(Experimental) Overview of the Higgs Physics at LHC

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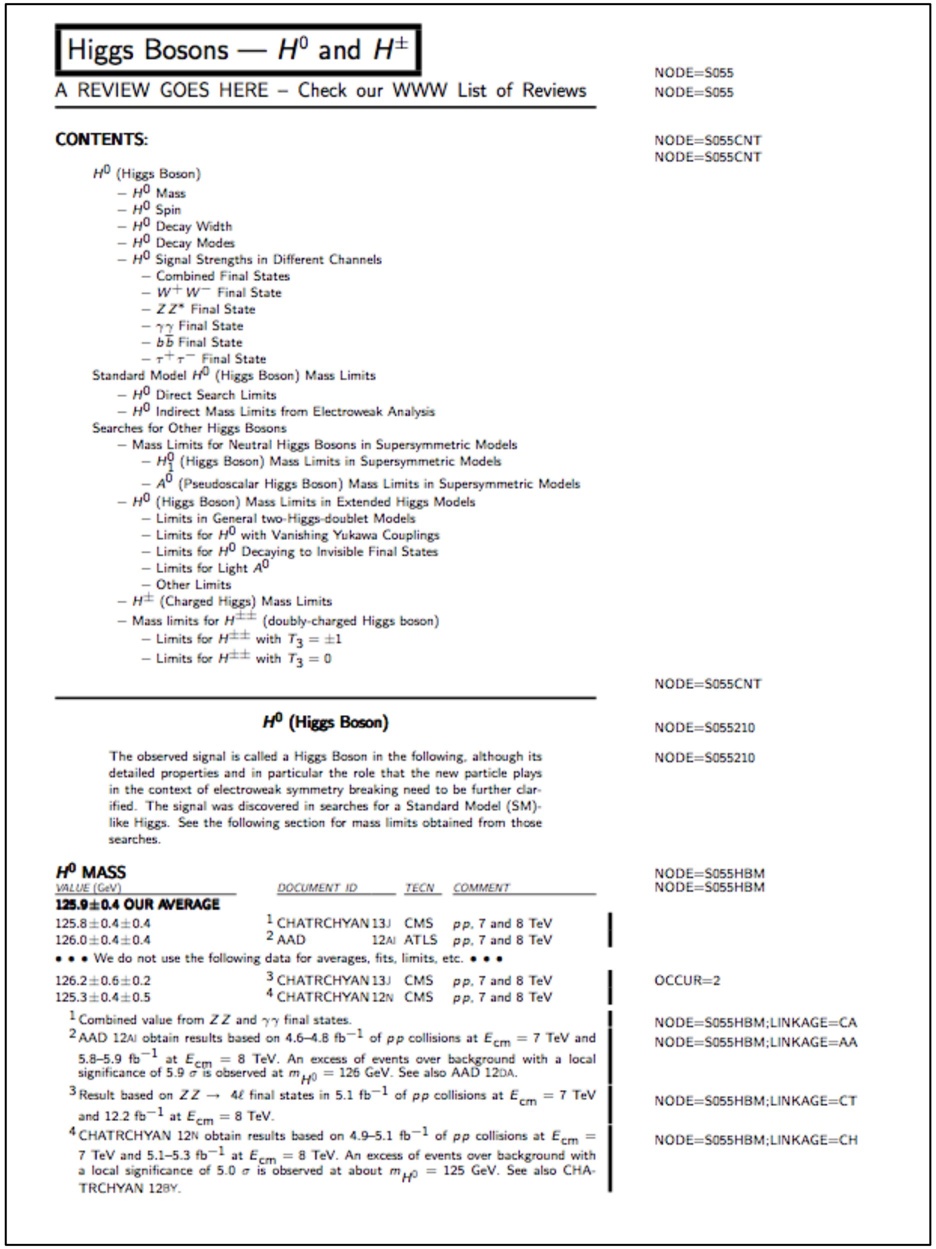
Disclaimer

The Higgs boson

“The” refers to the one discovered

Entrance of the H^0 in the PDG this week !



Higgs Bosons — H^0 and $H^{\pm}$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

H^0 (Higgs Boson)
- H^0 Mass
- H^0 Spin
- H^0 Decay Width
- H^0 Decay Modes
- H^0 Signal Strengths in Different Channels
  - Combined Final States
  - W^+W^- Final State
  - ZZ^* Final State
  - $\gamma\gamma$ Final State
  - $b\bar{b}$ Final State
  - $\tau^+\tau^-$ Final State

Standard Model H^0 (Higgs Boson) Mass Limits
- H^0 Direct Search Limits
- H^0 Indirect Mass Limits from Electroweak Analysis

Searches for Other Higgs Bosons
- Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
  - H_1^0 (Higgs Boson) Mass Limits in Supersymmetric Models
  - A^0 (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
- H^0 (Higgs Boson) Mass Limits in Extended Higgs Models
  - Limits in General two-Higgs-doublet Models
  - Limits for H^0 with Vanishing Yukawa Couplings
  - Limits for H^0 Decaying to Invisible Final States
  - Limits for Light A^0
  - Other Limits
- $H^{\pm}$ (Charged Higgs) Mass Limits
- Mass limits for $H^{\pm\pm}$ (doubly-charged Higgs boson)
  - Limits for $H^{\pm\pm}$ with $T_3 = \pm1$
  - Limits for $H^{\pm\pm}$ with $T_3 = 0$

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
125.9±0.4 OUR AVERAGE				
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

OCCUR=2

[1] Combined value from ZZ and $\gamma\gamma$ final states.

NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA.

NODE=S055HBM;LINKAGE=AA

[3] Result based on $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV.

NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY.

NODE=S055HBM;LINKAGE=CH

Inaugural entrance of the Higgs boson in the PDG particle listing !

$$H^0$$

… One year after the discovery

- New era "under the Higgs lamp post" (T. Han LP 2013)
  - Is it a natural EW theory?
  - Is it composite? Is there an underlying strong dynamic?
  - Does it couple to DM?

- Reshaping the experimental program
  - Focused searches for natural SUSY
  - Supporting measurements to improve precision on the Higgs measurements (EW, top, PDFs, main background processes, etc…)
  - …of course reappraising the LHC Higgs program

The (Experimental) Outstanding Questions

1.- Measuring properties of the H^0

- Measure its coupling properties through production and decay
- Measure it spin and CP properties
- Measure rare and invisible decays
- Cross section measurements (differential)

2.- Search for additional states of the EWSB breaking sector

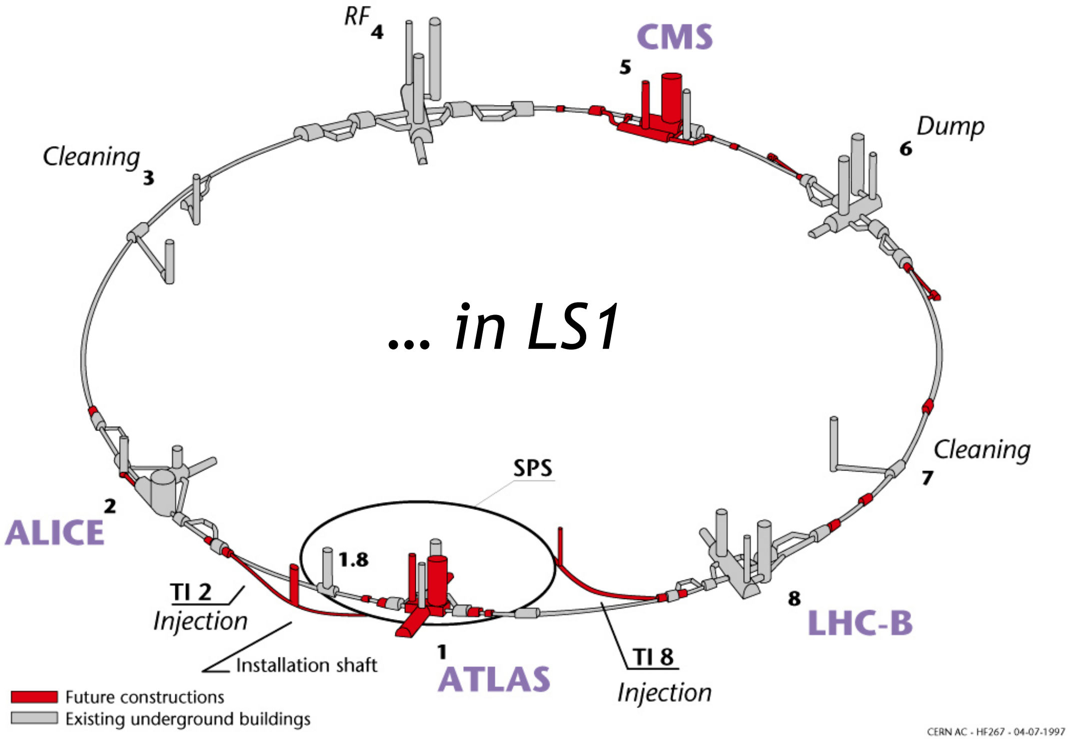
- Simply one additional singlet
- 2HDMs (all types)
- MSSM and NMSSM

3.- Exotic or unexpected modes

- Exotic decays (hidden valley pions or Z')
- Model independent searches
- Searches for doubly charged Higgs bosons
- Top FCNC decays cH

The First LHC Run

Three Years of LHC operations at the Energy frontier

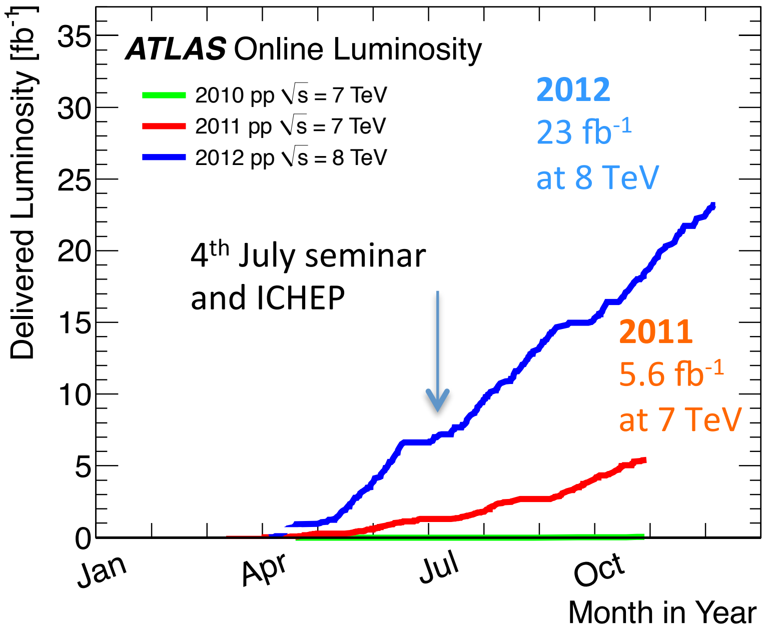


The LHC
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

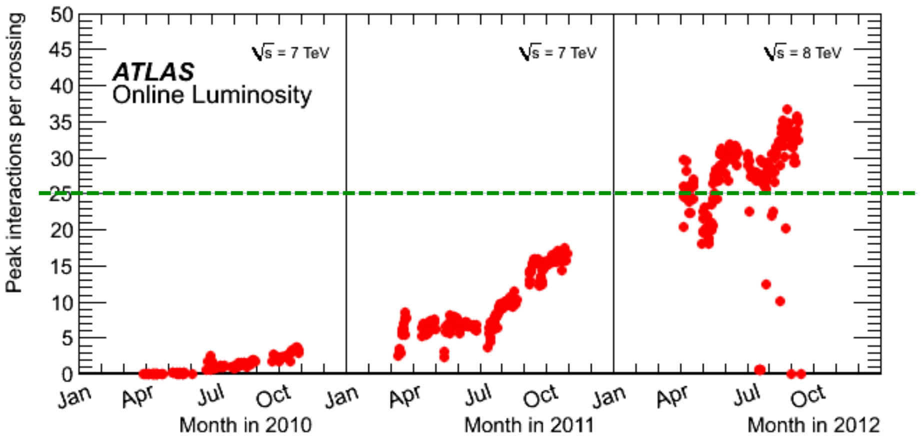
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β* (m)	3.5	1.5-1	0.6	0.55
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	10^{34}

The first LHC run

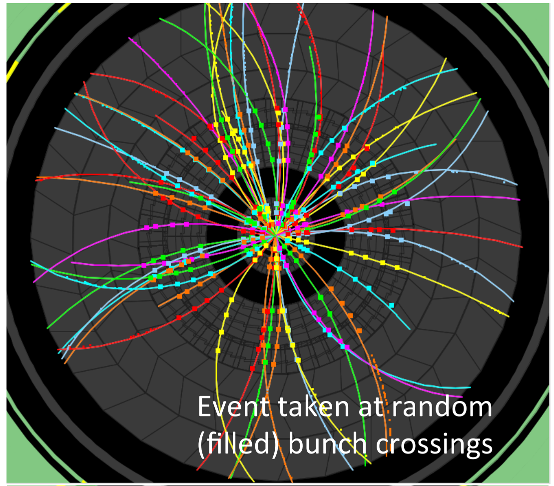


2010
0.05 fb^{-1}
at 7 TeV



Design value
(expected to be
reached at L=10^{34} !)

2010
O(2) Pile-up events
150 ns inter-bunch spacing



2011
O(10) Pile-up events
50 ns inter-bunch spacing

2012
O(20) Pile-up events
50 ns inter-bunch spacing

Main H^0 Channels Mini Review

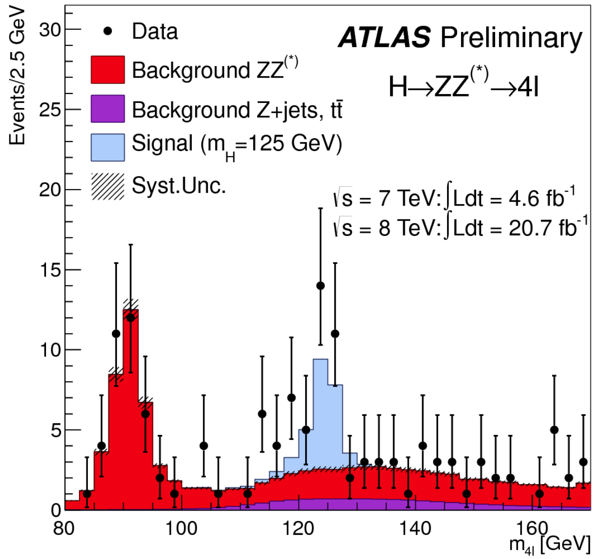
Overview of Coupling Properties Analyses

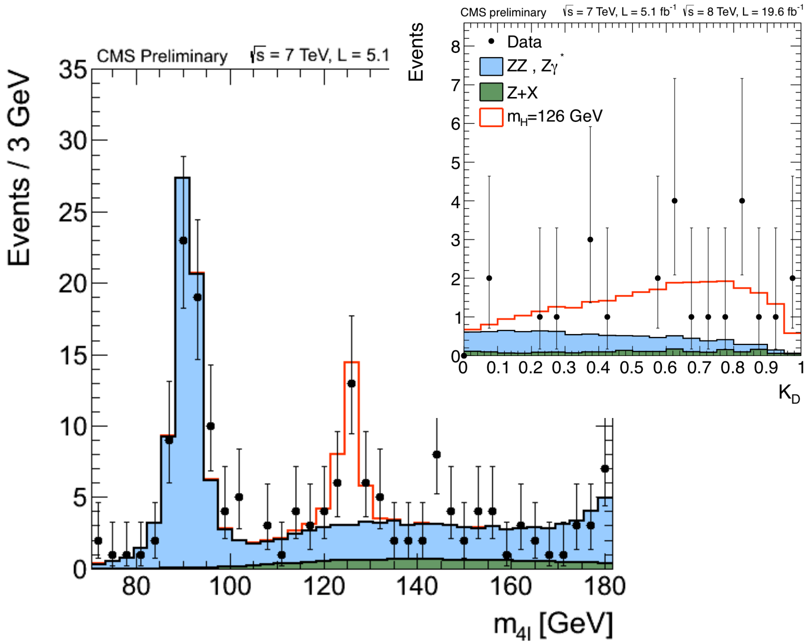
Channel categories	ATLAS				CMS				TeVatron	
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH	VH	ggF
$\gamma\gamma$	✓	✓	✓		✓	✓	✓	✓	(inclusive) ✓	
ZZ (llll)	✓	✓			✓	✓			✓	
WW ($l\nu l\nu$)	✓	✓	✓		✓	✓	✓		✓	✓
$\tau\tau$	✓	✓	✓		✓	✓	✓		✓	
H (bb)			✓	✓		✓	✓	✓	✓	
$Z\gamma$	(inclusive) ✓				✓					
$\mu\mu$	(inclusive) ✓									
Invisible			✓							

✓ Channels studied at LHC so far

✓ Results completed with full run I luminosity

$$H \rightarrow ZZ^{*} \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$$





Analysis strategy:

four prompt leptons (low p_T is important!)

four-lepton mass is the key observable

split events into 4e, 4μ, 2e2μ channels:

Different resolutions and S/B rates

CMS specificities:

