Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

Higgs Boson Physics

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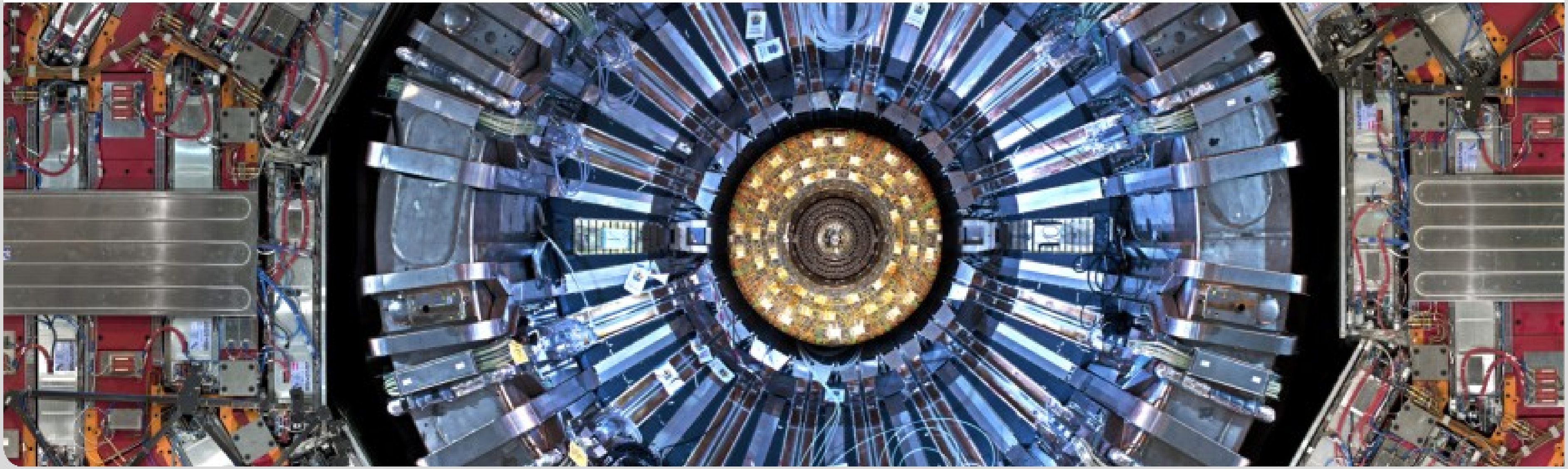
WS20/21



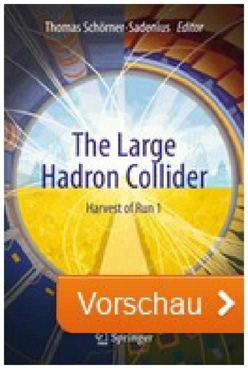
1. History
2. Basics principles
3. Detectors and Accelerators
4. Theoretical Foundations
   1. Relativistic Quantum Mechanics
   2. Quantum Field Theory and symmetries
   3. Elctroweak Symmetry and Higgs Mechanism
5. QCD and Jets
6. Analysis Chain
7. Flavour Physics
   1. Quark mixing and CKM Matrix
   2. Meson-Antimeson Mixing
   3. CP Violation

8. Tests of Electroweak Theory
   1. Discoveries
   2. Precision Physics with Z bosons
   3. W Boson and electroweak fit

9. Higgs Physics
   1. Historical searches
   2. Higgs Boson Discovery
   3. Latest results
   3. Future Measurements and Experiments

Literature (4)

Review of results from RUN 1 (2010- 2012) of the LHC:



© 2015

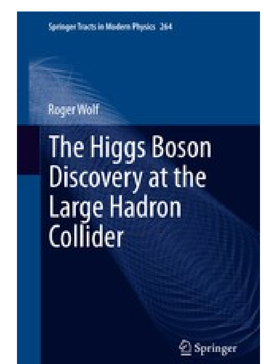
The Large Hadron Collider   Springer (2015)

Harvest of Run 1

Herausgeber: **Schörner-Sadenius**, Thomas (Ed.)

This comprehensive volume summarizes and structures the multitude of results obtained at the LHC in its first running period and draws the grand picture of today's physics at a hadron collider. Topics covered are Standard Model measurements, Higgs and top-quark physics, flavour physics, heavy-ion physics, and searches for supersymmetry and other extensions of the Standard Model. Emphasis is placed on overview and presentation of the lessons learned. Chapters on detectors and the LHC machine and a thorough outlook into the future complement the book. The individual chapters are written by teams of expert authors working at the forefront of LHC research.

The Higgs Boson discovery at the large Hadron Collider
R. Wolf, Springer, 2015



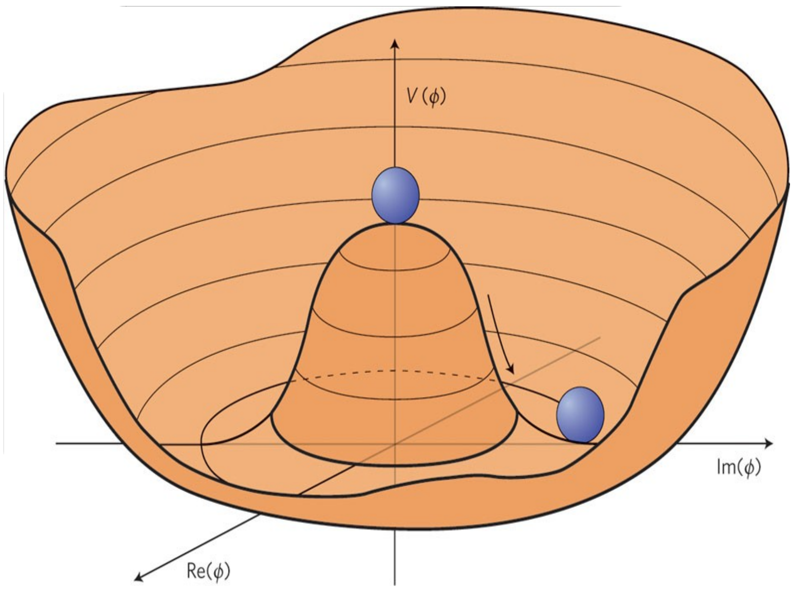
Reminder: Particle masses in the Standard Model

- Standard model based on "local gauge invariance"
  Electrodynamics can be deduced from this principle
  → model for weak and strong interactions
  simplified:
  electrodynamics: **one** electric charge
  weak interaction: **two** weak charges (weak isospin ↑↓)
  strong interaction: **three** (colour) charges (r g b)

Symmetry Group U(1) x SU(2)$_L$ x SU(3)

- Problem:
  Weak bosons have mass,
  which cannot be put „by hand"
  because gauge symmetry would
  be destroyed

theoretical solution: Introduction of a
scalar, (complex) field, with
ground state breaking gauge symmetry
„Higgs potential"

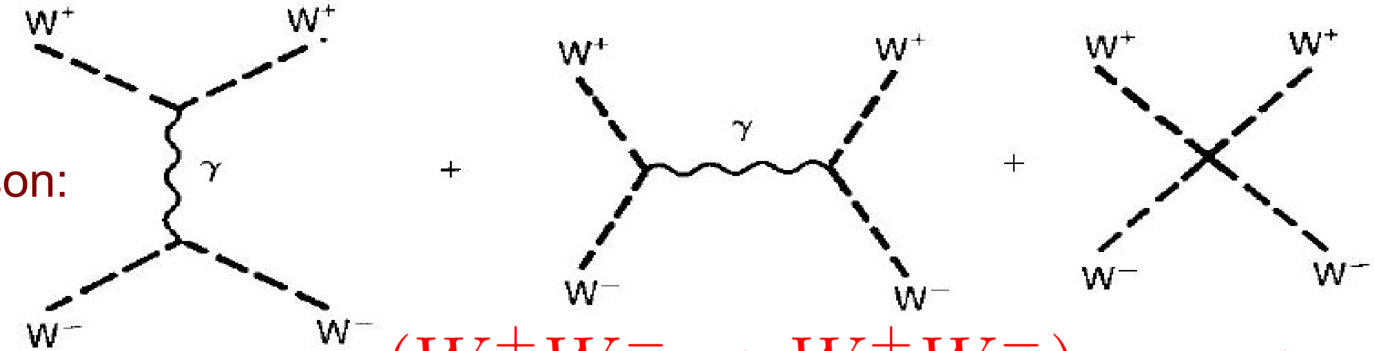


(see lecture 10)

Higgs in the Standard Model

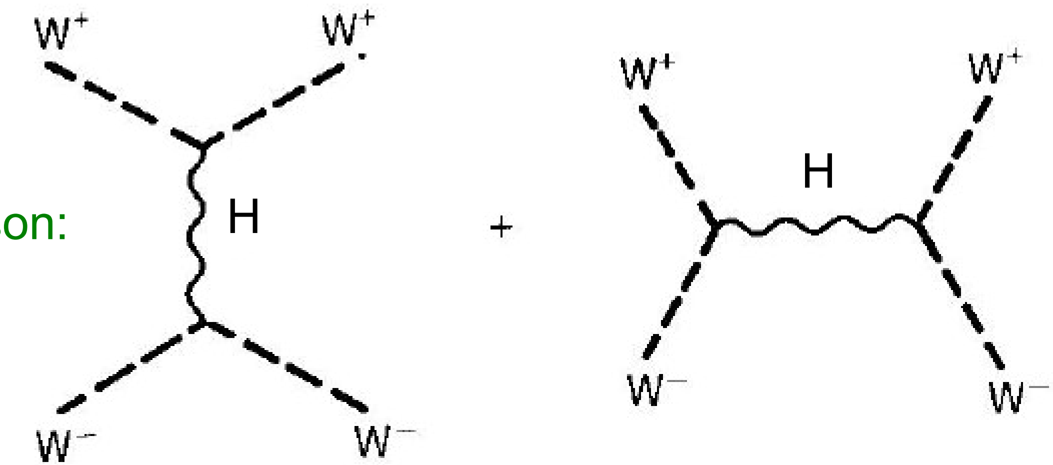
Higgs Boson prevents divergencies

without Higgs boson:



$$\sigma(W^+W^- \rightarrow W^+W^-) \propto s \rightarrow \infty$$

additional diagrams with Higgs boson:



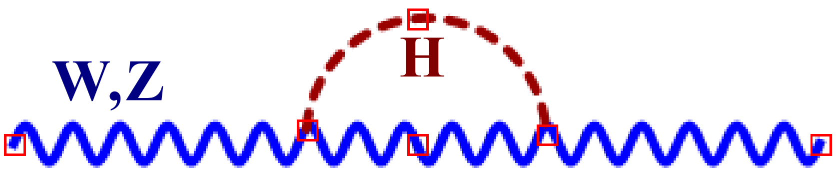
$\longrightarrow$ **Cross section of WW scattering remains finite**

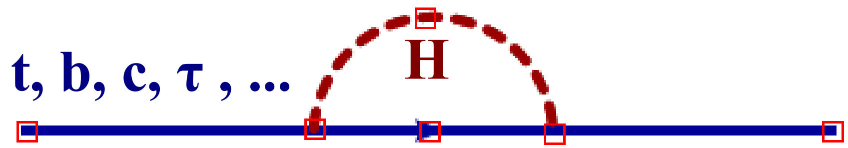
Higgs boson must not be too heavy: < ~1 TeV/c²

Higgs in the Standard Mode

Within the frame work of the Standard model,
we **know everything about the Higgs** boson **except its mass.**
In particular, all couplings to gauge bosons and fermions are fixed.

Via **loop diagrams**,





Higgs Boson influences all processes:

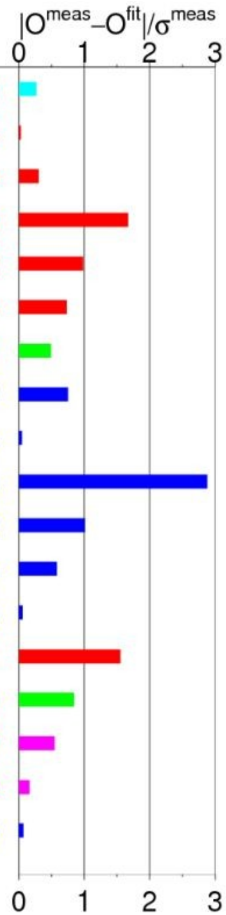
→ Observables depend on couplings, fermion masses and the Higgs mass :

$$\boxed{O = O(\alpha_{em}, G_F, M_Z, M_W, M_H, M_{\text{top}}, m_{\text{f}\,i}, V_{CKM})}$$

If everything else is known, **precision measurements provide information on Higgs mass**

Reminder: Precision Tests of the Theory

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



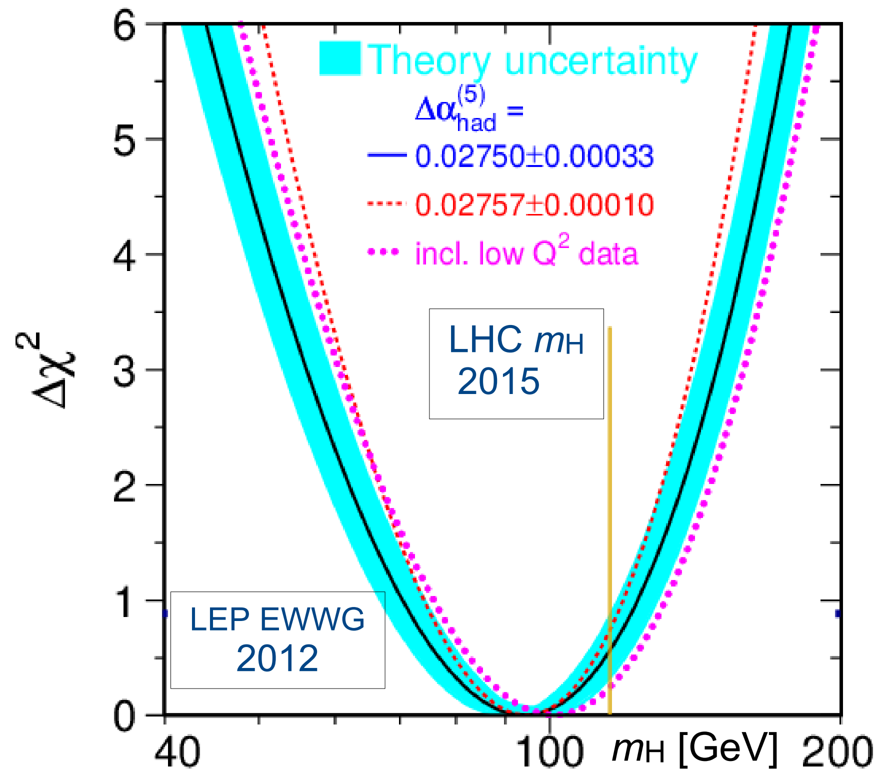
March 2012

χ^2/dof = 16.8/13, prb.= 21.0%

extremely successfully passed many ***precision tests*** *over the past decades at e^+e^- and hadron colliders*

last piece: the **Higgs Boson**

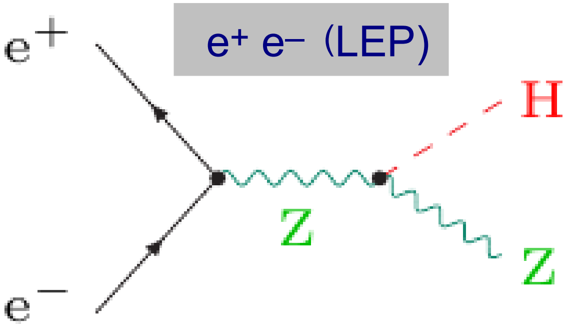
are **all consistent** with the Standard Model for a Higgs Boson Mass ~100 GeV



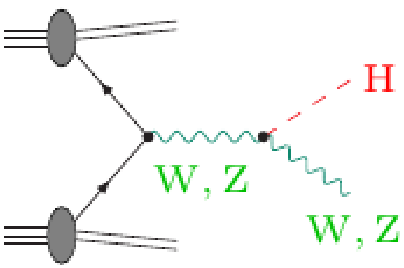
Direct Searches: LEP

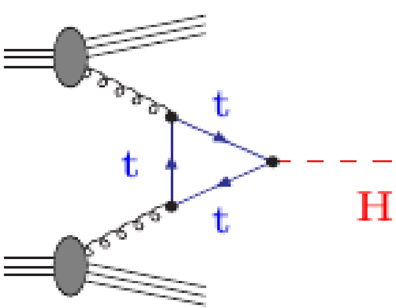
Higgs production mechanisms:

e⁺ e⁻ (LEP)



dominant in $p\bar{p}$ (Tevatron)





[last one is dominant in pp (LHC)]

Higgs decays to heaviest possible particles, depending on M_H:

– light Higgs: $b\bar{b}$, $t^{+\,-}$, $\gamma\gamma$

– medium mass Higgs: W^+W^-, ZZ

– heavy Higgs: $t\bar{t}$, W^+W^-, ZZ

signatures to look for !

unfortunate:
all of these processes possible in other ways, **without Higgs**

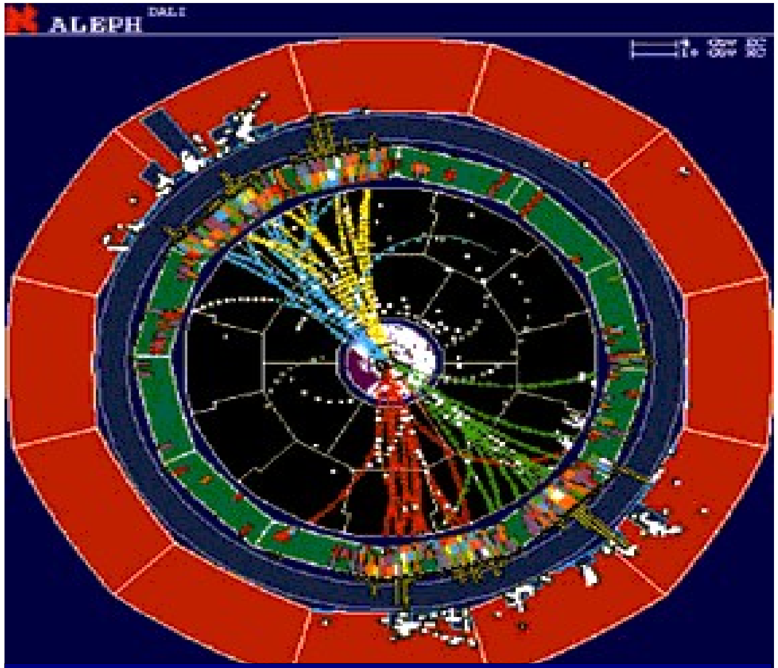
→ search for Higgs-like signatures on top of **large background** !

