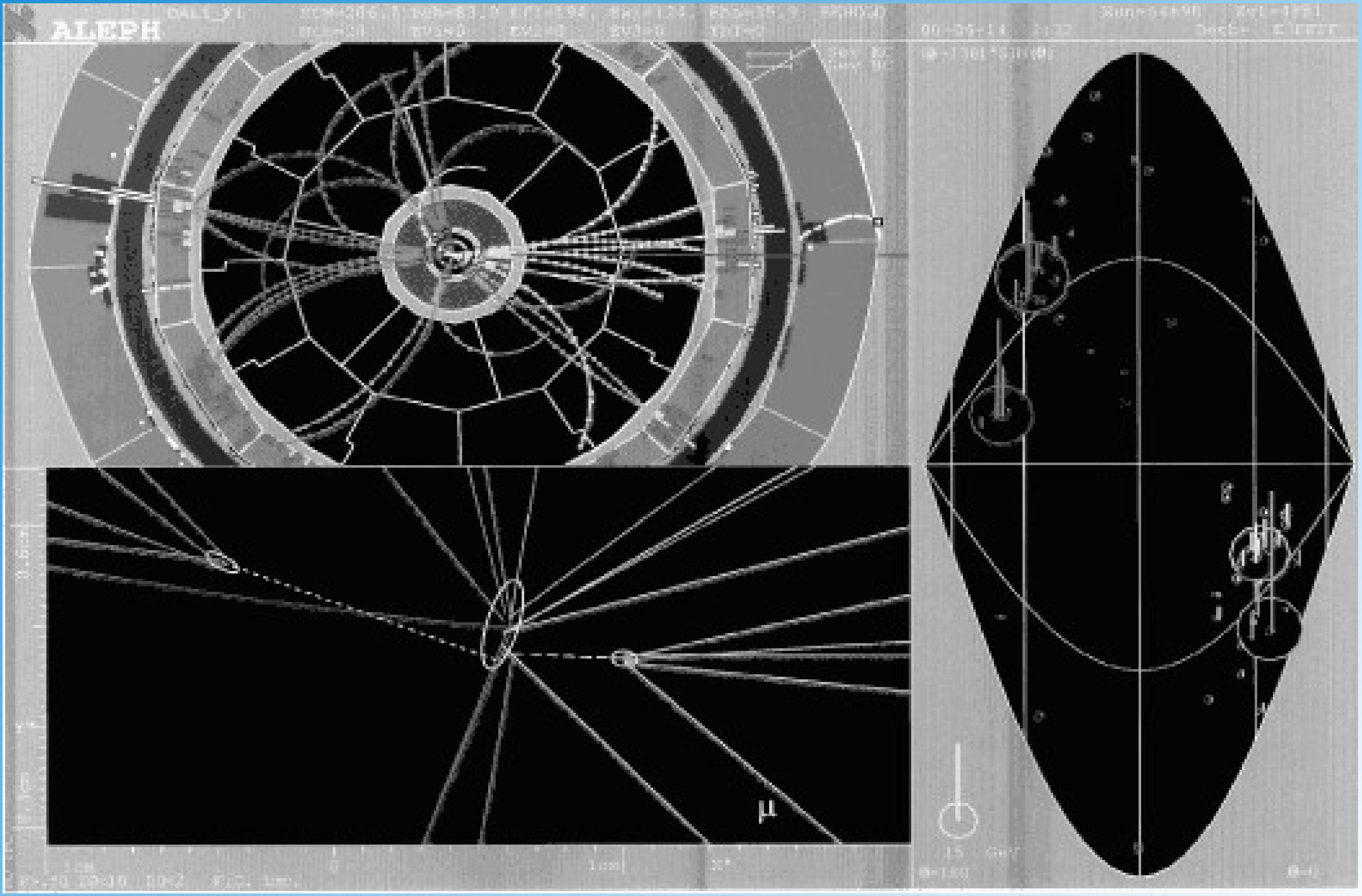
$ZH \to Z\,bb \to ll\,bb,\ jj\,bb,\ bbbb,\ \nu\nu\,bb$

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

LEP2 with E_{cms}=205 GeV:

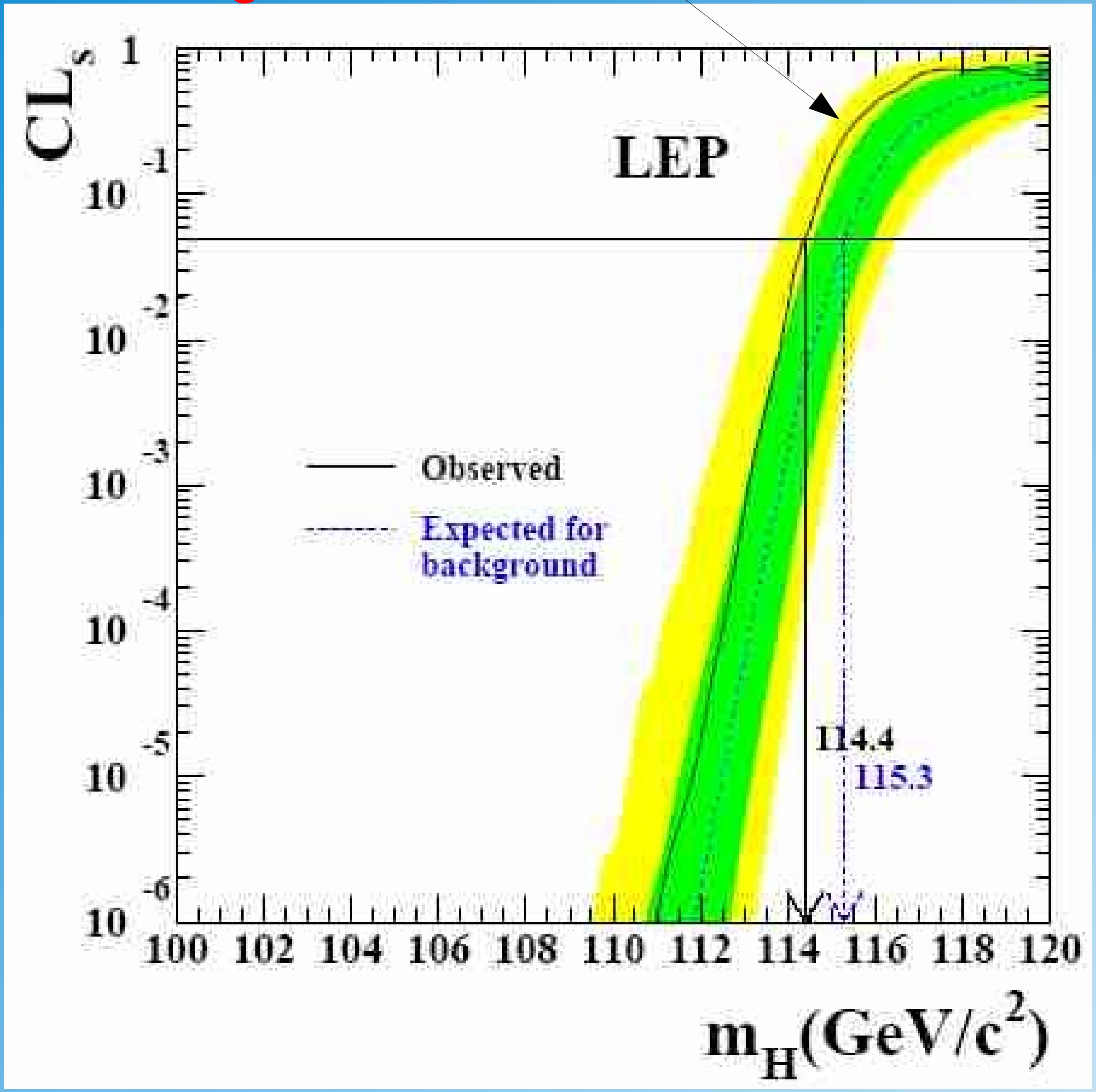
- installation of vertex detectors
- sensitivity up to m_H=114 GeV   ($E_{cms} = m_H + m_Z$)

bbjj-candidate at ALEPH



Combined LEP2 Higgs Limit

no signficant excess



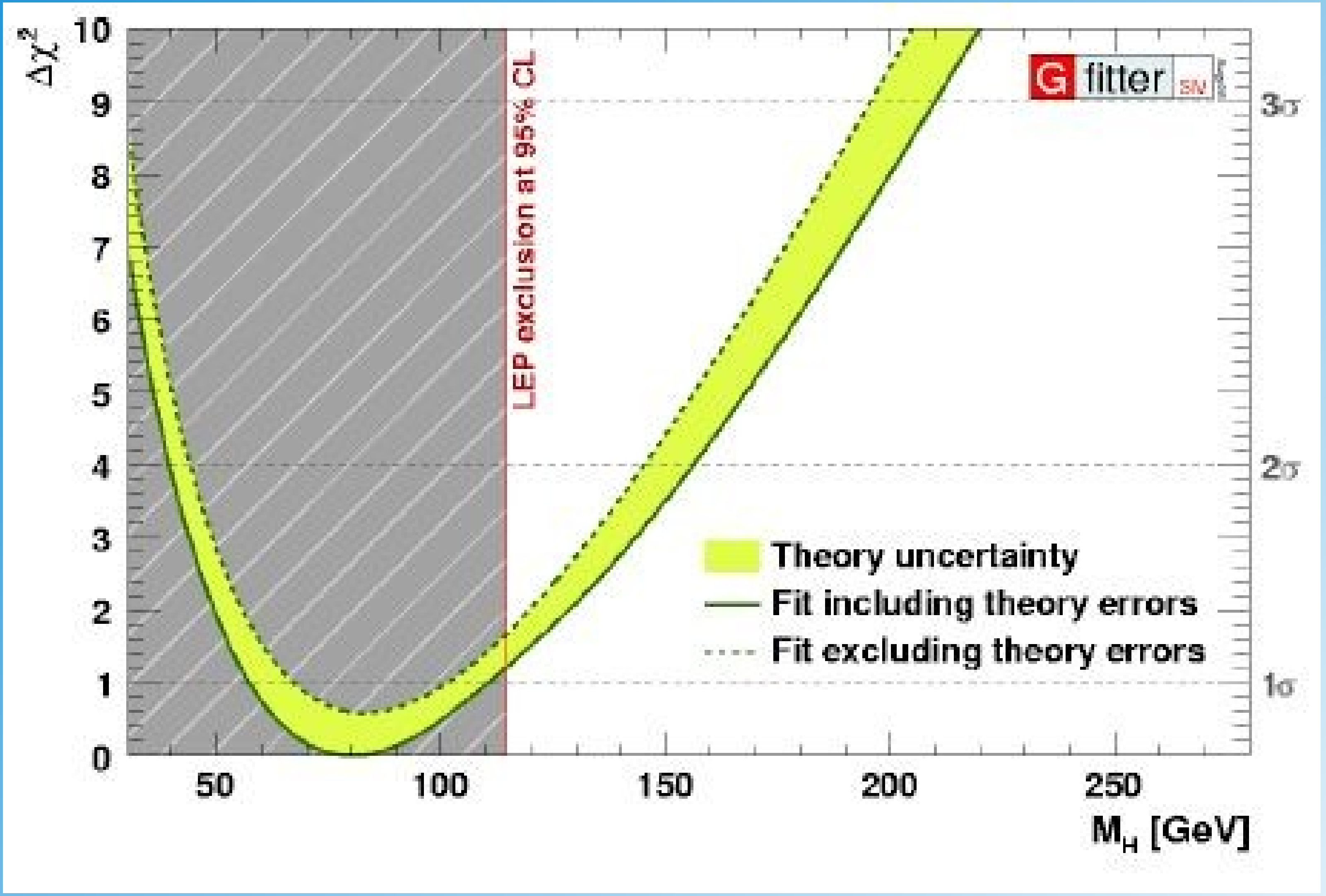
Higgs excluded with:

m_H < 114.4 GeV
(expected 115.3)

