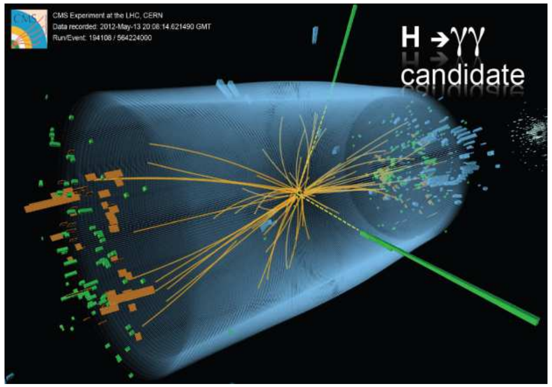
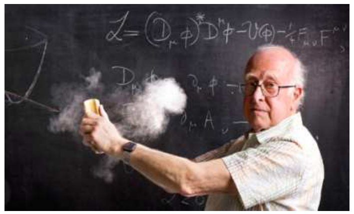
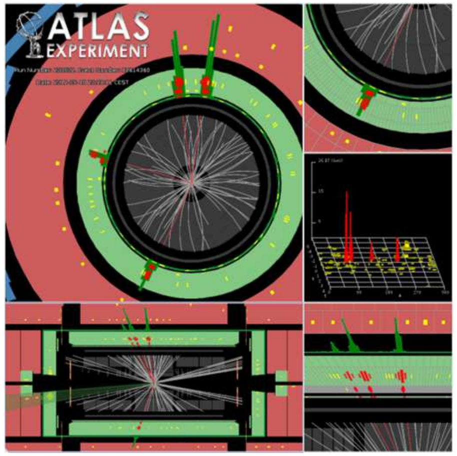
The Higgs candidate: experimental status

Fabrice Hubaut (hubaut@in2p3.fr)

CPPM/IN2P3 – Aix-Marseille Université (Marseille, FRANCE)





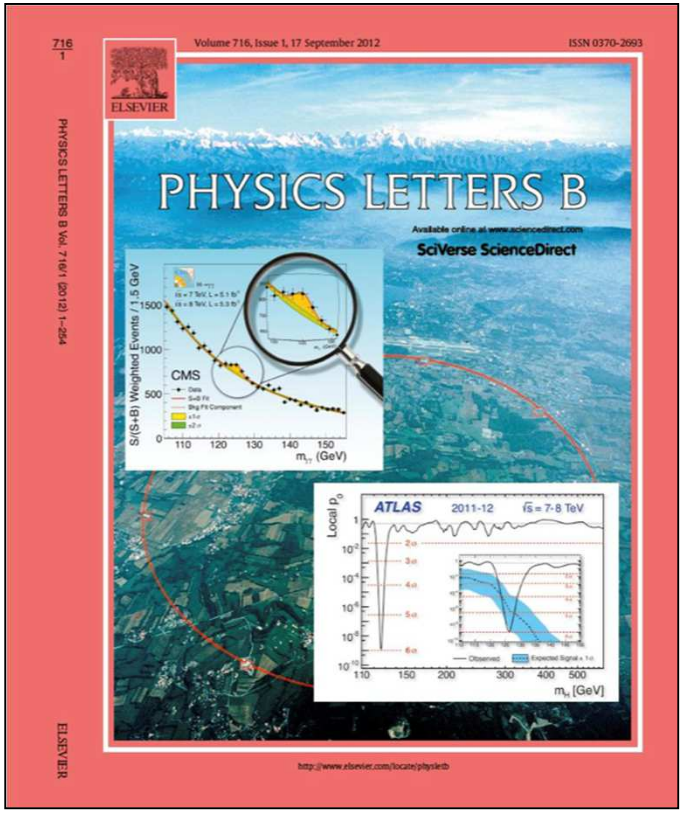


9th Franco-Italian meeting on B physics - 18/02/2013

Introduction and outline

What do we know (experimentally) about the newly discovered boson?

[6 months ago]



PLB 716 (2012) 1-29 | PLB 716 (2012) 30-61

ELSEVIER
Physics Letters B
Volume 716, Issue 1, 17 September 2012, Pages 1–29

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

Universally Available

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ATLAS Collaboration *

ELSEVIER
Physics Letters B
Volume 716, Issue 1, 17 September 2012, Pages 30–61

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

Universally Available

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

CMS Collaboration *

Introduction and outline

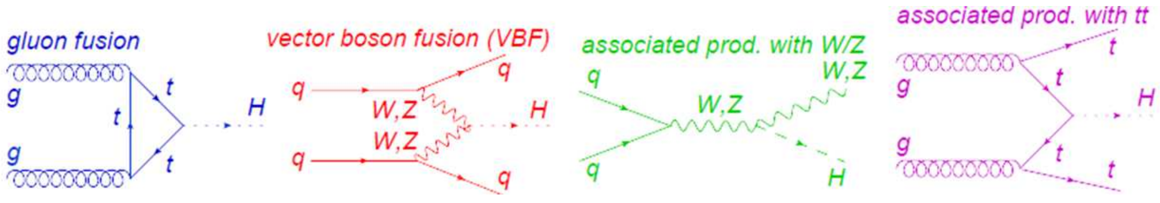
What do we know (experimentally) about the newly discovered boson?

Outline

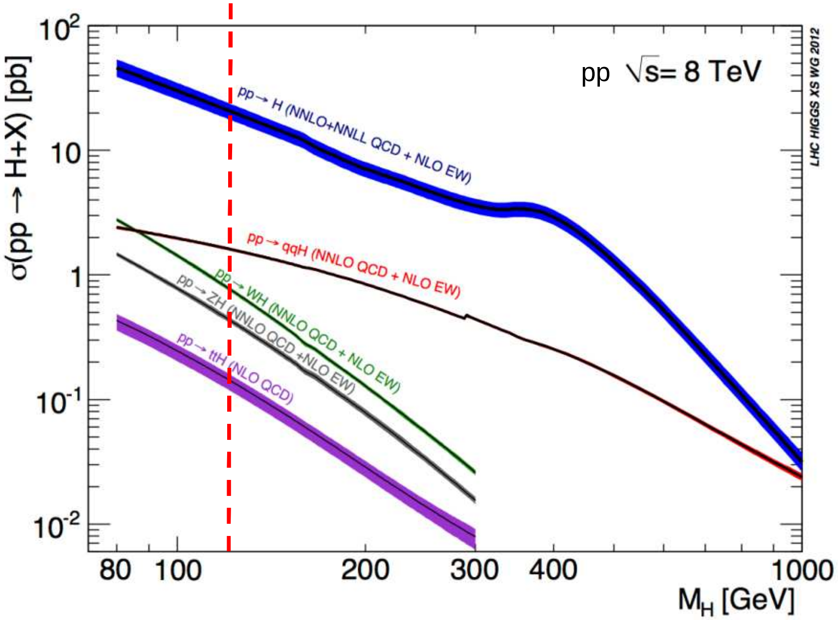
1. Reminder: SM Higgs production and decay
2. Analysis channels and latest LHC / Tevatron results
3. Mass and Spin-Parity measurements of the observed state
4. Coupling properties measurements and compatibility with SM
5. Perspectives at HL-LHC and outlook

?

SM-Higgs production @ p(-)p colliders



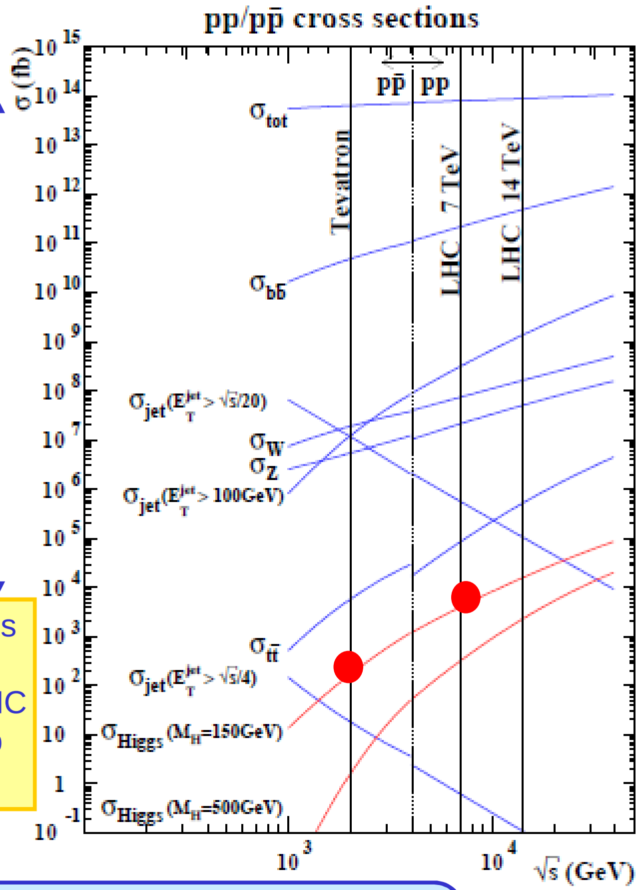
19.5 pb (87%) | 1.6 pb (7%) | 1.1 pb (5%) | 0.1 pb (1%)



σ(pb) @125 GeV for pp √s=8TeV

Total 22.3 pb (1.2 pb for pp̄ √s=2TeV)

2 Higgs bosons @ 125GeV produced at LHC out of 10^{10} pp collisions

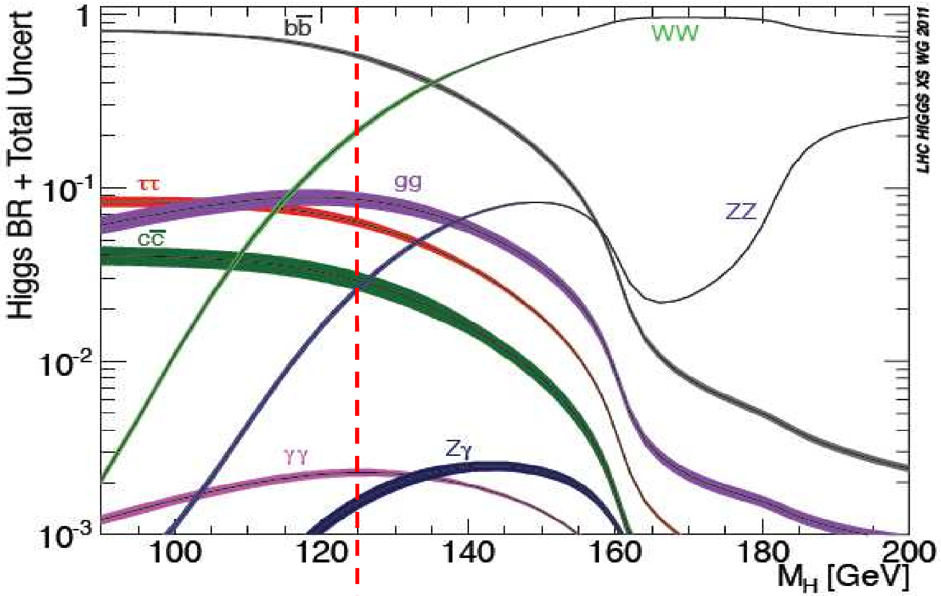


➔ **LHC is a Higgs factory (large cross-sections) but S/B ratio is low**
[~10 SM Higgs bosons @125 GeV / minute at LHC peak luminosity in 2012]

➔ **Cross-section at Tevatron ~20 times lower with similar S/B** **[see slide 8]**

SM-Higgs decay

SM Higgs: decay branching ratio (BR) in %

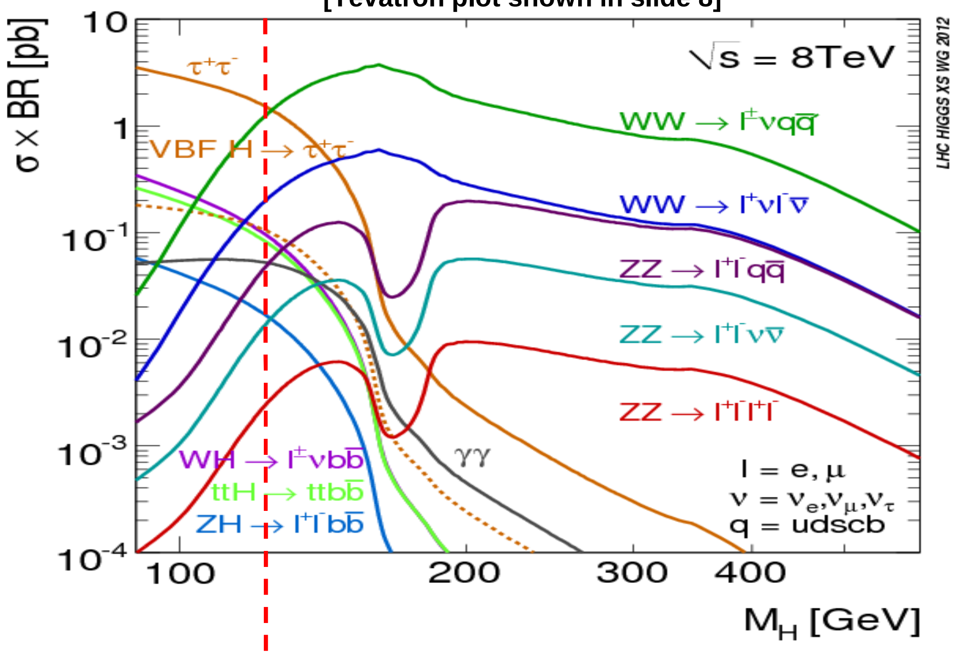


Branching ratios at 125 GeV:

bb:	***57.7%***	***ZZ:***	***2.6%***
WW:	***21.5%***	***γγ:***	***0.23%***
ττ:	***6.3%***		

σ*BR at LHC for « <u>useable</u> » final states

[Tevatron plot shown in slide 8]



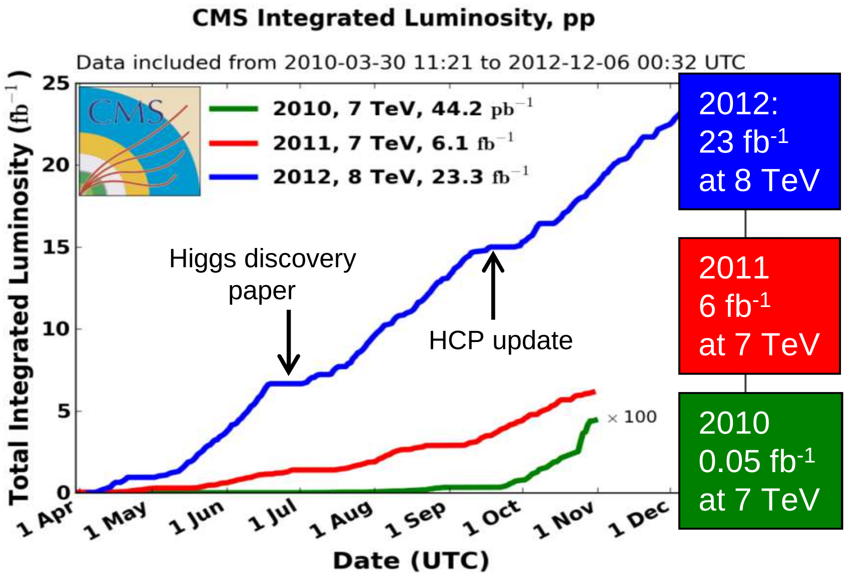
Many final-states topologies;

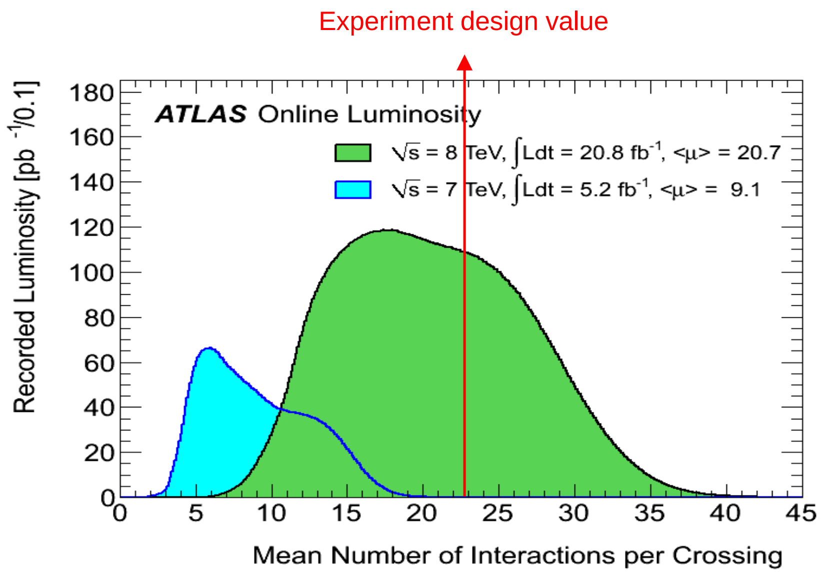
Leptons/photons are essential for any search

➔ 5 main decay modes exploited: $H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$, $H \to \tau\tau$ and $VH \to Vb\bar{b}$

[at low mass]

Colliders & Detectors performance





Outstanding LHC and detector performance

- L_{peak} up to $7.7 \cdot 10^{33}$ $cm^{-2} \cdot s^{-1}$ in 2012 at 8 TeV
- $L_{delivered}$ ~23 fb^{-1} (8 TeV) + 6 fb^{-1} (7 TeV)
- ~90% of delivered collisions are used in ATLAS and CMS analyses

Price to pay is large pile-up

- Above design value (50 ns bunch Xing)
- Many challenges to mitigate pile-up impact at all levels: trigger, computing, reco/identification of physics objects, …

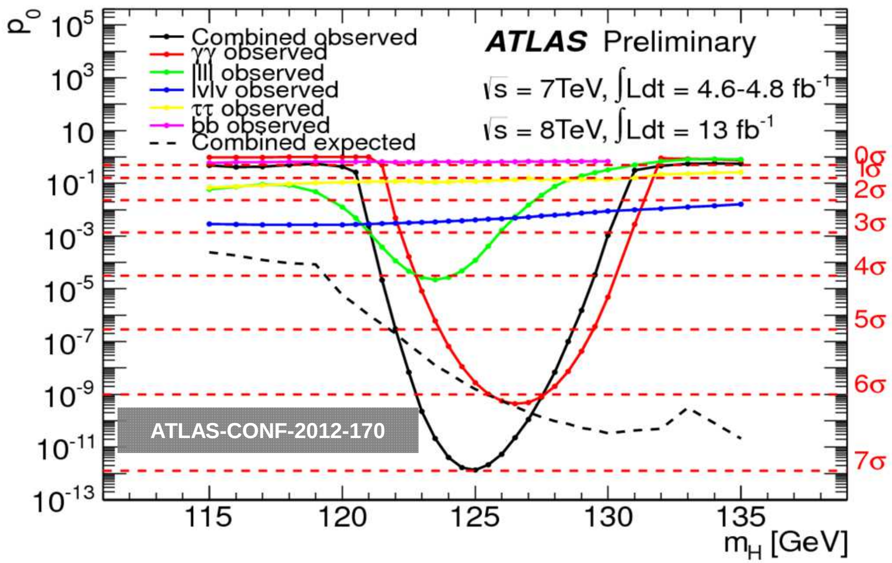
[unfortunately, no time to further discuss these issues]

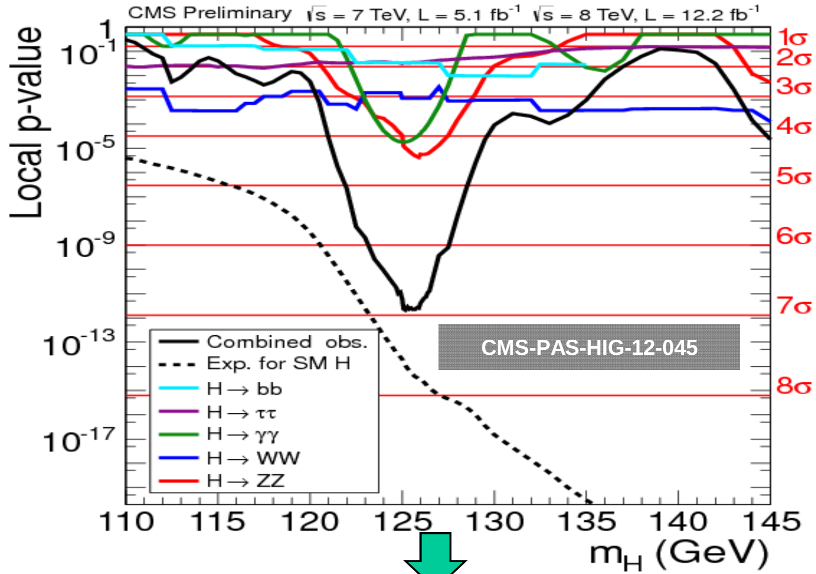
Also excellent performance of Tevatron ($L_{delivered}$ ~12 fb^{-1}) and DØ/CDF detectors

Latest channel combination @ LHC

- Latest ATLAS and CMS results combining the 5 main decay channels

[p-value: probability that observation is compatible with background-only hypothesis]





- Most analyses use so far ~13 fb^{-1} (8 TeV) + 5 fb^{-1} (7 TeV)
  - Last ~8 fb^{-1} (8 TeV) still to be included

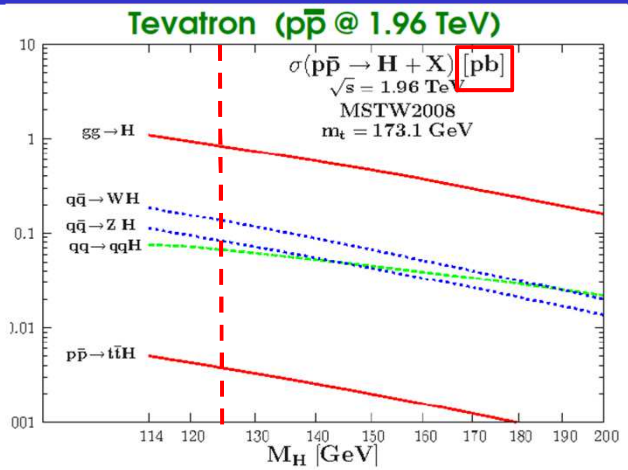
➔ **Local excesses ~7 σ for both ATLAS/CMS experiments at ~125 GeV** **[mostly bosonic channels]**

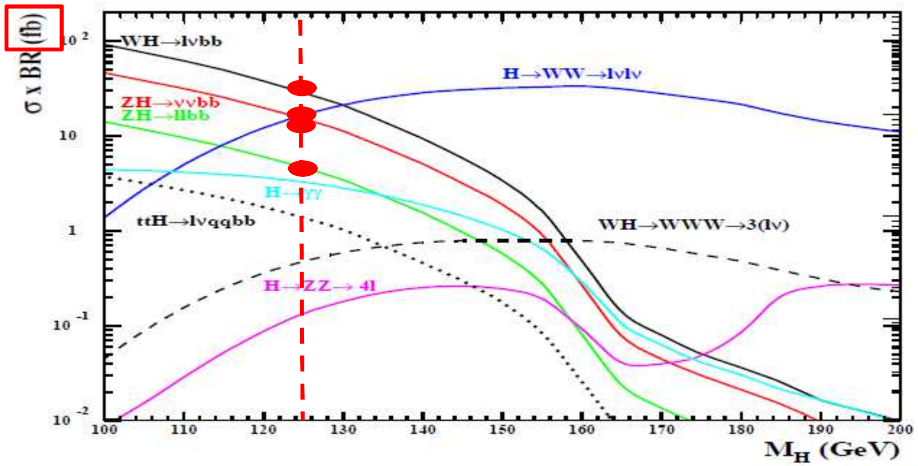
➔ **Nothing else visible in range [110-600] GeV**
[same for direct MSSM Higgs searches – see backup]