1990 – 2000: Direct Higgs Search @ LEP

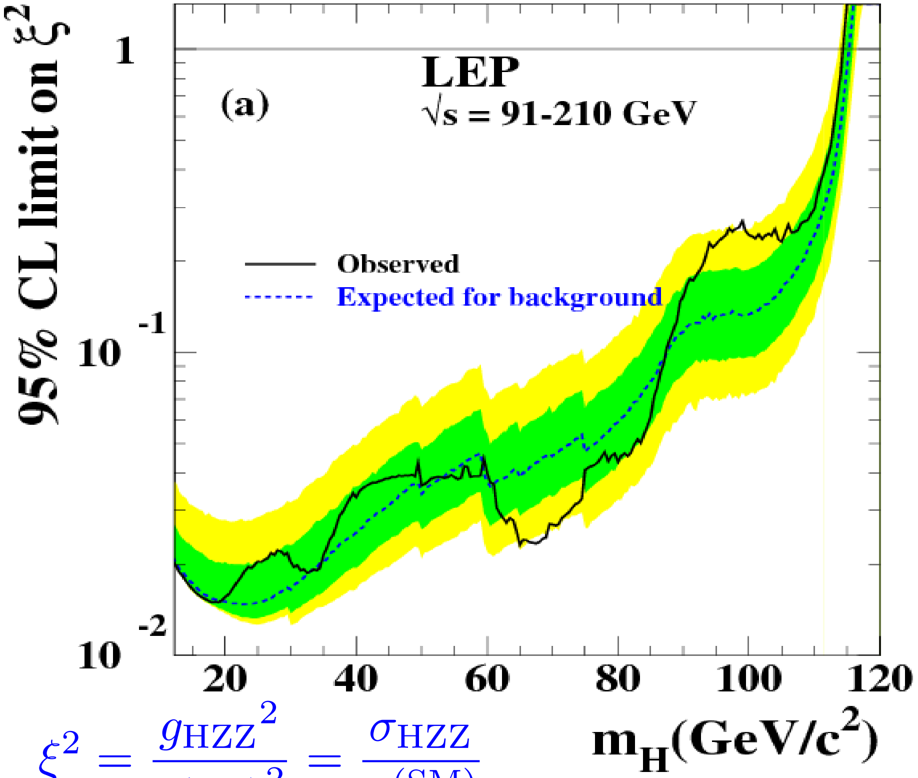
Channel: $e^+e^- \rightarrow ZH$, $H \rightarrow b\bar{b}$

Signatures:

$b\bar{b}q\bar{q}$	$(\sim 64\,\%)$
$H\nu\bar{\nu}$	$(\sim 20\,\%)$
$H\ell^+\ell^-$ (i.e. $e^+e^-, \mu^+\mu^-$)	$(\sim 7\,\%)$
$H\tau^+\tau^-, \tau^+\tau^- q\bar{q}$	$(\sim 9\,\%)$



Higgs Candidate @ LEP (ALPEH)
with 4 jets, 2 of them identified as b jets



$$\xi^2 = \frac{{g_{HZZ}}^2}{{g^{(SM)}_{HZZ}}^2} = \frac{\sigma_{HZZ}}{\sigma^{(SM)}_{HZZ}}$$

Exclusion

expected: $M_H > 115.3$ GeV/c^2

observed: $M_H > 114.4$ GeV/c^2

Aleph, Delphi, L3, OPAL, all LEP2 data, publ. 25/4/2003

Statistics: Hypothesis test

Choose Tests Statistic q_μ for Hyposesis test:

negative logarithm of profile likelihood ratio

(see lecture modern methods of data analysis for details)

- determination of p-values:

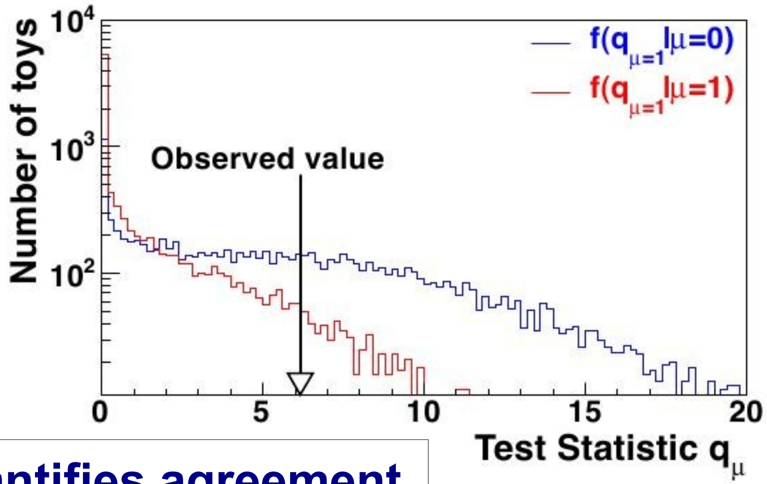
$$P_\mu = \mathrm{Prob}(q_\mu > q_\mu^{\mathrm{obs}} | \mu \cdot s + b)$$

$$P_0 = \mathrm{Prob}(q_\mu > q_\mu^{\mathrm{obs}} | b)$$

- calculation of a confidence level using "CL$_s$ method"

$$\mathrm{CL_s} = \frac{p_\mu}{p_0}$$

robust against downward fluctuations of background



CL$_s$ quantifies agreement with signal hypothesis

- For μ=1, CL$_s$ = α : a Higgs boson is excluded with confidence level (1- α)
  convention: α=0.05, exclusion at 95% CL
- usually: specify value of μ which is excluded at 95% CL

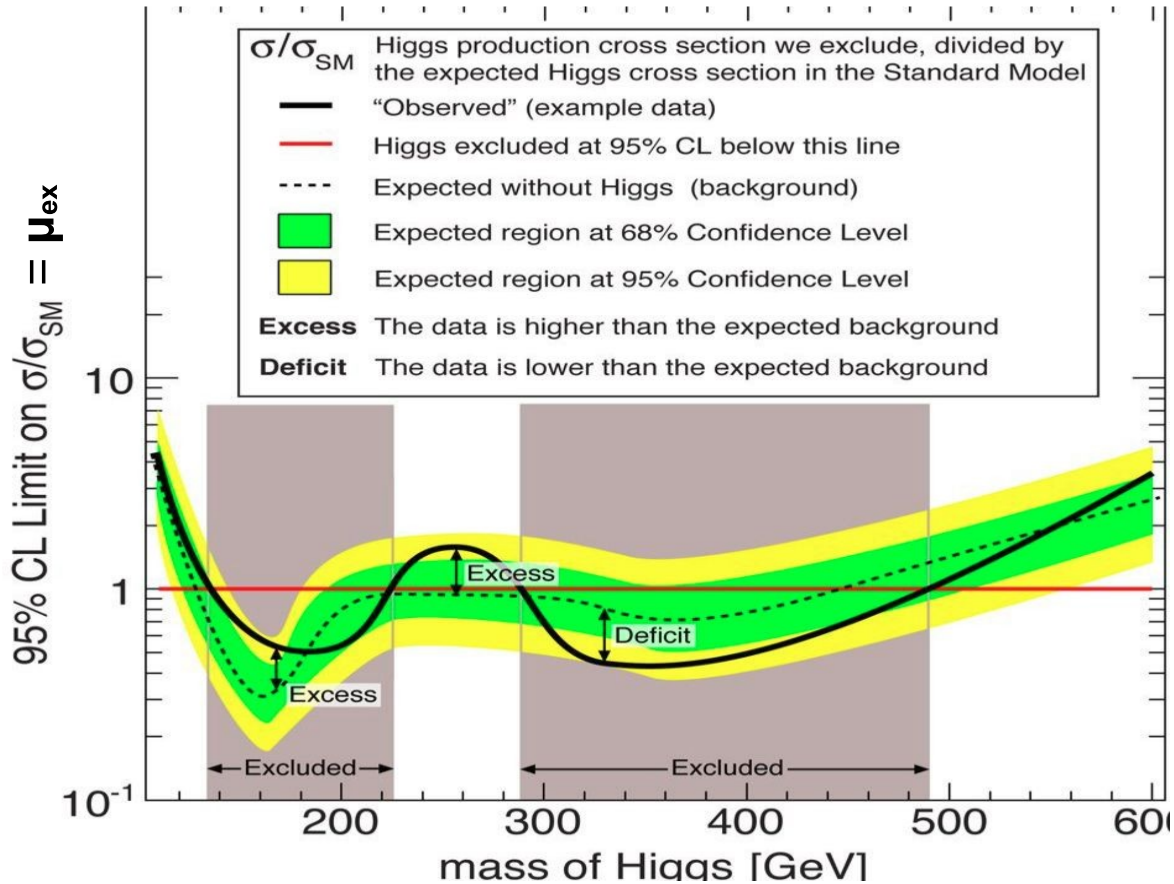
Then: run **pseudo experiments** to determine **expected limit**,
i. e. the median of the limit distribution (**dashed line**), and the regions for 68% („**1 σ**“, **green band**) and 95% („**2σ**“, **yellow band**)

(see figure below)

Statistics (2) : Exclusion plot

Graph of **signal strength μ_{ex} excluded @ 95% CL** for

- limit observed in data (**black line**)
- median and 68% / 95% regions of the expectation from pseudo experiments (dashed line and green resp. yellow band)



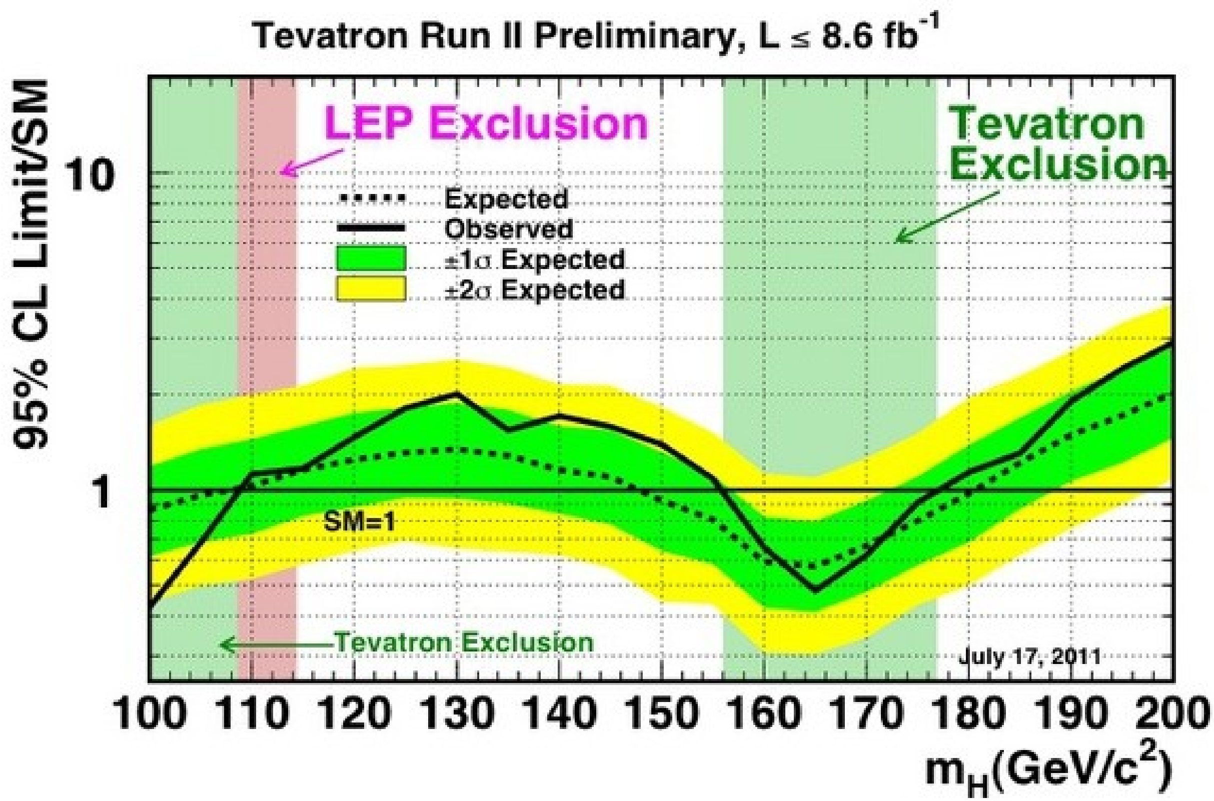
Higgs boson excluded for $\mu_{ex} < 1$

(below red line, vertical grey bands)

2000-2011: Higgs Search in $p\bar{p}$ Collisions @ Tevatron

dominant production channel: $p\bar{p} \rightarrow W, Z + H$ (gluon fusion & VBF taken into account)
dominant decays: $M_H < 135$ GeV/c²: $H \rightarrow b\bar{b}$ (also $\tau^+\tau^-$, gg)
$M_H > 135$ GeV/c²: $H \rightarrow W^+W^-$ (also ZZ)

⅔ data analysed up to Sept. 2011 (ca. 8.5 fb^{-1})



Exclusion expected: $148 < M_H < 180$ GeV/c²
observed: $156 < M_H < 177$ GeV/c² (**CDF** & **D0**, Sept. 2011)

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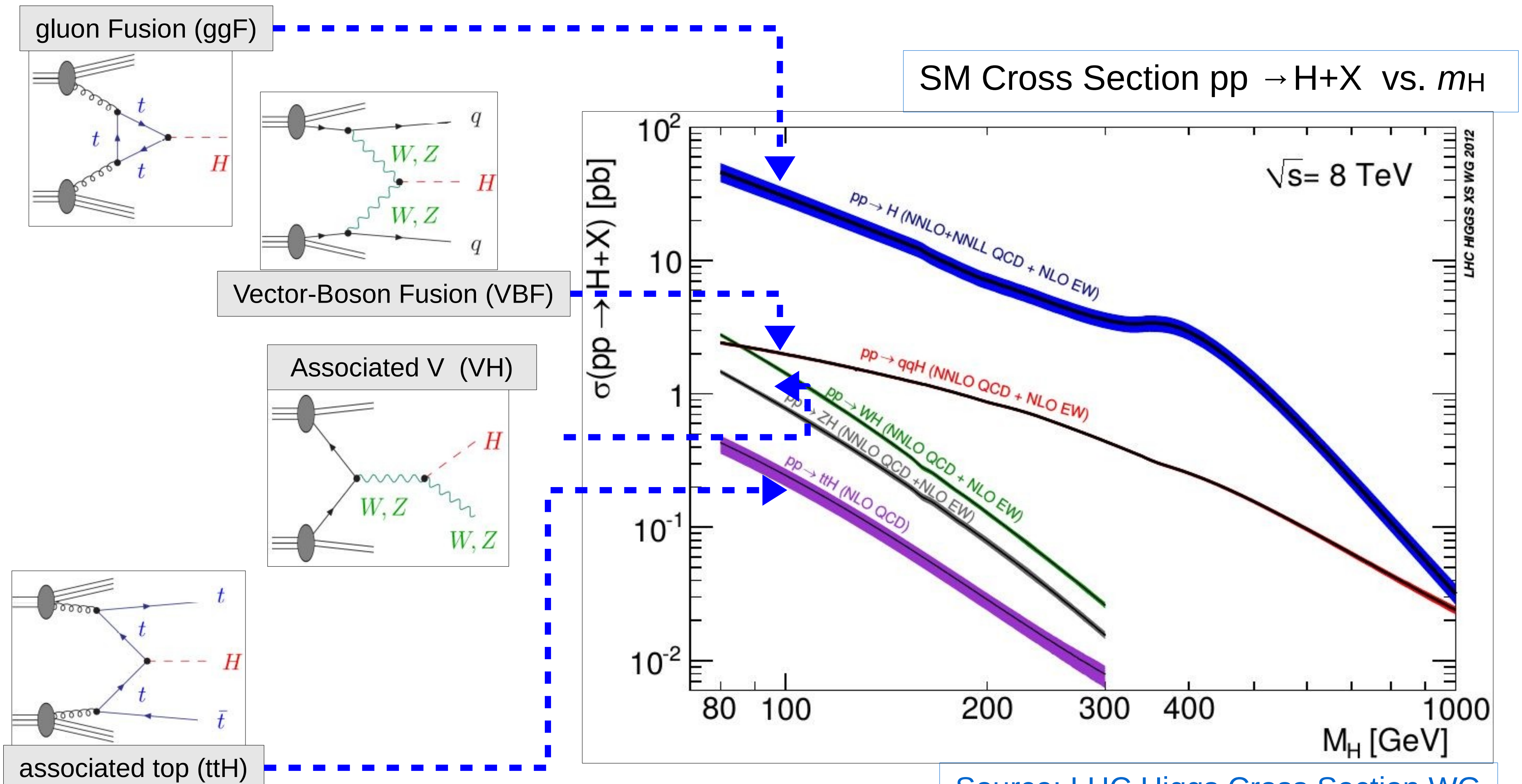
Higgs Production @ LHC

(SM) Higgs Boson Phenomenology @ LHC fixed if $\boldsymbol{m_H}$ is known

(main) production channels @ LHC:



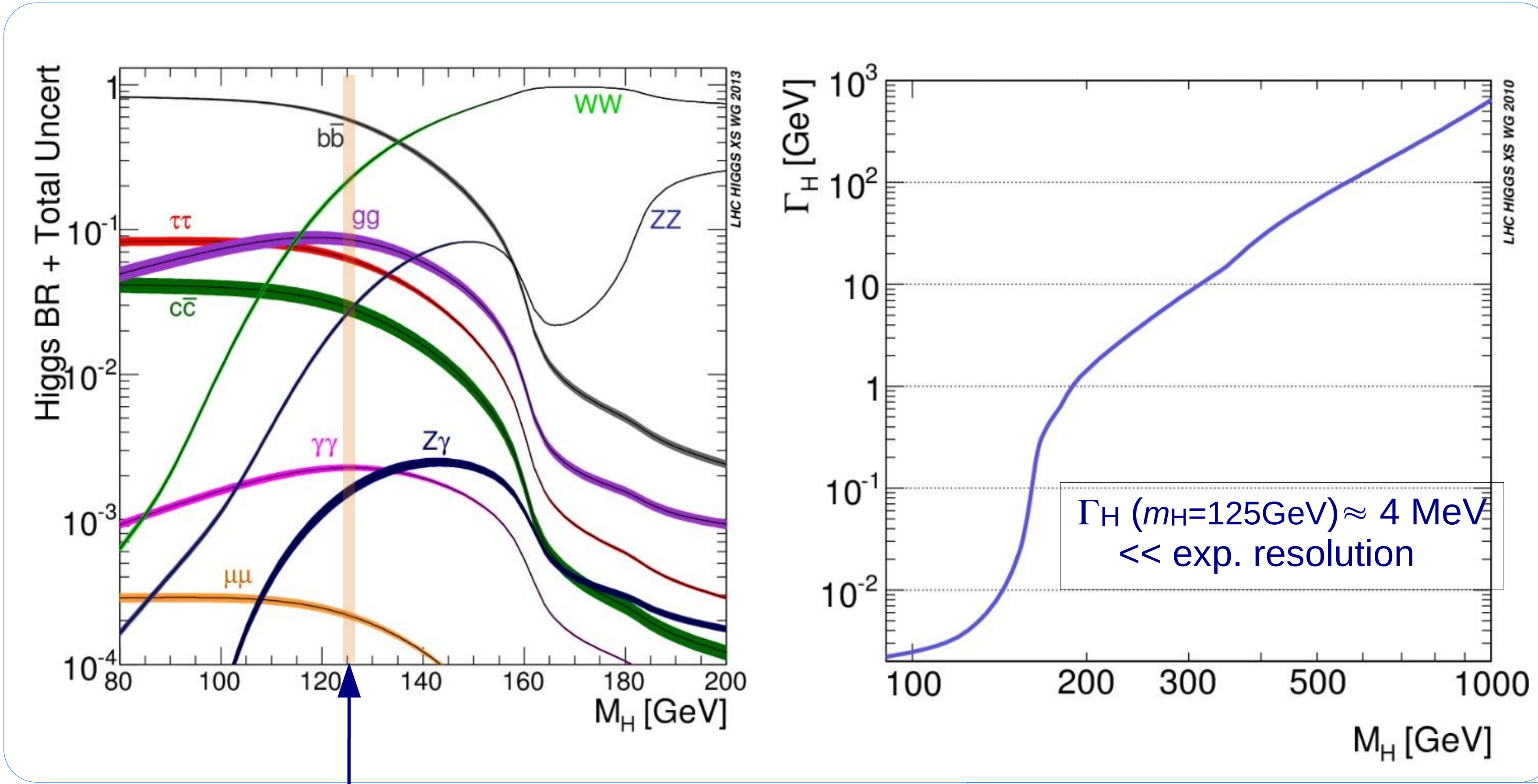
Source: LHC Higgs Cross Section WG

Higgs Decay Modes

Higgs Decay:

SM branching ratios and total width

uncertainties 2 - 5 % for most relevant decays



Source: LHC Higgs Cross Section WG

m_H = 125 GeV

Higgs-Boson Decays

cross section × branching ratio

determines number of events in detector

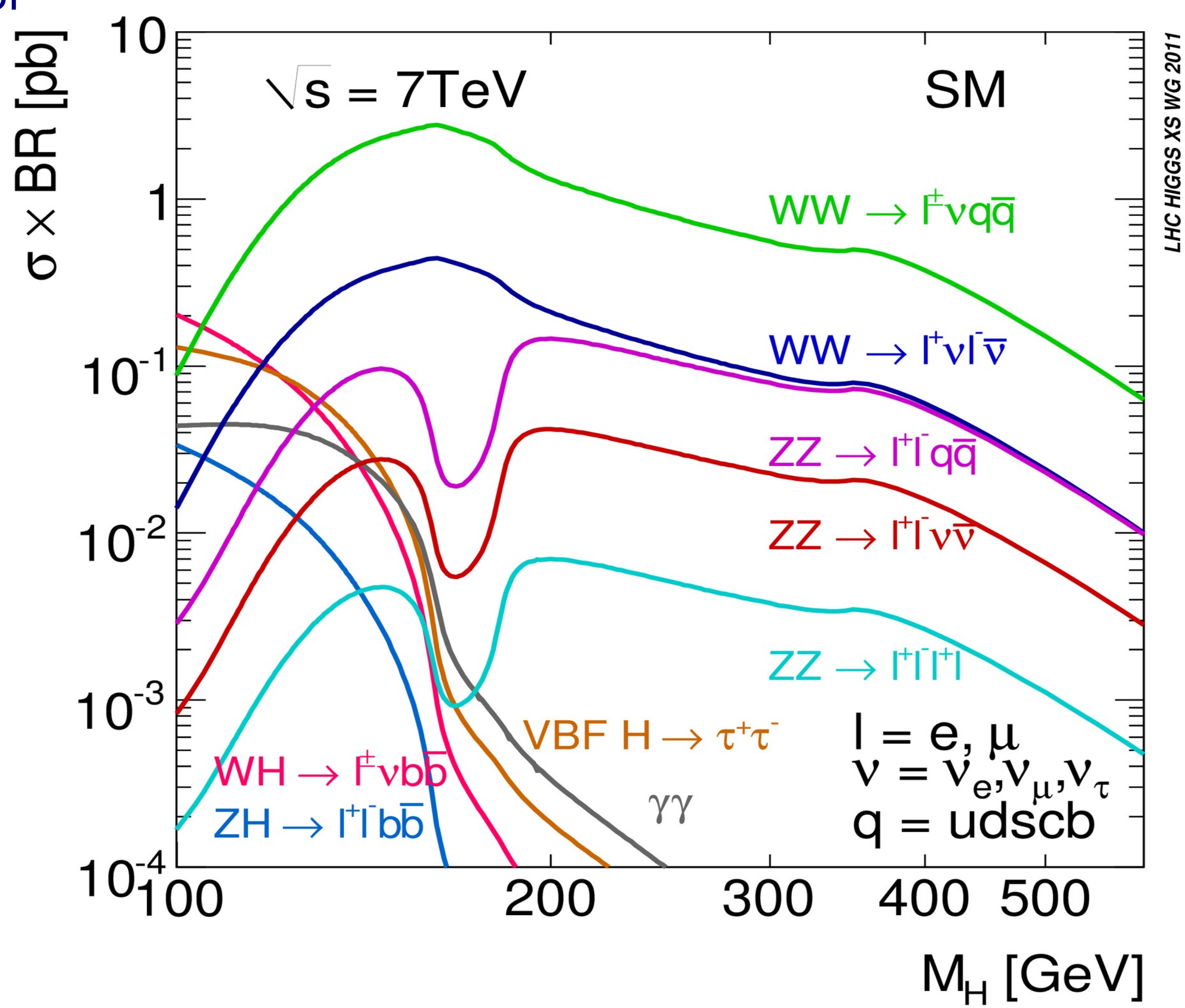
at high H masses:

