Ecole de Gif - 2015

Quel futur pour le Modèle Standard après la découverte du Higgs ?

This course:

Higgs Boson and Electroweak Physics

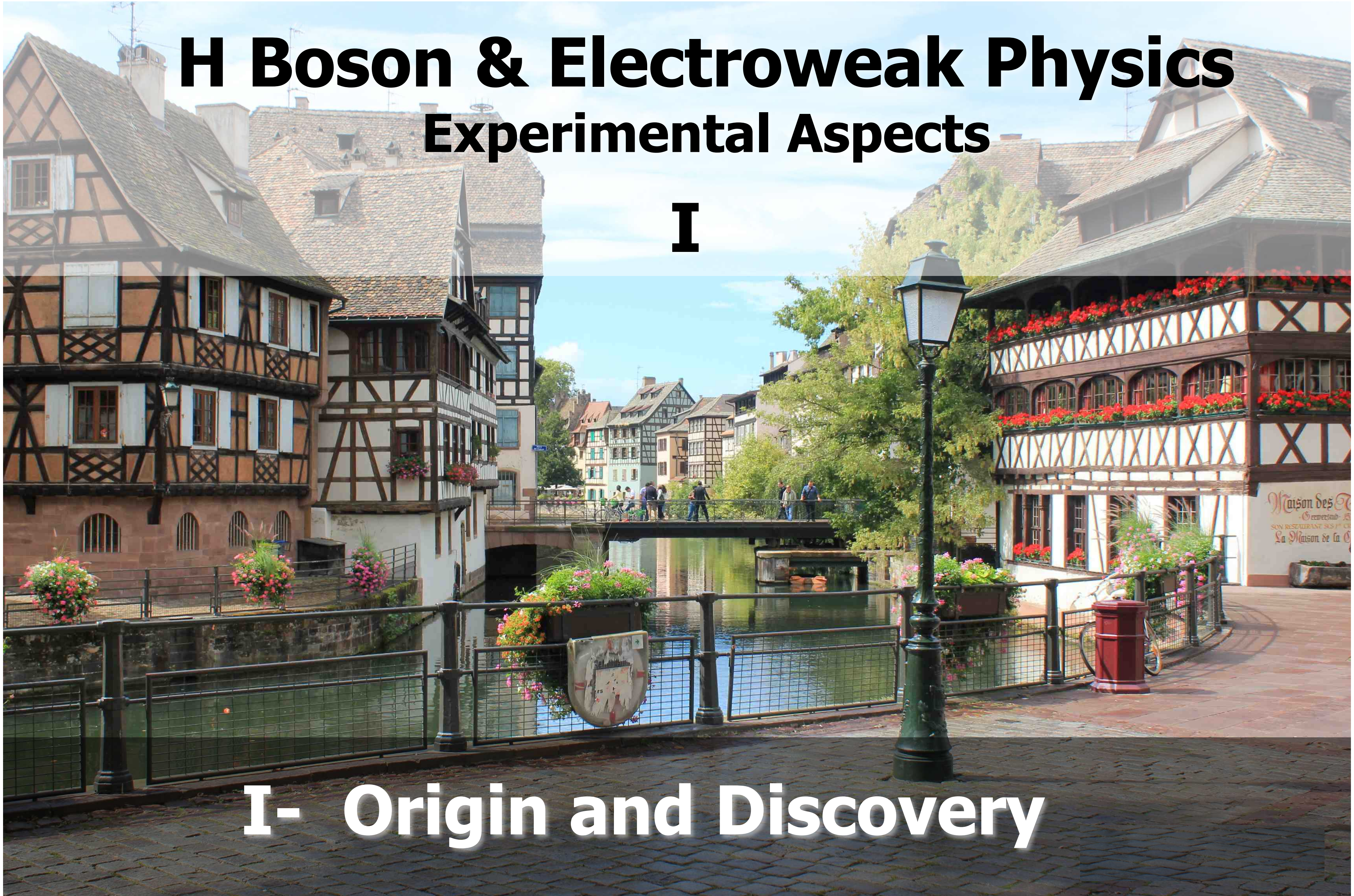
I Origin and Discovery
Stand-alone results from ATLAS and CMS

II H Boson Properties … and beyond
Full combination of ATLAS and CMS (september 2015)

III H Boson Aftermath
Next steps and extension of the scalar sector

H Boson & Electroweak Physics
Experimental Aspects

I



I- Origin and Discovery

Ecole de Gif, September 2015

Yves Sirois
Ecole Polytechnique
CNRS

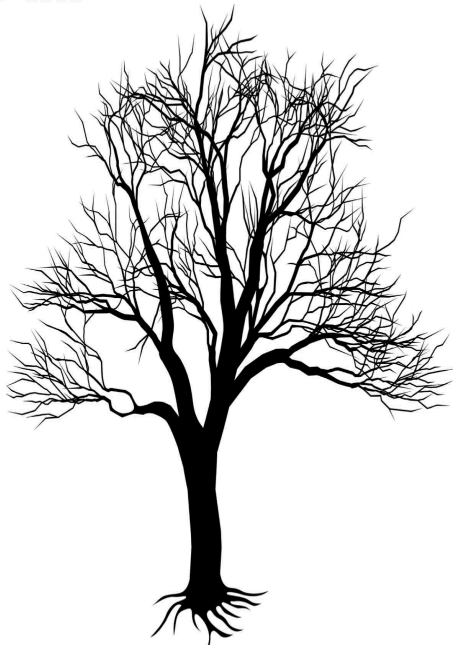
The H Quest

- Motivation and constraints
- Experimental constraints
- Main production & decay at LHC
- Discovery in the di-boson channels

The Elegance of the SM

The standard model (SM) finds

- Its **roots** in the unification of electricity and magnetism in 19th century
- Its **body** in the marriage of relativity and quantum mechanics in the 20th century
- Its **shape** from symmetry principles (gauge symmetries)

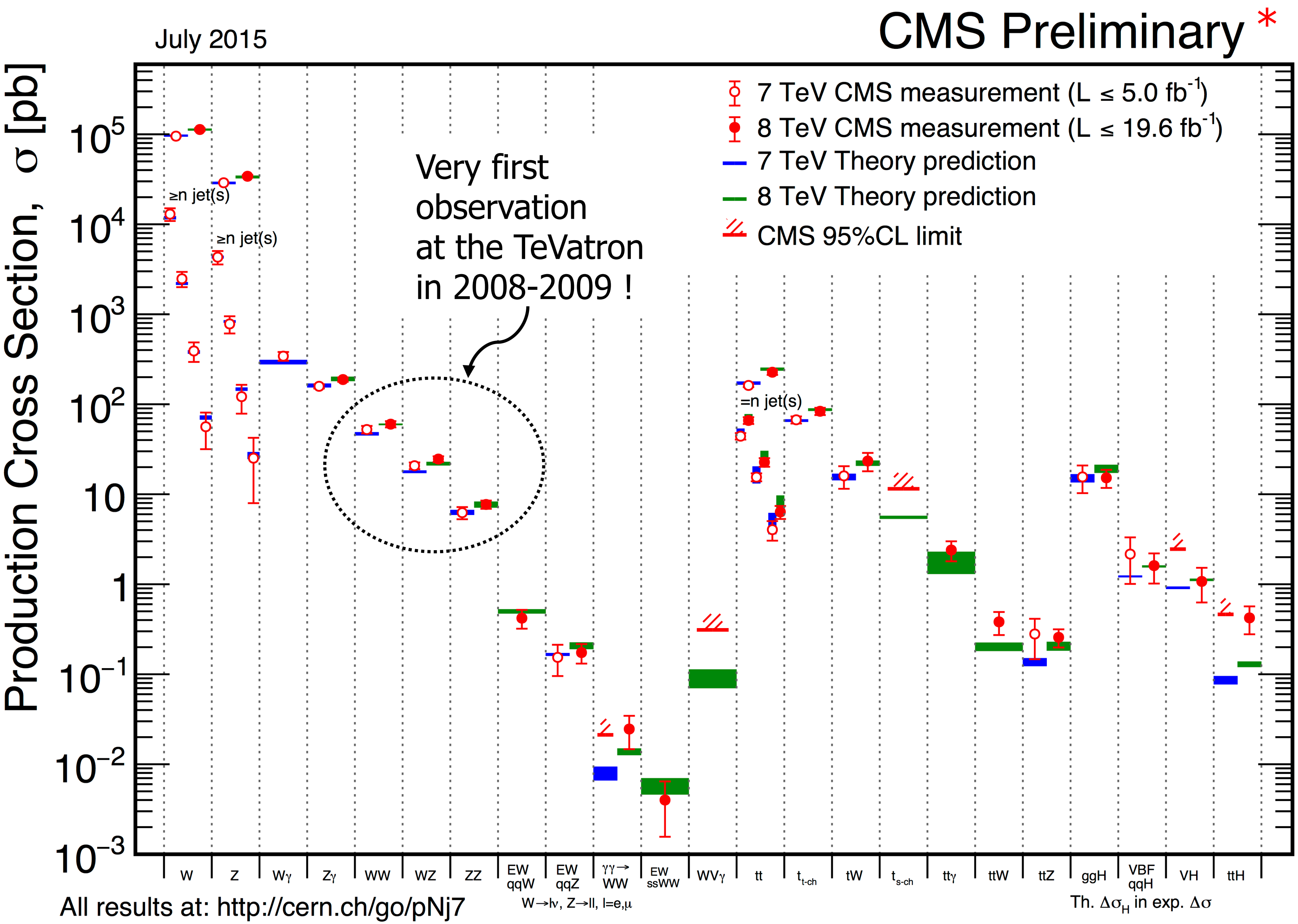


The existence of identical fermions + marriage of relativity and QM ⇒

- The "underlying reality" is made of quantum fields
- There are interactions (gauge bosons) as a consequence of gauge symmetries
- All "particles" must be massless.
- All ordinary particles must have spin 0, ½, or 1

Notes:
Particles with spin 2 (graviton) appear in relation to quantum fluctuations of space-time
Particles of spin 3/2 (gravitino) appear if adding new quantum dimensions (supersymmetry)

The Predictive Power of the SM

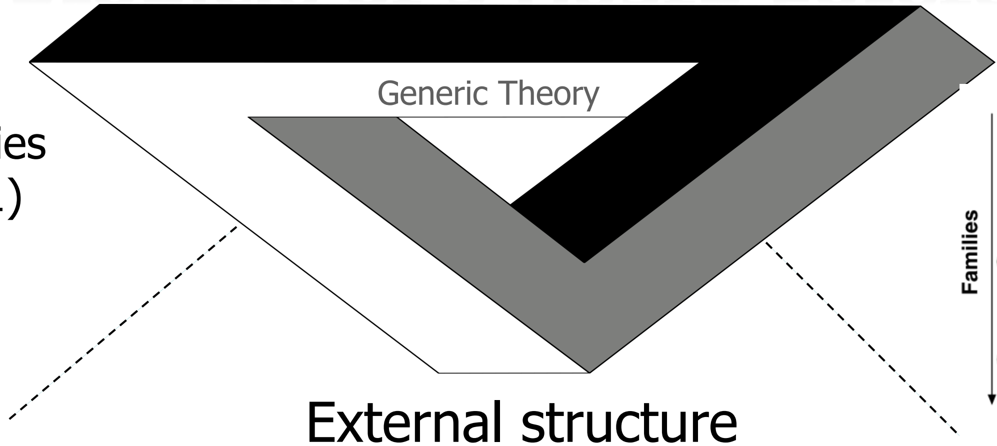


* Similar results from ATLAS

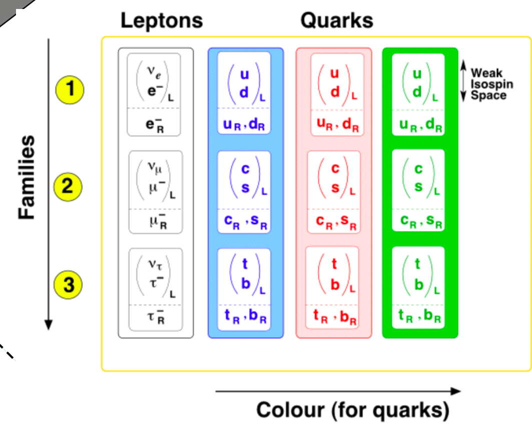
Chronicle of a Death Foretold

Gauge Bosons

Gauge Symmetries
SU(3)xSU(2)xU(1)



Fermions

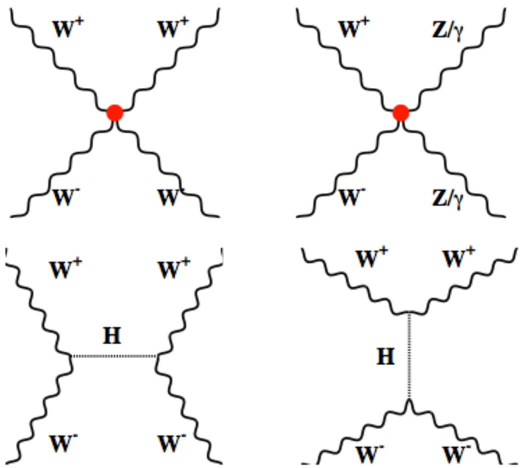


External structure

BEH Mechanism, Higgs boson

- There must exist additional structure to explain the origin of mass, i.e. to preserve gauge symmetries at the fundamental level
- Additional structure is needed to preserve unitarity

One cannot save the theory by injecting measured observables i.e to allow for renormalization as for electrodynamics



$$A\left(W_L^+W_L^- \rightarrow Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

SM limited to E < ~ 1 TeV in absence of regularisation

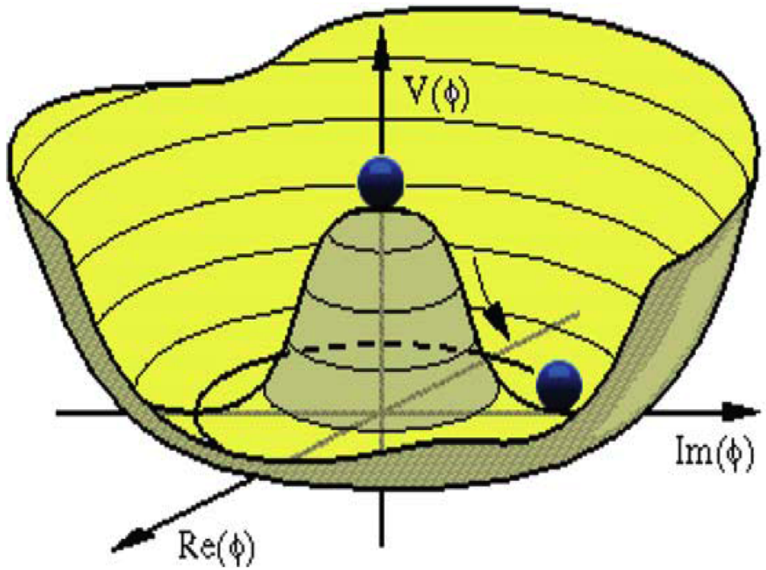
e.g. the H boson allows for exact unitarization

H boson or equivalent or new physics at the TeV scale ?

The BEH Mechanism and the H boson

- One postulates the existence of a scalar field which pervades the Universe
- Below a critical temperature, the potential acquires a minimum at a non-zero value <vev>≠0

  ⇒ **Spontaneous breaking of EWK symmetry**

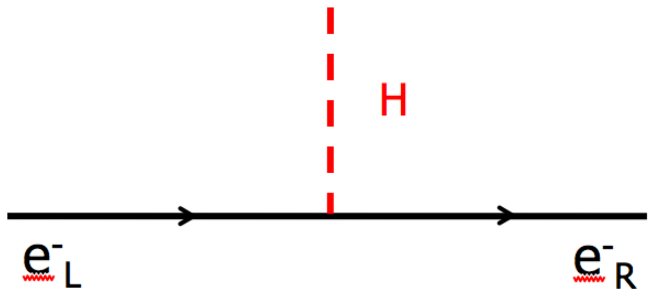


- The Z et W± bosons acquire mass (absorb golstone bosons as longitudinal components)

  → Gauge symmetries are preserved at fundamental level
  → The propagation in the physics vacuum breaks the symmetry

- Elementary fermions interact with the field and acquire mass

  Fields of right- and left-handed chiralities get mixed:



… There exists one physical H boson

H boson: Theoretical Constraints

SM: 1 SU(2) doublet of Higgs fields ⇒ 1 physical boson (CP-even)
M_H is a free parameter $M_H^2 = 2\lambda v^2$; $v \sim 246$ GeV

Theoretical constraints :

Unitarity:

$$M_H < 700 - 800\ GeV/c^2$$

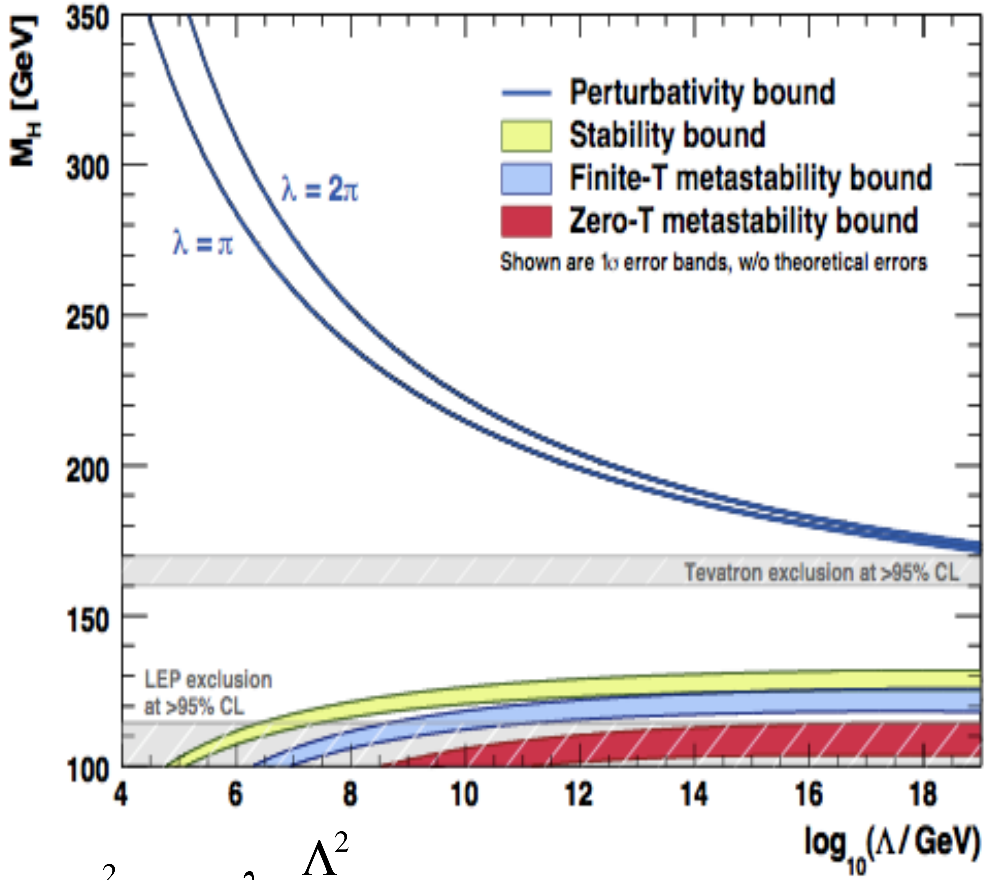
"Triviality" (self-coupling of the H boson) :

$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

"Stability" of vaccuum:

$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2}\ln(\Lambda/v)$$

Λ = "cut-off" scale



⚠ Quadratic divergencies: $m^2 = m_0^2 + \alpha\lambda\frac{\Lambda^2}{16\pi^2}$

If H boson and Λ << Planck scale : then new physics at the TeV scale ?

Nuclear Physics B106 (1976) 292–340
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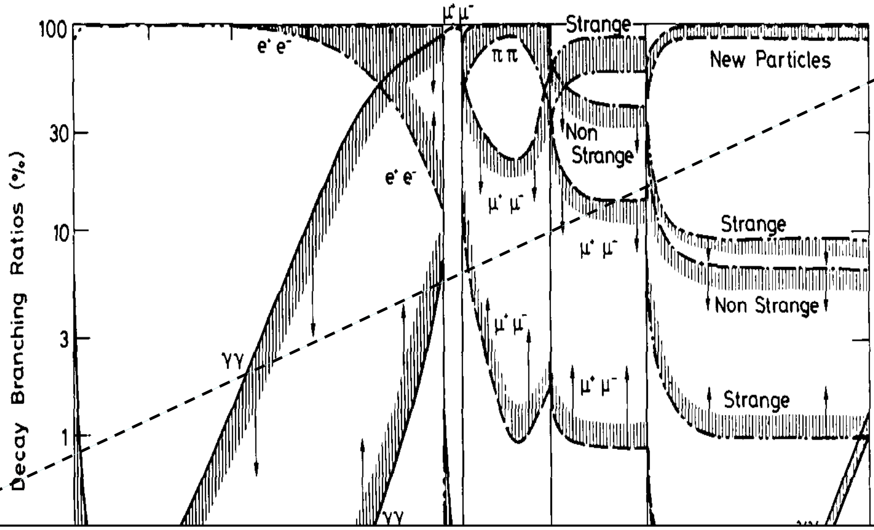
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975



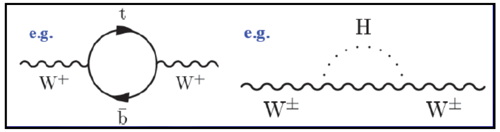
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

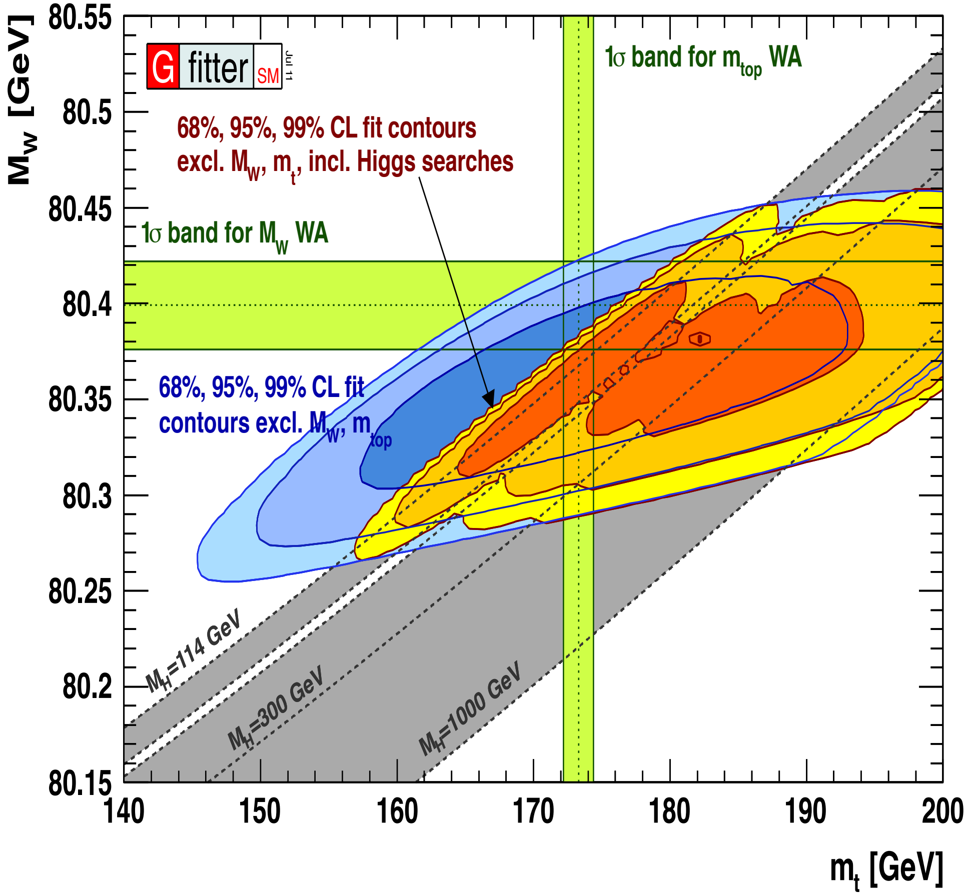
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, ...

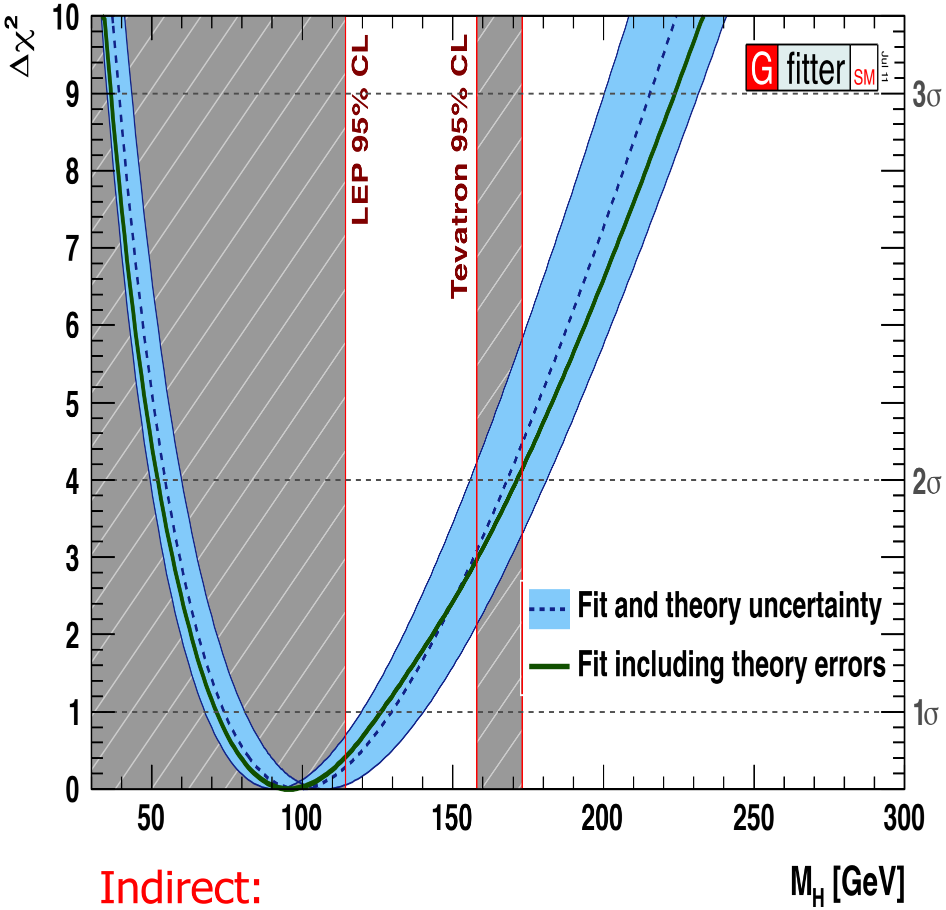
... and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson,

The Landscape at EPS 2011

W, Z meas. sensitive to M_{top} M_H via radiative corrections:







The H boson is preferably light …
if it exists !