- **ME-based discriminant K_D**
- Per event (mass) errors

split events further into exclusive categories:

untagged (CMS: add a 3rd observable: **four-lepton p_T/ m**)

di-jet tagged (CMS: add a 3rd observable: **$V_D(m_{jj}, \Delta\eta_{jj})$**)

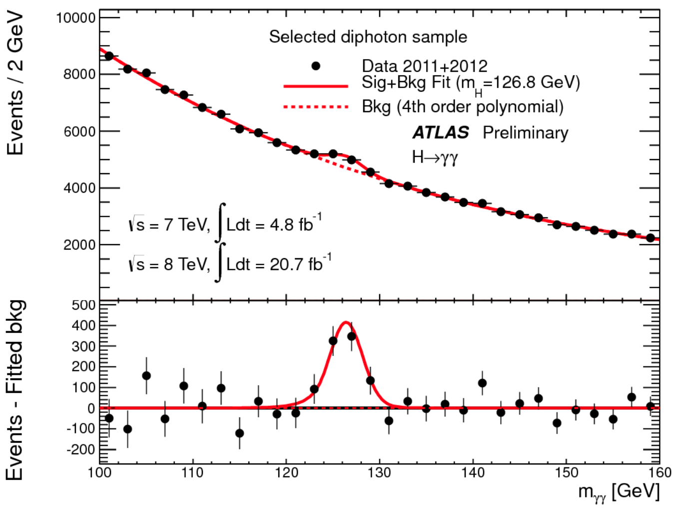
Analysis key features:

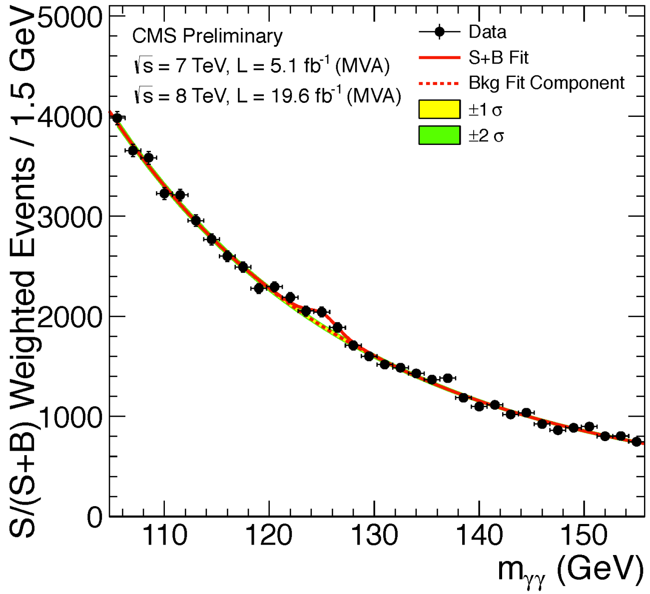
High S/B-ratio,

But small event yield

mass resolution = 1-2%

$H \rightarrow \gamma\gamma$





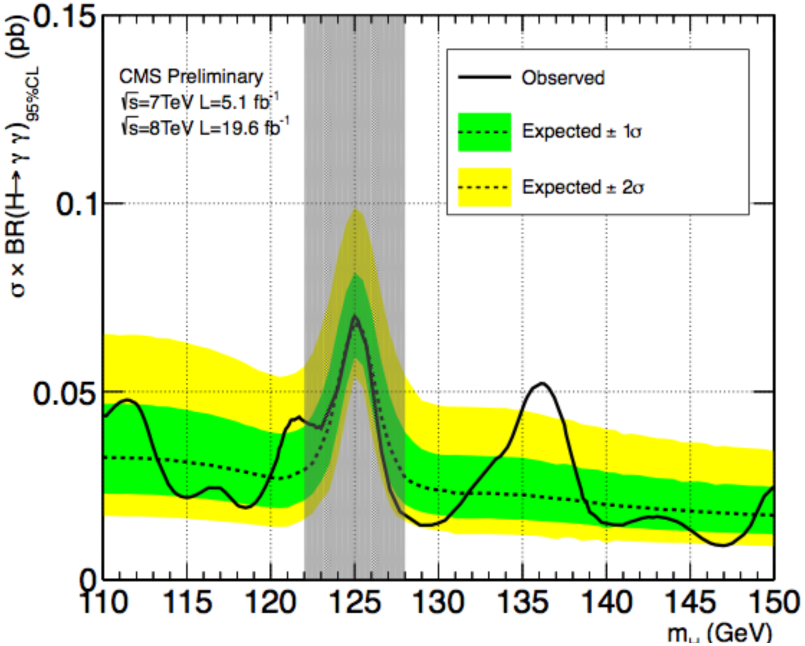
Analysis strategy:

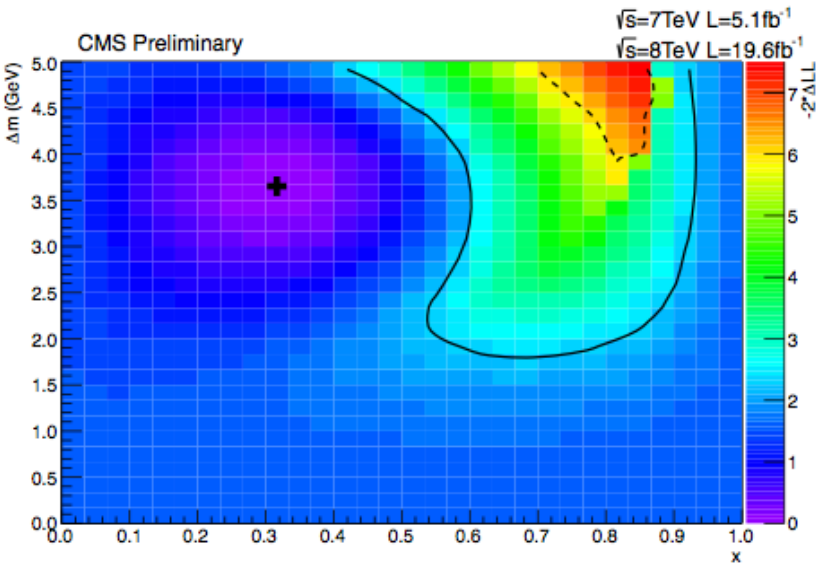
- **Di-photon mass** is the key observable
- two isolated high-p_T photons
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - split events into exclusive categories:
    - untagged, and further divided into 4/9 classes based on
      - expected mass resolution
      - expected S/B-ratio
    - di-jet tagged (VBF), and further divided into 2 classes based on
      - expected S/B-ratio
    - ATLAS: low mass di-jet tag (VH)
    - MET-tagged (VH)
    - lepton-tagged (VH)
  - background: from $m_{\gamma\gamma}$ distribution (in the sidebands)

Key Analysis Features to note:

- Small S/B-ratio,
- High event yield
- di-photon mass resolution = 1-2%

$H \rightarrow \gamma\gamma$





News :

- CMS estimate of the potential presence of two nearly degenerate states (CMS-PAS-HIG-13-016)

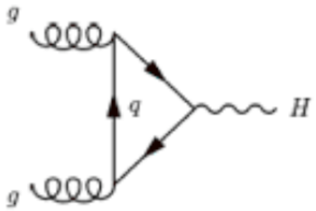
- CMS obs. (exp.) limit on natural width 6.9 (5.9) GeV

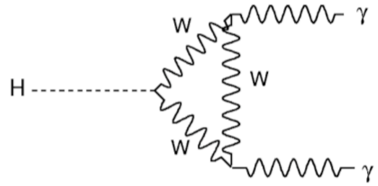
- CMS limit on higher mass states (an excess at around 136 GeV <2 s.d. with LEE)

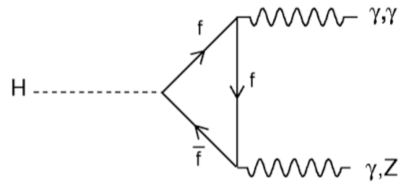
- ATLAS Update of the signal strength from 1.65 ± 0.33 to 1.55 ± 0.30 (reappraisal of Dalitz efficiency) Ref. HIGG-2013-02

Digression on the γγ Signal Strength

known at NNnLO, still rather large uncertainty O(10%)







A priori potentially large possible enhancements…

$$1.6 \times A_W^2 - 0.7 \times A_t A_W + 0.1 \times A_t^2$$

… Not so obviously enhanced (e.g. SM4)

Seldom larger yields : e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia…

Experimental facts worth noting:

1.- Channel dominated by background systematics (see larger variation of CMS value of the signal strength after recalibration)

2.- It is subject to local “look elsewhere effect”, but this effect decreases substantially with at high signal significance.

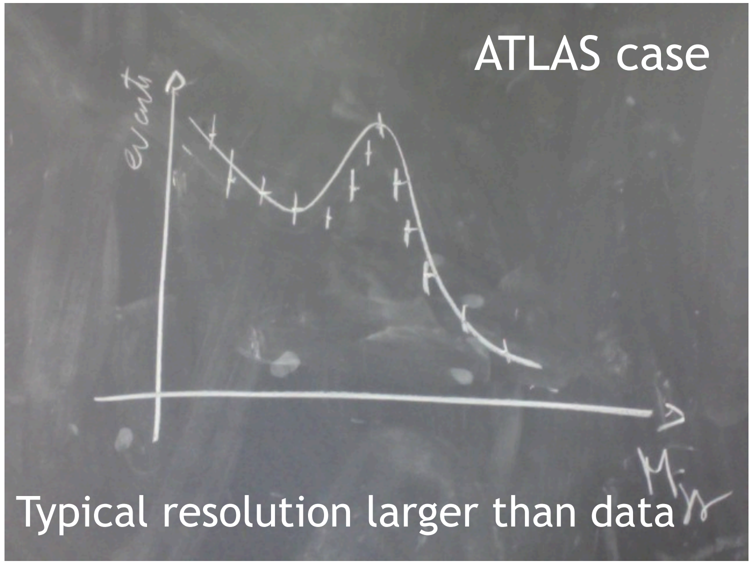
3.- Systematic on resolution is largest experimental systematic on μ

4.- The resolution is constrained within its error in the fit…

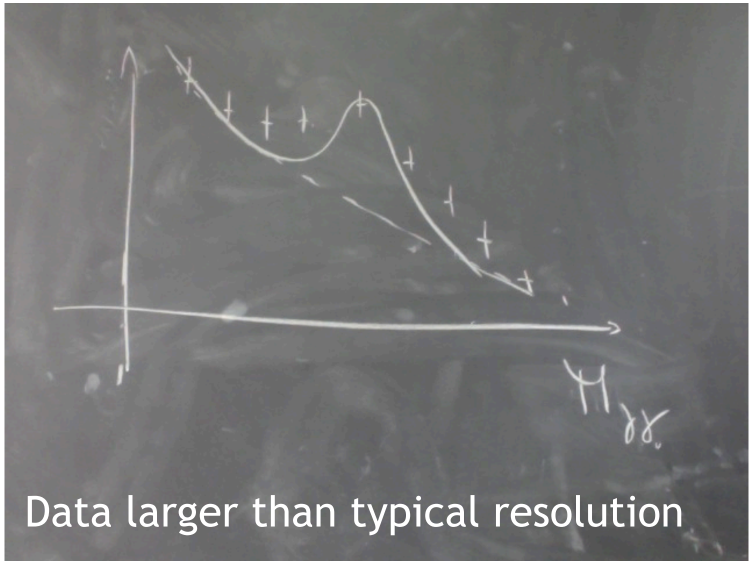
The compatibility in the signal strength parameter between the data and the SM Higgs boson signal plus background hypothesis is estimated with the test statistic $\lambda(\mu)$ with $\mu = 1$ [4], and is found to be at the 2.3 σ level.

The results reported above are extracted from a fit in which the mass resolution uncertainty, which is ~20%, is treated as a nuisance parameter with a Gaussian constraint. As a check, the fit was repeated with no constraint on the mass resolution parameter, giving $\mu = 1.49 \pm 0.33$ (1.8 σ compatibility with the SM Higgs boson signal hypothesis). This fit prefers a narrower mass resolution than the nominal one by 1.8 σ, which is better than the resolution corresponding to a perfectly uniform calorimeter. Dedicated studies revealed no indication that the systematic uncertainty on the resolution is underestimated; the large pull in this test fit can also be a statistical effect arising from background fluctuations.

Higher prob. to overestimate μ



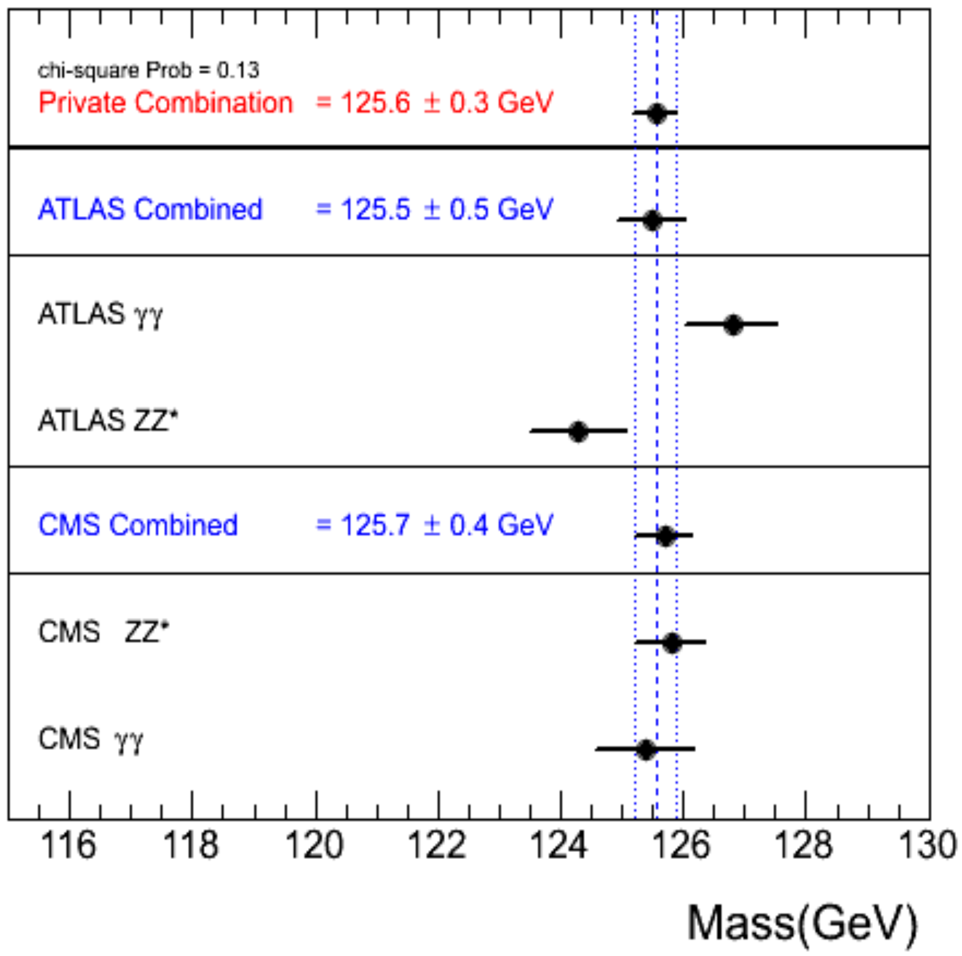
Higher prob. To underestimate μ



(Conditionnal) Probability for a fluctuation in the mass also higher
(of course not necessarily the case)

