Combined Higgs boson measurements at the ATLAS experiment

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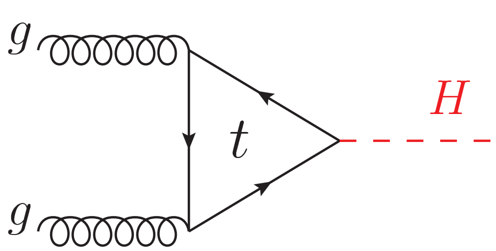
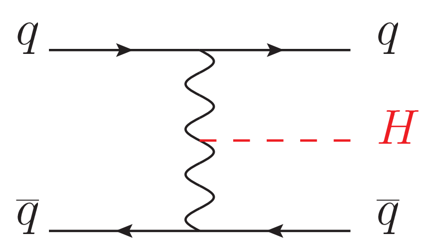
on behalf of the ATLAS Collaboration

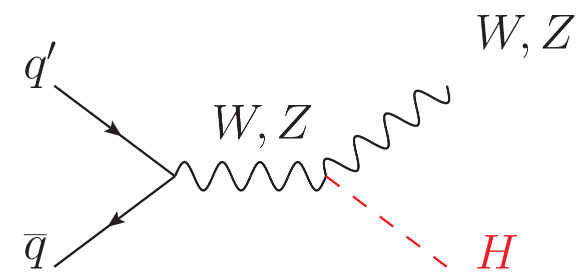
Higgs production and decay at the LHC (@13 TeV)



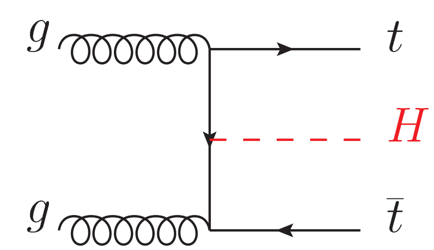
gluon fusion (ggF)
σ = 48.6 pb



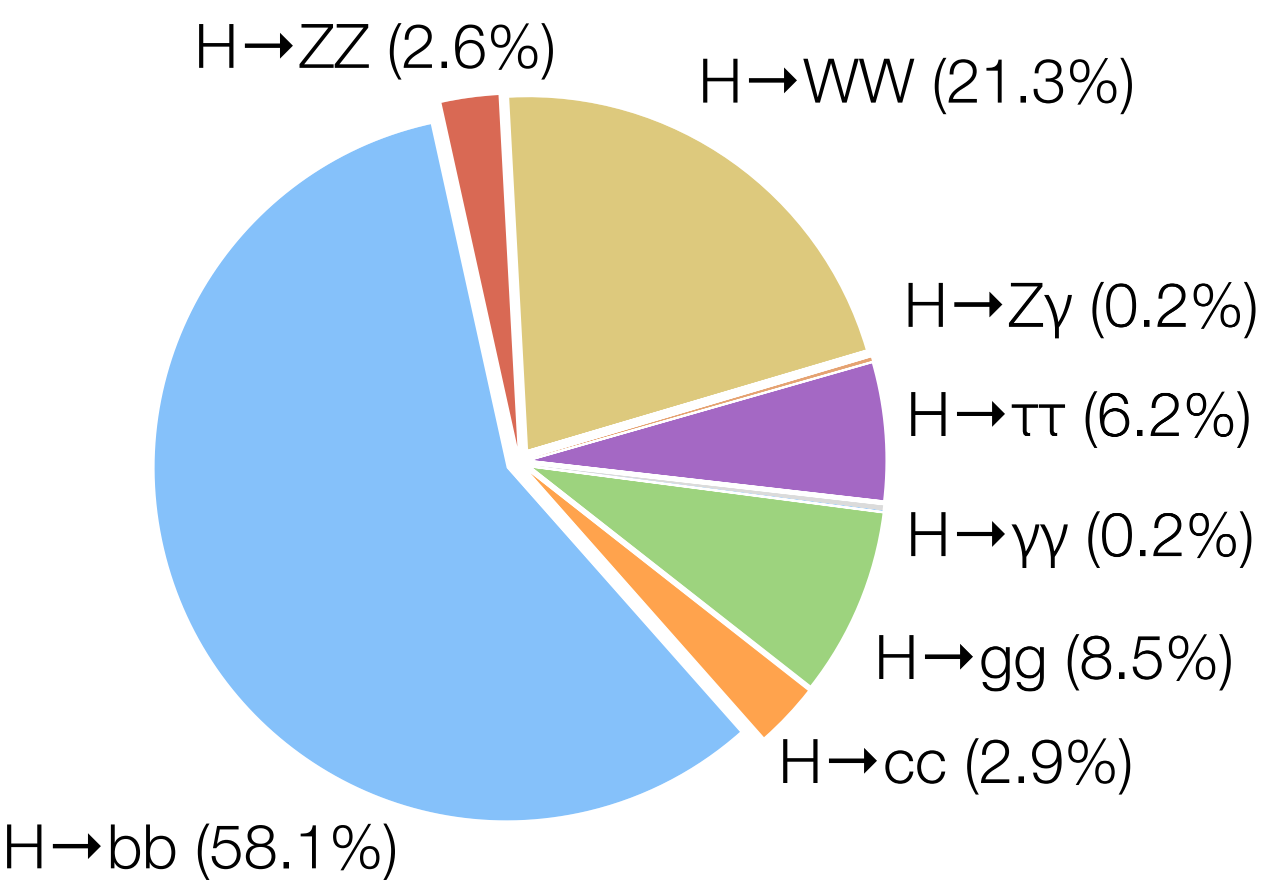
Vector-boson fusion (VBF)
σ = 3.78 pb



Higgs-strahlung (*WH/ZH*)
σ = 2.25 pb



associated prod. with top pair (*ttH*)
σ = 0.5 pb



not all channels visible on this chart!

- Access to many:
  - production mechanisms (see top)
  - decay channels (see left)
- Stringent test of the SM validity can be derived by combining all experimental accessible channels!

Latest ATLAS combined Higgs measurements

- ATLAS has recently performed a very comprehensive combination of all the available channels, summarised in ATLAS-CONF-2019-005

- In this talk:
  - global signal strength measurement
    (ratios of the measured Higgs boson yields and their SM expectations)
  - measurements of production cross sections
  - measurements in kinematic regions defined within the simplified template cross section (STXS) framework
  - measurements in the framework of multiplicative modifiers κ

Overview: input analyses

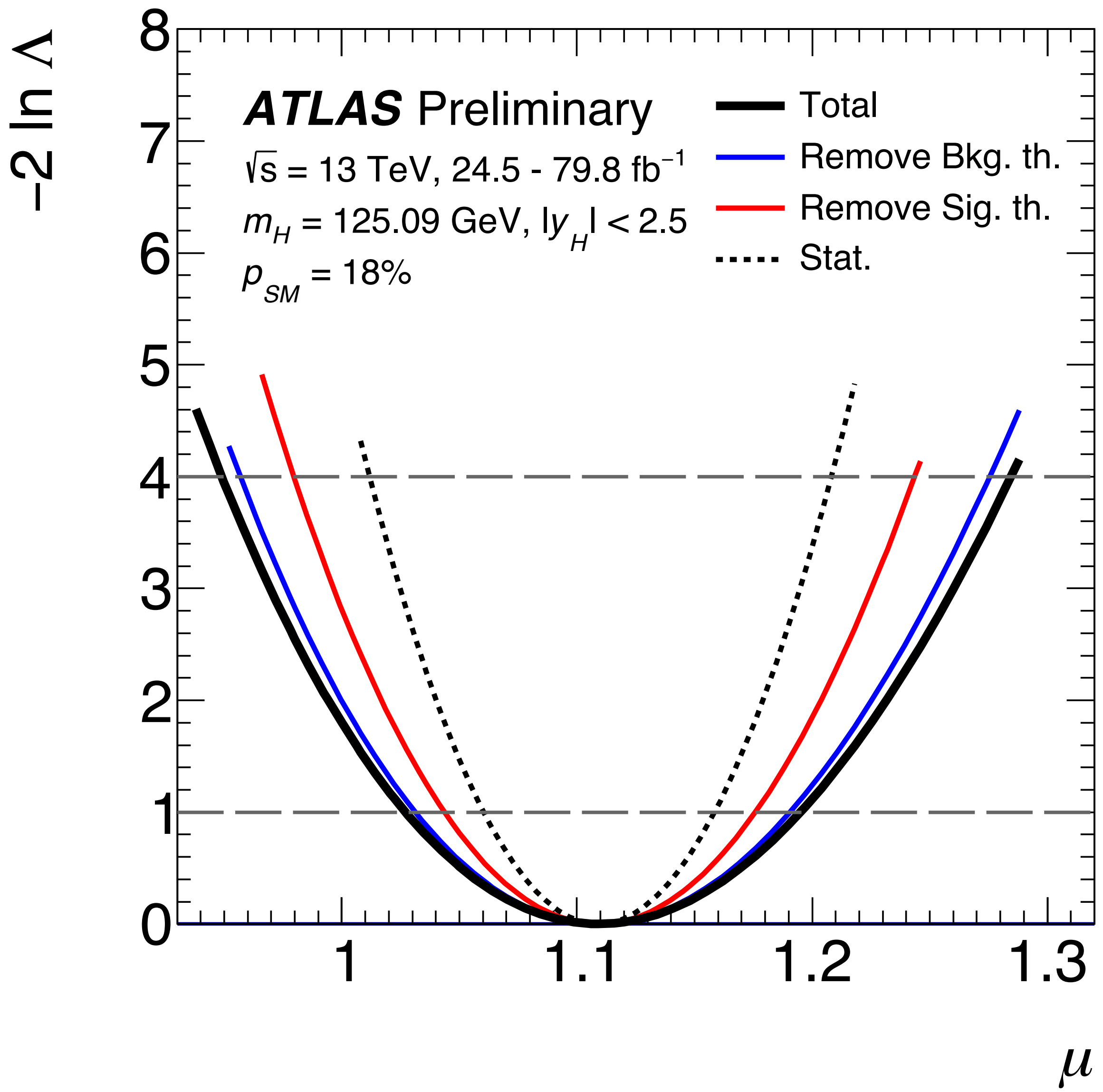
Analysis	Integrated luminosity (fb^{-1})
$H\to\gamma\gamma$ (including $t\bar{t}H$, $H\to\gamma\gamma$)	79.8
$H\to ZZ^*\to 4\ell$ (including $t\bar{t}H$, $H\to ZZ^*\to 4\ell$)	79.8
$H\to WW^*\to e\nu\mu\nu$	36.1
$H\to\tau\tau$	36.1
VH, $H\to b\bar{b}$	79.8
VBF, $H\to b\bar{b}$	24.5 – 30.6
$H\to\mu\mu$	79.8
$t\bar{t}H$, $H\to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H\to$ invisible	36.1
Off-shell $H\to ZZ^*\to 4\ell$ and $H\to ZZ^*\to 2\ell 2\nu$	36.1

- Off-shell and H→invisible only used for results in the κ-framework
- H→μμ used in the κ-framework and BSM interpretation
- VBF, H→bb not used in the simplified template cross sections results

Inclusive signal strength (μ)

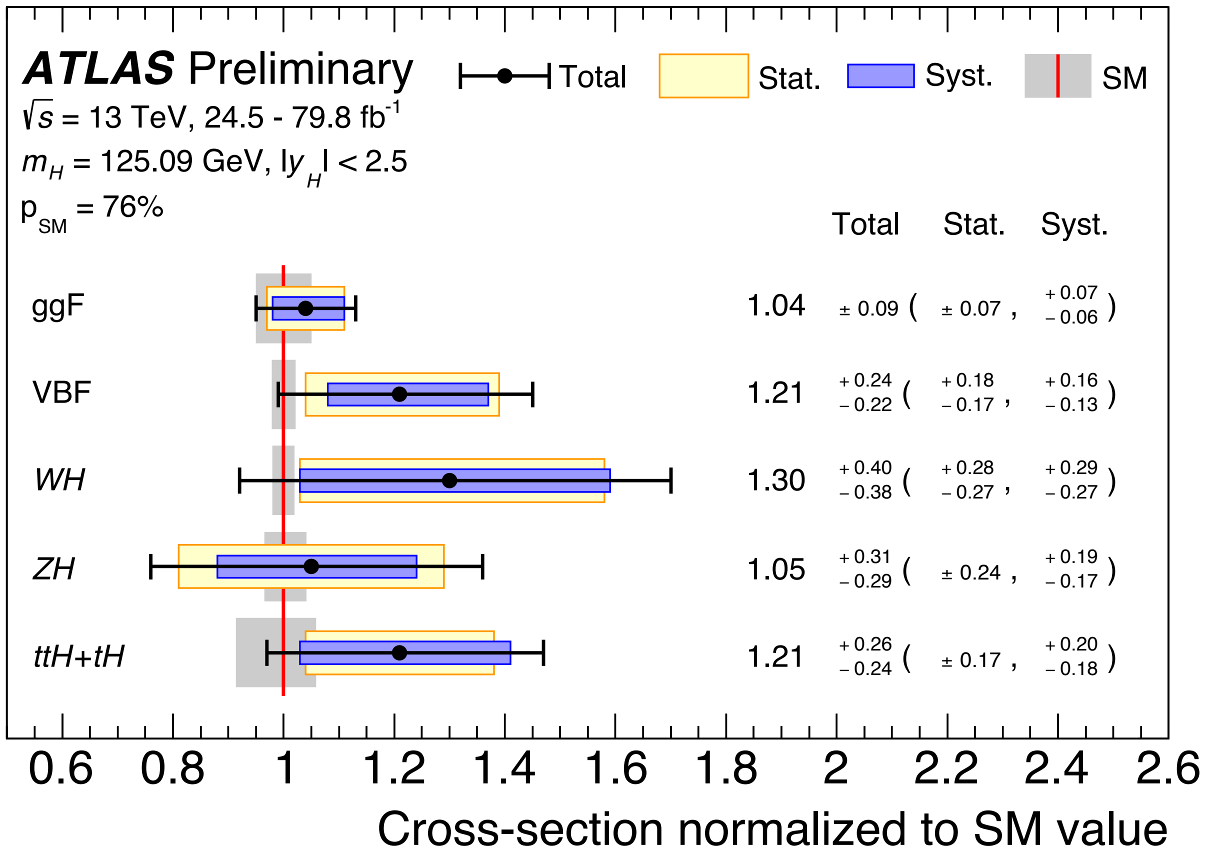
Signal strength: ratio of the total Higgs boson signal yield to its SM prediction

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



Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

Production cross-sections



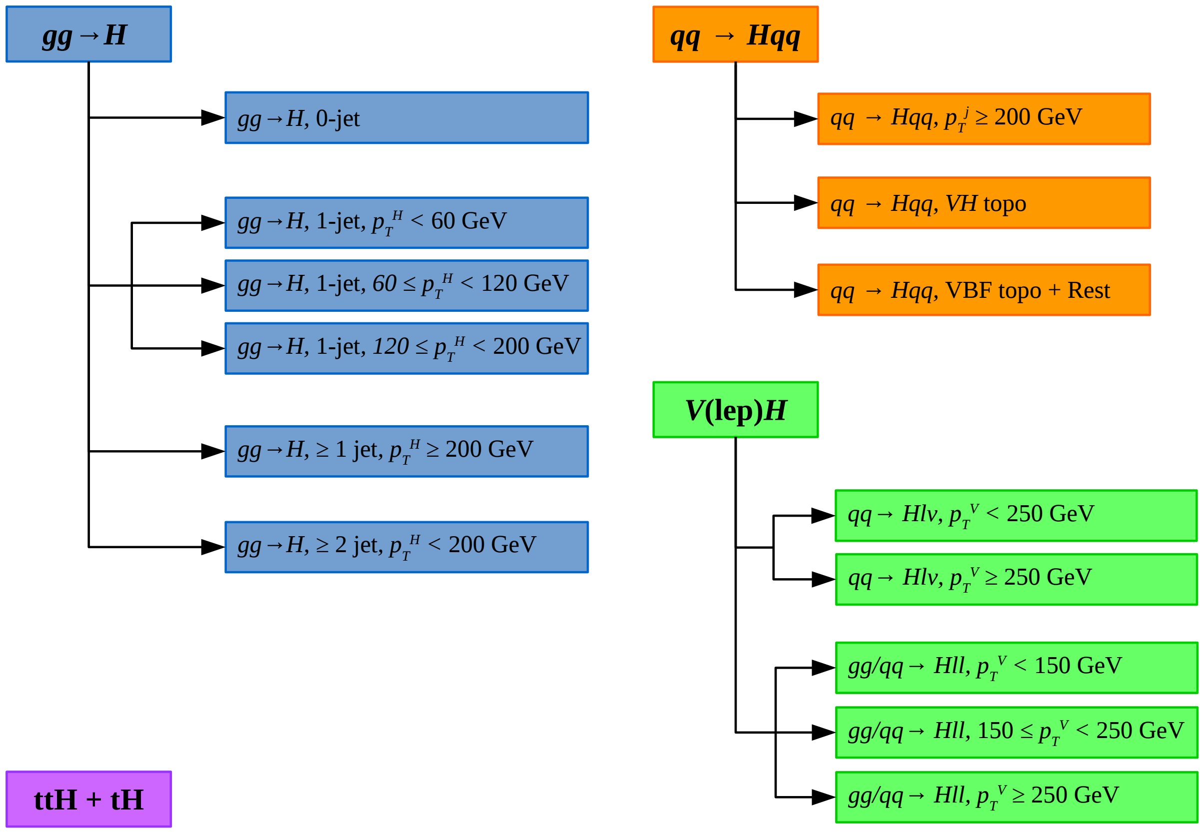
- Much smaller correlations with respect to previous analyses (here and here)
  - mild correlation between ggF and VBF (-15%) remaining
- Statistical and systematic uncertainties at the same level
- SM BR assumed here (and uncertainty included)
- bbH included in ggF, tH included in ttH, ggZH fully attributed to ZH
- Production cross-section times BR also measured (see backup)

Process ($\|y_H\| < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [pb]	Significance obs. (exp.)
ggF	46.5	± 4.0	± 3.1	± 2.2	± 0.9	± 1.3	44.7 ± 2.2	-
VBF	4.25	$^{+0.84}_{-0.77}$	$^{+0.63}_{-0.60}$	$^{+0.35}_{-0.32}$	$^{+0.42}_{-0.32}$	$^{+0.14}_{-0.11}$	3.515 ± 0.075	6.5 (5.3)
WH	1.57	$^{+0.48}_{-0.46}$	$^{+0.34}_{-0.33}$	$^{+0.25}_{-0.24}$	$^{+0.11}_{-0.07}$	± 0.20	1.204 ± 0.024	3.5 (2.7) } 5.3 (4.7)
ZH	0.84	$^{+0.25}_{-0.23}$	± 0.19	± 0.09	$^{+0.07}_{-0.04}$	± 0.10	$0.797^{+0.033}_{-0.026}$	3.6 (3.6)
$t\bar{t}H+tH$	0.71	$^{+0.15}_{-0.14}$	± 0.10	± 0.07	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	$0.586^{+0.034}_{-0.049}$	5.8 (5.4)

Simplified template cross section (STXS)

Les Houches '15
YR4

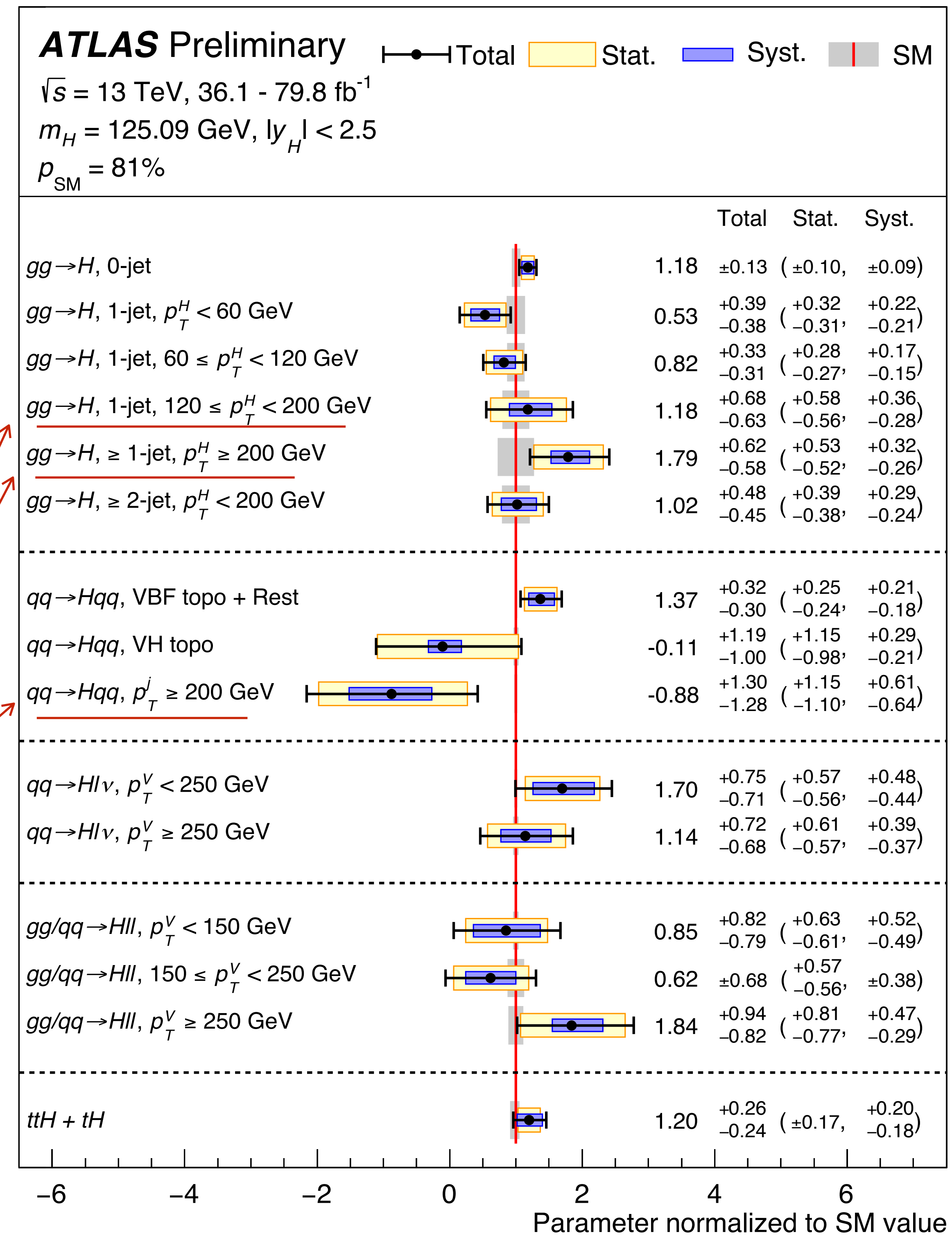
- Main goal: reduce model dependence and maximise sensitivity to BSM physics, by measuring cross-sections per production mode in different phase-space regions
- Benefits greatly by the combination of all available decay channels!



- “Staged” approach necessary, as these regions need to match the experimentally accessible ones
  - so-called “stage 1” used here, with some regions grouped due to limited experimental sensitivity

STXS results

- Here showing results with BR fixed to the SM expectation
- Also available (see backup):
  - cross sections times $H \rightarrow ZZ^*$ BR (with further measurements of BR_f/BR_{ZZ})
  - finer granularity
- No significant deviation from SM expectations: p-value = 81%
- Large anti-correlation when cross-contaminations between processes in the experimental selections are present



κ-framework

- Study modifications of the Higgs boson couplings related to BSM physics
- Assume production and decay can be factorised
- Cross section times branching fraction parametrised as

$$\sigma_i \times \mathrm{B}_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

- Coupling strength modifiers defined as

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}.$$

- Higgs boson total width also modified:

$$\kappa_H^2 = \sum_j \mathrm{B}_f^{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_H(\boldsymbol{\kappa}, \mathrm{B}_{\mathrm{inv}}, \mathrm{B}_{\mathrm{undet}}) = \frac{\kappa_H^2(\boldsymbol{\kappa})}{(1 - \mathrm{B}_{\mathrm{inv}} - \mathrm{B}_{\mathrm{undet}})} \Gamma_H^{\mathrm{SM}}$$

- LHC data insensitive to κ_c and κ_s (assumed here to vary like κ_t and κ_b, respectively)

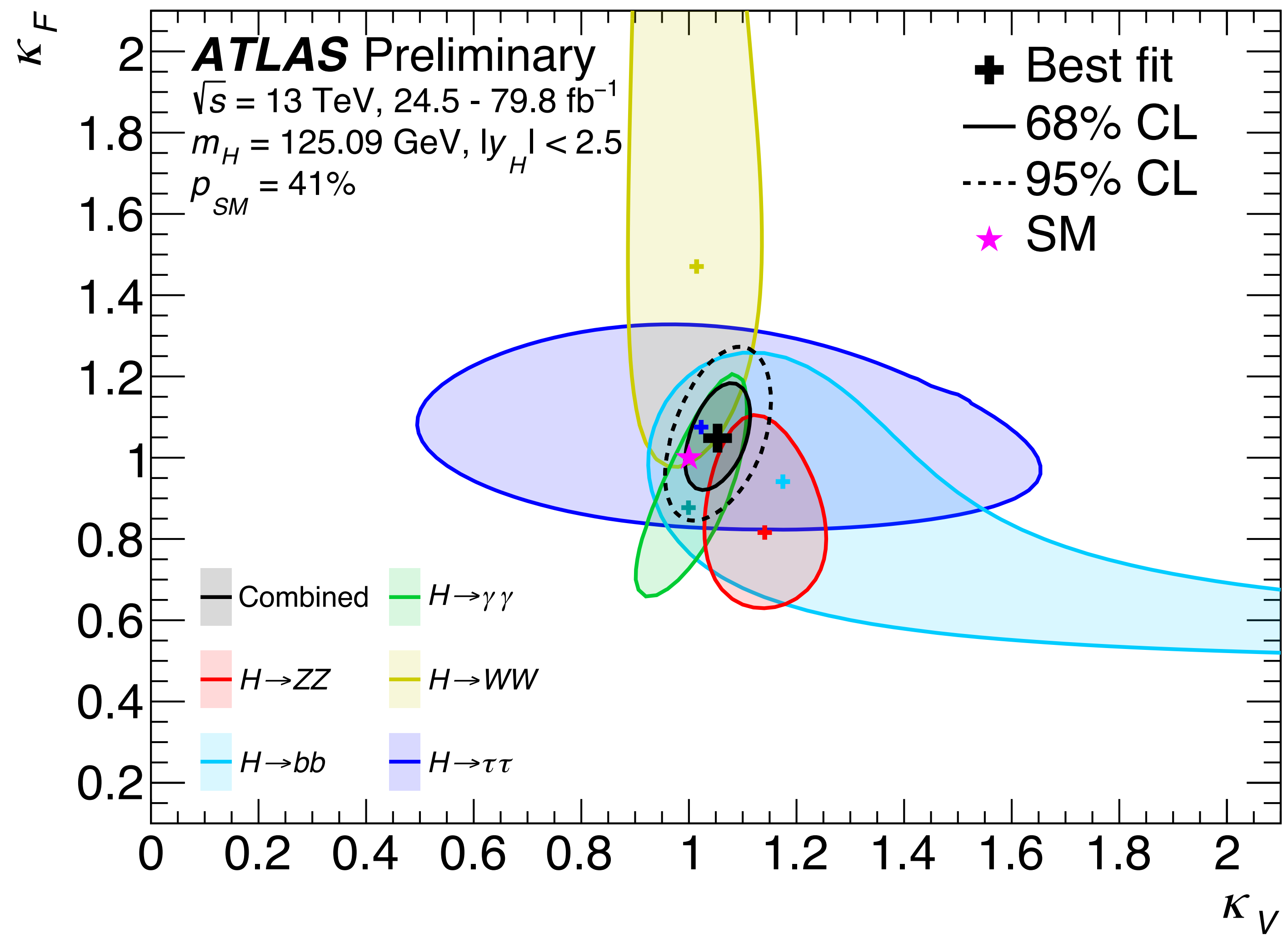
Fermion and gauge boson couplings

- $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$
- no invisible or undetected decay assumed
- only relative sign is physical, and a negative sign has already been excluded

$$\kappa_V = 1.05 \pm 0.04$$

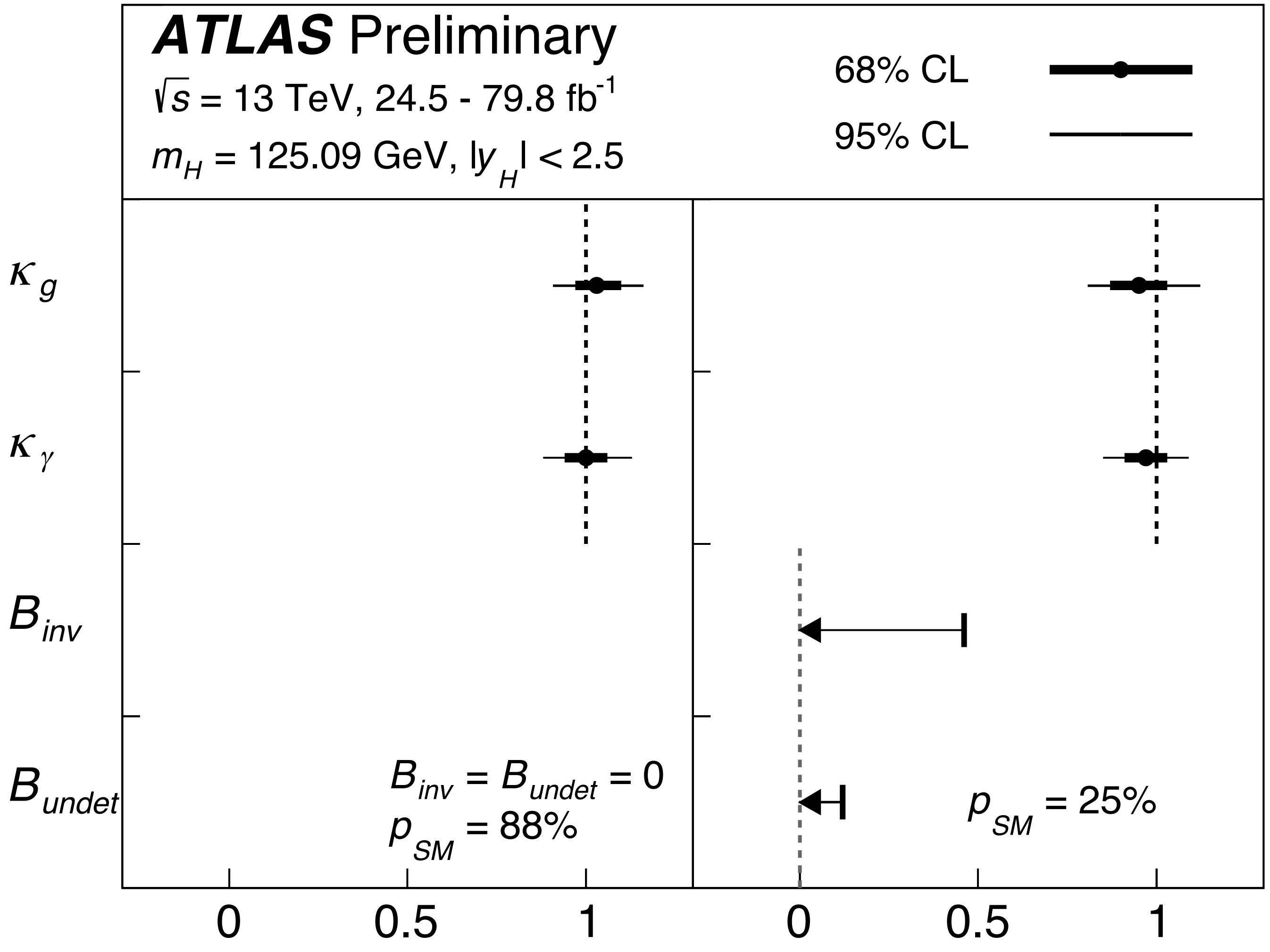
$$\kappa_F = 1.05 \pm 0.09$$

- no deviation from the SM prediction
- linear correlation of 44% observed in combined measurement



BSM contributions in loops and decays

- Measure $\boldsymbol{\kappa_g}$ and $\boldsymbol{\kappa_\gamma}$ to probe for BSM effects in loops and decays
- All other coupling strength modifiers fixed to their SM values
- Either assuming no invisible or undetected decay (B_{inv}=B_{undet}=0), or including B_{inv} and B_{undet} as free parameters



Coupling to different particles

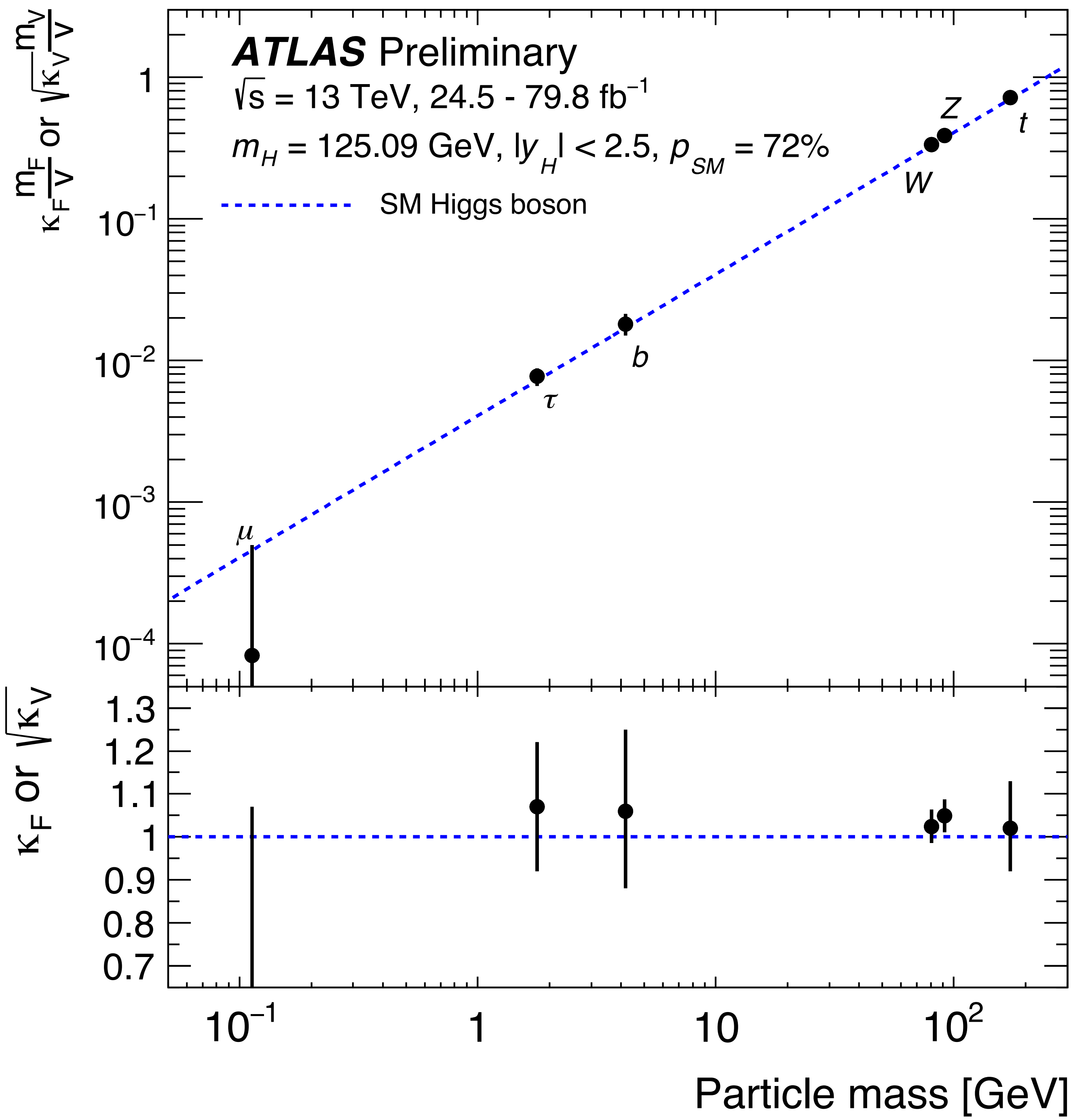
- Coupling strengths to W, Z, t, b, τ and μ treated independently

$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

  - assuming no BSM contributions to the Higgs decays, and SM loop structure for ggF, H→γγ and H→gg

Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06^{+0.19}_{-0.18}$
κ_t	$1.02^{+0.11}_{-0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.51 at 95% CL.



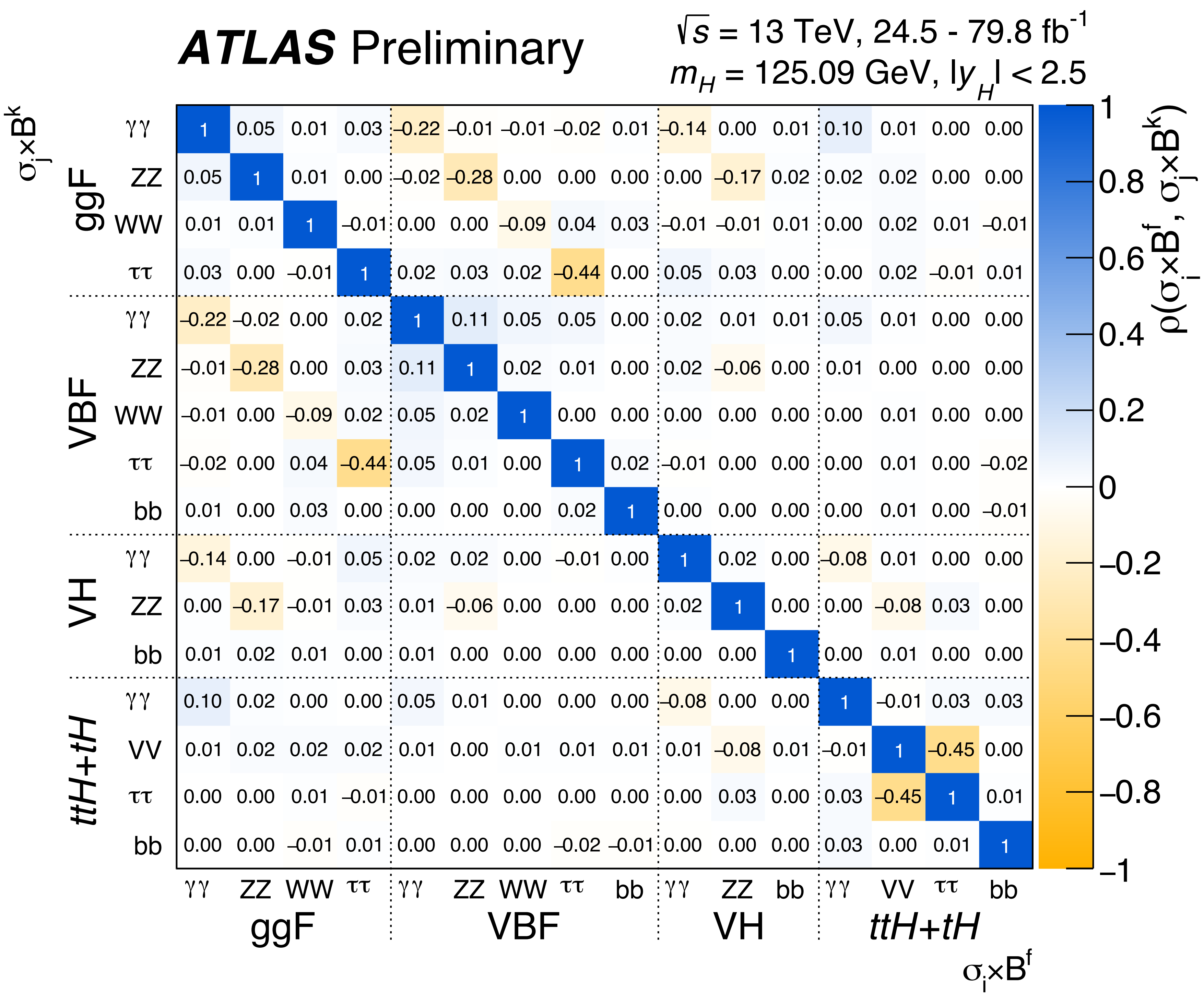
Conclusions

- Measurement of Higgs boson production cross sections and branching ratios performed based on up to 79.8 fb-1 recorded during LHC's Run 2
- Global signal strength: $\boldsymbol{\mu = 1.11^{+0.09}_{-0.08}}$
- Observation of all main LHC Higgs production modes
    - **VBF**, **VH** and **ttH** production mode significances of **6.5σ**, **5.3σ** and **5.8σ**, respectively
- Comprehensive STXS measurement based on all major Higgs decay channels
- Data also interpreted using κ framework and BSM models
- No significant deviation from the SM!
    - Increased precision (up to a factor 2) can be reached with full Run 2 results and ATLAS-CMS combination

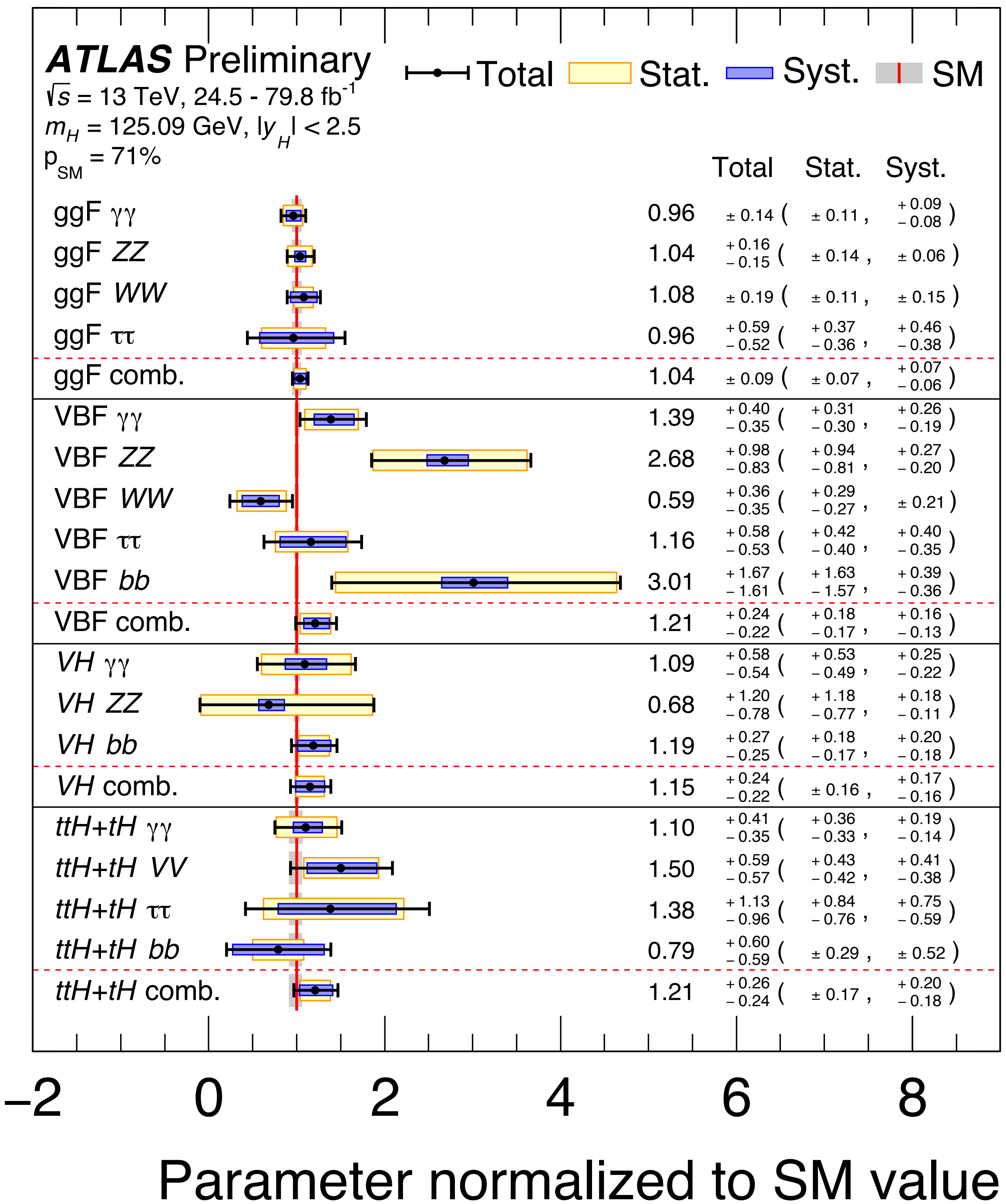
Backup Slides

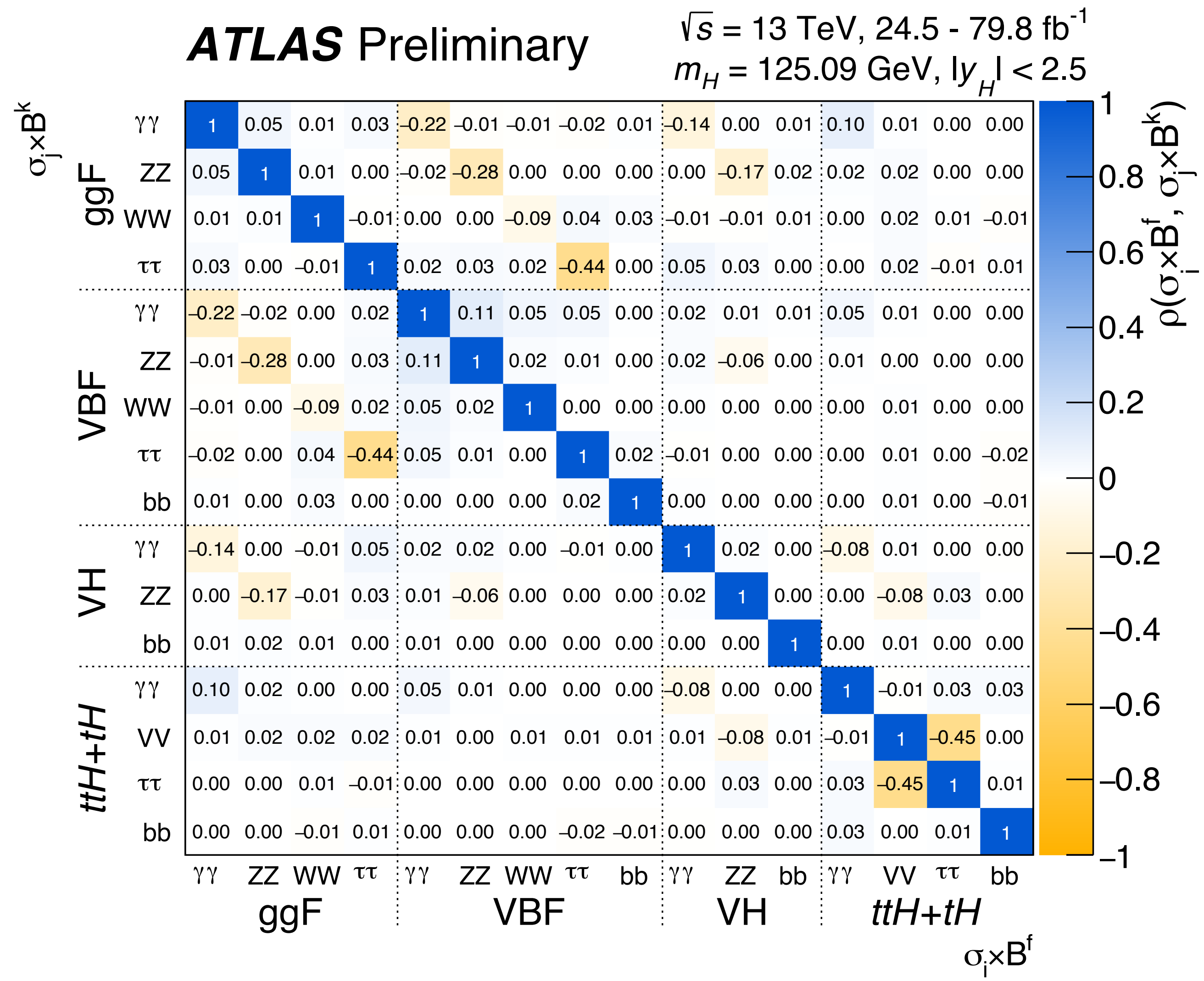
(to be completed)

Production cross sections: correlations



Products of production cross sections and branching ratios

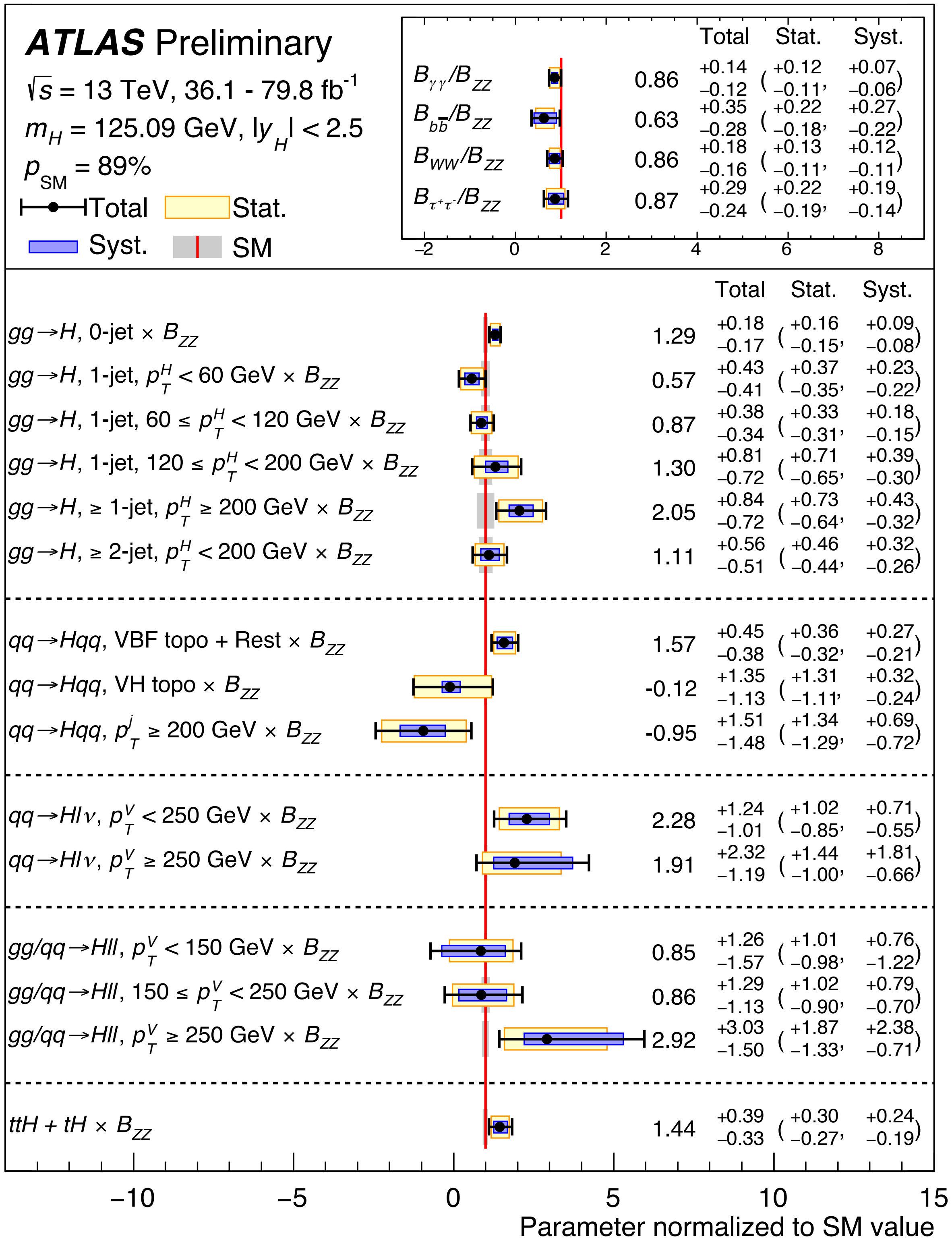


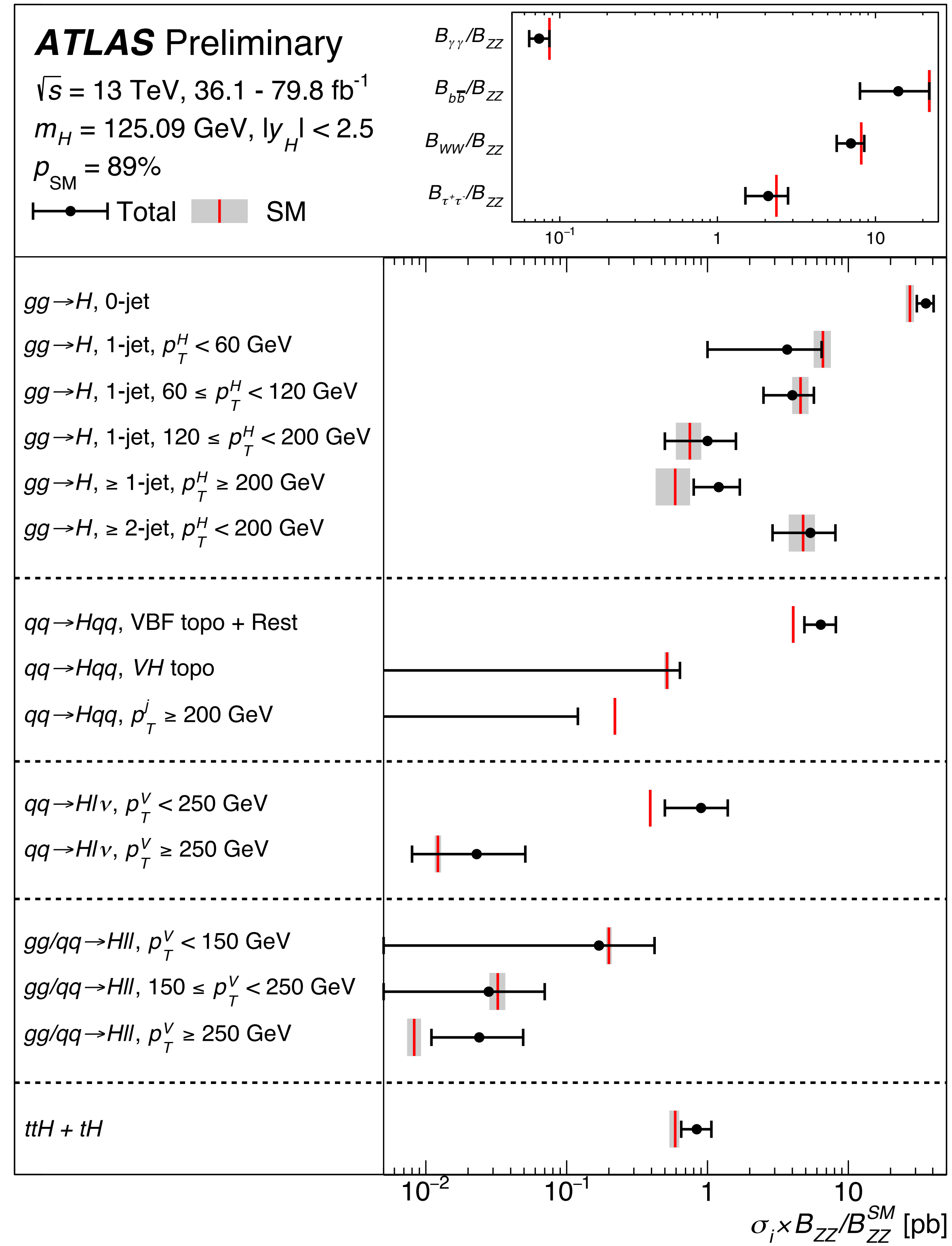


Products of production cross sections and branching ratios

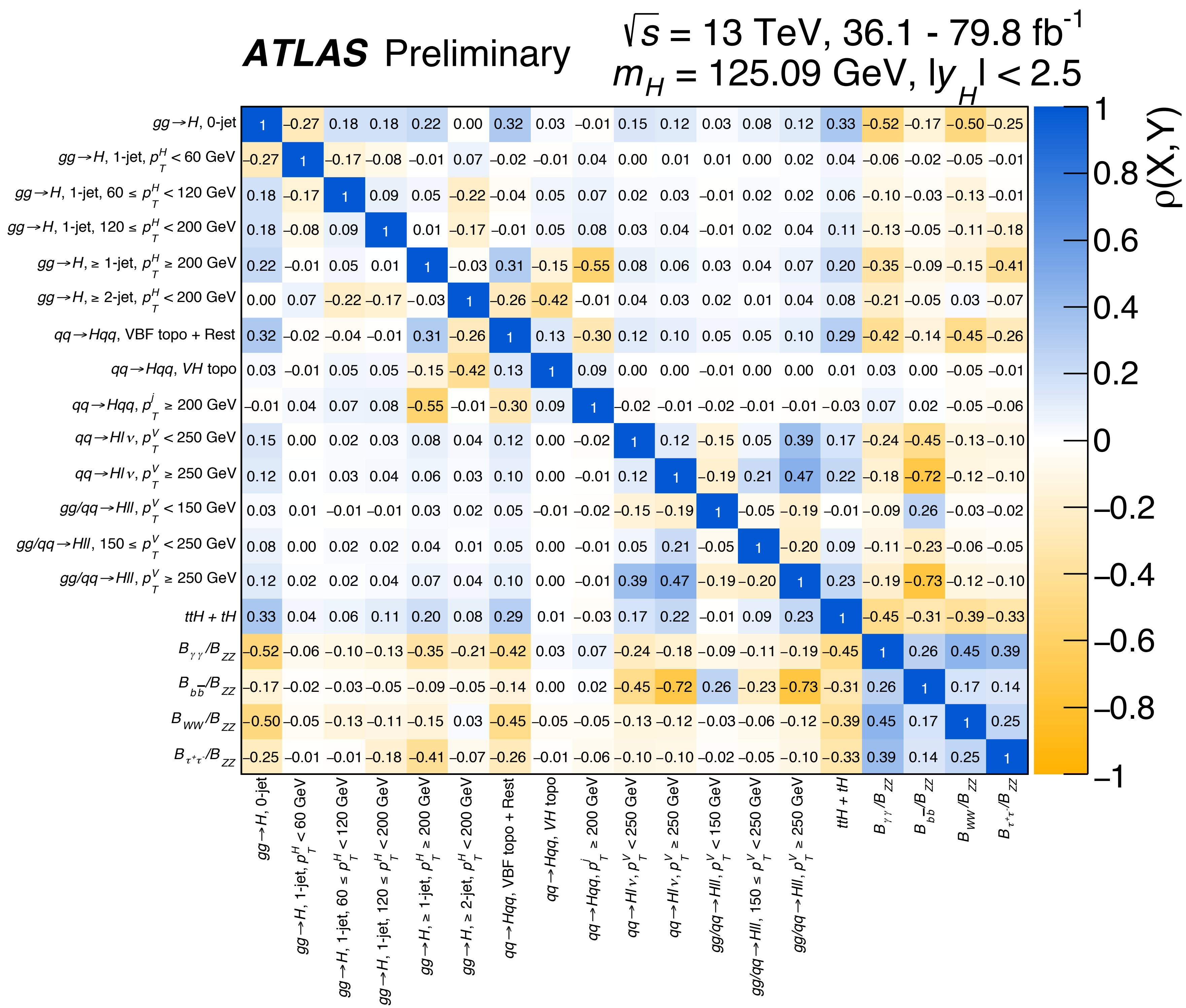
Process ($\|y_H\| < 2.5$)	Value [fb]	Uncertainty [fb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [fb]
ggF, $H\to\gamma\gamma$	97	± 14	± 11	± 8	± 2	$^{+2}_{-1}$	101.5 ± 5.3
ggF, $H \to ZZ^*$	1230	$^{+190}_{-180}$	± 170	± 60	± 20	± 20	1181 ± 61
ggF, $H \to WW^*$	10400	± 1800	± 1100	± 1100	± 380	$^{+960}_{-870}$	9600 ± 500
ggF, $H \to \tau\tau$	2700	$^{+1700}_{-1500}$	± 1000	± 920	$^{+810}_{-310}$	$^{+390}_{-420}$	2800 ± 140
VBF, $H\to\gamma\gamma$	11.1	$^{+3.2}_{-2.8}$	$^{+2.5}_{-2.4}$	$^{+1.4}_{-1.0}$	$^{+1.5}_{-1.1}$	$^{+0.3}_{-0.2}$	7.98 ± 0.21
VBF, $H \to ZZ^*$	249	$^{+91}_{-77}$	$^{+87}_{-75}$	$^{+16}_{-11}$	$^{+17}_{-12}$	$^{+9}_{-7}$	92.8 ± 2.3
VBF, $H \to WW^*$	450	$^{+270}_{-260}$	$^{+220}_{-200}$	$^{+120}_{-130}$	$^{+80}_{-70}$	$^{+70}_{-80}$	756 ± 19
VBF, $H \to \tau\tau$	260	$^{+130}_{-120}$	± 90	$^{+80}_{-70}$	$^{+30}_{-10}$	$^{+30}_{-20}$	220 ± 6
VBF, $H \to b\bar{b}$	6100	$^{+3400}_{-3300}$	$^{+3300}_{-3200}$	$^{+700}_{-600}$	± 300	± 300	2040 ± 50
VH, $H\to\gamma\gamma$	5.0	$^{+2.6}_{-2.5}$	$^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	± 0.5	± 0.1	$4.54^{+0.13}_{-0.12}$
VH, $H \to ZZ^*$	36	$^{+63}_{-41}$	$^{+62}_{-41}$	$^{+5}_{-4}$	$^{+6}_{-4}$	$^{+4}_{-2}$	52.8 ± 1.4
VH, $H \to b\bar{b}$	1380	$^{+310}_{-290}$	$^{+210}_{-200}$	± 150	$^{+120}_{-80}$	± 140	1162^{+31}_{-29}
$t\bar{t}H+tH$, $H\to\gamma\gamma$	1.46	$^{+0.55}_{-0.47}$	$^{+0.48}_{-0.44}$	$^{+0.19}_{-0.15}$	$^{+0.17}_{-0.11}$	± 0.03	$1.33^{+0.08}_{-0.11}$
$t\bar{t}H+tH$, $H \to VV^*$	212	$^{+84}_{-81}$	$^{+61}_{-59}$	$^{+47}_{-44}$	$^{+17}_{-10}$	$^{+31}_{-30}$	142^{+8}_{-12}
$t\bar{t}H+tH$, $H \to \tau\tau$	51	$^{+41}_{-35}$	$^{+31}_{-28}$	$^{+26}_{-21}$	$^{+6}_{-4}$	$^{+8}_{-6}$	$36.7^{+2.2}_{-3.1}$
$t\bar{t}H+tH$, $H \to b\bar{b}$	270	± 200	± 100	± 80	$^{+40}_{-10}$	$^{+150}_{-160}$	341^{+20}_{-29}

Cross sections times H→ZZ* BR

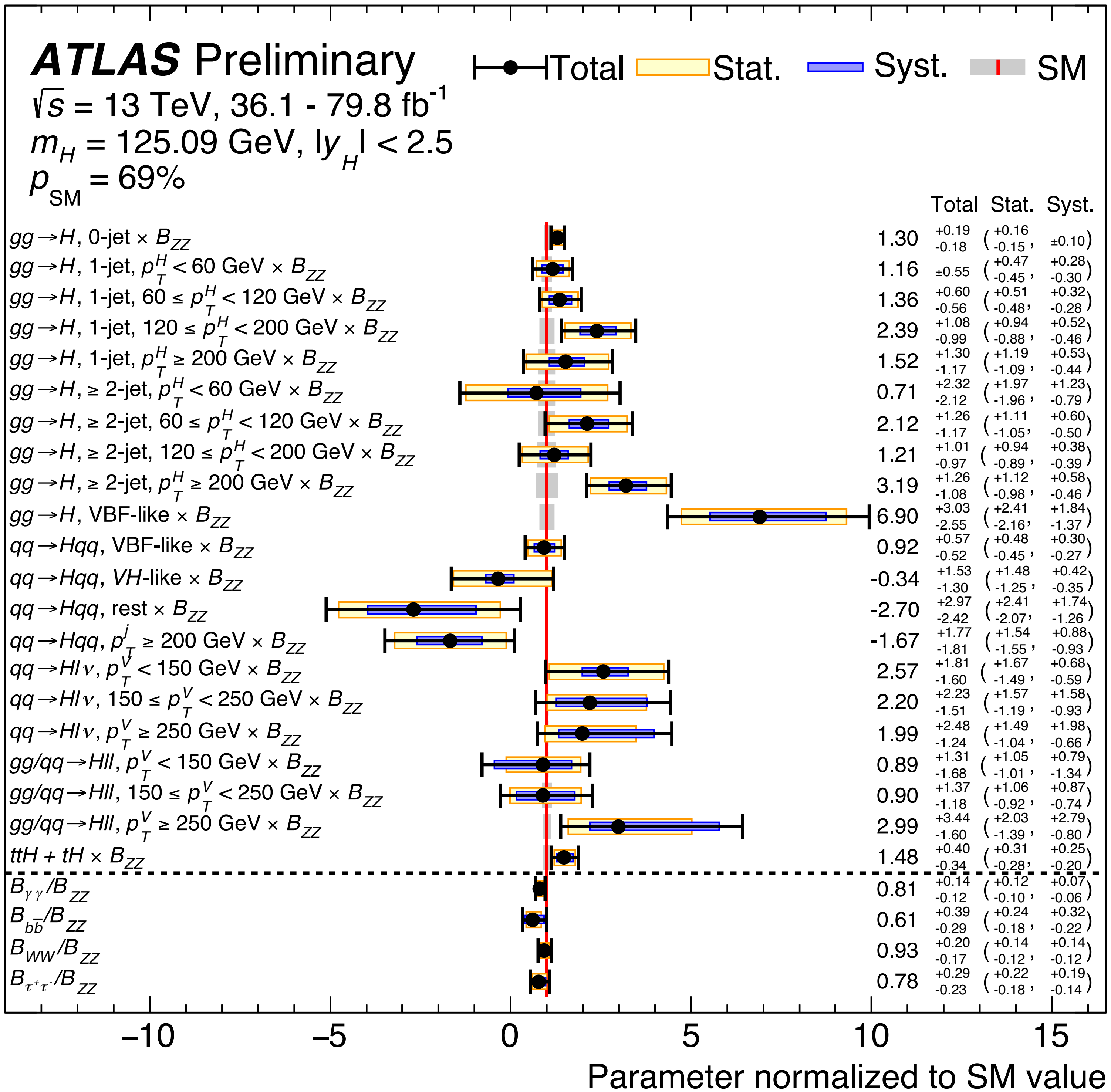




Cross sections times H→ZZ* BR (correlations)



Cross sections times H→ZZ* BR (finer granularity)



Cross sections times H→ZZ* BR (finer granularity)