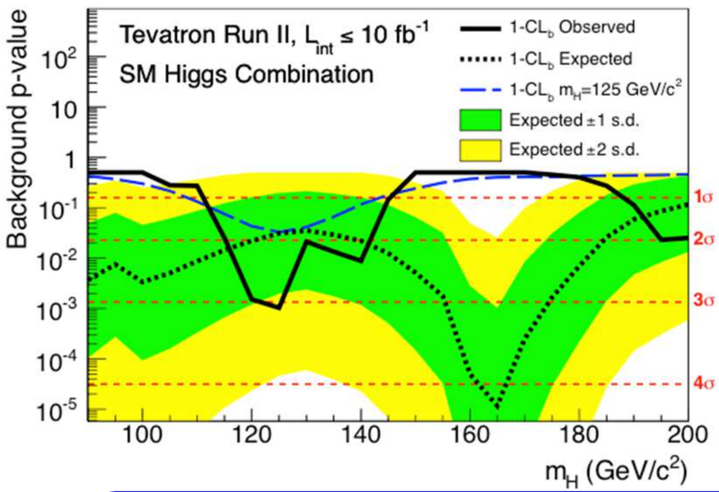
M_H=125.8 GeV	Expected (σ)	Observed (σ)
ZZ	5.0	4.4
γγ	2.8	4.0
WW	4.3	3.0
bb	2.2	1.8
ττ	2.1	1.8
Combination	7.8	6.9

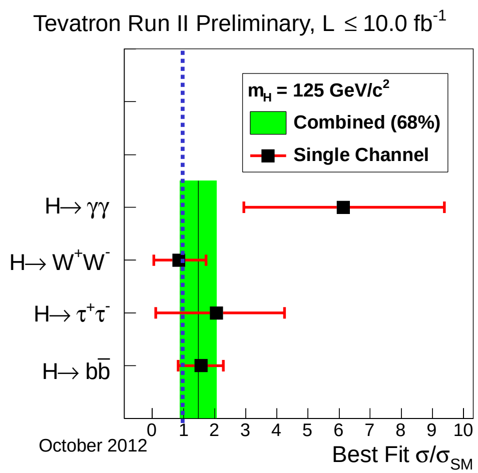
Latest channel combination @ Tevatron

950 fb
(77%)
210 fb
(17%)
65 fb
(5%)
4 fb
(<1%)









- Slight broad excess [115-140] GeV with 3σ local significance (2.5σ global)
- Majority of this excess comes from H→bb̄

➔ **First direct evidence for decay into fermions (consistent with SM)**

➔ **Complementarity on H→bb̄ channel between LHC and Tevatron**

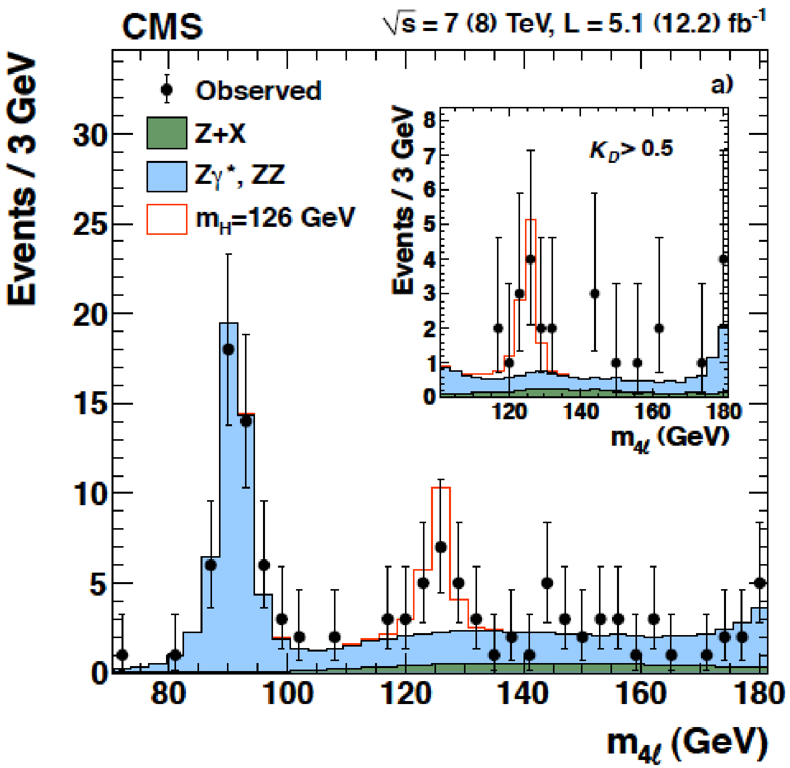
Mass measurement

[only missing parameter in SM Higgs sector]

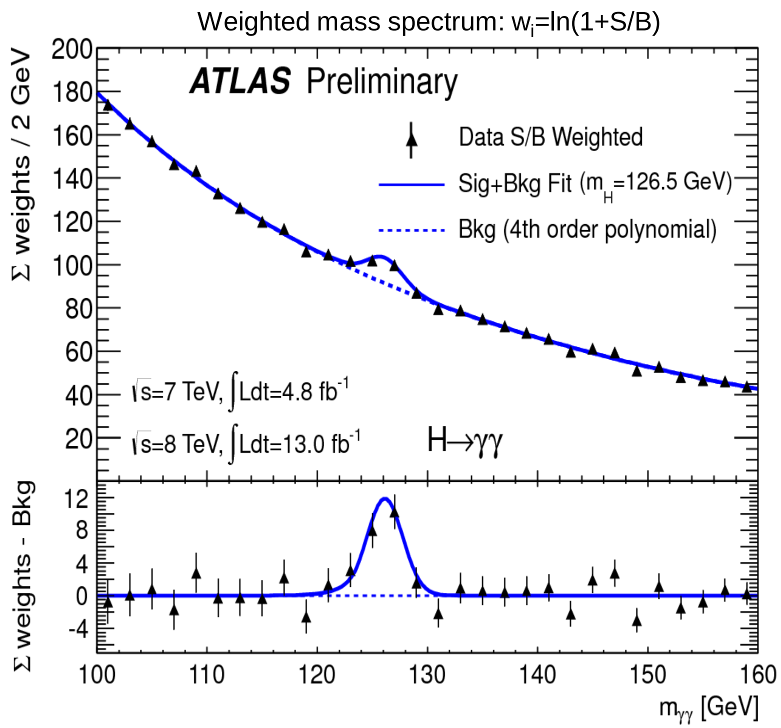
- 2 high-resolution channels (H→γγ and H→ZZ→4l) used for mass measurement @LHC

Example: 4-lepton invariant mass [CMS]

Example: di-photon invariant mass [ATLAS]



1212.6639



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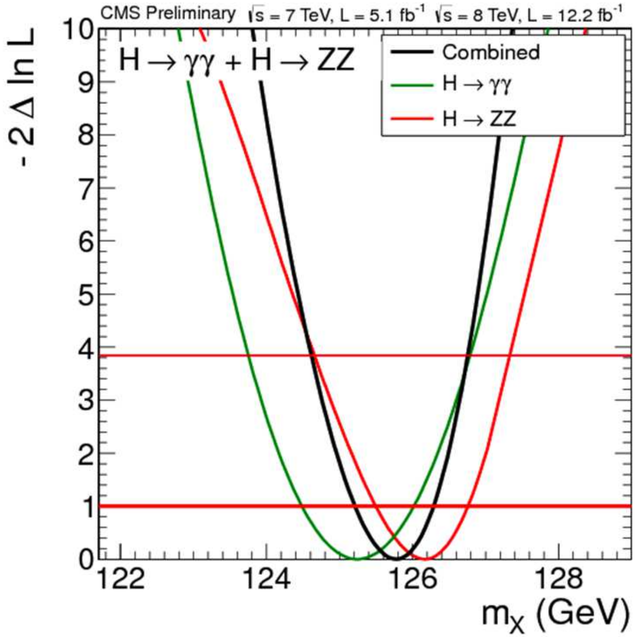
Mass measurement
[only missing parameter in SM Higgs sector]

➢ 2 high-resolution channels (H→γγ and H→ZZ→4l) used for mass measurement @LHC

CMS-PAS-HIG-12-045



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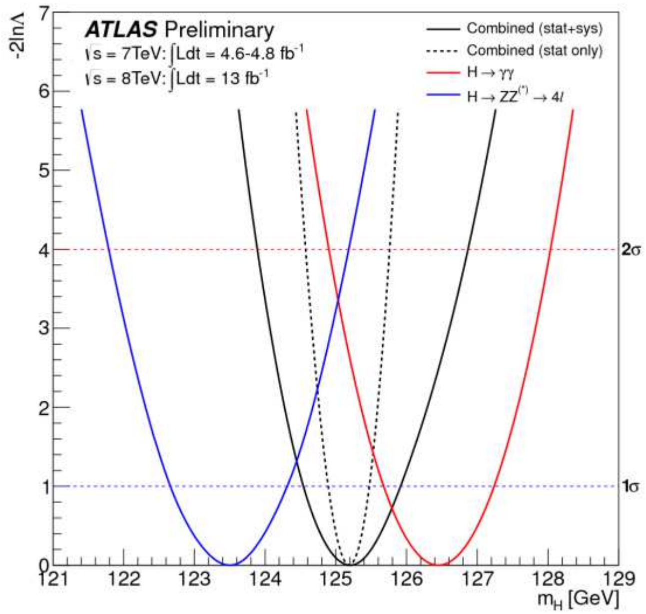


125.8 ± 0.4 (stat) ± 0.4 (syst) GeV

Best fit results for m_H

125.2 ± 0.3 (stat) ± 0.6 (syst) GeV

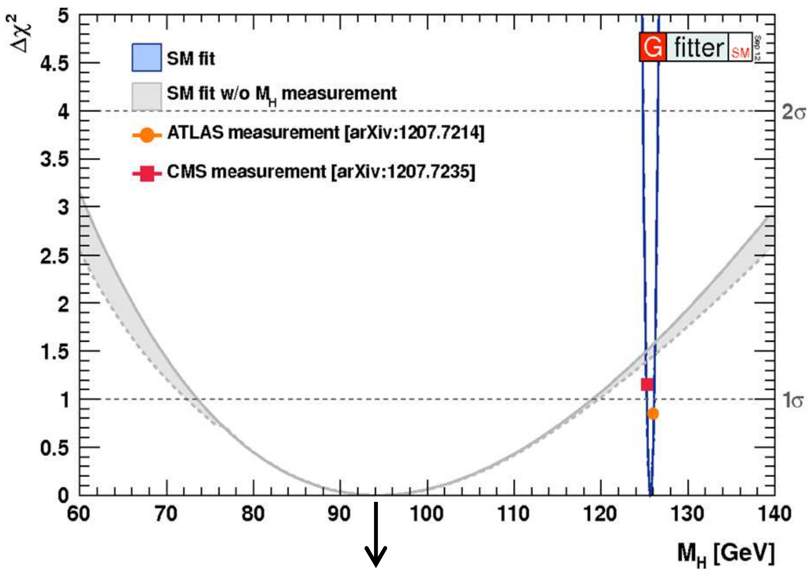
➔ **Mass measurements from both experiments already at ~0.5% level**

➔ **Systematics dominated so far by photon energy-scale**

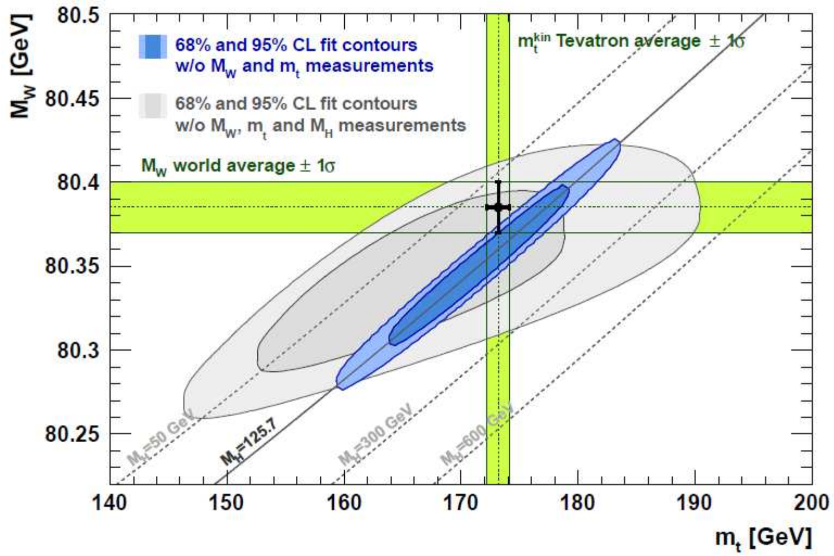
Standard Model consistency

➢ Latest results from electroweak fit w/wo Higgs mass measurement

1209.2716



Best fit $m_H = 94^{+25}_{-22}$ GeV



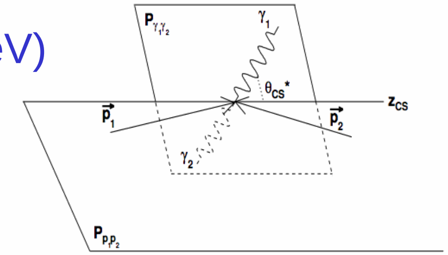
➔ **A remarkably consistent picture**

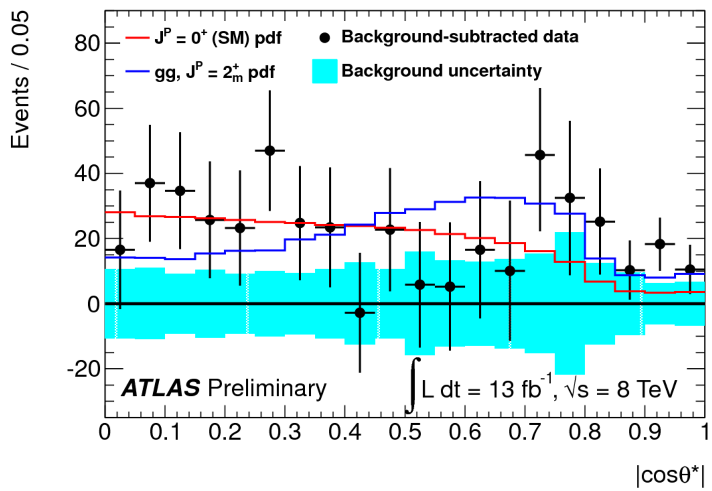
Spin studies with H→γγ

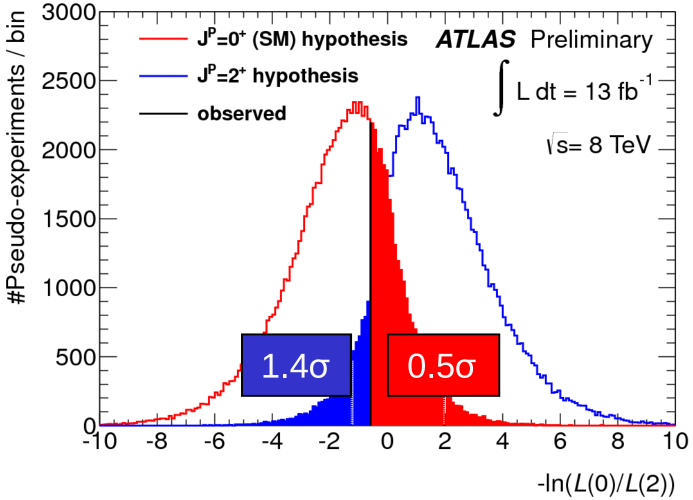
ATLAS-CONF-2012-168

- From distribution of polar angle θ* of the photons in the resonance rest frame
  - Signal region: events within ±1.5σ around the peak (m_H=126.5 GeV)
  - Compare dN/d|cosθ*| for:
    - spin-0 hypothesis: flat before cuts
    - spin-2 hypothesis: ~ $1+6\cos^2\theta^* + \cos^4\theta^*$ for G-like gg production

    [spin-1 hypothesis excluded by H→γγ observation: Landau-Yang theorem]
  - Normalisation and distribution of dN/d|cosθ*| for background from data (side-bands)







- **Expected sensitivity: 1.8σ separation between 0^+ and 2^+ hypotheses**
- **Fit to data: compatibility within 0.5σ with spin-0 and 1.4σ with spin-2** (i.e. disfavoured at 91% CL)

Spin-parity studies with H→ZZ$^{(*)}$→4l

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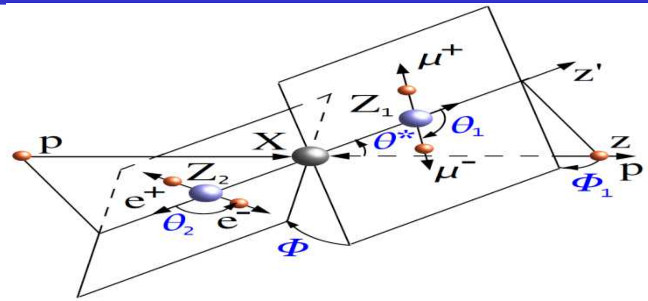
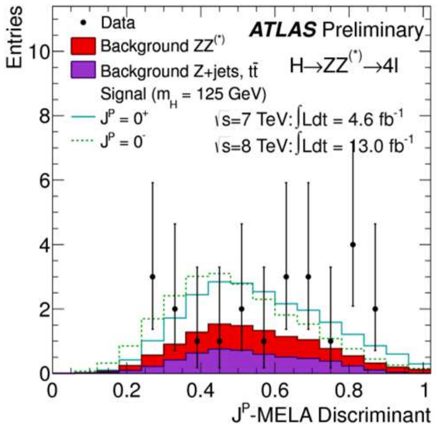
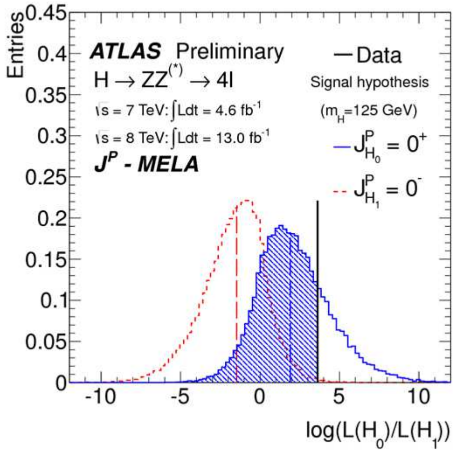
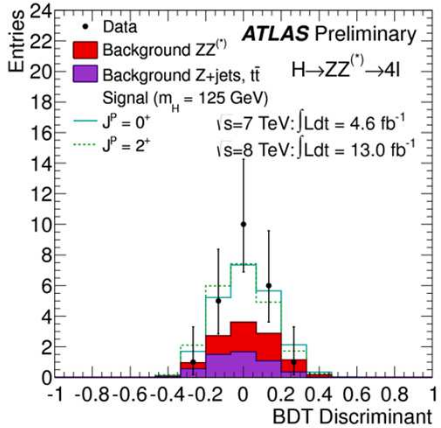
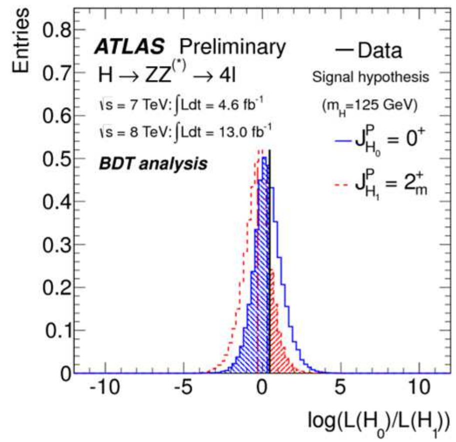
- Kinematics of production and decay in ZZ→4l channel (5 angles, Z masses) sensitive to spin and parity of the new boson
- 23 candidate events in region 115 GeV <m_{4l}<130 GeV are used











(similar results from CMS 1212.6639)

0^+ vs 0^-

Expected exclusion of 0^- at 97% CL (1.9σ)
Observed exclusion of 0^- at 99% CL (2.7σ)
Observation fully compatible with 0^+

0^+ vs 2^+

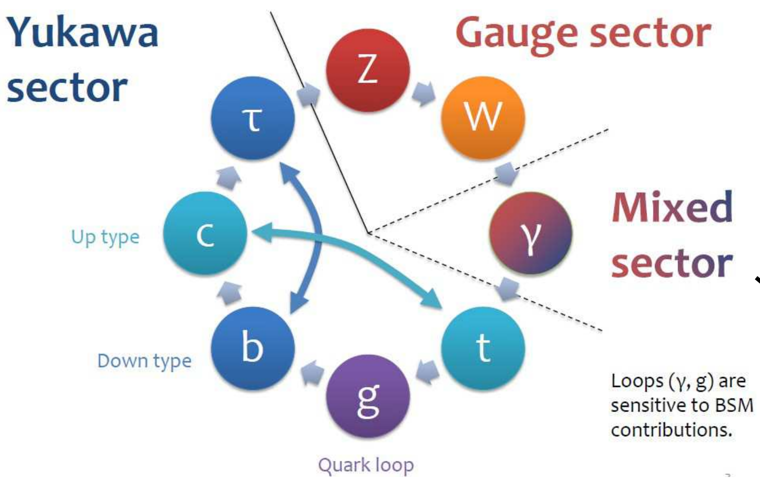
(Low) expected exclusion of 2^+ at 80% CL
Observed exclusion of 2^+ at 85% CL (1σ)
Observation fully compatible with 0^+

→ Pseudoscalar hypothesis (0^-) excluded at >2.5σ level (under the assumption that the new boson has spin 0)

SM Higgs couplings

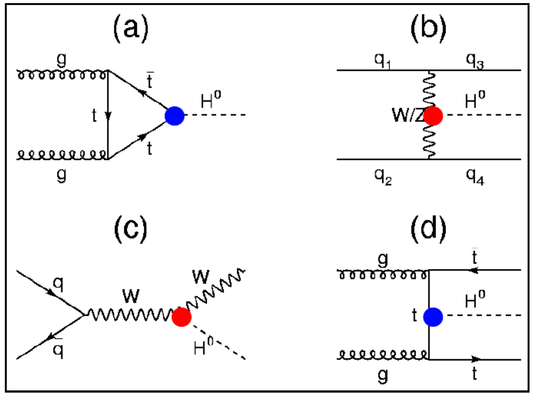
❑ Higgs couplings to SM particles and link with production/decay modes at LHC

- Gauge couplings ●
- Yukawa couplings ●



- Remark: a mass measurement to O(100 MeV) is enough and does not contribute to coupling uncertainties
- Theoretical uncertainties need improvements for O(1%) level precisions

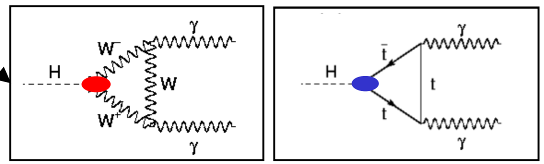
➢ Production: access to top (direct and gg→H loop) and W,Z couplings



σ(pb) for pp √s=8TeV

19.5 (87%)	1.6 (7%)
1.1 (5%)	0.1 (1%)

➢ Decays accessible at LHC: b, τ, W, Z, μ (direct) and γ (loop)



➔ Link between our observables (event yields ∝ cross-sections*branching ratios) and Higgs couplings

Observables ↔ SM Higgs couplings

→ **Link between event yields (cross-section * branching ratio) and Higgs couplings**

$$\sigma \cdot BR(ii \rightarrow H \rightarrow ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2} \quad \sim \Gamma_i \cdot \Gamma_f / \Gamma_H$$

- Observed yield can be parametrized as SM prediction * $\boxed{\text{coupling scale factor } \kappa^2}$ (SM: κ_i=1)

❑ Gauge couplings (coupling scale factors κ_W and κ_Z)

- Pure measurements from VBF/VH production and H→ZZ/WW
- For now: main constraints from gg→H→WW/ZZ and W-loop from H→$\gamma\gamma$

❑ Yukawa couplings (coupling scale factors κ_b, κ_τ, κ_t, κ_μ)

- κ_b and κ_τ : main direct constraint from bb and $\tau\tau$ decays → weak for now
- κ_t: can not be measured from Higgs decay. No sensitivity yet to ttH production, so main constraint comes from now from top-loop in gluon-fusion → very weak!
- κ_μ: need very high integrated luminosities

❑ Total Higgs width (scale factor κ_H)

- At LHC total Higgs width is not accessible [SM Γ_H~4 MeV @125 GeV and there exist invisible/undetectable decays]
- → only ratios of partial widths ($\propto$ square of coupling constants) can be measured [unless assumptions are made]

Current situation: Measurement channels

- Most ATLAS and CMS analyses for a given decay channels are divided in categories, some targeting a particular production mode
- Remark: none of the analyses targeting a particular production mode are 100% pure and all have an admixture of other production mechanisms !