Digression on $H \to \gamma\gamma$ and $H \to 4l$ Combination

Review of mass measurements across channels and experiments

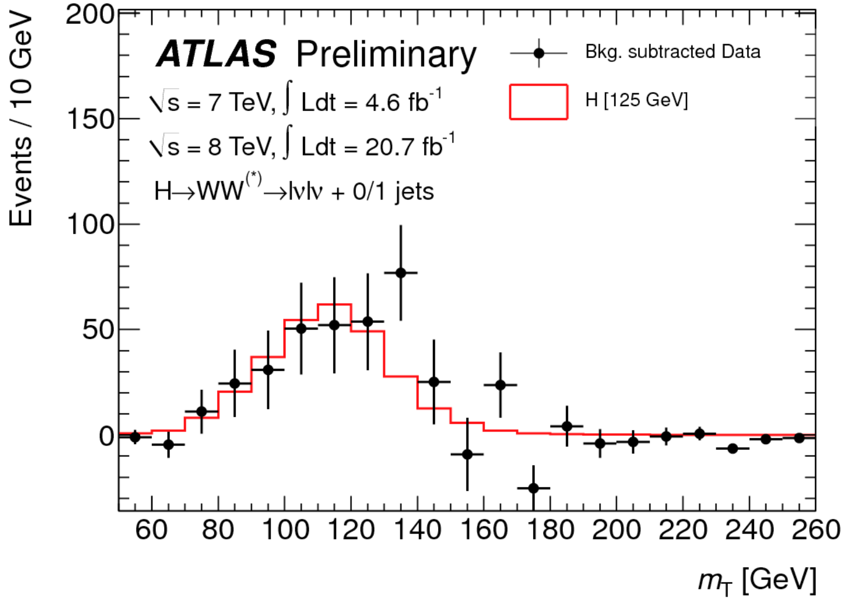


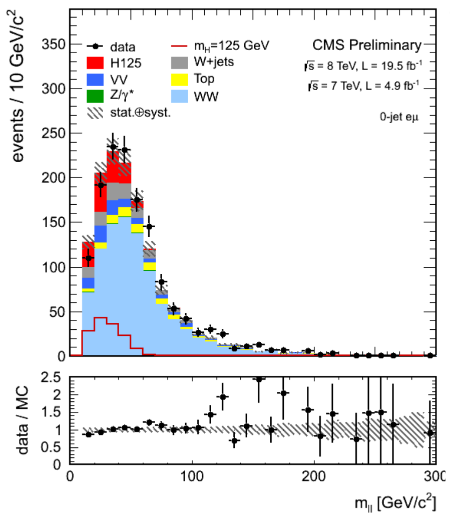
Unofficial combination

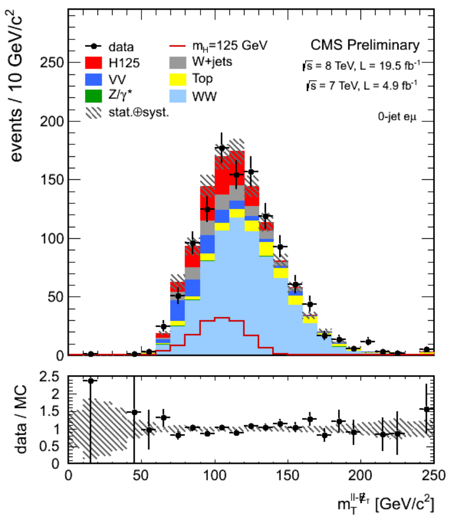
χ^2 Probability of 13%

Final word on mass and m from both ATLAS and CMS will require final Run I calibration

$H \to WW^* \to \ell^+ \upsilon \ell^- \upsilon$







- Analysis strategy:
  - two prompt high-p_T leptons
  - Use spin-0 and V-A structure of W decay
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **CMS:**
    - Different-flavor: **2D distribution N(m_{ll},m_T)**
    - Same-flavor dileptons: **cut-based analysis**
  - Backgrounds (for low mass Higgs):
    - WW, tt, W+jets, DY+jets, Wγ: from control regions
    - ZW, ZZ: from MC (very small contribution)

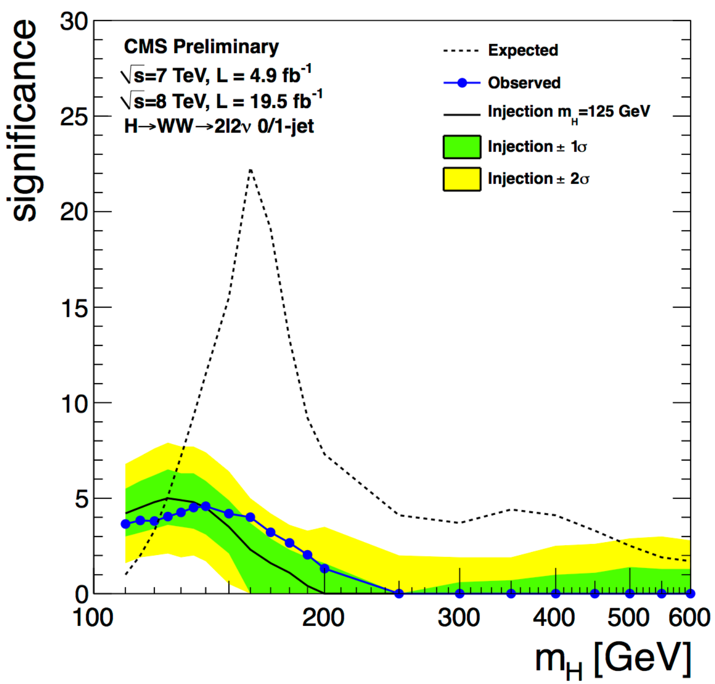
- Analysis features to note (m_H=125):
  - Fair S/B
  - Fair signal event yield (200 events)
  - Poor mass resolution ≈20%

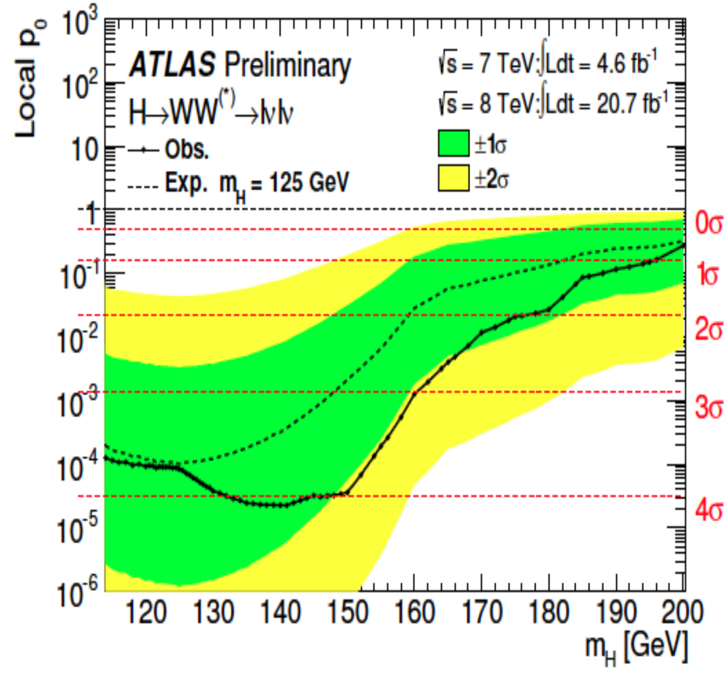
- New:
  - CMS: Associated production VH update with hadronic V (combined sensitivity 3.5-4 SM) CMS-PAS-HIG-12-017
  - ATLAS: Update for publication HIGG-2013-02

Background Uncertainties Digression

TH uncertainty on the WW background kinematics

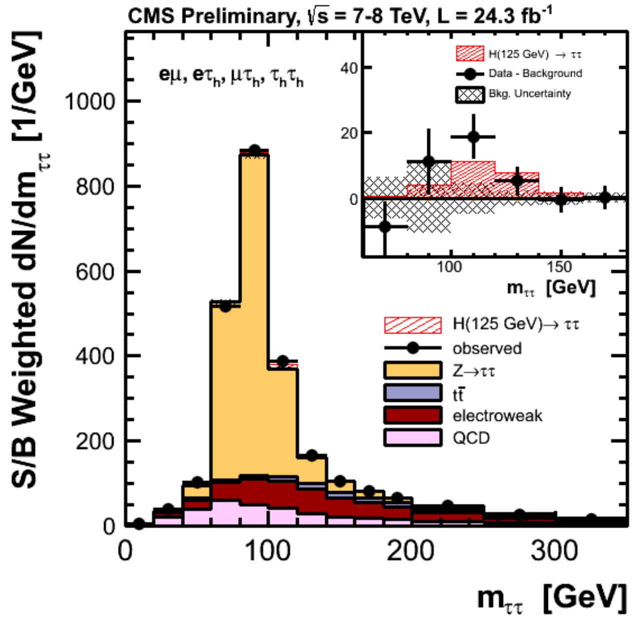
$$\mu_{obs} = 1.01 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{theo. syst.}) \pm 0.12\,(\text{expt. syst.}) \pm 0.04\,(\text{lumi.})$$
$$= 1.01 \pm 0.31.$$

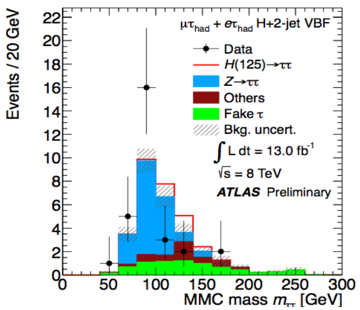


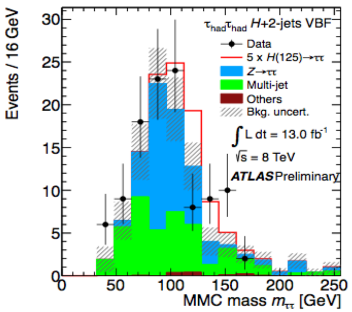


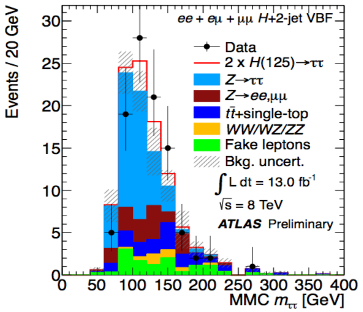
NNLO calculation underway

$H \to \tau^+\tau^-$









Analysis strategy:

- di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- MET
- **DiTau mass (including MET)**: key distribution

split events into jet categories:

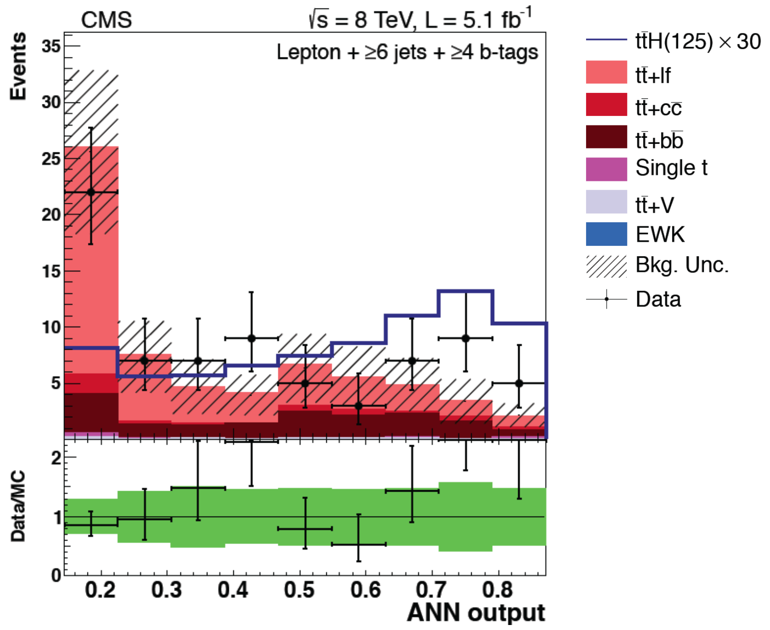
- **2-jets (VBF-tag)**: best S/B-ratio
- **2-jets (VH-tag)**: best S/B-ratio
- **VH Lepton tag**
- **1-jet (ggF, VH)**: acceptable S/B-ratio
- untagged: control region (S/B≅0)

- Split 1-jet events further high/low p_T tau
  - different S/B rates
- Backgrounds:
  - Z→ττ: Z→μμ (data) with embedding
  - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

Key Analysis features:

- poor S/B-ratio
- small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

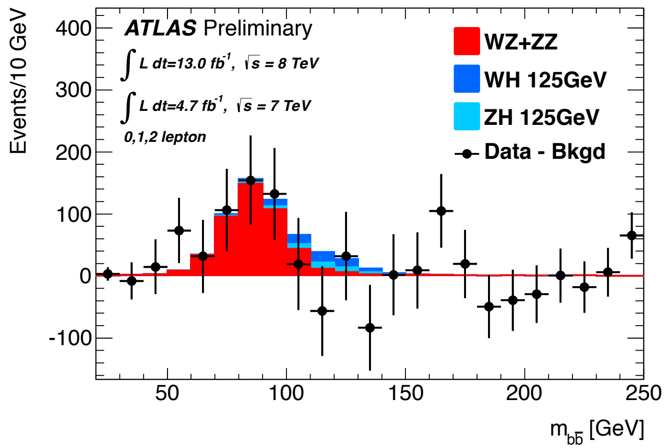
$VH \rightarrow Vbb$



Analysis strategy:

- Channels separated in 0 (MET), 1 (MET) and 2 leptons
- With two b-tagged jets (using 0 and 1 for control)
- Further categorize in pT of the V
- Mass reconstruction is Key
- Simulation ISR and gluon splitting is also Key
- Diboson reconstruction also important element

- Main Backgrounds:
  - V+bb and top
  - Uses mainly control regions except



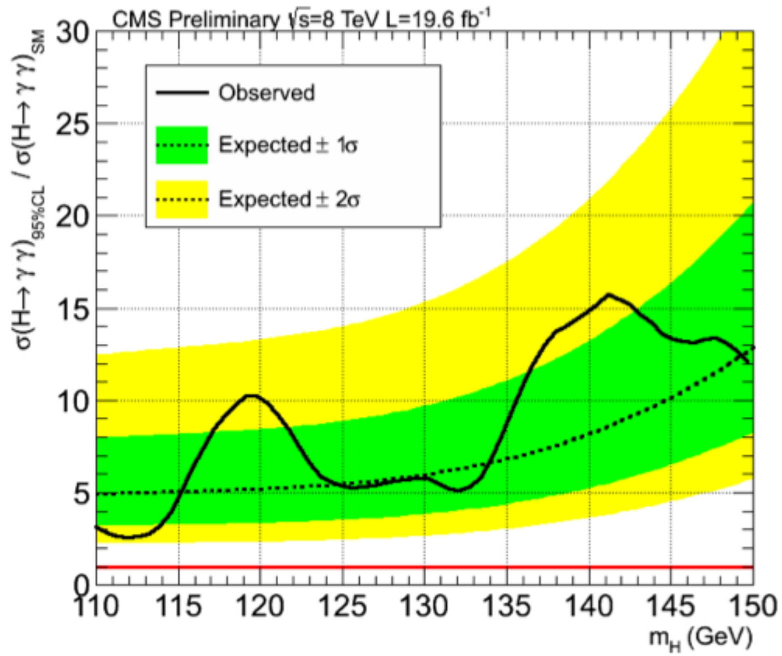
Key Analysis features:

- Rather low S/B-ratio
- small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

New: CMS combination of VBF channel with VH

ttH

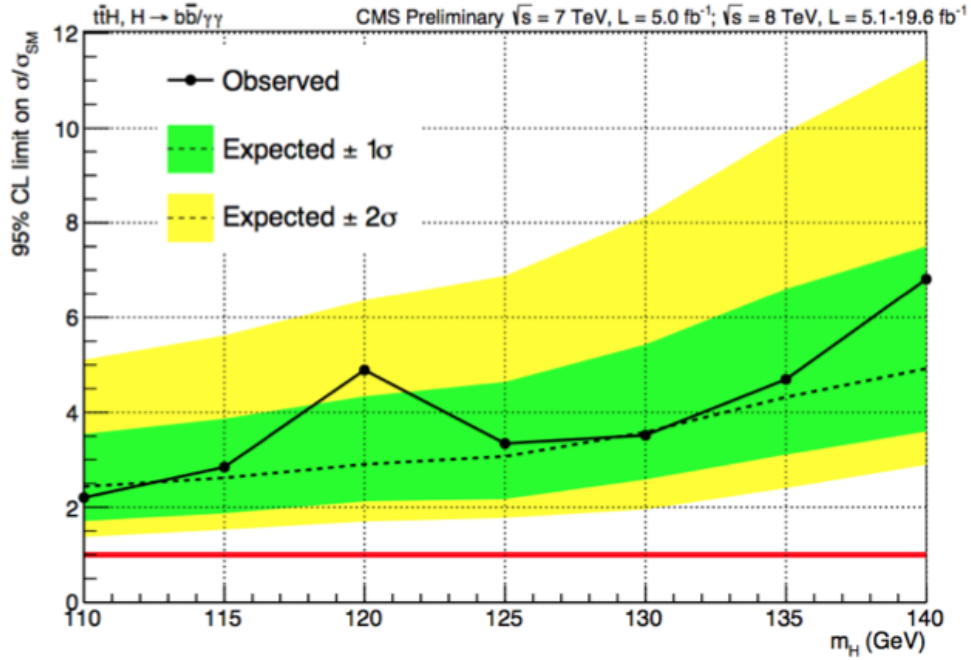
$H \rightarrow \gamma\gamma$



Key Features:

