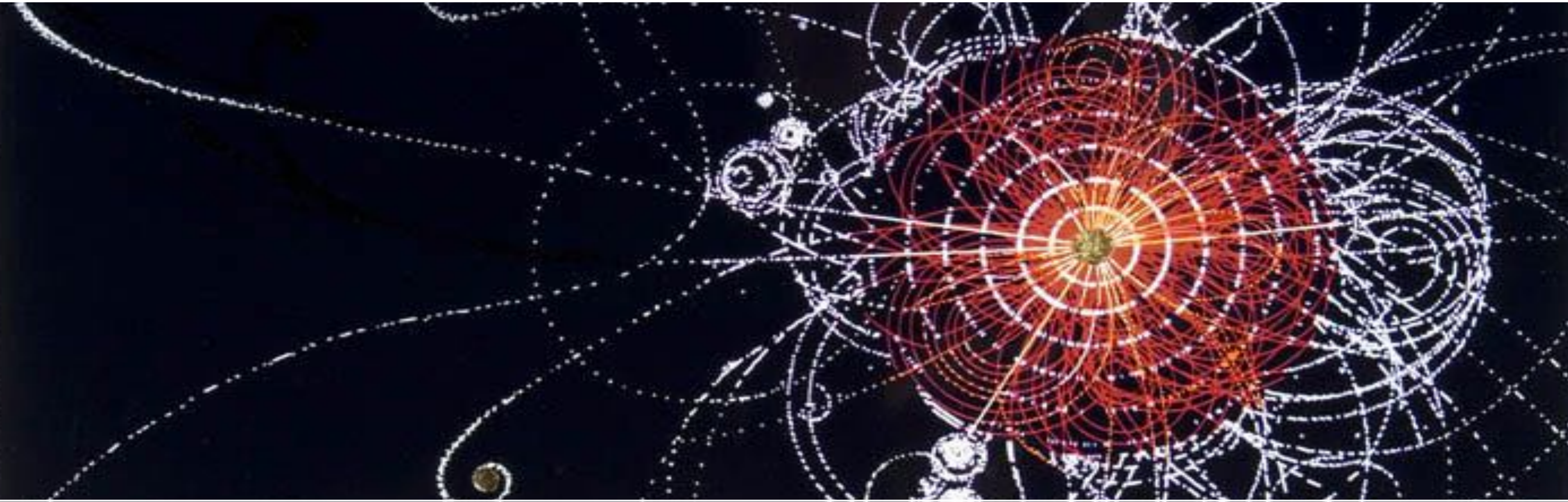
The Higgs boson discovery



Kern-und Teilchenphysik II

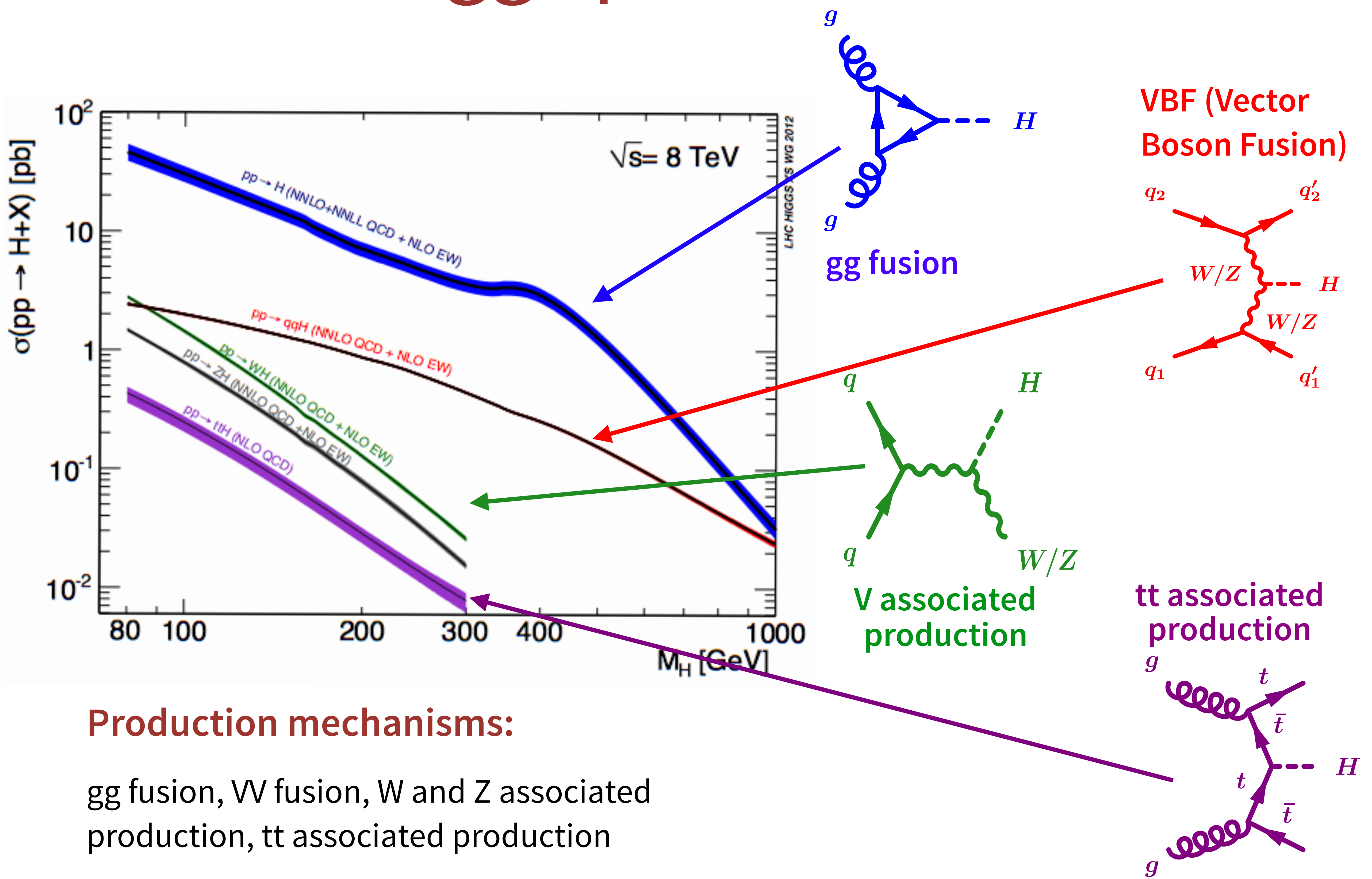
Prof. Nicola Serra

Dr. Annapaola de Cosa

Dr. Marcin Chrzaszcz

Universität Zürich[UZH]

Higgs production at the LHC

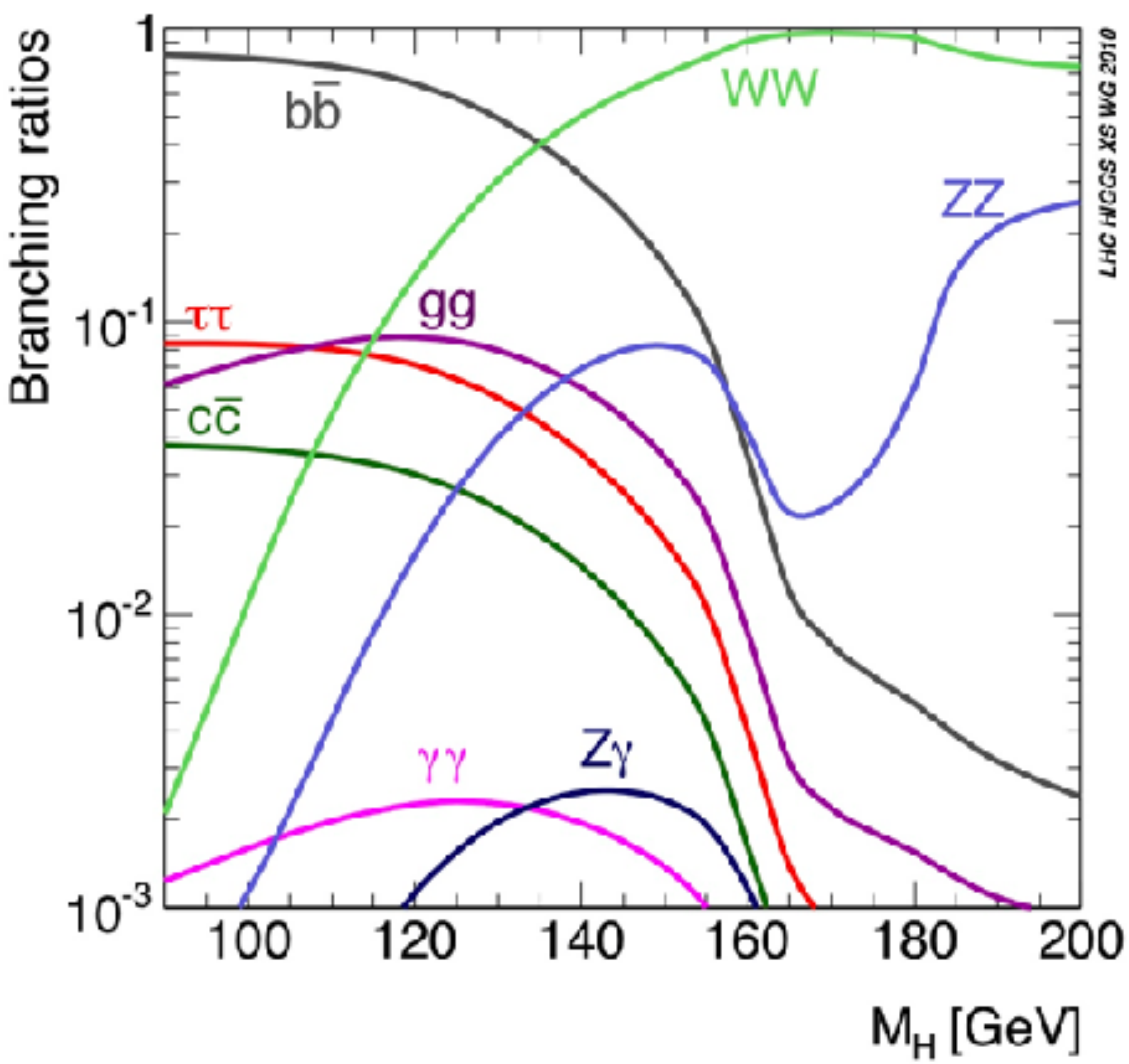


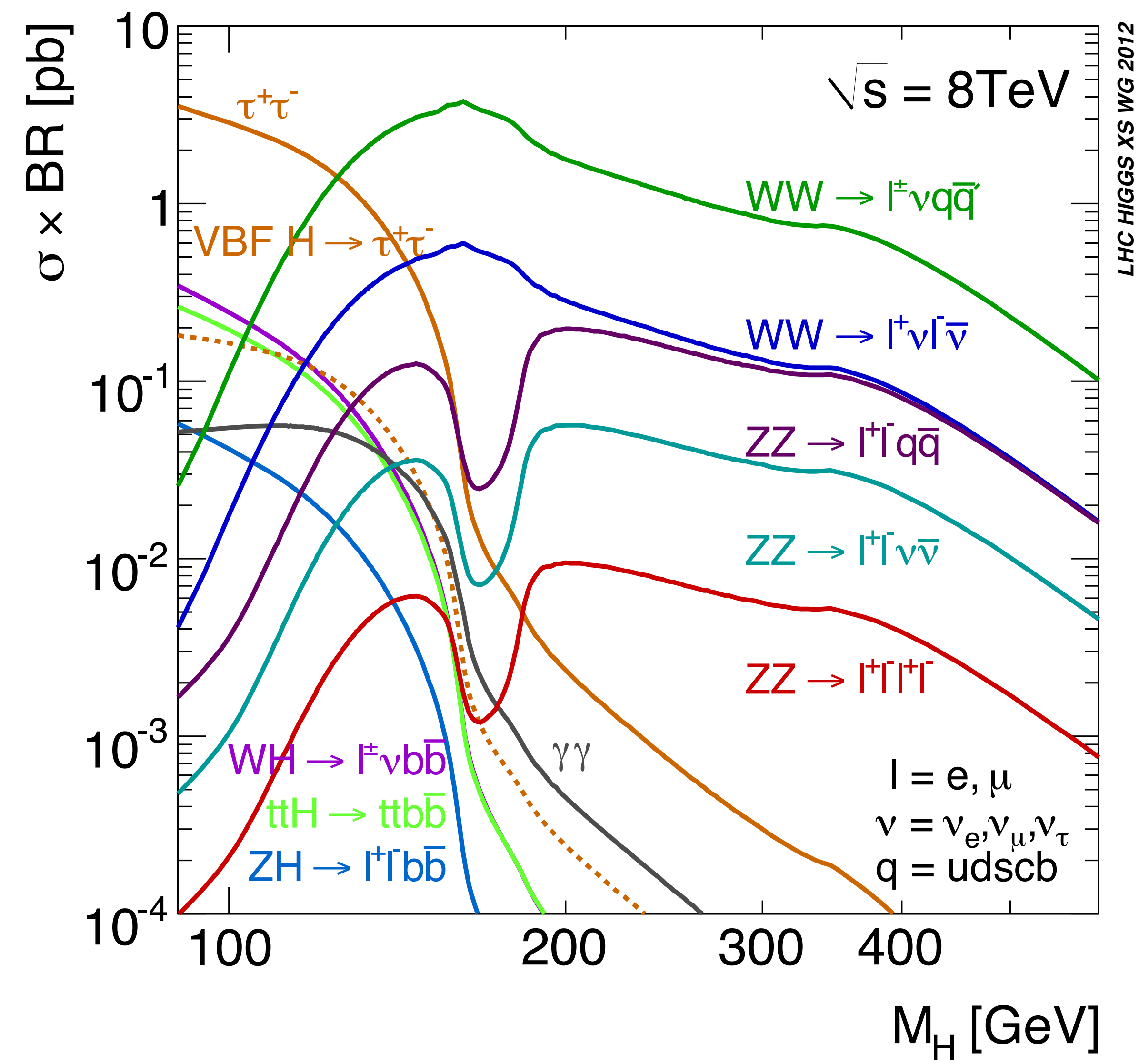
Production mechanisms:

gg fusion, VV fusion, W and Z associated production, tt associated production

Gluon fusion is the dominant production mode

Discovery channels





- Gluon fusion is the dominant production mechanism
- H→bb: highest branching ratio (~58% @ 125 GeV)
  - Inclusive H→bb search not feasible due to overwhelming QCD background
- Instead H→ZZ, H→γγ has lower BR but very clean signature!

Observation of the Higgs boson at LHC

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012. Individual searches in the channels $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \rightarrow ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^{+}\tau^{-}$ in the 7 TeV data and results from improved analyses of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the

Abstract

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, $W^{+}W^{-}$, $\tau^{+}\tau^{-}$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Discovery channels

$H \to ZZ \to 4l$

- Clean experimental signature: four isolated leptons
- Narrow resonance peak in four lepton mass spectrum

$H \to \gamma\gamma$

- Clean experimental signature: 2 high energy and isolated photons
- Narrow resonance in di-photon mass spectrum over a falling continuous background

Commonalities

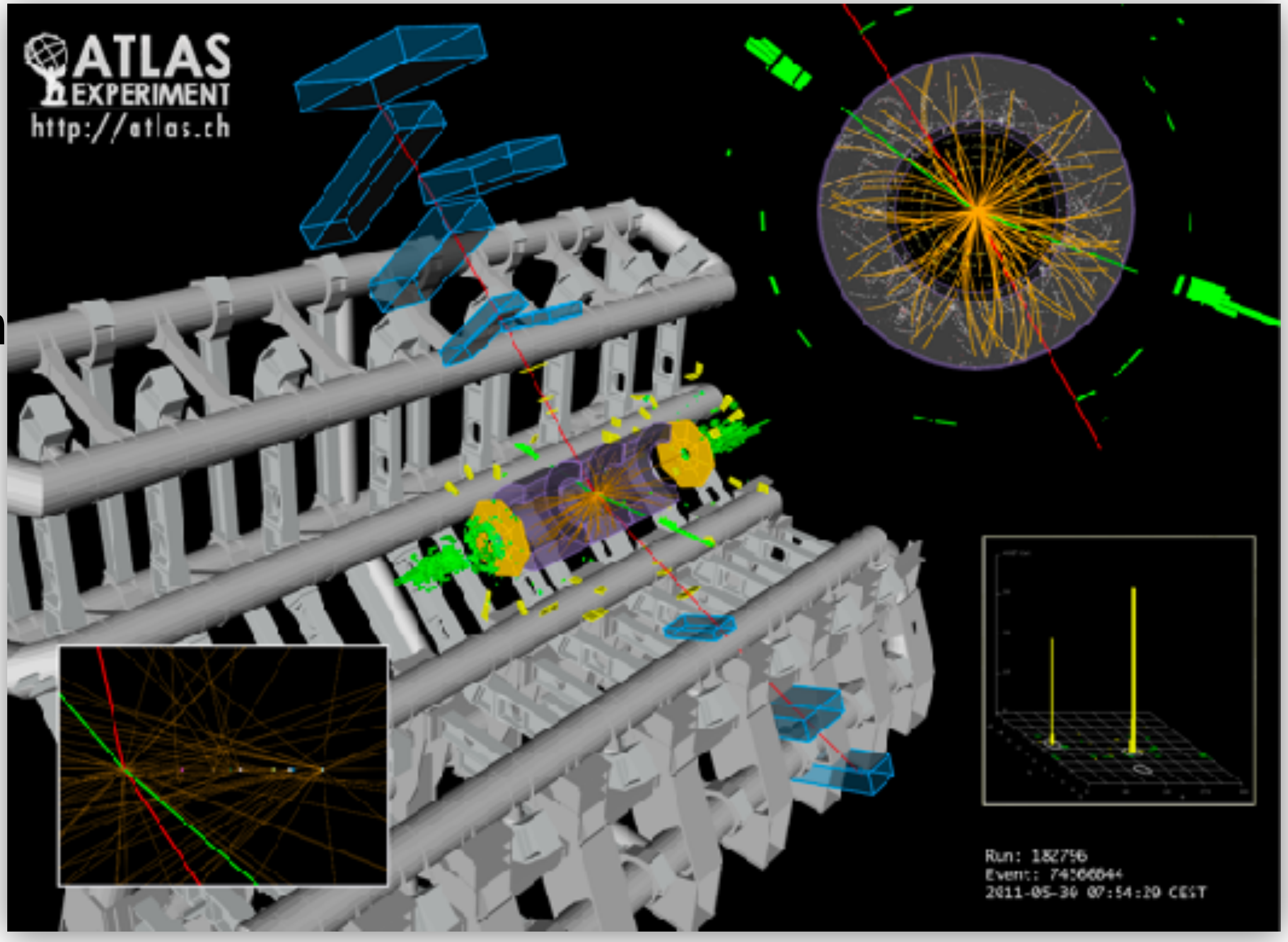
- Both channels suffer low BR
- Both allow mass peak reconstruction with very good resolution