	Untagged	VBF-tag	VH-tag	ttH-tag
$H \rightarrow ZZ$	✔			
$H \rightarrow WW$	✔	✔	✔	
$H \rightarrow bb$			✔	✔
$H \rightarrow \tau\tau$	✔	✔	✔	
$H \rightarrow \gamma\gamma$	✔	✔	✔ (ATLAS)	

- Luminosity used by most analyses is now ~13 fb^{-1} (8 TeV) + 5 fb^{-1} (7 TeV)
  - Last ~8 fb^{-1} (8 TeV) still to be included in the analyses
  - Further optimisation of categorisation for best coupling sensitivity is underway

Signal strength per decay mode

- Signal strength μ defined as observed event yield normalised to expected SM yield

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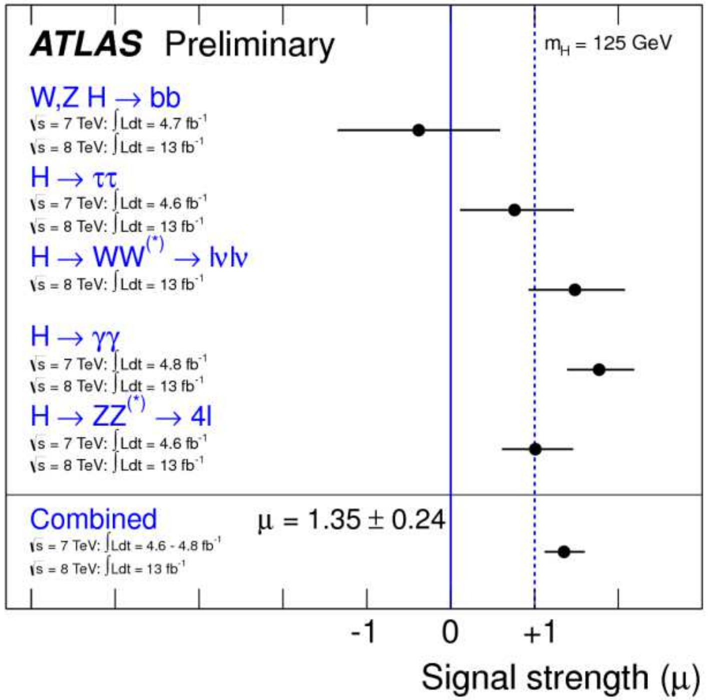
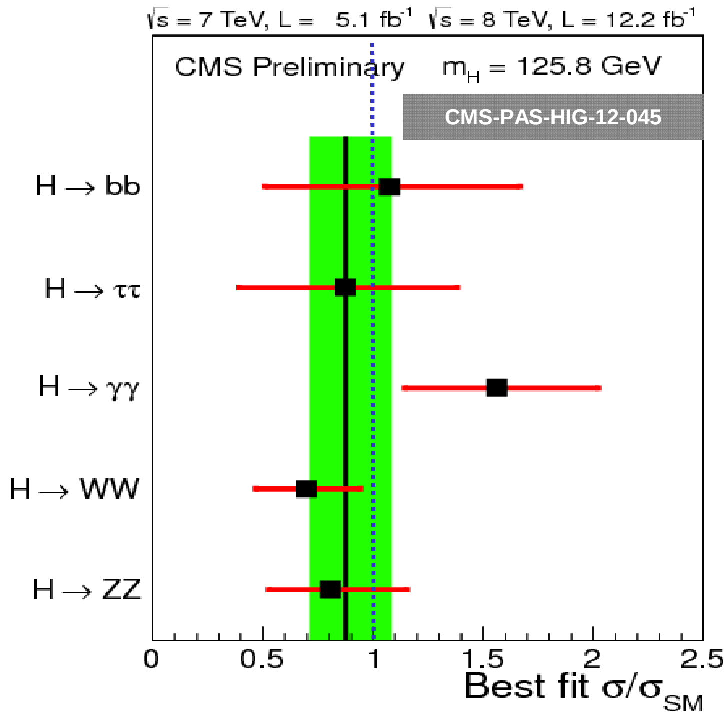




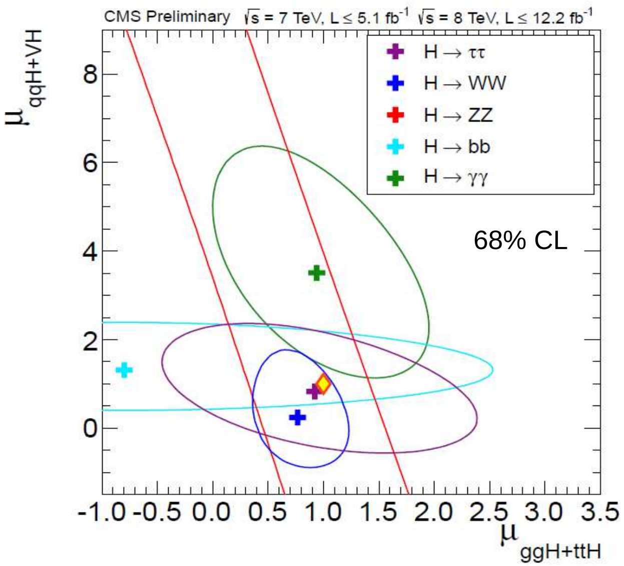
Combined μ= 1.35 ± 0.19 (stat) ± 0.15 (syst) @125 GeV

Combined μ=0.88±0.21 @ 125.8 GeV

➔ Agreement with SM expectations – precision on combined μ ~20 %

Signal strength per production mode

- Signal strength μ defined as observed event yield normalised to expected SM yield
- Production mechanisms associated with either top (ggF+ttH) or gauge (VBF+VH) couplings
- Production signal strengths are varied separately for each individual decay mode



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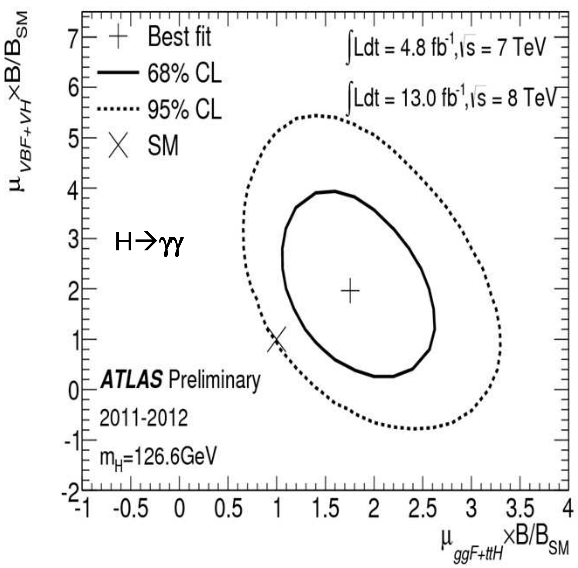

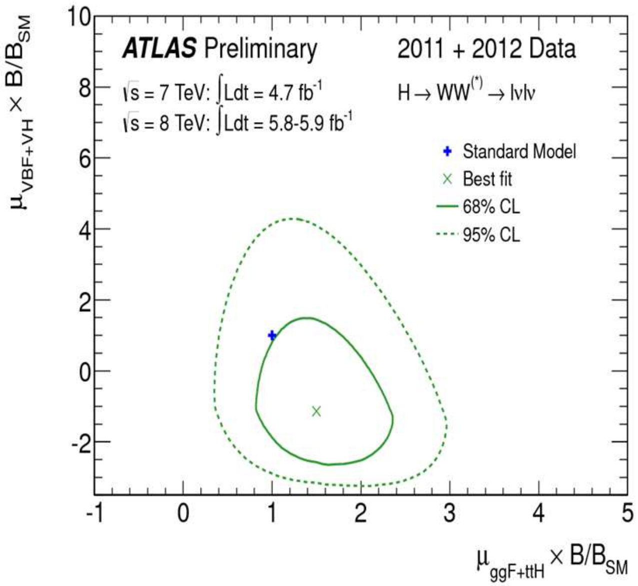

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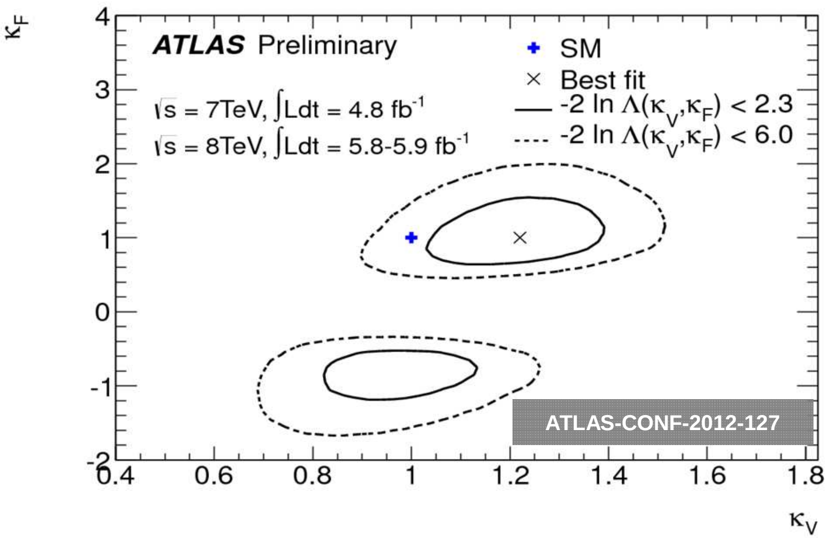
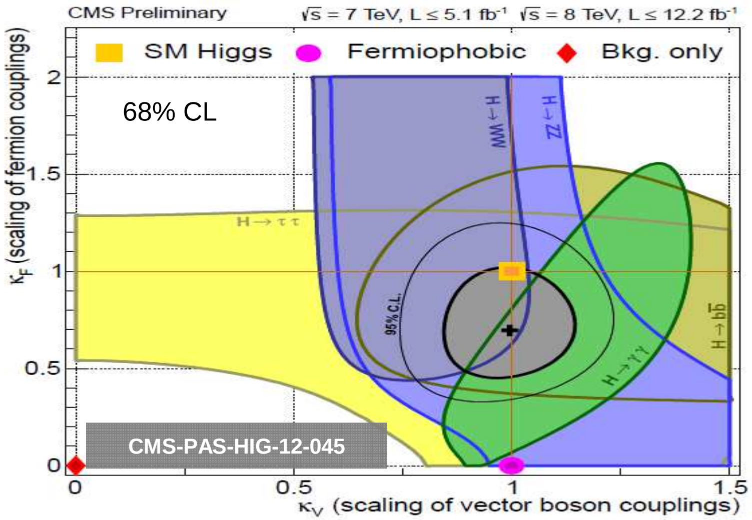
➔ Agreement with SM expectations at better than 2σ for all channels

Higgs coupling measurements (1/3)

- Most general coupling fit involves 7 partial widths and total Higgs width → dataset too limited
- Simplifications, using the recommended framework from the LHC-XS WG 1209.0040
- Under hypotheses, reduction of number of degrees of freedom → several well motivated tests
  - Example 1: Couplings to fermions ($\kappa_F=\kappa_t=\kappa_b=\kappa_\tau$) vs gauge couplings ($\kappa_V=\kappa_W=\kappa_Z$)

Main assumption: only SM particles contribute to Higgs total width (Γ_{BSM}=0)





κ_F: weak constraint so far from direct measurements at LHC H→ττ,bb **(*)**– indirect constraints from loops (amplitude from top loops gg→H and sign from interference term btwn top and W loops in H→γγ)

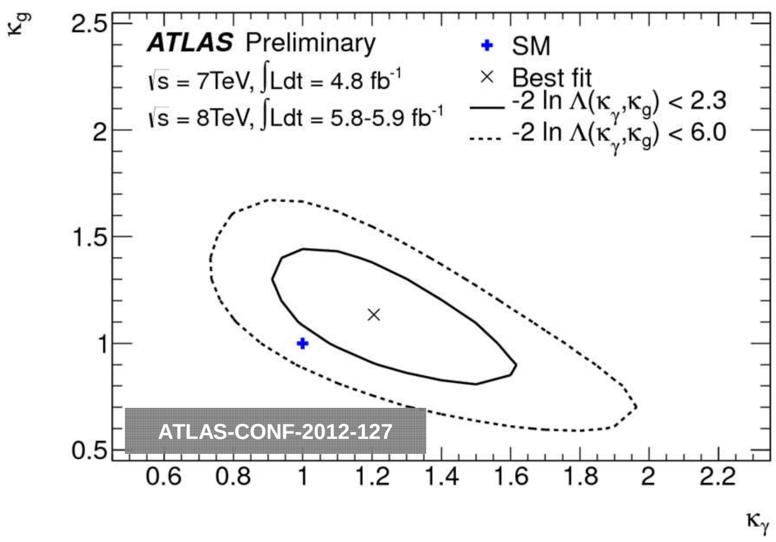
→ Agreement with SM expectations tested at 20-30% level

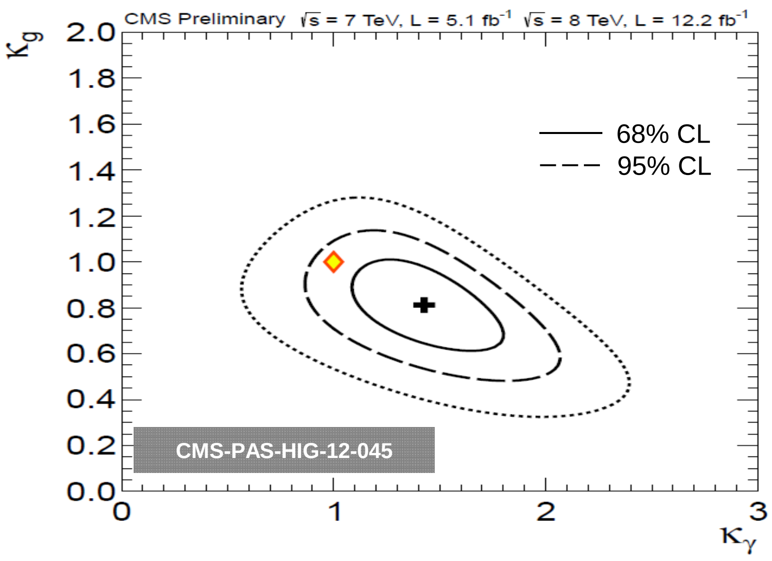
*** best direct constraint from Tevatron (slide 8)**

Higgs coupling measurements (2/3)

- Most general coupling fit involves 7 partial widths and total Higgs width → dataset too limited
- Simplifications, using the recommended framework from the LHC-XS WG 1209.0040
- Under hypotheses, reduction of number of degrees of freedom → several well motivated tests
  - Example 2: Test presence of new particles in loops gg→H and H→γγ

Main assumption: Direct couplings to known SM particles are standard and no extra contribution to Γ_H





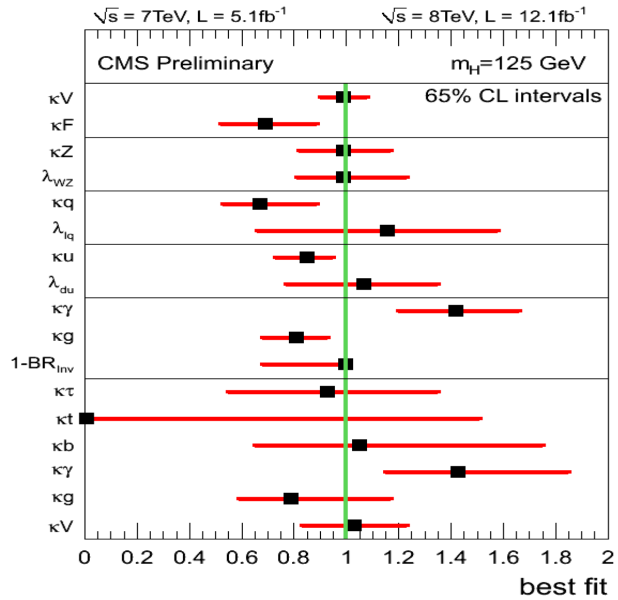
→ **Agreement with SM expectations at better than 2σ**

Higgs coupling measurements (3/3)

- Most general coupling fit involves 7 partial widths and total Higgs width → dataset too limited
- Simplifications, using the recommended framework from the LHC-XS WG 1209.0040
- Under hypotheses, reduction of number of degrees of freedom → several well motivated tests
  - ➢ Other examples: test custodial symmetry of W and Z bosons, test up/down and quark/lepton symmetries
  - ➢ More global fit still too weakly constrained

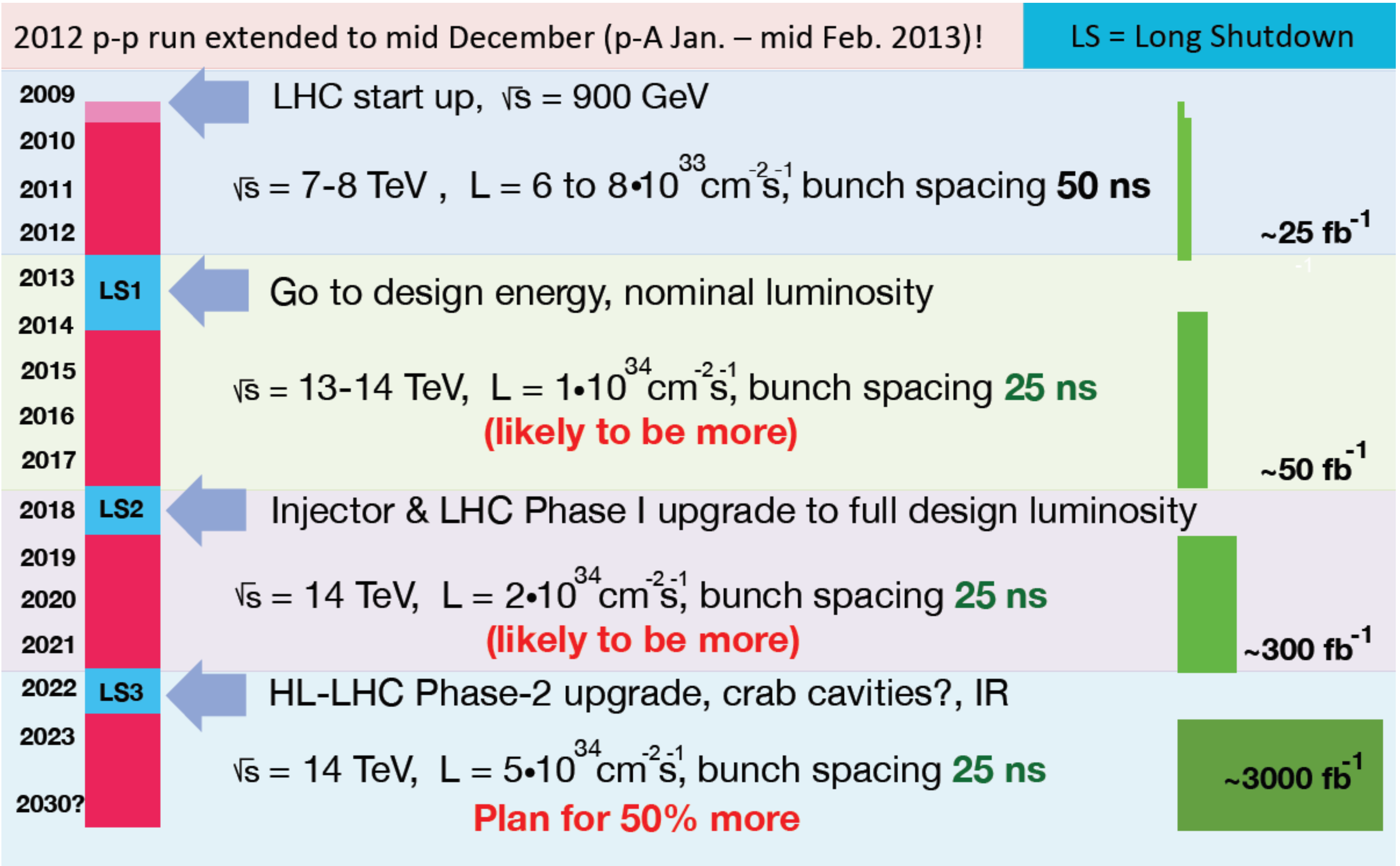
CMS-PAS-HIG-12-045

Model parameters	Assessed scaling factors (95% CL intervals)	
λ_{WZ}, κ_Z	λ_{WZ}	[0.57–1.65]
$\lambda_{WZ}, \kappa_Z, \kappa_f$	λ_{WZ}	[0.67–1.55]
κ_V	κ_V	[0.78–1.19]
κ_f	κ_f	[0.40–1.12]
κ_γ, κ_g	κ_γ	[0.98–1.92]
	κ_g	[0.55–1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00–0.62]
$\lambda_{du}, \kappa_V, \kappa_u$	λ_{du}	[0.45–1.66]
$\lambda_{\ell q}, \kappa_V, \kappa_q$	$\lambda_{\ell q}$	[0.00–2.11]
$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_V	[0.58–1.41]
	κ_b	[not constrained]
	κ_τ	[0.00–1.80]
	κ_t	[not constrained]
	κ_g	[0.43–1.92]
	κ_γ	[0.81–2.27]



→ More data needed for a more global fit (relaxing assumptions), to be further sensitive to presence of new physics and measure κ_t, κ_μ and self-coupling

LHC and HL-LHC projections

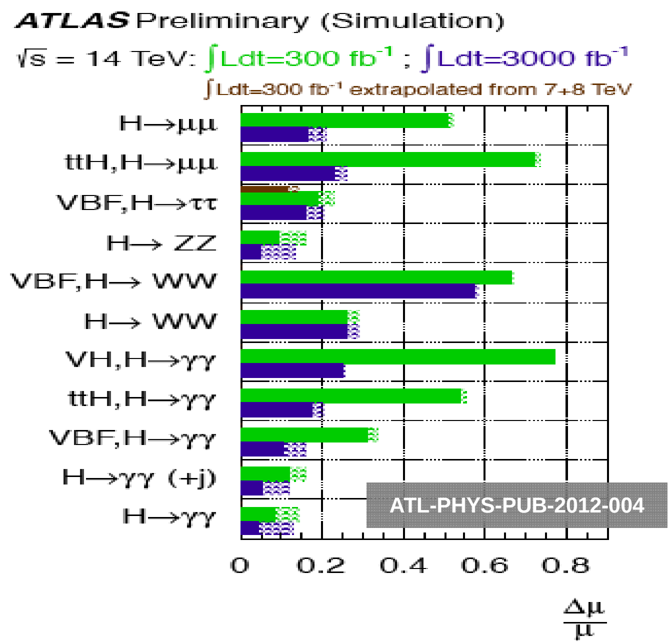


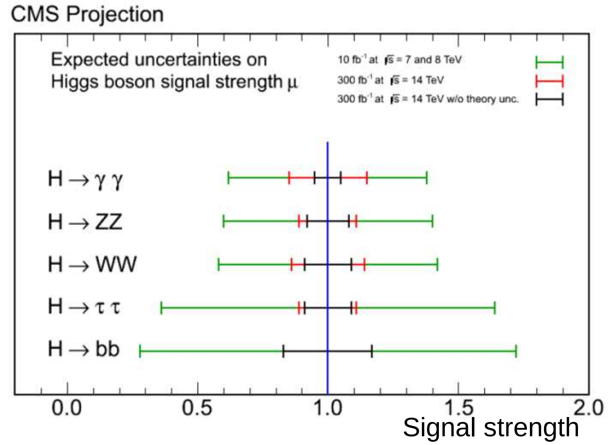
➔ **the LHC physics programme is in its early stage !**

Higgs couplings at HL-LHC (1/4)

[more details in A. Nisati's talk tomorrow]

