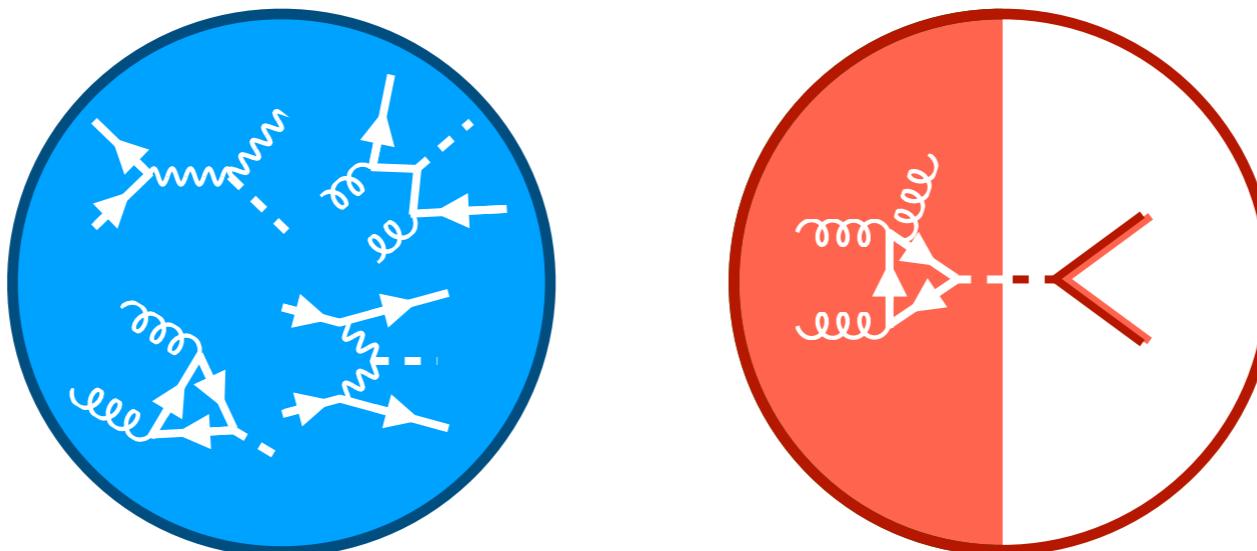


Latest results of Higgs boson couplings and combination analyses with the ATLAS experiment



Philipp Windischhofer

University of Oxford

For the ATLAS Collaboration

DIS 2022, May 2-6, 2022
Santiago de Compostela



What can you expect?

A summary of our knowledge of the interactions of the Higgs boson ...
... and the consequences for physics (*at high scales*)

(Our) answers to questions such as:

This talk

*How to build a global couplings measurement?
What are the implications for the
structure of new interactions?*

Sagar Addepalli

Next talk [[link](#)]

Can differential measurements help?

Jana Schaarschmidt

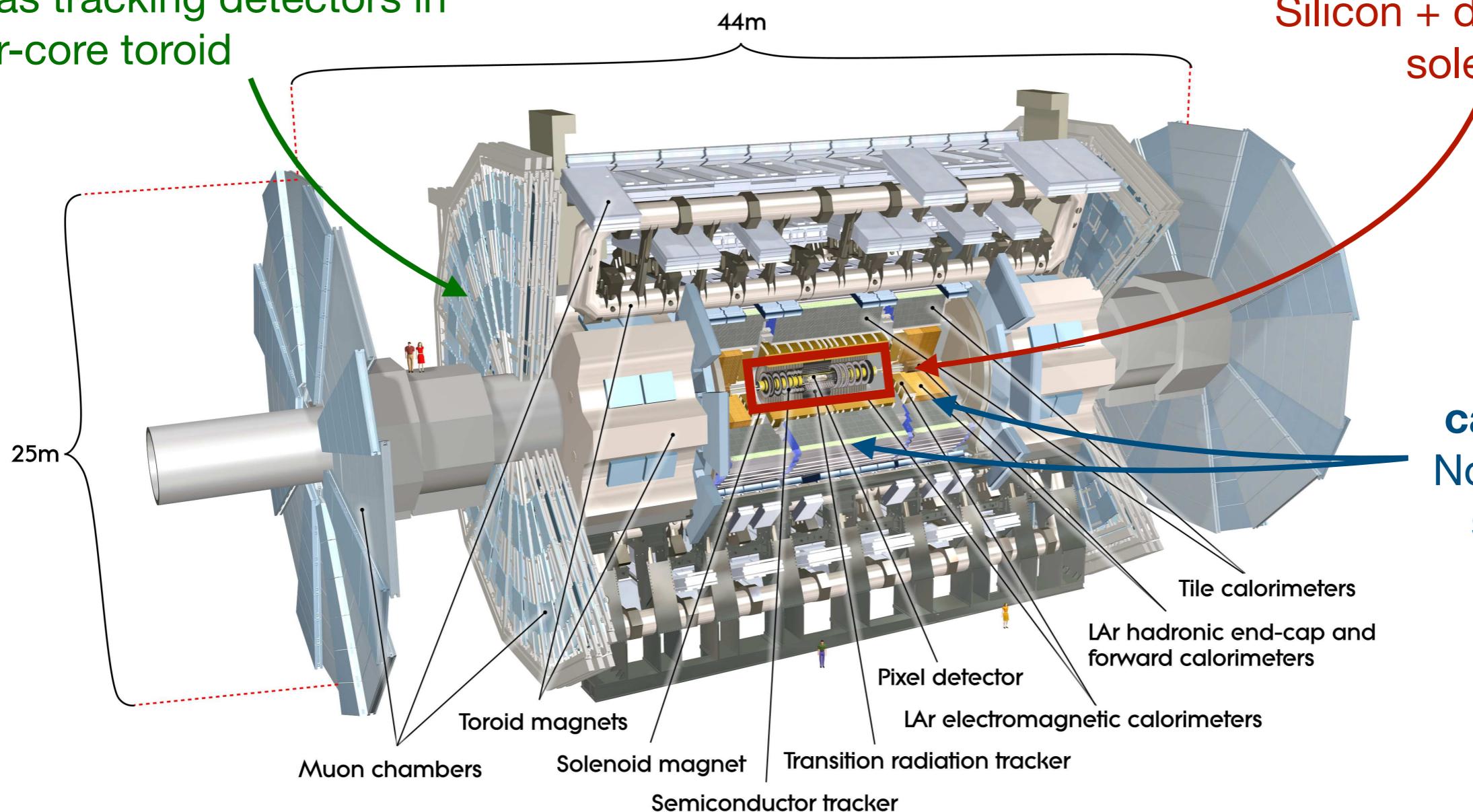
This session, 10:20 [[link](#)]

Does the Higgs boson interact with itself?

The ATLAS experiment at the LHC

Muon spectrometer:

Gas tracking detectors in air-core toroid



Tracking & vertexing:

Silicon + drift tubes in solenoidal field

Sampling calorimetry:

Noble liquid / scintillators

Run 2 proton-proton data set (2015-2018):
139 fb^{-1} at 13 TeV centre-of-mass (\approx 8 million Higgs bosons)

Overview of recent couplings measurements

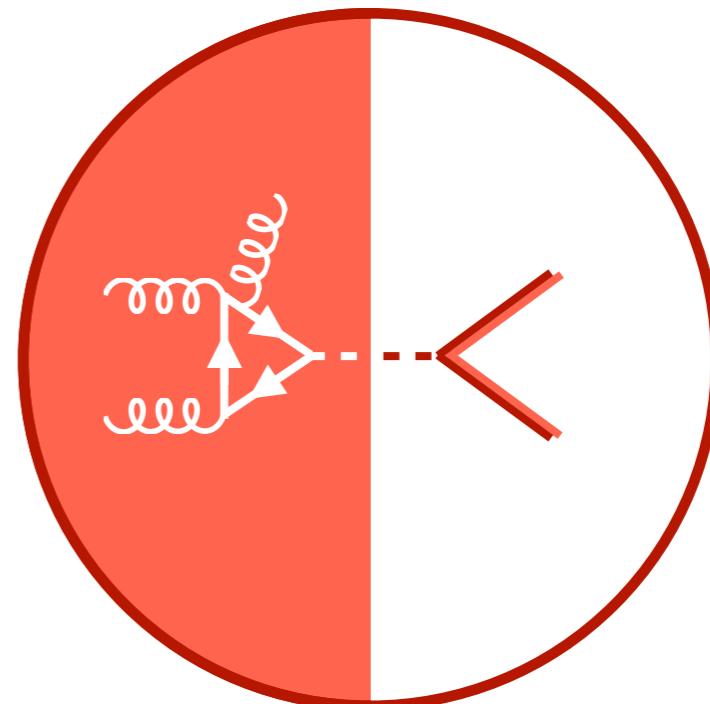
Combined analyses of multiple production modes and decay channels



***Main production / decay modes;
constraints on high-scale physics***

**Higgs couplings
combination**

[ATLAS-CONF-2021-053]



2nd / 3rd gen. quark couplings

**VH($\rightarrow bb/cc$)
combination**

[CERN-EP-2021-251] [ATLAS-CONF-2022-002]

**H($\rightarrow \gamma\gamma/4\ell$)
combination**



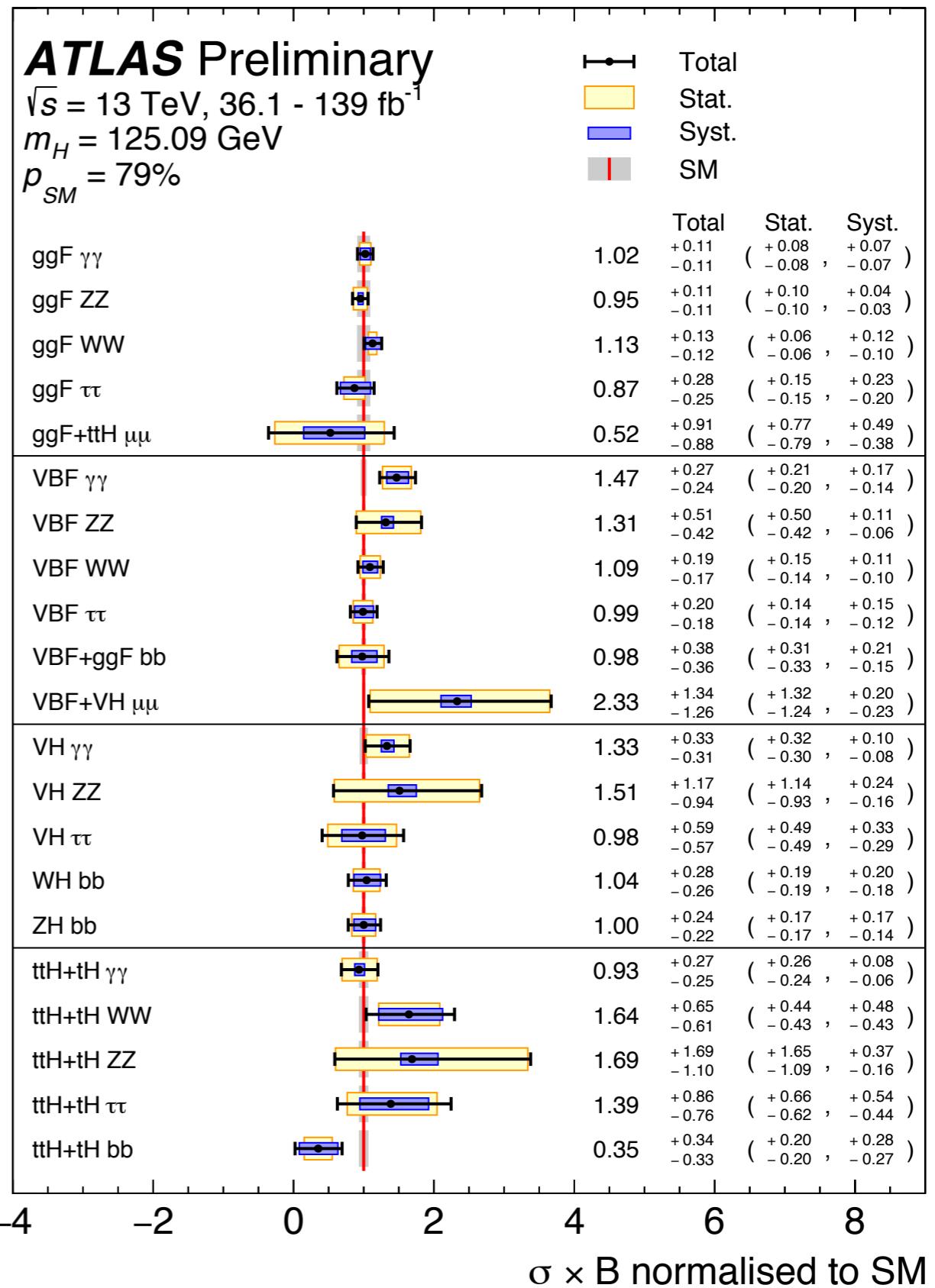
Higgs couplings combination

[[ATLAS-CONF-2021-053](#)]

We already know a lot!

Latest **combined measurement** probes
21 (production mode) x (decay channel)
combinations

O(300) reconstructed regions,
predominantly with full Run 2 data set;
see backup



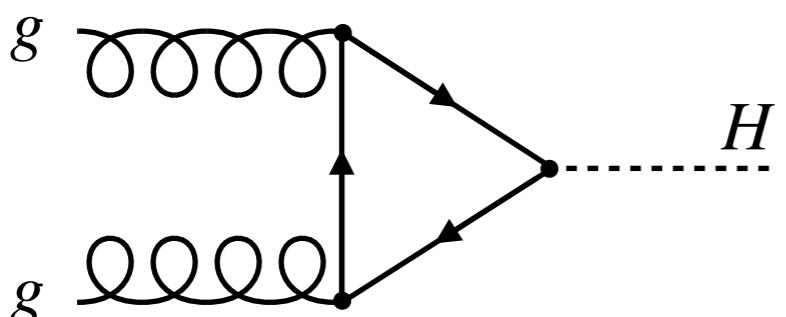
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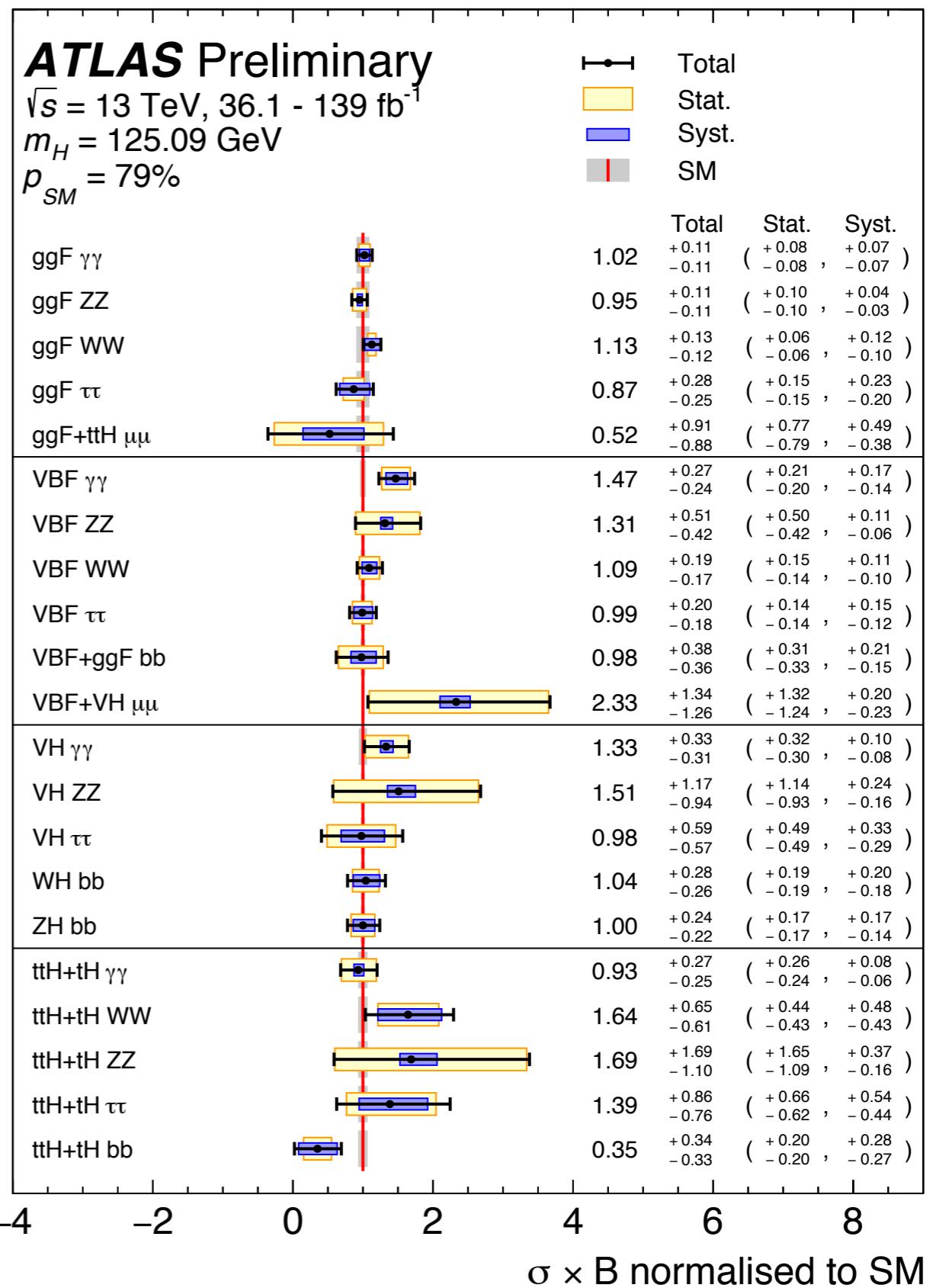
O(300) reconstructed regions,
predominantly with full Run 2 data set;
see backup

Gluon fusion (ggF)

Dominant production mode



Most sensitive:
Bosonic decay channels $H \rightarrow \gamma\gamma, ZZ, WW$

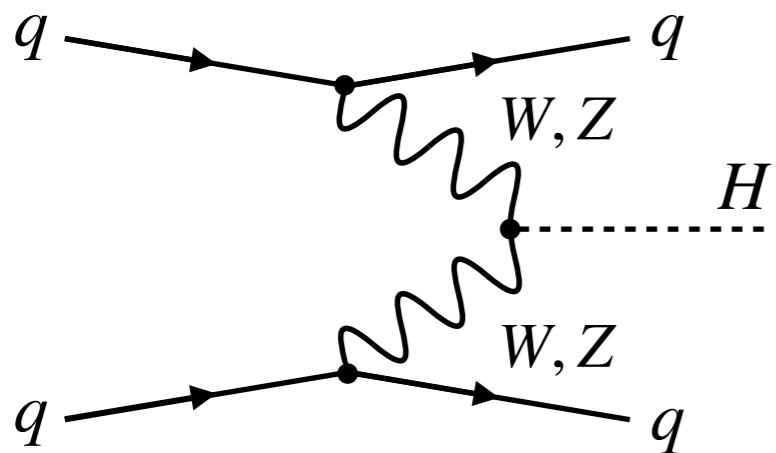


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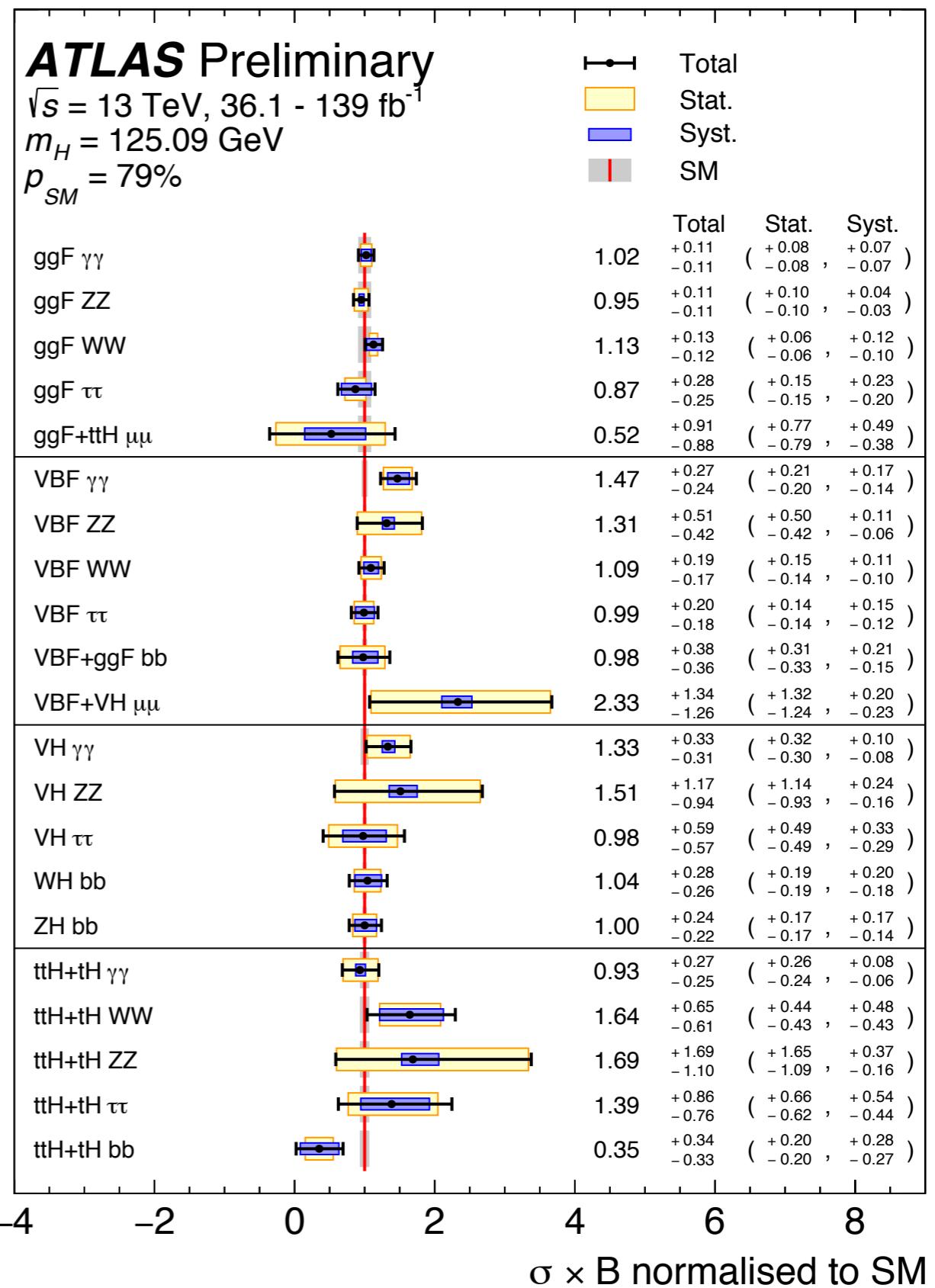
O(300) reconstructed regions,
predominantly with full Run 2 data set;
see backup

Vector boson fusion (VBF)



Most sensitive:

$H \rightarrow \tau\tau, WW$

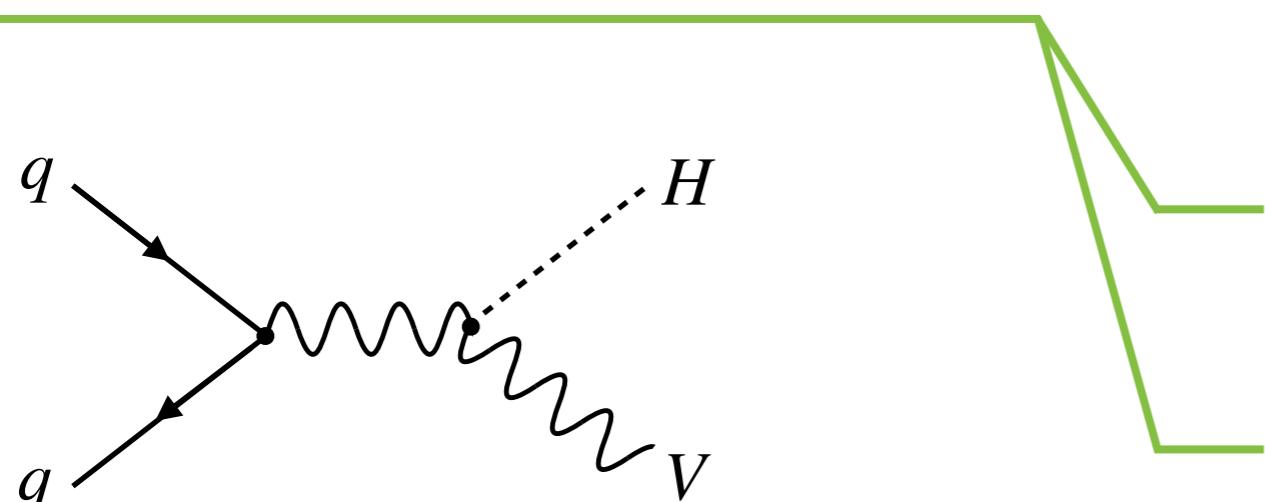


We already know a lot!

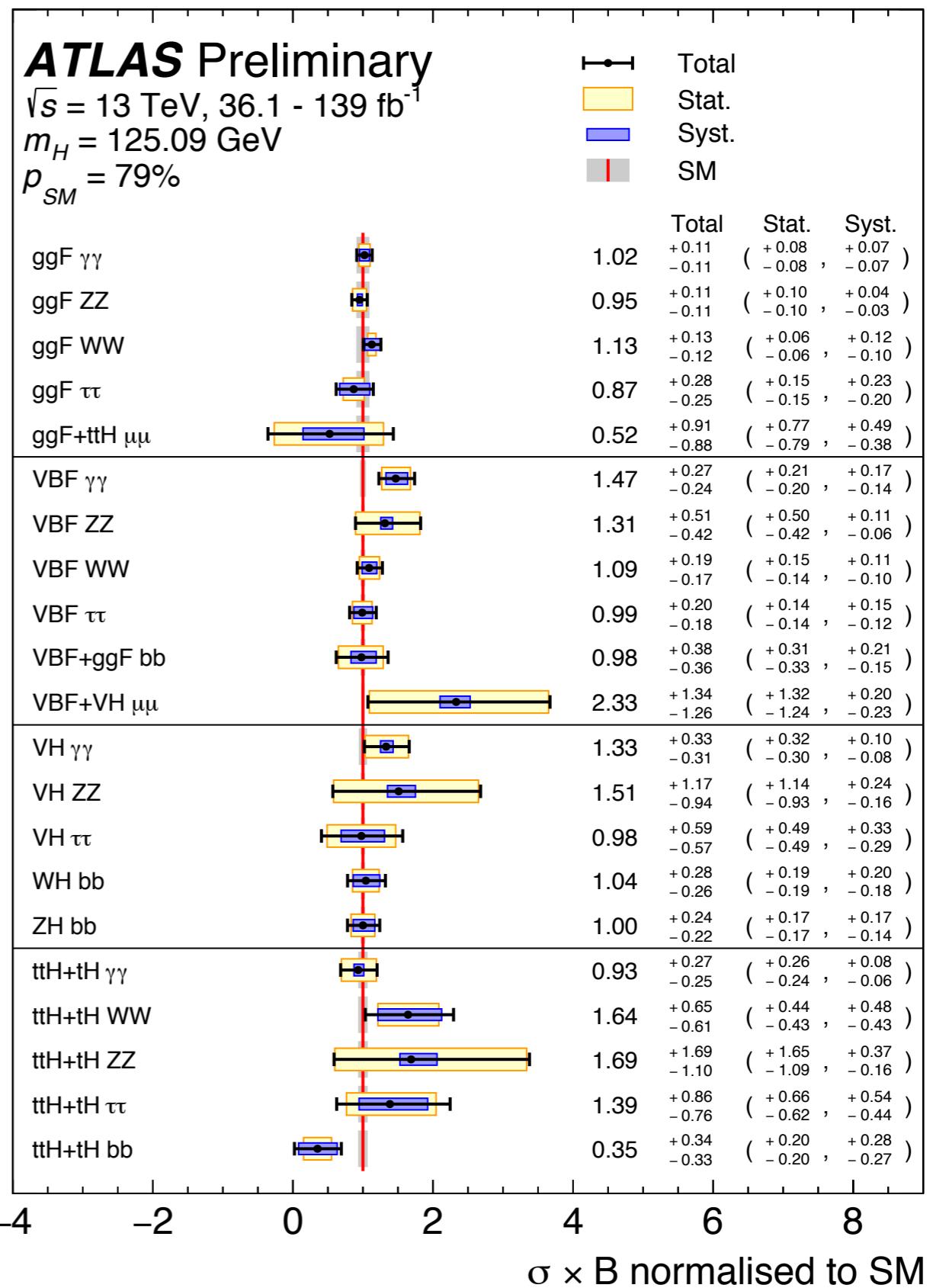
Latest **combined measurement** probes
21 (production mode) x (decay channel)
combinations

O(300) reconstructed regions,
predominantly with full Run 2 data set;
see backup

Higgsstrahlung (VH, V = W, Z)



Most sensitive:
 $H \rightarrow bb$

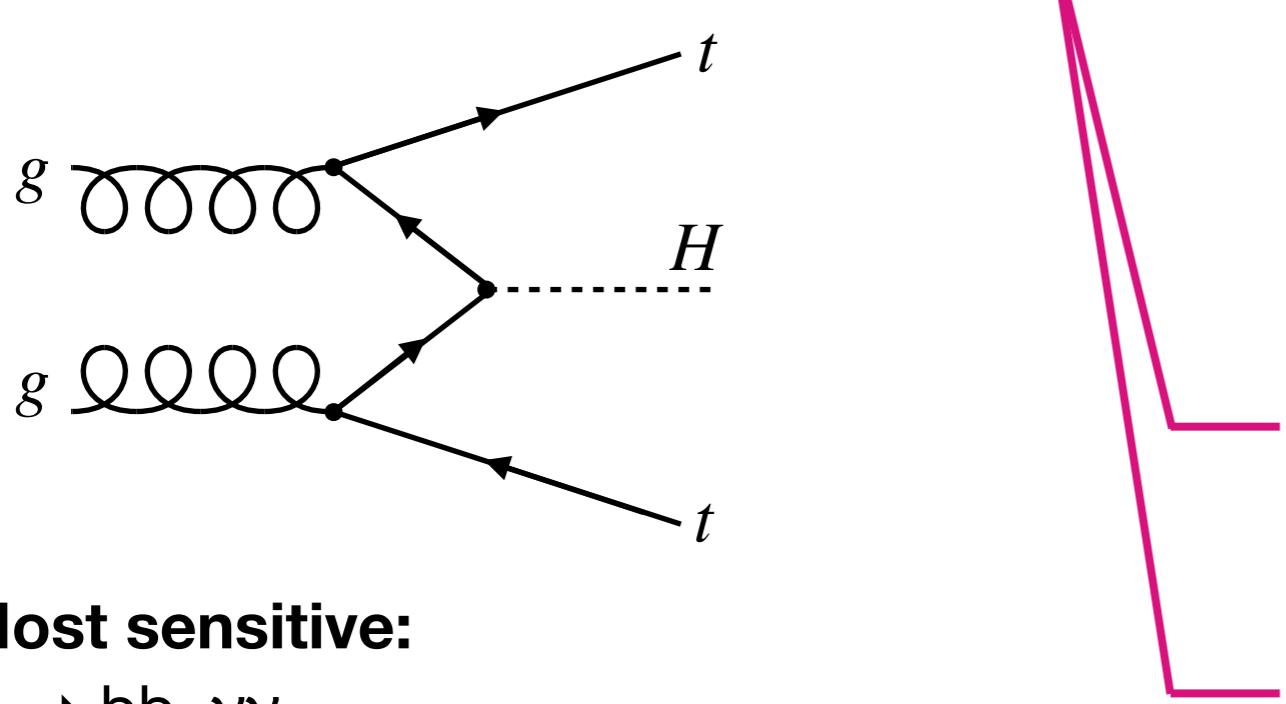


We already know a lot!

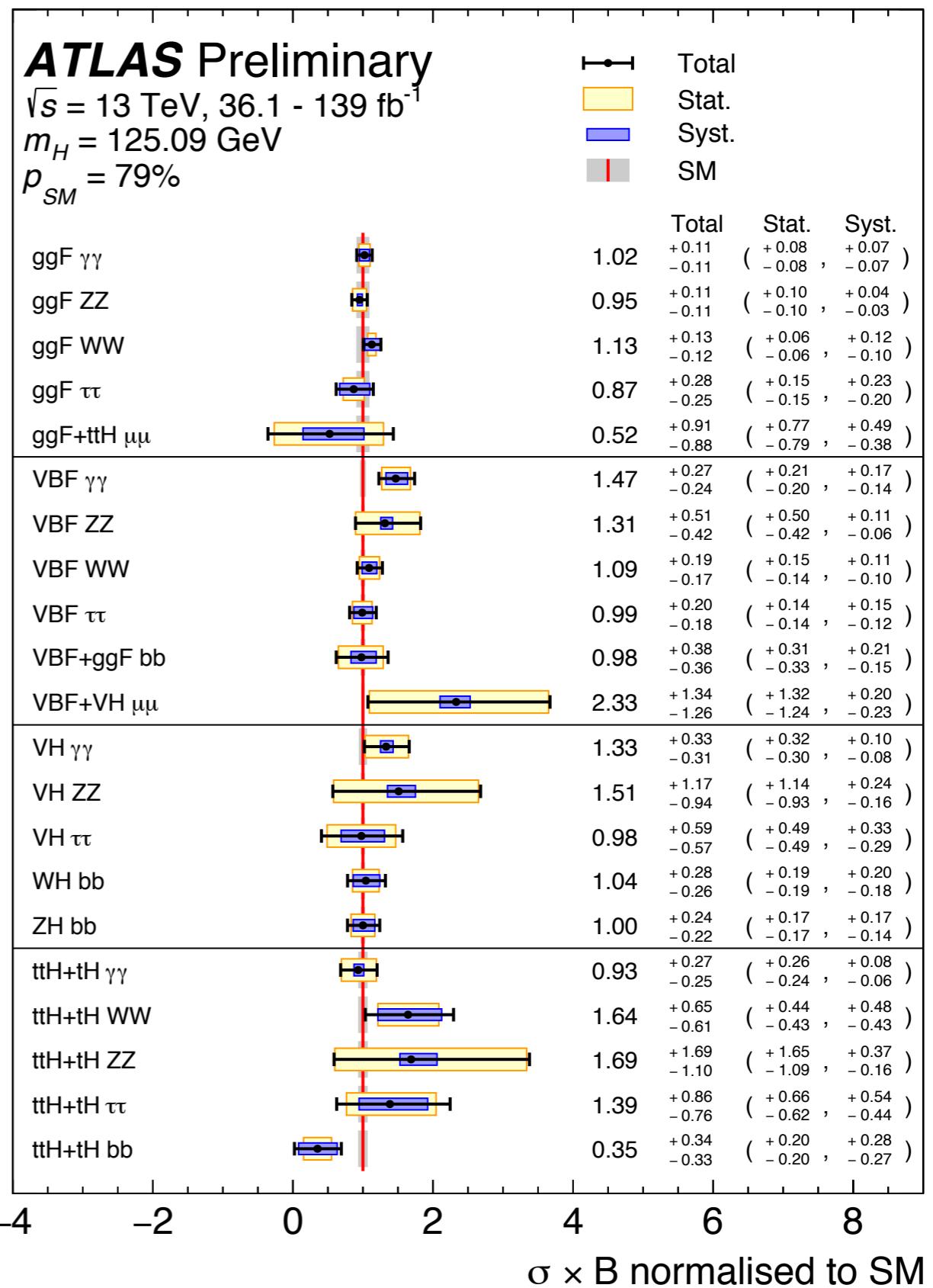
Latest **combined measurement** probes
21 (production mode) x (decay channel)
combinations

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predominantly with full Run 2 data set;
see backup

Top-associated production (ttH, tH)



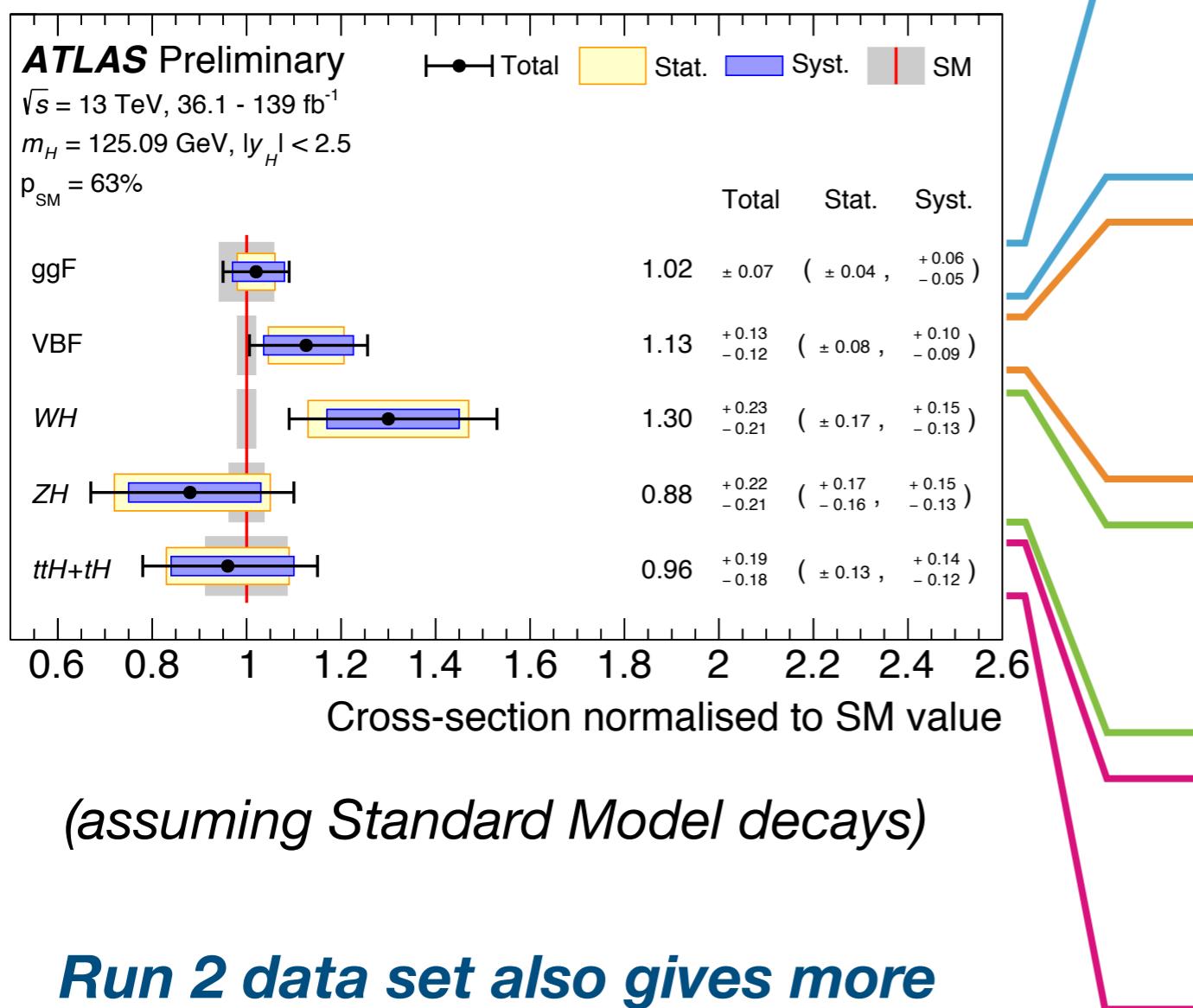
Most sensitive:
 $H \rightarrow bb, \gamma\gamma$



Production-mode cross-sections

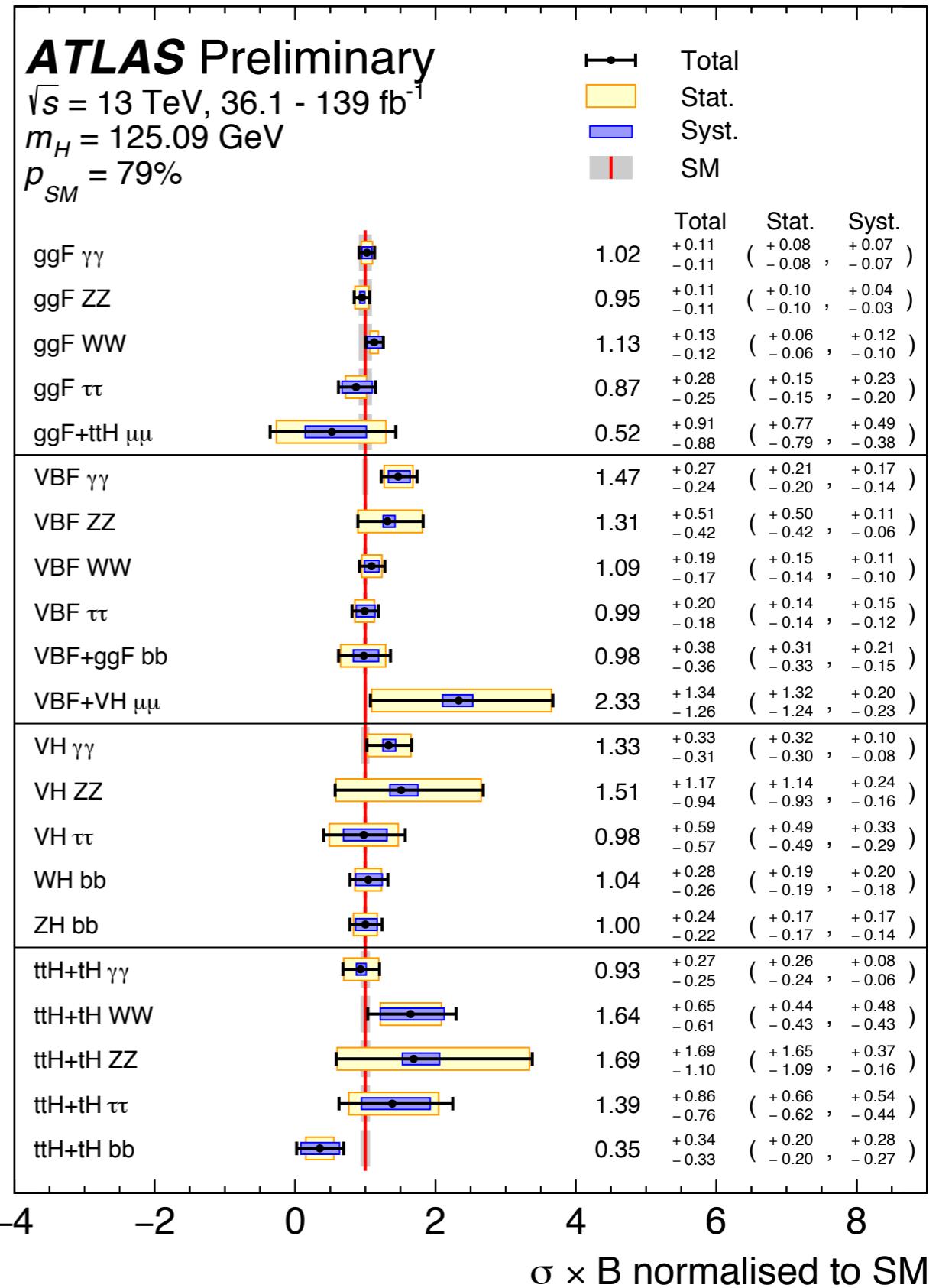
**Production mode cross-sections
measured to O(10-20%) precision**

(*ggF competitive with theo. unc.!*)



(assuming Standard Model decays)

**Run 2 data set also gives more
“differential information”**



Simplified template cross-sections (STXS)

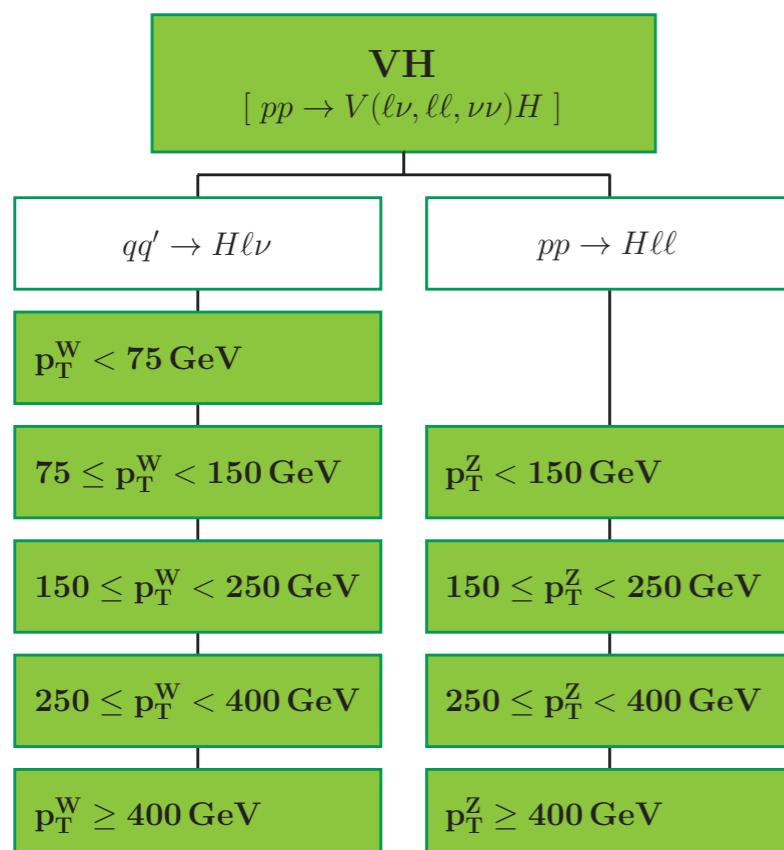
Fiducial volumes defined w.r.t. kinematic scale of production process
(but inclusive in Higgs boson decay)

“Simplified”

not *fully* differential; residual acceptance changes /
model dependence allowed, but reduced

V(\rightarrow lep.)H

$p_T^V \sim$ partonic
centre-of-mass energy

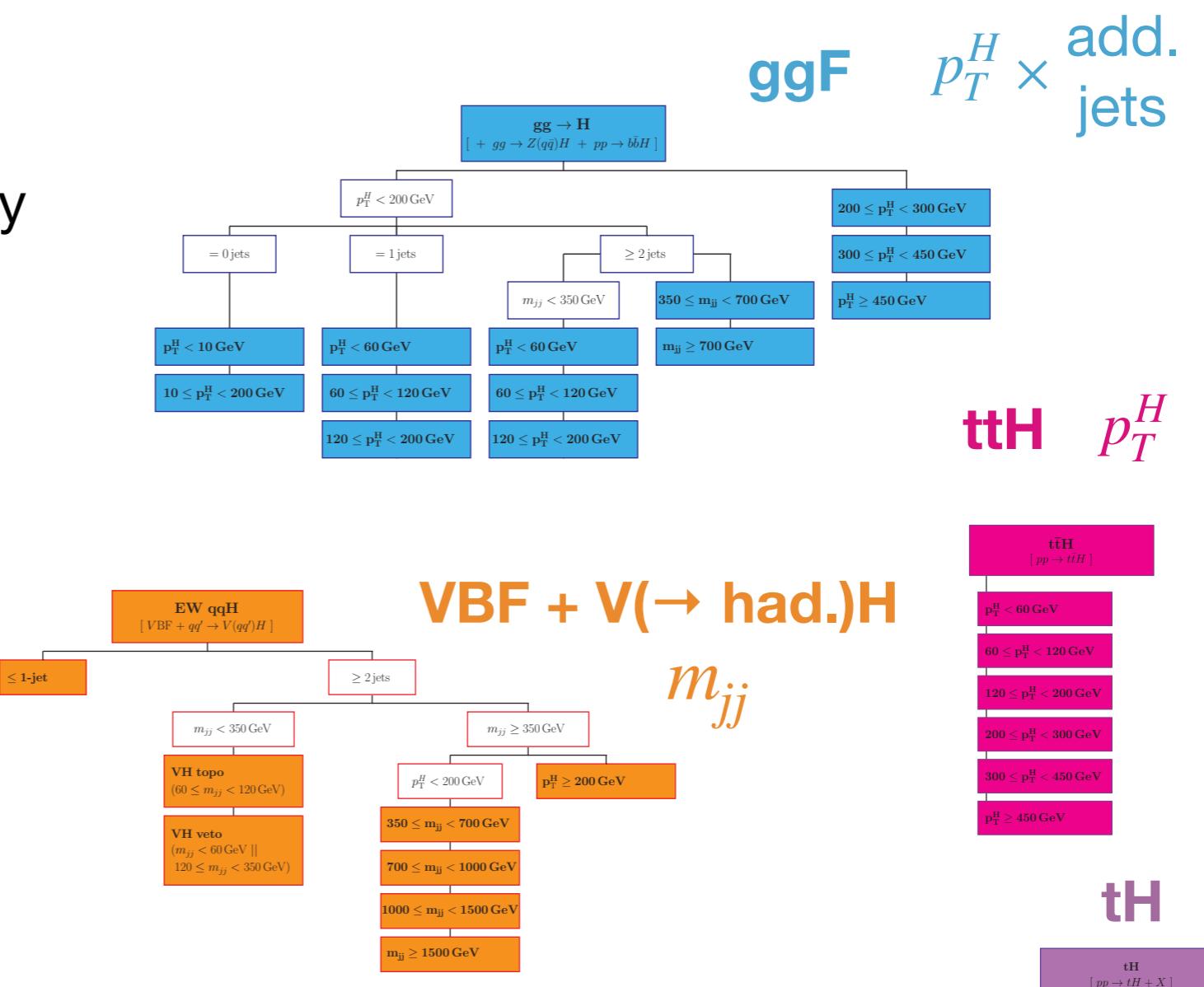
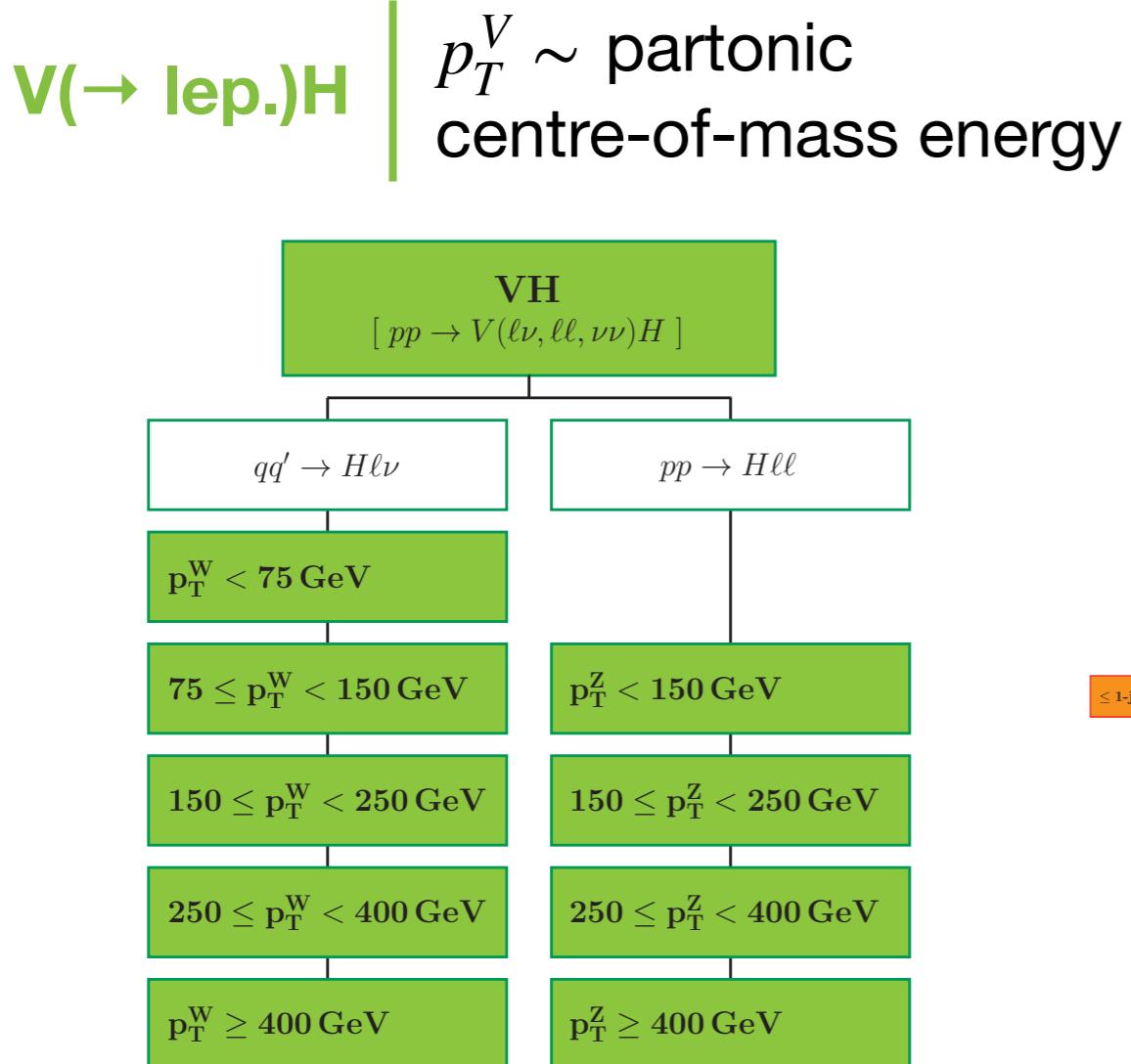


Simplified template cross-sections (STXS)

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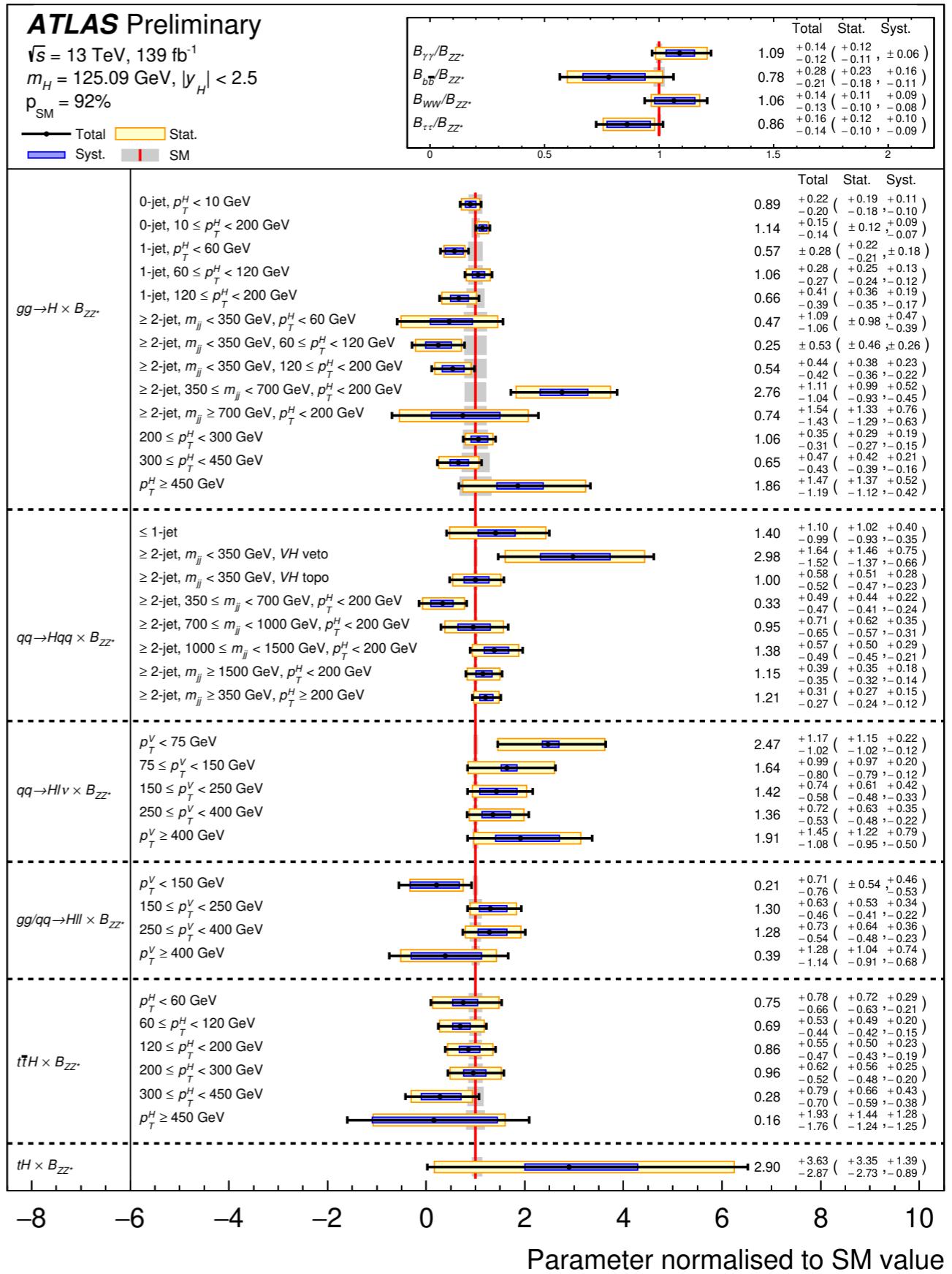
Combined STXS measurement

Combined measurement unfolds cross-sections in **37 kinematic bins** across **4 orders of magnitude**

(Decay branching ratio relative to $H \rightarrow ZZ$, see backup)

Probe the tails of kinematic distributions ...

... analysis advances important!



Combined STXS measurement

Combined measurement unfolds cross-sections in **37 kinematic bins** across **4 orders of magnitude**

(Decay branching ratio relative to $H \rightarrow ZZ$, see backup)

Gluon fusion (ggF)

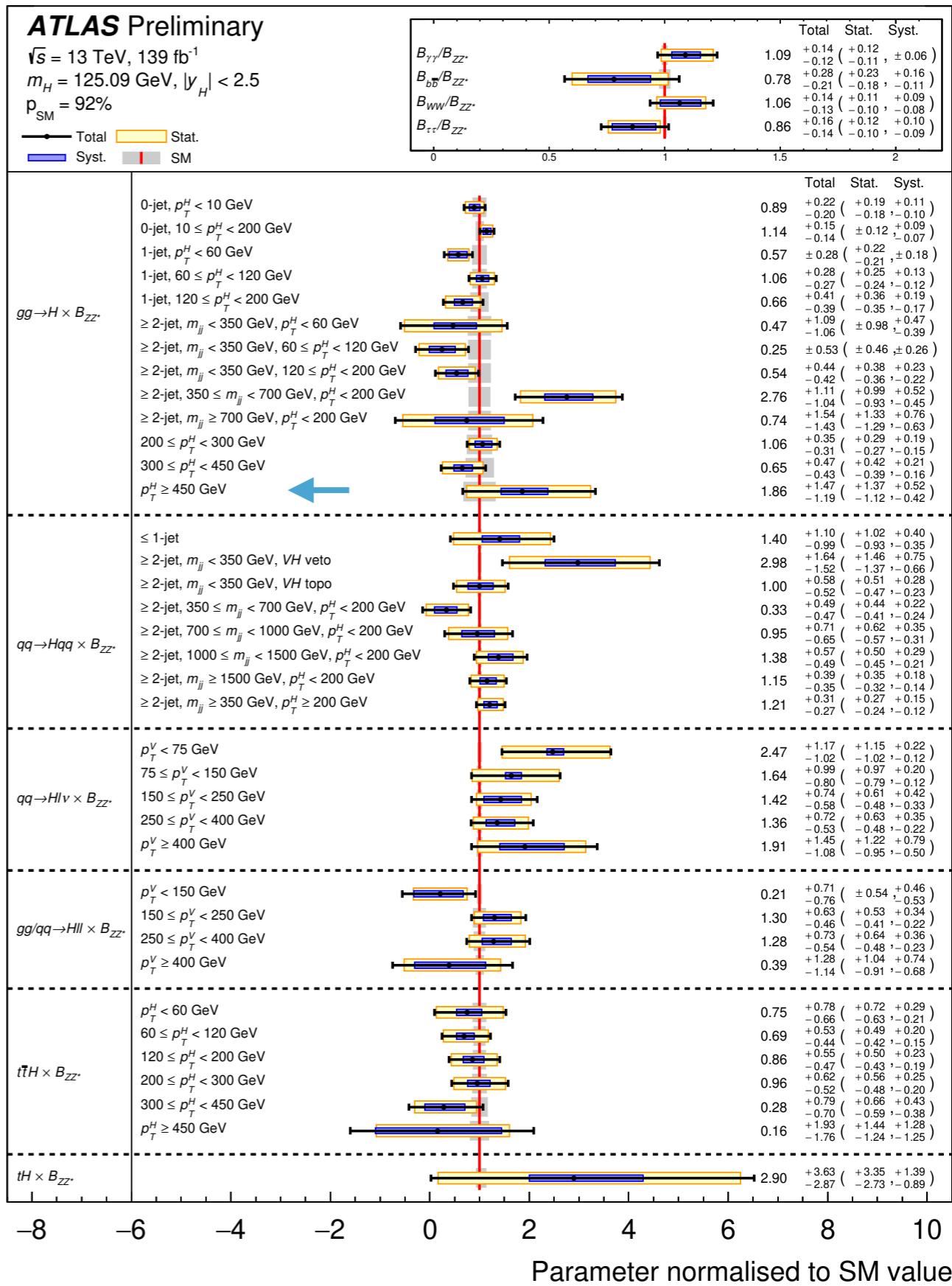
Largest number of STXS bins

High- p_T reach ($p_T^H > 450$ GeV) through $H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$

$H \rightarrow \gamma\gamma$: [\[ATLAS-CONF-2020-026\]](#)

$H \rightarrow ZZ$: [\[CERN-EP-2020-034\]](#)

$H \rightarrow \tau\tau$: [\[CERN-EP-2021-217\]](#)



Combined STXS measurement

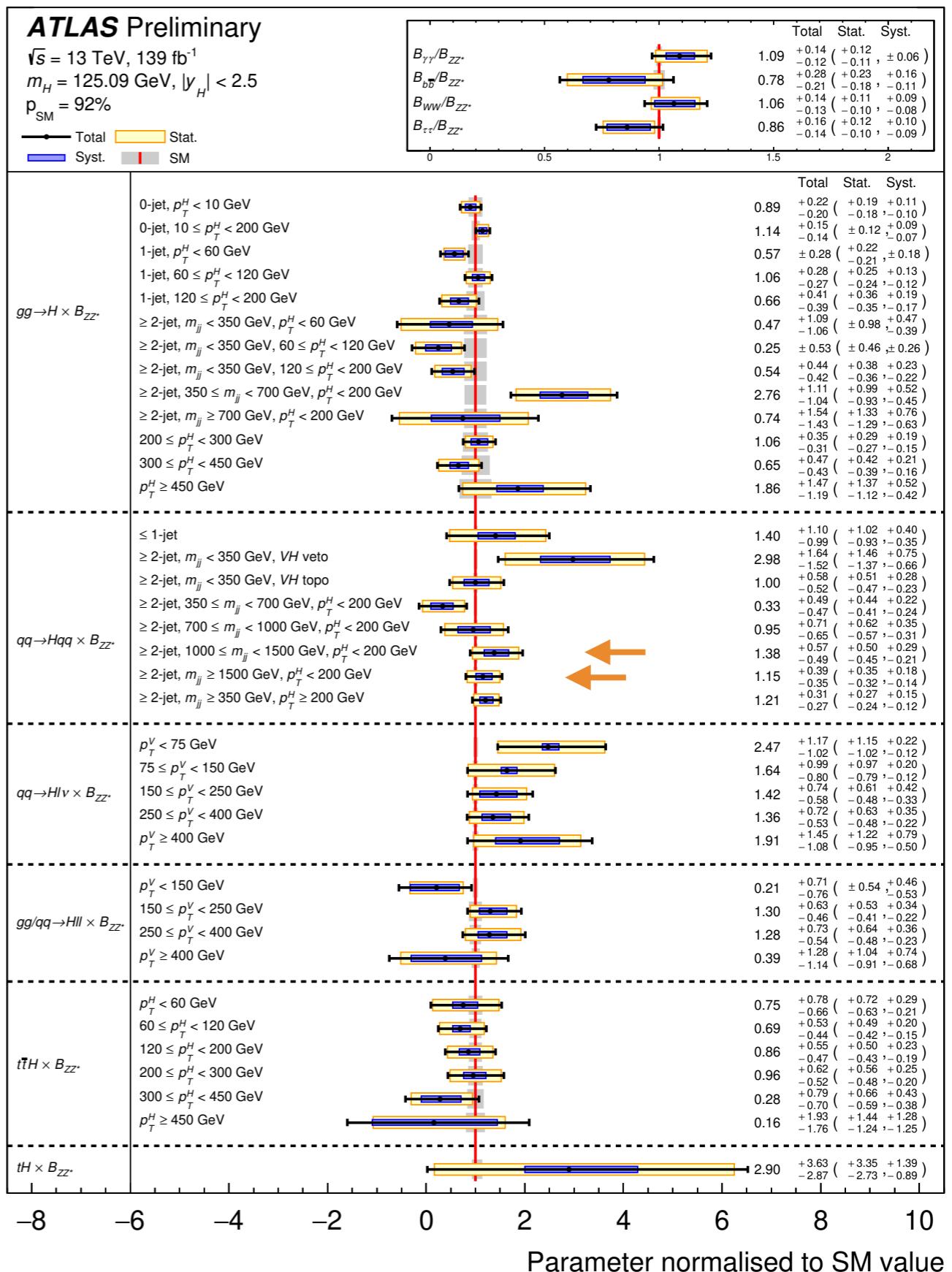
Combined measurement unfolds cross-sections in **37 kinematic bins** across **4 orders of magnitude**

(Decay branching ratio relative to $H \rightarrow ZZ$,
see backup)

VBF + V(\rightarrow had.)H

Up to $m_{jj} \sim 1.5$ TeV with STXS measurement in VBF, $H(\rightarrow WW)$

[ATLAS-CONF-2021-014]



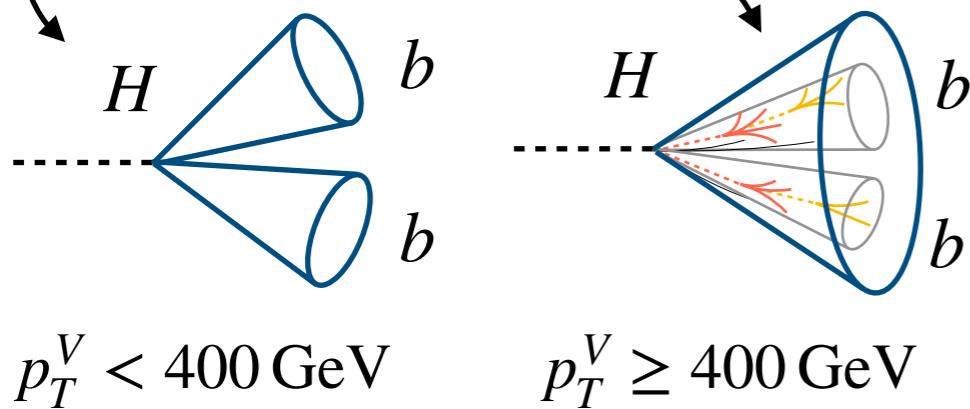
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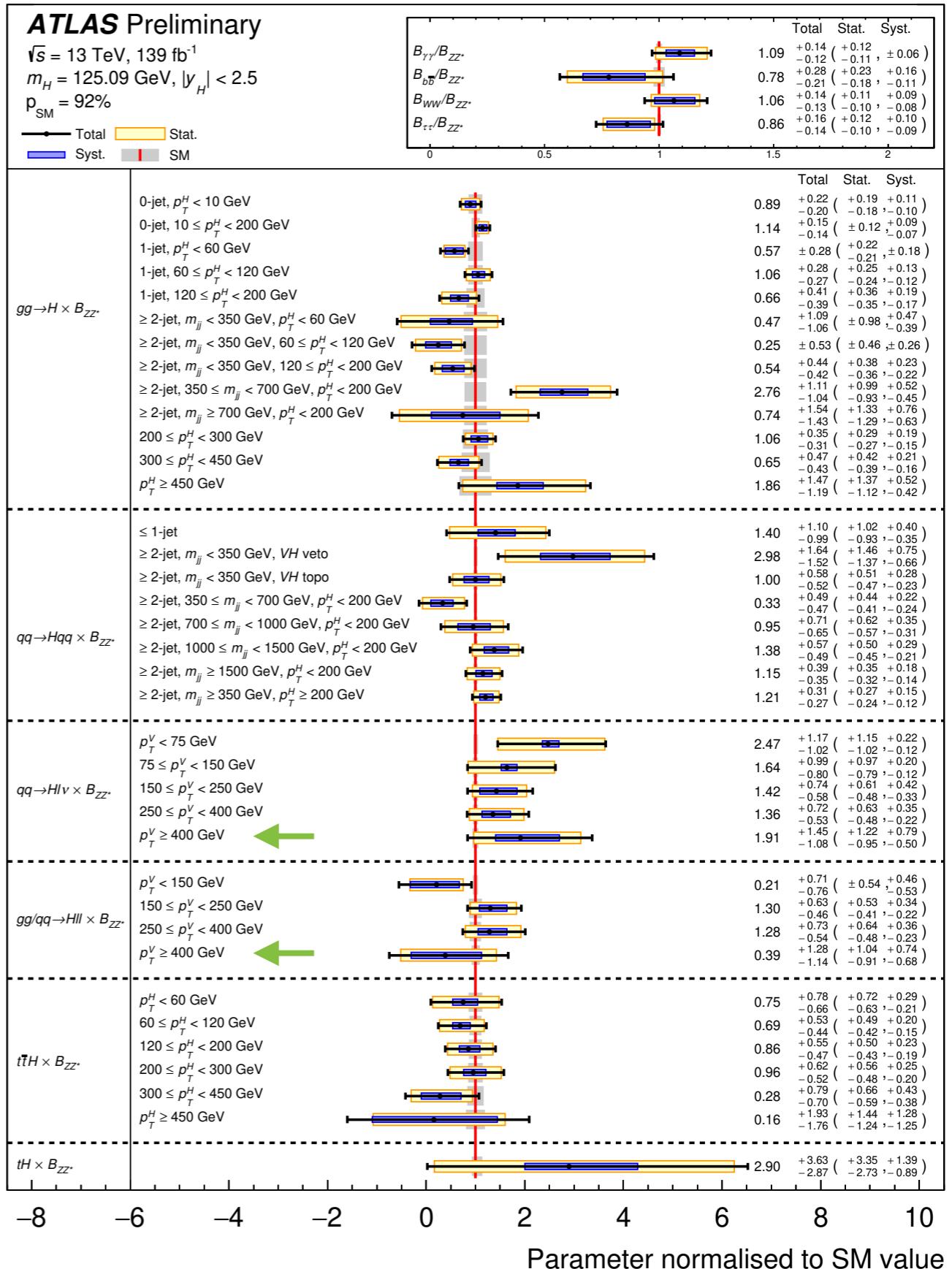
V(\rightarrow lep.)H

Combination of $V(\rightarrow \text{lep.})H(bb)$ resolved + boosted



Better granularity at high scales

[ATLAS-CONF-2021-051]



Combined STXS measurement

Combined measurement unfolds cross-sections in **37 kinematic bins** across **4 orders of magnitude**

(Decay branching ratio relative to $H \rightarrow ZZ$, see backup)

Top-associated production

ttH

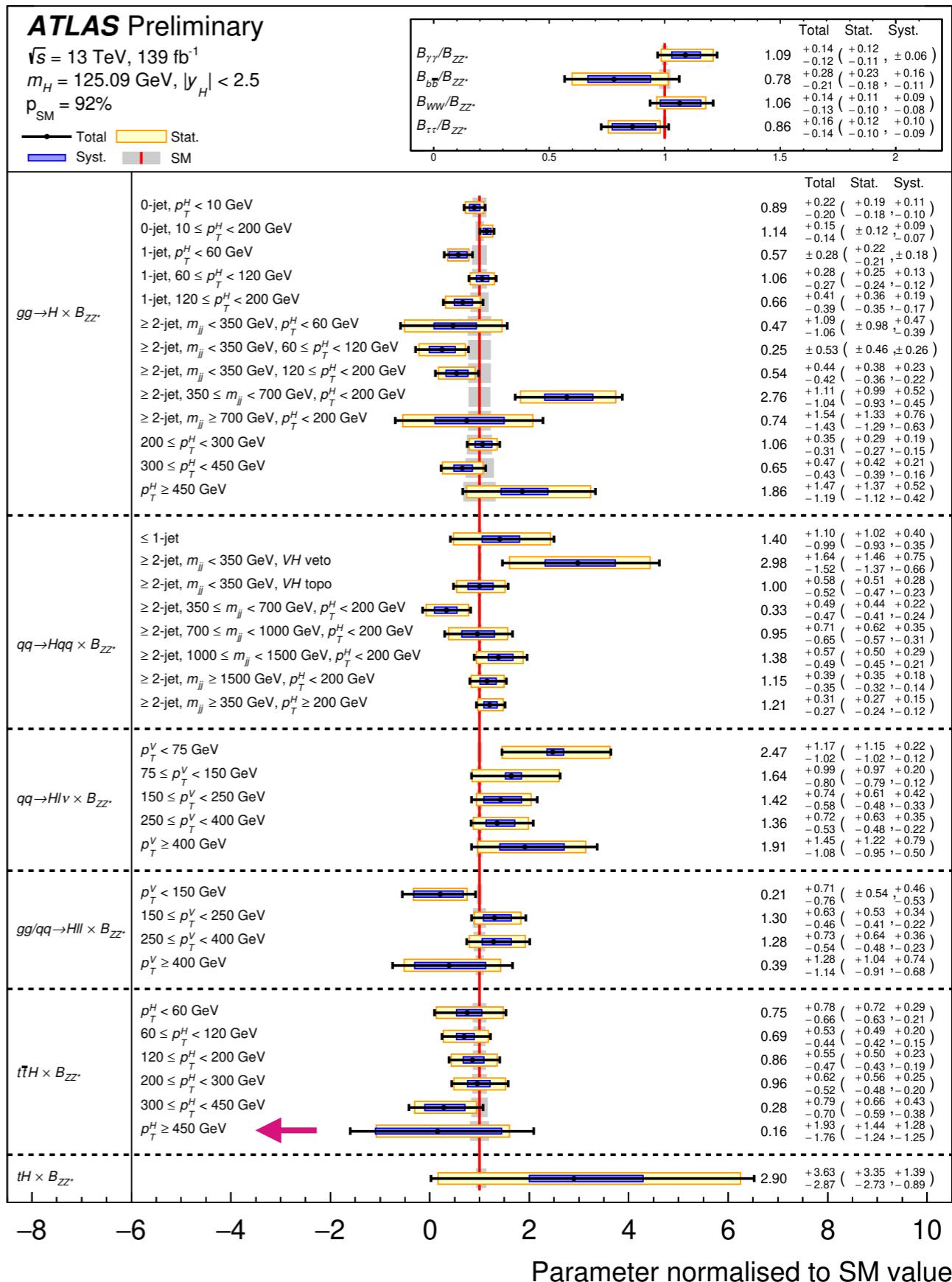
Finer binning; higher kinematic reach ($p_T^H > 450$ GeV) through ttH($\rightarrow bb$)

ttH($\rightarrow \gamma\gamma$): [ATLAS-CONF-2020-026]

ttH($\rightarrow bb$): [CERN-EP-2020-034]

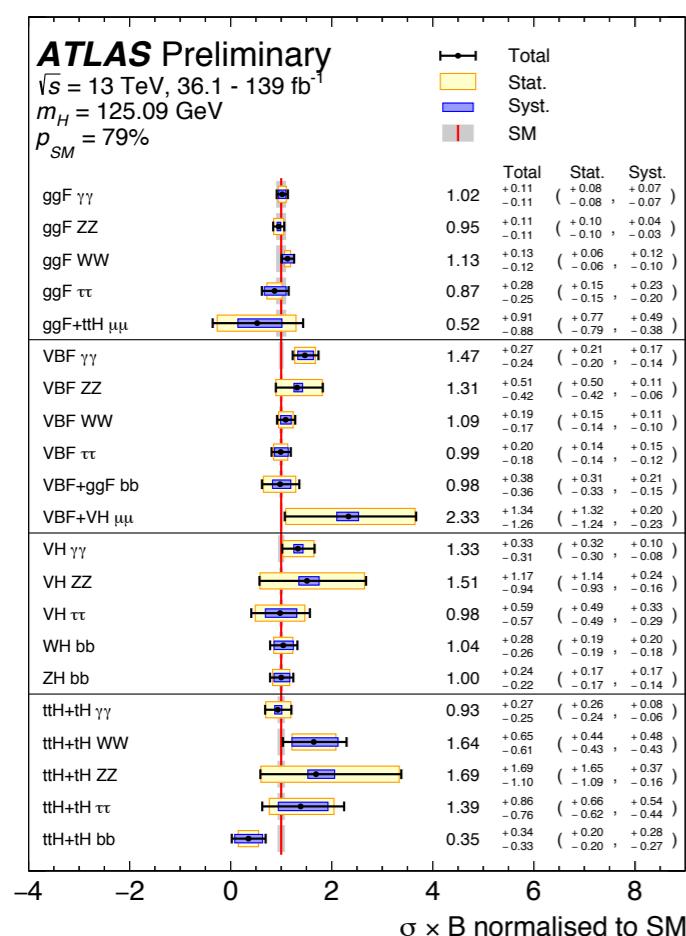
tH

Inclusive bin (from $H \rightarrow \gamma\gamma$)



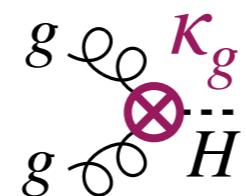
From observables to interpretations

What do these results imply for physics beyond the Standard Model?

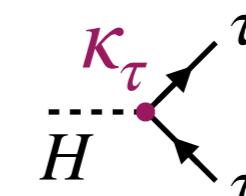


κ -framework:

Rescaling of (effective) Higgs boson couplings



$$\sigma \sim \sigma_{\text{SM}} \kappa_g^2$$



$$\Gamma \sim \Gamma_{\text{SM}} \kappa_\tau^2$$

Only modifications of absolute rates parametrised

Standard model effective field theory (SMEFT):

Model-independent parametrisation of low-energy effects of high-energy BSM physics

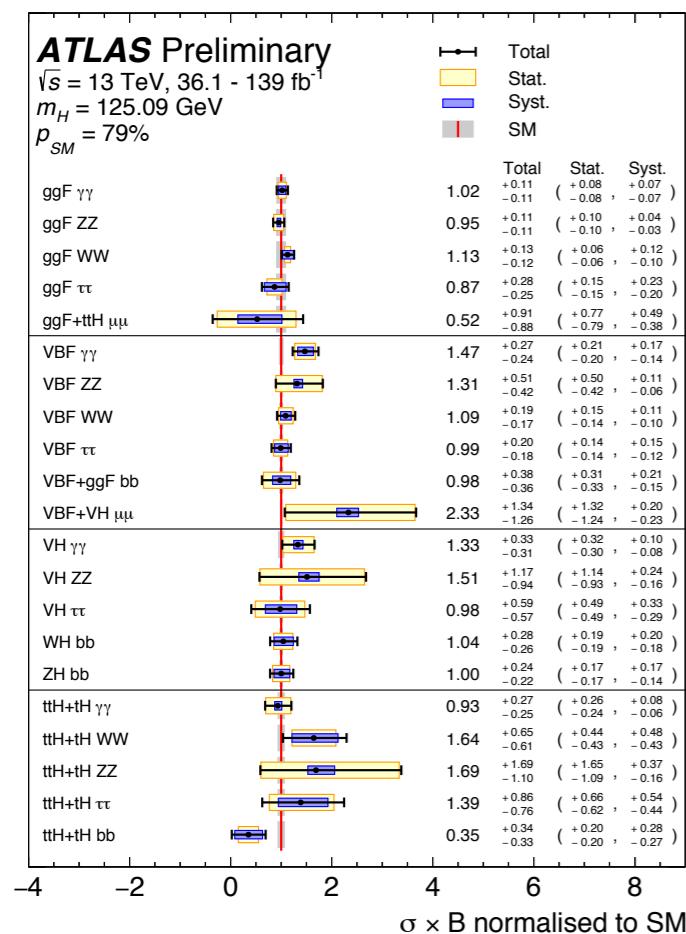
Differential modifications included

UV-complete theory:

Model-dependent (*by construction*)

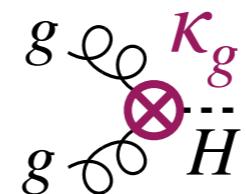
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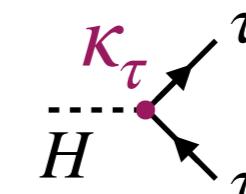


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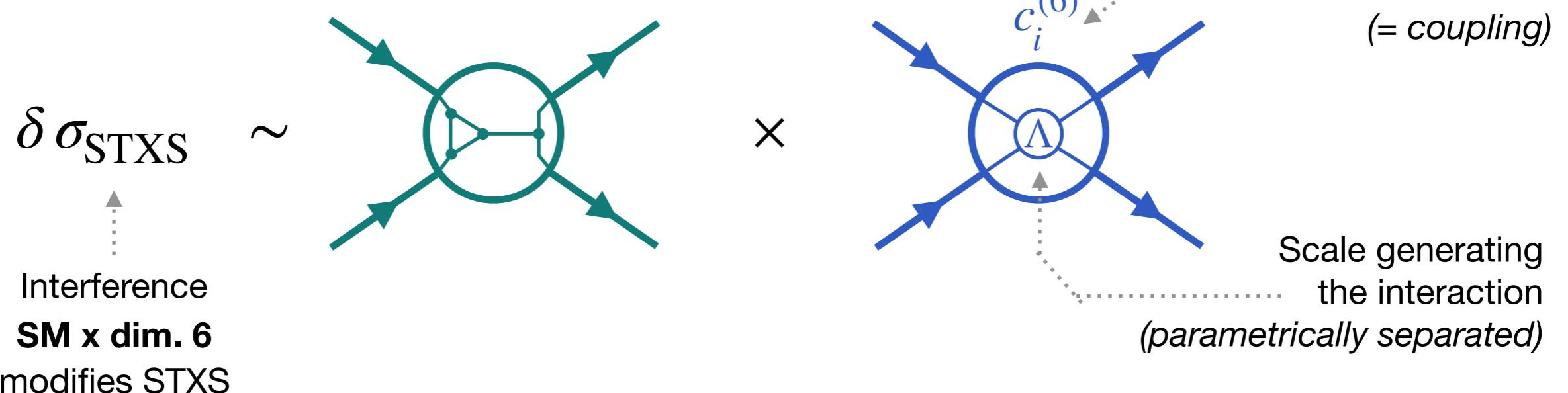
The Standard Model Effective Field Theory

**High-energy physics affects low-energy observables
in a finite (and parametrisable!) number of ways**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \dots$$

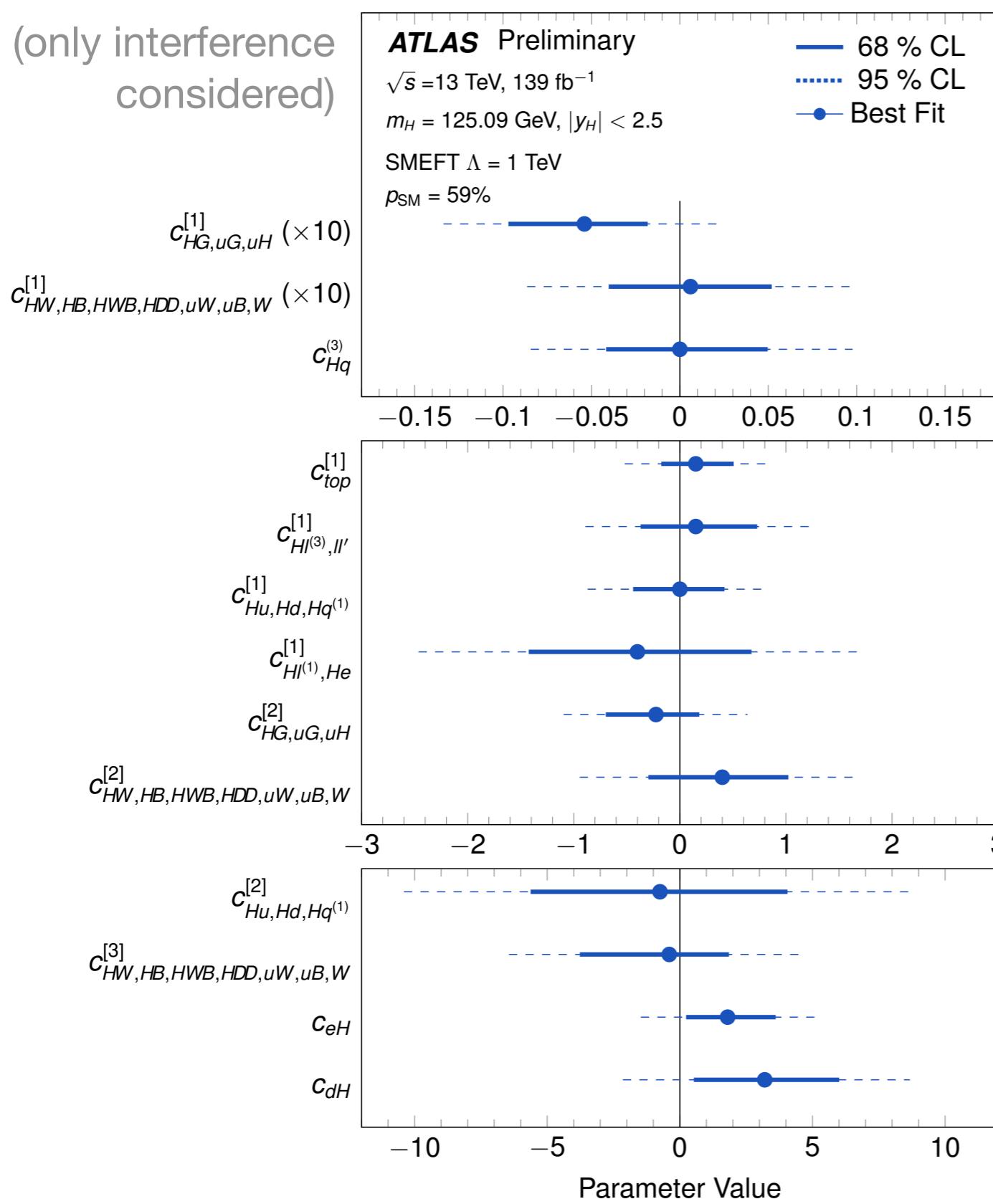
Mass dimension ≤ 4
Uniquely determined
by symmetry

**Mass dimension 6,
(Assume $U(3)^5$ symmetry, Warsaw basis)**
**Corrections to SM interactions +
new contact interactions**



One-dimensional limits

(only interference considered)



1d limits on Wilson coefficients
from **simultaneous fit** to
13 parameters

(Similar operators grouped together)

Constraints on Wilson coefficients

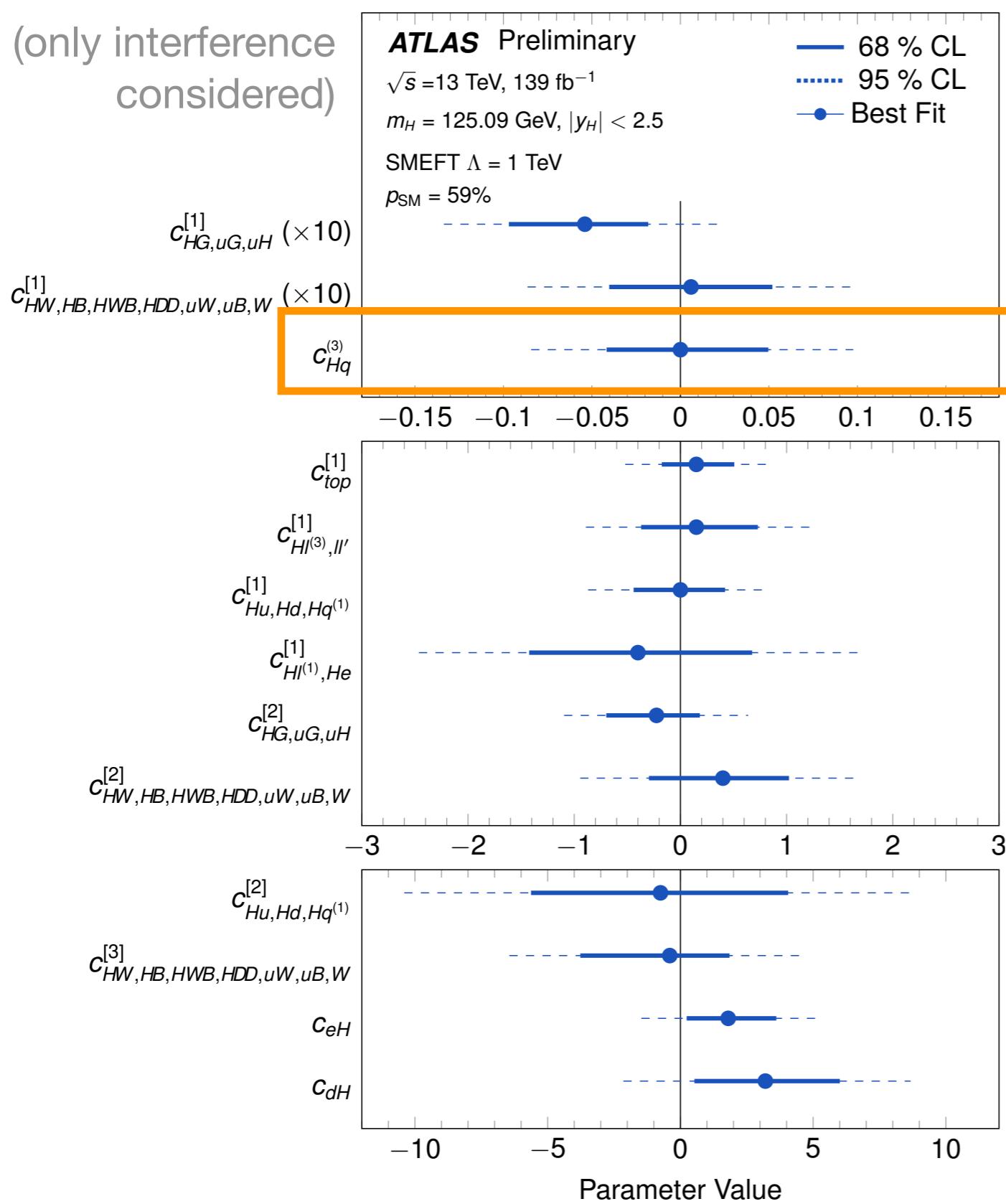
$$\mathcal{O}(0.1-5)$$

$$\frac{\Lambda}{\sqrt{c_i}} = 3 \text{ TeV}$$

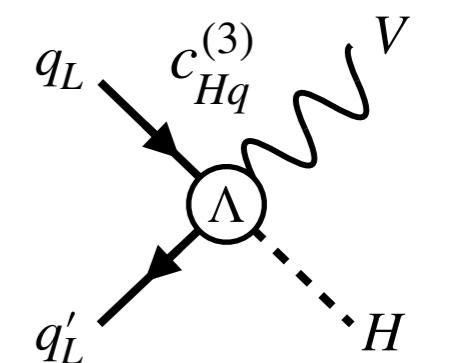
$$\frac{\Lambda}{\sqrt{c_i}} = 0.45 \text{ TeV}$$

One-dimensional limits

(only interference considered)



qqVH contact interaction, strong p_T^V dependence



$$Q_{Hq}^{(3)} \sim (H^\dagger D H)(\bar{Q}_L Q_L)$$

$\delta \sigma_{\text{STXS}}$

WH

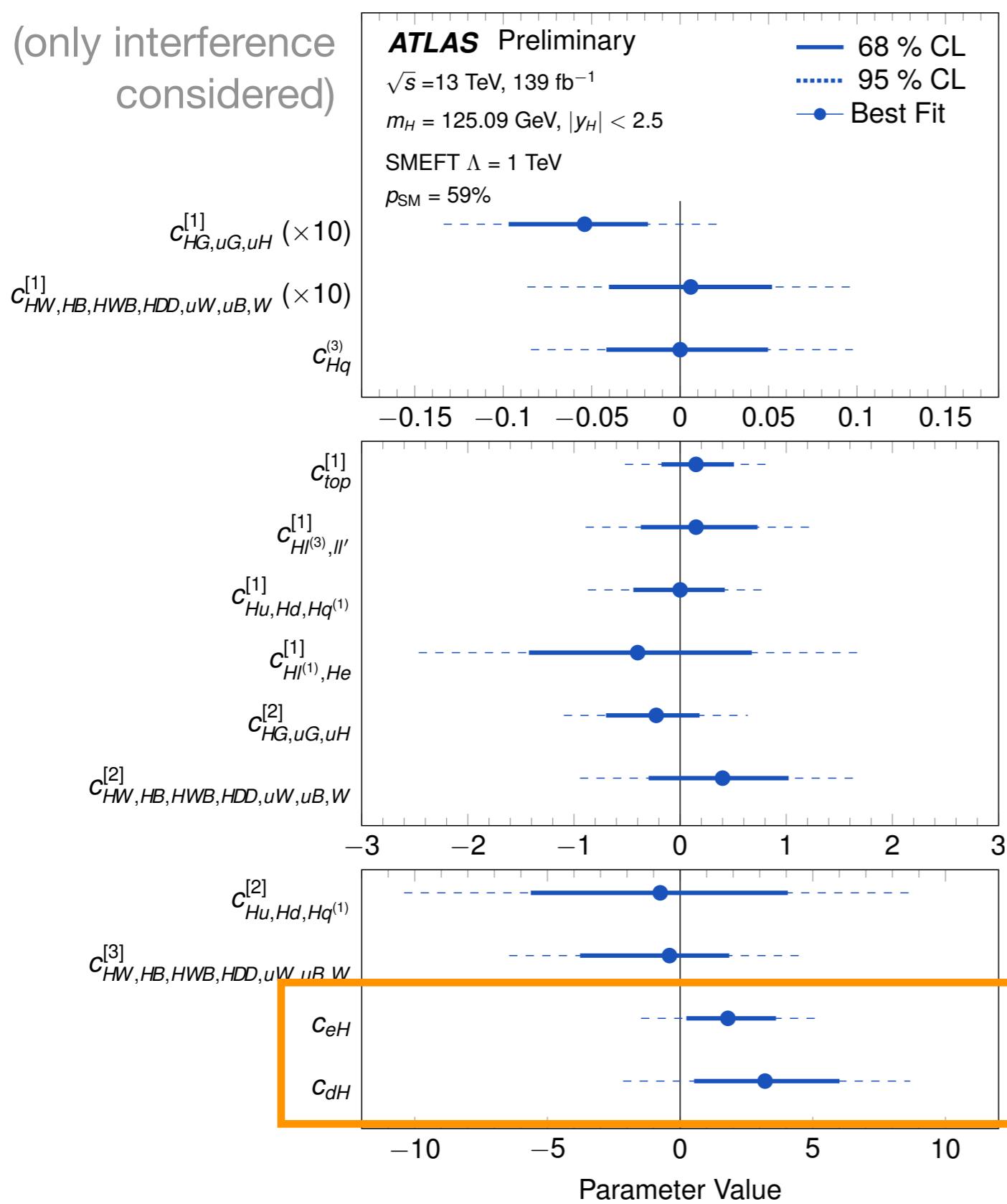
ZH

p_T^V

Constraint benefits from VH($\rightarrow bb$) granularity

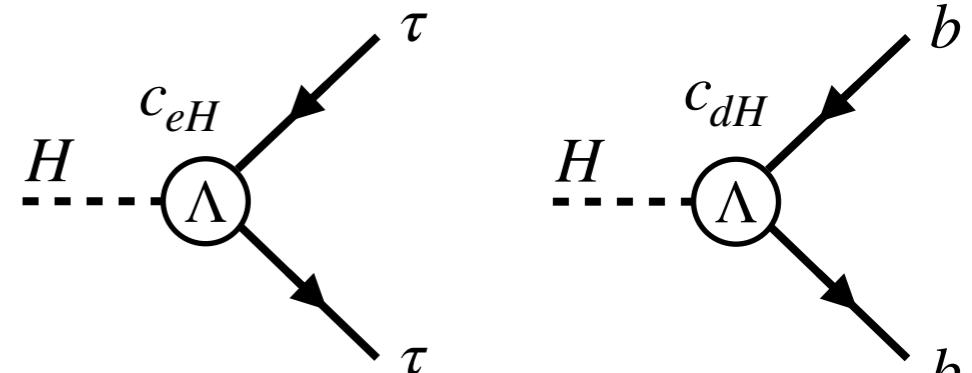
One-dimensional limits

(only interference considered)



Modifications to bottom / tau Yukawa couplings y_τ and y_b

(Positive Wilson coeff. reduces coupling)



$$Q_{eH} \sim (H^\dagger H)(\bar{L}_L e_R H)$$

From $H \rightarrow \tau\tau$

[\[CERN-EP-2021-217\]](#)

$$Q_{dH} \sim (H^\dagger H)(\bar{Q}_L d_R H)$$

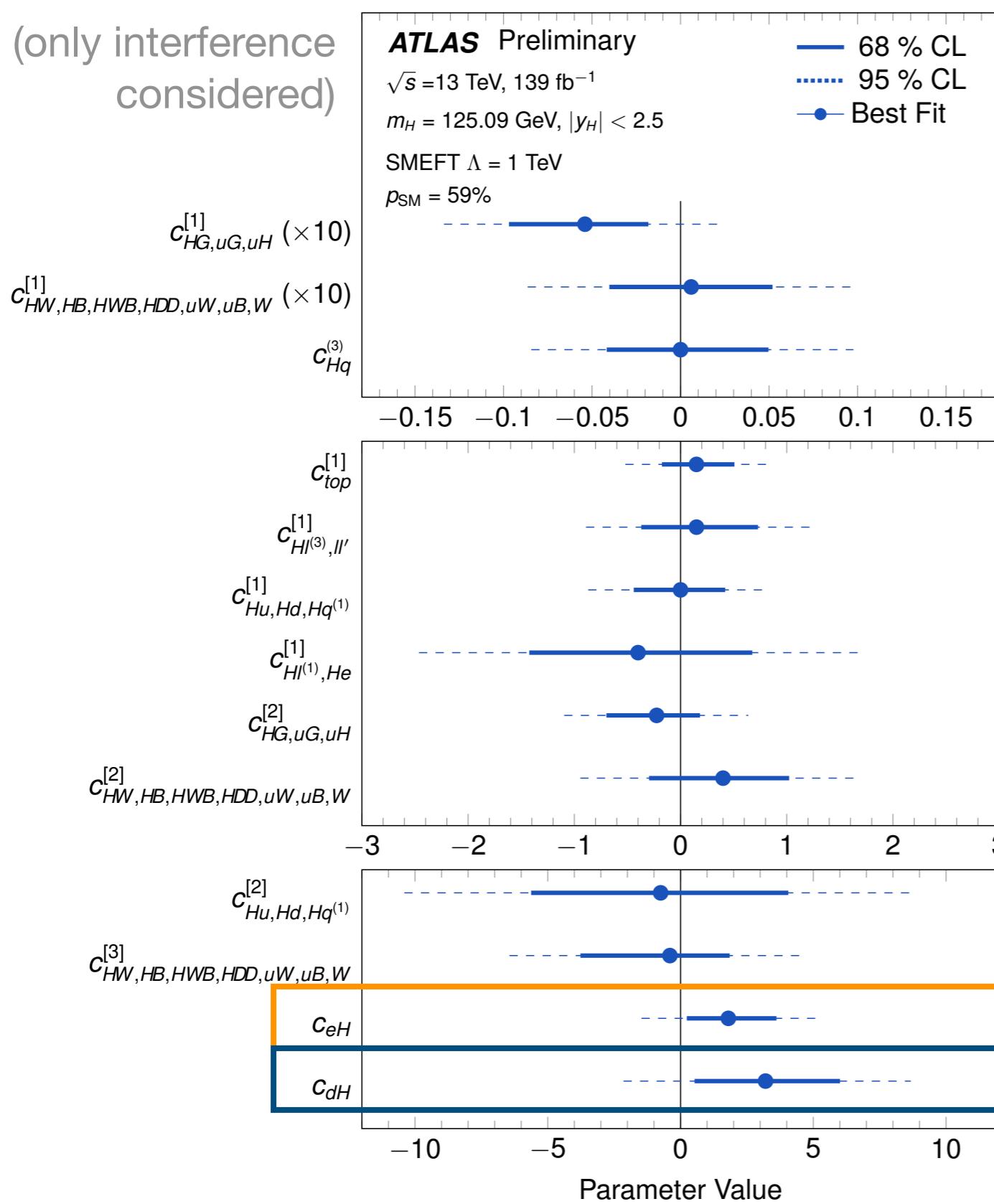
From $V(H \rightarrow bb)$

[\[ATLAS-CONF-2021-051\]](#)

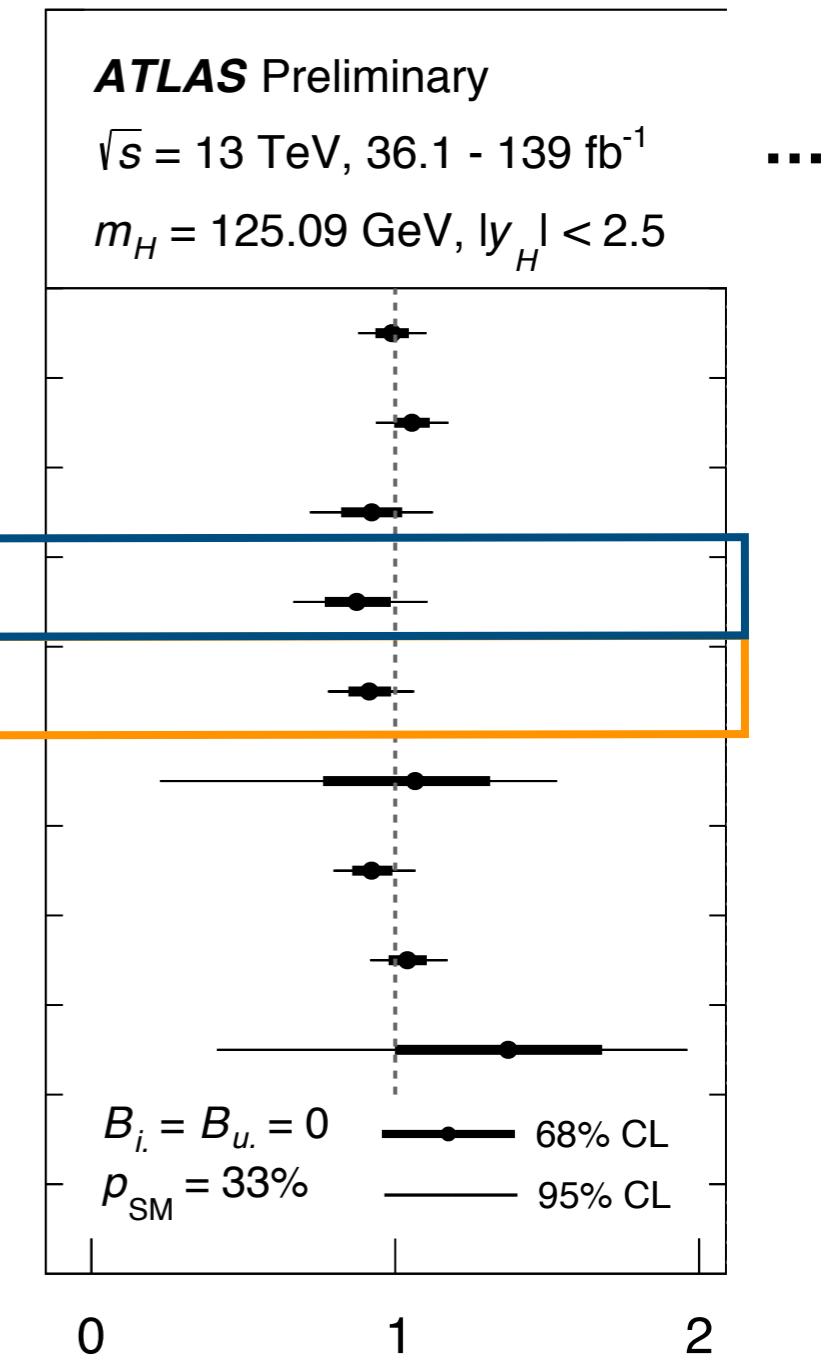
Independent of event kinematics

SMEFT and κ -framework

(only interference considered)

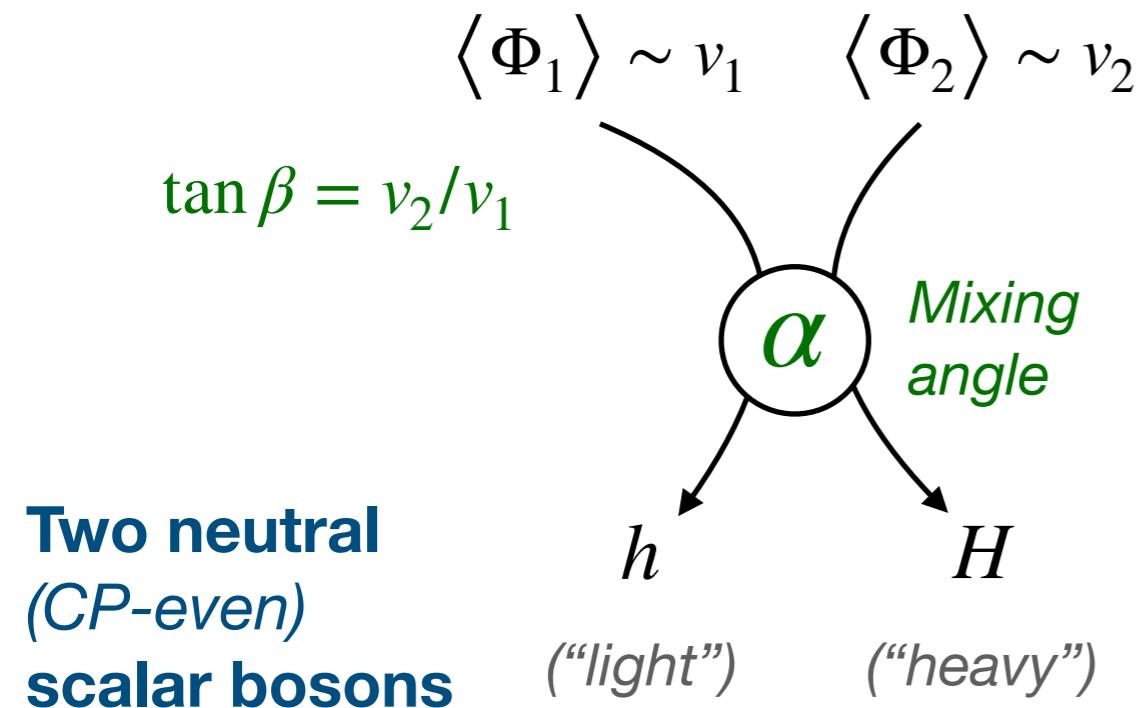


Modifications of overall yield
→ also captured by κ -framework



Two-Higgs doublet model (2-HDM)

**Two $SU(2)$ doublets with
vacuum expectation values**



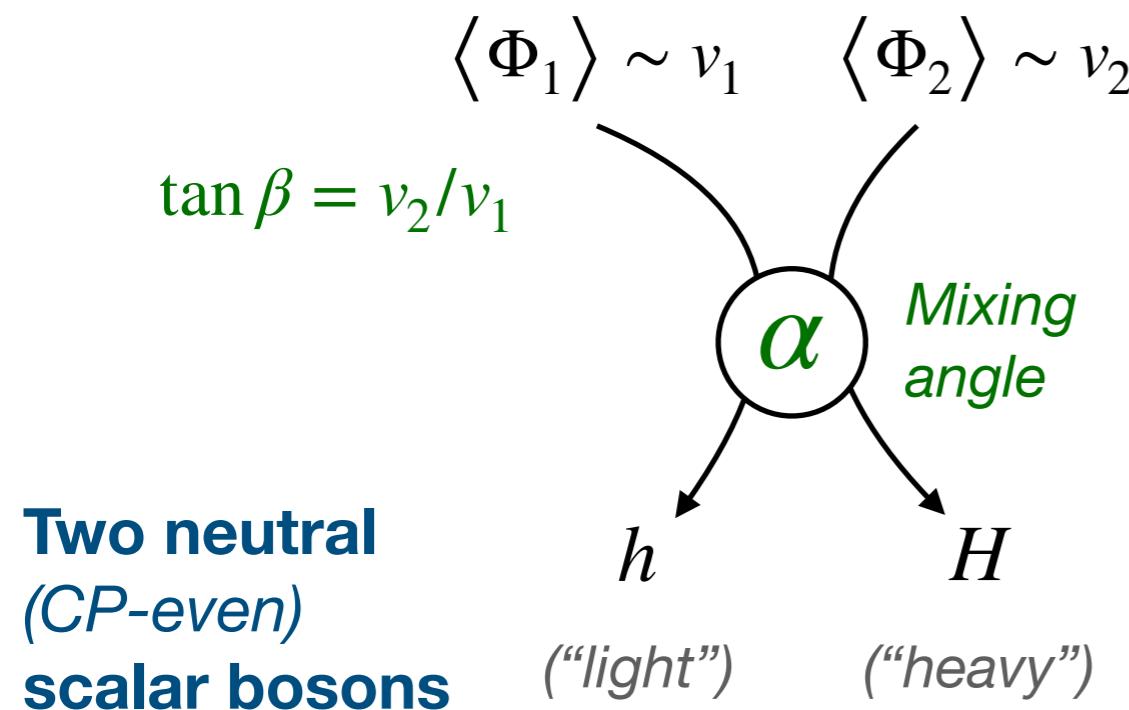
**Prevent flavour-changing
neutral currents at tree-level**

→ Different ways to couple fermions &
vectors to Φ_1 and Φ_2

“Type-I”, “Type-II”,
“Lepton-specific”, “Flipped”

Two-Higgs doublet model (2-HDM)

Two $SU(2)$ doublets with vacuum expectation values

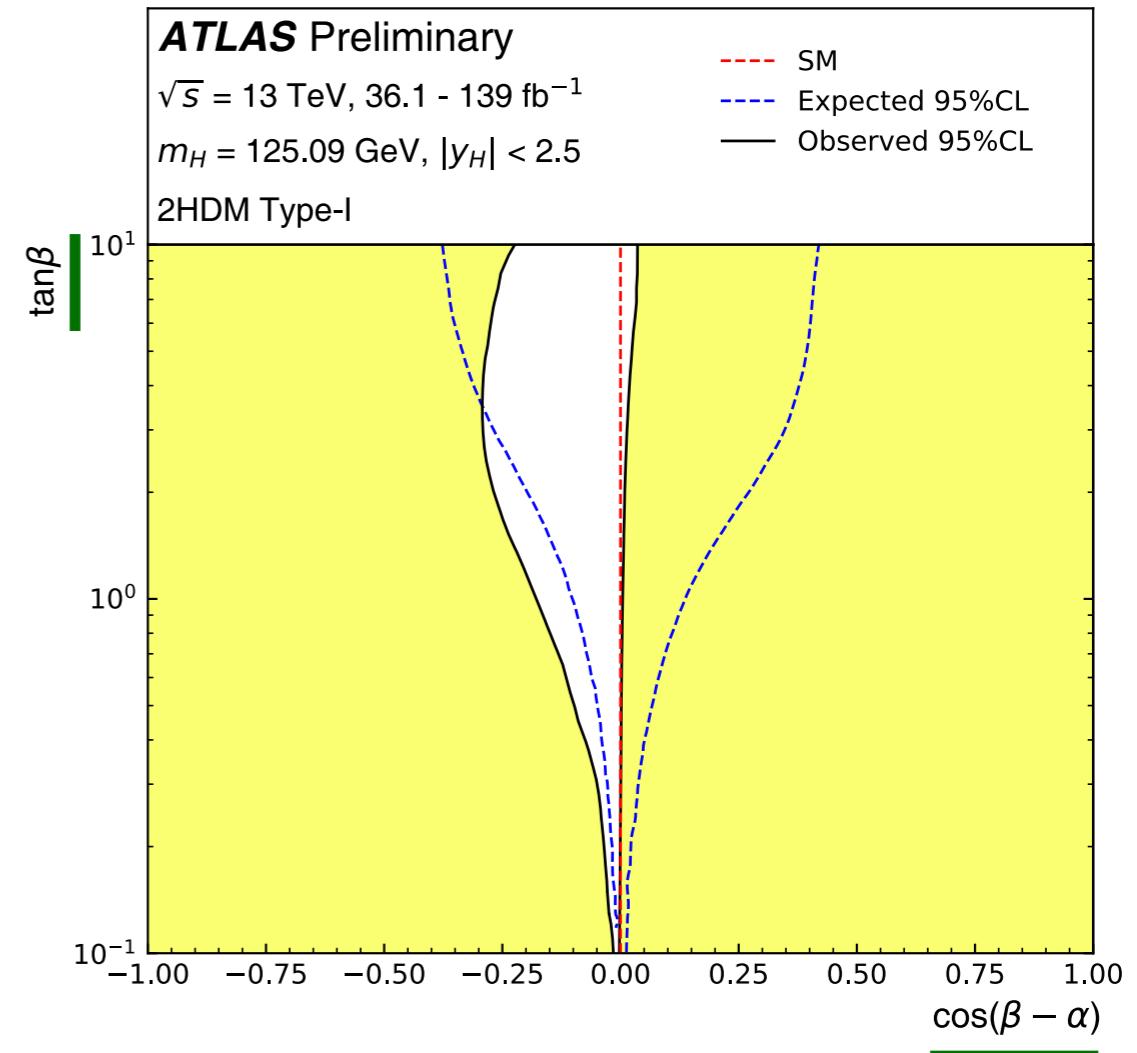


Two neutral (CP -even) scalar bosons

Prevent flavour-changing neutral currents at tree-level

→ Different ways to couple fermions & vectors to Φ_1 and Φ_2

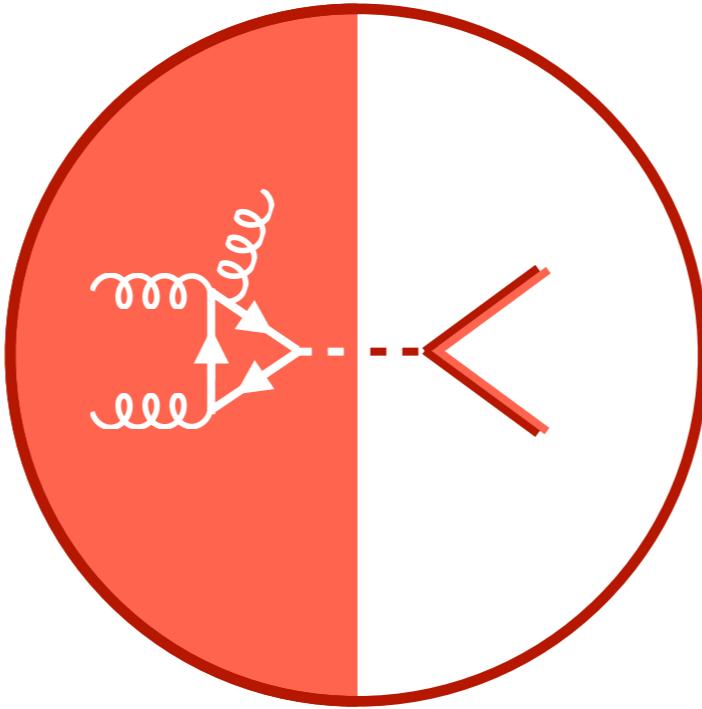
“Type-I”, “Type-II”,
“Lepton-specific”, “Flipped”



Wilson coefficients compatible with SM

“Alignment limit” of 2-HDM
 $\cos(\beta - \alpha) \rightarrow 0$

→ *Light Higgs becomes SM-like*



Constraints on κ_b and κ_c

$H \rightarrow \gamma\gamma/4\ell$
combination

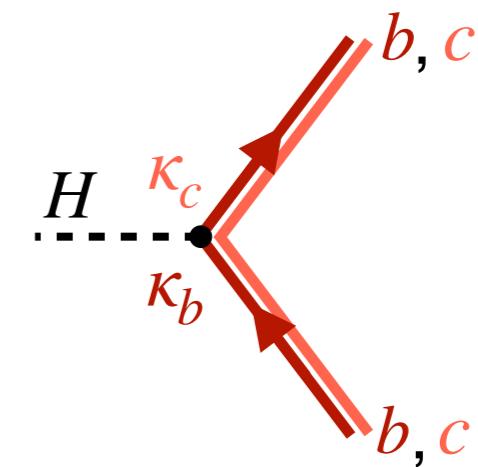
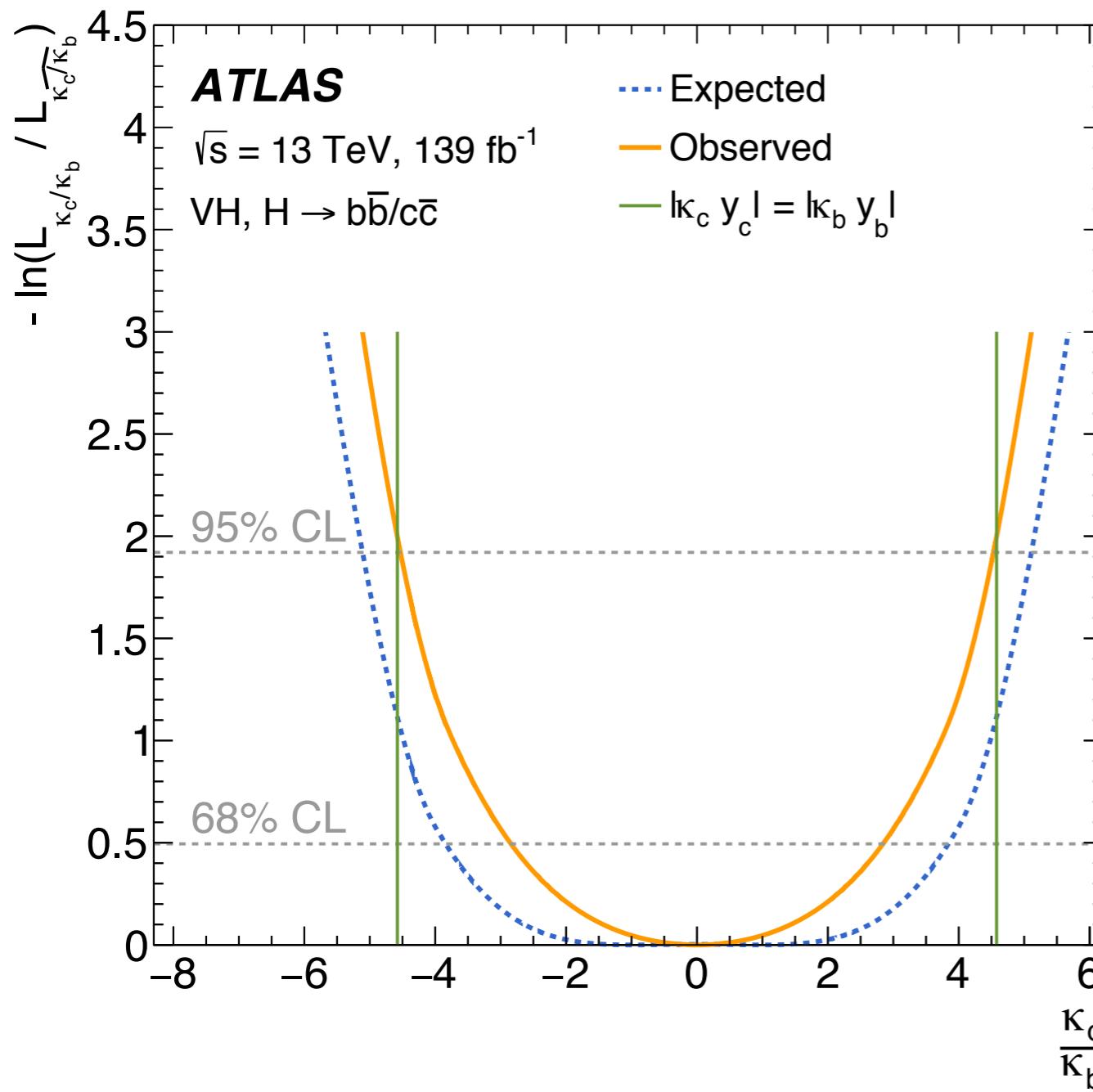
[[ATLAS-CONF-2022-002](#)]

$VH \rightarrow bb/cc$
combination

[[CERN-EP-2021-251](#)]

Direct constraints on κ_b and κ_c

Direct demonstration of **flavour-nonuniversality** in b/c-coupling: $\left| \frac{\kappa_c}{\kappa_b} \right| < \frac{m_b}{m_c}$

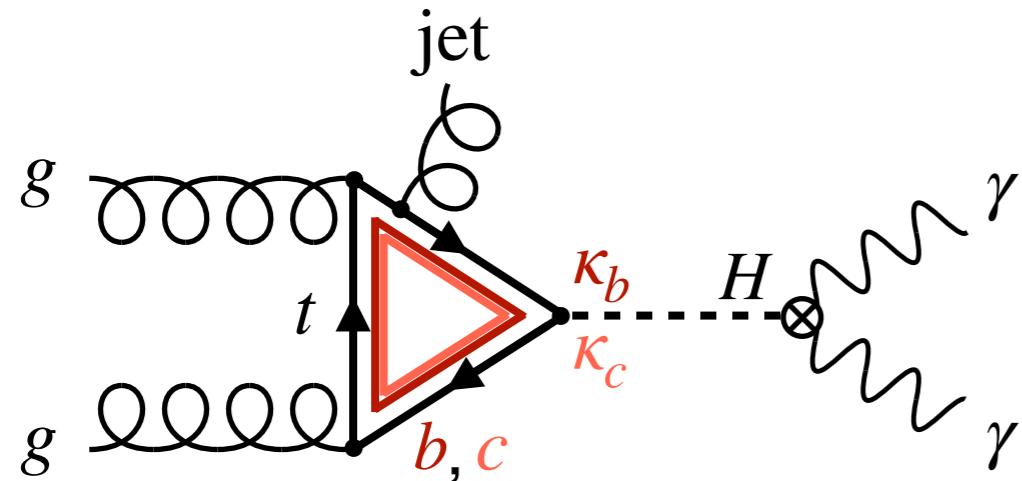


**H($\rightarrow b\bar{b}/c\bar{c}$) accessible
in V($\rightarrow \text{lep.}$)H**

Simultaneous measurement
of VH($\rightarrow b\bar{b}$) and VH($\rightarrow c\bar{c}$)
signal strength in
resolved topology

Orthogonal b- and c-tagging
[\[CERN-EP-2021-251\]](#)

Indirect constraints on κ_b and κ_c



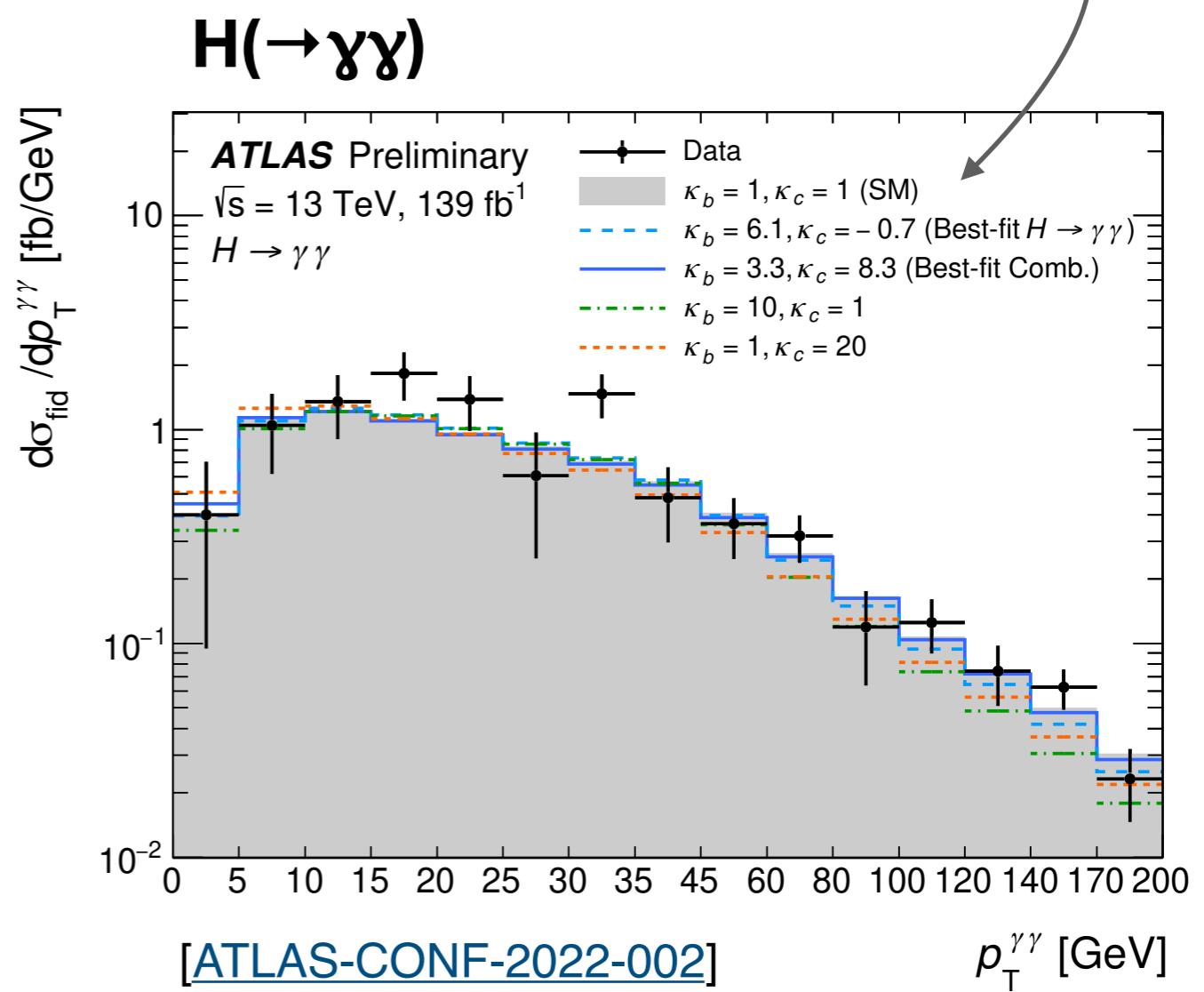
**Shape of p_T^H spectrum
sensitive to κ_b, κ_c**
(Production mode-inclusive)

Jet emissions probe loop structure;
interference between **b** / **c** and top

Bishara et al. [[PRL 118, 121801](#)]

Differential measurements
for $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
(See Sagar's talk)

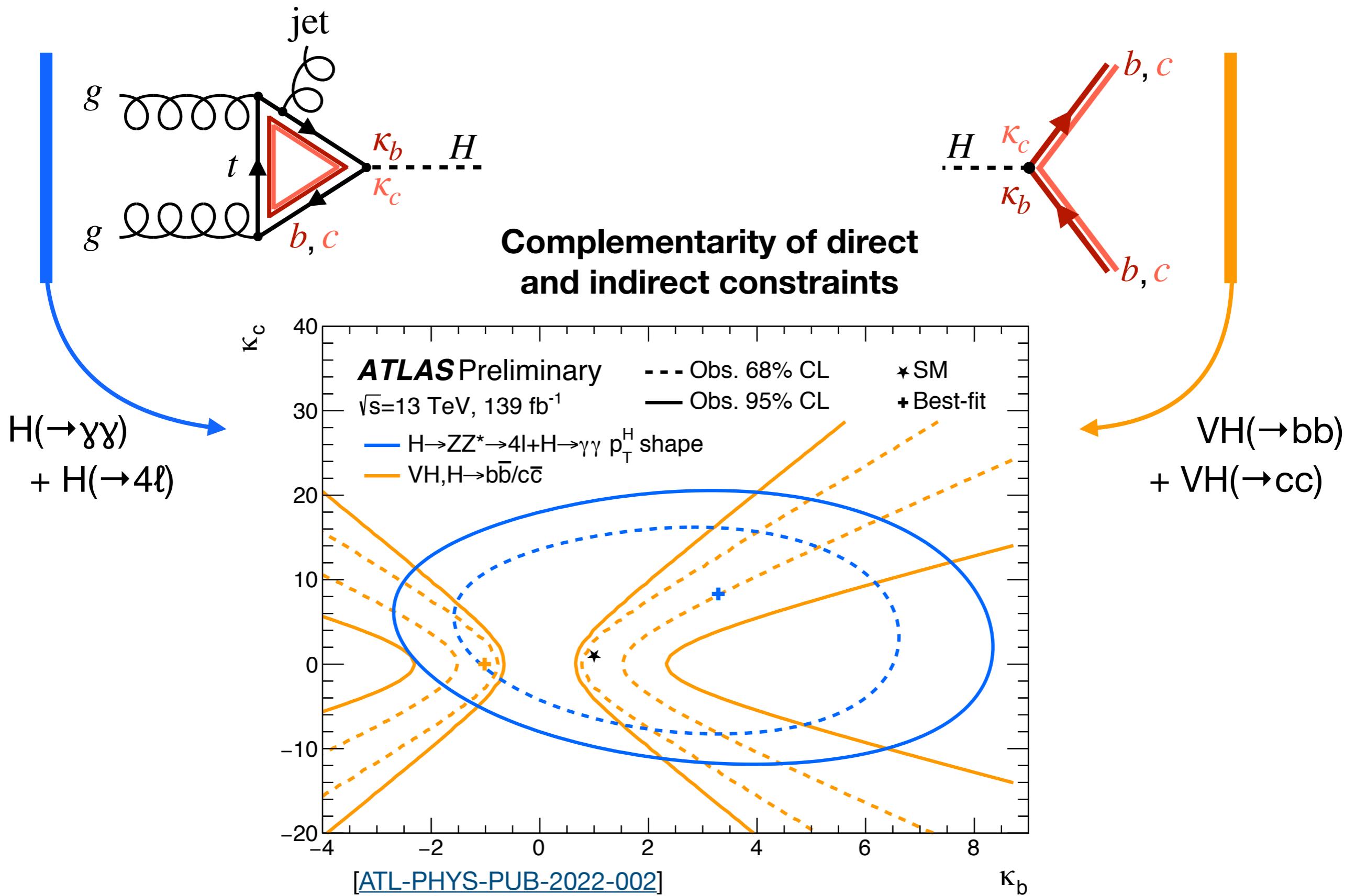
Modifications of p_T spectrum
for different κ_b, κ_c



[[ATLAS-CONF-2022-002](#)]

$p_T^{\gamma\gamma} [\text{GeV}]$

Comparison of constraints



Summary and outlook

**Combination analyses
summarise experimental
knowledge**

Higgs couplings combination

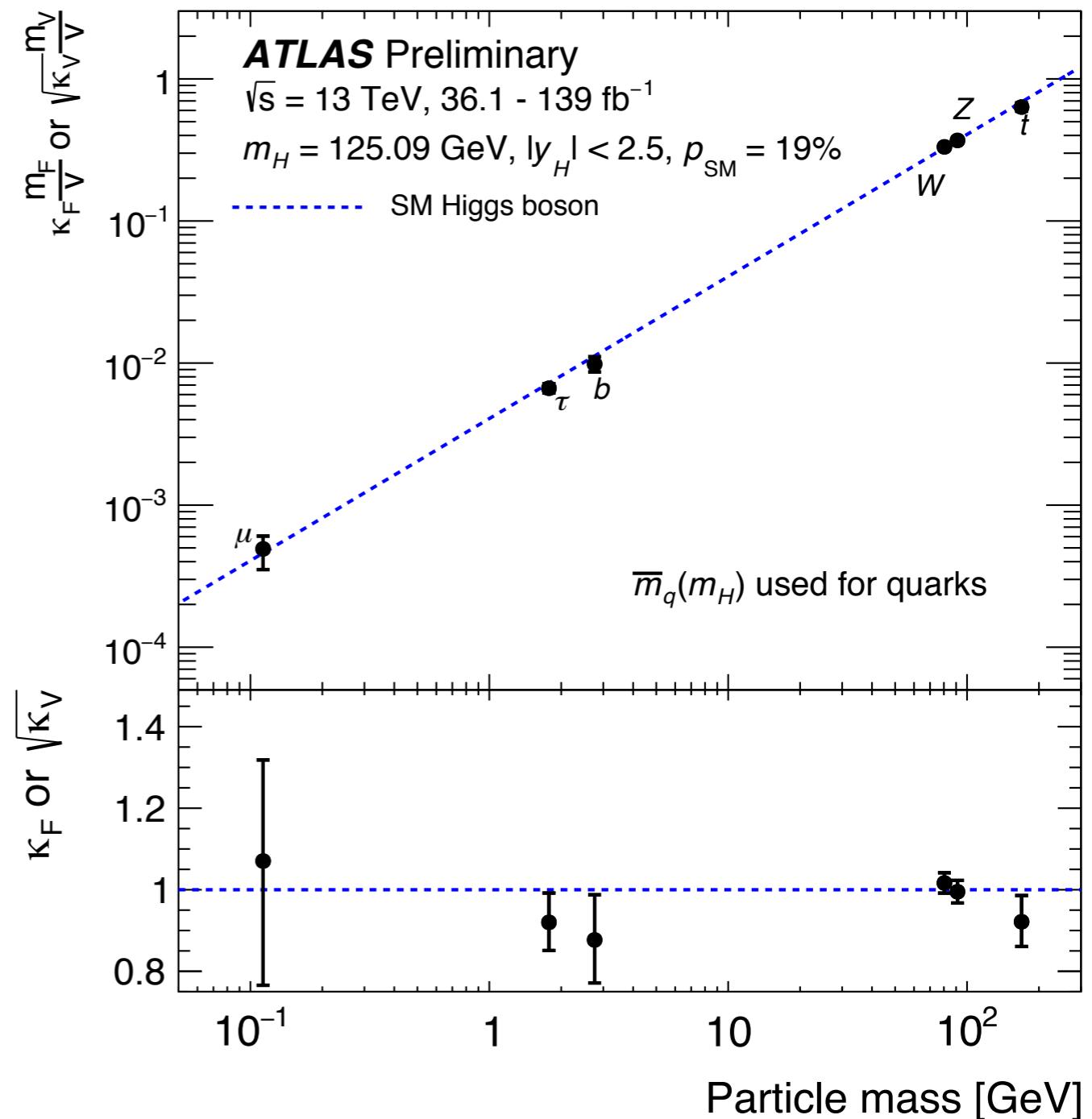
*Main production modes
and decay channels*

STXS measurements → Physics interpretations

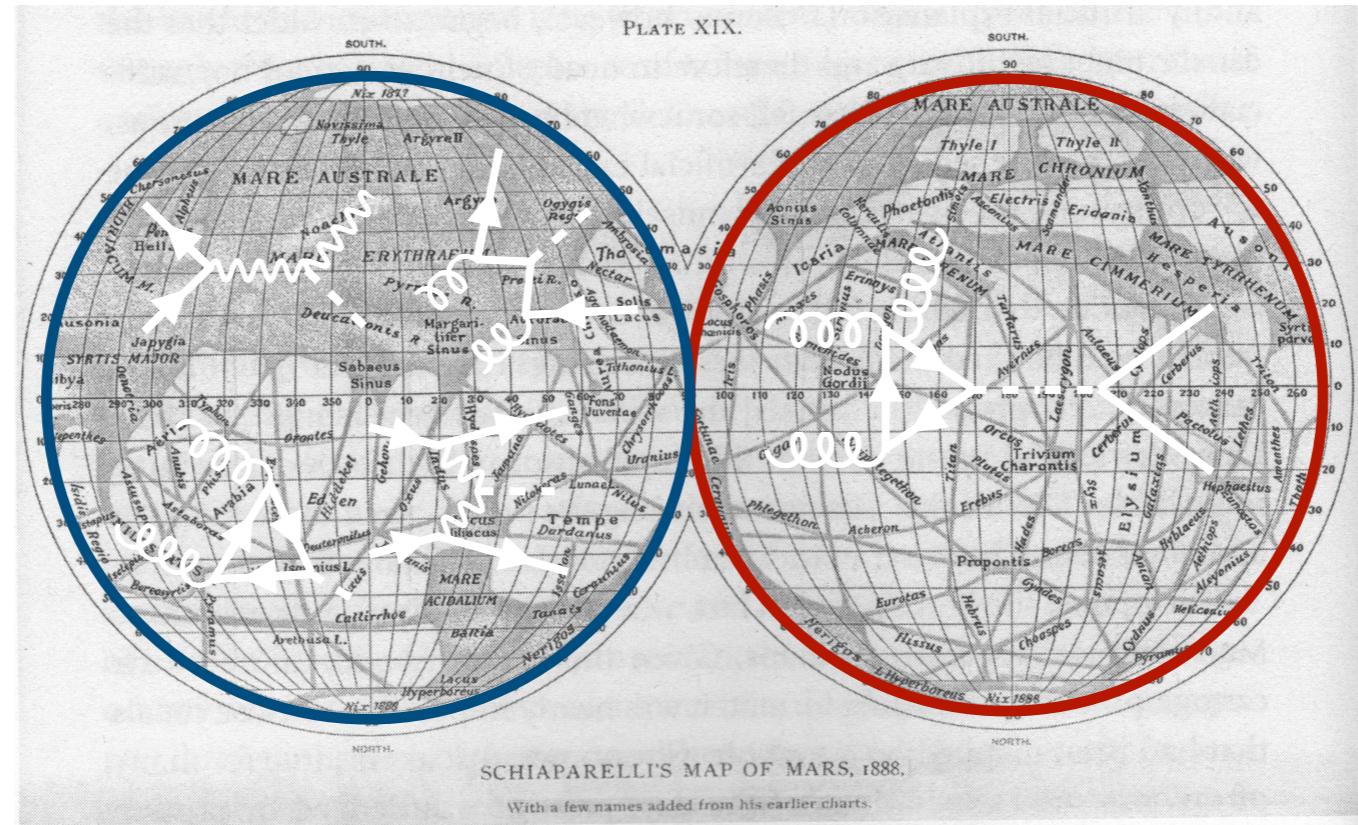
2nd / 3rd gen. Yukawa couplings

Differential spectra *Direct measurement*

**Stay tuned for more data
and more results!**



J. V. Schiaparelli, 1888 [[link](#)]



Backup

During the late 19th and early 20th centuries, it was erroneously believed that there were “canals” on the planet Mars.

https://en.wikipedia.org/wiki/Martian_canal



Higgs couplings combination

[[ATLAS-CONF-2021-053](#)]

List of included analyses

Only ttH multilepton measurement
based on partial Run 2 data set

Decay channel	Target Production Modes	\mathcal{L} [fb $^{-1}$]	Ref.	Used in combined measurement
$H \rightarrow \gamma\gamma$	ggF, VBF, WH , ZH , $t\bar{t}H$, tH	139	[10]	Everywhere
$H \rightarrow ZZ^*$	ggF, VBF, WH , ZH , $t\bar{t}H(4\ell)$	139	[11]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow WW^*$	ggF, VBF	139	[12]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow \tau\tau$	ggF, VBF, WH , ZH , $t\bar{t}H(\tau_{had}\tau_{had})$	139	[13]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow b\bar{b}$	WH , ZH	139	[14,15,16]	Everywhere
	VBF	126	[17]	Everywhere
	$t\bar{t}H$	139	[18]	Everywhere
$H \rightarrow \mu\mu$	ggF, VBF, VH , $t\bar{t}H$	139	[20]	Everywhere but STXS and SMEFT
$H \rightarrow Z\gamma$	ggF, VBF, VH , $t\bar{t}H$	139	[21]	Everywhere but STXS and SMEFT
$H \rightarrow inv$	VBF	139	[22]	Sec. 6.2 & 6.3

[\[ATLAS-CONF-2021-053\]](#)

Combination methodology

Combined likelihood as product of likelihoods of input measurements

No / negligible overlap in event selections between analyses

*(In some cases explicitly removed before combination,
e.g. boosted & resolved VH($\rightarrow bb$))*

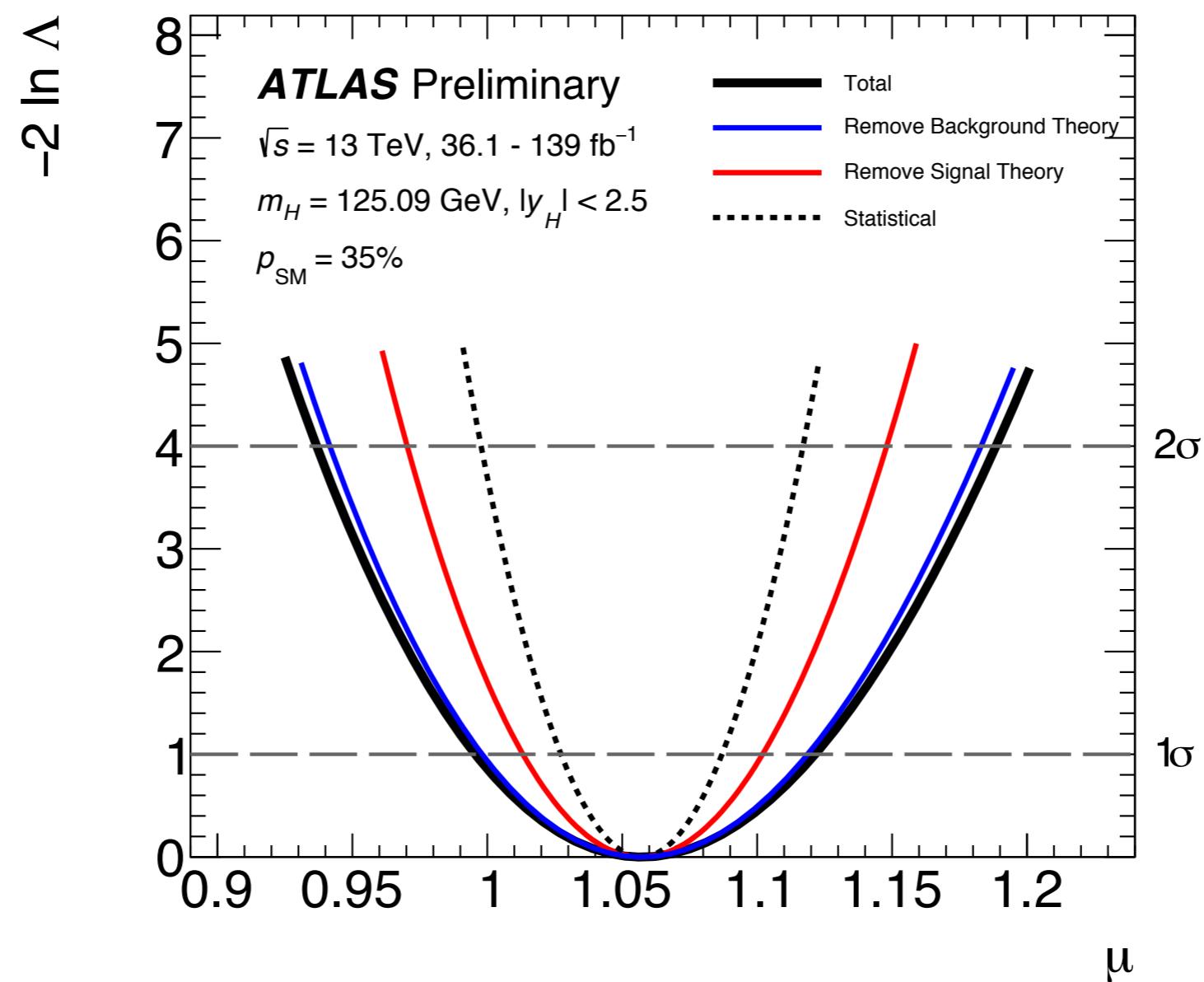
Coherent signal modelling across all regions

Nuisance parameters correlated where possible

*E.g. experimental uncertainties: jet calibration,
lepton reconstruction, luminosity measurement, ...*

Inclusive signal strength

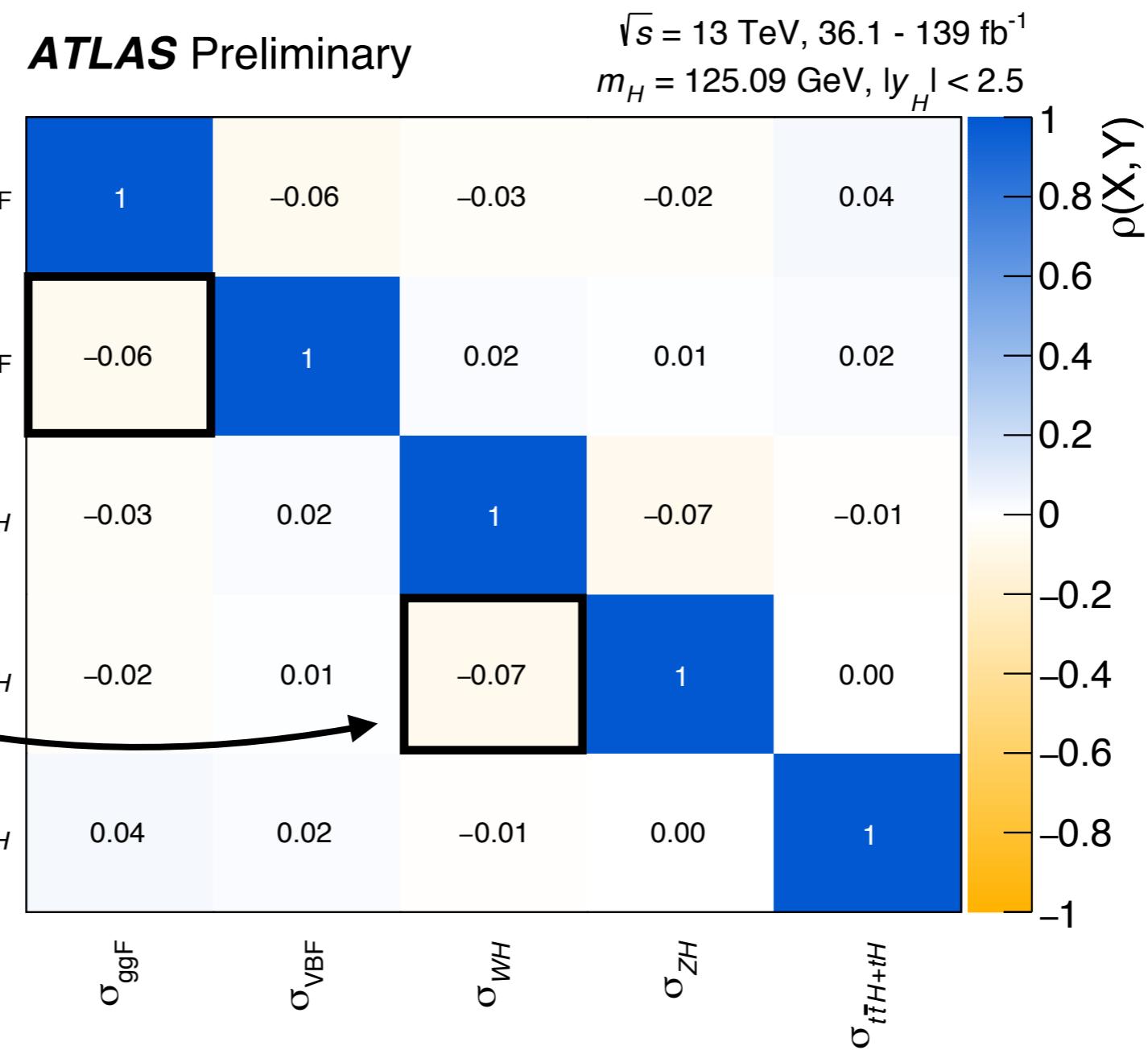
$$\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (exp.)} \pm 0.04 \text{ (sig. th.)} \pm 0.02 \text{ (bkg. th.)}$$



Production mode cross-sections: correlations

Residual cross-contamination between ggF and VBF

Increased correlation after inclusion of $H \rightarrow \tau\tau$



$\sigma \times B$: correlations

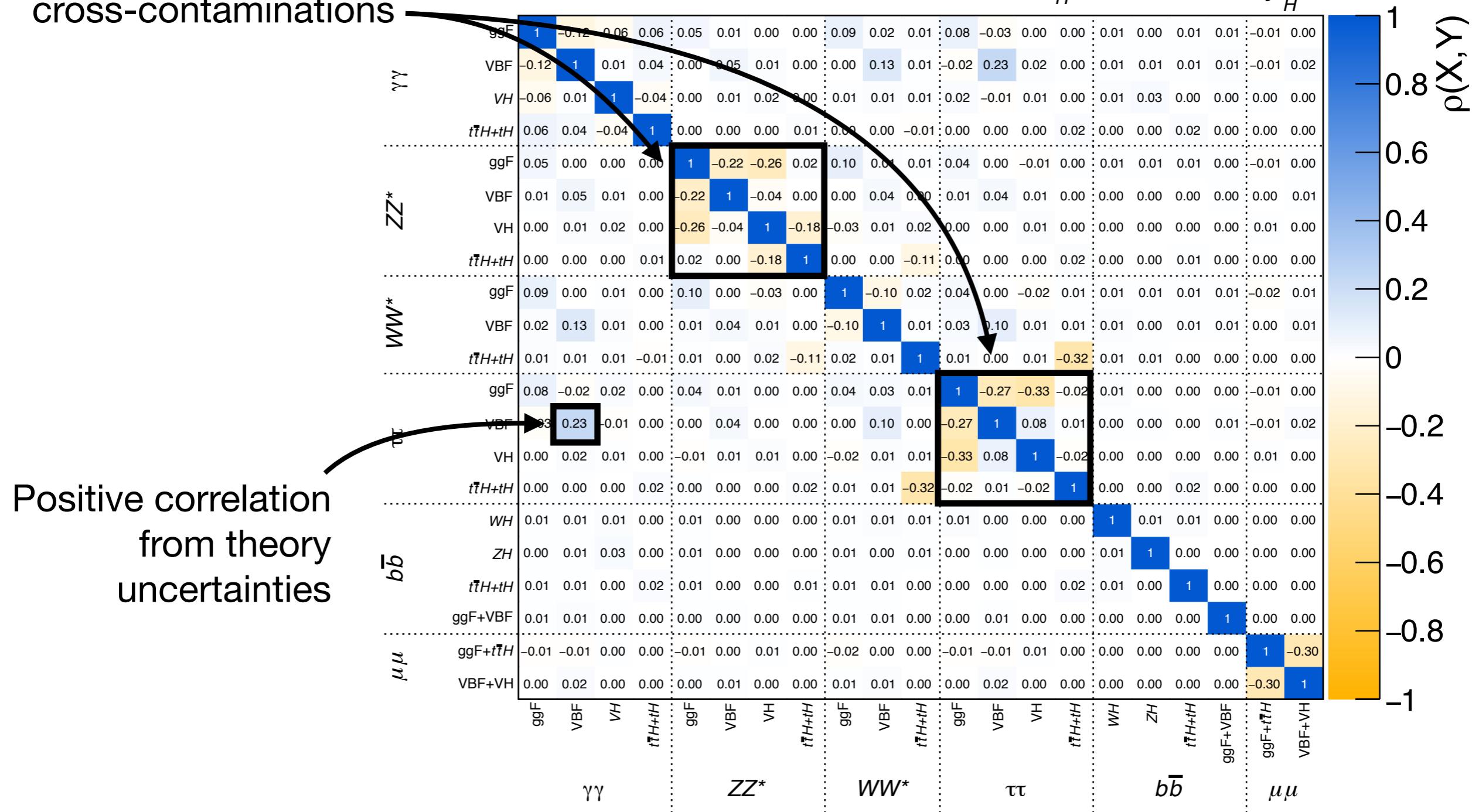
Negative correlations:
cross-contaminations -

ATLAS Preliminary

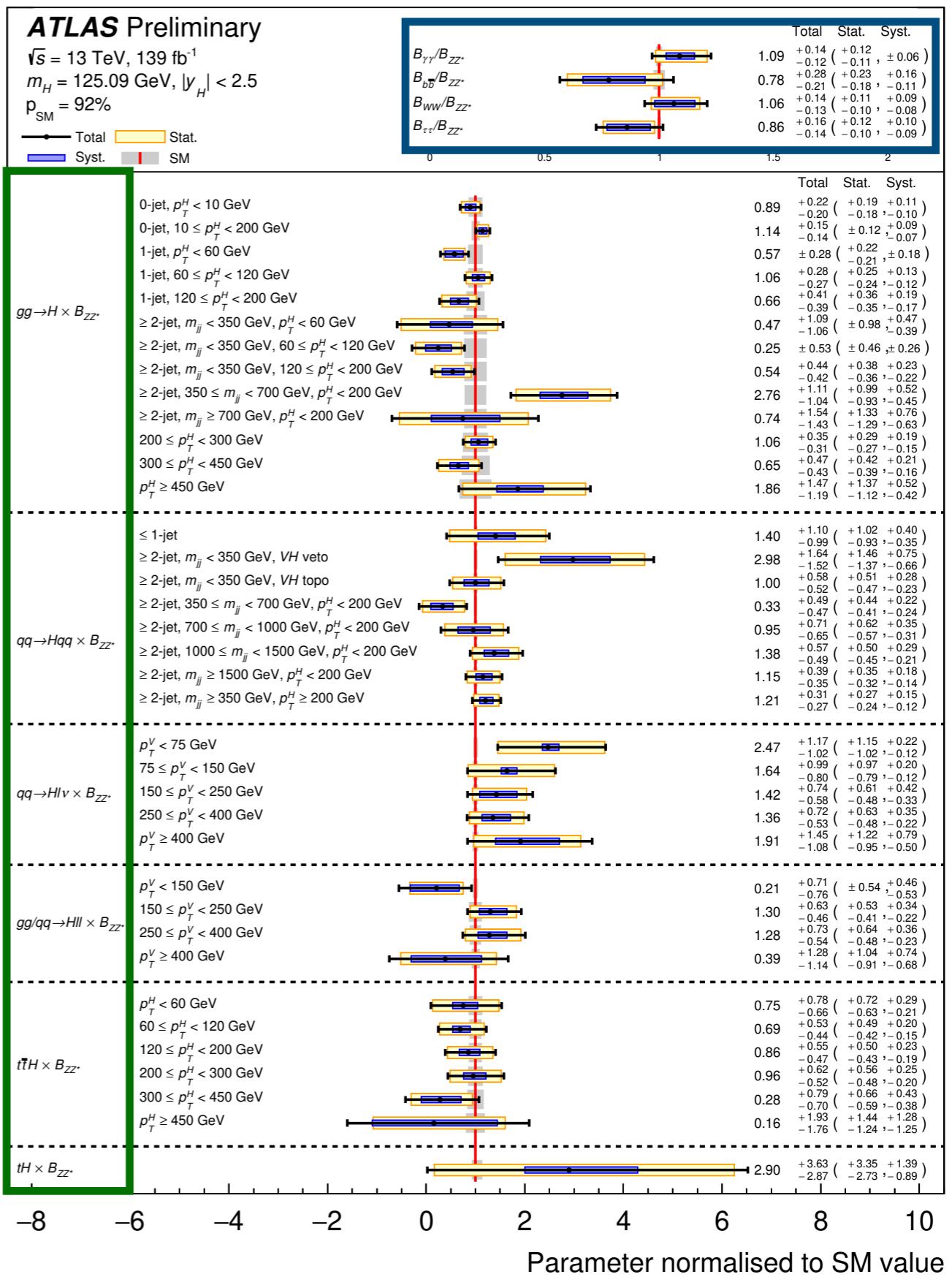
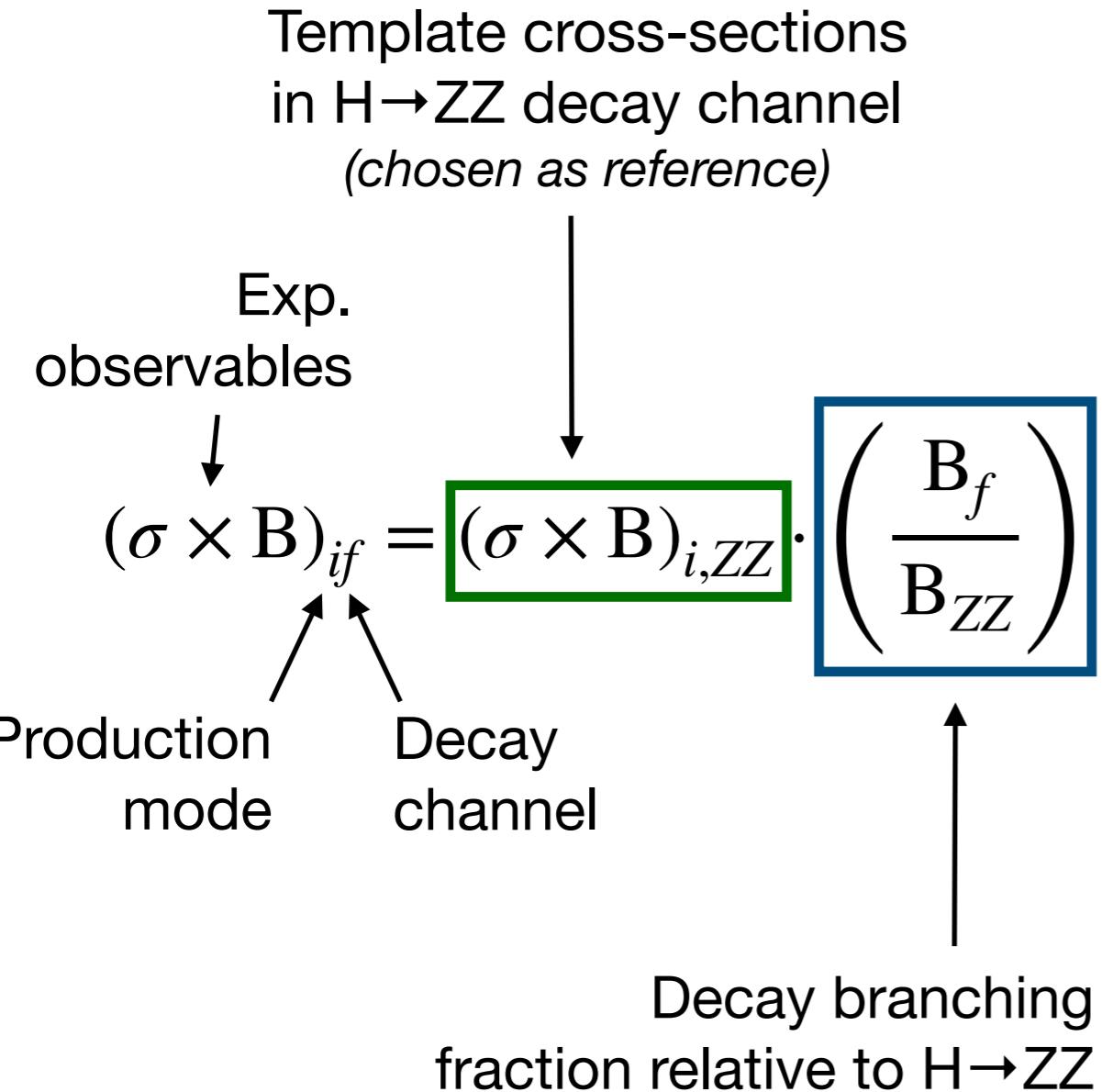
$\sqrt{s} = 13 \text{ TeV}, 36.1 - 139 \text{ fb}^{-1}$

$m_H = 125.09 \text{ GeV}, |\eta_H| < 2.5$

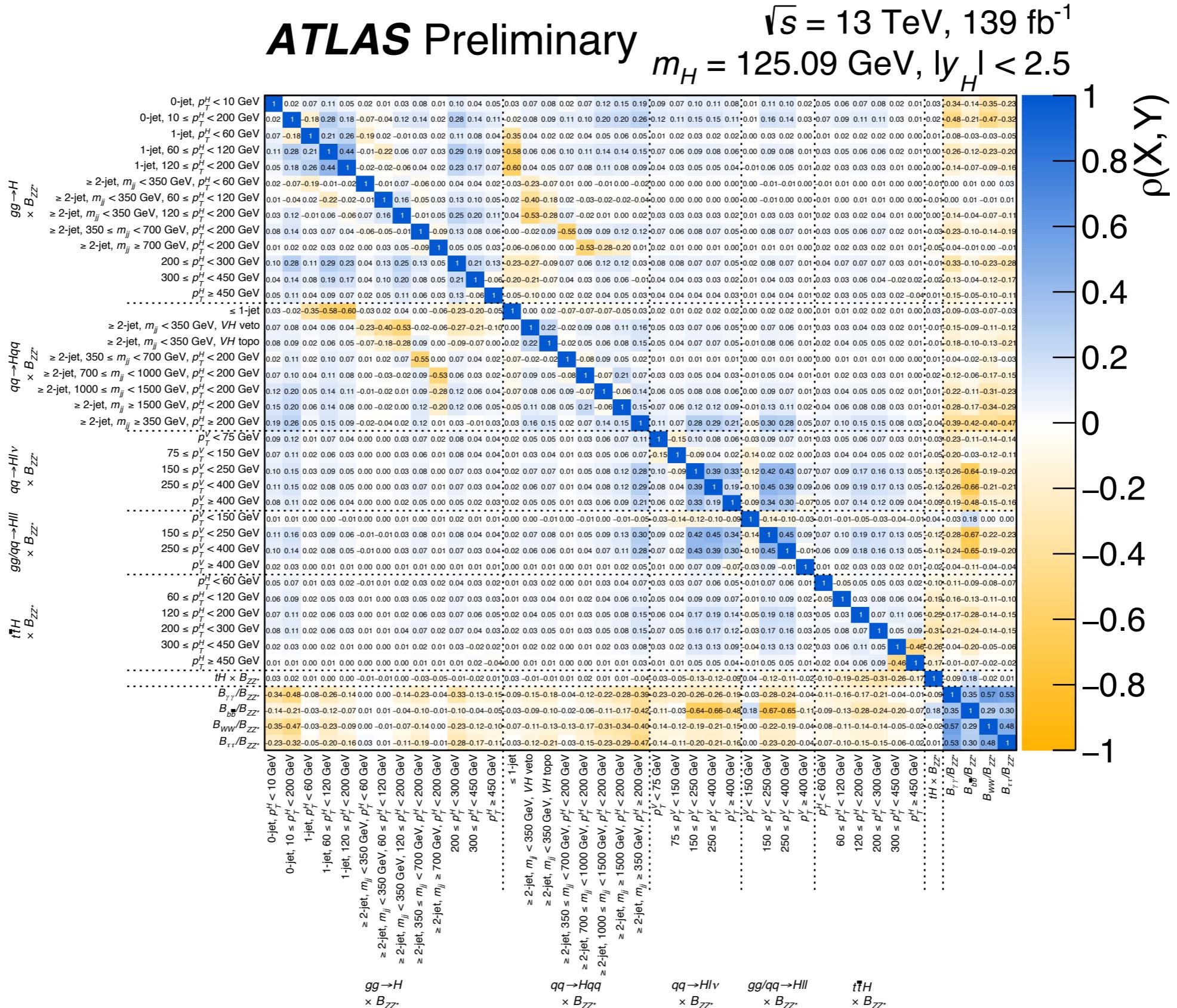
$\rho(X, Y)$



STXS measurement: fitted parameters



STXS measurement: correlation matrix



SMEFT parametrisation details

Observables are polynomial in Wilson coefficients $c_i^{(6)}$:

$$\frac{[\sigma \times \text{Br}(H \rightarrow \text{f. s.})]_{\text{SMEFT}}}{[\sigma \times \text{Br}(H \rightarrow \text{f. s.})]_{\text{SM}}} = \frac{\sigma_{\text{SMEFT}}}{\sigma_{\text{SM}}} \times \frac{\frac{1 + \alpha_i c_i^{(6)}}{\Gamma(H \rightarrow \text{f. s.})_{\text{SMEFT}}}}{\frac{1 + A_i^f c_i^{(6)}}{\Gamma(H)_{\text{SMEFT}}}} \rightarrow 1 + A_i^f c_i^{(6)}$$

$\frac{\Gamma(H \rightarrow \text{f. s.})_{\text{SMEFT}}}{\Gamma(H \rightarrow \text{f. s.})_{\text{SM}}} \rightarrow 1 + A_i c_i^{(6)}$

(Expanded further in powers of Λ^{-1})

Coefficients for linear interference contributions obtained from simulation:

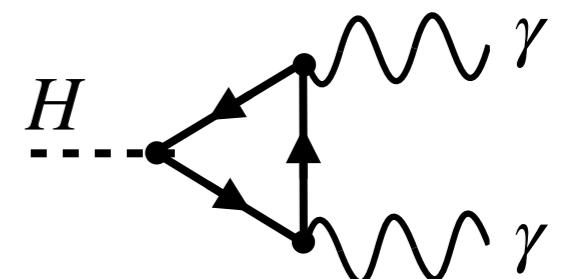
MadGraph + SMEFT@NLO for loop-induced processes (e.g. $gg \rightarrow ZH$, $H \rightarrow gg$)

MadGraph + SMEFTsim v3 for tree-level processes (LO)

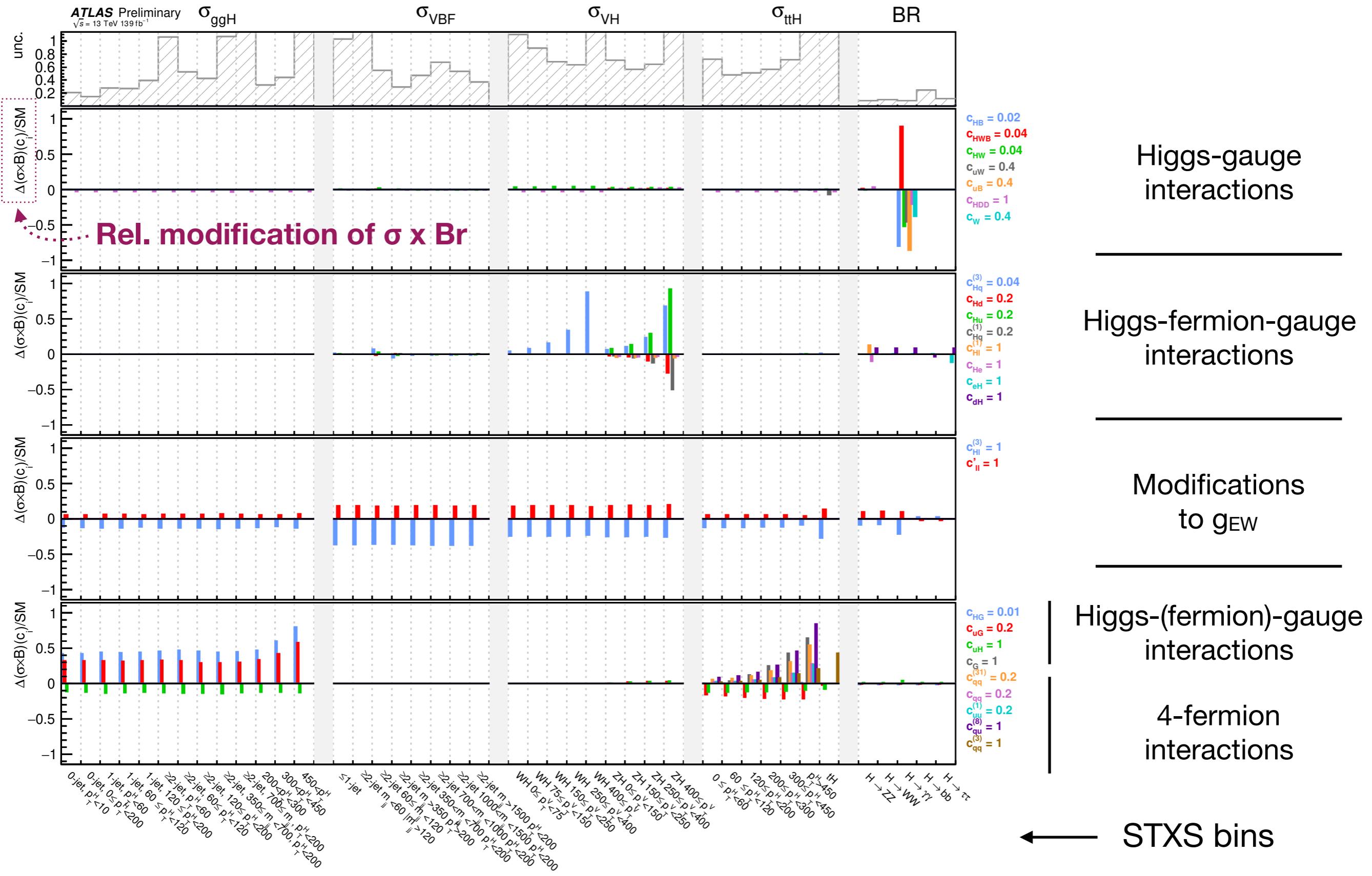
Use Warsaw basis,

{ m_W , m_Z , G_F } input scheme,

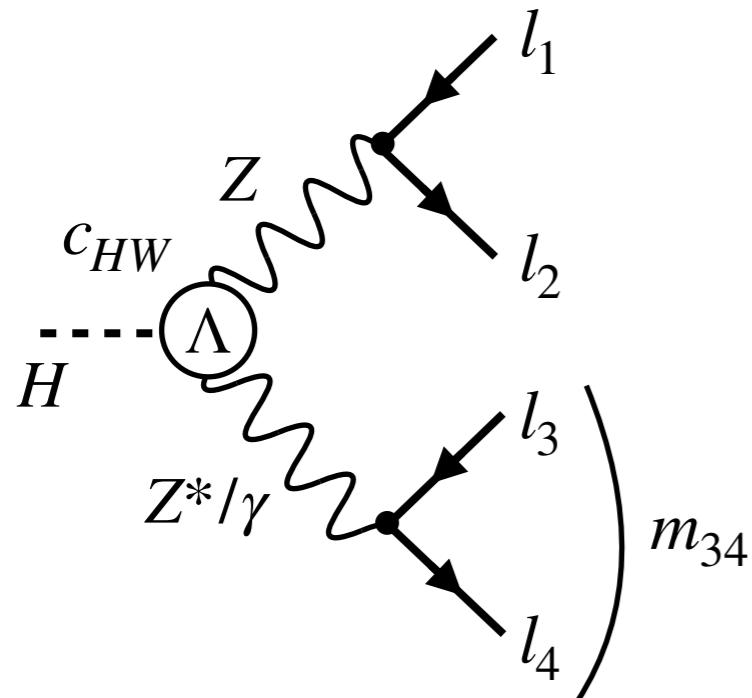
$U(3)^5$ flavour structure, $\Lambda=1\text{TeV}$



All operators at a glance



Acceptance modifications in $H \rightarrow ZZ^* \rightarrow 4l$

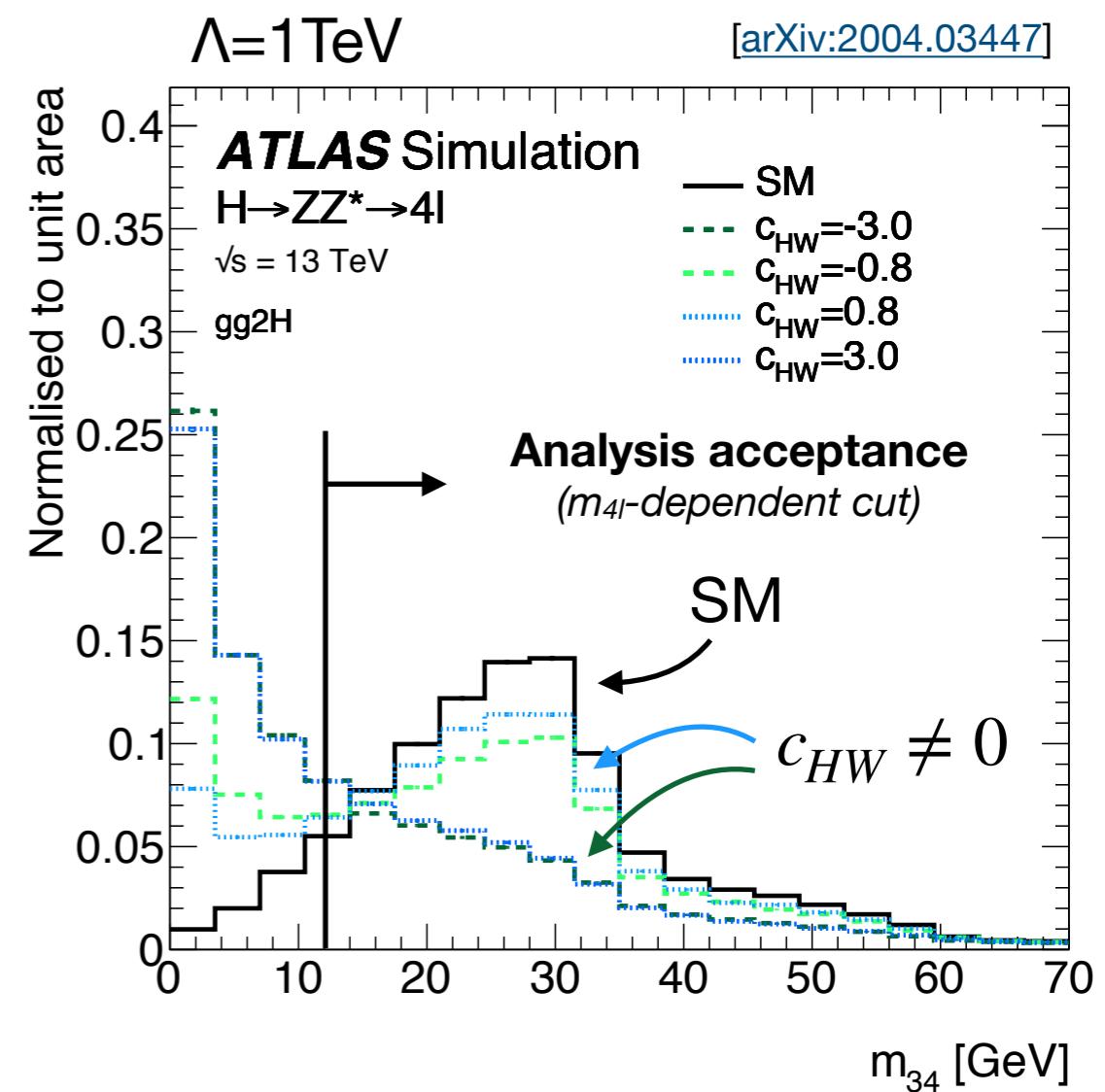


m_{34} -distribution can change significantly in SMEFT (e.g. caused by c_{HW})

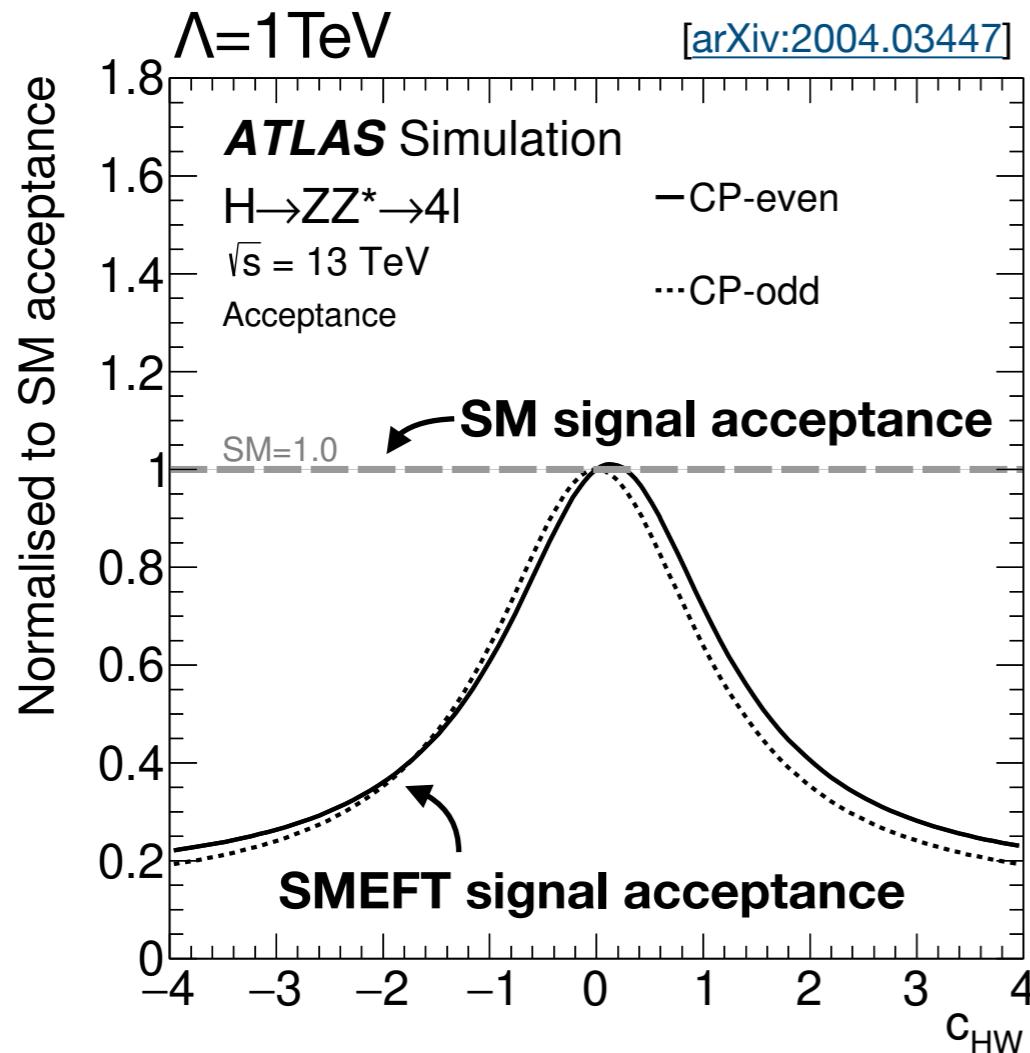


Analysis signal acceptance drops!

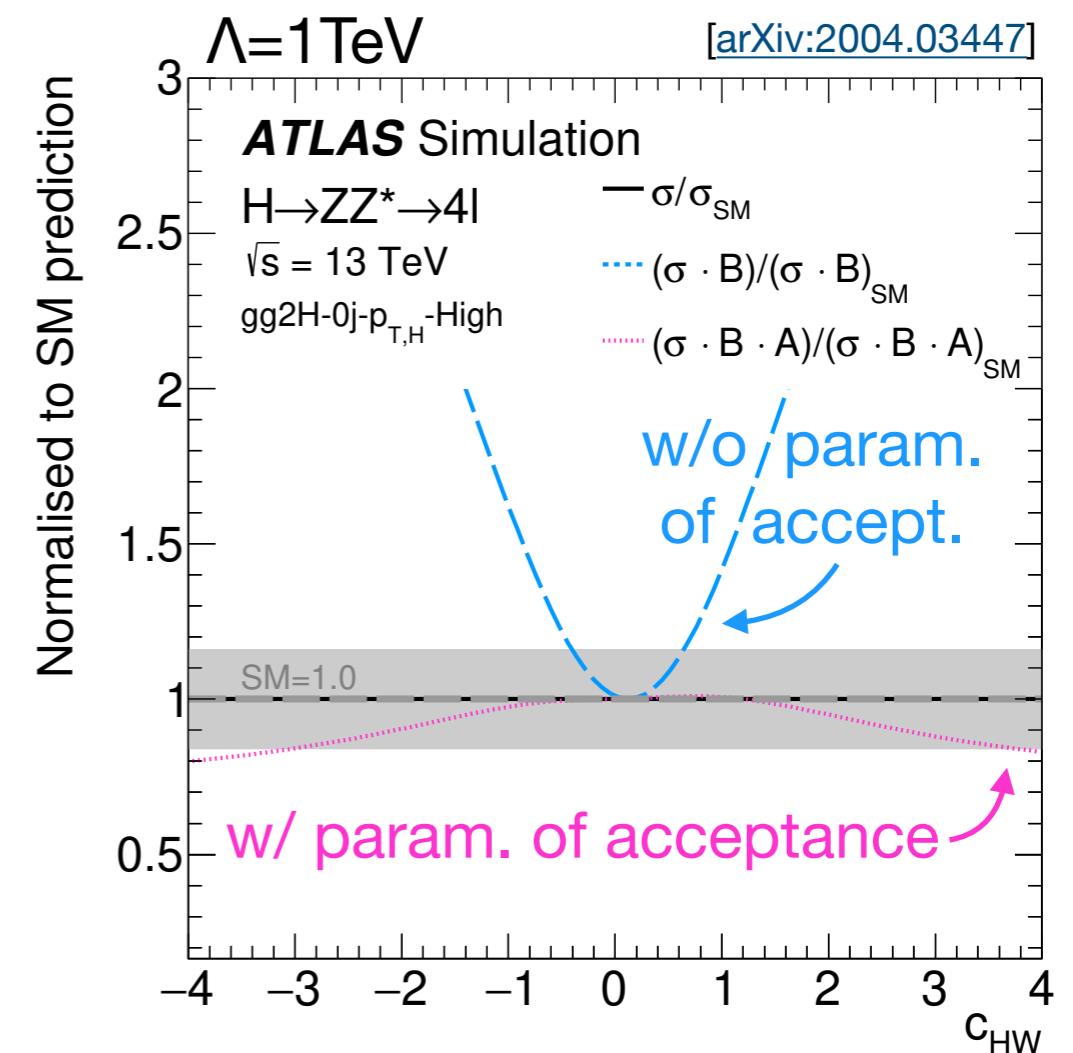
$H \rightarrow 4l$ analysis applies cut on inv. mass of off-shell Z (m_{34})



Acceptance modifications in $H \rightarrow ZZ^* \rightarrow 4l$



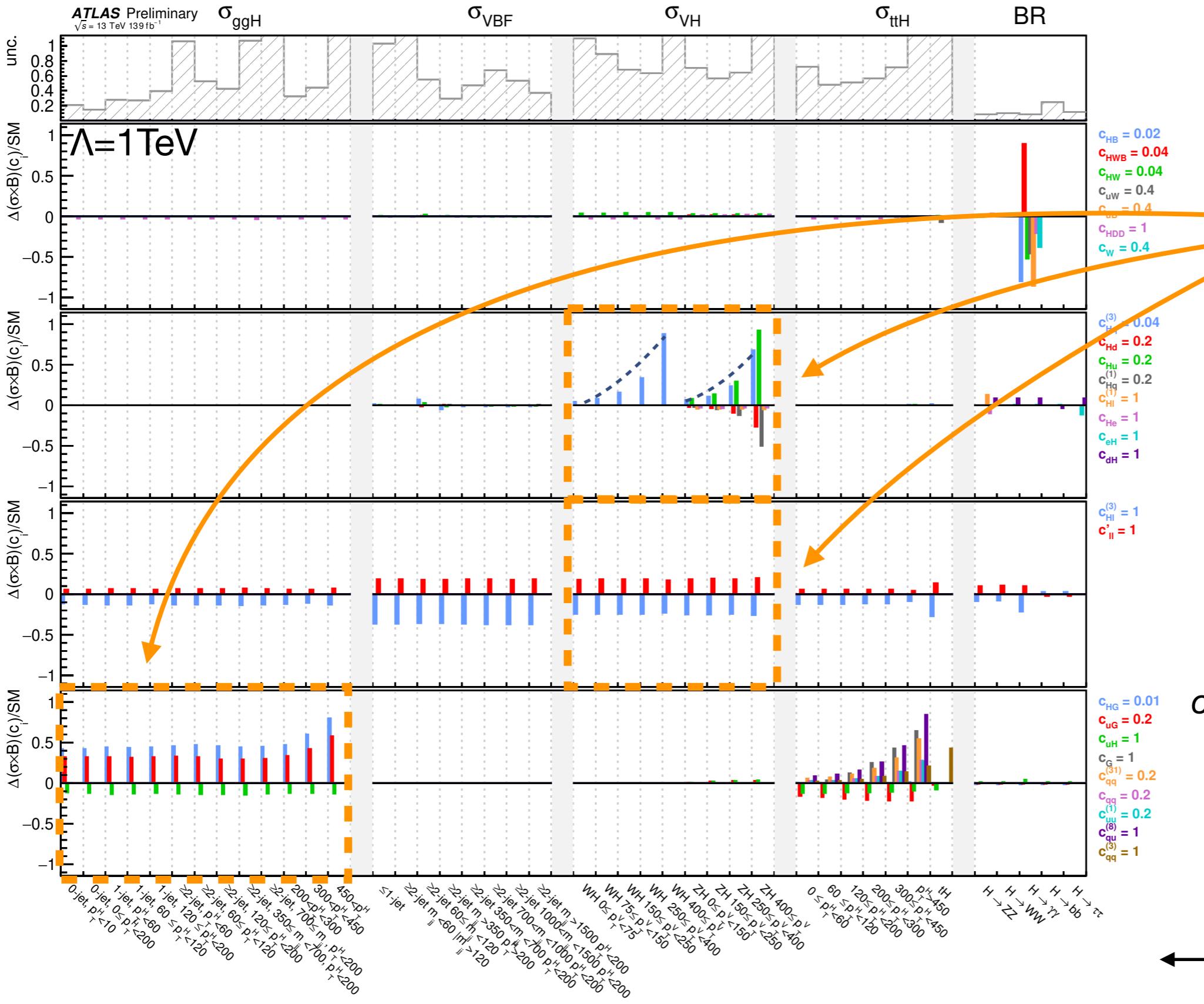
Analysis signal acceptance drops!



Parametrisation of $\sigma \times Br$
Acceptance modification totally changes trend!

SMEFT-modifications to analysis acceptance significant!

All operators at a glance



Impact of many operators degenerate!

No simultaneous constraints possible

Identify operator combinations that can be independently constrained

← STXS bins

Principal components

Group together operators with similar effects (on the available data) ...

... drop combinations that cannot be well constrained (on the available data) ...

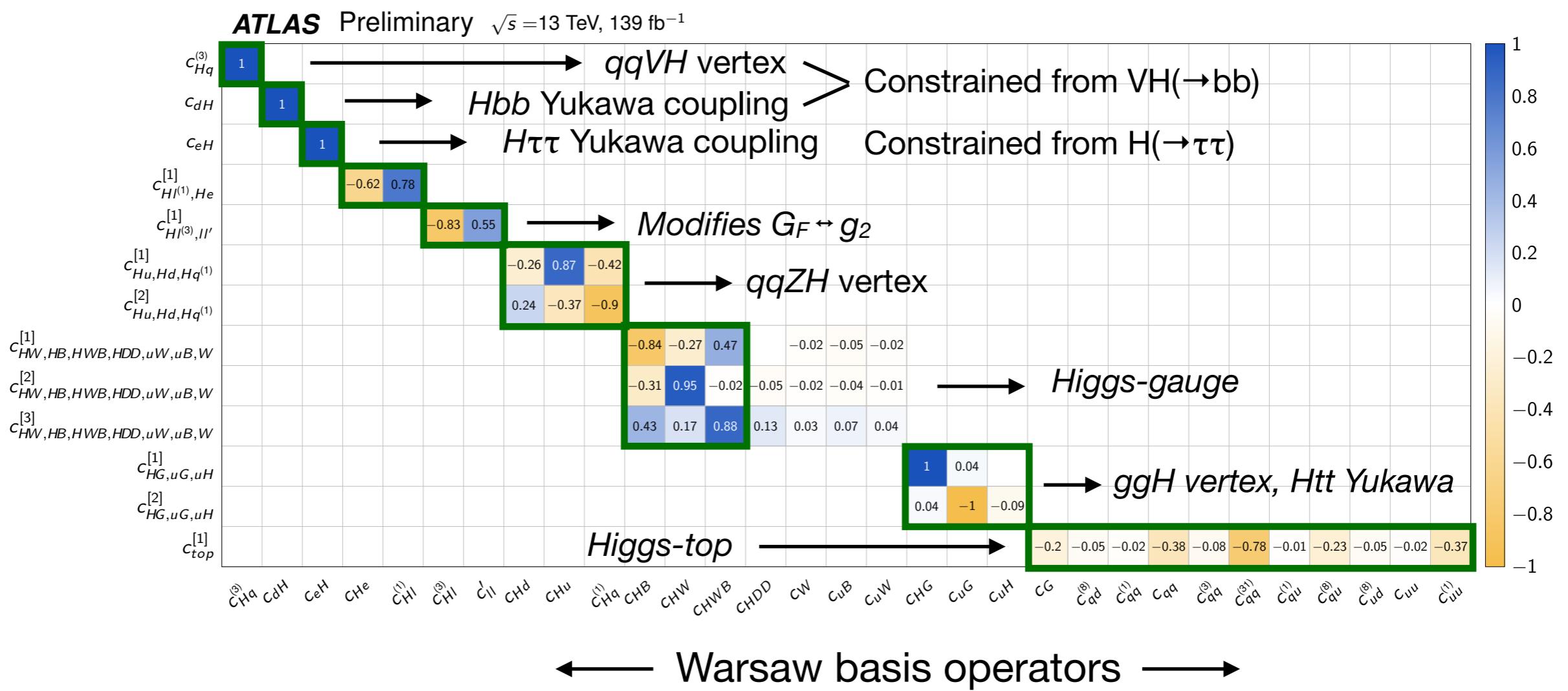
... and keep the rest

"Principal component analysis"

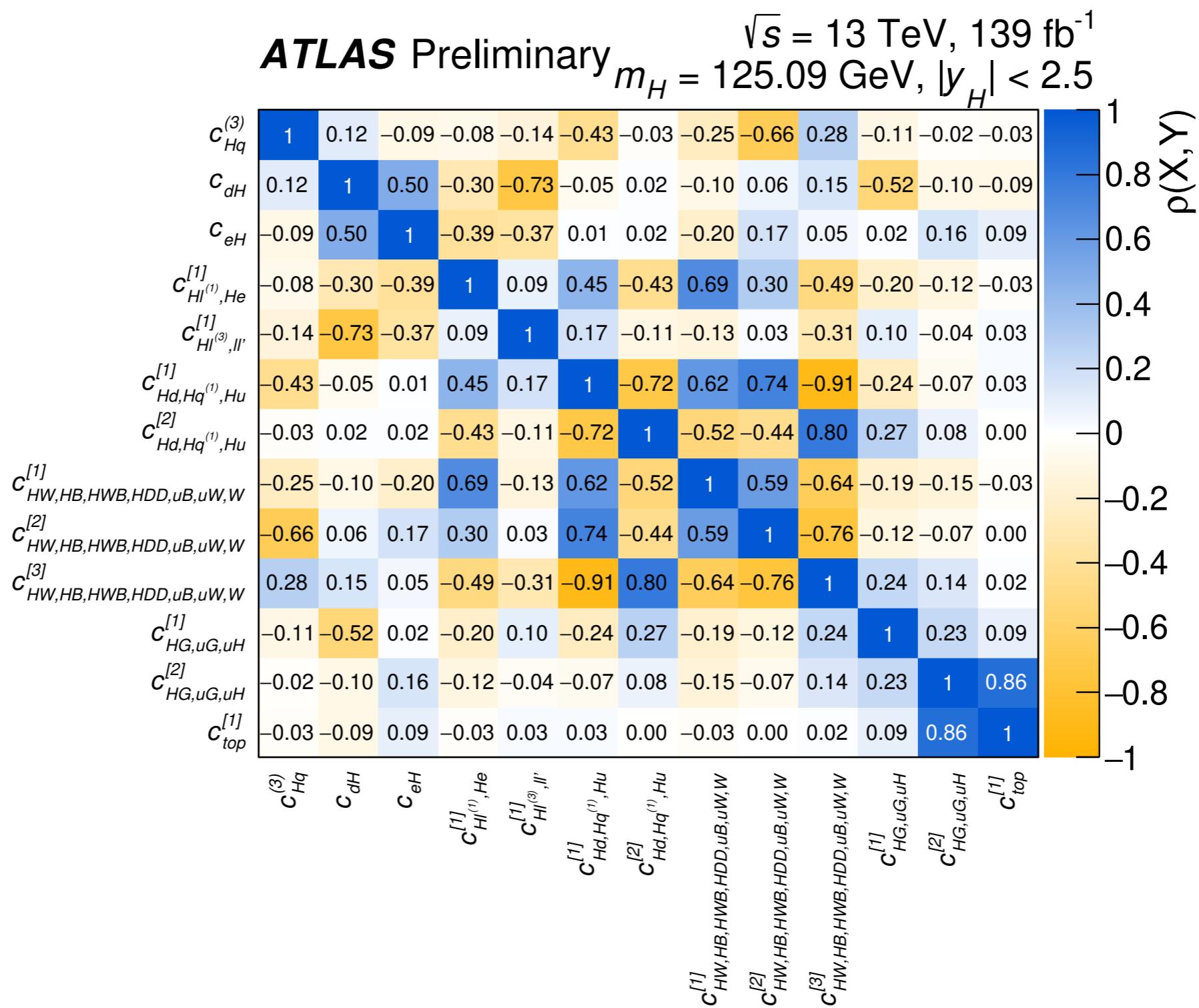
Can “simultaneously” constrain 13 operator combinations

(with manageable correlations)

Operator combinations

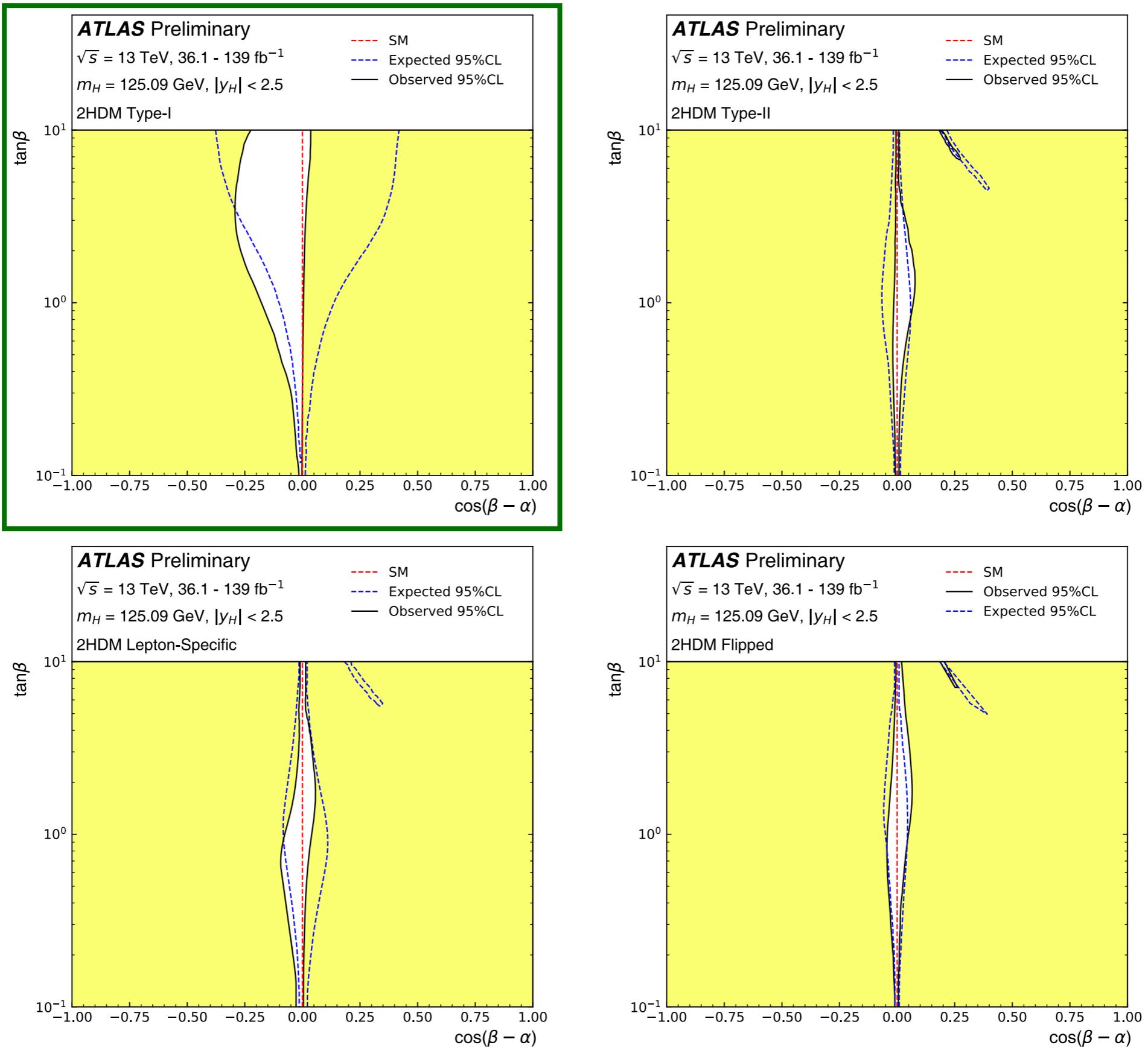


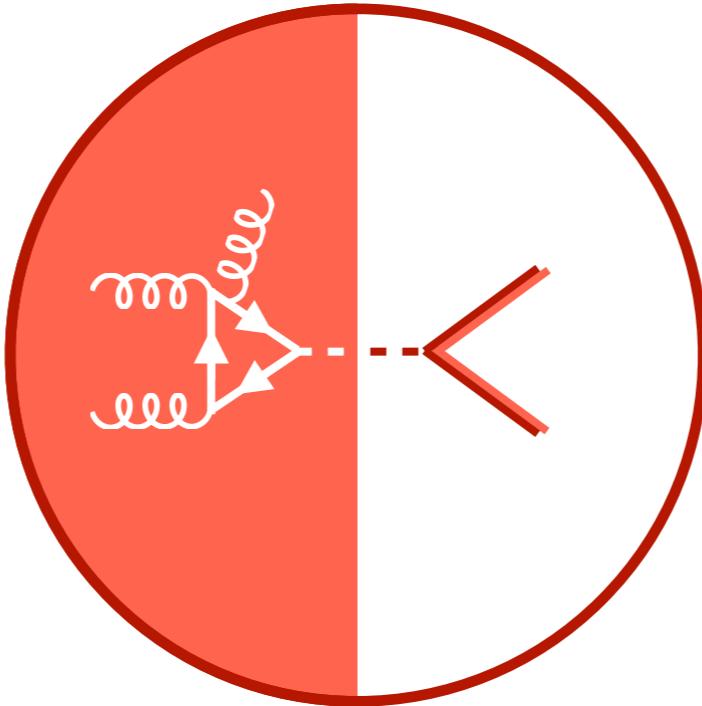
SMEFT constraints: correlations



Other types of 2-HDM

From
slide 27





Constraints on κ_b and κ_c

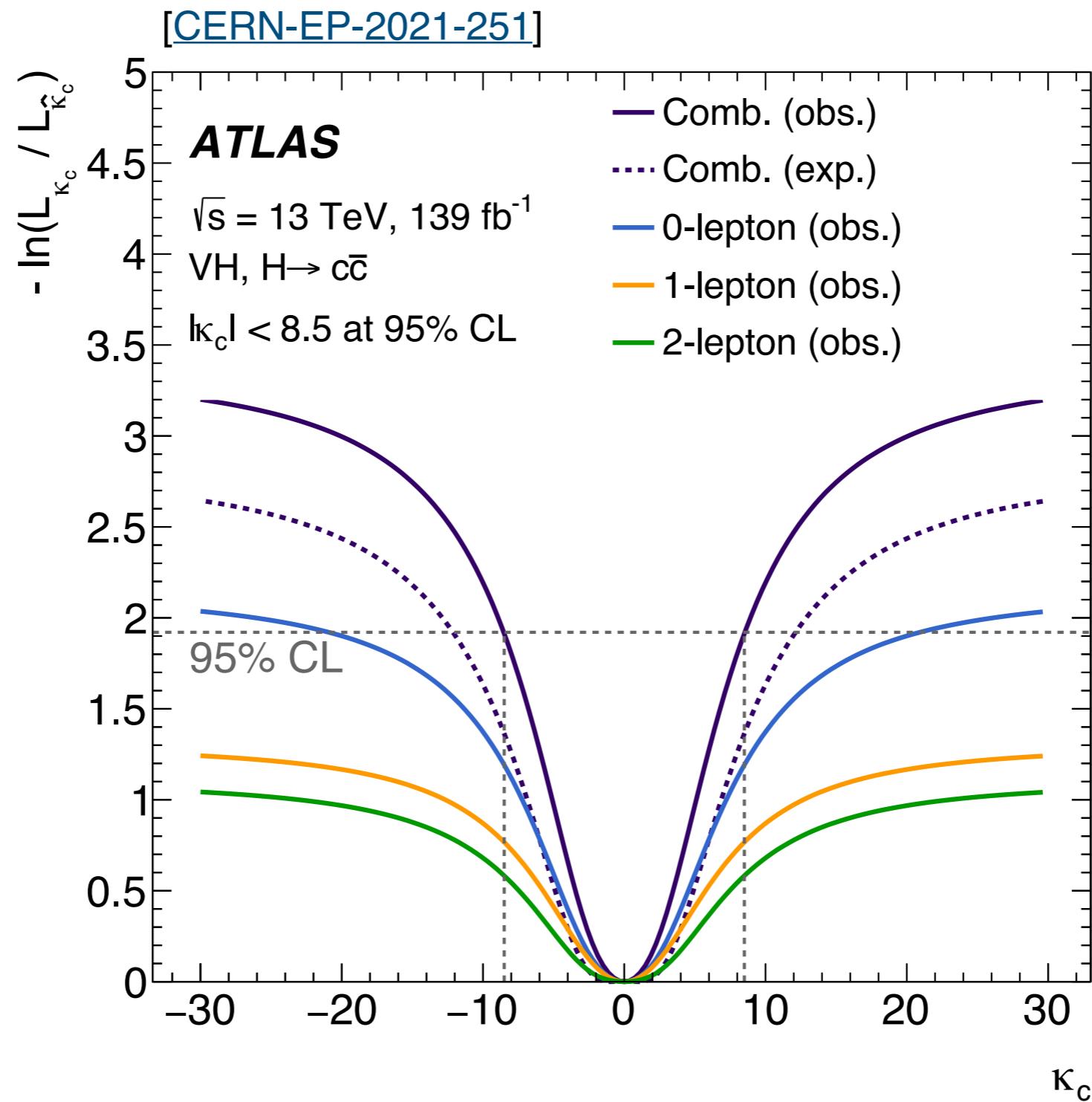
$H \rightarrow \gamma\gamma/4\ell$
combination

[[ATLAS-CONF-2022-002](#)]

$VH \rightarrow bb/cc$
combination

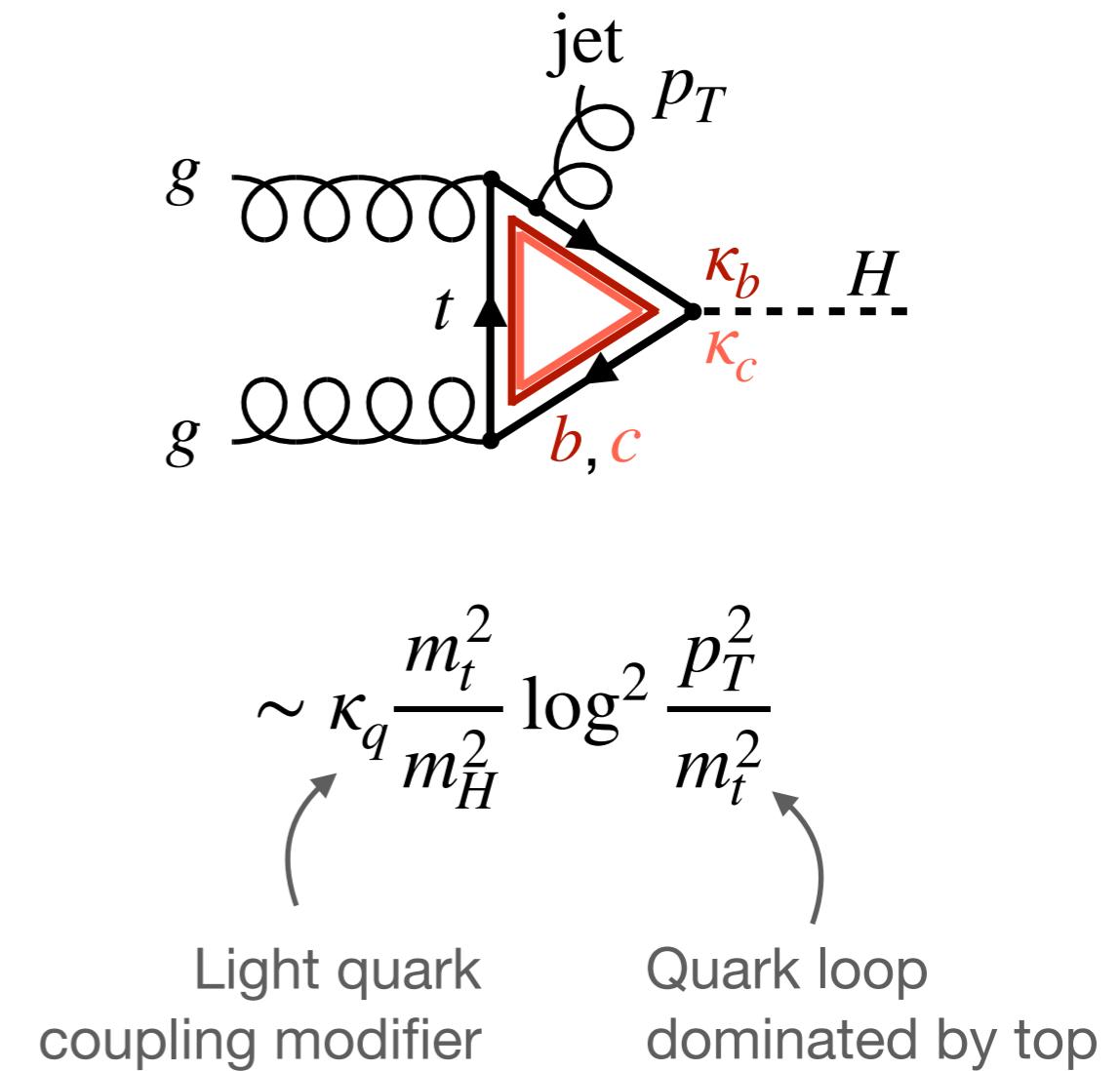
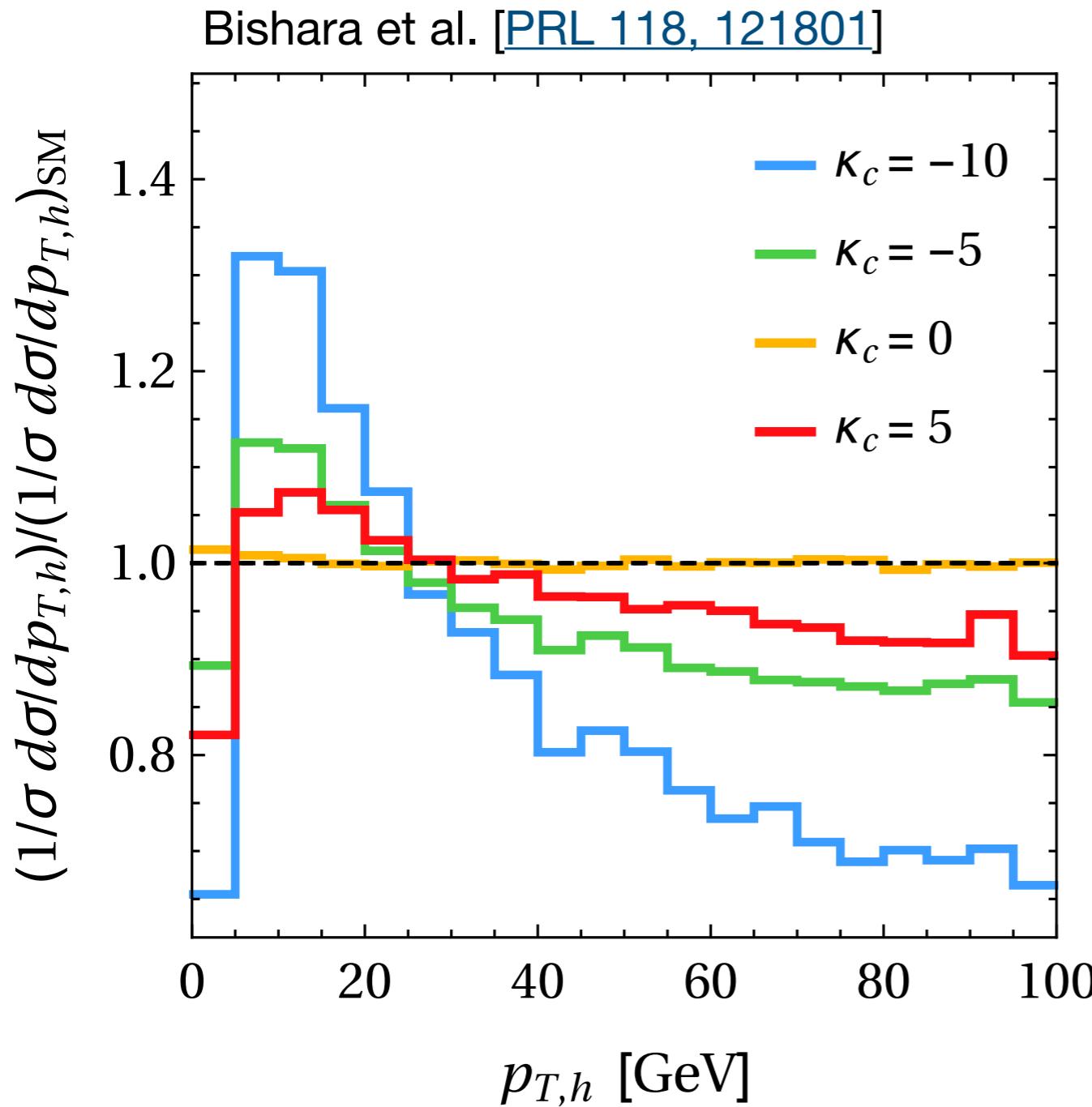
[[CERN-EP-2021-251](#)]

Direct constraints on κ_c



Methodology of the interpretation

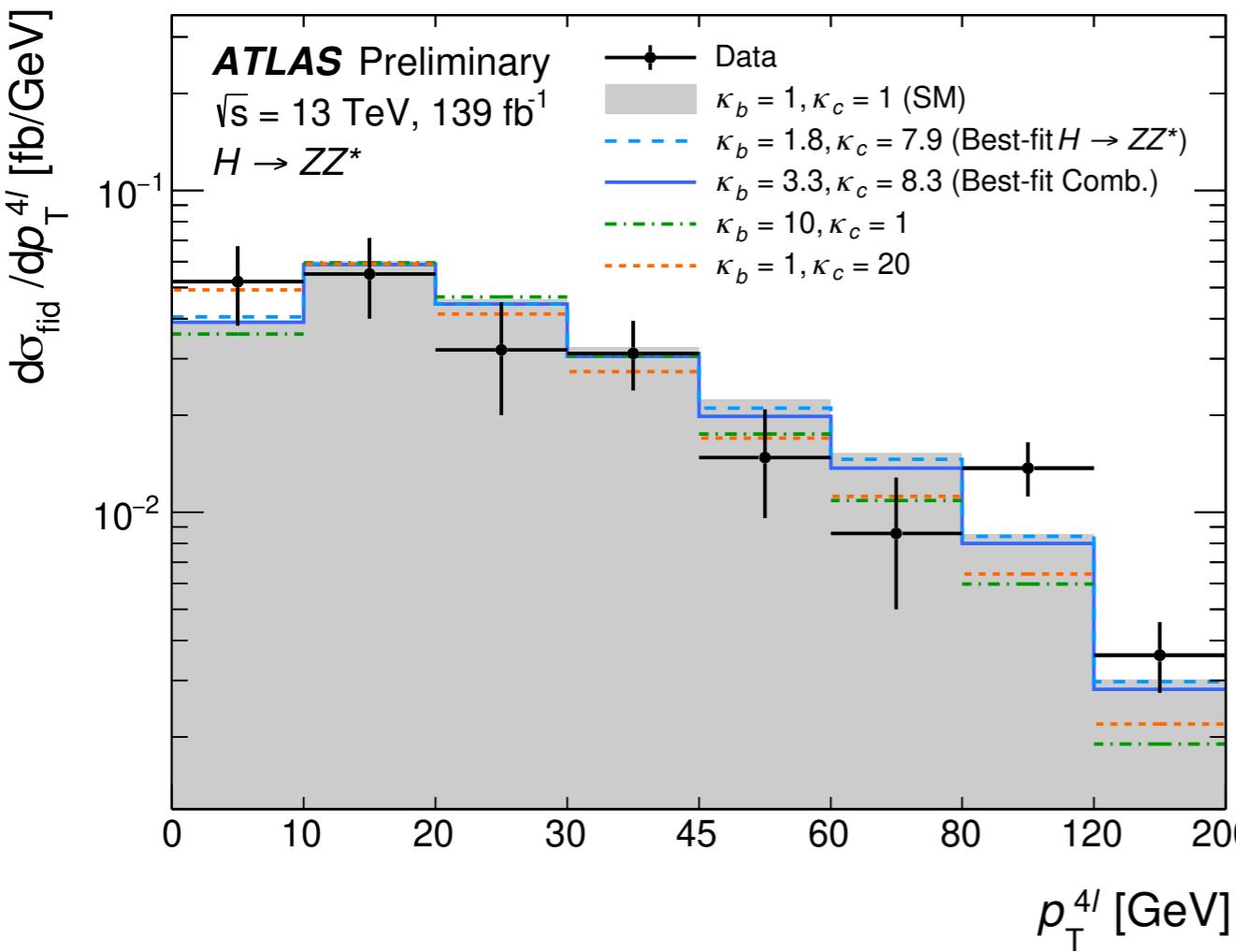
Inclusive p_T spectrum is sensitive to κ_b and κ_c



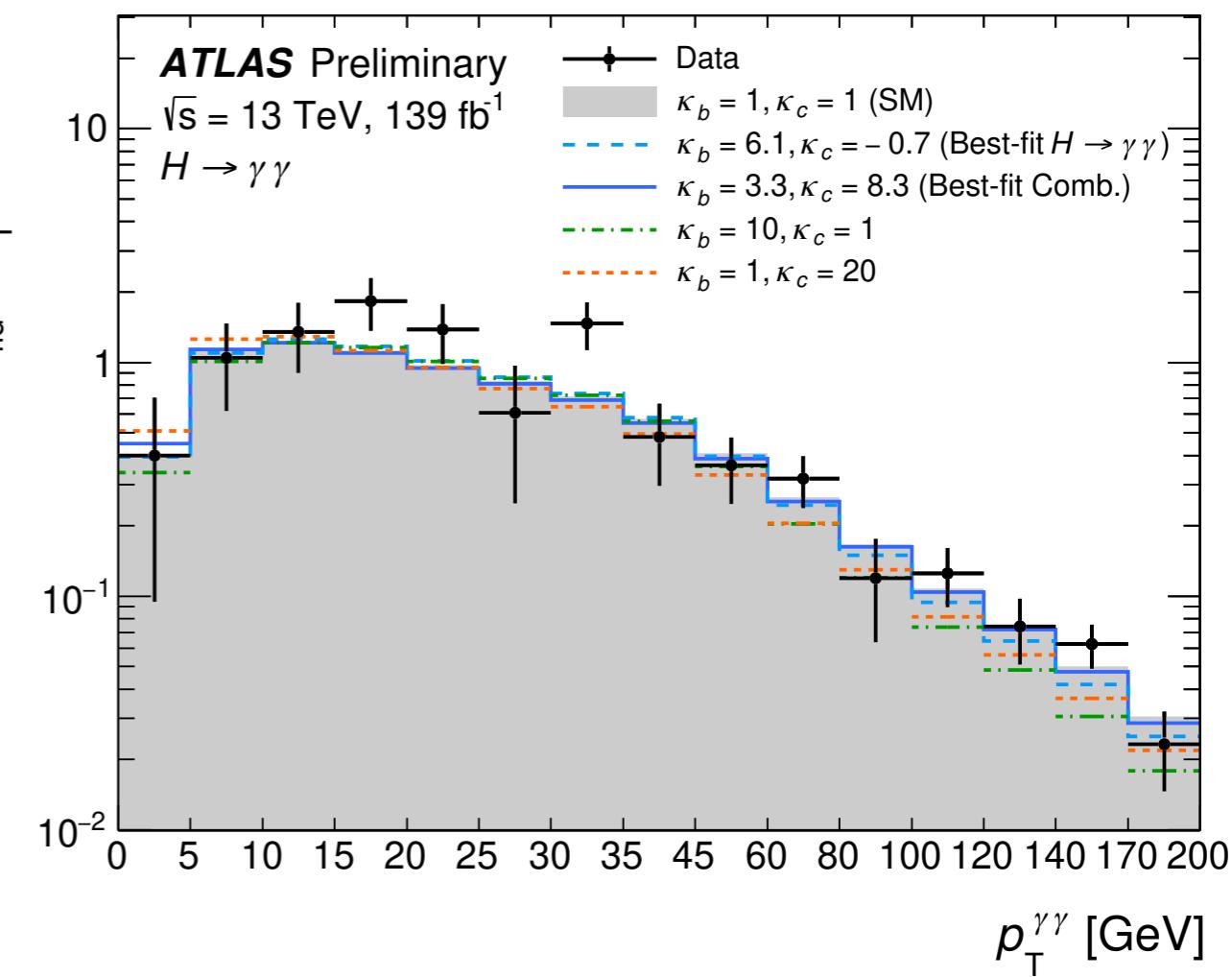
Inputs for interpretation

Differential cross-section measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

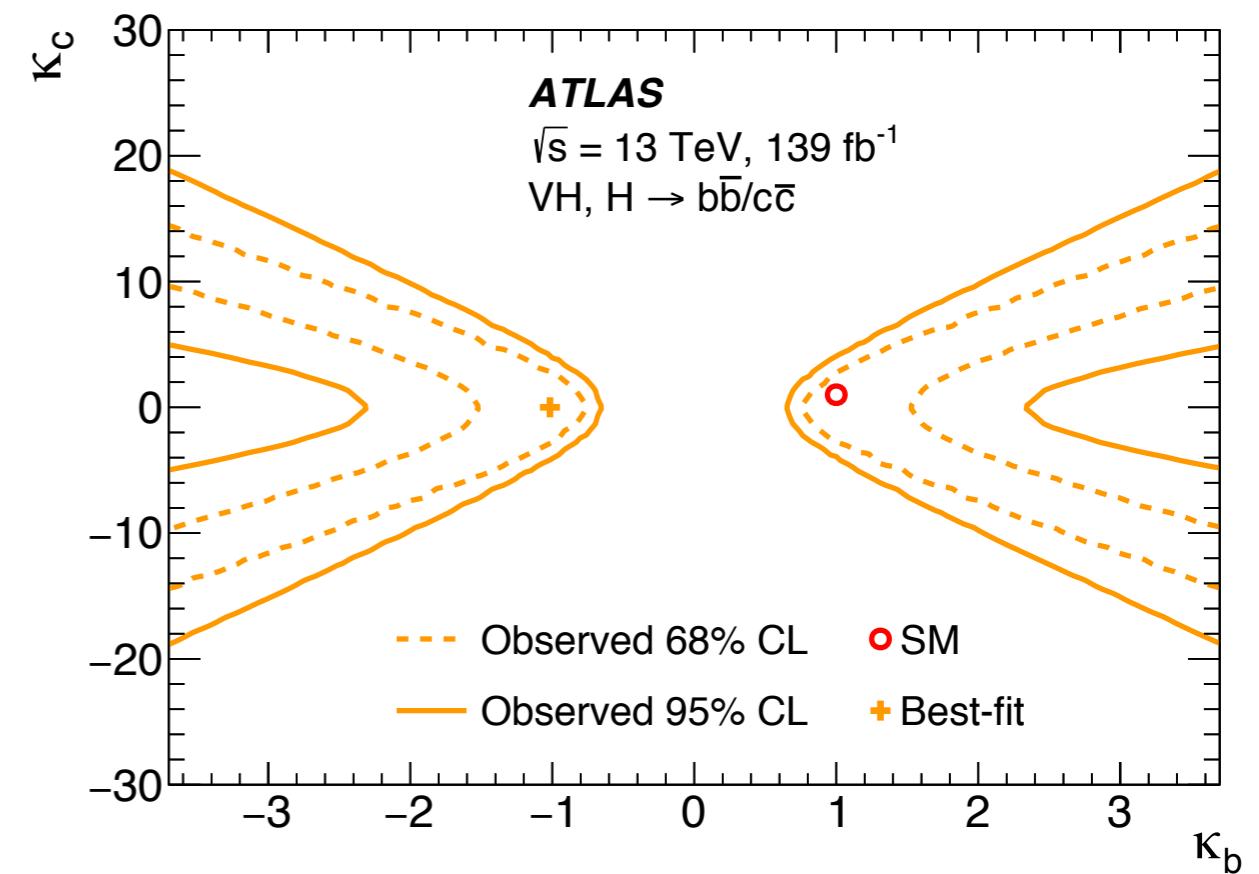
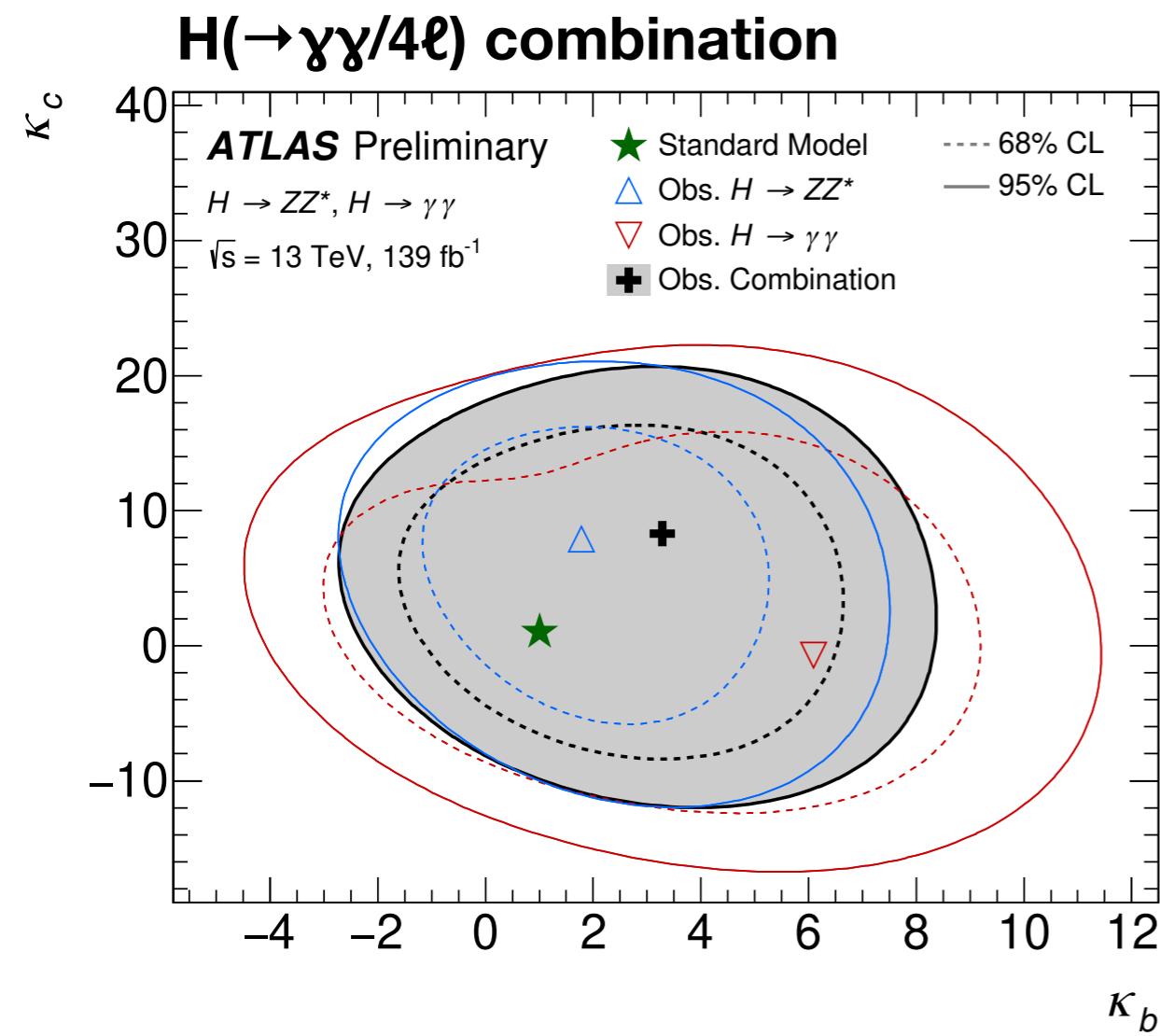
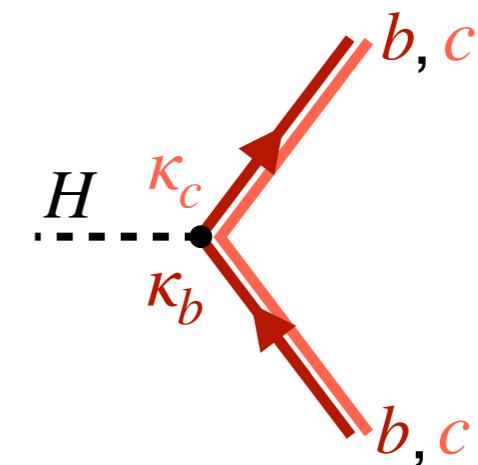
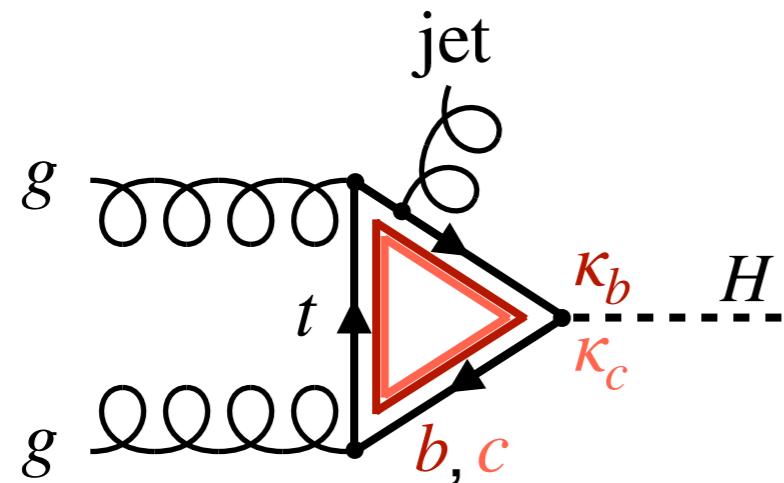
$H \rightarrow 4\ell$



$H \rightarrow \gamma\gamma$



Complimentary constraints on κ_b and κ_c



Direct demonstration of
flavour non-universality:

$$\left| \frac{\kappa_c}{\kappa_b} \right| < \frac{y_b}{y_c}$$