The Discovery of the Higgs Boson

And Recent Developments…

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Benasque Taller de Altas Energias

Menu "A la Carte…"

1.- Historical context

2.- Brief History of the Discovery

3.- How to read an exclusion or significance plot?

4.- Overview of channels and their results

5.- Couplings analysis

6.- Main quantum numbers

7.- Implications (Vacuum stability, SUSY)

8.- Electroweak precision data

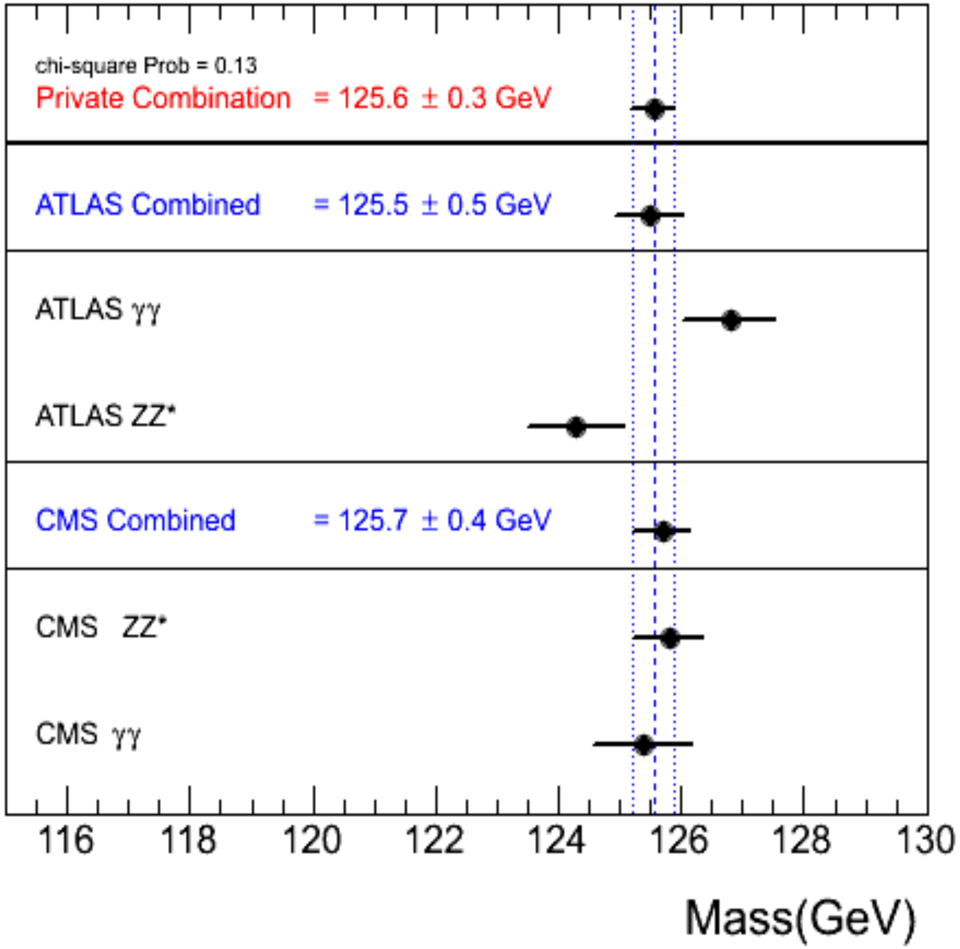
9.- Searches for BSM Higgs (concise review)

10.- Total width through interferometry

11.- Future projects

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

Review of mass measurements across channels and experiments



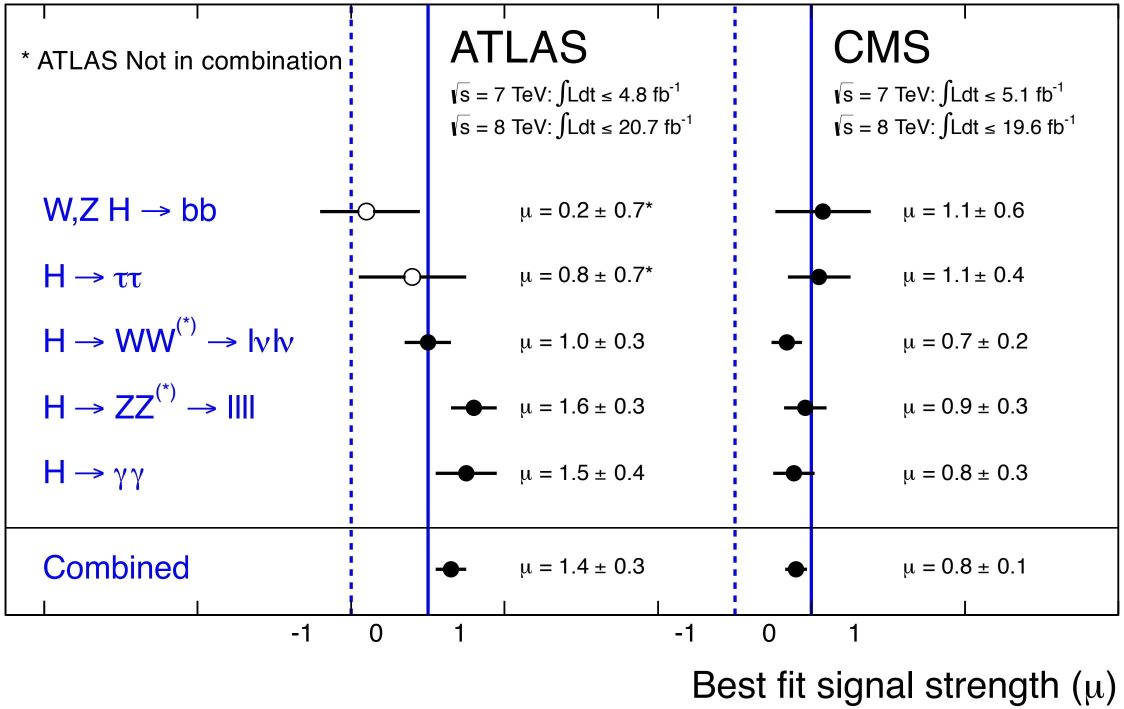
Unofficial combination

χ^2 Probability of 13%

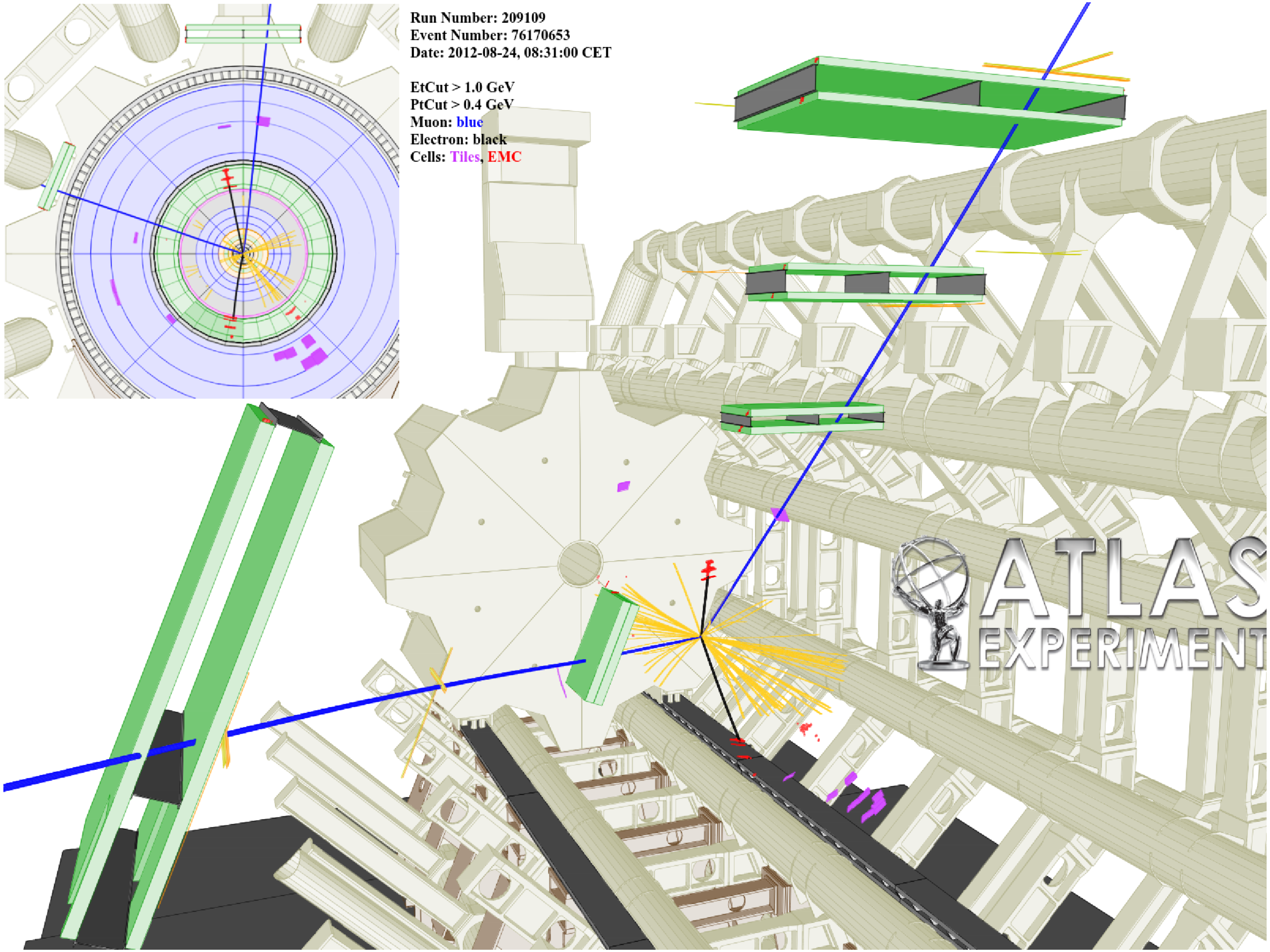
Final word on mass and m
from both ATLAS and CMS
will require final Run I
calibration

H_{125} Summary

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±0.4	4.1	7.4	126.8±0.2±0.7	0.8±0.3	4.2	3.1	125.4±0.5±0.4
ZZ (llll)	1.6±0.3	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	-	0.7±0.2	5.3	3.9	-
ττ	0.8±0.7	1.6	1.1	-	1.1±0.4	2.6	2.8	120^{+9}_{-7}
W,Z H (bb)	0.2±0.7	1.4	0.3	-	1.1±0.6	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

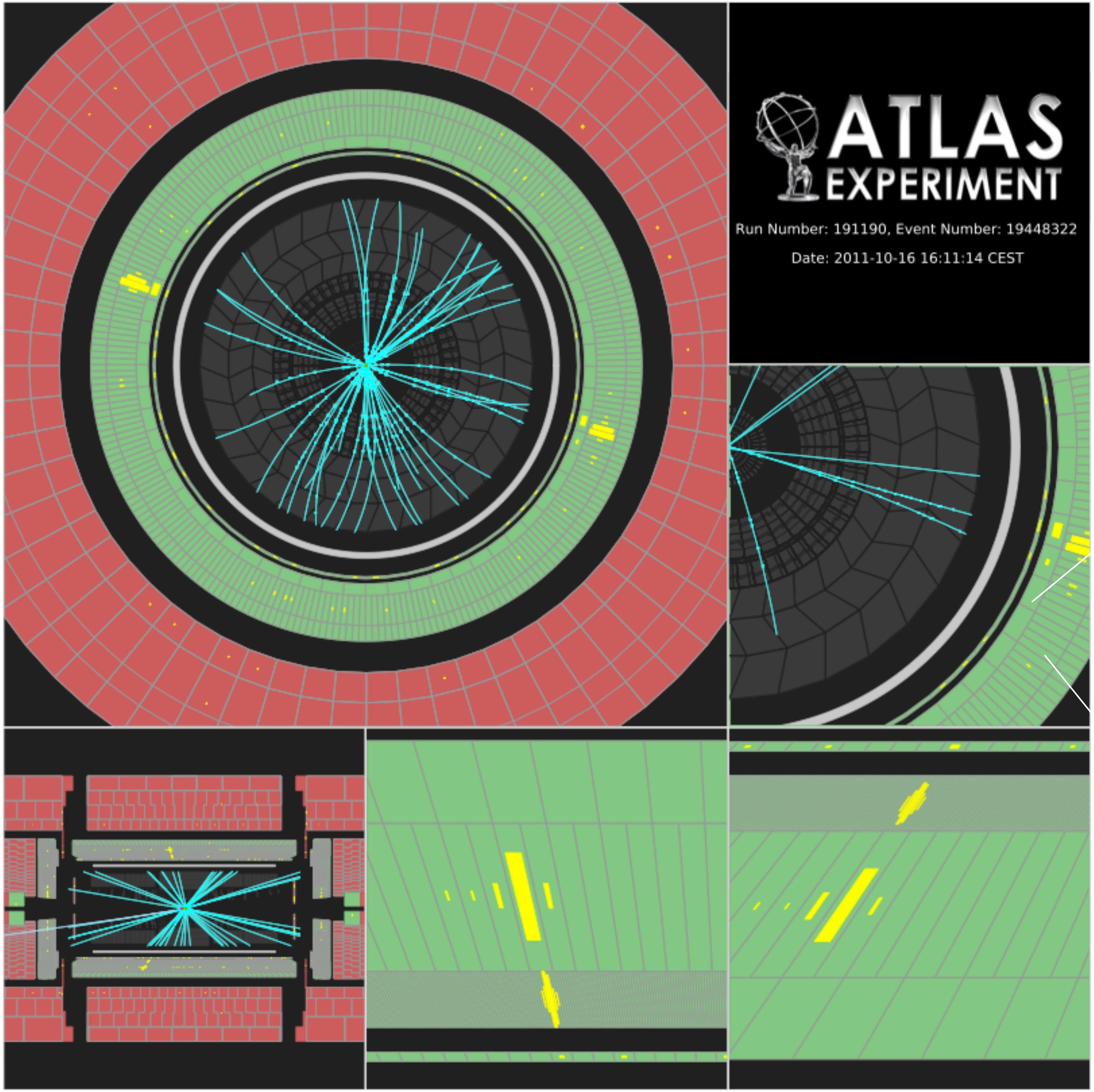


$H \rightarrow 4l$ Single Highest Purity Candidate Event $(2e2\mu)$

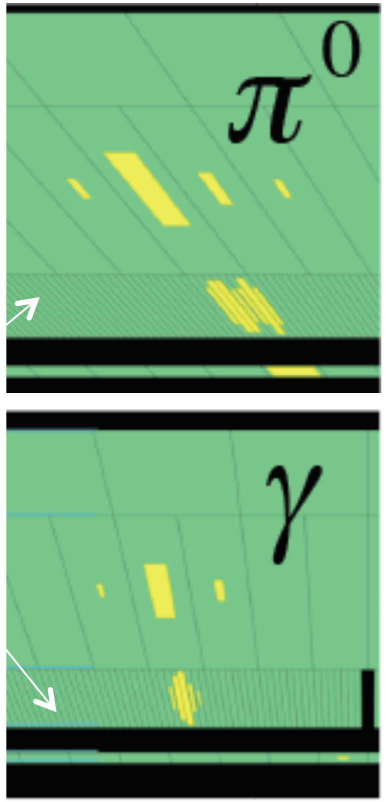


$$H \to \gamma\gamma$$

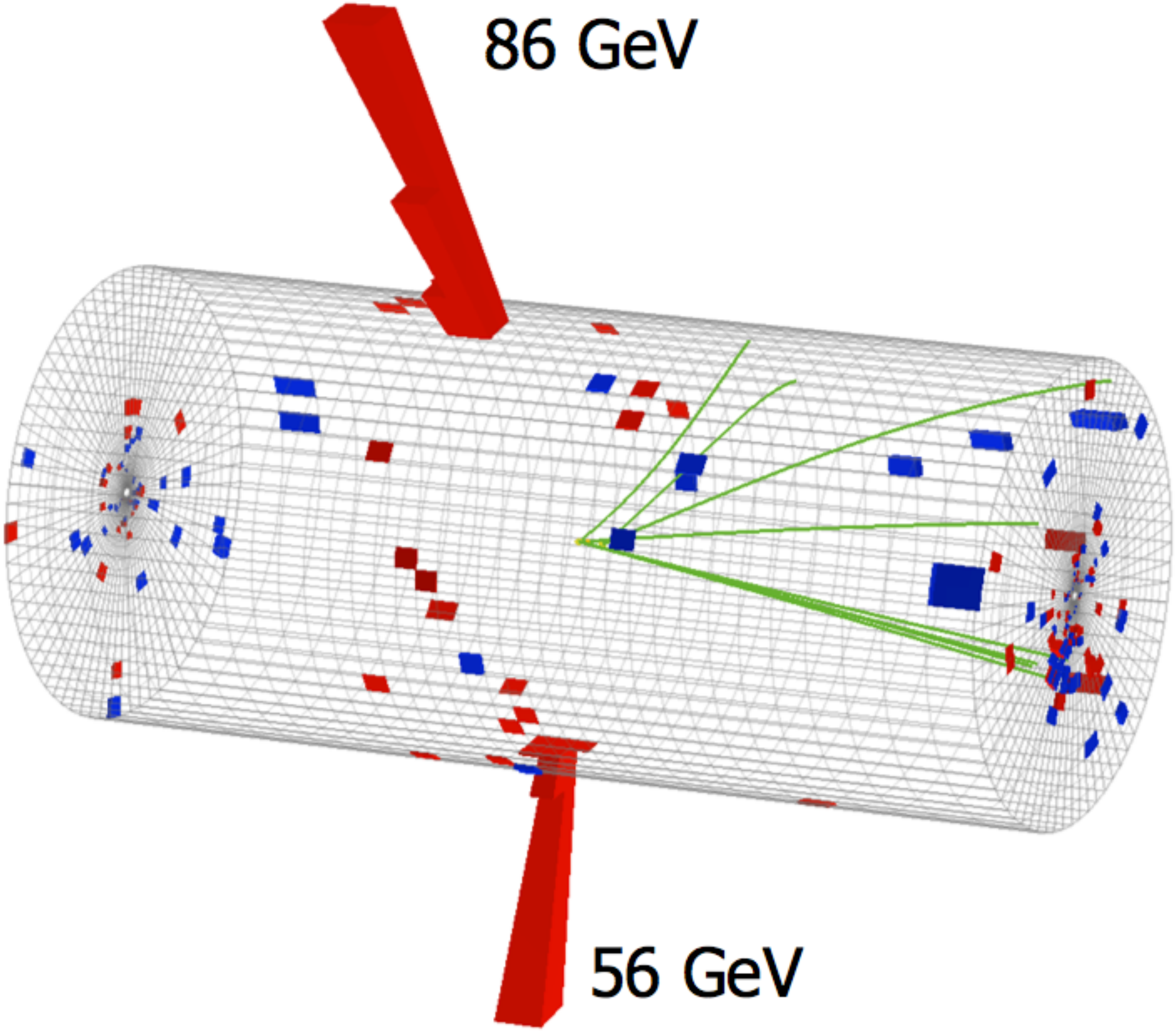
Somewhat detailing one example
(rather important one)

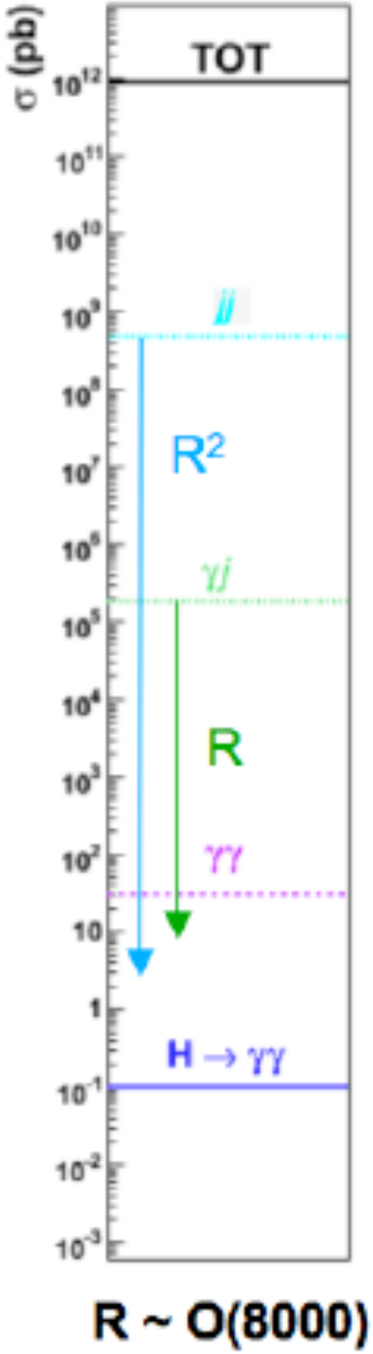


Background
From jets



Signal

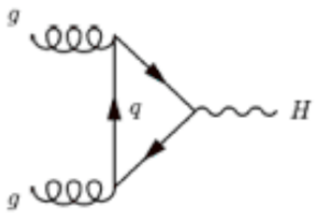

86 GeV
56 GeV

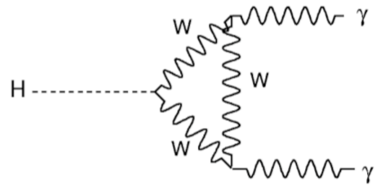

σ (pb)
TOT
jj
R²
γj
R
γγ
H → γγ
R ~ O(8000)

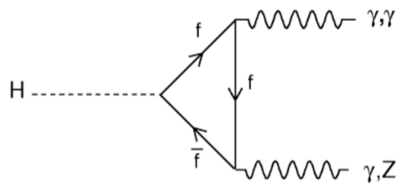
Interesting Facts about the $\gamma\gamma$ Channel

- Main production and decay processes occur through loops : Excellent probe for new physics !