Indirect:

Best fit: $M_H = 96^{+31}_{-24}$ GeV

$M_H < 169$ GeV (95% CL)

Direct:

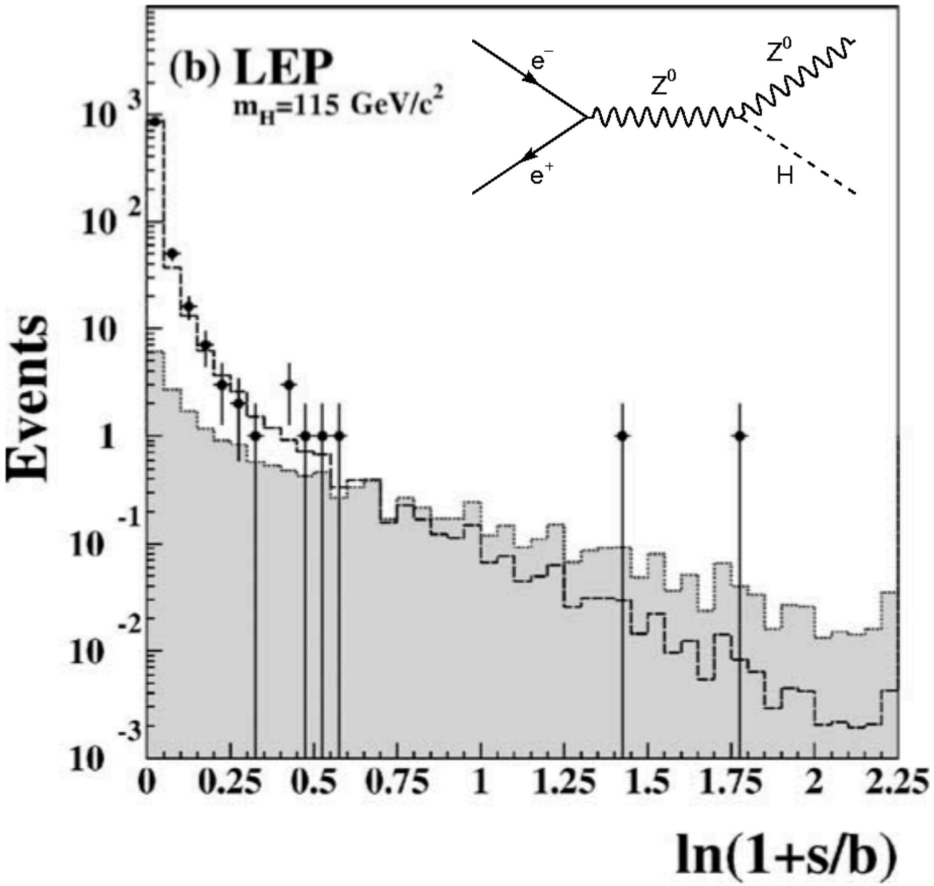
$M_H > 114.5$ GeV (95% CL) LEP

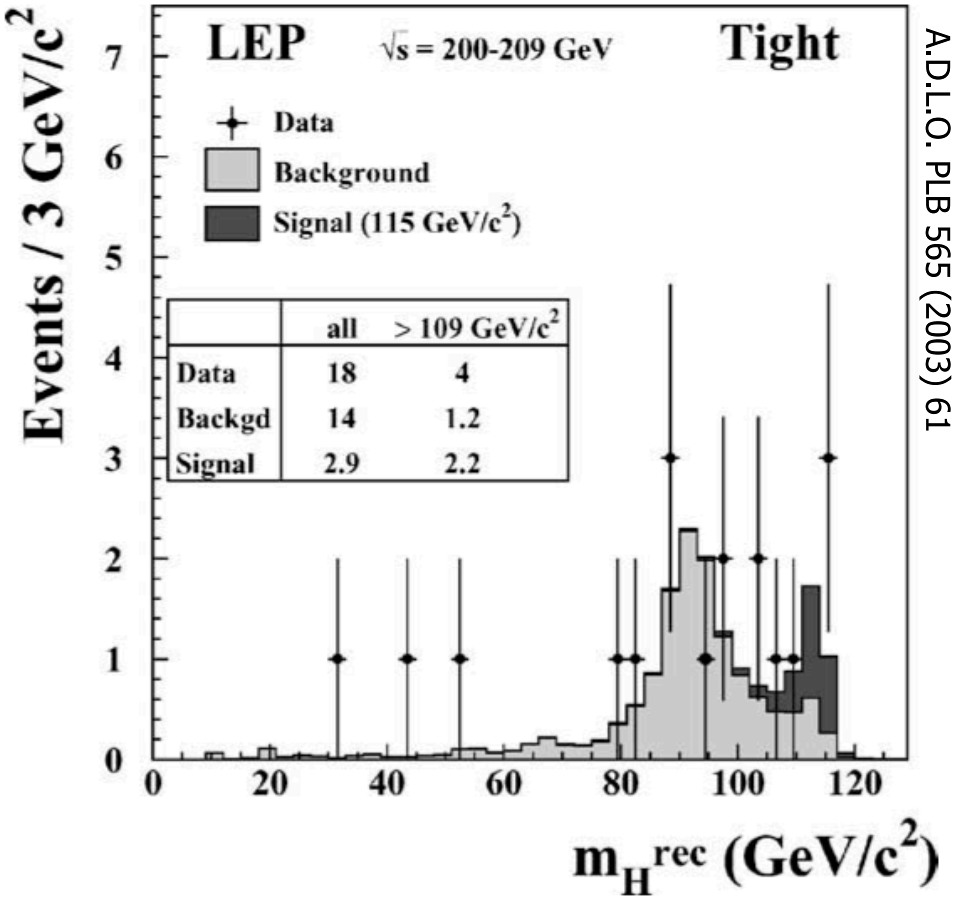
$M_H \notin$ 158 – 173 GeV (95% CL) Tevatron

http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/2011_07_21_index.html

The Landscape at EPS 2011

LEP Legacy:





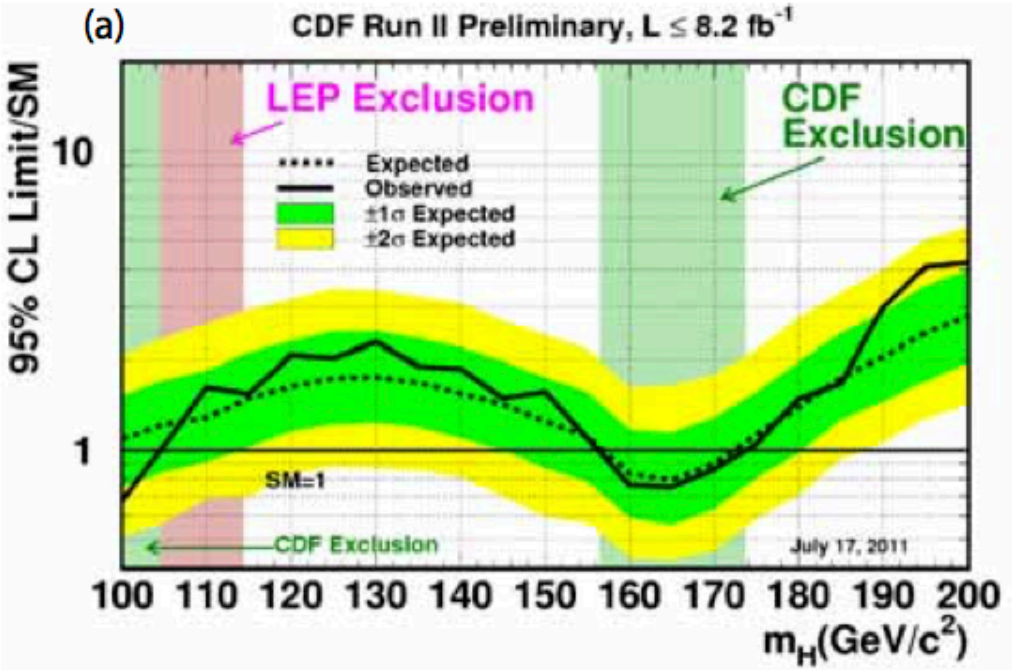
A.D.L.O. PLB 565 (2003) 61

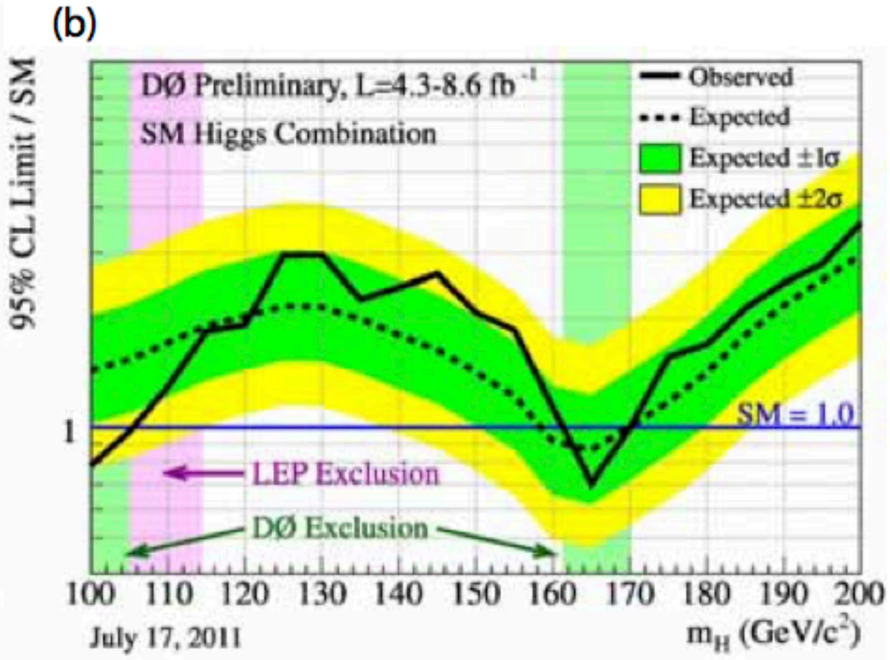
- A few events with very high weights assuming M_H = 115 GeV
- Small « excess » compatible with a SM Higgs boson of M_H = 115 GeV (ALEPH) …

Sets LEP lower limit at M_H > 114.5 GeV (95% CL)

The Landscape at EPS 2011

M.E. Peskin, « Summary of Lepton-Photon 2011 », SLAC PUB 14612





- Not yet excluding LEP “fluctuation” at M_H = 115 GeV
- No deviations > 1 σ
- Mass region 158 < mH < 173 GeV excluded [CDF+D0 FERMILAB-CONF-11-044-E]

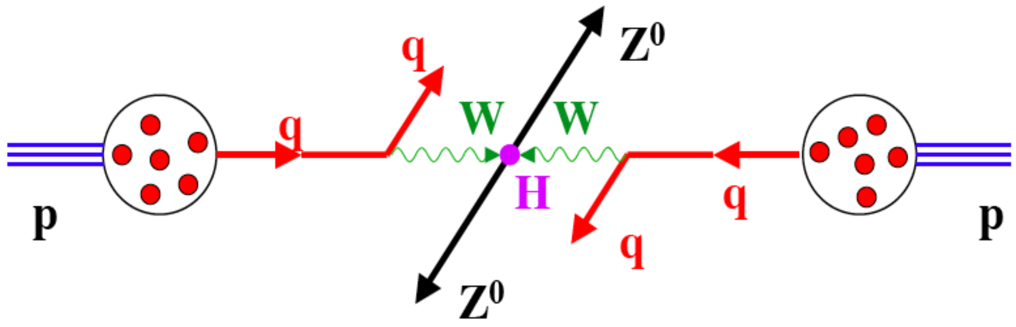
Note:

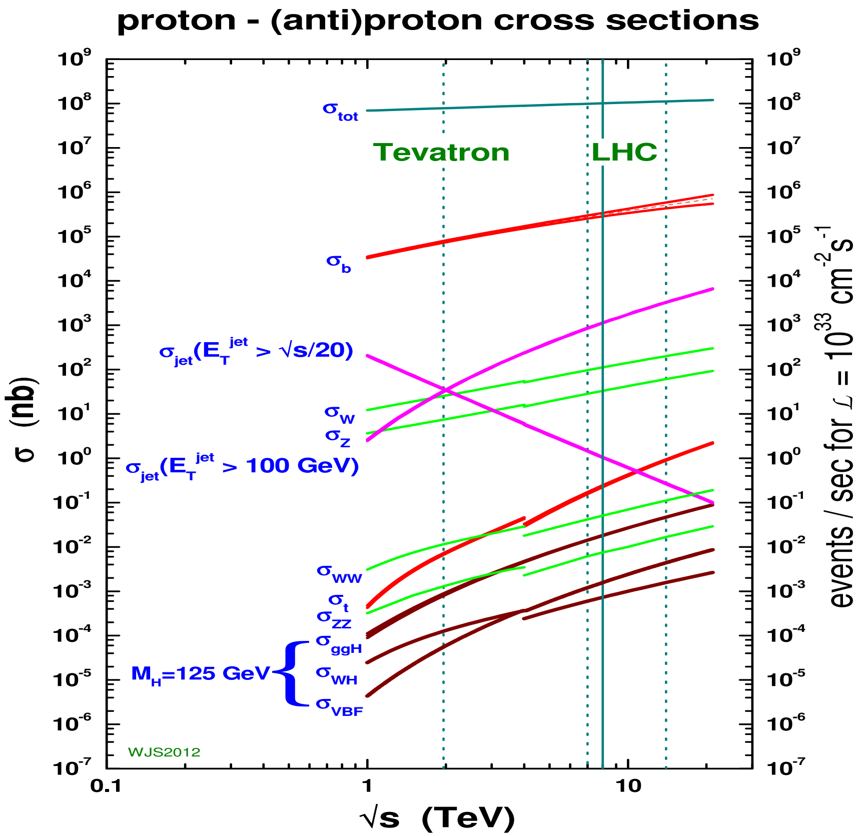
- CDF+D0 combination paper FERMILAB-CONF-11-044-E from August 2011 only shows the range 130 < M_H < 200 GeV
- CDF+D0 combination paper FERMILAB-CONF-11-354-E is actually an updated version with figures from May 2013 !!! [i.e. after ATLAS + CMS first Hints at M_H = 125 GeV)

The Large Hadron Collider

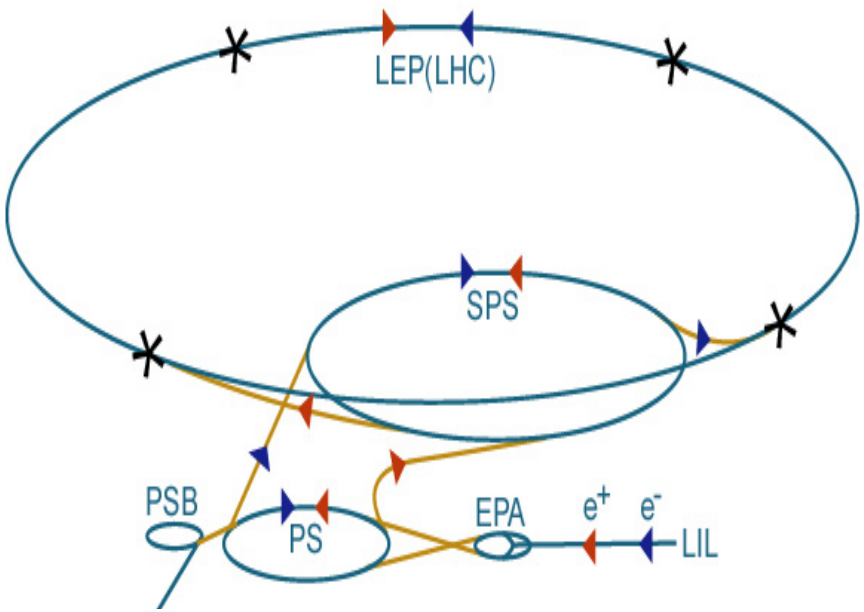
Conceived 30 years ago as an exploration machine with a large bandwidth

- High luminosity:
  search for the H boson
- High energy:
  W_L-W_L scattering at TeV scale
  $\Rightarrow \sqrt{s}_{pp} \sim 14$ TeV

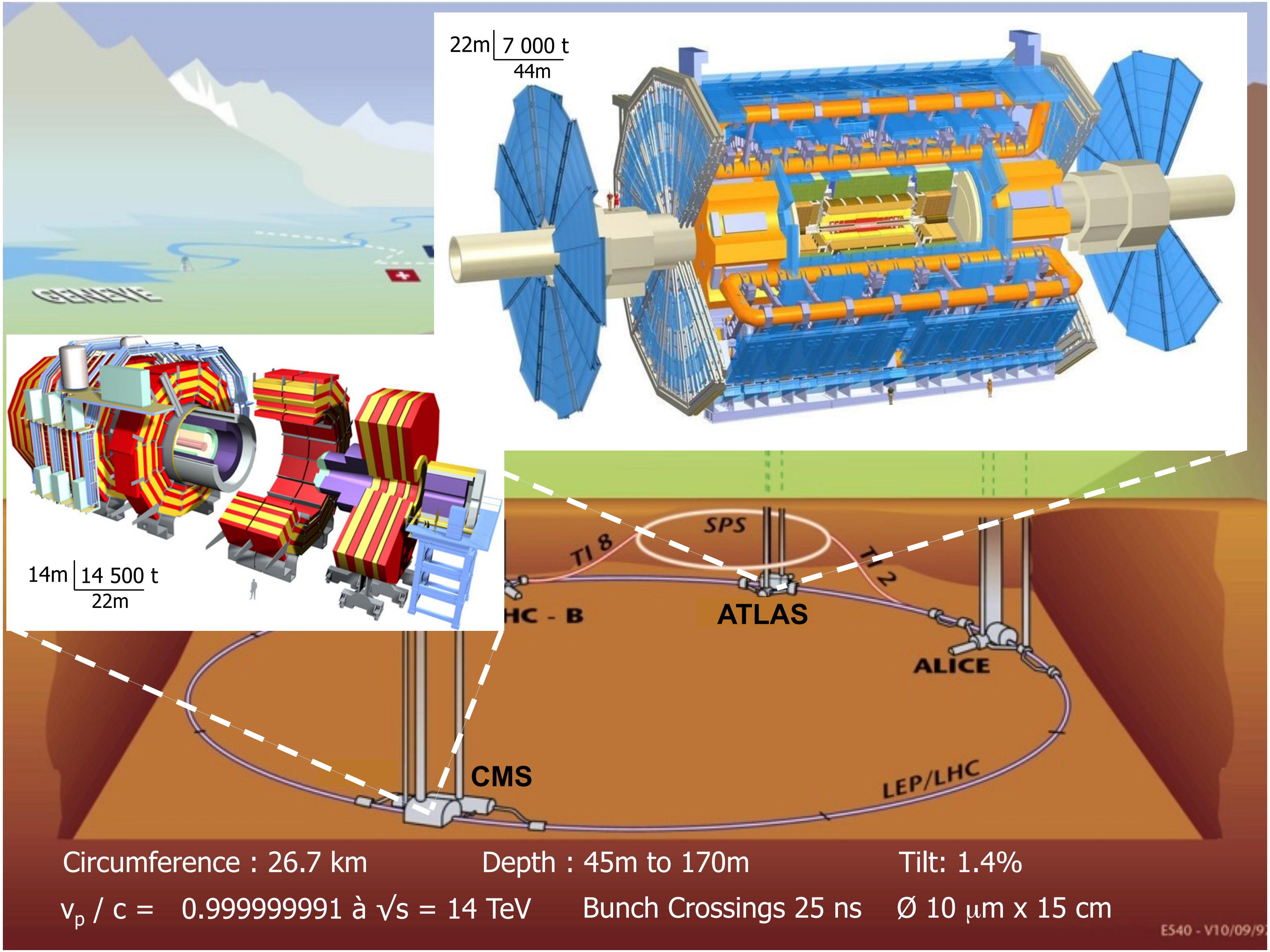


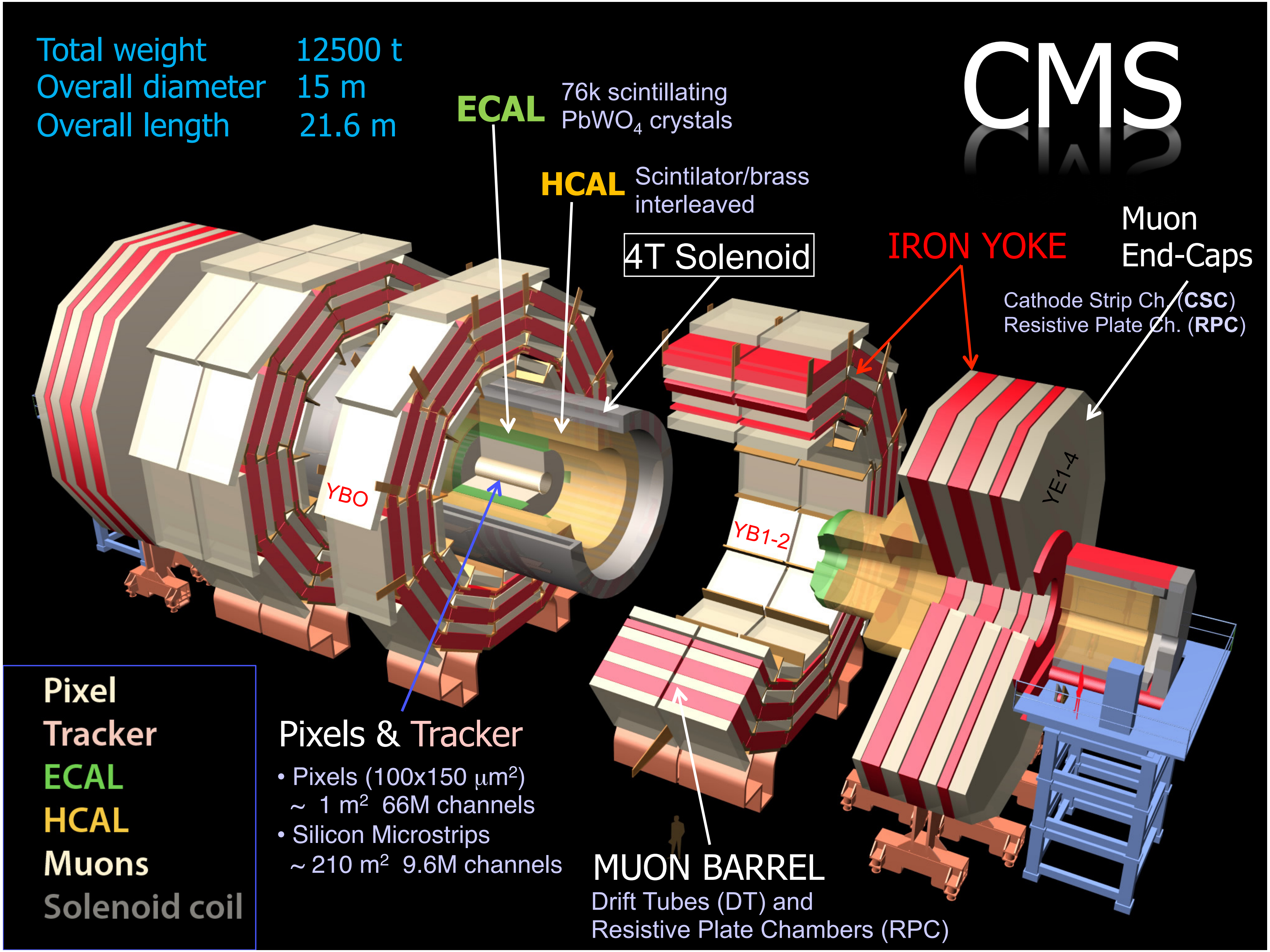


It all starts with a small hydrogen bottle !



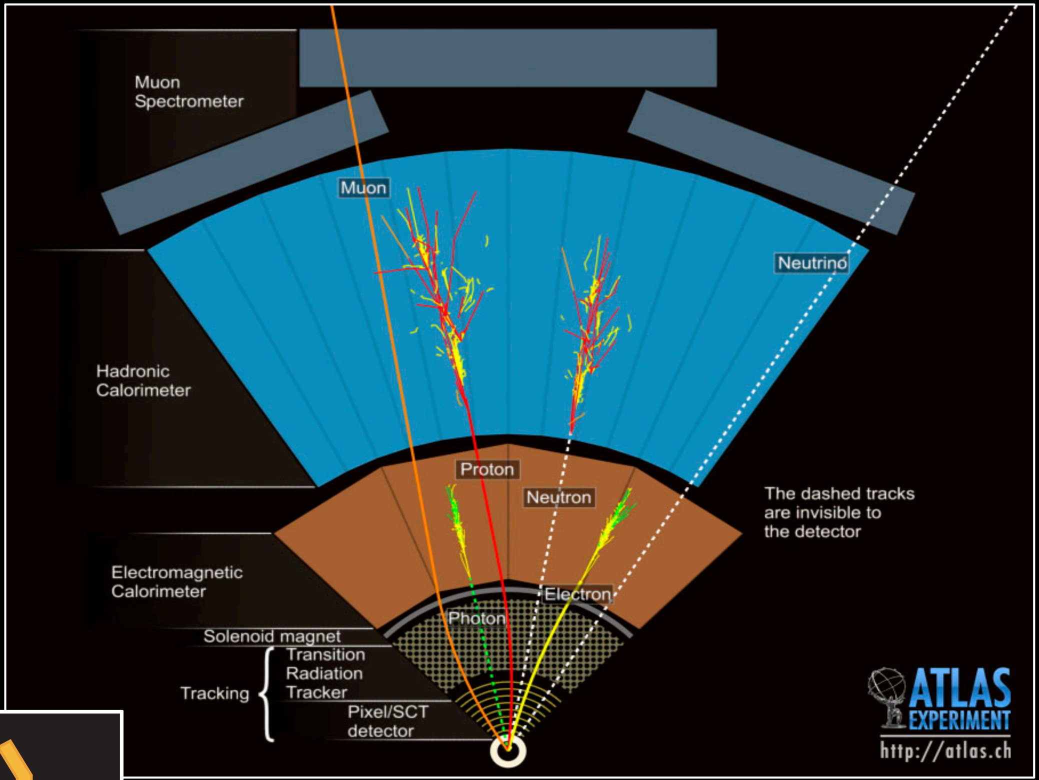
$(\sigma^{tot}_{(H125)} \times L)_{Tevatron} \times 50 \sim (\sigma^{tot}_{(H125)} \times L)_{LHC}$

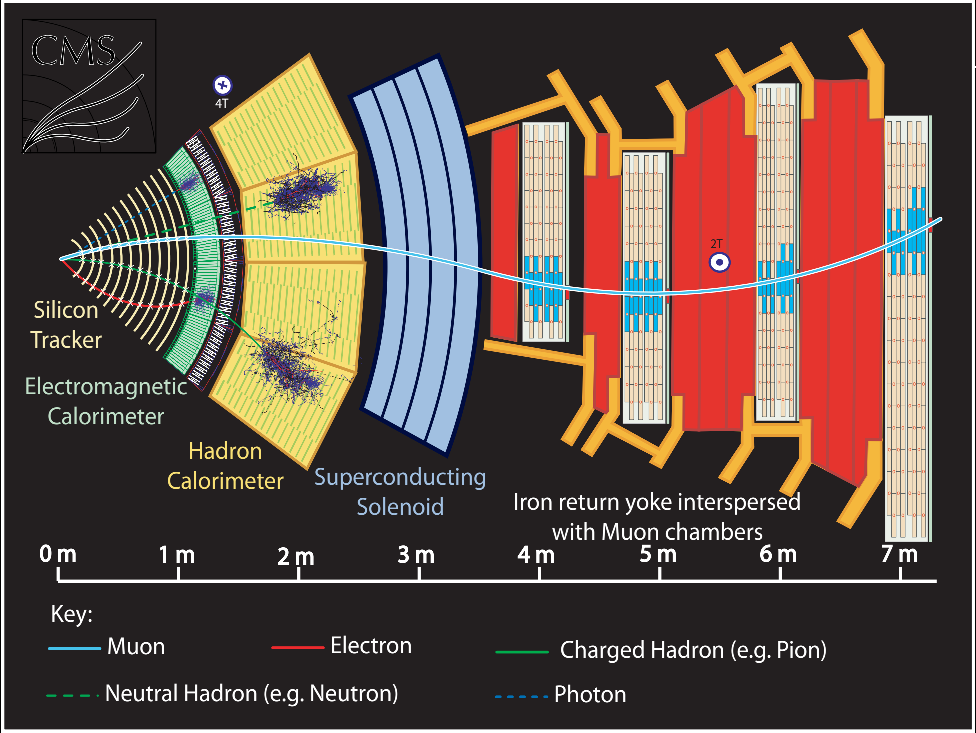

22m 7 000 t
44m
GENEVE
14m 14 500 t
22m
SPS
TI 8
TI 2
HC - B
ATLAS
ALICE
CMS
LEP/LHC
Circumference : 26.7 km
Depth : 45m to 170m
Tilt: 1.4%
v_p / c = 0.999999991 à $\sqrt{s}$ = 14 TeV
Bunch Crossings 25 ns
Ø 10 μm x 15 cm
ES40 - V10/09/9


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
ECAL
76k scintillating PbWO4 crystals
HCAL
Scintilator/brass interleaved
4T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 66M channels
• Silicon Microstrips
~ 210 m2 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

Detector Signatures

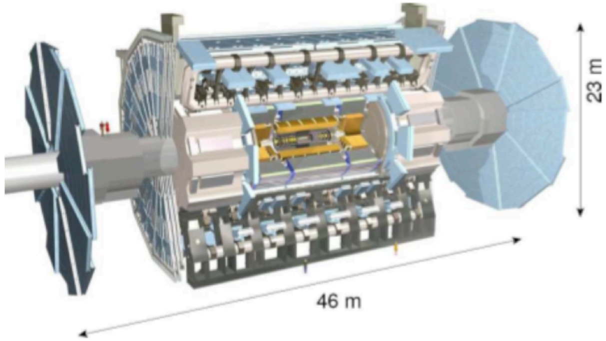
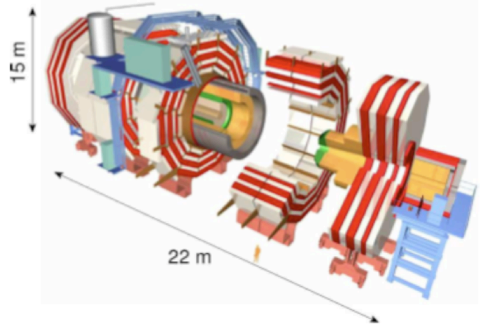
ATLAS:
Silicon Pixel & Tracking
Superconducting solenoid
Lar eletromagnetic calo.
Tiles hadronic calo.
Toroid – μ spectrometer





CMS:
Silicon Pixel and Tracking
$PbWO_4$ crystal electromagnetic calo.
Tiles hadronic calo.
Superconducting solenoid 3.8 T
Return yoke (μ ID)