- Very robust channel
- Will require (very) large statistics

$H \rightarrow bb$

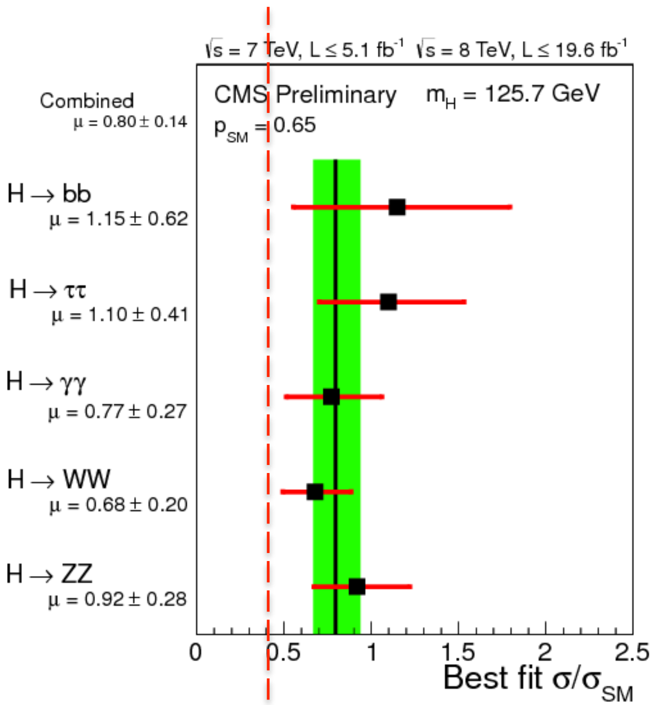


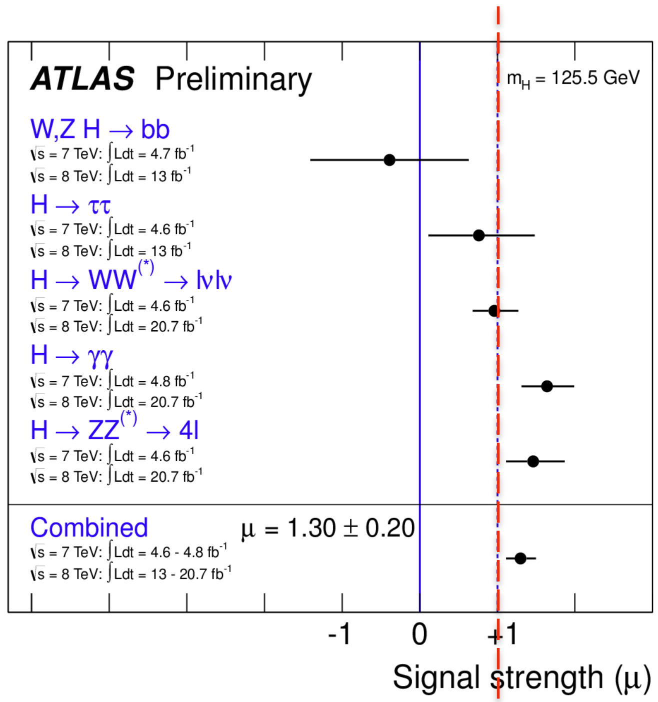
Key Features:

- Will it ever be possible to be sensitive in this channel?
- Relies on the control of the tt+HF background

H^0 Summary and inputs to the combination

Channel categories	ATLAS				CMS			
	μ (at 125.5 GeV)	Z exp	Z obs	M (GeV)	μ	Z exp	Z obs	M (GeV)
γγ	1.6±0.3	4.1	7.4	126.8±0.2±0.7	0.8±0.3	3.9	6.7	125.4±0.5±0.4
ZZ (llll)	1.5±0.4	4.4	6.6	124.3±0.5±0.5	0.9±0.3	7.1	3.2	125.8±0.5±0.2
WW (lnln)	1.0±0.3	3.8	3.8	-		5.3	3.9	-
ττ	0.8±0.7	1.6	1.1	-	1.1±0.4	2.6	2.8	125^{+9}_{-7}
W,Z H (bb*)	-0.4±1.0	1.0	0.0	-		2.1	2.1	-
Combination	1.30±0.20	7.3	10	125.5±0.2±0.6	0.80±0.14	-	-	125.7±0.3±0.3

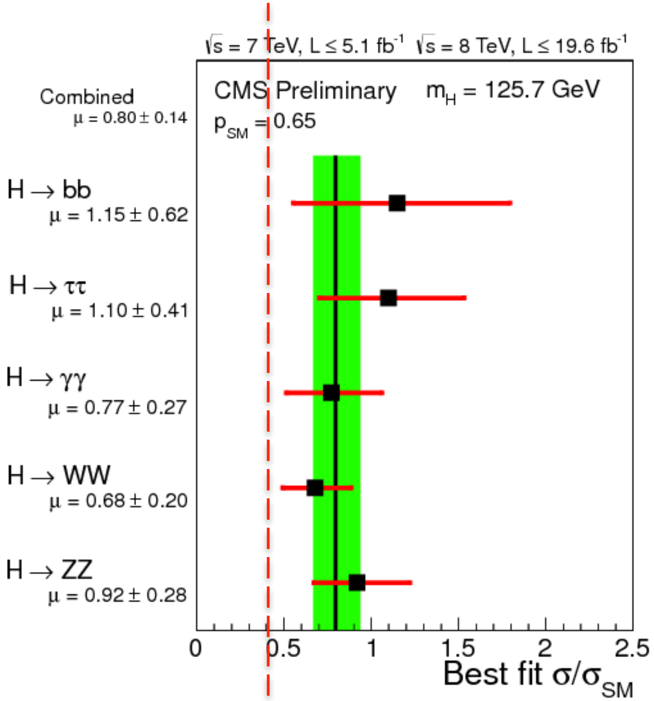


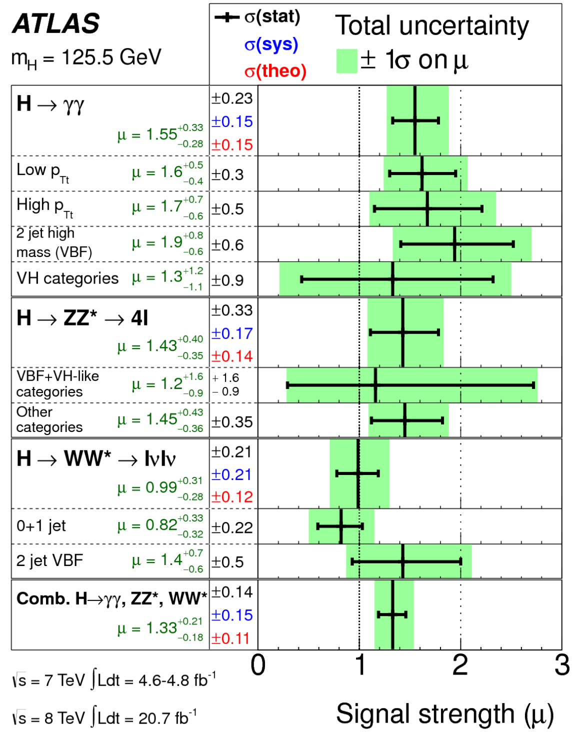


*CMS also uses ttH in the combination from 1303.0763

H^0 Summary and inputs to the combination

Channel categories	ATLAS				CMS			
	μ (at 125.5 GeV)	Z exp	Z obs	M (GeV)	μ	Z exp	Z obs	M (GeV)
γγ	1.5±0.3	4.1	7.4	126.8±0.2±0.7	0.8±0.3	3.9	6.7	125.4±0.5±0.4
ZZ (llll)	1.5±0.4	4.4	6.6	124.3±0.5±0.5	0.9±0.3	7.1	3.2	125.8±0.5±0.2
WW (lnln)	1.0±0.3	3.8	3.8	-		5.3	3.9	-
ττ	0.8±0.7	1.6	1.1	-	1.1±0.4	2.6	2.8	125^{+9}_{-7}
W,Z H (bb*)	-0.4±1.0	1.0	0.0	-		2.1	2.1	-
Combination	1.30±0.20	7.3	10	125.5±0.2±0.6	0.80±0.14	-	-	125.7±0.3±0.3



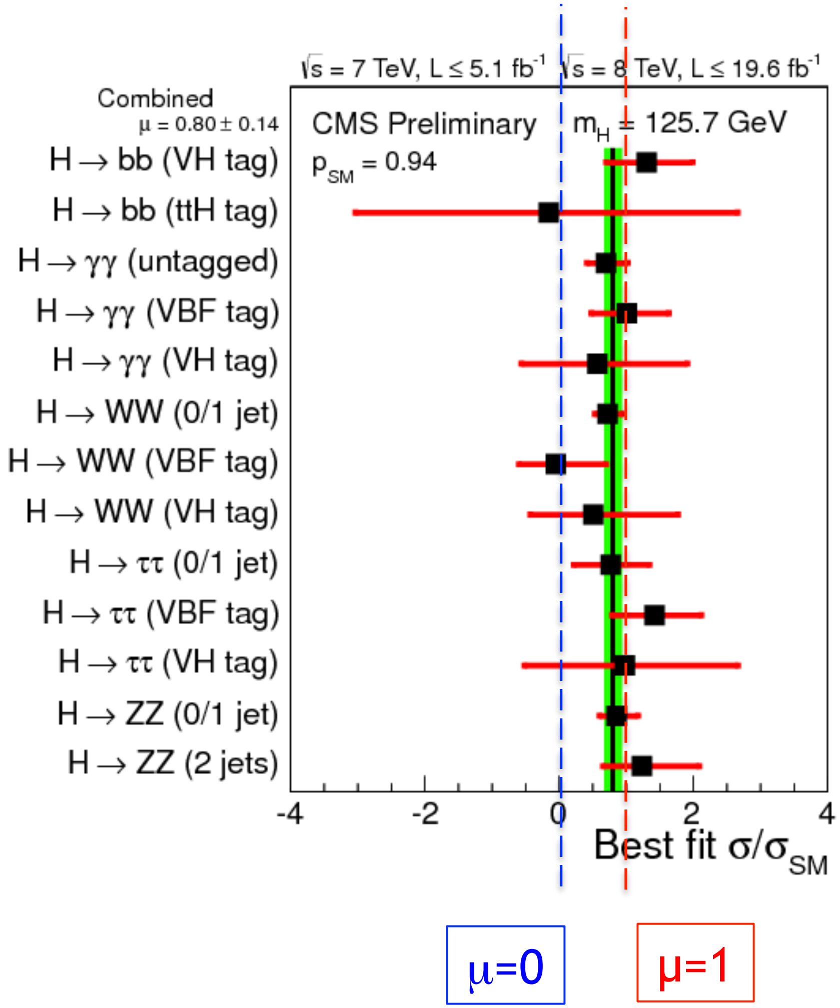


*CMS also uses ttH in the combination from 1303.0763

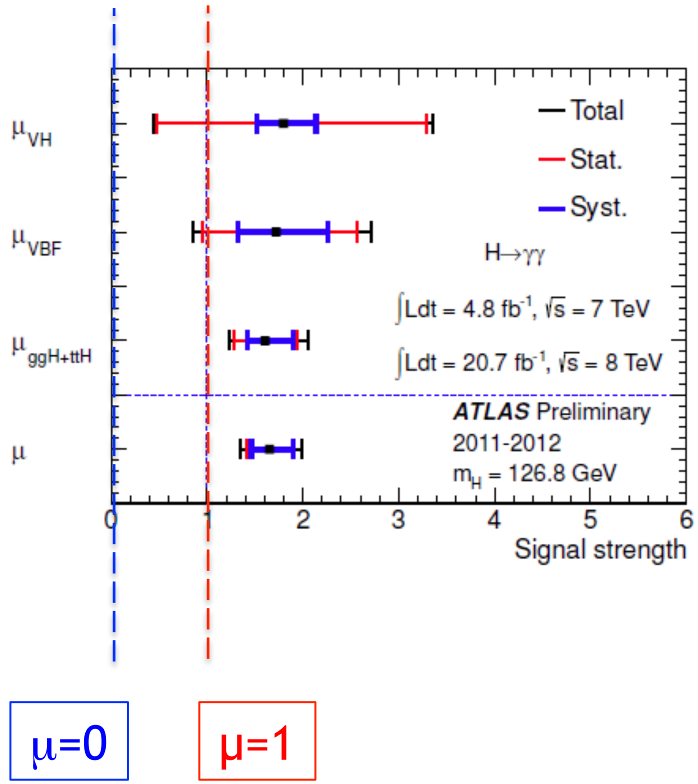
Digression on Information Format

$$n_s^c = \left(\sum_{i \in \{ggF, VBF, VH, ttH\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths

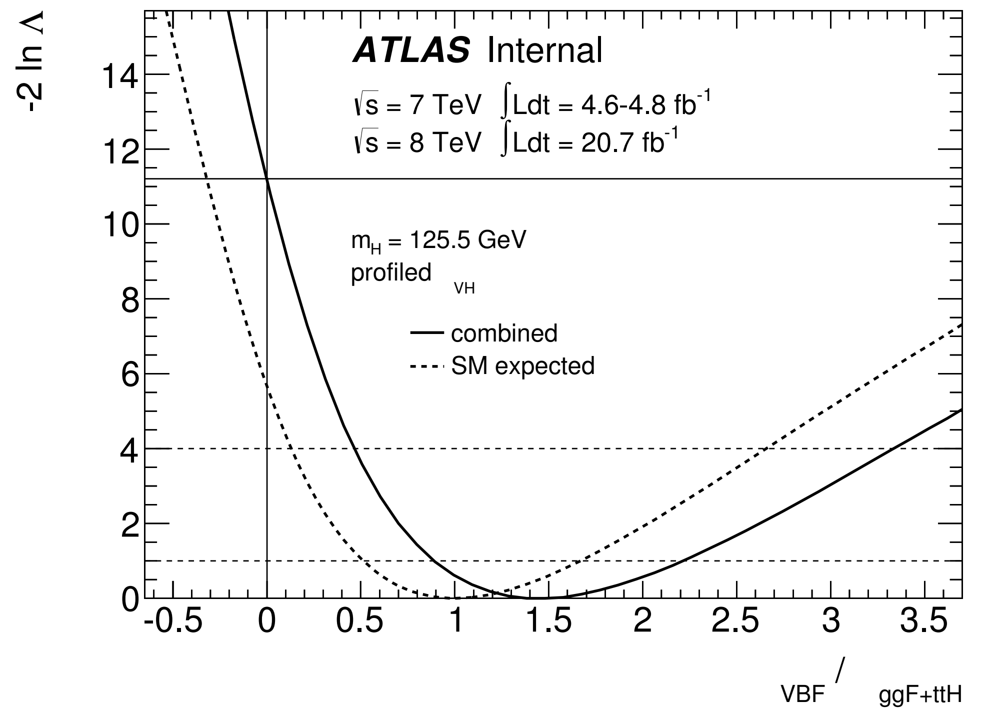


Production mode signal strengths (per channel)



Evidence for VBF production

From the ratio of individual production signal strengths



Coupling Properties Measurements

Further re-parameterization of the n_s^c yields per categories

- Assuming narrow width approximation
- Assume the same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$
- Link to an effective Lagrangian and use scale factors

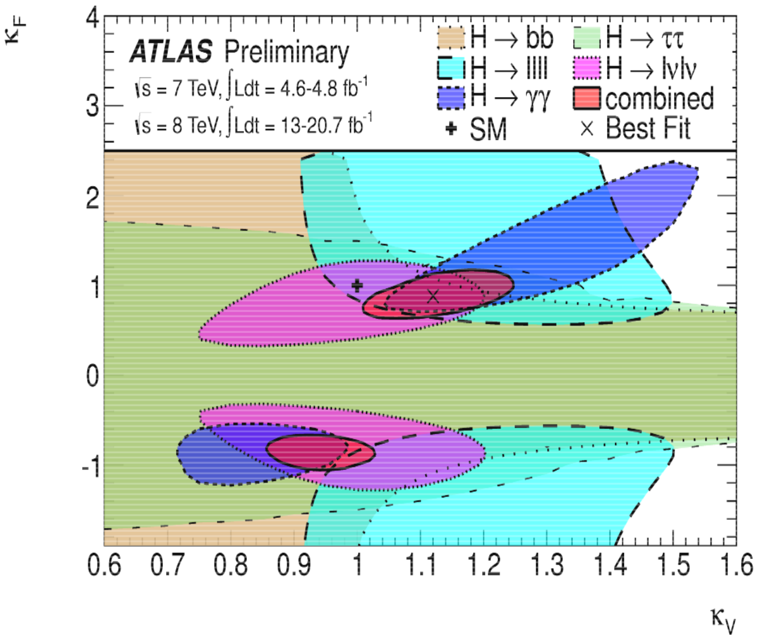
$$\mathcal{L} = \kappa_W \frac{2m_W^2}{v} W^+_\mu W^-_\mu H + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f \bar{f} H + c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^a_{\mu\nu} H + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} H$$

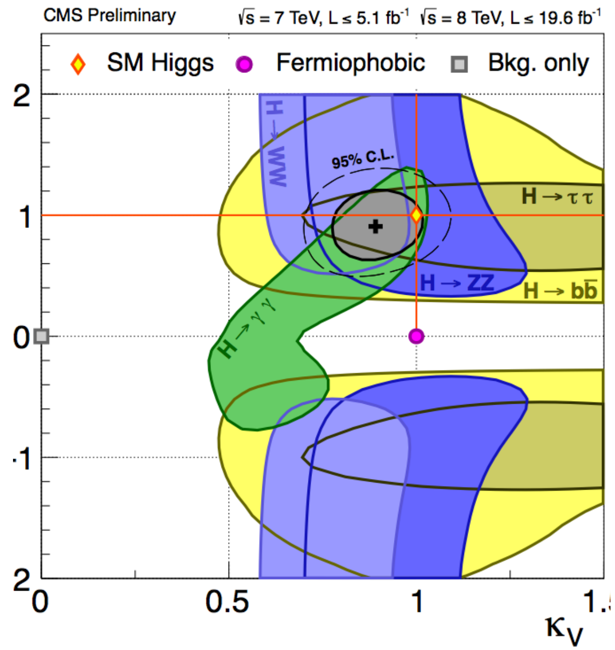
Parametrize μ_i and μ_f as a function of κ's

