CEPC fit framework

Zhang Kaili

zhangkl@ihep.ac.cn

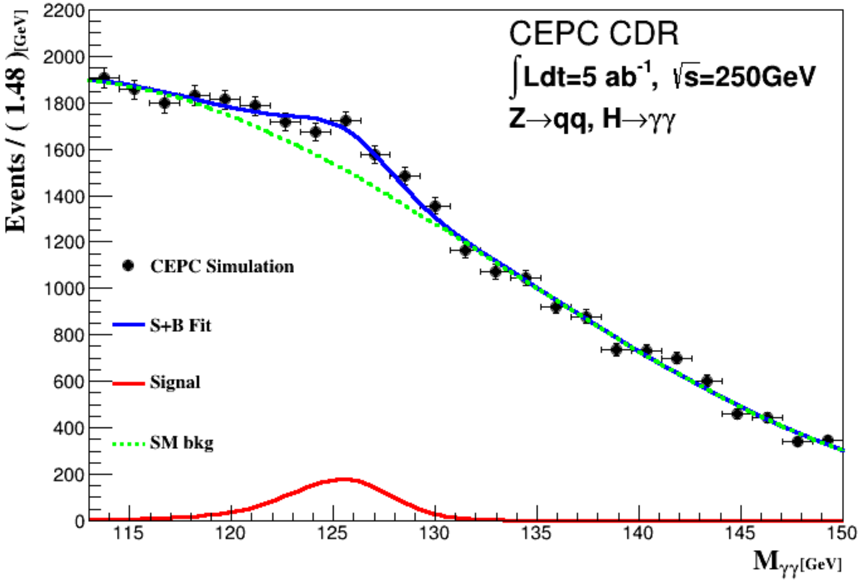
2018-03-19

Outline

- Statistics introduction
    - parameters of interest
    - Asimov Data
- Fit framework
- Example
    - H->invisible
    - vvH->bb
- Fit result

Statistics in CEPC

- After get this distribution:
  - what can we expect?
  - signal strength $\mu \equiv \frac{N_{obs}}{N_{exp}}$
  - μ=CrossSection*Br, $\Delta\mu$
  - ΔBr, with known $\Delta\sigma(ZH)(0.5\%)$
  - For discovery: significance
  - For exclusion: upper limit
  - More: κ, EFT……



if not familiar with these,
please refer to
Cowan's tutorial here (3 talks)
or see the backup slides
or come to find me ☺

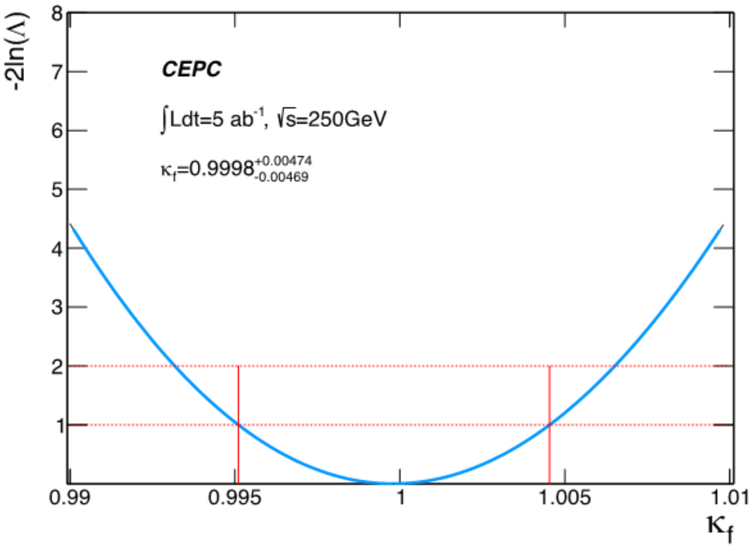
Combination framework

- Advantages to individual study
  - Fit result more robust & reliable
  - Treatment for correlation: ZH bkg
  - Extensibility in future for systematic uncertainties

  - Currently finished the combine model
  - All functional making workspace, fitting, plotting
  - For individual channel, the tutorial fit code undergoing
    - when finished, will upload to http://cepcsoft.ihep.ac.cn/

Fit method: likelihood scan

- Most robust
  - deviation at 1σ: precision $\Delta\mu$
  - deviation at 2(1.95) σ: upper limit
  - clear definition



Fit functions

- Crystal ball/Crystal ball + bifurcated Gaussian
- 2nd exponential like $\exp(a\frac{m-100}{100} + b\frac{(m-100)^2}{100^2})$
  - for smooth/flat background
- 5th chebshev
- RooKeysPdf(Kernel estimation)
- ……undergoing

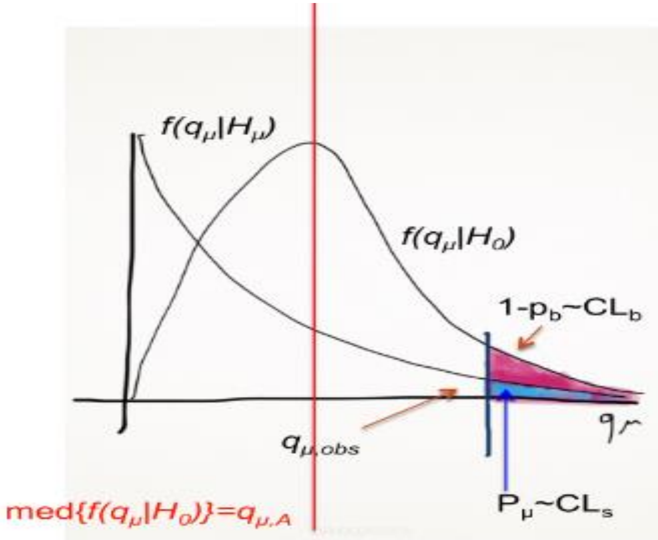
Inputs for the fit

- (After your final selection) distribution of signal & bkg
  - Mass(higgs & Z, invariant & recoil), 4 momentum
    - for further treatment on the shape
  - Event weight, if scaled
  - bkg, separate ZH/non ZH process and specify which ZH it is.
    - e.g H->WW, other modes like H->bb/cc/gg, ZZ, $\tau\tau$ ... ...
  - Mass ntuples (Most recommened) -> 1d unbinned fit
  - Flavor template/ Histograms -> 1/2d binned fit
  - esp. only signal/bkg event number -> 1d binned (1 bin) fit
  - ……

Asimov Data

Name come from scifi writer Asimov

- In principle, we can have infinite MC events as long as we want.
  - May not in reality, low MC stats would bring external uncertainty
- Idea of Asimov Data
  - Replace the shape to its median value (which is, the fit pdf)
  - Use the fit pdf to generate the exactly same datasets, as much as we want
  - Suppresses all statistical uncertainty from MC
  - Very useful for approximation
- Shows best performance in comparison
  - H->invisible, an example



H->Invisible

- Xin's result: (Assume Br in SM value 0.106%)

TABLE I: Branching ratio measurements and upper limits

	$Z(e^+e^-)H(\text{inv})$	$Z(\mu^+\mu^-)H(\text{inv})$	$Z(q\bar{q})H(\text{inv})$	Combined
BR	$(0.350 \pm 0.510)\%$	$(0.350 \pm 0.290)\%$	$(0.094 \pm 0.150)\%$	$(0.103 \pm 0.075)\%$
95% CL upper limit	1.30%	0.90%	0.37%	0.24%

- Note: Current all CEPC result is MC, which is set to the expected value, so μ should be always close to 1.
- If deviation too large: Not reliable
- Huge bkg-> large fluctuations

In mH 120~150 (L=5ab^{-1})	signal	bkg	s/b
Z->ee	12.86	4205	0.003
Z->mm	23.69	36540	0.0006
Z->qq	224.41	426540	0.0005

Using Asimov data

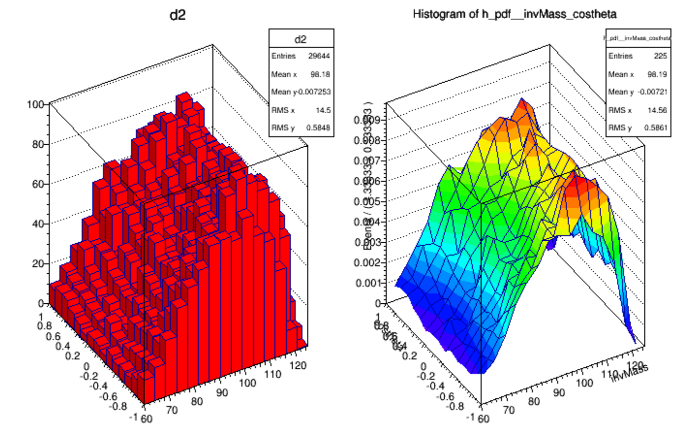
- Using same ntuples
  - on Asimov Data
  - Based on Br*σ, same range 120-150
  - Using more npoints when building
  - $Br_{BSM}(H \to inv) < 0.31\%$ at 95% CL.