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)

© M. Kado, 2011

Reconstruction

Objective: Identify and reconstruct the energy-momentum four-vector of particles emerging from the primary (and main secondary) vertex

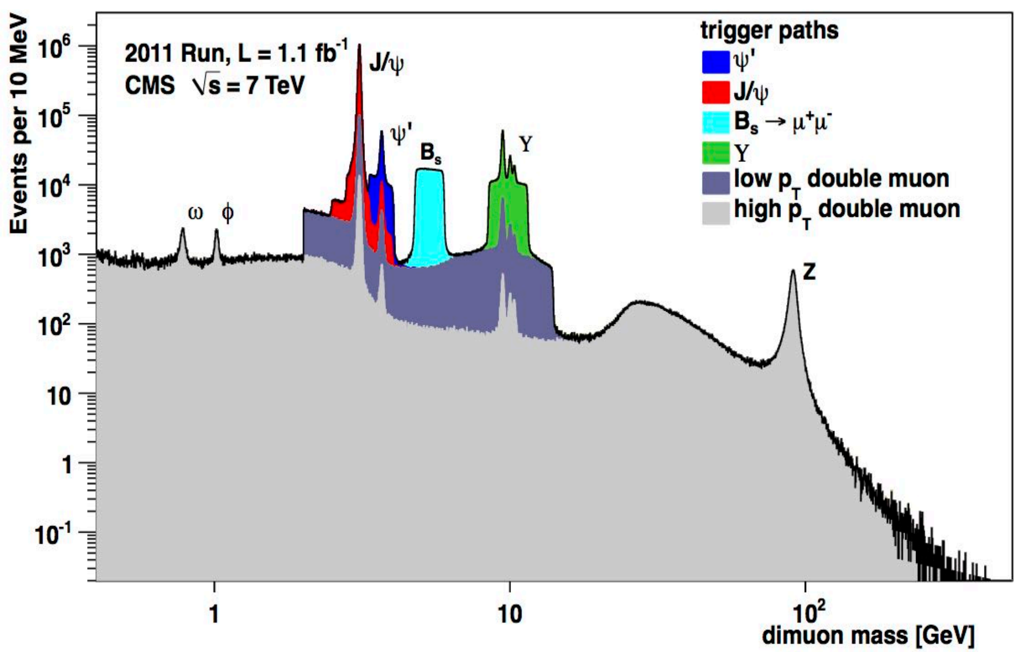
Strategy: - Proceed sequentially: start with particles with lowest expected fake rates [event cleaning]

- Require a matching to primary vertex for charged particles [« Pile-Up » mitigation]

- Subtract PU contribution in E and Iso. measurements of neutrals

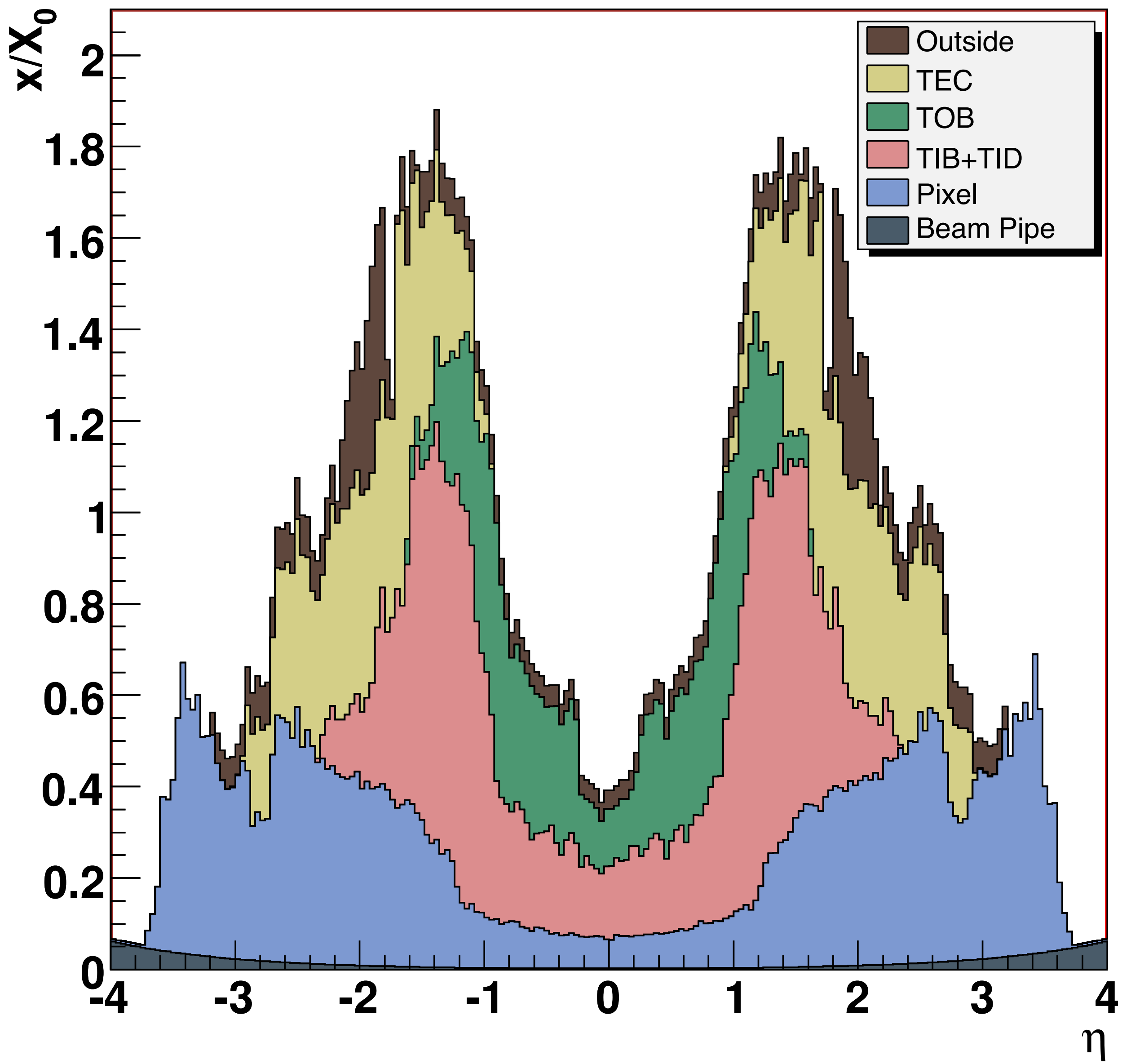
Typically

- First reconstruct μ's
- Then reconstruct e/γ [with effect of PU subtracted]
- Follow with $\pi^{\pm}$ and and π^{0}
- Form jets; identify τ-jets and b-jets
- Built global event quantities [missing ET or vectorial PT]



The procedure is severely hampered by the amount of material in front of the ECAL for both ATLAS and CMS

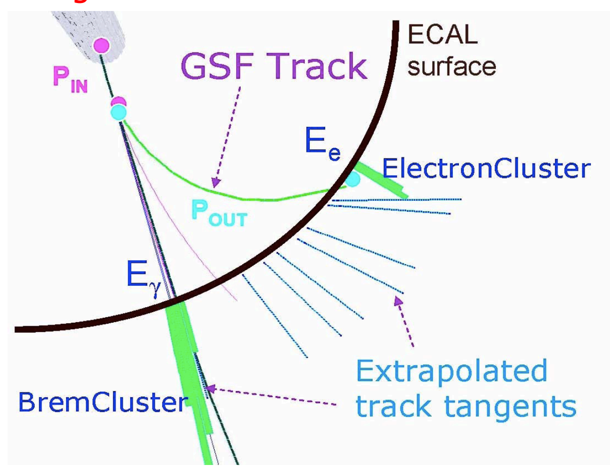
Climbing Mountains: Reconstructing photons and electrons



30-40 % of primary γ's convert before reaching the ECAL

Electrons radiate when traversing the tracker Si layers (showering)

e.g. CMS

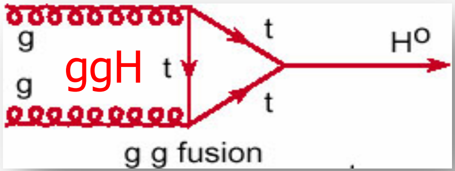


ATLAS and CMS use e's and γ's categories for the H analyses

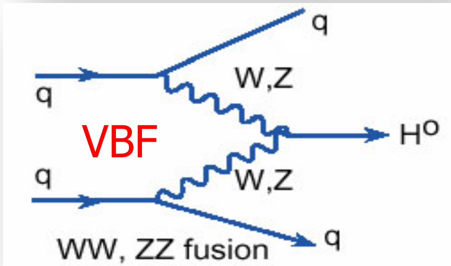
Higgs Boson : Production Cross-Sections

At the LHC

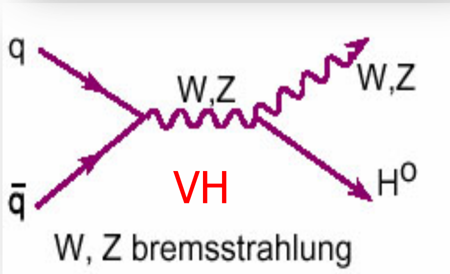
87%



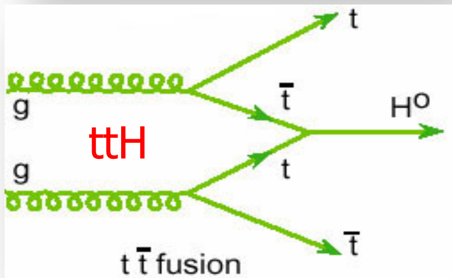
7.1%

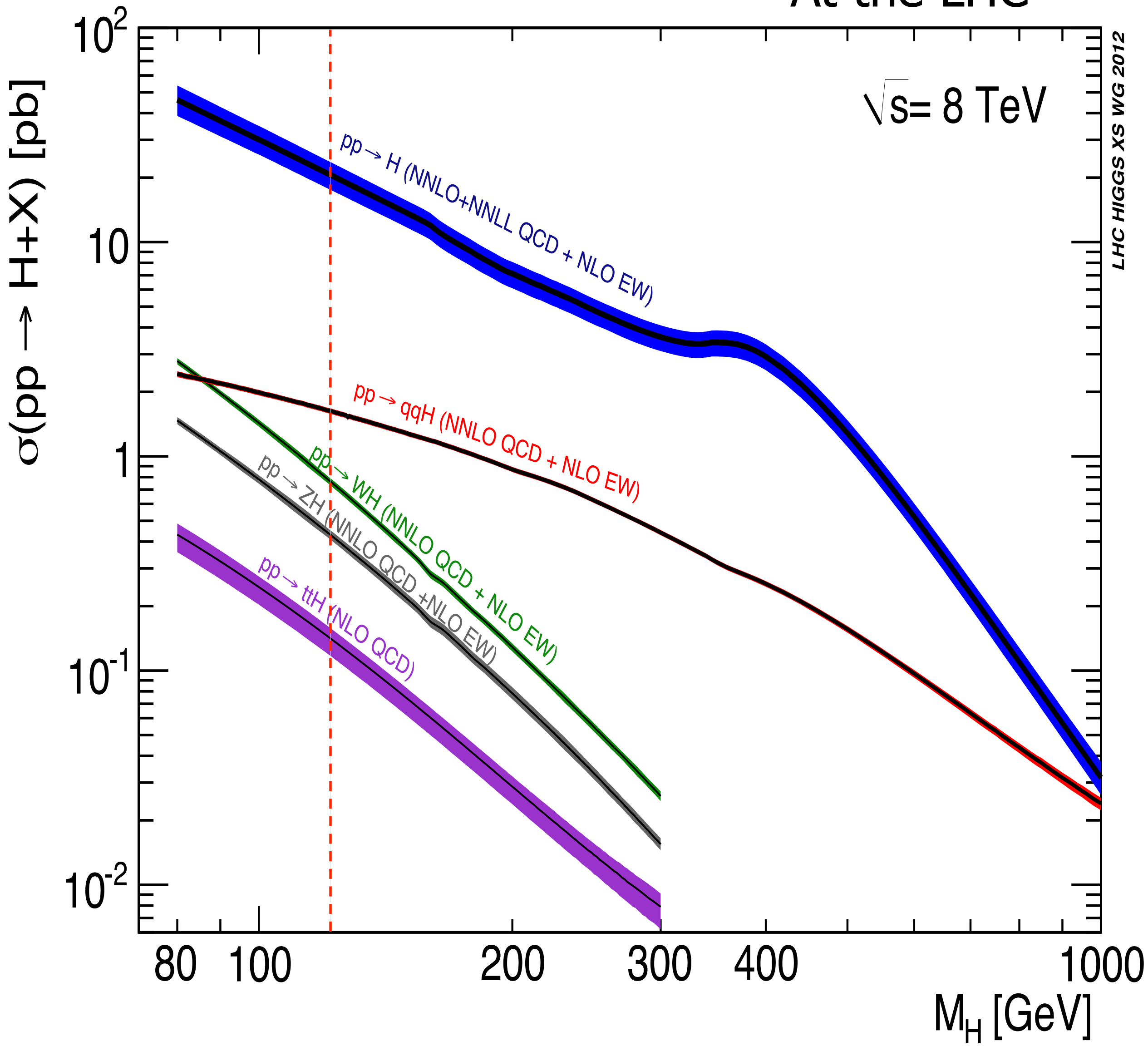


4.9%



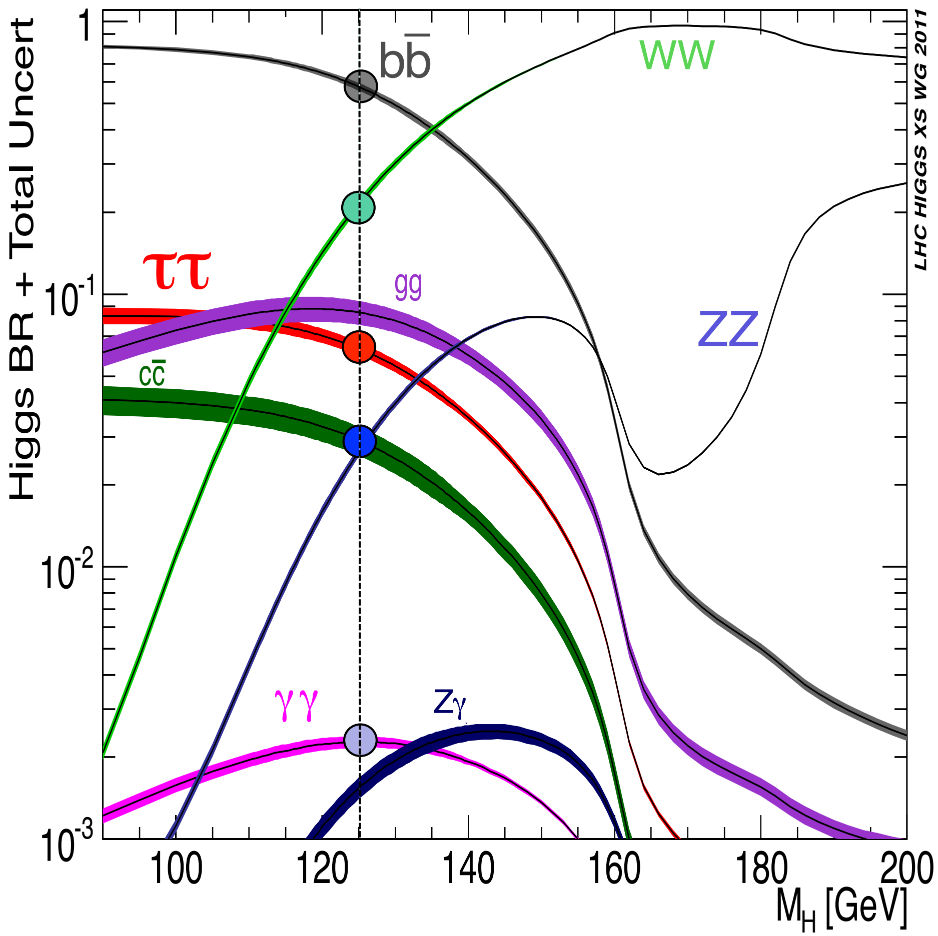
0.6%





σ/σ_{tot} (M_H = 125 GeV)

Higgs Boson : Decay Channels



ΔM/M ~ 1-2% High resolution

H → γγ Rare, S/B < 1

H → ZZ* → 4ℓ Very rare, S/B >> 1

ΔM/M ~ 10-20% Medium resolution

H → bb Abundant, S/B << 1

H → ττ Abundant, S/B < 1

ΔM/M > 30% Low resolution

H → WW*→ 2ℓ2ν Very abundant, S/B < 1

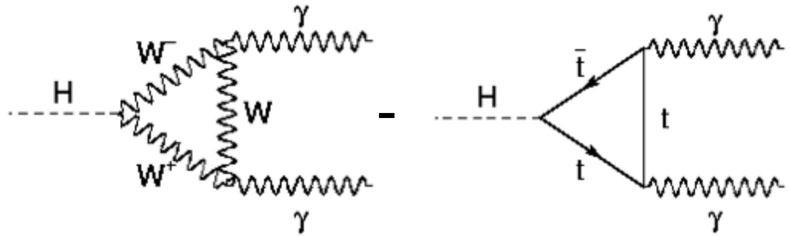
4 production modes × 5 decay modes (γγ, ZZ, WW, ττ, bb)

~ 100 exclusive final states (production, decay, event categories) are contributing for M_H ~ 125 GeV !

The H → γγ Channel (1)

Narrow peak over falling ~ monotonic background
Very high mass resolution but S/B < 1
in gg-fusion production mode

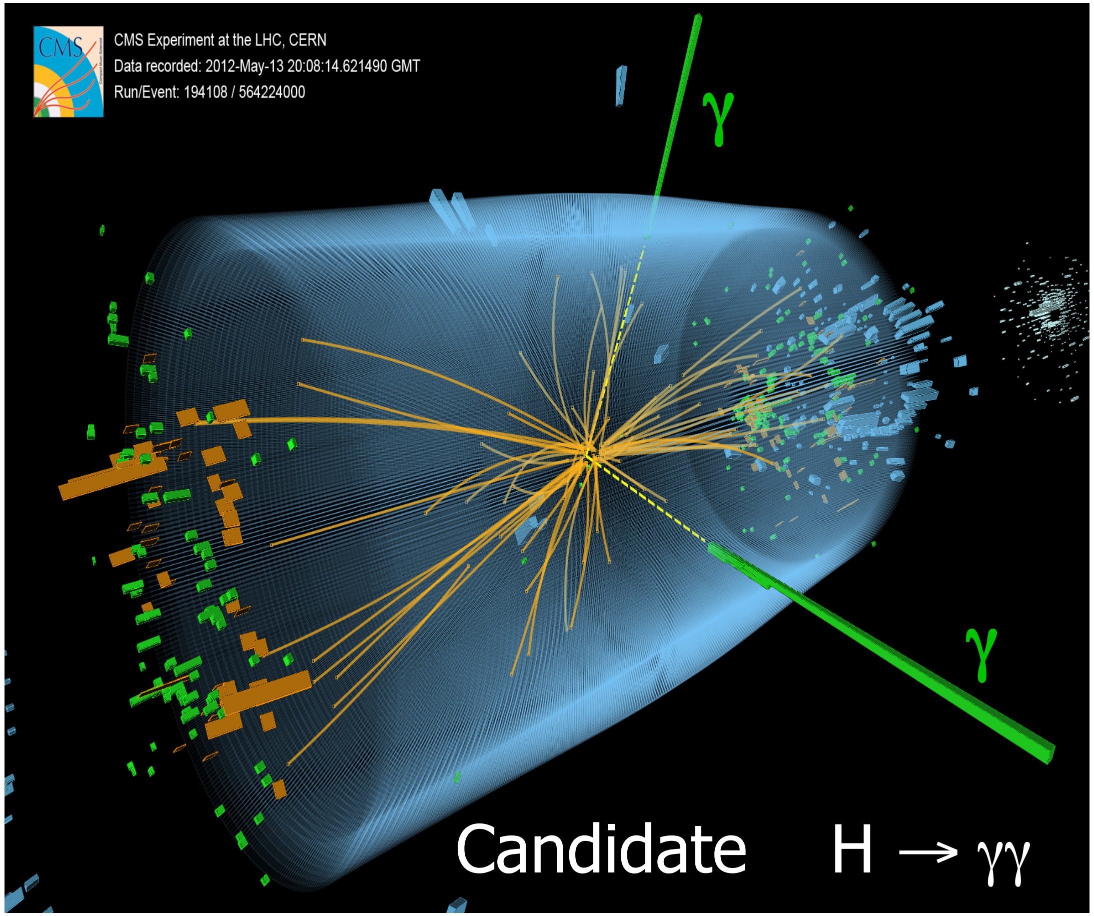
Low rates (σ x β ~ 48.6 fb at 125 GeV);



Signature:
Two isolated photons

Analysis key:
Photon E measurement (ECAL)
Photon angles
(ECAL and primary vertex)
Photon ID and Isolation

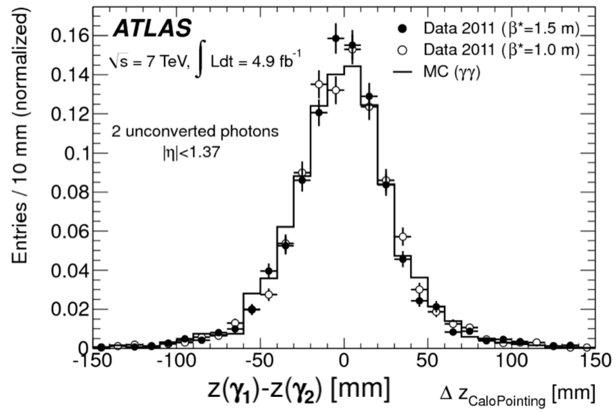
Discriminating variables:
$M_{\gamma\gamma}$, $P_{T\gamma}$
Event categorization
(Optimize sensitivity to different $M_{\gamma\gamma}$ resolution, or different production modes)



The H → γγ Channel (2)

Determination of primary vertex:

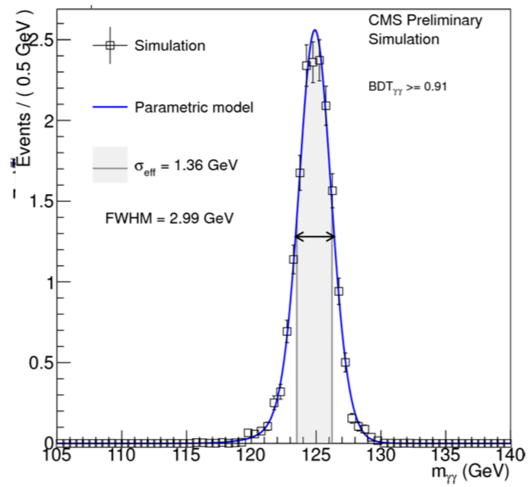
	ATLAS	CMS
input variables	*photon pointing* $\sum pT^2$ $\sum pT$ $\Delta\phi(\overrightarrow{p^T_{vtx}}, \overrightarrow{p^T_{\gamma\gamma}})$ *conversions*	$\sum pT^2$ $ptasym = (p^T_{vtx} - p^T_{\gamma\gamma})/(p^T_{vtx} + p^T_{\gamma\gamma})$ $ptbal = -\sum \overrightarrow{p^T} \cdot \overrightarrow{p^T_{\gamma\gamma}} / p^T_{\gamma\gamma}$ *conversions*
Vertex finding efficiency	75% for $\lvert z-z_{true}\rvert<0.3$ mm	79 % for $\lvert z-z_{true}\rvert<10$ mm (74.5% for $\lvert z-z_{true}\rvert<0.3$ mm)



~15 mm resolution from pointing

Photon energy resolution:

		ATLAS	CMS
Parametric model		CB + gaussian[1]	Sum of gaussians
Mass resolution [2] **(FWHM/2.35) GeV**	overall	1.77	1.64
	best cat.	1.40	1.27
	other cats.	1.50 – 2.52	1.39 – 2.14



Very different techniques … comparable performances

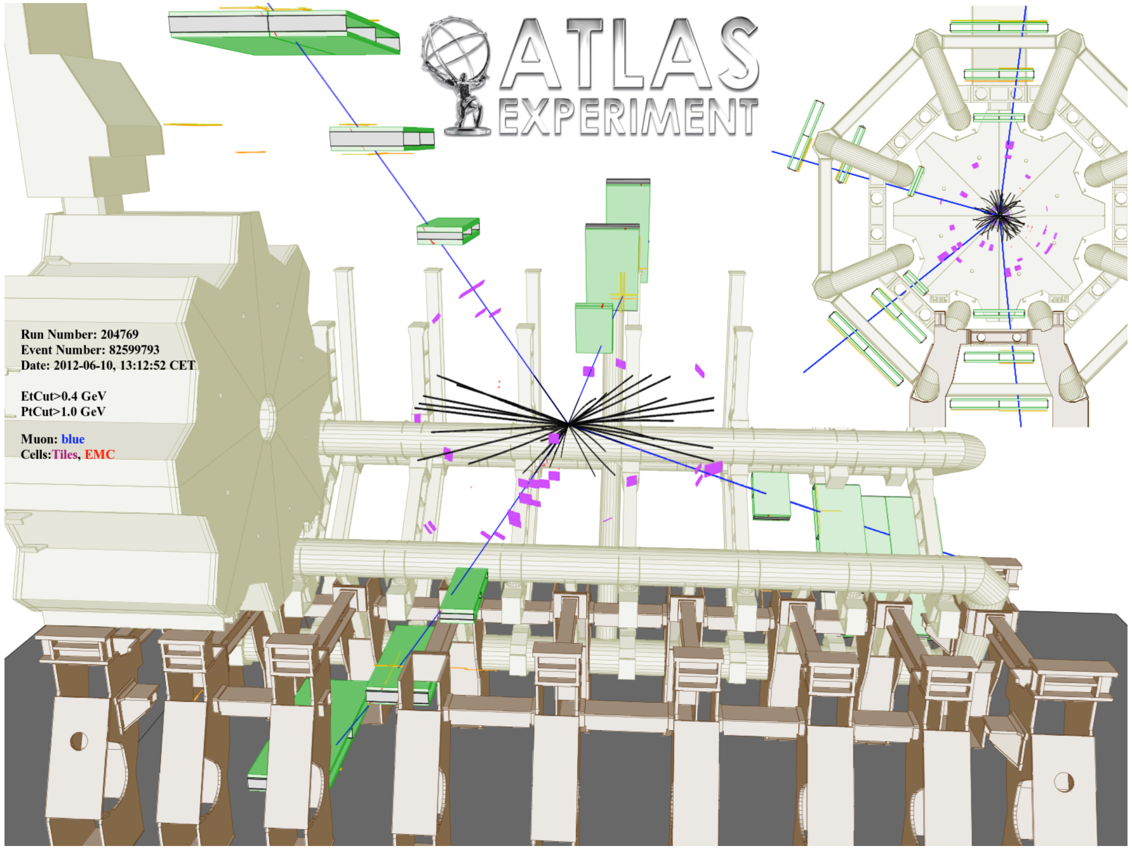
M. Malberti; April 2013

The H → ZZ* → 4ℓ Channel (1)

The “golden” channel – Narrow peak over a locally flat continuum
Very high mass resolution and S/B >> 1
Very low rates ($\sigma \times \beta \sim 0.8$ fb at 125 GeV)

Signature:
Four isolated leptons from
Common primary vertex

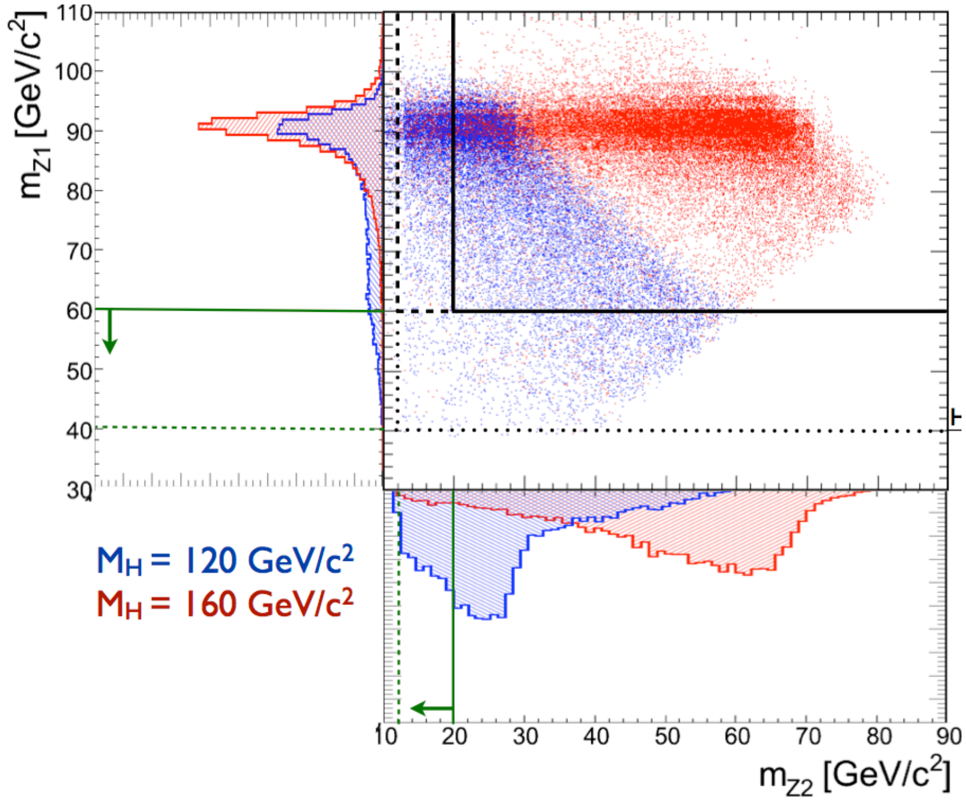
Analysis key:
- Precision on lepton (E,**P**) & highest possible ε_ℓ down to lowest P_T
- Maintain the reducible background well below the ZZ* continuum



