Higgs Physics

A story of one discovery (Lecture II)

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DESY Summer Student Program

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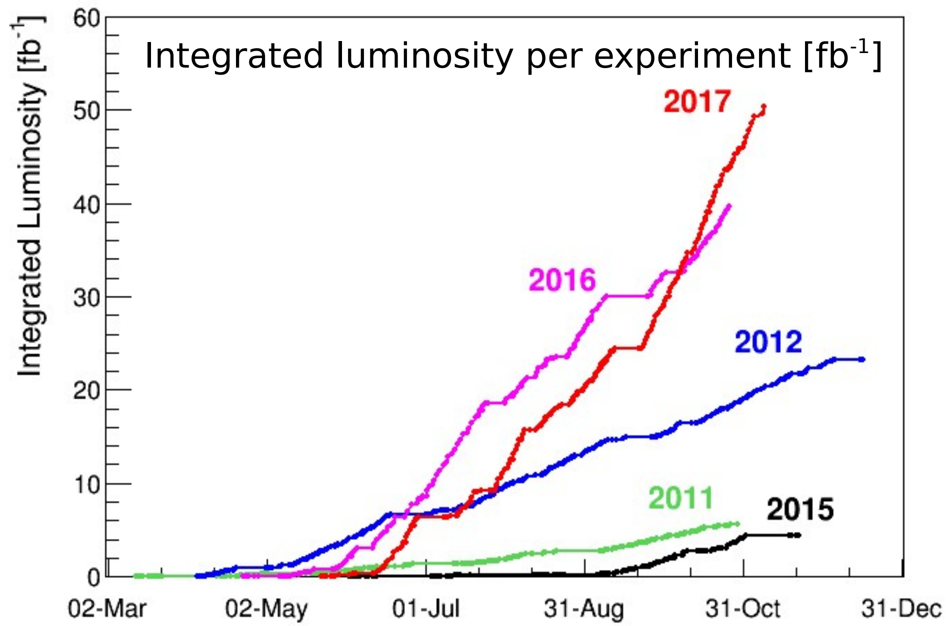
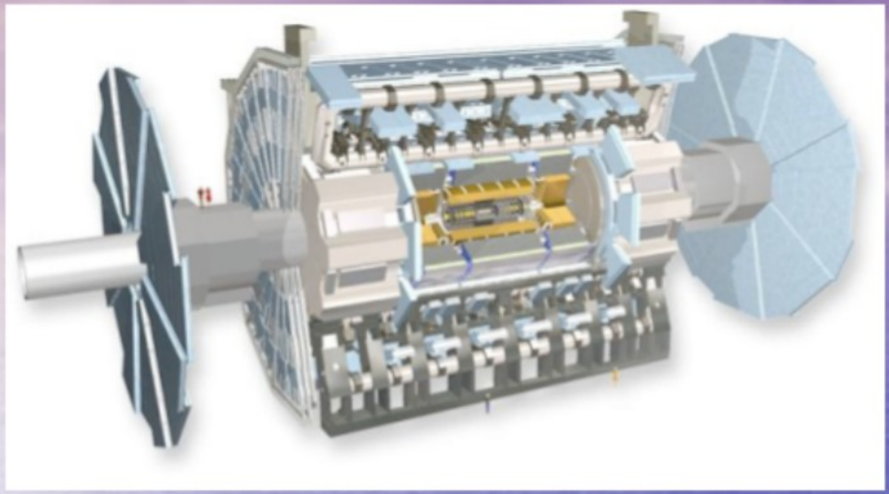
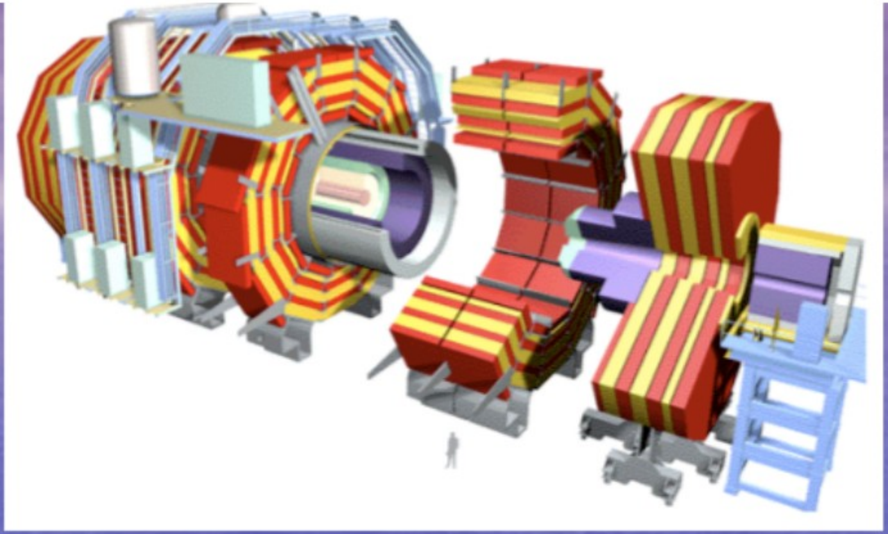
Large Hadron Collider

- high luminosity pp collider at CERN
- circumference : 27 km (former LEP tunnel)
- instantaneous luminosity
  - up to 10^{33} $cm^{-2}s^{-1}$ in Run1
  - up to $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$ in Run2
- center-of-mass energy
  - 7 TeV (2010-2011)
  - 8 TeV (2012)
  - 13 TeV (2016-2017)



ATLAS and CMS Experiments



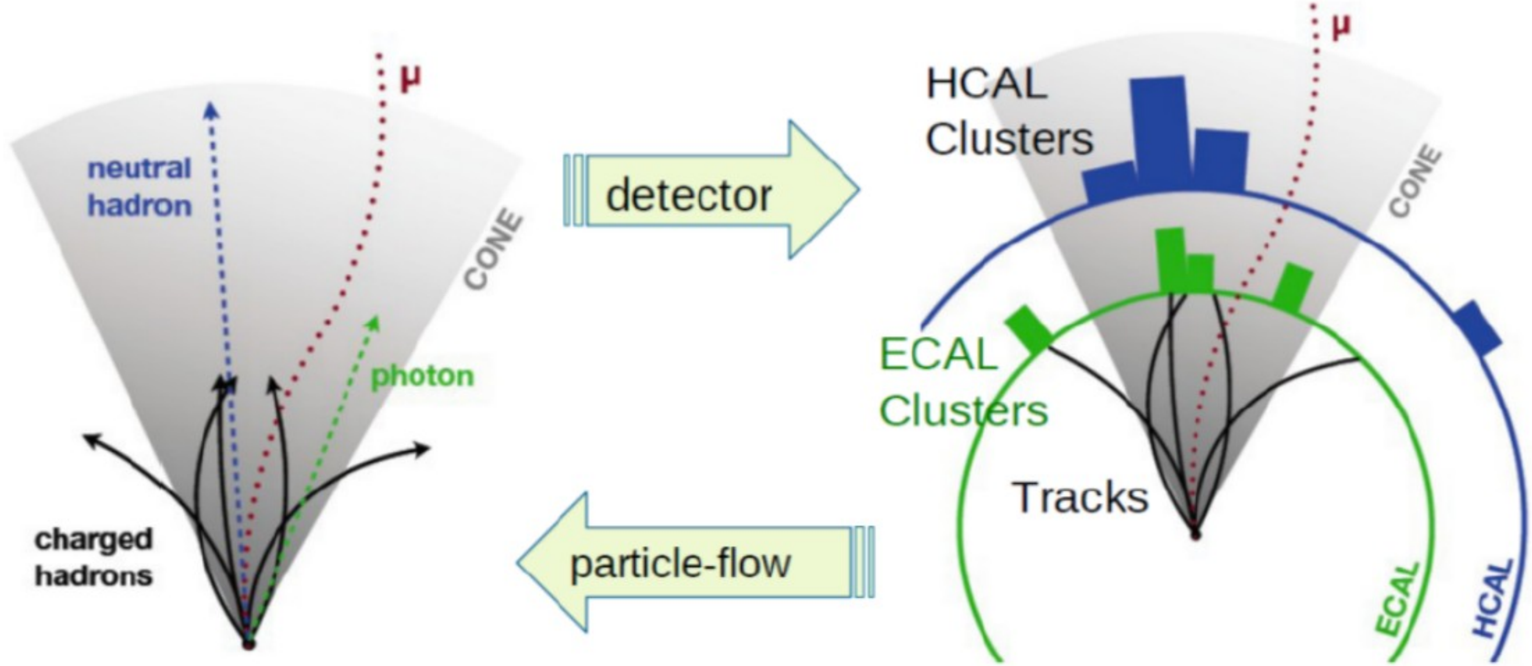


	ATLAS	CMS
Tracker	$|\eta|<2.5$ coverage $\sigma / p_T \approx 5 \cdot 10^{-5} p_T \oplus 0.01 [\mathrm{GeV}]$	$|\eta|<2.6$ coverage $\sigma / p_T \approx 1.5 \cdot 10^{-5} p_T \oplus 0.005$
EM Calorimeter	$|\eta|<4.9$ coverage $\sigma / E \approx 10\% / \sqrt{E} [\mathrm{GeV}]$	$|\eta|<4.9$ coverage $\sigma / E \approx 2-5\% / \sqrt{E}$
HAD Calorimeter	$|\eta|<4.9$ coverage $\sigma / E \approx 50\% / \sqrt{E} \oplus 0.03 [\mathrm{GeV}]$	$|\eta|<4.9$ coverage $\sigma / E \approx 100\% / \sqrt{E} \oplus 0.05$
Muon Spectrometer	$|\eta|<2.7$ coverage: $\sigma / p_T \approx 0.07$ *(1TeV muons)*	$|\eta|<2.6$ coverage: $\sigma / p_T \approx 0.10$ *(1TeV muons)*

Particle Flow Concept

Consistent Interpretation of all detector Signal in terms of individual Particles:

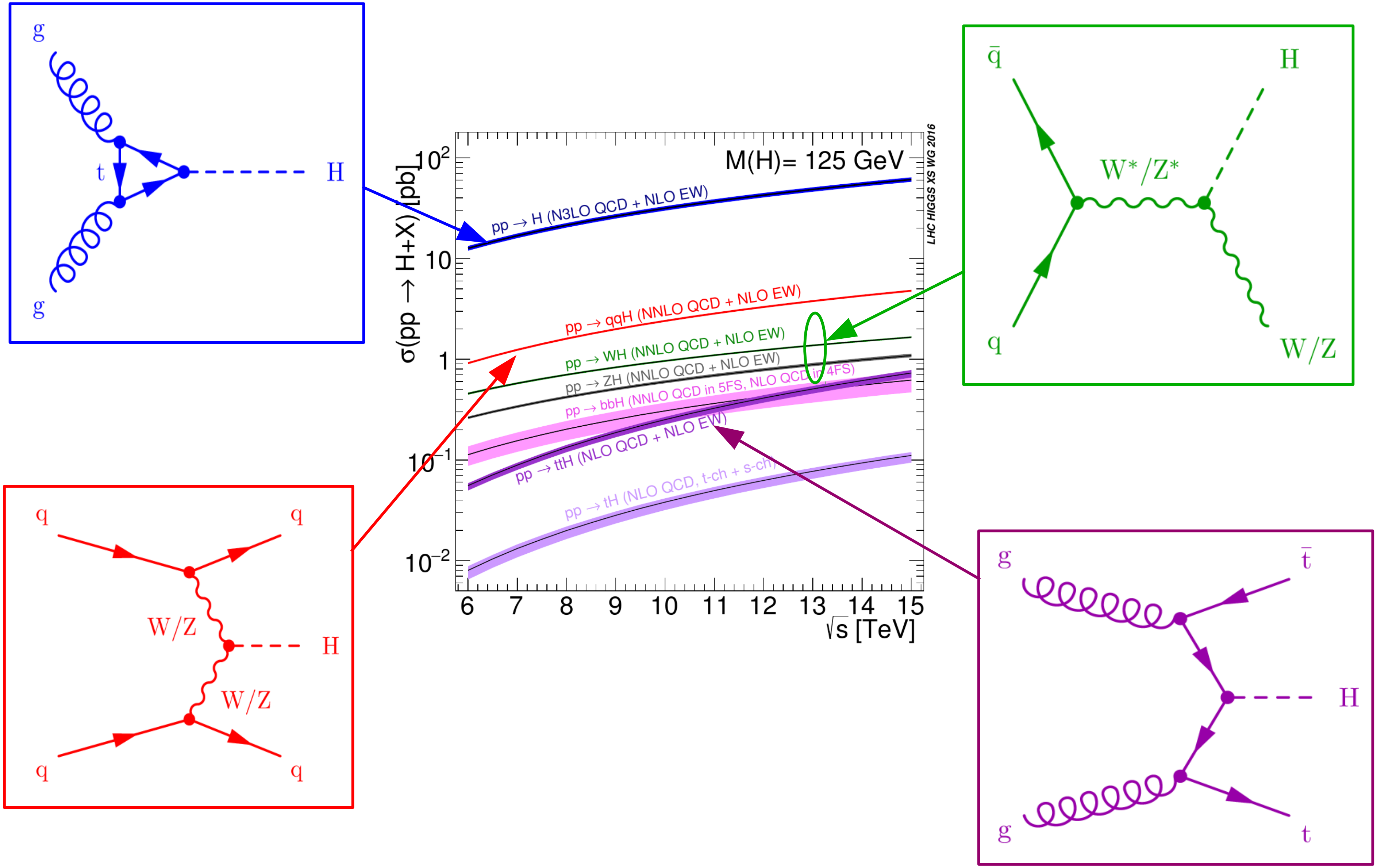
- e, μ, photons, charged Hadrons, neutral Hadrons