- WW
- ZZ

at low H masses:

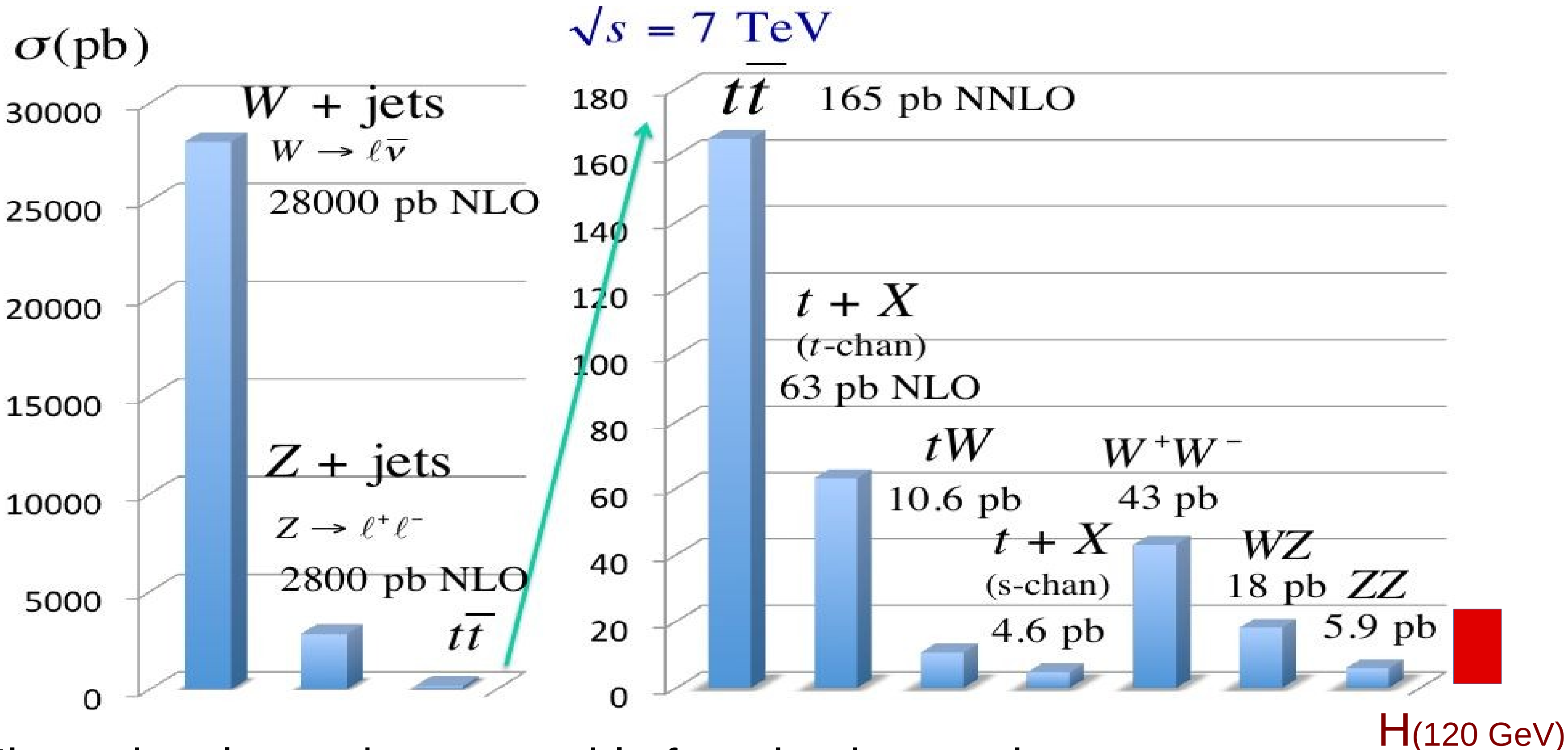
- bb (not shown)
- $\tau^+ \tau^-$
- $\gamma \gamma$

this is not all . . .



there is huge **Background**

Production rate of <u>other processes</u> is larger by many orders of magnitude



Higgs signal must be separable from background

→ **background changes importance of individual decay channels**

<u>statistical significance</u> also plays a role:

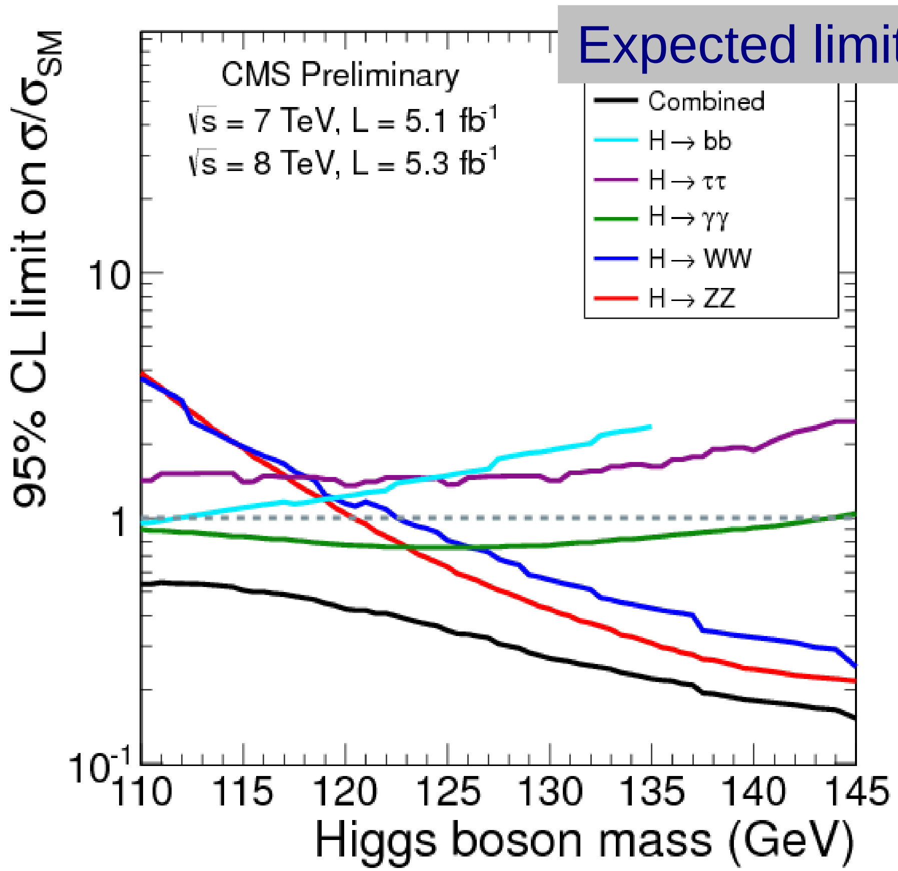
higher experimental resolution of a Higgs signal lead to higher significance

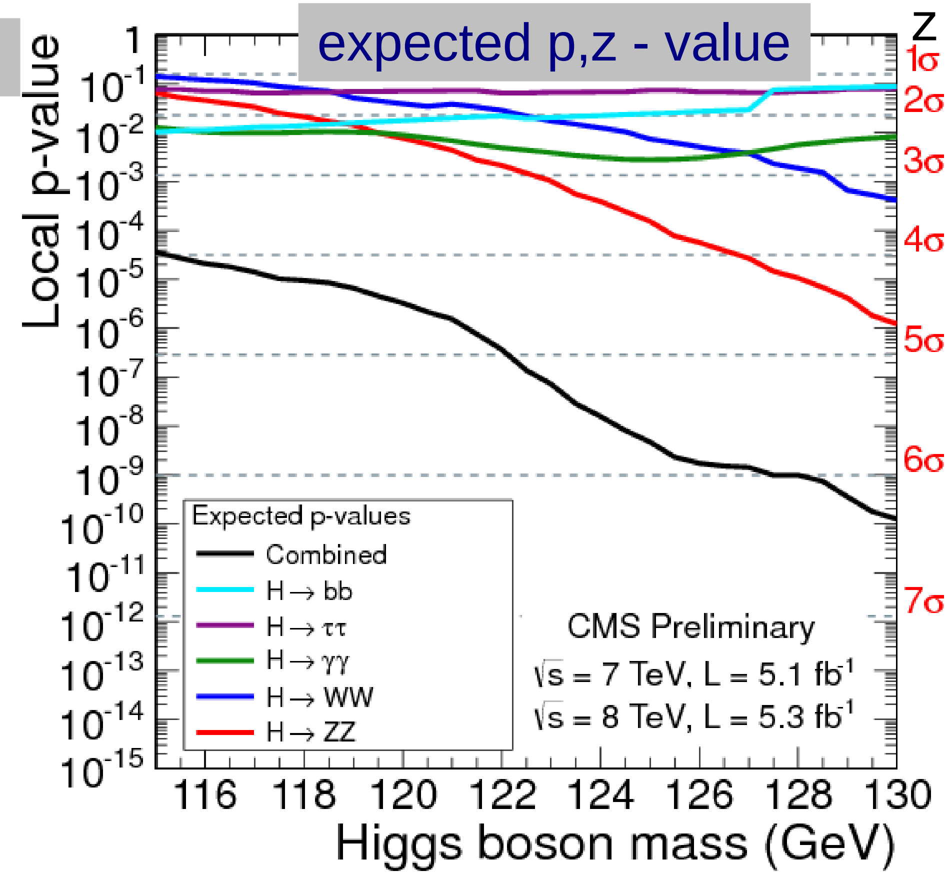
→ **disfavours signatures with jets and / or missing energy**

Higgs Signatures in Detector

- event selection in trigger and analysis
- separation of Higgs events from background

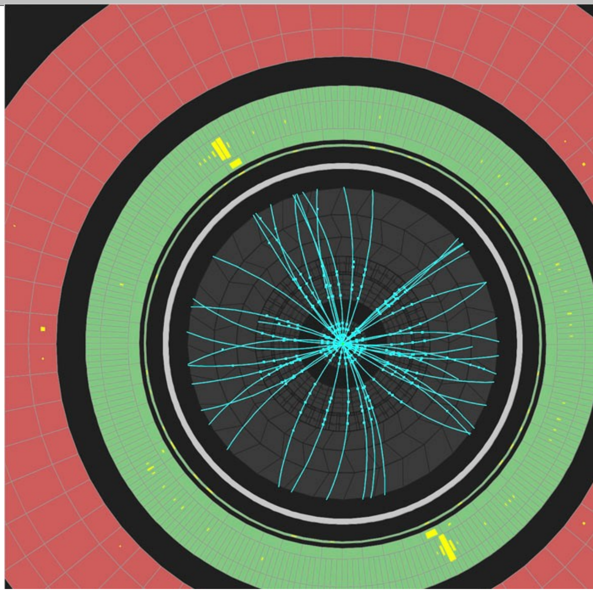
change relative importance of decay channels :





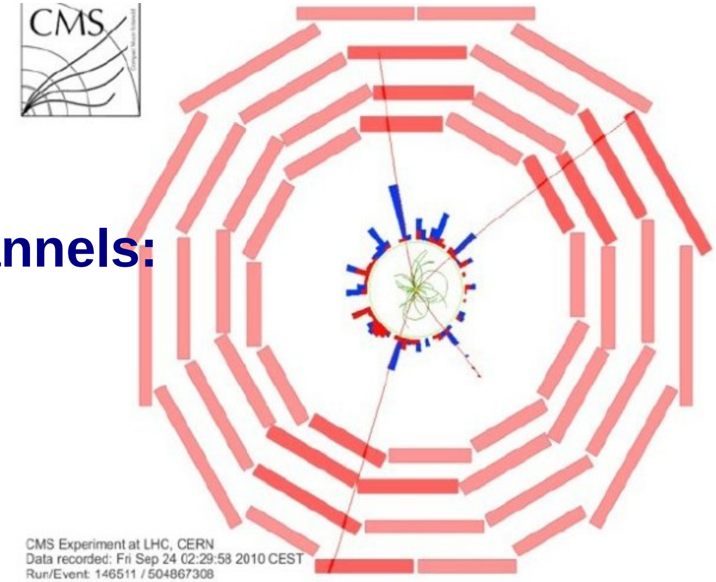
- high and medium range mass: **H → ZZ, H → WW**
- low mass region: **H →γγ gg H→ττ tt , H → b$\bar{b}$**

Higgs candidate events 2010/11



most sensitive channels:

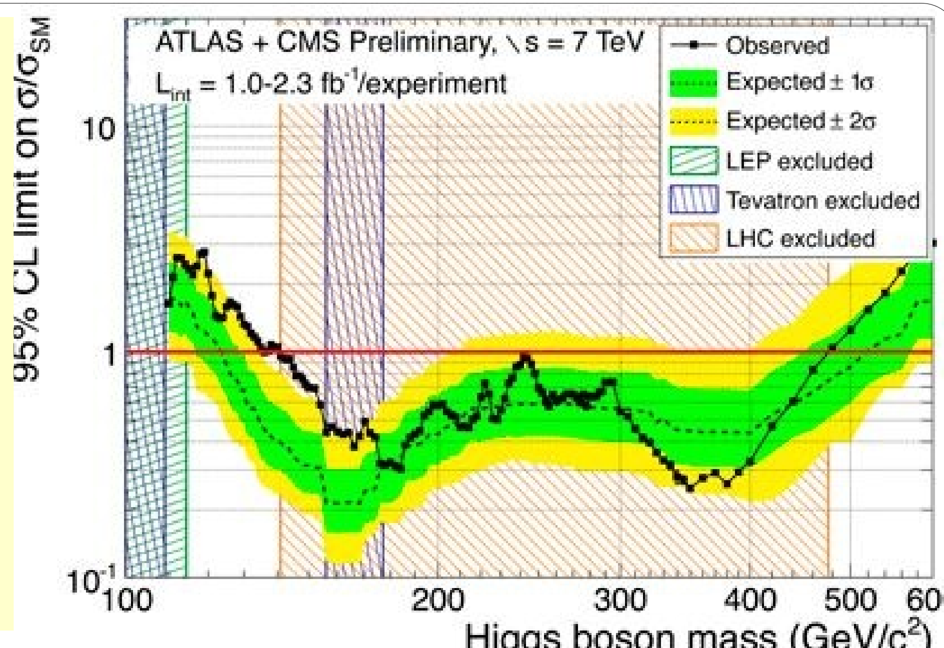
H → ZZ
H → γγ
H → WW



Exclusion Autumn 2011 (95% CL):

ATLAS:
expected: 125 – 520 GeV/c^2
observed: 113–115.5, 131–453 GeV/c^2

CMS:
expected: 117 – 543 GeV/c^2
observed: 127 – 600 GeV/c^2

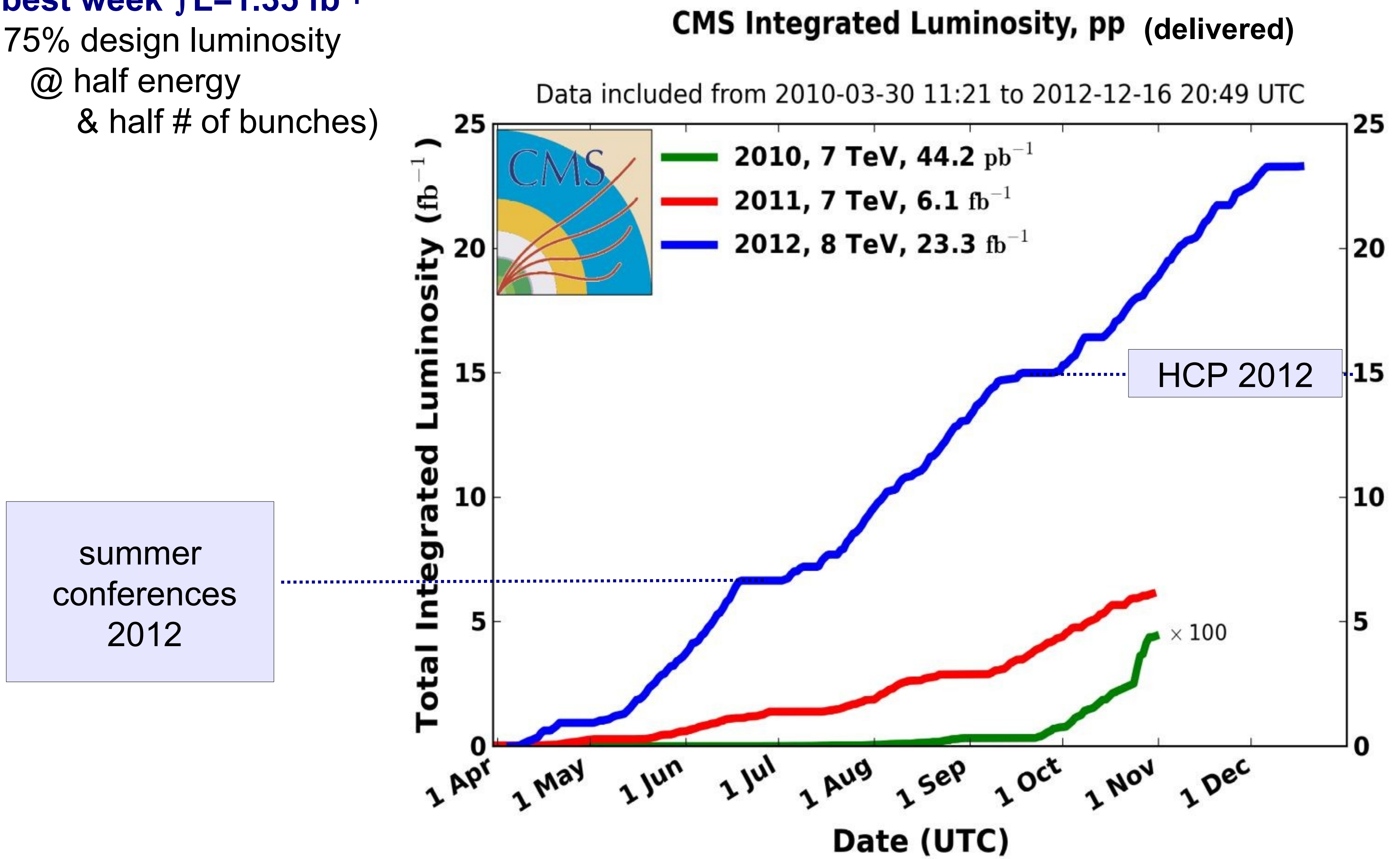


LHC Data taking 2012

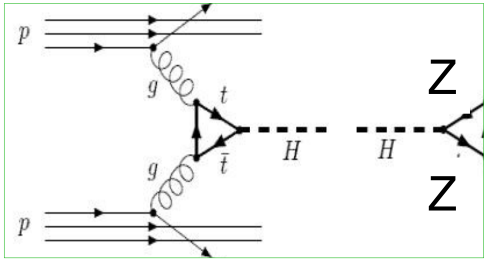
New records:

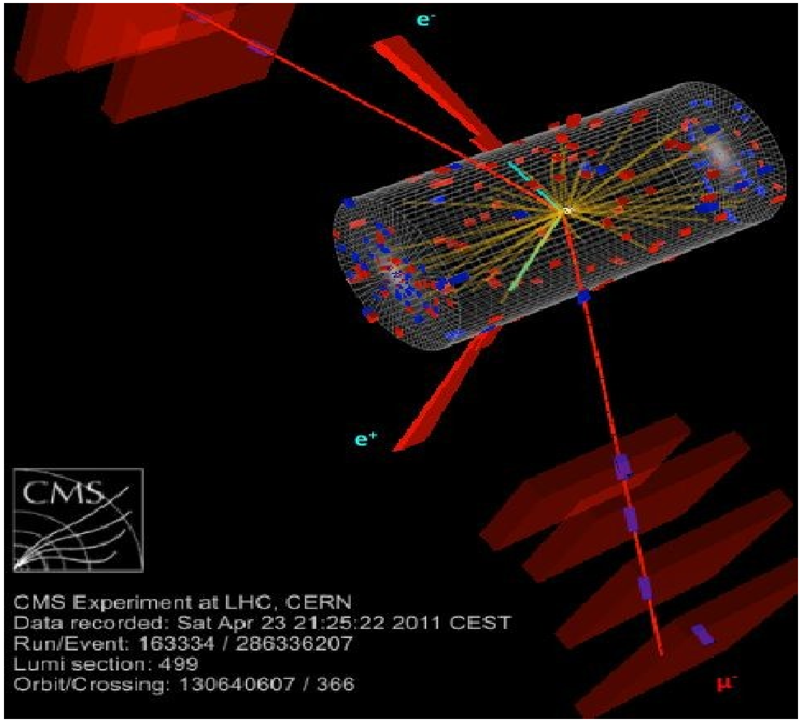
- **centre-of-mass energy 8 TeV**
- **peak luminosity 0.77· 10^{34} / cm² /sec**
- **best week ∫L=1.35 fb^{-1}**