	Mine	Mo's
Z->ee	$0.97 \pm 350\%$	$3.30 \pm 481\%$
Z->mm	$1.00 \pm 242\%$	$3.30 \pm 273\%$
Z->qq	$1.03 \pm 226\%$	$0.88 \pm 141\%$
Combined	$1.01 \pm 148\%$	$0.97 \pm 71\%$

	Mine	significance	Upper limit	Br Upper limit
Z->ee	$0.97 \pm 350\%$		7.97	0.84%
Z->mm	$1.00 \pm 242\%$		5.84	0.62%
Z->qq	$1.03 \pm 226\%$		5.55	0.59%
Combined	$1.01 \pm 148\%$	0.68	3.97	0.42%

- Also, Toy MC test may lead to external uncertainly, Asimov fit shows better
  - in ZH->qqyy, Yitian: 15.6% Mine: 12.8%

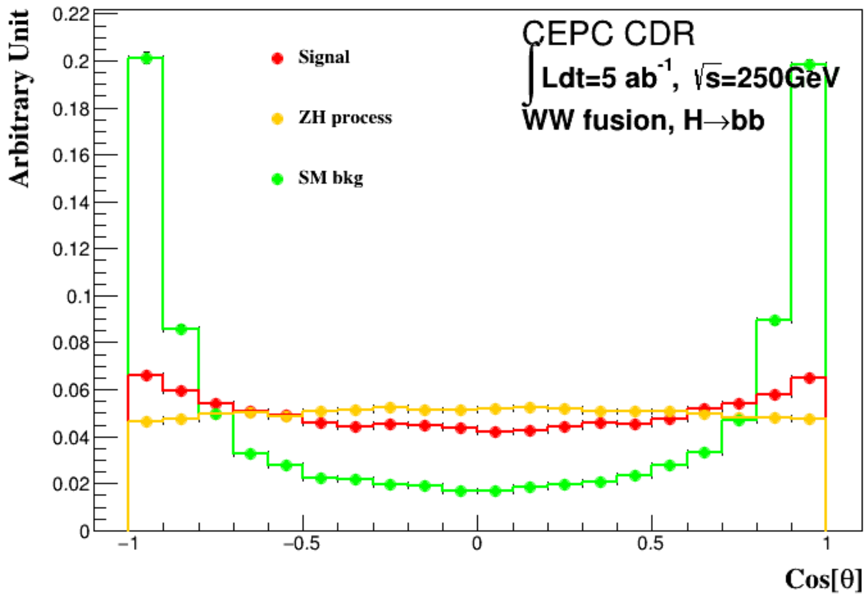
Correlation: $vvH \rightarrow bb$

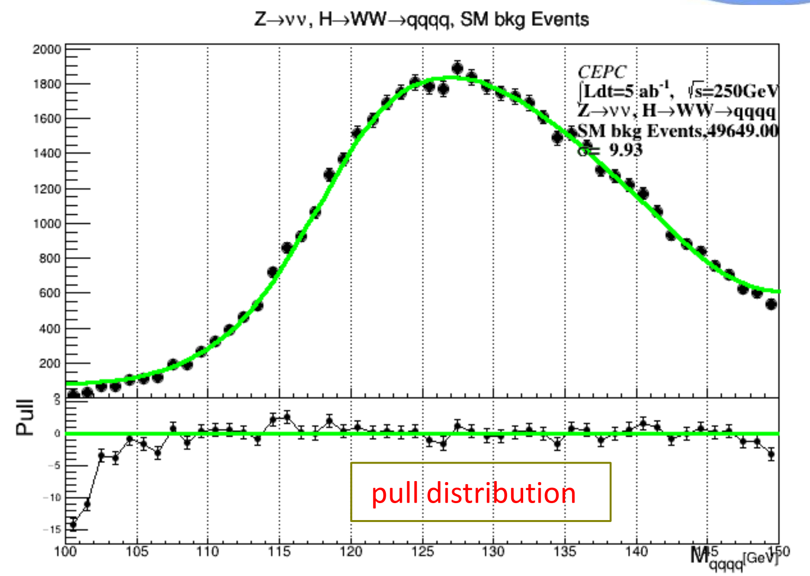


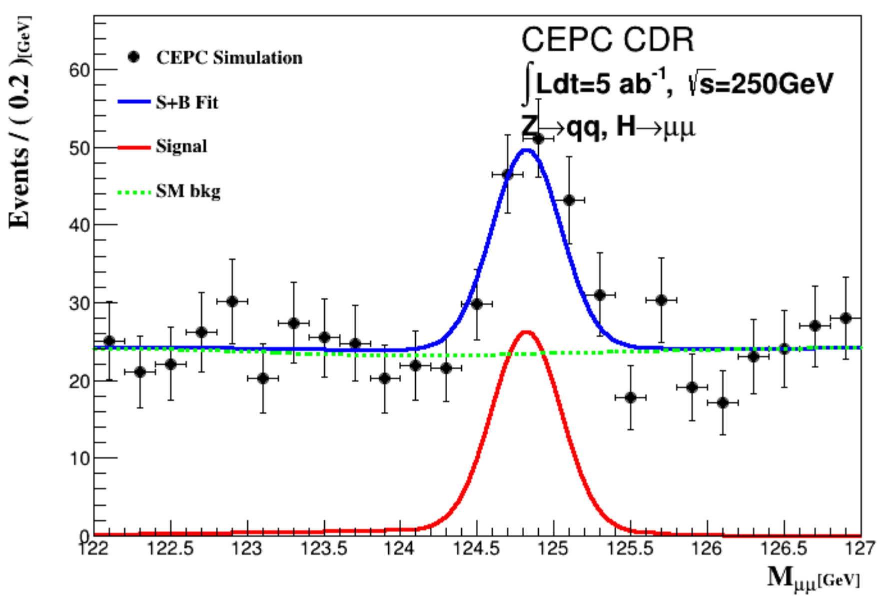
2d fit
Mass &cos of 2 jets

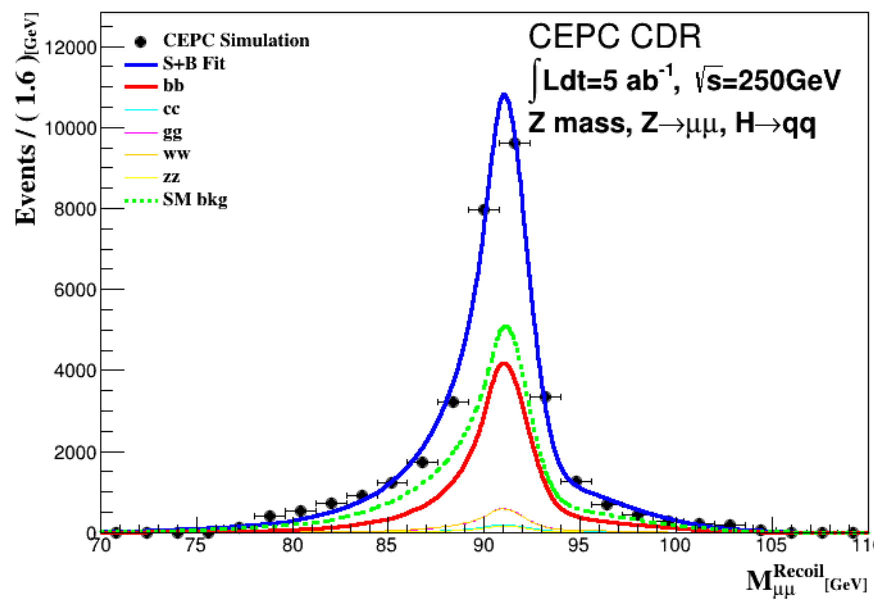
- WW fusion channel contains many ZH bkg;
  - Initial error is 2.89%, (Pre_CDR 2.8%)
  - But must consider the uncertainty of ZH process(~0.4%)
- In individual analysis
  - assume the error is Gaussian distribution
  - $-\text{Log}L = 0.5\left(\frac{\mu_{ZH}-1}{0.375\%}\right)^2 - P\left(data \middle| \mu_{\text{ZH}} N_{ZH} Pdf_{ZH} + \mu_{\text{wwf}} N_{wwf} Pdf_{wwf} + N_{SM} Pdf_{SM}\right)$
- Here we can directly use the likelihood in Z->ee/mm/qq, H->bb channel
  - Already have the form of μ_{ZH} no assumption made;
- Combine Fit $\{^{+3.13\%}_{-3.12\%}$; consistent with individual result 3.1%.