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







A priori potentially large possible enhancement…

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

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

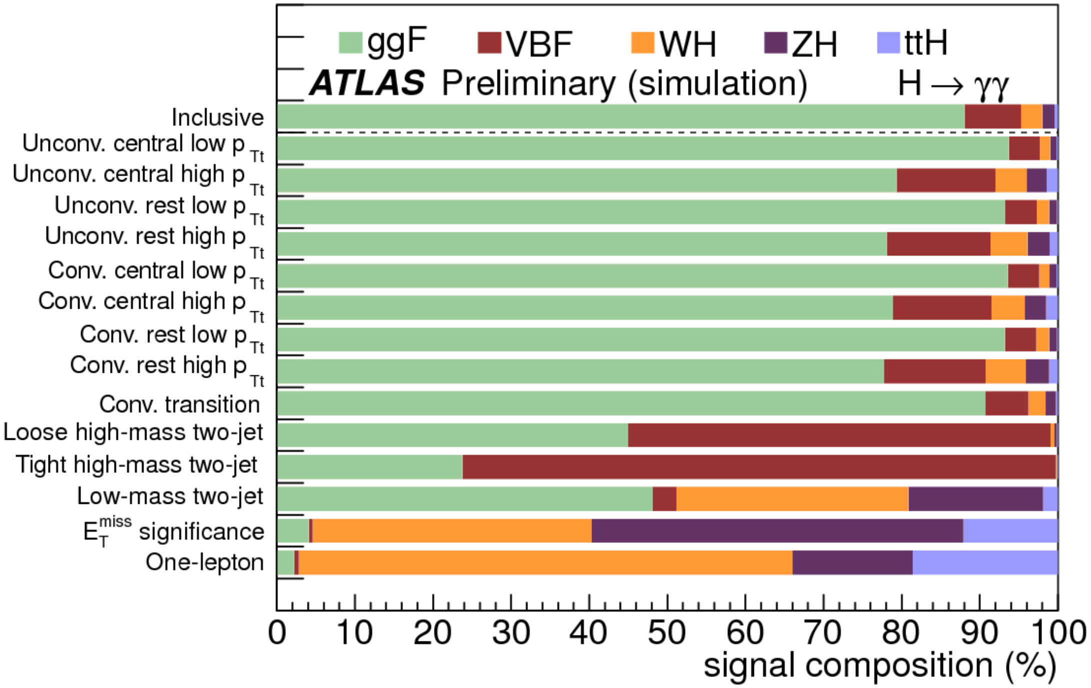
Seldom larger yields : e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia…

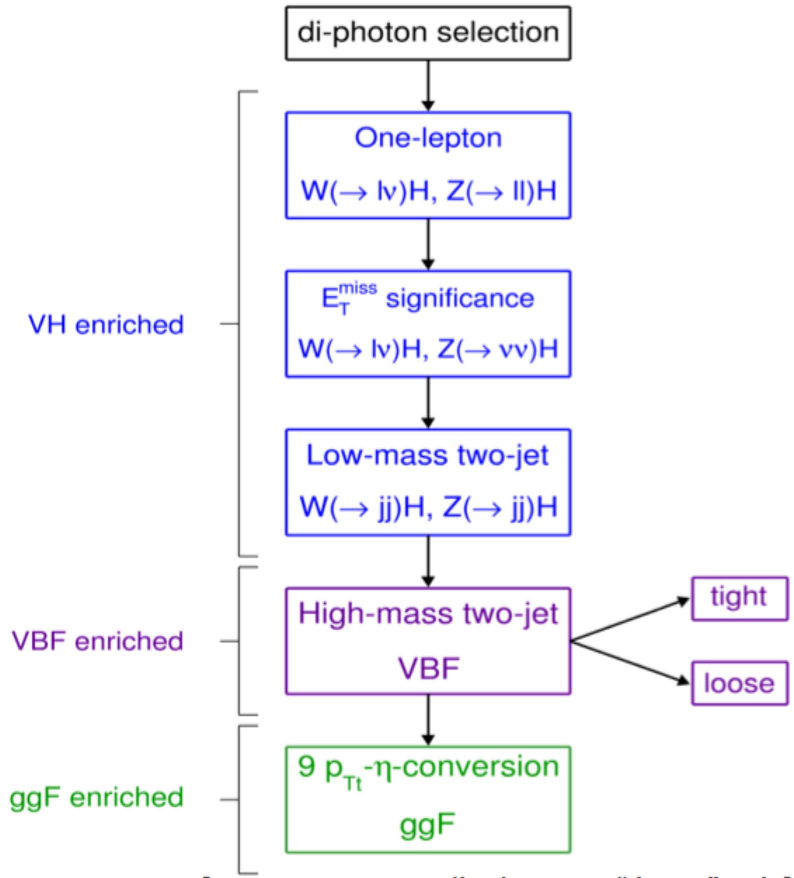
- High mass resolution channel
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem
- If observed implies that its Charge Conjugation is +1

Improving Sensitivity and Probing Other Production Modes

Performing analysis with ***categories***

- 9 (central/forward and converted/not converted photons, p_{Tt} ($\gamma\gamma$))
- +3 (low mass di-jet, lepton and MET disentangling VH)
- +2 (two 2-jet VBF categories MVA)





[$p_{Tt} = p_T^{\gamma\gamma}$ perpendicular to $\gamma\gamma$ "thrust" axis]

Why Categories?

Let's take a simple example with two categories:

- C1: s=12 and b=60
- C2: s=18 and b=40

Inclusively we have a significance of 3

Separating in two categories:

- C1 2.85 σ
- C2 1.55 σ

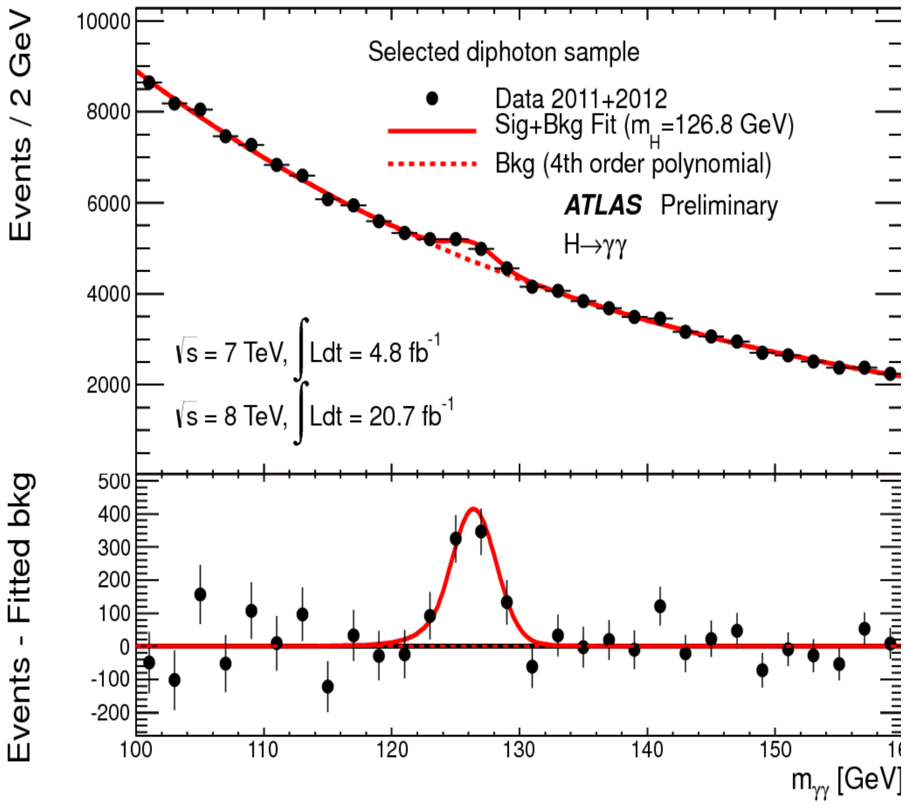
Combined significance: 3.24

Illustration of the Impact of Categories

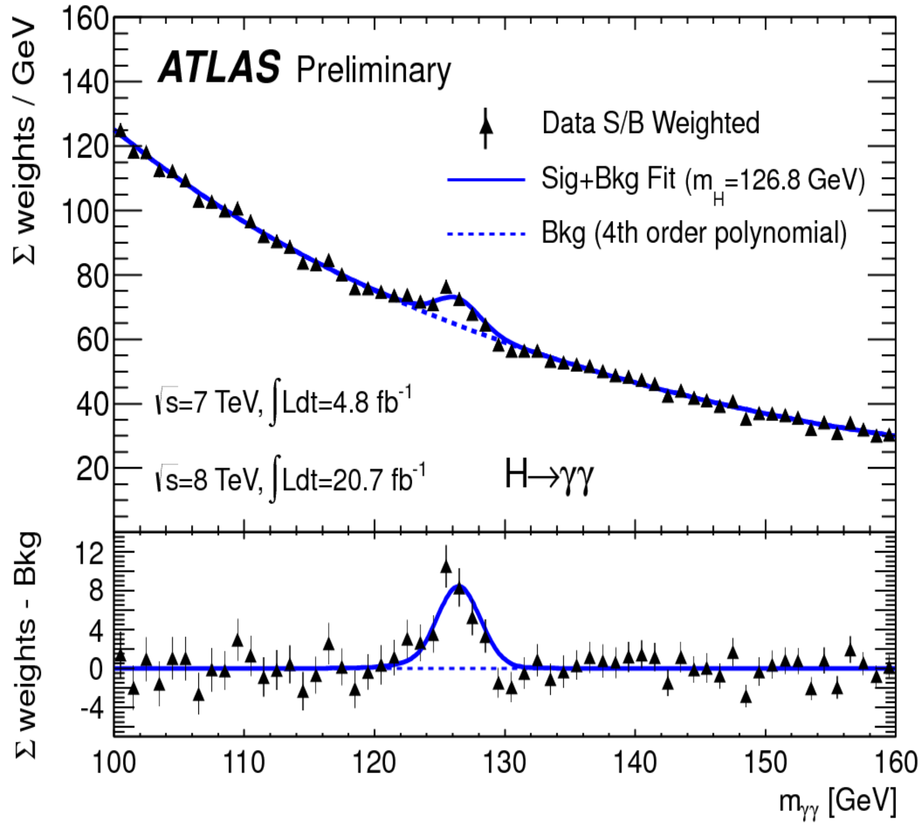
Using constant weight per category (based on expected signal and background in each category i) :

$$\ln(1 + \frac{s_i}{b_i})$$

Unweighted



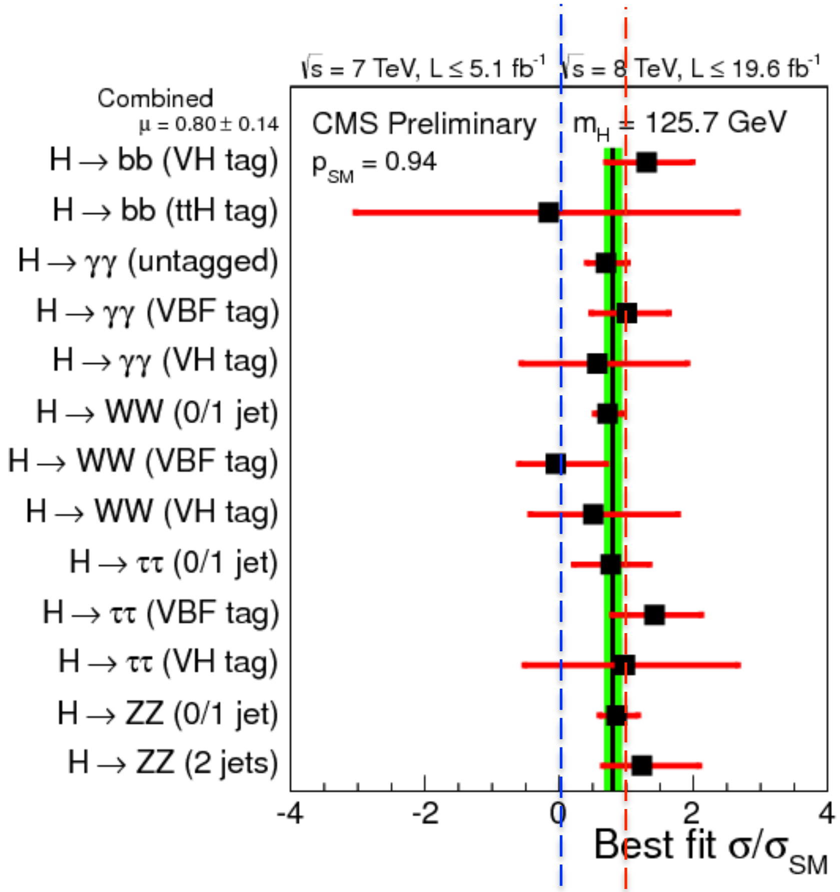
Weighted



Digression on Information Format

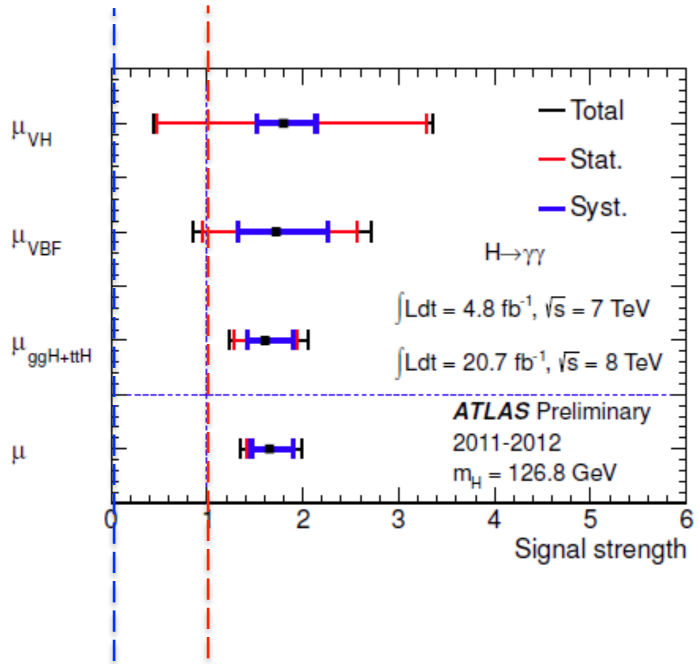
$$n_s^c = \left(\sum_{i \in \{ggF, VBF, VH, ttH\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths



μ=0 μ=1

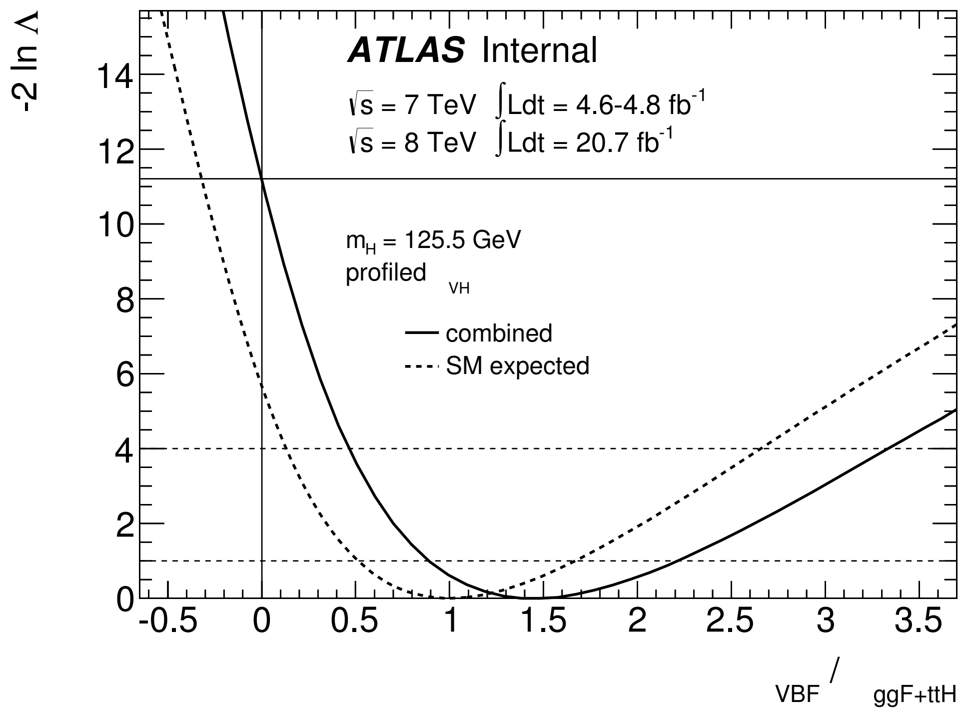
Production mode signal strengths (per channel)



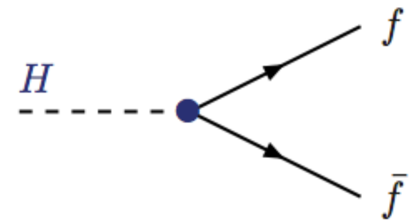
μ=0 μ=1

Evidence for VBF production

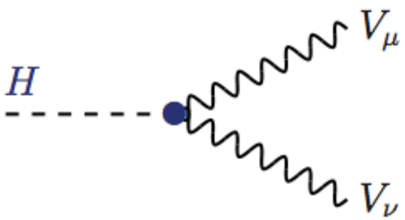
From the ratio of individual production signal strengths



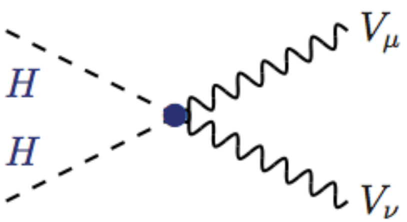
Measuring the Coupling Properties of the Observed State



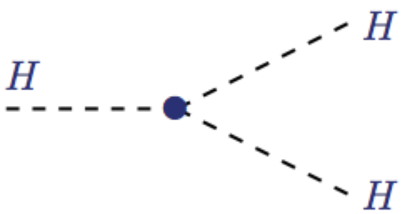
$$g_{Hff} = m_f/v$$



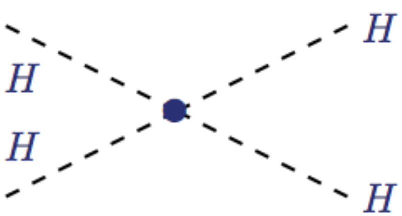
$$g_{HVV} = 2M_V^2/v$$



$$g_{HHVV} = 2M_V^2/v^2$$



$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

For the time being only test the bosonic and fermionic sector

Coupling Properties (Deviations) Measuremens

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

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

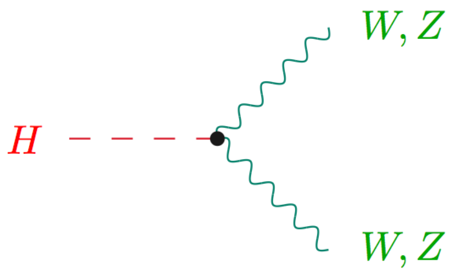
Parametrize μ_i and μ_f as a function of κ's

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

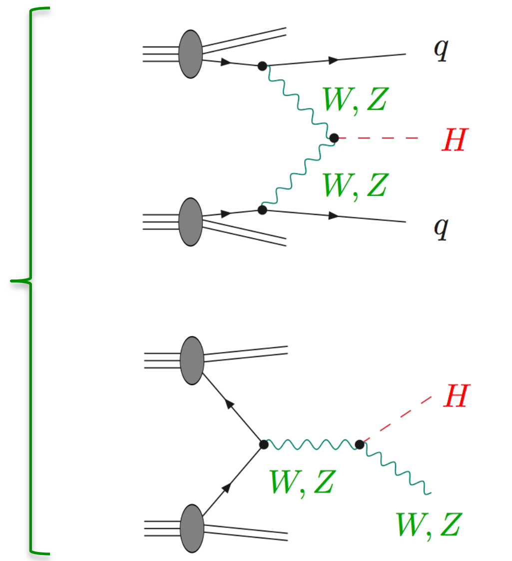
$$\sigma \cdot \mathrm{BR}\,(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Relating Couplings and Event Yields

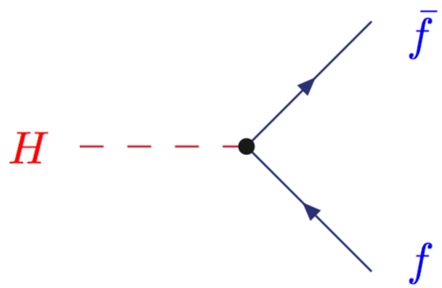
(I) Tree Level Couplings scale factors w.r.t. SM