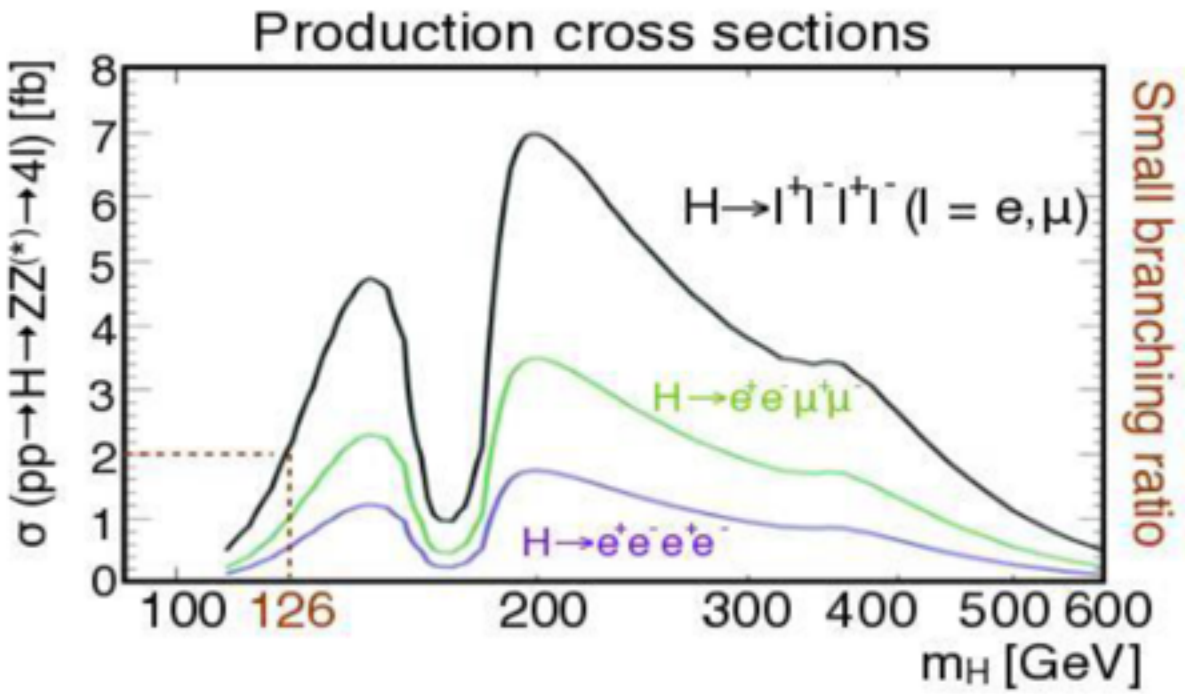
H→ZZ*→4l

The golden channel

- Very clean signature
  - four isolated leptons (*e* or **μ**)
- And very small background
- Challenges: requires **high lepton identification/reconstruction/Isolation efficiency**

H→ZZ*→2μ2e





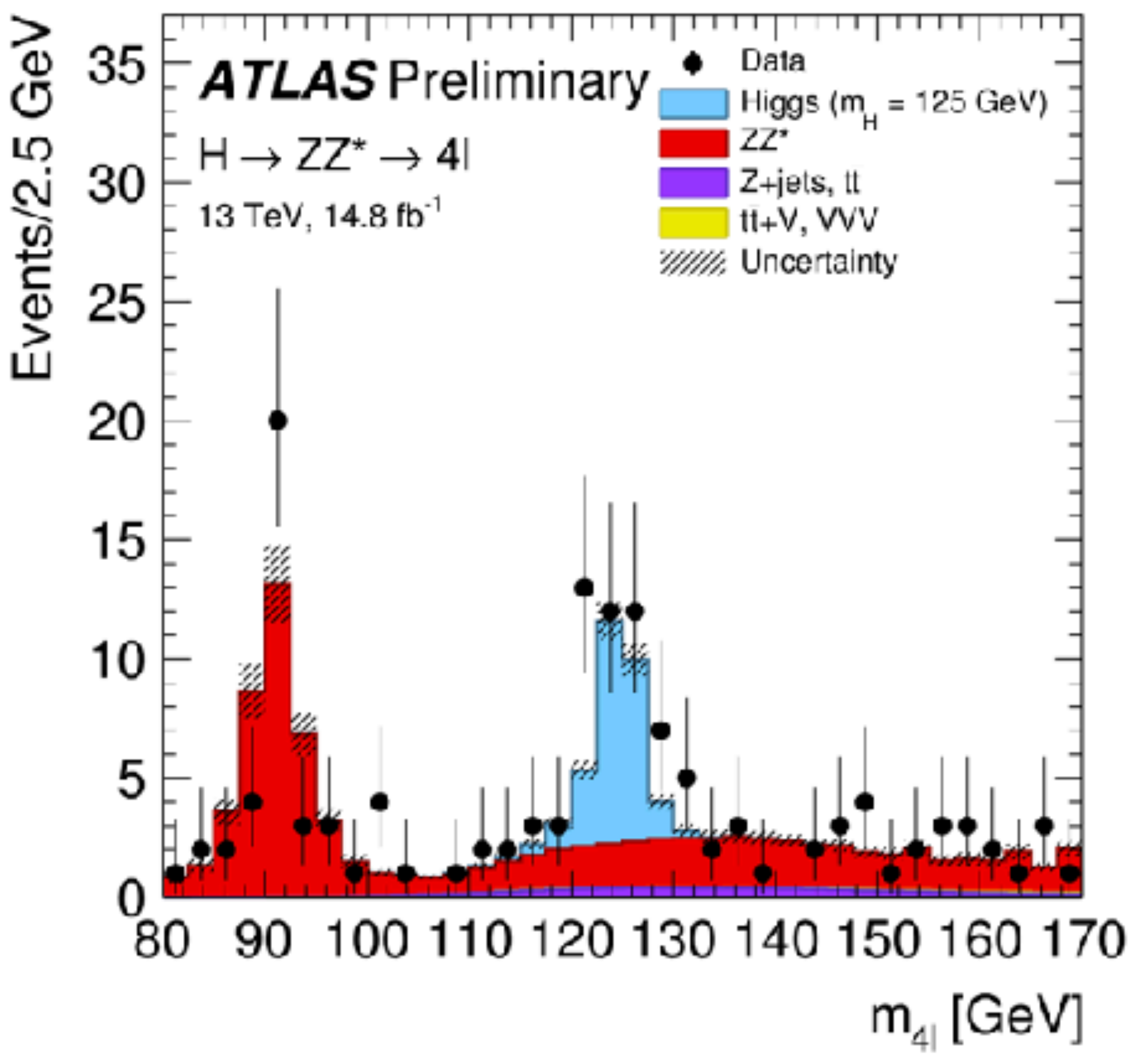
H→ZZ*→4l: Backgrounds and selection

Reducible background

- Z+bb, tt, tt+ jets. Z+jets, WZ+jets

Irreducible background

- ZZ*



Event selection

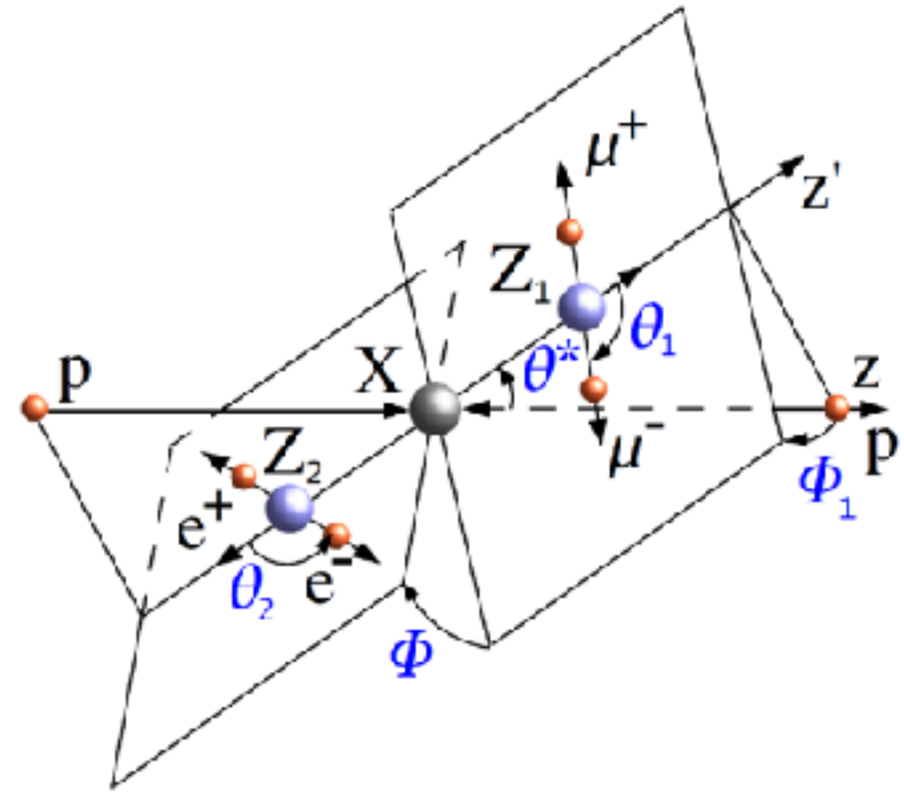
- Double-lepton trigger
- Selection of events with 4 identified and isolated leptons
- Use of impact parameter
- Constraint on dilepton mass (m_Z and m_{Z^*})
- Kinematical discrimination (exploits secularity of the Higgs boson)

H→ZZ*→4l: Kinematical discriminant

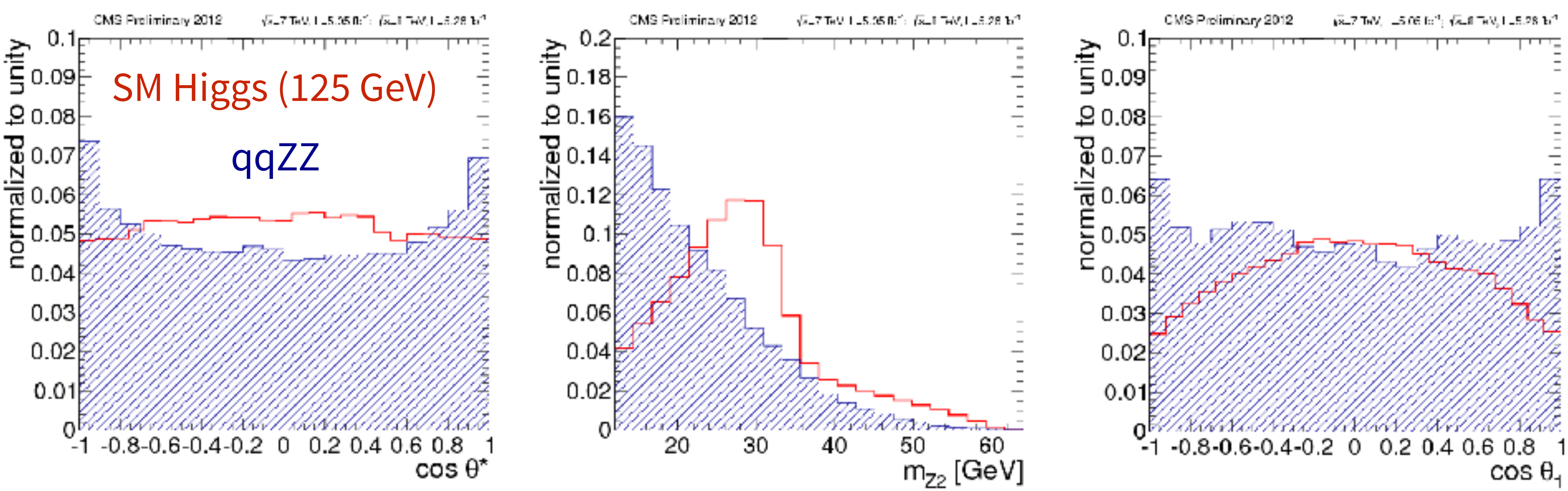
Matrix **E**lement **L**ikelihood **A**nalysis (**MELA**)

uses kinematic inputs for signal to background discrimination

$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

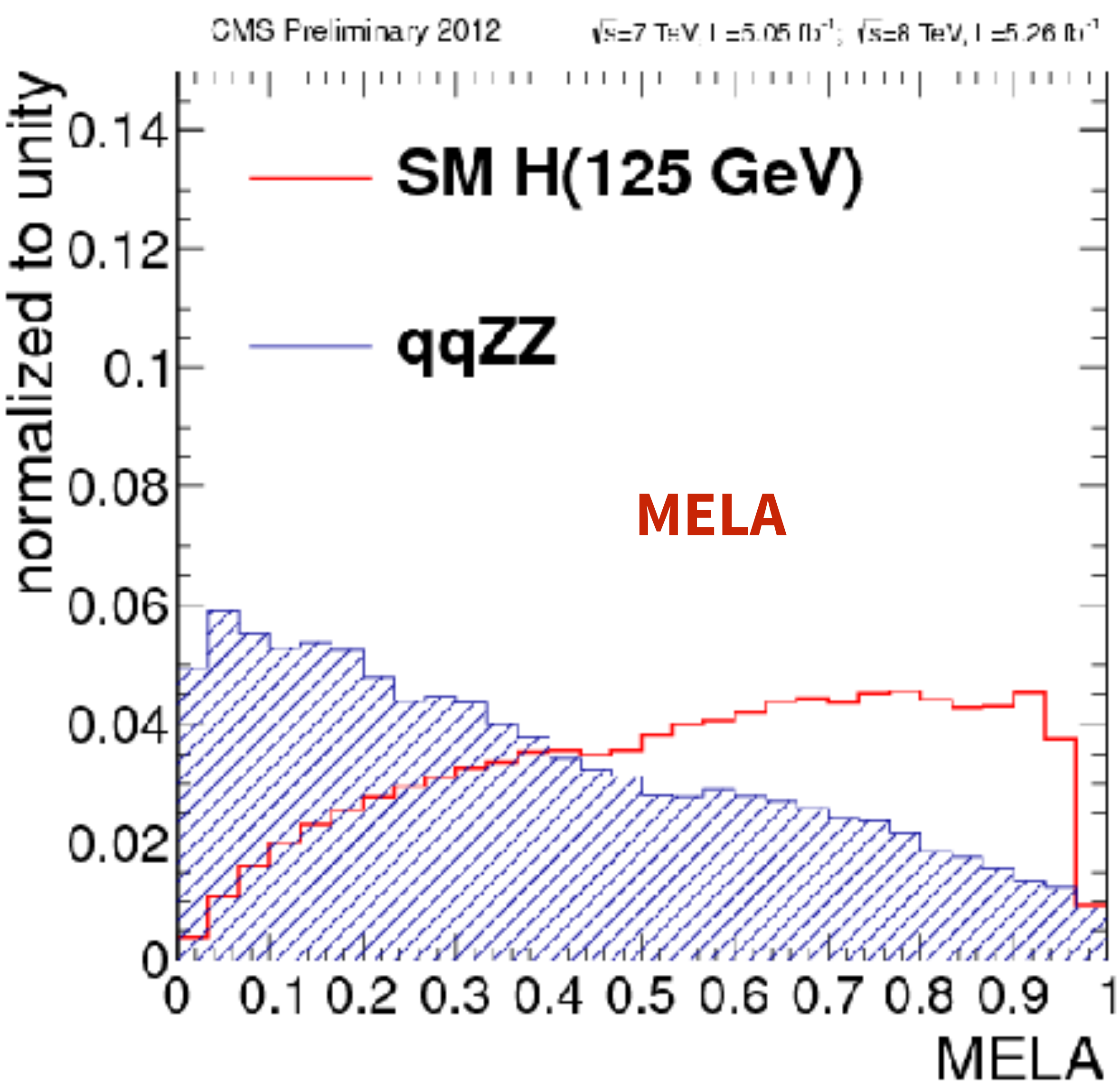


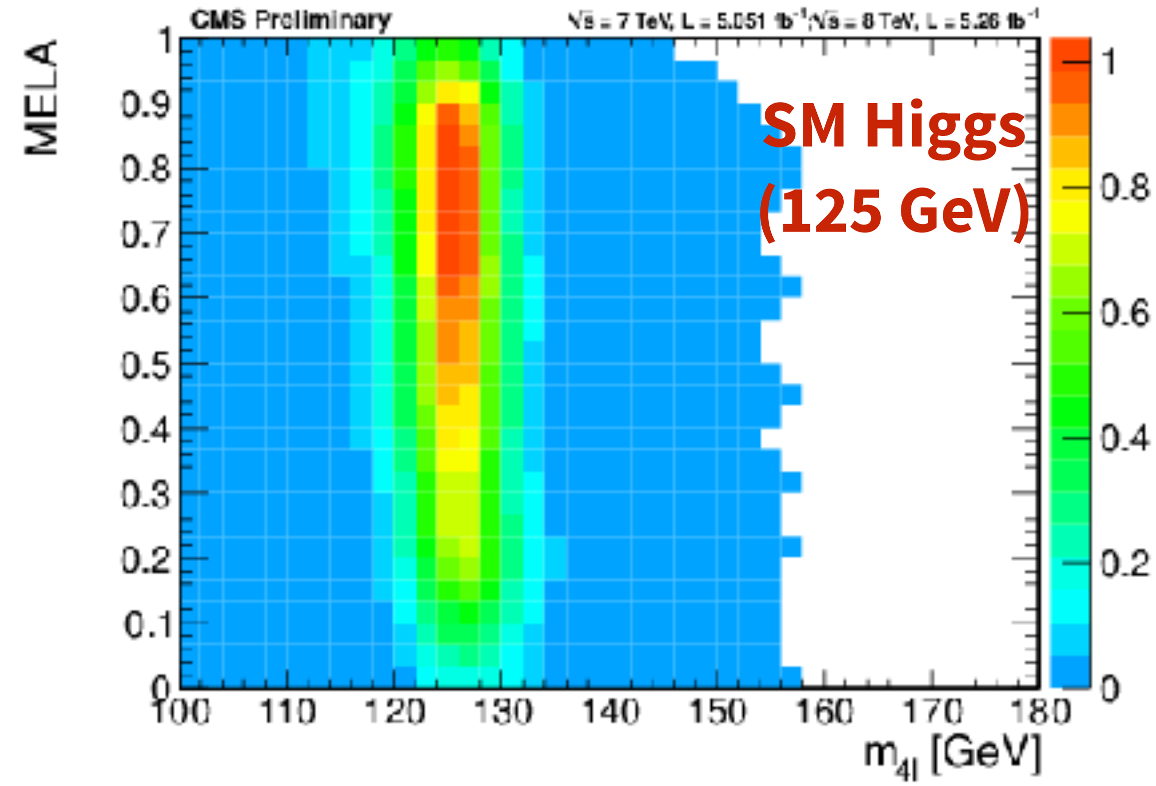
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