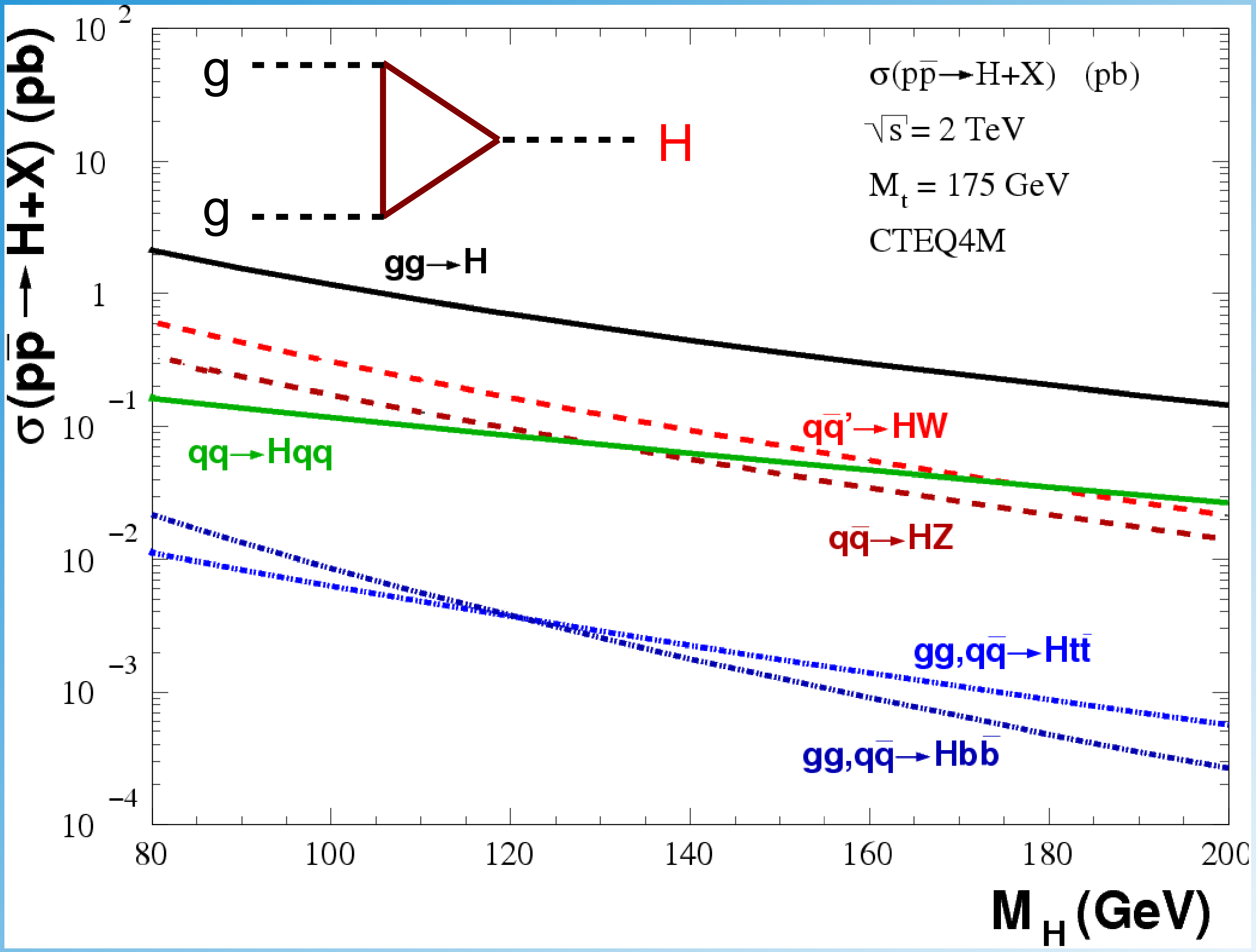
at 95% CL

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

Higgs LEP2 Direct Limits

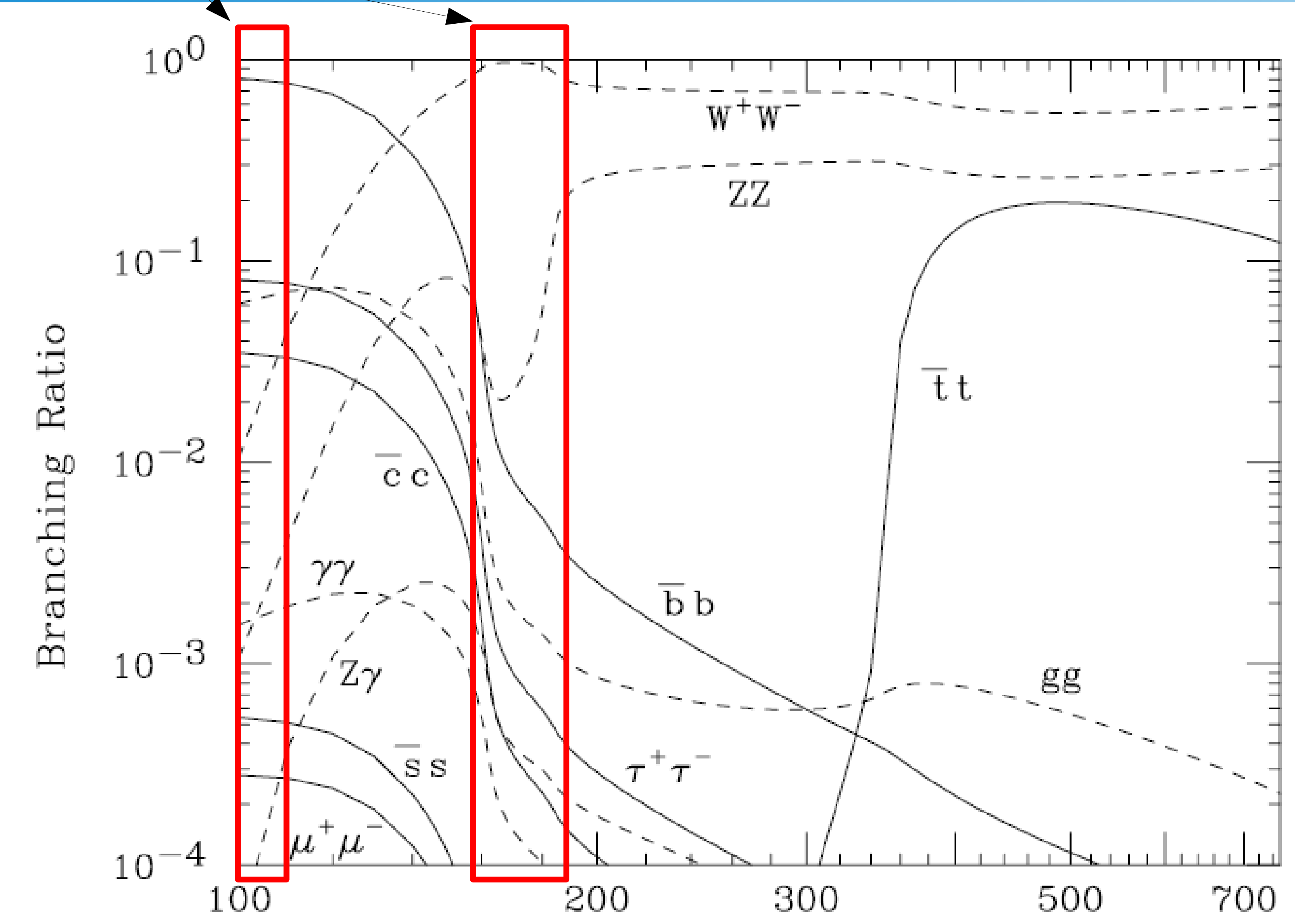


Higgs Production at Tevatron



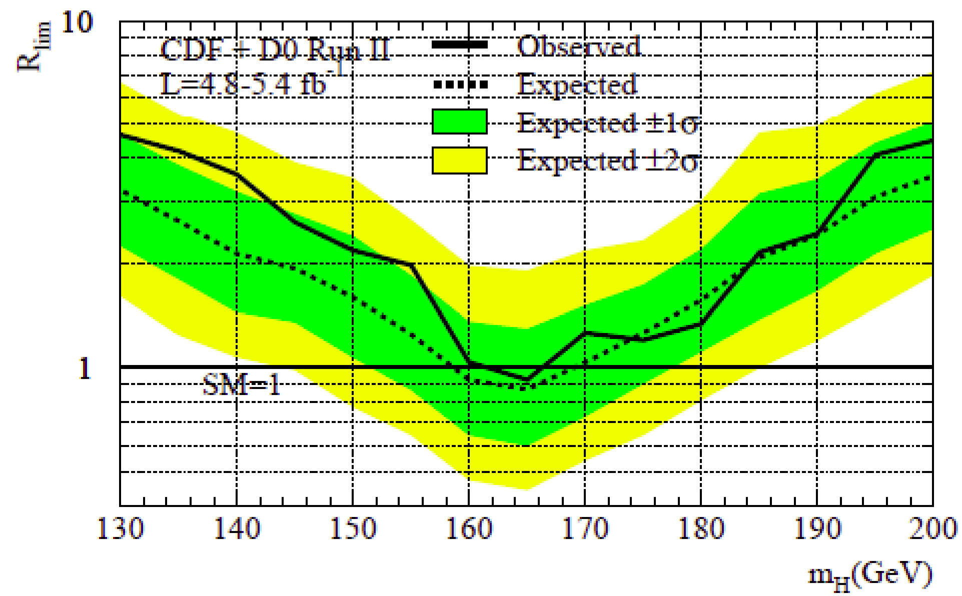
Higgs Decays

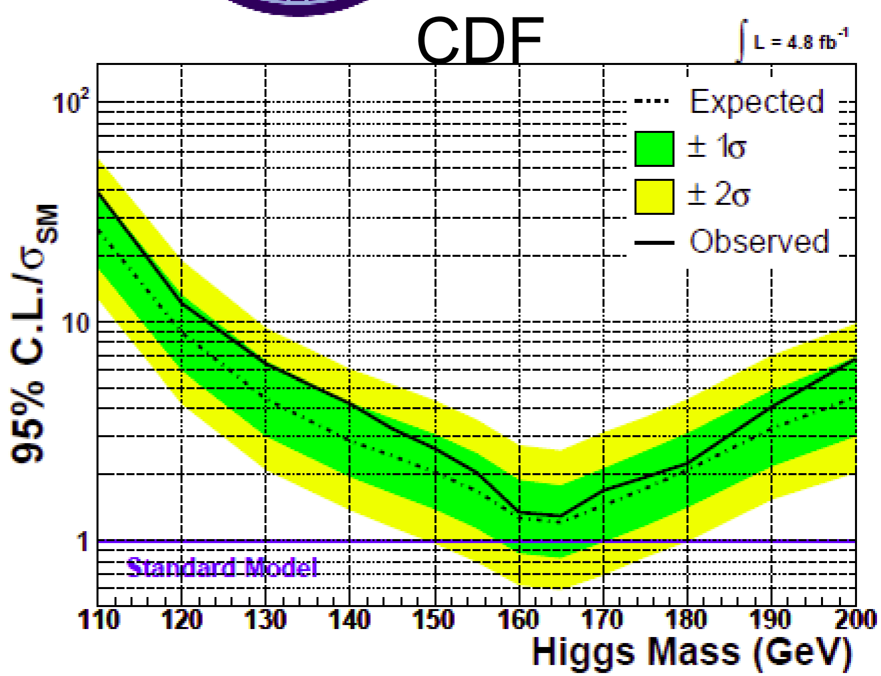
"easy" regions

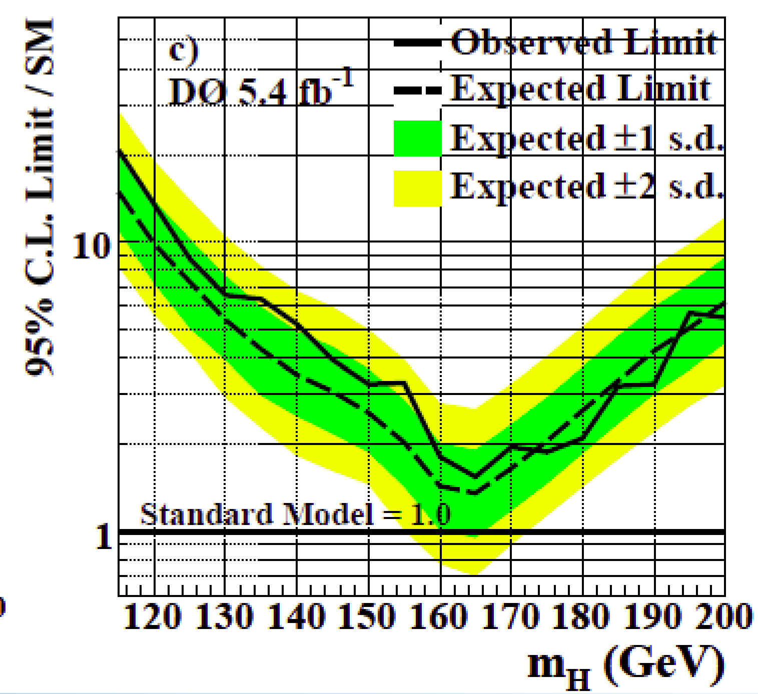


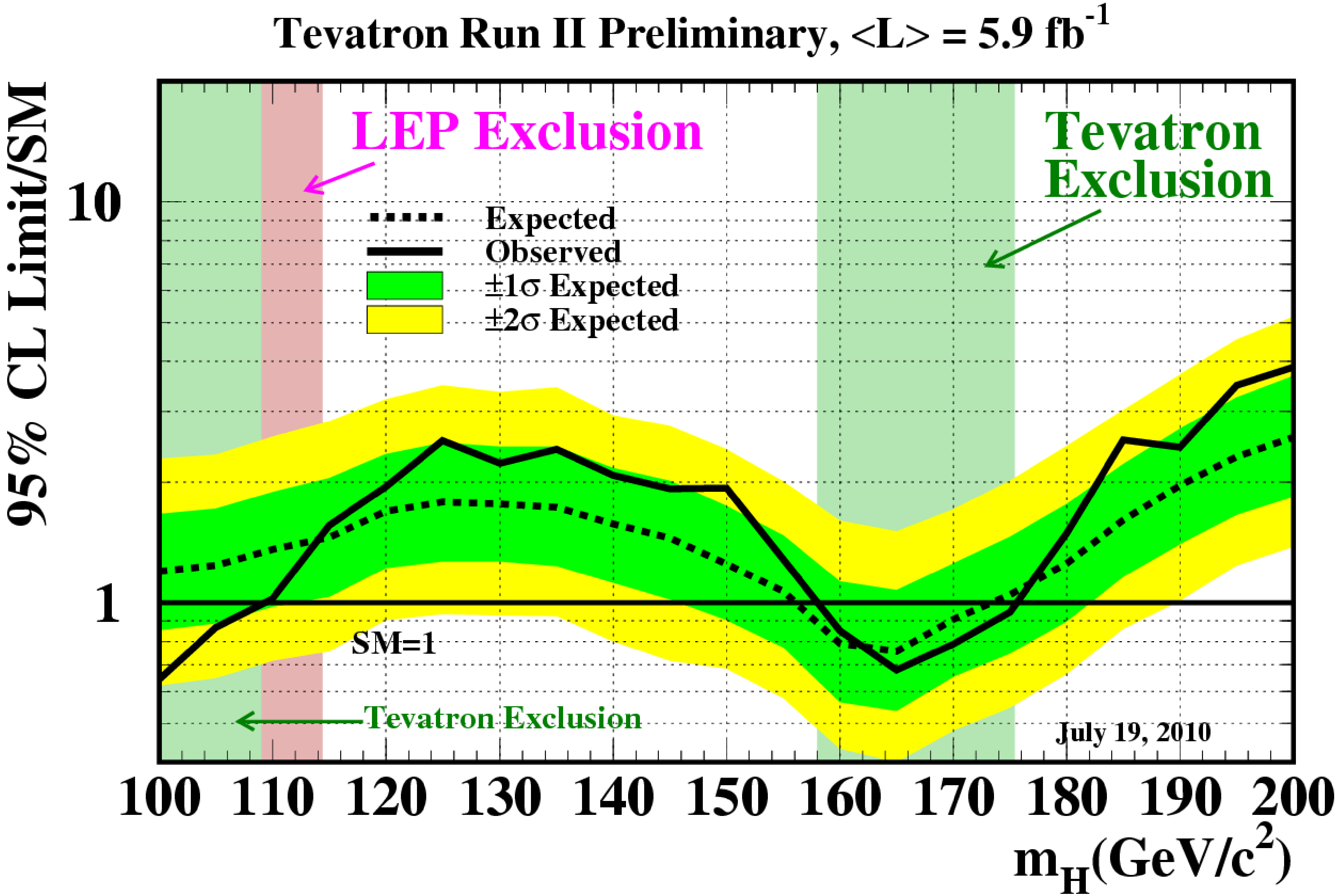
Searches are performed at about 100 channels!

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

Fits to electro-weak data:

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

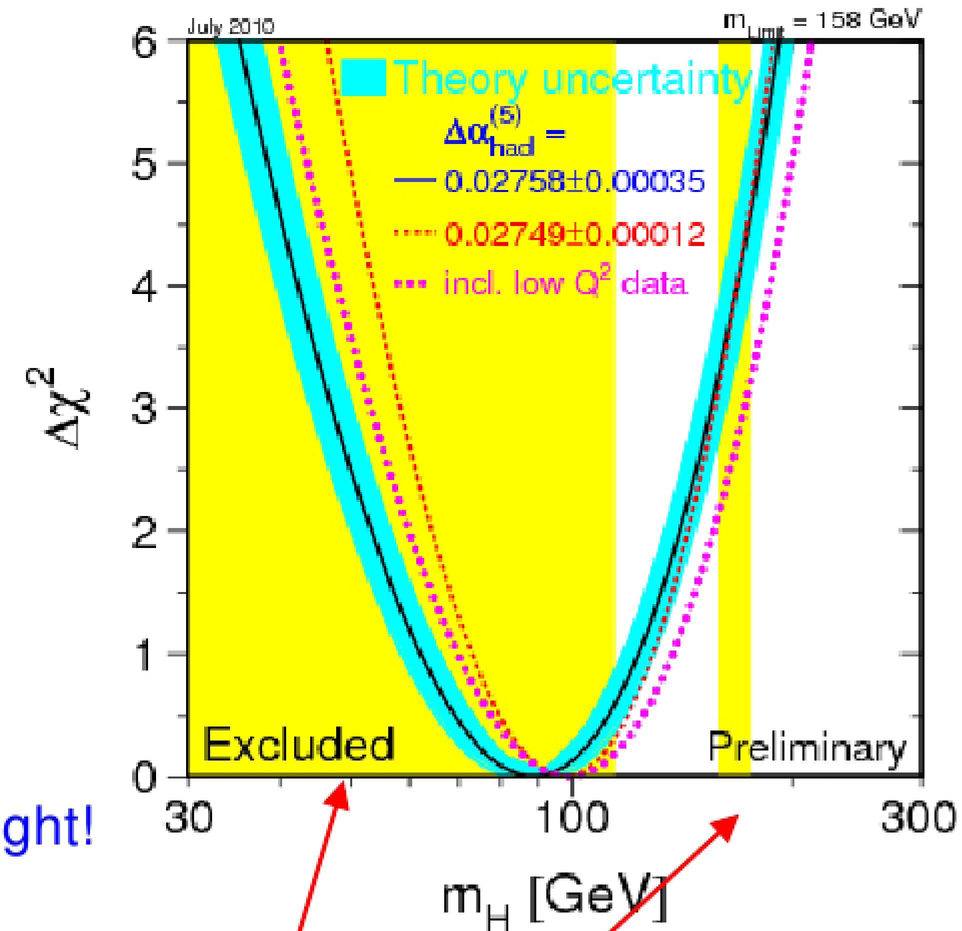
$m_H < 158$ GeV (95% CL)

Assumption for fit:

- SM including Higgs

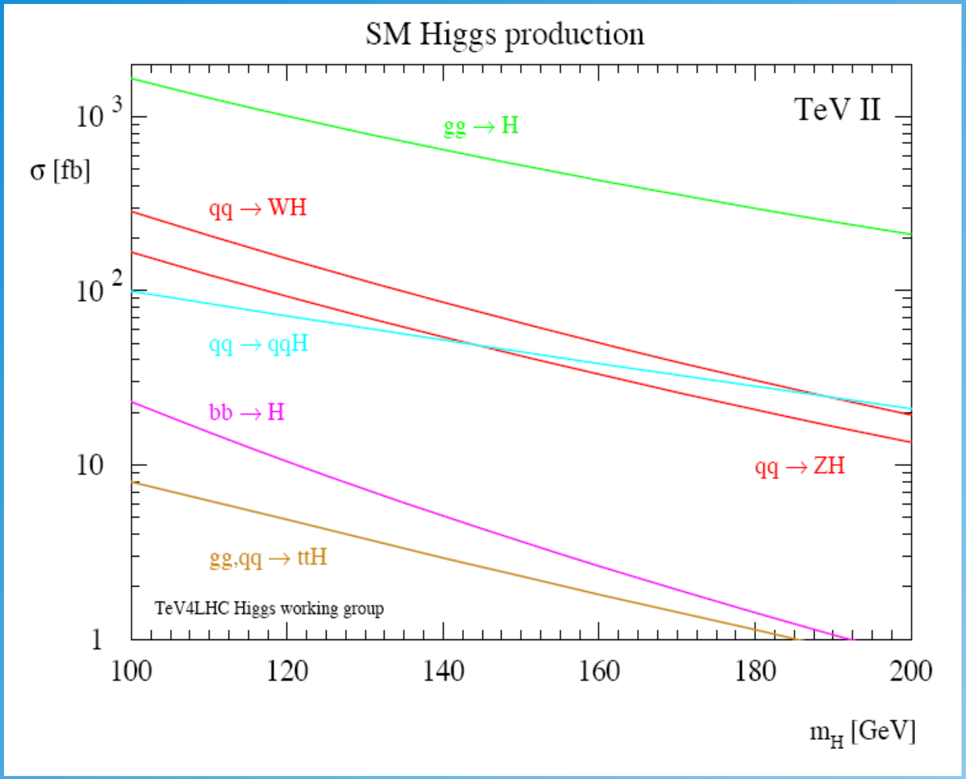
If existing, Higgs seems to be light!

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

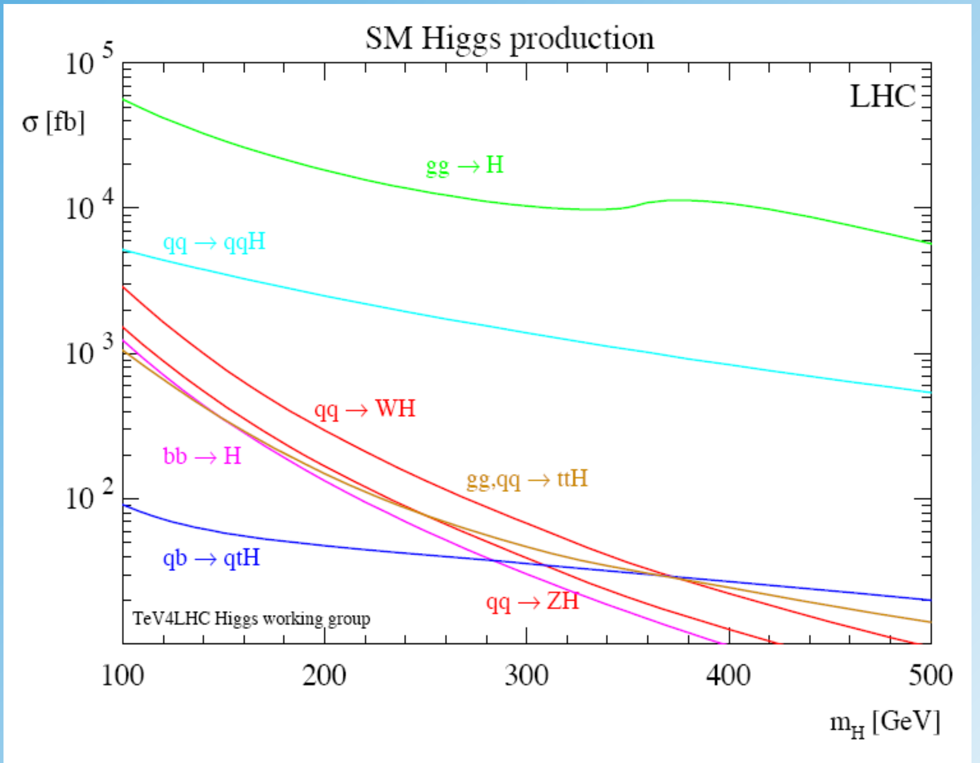


- Direct searches at LEP: $m_H > 114.4$ GeV @ 95 % CL
- Direct searches at Tevatron