- **Typical precisions that can be achieved on couplings with 30-3000 fb^{-1}**
  - Measurement of Higgs couplings with 2011+2012 data (~30 fb^{-1}) → 15% on combined **signal strength** expected - precision of individual channels ~25-30% ($H\to\gamma\gamma$, ZZ, WW)
  - With 300 fb^{-1}, precision of **signal strength** ~10% per channel expected at best ($\gamma\gamma$, ZZ)
  - Experimental uncertainties on most **signal strengths** reduced by factor ~ 2 or more when going from 300 to 3000 fb^{-1} → < 5% uncertainty for best cases ($\gamma\gamma$, ZZ) to ~20% (WW)
    - Addition of rare channels like VH (H→WW, ZZ) will improve the overall results and yield more precise measurements of W-coupling



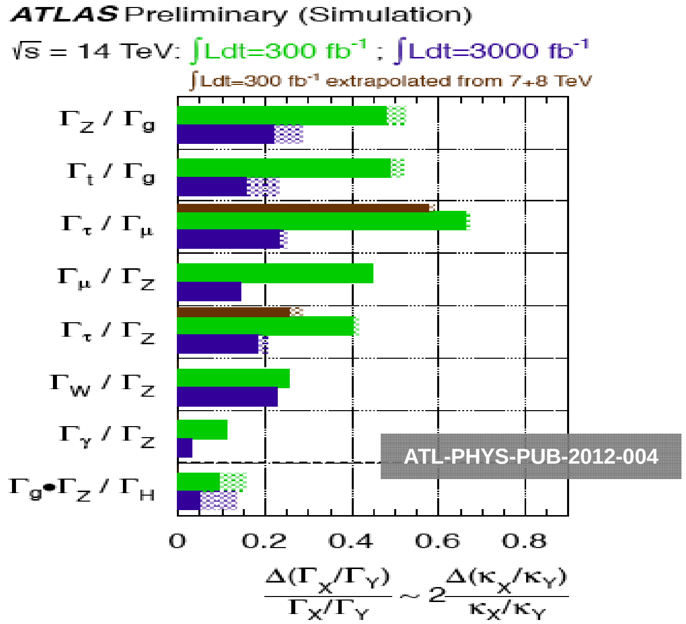


Higgs couplings at HL-LHC (2/4)

[more details in A. Nisati's talk tomorrow]

- **Typical precisions that can be achieved on couplings with 3000 fb^{-1}**
  - Without constraints, **ratios of partial widths** can be measured with typical precisions of 20-50% (5-25%) with ~300 fb^{-1} (3000 fb^{-1}) per experiment
    - Ratios Γ_γ/Γ_Z and Γ_t/Γ_g probe new physics in $H\rightarrow\gamma\gamma$ and $gg\rightarrow H$ loops at 5-15% level
  - Assuming Γ_H (SM) and one scale factor for the fermion/vector sector → measure **couplings** κ_F to 3-6% and κ_V to 2-4% with 3000 fb^{-1} per experiment

General coupling fit (no assumption)



Minimal coupling fit (assumptions)

[NO invisible/undetectable contribution to Γ_H]

CMS projection

Coupling	Uncertainty (%) 300 fb^{-1} Scenario 1	300 fb^{-1} Scenario 2	3000 fb^{-1} Scenario 1	3000 fb^{-1} Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Scenario 1:
- 2012 systematics

Scenario 2:
- theory syst: scaled by a factor ½
- other systematics scaled by 1/√L

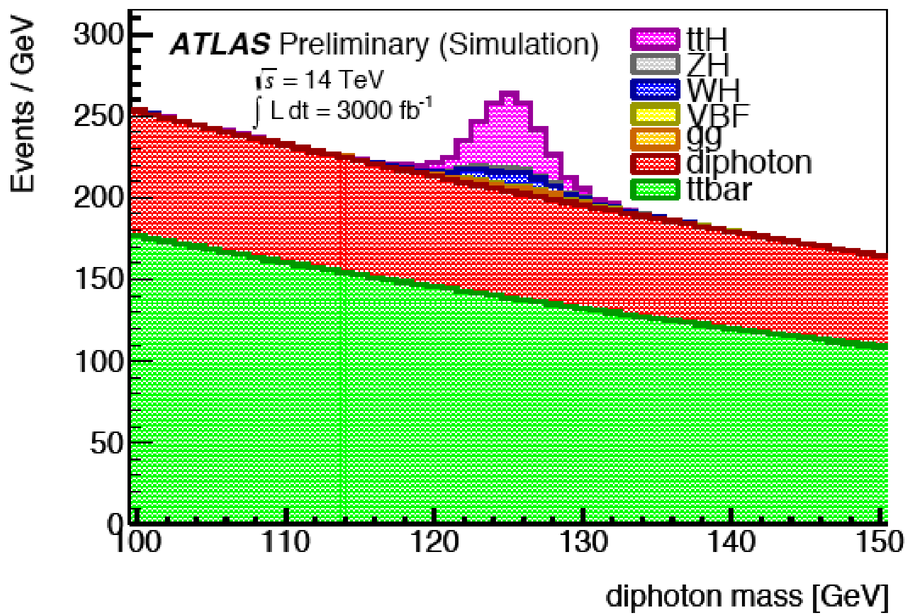
Higgs couplings at HL-LHC (3/4)

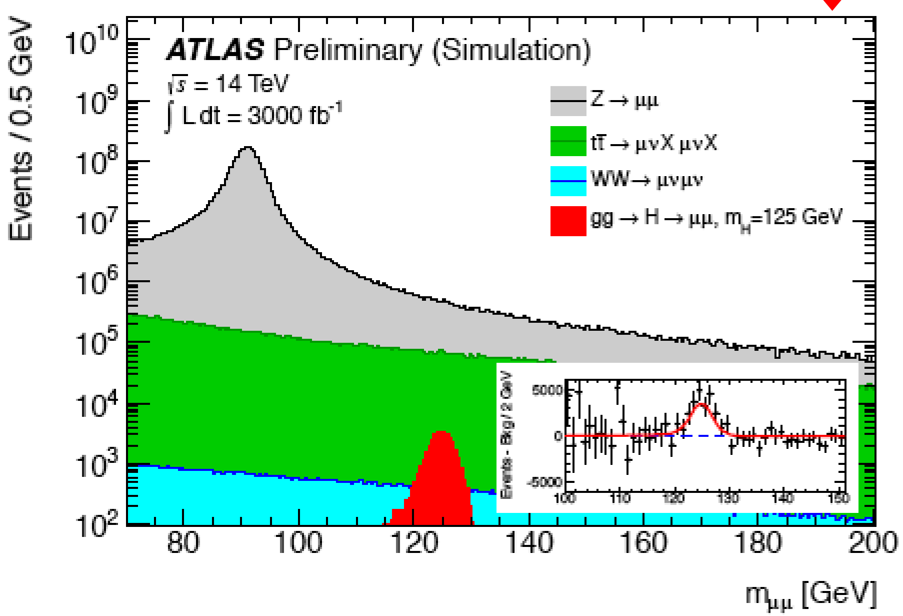
[more details in A. Nisati's talk tomorrow]

❑ Measurements of rare decays with 3000 fb^{-1}

ATL-PHYS-PUB-2012-004

- ttH → tt$\gamma\gamma$: 200 events, 6σ per experiment (factor 2 better than with 300 fb^{-1})
  → measurement of top Yukawa coupling at ~10% level
- H → $\mu\mu$: one of the best channel to study Higgs coupling to fermions but very rare! Simple analysis → S/B~0.2%, 6σ per experiment (~2σ with 300 fb^{-1})
  → measurement of Higgs-muon coupling κ_μ at ~10% level





Higgs couplings at HL-LHC (4/4)

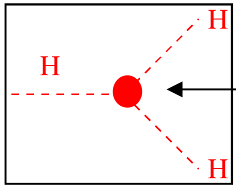
[more details in A. Nisati's talk tomorrow]

❑ Measurement of Higgs self-coupling to firmly establish Higgs role in EWSB

In SM Lagrangian:

$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$
$$\lambda = \lambda_{SM} = M_H^2/(2v^2)$$

→ appearance of Higgs self coupling interactions



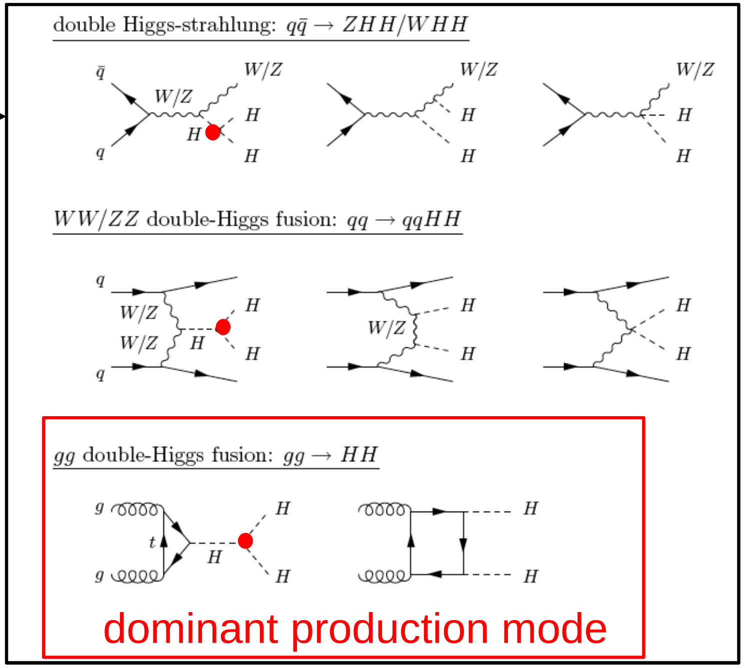
λ = Higgs self-coupling

$\lambda_{HHH} \sim \lambda v \sim M_H^2/v$

$(\lambda_{HHHH} \sim \lambda \sim M_H^2/v^2)$

- Quartic coupling not accessible, but tri-linear self-coupling is: intereference effect in di-Higgs boson production [SM cross section is 34 fb at 14 TeV for m_H=125 GeV – 71/16 fb if λ_{HHH}=0/2 * SM]
- With 3000 fb^{-1}: 15 events, ~3σ observation per experiment for λ_{HHH}=1 expected from HH → bbγγ channel (BR~0.27%); HH→ bbττ also promising
- ~ 30% measurement of $\lambda_{HHH}/\lambda_{SM}$ may be achieved by combining channels and experiments

→ knowing M_H, check that Higgs potential is SM



Conclusions and outlook

❑ The era of precise "Higgs measurements" has started

- So far, all measured properties are consistent with Standard Model expectations
- With LHC run I, expect per experiment from a SM Higgs: 4-5 σ from each of $H\rightarrow\gamma\gamma$, $H\rightarrow l\nu l\nu$, $H\rightarrow 4l$; ~3 σ from $H\rightarrow\tau\tau$ and from $W/ZH\rightarrow W/Z\ bb$ (already achieved by Tevatron); Separation $0^+/2^+$ and $0^+/0^-$ at 4σ level combining ATLAS and CMS

➔ First results with whole LHC run I statistics expected at Moriond next month

❑ More data (approved LHC program, HL-LHC?, next facilities?) will be essential to:

- Measure nature and properties of the new boson with increasing precision. Ultimate (sub-% level?) coupling measurements at a future lepton collider? (linear/circular? $\sqrt{s}$?)

➔ Search for New Physics effects through deviations from SM predictions

➔ Complementarity with flavour-physics programme

- Answer if natural Higgs or fine-tuned Higgs ? If natural: what stabilizes its mass (SUSY?)?

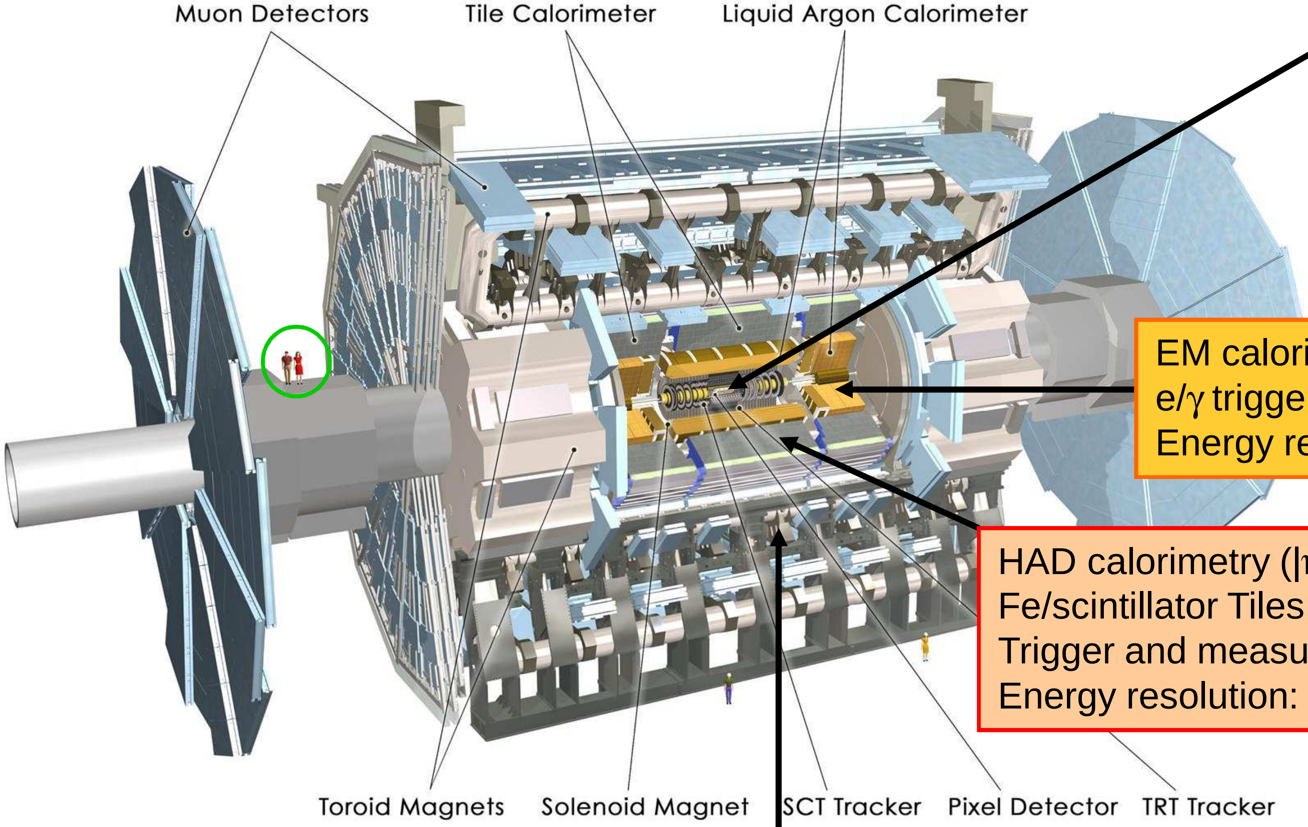
➔ Complementarity of Higgs precision measurements with direct searches for New Physics @ high-energy frontier! The LHC run at 13 TeV will hopefully already give first hints!

SPARES

The ATLAS detector

L ~ 46 m, ∅ ~ 22 m, 7000 tons
~10^8 electronic channels

Inner Tracker ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws).
Precise tracking and vertexing, e/π separation.
Momentum resolution:
$\sigma/p_T \sim 0.04\% \, p_T \, (\text{GeV}) \oplus 1.5\%$

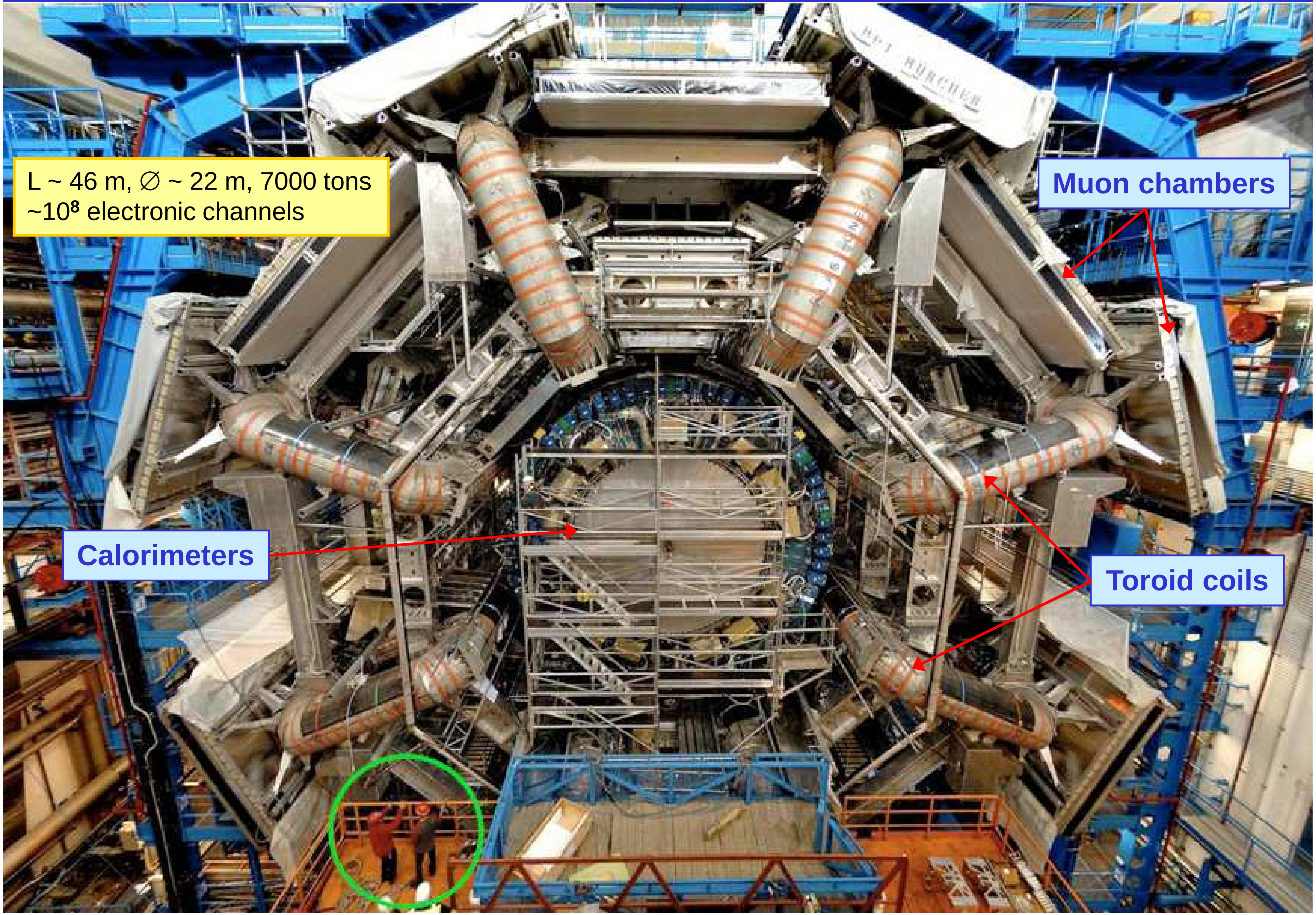


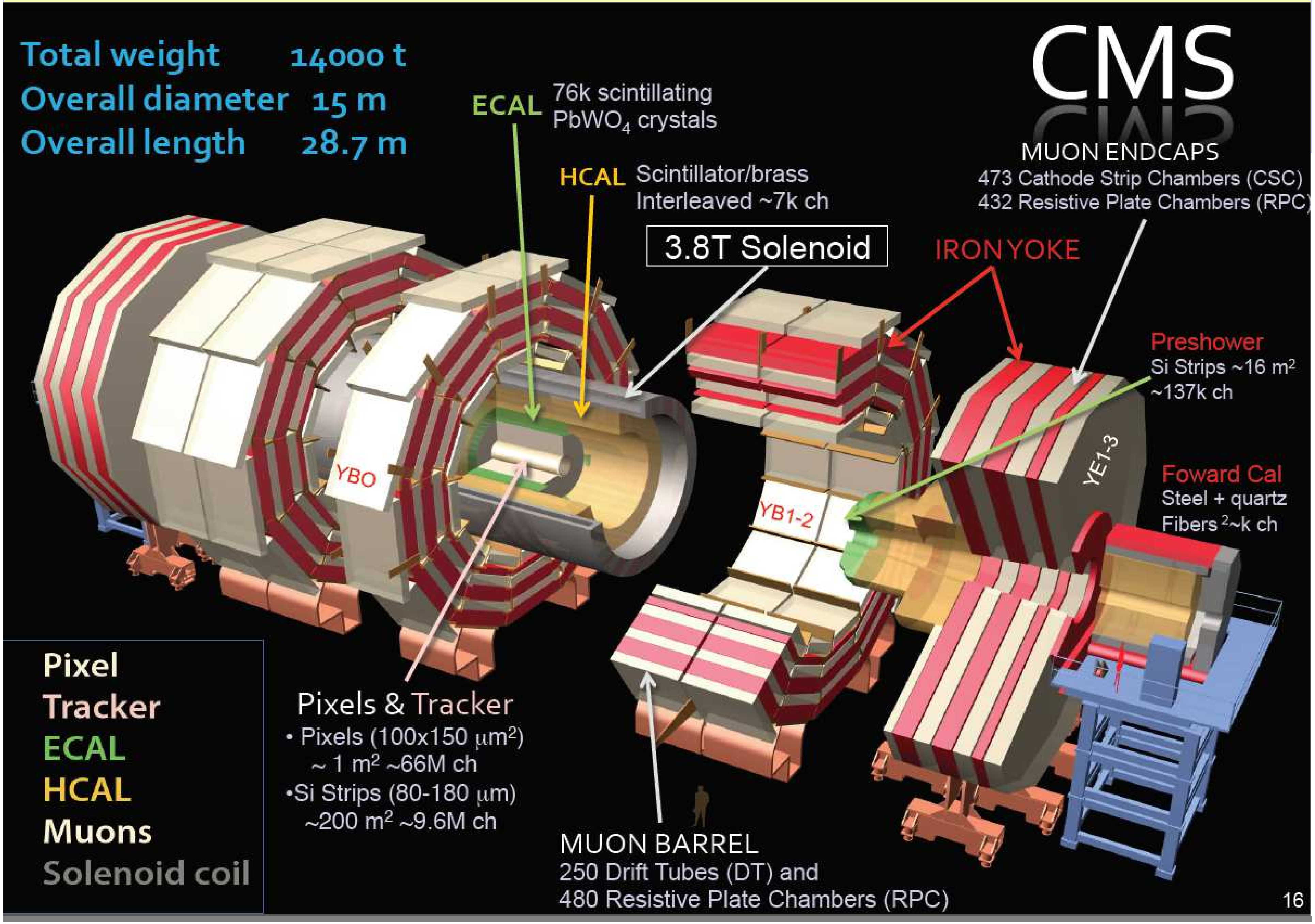
EM calorimeter: Pb-LAr Accordion.
e/γ trigger, identification and measurement
Energy resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity.
Fe/scintillator Tiles (central), Cu/W-LAr (forward).
Trigger and measurement of jets and missing E_T.
Energy resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