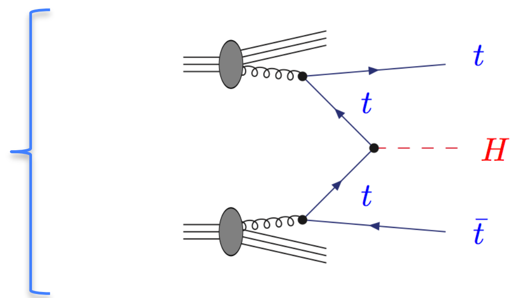
$$\propto \kappa_V$$



Affecting decay and production modes

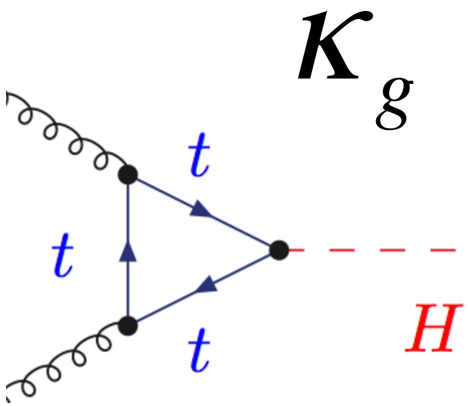


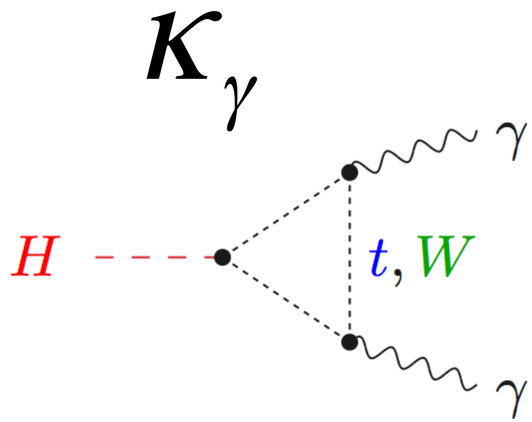
$$\propto \kappa_F$$



Relating Couplings and Event Yields

(II) Scale factors of loop induced couplings w.r.t. SM



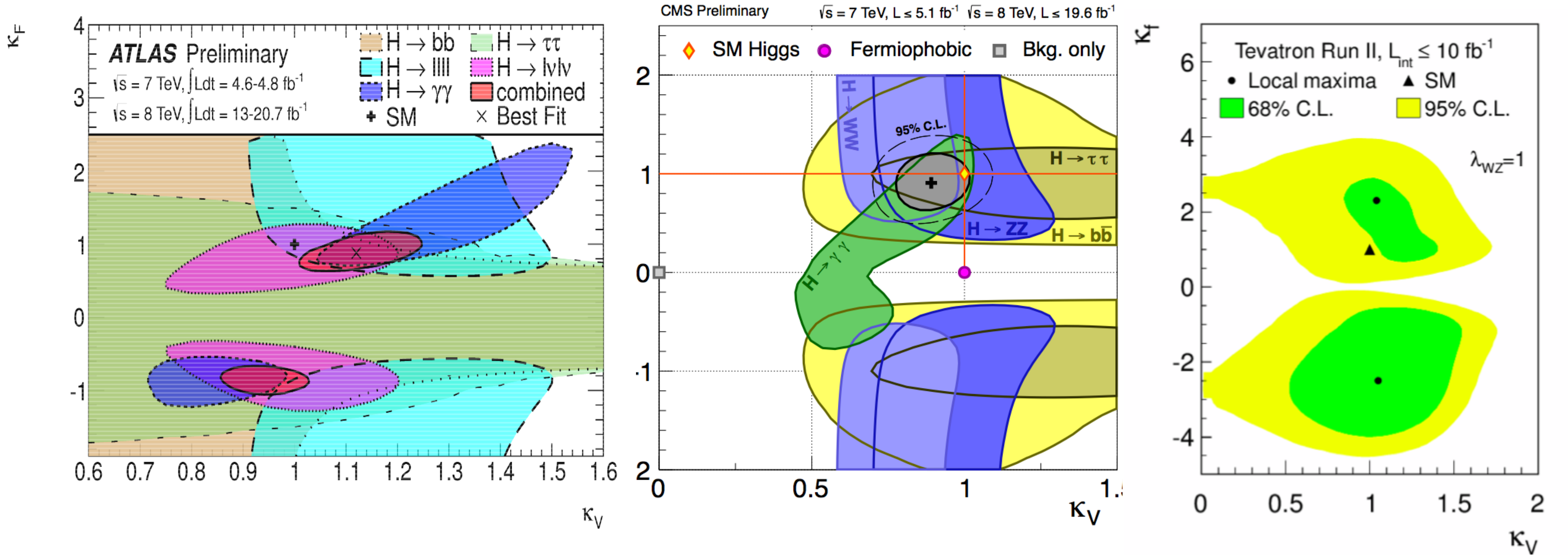


- Loop expression ambiguity :
  - Can be expressed in terms of k_F and k_V (Assuming the SM field content)
  - Or treated effectively (Allowing for possible additional particles)

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Main results I : Probing the coupling to SM particles

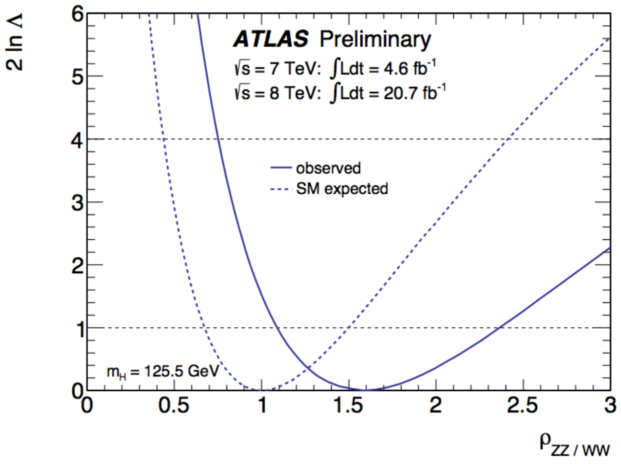


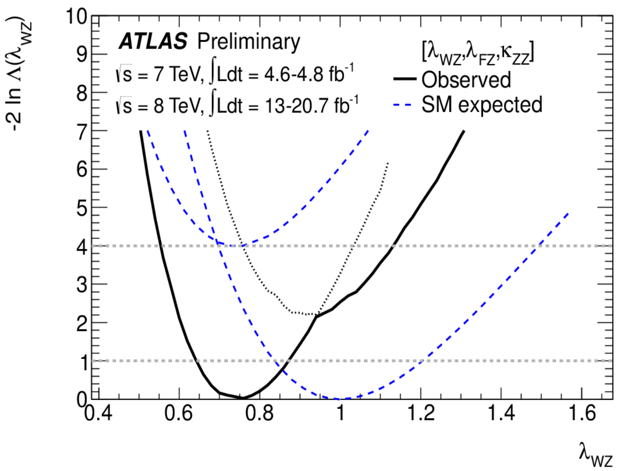
- By convention sign on the fermion yukawa strength multiplier (relying on the γγ strength primarily)… ambiguity inspired tH analyses

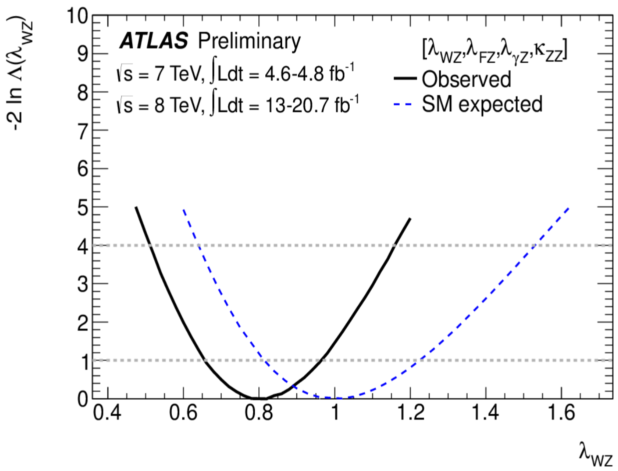
- Checking the direct and indirect couplings to fermions

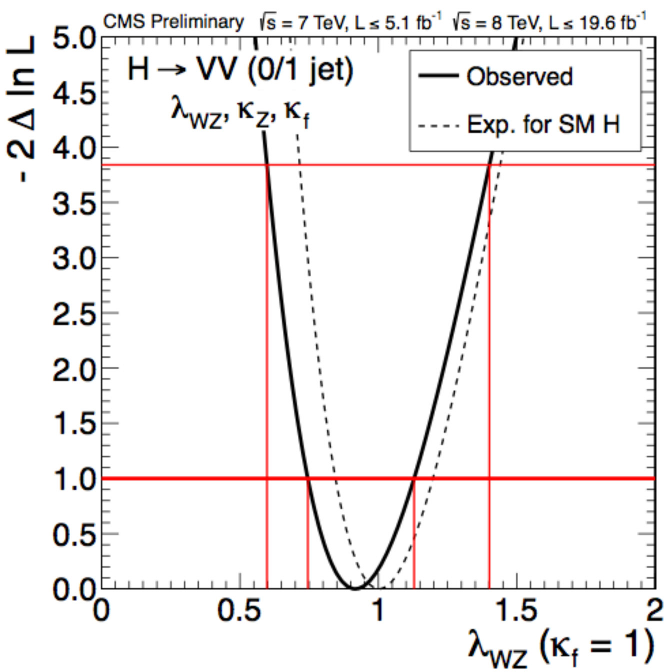
- Checks of specific composite models

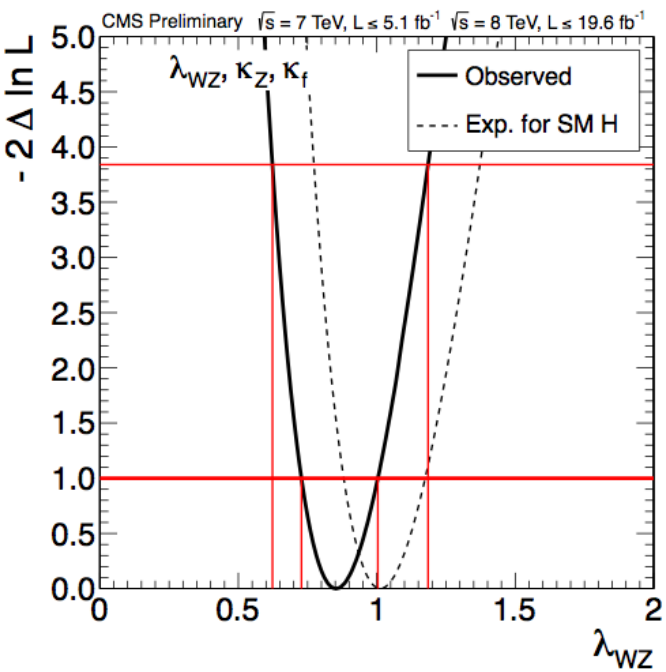
Main results II : Probing the W to Z ratio (custodial symmetry)





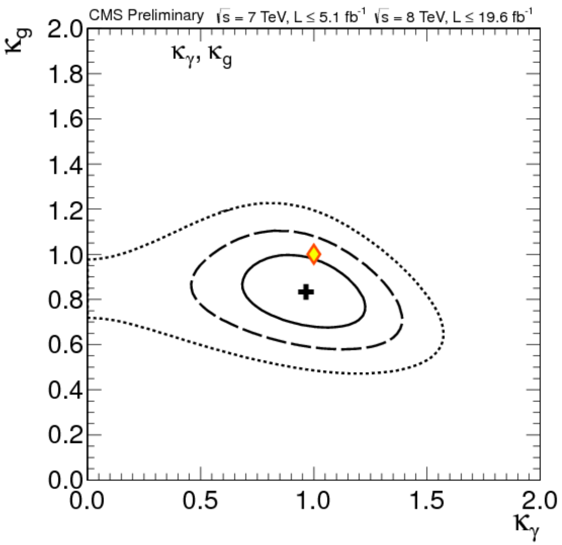


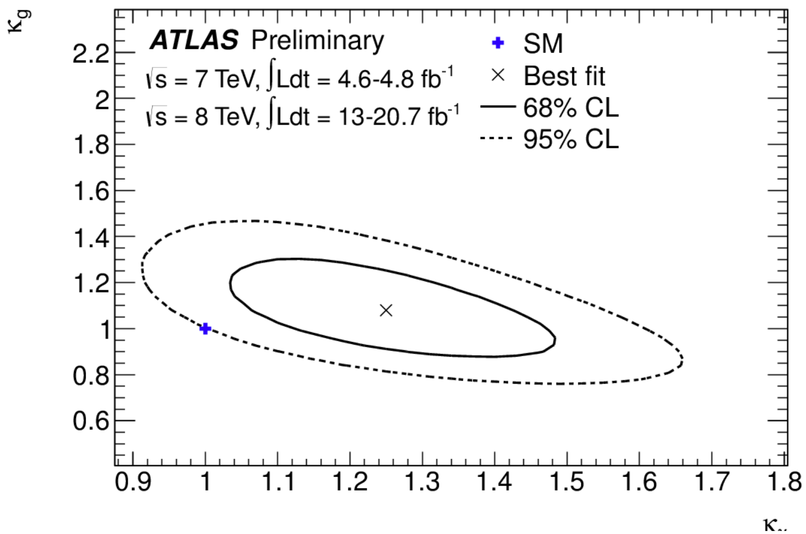




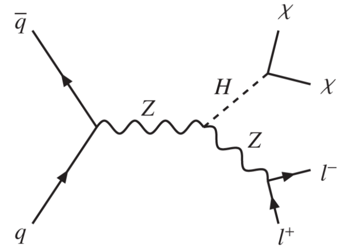
Main results III : Probing physics beyond the Standard Model

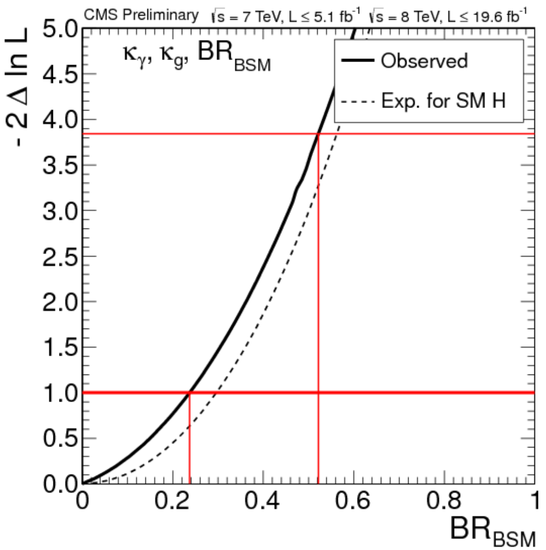
(In the decays and/or in the loops)

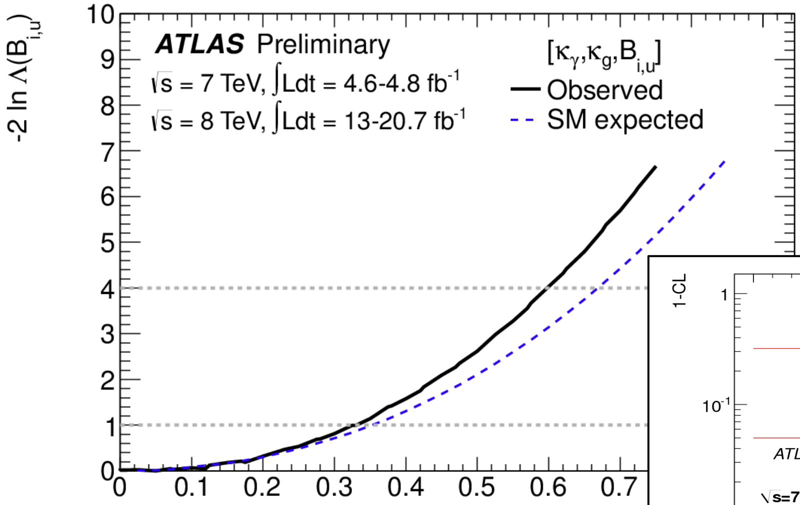


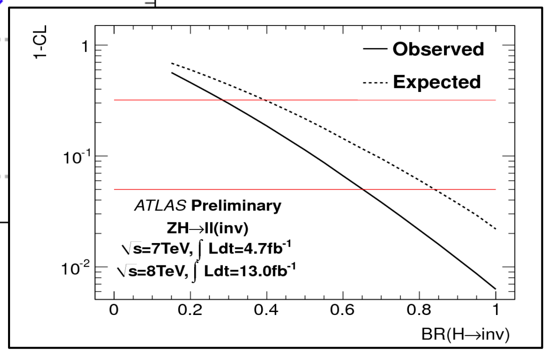


Also direct invisible only search

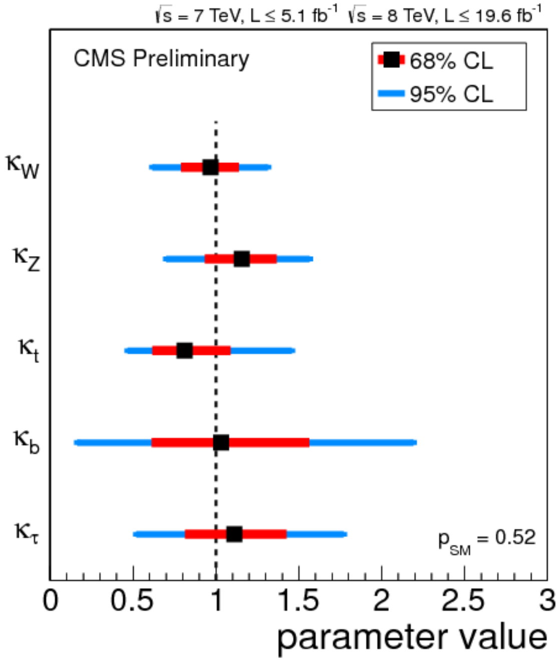


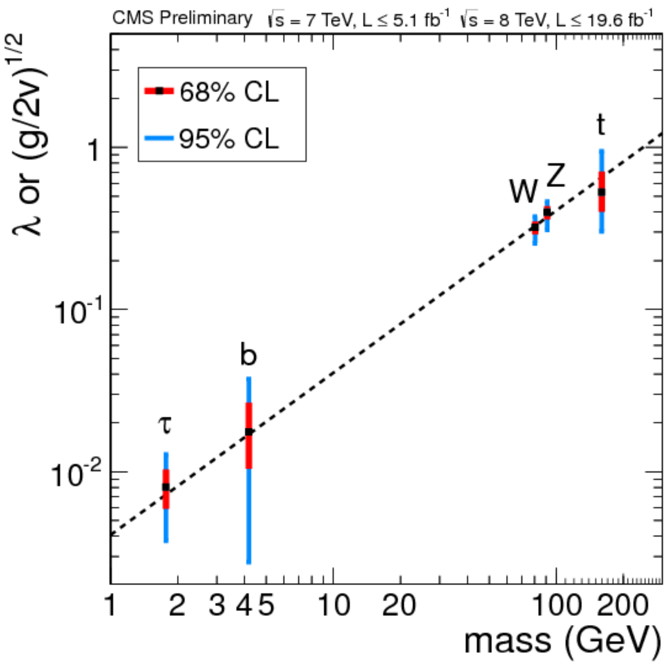


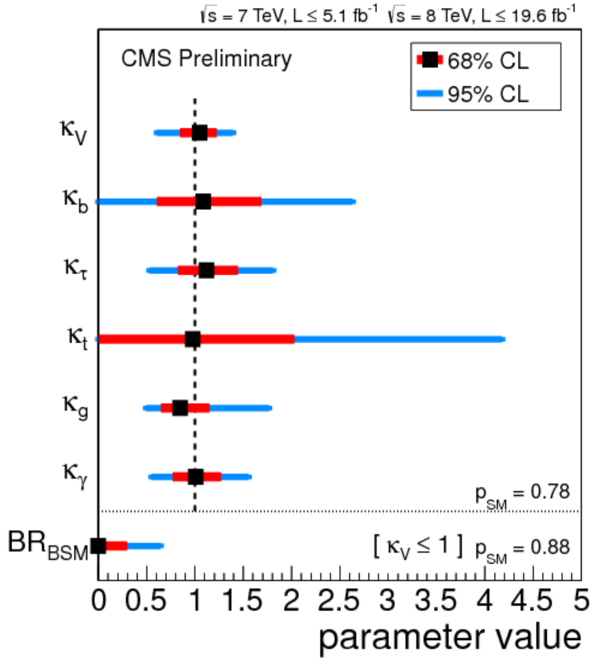




Main results IV : Other Relevant Models







- Illustrating the mass dependence

- 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.

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2.- Brief History of the Discovery

3.- How to read an exclusion or significance plot?

4.- Overview of channels and their results

5.- Couplings analysis

6.- Main quantum numbers

7.- Implications (Vacuum stability, SUSY)

8.- Electroweak precision data

9.- Searches for BSM Higgs (concise review)

10.- Total width through interferometry

11.- Future projects

$$J^{PC}$$

« The outcome of the spin analysis has as much suspens as a football game between Brazil and Tonga »

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 $\cos\theta^*$ distribution
- From the decay angles and the spin correlation when applicable

The philosophy of the approach :

- Measure compatibility with the 0^+ hypothesis
- Try to exclude alternative hypotheses simulated using an effective Lagrangian including higher order couplings.