Higgs Production at LHC



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

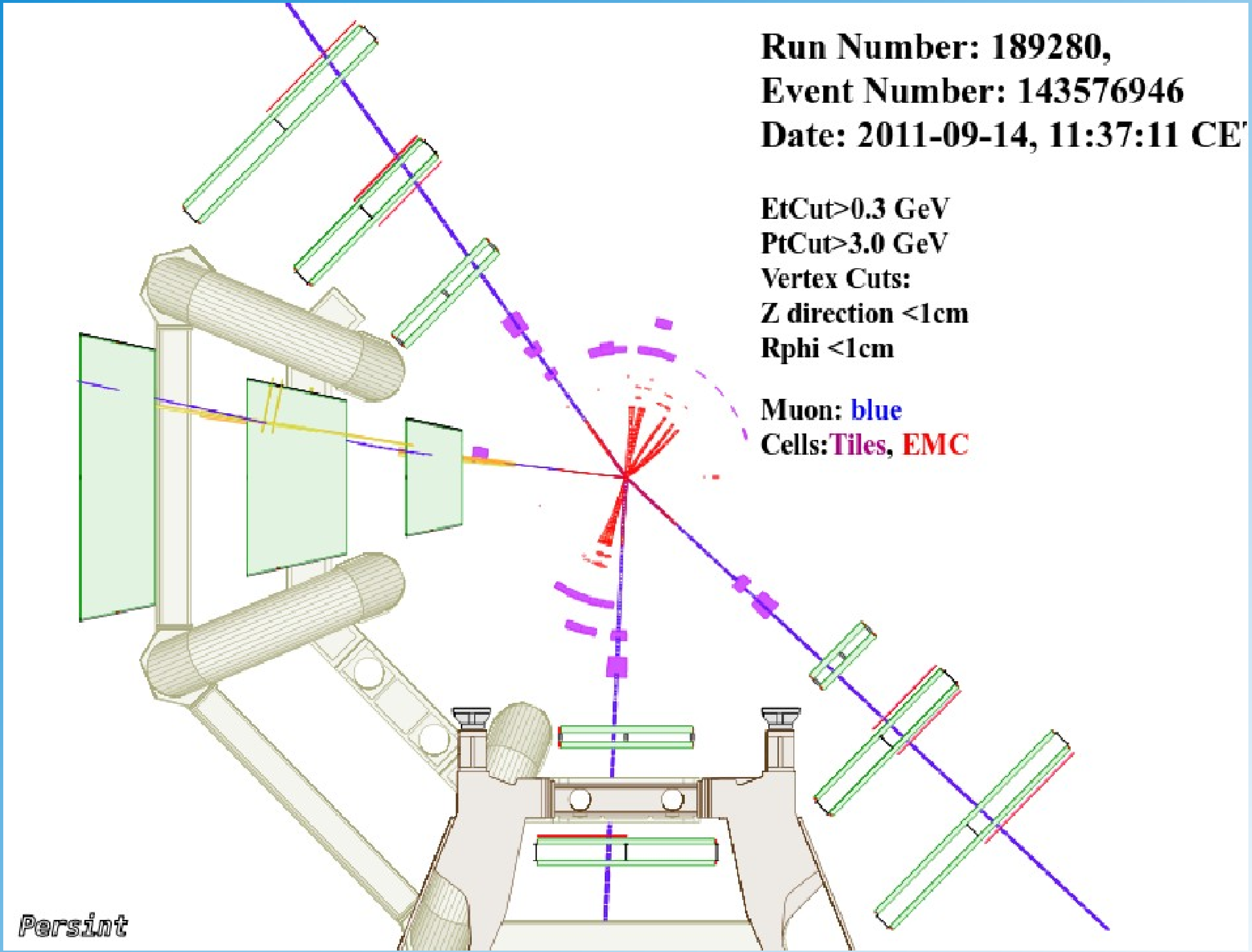


proton-proton at LHC $s^{1/2}$=14 TeV

much larger cross sections!

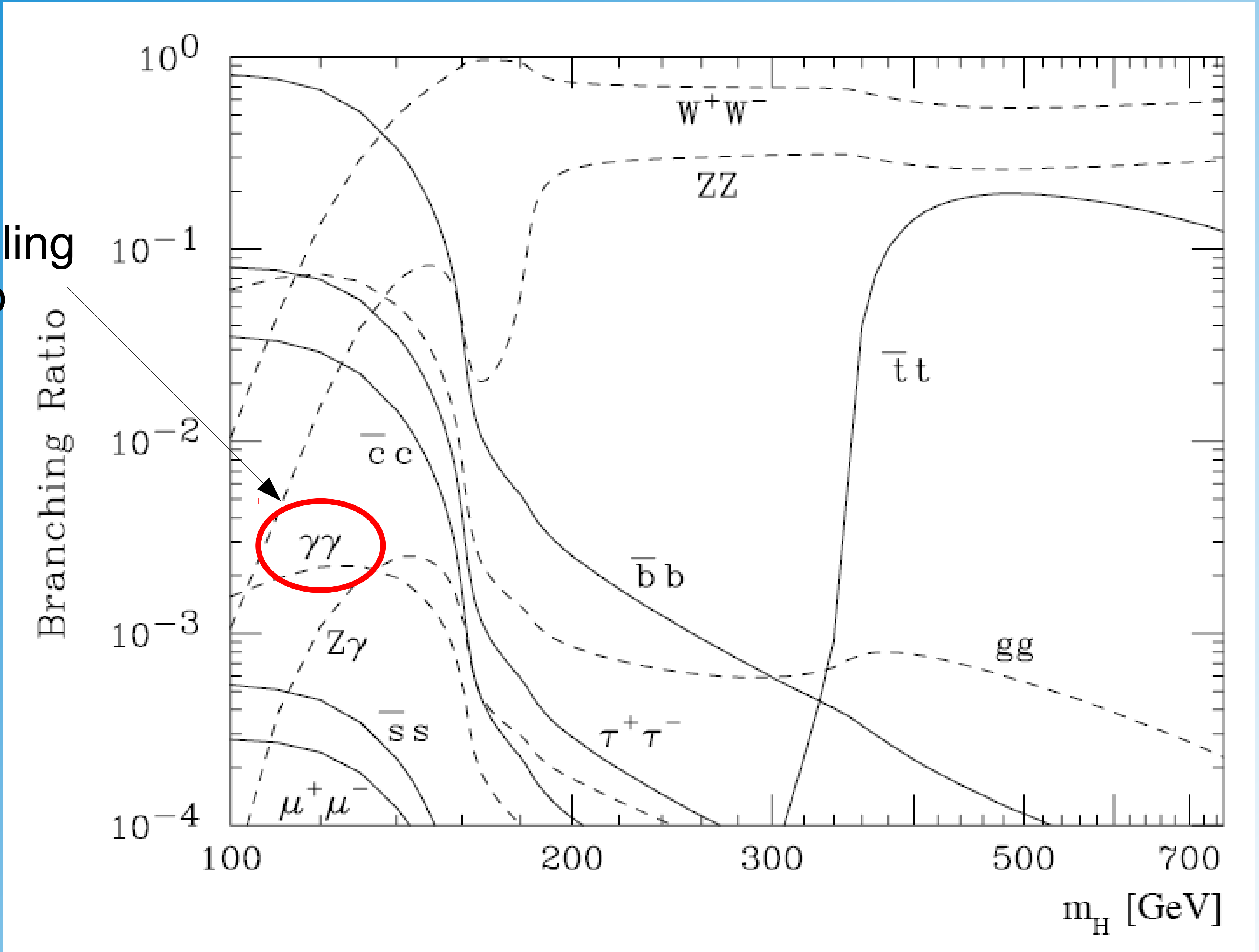
also higher luminosity!