Plots to show









Channels Table

Done/Almost Done:

Signal		Precision
Z	H	
H->qq		
ee	bb	1.6%
	cc	23.6%
	gg	13.3%
μμ	bb	1.1%
	cc	14.8%
	gg	8.0%
qq	bb	0.5%
	cc	11.9%
	gg	3.9%
νν	bb	0.4%
	cc	3.9%
	gg	1.5%
H→ττ		
ee	ττ	3.0%
μμ		2.8%
qq		0.9%
νν		3.7%
H→γγ, Zγ		
μμ+ττ	γγ	24.8%
νν		11.7%
qq		12.8%
νν	Zγ(qqγ)	21.2%

Signal		Precision
Z	H	
H->WW		
μμ	μνμν	7.3%
	eνeν	
	eνμν	
	eνqq	4.0%
	μνqq	4.0%
ee	μνμν	9.2%
	eνeν	
	eνμν	
	eνqq	4.6%
	μνqq	3.9%
νν	qqqq	2.0%
	eνqq	4.7%
	μνqq	4.2%
qq	lνqq	2.2%(ILC)
ZH bkg contribution		3.0%
H->ZZ		
νν	μμqq	8.2%
νν	eeqq	35.2%
μμ	ννqq	7.3%
ee	eeqq	35.1%
ee	μμqq	23.0%
ZH bkg contribution		19.4%

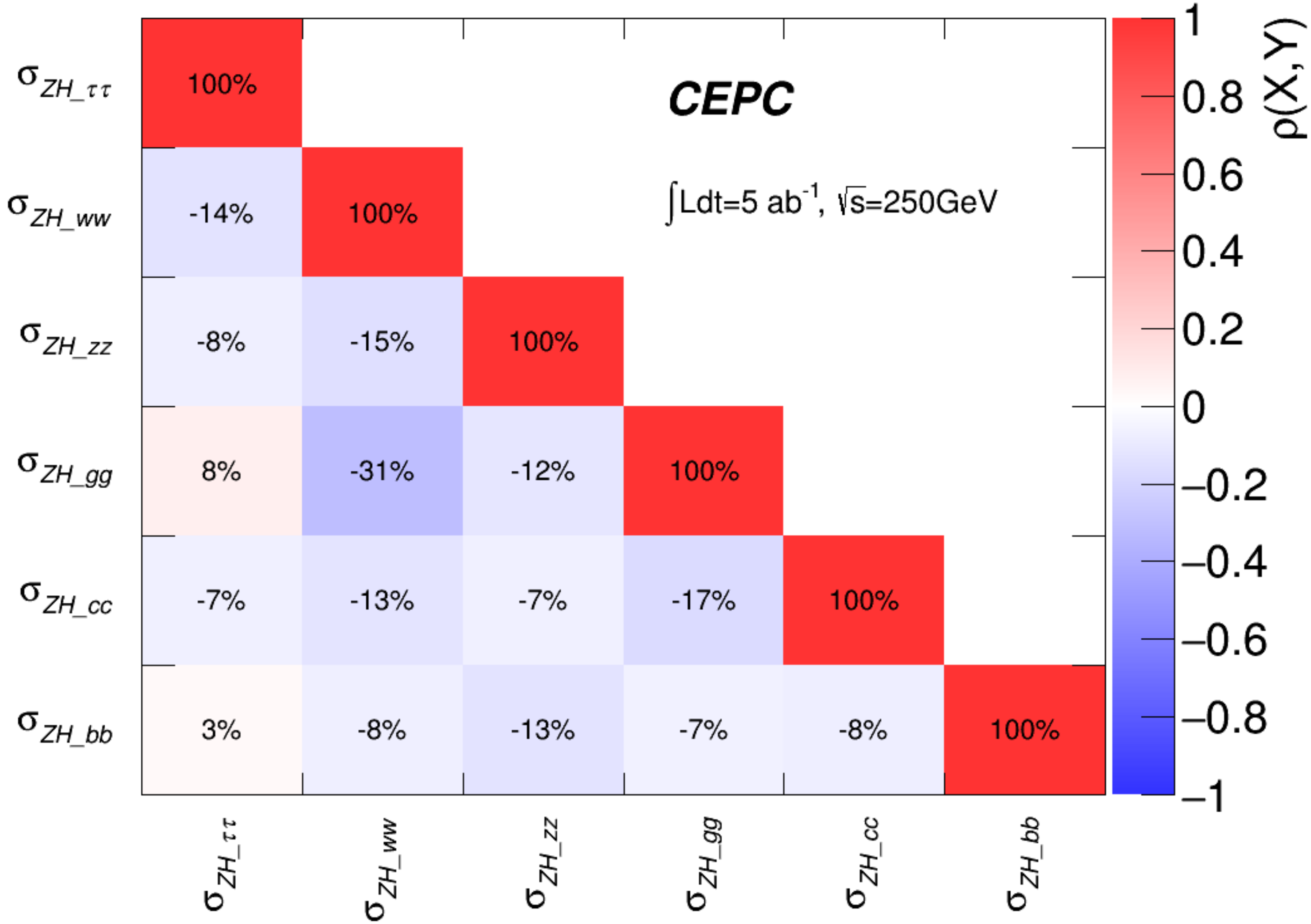
Signal		Precision
Z	H	
ννH(WW fusion)		
νν	bb	3.1%
Rare Decays		
H→μμ		
qq	μμ	15.9%
ee		
μμ		
νν		
H->Invisible		Br, Upper
qq	ZZ(νννν)	0.8%
ee		0.6%
μμ		0.6%

Fit results

Standalone: Regardless any ZH bkg contribution;
Different impact on w/z and b/c/g/τ.

($5ab^{-1}$)	Pre_CDR	Combined	Standalone
$\sigma(ZH)$	0.51%	0.50%	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	0.28%	0.3%	0.3%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{cc})$	2.20%	3.5%	3.5%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{gg})$	1.60%	1.4%	1.4%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$	1.50%	1.0%	1.2%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{ZZ})$	4.30%	5.0%	5.2%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \tau\tau)$	1.20%	0.8%	0.8%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \gamma\gamma)$	9.00%	8.1%	8.2%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mu\mu)$	17%	15.9%	15.9%
$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	2.80%	3.1%	3.1%
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$	0.28%	0.42%	0.42%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$	\	4σ	4σ

Correlations in channel



Esp., $vvH \rightarrow bb$ and $ZH \rightarrow bb$ is -46%.

Statistics backup

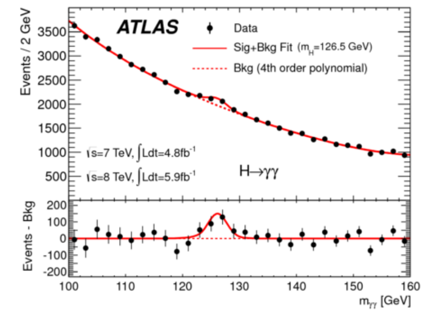
From a course talk presented last year

Higgs: Stats & Fit

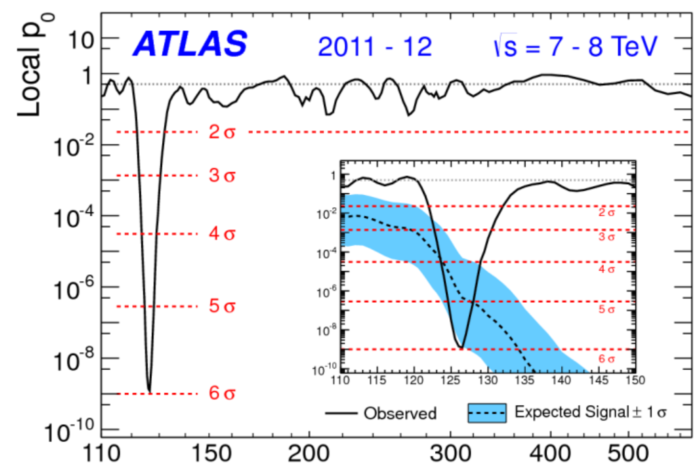
How can we claim a discovery

Is that Higgs?

- Now we have series plots with bump.
  - Could it be fluctuation? Is that Higgs?
  - Can we use data-bkg=signal?



- In modern particle physics, we develop a series statistic techniques to deal.
  - 5 sigma
  - Likelihood fit 似然拟合
  - Local p0, global p0, CL……



How to read this?

5 sigma

- $p = \int_Z^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} = 1 - \Phi(Z)$ Z=5   Gaussian, One side
- p=2.87*10^{-7} or $\frac{1}{3500000}$ (when p=0.05, Z=1.64)
- A very strict threshold in HEP we set
  - when p is low, it may be explained by fluctuation or systematic error

$<2\sigma$(2%)	: not worthy to discuss
$<3\sigma$(0.1%)	: hint
$<5\ \sigma$	: evidence
$>5\ \sigma$	: discovery

Statistics definitions

- Null Hypotheses H_0 SM, without Higgs
- Alternate Hypotheses H_1 SM, with Higgs at m_H

- Reject H_0 in favor of H_1 ——A DISCOVERY
- Reject H_1 in favor of H_0 ——We excluded Higgs with m_H

Hint: these two are not opposite.

- We prove Higgs exist by reject null hypotheses

由于我们永远无法直接证明H1,
通过拒绝H0假设来证明Higgs存在

Understand 5 sigma

- We calculate the probability

计算假设能构成观测到的数据的概率

  - of test statistic at least as extreme as that observed.