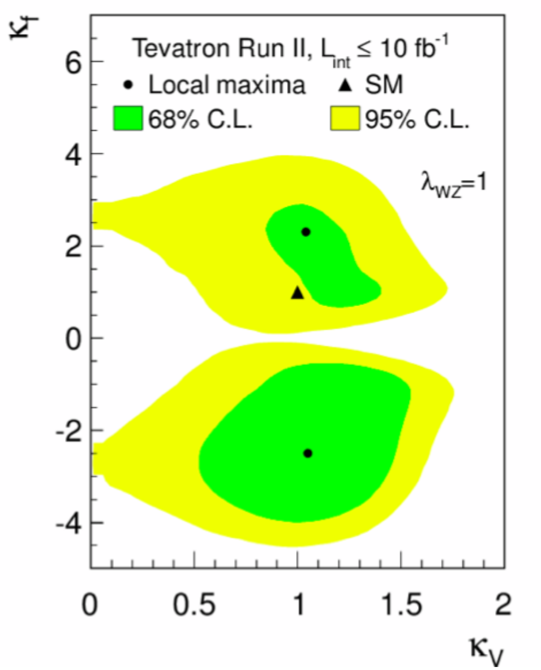
For example, the main contribution (ggF) to the gg channel can be written as:

$$\sigma \cdot \mathrm{BR}(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Main results I : Probing the coupling to SM particles





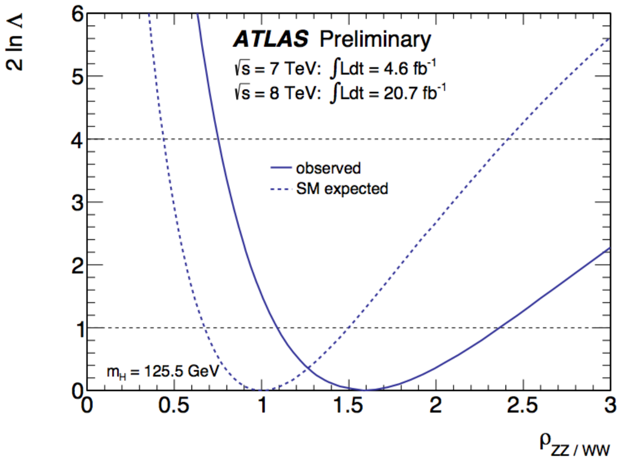


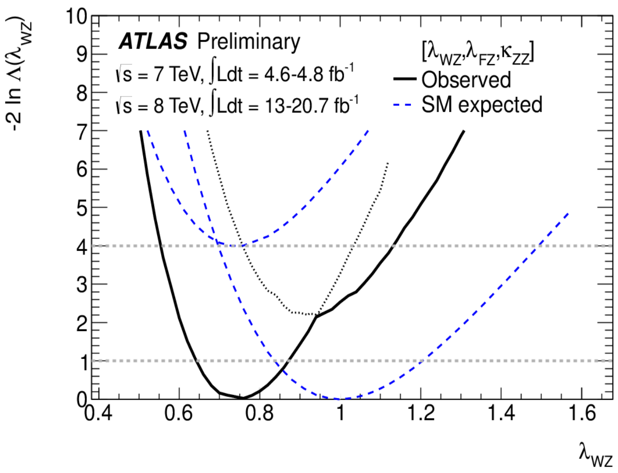
- By convention sign on the fermion yukawa strength multiplier (relying on the γγ strength primarily)… ambiguity inspired tH analyses

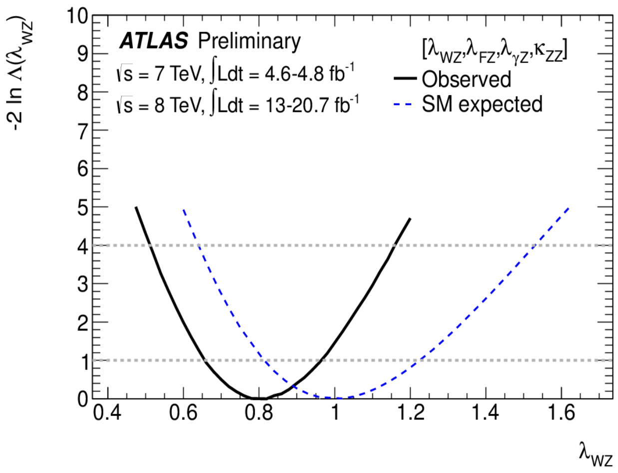
- Checking the direct and indirect couplings to fermions

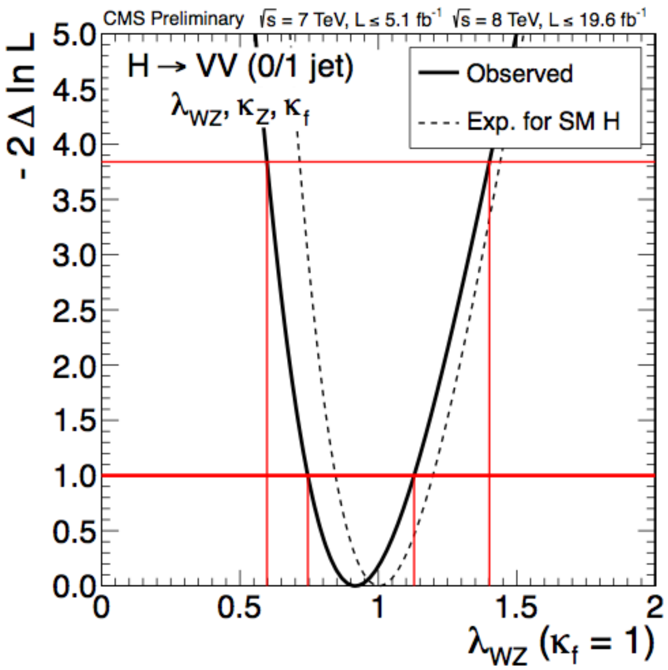
- Checks of specific composite models

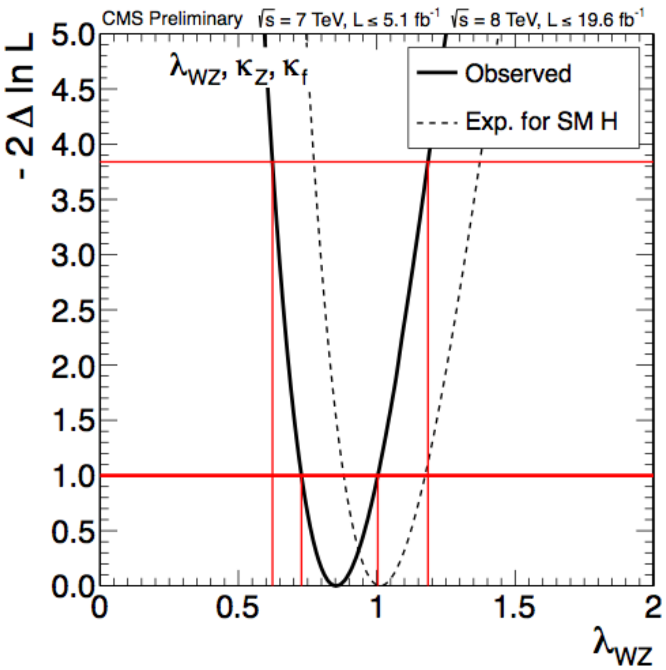
Main results II : Probing the W to Z ratio (custodial symmetry)





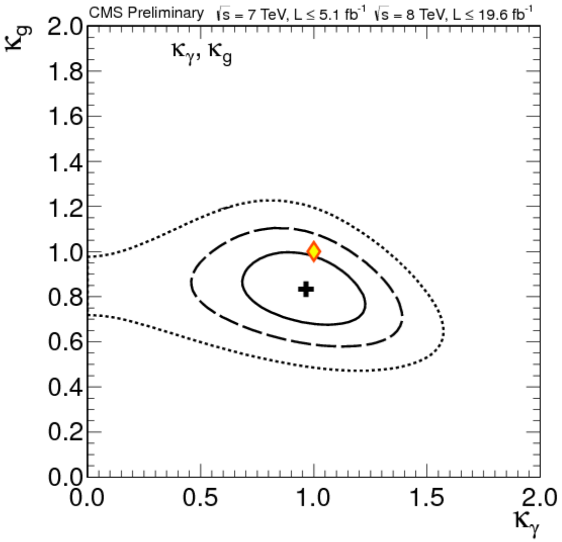


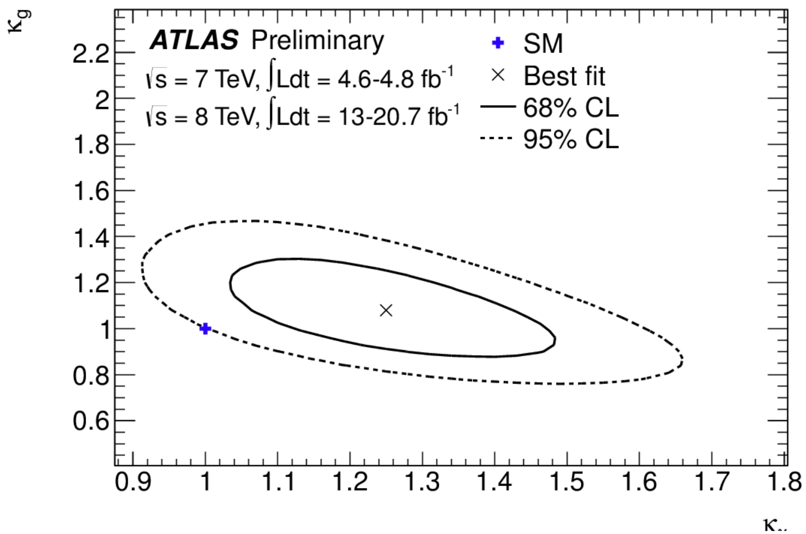




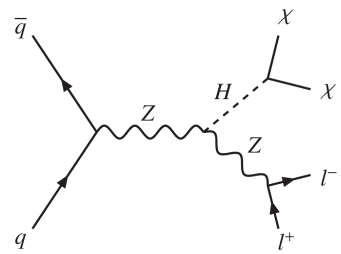
Main results III : Probing physics beyond the Standard Model

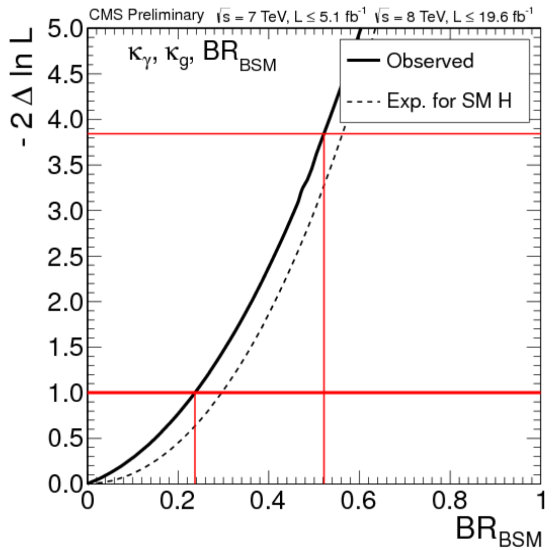
(In the decays and/or in the loops)

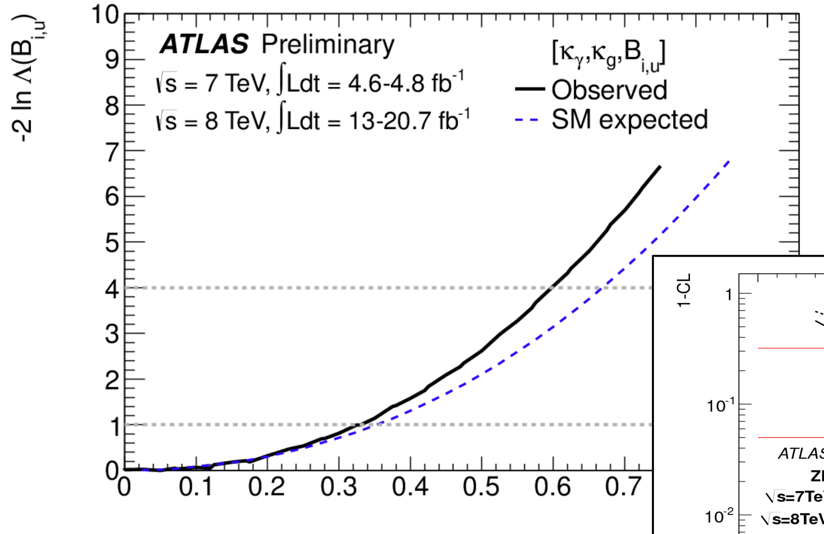




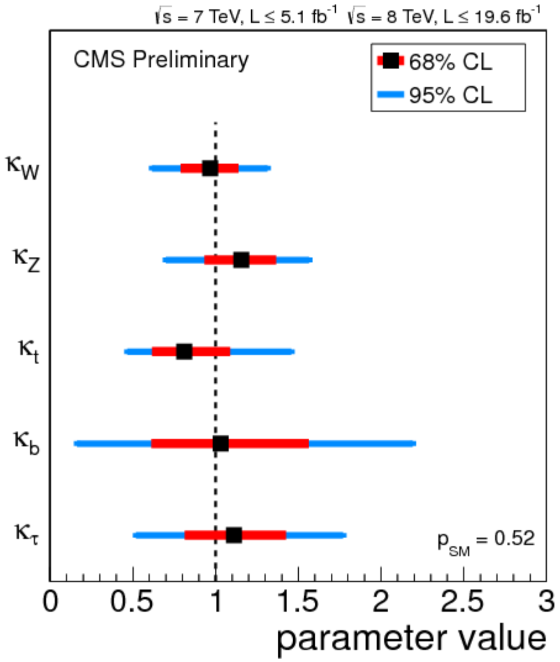
Also direct invisible only search

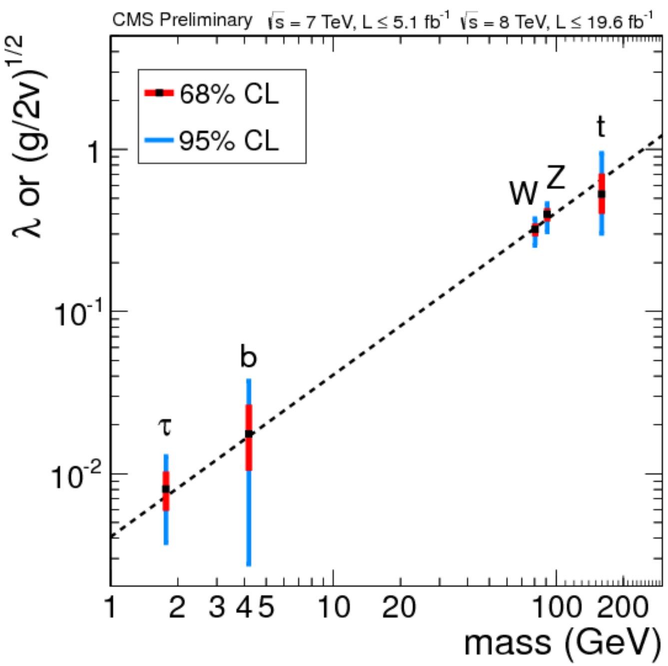


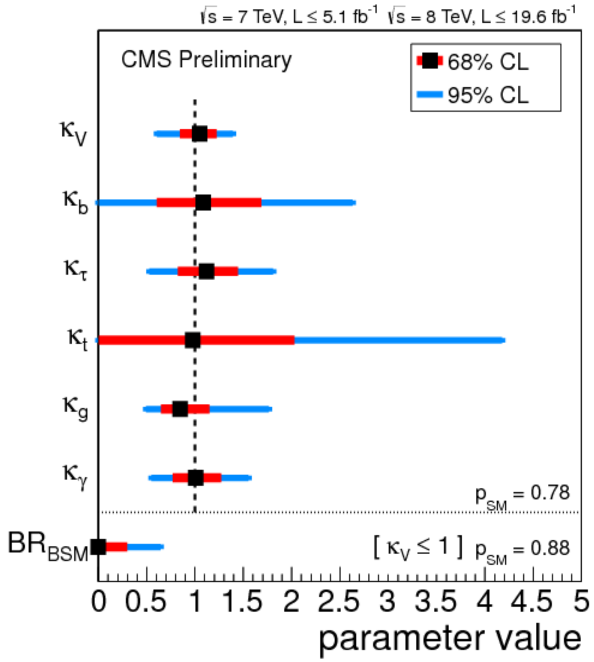




Main results IV : Other Relevant Models







- Illustrating the mass dependence (also Ellis and You *vev* and critical coef.)
- 3 coupling strength parameter fits κu, κd and κV for MSSM and 2HDM limits

Beyond any reasonable doubt…

The consistency of rates of the three discovery channels and the supporting evidence from the additional channels leaves little doubt about the nature of the particle.

For it NOT to be a Higgs boson would require a very savvy conspiring impostor

- Observation in the diphoton channel implies $C = 1$
- Observation in the diphoton channel (Landau-Yang theorem) implies $J \neq 1$
- Observation in WW channel favors $J=0$
- Observation in the ZZ and WW channels disfavors $P=-1$

This being said we still perform analyses to test the main quantum numbers directly from model independent observables.