What are we trying to exclude ? J^{PC}

Event definition directly from general amplitudes

Spin 0

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right) \tilde{f}^{*(2),\mu\nu} \Big)$$

Spin 1

$$A(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

Spin 2

$$\begin{aligned} A(X \to V_1 V_2) = \Lambda^{-1} \Bigg[& 2 g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2 g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2 g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2 g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q \epsilon_2^*) + \epsilon_2^{*\nu} (q \epsilon_1^*) \right) \right) \Bigg] \end{aligned}$$

What are we trying to exclude ? J^{PC}

Event definition directly from general amplitudes

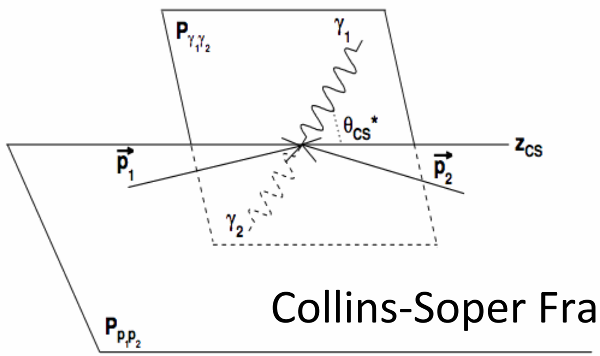
scenario	X production	$X \to VV$ decay	
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs scalar boson
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar higher-dim. op.
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
1^+	$q\bar{q} \to X$	$b_2 \neq 0$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	$b_1 \neq 0$	exotic vector
2_m^+	$g_1^{(2)} \neq 0$	$g_1^{(2)} = g_5^{(2)} \neq 0$	RS graviton min. coupl.
2_h^+	$g_4^{(2)} \neq 0$	$g_4^{(2)} \neq 0$	tensor higher-dim. op.
2_h^-	$g_8^{(2)} \neq 0$	$g_8^{(2)} \neq 0$	“pseudo-tensor”

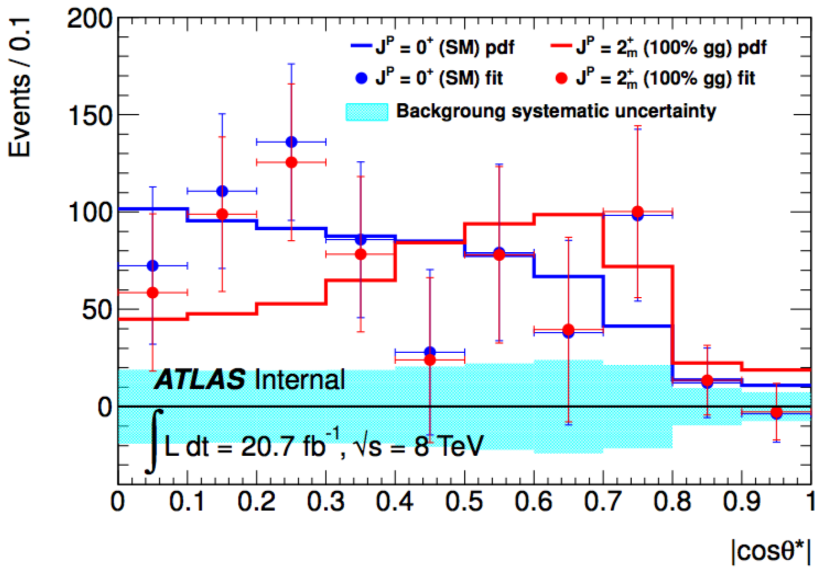
Nothing on the rates !!!

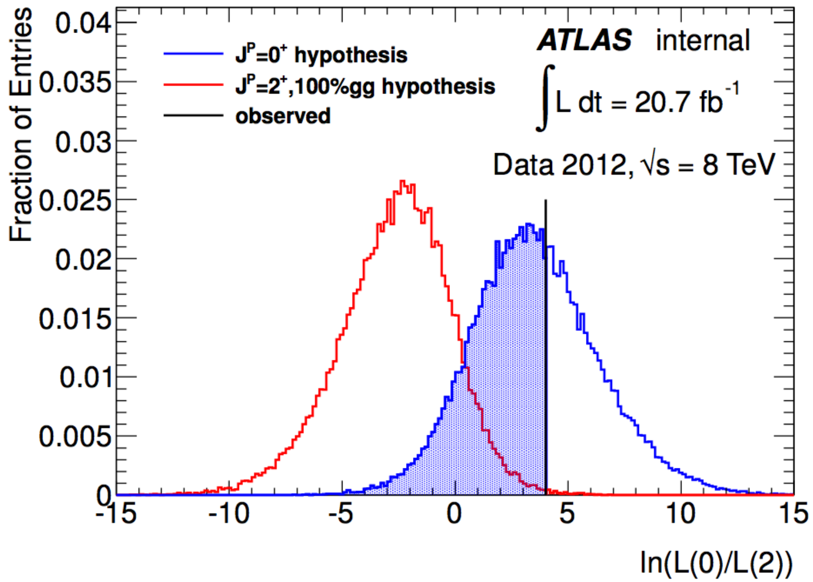
First Analysis of Spin in the $H \to \gamma\gamma$ Channel

Using the inclusive analysis

- Sensitive variable is dihoton cos θ* distribution
- Use events within 1.5σ of the peak (m_H=126.5 GeV)



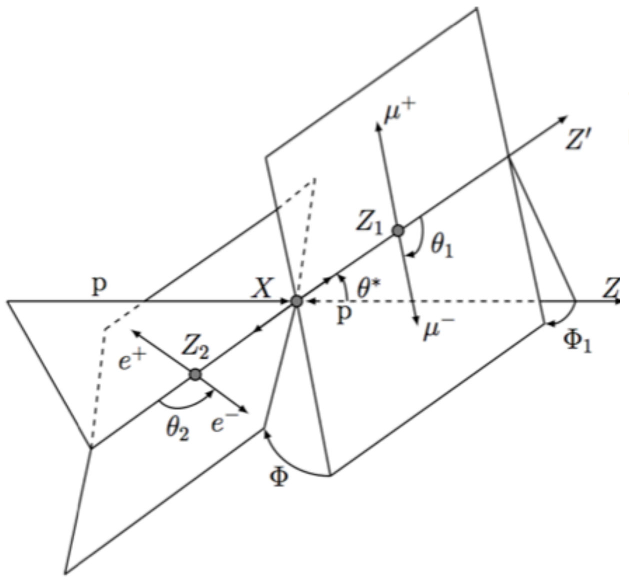


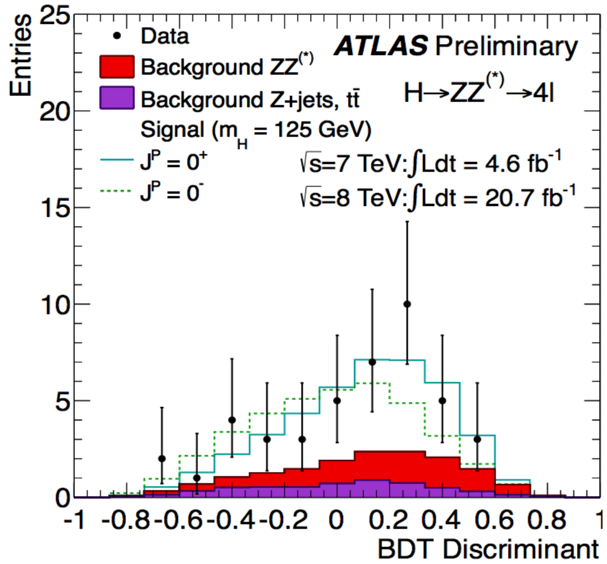


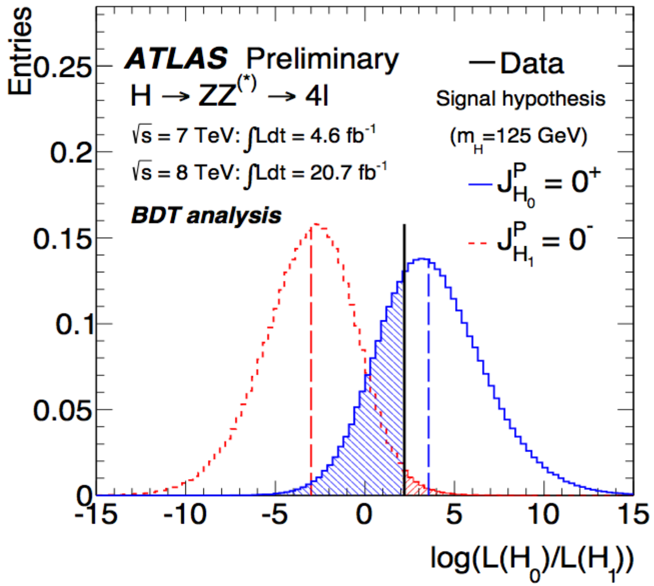
Expected sensitivity and observation are quite close ~99% CL and good compatibility with SM

Analysis of Parity in the $H \rightarrow 4l$ Channel

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants





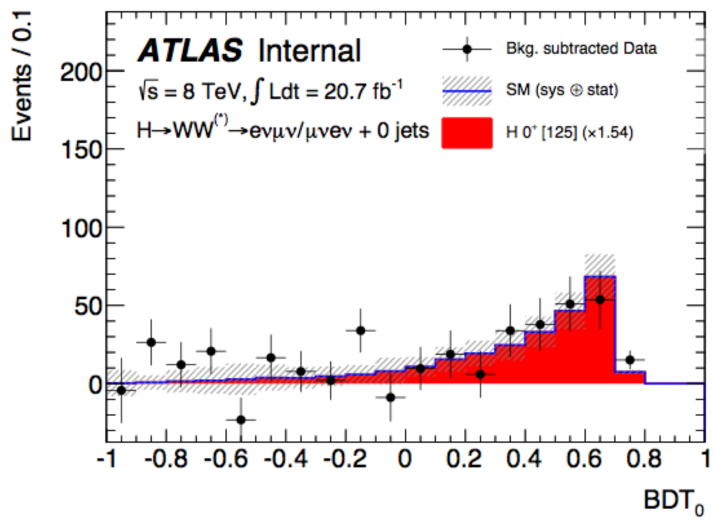


$H \rightarrow ZZ$ Spin and Parity analyses

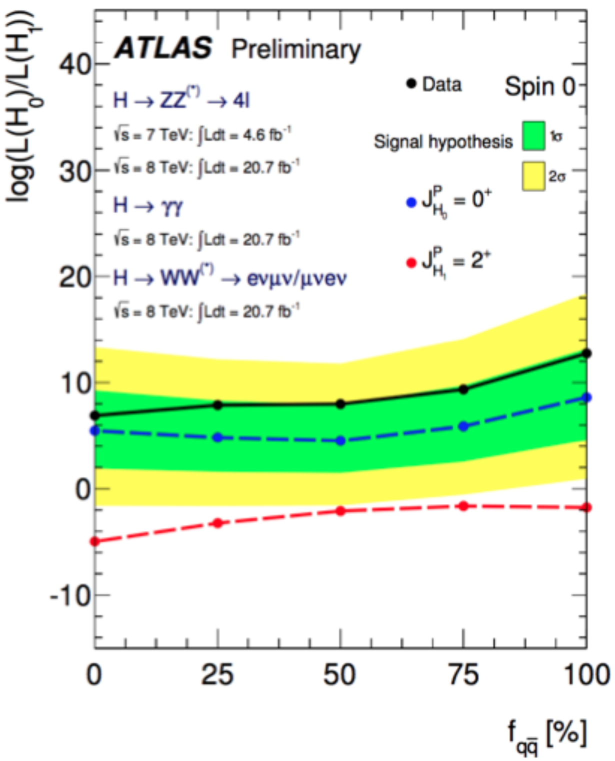
- Use production and decay angles as well as Z_1 and Z_2 masses with ME and BDT approaches.
- Probes 0^- , 1^+, 1^-, and spin-2 hypotheses as WW and $\gamma\gamma$
- Not very sensitive for spin

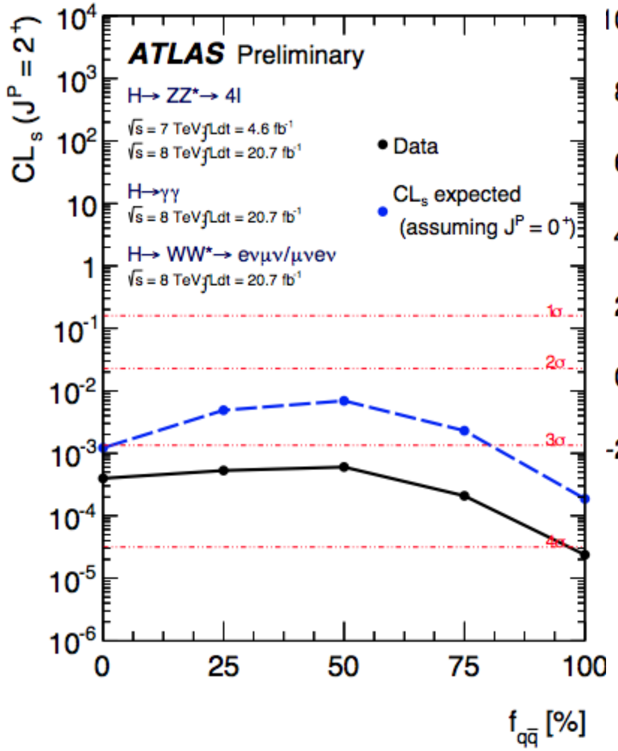
$H \rightarrow WW$ Spin analysis

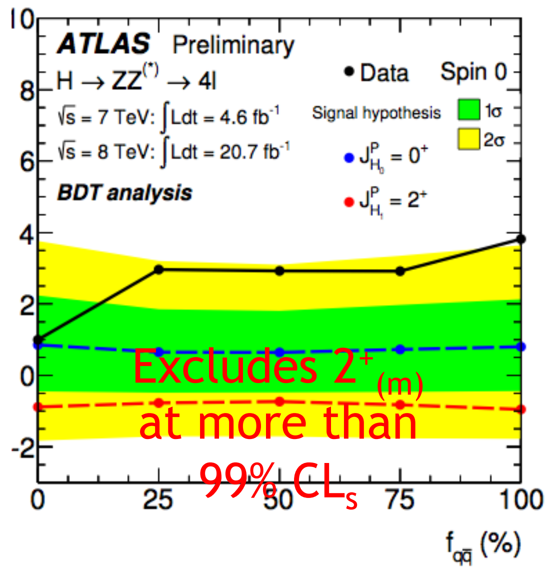
- Use Spin correlation (from V-A W decays) and a BDT analysis using all kinematic variables probing the same hypotheses as $H \rightarrow \gamma\gamma$ analysis.
- Analysis done inclusively with very different preselection cuts.



Spin Combination







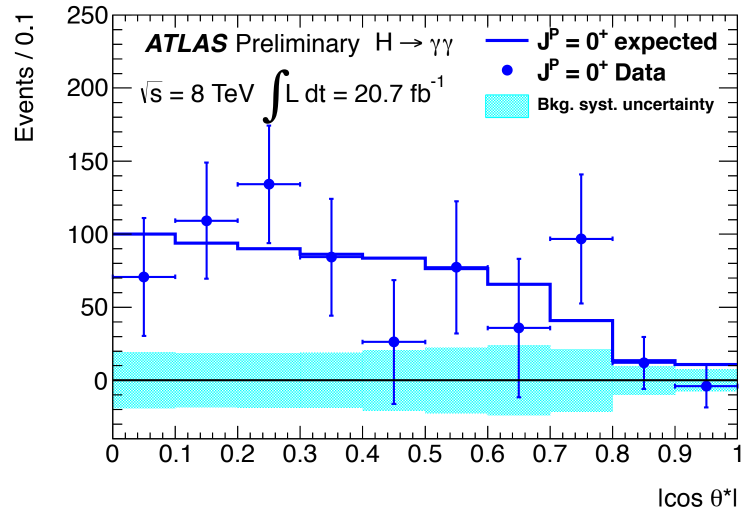
Excludes $2^+_{(m)}$ at more than 99% CL_s

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^+

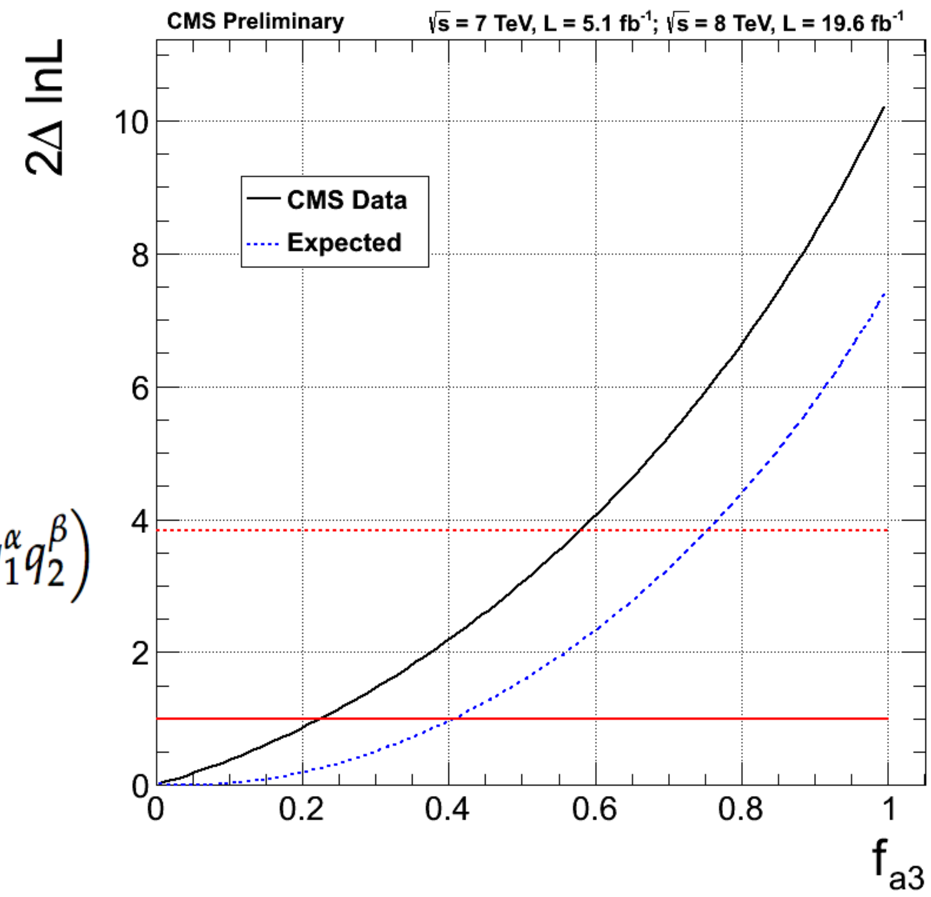
- No VH or VBF threshold distribution analysis yet at LHC.



CP Mixing

Our efforts now oriented towards CP-violating terms f_{a3} first results from CMS

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$$



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Implications (G. Altarelli Nobel Lectures)

The minimal SM Higgs: what was considered just as a toy model, a temporary addendum to the gauge part of the SM, is now promoted to the real thing.

The only known example in physics of a fundamental, weakly coupled, scalar boson with VEV

A death blow not only to Higgsless models, technicolor models.... but also a threat to all models with no fast enough decoupling

[If new physics comes in a model with decoupling the absence of new particles at the LHC implies small corrections to the H couplings]

The absence of accompanying new physics puts the issue of the relevance of naturalness at the forefront

Open questions

Is the SM really minimal?

Is it really fundamental?

Is there a reason why is μ^2 should be negative?

What could explain the flavor mass hierarchy?

Is the mechanism responsible for the mass of gauge boson also responsible for fermion masses ?

What is dark matter made of? Does it (how) to the Higgs boson?