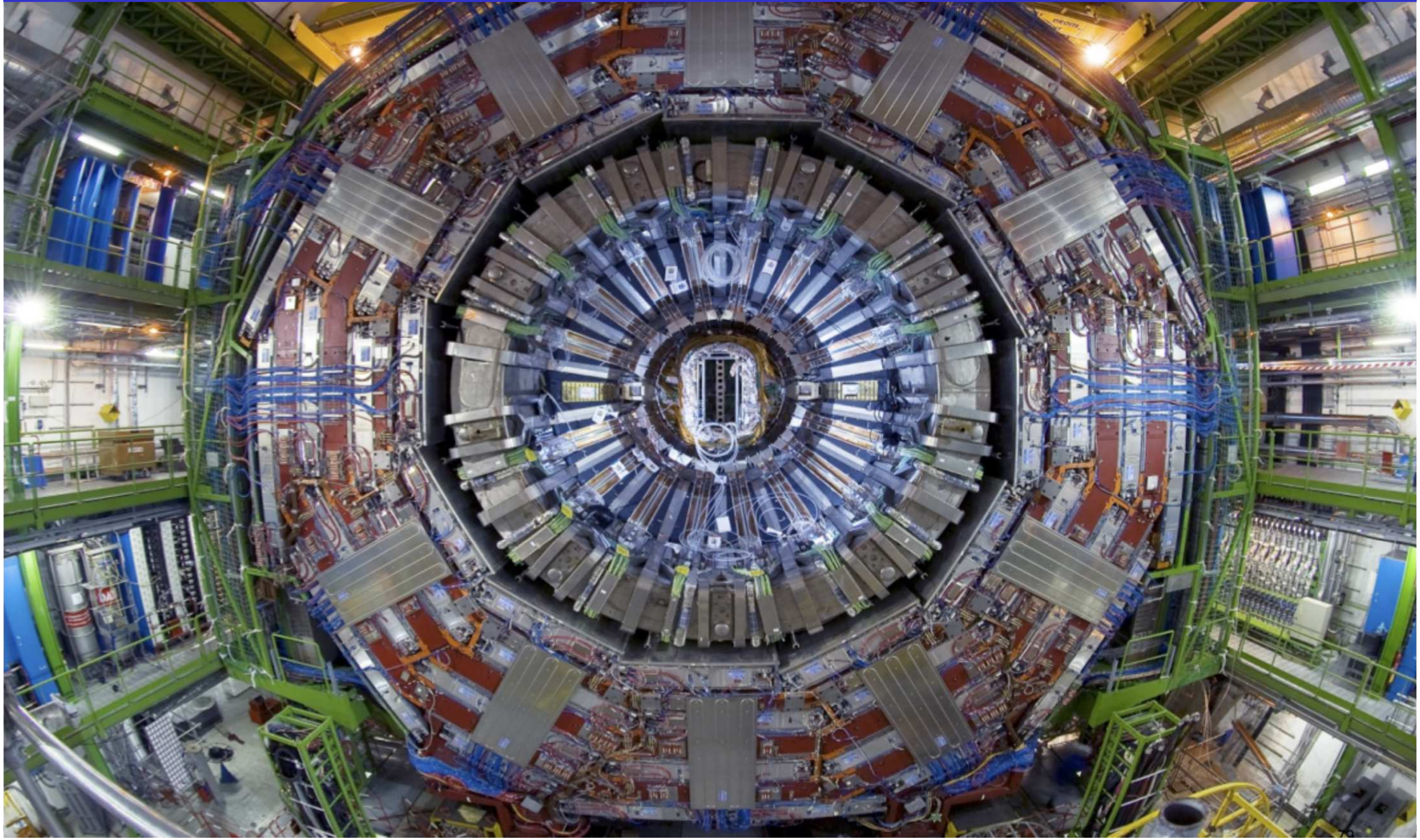
Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers.
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

3-level trigger reducing the rate from 40 MHz to ~200 Hz


L ~ 46 m, ∅ ~ 22 m, 7000 tons
~10⁸ electronic channels
Muon chambers
Calorimeters
Toroid coils


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL
76k scintillating PbWO4 crystals
HCAL
Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
IRON YOKE
Preshower
Si Strips ~16 m²
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers ²~k ch
YB0
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m² ~66M ch
•Si Strips (80-180 μm)
~200 m² ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)
16

The CMS detector

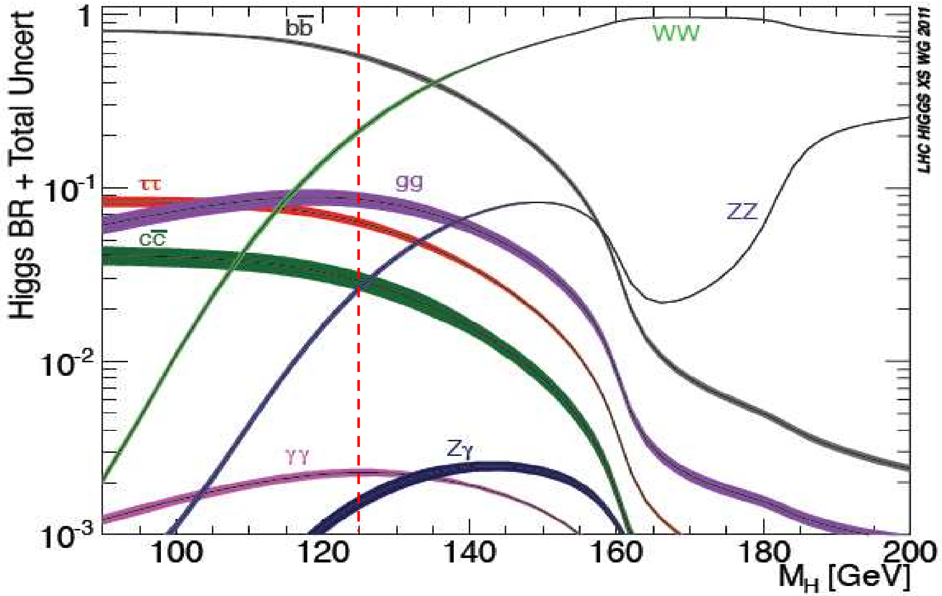


ATLAS/CMS

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\mathrm{x}10^{-4}\ p_T \oplus 0.01$	Si pixels + strips B=4T $\sigma/p_T \sim 1.5\mathrm{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

SM-Higgs decay

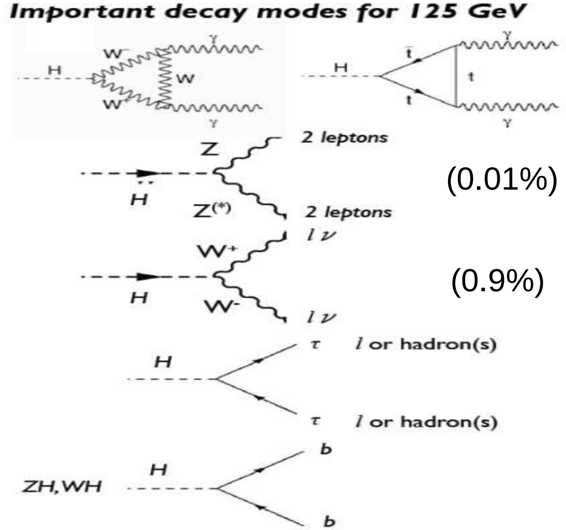
SM Higgs: decay braching ratio (BR) in %



Branching ratios at 125 GeV:

bb:	57.7%	ZZ:	2.6%
WW:	21.5%	$\gamma\gamma$:	0.23%
$\tau\tau$:	6.3%		

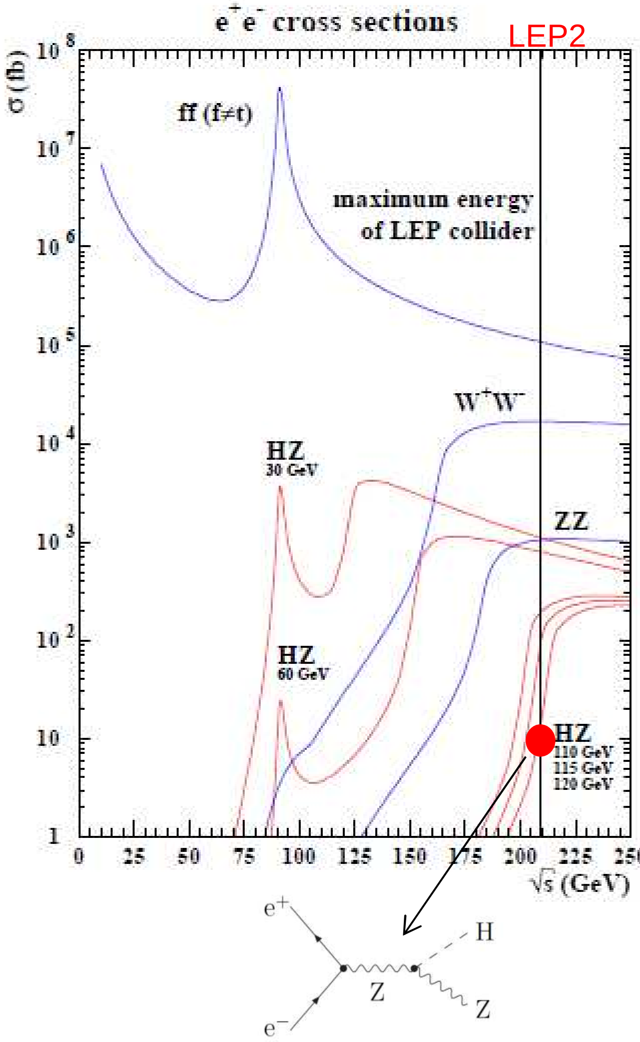
Important decay modes for 125 GeV



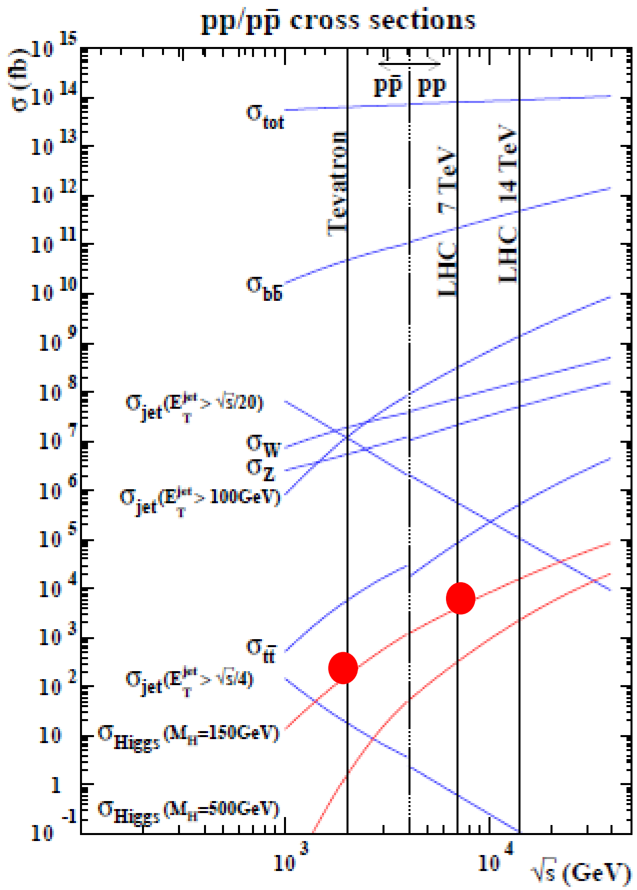
(0.01%)

(0.9%)

Production cross-sections



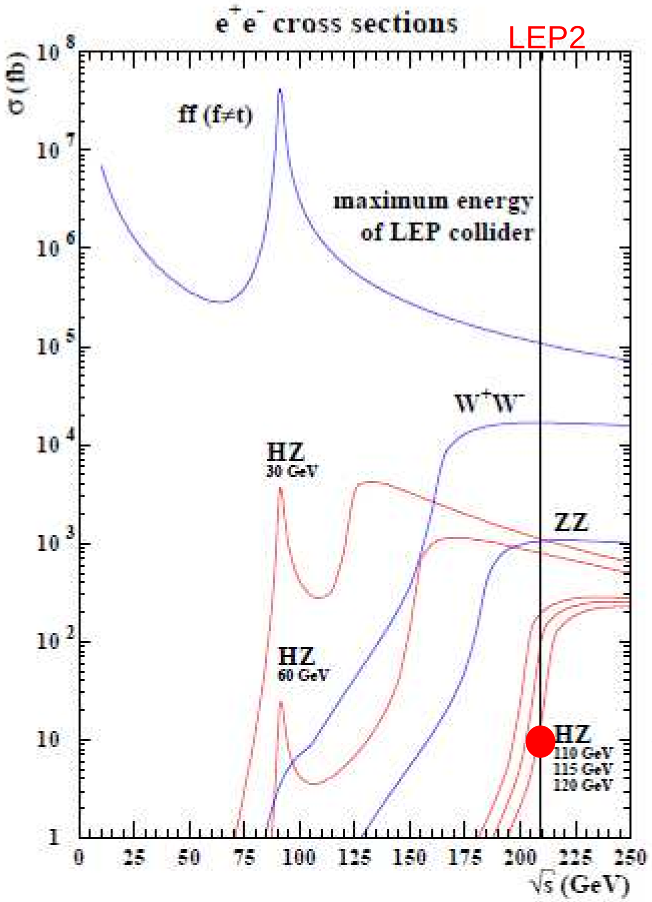
S/B~10^{-4}



S/B~10^{-10}

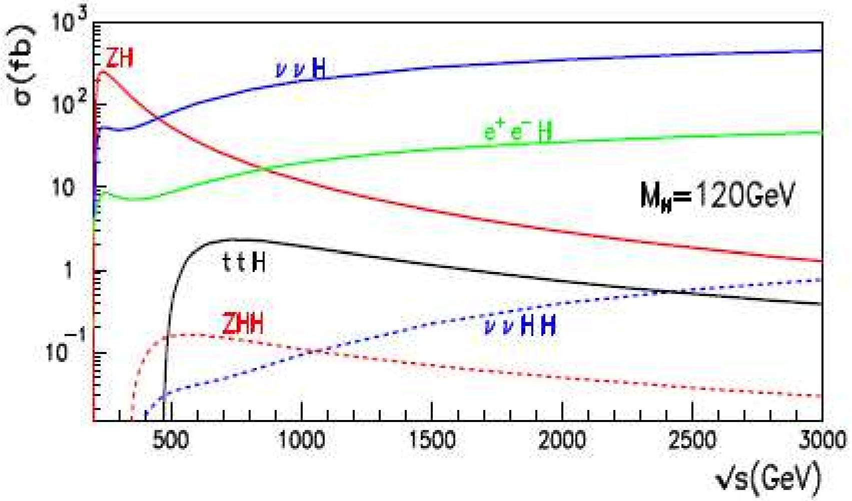
→ Production at LHC for m_H~120 GeV is 2000 times higher than at LEP2 but S/B much worse!

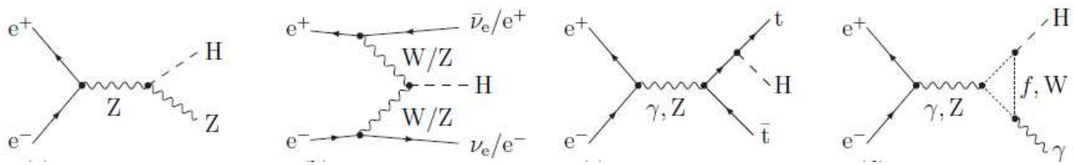
Production cross-sections



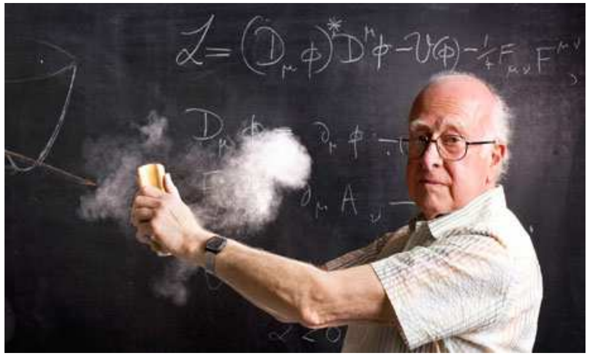
S/B~10^{-4}

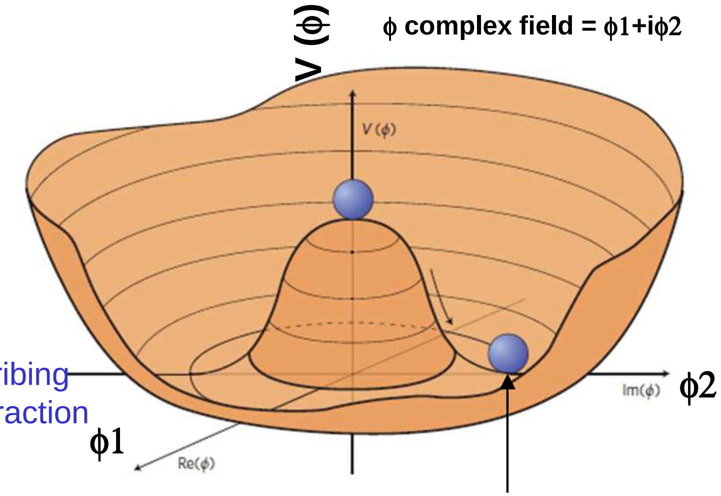
Future e+e- collider ?





Higgs field





ϕ complex field = ϕ1+iϕ2

vev = value minimising the Higgs potential

ϕ1=0, ϕ2=v/√2
→ symmetry broken

Interactions between gauge particles and Higgs field

Potential describing Higgs self-interaction

$$\mathcal{L}_{\rm H} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$$V(\Phi) = -\mu^2 (\Phi^\dagger \Phi) + \frac{\lambda}{4} (\Phi^\dagger \Phi)^2$$

with $\lambda>0$ and $\mu^2>0$

→ Vacuum expectation value $v = 2\sqrt{\frac{\mu^2}{\lambda}}.$ $\xrightarrow{\text{SM}}$ $v = \frac{1}{(\sqrt{2}G_F)^{1/2}} = \frac{2m_{\rm W}}{g}.$ = 246 GeV

($g=e/s_W$)

→ Higgs mass $M_{\rm H} = \sqrt{2\mu^2},$

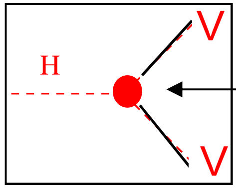
$$\cos\theta_{\rm w} = c_{\rm w} = \sqrt{1-s_{\rm w}^2} = \frac{g}{\sqrt{g^2+(g')^2}}, \qquad e = \frac{gg'}{\sqrt{g^2+(g')^2}}.$$

(g and g’ are the SU(2) and U(1) coupling constants)

→ M_H is the only free parameter in the SM Higgs sector (others fixed by weak gauge boson masses and gauge couplings)

SM Higgs couplings

❑ Gauge couplings (to bosons)

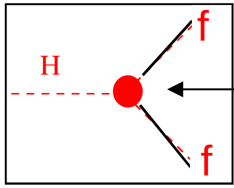


$-2i\, M_V^2/v$ → $-igM_W$ for W ; $-igM_Z/2c_W$ for Z

SM custodial symmetry $\rho = M_W^2/(c_W^2 M_Z^2) = 1$

$$\cos\theta_W = c_W = \sqrt{1 - s_W^2} = \frac{g}{\sqrt{g^2 + (g')^2}},$$ ~0.88

❑ Yukawa couplings (to fermions)



iM_f/v

→ Proportionality of Higgs couplings to all particle masses

$$v = \frac{1}{(\sqrt{2}G_F)^{1/2}} = \frac{2m_W}{g}.$$

❑ SM Higgs partial widths:

(total width Γ_H @125 GeV = 4 MeV, dominated by bb ~57%)

- Γ_{ff} α $(m_f/v)^2$
- Γ_{WW} α $(2\,M_W^2/v)^2$
- Γ_{ZZ} α $(M_Z^2/v)^2$
- Γ_{HH} α $(M_H^2/v)^2$
- $\Gamma_{\gamma\gamma}$ α $(1.6\,\Gamma_{WW} + 0.07\,\Gamma_{tt} - 0.7\,\Gamma_{Wt})$ → Wt interference
- Γ_{gg} α $(1.1\,\Gamma_{tt} + 0.01\,\Gamma_{bb} - 0.12\,\Gamma_{bt})$ → bt interference
- $\Gamma_{Z\gamma}$ α $(1.12\,\Gamma_{WW} + 0.003\,\Gamma_{tt} - 0.12\,\Gamma_{Wt})$ → Wt interference

Observables ↔ SM Higgs couplings

Production/ Decay	ggF	VBF	VH	ttH
$H \to ZZ$	$\kappa_g(\kappa_t, \kappa_b) \cdot \kappa_Z$	$\kappa_{VBF}(\kappa_W, \kappa_Z) \cdot \kappa_Z$	$\kappa_V \cdot \kappa_Z$	$\kappa_t \cdot \kappa_Z$
$H \to WW$	$\kappa_g(\kappa_t, \kappa_b) \cdot \kappa_W$	$\kappa_{VBF}(\kappa_W, \kappa_Z) \cdot \kappa_W$	$\kappa_V \cdot \kappa_W$	$\kappa_t \cdot \kappa_W$
$H \to bb$	$\kappa_g(\kappa_t, \kappa_b) \cdot \kappa_b$	$\kappa_{VBF}(\kappa_W, \kappa_Z) \cdot \kappa_b$	$\kappa_V \cdot \kappa_b$	$\kappa_t \cdot \kappa_b$
$H \to \tau\tau$	$\kappa_g(\kappa_t, \kappa_b) \cdot \kappa_\tau$	$\kappa_{VBF}(\kappa_W, \kappa_Z) \cdot \kappa_\tau$	$\kappa_V \cdot \kappa_\tau$	$\kappa_t \cdot \kappa_\tau$
$H \to \gamma\gamma$	$\kappa_g(\kappa_t, \kappa_b) \cdot \kappa_\gamma(\kappa_W, \kappa_t)$	$\kappa_{VBF}(\kappa_W, \kappa_Z) \cdot \kappa_\gamma(\kappa_W, \kappa_t)$	$\kappa_V \cdot \kappa_\gamma(\kappa_W, \kappa_t)$	$\kappa_t \cdot \kappa_\gamma(\kappa_W, \kappa_t)$

κ_F:Yukawa couplings

Pure Yukawa couplings

Pure Yukawa couplings [if no new physics in gluon loop]

κ_V: Gauge couplings

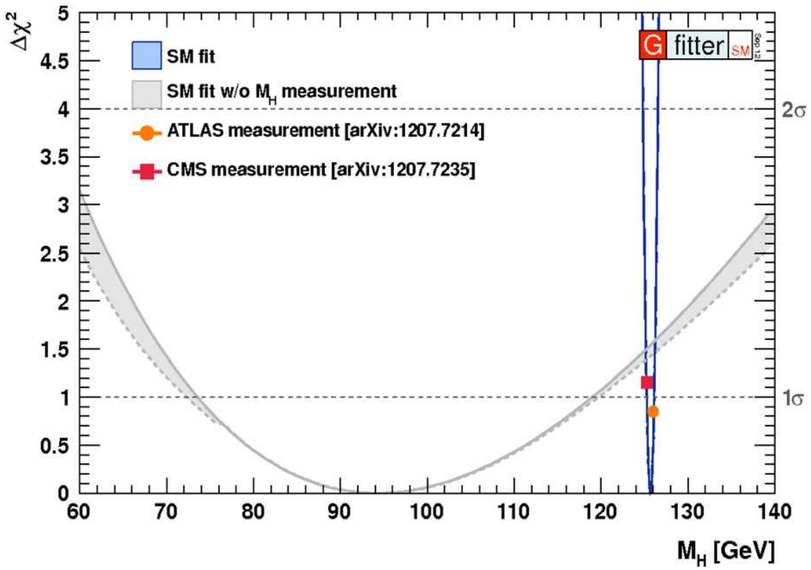
Pure Gauge couplings

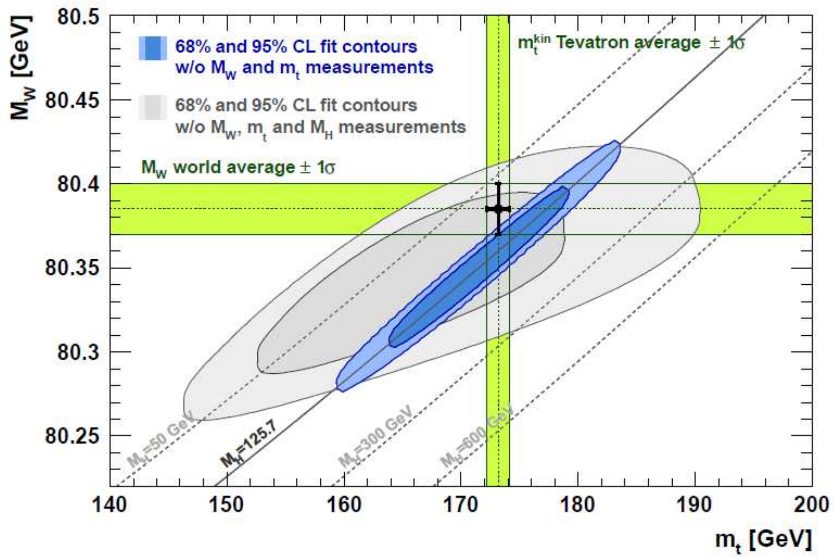
κ_g, κ_γ:Coupling to photon and gluon through loop diagrams. They are functions of the other κ_i in SM