Main Quantum Numbers J^{PC}

A large number of options to probe the spin directly from angular (or threshold behavior) distributions.

- From the associated production modes (VH, VBF or ggF+jets)
- From the production angle cos θ^* distribution
- From the decay angles and the spin correlation when applicable

The philosophy of the LHC approach

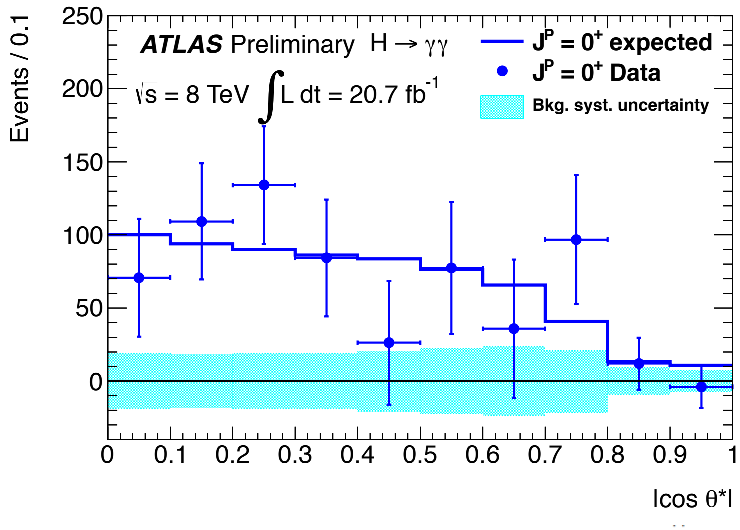
- Measure the compatibility with the 0^+ hypothesis in specific framework
- Probe alternative hypotheses simulated using an effective Lagrangian including higher order couplings.

Overview of Spin and Parity Results

J^P CL_S	ATLAS				CMS			
	$ZZ^*(4l)$	$\gamma\gamma$	WW^*	Comb.	$ZZ^*(4l)$	WW^*	Comb.	$\gamma\gamma$
0^-	2.2%	-	-	-	0.16%		0.16%	
0^-_h	-	-	-	-	8.1%		8.1%	
1^-	6.0%	-	-	-				
1^+	0.2%	-	-	-				
2^+_m (gg)	16.9%	0.7%	5%	<0.1%	1.5%	14%	0.5%	Not excl.
2^+_m (qq)	<0.1%	2%	1%	<0.1%	<0.1%		<0.1%	Not excl.
2^-	<0.1%	-	-	-	<0.1%		<0.1%	

- Most important is the compatibility with 0^+

- No VH or VBF threshold distribution analysis yet at LHC.

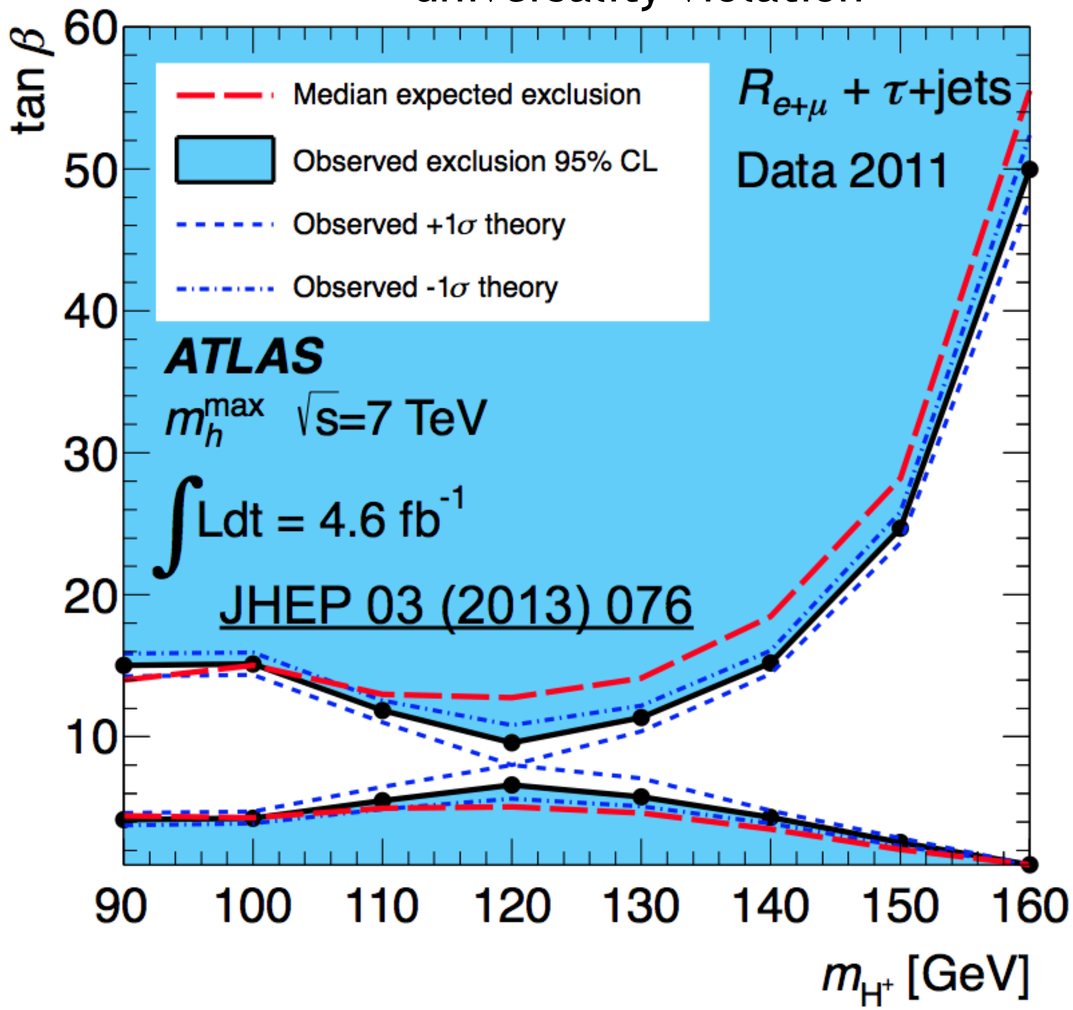


Main BSM Channels Nano Review

Overview of BSM Channels (I)

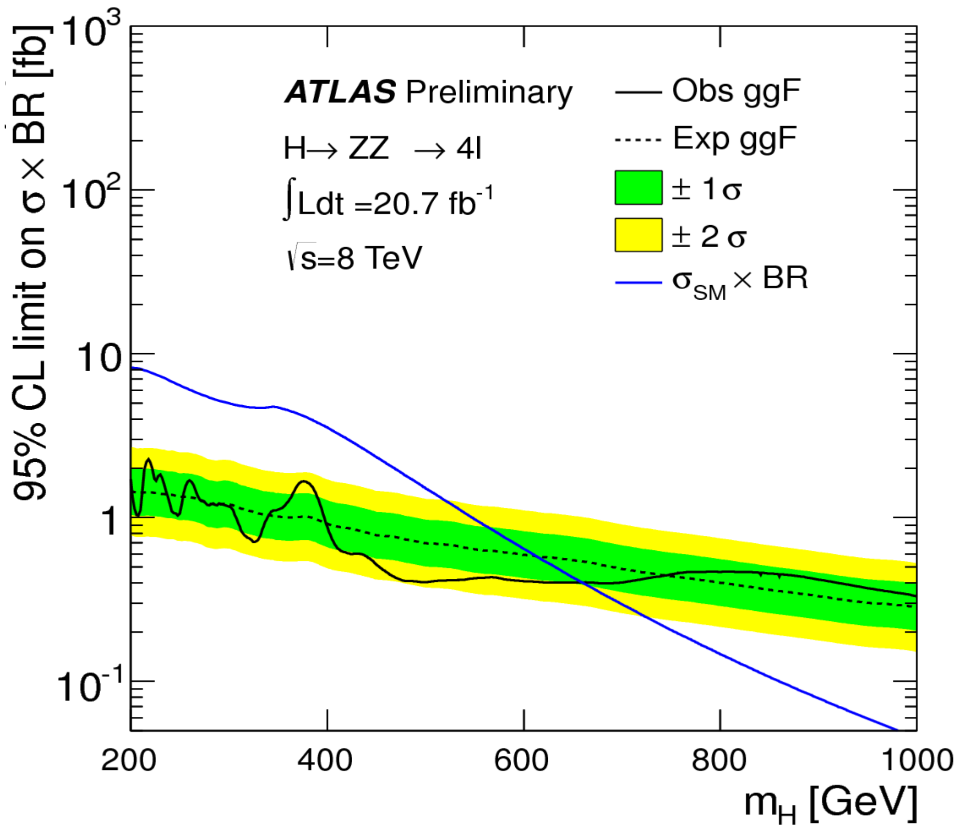
- Charged Higgs
  - Main current analysis $H^{\pm}$ to $\tau\nu$
  - $H^{\pm}$ to cs
  - High mass specific $H^{\pm}$ to AW
  - High mass specific $H^{\pm}$ to tb
- MSSM h, H, and A
  - Main current analysis $\tau\tau$
  - Also searched for in $\mu\mu$
  - Also searched for in bb(b)
  - New open channel in the intermediate-high mass: hh
- NMSSM a (Main search at LHC $\mu\mu$)

ATLAS Search through lepton universality violation



Overview of BSM Channels (II)

- Singlet interpretation with unitarity constraint (High mass analyses)
  - ZZ to llnn channel (most powerfull, overlap with invisible search)
  - ZZ to llqq channel (potentially interesting lower mass reach)
  - ZZ to llll: Interesting to fit all h and H simultaneously
  - WW to lvlv can also fit h and H simultaneously
  - WW to lvqq high mass only
  - $\gamma\gamma$ See latest CMS result and extending mass domain



- 2HDM Interpretation
  - ZZ to llll simultaneous fit
  - WW to lnln simultaneous fit
  - $\gamma\gamma$ simultaneous fit

LHC future prospects

Made for two scenarios 300 fb^{-1} and 3ab^{-1}

- Need to investigate more scenarios
- Need to investigate more channels

The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

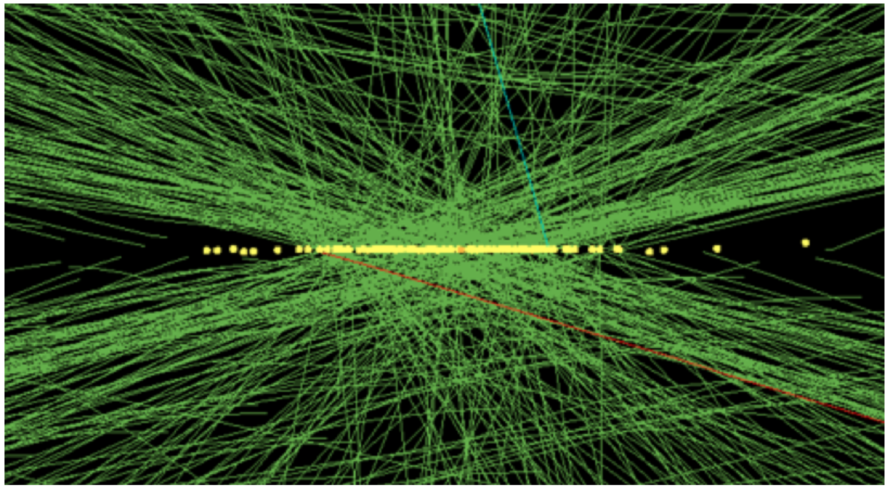
~2030

HL-LHC Beam Parameters

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Two HL-LHC scenarios

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.0\ 10^{11}$	$3.3\ 10^{11}$
Bunch spacing / k	50 ns /1380	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.5	3.75	2.5	3.0
β^* (m)	0.6	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	$\sim 7x10^{33}$	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260



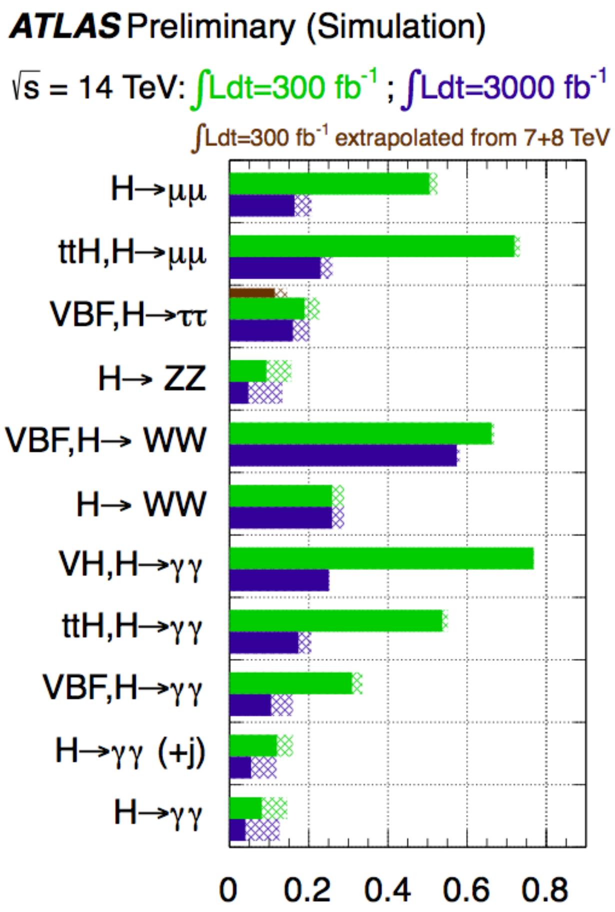
Pile up is a crucial issue!

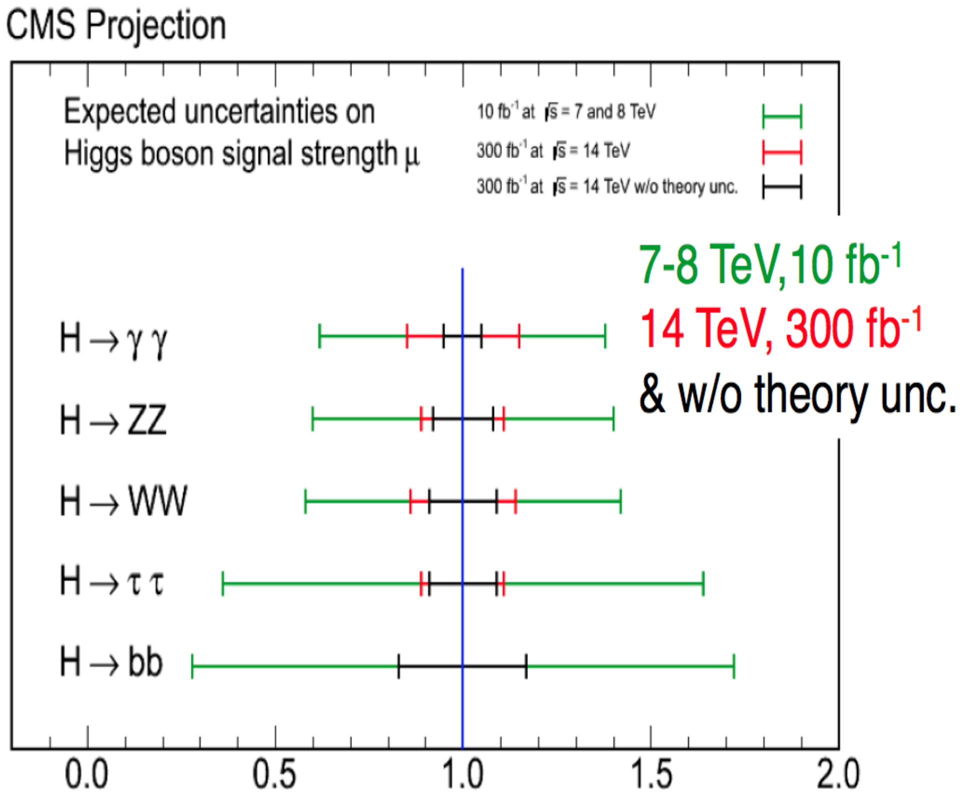
CMS event with 78 reconstructed vertices

ATLAS Higgs Physics Program: Main Couplings

Couplings Projections Only a sample of analyses

Uncertainty on signal strengths



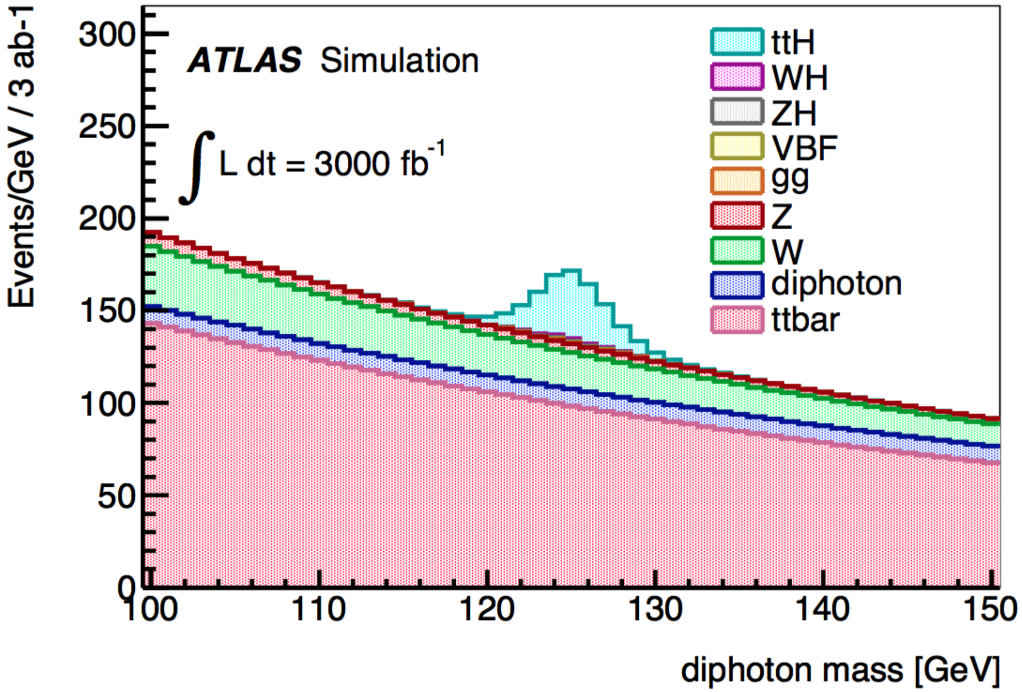


Only indirect (however not negligible) constraint on the total width

Necessary to use assumptions or measure ratios: Precision down to 5% level

Reaching ttH Production in (robust) rare modes

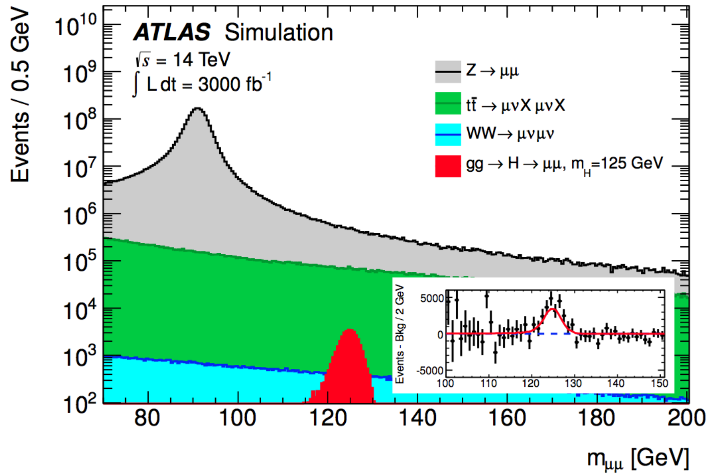
Analyses not relying on more intricate decay channels (bb, tt and WW)



- $\gamma\gamma$ channel: more than 100 Events expected with s/b~1/5
- $\mu\mu$ channel: approximately 30 Events expected with s/b~1

Analyses (rather) robust to PU

$\mu\mu$ decay mode should reach more than 5 standard deviation



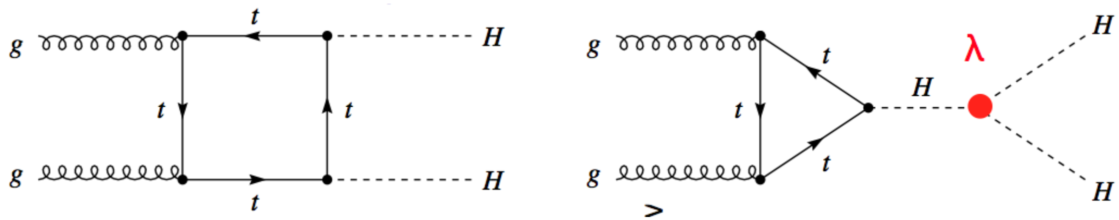
Self Couplings

Determination of the scalar potential, essential missing ingredient : **self couplings !**

Are they as predicted : $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$

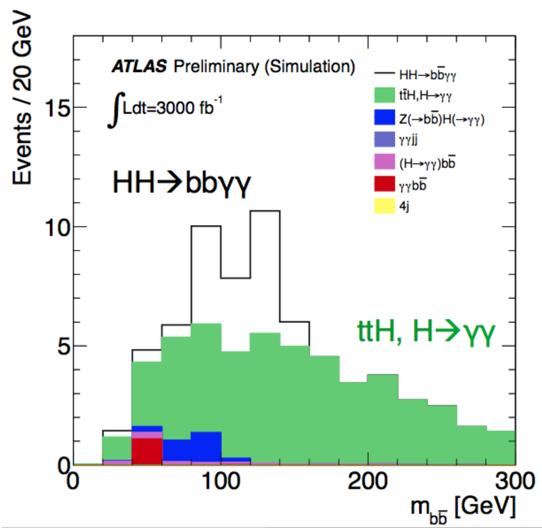
λ_4 : hopeless in any planed experiment (?)

λ_3 : very very hard in particular due to the double H production, which also interferes with the signal…



… but some hope, in (rather) robust
$pp \to HH \to bb\gamma\gamma$
(S ~ 15, B ~ 21 for 3 ab^{-1} and some faith…) $bb\tau^+\tau^-$ (under study)

~3 standard deviations expected on λ_3 with 3 ab^{-1}



Beyond LHC Programs

e$^+$e$^-$ collider
(linear or circular?)

	LHC(300)	LHC (3000)	ILC (250+350+500)	TLEP (240+350)
Δm_H (MeV)	~100	~50	~30	~7
$\Delta\Gamma_H/\Gamma_H(\Delta\Gamma_{inv})$			5.5(1.2)%	1.1(0.3)%
H spin	✓	✓	✓	✓
Δm_W (MeV)	~10	~10	~6	<1
Δm_t (MeV)	800-1000	500-800	20	15
$\Delta g_{HVV}/g_{HVV}$	2.7-5.7%*	1-2.7%*	1-5%	0.2-1.7%
$\Delta g_{Hff}/g_{Hff}$	5.1-6.9%*	2- 2.7%*	2-2.5%	0.2-0.7%
$\Delta g_{Htt}/g_{Htt}$	8.7%*	3.9%*	~15%	~30%
$\Delta g_{HHH}/g_{HHH}$	--	~30%	15-20%**	--

From R. Aleksan

- High-energy pp machine
  - HE-LHC (33 TeV)
  - Something bigger (TLHC 100 TeV)
- Muon collider
- ep, eγ and $\gamma\gamma$ Machines investigated as well

Conclusion

- No significant deviations (so far) from the SM Higgs

- LHC Higgs physics program reappraised

    - Exciting vast program to measure as precisely as possible the H^0 properties

    - Exciting vast program to search for additional states of the EWSB sector

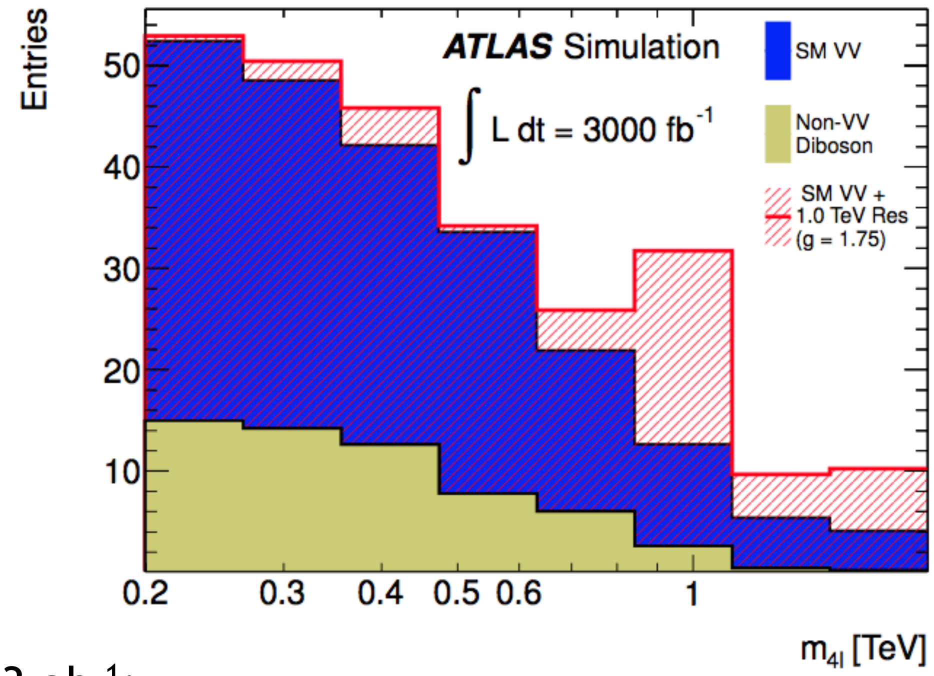
Backup Slides

Completing the Picture WBS

Weak Boson Scattering

Only taking into account the cleanest signals : ZZjj in the 4 leptons final state

Very clean signature for a TeV resonance (in anomalous WBS models)

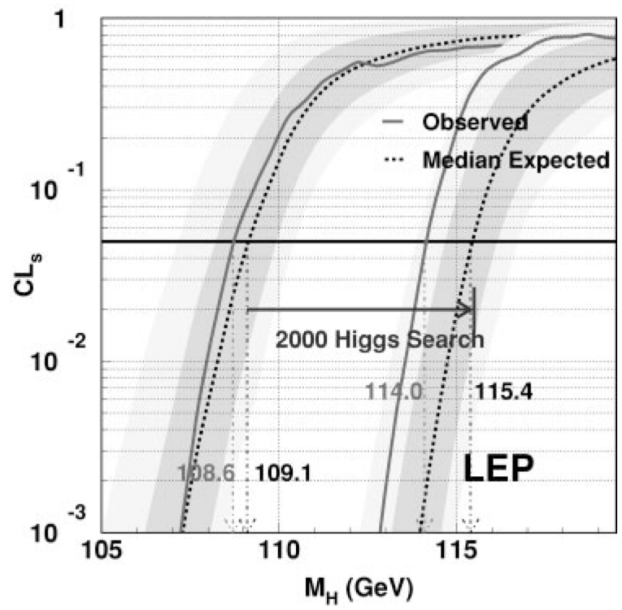


Sensitivities for 300 fb^{-1} and 3 ab^{-1}:

Model (anomalous WBS)	300 fb^{-1}	3 ab^{-1}
500 GeV and g=1	2.4 σ	7.5 σ
1 TeV and g=1.75	1.7 σ	5.5 σ
1 TeV and g=2.5	3.0 σ	9.4 σ

Other Higgs Programs

- LEP limits m_H > 114 GeV covering down to 32 MEV

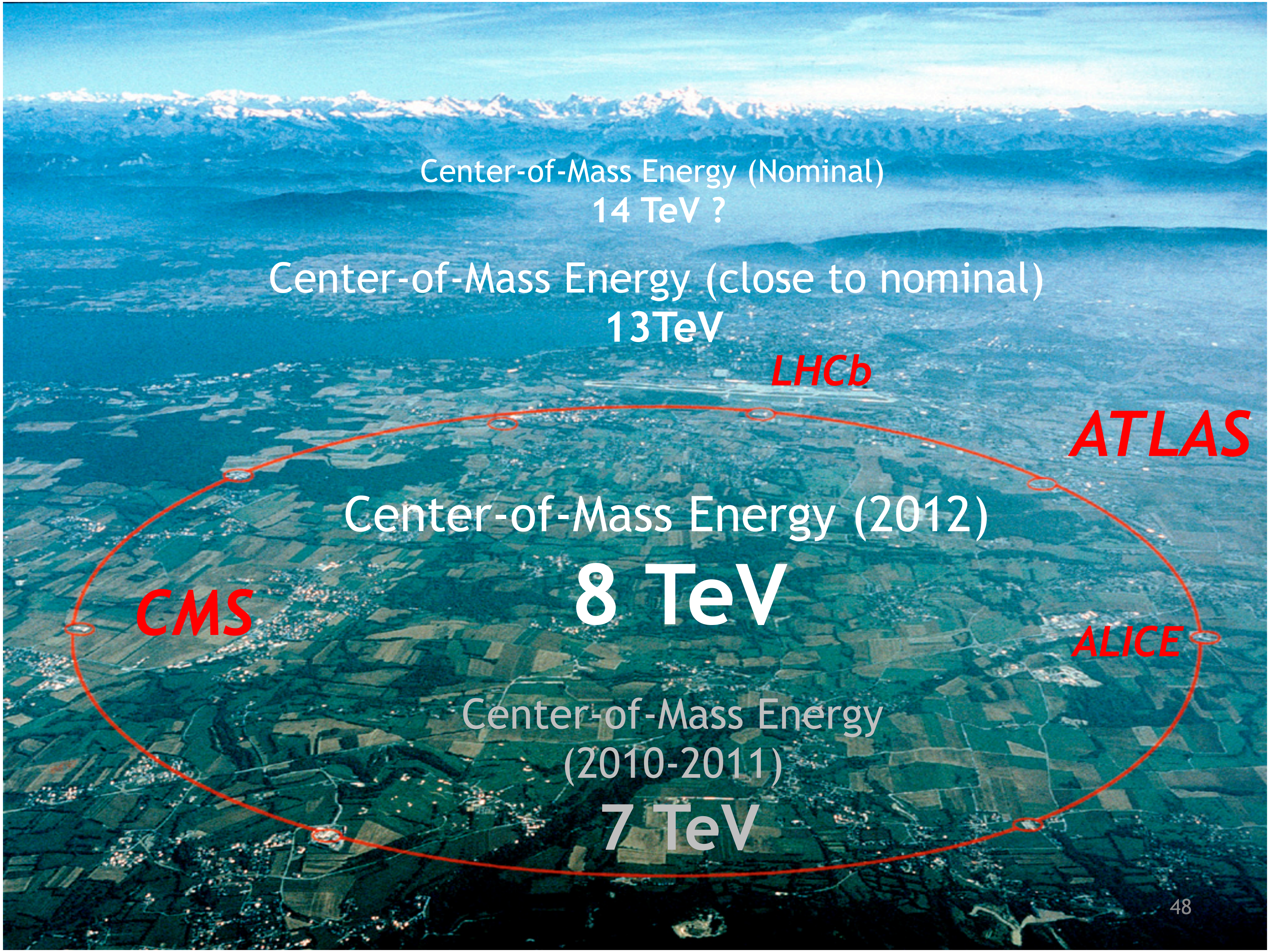


- In general reinterpretation of low mass searches

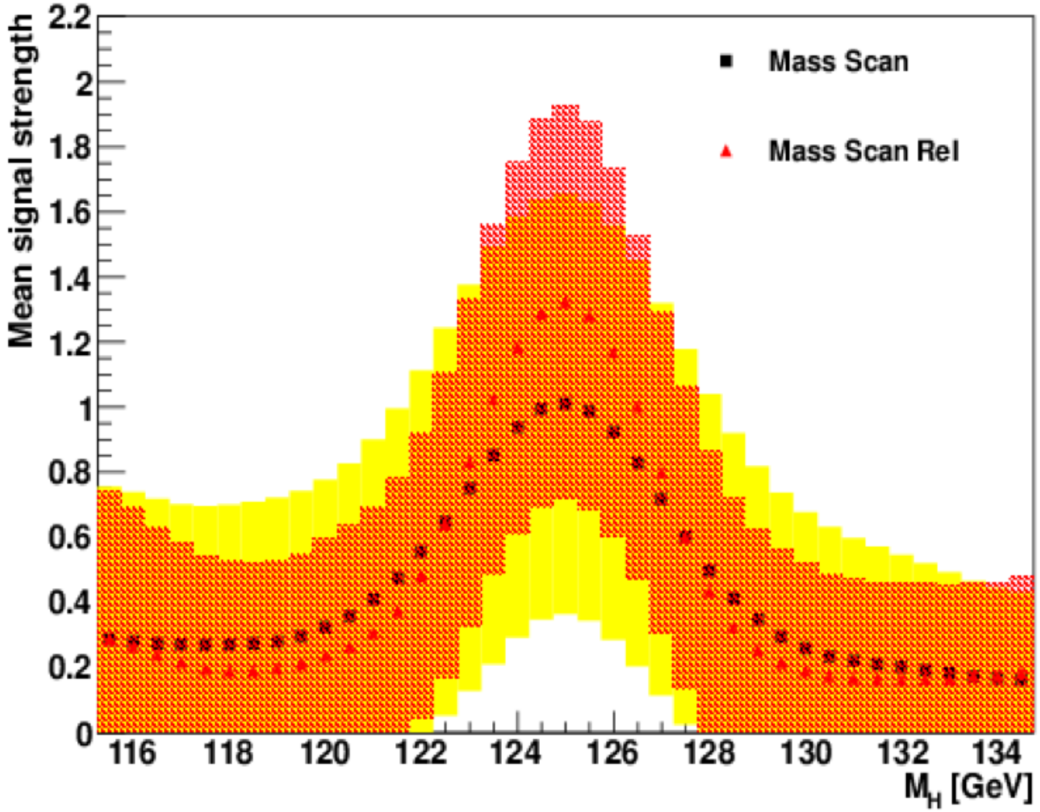
- PreLEP era
  - Absence of Higgs related effects in Nuclear Physics, neutron stars and neutron scattering experiments m_H>20 MeV
  - Kaon abd B-Meson decays limits m_H>5 GeV