…by the way…

Knowing the Higgs mass…

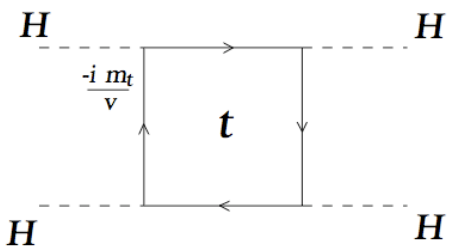
$$\lambda = 0.126$$

Running Quartic Coupling : Vacuum stability

Looking closer into the limit where the Higgs boson mass is small :

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :



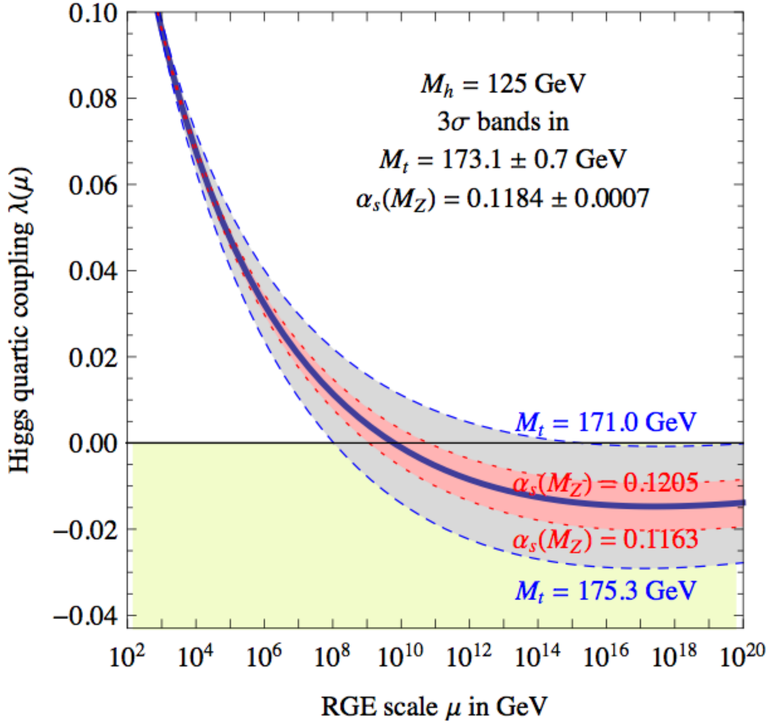
$\sim \frac{m_t^4}{v^4}$

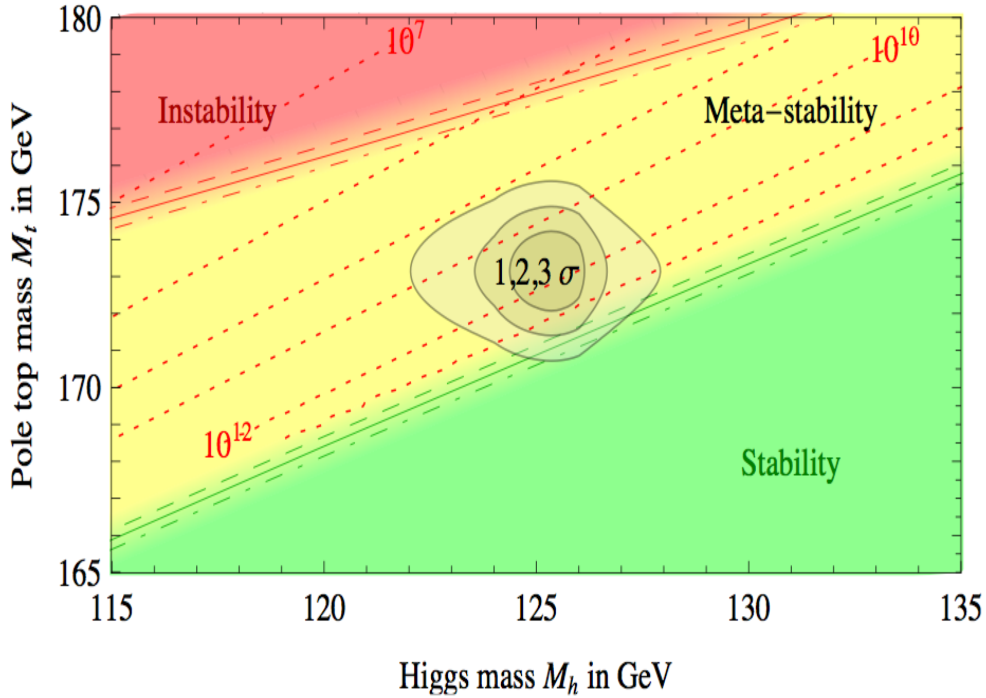
The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$

Requiring that the solutions are stable (non-negative quartic coupling) :

$\lambda(\Lambda) > 0$ then $$\boxed{M_H^2 > \frac{3v^2}{2\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)}$$

Running of the Quartic Coupling, Metastability





$\lambda \sim 0$
(at the high scale)

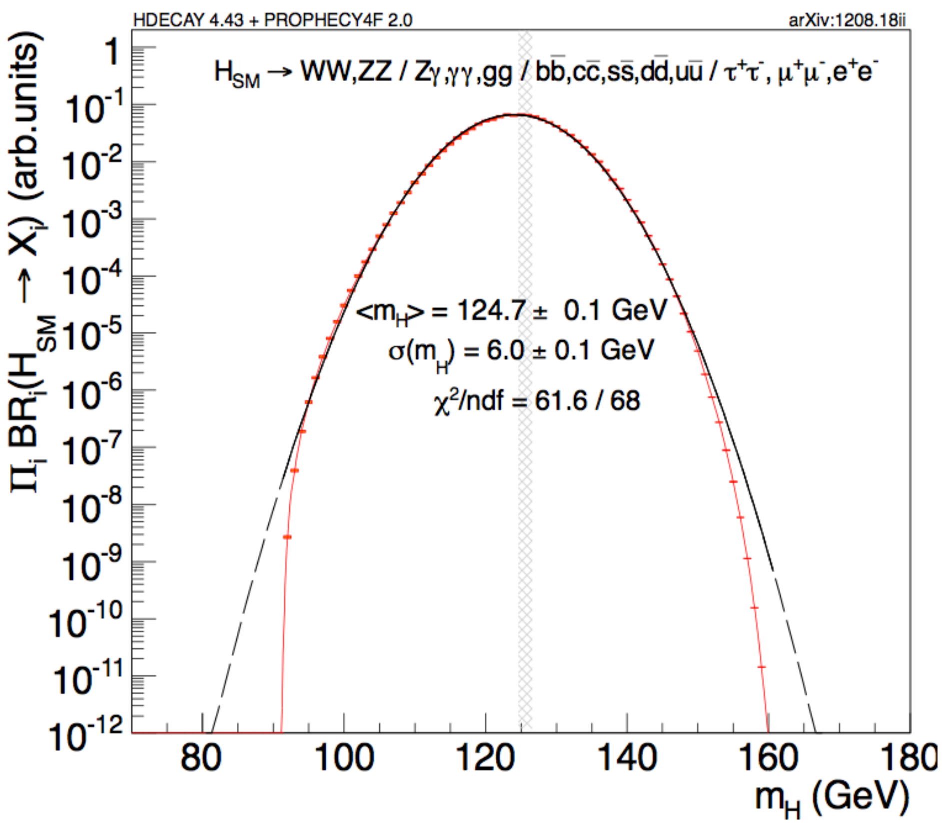
Large dependence on top mass and of course Higgs boson mass

Intriguing/Amusing Coincidences (?)

- $m_H = (m_W + m_W + m_Z)/2 = 126.0$ GeV (http://arxiv.org/abs/0912.5189)

- $m_H^2 = m_Z \times m_t \Rightarrow m_H = 125.8$ GeV (http://arxiv.org/pdf/1209.0474.pdf)

- Π BR peak at mH =124.7 GeV (http://arxiv.org/pdf/1208.1993.pdf)



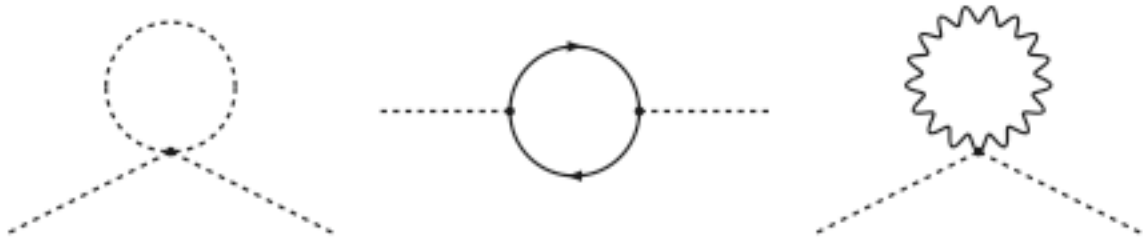
Gauge Hierarchy and Fine Tuning

How the Higgs boson may not only SOLVE problems

The Hierarchy Problem

The Higgs potential is fully renormalizable, but…

Loop corrections to the Higgs boson mass…



…are quadratically divergent : $$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

If the scale at which the standard model breaks down is large, the Higgs natural mass should be of the order of the cut-off. e.g. the Planck scale

$m = m_0 + \Delta m + \ldots$ Higher orders

…but if the Higgs boson exists it should have a low mass!

This can be achieved by fine tuning our theory… Inelegant…

(note that technicolor models are not concerned by this problem)

Supersymmetry

The Hierarchy problem is not only a problem of esthetics : If the difference is imposed at tree level, the radiative corrections will still mix the scales and destabilize the theory.

One may note that :

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + ...)$$ → Contribution of fermions

$$\Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2}(\Lambda^2 + 2m_f^2 \ln\frac{\Lambda}{m_s} + ...)$$ → Contribution of scalars

Therefore in a theory where for each fermion there are two scalar fields with

$$\lambda_s = |\lambda_f|^2$$

(which is fulfilled if the scalars have the same couplings as the fermions) quadratic divergencies will cancel

The field content of the standard model is not sufficient to fulfill this condition

A solution is given by supersymmetry where each fermionic degree of freedom has a symmetrical bosonic correspondence

In supersymmetry the quadratic divergences naturally disappear but…

Immediately a problem occurs : Supersymmetry imposes $m_{boson} = m_{fermion}$

Supersymmetry must be broken!

But in the case of SUSY a SSB mechanism is far more complex than for the EWSB and no satisfactory SSB solution exists at this time…

…However an explicit breaking "by hand" is possible provided that it is softly done in order to preserves the SUSY good UV behavior…

$$\Delta m_H^2 \propto m_{soft}^2 (\ln \frac{\Lambda}{m_{soft}} + ...)$$

Interestingly similar relation to that of the general fine tuning one

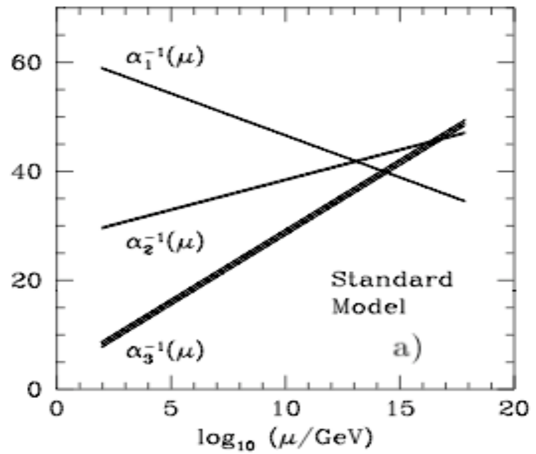
Implies that the m_{soft} should not exceed a few TeV

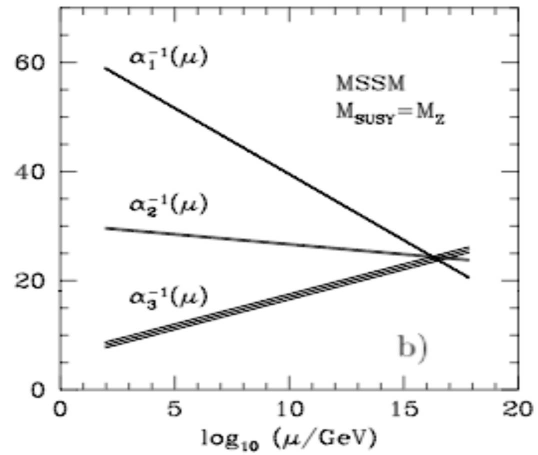
The Minimal Supersymmetric Standard Model's Higgs Sector

In a tiny nut shell

Additional motivations for supersymmetry :

- Allows the unification of couplings
- Local SUSY: spin 3/2 gravitino (essential ingredient in strings)
- Natural candidate for Dark Matter





The Higgs Sector : Two doubets with opposite hypercharges are needed to cancel anomalies (and to give masses independently to different isospin fermions)

- MSSM : 5 Higgs bosons
- Lightest mass < m_z at tree level and smaller than ~130 GeV/c^2 w/ rad. Corr.

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Experimental Indirect Constraints : Electroweak Precision Data and the Higgs Mass

The standard model has 3 free parameters not counting the Higgs mass and the fermion masses and couplings.

Particularly useful set is :

1.- The fine structure constant : $\alpha = 1/137.035999679(94)$ 10^{-9}

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

2.- The Fermi constant : $G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$ 10^{-5}

Determined from muon lifetime

3.- The Z mass : $M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$ 10^{-5}

Measured from the Z lineshape scan at LEP

Experimental Constraint : Electroweak Precision Data and the Higgs Mass

Taking the hypothesis of a Minimal Standard Model, the radiative corrections to numerous observables can be computed in order to assess the impact of certain particles e.g. the Higgs boson

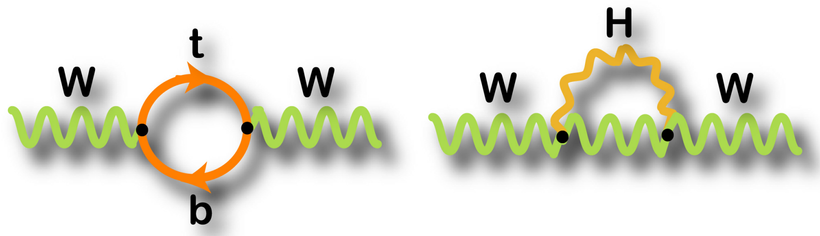
From the measurement of these observables a constraint is derived

For example the corrections to the Fermi coupling constant can be written as :

$$G_F = \frac{\pi \alpha_{QED}}{\sqrt{2} m_W^2 (1 - m_W^2/m_Z^2)} (1 + \Delta r)$$

With :

$$\begin{cases} \Delta r_t \propto m_t^2 \\ \underline{\Delta r_H \propto \log(m_H/m_W)} \end{cases}$$



Essential ingredients top, W and Z masses and a_{QED}

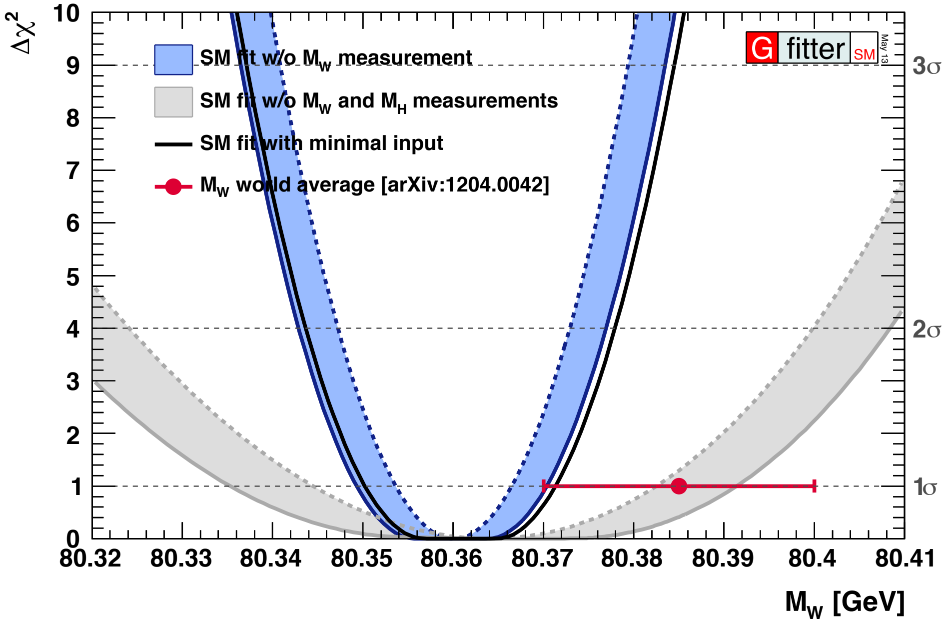
The Complete Data

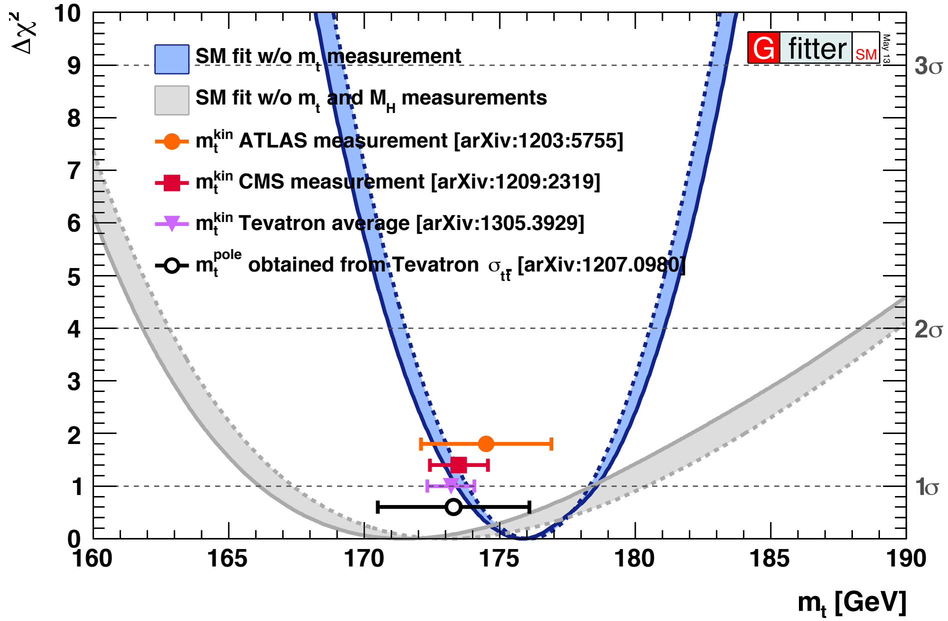
Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^\circ$	125.7 ± 0.4	yes	125.7 ± 0.4	94.1^{+25}_{-22}	94.1^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.380^{+0.011}_{-0.012}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0115
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4953 ± 0.0014	2.4957 ± 0.0015	2.4949 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.480 ± 0.014	41.479 ± 0.014	41.472 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.739 ± 0.017	20.741 ± 0.017	20.713 ± 0.026
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	$0.01627^{+0.0001}_{-0.0002}$	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	$0.1477^{+0.0009}_{-0.0008}$	–
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6681^{+0.00021}_{-0.00042}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93468^{+0.00008}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	$0.0740^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	$0.1036^{+0.0007}_{-0.0006}$	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17222^{+0.00006}_{-0.00005}$	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21491 ± 0.00005	0.21492 ± 0.00005	0.21490 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.49 ± 0.82	173.17 ± 0.86	$175.83^{+2.74}_{-2.42}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M^2_Z)$ $^{(\dagger\triangle)}$	2756 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	$0.1188^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1188 ± 0.0027
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	–
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-1.4	4.7	–

$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

- Numerous observables O(40)
- Numerous experiments (with different systematics)
- Within experiments numerous analyses (with different systematics)
- Various theoretical inputs

