# EFT Constraints from Higgs measurements

Nicholas Wardle – Imperial College London

**Pushing the Boundaries - Standard Model and Beyond at LHC**
**Durham, UK**

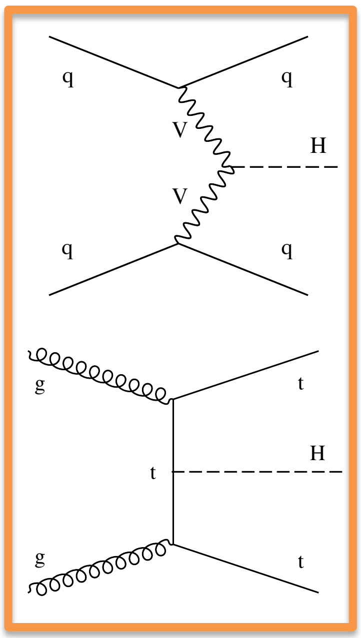
**19/09/2019**

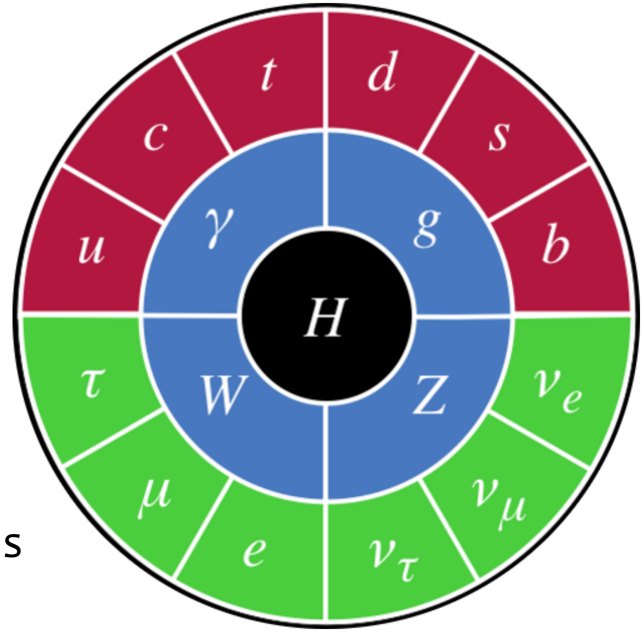
# Completing the SM

Discovery of the Higgs boson completed the Standard Model

→ Great success of LHC @ Run-1

→ Coupling structure in SM allows for rich program of Higgs boson studies @ LHC




**Tree level** coupling to vector bosons and heavy fermions

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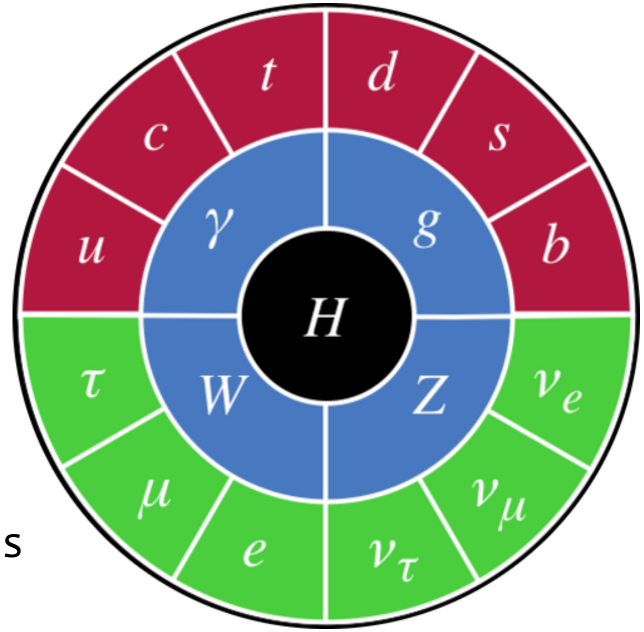


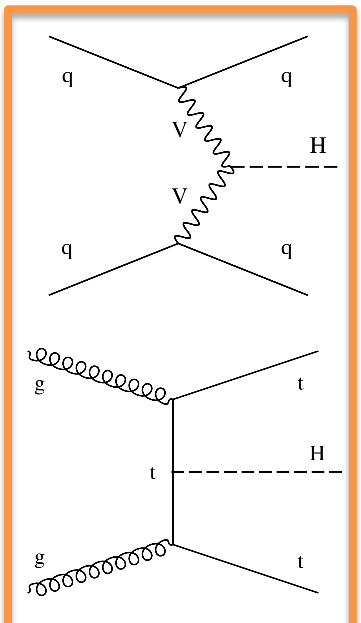


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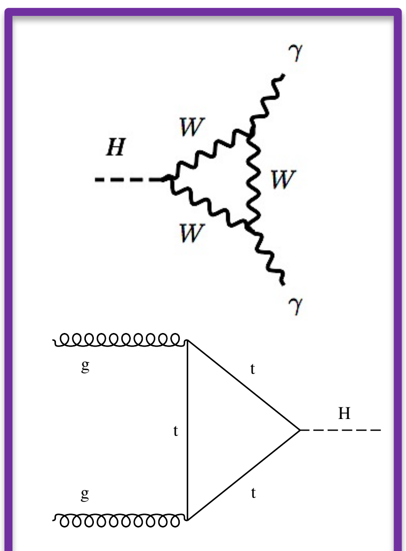


**Loop induced** processes sensitive to interference & BSM effects

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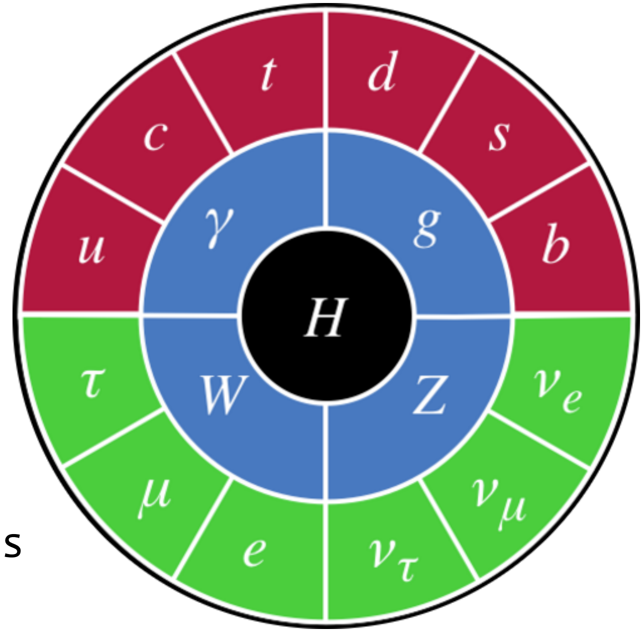


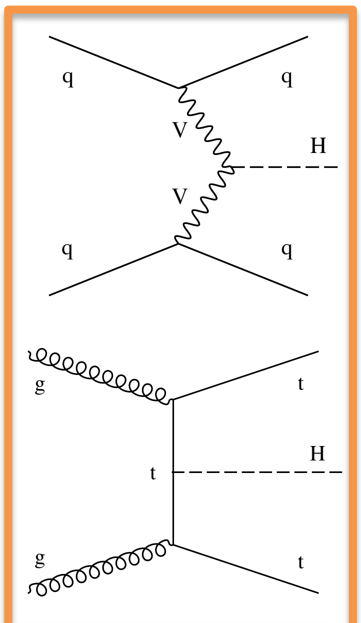


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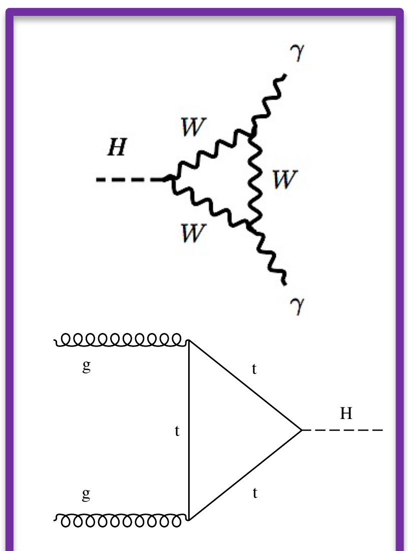
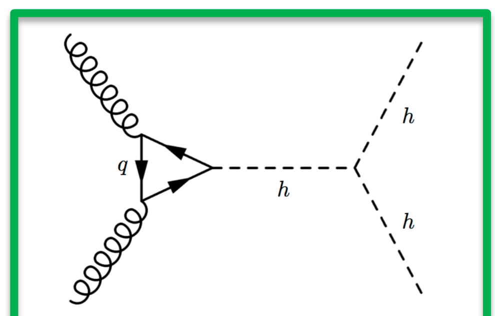


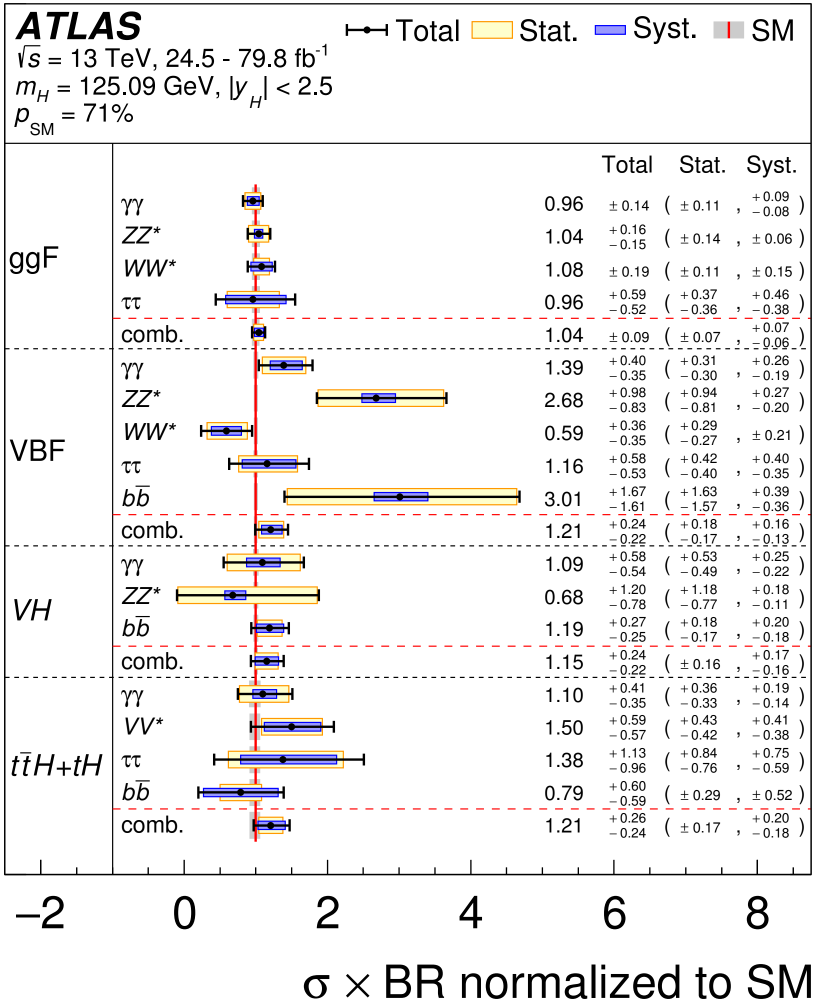

**Loop induced** processes sensitive to interference & BSM effects




Higgs boson the only particle that **couples to itself**!

# Great for experiments!

arXiv:1909.02845 (sub to Phys Rev D)

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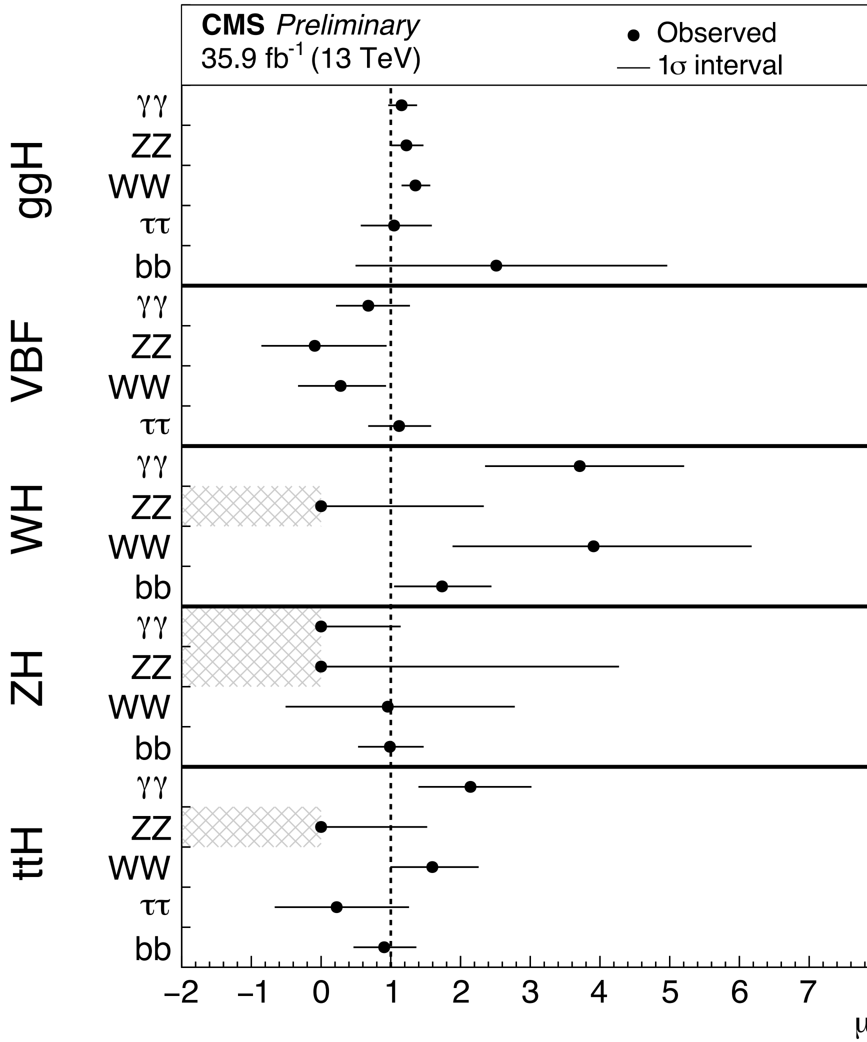
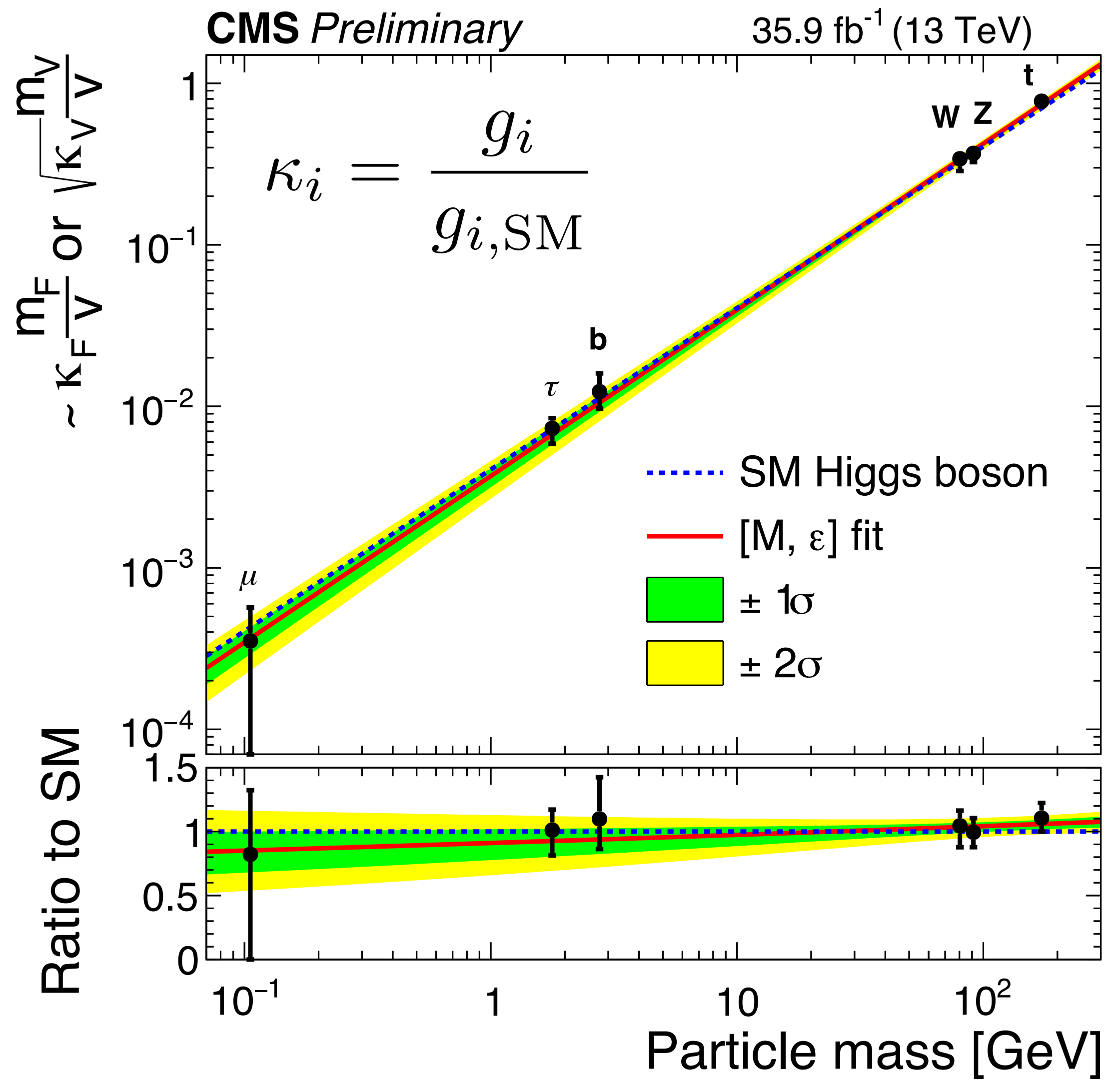



Wide range of measurements possible to study Higgs boson properties

# What do we know?

Couplings to heavy fermions and bosons well established!

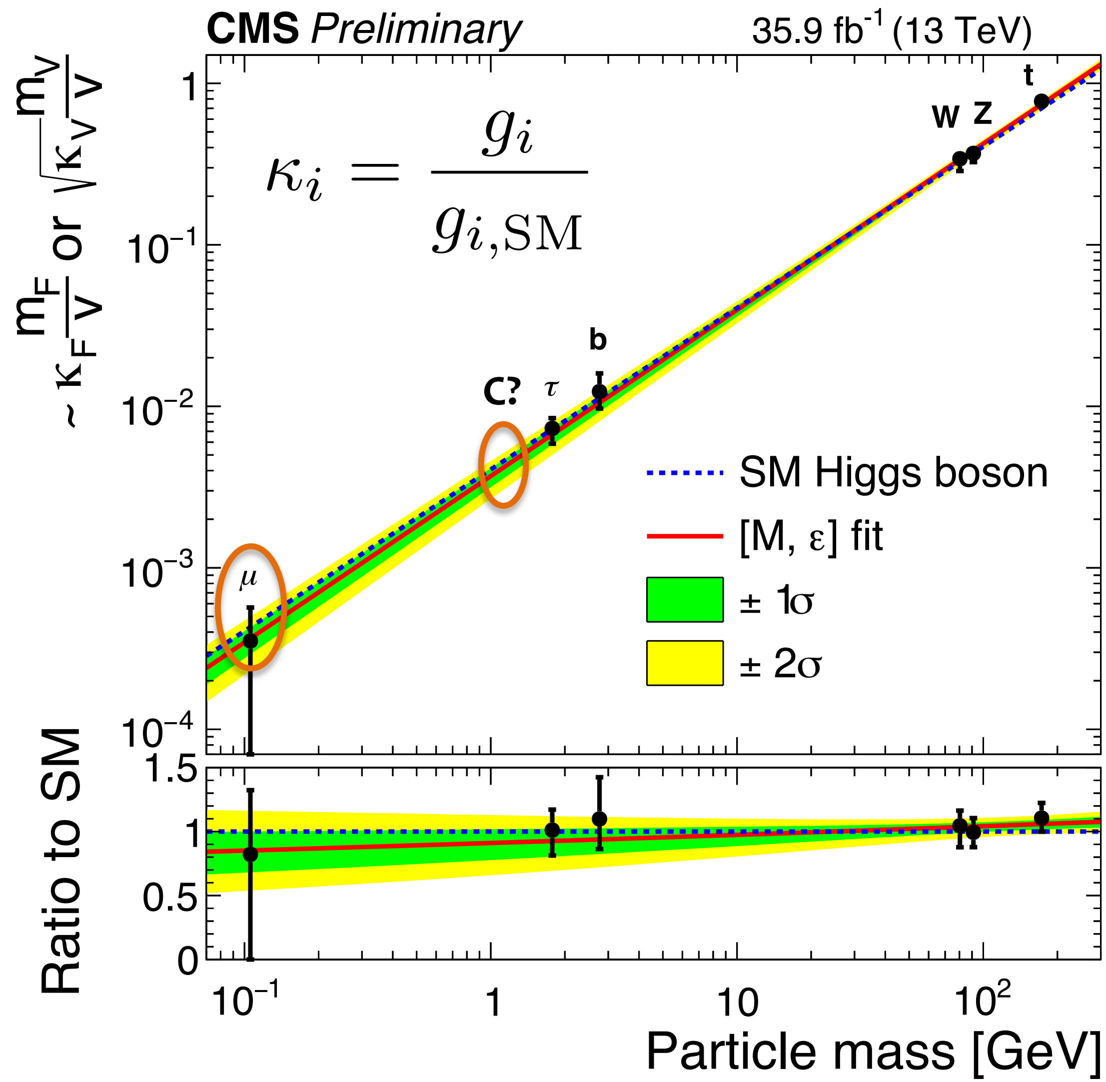


# What don't we know?

Couplings to heavy fermions and bosons well established!

Yet to confirm **coupling to 2nd Generation**

- B(H→μμ) < 1.7 x SM @ 95% CL **(ATLAS-CONF-2019-028)**
- B(H→cc) < 70 x SM @ 95 % CL **(CMS-PAS-HIG-18-031)**



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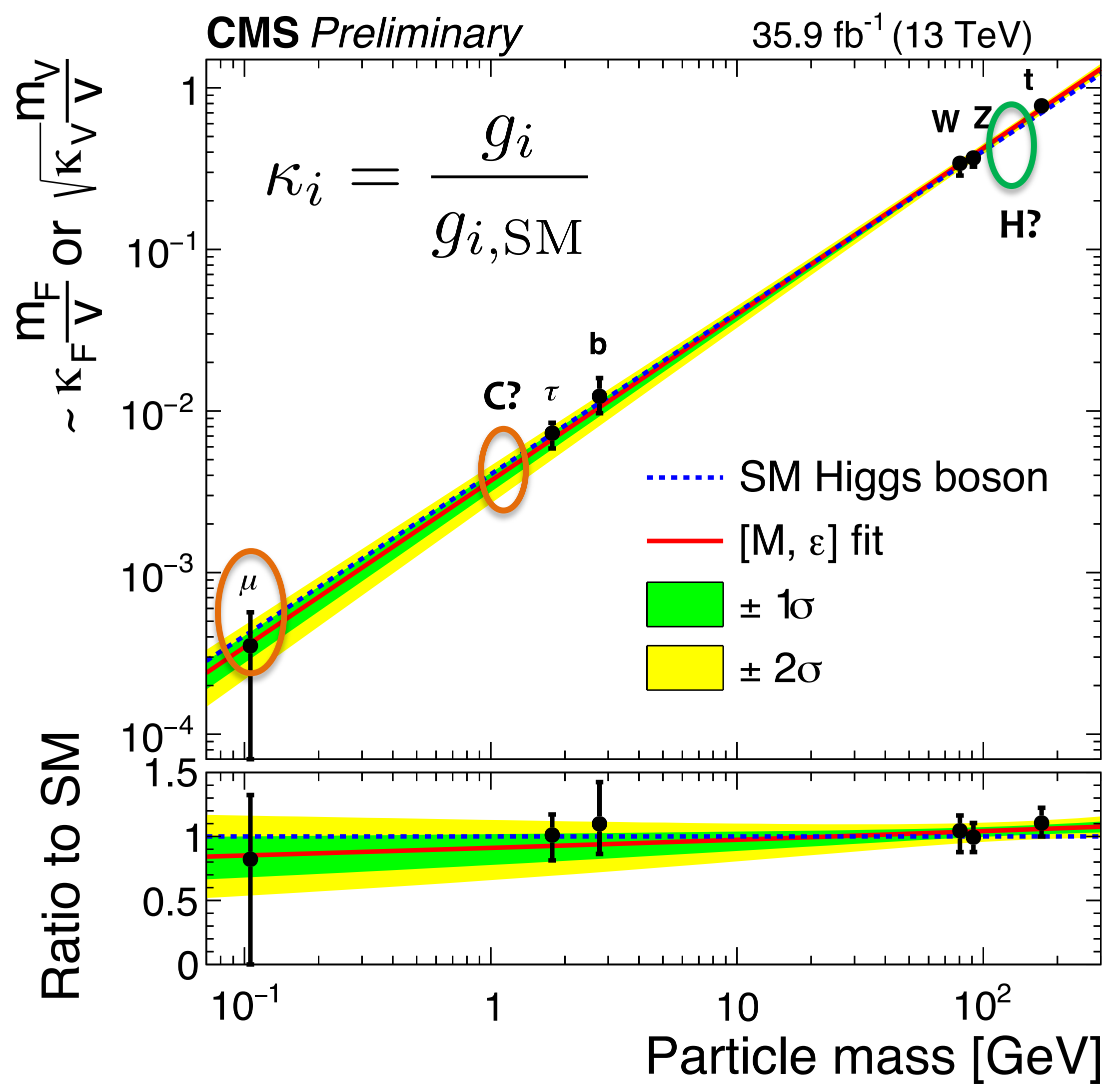
Haven't observed **self-coupling** of the Higgs boson

- pp → HH searches severely limited by statistics @LHC

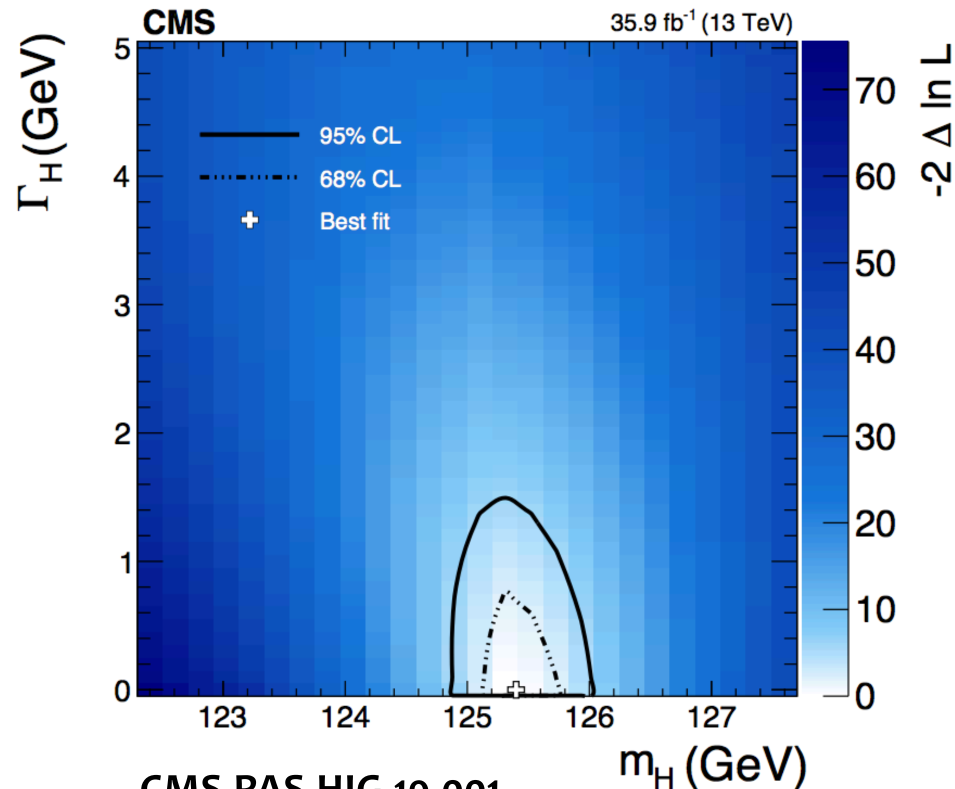


# What don't we know?

$\Gamma_{SM}$ = 4 MeV

Relatively large modifications possible from new physics
- Modifications to B(→SM) values
- Additional decays present if NP includes light objects

Width (directly) constrained from H->4l line-shape
- Large uncertainty with Run-2 measurements
- Plenty of available room from BSM contributions with current data




CMS-PAS-HIG-19-001

$\Gamma_H$ < 1.1 GeV @ 95% CL

# Effective field theory

$$\mathcal{L} = L_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \ldots$$

Well-defined theoretical approach to explore physics beyond the SM

- Assume new states are Heavy → only include light (SM) states in effective Lagrangian
- BSM effects show up as deviations of expansion coefficients from 0 in the data

Not specific to Higgs interactions …

→ Great framework to combine electroweak, top, Higgs measurements!

Matching to UV complete theories ~straightforward …

→ Complimentary to direct searches for heavy states

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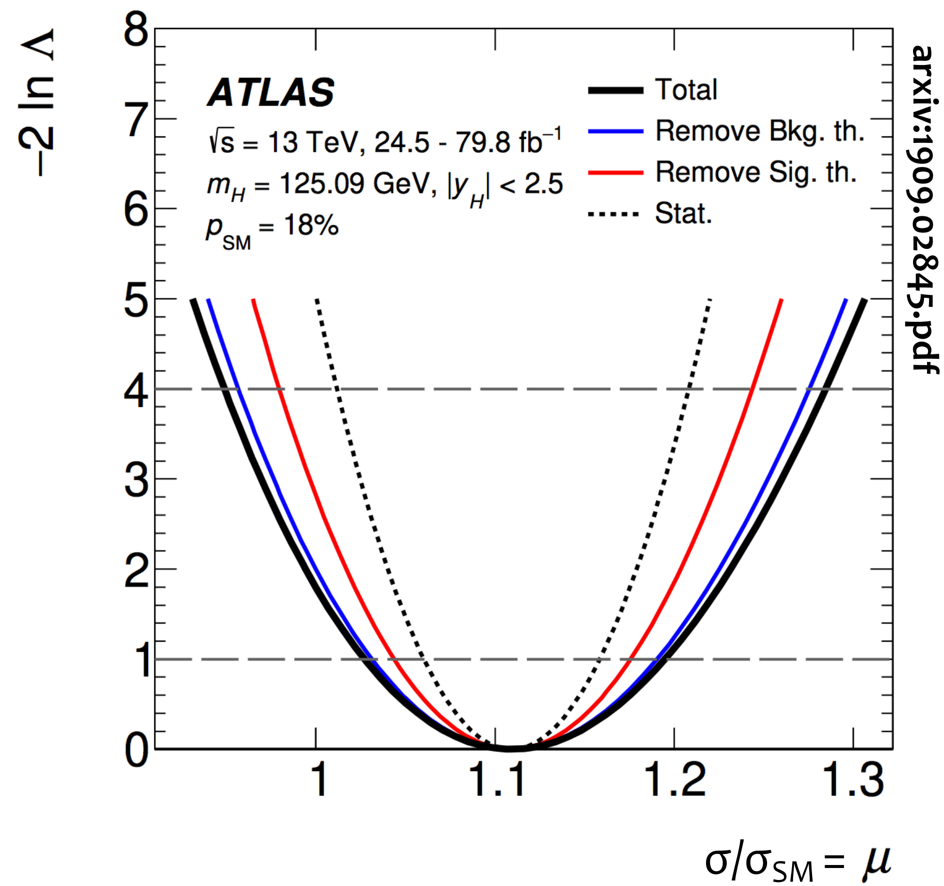
In Higgs, limited sensitivity with Run-2 → Focus on dim-6 operators in experiments

# Overall signal rate

Measuring the inclusive Higgs rate compared to that expected under the SM ($\mu$)...

Uncertainty in overall rate < 10% with latest combinations

- Dominated by systematic component
- Theoretical uncertainty on signal cross-sections are major component of measurement




$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

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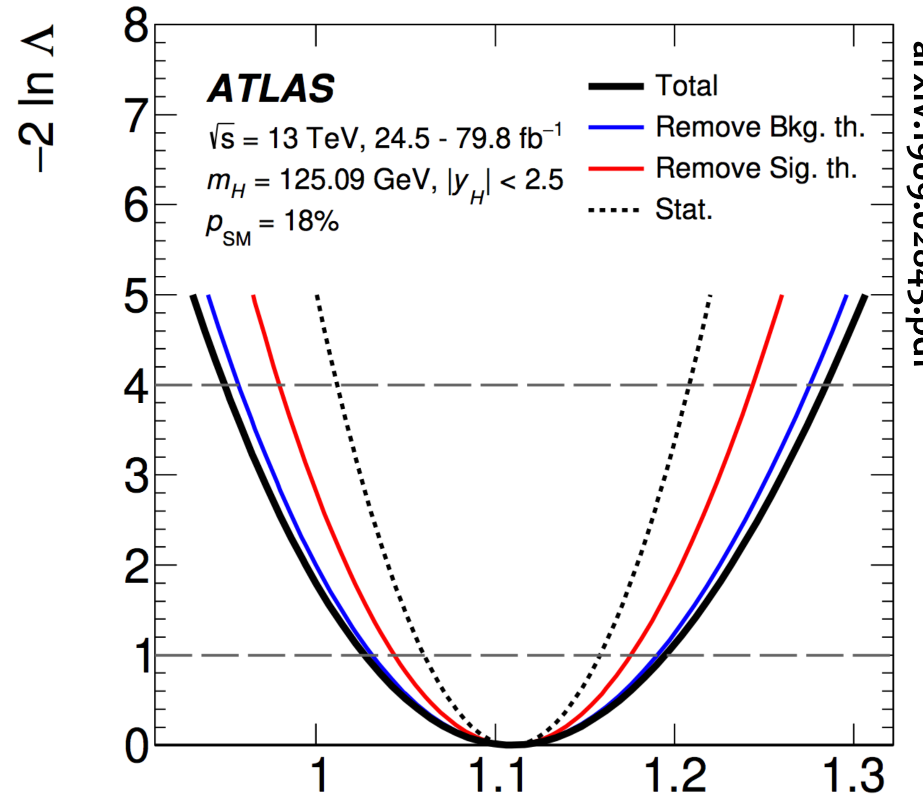
$$\mathcal{O}_H \sim \frac{c_H}{\Lambda^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)$$




Related to constraint on $c_H$ → $O_H$ rescales all Higgs prod/decay processes

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

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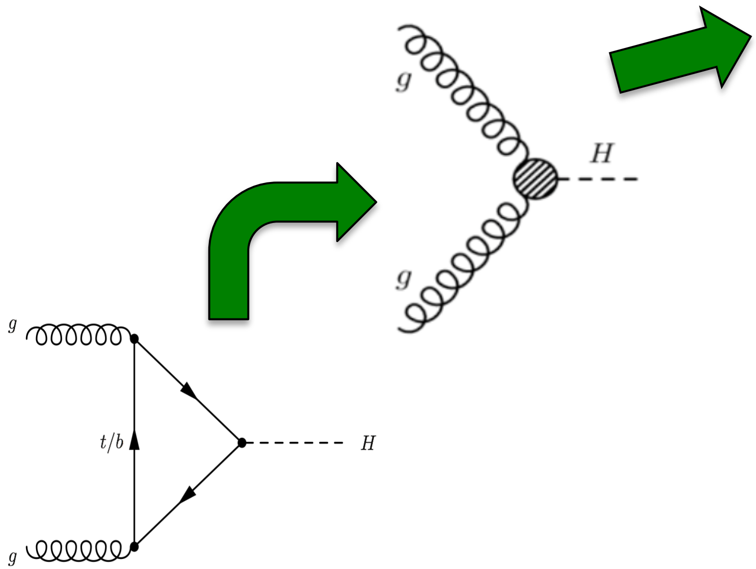
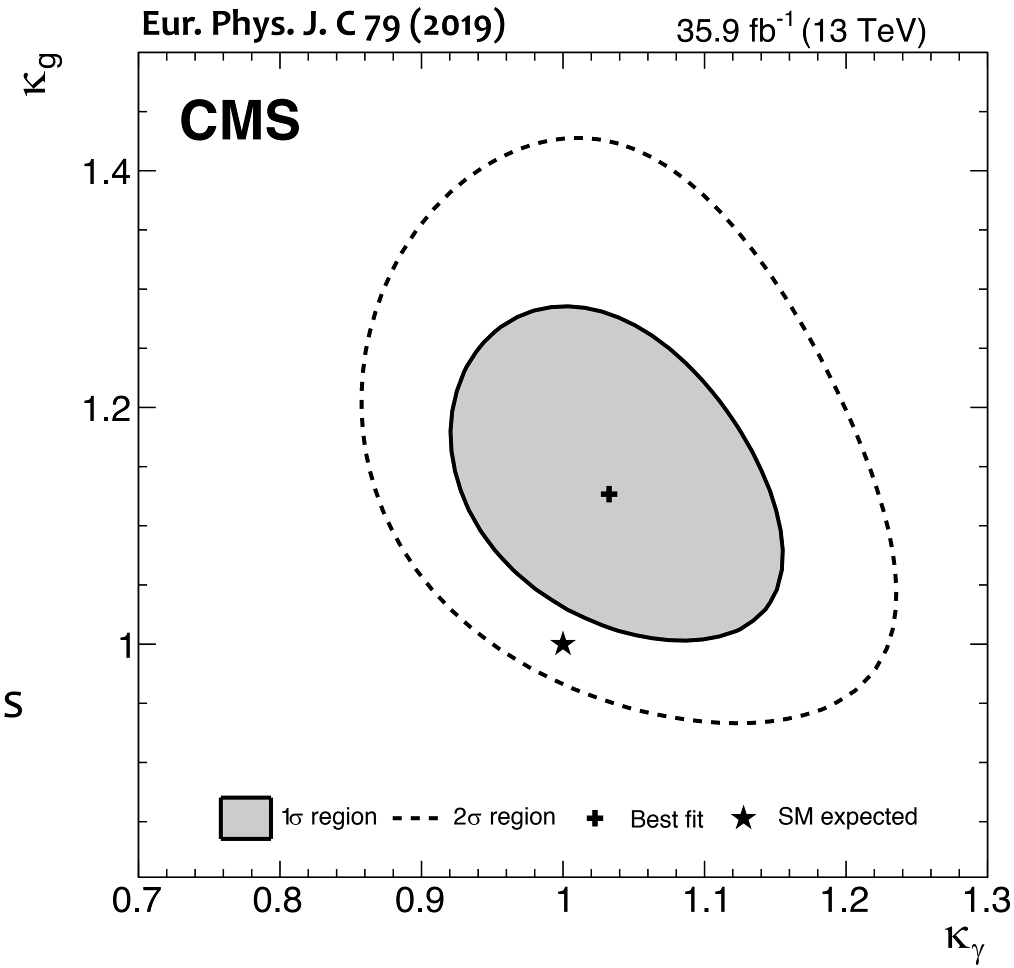
# Effective Couplings (κ-framework)

In LO κ-framework from Run-1, we also relax assumption on loop-induced processes and treat as "**effective couplings**"




Assume BSM physics at Heavy scales

→ Accessible only in loops

→ No additional direct decays ( **$BR_{BSM}$=0** )

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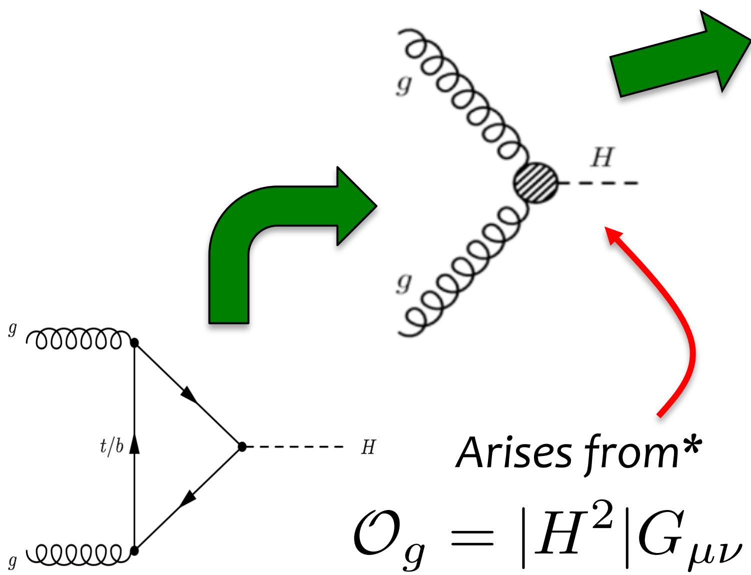


*Arises from**

$$\mathcal{O}_g = |H^2| G_{\mu\nu} G^{\mu\nu}$$

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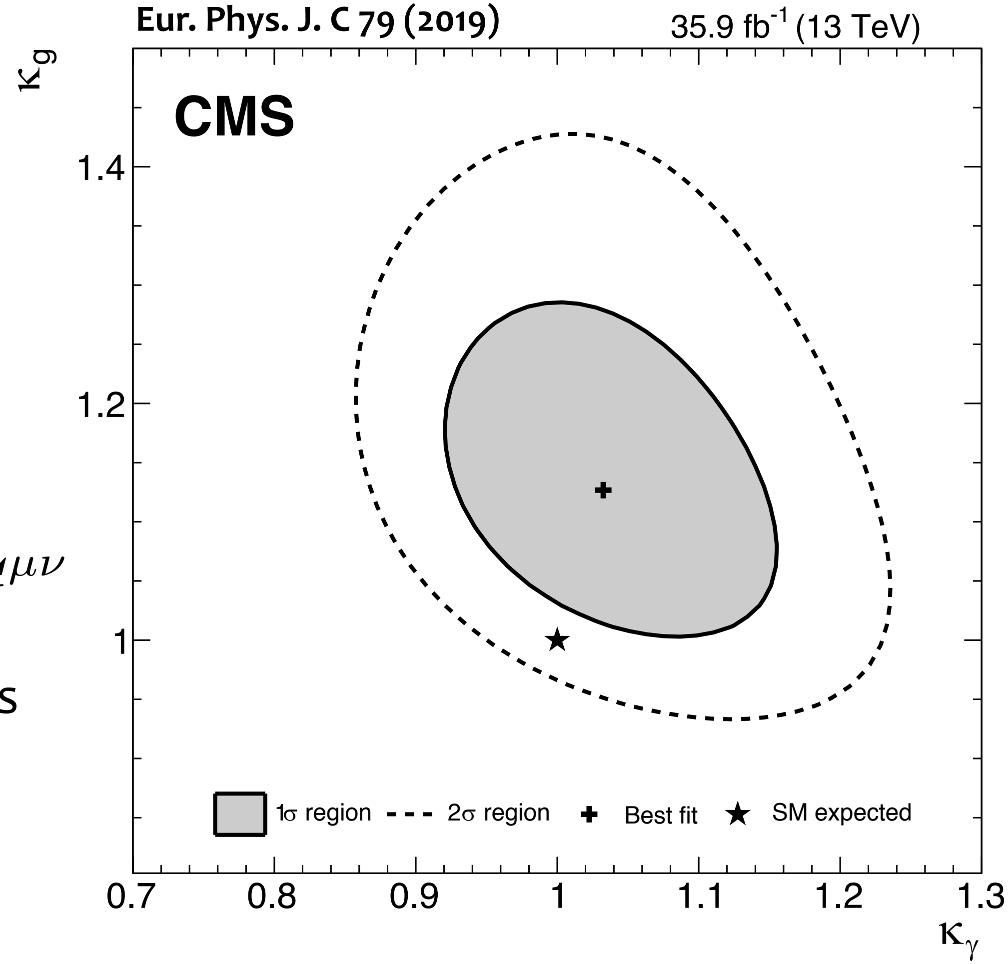


Assume BSM physics at Heavy scales

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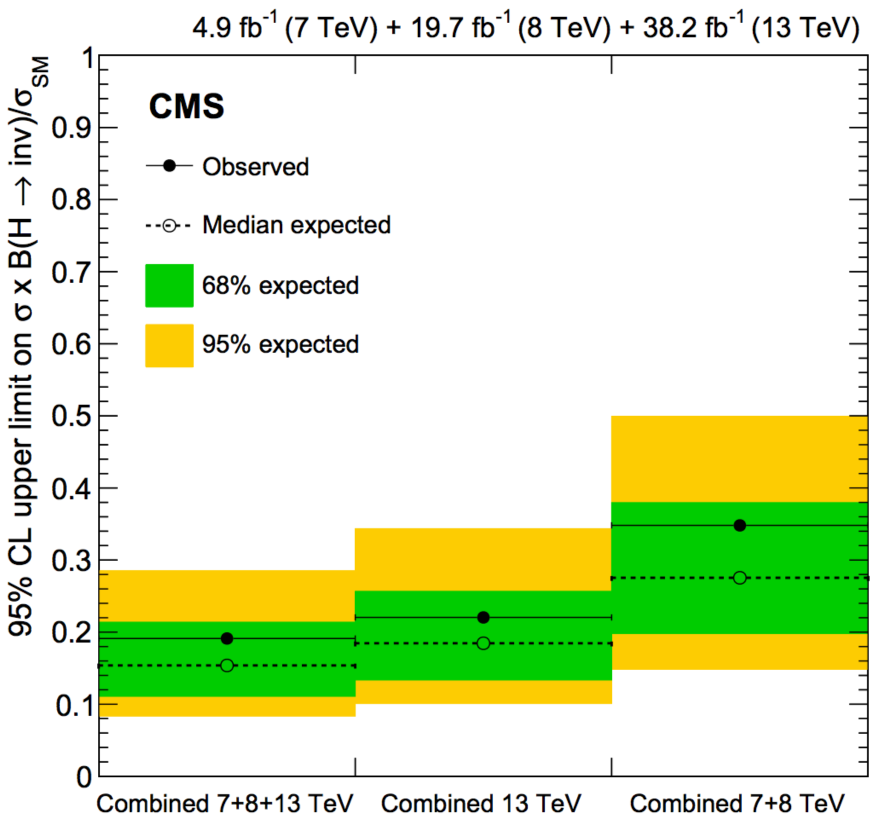
→ No additional direct decays ( **$BR_{BSM}$=0** )

(*In SILH basis)

# Effective theories to compare experiments

Searches for H→invisibles can be interpreted under EFTs for DM* → Higgs portal models [1]




[1] Review in https://arxiv.org/abs/1903.03616

*note this ***does*** require addition of new light states!

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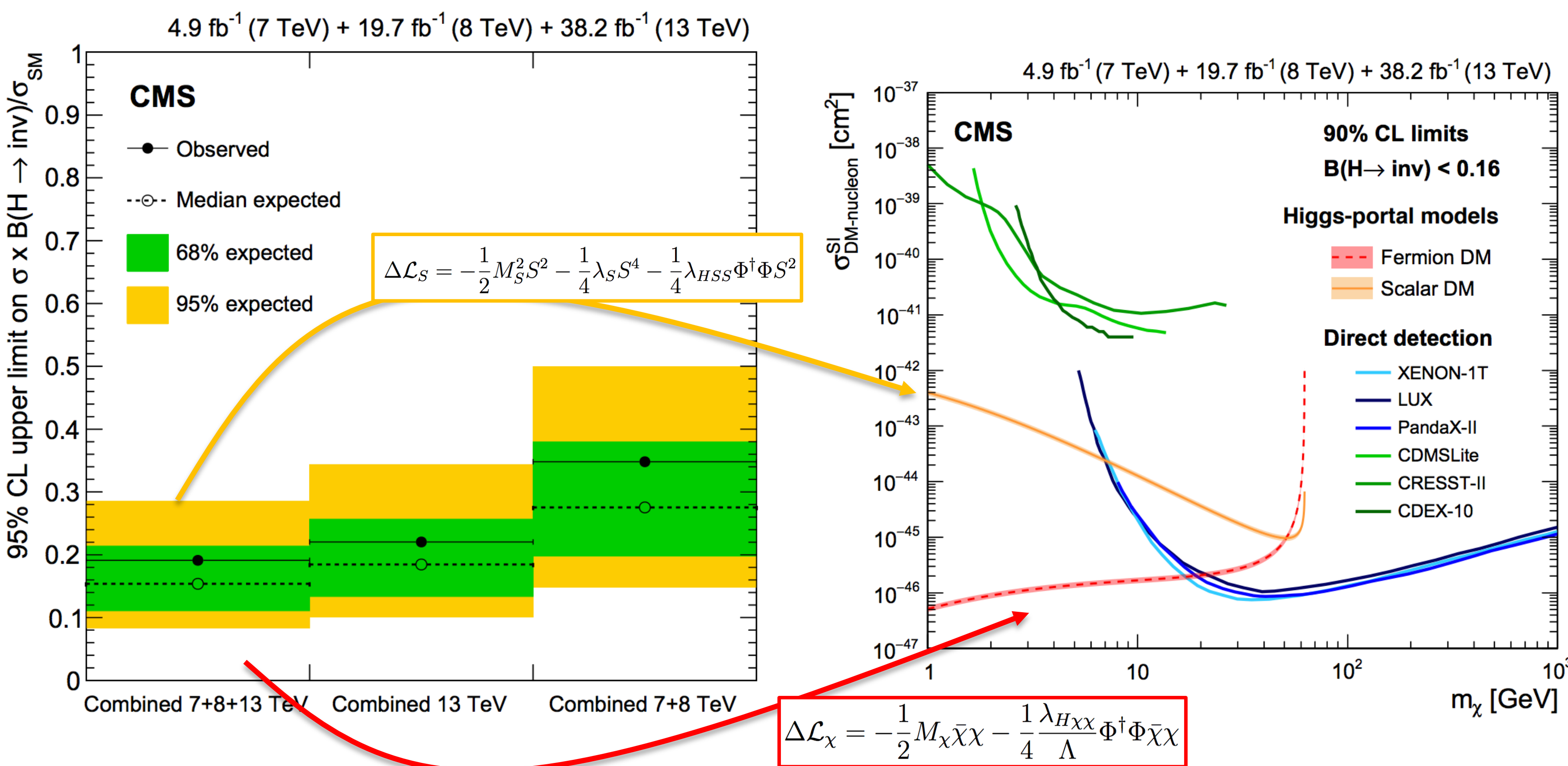


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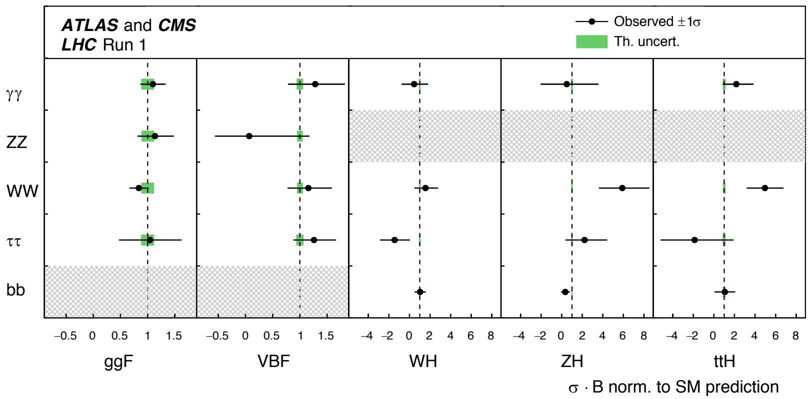
**On-shell**




$$\delta\mu \approx \left(\frac{v}{\Lambda}\right)^2$$

Inclusive $\mu/\kappa$ : high-precision yields precision on new physics scale

**δμ = 1% → Λ ~ 2.5 TeV )**

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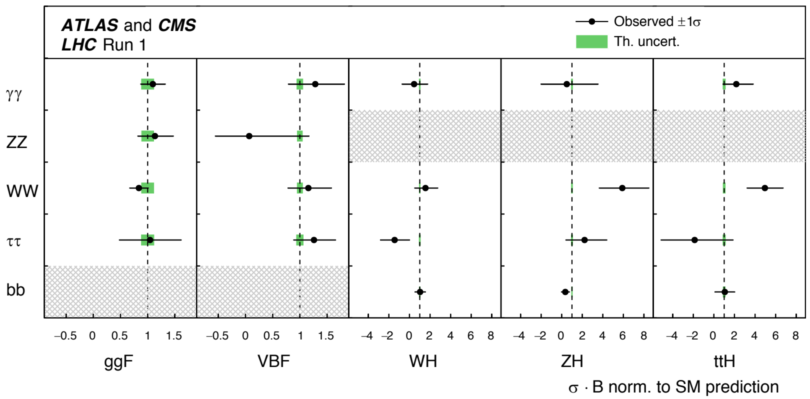


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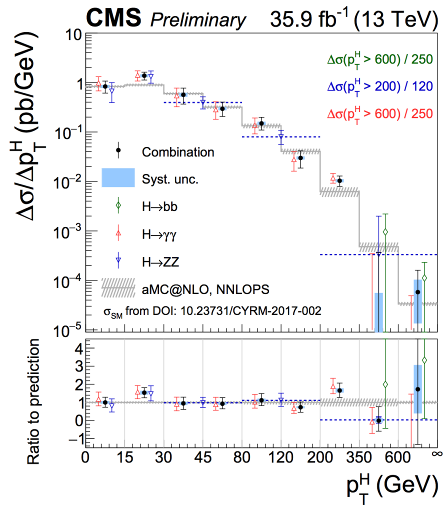
## Off-shell / large q²




$$\delta\mu \approx \left(\frac{q}{\Lambda}\right)^2$$

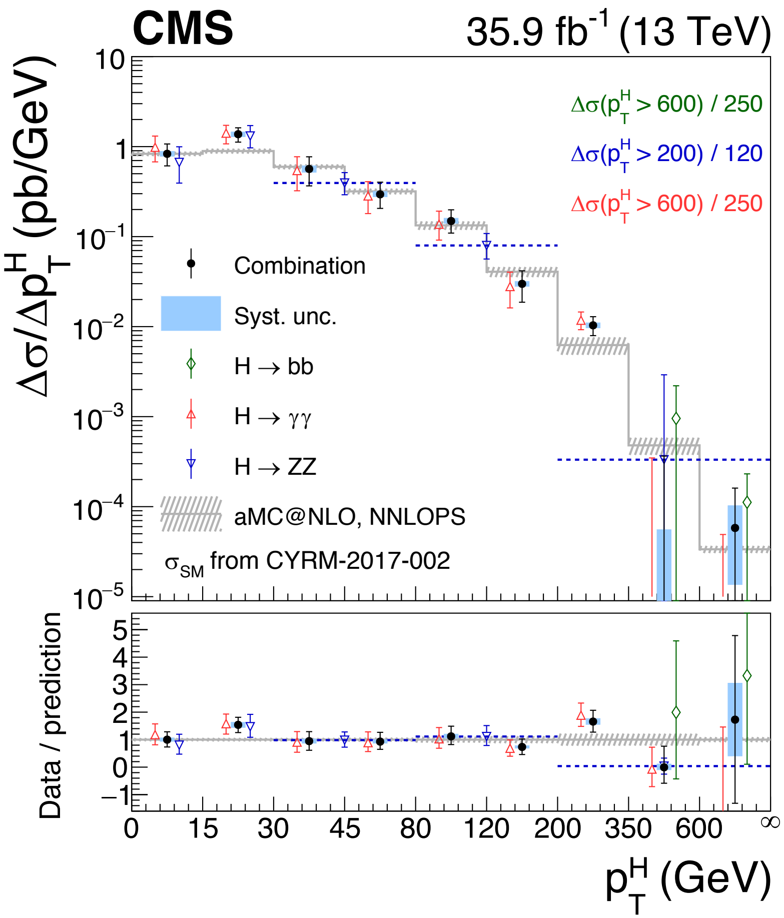
Differential: High momentum production sensitive to new physics

**δσ = 15% (q=1TeV) → Λ ~ 2.5 TeV**

Need to use differential measurements to exploit sensitivity at LHC!

# Differential Higgs

Differential $p_T(H)$ Combination in gg→H mode: H→ZZ + H→γγ (+boosted H→bb)




Phys. Lett. B 792 (2019) 369

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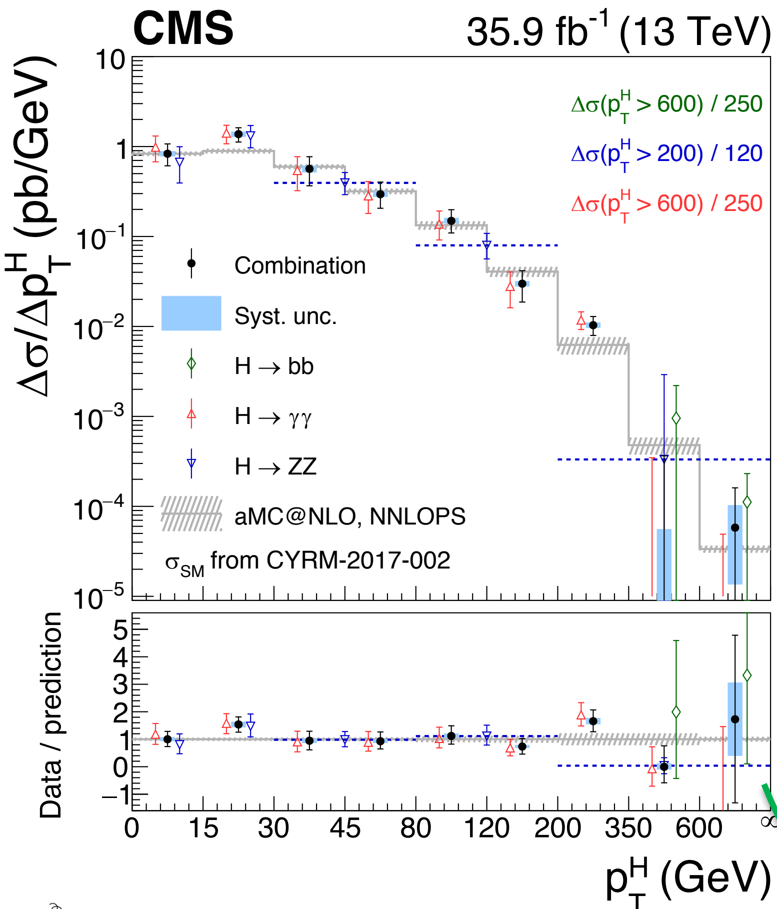
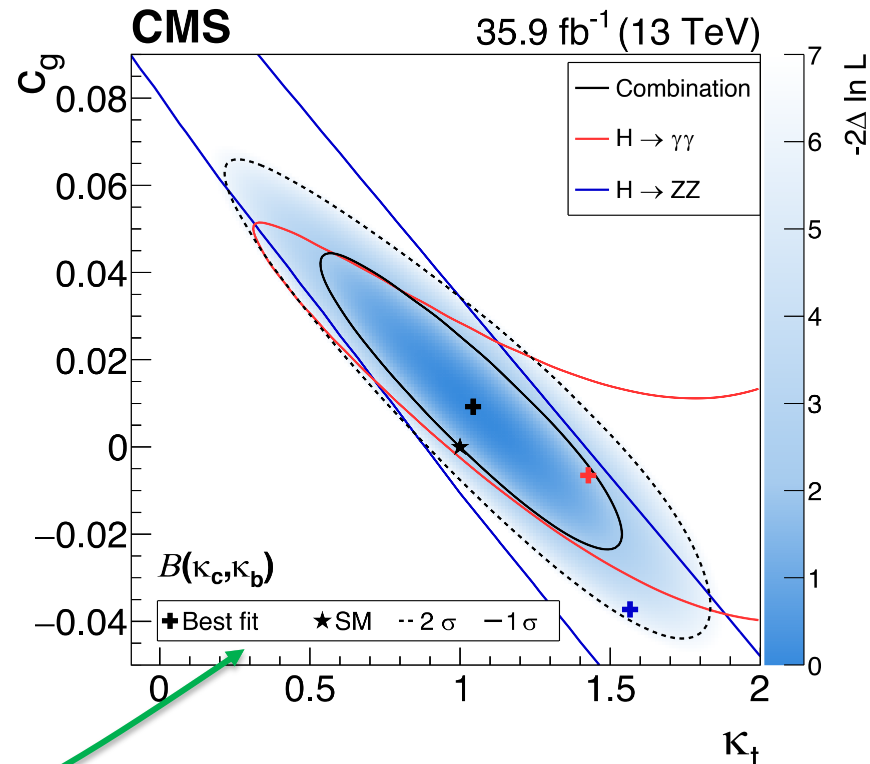
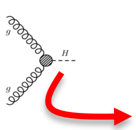



Phys. Lett. B 792 (2019) 369




Use measurements to constrain Yukawas/Wilson coeffs (following [1])



$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \quad \mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.\,, \quad \mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$

*Yukawas*

[1] https://arxiv.org/abs/1705.05143

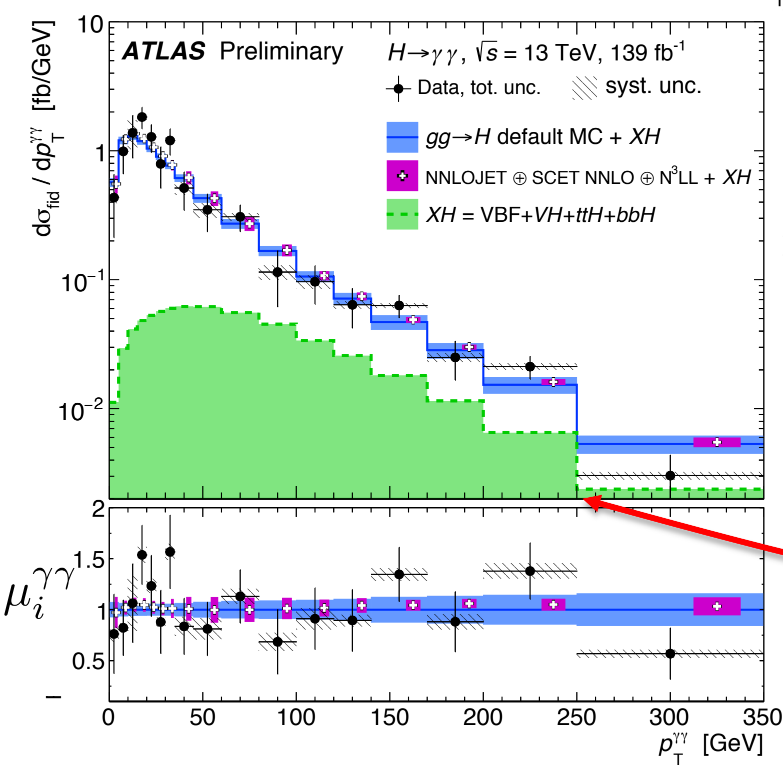
# Differential Higgs

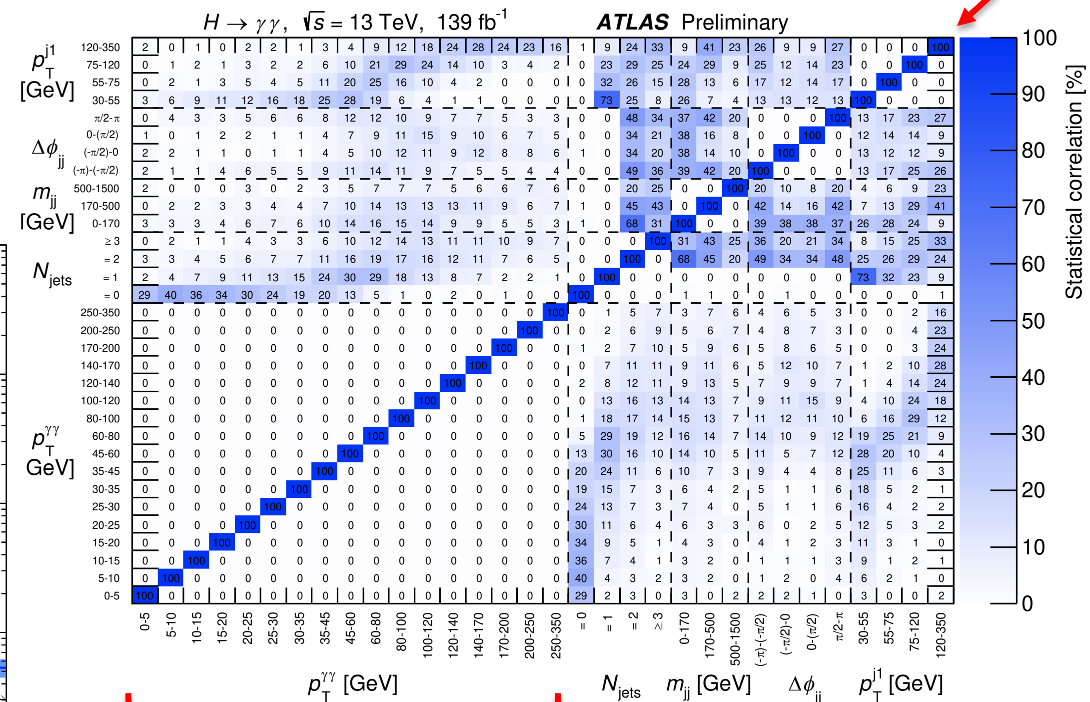
$\rho(\mu_i^{\gamma\gamma}, \mu_j^{\gamma\gamma})$

Fiducial differential Higgs measurements in several (1D) variables with H→γγ

- $p_T^{\gamma\gamma}$, $\Delta\varphi_{jj}$, $p_T^{j1}$, $m_{jj}$, $N_{jets}$

ATLAS-CONF-2019-029

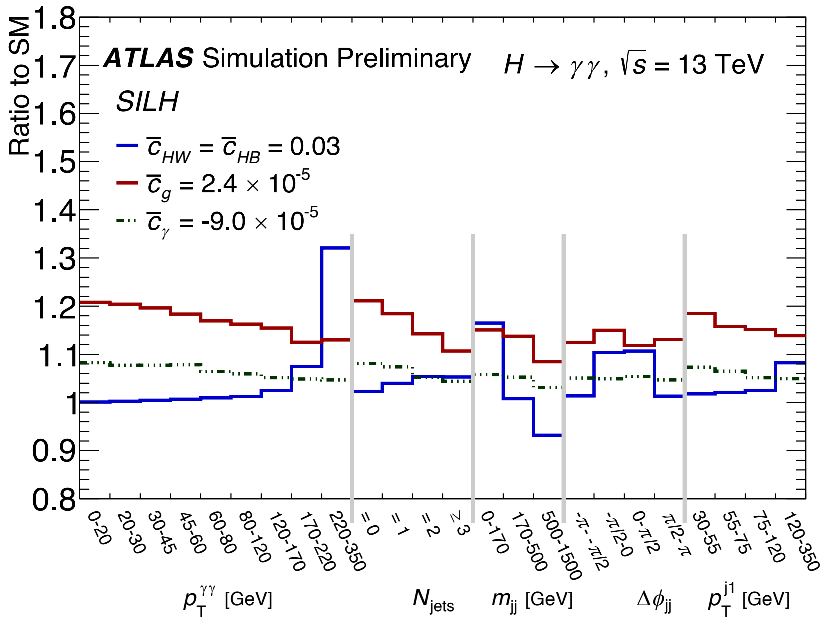


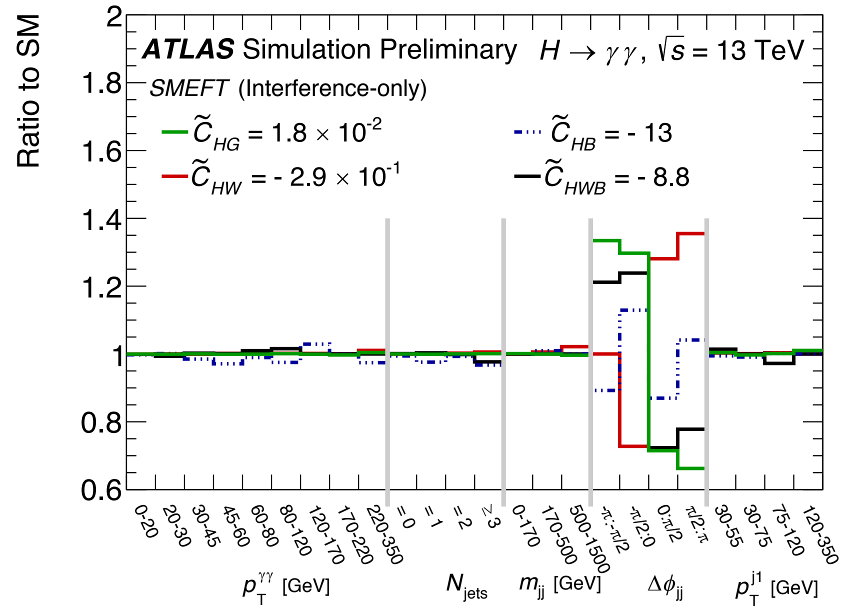




Correlations (ρ) between different bins in different distributions calculated using bootstrapping

# Differential Higgs

Deviation from SM expressed in terms of Wilson coefficients $\mu_i^{\gamma\gamma} \rightarrow \mu_i^{\gamma\gamma}(\bar{\mathbf{c}}, \tilde{\mathbf{c}})$
(using SILH / SMEFT basis @ LO)




Build parameterization of $\mu_i^{\gamma\gamma}(\bar{\mathbf{c}}, \tilde{\mathbf{c}})$ using many MC points + professor algorithm [1] and construct log-likelihood function …

$$-2\log L = \left(\hat{\boldsymbol{\mu}}^{\gamma\gamma} - \boldsymbol{\mu}^{\gamma\gamma}(\bar{\boldsymbol{c}}, \tilde{\boldsymbol{c}})\right)^T V^{-1} \left(\hat{\boldsymbol{\mu}}^{\gamma\gamma} - \boldsymbol{\mu}^{\gamma\gamma}(\bar{\boldsymbol{c}}, \tilde{\boldsymbol{c}})\right)$$

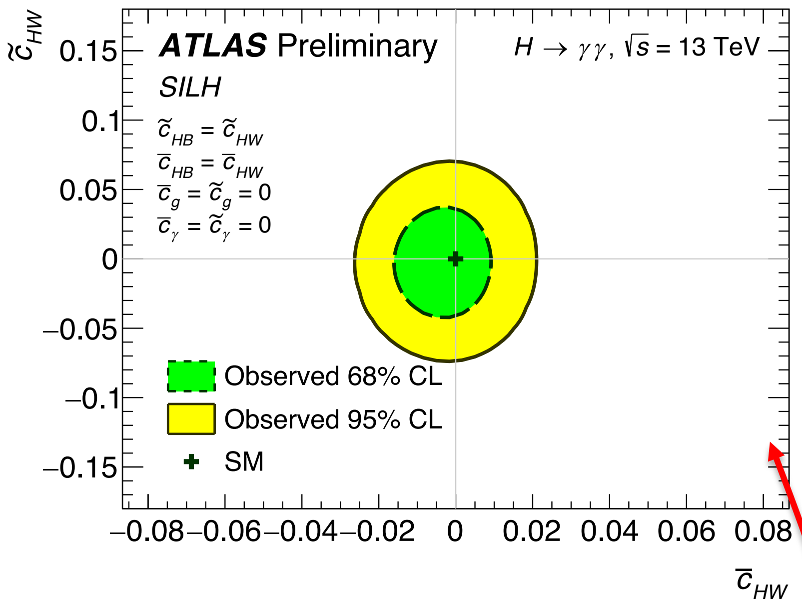
[1] https://arxiv.org/pdf/0907.2973.pdf

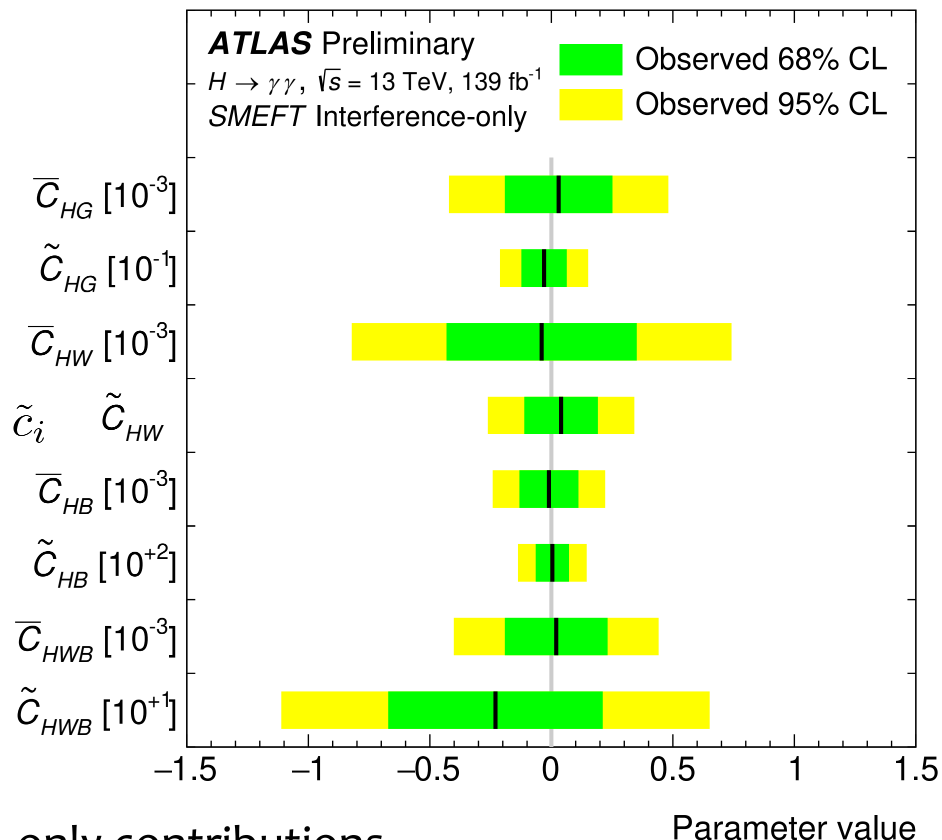
$$V_{i,j} = \rho(\mu_i^{\gamma\gamma}, \mu_i^{\gamma\gamma})\sigma_{\mu_i^{\gamma\gamma}}\sigma_{\mu_j^{\gamma\gamma}}$$

# Differential Higgs

Minimize log-likelihood to extract constraints on Wilson coefficients

→ Limits extracted fixing other coeffs to 0




$\tilde{c}_i$

Sensitivity to both CP-even and CP-odd contributions through inclusion of distributions like $\Delta\varphi_{jj}$

Also studied effects of including or not BSM-only contributions

→ Constraints much greater when including BSM only contributions for CP-odd operators ~ $\tilde{c}_i$

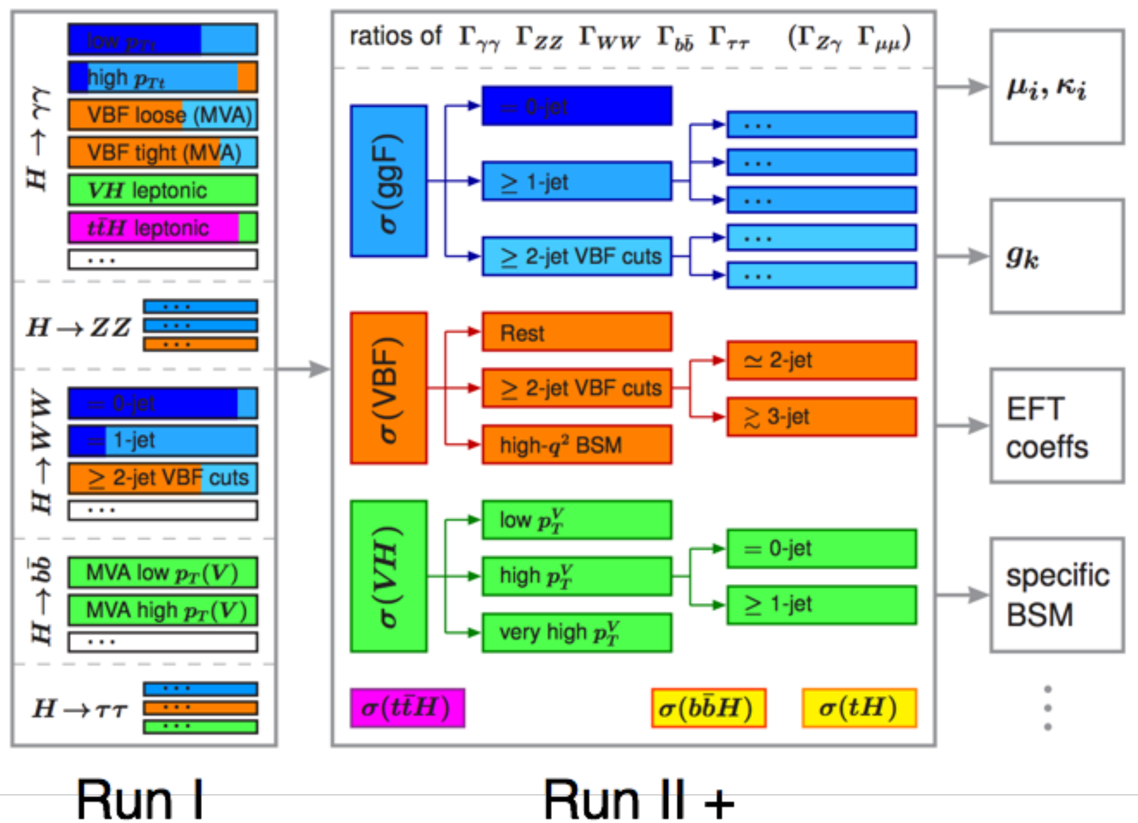
# Simplified Template X-Sections (STXS)

For Run-2 ATLAS/CMS have additional produced Higgs results in terms of STXS measurements

- Introduce differential binning but maintain process distinction

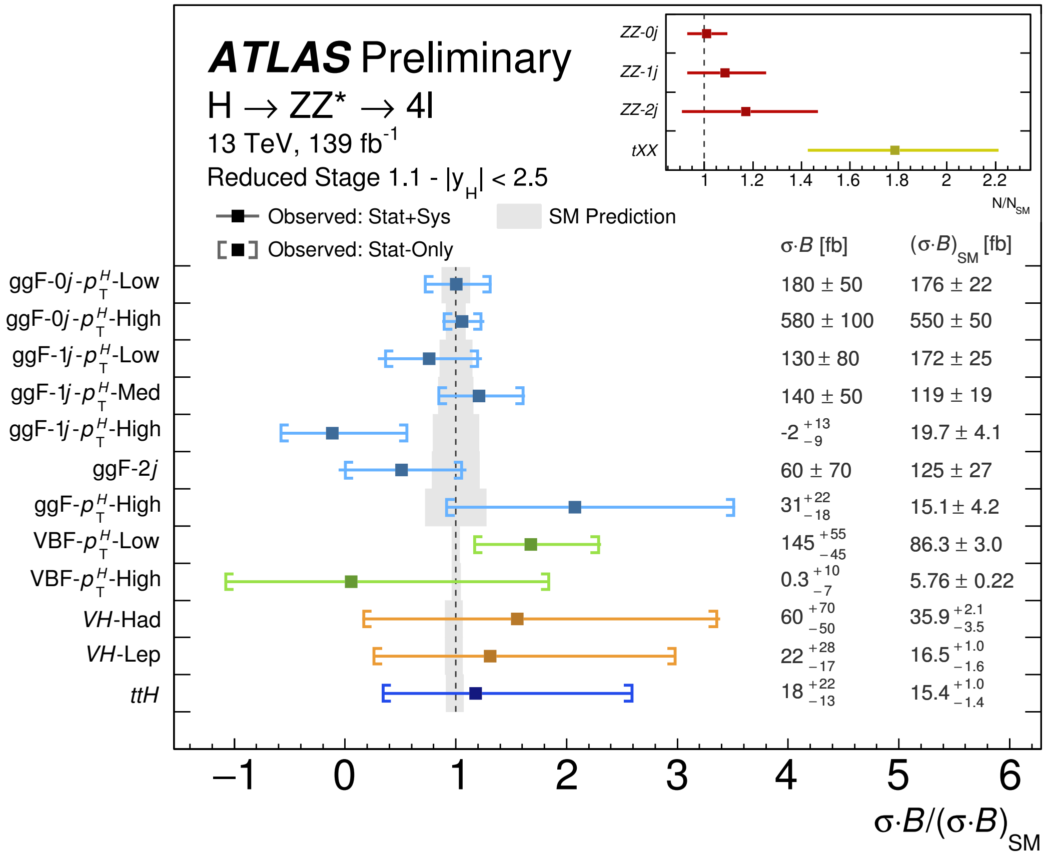
- Binning chosen to decouple theory uncertainty from measurement and maintain experimental sensitivity

- In principle, measurements can be (re)interpreted under generic BSM scenarios → κ-framework, EFTs …

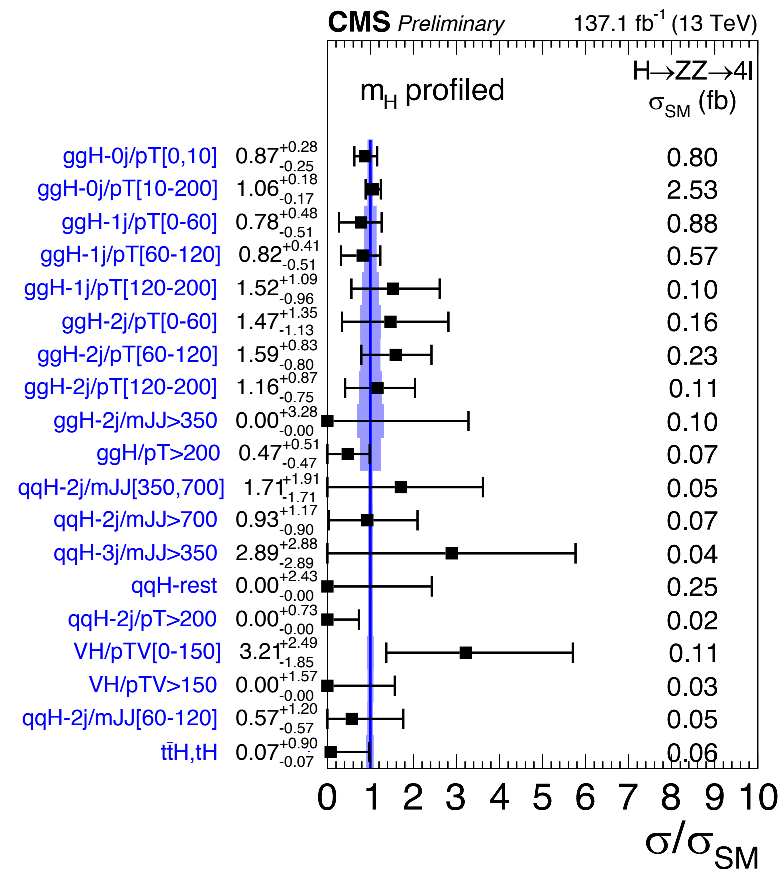


# Simplified Template X-Sections (STXS)

ATLAS-CONF-2019-005




CMS-PAS-HIG-19-001

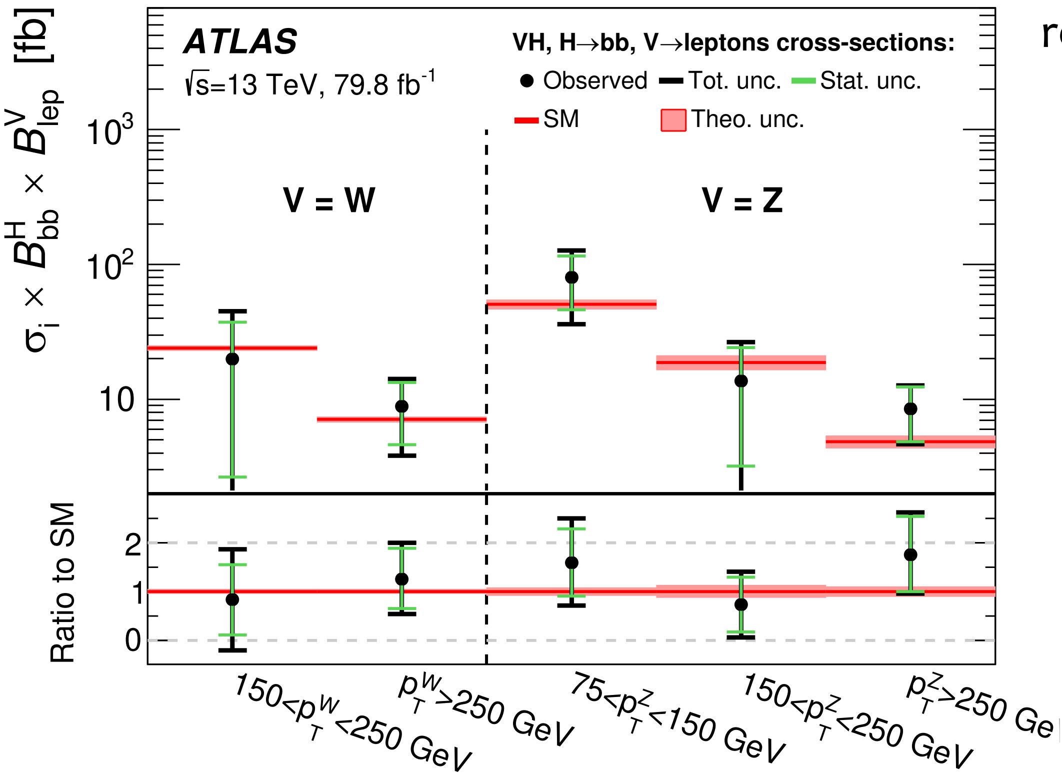



ATLAS/CMS have results using full Run-2 datasets (several more STXS measurements with partial Run-2 also)

# STXS VH(→bb)

ATLAS V(→lep)H(→bb) cross-sections measured in bins of $p_T(V)$

[JHEP 05 (2019) 141]




Parameterise* VH cross-sections, relative to SM, in terms of

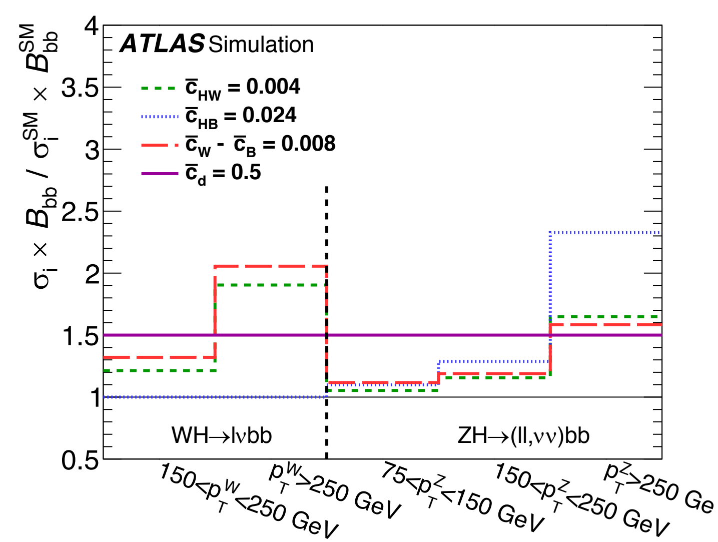
$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu},$$

$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu},$$

$$\mathcal{O}_{W} = \frac{i}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu},$$

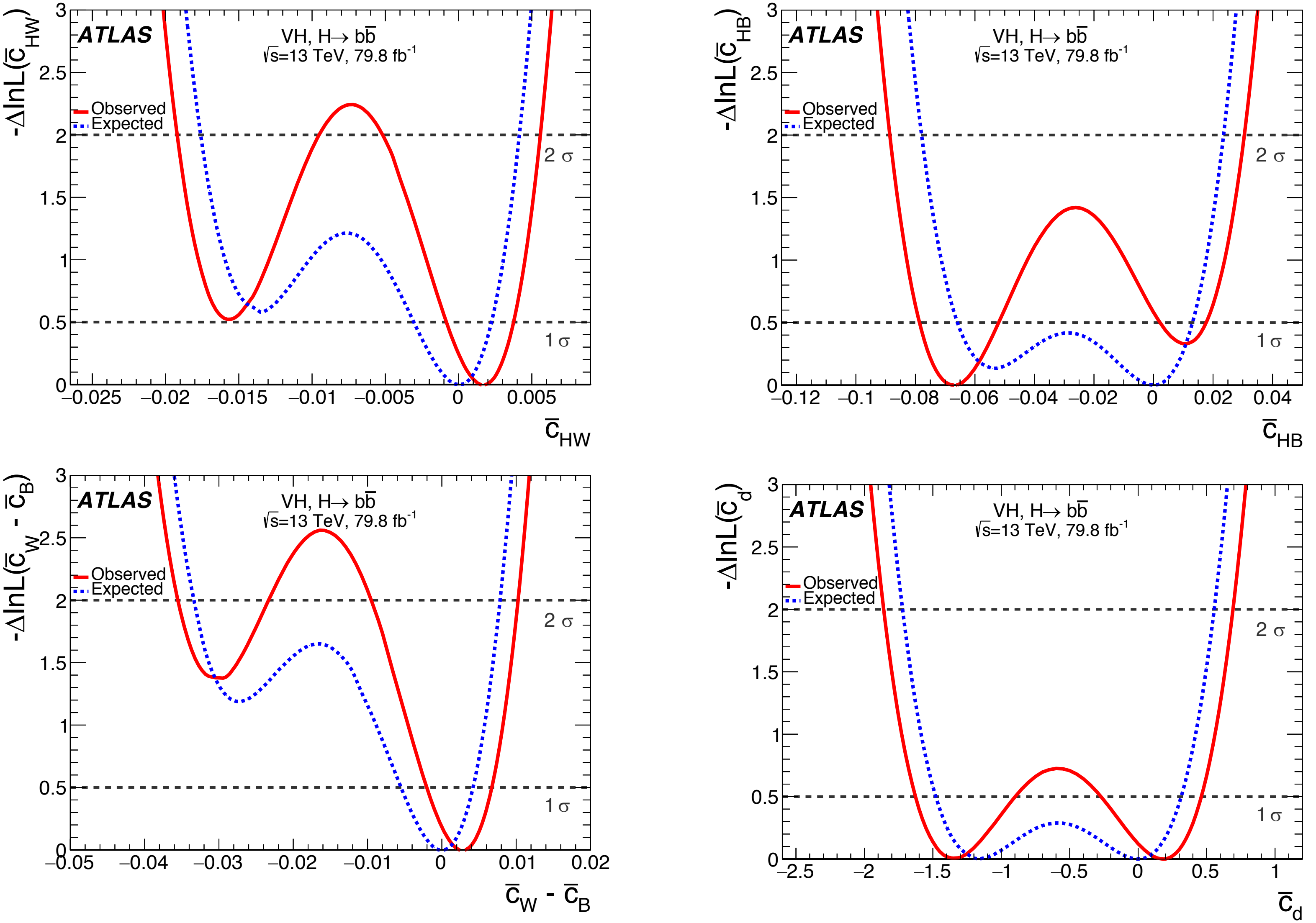
$$\mathcal{O}_{B} = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}.$$

Include $\mathcal{O}_d = y_d|H|^2\bar{Q}_L H d_R$ for H→bb branching ratio




*Based on LHCHXSWG-INT-2017-001

# STXS VH(→bb)


ATLAS
VH, H→ $b\bar{b}$
$\sqrt{s}$=13 TeV, 79.8 fb$^{-1}$
Observed
Expected
2 σ
1 σ
$-\Delta\ln L(\bar{c}_{HW})$
$\bar{c}_{HW}$
$-\Delta\ln L(\bar{c}_{HB})$
$\bar{c}_{HB}$
$-\Delta\ln L(\bar{c}_W - \bar{c}_B)$
$\bar{c}_W - \bar{c}_B$
$-\Delta\ln L(\bar{c}_d)$
$\bar{c}_d$

# STXS combinations

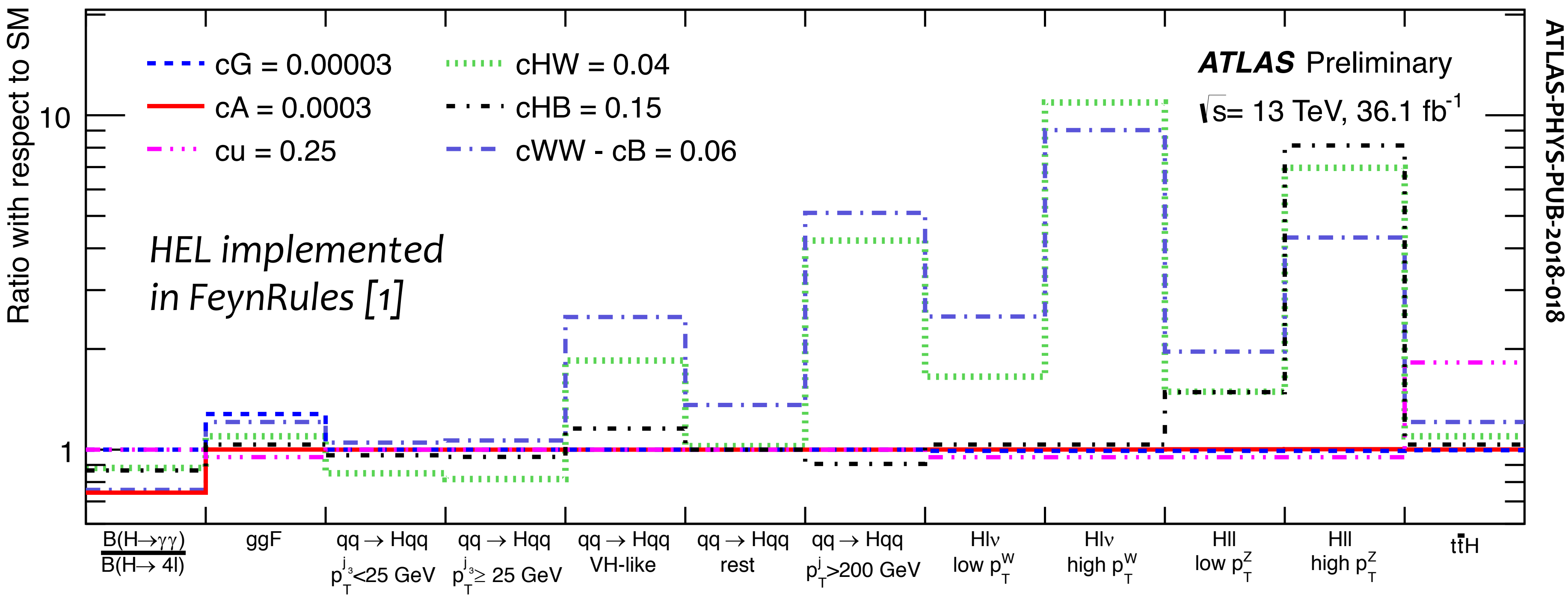
Common "fiducial" definitions for each STXS bin

→ Parametrise STXS scaling as,

$$\mu = \frac{\sigma}{\sigma_{SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$

Calculated from MC with MadGraph+STXS Rivet routine

→ STXS includes ratios of Branching ratios to allow combinations of decay channels



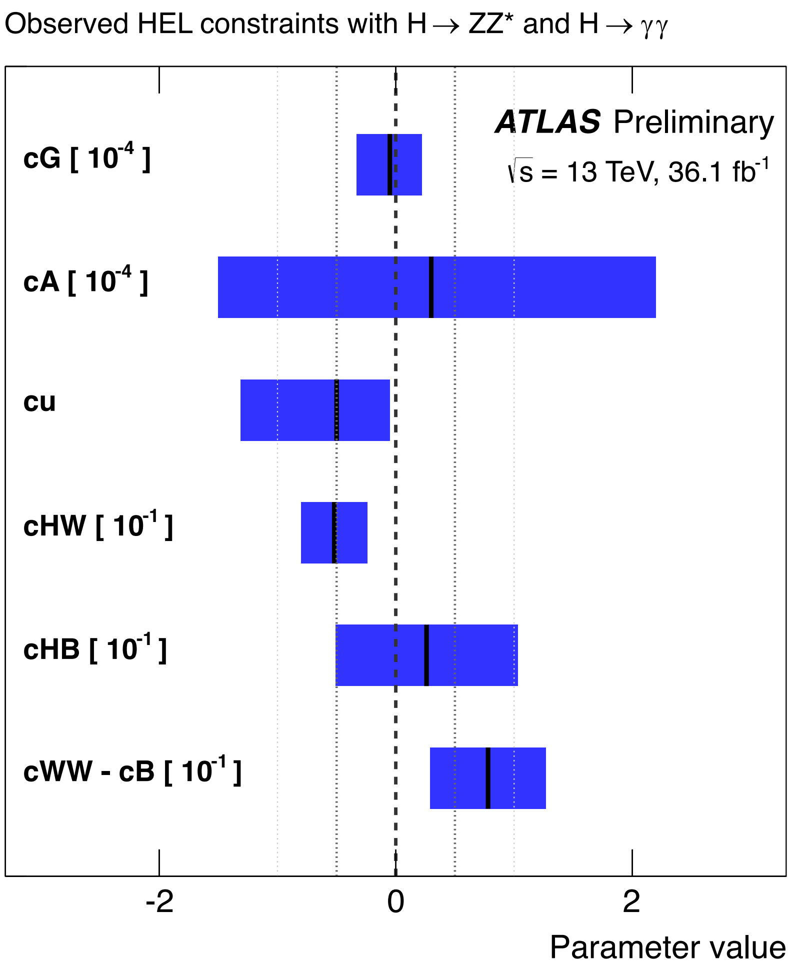

*HEL implemented in FeynRules [1]*

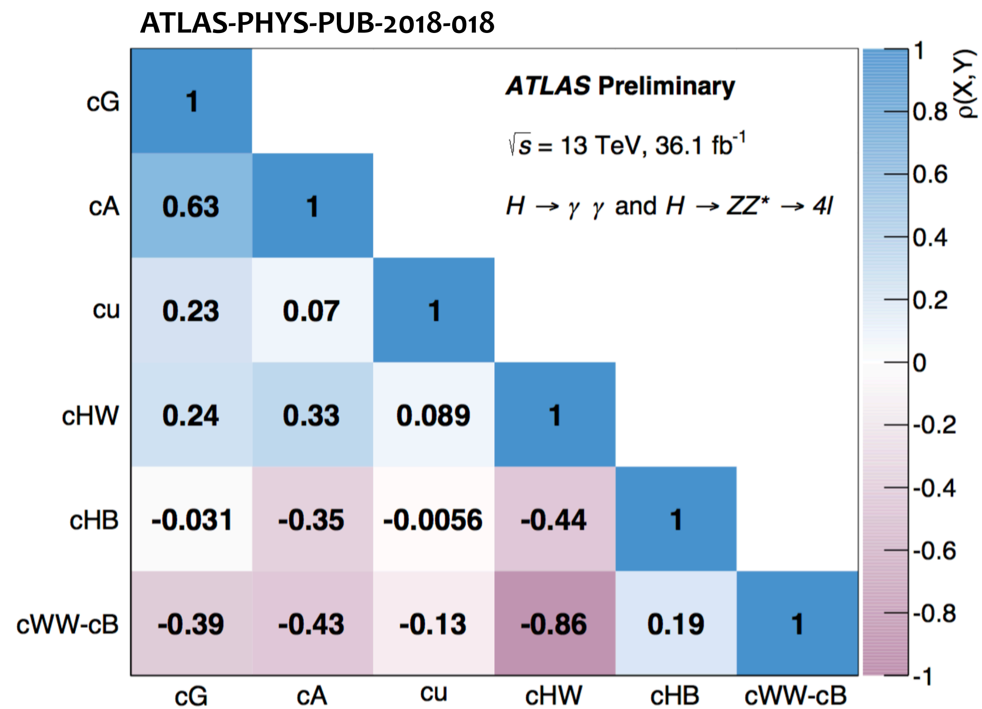
Similar studies @ CMS (*See talk from J. Langford*)

[1] JHEP 1404 (2014) 110

# STXS combinations

Combinations allow for exploring more EFT operators, simultaneously, without introducing (strong) degeneracies between coefficients

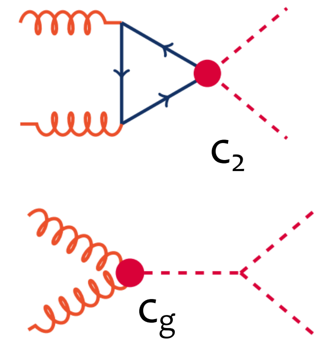


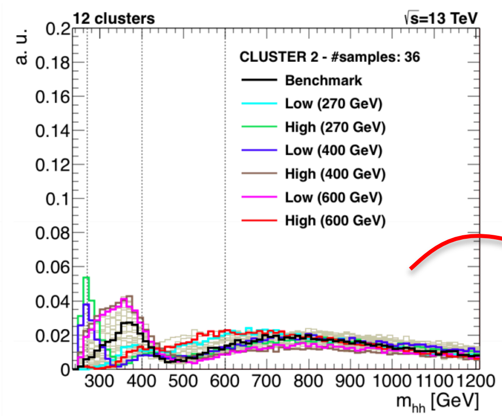



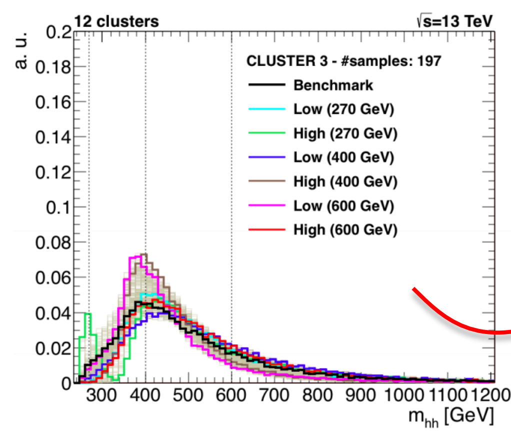
# Double Higgs

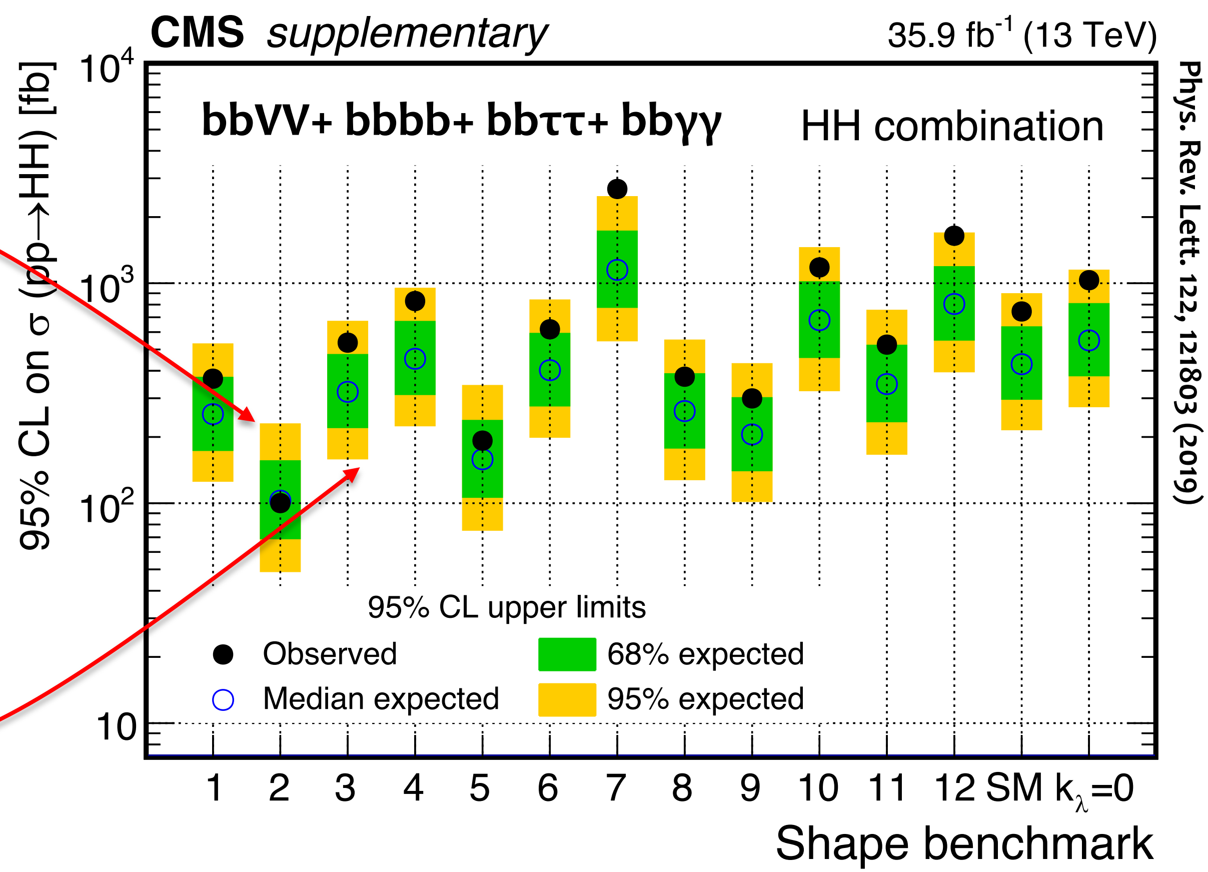
Limits on HH production expressed under 12 different EFT scenarios varying 5 effective couplings … $c_g$, $c_2$, $c_{2g}$, $y_t$, $k_\lambda$

→Benchmarks picked from clusters of scenarios [1] which share kinematic properties (rather than full 5D exploration)




[1] https://arxiv.org/abs/1608.06578

# Self-coupling

"Higgs potential has only been observed as a formula in text-books" → no direct experimental confirmation …

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

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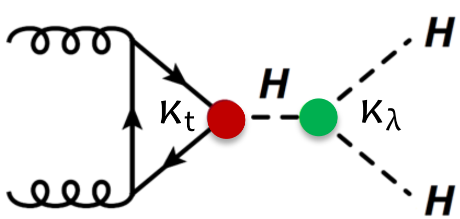
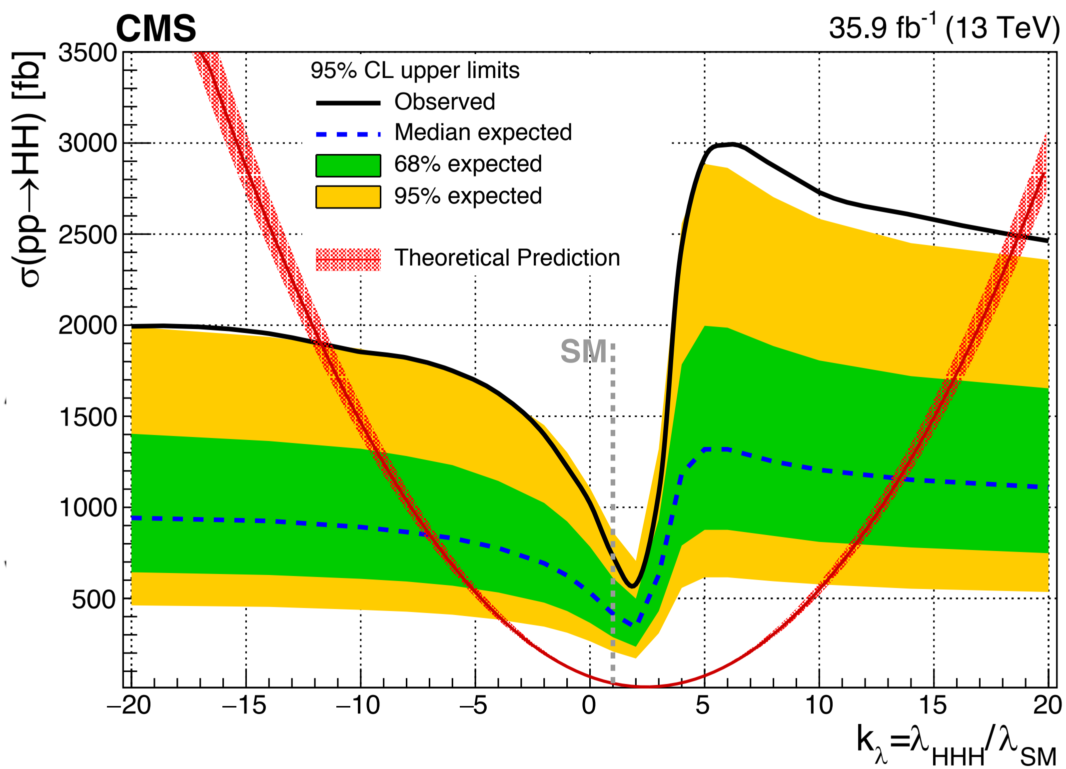
Double Higgs production sensitive to Higgs self-coupling $\kappa_\lambda$




Phys. Rev. Lett. 122, 121803 (2019)

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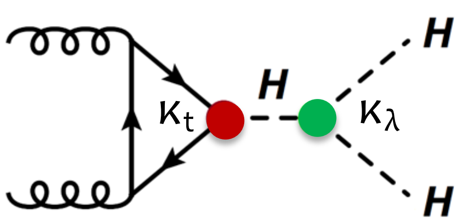
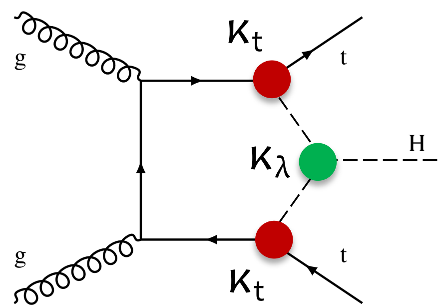
Double Higgs ***and single Higgs*** processes can be expressed in terms of effective coupling modifier $\kappa_\lambda$




"LO"



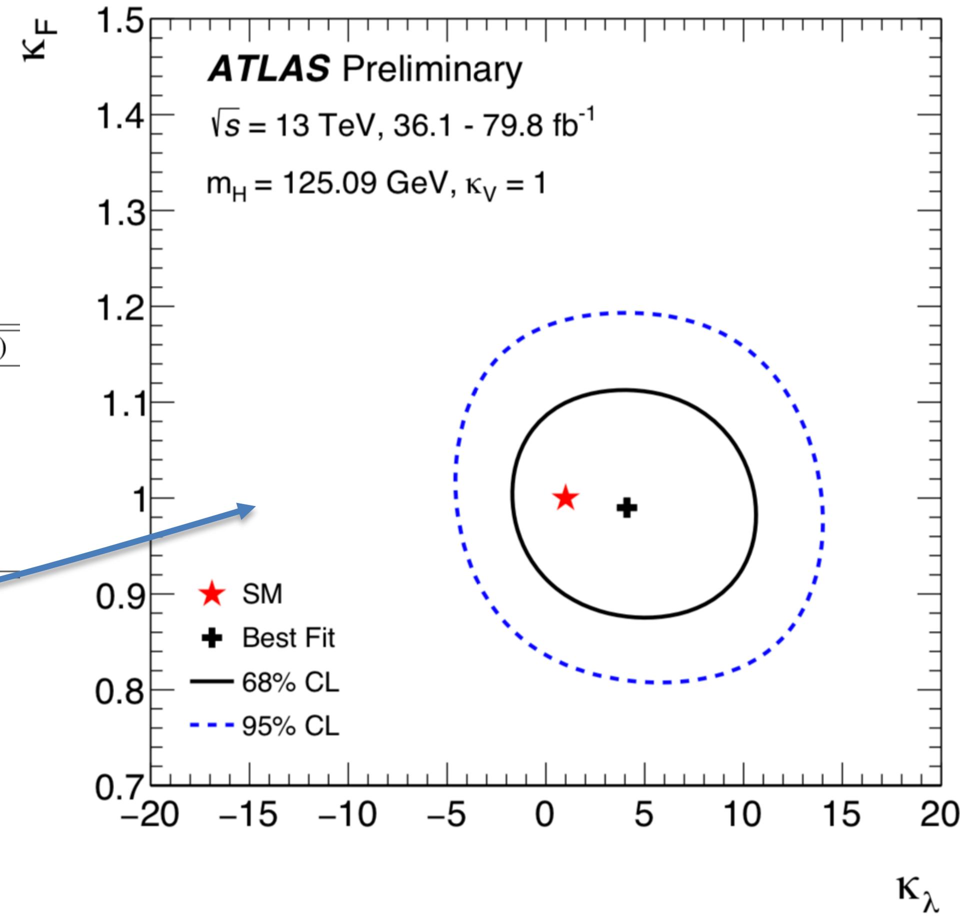

"NLO"

# Self-coupling

ATLAS-PHYS-PUB-2019-009

Re-interpretation of single Higgs production measurements in terms of Higgs self-coupling and H-fermion coupling (following [1-2])

| Analysis | Integrated luminosity ($fb^{-1}$) |
|---|---|
| $H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$) | 79.8 |
| $H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$) | 79.8 |
| $H \to WW^* \to e\nu\mu\nu$ | 36.1 |
| $H \to \tau\tau$ | 36.1 |
| $VH$, $H \to b\bar{b}$ | 79.8 |
| $t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton | 36.1 |




Introducing additional degrees of freedom leads to large degeneracies in the fit.

Can we combine single + double Higgs measurements under EFT?

[1] Eur. Phys. J. C77 (2017) 887, [2] JHEP 12 (2016) 080)

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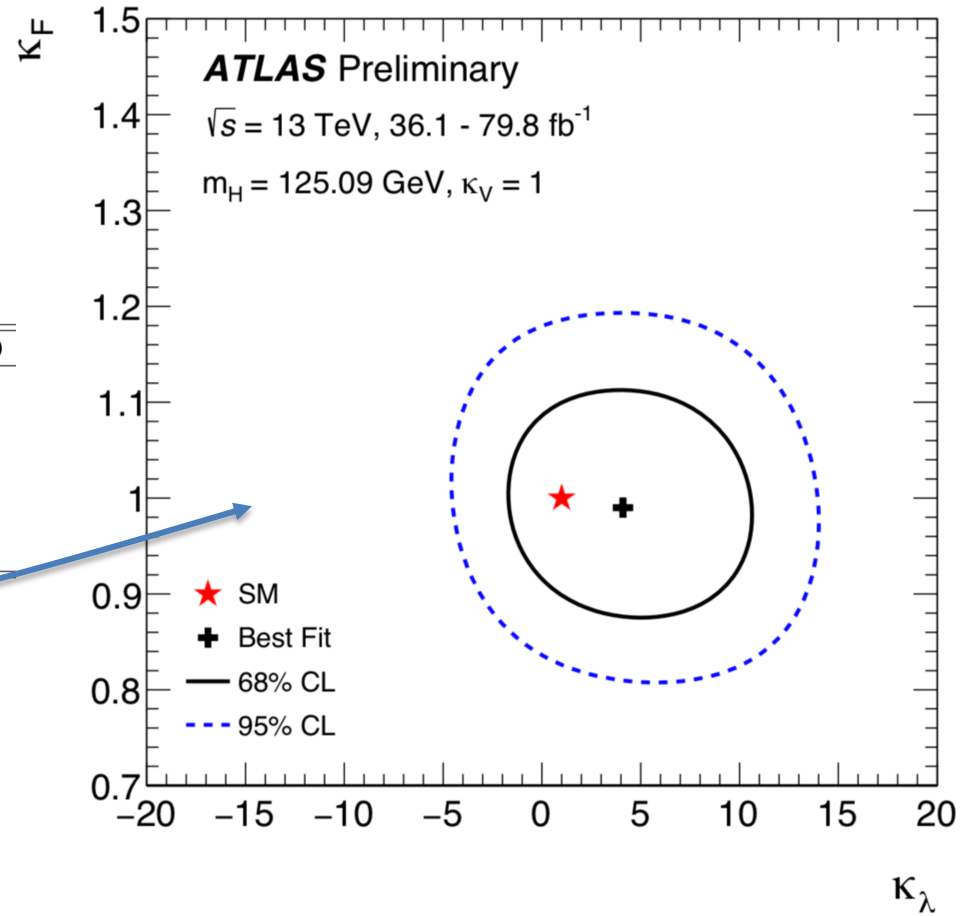



Introducing additional degrees of freedom leads to large degeneracies in the fit.

Can we combine single + double Higgs measurements under EFT?

→ Yes but we need NLO implementation (SMEFTsim @ NLO?)

$$\frac{\bar{c}_6 \lambda}{v^2}\left[\Phi^\dagger \Phi\right]^3$$

[1] Eur. Phys. J. C77 (2017) 887, [2] JHEP 12 (2016) 080)

# EFT Caveats 1.

STXS (and differential measurements) are great for EFT interpretations …

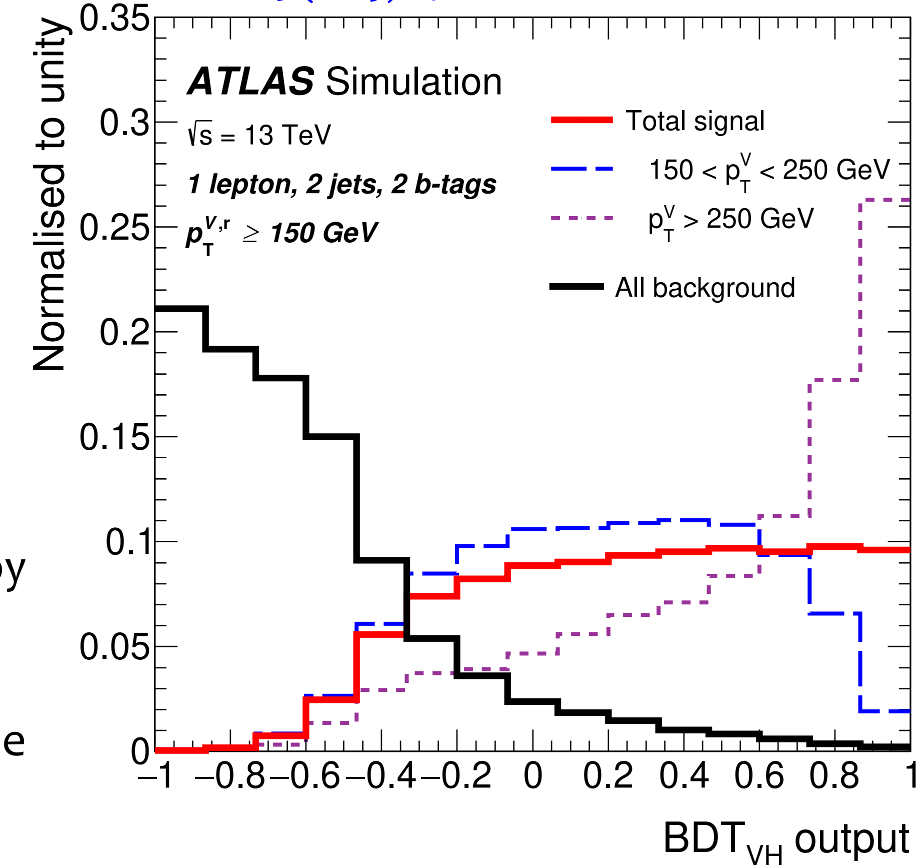
However, need to be careful when extrapolating to "fiducial regions"

→ Often experiments rely on SM templates* to determine efficiencies/acceptances etc

→ Furthermore, experiments often employ sophisticated categorization methods (eg BDTs) to perform measurements. What happens to $WH_{[150<pT<250]}$(BDT) if we include dim-6 operators?

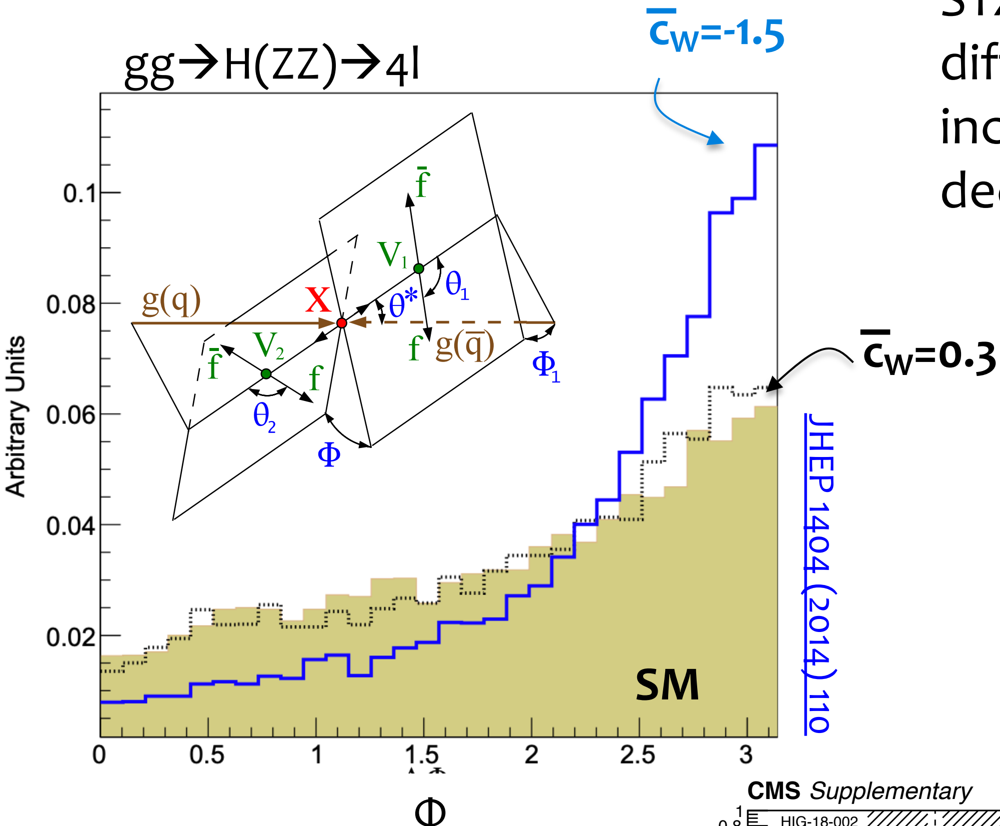
JHEP 05 (2019) 141

WH(→bb)




* The "T" in STXS is exactly this!

# EFT Caveats 2.

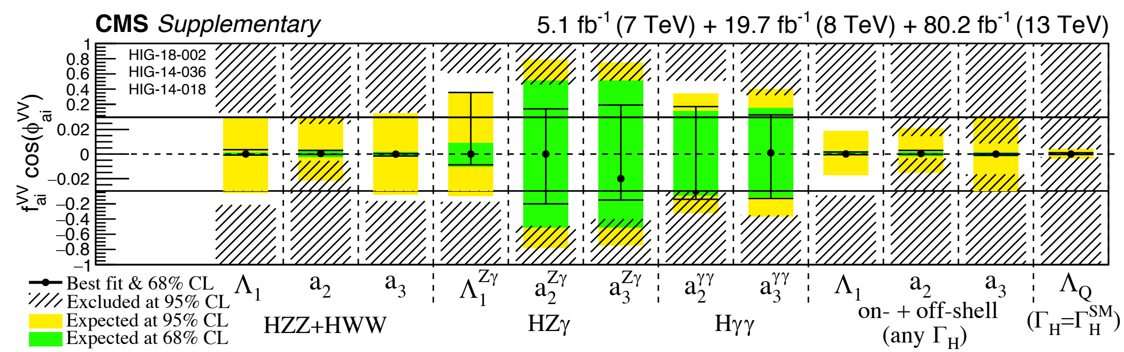



STXS (and combinations of differential measurements) don't include relevant information about decay of the Higgs

- Angular information (eg in 4l final state) sensitive to BSM effects
- ALTAS/CMS use MELA/BDT to exploit this information – with SM templates

Can STXS be extended - eg with Pseudo Observables?*

Phys. Rev. D 99 (2019) 112003

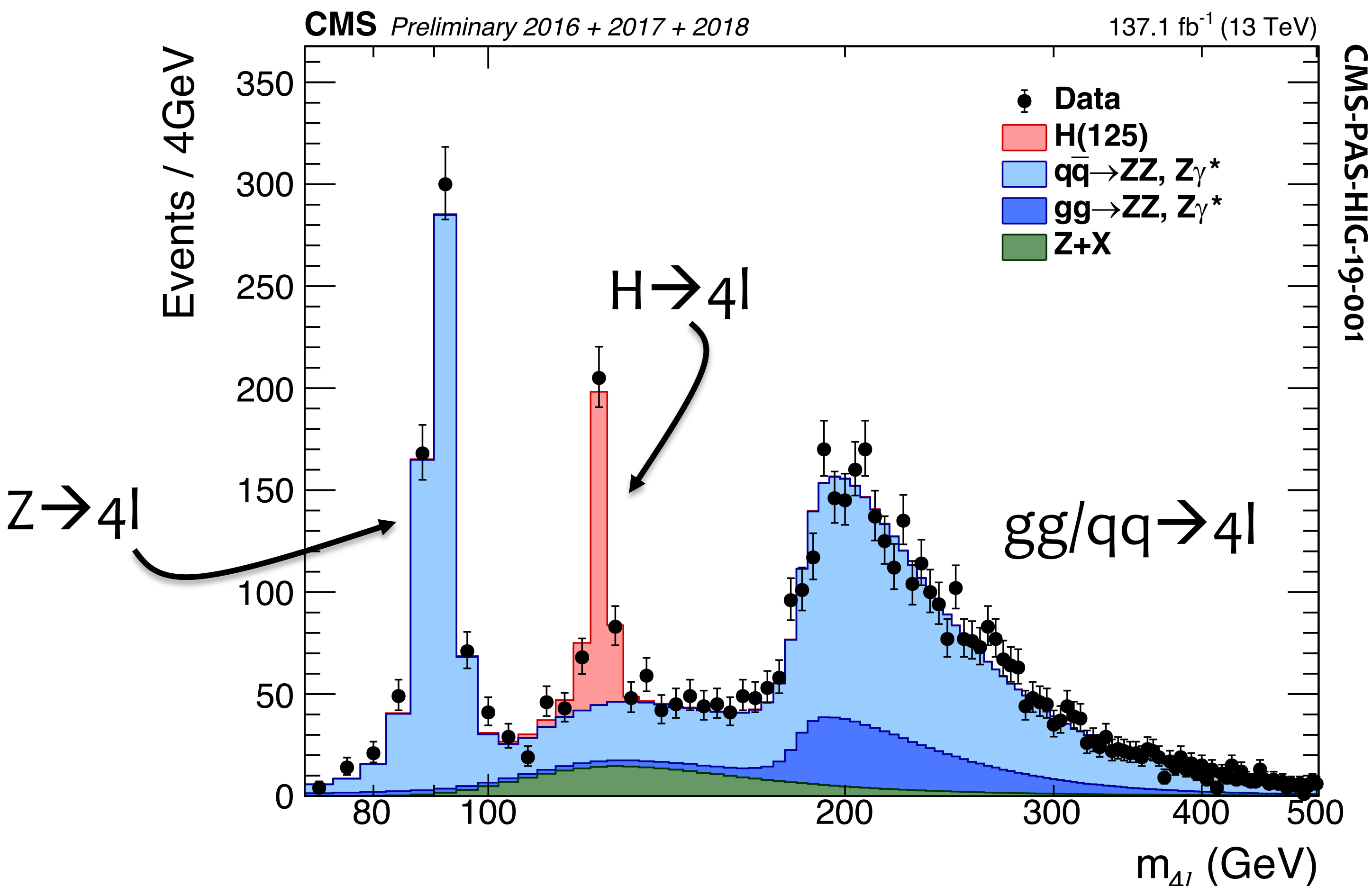



*Discussions at LesHouches this year : https://phystev.cnrs.fr/lh2019

# EFT Caveats 3.

*See talk from Z. Grout*

In CMS/ATLAS we are used to thinking of **Signal** / **Background**
→ But EFT is a global approach!



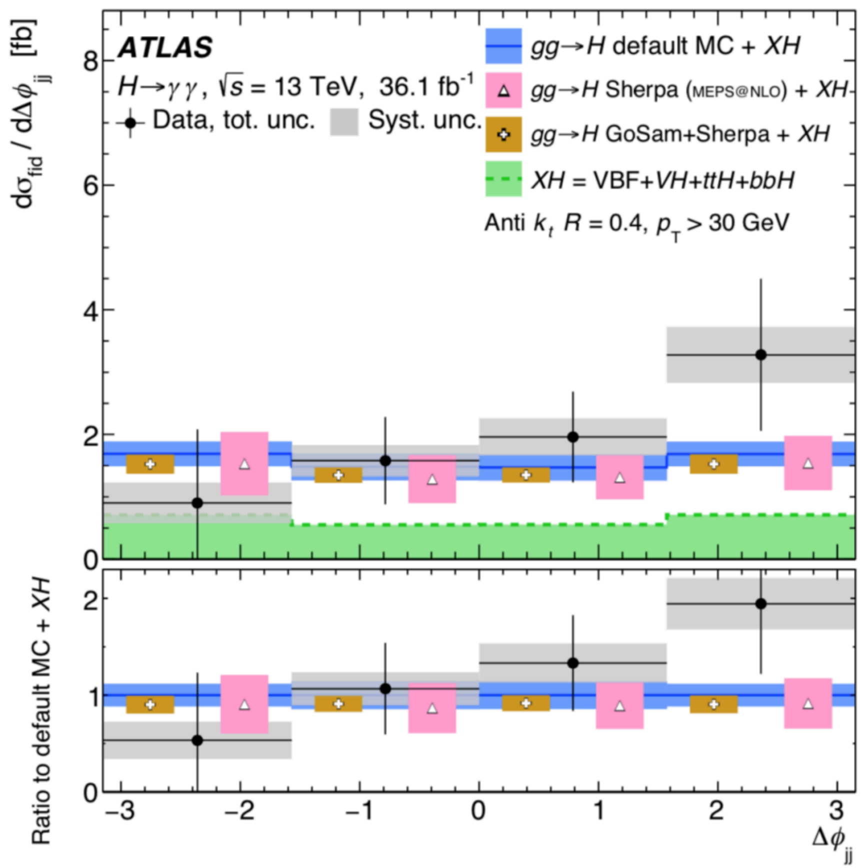

Full pp→4l combinations are the correct way to interpret the data
→Need to consider all contributions together

# (Re)Interpretations

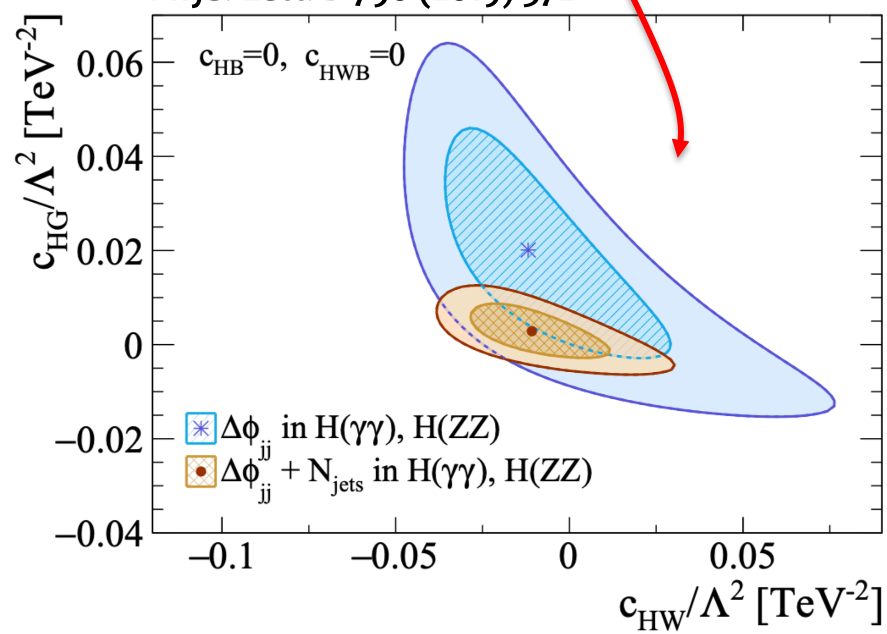
$$L_i(\boldsymbol{c}/\Lambda^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\boldsymbol{o}_i - \boldsymbol{\tau}_i)^2}{2\sigma^2}\right)$$

Providing differential measurements allows theorists to produce EFT interpretations

**Phys. Rev. D 98 (2018) 052005**




**Phys. Lett. B 790 (2019) 372**



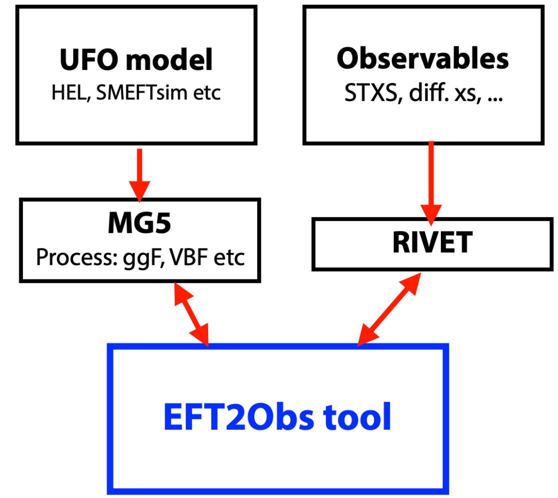

Aside from the caveats mentioned, what other effects (approximations) could yield inaccuracies?

→ Experiments should help validate these approaches by including EFT interpretations in papers **– how much do correlations / HO moments matter**?

# Speaking the same language

Outcome of LesHouches-2019 :
https://github.com/ajgilbert/EFT2Obs-Demo

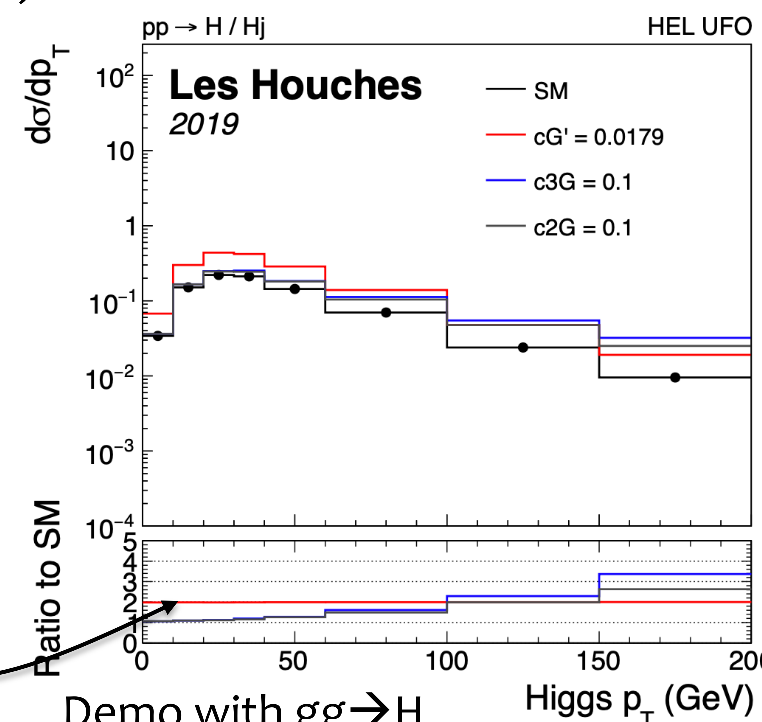
- Usable by both inside & outside CMS, therefore built on public tools (+ theorists prefer not to use ROOT*?)
- Agnostic to specifc EFT implementation, easy to implement new models (currently extensively tested with HEL, ongoing validations with SMEFTsim too)




Reweighting steering with simple configs

```
[
    {
        "block": "newcoup",
        "index": 12,
        "name": "cg",
        "step": 0.0001
    },
    {
        "block": "newcoup",
        "index": 30,
        "name": "c3g",
        "step": 0.0001
    },
...
]
```

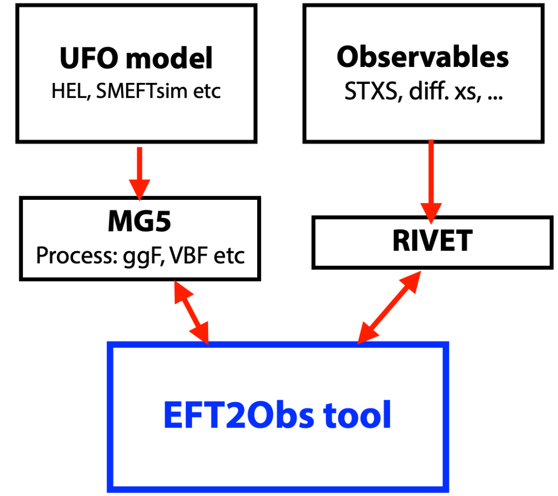
$$\mu_i = 1 + \sum_j c_j A_{i,j} + \sum_{jk} c_j c_k B_{i,jk}$$




Demo with gg→H

*Outputs in YODA (also supports ROOT)

# Speaking the same language

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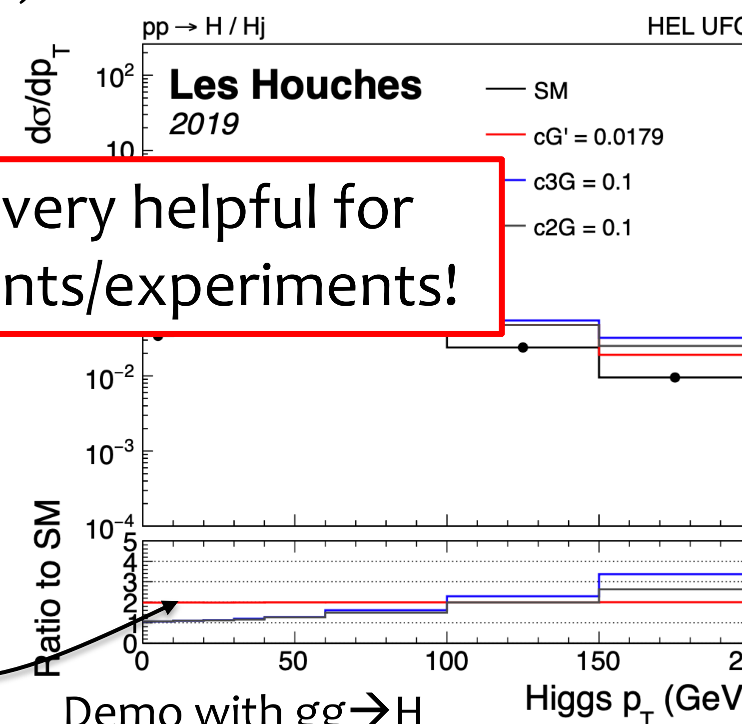
```

**Common tool will be very helpful for combining measurements/experiments!**

$$\mu_i = 1 + \sum_j c_j A_{i,j} + \sum_{jk} c_j c_k B_{i,jk}$$

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# EFT Roadmap from H-perspective?


Image from https://tau0.wordpress.com/2011/06/12/down-the-road-again/

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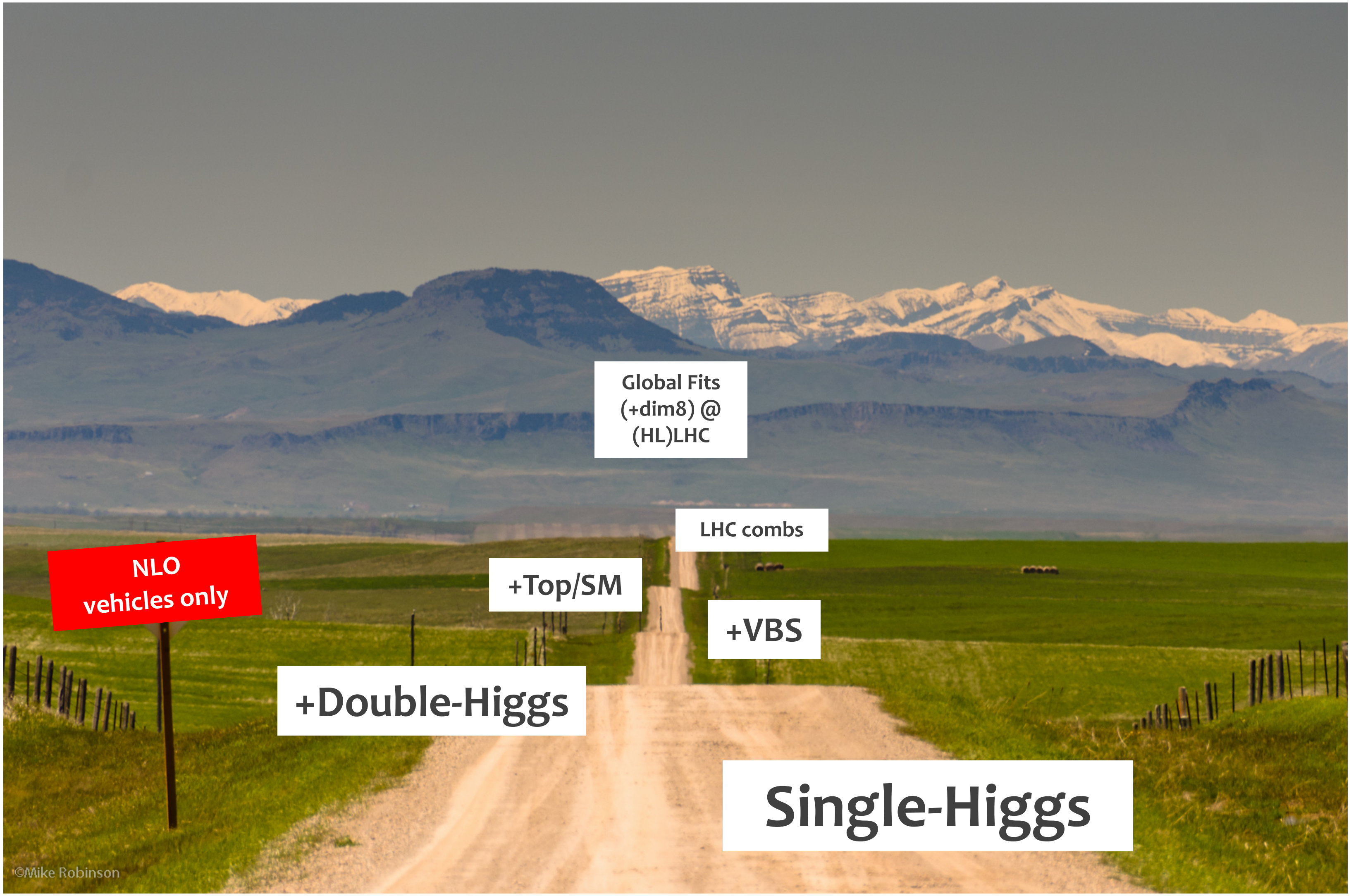



Image from https://tau0.wordpress.com/2011/06/12/down-the-road-again/

# Summary

EFT is a great tool to explore potential BSM physics in the Higgs sector

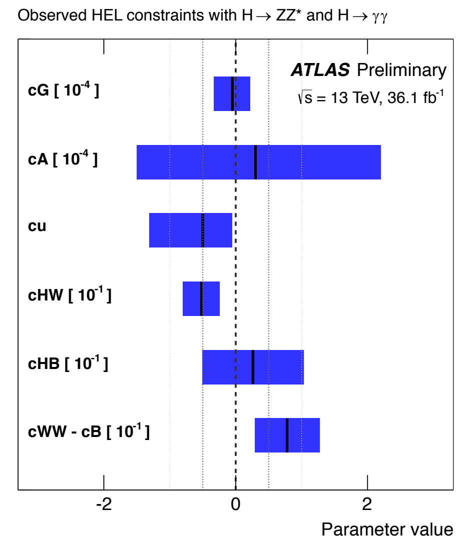
- A number of interpretations already from ATLAS/CMS
- Differential / STXS measurements already being used to explore EFT scenario

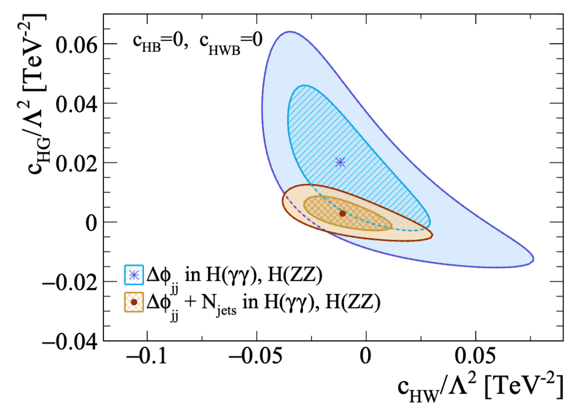
Experiments ultimately provide ***measurements*** (cross-sections/rates etc)

- EFT Interpretations within the experiments exciting
- Can provide additional info if needed for accurate interpretations *outside of the experiment*

Global fits/combinations are the challenging but exciting way forward

- Common tools (eg EFT implementations) help experiments+theorists
- Need to continue synergy among similar efforts (LHC HXS WG, Les Houches, HiggsTools, HiggsDays, this workshop… )



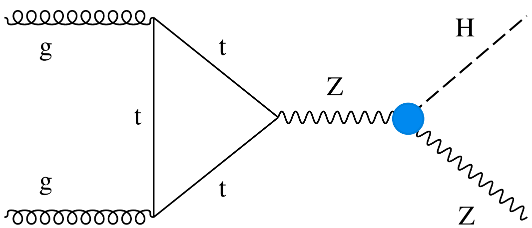

**LHC is not done yet → More results with EFT to come, but let's keep in touch!**

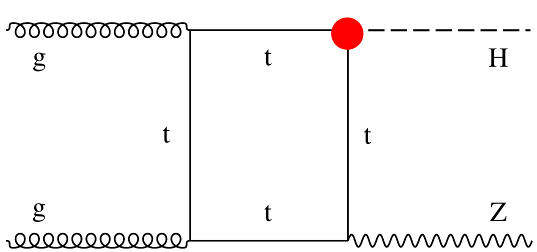
# THANKS!

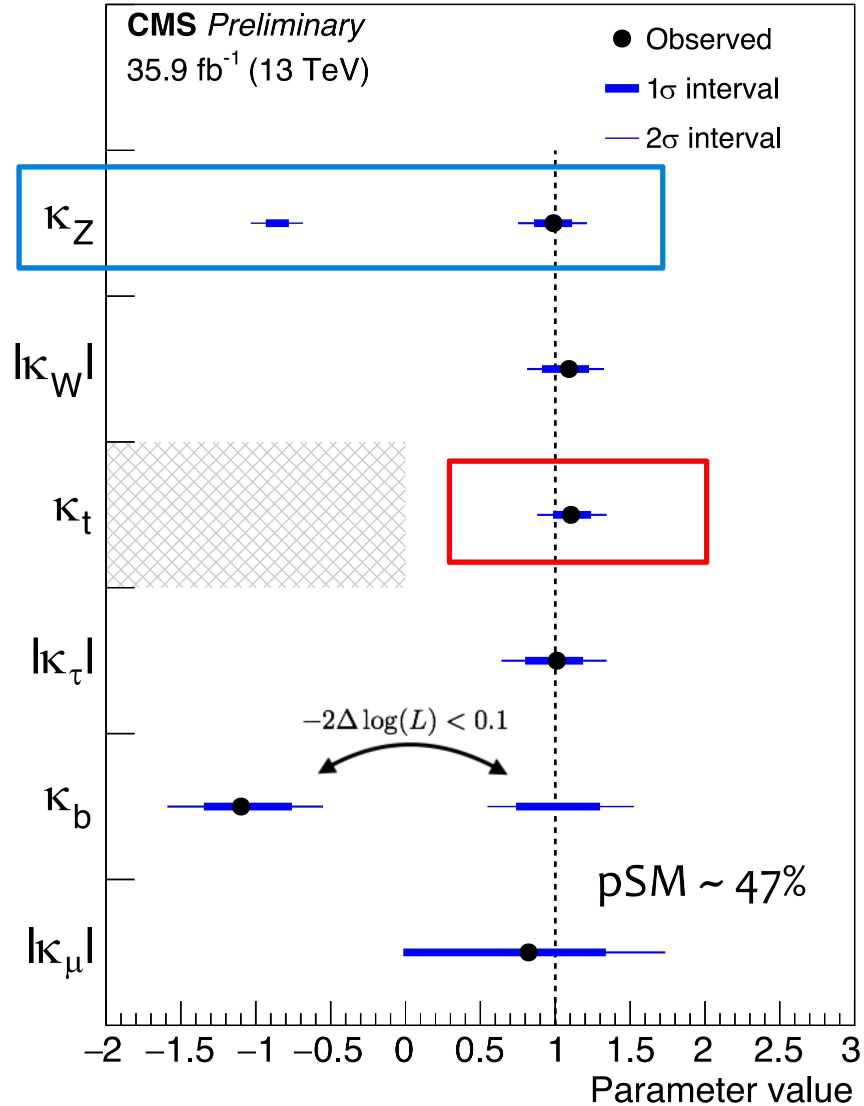
# SM Coupling Constraints

Leading order coupling modifier framework used to correlate prod/decay rates

Interference between diagrams helps constrain degeneracies EG:
$\kappa_Z$ sign degeneracy broken in gg→ZH production



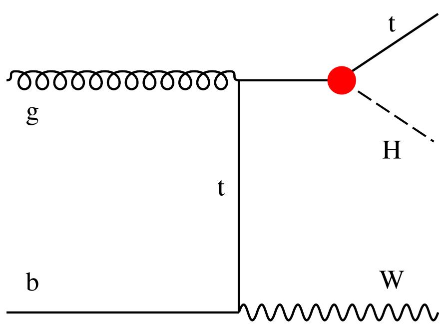



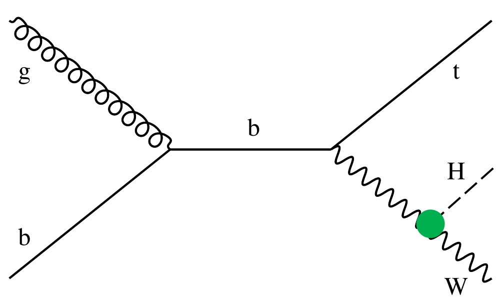

-ve sign for $\kappa_b$ slightly preferred due to small excess in ggH

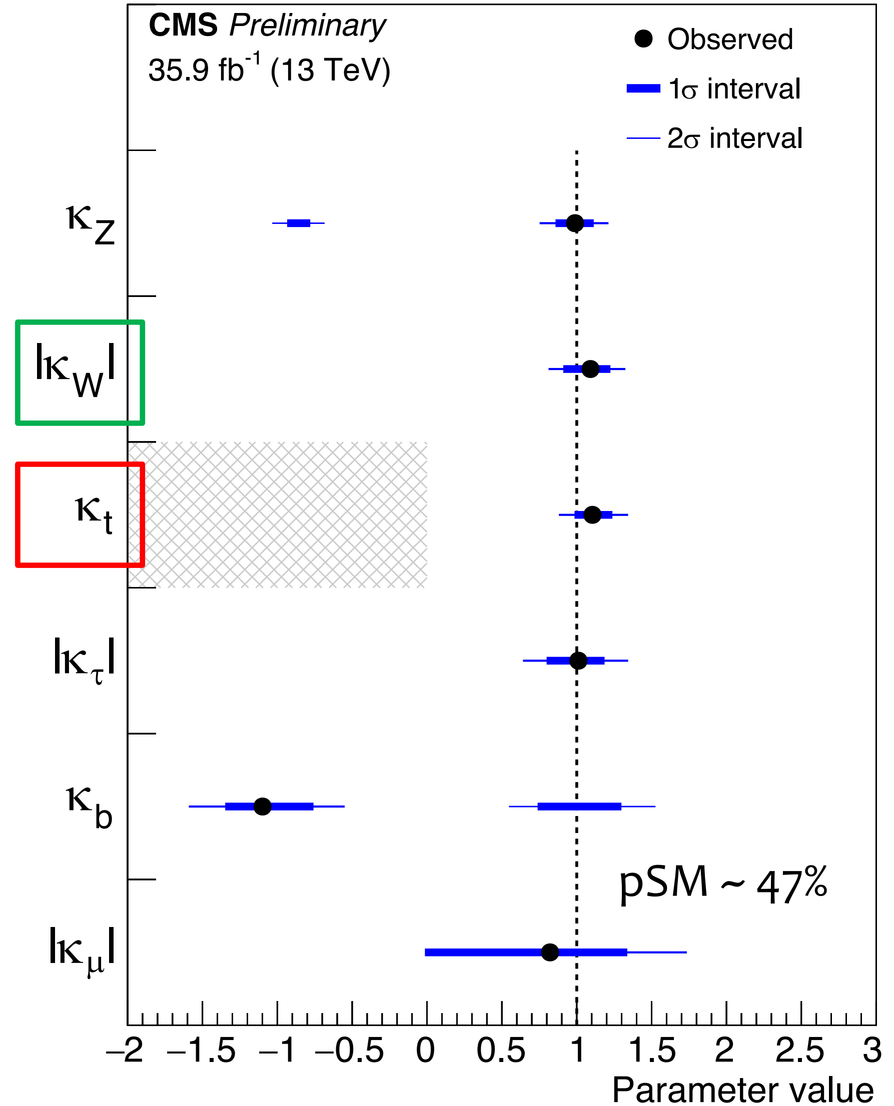
# SM Coupling Constraints

Overall sign degeneracy – here we fix $\kappa_t > 0$ and only look at +ve combination of $\kappa_W \times \kappa_t$

Relative sign probed in single-top Higgs production Eg: tHW




Contribution from +ve sign combination included in relevant categories

| Operator | Expression | HEL coefficient | Vertices |
|---|---|---|---|
| $\mathcal{O}_g$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ | $\texttt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$ | $Hgg$ |
| $\mathcal{O}_\gamma$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ | $\texttt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$ | $H\gamma\gamma, HZZ$ |
| $\mathcal{O}_u$ | $y_u\lvert H\rvert^2 \bar{u}_l H u_R +$ h.c. | $\texttt{cu} = v^2\bar{c}_u$ | $Ht\bar{t}$ |
| $\mathcal{O}_{HW}$ | $i\left(D^\mu H\right)^\dagger \sigma^a \left(D^\nu H\right) W^a_{\mu\nu}$ | $\texttt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$ | $HWW, HZZ$ |
| $\mathcal{O}_{HB}$ | $i\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu}$ | $\texttt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$ | $HZZ$ |
| $\mathcal{O}_W$ | $i\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$ | $\texttt{cWW} = \frac{m_W^2}{g}\bar{c}_W$ | $HWW, HZZ$ |
| $\mathcal{O}_B$ | $i\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$ | $\texttt{cB} = \frac{m_W^2}{g'}\bar{c}_B$ | $HZZ$ |

# Why Higgs Couplings?

Measuring Higgs bosons couplings remain a key goal of Future Higgs measurements

- Higgs coupling measurements are good to test SM compatibility
  - Synergies with EFT approaches

BSM contributions requite O(%) level Higgs property measurements

arXiv:1310.8361 $M_{NP} \sim$ 1TeV

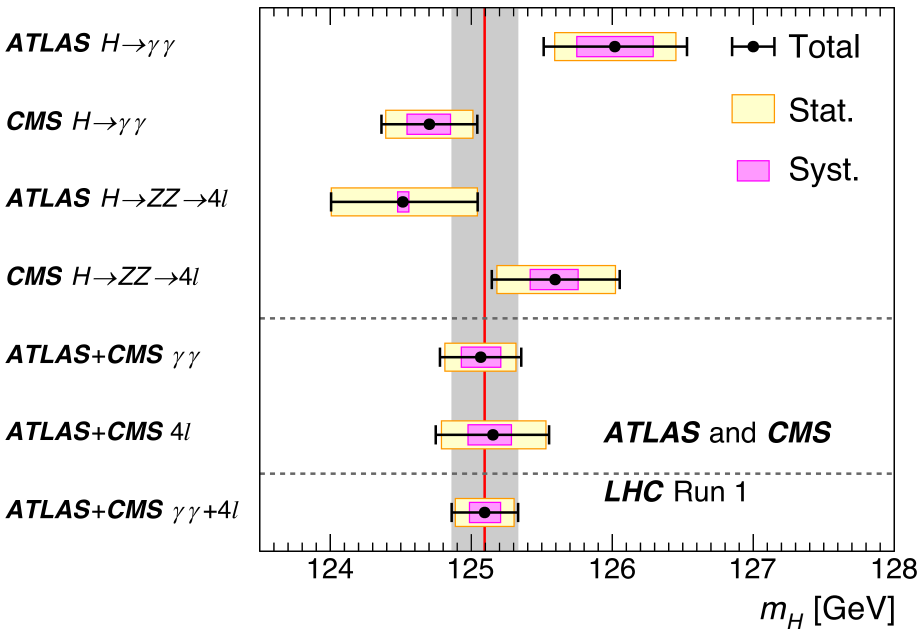
| Model | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| Singlet Mixing | $\sim 6\%$ | $\sim 6\%$ | $\sim 6\%$ |
| 2HDM | $\sim 1\%$ | $\sim 10\%$ | $\sim 1\%$ |
| Decoupling MSSM | $\sim -0.0013\%$ | $\sim 1.6\%$ | $\sim -.4\%$ |
| Composite | $\sim -3\%$ | $\sim -(3-9)\%$ | $\sim -9\%$ |
| Top Partner | $\sim -2\%$ | $\sim -2\%$ | $\sim +1\%$ |

# Completing the SM

Discovery of the Higgs boson completed the Standard Model
→ Great success of LHC @ Run-1

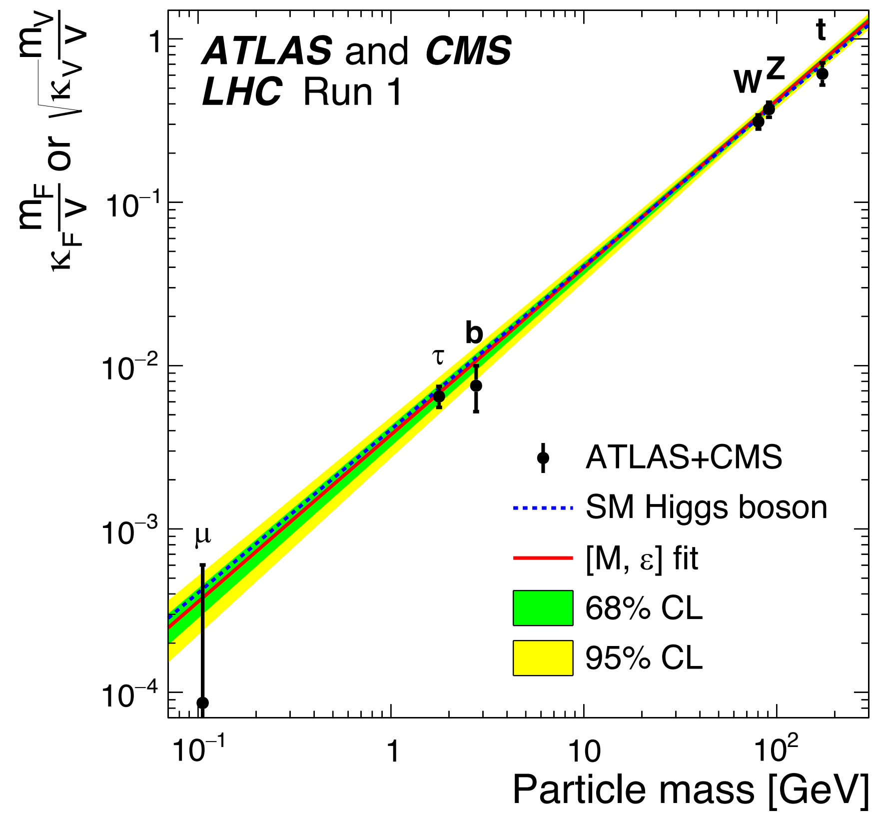
Precision measurements of Higgs boson properties through its couplings to SM particles …

Phys. Rev. Lett. 114, 191803 (2015)



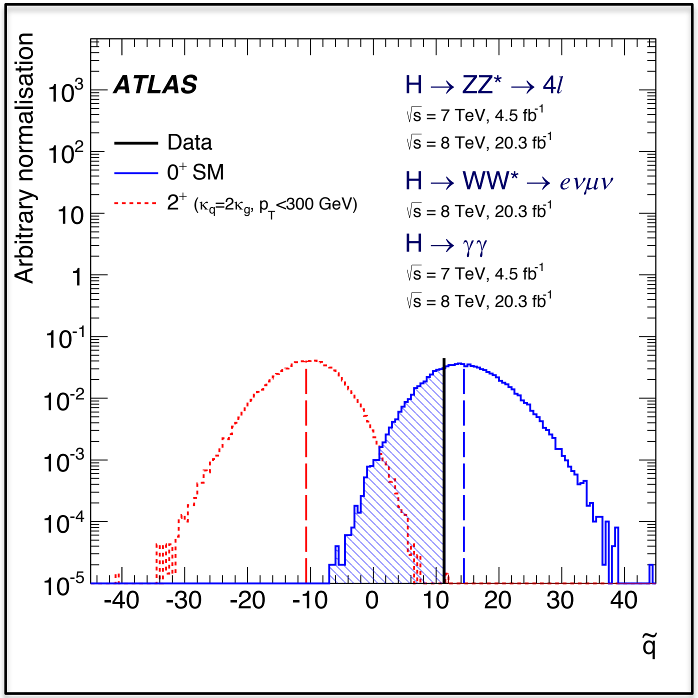

$m_H$ = 125.09 ± 0.24 GeV

JHEP08(2016)045




… and remarkable precision on mass measurement ( < 0.2% uncertainty)

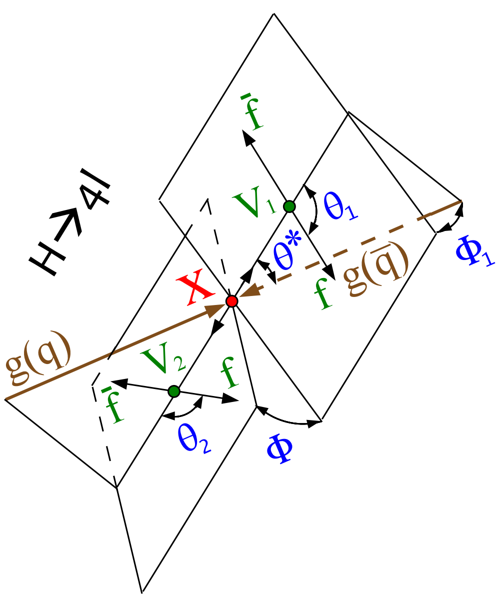
# Spin-Parity



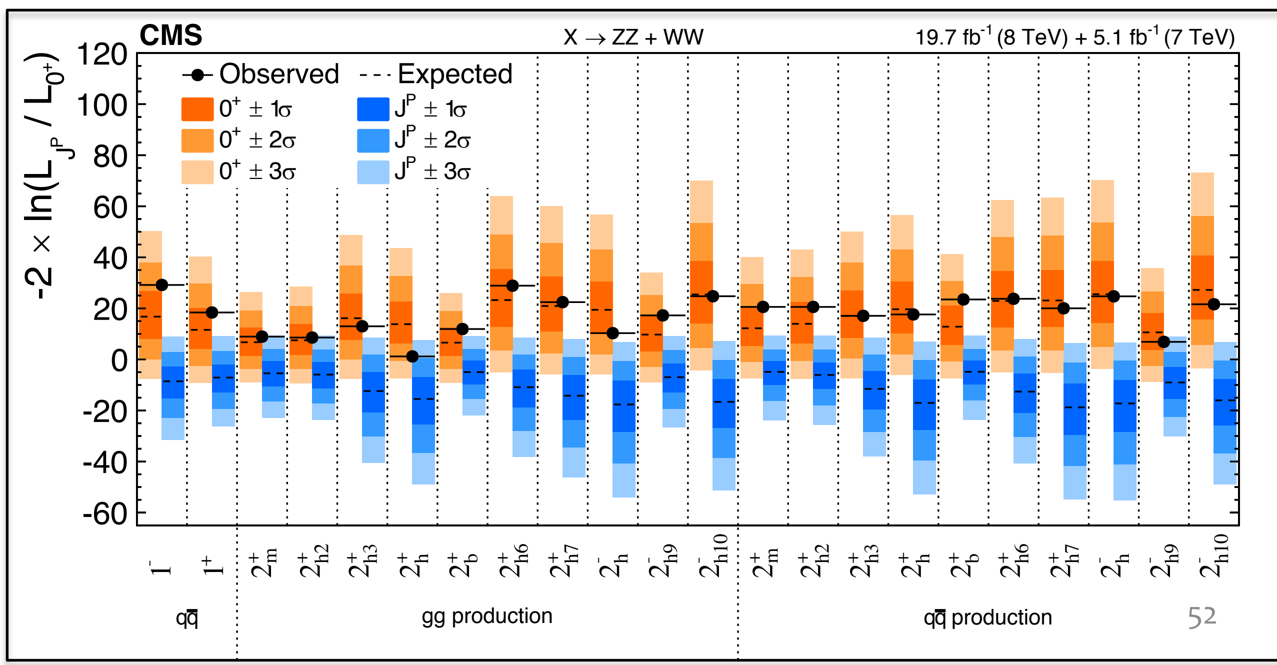

Eur. Phys. J. C75 (2015) 231

ATLAS and CMS H→WW,ZZ,γγ modes use angular information to distinguish between various $J^P$ hypotheses…

*Run-1 data is enough to rule out spin-2 (and many other $J^P$ states) at > 99.9% confidence level*



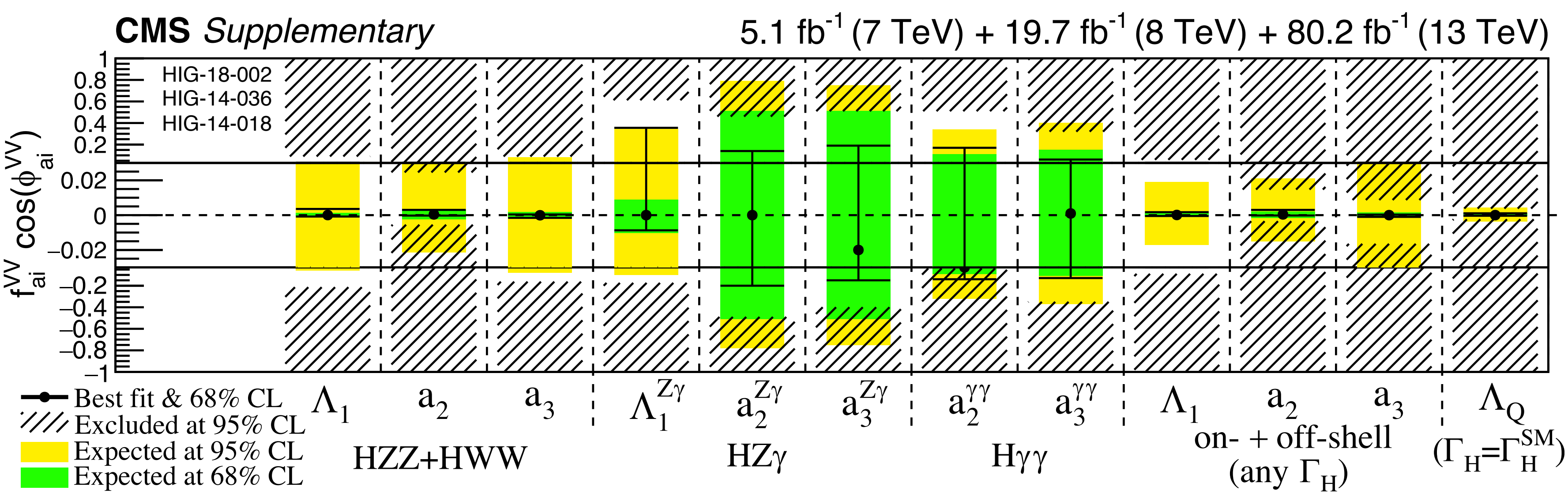

**PRD 92 (2015) 012004**



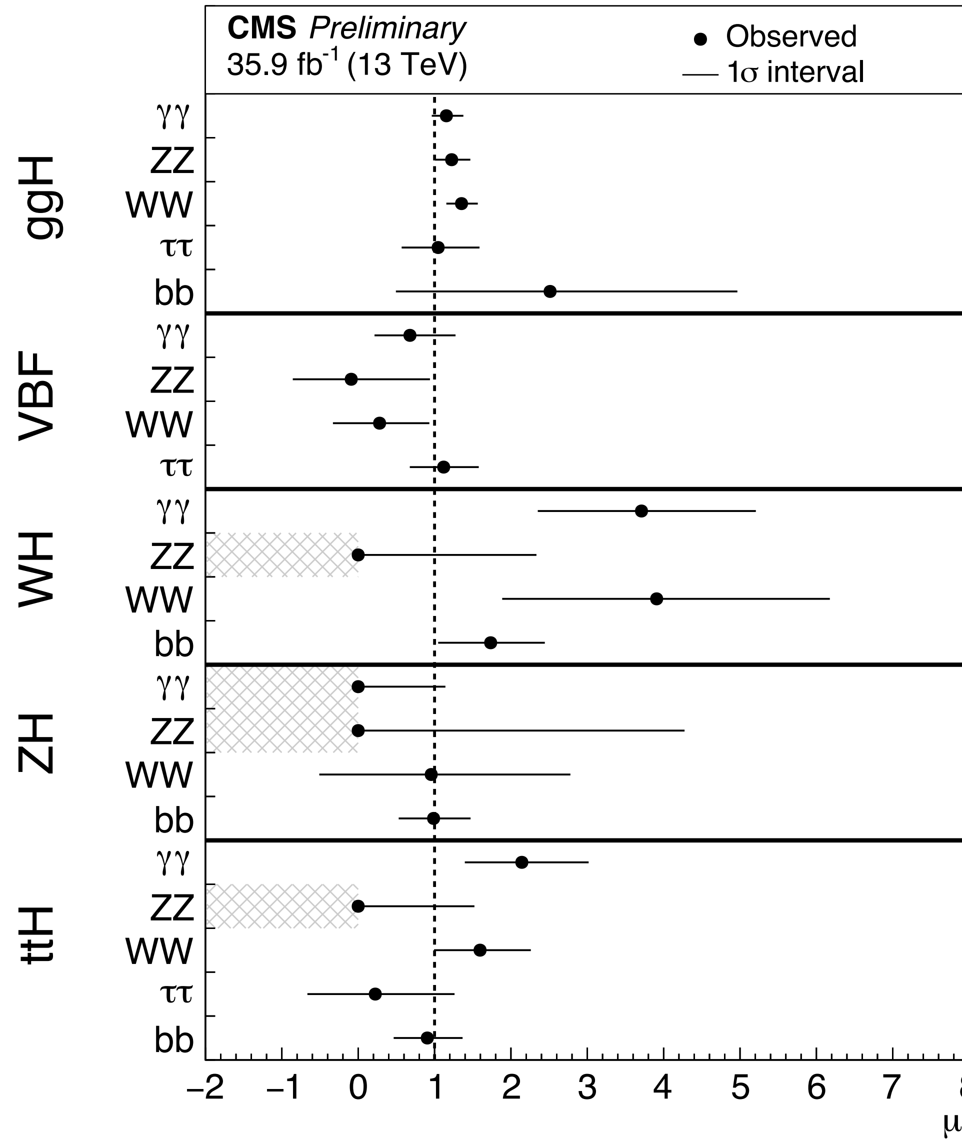
$$A(\mathrm{HVV}) \sim \left[ a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3\ldots} |a_j|^2 \sigma_j},$$

$$\phi_{ai} = \arg\left(\frac{a_i}{a_1}\right),$$



# What do we actually measure?



# What do we actually measure?

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

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

Extract "**signal strengths**" from Maximum likelihood estimators

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{(\text{BR}^f)_{\text{SM}}}.$$

Re-parameterize strengths in terms of "coupling modifiers" $\boldsymbol{\kappa}$

$$\mu \rightarrow \mu(\boldsymbol{\kappa})$$

Standard model defined by: $\boldsymbol{\mu}_i = \boldsymbol{\mu}^f = 1$ or $\boldsymbol{\kappa} = 1$

# What do we actually measure?

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

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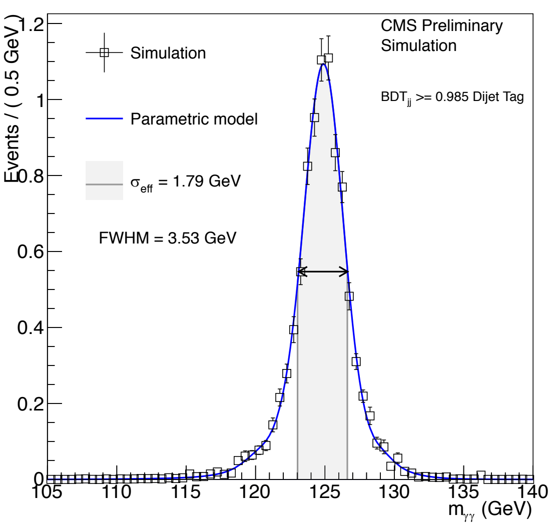
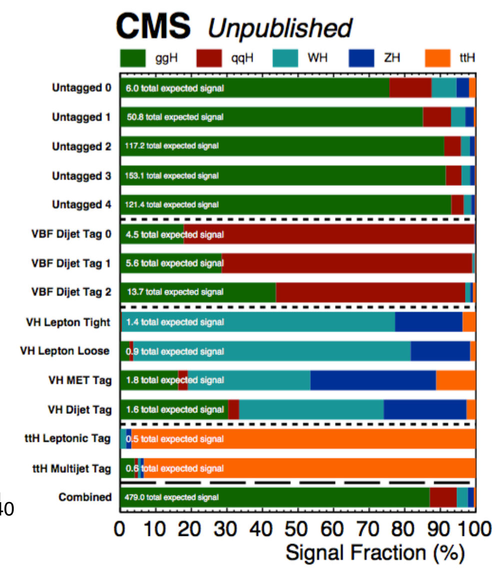



CMS H→γγ analysis




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

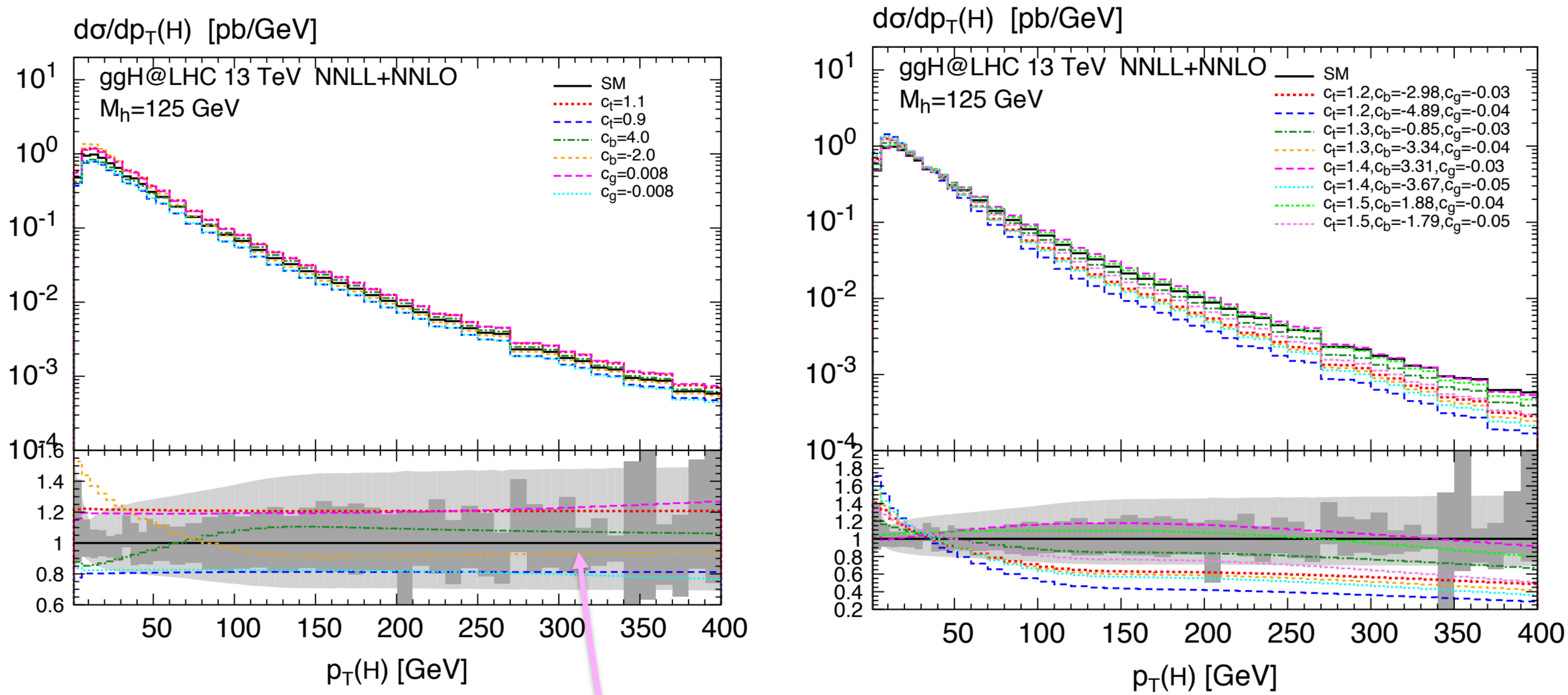
- Efficiency * acceptance
- Relative composition across signal regions (analysis bins, BDT output … )

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

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

# Differential Higgs @ NLL+NLO

$$\frac{c_1}{\Lambda^2}\mathcal{O}_1 \to \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}\,, \quad \frac{c_2}{\Lambda^2}\mathcal{O}_2 \to \frac{m_t}{v} c_t h \bar{t} t\,, \quad \frac{c_3}{\Lambda^2}\mathcal{O}_3 \to \frac{m_b}{v} c_b h \bar{b} b\,,$$

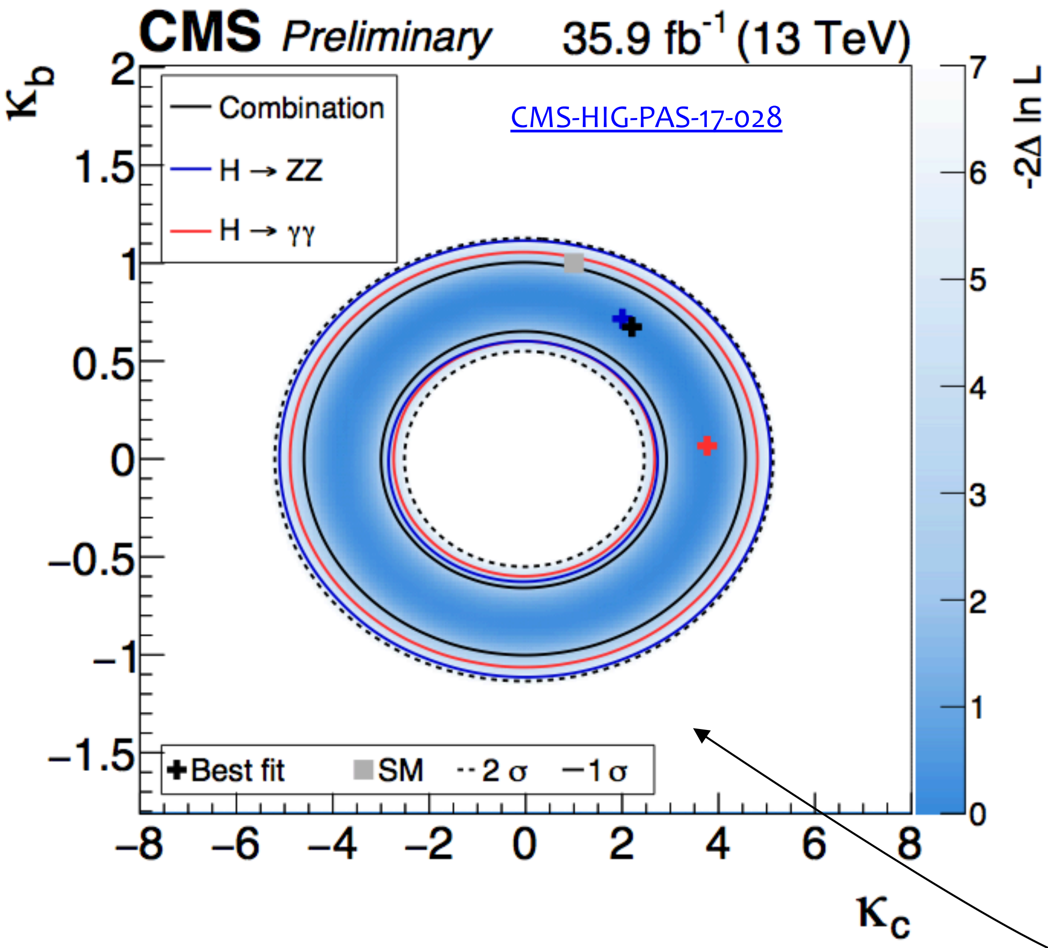


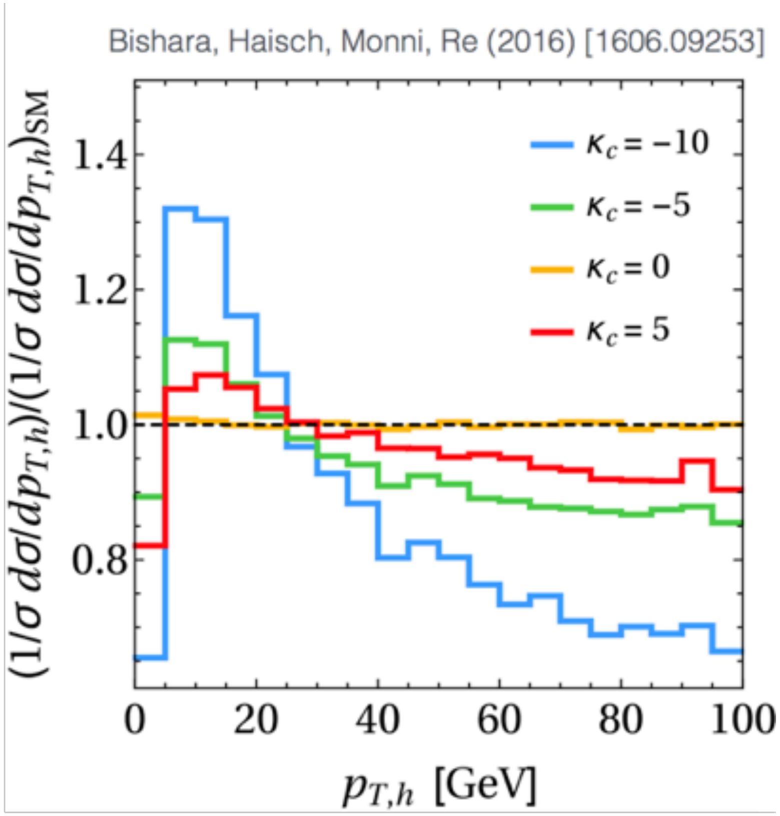

https://arxiv.org/abs/1705.05143

Relatively small variation from $c_g$ vs $p_T(H)$

# Differential Measurements

Constrain b & c Yukawa couplings from Differential measurements of inclusive Higgs production




Large constraint from overall normalization (as in inclusive couplings) but also access more info via "shape"

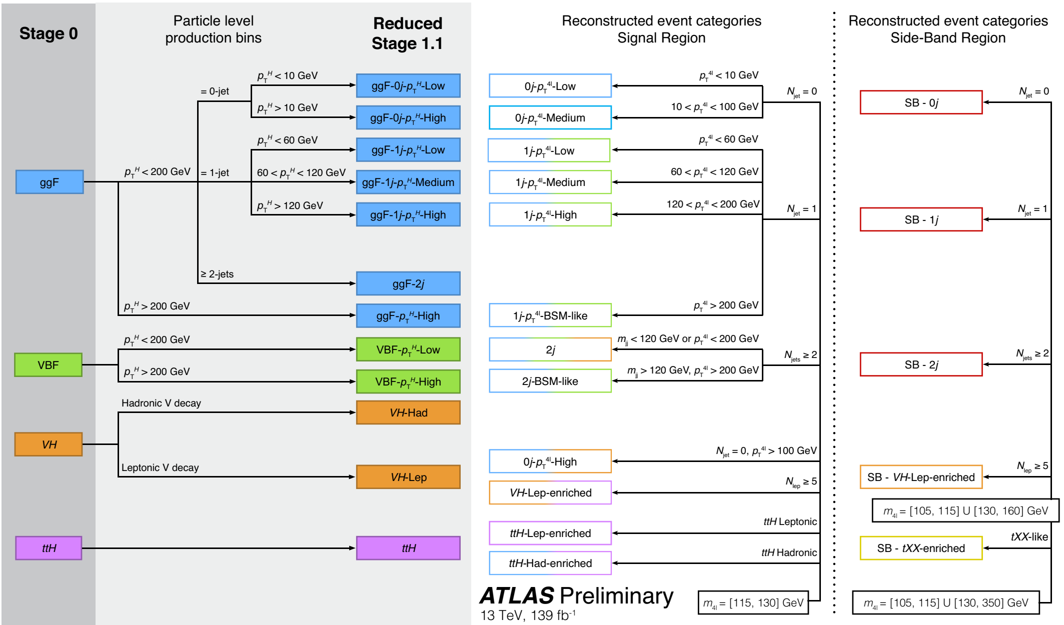
# ATLAS differential diphoton SMEFT

Table 6: The 95% CL observed limits on the $\overline{C}_{HG}$, $\overline{C}_{HW}$, $\overline{C}_{HB}$, $\overline{C}_{HWB}$ Wilson coefficients of the SMEFT basis and their CP-odd counterparts using interference-only terms and using both interference and quadratic terms. Limits are derived fitting one Wilson coefficient at a time while setting the other coefficients to zero.

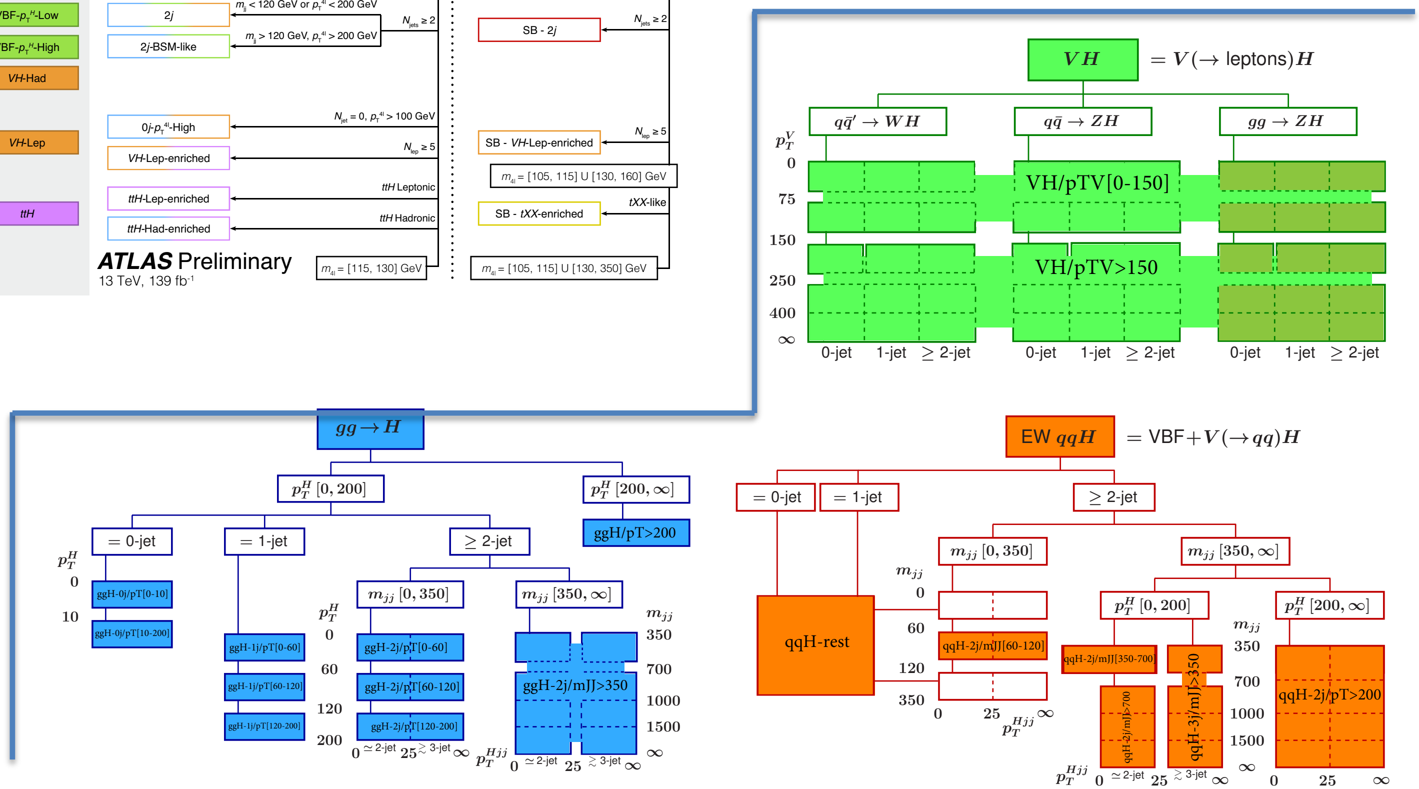
| Coefficient | 95% CL, interference-only terms | 95% CL, interference and quadratic terms |
|---|---|---|
| $\overline{C}_{HG}$ | $[-4.2, 4.8] \times 10^{-4}$ | $[-6.1, 4.7] \times 10^{-4}$ |
| $\widetilde{C}_{HG}$ | $[-2.1, 1.6] \times 10^{-2}$ | $[-1.5, 1.4] \times 10^{-3}$ |
| $\overline{C}_{HW}$ | $[-8, 2, 7.4] \times 10^{-4}$ | $[-8.3, 8.3] \times 10^{-4}$ |
| $\widetilde{C}_{HW}$ | $[-0.26, 0.33]$ | $[-3.7, 3.7] \times 10^{-3}$ |
| $\overline{C}_{HB}$ | $[-2.4, 2.3] \times 10^{-4}$ | $[-2.4, 2.4] \times 10^{-4}$ |
| $\widetilde{C}_{HB}$ | $[-13.0, 14.0]$ | $[-1.2, 1.1] \times 10^{-3}$ |
| $\overline{C}_{HWB}$ | $[-4.0, 4.4] \times 10^{-4}$ | $[-4.2, 4.2] \times 10^{-4}$ |
| $\widetilde{C}_{HWB}$ | $[-11.1, 6.5]$ | $[-2.0, 2.0] \times 10^{-3}$ |

# CMS/ATLAS H→ZZ STXS defs

ATLAS

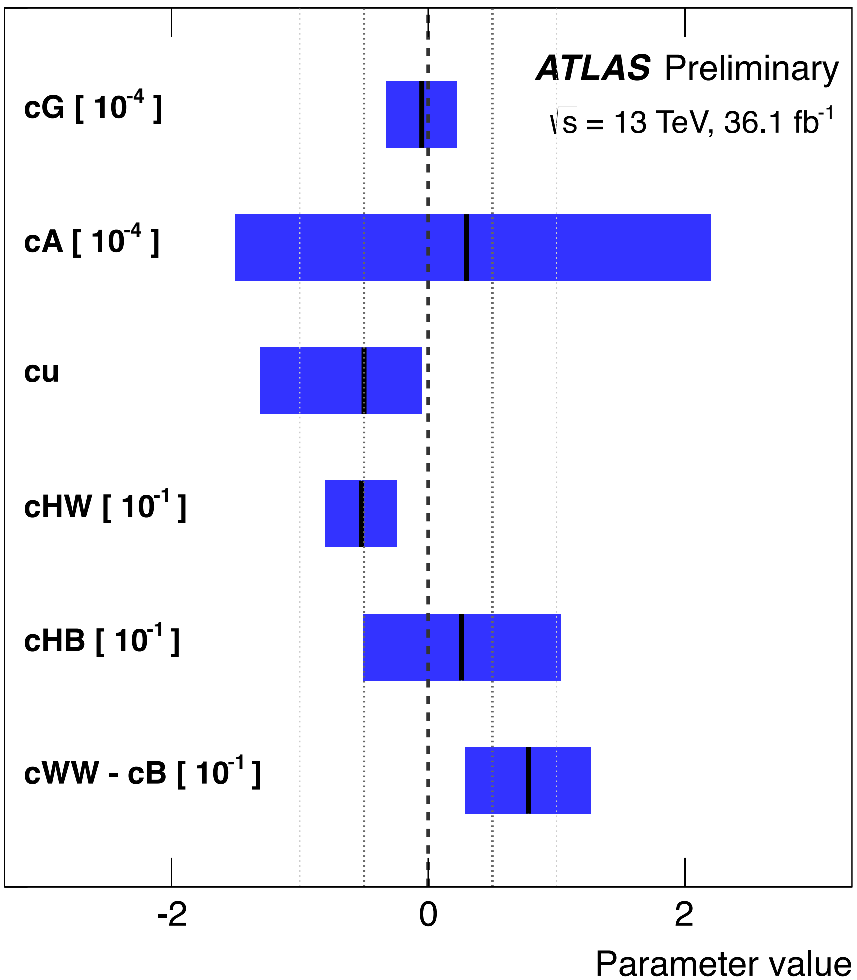



CMS

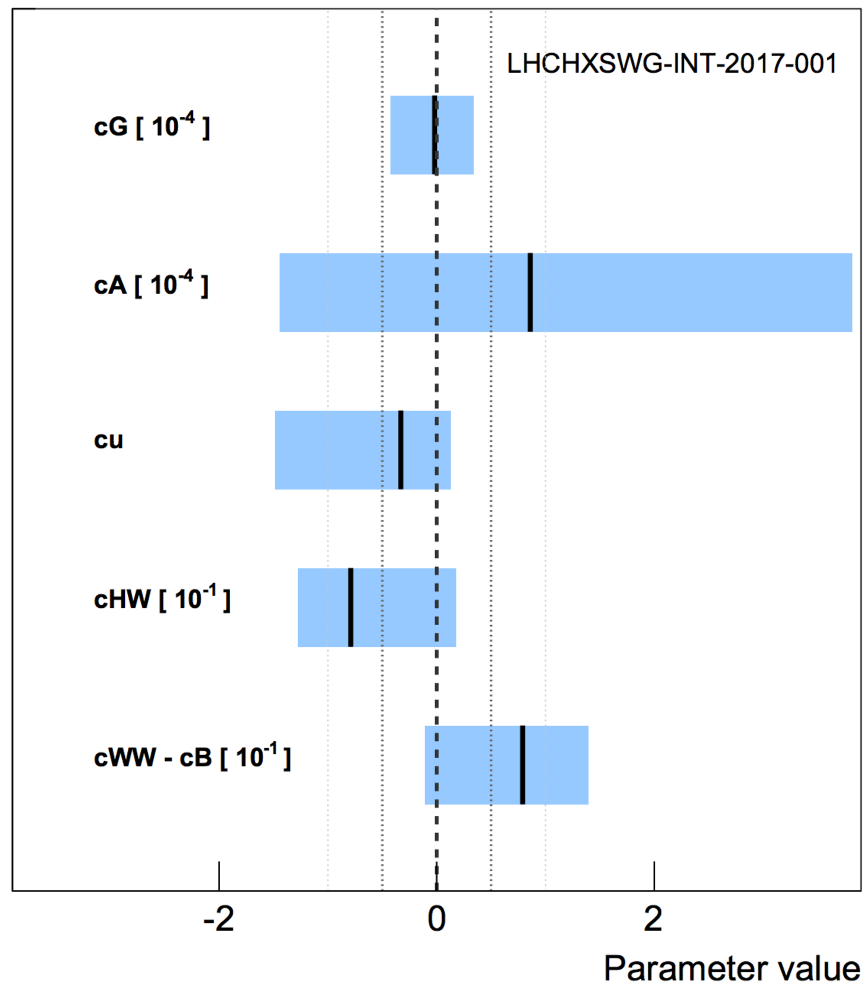


# Compare ~full LH vs $\chi^2$

Observed HEL constraints with H → ZZ* and H → γγ




Fit to ATLAS STXS measurements (ATLAS-CONF-2017-047)



# Clusters for double Higgs

| Benchmark | $\kappa_\lambda$ | $\kappa_t$ | $c_2$ | $c_g$ | $c_{2g}$ |
|---|---|---|---|---|---|
| 1 | 7.5 | 1.0 | -1.0 | 0.0 | 0.0 |
| 2 | 1.0 | 1.0 | 0.5 | -0.8 | 0.6 |
| 3 | 1.0 | 1.0 | -1.5 | 0.0 | -0.8 |
| 4 | -3.5 | 1.5 | -3.0 | 0.0 | 0.0 |
| 5 | 1.0 | 1.0 | 0.0 | 0.8 | -1.0 |
| 6 | 2.4 | 1.0 | 0.0 | 0.2 | -0.2 |
| 7 | 5.0 | 1.0 | 0.0 | 0.2 | -0.2 |
| 8 | 15.0 | 1.0 | 0.0 | -1.0 | 1.0 |
| 9 | 1.0 | 1.0 | 1.0 | -0.6 | 0.6 |
| 10 | 10.0 | 1.5 | -1.0 | 0.0 | 0.0 |
| 11 | 2.4 | 1.0 | 0.0 | 1.0 | -1.0 |
| 12 | 15.0 | 1.0 | 1.0 | 0.0 | 0.0 |
| SM | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 |