Measurements of Higgs boson cross-sections and their interpretation with the ATLAS experiment

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on behalf of the ATLAS Collaboration

DIS 2024 conference
Grenoble, 09.04.2024

GEFÖRDERT VOM
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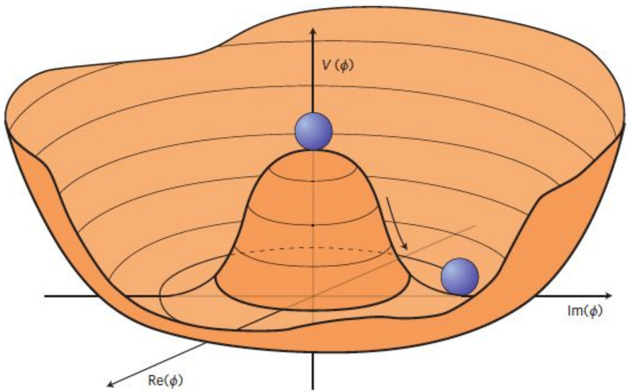
The Higgs boson

Emerges from electroweak symmetry breaking, which makes Standard Model gauge invariant despite *W* and *Z* masses



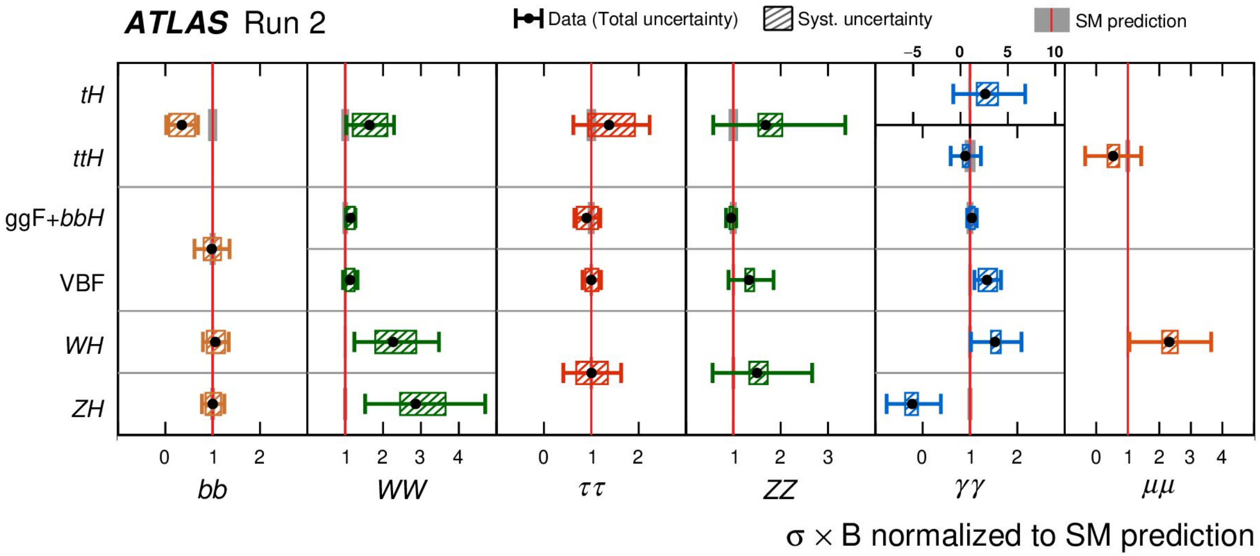
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

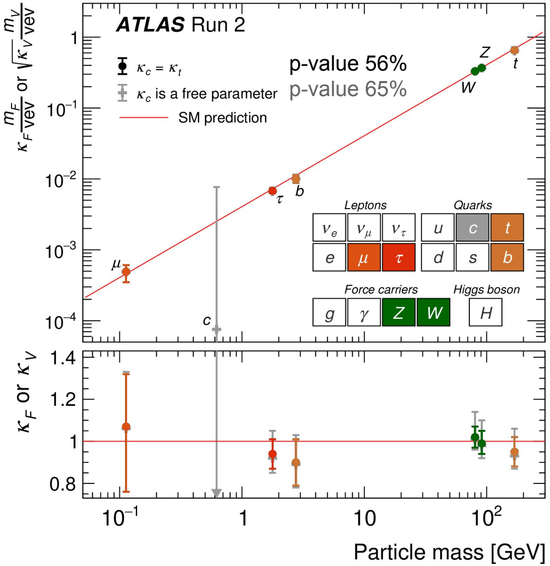
Couplings

- to ***W* and *Z* bosons** and **self-coupling** dictated by symmetry breaking
  →see Shahzad Ali's talk for self coupling
- **to fermions** introduced ad-hoc to generate their masses
  →more on couplings to fermions and rare decays by Louis-Guillaume Gagnon
- to **massless particles vanish**

Couplings to Standard Model particles

[Nature 607 (2022) 52-59](https://www.nature.com/articles/s41586-022-04893-w)



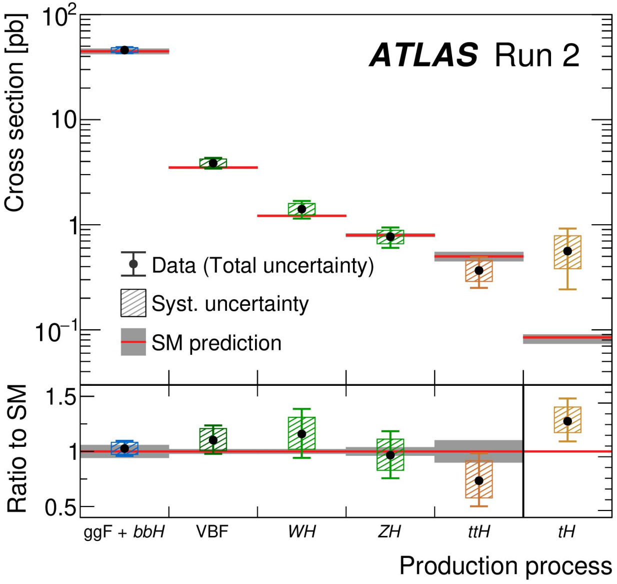


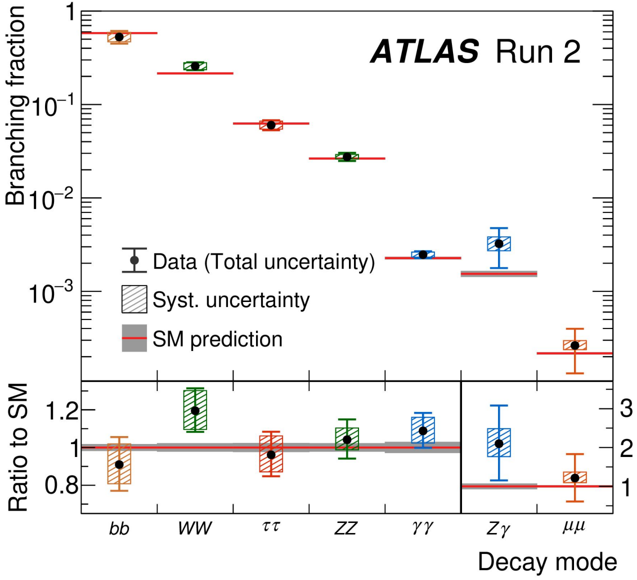
Combination of inclusive results consistent with Standard Model

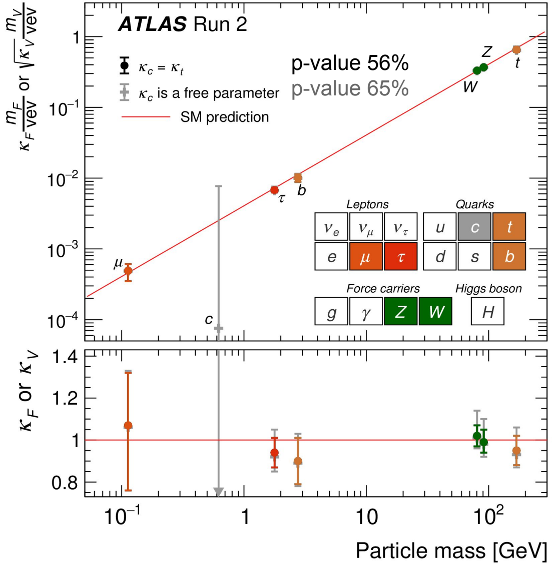
- (cross-section x branching ratio) per (production process x decay mode)
- couplings to Standard Model particles assuming
  - absence of BSM decays
  - loop processes have Standard Model structure

Couplings to Standard Model particles

[Nature 607 (2022) 52-59]







Combination of inclusive results consistent with Standard Model

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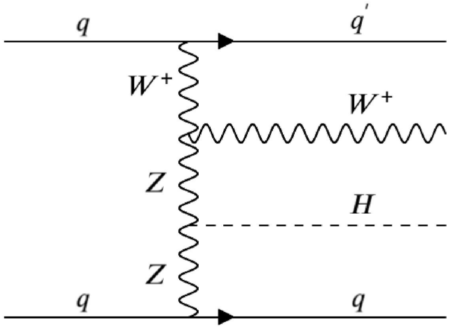
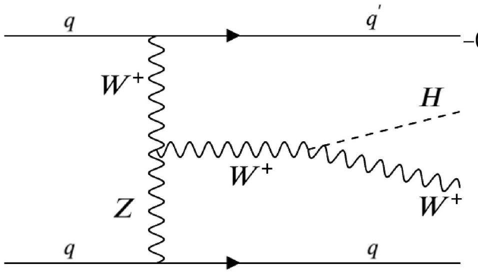
Couplings to *W* and *Z*

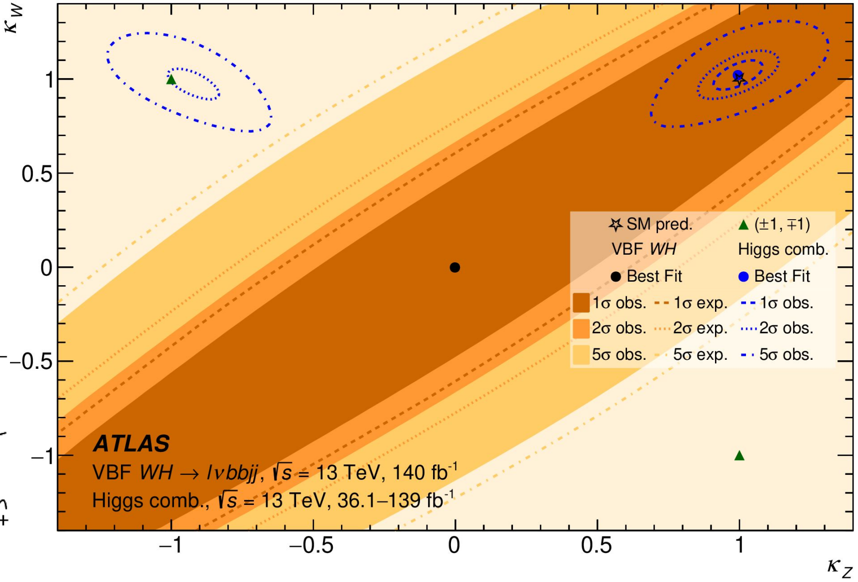
Feb 2024 arXiv:2402.00426

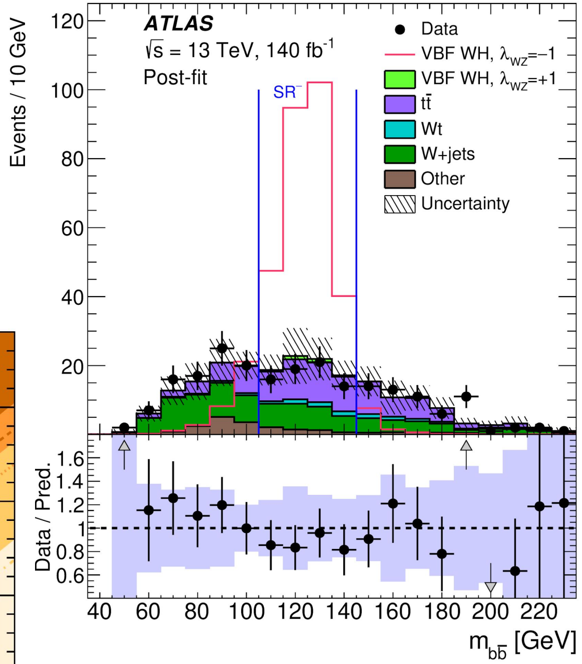
Search for *WH* production via VBF with *H*→*bb*

- observed upper limit: 9.0 times Standard Model (8.7 expected)
- *HWW* and *HZZ* couplings **have same sign**. Otherwise process observable due to constructive interference









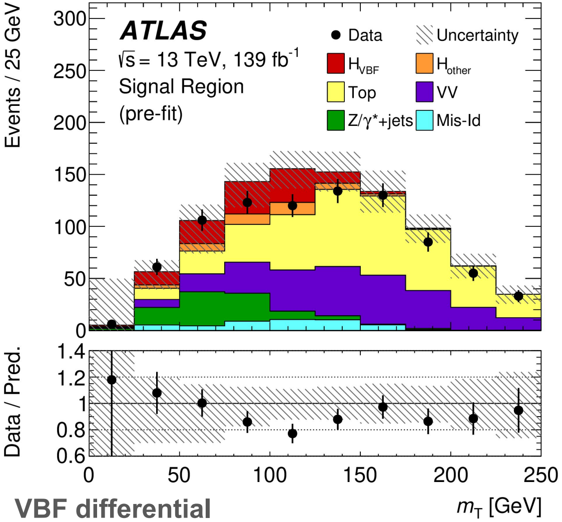
Opposite signs possible if Higgs part of multiplet larger than doublet (e.g. Georgi–Machacek model)

$H \to WW^* \to \ell\nu\ell\nu$

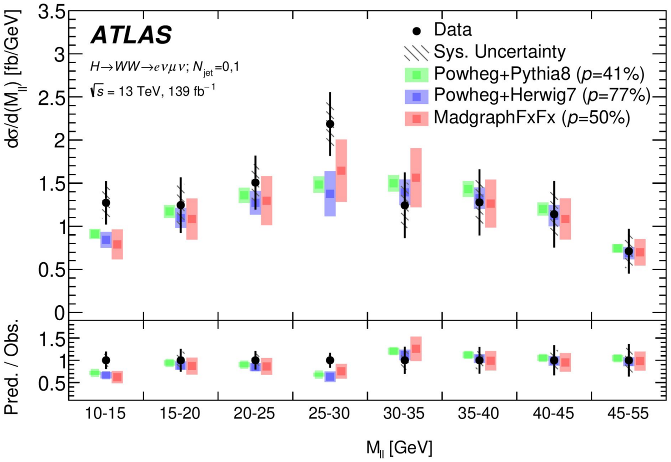
- sizable branching ratio, rich phenomenology in 2-stage decay
- no full reconstruction, complex and diverse backgrounds

ggF and VBF: fiducial/differential, in-likelihood **unfolding** to particle level for **various observables**

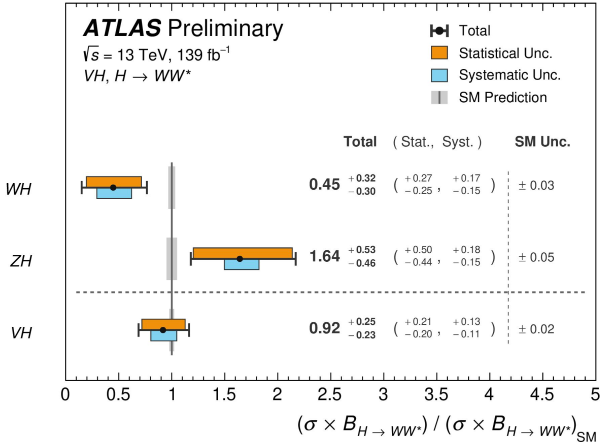
strong **evidence (4.6σ)** for ***VH* with $H \to WW^*$**



VBF differential
Apr 2023 Phys. Rev. D 108 (2023) 072003



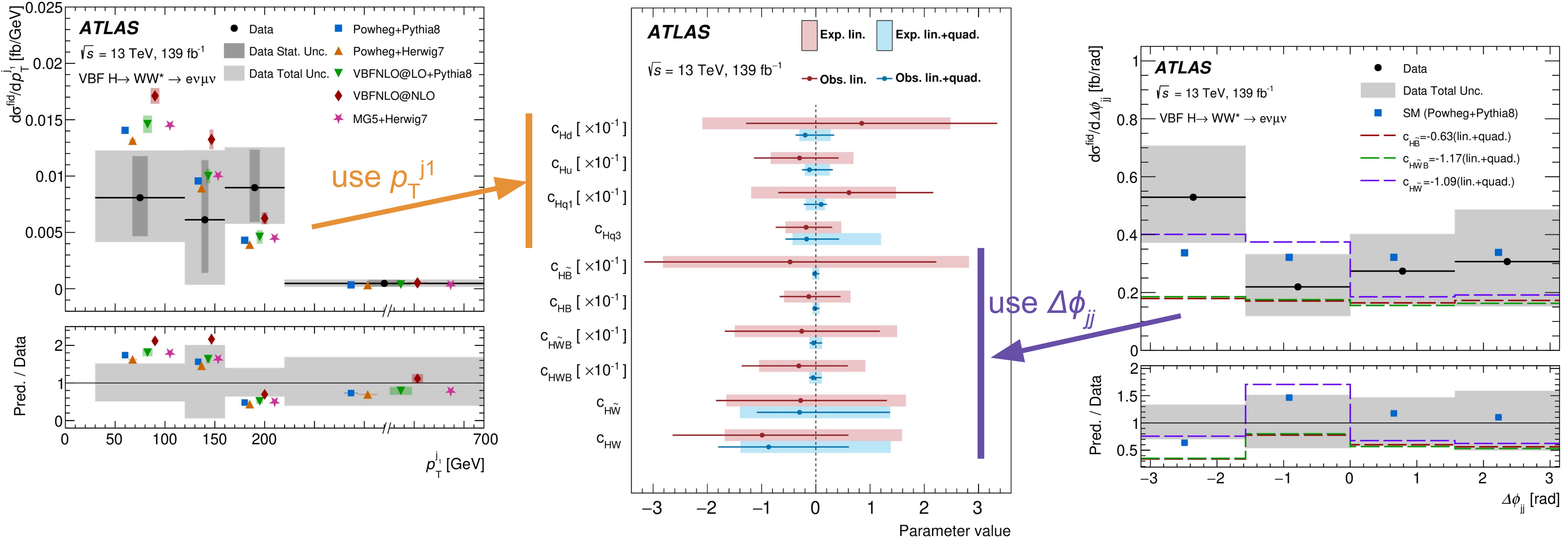
ggF differential Eur. Phys. J. C 83 (2023) 774



***VH* inclusive** ATLAS-CONF-2022-067

Effective field theory interpretation for VBF

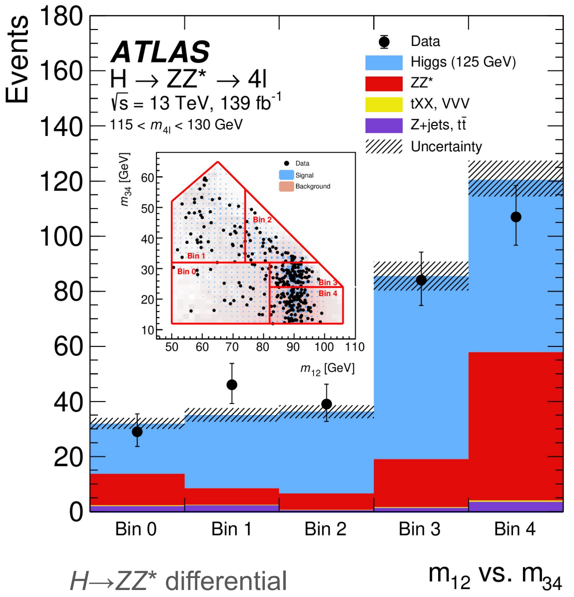
Apr 2023 Phys. Rev. D 108 (2023) 072003



- one SMEFT dimension-6 operator c_i floating at a time, use Warsaw basis
- sensitivity to *CP*-odd operators $\tilde{c}_i$ thanks to $\Delta\phi_{jj}$
- limits given for linear terms ~c_i/Λ^2 only and linear + quadratic terms ~c_i^2/Λ^4

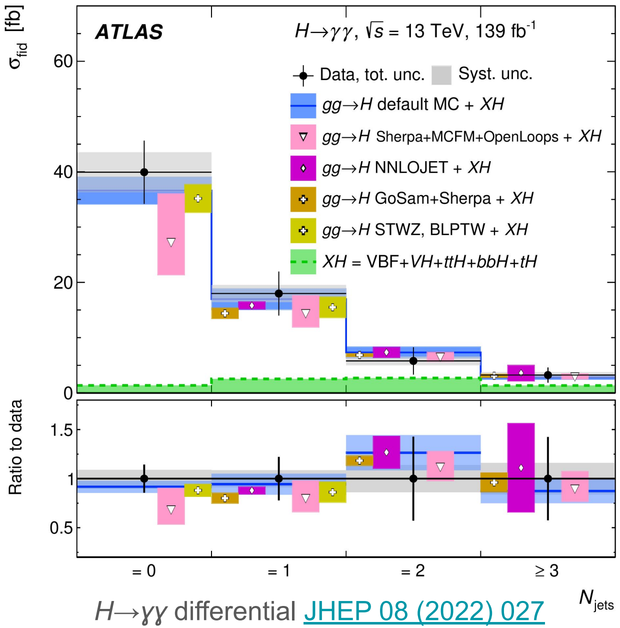
$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ differential

- fully reconstructed final states; small branching ratio
- *$H \rightarrow ZZ^*$*: small background, rich phenomenology in 2-stage decay
- *$H \rightarrow \gamma\gamma$*: background sizable but estimated precisely from sidebands

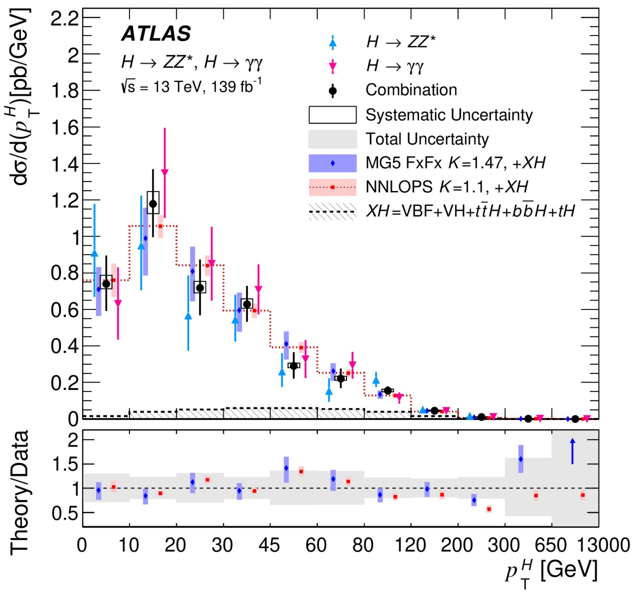


$H \rightarrow ZZ^*$ differential

Eur. Phys. J. C 80 (2020) 942

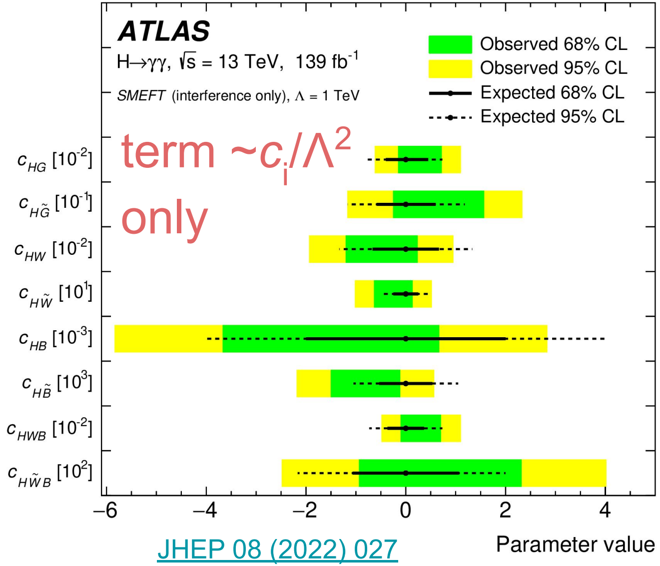


$H \rightarrow \gamma\gamma$ differential JHEP 08 (2022) 027



Combination JHEP 05 (2023) 028

Interpretations



[JHEP 08 (2022) 027]

from

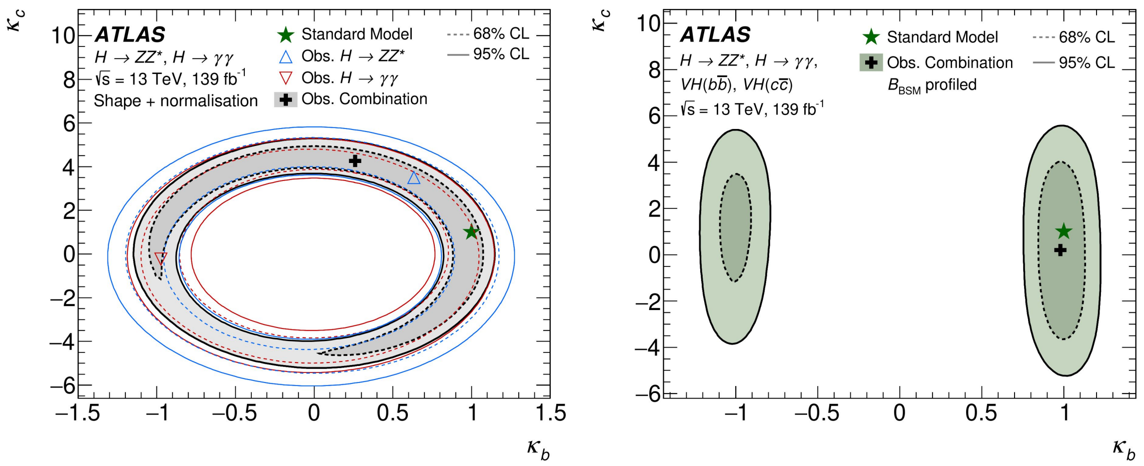
$H\to\gamma\gamma$ and $H\to ZZ^*$

only

also consider measurements of

$H\to bb$ and $H\to cc$.

Allow BSM Higgs decays



[JHEP 05 (2023) 028]

EFT interpretation for *H→γγ*

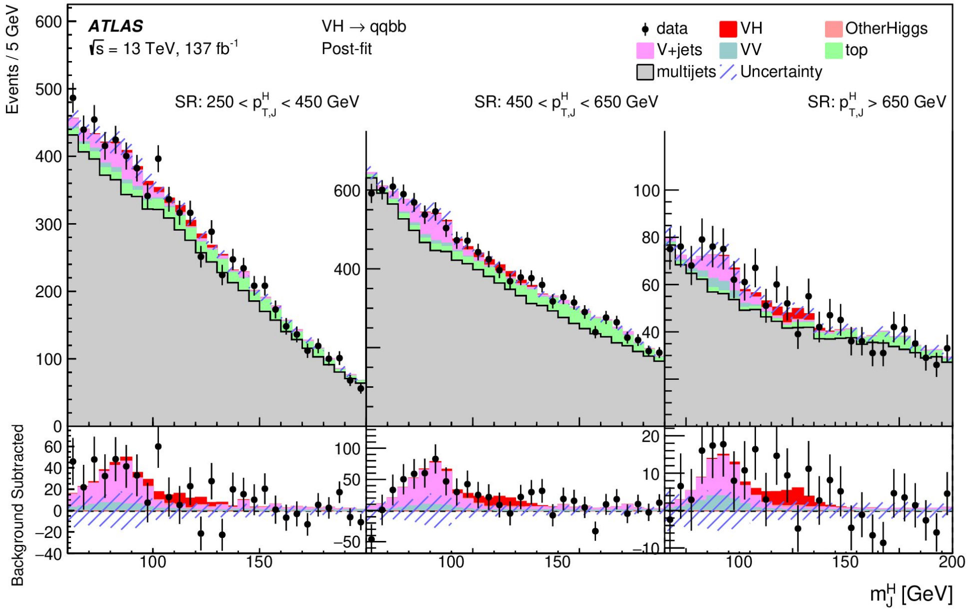
- one c_i floating at a time
- use p_T^H , N_{jets} , m_{jj} , $\Delta\phi_{jj}$, p_T^{j1} distributions simultaneously

Constrain ***bbH*** and ***ccH*** **Yukawa couplings** from **combined p_T^H spectrum**

- direct constraint: $|\kappa_c| < 8.5$ (95% CL)
  [Eur. Phys. J. C 82 (2022) 717]

VH production with p_T^H > 250 GeV

Dec 2023 arXiv:2312.07605



Final state with **large *R* jets** from **boosted *V*→*qq*** and ***H*→*bb***

- *H*→*bb* tagging via neural network
- cut-based *V*→*qq* tagging

Multijet and *V*→*qq*+jets backgrounds estimated from data, others from MC

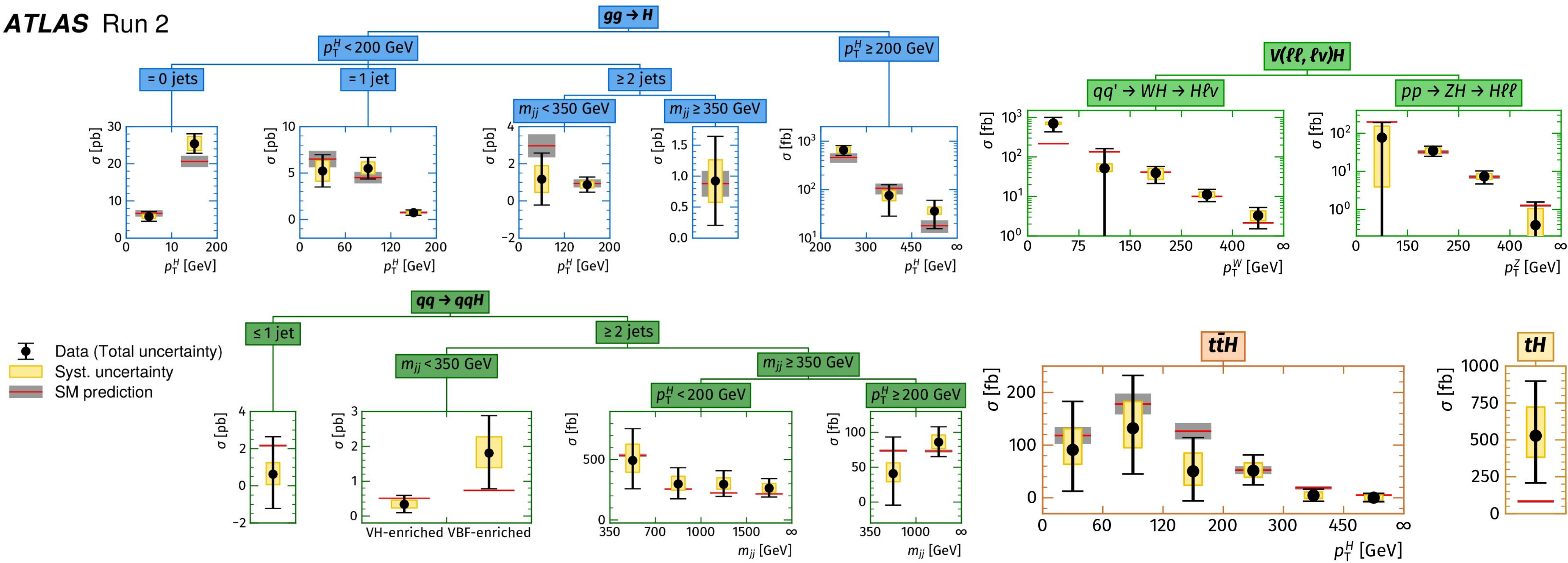
Fit m_J^H spectrum in three SRs and CRs

Inclusive cross-section:
3.1 ± 1.3 (stat.) $^{+1.8}_{-1.4}$ (syst.) pb

Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \leq p_T^H < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \leq p_T^H < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_T^H \geq 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2

Significance: 1.7σ obs. (1.2σ exp.)

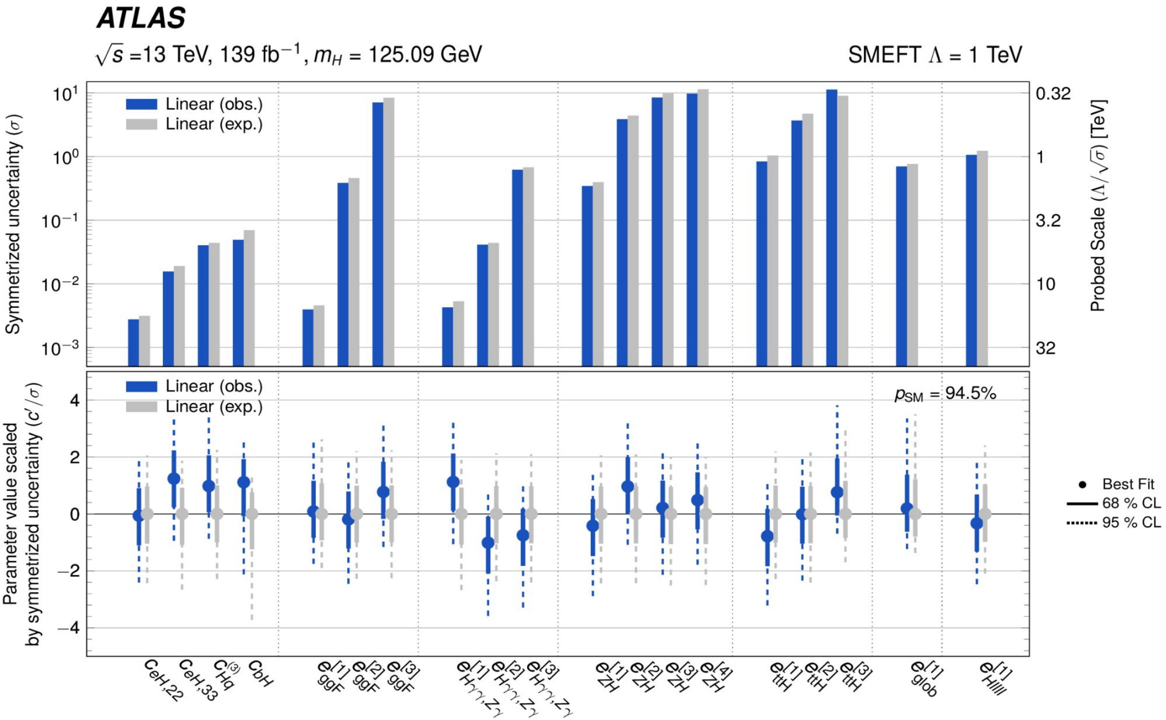
Simplified Template Cross Sections (STXS) Nature 607 (2022) 52-59

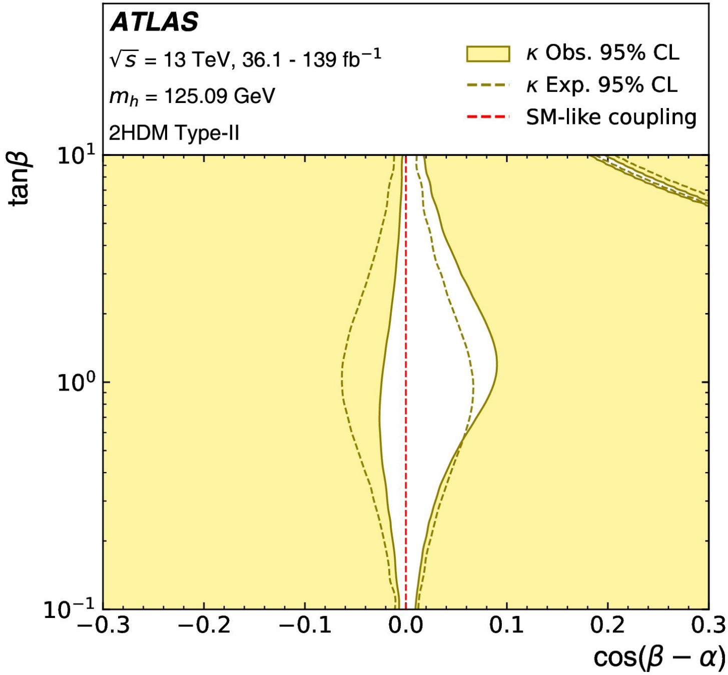


- Categorize Higgs production via key observables for each production mode
- Same scheme for all decay channels and ATLAS/CMS, so can combine
  - here: 2022 **ATLAS combination**, mostly based on **full Run 2 results**

Interpretations

Feb 2024 arXiv:2402.05742



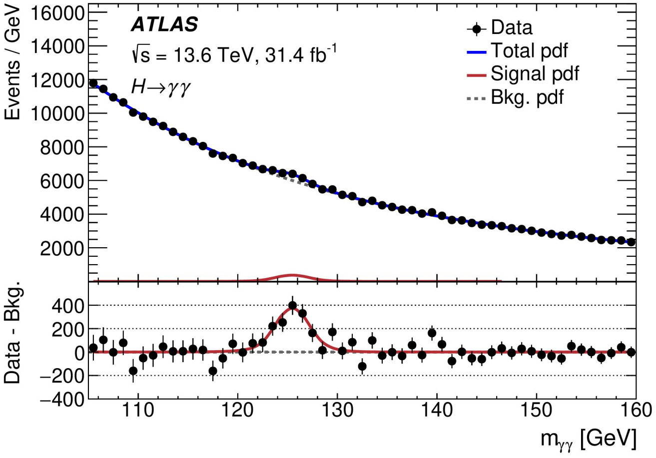


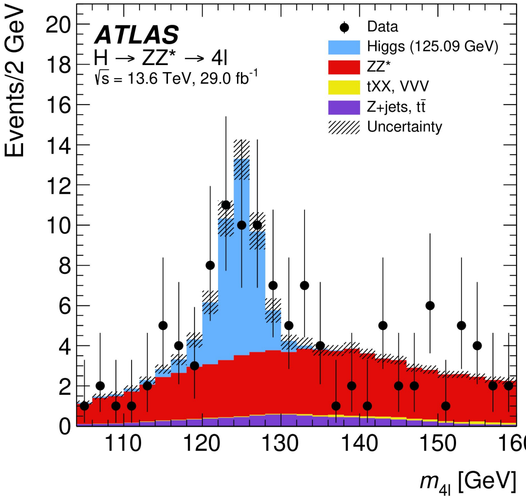
- **EFT:** some c_i have similar effect
- **measurable parameters** c_i' found via eigenvalue decomposition and **constrained simultaneously**

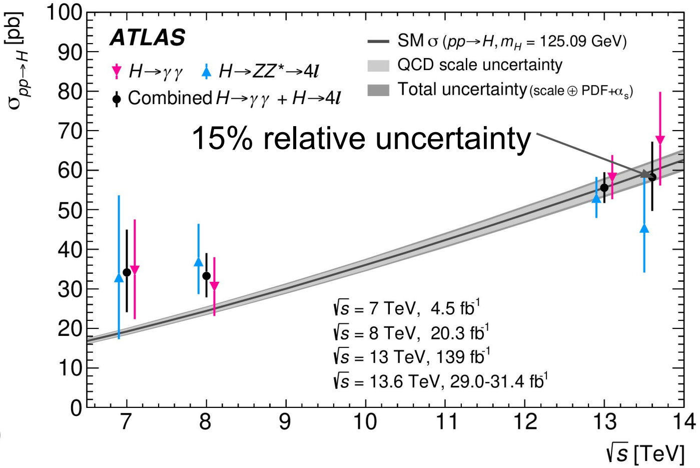
- **Constrain** parameter space for **2HDM** and **MSSM**

Outlook: Run 3 and HL-LHC

Eur. Phys. J. C 84 (2024) 78

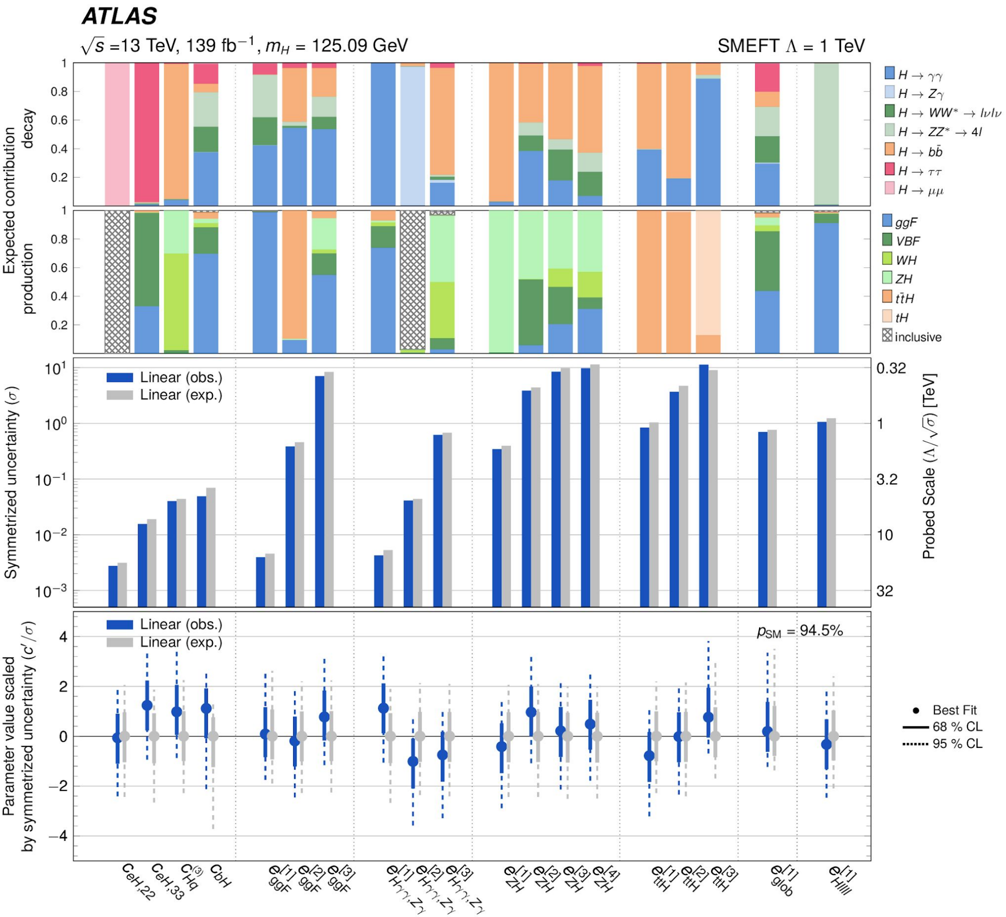






- **BSM sensitivity** often **enhanced** in extreme phase space
- **higher dimensional** BSM constraints (e.g. EFT) and differential measurements
- **further highlights**: *CP* (→Simen Hellesund), width (→ Leonardo Carminati), self-coupling, *H→cc*, *H→μμ, H→Zγ*, *H*→invisible

Backup: contributions to STXS EFT interpretation



analyses used; for references see

Nature 607 (2022) 52-59

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H\to\gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[31]	All
$H\to ZZ$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	[28]	All
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H\to b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H+tH$	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H\to\tau\tau$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	[38]	All
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to\mu\mu$	ggF + $t\bar{t}H+tH$, VBF + $WH+ZH$	139	[40]	All but fit of kinematics
$H\to c\bar{c}$	$WH+ZH$	139	[41]	Only for free-floating κ_c
$H\to$ invisible	VBF	139	[42]	κ models with $B_{u.}$& $B_{inv.}$
	ZH	139	[43]	κ models with $B_{u.}$& $B_{inv.}$

Rotated Wilson coefficients for STXS interpretation