W and Top quark mass measurements





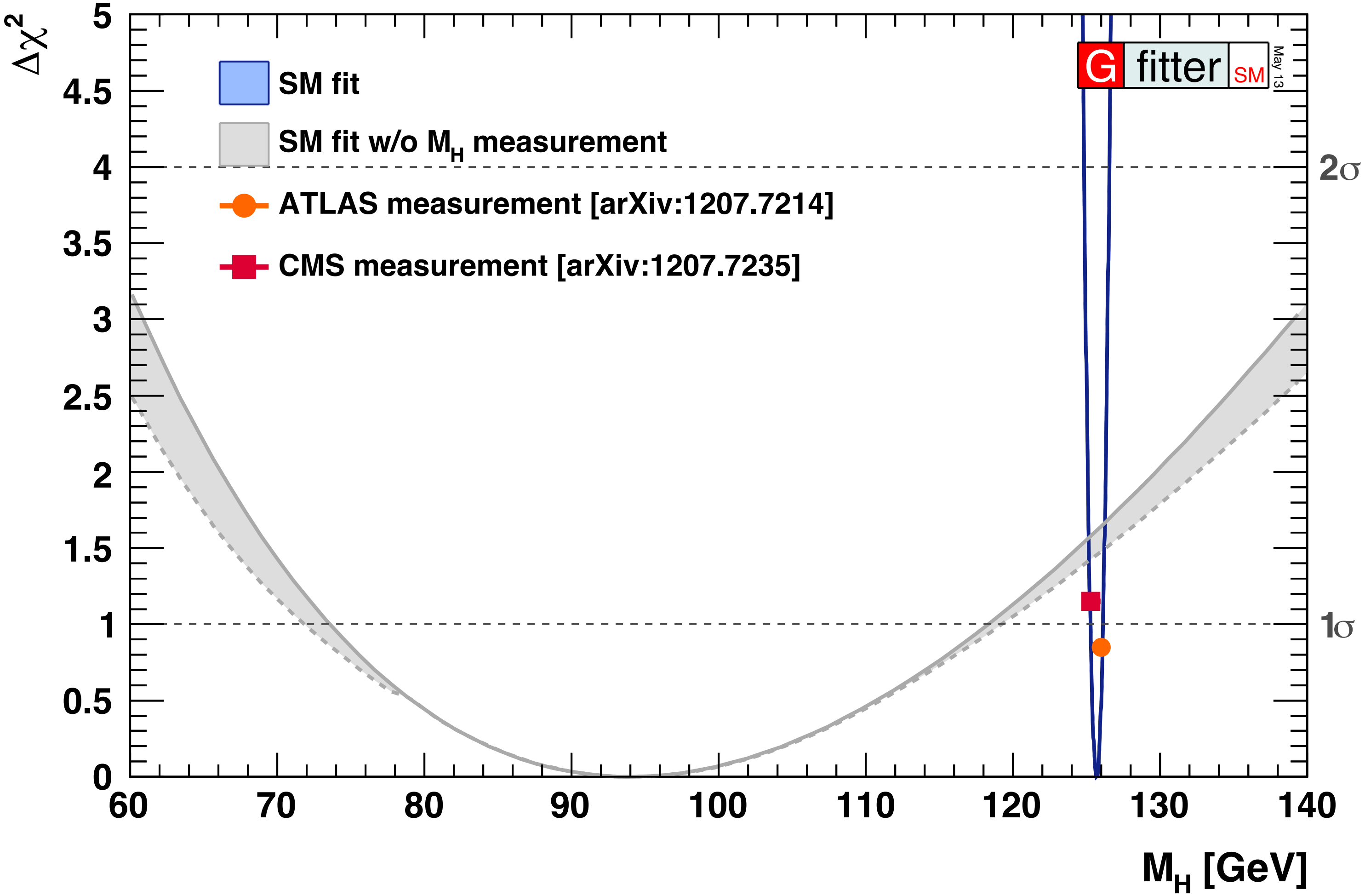
Precision of ~0.02%

- TeVatron reached ~15 MeV
- LHC should reach ~15 MeV or better

Precision of ~0.8%

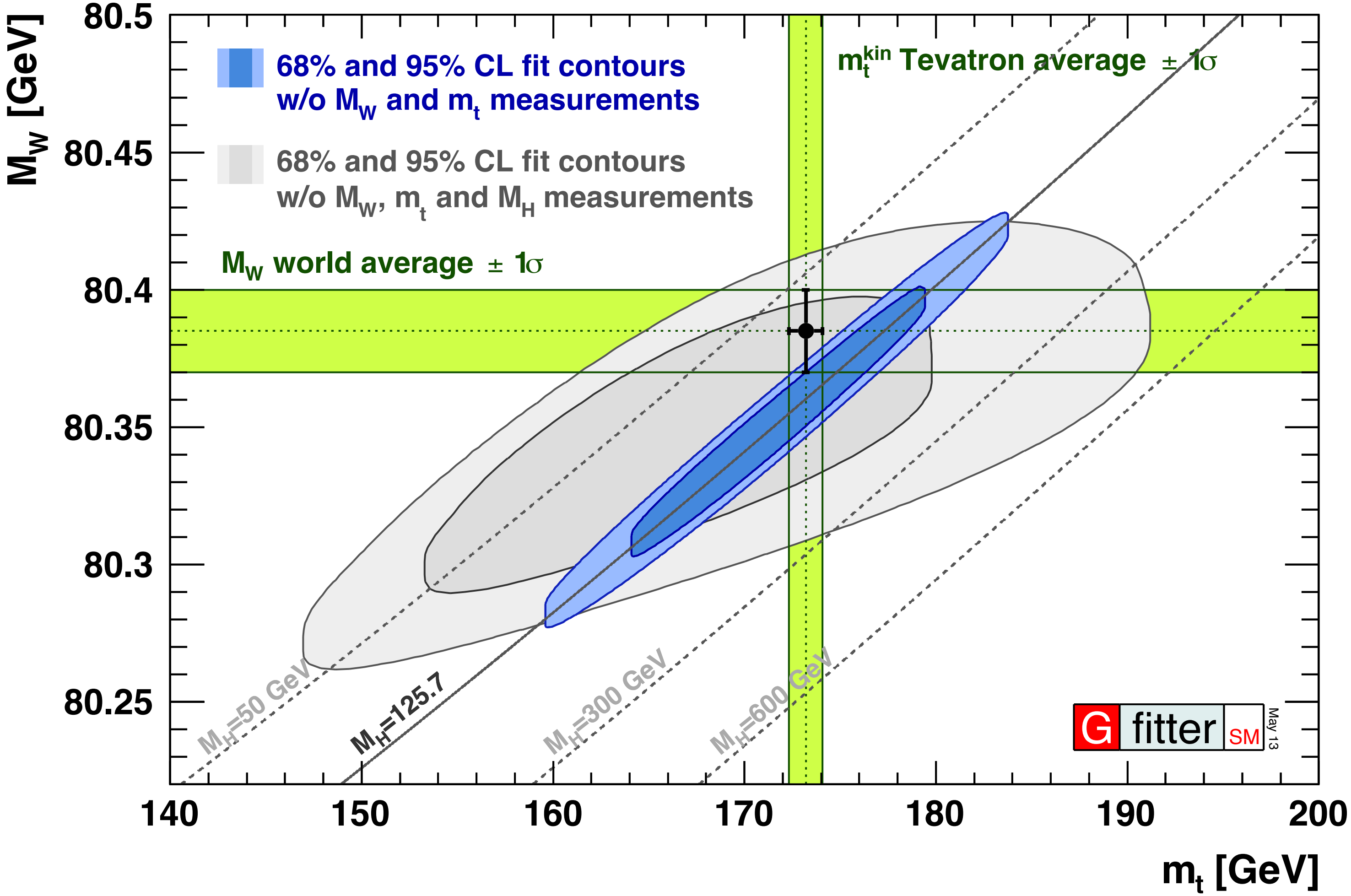
- TeVatron is aiming at ~ 0.9 GeV
- Not so clear that LHC will be able to do much better.

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

Indirect Measurement of Higgs Boson Mass



M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$

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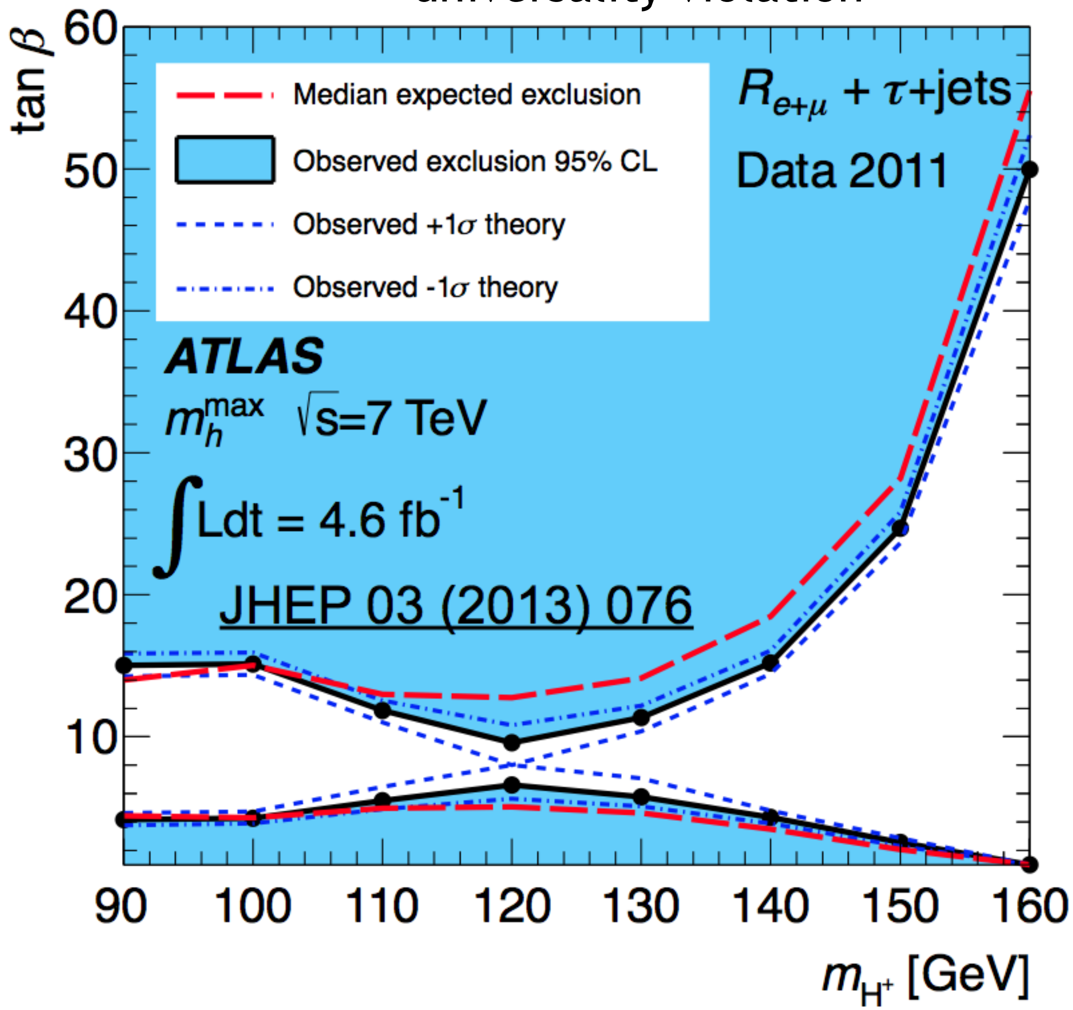
Overview of BSM Channels (I)

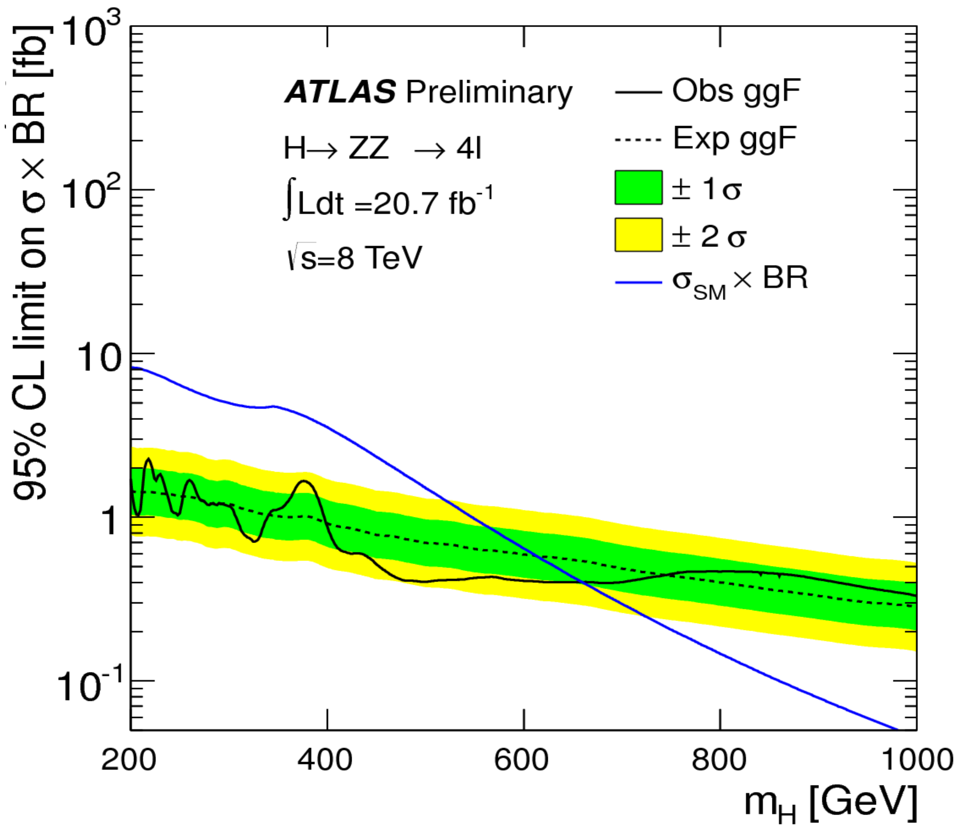
- Charged Higgs
  - Main current analysis $H^{\pm}$ to $\tau\nu$
  - $H^{\pm}$ to cs
  - High mass specific $H^{\pm}$ to AW
  - High mass specific $H^{\pm}$ to tb
- MSSM h, H, and A
  - Main current analysis $\tau\tau$
  - Also searched for in $\mu\mu$
  - Also searched for in bb(b)
  - New open channel 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

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Higgs width determination

- Direct measurement will only be possible at muon collider… what can be done at the LHC?

- Direct measurement at LHC from the Higgs lineshape in diphoton and 4l will be limited by systematics and in particular the modeling of the resolution systematic uncertainties (See CMS result)

- Direct measurement through decay length in the 4l channel has also very limited sensitivity.

- Very indirect estimates through coupling fit (with various assumptions)

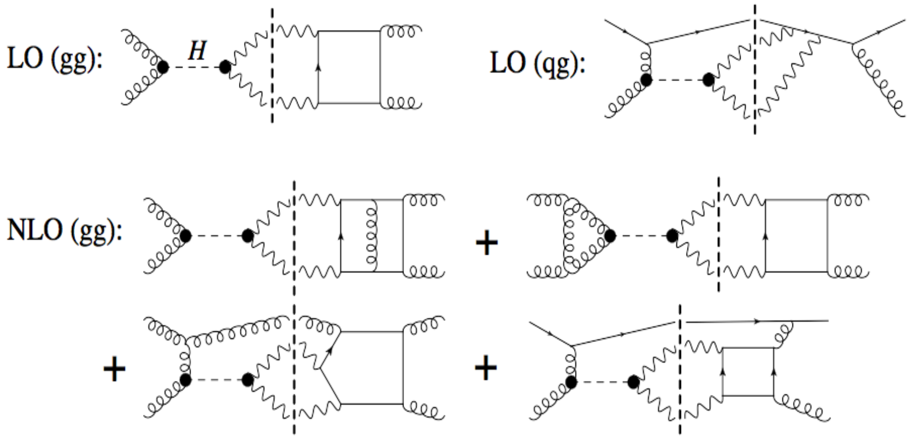
- New trends in trying to constrain the Higgs width (still indirect, but little to no assumptions):

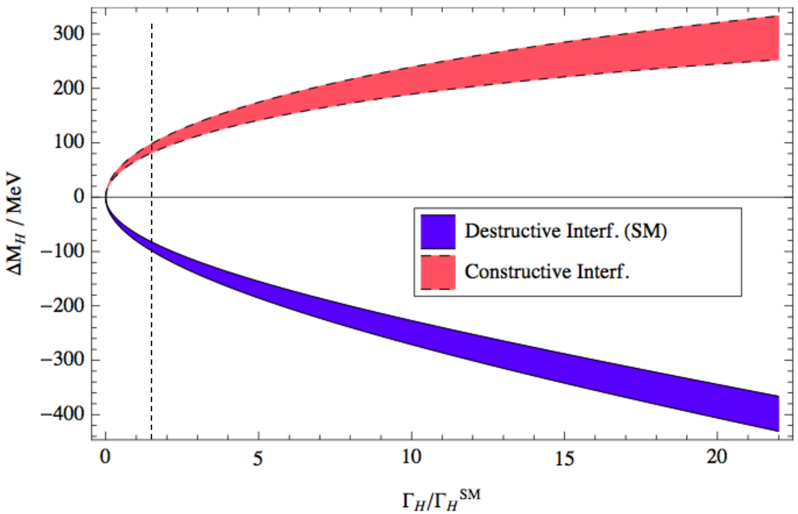
    - Width through mass differences

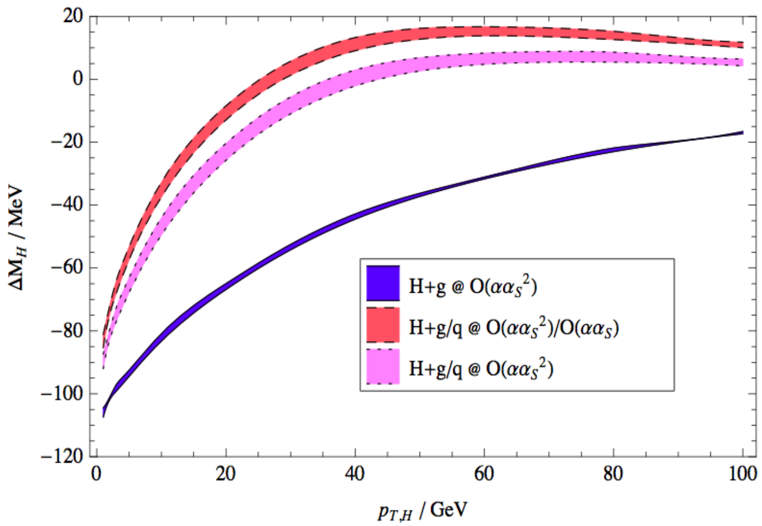
    - Width through precise high mass VV cross section measurements

Interferometry and mass shift

- Adding detector resolution effects, mass shift induced: ~70 MeV at NLO
- Interference dependent on Γ_H → measure of the shift could allow to bound the width.
- Measurement of the shift can be done:
  - by comparing the masses in H→ZZ and H→γγ
  - by exploiting dependence with Higgs boson pT







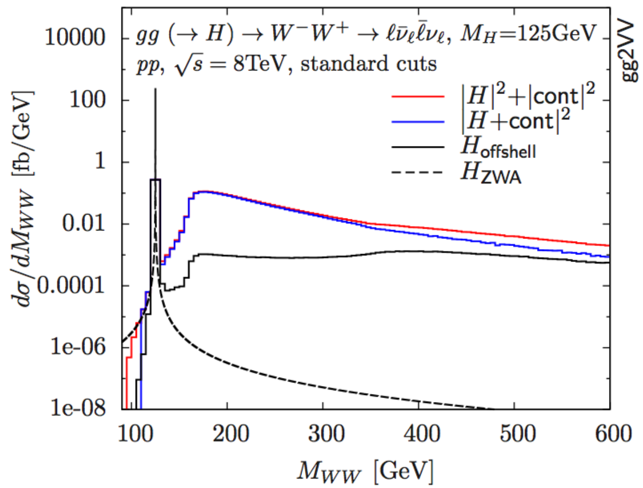
Lance J. Dixon and Ye Li.. Submitted to Phys. Rev. Lett., 2013

ZZ High Mass cross section

(From N. Kauer)

- Off shell
- Interference in the high mass range

$gg \to H \to WW \to \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$



Standard cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV, $M_{\ell\ell} > 12$ GeV

First study by Fabrizio Caola, Kirill Melnikov (arXiv:1307.4935) for $M_H = 126$ GeV using CMS data (LHC7: 5.1fb^{-1}, LHC8: 19.6fb^{-1}) and gg2VV (NK)

Signal process: $pp \to H \to ZZ \to 2e2\mu, 4e, 4\mu$

resonance contribution to signal cross section ("on-peak")): $M_{ZZ} < 130$ GeV
off-resonance contribution to signal cross section ("off-peak"): $M_{ZZ} > 130$ GeV

Energy	$\sigma^{\text{H}}_{\text{on-peak}}$	$\sigma^{H}_{\text{off-peak}}$	$\sigma^{\text{interference}}_{\text{off-peak}}$
7 TeV	0.203	0.044 (21%)	−0.108
8 TeV	0.255	0.061 (24%)	−0.166
$N^{\text{SM}}_{2e2\mu}$	9.8 (CMS)	1.73	−4.6
$N^{\text{SM}}_{2e2\mu+4e+4\mu}$	21.1 (CMS)	3.72	−9.91

ZZ High Mass cross section

(From N. Kauer)

rescale Higgs couplings and Higgs width keeping σ_{peak} fixed to SM

$$N_{4l}^{\text{off}} = 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}$$

CMS in $pp \to ZZ \to 4\ell$: 451 evts observed, 432 ± 31 evts expected (on-peak only/ZWA)

expected total number of events with rescaled Higgs couplings/width:

$$N_{\text{exp}} = 432 + 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}} \pm 31$$

95% CL (2σ) upper limit: $\Gamma_H \leq 38.8\,\Gamma_H^{\text{SM}} \approx 163$ MeV

(Caola and Melnikov)

Ultimately (assuming 3% uncertainty) the limit ~20-40 MeV

Menu “A la Carte…”

1.- Historical context

2.- Brief History of the Discovery

3.- How to read an exclusion or significance plot?

4.- Overview of channels and their results

5.- Couplings analysis

6.- Main quantum numbers

7.- Implications (Vacuum stability, SUSY)

8.- Electroweak precision data

9.- Searches for BSM Higgs (concise review)

10.- Total width through interferometry

11.- Future projects

Future Prospects

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

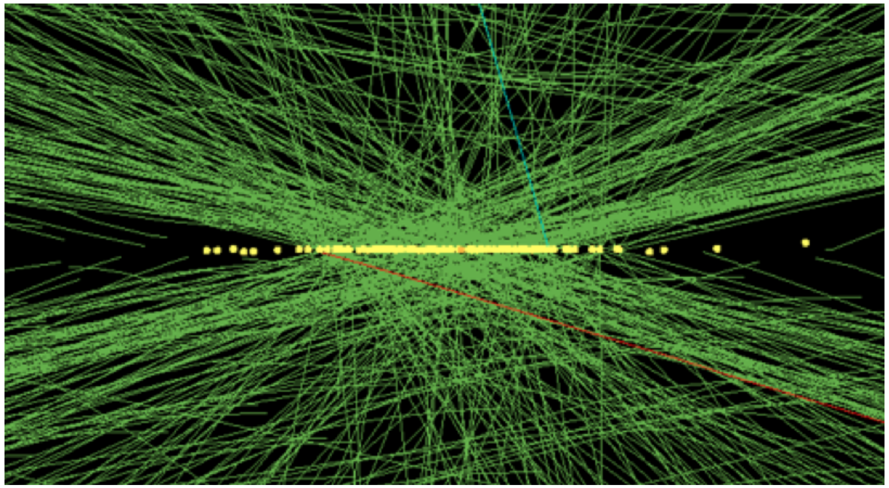
~2030

HL-LHC Beam Parameters

Two HL-LHC scenarios

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

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 ($cm^{-2}s^{-1}$)	$\sim 7 \times 10^{33}$	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260



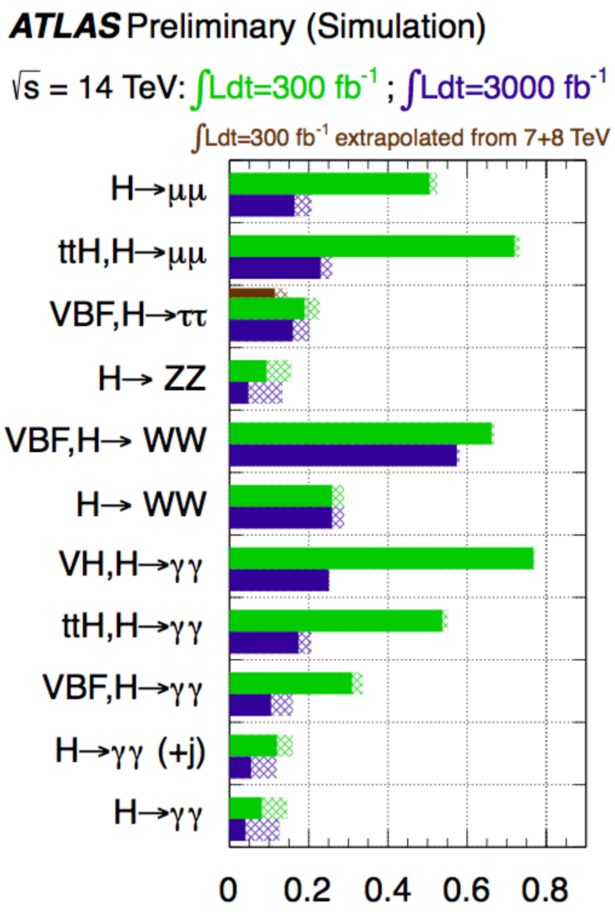
Pile up is a crucial issue!

