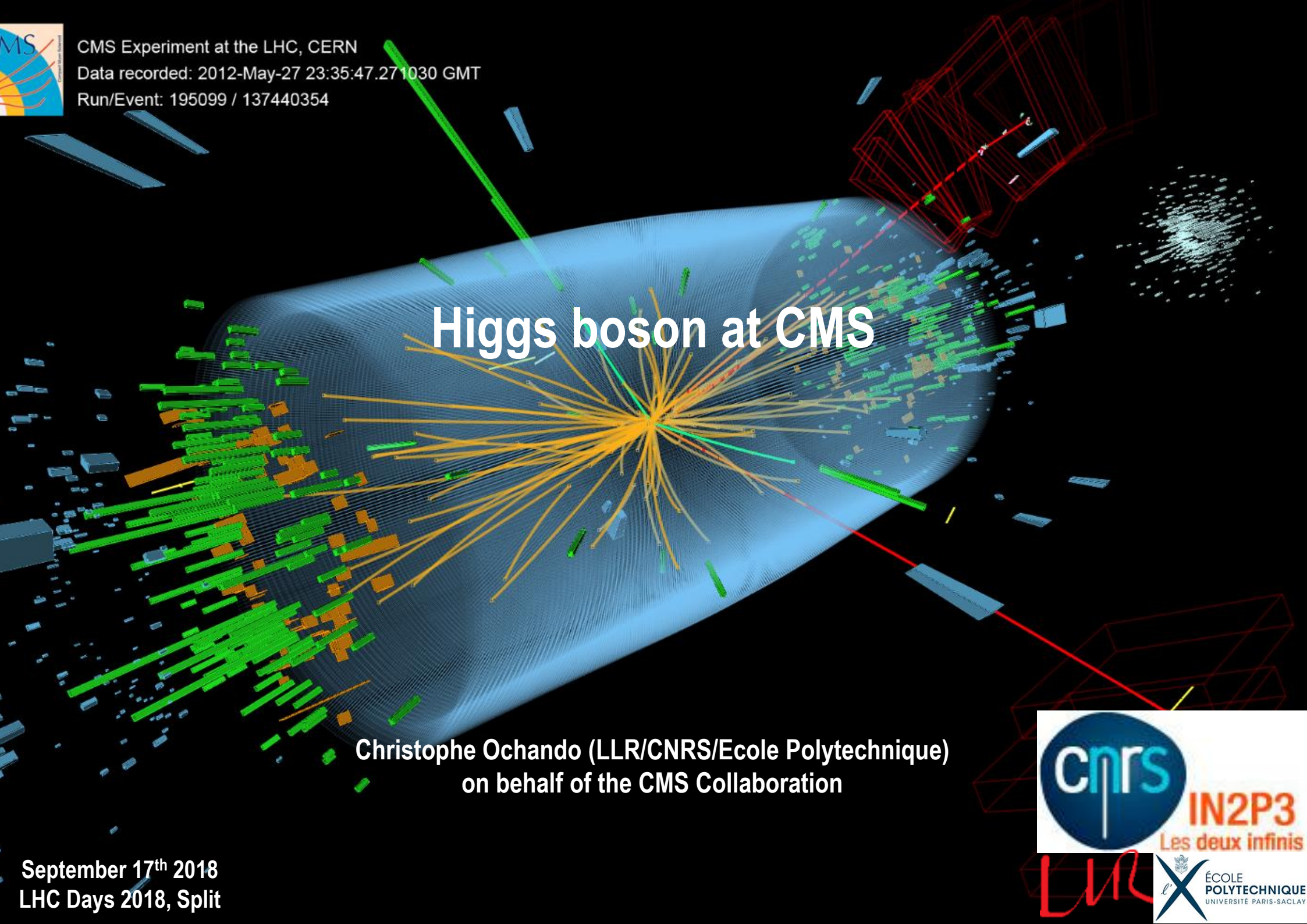



# Higgs boson at CMS

Christophe Ochando (LLR/CNRS/Ecole Polytechnique)
on behalf of the CMS Collaboration

September 17th 2018
LHC Days 2018, Split

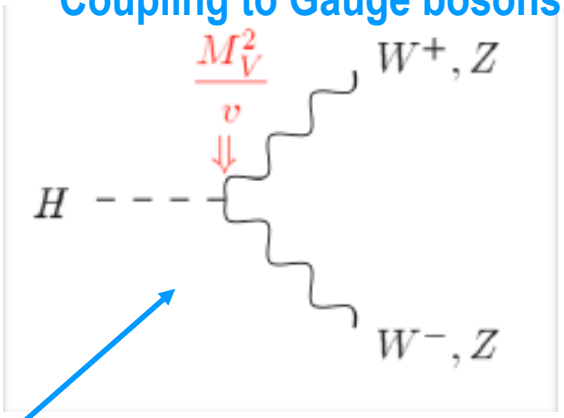
# Higgs Lagrangian: back to basics…

**Standard Model Lagrangian: 2 main parts:**

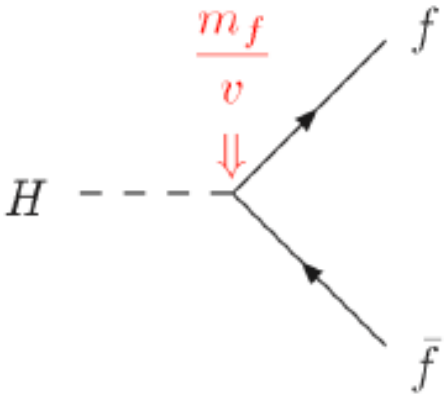
- **Gauge:** based on symmetries, elegant
- **Higgs mechanism:** Ad-hoc… but necessary to describe reality (gives mass to elementary particles, allows unitarity, …)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Coupling to Gauge bosons.




Coupling to fermions




Completely defines the production and decay modes of the Higgs boson

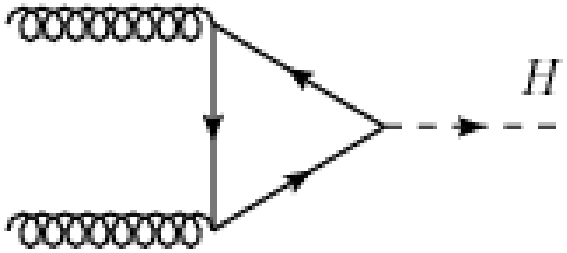
# Reminder: Higgs production & decay at colliders

## Main production Modes

(for mH=125 GeV, LHCXSWG 4)

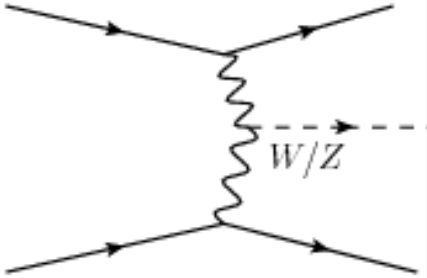
**Glusion fusion (ggH)**

48.58 pb



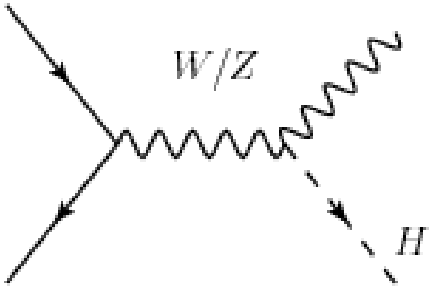

**Vector Boson Fusion (VBF)**

3.78 pb



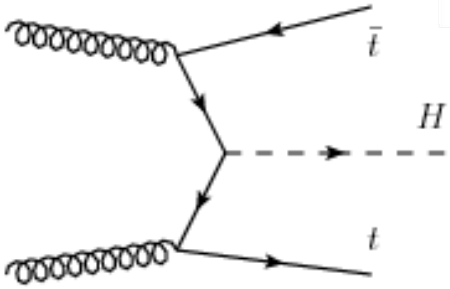

**Associated production with Vector Boson (VH)**

1.373 pb (WH)
0.8839 pb (ZH)

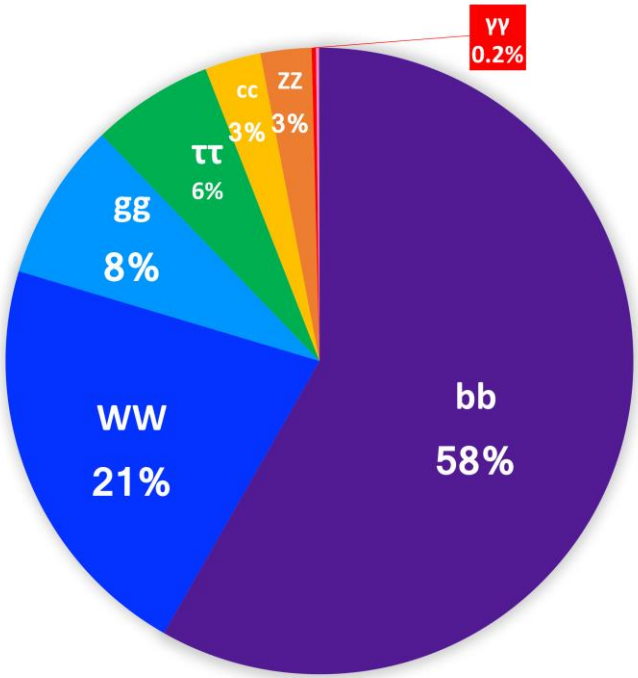



**Associated production with quarks (ttH, bbH)**

0.5071 pb (ttH)
0.488 pb (bbH)

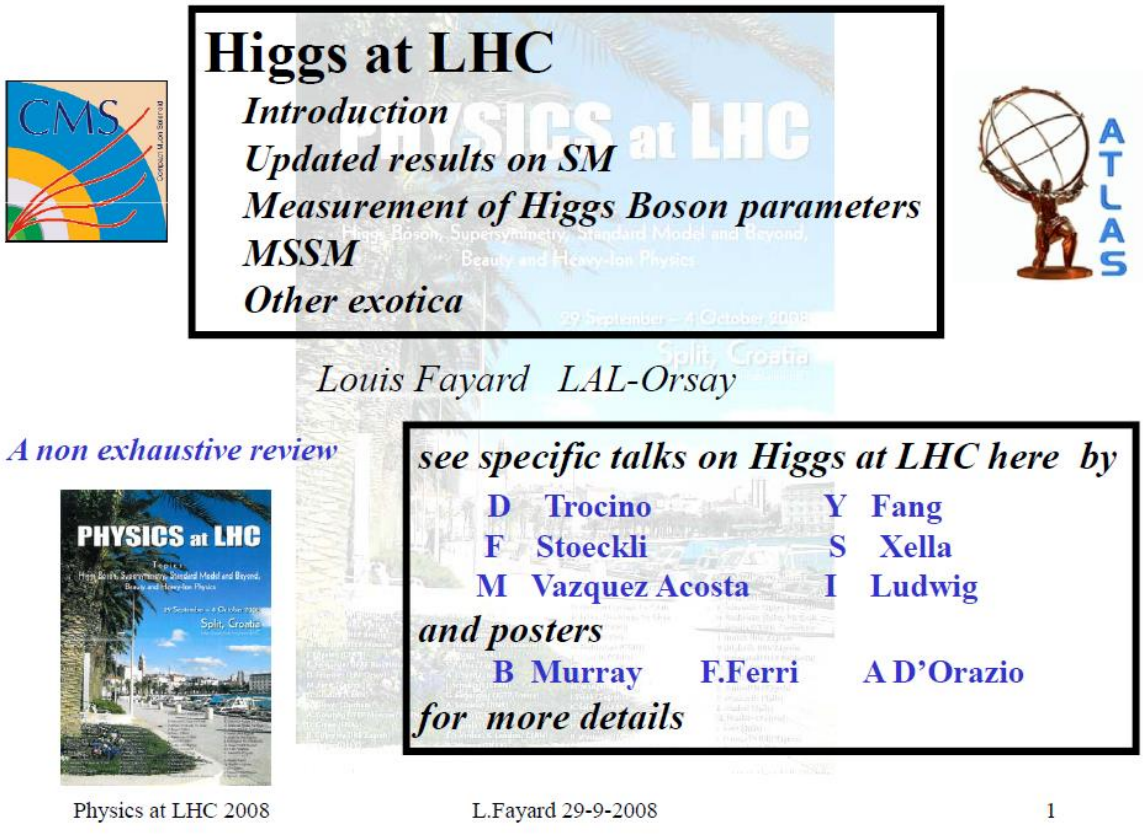


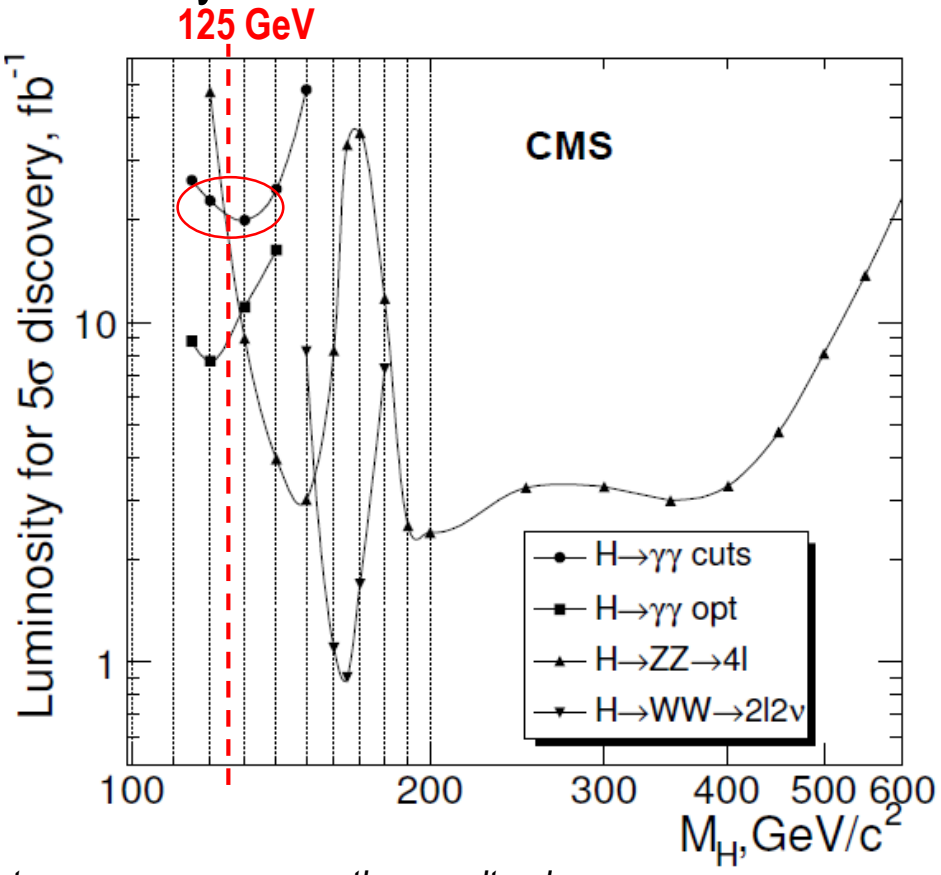

## Main decay Modes



# (interlude) let's go back in time…

- September 2018: 10 years Birthday of LHC first operations…
- 10 years ago, Higgs was discuss at Split in "Physics at LHC 2008"…



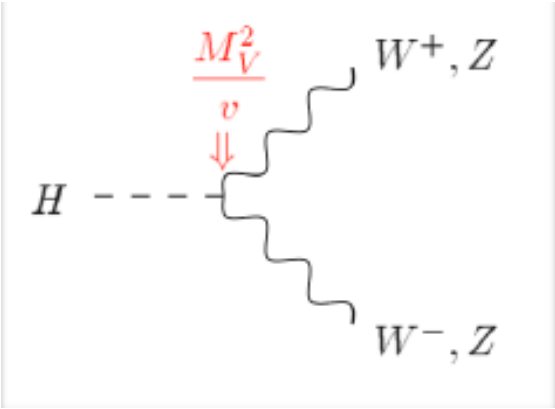

*As elegant as it is, the Higgs mechanism is an invention that poses as many questions as it solves…*
by: a theorist, cited in Split 2008 L. Fayard's talk, who developed a no-Higgs model…

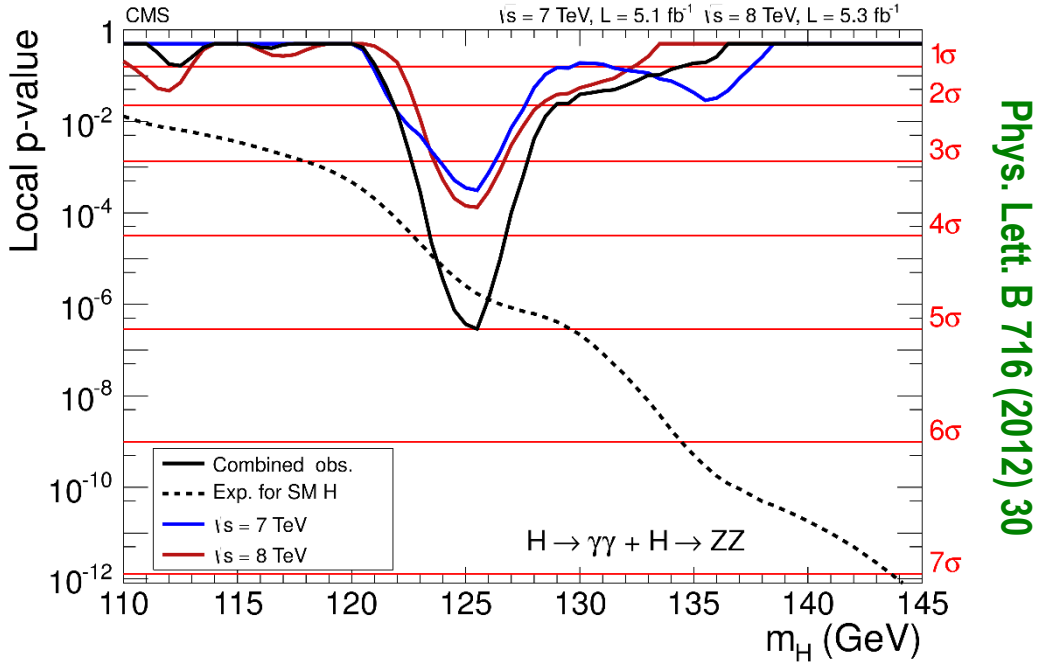
- At that time, one of the claim was:
  - ~20 fb-1 @ 14 TeV needed for discovery in H->ZZ->4l
  - We actually did it with less than 20 fb-1… at 8 TeV (production cross section divided by ~2)
    - **Thanks to big improvements in theoretical calculations and experimental techniques**
- **Where are we now ?**

# Higgs coupling to gauge bosons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

**Coupling to Gauge bosons.**



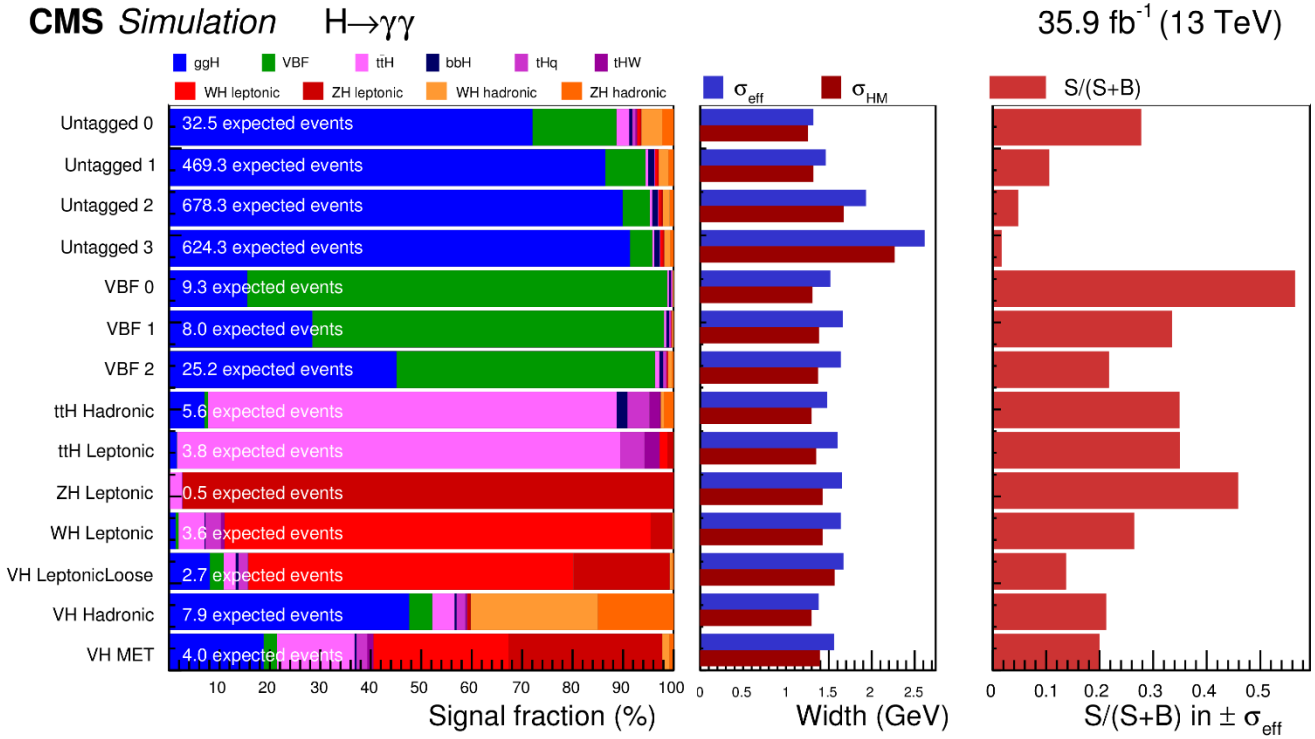

Phys. Lett. B 716 (2012) 30

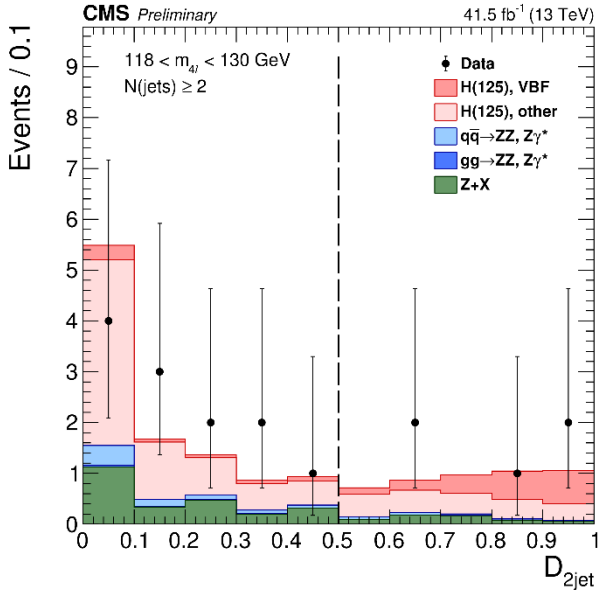
Main decay modes used for discovery in 2012
Moving to (precise) measurements…

