Higgs boson properties measurement in the diphoton decay channel at LHC

Gouranga Kole

Postdoctoral Research Fellow
University of California San Diego, USA

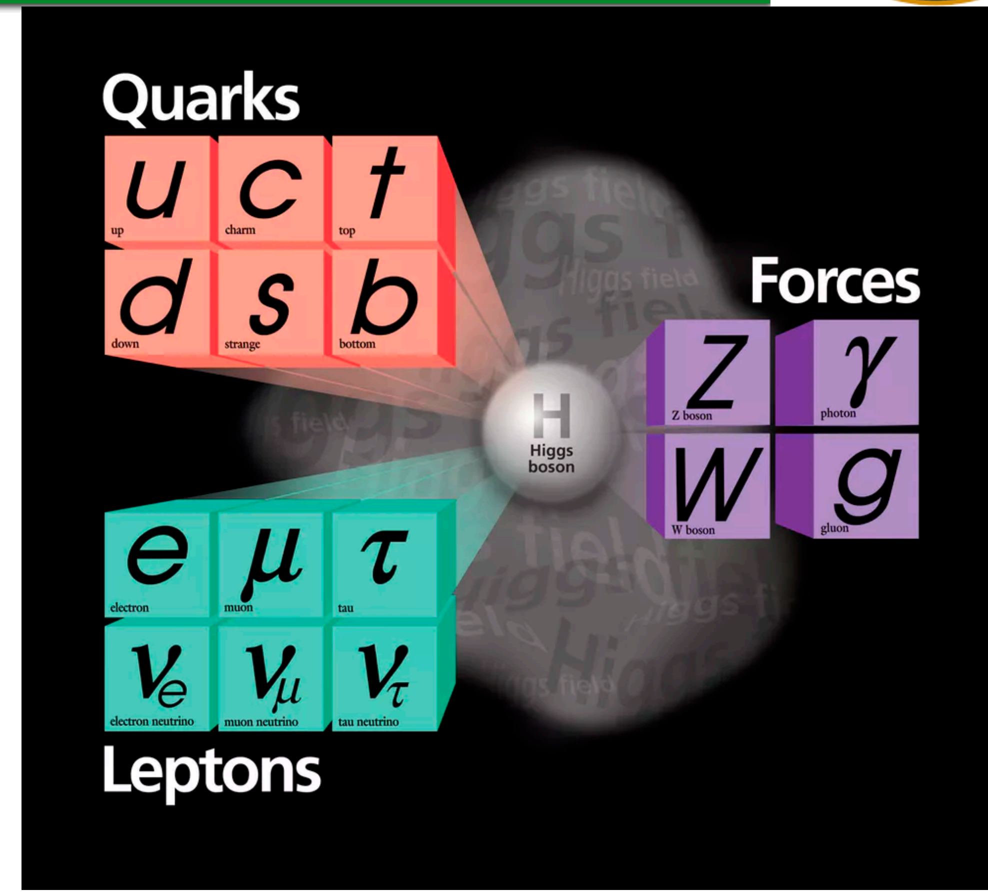
TIFR Mumbai
18th Feb, 2019

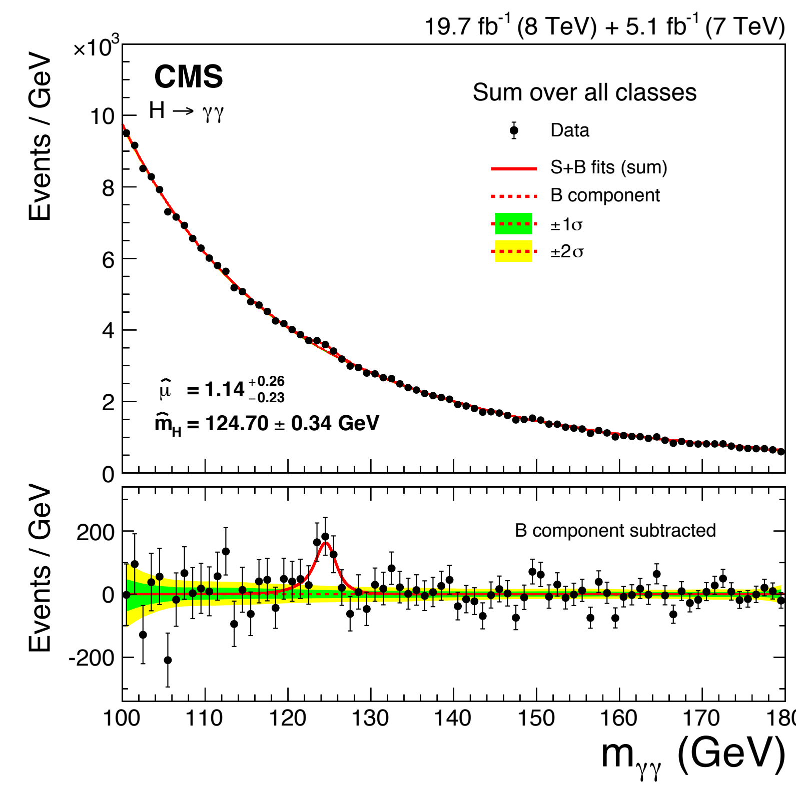
Outline

- ☑ Theoretical motivation
- ☑ Higgs boson signal and backgrounds
- ☑ The CMS detector and trigger system
- ☑ The object identification
- ☑ Analysis strategy
- ☑ Results

Motivation: Why Higgs boson?

- ☑ Standard Model of particle physics is the most successful theory
- ☑ Almost all the particles predicted by SM were discovered during the last century except one, the Higgs boson
- ☑ In 2012 ATLAS and CMS discovered a new scalar particle with mass ~125 GeV
- ☑ It seems to be compatible with the standard model (SM) Higgs boson
- ☑ Now the emphasis is on properties measurement and couplings to other particles





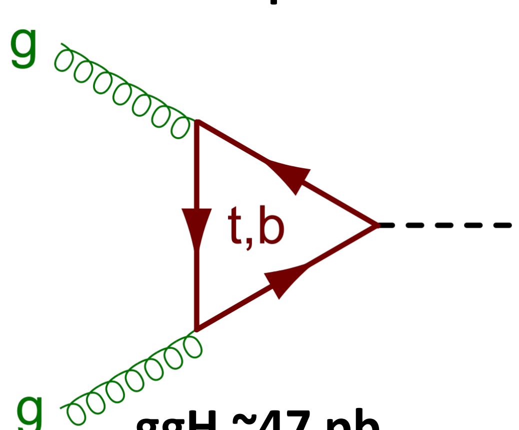
Ref

Eur.Phys.J. C74 (2014) no.10, 3076

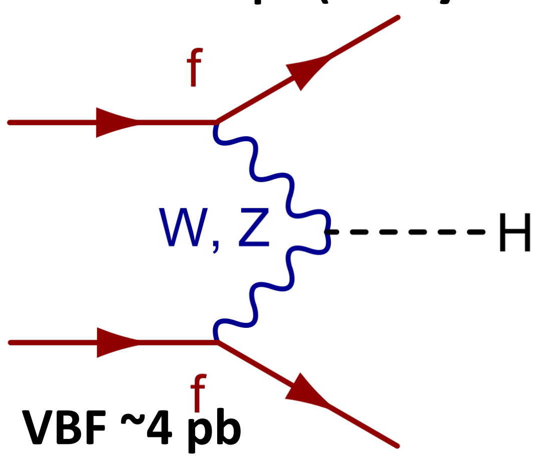
Higgs production mechanisms and decay channels

Higgs production mechanisms:

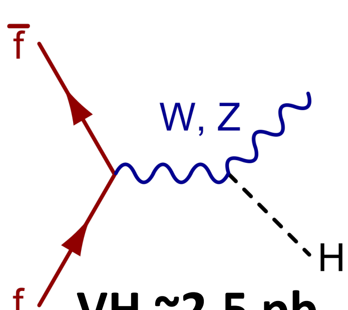
- ☑ gluon-gluon fusion **(ggH)**
- ☑ Vector boson fusion **(VBF)**
- ☑ Associate production with Vector boson **(VH)**
- ☑ Associate production with top **(ttH)**



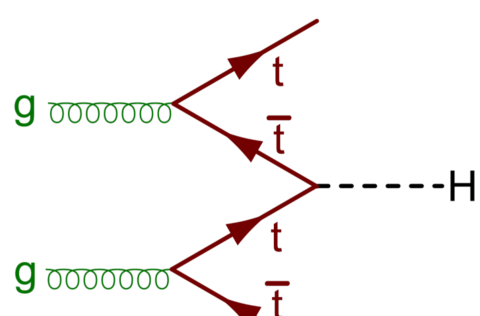
ggH ~47 pb



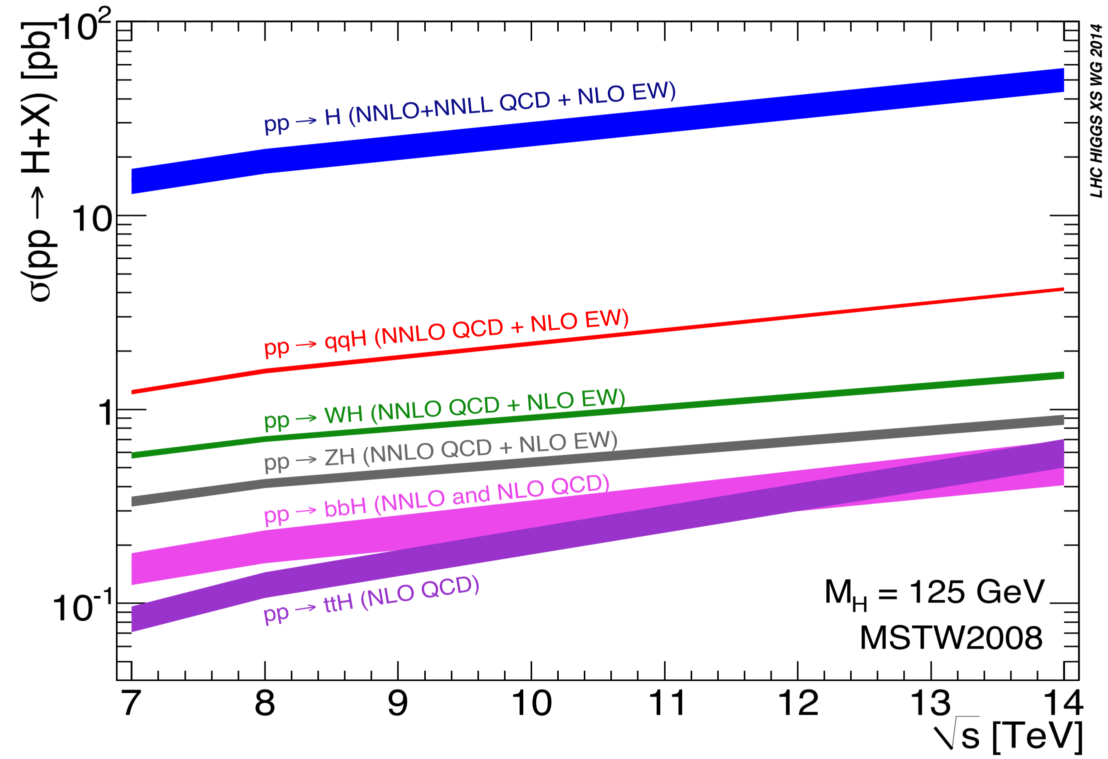
VBF ~4 pb

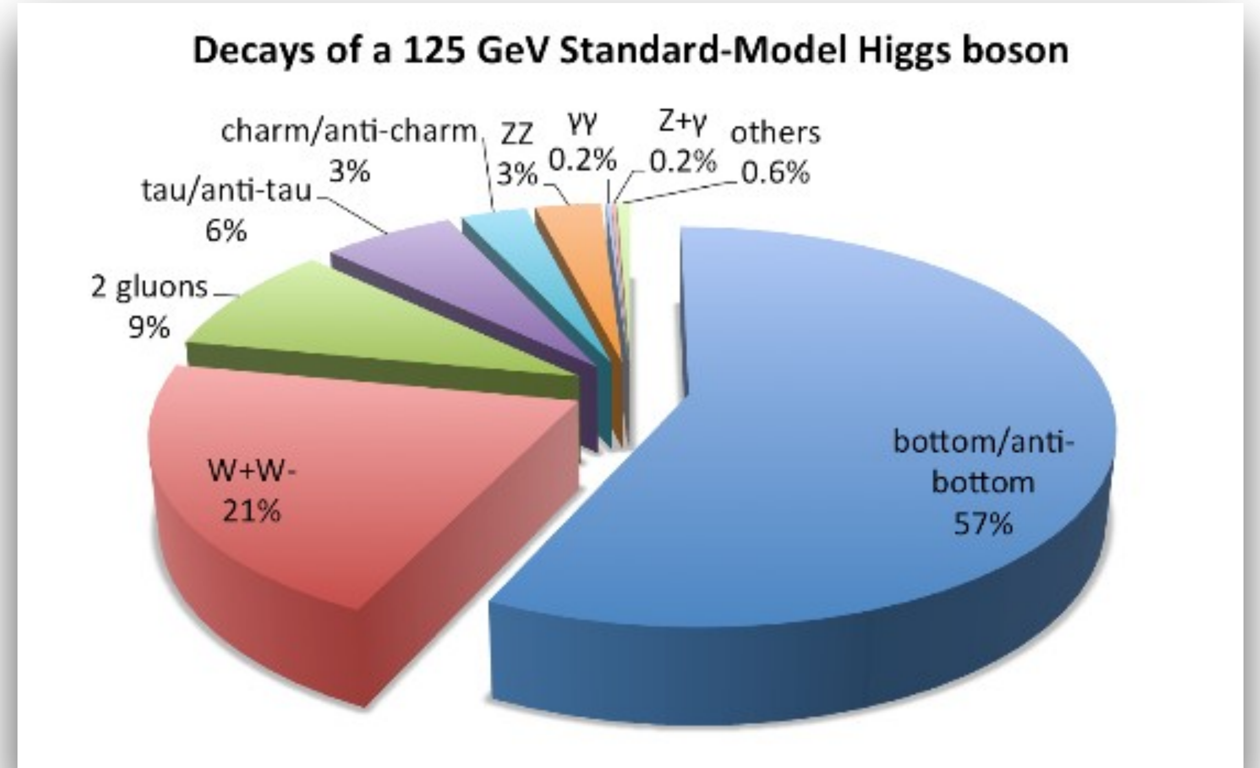


VH ~2.5 pb



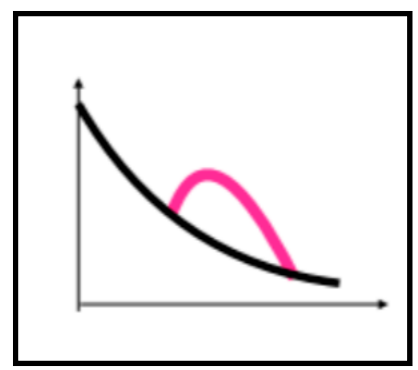
ttH ~0.56 pb

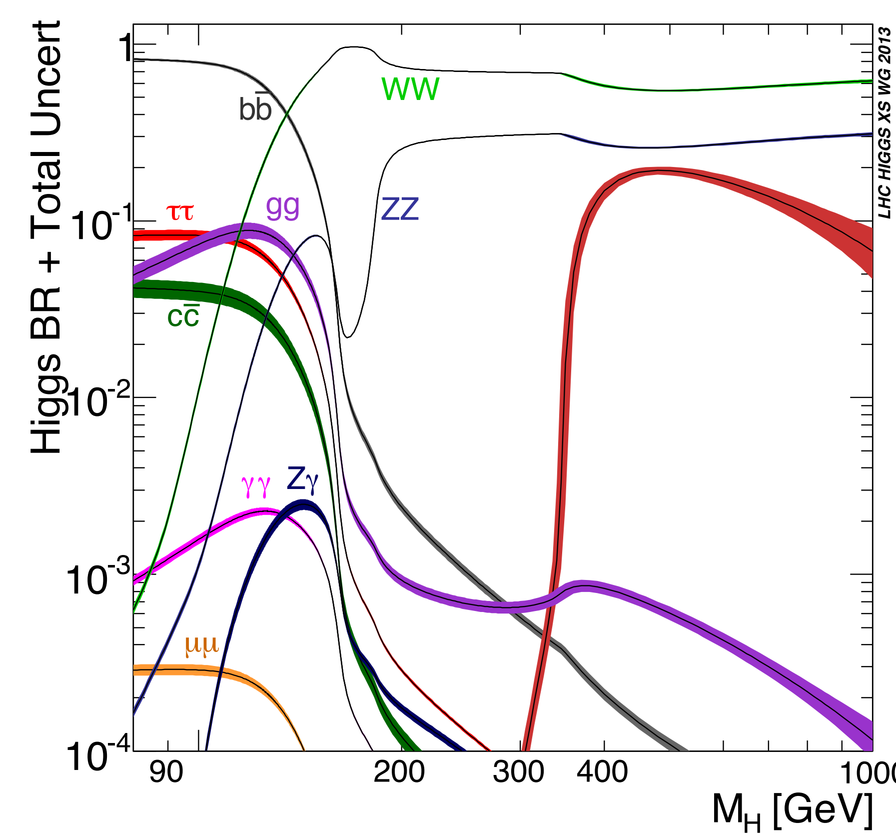




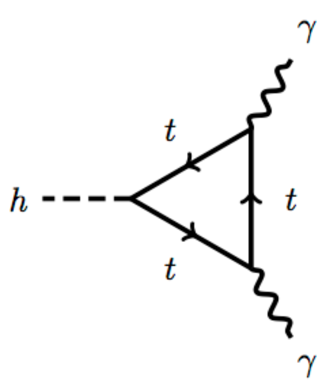
Why H → γγ decay?

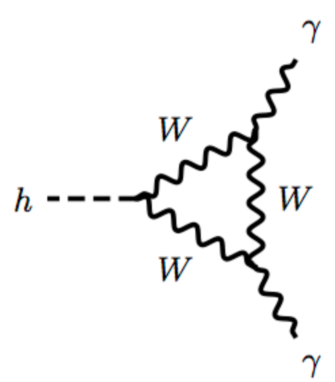
- Clean final state: **two highly energetic photons,** low branching fraction $\mathscr{B}(H \to \gamma\gamma) \approx 0.2\,\%$
- An invariant mass narrow peak can be reconstructed with high resolution over a falling background in mass distribution





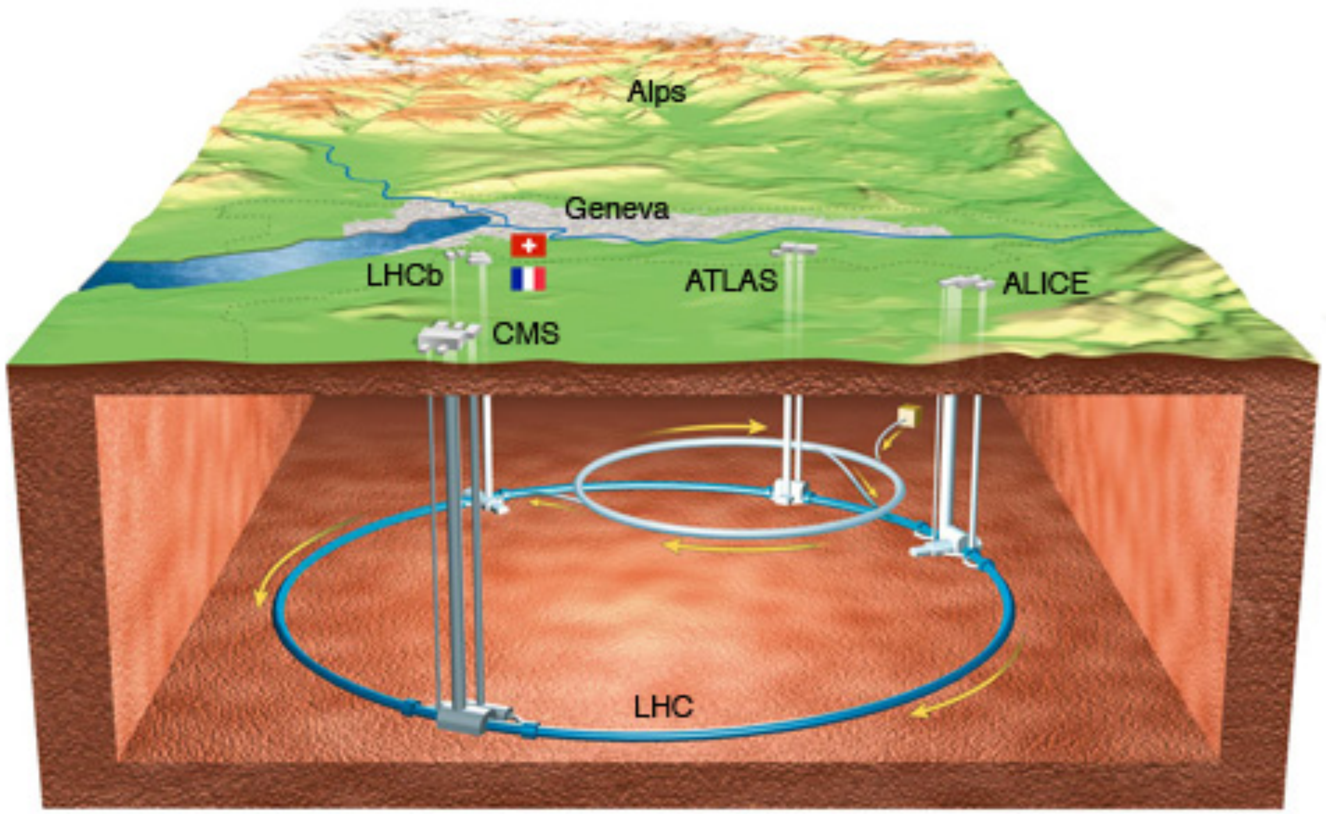
- Higgs to di-photon signal



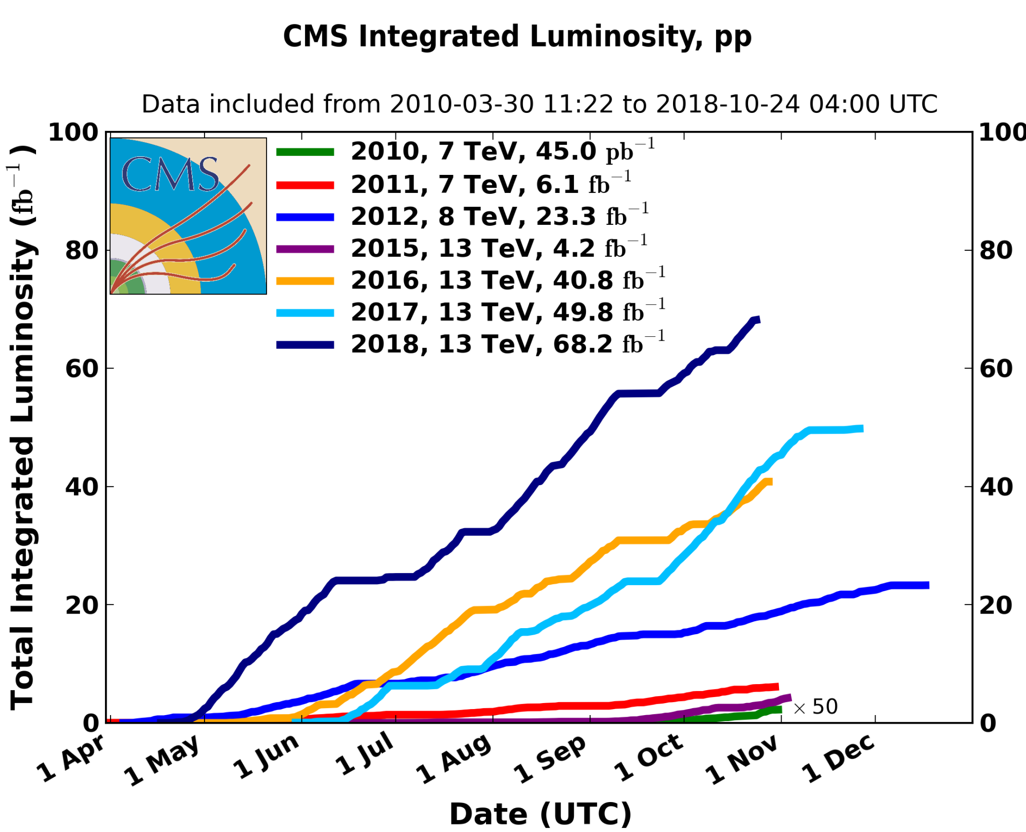


- Backgrounds:
  - Irreducible: γ + γ
  - Reducible: γ + jet, jet + jet

Large Hadron Collider

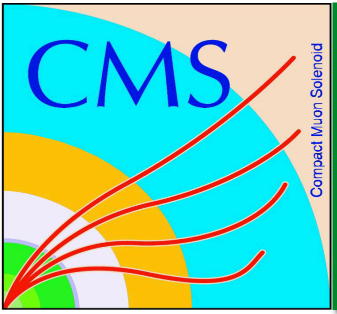


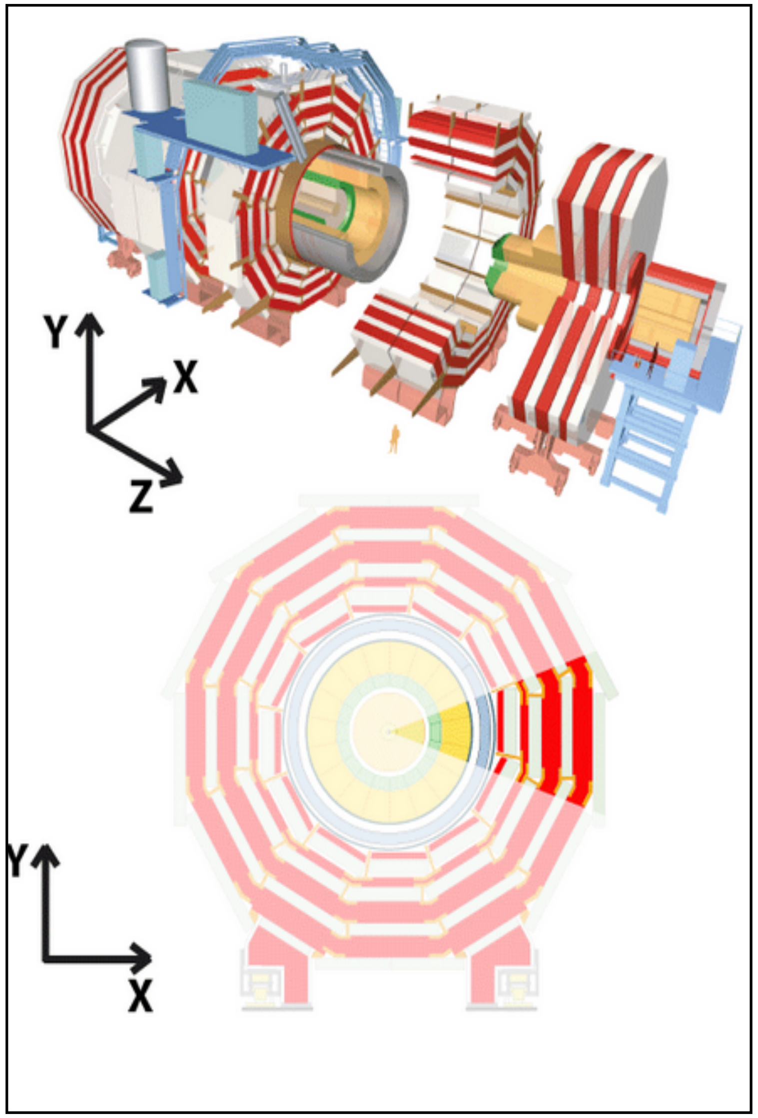
- LHC is the largest (27-km ring) and most expensive scientific machine
- The beams (p-p, p-Pb, Pb-Pb) travel in opposite directions in separate beam pipes at ultrahigh vacuum
- The beams are made to collide at four locations: ATLAS, ALICE, CMS and LHCb