Candidate H → ZZ → μμμμ

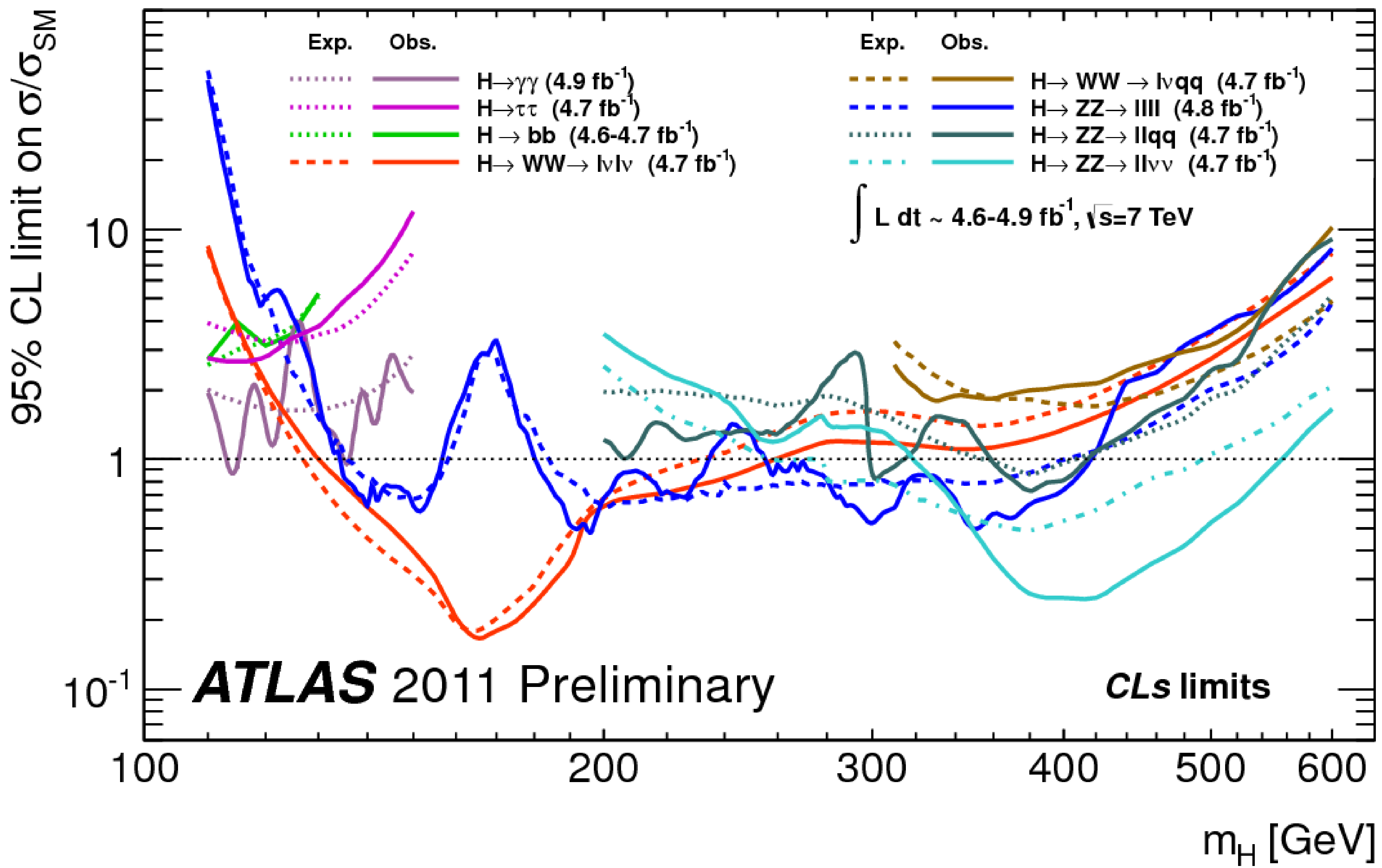


Special Importance H $\rightarrow \gamma\gamma$

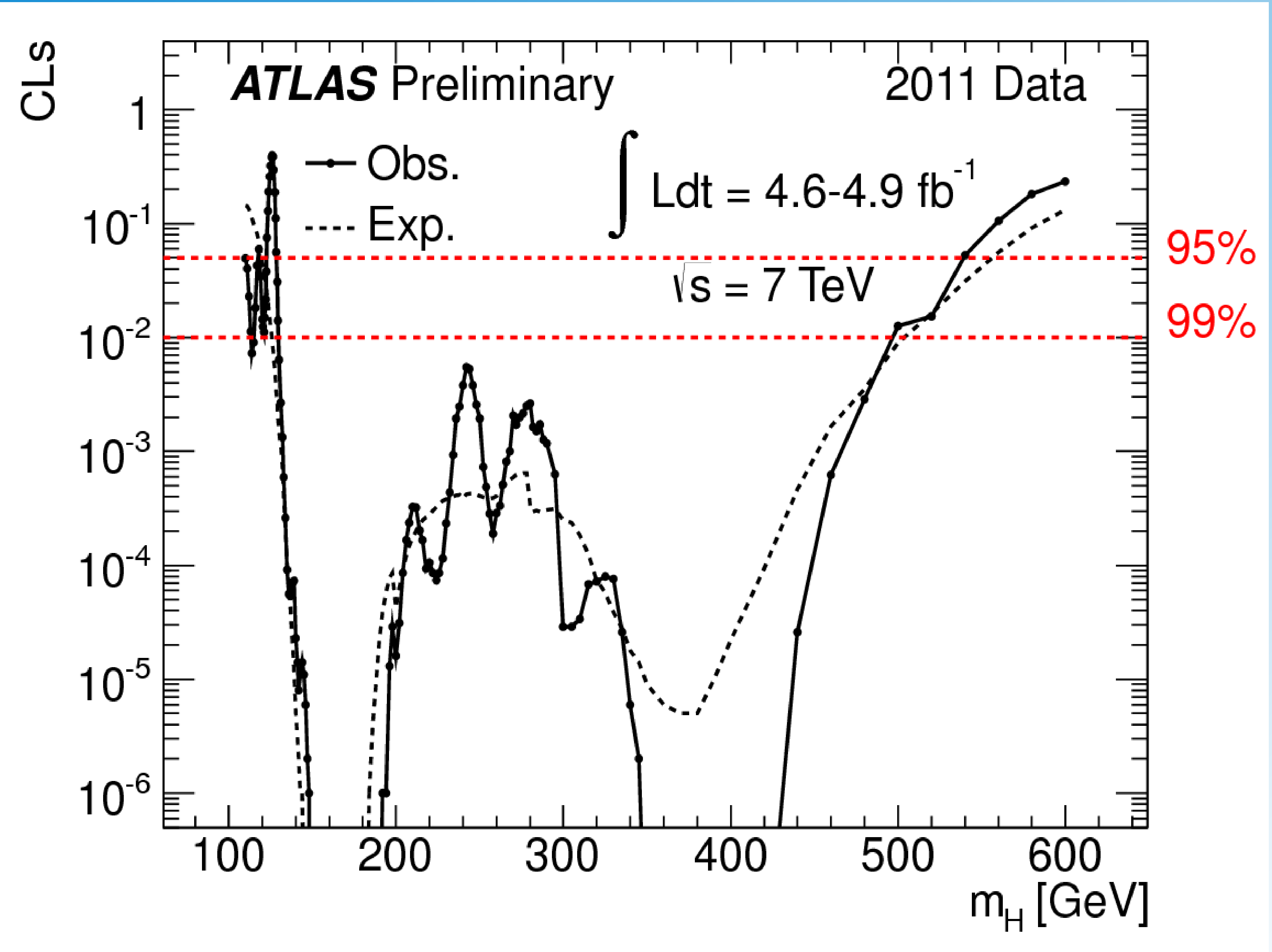
Higgs coupling via top loop



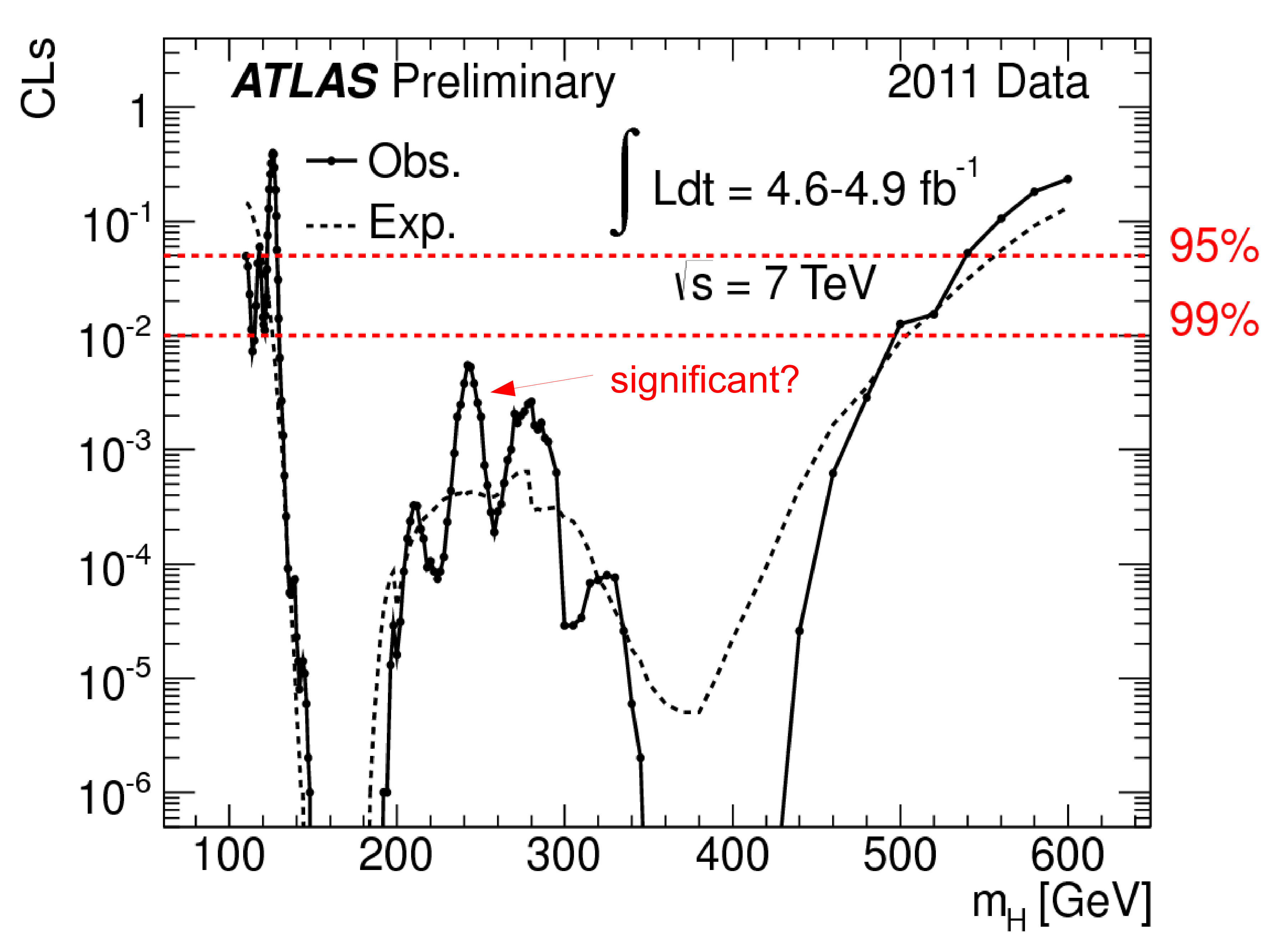
Summary ATLAS Searches



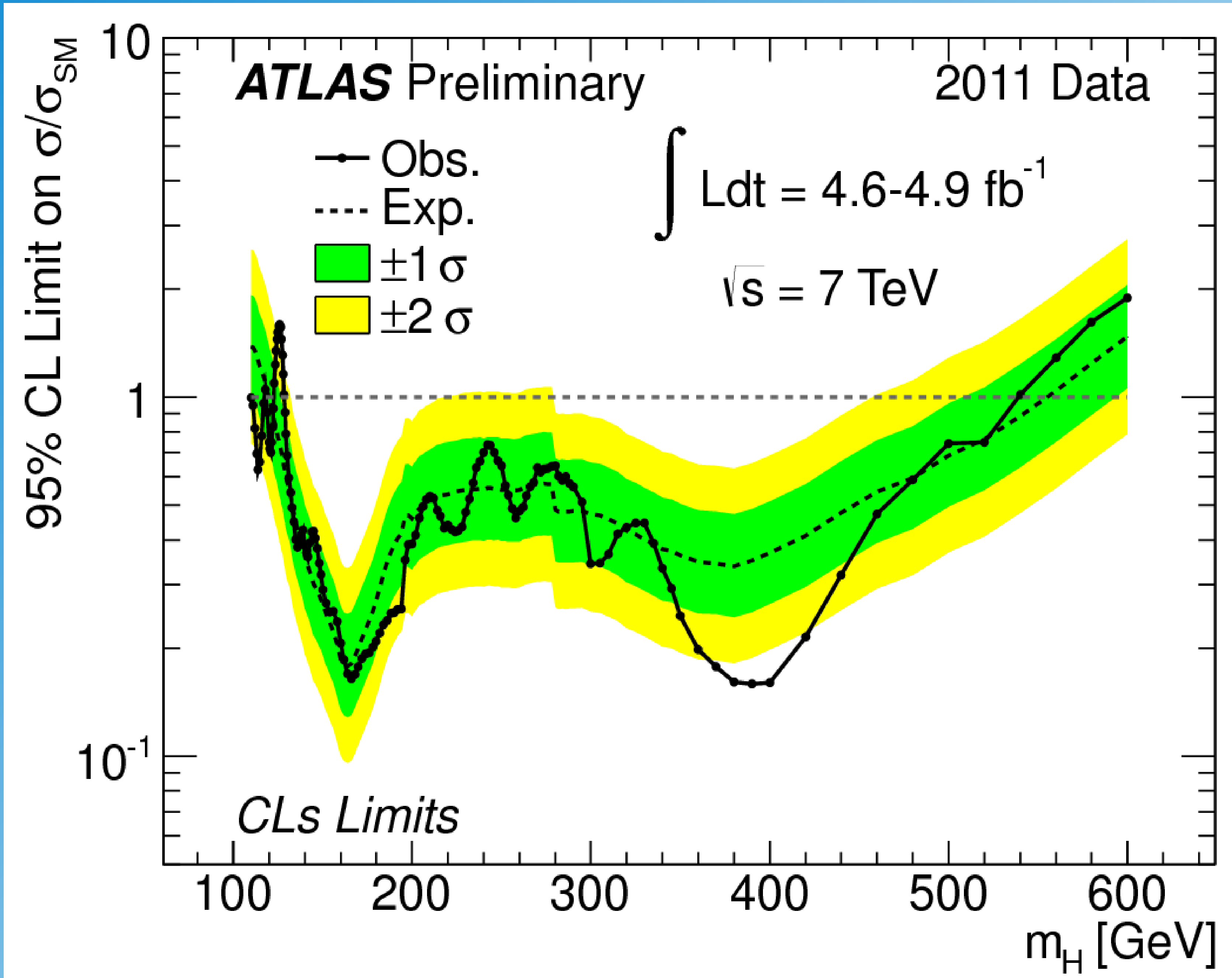
ATLAS Combined Result



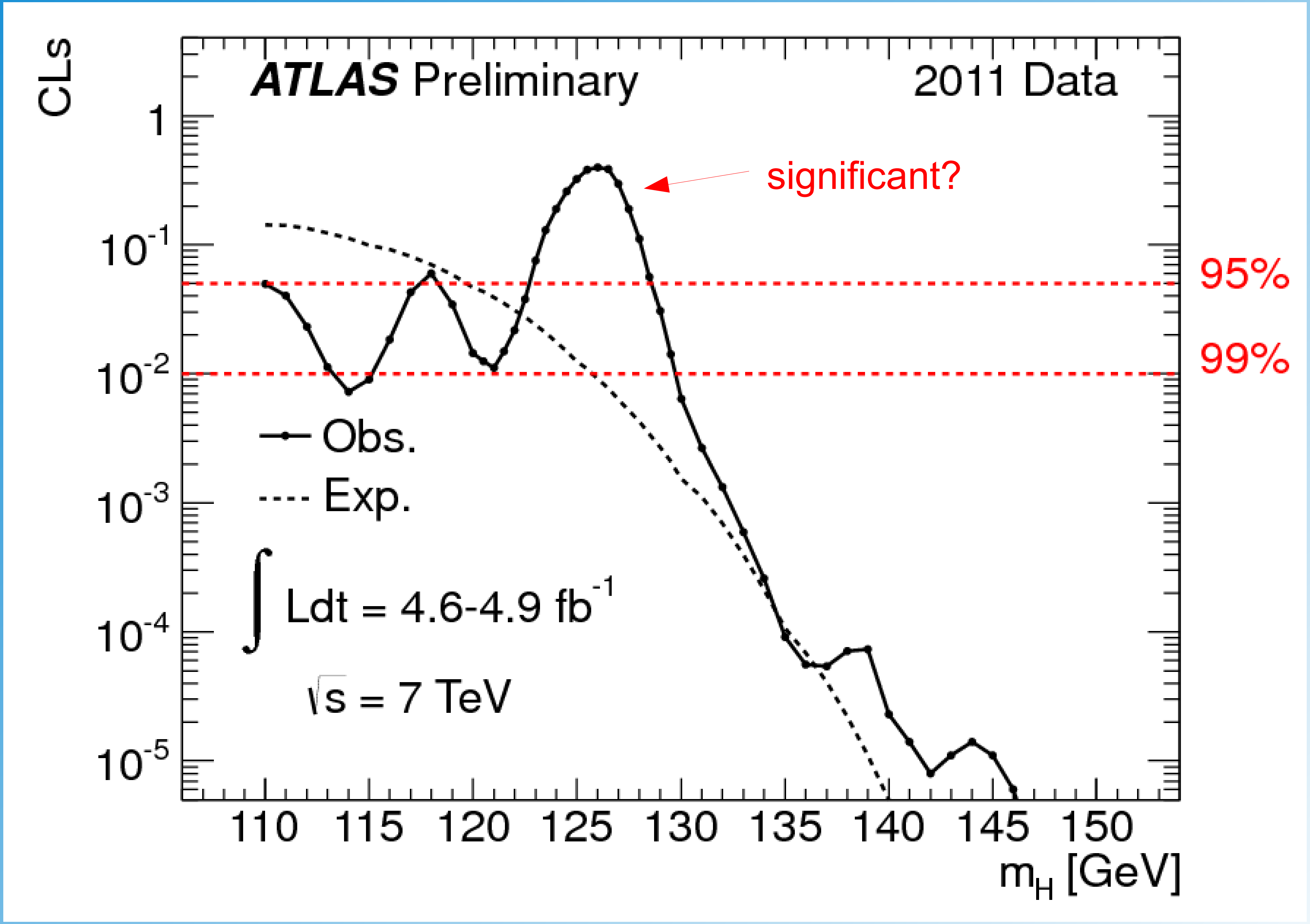