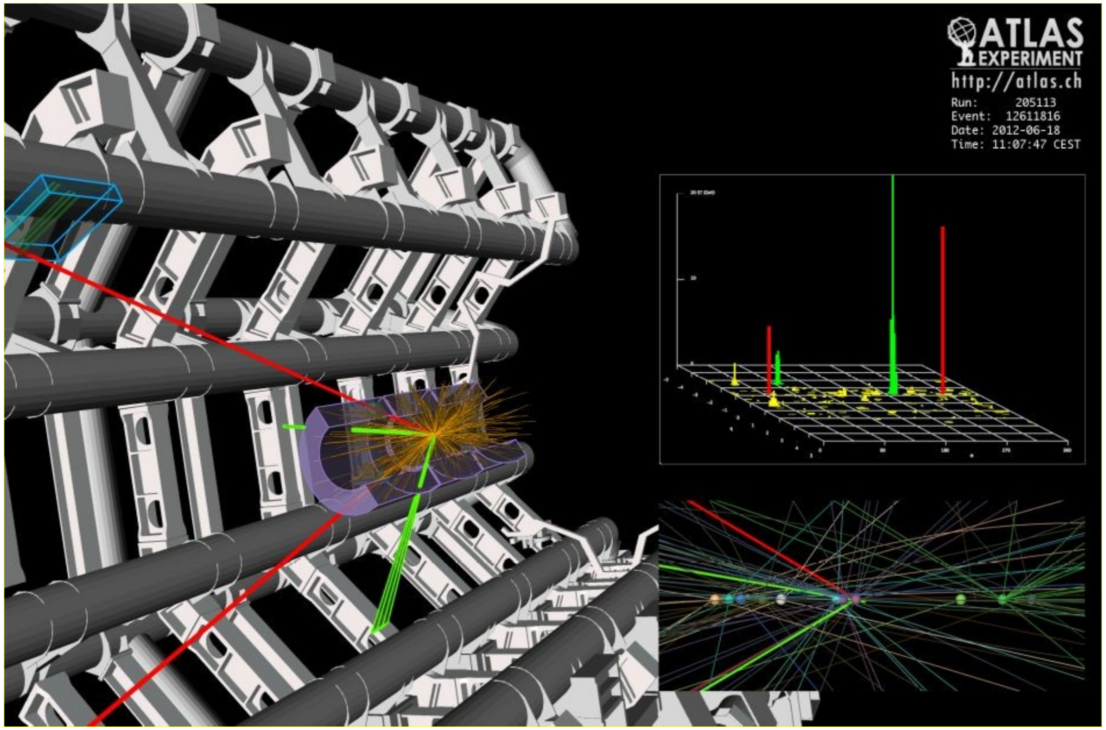
(75% design luminosity
@ half energy
& half # of bunches)



more events $H \to ZZ \to 4e, 4\mu, 2e2\mu$

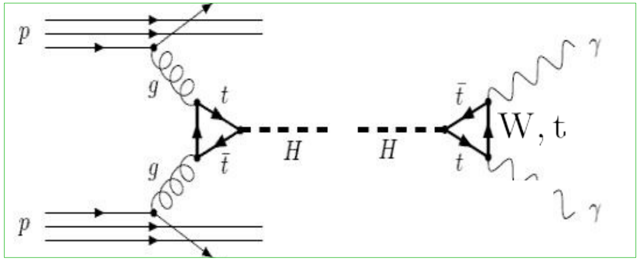


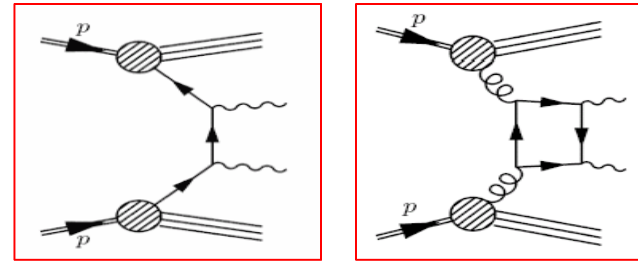




- Background $t\bar{t}$, $Zb\bar{b}$, irreducible: ZZ
- **favourable** ratio (~1) of signal to background
- **signal very small a low H mass**

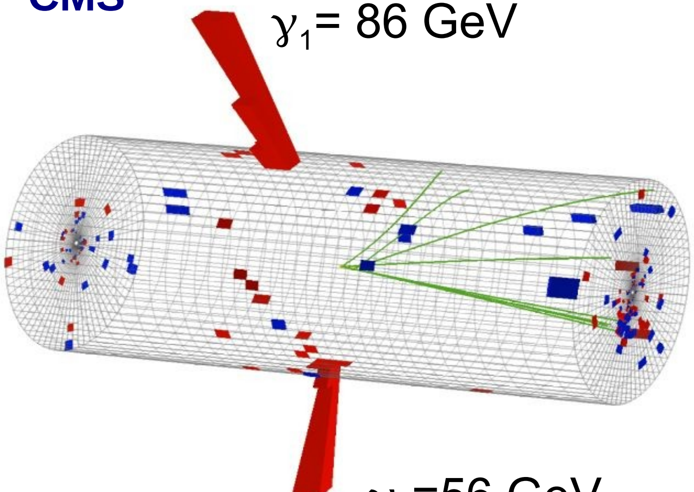
Higgs search in $\gamma\gamma$ channel – small H masses