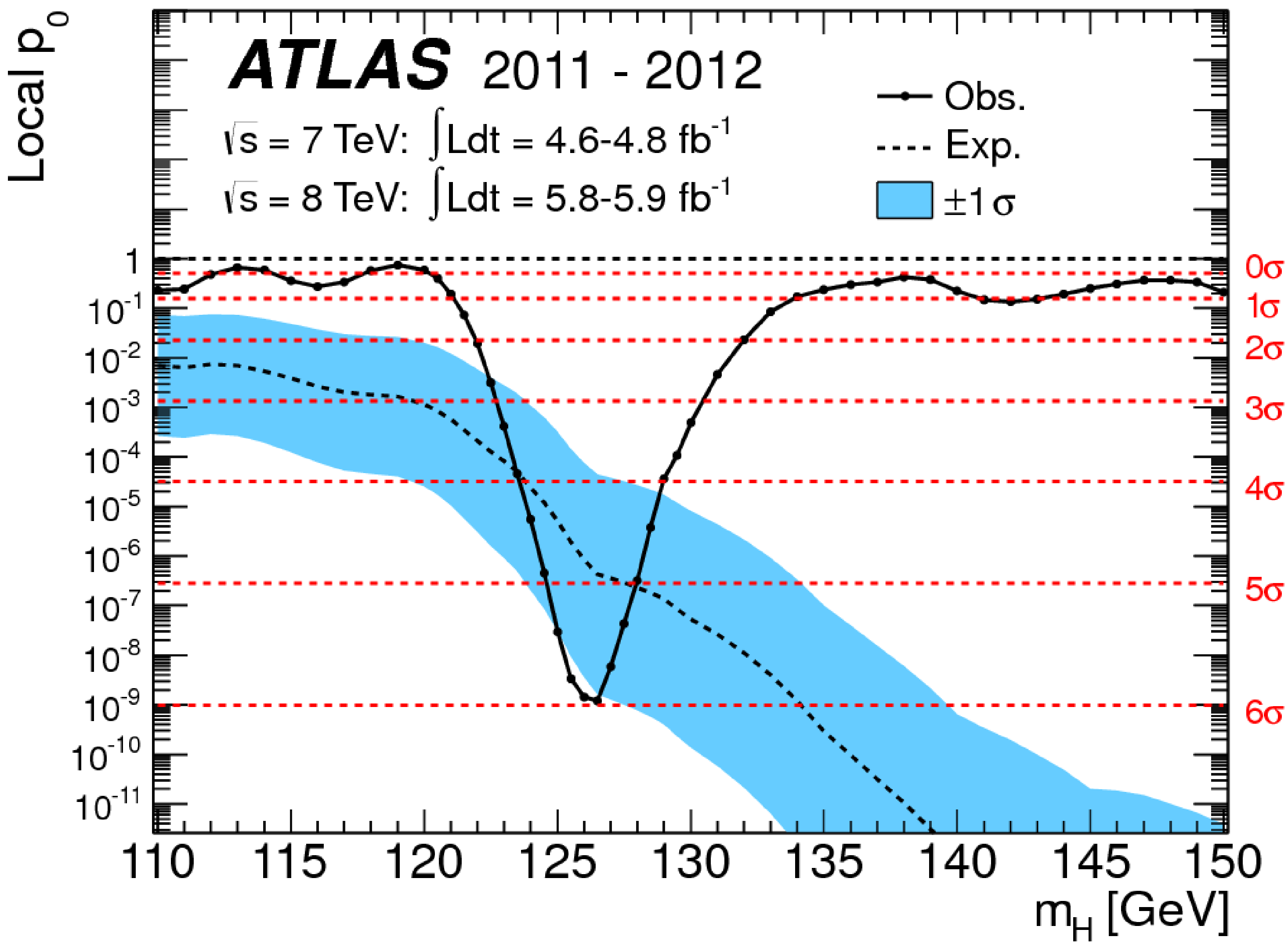
- P(result is compatible with the tested (bkg only) hypotheses)
  - If low enough ($< 2.87 \times 10^{-7}$) 5 sigma

  Means SM can't explain current distribution (the bump)

  - The null hypotheses H_0 is rejected. We claim discovery.
  - Local p0
    - Local ->Regardless Look elsewhere effect
    - P_0 -> tested (bkg only) hypotheses H_0

For discovery

*when we say "raise significance", it means raise Z. Z=$\Phi^{-1}(1-p_0)$

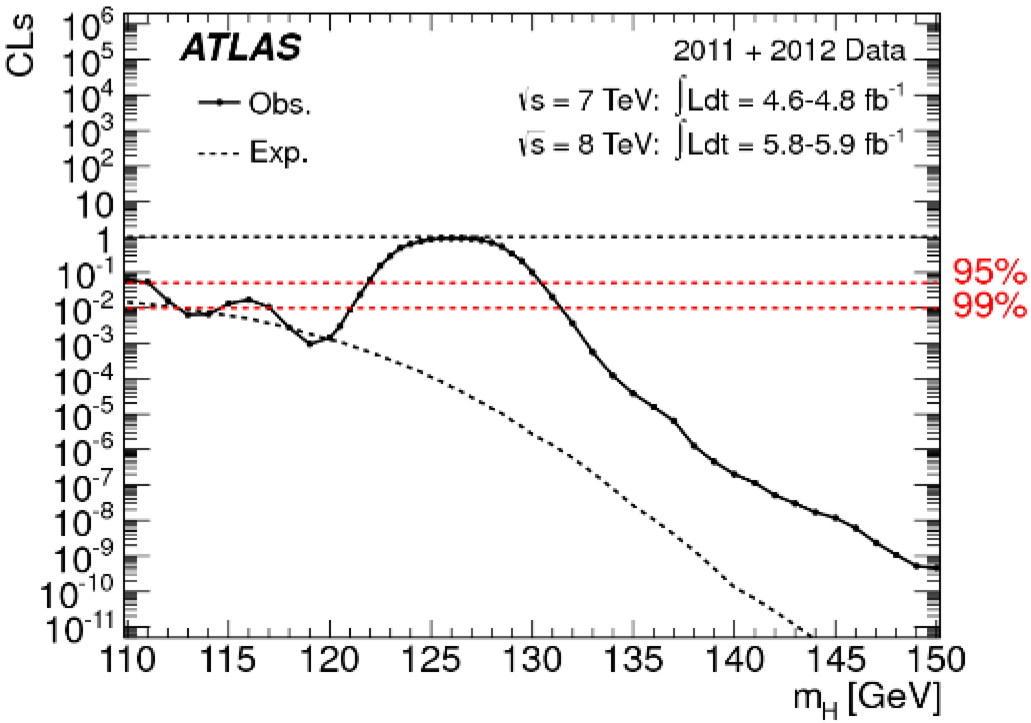


For exclusion

S+B模型能够解释实验数据的概率
过小则不承认这里有Higgs
不断排除区间以设置"排除上限" upper limits

=P(result is compatible with the tested (signal+bkg) hypotheses)

- when $p < 0.05$ 95% Confidence Level(CL)
- The alternate hypotheses H1 is rejected. We exclude this region at 95% CL.



Statistic errors

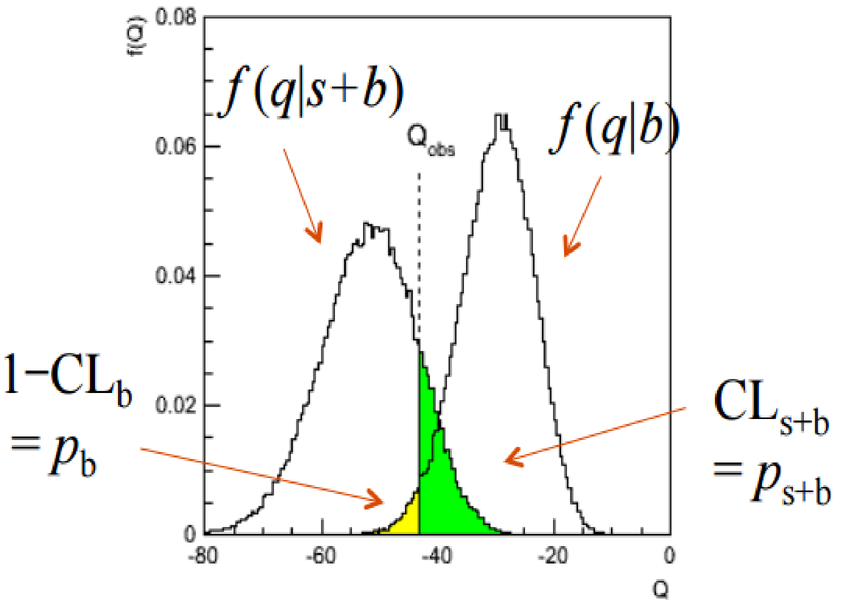
- Type-1 Error第一类统计错误
  - P(reject the tested(null) hypotheses when it is true)
  - $\alpha = P(reject\ H_0|H_0)$ α ~significance=p-value
- Type-2 Error第二类统计错误
  - P(accept the null hypothesis when it is wrong)
  - $\beta = P(accept\ H_0|\overline{H_0}) = P(reject\ H_1|H_1)$
- Power, reject null when alternate is true
  - Power=1- β Power~sensitivity
  - Given same significance, methods with higher Power is better.

$\mathrm{CL_s}$ issue for exclusion

- Usually we calculate $\mathrm{CL_{s+b}}$ for exclusion.
- Sometimes distribution b and s+b are close
  - Usual CL method (compare $p_{s+b} < \alpha$) has low sensitivity

  Define

  - $\mathrm{CL_s} = \frac{CL_{s+b}}{CL_b} = \frac{p_{s+b}}{1-p_b}$
  - If $\mathrm{CL_s} < \alpha$
  - Reject s+b Hypothesis: H_1



How to calculate?

Use likelihood model to quantify.

- Signal strength $\mu \equiv \frac{\sigma_{obs}}{\sigma_{exp}}$
- For each bin, $\mathrm{E}(n) = \mu * s_i + b_i$ Poisson
- Basic form:

$$L(\mu) = \frac{(\mu s + b)^n}{n!} e^{-(\mu s + b)}$$

- Add nuisance parameters (NP) to model.
  - besides POI(parameter of interest, here is μ)
  - describe uncertainty, bkg parameterization, …… anything we need.

Likelihood function: an example

$$\mathcal{L} = \prod_i \left\{ \frac{e^{-v_i}}{n_{i!}} \prod_j^{n_i} [v_i^{sig} \mathcal{F}_i^{sig}(m^j, \theta; m_H) + v_i^{bkg} \mathcal{F}_i^{bkg}(m^j)] \right\} \times \prod_l G_l(\theta)$$

- Function form: $$f = N \cdot \begin{cases} e^{-\frac{1}{2}\alpha_L^2} \cdot \left[\left(\frac{\alpha_L}{n_L}\right)\left(\frac{n_L}{\alpha_L} - [\alpha_L + x]\right)\right]^{-n_L}, x < -\alpha_L \\ e^{-\frac{1}{2}x^2}, \quad -\alpha_L \le x \le \alpha_H \\ e^{-\frac{1}{2}\alpha_H^2} \cdot \left[\left(\frac{\alpha_H}{n_H}\right)\left(\frac{n_H}{\alpha_H} - [\alpha_H - x]\right)\right]^{-n_H}, x > \alpha_H \end{cases}$$
- $\mathcal{F}^{sig}$: pdf(probability distribution function) of signal, describe the signal shape.
- $\mathcal{F}^{bkg}$: pdf of background
- Function minimizes the bias observed in the extracted signal yield
- The bkg model with the least parameters is chosen
- G_l: Uncertainties.

Powerful likelihood model

- Easy to do combination each channels/categories.

Times the subpart directly!

$$L(\mu, \theta) = \prod_i L_i(\mu, \theta_i)$$

  - uniformed, simultaneous statistical procedure and framework
  - can easily include necessary correlations   Share the same name
  - Final model can be very complicated to consider all info from the analysis.

- Maximize Likelihood (ML) estimation/fit
  - Determine all the parameter’s value.

Profile likelihood ratio

Maximize L for specified μ

Under NPs with θ

$$\lambda(\mu) \equiv \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

Maximize L

$$0 \leq \lambda \leq 1$$

Larger λ, better agreement data & hypothesis

- Test statistics

$$\mathrm{q}(\mu) \equiv -2 \ln \lambda(\mu)$$

Higher q, less incompatible.

To reject background-only (μ = 0) hypothesis using

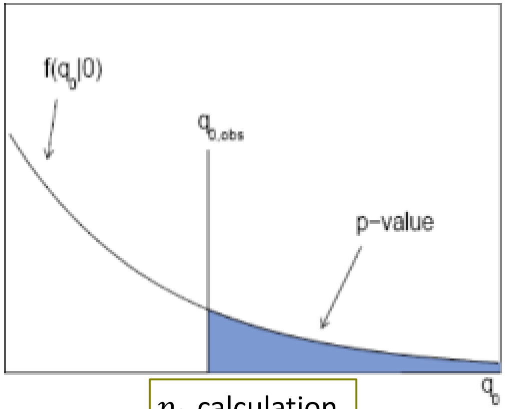
- $$\mathrm{q}_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

Even physically $\mu > 0$, we allow $\hat{\mu} < 0$ for convenience.

Calculate p-value

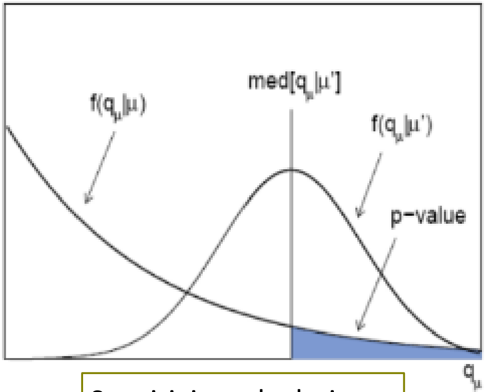
- $p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0)\,\mathrm{d}q_0$

Currently the shape of f is unknown, later I'll show an approximation.



p_0 calculation

- Use $f(q_0|0)$ to announce discovery
- Use $f(q_0|\mu')$ to calculate sensitivity
- Use $f\left(q_\mu\middle|\mu'\right)$ to calculate exclusion
  - $q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases}$ $\quad p_\mu = \int_{q_{\mu,obs}}^{\infty} f(q_\mu|\mu)\,\mathrm{d}q_\mu$



Sensitivity calculation

Look elsewhere effect(LEE)

- In local p0 calculation, the m_H is fixed. $q_{fix}(\mu) = -2\ln\frac{L(0,m_0)}{L(\hat{\mu},m_0)}$

Each mH point has a local p0.

$$p_{local} = \int_{q_{fix,obs}}^{\infty} f(q_{fix}|0)\,\mathrm{d}q_{fix}$$

- Suppose we don't know where to find the peak.
  - It can occur anywhere: mass is float. $q_{float}(\mu) = -2\ln\frac{L(0)}{L(\hat{\mu},\hat{m}_0)}$

One region has a glocal p0.

$$p_{global} = \int_{q_{float,obs}}^{\infty} f(q_{float}|0)\,\mathrm{d}q_{float}$$

We can get p_{global} by fit or an "upcrossion" correction.

LEE only in discovery, not in exclusion.

In Higgs finding 2012, the global p_0 is 5.1 sigma.

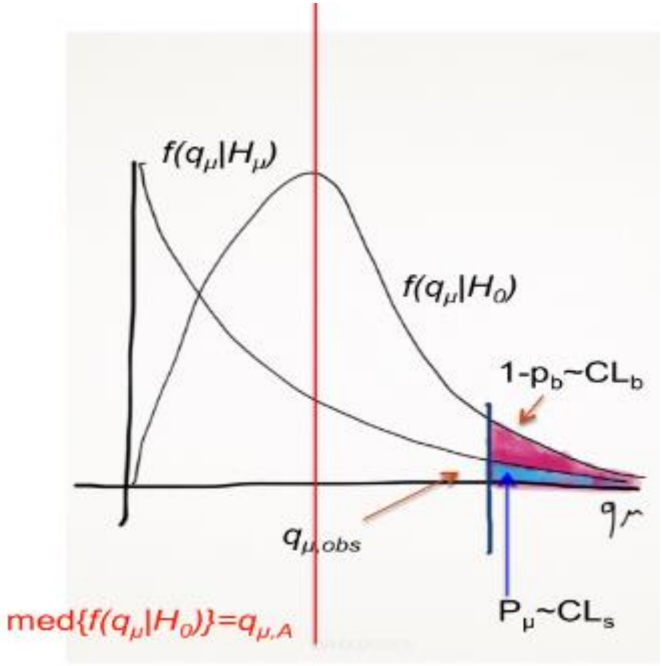
Global & local p0 max at same point, global a bit lower;

Even global p0 is more "reasonable", we use 5sigma local p0 as symbol.

Asimov data

阿西莫夫，科幻小说家

- Use Asimov dataset in fit
  - Suppresses all stats. uncertainties.
  - Parameters all replaced to their expected value
  - The median of $f(q_{\mu}|H_0)$
  - Can be determined by MC
  - Very useful for approximation



Distribution of q_0

- To estimate -2 $\ln \lambda(\mu)$ Wilks & Wald theorem
- Assuming the Wald approximation
  - NP independent, one degree of freedom

$$f(q_0|\mu') = \left(1 - \Phi\left(\frac{\mu'}{\sigma}\right)\right)\delta(q_0) + \frac{1}{2}\frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{q_0}}\exp[-\frac{1}{2}\left(\sqrt{q_0} - \frac{\mu'}{\sigma}\right)^2]$$

- $\mu' = 0$, special "half chi-square" distribution

$$f(q_0|0) = \frac{1}{2}\delta(q_0) + \frac{1}{2}\frac{1}{\sqrt{2\pi}}\frac{1}{\sqrt{q_0}}\exp[-q_0/2]$$

- Finally, significance

$$Z = \sqrt{q_0}$$

The conclusion ☺

Simplified: number counting

ATLAS EXPERIMENT

- with bkg known, we get significance Z:
  - $\frac{s}{\sqrt{b}}$, for s ≪ b
  - $or,\ \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$
  - with uncertainty σ_b: $\left[2\left((s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right]-\frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right)\right]^{\frac{1}{2}}$

S: signal yields in region.
s_{exp} & s_{obs}
b: background yields in region
Always use b_{obs}