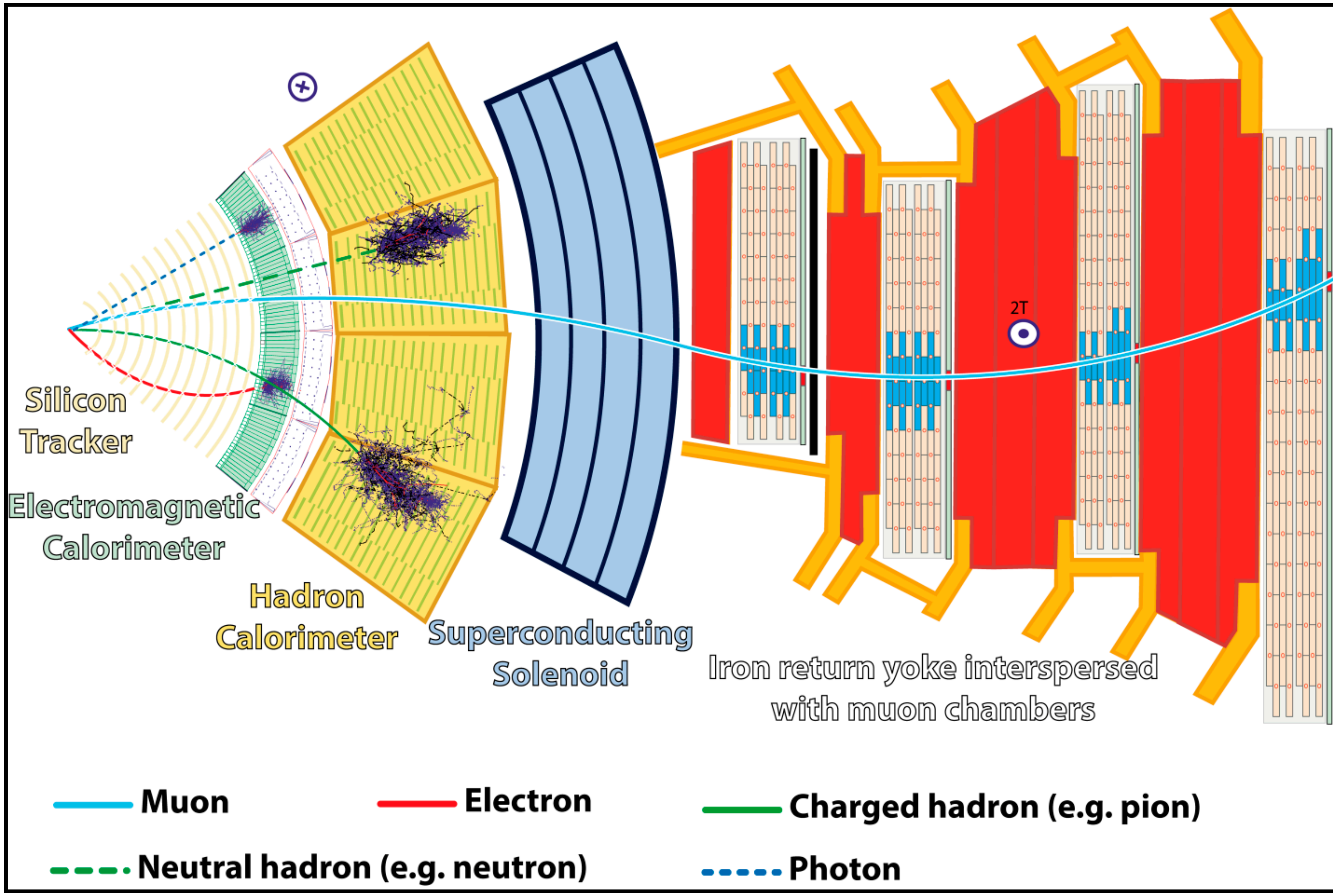


Results showed today used 2016 data

CMS Detector







Trigger System

Trigger system allows us to record only interesting events for further analysis

- For LHC designed luminosity of 10^{34} cm^{-2} s^{-1} with a bunch crossing space of 25 ns pp collision rate is **40 MHz**

- Only a fraction of all the events is important for CMS physics program

- CMS uses a two level trigger system for recording events with interesting physics with great efficiency

  - **Level1 trigger (L1):** Hardware level trigger
    - Reduces event rate to ~ **100 kHz**

  - **High Level Trigger (HLT):** Uses partially reconstructed object information
    - Reduces event rate to **~1 kHz**

Object Identification

- Objects are reconstructed using information from various CMS sub-detectors with the particle flow (PF) algorithm *JINST 12 (2017) no.10, P10003*

- Muons are reconstructed by combining information from the tracker and muon detector

- Electrons are identified by matching energy deposits in the electro-magnetic calorimeter with tracks in the tracker

- Jets are reconstructed based on PF candidates using the anti-k_T algorithm with a radius parameter of 0.5 ***JHEP 0804 (2008) 063***

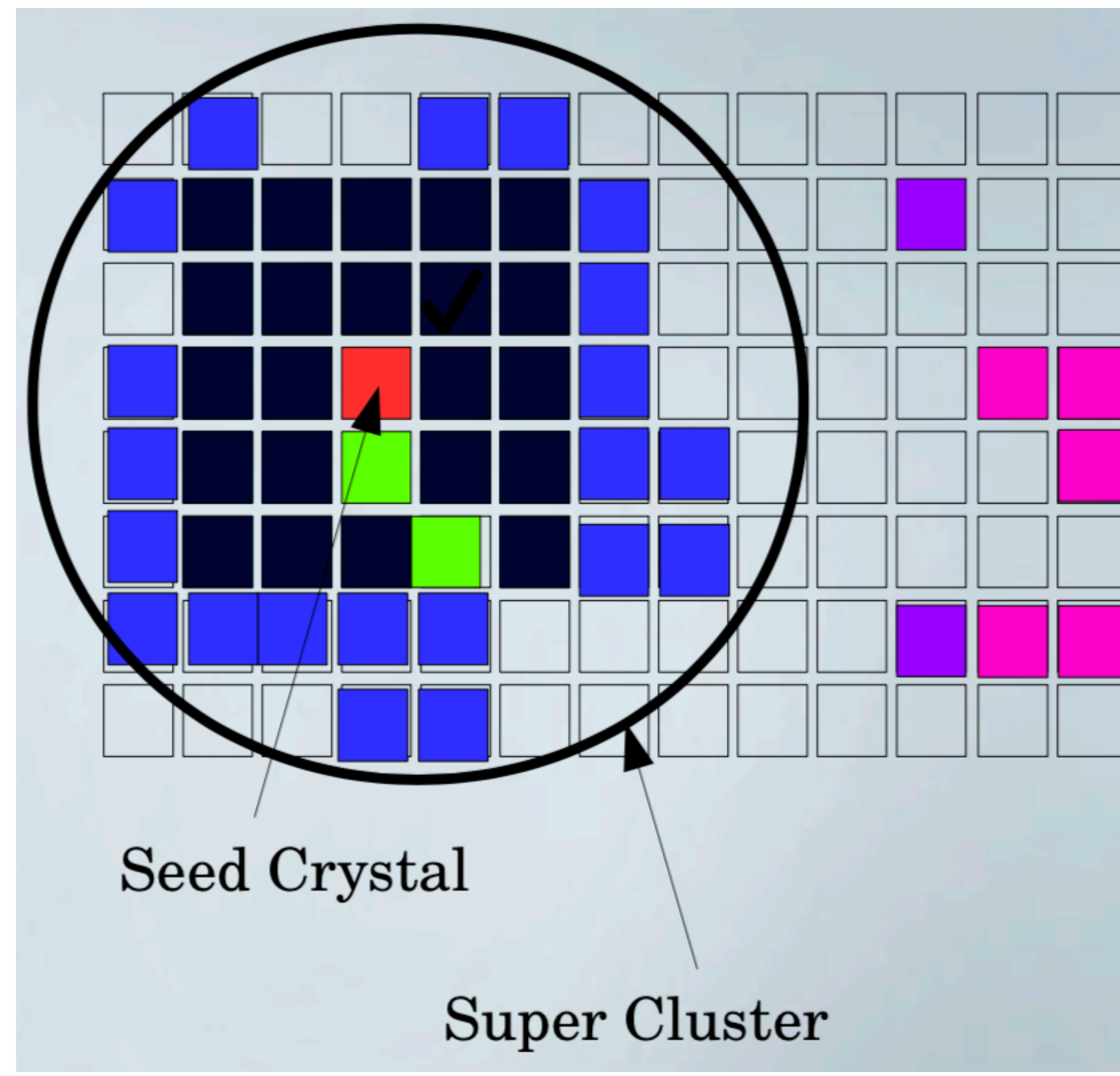
- Missing transverse momentum (p^{miss}_T) is calculated as the negative vector sum of the transverse momenta of all PF objects

Photon Reconstruction

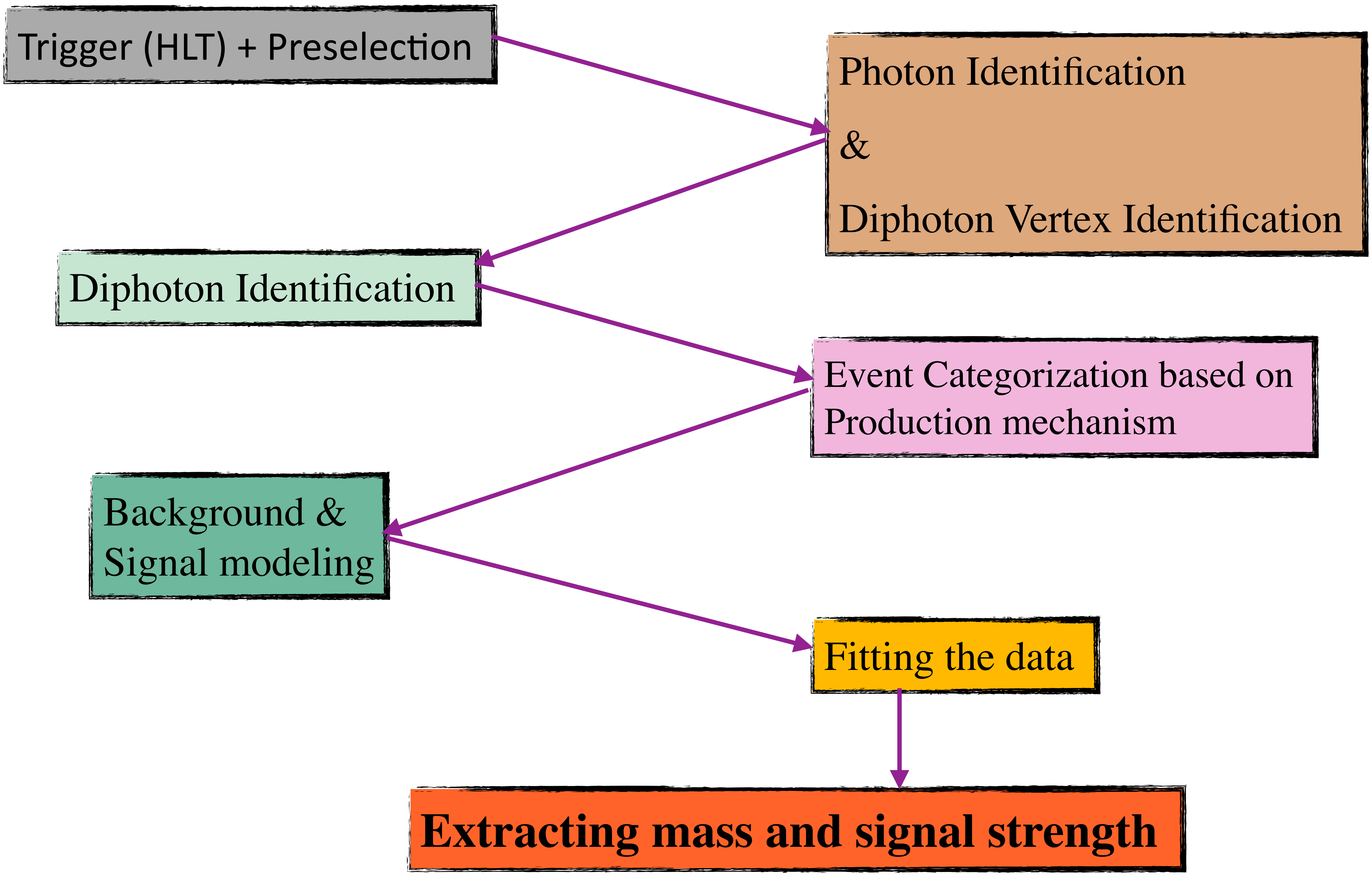
Shower in Electromagnetic Calorimeter → No associated charged particle track → The shower correspond to a photon object

Photons are reconstructed in three steps

- Local maxima in energy are found among the ECAL crystals above a threshold
- A cluster topology is built around the seeded crystal
- Adding crystals which satisfy:
  - -> At least one immediate neighbour clustered crystal
  - -> Have energy above a threshold
- The aggregated clusters -> *"Super Cluster"*
- Photon energy = sum of calibrated energy for the super cluster in the ECAL



Analysis flow



Trigger and Preselection

HLT for this analysis:

- ☑ Two photon candidates with transverse momentum (p_T) > 30 and 18 GeV
- ☑ Other selection applied on:
  - Transverse energy of the photons
  - Diphoton invariant mass
  - Shower shape and isolation variables of the photons
  - Hadronic energy over electromagnetic energy
  - Electron veto

ECAL Coverage	EB ($\|\eta\| < 1.4442$), EE ($1.566 < \|\eta\| < 2.5$)
Transverse momentum (p_T)	Lead (Sublead) photon > 40 (30) GeV
Invariant mass of diphoton pair ($m_{\gamma\gamma}$)	> 90 GeV

Data and MC simulations

Data: 35.9 fb^{-1} of 13 TeV data

Signal:
gluon gluon fusion (ggH), vector boson fusion (VBF),
W/Z associated production (WH/ZH), top quark fusion (ttH)

Backgrounds:
Diphotons , Gamma+ jets, QCD and DY->ll+jets

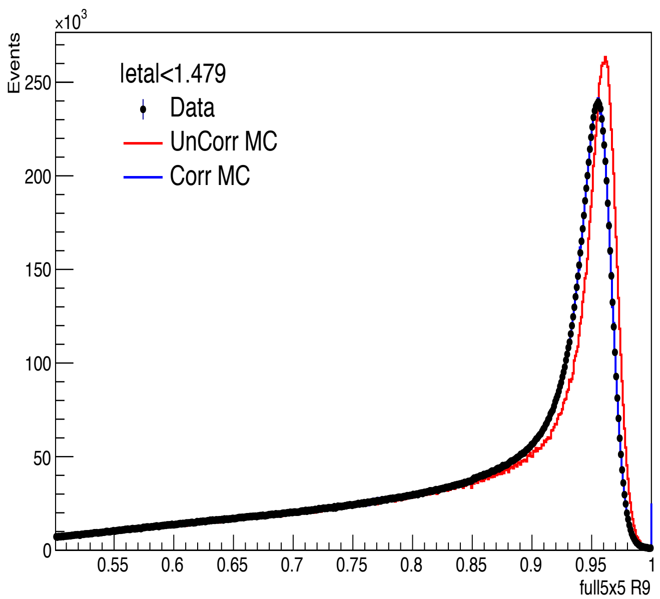
$$R9 = \frac{\text{E (3x3 crystals)}}{\text{E (SuperCluster)}}$$

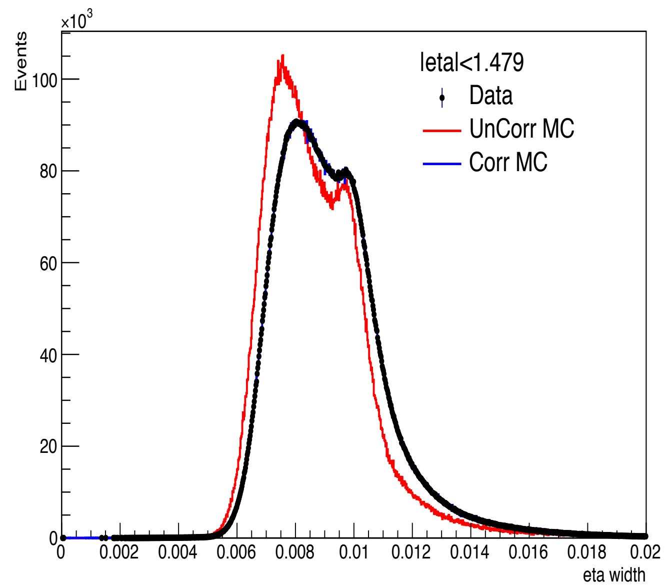
Preselection

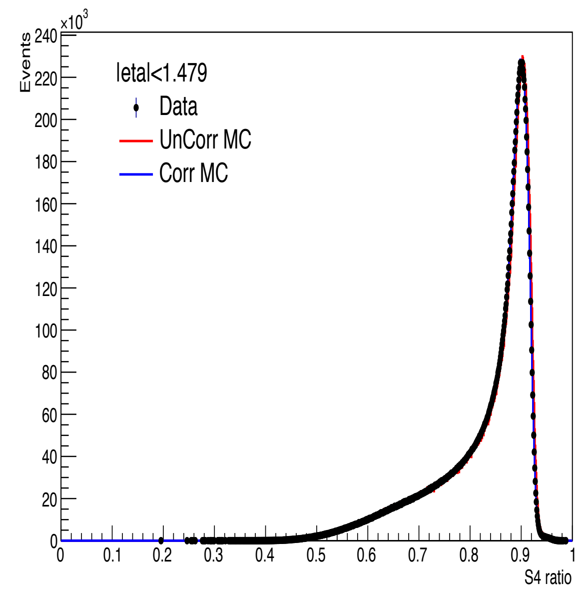
	R_9	H/E	$\sigma_{\eta\eta}$	$\mathcal{I}_{\text{ph}}$ (GeV)	$\mathcal{I}_{\text{tk}}$ (GeV)
Barrel	[0.5, 0.85]	<0.08	<0.015	<4.0	<6.0
	>0.85	<0.08	—	—	—
Endcaps	[0.8, 0.90]	<0.08	<0.035	<4.0	<6.0
	>0.90	<0.08	—	—	—

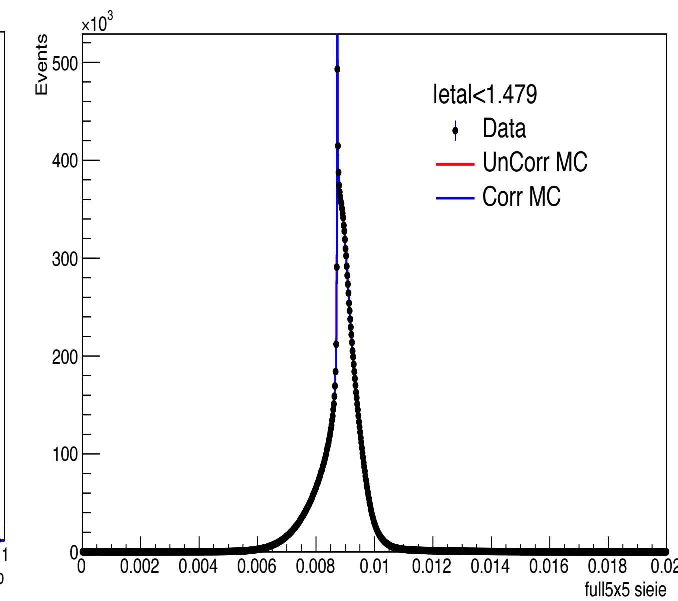
Showershape Correction

Four important shower shape variables in EB(top) and EE(bottom)