A remarkably consistent picture

➢ Latest results from electroweak fit w/wo Higgs mass measurement

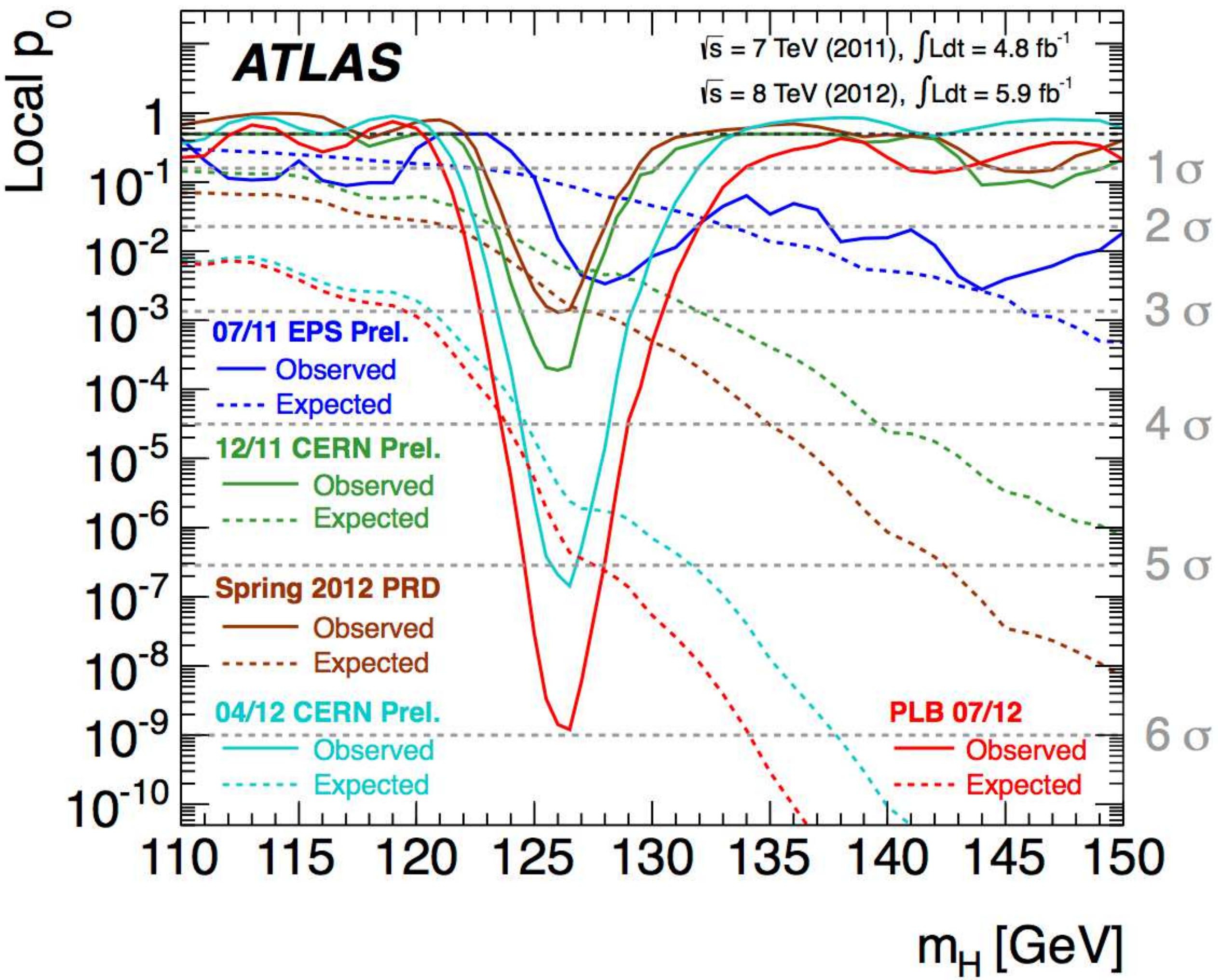
1209.2716



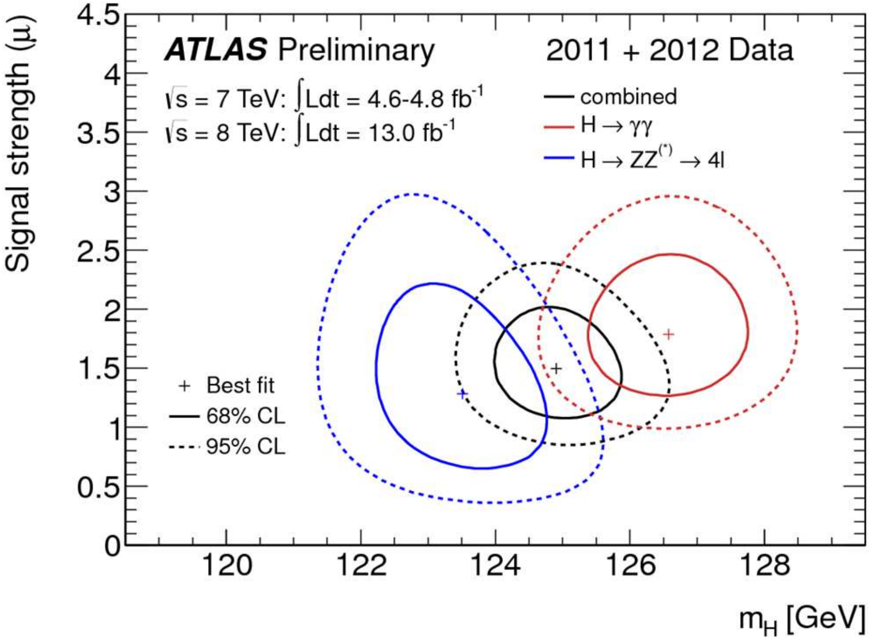


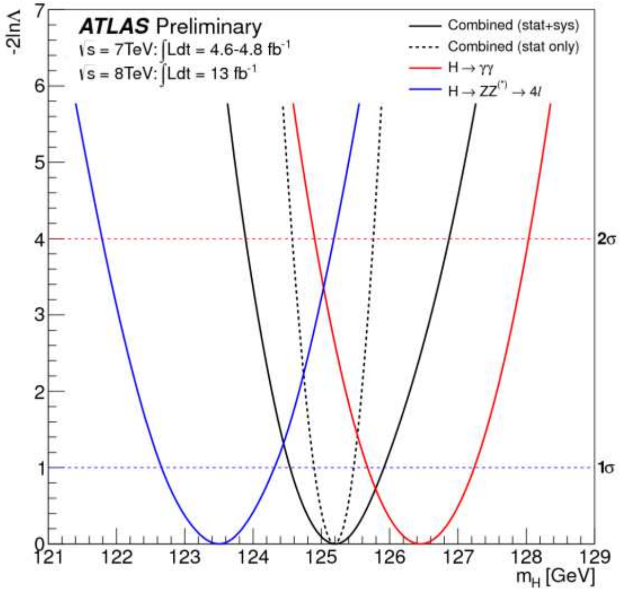
Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	$\boxed{94^{+25}_{-22}}$	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$

Evolution of excess with time
(July 2012)



ATLAS mass measurements





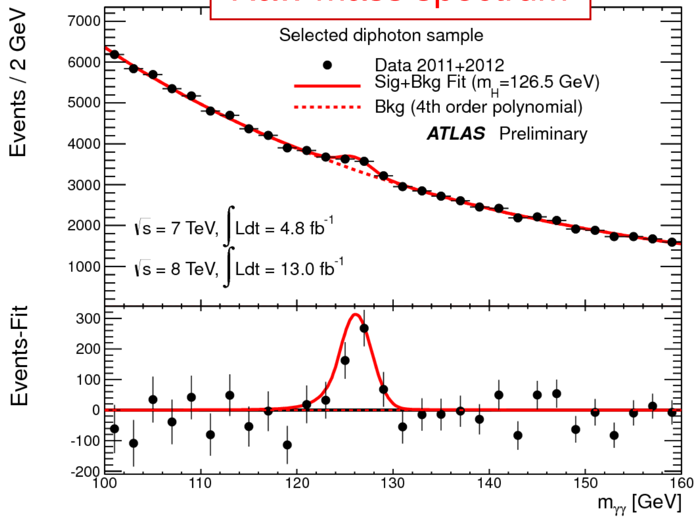
$$\Delta m_H = m_H(\gamma\gamma) - m_H(4\ell) = 3.0 \pm 0.8\,(\text{stat})\,^{+0.7}_{-0.6}\,(\text{syst})\,\text{GeV} = 3.0\,^{+1.1}_{-1.0}\,\text{GeV}$$

➔ **Taking mass scale systematic uncertainties and their correlations into account, compatibility of the two measurements estimated at 2.7σ level (~0.8% probability)**

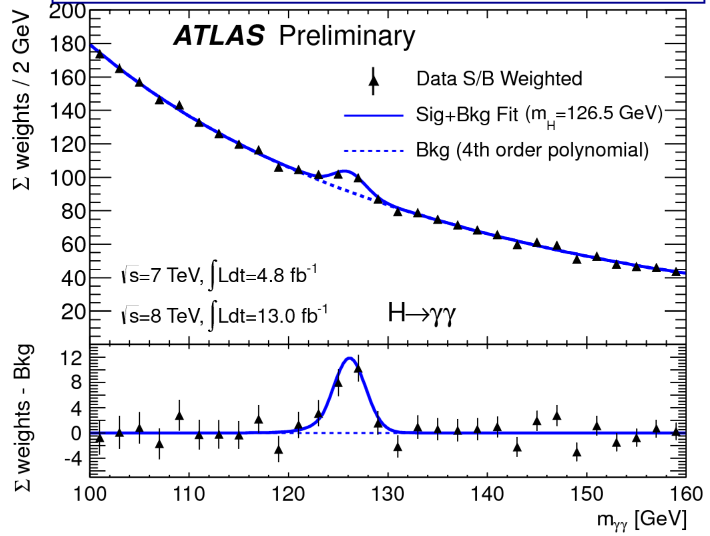
[an alternative treatment of systematics yields a compatibility at 2.3σ level]

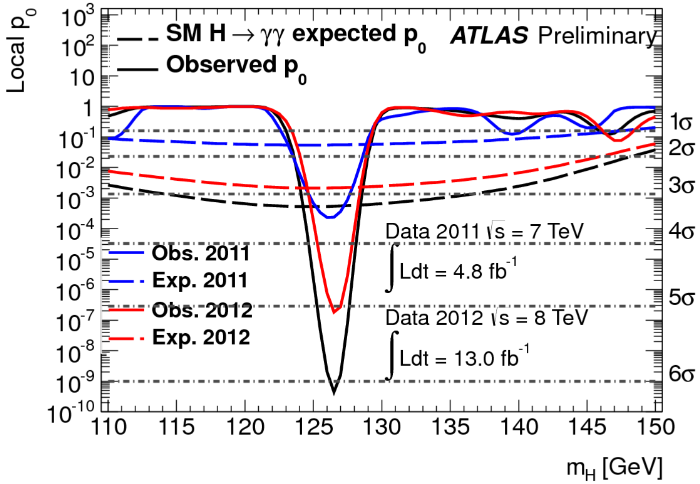
H→γγ : ATLAS latest results (Dec. 2012)

Raw mass spectrum



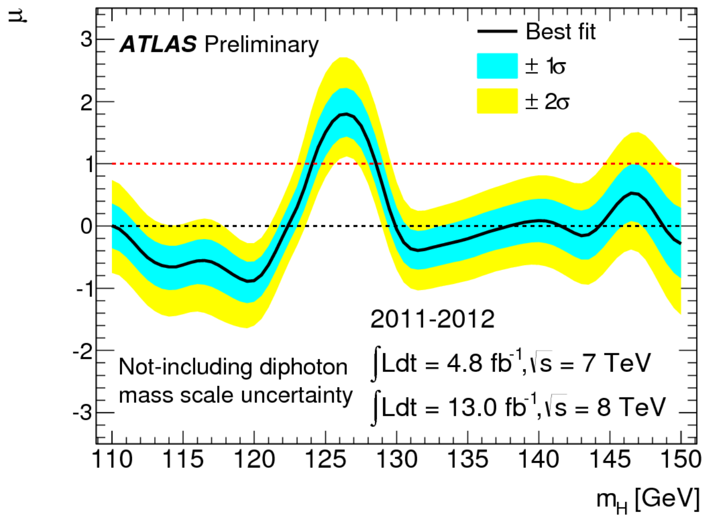
Weighted mass spectrum: w_i=ln(1+S/B)

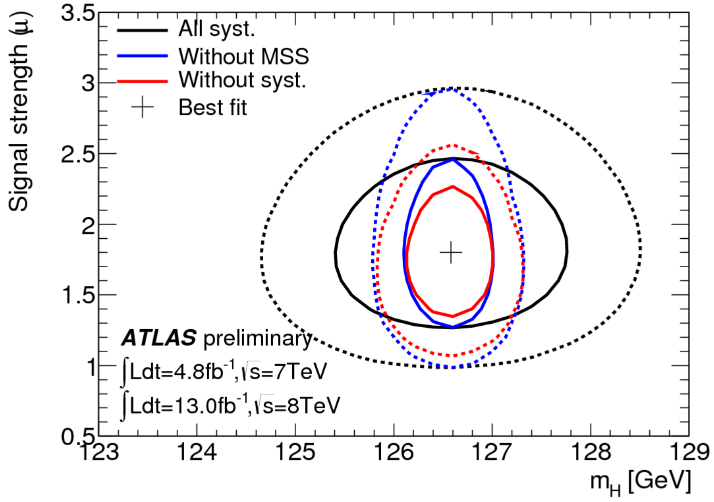




➔ **Local excess 6.1σ** (3.3σ expected for SM Higgs)
Global excess 5.4σ

H→γγ : ATLAS latest results (Dec. 2012)





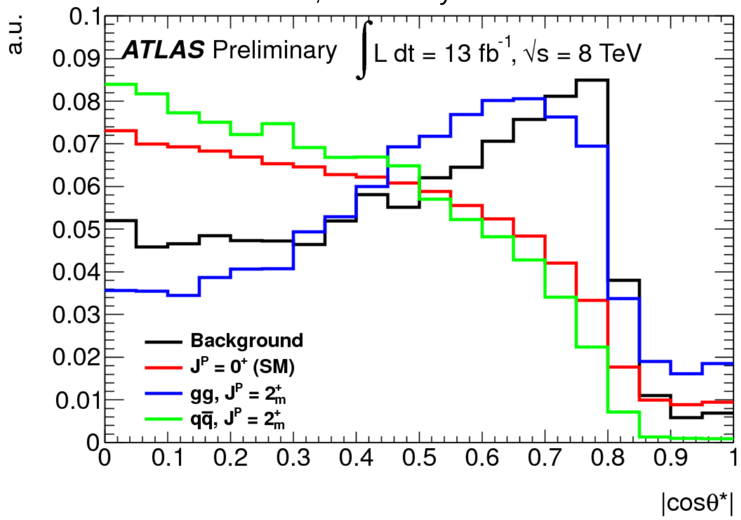
$\mu = 1.80 \pm 0.3\ \text{(stat)}\ ^{+0.21}_{-0.15}\ \text{(syst)}\ ^{+0.20}_{-0.14}\ \text{(theory)}$ **@126 GeV**

[~2.4σ from SM Higgs + bknd hypothesis]

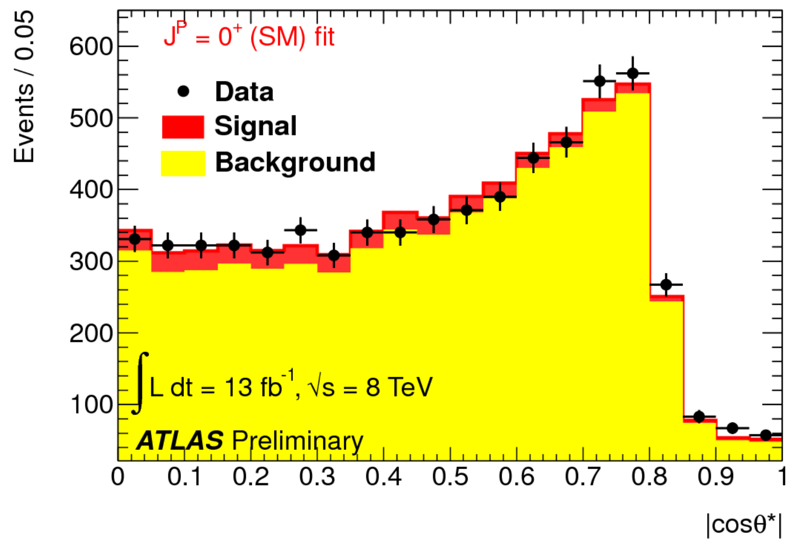
Best mass fit: **126.6 ± 0.3 (stat) ± 0.7 (syst) GeV**

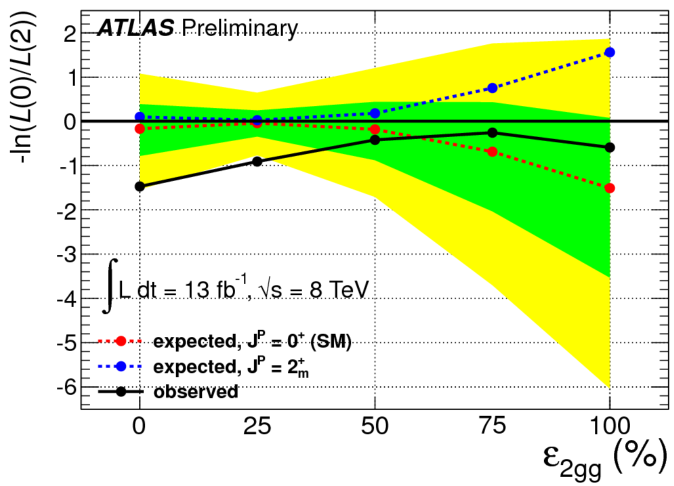
H→γγ : ATLAS latest results (Dec. 2012)

Simulations, after analysis selection cuts



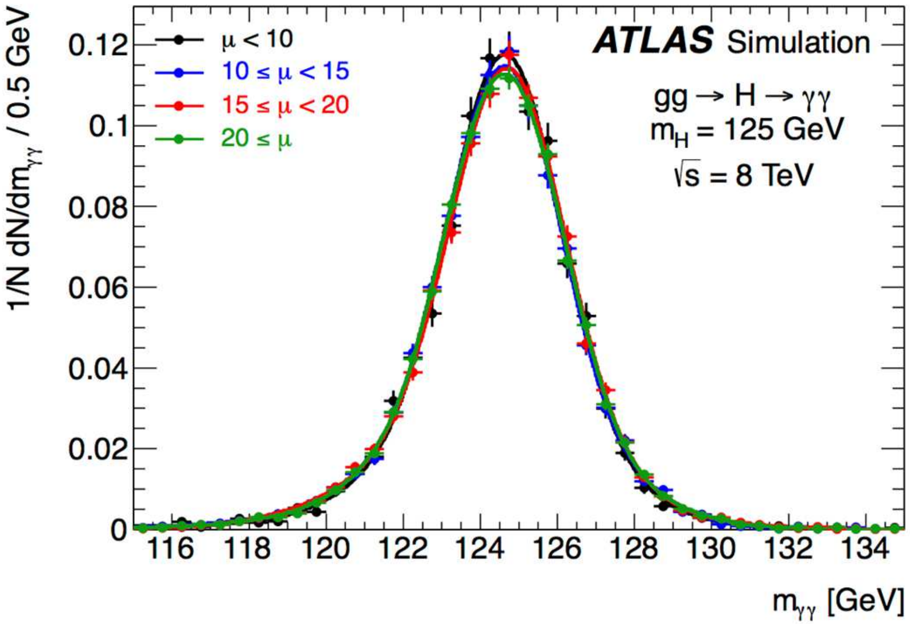
Fit to data for SM signal + background hypothesis

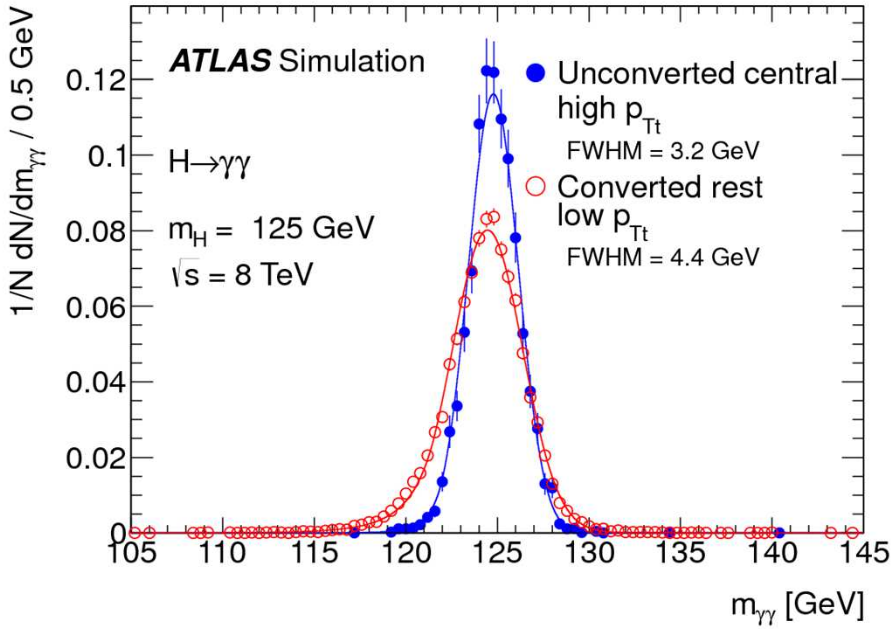




Results with 5 different fractions of gluon initiated process for spin-2 resonance production

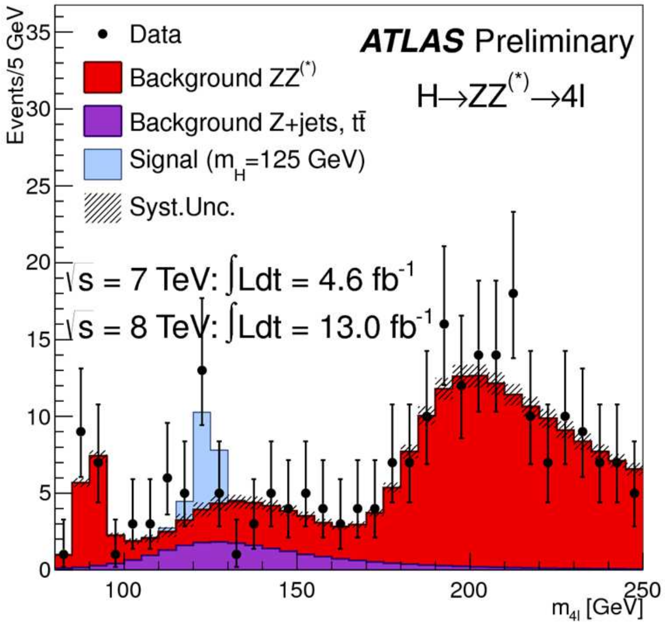
H→γγ : ATLAS mass resolution

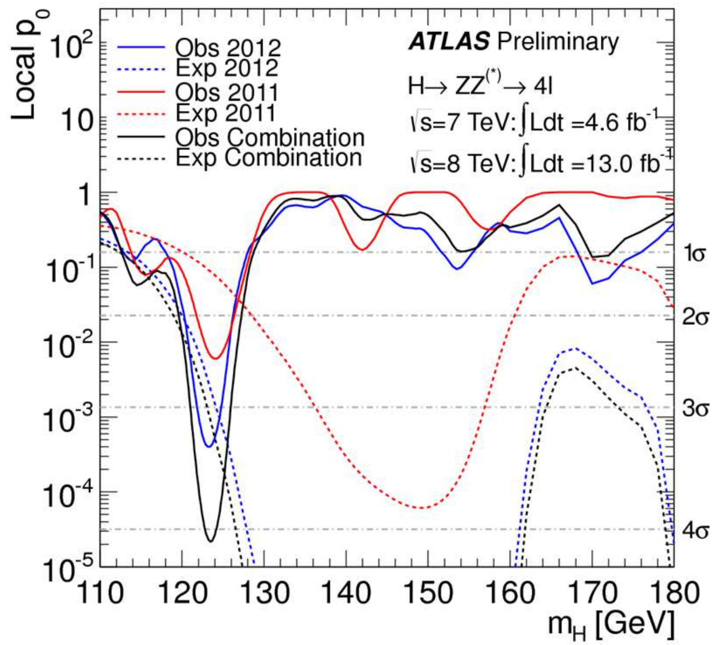


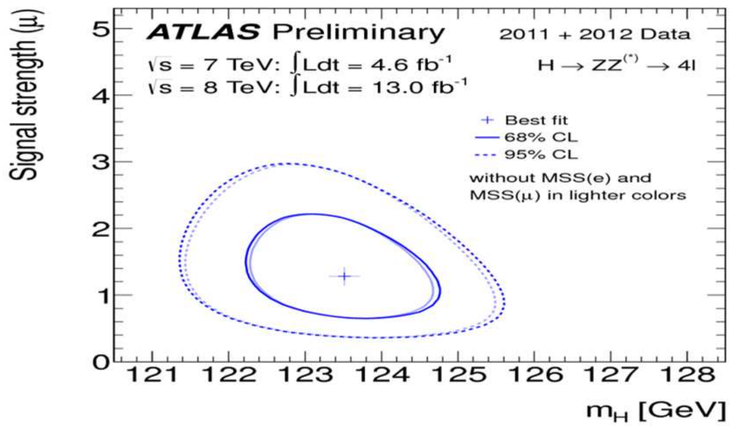


- (Inclusive) mass resolution: 1.6 GeV
- Pile-up robust
- Fraction of events within ±2σ: 90%
- S/B in window containing 90% of signal: ~3%