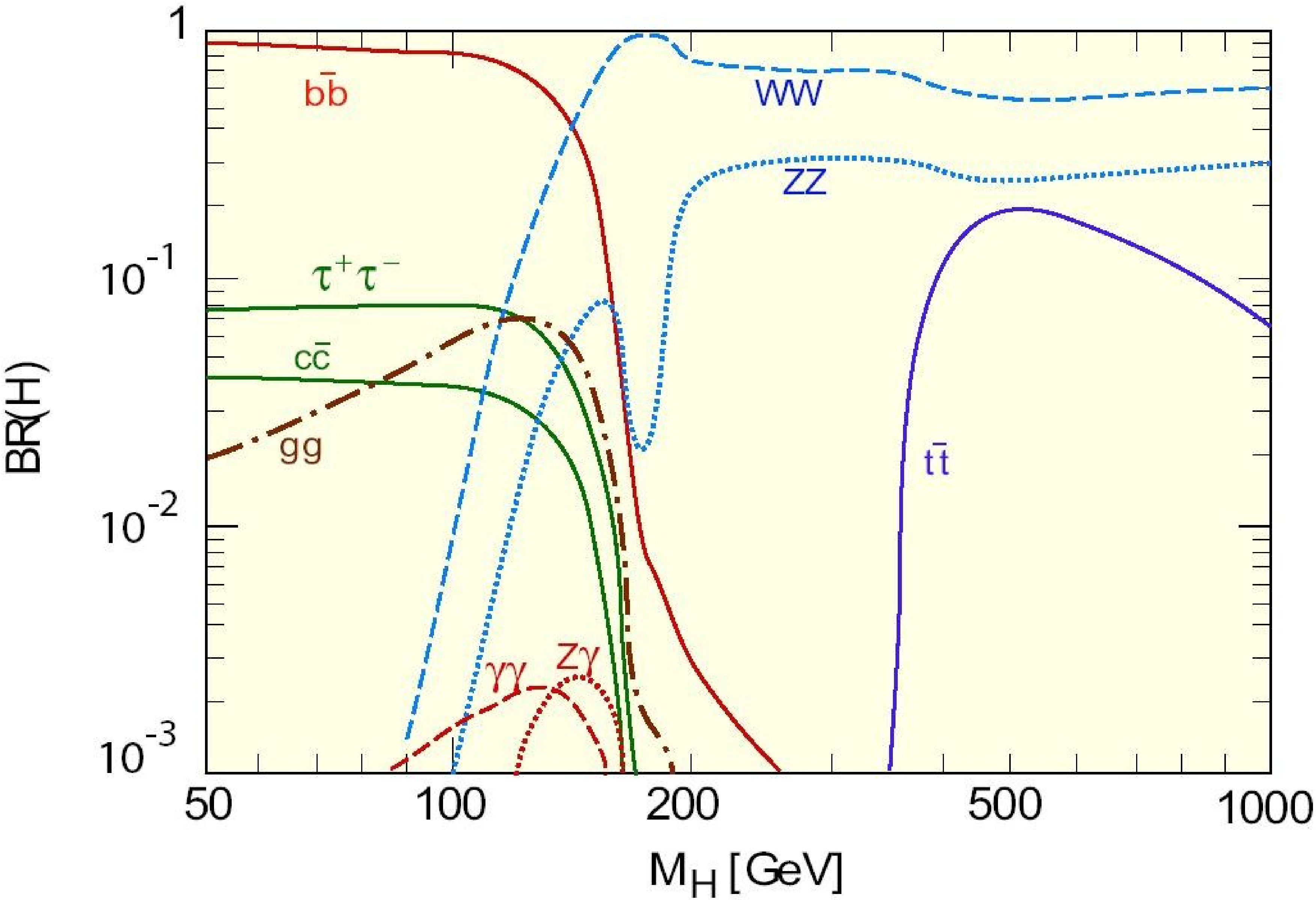
Higher level Objects are reconstructed using individual Particles as Input:

- τ_h, Jets (incl. b-tagging), E_T^{miss}
- Particle Isolation

Standard Model Higgs Boson at LHC

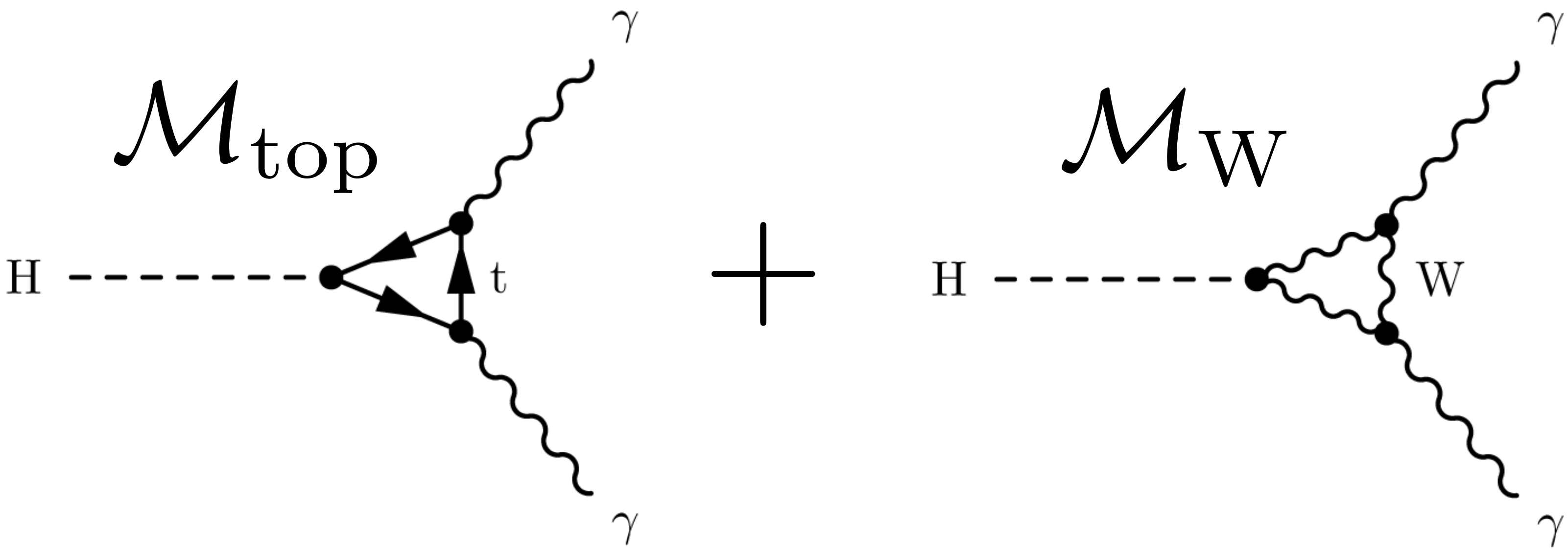


Higgs Boson Decay Branching Ratios



H → γγ Decay

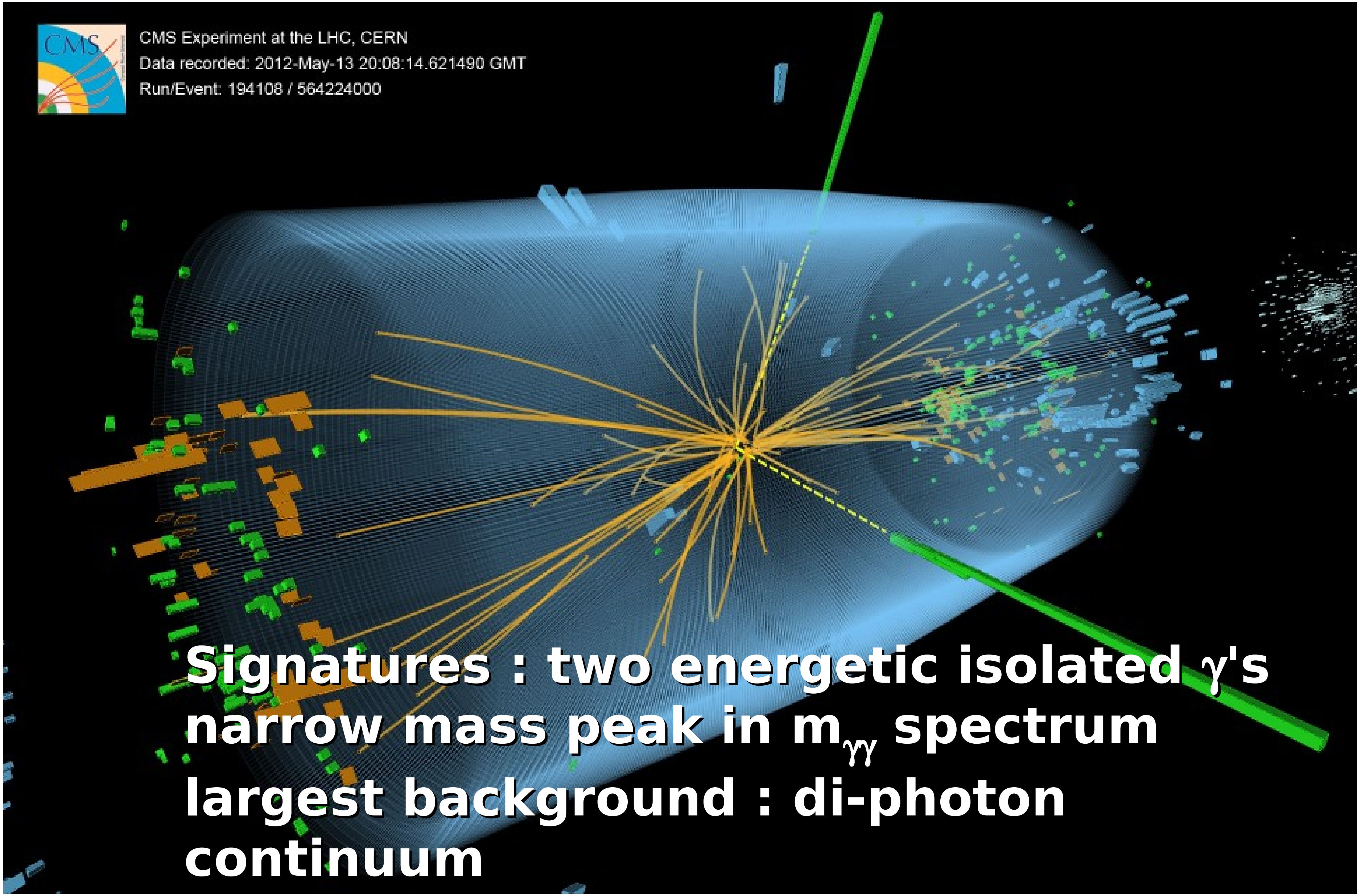
- **Higgs boson does not directly couple to photon (photon is massless)**
- **H → γγ decay proceeds via top- and W-loops**



$$|\mathcal{M}_{\mathrm{H}\to\gamma\gamma}|^2 = |\mathcal{M}_{\mathrm{top}} + \mathcal{M}_{\mathrm{W}}|^2$$

- two diagrams contribute with opposite signs to the total matrix element $\mathcal{M}_{\mathrm{H}\to\gamma\gamma}$ → destructive interference