- purity $f_{exp} \equiv \frac{S_{exp}}{S_{exp}+B_{obs}}$ $f_{obs} \equiv \frac{S_{obs}}{S_{obs}+B_{obs}}$
- Z $Z_{exp} \equiv \sqrt{2\left(\left(S_{exp}+B_{obs}\right)\ln(1+\frac{S_{exp}}{B_{obs}})-S_{exp}\right)}$ $Z_{obs} \equiv \sqrt{2\left(\left(S_{obs}+B_{obs}\right)\ln(1+\frac{S_{obs}}{B_{obs}})-S_{obs}\right)}$

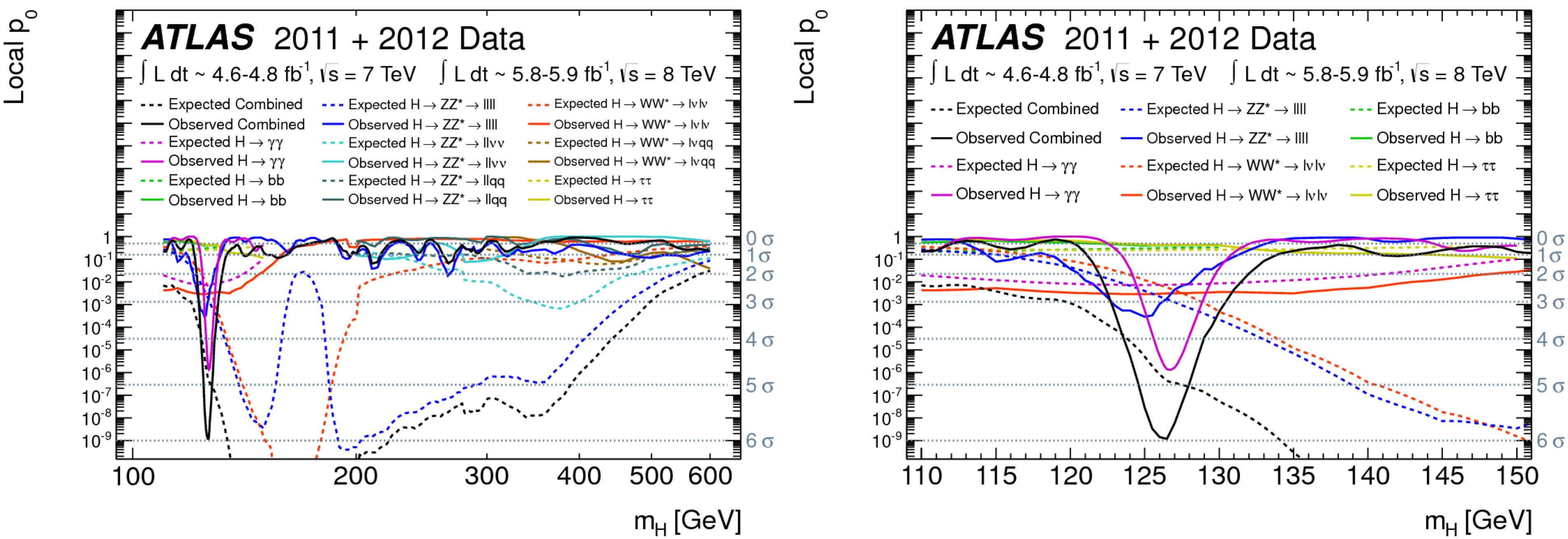
Actually: simultaneous fit

Number counting is awesome.
But we didn't know the real signal yields;
And none NP has taken into account!
Go back to our model.

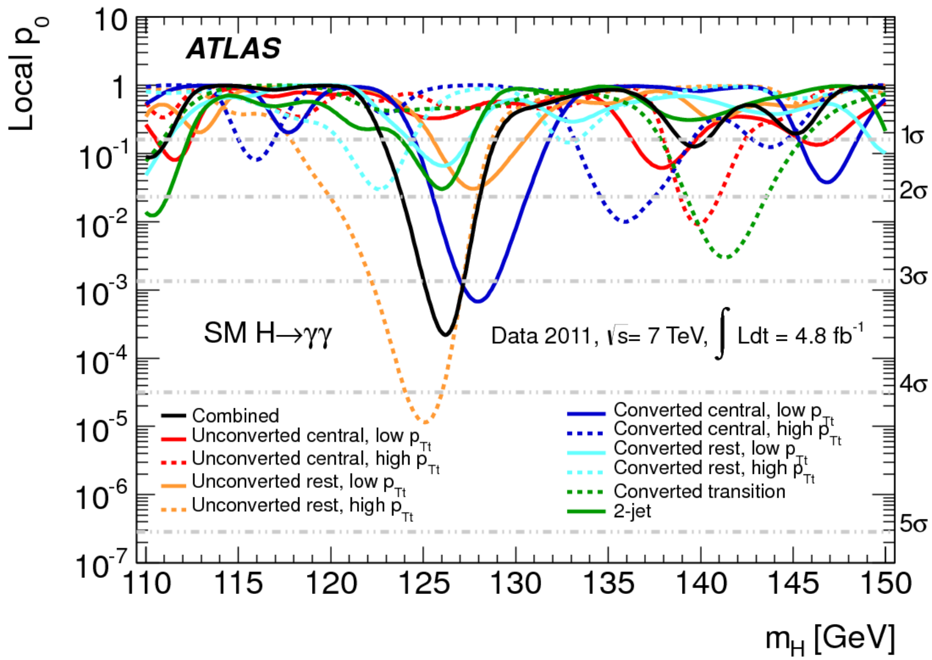
- Use fit
  - to determine POI: μ.
  - to calculate signal yields, significance and so on.
  - to check the influence of NP   corresponds to uncertainties
- Use p_0 to announce discovery
- Use CL to set upper limits (exclusion)
- Use μ & m_H 2-dimension fit to determine best μ & m_H

