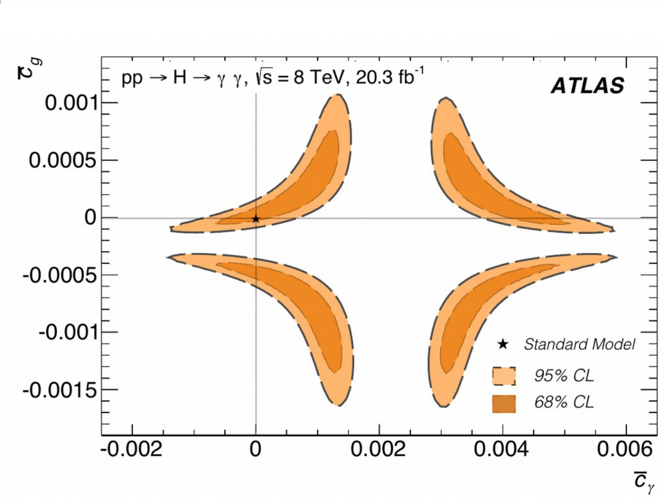
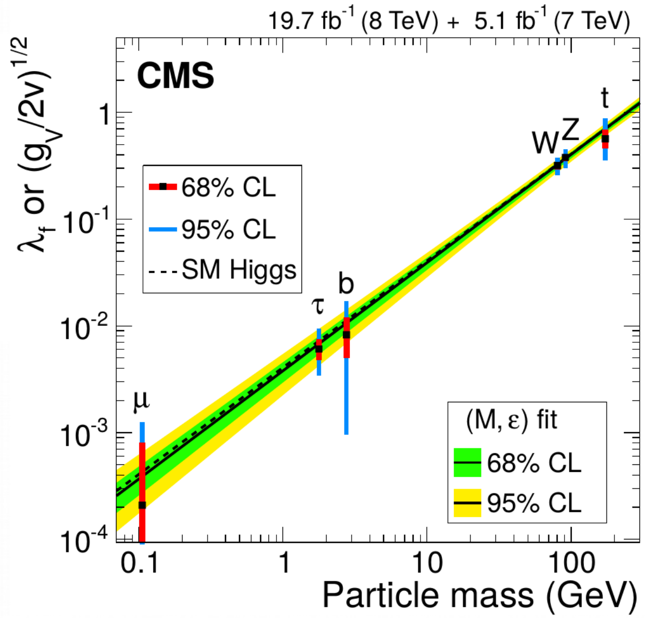
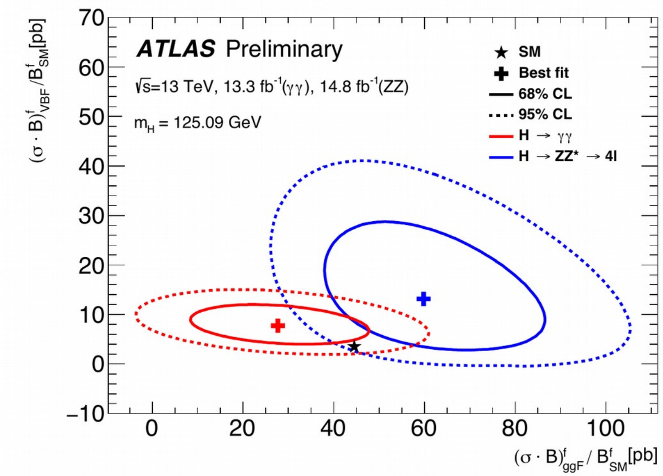






Higgs Couplings Measurements in ATLAS and CMS for Run 2 and Beyond

(SMEFT, STXS, POs and all that)

Nicolas Berger (LAPP Annecy)

Reporting results from the ATLAS and CMS collaborations

GDR TeraScale Paris, 25/11/2016

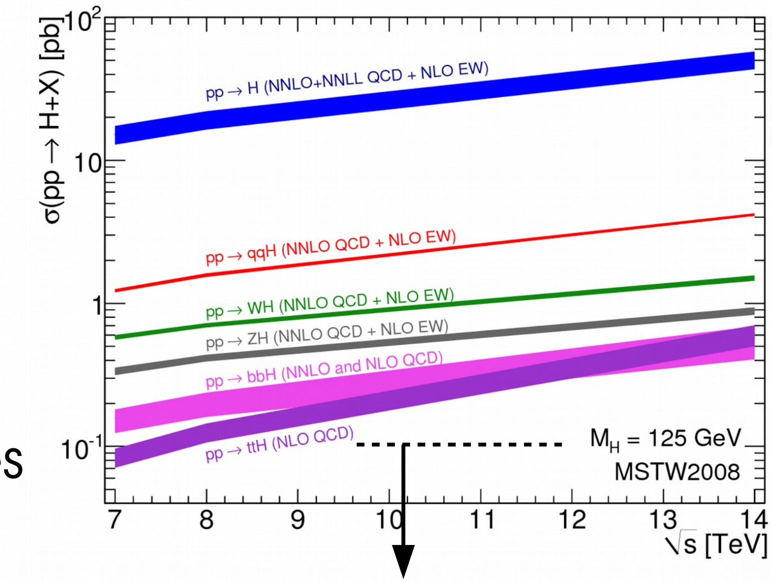
Introduction

- **Rich experimental program** for studies of the Higgs boson at m_H=125 GeV
  - Many **production** and **decay** modes
  - Many observables: **event yields**, Higgs **kinematics**, **associated production** properties

- **Higher precision in Run 2**
  - Higher integrated luminosity
  - Higher cross-sections at √s = 13 TeV
  - **How to report and interpret the measurements ?**

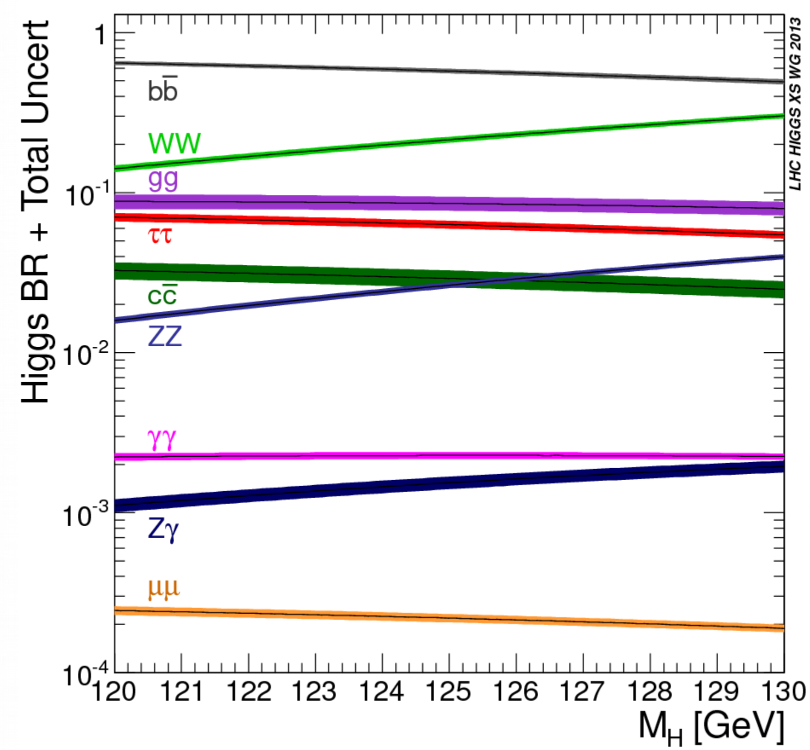
- **Contents:**
  - Run 1 & Run 2 measurements
  - New interpretation/reporting frameworks in Run 2

Production



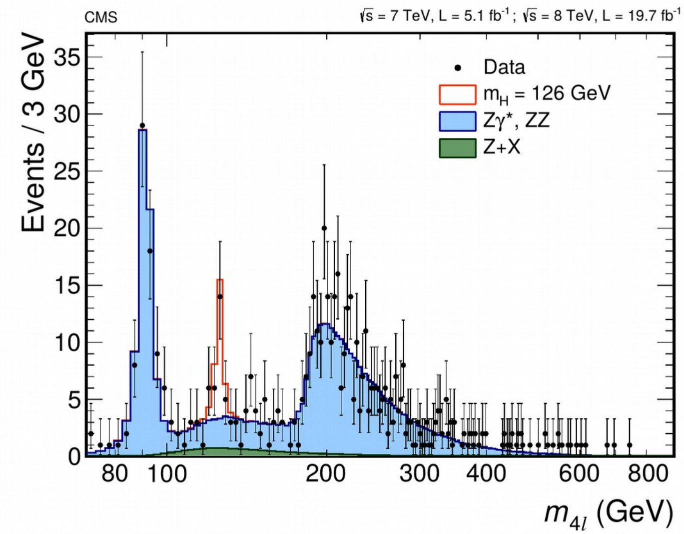
1000 events in 10 fb^{-1}

Decay

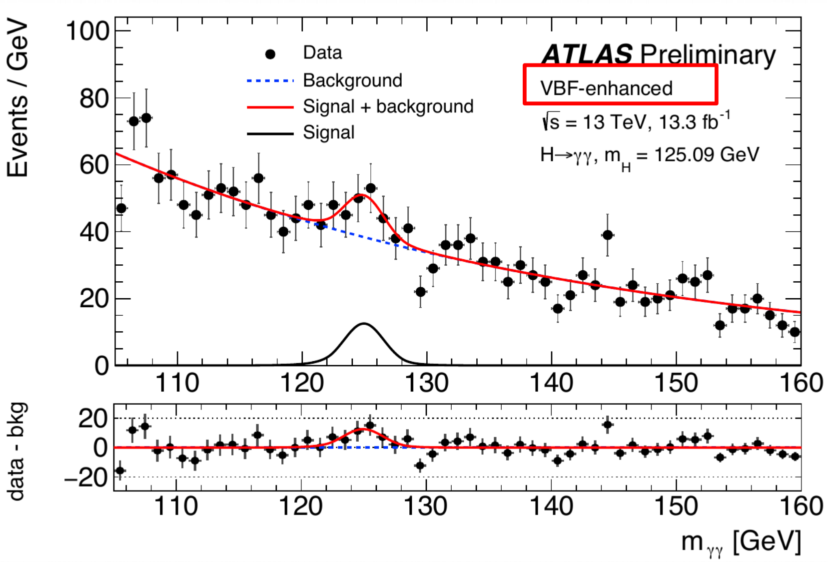


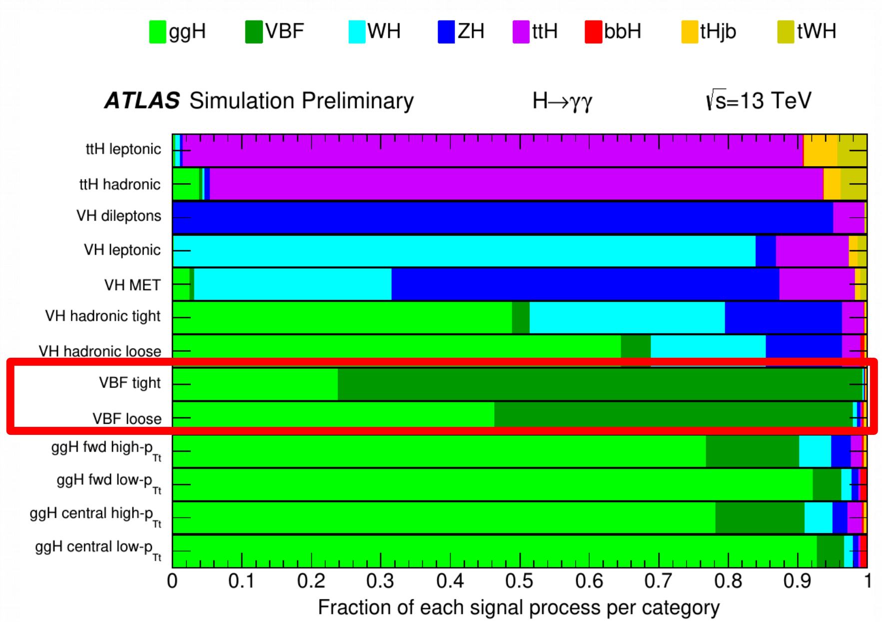
"Typical" Higgs Couplings Measurement

- **Measure Higgs event yields:**
  - separate Higgs signal from bkg usually by fitting an invariant mass spectrum
  - Report production (σ x BR)



- **Measure yields in particular prod. modes/kinematic regions**
  - Select regions enriched in the target process (using BDTs, etc.)
  - Extract target event yields using similar methods as above



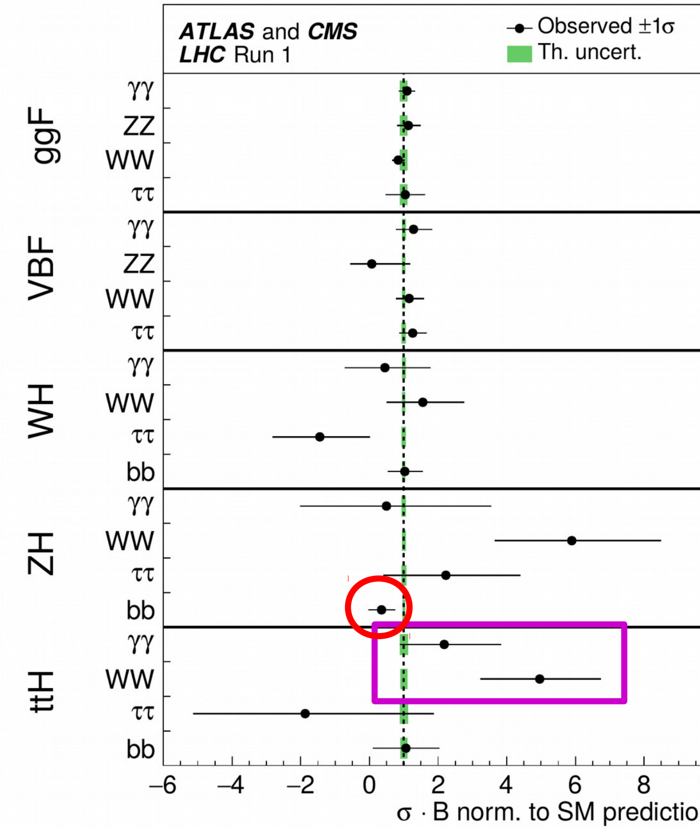


Couplings Measurements: Run 1 and Run 2

- **"Couplings"** in Run 1: mainly **event yields** ⇒ **($\sigma \cdot B$)** in all available **production** and **decay** modes

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
ggF	**Run 1** ATLAS CMS **Run 2** ATLAS CMS(*) (*) no VH	**Run 1** ATLAS CMS **Run 2** ATLAS CMS	**Run 1** ATLAS CMS **Run 2** ATLAS(*) CMS (*)no ggF	Boosted ggF only	Background too large
VBF				**Run 1** ATLAS: ggF+VBF and VH CMS	**Run 1** ATLAS, CMS **Run 2** ATLAS, CMS
VH					Run 1: ATLAS,CMS Run 2: ATLAS
ttH		ttH "Multilepton" Analysis Run 1: ATLAS, CMS Run2 : ATLAS, CMS			Run 1: ATLAS, CMS Run 2: ATLAS, CMS
Comb	Run 1: ATLAS+CMS Run 2:ATLAS				

ATLAS+CMS Run 1 Combination



- **Overall agreement with SM**
- **5.5σ for H→ττ !**
- **$\sigma_{ttH}/\sigma_{ggF}$: 3.0σ above SM**
- **B_{bb}/B_{ZZ} : 2.5σ below SM**

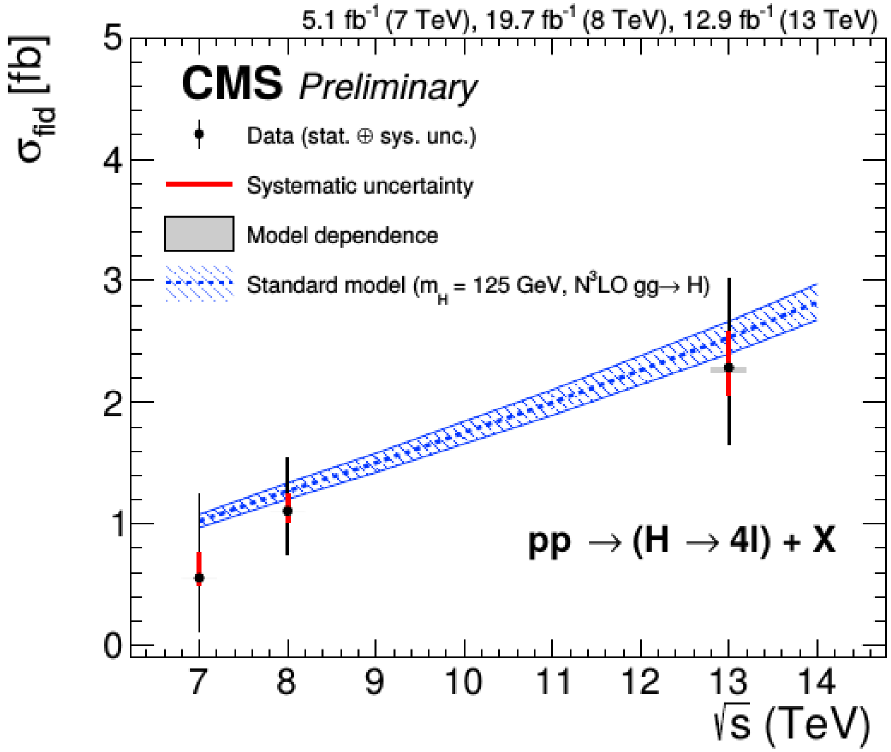
Fiducial Cross-Section Measurements

Unfold cross-section to truth-level
fiducial region matching reco acceptance:

- Detector **acceptance, kinematic cuts**
- Particle-level **isolation**

Slightly different definitions in CMS and ATLAS

Perform in **bins** of an event variable
⇒ **Differential cross-section** measurements



		SM Prediction	Measurement at √s=13 TeV
H→γγ	ATLAS	62.8 ± 3.9 fb	σ_{fid} = 43.2 ± 14.9 (stat.) ± 4.9 (syst.) fb
	VBF-like	2.04 ± 0.13 fb	σ_{fid} = 4.0 ± 1.4 (stat.) ± 0.7 (syst.) fb
	CMS	73.8 ± 3.8 fb	$\sigma_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\,\text{fb}$
H→ZZ	ATLAS	3.07 ± 0.23 fb	$\sigma_{fid} = 4.54^{+1.02}_{-0.90}$ fb
	CMS	2.53 ± 0.13 fb	$\sigma_{fid} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\,\text{fb}$

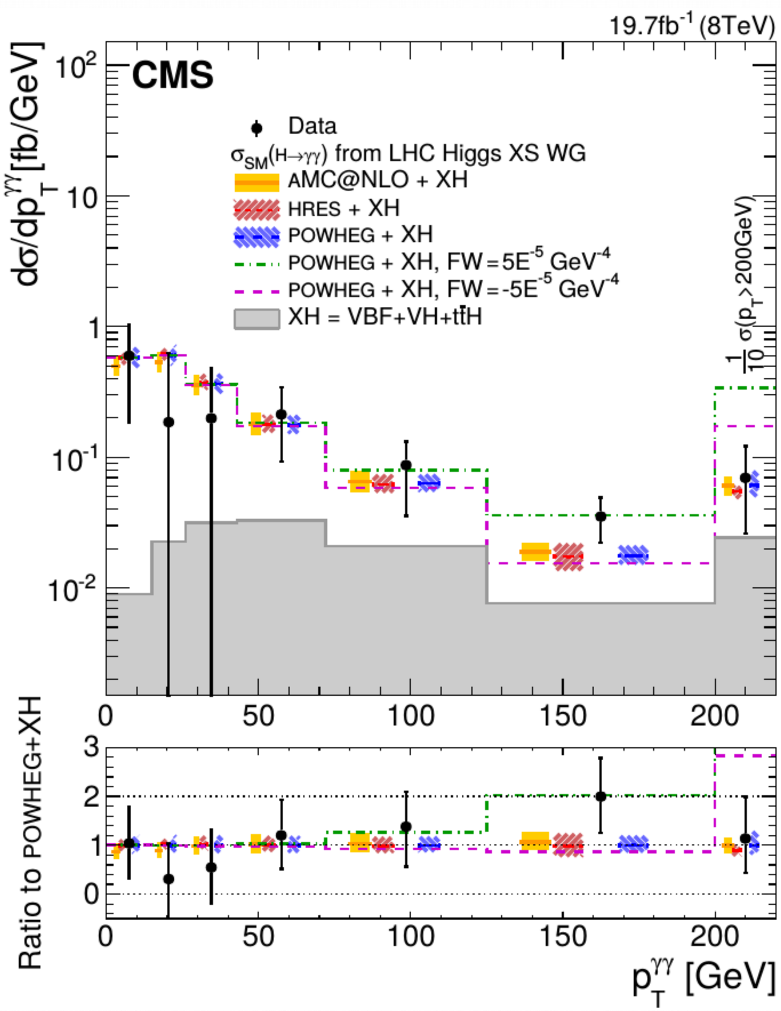
Run 1 Differential Cross-Sections

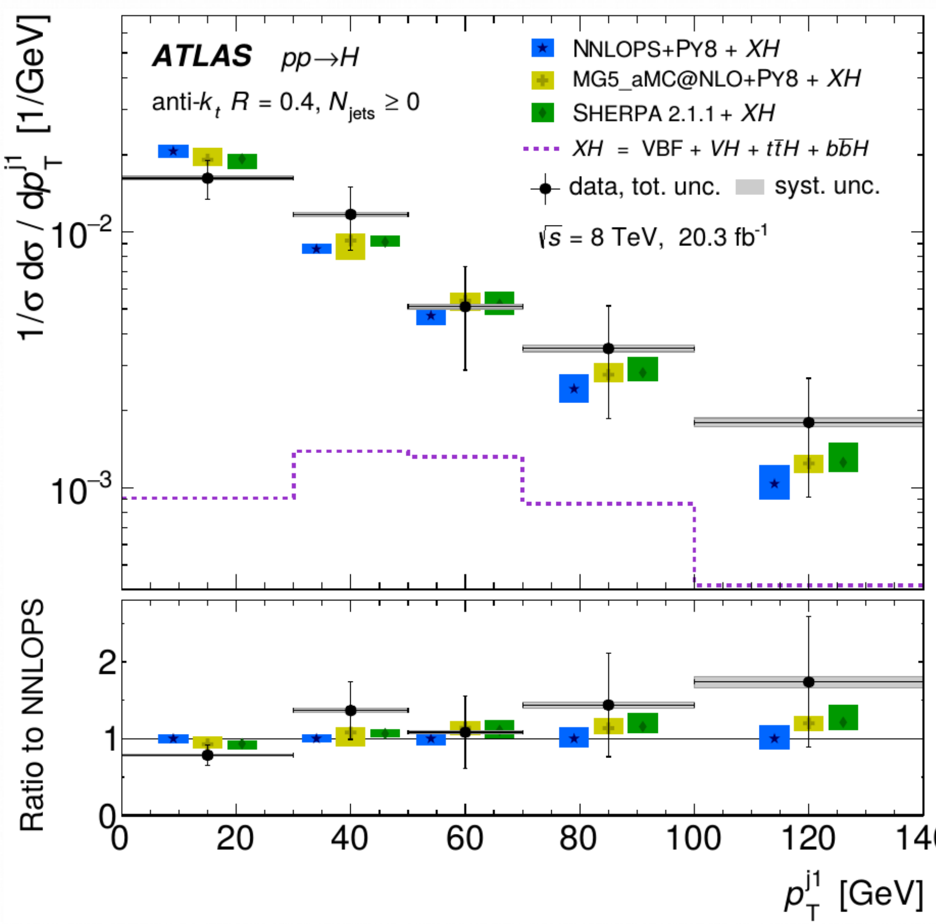
Results at √s = 8 TeV from:

- **H→γγ** (ATLAS, CMS)
- **H→ZZ** (ATLAS, CMS)
- **H→γγ** & **H→ZZ** Combination (ATLAS)
- **H→WW** (ATLAS)

Many variables:

- **Higgs**: p_T^H, $|y^H|$, $|\cos\theta^*|$
- **Jets**: N_{jets}, p_T^{j1}, $|\eta^{j1}|$, p_T^{j2}, Δy_{jj}, $\Delta\phi_{jj}$, m_{jj}
- **Event**: H_T, $\Delta\phi_{\gamma\gamma,jj}$
- ...



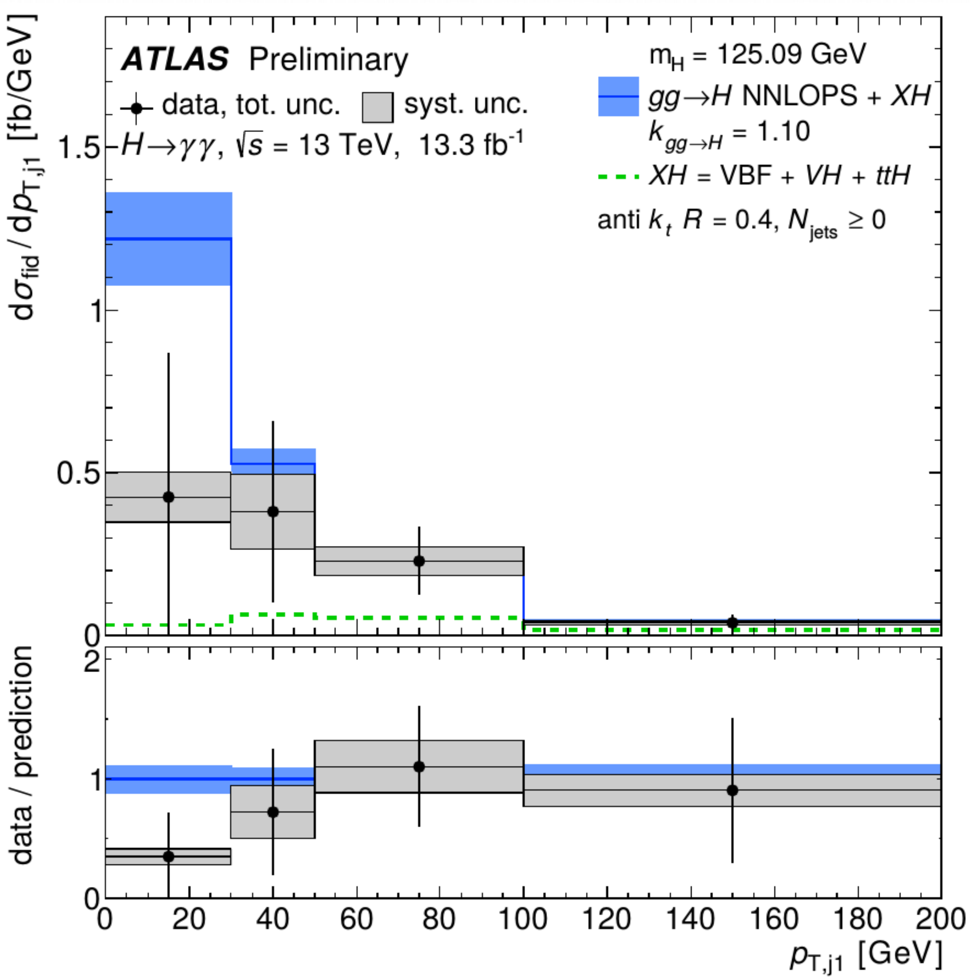


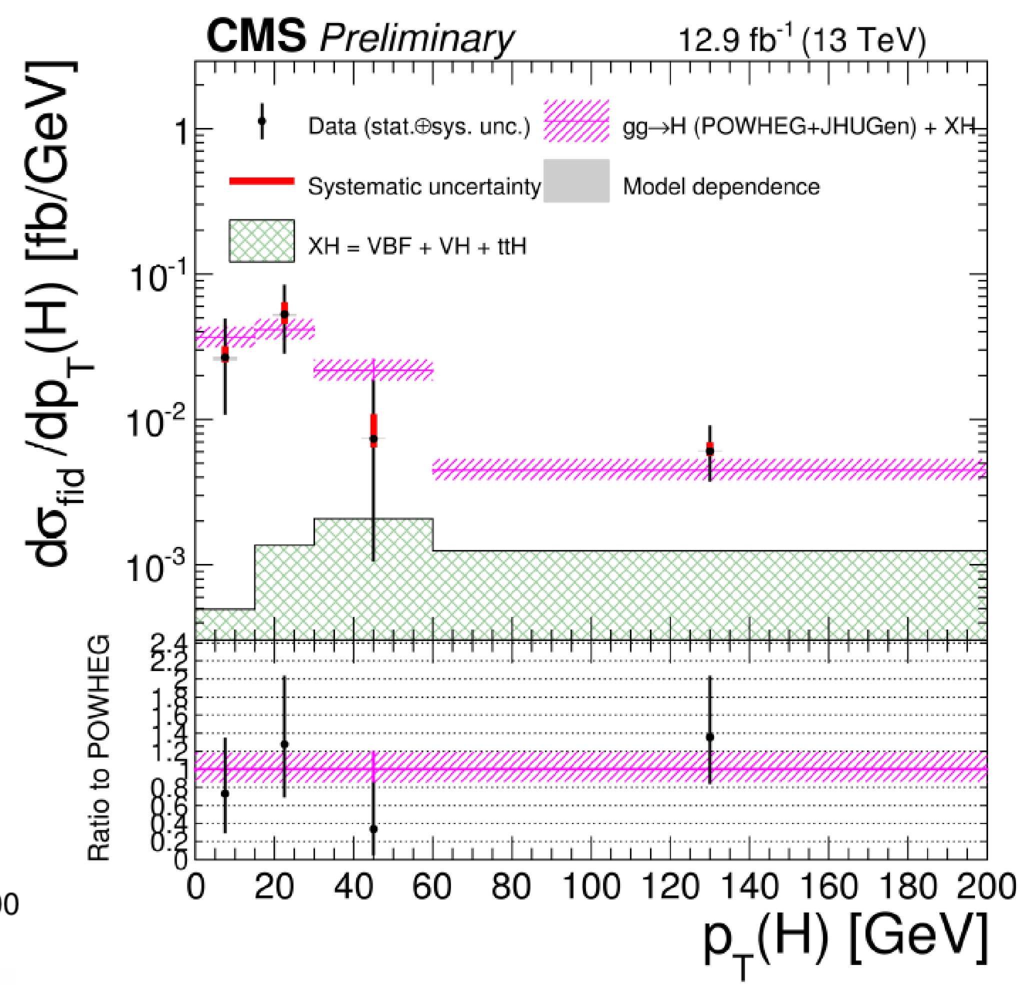
Run 2 Differential Measurements

Preliminary results at √s = 13 TeV from

- **H→γγ** (ATLAS)
- **H→ZZ** (CMS)

Reaching similar precision to Run 1, still statistics-dominated in all cases





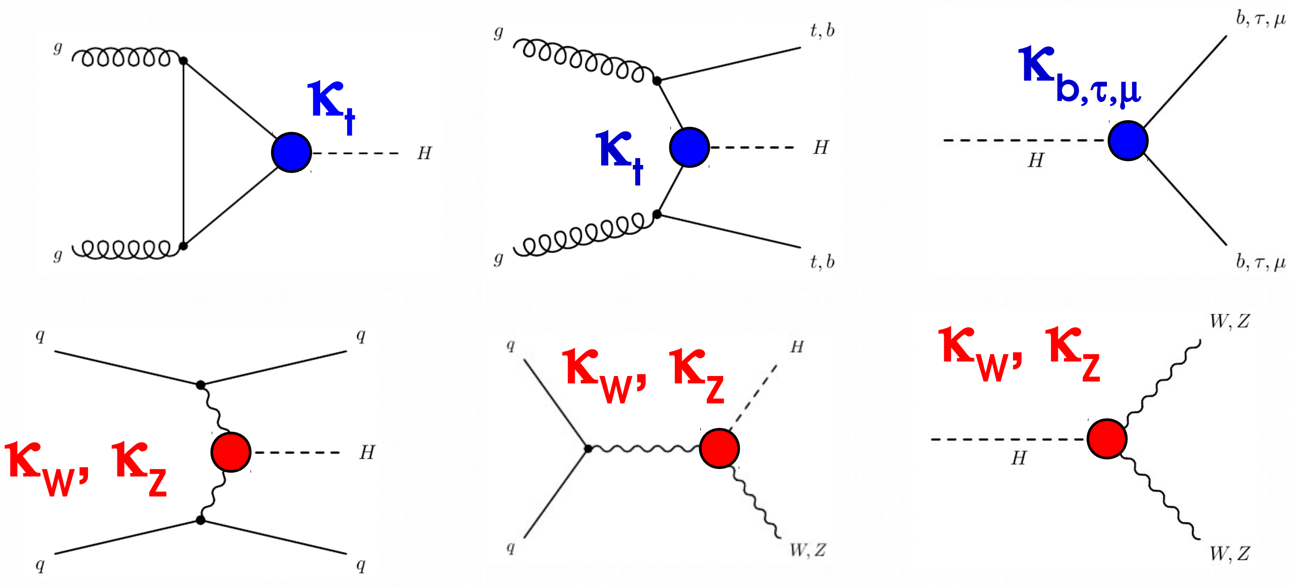
κ Framework

JHEP 08 (2016) 045

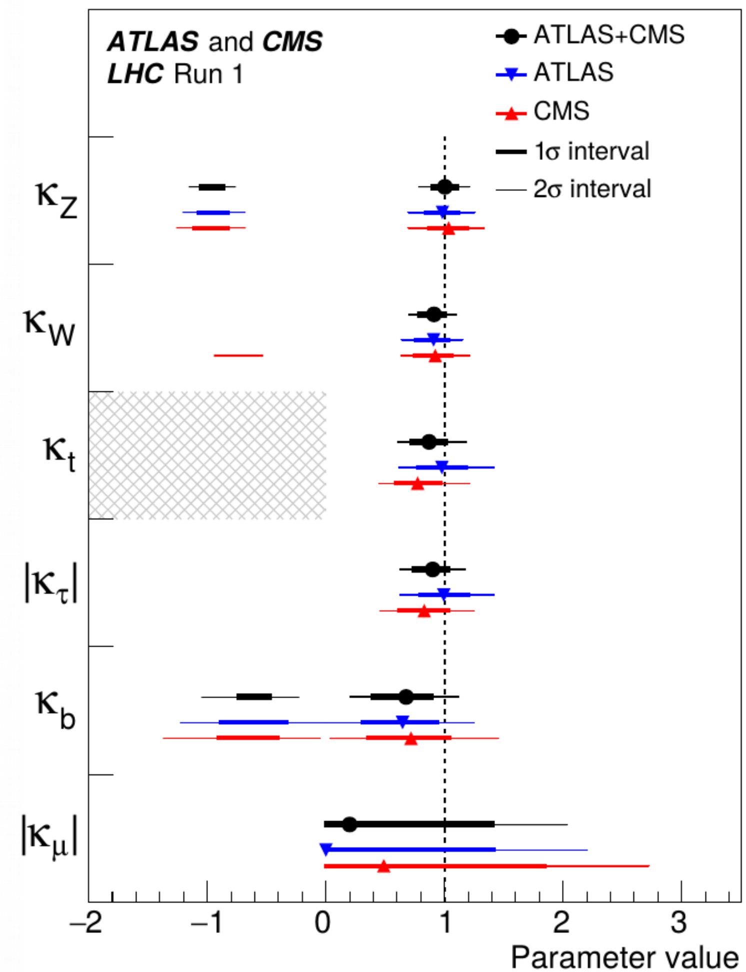
YR3 Section 10.2

In Run 1, Higgs couplings interpreted within the "**κ-framework**":

- κ_x modifiers for **all Hxx vertices**
  - also κ_g and κ_γ for effective **ggH** and **Hγγ** loops, κ_H for Higgs total width
- **"LO-inspired" scaling** for **i→H→f** (use the best available SM prediction for κ=1)



$$\sigma(i \rightarrow H)\cdot B(H \rightarrow f) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\left[\sigma_{SM}(i \rightarrow H)\cdot B_{SM}(H \rightarrow f)\right]$$



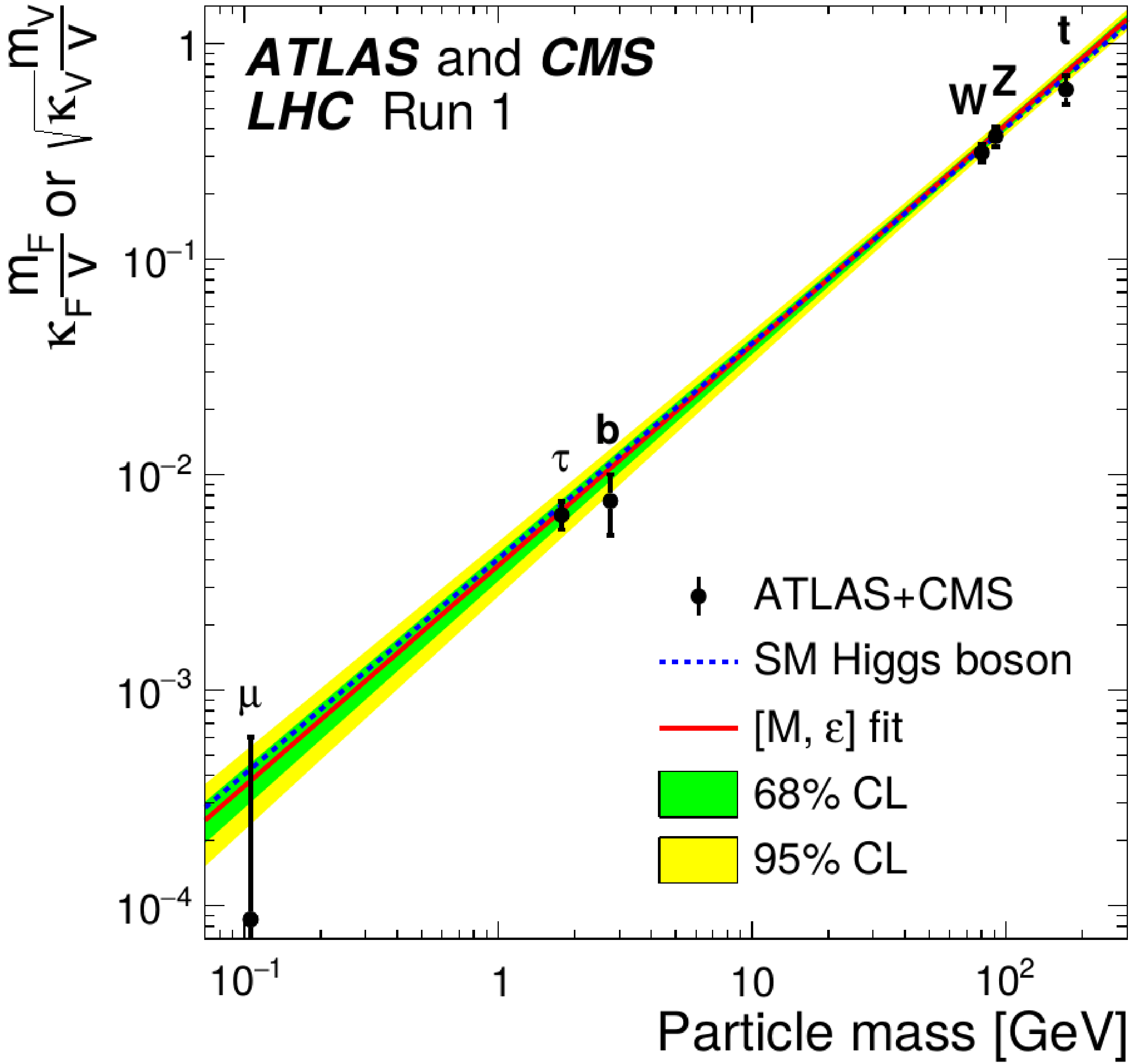
"Resolved loops" (no κ_g and κ_γ):

- Good agreement with all SM couplings
- slightly low κ_b

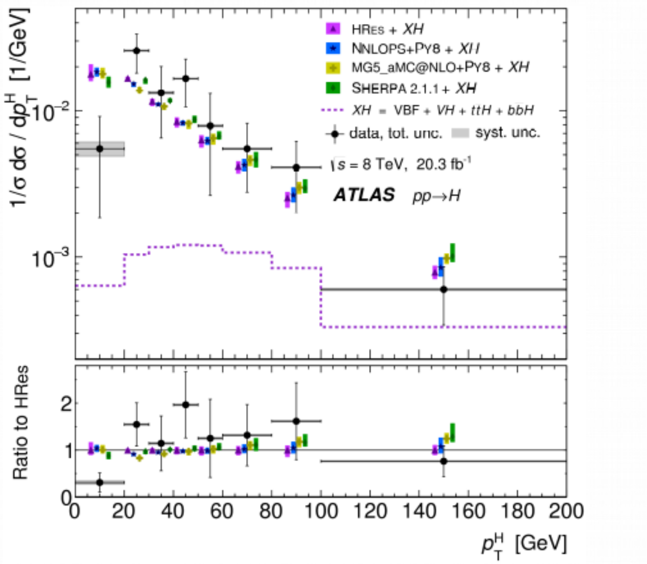
Same conclusion when including κ_g and κ_γ.

κ Framework "PR Plot"

JHEP 08 (2016) 045



Beyond the κ Framework



- **Pros**
  - Easy to implement
  - Well-defined **near the SM limit** $\kappa_x \rightarrow 1$
- **Cons**:
  - **Only well-defined at LO**
    - Scaling inspired by LO diagrams, cannot be systematically extended to higher orders
      - e.g. breaks gauge symmetries ⇒ Divergences
  - **Does not include interactions not already in the SM**
    - **CP-odd operators**
    - **Non-SM tensor structures**

      ⇒ e.g. **no freedom for shape deviations in differential measurements**

SMEFT

- SM scale ~ v = **246 GeV**, no BSM physics seen below **Λ ~ 1 TeV**
  ⇒ parameterize the BSM using an **EFT extension of the SM**

$$L = L_{SM}^{(d\leq 4)} + \boxed{\frac{1}{\Lambda^2}\sum_i c_i^{(d=6)} O_i^{(d=6)}} + \frac{1}{\Lambda^4}\sum_i c_i^{(d=8)} O_i^{(d=8)} + \ldots$$

- Usually(*) leading effect from **interference of d=6 and SM ~(v/Λ)²** and can **neglect d≥8** and $|c^{(d=6)}|^2$.

  ⇒ **Report experimental constraints on the c_i, compare to model predictions**
- Straightforward to extend to higher orders in SM couplings

- **Many operators**: **2499** for n_{gen}=3
  - For n_{gen}=1 (or MFV): "only" **59**
    - Operators **involving the Higgs boson** can be reduced to **17**.
- Many ways to define the operator basis on which to expand: **SILH** basis, **Warsaw** basis, **Higgs** basis etc.

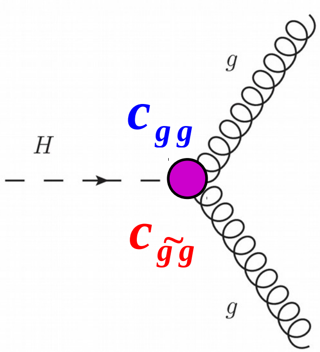
(*) Some restrictions may apply, see YR4 Section II.2.2 for details

A Bestiary of SMEFT Operators (1)

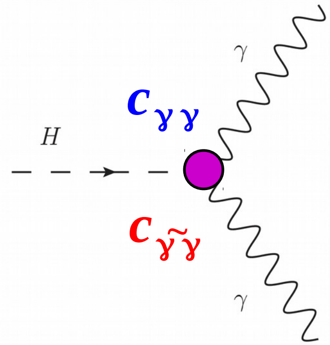
Using **Higgs Basis**, as defined in YR4, ignoring flavor (n_{gen}=1 or MFV)

→ **17 operators (10 CP-even + 7 CP-odd) involving the Higgs boson**

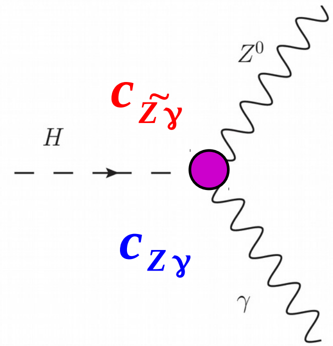
Tree-level ggH (κ_g)



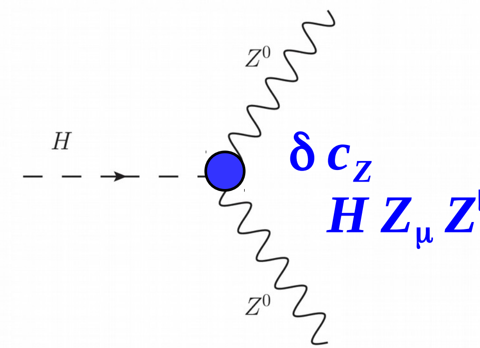
Tree-level Hγγ (κ_γ)



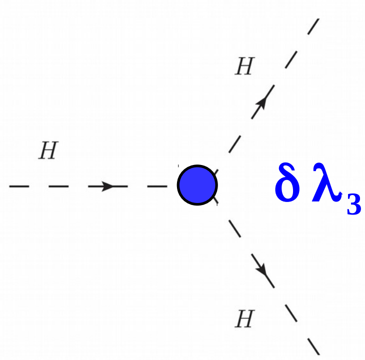
Tree-level HZγ



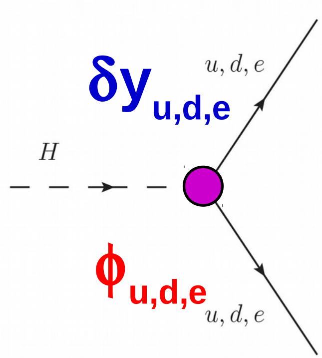
HZZ coupling modifier (κ_Z)



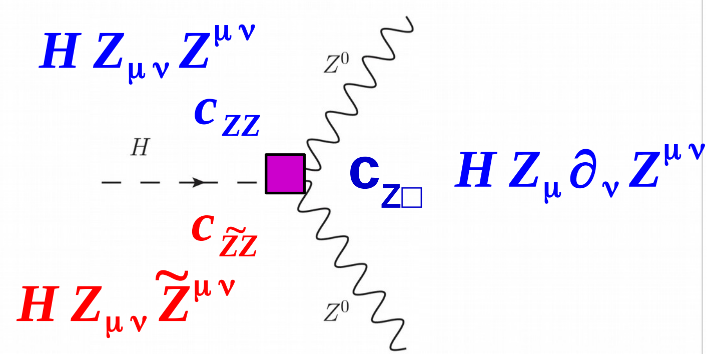
Modified H³ Coupling



Modified Yukawa coupling magnitudes (κ_f) and phases



Modified HZZ interaction with derivative couplings

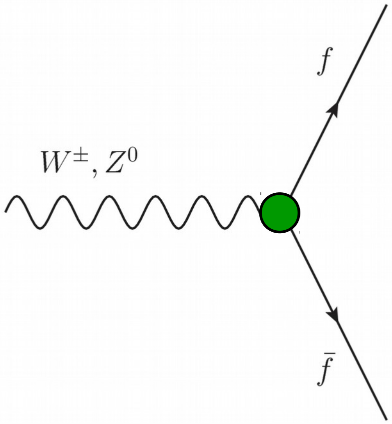


⇒ κ framework with effective (κ_g,κ_γ) + CP-odd couplings + modified HZZ structure

A Bestiary of SMEFT Operators (2)

YR4 Section II.2.1

→ **46** operators not involving the Higgs boson

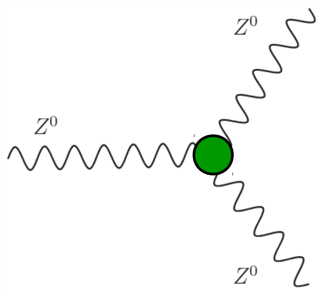


- **16 W,Z→ff couplings modifiers + W mass shift δm**

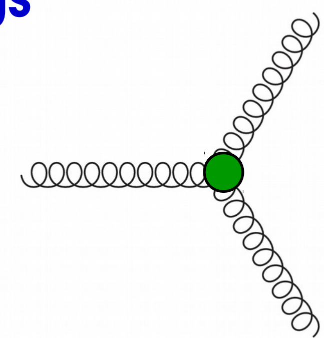
$$\delta m,\ [\delta g_L^{Ze}]_{ij},\ [\delta g_R^{Ze}]_{ij},\ [\delta g_L^{W\ell}]_{ij},\ [\delta g_L^{Zu}]_{ij},\ [\delta g_R^{Zu}]_{ij},\ [\delta g_L^{Zd}]_{ij},\ [\delta g_R^{Zd}]_{ij},\ [\delta g_R^{Wq}]_{ij},$$
$$[d_{Gu}]_{ij},\ [d_{Gd}]_{ij},\ [d_{Ae}]_{ij},\ [d_{Au}]_{ij},\ [d_{Ad}]_{ij},\ [d_{Ze}]_{ij},\ [d_{Zu}]_{ij},\ [d_{Zd}]_{ij}.$$

- **4 corrections to triple-Z and triple-g couplings**

$$\lambda_z,\ \tilde{\lambda}_z$$

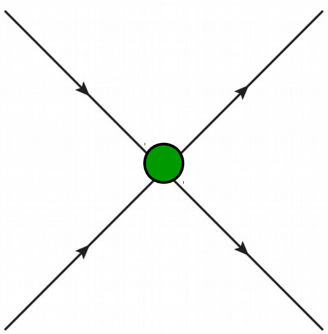


$$c_{3G},\ \tilde{c}_{3G}$$



- **25 four-fermion couplings**

$$c_{\ell\ell},\ c_{qq},\ c'_{qq},\ c_{\ell q},\ c'_{\ell q},\ c_{quqd},\ c'_{quqd},\ c_{\ell equ},\ c'_{\ell equ},\ c_{\ell edq},$$
$$c_{\ell e},\ c_{\ell u},\ c_{\ell d},\ c_{qe},\ c_{qu},\ c'_{qu},\ c_{qd},\ c'_{qd},\ c_{ee},\ c_{uu},\ c_{dd},\ c_{eu},\ c_{ed},\ c_{ud},\ c'_{ud}$$



Can be constrained using **precision EW** and **flavor** measurements
⇒ **Global SM fits are critical to fully constrain the SMEFT**
⇒ For **Higgs measurements**, can focus on the other 17 operators

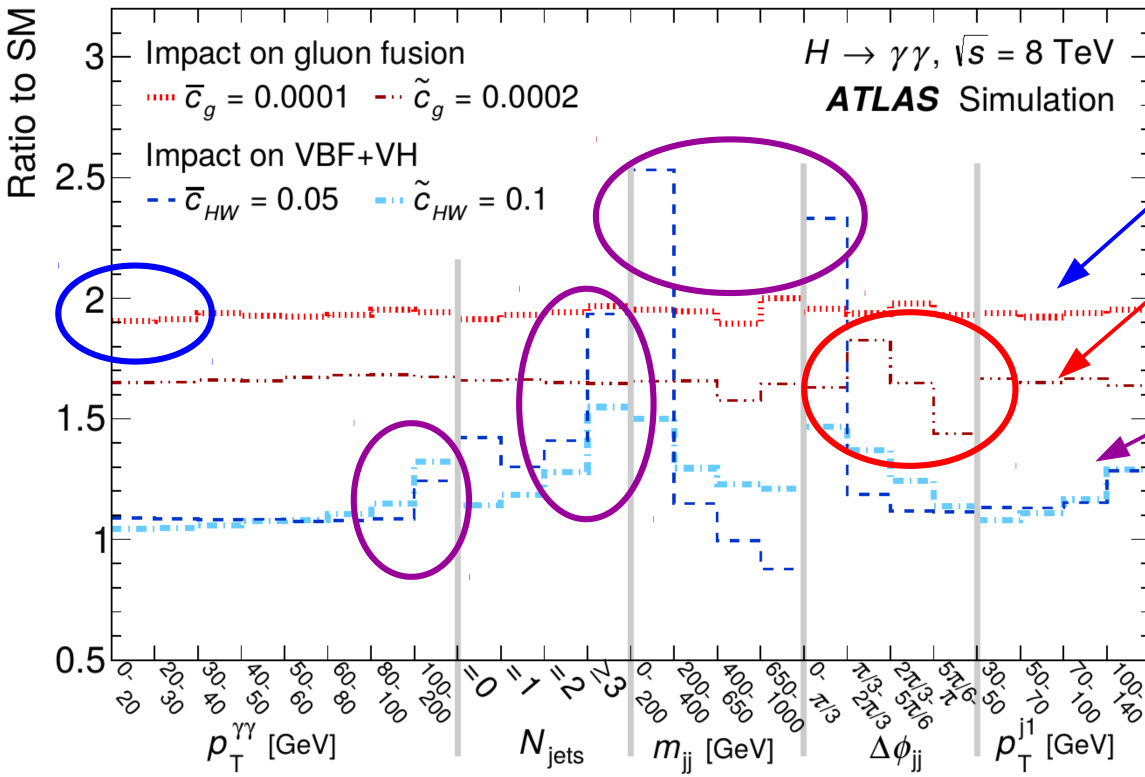
Effective Lagrangian Interpretation of $H\to\gamma\gamma$ Differential Results

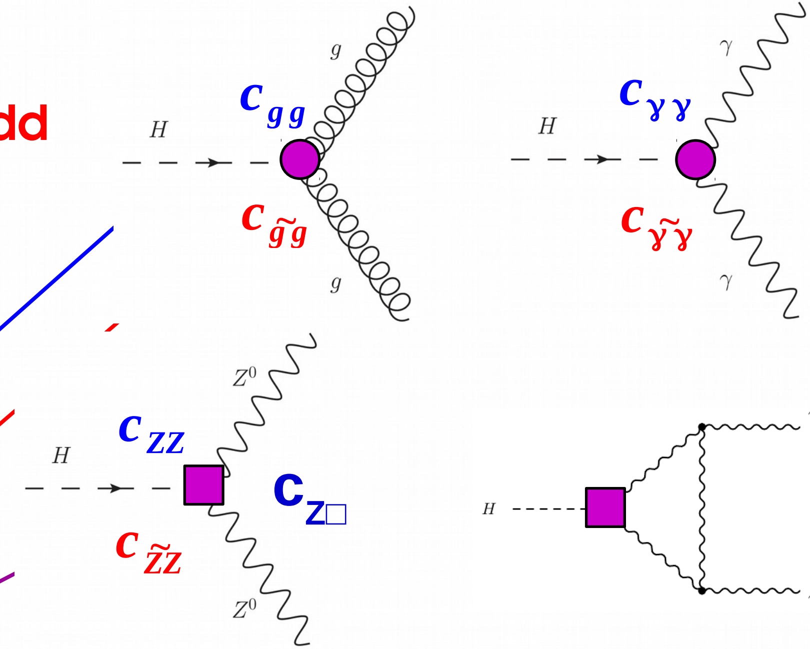
PLB 753 (2016) 69-85

Reinterpret ATLAS Run 1 $H\to\gamma\gamma$ differential results in **SMEFT-inspired effective Lagrangian**

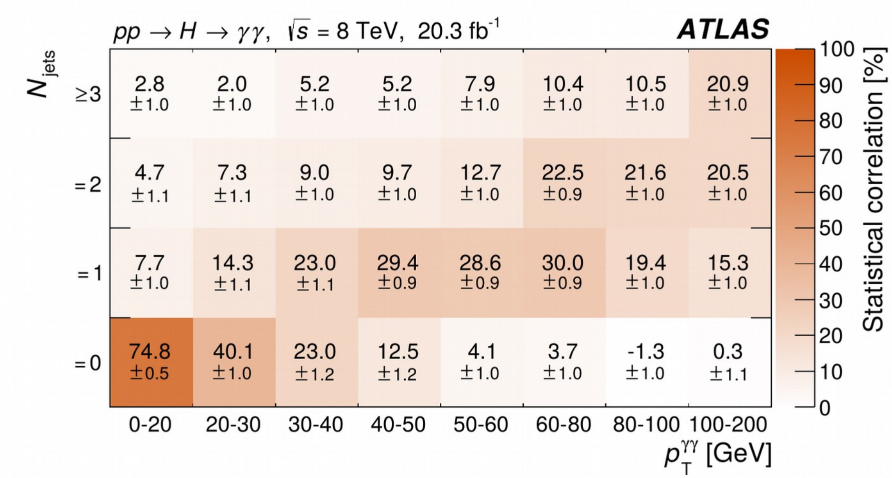
Use **5 distributions** : p_T^H, N_{jets}, m_{jj}, $\Delta\phi_{jj}$, p_T^{j1}, **24 bins**

Consider 6 coefficients: c_γ, c_g, c_{HW} + matching CP-odd





$$c_{zz} = -\frac{4}{g^2+g'^2}\left[\bar{c}_{HW} + \frac{g'^2}{g^2}\bar{c}_{HB} - 4\frac{g'^2}{g^2}s_\theta^2\bar{c}_\gamma\right]$$

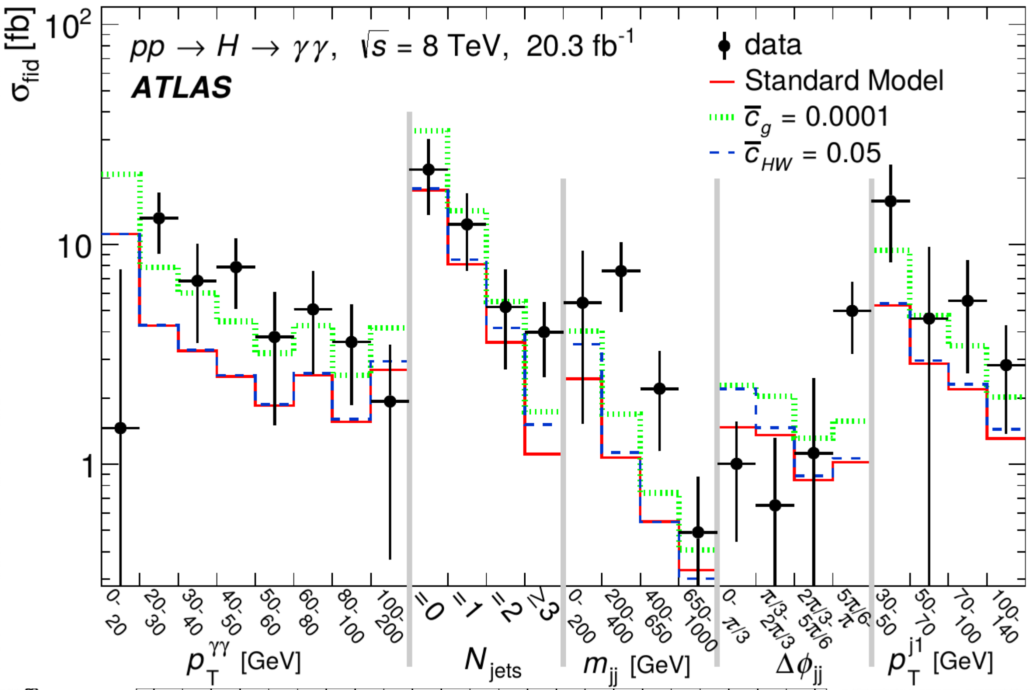


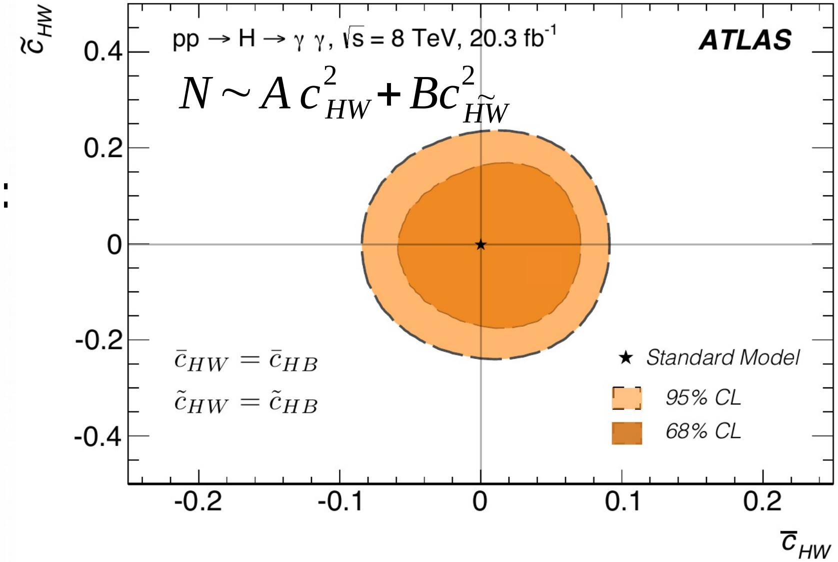
Same data for each of the 5 distributions

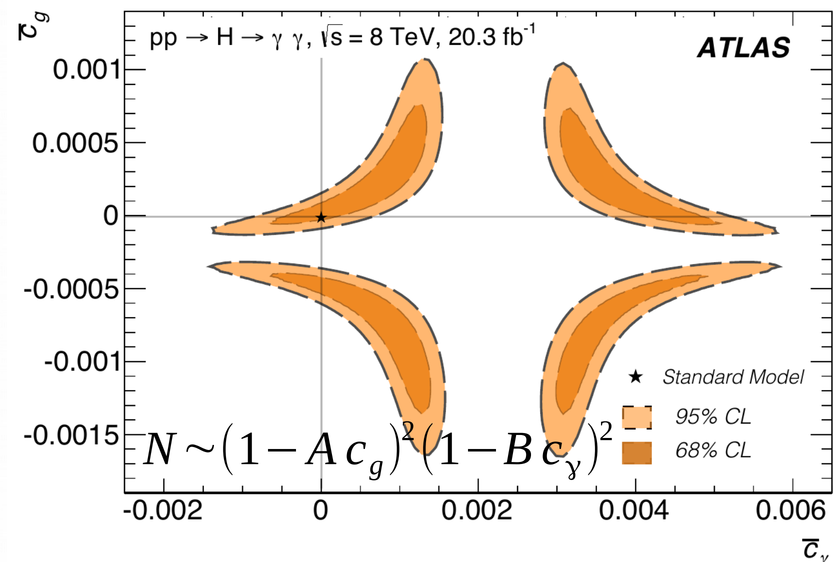
⇒ Include correlations, measured in data using bootstrap.

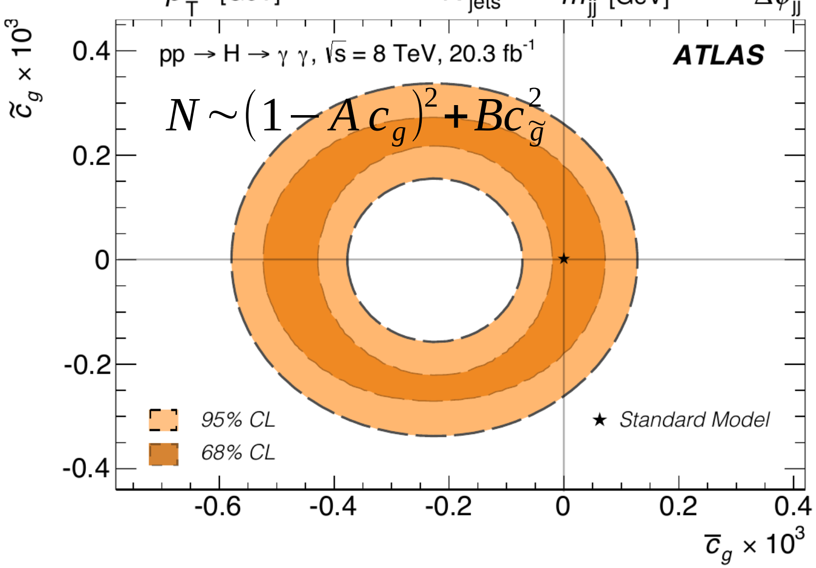
Effective Lagrangian (2)

Fit deviations in H→γγ differential measurements:









Most information still coming from rates

⇒ Strong constraints on odd+even c_g, c_γ.

⇒ Weak constraints on c_{HW}, and odd vs. even

Vary at most 2 parameters simultaneously

Need to include all relevant parameters simultaneously for a full SMEFT analysis

SMEFT: Open Questions

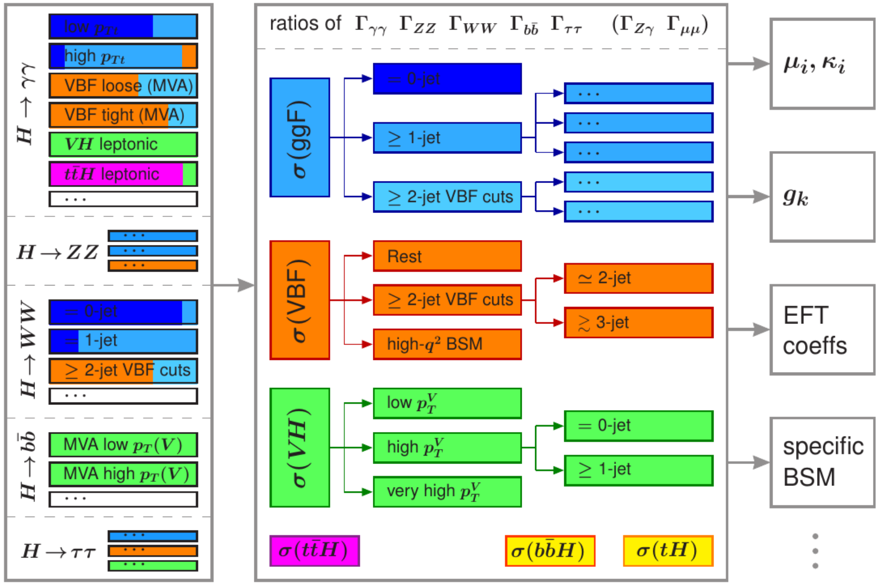
- **Full SMEFT measurements should include all operators which induce measurable deviations (can restrict only on symmetry grounds)**
  - Many possible deformations to consider
  - Need to **interpolate predictions in many dimensions**
    - **Matrix element reweighting, Morphing**…

- **Already significant information in current rate + differential measurements**
  - Need to establish which combinations of operators can be constrained

- **What measurements could increase sensitivity ?**
  - Different measurements targeted for different deformations
  - Identify sensitive **regions in phase space**
  - Identify sensitive **variables**
    - Need to model correlations if fitting multiple distributions

Simplified Template Cross-Sections

YR4 Section III.2



Similarities to fiducial cross-sections:

- measure cross-sections in **truth-level phase space regions**.
- Separate out regions to :
  - **Maximize sensitivity to SM or BSM effects**
  - **Minimize sensitivity to theory uncert., models**

Points of Difference:

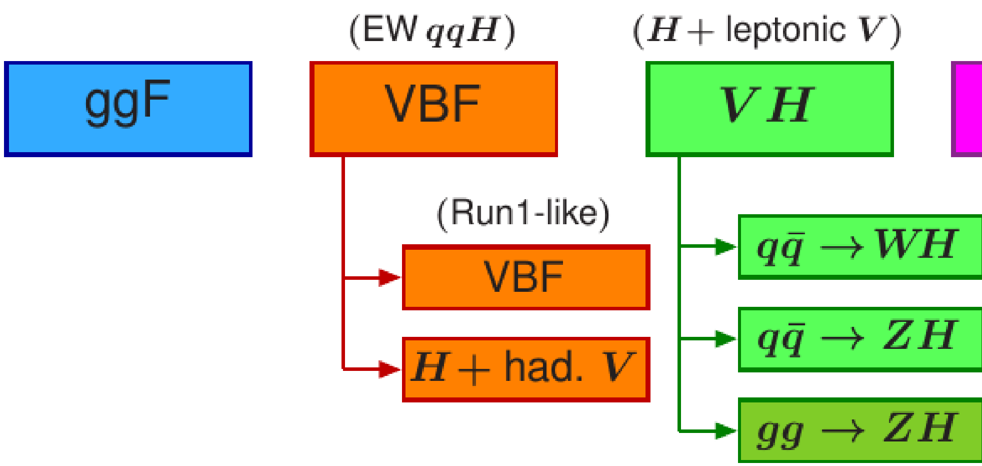
- Split production modes/final states
- Partitions the **entire phase space** into **non-overlapping regions**
- **No strong matching between truth and reco-level selections**: compromise between
  - "complicated" reco selections (BDTs, etc.)
  - simple and well-defined theory selections

$\Rightarrow$ **Point of contact between theory and experiment**

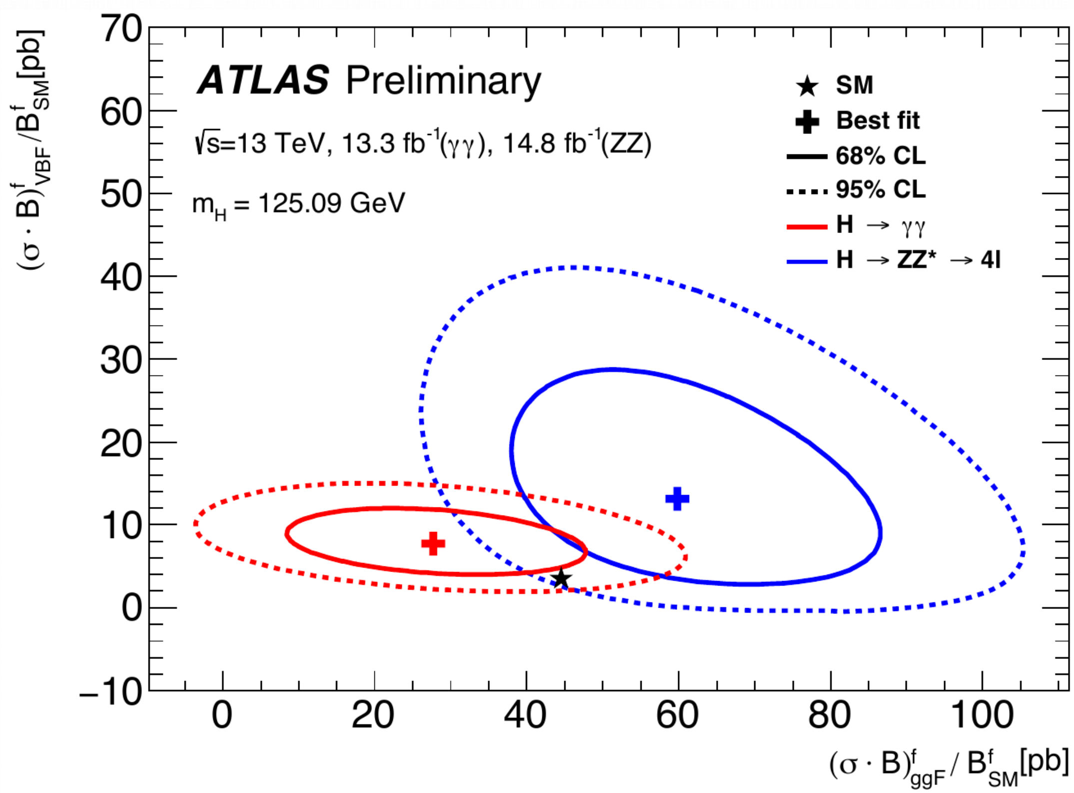
Complementary to diff. measurements: fully exclusive split along many variables

- **No need for statistical correlations**
- **Coarser binning**

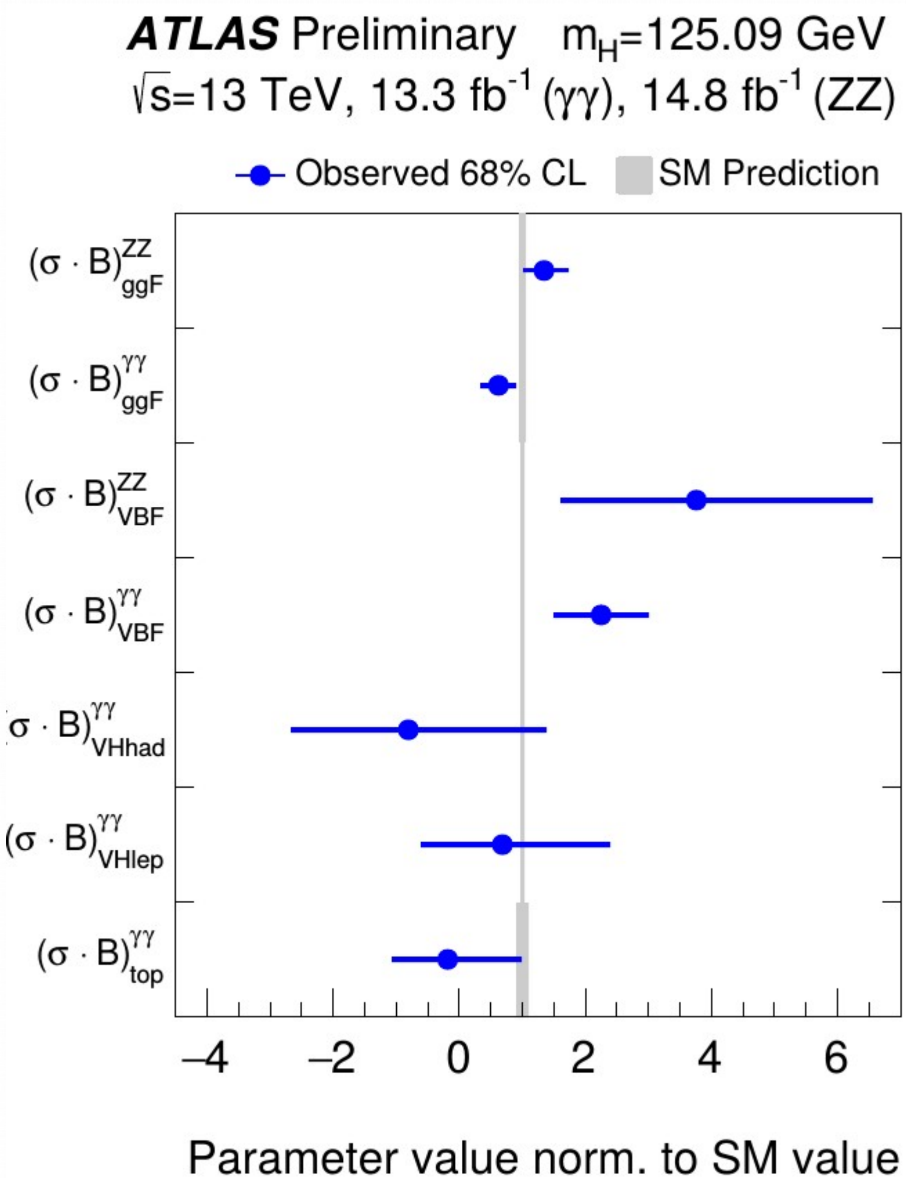
STXS Stage 0

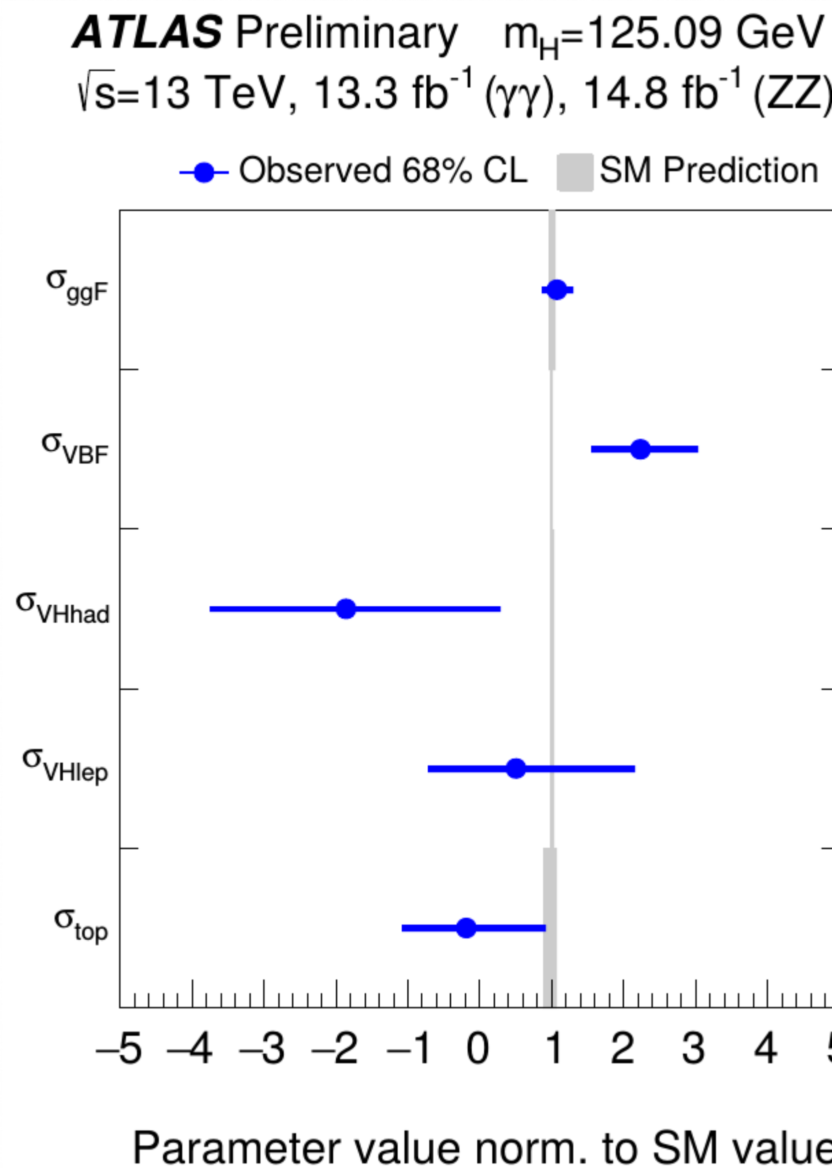


- **Splitting evolves with dataset size** (more data ⇒ finer split)
- **"Stage 0"** based on "**production modes" (final states) only**
  - Group **VBF**+ **(V→had)H** since same final state
  - Restricted to **$|y_H|<2.5$** to avoid extrapolation
- Used for ATLAS ICHEP results: **H→γγ and combination with H→ZZ.**



STXS Stage 0





bbH included in ggF
top = ttH + tH

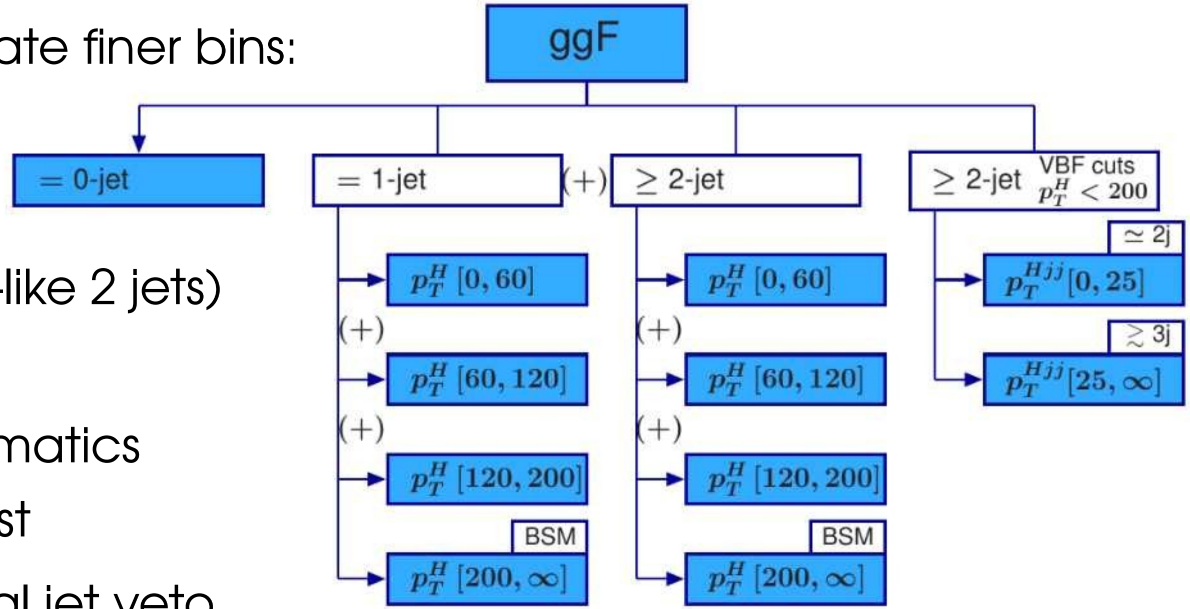
Assuming SM values for relative fractions

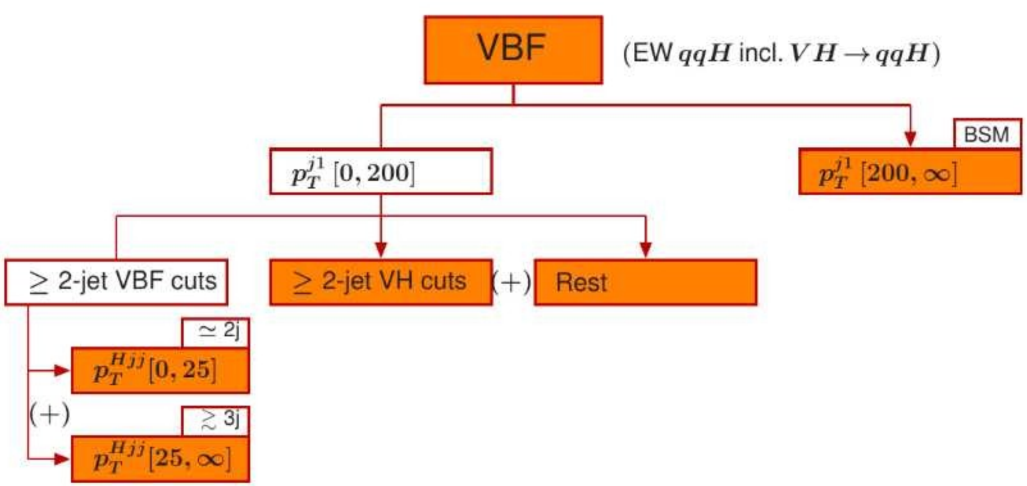
Everything compatible with the SM

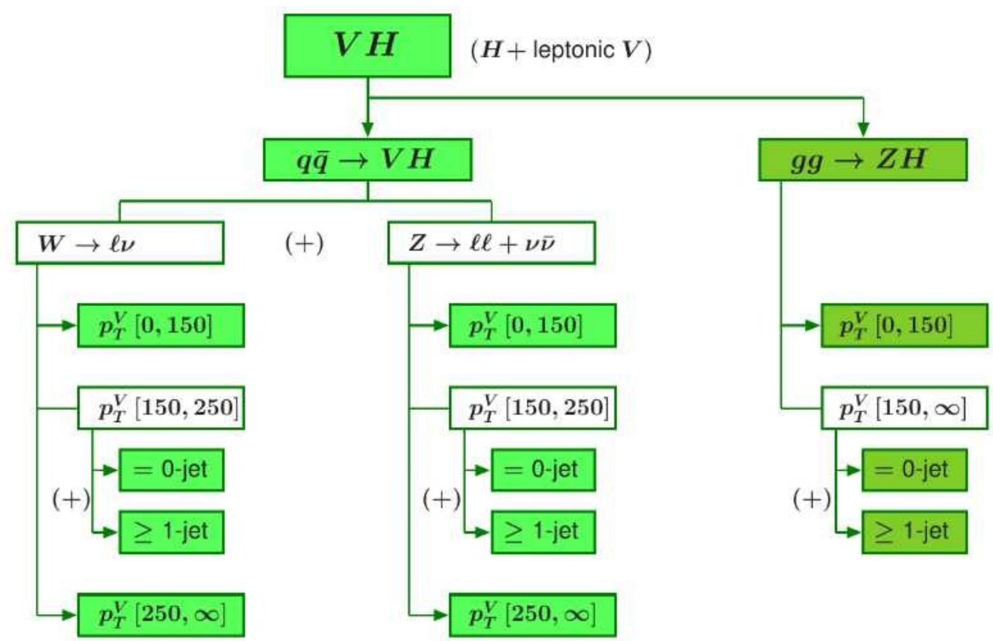
STXS Stage 1

Larger 2016 dataset ⇒ Can populate finer bins:

- **ggF :**
  1. **N_{jets}** split
- 2. **p_T^H** split for 1,2 jets (**p_T^{Hjj}** for VBF-like 2 jets)
- **VBF & (V→had)H :**
  1. Split **VBF, (V→had)H** from kinematics
  2. split off **"BSM" (high p_T)** and rest
- 3. **p_T^{Hjj}** split to match experimental jet veto
- **(V→lep)H** :
  - Split **W→lν** and **Z→ll/νν** from qq/gg
  - **p_T^V, N_{jets}**







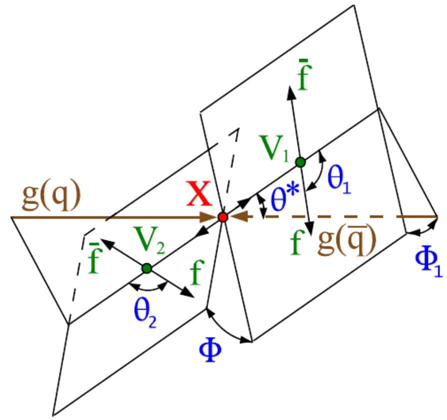
Effective Lagrangians

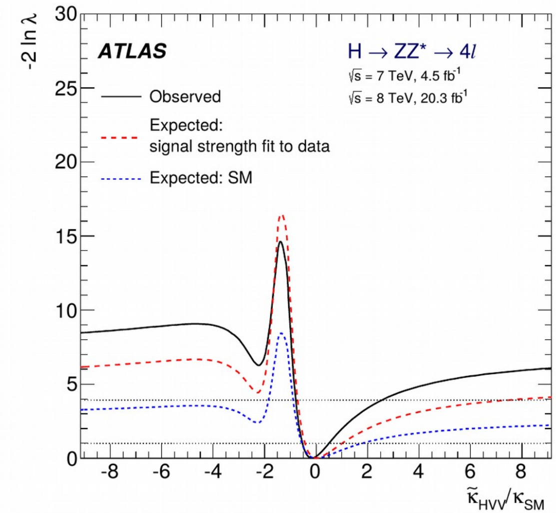
Eur. Phys. J. C75 (2015) 476

Eur. Phys. J. C75 (2015) 476

- **ATLAS: Higgs Characterization Model**

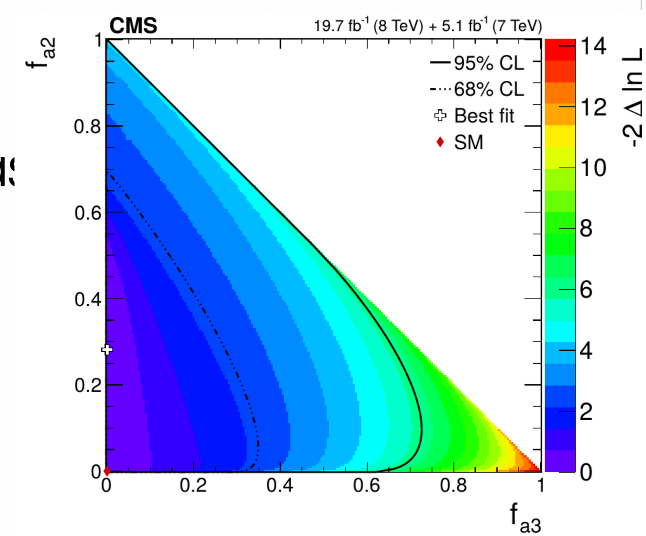
$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\mathrm{SM}}\left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\right] \\
& - \frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\right] \\
& - \frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\right] \\
& - \frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\right] \\
& - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\right] \\
& - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\right] \\
& - \frac{1}{\Lambda} c_\alpha\left[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W}\, W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\right)\right]\Big\} X_0
\end{aligned}
$$





- **CMS: "JHU Model"**: based on Lorentz structure, also a

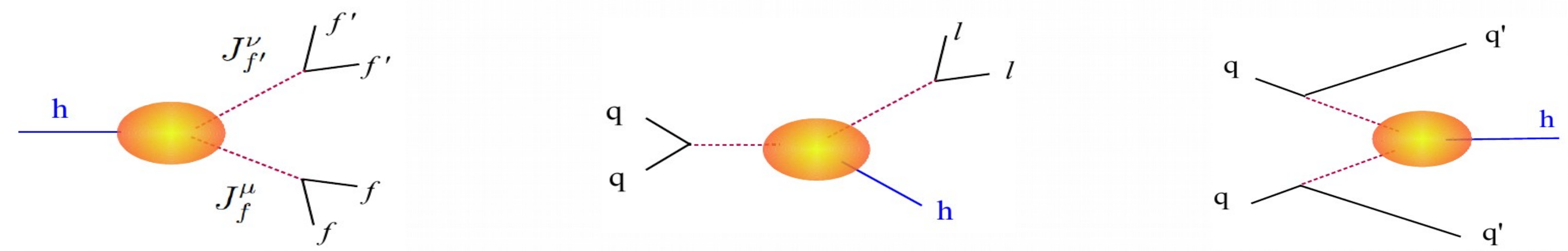
$$
\begin{aligned}
L(\mathrm{HVV}) \sim\; & a_1 \frac{m_Z^2}{2}\mathrm{H Z}^\mu \mathrm{Z}_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H Z}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{H Z}^{\mu\nu}\mathrm{Z}_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H Z}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu} \\
& + a_1^{\mathrm{WW}} m_{\mathrm{W}}^2 \mathrm{H W}^{+\mu}\mathrm{W}^-_\mu - \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_{\mathrm{W}}^2 \mathrm{H}\left(\kappa_1^{\mathrm{WW}} \mathrm{W}^-_\mu \Box \mathrm{W}^{+\mu} + \kappa_2^{\mathrm{WW}} \mathrm{W}^+_\mu \Box \mathrm{W}^{-\mu}\right) \\
& - a_2^{\mathrm{WW}} \mathrm{H W}^{+\mu\nu}\mathrm{W}^-_{\mu\nu} - a_3^{\mathrm{WW}} \mathrm{H W}^{+\mu\nu}\tilde{\mathrm{W}}^-_{\mu\nu} \\
& + \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H Z}_\mu \partial_\nu \mathrm{F}^{\mu\nu} - a_2^{Z\gamma}\mathrm{H F}^{\mu\nu}\mathrm{Z}_{\mu\nu} - a_3^{Z\gamma}\mathrm{H F}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma}\mathrm{H F}^{\mu\nu}\mathrm{F}_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma}\mathrm{H F}^{\mu\nu}\tilde{\mathrm{F}}_{\mu\nu}
\end{aligned}
$$



- **Almost identical** – in both cases include **κ + modified HVV dynamics**
  - More freedom than SMEFT (no gauge invariance) ⇒ **more parameters**
  - Some **missing contributions** (e.g. HVff operators)

Higgs Pseudo-Observables

Idea: encode all the experimentally available information with only weak assumptions (e.g. crossing symmetry)



- Report experimental measurements as POs, and compute them in specific models
- One PO per accessible observable
  - **H→γγ** : Γ(H→γγ), or **$\kappa_{\gamma\gamma}$ = Γ(H→γγ)/Γ_{SM}(H→γγ)**
  - **H→ff** : Γ(H→ff), or **κ_f = Γ(H→ff)/Γ_{SM}(H→ff)**
  - **H→VV→4l**: Separate POs for
    - **H→V_TV_T** and **H→V_LV_L**
    - Resonant and non-resonant contributions (**H→Vff**)

+ CP-odd parameters where experimentally accessible

→ **Use the same "VV" POs for VBF and VH production**

Higgs Pseudo-Observables

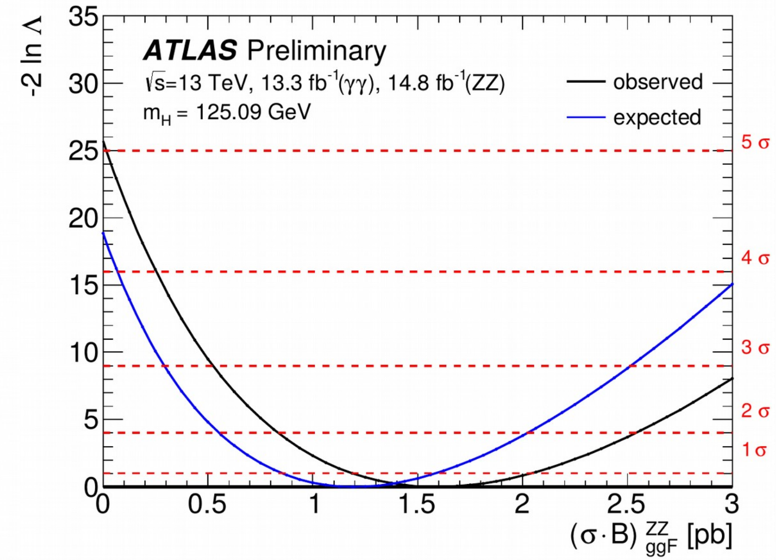
From YR4 and
G. Isidori's talk at HC16

Process	CP-even	CP-odd
H→VV	κ_{ZZ}, ε_{ZZ}, $\kappa_{Z\gamma}$, $\kappa_{\gamma\gamma}$	ε_{ZZ}^{CP}, $\delta_{Z\gamma}^{CP}$, $\delta_{\gamma\gamma}^{CP}$
(no custodial symm.)	(κ_{WW}, ε_{WW})	(ε_{WW}^{CP})
H→Vll	ε_{ZeL}, ε_{ZeR}, $\varepsilon_{Z\nu}$	
(no custodial symm.)	(Re ε_{WeL})	(Im ε_{WeL})
VBF, VH	ε_{ZuL}, ε_{ZuR}, ε_{ZdL}, ε_{ZdR}	
(no custodial symm.)	(Re ε_{WeL})	(Im ε_{WeL})
H→ff	κ_f (f=t,b,τ)	δ_f^{CP}
ggF	κ_g	
Γ_H	κ_H	

Total : **17 CP-even** + **6 CP-odd** POs (no custodial symm. : **21** + **8**)

Assuming flavor universality

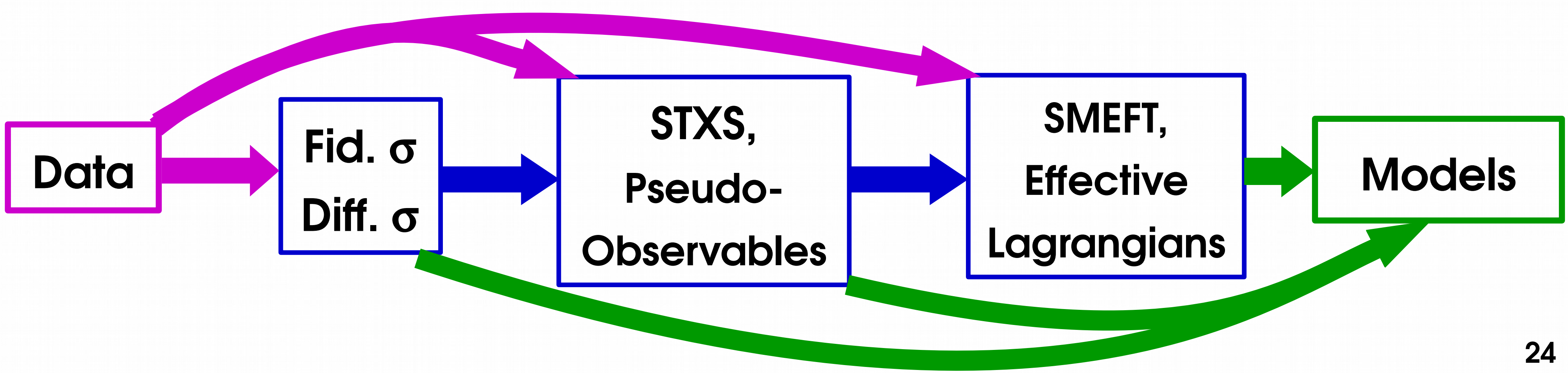
Open Issues



- Need **MC generators** to provide predictions:
  - **HC/JHU**: used in Run 1
  - **SMEFT**: NLO generators being validated
  - **POs**: under development
- Tools for multidimensional measurements (Morphing)

- **How to report the likelihoods ?**
  - Last bins in distributions always have low statistics, not Gaussian
  - Not very Gaussian even now ⇒ **Covariance matrix is not sufficient**

- **Which framework to use for reporting** ? Many possibilities:

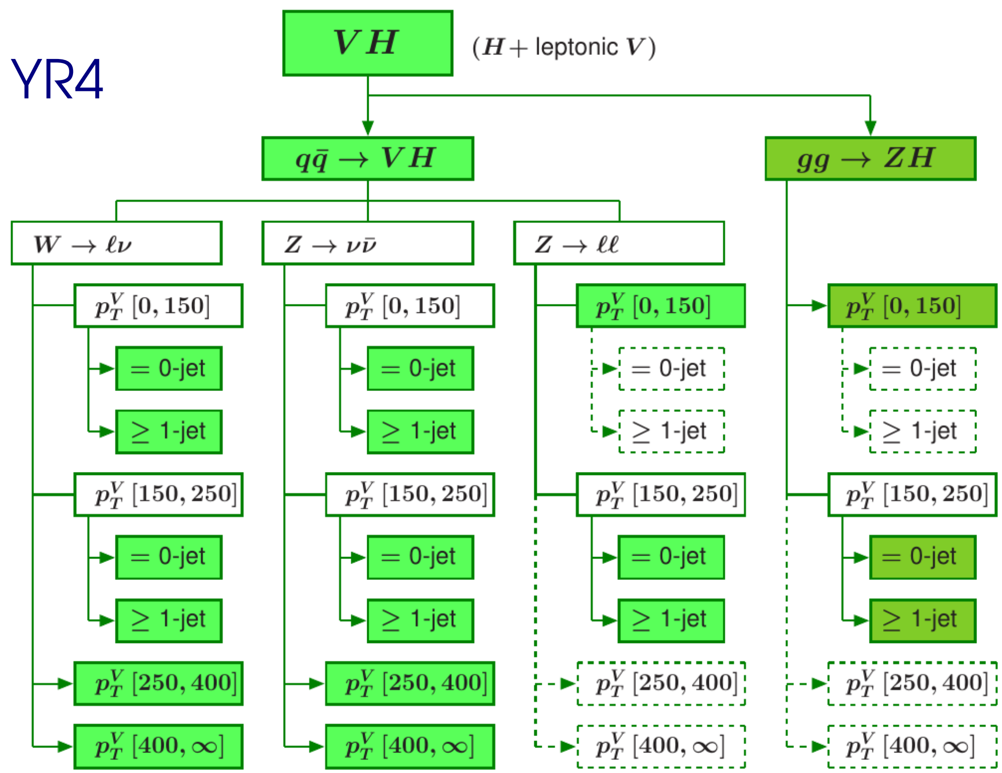


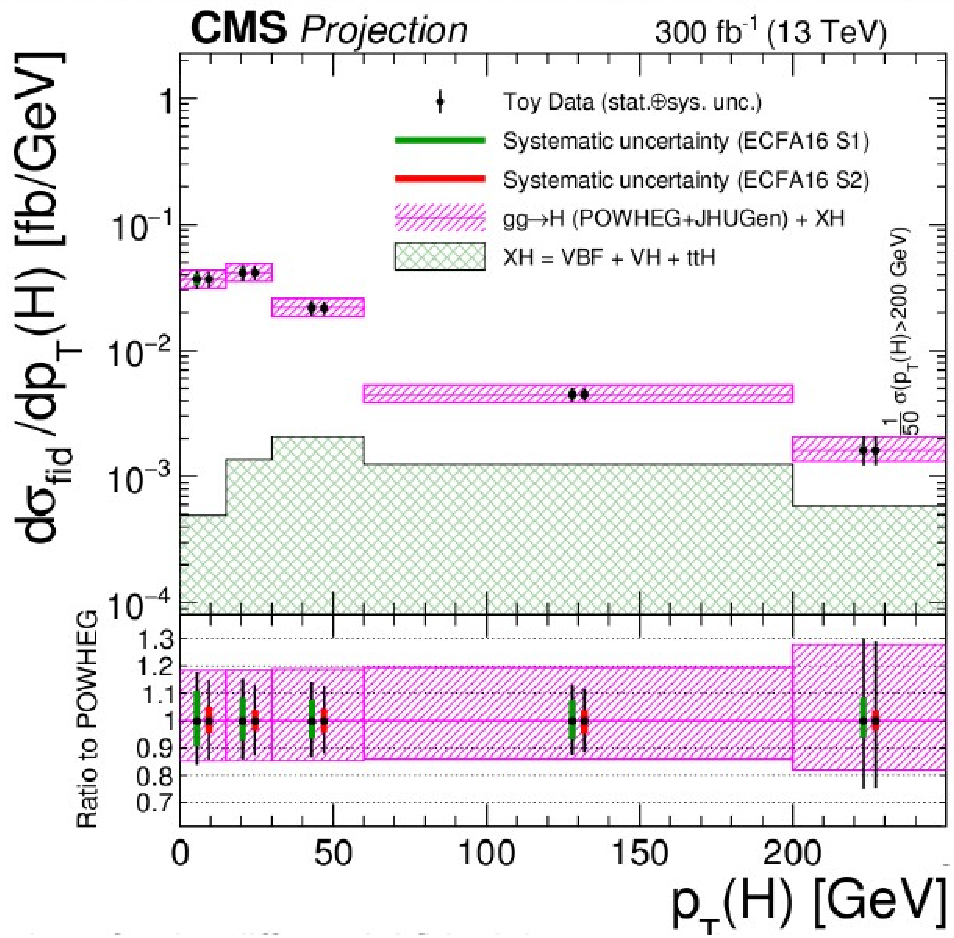
Outlook

- **Many new ideas and possibilities being put forward recently**
  - Still **many open issues** to be resolved, theory/experiment interactions very important now to define this program.

CMS-DP-2016-064

YR4





- **Many interesting measurements possible in Run 2 and beyond!**

Additional Material

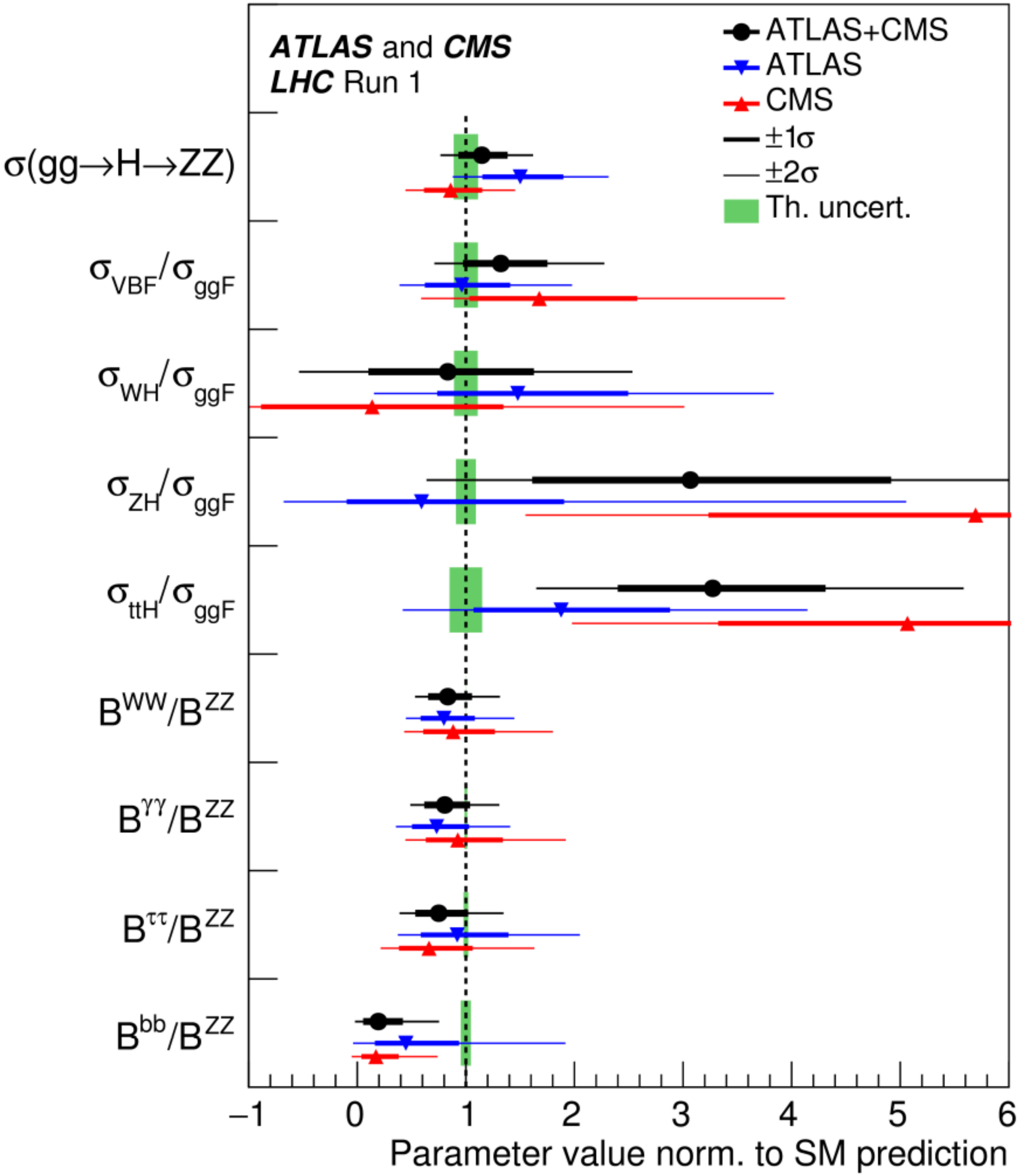
Fiducial Cross-Section Measurements

Lepton definition	
Muons: $p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading leptons $p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

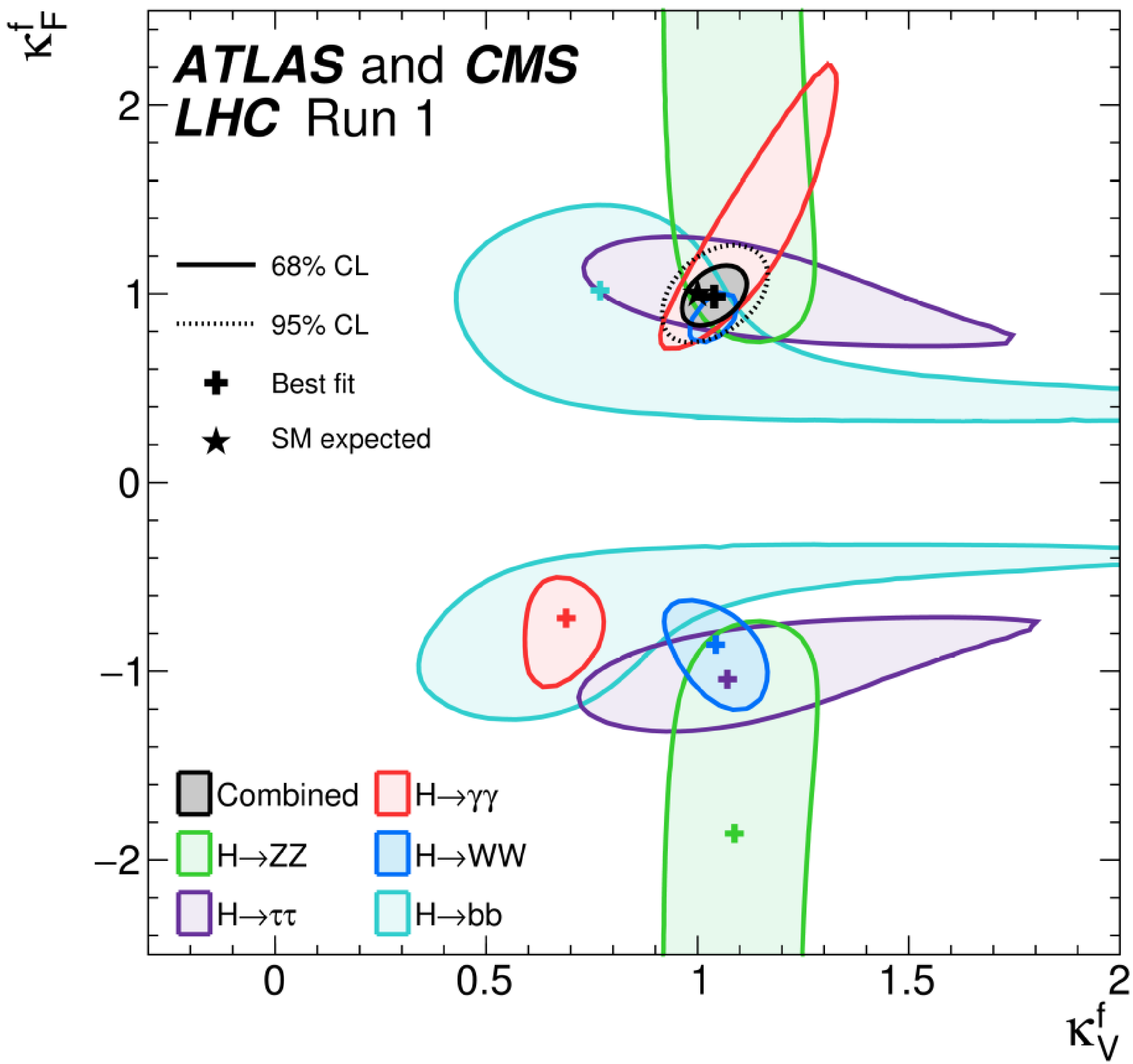
Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m_{Z_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m_{Z_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

- $\frac{p_{T,gen}^{\gamma_{1,(2)}}}{m_{\gamma\gamma}} > \frac{1}{3}(\frac{1}{4})$ for the generator-level transverse momentum of the leading (subleading) photon,
- $\lvert\eta_{gen}^{\gamma}\rvert < 2.5$ for the generator-level pseudorapidities of both photon
- the generator-level isolation of the photons, calculated as the sum of the transverse momenta of all stable particles inside a cone of aperture $R = 0.3$ around the photon, is required to be smaller than 10 GeV.

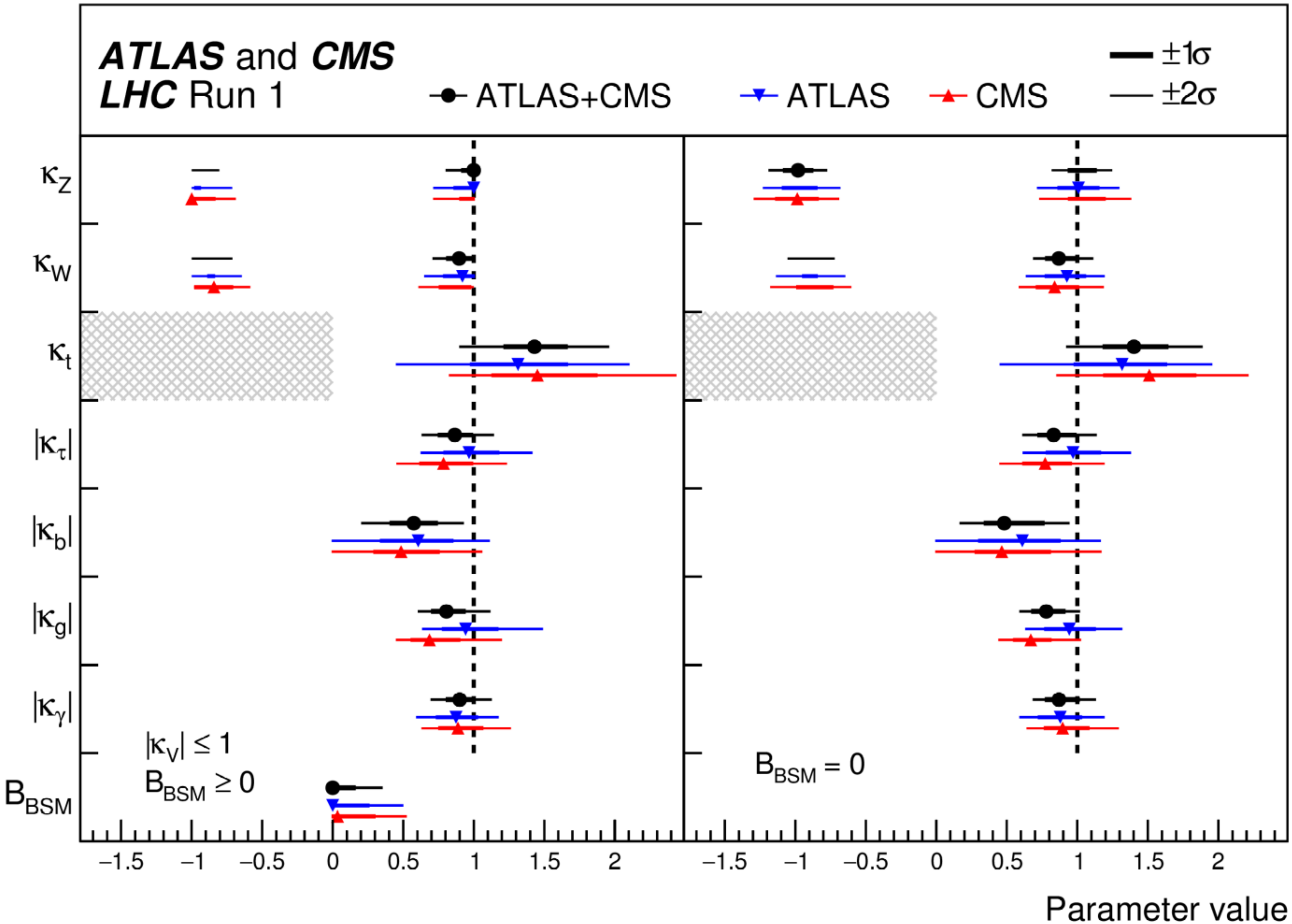
Interpretation: ATLAS+CMS Combination



Interpretation: ATLAS+CMS Combination



Interpretation: ATLAS+CMS Combination



STXS Stage 1

- ATLAS measurements of STXS Stage 1 : H→gg, H→ZZ and combination

$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \mathrm{pb}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \mathrm{pb}$$

$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb} \qquad \sigma_{\mathrm{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \mathrm{pb}$$

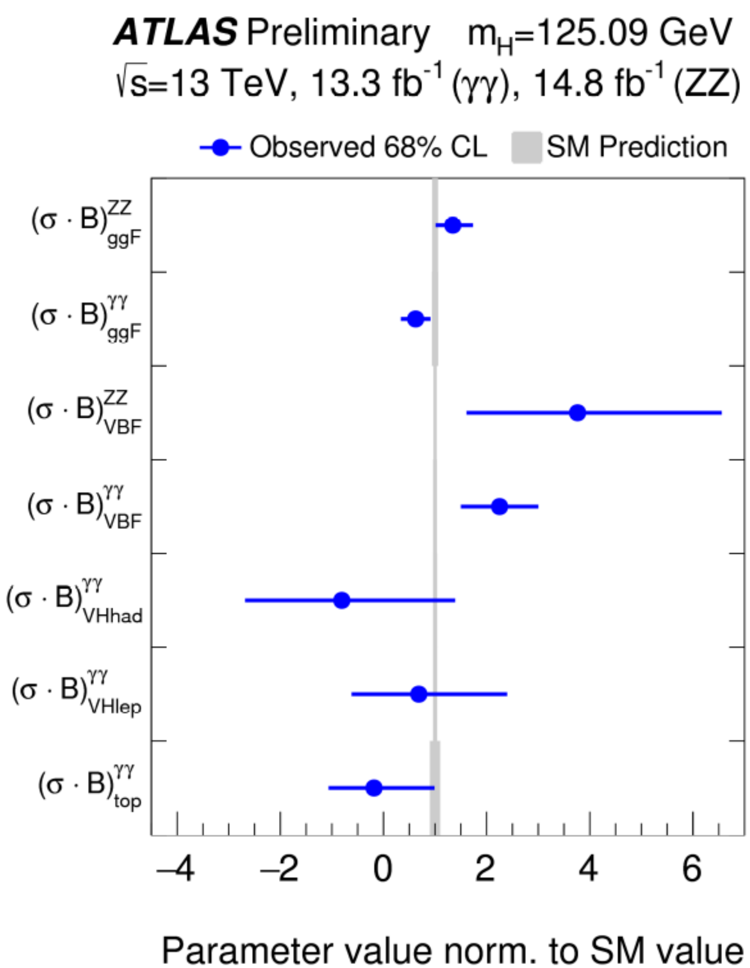
$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 63\ ^{+30}_{-29}\ \mathrm{fb}$$

$$\sigma_{\mathrm{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 17.8\ ^{+6.3}_{-5.7}\ \mathrm{fb}$$

$$\sigma_{\mathrm{VHlep}} \times \mathcal{B}(H \to \gamma\gamma) = 1.0\ ^{+2.5}_{-1.9}\ \mathrm{fb}$$

$$\sigma_{\mathrm{VHhad}} \times \mathcal{B}(H \to \gamma\gamma) = -2.3\ ^{+6.8}_{-5.8}\ \mathrm{fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\ ^{+1.4}_{-1.1}\ \mathrm{fb}$$



Better Frameworks: POs

- H→VV→4l: more kinematic information available (mll, mT, etc.), so more POs:

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu)\times\left[F_L^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_T^{e\mu}(q_1^2,q_2^2)\,T^{\alpha\beta} + F_{\rm CP}^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

longitudinal *transverse* *CP-odd*

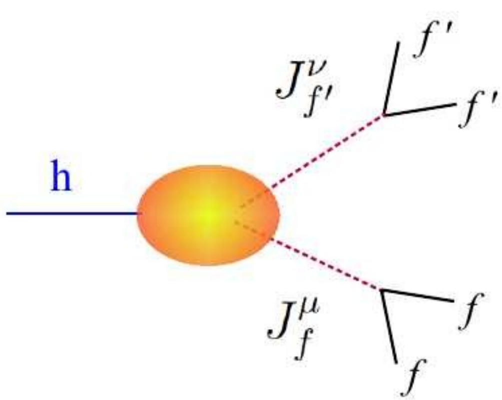
↑

$$\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)} + \Delta^{\rm SM}_{\text{non-loc}}(q_1^2,q_2^2)\right)$$

double-pole *single-pole* *non-resonant (negligible)*

G. Isidori

- Separate POs for transverse and longitudinal \
- Applies to Z(*)Z(*), W(*)W(*), Z(*)g,



SMEFT Measurement Sensitivity

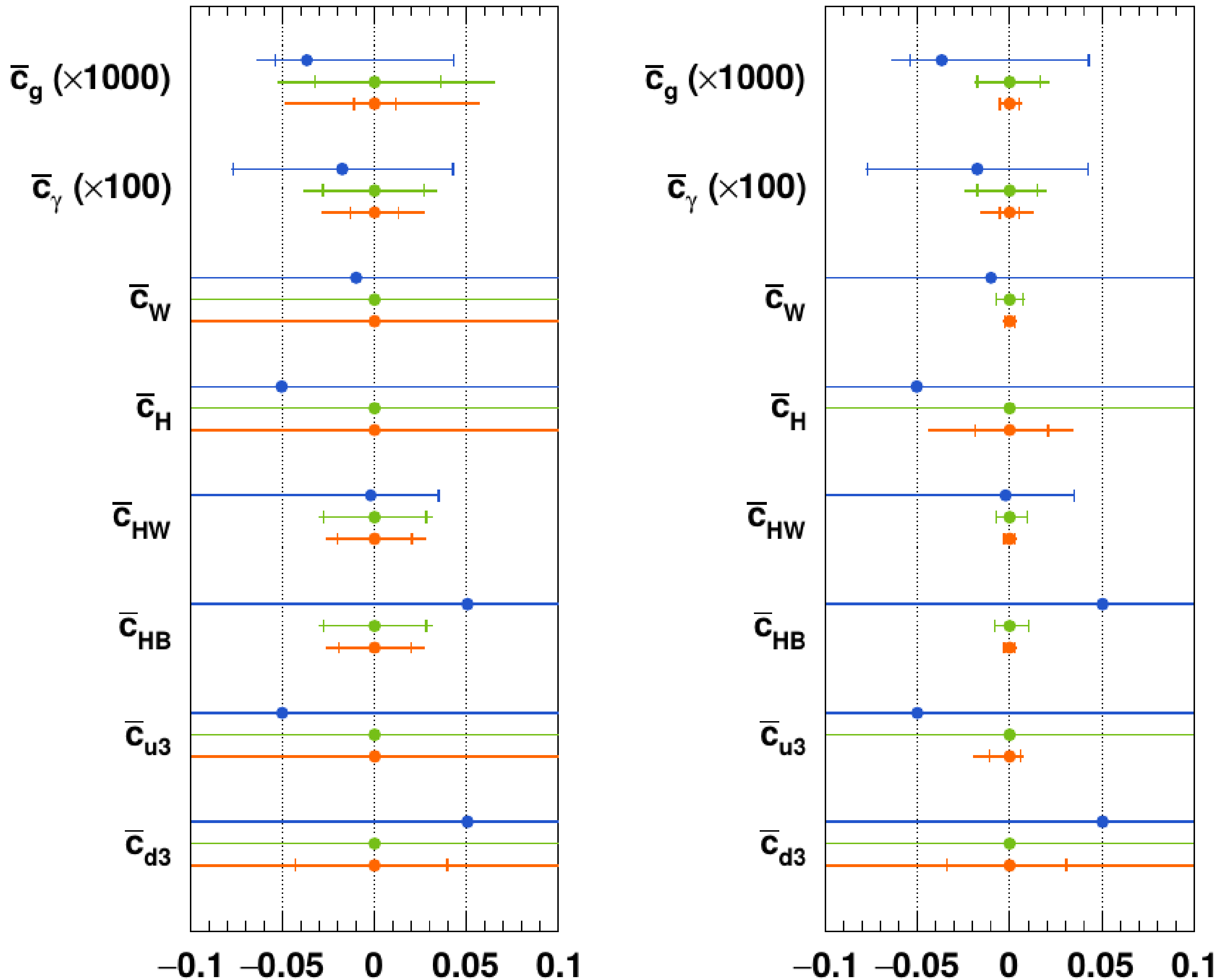


Figure 196: Marginalized 95% confidence level constraints for the dimension-six operator coefficients for current data (blue), the LHC at 14 TeV with 300 fb^{-1} (green), and with 3000 fb^{-1} (orange). The expected constraints are centred around zero by construction. For the left panel we only use signal strengths, while on the right differential $p_{T,h}$ measurements are included. The inner error bar depicts the experimental uncertainty, the outer error bar shows the total uncertainty. Figure from Ref. [848].