H→ZZ : ATLAS latest results (Dec. 2012)





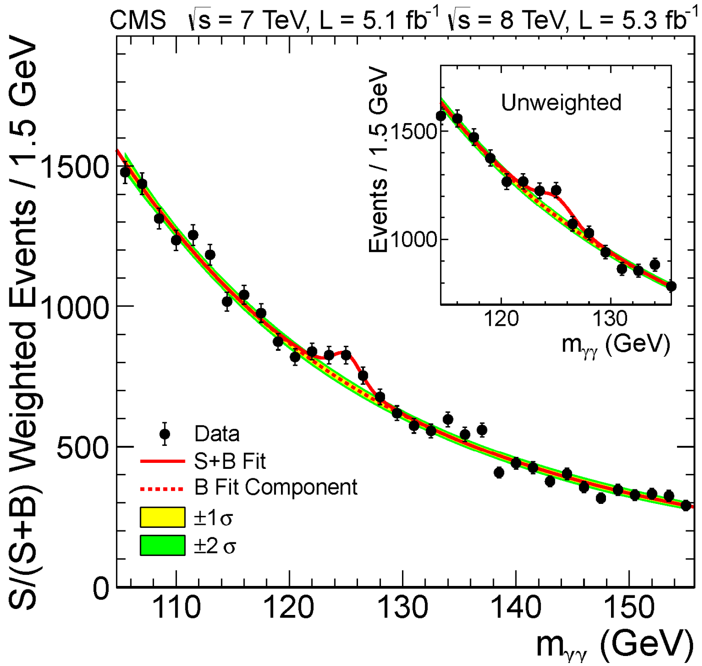


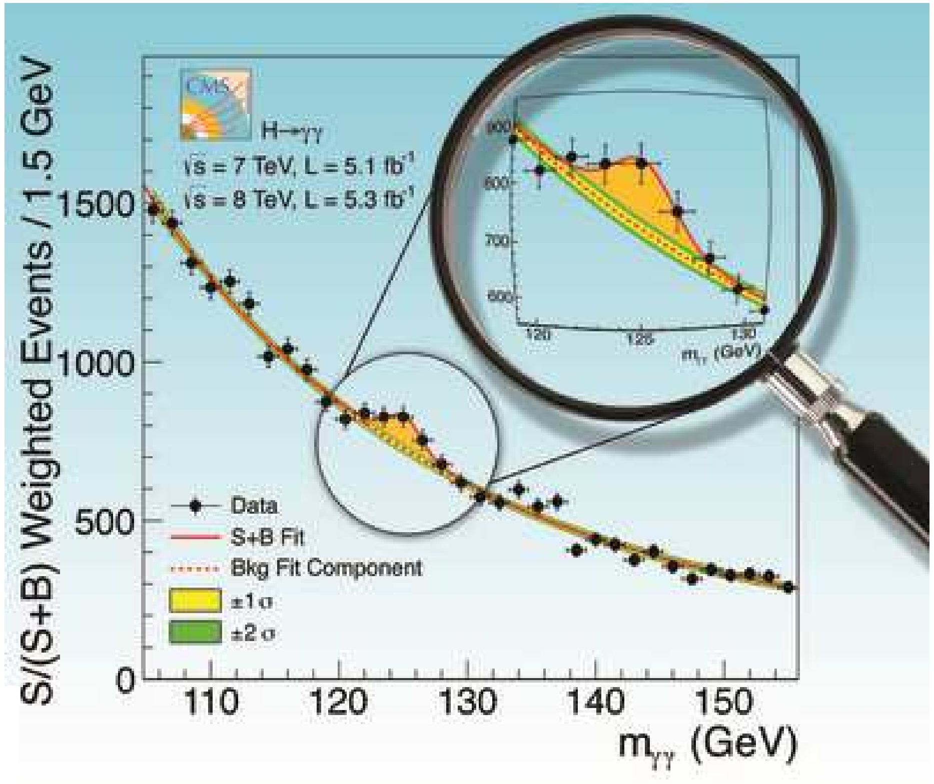
Local excess 4.1σ (3.1σ expected for SM Higgs)

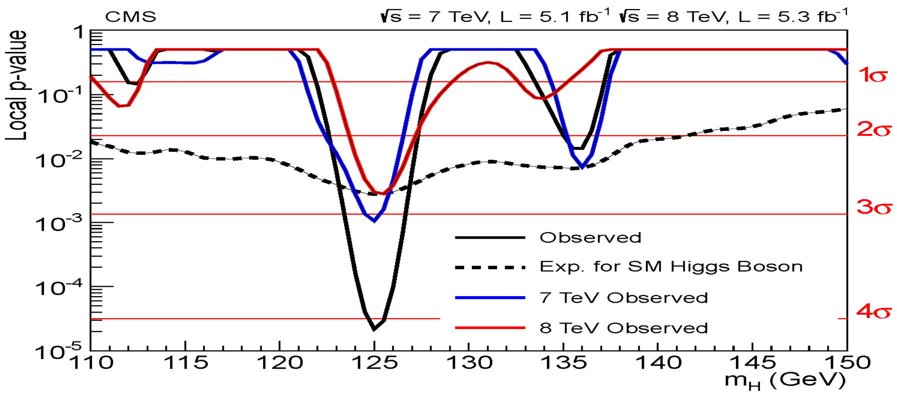
Best mass fit: **123.5 ± 0.9 (stat) ± 0.3 (syst) GeV**

μ= 1.3$^{+0.5}_{-0.4}$ @123.5 GeV

CMS results H→γγ



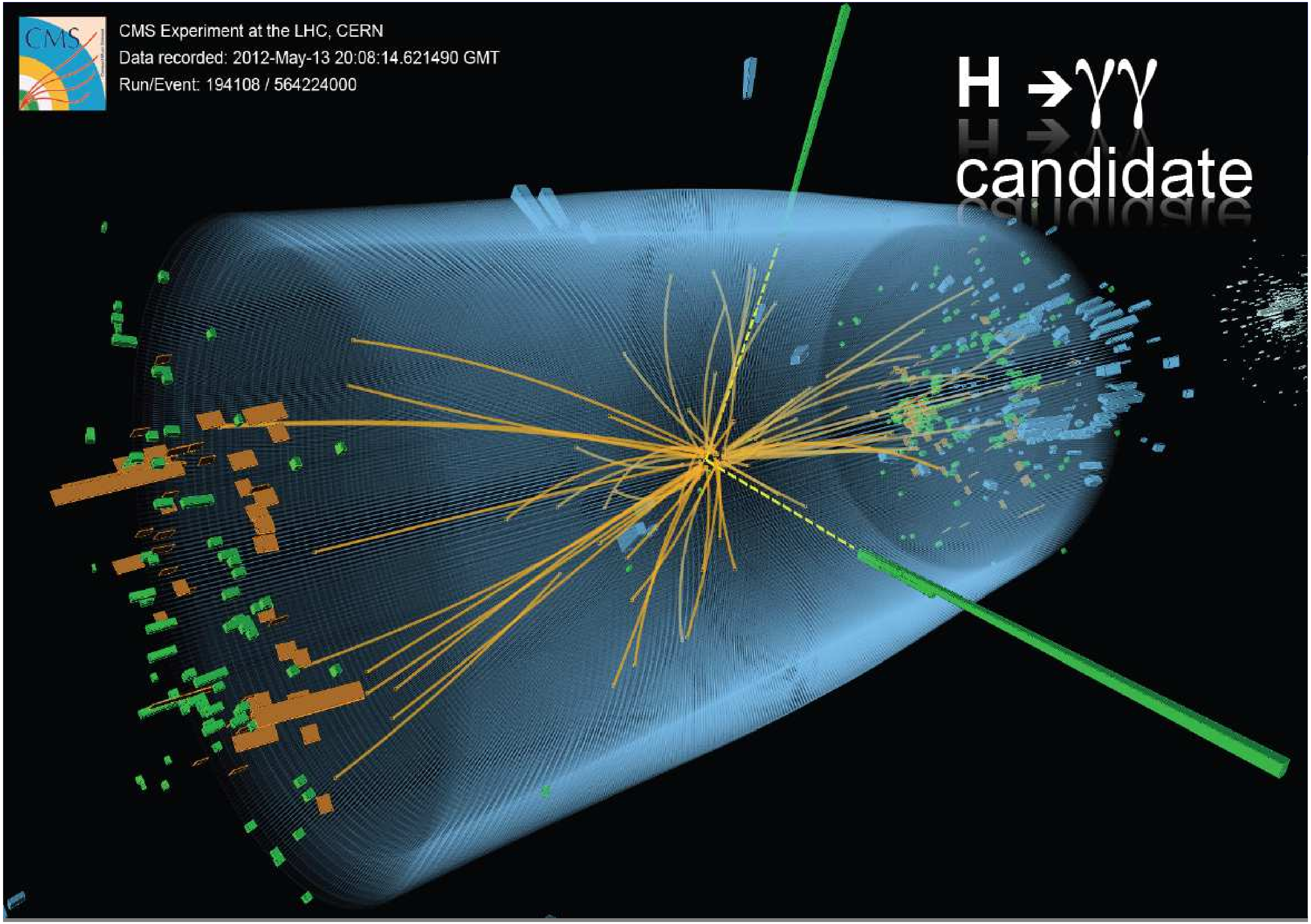




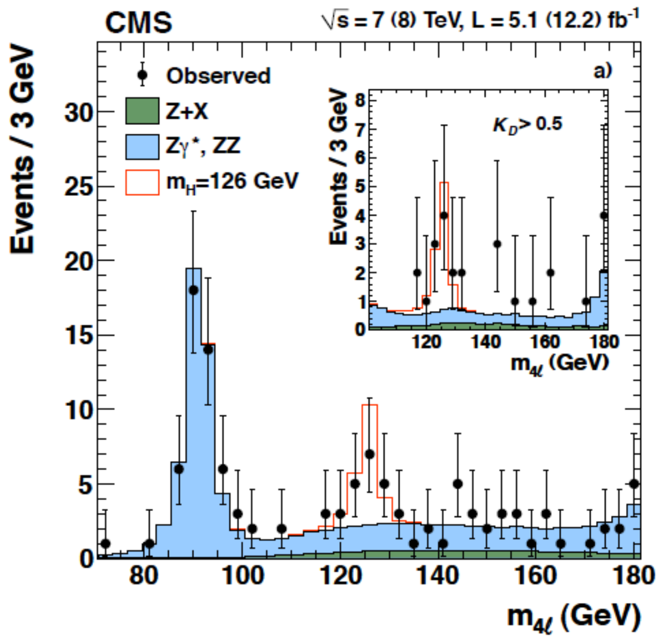
➔ **4.1σ** (2.8σ expected) local - **3.2σ** global

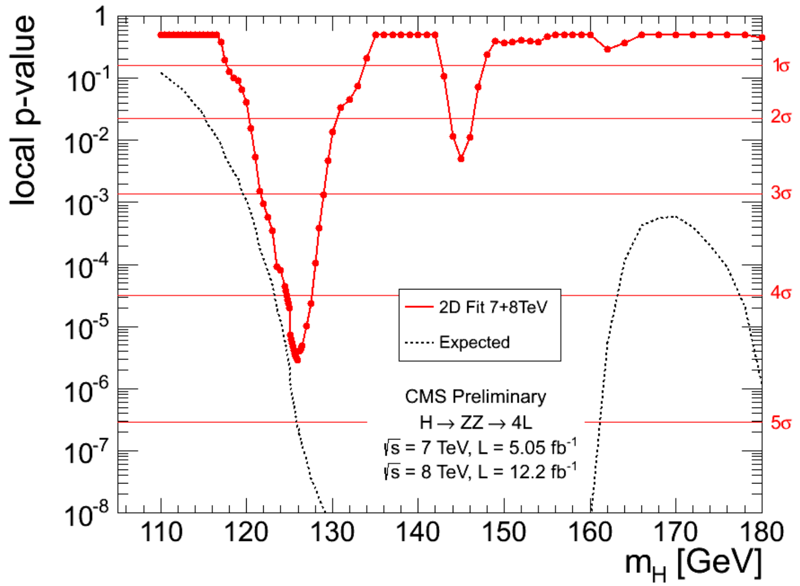
➔ **μ=1.6±0.4 @ 125 GeV**

Best mass fit: **125.1 ± 0.4 (stat) ± 0.6 (syst) GeV**


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

CMS results H→ZZ (Nov. 2012)





For m(4l) = 121.5..130.5 GeV:

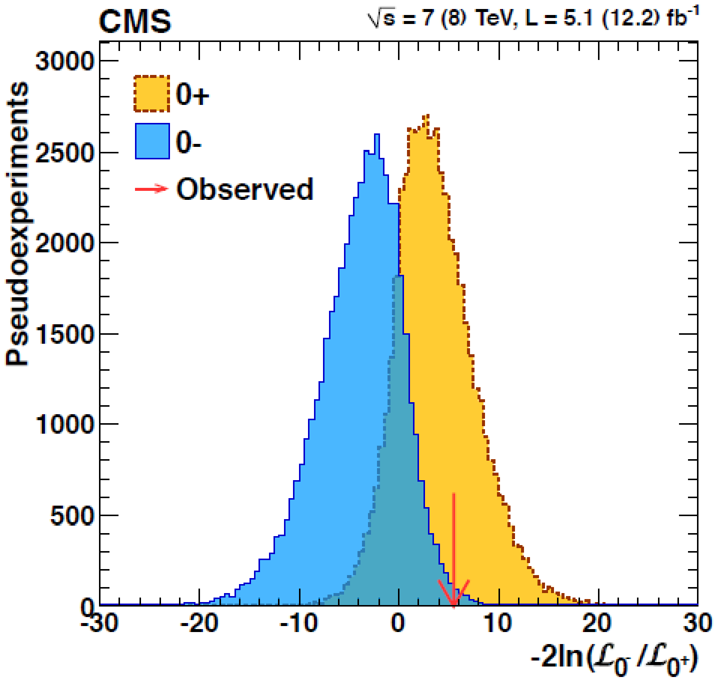
- Expected background: 6.5 events
- Expected signal (mH=126 GeV): 12.5 events
- Signal:Bckg ~ 2:1
- Observed: 17 events

➔ **4.5σ** (5.0σ expected) local

➔ **μ=0.8±0.3 @ 126 GeV**

Best mass fit: **126.2 ± 0.6 (stat) ± 0.2 (syst) GeV**

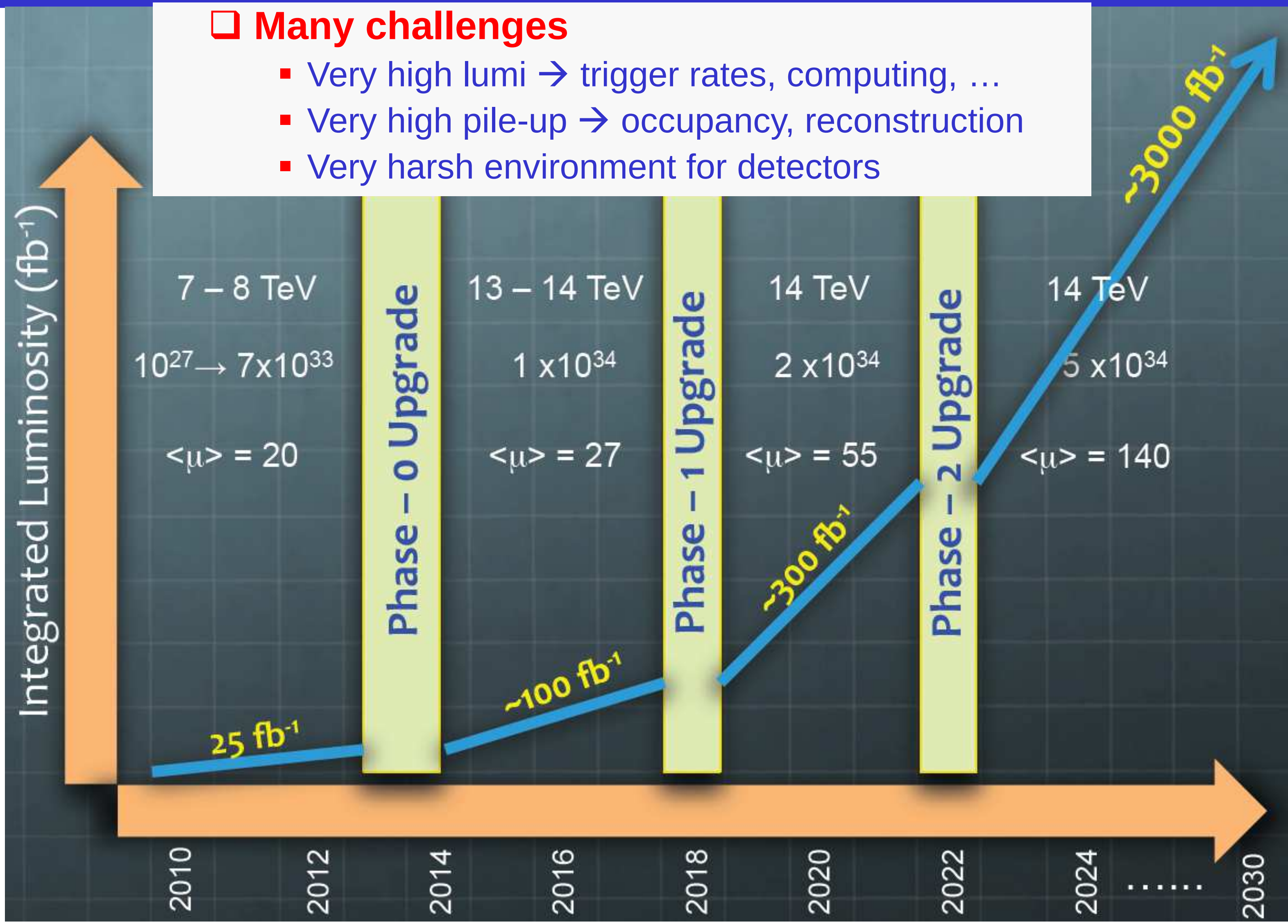
CMS results H→ZZ (Nov. 2012)



Pseudoscalar hypothesis (0^-) excluded at 2.5σ level (under the assumption that the new boson has spin 0)

LHC and HL-LHC projections

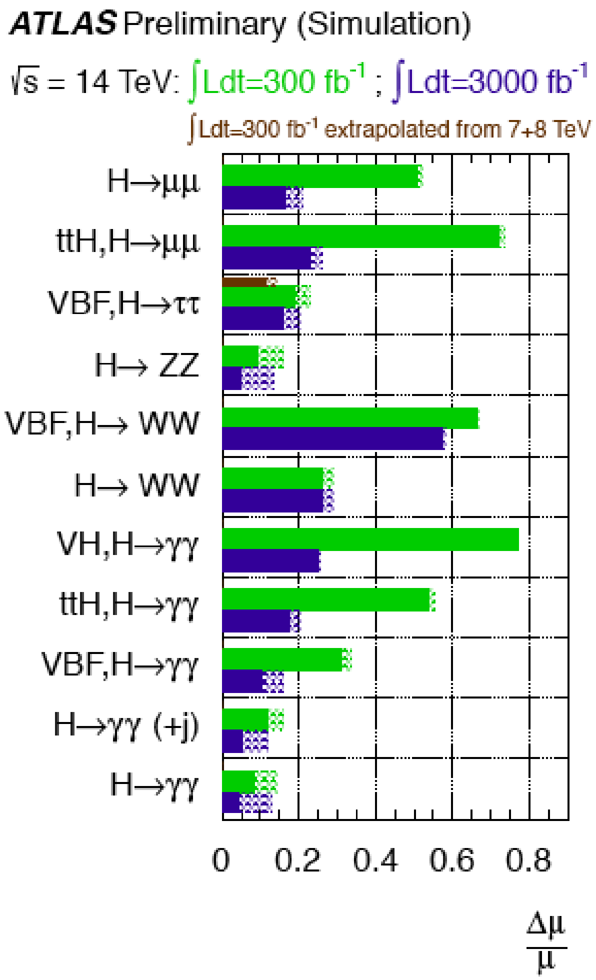
- **Many challenges**
  - Very high lumi → trigger rates, computing, …
  - Very high pile-up → occupancy, reconstruction
  - Very harsh environment for detectors

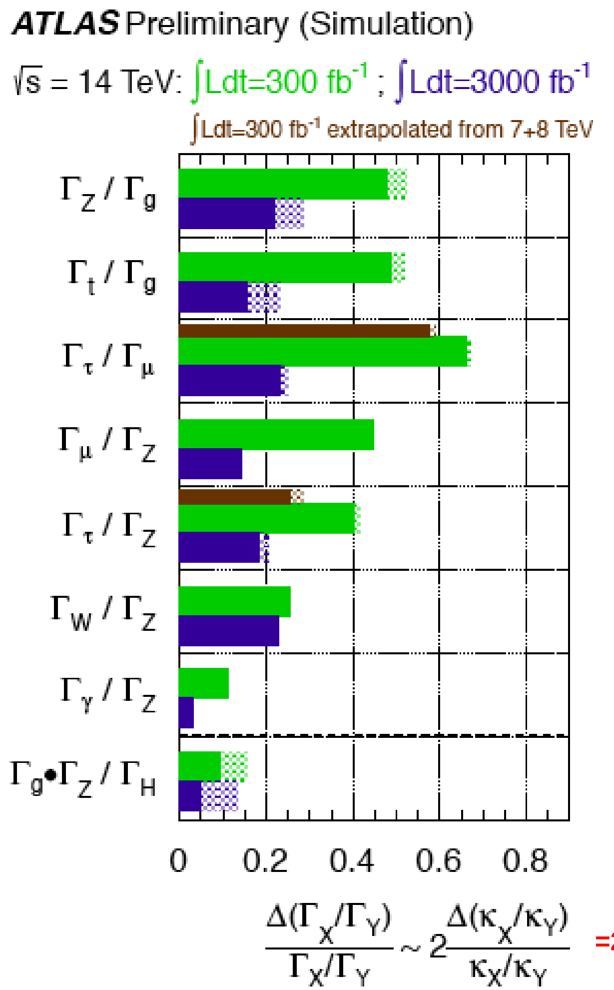


Higgs couplings at HL-LHC

[very preliminary results]

General coupling fit (no assumption)





