Measurement of cross sections and properties of the Higgs boson in decays to bosons with the ATLAS experiment

Lake Louise Winter Insitute 2019

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on behalf of the ATLAS Collaboration

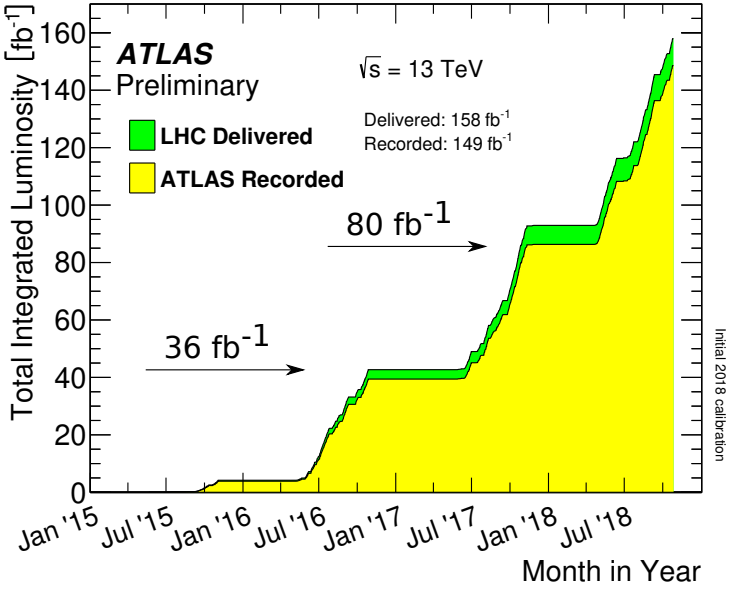
INFN Milano

11 February, 2019

References for Run2 13 TeV 36 fb^{-1} and 80 fb^{-1}

Latest Summer Run 2 results with 80 fb^{-1} 13 TeV:

- $H \to \gamma\gamma$: ATLAS-CONF-2018-028
- $H \to 4\ell$: ATLAS-CONF-2018-018
- combination $\gamma\gamma + 4\ell + e\nu\mu\nu + \tau\tau + \mathrm{VH}(bb) + \mu\mu$ + ttH(bb and multilepton): ATLAS-CONF-2018-031
- combination ttH $\gamma\gamma + 4\ell + bb +$ multilepton (5.8σ): Phys. Lett. B 784 (2018) 173



Latest Run 2 results with 36 fb^{-1} 13 TeV:

- Mass $\gamma\gamma$+4ℓ: Phys. Lett. B 784 (2018) 345
- xsections combination $\gamma\gamma$+4ℓ: Phys. Lett. B 786 (2018) 114
- $H \to \gamma\gamma$: Phys. Rev. D 98 (2018) 052005
- $H \to 4\ell$: JHEP 03 (2018) 095
- EFT interpretation $\gamma\gamma$+4ℓ: ATL-PHYS-PUB-2017-018
- $H \to WW \to e\nu\mu\nu$: Phys. Lett. B 789 (2019) 508

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Higgs properties

Excess compatible with Higgs boson firmly established by ATLAS+CMS in 2012.

Measurements

- Mass: m_H known at 0.2% (single experiment)
- $\sigma \times Br$: inclusive, for each production-mode, fiducial region (STXS), decay (strong SM assumption: very optimized analyses, acceptance extrapolations)
- Fiducial cross sections (minimal model dependence)
- Differential kinematic distributions for each decay in fiducial regions (minimal model dependence)

Interpretations

- Spin and parity: 0^+, other models excluded in Run 1
- Signal strengths: $\mu_i = \sigma_i/\sigma_i^{SM}$, $\mu_f = BR_f/BR_f^{SM}$ (inclusive, per-production-mode, ...)
- Coupling modifiers to SM particles (k-framework)
- EFT interpretations

Higgs properties

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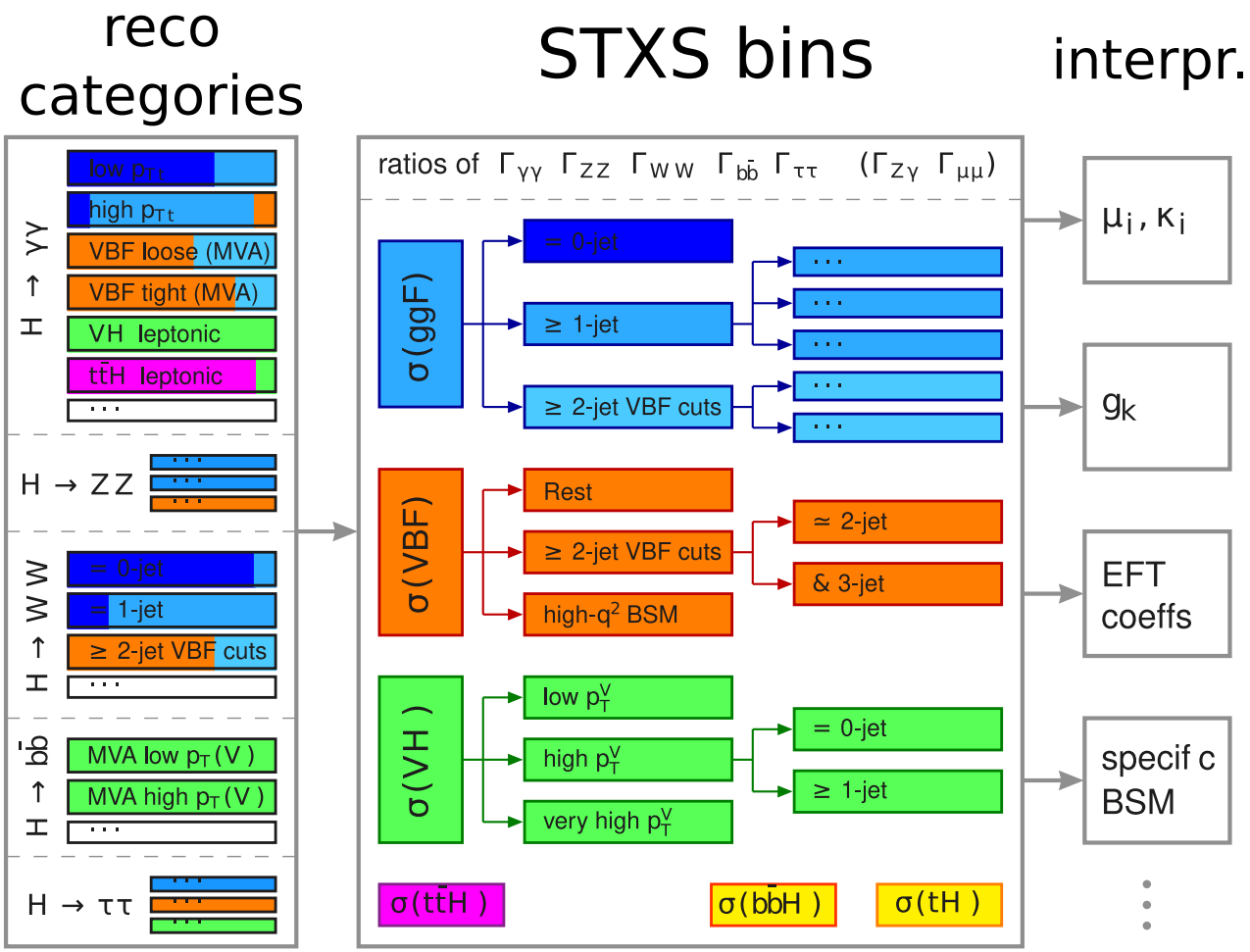
Simplified template cross sections (STXS) stage 1

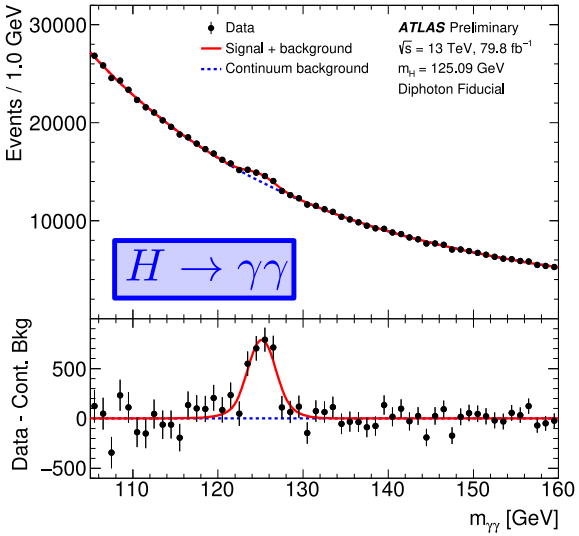
- Defined in the CERN Yellow Report 4
- Exclusive fiducial regions defined by production mode, p_T^H, N_j, VBF-topology, $p_T^{j_1}$, p_T^{Hjj}, p_T^V

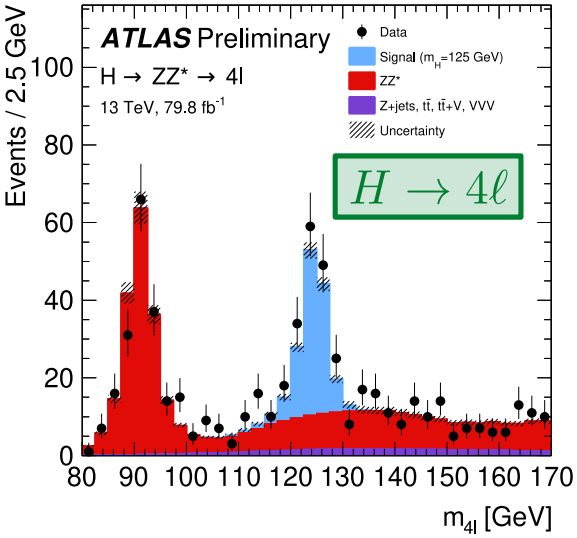


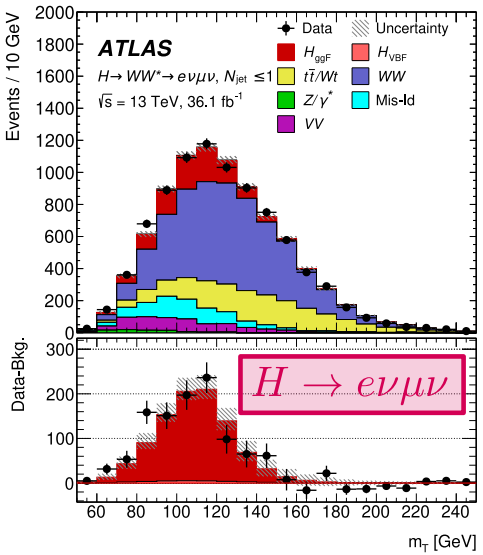
- Design measurement to split events according to STXS

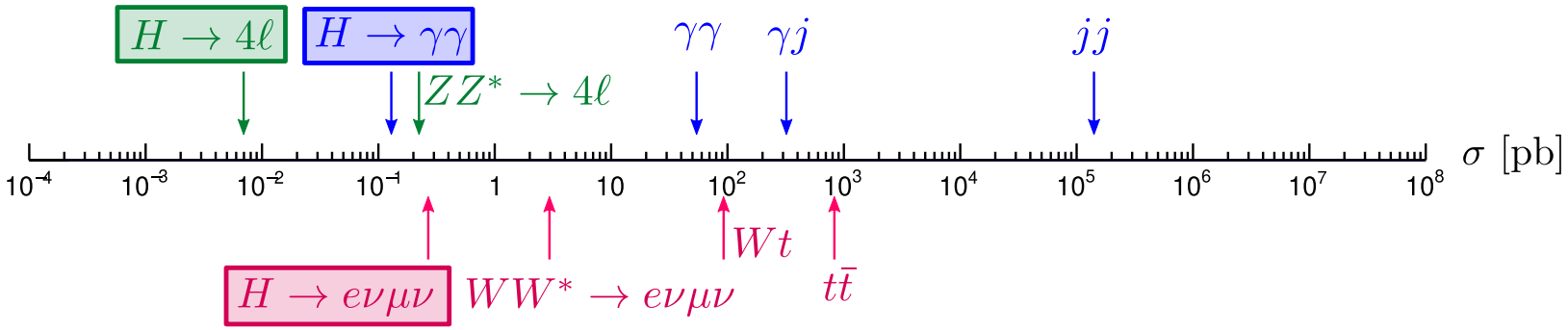
$\gamma\gamma$, $ZZ^* \to 4\ell$, $WW^* \to e\nu\mu\nu$

	BR/10^{-3}	sig. eff.	mass resolution	Backgrounds
$\gamma\gamma$	2.27	42%	1.41–2.10 GeV	Large: $q\bar{q}/gg \to \gamma\gamma$ and fakes
4ℓ	0.124	24%	1.6–2.4 GeV	Small: $q\bar{q}/gg \to ZZ^*$ and fakes
$e\nu\mu\nu$	5.04	$\sim 11\%$	Transverse mass	$q\bar{q}/gg \to WW^*$, $t\bar{t}$, Wt, ...



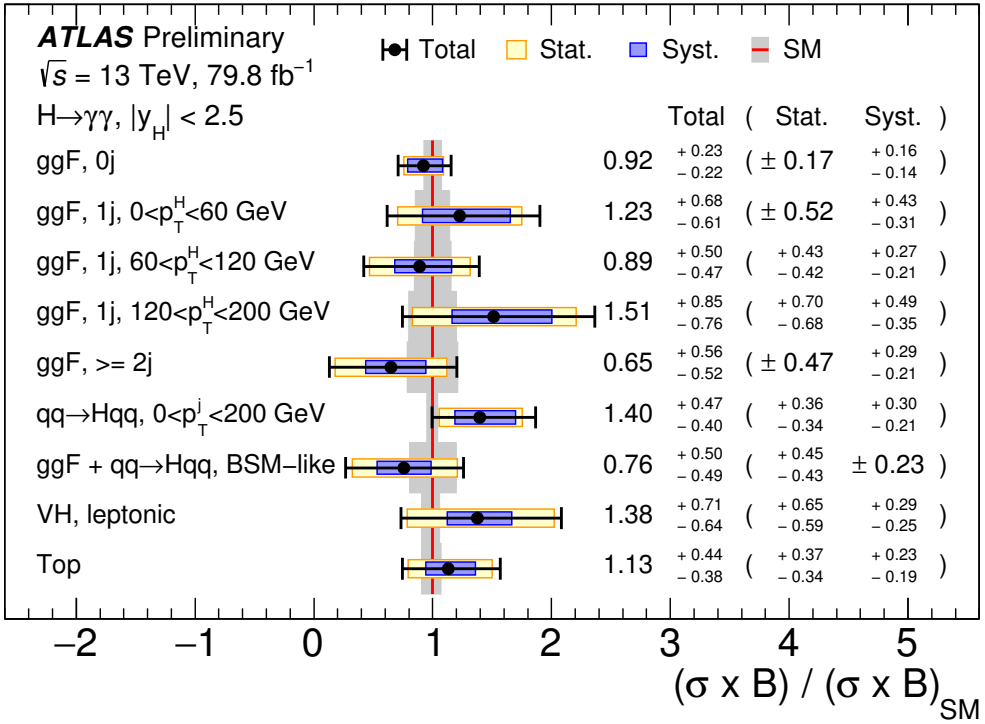


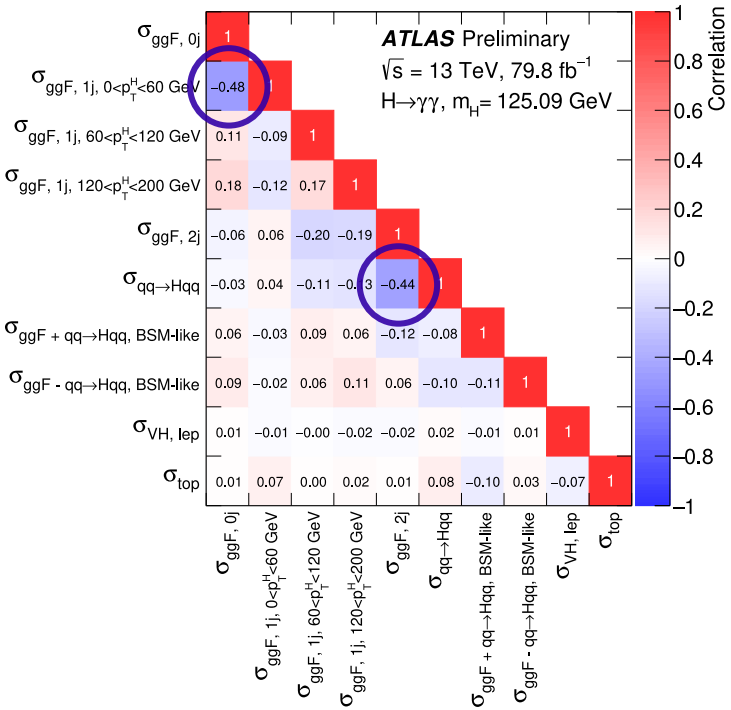




$H \to \gamma\gamma$ coupling

- Decay with loop: can probe coupling to both fermions and vectors; sensitive to BSM
- Model large smooth background as a functional form, fitted on data
  - Difficult to validate the potential bias on the signal: important systematics
- Lot of data: categorize the events in a fine way, targeting STXS
- Observable: diphoton mass, direction from calorimeter pointing

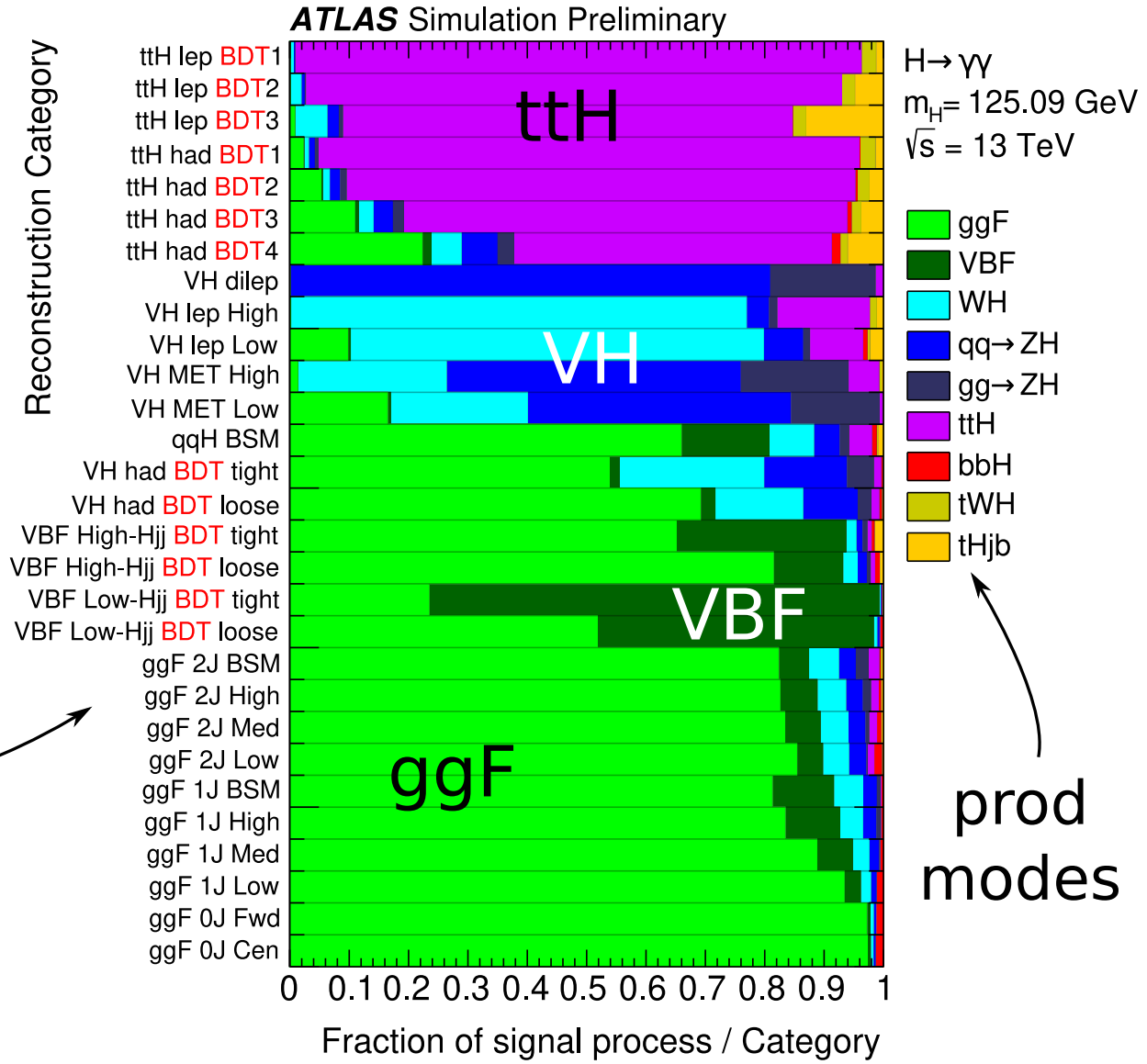




- Difficult to separate $\boxed{\text{ggF 0j/ggF 1j } p_T < 60\,\text{GeV}}$ and $\boxed{qq \to Hqq/\text{ggF 2j}}$

$H \to \gamma\gamma$ coupling categorization

To measure many cross-sections with small correlation split events in pure categories

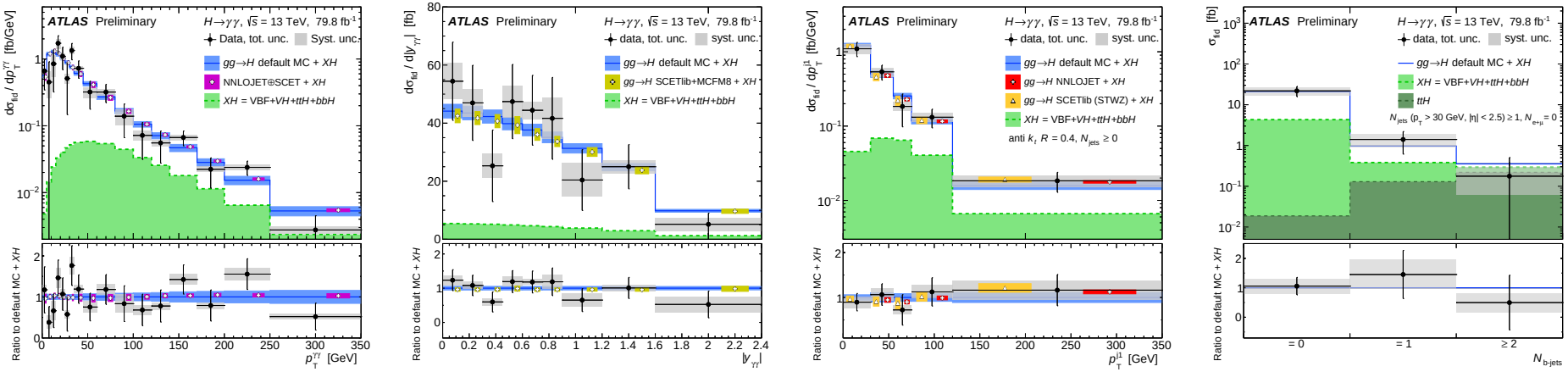


29 reco-categories inspired by STXS

prod modes

$H \to \gamma\gamma$ cross sections

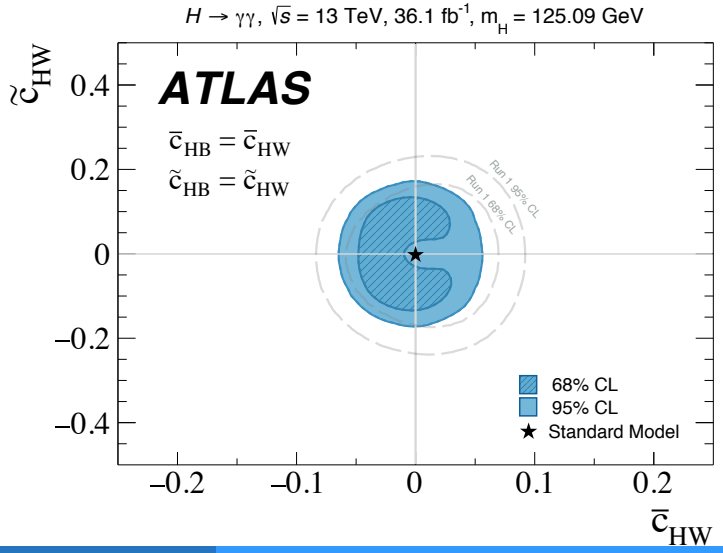
With 80 fb^{-1} unfolded (bin by bin) distribution for $p_T^{\gamma\gamma}$, $y_{\gamma\gamma}$, $p_T^{j_1}$, N_{b-jets} (lepton-veto)



Define fiducial regions only with kinematic cuts, close to the ones used in the analysis: small model dependency. p-value(χ^2) data/SM $> 30\%$

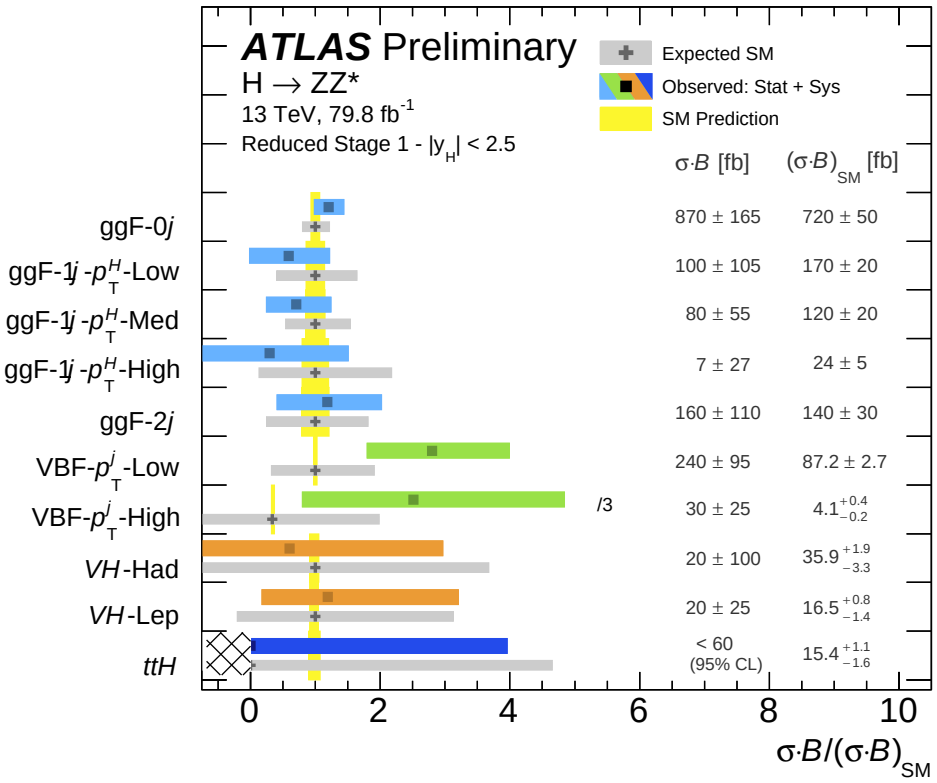
Can be used as input of EFT interpretation (36 fb^{-1}):

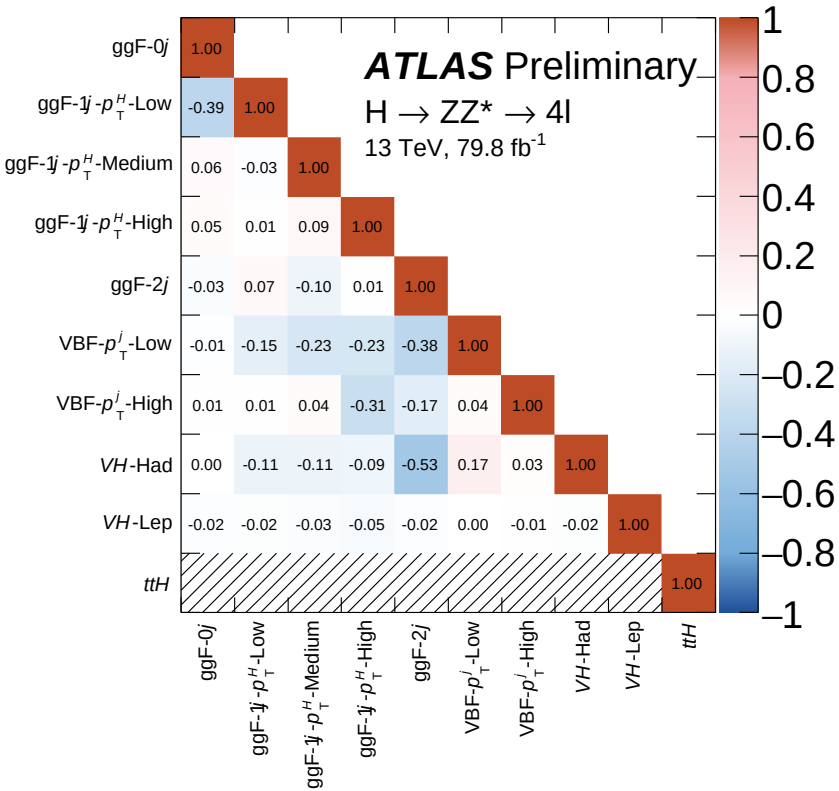
- introduce additional CP-even and CP-odd interactions in SILH framework
- inputs: $p_T^{\gamma\gamma}$, N_j, m_{jj}, $|\Delta\phi_{jj}|$, $p_T^{j_1}$ and their correlations



$H \to ZZ \to 4\ell$ coupling

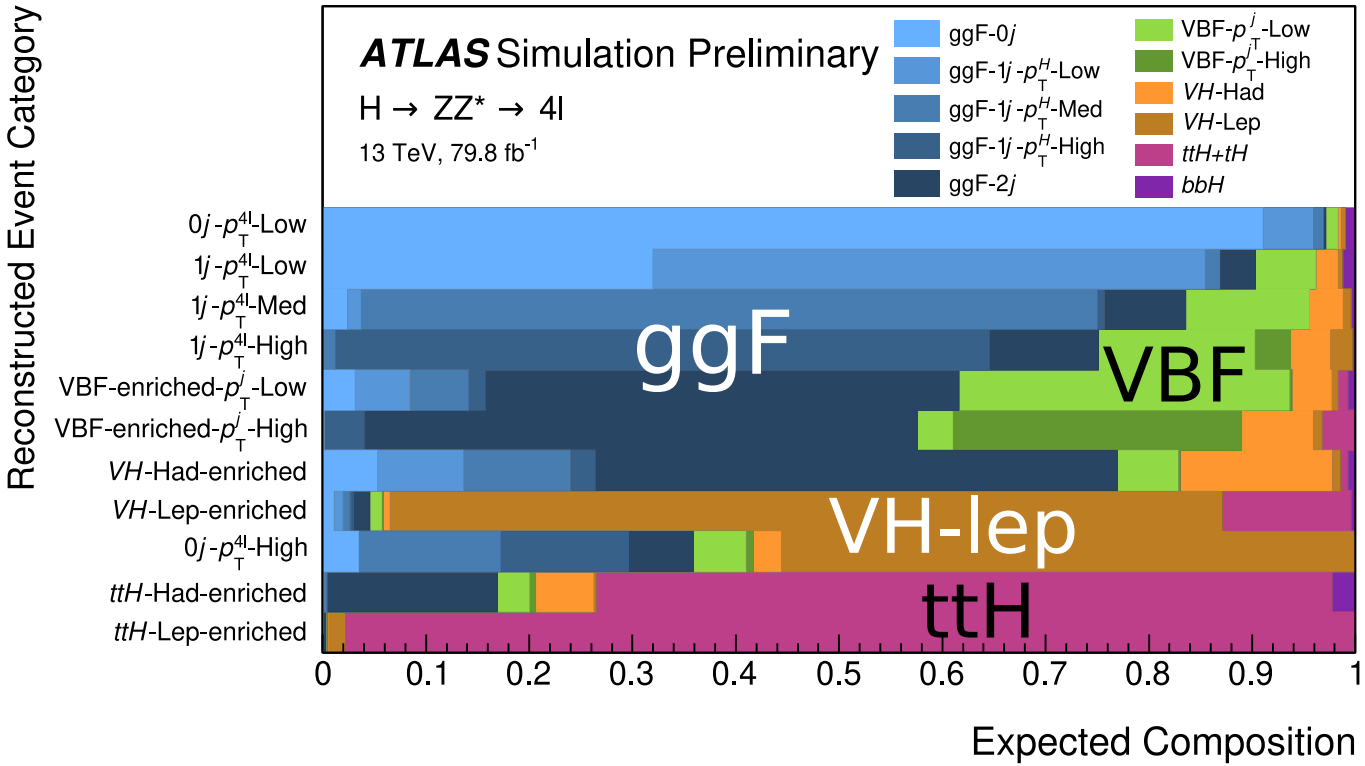
- Very pure channel, but less statistics
- Correct the mass for FSR photons
- Largest backgrounds from MC, fakes data driven





Use a reduced scheme due to limited statistics

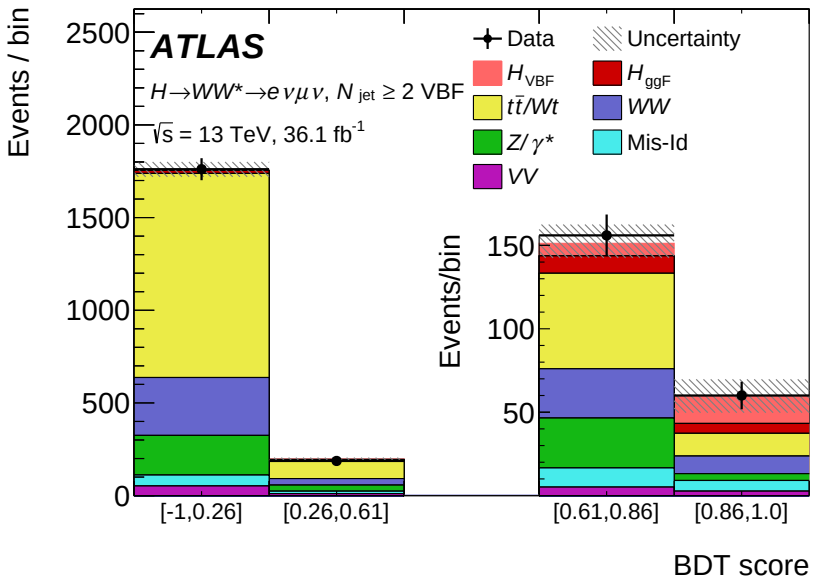
$H \to ZZ \to 4\ell$ coupling categorization

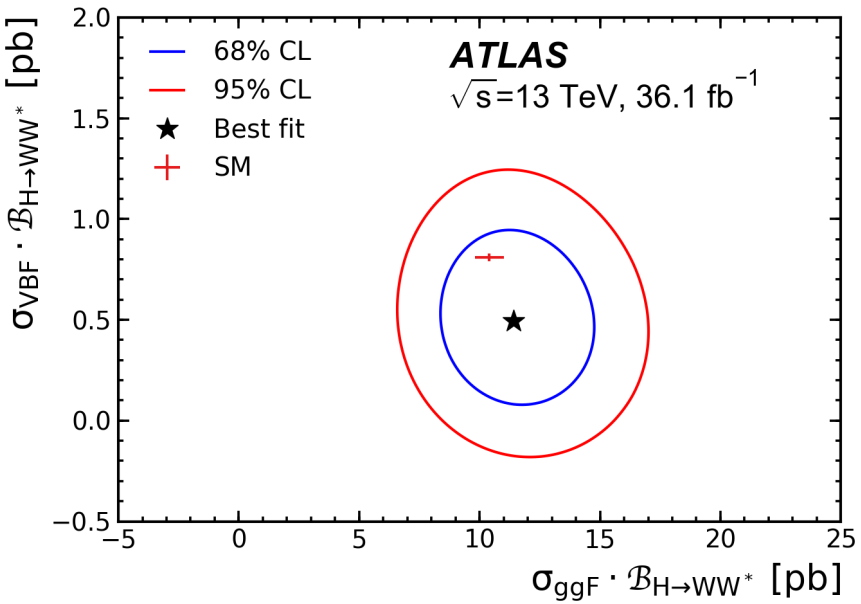


- Categorization of the events with simple cuts that mimic STXS definitions
- For each region as observable use the output of BDT distributions.
  - BDT using kinematic discrimintat (based on matrix elements) and other kinematic variables trained to remove ZZ^* background and ggF from other production modes.
- Main uncertainty from luminostiy and lepton efficiency

$H \to WW \to e\nu\mu\nu$

- Categorize by $N_j, m_{\ell\ell}, p_T^{\text{subl}}, (e/\mu)^{\text{subl}}$
- Use transverse mass (for ggF, i.e. 0,1 j) or BDT (for VBF i.e. 2j) as observable
- Background normalization from dedicated CR





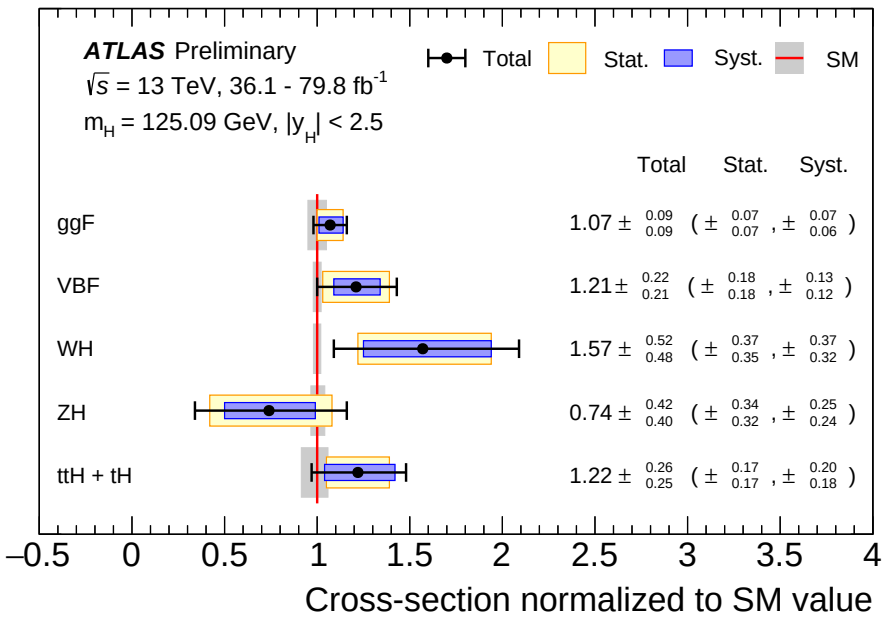
process	$\sigma \times$ BR	SM prediction
ggF	$11.4^{+1.2}_{-1.1}(\text{stat.})^{-1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp. syst.})$ pb	10.4 ± 0.6 pb
VBF	$0.50^{+0.24}_{-0.22}(\text{stat.}) \pm 0.10(\text{theo syst.})^{+0.12}_{-0.13}(\text{exp. syst.})$ pb	0.81 ± 0.02 pb

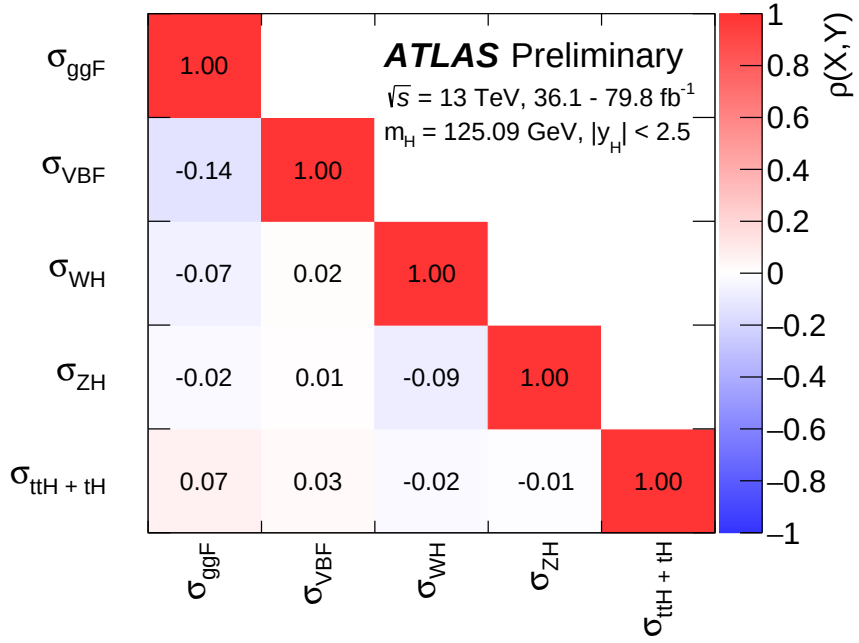
Important systematics from theory uncertainty on WW background.

Combination

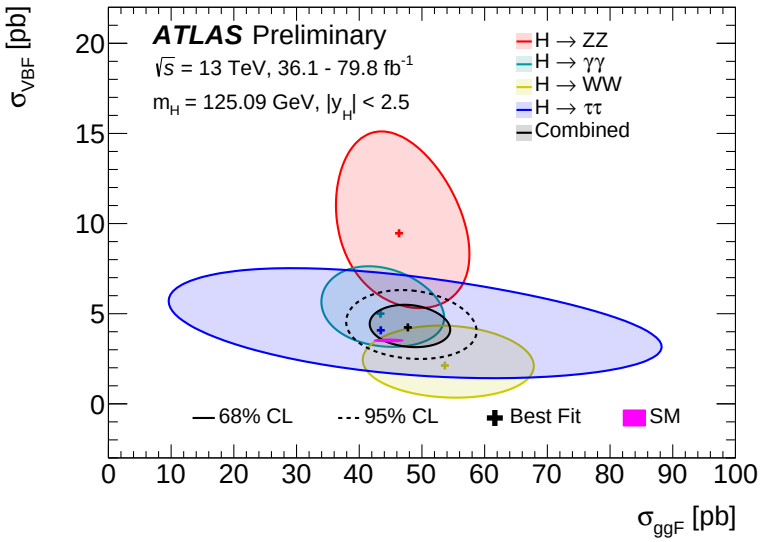
$\gamma\gamma + 4\ell + e\nu\mu\nu + \tau\tau + \mathrm{VH}(bb) + \mu\mu + \mathrm{ttH}(\mathrm{bb\ and\ multilepton})$

Cross sections per production mode $|y_H| < 2.5$





- All the measurement still dominated by statistics
- Main correlation from the contamination ggF in VBF
- Br fixed to SM (with uncertainties)

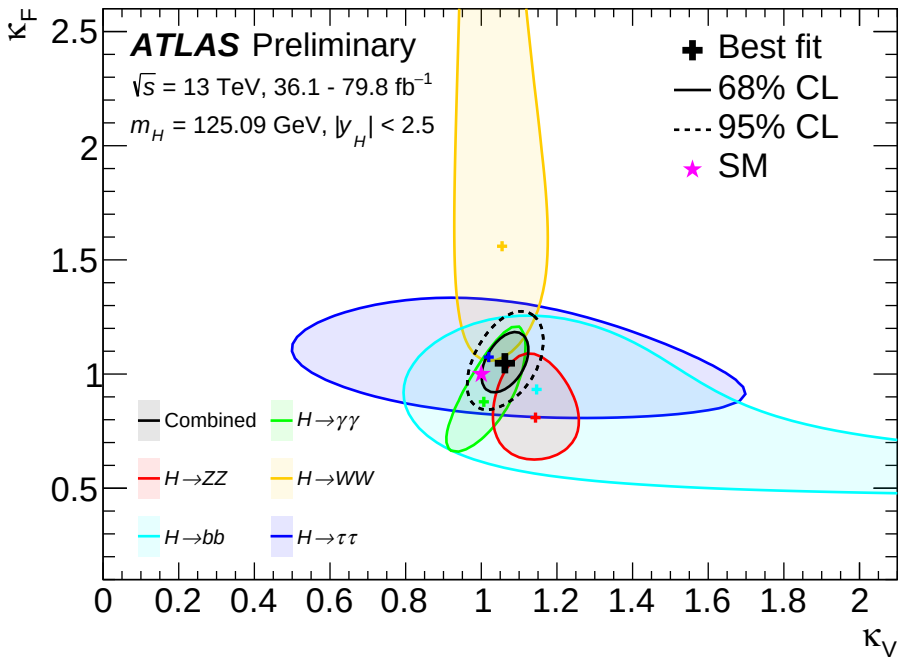


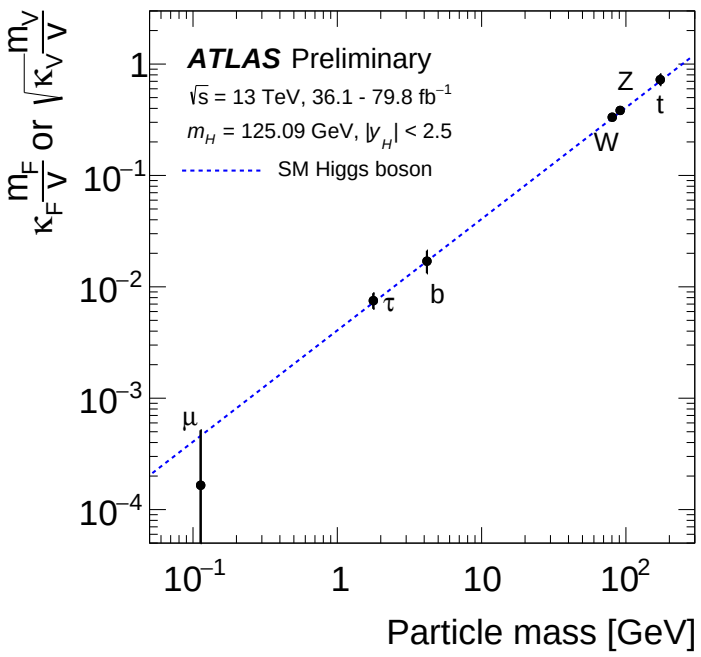
k-framework interpretation

$$(\sigma \times \mathrm{BR})_{if} = k_i^2 \sigma_i^{\mathrm{SM}} \times \frac{k_f^2 \Gamma_f^{\mathrm{SM}}}{k_H^2 \Gamma_H^{\mathrm{SM}}}$$

In the simpler case only two modifiers: k_V and k_F, $k_H^2 = k_H^2(k_V, k_F)$

or with more modifiers: k_μ, k_τ, k_t, k_b, k_W, k_Z

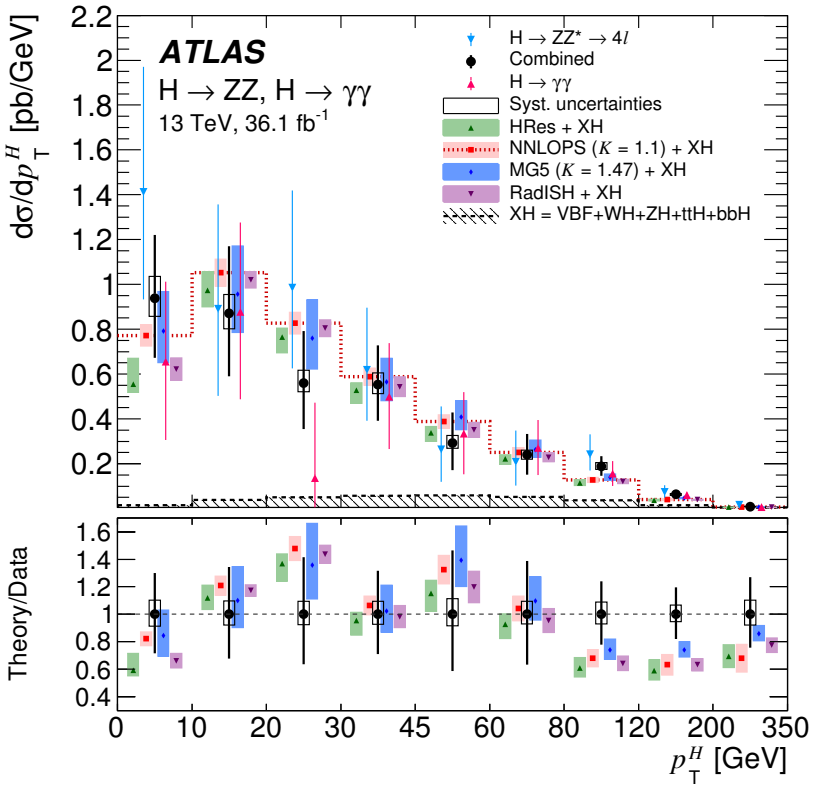


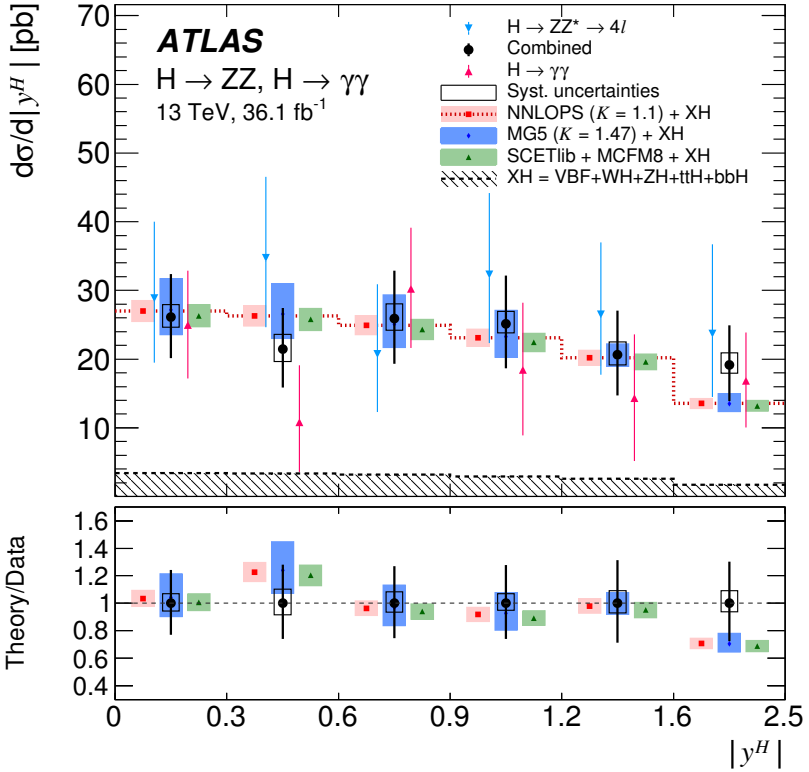


or k_g and k_γ and BSM contributions

Differential cross sections (p_T^H and $|y^H|$) with 36 fb^{-1} $\gamma\gamma$+4ℓ

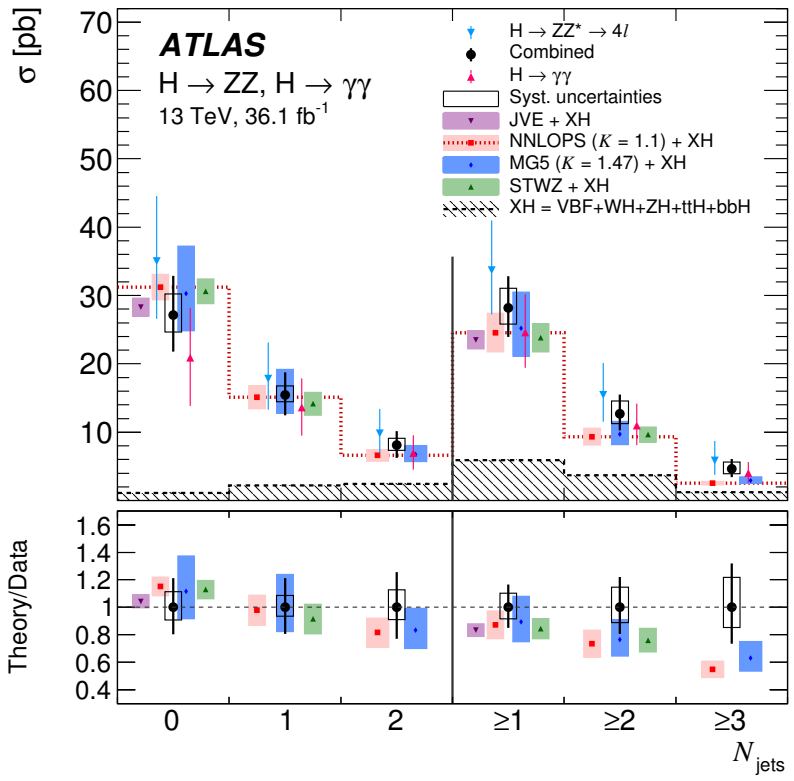
p_T^H sensitive to pQCD, $|y_H|$ sensitive to PDF

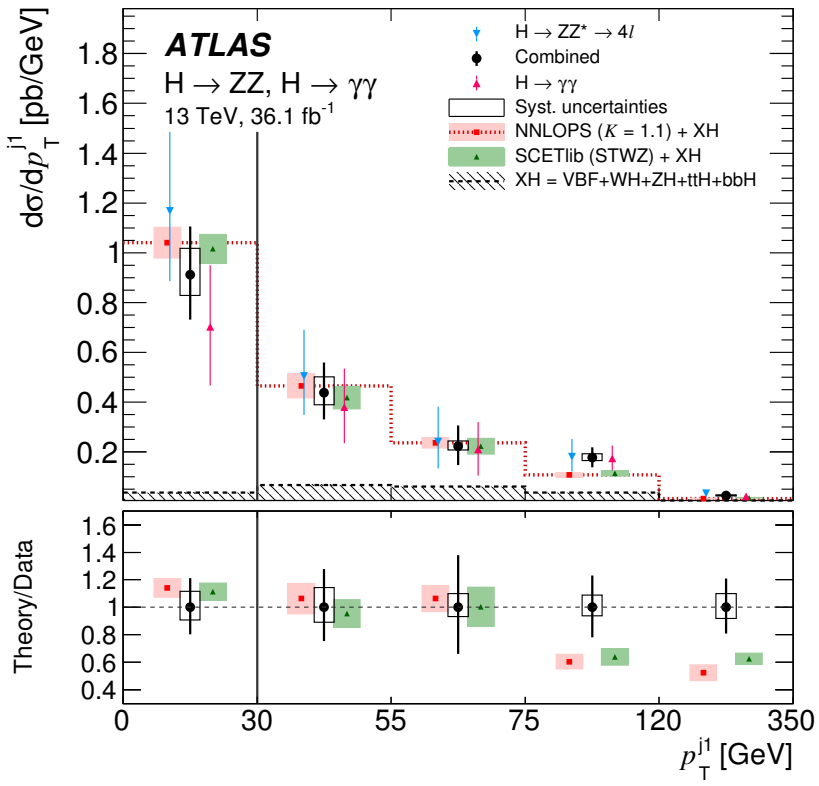




Differential cross sections (N_j and $p_T^{j_1}$) with 36 fb^{-1} $\gamma\gamma$+4ℓ

N_j and $p_T^{j_1}$ sensitive to high-p_T QCD radiation and to different production modes

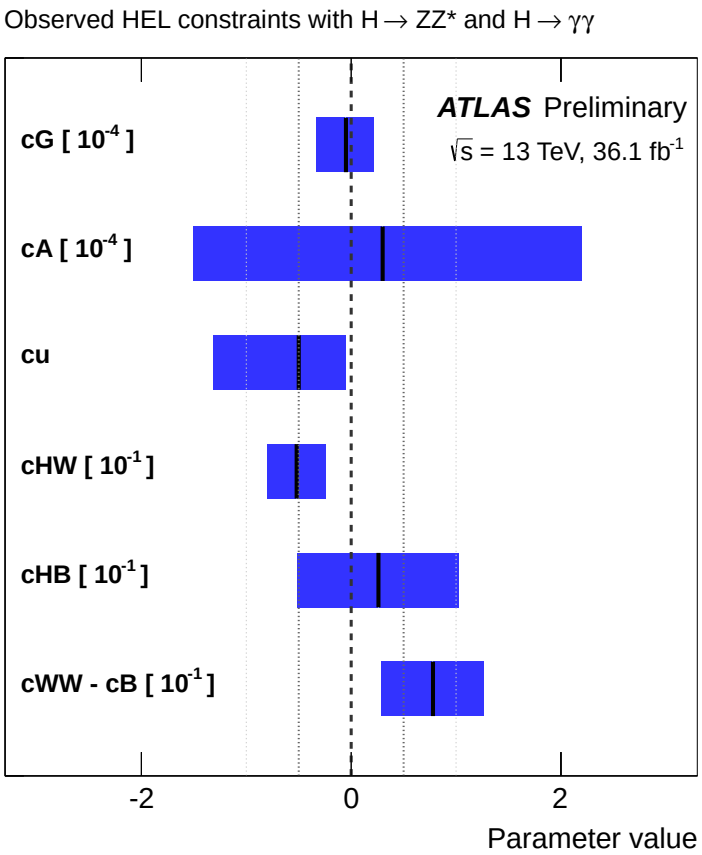


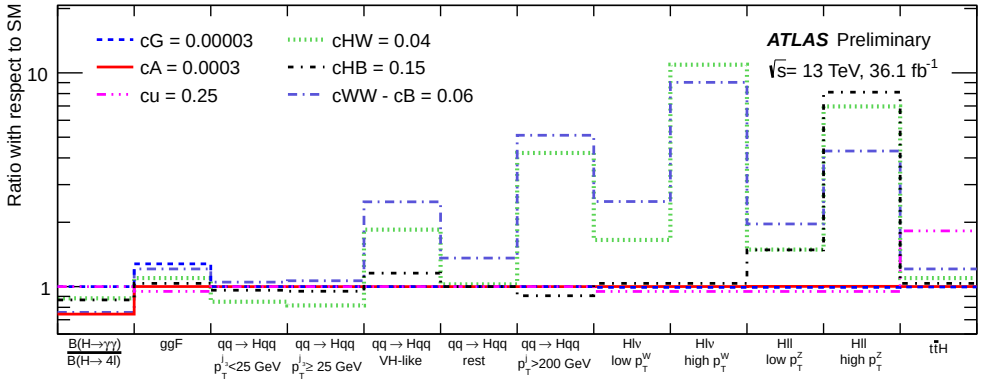


EFT interpretation from coupling STXS measurements with 36 fb^{-1}

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

Six coefficients $\bar{c}_i = c_i/\Lambda$ in the SIHL basis related to STXS cross-sections

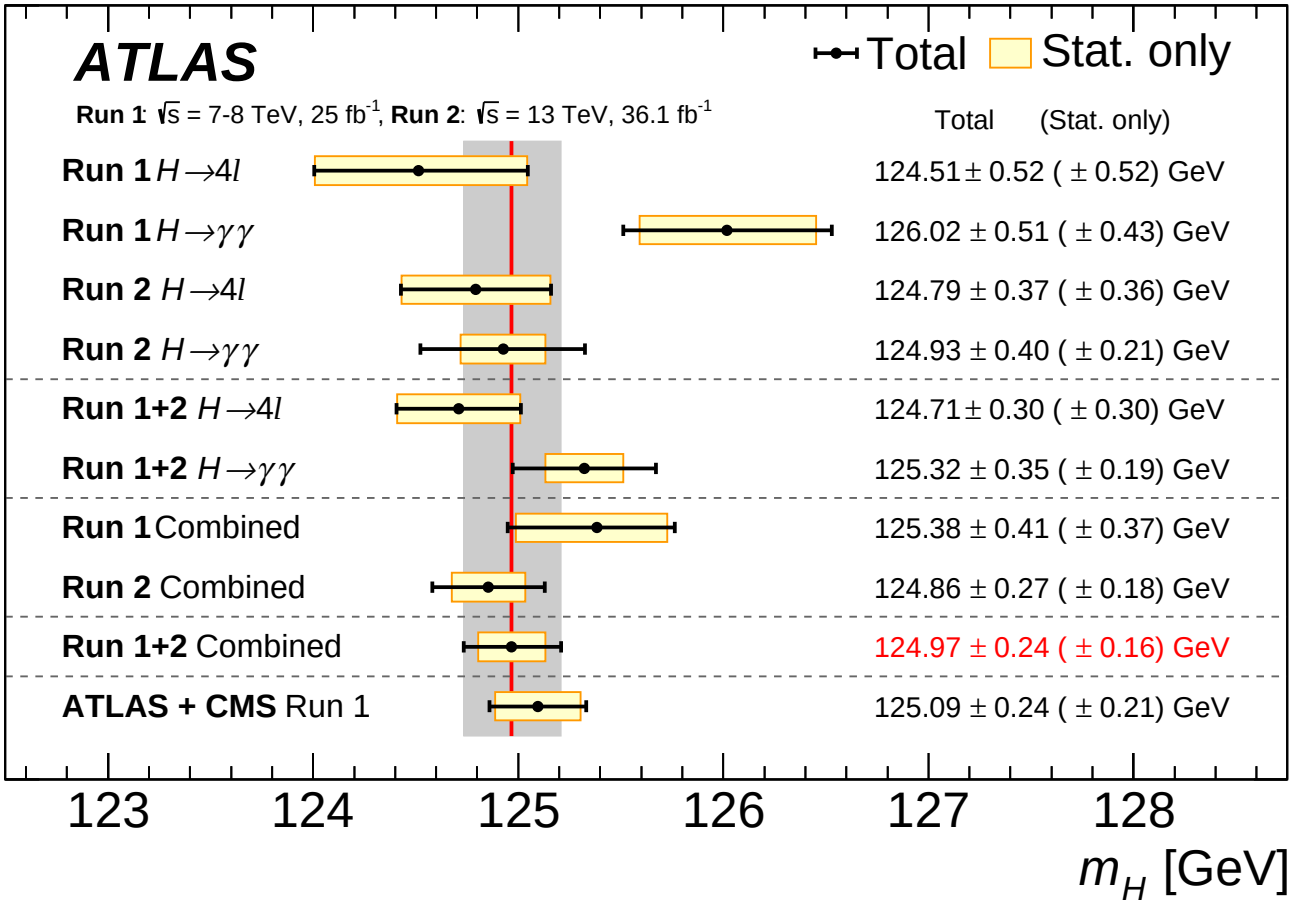


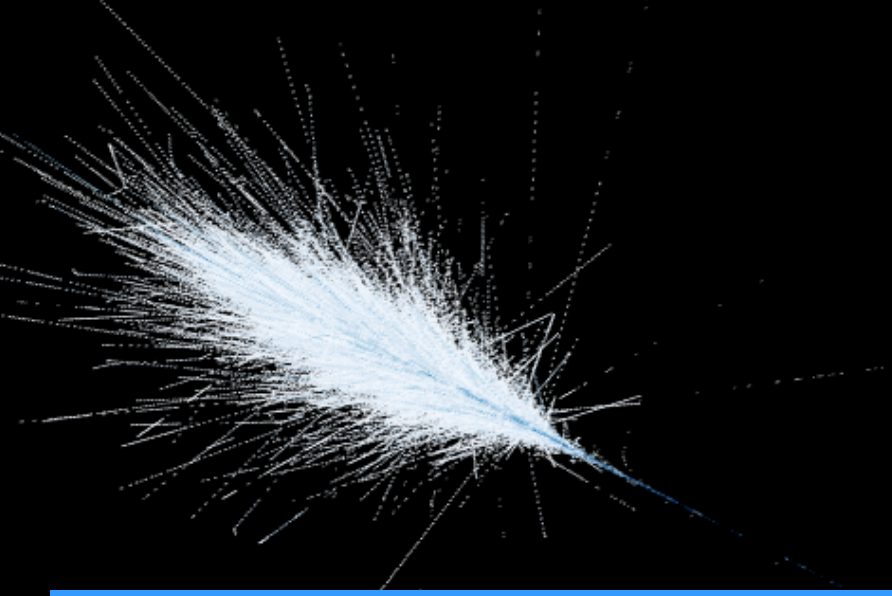


- Some correlations between parameters
- Good compatibility with SM (p-value 47%)
- Will add more measurements, larger set of operators

Mass measurement $\gamma\gamma + 4\ell$ with 36 fb^{-1}

- Hundreds of systematics on the energy/momentum scale of $\gamma/e/\mu$
- Energy scale mostly from $Z \to \ell\ell$ ($\langle p_T^\ell \rangle \simeq 40$ GeV) comparing data/MC
  - $H \to \gamma\gamma$ ($\langle p_T^\gamma \rangle \simeq 60$ GeV) starts to be dominated by systematics



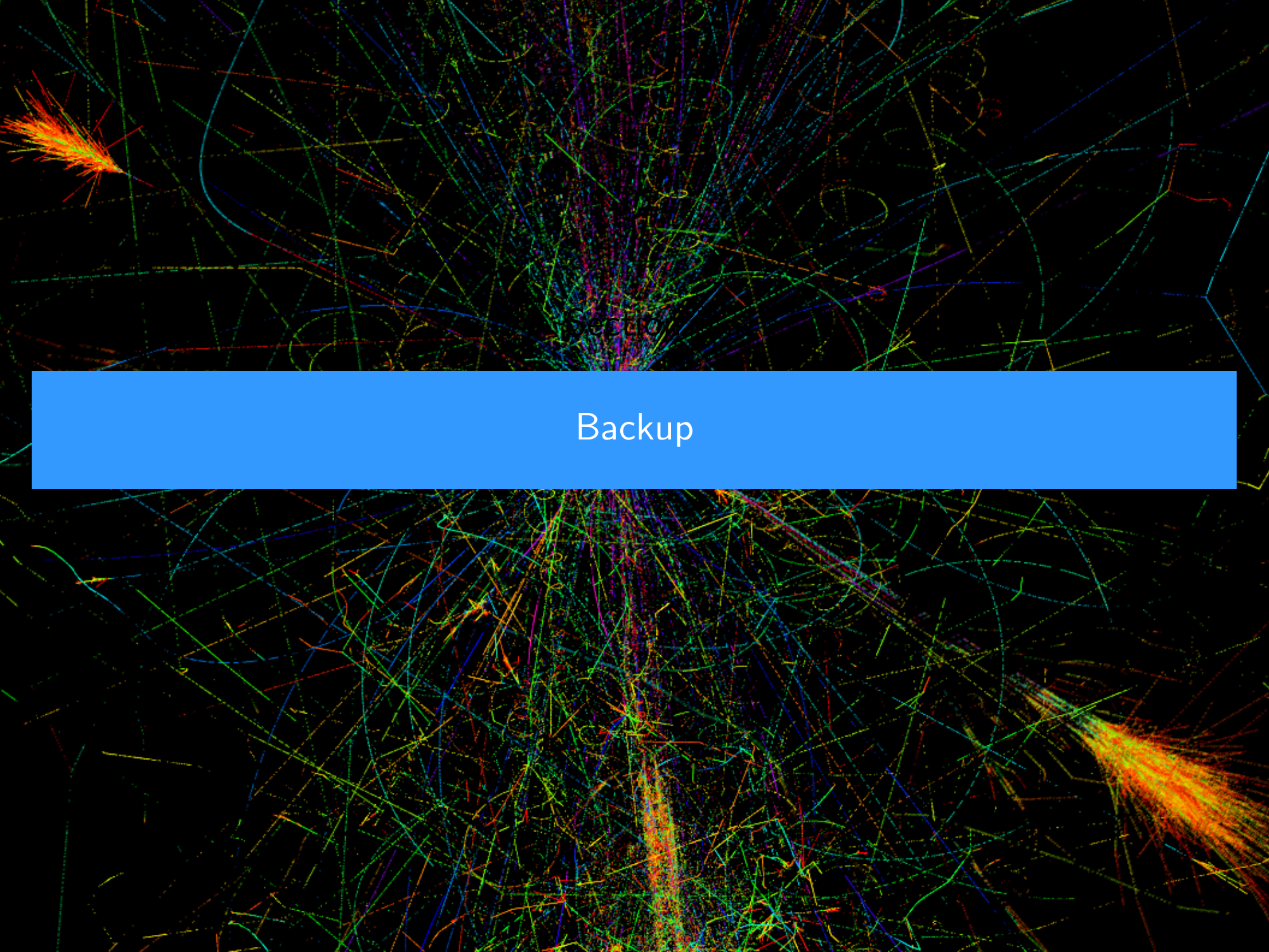


Conclusions

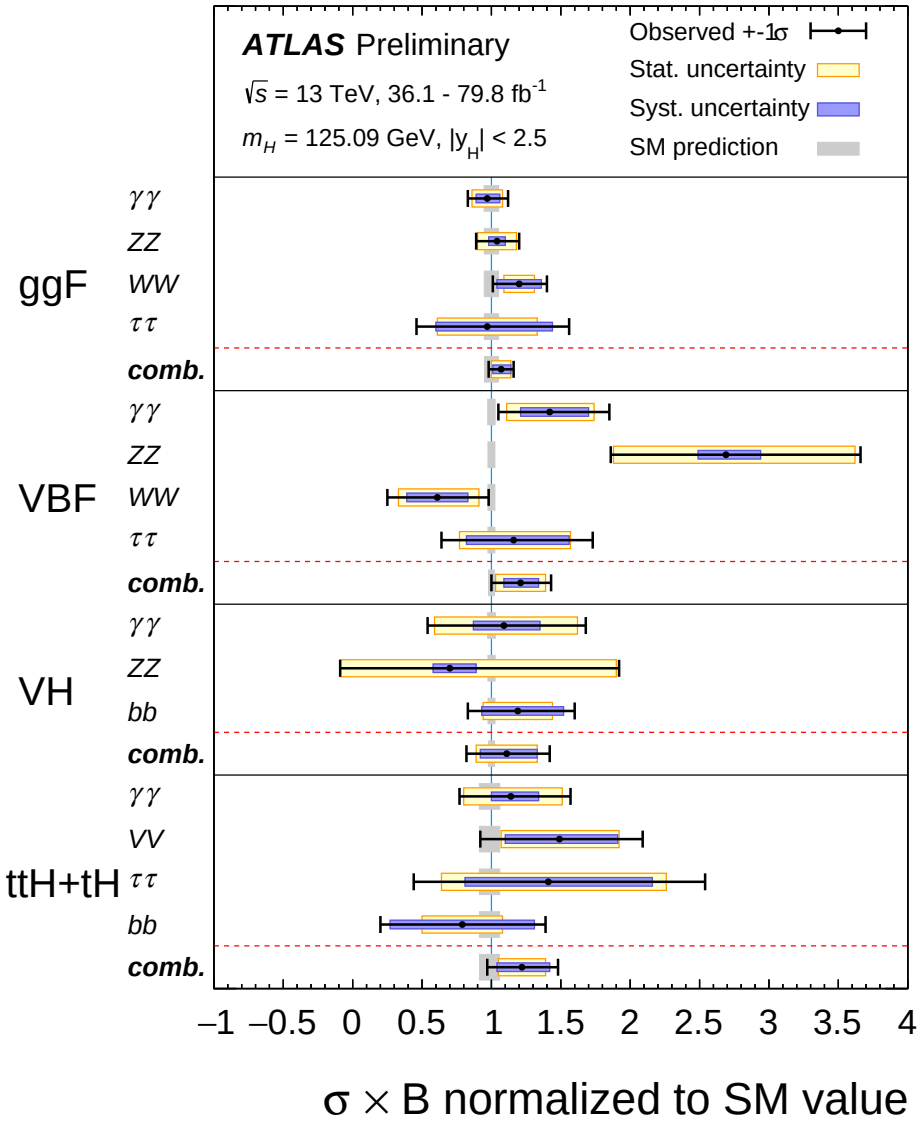
Conclusions

- Precision studies about Higgs boson from ATLAS have been presented: fiducial/differential cross sections, couplings, mass
- Preliminary results based on $80\,\mathrm{fb}^{-1}$, or $36\,\mathrm{fb}^{-1}$, using $\gamma\gamma$, $ZZ(4\ell)$, $WW(e\nu\mu\nu)$ decays
- More data $\Rightarrow$ more measurements, more differential, more complicated interpretations ($\mu \rightarrow k_i \rightarrow EFT/PO$)
- No deviation from SM
- Now working on final Run2 papers with $140\,\mathrm{fb}^{-1}$


Thanks for your attention

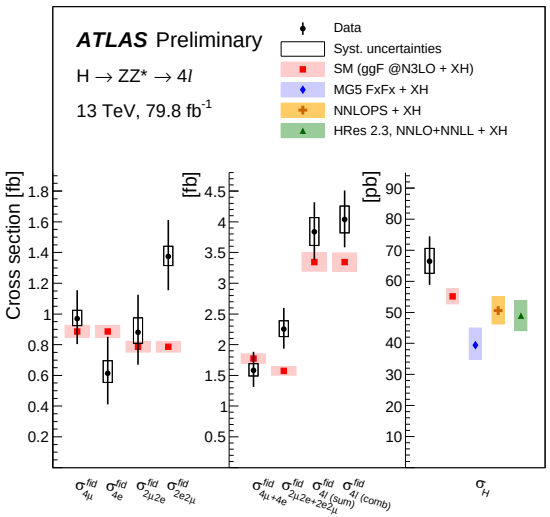


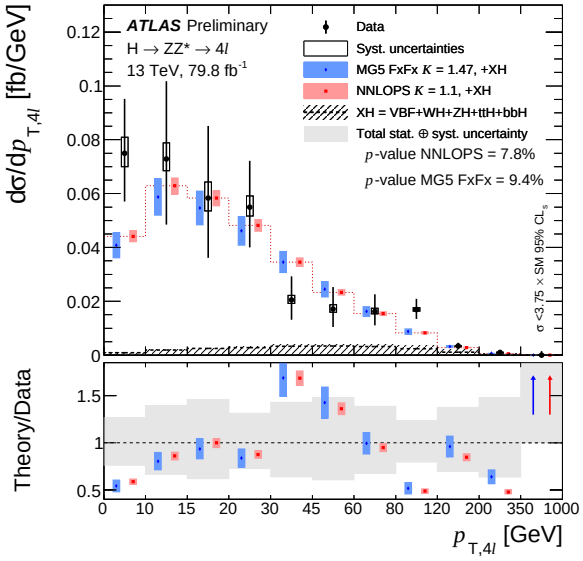
Backup

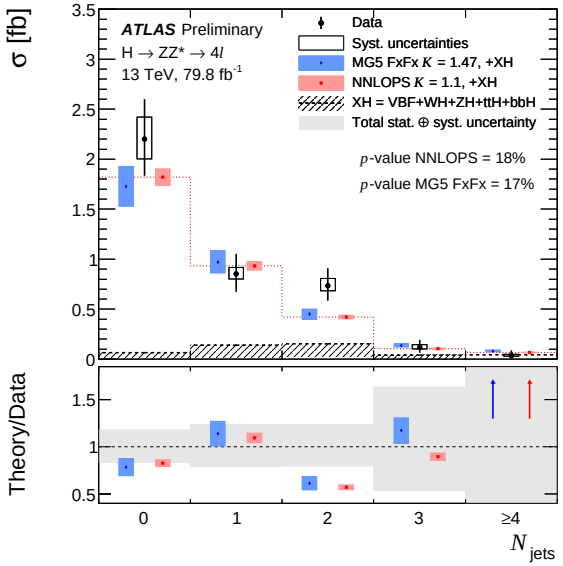

ATLAS Preliminary
√s = 13 TeV, 36.1 - 79.8 fb-1
mH = 125.09 GeV, |yH| < 2.5
Observed +-1σ
Stat. uncertainty
Syst. uncertainty
SM prediction
ggF
γγ
ZZ
WW
ττ
comb.
VBF
γγ
ZZ
WW
ττ
comb.
VH
γγ
ZZ
bb
comb.
ttH+tH
γγ
VV
ττ
bb
comb.
–1 –0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
σ × B normalized to SM value

$H \to ZZ \to 4\ell$ (differential) cross sections

- Categorize by flavour: 4μ, $2\mu 2e$, $2e2\mu$, $4e$
- Fit $m_{4\ell}$ distribution
- Fiducial regions (by flavours), total and differential ($p_T^{4\ell}$, N_j) cross sectionss



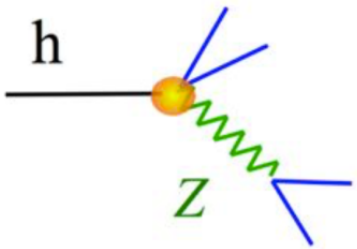


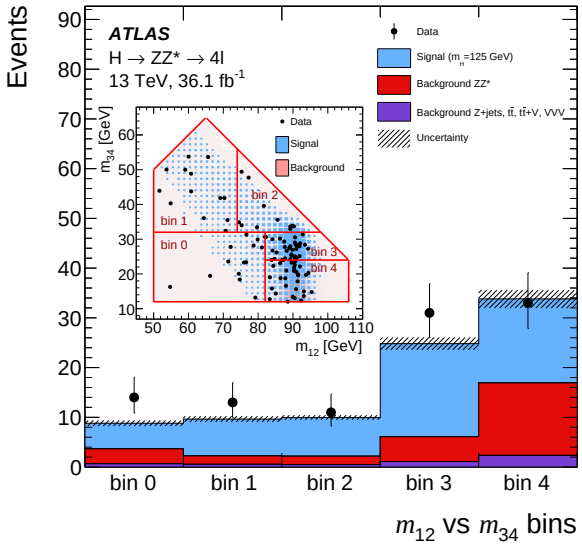


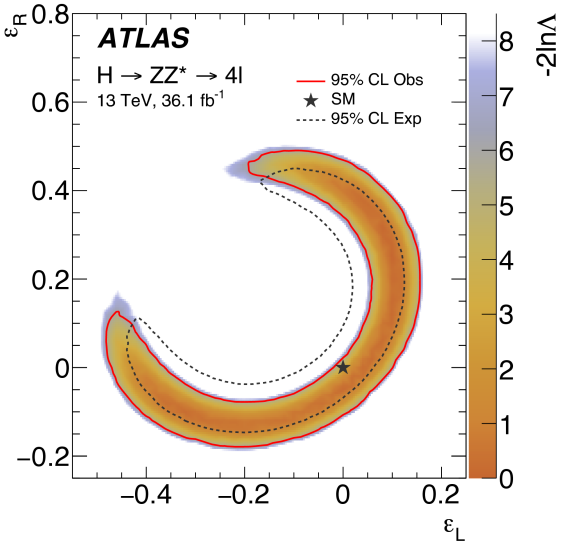
In addition study contact interaction with the Z boson, and left or right-handed leptons (in the pseudo-observable framework)

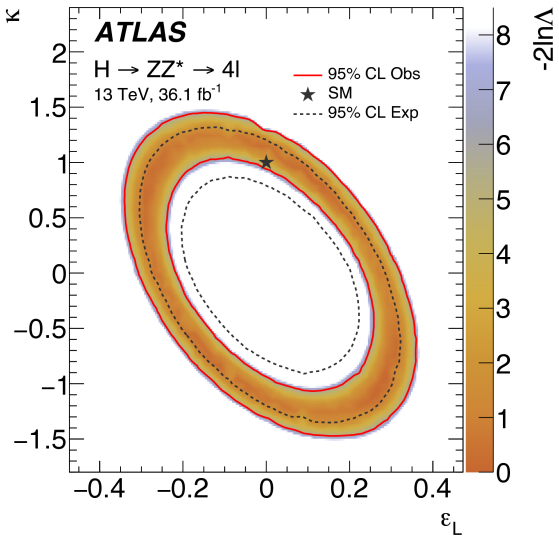
Contanct interaction with pseudo observables $H \to 4\ell$

- Using double differential $m_{12} \oplus m_{34}$
- Extension to k-framework: probe anomalous coupling to leptons (left ε_L, right ε_R) and Z (k)

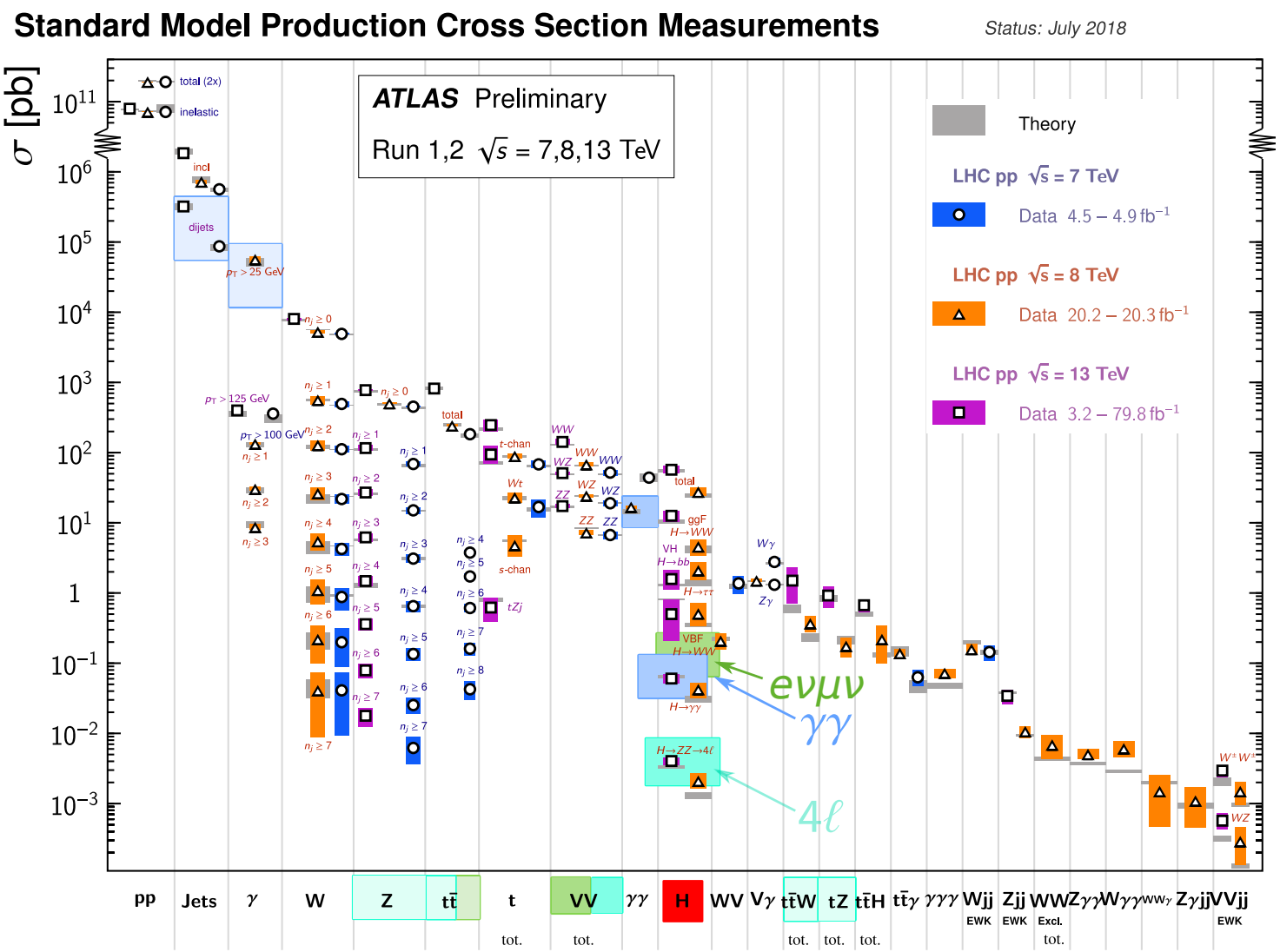








$\gamma\gamma$, $ZZ^* \to 4\ell$, $WW^* \to e\nu\mu\nu$



$H \to \gamma\gamma$ efficiencies