La découverte du Boson H au LHC

Y. Sirois LLR Polytechnique CNRS-IN2P3

Discovery and measurements of the H boson
with ATLAS and CMS experiments at the LHC

I La Quête / The Quest 1964-2011

II La Découverte / The discovery 2011-2012

III Les Mesures / The measurements 2012-2014

IV Les Séquelles / The Aftermath

NDLR: à la demande des organisateurs, la présentation est effectuée
en français avec un support de diapositives en anglais

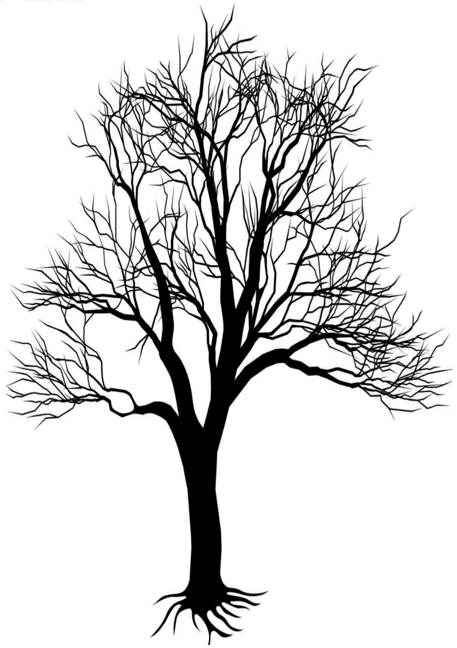
The Quest

1964 - 2011

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 ⇒

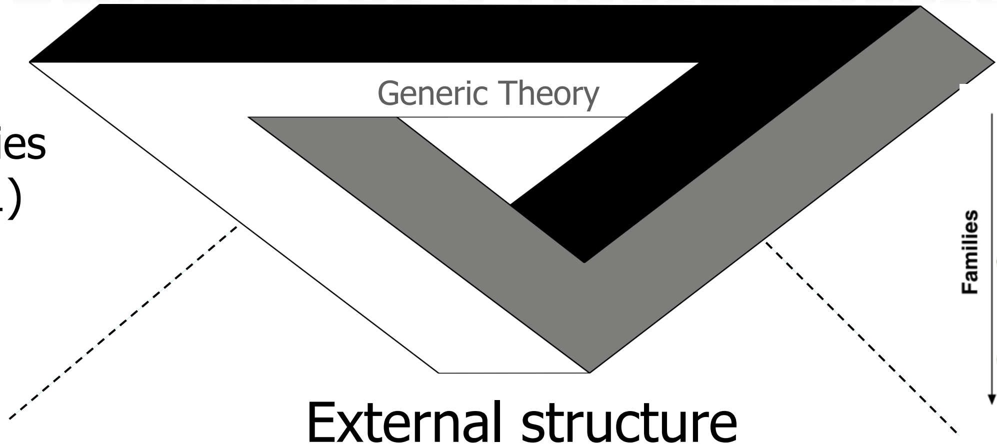
- The "underlying reality" is made of quantum fields
- There are interactions (gauge bosons) as a consequence of gauge symmetries
- All "particles" must be massless.
- All ordinary particles must have spin 0, ½, or 1

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)

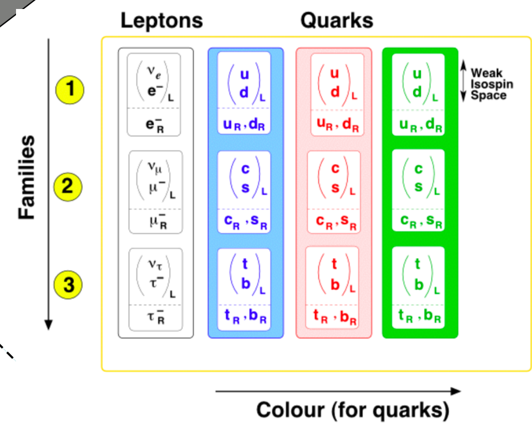
Chronicle of a Death Foretold

Gauge Bosons

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



Fermions

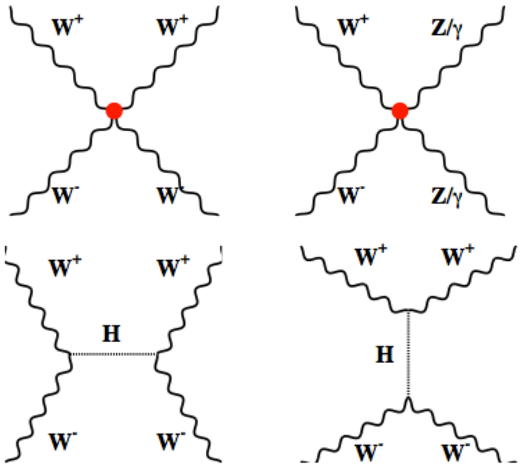


External structure

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



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

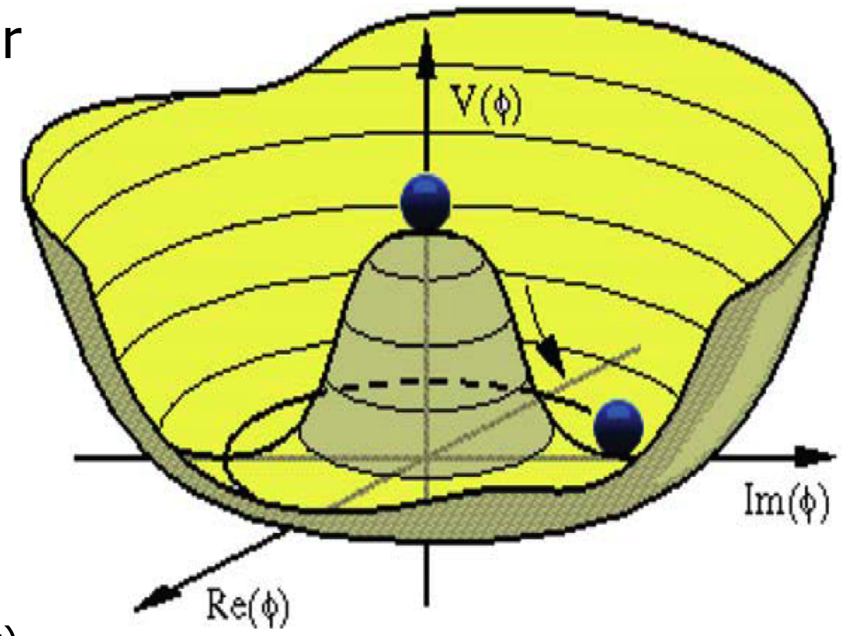
SM limited to E < ~ 1 TeV in absence of regularisation

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



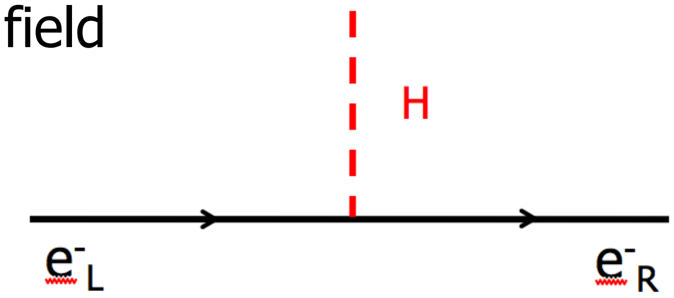
Spontaneous breaking of EWK symmetry

… 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

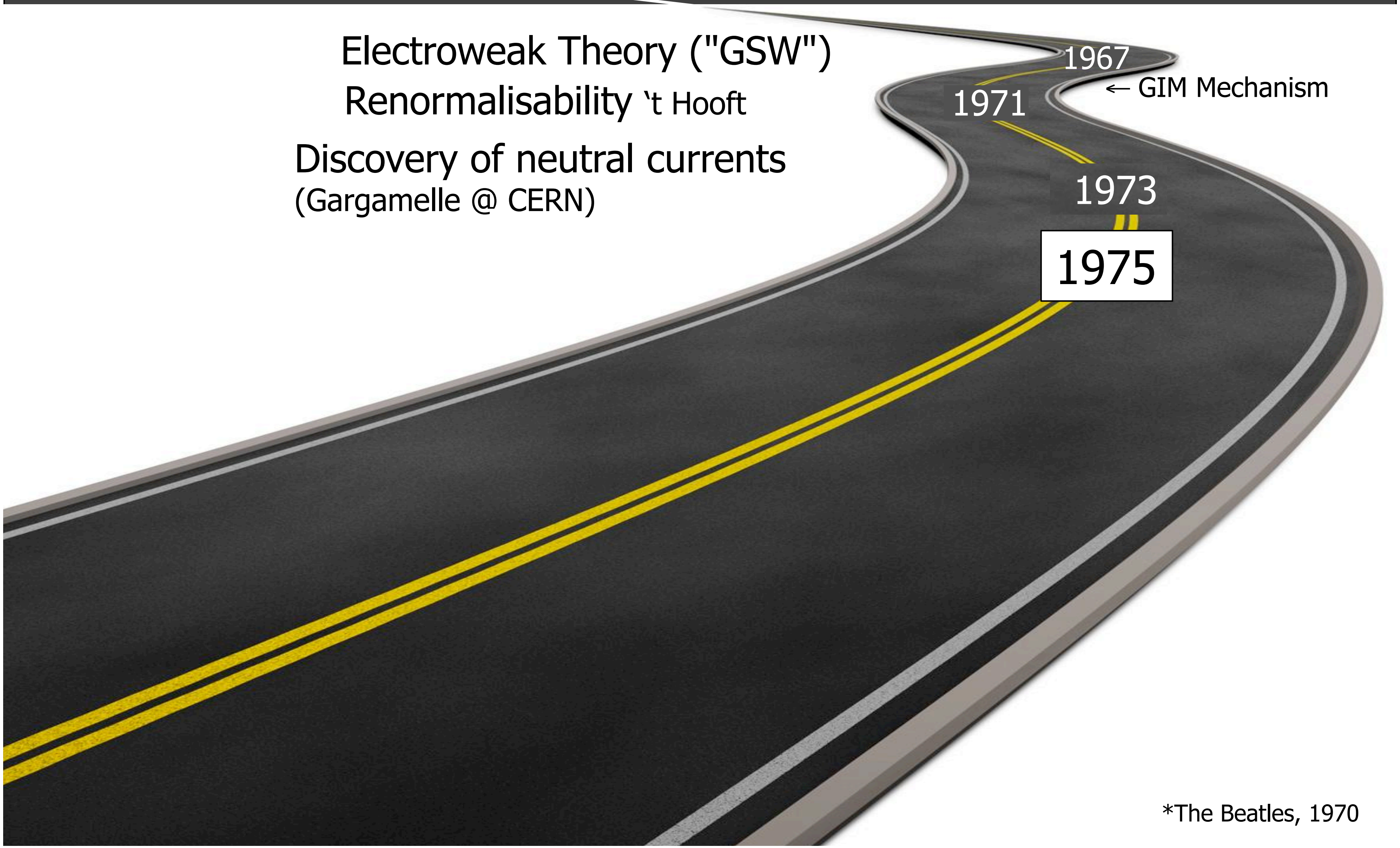
The Long and Winding Road*

Spontaneous symmetry breaking ("BEH") mechanism - 1964

Electroweak Theory ("GSW")

Renormalisability 't Hooft

Discovery of neutral currents
(Gargamelle @ CERN)



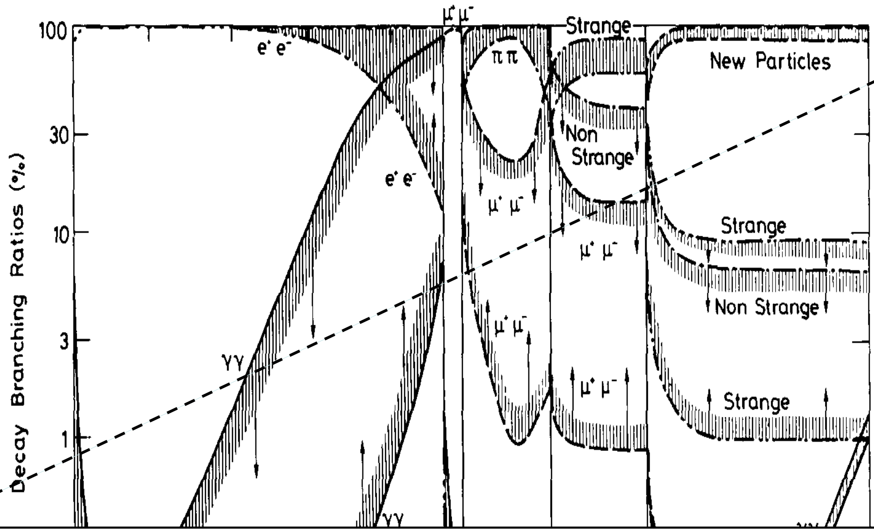
*The Beatles, 1970

Nuclear Physics B106 (1976) 292–340

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.

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... 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,

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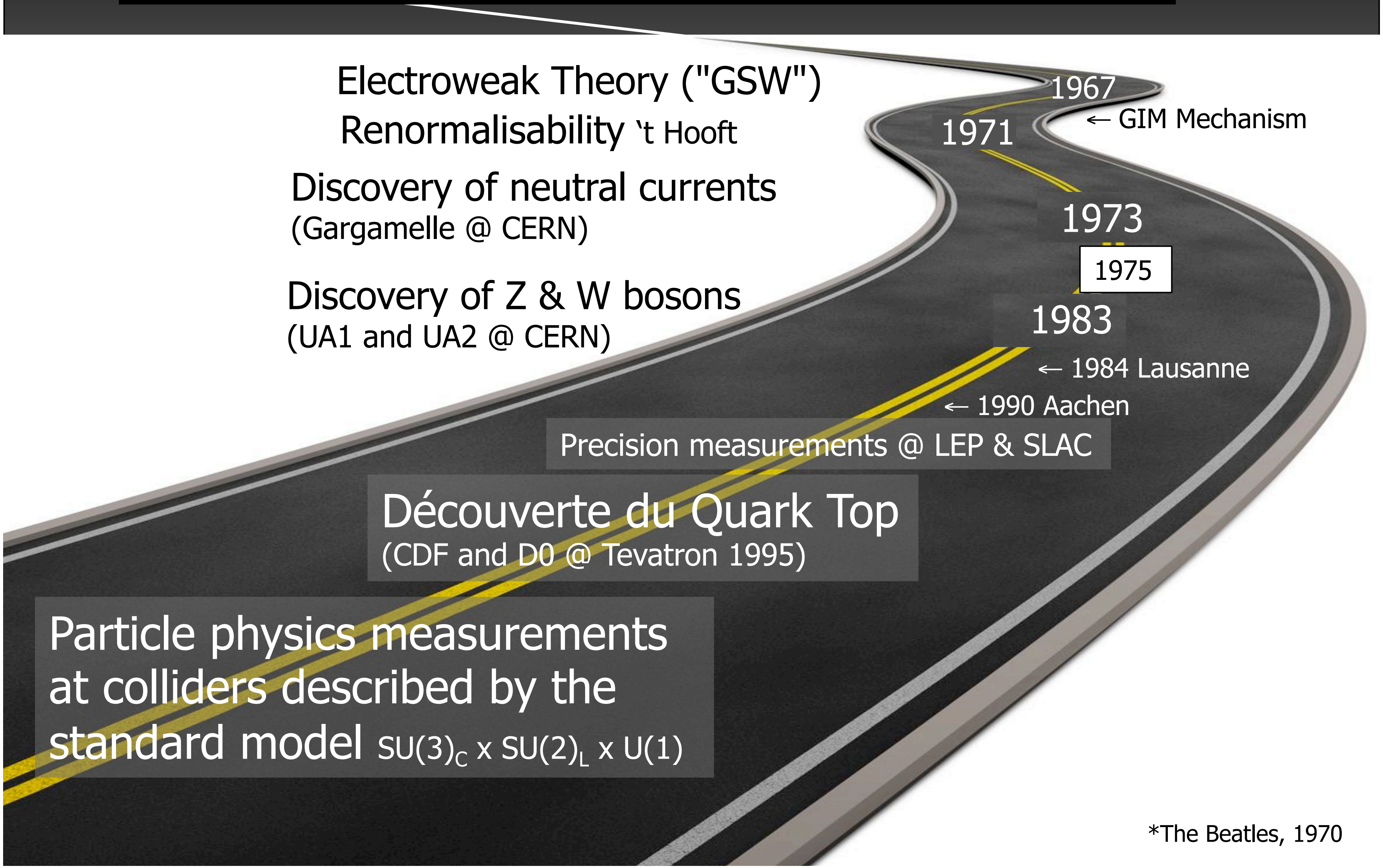
Spontaneous symmetry breaking ("BEH") mechanism - 1964



Electroweak Theory ("GSW") 1967

← GIM Mechanism

Renormalisability ‘t Hooft 1971

Discovery of neutral currents
(Gargamelle @ CERN) 1973

1975

Discovery of Z & W bosons
(UA1 and UA2 @ CERN) 1983

← 1984 Lausanne

← 1990 Aachen

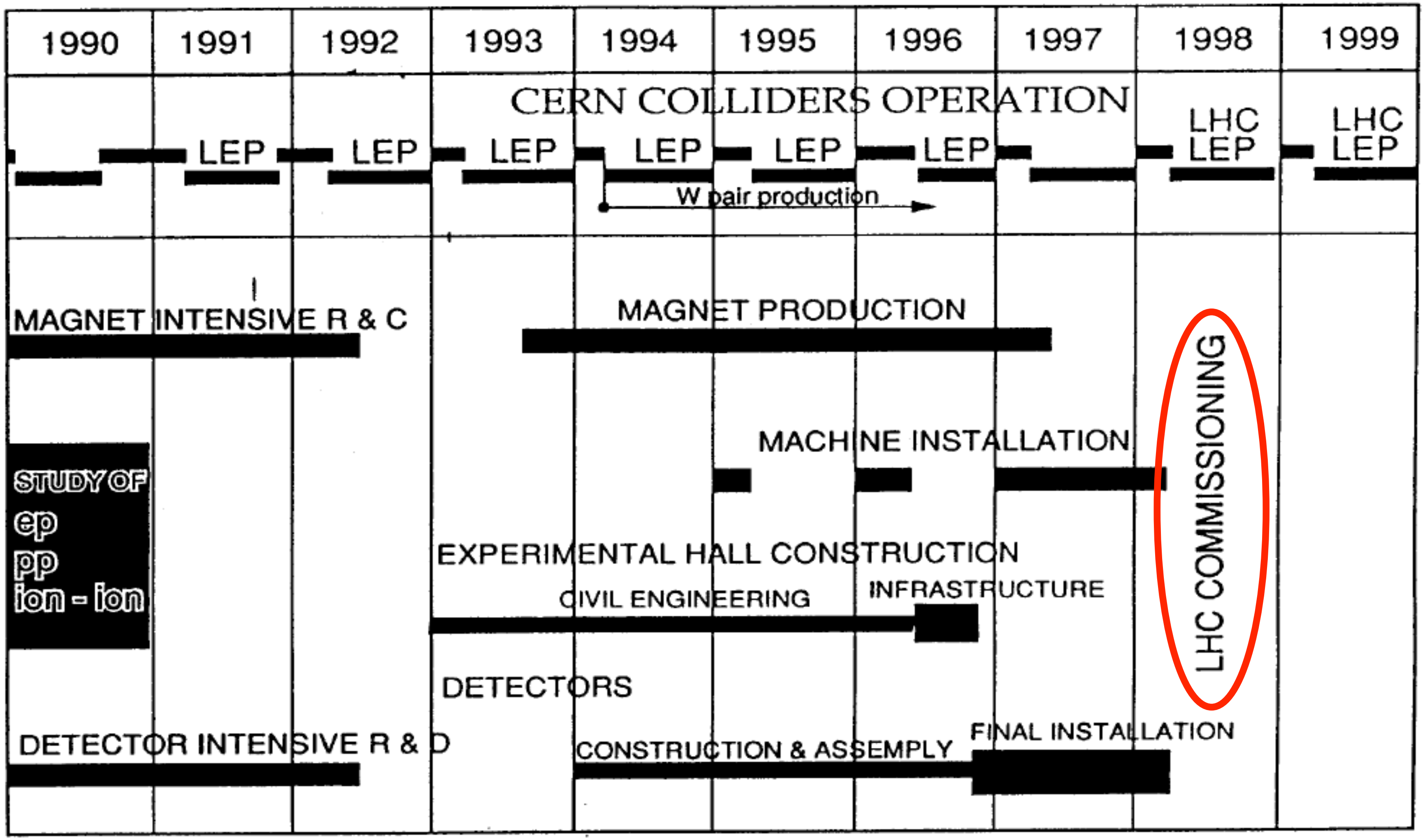
Precision measurements @ LEP & SLAC

Découverte du Quark Top
(CDF and D0 @ Tevatron 1995)

Particle physics measurements at colliders described by the standard model $SU(3)_C \times SU(2)_L \times U(1)$

*The Beatles, 1970

First meetings of the LHC proto-collaborations in 1989 …



C. Rubbia - Large Hadron Collider Workshop, Aachen 1990

Figure 18 – Construction schedule of the LHC

!!!