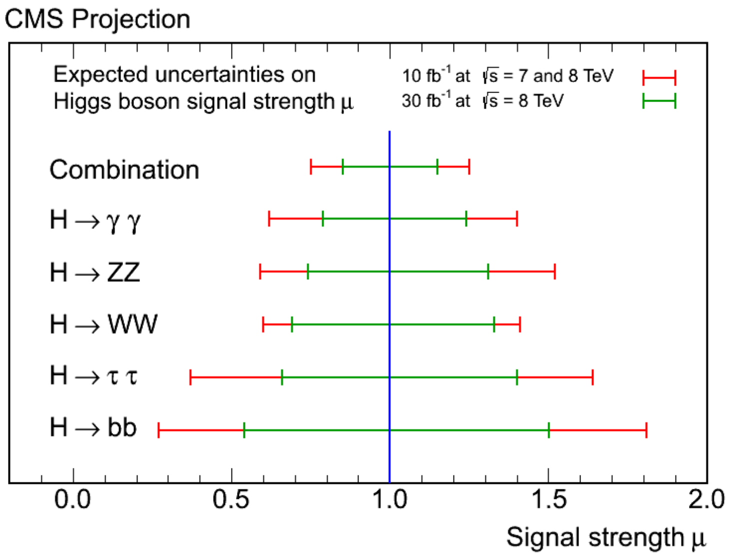
$=2\Delta(g_{HXX}/g_{HYY})/(g_{HXX}/g_{HYY})$

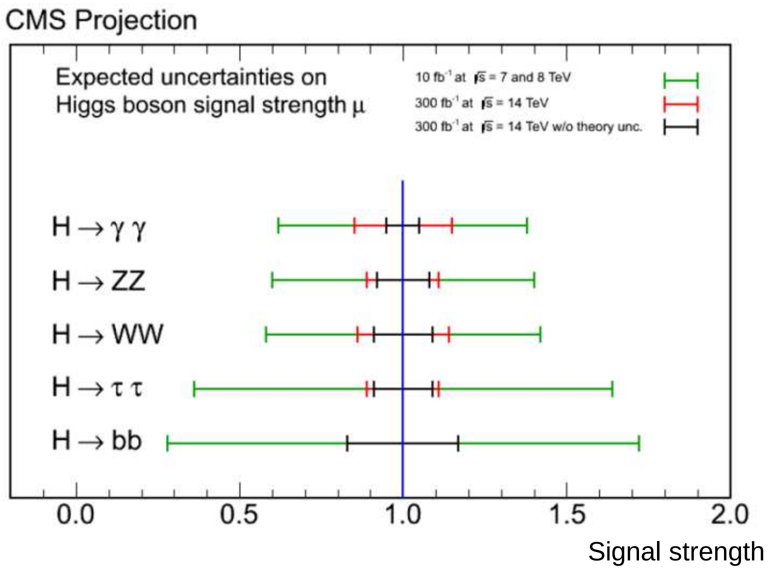
Higgs couplings at HL-LHC

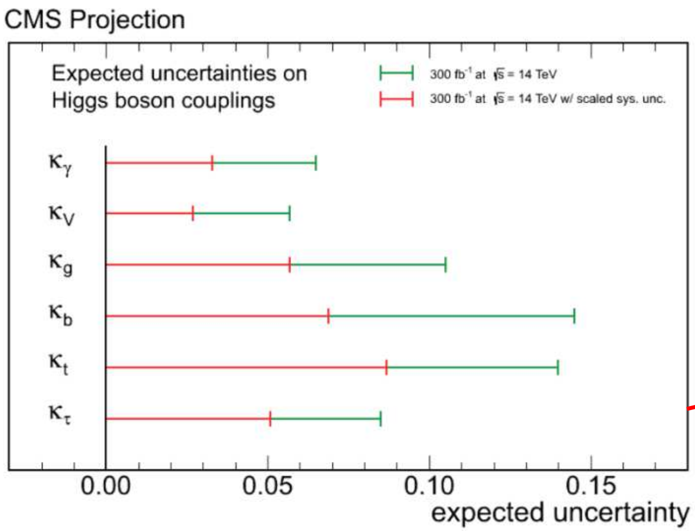
[very preliminary results]

Minimal coupling fit (assumptions!)

[NO invisible/undetectable contribution to Γ_H]







Coupling	Uncertainty (%)			
	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Scenario 1:
- 2012 systematics

Scenario 2:
- theory syst: scaled by a factor ½
- other systematics scaled by 1/√L

Precision needs on Higgs couplings

- X(125 GeV) discovery in 2012
- No sign of new physics in direct searches

→ Measure Higgs couplings as precisely as possible: indirect hints of New Physics/SUSY if deviations

→ Search for heavier particles predicted by BSM theories

❑ Which precision on Higgs couplings would be desirable?

- New physics can lead to modified couplings (e.g. SUSY, composite Higgs)
- Percent level measurements would be sensitive to new physics at the TeV scale
  - Multi-TeV new physics needs sub-percent precision
  - Some models/parameters can give effects of O(5%)

→ more details in P. Janot seminar: http://indico.cern.ch/conferenceDisplay.py?confId=214133

- Remark: a mass measurement to O(100 MeV) is enough and does not contribute to coupling uncertainties [current impact on signal strength < 4%]
- Theoretical uncertainties (mostly QCD) need improvements [BR 3-6%]

  [Theory systematics ~15% for ggF and ttH (~5% for VBF and VH) production modes]

m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.9	3.
$\tau\tau$	6.4	6.
cc	2.8	12.
$\mu\mu$	0.022	6.
WW	21.6	4.
gg	8.2	10.
ZZ	2.6	4.
$\gamma\gamma$	0.27	5.
$Z\gamma$	0.16	9.
Γ_H [MeV]	4.0	4.

Precision needs on Higgs couplings

@ **P. Janot**: CERN seminar http://indico.cern.ch/conferenceDisplay.py?confId=214133

- **Couplings (cont'd)**
  - Typical tree-level coupling modifications from SUSY
    - Pseudo-scalar A very hard to find at the LHC for moderate tanβ and m_A > 200 GeV

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4 \quad \frac{g_{htt}}{g_{h_{SM}tt}} = \frac{g_{hcc}}{g_{h_{SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 \quad \frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

➨ Large effect on Hbb and Hττ coupling

$$\boxed{\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2}$$

(tanβ=5)

To be measured a priori as precisely as possible

Essentially decoupled from Electroweak Precision Measurements

  - Typical coupling modifications from composite Higgs models
    - All couplings reduce together according to the compositeness scale f

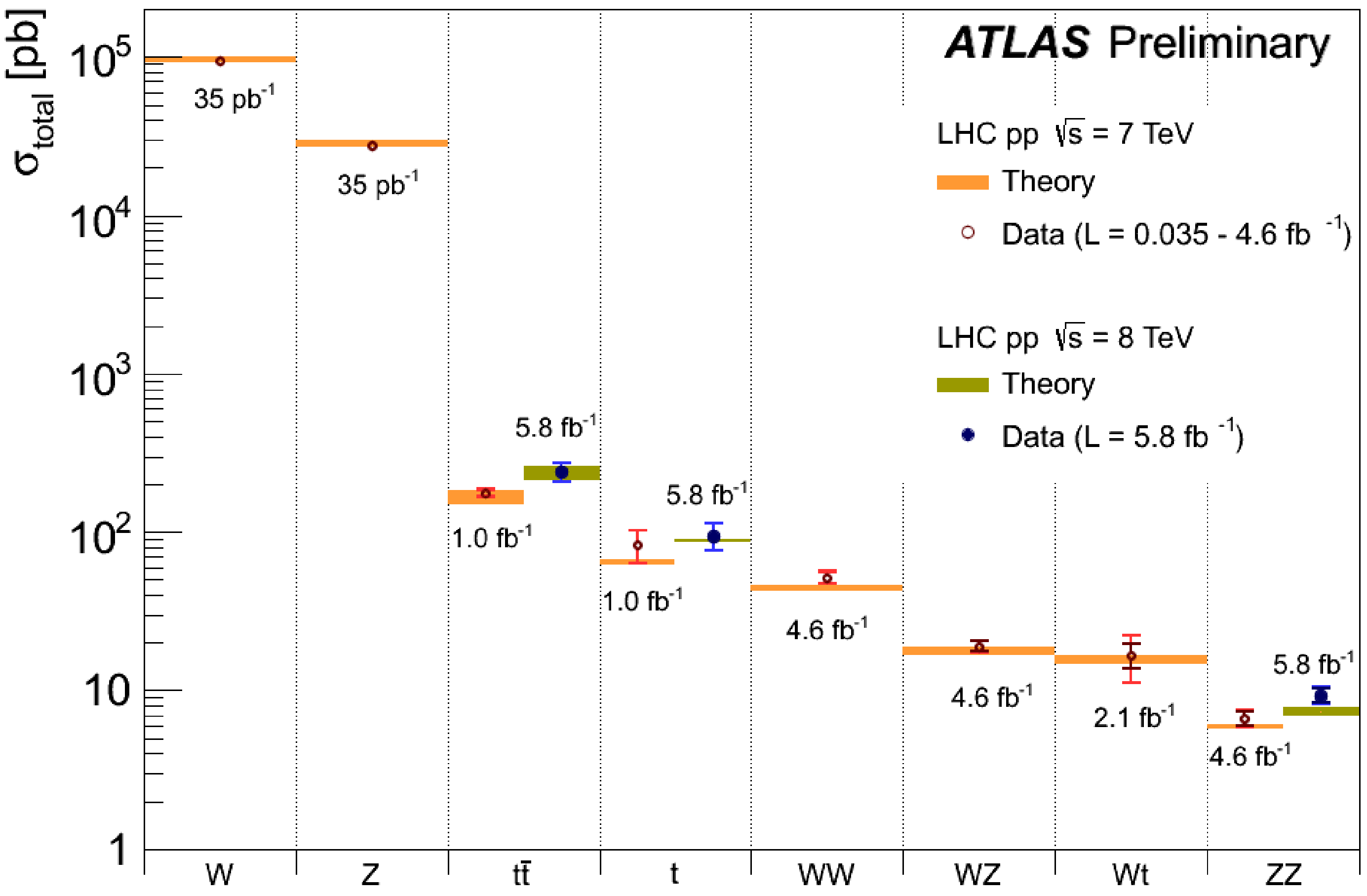
$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

To be measured a priori as precisely as possible

Eventually visible in Electroweak (High) Precision Measurements

More details: H. Baer et al., "Physics at the International Linear Collider", in preparation, see http://lcsim.org/papers/DBDPhysics.pdf

Electroweak and top cross-section measurements

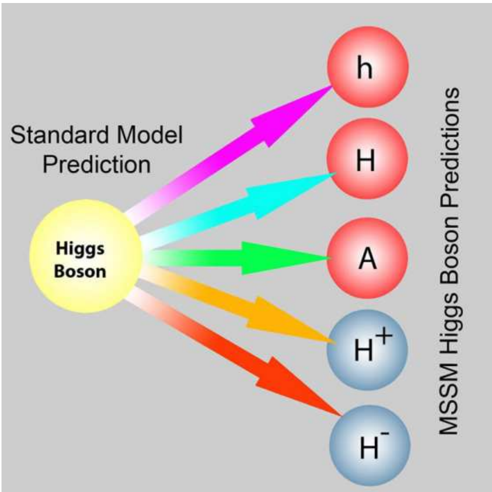


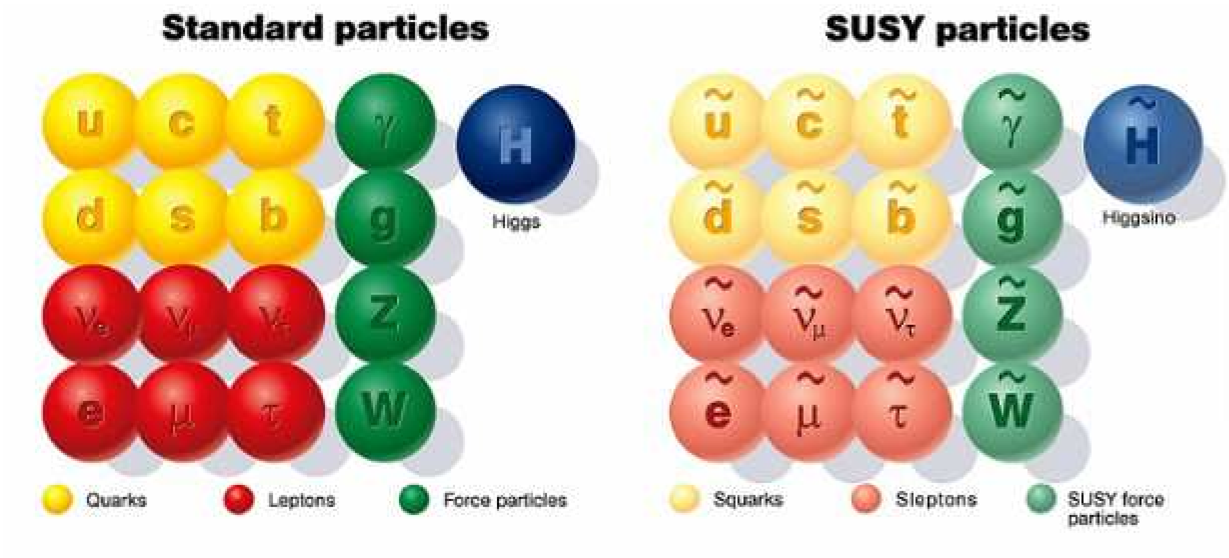
Inner error: statistical
Outer error: total

- Important ground for Higgs searches: most of processes are backgrounds for Higgs
- All SM processes well measured and in good agreement with theory

MSSM Higgs

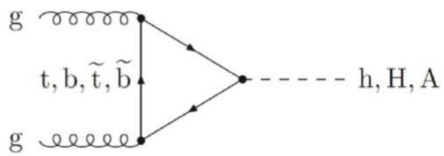
- **MSSM Higgs sector → 5 Higgs bosons**
  - 3 neutral: CP even (h, H), CP odd (A)
  - 2 charged: $H^{\pm}$
  - Two free parameters describe couplings at tree level :
    m_A - $\tan\beta$ or m_{H+} - $\tan\beta$ with $\tan\beta = v_u/v_d$ (ratio of Higgs VEV)
  - Couplings to vector bosons suppressed and couplings to down-type fermions enhanced for large $\tan\beta$

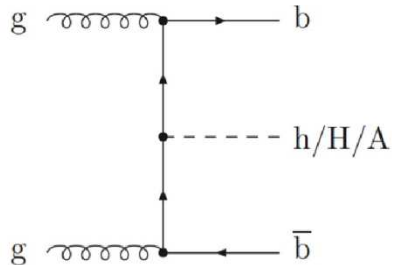


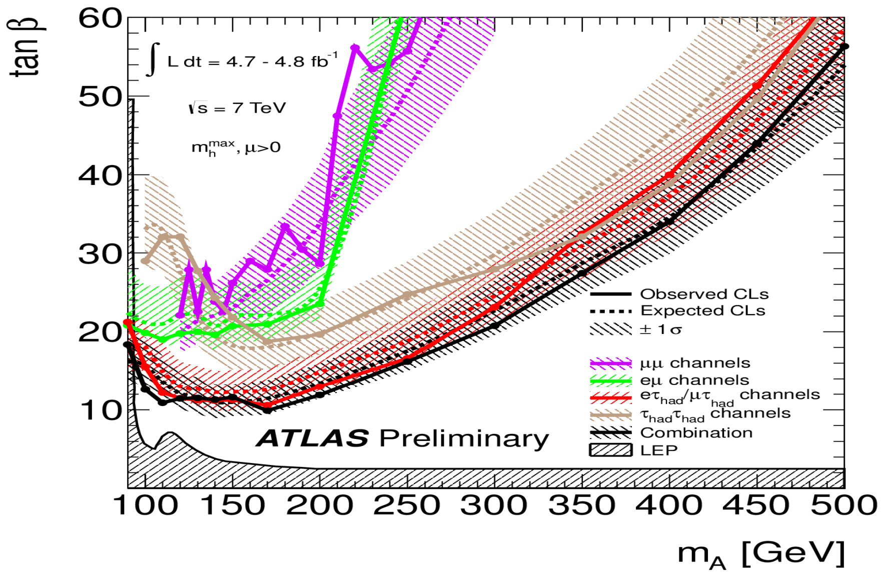


MSSM neutral Higgs search

- **Neutral Higgs**
  - gluon-fusion and b-quark associated production are the most copious production modes
  - Higgs couplings to b-quarks and tau-leptons enhanced compared to SM
  - Search for $\Phi(h/H/A) \rightarrow \tau\tau$ (BR~10% at high tanβ), $\mu\mu$ (BR~0.04%) with/without b-tagged jets







➔ **No excess above SM background**

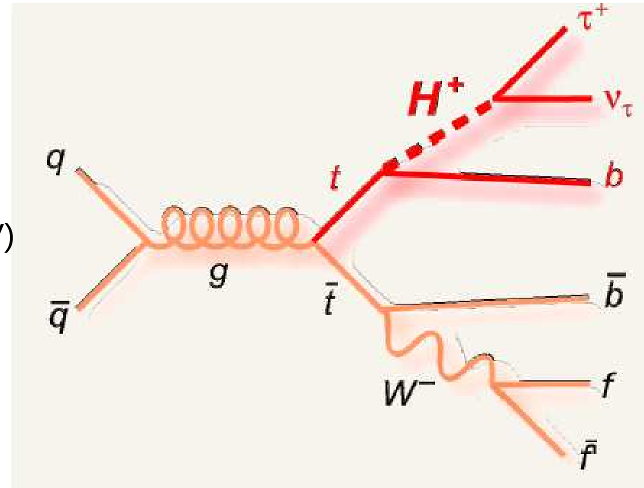
➔ **Stringent tanβ limits (~10) for low m_A**

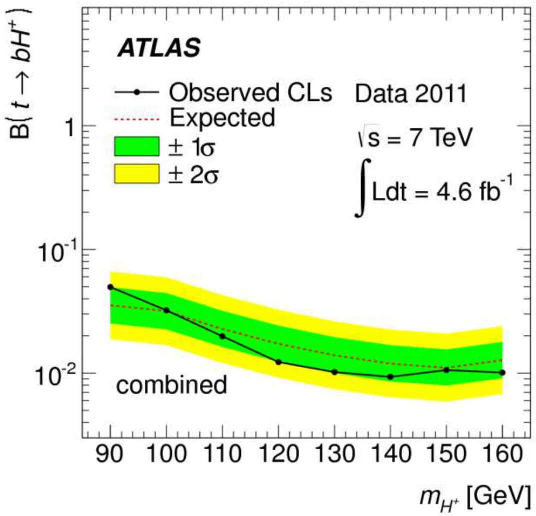
(m_h^{max} scenario: m_h=125 GeV requires maximal stop mixing and heavy stops)

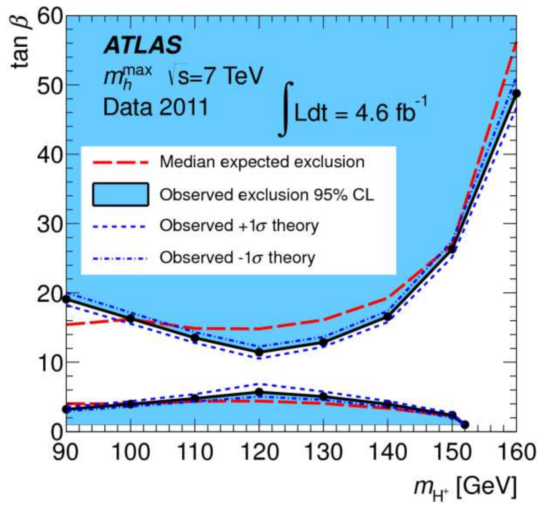
MSSM charged Higgs search

❑ Charged Higgs

- for $m_{H\pm} < m_t$, primary production mode is $t \rightarrow H^\pm b$
- for tanβ<1, decay $H^\pm \rightarrow cs$ important (40% for $m_{H\pm}$=130 GeV)
- for tanβ>2, decay $H^\pm \rightarrow \tau\nu$ dominates → 3 final states considered (lep. or had. decay of τ and W)





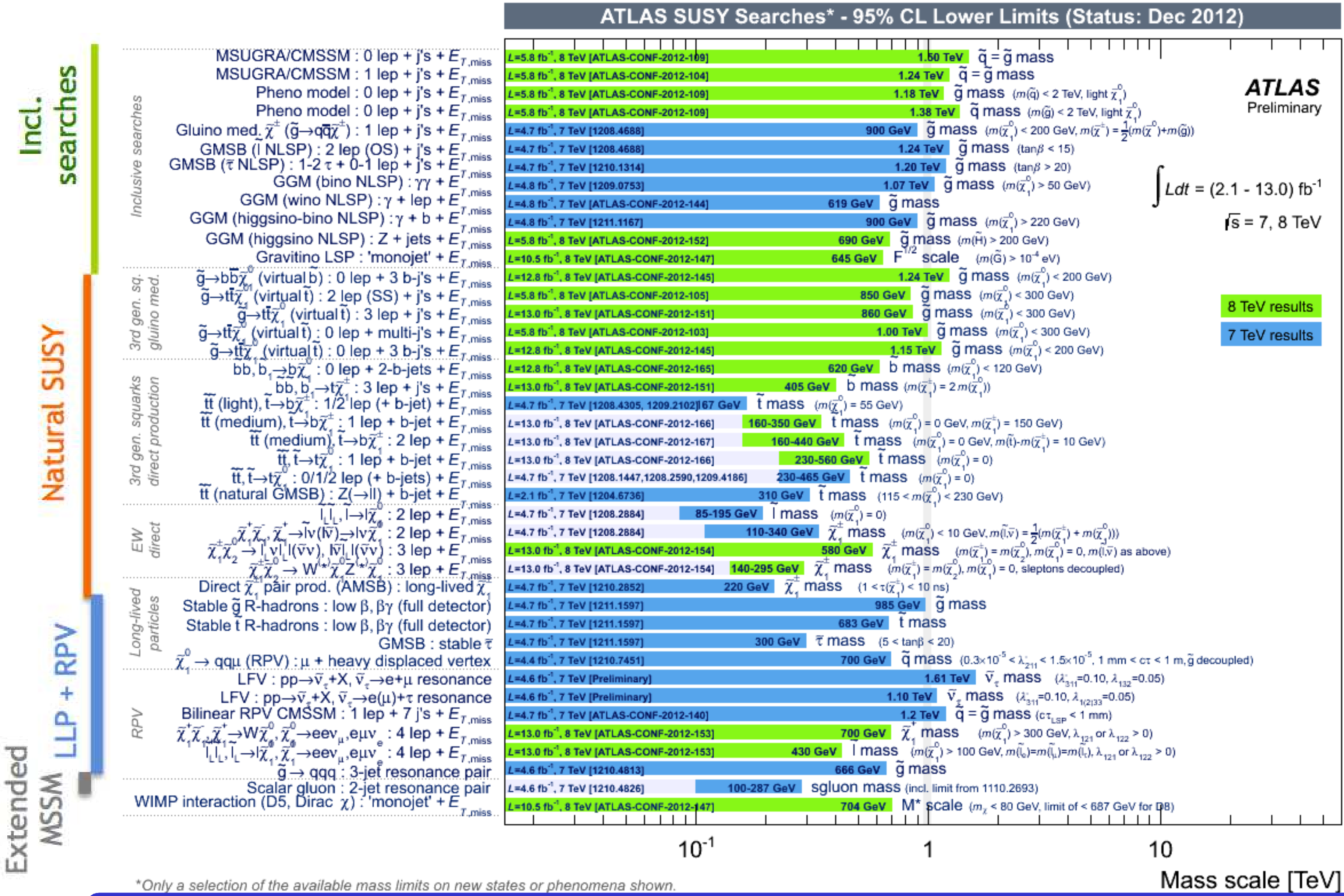


→ **No excess above SM background**

→ **$H^\pm$ allowed phase space heavily constrained** (m_h^{max} scenario
→ tanβ>12-26 excluded for $90<m_{H\pm}<150$ GeV)

→ Assuming $Br(H^\pm \rightarrow \tau^\pm \nu)$=100%, limits on $Br(t \rightarrow bH^\pm)$ between 1 and 5% (significant improvements wrt Tevatron)

SUSY searches



➔ **ATLAS seriously bites in weak scale SUSY between 100 GeV and 1 TeV**

Non-SUSY searches

Extra dimensions

Contact interaction

Heavy gauge bosons

Lepto quarks

New quarks

Excited fermions

Other