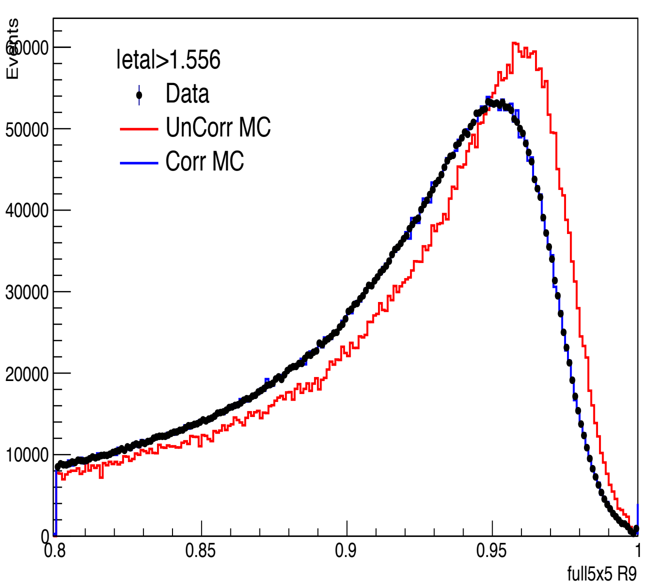


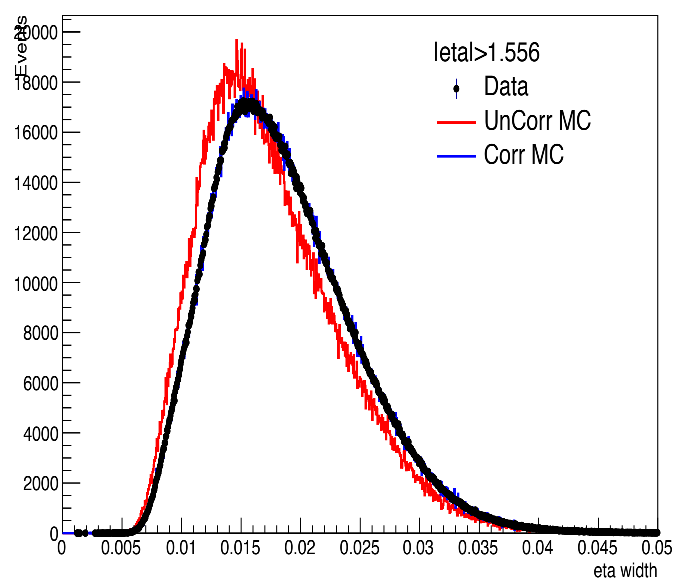


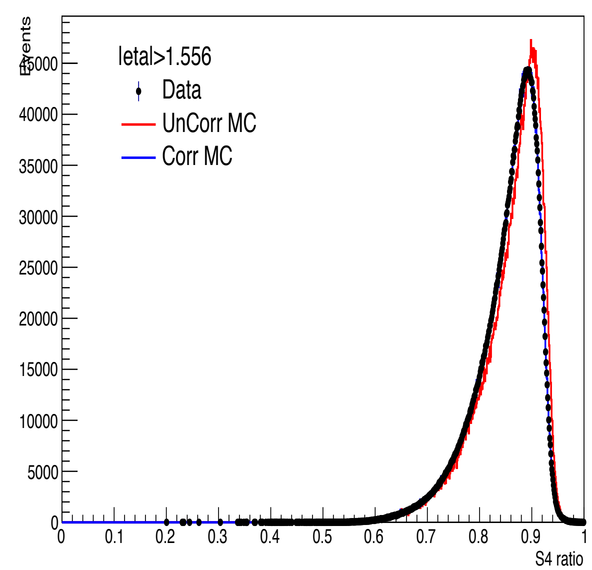


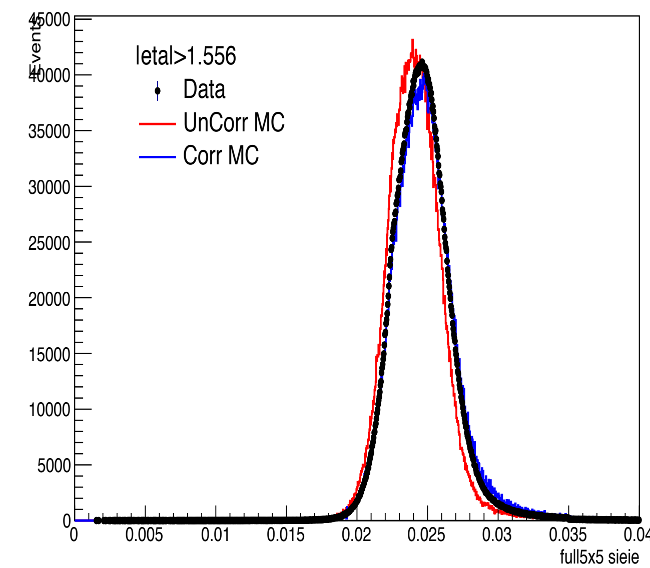


R9 **Eta width** **S4 ratio** **sieie**



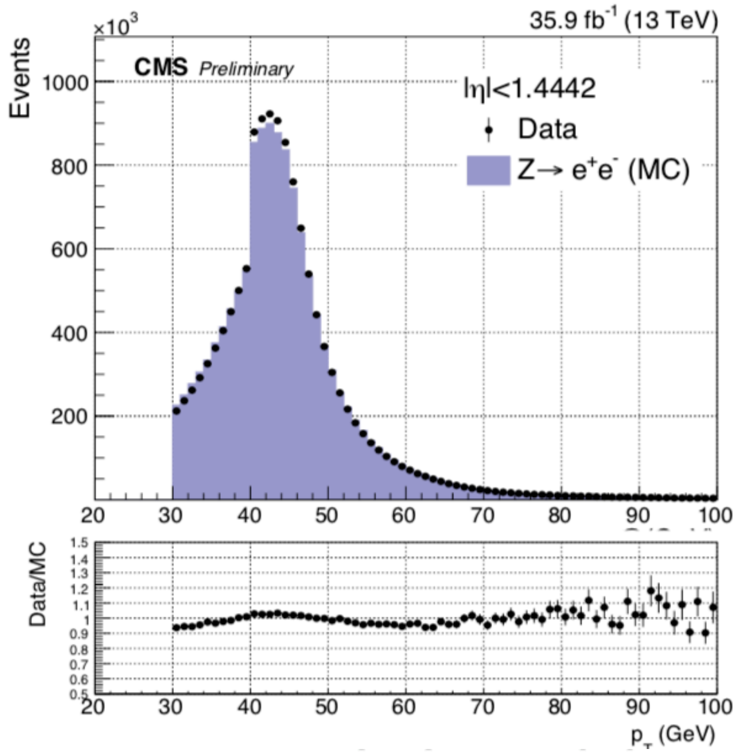


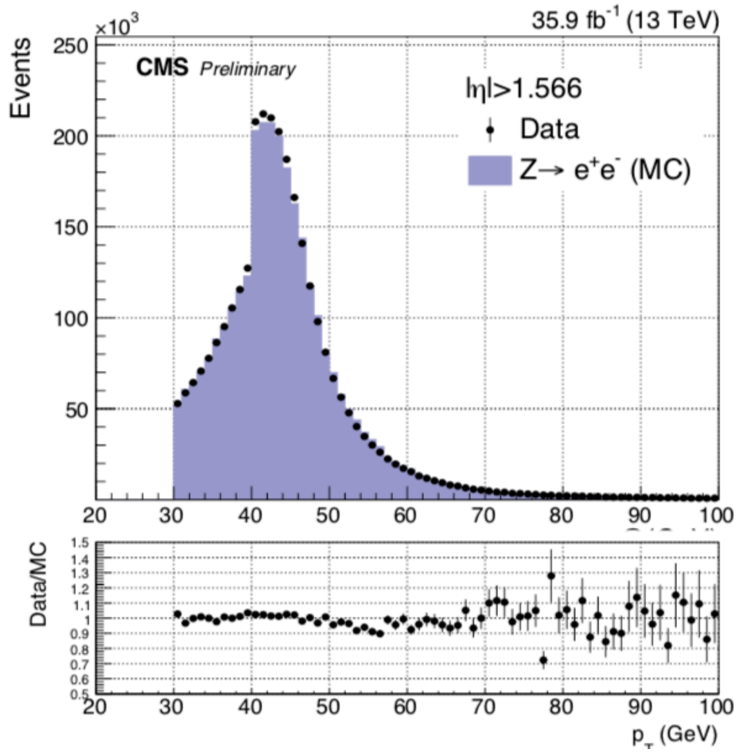




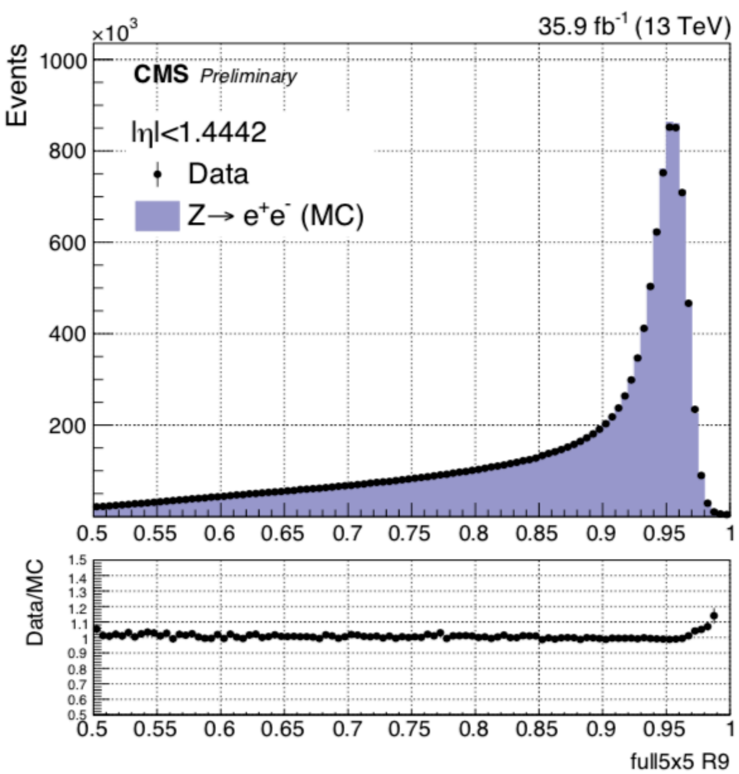
Preselection Validation - I

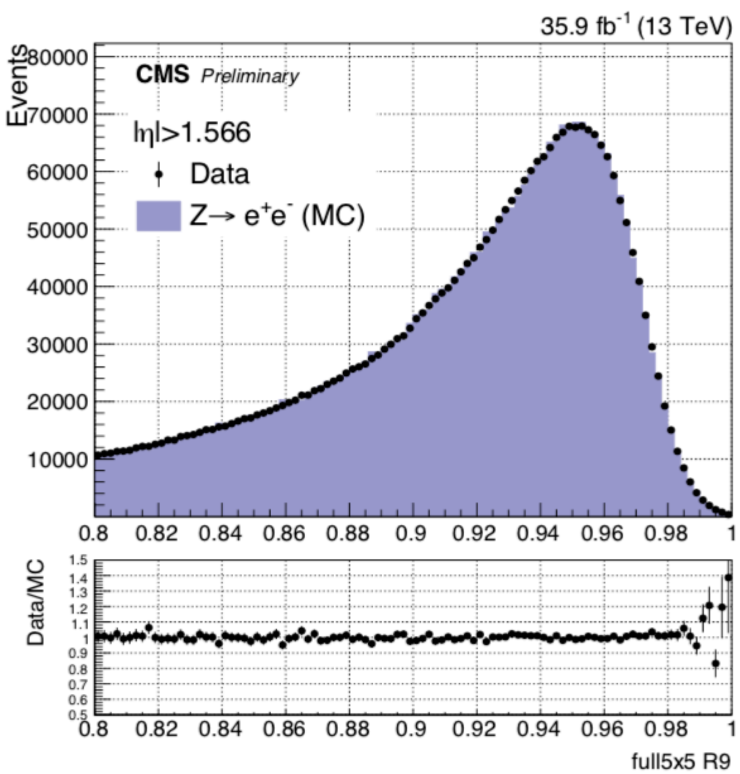
Electron pT





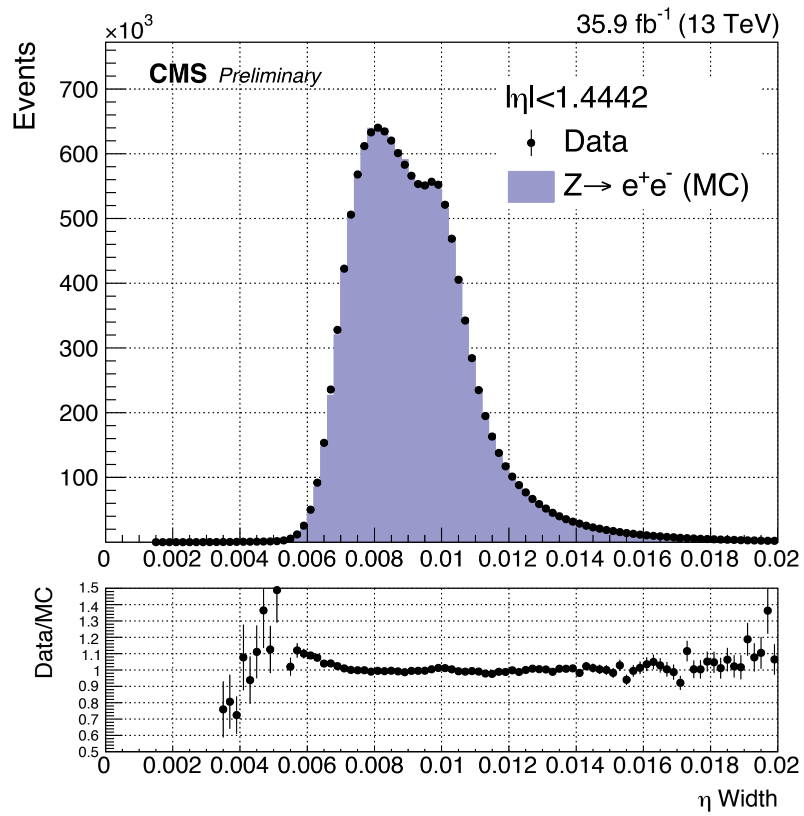
Electron R9

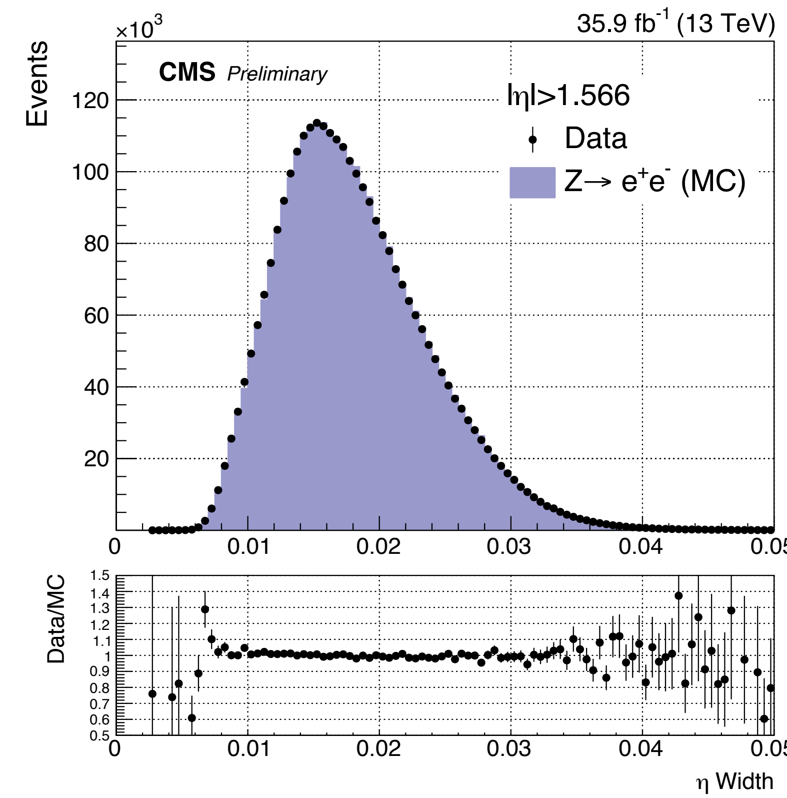




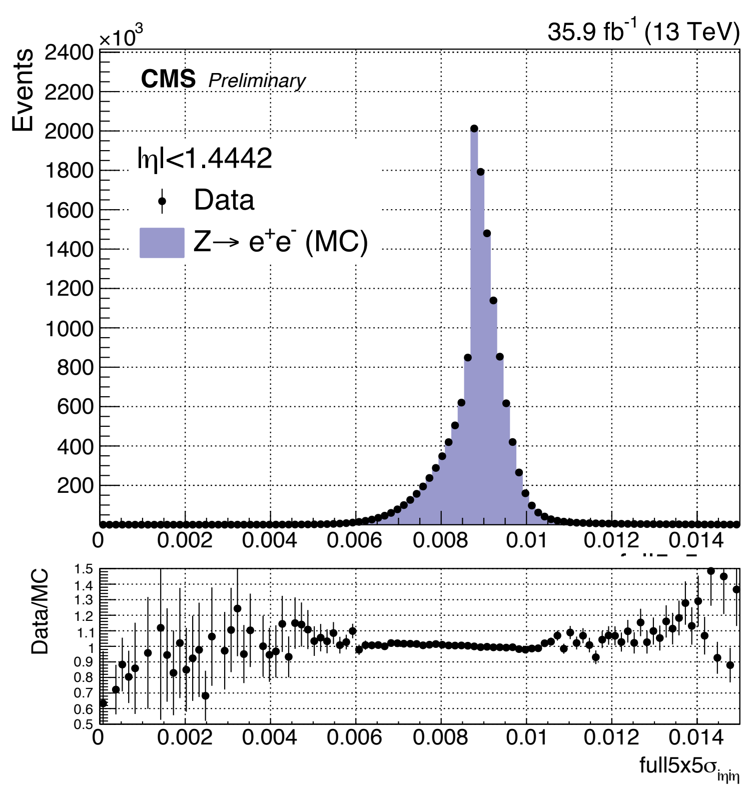
Preselection Validation - II

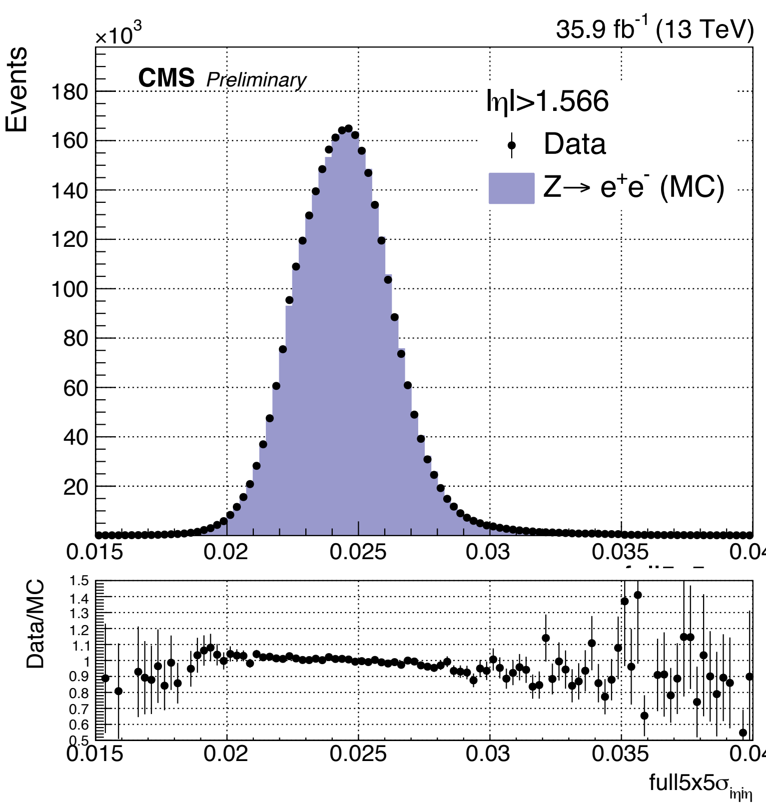
Electron etawidth





Electron sigma ieie

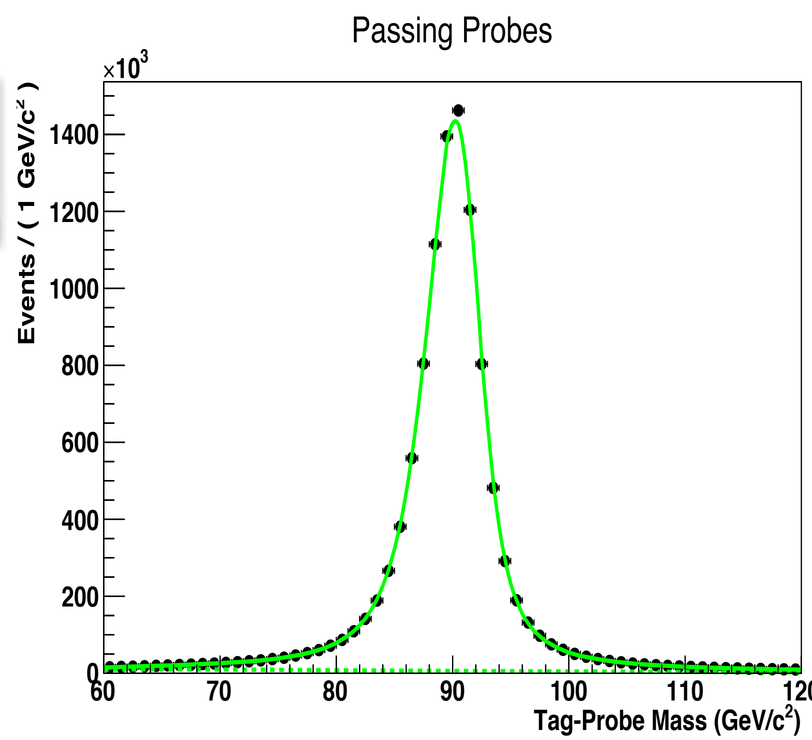


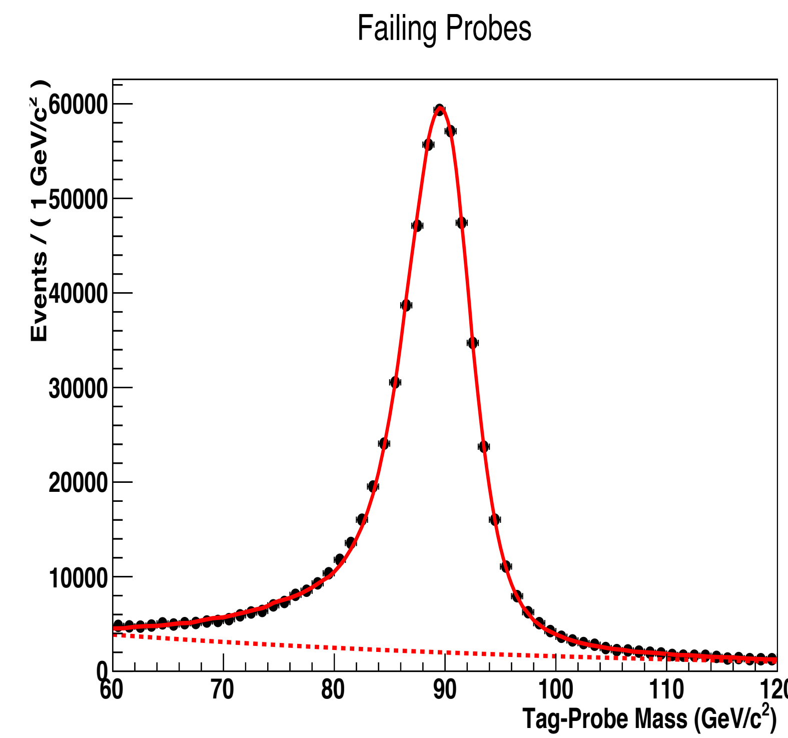


Preselection Scale Factor

$$SF = \frac{(No - of - passing - probe)}{(No - of - passing + failing - probe)}$$

- Scale factors are measured using Z -> ee events by "*Tag n Probe*" method
- SF measured in four categories (EB, high R9), (EB, low R9), (EE, high R9) and (EE, low R9)





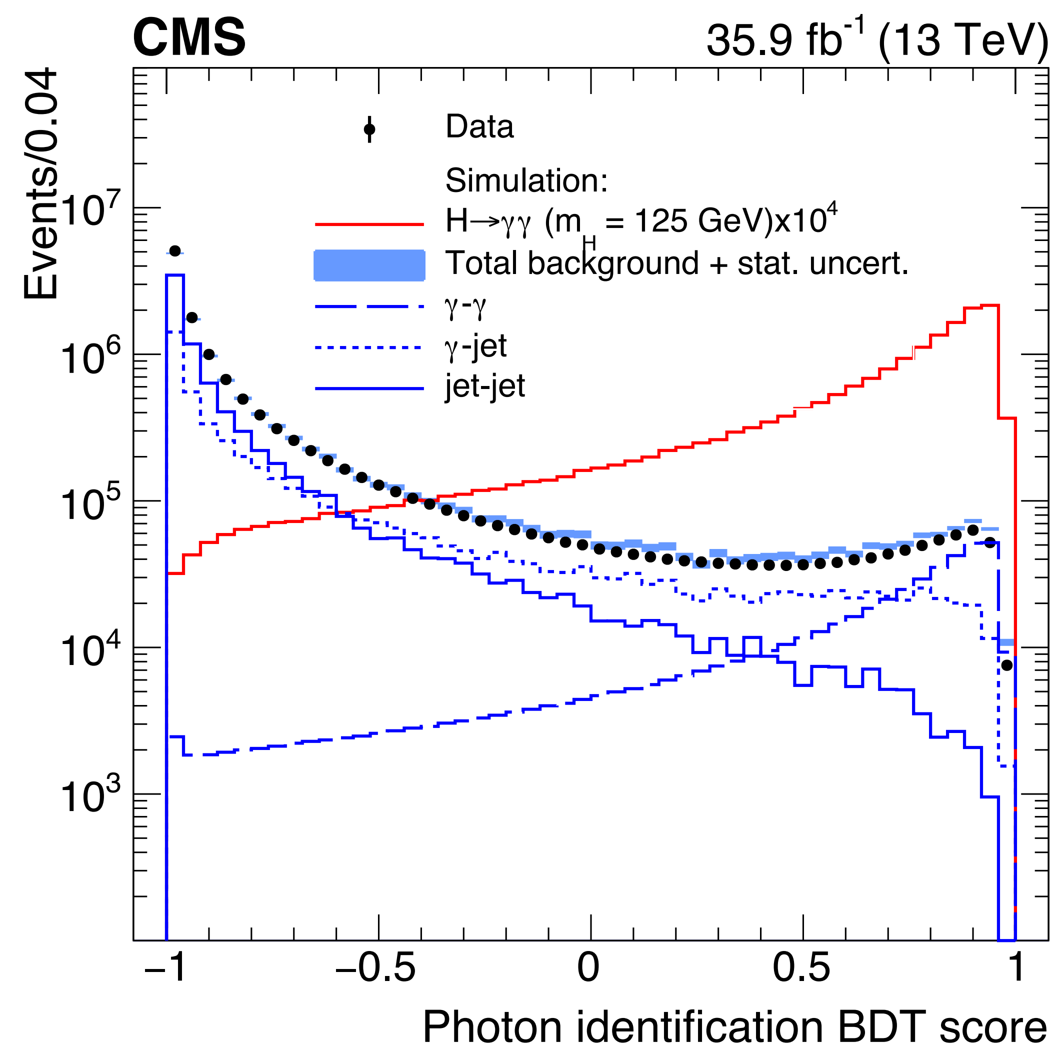
(EB, high R9)

	Data		Simulation		Ratio		
	Eff.	Stat	Eff.	Stat.	Scale	Stat. Unc.	Syst. Unc
Barrel; R_9 >0.85	0.9488	0.0001	0.9499	0.0001	0.9988	0.0001	0.0009
Barrel; R_9 <0.85	0.8471	0.0001	0.8423	0.0002	1.0057	0.0002	0.0010
Endcap; R_9 >0.90	0.9207	0.0004	0.9256	0.0002	0.9947	0.0004	0.0051
Endcap; R_9 <0.90	0.5309	0.0001	0.5622	0.0003	0.9443	0.0005	0.0071

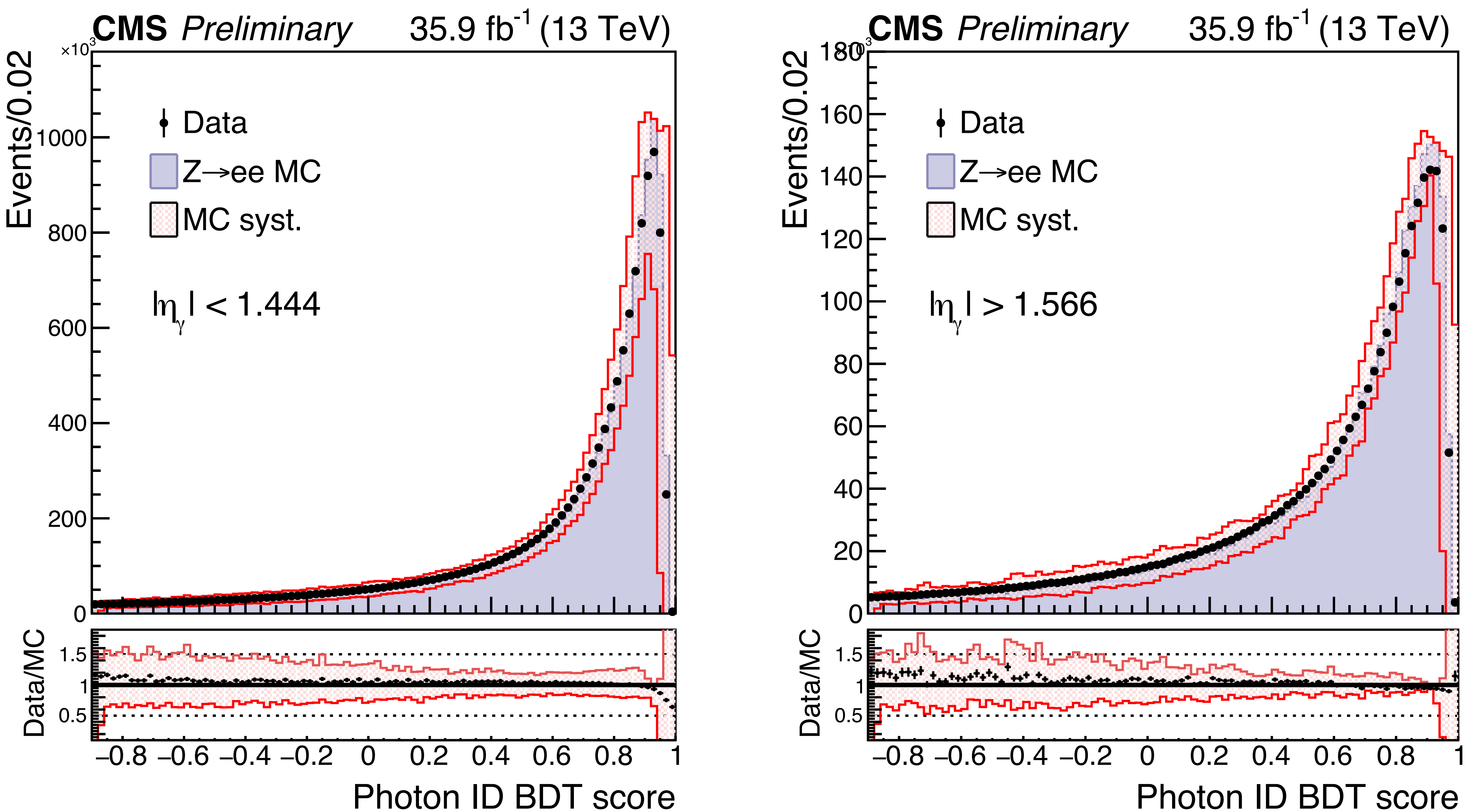
Photon Identification

Two different kind of background components for this analysis considered

- **Irreducible**: Diphoton production
- **Reducible**: Jets reconstructed as photons
  - Both photon + jet & jet + jet events may mis-identified a H -> γγ event
  - Proper identification of photons is crucial
  - To identify photons from jets, a multivariate discriminator is used
- **Photon ID BDT**: Input Variables
  - Shower shape variables
  - Isolation variables
  - Super cluster variables
  - Median energy density per unit area of ECAL per event



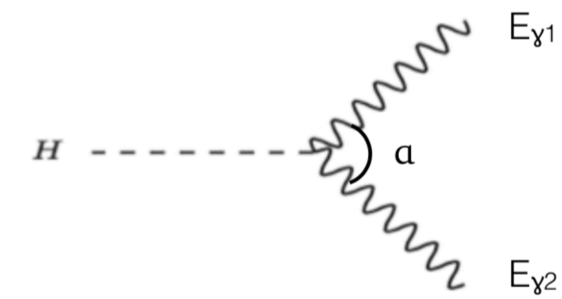
Photon ID Validation



Photon identification BDT score for Z→e^+e^- events in data and simulation

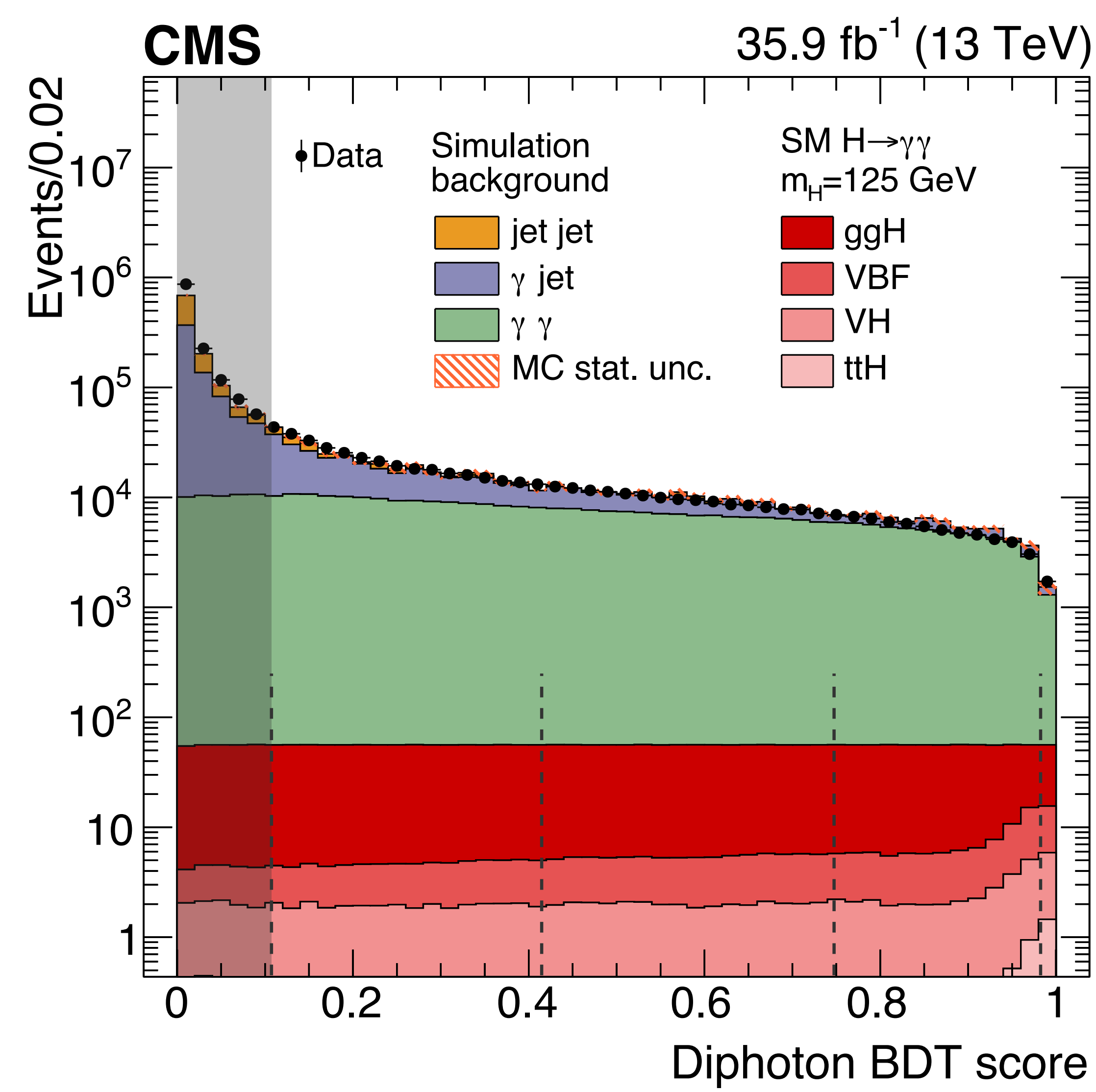
Diphoton Selection

- Vertex assignment is important for $m_{\gamma\gamma}$ resolution $|z_{choosen}-z_{true}| < 1$ cm => angular contribution negligible w.r.t. energy resolution
- **Vertex ID uses Multivariate approach (BDT):** exploits tracks recoiling from $m_{\gamma\gamma}$ system and conversion tracks. Estimate of vertex probability extracted for use in diphoton classification.



$$m_H = m_{\gamma\gamma} = \sqrt{2E_{\gamma1}E_{\gamma2}(1-\cos\alpha)}$$

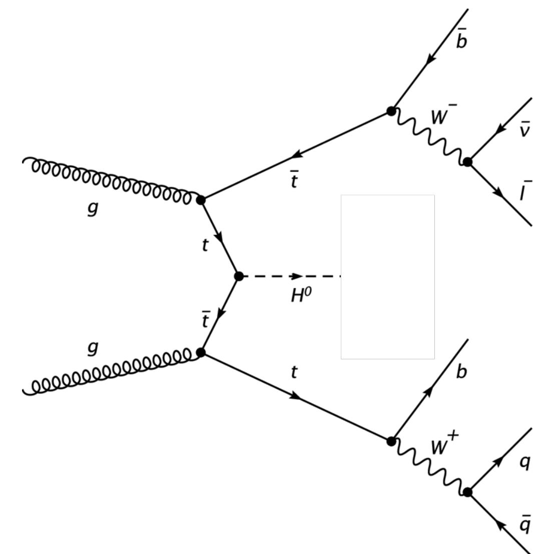
- Used a Boosted Decision tree (BDT) classifier to identify a signal like diphoton pair
- BDT input variables:
  - Kinematic variables of the diphotons
  - Multivariate scores for each photons
  - Diphoton mass resolution



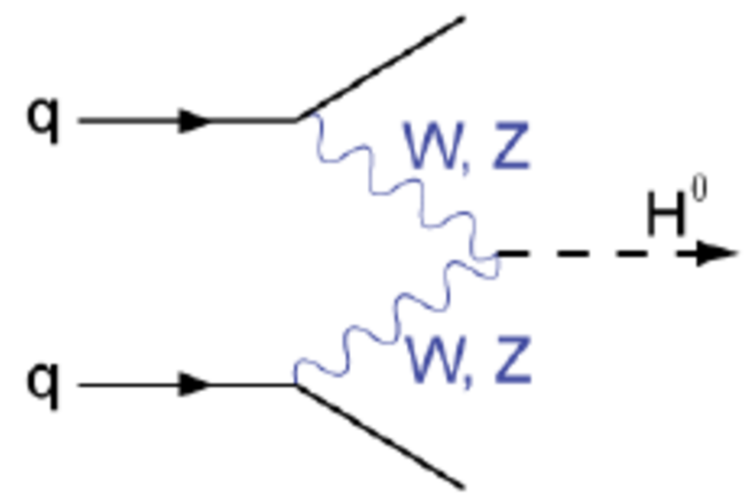
Event categorization-I

Selection for different tags

- **ttH Leptonic:**
  - At least one lepton
  - At least 2 jets (1 b tagged jet)

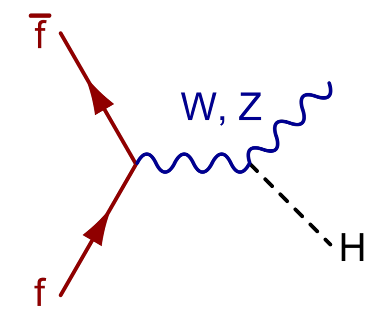


- **ttH Hadronic:**
  - No lepton
  - At least 3 jets (1 b tagged jet)
- **VBF:**
  - Two jets along with two photons
  - Separate MVA based analysis done for the dijets
  - Final MVA = dijet MVA + diphoton MVA

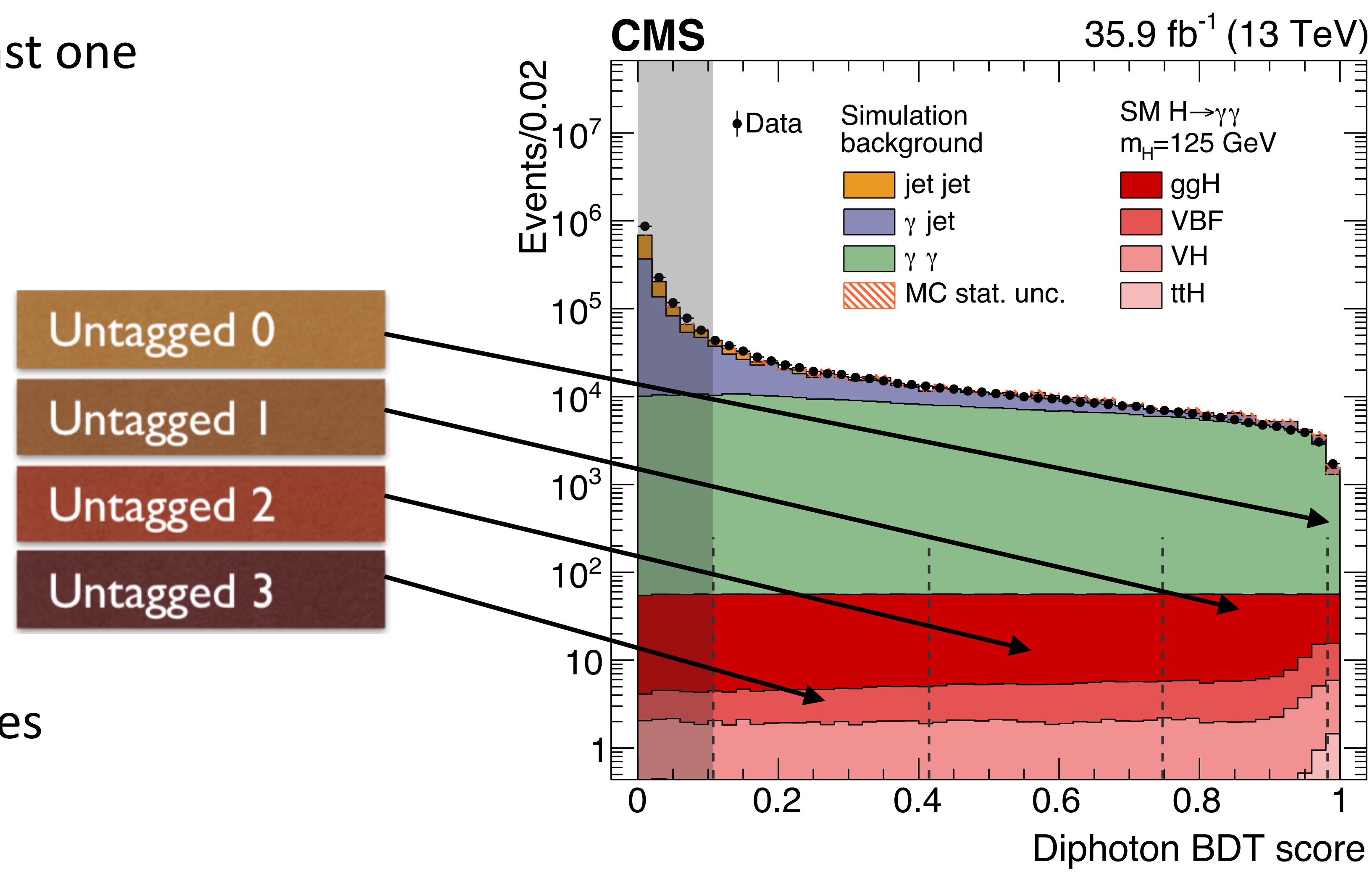


Event categorization-II

- **VH Tags:**
  - leptonic Z decays (ZH Leptonic)
  - leptonic W decays (WH Leptonic)
  - W or Z leptonic decays, relaxed selection (VH LeptonicLoose)
  - W or Z leptonic decays, with at least one missing lepton (VH MET)
  - hadronic decays of W and Z (VH Hadronic)

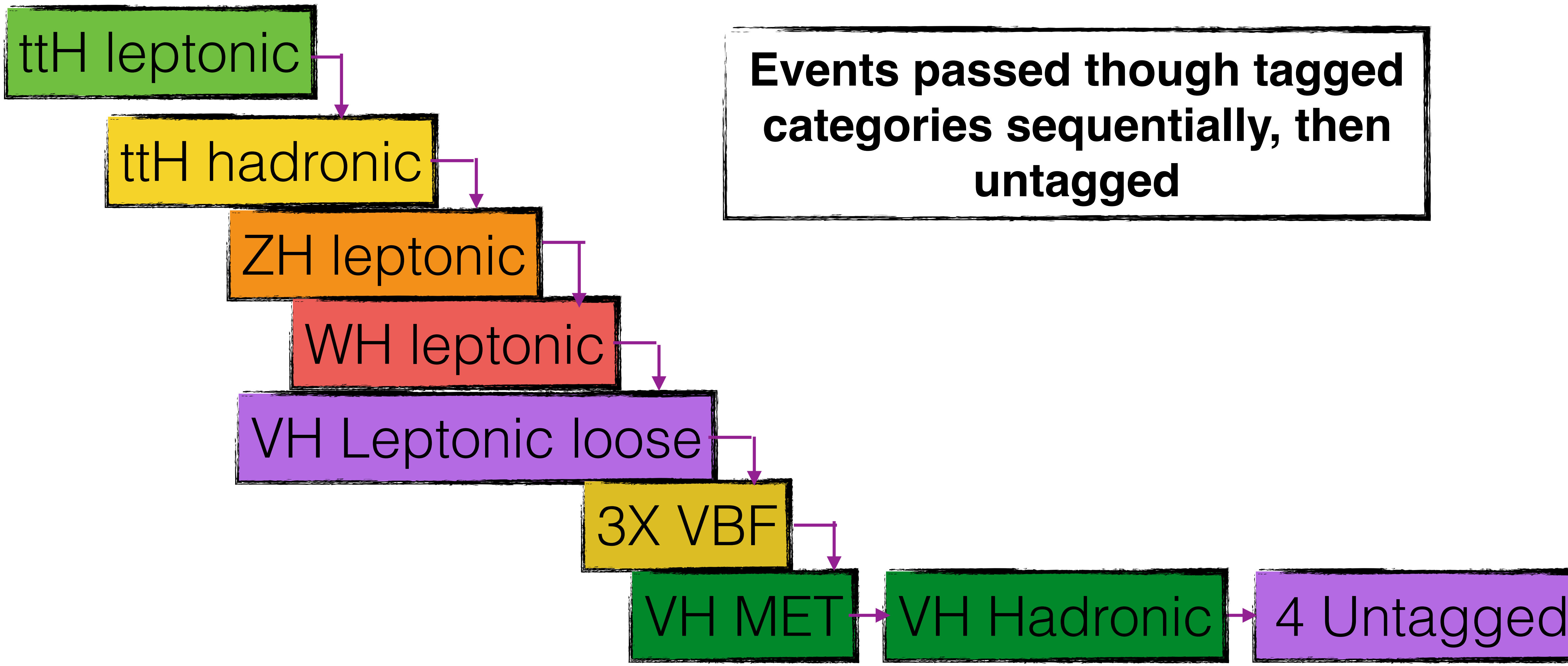


- **Untagged (ggH):**
  - Remaining events are from ggH
  - Further classified into subcategories



All categories

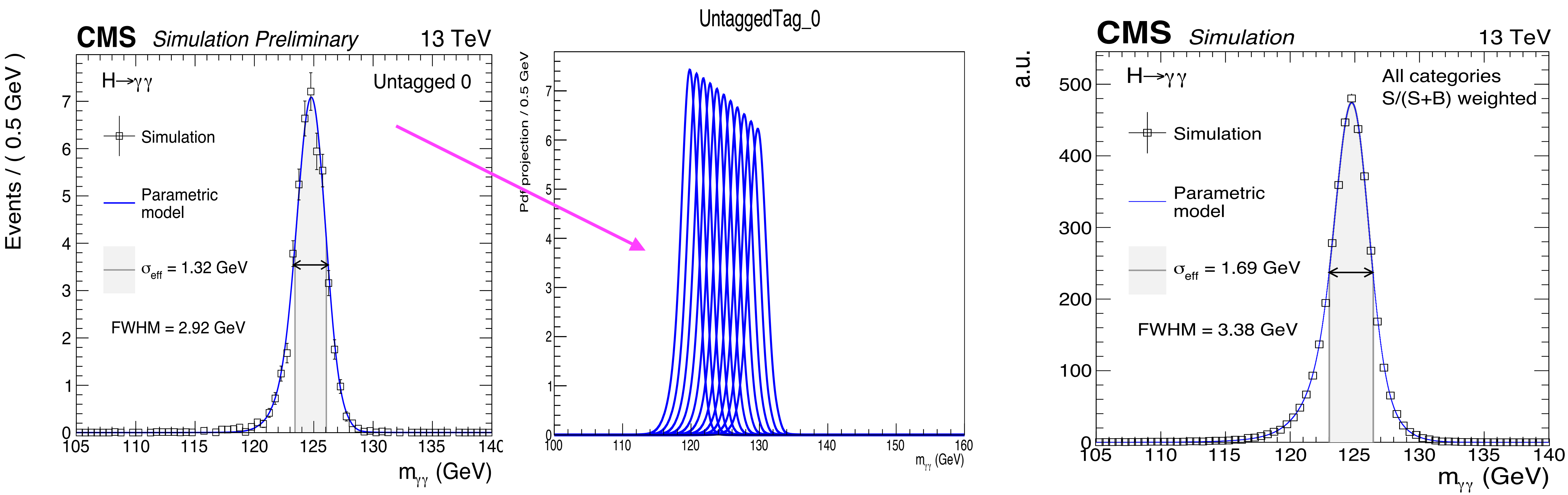
- **Tagged categories:** ttH, VH and VBF processes (10 in total)
- **Untagged categories:** ggH process (4 in total depending to different S/B)