ATLAS Combined Result



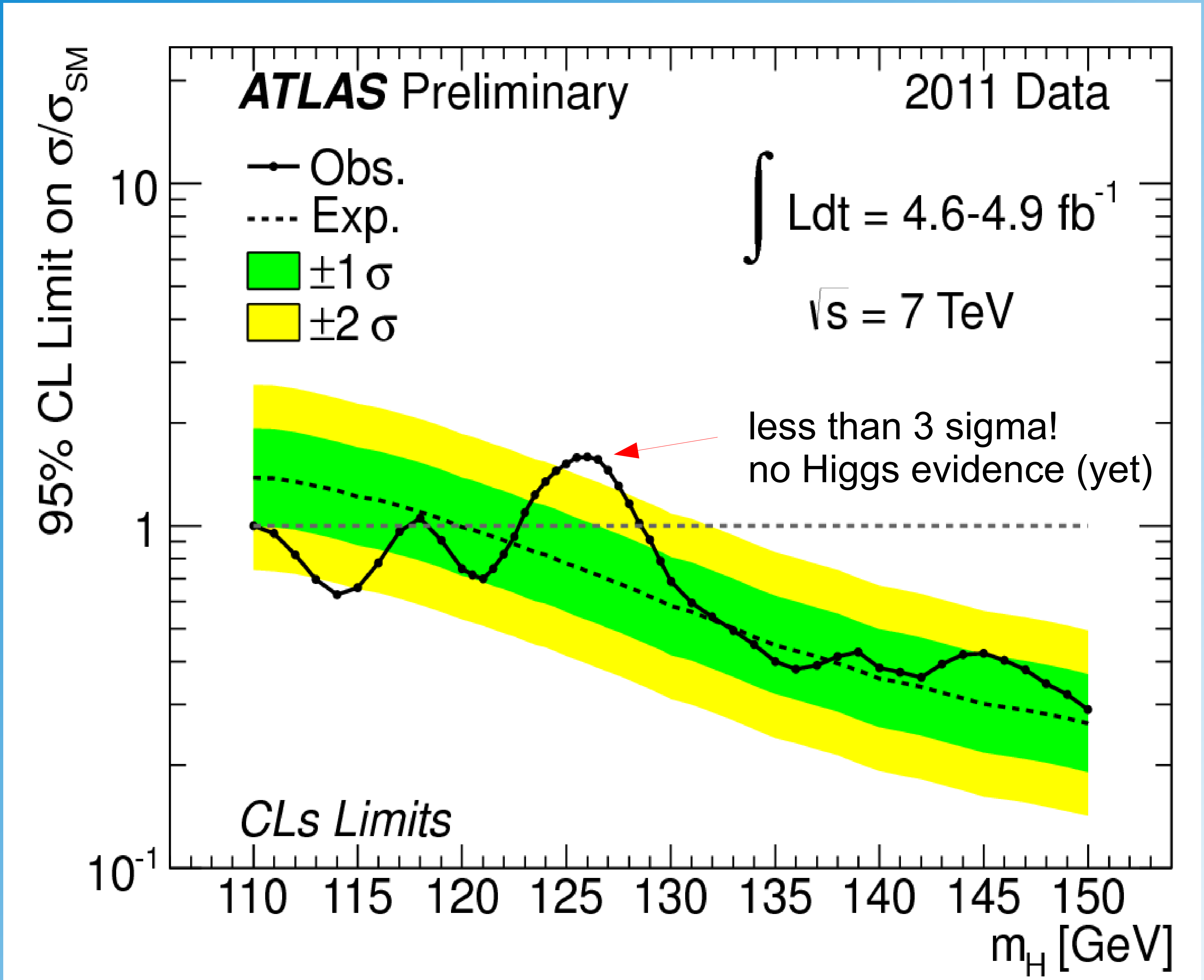
ATLAS Combined Result



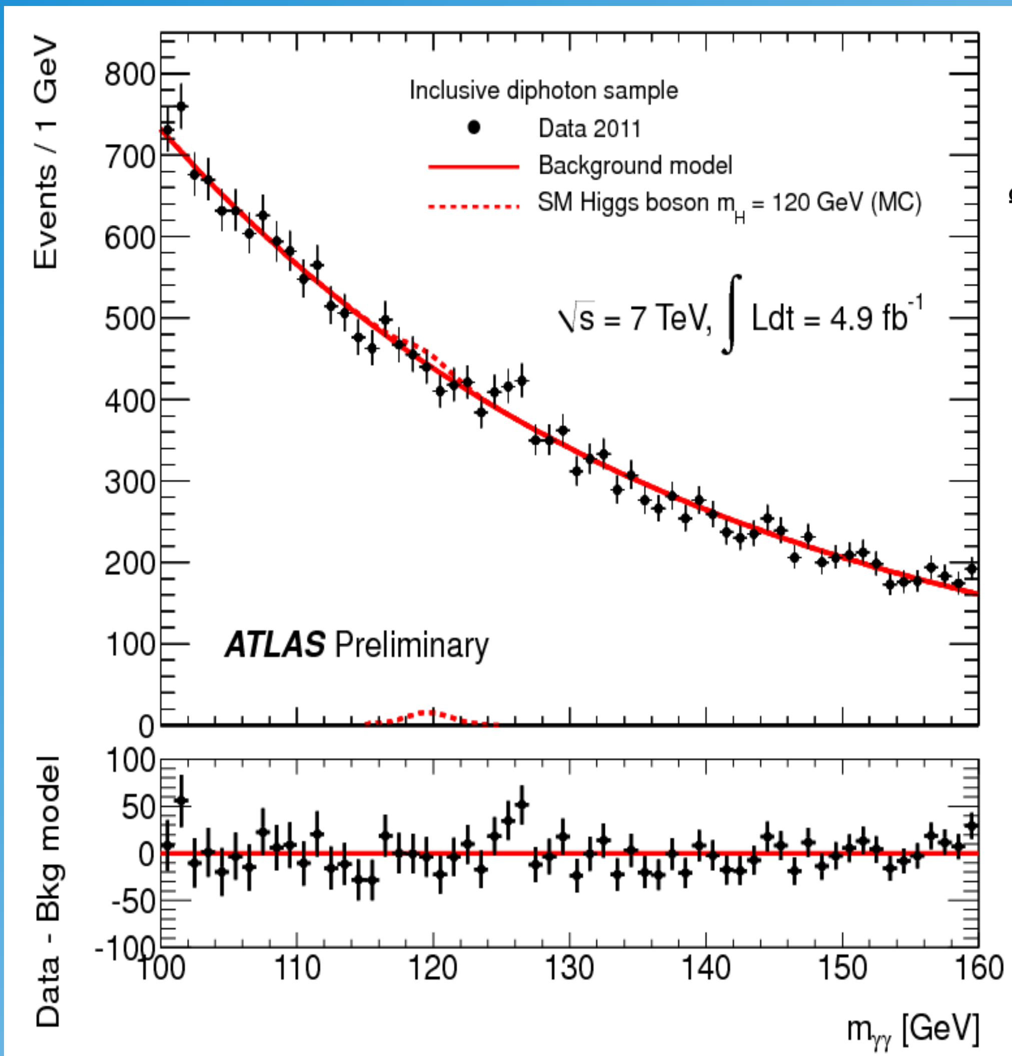
ATLAS Combined Result

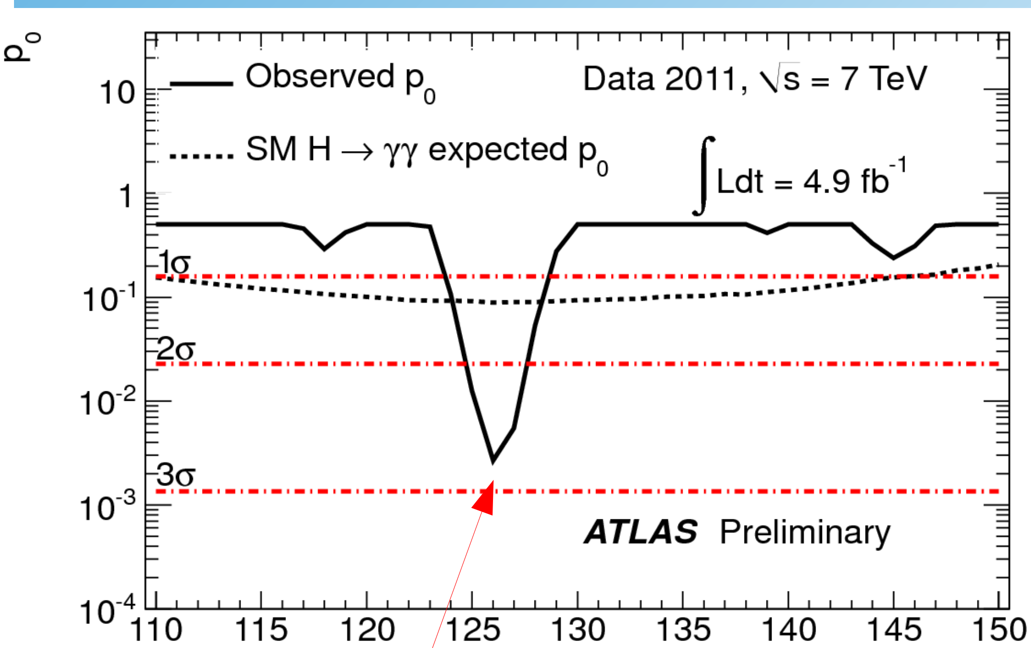


ATLAS Combined Result



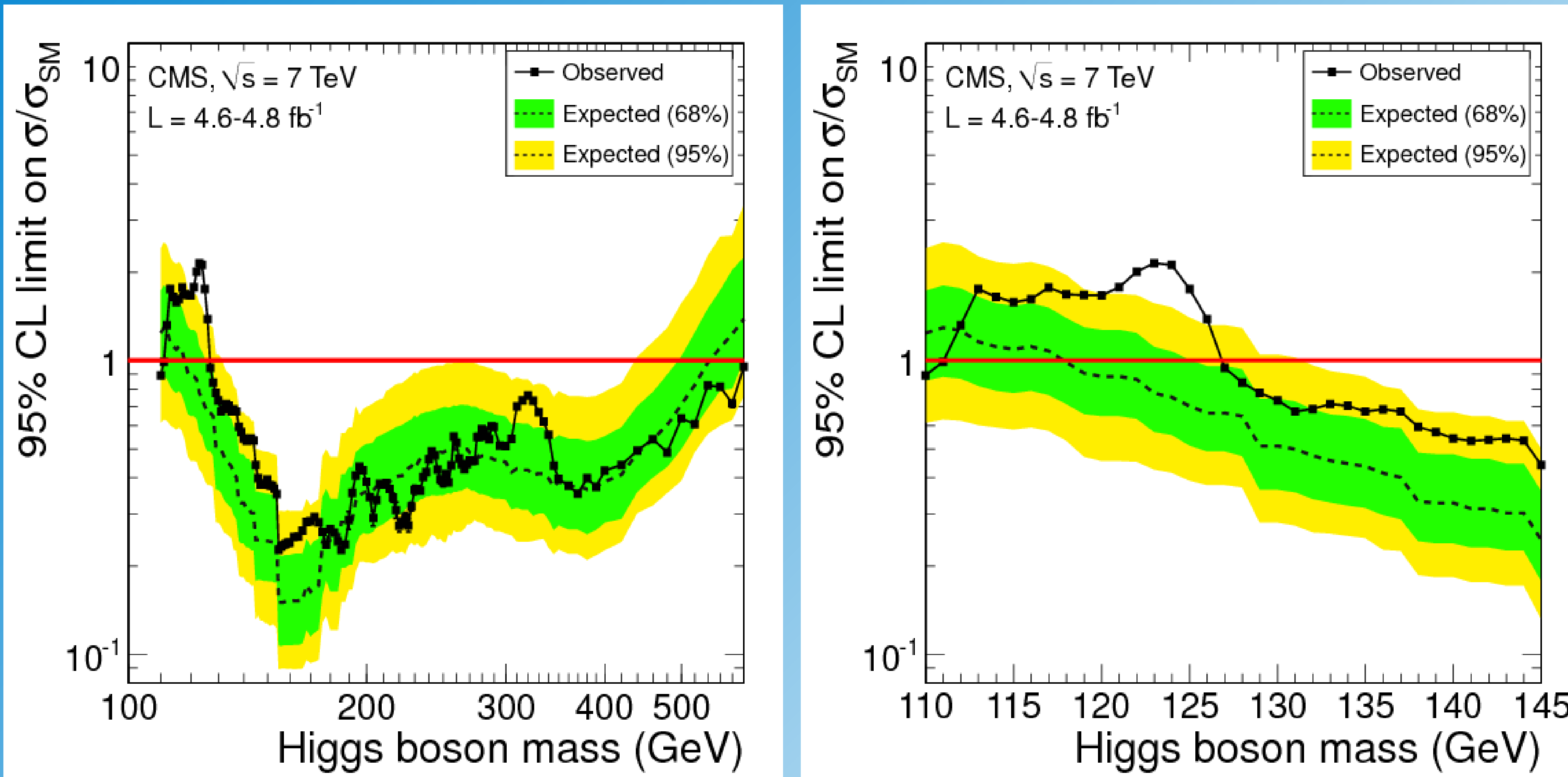
Higgs → γγ Search





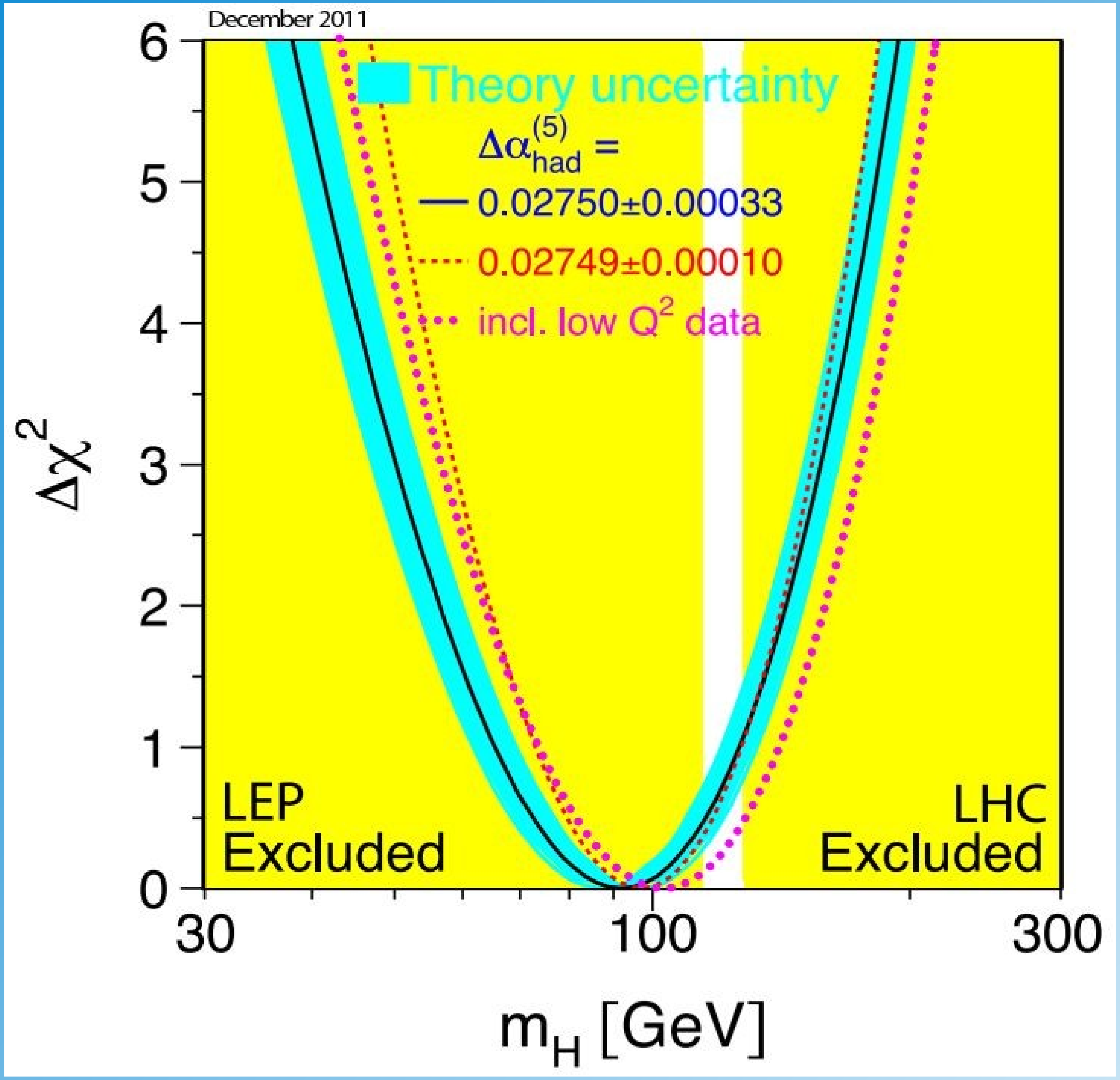
note, signal too strong for Higgs!

CMS Higgs Search (2011 data)



very consistent with ATLAS results, Higgs?

Situation in June 2012
(before summer conferences)

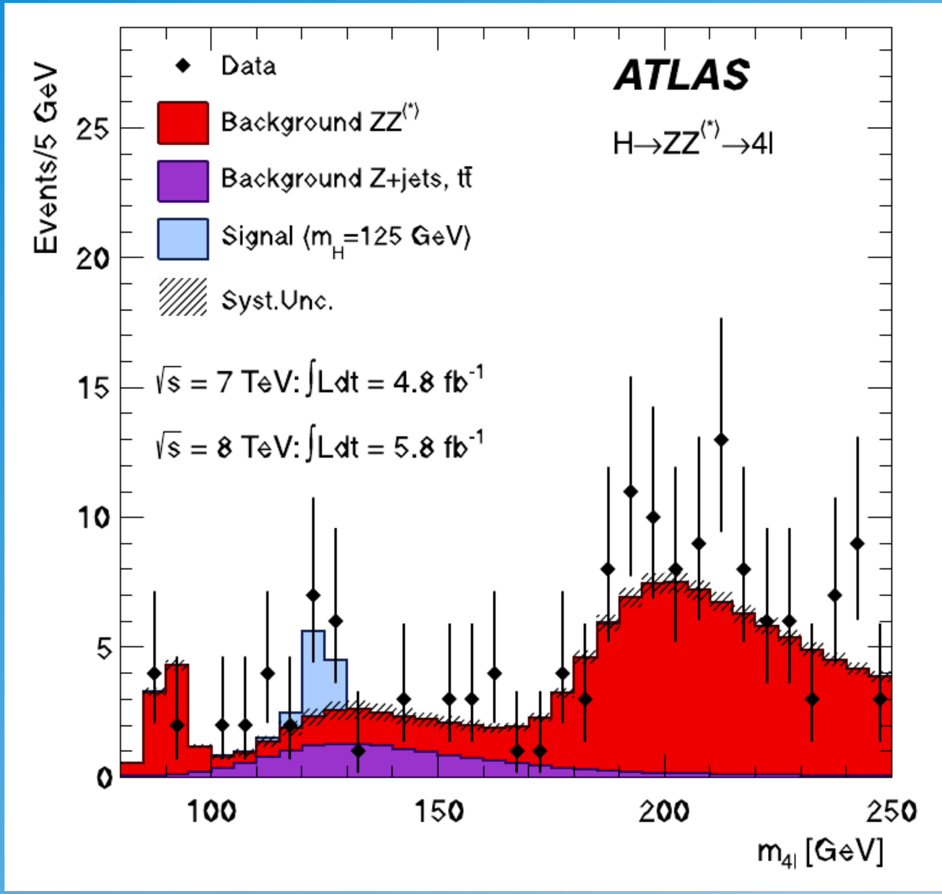


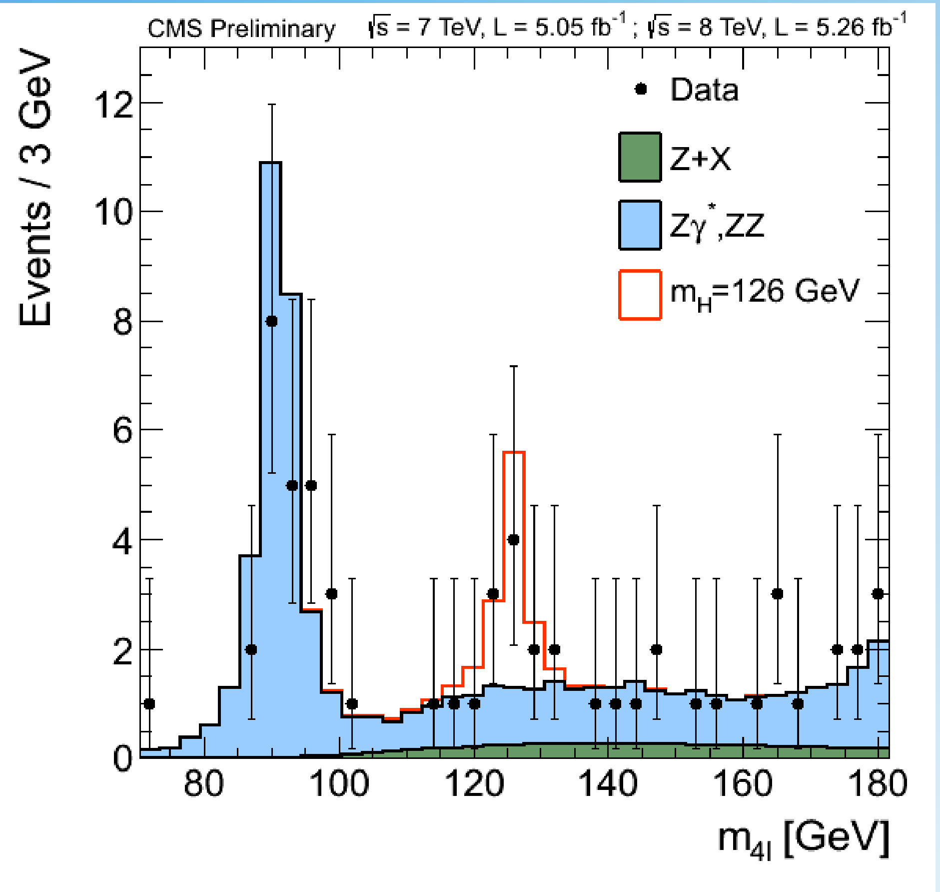
Non-excluded region is the most difficult!

small window around 125 GeV not excluded at 95% CL

→ Updates July 4th 2012!