We determine m_H here

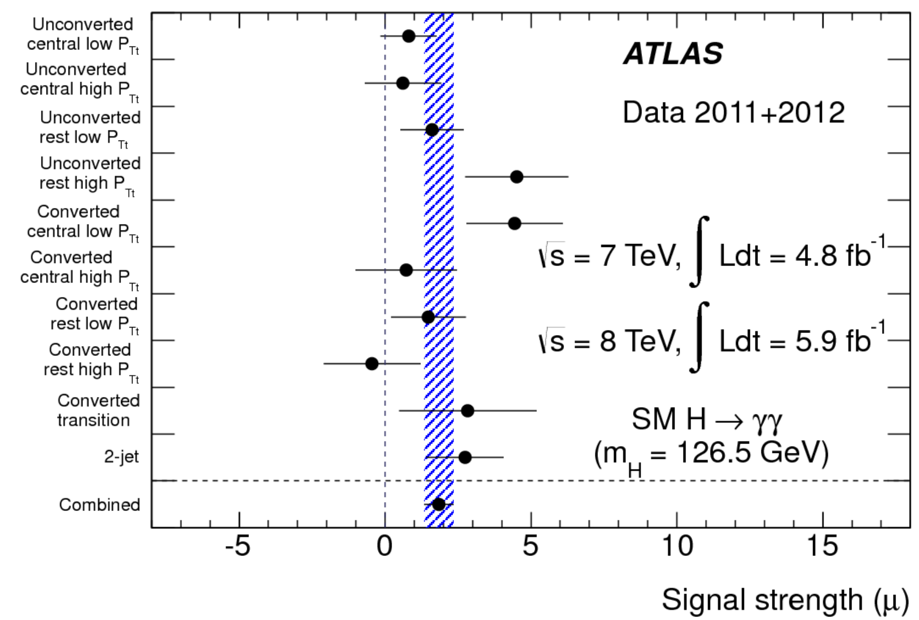
Combine channels



Categories

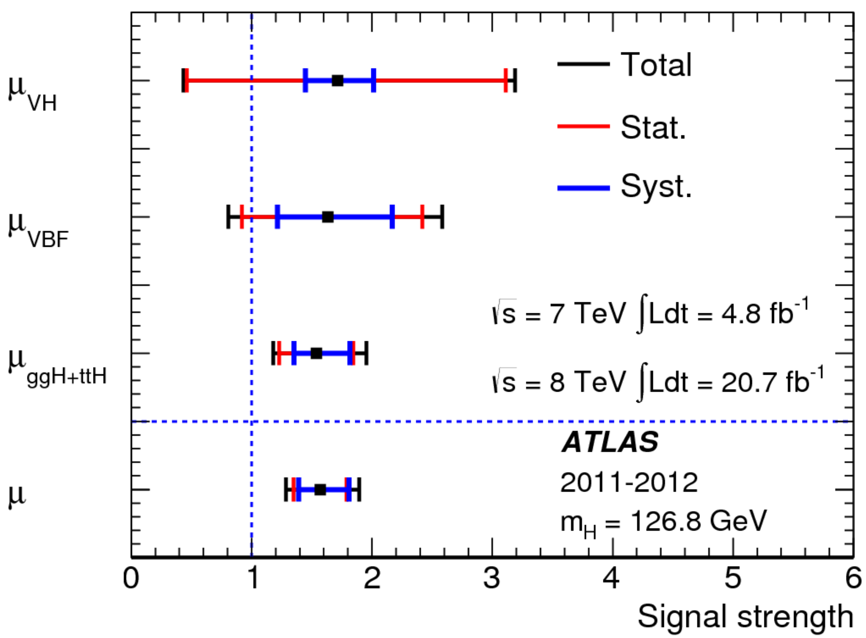


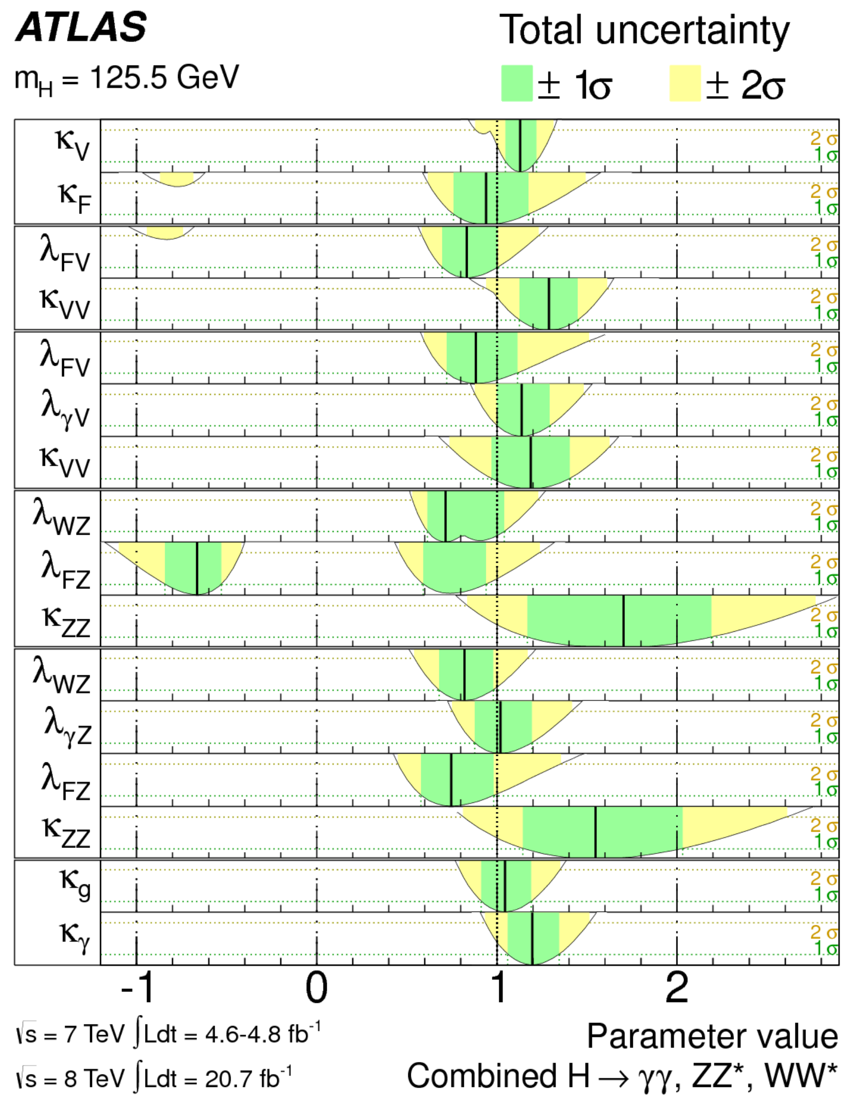
ATLAS
Local p_0
SM $H\to\gamma\gamma$
Data 2011, $\sqrt{s}$= 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
1σ
2σ
3σ
4σ
5σ
Combined
Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition
2-jet
m_H [GeV]



Unconverted central low P_{Tt}
Unconverted central high P_{Tt}
Unconverted rest low P_{Tt}
Unconverted rest high P_{Tt}
Converted central low P_{Tt}
Converted central high P_{Tt}
Converted rest low P_{Tt}
Converted rest high P_{Tt}
Converted transition
2-jet
Combined
ATLAS
Data 2011+2012
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 5.9 fb^{-1}
SM $H\to\gamma\gamma$
(m_H = 126.5 GeV)
Signal strength (μ)

Production Modes (1307.1427, Full Run1)





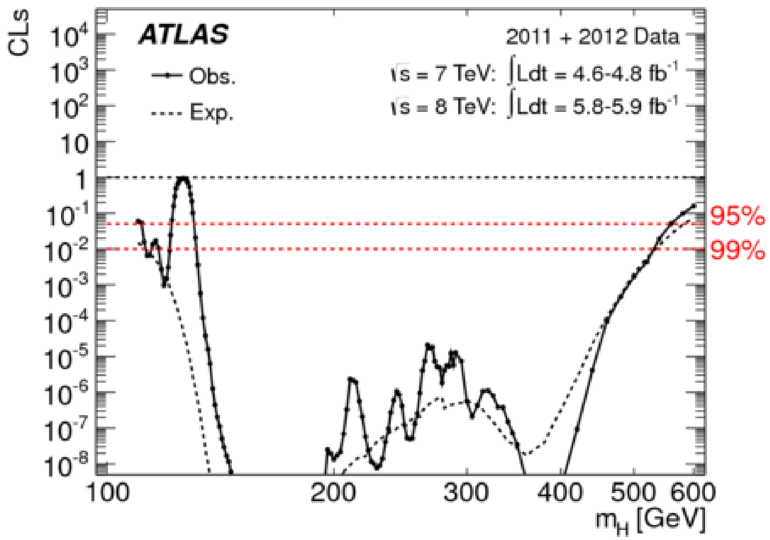
Summary plot on 12Atlas result

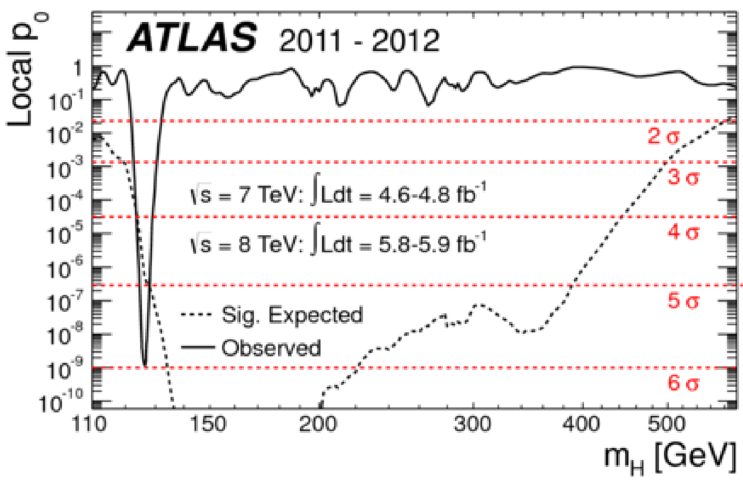
*126.5GeV is not Higgs Mass!

Exclusion region:
Exp 95%CL:110-582GeV
Obs 95%CL:111-122,131-559GeV
Exp 99%CL:113-532GeV
Obs 99%CL:113-114,117-121, 132-527GeV

Peak:at 126.5GeV
Obs local p0:6.0σ
Exp local p0:4.9σ
Global p0 in 110-600GeV:5.1σ
Global p0 in 110-150GeV:5.3σ

6.0->5.9 due to uncertainty





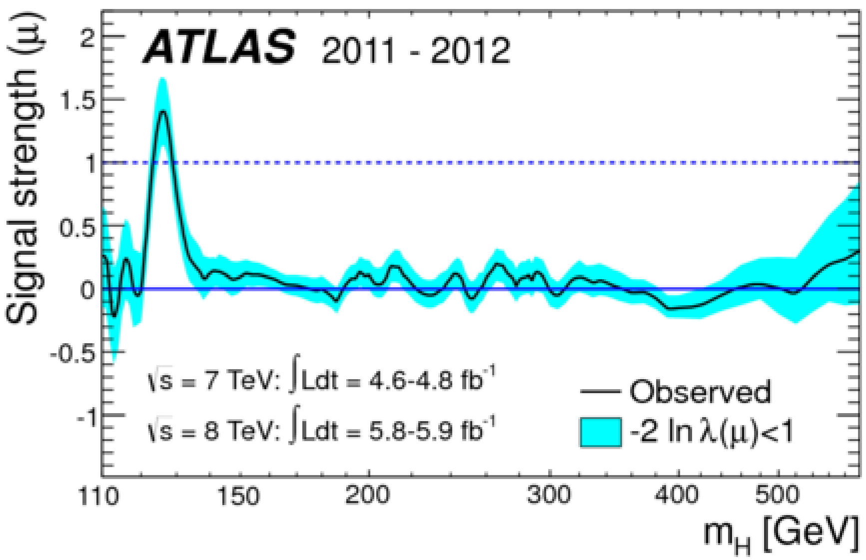
*quiz: before experiment begin,
can we calculate the expected local p0 by theory?