# H→γγ, H→ZZ→4l, H→WW→2l2ν: short summary

- **H→γγ:** 2 high pT photons,
  - signal as high resolution peak on top of falling background. Low S/B.
- **H→ZZ→4 leptons (e or μ):** 4 isolated primary leptons (down to 5 GeV!),
  - signal as a high resolution peak over ~small background. But small statistics.
- **H→WW→2l2ν:** 2 opposite sign leptons + Missing ET from neutrinos.
  - Large yield but no full reconstruction of Higgs boson mass

- With increasing luminosity, move from inclusive analysis (for discovery) to categories targeting rare production modes (+ increase S/B):
  - Asking for additional leptons, (b-)jets, MET, kinematics, …
    … with simple cuts, BDT's or Matrix Element techniques

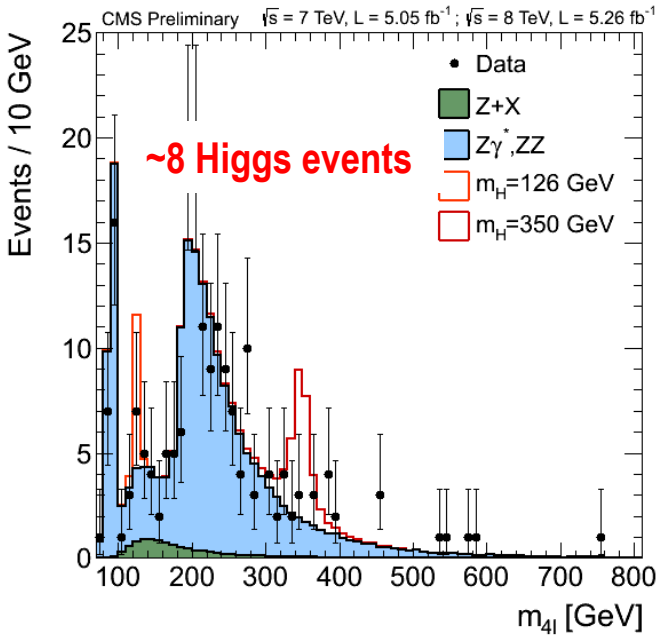


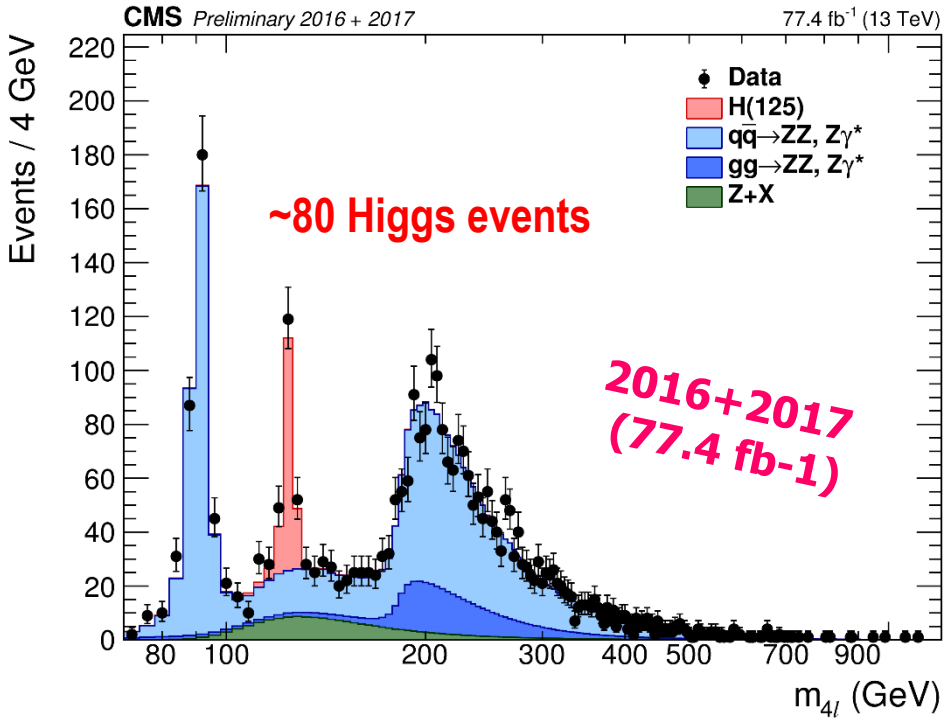

**Kinematic Discriminant to separate ggH vs VBF**

# H→γγ, H→ZZ→4l, H→WW→2l2ν: Spectrum

## We've come a long way since the discovery…

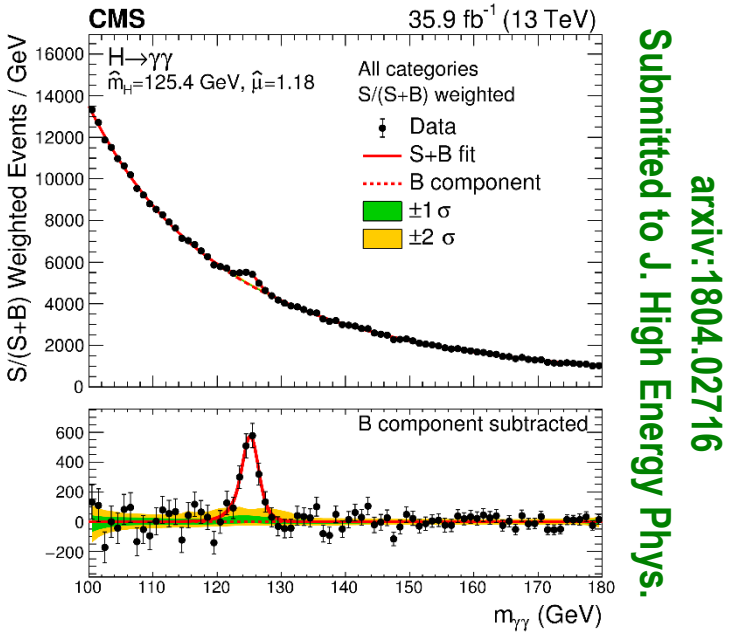



From early Run I to Run II

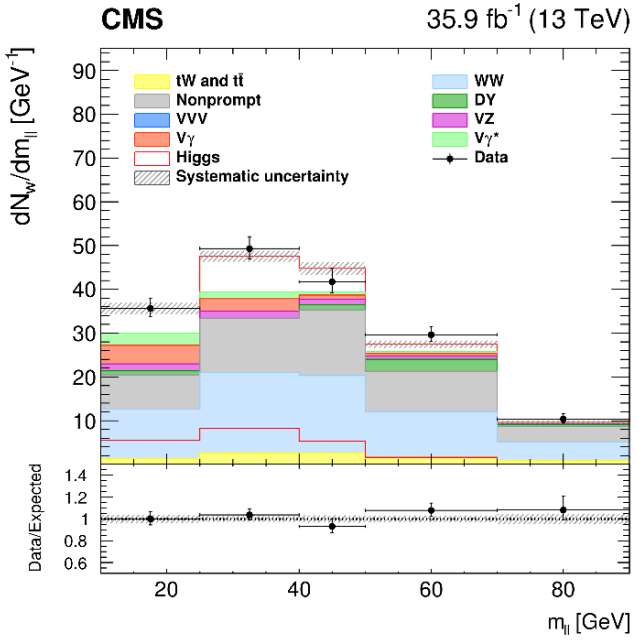



CMS-PAS-HIG-18-001

2016 (~36 fb-1)



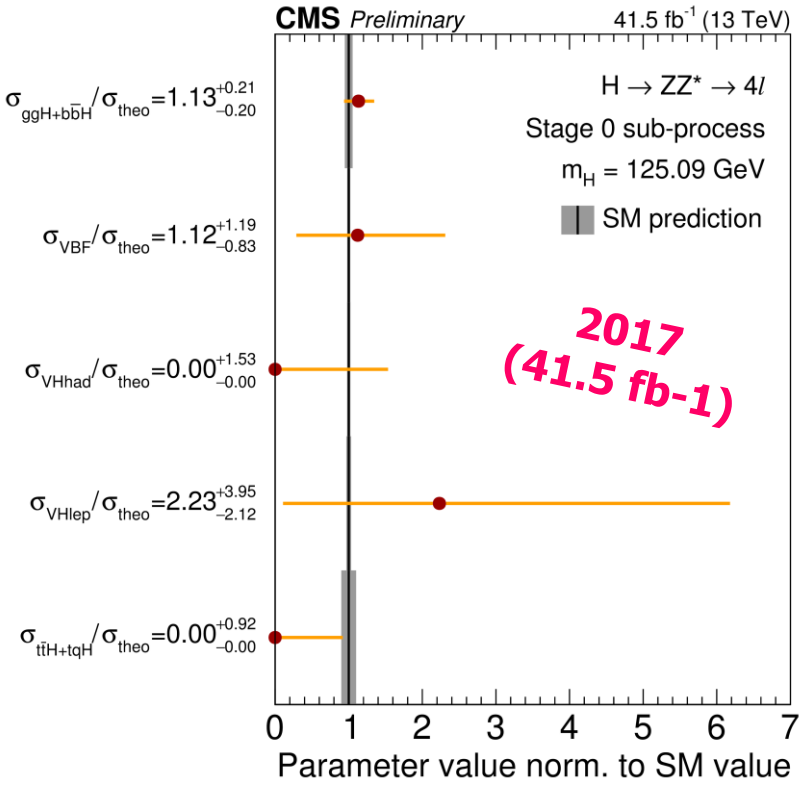

arxiv:1804.02716 Submitted to J. High Energy Phys.

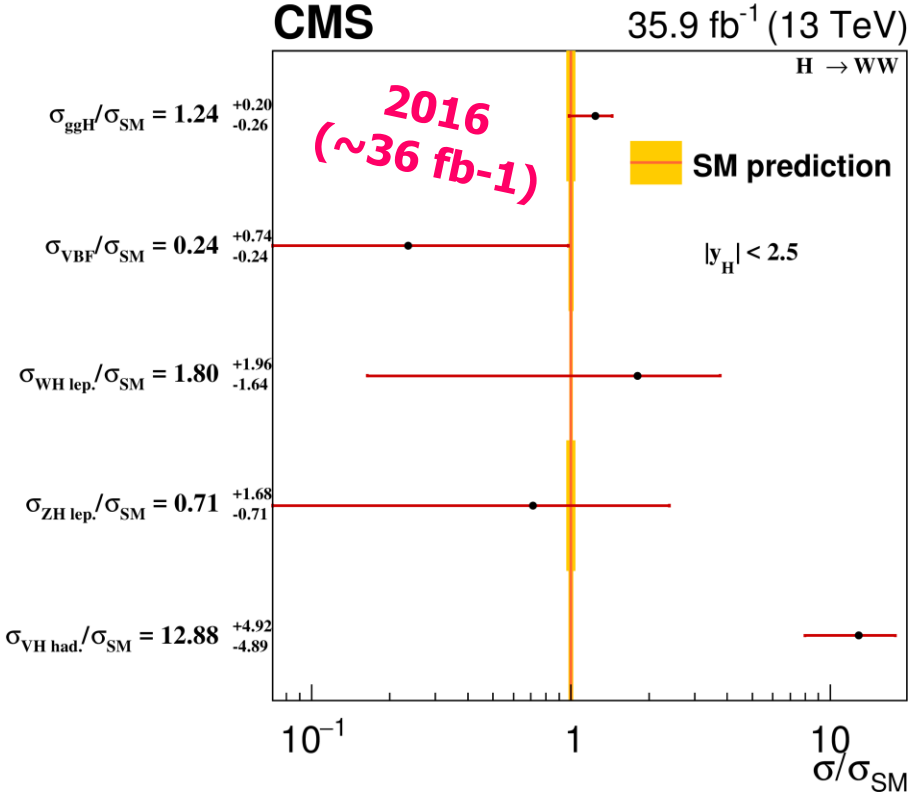



arxiv:1806.05246 Submitted to Phys. Lett. B

# Simplified Template Cross-section

- Measurement of the fiducial cross-section in the "stage-0" simplified template cross-section framework, for various signal processes (ggH, VBF, VH, ttH) [aim at minimizing dependence to theory]
  - Signal processes defined requiring |yH|<2.5 at generator level
  - SM prediction for signal cross sections taken from LHC Higgs XS WG (YR4)




(also for Hgg, see back-up)

$\frac{\sigma}{\sigma_{SM}}$ (inclusive)

| | |
|---|---|
| H→γγ | $1.18^{+0.12}_{-0.11}(\text{stat})^{+0.09}_{-0.07}(\text{syst})^{+0.07}_{-0.06}(\text{theo})$ |
| H→ZZ | $1.06^{+0.10}_{-0.10}(\text{stat})^{+0.08}_{-0.06}(\text{syst})^{+0.07}_{-0.05}(\text{theo})$ |
| H→WW | $1.28^{+0.10}_{-0.10}(\text{stat})^{+0.11}_{-0.11}(\text{syst})^{+0.10}_{-0.07}(\text{theo})$ |

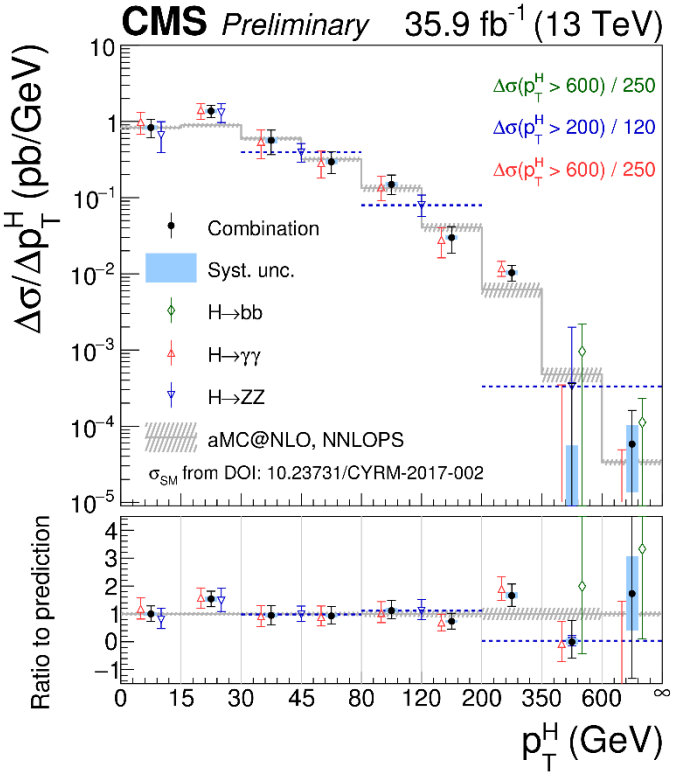
**Now dominated by systematic (exp+theo) uncertainties**

# Differential cross-sections (1/2)

- Increasing luminosity of Run II now **allows precision measurement on differential cross-section**.
  - Combination of H→γγ and H→ZZ measurements (also boosted H→bb for high pT)

## pT(H)

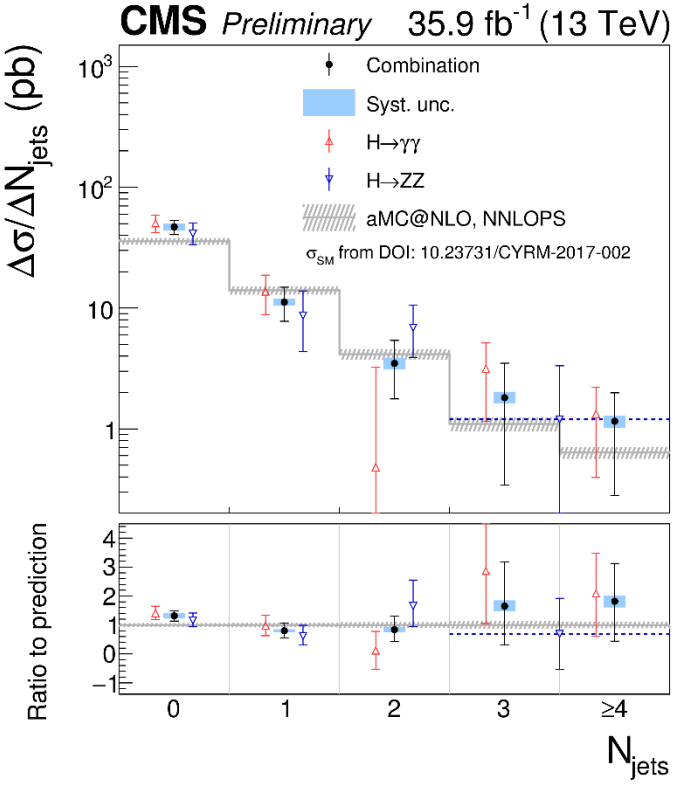
Sensitive to perturbative QCD modelling, production mode, yukawa couplings,…




30-40% precision up to 350 GeV

## N(jets)

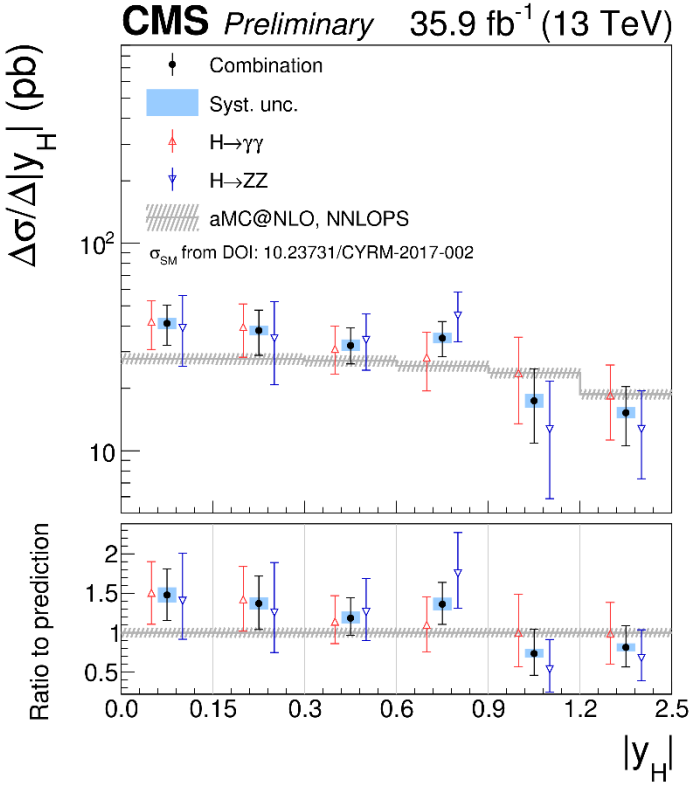
Test of modelling QCD radiation, production mechanism




20% precision in 0-jet bin

## Y(H)

Probes of PDFs, production mode,…




30-50% precision across the spectrum

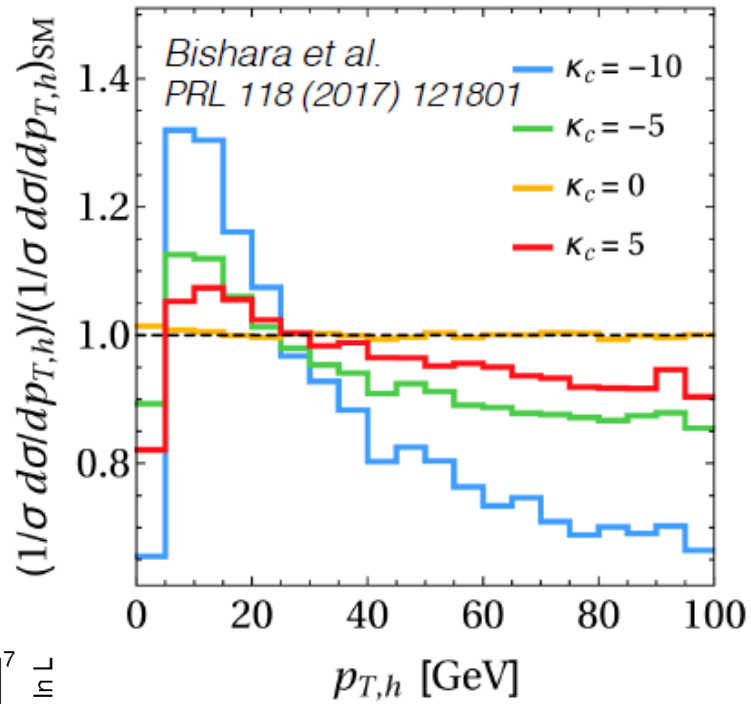
CMS-PAS-HIG-17-028

2016 (~36 fb-1)

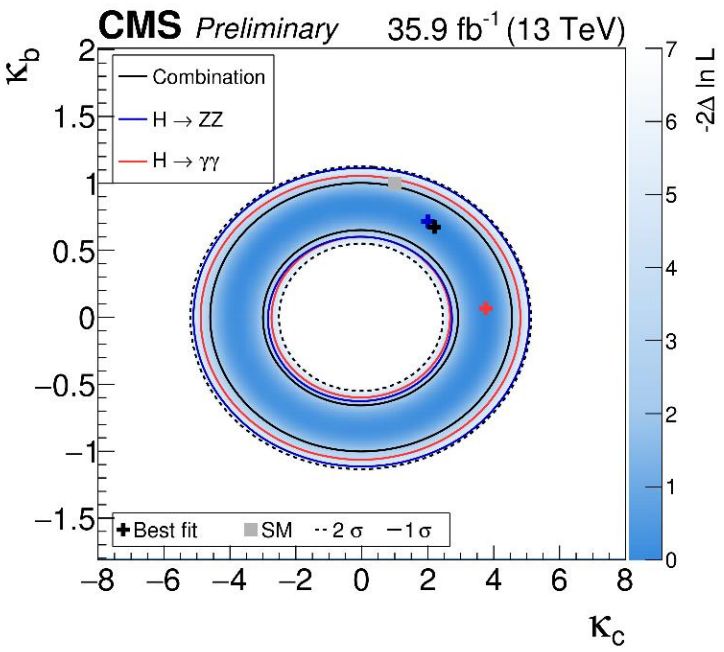
Measurement largely dominated by statistics ! Great improvements to come