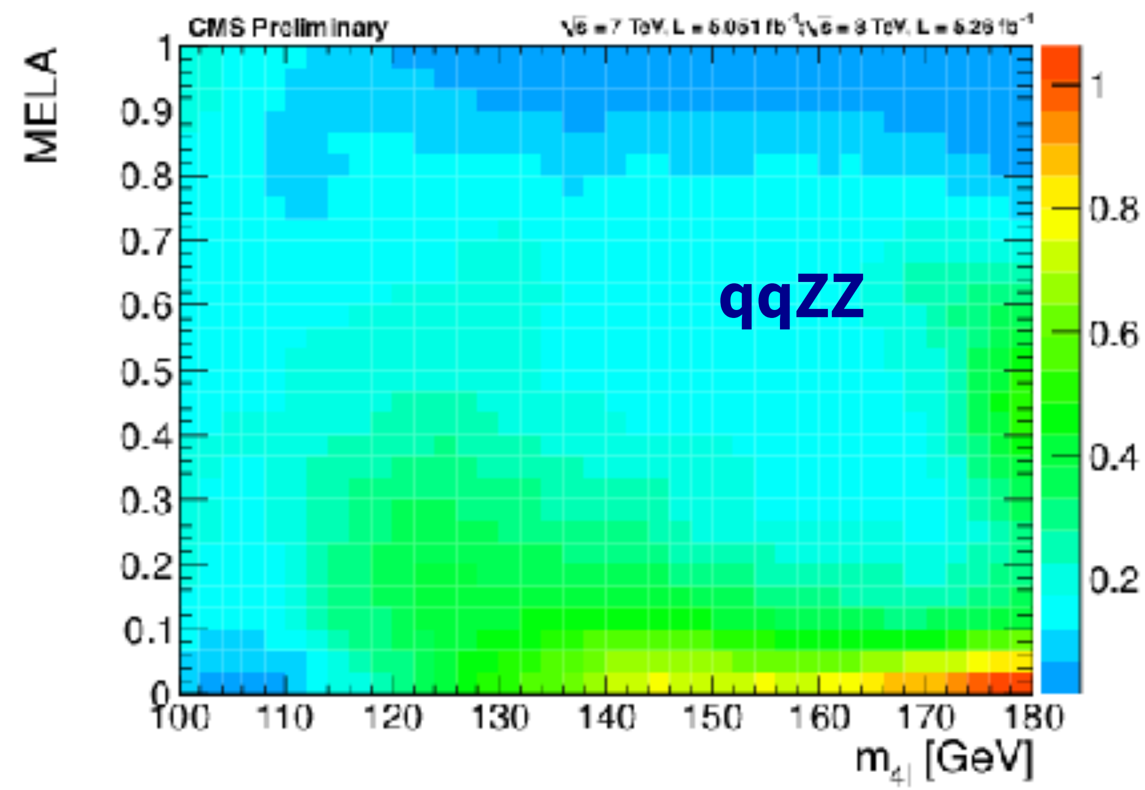


H→ZZ*→4l: Kinematical discriminant

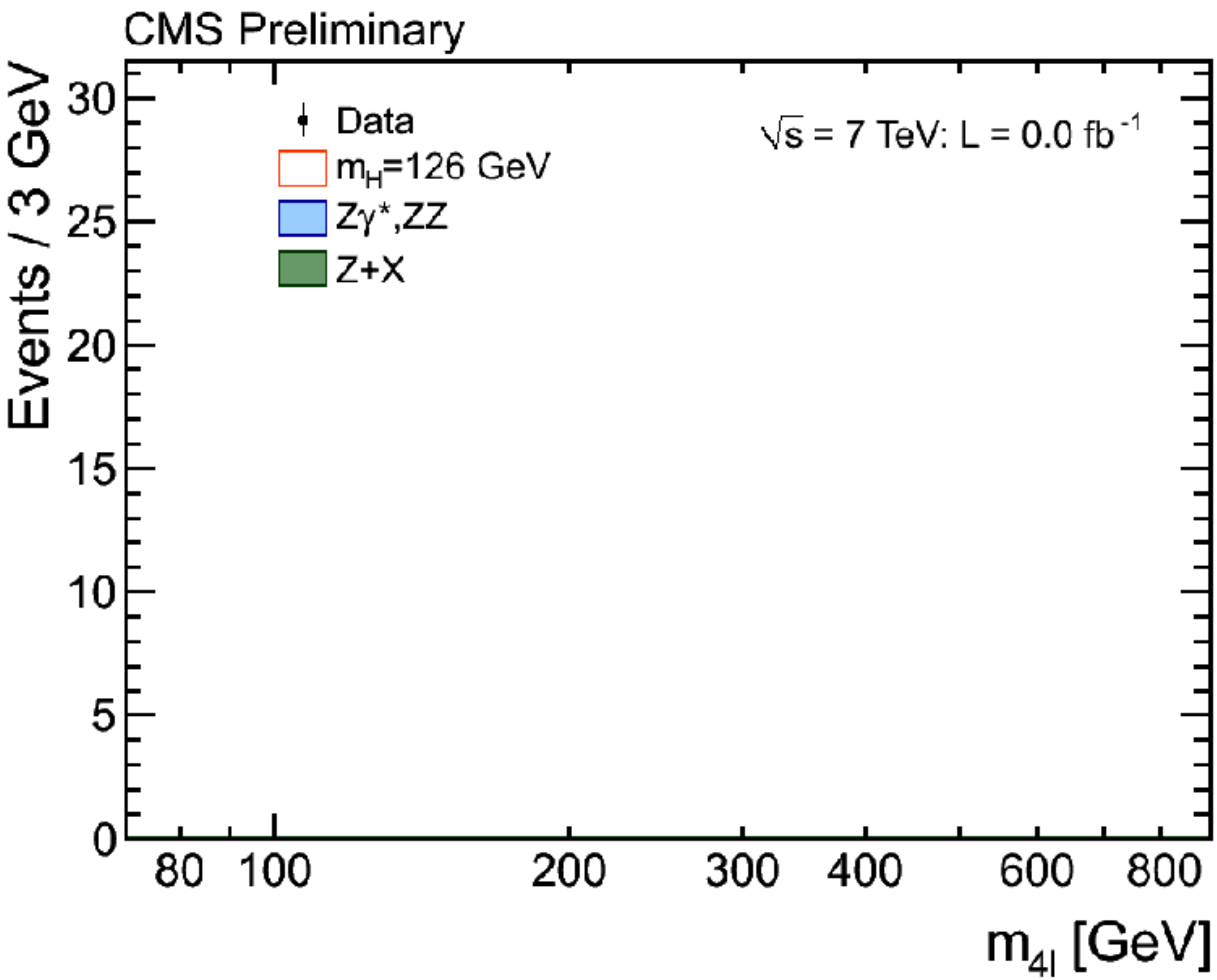
2D analysis using m_{4l} vs MELA

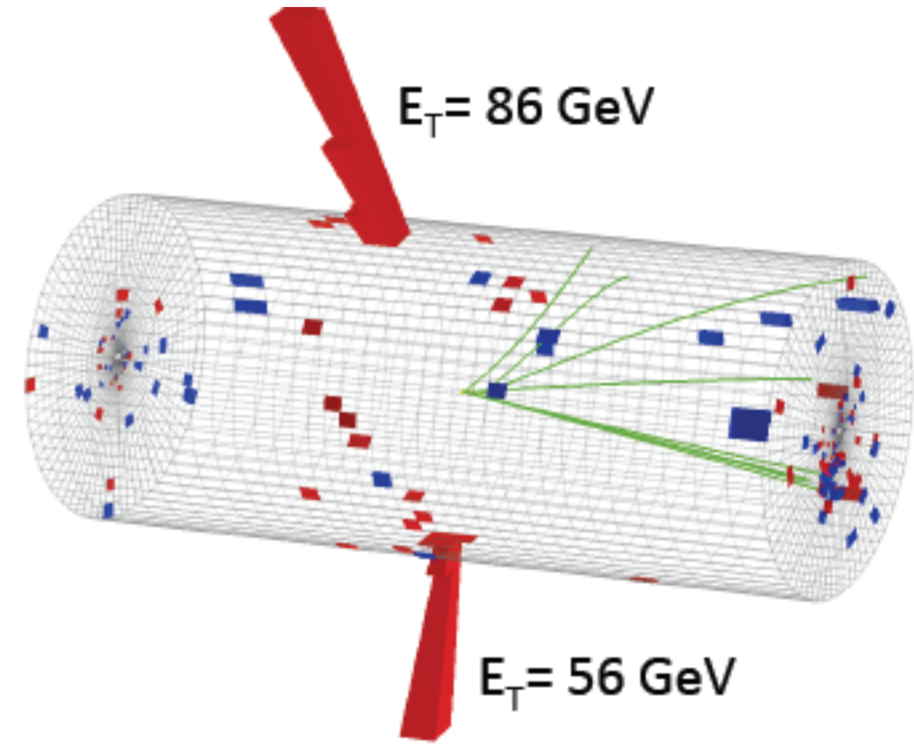






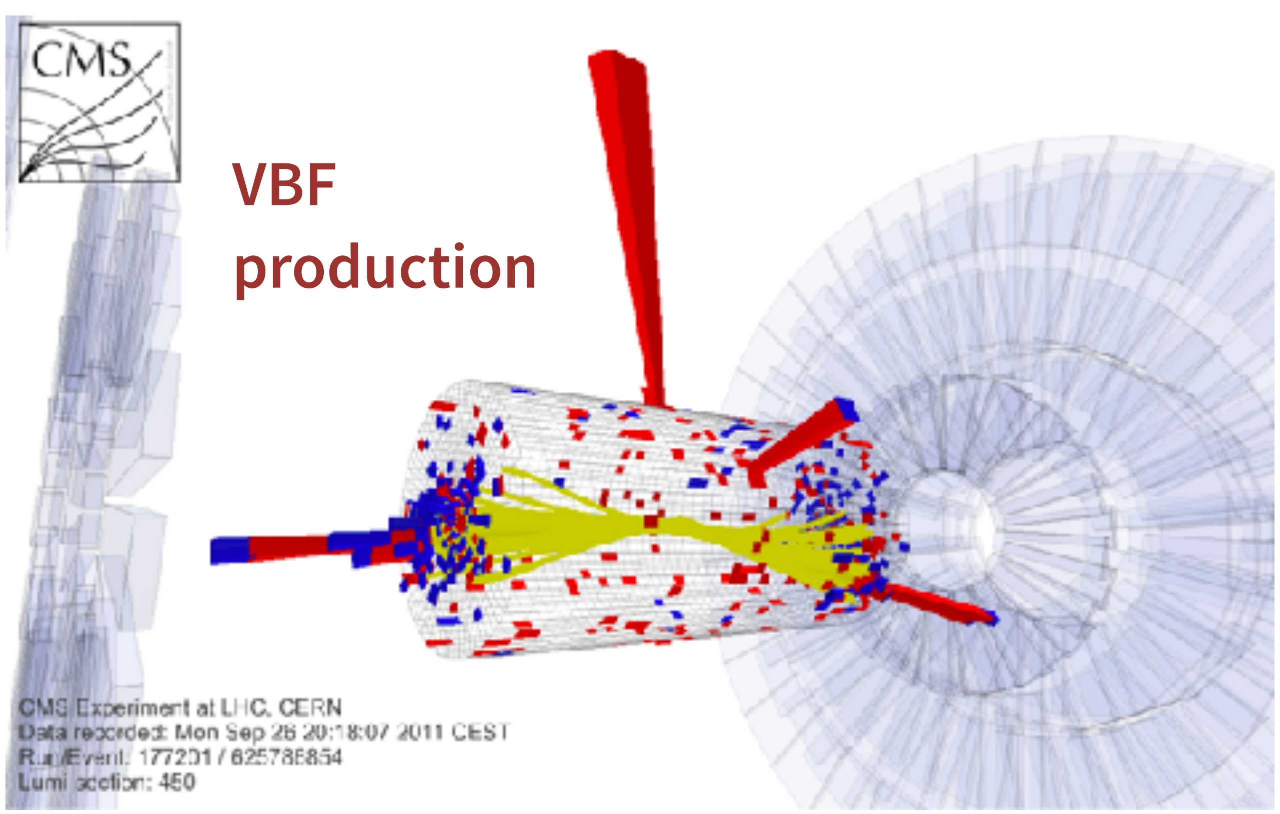
4 lepton invariant mass spectrum

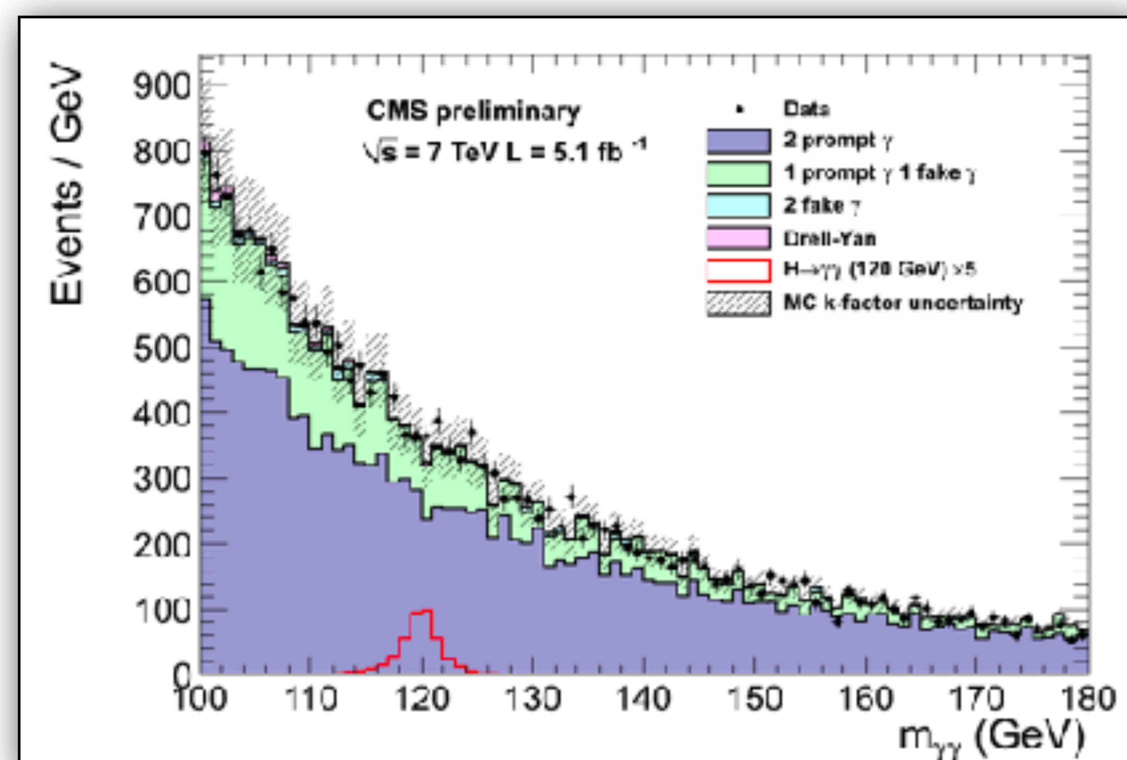




Critical channel for the discovery of the Higgs

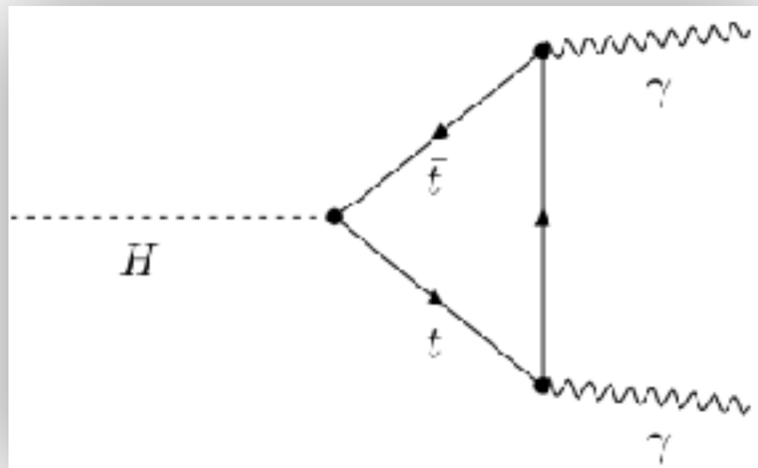
- Small BR (~0.2%) but very clear signature:
  - 2 isolated highly energetic photons
  - Search for a narrow peak over a falling background
    - very good mass resolution (~1-2%m $_{\gamma\gamma}$)
- VBF production channel helpful for background rejection
  - 2 forward jets from outgoing quarks





H→γγ - Backgrounds

H→γγ Signal



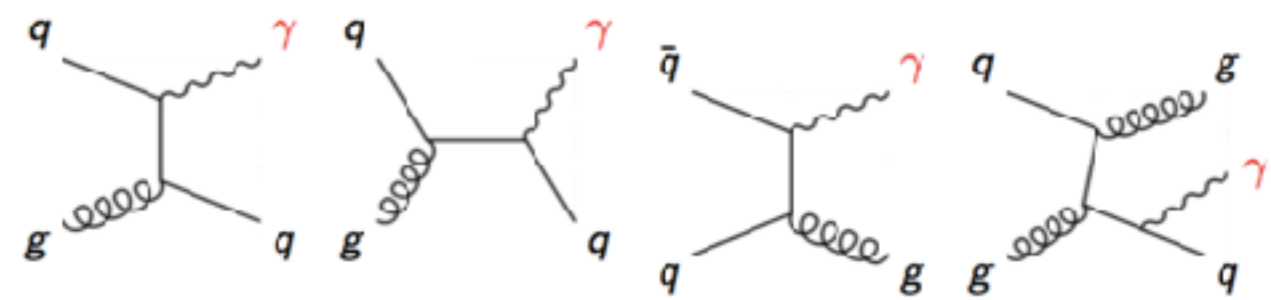
$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 m_H^3}{256\pi^3 v^2} \left| A_V\left(m_H^2 / 4m_W^2\right) - \sum_q A_f\left(m_H^2 / 4m_q^2\right) \right|^2$$

Photons do not couple directly to H because massless

Process takes place through a top (or W) loop

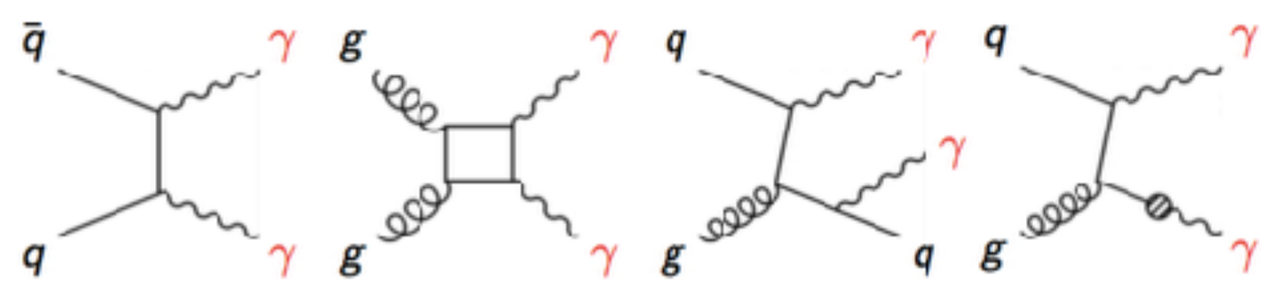
Reducible backgrounds

- Mainly due to jets identified as photons



Irreducible backgrounds

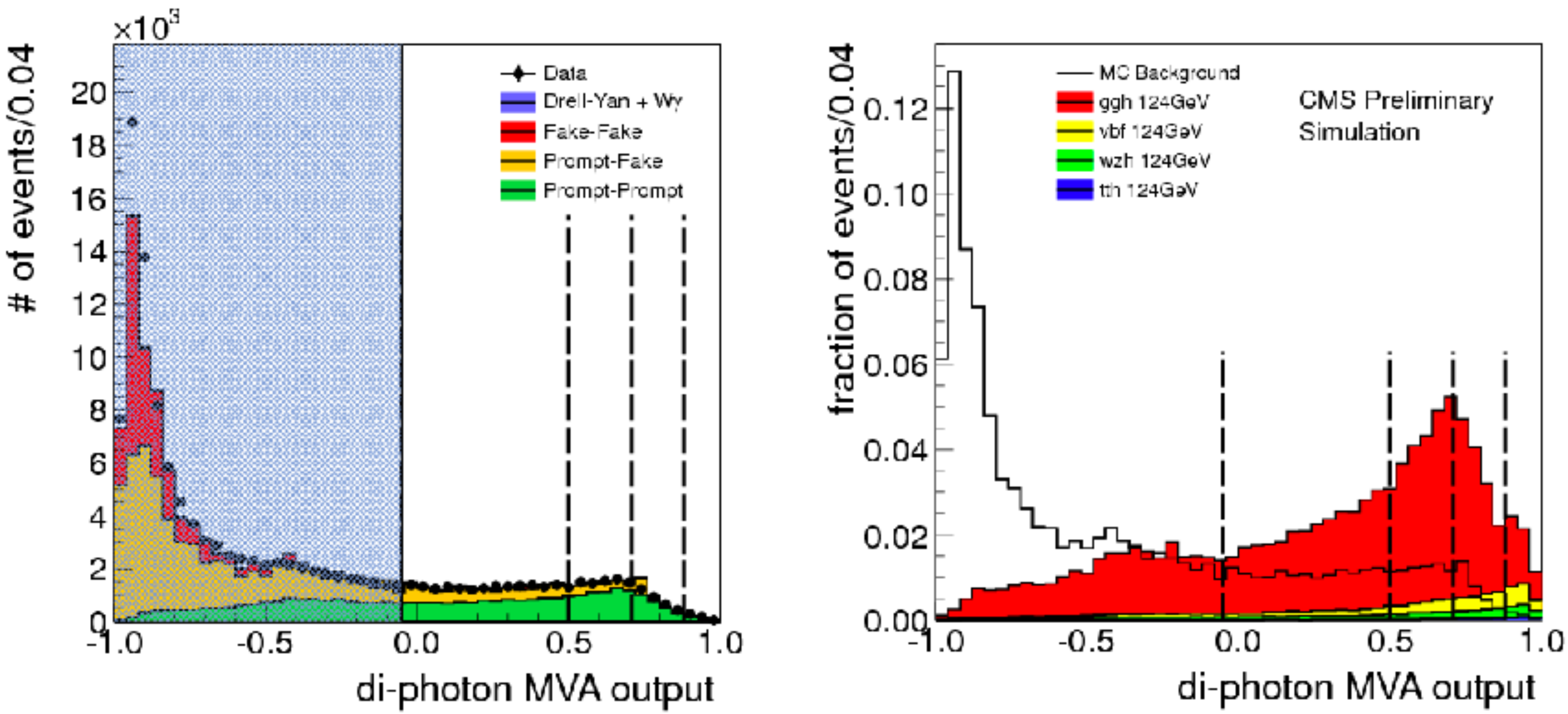
- γγ pair production from non-Higgs decays



H→γγ - Event selection

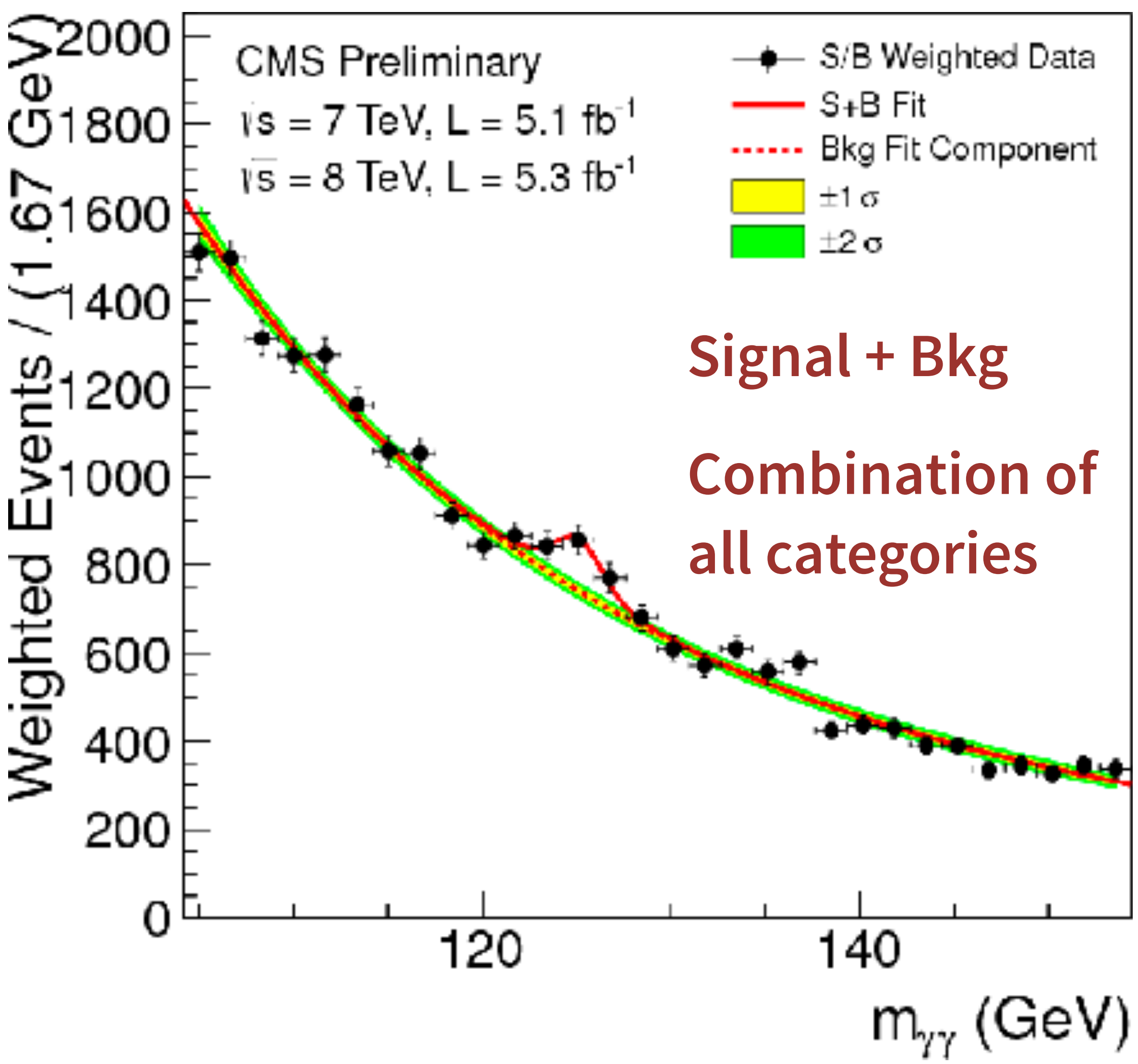
Only events with 2 identified and isolated photons are selected

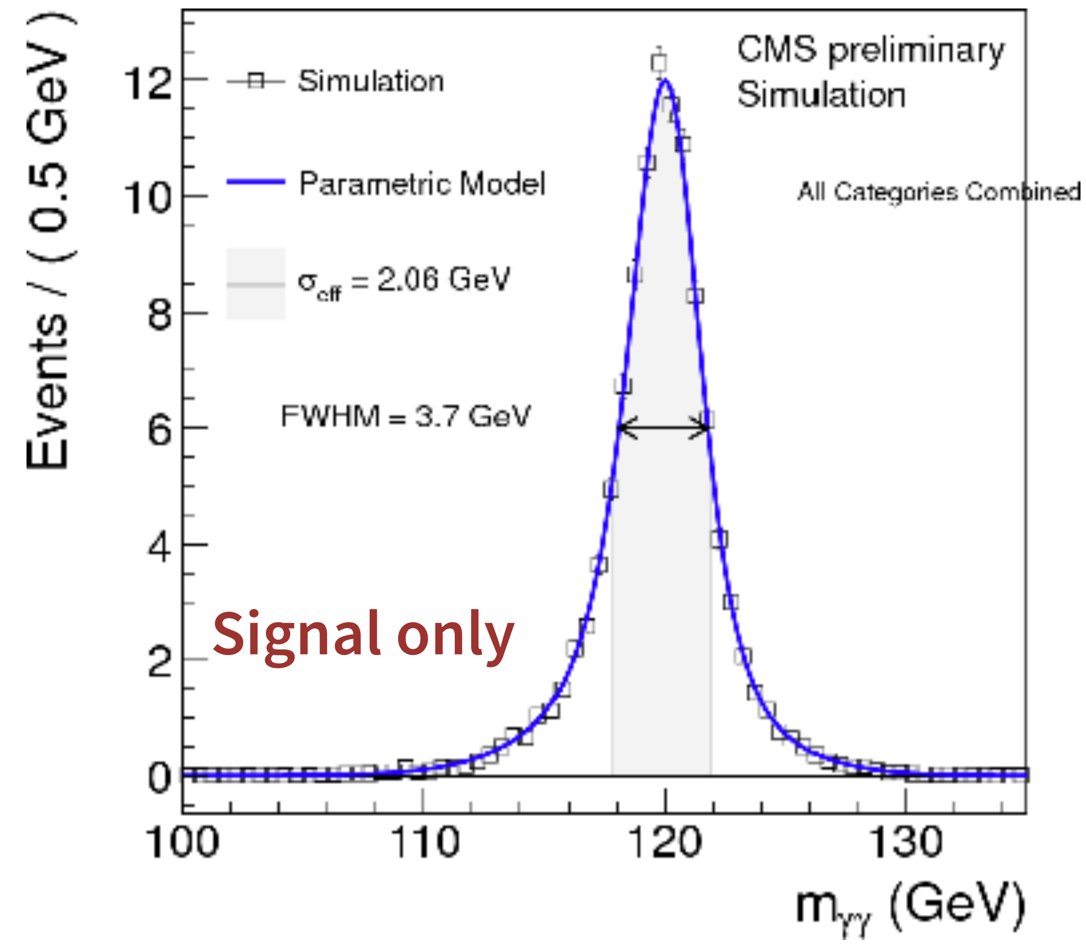
- Events are then split in orthogonal categories:
  - defined according to a **Multivariate Analysis Discriminant** based on the properties of identified photons and on the presence of 2 jets at large rapidity (VBF-like events)



H→γγ - Signal and background modelling

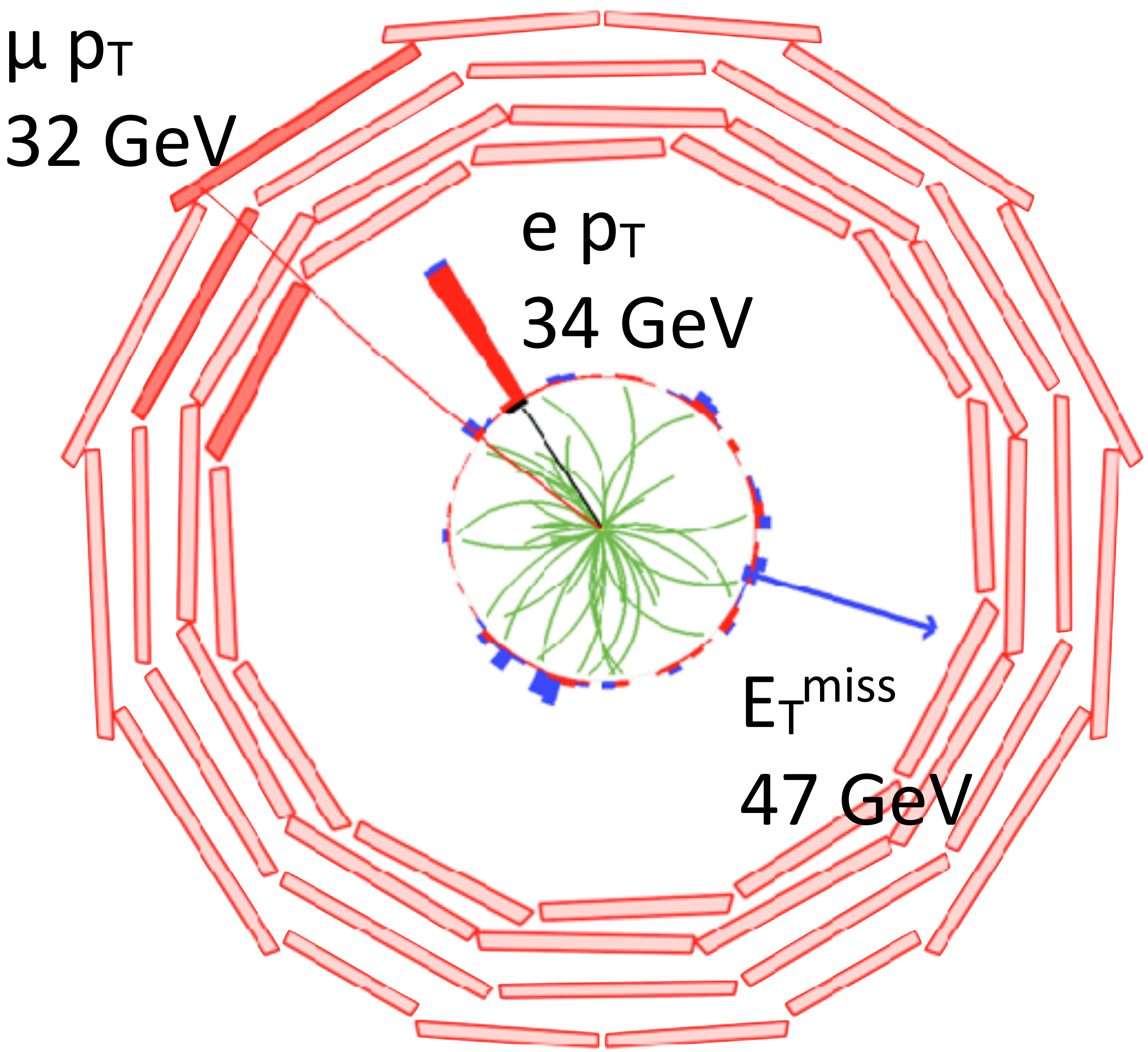
- Signal is parametrised from MC simulation
  - Crystal Ball + Gaussian
- Background is estimated by fitting a polynomial function to data in the full mass range





From the fit is clearly visible a nice peak over a falling background

H→WW→ℓνℓν in a nutshell



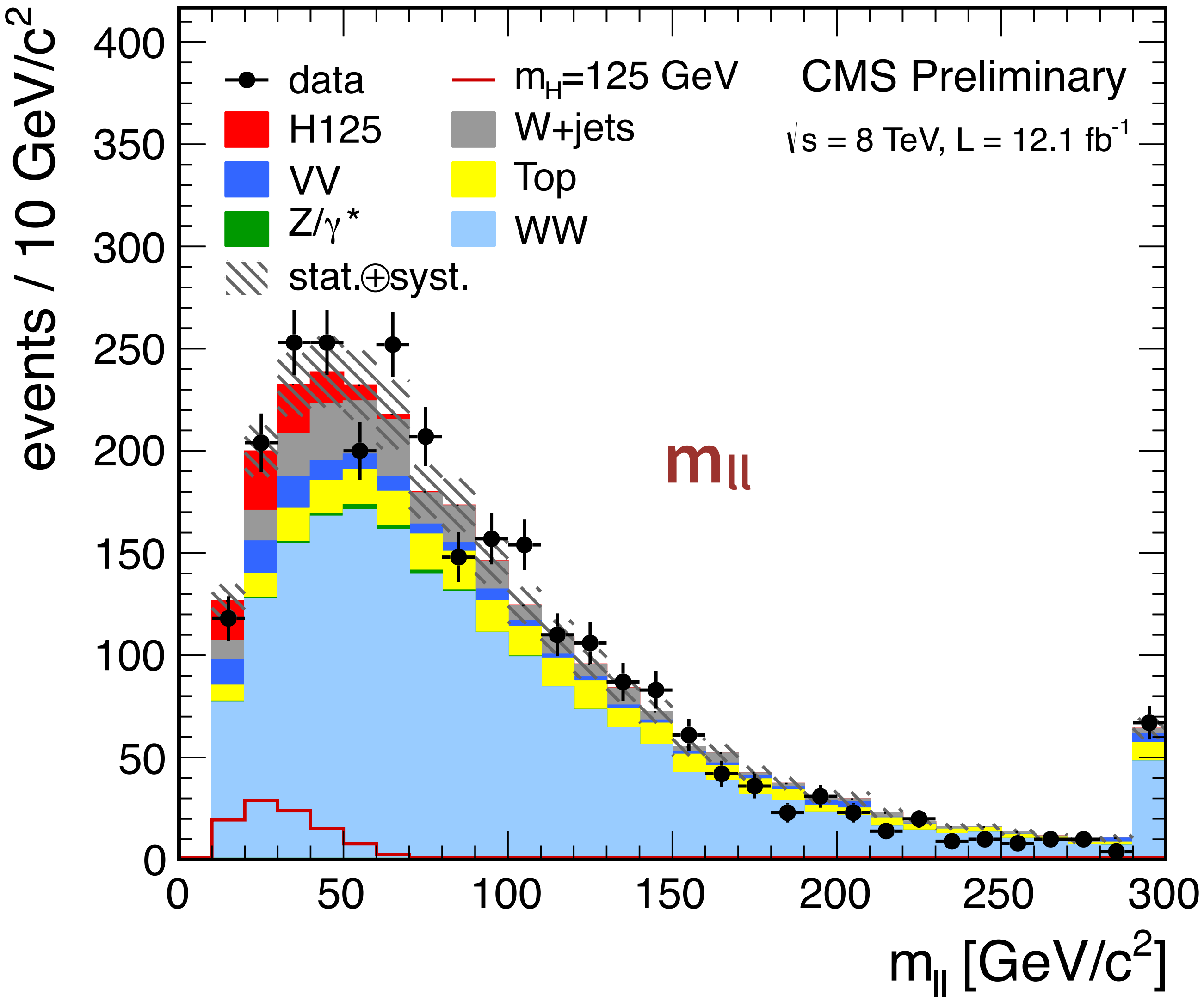
Signature

- 2 high p_T leptons (e,μ)
- large missing E_T
- small $\Delta\phi_{\ell\ell}$ and low $M_{\ell\ell}$ for low m_H
- no resonance peak

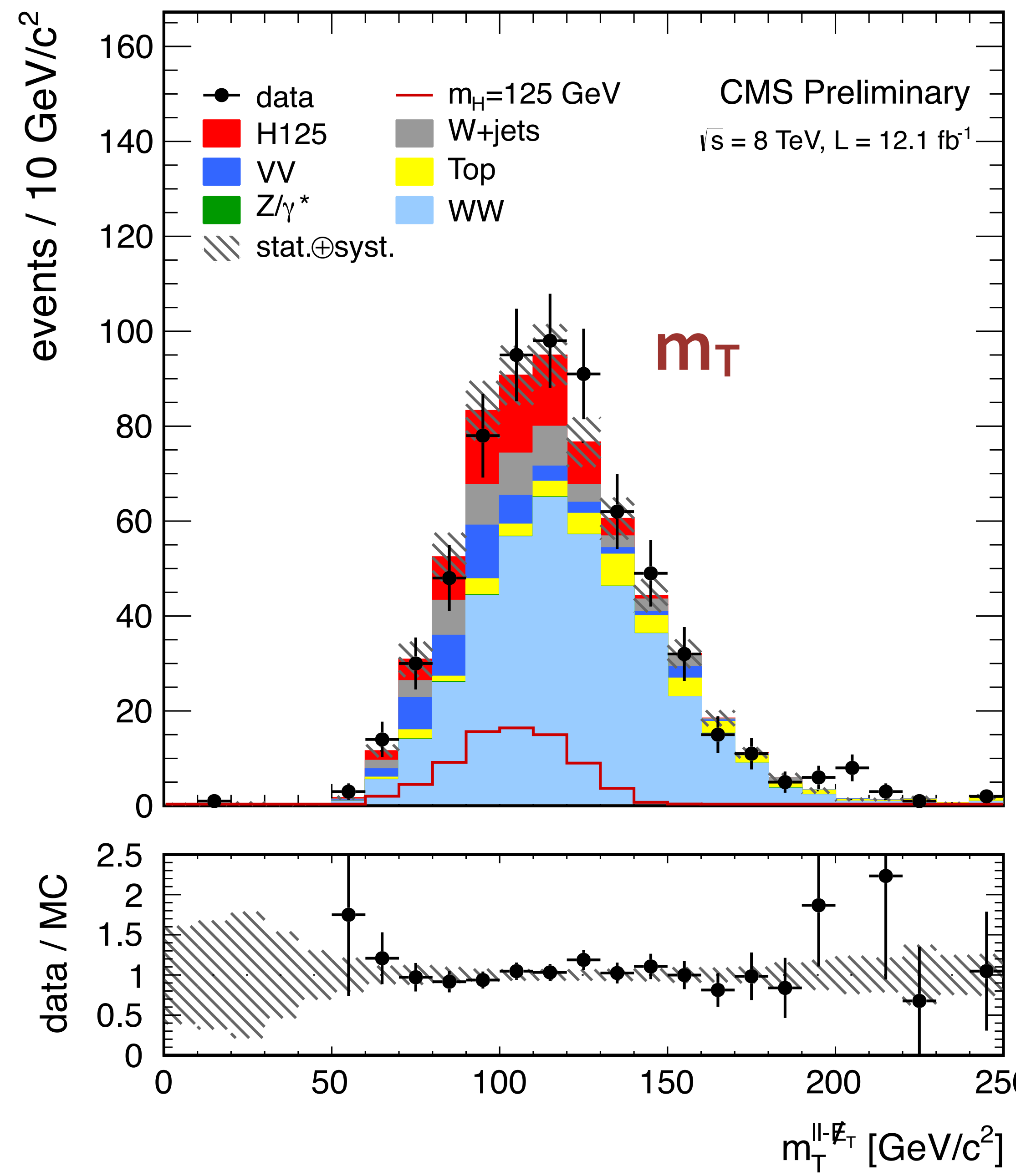
Backgrounds

- WW: continuum
- tt/tW: b-jets
- W+jets: "fake" lepton
- Z/γ*: mis-measured ME_T
- W/Z+γ(*): $\gamma^{(*)} \rightarrow \ell\ell$
- WZ/ZZ: V+jj/νν or missing lepton

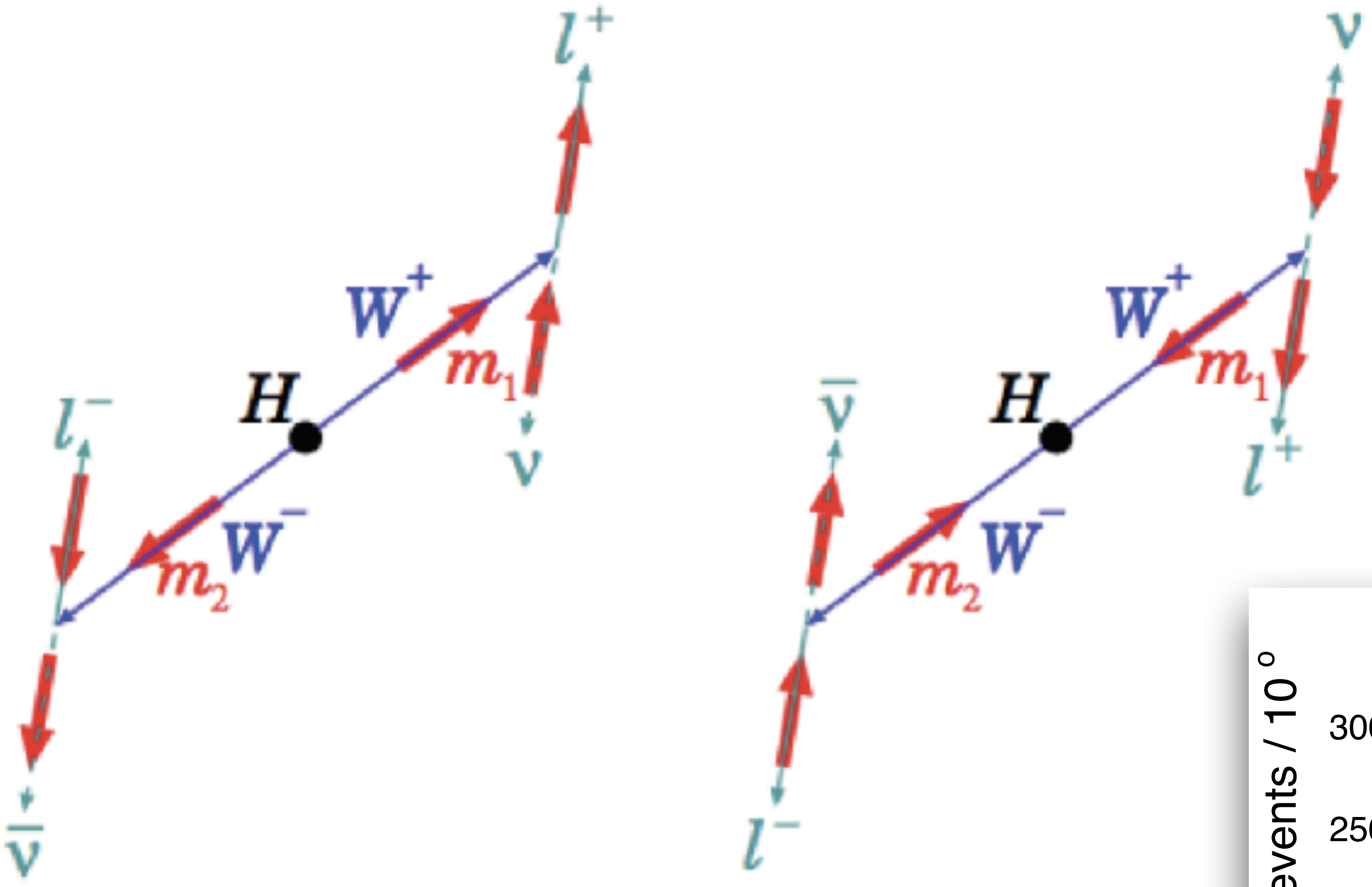
H→WW→ℓνℓν

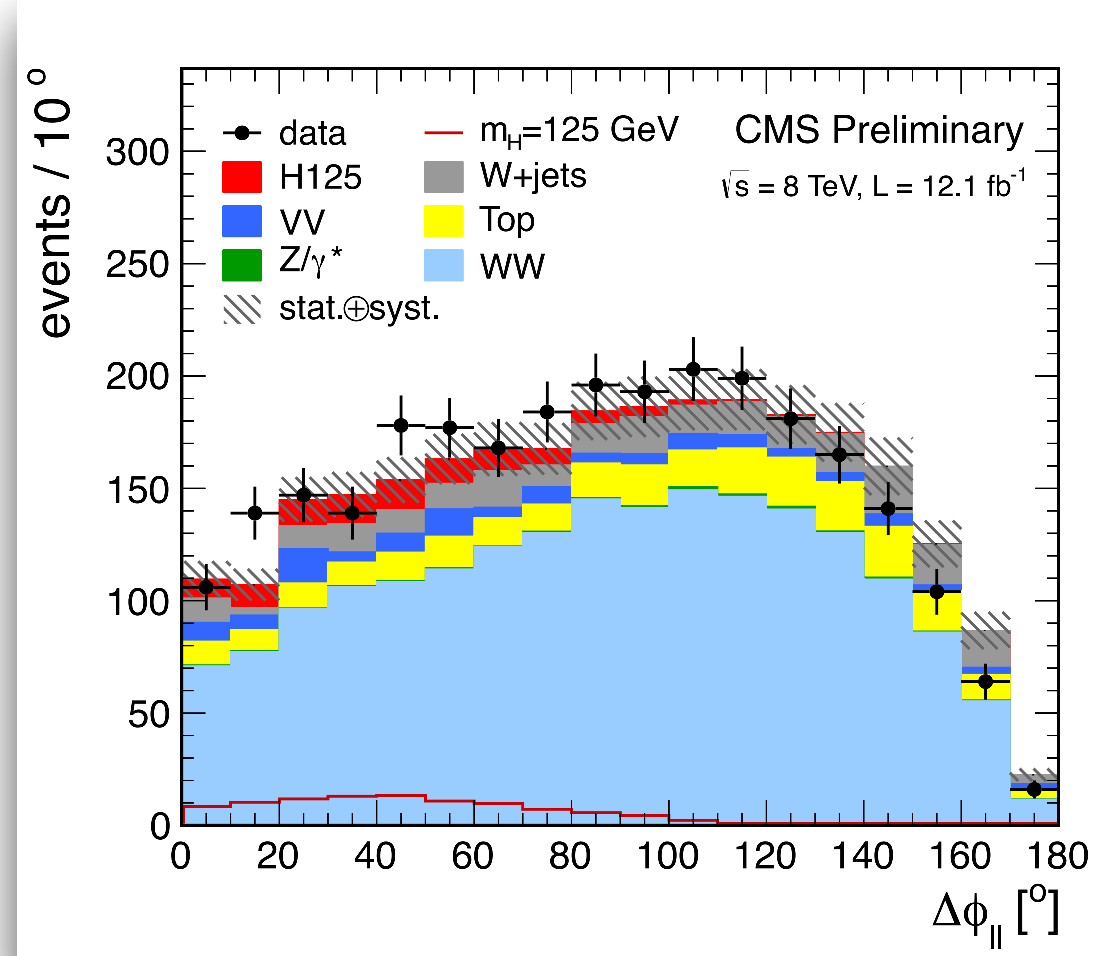


$$m_T = \sqrt{2p_T^{ll} E_T^{\text{miss}}(1 - \cos\Delta\phi_{E_T^{\text{miss}}ll})}$$



H→WW→ℓνℓν: spin properties





If the Higgs boson **has spin 0**, the two leptons expected to be emitted in the same direction (small azimuthal opening between the two)

Statistical interpretation

Claiming a discovery

We can claim discovery if we measure a signal yield sufficiently inconsistent with zero

- What does it mean sufficiently? How do we quantify it?
  - We can quantify how relevant is the excess by stating what is its ***significance***.

Statistical significance = probability ***p*** to observe ***s*** or larger signal yield in the case of pure background fluctuations

- Often preferred to quote "nσ" significance, where:

$$p = \int_{n\sigma}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \mathrm{d}x = 1 - \frac{1}{2}\mathrm{erf}\left(\frac{n}{\sqrt{2}}\right)$$

- It is common habit to claim:
  - "Evidence of", if the significance is > 3 σ
  - "Observation", if the significance is > 5 σ **Discovery**
    - which corresponds to probability of background fluctuation = 2.87×10^{-7}

More details in "Statistical methods for Data Analysis in Particle Physics", L.Lista

Significance and corresponding p-value

$Z\ (\sigma)$	p
1.00	1.59×10^{-1}
1.28	1.00×10^{-1}
1.64	5.00×10^{-2}
2.00	2.28×10^{-2}
2.32	1.00×10^{-2}
3.00	1.35×10^{-3}
3.09	1.00×10^{-3}
3.71	1.00×10^{-4}
4.00	3.17×10^{-5}
5.00	2.87×10^{-7}
6.00	9.87×10^{-10}

What if we do not observe a significant excess?