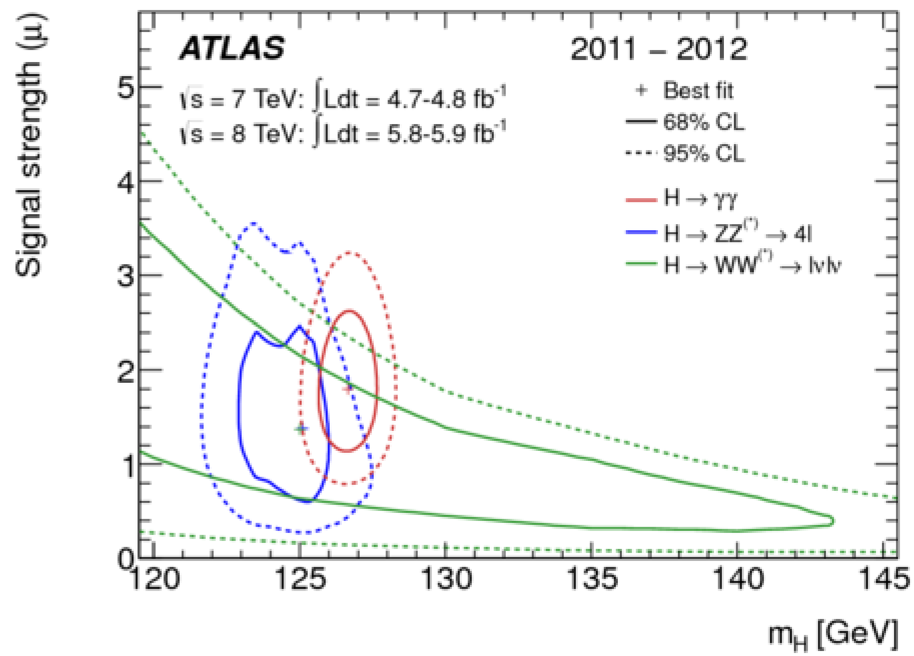
Summary plot on 12Atlas result

Best Fit:

m_H=126.0 $\pm$ 0.4 (stat) $\pm$ 0.4 (sys) GeV.

$\mu = 1.4 \pm 0.3$





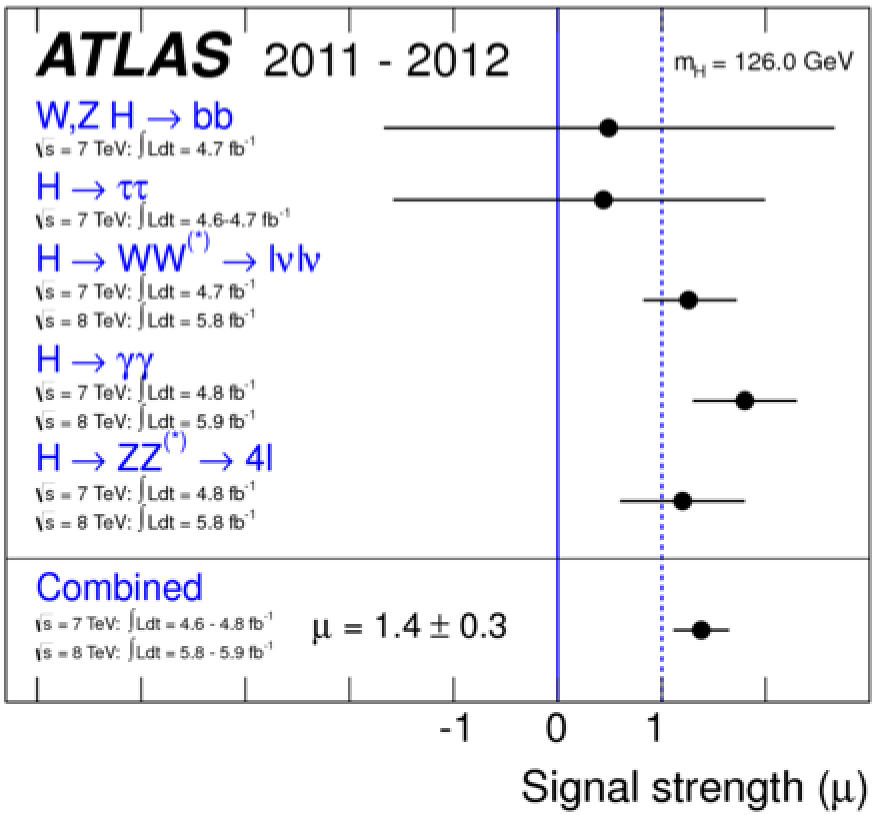
Conclusion on 2012

(in 1207.7214), ATLAS announced:

- Clear evidence for the production of a neutral boson with a measured mass of

  $$126.0 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{sys})\ \text{GeV}.$$

- A significance of 5.9 standard deviations.
- Considering LEE, the global p_0 is 5.1 sigma.
- The measured signal strength is 1.4 ± 0.3.
- It is compatible with the production and decay of the Standard Model Higgs boson.
  - We didn't directly say "it is Higgs."



2013, after more data collection, LHC announced,

"it strongly indicates that it is a Higgs boson."

Uncertainty

In 1207.7214 uncertainties are not in detail.

List	Dominant
Stats.	*
Integrated Luminosity	
e/mu/gamma PID	*
e/mu/gamma energy scale	*
muon reconstruction	
jet energy scale	
jet energy resolution	
signal predictions	
background normalizations	
background model parameters	
Other theoretic errors……	

In ATLAS/CMS experiment, theoretical uncertainties can be 500+.
Leading source: $\gamma/e/\mu$, energy resolution/PID
High energy interactions' accuracy has potential to improve.

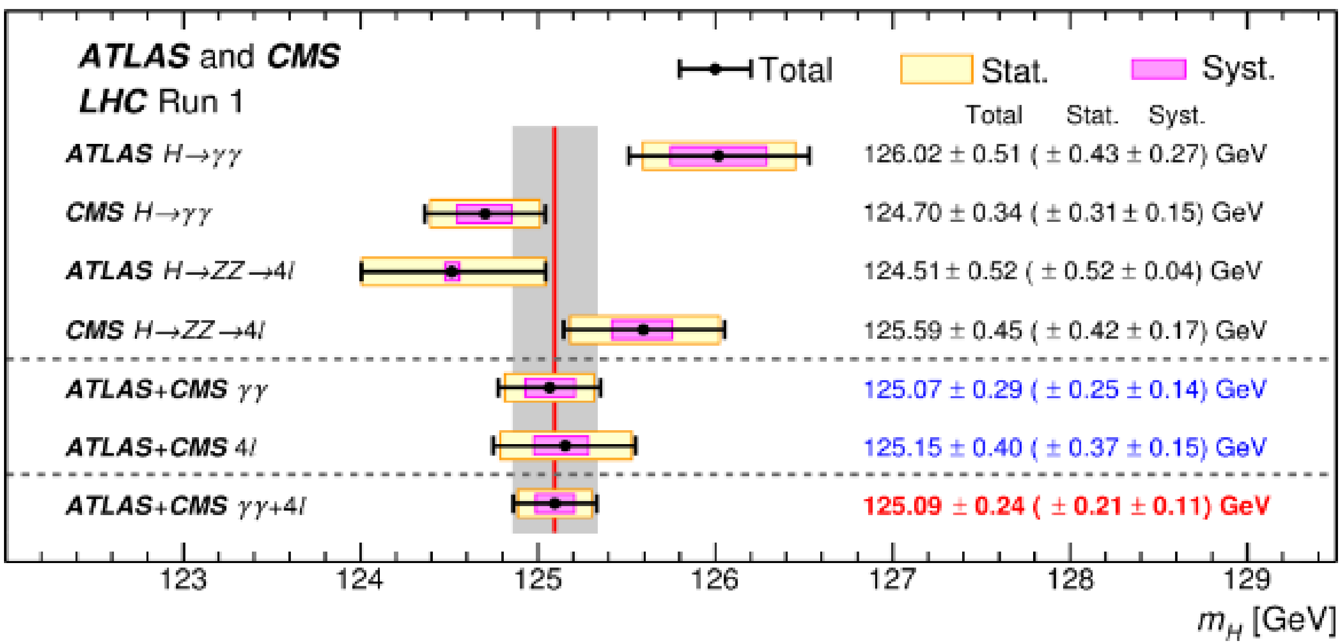
Uncertainty on 1503.07589

Combined Measurement of the Higgs Boson Mass
in pp Collisions at s√=7 and 8 TeV with the ATLAS and CMS Experiments

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–	0.01 (0.01)	–
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–	0.01 (0.01)	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	–	

Current Higgs (update to Run1)

Mass	$125.09 \pm 0.21 \pm 0.11\text{GeV}$
Width	$\Gamma < 1.7 Gev, CL\% = 95\%$
Combined signal strength	1.10 ± 0.11
Spin, CP	0^{++}



References

- Statistical issues for Higgs Physics, Eilam Gross
- Asymptotic formulae for likelihood-based tests of new physics, Glen Cowan, 1007.1727
- Statistical Methods for Particle Physics Lecture, Glen Cowan
- Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC, ATLAS Collaboration, 1207.7214
- Combined Measurement of the Higgs Boson Mass in pp Collisions at s√=7 and 8 TeV with the ATLAS and CMS Experiments, 1503.07589
- Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC, 1307.1427
- Review of physics, Particle Data Group, Chin. Phys. C, 40, 100001 (2016).