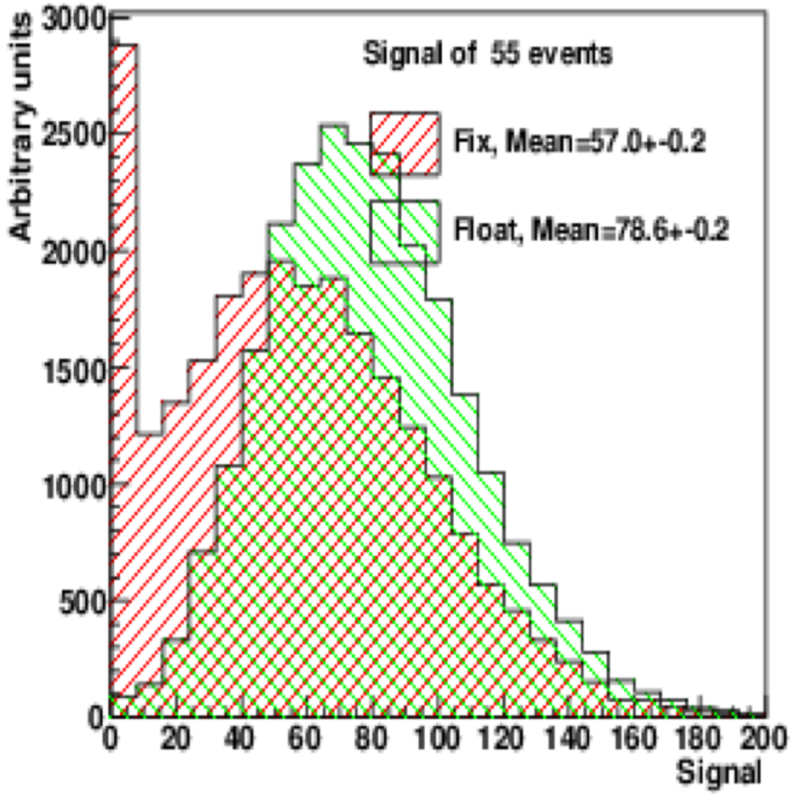
- LHCb
  - Standard Model H in bb
  - Higgs decays to long lived partices
  - (MSSM) Higgs to $\tau\tau$

- BaBar and Belle search for NMSSM a


Center-of-Mass Energy (Nominal)
14 TeV ?
Center-of-Mass Energy (close to nominal)
13TeV
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy
(2010-2011)
7 TeV

The (experimental) μ Problem





Unbiased at true mass

Statistical Interpretation

How to read Higgs Search Plots

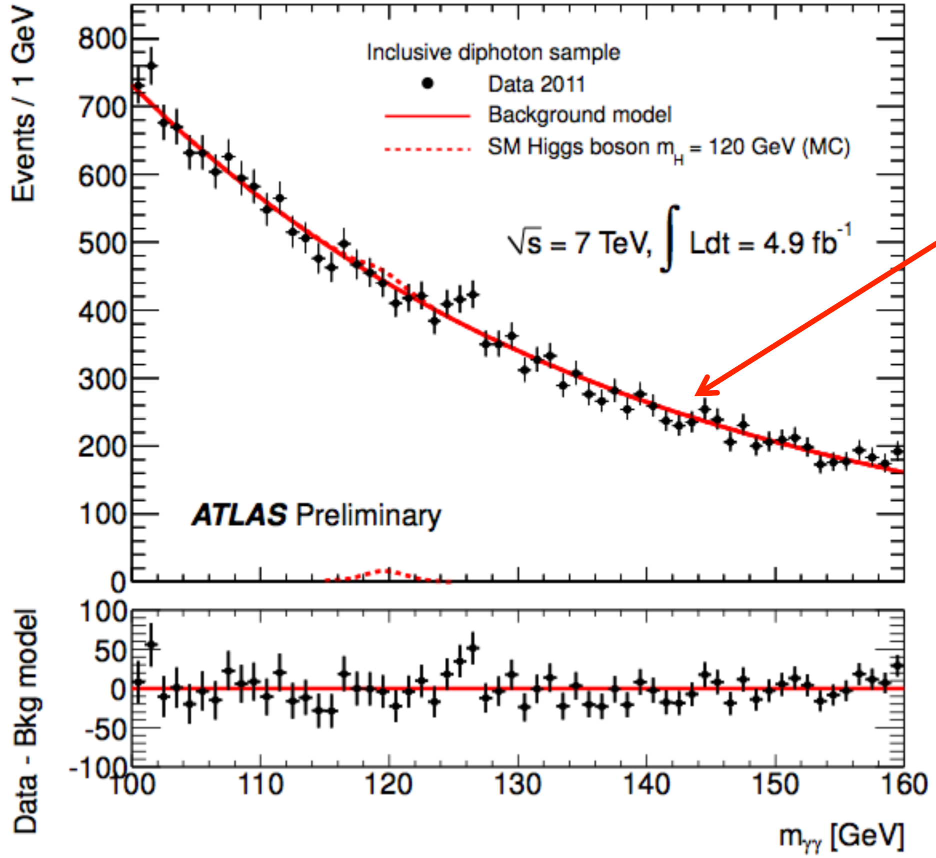
Hypothesis testing using the

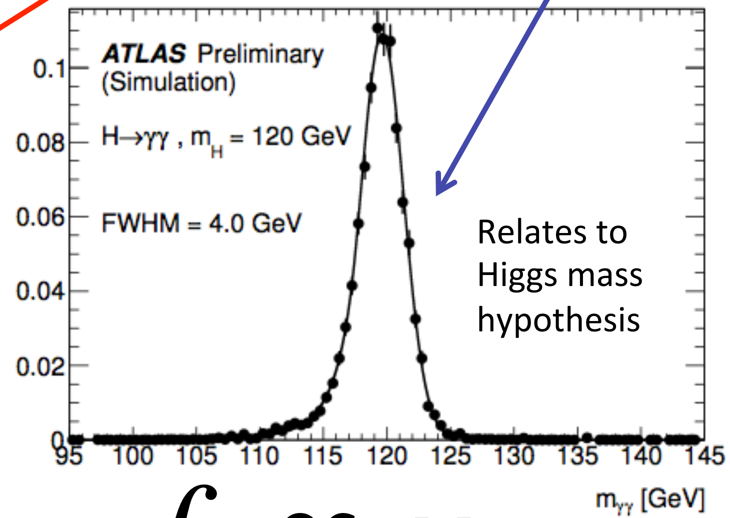
Profile likelihood ratio…

Likelihood Definition:

Simplified

$$L(\mu,\theta) = f_b\psi_b(M_{\gamma\gamma}) + f_s\psi_s(M_{\gamma\gamma})$$





Relates to Higgs mass hypothesis

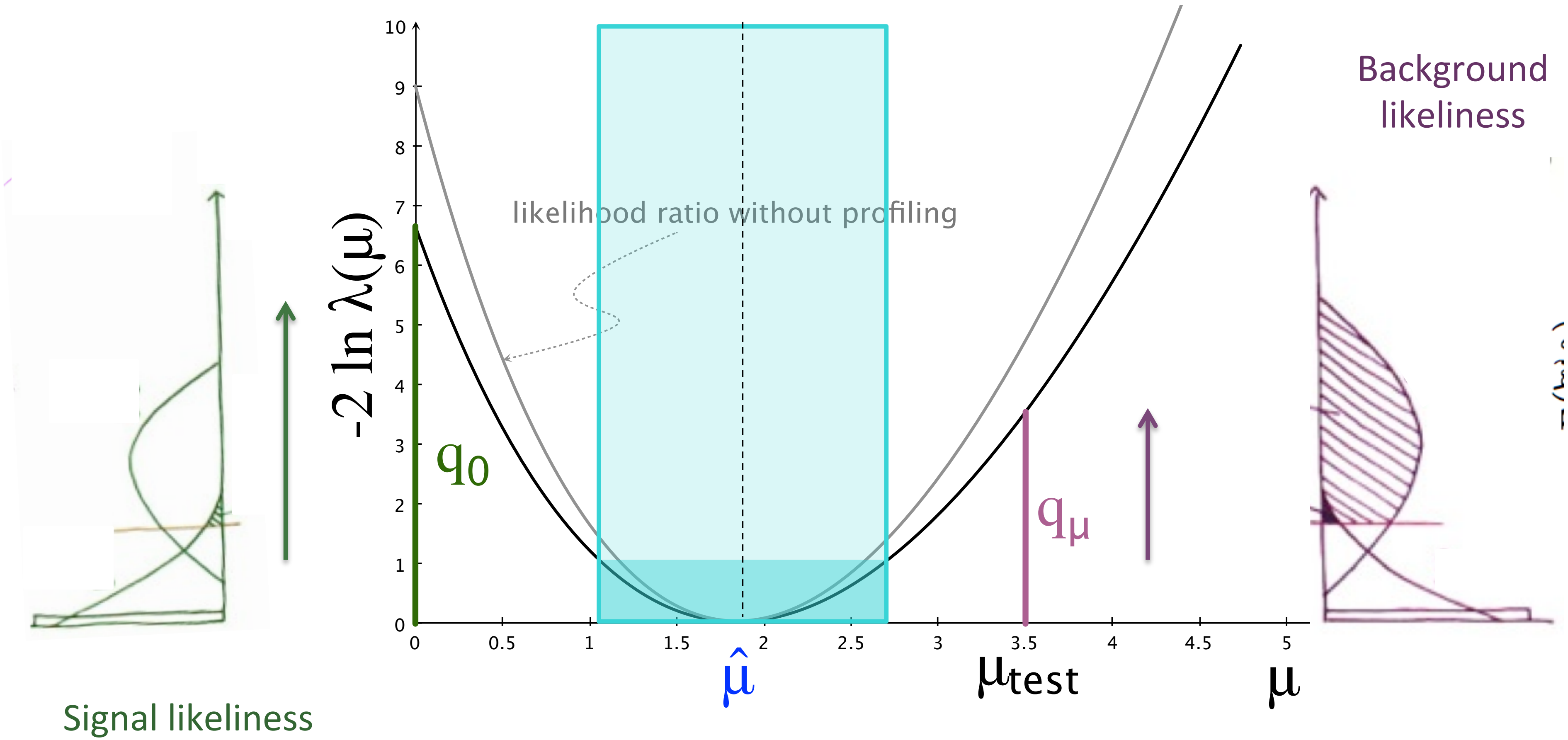
$$f_s \propto \mu$$

Global coherent factor

$$n_s = \mu\sigma BrL\varepsilon$$

How to Read Higgs Exclusion Limits Plots

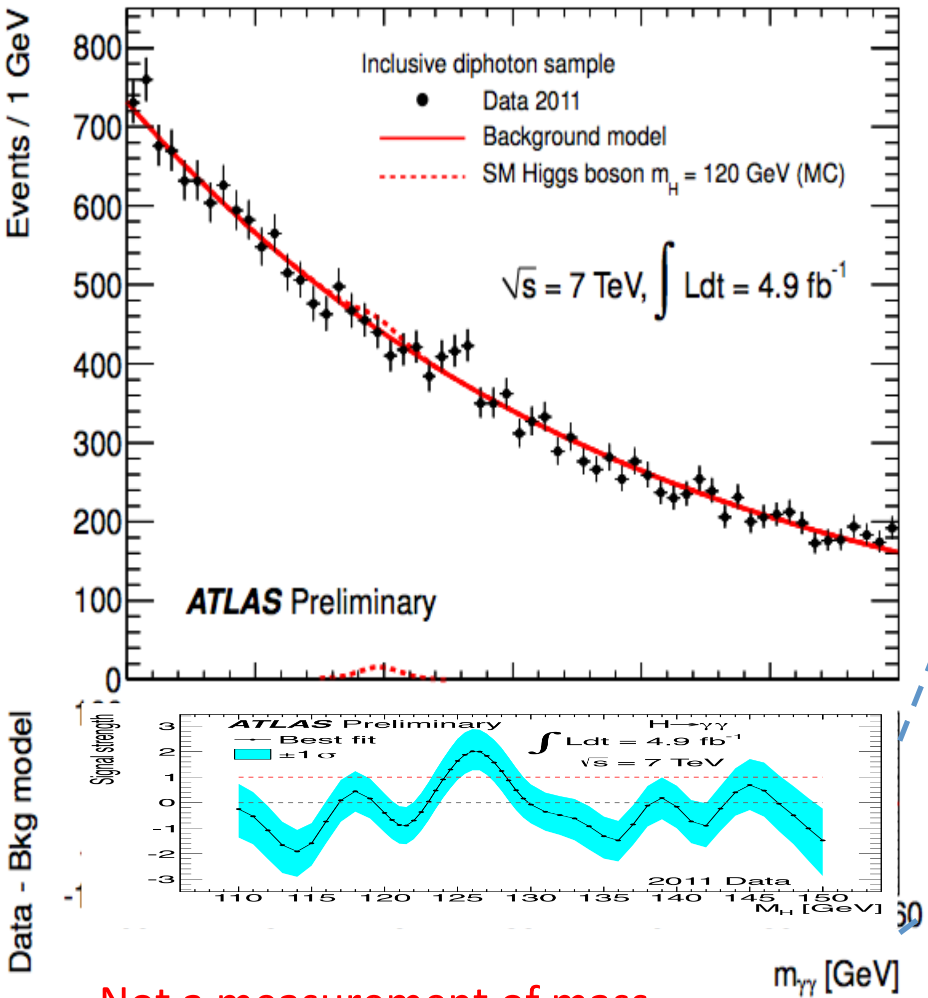
$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$



Statistical Interpretation

How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio…



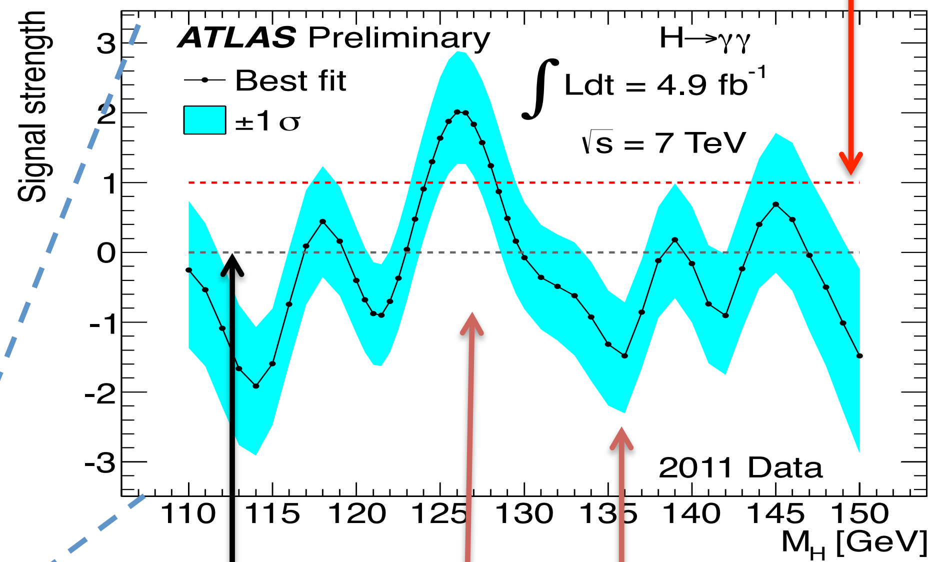
Not a measurement of mass

Not a measurement of cross section

$\hat{\mu}$

Relate to Higgs mass hypothesis

Expected Signal

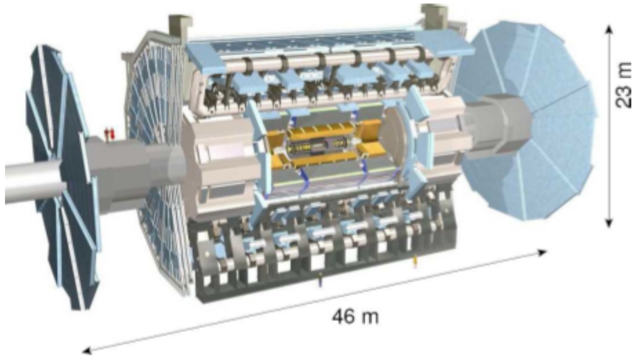
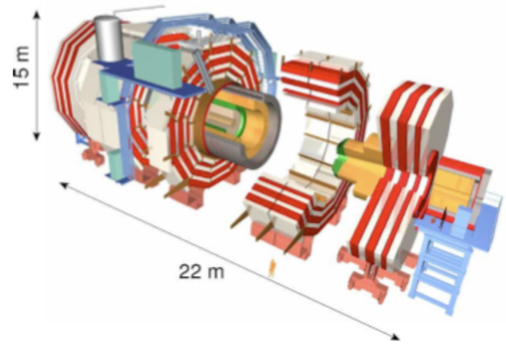


Expected Background

Excess

Deficit

The ATLAS and CMS Detectors In a Nutshell

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)