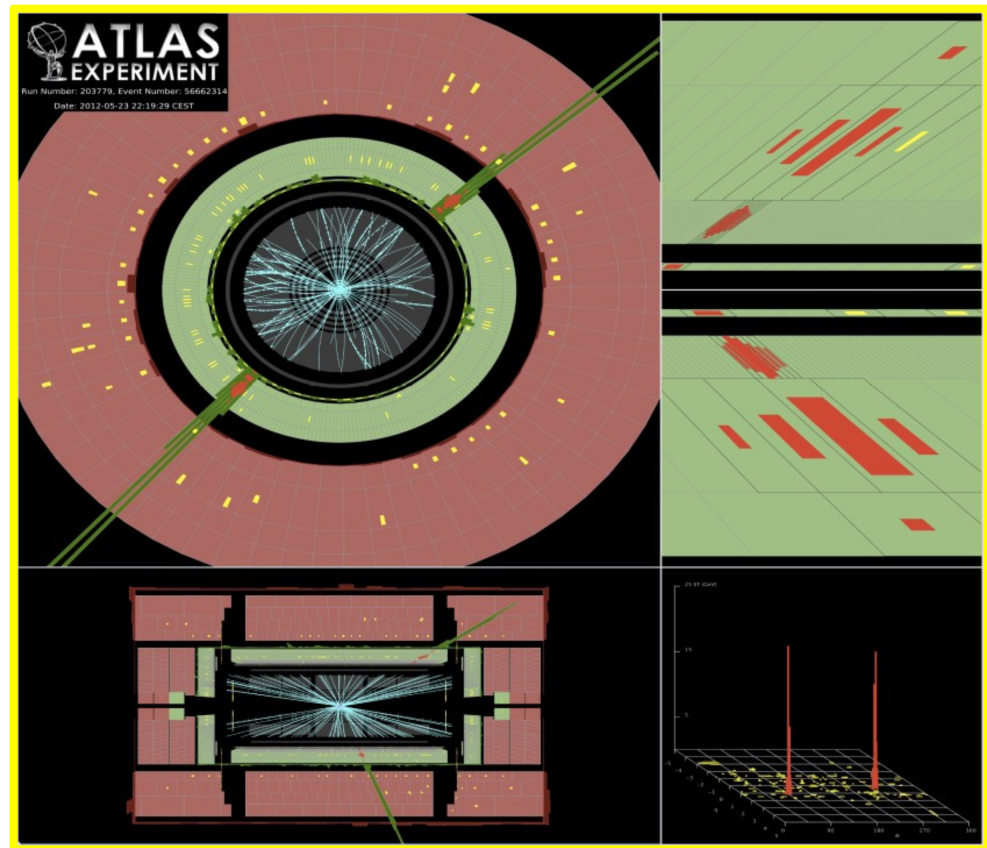




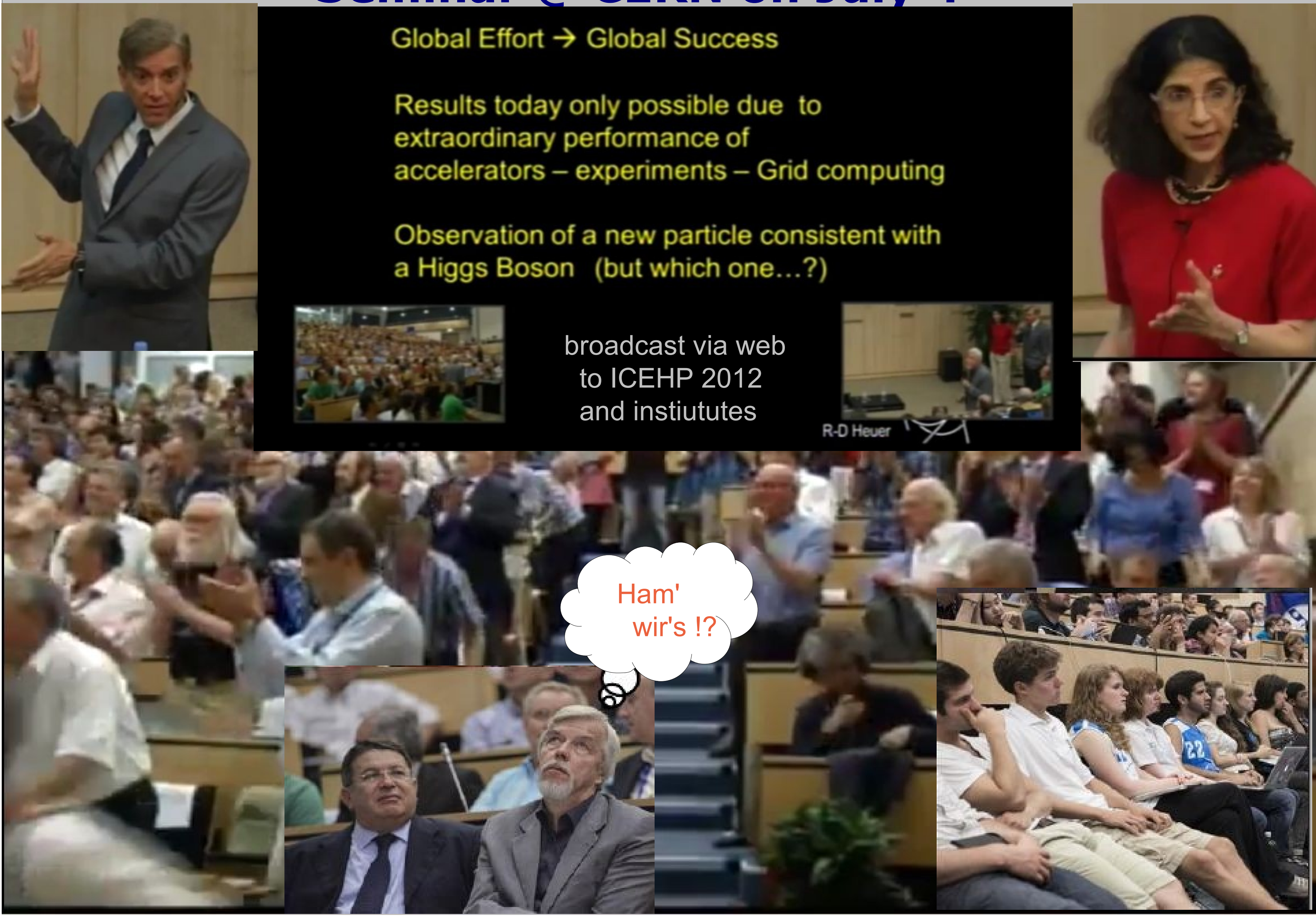
QCD background

CMS

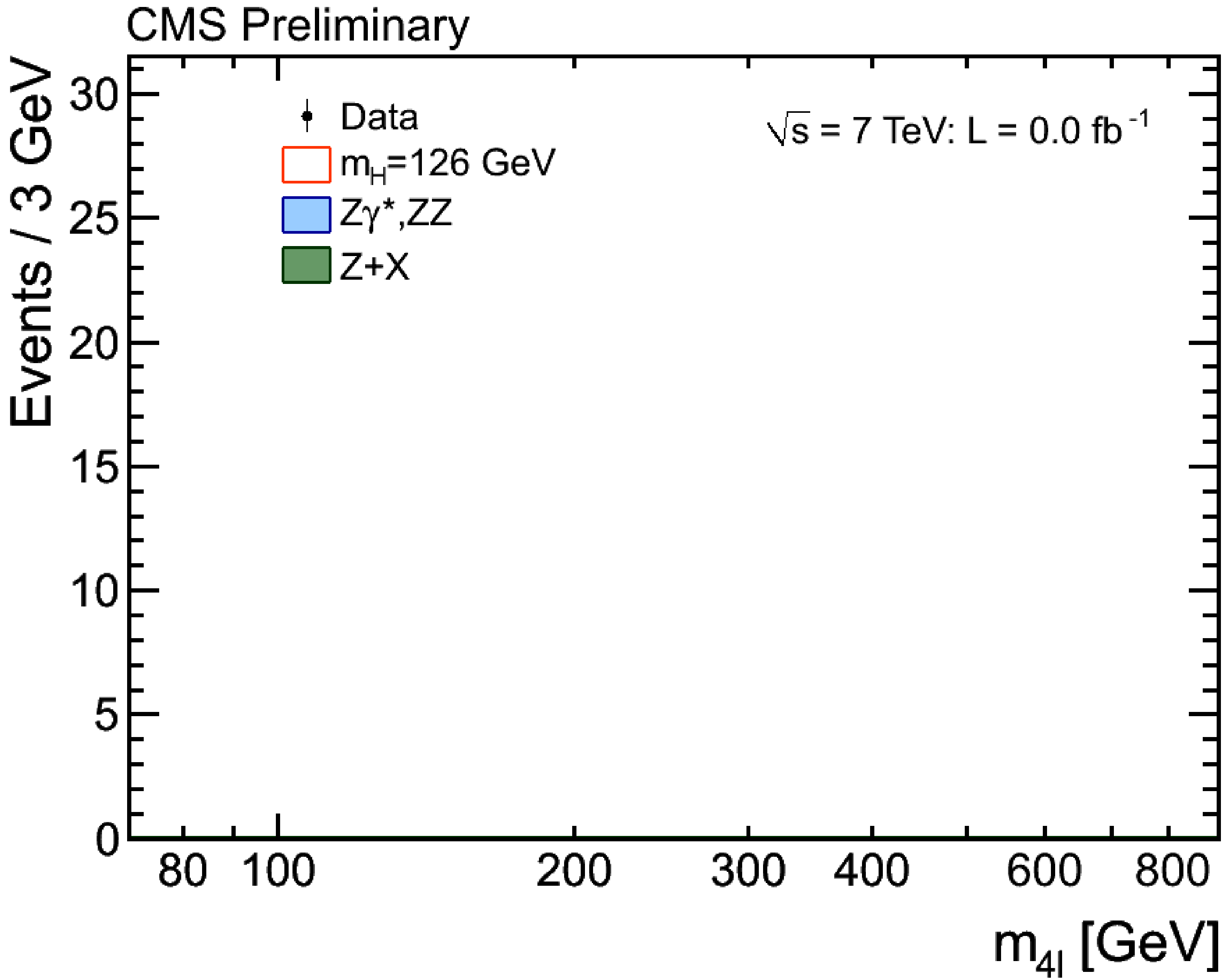




Seminar @ CERN on July 4th

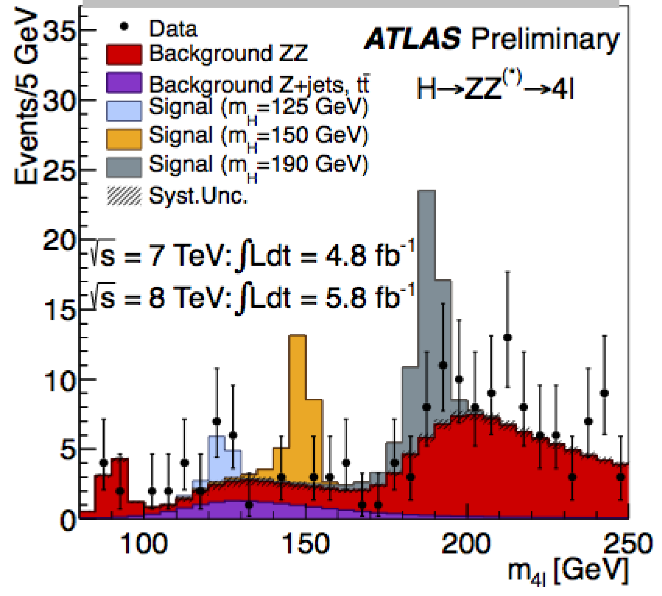


H → ZZ signal vs. time

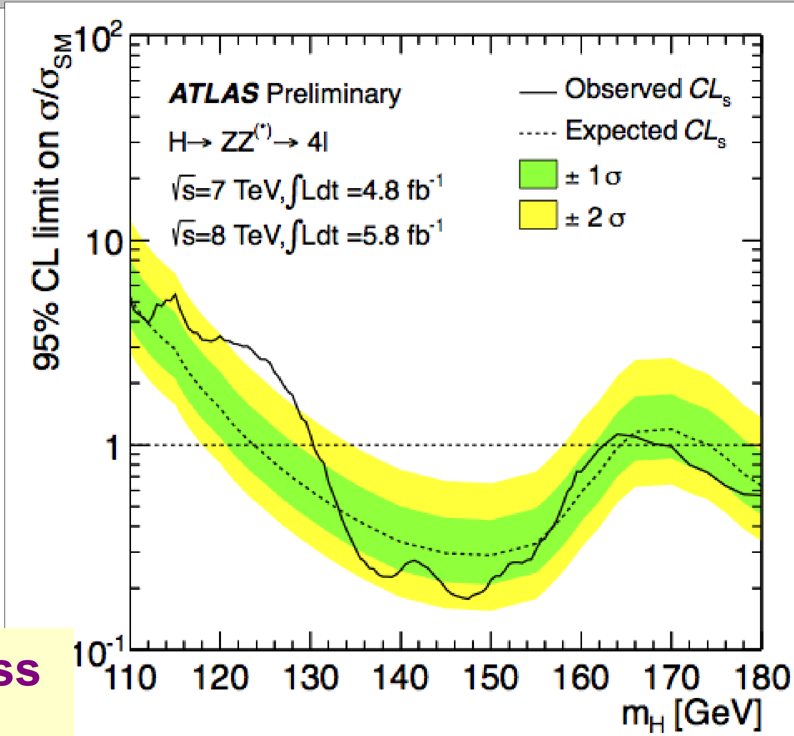


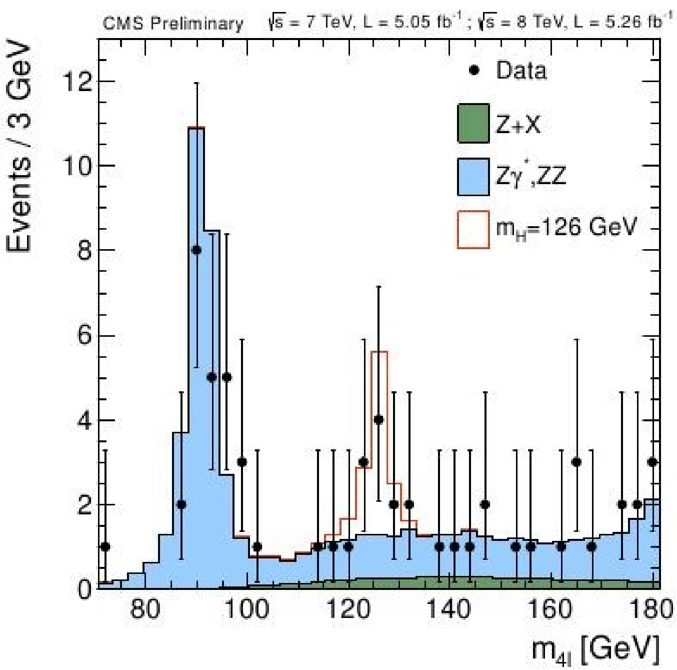
H → ZZ → 4e, 4μ, 2e2μ

Distribution of 4l mass

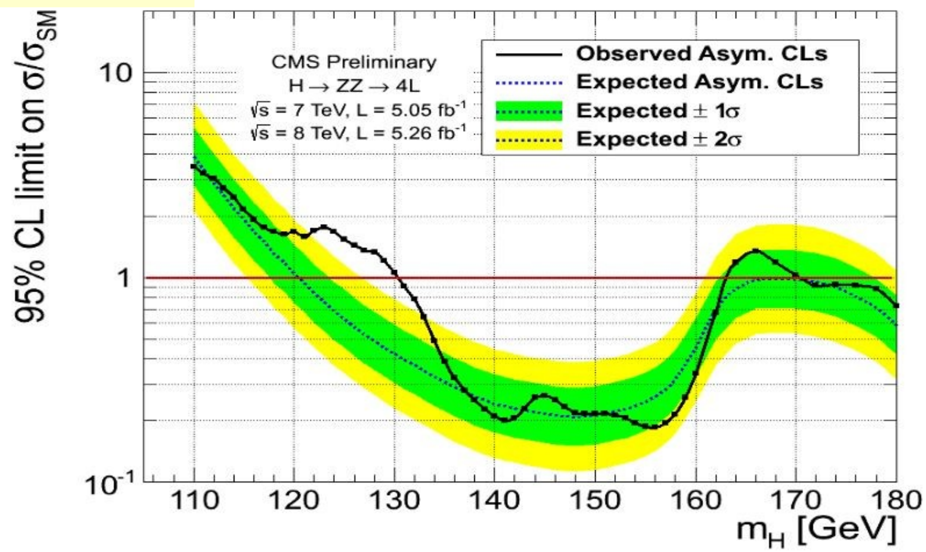


events 125+/-5 GeV
observed: 13
expected: b=5,1,
s(125 GeV)=5,3

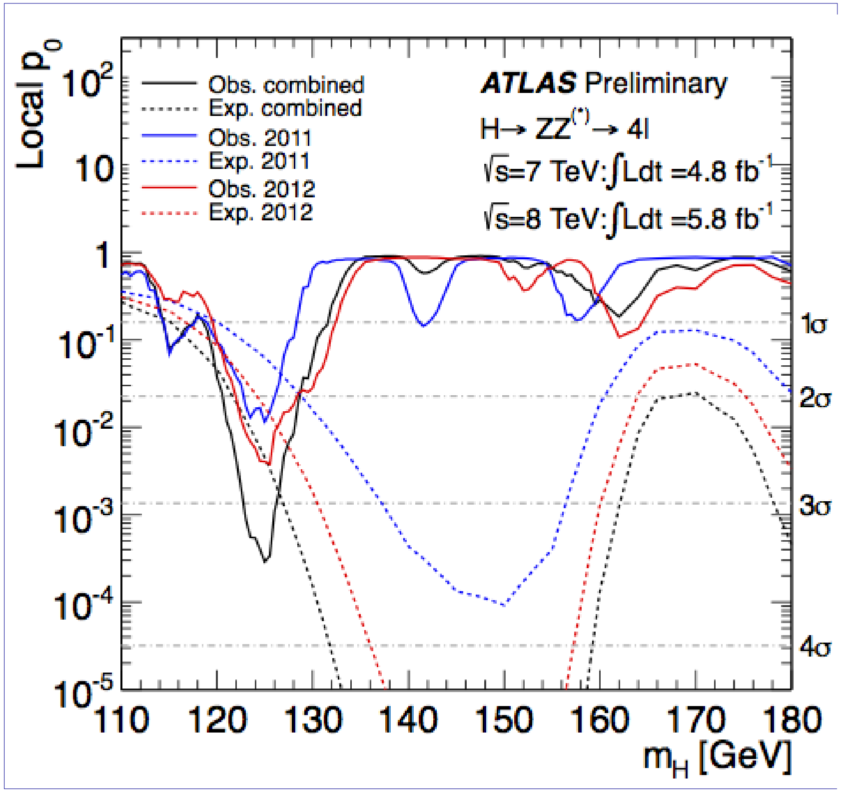


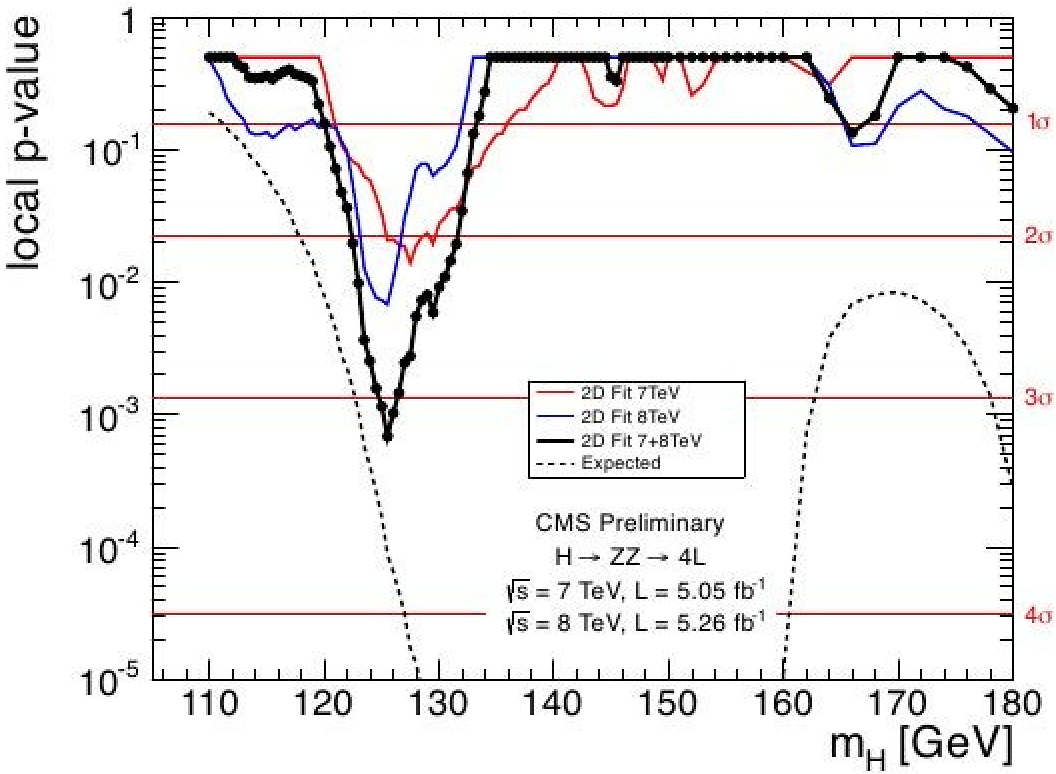


Signal-like excess
around125 GeV



H → ZZ →4e, 4μ, 2e2μ   p-value w.r.t. background



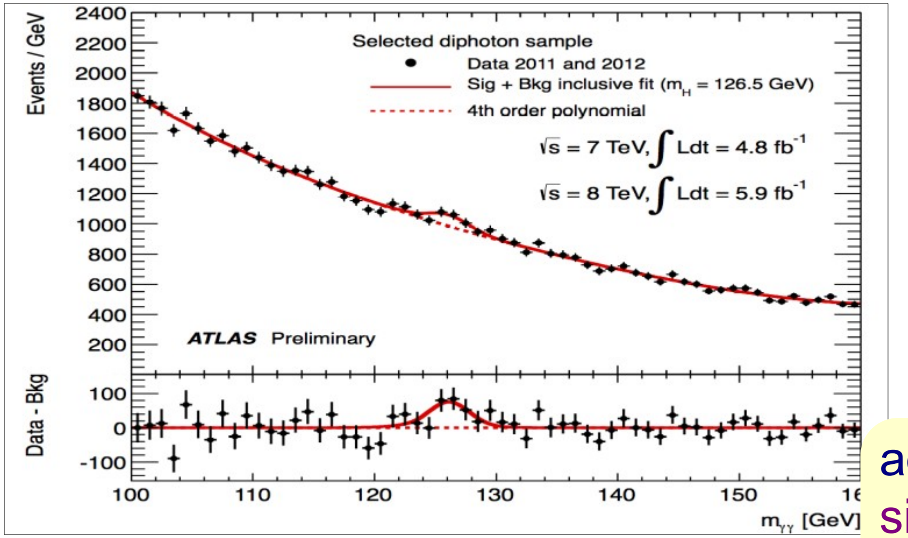


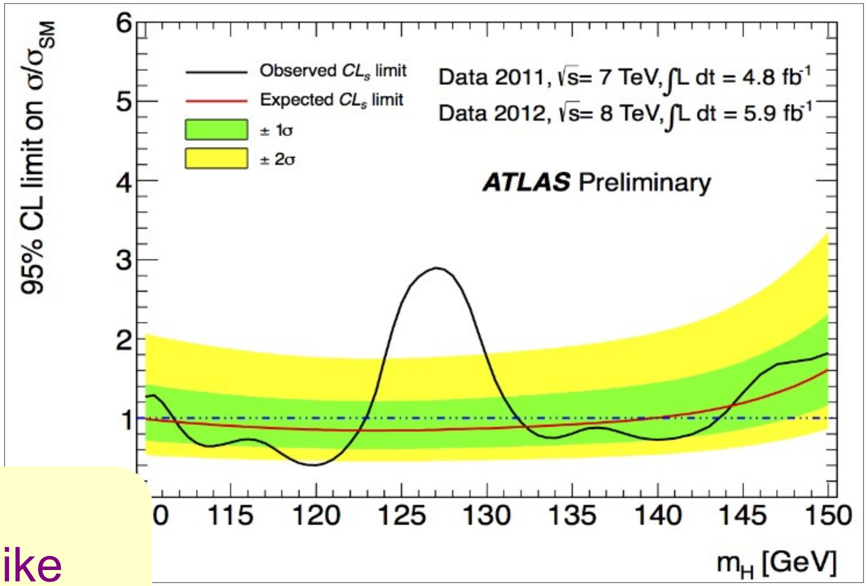
consistent signal excess in Atlas and CMS,

compatible with background at a probability of only ~0.1%

Higgs Search in γγ channel

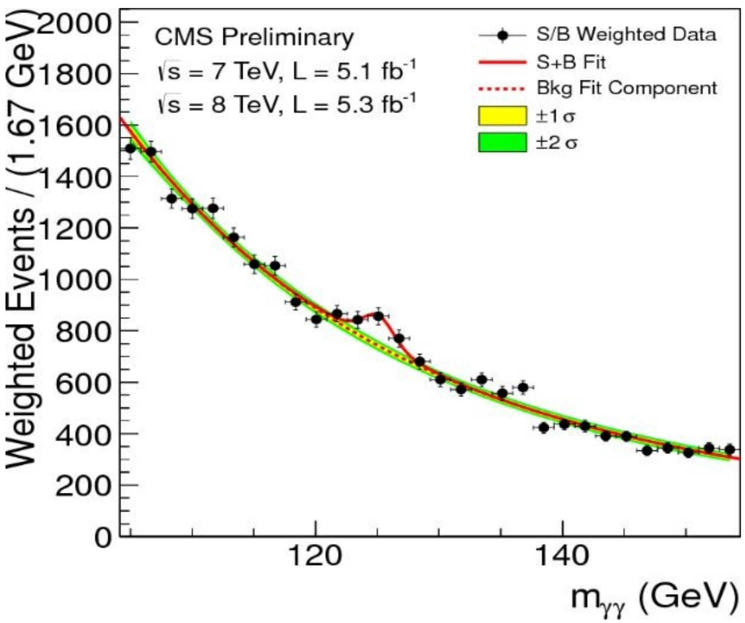
γγ spectrum ATLAS

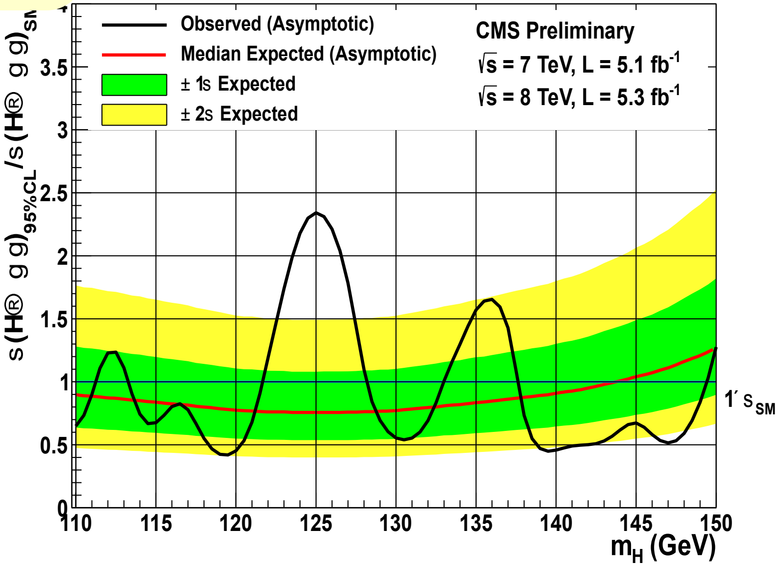




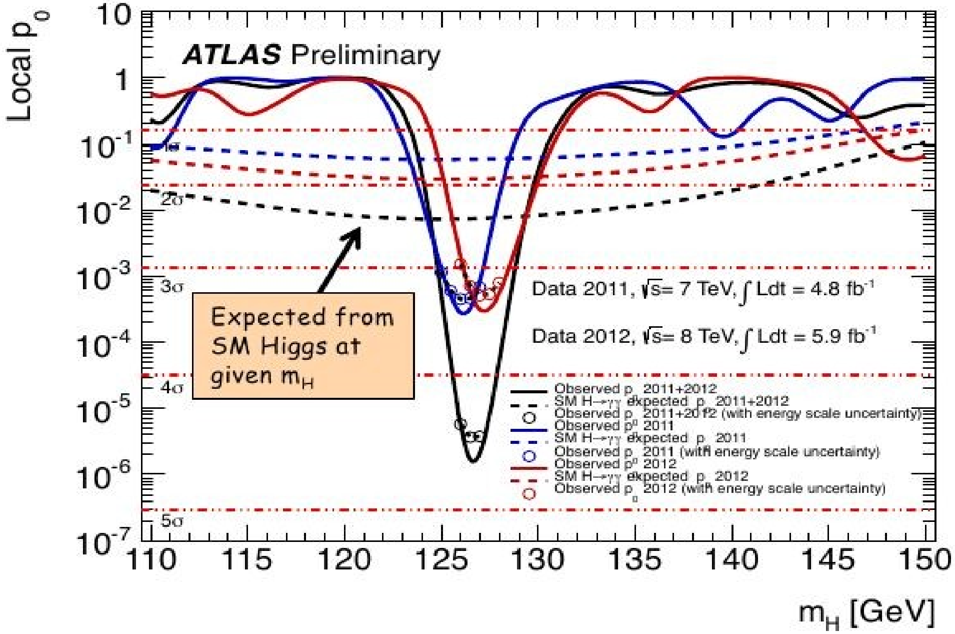
again:
signal-like
excess
at 125 GeV !

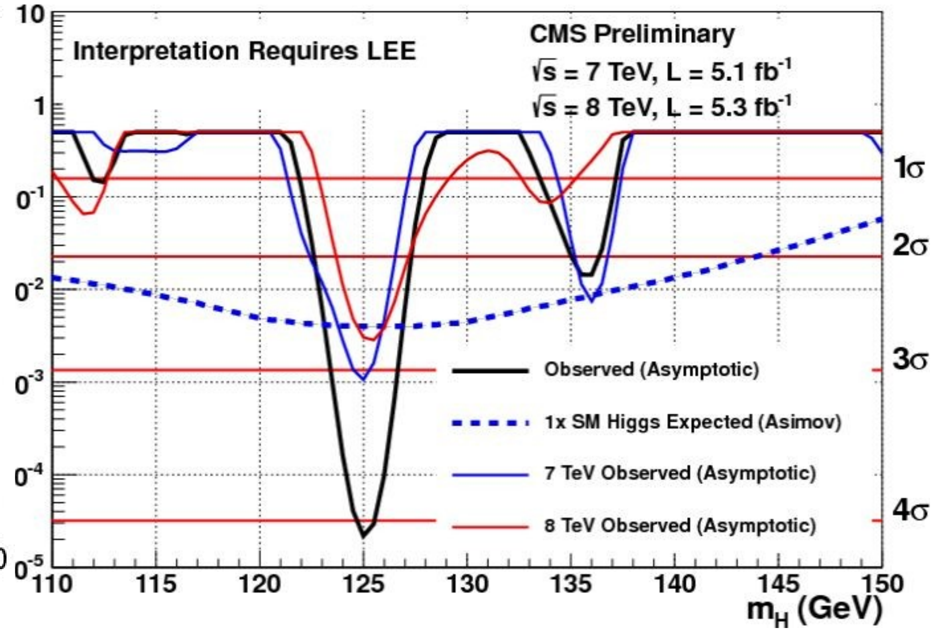
γ spektrum CMS





Higgs Search in γγ channel – background compatibility



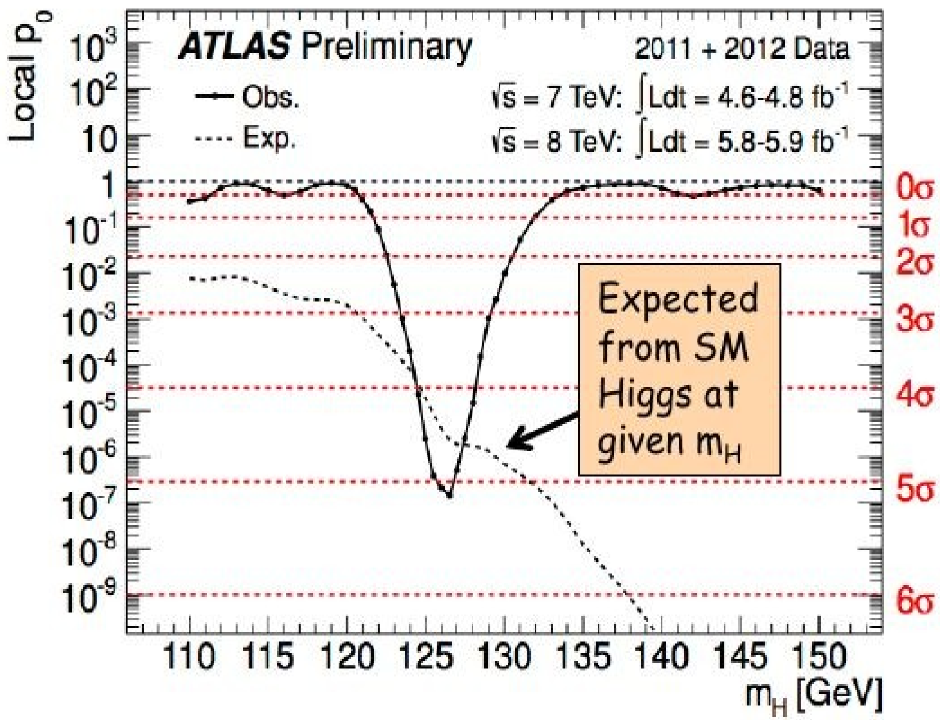


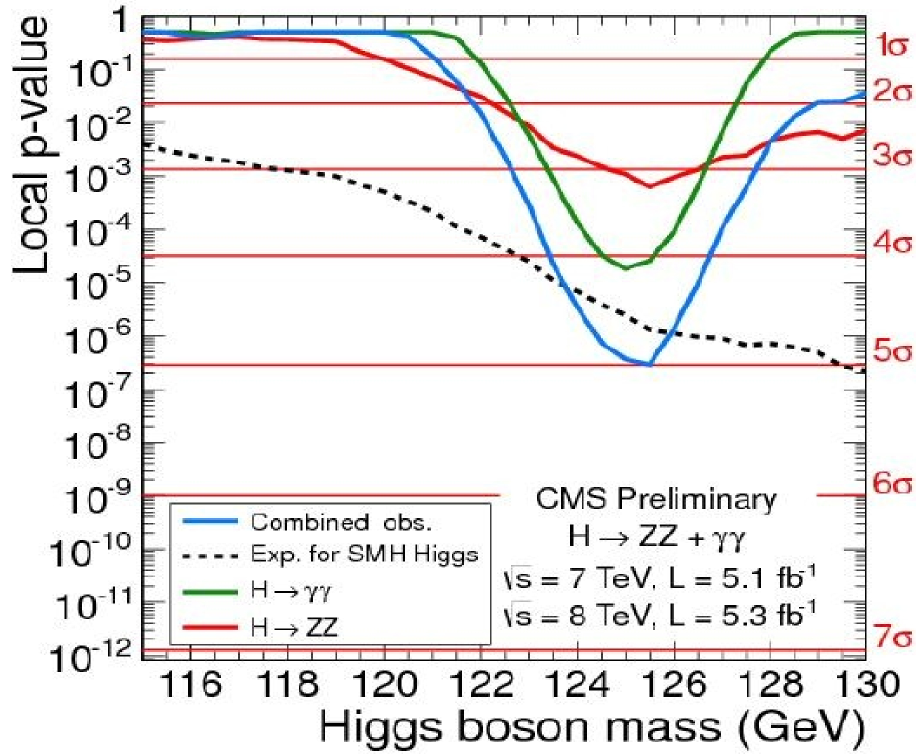
again:

consistent signal excesses in Atlas and CMS,

compatible with background only at a probability < 0.01%

$\gamma\gamma$ and ZZ channel combined – Background Compatibility



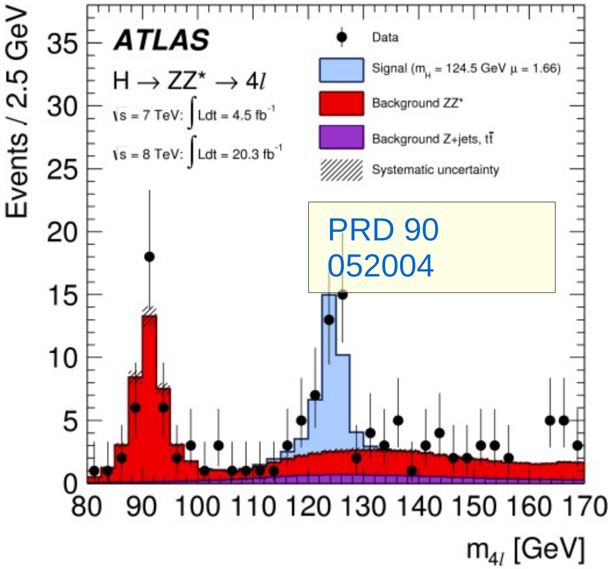


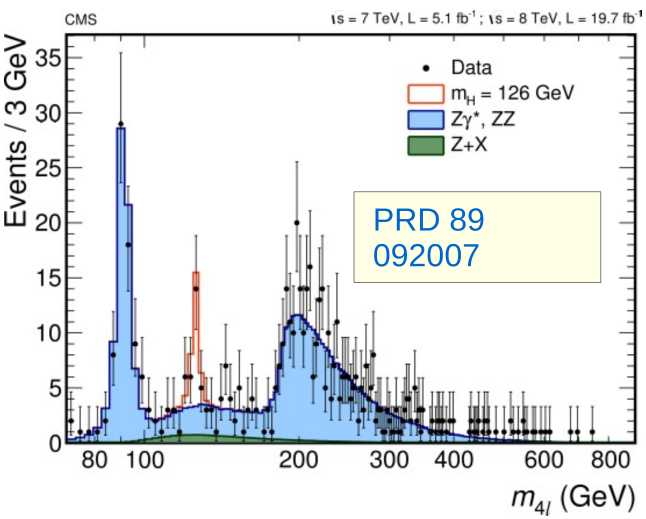
Both ATLAS and CMS observe consistent excess
in $\gamma\gamma$ and ZZ ~5.0 σ larger than background fluctuations !

Discovery of a new “Higgs-like” particle at the LHC

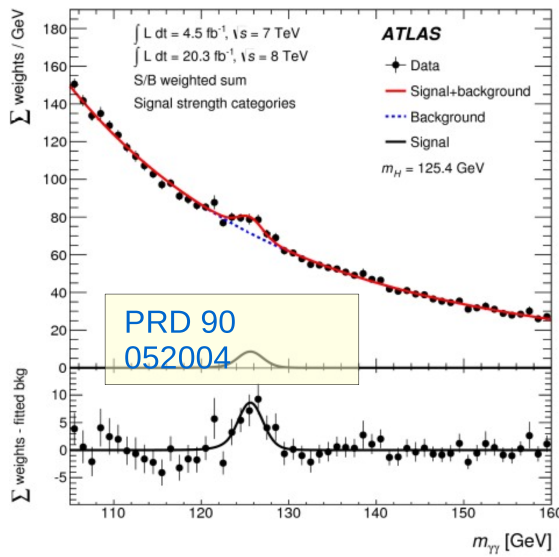
Individual Channels: H → bosons

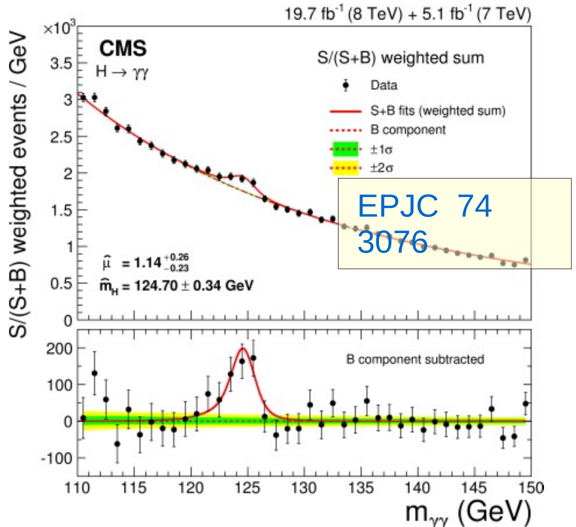
The original “discovery channels” *- updated to full Run1 luminosity, final and published*



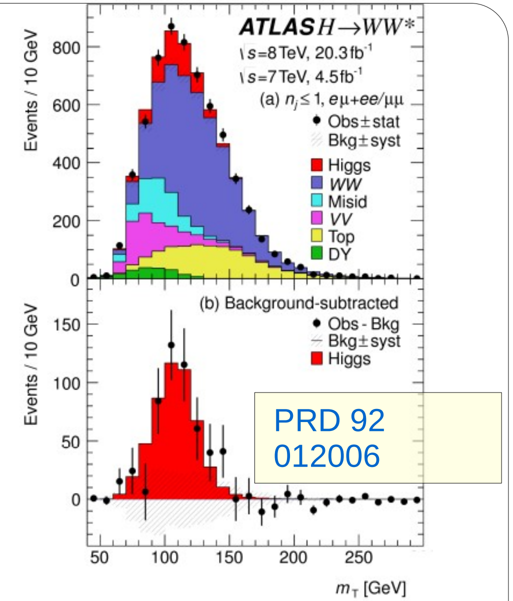


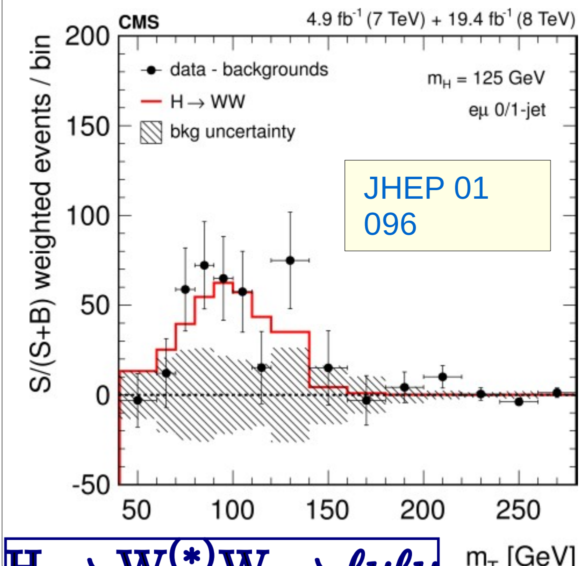
$\mathbf{H \to Z^{(*)}Z \to 4\ell}$





$\mathbf{H \to \gamma\gamma}$

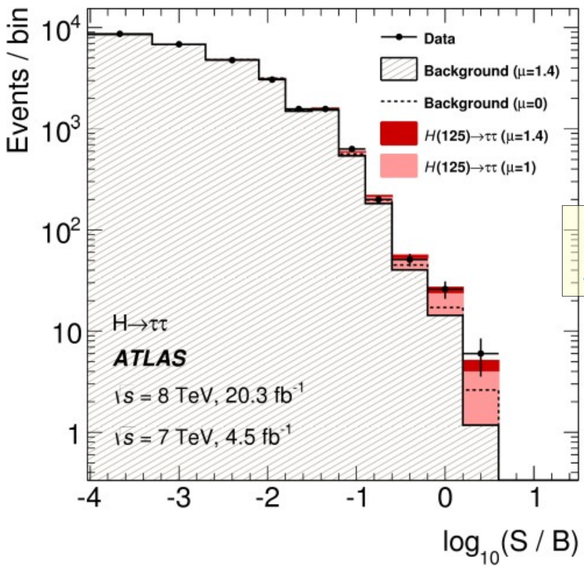




$\mathbf{H \to W^{(*)}W \to \ell\nu\ell\nu}$

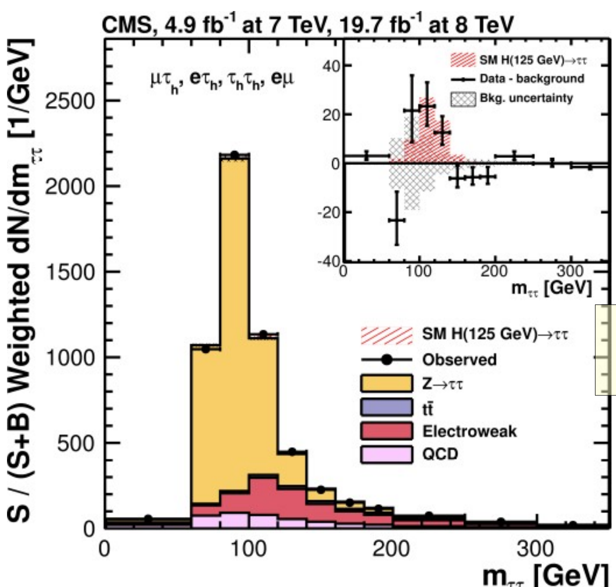
Individual Channels: Higgs → fermions

$H \to \tau\tau$



JHEP 04 117

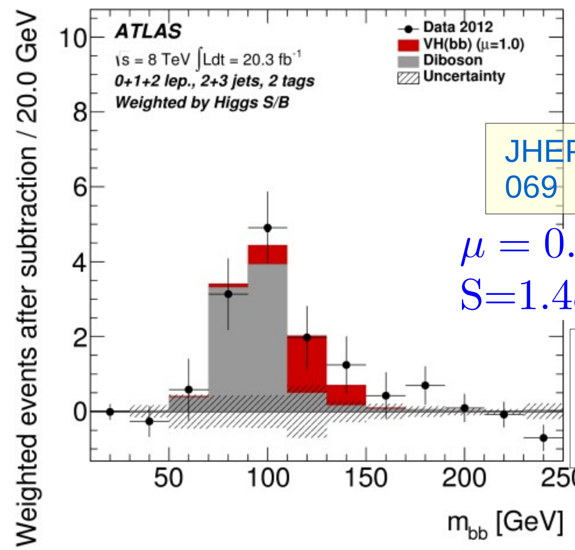
$\mu = 1.43^{+0.43}_{-0.37}$
S=$4.5\sigma(3.4\sigma)$



JHEP 05 104

$\mu = 0.78 \pm .27$
S=$3.2\sigma(3.7\sigma)$

VH/VBF, $H \to bb$

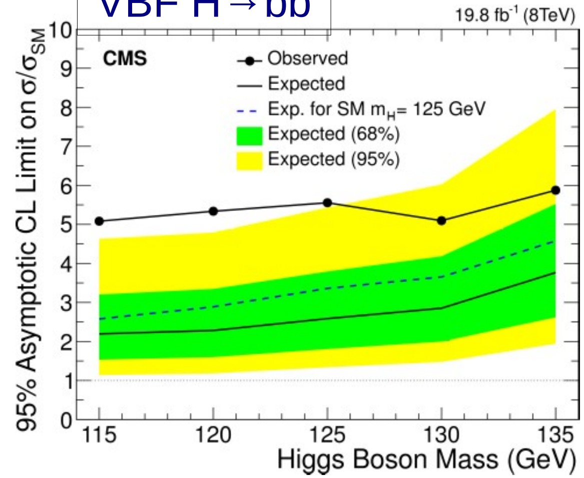


JHEP 01 069

$\mu = 0.52 \pm .32 \pm .24$
S=$1.4\sigma(2.6\sigma)$

there is a deficit in 2011 data (not shown here)

VBF H→bb



subm. PRD arXiv:1506.01010

$\mu = 2.8^{+1.6}_{-1.4}$
S=$2.2\sigma(0.8\sigma)$

combined with VH(bb) from

PRD 89 012003

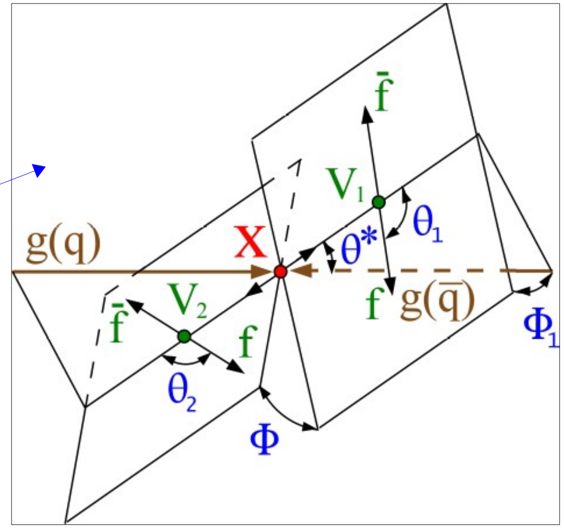
$\mu = 1.0 \pm .4$
S=$2.6\sigma(2.7\sigma)$

Spin – CP (methods)

sufficiently high statistical precision and cleanliness of di-boson channels
allows exploitation of kinematic variables for discriminating spin-parity hypotheses

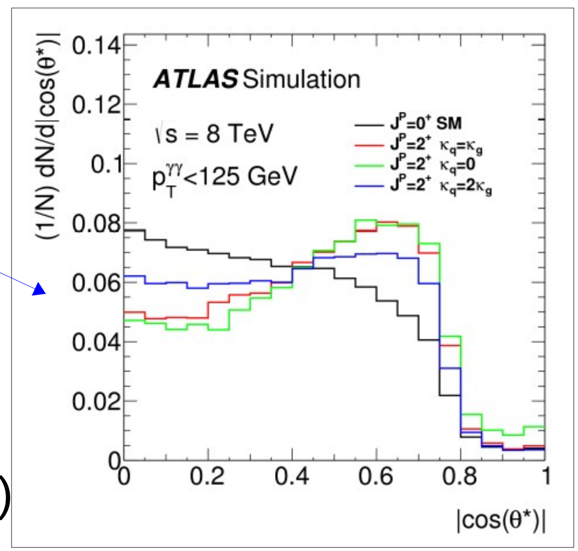
$H \to Z^{(*)}Z \to 4\ell$

matrix element
depends on
- 5 angles
- 3 masses



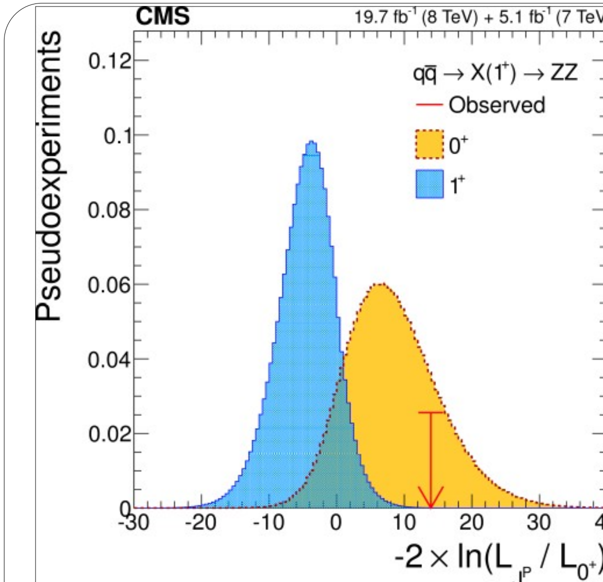
$H \to \gamma\gamma$

variables used:
- $p_T(\gamma\gamma)$
- $\cos\theta^*$ in Collins-Soper frame



$H \to W^{(*)}W \to \ell\nu\ell\nu$

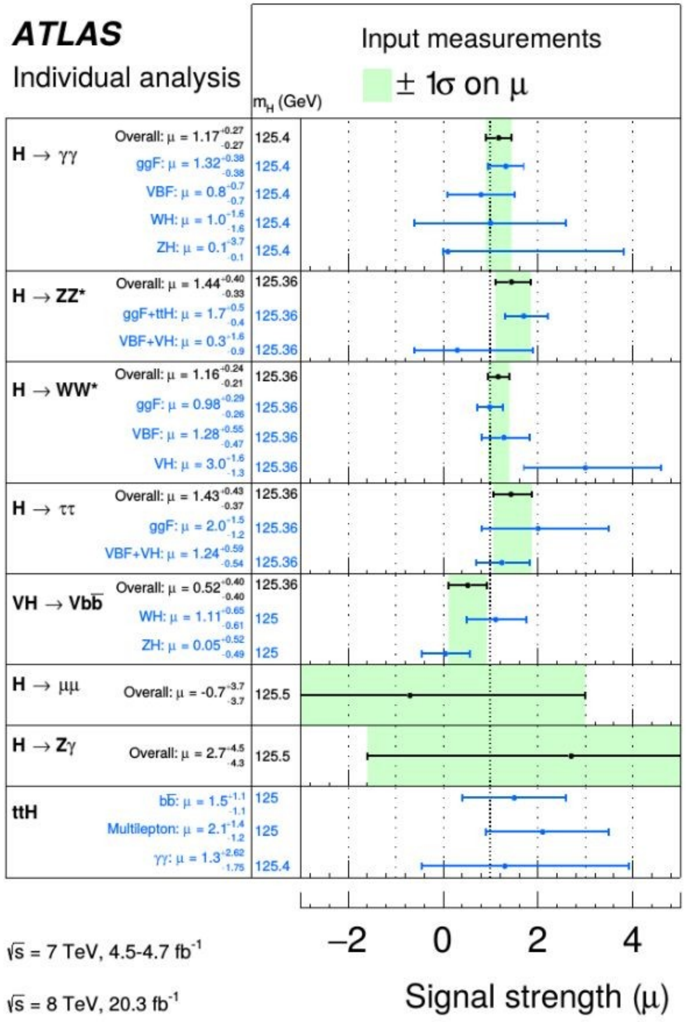
ATLAS:
BTD with $\Delta\Phi(ll)$, $p_T(ll)$, $m(ll)$
CMS:
2D-distribution of $m(ll)$ & m_T

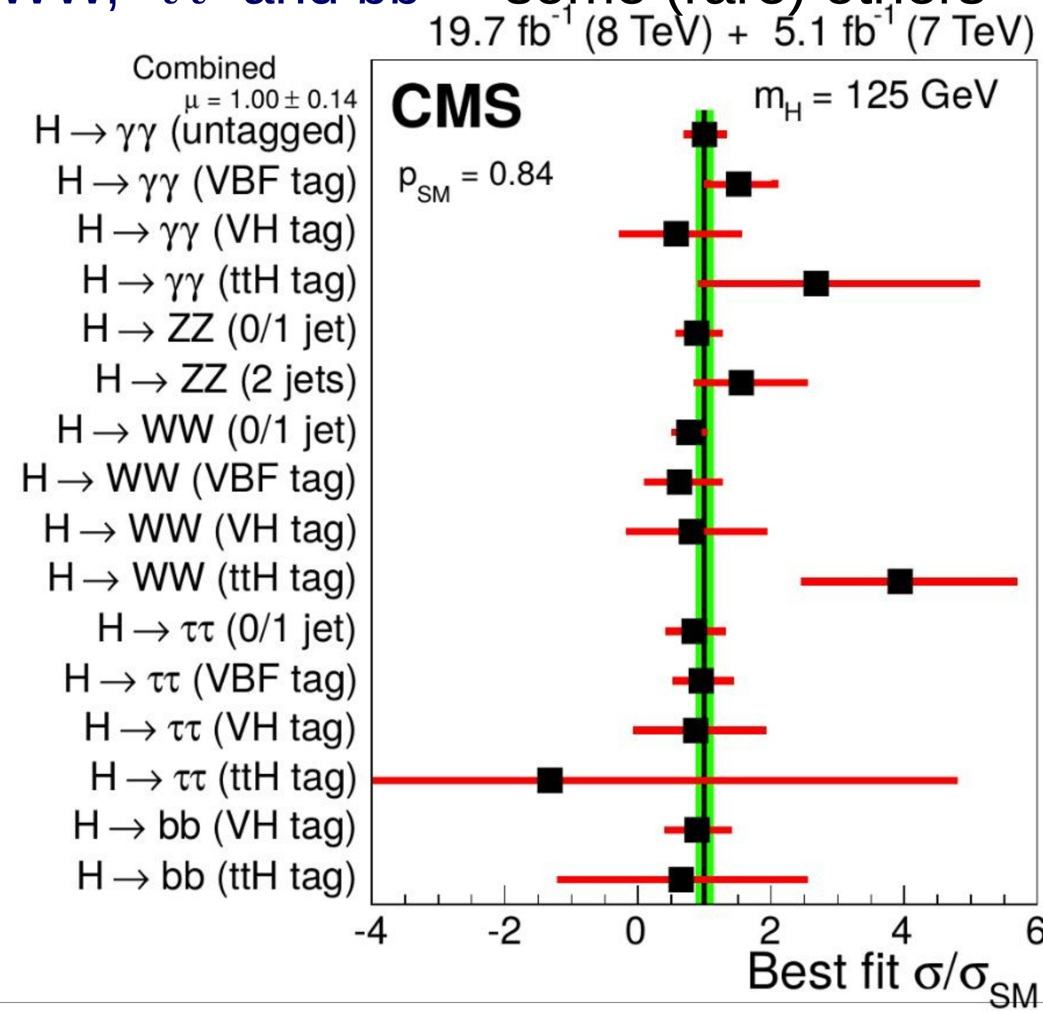


example of hypothesis test inZZ*
1^+ vs. 0^+

classical hypothesis test using log-Likelihood ratio of the SM vs. the alternative scenario as the test-statistic

Results based on integrated luminosities of
~5/fb @ 7 TeV (2011) and ~20/fb @ 8 TeV (2012) per experiment
for the “big five” H→ ZZ, $\gamma\gamma$, WW, $\tau\tau$ and bb + some (rare) others