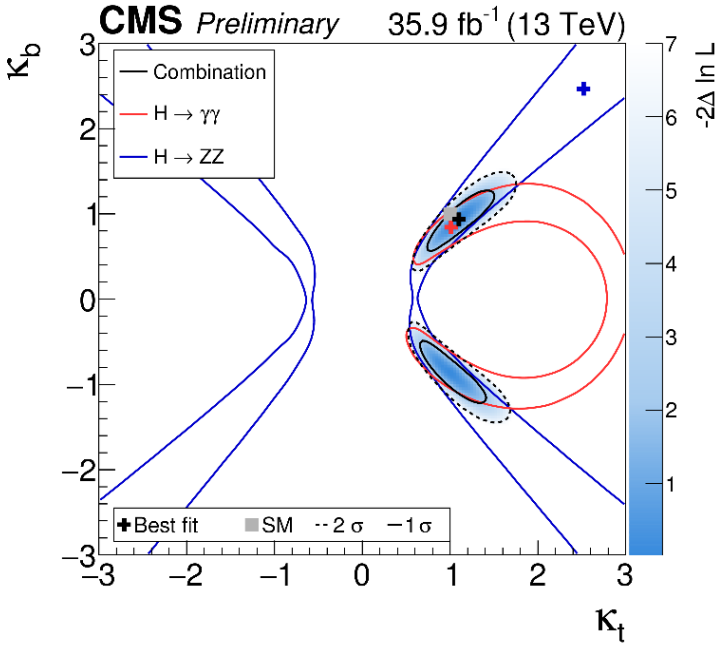
# Differential cross-sections (2/2)

- Higgs pT spectrum very sensitive to modifications of the couplings
  - Can give information on couplings not possible via inclusive measurements




- Couplings to b, c & top quarks in k-framework



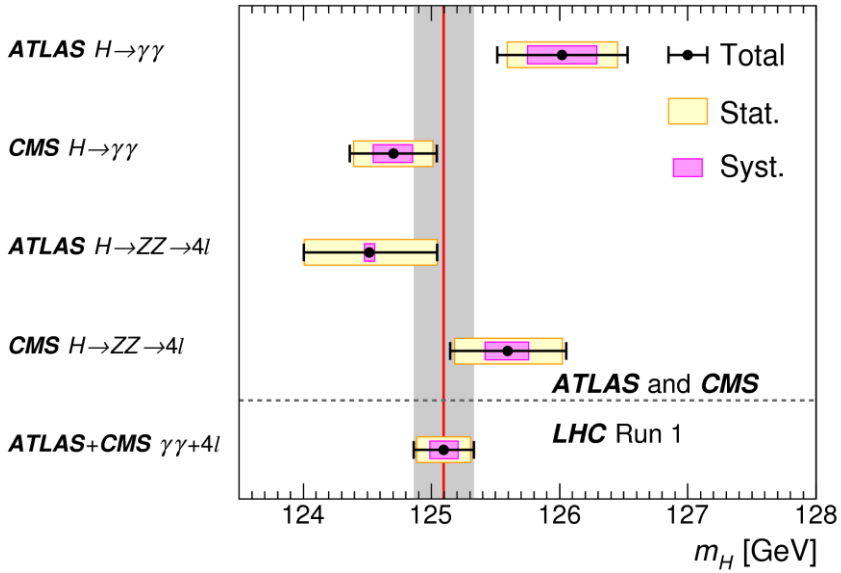




Results are dependant on the assumptions about Branching Ratios (here, assume BR scaling with couplings)

$-0.9 < k_b < 0.9 \quad (-1.2 < k_b < 1.2 \text{ expected})$

$-4.3 < k_c < 4.3 \quad (-5.4 < k_c < 5.3 \text{ expected})$

# Higgs boson mass measurement



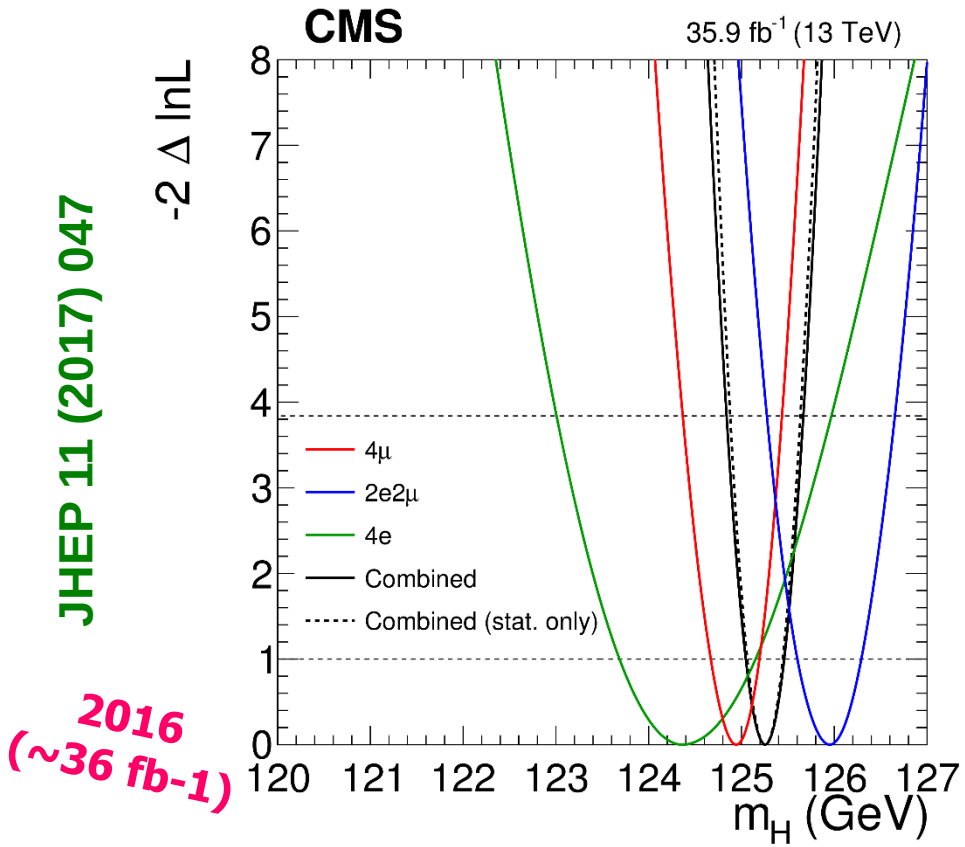

**ATLAS + CMS Run I (~25 fb-1 each, 7+8 TeV)**

H→ZZ→4 leptons + H→γγ

$m_H = 125.09 \pm 0.24$ GeV

$= 125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$ GeV

(1.9 per-mille precision)




**CMS Run II (~36 fb-1 each, 13 TeV)**

H→ZZ→4 leptons only

**$m_H = 125.26 \pm 0.21$ GeV**

**$= 125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})$ GeV**

**Most precise LHC measurement of $m_H$ (1.7 per-mille!)**

# Higgs width & anomalous couplings (1)

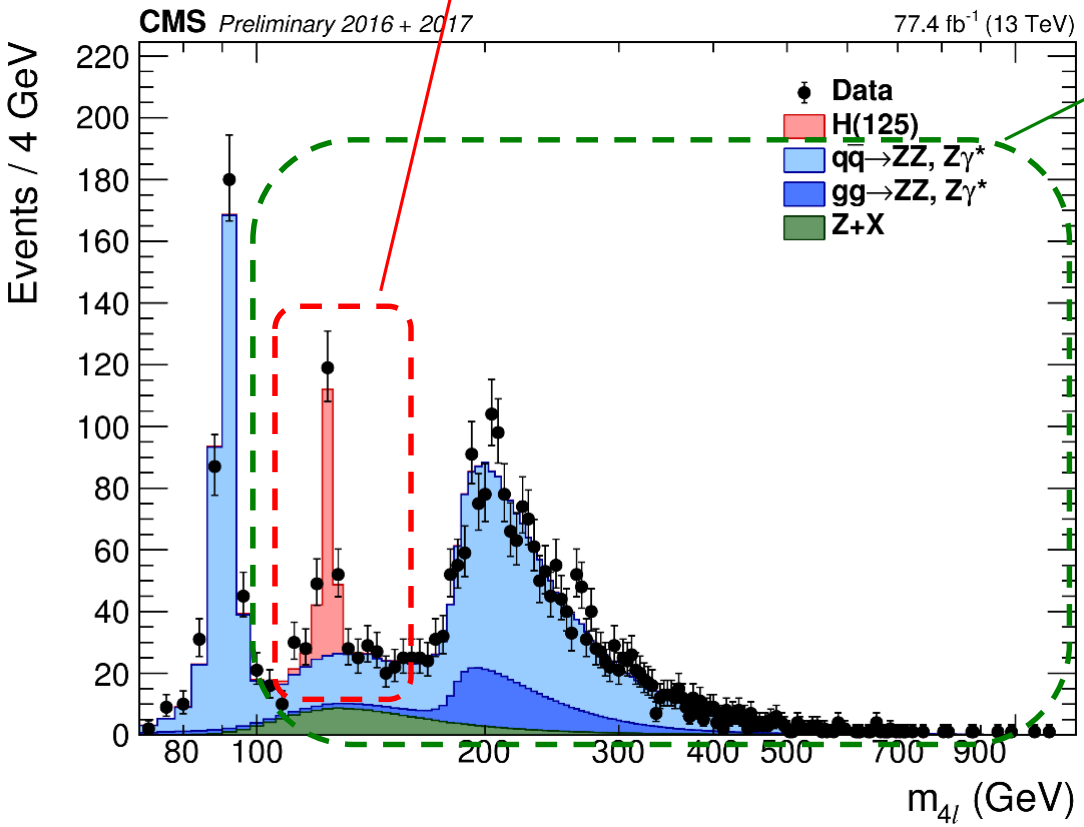
Higgs boson width (4.1 MeV @ 125 GeV) not directly measureable due to limitations from detector resolution (~1 GeV)

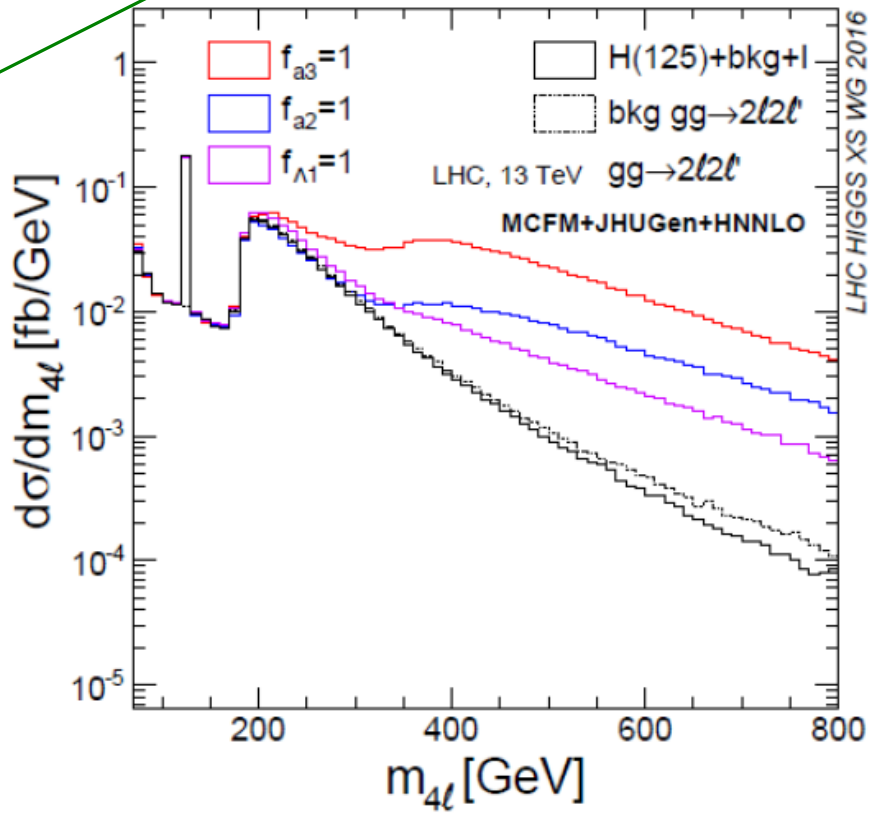
- Can be probed by analysing **on-shell & off-shell distributions**:

HOT OFF THE PRESS

On-shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{m_H^2 \Gamma_H^2} dq_H^2 \propto \mu_{prod}$

Off-shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2} dq_H^2 \propto \mu_{prod} \cdot \mu_H$



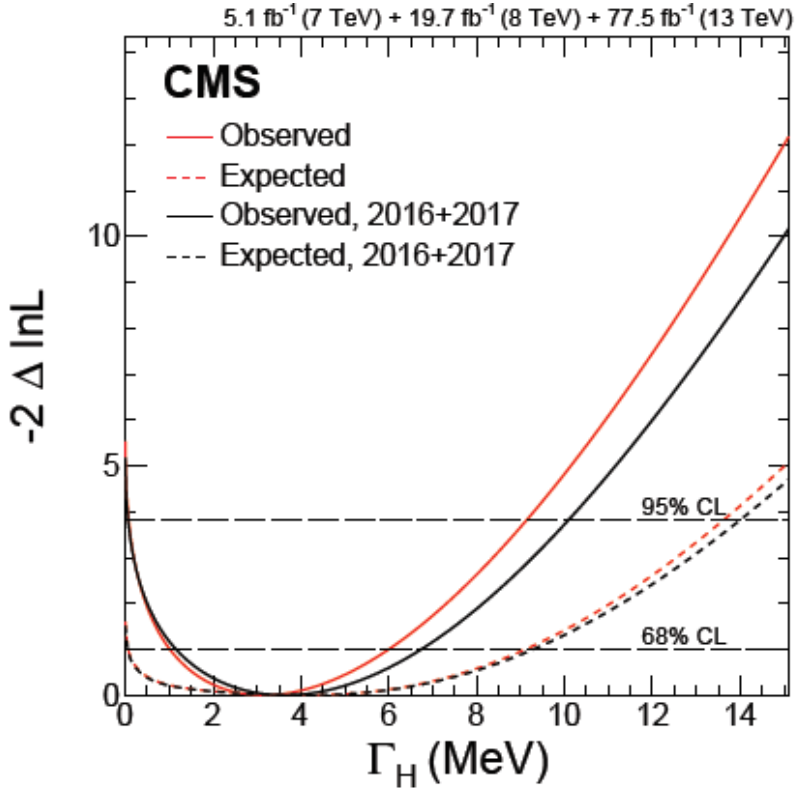

CMS-PAS-HIG-18-002

Anomalous couplings enhance off-shell yield, change m4l & other kinematics

# Higgs width & anomalous couplings (2)

HOT OFF THE PRESS

CMS-PAS-HIG-18-002




**RunI + Run II combination**

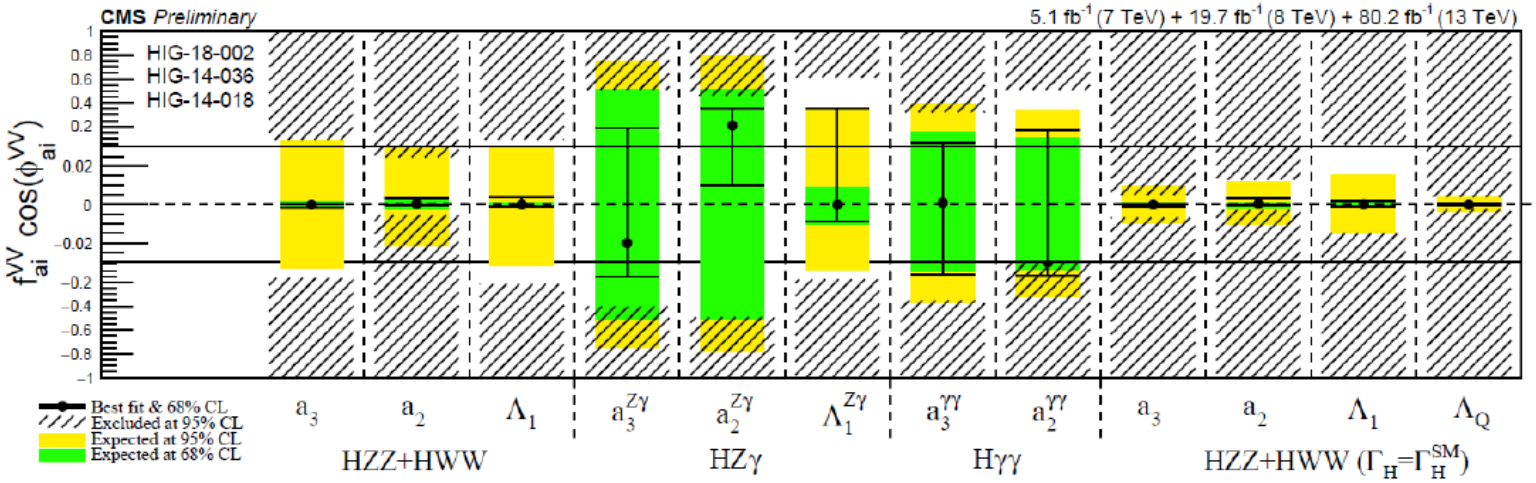
| Parameter | Observed | Expected |
|---|---|---|
| $\Gamma_H$ (MeV) | $3.2^{+2.8}_{-2.2}$ [0.08, 9.16] | $4.1^{+5.0}_{-4.0}$ [0.0, 13.7] |

**Best LHC result**

$$A(HVV)\sim\left[a_1 - e^{i\phi_{\Lambda Q}}\frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}^{VV'}}\frac{(\kappa_1 q_{V1}^2+\kappa_2 q_{V2}^2)}{\Lambda_1^2}\right]m_V^2\epsilon_{V1}^*\epsilon_{V2}^*$$

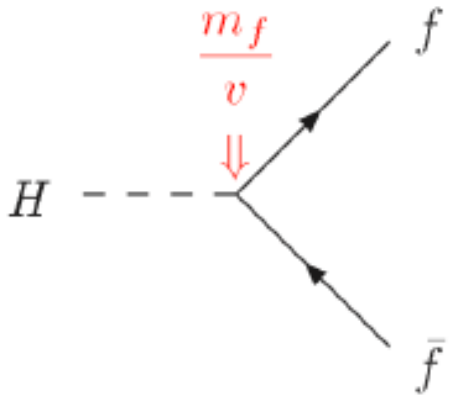
$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)}\tilde{f}^{*(2),\mu\nu}$$

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j} \qquad \phi_{ai} = \tan^{-1}(a_i/a_1)$$

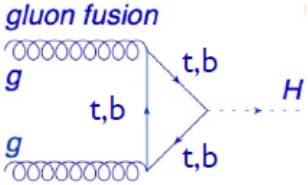


# Higgs coupling to fermions

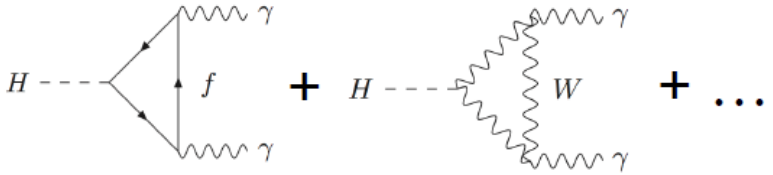
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$




- **Can be probed:**
  - Indirectly (through loop diagrams)
  - Directly (tree-level diagrams)

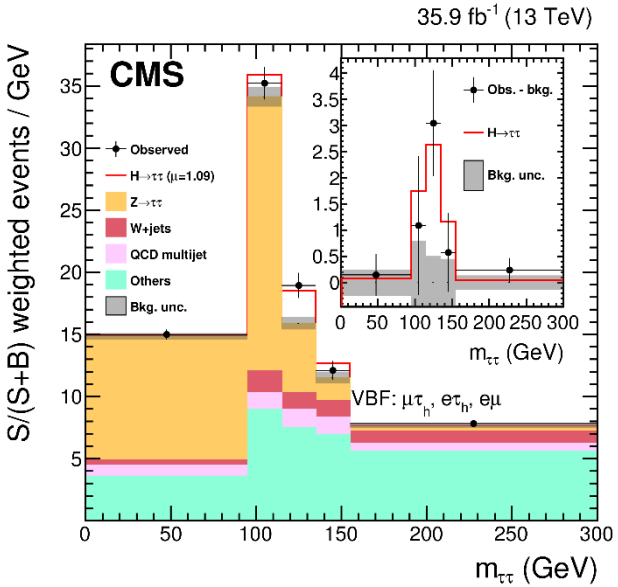



$gg \to H$




$H \to \gamma\gamma$

Phys. Lett. B 779 (2018) 283




- Observation of coupling to taus announced on May 2017
  - **first single experiment observation of coupling to leptons**
    - Combining Run I + Run II
  - Run II now reaches >5 sigmas alone as well (ggH+VBF+ new VH)
- **What about quarks ?**

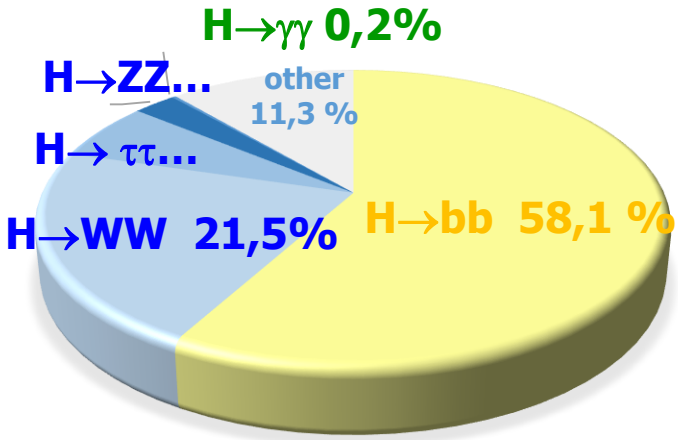
arxiv:1809.03590
Submitted to J. High Energy Phys.

# ttH overview

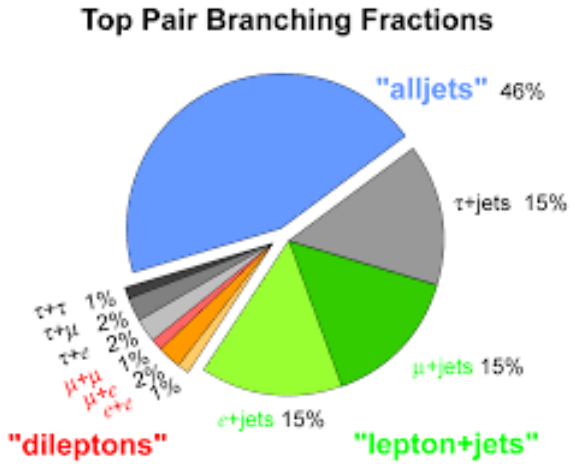
**ttH:** directly probe top Yukawa coupling at tree level through associated production

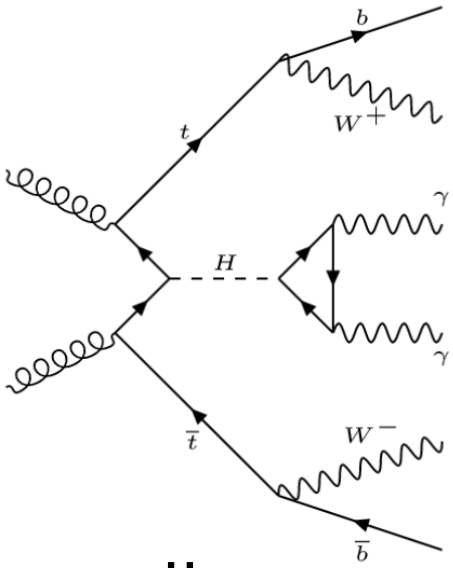
## RunII ttH analysis in CMS:

Final states combine Higgs & Top decay



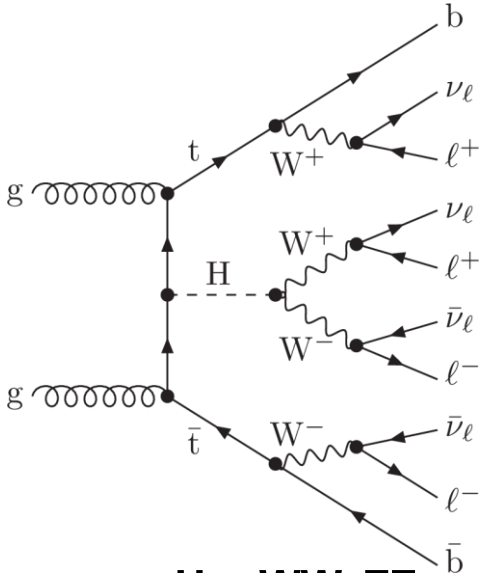

X



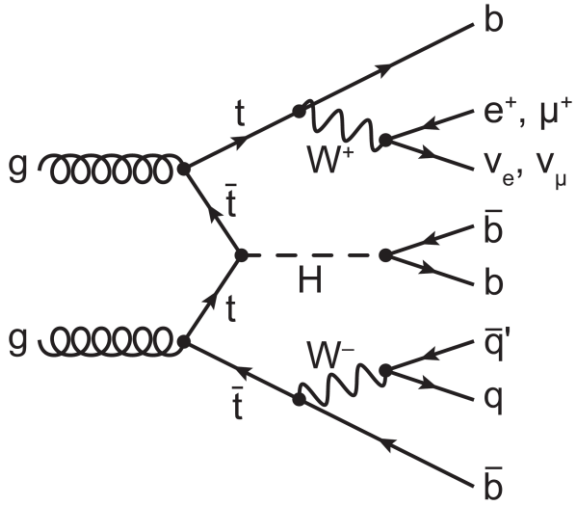

**H→γγ**

High purity, low yield




**H→WW, ZZ, ττ**

**"multileptons"**

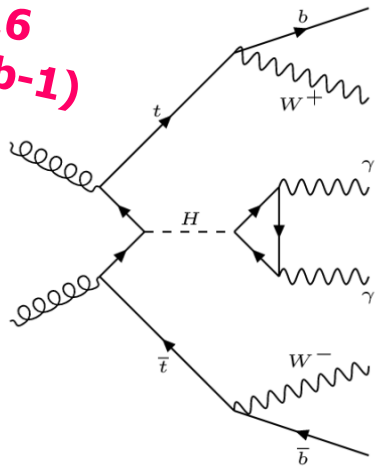



**H→bb**

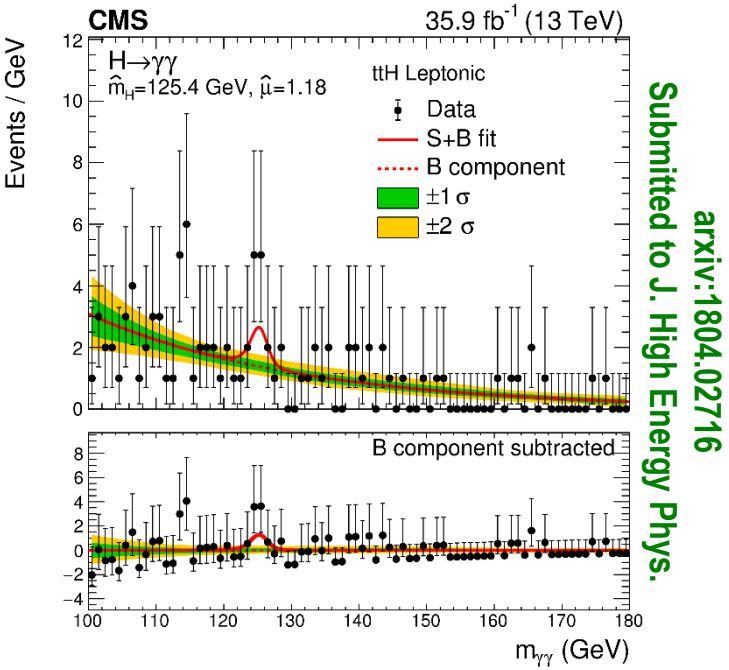
Low purity, high yield

# ttH results (2016 data)

2016 (~36 fb-1)

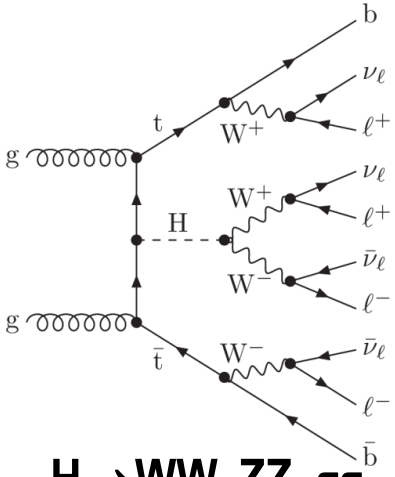


## H→γγ

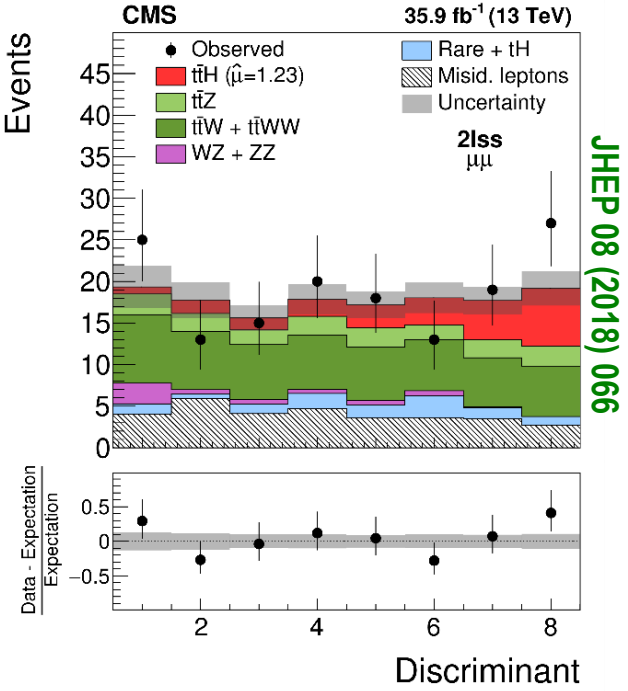



arxiv:1804.02716 Submitted to J. High Energy Phys.

$\mu=(\sigma/\sigma_{SM})=2.2^{+0.9}_{-0.8}$



## H→WW, ZZ, ττ "multi-leptons"

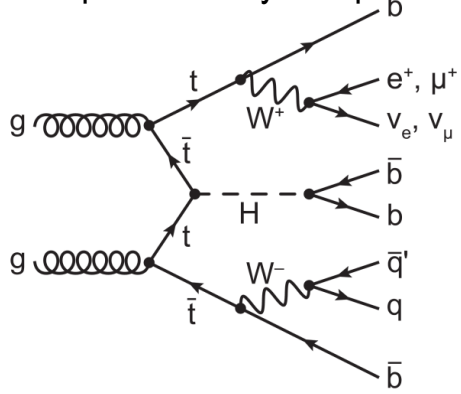



JHEP 08 (2018) 066

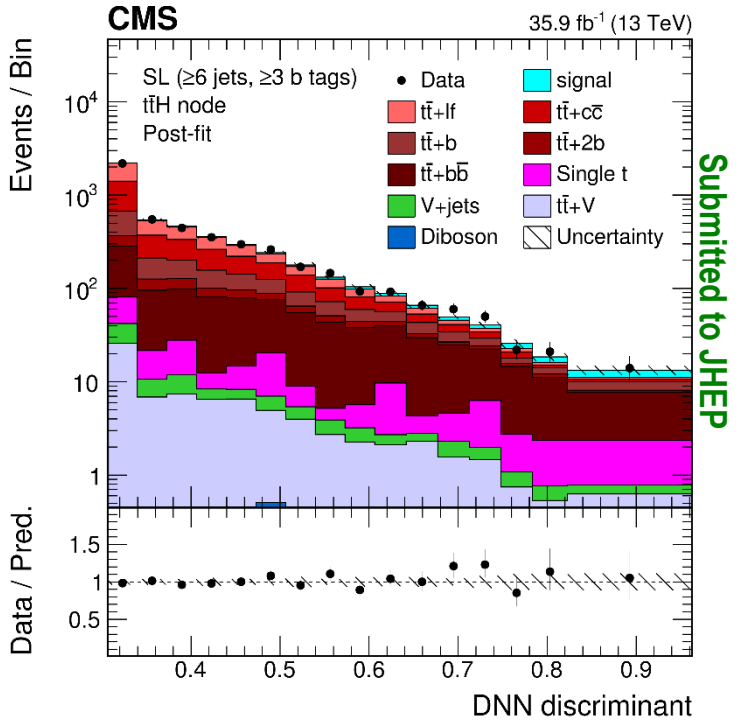
Significance: 3.2 σ (2.8 σ)

$\mu=(\sigma/\sigma_{SM})=1.23^{+0.45}_{-0.43}$

With either hadronic or leptonic decay of top



## H→bb



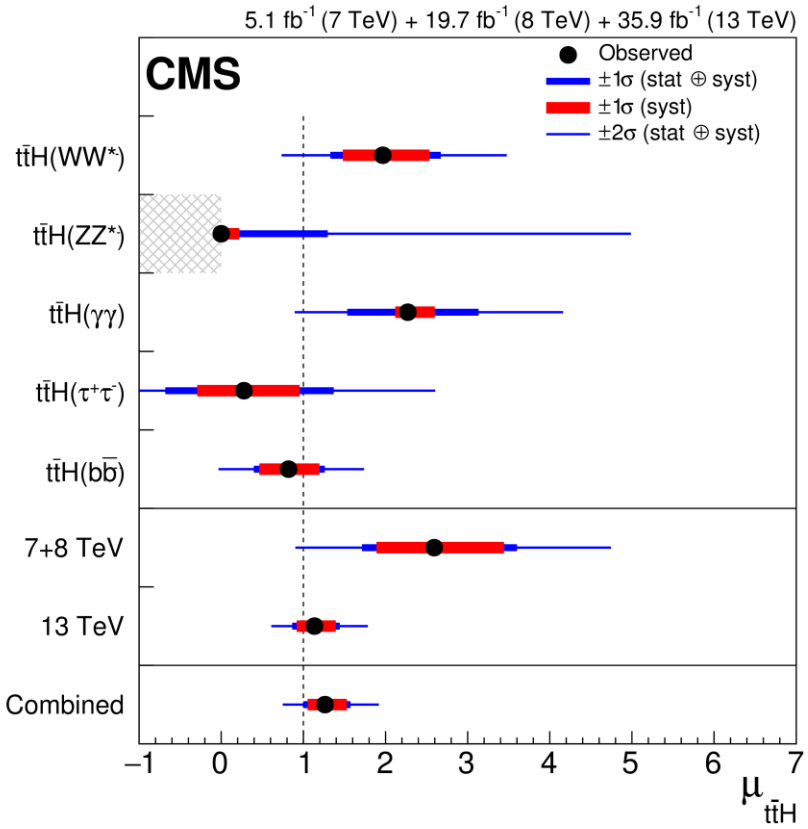

arXiv:1804.03682 Submitted to JHEP

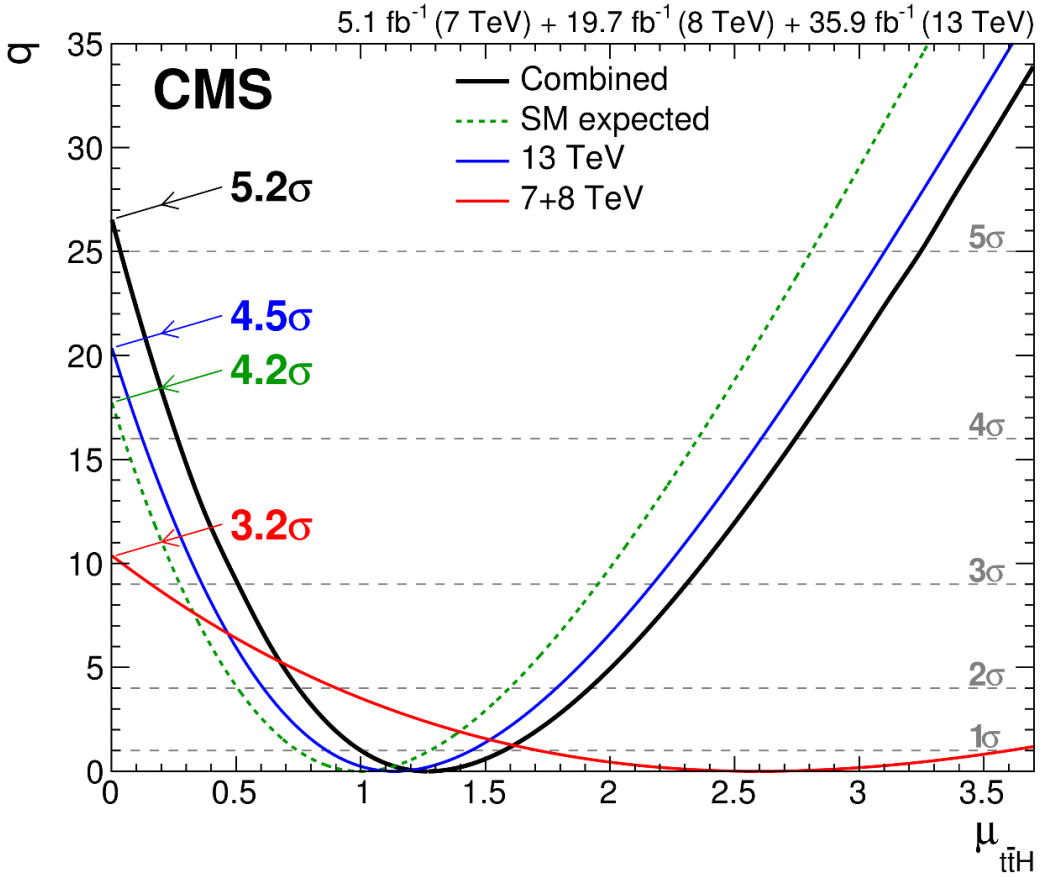
Significance: 1.6 σ (2.2 σ)

$\mu=(\sigma/\sigma_{SM})=0.72^{+0.45}_{-0.45}$

# Observation of ttH

- **Grand combination of all ttH analyses (multileptons, bb, γγ) from Run I + Run II (2016)**
  - Inclusive signal theory and some background theory uncertainties are treated as correlated
  - Experimental uncertainties largely uncorrelated




Phys. Rev. Lett. 120 (2018) 231801

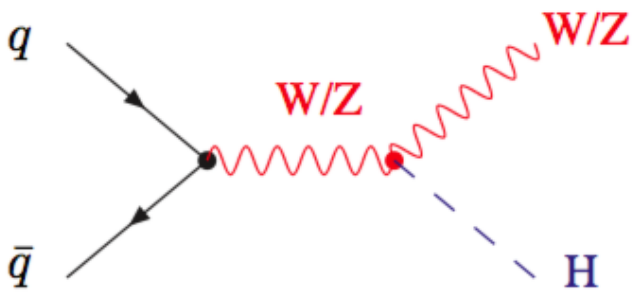
Measured signal strength
$\mu=(\sigma/\sigma_{SM})=1.26^{+0.31}_{-0.26}$

Significance: **5.2 σ observed**
(4.2 σ expected)

**Observation ttH by the CMS Collaboration**

**First single experiment observation** (paper submitted April 8th)

# VH→bb (2017 data)

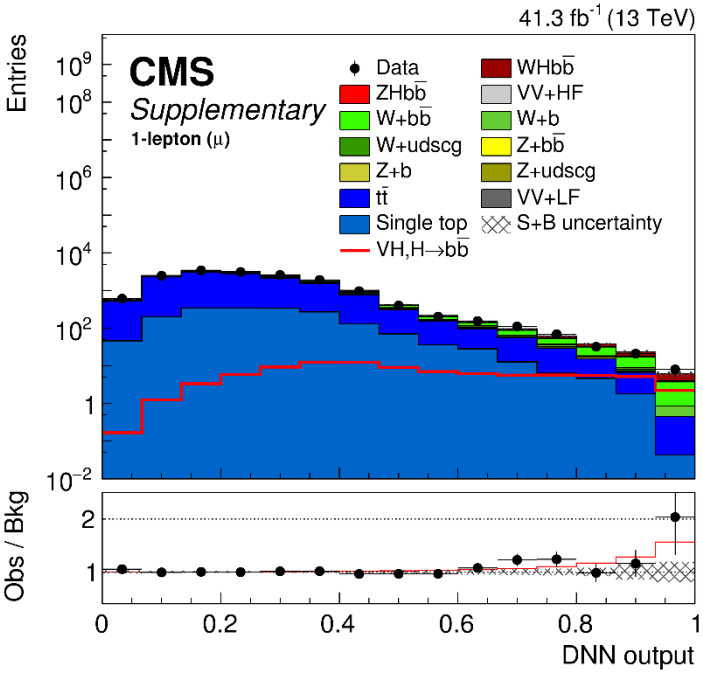


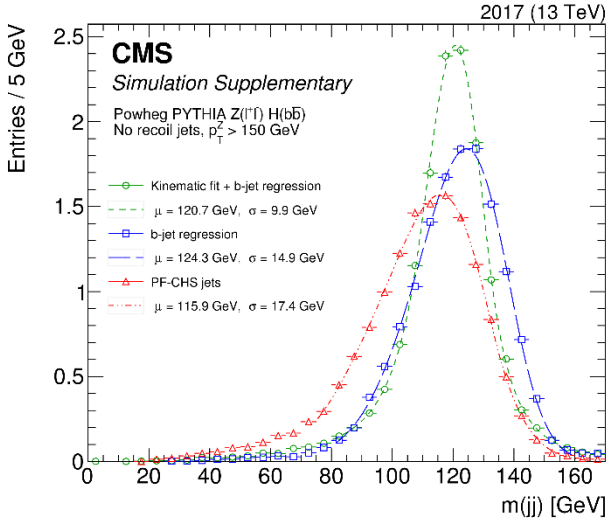

- Highest BR (58%) but low S/B

2017 (41.3 fb-1)

- 3 channels with 0, 1 and 2 leptons
  - Target: Z(→νν)H, W (→lν)H and Z(→ll)H

- Require large boost for vector boson to increase S/B
- Large usage of MVA for b-tagging, b-jet energy regression or final discriminant (Deep Neural Network with b-jet properties, di-jet kinematics, event topology)
- Control of backgrounds (V+bb, ttbar, VZ, …) is critical !

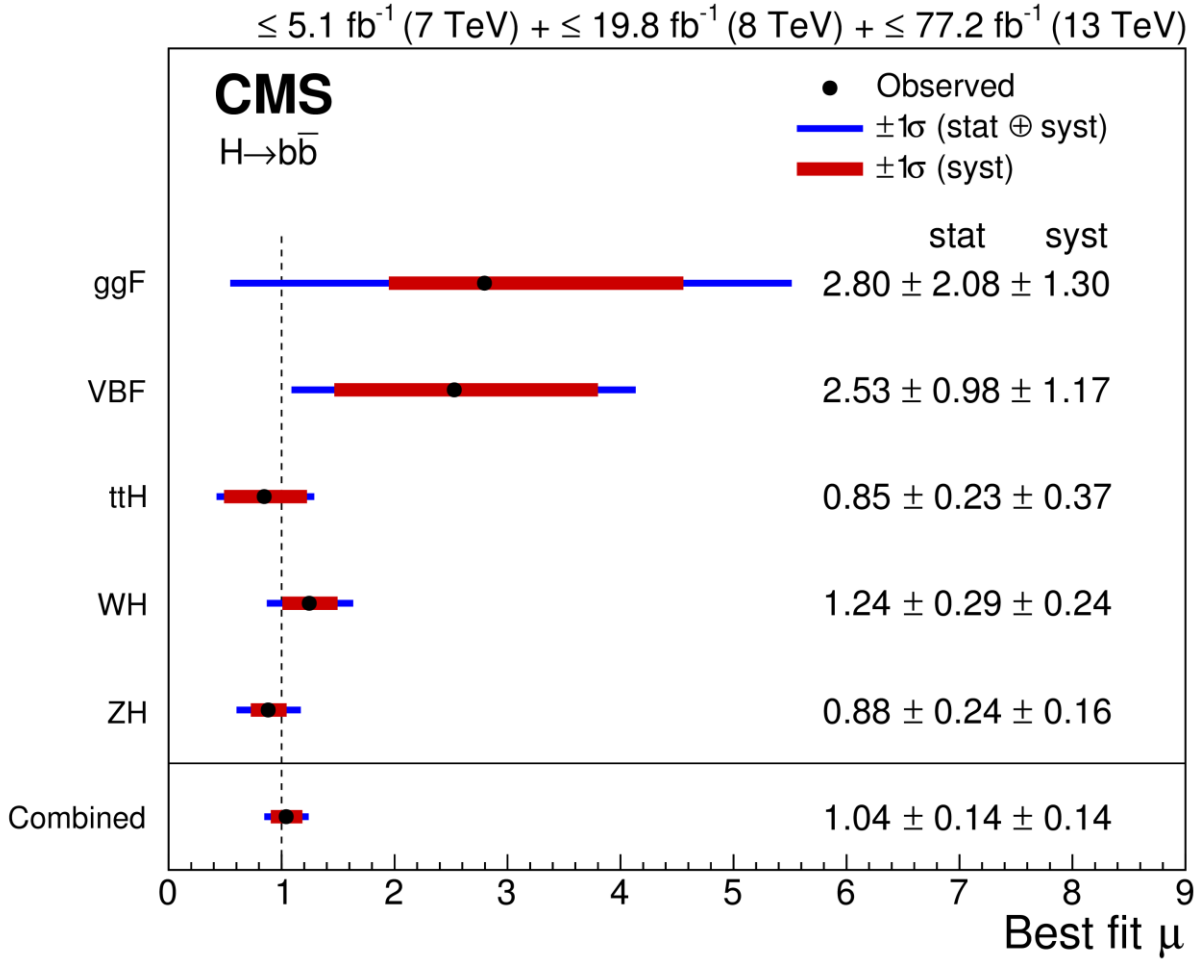



| Data set | Significance ($\sigma$) Expected | Observed | Signal strength |
|---|---|---|---|
| 2017 | | | |
| 0-lepton | 1.9 | 1.3 | $0.73 \pm 0.65$ |
| 1-lepton | 1.8 | 2.6 | $1.32 \pm 0.55$ |
| 2-lepton | 1.9 | 1.9 | $1.05 \pm 0.59$ |
| Combined | 3.1 | 3.3 | $1.08 \pm 0.34$ |
| 2016+2017 → Run 2 | 4.2 | 4.4 | $1.06 \pm 0.26$ |
| Run 1 + Run 2 | 4.9 | 4.8 | $1.01 \pm 0.23$ |

# Observation of H→bb

- **Grand combination of all Run I + Run II CMS H→bb measurements: VH, boosted ggH, VBF and ttH**
  - Most sources of systematic uncertainty are treated as uncorrelated
  - Theory uncertainties are correlated between all processes and data sets




arXiv:1808.08242
Accepted for publication by Phys. Rev. Lett.

Measured signal strength
$(\sigma/\sigma_{SM})=1.04\pm0.20$

Significance: **5.6 σ observed**
(5.5 σ expected)

**Observation of the H→bb decay by the CMS Collaboration**

**More details in Luca Mastrolorenzo's talk**

# Combination

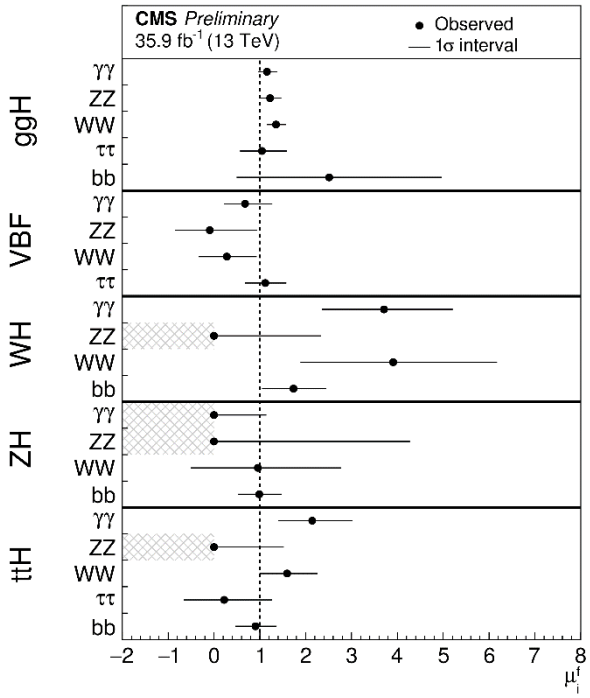
- **Grand combination of 11 analyses from 2016 (~36 fb-1)**
  - 265 event categories, 5500+ nuisance parameters, …

2016 (~36 fb-1)

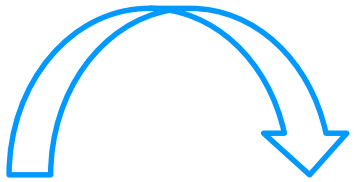
Most generic parameterization: one signal strength per prodxdecay mode

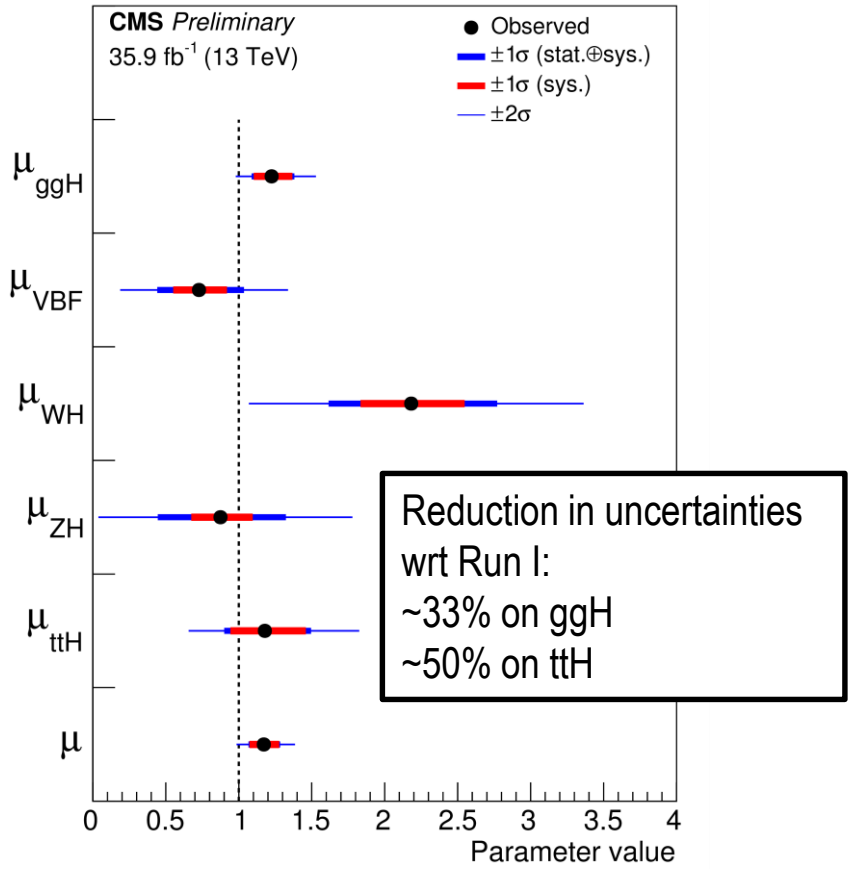
$$\mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathcal{B}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

CMS-PAS-HIG-17-031




Assuming SM predictions for Branching Ratios






Reduction in uncertainties wrt Run I:
~33% on ggH
~50% on ttH

$$\mu = 1.17^{+0.10}_{-0.10}$$
$$= 1.17^{+0.06}_{-0.06}\,(\mathrm{stat.})\,^{+0.06}_{-0.05}\,(\mathrm{sig.\ th.})\,^{+0.06}_{-0.06}\,(\mathrm{other\ sys.})$$

**Dominated by systematic uncertainties !**

**See talk by Karsten Koeneke**

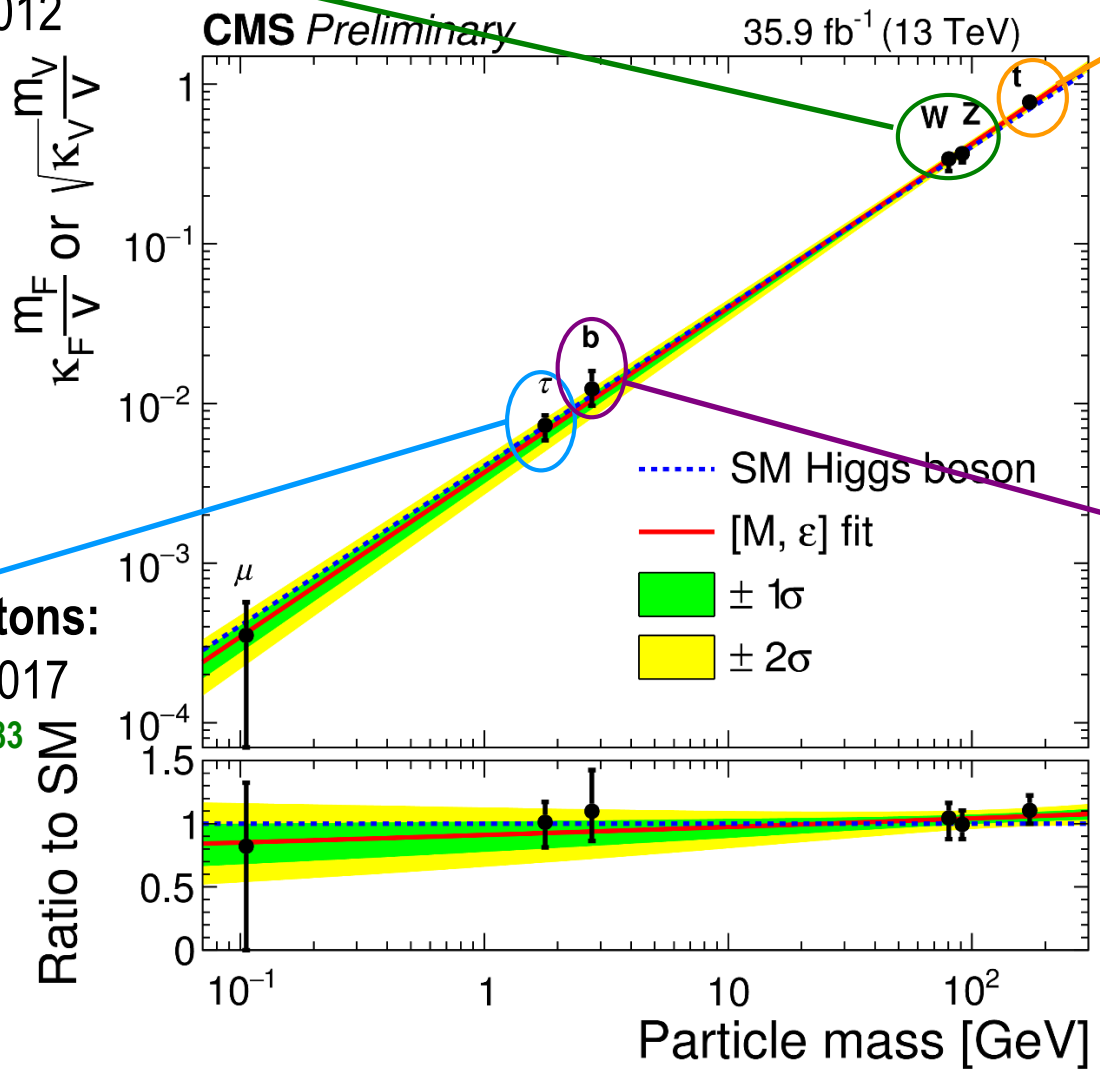
# Summary & Next steps

**Couplings to bosons**:
Observed in July 2012
Phys. Lett. B 716 (2012) 30

**(direct) Coupling to top**:
Observed in April 2018
Phys. Rev. Lett. 120 (2018) 231801

**Couplings to (τ) leptons:**
Observed in May 2017
Phys. Lett. B 779 (2018) 283

**Coupling to b-quarks**
Observed in August 2018
arXiv:1808.08242
Accepted for publication by Phys. Rev. Lett.



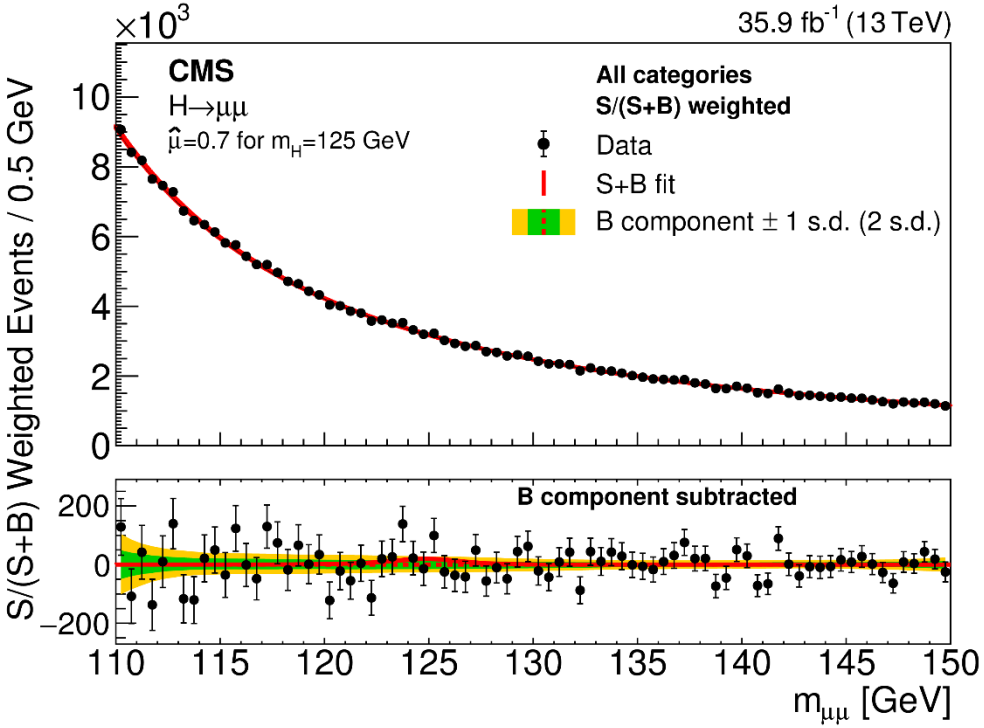

- **Run II (>= 2015) gave a clear boost to the exploration of the scalar sector**
- Couplings to gauge bosons (resp. 3rd generations fermions) known to ~10 (resp. ~20) %
- **What are the next milestones ?**

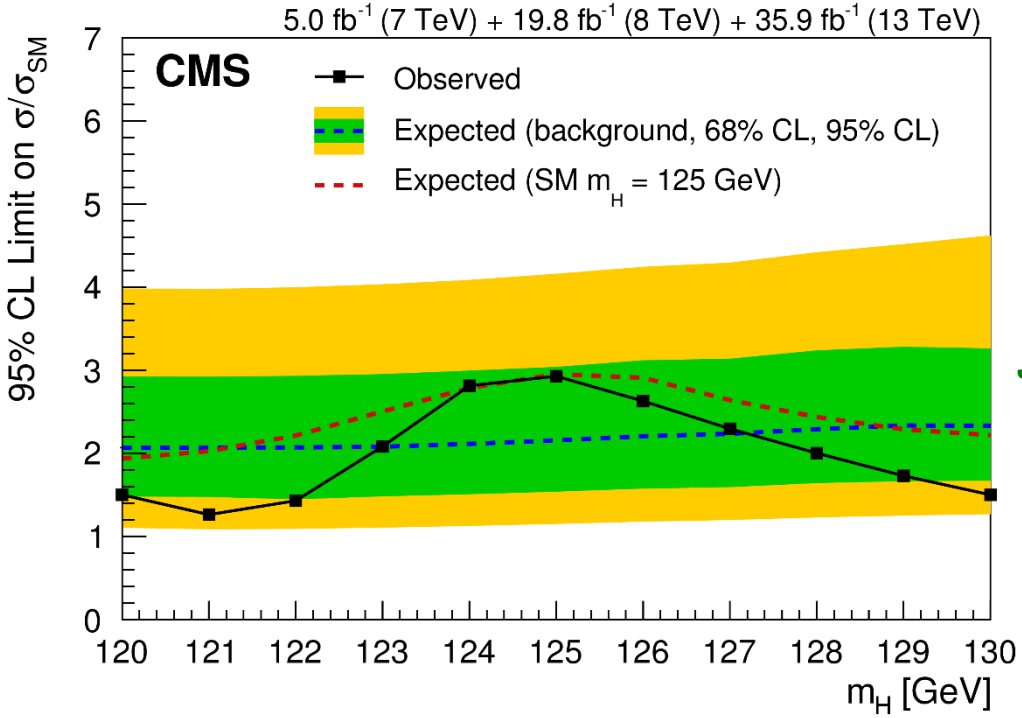
# Next target: Coupling to 2nd generation

**H→ μμ:** first channel accessible at LHC to probe 2nd generation couplings

2016 (~36 fb-1)

- **Clean signature**: high resolution peak from 2 high pT isolated muons
- But SM backgrounds (Drell-Yann, top, VV) very large. **S/B~0.01**
- Use kinematics & muon resolution information into BDT
  - + additional jet activity, b-jets and MET to distinguish between production modes




arXiv:1807.06325 Submitted to Phys. Rev. Lett.

Observed (Expected) 95% CL limit on B(H→μμ): 2.92 (2.16) x SM

Run I + 2016 data

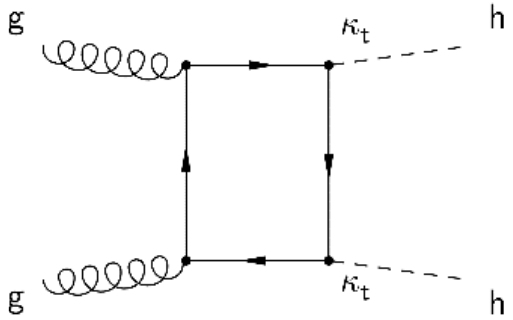
**Can we claim 3σ Evidence for Run III ?**

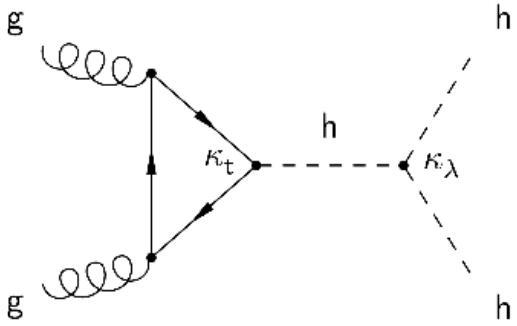
# Next target: Higgs self-coupling

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

$$V(\Phi) = -\mu|\Phi|^2 + \lambda|\Phi|^4$$

- **Can probe the Higgs potential via di-Higgs production**
  - Quadri-linear coupling not accessible at LHC…




**Tri-linear coupling**

$$\sigma(gg \to HH) = (33.4 \pm 5.9)\ \text{fb}$$

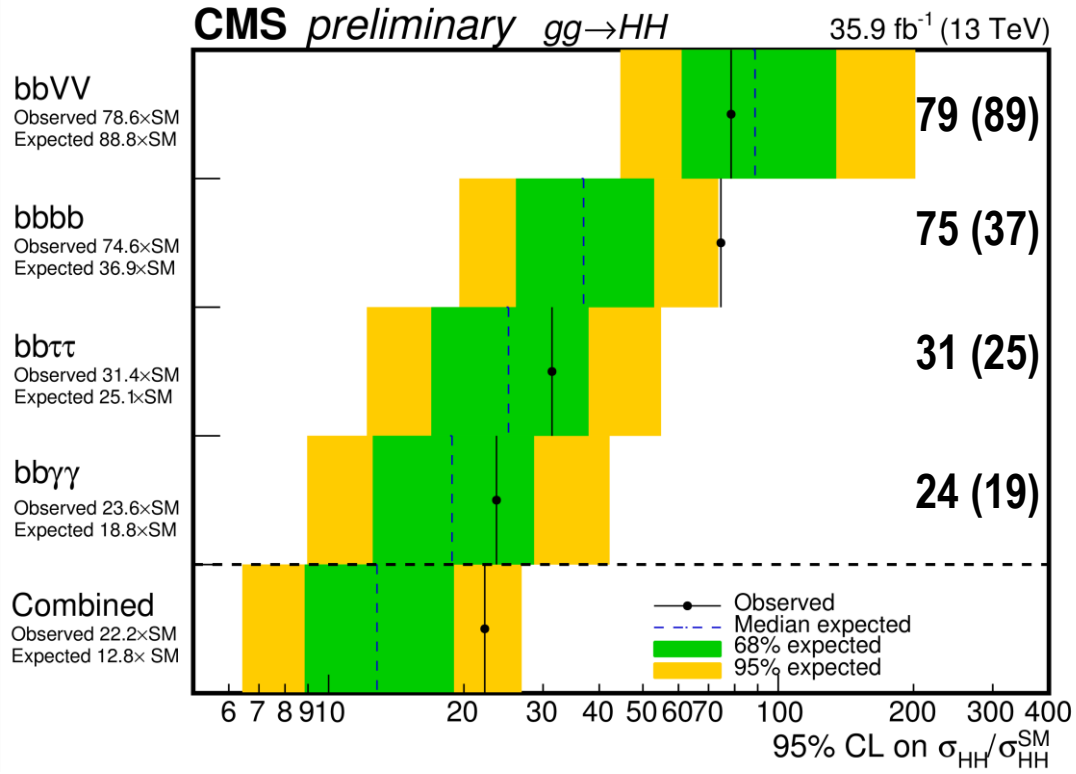
1/500 vs single H production…

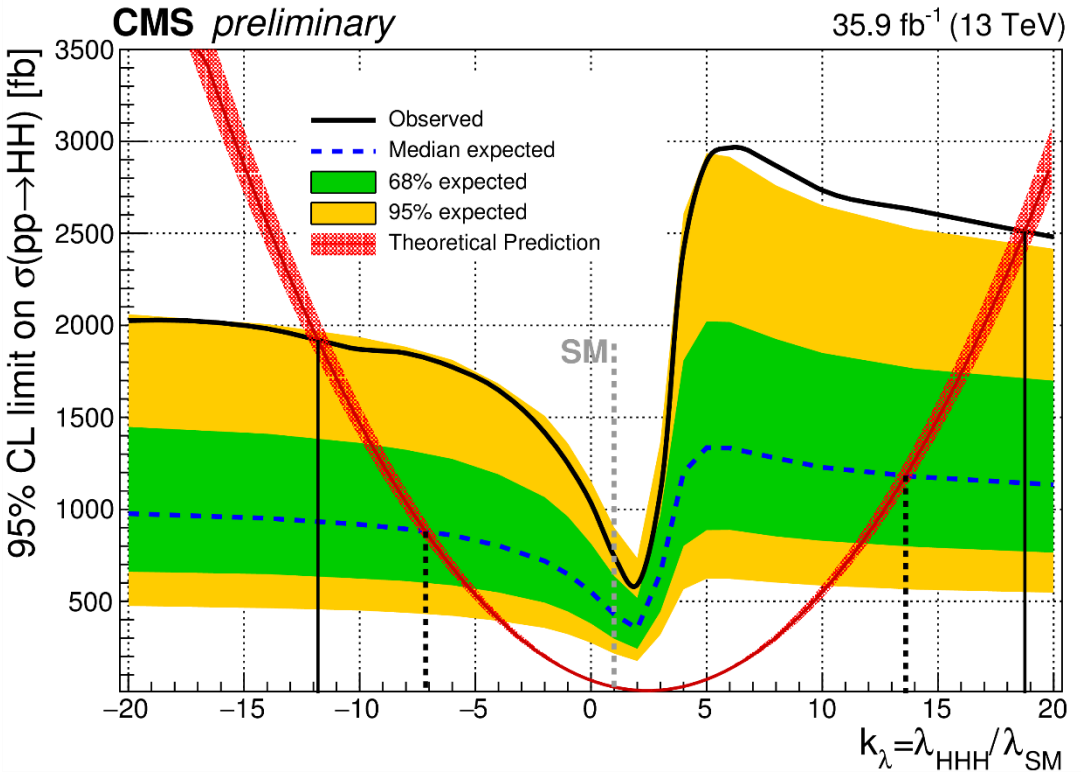
(due to destructive interference)

Can be enhanced by BSM contributions (non-SM top coupling, …)

# Constraints on HH

2016 (~36 fb-1)




$\sigma_{HH}$ < 22 x SM (13 expected)

**Approaching the x10 SM sensitivity…**

**Constraint on tri-linear coupling:**

-11.8 < kλ < 18.8
(-7.1 < kλ < 13.6 exp.)
@ 95 CL

See talk by Dinko Ferencek

# Outlook

## We have come a long way since the starting of the LHC 10 years ago…

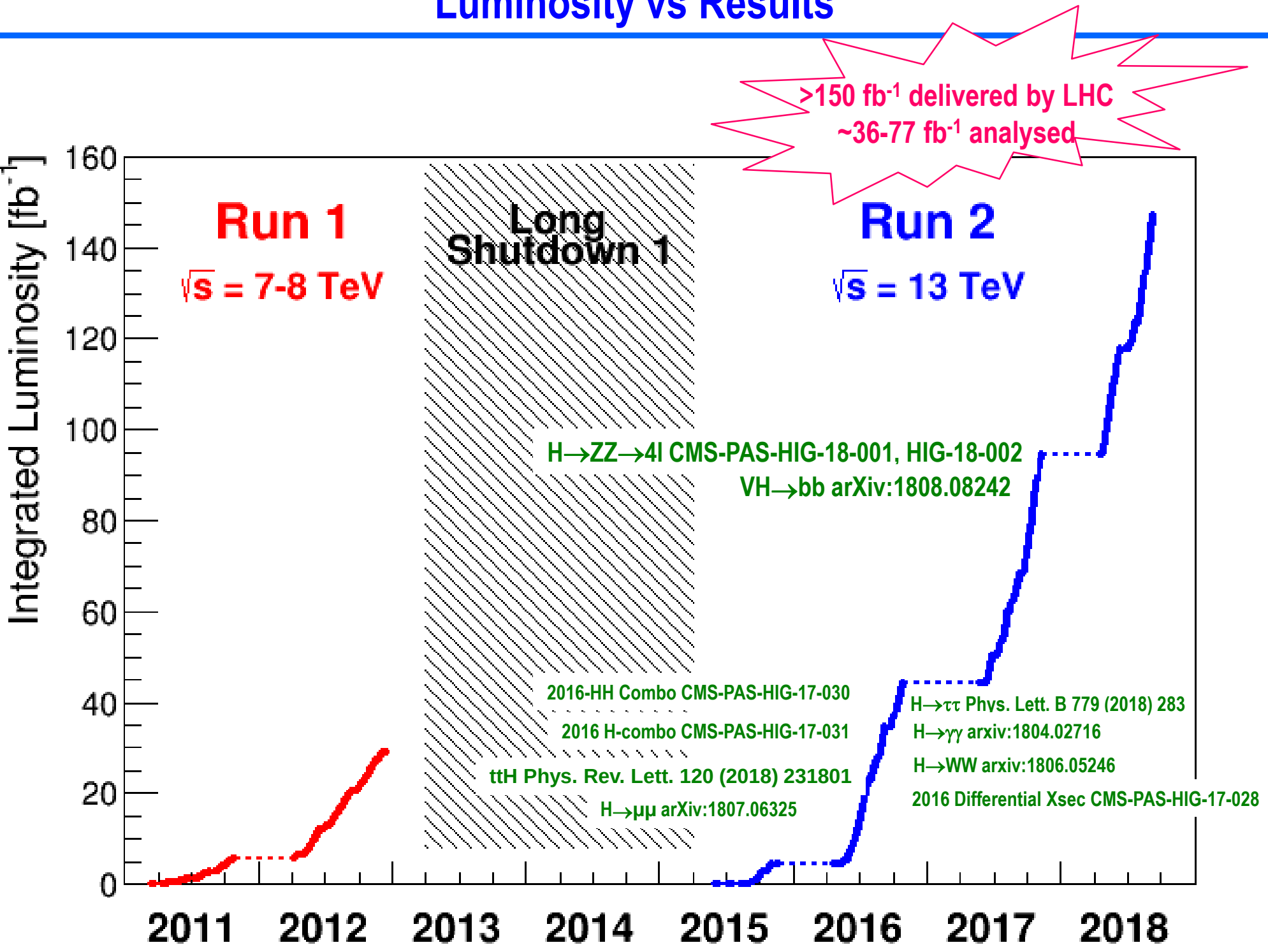
- **The Higgs boson has been found, with a mass of ~125 GeV** (1.7 per mille precision!)
  - Its total width has been constrained to a few MeV **(NEW)**
  - All production modes have been observed.
  - The coupling to gauge boson is now entering a precision era.
  - **The Run II results proves the existence of a new type of interaction**, Yukawa couplings to up and down fermions (for the 3rd generation)
  - Couplings to 2nd generation is within reach
  - Sensitivity to Di-Higgs is approaching 10 times the SM predictions

- But the scalar sector is not just an "era of precision". **It remains the best portal we have to new physics:**
  - Search for Dark Matter via "invisible" decay
  - Searches for extended scalar sector
  - Searches for rare or forbidden decay ($H \to Z\gamma$, $H \to \tau\nu$, …)
  - Link with Cosmology ?
  - Etc…

**See talk by S. Nikitenko**

*We must not underestimate our ignorance about the Higgs sector*
*We must not undersell the value of exploring and establishing it*
*G. Salam, LHCP 2018 "Theory vision" talk*

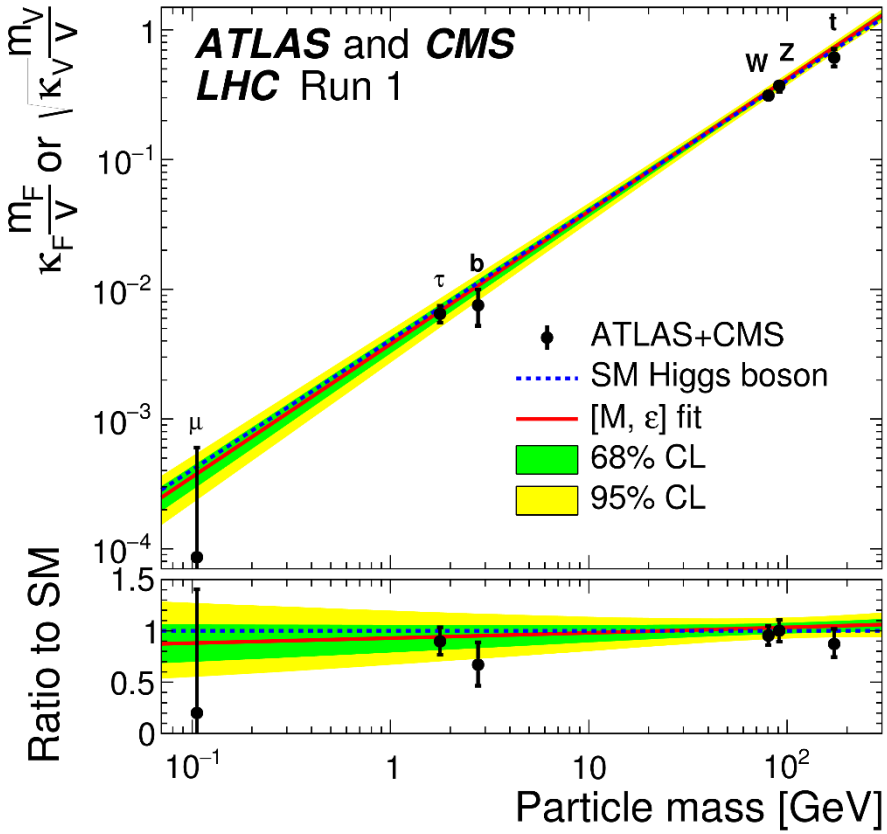
# Luminosity vs Results

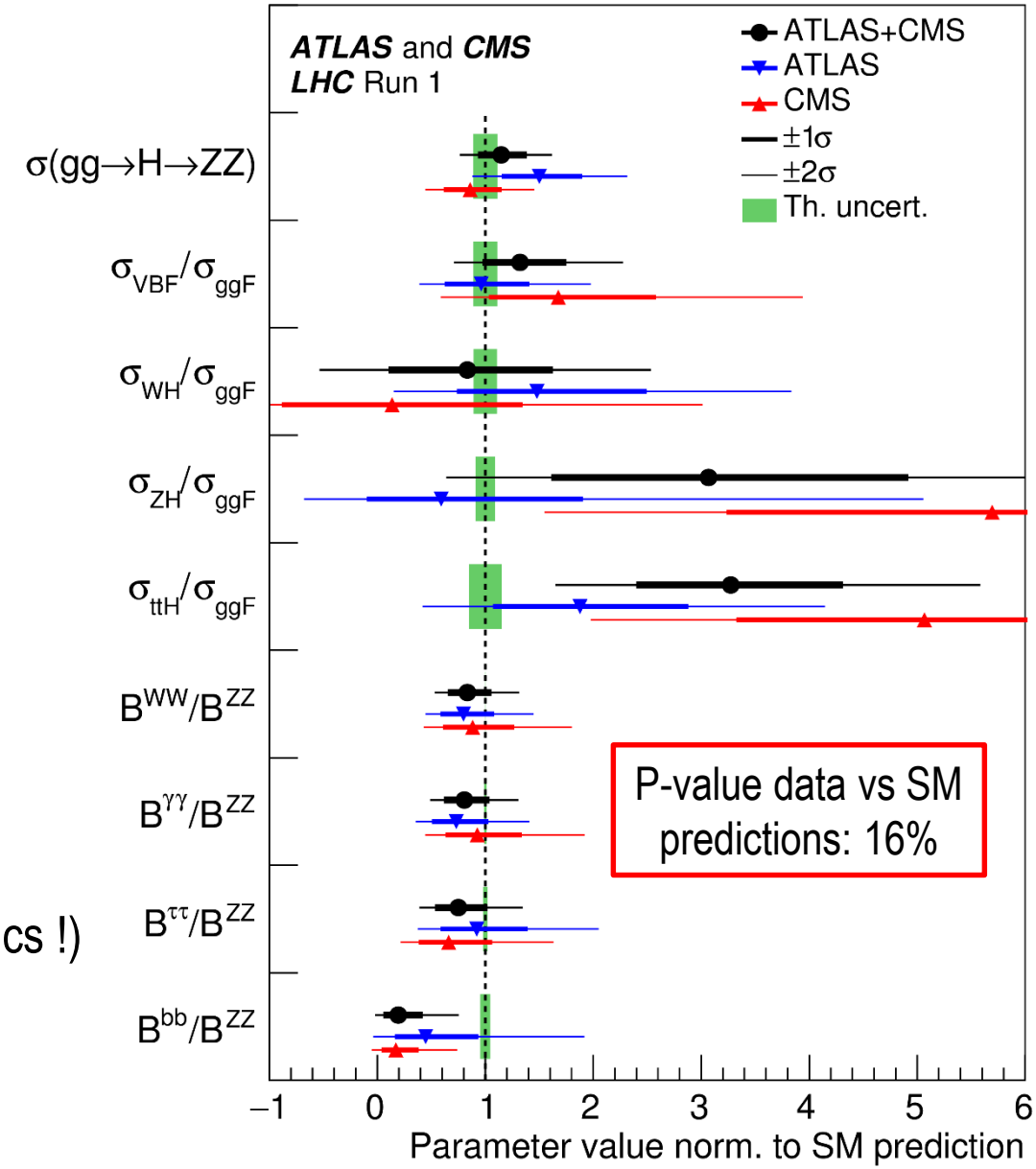


# BACK UP SLIDES

# Run I Higgs boson Grand Summary

JHEP 08(2016)045




- **Higgs boson discovery with bosonic decays,**
  - **now also observation with taus**
- $m_H$=125.09 with 0.2% precision (dominated by statistics !)
- 0+ state favoured over other $J^{PC}$ hypothesis
- narrow width ($\Gamma_H$< ~20 MeV @ 95% CL)

- Couplings to third-generation fermions and W/Z known with 10-30% precision.
- **Slight excess in ttH (3 σ)… slight deficit in bbar decay (-2.5 σ)…**

# CMS analysis: HVV couplings

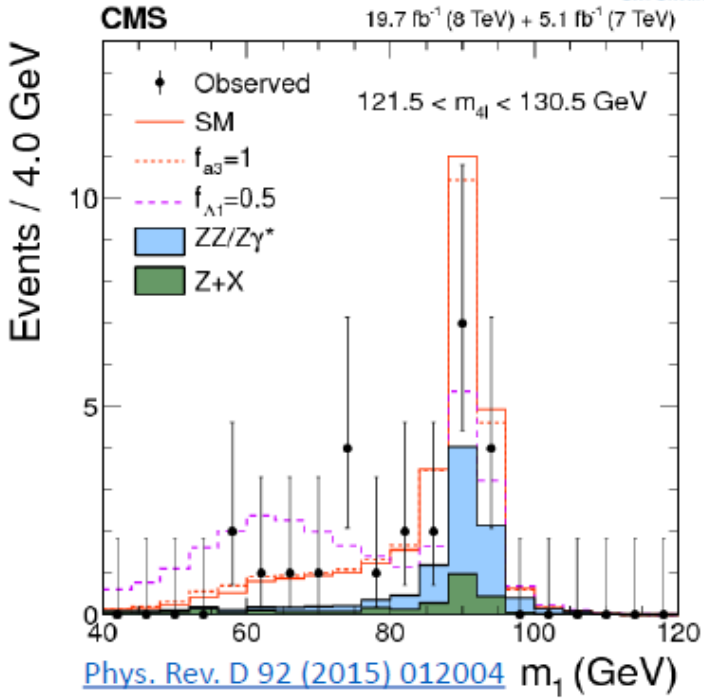
$$A(HVV) \sim \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}^{VV'}} \frac{(\kappa_1 q_{V1}^2 + \kappa_2 q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase defined for $2f2f'$ decay:

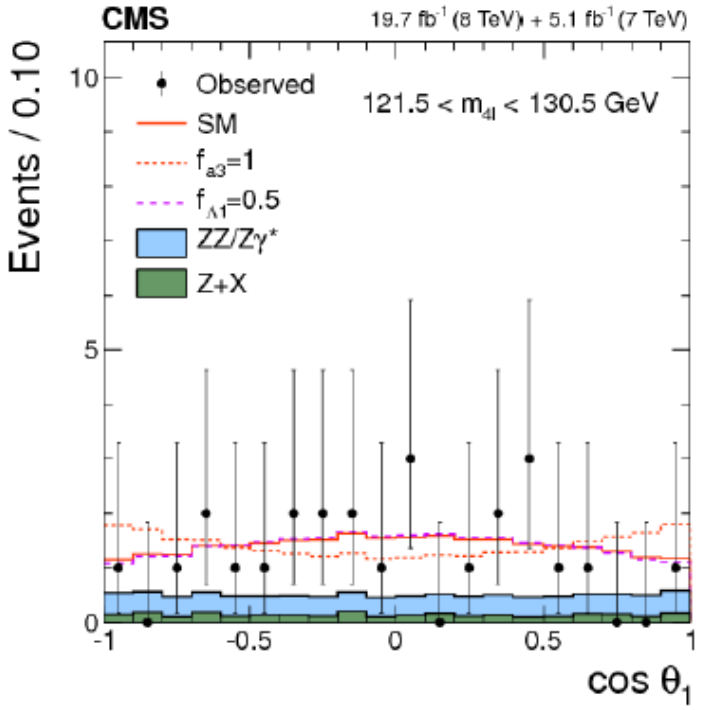
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \qquad \phi_{ai} = \tan^{-1}(a_i/a_1)$$

→ $f_{\Lambda Q}$ observable only from off-shell. Others can be measured from either on-shell or off-shell.

→ Formalisms used by ATLAS are equivalent with different ways of parameterizing AC couplings




Phys. Rev. D 92 (2015) 012004



# CMS results: $f_{ai}\cos(\phi_{ai})$

| Parameter | Observed | Expected |
|---|---|---|
| $f_{a3}\cos(\phi_{a3})$ | $-0.0001^{+0.0005}_{-0.0015}$ $[-0.16, 0.09]$ | $0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$ |
| $f_{a2}\cos(\phi_{a2})$ | $0.0004^{+0.0026}_{-0.0007}$ $[-0.006, 0.025]$ | $0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$ |
| $f_{\Lambda1}\cos(\phi_{\Lambda1})$ | $0.0000^{+0.0035}_{-0.0008}$ $[-0.21, 0.09]$ | $0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$ |
| $f_{\Lambda1}^{Z\gamma}\cos\left(\phi_{\Lambda1}^{Z\gamma}\right)$ | $0.000^{+0.355}_{-0.009}$ $[-0.17, 0.61]$ | $0.000^{+0.009}_{-0.010}$ $[-0.10, 0.34]$ |

On-shell results

On-shell + off-shell combination

| Parameter | Observed | Expected |
|---|---|---|
| $f_{a3}\cos(\phi_{a3})$ | $0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$ | $0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$ |
| $f_{a2}\cos(\phi_{a2})$ | $0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$ | $0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$ |
| $f_{\Lambda1}\cos(\phi_{\Lambda1})$ | $0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$ | $0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$ |

Different HVV couplings

| Parameter | Unconstrained Parameter | Observed | Expected |
|---|---|---|---|
| $\Gamma_H$ (MeV) | $f_{a3}\cos(\phi_{a3})$ | $2.4^{+2.7}_{-1.8}$ $[0.02, 8.38]$ | $4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$ |
| $\Gamma_H$ (MeV) | $f_{a2}\cos(\phi_{a2})$ | $2.5^{+2.9}_{-1.8}$ $[0.02, 8.76]$ | $4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$ |
| $\Gamma_H$ (MeV) | $f_{\Lambda1}\cos(\phi_{\Lambda1})$ | $2.4^{+2.5}_{-1.6}$ $[0.06, 7.84]$ | $4.1^{+5.2}_{-4.1}$ $[0.0, 13.9]$ |

Imperial College London

# Measurements

CMS

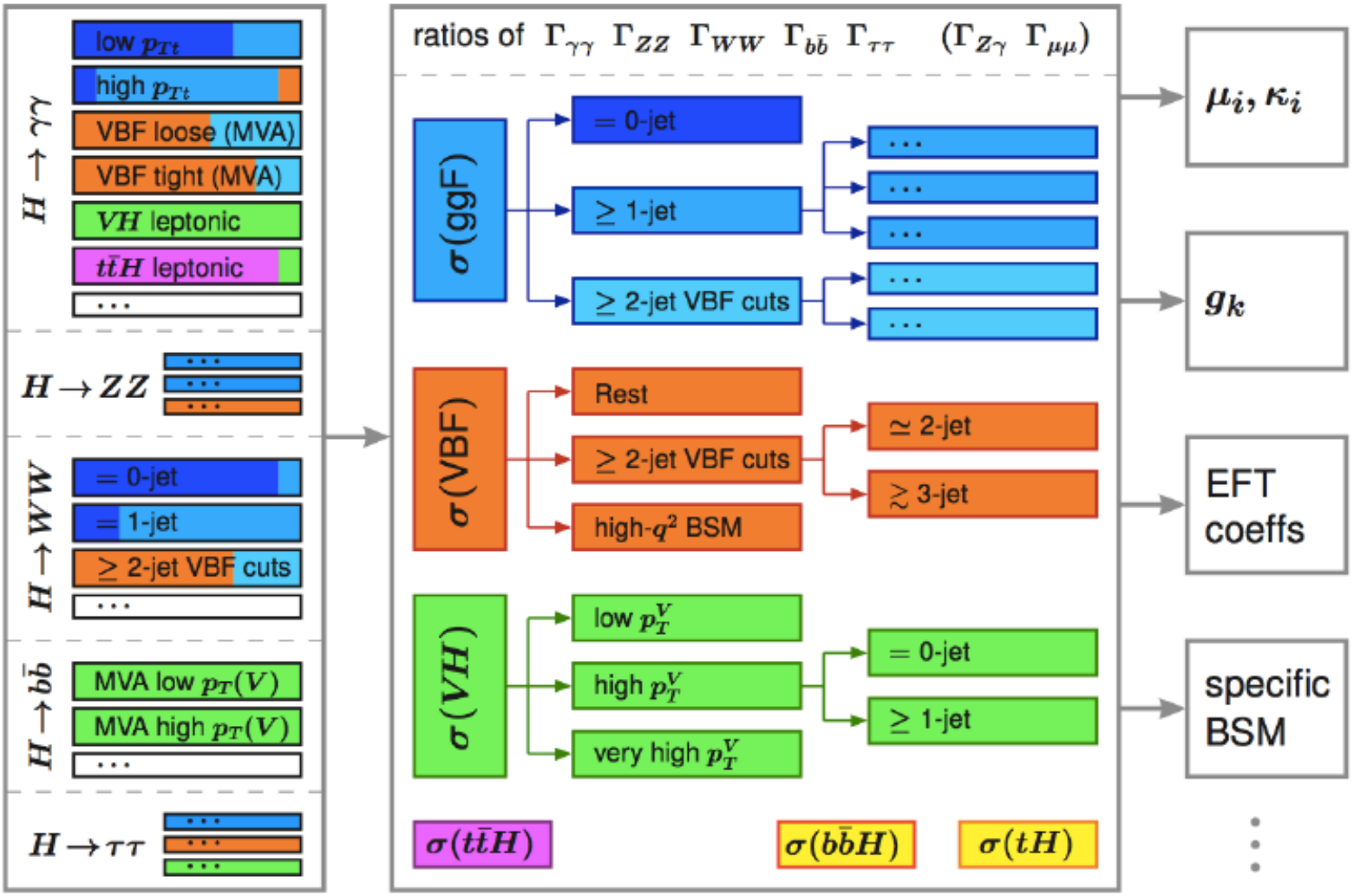
**Cross-sections**

- **Differential**
  - Shape information; strongly stat-limited
- **Signal strengths**
  - **Inclusive**
    - Used for discovery
    - Now limited by systematics
  - **Per process**
    - Mostly stat-limited
    - Also use Simplified Template Cross-Section (STXS) framework
- **Couplings**
  - usually $\kappa$ framework

**Mass**

- Only $\gamma\gamma$ and ZZ contribute
- Requires excellent understanding of systematic uncertainties

# Simplified Template Cross-Section




- Results can then be re-interpreted with new theories
- Kinematic regions isolate BSM effects
- And provide coherent framework for combination of channels & experiments

- **Simplified Template Cross-section (STXS)** framework aims to minimise measurements' dependence on theory

# Fiducial and Simplified template cross-section

Fiducial cross-section

- Optimized for maximal theoretical independence
- Fiducial in Higgs decay
- Smallest acceptance corrections
- Simple signal cuts
- "Exact" fiducial volume
- Targeted object definitions
- Agnostic to production mode

Can be done with single and differential distributions

Only feasible in HZZ,H$\gamma\gamma$,HWW

Combination not straightforward

Simplified templates cross section

- Target maximum sensitivity, while keeping theoretical dependence as small as possible
- Cross section split by production mode
- Cross section divided in **exclusive** regions of phase space (bins)
- Larger acceptance corrections
- Abstracted fiducial volumes
- Inclusive in Higgs decay
- Allows complex event selections, categorisation

Common abstracted object definitions

Can be done in all decay modes

Explicitly designed for combination

# Tools for discovery and measurements (2)

## ➢ Signal Extraction via Matrix Element Methods (MEM):

- Event-by-event discriminator built upon Matrix Elements. Combined with reco level info.

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

Phase Space

Momentum conservation

PDF's

LO ME from Madgraph5_aMC@NLO

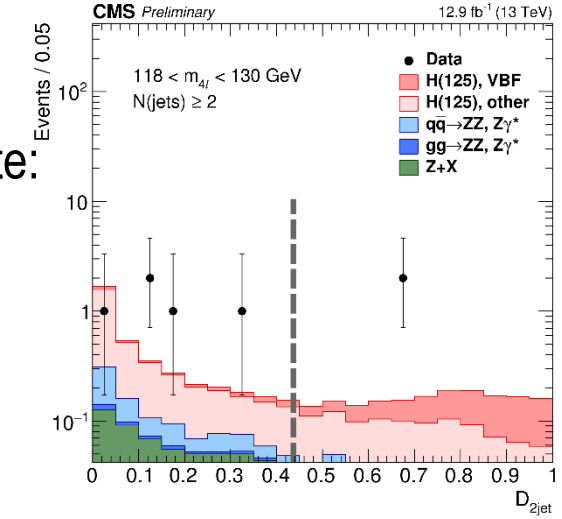
Transfer Function (relates parton and reco quantities)

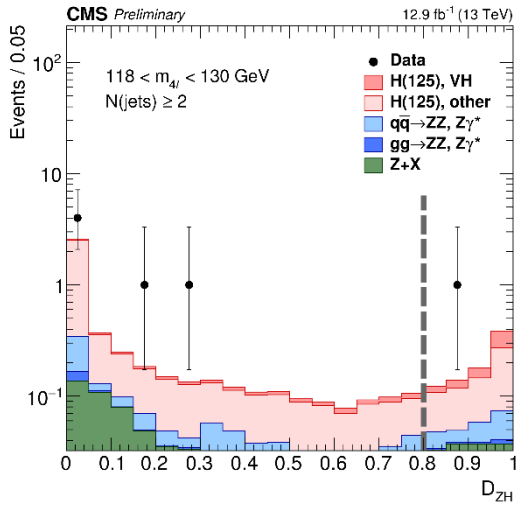
- **MEM weights** used in ttH→multileptons (**see later**) as input to BDT.

- **Matrix Element Likelihood Analysis** (H→ZZ→4l):
  - Simplified MEM. No integration, no transfer function

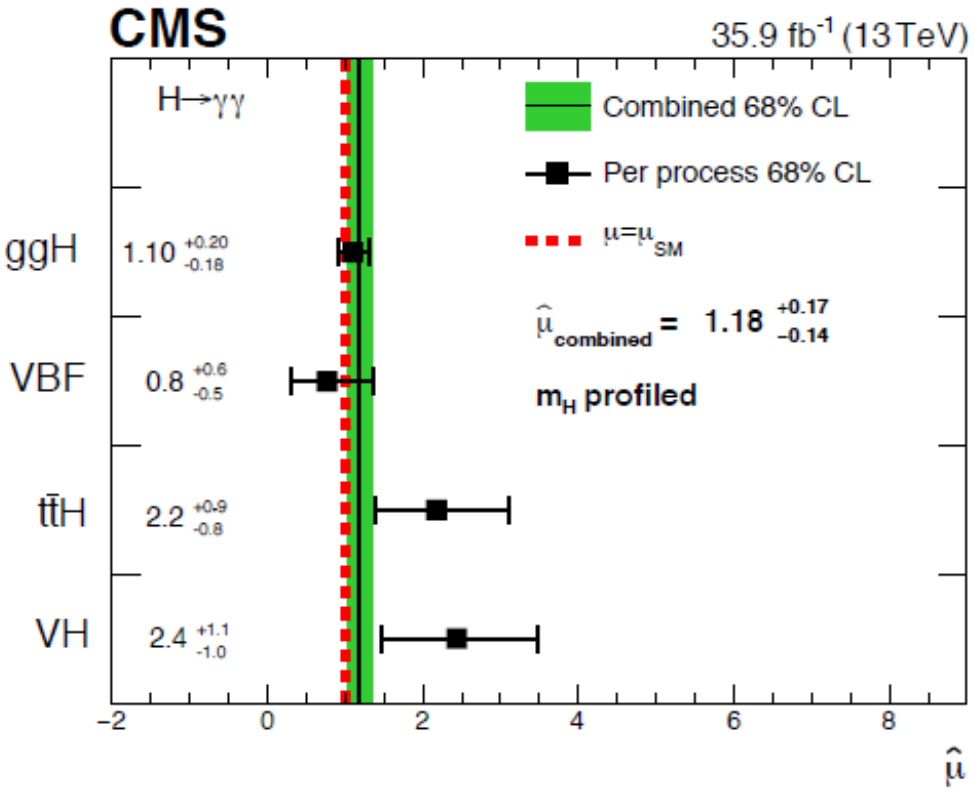
$$\mathcal{D}_{\text{bkg}}^{\text{kin}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}^{q\bar{q}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\text{sig}}^{gg}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}\right]^{-1}$$

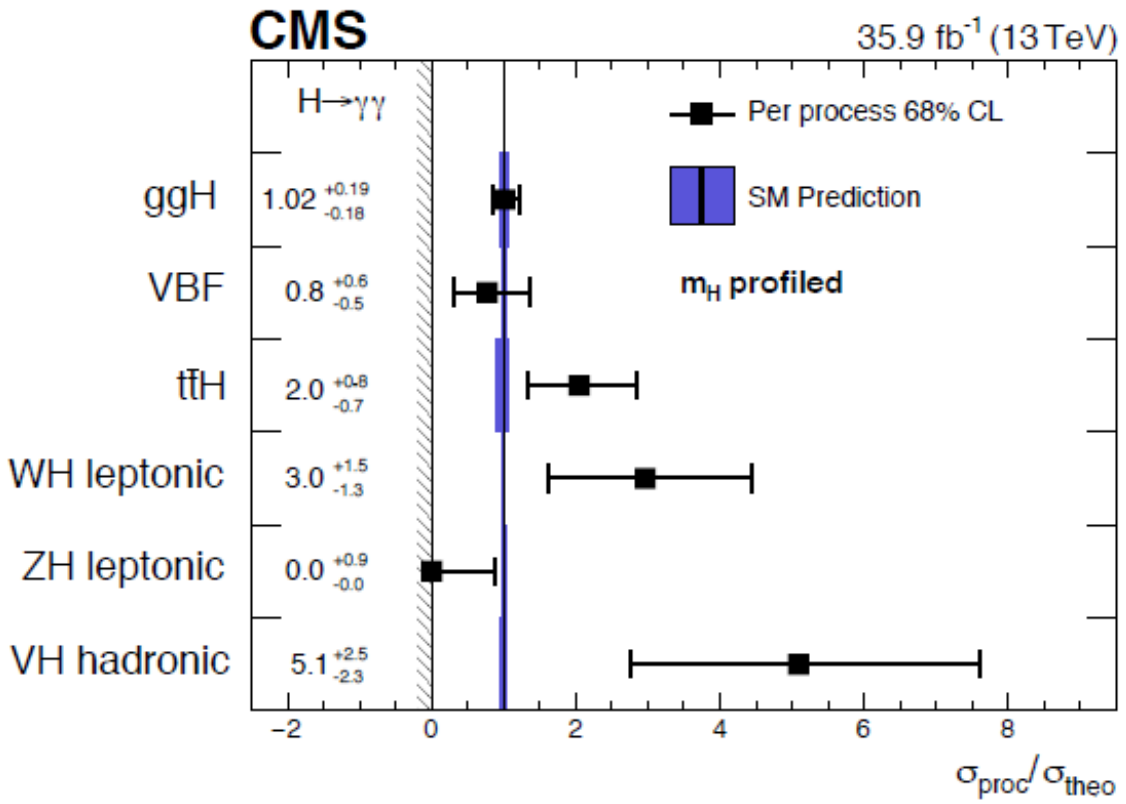
  - ME from JHUGen or MCFM
  - Several discriminants (**see later**) built to separate:
    - ❖ gg vs qq→4 leptons
    - ❖ ggH vs VBF or VH or ttH
    - ❖ Different $J^{PC}$ hypothesis, …



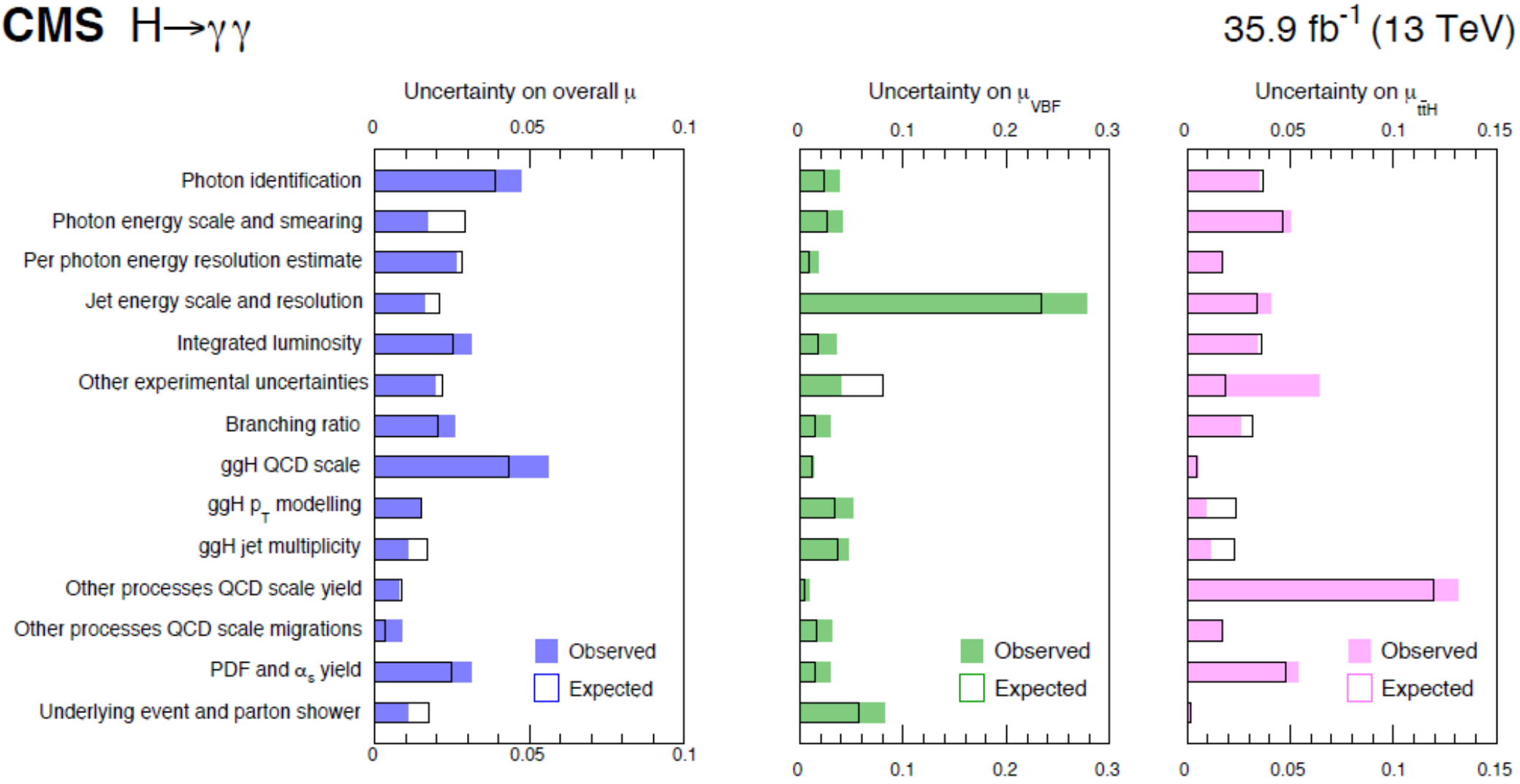
# Hgg: Simplified Template Cross-Section




- Two types of per-process signal strength measurement
  - traditional signal strengths: theory uncertainty included in the measurement
  - Stage 0 STXS: factorise theory uncertainty on overall yield
- Significance of ttH observed to be 3.3σ (1.5σ expected)

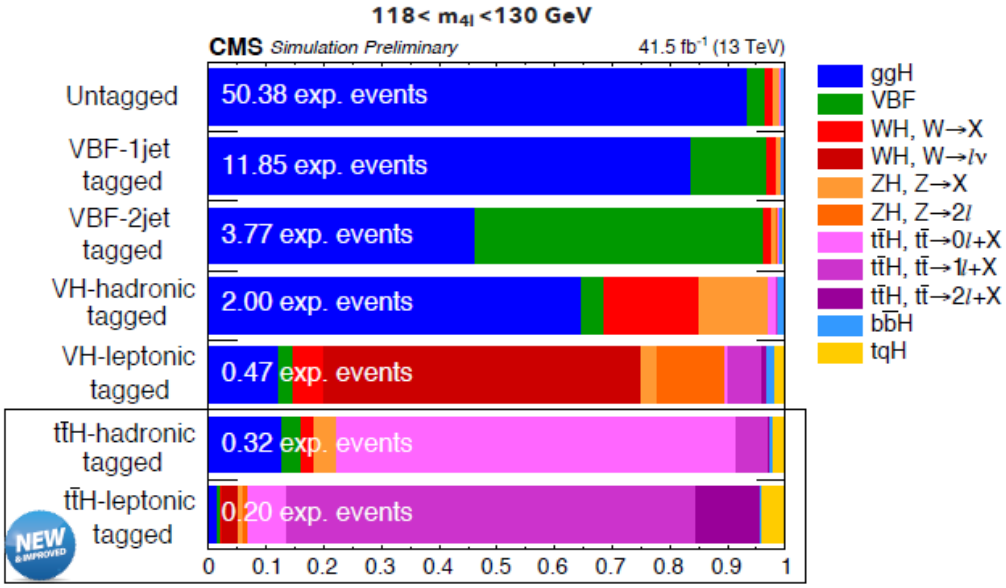
# Hgg: impact of systematics

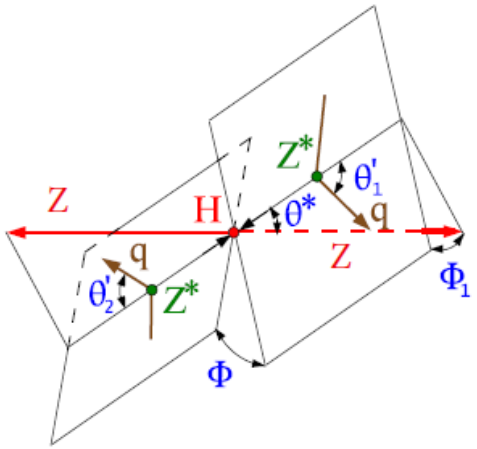


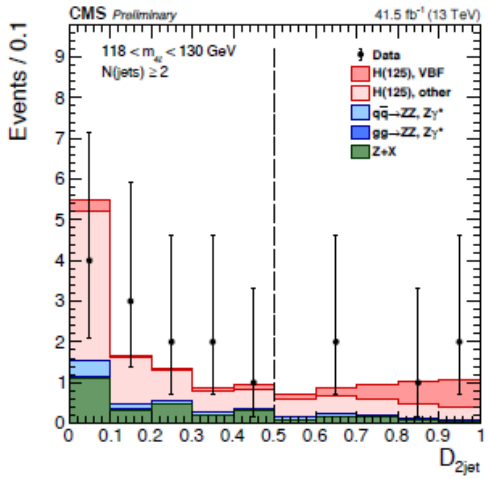

- Inclusive signal strength on point of becoming systematics-limited
- Important contributions from both theoretical and experimental uncertainties

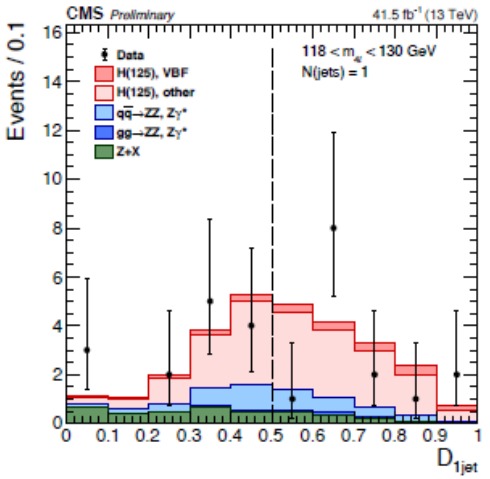
# HZZ Strategy

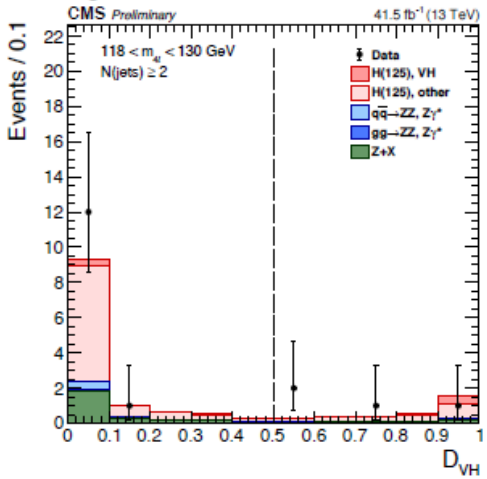
- ZZ candidates classified into 7 categories:
  - hunt for H(125) production modes
  - new ttH categories
  - selection based on number of jets, b-tags, extra leptons and cuts on the 3 matrix-element based production discriminants ($D_{2jet}$, $D_{1jet}$ and $D_{VH}$)



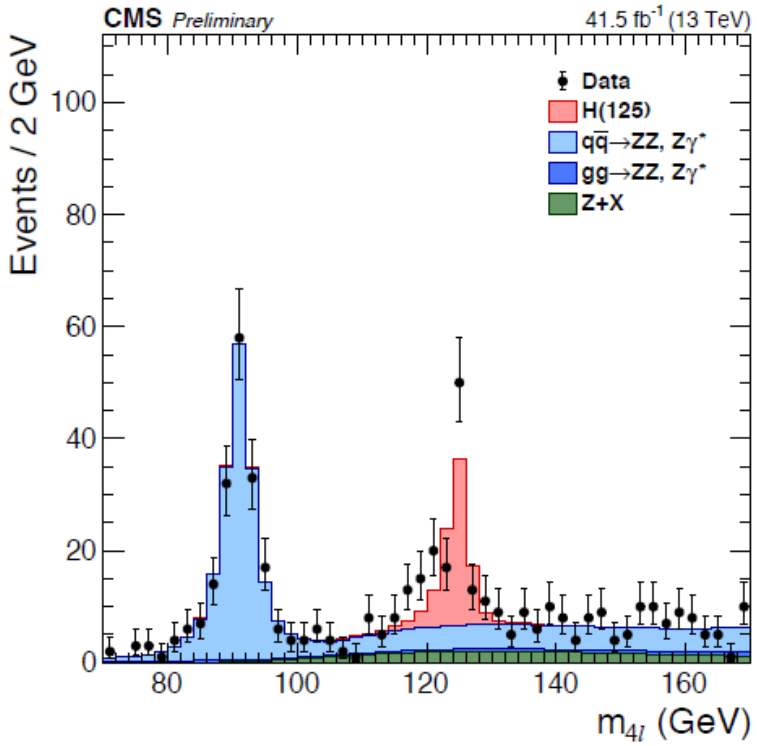



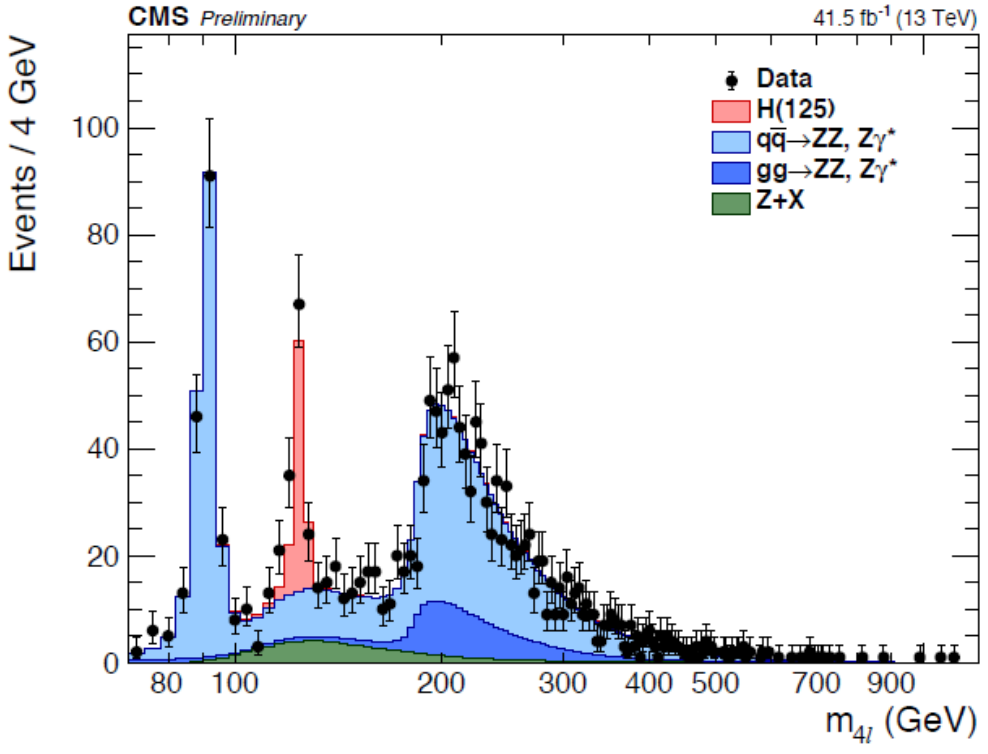
# RESULTS OF EVENT SELECTION



- Good data/MC agreement over the whole $m_{4l}$ range in all 3 final states (4e, 4μ, 2e2μ)

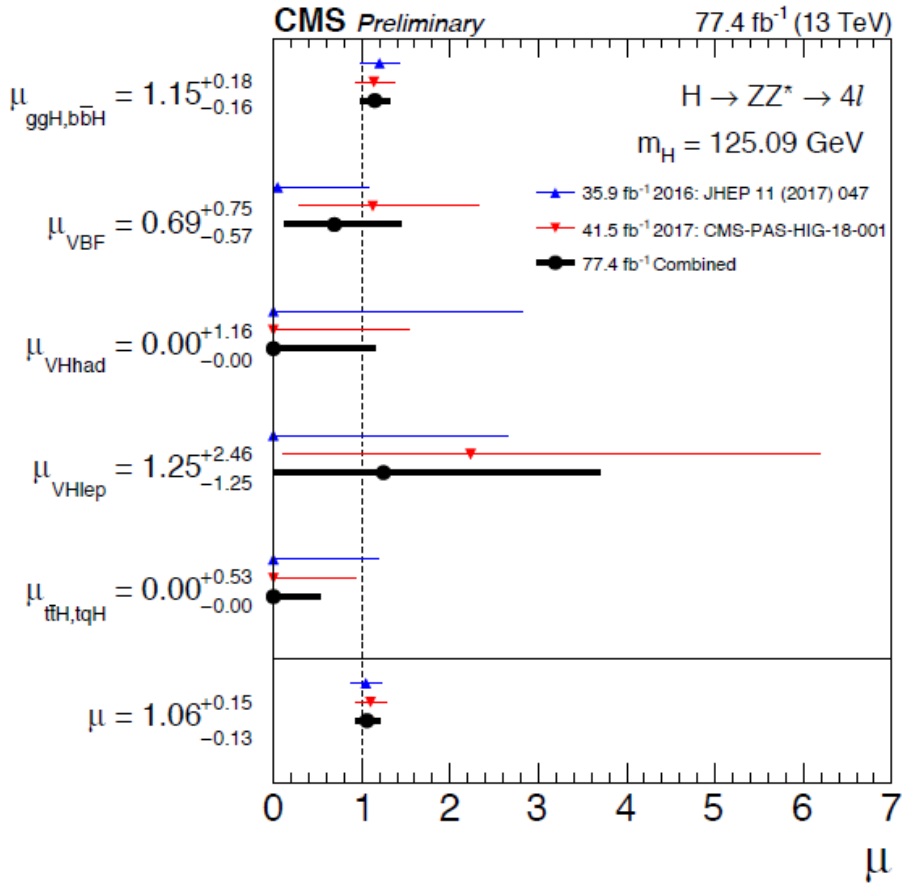
| Channel | 4e | 4μ | 2e2μ | 4ℓ |
|---|---|---|---|---|
| $q\bar{q} \to ZZ$ | $235^{+32}_{-36}$ | $443^{+36}_{-40}$ | $572^{+50}_{-54}$ | $1250^{+104}_{-114}$ |
| $gg \to ZZ$ | $49.1^{+8.7}_{-8.8}$ | $81.8^{+11.2}_{-10.7}$ | $121.5^{+17.1}_{-16.3}$ | $252.4^{+35.1}_{-33.5}$ |
| Z + X | $17.1^{+6.4}_{-6.1}$ | $35.4^{+12.7}_{-11.4}$ | $47.8^{+16.4}_{-15.8}$ | $100.3^{+21.3}_{-20.6}$ |
| Sum of backgrounds | $301^{+39}_{-43}$ | $560^{+43}_{-47}$ | $741^{+62}_{-65}$ | $1602^{+126}_{-135}$ |
| Signal ($m_H = 125$ GeV) | $13.9^{+1.9}_{-2.1}$ | $28.9^{+2.5}_{-2.6}$ | $35.8 \pm 3.3$ | $78.5^{+7.0}_{-7.1}$ |
| Total expected | $315^{+41}_{-45}$ | $589^{+45}_{-49}$ | $777^{+64}_{-67}$ | $1681^{+131}_{-140}$ |
| Observed | 307 | 602 | 797 | 1706 |



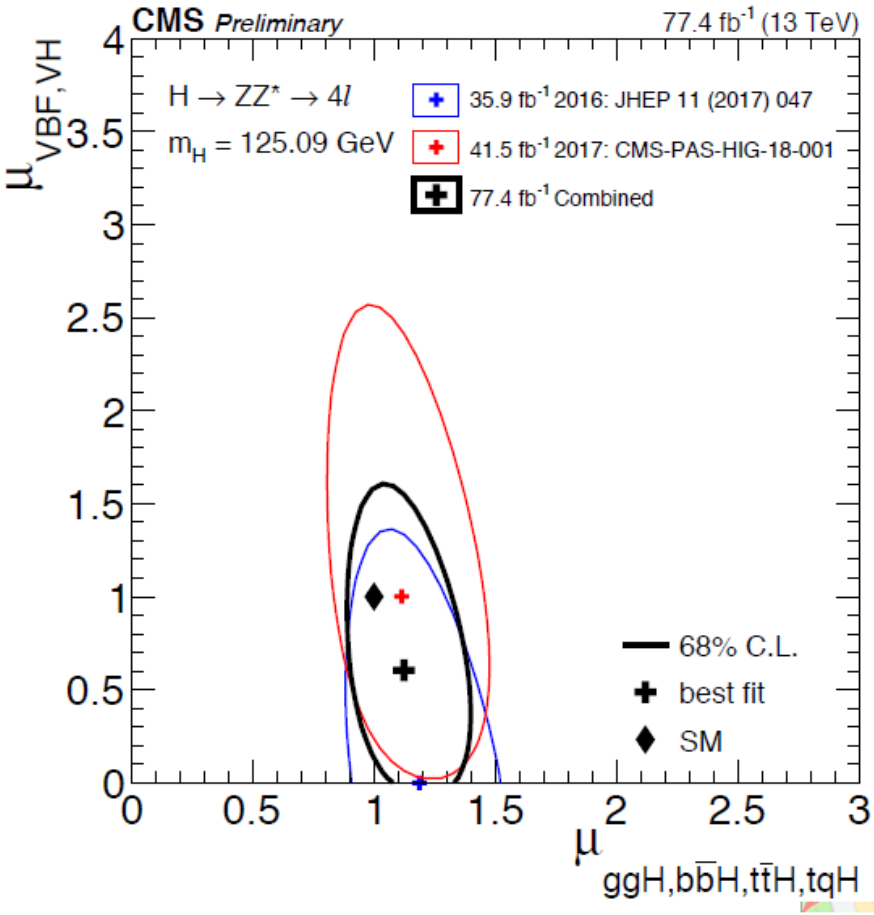



# HZZ Combination

$$\mu = 1.06 \pm 0.10(stat)^{+0.08}_{-0.06}(exp.syst)^{+0.07}_{-0.05}(th.syst)$$




$$\mu_{VBF,VH} = 0.60^{+0.62}_{-0.49}$$
$$\mu_{ggH,t\bar{t}H,b\bar{b}H,tqH} = 1.12^{+0.16}_{-0.18}$$



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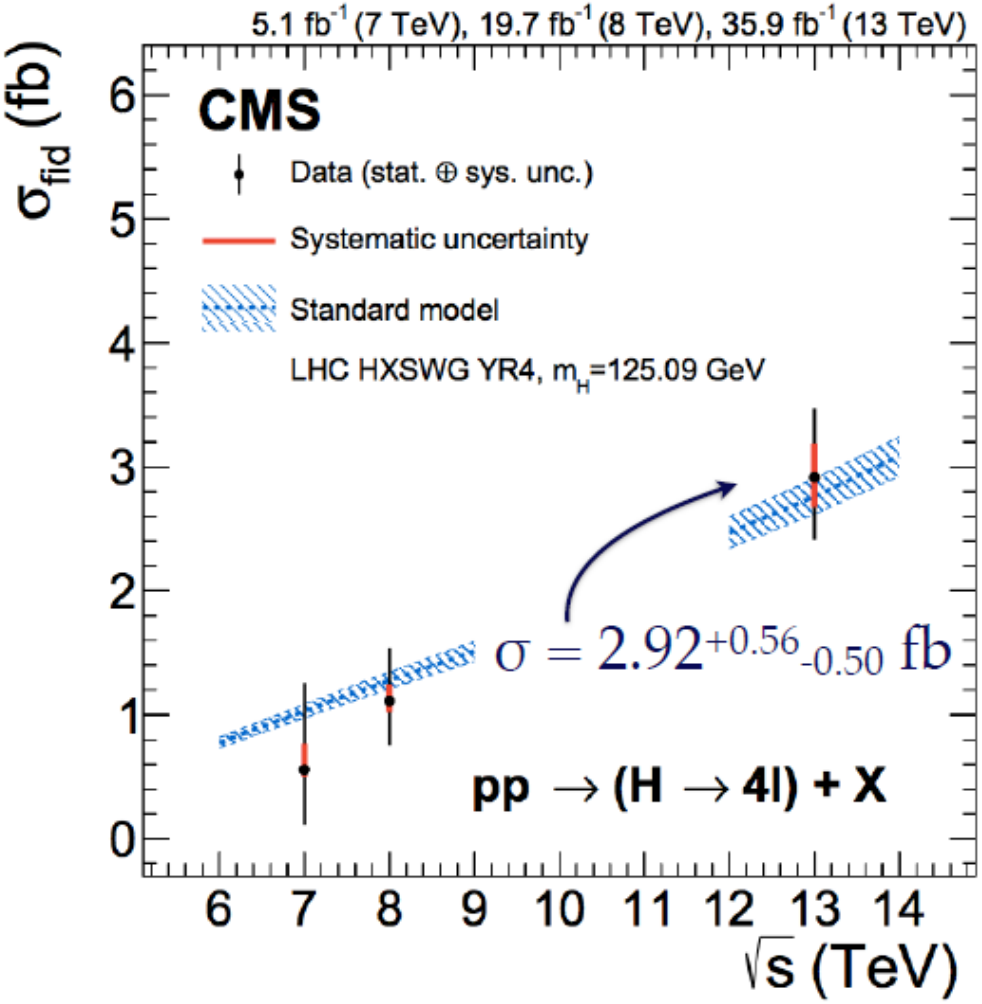
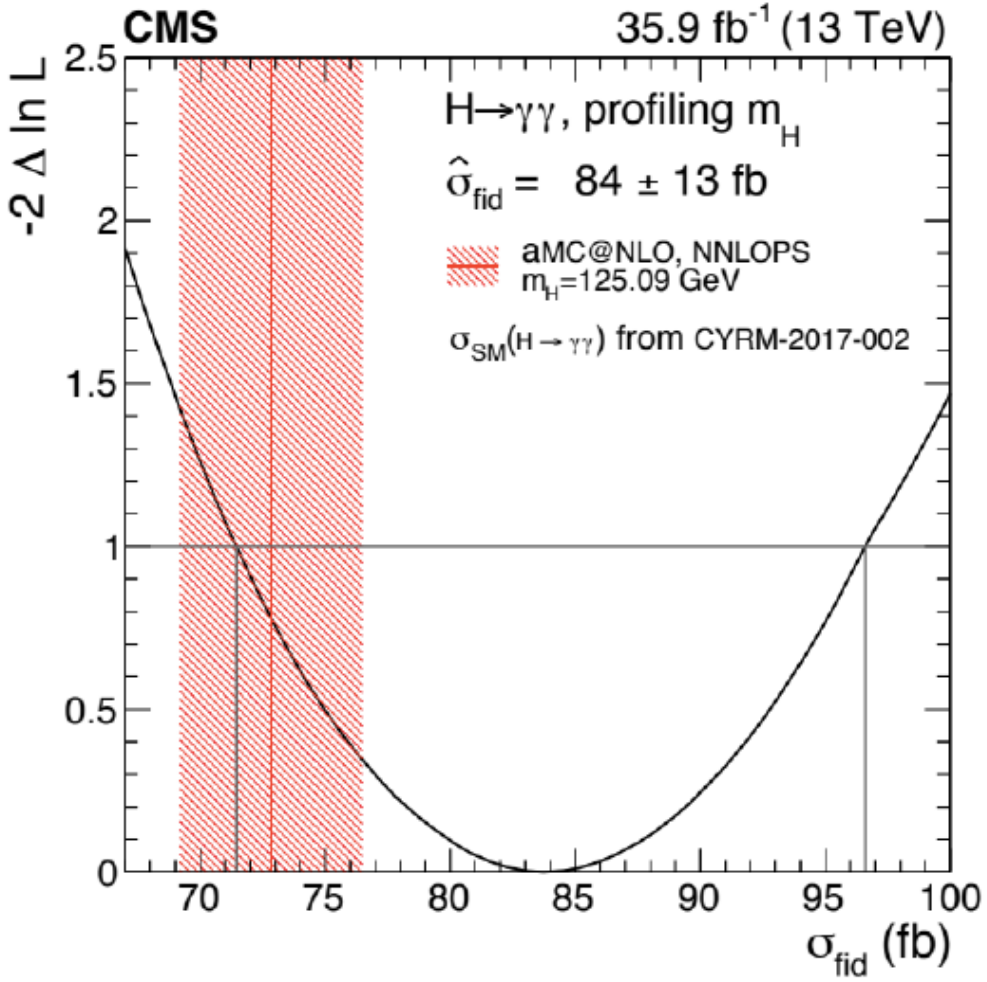
# Fiducial cross-sections




- Define simplified fiducial regions for maximally model-independent results
- New H→γγ fiducial and differential result recently submitted to JHEP

# Signal strengths

**Signal strengths, μ**

**Parameters scale cross sections and BRs relative to SM**

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}$$

**Scaling of generic i → H → f process**

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Most immediate quantity: ratio of observed "rate" with respect to the expected results

Production: ratio of cross-sections

Decay: ratio of branching fractions

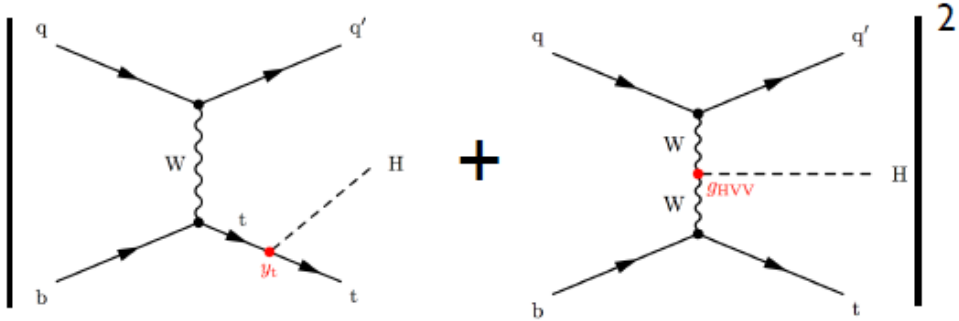
Many systematic uncertainties and theory assumptions cancel out in the ratio

- Easy to interpret
- Deviation from SM immediately visible
- Can decouple production and decay mechanisms
- Only effects modifying the absolute normalisation are visible, no sensitivity to shapes

No immediate relation with the width, each signal strength is independent from each other, but possible reinterpretation in the k-framework

# Single top + Higgs

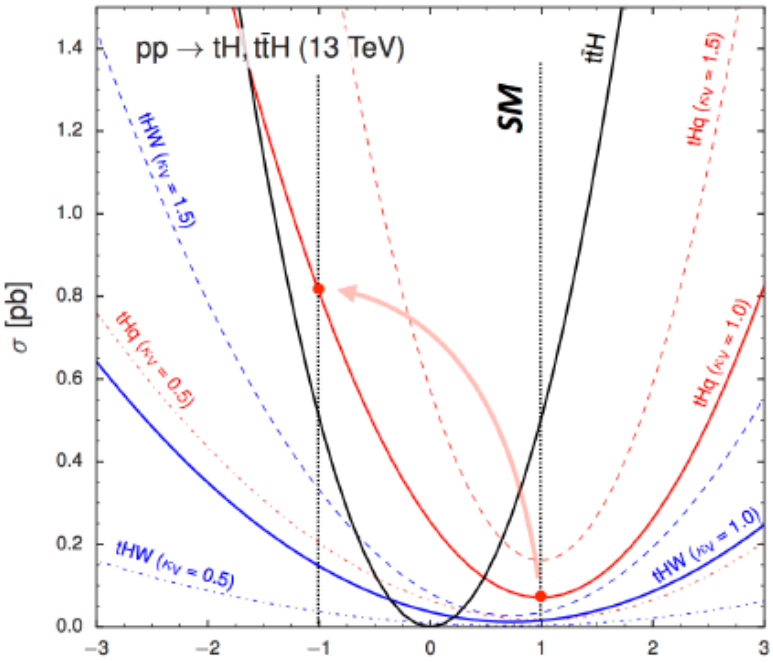
$$\sigma_{tH} \propto \left| \; \right|^2 + \left| \; \right|^2$$




$$\propto \kappa_t \equiv y_t / y_t^{SM} \qquad \propto \kappa_V \equiv g_{HVV} / g_{HVV}^{SM}$$

- Very small production cross section in SM (t-channel = ~71 fb)
- But enhanced by factor x ~10 if sign($\kappa_t/\kappa_V$) opposite to SM ⇒ $\sigma_{tH} > \sigma_{ttH}$
  - So can be used with present Run-2 dataset to constraint relative sign of $\kappa_t$ and $\kappa_V$.

[B. Stieger, ICHEP2018 talk]






YR4 Numbers

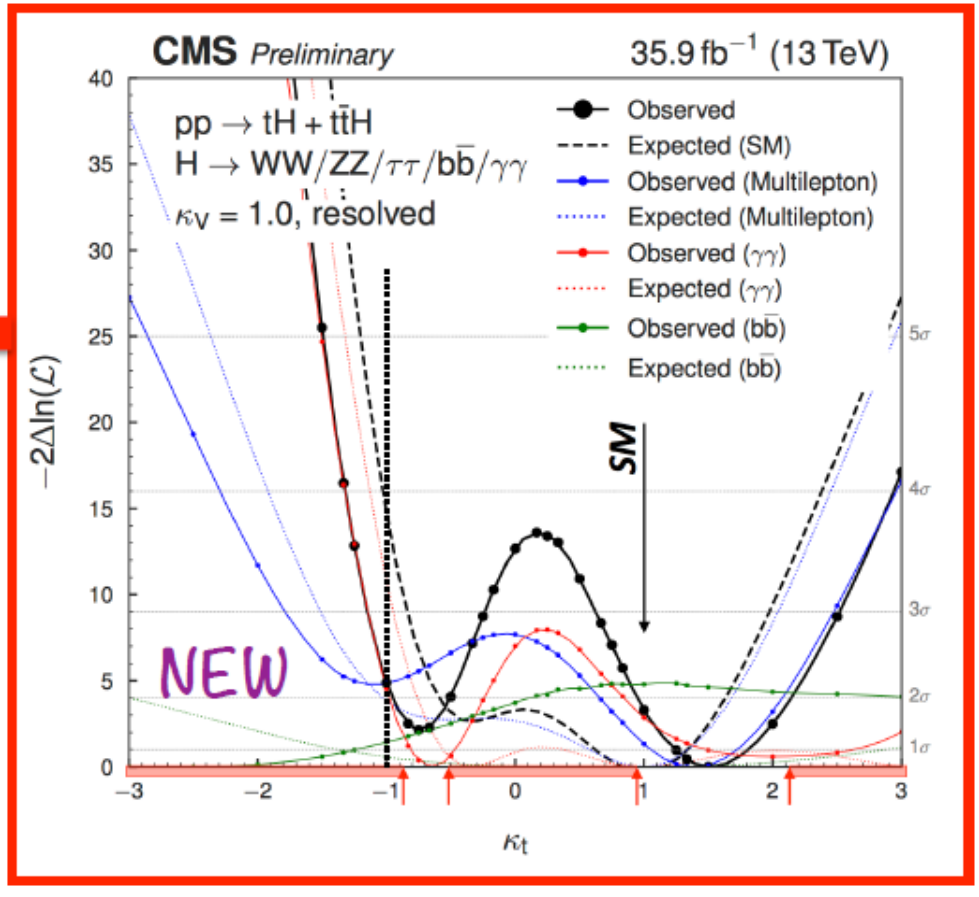
B. Stieger

# Single top + Higgs

- NEW **CMS** Run-2 **combination** of:
  - tH, H → Multi-leptons (WW/ZZ/ττ)
  - tH, H → bb
  - ttH, H → γγ (use ttH categories)

- Data favors sign($\kappa_t/\kappa_V$) = 1 at 1.5σ level (~4σ expected)
  - Complementary to constraints from H → γγ and gg → ZH production
- Assuming SM ttH yield and SM tH acceptance, can constraint σ(tH):

$$\mu_{tH} < 26.5 \ (13.6 \text{ exp.})$$

$\kappa_V = 1$

[CMS-PAS-HIG-18-009]