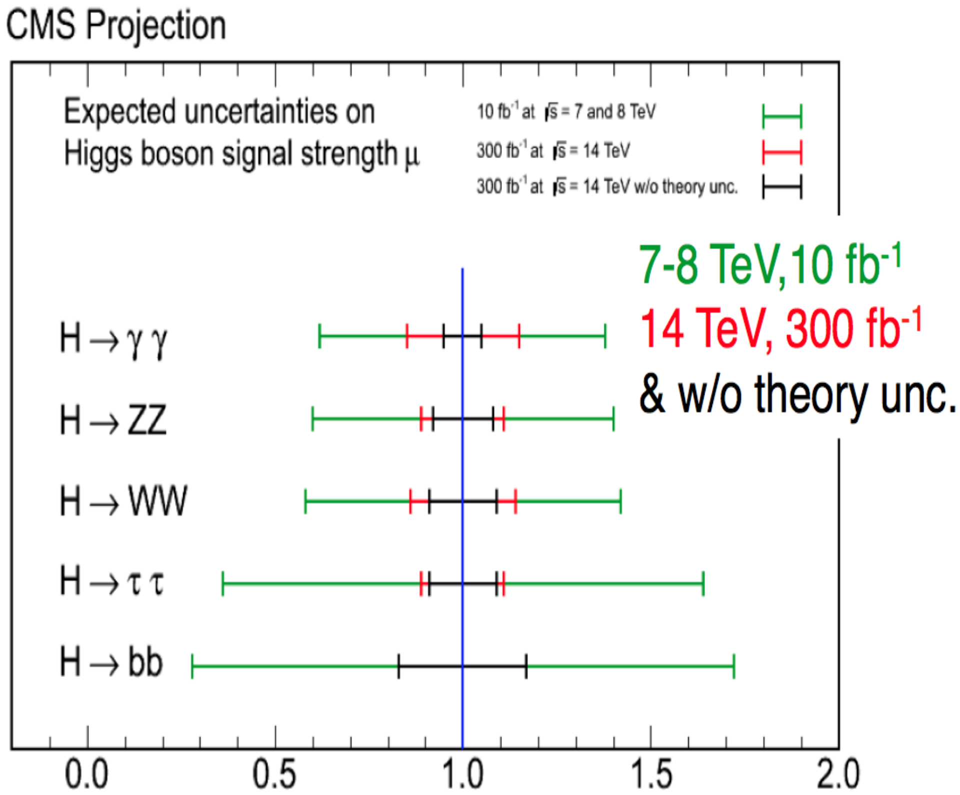
CMS event with 78 reconstructed vertices

ATLAS Higgs Physics Program: Main Couplings

Couplings Projections Only a sample of analyses

Uncertainty on signal strengths



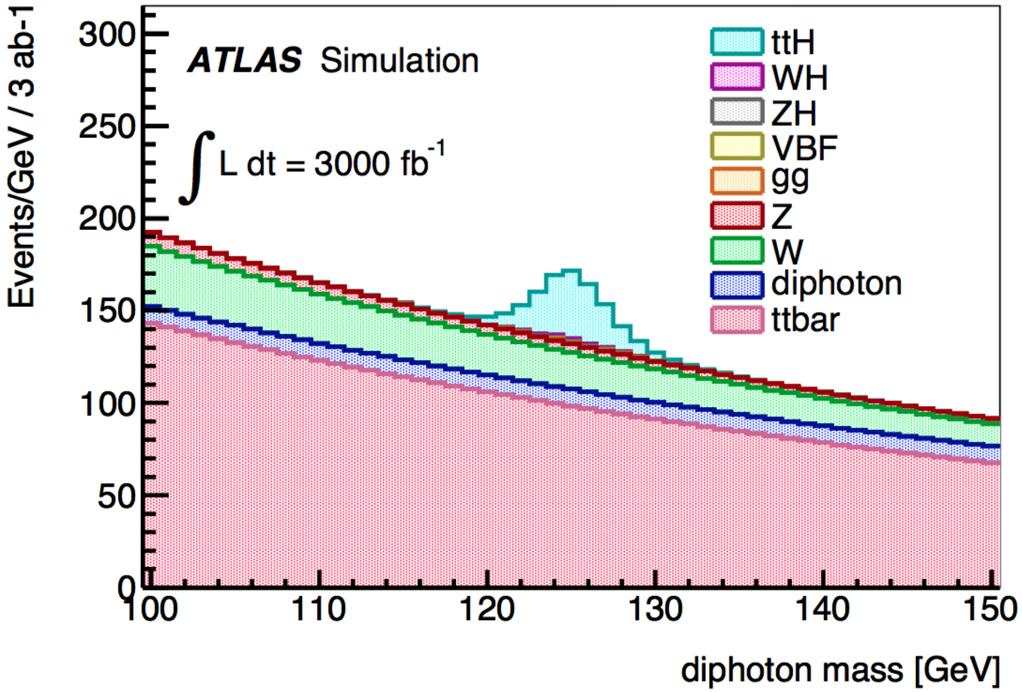


Only indirect (however not negligible) constraint on the total width

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

Reaching ttH Production in (robust) rare modes

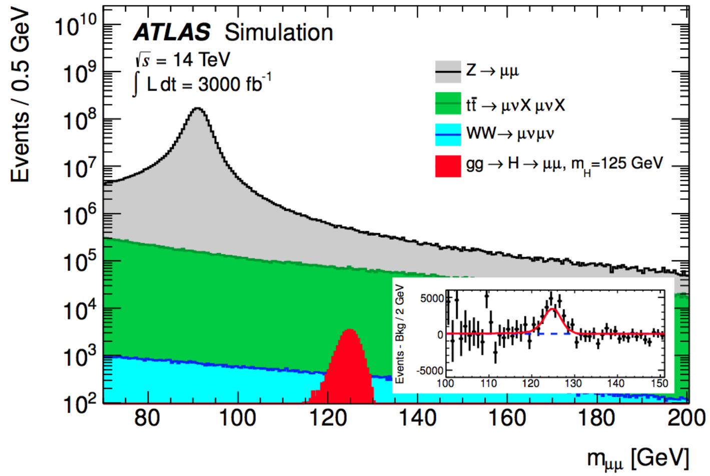
Analyses not relying on more intricate decay channels (bb, tt and WW)



- $\gamma\gamma$ 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



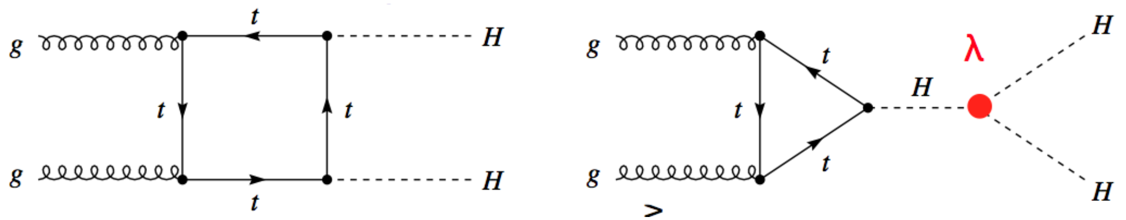
Self Couplings

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

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

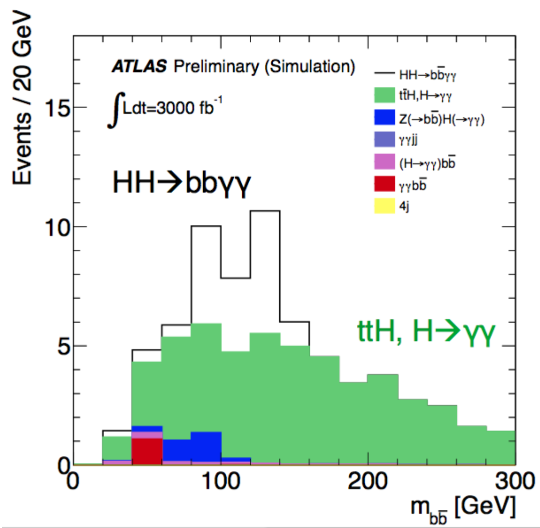
λ_4 : hopeless in any planed experiment (?)

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



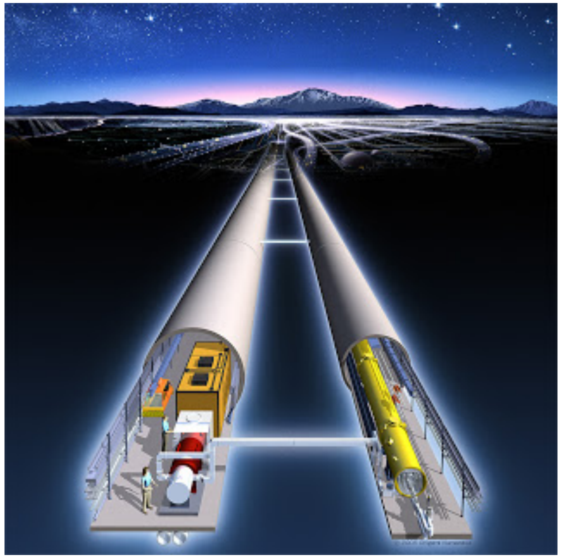
… but some hope, in (rather) robust
$pp \to HH \to bb\gamma\gamma$
(S ~ 15, B ~ 21 for 3 ab^{-1} and some faith…) $bb\tau^+\tau^-$
(under study)

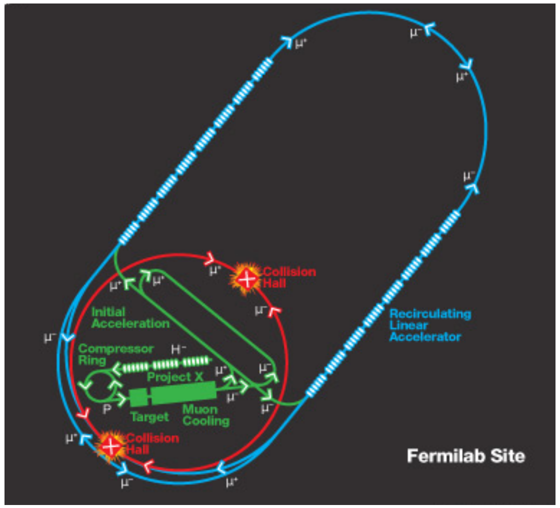
~3 standard deviations expected on λ_3 with 3 ab^{-1}



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

- Higher COM with CLIC
- 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

- Need to probe further the properties of H^0
- Use H^0 to probe new physics beyond the SM
- Very important: search for new states of the EWSB sector

The LHC Higgs physics program is very rich and exciting…

Join us !

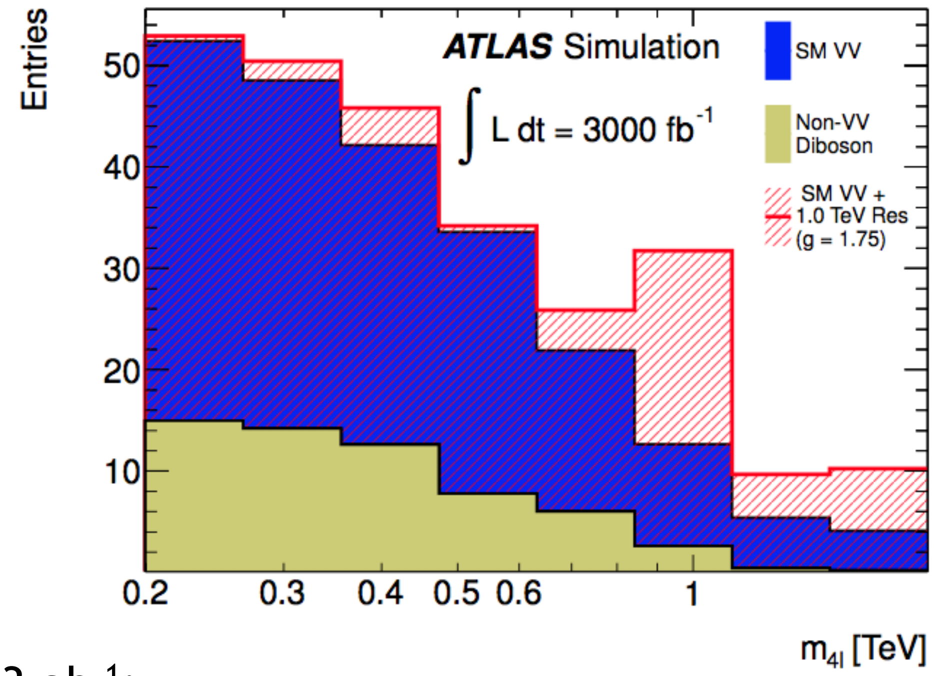
Backup Slides

Completing the Picture WBS

Weak Boson Scattering

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

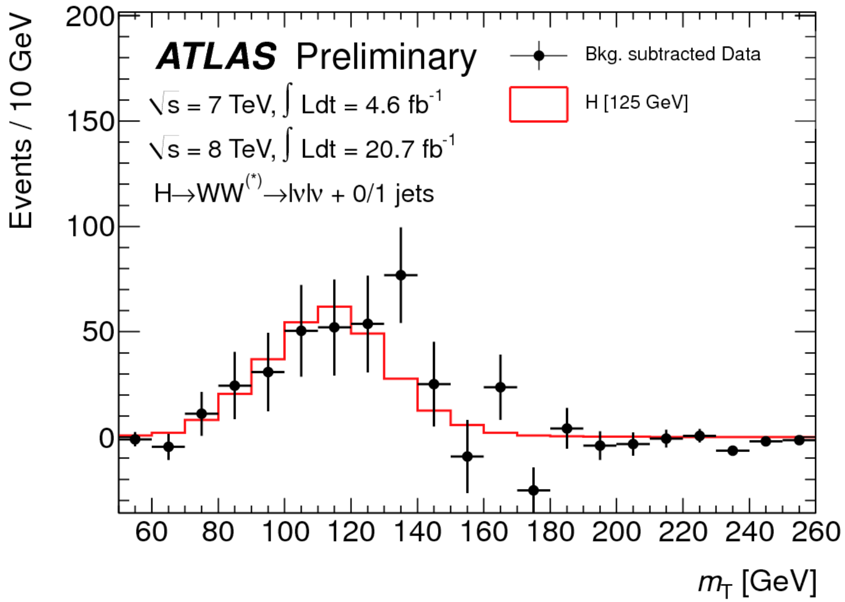
Very clean signature for a TeV resonance (in anomalous WBS models)



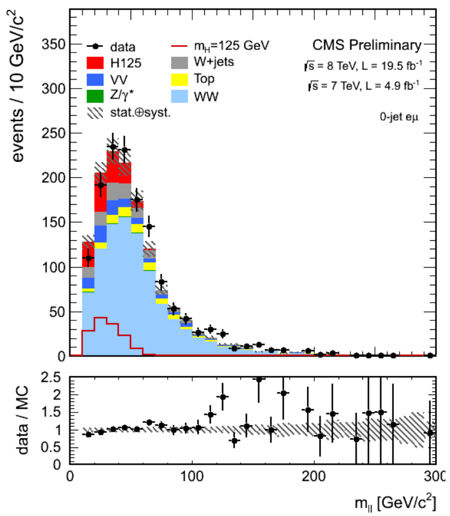
Sensitivities for 300 fb^{-1} and 3 ab^{-1}:

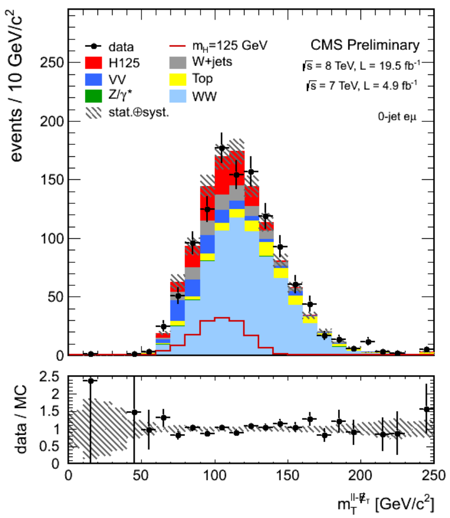
Model (anomalous WBS)	300 fb^{-1}	3 ab^{-1}
500 GeV and g=1	2.4 σ	7.5 σ
1 TeV and g=1.75	1.7 σ	5.5 σ
1 TeV and g=2.5	3.0 σ	9.4 σ

$H \rightarrow WW^{*} \rightarrow \ell^{+}\upsilon\ell^{-}\upsilon$



- 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)





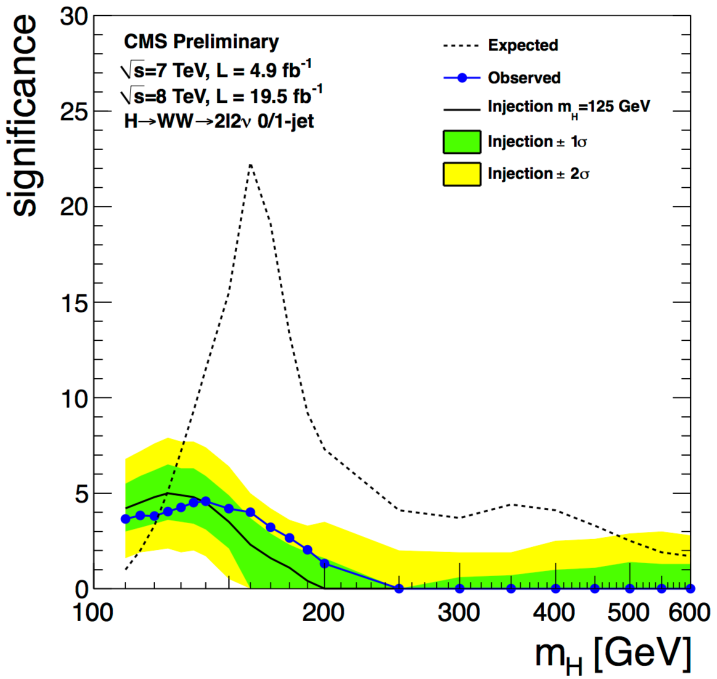
- Analysis features to note (m_H=125):
  - Fair S/B
  - Fair signal event yield (200 events)
  - Poor mass resolution ≈20%

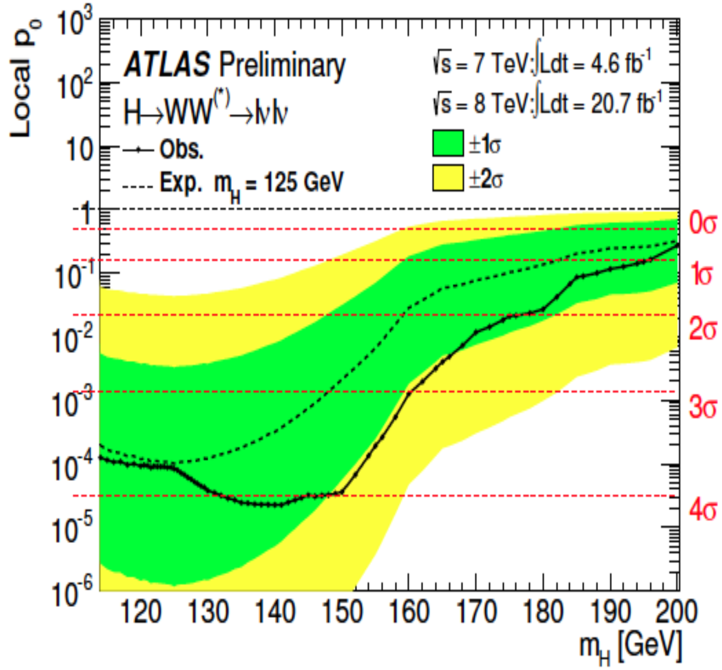
- New:
  - CMS: Associated production VH update with hadronic V (combined sensitivity 3.5-4 SM) CMS-PAS-HIG-12-017
  - ATLAS: Update for publication HIGG-2013-02