Signal Modeling

A parametric model is used to describe the shape of the H->γγ signal in each category

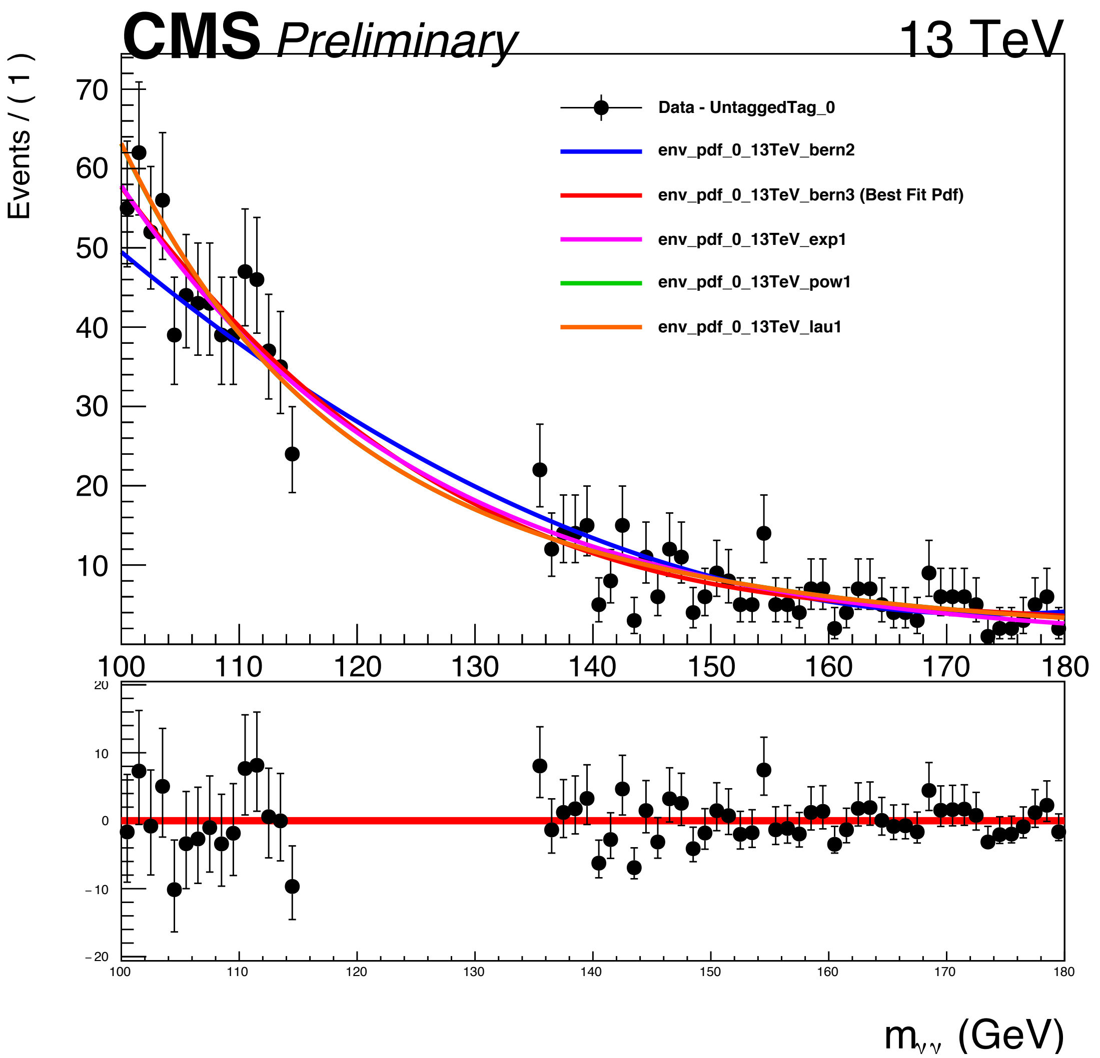
- Diphoton mass shapes in each 14 categories separately using analytic function
- Parameters are determined by fitting simulated events for each category and each of three Higgs mass points
- Full signal model is constructed by taking linear interpolation of each fit parameter between individual mass points



Background Modeling

Background Model:

- Background model is built from data sideband (180 > mass > 135 GeV) and (100 < mass < 115 GeV)
- Four families of analytic functions considered (sum of exponentials, sum of Bernstein's polynomials, Laurent series, sum of power laws)



Untagged 0

Systematic uncertainty

Different systematic uncertainties are treated separately depending on their effect on the diphoton mass distribution

- All possible source of uncertainties are considered. Some of them are listed below

Theoretical Uncertainties:

- Statistical uncertainty ~10%
- QCD scale uncertainty (<5%)
- PDF uncertainty (<1%)
- H->γγ branching ratio (~2%)

Experimental Uncertainties:

- Jet energy scale and smearing (at max 20%)
- Measurement of integrated luminosity (~2.5%)
- Photon energy scale and resolution (~2.5%)
- Photon ID BDT (<=~1%)
- Modeling of material budget in front of ECAL (< 1%)

Fit strategy in nutshell

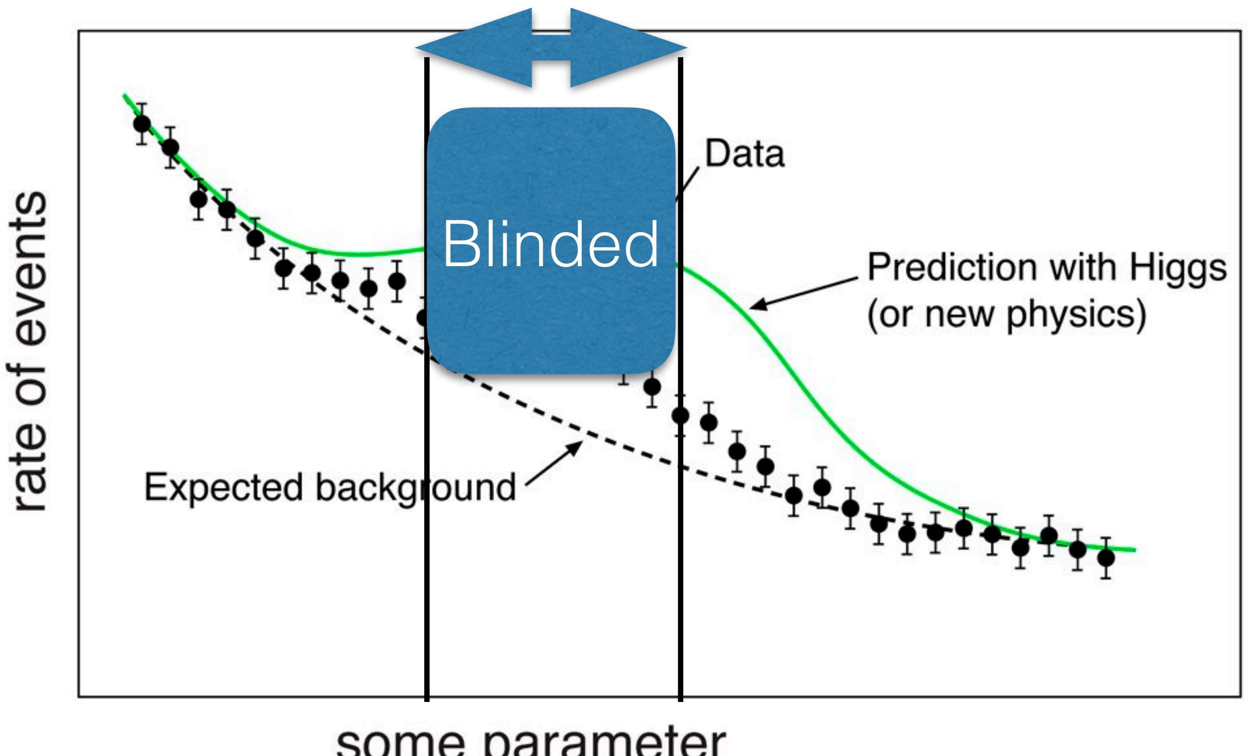


Figure B

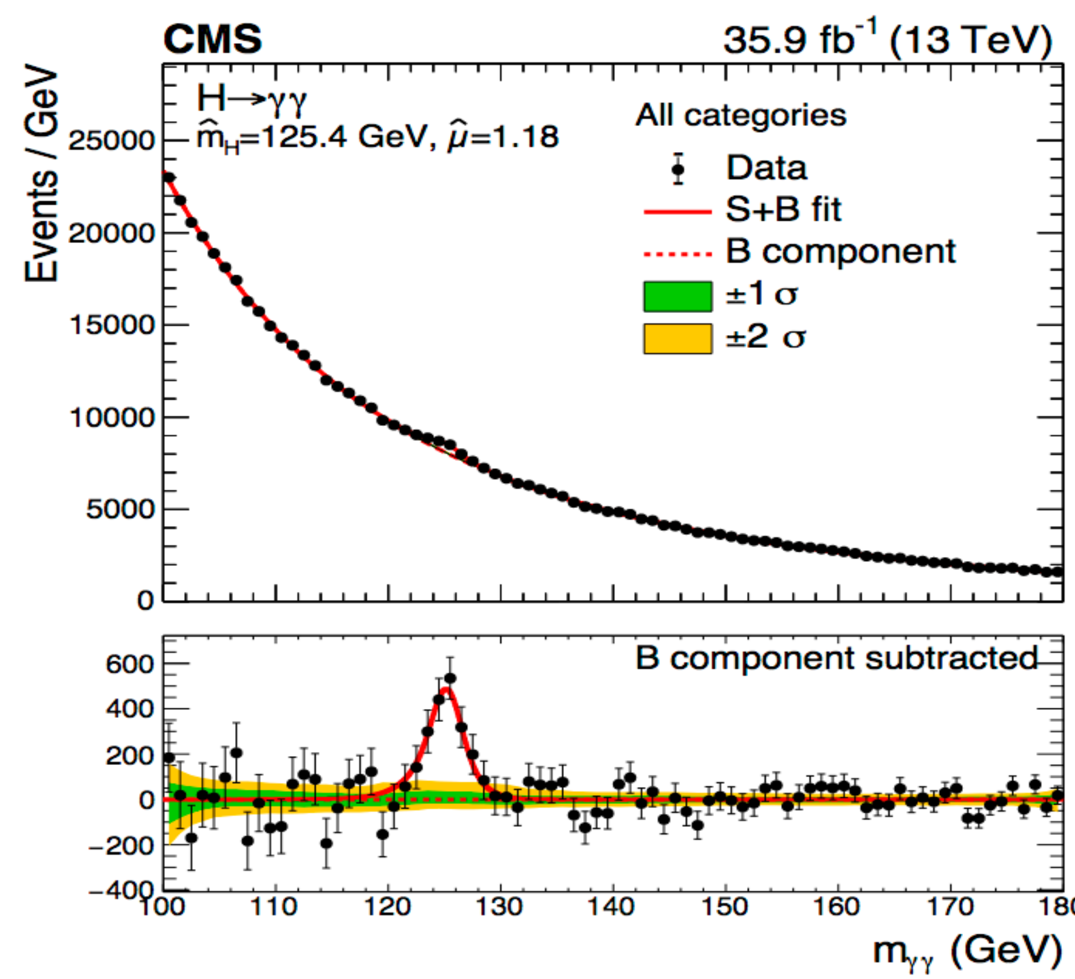
$$\mathcal{L} = \mathcal{L}(\text{data}|s(p, m_{\gamma\gamma}) + f(m_{\gamma\gamma}))$$

p -> parameters of the signal (signal strength or m_H)

$s(p, m_{\gamma\gamma})$ -> parametric signal model

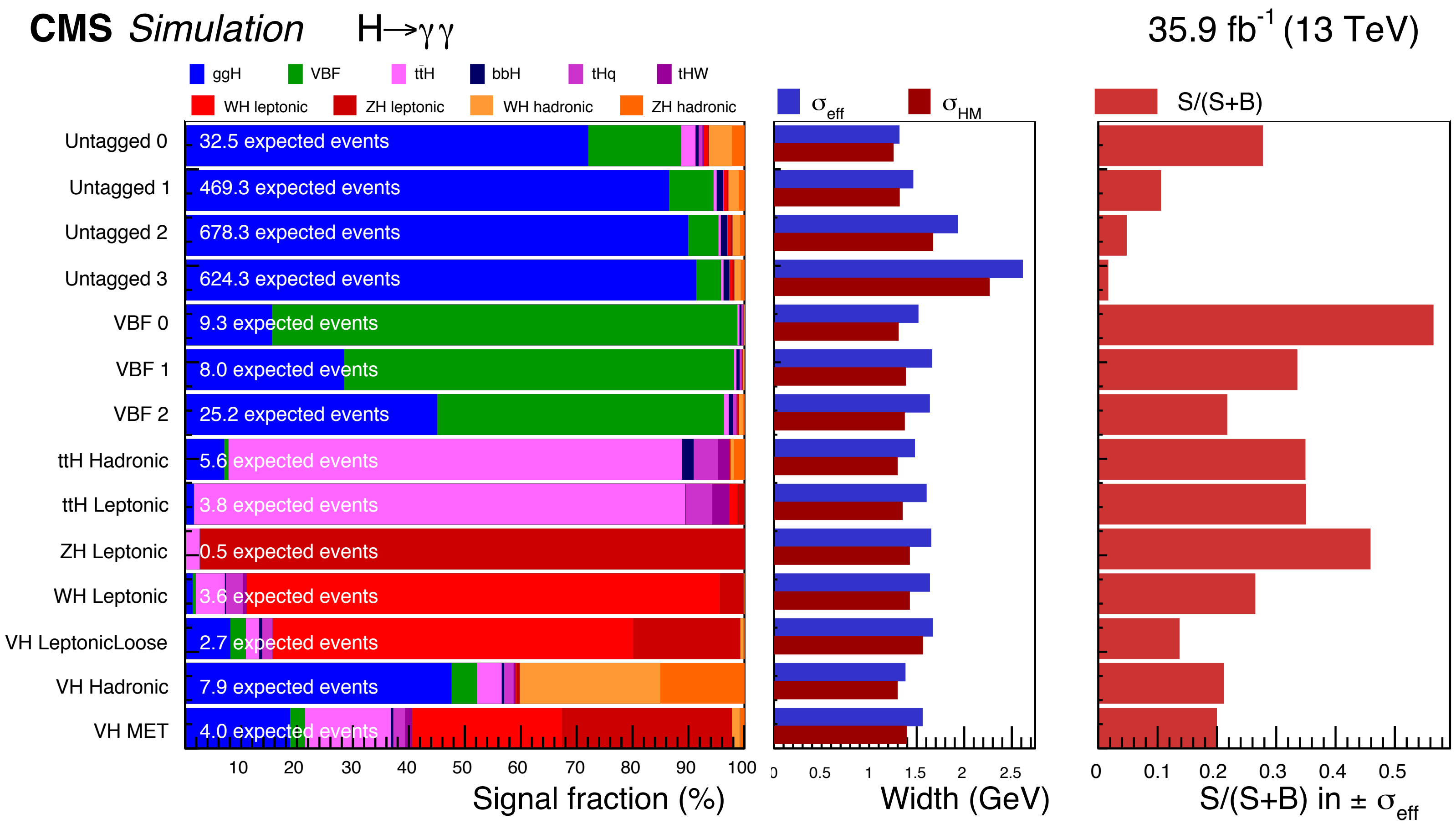
$f(m_{\gamma\gamma})$ -> background fit function

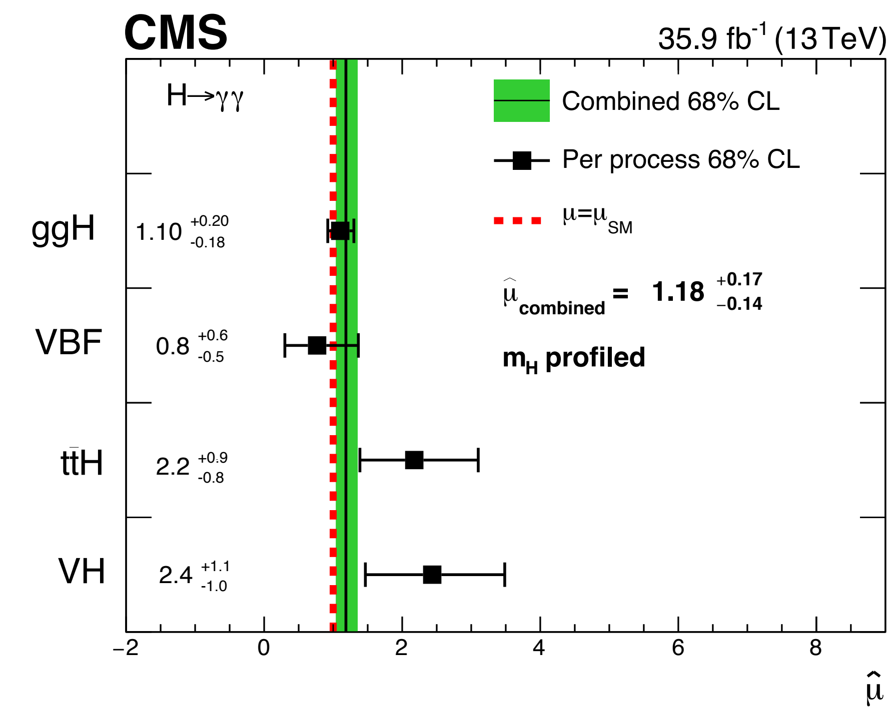
Results for combined categories



- Signal region: 115 < mass < 135 GeV
- Overall diphoton mass region: 100 < mass < 180 GeV

Results





Signal strength modifiers measured for each process (black points), with the SM Higgs boson mass profiled, compared to the overall signal strength modifier (green band) and to the SM expectation (dashed red line)

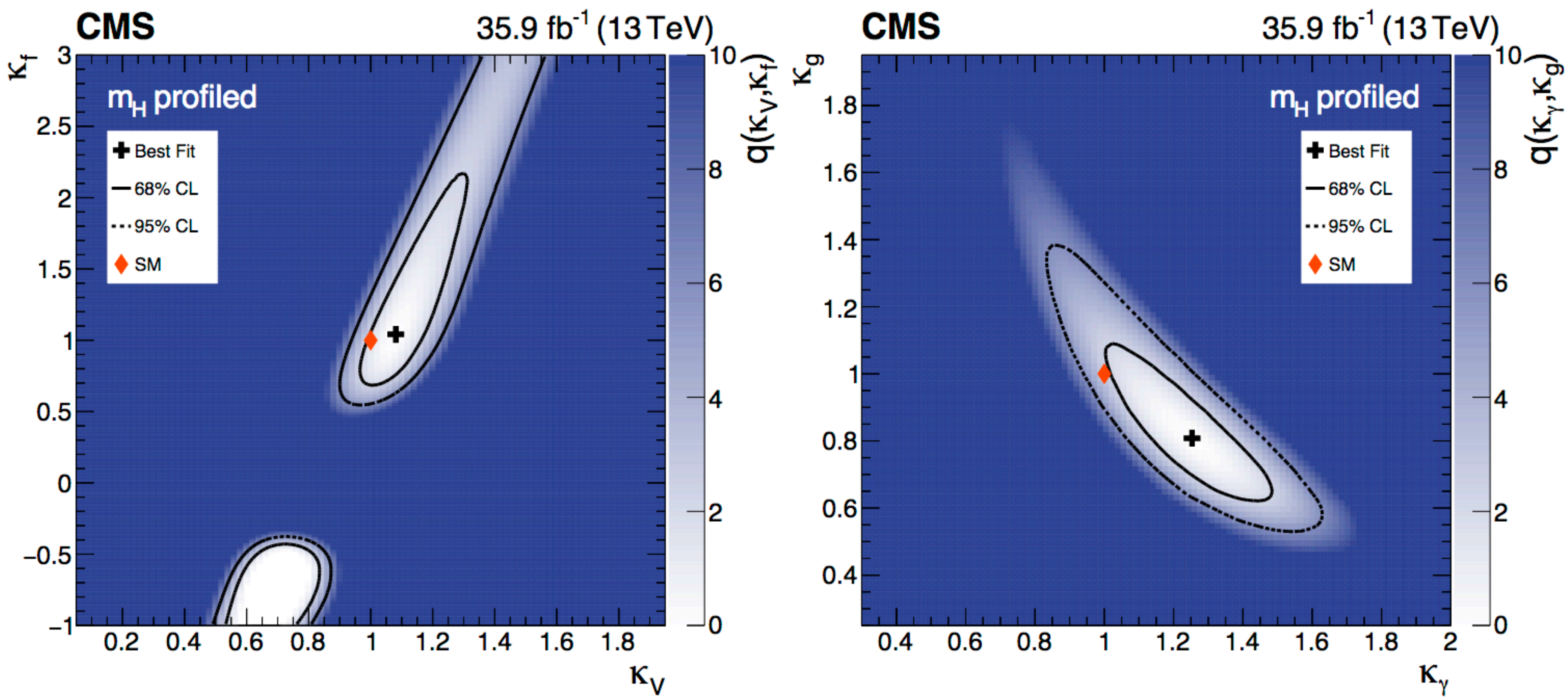
$$\hat{\mu} = 1.18^{+0.17}_{-0.14} = 1.18^{+0.12}_{-0.11}(\text{stat})^{+0.09}_{-0.07}(\text{syst})^{+0.07}_{-0.06}(\text{theo})$$

Best fit mass = 125.4 ± 0.3 GeV = 125.4 ± 0.2 (stat) ± 0.2 (syst) GeV.

JHEP 1811 (2018) 185

Higgs Coupling to fermion and vector boson

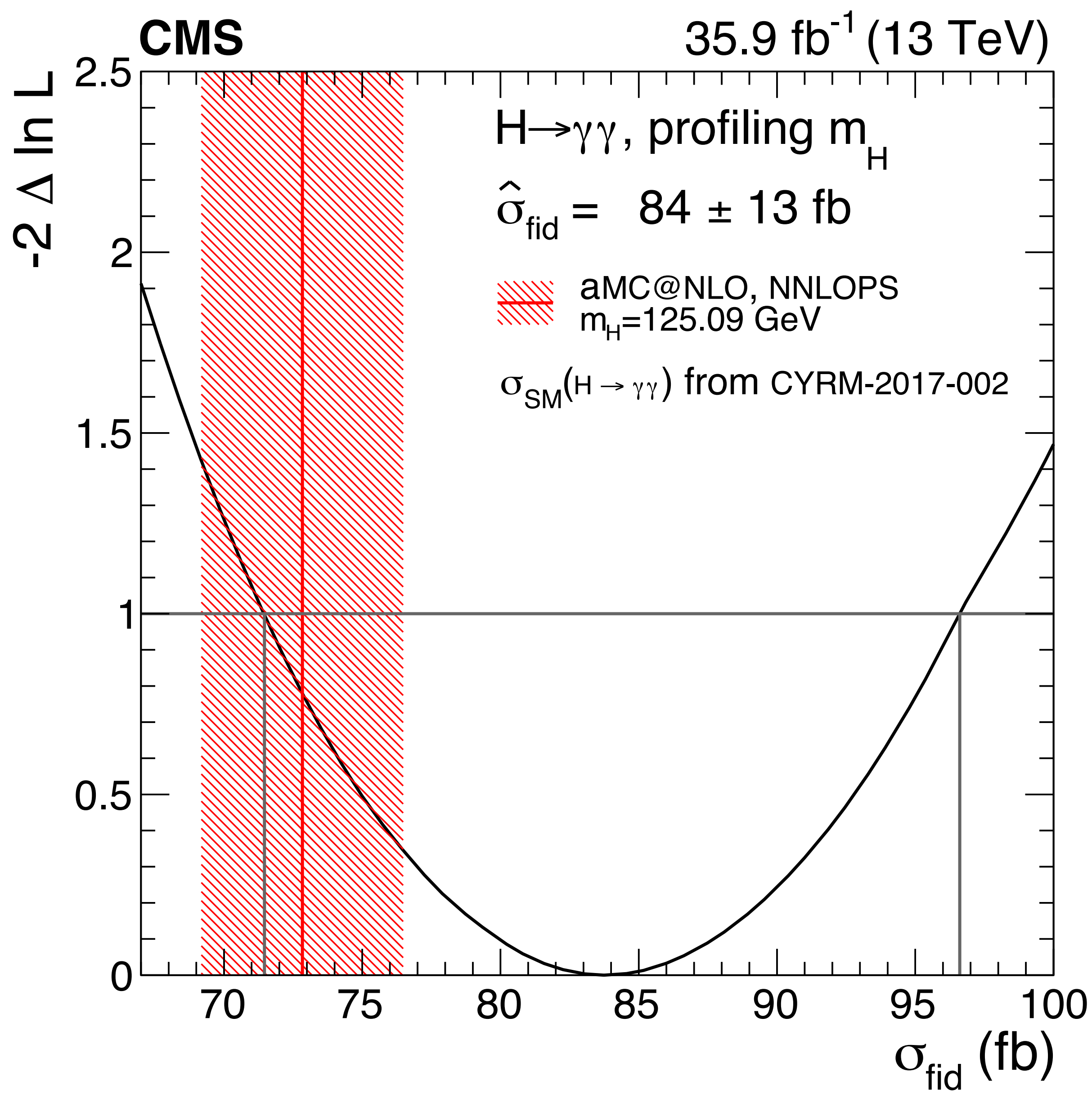
- κ_f , κ_V , κ_g *and* κ_γ measure strength of Higgs coupling to particles relative to SM
- Two-dimensional likelihood scans of κ_f versus κ_V (left) and κ_g versus κ_γ (right)

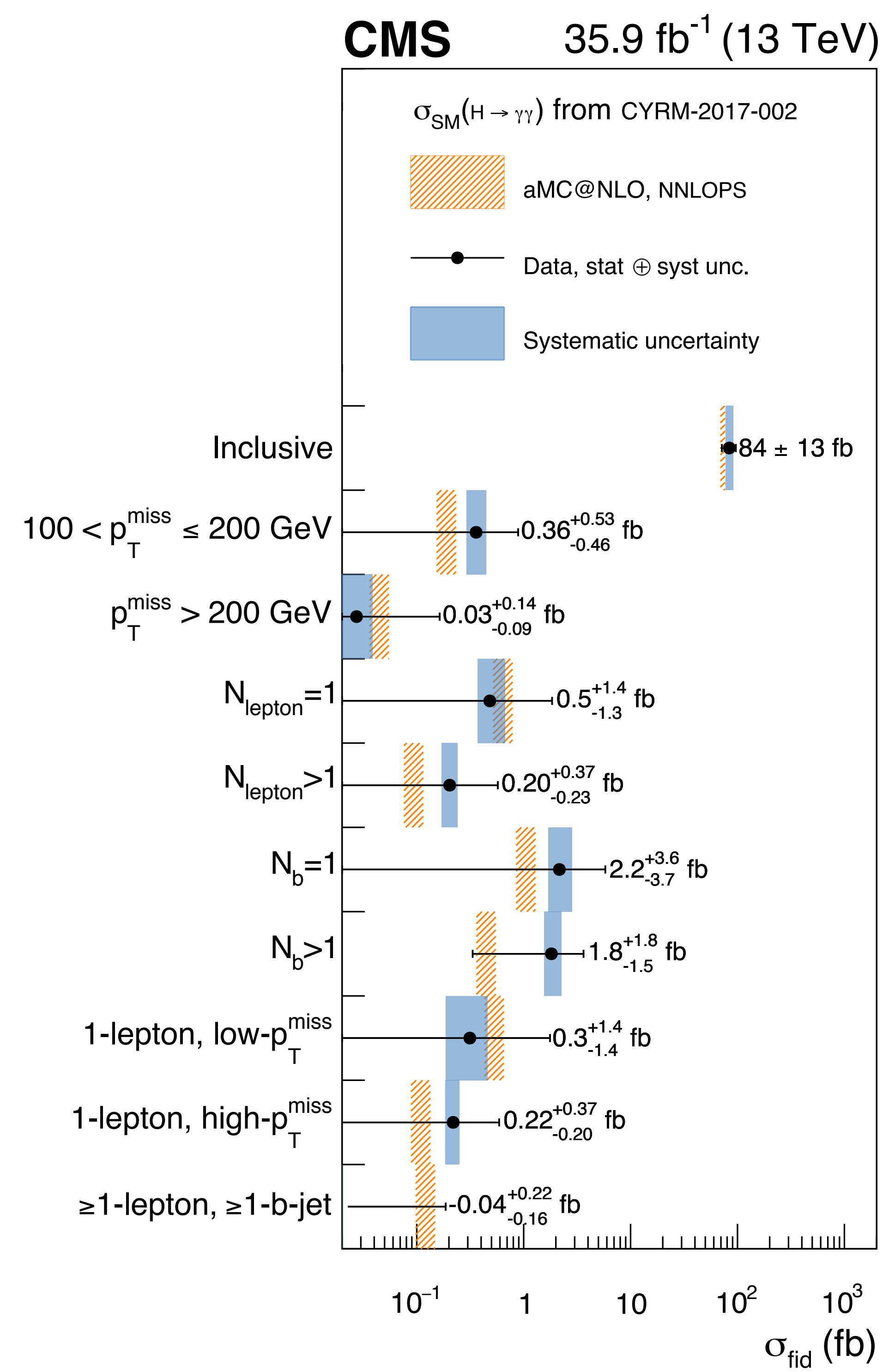


Results are consistent with SM expectation

Fiducial Cross-section measurement

JHEP 1901 (2019) 183





- Measurement of fiducial cross section using different categorization scheme
- Results consistent with SM expectation

Summary

- We presented the measurement of production cross-section of the Higgs boson using diphoton decay
- Results corresponds to 35.9 fb^{-1} at 13 TeV at pp collisions
- **Consistency with SM** when splitting signal strength into production modes
- Higgs physics: moving from **discovery to precision measurement** era.

CMS has already finished its data taking for the Run-II in pp collision

Stay tuned!

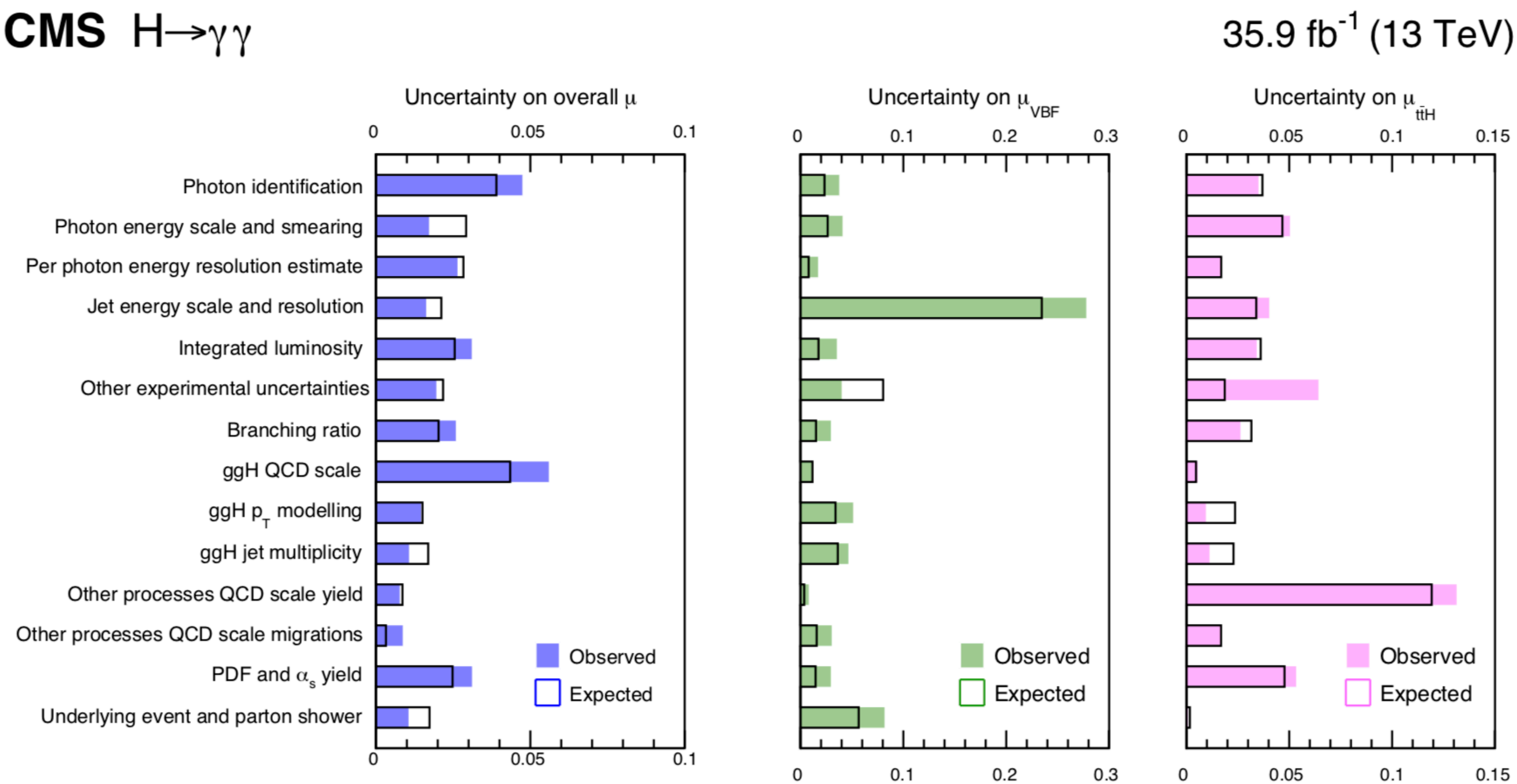
Back up

Number of events

Event categories	Expected SM 125 GeV Higgs boson signal												Bkg
	Total	ggH	VBF	ttH	bbH	tHq	tHW	WH lep	ZH lep	WH had	ZH had	σ_{eff} (GeV)	σ_{HM} (GeV)	(GeV^{-1})
Untagged 0	32.5	72.0 %	16.6 %	2.6 %	0.6 %	0.7 %	0.3 %	0.6 %	0.3 %	4.2 %	2.2 %	1.32	1.26	21.8
Untagged 1	469.3	86.5 %	7.9 %	0.6 %	1.2 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.9 %	1.1 %	1.46	1.32	925.1
Untagged 2	678.3	89.9 %	5.4 %	0.4 %	1.2 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.4 %	0.8 %	1.93	1.67	2391.7
Untagged 3	624.3	91.3 %	4.4 %	0.5 %	1.0 %	0.1 %	<0.05 %	0.5 %	0.3 %	1.2 %	0.7 %	2.61	2.27	4855.1
VBF 0	9.3	15.5 %	83.2 %	0.4 %	0.4 %	0.3 %	<0.05 %	<0.05 %	<0.05 %	0.2 %	<0.05 %	1.52	1.31	1.6
VBF 1	8.0	28.4 %	69.7 %	0.4 %	0.6 %	0.4 %	<0.05 %	0.1 %	<0.05 %	0.3 %	0.1 %	1.66	1.38	3.3
VBF 2	25.2	45.1 %	51.2 %	0.9 %	0.8 %	0.6 %	0.1 %	0.2 %	0.1 %	0.8 %	0.3 %	1.64	1.37	18.9
ttH Hadronic	5.6	7.0 %	0.7 %	81.1 %	2.1 %	4.3 %	2.1 %	0.1 %	0.1 %	0.7 %	1.9 %	1.48	1.30	2.4
ttH Leptonic	3.8	1.5 %	<0.05 %	87.8 %	0.1 %	4.7 %	3.1 %	1.5 %	1.2 %	<0.05 %	<0.05 %	1.60	1.35	1.5
ZH Leptonic	0.5	<0.05 %	<0.05 %	2.6 %	<0.05 %	<0.05 %	0.1 %	<0.05 %	97.3 %	<0.05 %	<0.05 %	1.65	1.43	0.1
WH Leptonic	3.6	1.3 %	0.6 %	5.2 %	0.2 %	3.0 %	0.7 %	84.5 %	4.3 %	0.1 %	0.1 %	1.64	1.43	2.1
VH LeptonicLoose	2.7	8.1 %	2.7 %	2.4 %	0.6 %	1.8 %	0.1 %	64.4 %	19.1 %	0.6 %	0.2 %	1.67	1.56	3.5
VH Hadronic	7.9	47.6 %	4.5 %	4.4 %	0.4 %	1.7 %	0.3 %	0.2 %	0.5 %	25.2 %	15.1 %	1.38	1.30	7.2
VH MET	4.0	18.7 %	2.6 %	15.4 %	0.4 %	2.1 %	1.2 %	26.8 %	30.4 %	1.4 %	0.9 %	1.56	1.39	3.5
Total	1875.0	86.9 %	7.1 %	1.0 %	1.1 %	0.2 %	<0.05 %	0.8 %	0.4 %	1.6 %	0.9 %	1.96	1.62	8237.8

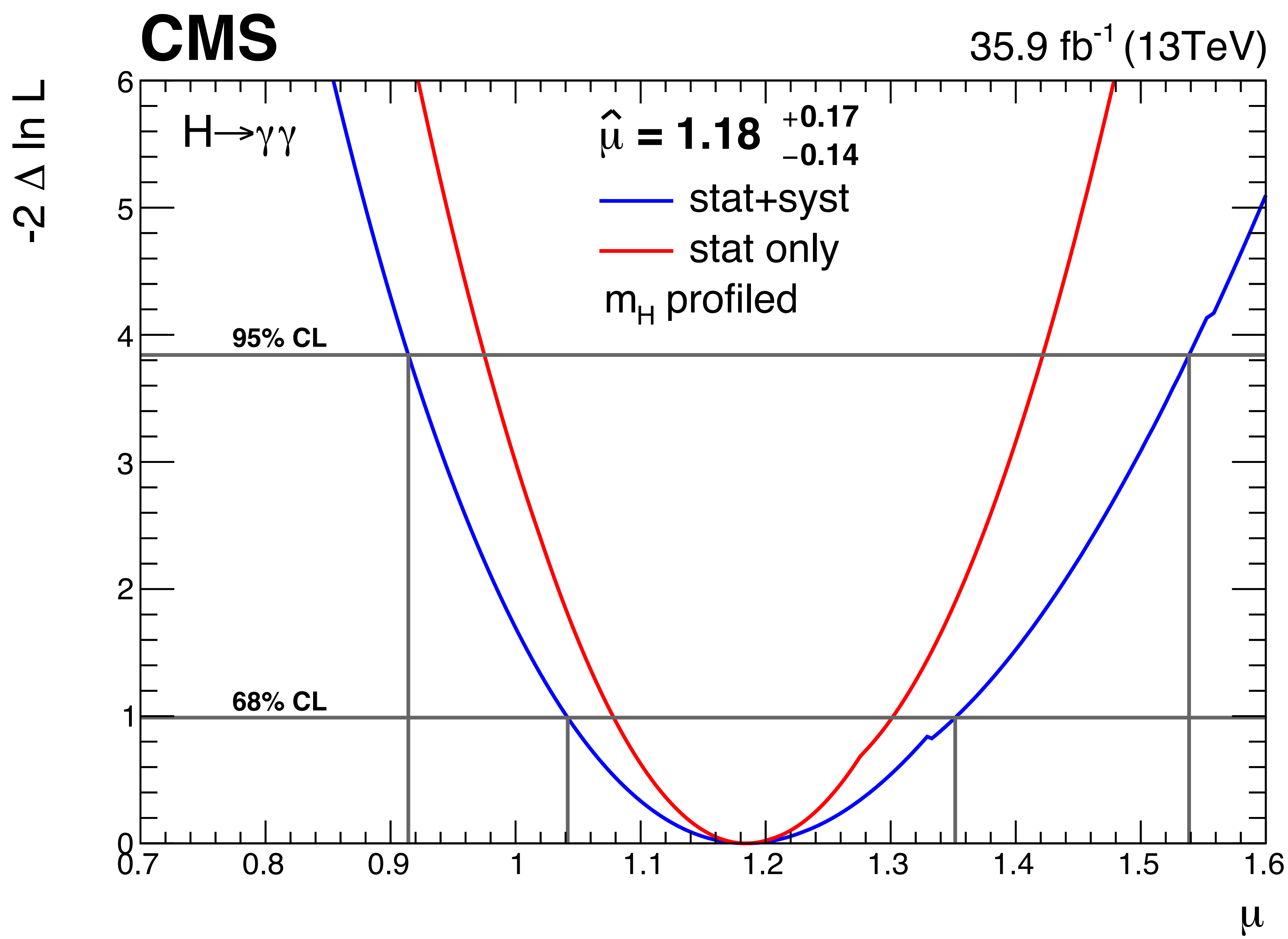
Process	$\hat{\mu}$	Uncertainties				*p*-value	Estimated significance (standard deviations)
		tot	stat	syst	theo		
ggH	1.10	$^{+0.20}_{-0.18}$	$^{+0.15}_{-0.15}$	$^{+0.09}_{-0.08}$	$^{+0.08}_{-0.06}$	3.1×10^{-12}	6.9
VBF	0.8	$^{+0.6}_{-0.5}$	$^{+0.5}_{-0.4}$	$^{+0.3}_{-0.2}$	$^{+0.2}_{-0.1}$	4.2×10^{-2}	1.7
$t\bar{t}H$	2.2	$^{+0.9}_{-0.8}$	$^{+0.9}_{-0.8}$	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.1}$	7.4×10^{-4}	3.2
VH	2.4	$^{+1.1}_{-1.0}$	$^{+1.0}_{-1.0}$	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.1}$	4.7×10^{-3}	2.6

Effect of Uncertainty on Signal strength



Signal strength Run-I vs Run-II

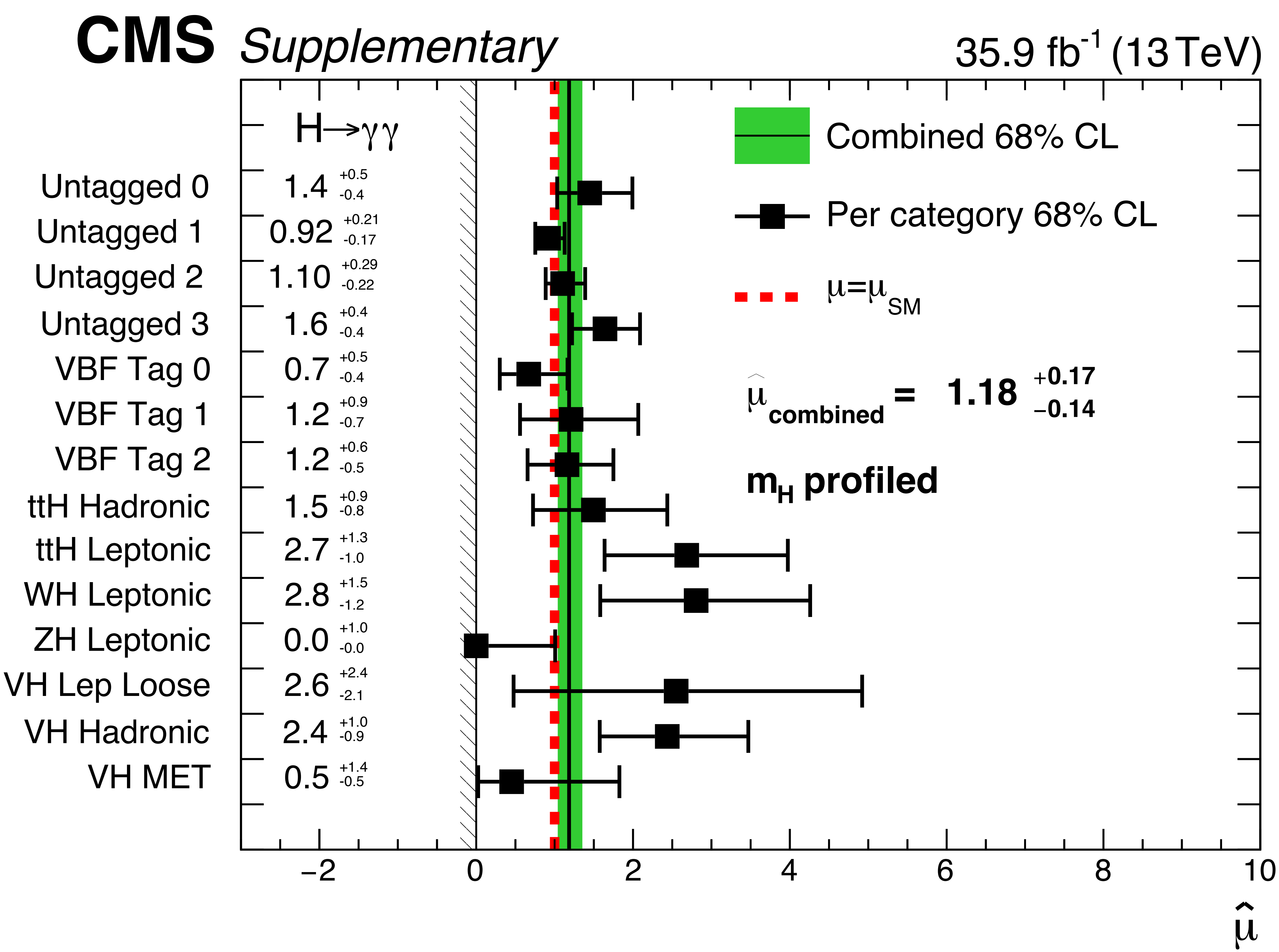
The likelihood scan for the signal strength modifier where the value of the SM Higgs boson mass is profiled in the fit.