Not always experiments lead to discoveries:

- The signal may indeed not be there
- Or the collected dataset is not enough to claim a discovery

We can still say something by **setting upper limits**

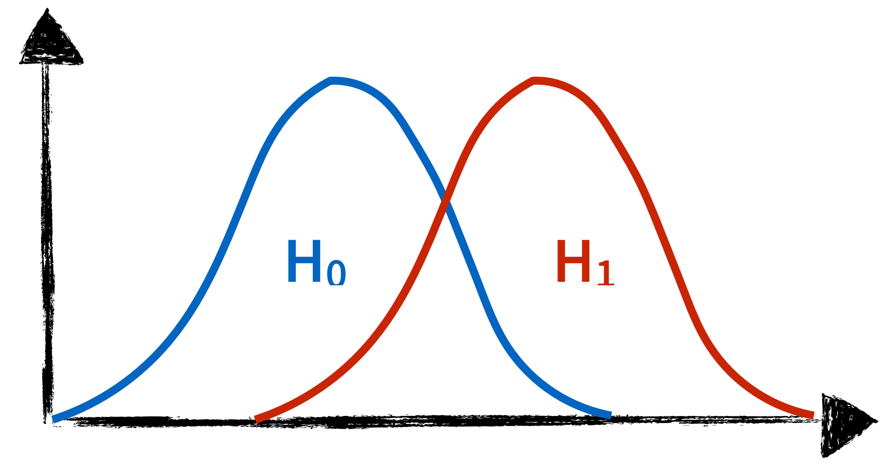
One possible definition of upper limit: "*largest value of the signal s for which the probability of a signal under-fluctuation smaller or equal to what has been observed is less than a given level (usually 10% or 5%)*"

- Upper limits for an exclusion are set requiring:
  - $p<0.05$ (95%CL) or $p<0.10$ (95%CL)
  - In this case *p* indicates the probability of a signal underfluctuation

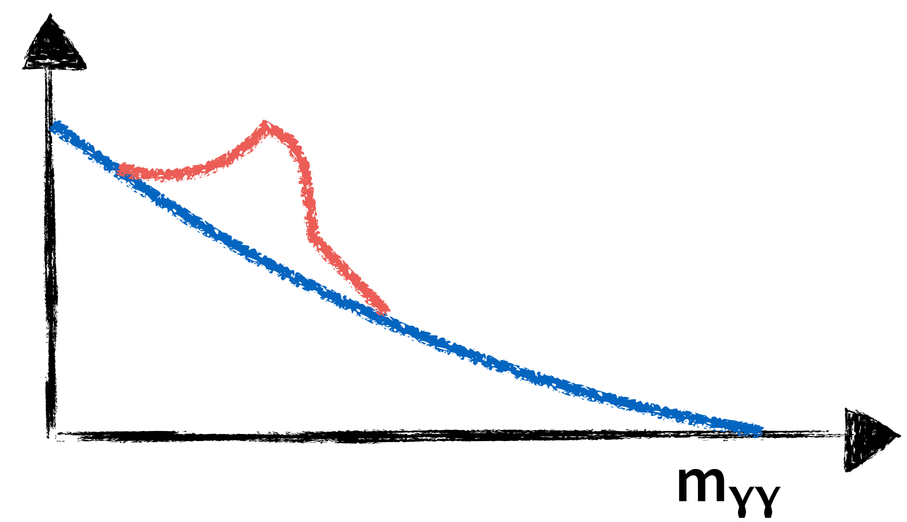
Statistical Interpretation of Higgs searches

Null Hypothesis (H_0) vs alternative hypothesis (H_1, Existence of Higgs)

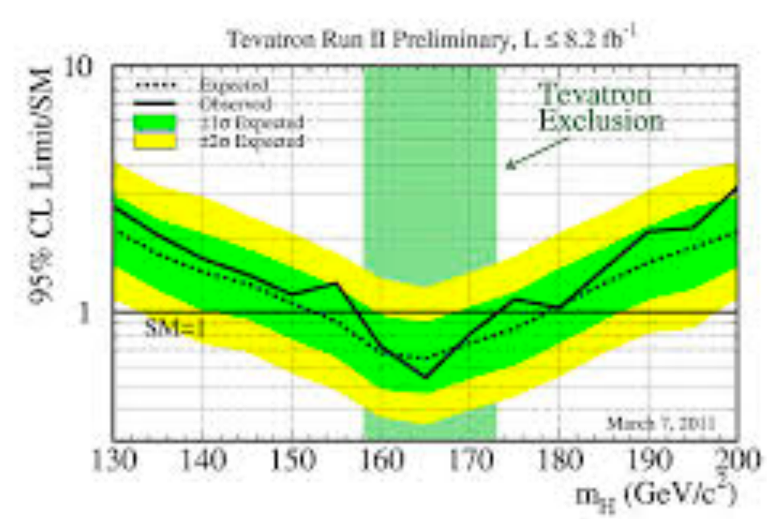
Need to quantify the level at which each hypothesis is accepted or rejected



Identify the experimental observables and define a statistical test and the parameters of the model



Compute the confidence level for exclusion or the significance of the excess



The CLs method

Signal strength $\mu = \sigma/\sigma_{SM}$

test statistic q_μ

$$q_\mu = -2\ln\frac{L(obs|\mu,\hat{\theta}_\mu)}{L(obs|\hat{\mu},\hat{\theta})}$$

$$0 < \hat{\mu} < \mu$$

CL_{s+b} (s+b hypothesis)

$$\mathrm{CL_{s+b}} = P(q_\mu \geq q_\mu^{obs}|\mu \neq 0)$$

CL_b (b-only hypothesis)

$$\mathrm{CL_b} = P(q_\mu \geq q_\mu^{obs}|\mu = 0)$$

CL_s

$$\mathrm{CL_s} = \frac{CL_{s+b}}{CL_b}$$

The **exclusion of a SM Higgs boson** is defined by the following condition:

- **$CL_s(\mu = 1) \leq \alpha$** at **$1-\alpha = 95\%$** confidence level, C.L.

We can say that $s < s^{up}$ at 95% C L (or 90% CL)

Likelihoods

$$L(obs, \tilde{\theta}|\mu, \theta) = \prod_{c=1}^{N_{ch}} L_c(obs_c|\mu, \theta) \times \prod_{i=1}^{N_\theta} p_i(\tilde{\theta}_i|\theta_i)$$

If we are combining more channels, the overall likelihood is the product of the likelihood functions of each channel (L_c)

product of the response function of the measurement associated to the nuisance parameters (systematic uncertainties)

In case of a counting experiment

$$L(obs|\mu, \theta) = Poisson(n_{obs}, \mu \cdot s(\theta) + b(\theta))$$

Inputs:

- Signal yield, $\mathbf{s(\theta)}$
- Background yield, $\mathbf{b(\theta)}$
- Observed data, $\mathbf{n_{obs}}$
- Systematic uncertainties on yields, $\boldsymbol{\theta}$

Likelihoods

$$L(obs, \tilde{\theta}|\mu, \theta) = \prod_{c=1}^{N_{ch}} L_c(obs_c|\mu, \theta) \times \prod_{i=1}^{N_\theta} p_i(\tilde{\theta}_i|\theta_i)$$

If we are combining more channels, the overall likelihood is the product of the likelihood functions of each channel (L_c)

product of the response function of the measurement associated to the nuisance parameters (systematic uncertainties)

Including informations from the shape

$$L(obs|\mu, \theta) = Poisson(n_{obs}, \mu \cdot s(\theta) + b(\theta)) \prod_{i=1}^{n_{obs}} f(x_i|\mu, \theta)$$

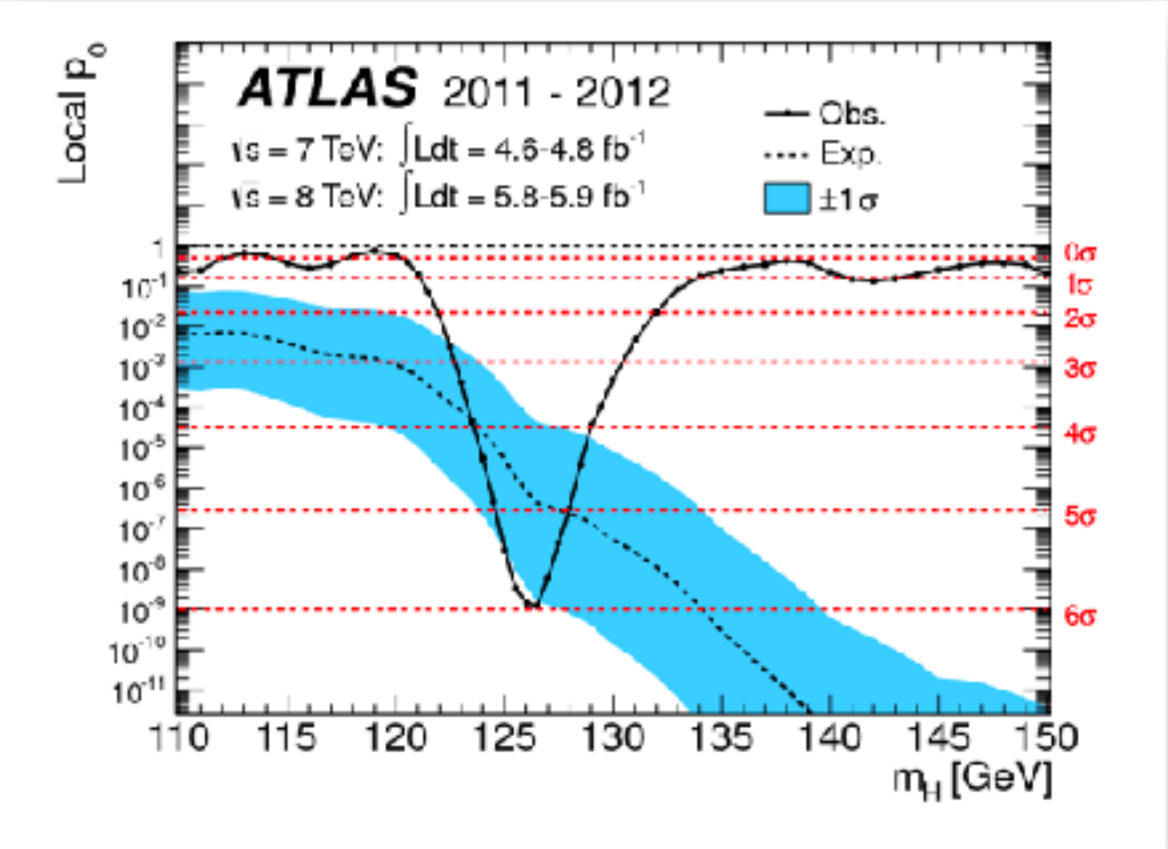
$$f(x_i|\mu, \theta) = \mu s(\theta) f_s(x_i, \theta) + b(\theta) f_b(x_i, \theta)$$

Inputs:

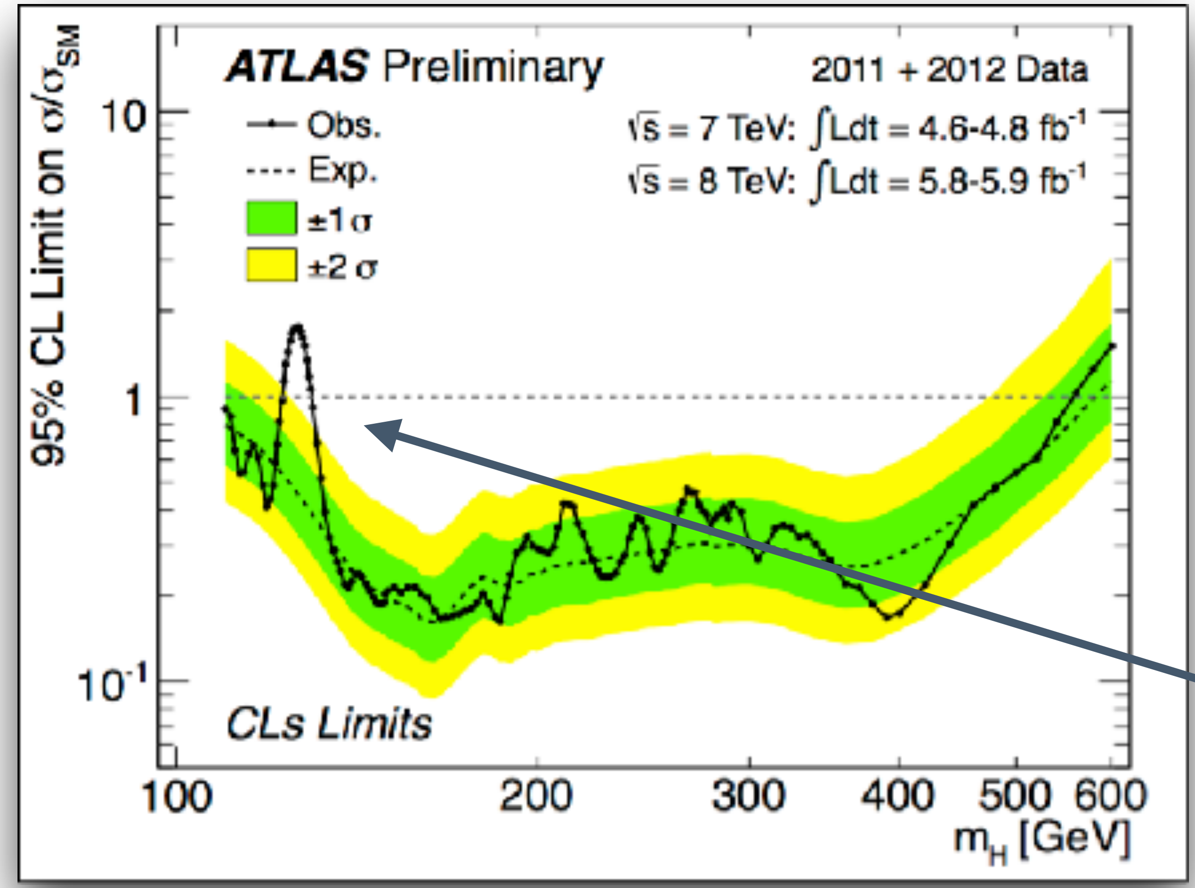
- Signal yield and shape, **$s(\theta)$** and **$f_s(x, \theta)$**
- Background yield and shape, **$b(\theta)$** and **$f_b(x, \theta)$**
- Observed data, **n_{obs}**
- Systematic uncertainties on yield and shape, **θ**

Combining all channels together

- Combining together results from Higgs boson searches in 5 decay modes: **H→γγ, H→ZZ, H→WW, H→bb, H→ττ**
- Early Summer 2012: sufficient statistics collected to claim the **observation of a new boson**



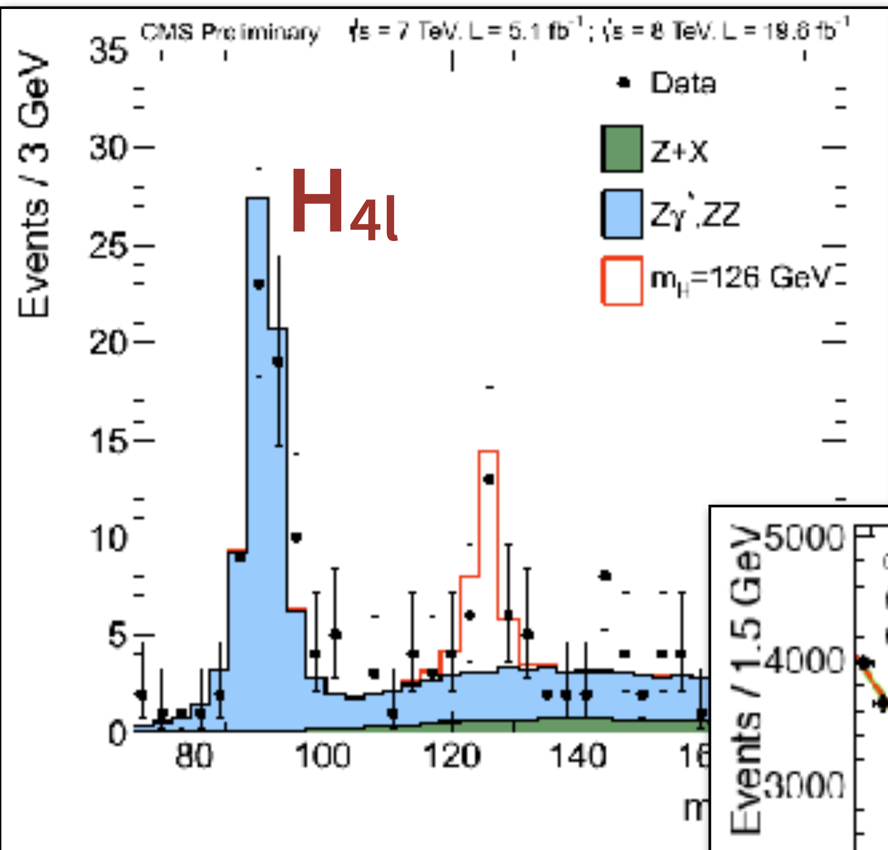
Observed excess of 7 σ around 125 GeV

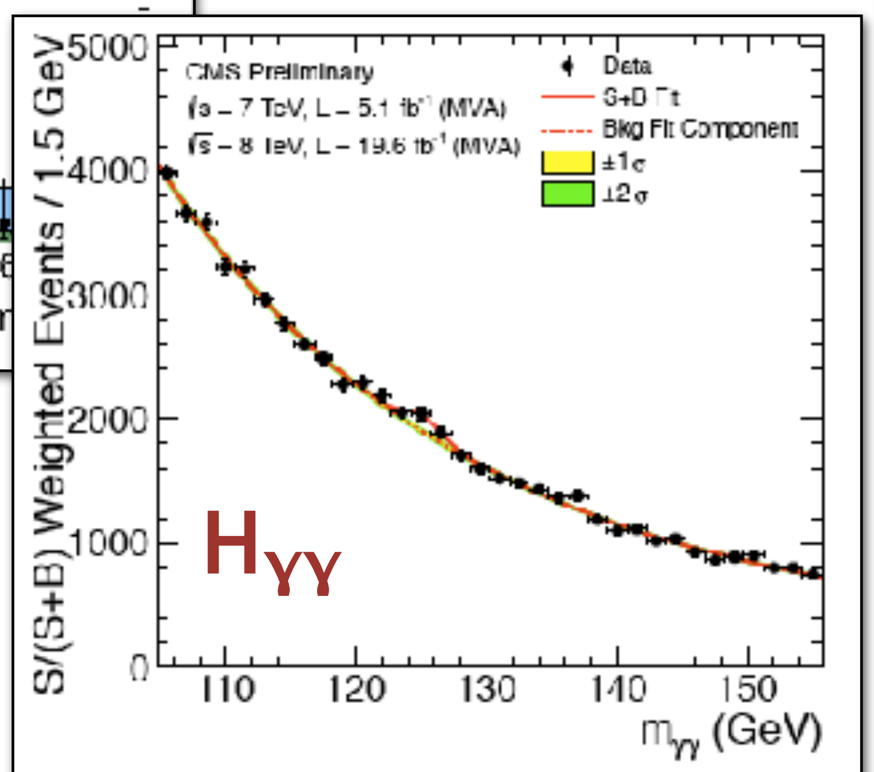


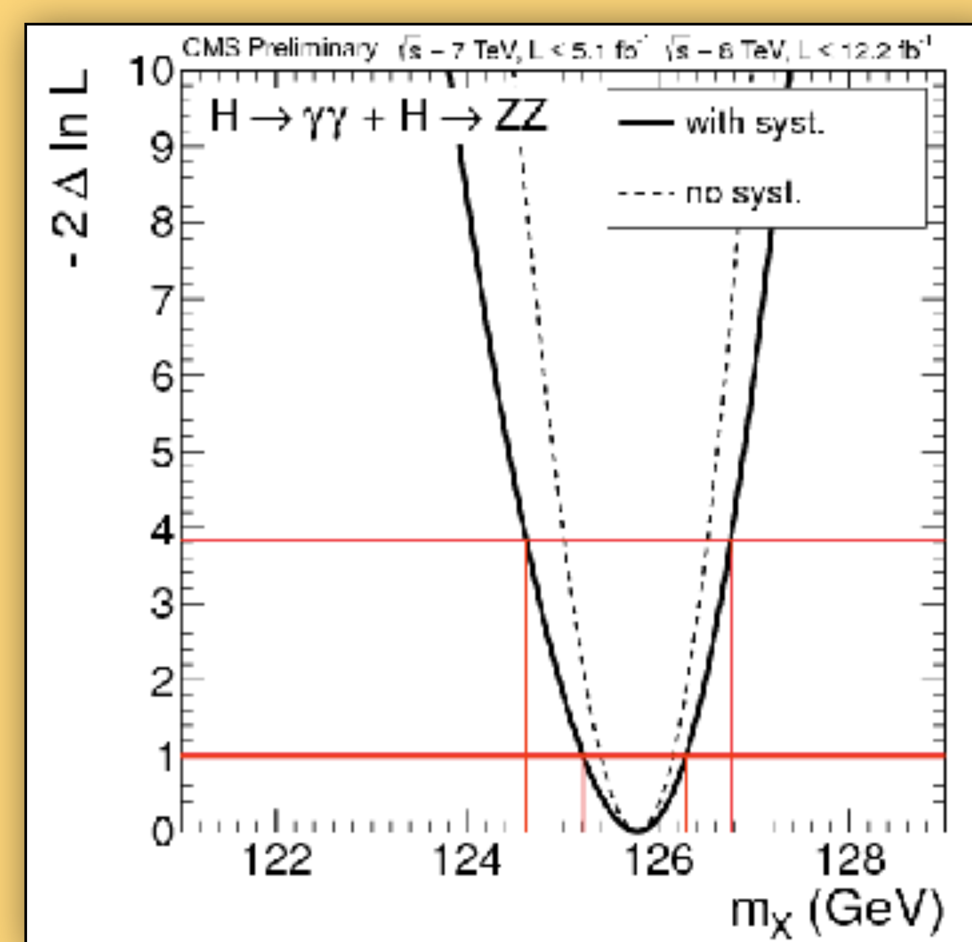
Clear excess in the upper limit plot ~ 125 GeV

Mass measurement of the new boson

High resolution channels, H→γγ and H→ZZ→4l, allowed already in early 2012 to get a good estimate of Higgs boson mass







Measurement of the observed boson mass:

$$\mathbf{m_H = 125.8 \pm 0.4^{(stat)} \pm 0.4^{(syst)}\ GeV}$$

Look-elsewhere effect

When searching for a signal over a wide range of parameters, such as the Higgs boson mass, we should be careful in stating the significance of the observation

- Let's say that we observe an excess of events for $m_H = X$
  - the probability that this excess is due to a background fluctuation, showing up exactly at $m_H = X$, is given by the p-value (***local significance***)
- However, such an excess could have appeared **everywhere** in the range considered
  - This is what is called ***"the look-elsewhere effect"***

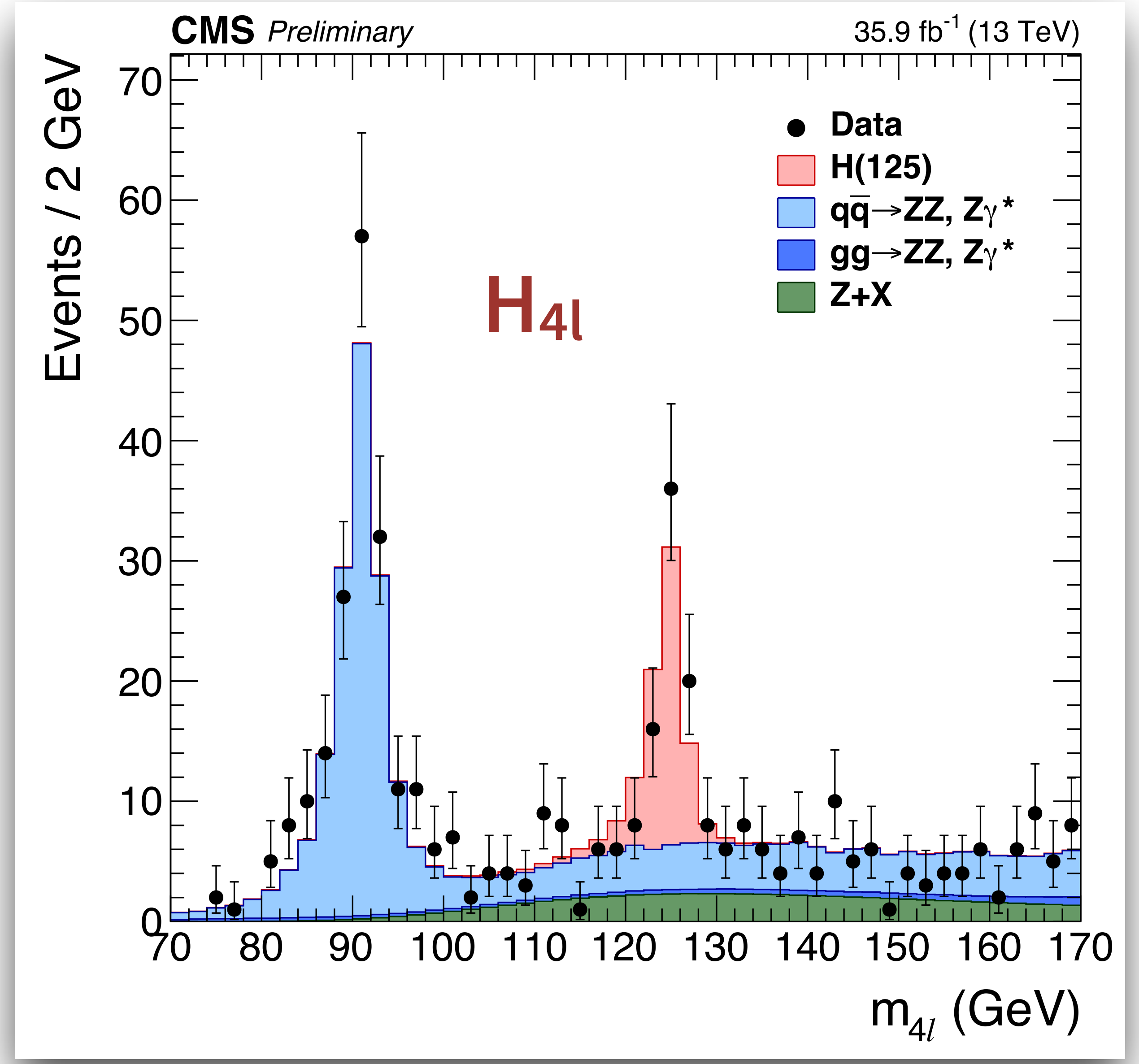
We need to consider not just what is the probability to have a background fluctuation at $m_H = X$, but more in general what is the probability to observe such a fluctuation everywhere in our range ***(global significance)***

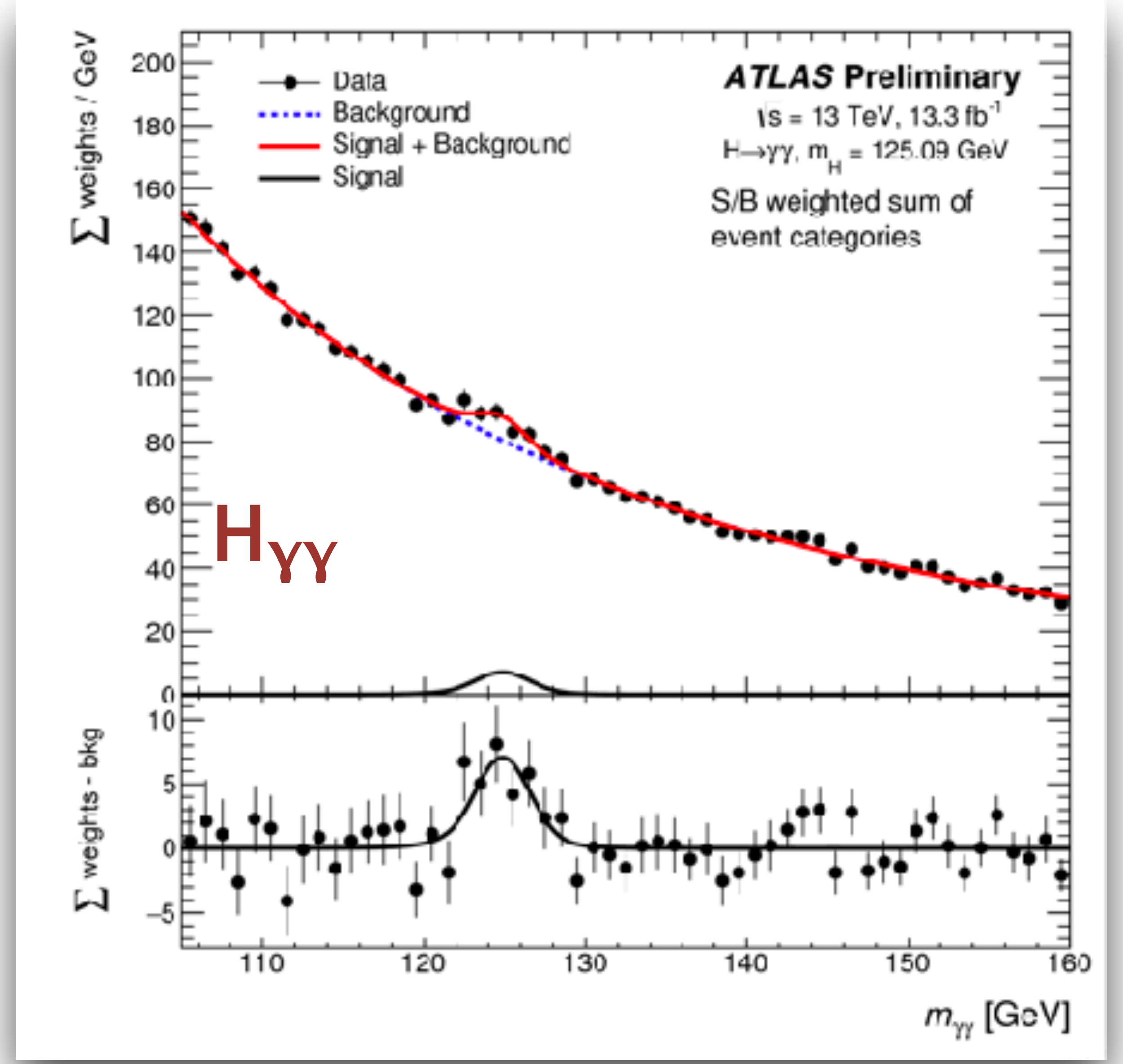
- The effect can be evaluated with brute-force Toy Monte Carlo
  - Run *N* experiments with background-only, find the largest '*local*' significance over the whole search range, and get its distribution to determine '*overall*' significance

OK, we have discovered a new particle…but is this the Higgs boson predicted by the SM?

Where do we stand now

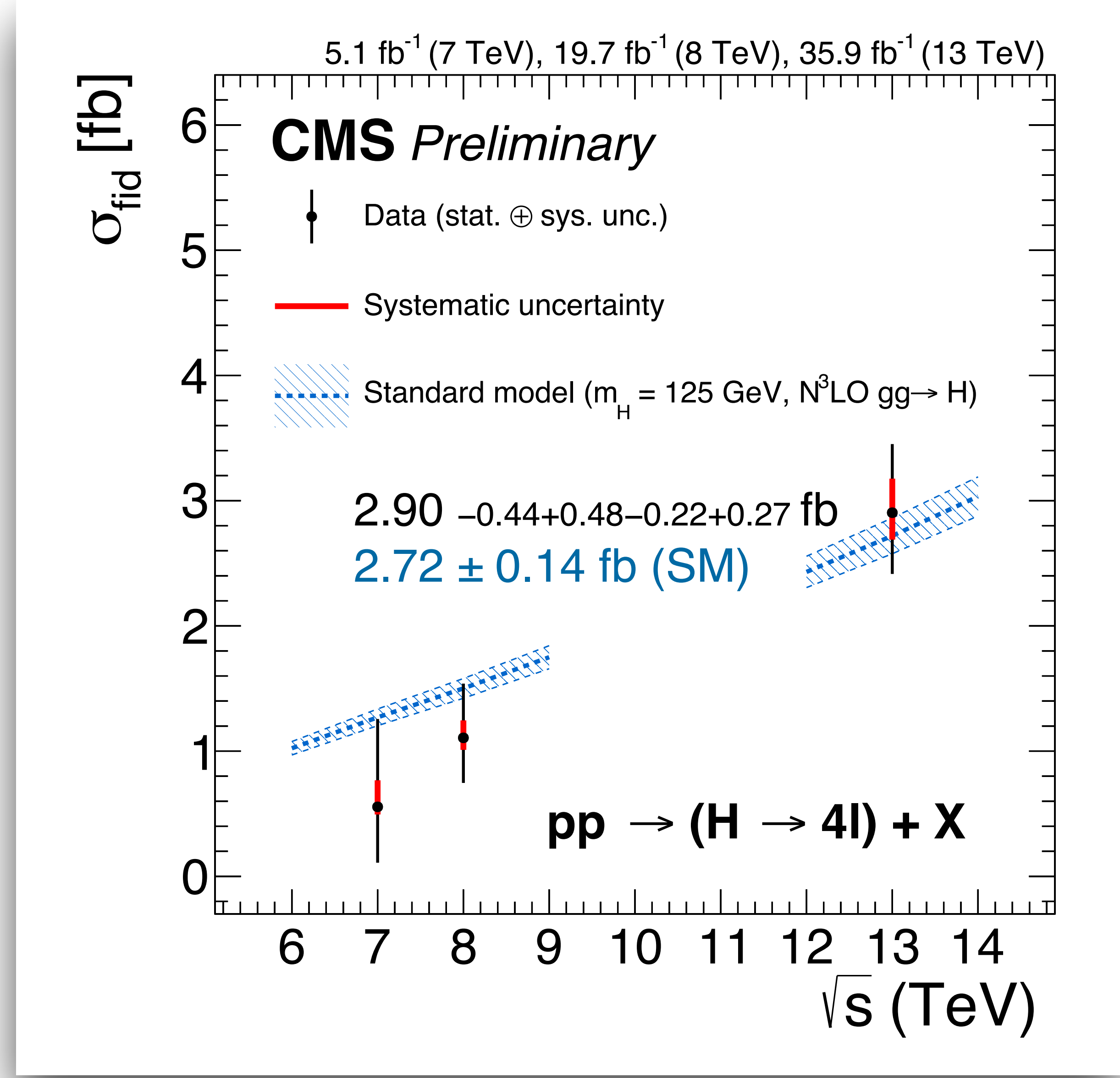
Latest invariant mass distributions produced with the statistics collected @ 13 TeV



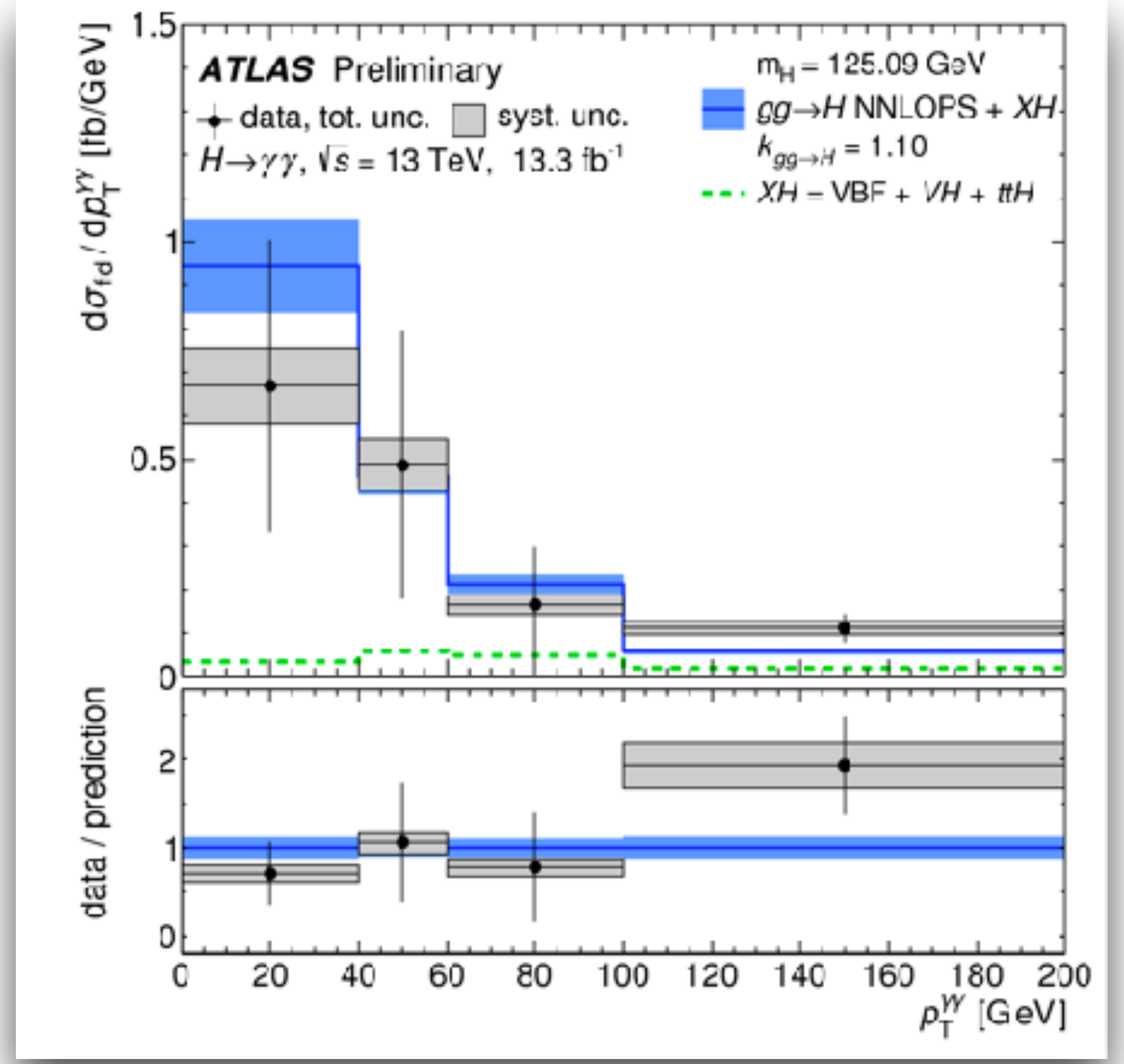


Cross section measurements

H→ZZ→4l cross section as a function of √s



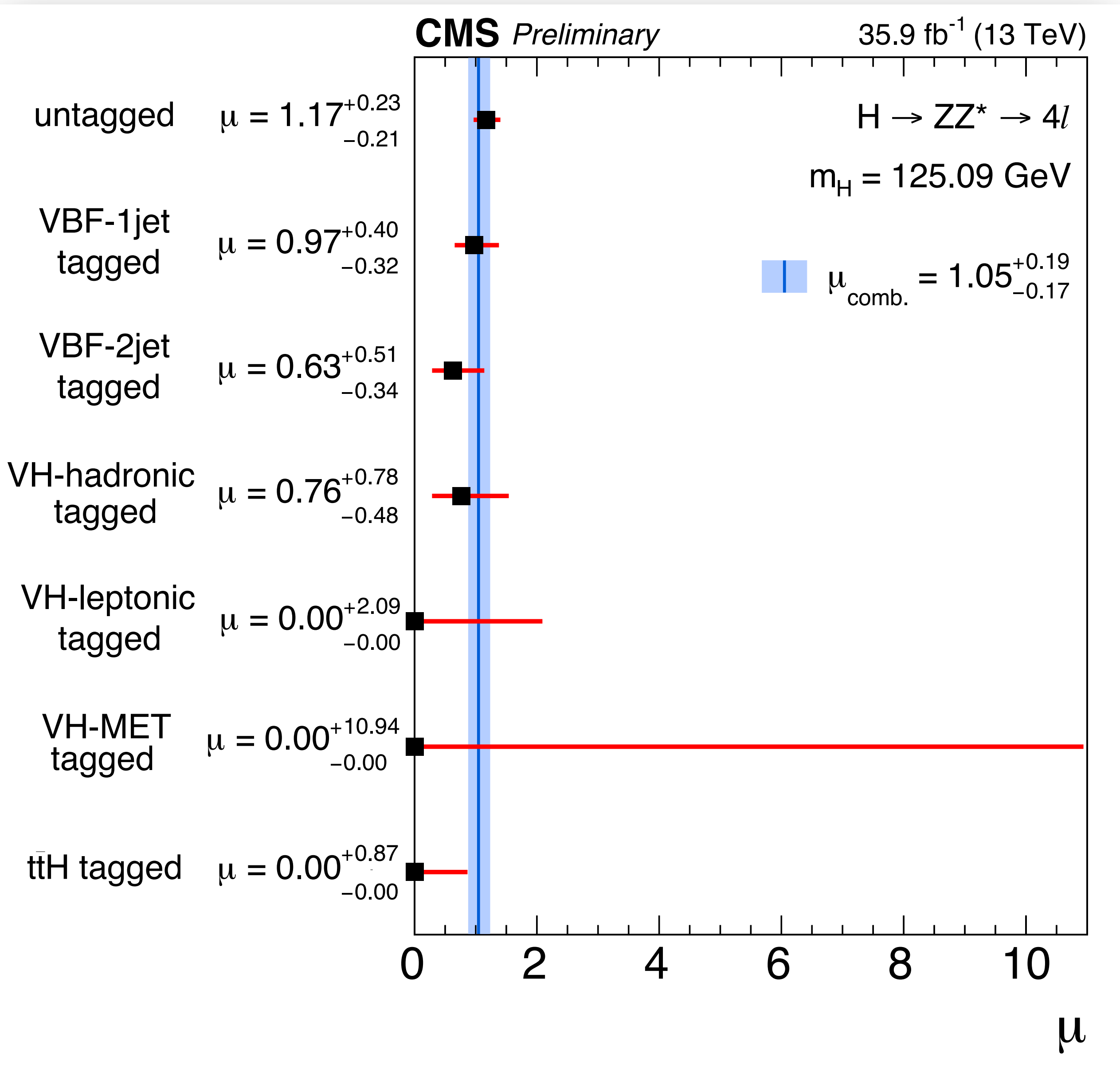
H→γγ cross section as a function of the di-photon p_T

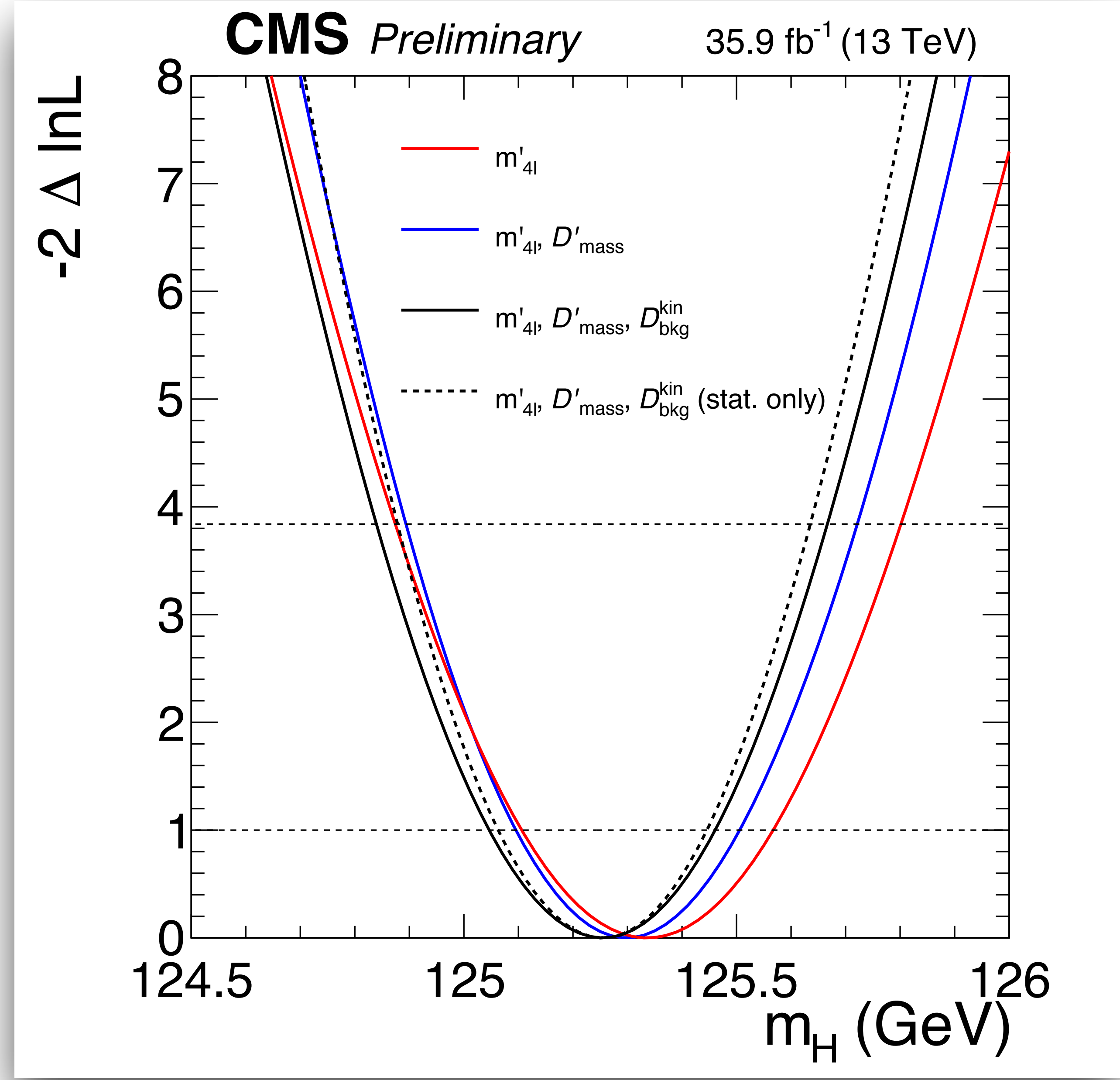


Signal strength and Higgs boson mass

$\mu = 1.05\,^{+0.15}_{-0.14}\,(\text{stat.})\,^{+0.11}_{-0.09}\,(\text{syst.})$

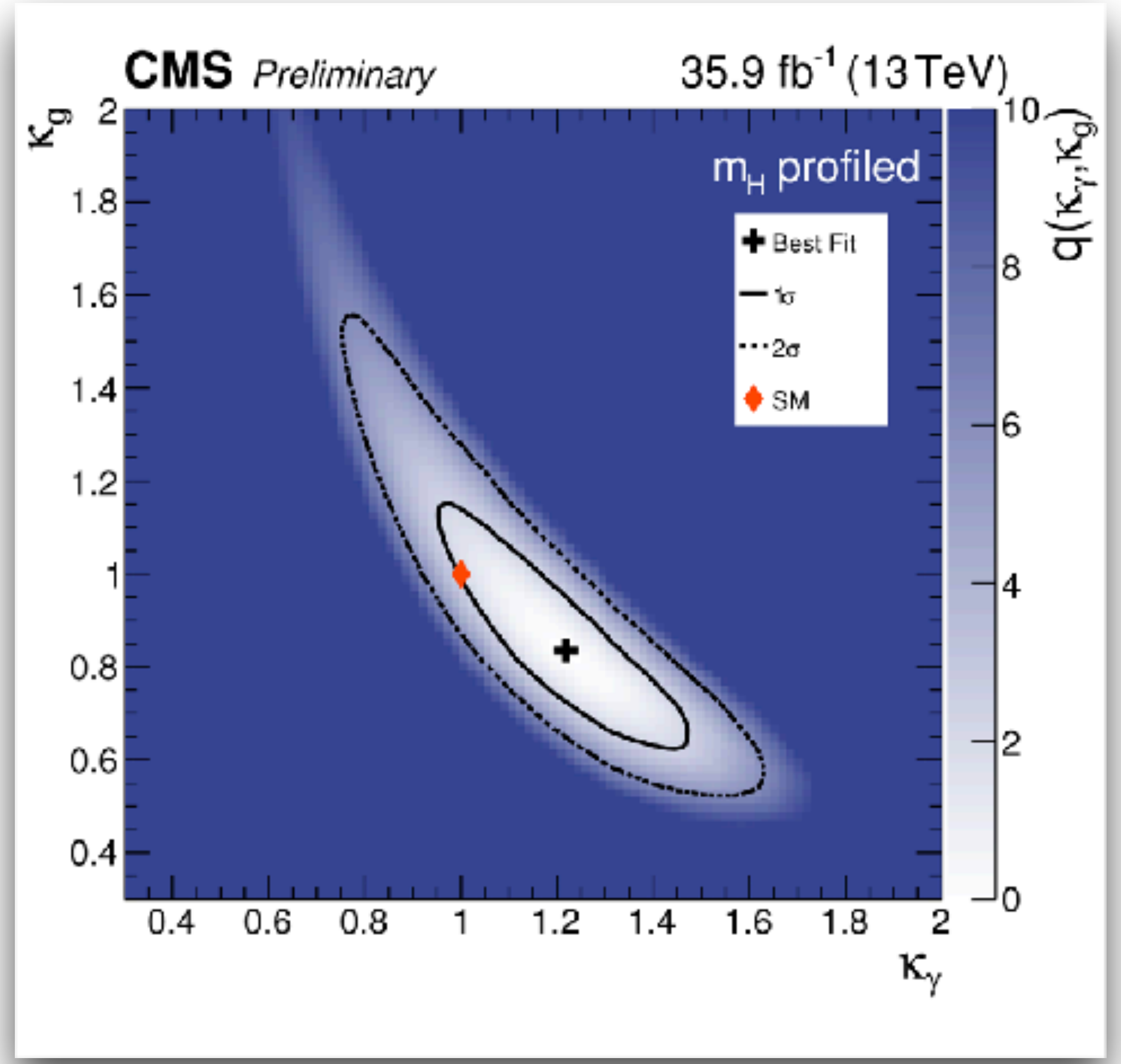
$m_H = 125.26 \pm 0.20\,(\text{stat.}) \pm 0.08\,(\text{syst.})$ GeV

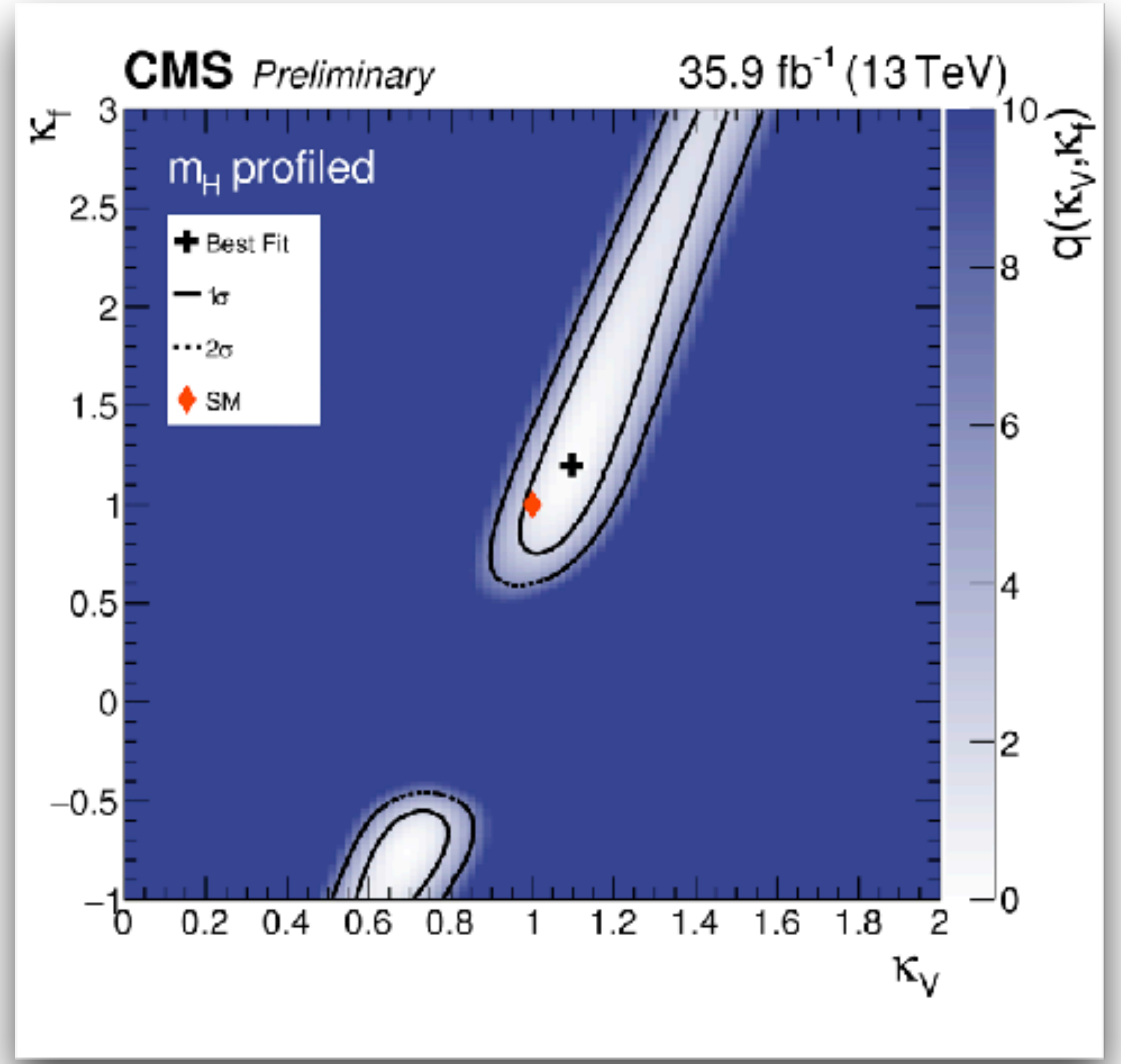




Couplings

Coupling to gluons and photons, k_g vs. k_γ (left), and coupling to fermions and bosons, k_f vs. k_V (right)





In conclusion, the newly discovered particle really looks like a the Higgs Boson predicted by the SM :)