Latest Results ATLAS+CMS

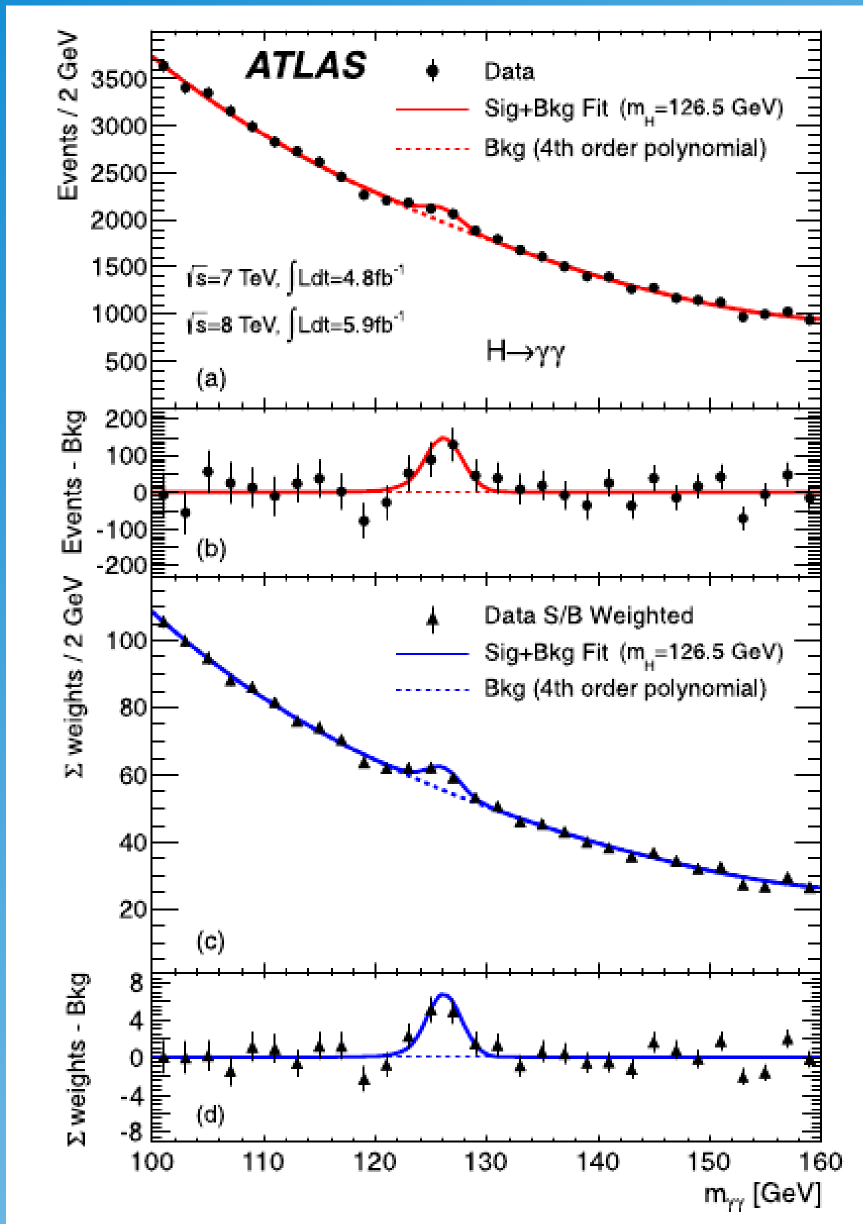




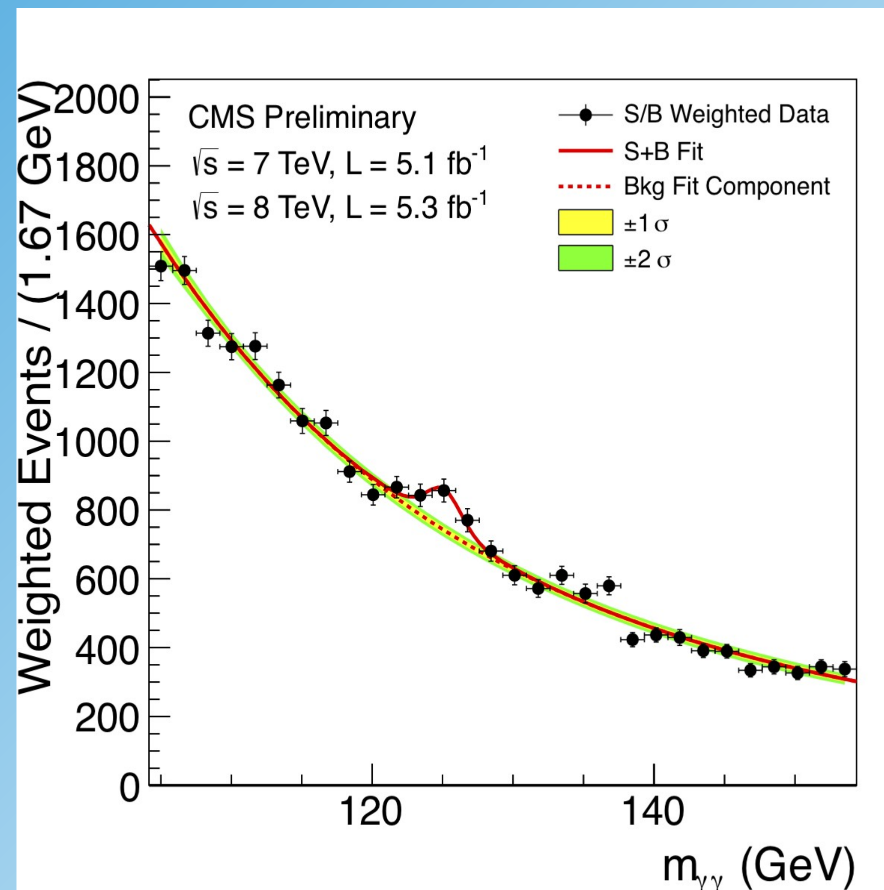
$H \rightarrow ZZ \rightarrow$ leptons

Growing Signal H $\rightarrow$ ZZ

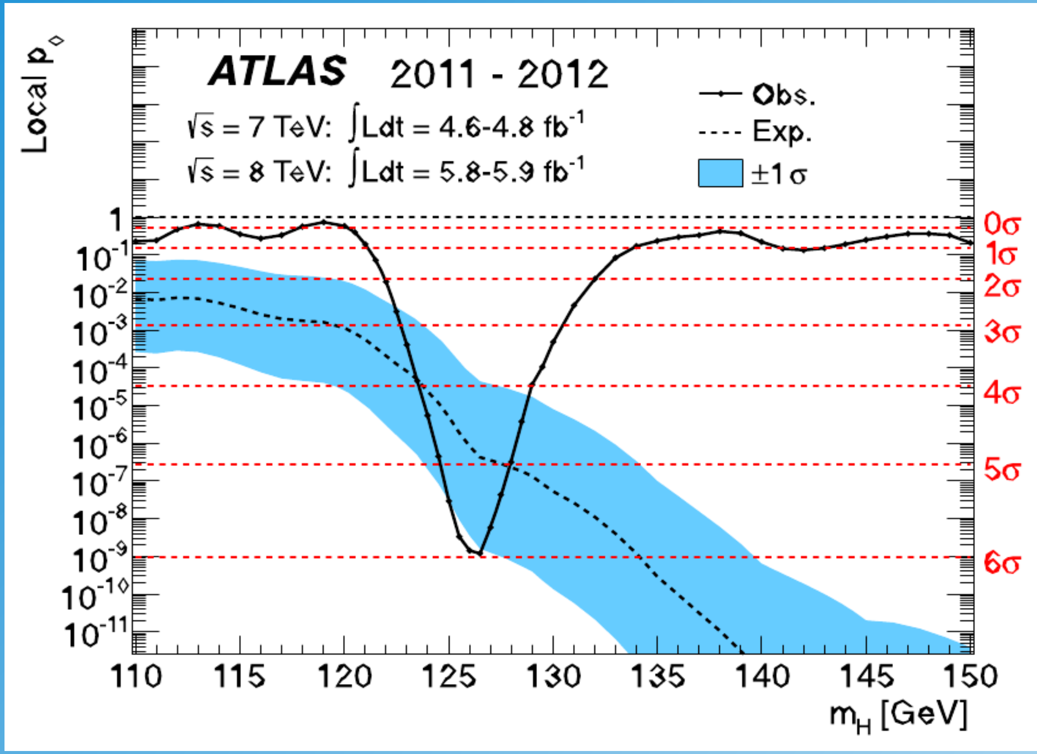
Latest Results ATLAS+CMS

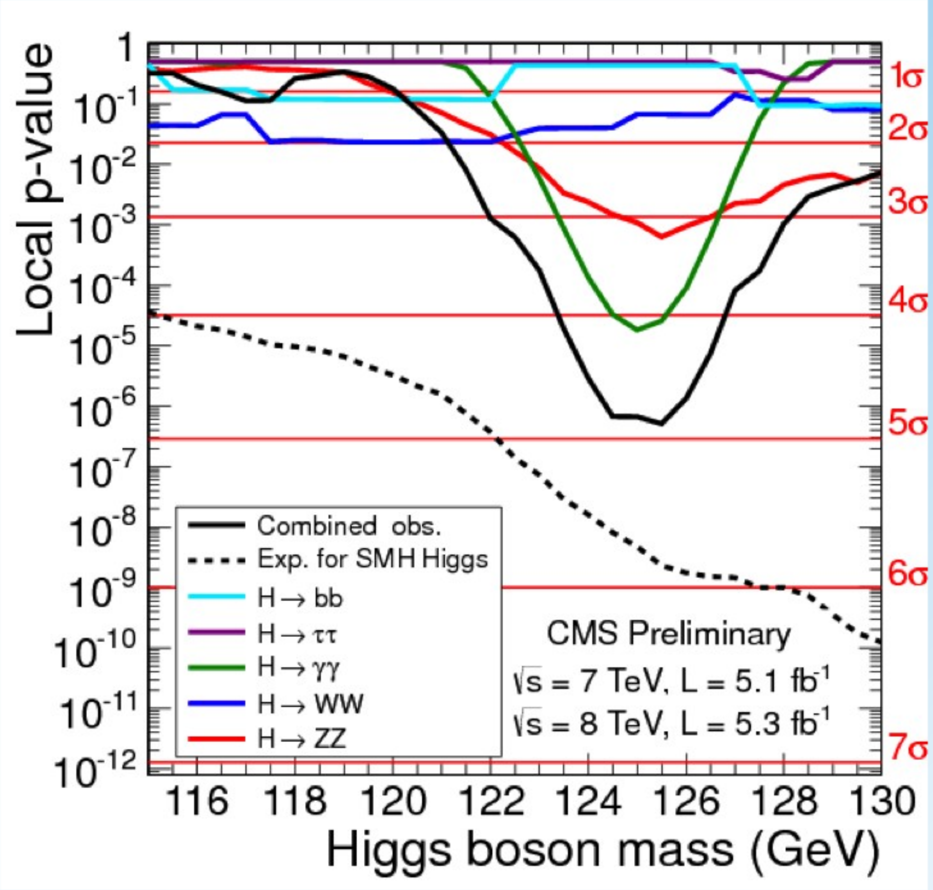


H → gamma gamma



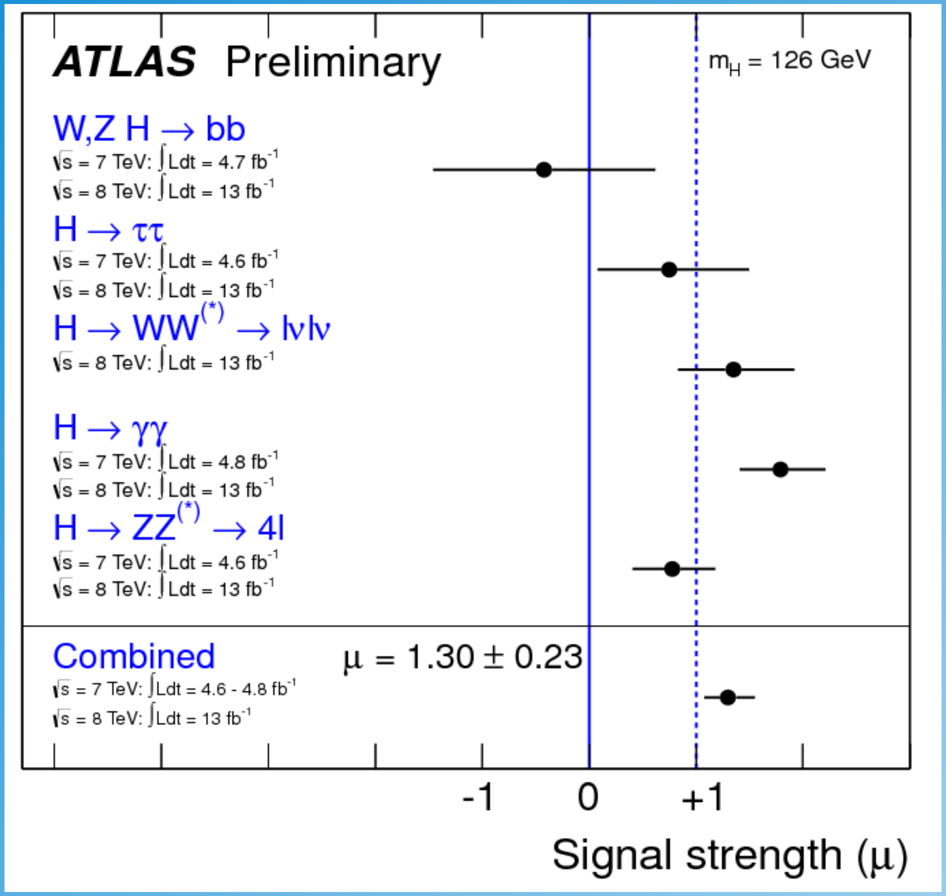
Latest Results ATLAS+CMS

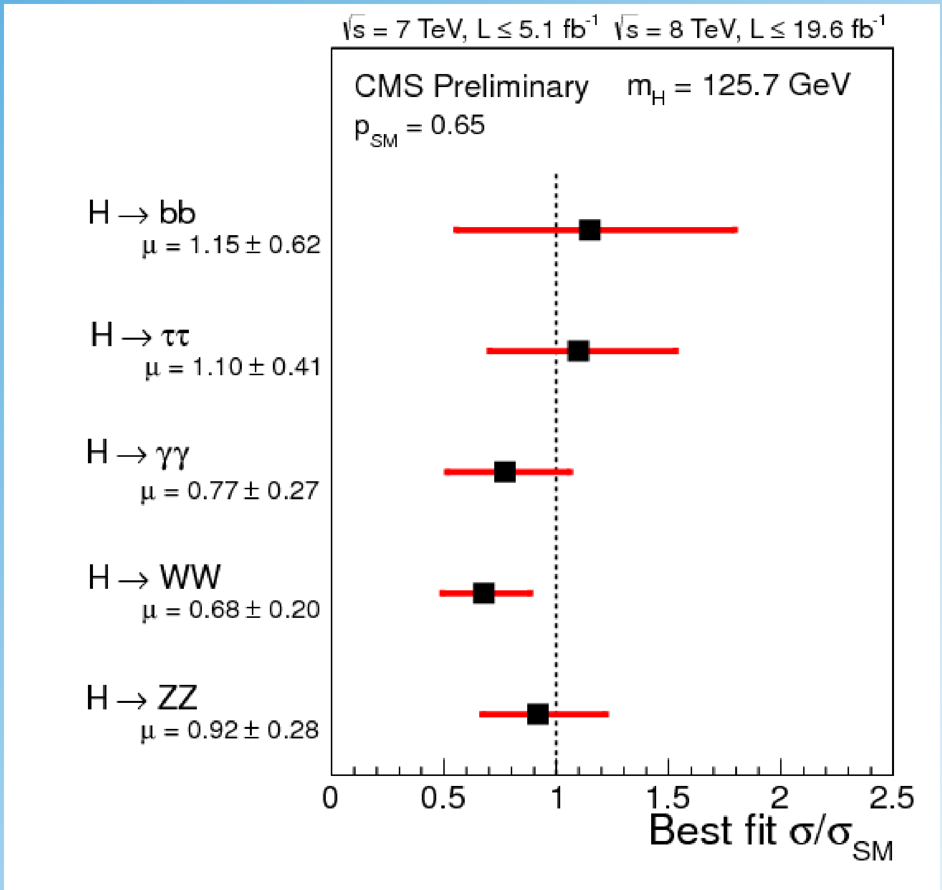




Combined local probabilities

Latest Results 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 (→ Werner Rodejohann). No new physics required up to very high mass scales!