Background Uncertainties Digression

TH uncertainty on the WW background kinematics

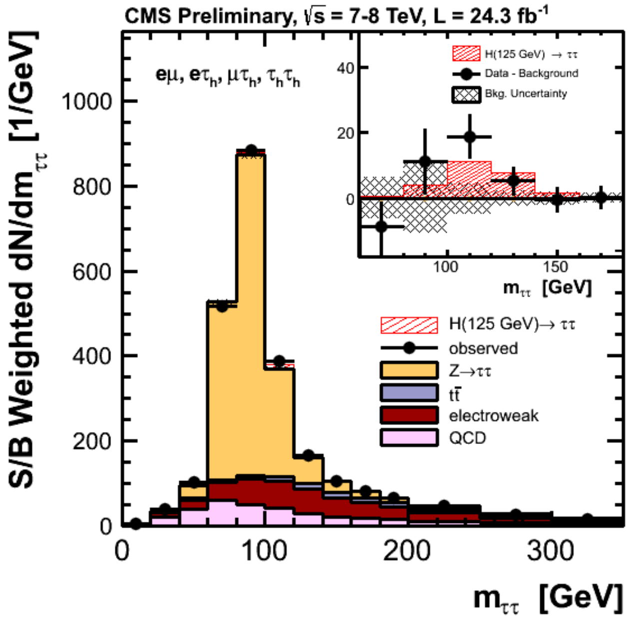
$$\mu_{obs} = 1.01 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{theo. syst.}) \pm 0.12\,(\text{expt. syst.}) \pm 0.04\,(\text{lumi.})$$
$$= 1.01 \pm 0.31.$$

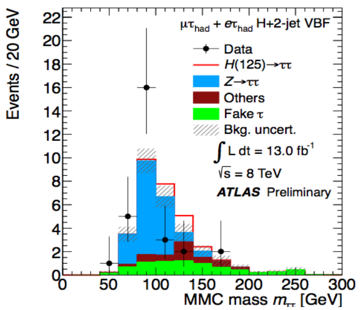


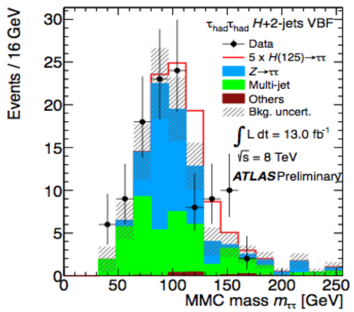


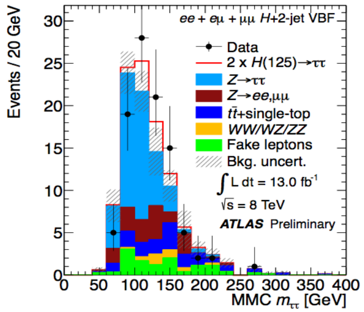
NNLO calculation underway

$H \rightarrow \tau^+\tau^-$









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:

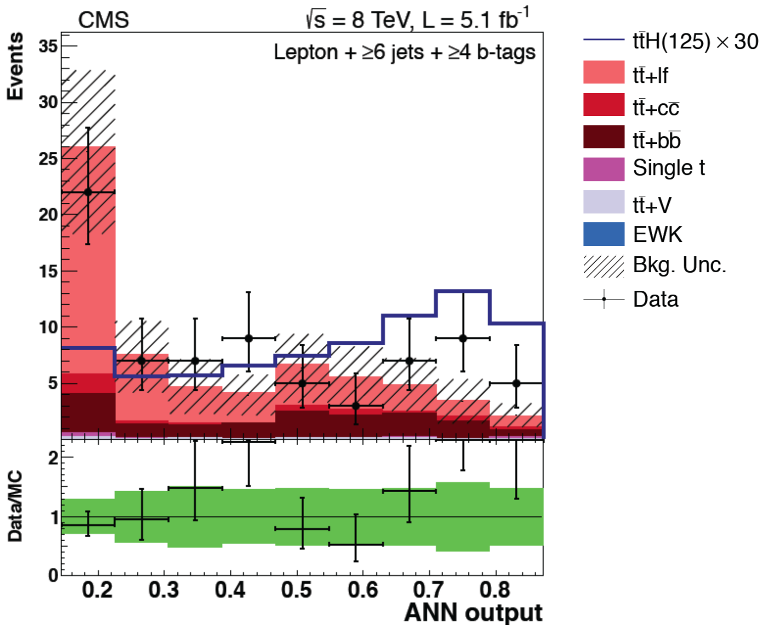
- **2-jets (VBF-tag)**: best S/B-ratio
- **2-jets (VH-tag)**: best S/B-ratio
- **VH Lepton tag**
- **1-jet (ggF, VH)**: acceptable S/B-ratio
- untagged: control region (S/B≅0)

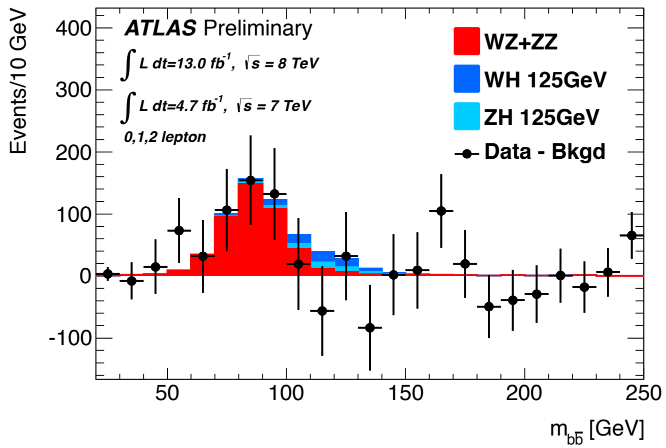
- Split 1-jet events further high/low p_T tau
  - different S/B rates
- Backgrounds:
  - $Z\rightarrow\tau\tau$: $Z\rightarrow\mu\mu$ (data) with embedding
  - $Z\rightarrow ee$, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

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

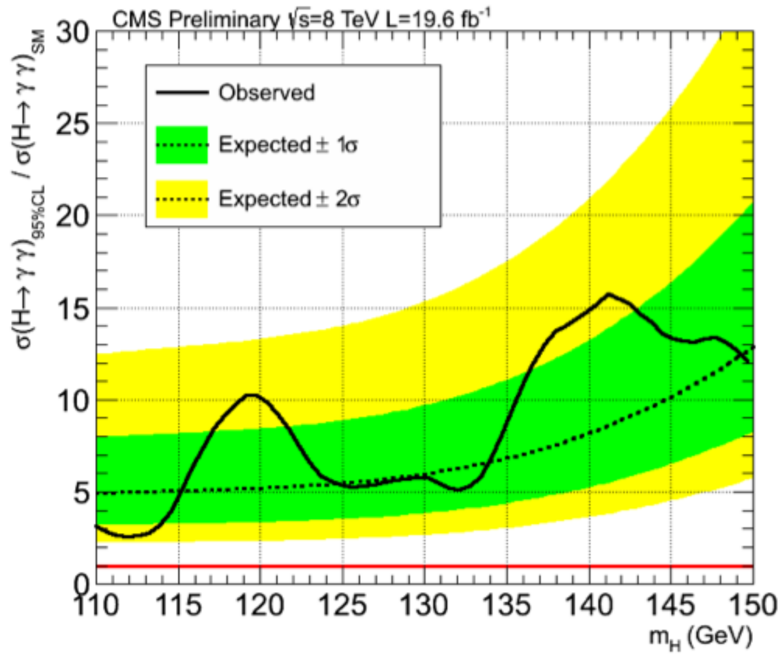
Key Analysis features:

- 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

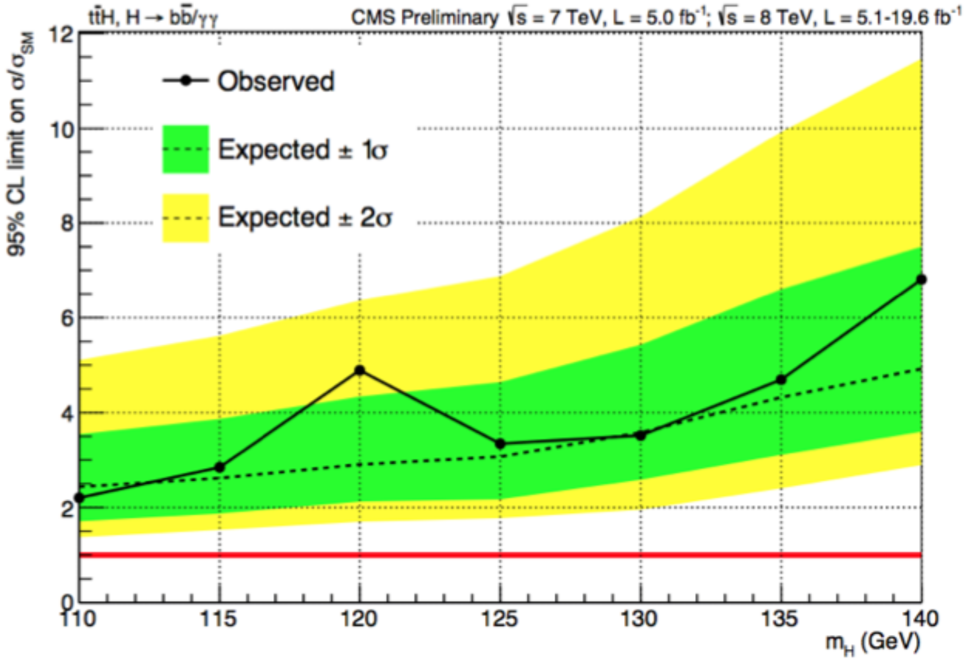
$H \rightarrow \gamma\gamma$



Key Features:

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

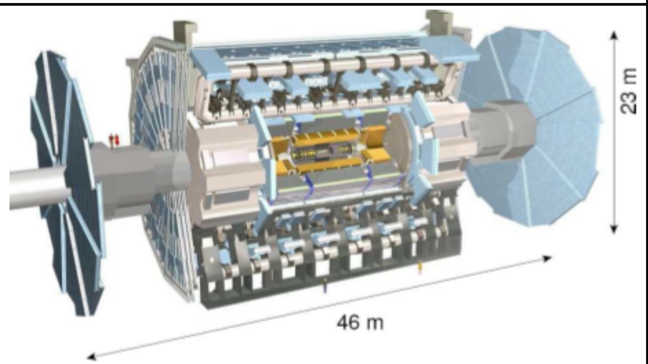
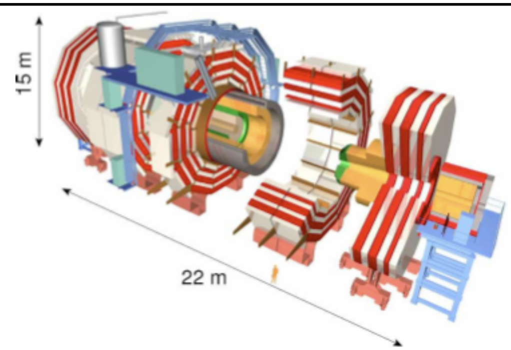
$H \rightarrow bb$



Key Features:

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

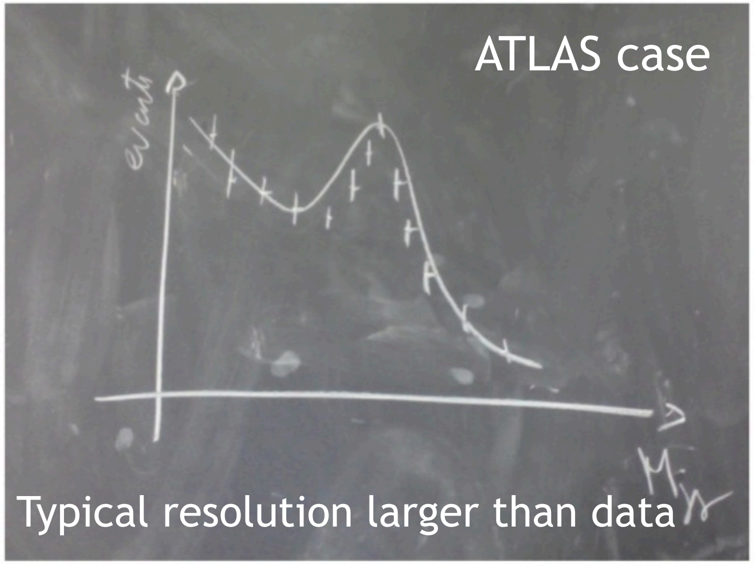
The ATLAS and CMS Detectors In a Nutshell

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 $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
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)

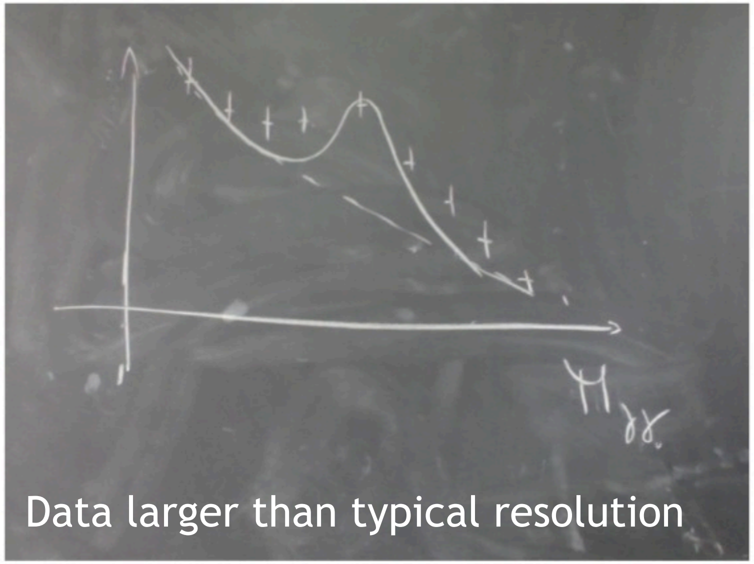
The compatibility in the signal strength parameter between the data and the SM Higgs boson signal plus background hypothesis is estimated with the test statistic $\lambda(\mu)$ with $\mu = 1$ [4], and is found to be at the 2.3 σ level.

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)

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

Additional Slides

The sector of Fermions (Fermionic neutral current)

Taking a closer look at the neutral current interaction part of the Lagrangian :

$$L_L = -\frac{1}{2}\overline{\psi}_L \gamma_\mu \begin{pmatrix} gW_3^\mu + g'Y_L B^\mu & 0 \\ 0 & -gW_3^\mu + g'Y_L B^\mu \end{pmatrix} \psi_L \qquad L_R = -\frac{1}{2}\overline{\psi}_R \gamma_\mu \begin{pmatrix} g'Y_R B^\mu & 0 \\ 0 & 0 \end{pmatrix} \psi_R$$

In the lepton sector :

$$\begin{aligned} -2L_{NC}^{leptons} = {} & \overline{\nu}_L \gamma_\mu \left[(c_W g - s_W g'Y_L) Z^\mu + (s_W g + c_W g'Y_L) A^\mu \right] \nu_L \\ & + \overline{e}_L \left[(-c_W g - s_W g'Y_L) Z^\mu + (-s_W g + c_W g'Y_L) A^\mu \right] e_L \\ & + \overline{e}_R \gamma_\mu \left[-s_W g'Y_R Z^\mu + c_W g'Y_R A^\mu \right] e_R \end{aligned}$$

1.- Eliminate neutrino coupling to the photon : $g \sin\theta_W = -g'Y_L \cos\theta_W$

2.- Same coupling e_R and e_L to the photon : $g'Y_R = 2g'Y_L$

3.- Link to the EM coupling constant *e* : $g \sin\theta_W = e$

Y the hypercharge is chosen to verify the Gell-Mann Nishijima formula : $Q = I_3 + \frac{Y}{2}$

The picture is now almost complete...

	Field	I_3	Y	Q	$SU(2)_L x U(1)_Y$	$SU(3)_C$
Leptons	(ν_L, e_L)	(1/2,-1/2)	-1	(0,-1)	(2,-1)	1
	e_R	0	-2	-1	(1,-2)	1
Quarks	(u_L, d_L)	(1/2,-1/2)	-1	(2/3,-1/3)	(2,1/3)	3
	u_R	0	4/3	2/3	(1,4/3)	$\bar{3}$
	d_R	0	-2/3	-1/3	(1,-2/3)	$\bar{3}$
IVB	B	0	0	-	(1,0)	1
	W	(1,0,-1)	0	-	(3,0)	1
	g	0	0	-	(1,0)	8
Higgs	H	(1/2,-1/2)	1	-	(2,1)	1

The Minimal Standard Model

Jean Iliopoulos

The sector of Fermions (kinematic)

Another important consequence of the Weinberg Salam Model…

A specific $SU(2)_L xU(1)_Y$ problem : $m\overline{\psi}\psi$ manifestly not gauge invariant

$$m\overline{\psi}\psi = m\overline{\psi}(\frac{1}{2}(1-\gamma^5) + \frac{1}{2}(1+\gamma^5))\psi = m(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$

- neither under $SU(2)_L$ doublet and singlet terms together
- nor under $U(1)_Y$ do not have the same hypercharge

Fermion mass terms are forbidden

Not the case when using Yukawa couplings to the Higgs doublet

Then after SSB one recovers :

$$\frac{\lambda_\psi v}{\sqrt{2}}\overline{\psi}\psi + \frac{\lambda_\psi}{\sqrt{2}}H\overline{\psi}\psi$$

Which is invariant under $U(1)_{EM}$

Very important : The Higgs mechanism DOES NOT predict fermion masses

…Yet the coupling of the Higgs to fermions is proportional to their masses

But wait...

The coupling to the Higgs fields is the following :

$$\lambda_d (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v + h \end{pmatrix} d_R + H.C. = \lambda_d \overline{Q}_L \ \phi \ d_R$$

Can be seen as giving mass to down type fermions...

To give mass to up type fermions, need to use a slightly different coupling :

$$\phi^C = i\sigma_2 \phi^* \qquad \lambda_u Q_L \ \phi^C \ \bar{u}_R = \lambda_u (\bar{u}_L, \bar{d}_L) \begin{pmatrix} v + h \\ 0 \end{pmatrix} d_R + H.C.$$

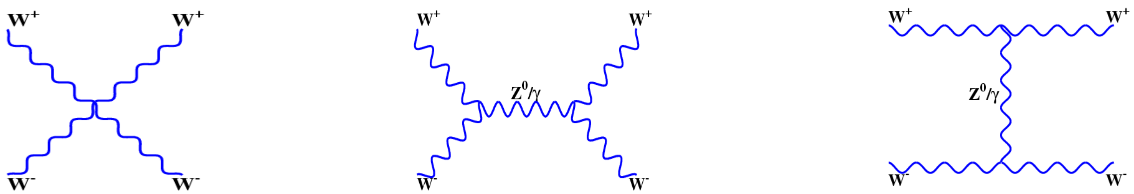
One doublet of complex scalar fields is sufficient to accommodate mass terms for gauge bosons and fermions !

... But not necessary.

Unitarity or why a Higgs Boson is Highly Desirable

The cross section for the thought scattering process :

$$W^+W^- \rightarrow W^+W^-$$



Does not preserve perturbative unitarity.

Introducing a Higgs boson ensures the unitarity of this process <u>PROVIDED</u> that its mass be smaller than :

$$\sqrt{4\pi\sqrt{2}/3G_F}$$ v.i.z. approximately 1 TeV

This is not only a motivation for the Higgs mechanism but is also a strong experimental constraint on its mass… if you believe in perturbative unitarity…

If you don't the electroweak interaction should become strong at the TeV scale and one would observe non perturbative effects such as multiple W production, WW resonances… (Technicolor…)

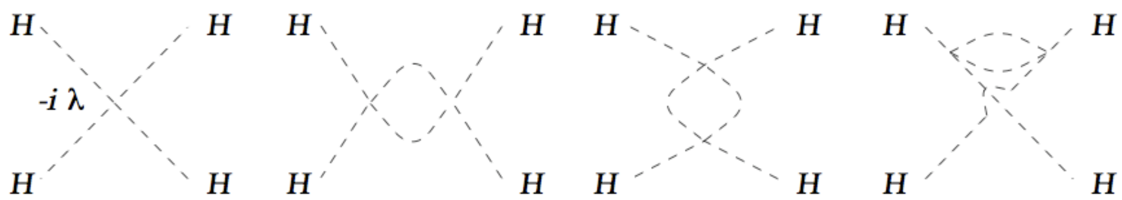
Running Quartic Coupling : Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling :

$$32\pi^2 \frac{d\lambda}{dt} = \boxed{24\lambda^2} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

In the case where the Higgs mass is large (large λ) : $M_H^2 = 2\lambda v^2$

The first term of the equation is dominant and due to diagrams such as :



$$\frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2}\lambda^2(Q^2) \longrightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2}\ln\left(\frac{Q^2}{Q_0^2}\right)$$

If Q can be high at will eventually lead to Landau pole

Triviality condition to avoid such pole : $1/\lambda(Q) > 0$

Then

$$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$