CMS Run-I results $\hat{\mu} = 1.14 \pm 0.21(\text{stat})^{+0.09}_{-0.05}(\text{syst})^{+0.13}_{-0.09}(\text{theo})$

Per-category signal strength

Signal strength modifiers measured for each category (black points), with the SM Higgs boson mass profiled



Legacy paper

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

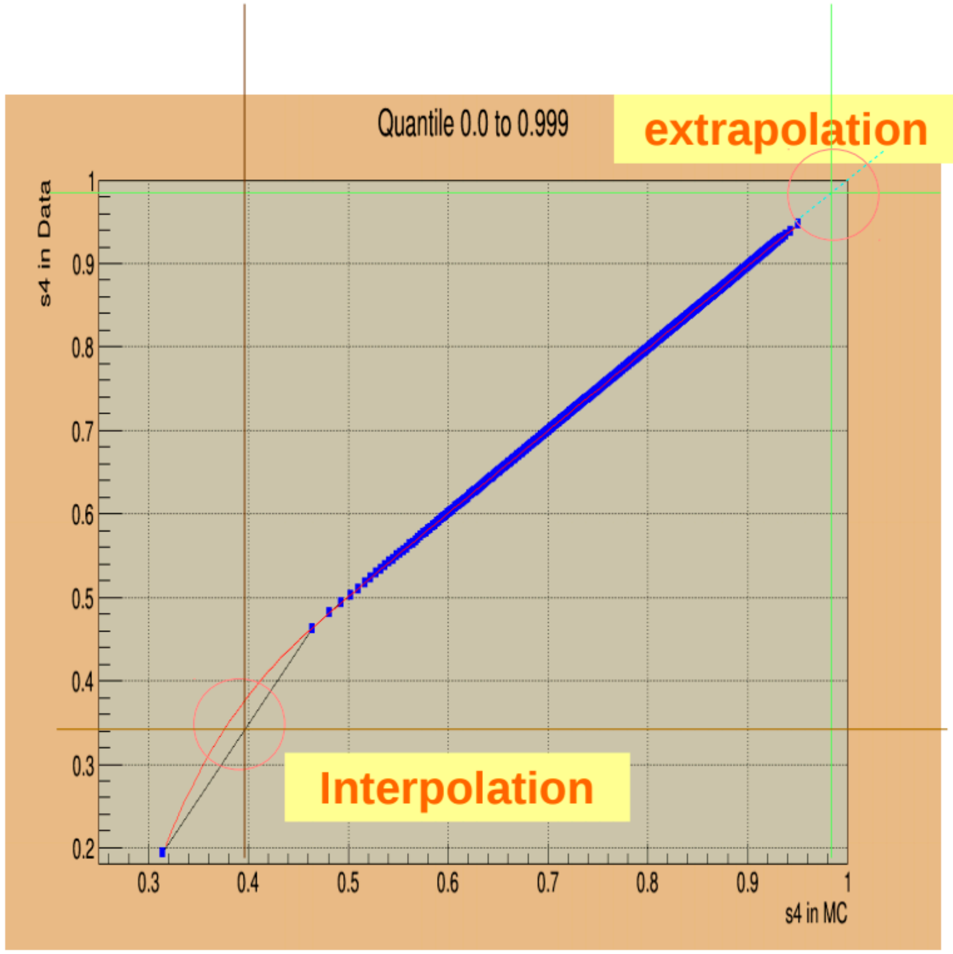
JHEP 1608 (2016) 045

Quantile method

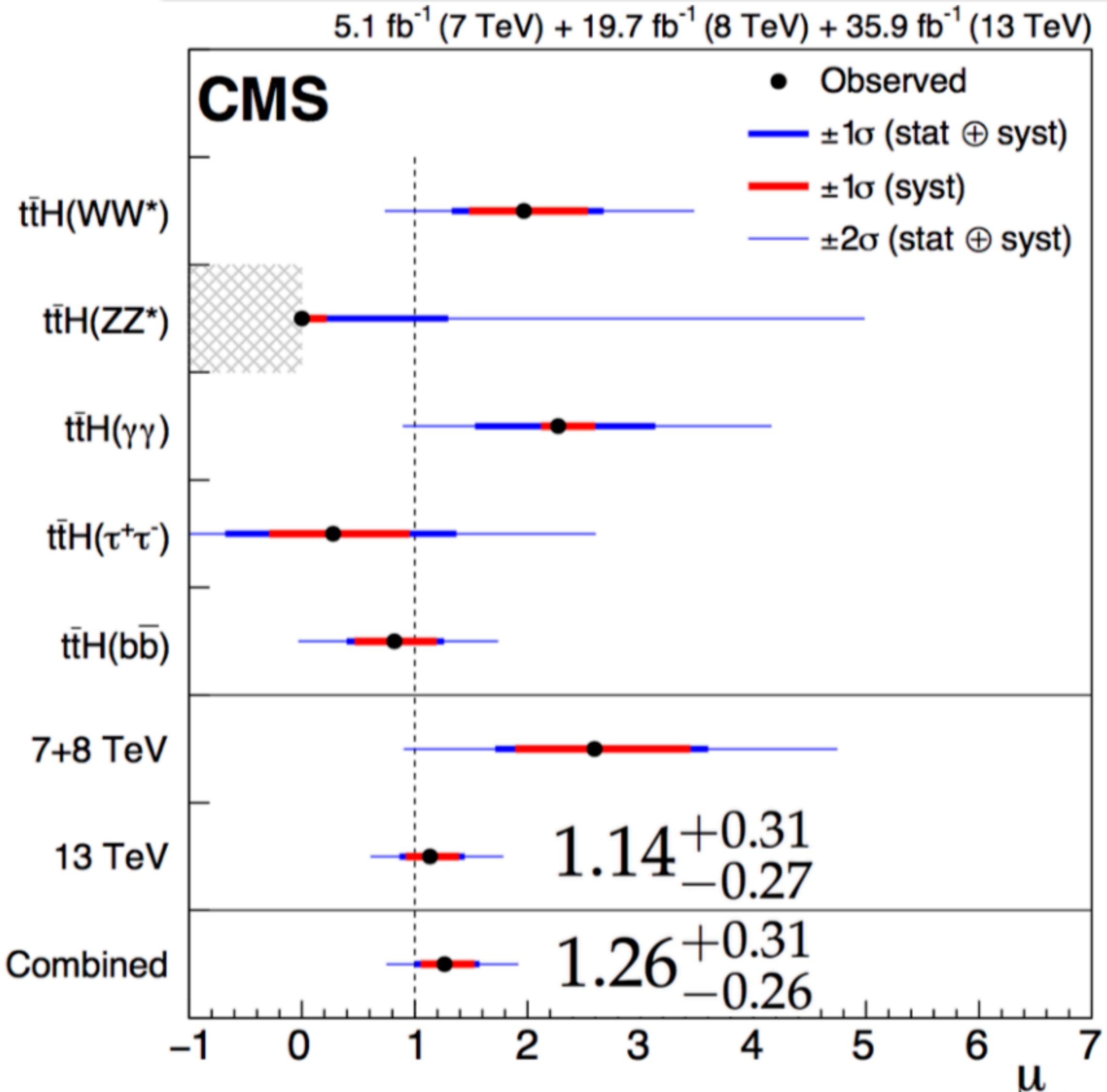
The correction of the discrepant shower shape observables is made with a morphing based on the cdf of the two histograms.

How correction works

- Produce quantile-quantile plot of the variable.
- It's a correction that changes the values of the variable to the same percentile in the data distribution.
- A linear interpolation between the two points close to x is computed. If x is outside the graph range, a linear extrapolation is computed.

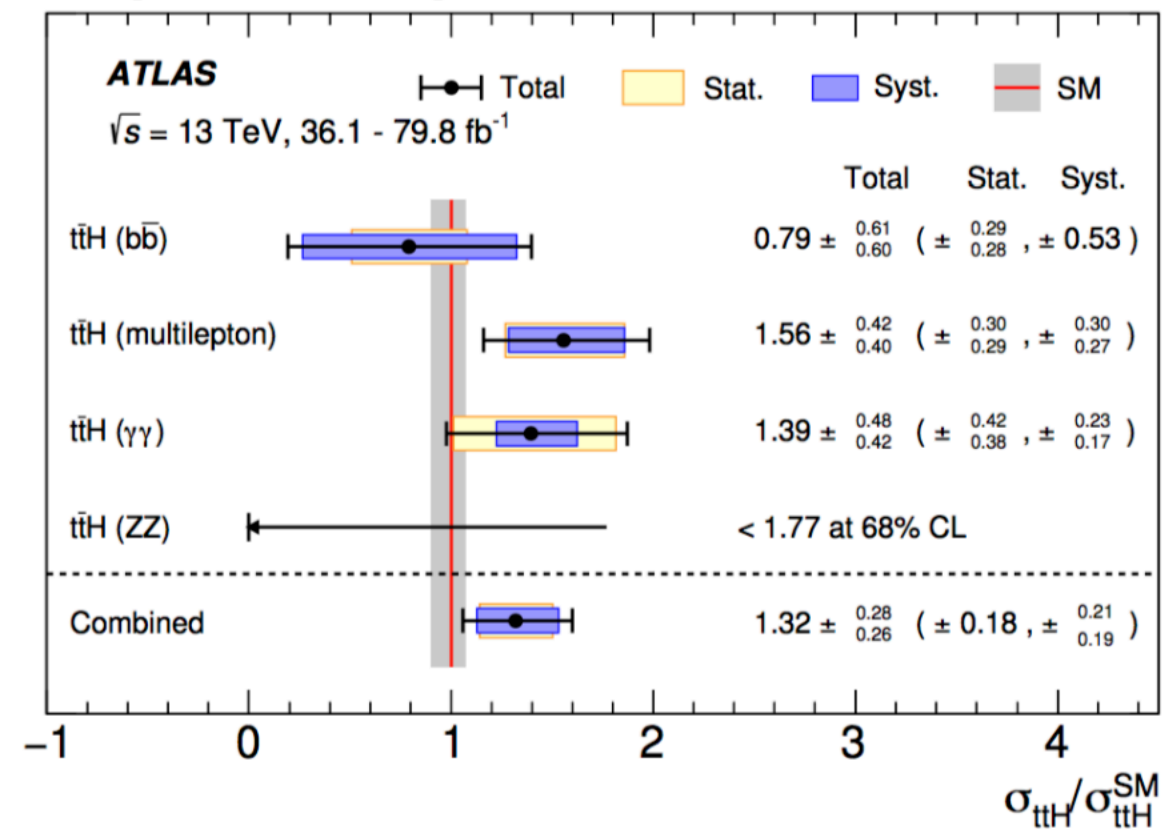


Combined ttH measurement



Phys. Rev. Lett. 120 (2018) 231801

[arXiv:1806.00425]

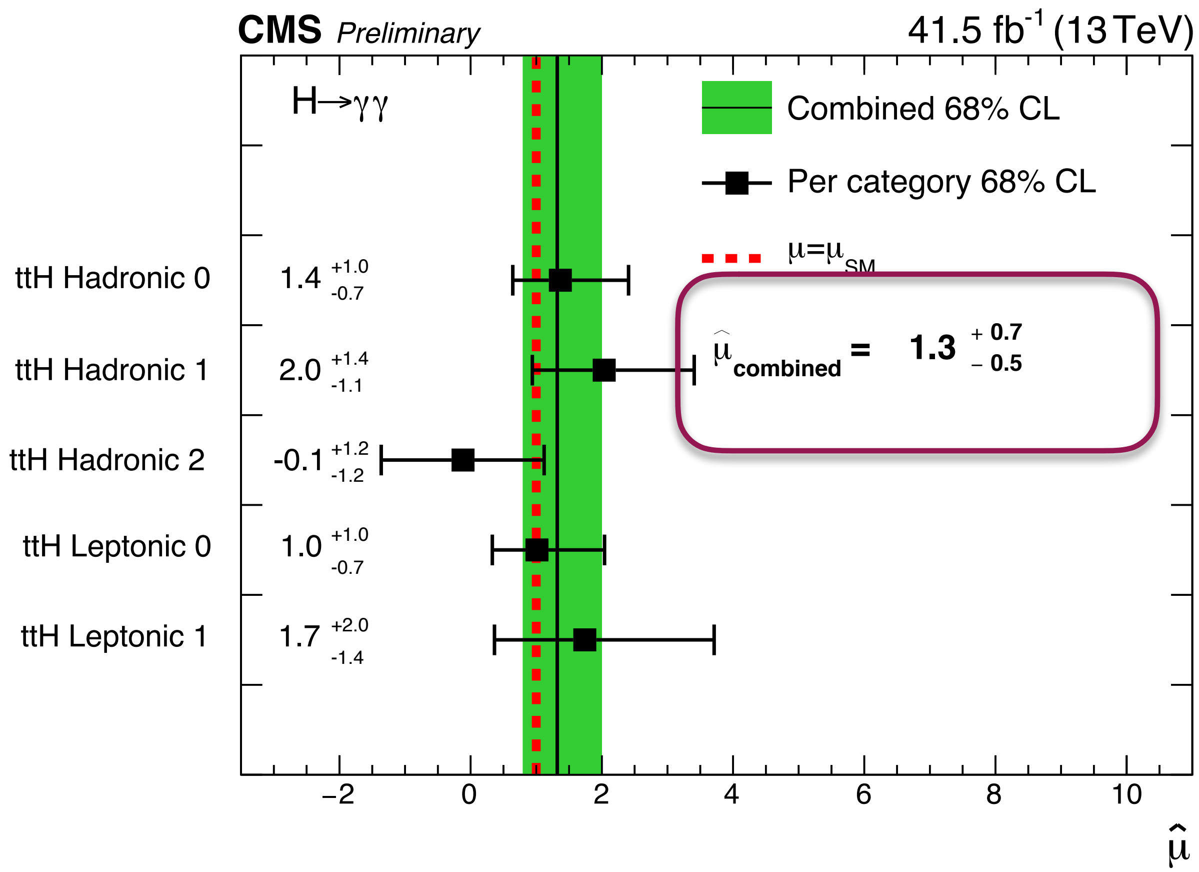


CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

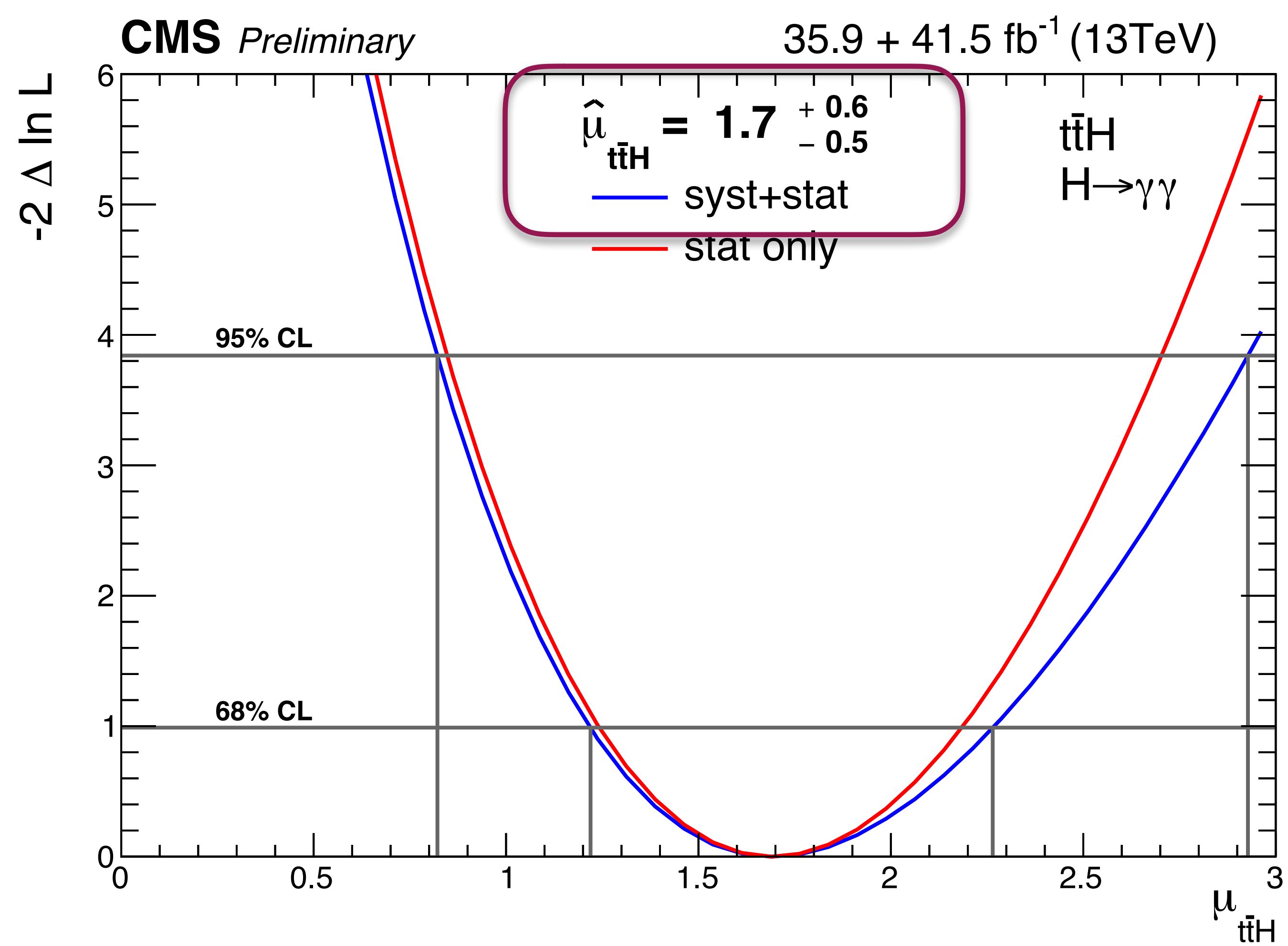
ATLAS (up to 80 fb^{-1})
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)

Observation of ttH production!

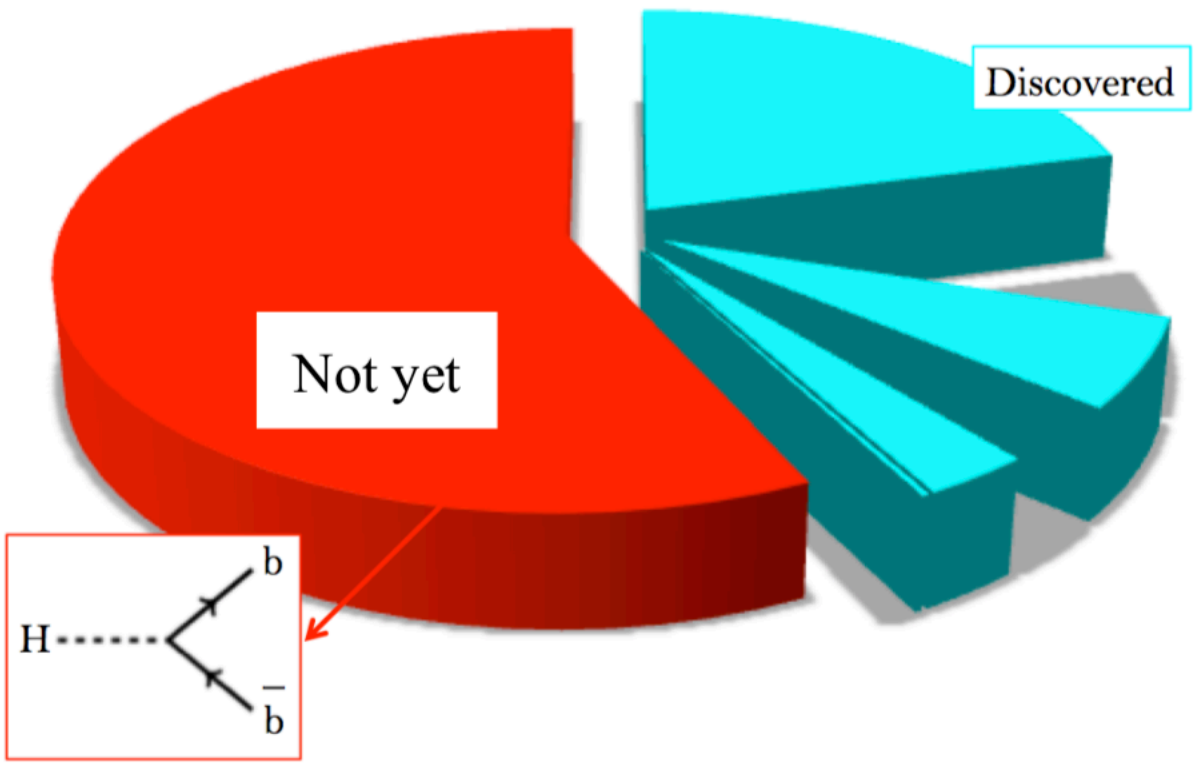
2017 data H->gamma gamma



CMS-PAS-HIG-18-018



H-> bb



- In addition to probing coupling to b-quarks:
  - **H → bb** drives the uncertainty on the total decay width, and thus on measurement of absolute couplings
  - it also drives the indirect limit on "undetected/invisible" decays

2012 CDF+DZero
Evidence [Phys. Rev. Lett. 109 (2012) 071804]

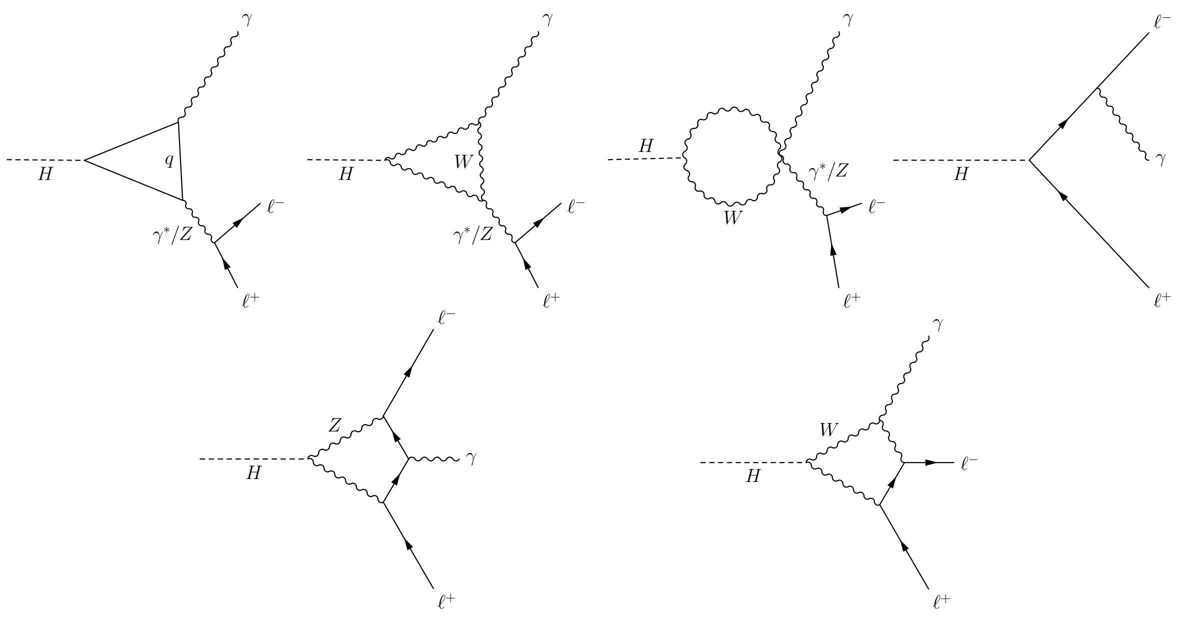
2.8σ (1.5σ exp.)
[3.1σ global]

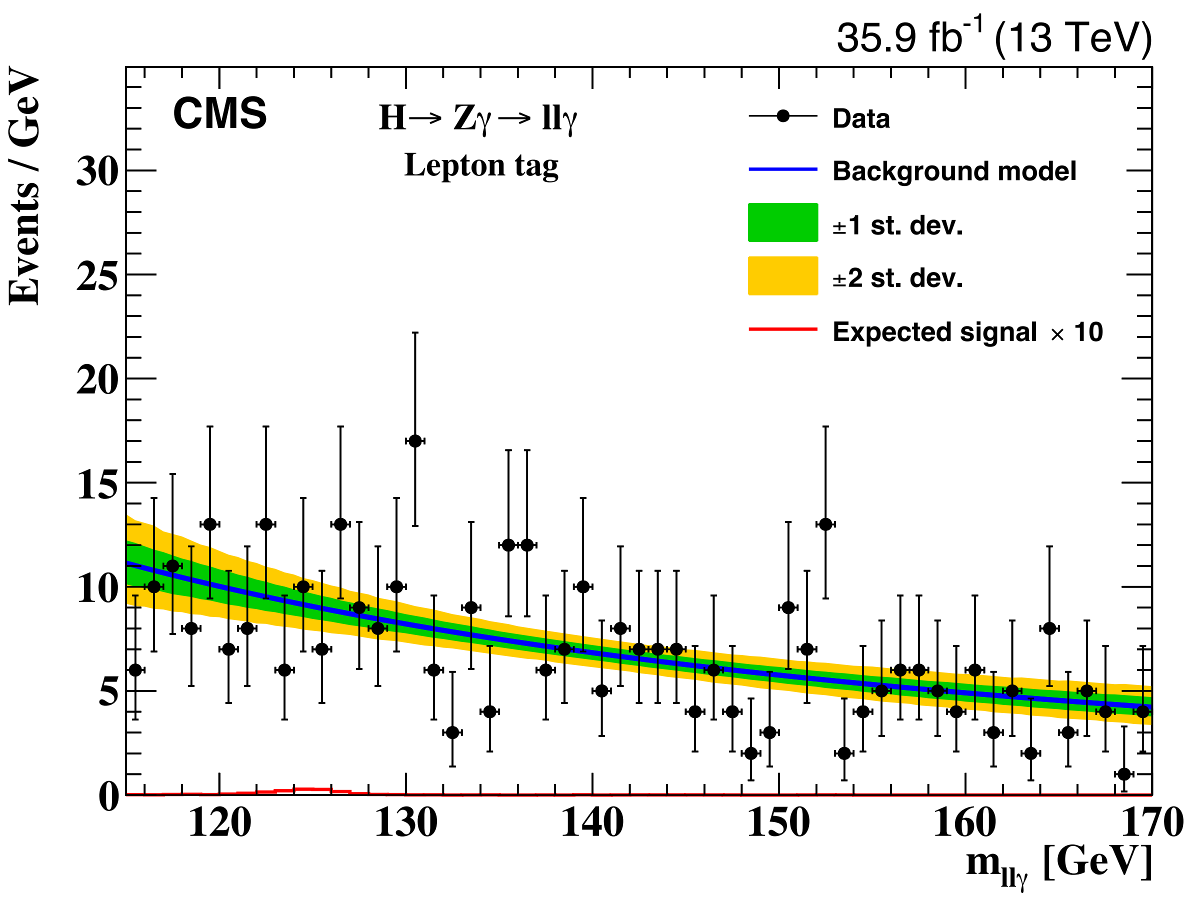
2017
Evidence by both **ATLAS** and **CMS** [JHEP 12 (2017) 024] [Phys. Lett. B 780 (2018) 501]

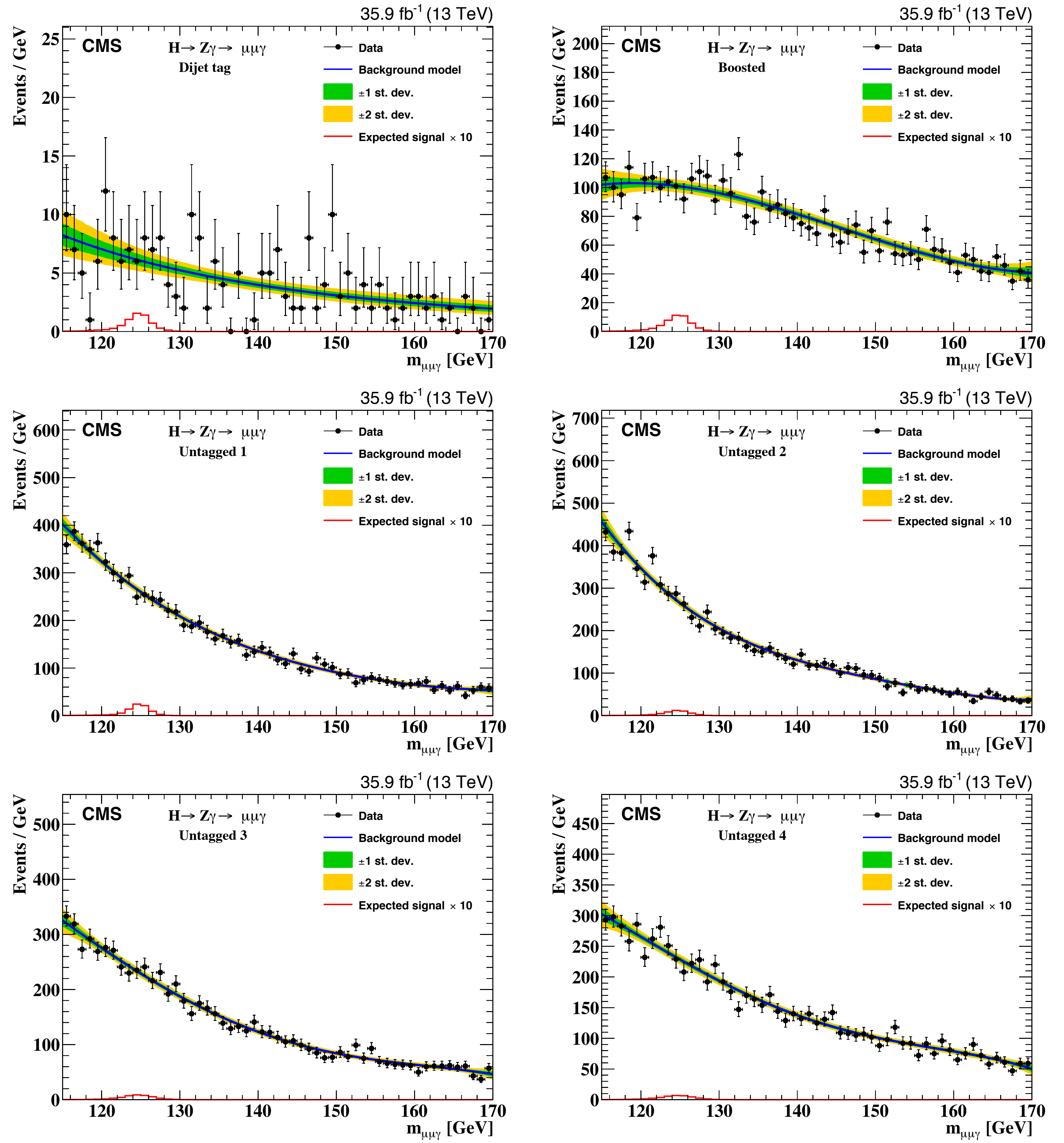
4.0σ (3.6σ exp.)

3.8σ (3.8σ exp.)

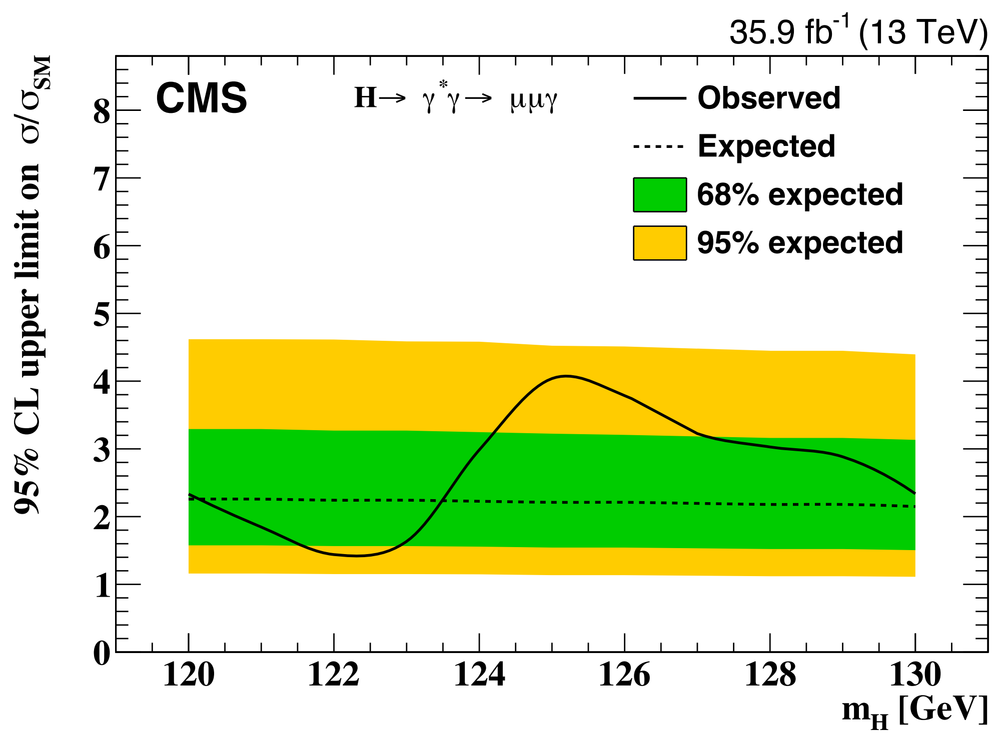
H->Z gamma

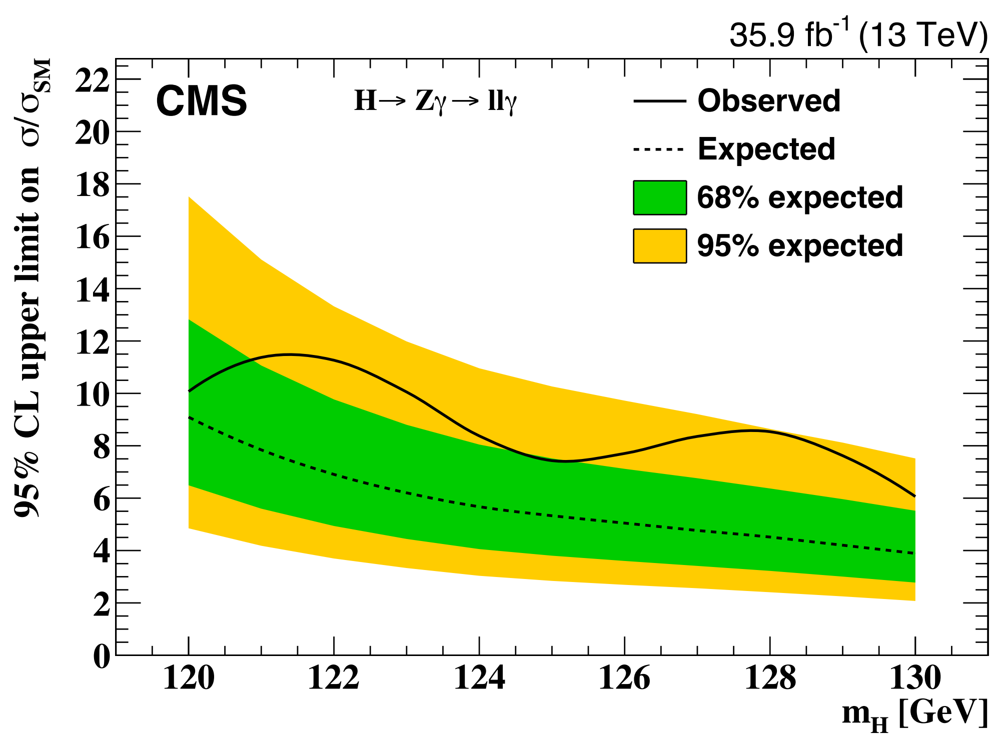

H
q
W
W
γ^*/Z
γ
ℓ^-
ℓ^+
Z

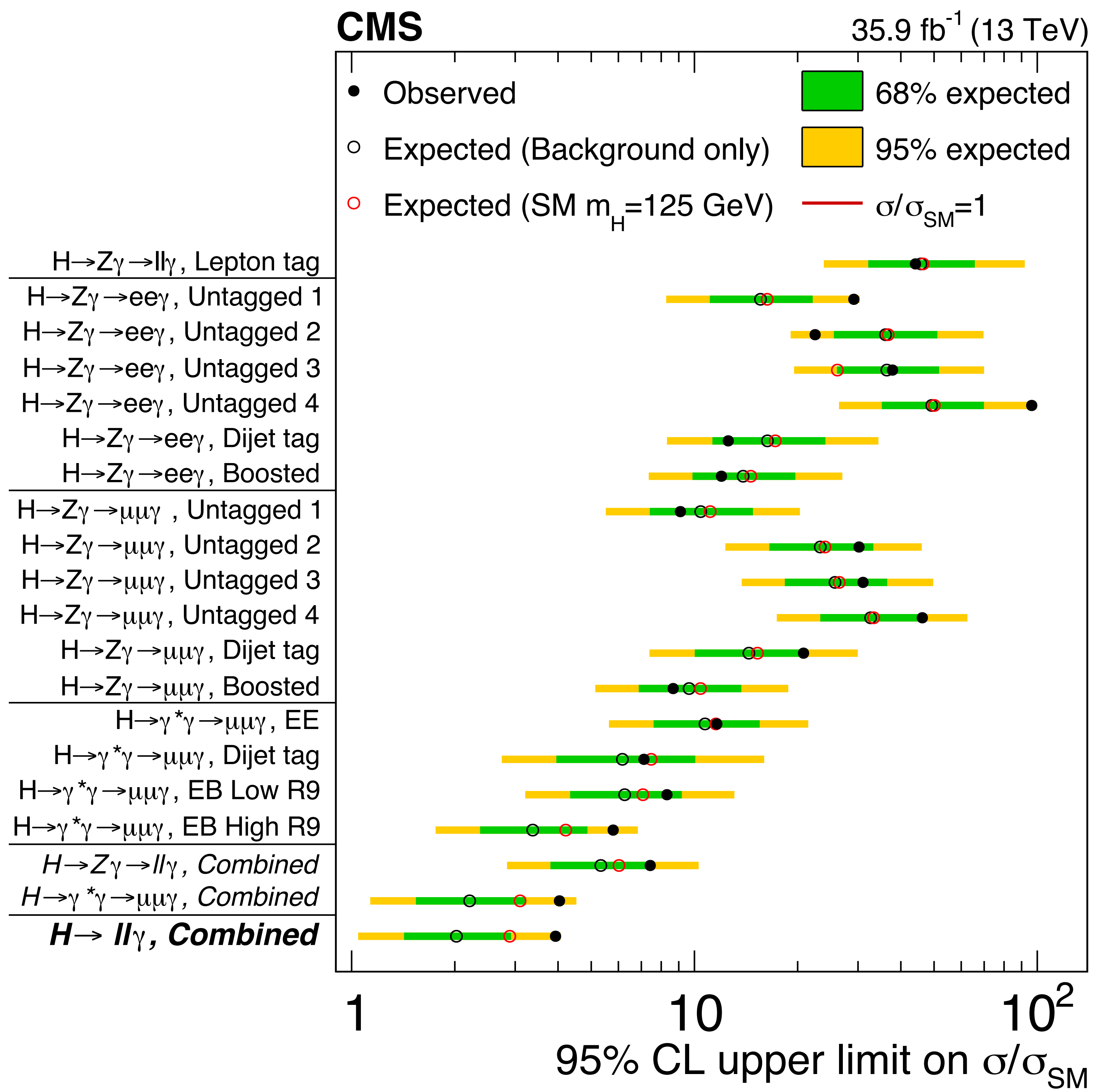

35.9 fb^{-1} (13 TeV)
CMS
H→ Zγ → llγ
Lepton tag
Data
Background model
±1 st. dev.
±2 st. dev.
Expected signal × 10
Events / GeV
$m_{ll\gamma}$ [GeV]


35.9 fb^{-1} (13 TeV)
CMS
H→ Zγ→ μμγ
Dijet tag
Boosted
Untagged 1
Untagged 2
Untagged 3
Untagged 4
Data
Background model
±1 st. dev.
±2 st. dev.
Expected signal × 10
Events / GeV
$m_{\mu\mu\gamma}$ [GeV]

H->Z gamma-II


35.9 fb^{-1} (13 TeV)
CMS
H→ γ*γ→ μμγ
Observed
Expected
68% expected
95% expected
95% CL upper limit on σ/σ$_{SM}$
m$_H$ [GeV]

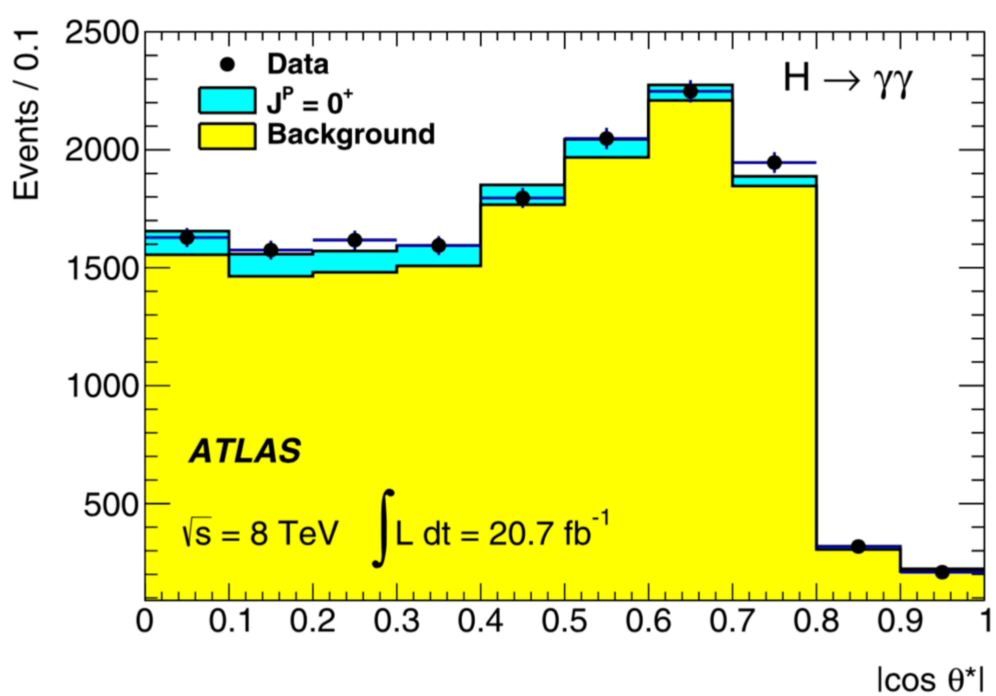

35.9 fb^{-1} (13 TeV)
CMS
H→ Zγ→ llγ
Observed
Expected
68% expected
95% expected
95% CL upper limit on σ/σ$_{SM}$
m$_H$ [GeV]

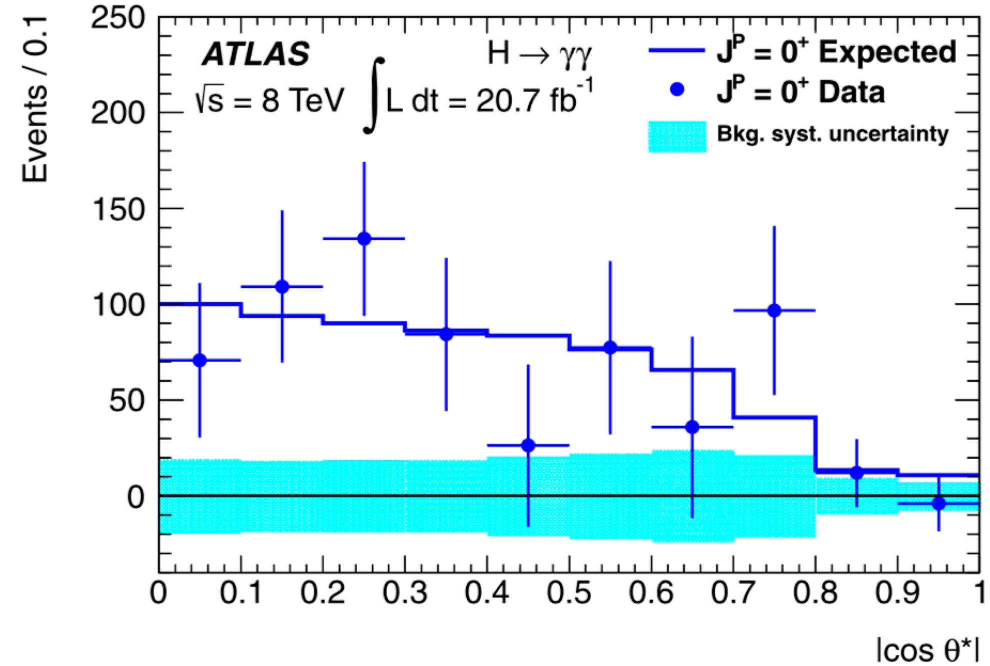

CMS
35.9 fb^{-1} (13 TeV)
Observed
Expected (Background only)
Expected (SM m$_H$=125 GeV)
68% expected
95% expected
σ/σ$_{SM}$=1
H→Zγ→llγ, Lepton tag
H→Zγ→eeγ, Untagged 1
H→Zγ→eeγ, Untagged 2
H→Zγ→eeγ, Untagged 3
H→Zγ→eeγ, Untagged 4
H→Zγ→eeγ, Dijet tag
H→Zγ→eeγ, Boosted
H→Zγ→μμγ , Untagged 1
H→Zγ→μμγ, Untagged 2
H→Zγ→μμγ, Untagged 3
H→Zγ→μμγ, Untagged 4
H→Zγ→μμγ, Dijet tag
H→Zγ→μμγ, Boosted
H→γ*γ→μμγ, EE
H→γ*γ→μμγ, Dijet tag
H→γ*γ→μμγ, EB Low R9
H→γ*γ→μμγ, EB High R9
H→Zγ→llγ, Combined
H→γ*γ→μμγ, Combined
H→ llγ, Combined
95% CL upper limit on σ/σ$_{SM}$

Higgs spin measurement

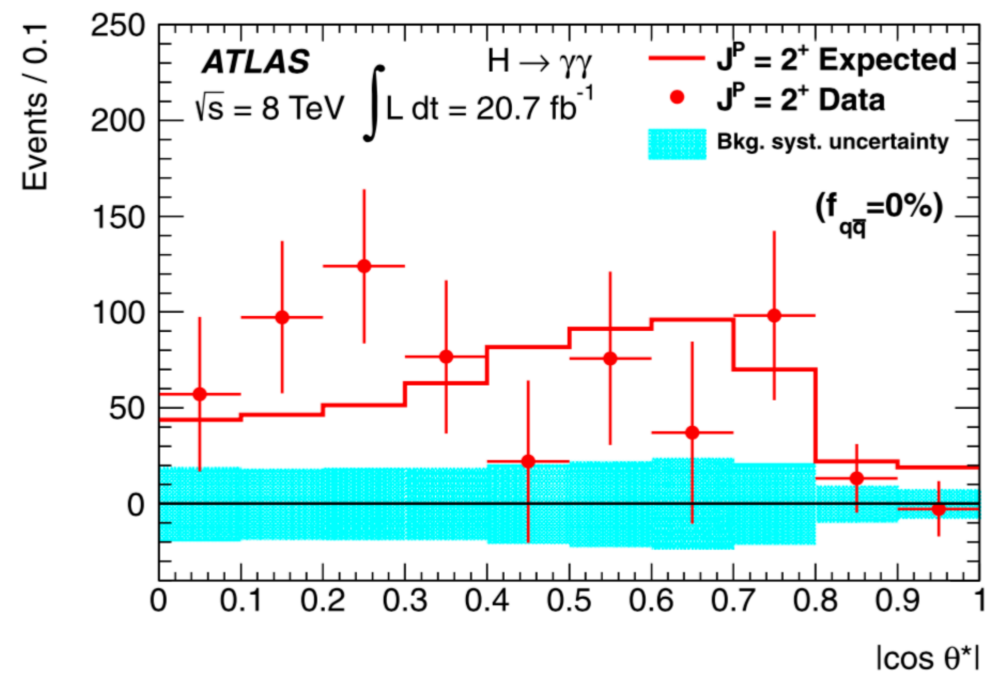
The H → γ γ decay mode is sensitive to the spin of the Higgs boson through the measurement of the polar angular distribution of the photons in the resonance rest frame. For this channel, the SM spin hypothesis is compared only to the $J^P = 2^+$ hypothesis. Spin information can be extracted from the distribution of the ab- solute value of the cosine of the polar angle θ* of the photons with respect to the z-axis of the Collins–Soper frame

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$





(a)



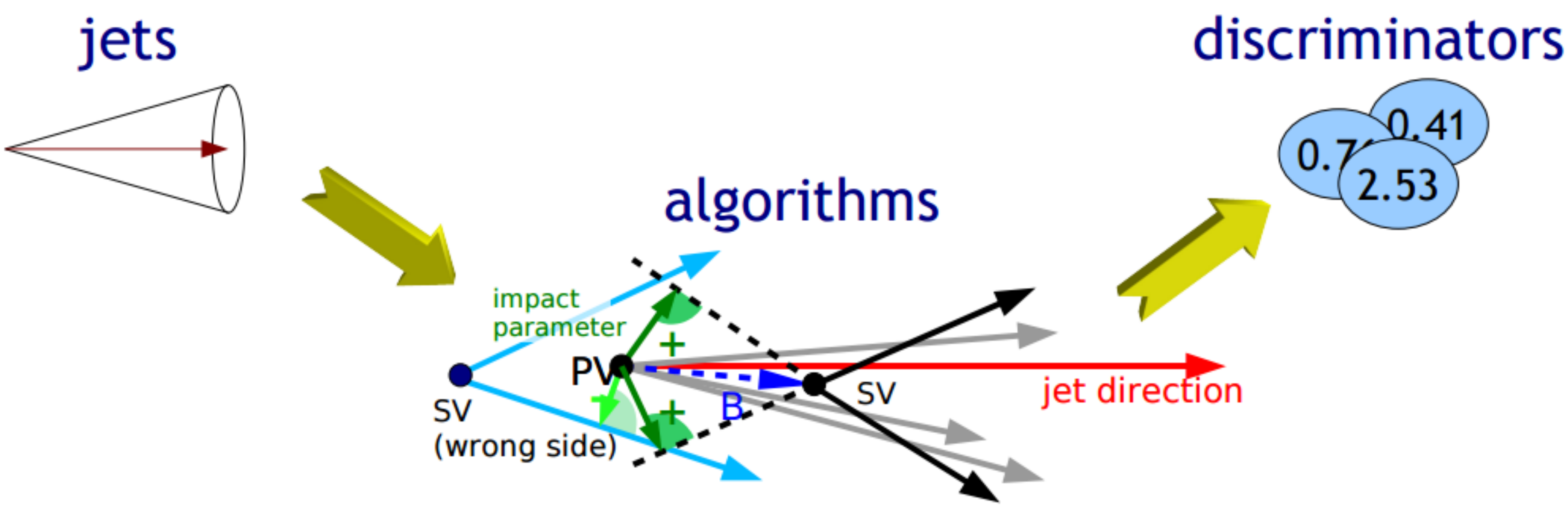
(b)

Phys.Lett. B726 (2013) 120-144

CSVM

b-quarks significantly differ from light flavour quarks by:

- mass: m = 4.2 GeV
- lifetime: $\tau \approx 1.5$ ps → ~1.8mm *(at 20 GeV)* before decay
- decay: weak, mostly into c-quarks *(→ 3rd decay)* → 20% into leptons
- tracks: high decay multiplicity, significant displacement
- Secondary vertices *(SV)*: tracks intersecting at a common vertex



Jet Algorithm

- Introduce angular radius R (NB: dimensionless!)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad d_{iB} = p_{ti}^2$$

1. Find smallest of d_{ij}, d_{iB}
2. if ij, recombine them
3. if iB, call i a jet and remove from list of particles
4. repeat from step 1 until no particles left.

Anti kT:
collinear and Infrared safe, hard object clustered first
Computationally takes less time