Experimental status on Kappa formalism and EFT approach

Mingshui Chen (IHEP, Beijing)

Precision theory for precise measurements at the LHC and future colliders

Quy Nhon, Vietnam

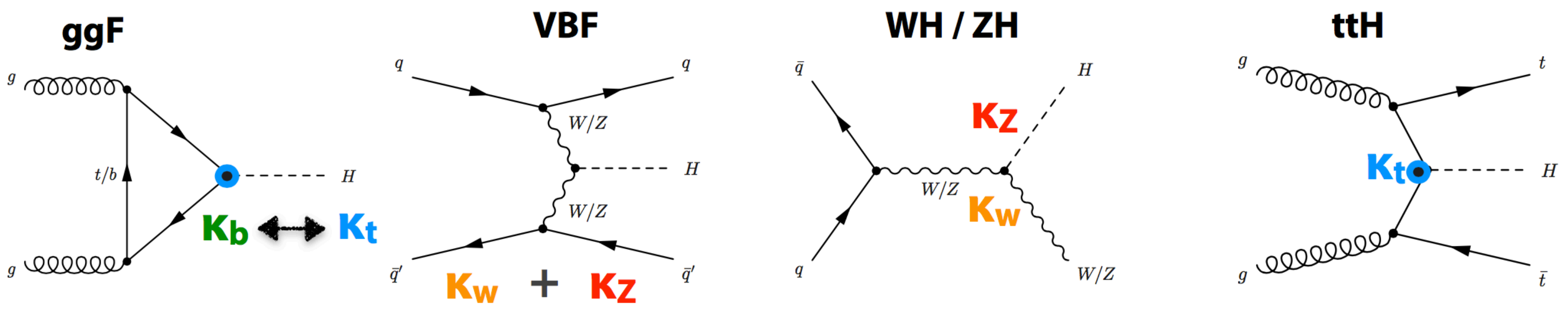
2016.9.25-10.1

Introduction

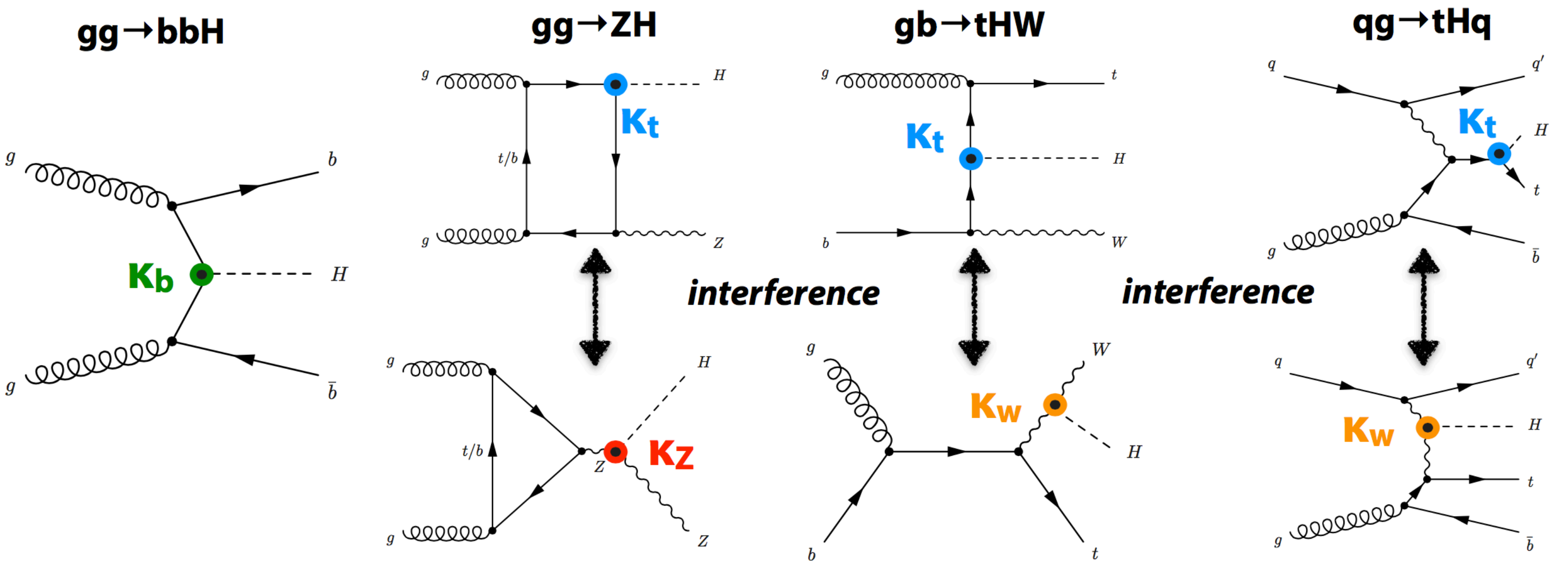
- ATLAS and CMS published in June the Run 1 legacy LHC combination on Higgs rates and couplings JHEP 1608 (2016) 045
  - Tremendous efforts from both experiments and theorists
  - Close the chapter on Run 1 Higgs experimental results
- Consistency tests performed with the κ-framework based on LHCHXSWG YR3
  - A LO-motivated framework
  - Stepping from signal strengths to couplings
- Further more, first results on differential cross sections and simplified template cross sections have been made with Run 1 and Run 2 data
  - To bridge the data and interpretations (e.g. EFT)

Higgs production processes

- Usual suspects:



- Rare processes:



Signal strengths, μ

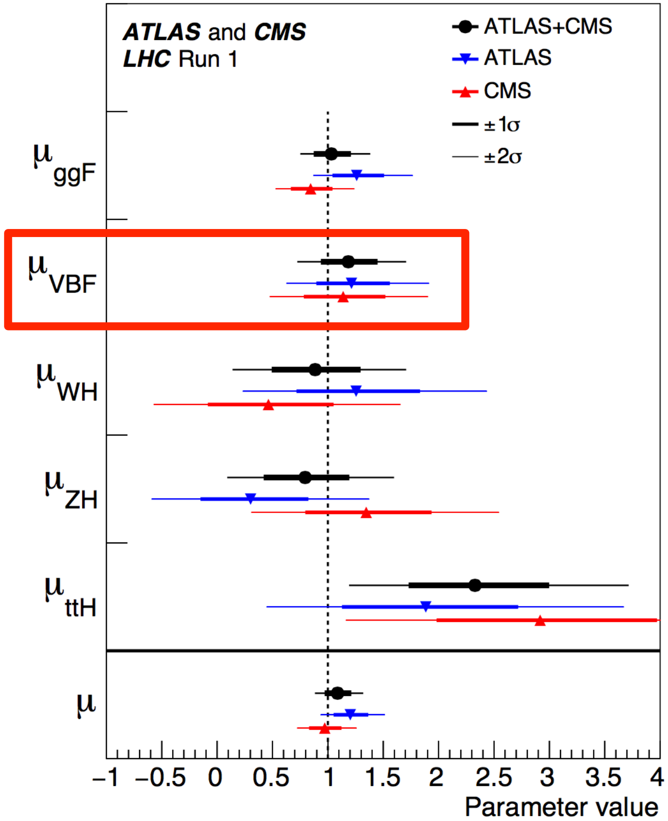
Parameters scale cross sections and BRs relative to SM

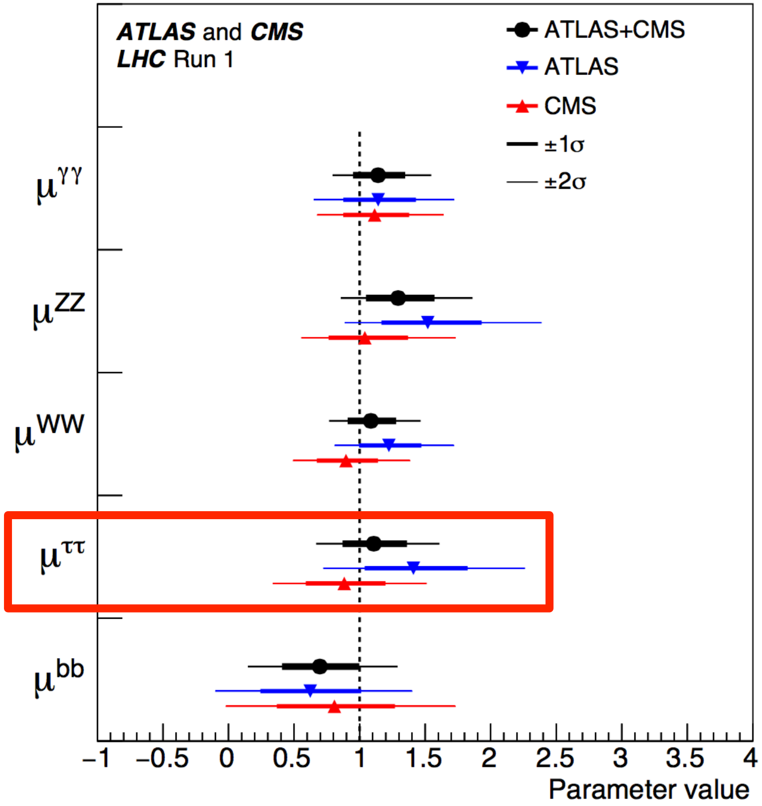
$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}.$$

Scaling of generic i → H → f process

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

Signal strengths, μ



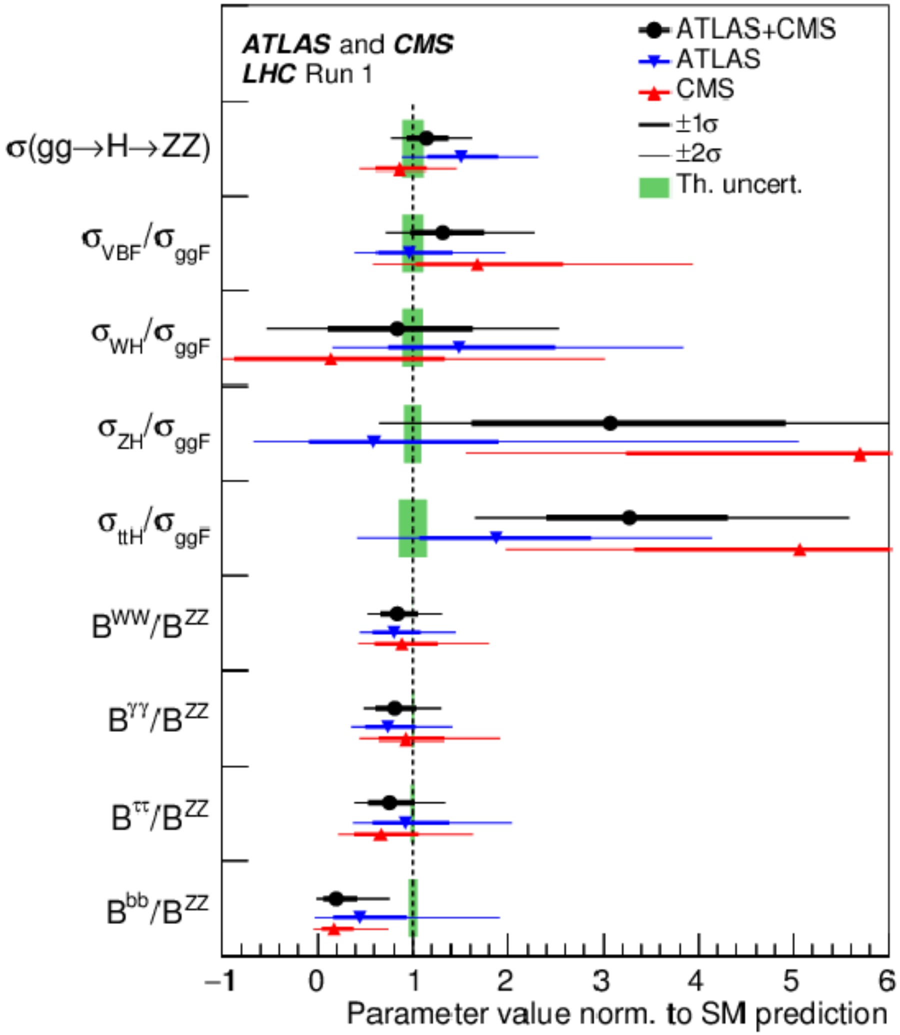


H→ττ decay mode and VBF process established through the ATLAS+CMS combination

Ratios of cross-sections and BRs

- Assumptions: **only the 7/8 ratios as in SM**
- Normalize the rate for any particular channel to a reference process using ratios of cross sections and branching ratios
- Motivation:
  - No assumptions on relative cross sections or BRs
  - Measured values independent of SM prediction and inclusive theory uncertainties
  - Cancellation of common systematic uncertainties in ratios
- Choose reference process as one measured with the **smallest systematic uncertainty: gg→H→ZZ**

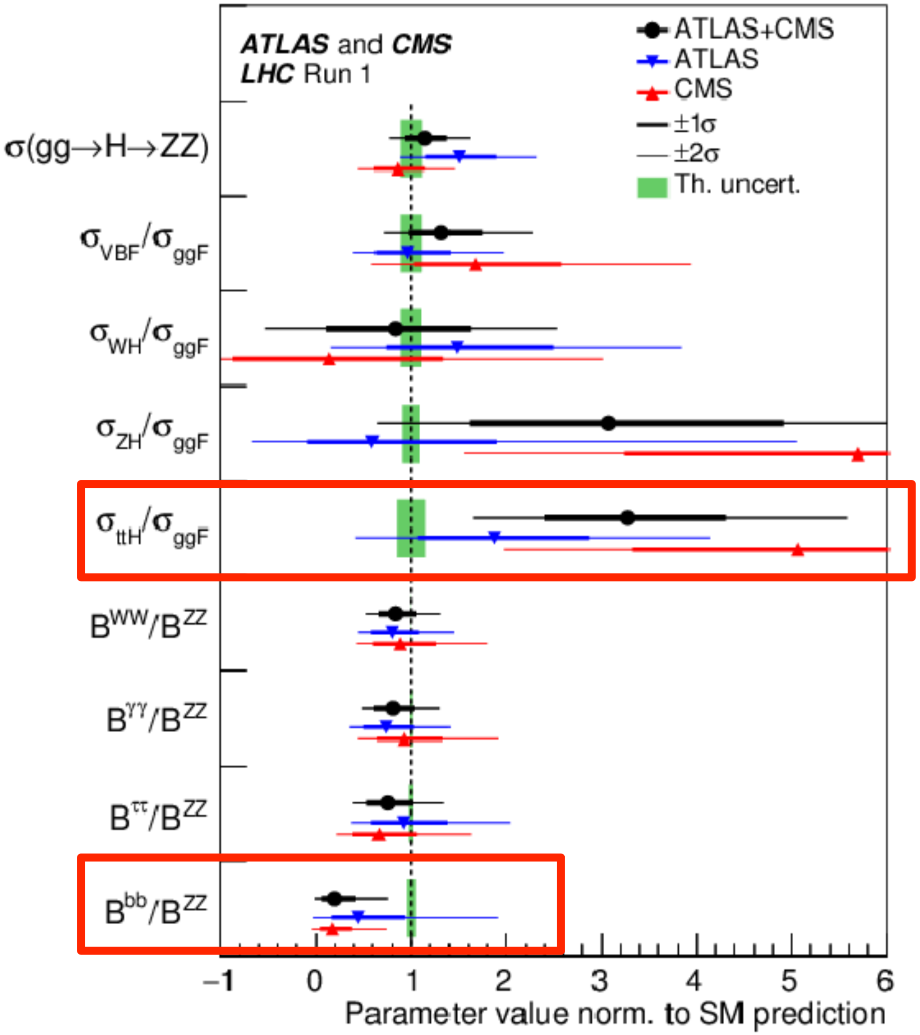
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$



Ratios of cross-sections and BRs

- Largest disagreement in **$\sigma_{ttH}/\sigma_{ggF}$ (~3σ)**
    - **mainly due to the multi-lepton categories**
- **BR_{bb}/BR_{ZZ} (2.5σ)**
    - High observed values **σ_{ZH}/σ_{ggF}** and **$\sigma_{ttH}/\sigma_{ggF}$** induce a low value for BR($H \to bb$)
    - $H \to bb$ decay mode does not contribute to the observed excesses
    - **Anti-correlated with above excesses**

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$



From μ to κ

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

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

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\mathrm{H}}},$$

Total width determined as

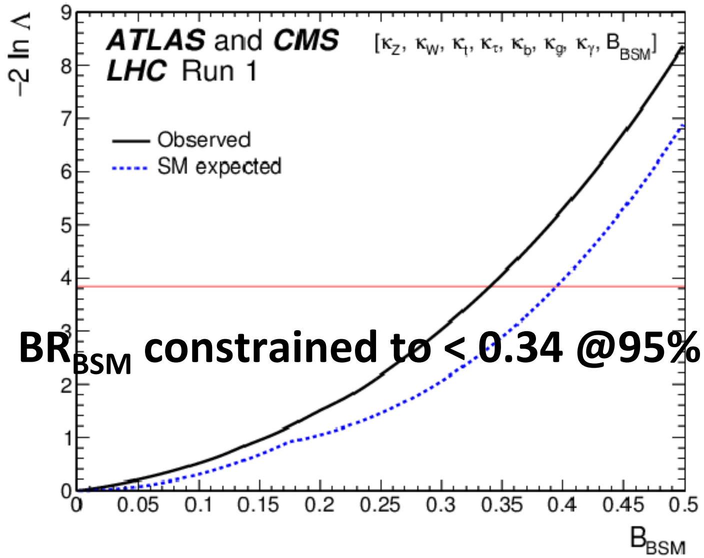
$$\Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Where

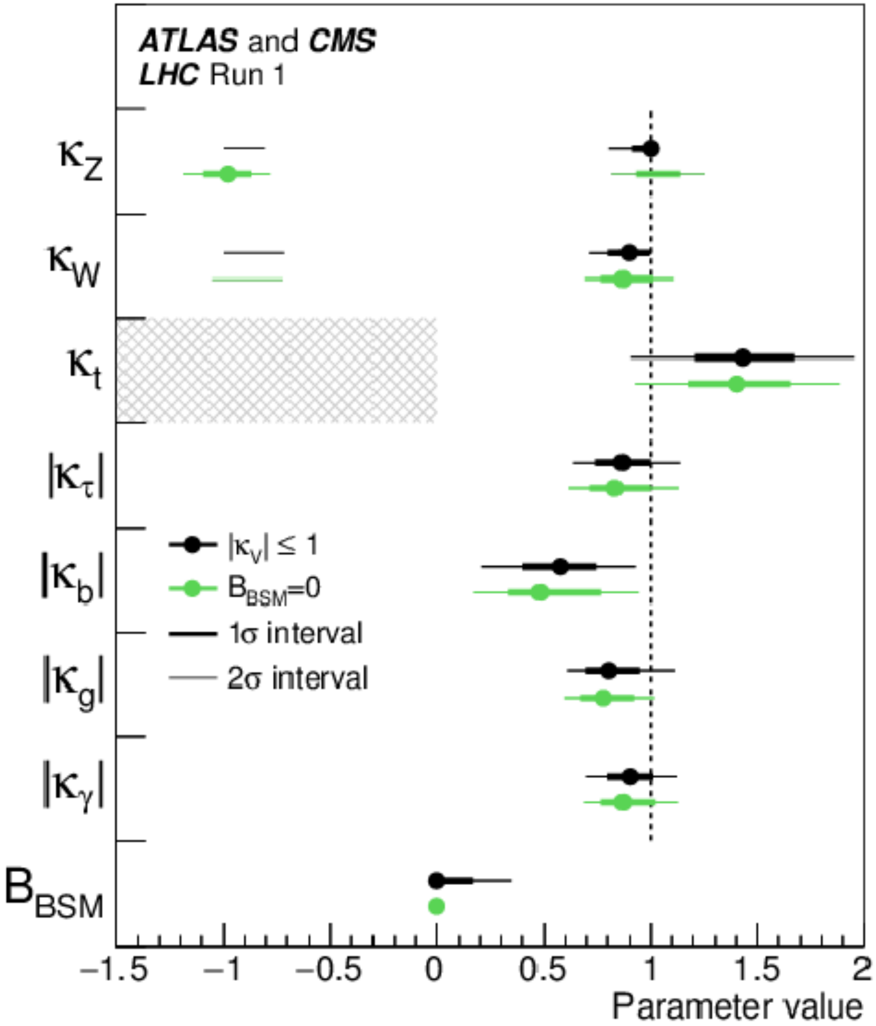
$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2$$

Allow BSM contribution to loop & decay

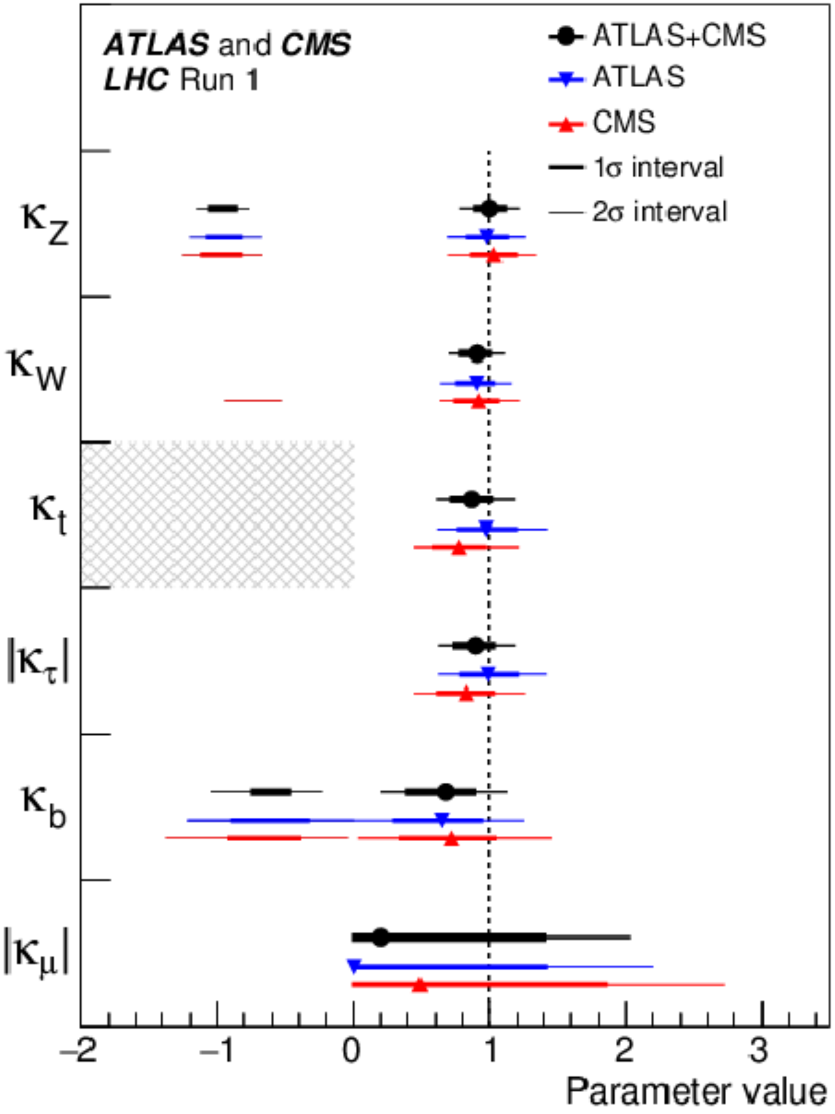
- Use effective couplings for ggH (**κ_g**) and H→γγ (**κ_γ**)
- BR_{BSM}: Higgs decays to BSM particles + non-SM BRs of unmeasured final states (gg,cc,..)
- Consider two scenarios:
  - **$BR_{BSM} = 0$**
  - **BR_{BSM} floating, but $|\kappa_V| < 1$**



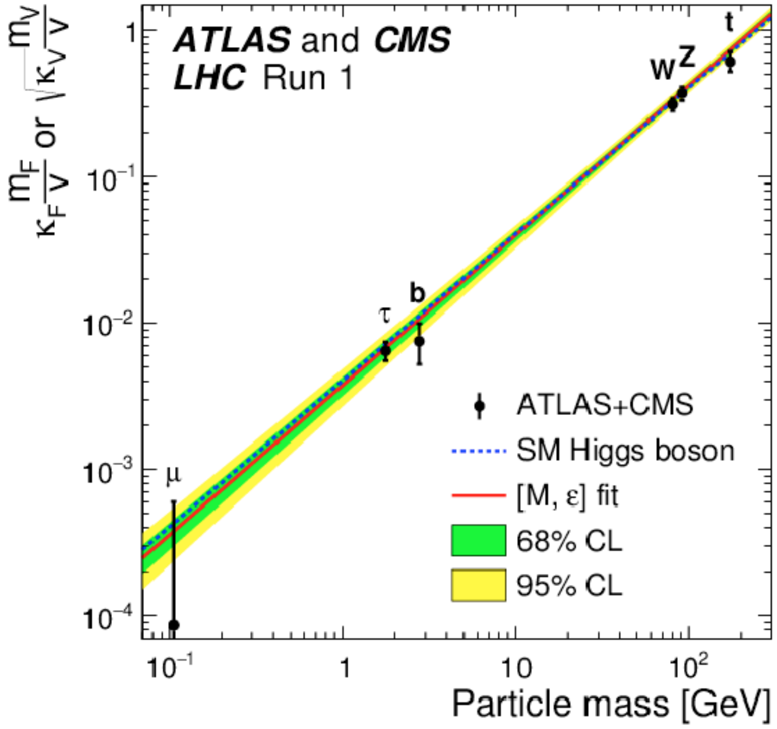
BR_{BSM} constrained to < 0.34 @95% CL



No BSM loop/decay contributions

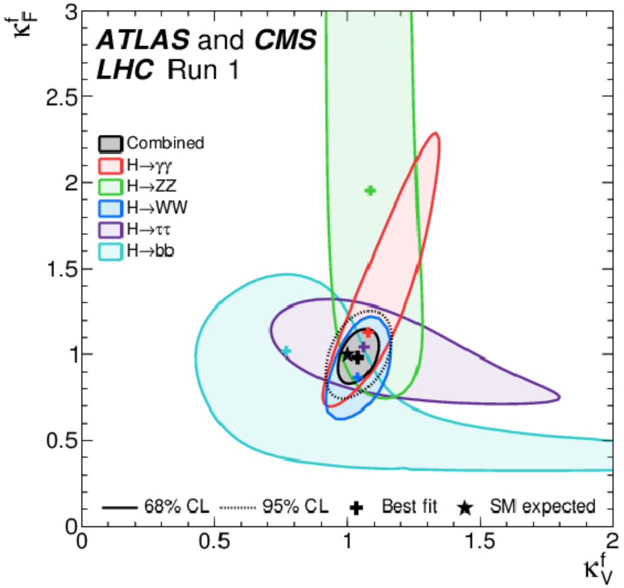


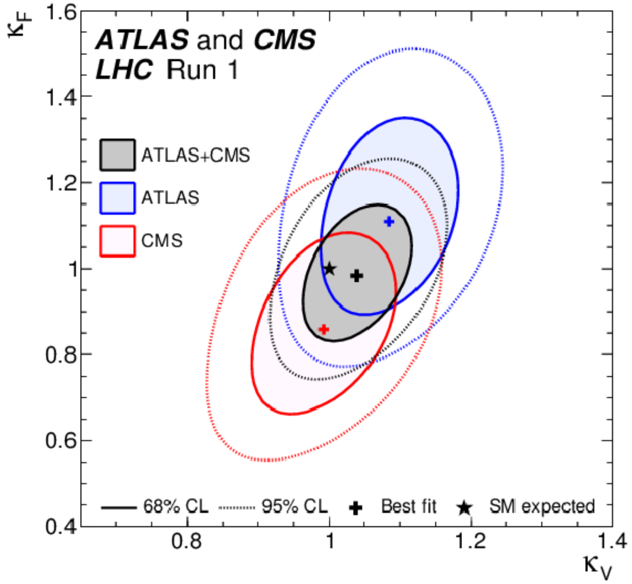
- **Resolve ggH (κ_g) and H→γγ (κ_γ) loops**
- Includes H→μμ analyses for reduced coupling vs. particle mass



2D scans of κ_V, κ_F

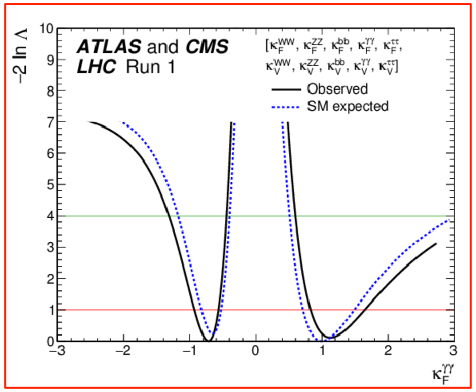
- Simplified model in which
  - $\kappa_V = \kappa_W = \kappa_Z$
  - $\kappa_F = \kappa_t = \kappa_b = k_\tau$
- Different final states give very different constrained region in the $\kappa_V \kappa_F$ (all channels compatible to SM)
- Combination of ATLAS and CMS also compatible within 1 σ with SM

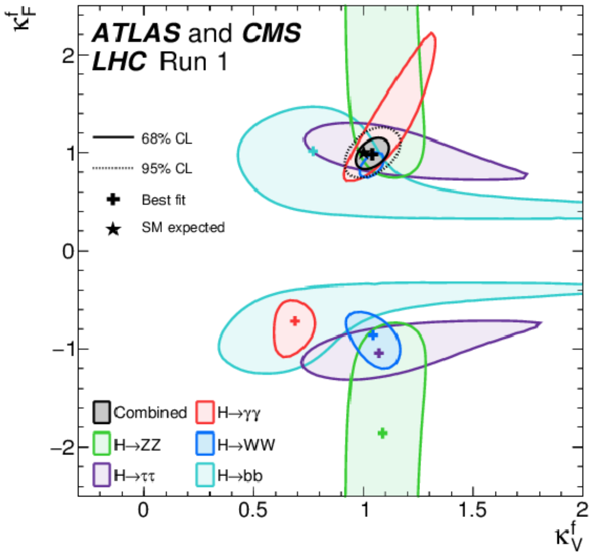


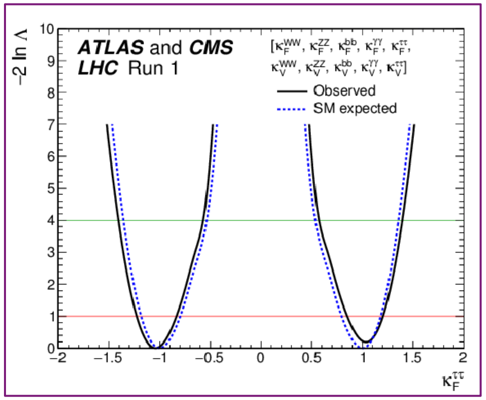


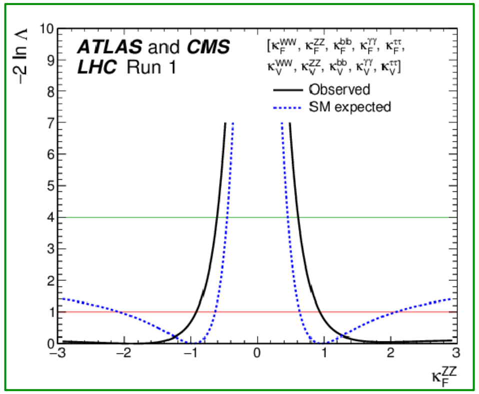
2D scans of κ_V, κ_F

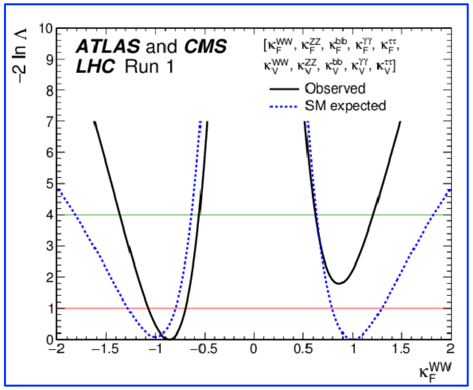
- Most channels nearly degenerate in relative sign of κ_V and κ_F

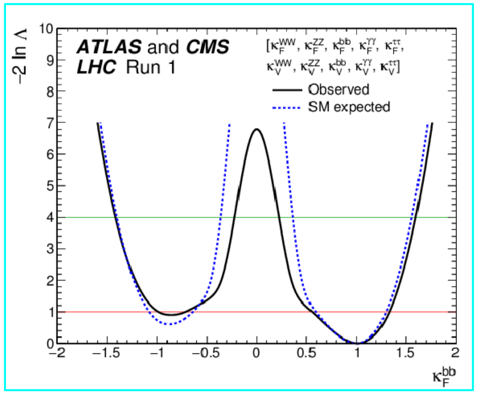






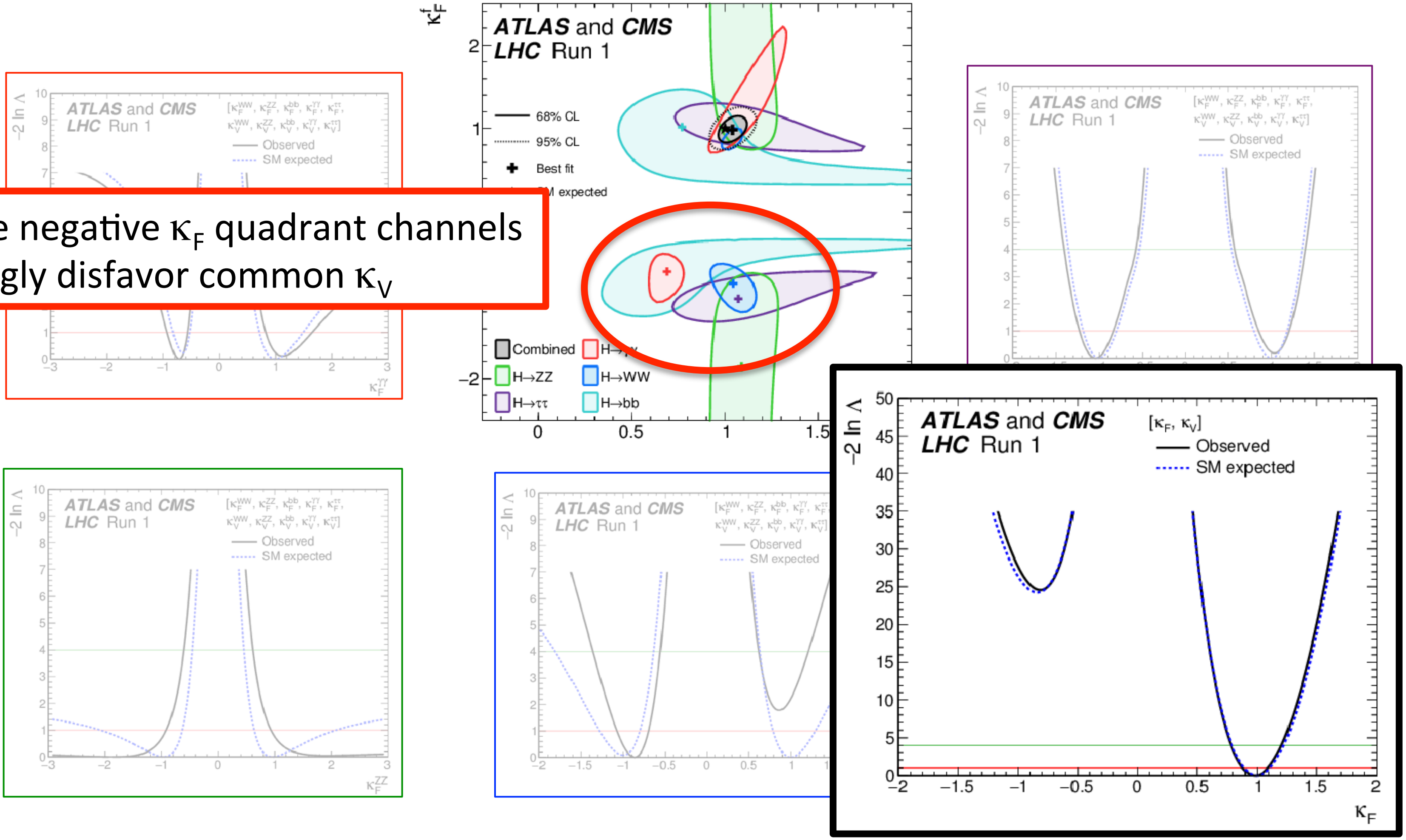






2D scans of κ_V, κ_F

- Most channels nearly degenerate in relative sign of κ_V and κ_F

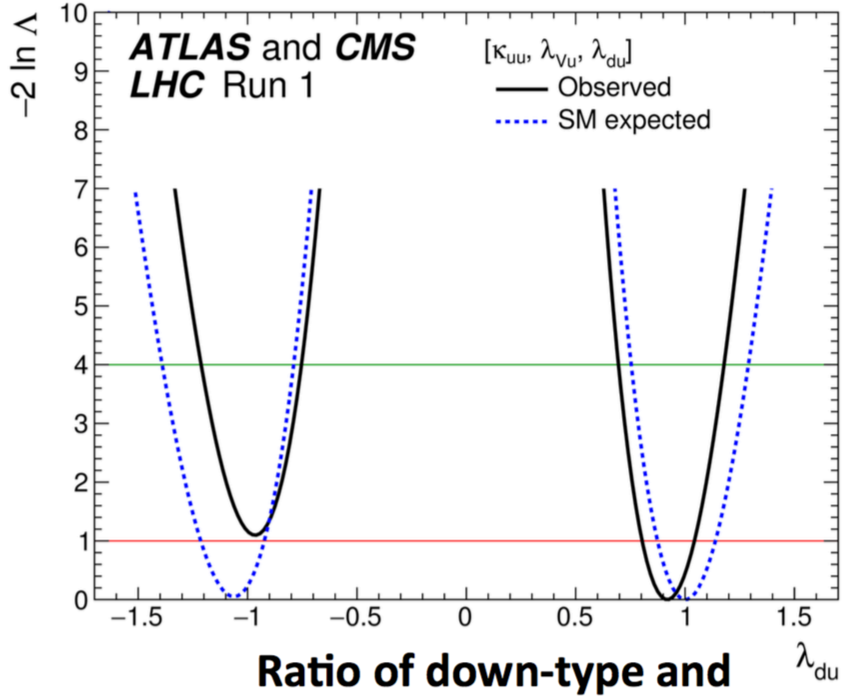


In the negative κ_F quadrant channels strongly disfavor common κ_V

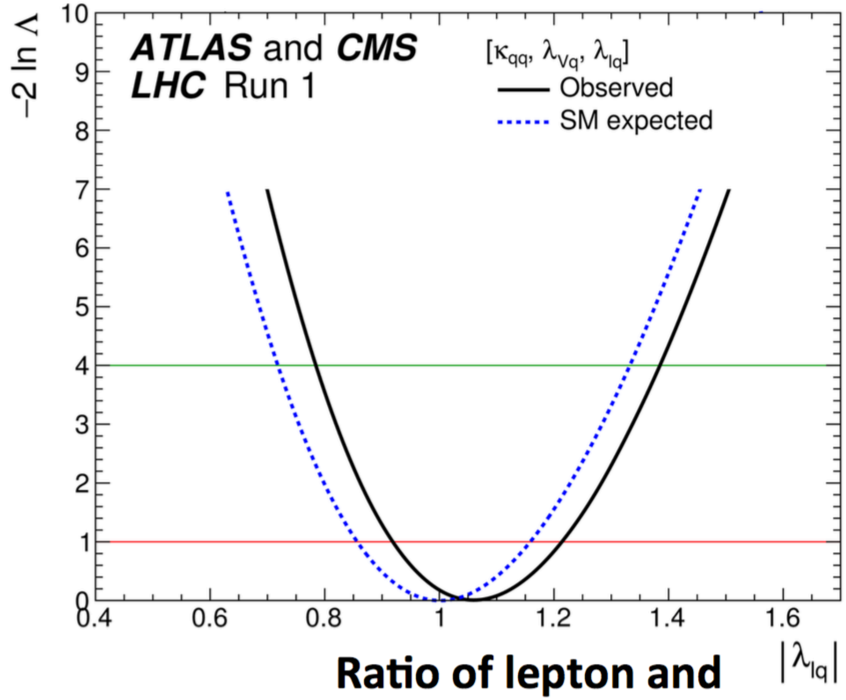
Fermion Couplings

- In MSSM / 2HDM Type II [κ_V, κ_d, κ_u], ratio of down-type (b, τ, μ) and up-type (t) fermion couplings is tested with ~10% precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit

- In 2HDM Lepton-Specific [κ_V, κ_l, κ_q], ratio of lepton (τ, μ) and quark couplings (t, b) would be enhanced at large tan β
- Also good agreement with SM



Ratio of down-type and up-type fermion couplings



Ratio of lepton and quark couplings

Going beyond the κ-framework

- The LO-motivated κ framework has the following assumptions/limitations
  - Single, narrow resonance with mH =125.09 GeV
  - Decay kinematics compatible with SM prediction
  - Tensor structure of interactions is the same as in SM
  - Zero-width approximation in the Higgs boson propagator
- To test kinematics distributions
  - Anomalous couplings
  - EFT interpretation through differential cross section measurements

CMS-PAS-HIG-2016-033

CMS 13 TeV H4l anomalous couplings

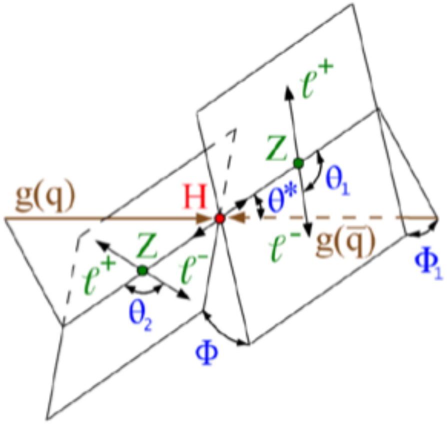
- Characterized through scattering amplitude

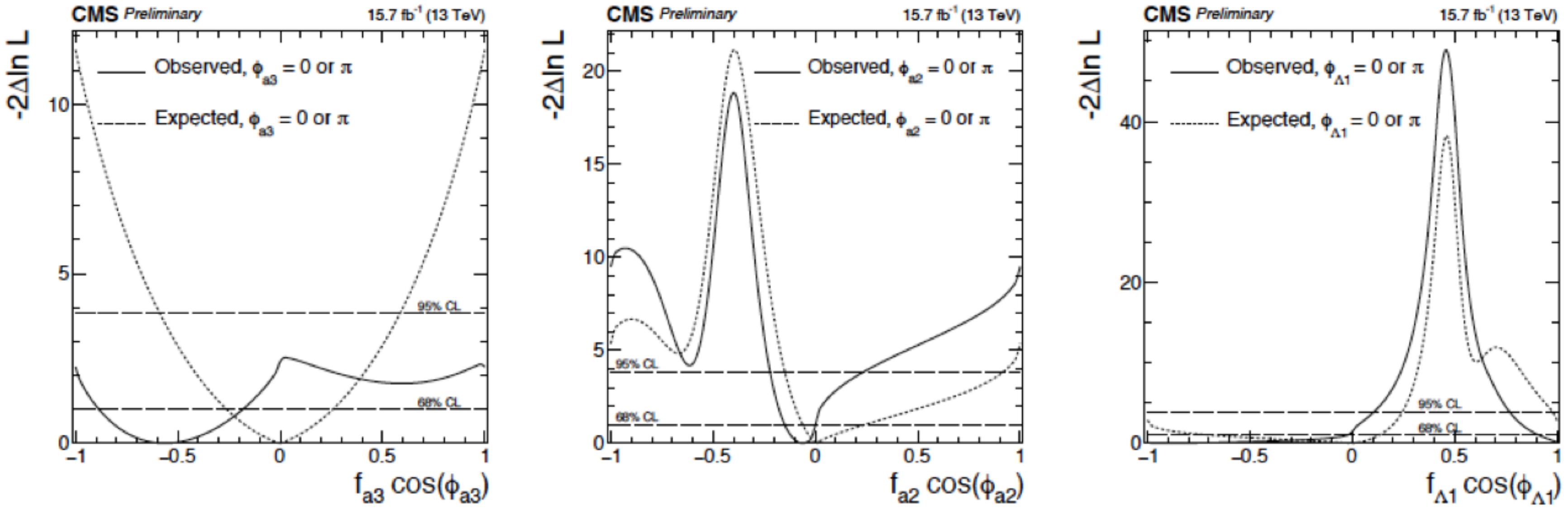
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}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

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda1} = \frac{\tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda1},$$





CMS-PAS-HIG-2016-033

CMS 13 TeV H4l anomalous couplings

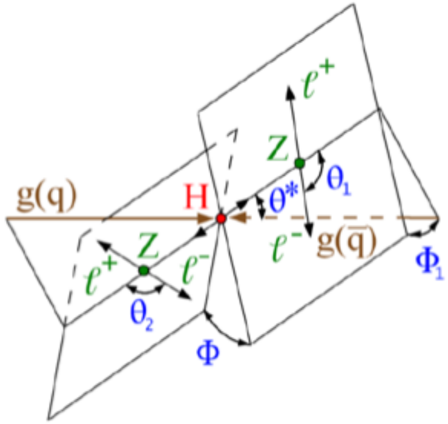
- Characterized through scattering amplitude

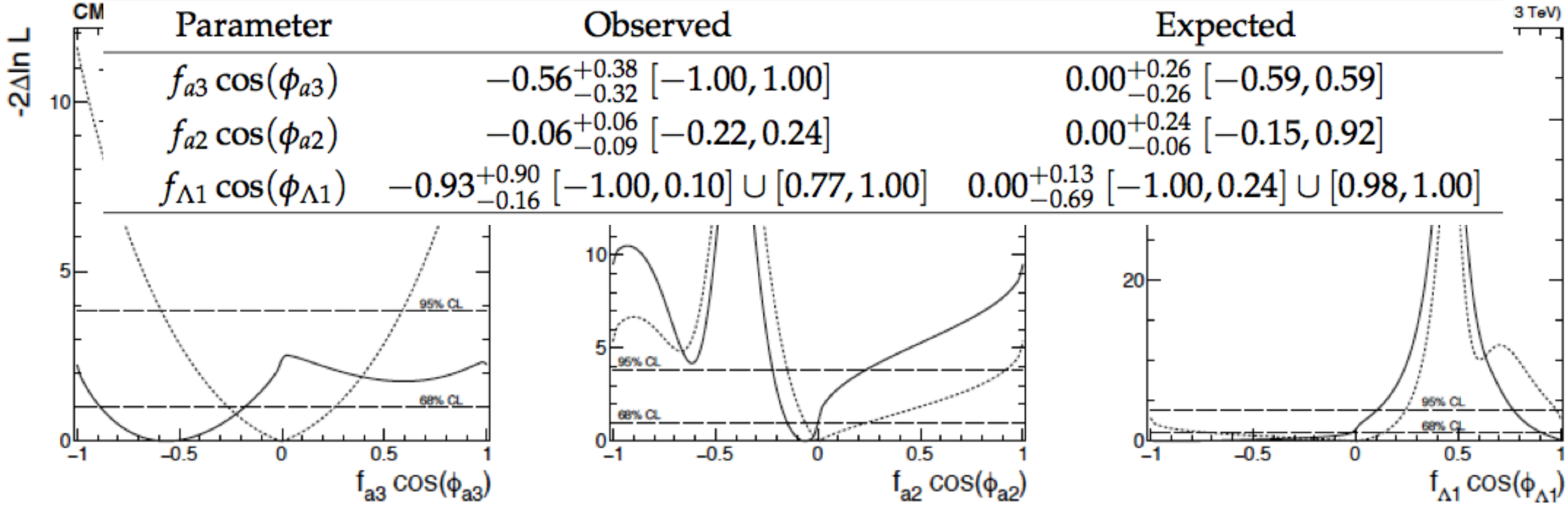
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}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

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda1} = \frac{\tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda1},$$





Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.56^{+0.38}_{-0.32}$ $[-1.00, 1.00]$	$0.00^{+0.26}_{-0.26}$ $[-0.59, 0.59]$
$f_{a2}\cos(\phi_{a2})$	$-0.06^{+0.06}_{-0.09}$ $[-0.22, 0.24]$	$0.00^{+0.24}_{-0.06}$ $[-0.15, 0.92]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$-0.93^{+0.90}_{-0.16}$ $[-1.00, 0.10] \cup [0.77, 1.00]$	$0.00^{+0.13}_{-0.69}$ $[-1.00, 0.24] \cup [0.98, 1.00]$

ATLAS-CONF-2016-079

ATLAS 13 TeV H4l

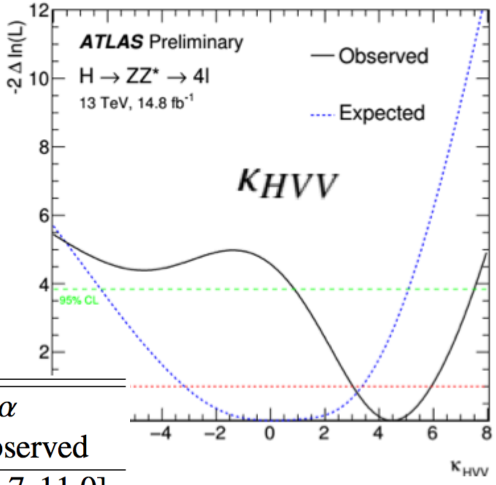
- In terms of EFT couplings defined in Higgs characterization model:

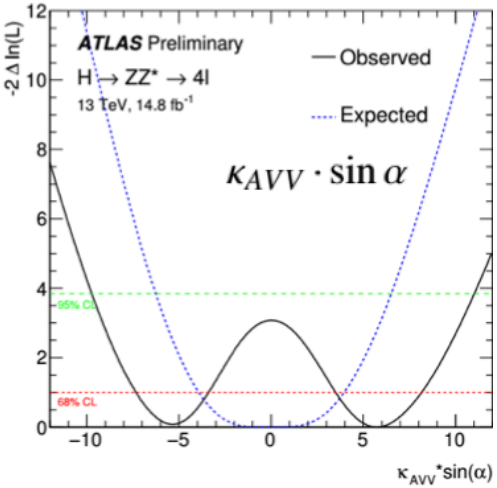
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right]$$

$$-\frac{1}{4}\frac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$

$$-\frac{1}{2}\frac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+\tilde{W}^{-\mu\nu}\right]\Big\} X_0$$

J^P	Model	Values of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	SM Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$





Not excluded range at 95% CL	κ_{HVV}		$\kappa_{AVV}\cdot\sin\alpha$	
	expected	observed	expected	observed
	$[-6.3, 5.1]$	$[0.9, 7.5]$	$[-6.3, 6.5]$	$[-9.7, 11.0]$

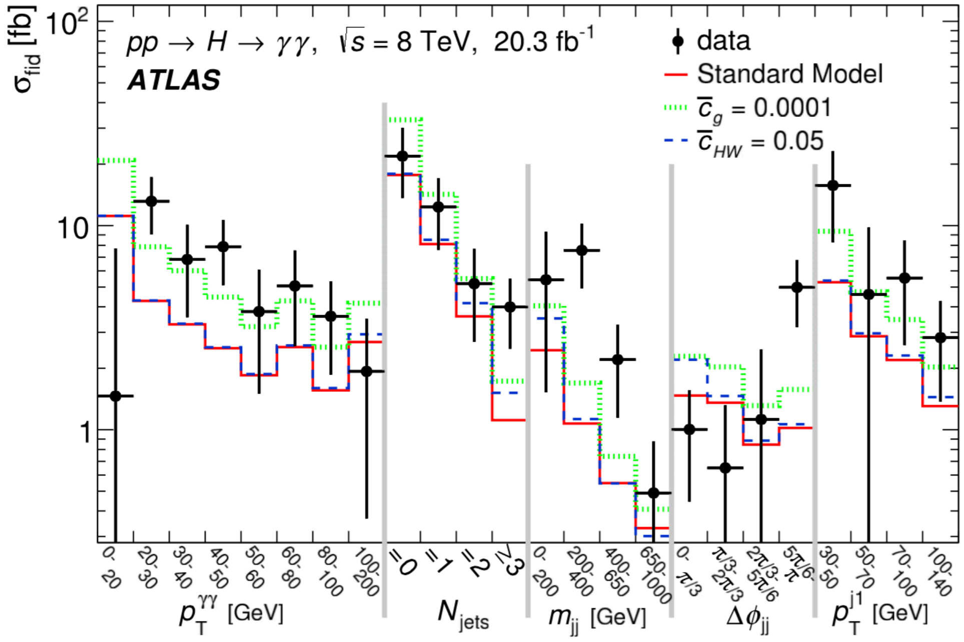
Phys.Lett. B753 (2016) 69-85

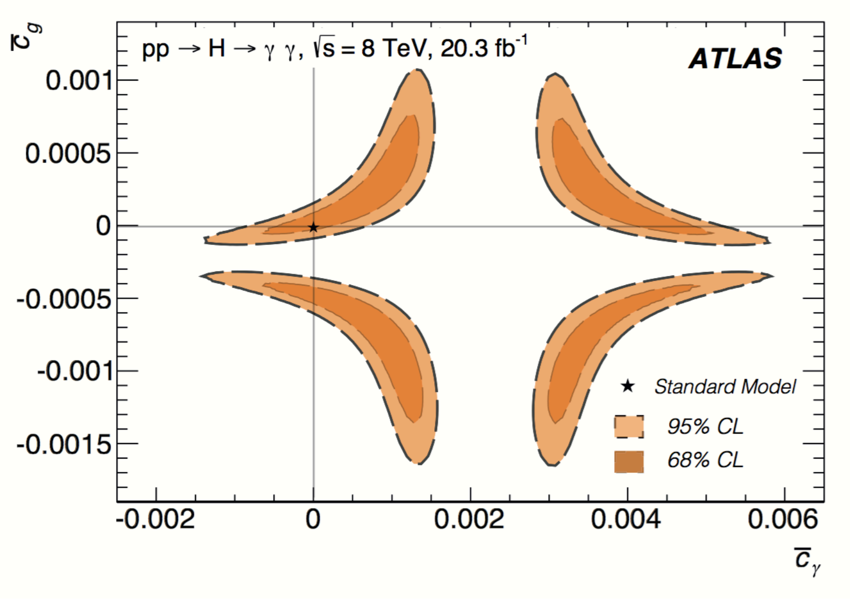
EFT with differential cross sections

- Probe BSM CP-even and CP-odd interactions using five differential cross sections in EFT framework and the Strongly Interacting Light Higgs (SILH) formulation:

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} \\ + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

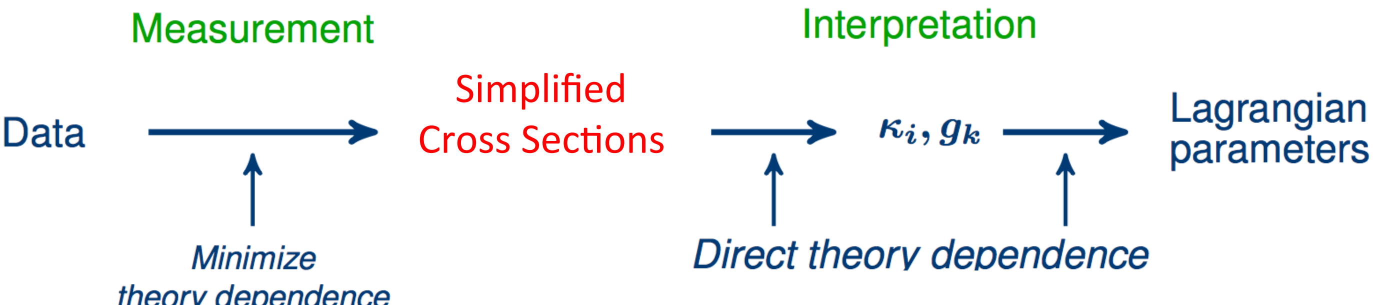
Wilson coefficients specifying the strength of the new interactions





Simplified Template Cross Sections

- Another complementary approach to connect data and theory interpretations



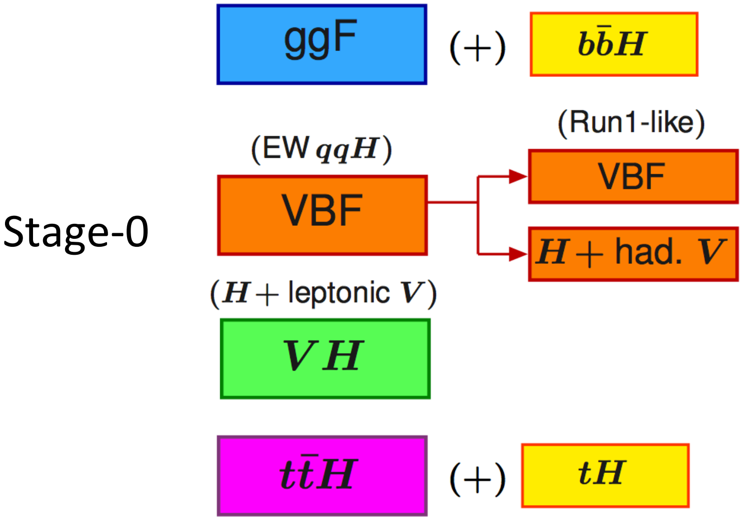
Measurement

Interpretation

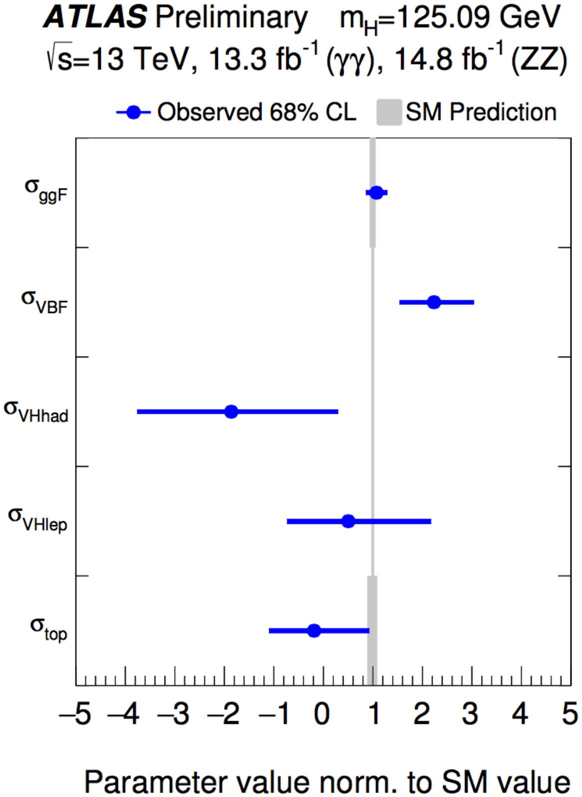
Data → Simplified Cross Sections → κ_i, g_k → Lagrangian parameters

Minimize theory dependence

Direct theory dependence



(Combined $\gamma\gamma$ and ZZ assuming SM BR)



Summary

- A comprehensive combined measurement of ATLAS and CMS Higgs boson couplings has been performed
  - Precision usually better by ~1/√2 wrt single experiment
- **First results beyond κ-framework have also been made**
  - **Including the interpretations in EFT approach**
- **Overall good consistency with SM** expectations
- Much more data ahead, stay tuned!

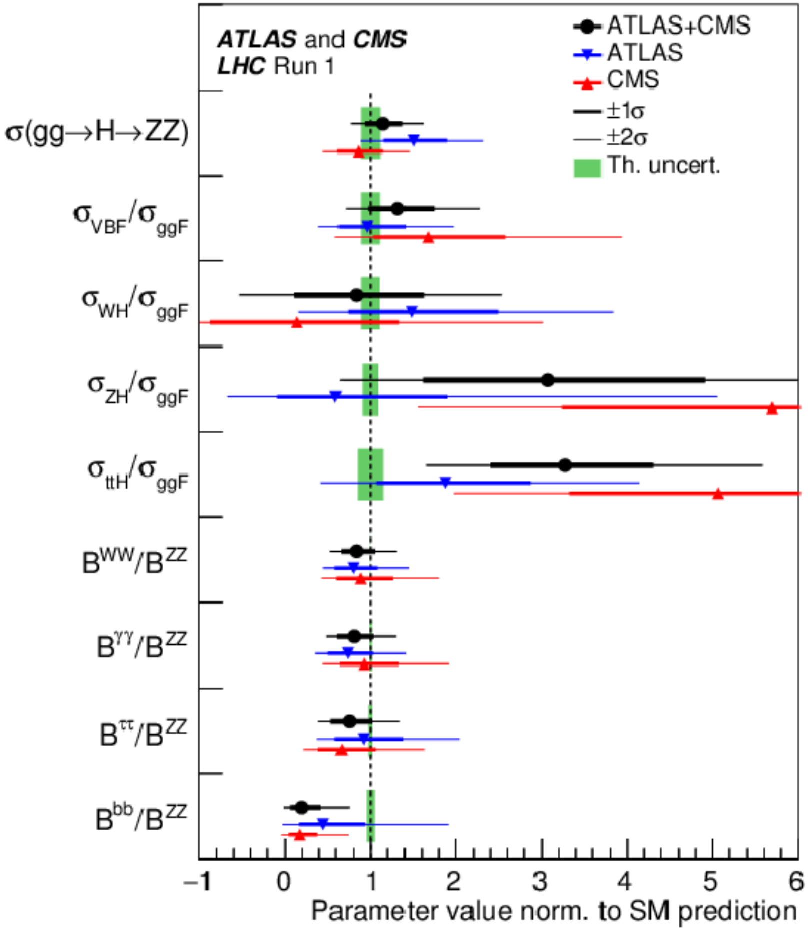
The era of Higgs precision measurements has just begun

Thanks !

Backup

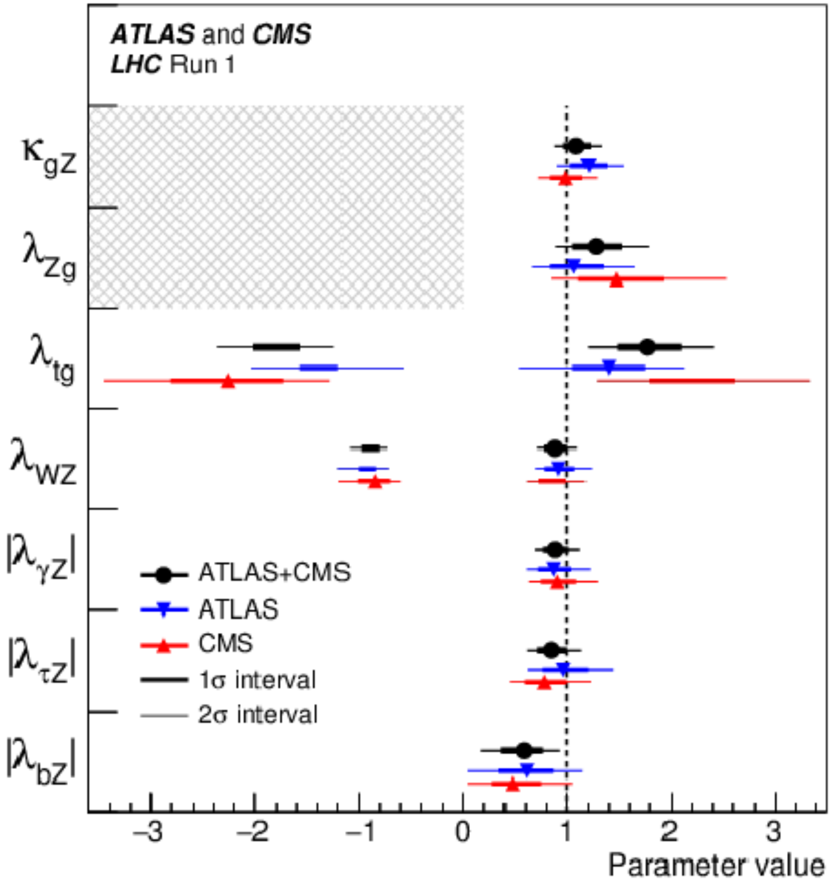
Ratio of rates → Ratio of couplings

Re-fit fewer couplings to actual particles as ratios to Z and gluon, $\lambda_{ij} = \kappa_i/\kappa_j$

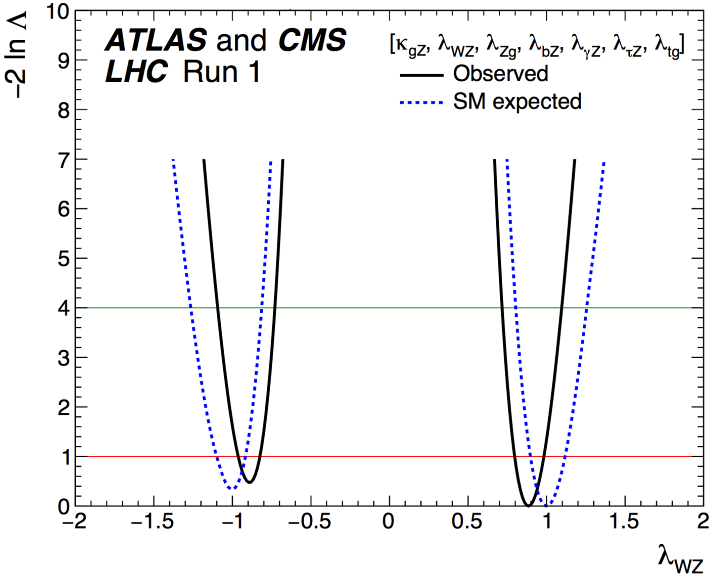


Refit

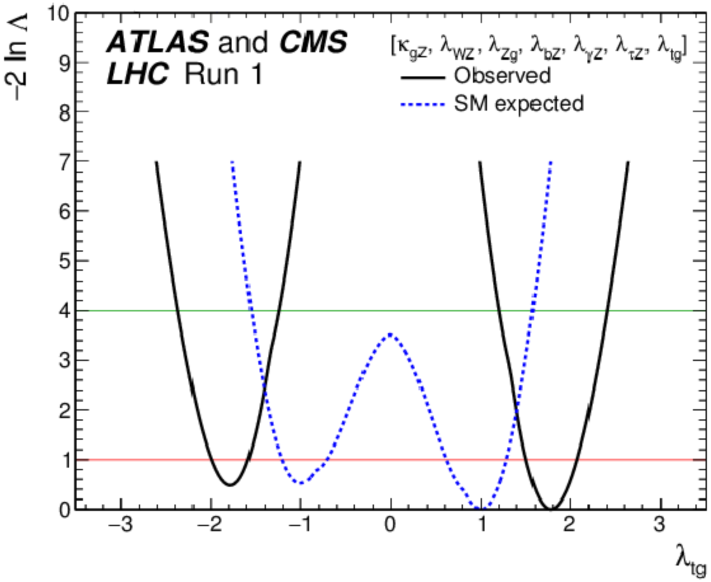
→

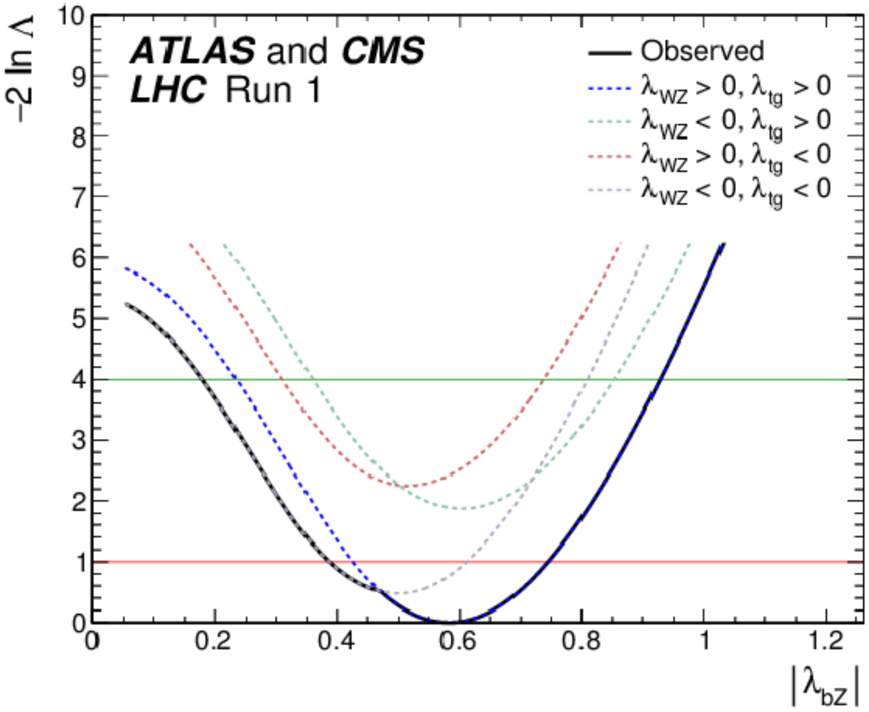


Ratio of couplings



Asymmetry on likelihood due to interference effects in ggZH, tHq/tHW





arXiv:1602.04516

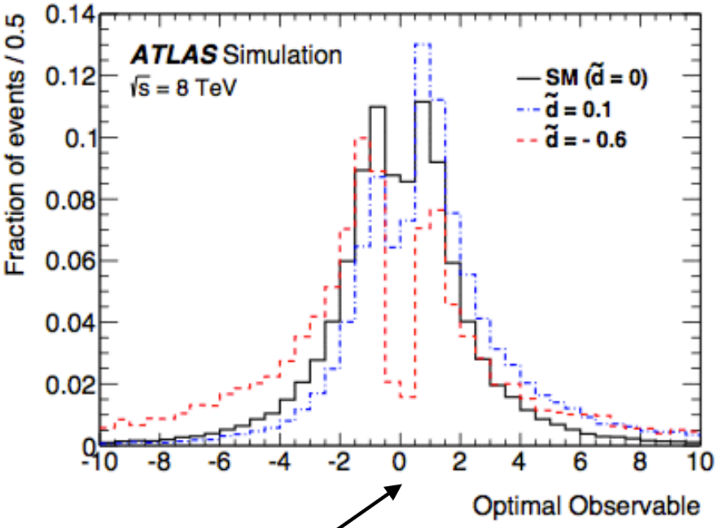
CP-invariance test: VBF H→ττ

- **HVV couplings as a test of CP-violation / CP-invariance**

HWW, HZZ decays and Hγγ differential cross-section
no deviations from Run1 data

Direct test through VBF production (H→ττ)

- **CP-odd observable:**
sensitive to interference between SM and CP-odd contributions
- **Optimal observable:** combine multi-dimensional information in a single variable from the VBF production LO matrix-element [independent from H decay mode]



$$\boxed{\mathcal{OO} = \frac{2\,\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^{2}}}$$

most sensitive for smallest values

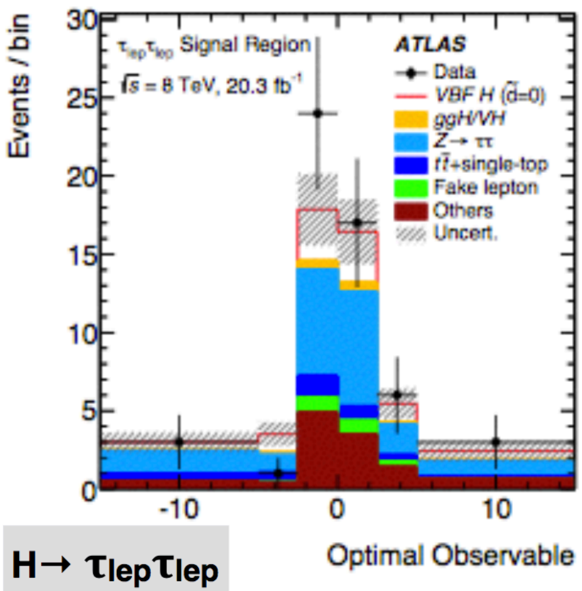
Results interpreted in the Effective Field Theory framework:
CP-violating effects from higher dimension operators on HVV: $\tilde{d}$ parameter

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

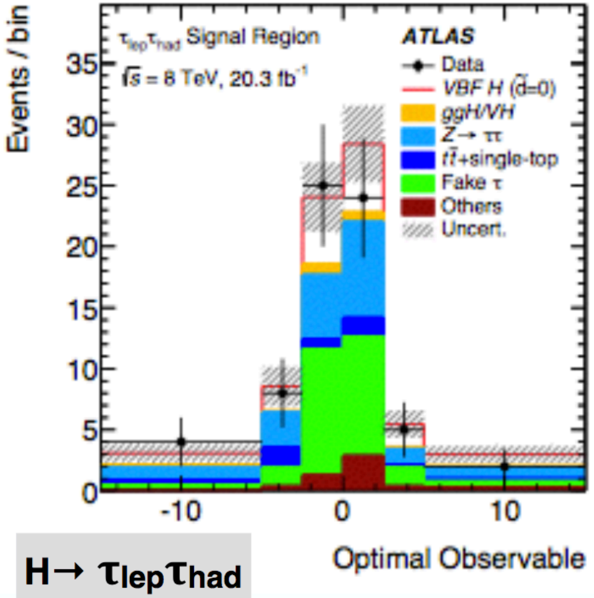
Couplings parametrisation: $\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$

arXiv:1602.04516

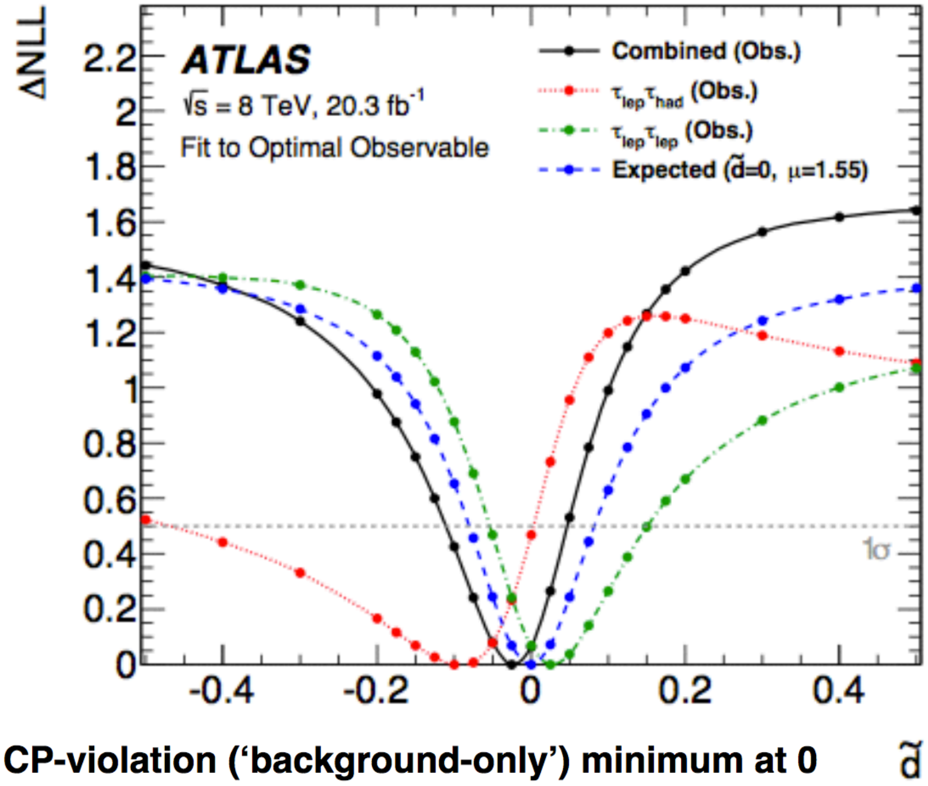
CP-invariance test: VBF H→ττ



H→ $\tau_{lep}\tau_{lep}$



H→ $\tau_{lep}\tau_{had}$



No CP-violation ('background-only') minimum at 0

- [$-0.11 < \bar{d} < 0.05$] compatible at 68% CL [competitive with limits from HWW, HZZ]
- same limit-setting with $\Delta\Phi^{sign}(jj)$ shows worse results [azimuthal angle between VBF-tagging jets]

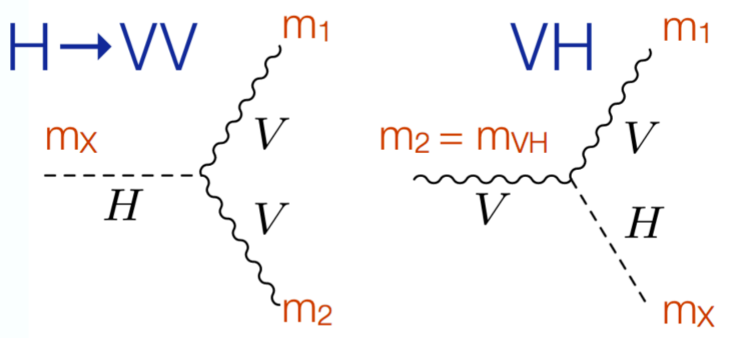
Channel	Fitted value of $\bar{d}$
$\tau_{lep}\tau_{lep}$	0.3 ± 0.5
$\tau_{lep}\tau_{had}$	-0.3 ± 0.4

HVV coupling: VHbb

arXiv:1602.04305

- Generic HVV scattering amplitudes for spin 0 H:

$$A_{00} = -\frac{m_X^2}{v}\left(a_1\sqrt{1+x} + a_2\boxed{\frac{m_1 m_2}{m_X^2}}x\right),$$
$$A_{++} = \frac{m_X^2}{v}\left(a_1 + ia_3\boxed{\frac{m_1 m_2}{m_X^2}}\sqrt{x}\right),$$
$$A_{--} = \frac{m_X^2}{v}\left(a_1 - ia_3\boxed{\frac{m_1 m_2}{m_X^2}}\sqrt{x}\right),$$



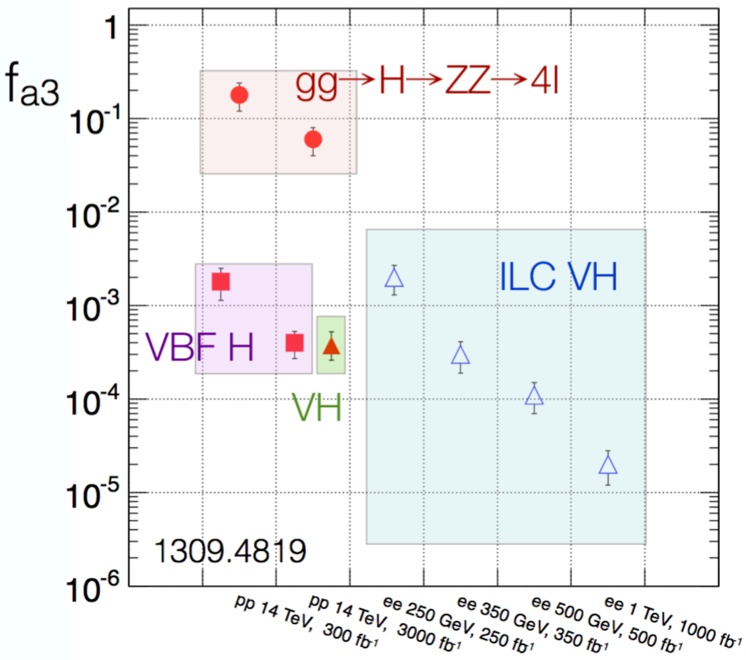
- VH sensitivity from order of magnitude larger $m_1 m_2/m_X^2$

- Effective fractional cross section to parameterize presence of anomalous pseudoscalar component

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$$

where σ_i is the cross section for $a_i=1$ and $a_{j\neq i}=0$

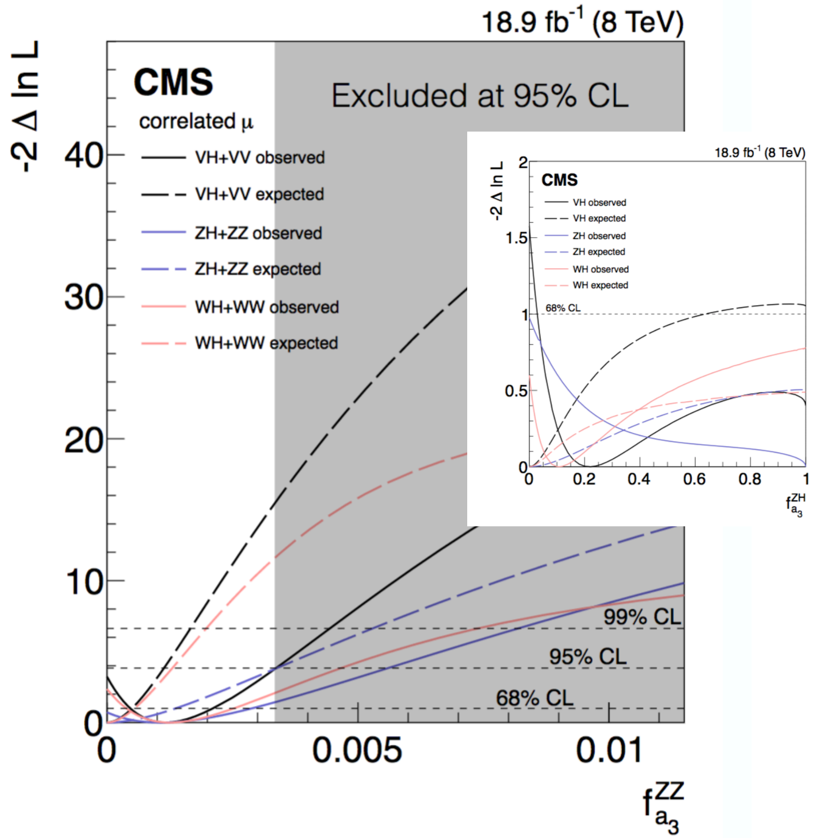
f_{a3} = 0 for pure a_1 (SM scalar)
f_{a3} = 1 for pure a_3 (pseudoscalar)



arXiv:1602.04305

HVV coupling: VHbb

- Individual and combined
- Combine with H→VV
  - Strongest assumption: $a_i^{HZZ}=a_i^{HWW}$ and no additional anomalous couplings, $f_{a3}^{ZZ} > 0.0034$ excluded at 95% CL
  - Big improvement on $f_{a3}^{ZZ} > 0.28$ exclusion from H→VV alone!



scalar → pseudo scalar

Submitted to PLB in Feb.

HVV anomalous couplings

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

$$+ \mathrm{a}_2 \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \mathrm{a}_3 \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ Any anomalous coupling can be described with an effective onshell cross sectional fraction and a phase

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

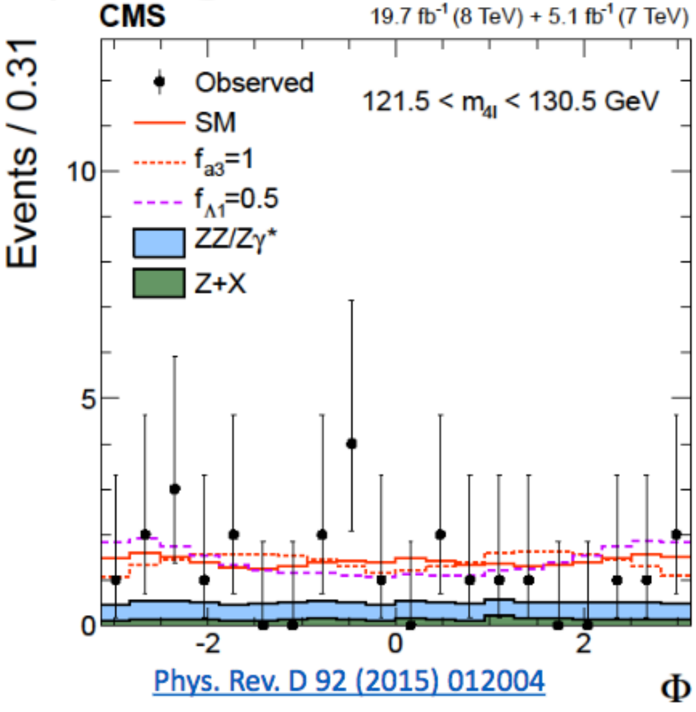
→ $f_{\Lambda Q}$ observable only from offshell, others measurable from either onshell or offshell

$$f_{\Lambda Q} = \frac{m_{\mathrm{H}}^4/\Lambda_Q^4}{|a_1|^2 + m_{\mathrm{H}}^4/\Lambda_Q^4}$$

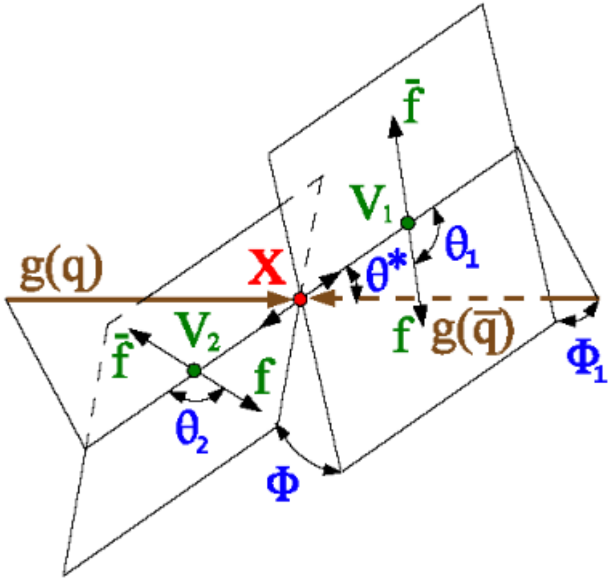
In $4l$, use discriminants based on MELA from MCFM/JHUGen:

$$D_{A\ vs\ B} = \frac{P_A}{P_A + P_B}$$

$$D_{A-B\ int.} = \frac{P_{A+B} - P_A - P_B}{P_A + P_B}$$



Phys. Rev. D 92 (2015) 012004



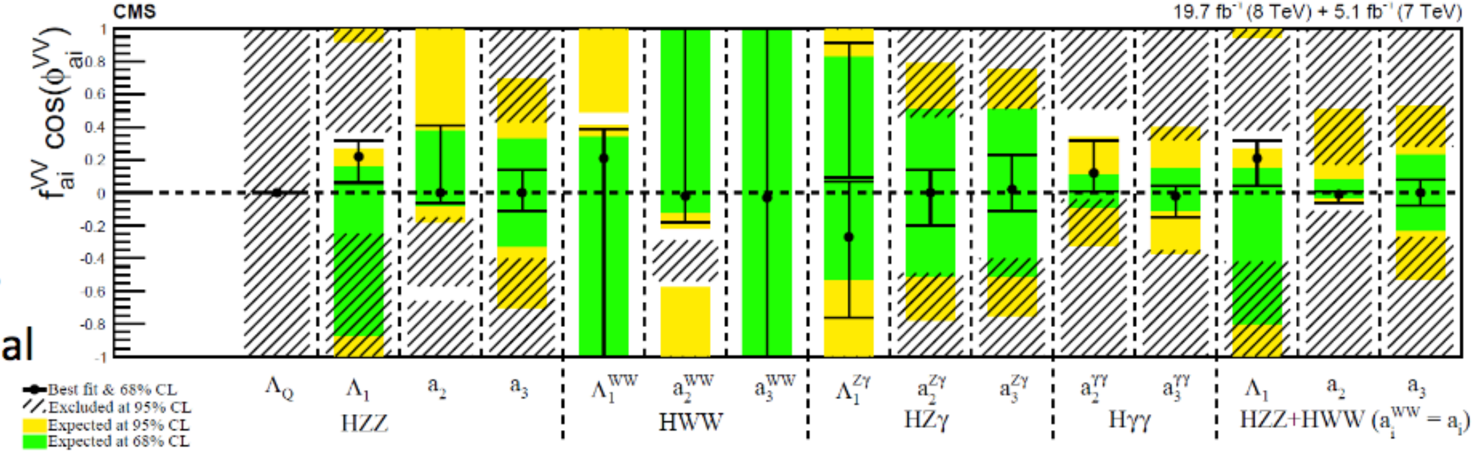
Run I: Anomalous couplings combination

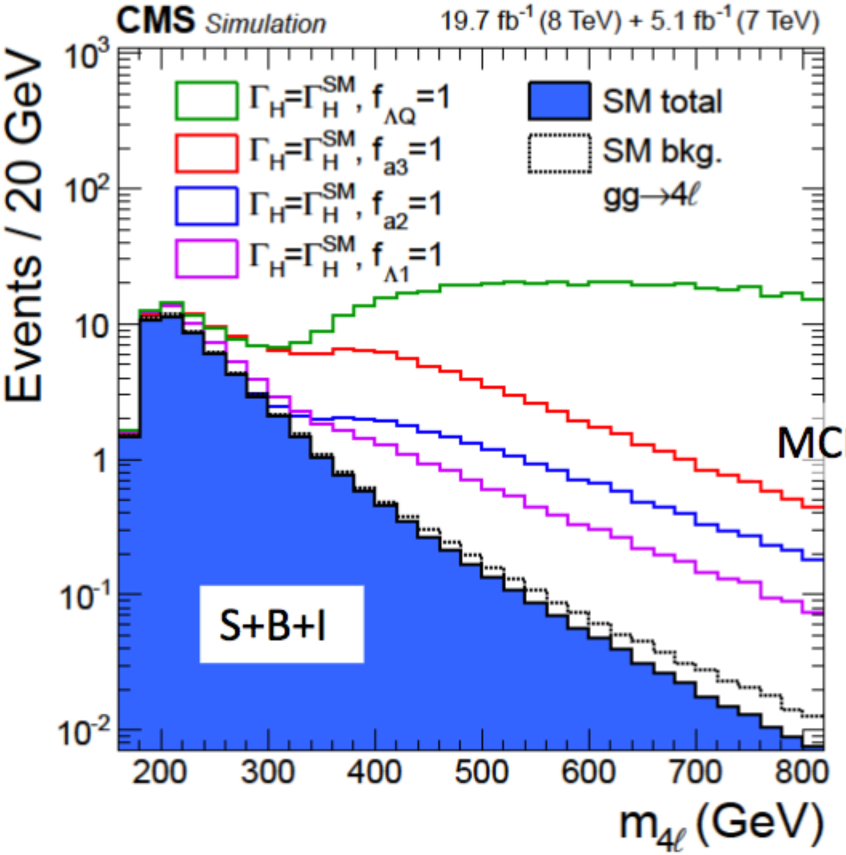
Phys. Rev. D 92 (2015) 012004

$4l + WW \rightarrow 2l2\nu \rightarrow$

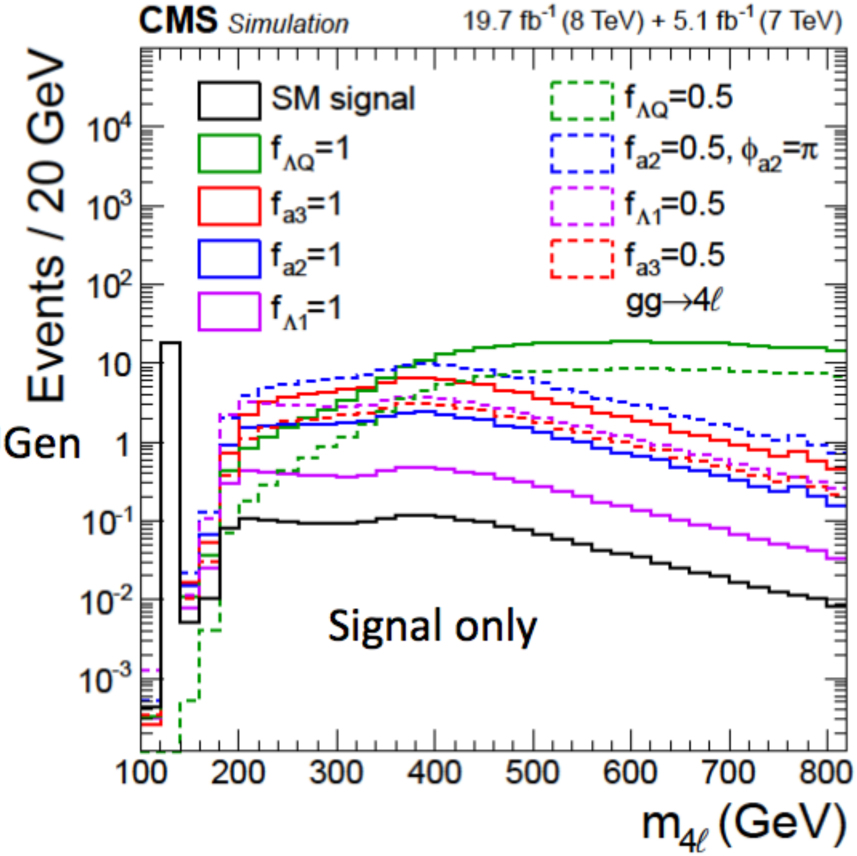
Phys. Rev. D 92 (2015) 072010

Offshell enhanced for the same onshell signal strength ↓

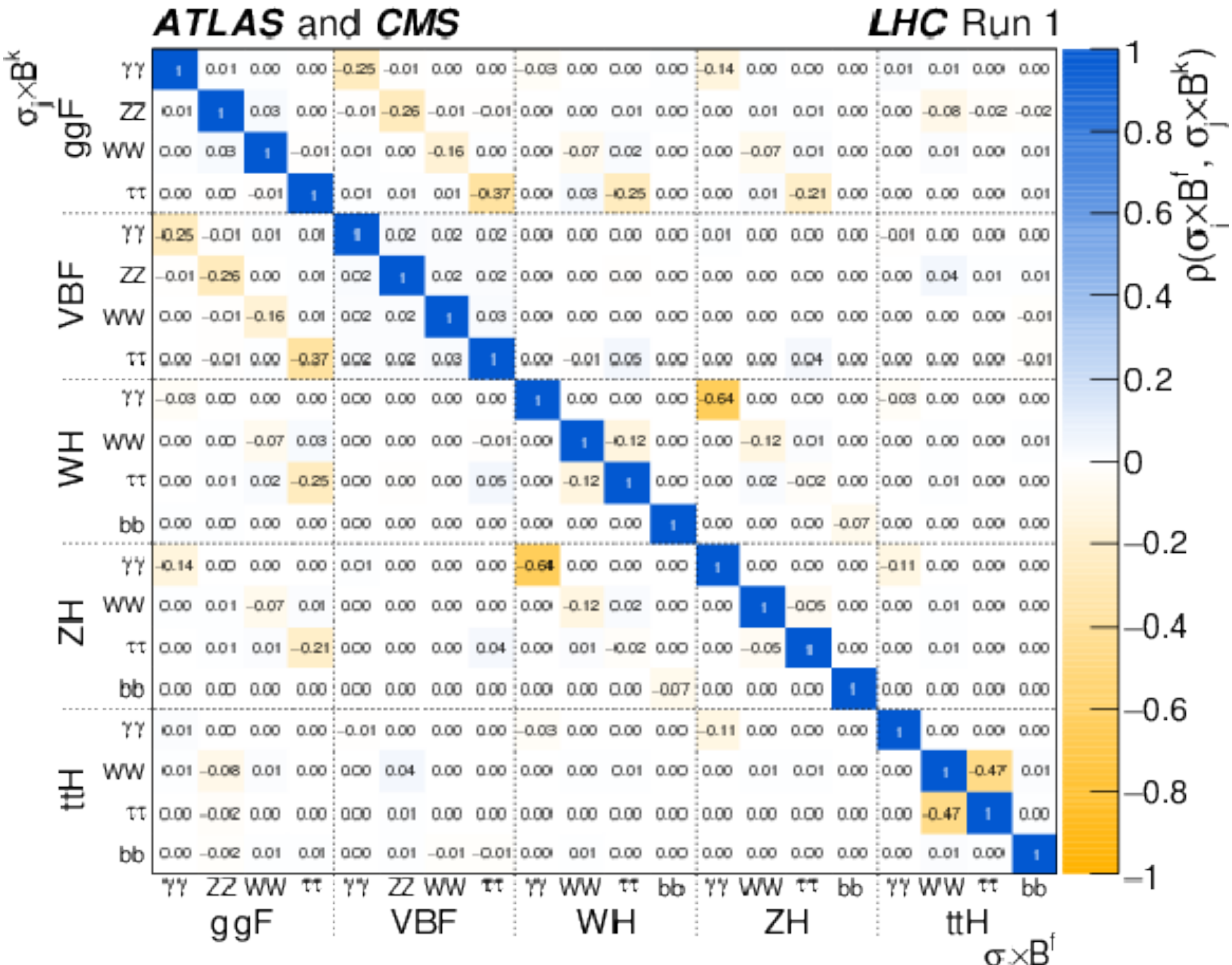




Using MCFM/JHUGen

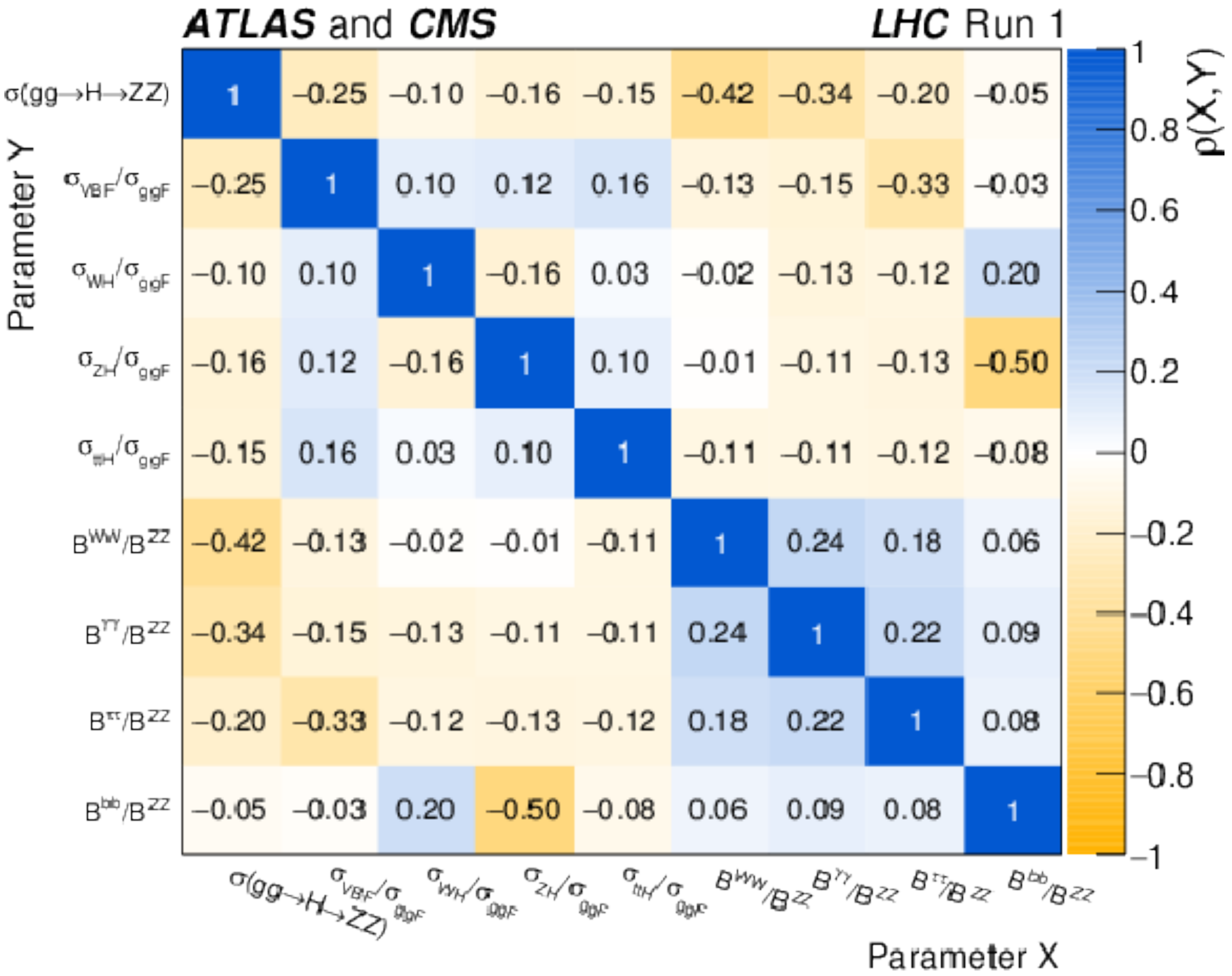


Correlation Matrix



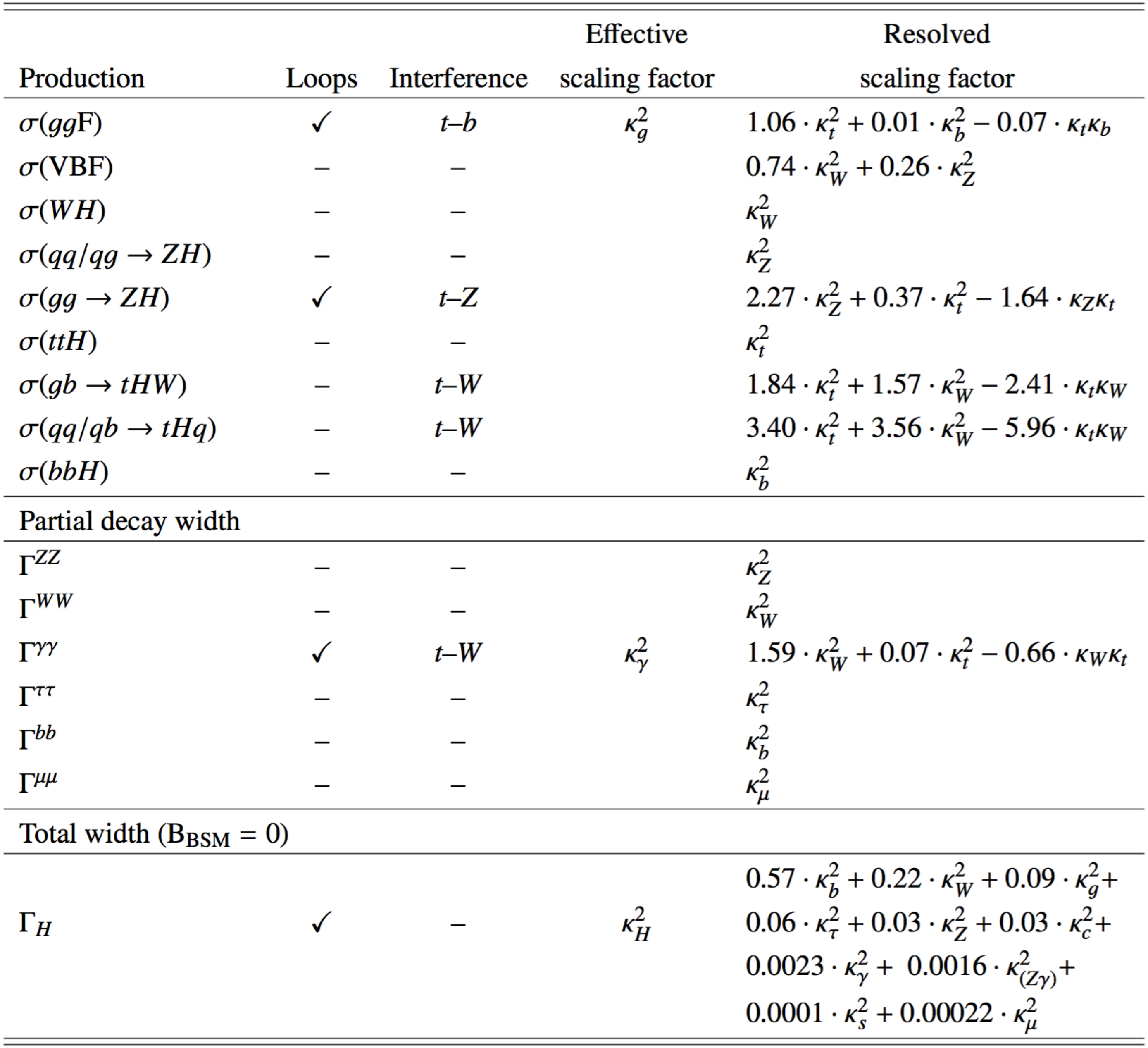
		ggF				VBF				WH				ZH				ttH			
		γγ	ZZ	WW	ττ	γγ	ZZ	WW	ττ	γγ	WW	ττ	bb	γγ	WW	ττ	bb	γγ	WW	ττ	bb
ggF	γγ	1	0.01	0.00	0.00	−0.25	−0.01	0.00	0.00	−0.03	0.00	0.00	0.00	−0.14	0.00	0.00	0.00	0.01	0.01	0.00	0.00
	ZZ	0.01	1	0.03	0.00	−0.01	−0.26	−0.01	−0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	−0.08	−0.02	−0.02
	WW	0.00	0.03	1	−0.01	0.01	0.00	−0.16	0.00	0.00	−0.07	0.02	0.00	0.00	−0.07	0.01	0.00	0.00	0.01	0.00	0.01
	ττ	0.00	0.00	−0.01	1	0.01	0.01	0.01	−0.37	0.00	0.03	−0.25	0.00	0.00	0.01	−0.21	0.00	0.00	0.00	0.00	0.01
VBF	γγ	−0.25	−0.01	0.01	0.01	1	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	−0.01	0.00	0.00	0.00
	ZZ	−0.01	−0.26	0.00	0.01	0.02	1	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01
	WW	0.00	−0.01	−0.16	0.01	0.02	0.02	1	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.01
	ττ	0.00	−0.01	0.00	−0.37	0.02	0.02	0.03	1	0.00	−0.01	0.05	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	−0.01
WH	γγ	−0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.64	0.00	0.00	0.00	−0.03	0.00	0.00	0.00
	WW	0.00	0.00	−0.07	0.03	0.00	0.00	0.00	−0.01	0.00	1	−0.12	0.00	0.00	−0.12	0.01	0.00	0.00	0.00	0.00	0.01
	ττ	0.00	0.01	0.02	−0.25	0.00	0.00	0.00	0.05	0.00	−0.12	1	0.00	0.00	0.02	−0.02	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.07	0.00	0.00	0.00	0.00
ZH	γγ	−0.14	0.00	0.00	0.00	0.01	0.00	0.00	0.00	−0.64	0.00	0.00	0.00	1	0.00	0.00	0.00	−0.11	0.00	0.00	0.00
	WW	0.00	0.01	−0.07	0.01	0.00	0.00	0.00	0.00	0.00	−0.12	0.02	0.00	0.00	1	−0.05	0.00	0.00	0.01	0.00	0.00
	ττ	0.00	0.01	0.01	−0.21	0.00	0.00	0.00	0.04	0.00	0.01	−0.02	0.00	0.00	−0.05	1	0.00	0.00	0.01	0.00	0.00
	bb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.07	0.00	0.00	0.00	1	0.00	0.00	0.00	0.00
ttH	γγ	0.01	0.00	0.00	0.00	−0.01	0.00	0.00	0.00	−0.03	0.00	0.00	0.00	−0.11	0.00	0.00	0.00	1	0.00	0.00	0.00
	WW	0.01	−0.08	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	1	−0.47	0.01
	ττ	0.00	−0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.47	1	0.00
	bb	0.00	−0.02	0.01	0.01	0.00	0.01	−0.01	−0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	1

Correlation Matrix



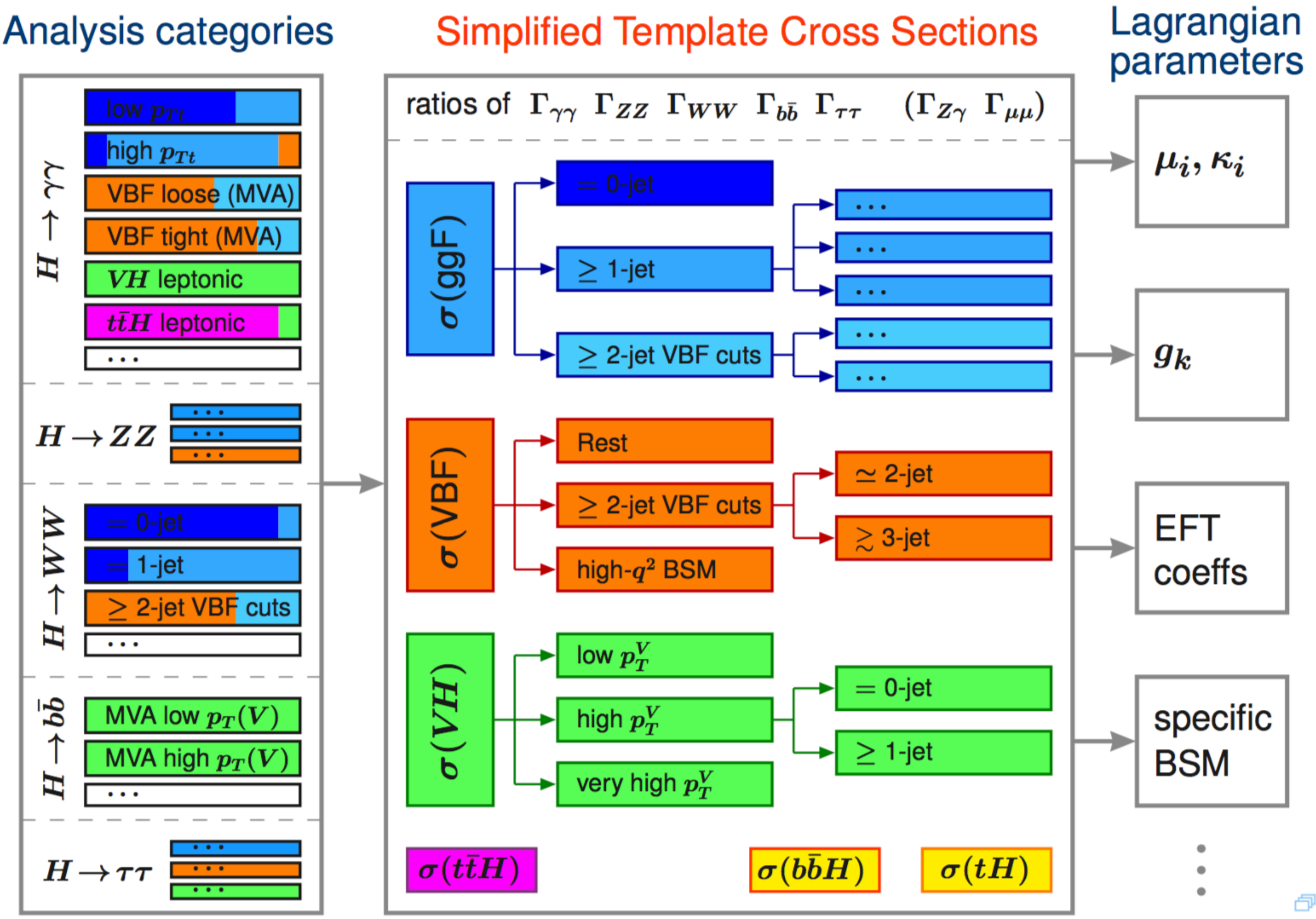
Parameter Y \ Parameter X	$\sigma(gg\to H\to ZZ)$	$\sigma_{VBF}/\sigma_{ggF}$	σ_{WH}/σ_{ggF}	σ_{ZH}/σ_{ggF}	$\sigma_{ttH}/\sigma_{ggF}$	B^{WW}/B^{ZZ}	$B^{\gamma\gamma}/B^{ZZ}$	$B^{\tau\tau}/B^{ZZ}$	B^{bb}/B^{ZZ}
$\sigma(gg\to H\to ZZ)$	1	−0.25	−0.10	−0.16	−0.15	−0.42	−0.34	−0.20	−0.05
$\sigma_{VBF}/\sigma_{ggF}$	−0.25	1	0.10	0.12	0.16	−0.13	−0.15	−0.33	−0.03
σ_{WH}/σ_{ggF}	−0.10	0.10	1	−0.16	0.03	−0.02	−0.13	−0.12	0.20
σ_{ZH}/σ_{ggF}	−0.16	0.12	−0.16	1	0.10	−0.01	−0.11	−0.13	−0.50
$\sigma_{ttH}/\sigma_{ggF}$	−0.15	0.16	0.03	0.10	1	−0.11	−0.11	−0.12	−0.08
B^{WW}/B^{ZZ}	−0.42	−0.13	−0.02	−0.01	−0.11	1	0.24	0.18	0.06
$B^{\gamma\gamma}/B^{ZZ}$	−0.34	−0.15	−0.13	−0.11	−0.11	0.24	1	0.22	0.09
$B^{\tau\tau}/B^{ZZ}$	−0.20	−0.33	−0.12	−0.13	−0.12	0.18	0.22	1	0.08
B^{bb}/B^{ZZ}	−0.05	−0.03	0.20	−0.50	−0.08	0.06	0.09	0.08	1

Coupling Parameterization



Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\mathrm{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Simplified Template Cross Section Framework.



Analysis categories

$H\to\gamma\gamma$
- low p_{Tt}
- high p_{Tt}
- VBF loose (MVA)
- VBF tight (MVA)
- VH leptonic
- $t\bar{t}H$ leptonic
- $\cdots$

$H\to ZZ$
- $\cdots$
- $\cdots$
- $\cdots$

$H\to WW$
- $= 0$-jet
- $= 1$-jet
- ≥ 2-jet VBF cuts
- $\cdots$

$H\to b\bar{b}$
- MVA low $p_T(V)$
- MVA high $p_T(V)$
- $\cdots$

$H\to\tau\tau$
- $\cdots$
- $\cdots$
- $\cdots$

Simplified Template Cross Sections

ratios of $\Gamma_{\gamma\gamma}$ Γ_{ZZ} Γ_{WW} $\Gamma_{b\bar{b}}$ $\Gamma_{\tau\tau}$ $(\Gamma_{Z\gamma}$ $\Gamma_{\mu\mu})$

$\sigma(\text{ggF})$
- $= 0$-jet
- ≥ 1-jet
  - $\cdots$
  - $\cdots$
  - $\cdots$
- ≥ 2-jet VBF cuts
  - $\cdots$
  - $\cdots$

$\sigma(\text{VBF})$
- Rest
- ≥ 2-jet VBF cuts
  - $\simeq 2$-jet
  - $\gtrsim 3$-jet
- high-q^2 BSM

$\sigma(VH)$
- low p_T^V
- high p_T^V
  - $= 0$-jet
  - ≥ 1-jet
- very high p_T^V

$\sigma(t\bar{t}H)$ $\sigma(b\bar{b}H)$ $\sigma(tH)$

Lagrangian parameters
- μ_i, κ_i
- g_k
- EFT coeffs
- specific BSM
- $\vdots$

Advantages of FXS and STXS

Fiducial: Optimized for maximal theory independence	Simplified: Maximize sensitivity while reducing theory dependence
- Minimize acceptance corrections	- Allow larger acceptance corrections
- Simple (rectangular) signal cuts	- Allow event categories, MVAs, ...
- “Exact” fiducial volume	- Abstracted/simplified fiducial volumes
- Fiducial in Higgs decay	- Inclusive in Higgs decay
- Targeted object definitions	- Common idealized object definitions
Agnostic to production modes	Xsec split by production mode
(Single-)differential distributions (overlapping events)	Xsec split into mutually exclusive regions of phase space
Only $H \to \gamma\gamma, ZZ, (WW)$ (by default no combination of channels)	Explicitly designed for combination of all decay channels