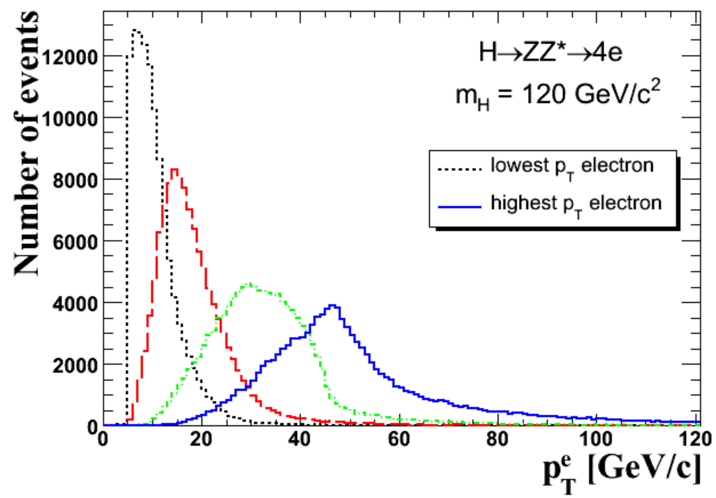
Discriminating variables:
$M_{4\ell}$
Kinematic Discriminant (e.g. M_{Z1}, M_{Z2}, 5 angles from decay chain)

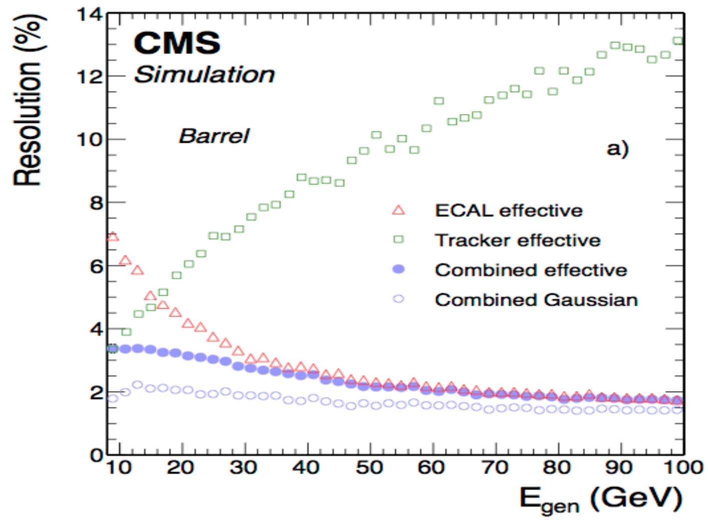
The H → ZZ* → 4ℓ Channel (2)

Kinematics:



H → 4l ; Lepton P_T spectrum





- Need to allow for off-shell Z bosons e.g. m_{Z2} down to 12 GeV

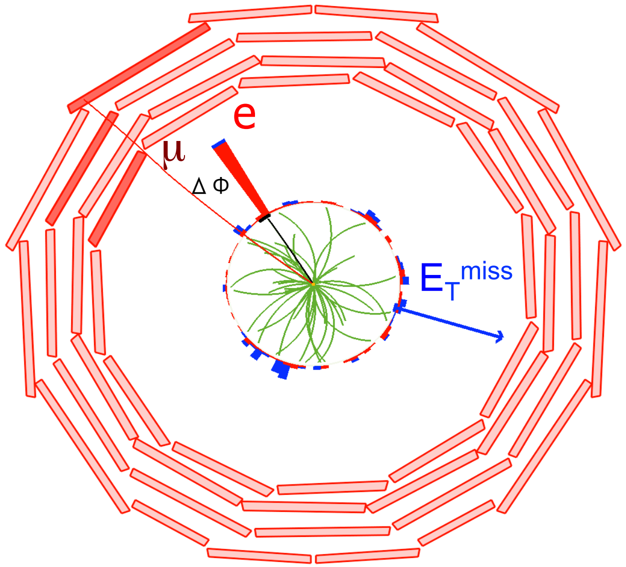
- Need high efficiency (overall acceptance ∝ ε^4) and good ℓ_{ID} down to very low lepton PT … and better combine tracker and calorimetry at low PT

The H → WW* Channel

Large rates (σ x β ~ 200 fb at 125 GeV) and low mass resolution

Signature:

Two opposite sign isolated high P_T leptons and missing E_T



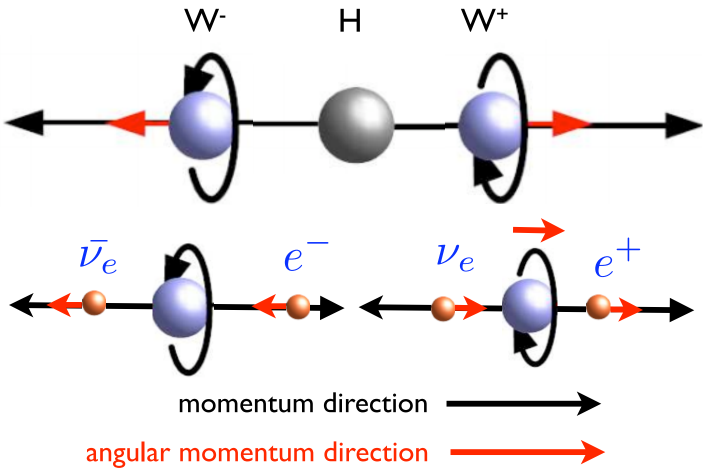
Analysis key:

Backgrounds from control regions with data

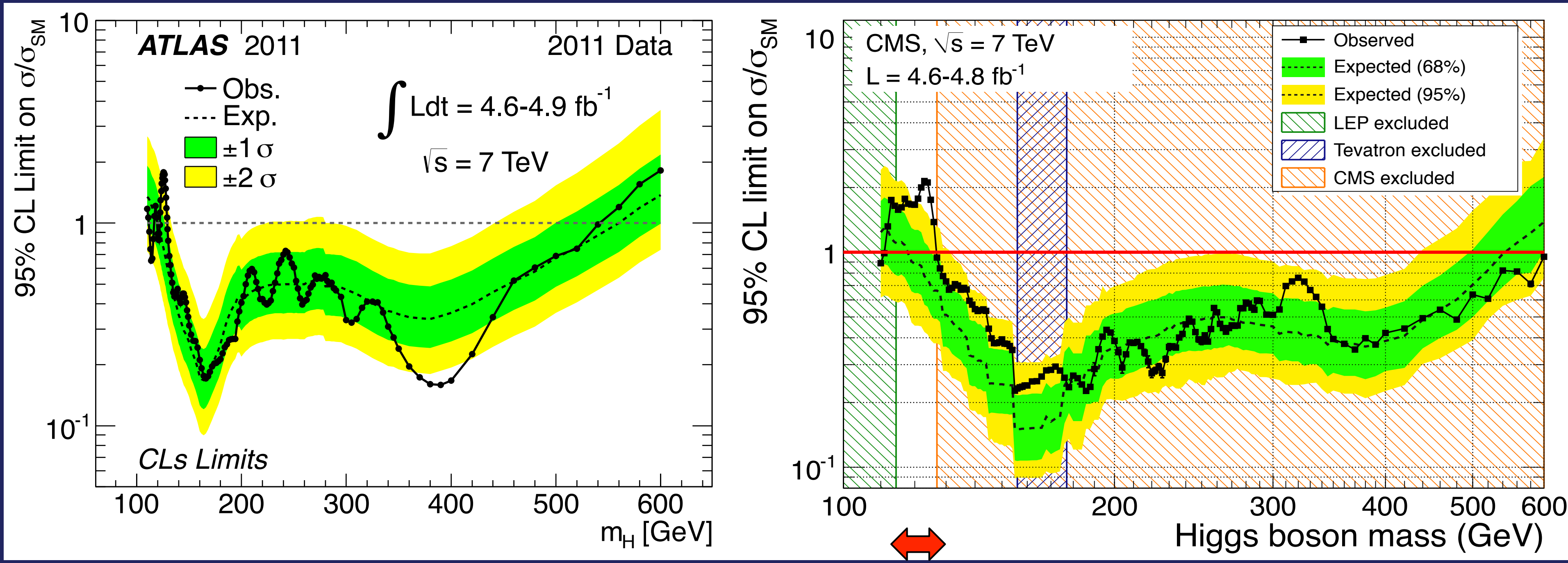
- Irreducible qq/$\gamma\gamma$ → non-resonant WW*
- Reducible: top, W+jets, di-boson, DY, …

Discriminating variables: $P_{T\ell\ell}$, $M_{\ell\ell}$ M_T, $\Delta\Phi_{\ell\ell}$

Small $M_{\ell\ell}$ & small opening angle $\Delta\Phi_{\ell\ell}$ ⇔ (especially for on-shell W's) exploits the scalar H nature and V-A structure of EWK interaction



December 2011



114.4 – 127.0 GeV/c^2

Only a small window survives !!! … some excess seen

No one ever said it would be this hard …

We could have(1) discovered the Higgs boson before there was nowhere else to go !

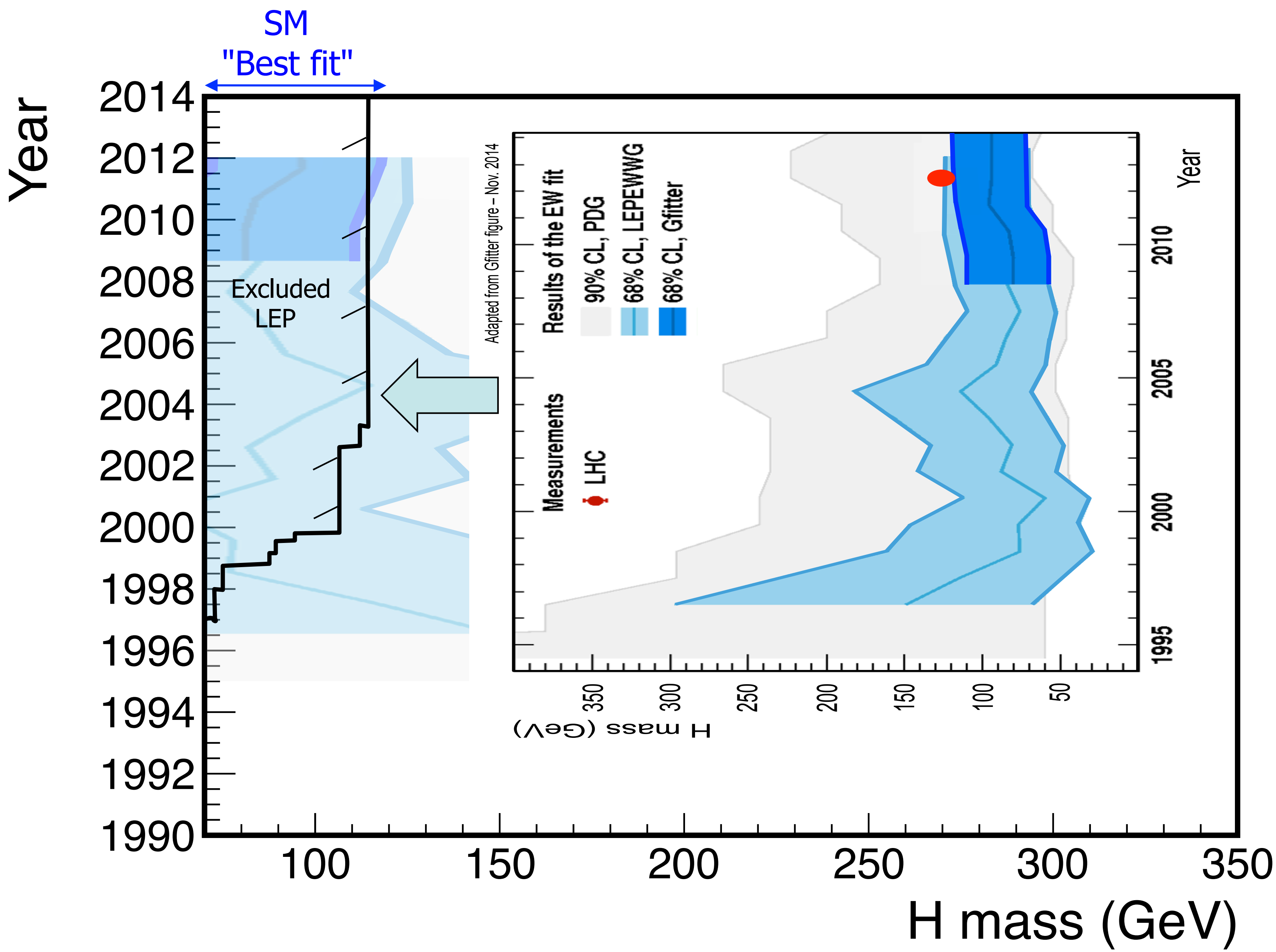
(1) At LEP, Tevatron, or early LHC

Does Nature hides her most precious treasure in a most innaccessible corner ?

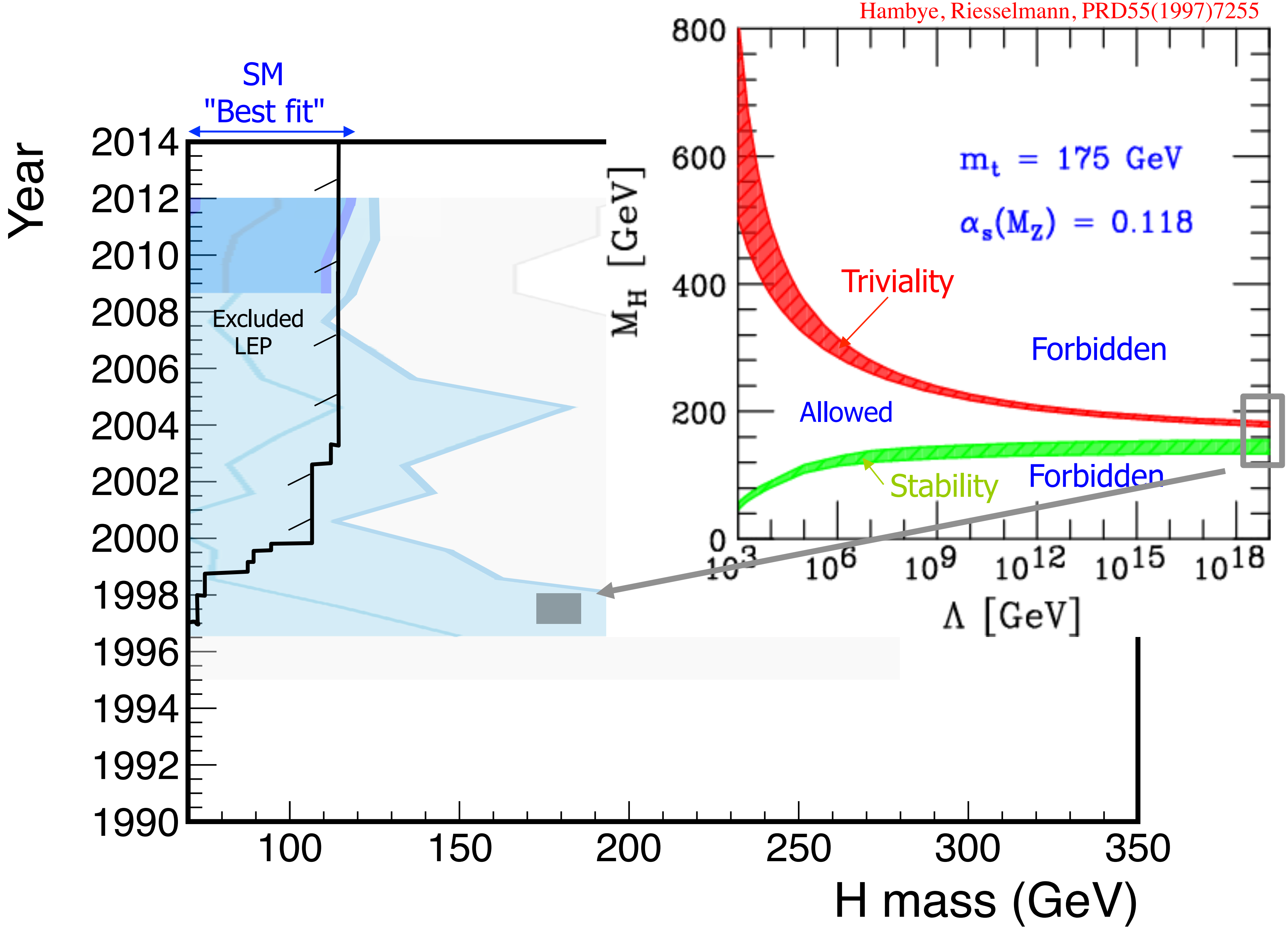
Maybe there is actually nothing in the remaining corner and we have to abandon the idea of a theory valid (at least in principle) at all scales (below Planck scale) ?

© Coldplay

The H boson mass : Theory vs Experiment

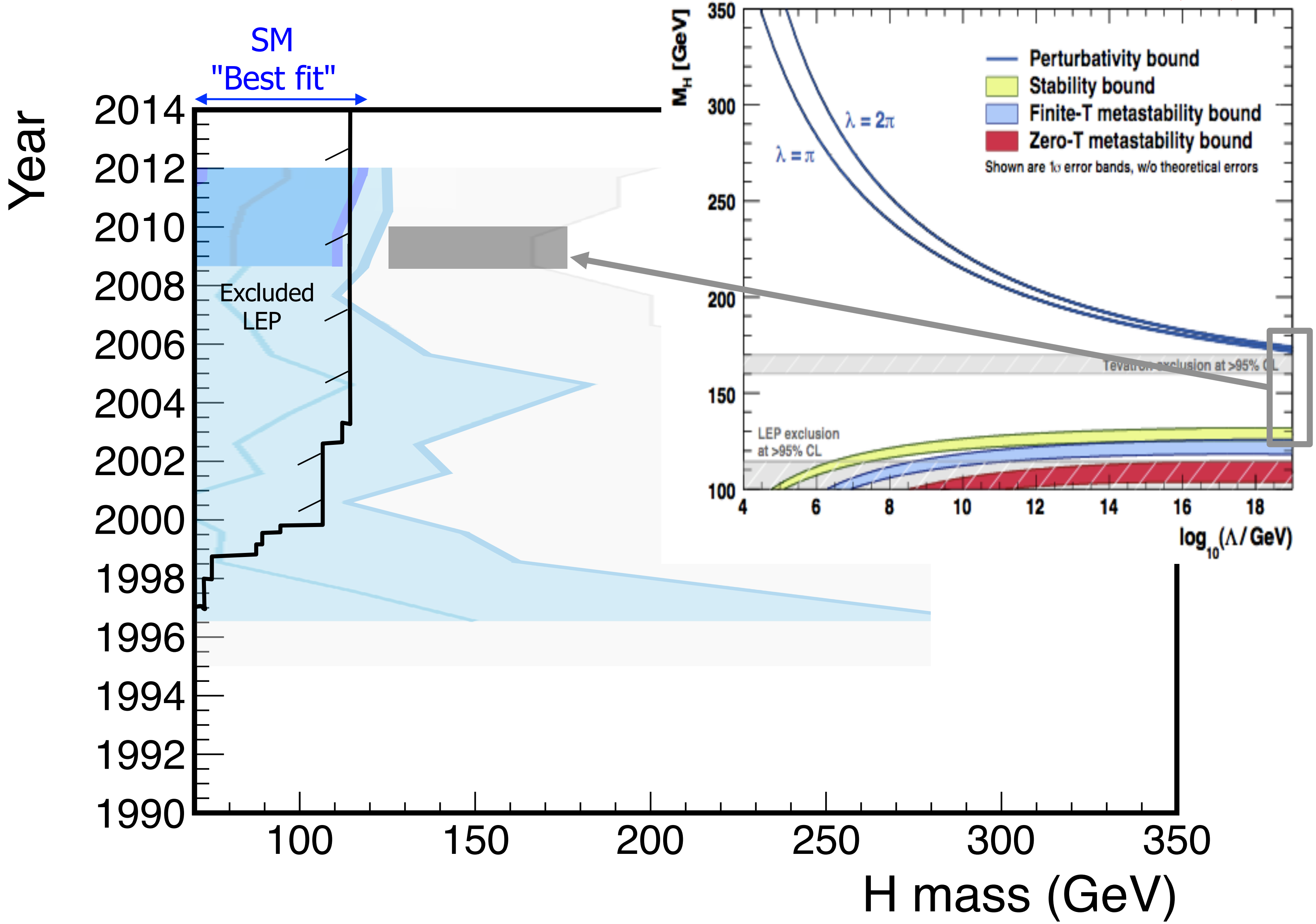


The H boson mass : Theory vs Experiment

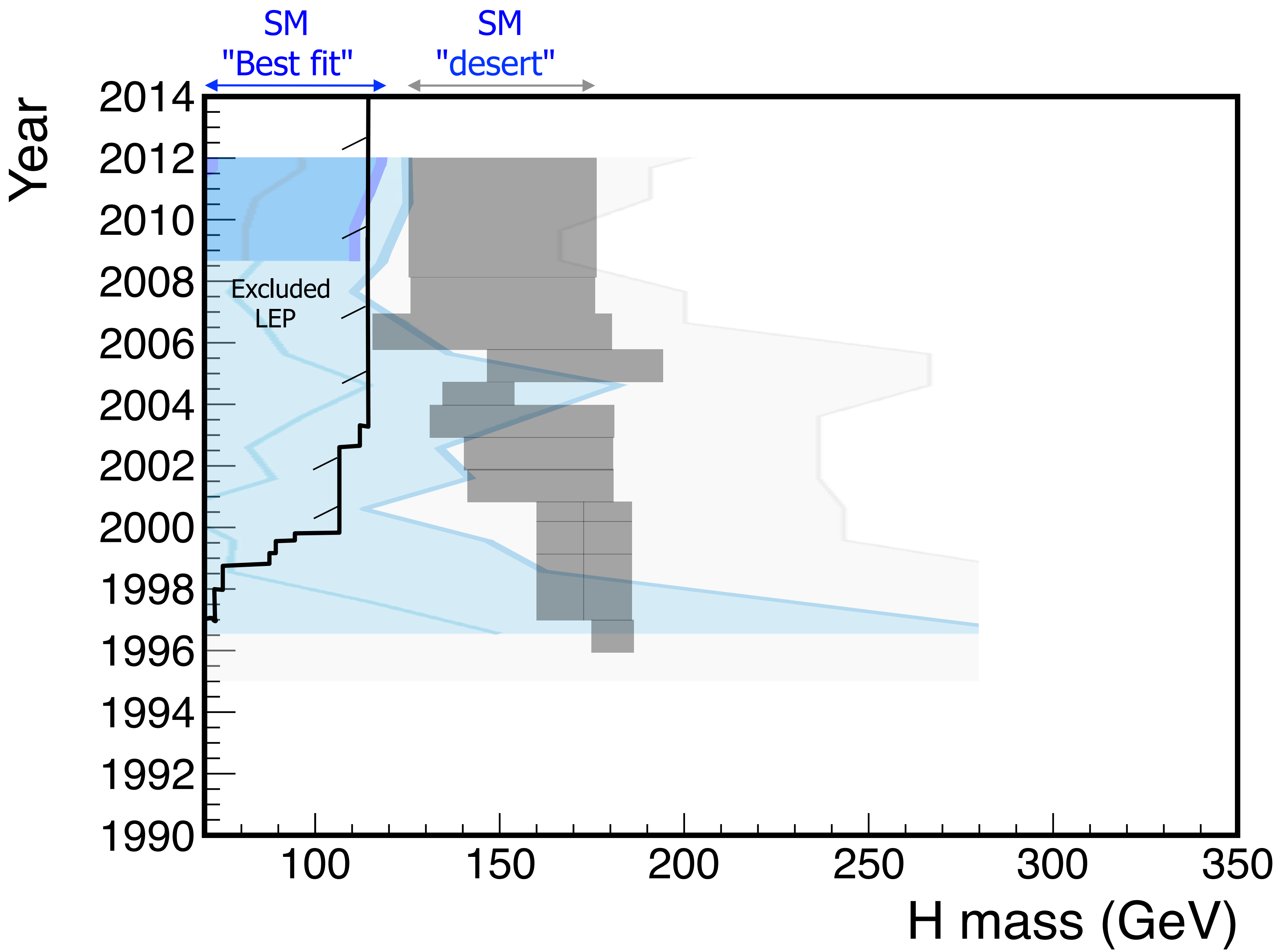


The H boson mass : Theory vs Experiment

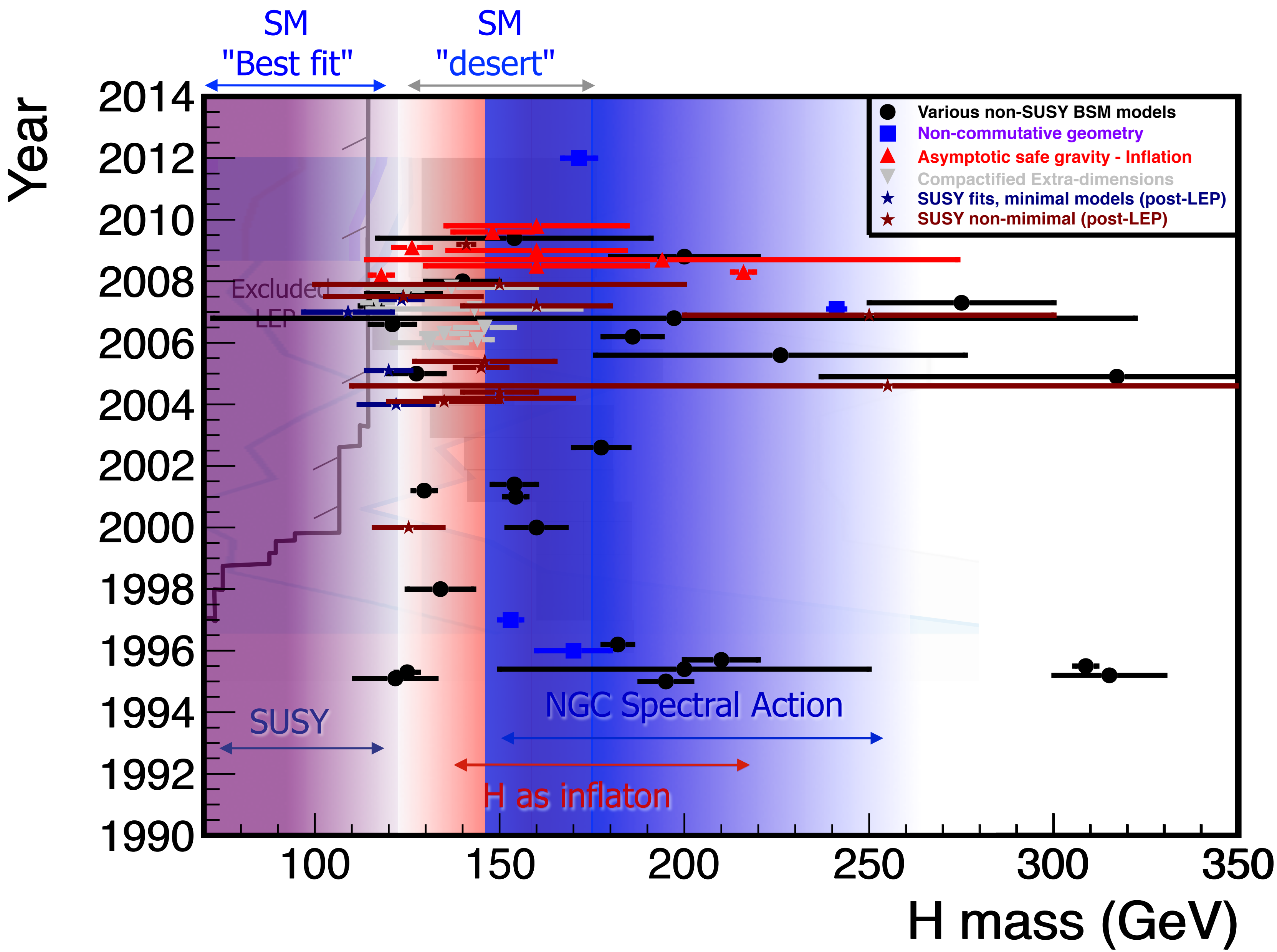
Ellis et al., PLB55(2009)369



The H boson mass : Theory vs Experiment

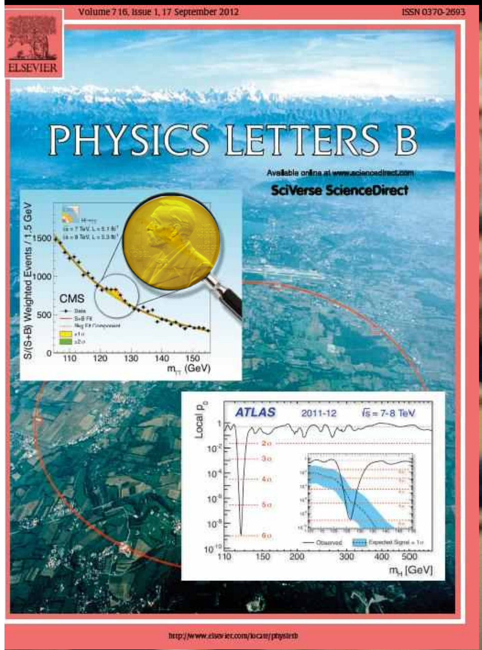


The H boson mass : Theory vs Experiment



What followed now belongs to the History of Science

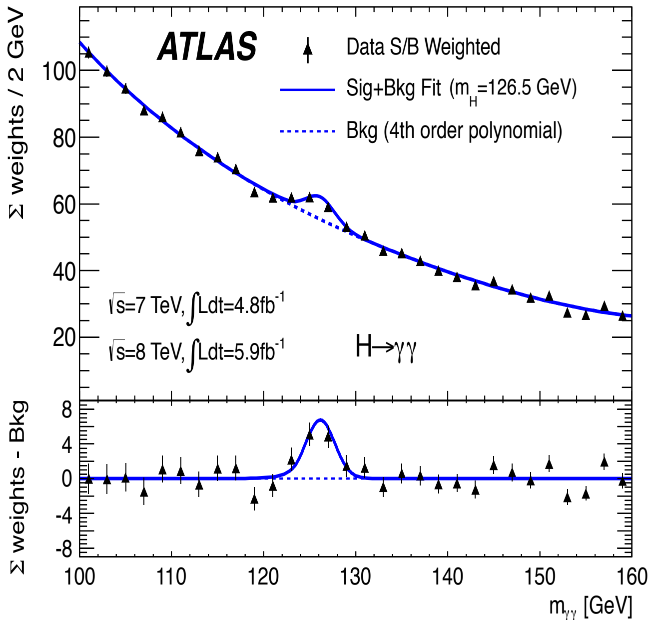
Each ~ 2500 citations so far

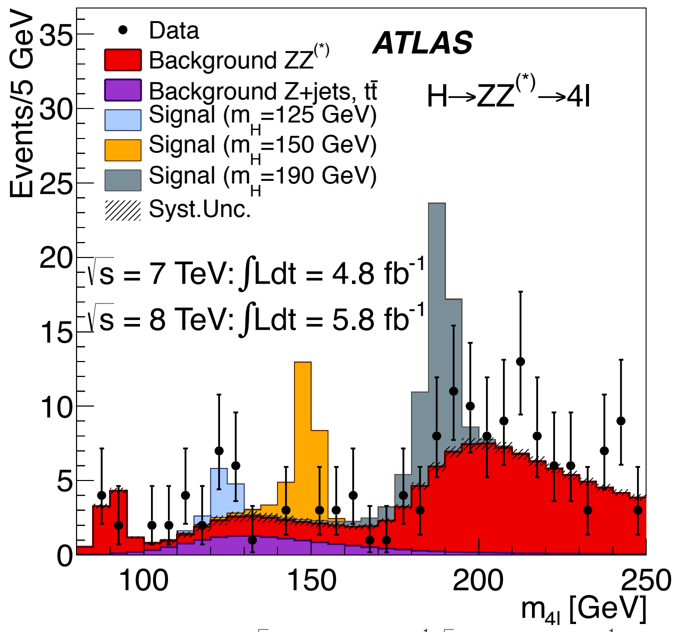


4 July 2012

ATLAS

Phys.Lett. B716 (2012) 1-29

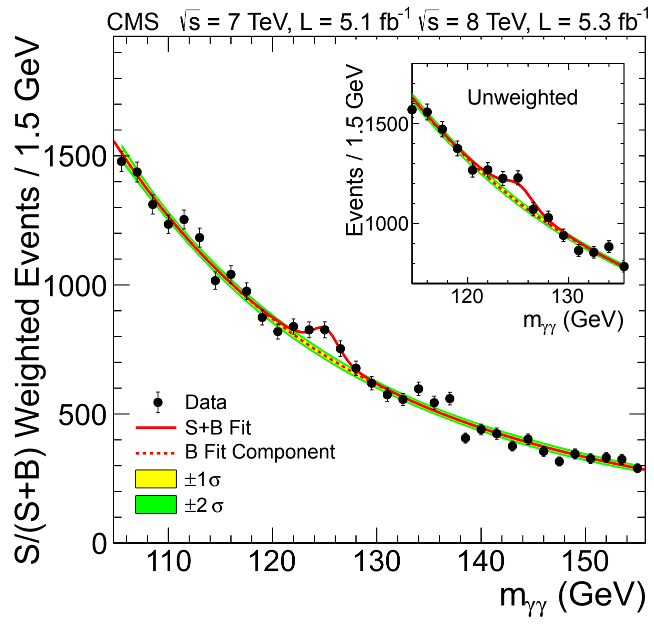


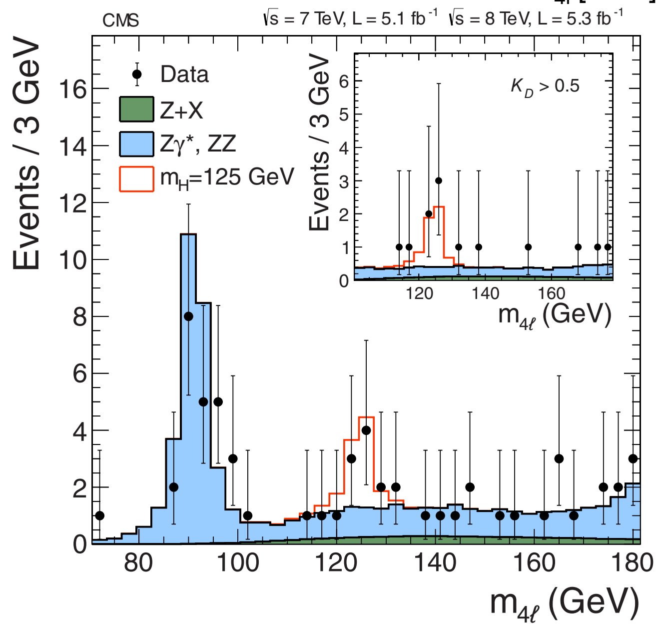


J U L Y 2 0 1 2

CMS

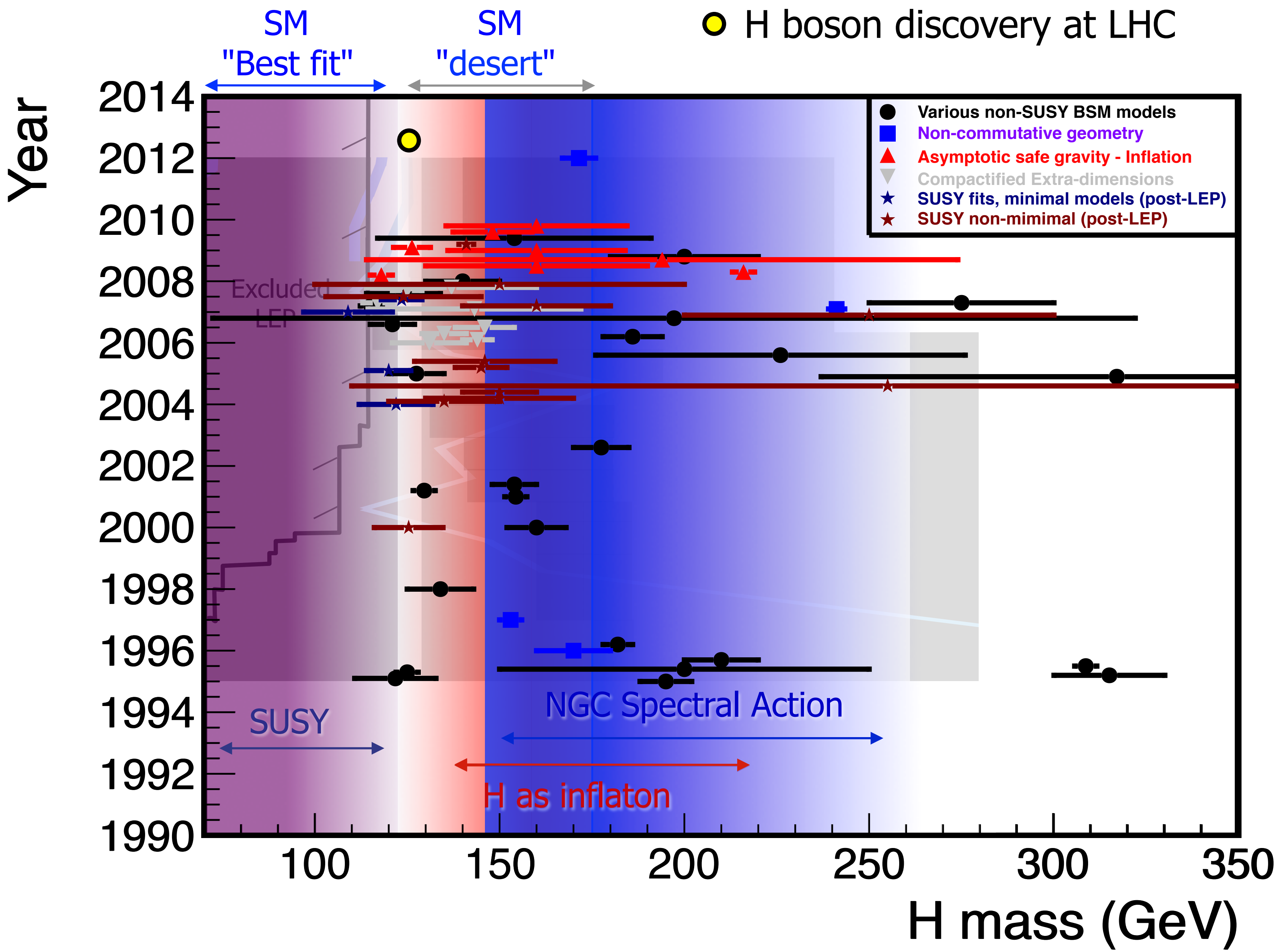
Phys.Lett. B716 (2012) 30-61





Discovery at M_X ~ 125 GeV, in both ATLAS and the CMS experiments combining $X \rightarrow \gamma\gamma$ and ZZ* channels (additional evidence from $X \rightarrow WW^*$)

The H boson mass : Theory vs Experiment

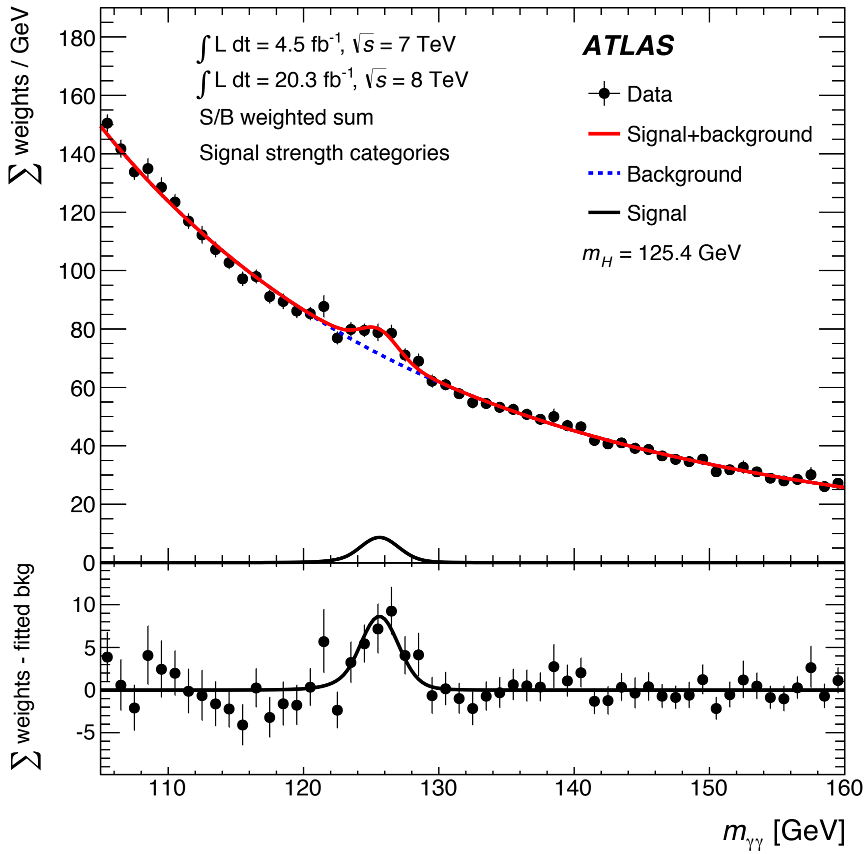


The H125 Boson
(stand-alone results)

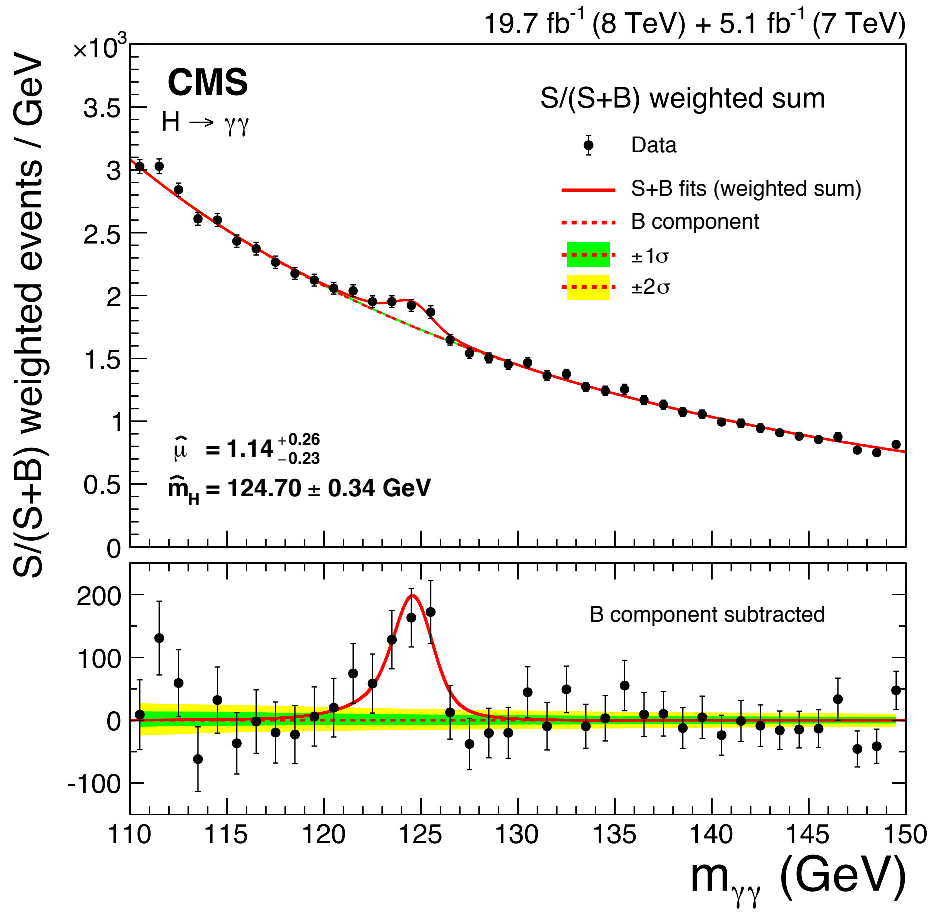
Mass, width, spin-parity
(Di-boson decay channels)

Mass Spectra: $H \rightarrow \gamma\gamma$

ATLAS, arXiv:1408.7084v2; Submitted to PRD



CMS, Eur. Phys. J. C74 (2014) 10, 3076



$\mu = 1.17 \pm 0.24$ (@ 125.4 GeV)

$\mu = 1.14^{+0.26}_{-0.23}$

$m_H^{\gamma\gamma} = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})$ GeV

$m_H^{\gamma\gamma} = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})$ GeV

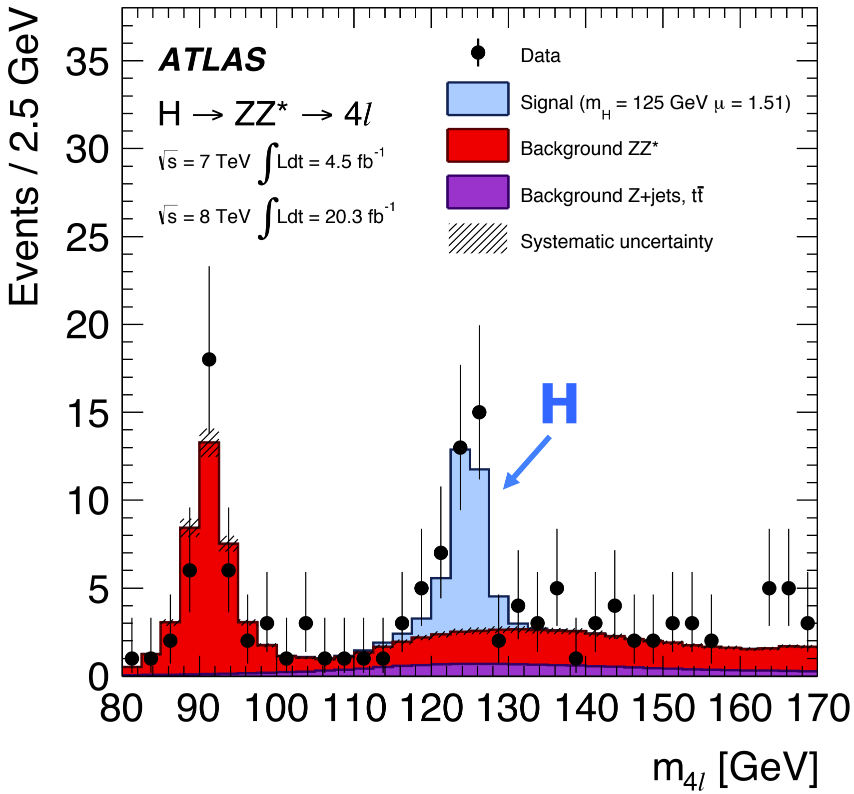
$\Gamma <$ 5.0 GeV (95% CL)

$\Gamma <$ 2.4 GeV (95% CL)

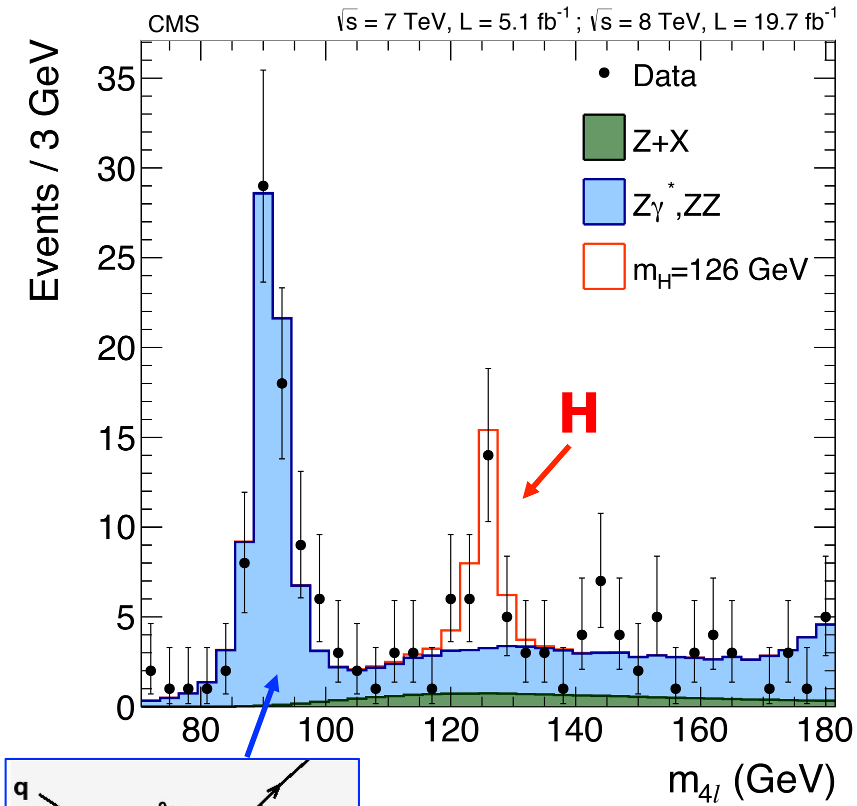
Results consistent, and compatible with a single narrow resonance

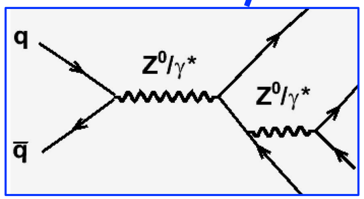
Mass Spectra: $H \rightarrow ZZ^* \rightarrow 4l$

ATLAS, arXiv:1408.5191v1; Submitted to PRD



CMS, Phys. Rev. D89 (2014) 092007





$\mu = 1.44^{+0.40}_{-0.33}$ (@ 125.4 GeV)

$\mu = 0.93^{+0.29}_{-0.25}$

$m_H^{ZZ} = 124.51 \pm 0.52$(stat) $\pm$ 0.06(syst) GeV

$m_H^{ZZ} = 125.6 \pm 0.4$(stat) $\pm$ 0.2(syst) GeV

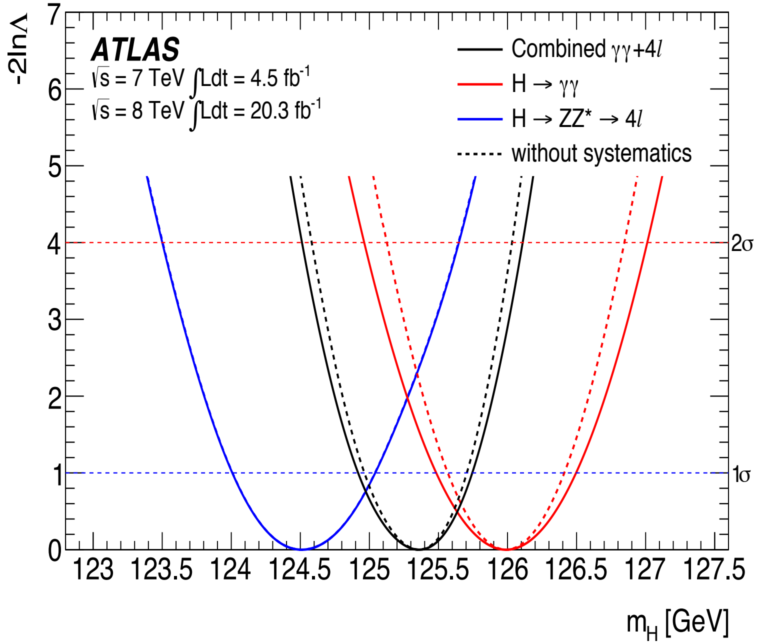
$\Gamma <$ 2.6 GeV (95% CL)

$\Gamma <$ 3.4 GeV (95% CL)

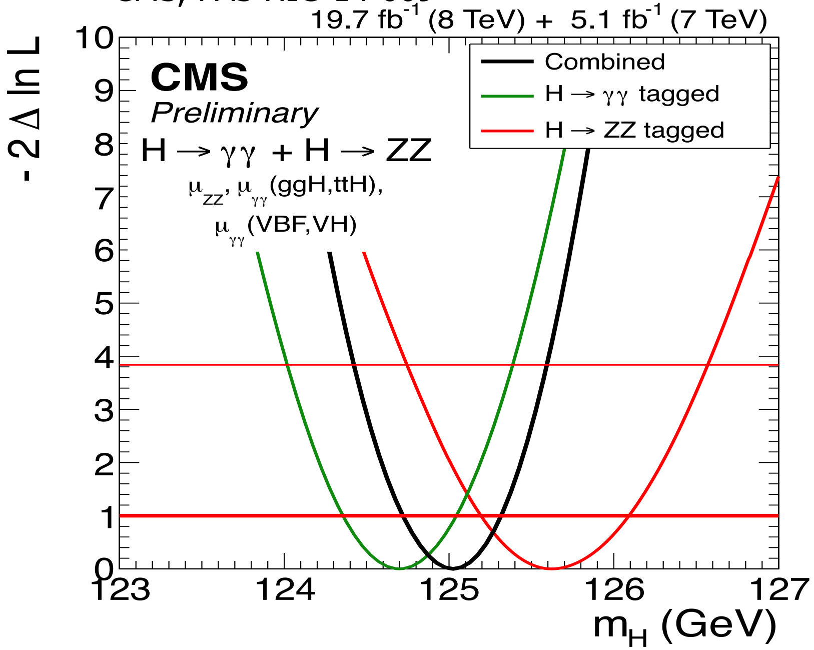
Results consistent, and compatible with a single narrow resonance

Precision Mass Measurements

ATLAS, arXiv:1406.3827v1; Submitted to PRD



CMS, PAS HIG-14-009



Expt.	Decay Channel	Signal Strength $\mu = \sigma_{meas.}/\sigma_{SM}$	Measured Mass (GeV) mass ± statistics ± systematics
ATLAS	H→ $\gamma\gamma$	$1.29^{+0.30}_{-0.30}$	$125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})$
	H→ZZ*→ 4ℓ	$1.66^{+0.45}_{-0.38}$	$124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst})$
	Combined	—	**125.36 ± 0.41**
CMS	H→ $\gamma\gamma$	$1.14^{+0.26}_{-0.23}$	$124.7 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})$
	H→ZZ*→ 4ℓ	$0.93^{+0.29}_{-0.25}$	$125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$
	Combined	—	**125.03 ± 0.30**

$m_H = 125.16 \pm 0.24$ GeV

Measuring S^{CP} at the LHC

- The spin-parity of the Higgs boson candidate (assuming pure J^P state) can be tested in di-boson decay channels or via associated production

H → γγ ATLAS, CMS

Test 0^+ against 2^+ states (spin 1 forbidden by Landau-yang theorem)

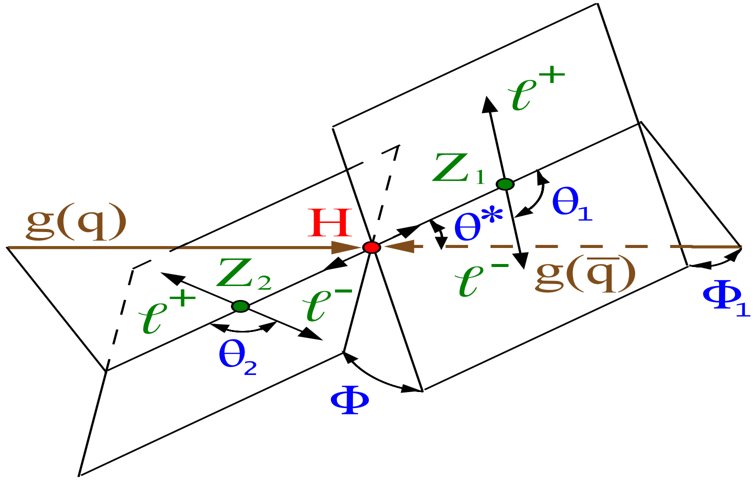
e.g. exploit the prod. dependent scattering angle in the Collins-Sopper frame

$$\cos(\theta^*_{CS}) = 2 \times \frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + p^2_{T\gamma\gamma}}}$$

H → ZZ* → 4l ATLAS, CMS

Test 0^+ against spin 0^-, $1^\pm$ and $2^\pm$ states

e.g. use kinematic discriminants exploiting production and/or decay angles



H → WW* → 2ℓ 2ν ATLAS, CMS

Test 0^+ against 0^- or 2^+

e.g. exploit the prod. dependent 2D distributions in m_T and $M_{\ell\ell}$

ATLAS PLB726 (2013) 120-144.
CMS PRD110 (2012) 081803 arXiv:1312.5353 & 1129, PAS-HIG-13-016

H → b anti-b D0

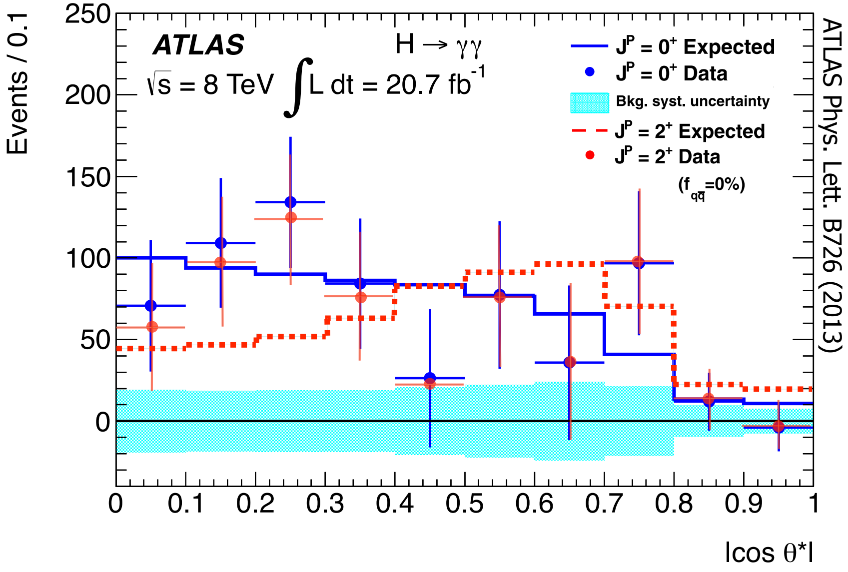
Test 0^+ against 0^- or 2^+

D0 Conf. Note 6404, 6387

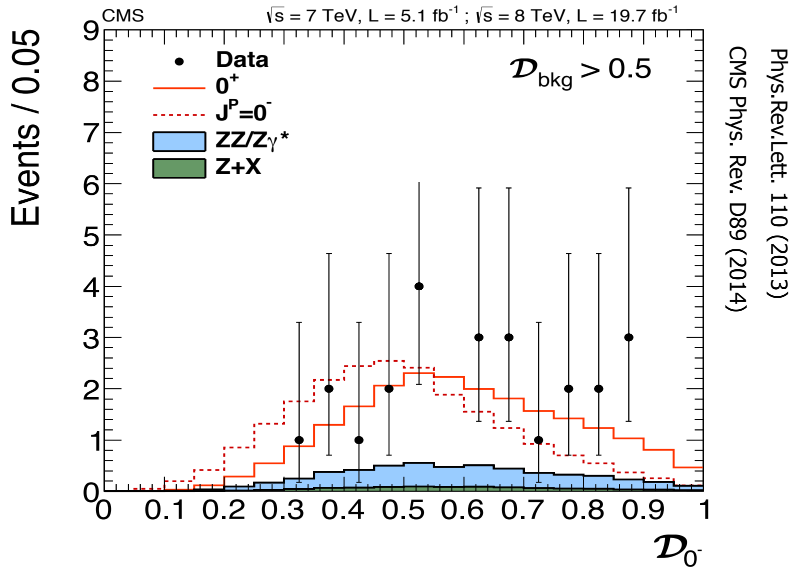
e.g. exploit the prod. dependent shape of invariant mass (Mbb) spectra in VH associated production (V = Z/W)

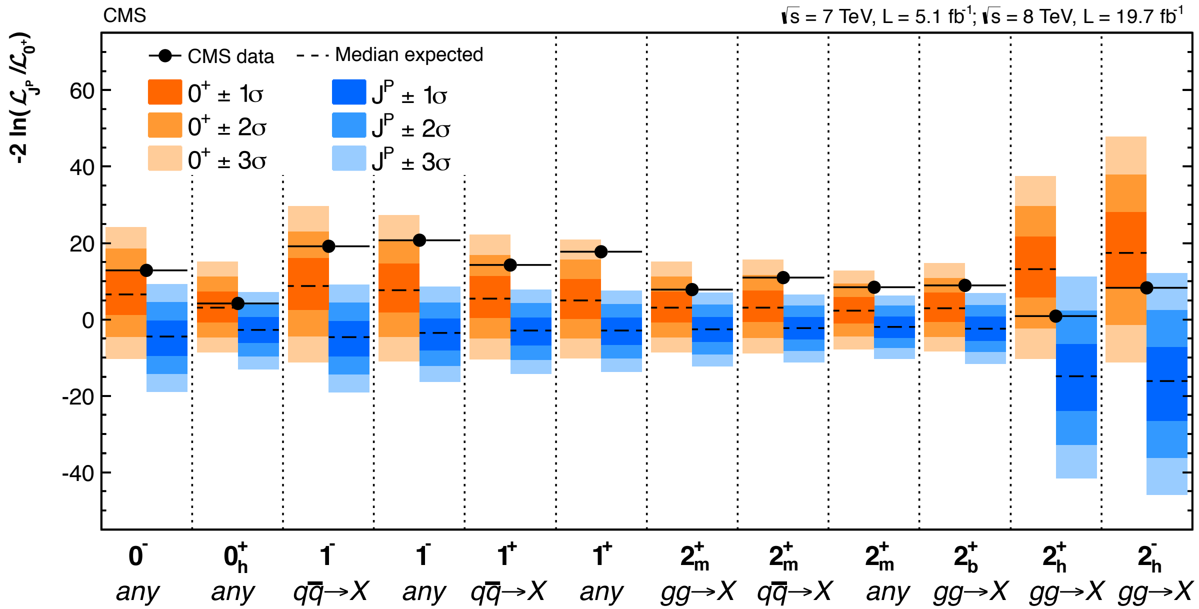
H boson: spin-parity

$H \to \gamma\gamma$ test 0^+ and 2^+



$H \to ZZ^* \to 4\ell$ test 0^+ vs 0^-





The pseudoscalar (0^-) hypothesis is excluded at > 99.9% CL (CL_S 0.05%)

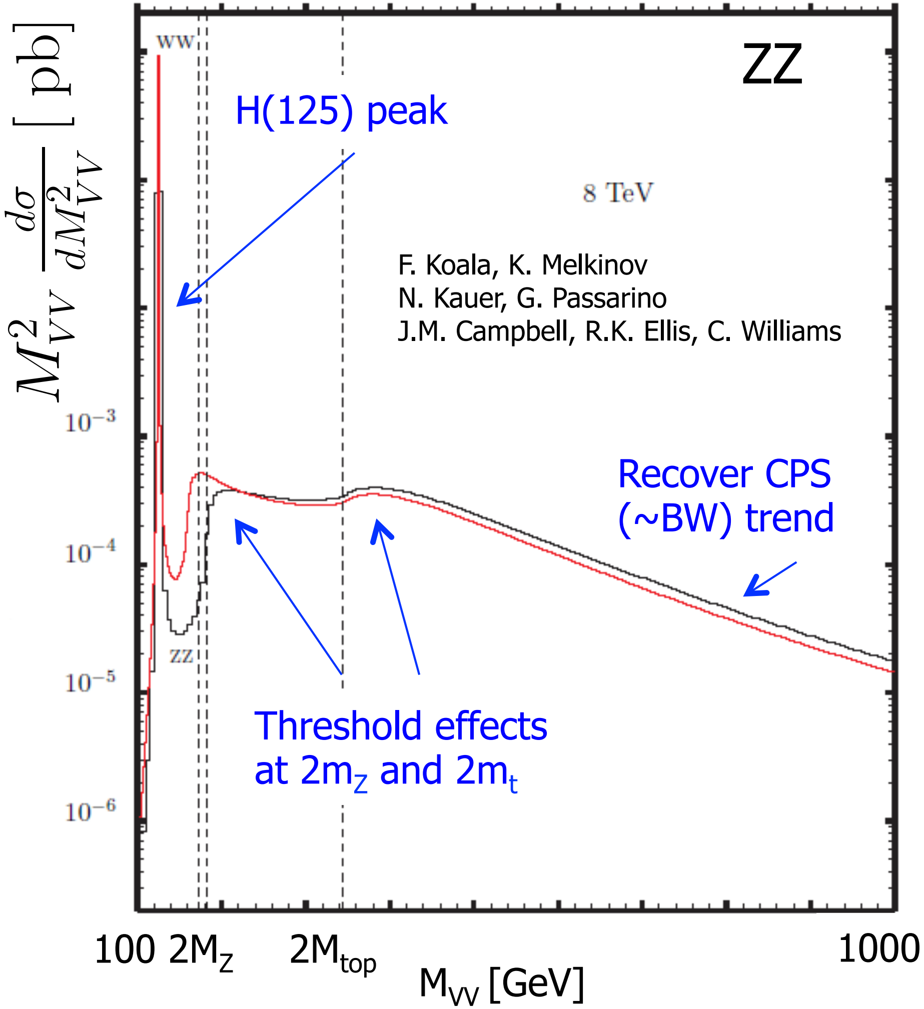
All spin-1 hypotheses excluded at > 99.9% CL

All spin-2 hypotheses excluded at > 95% CL

Measuring Γ_H at the LHC

- Expect $\Gamma_H \sim 4.2$ MeV in SM for a H at $m_H \sim 125$ GeV $\begin{cases} \Gamma_H \ll m_H \quad \Gamma_H \ll \Delta m_H^{meas} \\ \tau_H^0 = \hbar/\Gamma_H \simeq 2\times 10^{-22} s \end{cases}$
- No direct access to Γ_H at LHC ⇔ Indirect constraints "via the propagator" !

Exploit relative intensity of the signal on- and off-peak:



Principle:

- Use finite-width propagator scheme
- Profit from sizeable contribution of $H^* \to ZZ$ at $M_{4\ell} > 2 \times M_Z$
  enhancement of O(10) %
- Account for interference between gg → ZZ and gg → H* → ZZ
  \+ alteration of coupling to top quark

Observation:

Consider off- (H*) and on-shell (H) prod.

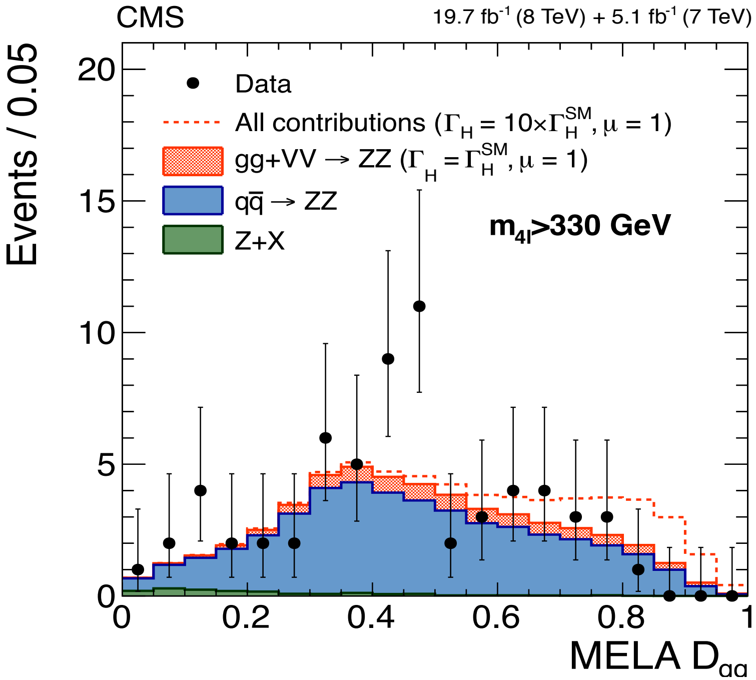
$$\mu_{ZZ}^{\rm on} \equiv \frac{\sigma_h \times {\rm BR}(h\to ZZ\to 4\ell)}{[\sigma_h \times {\rm BR}(h\to ZZ\to 4\ell)]_{\rm SM}} \sim \frac{\kappa_{ggh}^2\,\kappa_{hZZ}^2}{\Gamma_h/\Gamma_h^{\rm SM}}$$

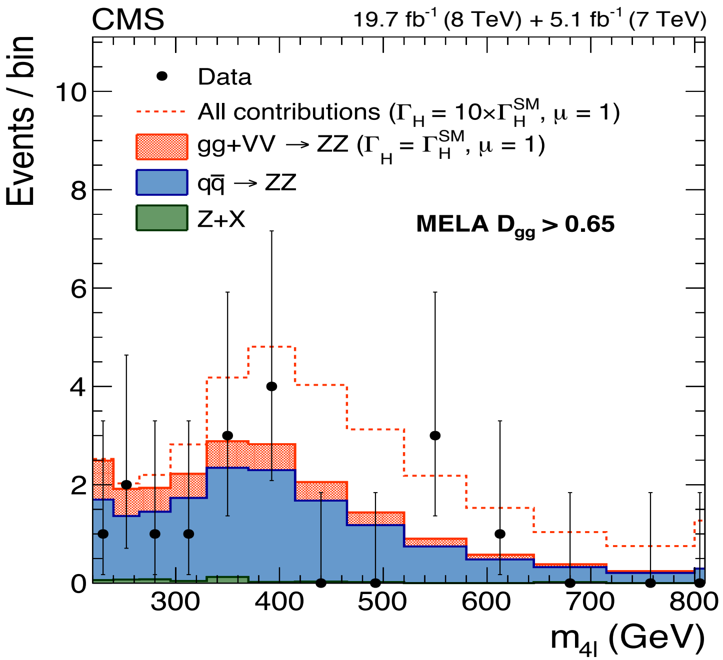
$$\mu_{ZZ}^{\rm off} \equiv \frac{{\rm d}\overline{\sigma}_h}{[{\rm d}\overline{\sigma}_h]_{\rm SM}} \sim \kappa_{ggh}^2(\hat{s})\,\kappa_{hZZ}^2(\hat{s})\,,$$

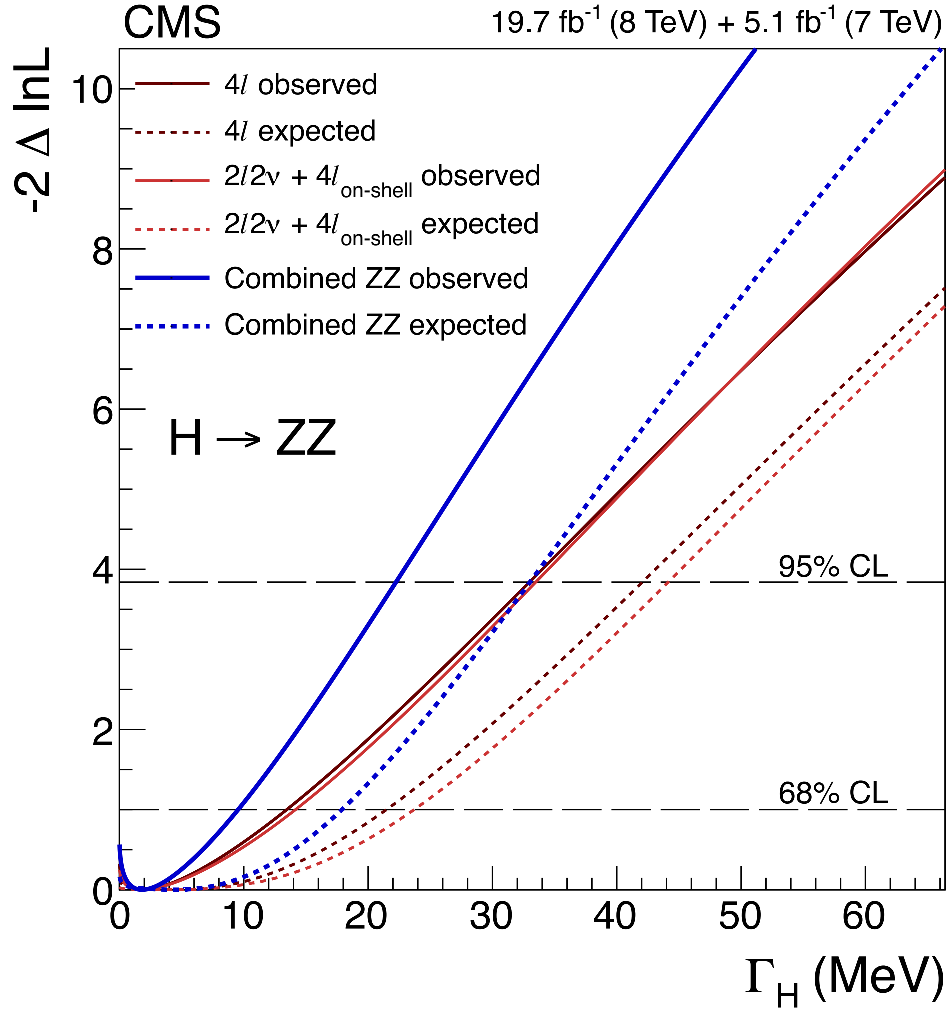
Access ⇒ Γ_H / Γ_H^{SM}

C. Englert, Y. Soreq, M. Spannowsky

Constraints on Intrinsic Width Γ_H







CMS Phys. Lett. B736 (2014) 64

	Observed	Expected
$\Gamma_H = 1.8\,^{+12.4}_{-1.8}$ MeV	$\Gamma_H <$ 22 MeV 95% CL	33 MeV

Similar results from ATLAS in
ATLAS-CONF-2014-042 (July 2014)

Direct Coupling to Fermions
(stand-alone results)

The H → Fermions

Large rates ($\beta_{H \rightarrow bb}$ ~ 58%) and medium mass resolution

Signature:

H → bb ggH, H → bb is saturated by QCD background ⇒ focus on WH and ZH prod. with b-tagged jets and ≥ 1 lepton

H → ττ Exploit production and τ lepton decay dependent categorisation

Analysis key:

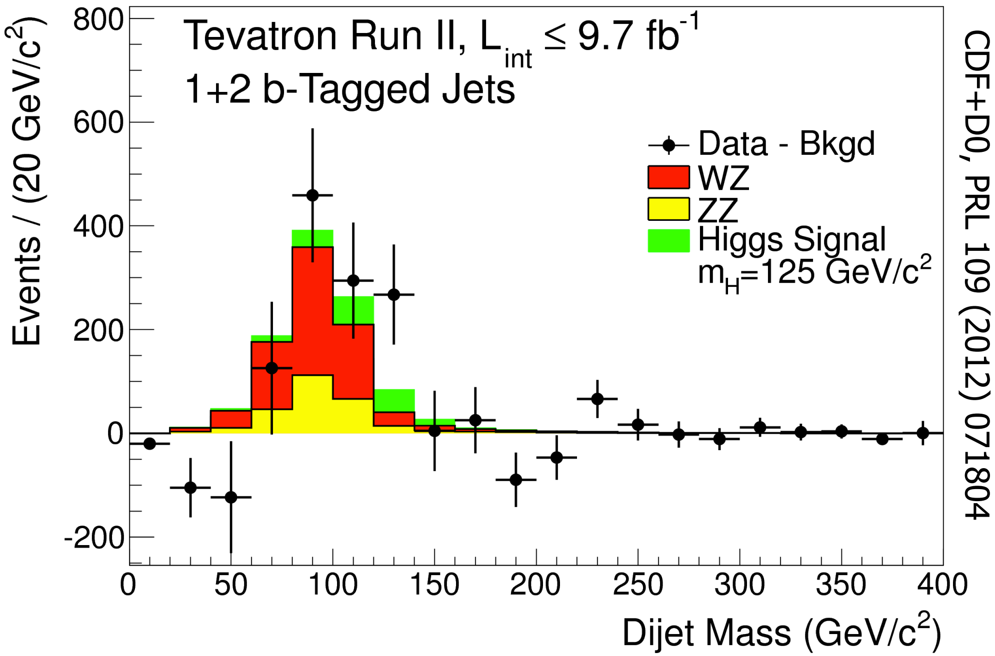
Mass discrimination against background from Z/W + heavy flavours

First evidence in the H → bb channel from Tevatron in 2012:

CDF + D0 10 fb^{-1}

WH → ℓν bb
ZH → ℓℓ bb
ZH → νν bb

Excess with more than 3 σ significance at ~ 135 GeV



H → ττ at the LHC (1)

- All leptonic and « hadronic » decay combinations considered $\tau_\ell\tau_\ell$, $\tau_\ell\tau_h$, $\tau_h\tau_h$
- Event categorisation to enhance sensitivity specific to ggH, VBF H, VH
- Z → ττ from Z → μμ with embedded (MC) τ leptons
- W/Z + jets, $t\bar{t}$, and QCD backgrounds from fake rate methods

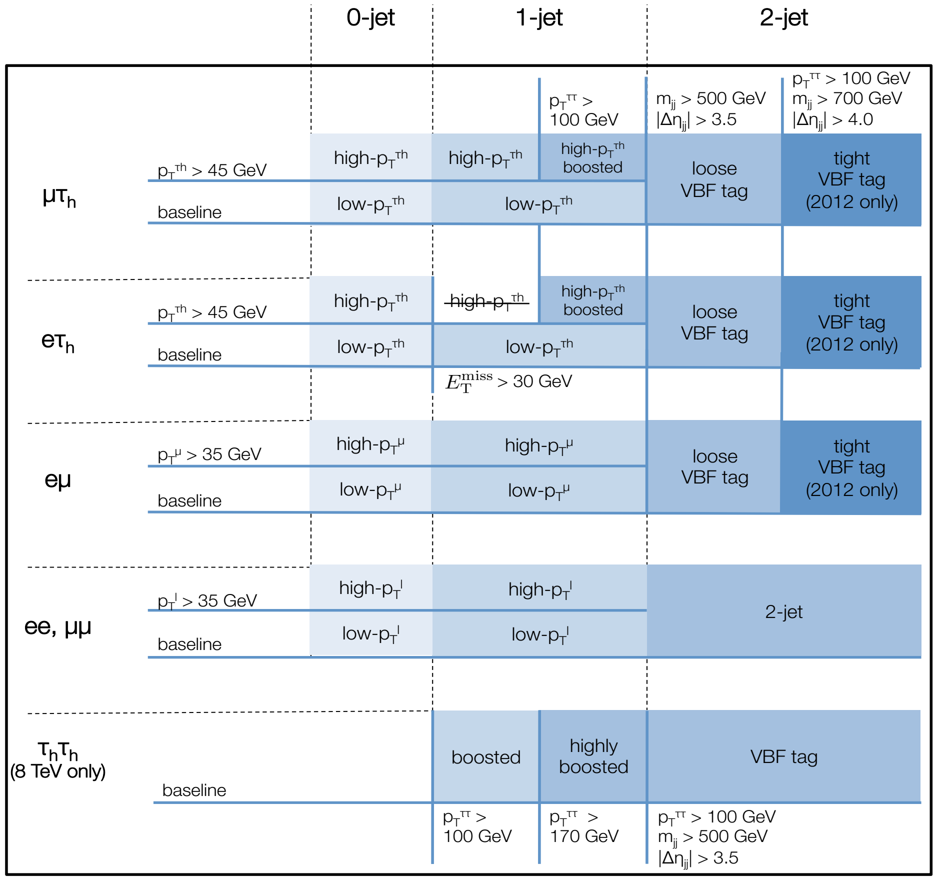
ATLAS

VBF and Boosted categories

Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j1} > 40$ GeV and $p_{\rm T}^{j2} > 30$ GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} > 50$ GeV and $p_{\rm T}^{j2} > 30$ GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} > 40$ GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j1} > 50$ GeV and $p_{\rm T}^{j2} > 30$ GeV $p_{\rm T}^{j2} > 35$ GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	**Boosted category selection cuts**
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} > 40$ GeV
All	Failing the VBF selection $p_{\rm T}^{H} > 100$ GeV

CMS

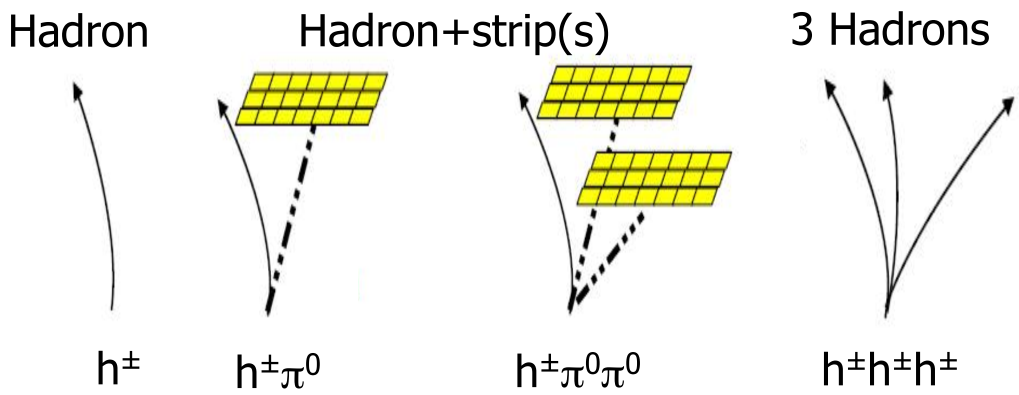
Jet Categories (VBF and Boosted)



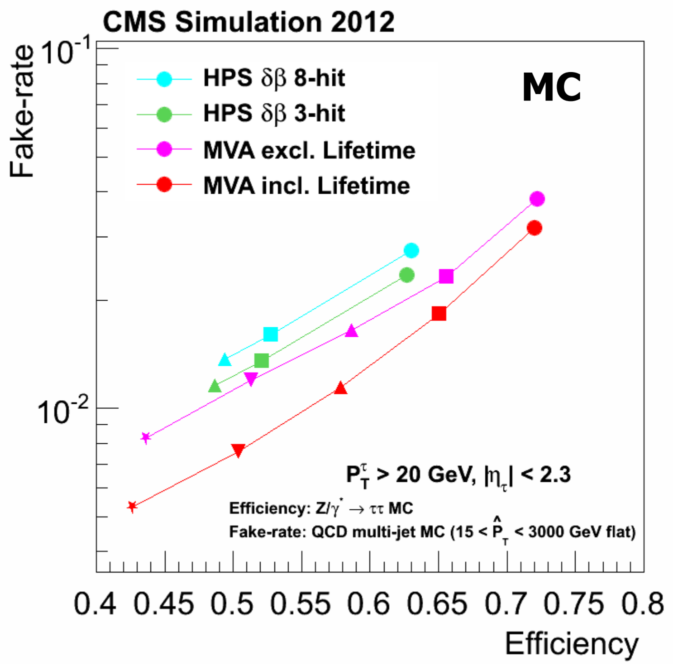
τ Identification

e.g. CMS

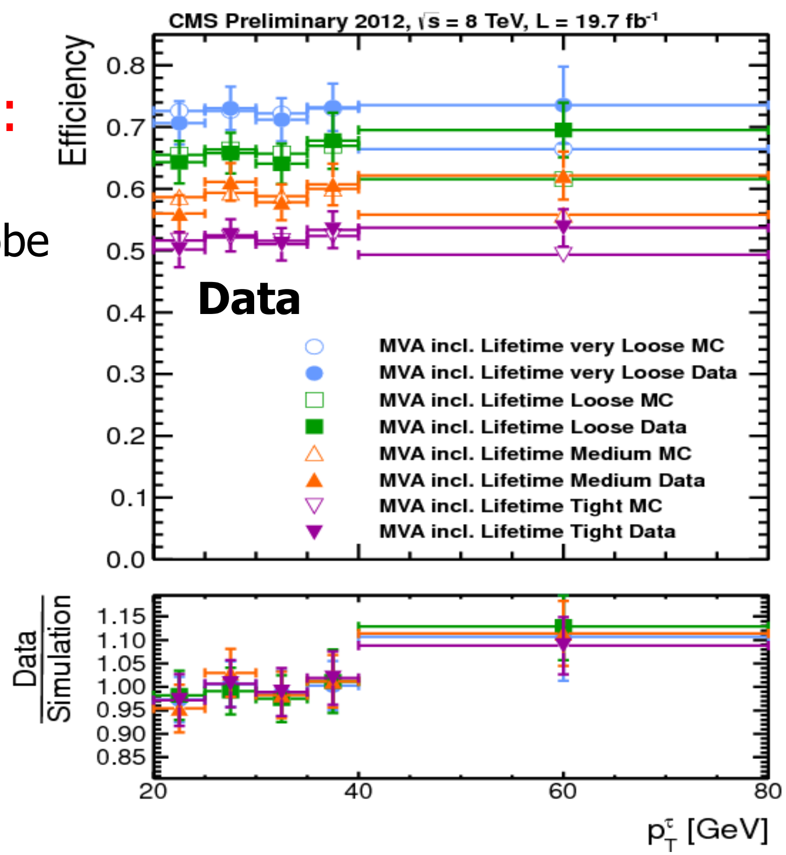
1) Decay mode finding
   Require a valide π, ρ, α
2) Isolation with Δβ vertex
   $\Sigma P_T < 2$ GeV ; cone of $\Delta R = 0.5$
3) Electron rejection
   Pflow e; Brem detection
4) Muon rejection
   Compatibility with leading track



New MVA based τ_{Id} using lifetime info:



Tag & Probe using $Z \to \tau\tau$ events :



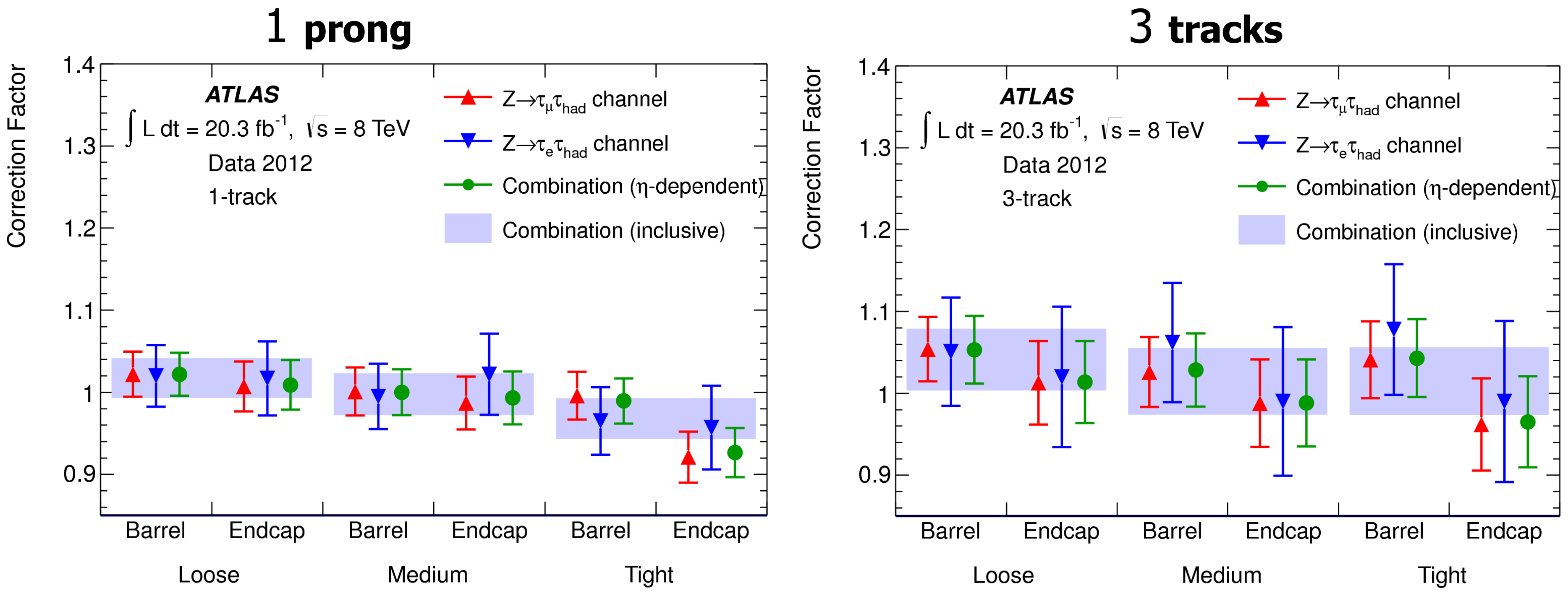
CMS DP-2014-015, CMS TAU-14-001

τ Energy Scale

e.g. ATLAS

ATLAS CONF-2013-044; CONF-2013-064; EPJ C75 (2015) 303

- Evaluate the correction factors needed to equalize data/MC τ_{ID} efficiencies for all τ_{ID} working points as a function of η
- Treat 1-prong and 3-track $\tau_{had\text{-}vis}$ candidates with p_T > 20 GeV.



All E scale factors well under control at all η's

Background Control

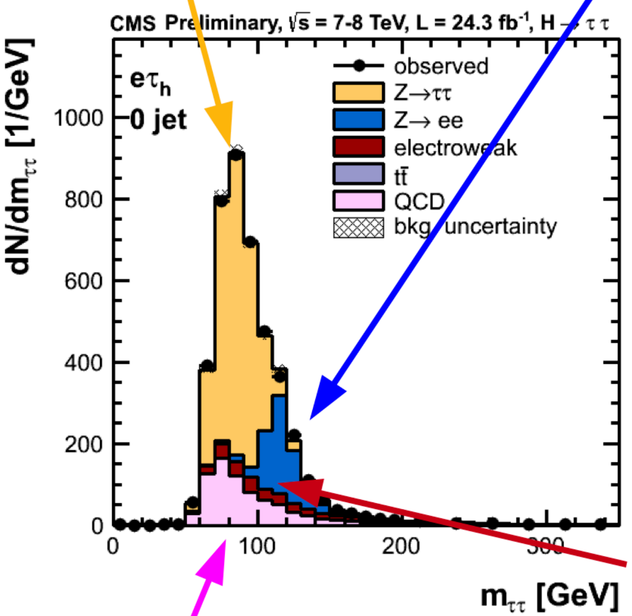
e.g. CMS

$Z \rightarrow \tau\tau$

Embedding: $Z \rightarrow \mu\mu$ data with μ replaced by simulated τ

$Z \rightarrow ll$

- $l/jet \rightarrow \tau_h$ fakes
- Shape from simulation corrected for yield in visible mass region



W+jets

- $Jet \rightarrow \tau_h$ fakes
- Suppressed by topological cuts (e.g. m_T)
- Simulation normalized to data in sideband

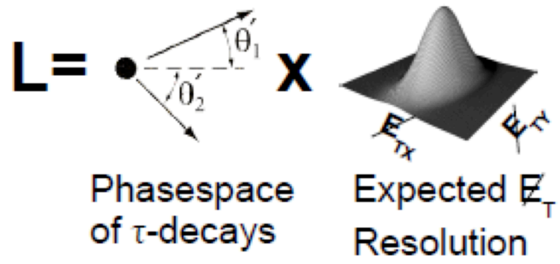
QCD

- $Jet \rightarrow l/\tau_h$ fakes
- Suppressed by isolation
- Same-sign data (corrected for OS/SS ratio)

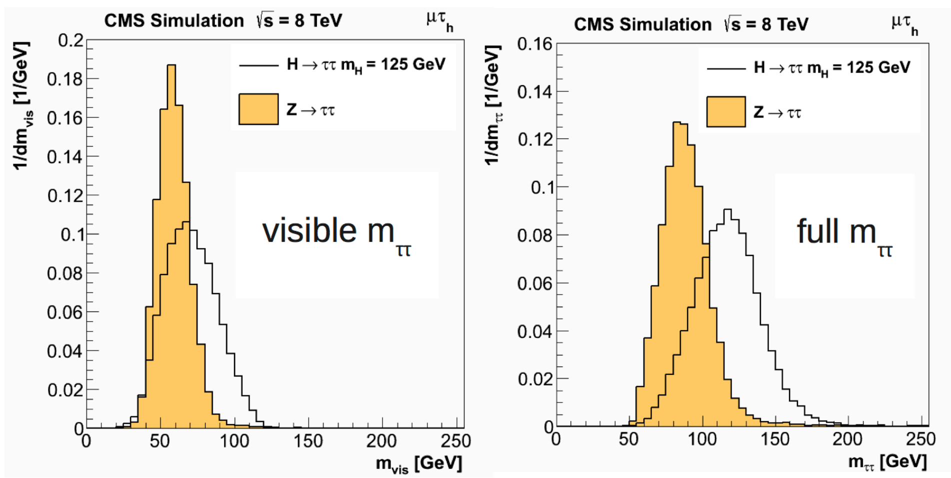
M. Bluj, EPS HEP 2013

mττ measurement

e.g. CMS

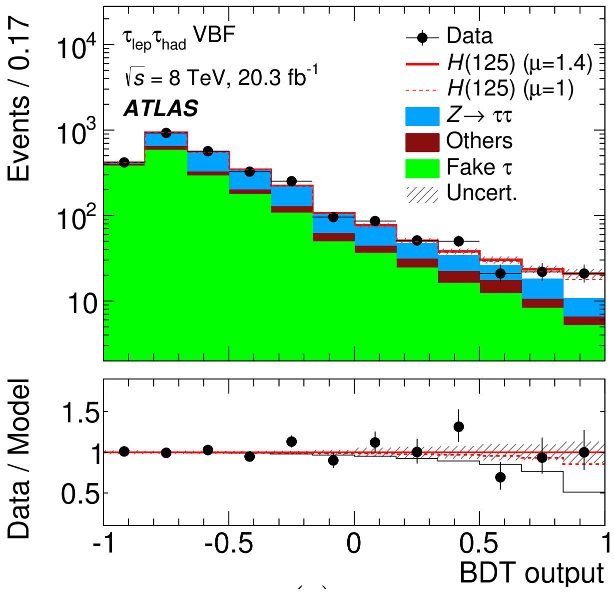


- The τ decays have invisible ν components
- Use max. likelihood-based $m_{\tau\tau}$ computed per-event using four-momenta of visible decay products, E_x^{miss}, E_y^{miss} and the expected E_T^{miss} resolution

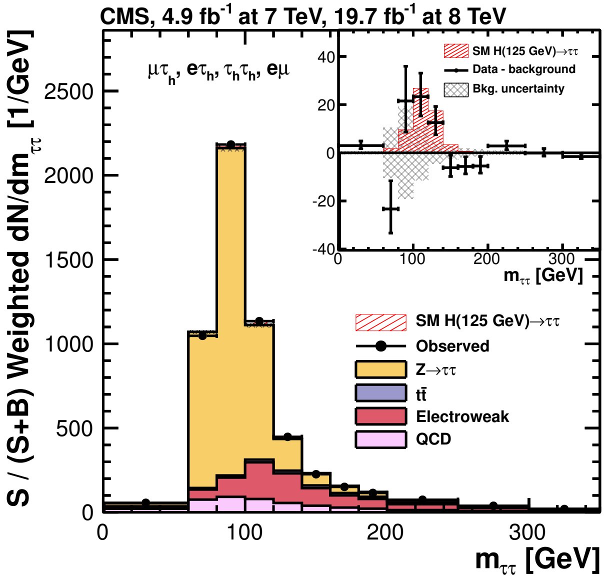


10-15% resolution on $m_{\tau\tau}$ at m_H = 125 GeV
Better Z to H separation

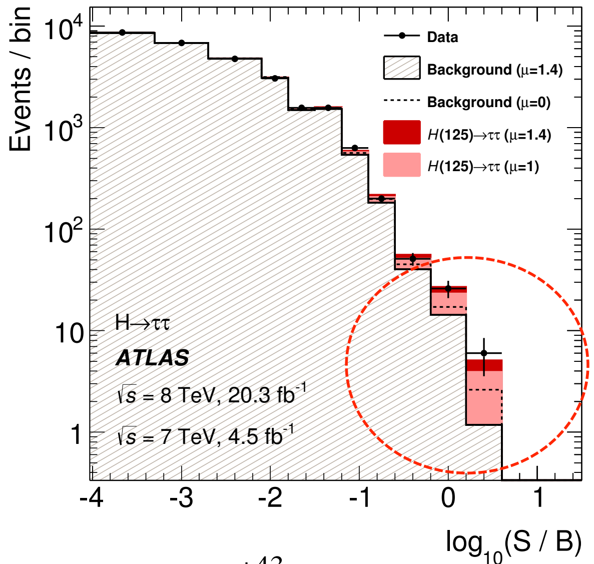
H → ττ at the LHC (2)

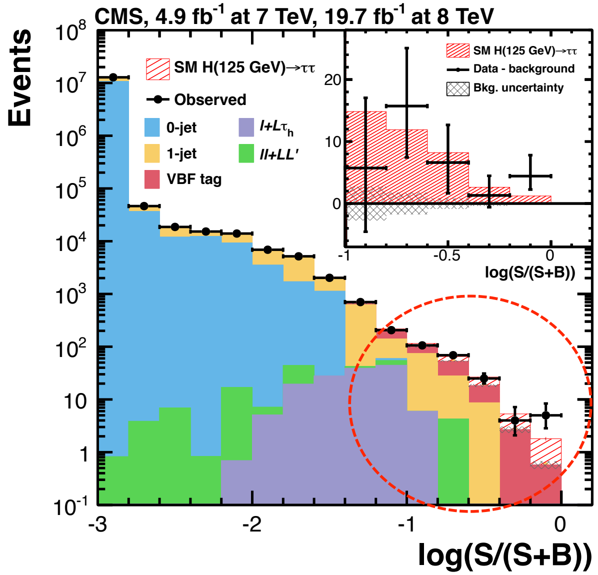


ATLAS JHEP 04 (2015) 117



CMS JHEP 05 (2014) 104





Significance mainly coming from VBF channels
(also boosted $\tau_h\tau_h$)

$\mu = 1.43^{+43}_{-37}$

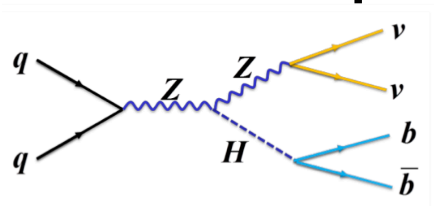
Obs. 4.5 σ (Exp. 3.4 σ)

$\mu = 0.78^{+27}_{-27}$

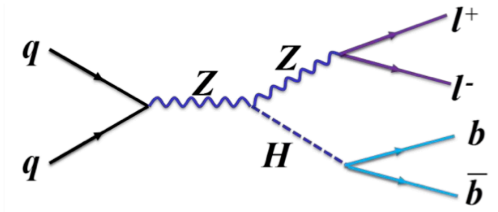
Obs. 3.2 σ (Exp. 3.7 σ)

$H \to b\bar{b}$ Analysis

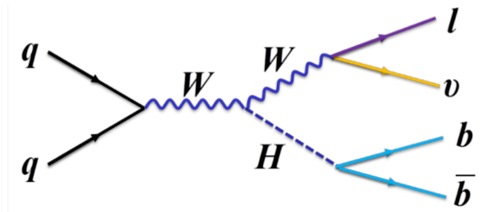
Focus on associated production:



Z(νν)H



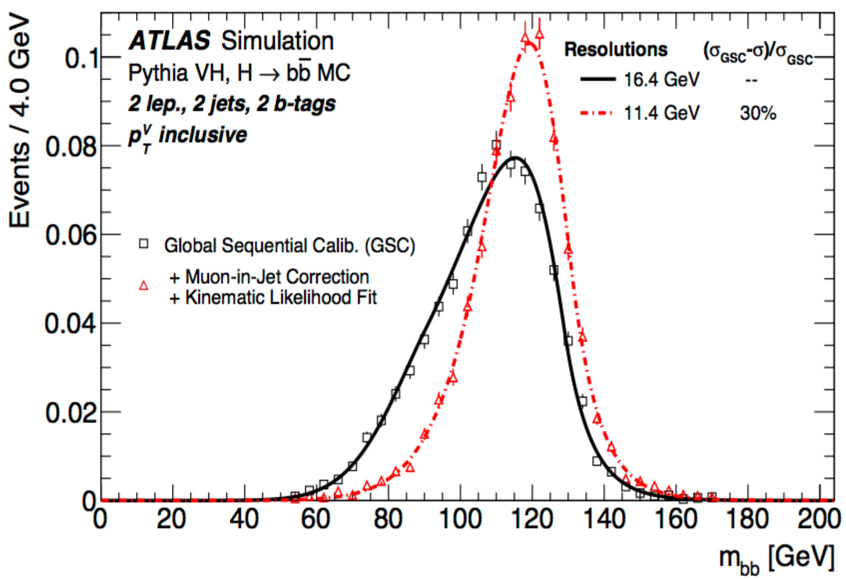
Z(ee,μμ)H



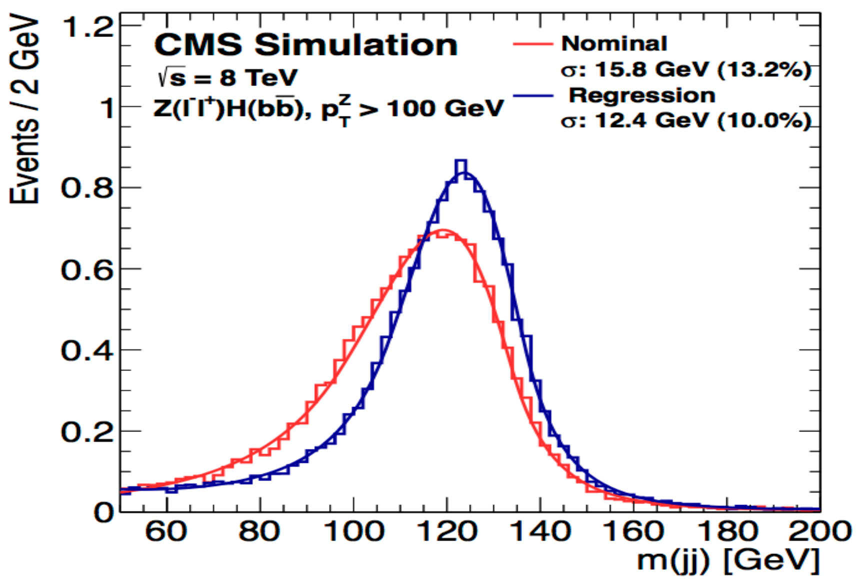
W(e/μ/τ)H

- **Backgrounds:** W/Z + leptons or heavy flavours, tt, dī-bosons
- **Signal extraction:** b-tagging, $P_T(V)$ categorisation , m_{bb} with E scale corrections

ATLAS – Response corrections and Likelihood fit



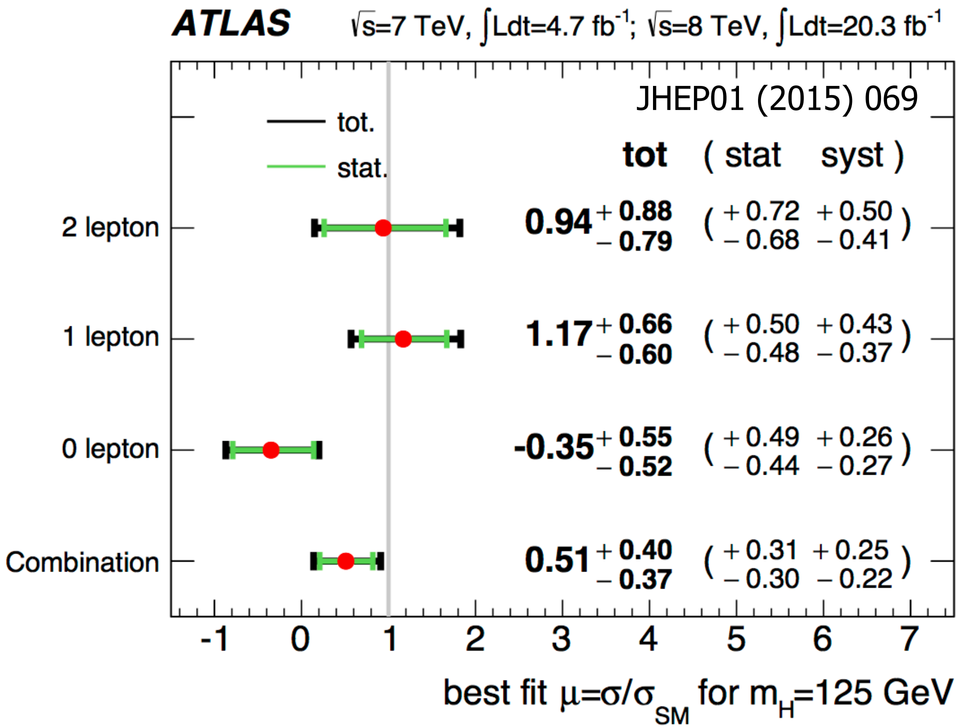
CMS – Multivariate regression



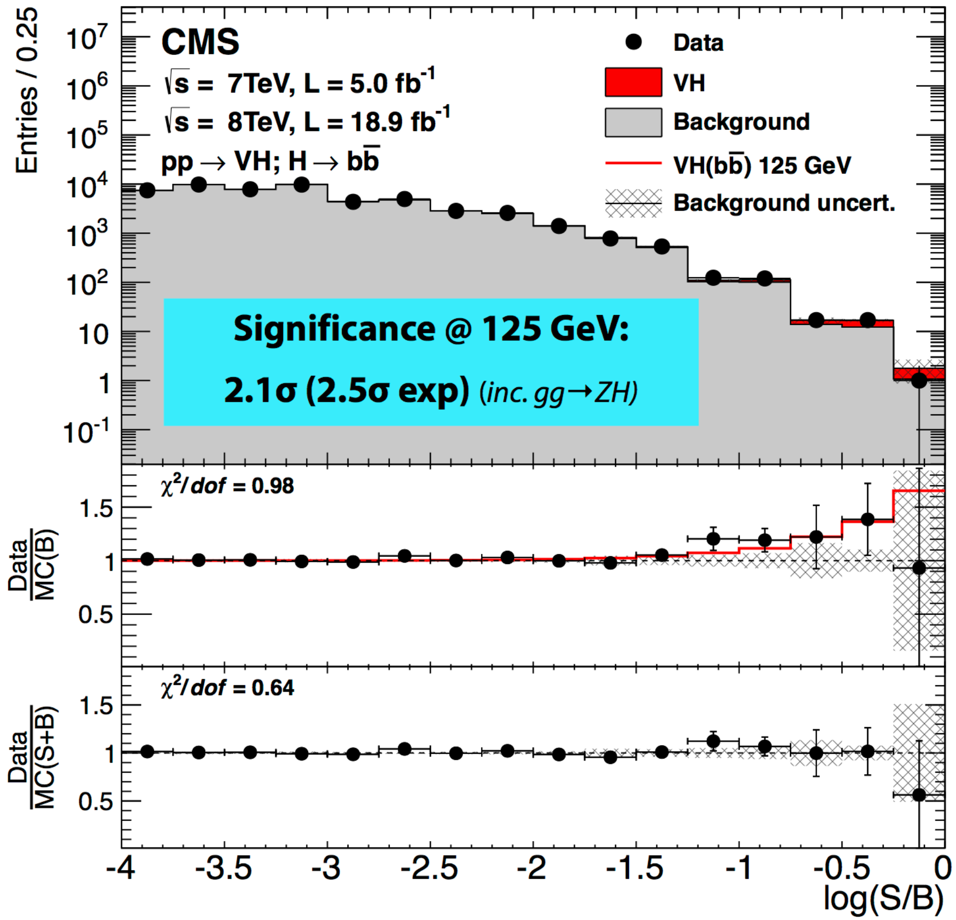
Resolution σ ~ 11-12 GeV (15-30% improvement from visible mass) !!

$H \to bb$ Results – Associated Production

ATLAS



CMS



For m_H = 125 GeV:

Significance 1.4 σ (2.6 σ expected)

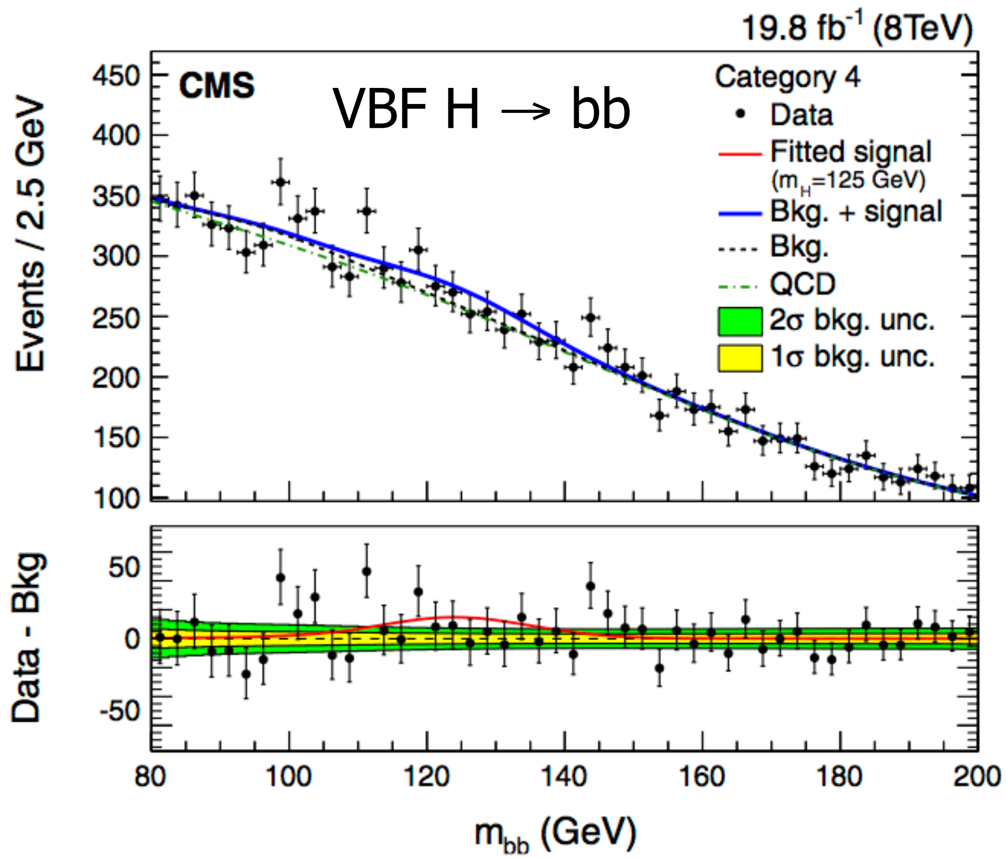
$\mu = 0.51^{+0.40}_{-0.37}$

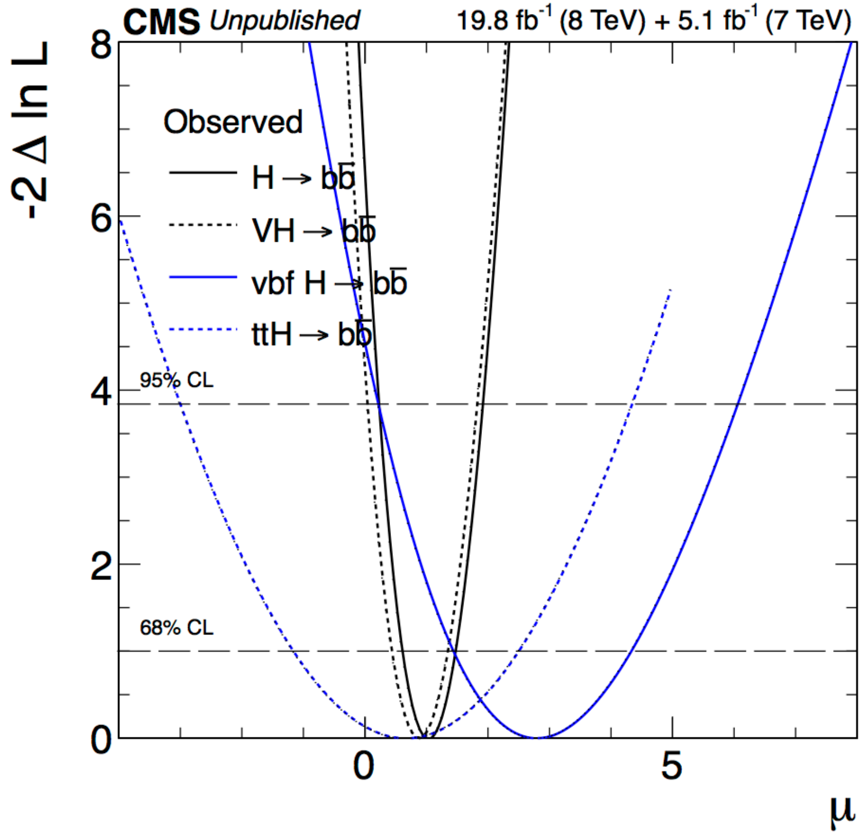
Significance 2.1 σ (2.5 σ expected)

$\mu = 0.89^{+0.47}_{-0.34}$

H → bb Results Including VBF

e.g. CMS PRD 92, 032008 (2015)





Signifiance:

2.2 σ observed (0.8 expect.)

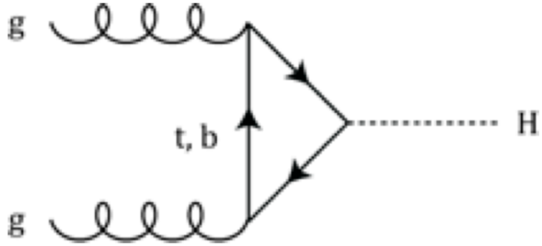
μ = 2.8 ± 1.5

Significance:

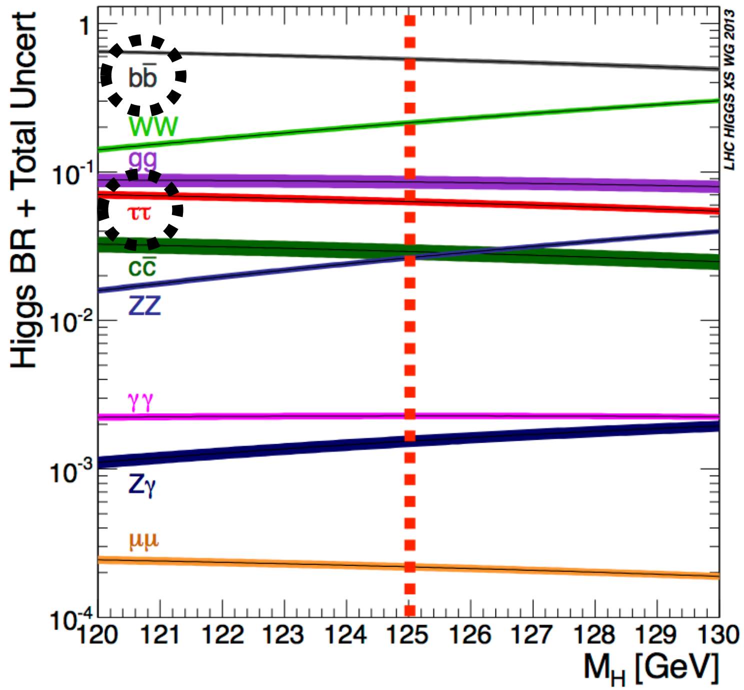
Combining H → bb from VF, VBF, and ttH gives 2.6 σ observed (2.7 expect.)

H → Fermions

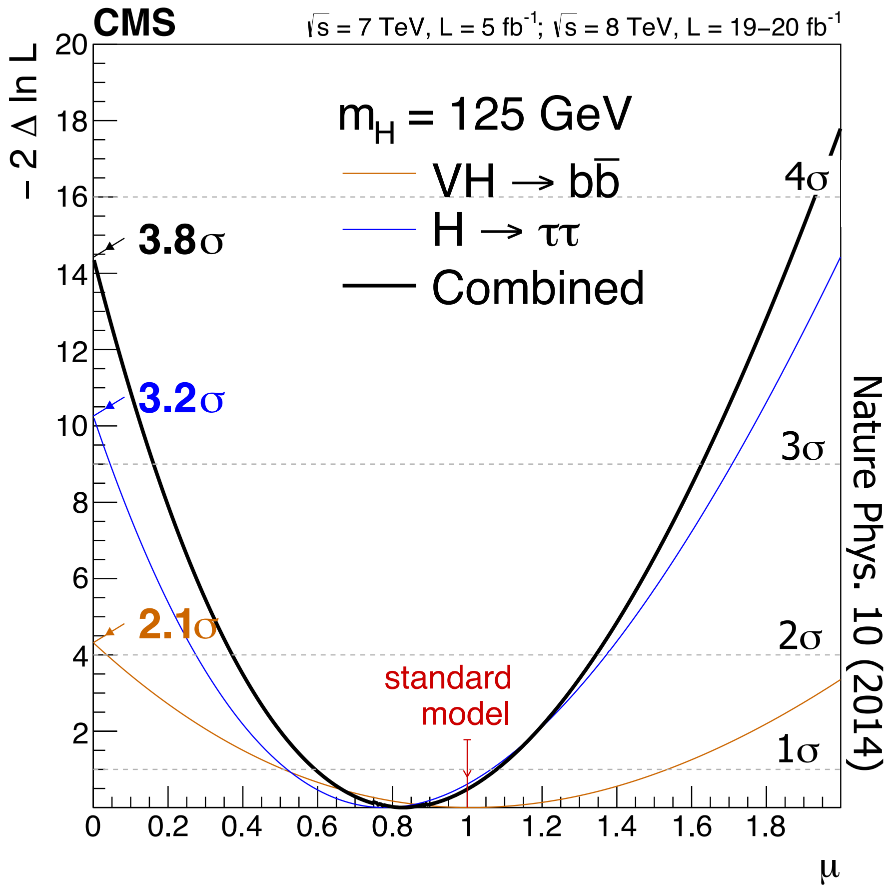
Indirect evidence for coupling to fermions from loops



Access to direct couplings in decays at the LHC mainly for H → bb and H → ττ



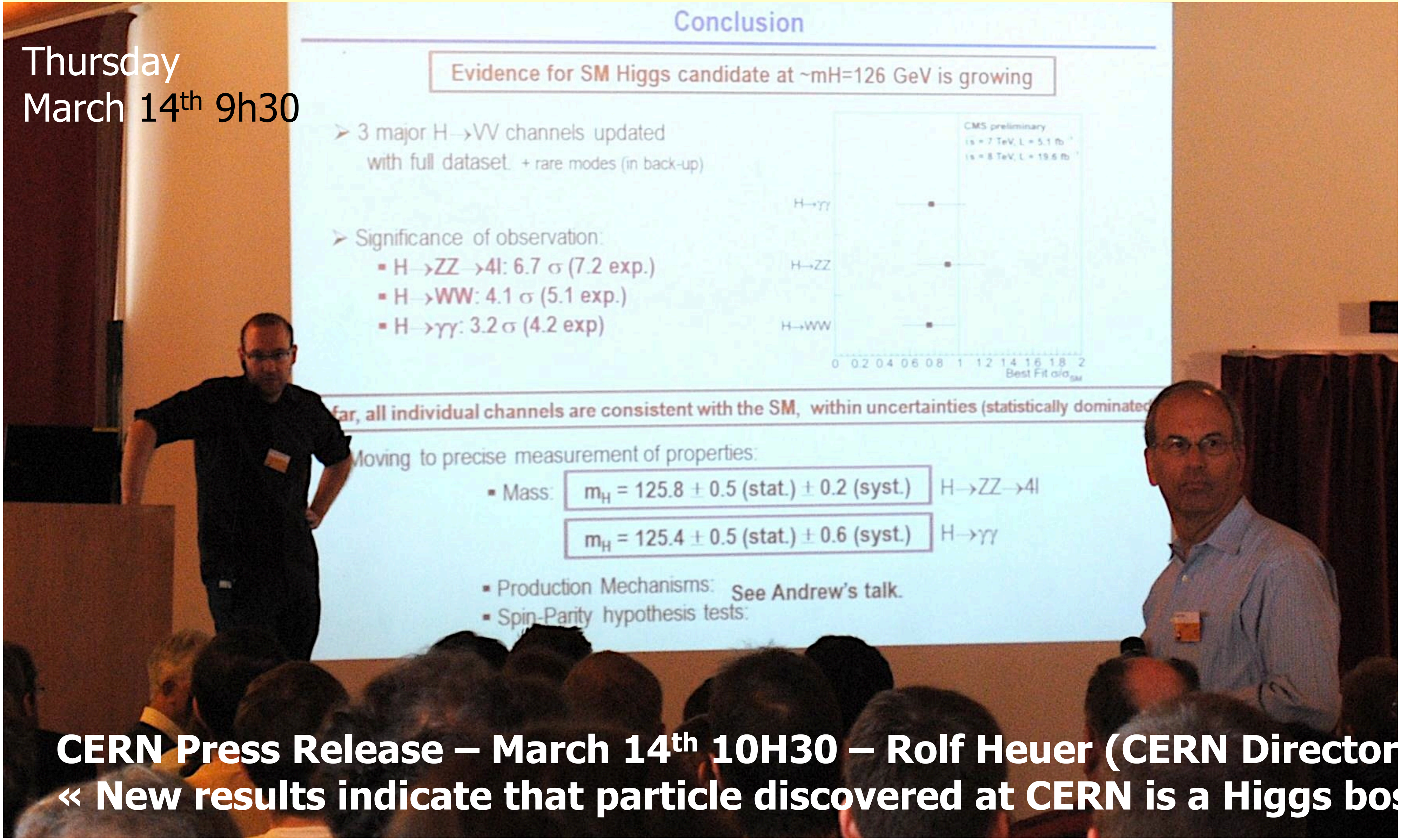
Combined **H → ττ** & **H → bb**



H → bb + ττ	CMS
Strength	0.83 ± 0.24
Significance	3.8σ (exp 4.4σ)

Rencontres de Moriond
QCD and High Energy Interactions

La Thuile, March 9-16, 2013

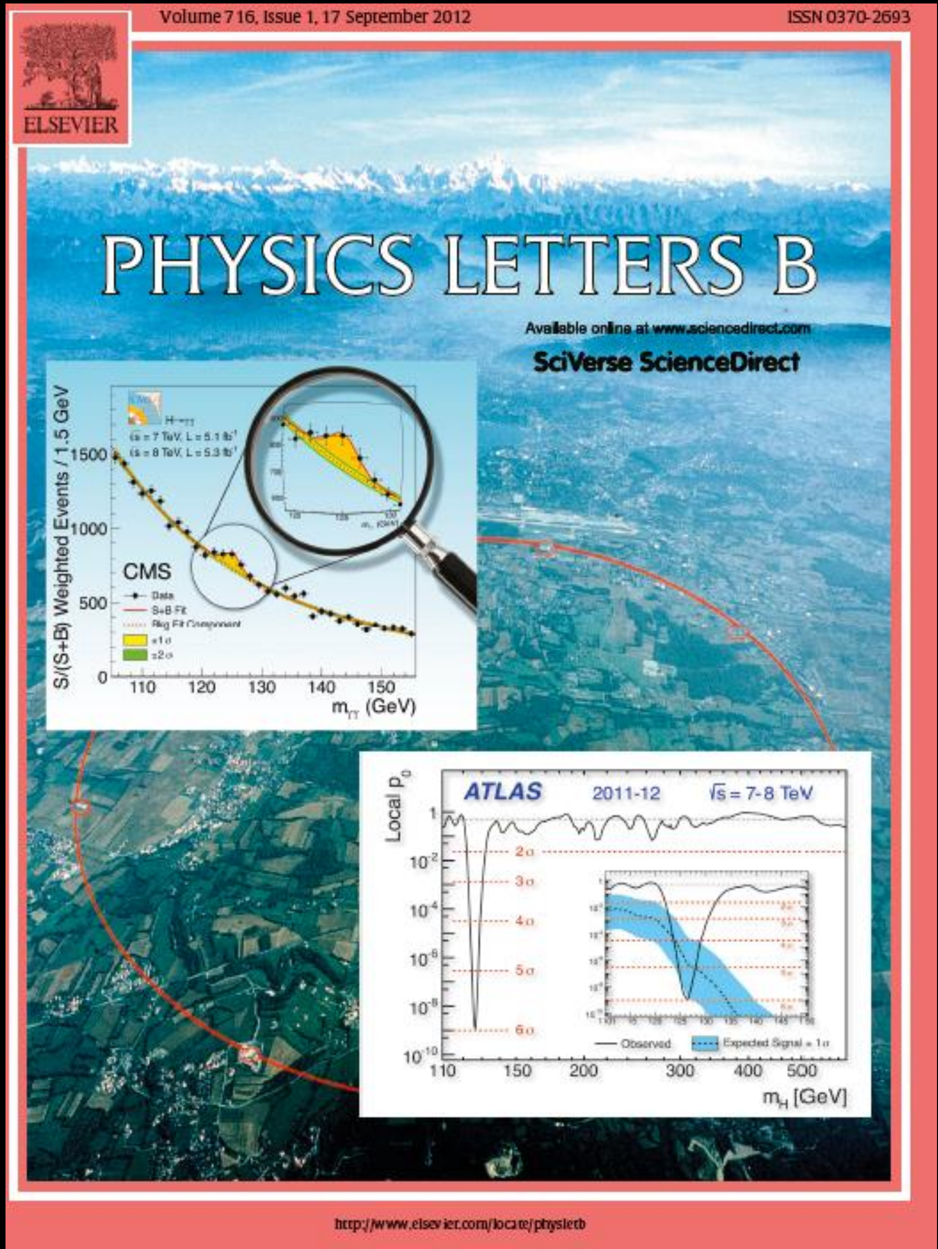


Thursday
March 14th 9h30

CERN Press Release – March 14th 10H30 – Rolf Heuer (CERN Director
« New results indicate that particle discovered at CERN is a Higgs bos

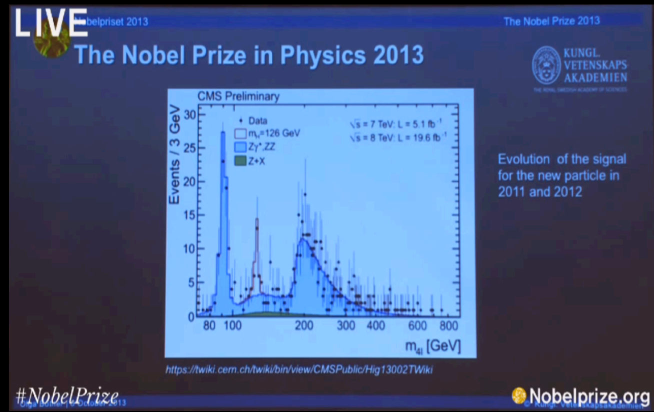
From the Discovery to the Nobel Prize

July 2012



~ 3800 citations / experiment so far

October 2013

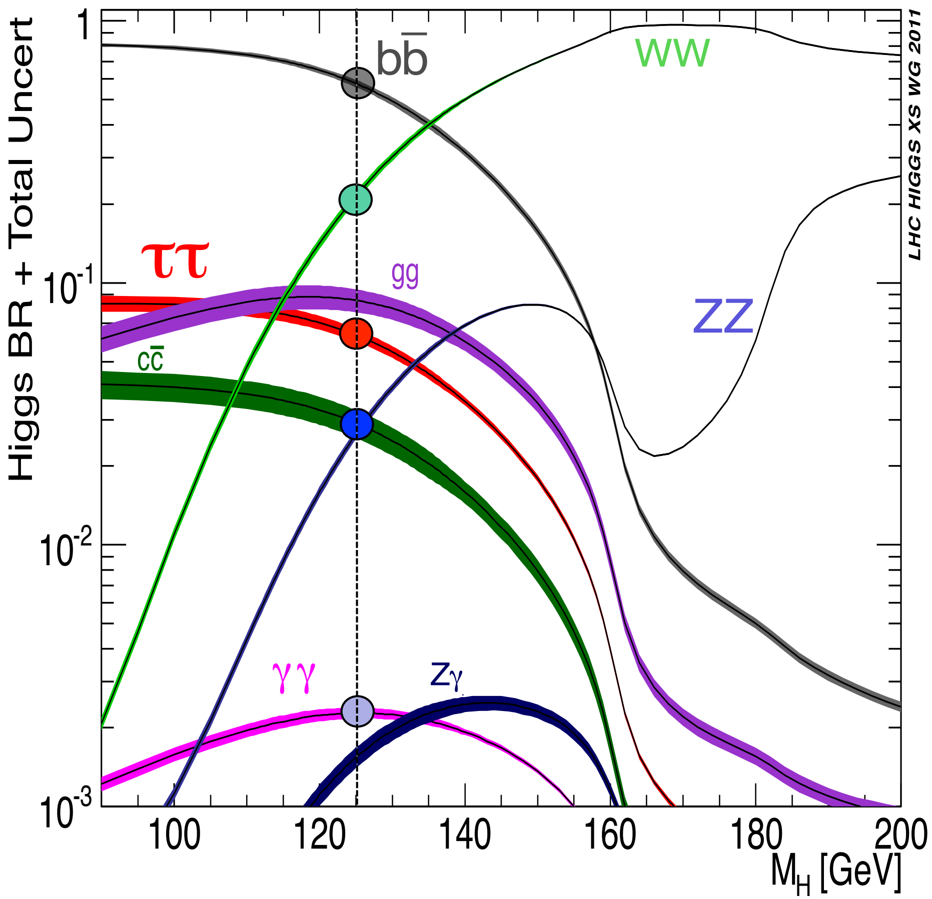


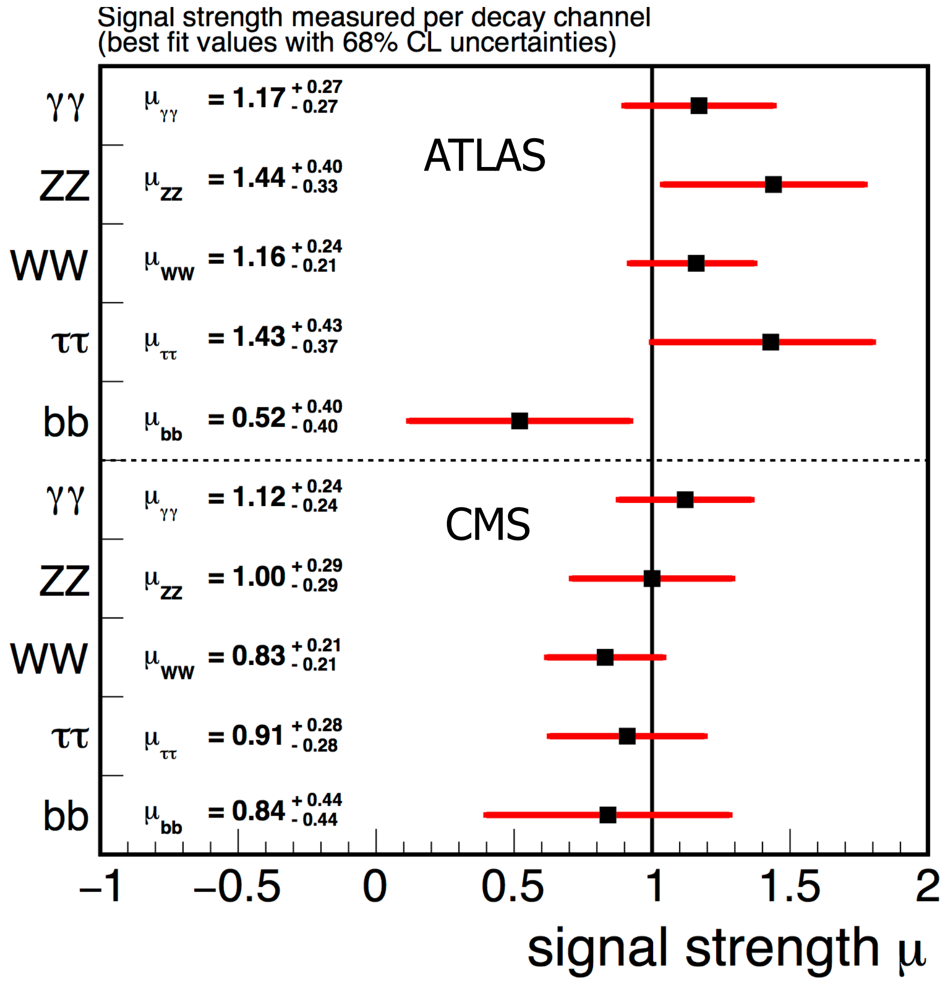
"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Signal Strength per Decay Modes
(stand-alone results)

Combination Results on the H Boson

Desintegration

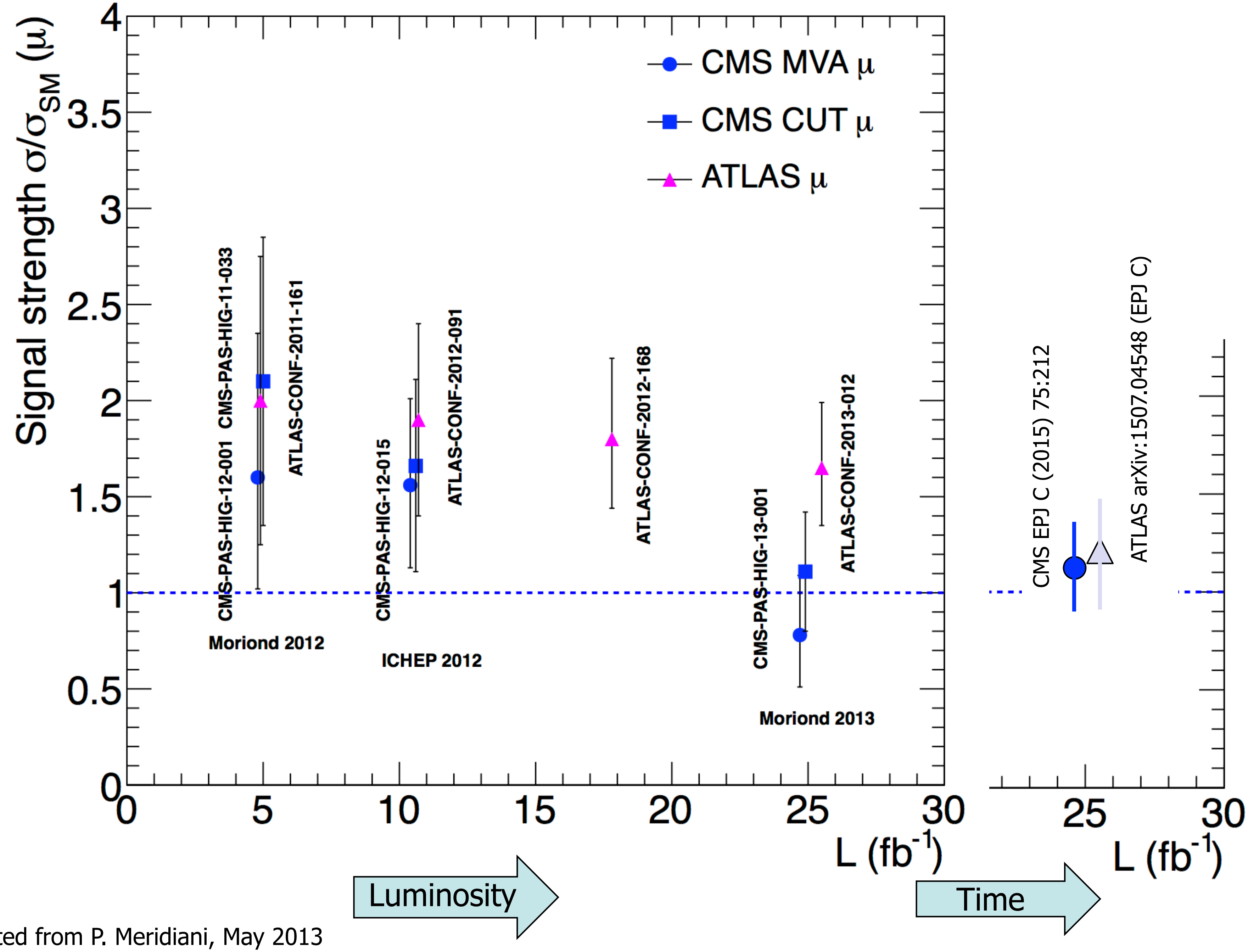




- Final « combination » results: ATLAS arXiv:1507.04548 (EPJ C) & CMS EPJ C75 (2015) 212
- All rates consistent with SM expectation (but slight excess in 4 main channels for ATLAS)

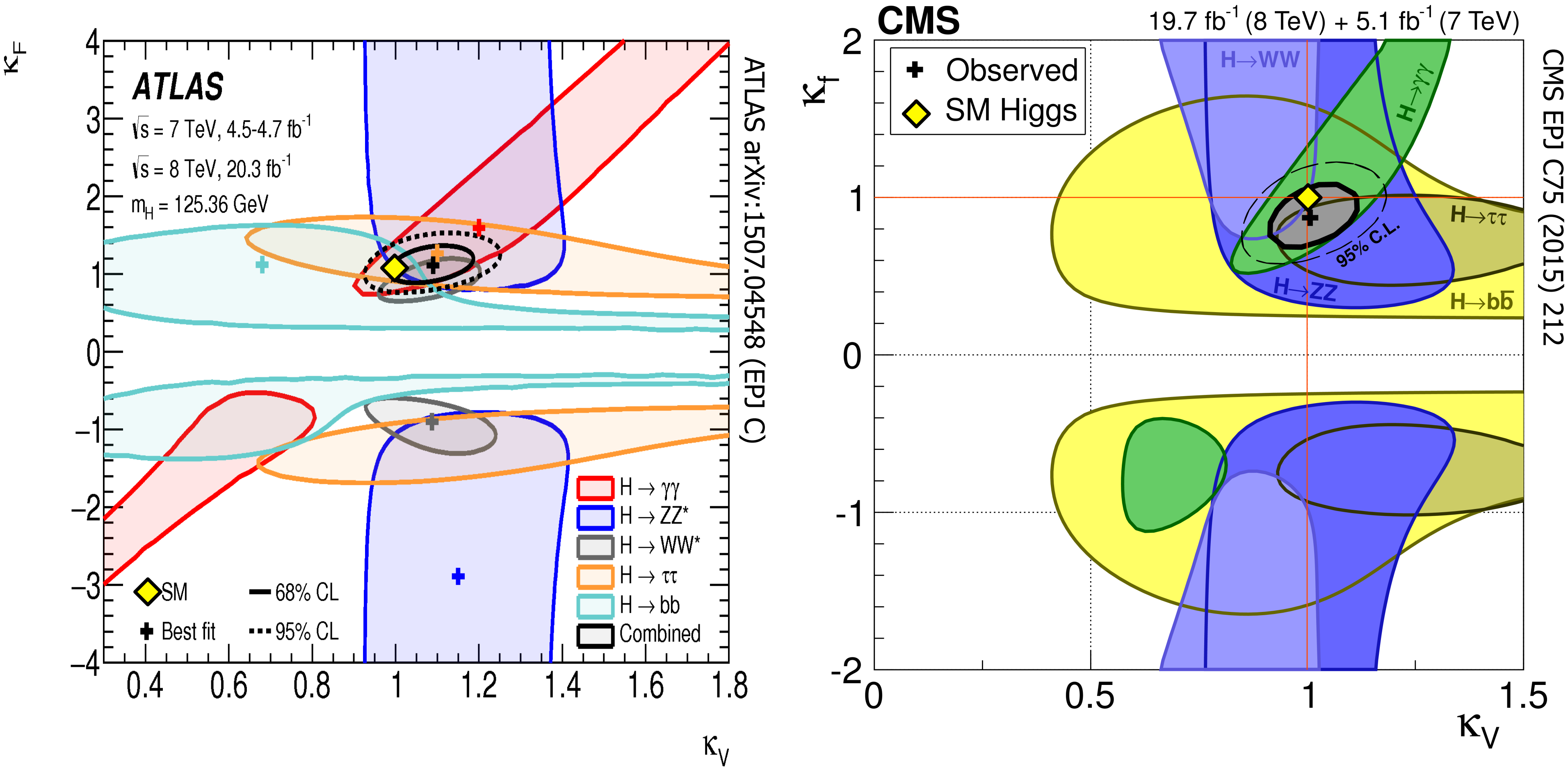
≥ 5 σ observation in di-boson channels and ≥ 3 σ evidence in di-τ channel

H → γγ signal strength – vs $\mathcal{L}$ and Time



Adapted from P. Meridiani, May 2013

H Couplings to Fermions and Bosons



Assume SM contributions to the total width +
Allow for common scaling for bosons (V) and fermions (F):

ATLAS: $(\kappa_V, \kappa_F) = (1.09^{+0.07}_{-0.07}, 1.11^{+0.16}_{-0.16})$

CMS: $(\kappa_V, \kappa_F) = (1.01^{+0.07}_{-0.07}, 0.87^{+0.14}_{-0.13})$

The $(\kappa_V, \kappa_F) = (1.0, -1.0)$ is disfavoured at ~ 2 to 3 σ level by each experiment

The H Boson discovery is now firmly established

- ✓ $M_H \sim 125$ GeV
- ✓ Couplings to fermions and to weak bosons (verified to ~10-20% precision) consistent with the minimal scalar sector required for the BEH mechanism
- ✓ Custodial symmetry verified (~ 15% precision) and the existence of a boson with non-universal family couplings established ($\tau\tau$ evidence + no $\mu\mu$ signal)

A truly astonishing achievement !

- Culmination of a reductionism strategy evolving from the question of the *structure of matter* to that of the *very origin of interactions (local gauge symmetries) and matter (interactions with Higgs field)*
- We understand the **origin of mass** (i.e. scalar field, BEH mechanism) for particles in a quantum field theory with local (i.e. point like) gauge interactions
- Ignoring gravitation, we have for the first time in the history of science a theory which is at least in principle complete, consistent, and coherent at all scales … (up to the Planck scale ?)

… but it is not over

Standard Model and the H Boson : a paradoxical triumph

3 major problems with a H boson at 125 GeV

- A problem of flavour **structure**
- A problem of **Hierarchy**
- A problem of vacuum **Stability**

… which now arise with unprecedented acuity

The discovery of the H boson at a masse 125 GeV could be the detonator of a new revolution in physics

More about this in my next lectures …

New Challenges

In addition to all the great SM precision measurements with Z, W and the top quarks, HI Physics, flavour physics etc. …

Driven by the new physics (i.e. the scalar sector) Discovered during run I

- Complete precision measurements of the Higgs boson
- Observe Di-Higgs production and access the self-coupling
- Measure trilinear and quartic couplings of weak bosons
- Measure rare decays and search for forbidden H decays
- Search for an extended scalar sector
- Search for extra-structure, supersymmetric matter, Exotica, …

Summary (I)

- Discovery in July 2012 of the H boson by ATLAS and CMS experiments at LHC exploiting di-boson channels
- The mass of new H boson is measured at ~ 125 GeV
- The spin-parity of the H boson is consistent with a pure CP-even state (0^{++}) as expected from the Brout-Englert-Higgs EWK symmetry breaking mechanism
- The intrinsic width is consistent with the SM expectation
- Signal rate in all 5 main decays have been measured with 20-40% precision
- Couplings to fermions and bosons are measured at the 10-20% precision

… and many questions remain unanswered * !!!

* More questions and answers in next lectures