H boson: Theory 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

Theory constraints :

Unitarity:

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

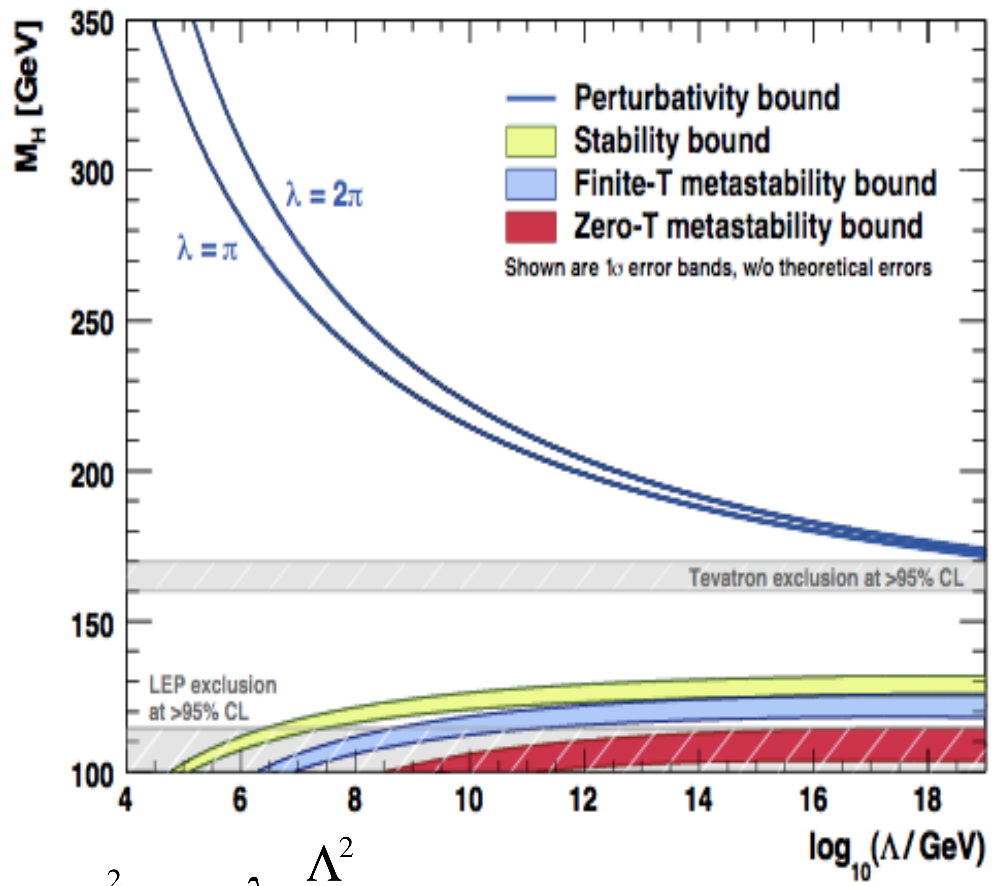
"Triviality" (self-coupling of the H boson) :

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

"Stability" of vaccuum:

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

Λ = "cut-off" scale

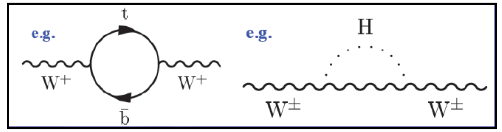


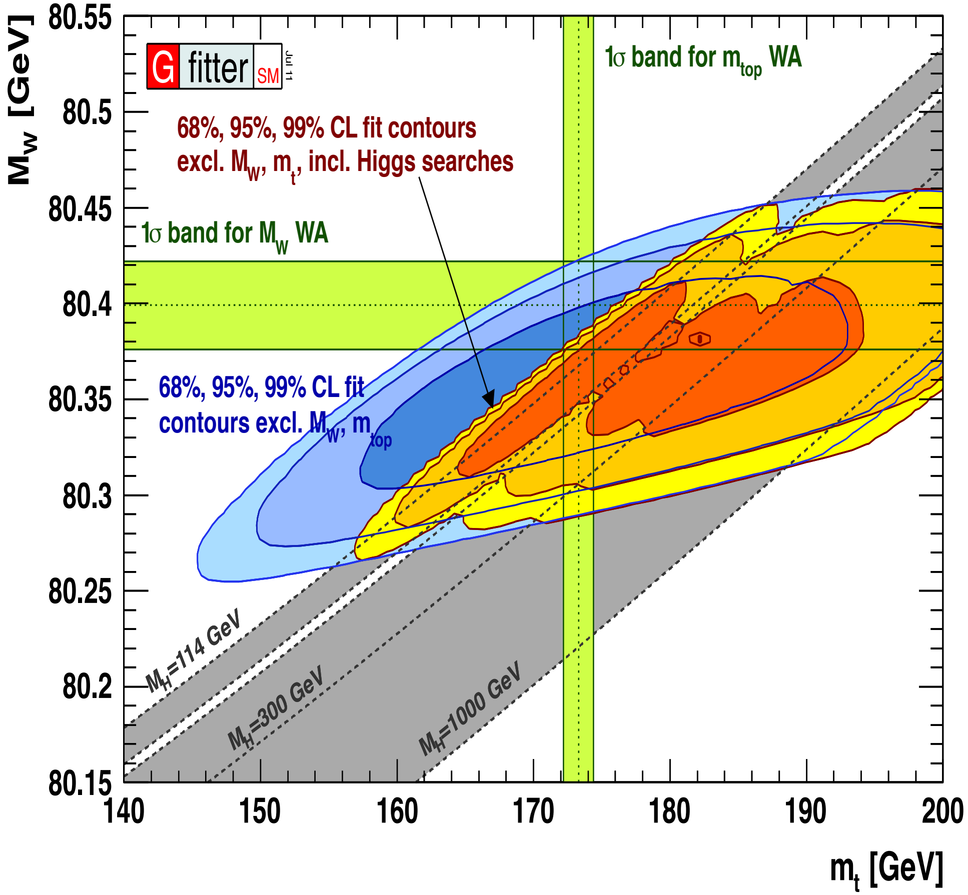
Quadratic divergencies: $m^2 = m_0^2 + \alpha\lambda\frac{\Lambda^2}{16\pi^2}$

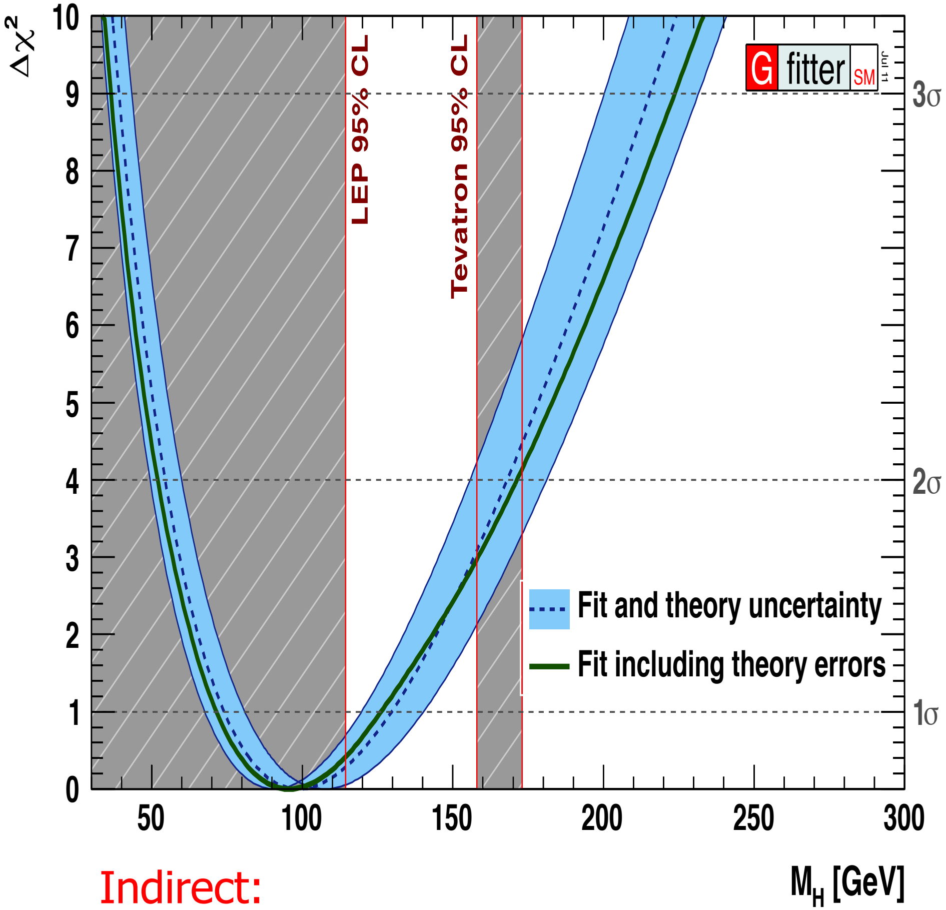
If H boson and Λ << Planck scale : then new physics at the TeV scale ?

The Landscape at EPS 2011

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







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

The H boson is preferably light …
if it exists !

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

La Découverte

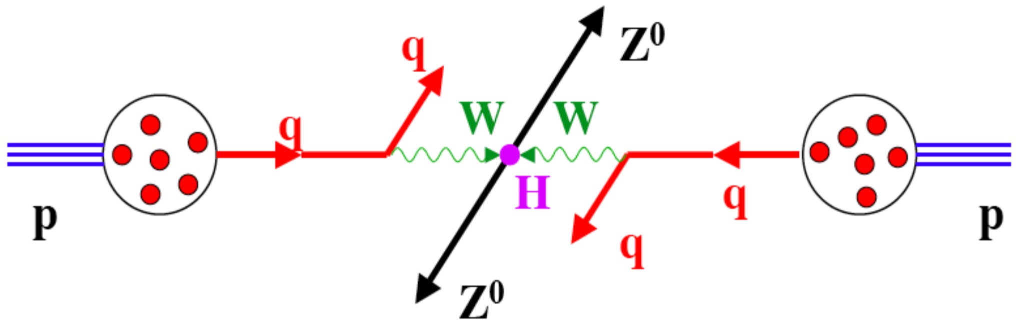
2011-2012

The Discovery

The Large Hadron Collider

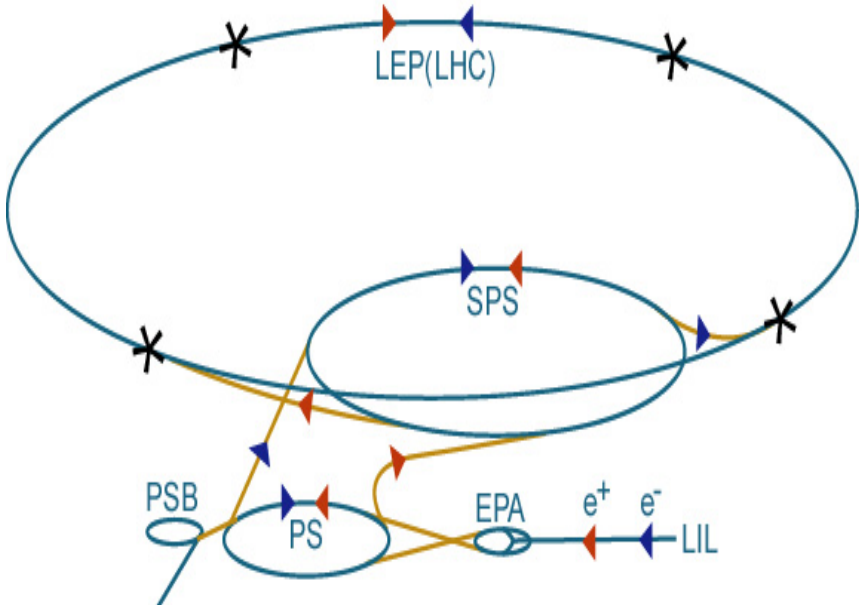
Conceived as an exploration machine with a large bandwidth

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



First beam at CERN in 1959 !

It all starts with a small hydrogen bottle !

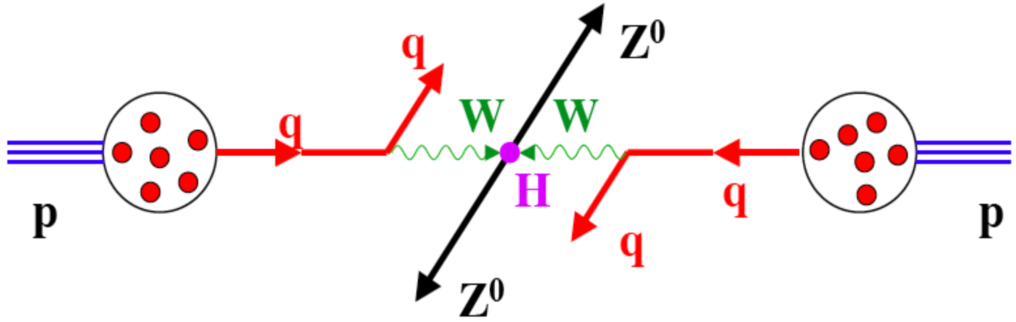


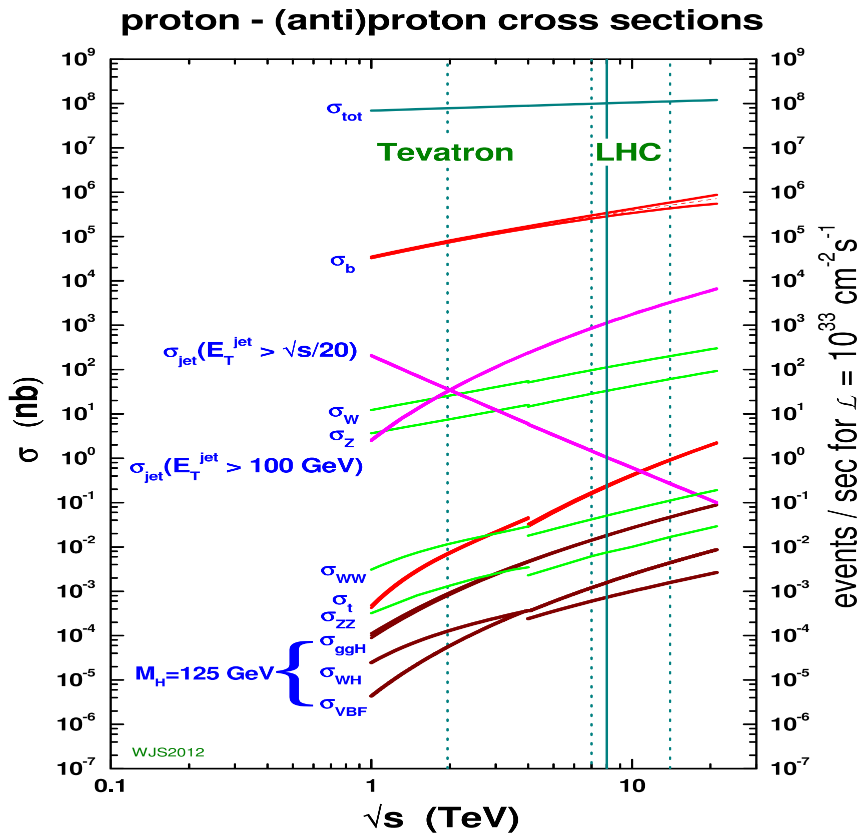
Proton (or Ion) injection

The Large Hadron Collider

Conceived 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





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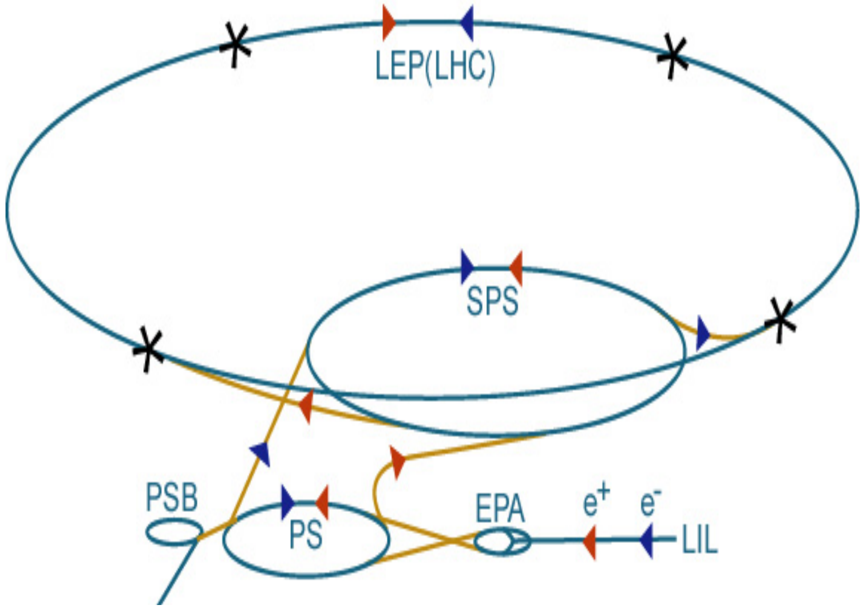
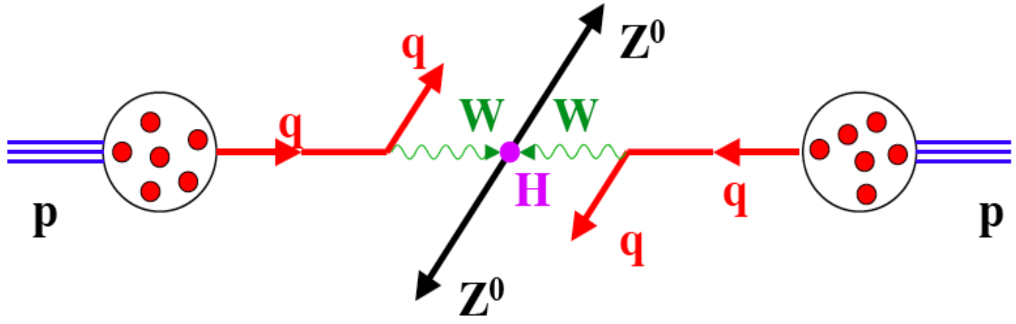


$(\sigma^{tot}_{(H125)} \times L)_{Tevatron} \times 50 \sim (\sigma^{tot}_{(H125)} \times L)_{LHC}$

Le Large Hadron Collider

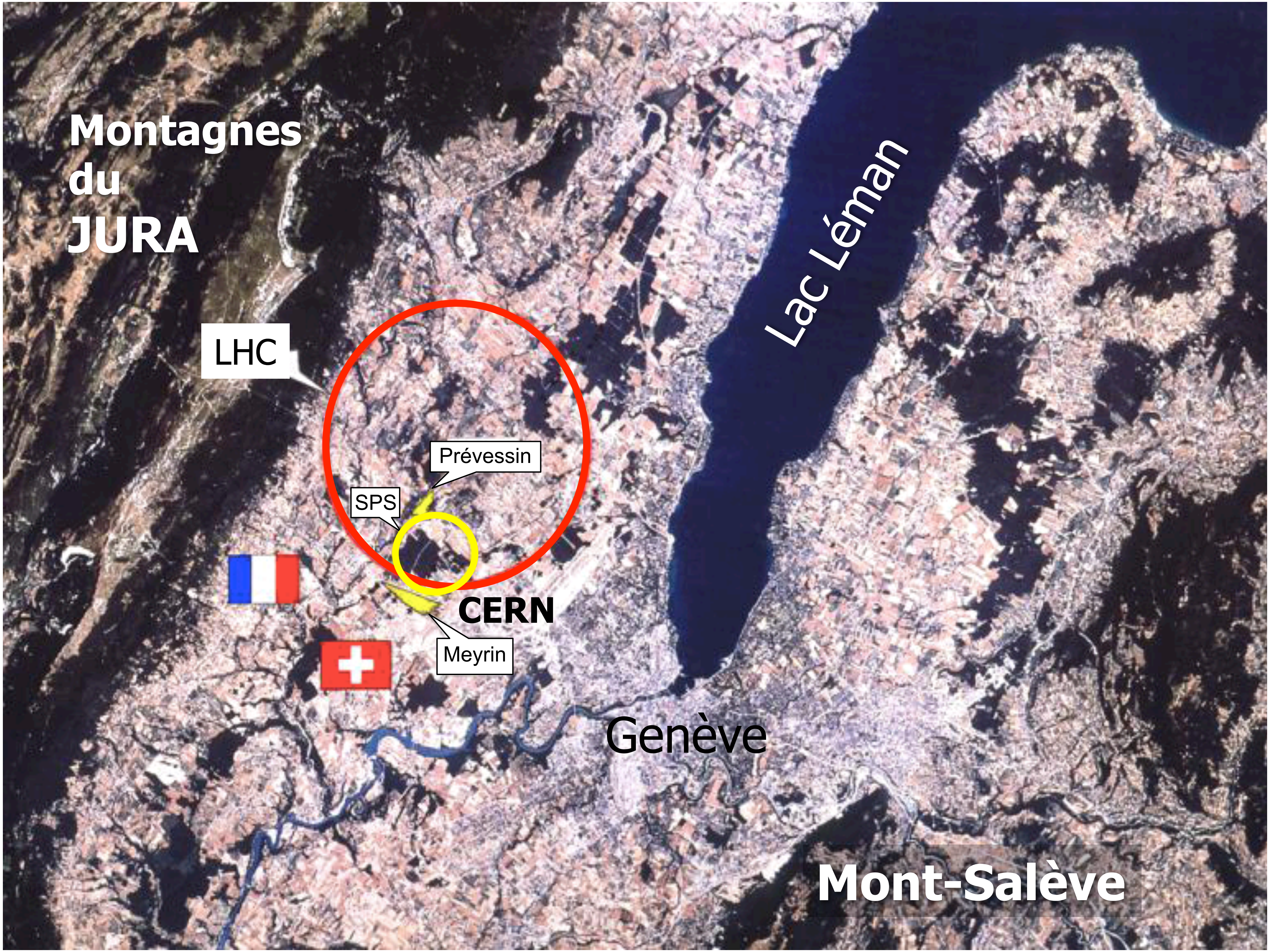
Une machine d'exploration avec un large bande passante

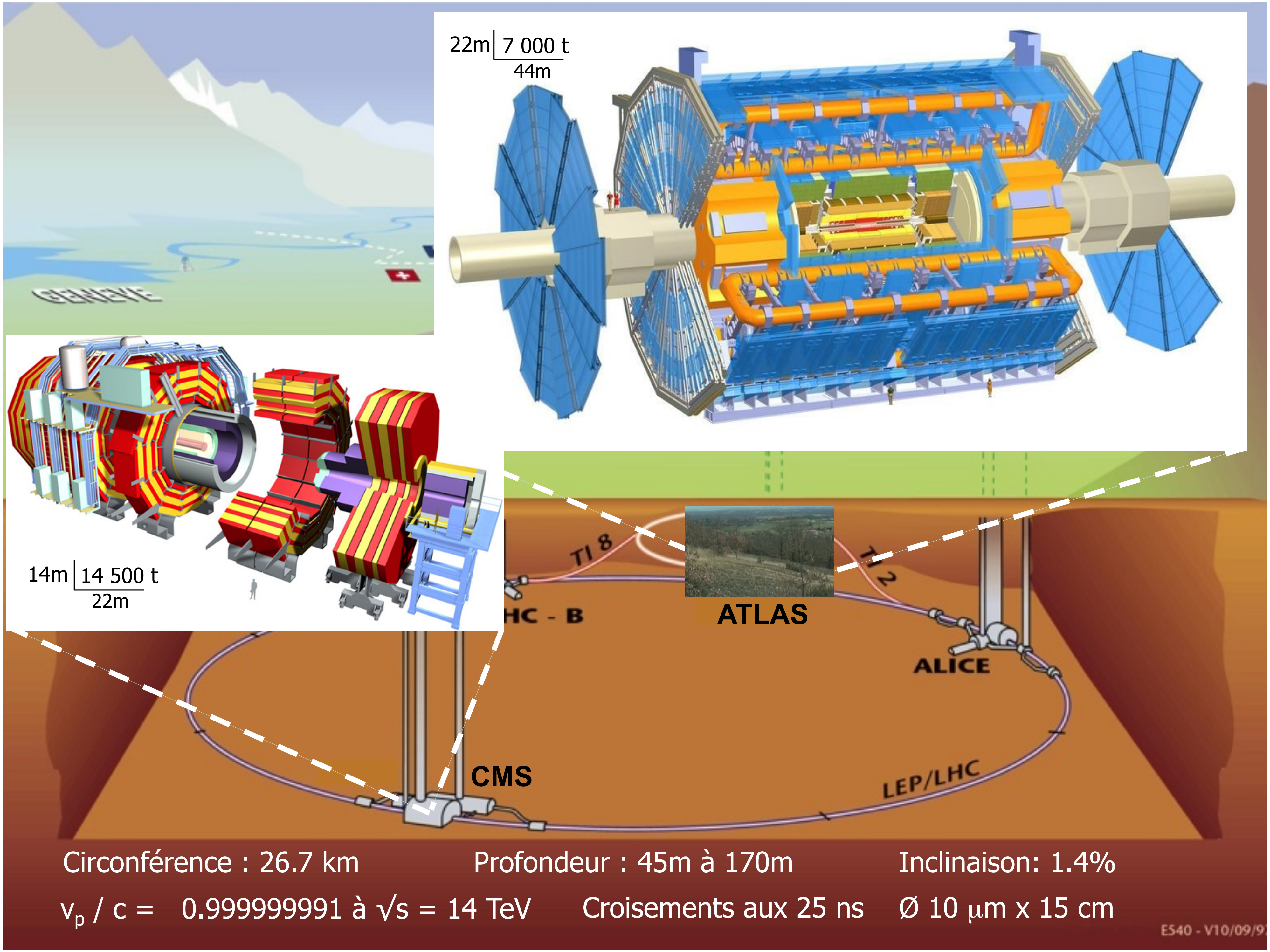
- Haute luminosité:
  recherche du boson de Higgs
- Haute énergie:
  diffusion W_L-W_L à l'échelle du TeV $\Rightarrow$ $\sqrt{s_{pp}} \sim 14$ TeV



- Aimants dipolaires: 8.3 Tesla
- Bobinage niobium-titane refroidis à l'hélium superfluide (1.9 °K)

- Cavités radio-fréquence à 400 MHz
- Collisions à 40 MHz – 25 ns/croisement

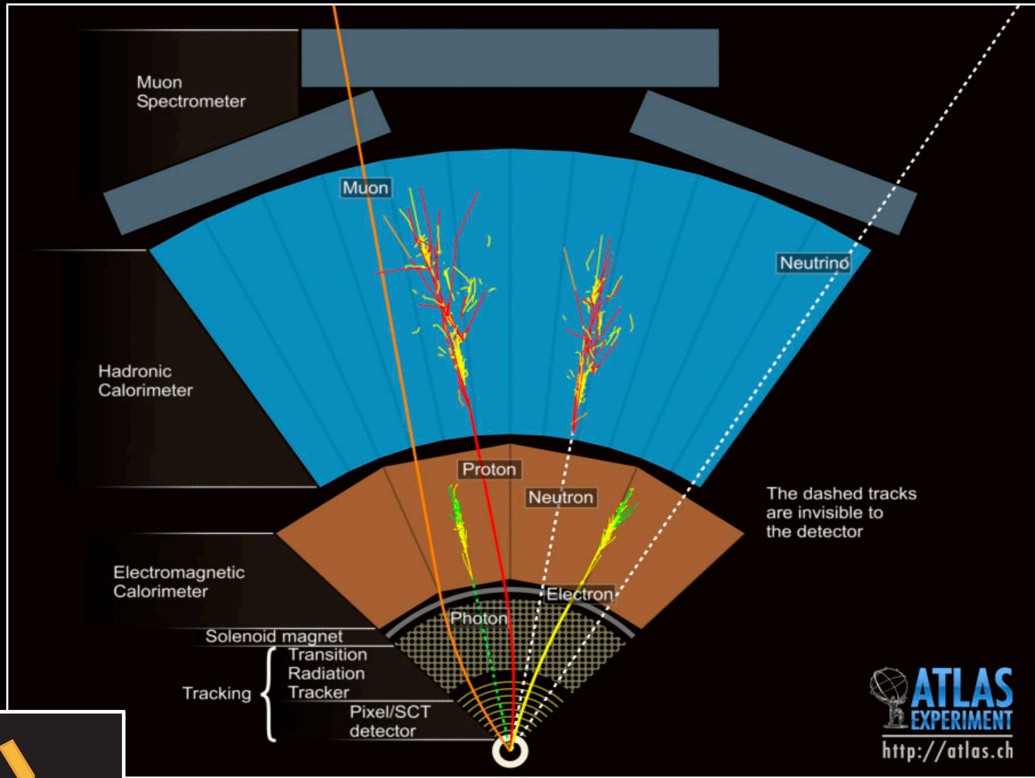

Montagnes
du
JURA
LHC
Lac Léman
Prévessin
SPS
CERN
Meyrin
Genève
Mont-Salève

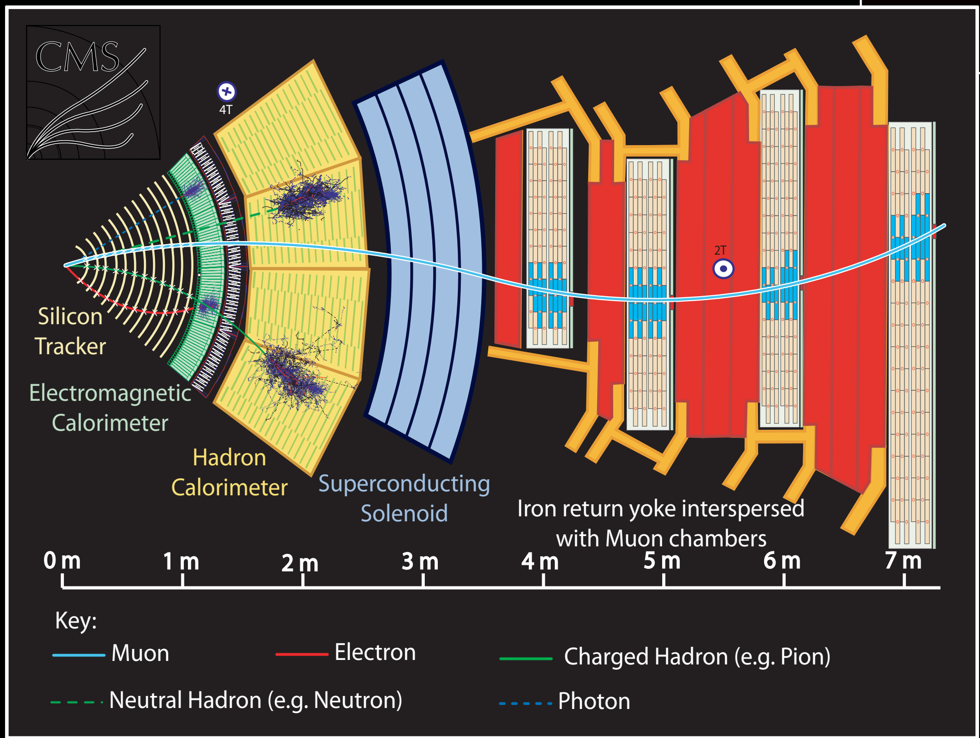


22m | 7 000 t
44m
GENEVE
14m | 14 500 t
22m
TI 8
TI 2
HC - B
ATLAS
ALICE
CMS
LEP/LHC
Circonférence : 26.7 km
Profondeur : 45m à 170m
Inclinaison: 1.4%
v_p / c = 0.999999991 à $\sqrt{s}$ = 14 TeV
Croisements aux 25 ns
Ø 10 μm x 15 cm
ES40 - V10/09/97

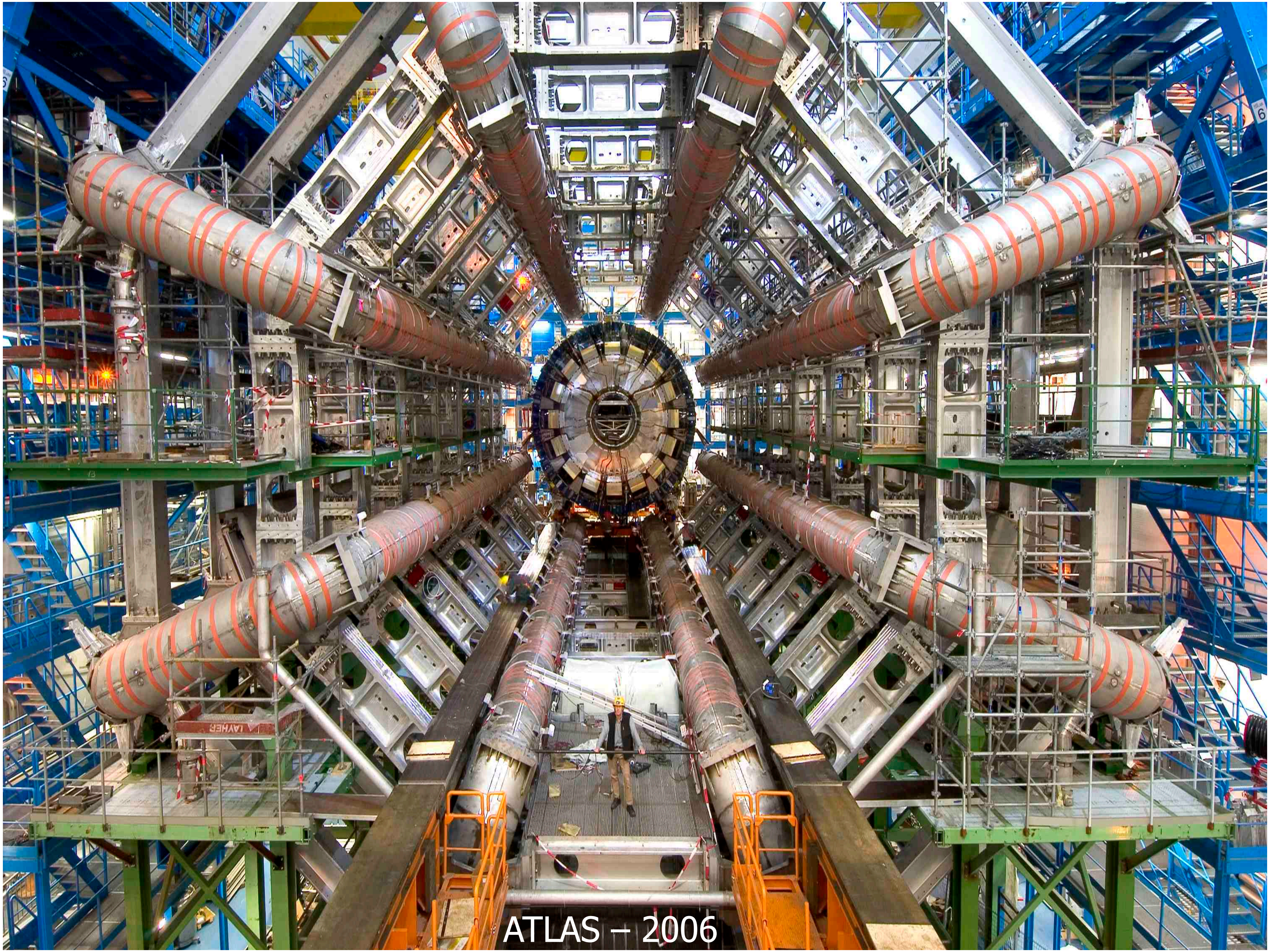
Signatures

ATLAS:
Pixel & trajectomètre Silicium
Solenoïd supra.
Calorimètre e.m. Lar
Calorimètre had. Tuiles
Toroïd – spectromètre μ





CMS:
Pixel & trajectomètre Silicium
Calorimètre Cristaux $PbWO_4$
Calorimètre had. Tuiles
Solénoïd supra.
Retour de fer (μ)



ATLAS – 2006

L' Europe prend le leadership en physique des particules

Les détecteurs du LHC

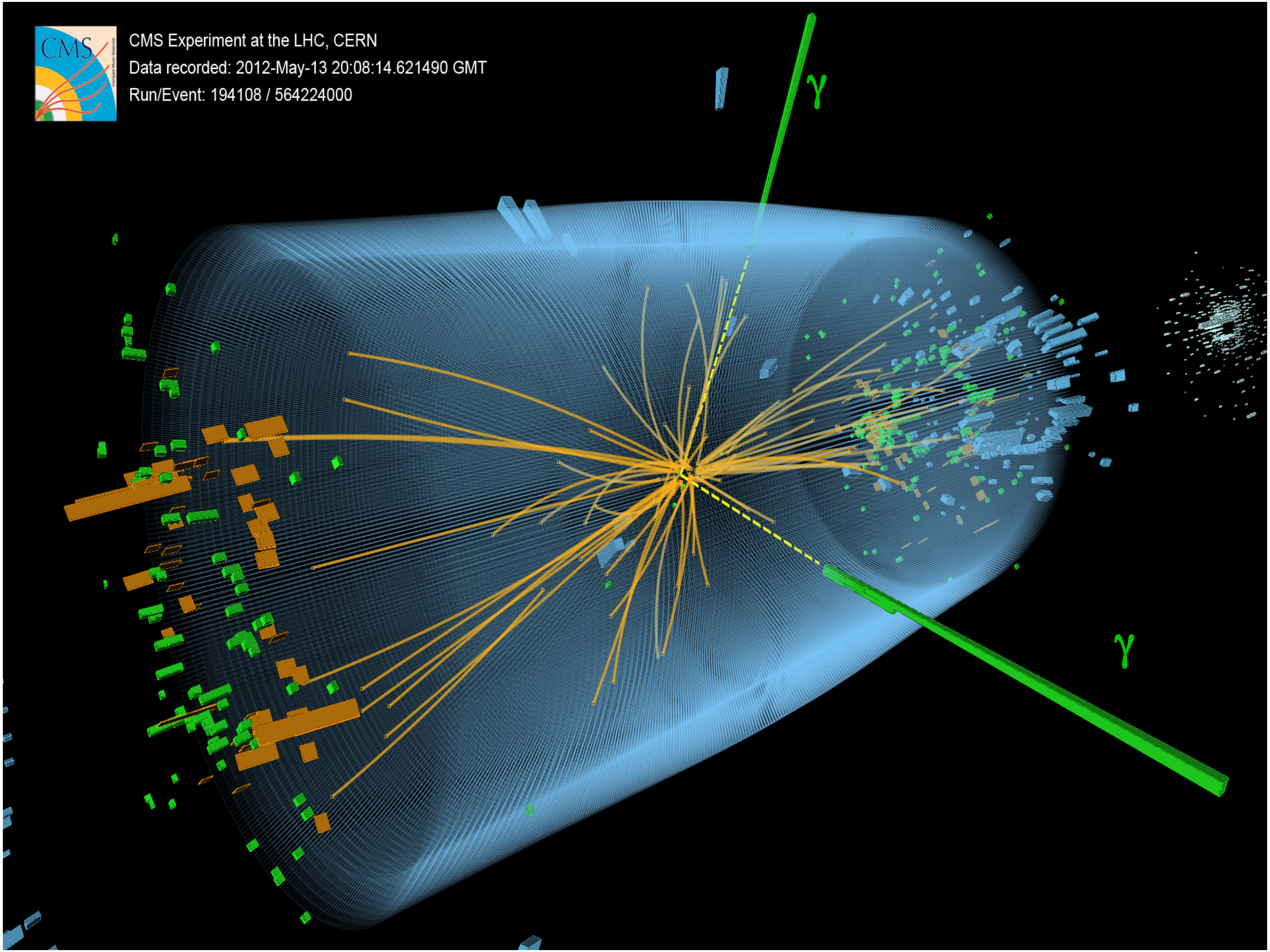
~ 18 ans de conception, R&D, et construction

Achèvement de la construction en ~ 2007

Des contributions françaises majeures ! (CEA et CNRS)

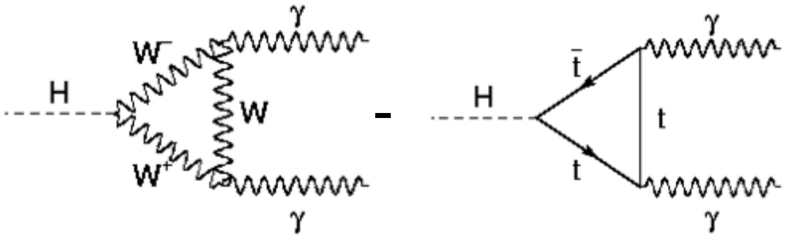
Collisions pour la physique à partir de mars 2010

CMS - 2007


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

The H → γγ Channel

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

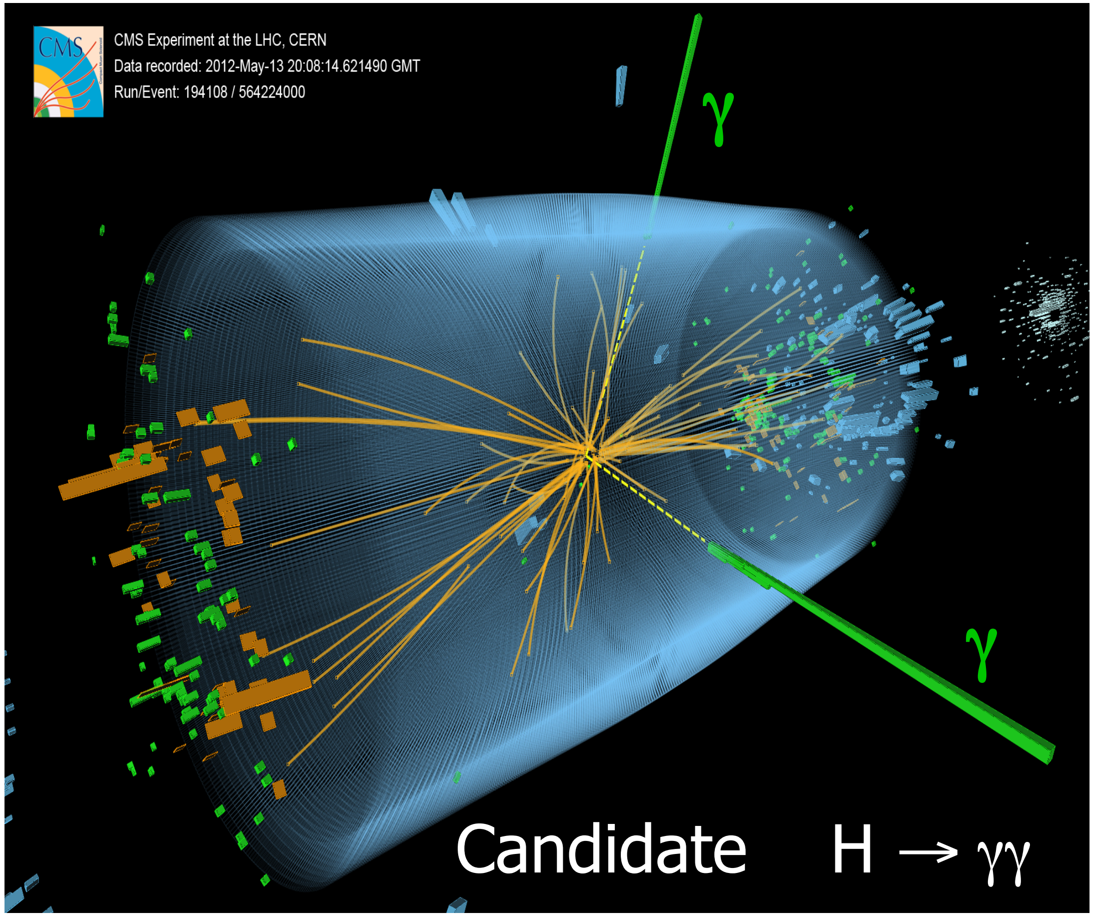


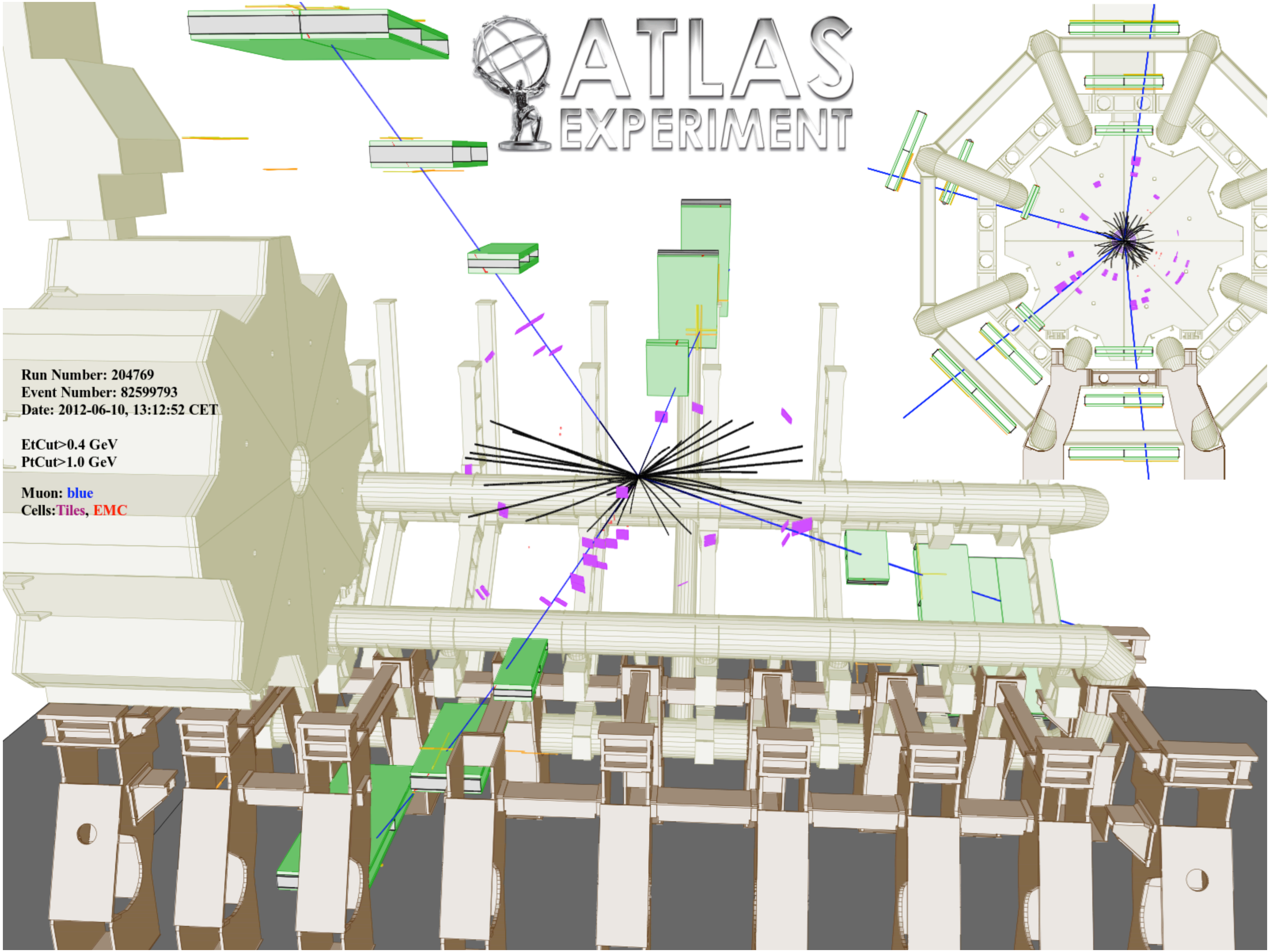
Low rates ($\sigma \times \beta \sim 48.6$ fb at 125 GeV);

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)



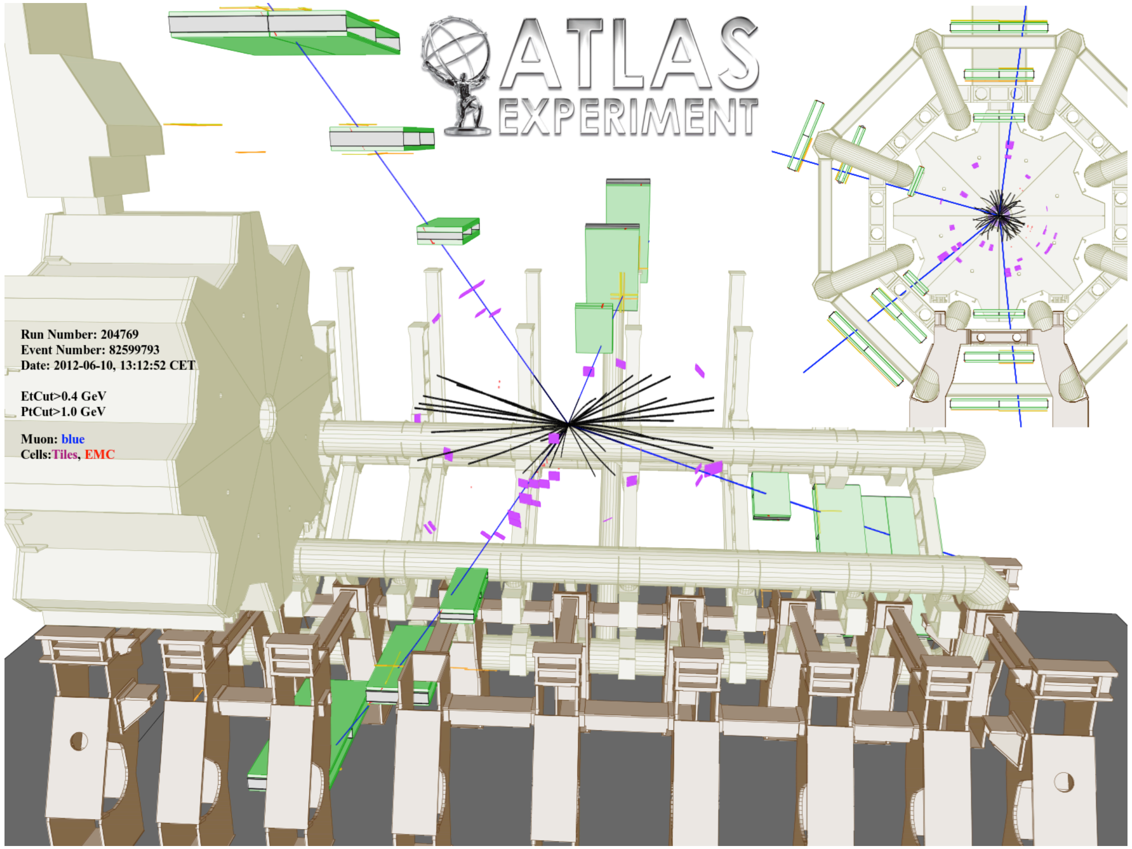

ATLAS EXPERIMENT
Run Number: 204769
Event Number: 82599793
Date: 2012-06-10, 13:12:52 CET
EtCut>0.4 GeV
PtCut>1.0 GeV
Muon: blue
Cells:Tiles, EMC

The $H \rightarrow ZZ^* \rightarrow 4\ell$ Channel

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)

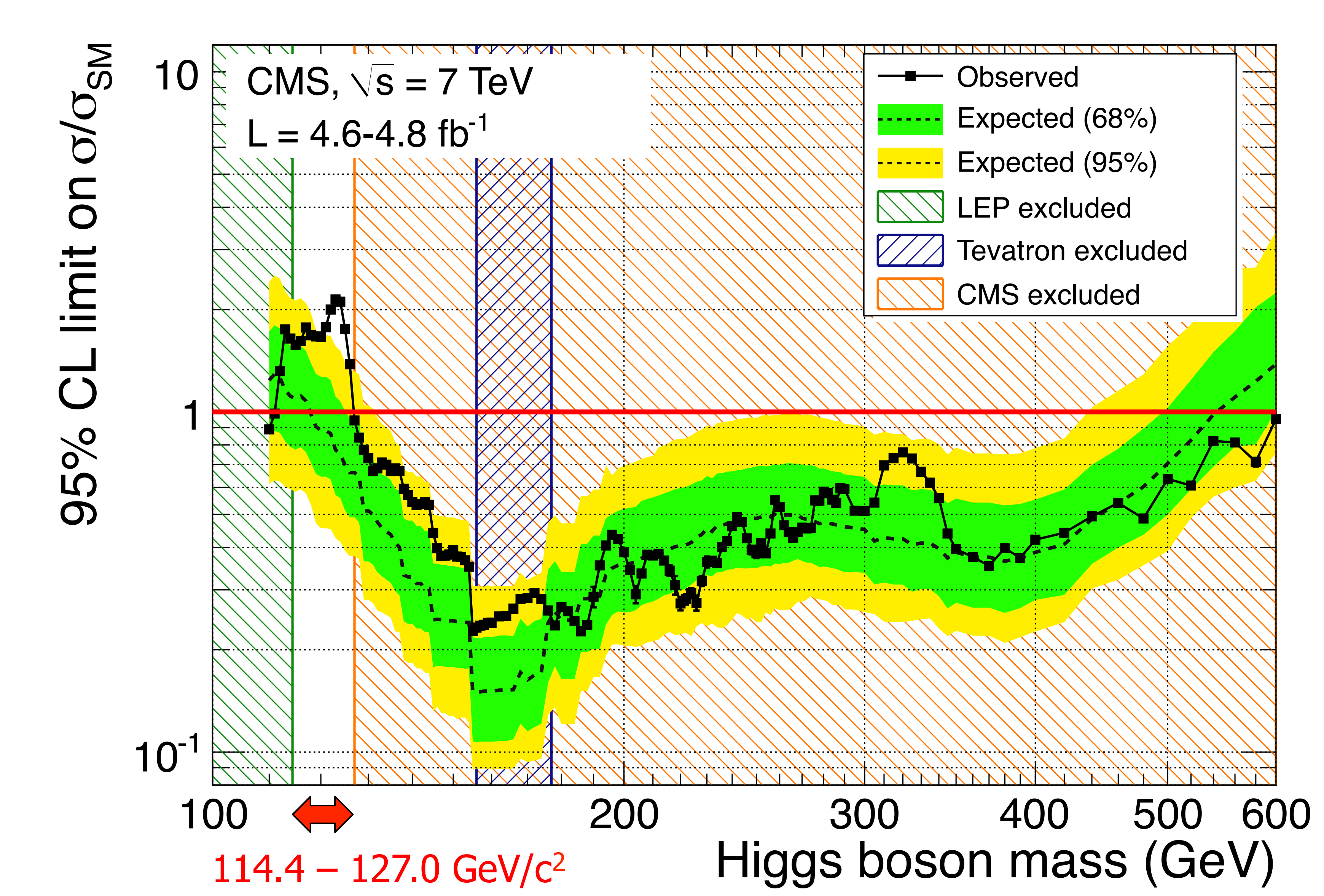
Signature:
Four isolated leptons from
Common primary vertex

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)

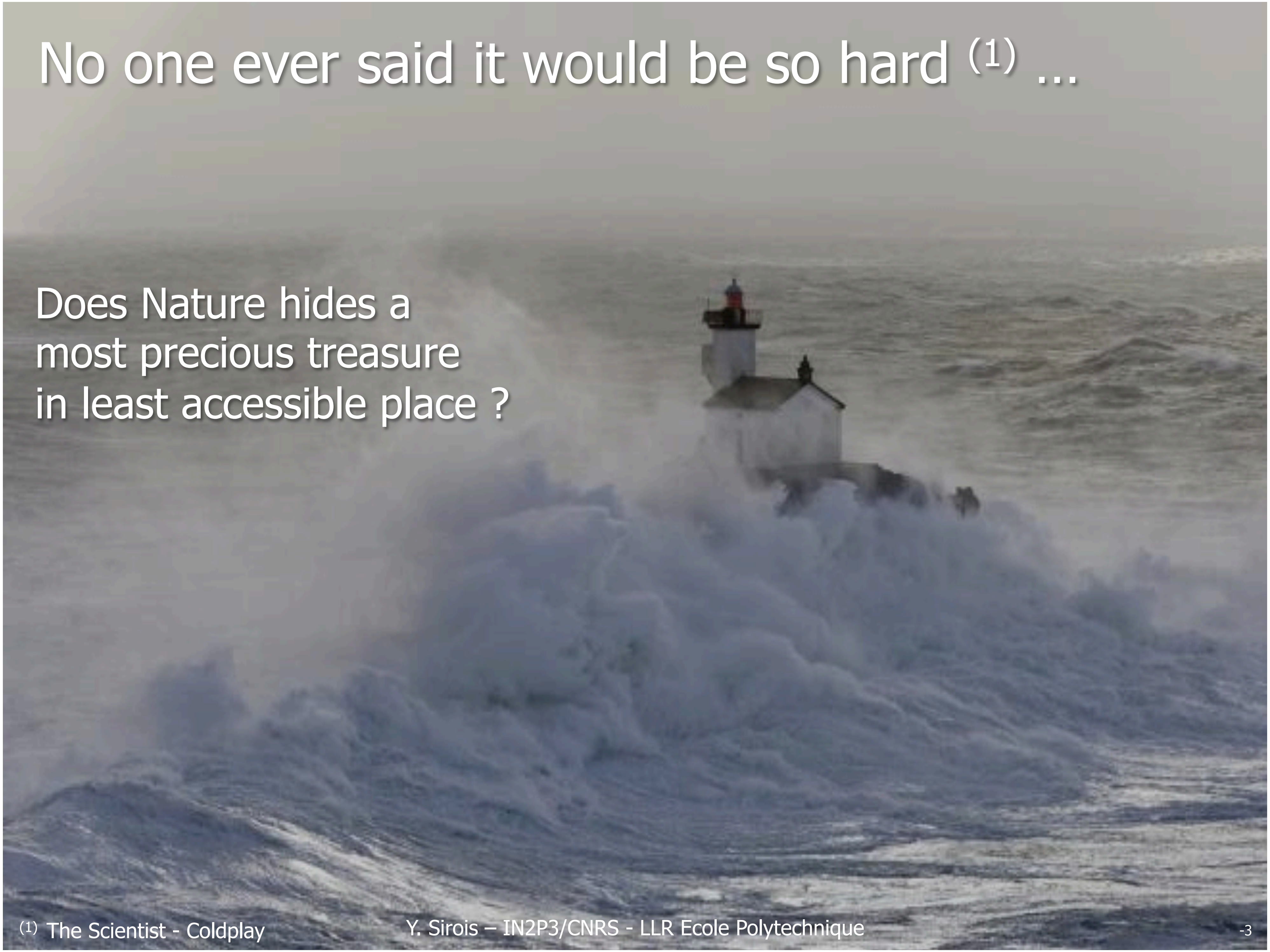
Décembre 2011



Moriond 2012

Similar results from ATLAS

No one ever said it would be so hard [1] …



Does Nature hides a
most precious treasure
in least accessible place ?

[1] The Scientist - Coldplay

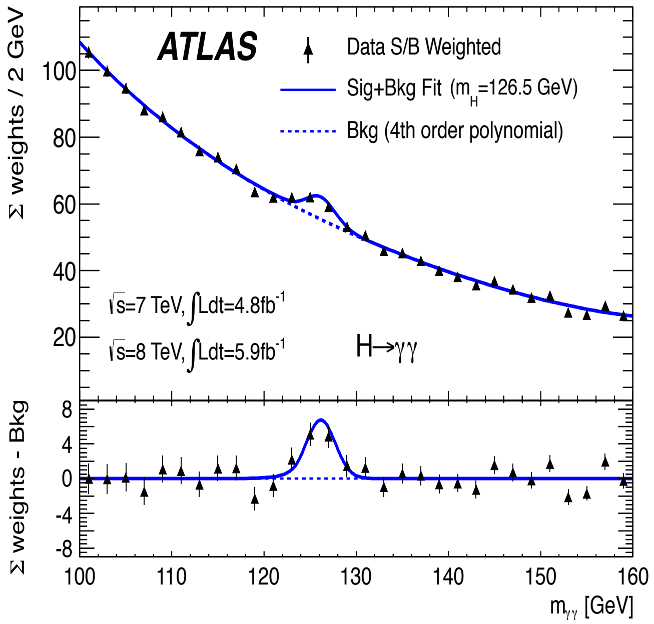
What followed now belongs to the History of Science

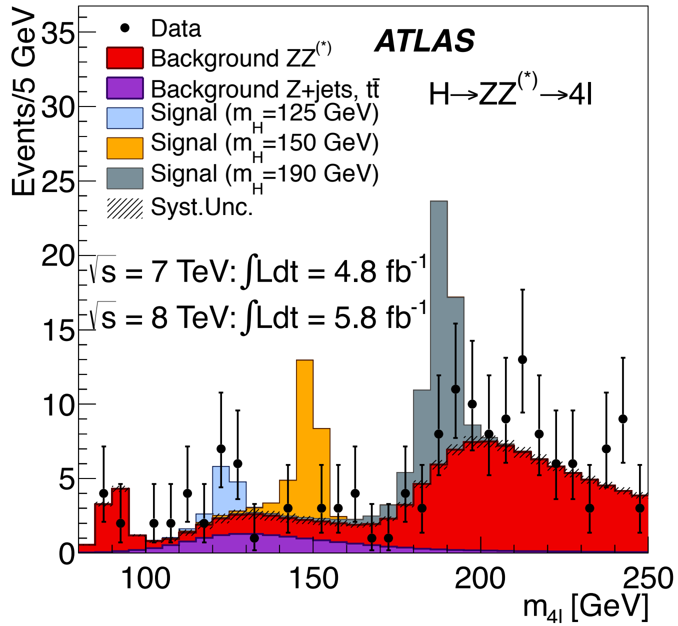
2 x 3500 citations so far

4 July 2012

ATLAS

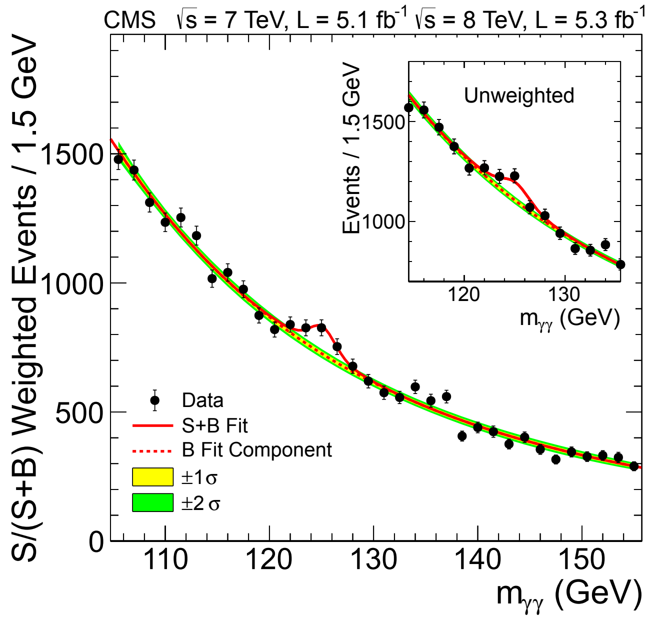
Phys.Lett. B716 (2012) 1-29

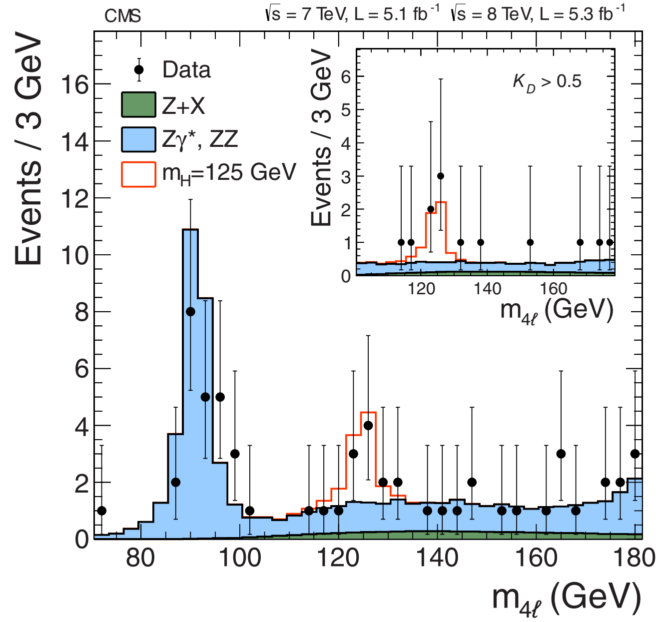




CMS

Phys.Lett. B716 (2012) 30-61





J U L Y 2 0 1 2

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

Les Mesures

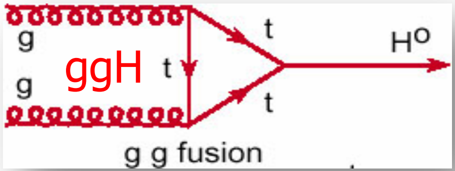
2012 - 2014

The Measurements

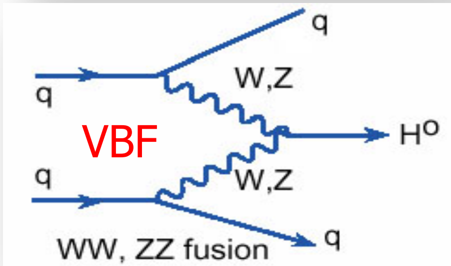
Higgs Boson : Production Cross-Sections

At the LHC

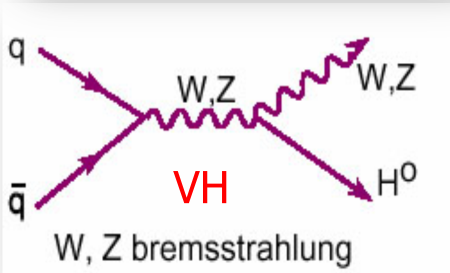
87%



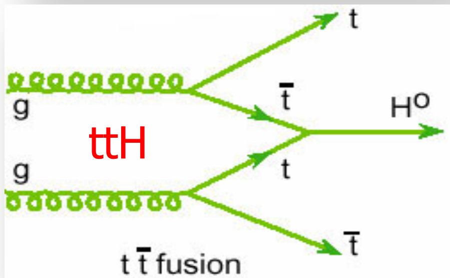
7.1%



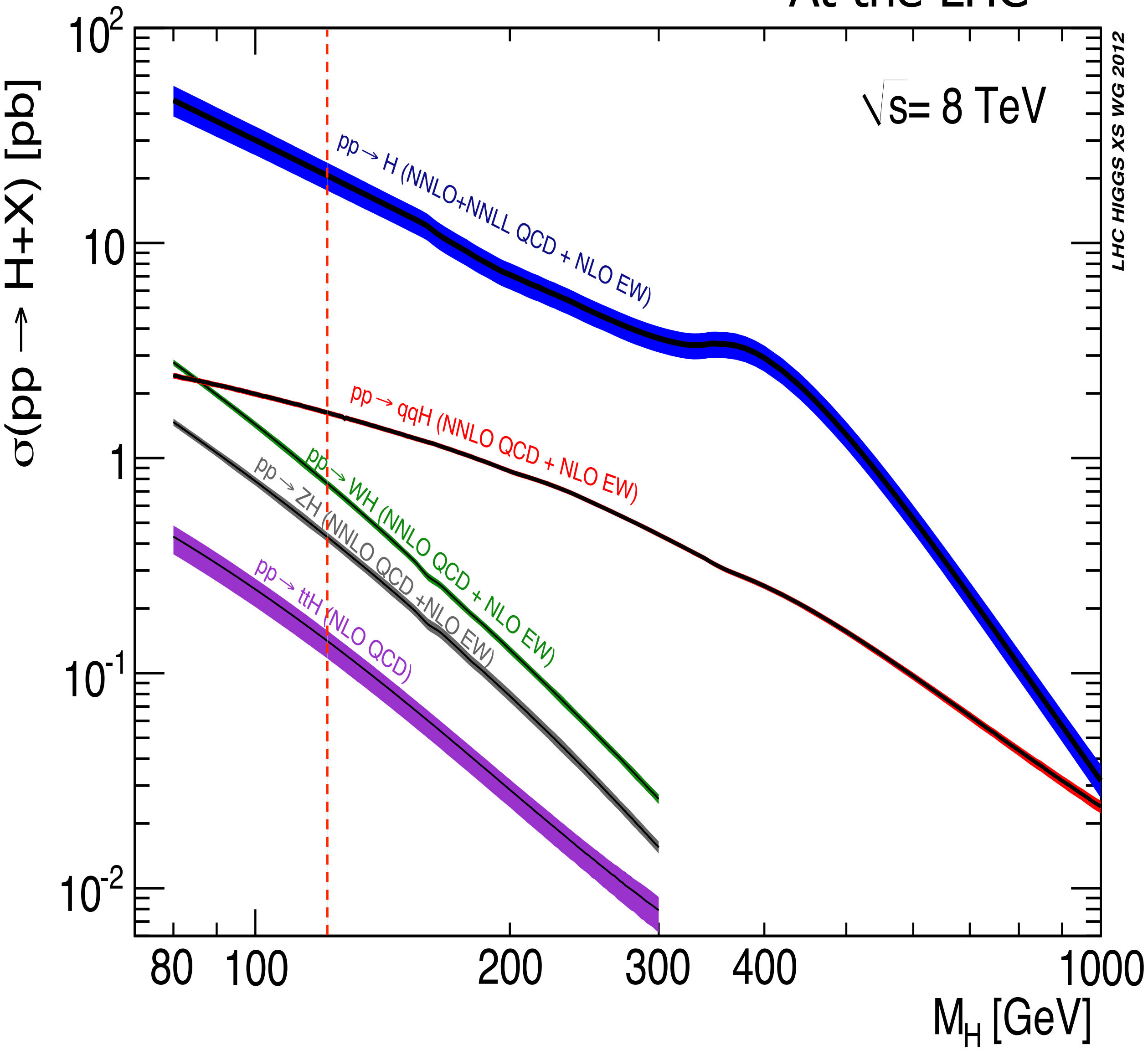
4.9%



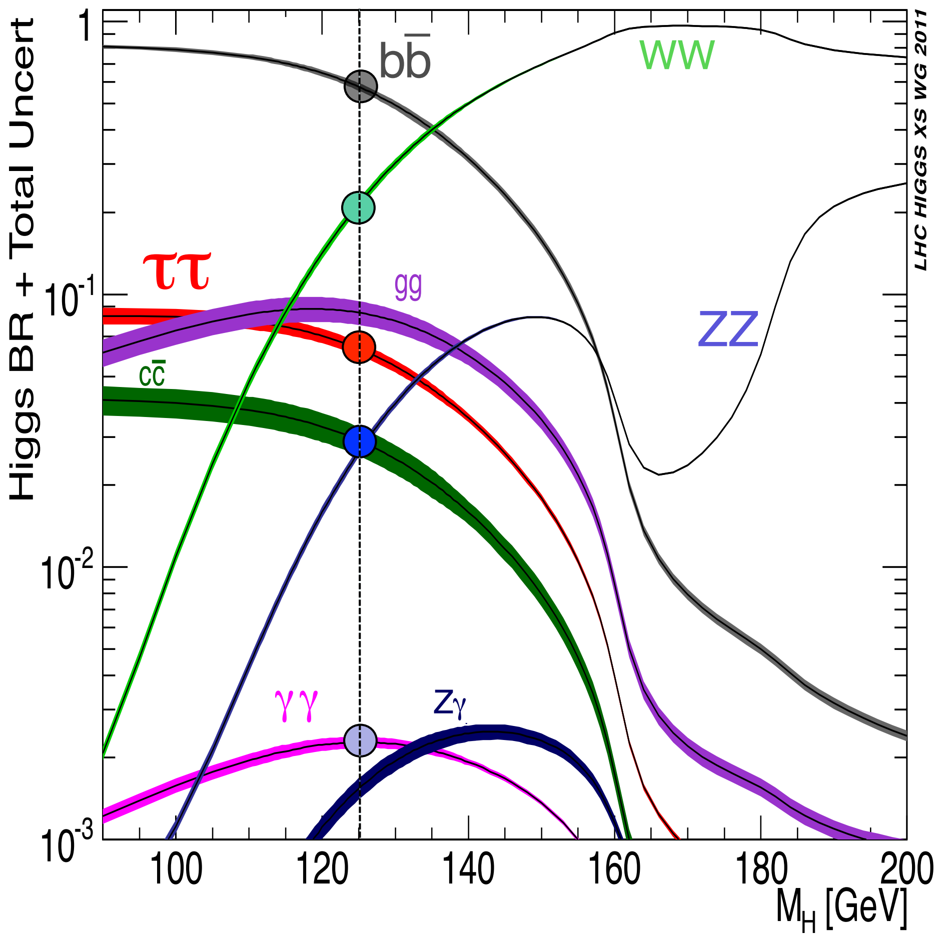
0.6%



σ/σ_{tot} (M_H = 125 GeV)



Higgs Boson : Decay Channels



ΔM/M ~ 1-2% High resolution

$H \to \gamma\gamma$ Rare, S/B < 1

$H \to ZZ^* \to 4\ell$ Very rare, S/B >> 1

ΔM/M ~ 10-20% Medium resolution

$H \to bb$ Abundant, S/B << 1

$H \to \tau\tau$ Abundant, S/B < 1

ΔM/M > 30% Low resolution

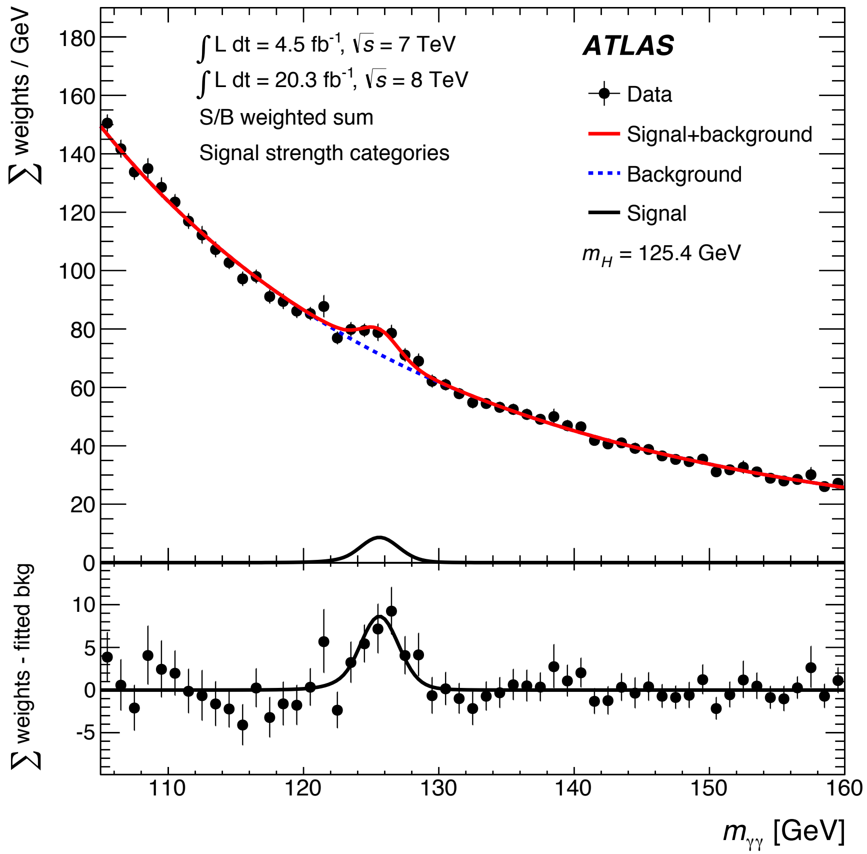
$H \to WW^* \to 2\ell 2\nu$ Very abundant, S/B < 1

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

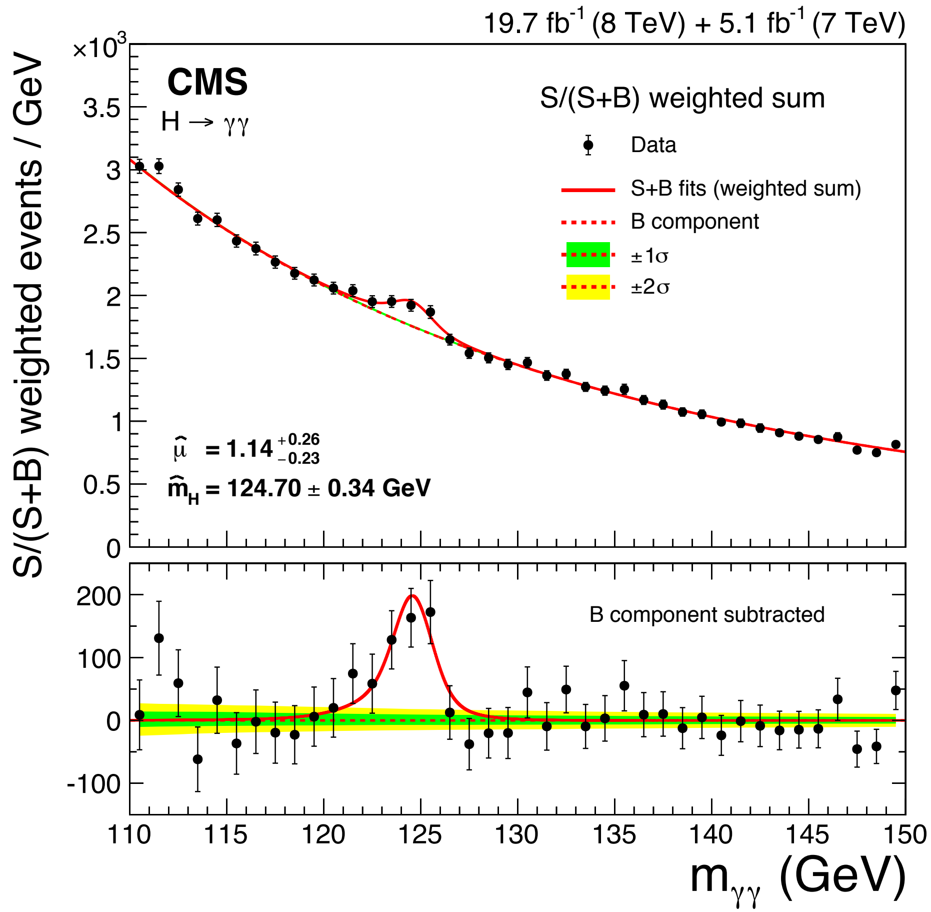
~ 100 exclusive final states (production, decay, event categories) are contributing for M_H ~ 125 GeV !

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)

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

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

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

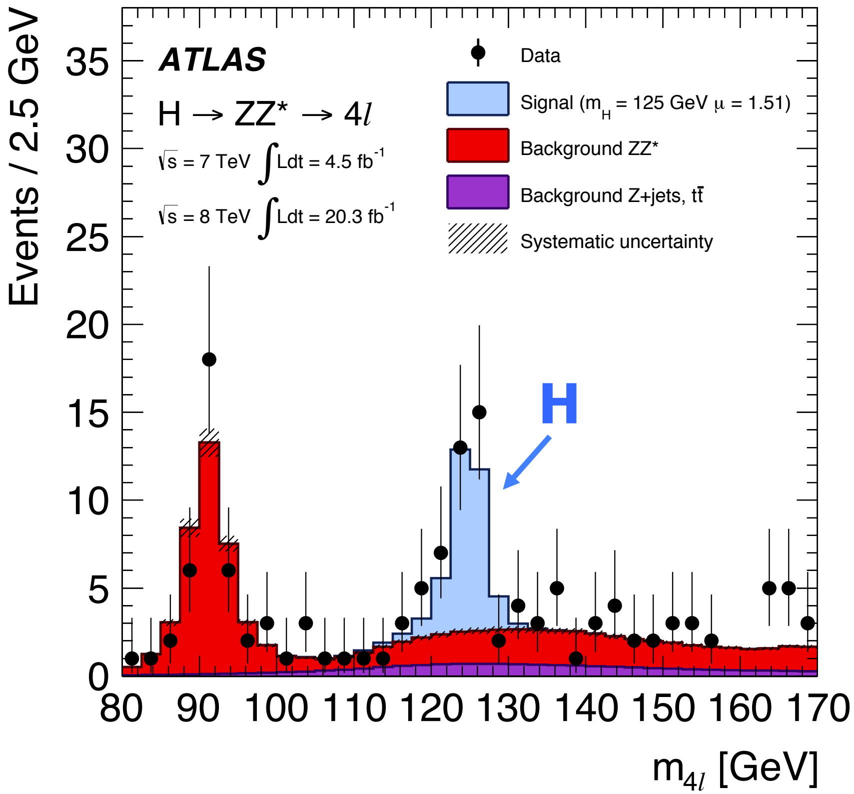
$m_H^{\gamma\gamma} = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})$ GeV

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

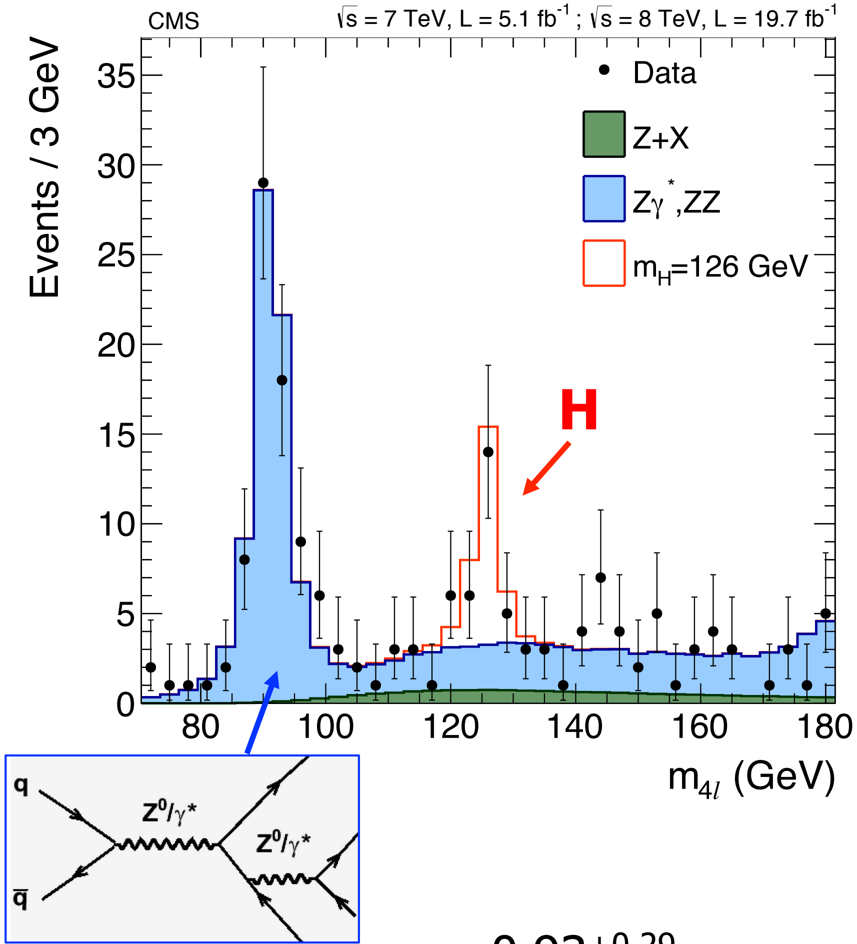
Results consistent, and compatible with a single narrow resonance

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

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

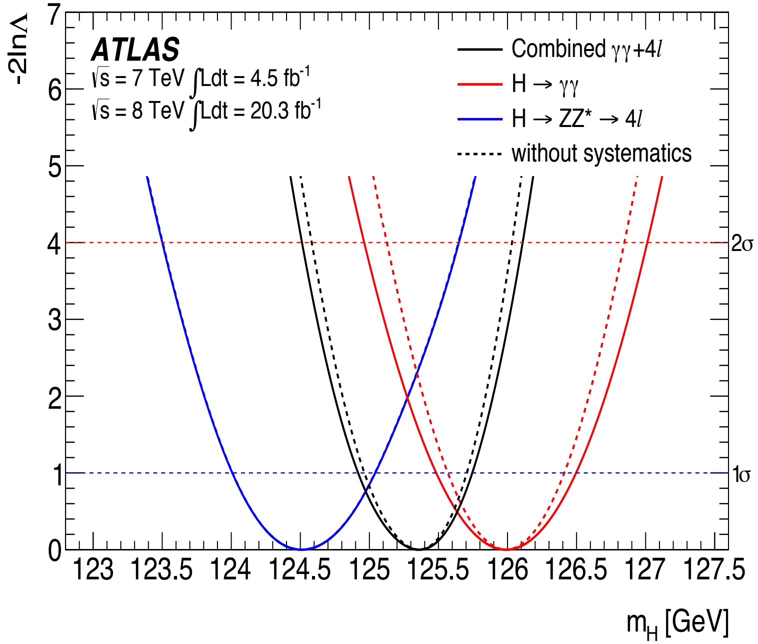
$\Gamma <$ 2.6 GeV (95% CL)

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

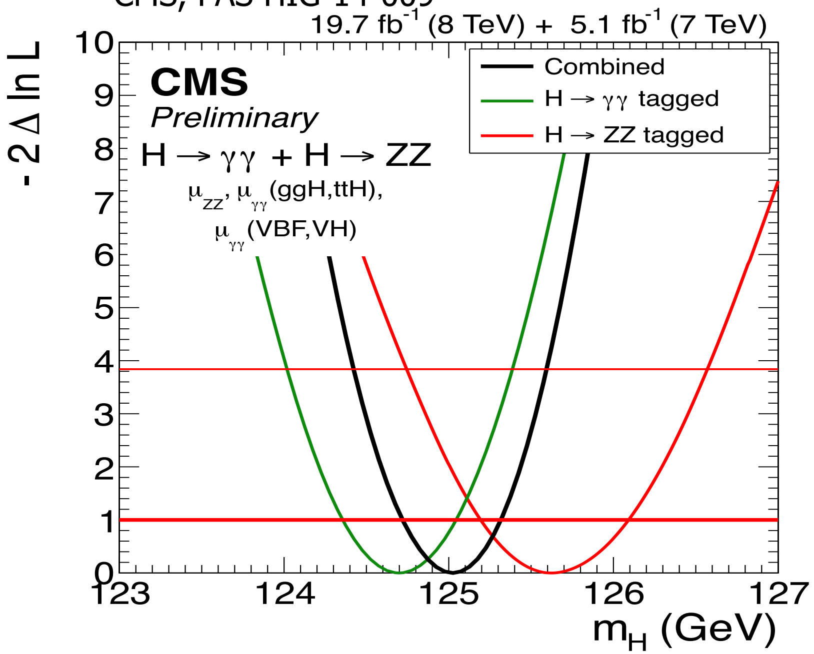
Results consistent, and compatible with a single narrow resonance

Precision Mass Measurements

ATLAS, arXiv:1406.3827v1; Submitted to PRD



CMS, PAS HIG-14-009



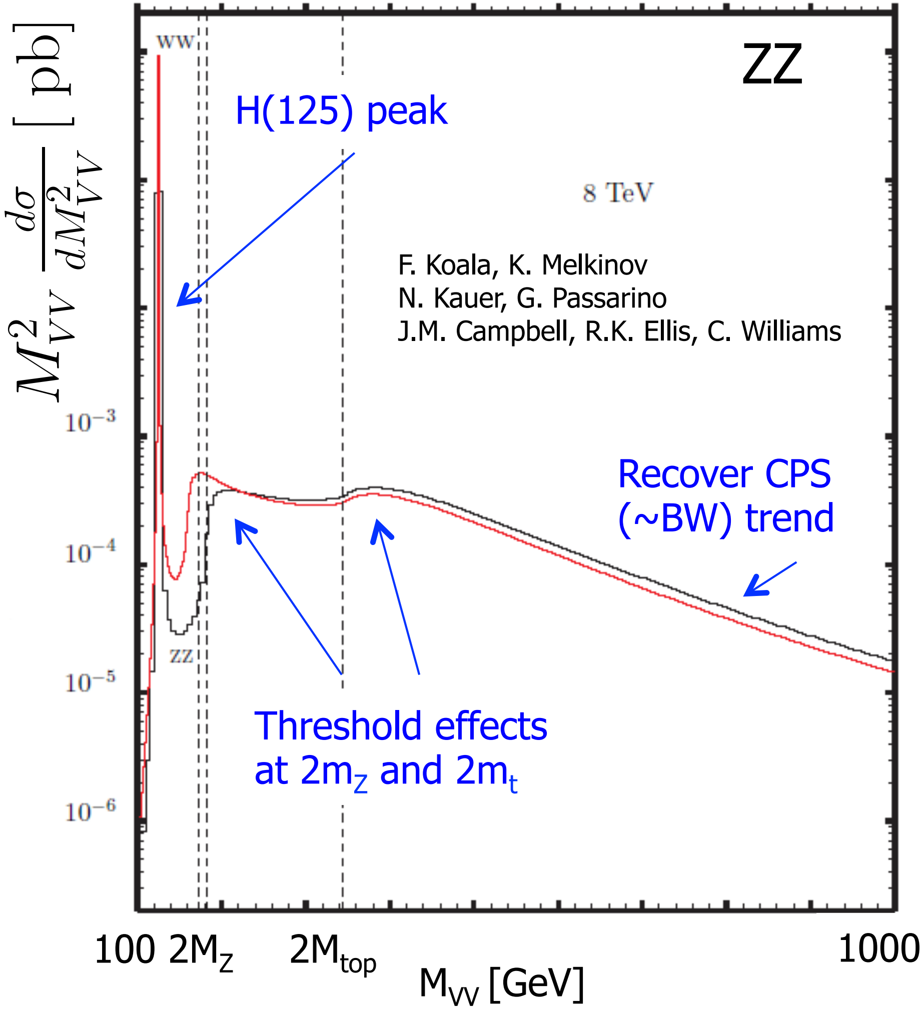
Expt.	Decay Channel	Signal Strength $\mu = \sigma_{meas.}/\sigma_{SM}$	Measured Mass (GeV) mass ± statistics ± systematics
ATLAS	$H \rightarrow \gamma\gamma$	$1.29^{+0.30}_{-0.30}$	$125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})$
	$H \rightarrow ZZ^* \rightarrow 4\ell$	$1.66^{+0.45}_{-0.38}$	$124.51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

$m_H = 125.16 \pm 0.24$ GeV

Measuring Γ_H at the LHC

- Expect Γ_H ~ 4.2 MeV in SM for a H at m_H ~ 125 GeV $\left\{ \begin{array}{l} \Gamma_H \ll m_H \quad \Gamma_H \ll \Delta m_H^{meas} \\ \tau_H^0 = \hbar/\Gamma_H \simeq 2 \times 10^{-22} s \end{array} \right.$
- 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 $gg \to ZZ$ and $gg \to H^* \to ZZ$ + alteration of coupling to top quark

Observation:

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

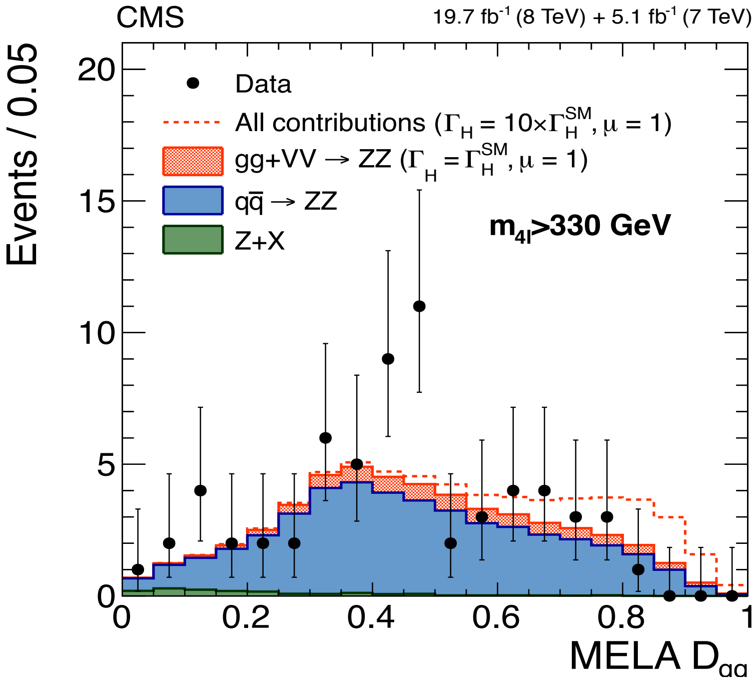
$$\mu_{ZZ}^{\text{on}} \equiv \frac{\sigma_h \times \text{BR}(h \to ZZ \to 4\ell)}{[\sigma_h \times \text{BR}(h \to ZZ \to 4\ell)]_{\text{SM}}} \sim \frac{\kappa_{ggh}^2\, \kappa_{hZZ}^2}{\Gamma_h/\Gamma_h^{\text{SM}}}$$

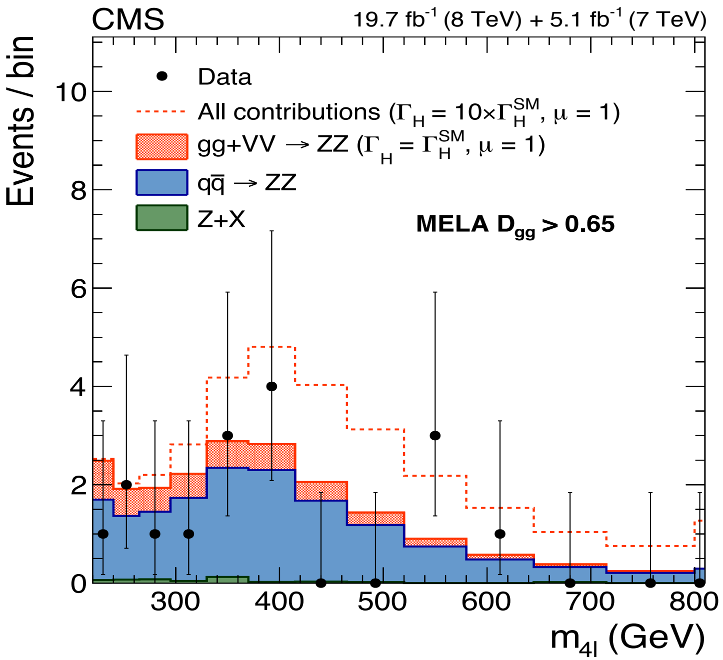
$$\mu_{ZZ}^{\text{off}} \equiv \frac{\text{d}\bar{\sigma}_h}{[\text{d}\bar{\sigma}_h]_{\text{SM}}} \sim \kappa_{ggh}^2(\hat{s})\, \kappa_{hZZ}^2(\hat{s}) \,,$$

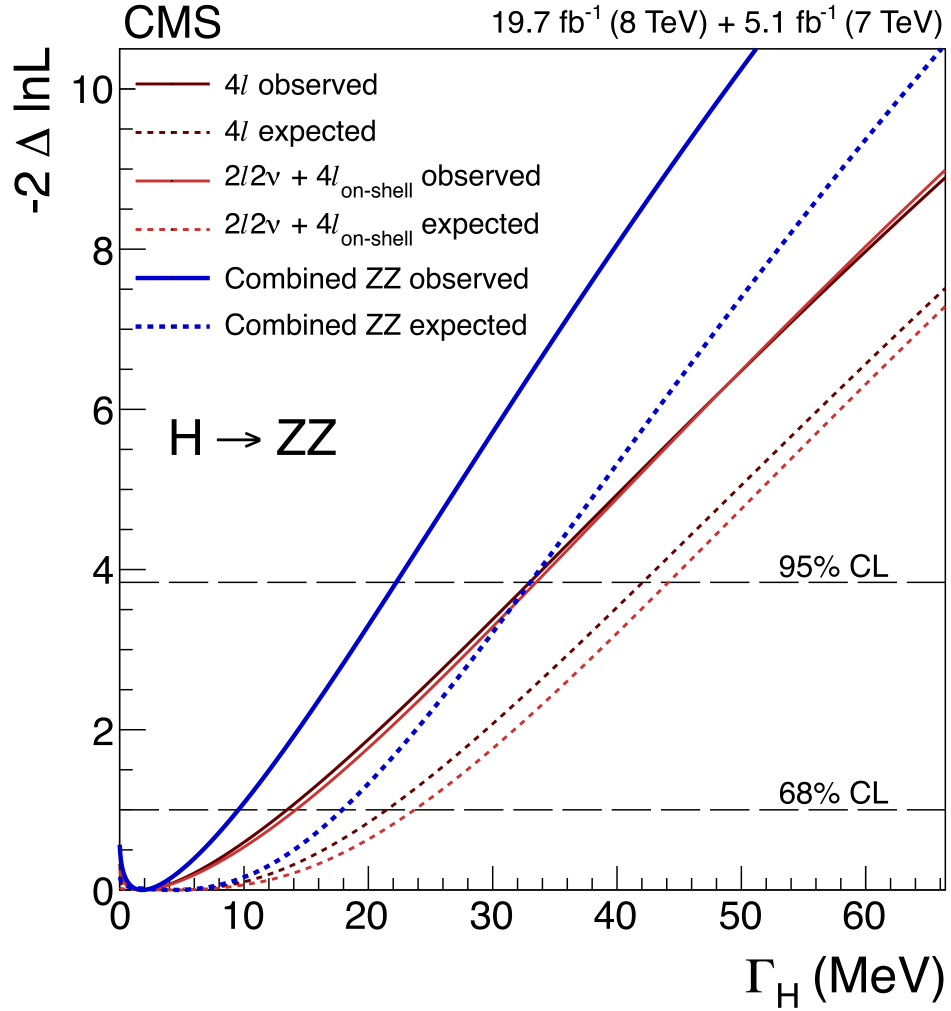
Access ⇒ Γ_H / Γ_H^{SM}

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)

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

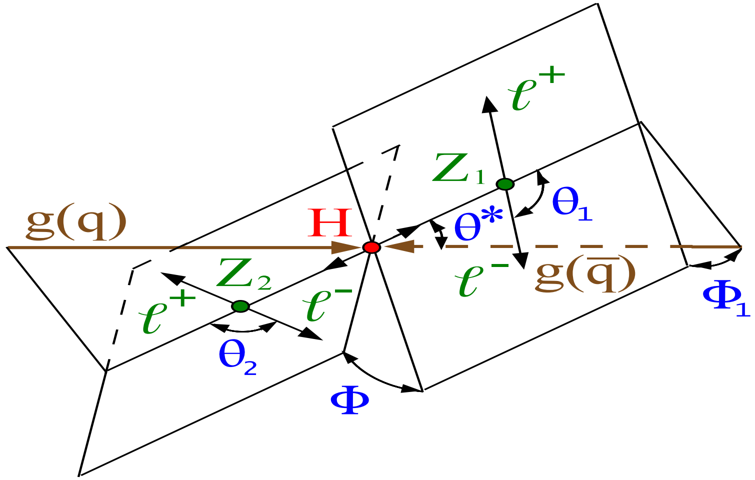
e.g. exploit the prod. dependent scattering angle in the Collins-Sopper frame

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

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

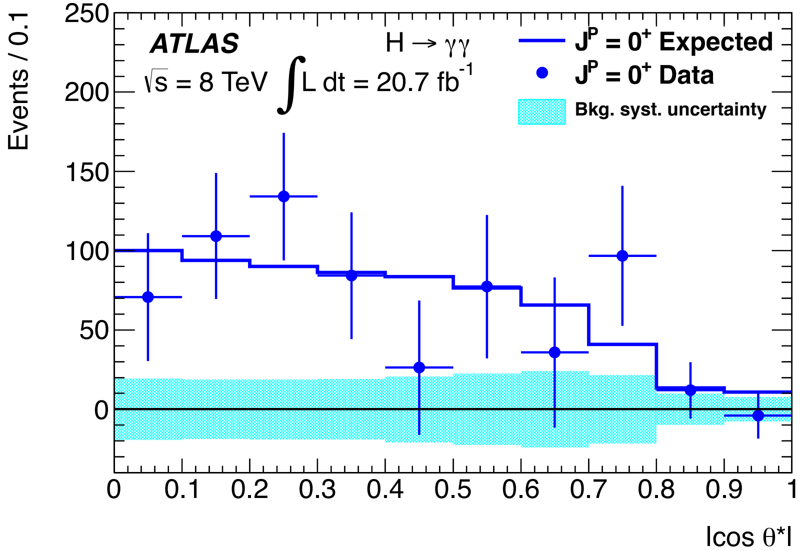
Test 0^+ against 0^- or 2^+

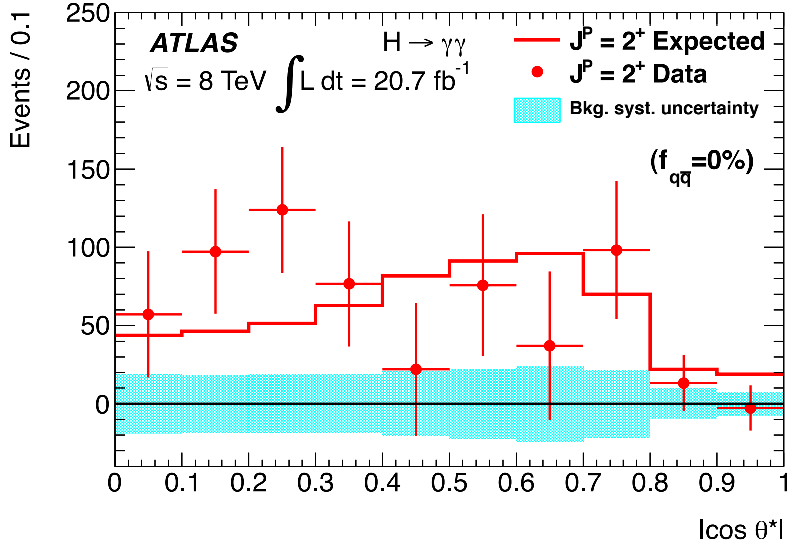
D0 Conf. Note 6404, 6387

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

H boson: spin-parity (1)

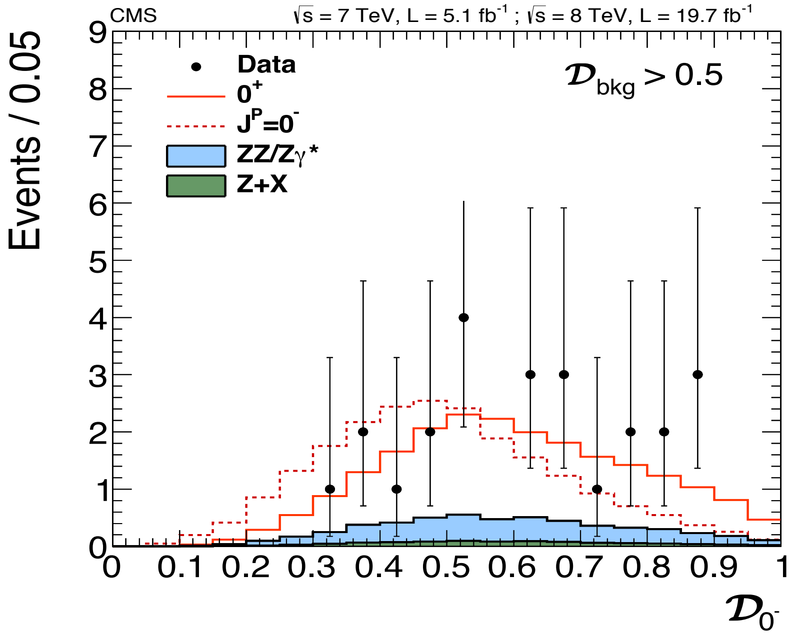
$H \to \gamma\gamma$ Testing 0^+ and 2^+ hypothesis

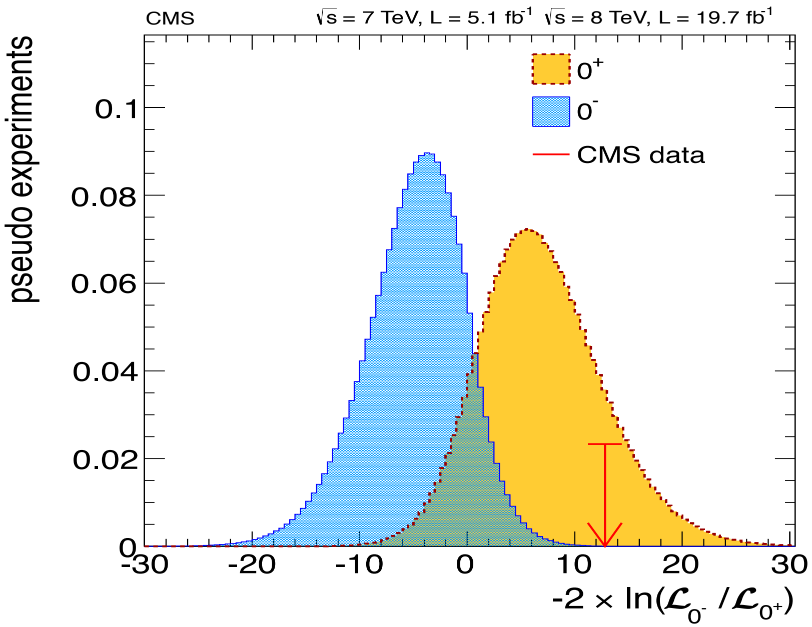




ATLAS Phys. Lett. B726 (2013)

$H \to ZZ^* \to 4\ell$ Testing 0^+ against 0^- hypothesis





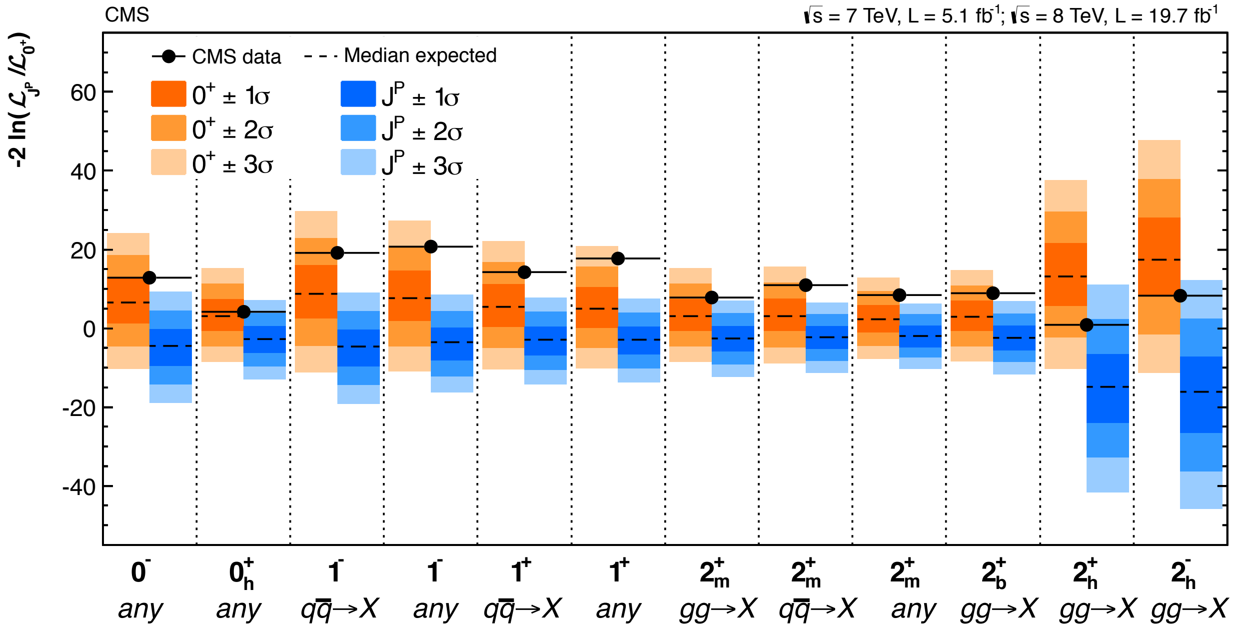
CMS Phys. Rev. D89 (2014)

Phys.Rev.Lett. 110 (2013)

compare 0^+ against background and against 0^-

H boson: spin-parity (2)

Testing 0^+ against various exotic S = $0^\pm$, $1^\pm$, and $2^\pm$ models

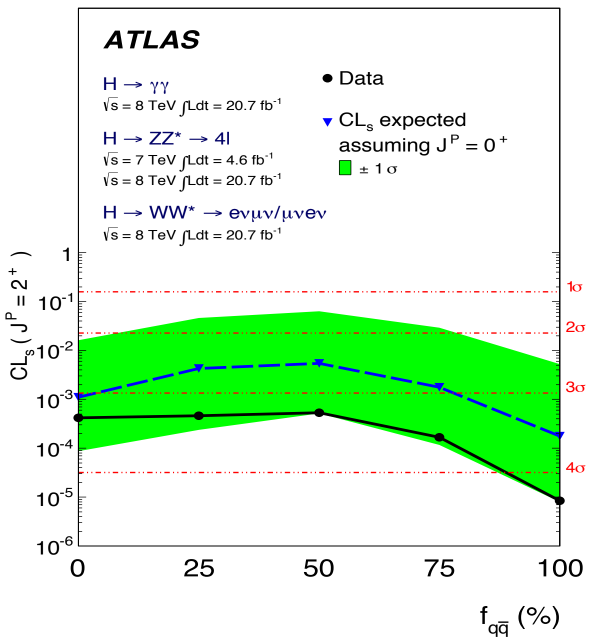


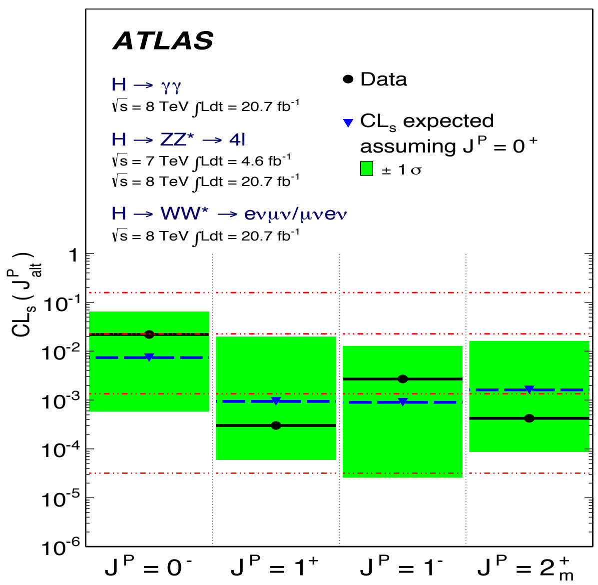
CMS Phys. Rev. D89 (2014)

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





ATLAS Phys. Lett. B726 (2014)

All 0^-,$1^\pm$,2^+ hypotheses excluded at > 97.8%

Other exotic states tested in CMS PAS HIG-14-018 (PRD)

The H → Fermions

Large rates ($\beta_{H \to bb} \sim 58\%$) 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:

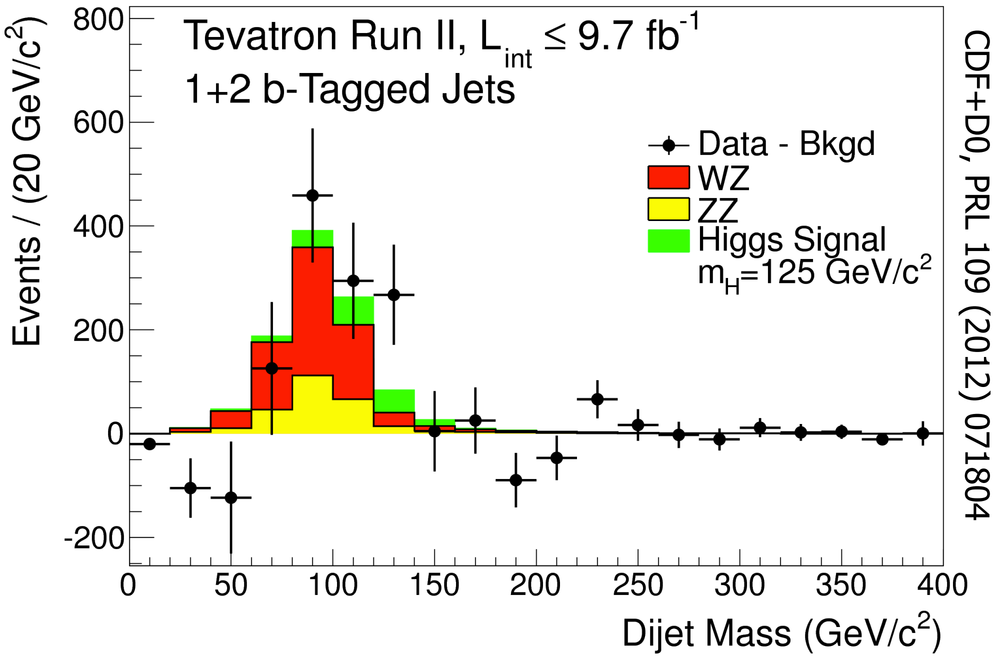
Mass discrimination against background from Z/W + heavy flavours

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

CDF + D0 10 fb^{-1}

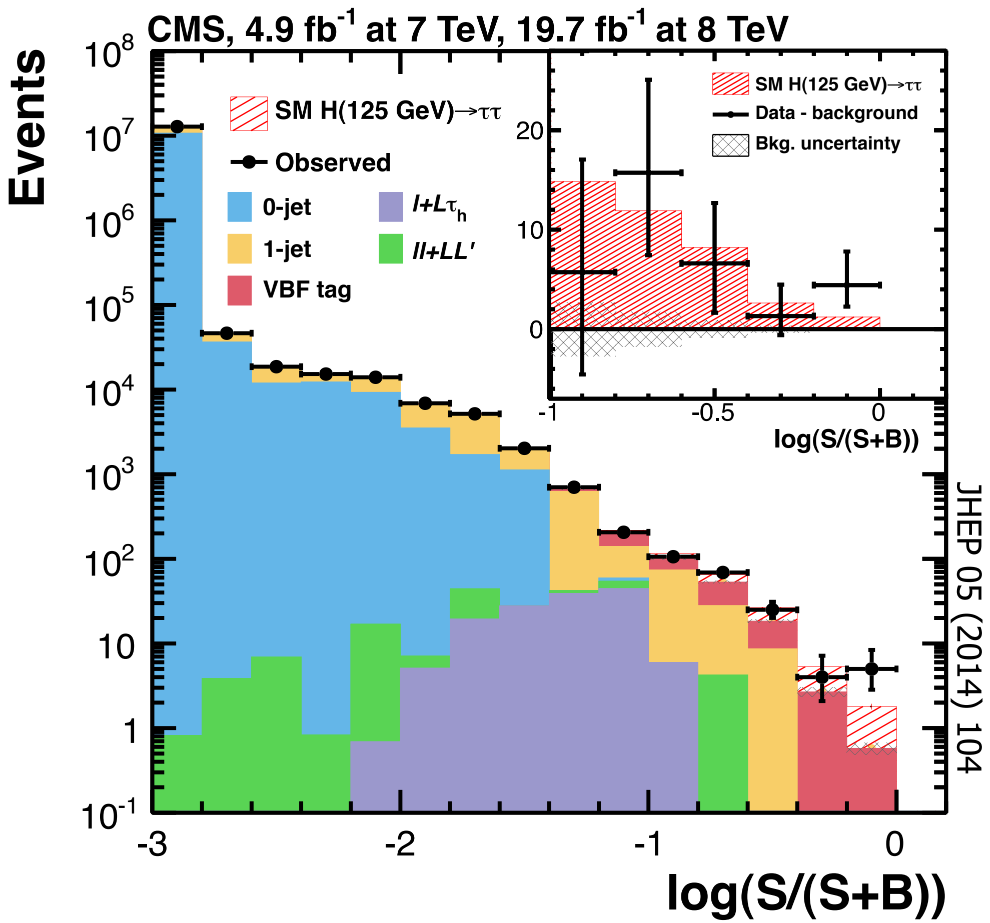
WH → ℓν bb
ZH → ℓℓ bb
ZH → νν bb

Excess with more than 3 σ significance at ~ 135 GeV

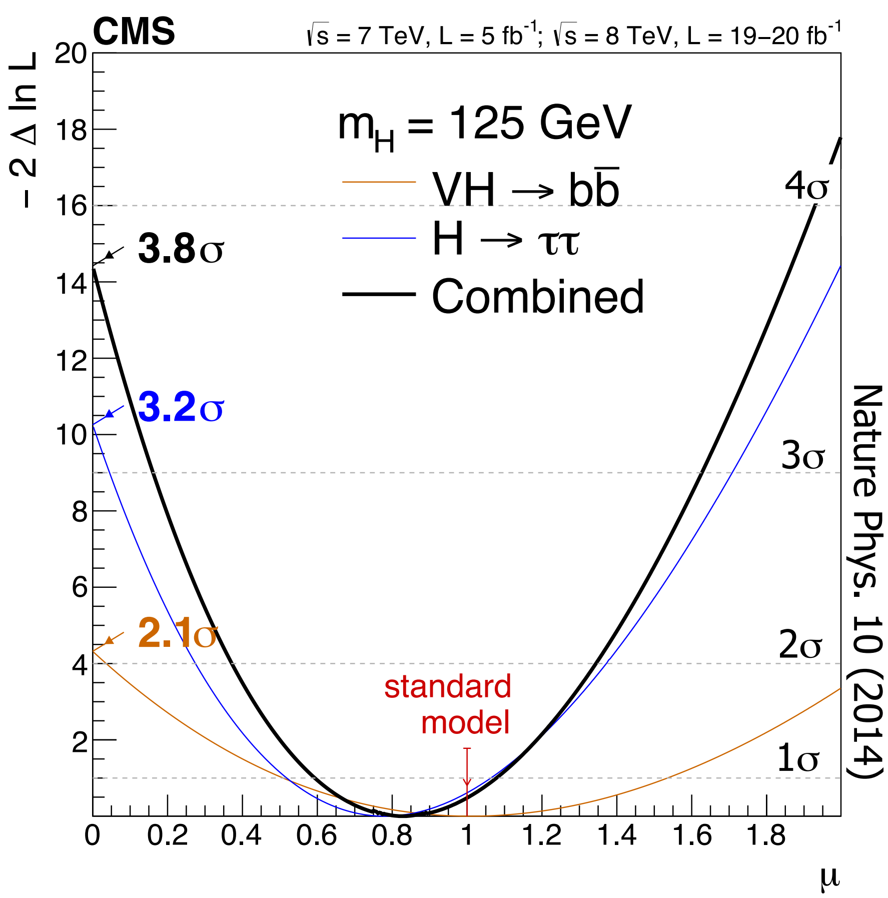


$H \rightarrow$ Fermions

$H \rightarrow \tau\tau$



Combined $H \rightarrow \tau\tau$ & $H \rightarrow bb$



$H \rightarrow \tau\tau$	ATLAS[1]	CMS
Strength	$1.4^{+0.5}_{-0.4}$	0.78 ± 0.27
Significance	4.1σ (exp 3.2σ)	3.2σ (exp 3.7σ)

$H \rightarrow bb + \tau\tau$	CMS
Strength	0.83 ± 0.24
Significance	3.8σ (exp 4.4σ)

See also: $H \rightarrow bb$ CMS PRD 89 (2014), ATLAS-CONF-2013-079 (1) $H \rightarrow \tau\tau$ ATLAS-CONF-2013-108

Signal Rates / H Decay modes

References:

ATLAS, arXiv:1408.7084

ATLAS, arXiv:1408.5191

ATLAS-CONF-2014-060

ATLAS, arXiv:1409.6212

ATLAS-CONF-2014-061

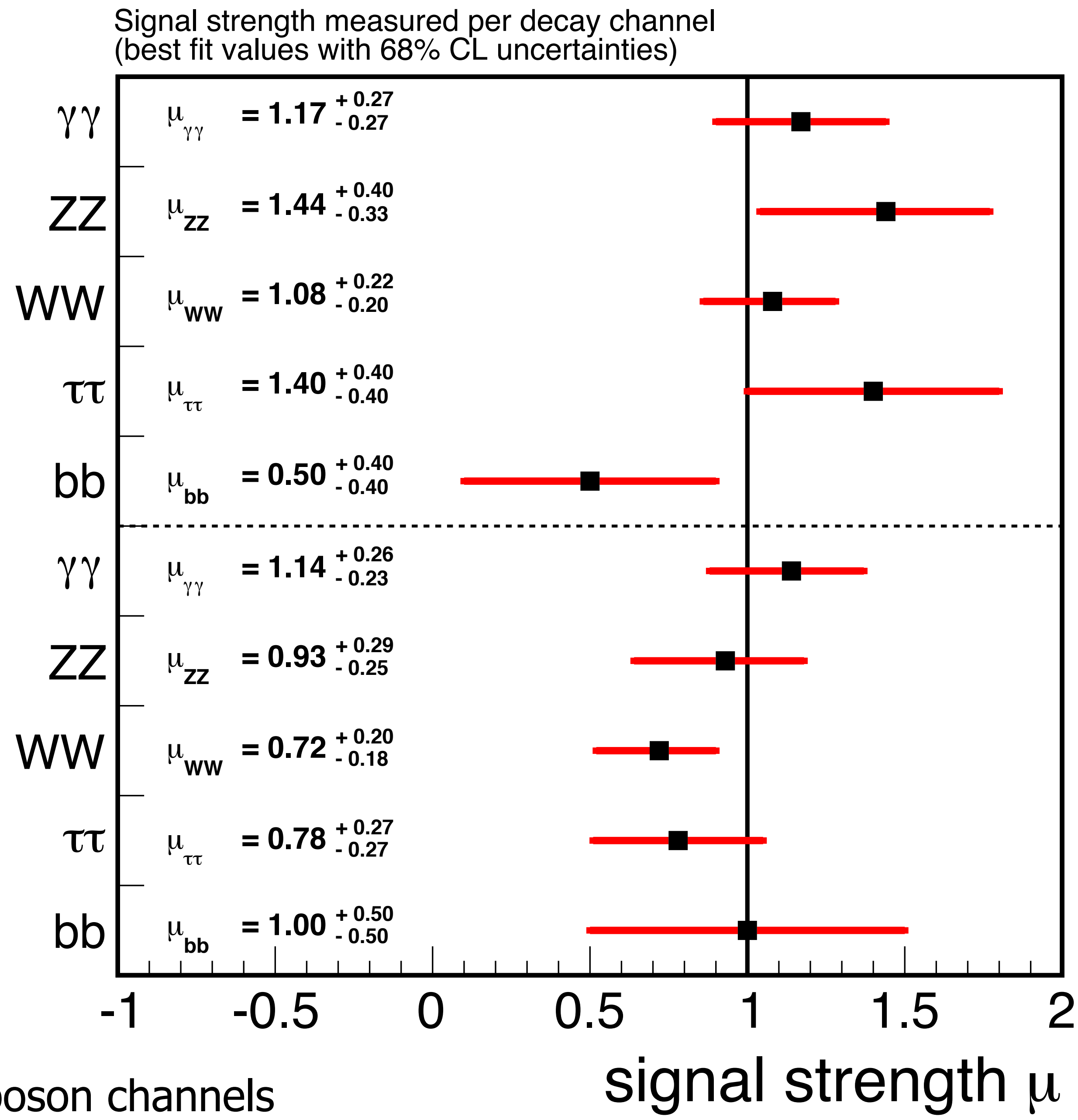
CMS, EPJ C74 (2014) 74:3076

CMS, PRD 89 (2014) 092007

CMS, JHEP01 (2014) 096

CMS, JHEP05 (2014) 104

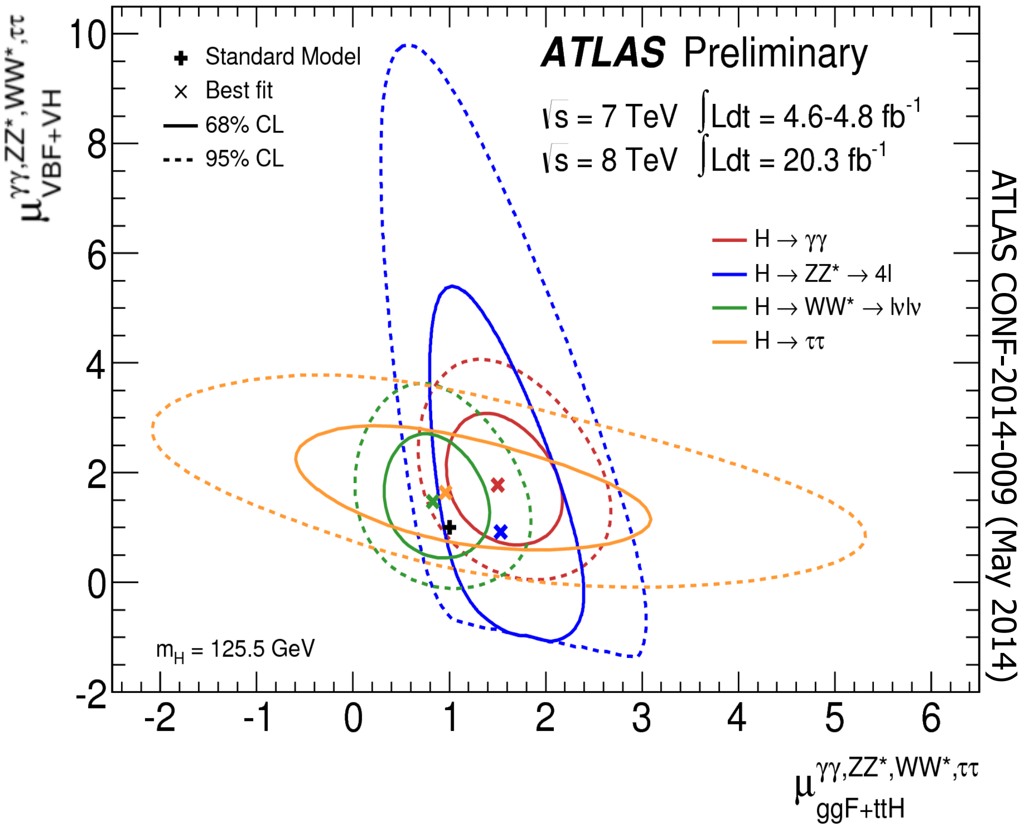
CMS, PRD 89 (2014) 012003

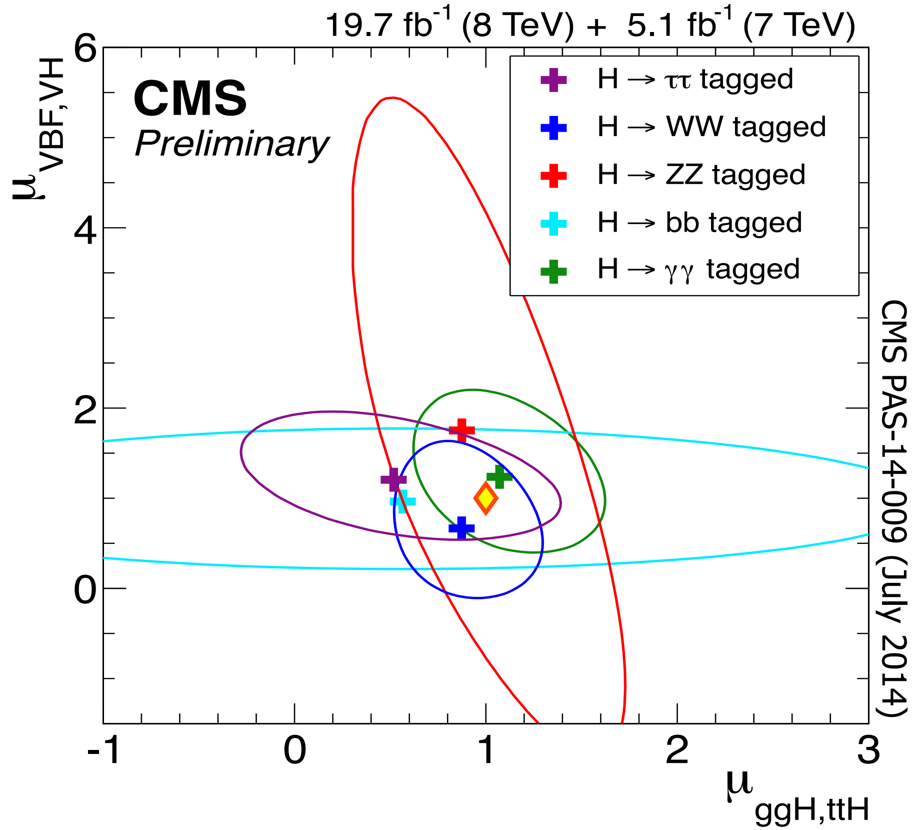


$\geq 5\,\sigma$ observation in di-boson channels

$\geq 3\,\sigma$ evidence in di-tau channel

Signal Rates / H Production modes





The ratio $\mu_{VBF+VH} / \mu_{ggH+ttH}$ is ~ independent of decay

ATLAS: $\mu_{VBF} / \mu_{ggH+ttH} = 1.4 \pm 0.3(stat.)^{+0.6}_{-0.4}(syst.)$ $\Leftrightarrow$ $\mu_{VH} / \mu_{ggH+ttH}$ profiled

CMS: $\mu_{VBF,VH} / \mu_{ggH,t\bar{t}H} = 1.25^{+0.63}_{-0.45}$

μ_{VBF} evidence established at ~4σ level

Note: ATLAS preliminary combination here does not included latest $H \to \gamma\gamma$ results

Setting H Coupling Constraints

- The production × decay are always sensitive at LO to a linear combination of products of two couplings ⇔ model assumptions required to disentangle

e.g. Prescription from HXSWG in arXiv:1209.0040

Consider a narrow width approximation $\sigma \times \beta_i = \dfrac{\sigma_i \times \Gamma_i}{\Gamma_H}$

Introduce SM modifiers for production $\kappa_i^2 = \dfrac{\sigma_i}{\sigma_i^{SM}}$ and decay $\kappa_j^2 = \dfrac{\Gamma_j}{\Gamma_j^{SM}}$

And $\kappa_H^2 = \dfrac{\sum \kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$

- Define benchmark scenarios:

  - Test custodial symmetry : $\lambda_{WZ} = \dfrac{\kappa_W}{\kappa_Z}$ (λ_{WZ} = 1 in SM)

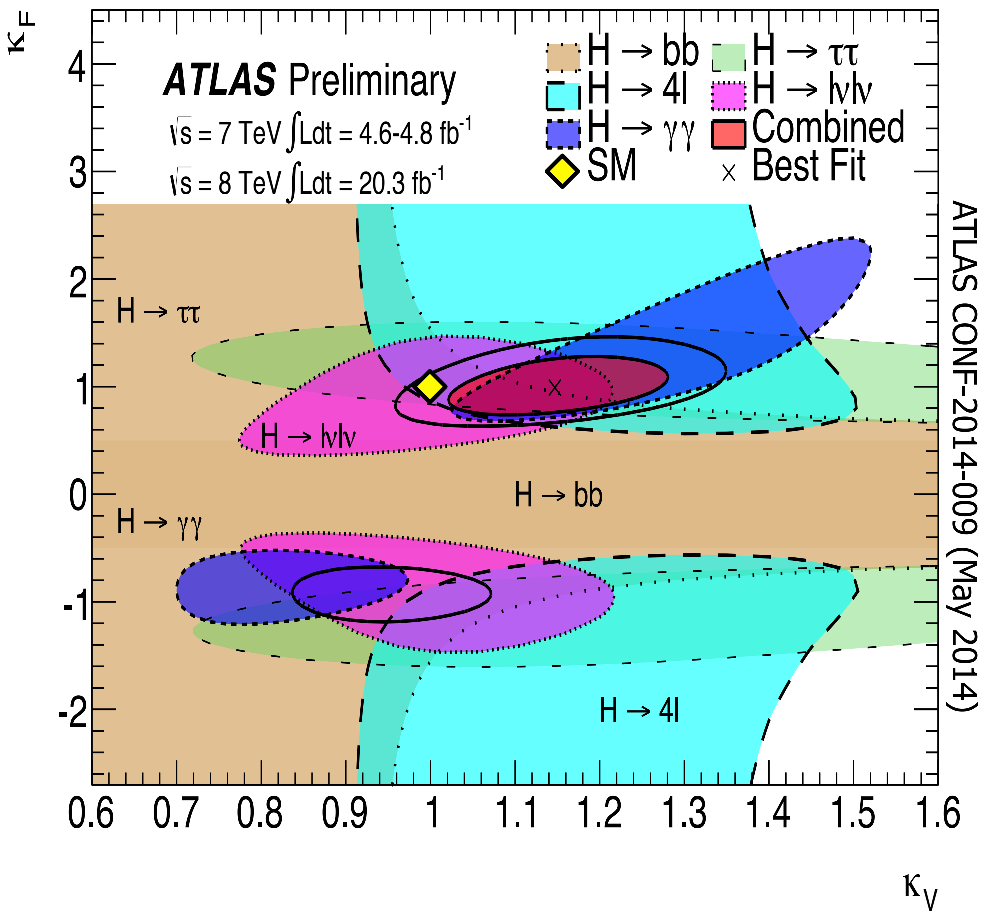
  - Test bosonic & fermionic couplings: consider $\kappa_V (= \kappa_W = \kappa_Z)$ & $\kappa_f (= \kappa_l = \kappa_q)$

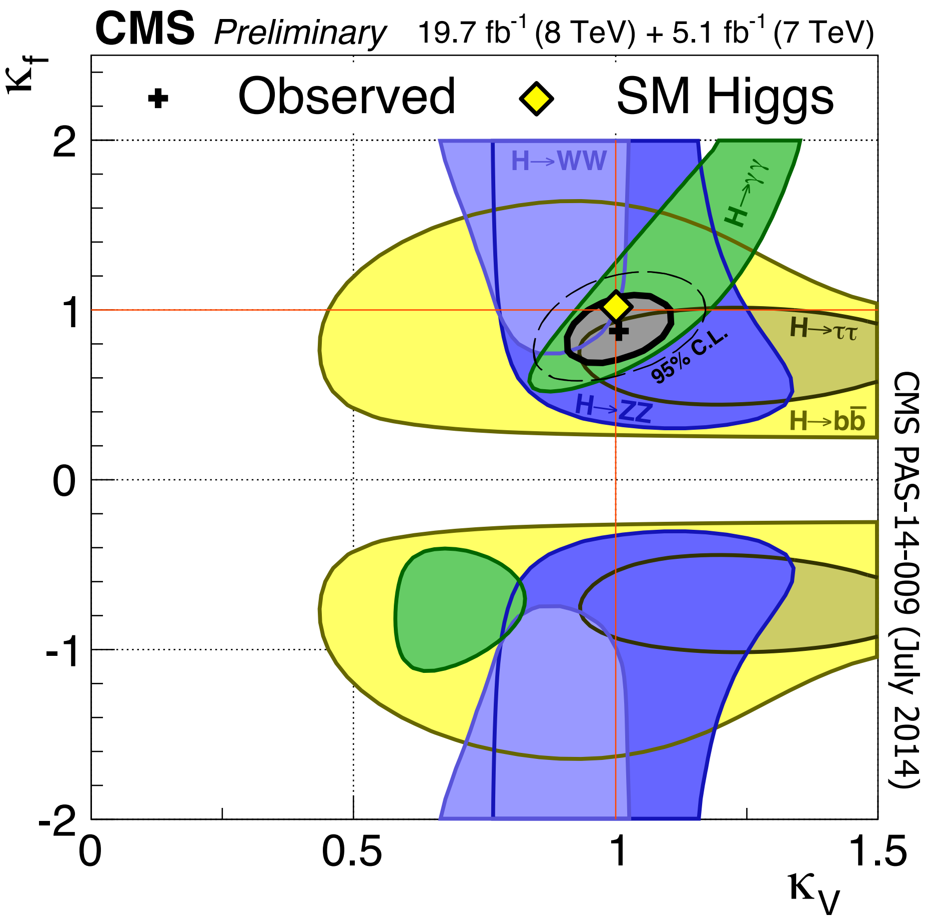
  - Assume either only SM particles in the loops,

    or

    "new physics" in width or loops (allowing or not invisible decay)

H Couplings to Fermions and Bosons



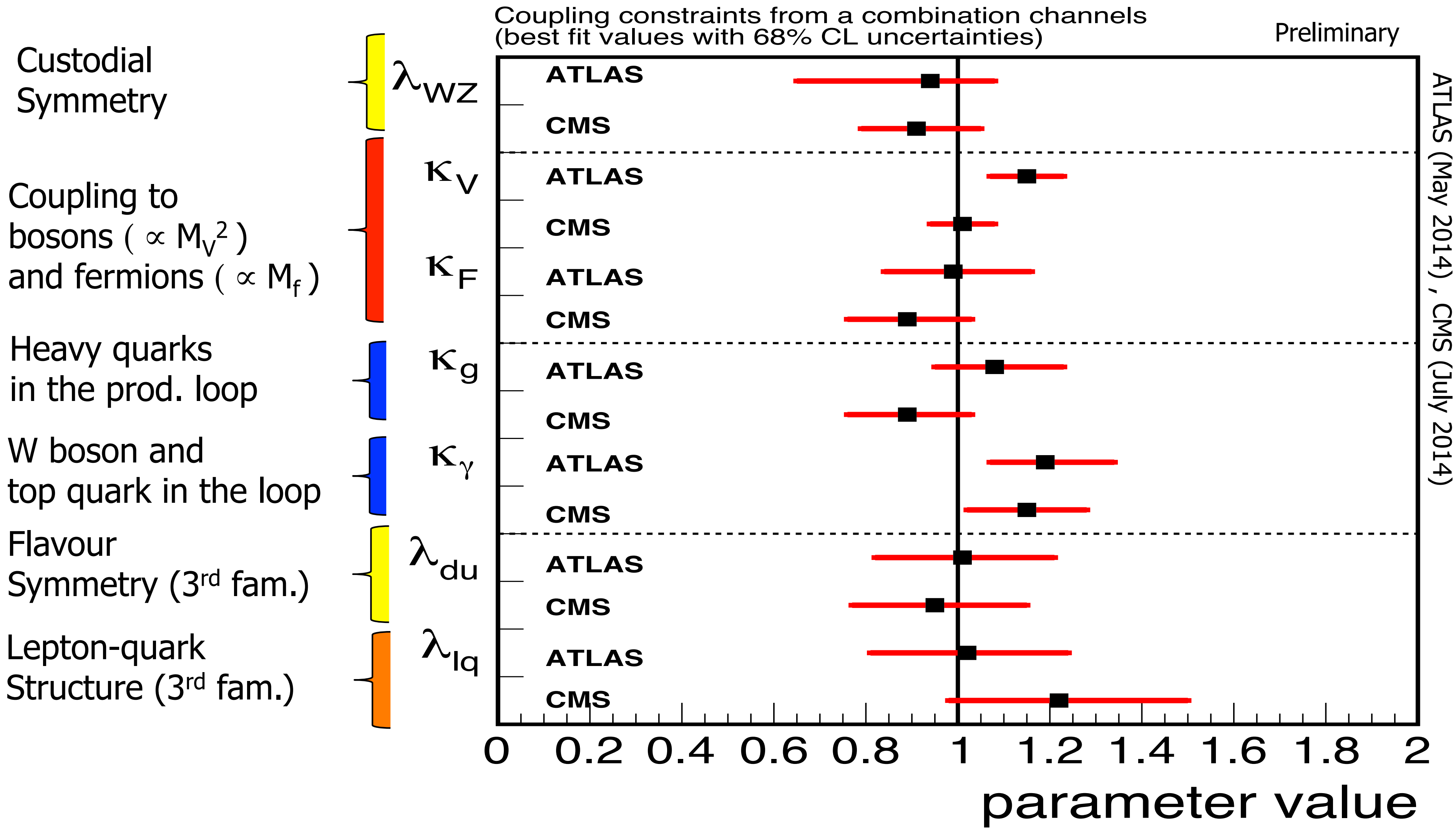


ATLAS: $(\kappa_V, \kappa_F) = (1.15^{+0.08}_{-0.08}, 0.99^{+0.17}_{-0.15})$

CMS: $(\kappa_V, \kappa_F) = (1.01^{+0.07}_{-0.07}, 0.89^{+0.14}_{-0.13})$

The $(\kappa_V, \kappa_F) = (1.0, -1.0)$ is disfavoured at 2σ level by ATLAS, and 3σ level by CMS

Coupling Constraints



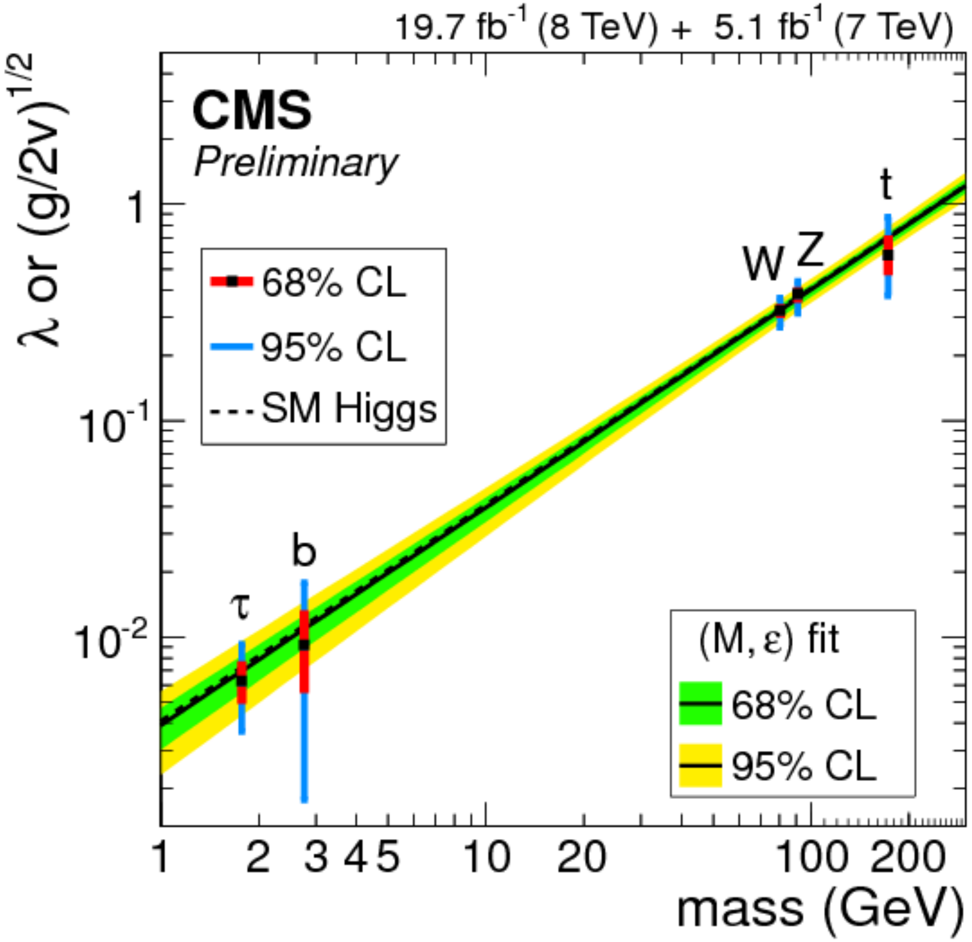
All combination of couplings found consistent with SM H expectation at a precision from ~15% (λ_{WZ}, κ_V) to 20-30% (κ_F, λ_{du})

Les Séquelles

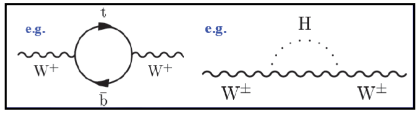
The Aftermath

The Landscape (1)

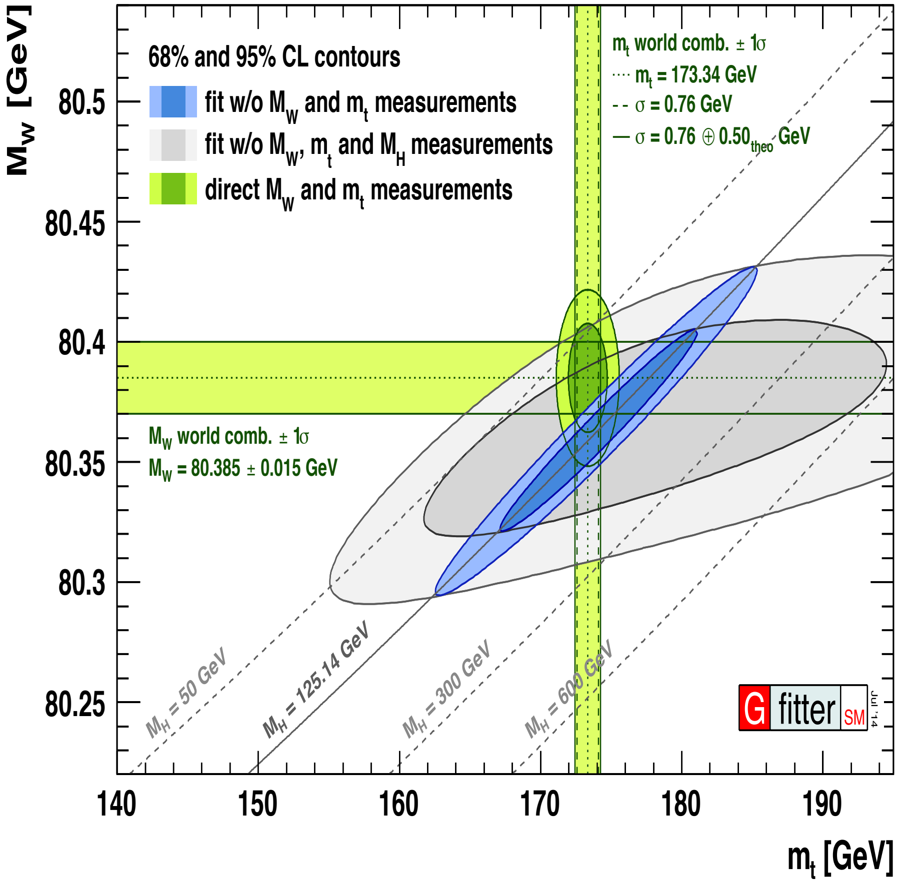
Couplings to fermions and to weak bosons
(verified to ~10-30% precision)



Rad. corrections:



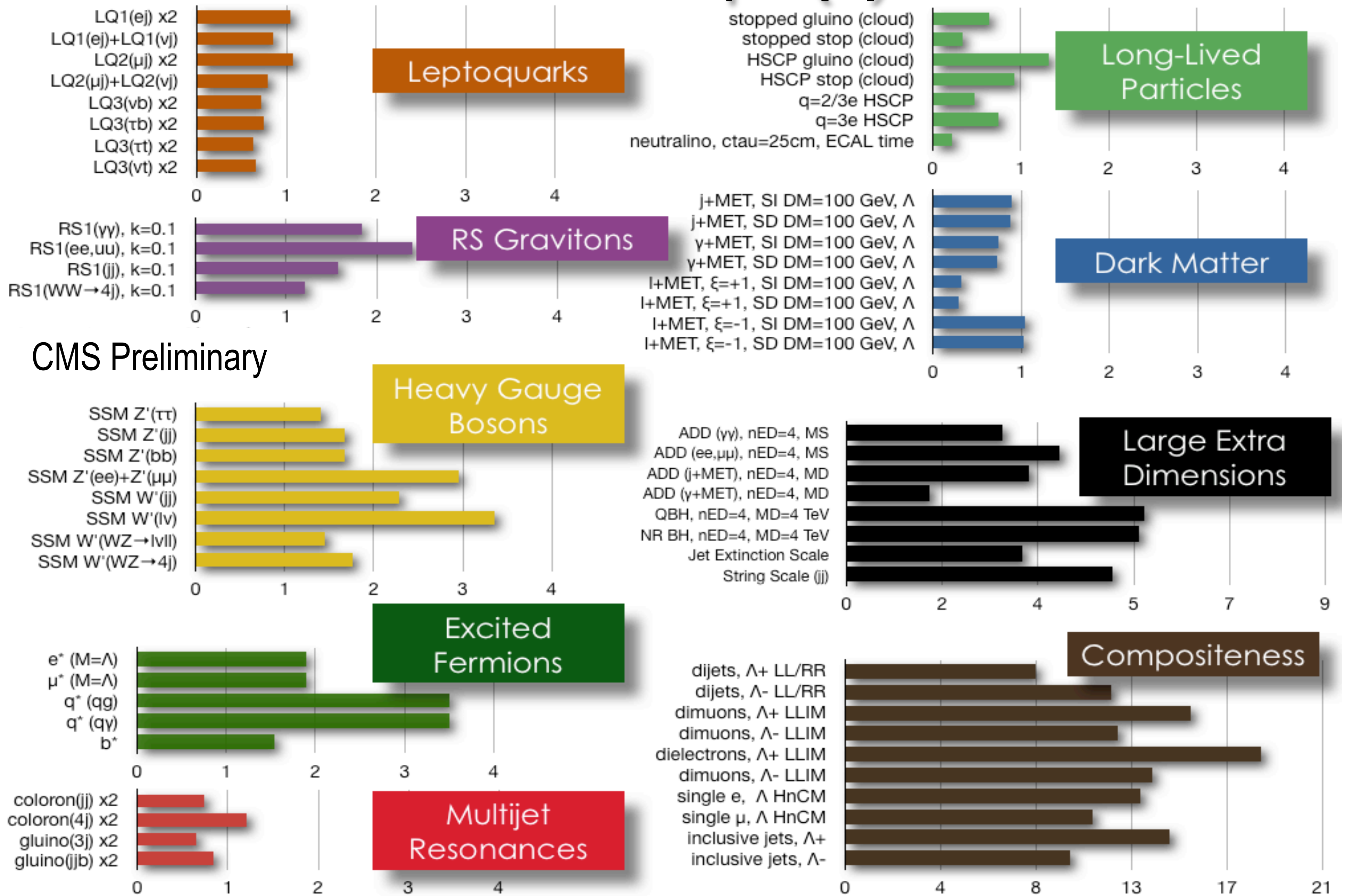
W, Z meas. sensitive to M_{top} M_H



- SM-like H at ~125 GeV is compatible with global EWK data at 1.3σ (p = 0.18)
- Indirect constraints now superior to some precise direct W, Z measurements

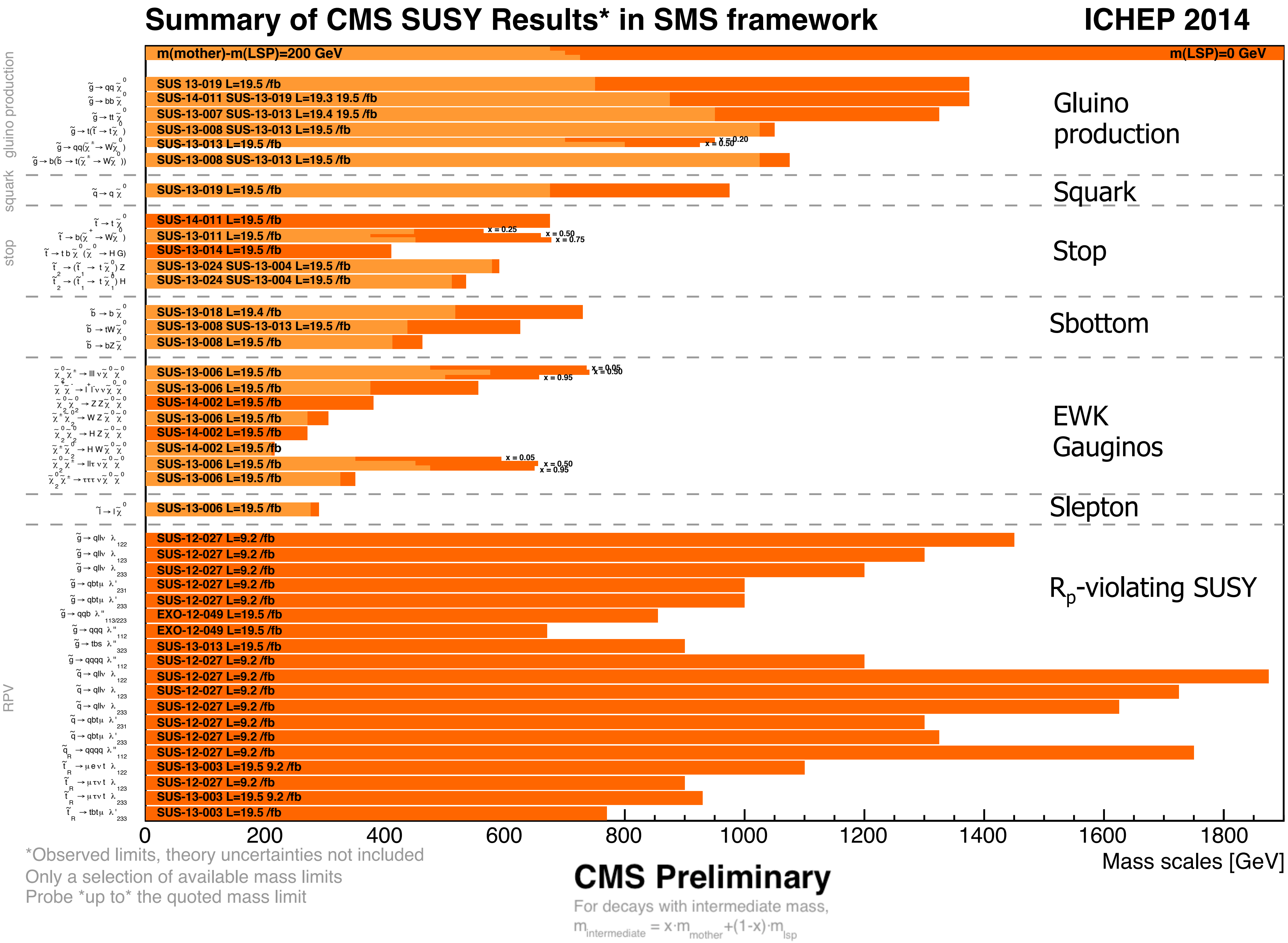
Indirect (EWK fit): $M_W = 80.359 \pm 0.011$
Direct (World average): $M_W = 80.385 \pm 0.015$

The Landscape (2)



CMS Exotica Physics Group Summary – ICHEP2014 95% CL Exclusion limits in TeV

The Landscape (3)



The H Boson discovery is now firmly established

- ✓ M_H ~ 125 GeV
- ✓ Couplings to fermions and to weak bosons (verified to ~10-30% 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

The Scalar Sector & the Malicious H Boson (1)

- The H boson is not a gauge boson
  (its mass is not protected by symmetries of the theory)

- Scalar fields "qualitatively" changes the nature of the vacuum

Cosmological problem:

Quantum fluctuations at Planck scale involves Planckian energies (space-time distorted)
→ contribute to a vacuum energy density disagreeing with our universe by 10^{120} orders
→ the principle of locality (a pillar of quantum field theory) breaks down at Planck scale !

Hierarchy problem:

Fine tuning by 10^{30} orders needed to cancel the scalar field coupling to quantum fluctuations of space-time at the Planck scale

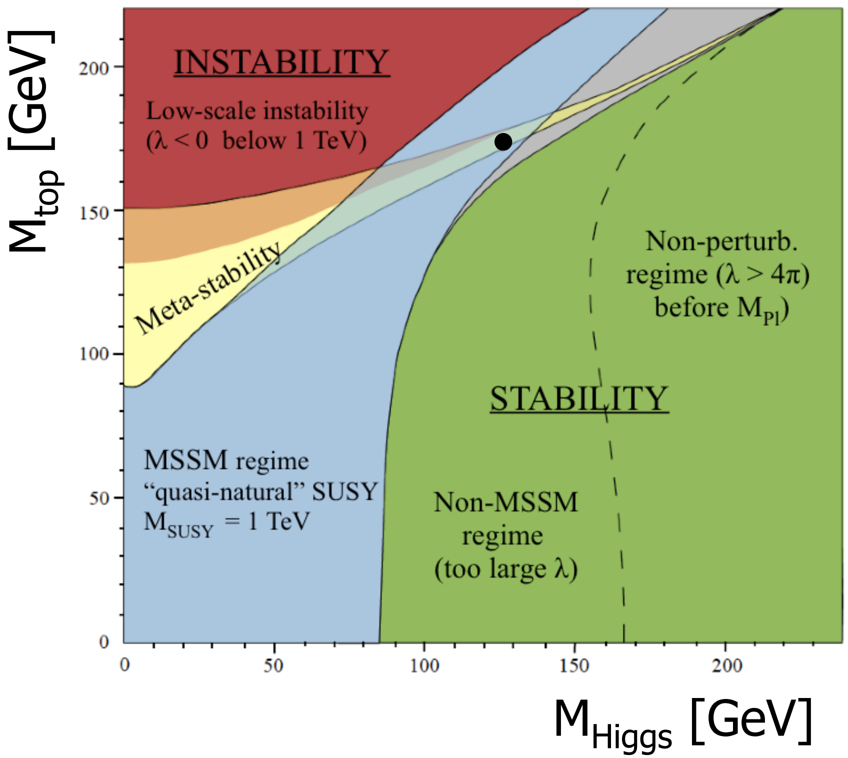
- The complexity of the Standard Model is encoded a scalar sector

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs\ (Symm.\ Break.)}}(\phi, A_a, \psi_i)$$

Natural
verified with high precision; stable with respect to quantum corrections; highly symmetric
(gauge and flavour symmetries)

Ad hoc
but necessary (other mass terms forbidden by EWK gauge symmetries); unstable with respect to quantum corrections; possibly at the origin of flavour structure and all other problems of the SM

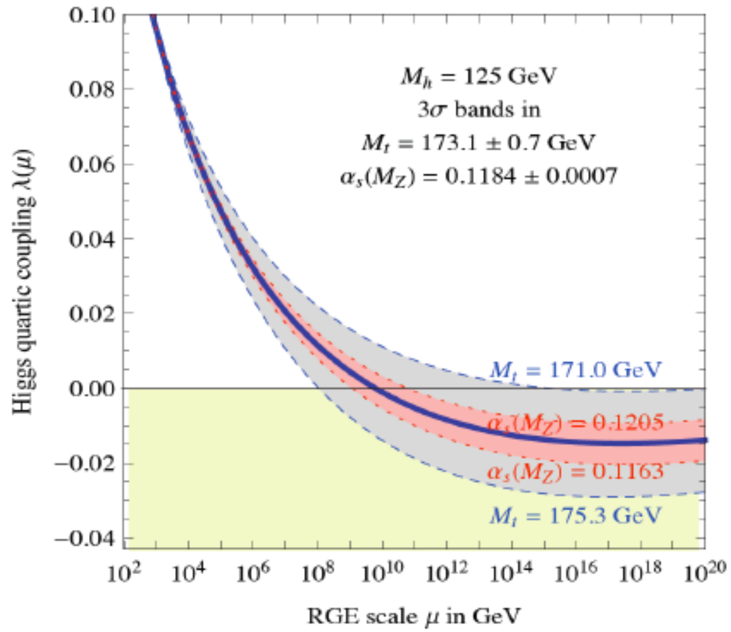
The Scalar Sector & the Malicious H Boson (2)

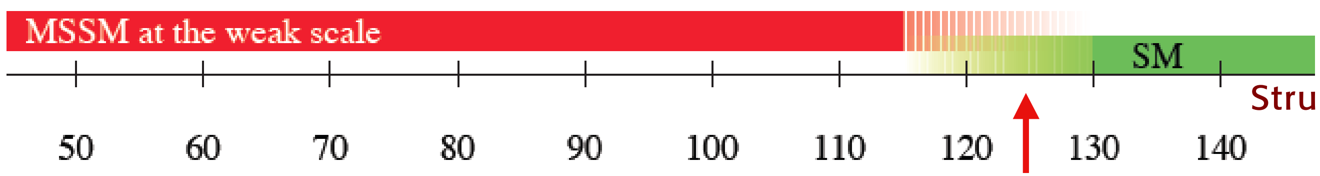


G. Isodori et al.

We live in a very particular corner of parameter space !

Assuming SM up to Planck scale, the fate of the Universe depends on the precise values of M_{top} and M_{Higgs} !





Strumia

The Higgs boson mass at ~ 125 GeV is very special !!! Extrapolation to very large scales seems possible but no indication provided for the scale for SUSY breaking

The Scalar Sector & the Malicious H Boson (3)

Most the "problems" with the SM remains, and new questions are raised !

The (many) "Exotic" models tested up to the ~ TeV scale, do not address many of the problems

Arbitrariness of the Higgs potential after EWSB

(arbitrary Higgs boson mass, of the self-coupling and sign of μ …)

Q? Can we avoid the arbitrariness ? By the gauge sector ? By the geometry ?

Q? Is the Higgs boson sufficient for an exact unitarization of the theory ($W_L W_L$ scattering) ?

Origin of the flavour structure of the theory

(3 families of fermions, flavour mixing, matter-antimatter asymmetry in the Universe …)

Q? Is the scalar sector at the origin of fermion families ($H \to \mu\mu$, $H \to \tau\tau$)

Origin of the specific gauge symmetry / set of conserved charges

(cancelation of triangle anomalies, gauge unification ? etc.)

Q? Is the scalar sector talking to neutrinos ($\nu_L \leftrightarrow \nu_R$) ?

Hierarchy between EWK and the Planck scale (and GUT scale ?)

(metastability of the EWK vacuum, problem of quantum gravity etc.)

Q? Can the scalar sector destabilize the vacuum ? (m_{top}, m_H)

Q? Can we avoid the problem of Hierarchy with respect to Planck scale ?

Q? Scalar fields play a vital role in cosmology (inflation and reheating): could the H field (BEH mechanism) be a key ingredient of cosmology

Q? Could the scalar sector be a portal to Dark Matter ? Address baryogenesis ?

Conclusions

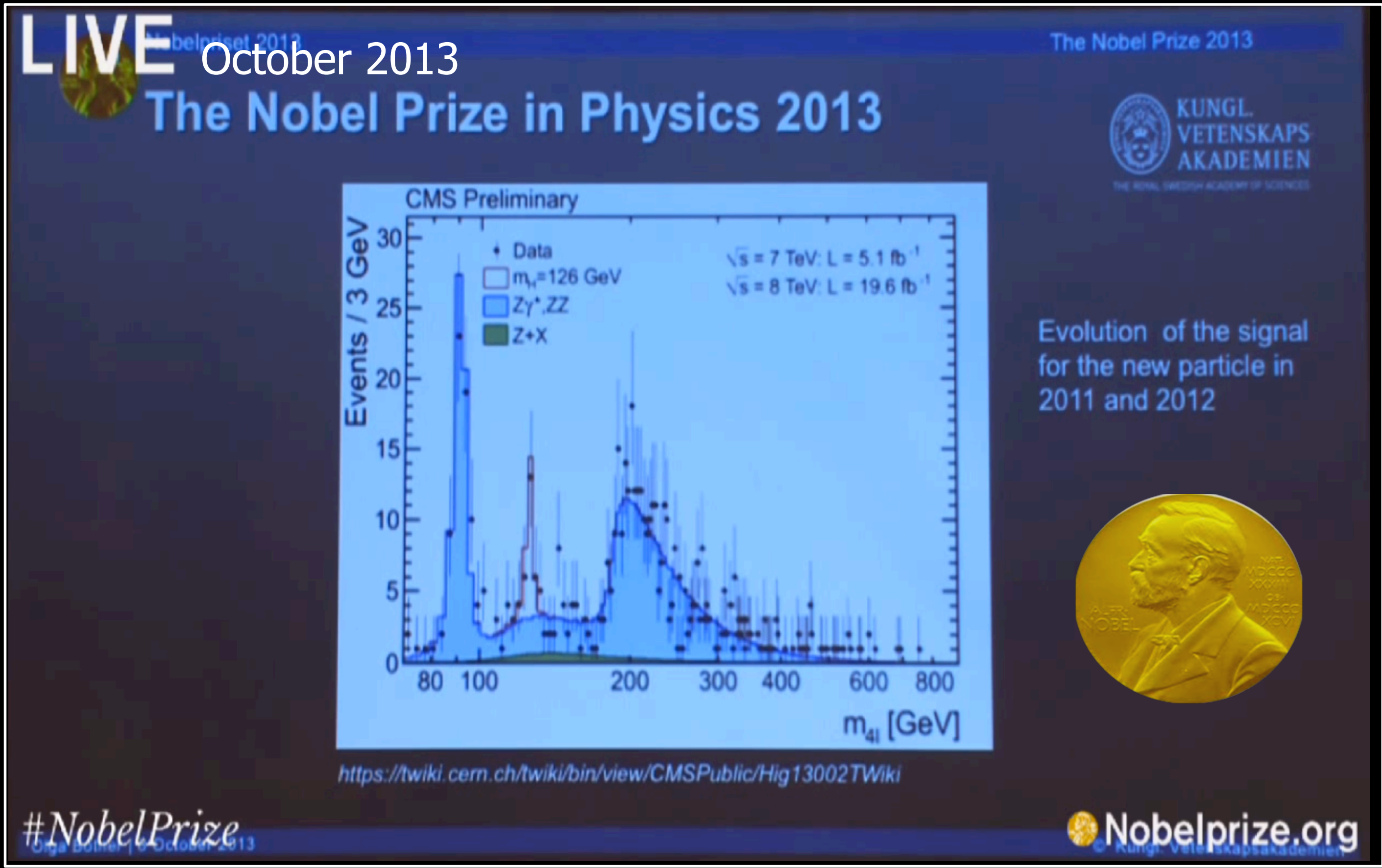
- The discovery of the H boson by ATLAS and CMS experiments at the LHC closes one chapter of a fantastic collective adventure … and opens up new avenues for the future…
- The boson discovered has properties so far consistent with the "H" scalar boson expected from the BEH mechanism (i.e. the minimal scalar sector incorporated in the SM)
- The precision reachable at the LHC or HL-LHC is possibly sufficient for the observation of deviations caused by possible extra structure or an extended scalar sector (talks this afternoon !)
- The capacity to establish additional new physics heavily depends on the progress in experimental and theory modeling of SM processes in the years to come (including extensive usage of V+jets, VV, and VVV production

CMS LHC/HL-LHC Specific Goals

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, …



F. Englert P. Higgs

"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"