H → $\gamma\gamma$ Channel



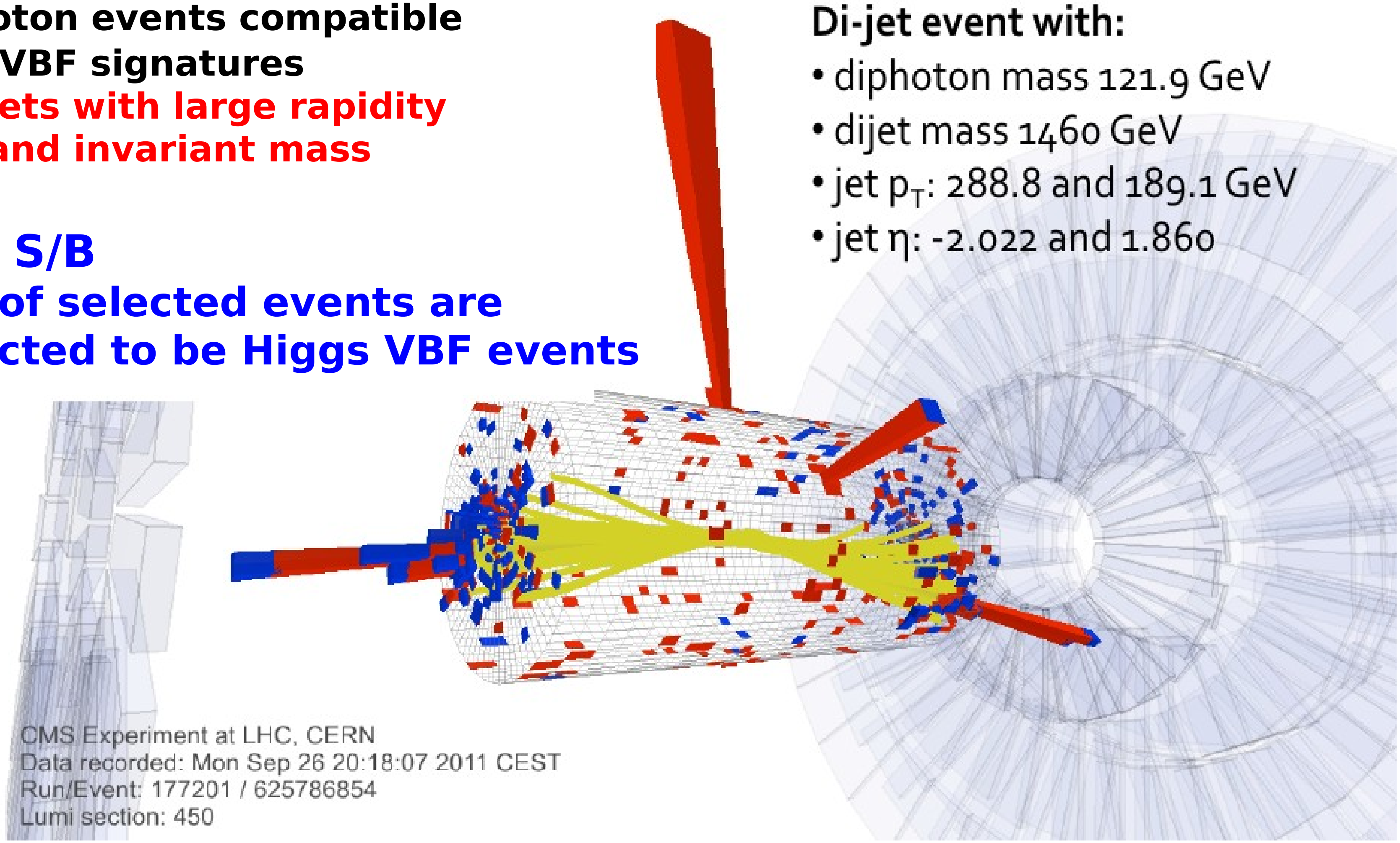
Signatures : two energetic isolated γ's
narrow mass peak in $m_{\gamma\gamma}$ spectrum
largest background : di-photon continuum

Exploiting specific Higgs boson production modes

Exclusive di-jet category

diphoton events compatible with VBF signatures
two jets with large rapidity gap and invariant mass

→ **high S/B**
80% of selected events are expected to be Higgs VBF events

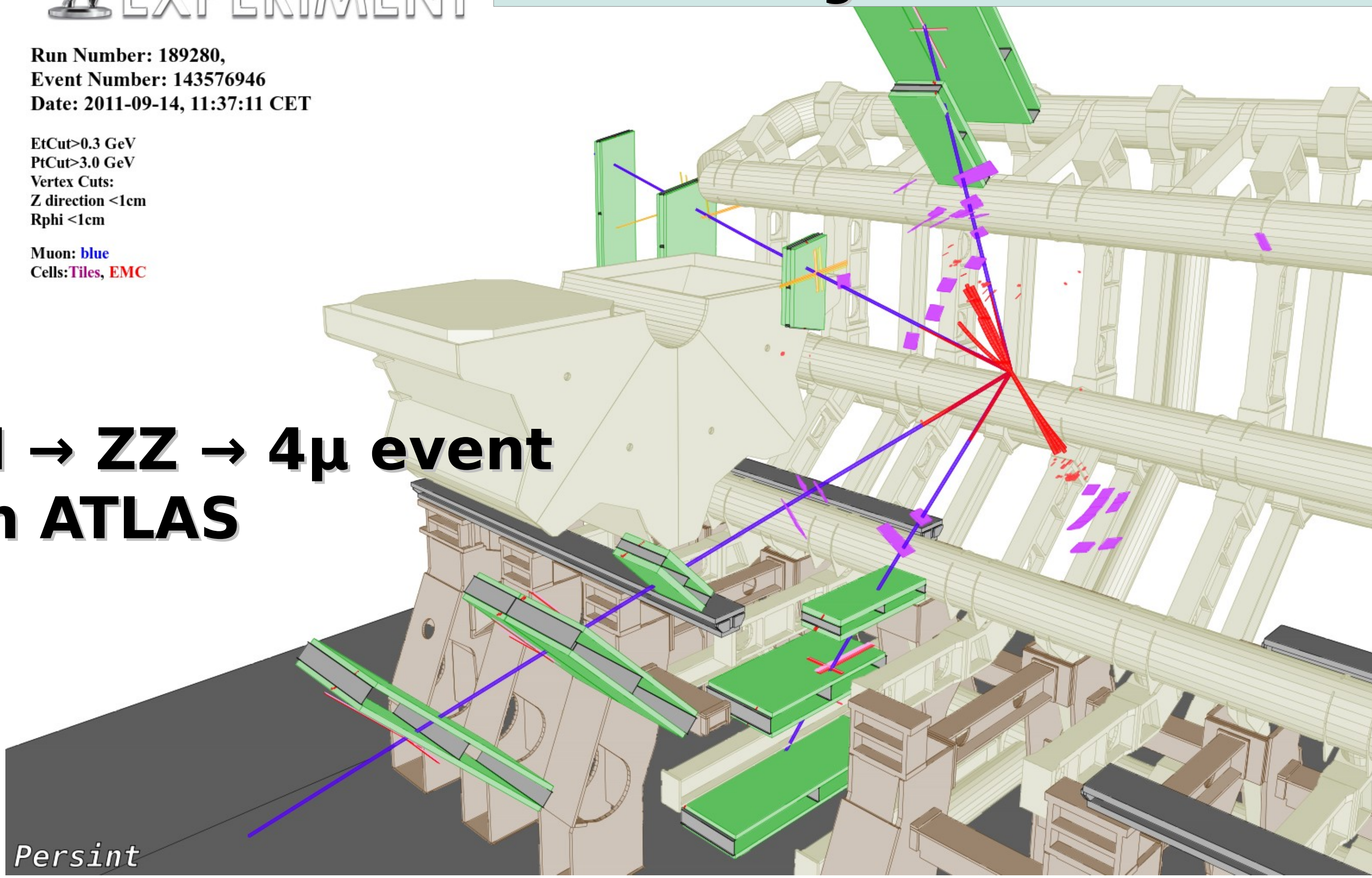


H → ZZ* → 4ℓ

Signatures : 4 isolated leptons

$H \to ZZ \to (e^+e^-)(e^+e^-) + (e^+e^-)(\mu^+\mu^-) + (\mu^+\mu^-)(\mu^+\mu^-)$

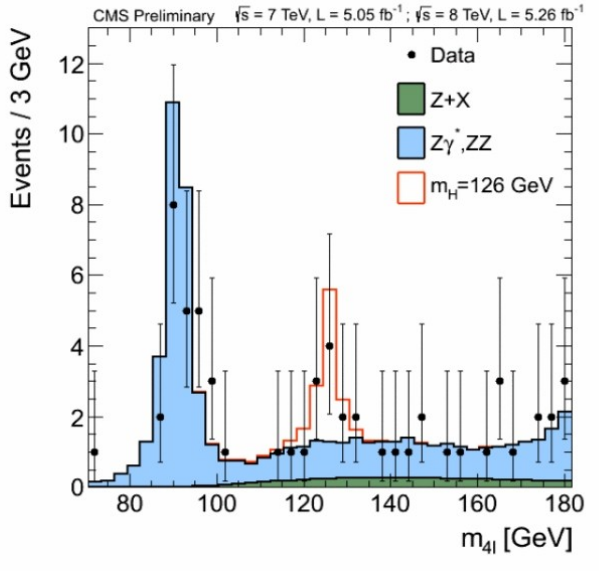
- **narrow mass peak in $m_{4\ell}$ spectrum**
- **main background : ZZ continuum**

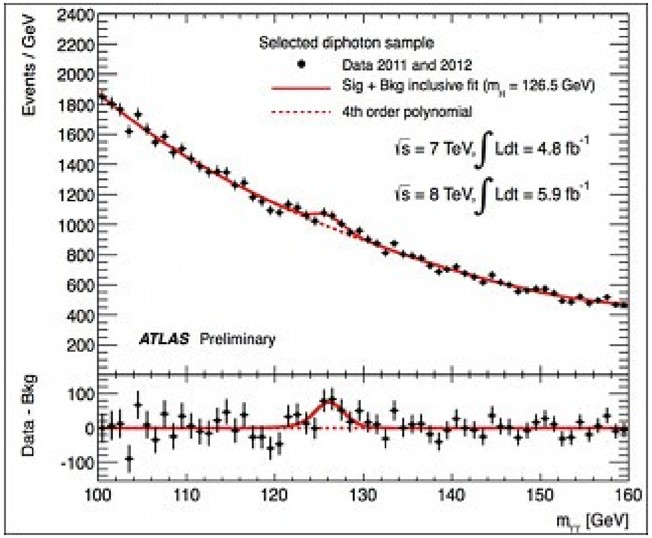


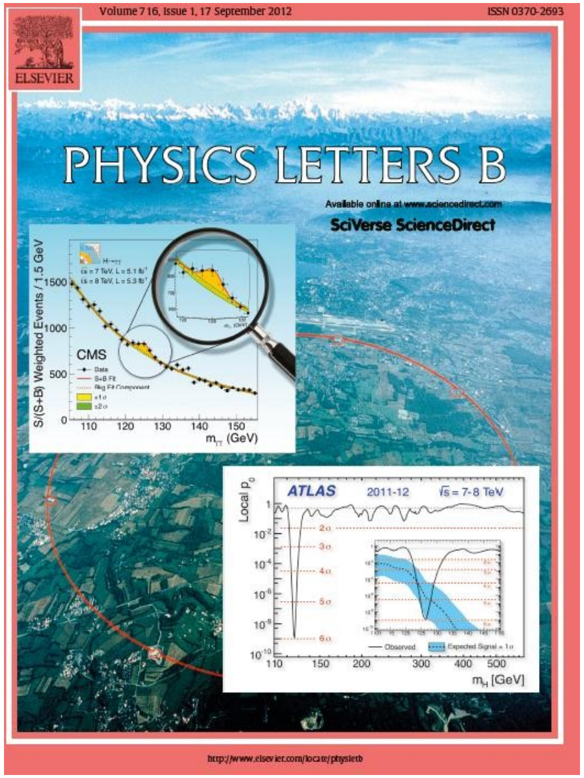
H → ZZ → 4μ event in ATLAS

Discovery of a Higgs Boson

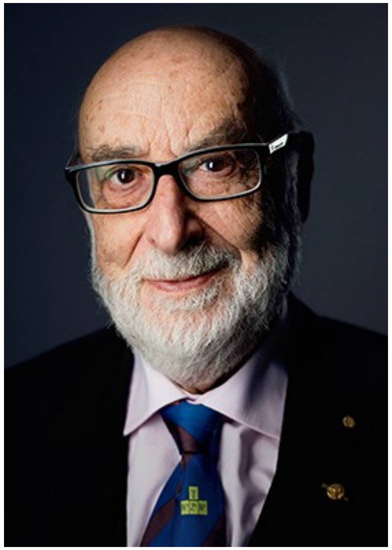
- **Search for a Higgs boson has a long history**
  - **(unsuccessful) attempts to find Higgs boson were made at LEP, SLAC, Tevatron**
- **Finally in 2012 ATLAS and CMS Collaborations announced discovery of a Higgs-like particle in decay channels with highest mass resolution : $H \to ZZ^* \to 4$leptons, $H \to \gamma\gamma$**