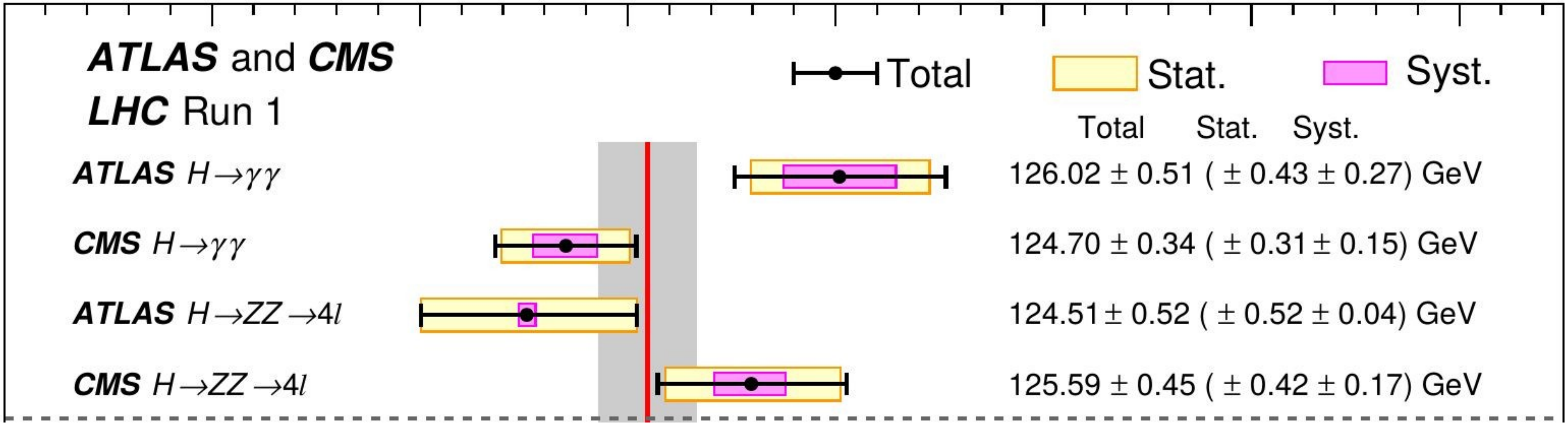




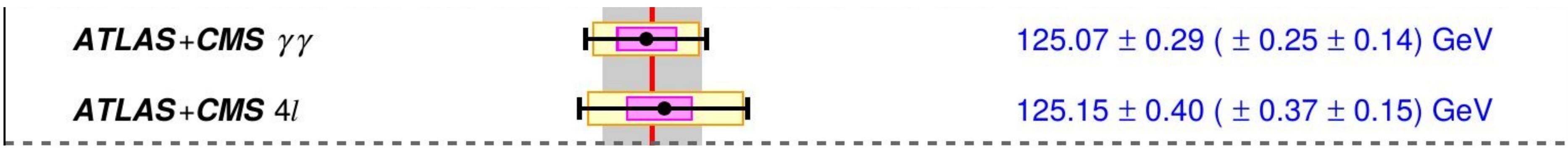
ATLAS Mass: PRL 114, 191803
ATLAS Couplings: arXiv:1507.04548

CMS Mass & Couplings
EPJ 75 (2015) 212

ATLAS & CMS Higgs Mass Measurements

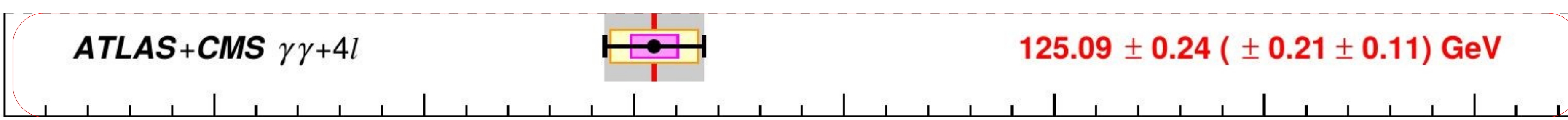


some “tension” between the four measurements (p-value ~10



approximate relative weights in averag

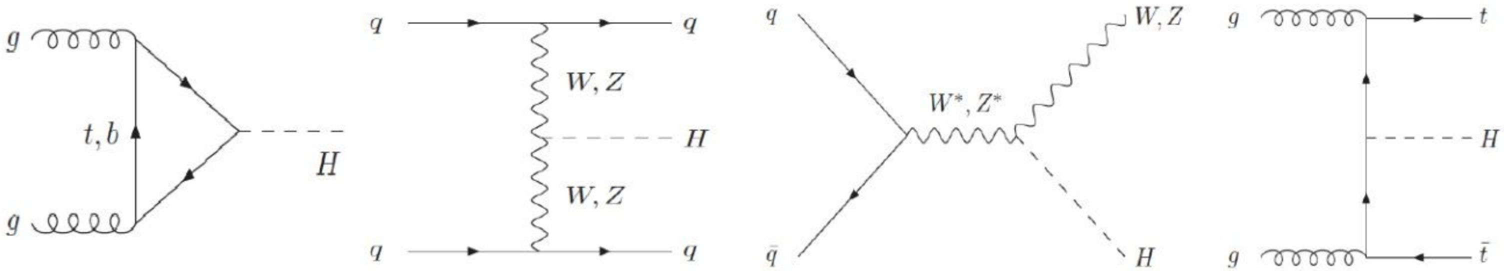
ATLAS H $\to \gamma\gamma$	19%
ATLAS H$\to 4\ell$	18%
CMS H$\to \gamma\gamma$	40%
CMS H$\to 4\ell$	23%



Kappa Framework

- **Combination of Measurements** of Higgs-Boson Production by ATLAS and CMS in

ggF **VBF** **W/Z H** **ttH**



production modes

in the **decay channels**

H→ ZZ **γγ** **WW** **ττ** and **bb** (and **μμ**)

note: γγ proceeds though W, t & b loops

- individual results corrected to common Higgs-boson mass of 125.09 GeV
  (and latest theory predictions, common treatment of background models etc. in some cases)

- **gain factor ~√2 in precision *w.r.t.* the individual results**,
  as measurements are dominated by independent errors

published in JHEP 08 (2016) 045

Signal parameterisations

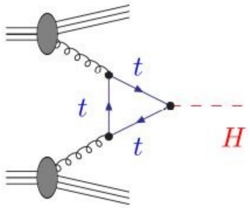
In the narrow width approximation, which decouples production and decay,

a measurement of **σ·Br** in the process $i \rightarrow H \rightarrow f$ is characterised by **signal strength modifiers μ**:

$$\mu_i^f = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \cdot \frac{\mathrm{Br}^f}{(\mathrm{Br}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

i = ggF, VBF, VH, ttH, … , *f = bb, WW, gg, ττ, cc, ZZ, γγ, Zγ,μμ*

alternatively:
loops resolved to contributing particles, *e.g.* ggF:



$$\kappa_g^2 \simeq 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$$

Or, at (LO) coupling level, introduce

coupling modifiers κ:

$$\sigma_i \cdot \mathrm{Br}^f = \frac{\sigma_i(\{\kappa\}) \cdot \Gamma^f(\{\kappa\})}{\Gamma_H(\{\kappa\})}$$

$$\kappa_i^2 = \frac{\sigma_j}{\sigma_i^{\mathrm{SM}}} \text{ or } \kappa_f^2 = \frac{\Gamma^f}{\Gamma_{\mathrm{SM}}^f}$$

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}$$

SM particles only:

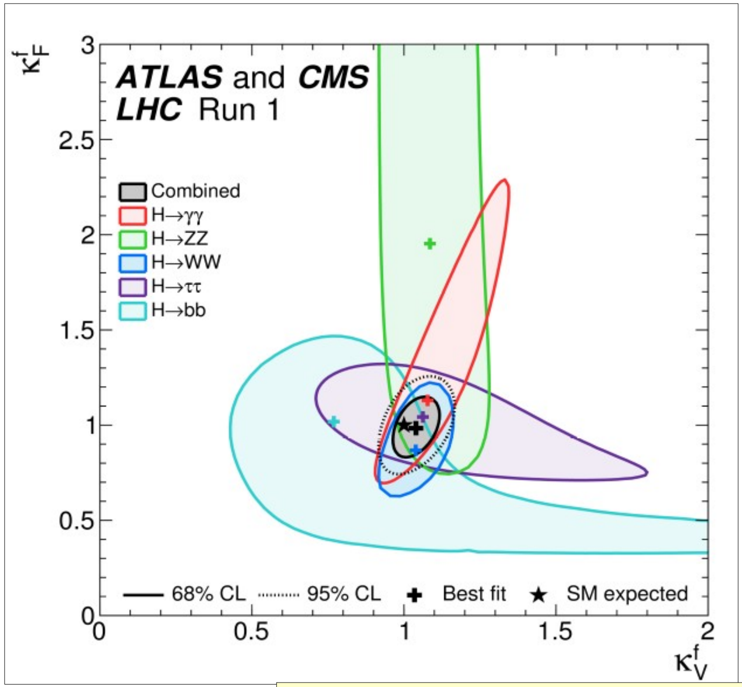
$$\kappa_H^2 = \sum_f \mathrm{Br}_{\mathrm{SM}}^f \kappa_f^2$$

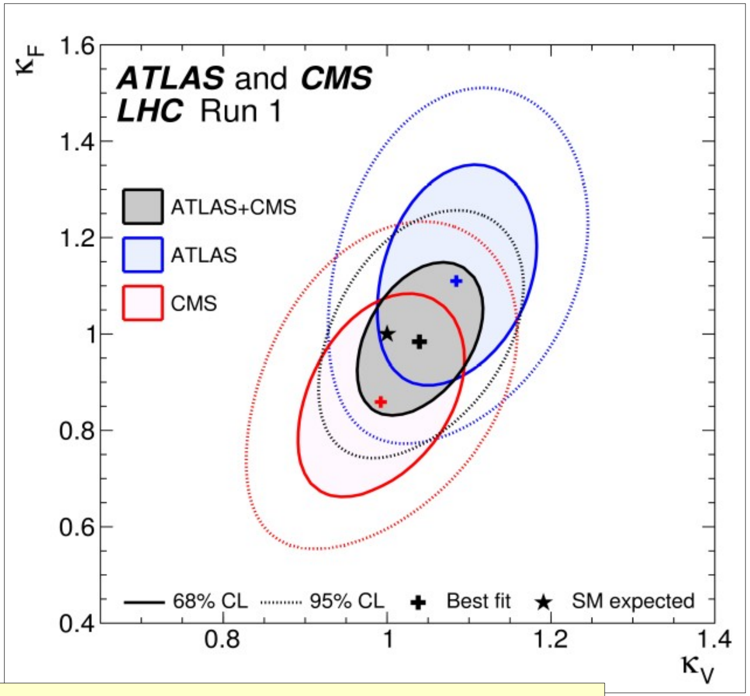
with BSM-contributions:

$$\kappa_H^2 = \frac{(1 - \mathrm{Br}_{\mathrm{BSM}})\Gamma_H}{\Gamma_H^{\mathrm{SM}}}$$

Result of Kappa-Fit

Global fit in all production and decay channels
with scale factors for couplings to vector bosons (κ_V) and fermions (κ_f)



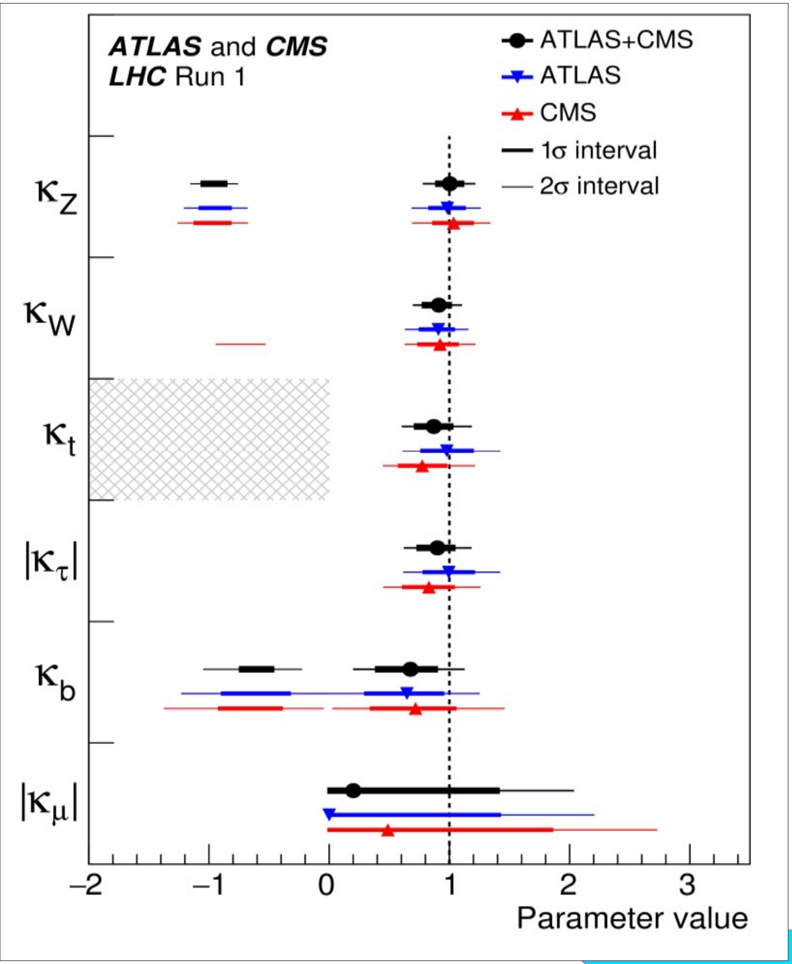


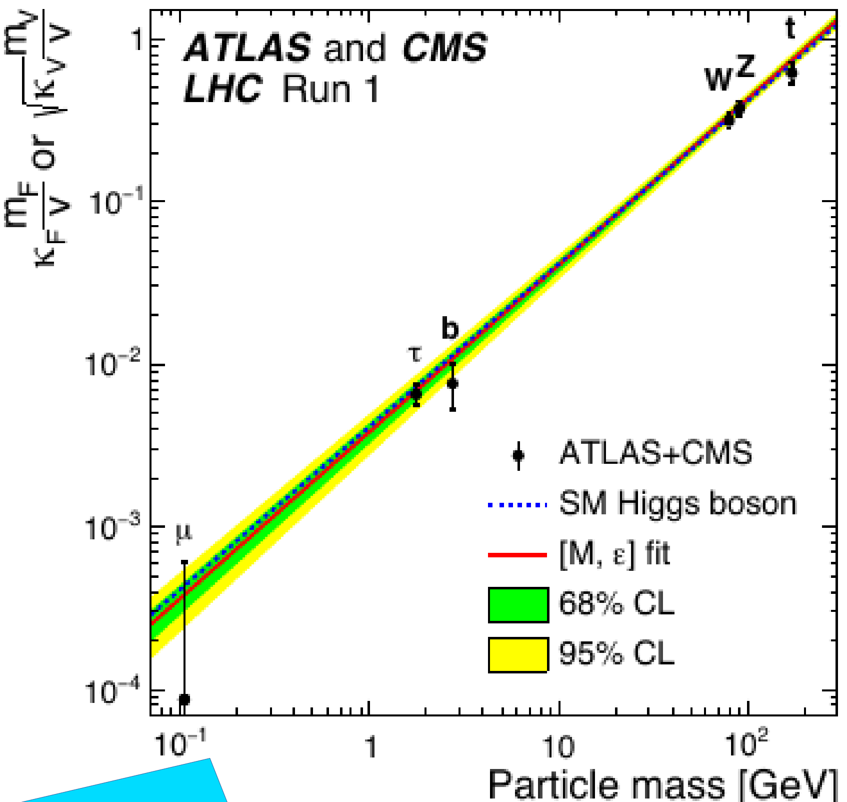
Cannels & Experiments
consistent
among each other and with SM expectation

Higgs Couplings (in SM)

Assumption: No other than SM particles couple to Higgs boson, $Br_{BSM} = 0$

remark: low value of κ_b reduces total width Γ_H $\Rightarrow$ **all κ_i come out a bit low**





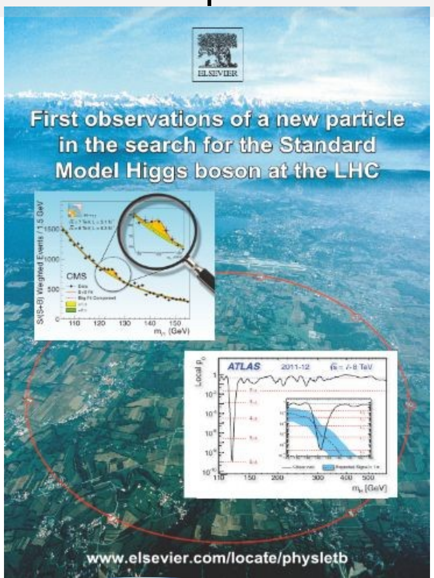
JHEP 08 (2016) 045

nicely illustrates the essence of the Higgs mechanism

intermediate summary: Higgs Hunt @ the LHC

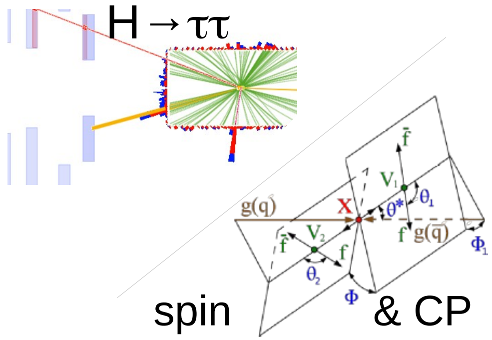
Summer '12 (~10 fb $^{-1}$)

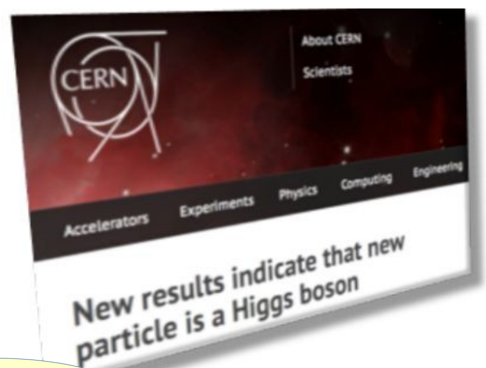
Announcement of
"a new particle"



New particle !

during 2013 (~20 fb $^{-1}$)





Higgs-like ?

Dec. 2013

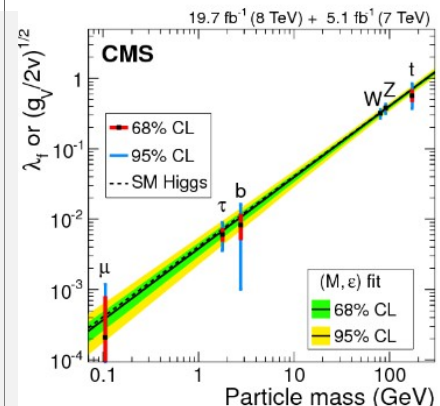
Nobel Prize

(& EPS Prize
+ many others)

A Higgs !

2014/15

refined analyses &
(many) final publications



THE SM-Higgs ???

LHC Run 1: pp-collisions at E_{CM} of 7 and 8 TeV

- Peak Luminosity: 7 x 10^{33} cm^{-2} s^{-1}
- Integrated Luminosity: ~5 fb $^{-1}$ (2011@7 TeV) ~(5+15) fb $^{-1}$ (2012@8 TeV)
- time between bunches: 50 ns ⇒ 9–21 overlayed pp-interactions on average

1. History
2. Basics principles
3. Detectors and Accelerators
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    1. Relativistic Quantum Mechanics
    2. Quantum Field Theory and symmetries
    3. Elctroweak Symmetry and Higgs Mechanism
5. QCD and Jets
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7. Flavour Physics
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9. Higgs Physics
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    3. Latest results
    3. Future Measurements and Experiments

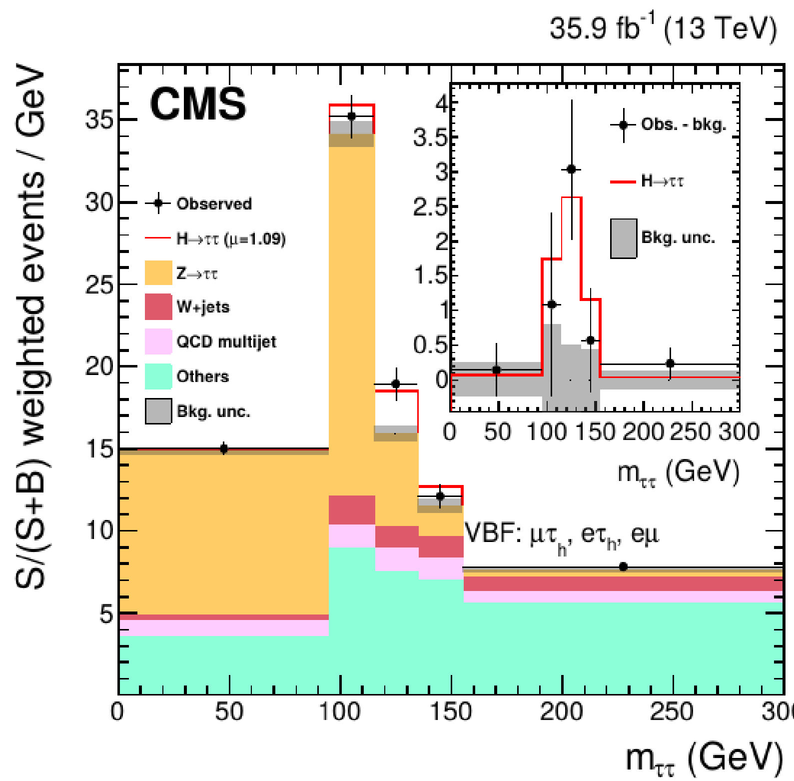
Higgs coupling to tau leptons

First observation of $H\to\tau\tau$ with ~5σ evidence in a single experiment

- integrated luminosity of 35.9/fb recorded in 2016 by the CMS experiment
- siginificance of 4.9σ for signal (4.7 exptected)
- signal strenght relative to SM expectation: $\mu = 1.09^{+0.27}_{-0.26}$
- combination with Run 1 data: significance 5.9σ

Illustration of the signal:

- most sensitive channels $e\tau_h$, $\mu\tau_h$, $e\mu$
- events weighted according to their relative contribution to the signal
- inset shows the difference between observed data and the background expectation, i.e. the signal

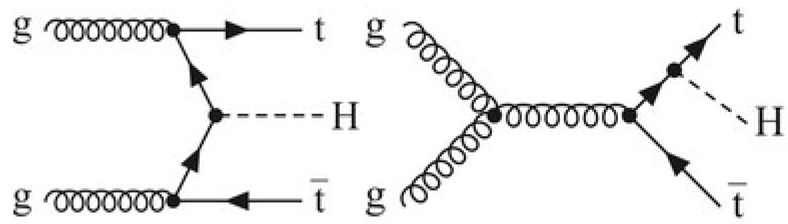


Phys. Lett. B 779 (2018) 283

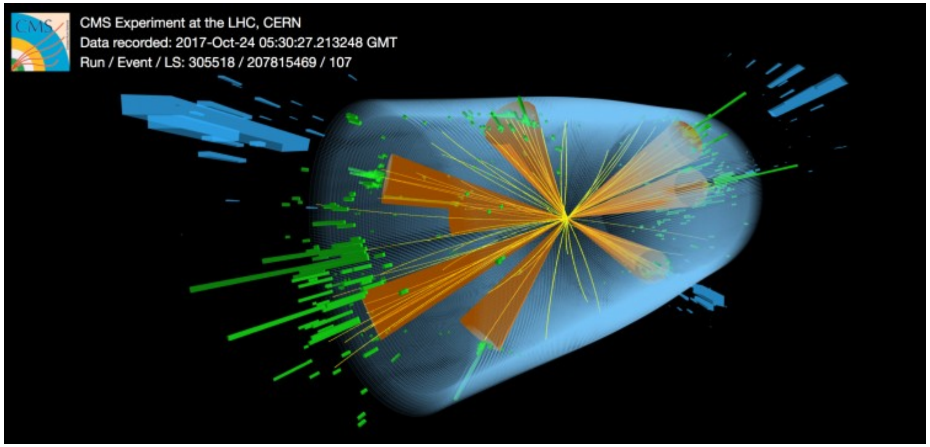
Higgs couplings to b and t quarks

Observation of ttH production:

- Feynman diagrams (leading order):

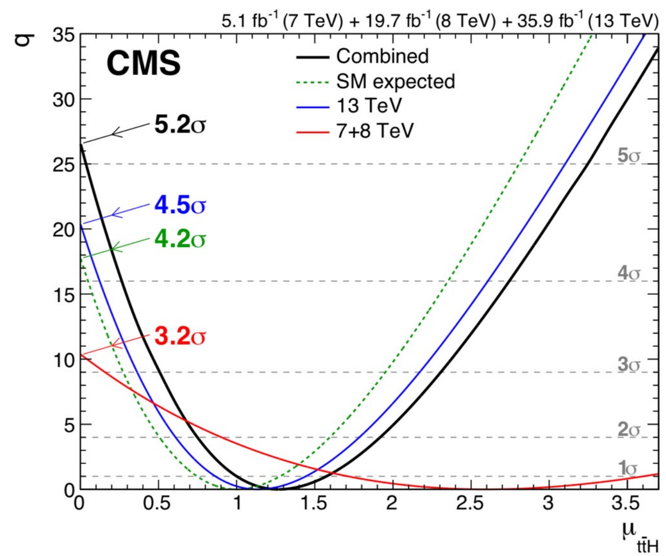


- candidate event eight jets:
  - 2 b-jets from H boson decay
  - 2 b-jets from top quark decays
  - 2 non-b jets from each of the
    2 W bosons



- H boson decays considered:
  pairs of W and Z bosons, τ leptons,
  photons and b-quarks

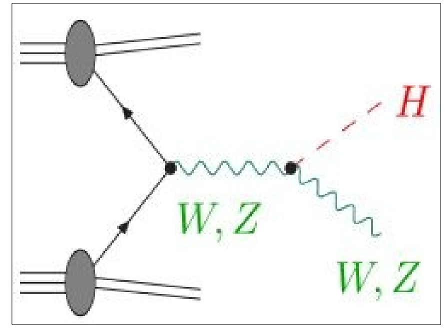
- **Result:**
  profile likelihood ratio (q = -2 ln L(μ)/L_{min})
  of the signal strength μ indicates a
  5.2σ evidence for ttH procuction



Phys. Rev. Lett. 120 (2018) 231801

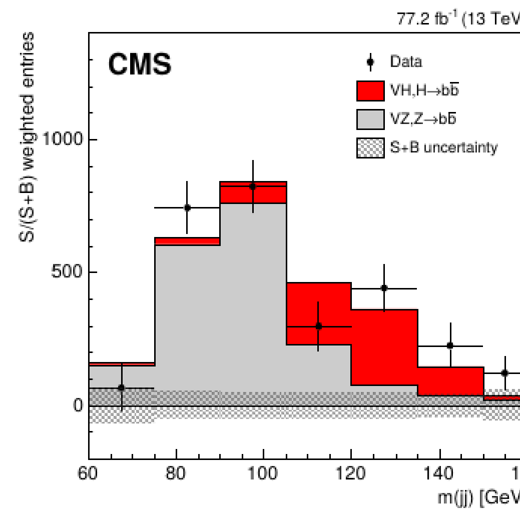
-
- ttH production also observed by ATLAS:
  evidence 6.3σ (5.1σ expected)
- Phys. Lett. B 784 (2018) 173

First clear evidence for H → $b\bar{b}$

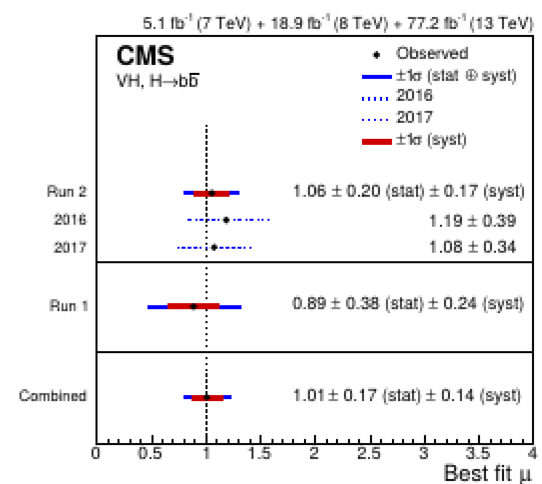


- main contribution to signal:
  associated production with a vector boson

  advantage: relatively clean signature to beat down the overwhelming background from QCD b-quark production



- **Result CMS:**
  - Evidence of 4.9σ in combined Run 1 and Run 2 data;
  - combination with other production channels yields an evidence of 5.6σ



Phys. Rev. Lett. 121, 121801 (2018)

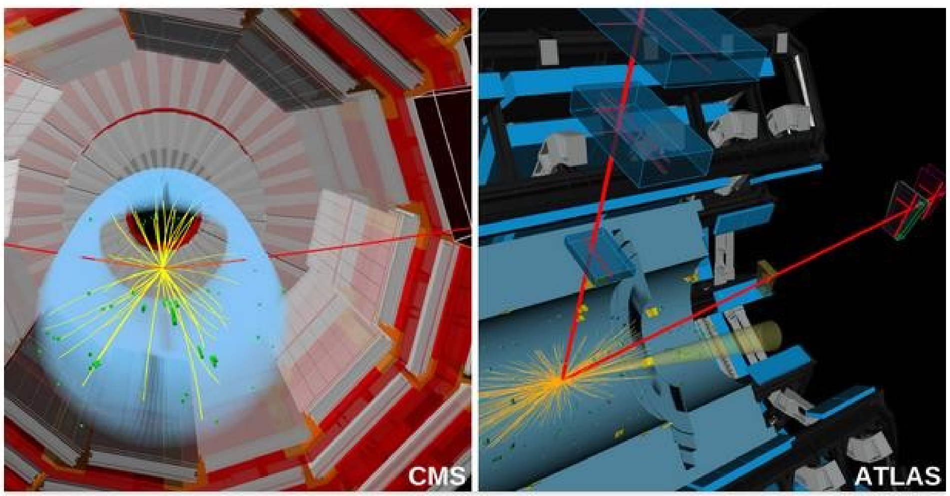
- H → $b\bar{b}$ also observed by ATLAS:
  evidence 4.9σ, signal strength
  1.01± 0.12(stat) ±0.16(syst)
  Phys. Lett. B 786 (2018) 59

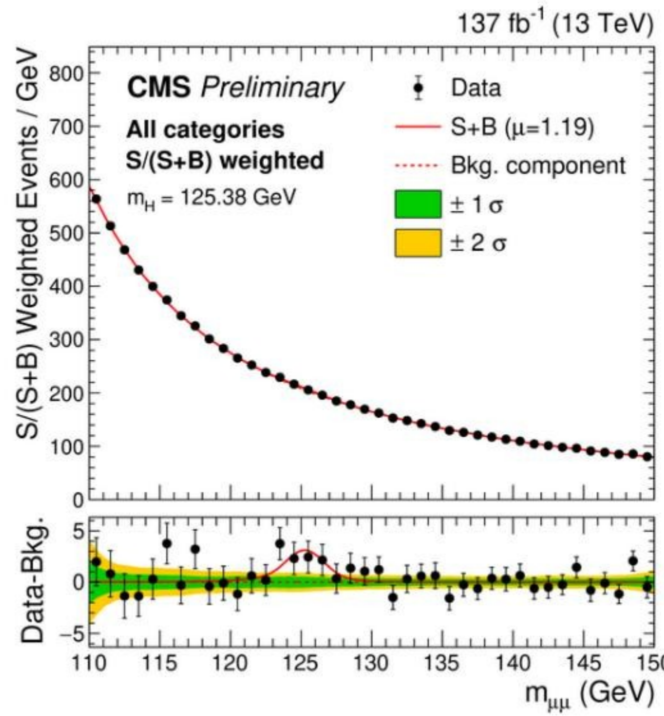
2020: $H \rightarrow \mu\mu$

CERN experiments announce first indications of a rare Higgs boson process

The ATLAS and CMS experiments at CERN have announced new results which show that the Higgs boson decays into two muons

3 AUGUST, 2020





Significance of observation:

ATLAS: 2.0 σ

CMS 3.0 σ

Higgs Analyses with full Run 2 data

The goal:

differential cross sections w.r.t production mode

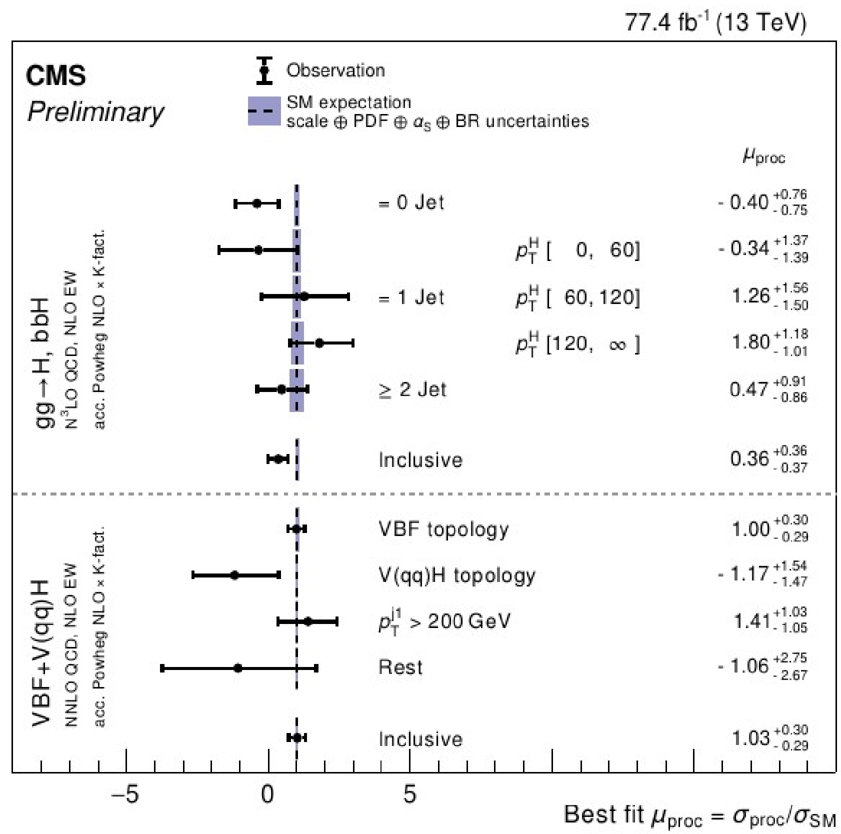
in bins of transverse momentum of the Higgs boson

- **κ- framework no longer suitable;**

  interpretation in terms of “effective field theories”, which allow for additional non-SM coupling terms

- **Example:**

  preliminary CMS H→ ττ:
  Signal strength in several categories



CMS PAS HIG-18-32

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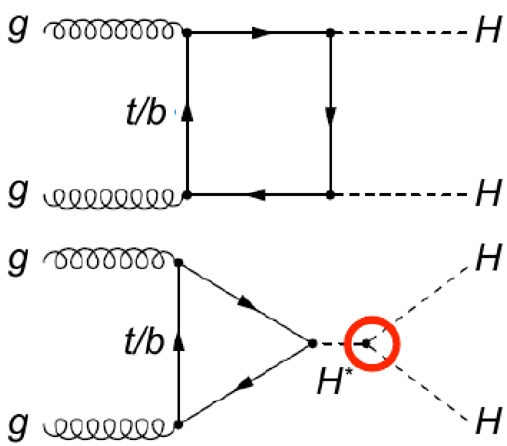
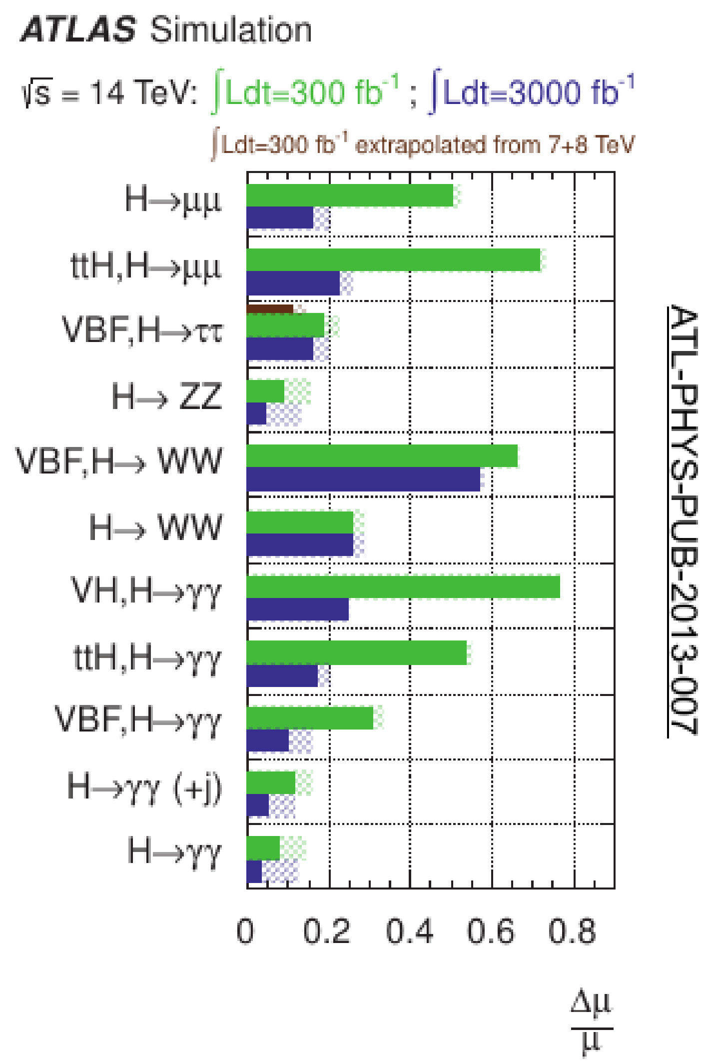
LHC Upgrade & Higgs Physics

Extrapolation: **expected uncertainty** of Higgs observables

- Benchmarks: **300 fb^{-1}** (end of Run 3) and **3000 fb^{-1}** (end of HL-LHC)
- Very clean channel accessible for the first time: ***H* → *μμ***
- Higgs-boson **self-coupling**: e.g. in Higgs **pair production** (arguably the "holy grail" of Higgs physics)

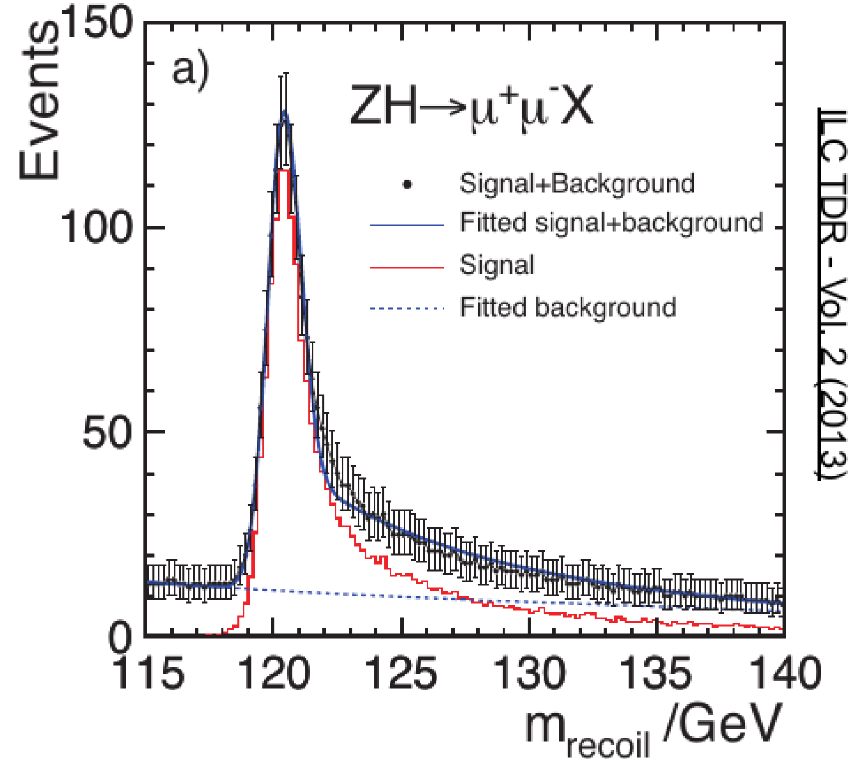




Higgs Physics at a future electron maching

- Production processes:
  - Dominant: **Higgs-strahlung** and ***WW* fusion** (as for LEP, for $\sqrt{s} \lesssim 250$ GeV)
  - Further processes, e.g. $t\bar{t}H$ (for $\sqrt{s} \lesssim 500$ GeV)

- Most important analysis channel: $e^+e^- \rightarrow ZH \rightarrow \ell^+\ell^- + X$
  - Higgs-boson mass from **recoil** against *Z* boson: m_{recoil}
  - "Higgs physics without looking at the Higgs": independent of Higgs model, access to **invisible** channels



$$
\begin{aligned}
m_H^2 &= \left(p_{\ell\ell} - (p_{e^+} + p_{e^-})\right)^2 \\
&= m_{\ell\ell}^2 + (p_{e^+} + p_{e^-})^2 - 2p_{\ell\ell} \cdot (p_{e^+} + p_{e^-}) \\
&= m_Z^2 + s - 2E_{\ell\ell}(E_{e^+} + E_{e^-}) + 2\,\mathbf{p}_{\ell\ell}\,(\mathbf{p}_{e^+} + \mathbf{p}_{e^-}) \\
&= m_Z^2 + s - 2E_Z\sqrt{s}
\end{aligned}
$$

Summary: Higgs Physics

- Higgs boson with a mass m_H=125 GeV discovered in 2012
- production and decay rates compatible with mass-dependent couplings to Bosons and Ferminons
- Decays to pairs of Z and W bosons, Photons, tau-leptons, top and b quarks established with a statistical significance $z > 5\sigma$ in a single experiment by both ATLAS and CMS
- Higgs mass is consistent with electroweak precision measurements
- Future tasks: initial measurement of couling to myons, precise determination of all couplings and CP value → deviations from Standard model would point to new physics
- measurement of Higgs Boson self coupling at a later stage of the LHC (High Lumi upgrade) or at a future electron-positron collider;
- measurement of the total Higgs width (including invisible or undetectable decay modes)
- Related: extended Higgs sector (e.g. 5 Higgs bosons in super-symmetric models) → later

see more specialized lecture in summer 2021: