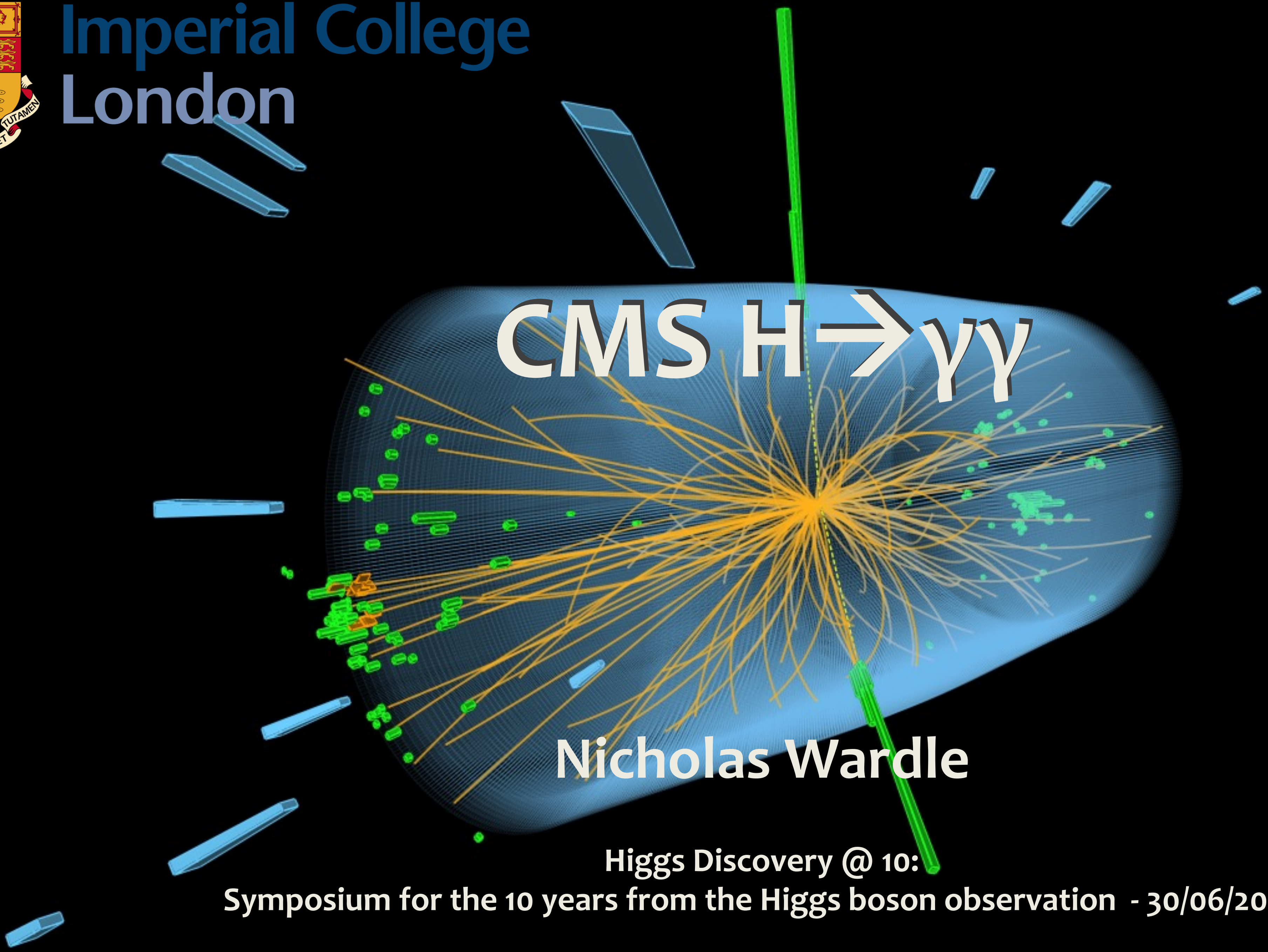
Imperial College London



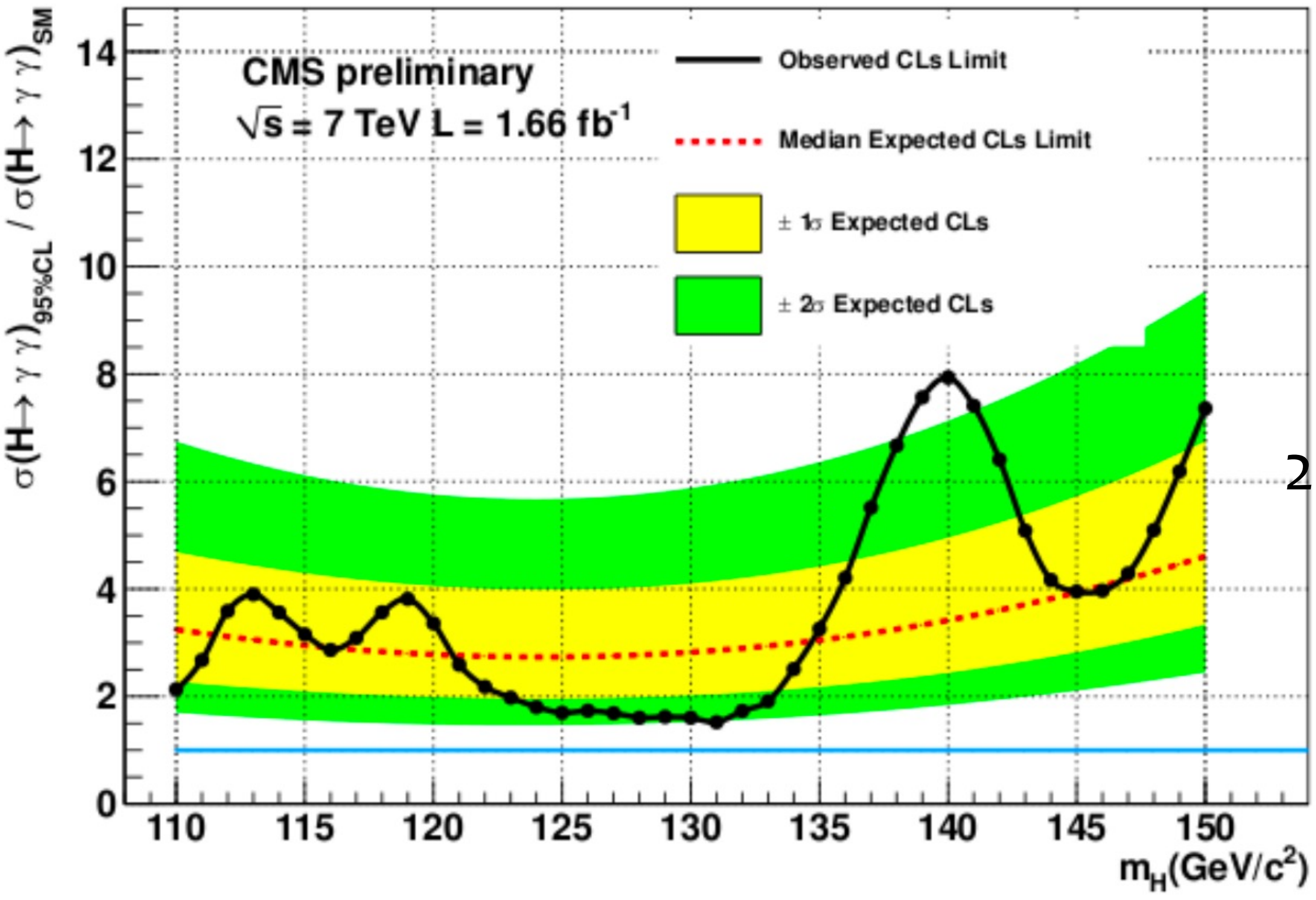
CMS H→γγ

Nicholas Wardle

Higgs Discovery @ 10:
Symposium for the 10 years from the Higgs boson observation - 30/06/2022

Observation of the Higgs boson (CMS)

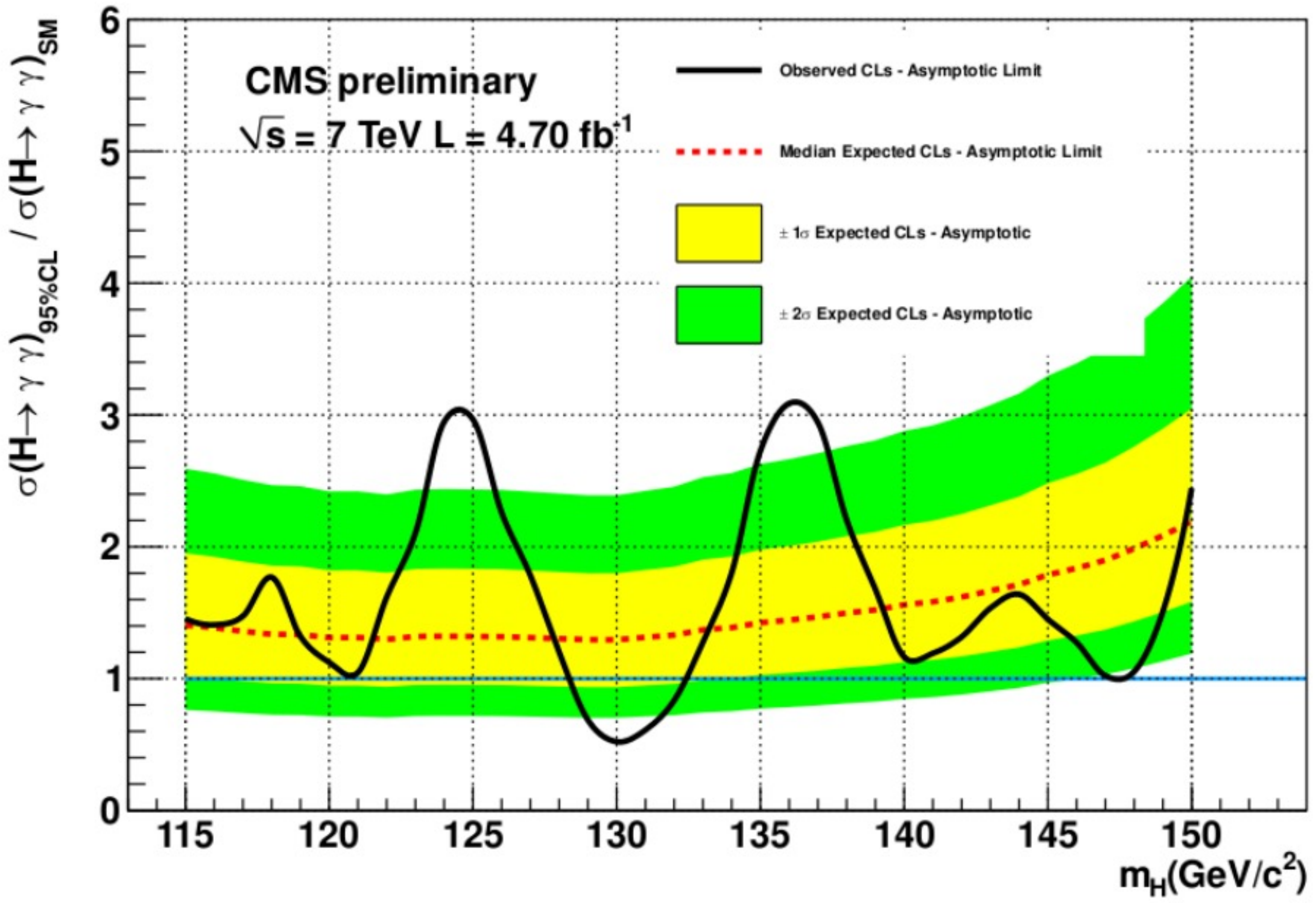
We found the 140 GeV Higgs!



20th November 2011!

Observation of the Higgs boson (CMS)

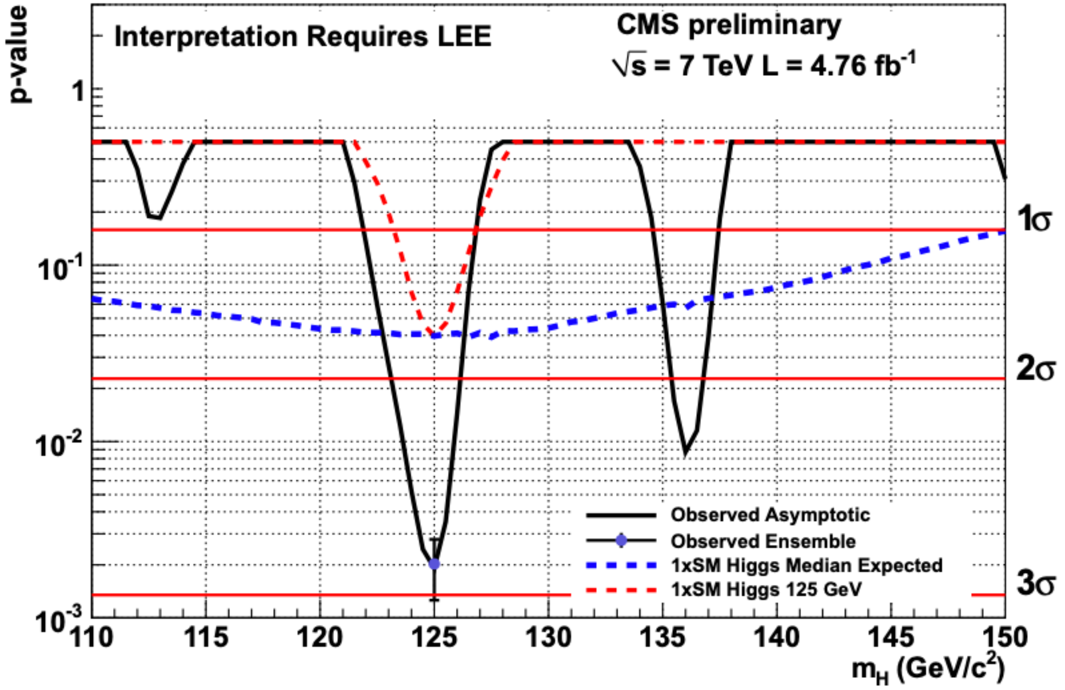
Ah wait, no there's 2 of them!



S/B binning

1^{st} December 2011!

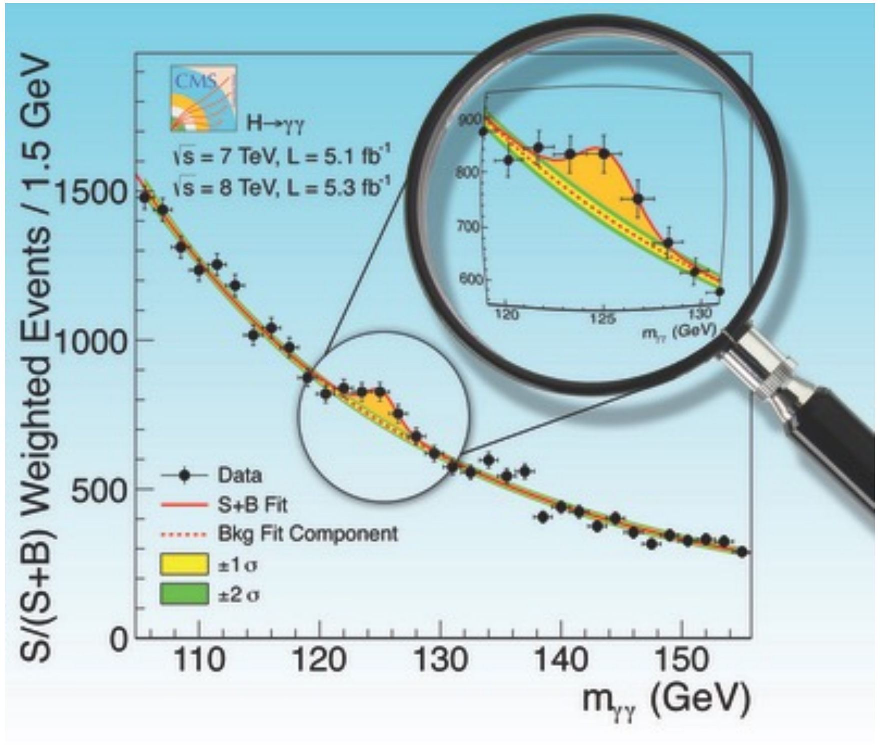
Trying not to give the game away



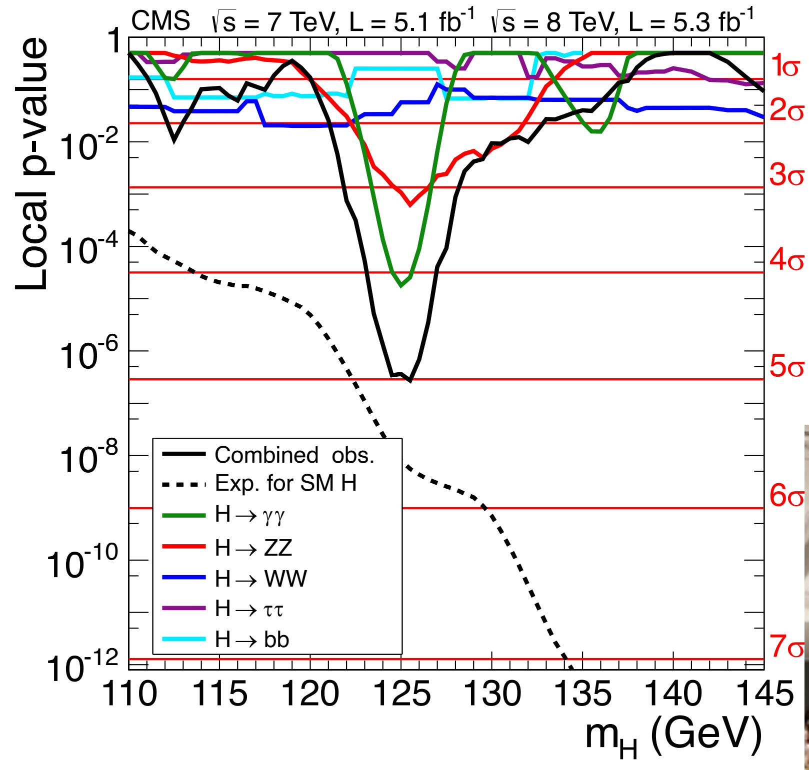
N. Wardle – PLHC Vancouver
8th-June 2012!

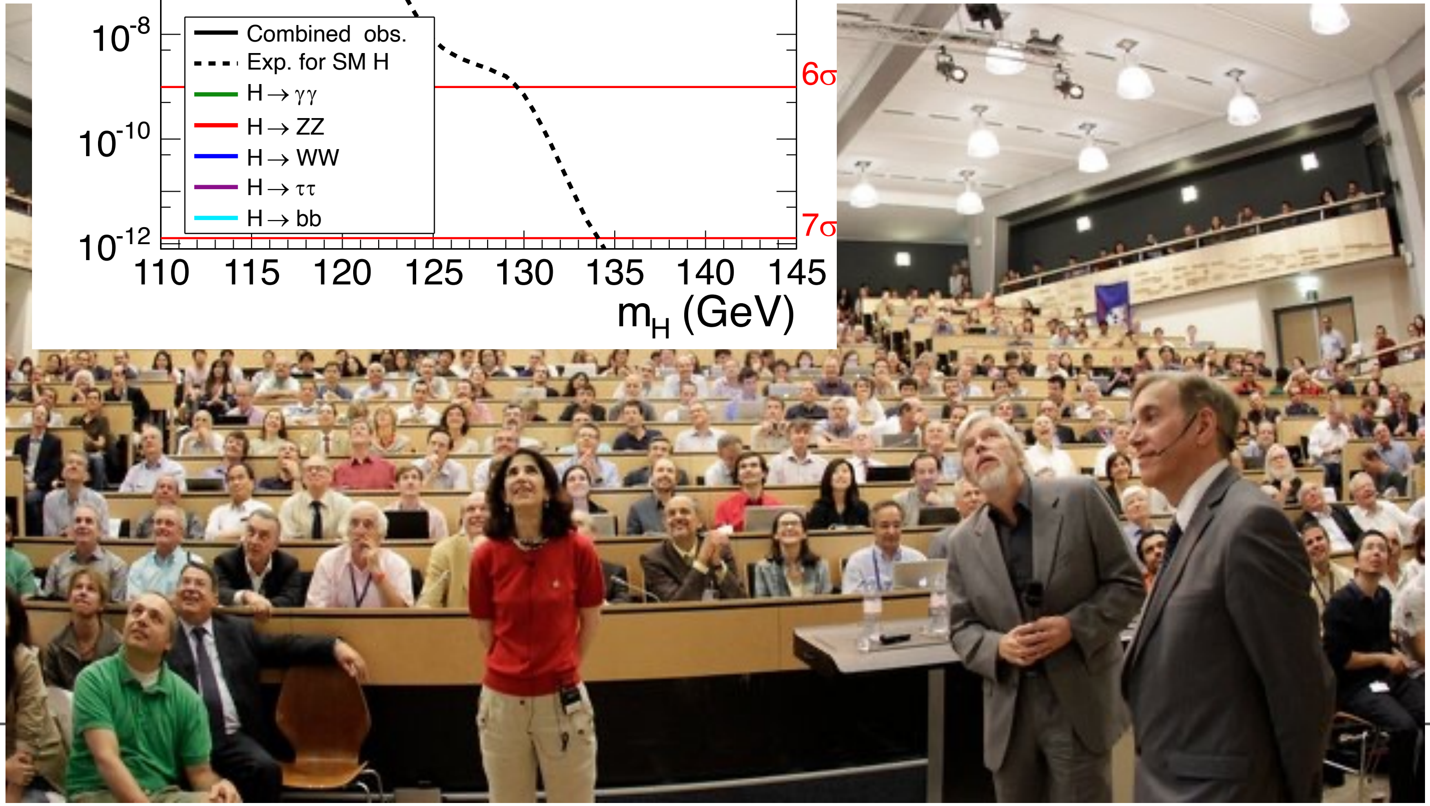
- **Excess observed at 125 GeV, local significance 2.8σ (1.6σ with LEE)**
- **CMS will continue to run in 2012 at 8 TeV. Can expect to be sensitive to SM this year**

Observation of the Higgs boson (CMS)



The **H→γγ decay analysis** was key contribution to the Observation of the Higgs boson at CMS!

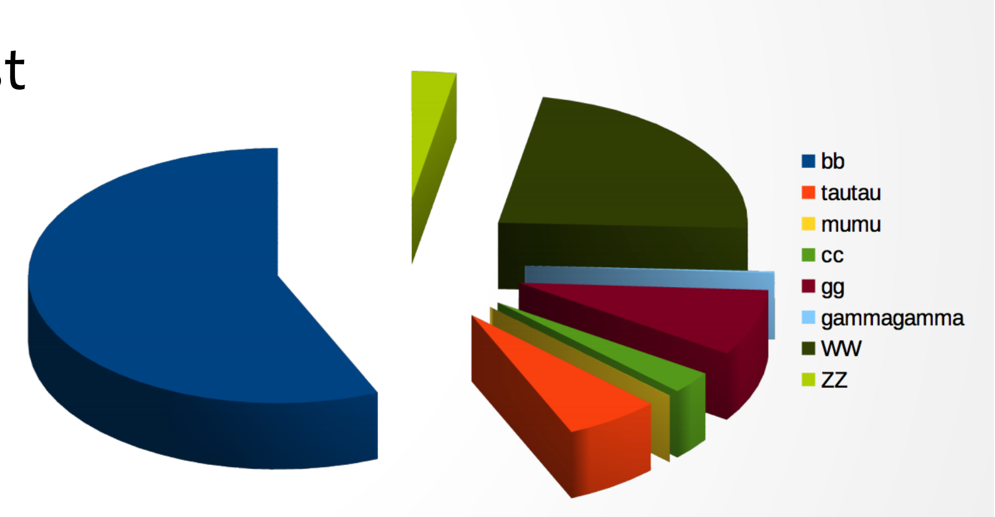




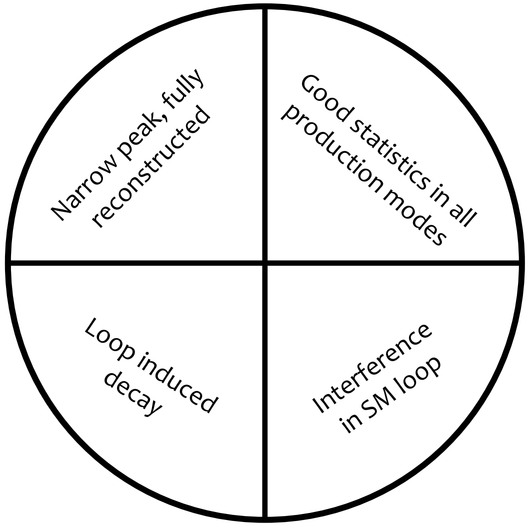
Not just for bump-hunting

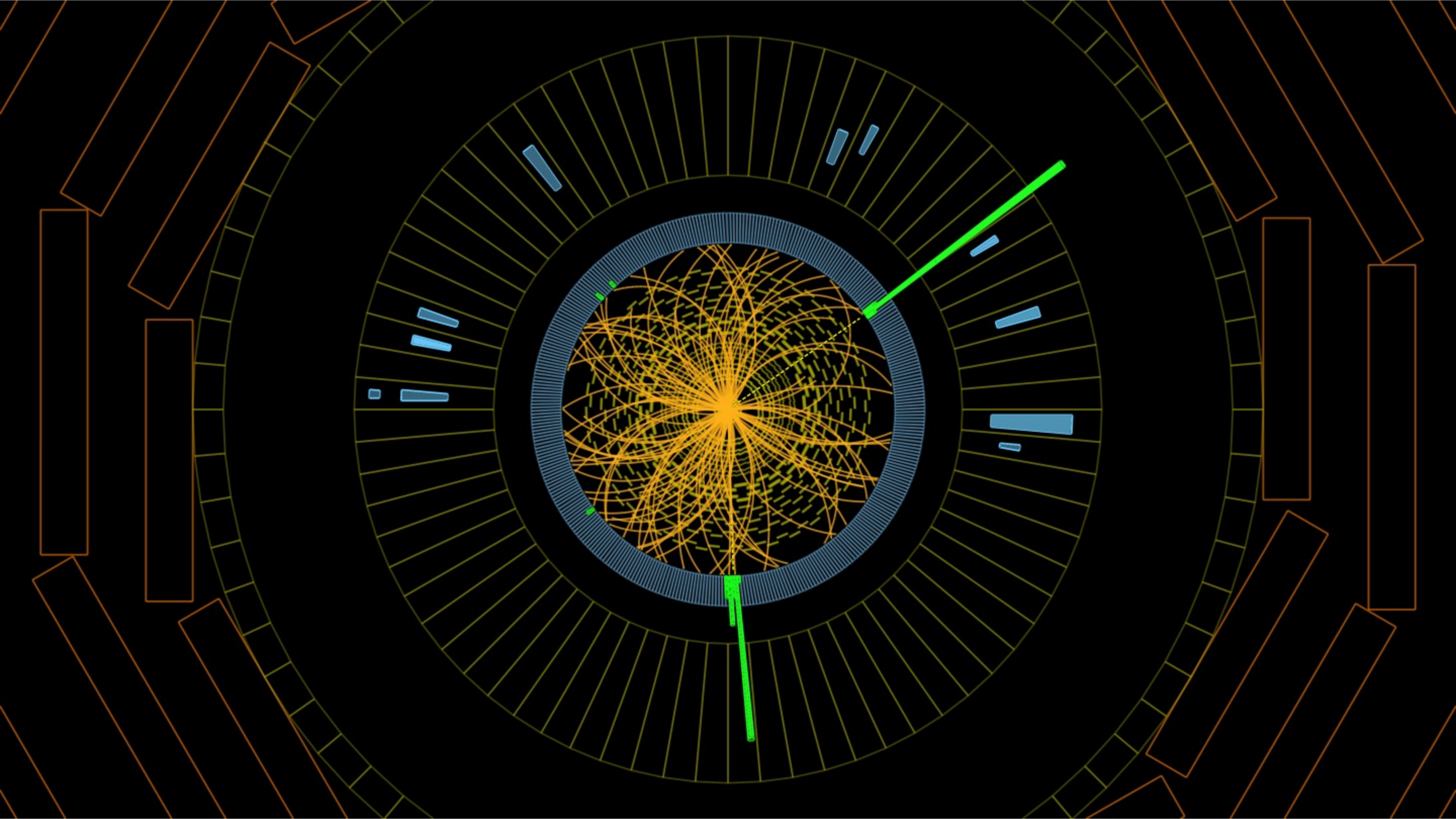
The **diphoton decay** of the Higgs boson comprises just **0.23%** of the total decay rate and yet with it we can …

- Measure the **mass** of the Higgs boson!
- Determine the **spin** of the resonance!
- Measure **differential cross-sections** of Higgs boson production!
- Hunt for **new physics** in extended Higgs models or production/decay loops!
- Measure the **Higgs boson self-coupling**!



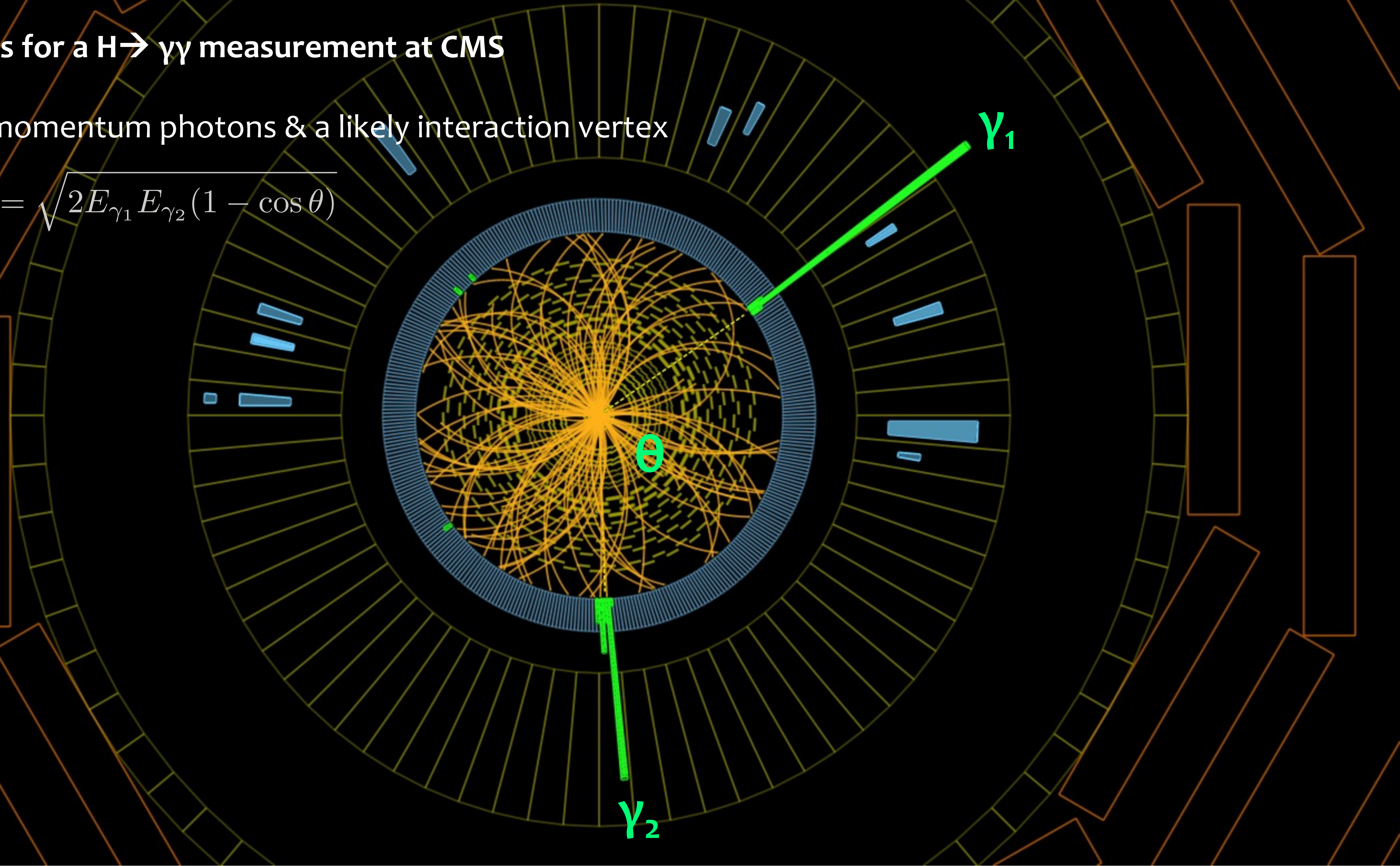
H→γγ useful features





Ingredients for a H→ γγ measurement at CMS

- 2 high momentum photons & a likely interaction vertex
  - $m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta)}$



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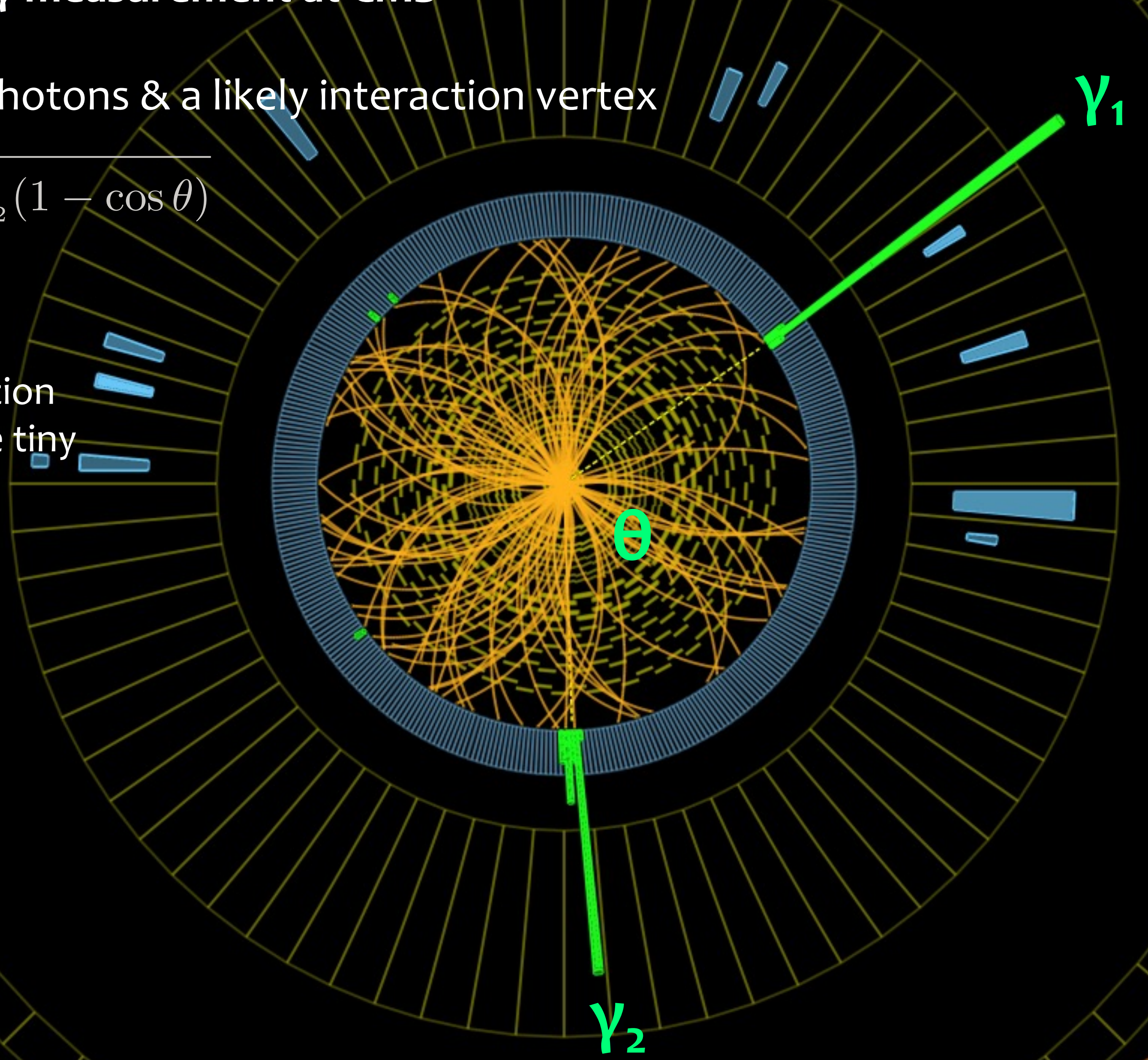
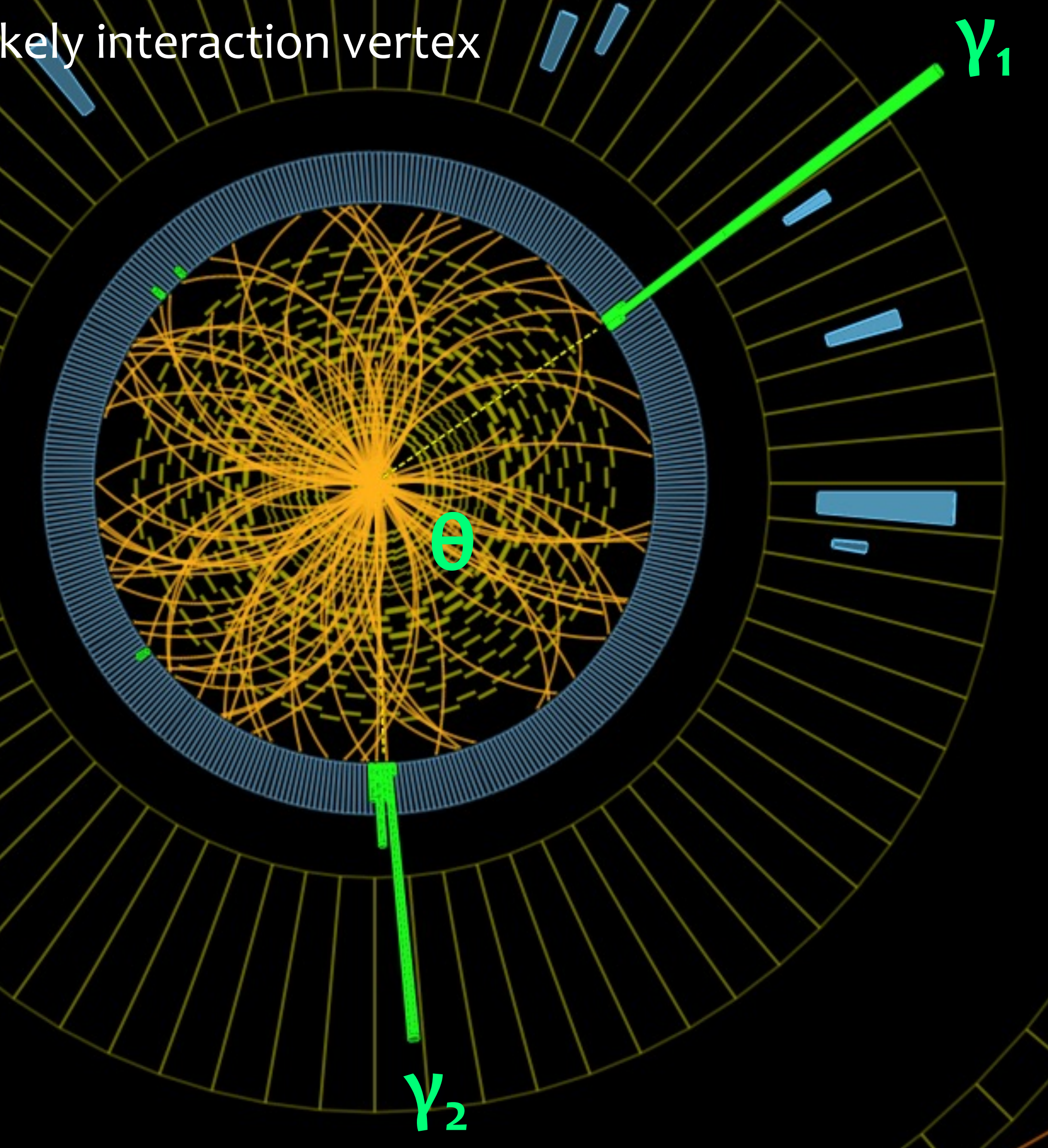
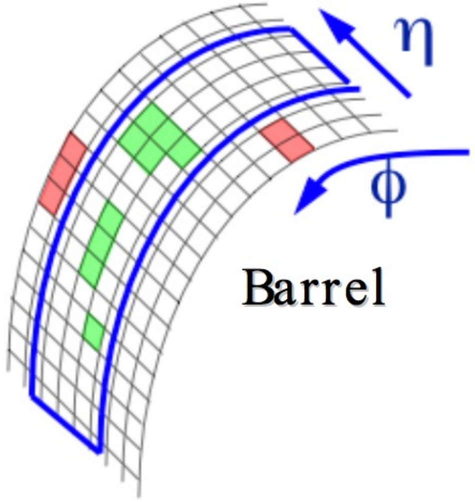


Ingredients for a H→ γγ measurement at CMS

- 2 high momentum photons & a likely interaction vertex
  - $m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta)}$
- A selection & classification strategy to pick out the tiny H→γγ signal
- A model for the remaining SM contributions
  - A resonance signal model
  - Background contributions from pp→γγ, pp→γj



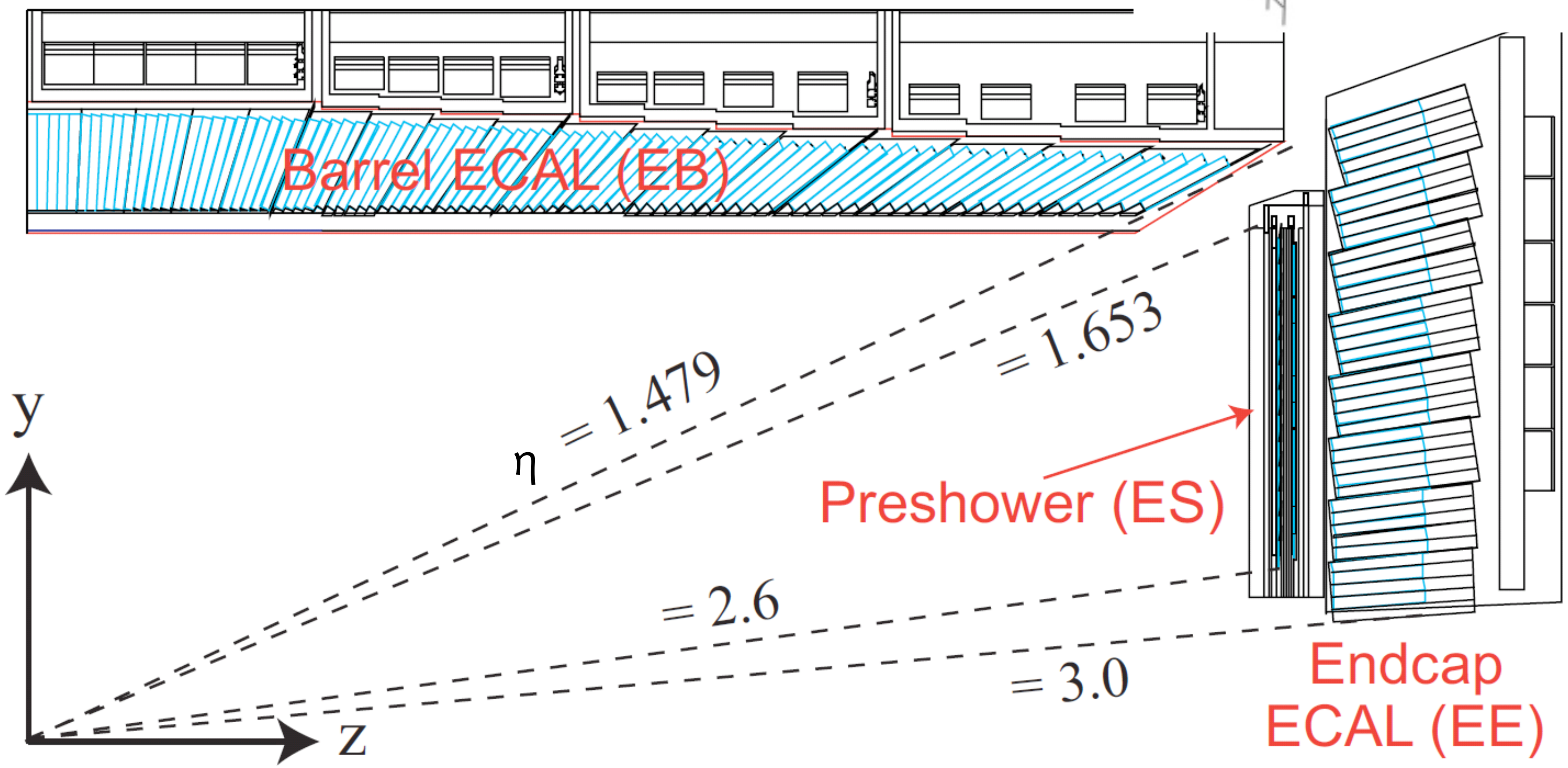
CMS Photon reconstruction



Photons (and electrons) reconstructed by clustering deposits in the CMS calorimeter

Sliding window / dynamic clustering algorithms to reconstruct bremsstrahlung and (converted) photons - “super-clusters” …

- High granularity $PbWo_4$ crystal layout
  → ($\delta\eta$, $\delta\varphi$ ~ 0.0174)
- Rely on tracks (recoil) to assign photon vertex
- Lateral shower shape distinguishes converted from unconverted photons



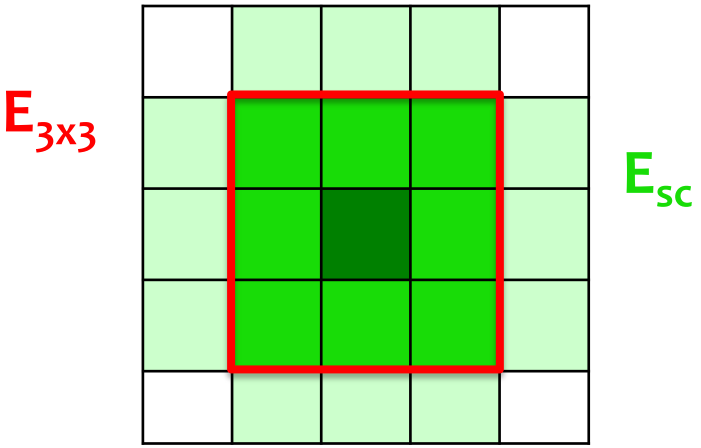
CMS Photon reconstruction

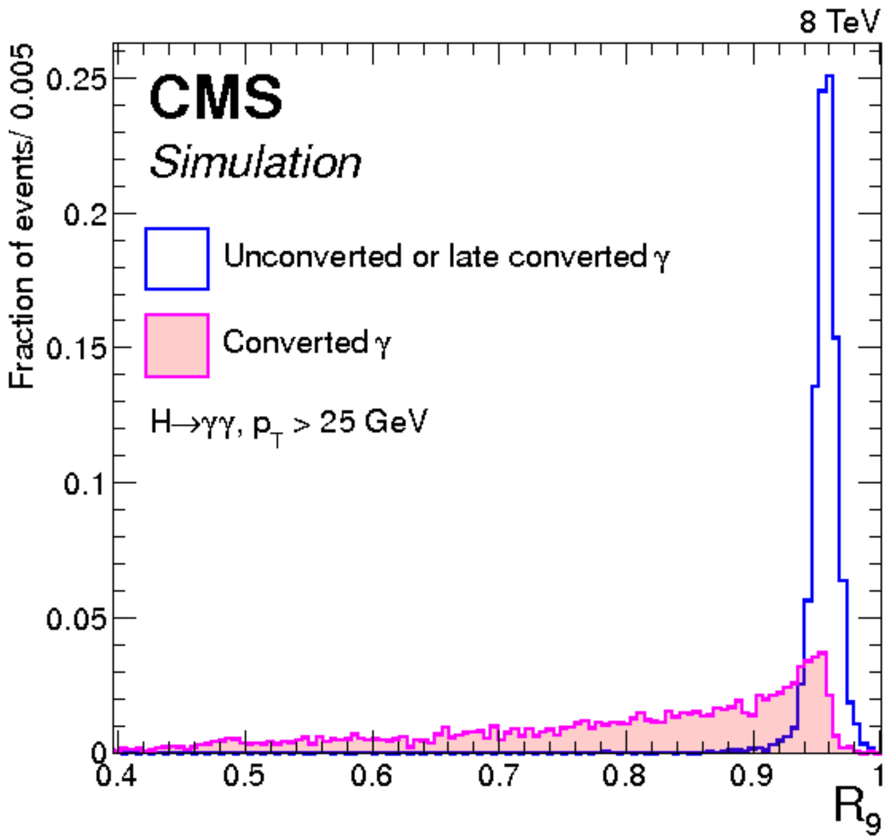
Photons (and electrons) reconstructed by clustering deposits in the CMS calorimeter

Sliding window / dynamic clustering algorithms to reconstruct bremsstrahlung and (converted) photons - “super-clusters” …

(R_9=E_{3x3}/E_{sc}) Ratio of energy sum around seed crystal to full supercluster

→ Large R9 indicates unconverted photon

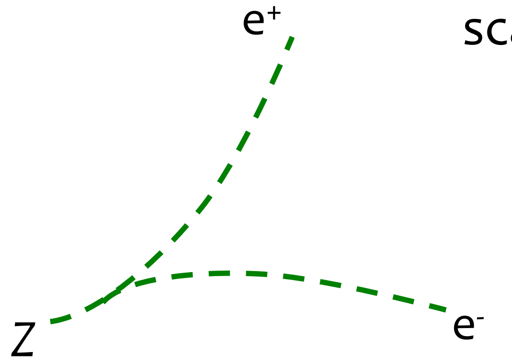


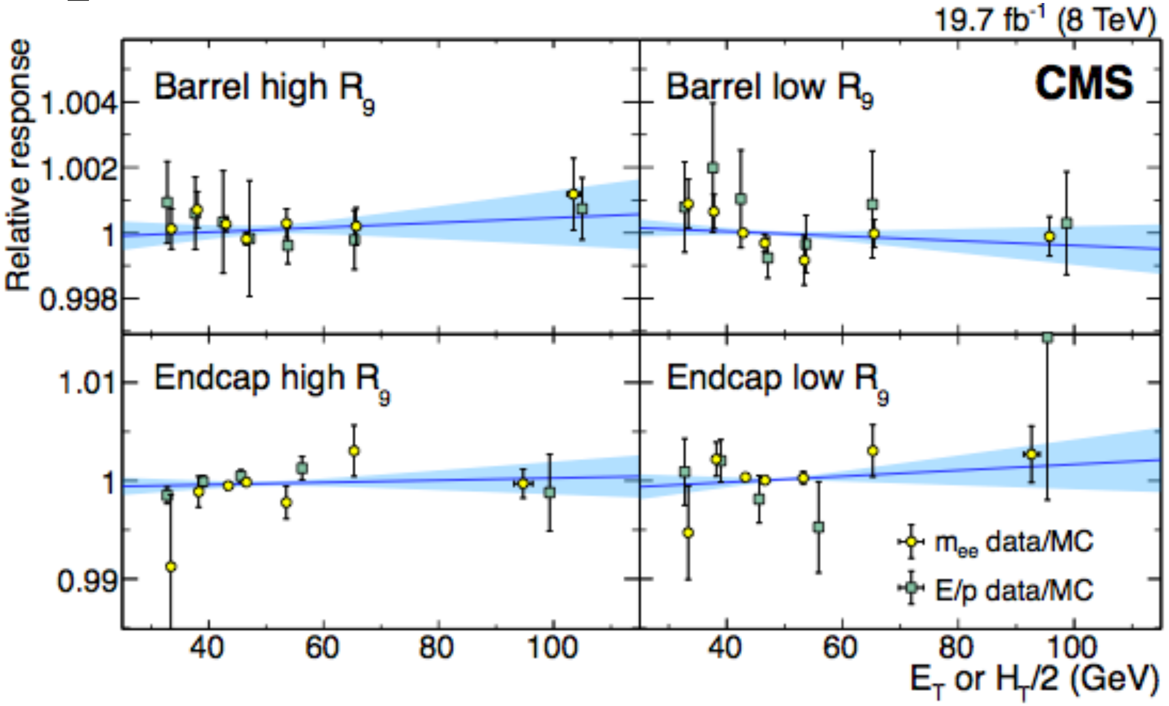


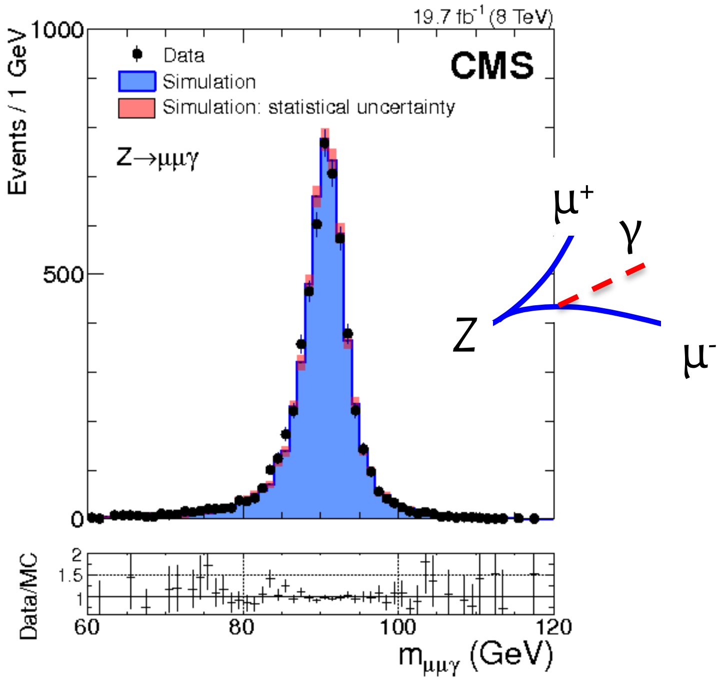
CMS Photon calibration

CMS uses a dedicated calibration of the photon/electron energy scales with Z boson "standard candle"

→ Z→ee Reconstruct "e as γ" by removing tracks & Z→μμγ to validate calibrations

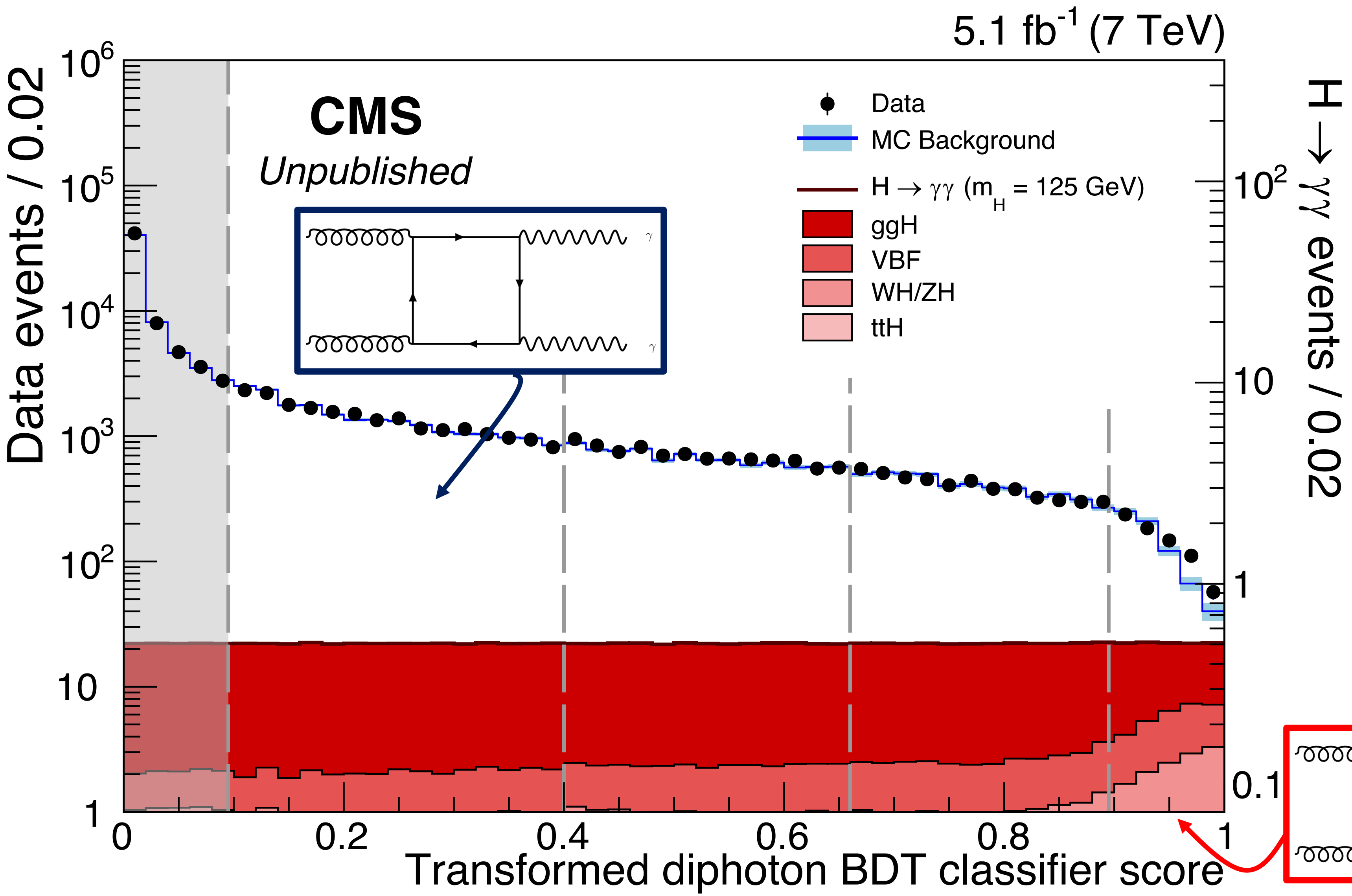


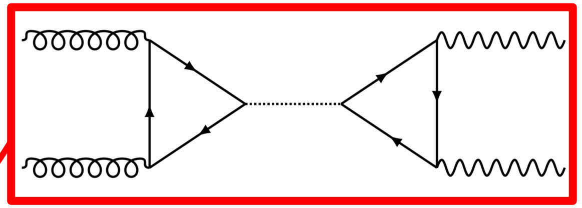




Calibrations determined as a function of photon E_T, $|\eta|$ and R_9 to account for iinhomogeneous response of the CMS calorimeter

Rejecting the background



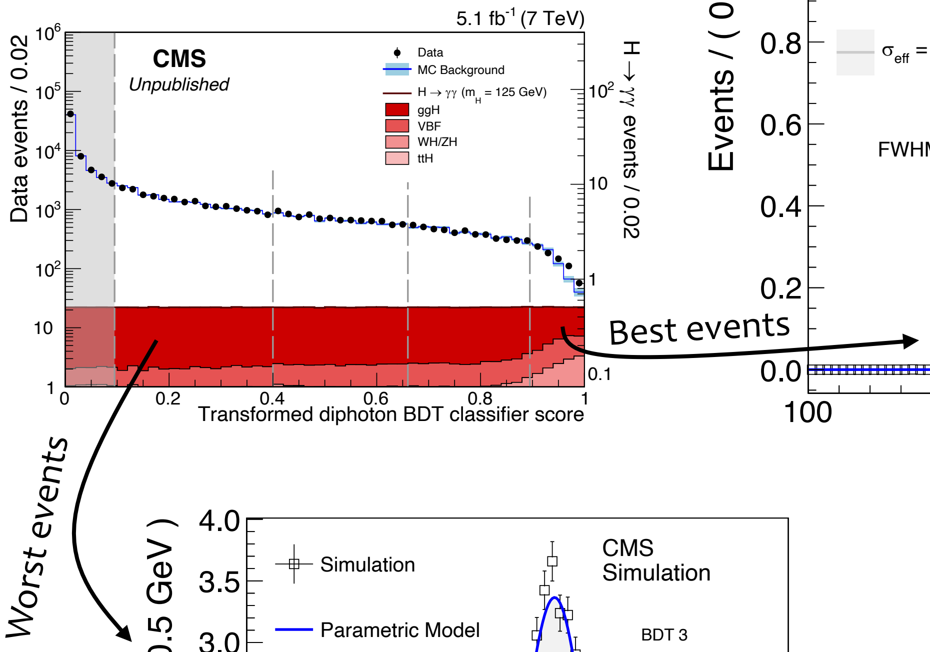


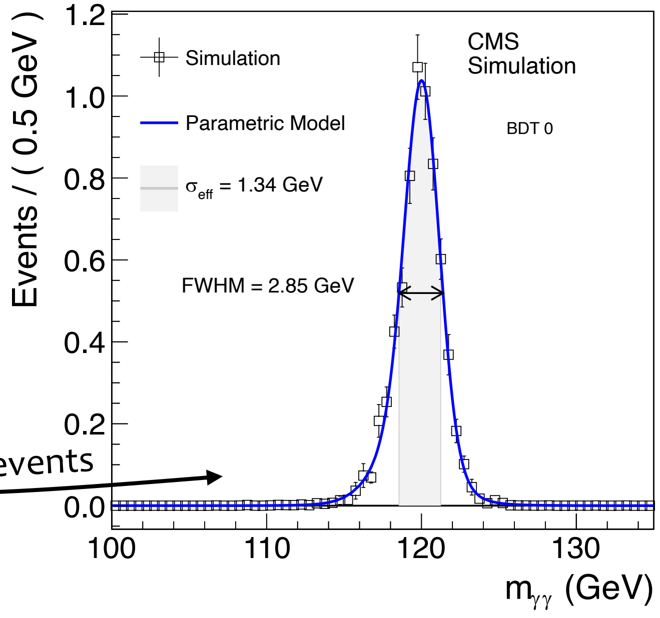
Boosted decision tree (BDT) discriminates **Higgs events** from **background** using …

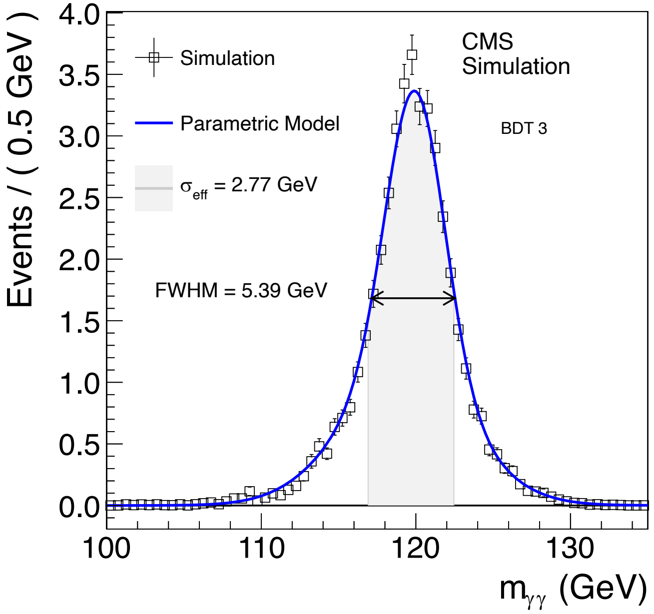
- *Kinematics of the photons and diphoton system*
- *Photon quality (reconstruction variables)*
- *Per-event resolution estimate*

The events are **split into categories** of increasing S/B using the BDT score & number of jets

Modeling the signal





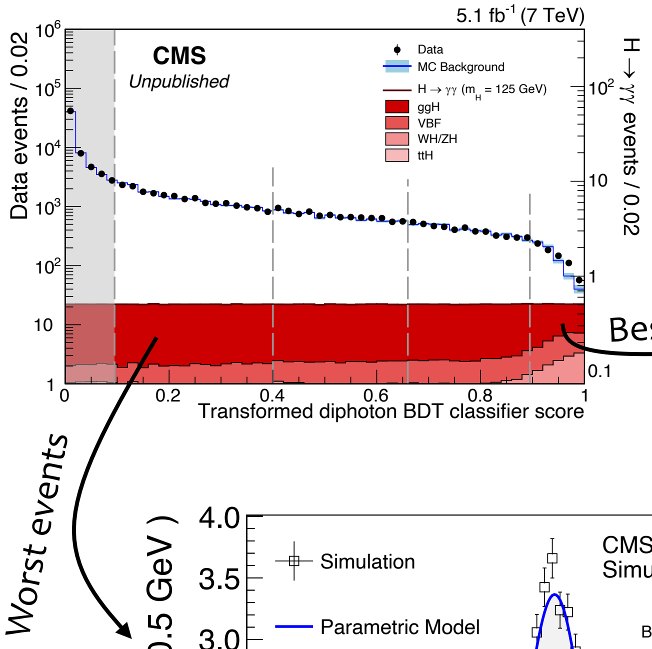


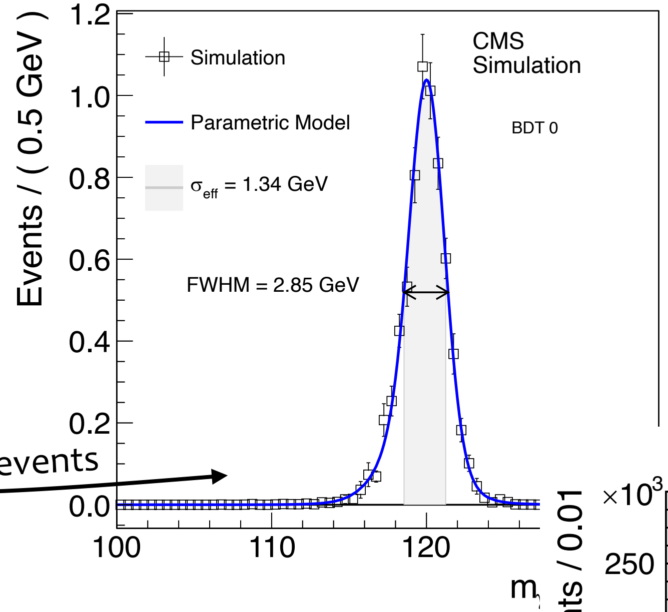
Calibrated signal simulation (MC) used to parameterize the $m_{\gamma\gamma}$ distribution of H→γγ decays in each category

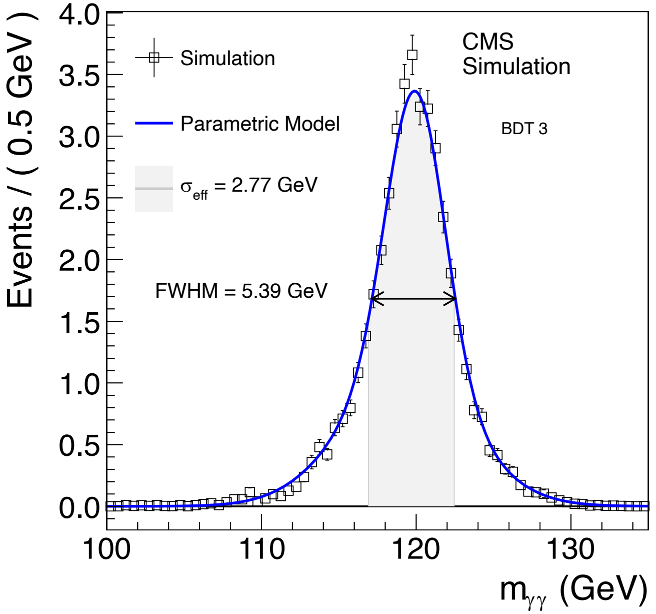
Modeling the signal

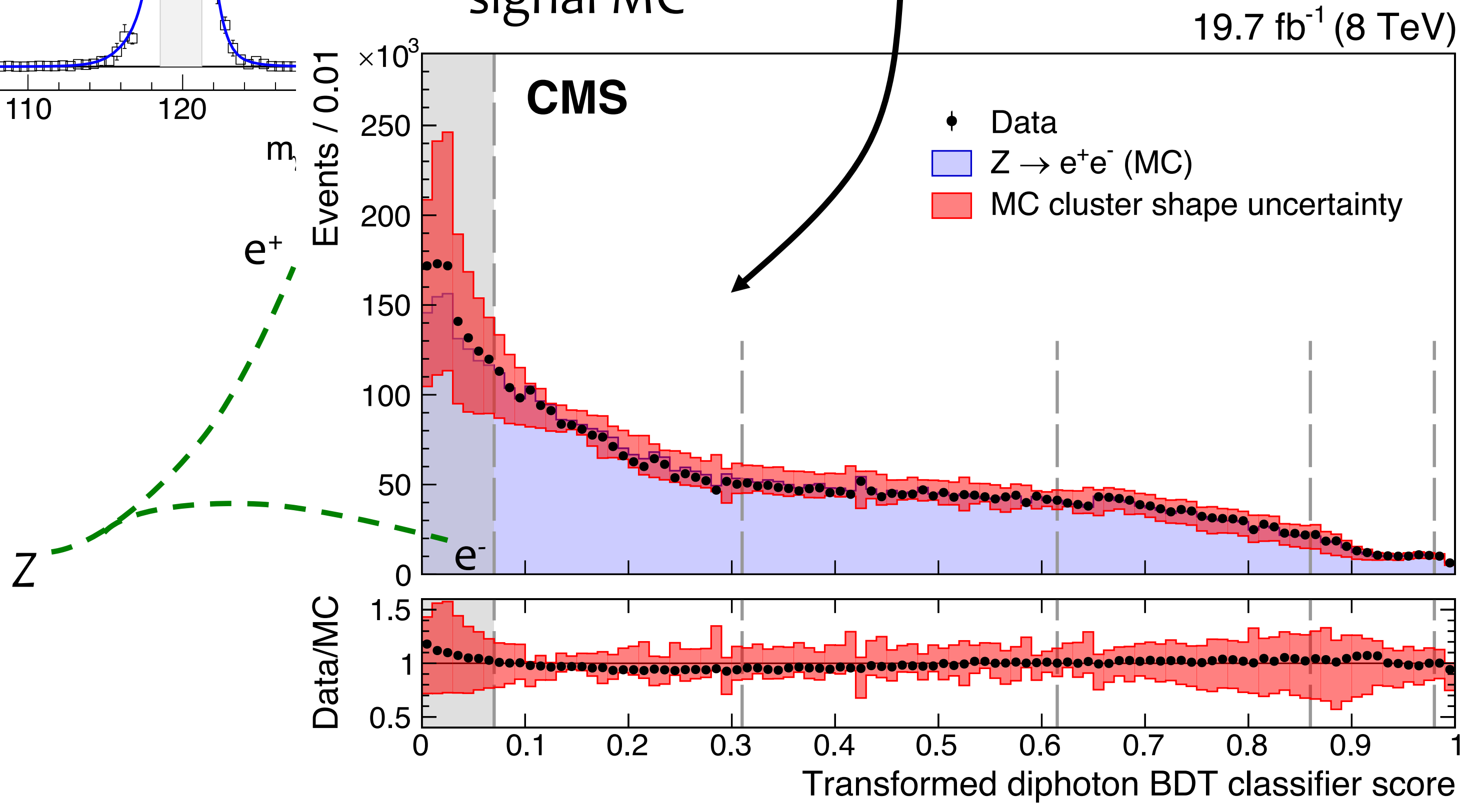
Calibrated signal simulation (MC) used to parameterize the $m_{\gamma\gamma}$ distribution of $H \rightarrow \gamma\gamma$ decays in each category

Use $Z \rightarrow ee$ events, with the **electrons reconstructed as photons**, to validate signal MC

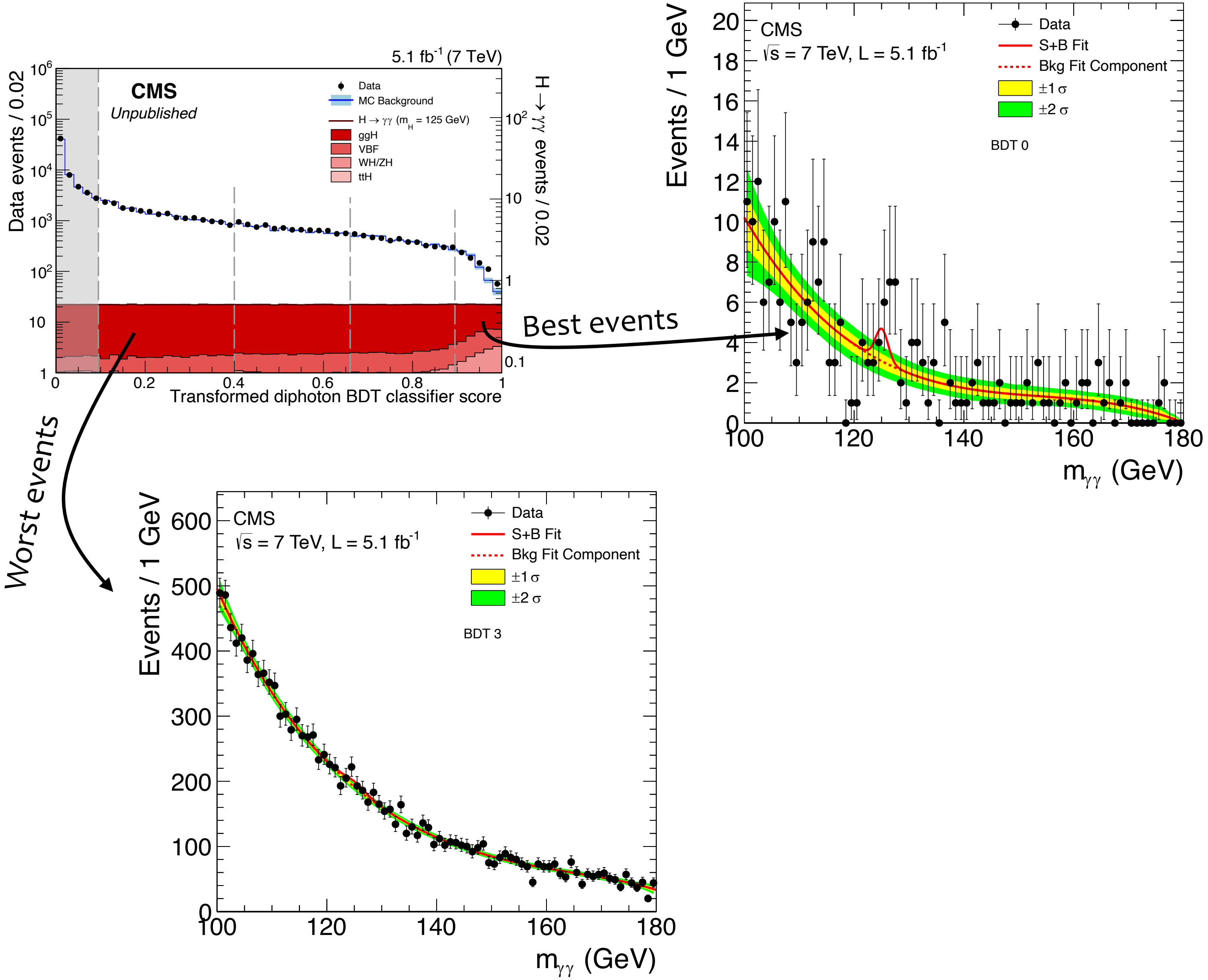






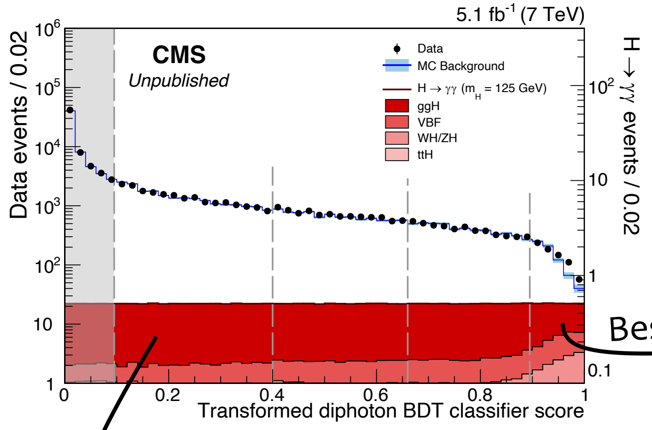


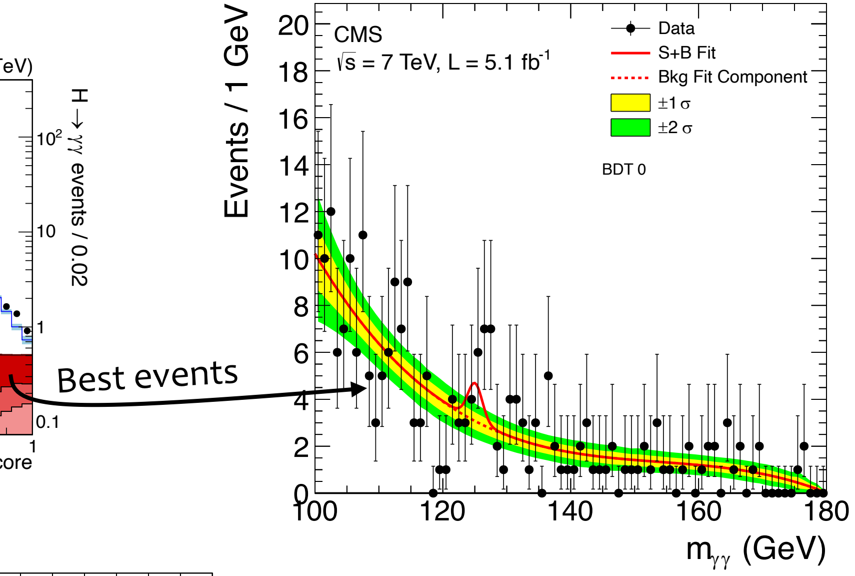
Modeling the background

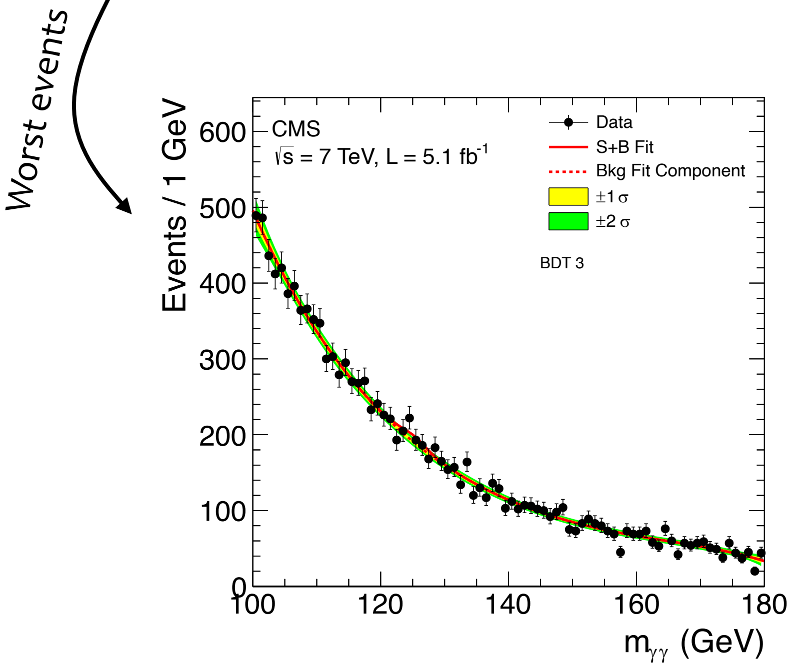


The background is modeled by fitting the data in the sidebands (outside the signal window) → **purely data driven background!**

Modeling the background



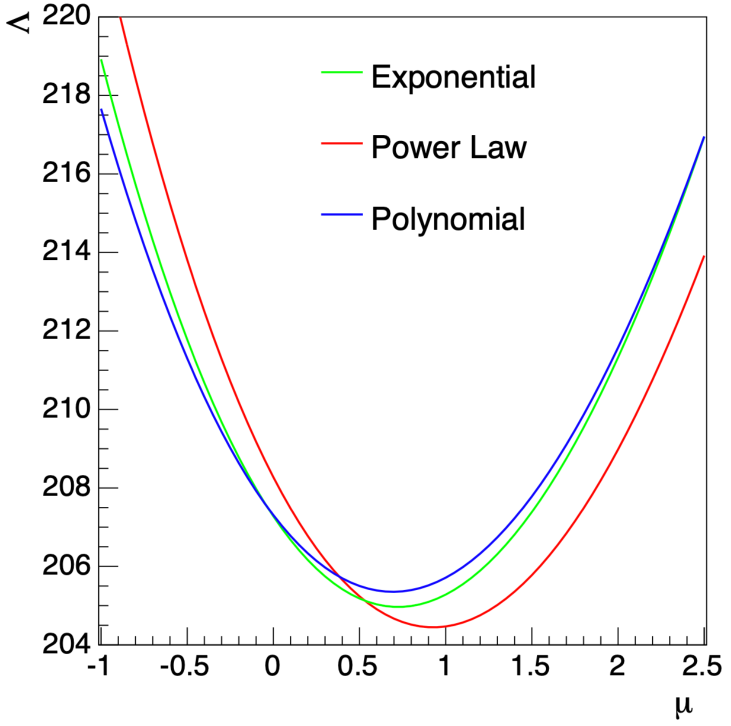


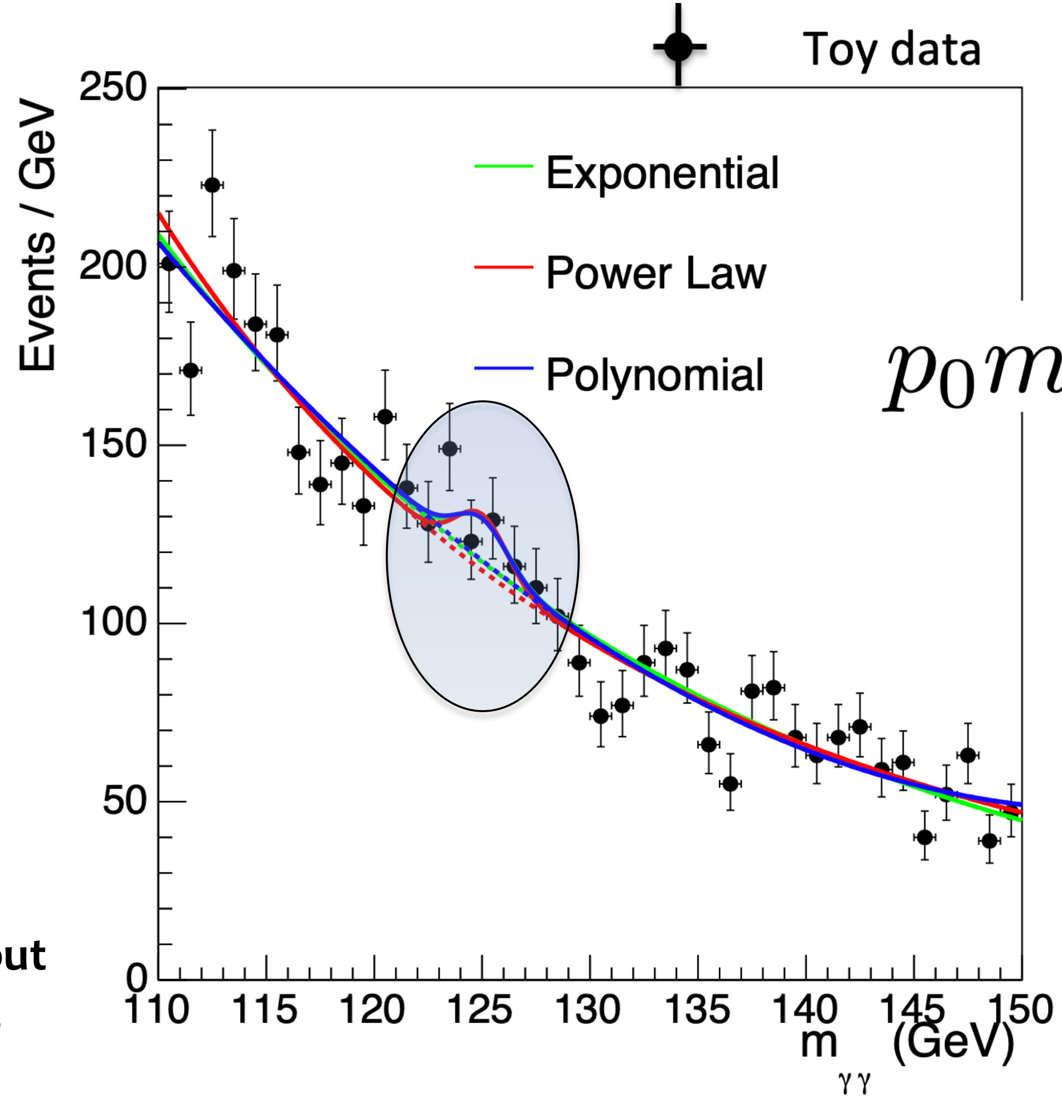


The background is modeled by fitting the data in the sidebands (outside the signal window) → **purely data driven background!**

How do we know ***which function*** we should use?

Modeling the background (aside)





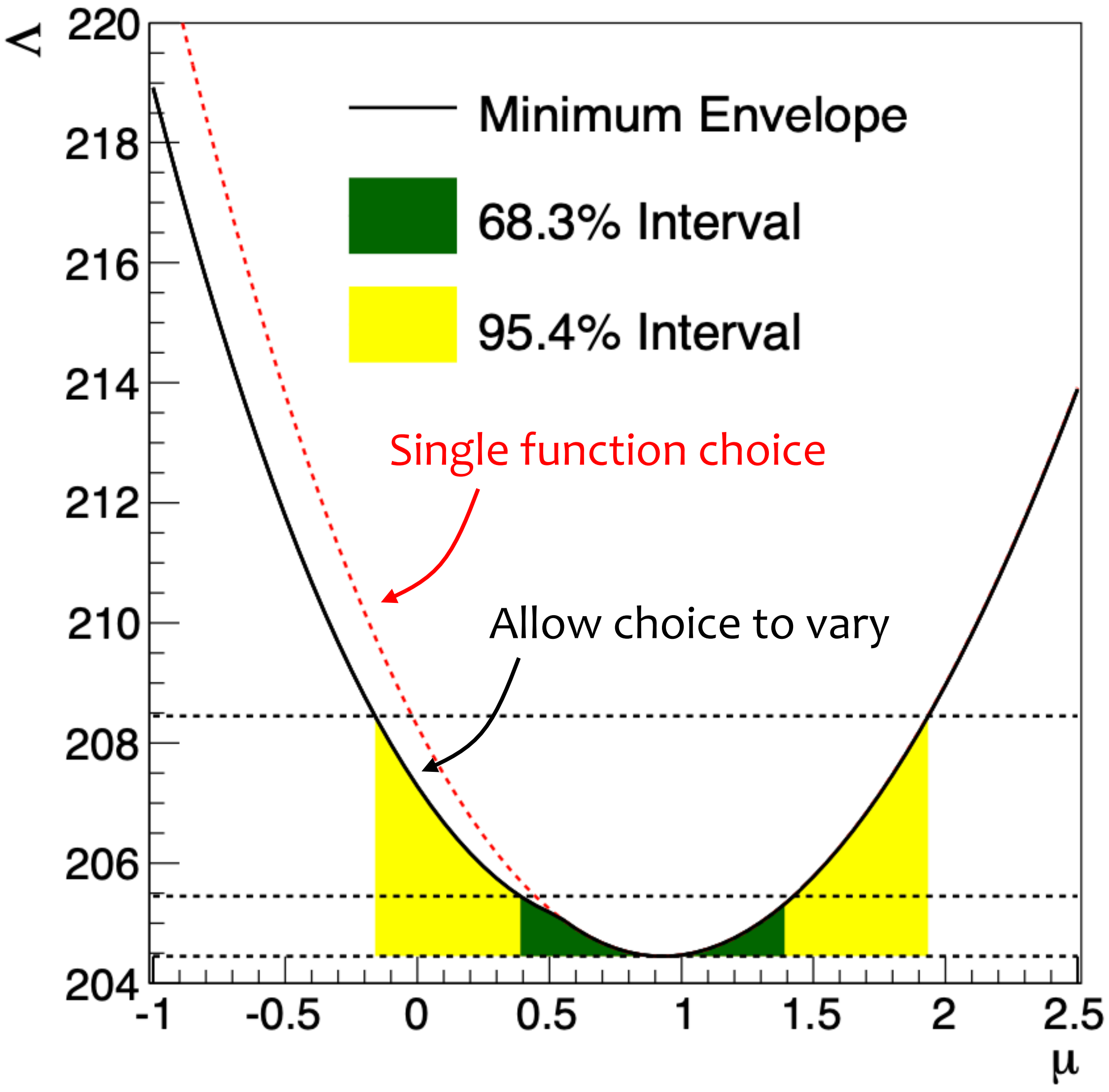
$$e^{-p_0 m}$$

$$m^{-p_0}$$

$$p_0 m + p_1 m^2 + p_2$$

For small signal-to-background scenarios, **different assumptions about the background** can lead to **different extracted signal rates**

Modeling the background (aside)



In CMS, we developed a method that allows to vary the background function choice during the minimization

→ Treat the choice of function as a **discrete nuisance parameter**

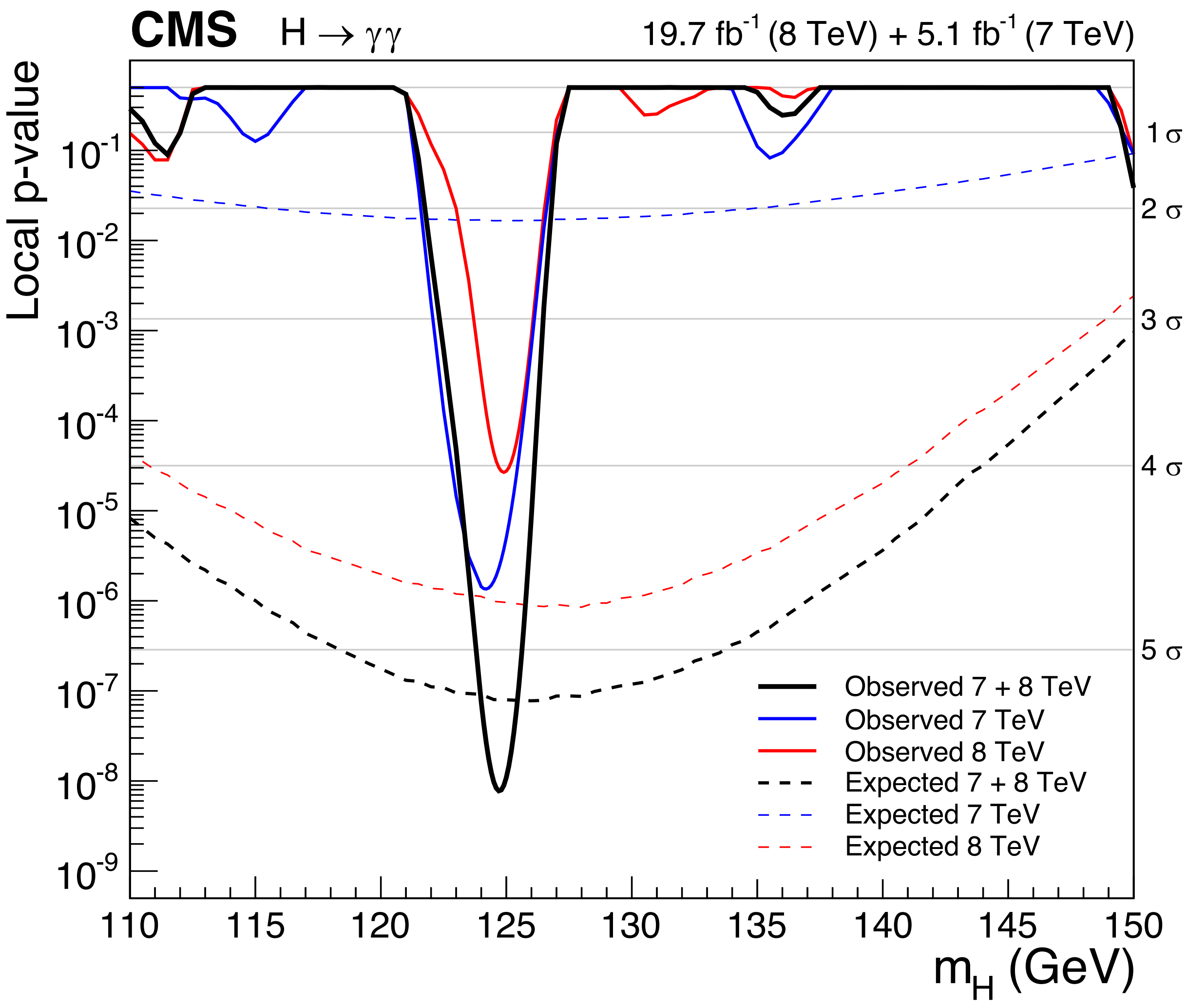
Uncertainty in fitted signal **is increased** due to additional functions contributing to the log-likelihood curve

Penalty term included to reduce influence from functions with lots of free parameters

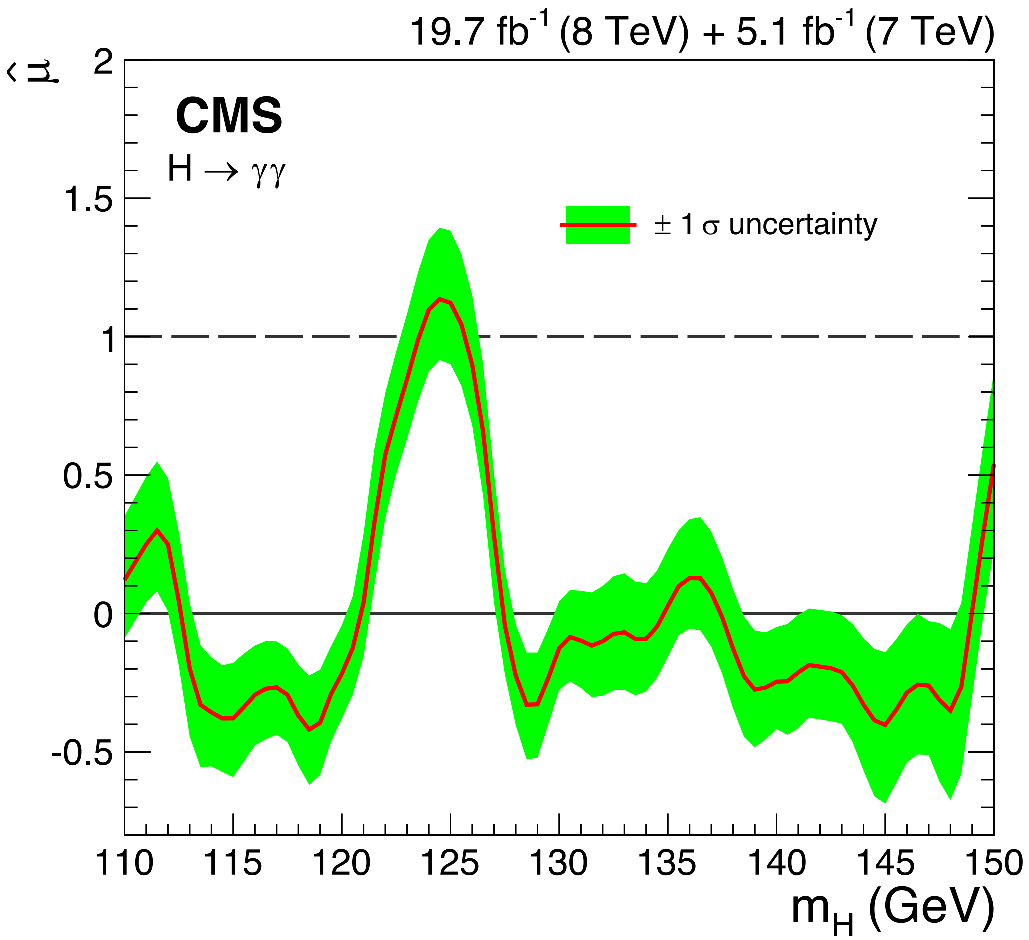
→ $\Lambda = 2\ln(L) + c$

Lots of studies on validity of method for CMS H→γγ.
See [JINST 10 P04015]

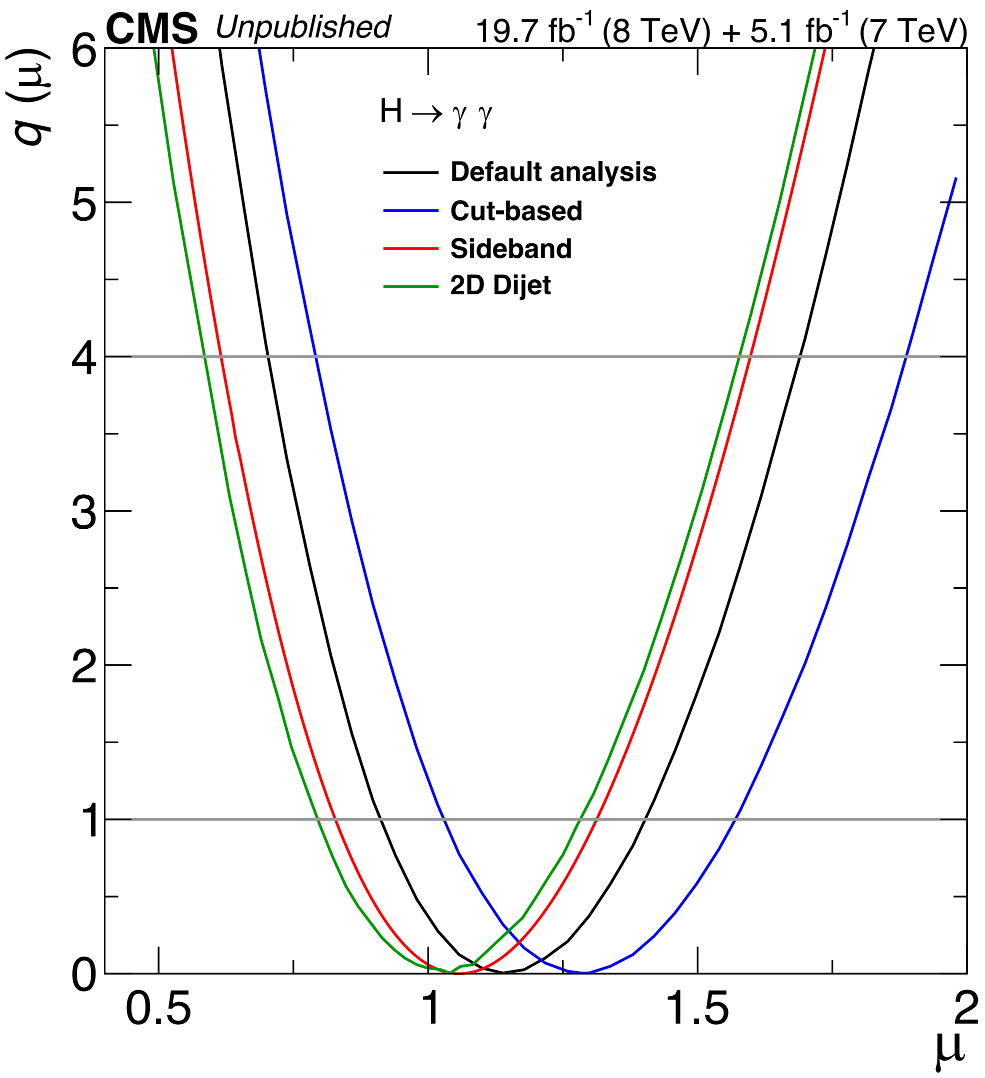
Putting everything together



Observation (**> 5σ**) of H→γγ decay with CMS Run-1 dataset!



Were we sure about that?



In CMS we convinced ourselves that we were seeing the Higgs in H→γγ decays with **3 cross-check analyses**

- **Cut based analysis:** No BDTs used to classify events. Categories based purely on photon location and R9

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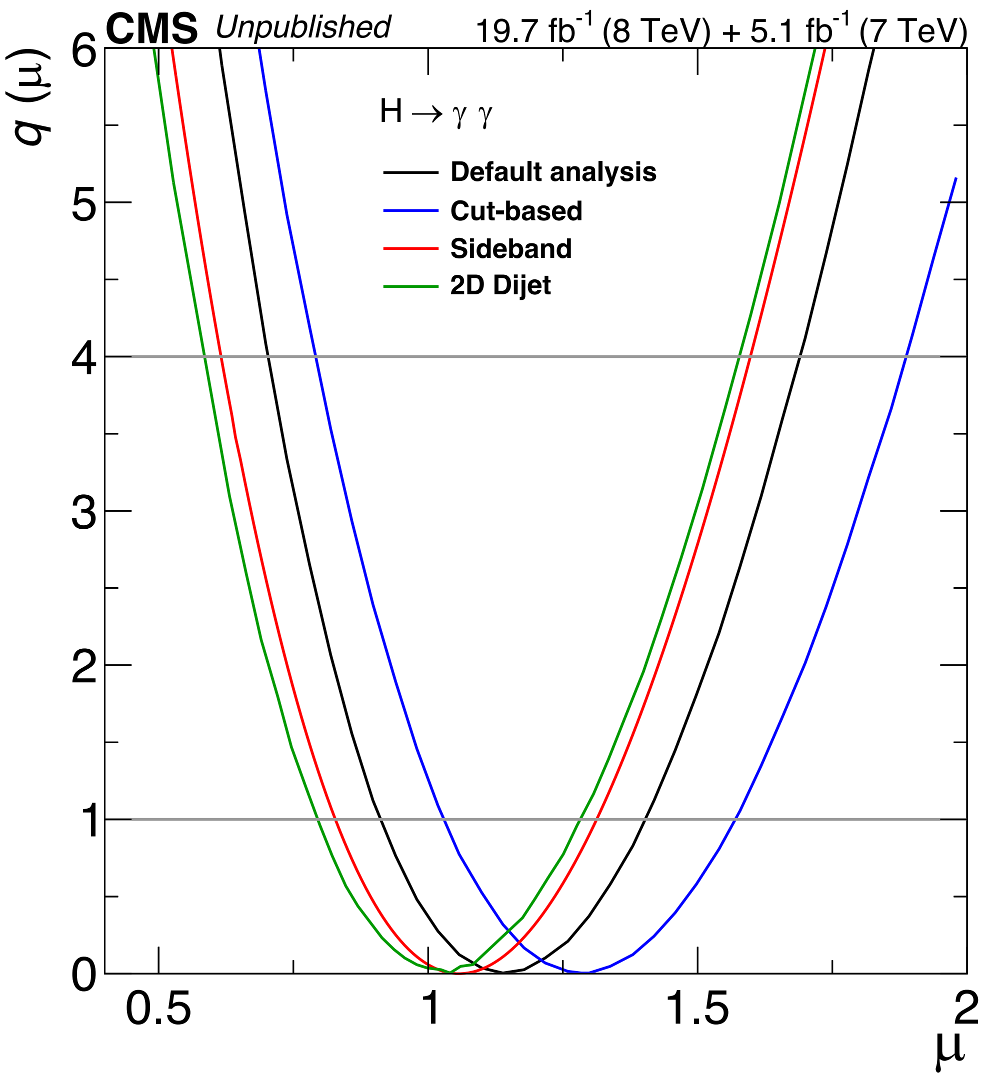

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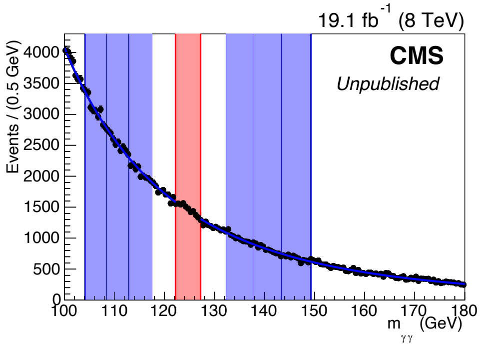

Interpolate sideband yields to estimate background under signal peak in BDT Bins

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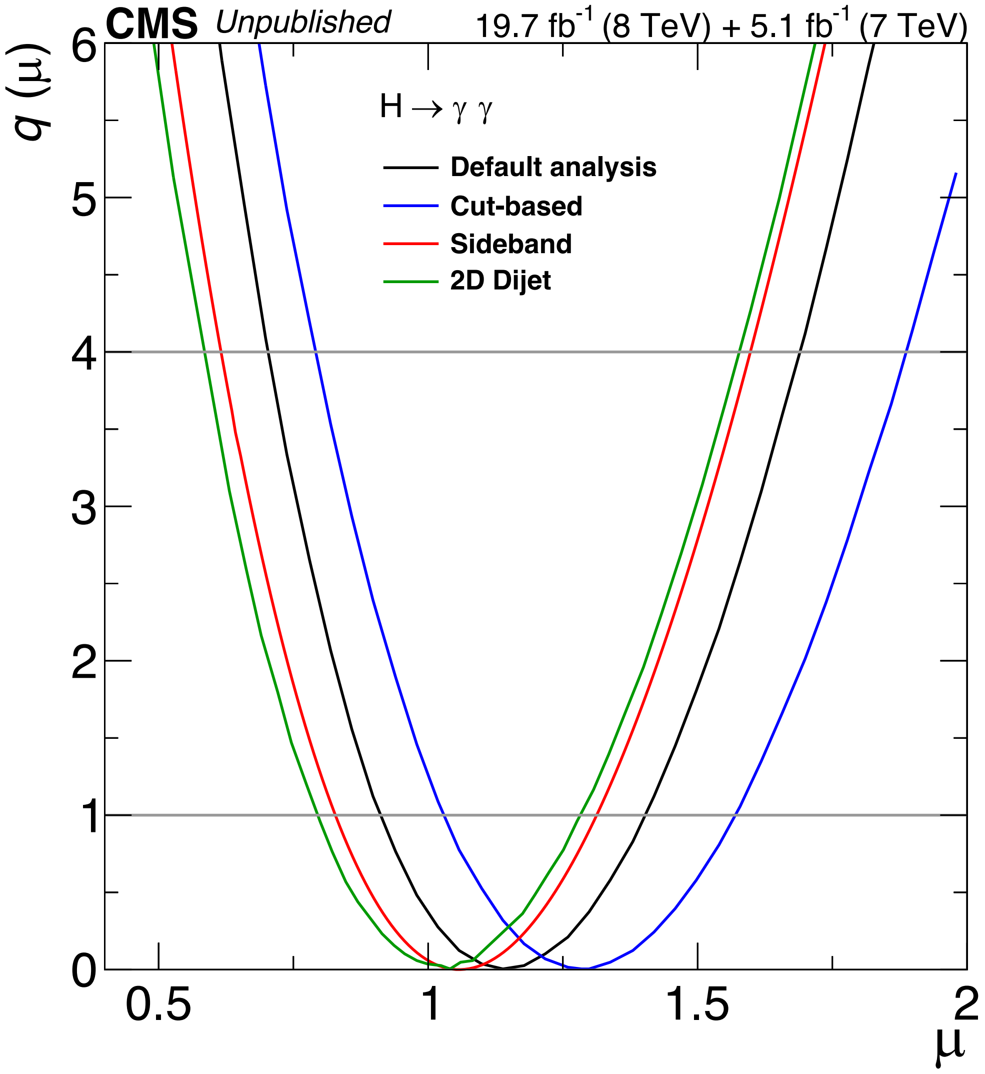

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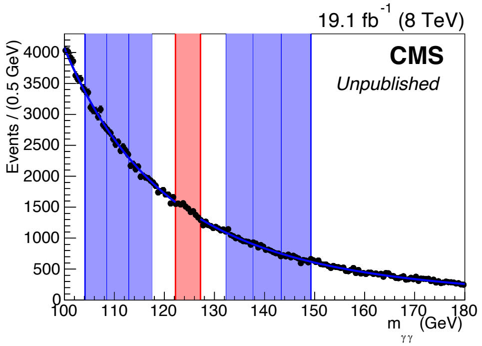


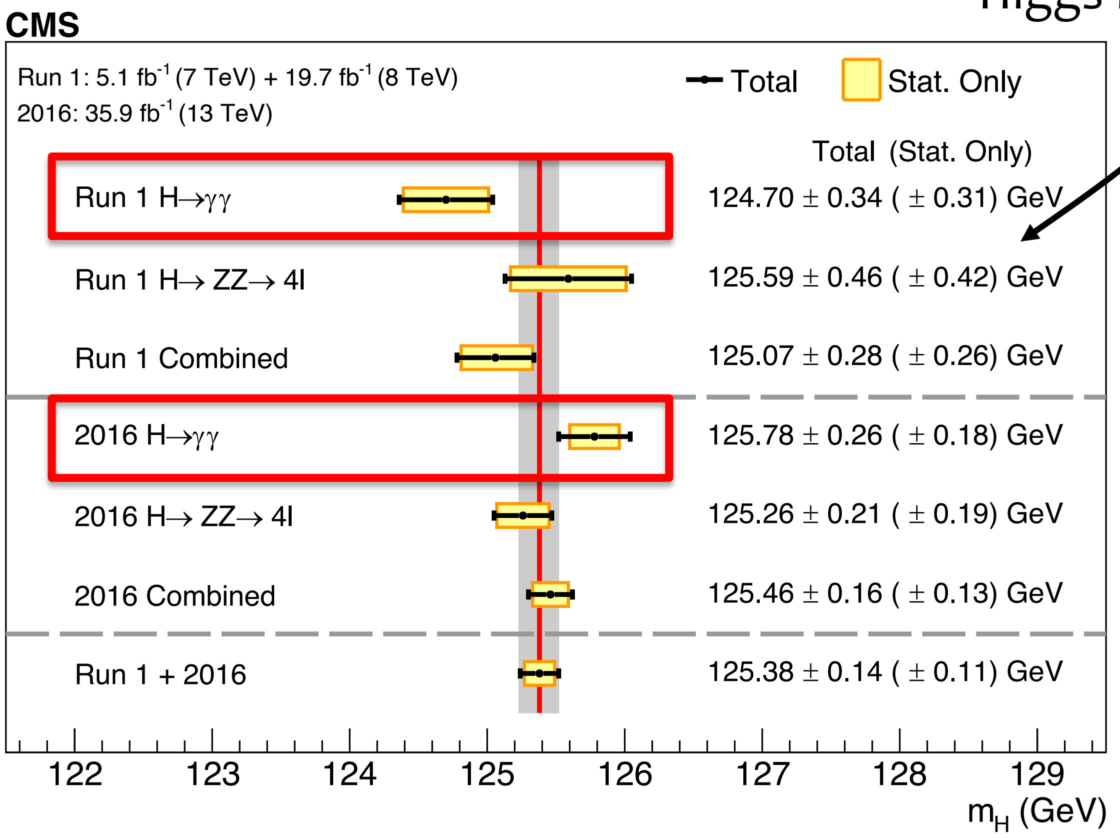
Interpolate sideband yields to estimate background under signal peak in BDT Bins

- **2D Dijet:** No BDT for 2-jet analysis. Fit directly to m_{jj} vs $m_{\gamma\gamma}$. Different assumptions about the modelling of VBF-like events

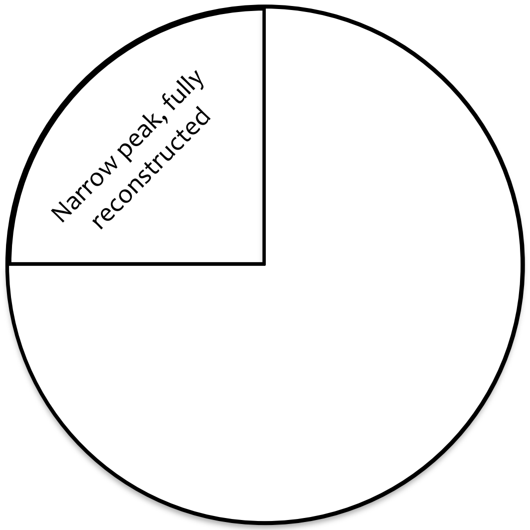
H→γγ to probe H-boson properties

With similar analysis strategies, the diphoton decay of the Higgs boson is used to measure Higgs boson properties

Higgs boson mass



H→γγ useful features



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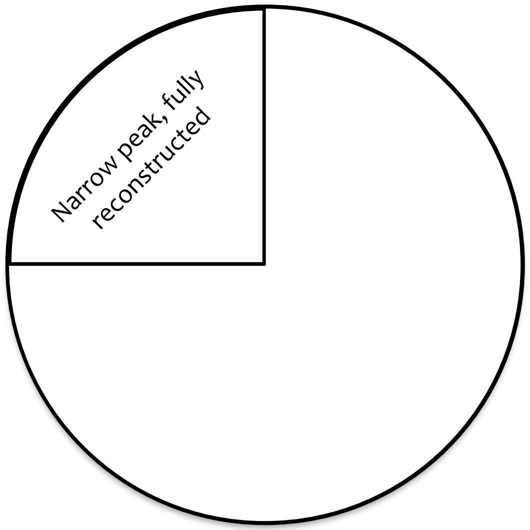

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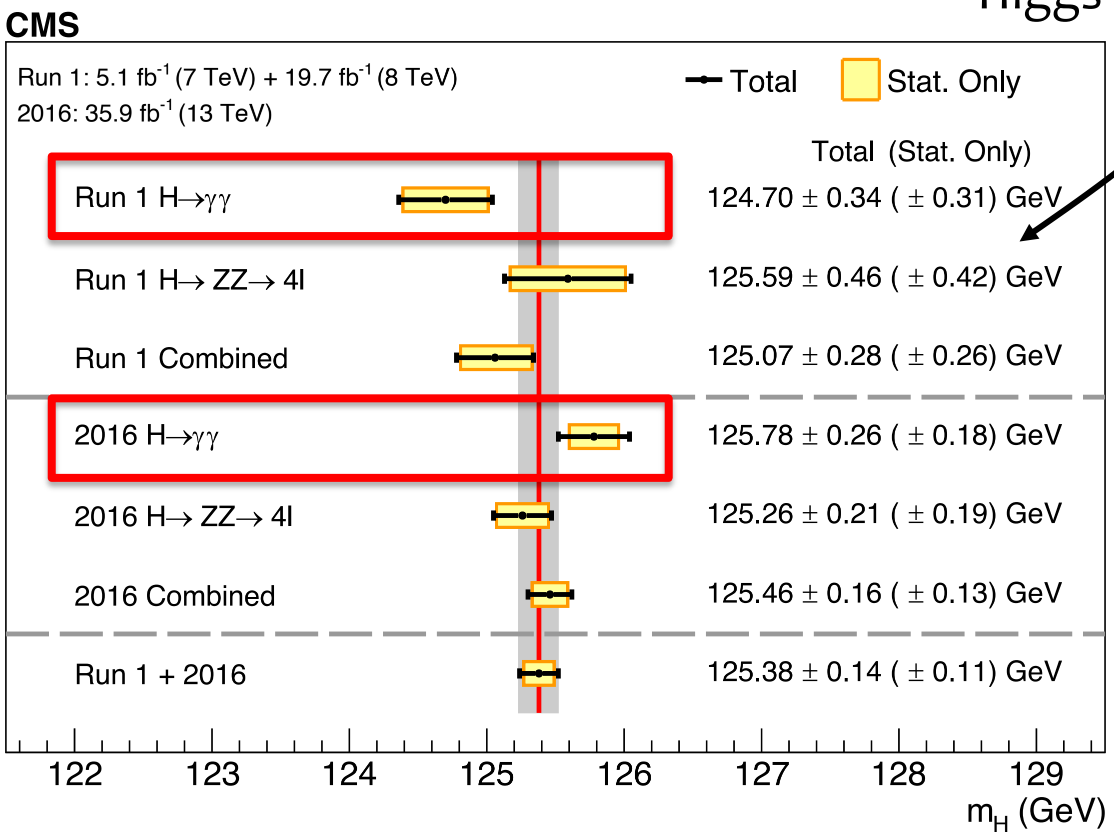
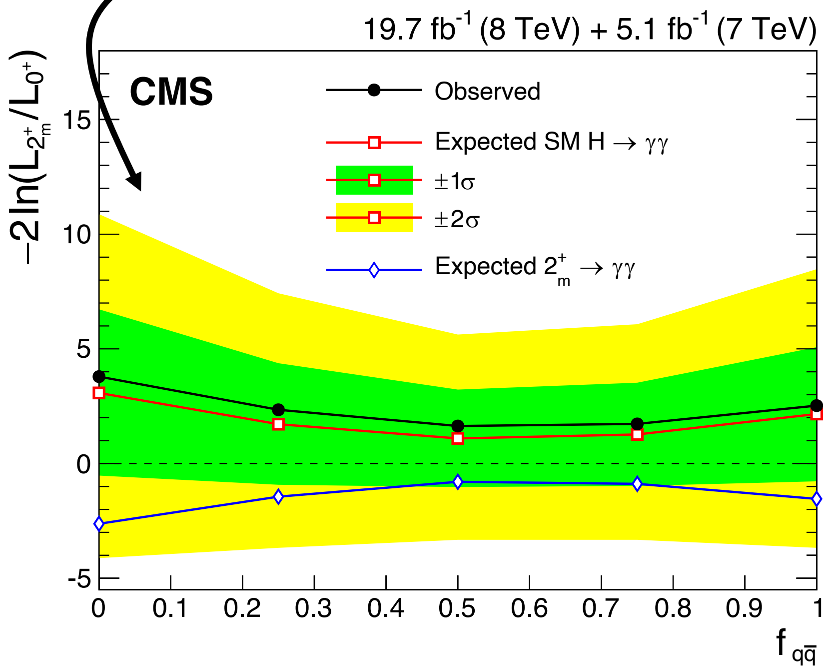


Spin hypothesis



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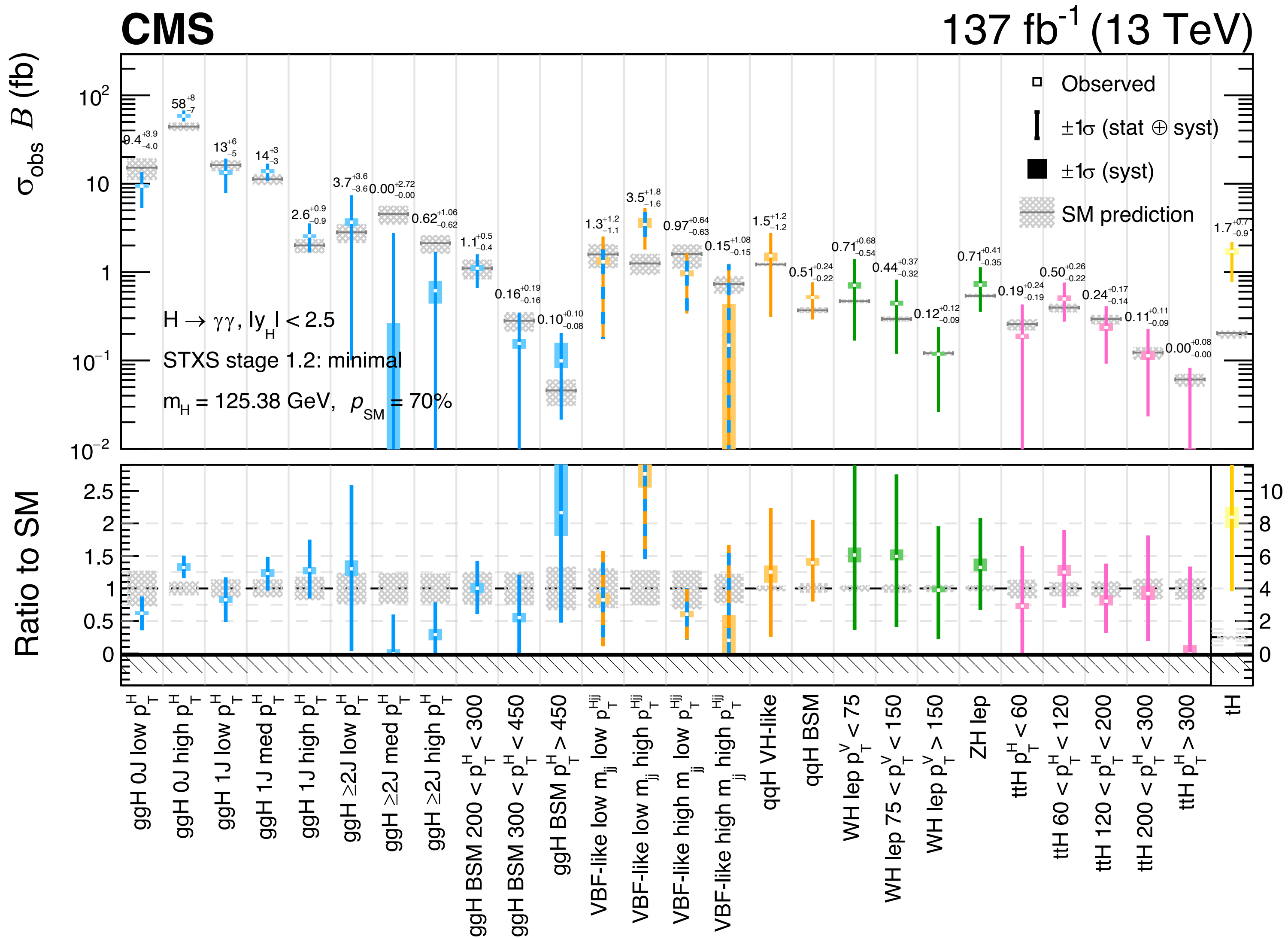

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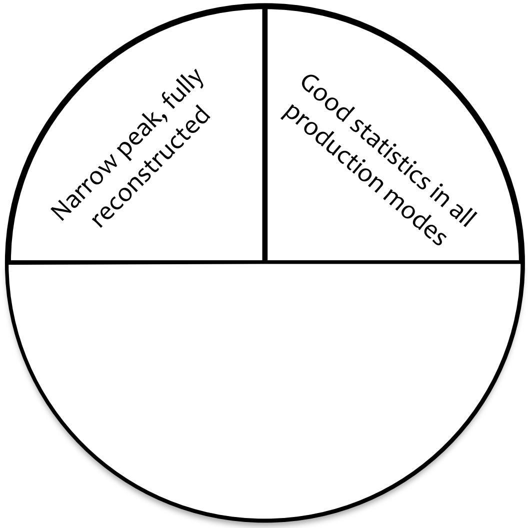
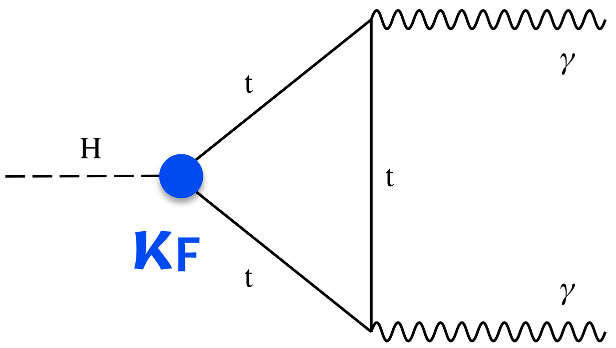


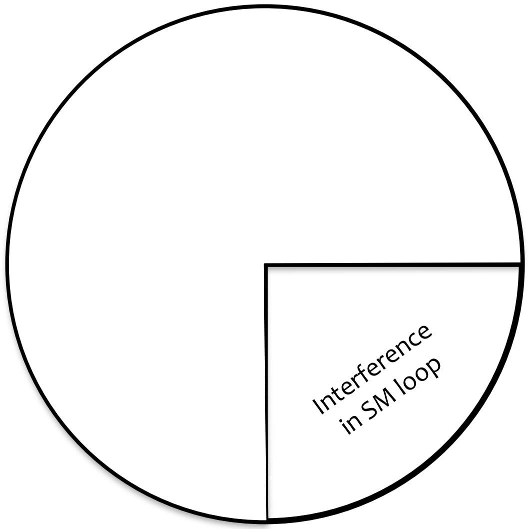
Higgs boson production cross-sections

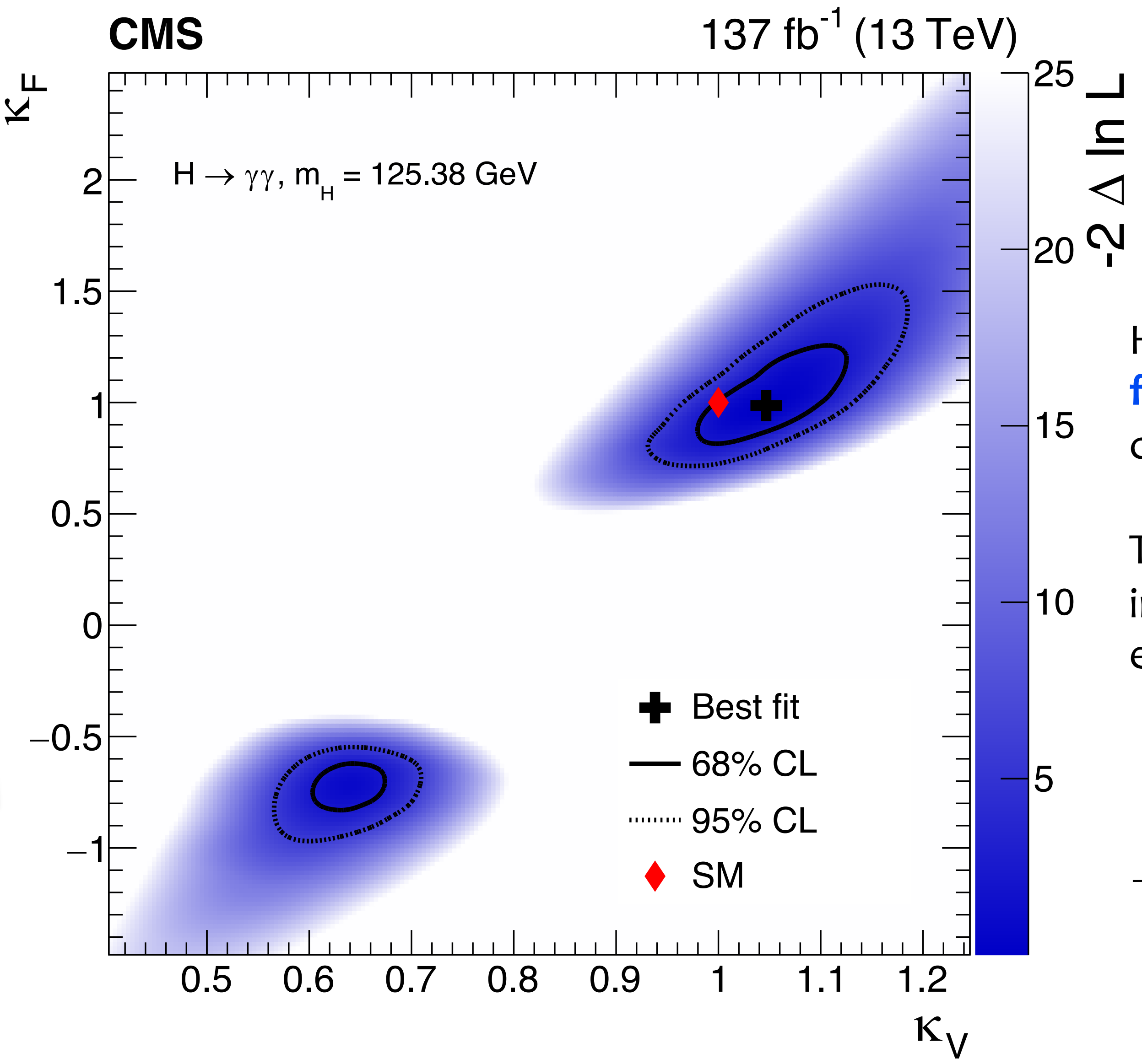
- Production mechanisms: **ggH**, **VBF**, **WH**, **ZH**, **ttH**, **tH**
- Kinematic observables: $p_T(H)$, $p_T(V)$, m_{jj}, N-jets

H→γγ to probe BSM physics



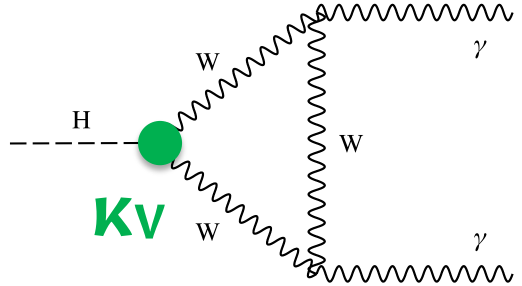
H→γγ useful features



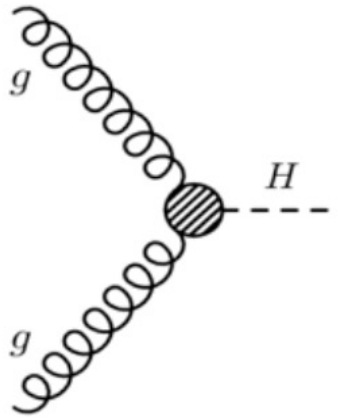


H→γγ decay sensitive to **fermion** and **vector boson** couplings

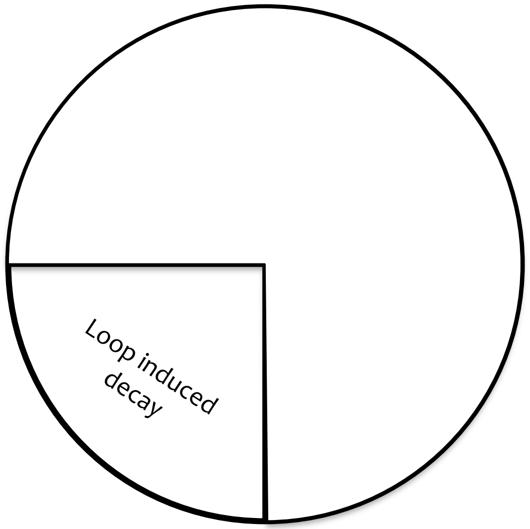
These couplings are modified in two-Higgs double model extensions to the SM

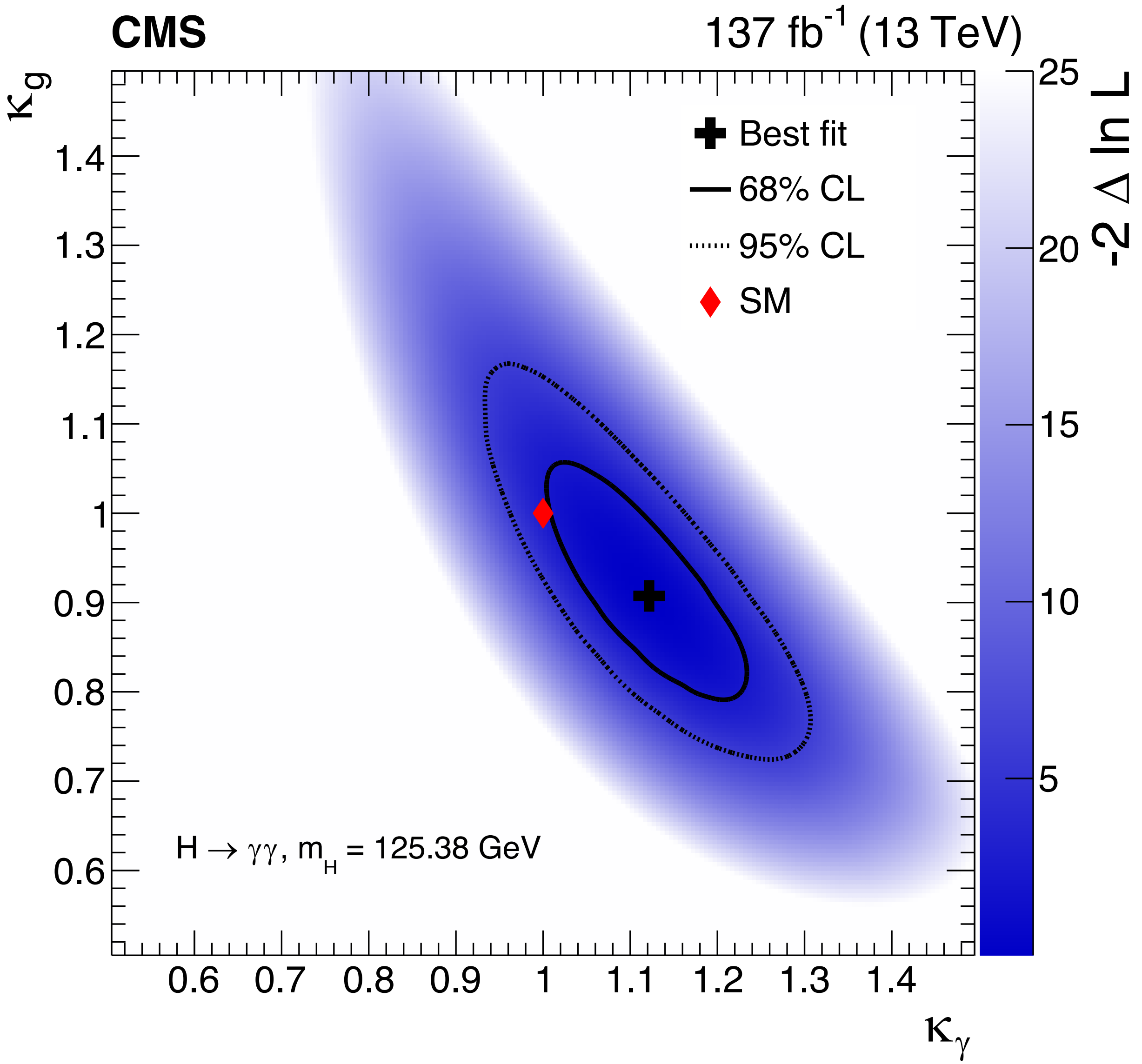


H→γγ to probe BSM physics



H→γγ useful features



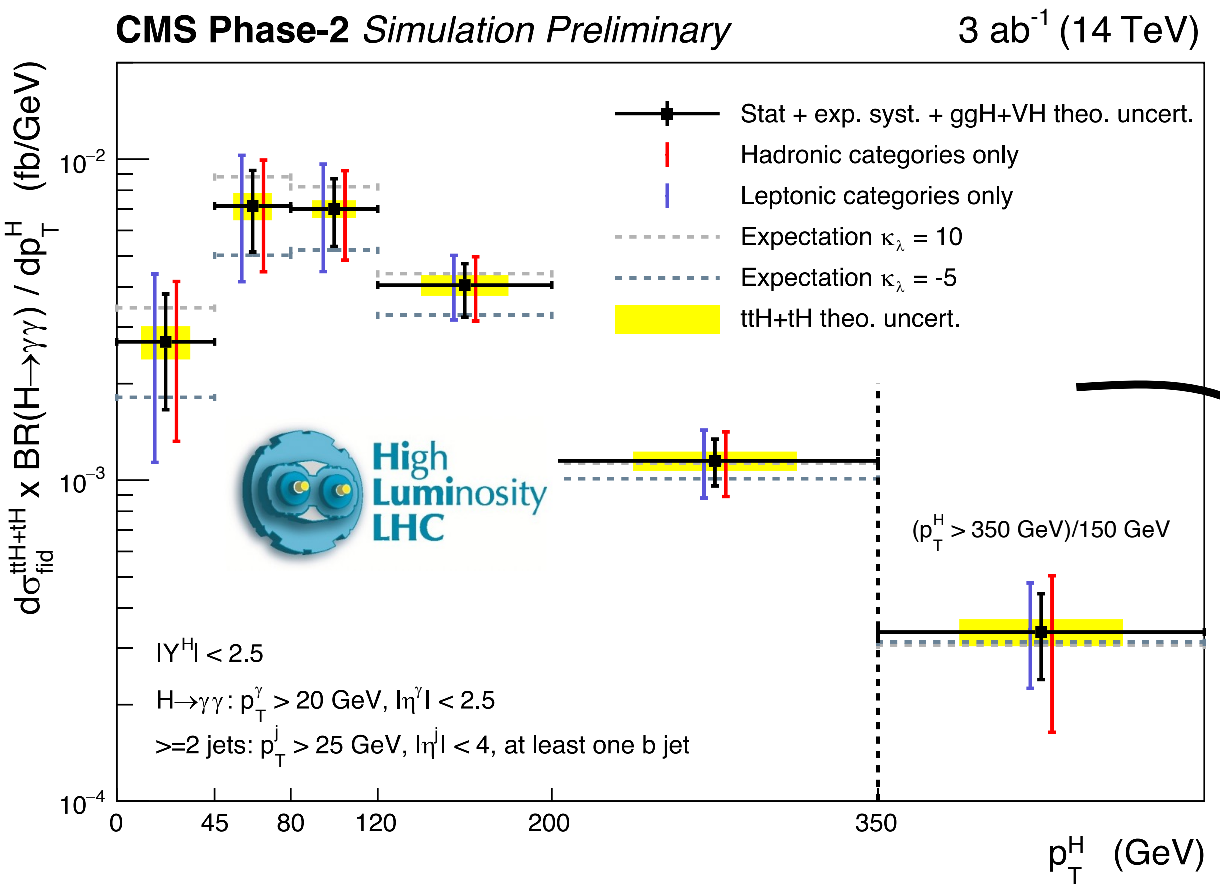


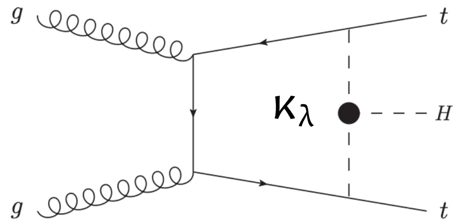
New (BSM) particles can appear in loops, modifying gg→H and H→γγ

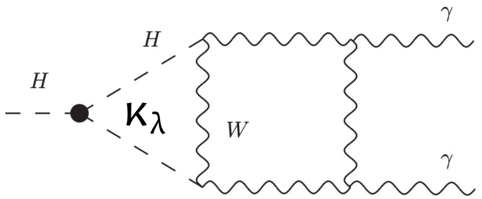
Effective couplings sensitive to BSM contributions to gg→H→γγ

H→γγ to probe Higgs self-coupling

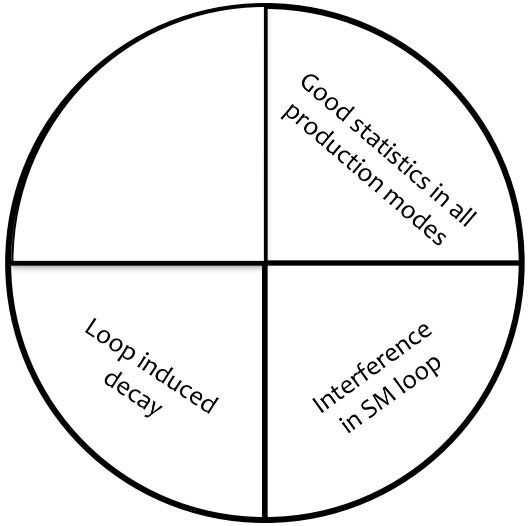
With data from the HL-LHC, measurements of rare processes like ttH(→γγ) will constrain the Higgs boson self-coupling

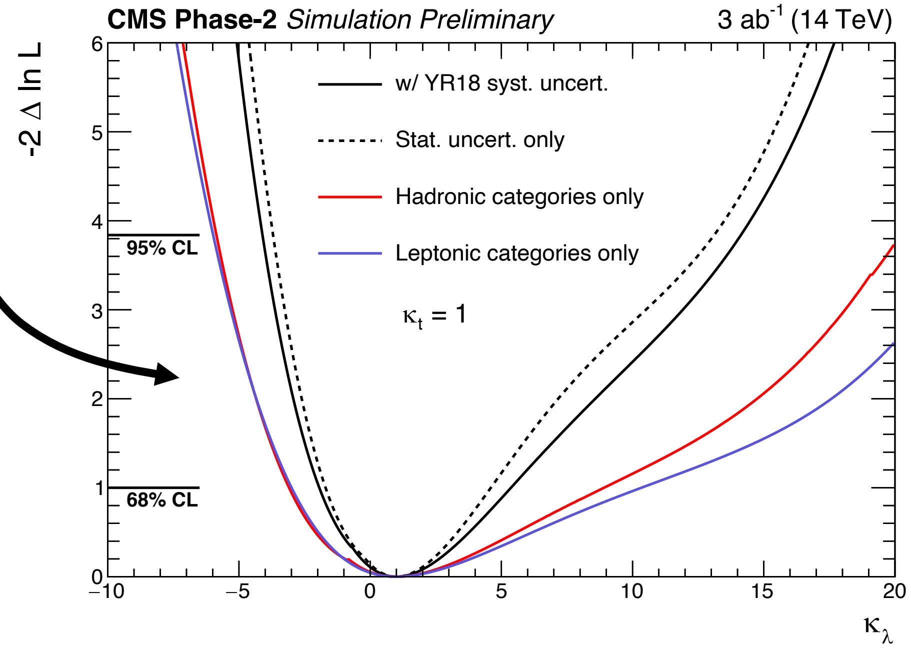






H→γγ useful features





Summary

H→γγ decay channel was key for the Higgs boson discovery

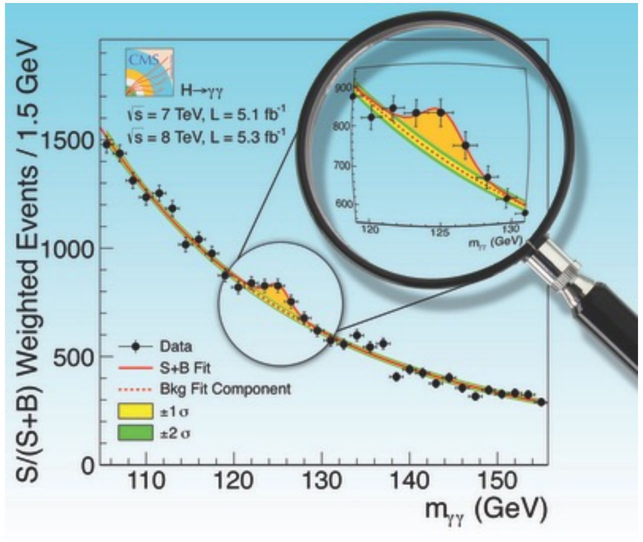
- Very high resolution channel with well calibrated final state objects (photons) in CMS
- Several cross-checks for analysis details (selection, background model)

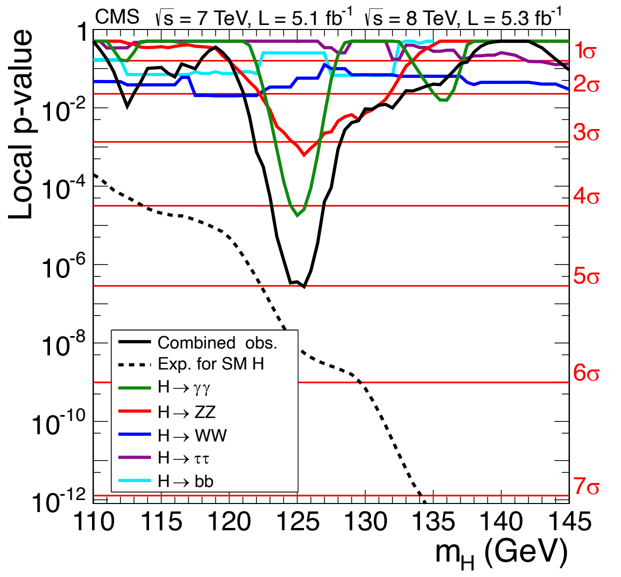
Despite small branching fraction, H→γγ channel ideal for measuring Higgs boson properties

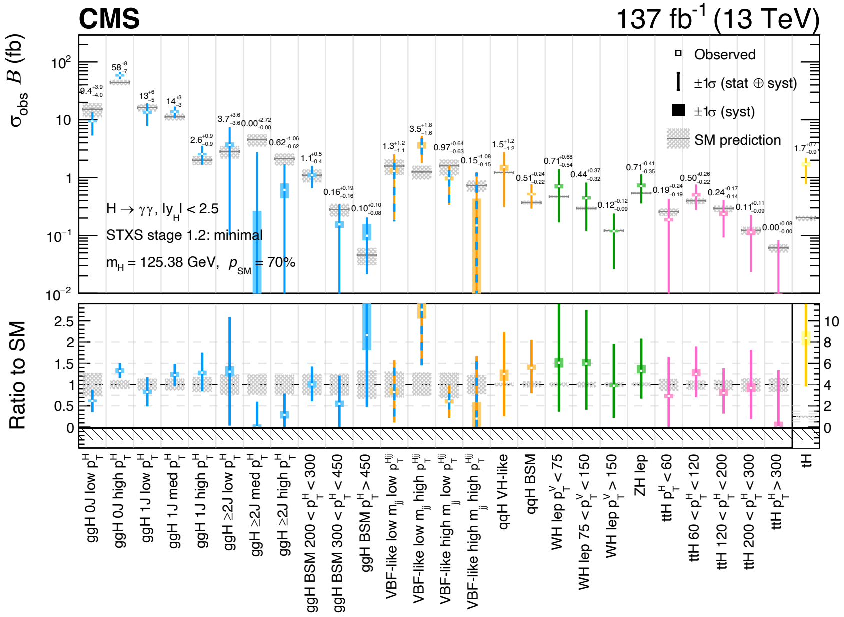
- Mass and spin
- Differential cross-sections and access to almost all production modes

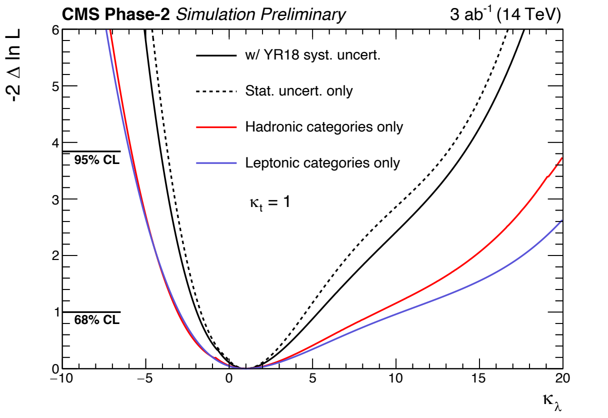
H→γγ channel is a major channel for probing new physics with Higgs boson measurements

- Extended Higgs sectors & new particles in loops
- Higgs boson self-coupling (Higgs potential)

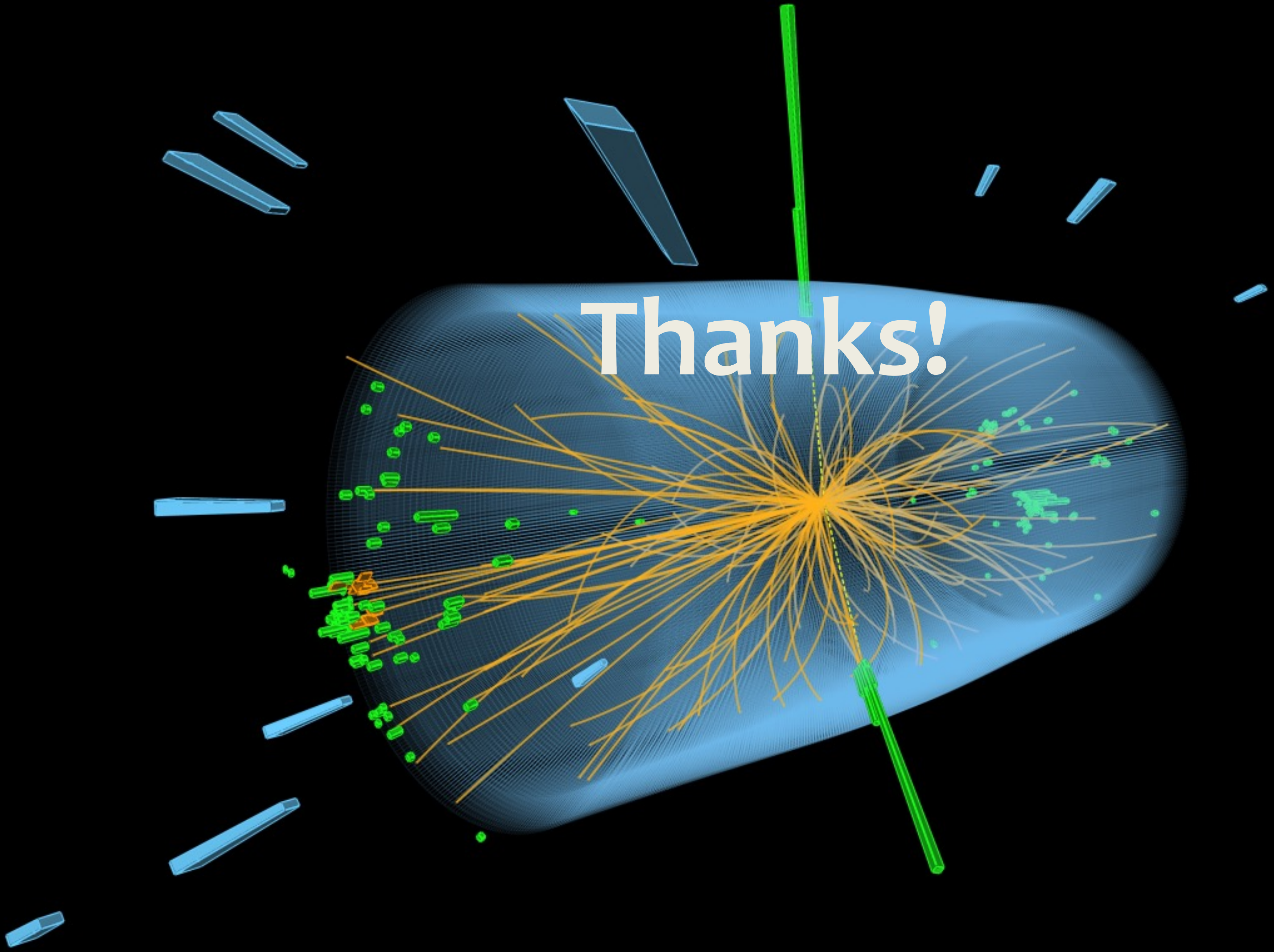








Thanks!

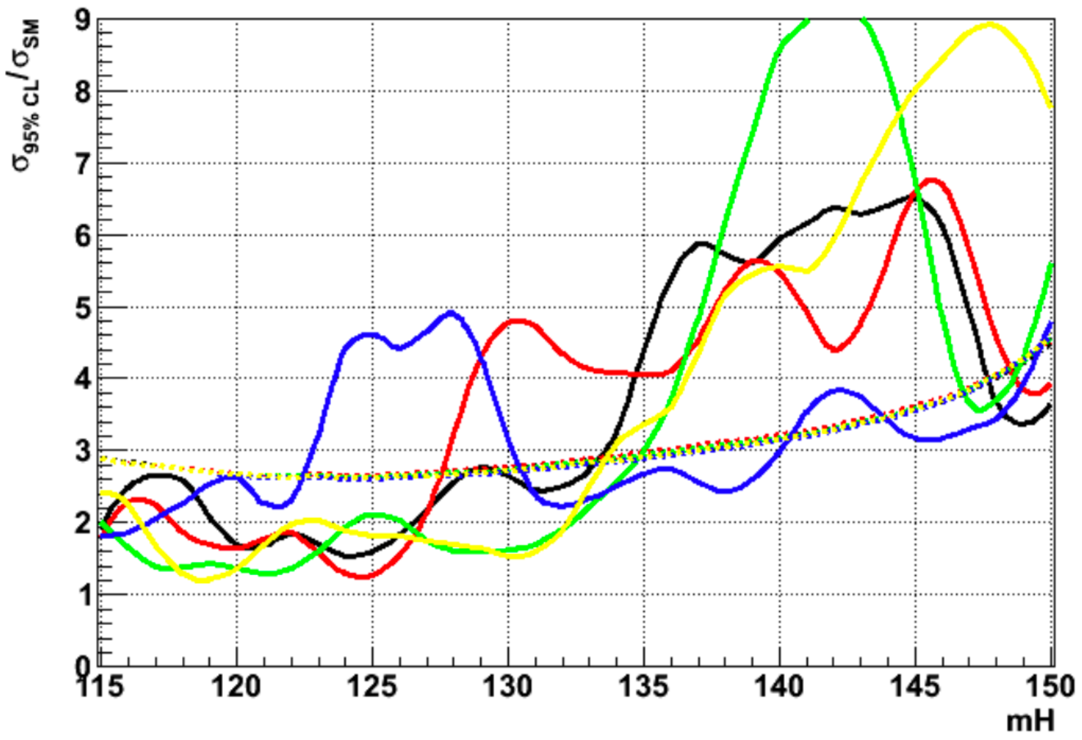


Backup slides

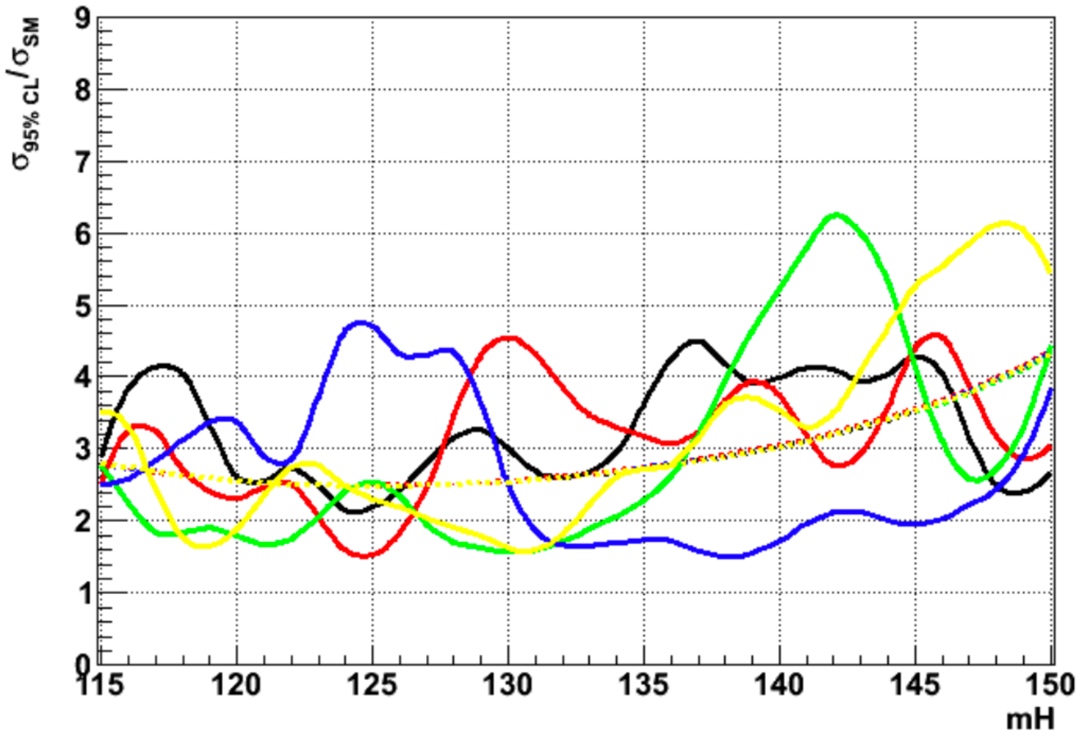
Which background function is right?

This is a figure from a study before the discovery that showed in toys how different the limits can be depending on whether you use the right function or not to fit the background