The Noble Prize in Physics 2013



François Englert

Peter Higgs

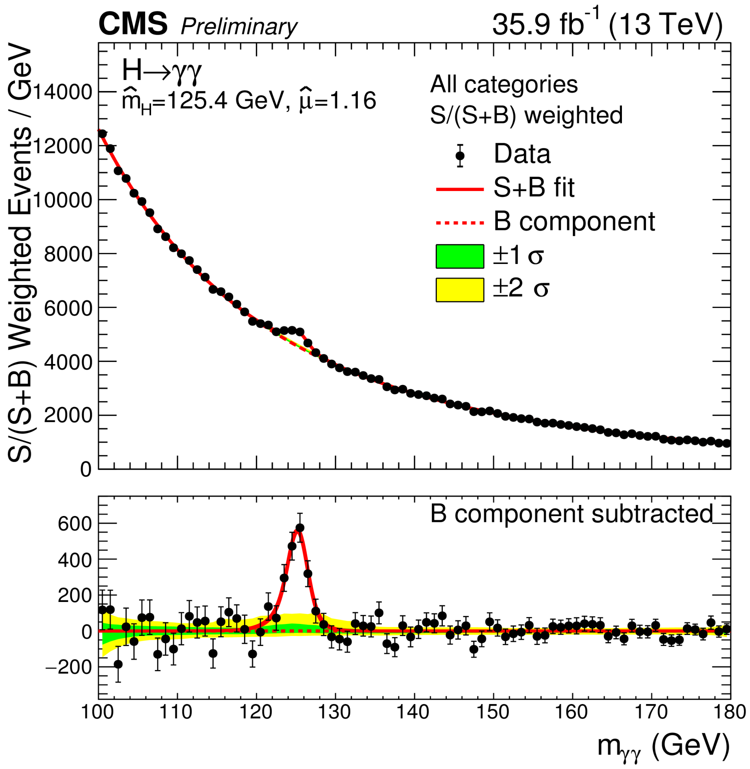
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Results from di-photon channel : CMS

Relatively clean channel

Excellent di-photon mass resolution : $m_{\gamma\gamma} \approx$ 3 GeV

Signal : peak in the di-photon mass spectrum over moderate background continuum



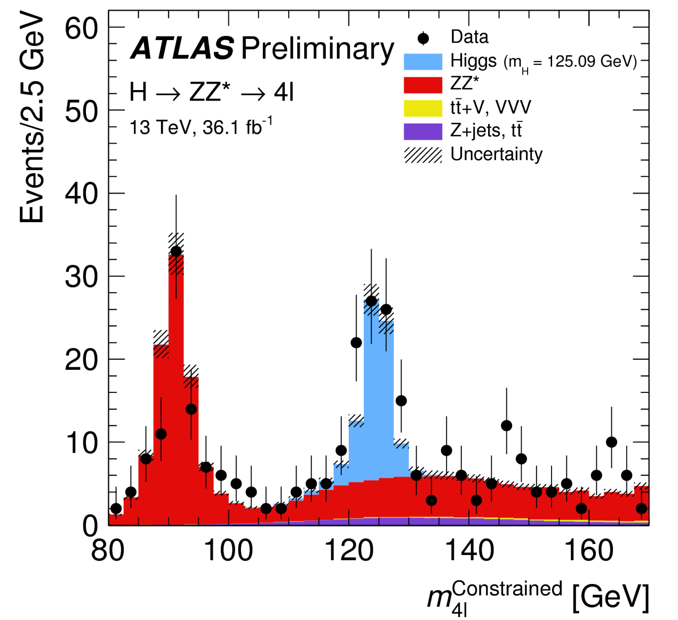
backgrounds

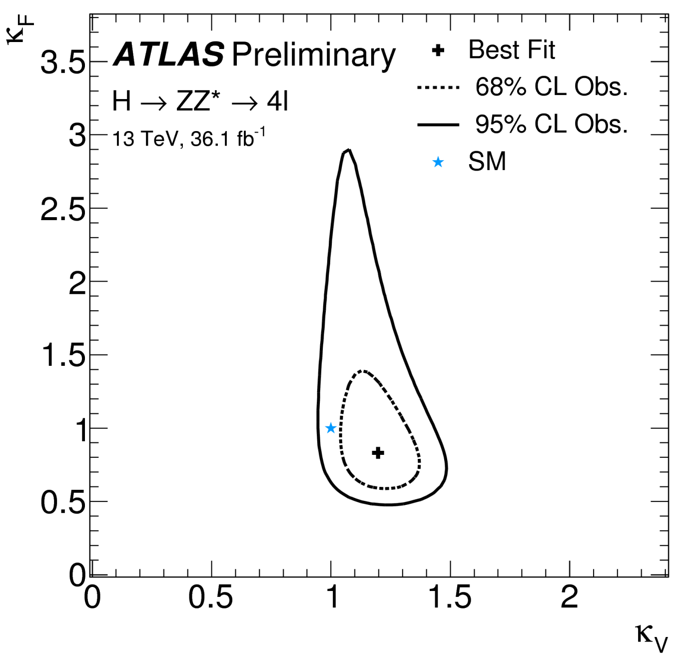
$$q\bar{q} \to \gamma\gamma, g\gamma, gg$$
$$gg \to gg, q\bar{q}$$
$$gq \to \gamma q, gq$$

Background comes from real photons or jets misidentified as photons!

H → ZZ* → 4ℓ : Results from ATLAS

- **golden channel : H → ZZ → 4ℓ**
  - **cleanest channel**
  - **excellent mass resolution**
  - **moderate statistics**
  - **small background**





Probing universal coupling modifiers by exploiting various production modes

$$\kappa_F = \frac{g_{Hf\bar{f}}}{g^{SM}_{Hf\bar{f}}}$$

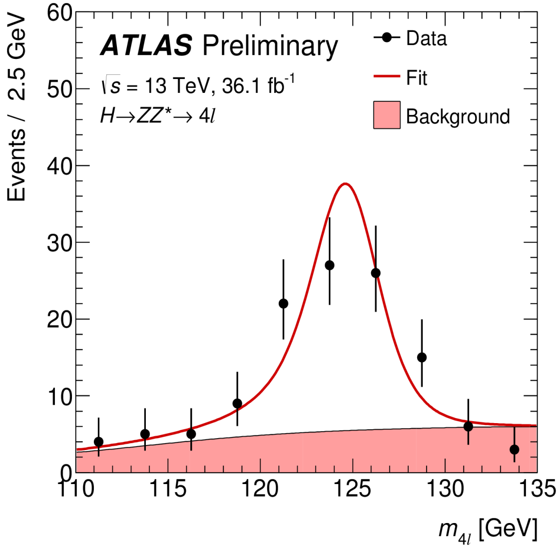
affects gg → H and ttH production rates

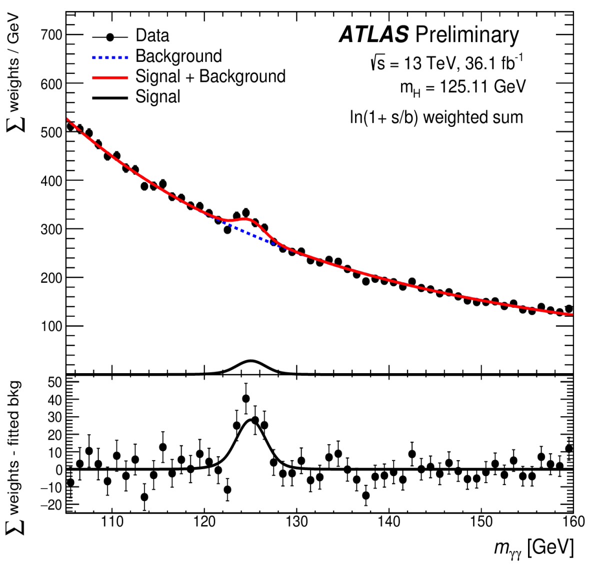
$$\kappa_V = \frac{g_{HVV}}{g^{SM}_{HVV}}$$

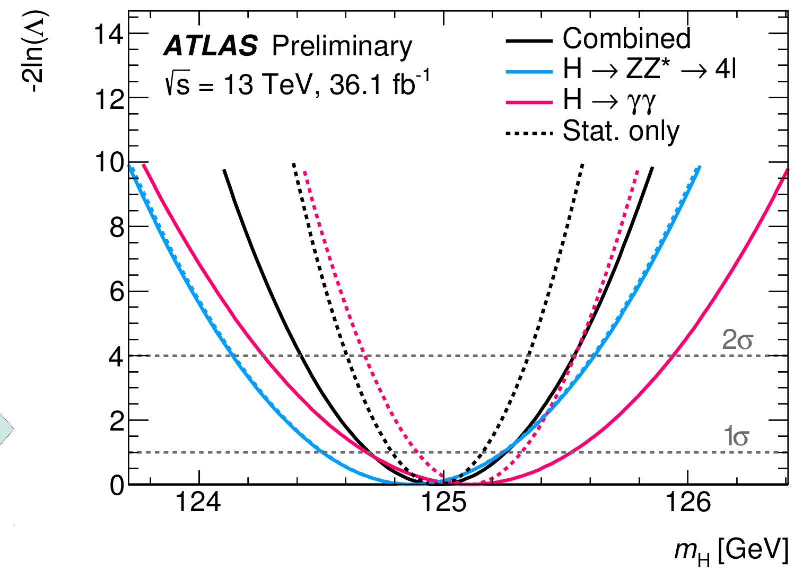
affects VBF and VH production rates

Measurement of Higgs Mass : ATLASresults

- **Measurement of m_H is driven by two high mass resolution channels : $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$**

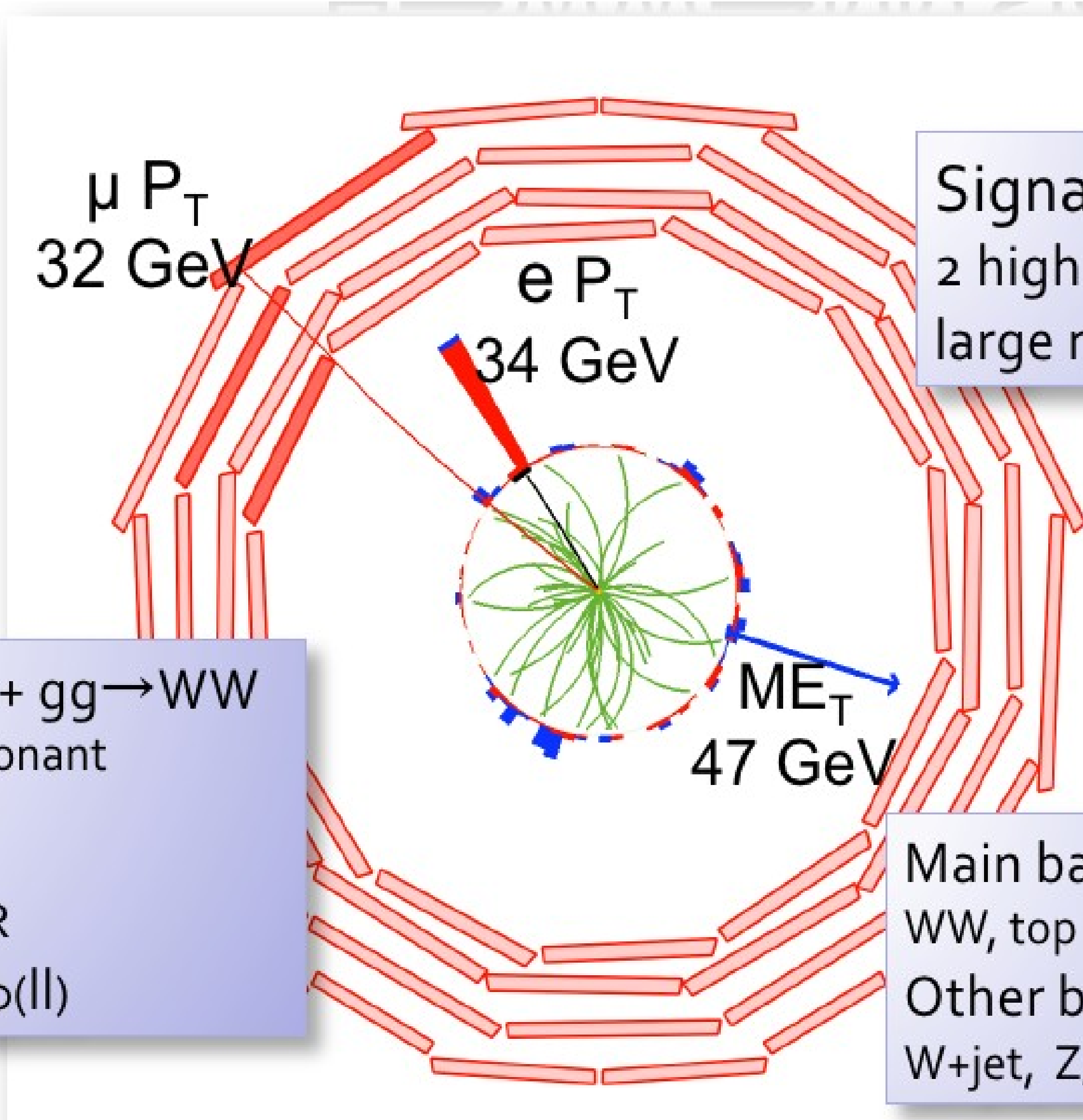






$m_H = 124.97 \pm 0.28$ GeV

H→WW→2ℓ2ν



Signature:

2 high p_T leptons

large missing E_T

qq→WW + gg→WW

- Non-resonant

H→WW

- Large BR
- Small $\Delta\phi(ll)$

Main backgrounds:

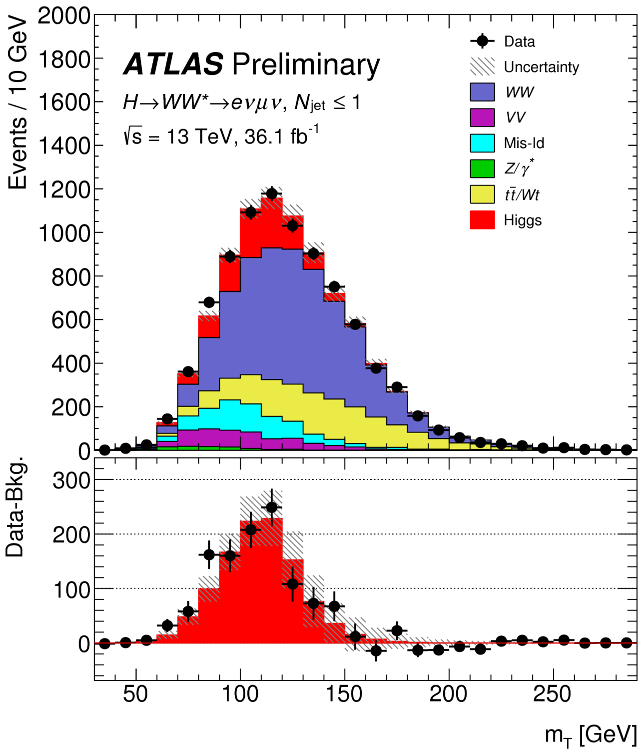
WW, top

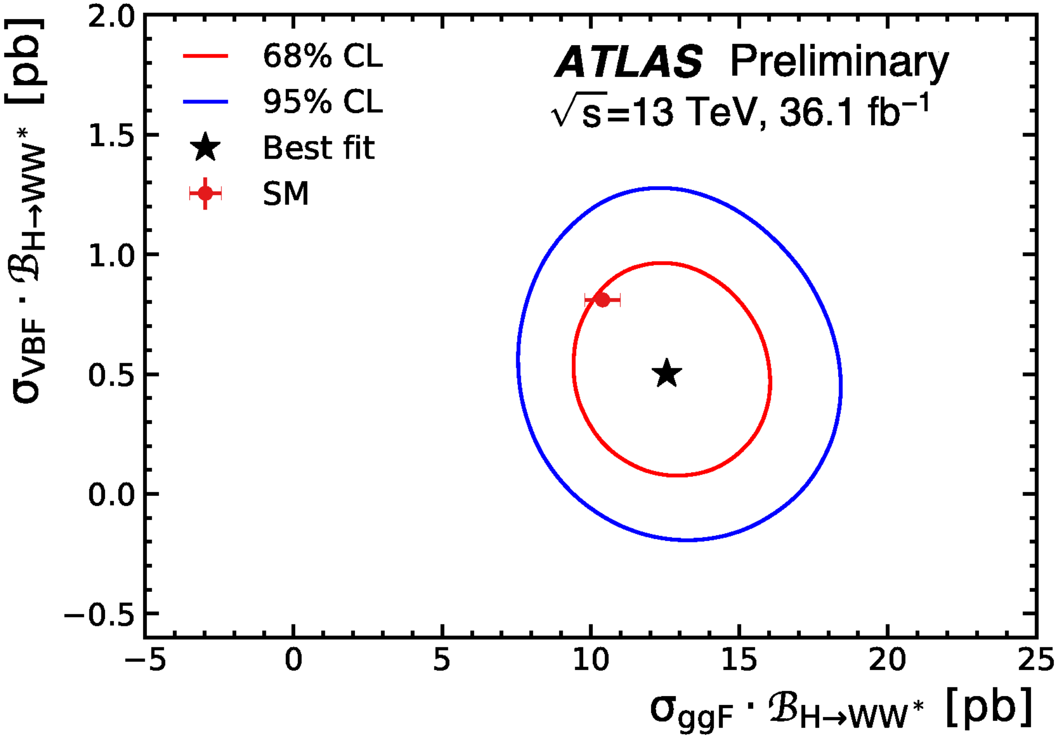
Other backgrounds:

W+jet, Z/γ*, WZ, ZZ, Wγ

Results from H→WW→2ℓ2ν Channel : ATLAS

- **H → WW → (ℓν)(ℓν) → (eν)(eν) + (μν)(μν) + (eν)(μν)**
  - **relatively clean channel**
  - **distinct production mechanisms probed**
  - **poor mass resolution (undetectable neutrinos)**
  - **sensitivity to the Higgs boson mass through transverse mass (m_T) distribution**





H → ττ Final States

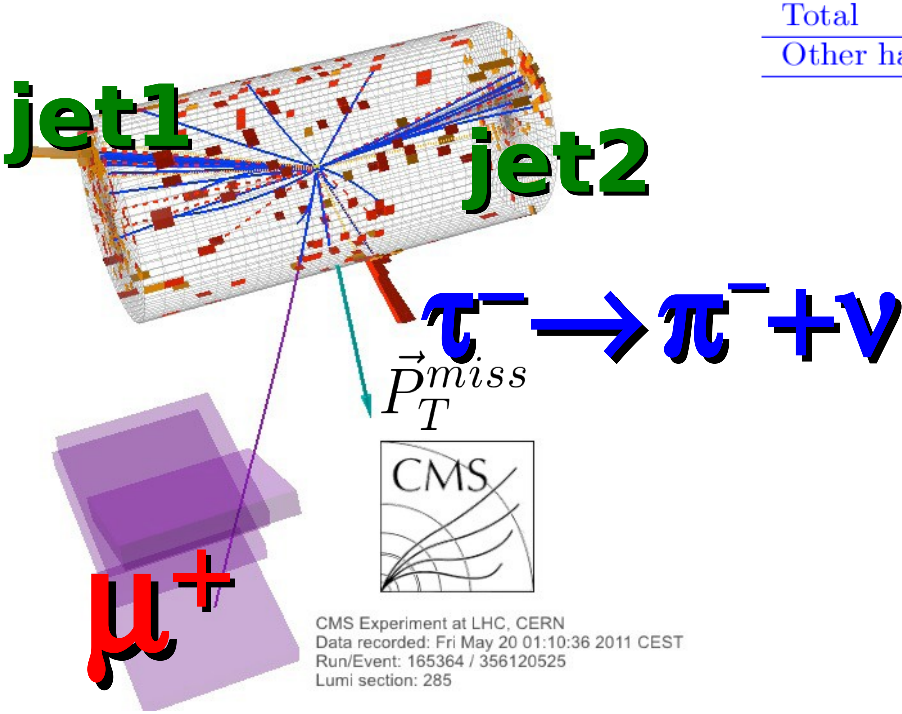
Leptonic tau decays

$$\tau \to e\nu_e\bar{\nu}_\tau \; : \; 17\%$$

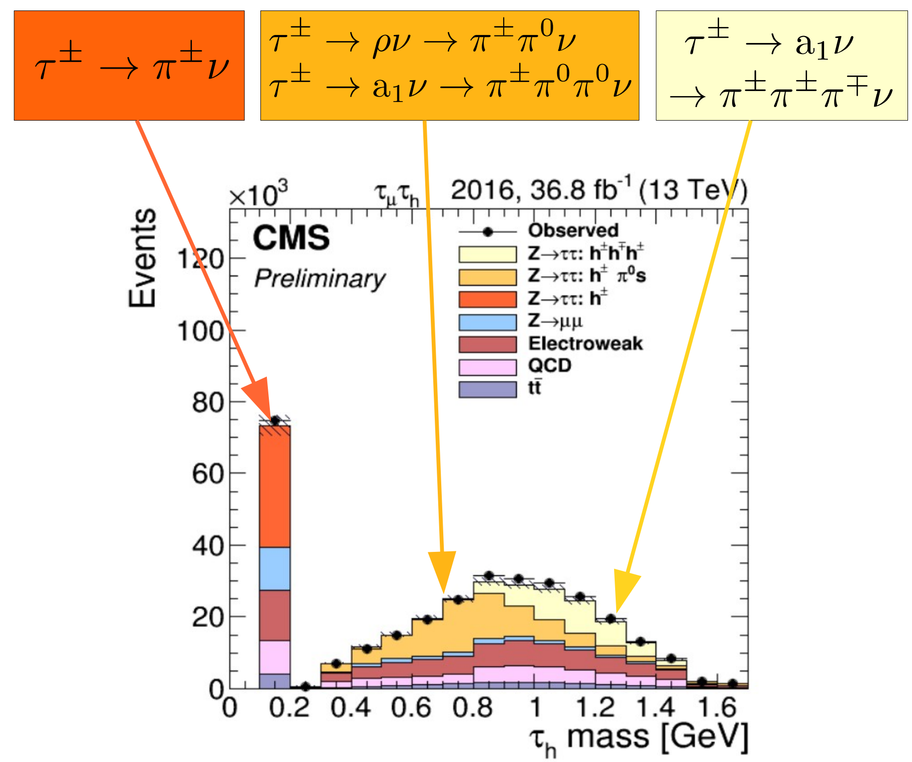
$$\tau \to \mu\nu_\mu\bar{\nu}_\tau \; : \; 17\%$$

hadronic tau decays

Decay mode	Resonance	Mass [MeV/c²]	Branching ratio
$\tau^- \to \pi^-\nu_\tau$	-	135	10.9%
$\tau^- \to \pi^-\pi^0\nu_\tau$	ρ	770	25.5%
$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$	a_1	1200	10.8%
$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$	a_1	1200	9.8%
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$	a_1	1200	4.5%
Total			59.2%
Other hadronic modes			5.6%



VBF H → ττ candidate



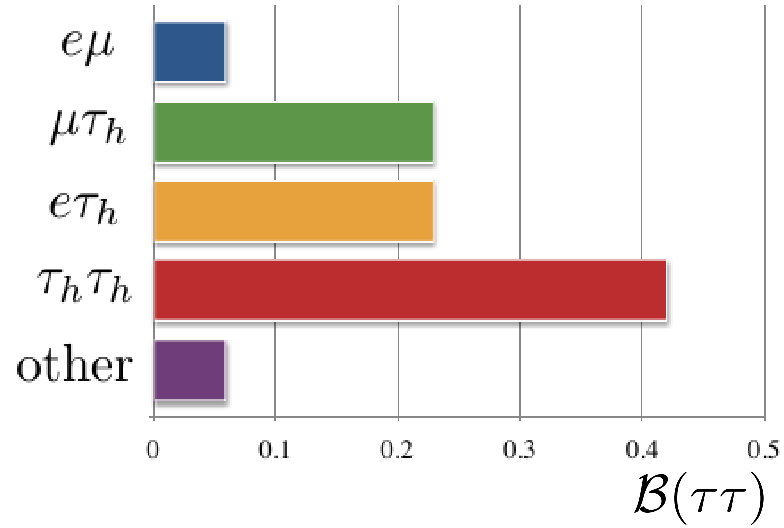
H(125) → ττ

- **second largest branching ratio (BR(H→ττ)=6.3%) among fermionic decays**
- **lower background compared to H → bb**
- **4 final states considered, accounting for 94% of all ττ decays**

  $e\mu, \quad \mu\tau_h, \quad e\tau_h, \quad \tau_h\tau_h$

- **3 event categories targeting different production mechanisms**

  0-jet, VBF, Boosted



- **In all categories but one signal is extracted from 2-dimensions**

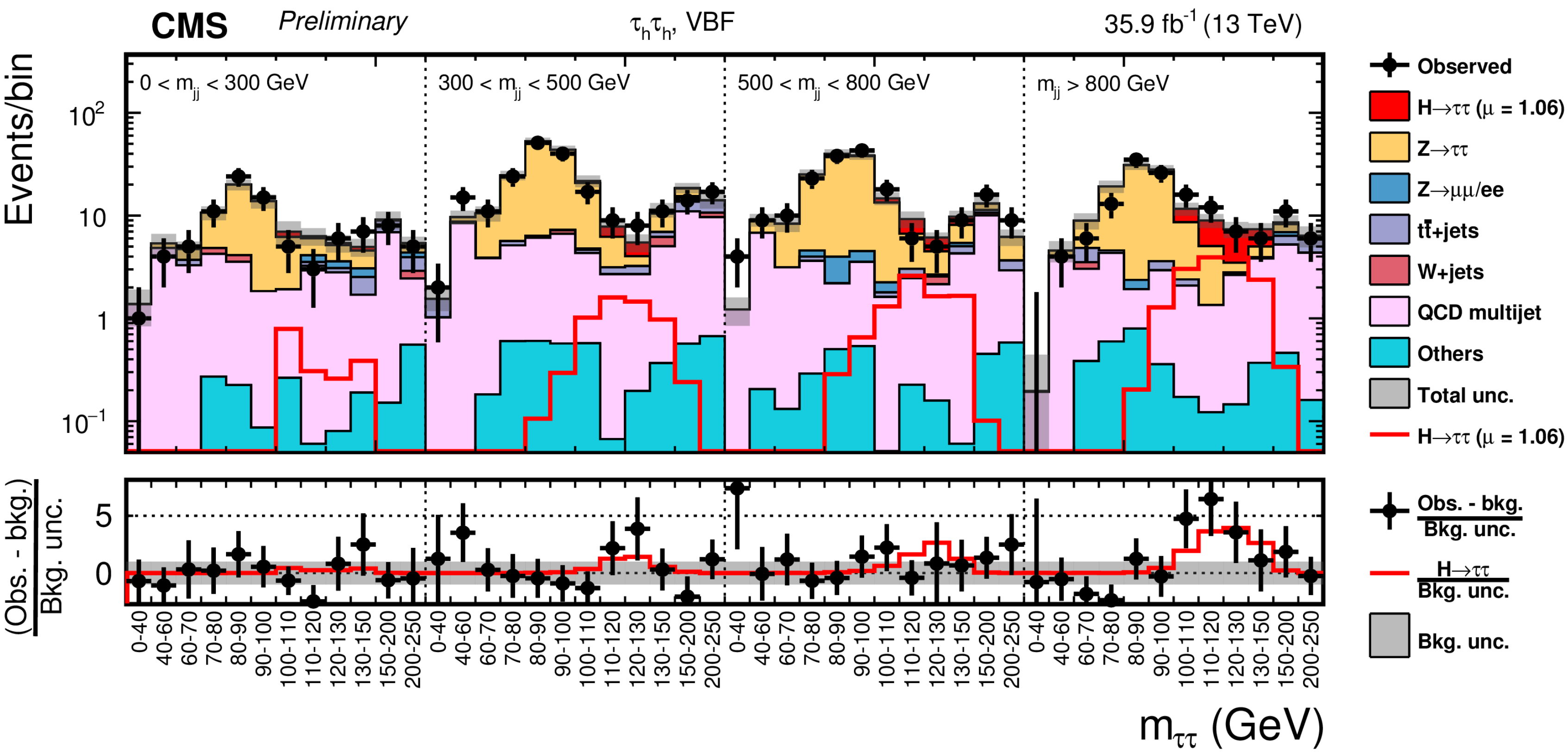
	Selection		
	0-jet	VBF	Boosted
$e\mu$	No jet	2 jets, $m_{jj} > 300$ GeV	Others
$\mu\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV, $p_T^{\tau_h} > 40$ GeV	Others
$e\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300$ GeV, $p_T^{\tau\tau} > 50$ GeV	Others
$\tau_h\tau_h$	No jet	≥ 2 jets, $p_T^{\tau\tau} > 100$ GeV, $\Delta\eta_{jj} > 2.5$	Others
	Variables used for the signal extraction		
$e\mu$	p_T^{μ}, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\mu\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\tau_h\tau_h$	$m_{\tau\tau}$	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$

Signal Extraction

- **Signal is extracted by simultaneous maximum-likelihood fit in 12 channels**

  4 final states (eμ , eτ_h μτ_h , $\tau_h\tau_h$) x 3 event category (0-jet, VBF, Boosted)

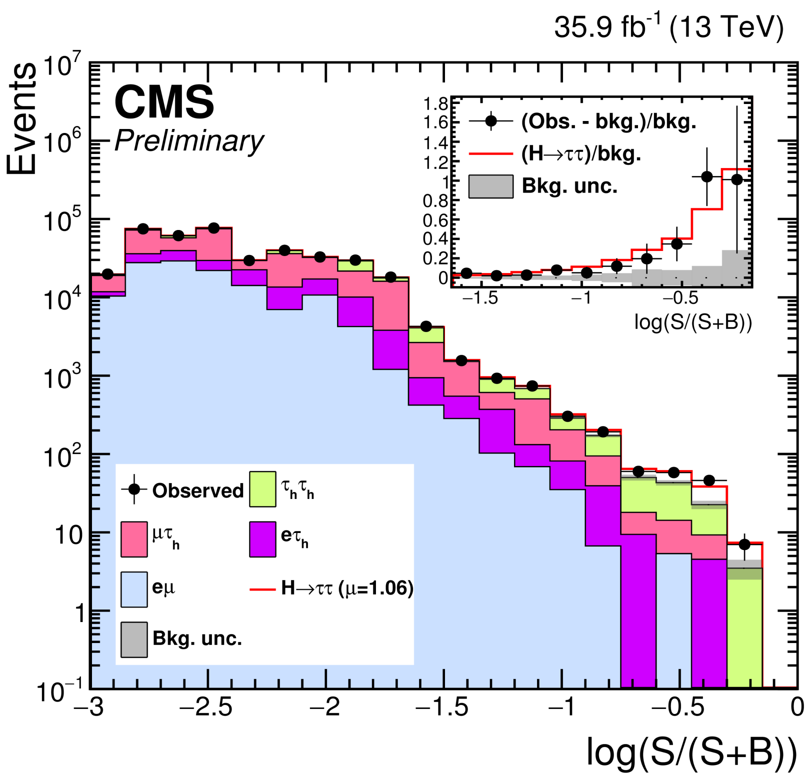
- **Representative example of unrolled postfit 2D distribution : VBF $\tau_h\tau_h$**

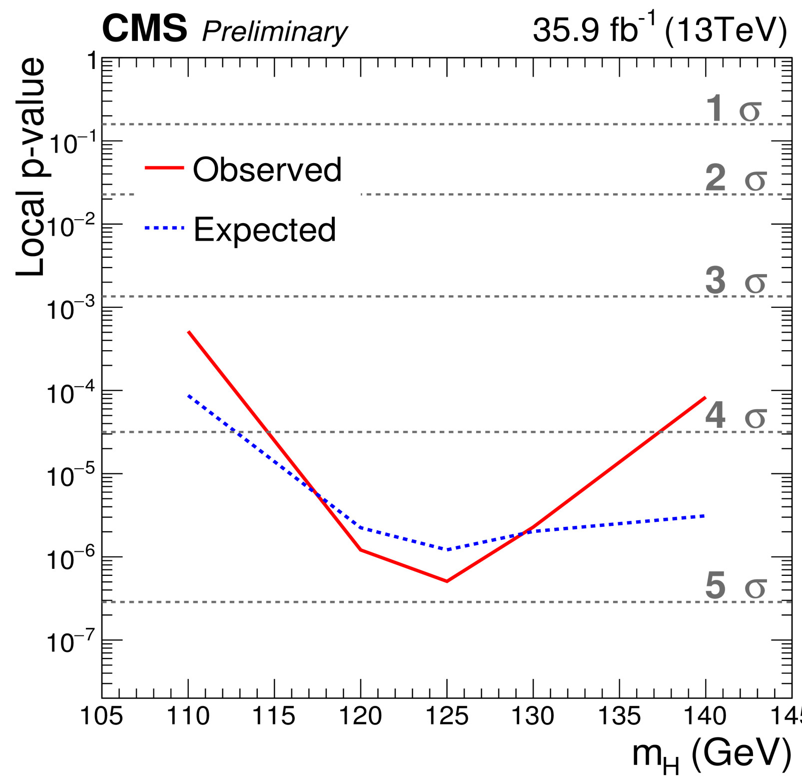


Observation of H → ττ Decays

- **Distribution of event yield in the analysis bins ordered by S/(S+B)**

→ **clearly visible excess in data w.r.t. background-only expectation**



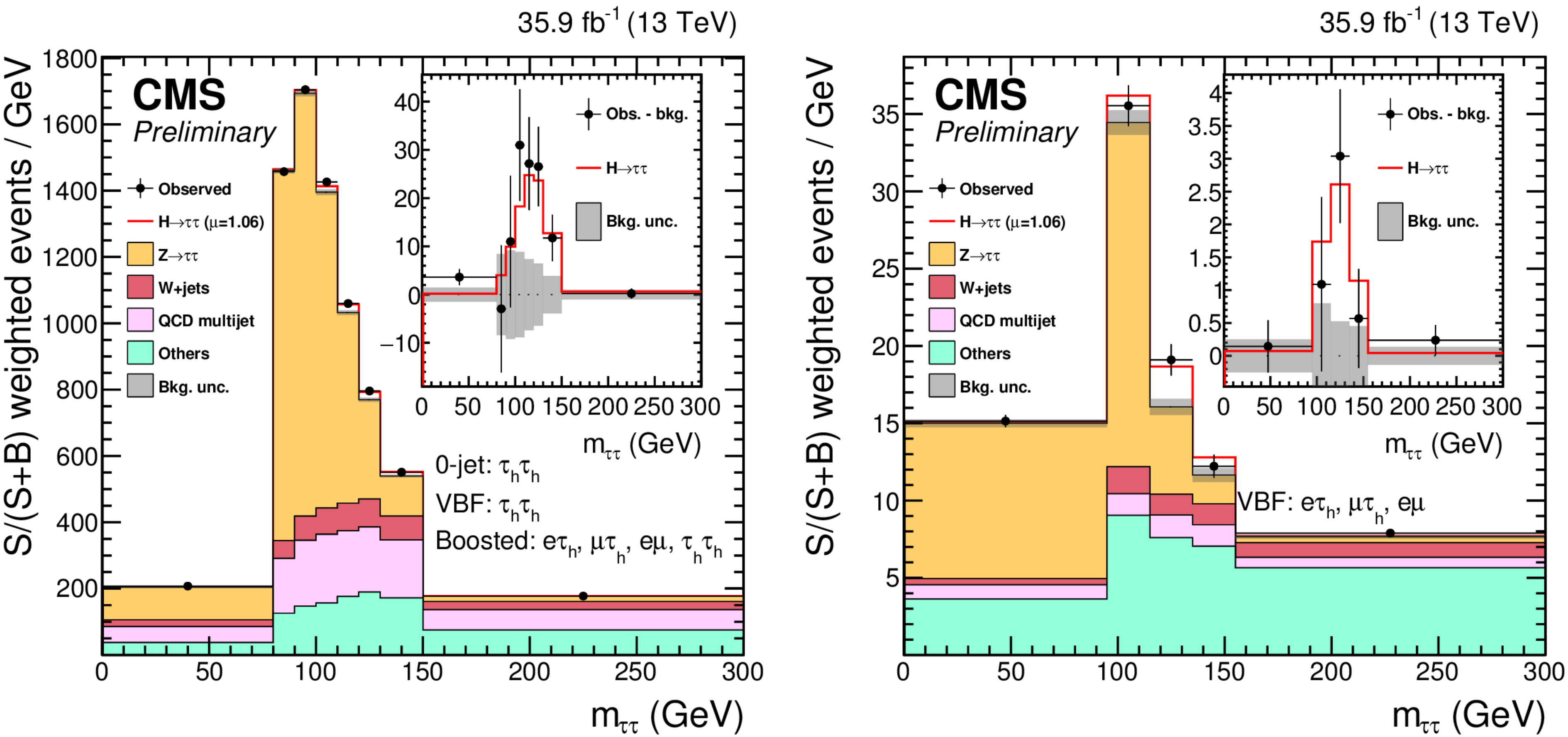


- **obs. (exp.) significance at m_H = 125 GeV**
- $4.9\sigma \ \ (4.7\sigma)$ **with Run II data only**
- **Combination with Run I CMS data yields**

$$5.9\sigma \ \ (5.9\sigma)$$

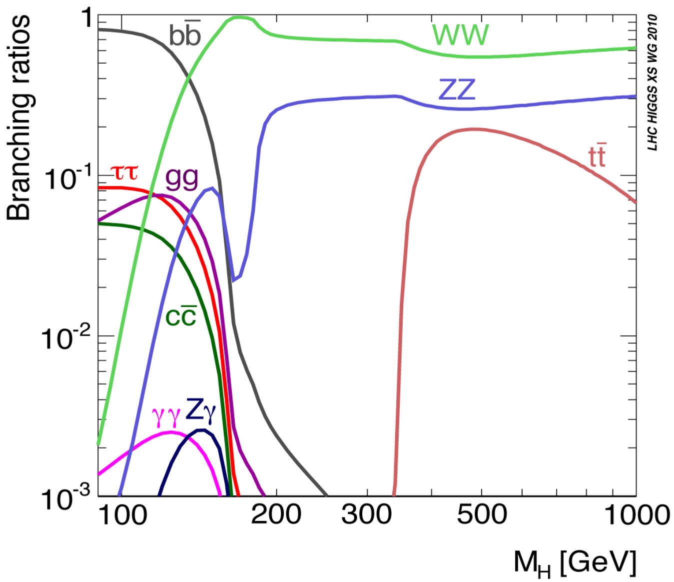
- **first observation of Yukawa coupling in single fermionic decay channel at CMS**

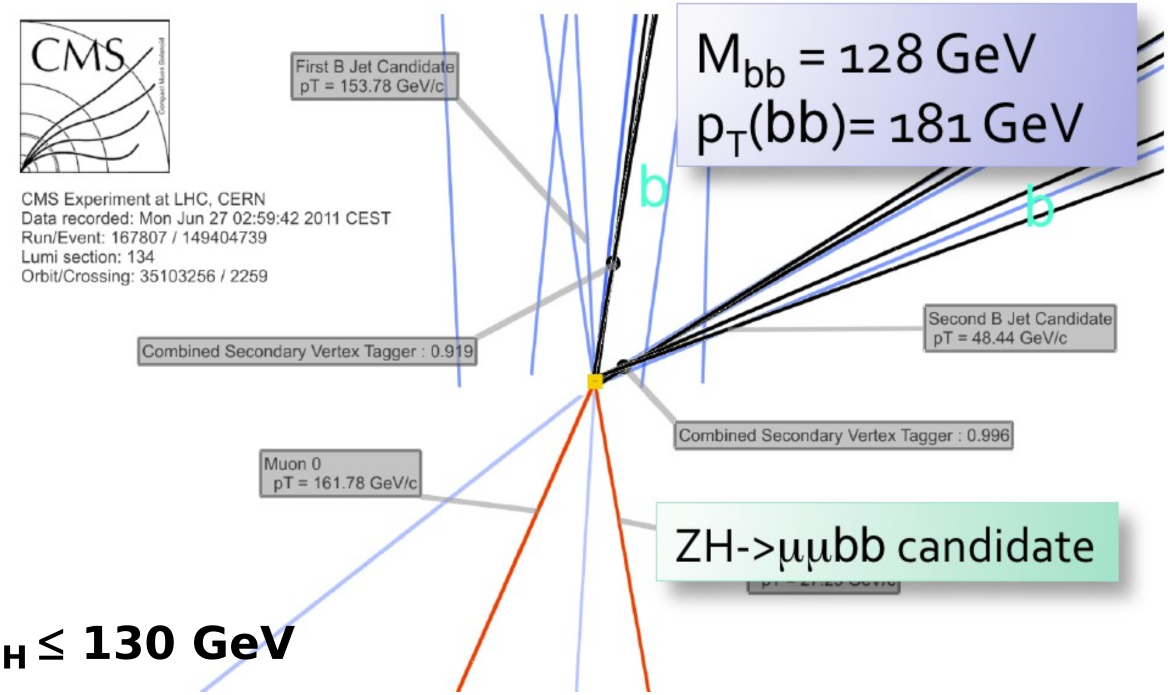
Visualization of signal : $m_{\tau\tau}$ distribution



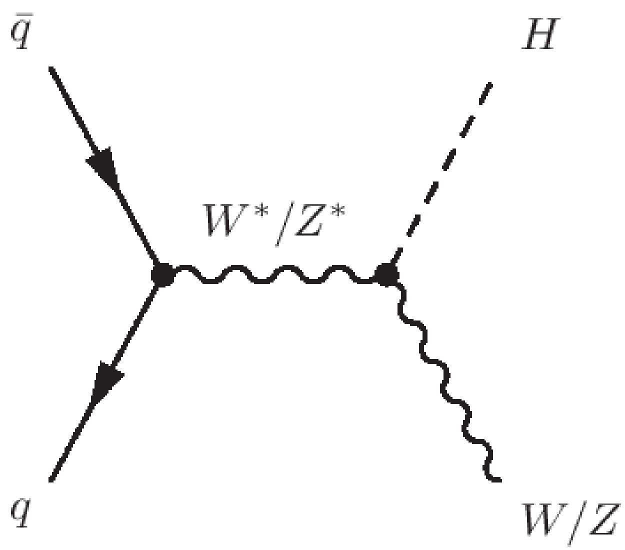
- **Events are weighted by S/(S+B) in bins of second variable of 2D distributions → unbiased mass spectrum**
- **Signal is clearly visible in the distribution of physical observable $m_{\tau\tau}$**

VH, H → bb Search





Br(H → bb) is largest @ $m_H \leq$ 130 GeV

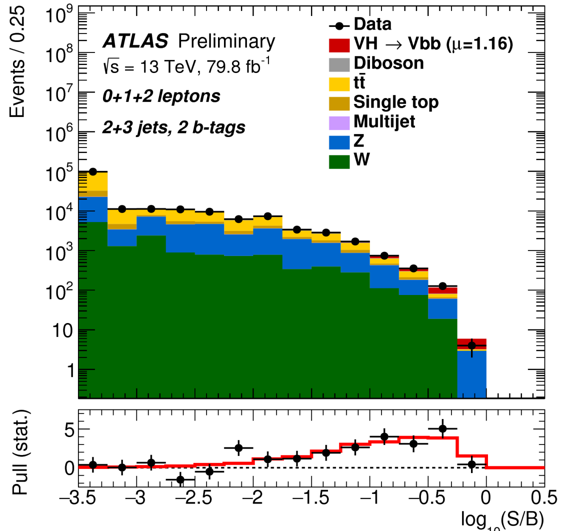


inclusive search impossible due to overwhelming QCD background

→ exploit VH production

$$Z \rightarrow ee, \mu\mu, \nu\nu$$
$$W \rightarrow e\nu, \mu\nu$$
$$H \rightarrow b\bar{b}$$

VH, H → bb Search : ATLAS results



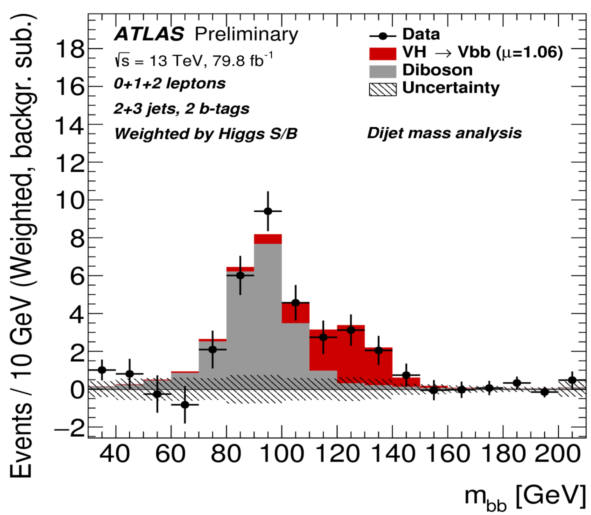
- **Analysis Strategy**
  - In each search channel multivariate analysis is employed
    - b-tagging information
    - missing E_T
    - lepton kinematics
  - Boosted Decision Tree discriminant

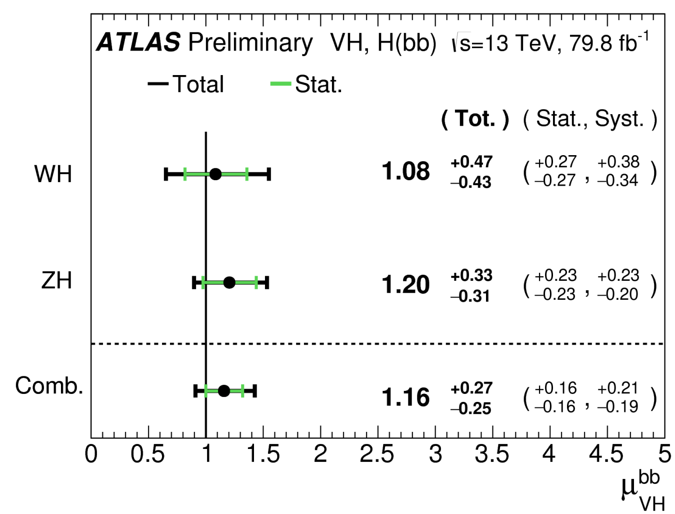
    → extraction of signal

Run1+Run2 data

5.3 σ excess observed at m_H = 125 GeV

4.8 σ excess expected for the SM Higgs at m_H = 125 GeV

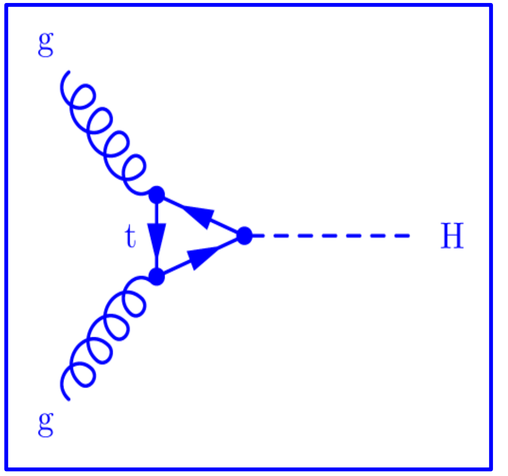




Accessing top – Higgs coupling

- **Observation of gg→H production**

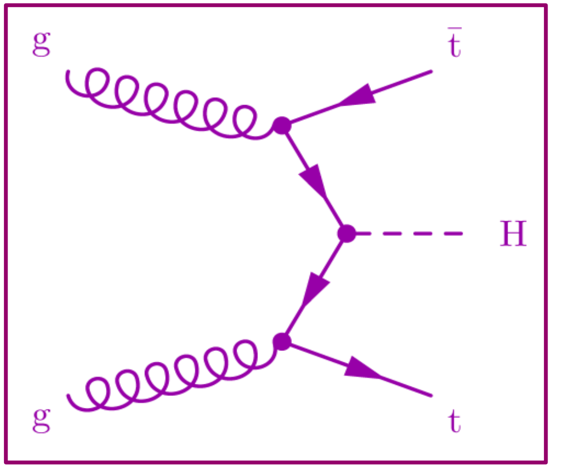
  → indirect evidence of ttH coupling (in loop)



- **ttH production → direct access to ttH coupling**
  - **top quark is heaviest SM particles**

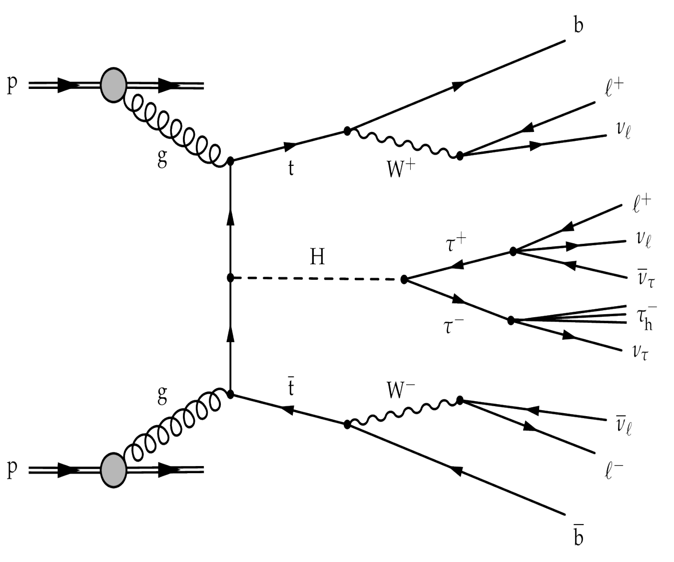
    → strongest coupling to Higgs

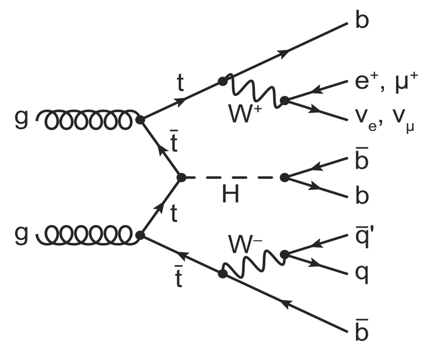
    → crucial measurement for establishing mass–coupling relation

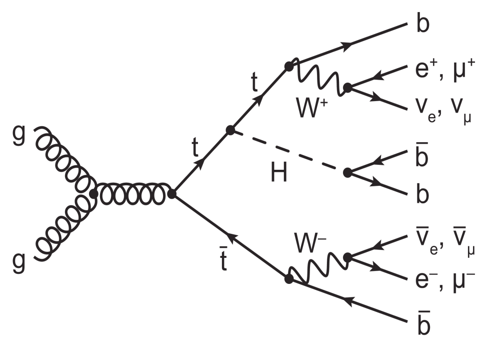


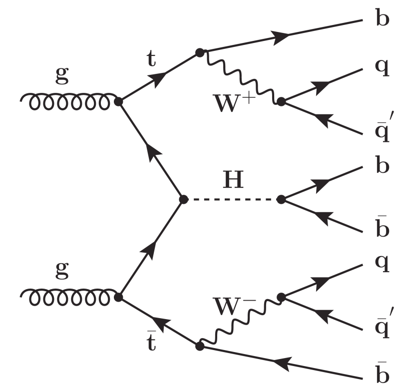
Search for ttH production

- **Analysis challenges**
  - **relatively low cross section (two orders of magnitude lower than that of gg → H)**
  - **large variety of complex final states**
    - **Various decay modes of W bosons**
    - **Various decay modes of Higgs boson**
  - **Irreducible ttZ background**



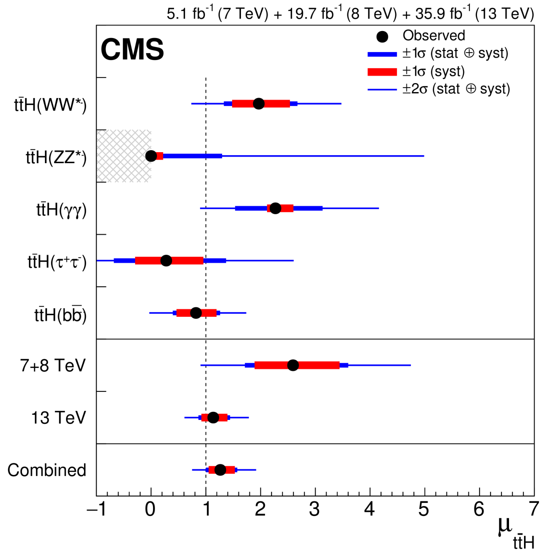






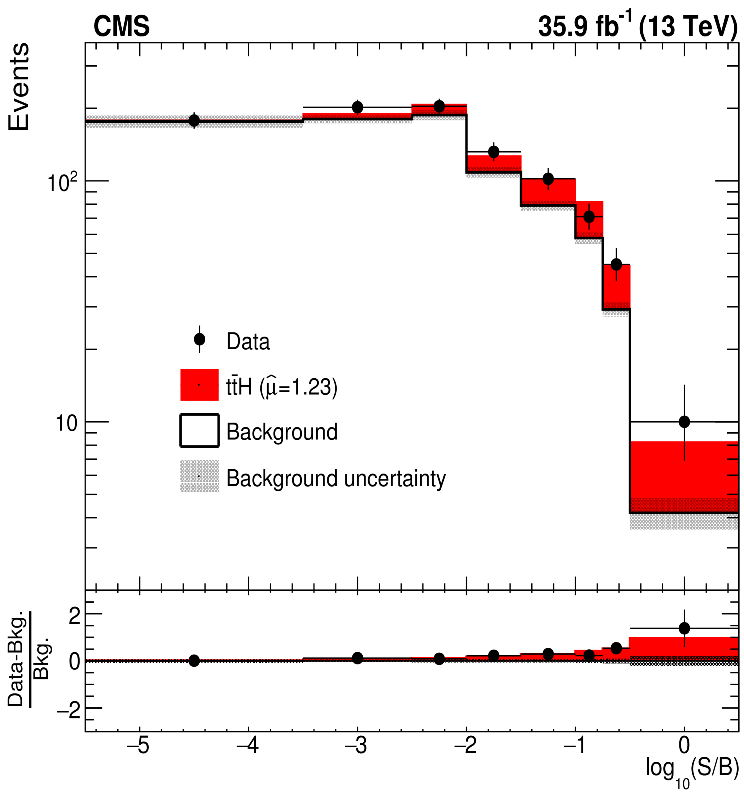
Observation of ttH production

- Decay modes exploited
  - $H \rightarrow ZZ, WW, \gamma\gamma, bb, \tau\tau$
- event categorization based on
  - Multiplicity of jets / b-jets / leptons
    → more than 50 channels combined!
- Signal is inferred from the distribution of MVA discriminant combining
  - lepton kinematic observables
  - missing E_T related information
  - b-tagging information
  - masses of W and H candidates



$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$$

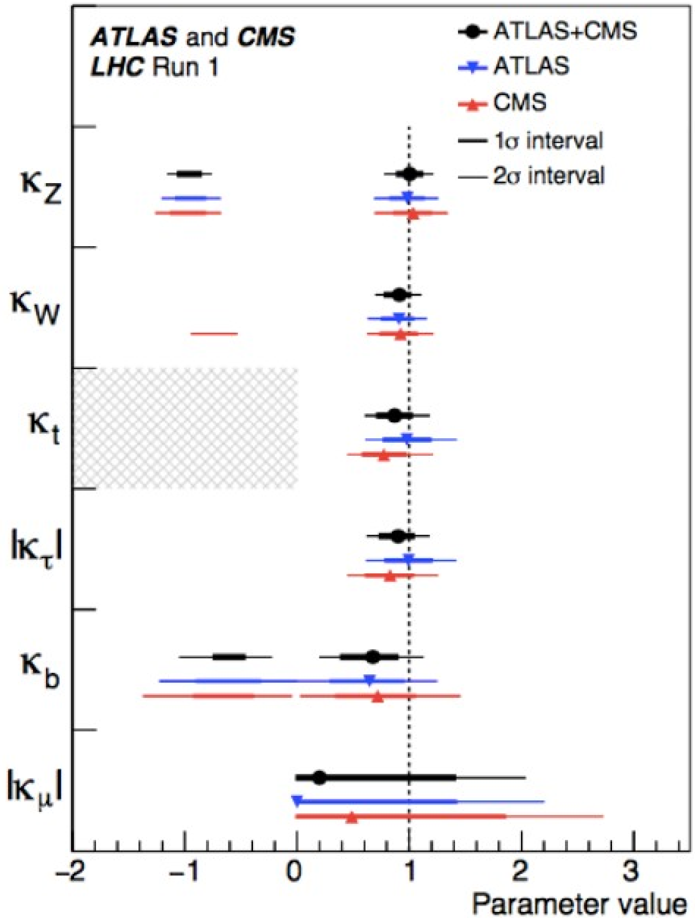
Representative example: distribution of analysis bins, ordered by S/B in all channels targeting $H \rightarrow \tau\tau$

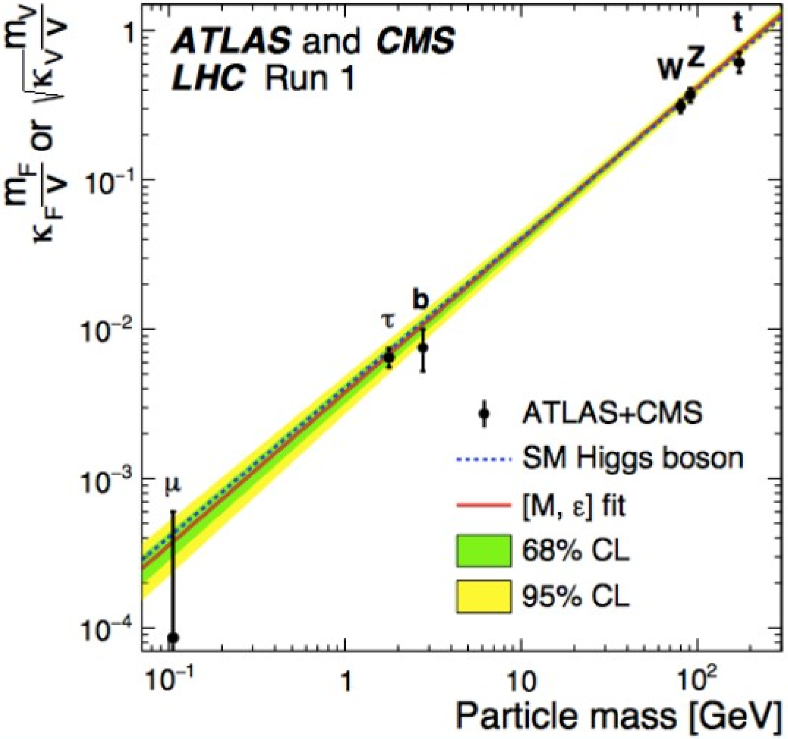


Global Coupling Analysis

- **Fit of the coupling modifiers accessible by the LHC**
  - **Loop coupling strengths are resolved** in expressions of tree-level coupling assuming the SM physics
  - One coupling parameter per SM particle
  - No Beyond-Standard-Model decays

$$\kappa_Z,\ \kappa_W,\ \kappa_t,\ \kappa_\tau,\ \kappa_b,\ \kappa_\mu$$





$$\kappa_{F,i} = \nu \cdot m_{F,i}^{\epsilon}/M^{1+\epsilon} \text{ and } \kappa_{V,i} = \nu \cdot m_{V,i}^{2\epsilon}/M^{1+2\epsilon}$$

- **All couplings are compatible with SM**
  - **($\varepsilon = 0$ and $M = 246$ GeV)**

$$\epsilon = 0.023^{+0.029}_{-0.027} \text{ and } M = 233^{+13}_{-12} \text{ GeV}$$

Summary

- **LHC performed excellently in Run1 and Run2 at c-o-m energies of 7, 8 and 13 TeV**
- **Large amount of data collected by CMS and ATLAS (more than 20 fb^{-1} per experiment at 8 TeV, more than 80 fb^{-1} at 13 TeV)**
- **Higgs-like particle discovered (July 2012)**
- **Crucial measurements of discovered state performed**
  - ✓ **mass (~ 125 GeV)**
  - ✓ **couplings to fermions and gauge bosons**
  - ✓ **spin-parity quantum numbers (not discussed in this lecture)**
  - ✓ **differential measurements (Higgs boson kinematics , multiplicity and properties of accompanying jets, etc.)**
  - ➔ **new state looks like Standard Model Higgs boson (so far)**
- **Mission accomplished? - not at all!**
- **Expect more data at higher energies (13-14 TeV) in Run2**
  - **improve precision of Higgs measurements → probe new physics**
  - **new Higgs measurements (top-Yukawa coupling, Higgs self-coupling)**
  - **search for new Higgs states predicted in theories, extending SM**
  - **direct search for new physics : SUSY, extra-dimensions, etc.**
- **<u>You are more than welcome to join us (LHC community) in physics studies at the new energy frontier</u>**