

# New Results on Particle and Astroparticle Physics with an Emphasis on Higgs Physics

Peter Fackeldey

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# O Higgs Boson, where art thou?

Preparation time: 1964 - 2008

- 400 ml Theorists! (Brout, Englert, Higgs and GHK)
- 800 g New theory: Higgs mechanism
- 3 cups 1964 Symmetry breaking papers
- 1 tbs� Circular collider (LHC)
- 1 cup Detector (CMS/ATLAS)

Cooking time: 2009 - 2012

- 2 tsp Proton bunches
- 10 oz Grid computing (CERN, FNAL, KIT, ...)
- 5 g Analysis software
- 1000 cans Low-paid grad students

# Higgs Mechanism: A New Hope

- > **Problem:** The Standard Model (SM) misses mass terms for the weak gauge bosons
- > **Proposal:** Spontaneous electroweak symmetry breaking (Higgs mechanism)
- > New scalar field  $\Phi$  based on the following lagrangian is introduced:

$$\mathcal{L}_{\text{Higgs}} = \underbrace{(D^\mu \Phi)^\dagger (D_\mu \Phi)}_{\text{Kinetic}} - \underbrace{\mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2}_{\text{Potential}} \quad \text{with} \quad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- > **Potential** contains two terms:
  - > Mass term:  $-\mu^2 \Phi^\dagger \Phi$ :  $\mu^2$  can be negative or positive
  - > Self-coupling term:  $-\lambda (\Phi^\dagger \Phi)^2$ :  $\lambda$  is a dimensionless positive constant

# Revenge of the Symmetry Breaking

- > If  $\mu^2 > 0$  there is only one ground state possible:  $\langle \Phi \rangle_0 = 0$
- > If  $\mu^2 < 0$  there are multiple ground states:

$$|\langle \Phi \rangle_0|^2 = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} \quad \text{with} \quad v = \text{vacuum expectation value}$$

- > Without the loss of generality:

$$\langle \Phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \Rightarrow \quad \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

- >  $H(x)$  describes the Higgs field

# The Mass Terms Awakens

- > Kinetic term  $|D_\mu \Phi|^2$ :

$$\begin{aligned} |D_\mu \Phi|^2 &= \frac{1}{8} v^2 g_2^2 |W_\mu^1 + i W_\mu^2|^2 + \frac{1}{8} v^2 |g_2 W_\mu^3 - g_1 B_\mu|^2 + \dots \\ &= \frac{1}{2} m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu + \dots \end{aligned}$$

- > Mass terms occur for the weak gauge bosons!
- > Potential of the lagrangian  $V(x)$ :

$$V = \frac{1}{2} \mu^2 (v + H)^2 + \frac{1}{4} \lambda (v + H)^4 \quad \Rightarrow \quad m_H = -\sqrt{2} \mu = v \sqrt{2 \lambda}$$

- > Mass term for the Higgs Boson, the excitation of  $H(x)$ , occurs

# The Yukawa Interaction Strikes Back

- > The fermion masses can not be described by the Higgs mechanism, due to the chirality
- > An interaction between Dirac (fermion) fields and a scalar (Higgs) field is described by Yukawa interaction:

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_f \psi_L^\dagger \Phi \psi_R$$

- > Lagrangian for fermion mass:

$$\mathcal{L}_{m_f} = -\lambda_f (\psi_L^\dagger \Phi \psi_R + \psi_R^\dagger \Phi^\dagger \psi_L) \quad \text{with} \quad \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

- > Yields:  $m_f = \frac{v}{2} \lambda_f$  and  $g_{Hff} = \frac{m_f}{v}$



SUISSE  
FRANCE

CMS

LHCb

CERN Meyrin

ATLAS

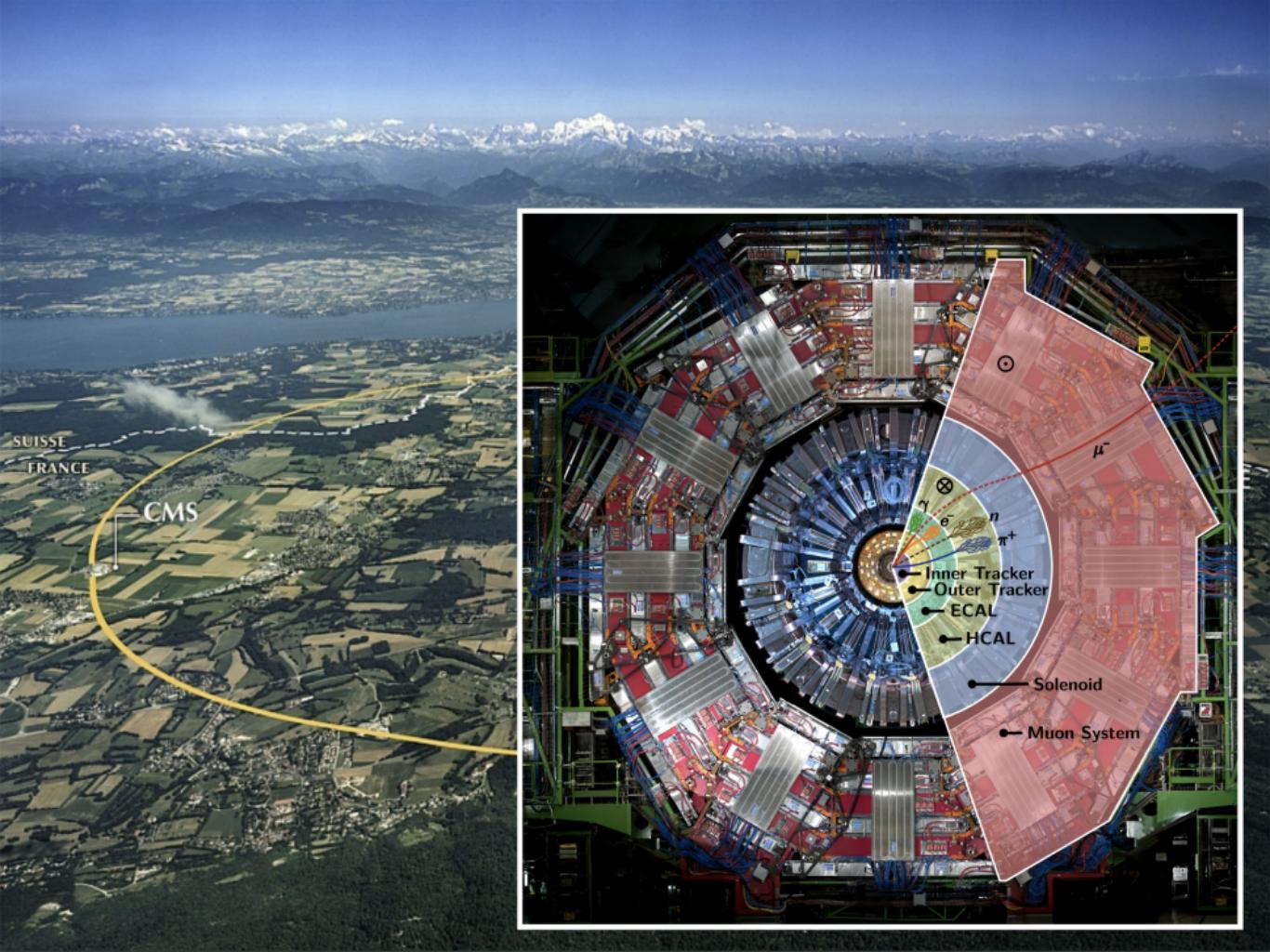
SPS 7 km

ALICE

LHC 27 km

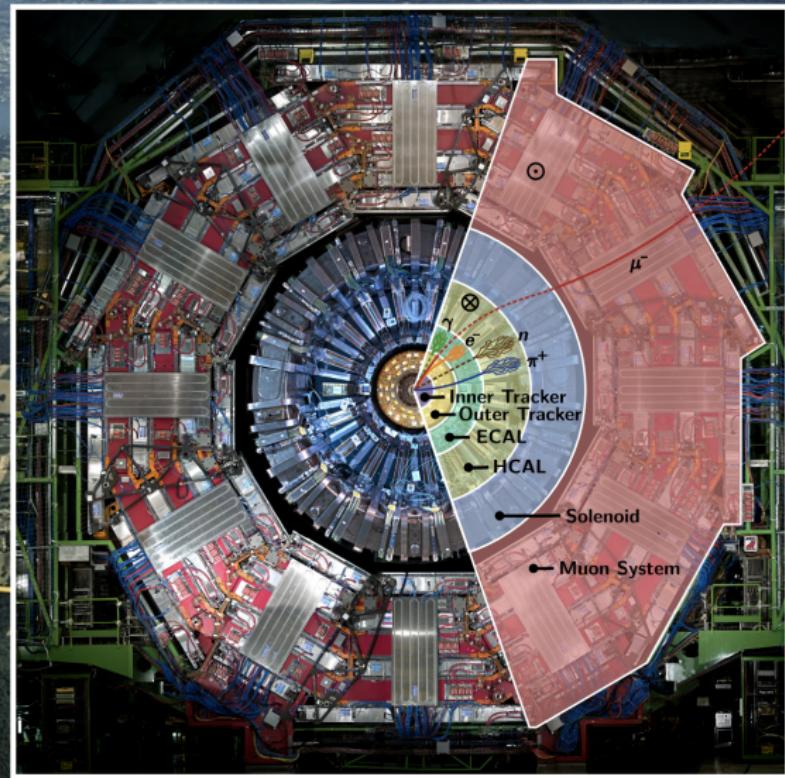
CERN Meyrin

Precyssin



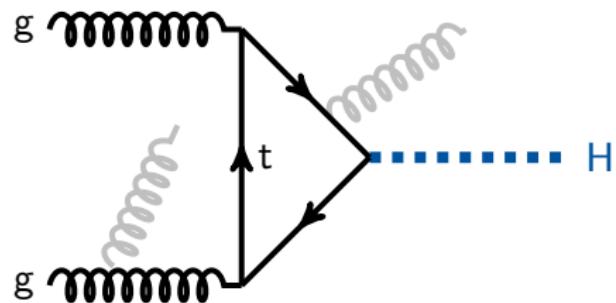
SUISSE  
FRANCE

CMS

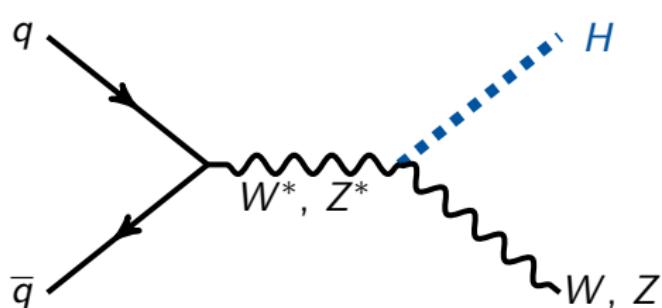


# Higgsproduction Modes @ LHC (pp Collider)

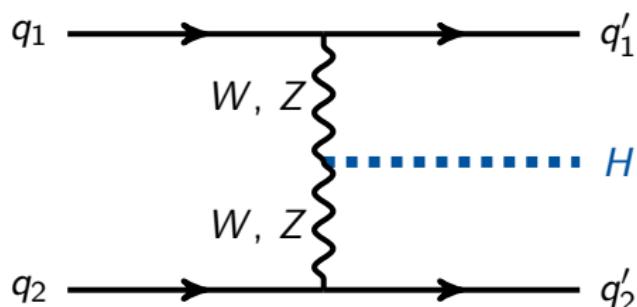
Gluon Fusion



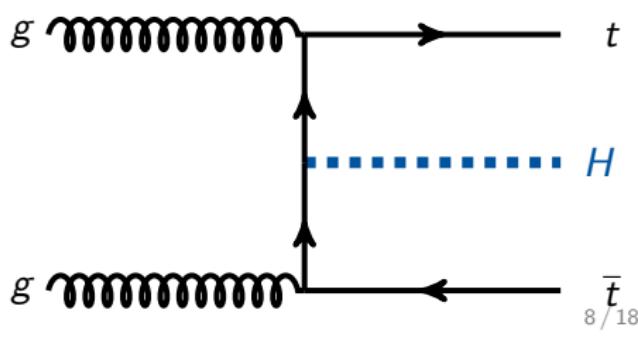
Higgs Strahlung



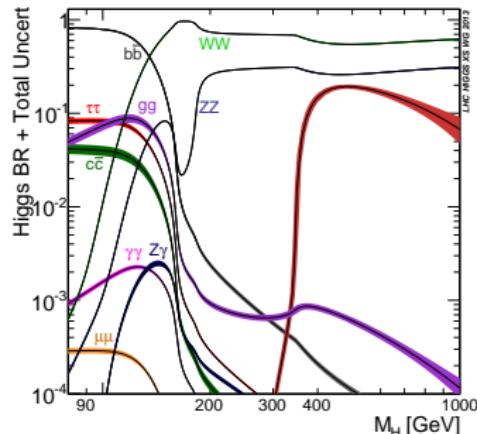
Vector Boson Fusion



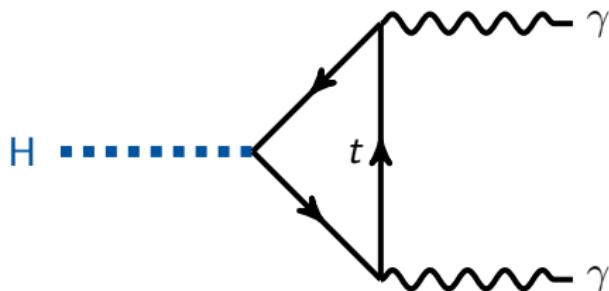
Quark Associated Production



# Higgs Decays



Special case:  $H \rightarrow \gamma\gamma$

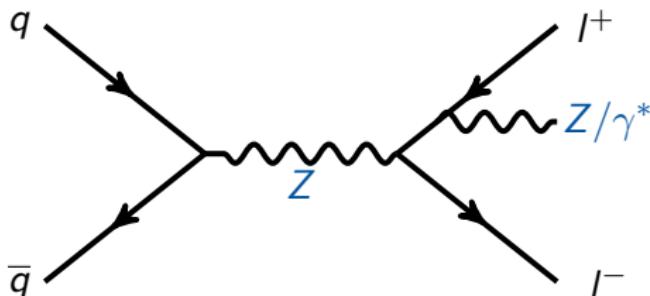


Decay Channel	Branching Fraction	Characteristics
$H \rightarrow b\bar{b}$	58.4%	High QCD
$H \rightarrow W^+W^-$	21.4%	Jets + MET
$H \rightarrow \tau^+\tau^-$	6.3%	Jets + MET
$H \rightarrow ZZ \rightarrow 4l$	2.6%	High mass resolution
$H \rightarrow \gamma\gamma$	0.2%	High mass resolution

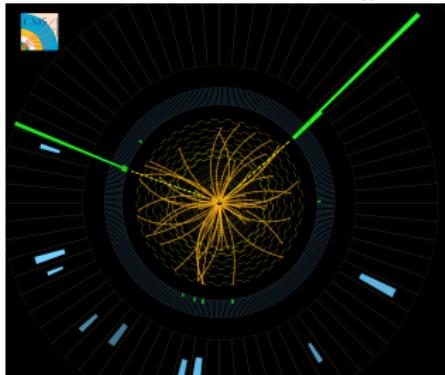
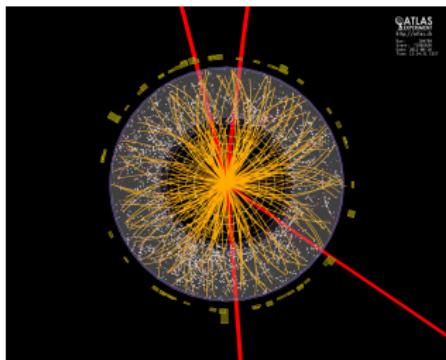
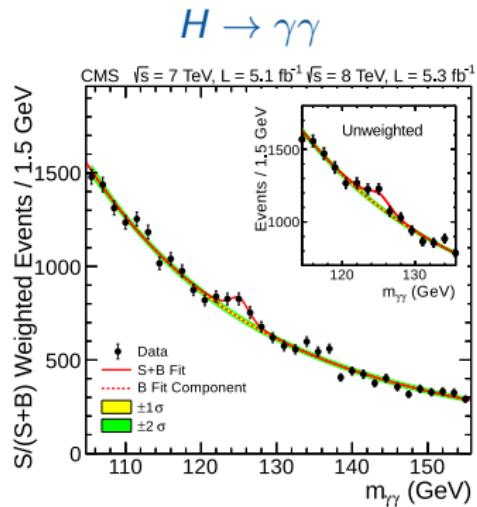
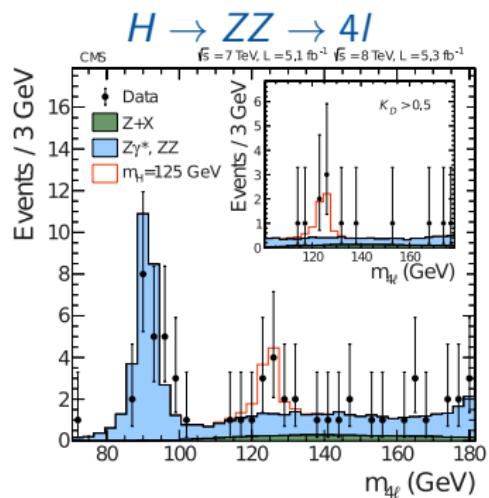
# SM $H \rightarrow ZZ \rightarrow 4l$ Search

- > 4 leptons in the final state: 4e, 4 $\mu$ , 2e2 $\mu$
- > Z candidates: opposite sign same flavour (OSSF) leptons with  $12 < m_{ll} < 120\text{GeV}$
- > ZZ candidates: 1 on-shell Z boson and 1 off-shell Z boson
- > Combine the leptons:
  - > On-shell Z boson:  $m_{ll} \approx 91\text{GeV}$
  - > Off-shell Z boson: the other combination
- > Remaining irreducible backgrounds: ZZ,  $Z\gamma^*$ , Z+X
- > Z+X:  $Z+\text{jets}$ ,  $t\bar{t}+\text{jets}$ ,  $Z\gamma+\text{jets}$ , WW+jets and WZ+jets

ZZ,  $Z\gamma^*$

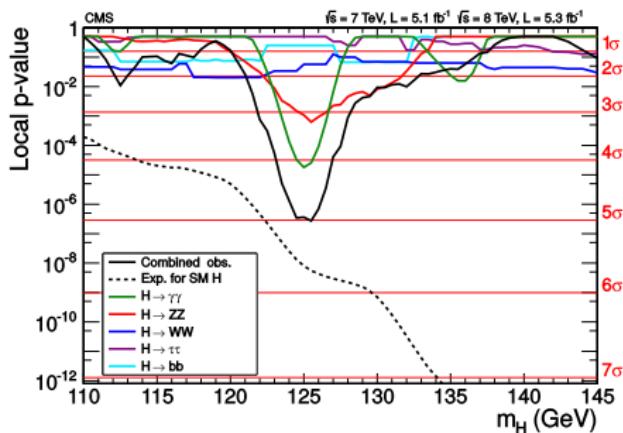
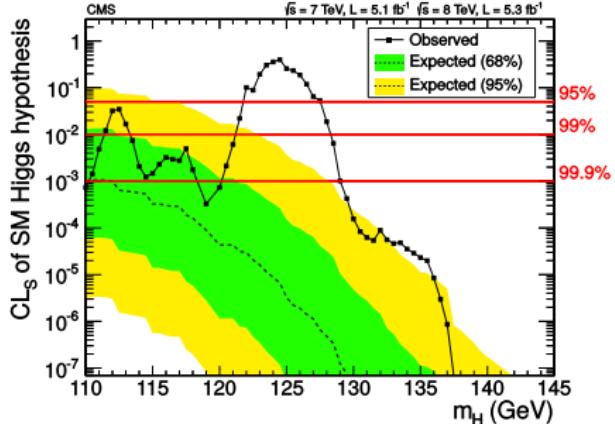


# July 2012: Higgs Discovery @ CMS & ATLAS



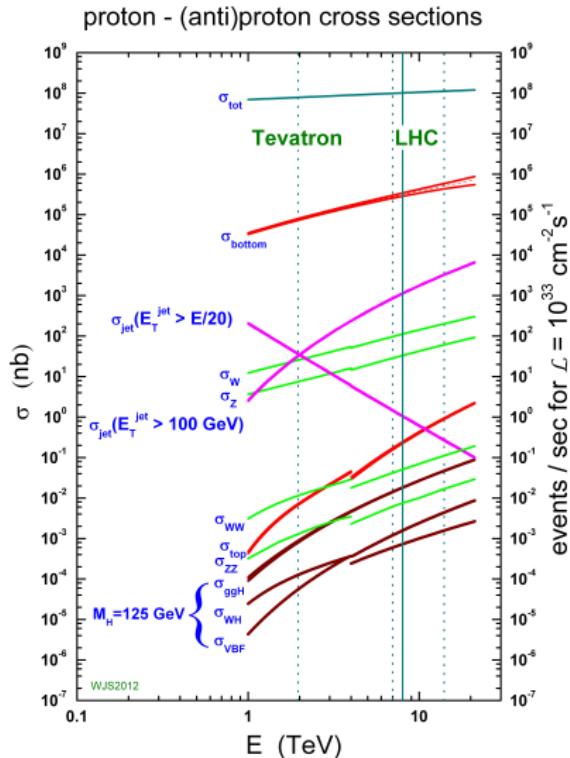
# July 2012: Higgs Discovery @ CMS & ATLAS

- > CMS-HIG-12-028:
  - >  $5.0\sigma$ :  $125.3 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (sys) GeV}$
- > CERN-PH-EP-2012-218:
  - >  $5.9\sigma$ :  $126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (sys) GeV}$



Decay mode/combination	Expected ( $\sigma$ )	Observed ( $\sigma$ )
$\gamma\gamma$	2.8	4.1
$ZZ$	3.8	3.2
$\tau\tau + bb$	2.4	0.5
$\gamma\gamma + ZZ$	4.7	5.0
$\gamma\gamma + ZZ + WW$	5.2	5.1
$\gamma\gamma + ZZ + WW + \tau\tau + bb$	5.8	5.0

# The Next Generation: 13 TeV & More Data...

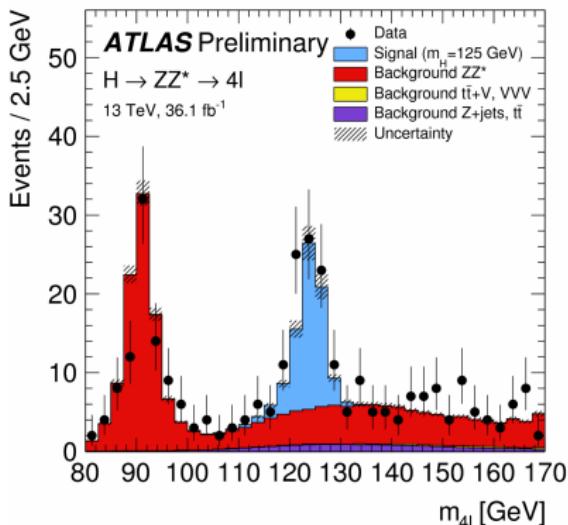


- > More integrated luminosity (higher statistics)
- > Higher cross sections for interesting physics

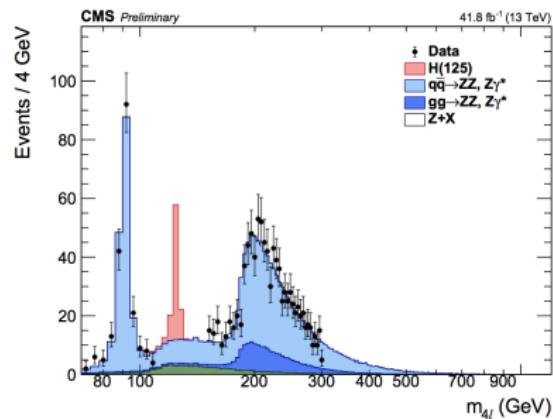
# Return of the Higgs Boson

- > Rediscovered with 2015/2016 Data!!!
- > HIG-18-001 Status: Currently @ preapproval
- > Signal region is still blinded
- > Improvements: b-tagging, new ttH categorization, electron ID

2016 Data of  $36.1\text{fb}^{-1}$



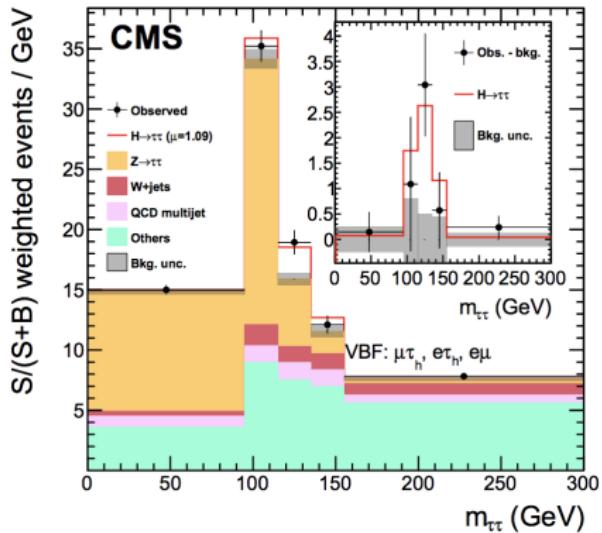
2017 Data of  $41.8\text{fb}^{-1}$



# $H \rightarrow \tau\tau$ Discovery

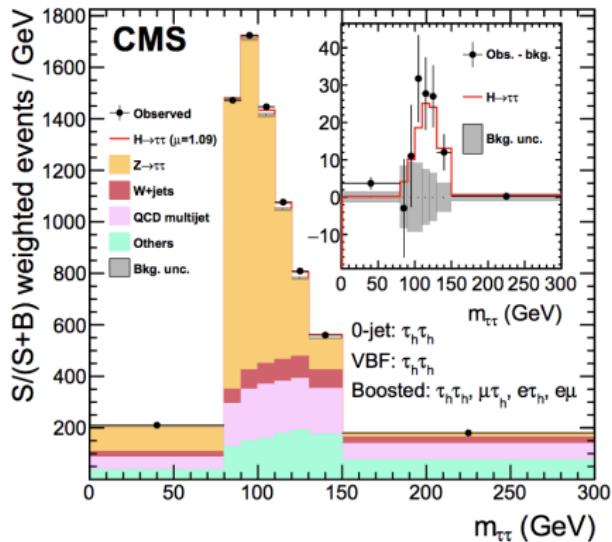
$H \rightarrow e\tau_h, \mu\tau_h, e\mu$

$35.9 \text{ fb}^{-1}$  (13 TeV)



$H \rightarrow \tau_h\tau_h$

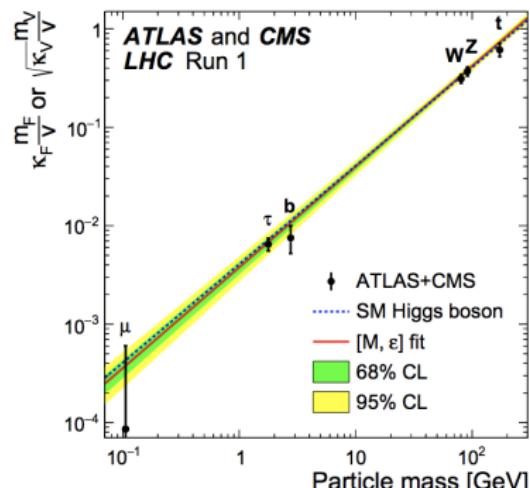
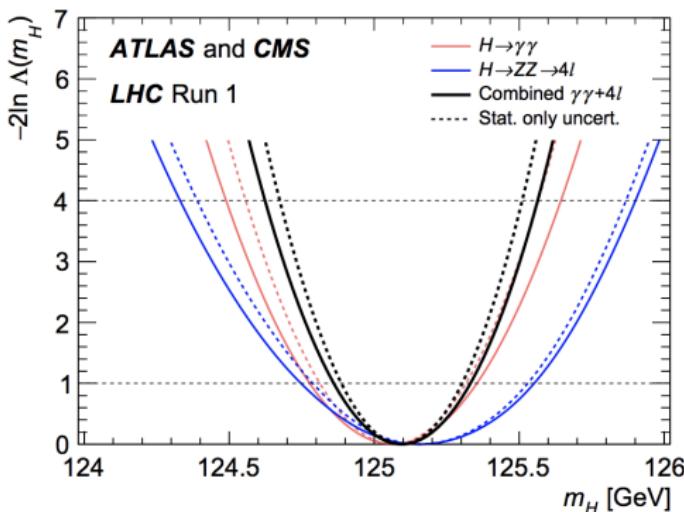
$35.9 \text{ fb}^{-1}$  (13 TeV)



- >  $H \rightarrow \tau\tau$  found with  $5.9\sigma$
- > Best fit value:  $\mu = 1.09^{+0.27}_{-0.26}$  at  $m_H = 125.09 \text{ GeV}$ .

# Properties of the Higgs boson

- >  $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\text{GeV}$
- > Coupling is proportional to fermion masses:  $g_{Hff} = \frac{m_f}{v}$
- > Electrical charge: neutral, e.g.  $H \rightarrow \tau^+ \tau^-$  discovery
- > Spin: 0,  $H \rightarrow \gamma\gamma$  discovery
- > No color charge: measured in e.g.  $H \rightarrow b\bar{b}$
- > CP eigenvalue not measured yet; predicted to be +1

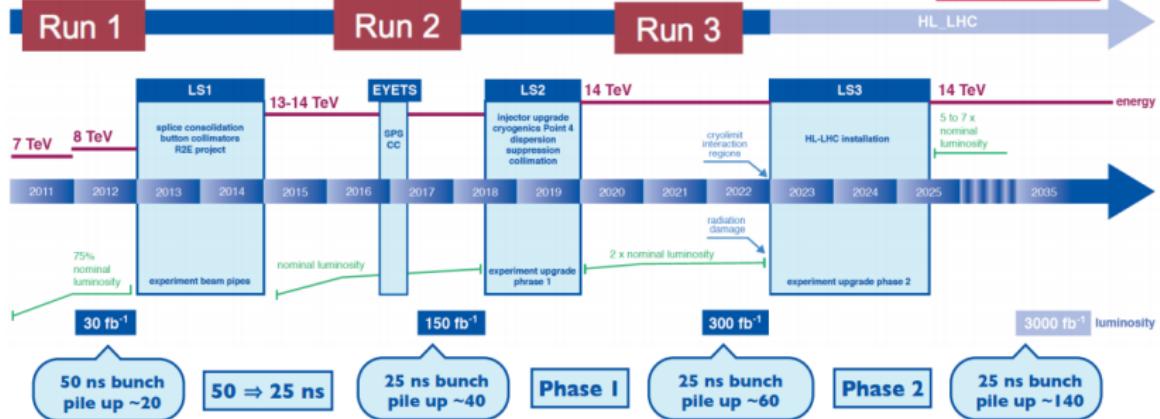


## High Luminosity LHC

### LHC / HL-LHC Plan



BUL-NA-2014-272



# Exciting Times Ahead...

- > Higgs boson as a probe for new physics
- > Measurement of CP properties
- > Discovery in missing decay channels
- > More Higgs bosons? (2HDM)
- > ILC: Higgs factory
- > Stay tuned!!!



<http://phdcomics.com/comics.php?f=1489>