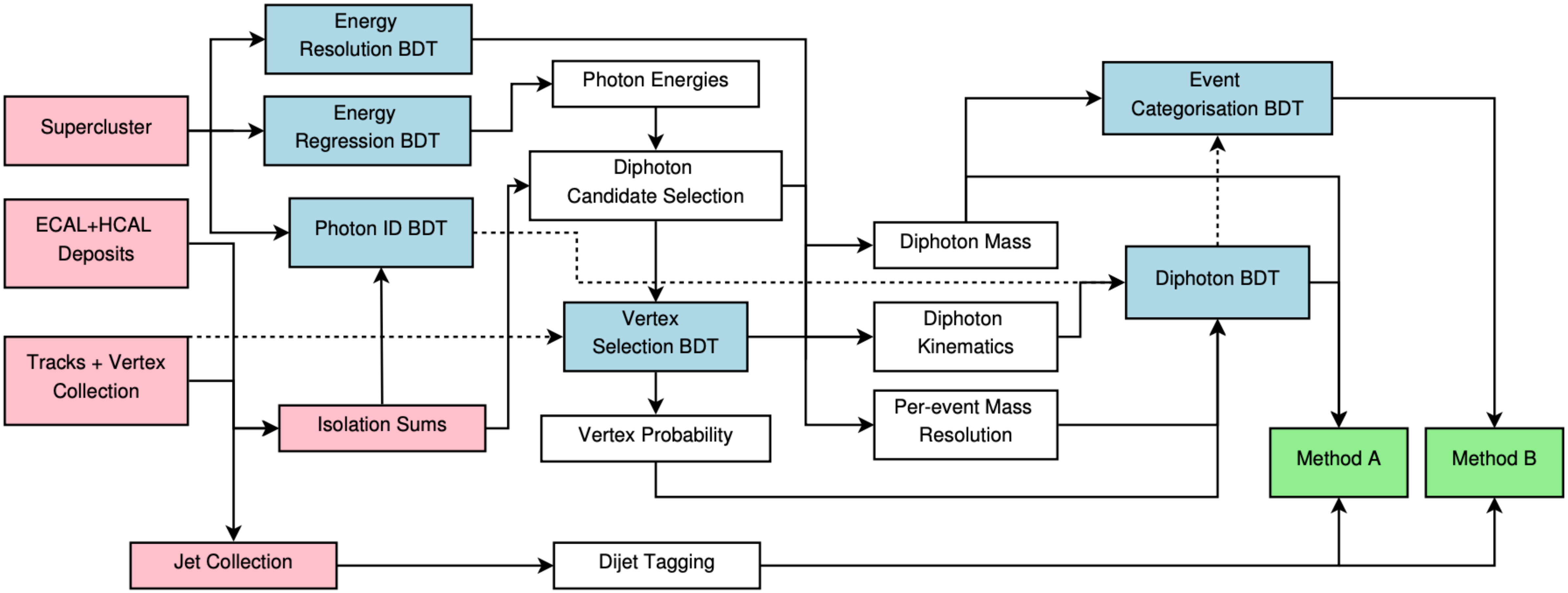
Gen Power, Fit Poly



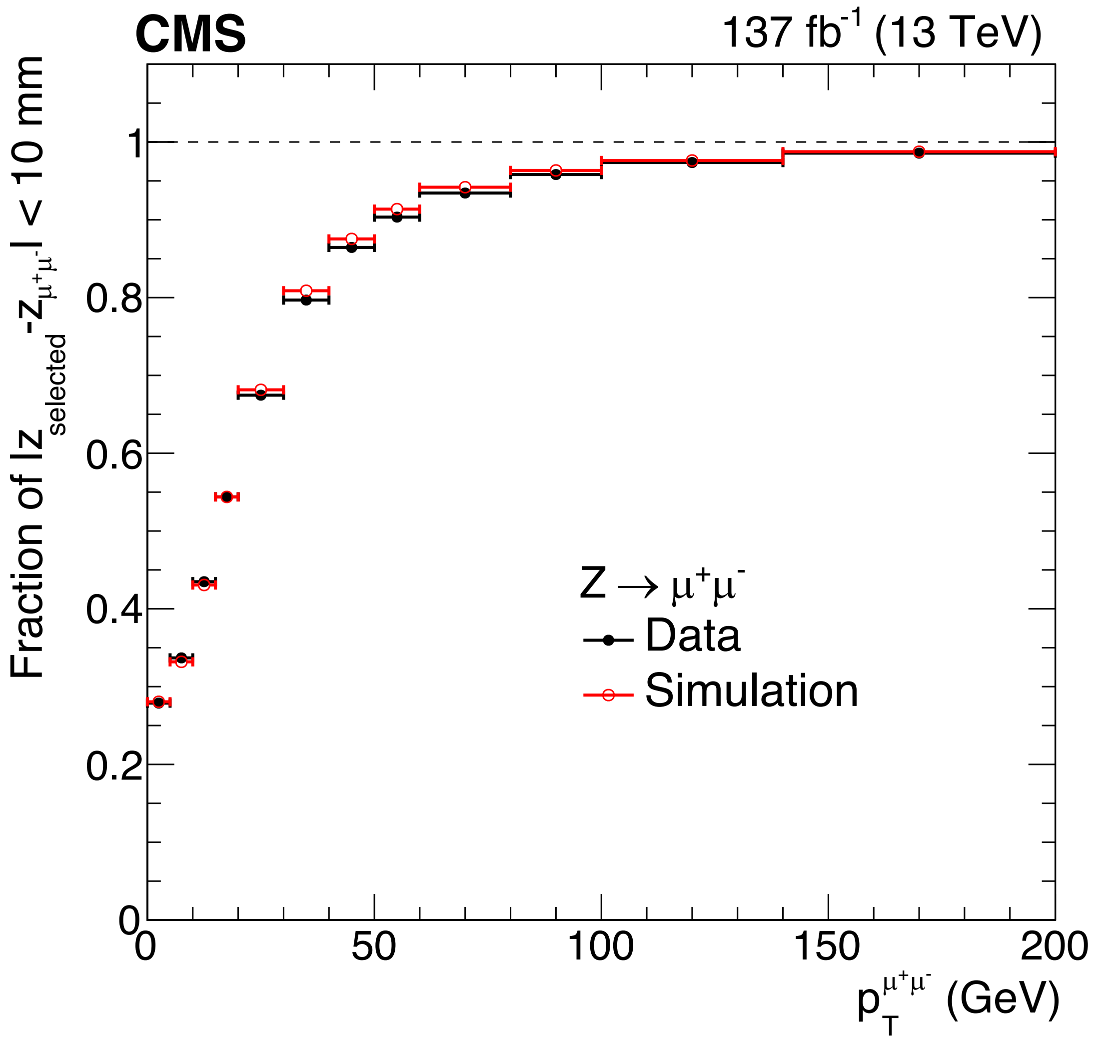
Gen Poly, Fit Power

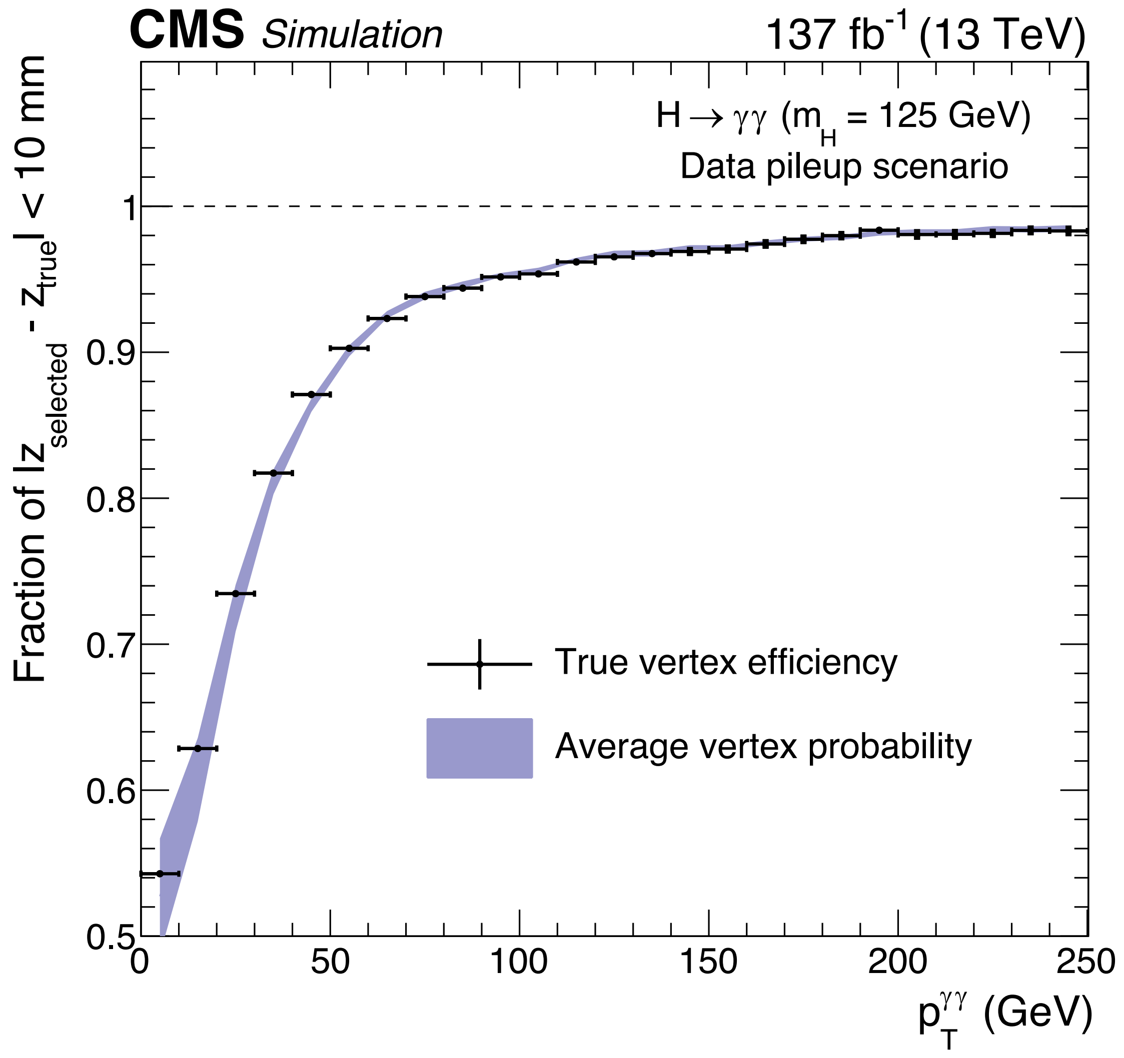


Flowchart for a CMS H→γγ analysis

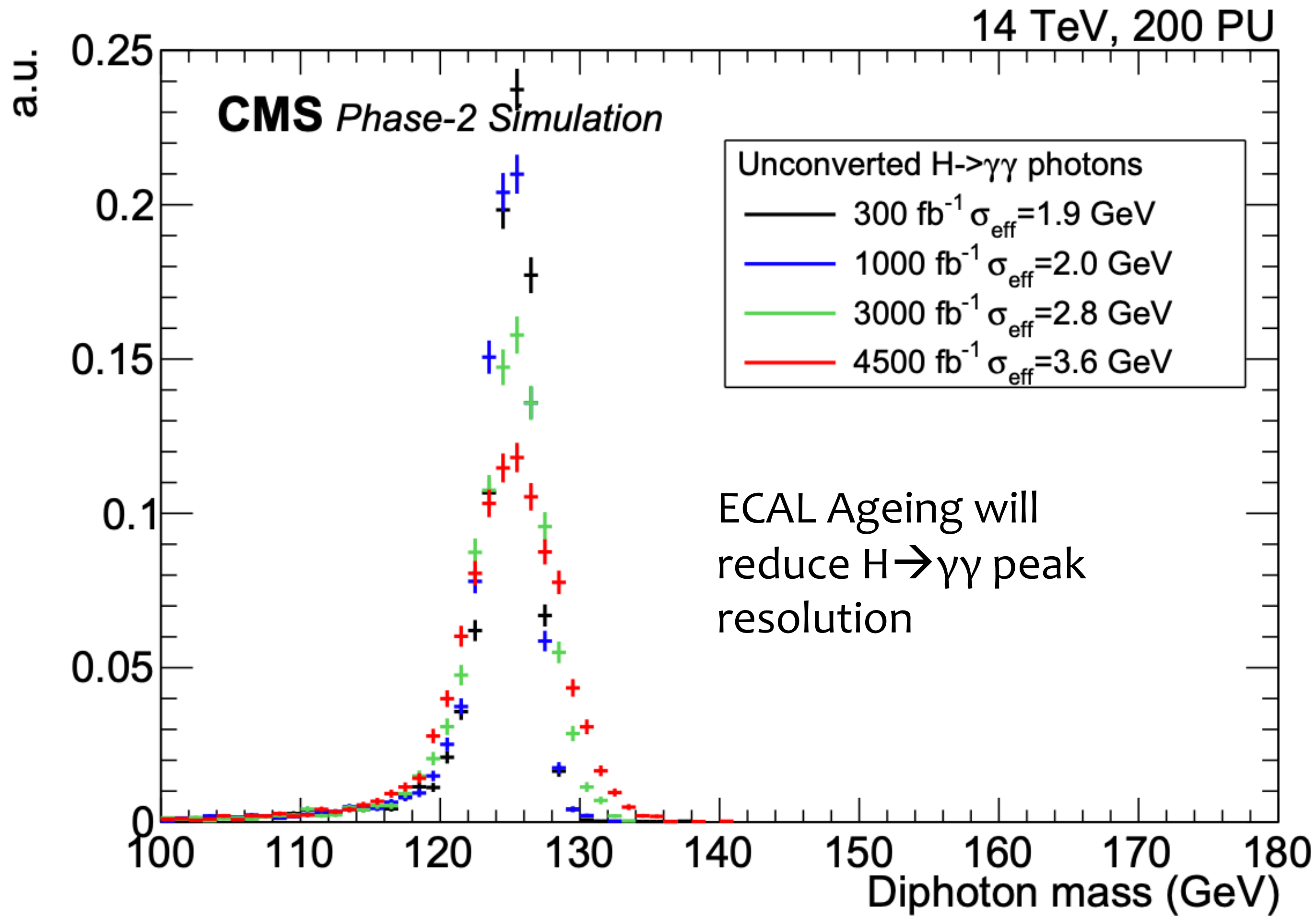


CMS diphoton vertex efficiency

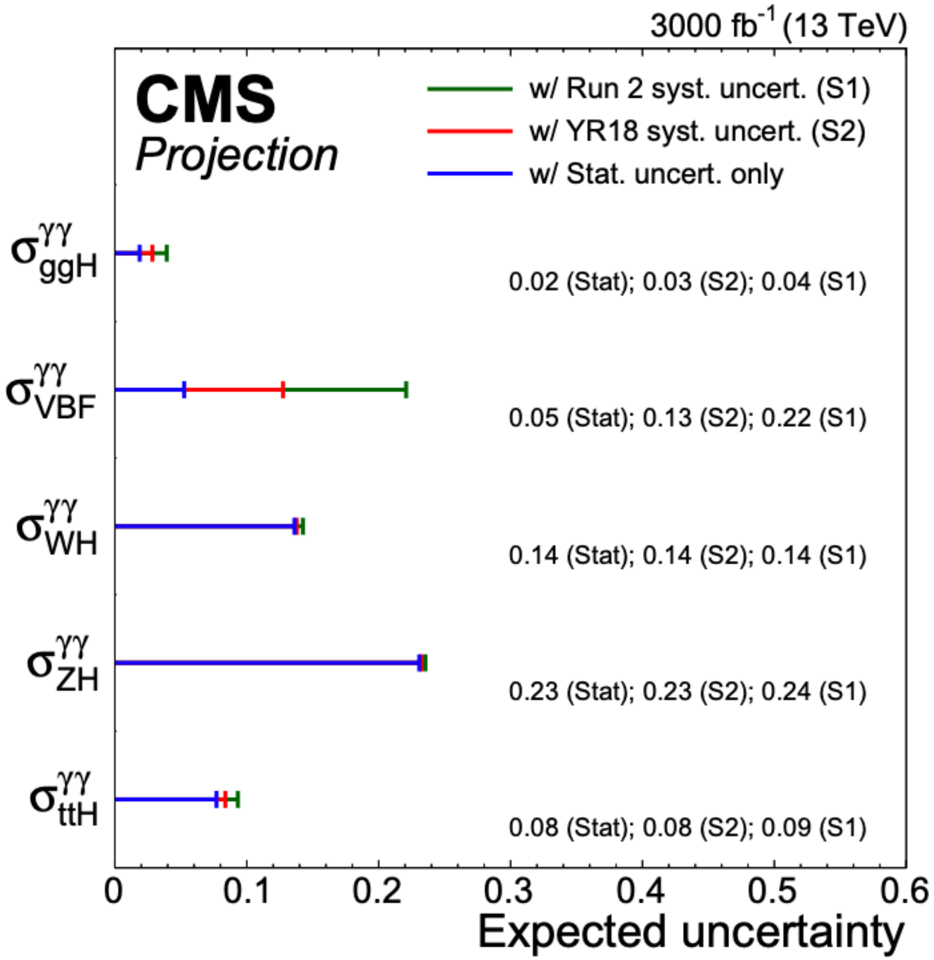




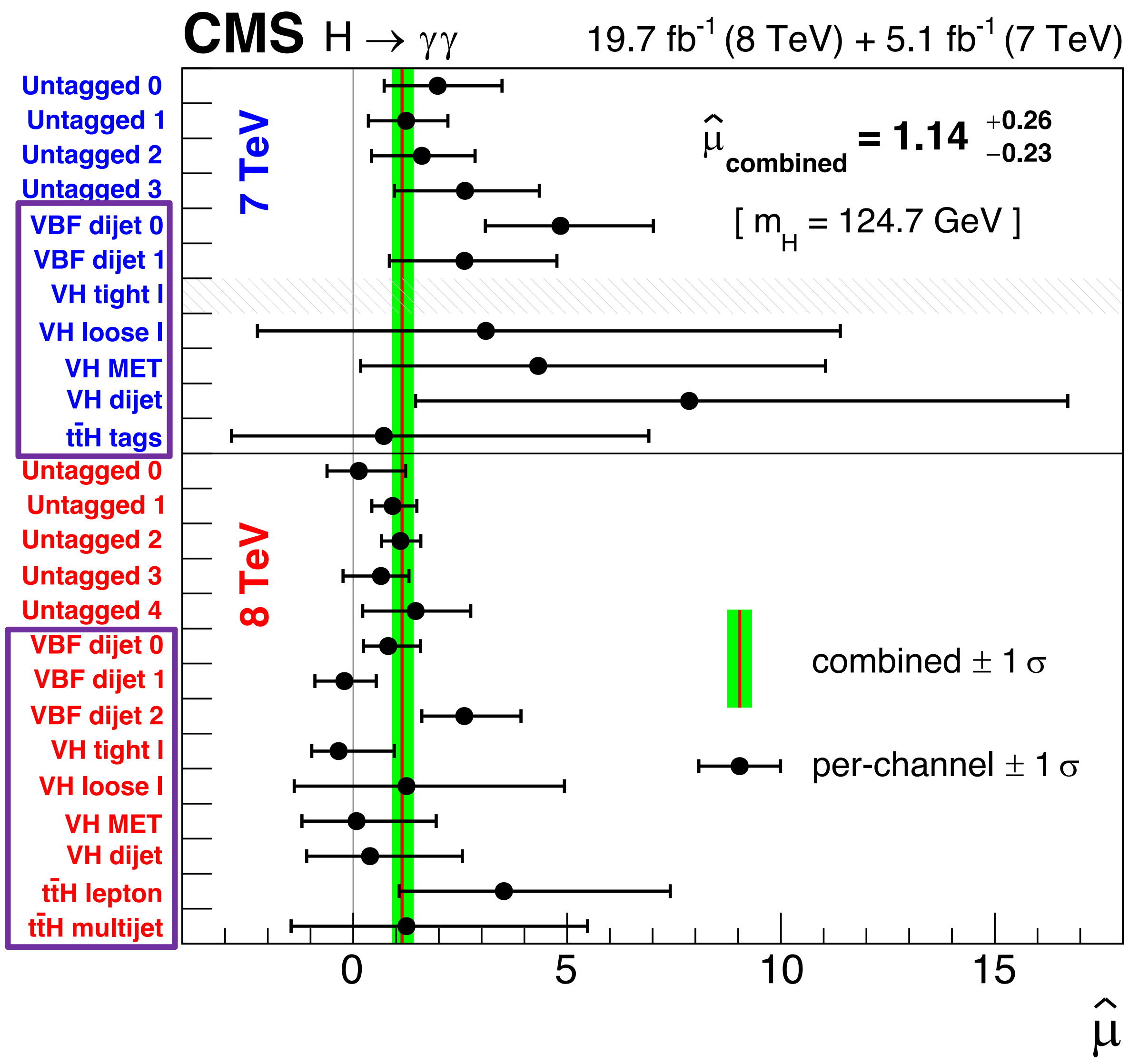
H→γγ at the HL-LHC



ECAL Ageing will reduce H→γγ peak resolution

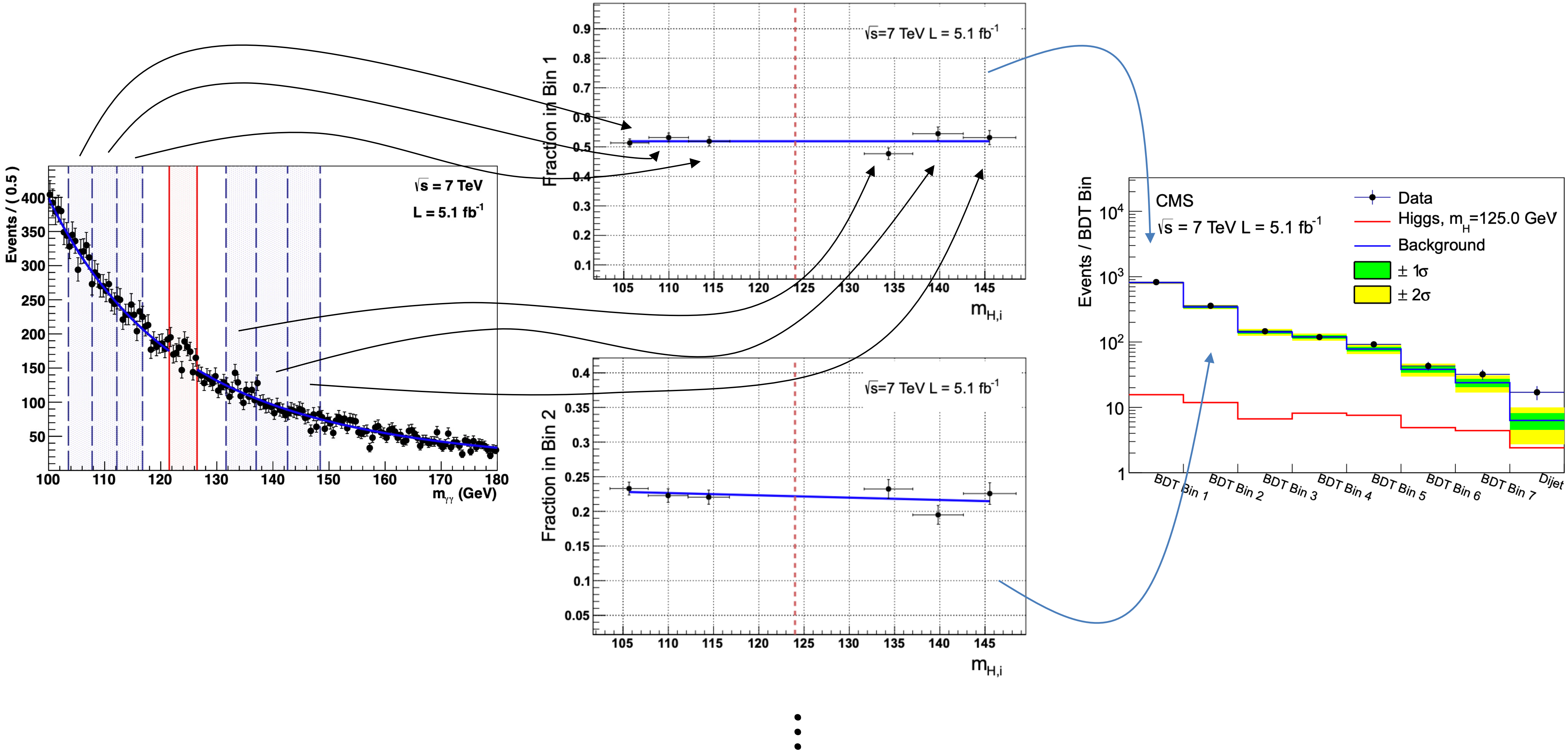


Other categories for H→γγ obs

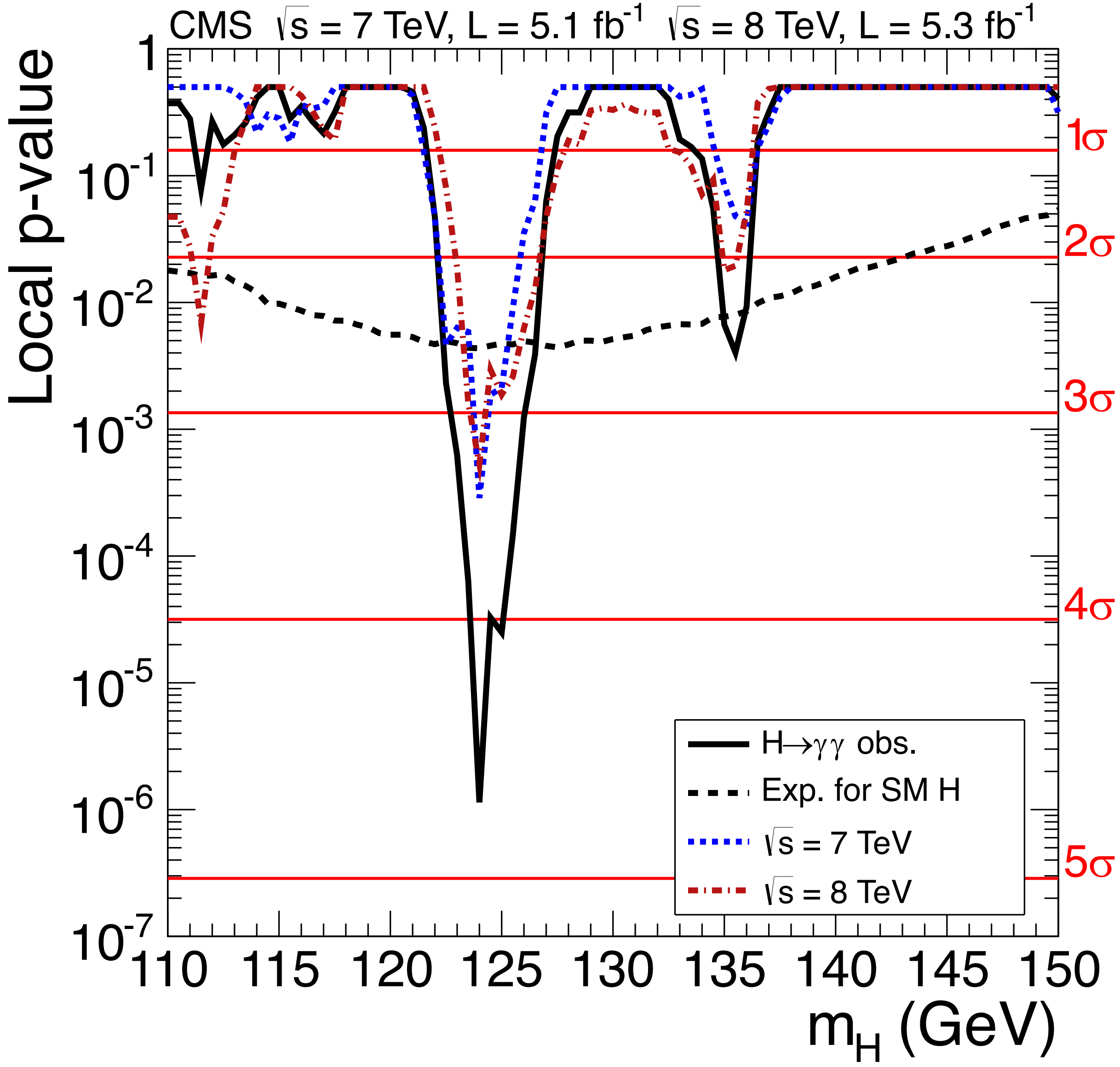


H→γγ observation paper included additional categories targeting **other Higgs production modes**

Sideband Analysis



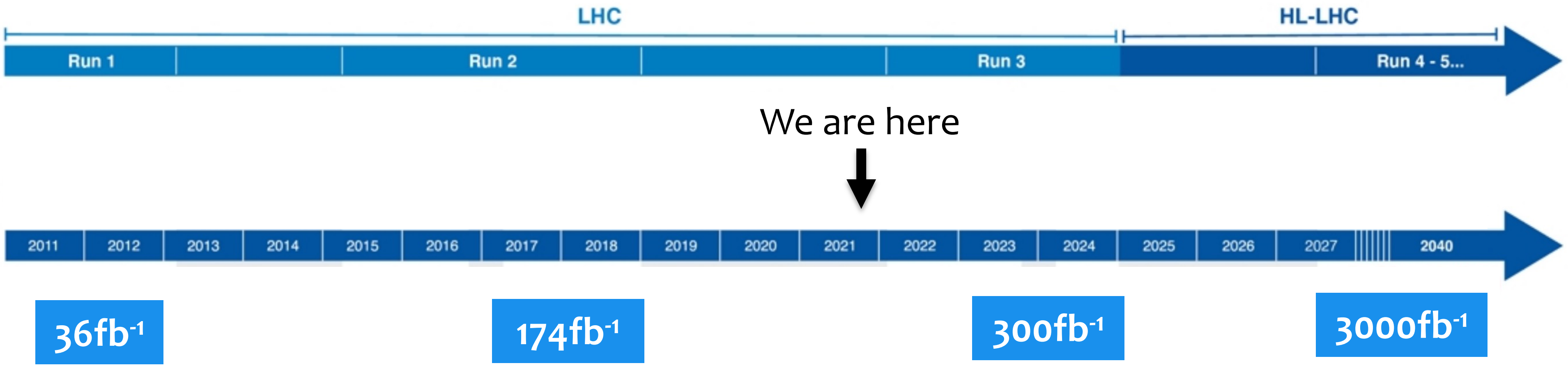
Sideband Analysis



The Future of the LHC

After Run-3 of the LHC, the next phase is the **high-luminosity** (HL)-LHC

~20x the data we have today!

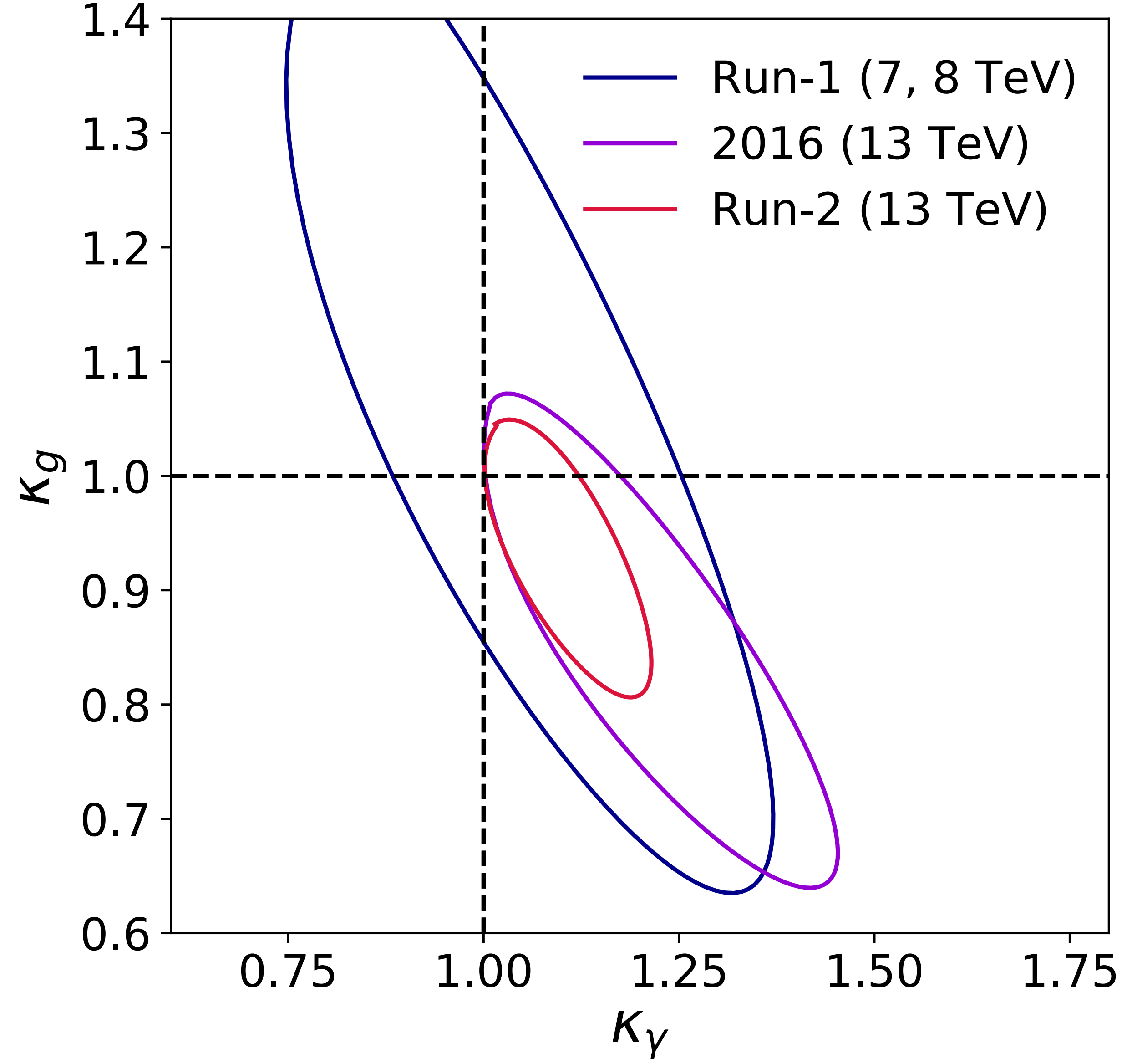


LHC

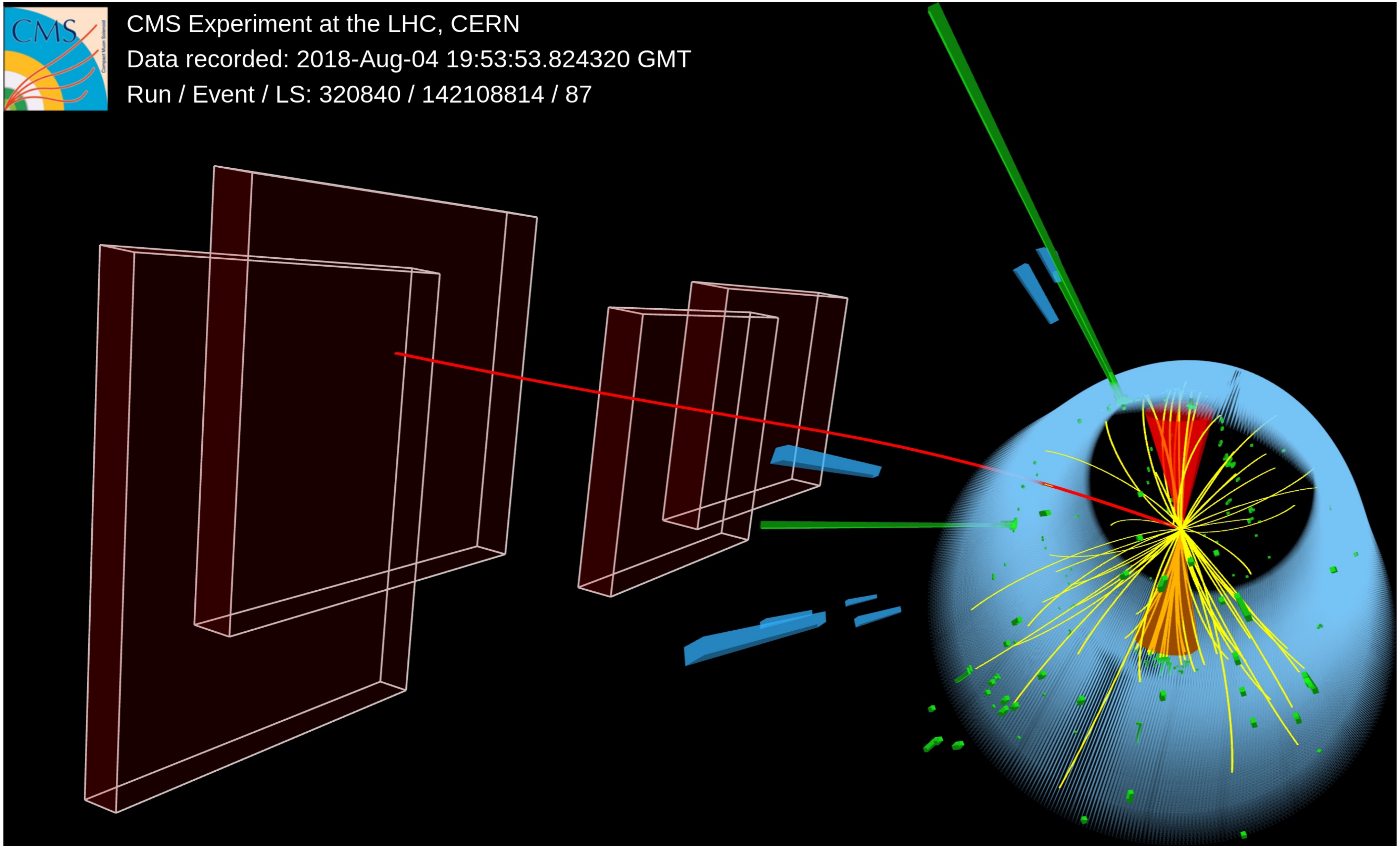
HL-LHC

Expect **> 160M H-bosons / 120k HH pairs** at CMS by the end of the **HL-LHC** !

History of BSM couplings

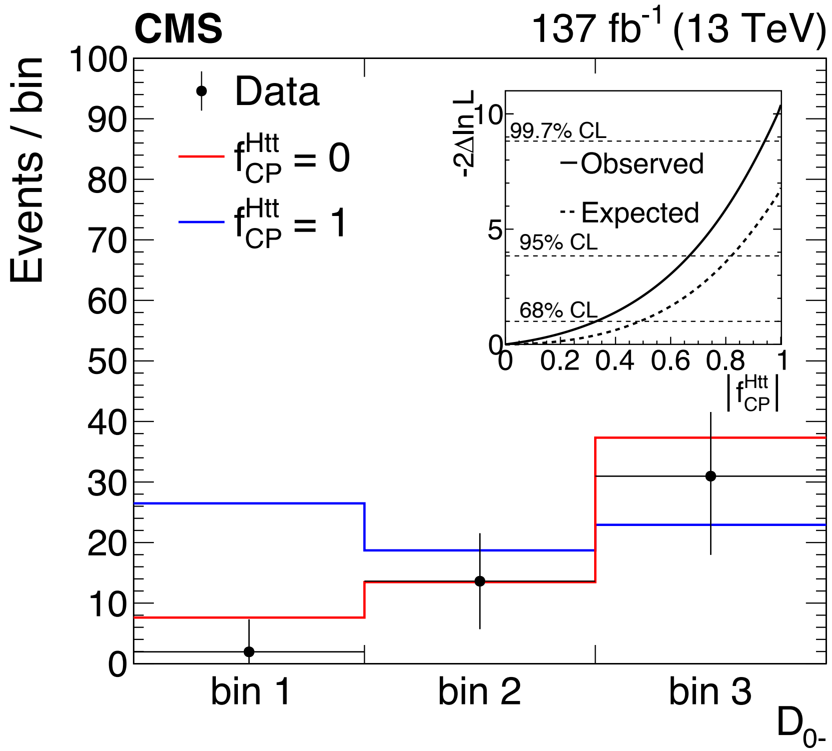


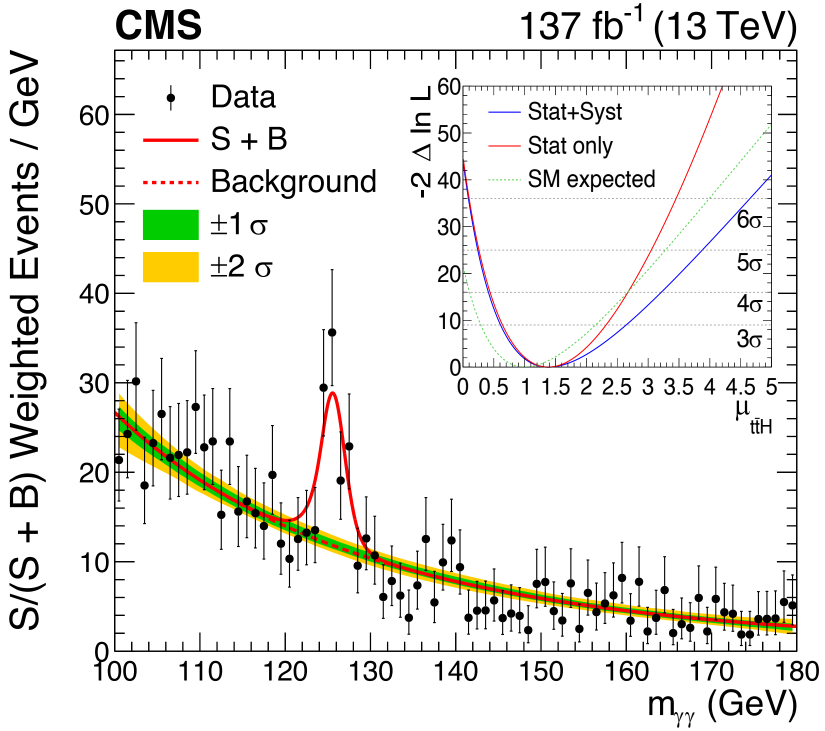
H→γγ tH


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-04 19:53:53.824320 GMT
Run / Event / LS: 320840 / 142108814 / 87

CP violating couplings

Sensitive to CP of Higgs-top coupling in ttH H→γγ events



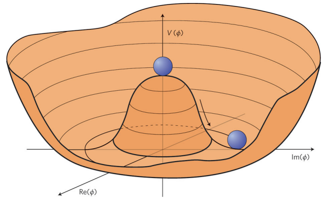


Phys. Rev. Lett. 125 (2020) 061801

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\overline{\psi}_t\left(\kappa_t + \mathrm{i}\tilde{\kappa}_t\gamma_5\right)\psi_t,$$

$$f_{CP}^{Htt} = \frac{|\kappa_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$

Modified Higgs potentials & Baryogenesis



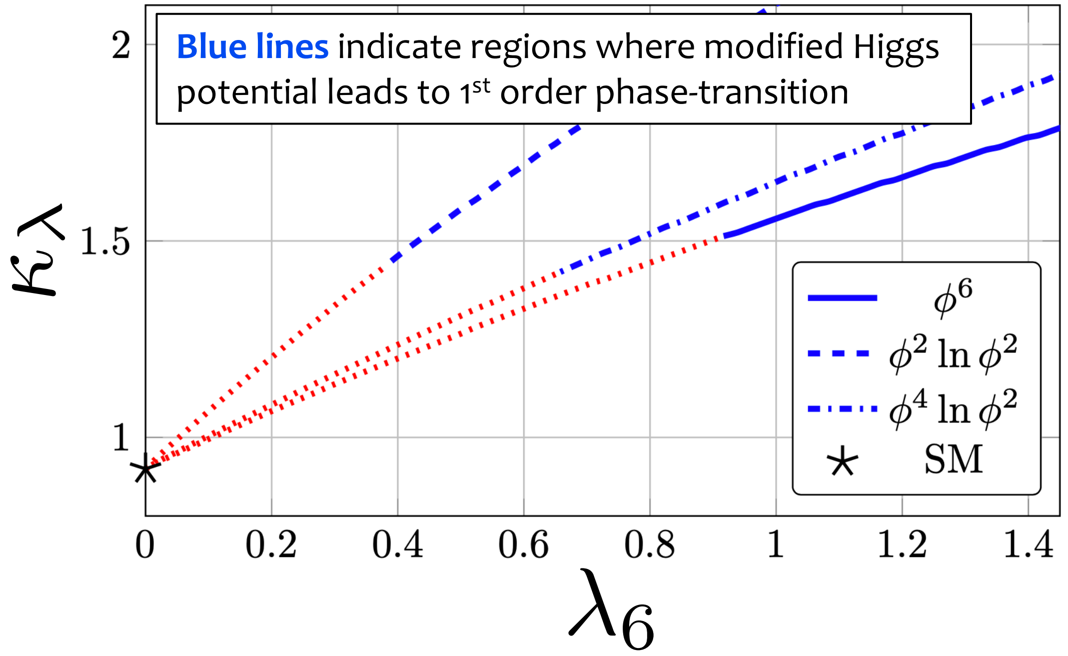
BSM physics in **Higgs potential** could be the solution!

$$\underbrace{V(H) = \frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4}_{\text{SM}} + \underbrace{\frac{\lambda_6}{\Lambda}(v+H)^6}_{\text{BSM}}$$

Inclusion of **Dimension-6 (BSM)** term in potential **changes the relationships between** the fundamental Higgs **parameters**

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}$$

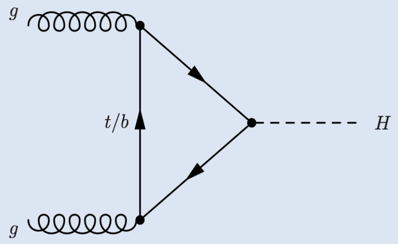
Measuring κ_λ to **~50% accuracy crucial goal**



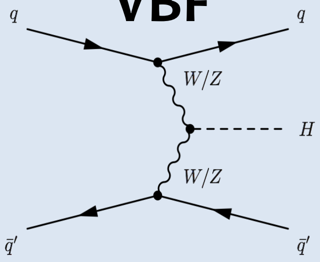
Phys. Rev. D 97, 075008 (2018)

Higgs Production @ LHC

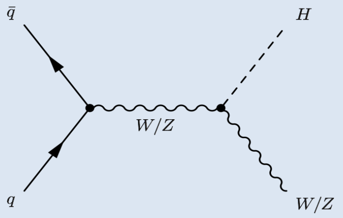
ggF

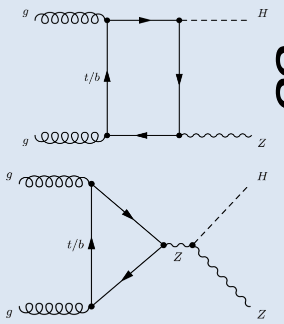


VBF



WH / ZH



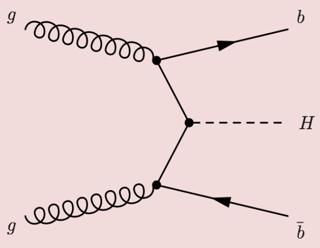


gg→ZH

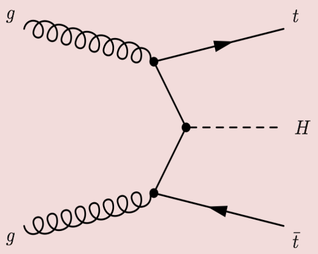
Decreasing cross-section

Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

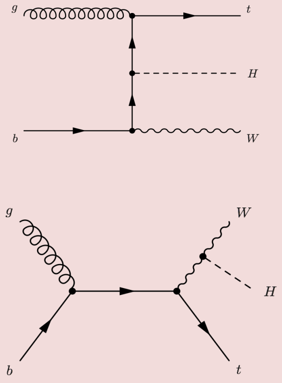
bbH



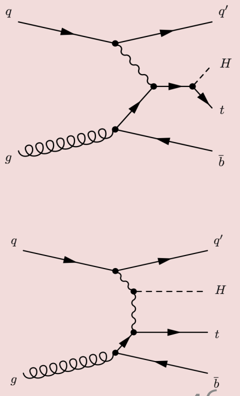
ttH



gb→tHW



qg→tHq



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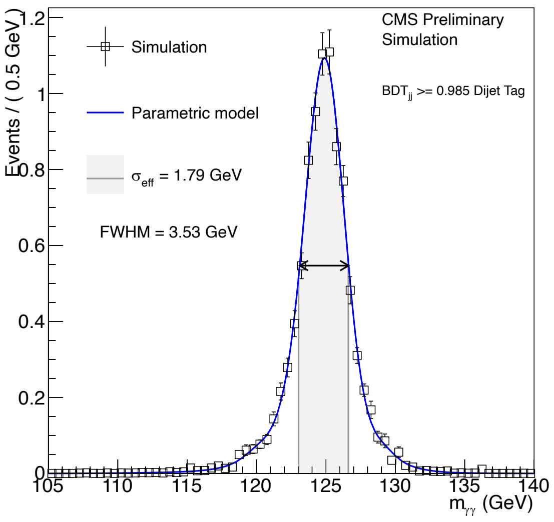
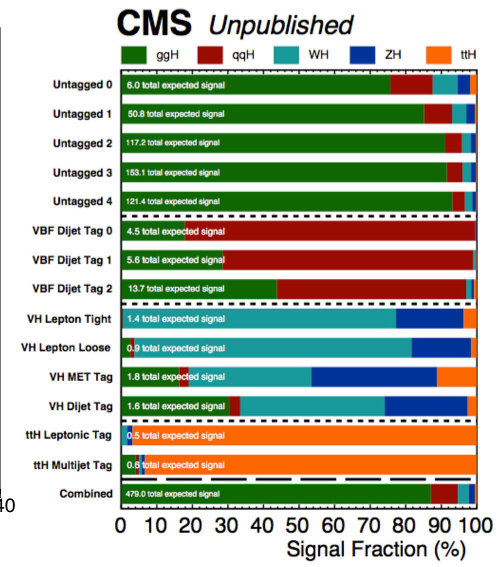
What do we actually measure?

Likelihood to interpret the combined datasets from across Higgs channels … .

$$L(D|\boldsymbol{\mu},\boldsymbol{\theta}) = \prod_{n} Prob\left(d_n | \sum_{i,f} \mu_i \mu^f \boxed{S^f_{i,n}(\boldsymbol{\theta})} + \sum_k B_k(\boldsymbol{\theta}) \right) \times Gauss(\tilde{\boldsymbol{\theta}}|\theta)$$



CMS H→γγ analysis



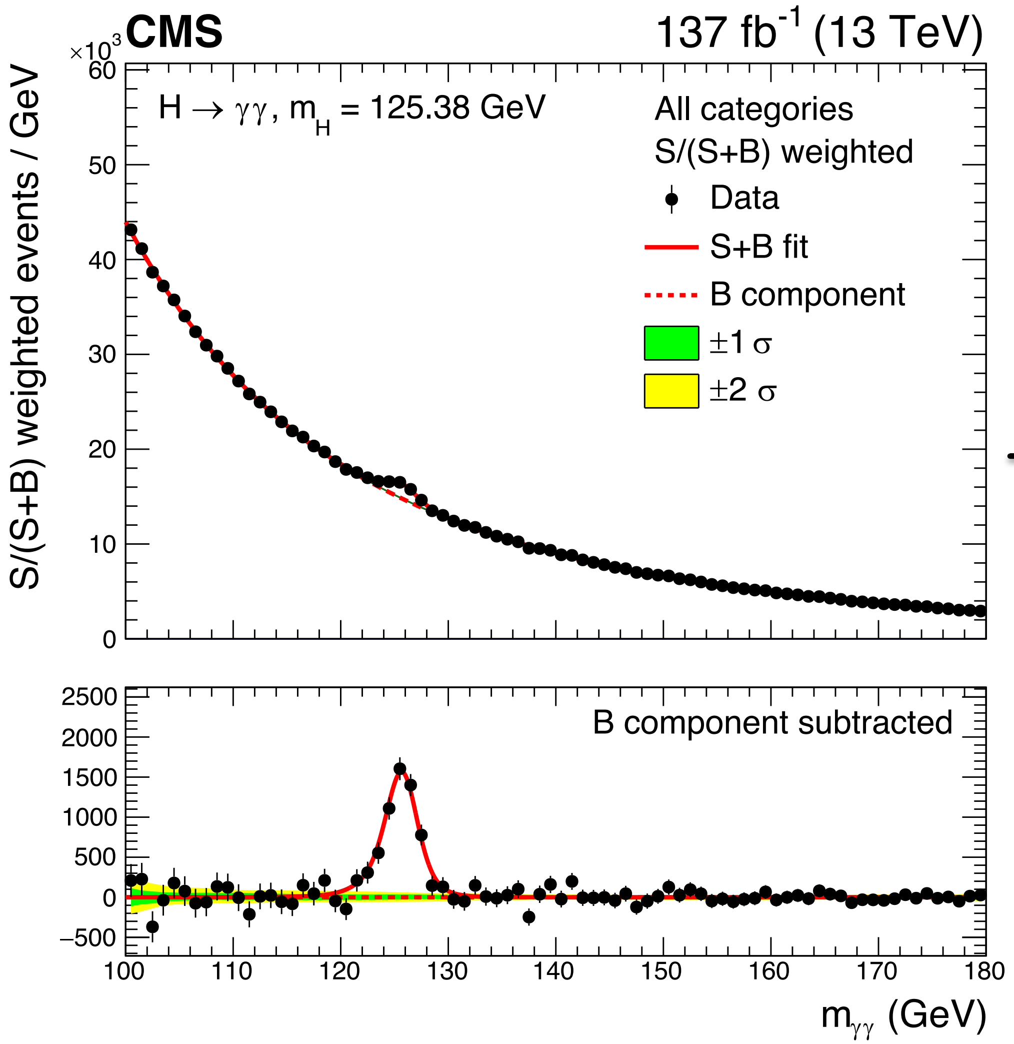
Signal model, accounts for ”**shape**” of signal processes

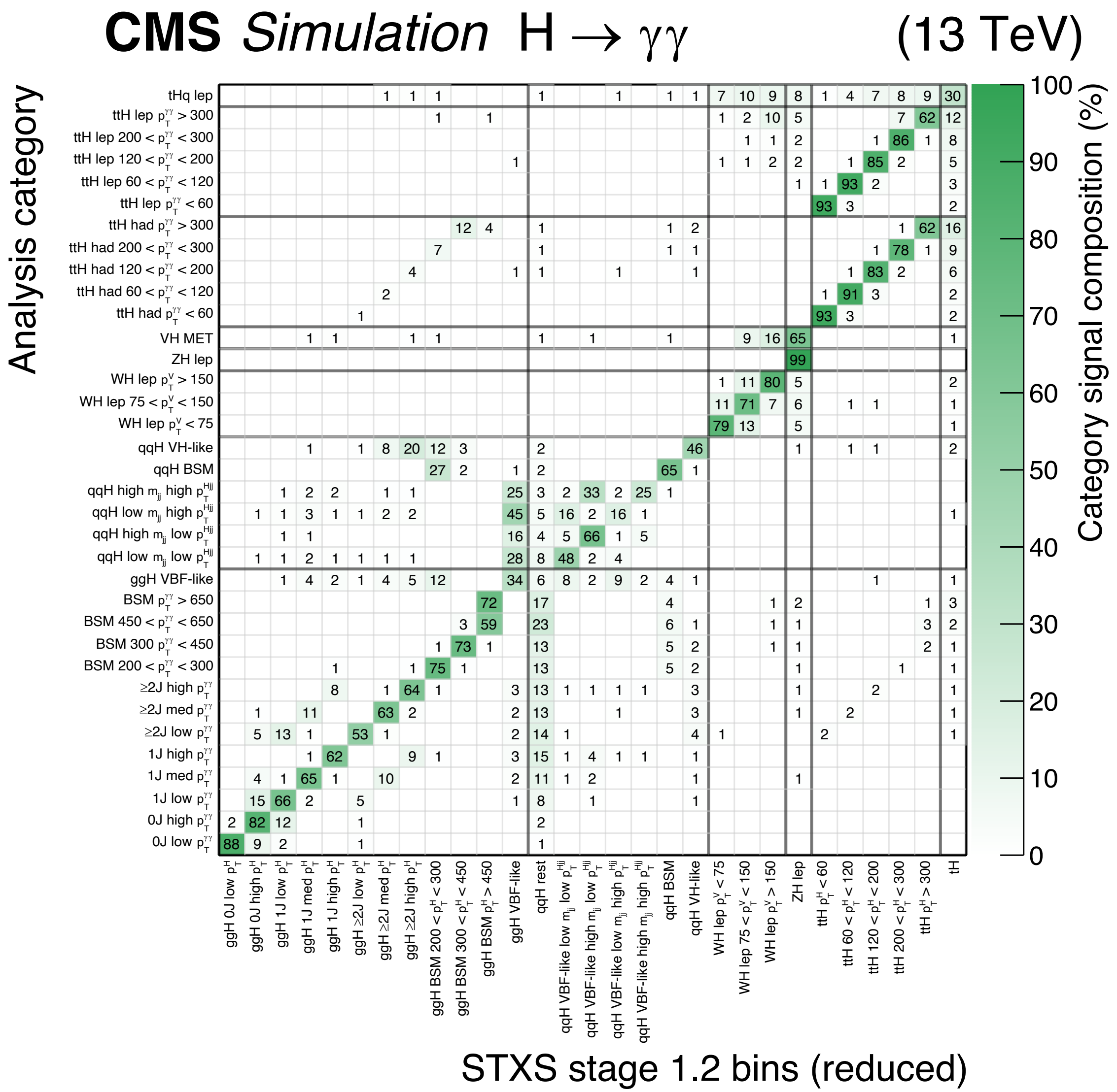
- Efficiency * acceptance
- Relative composition across signal regions (analysis bins, BDT output …)

$$\times \mathcal{L} \times \varepsilon \times A$$

Rely on SM Higgs Predictions to calculate in each channel (V-p_T, n-jets etc)

H→γγ signal compositions

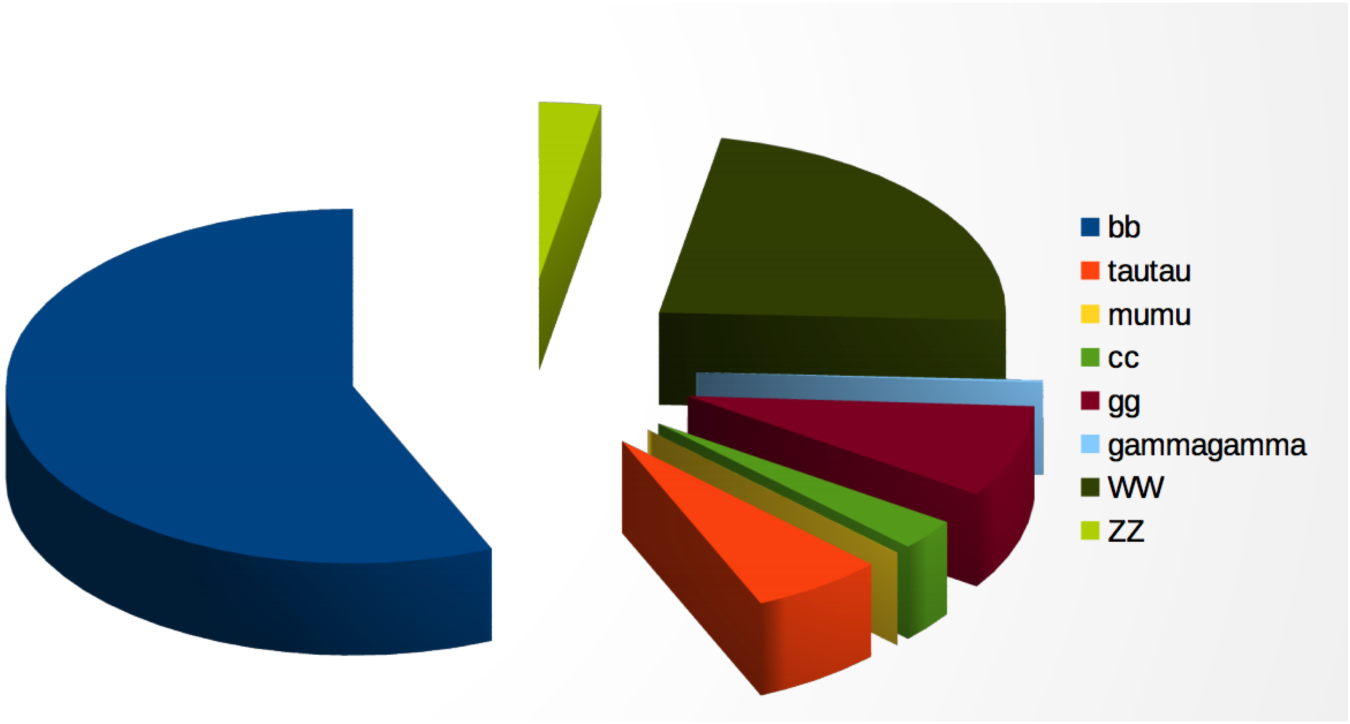




Higgs boson decay

If we know the mass, all of the Higgs boson couplings to SM particles (and hence **production x-sections** and **decay rates**) are defined …

Decay	BR (%)
$H \to bb$	58
$H \to WW$	21.6
$H \to \tau\tau$	6.3
$H \to cc$	2.9
$H \to ZZ$	2.7
$H \to \gamma\gamma$	0.23
$H \to Z\gamma$	0.115
$H \to \mu\mu$	0.022



Reporting on H→γγ in "Jim's office"

Limits

Nick Wardle
07 June 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » Nati

Higgs Reference Analysis

Nick Wardle
15 March 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Progress towards the final Analysis

Nick Wardle
10 May 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Photon Purity

Nick Wardle
05 April 2011 09:50
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg