ATLAS-CONF-2023-052

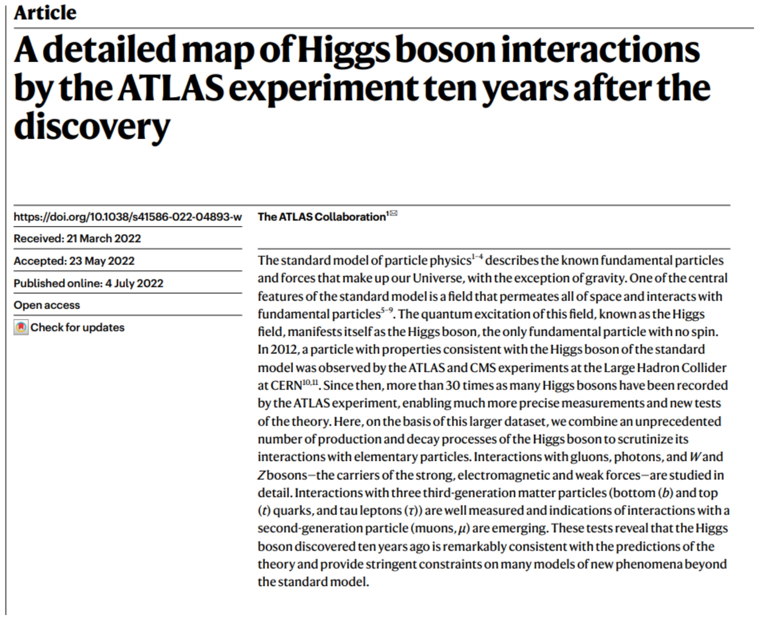
Effective-Field Theory interpretations of Higgs boson production and decay rates with the ATLAS experiment

Aleksei Lukianchuk
On behalf of ATLAS experiment

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Introduction

- 10 years after Higgs discovery: publication in **Nature** with **combined Higgs analysis**


Article

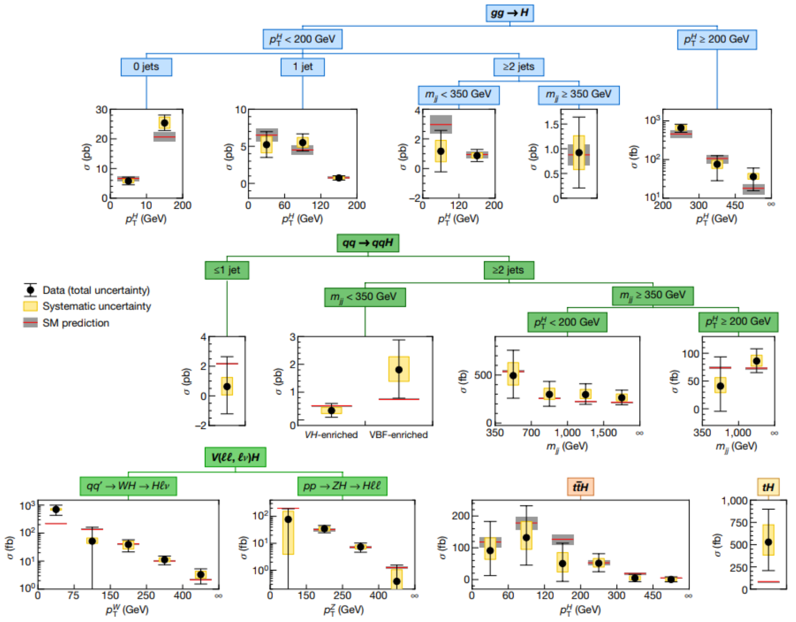
A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04893-w
Received: 21 March 2022
Accepted: 23 May 2022
Published online: 4 July 2022
Open access
Check for updates

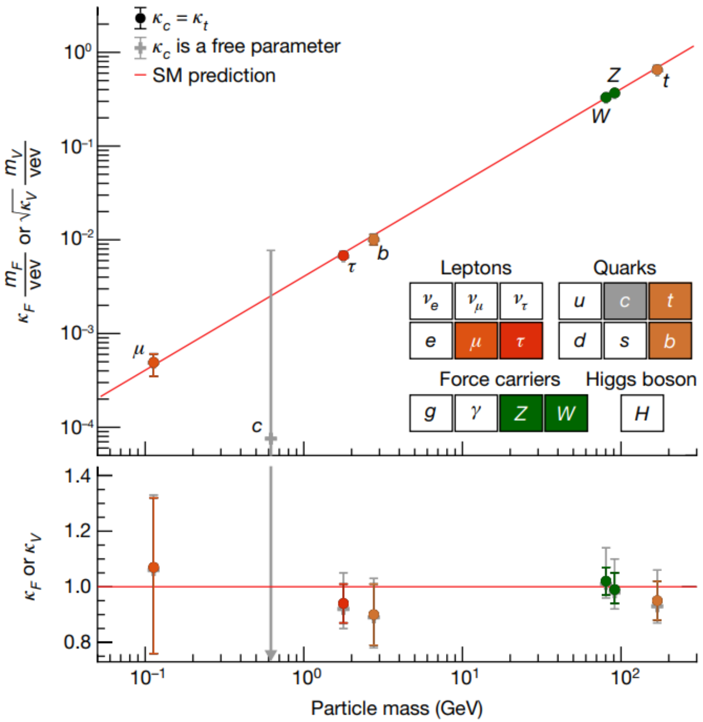
The ATLAS Collaboration*

The standard model of particle physics[1–4] describes the known fundamental particles and forces that make up our Universe, with the exception of gravity. One of the central features of the standard model is a field that permeates all of space and interacts with fundamental particles[5–9]. The quantum excitation of this field, known as the Higgs field, manifests itself as the Higgs boson, the only fundamental particle with no spin. In 2012, a particle with properties consistent with the Higgs boson of the standard model was observed by the ATLAS and CMS experiments at the Large Hadron Collider at CERN[10,11]. Since then, more than 30 times as many Higgs bosons have been recorded by the ATLAS experiment, enabling much more precise measurements and new tests of the theory. Here, on the basis of this larger dataset, we combine an unprecedented number of production and decay processes of the Higgs boson to scrutinize its interactions with elementary particles. Interactions with gluons, photons, and W and Z bosons—the carriers of the strong, electromagnetic and weak forces—are studied in detail. Interactions with three third-generation matter particles (bottom (b) and top (t) quarks, and tau leptons (τ)) are well measured and indications of interactions with a second-generation particle (muons, μ) are emerging. These tests reveal that the Higgs boson discovered ten years ago is remarkably consistent with the predictions of the theory and provide stringent constraints on many models of new phenomena beyond the standard model.

STXS



STXS measurements

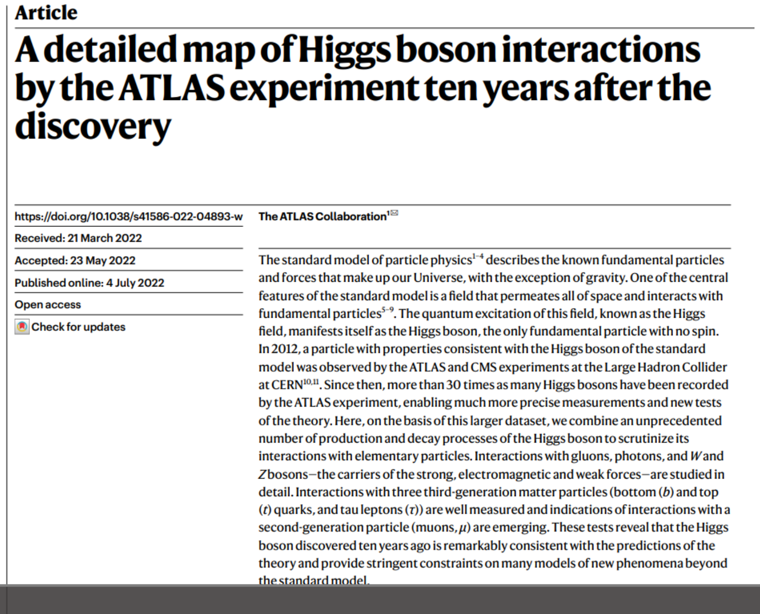


Kappa-framework measurements

Introduction

- 10 years after Higgs discovery: publication in **Nature** with **combined Higgs analysis**

STXS

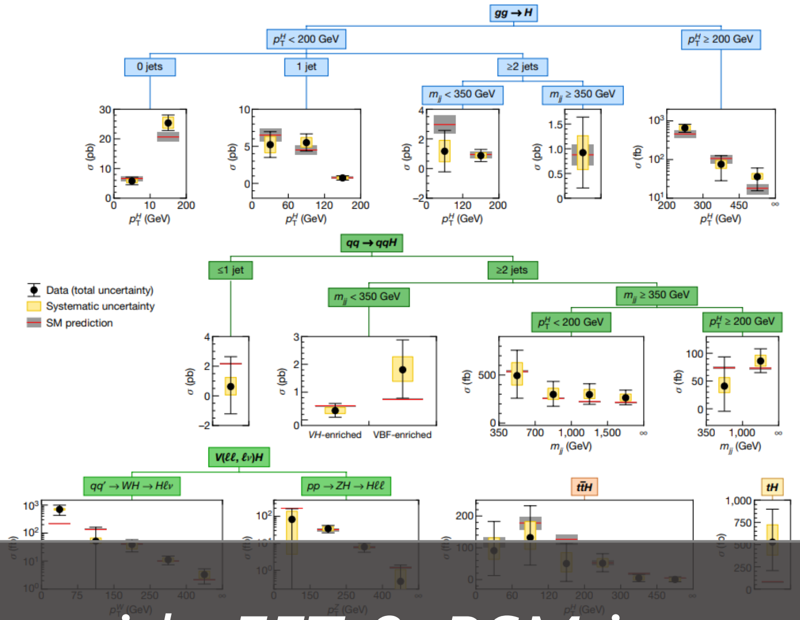

Article

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

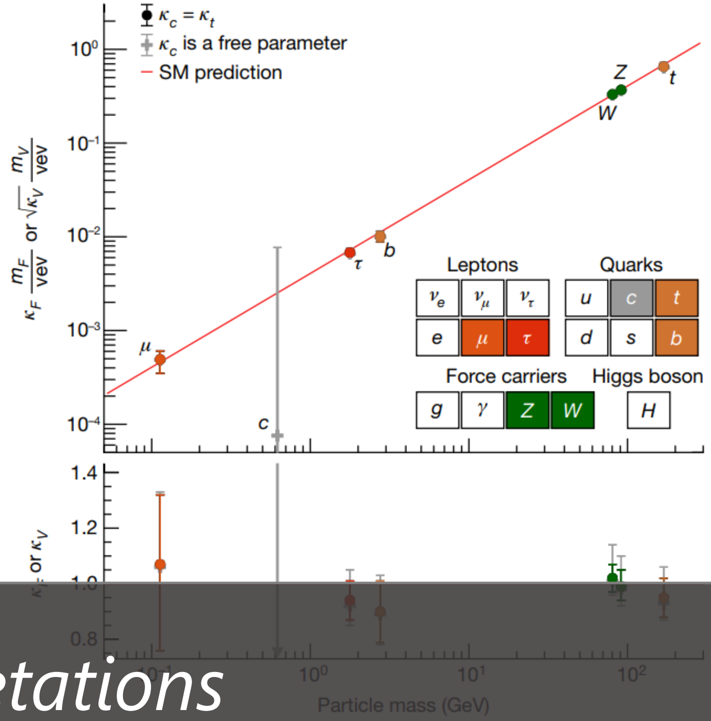
https://doi.org/10.1038/s41586-022-04893-w
Received: 21 March 2022
Accepted: 23 May 2022
Published online: 4 July 2022
Open access
Check for updates

The ATLAS Collaboration*

The standard model of particle physics[1–4] describes the known fundamental particles and forces that make up our Universe, with the exception of gravity. One of the central features of the standard model is a field that permeates all of space and interacts with fundamental particles[5–9]. The quantum excitation of this field, known as the Higgs field, manifests itself as the Higgs boson, the only fundamental particle with no spin. In 2012, a particle with properties consistent with the Higgs boson of the standard model was observed by the ATLAS and CMS experiments at the Large Hadron Collider at CERN[10,11]. Since then, more than 30 times as many Higgs bosons have been recorded by the ATLAS experiment, enabling much more precise measurements and new tests of the theory. Here, on the basis of this larger dataset, we combine an unprecedented number of production and decay processes of the Higgs boson to scrutinize its interactions with elementary particles. Interactions with gluons, photons, and W and Z bosons—the carriers of the strong, electromagnetic and weak forces—are studied in detail. Interactions with three third-generation matter particles (bottom (b) and top (t) quarks, and tau leptons (τ)) are well measured and indications of interactions with a second-generation particle (muons, μ) are emerging. These tests reveal that the Higgs boson discovered ten years ago is remarkably consistent with the predictions of the theory and provide stringent constraints on many models of new phenomena beyond the standard model.



STXS measurements



Kappa-framework measurements

Need to provide EFT & BSM interpretations

Input measurements

		SMEFT	Dedicated BSM
$H \to \gamma\gamma$	STXS-1.2	✓	✓
	differential	✓(subset)	
$H \to ZZ$	STXS-1.2	✓	✓
	differential	✓(subset)	
	STXS-0		✓
$H \to \tau\tau$	STXS-1.2	✓	✓
	STXS-0		✓
$H \to WW^{(*)}$	STXS-1.2	✓	✓
	STXS-0		✓
	STXS-0		✓
$H \to b\bar{b}$	STXS-1.2	✓	✓
	STXS-1.2	✓	✓
	STXS-1.2	✓	✓
	STXS-1.2	✓	
$H \to Z\gamma$	STXS-0	✓	✓
$H \to \mu\mu$	STXS-0	✓	✓

SMEFT of Differential XS
&
comparison with STXS

SMEFT of STXS

Not in this presentation

SMEFT methodology

Jay Sandesara ("EFT interpretations using Higgs boson at ATLAS")

Victor Miralles ("Higgs global fits")

Angela Taliercio lk ("Higgs boson anomalous couplings and EFT at CMS")

SMEFT Lagrangian

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\mathcal{O}_k + O(\Lambda^{-4})$$

$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{BSM}$$

- $\mathcal{C}_k^{(6)}$ - Wilson coefficients (WC)
- First term kept in the expansion of the SM lagrangian is Dim=6.
- Dim-5 (7, …) terms – violate baryonic and leptonic numbers
- Impact of dim-8 terms might be crucial

+ [SM- $\mathcal{C}^{(8)}$] interference

SMEFT methodology

Jay Sandesara ("EFT interpretations using Higgs boson at ATLAS")

Victor Miralles ("Higgs global fits")

Angela Taliercio1k ("Higgs boson anomalous couplings and EFT at CMS")

SMEFT **Lagrangian**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\mathcal{O}_k + O(\Lambda^{-4})$$

$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{BSM}$$

- $\mathcal{C}_k^{(6)}$ - Wilson coefficients (WC)
- First term kept in the expansion of the SM lagrangian is Dim=6.
- Dim-5 (7, ...) terms – violate baryonic and leptonic numbers
- Impact of dim-8 terms might be crucial

Cross-section (production rate, width) of a process:

$$\sigma \approx |\mathcal{M}|^2 \approx$$

$$\underbrace{|\mathcal{M}_{SM}|^2}_{\text{SM}} + \underbrace{2\mathcal{R}\left\{\sum_k \mathcal{M}_{SM}\frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\mathcal{M}_k^*\right\}}_{\text{SM-D6 interference}} + \underbrace{\sum_k \left(\frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\right)^2 |\mathcal{M}_k|^2}_{\text{BSM}} + \underbrace{\sum_{i<j}\left(\frac{\mathcal{C}_i^{(6)}\mathcal{C}_j^{(6)}}{\Lambda^4}\right)\mathcal{M}_i\mathcal{M}_j^*}_{\text{Interference between WC}}$$

+ [SM- $\mathcal{C}^{(8)}$] interference

SMEFT methodology

Jay Sandesara ("EFT interpretations using Higgs boson at ATLAS")

Victor Miralles ("Higgs global fits")

Angela Taliercio1k ("Higgs boson anomalous couplings and EFT at CMS")

SMEFT Lagrangian

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\mathcal{O}_k + O(\Lambda^{-4})$$

$$\mathcal{M} = \mathcal{M}_{SM} + \mathcal{M}_{BSM}$$

- $\mathcal{C}_k^{(6)}$ - Wilson coefficients (WC)
- First term kept in the expansion of the SM lagrangian is Dim=6.
- Dim-5 (7, …) terms – violate baryonic and leptonic numbers
- Impact of dim-8 terms might be crucial

Cross-section (production rate, width) of a process:

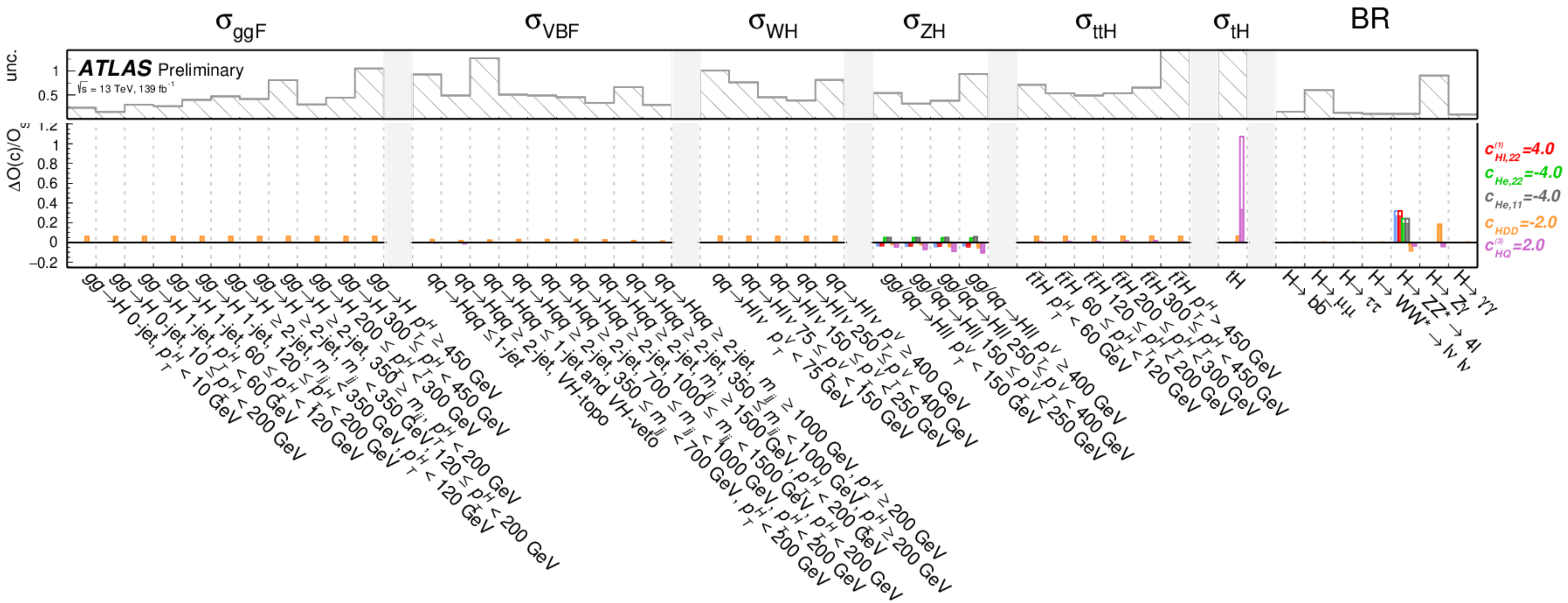
$$\sigma \approx |\mathcal{M}|^2 \approx \underbrace{|\mathcal{M}_{SM}|^2}_{\text{SM}} + \underbrace{2\mathcal{R}\left\{\sum_k \mathcal{M}_{SM}\frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\mathcal{M}_k^*\right\}}_{\text{SM-D6 interference}} + \underbrace{\sum_k \left(\frac{\mathcal{C}_k^{(6)}}{\Lambda^2}\right)^2 |\mathcal{M}_k|^2}_{\text{BSM}} + \underbrace{\sum_{i<j}\left(\frac{\mathcal{C}_i^{(6)}\mathcal{C}_j^{(6)}}{\Lambda^4}\right)\mathcal{M}_i\mathcal{M}_j^*}_{\text{Interference between WC}}$$

Linear / interference → σ_{Int}

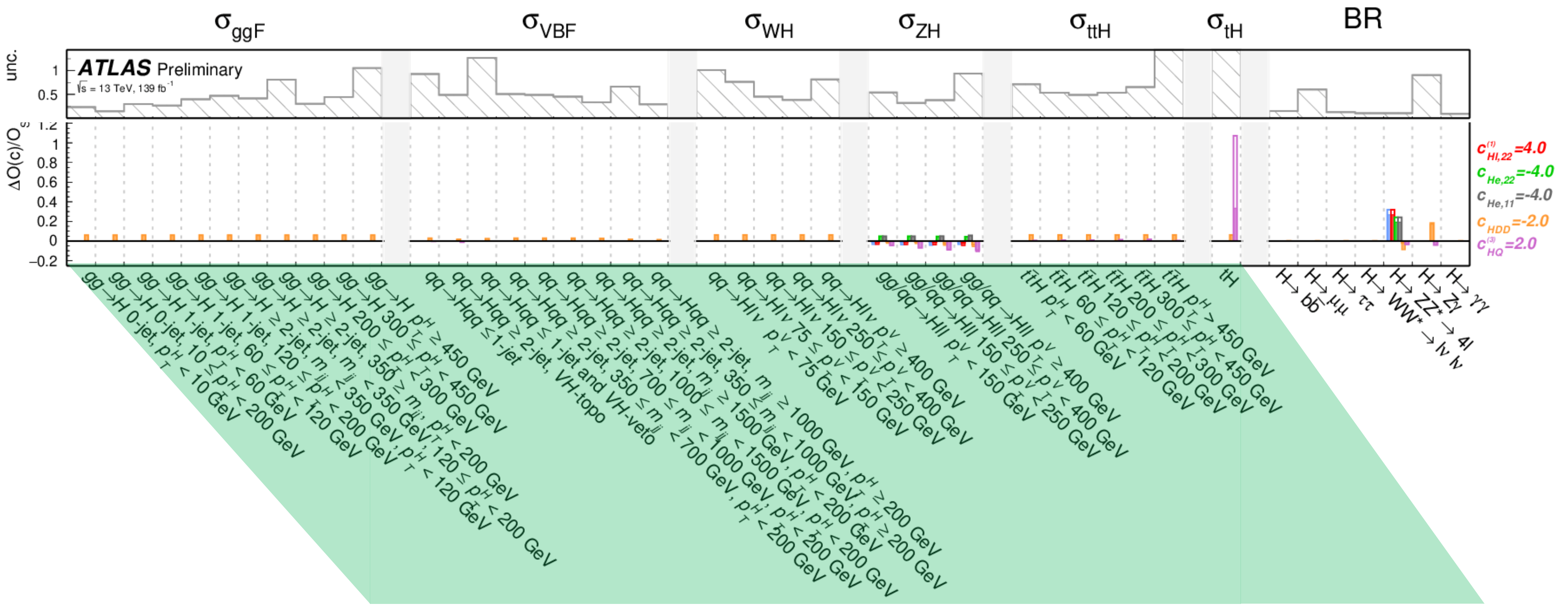
Quadratic / pure BSM → σ_{BSM}

+ [SM- $\mathcal{C}^{(8)}$] interference

STXS: Impact plot: linear (and linear + quadratic)



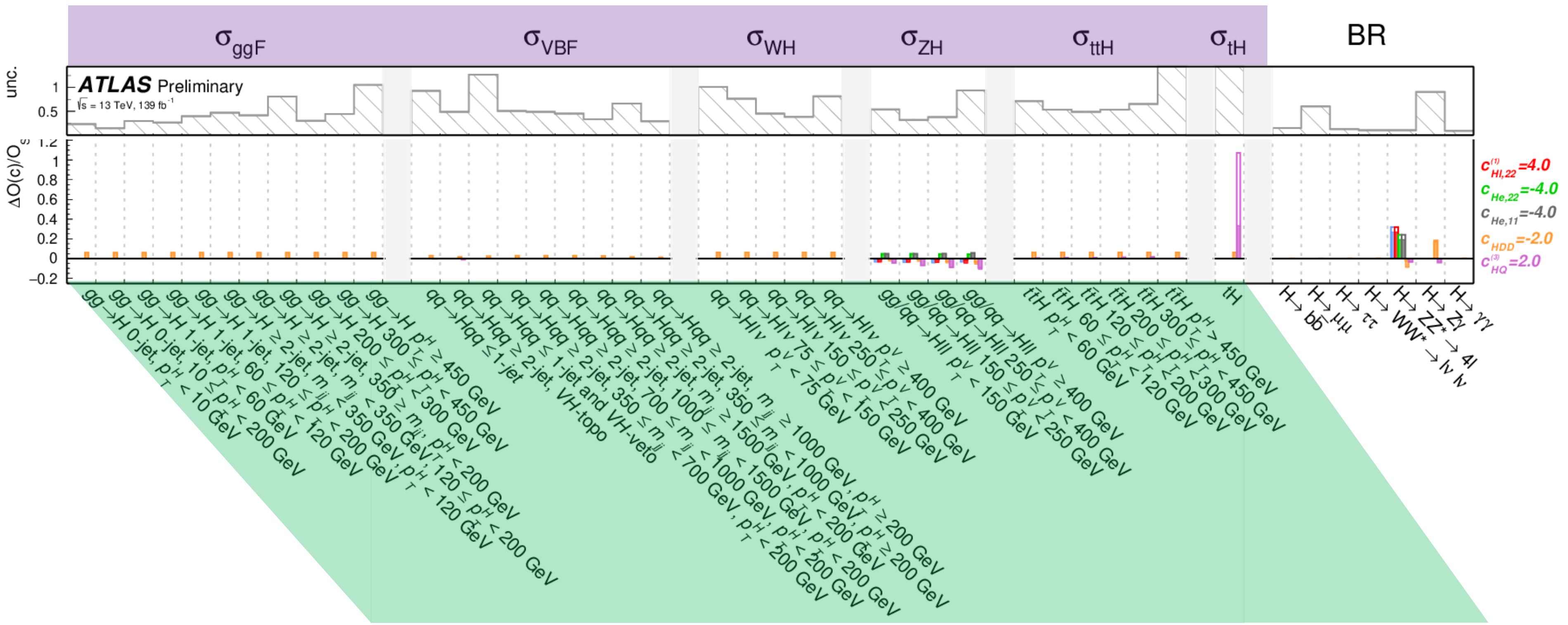
STXS: Impact plot: linear (and linear + quadratic)



STXS bins

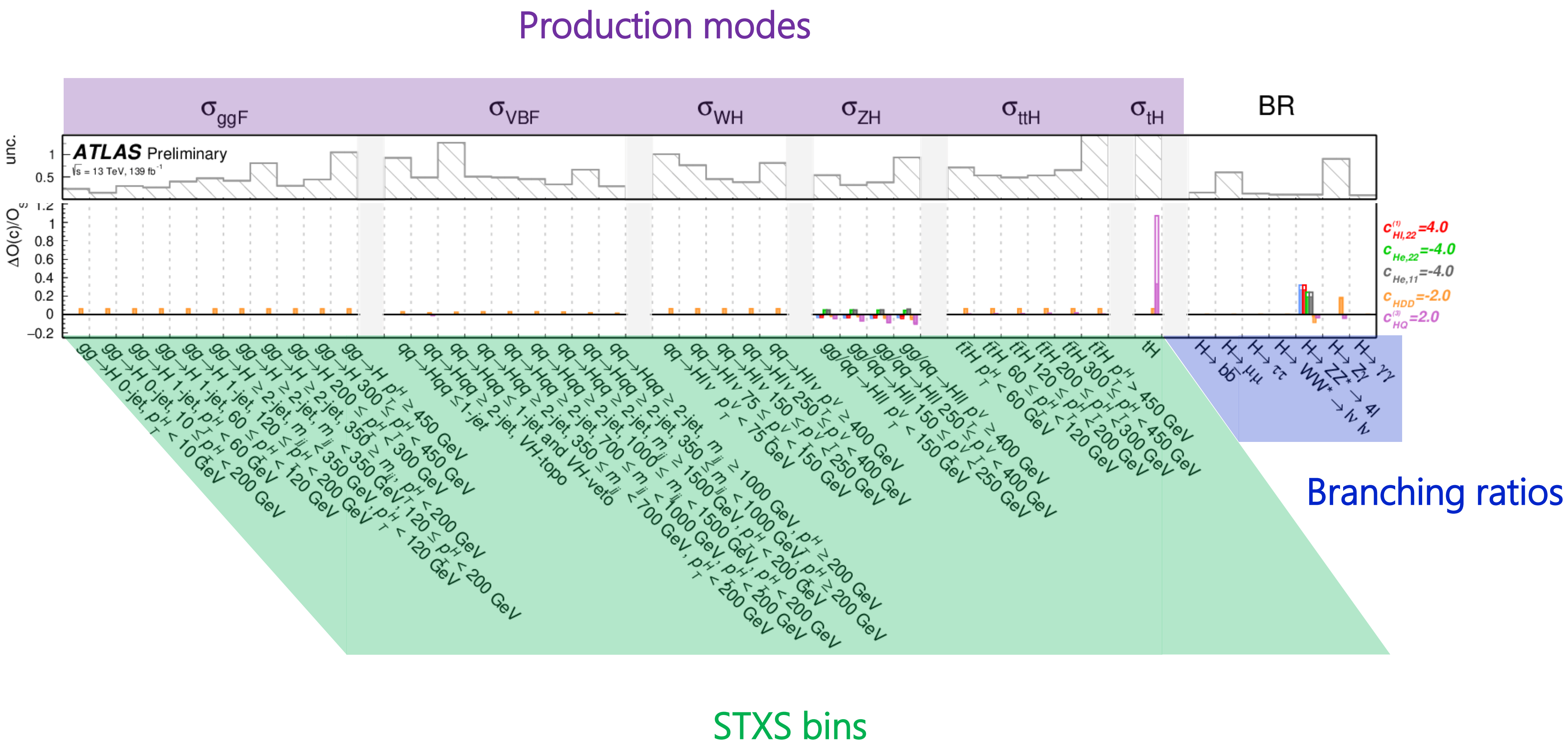
STXS: Impact plot: linear (and linear + quadratic)

Production modes

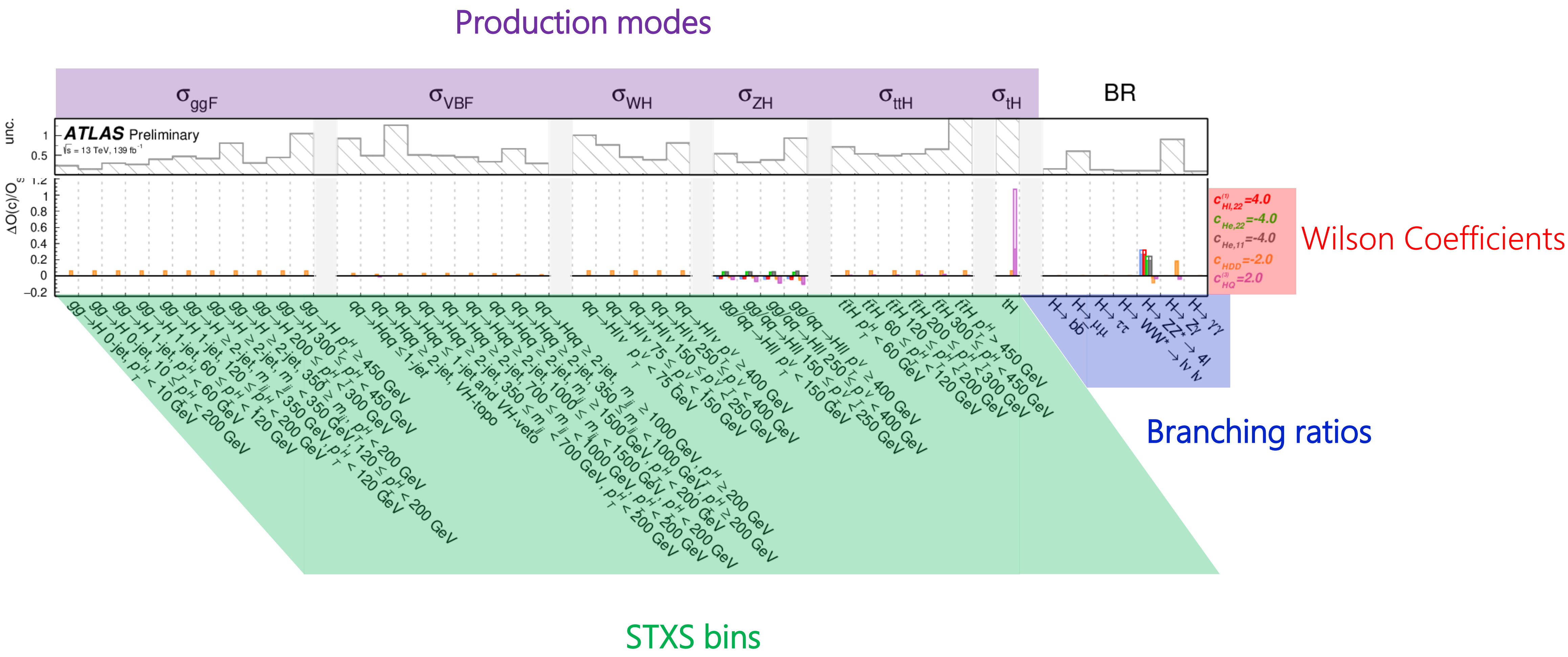


STXS bins

STXS: Impact plot: linear (and linear + quadratic)

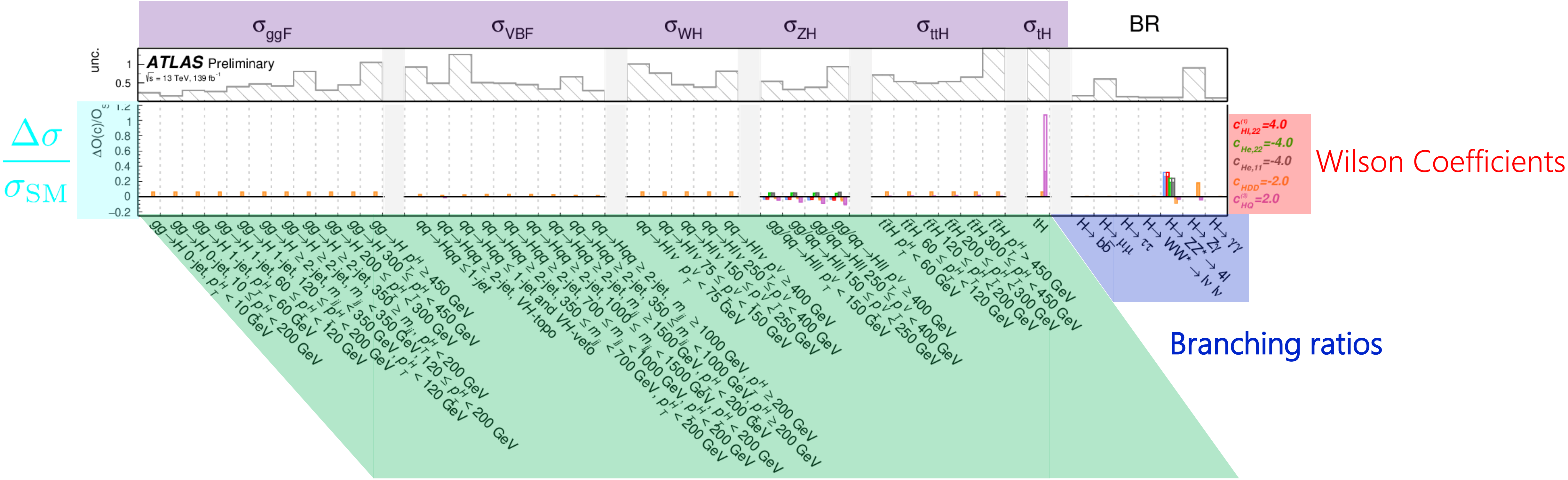


STXS: Impact plot: linear (and linear + quadratic)

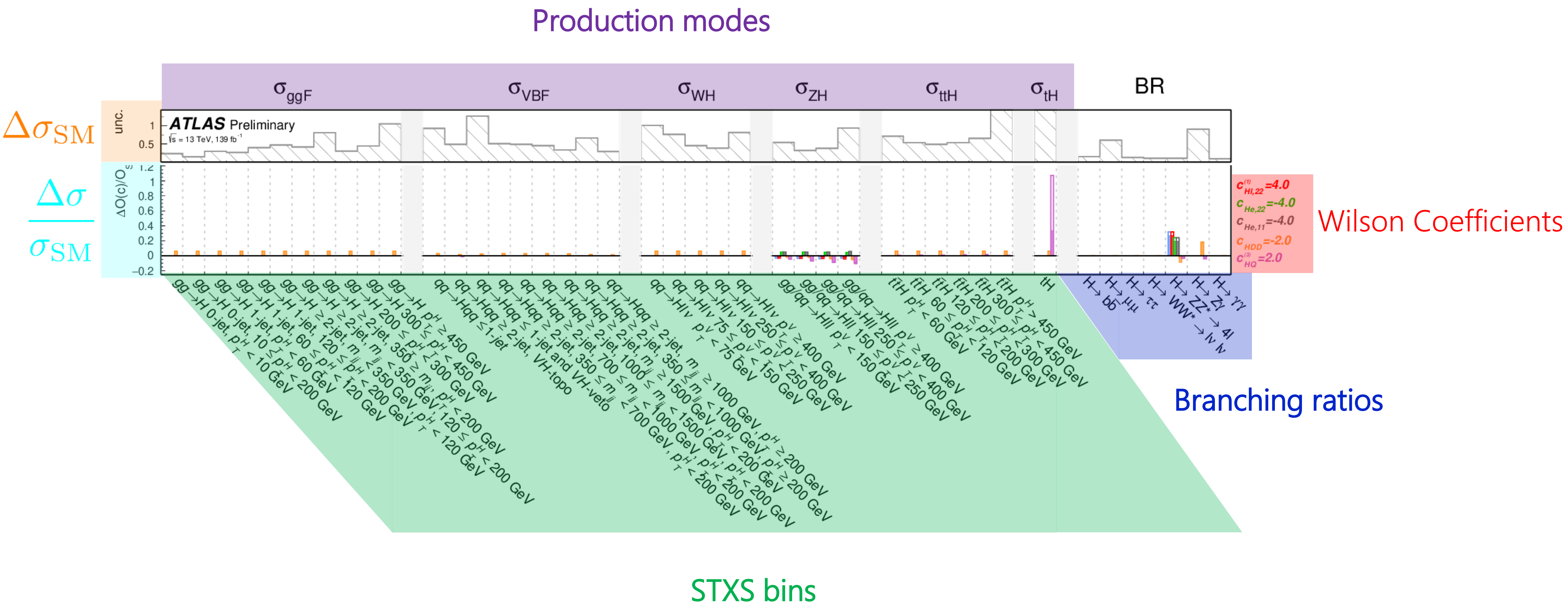


STXS: Impact plot: linear (and linear + quadratic)

Production modes

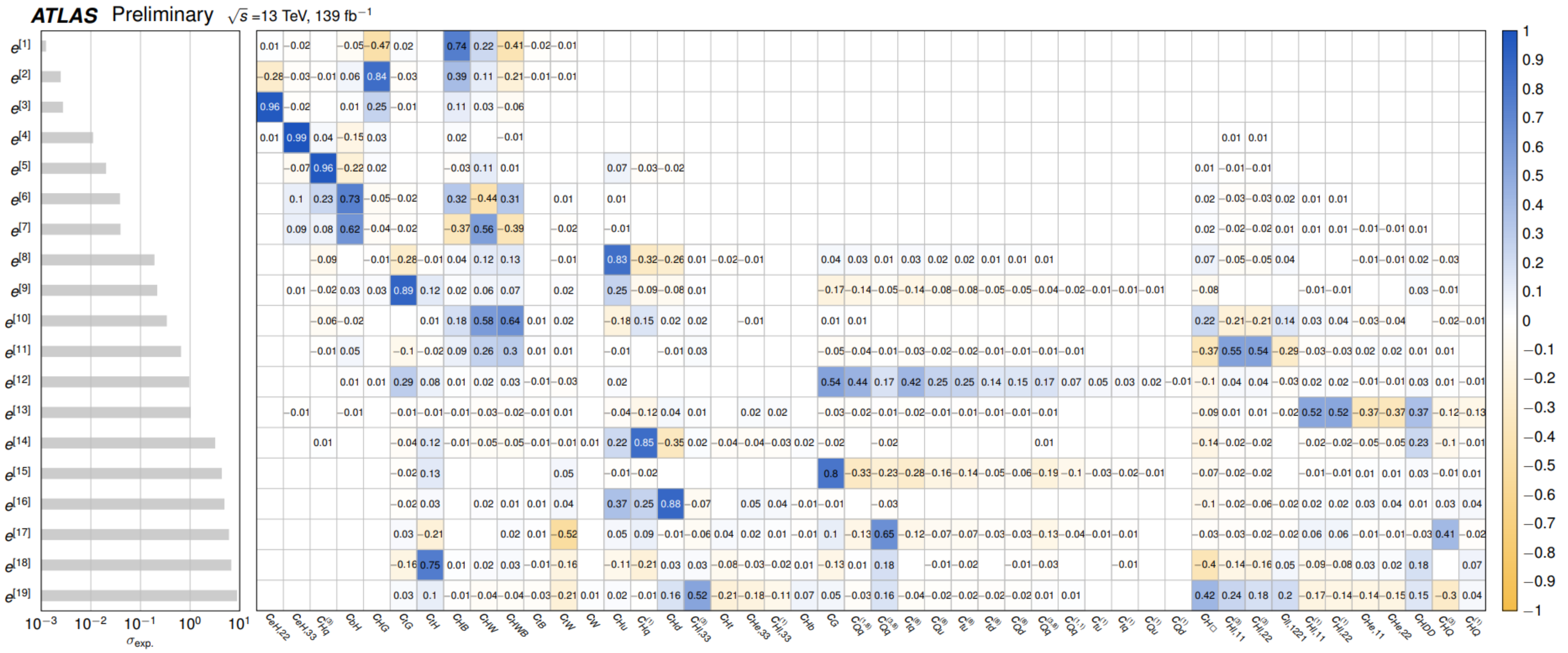


STXS: Impact plot: linear (and linear + quadratic)



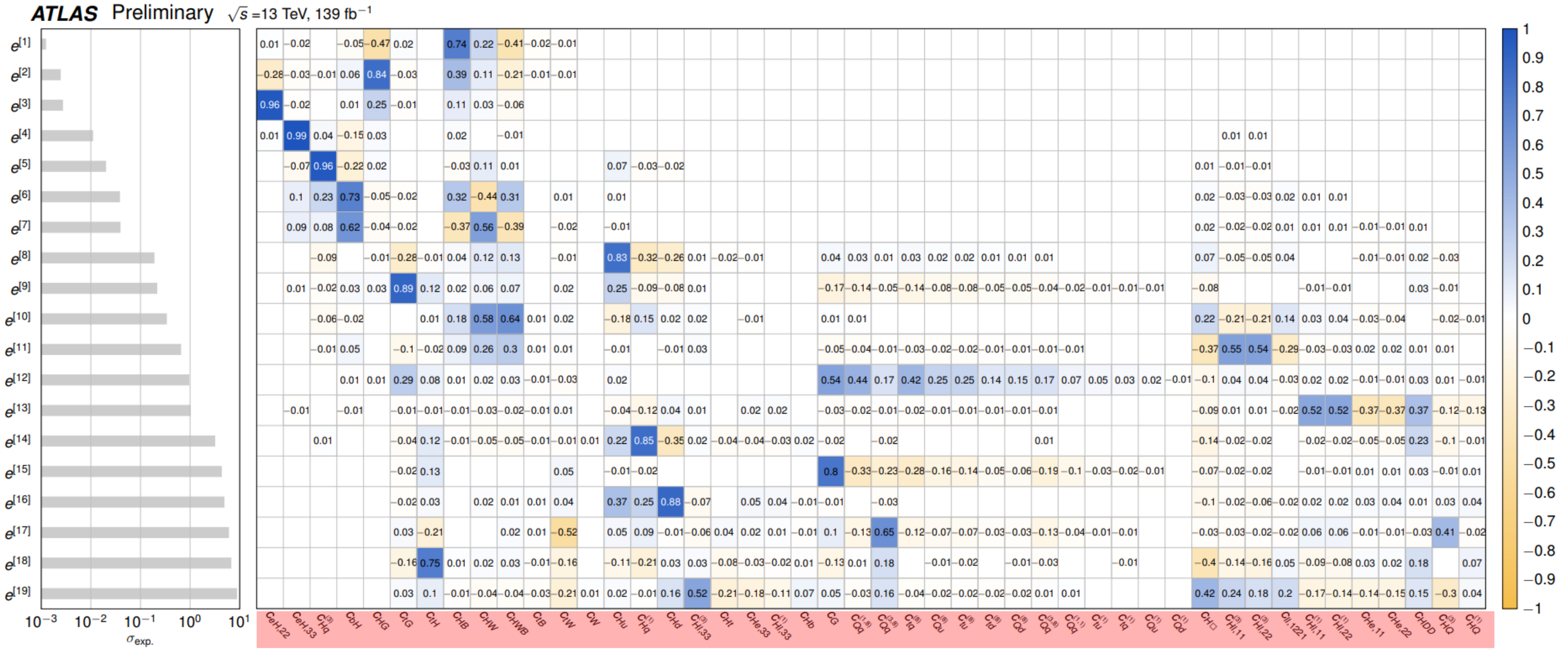
STXS: Principle Component analysis

- Simultaneous WC measurement not feasible. Identify sensitive directions from information matrix



STXS: Principle Component analysis

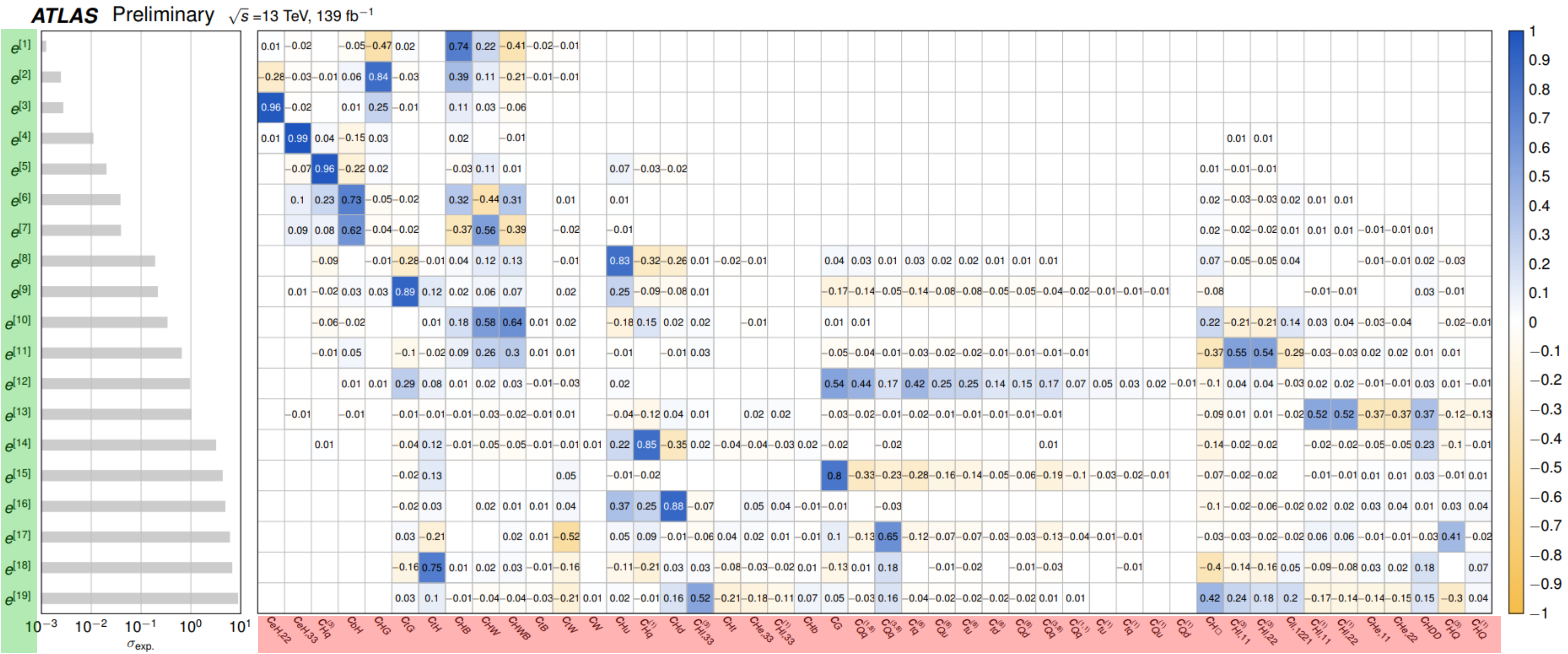
- Simultaneous WC measurement not feasible. Identify sensitive directions from information matrix



Wilson Coefficients (Warsaw basis)

STXS: Principle Component analysis

- Simultaneous WC measurement not feasible. Identify sensitive directions from information matrix

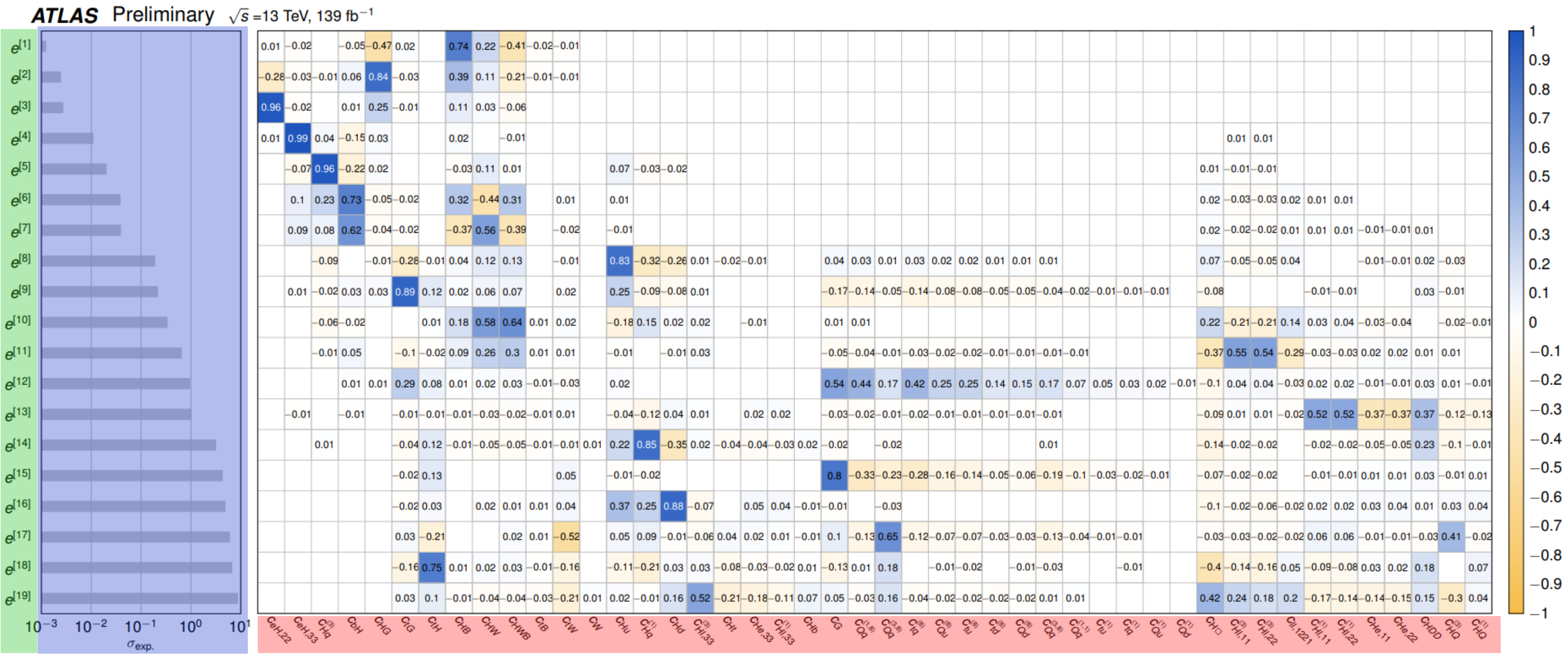


Wilson Coefficients (Warsaw basis)

STXS: Principle Component analysis

- Simultaneous WC measurement not feasible. Identify sensitive directions from information matrix

Eigenvectors

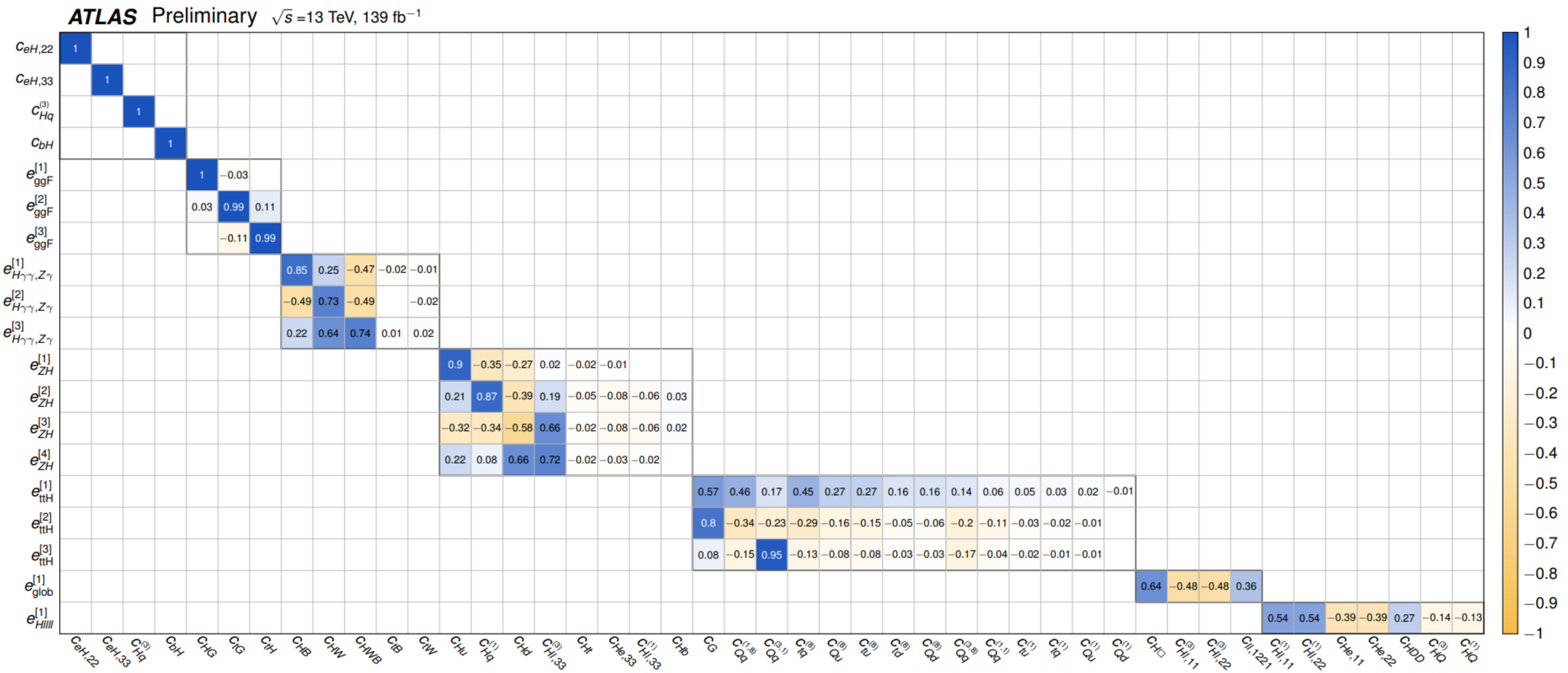


Uncertainties

Wilson Coefficients (Warsaw basis)

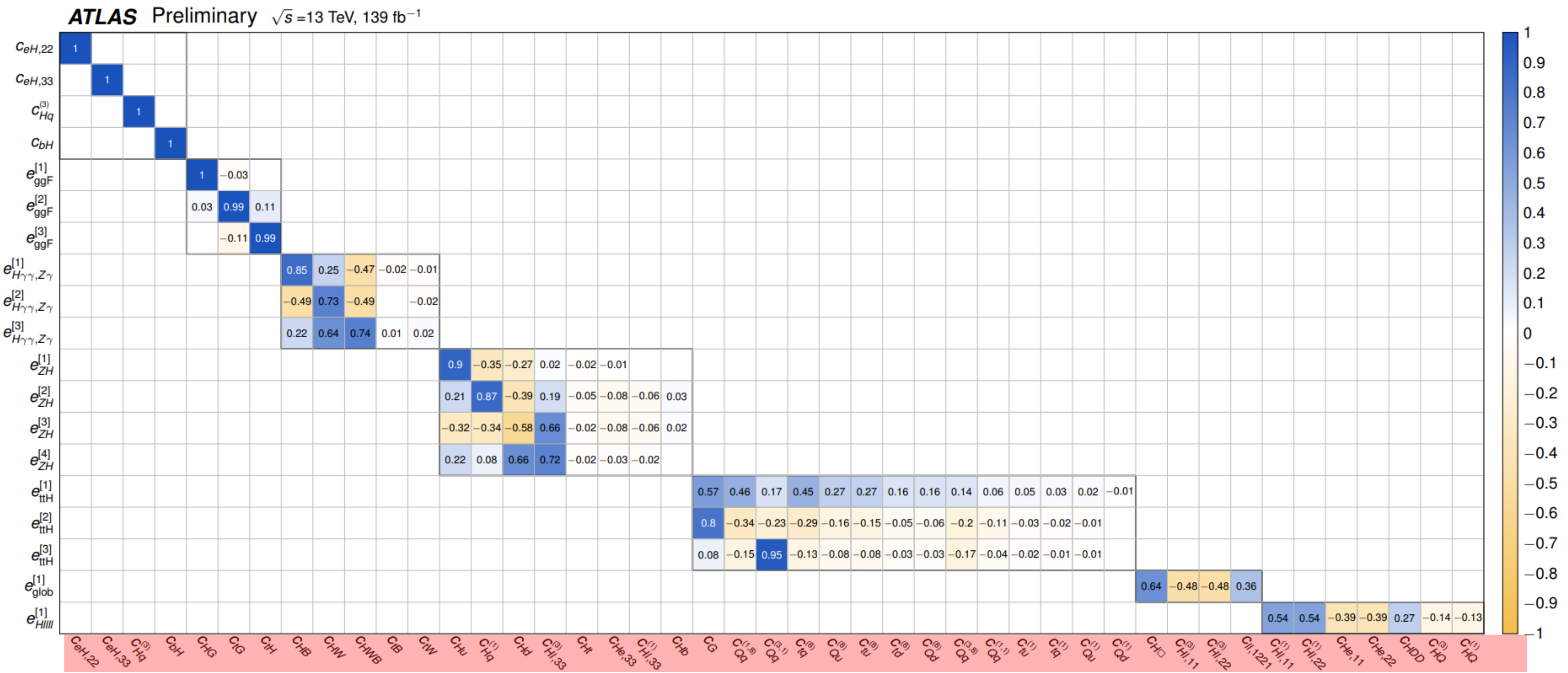
STXS: Principle Component analysis: fit basis

- Not "full" **rotation**, but in **groups** of **same** "**physics**"



STXS: Principle Component analysis: fit basis

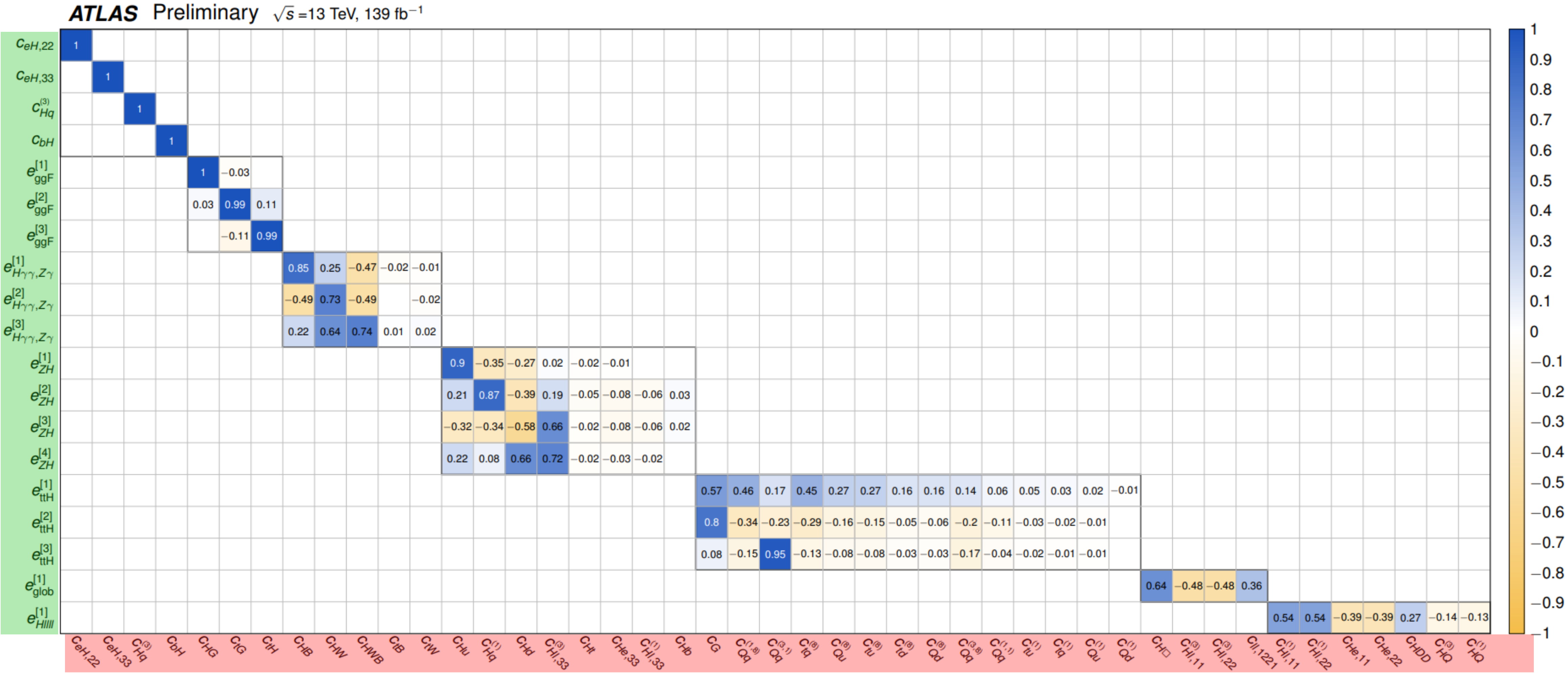
- Not "full" **rotation**, but in **groups** of **same** "**physics**"



Wilson Coefficients (Warsaw basis)

STXS: Principle Component analysis: fit basis

- Not "full" **rotation**, but in **groups** of **same** "**physics**"

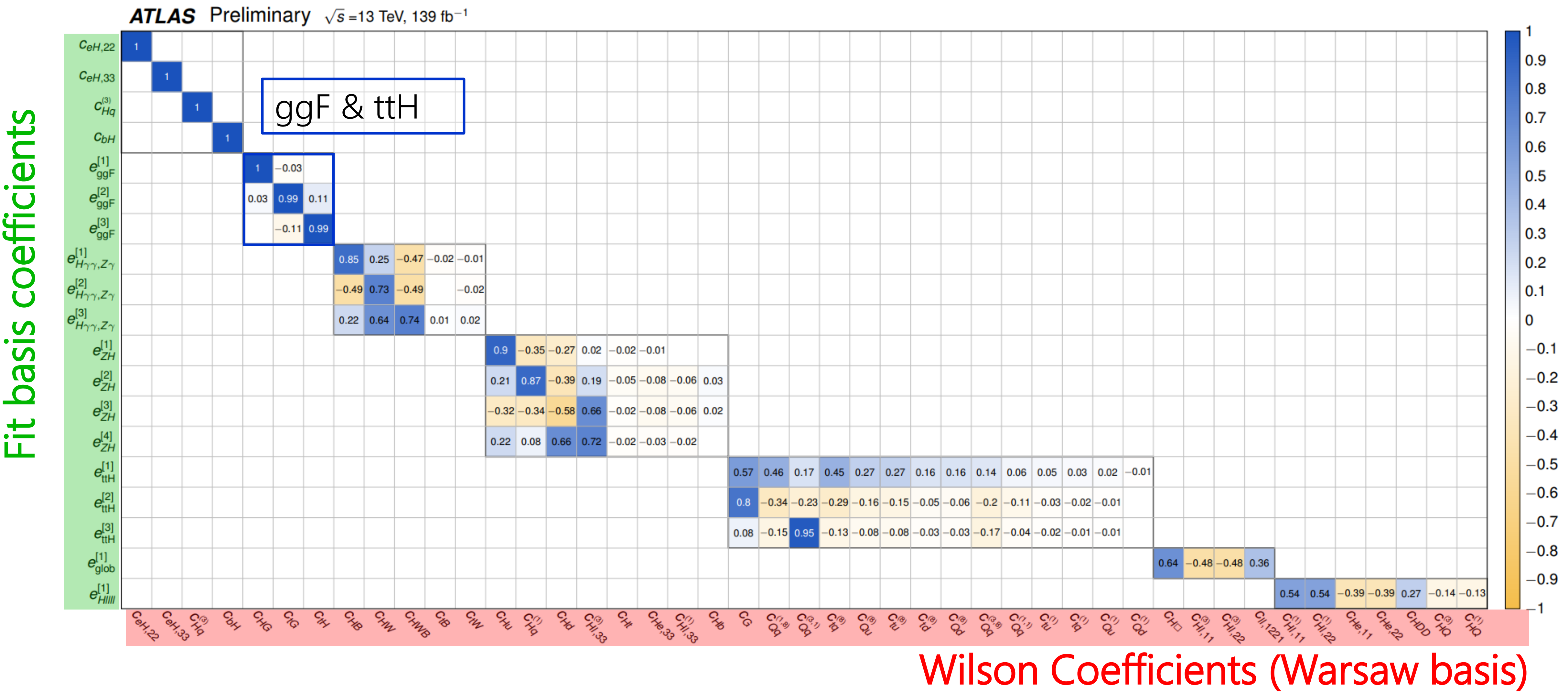


Fit basis coefficients

Wilson Coefficients (Warsaw basis)

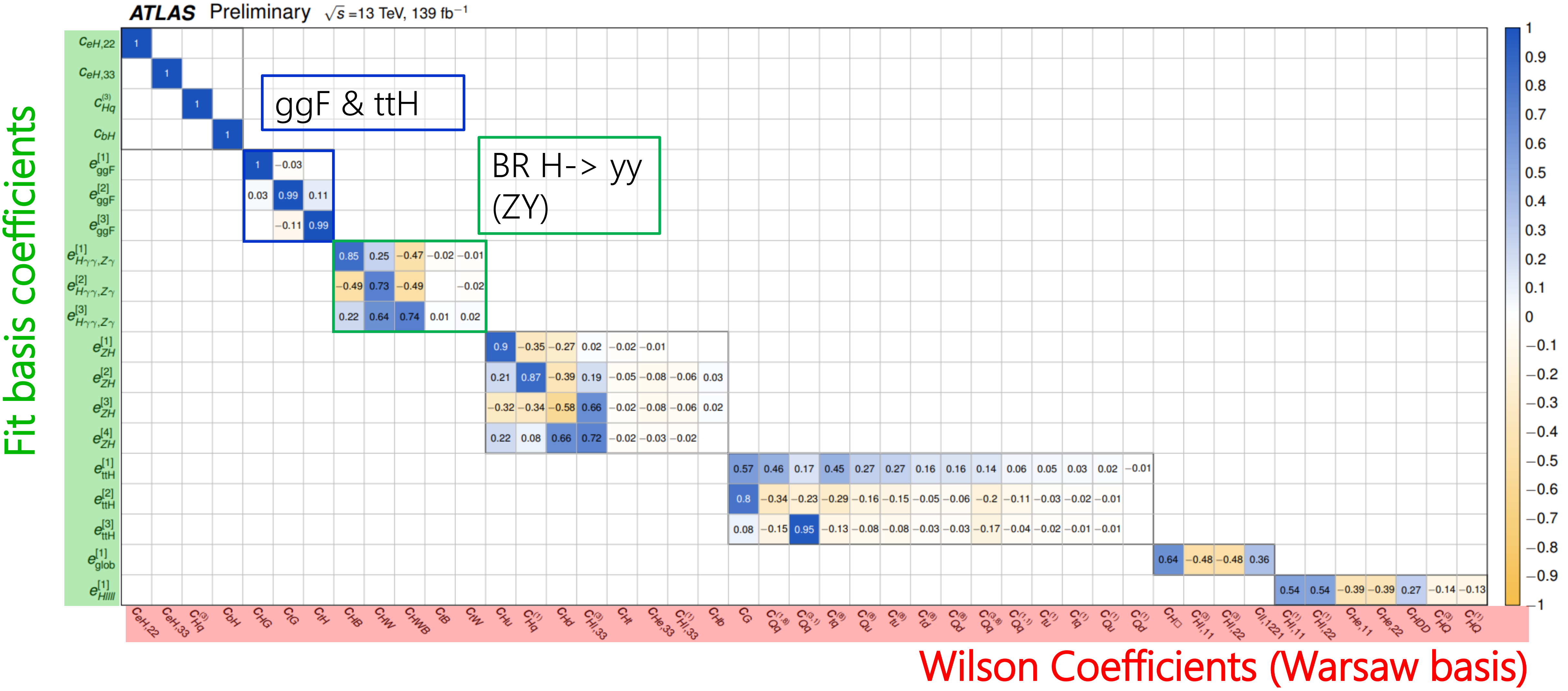
STXS: Principle Component analysis: fit basis

- Not "full" **rotation**, but in **groups** of **same** "**physics**"



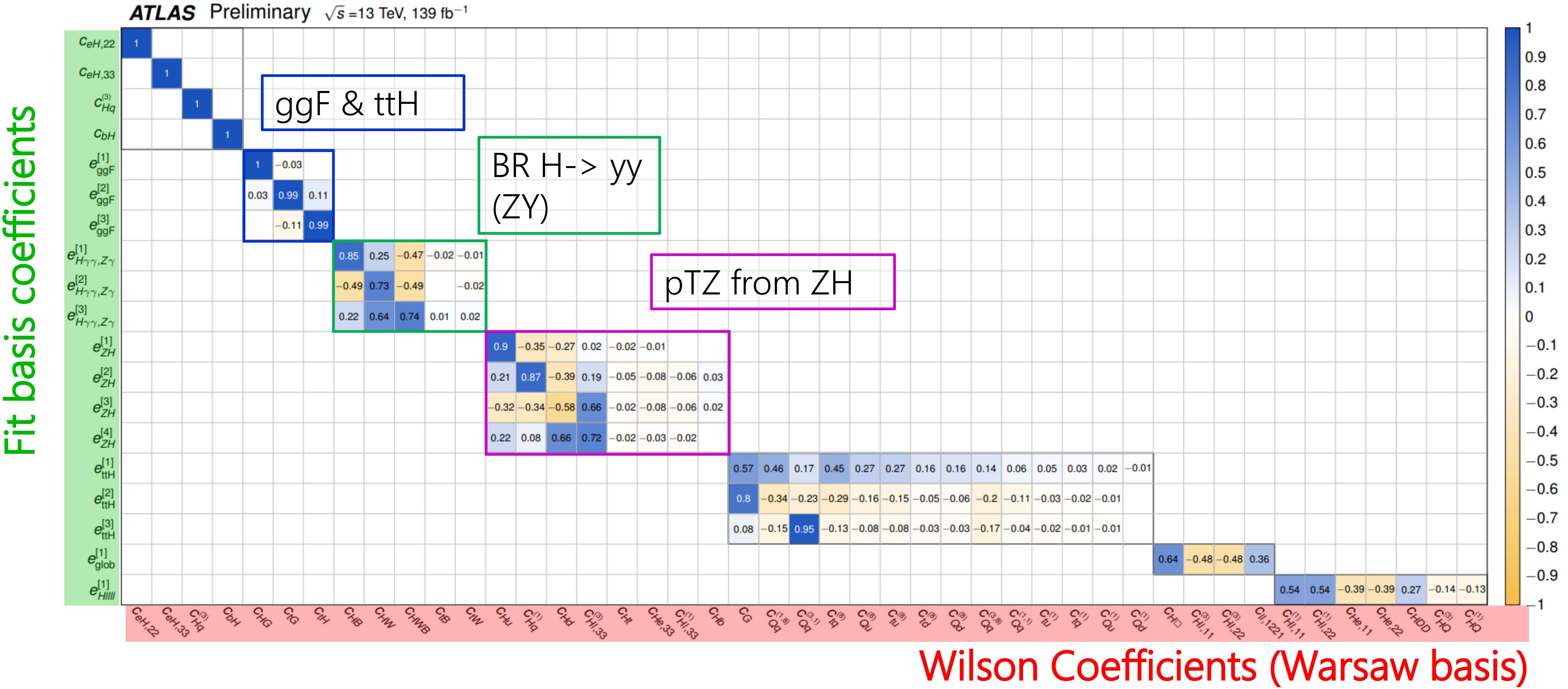
STXS: Principle Component analysis: fit basis

- Not "full" **rotation**, but in **groups** of **same** "**physics**"



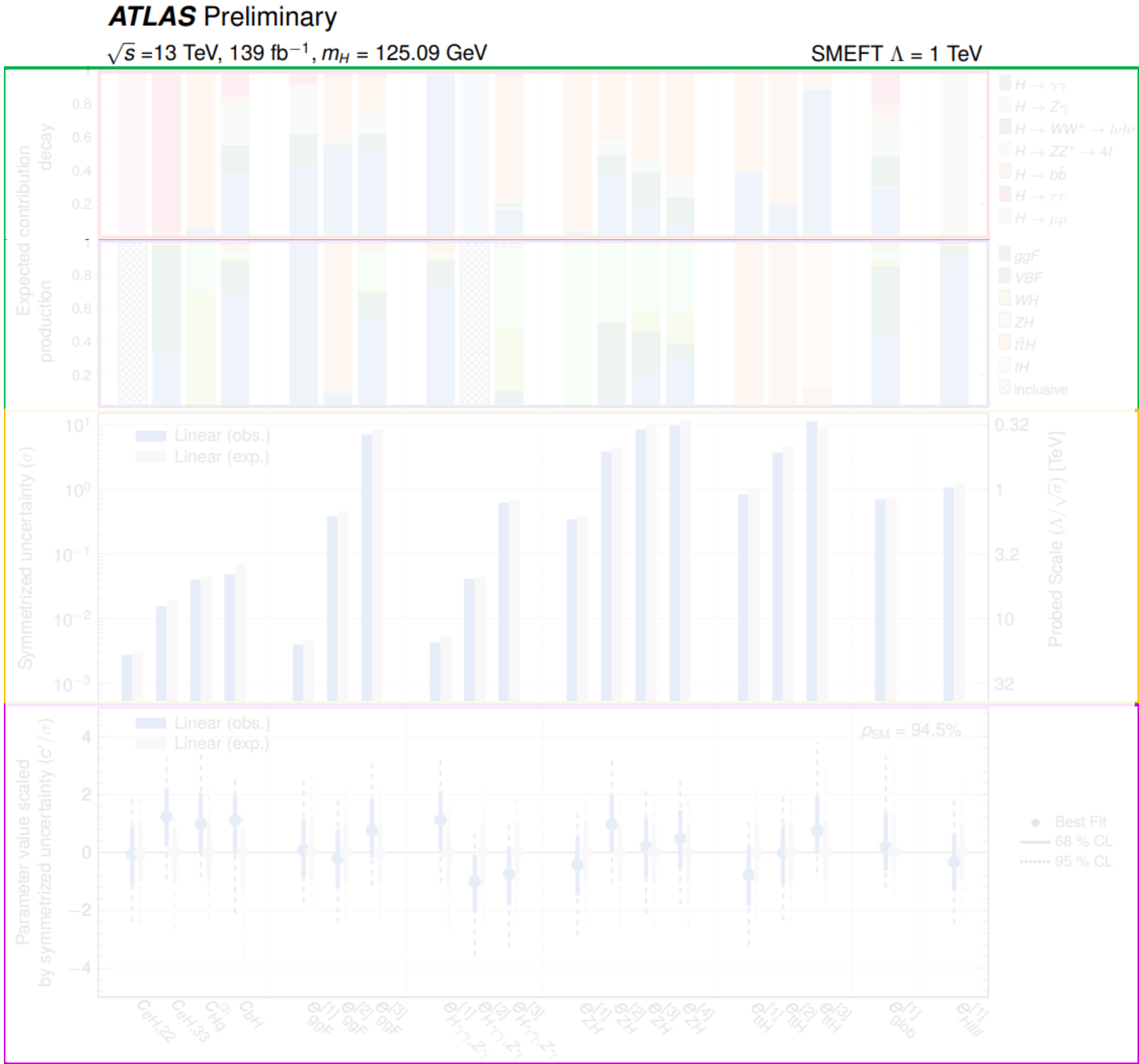
STXS: Principle Component analysis: fit basis

- Not "full" **rotation**, but in **groups** of **same** "**physics**"



STXS: fit basis results

Linear

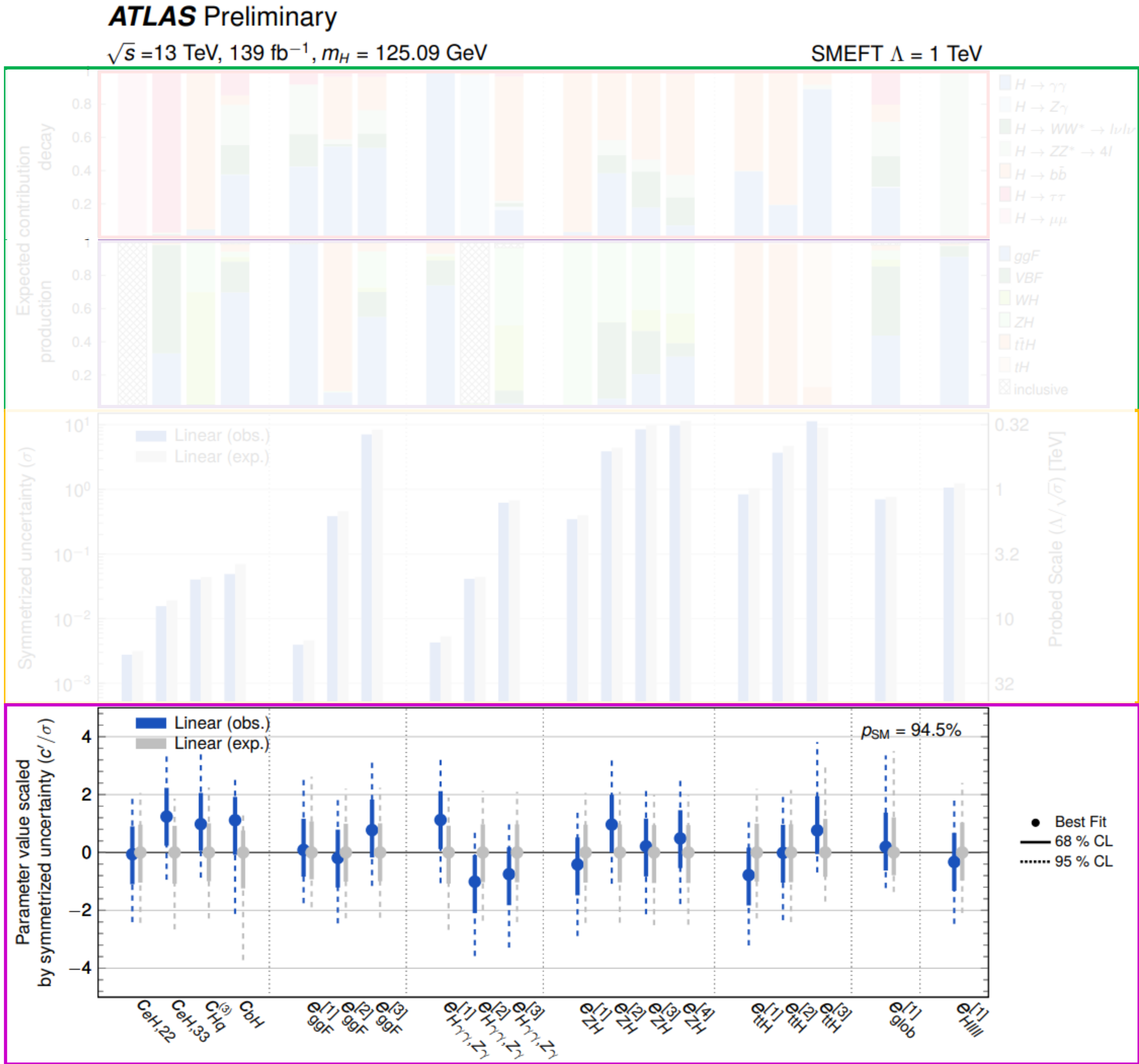


Grey -> Expected

Blue -> Observed

STXS: fit basis results

Linear



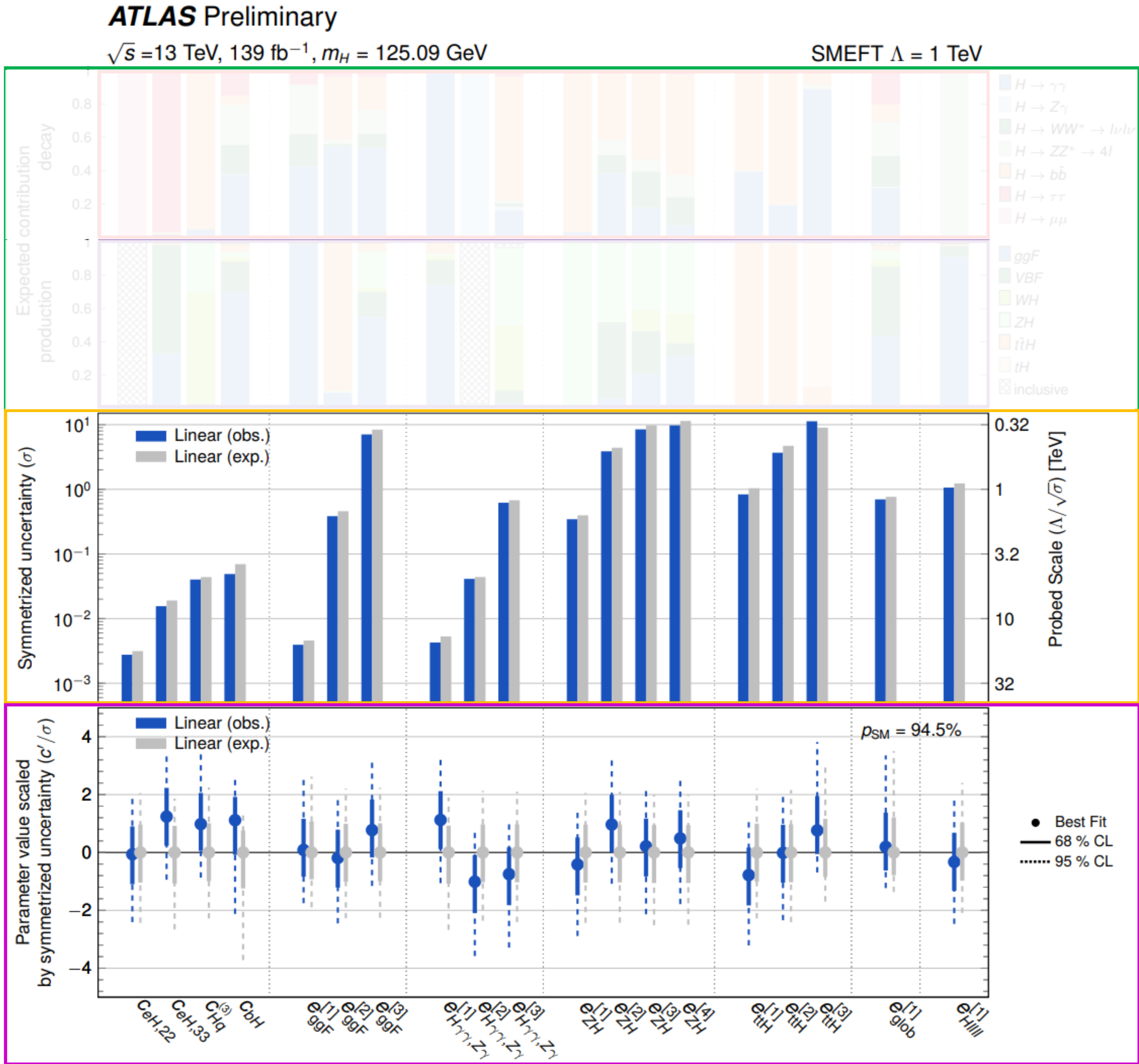
Pull of best-fit-values

Grey -> Expected

Blue -> Observed

STXS: fit basis results

Linear



Uncertainty

Pull of best-fit-values

Grey -> Expected

Blue -> Observed

STXS: fit basis results

Linear

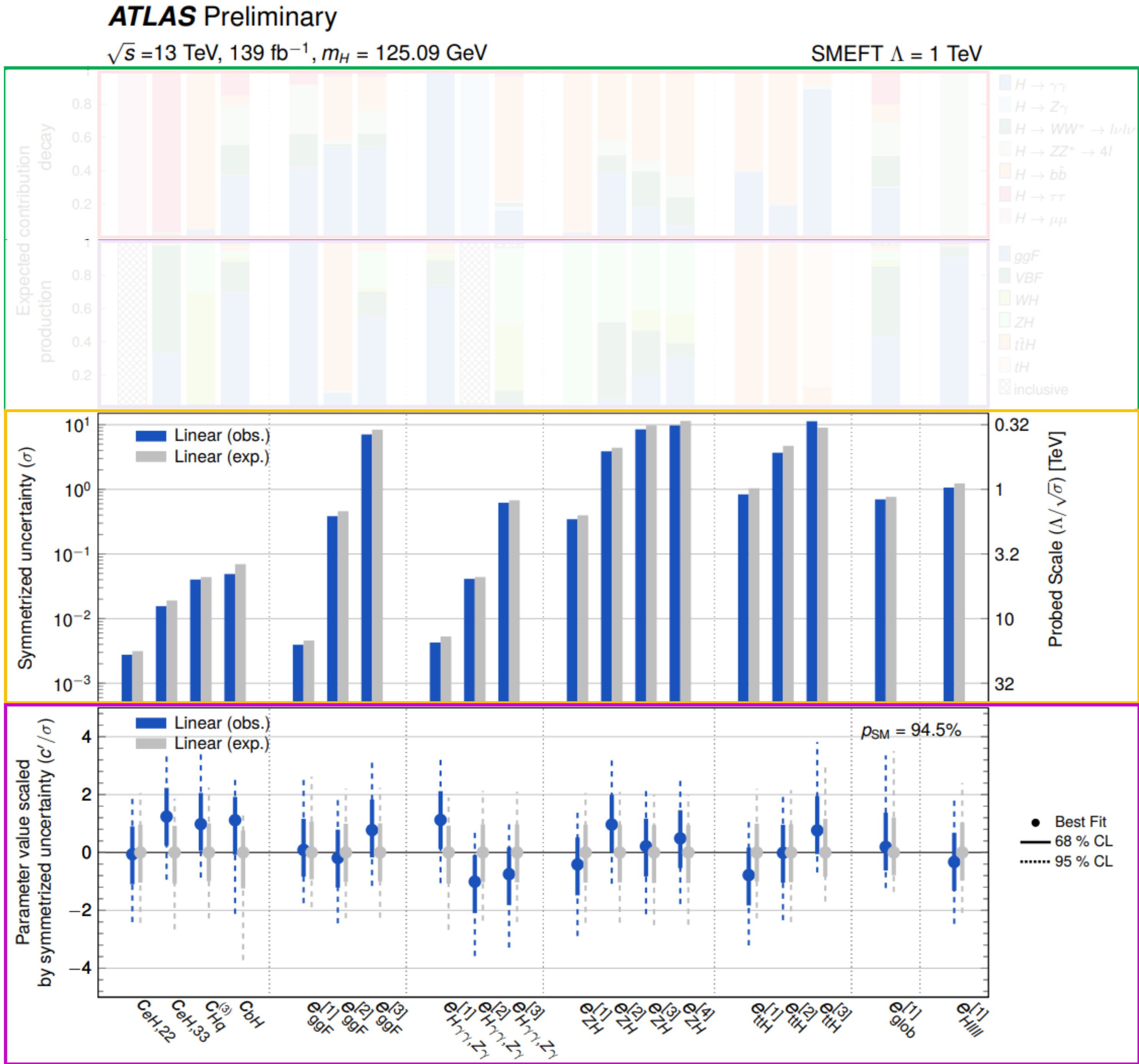
Contribution of each:

Uncertainty

Pull of best-fit-values

Grey -> Expected

Blue -> Observed



STXS: fit basis results

Linear

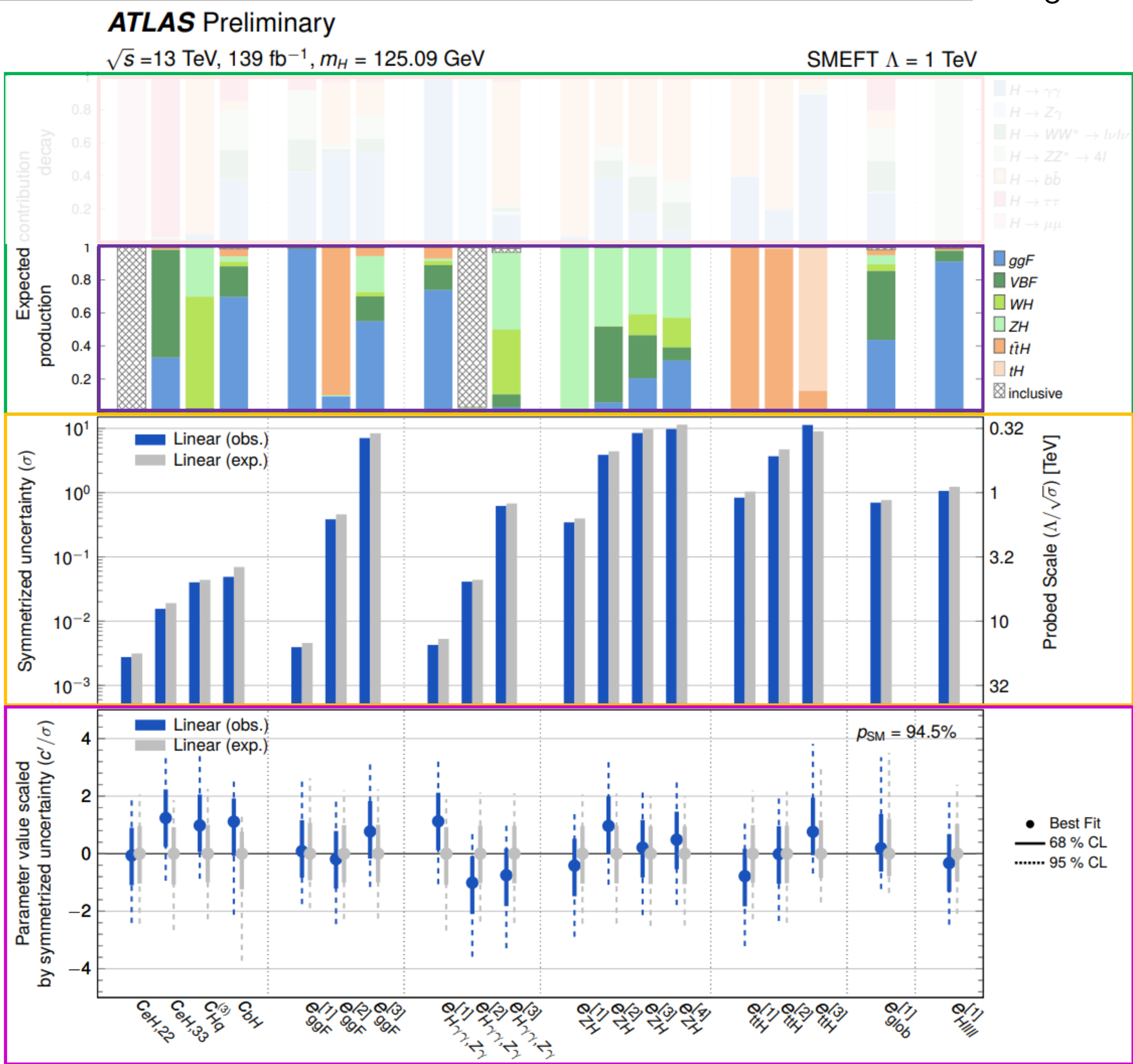
Contribution of each:

production mode

Uncertainty

Pull of best-fit-values

Grey -> Expected
Blue -> Observed



STXS: fit basis results

Linear

Mostly, **statistically dominated**

Contribution of each:

Decay channel

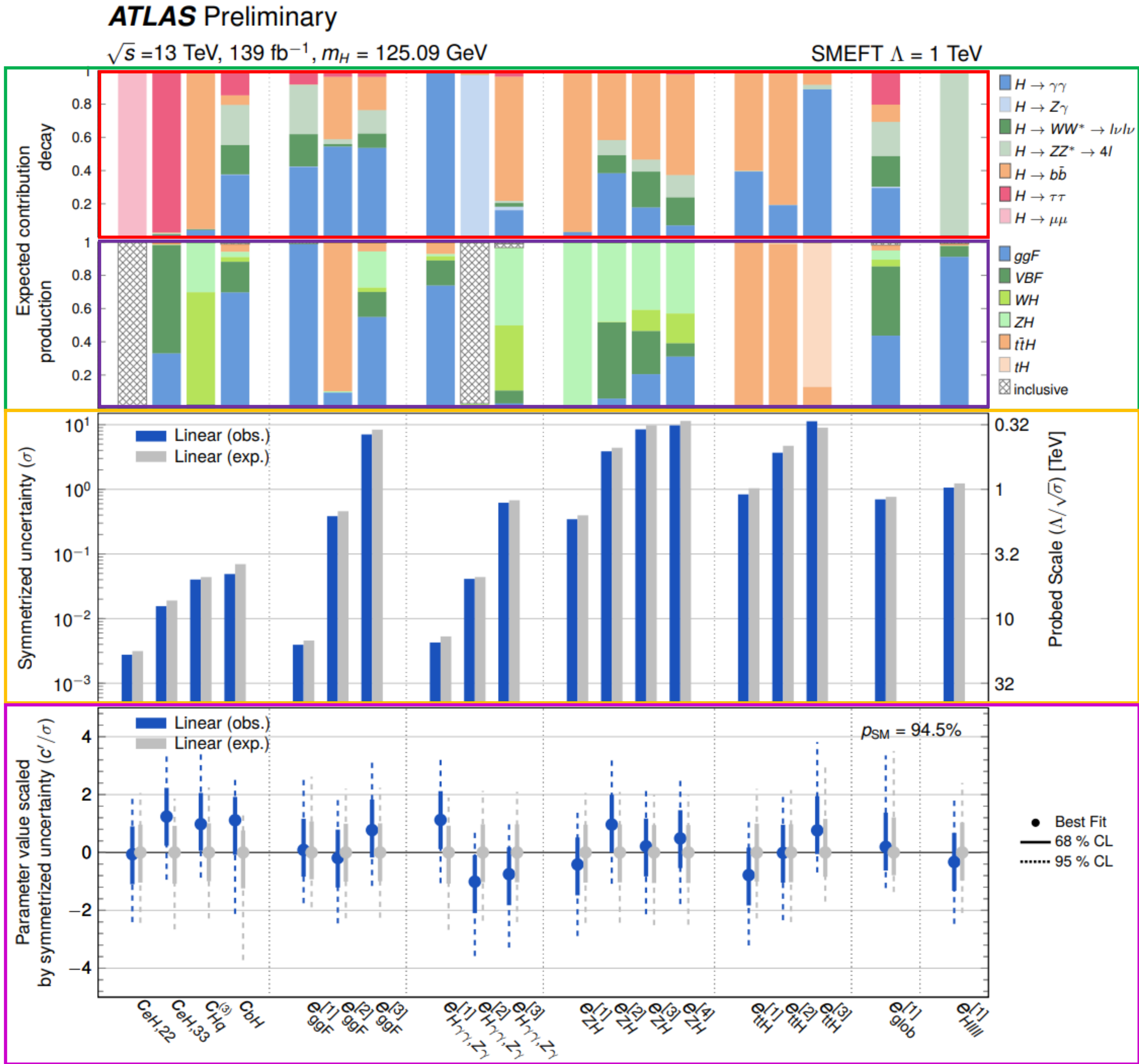
production mode

Uncertainty

Pull of best-fit-values

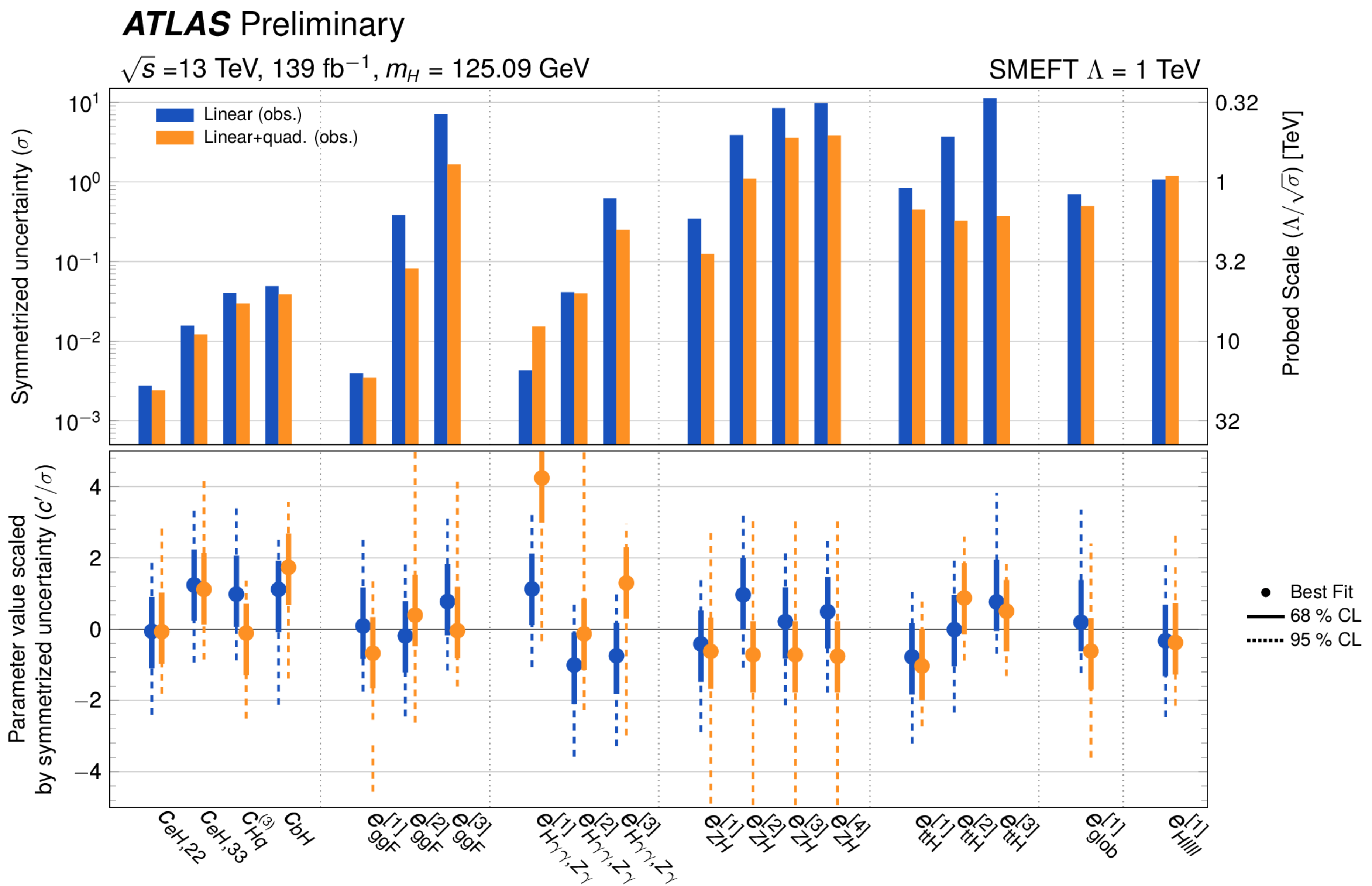
Grey -> Expected

Blue -> Observed



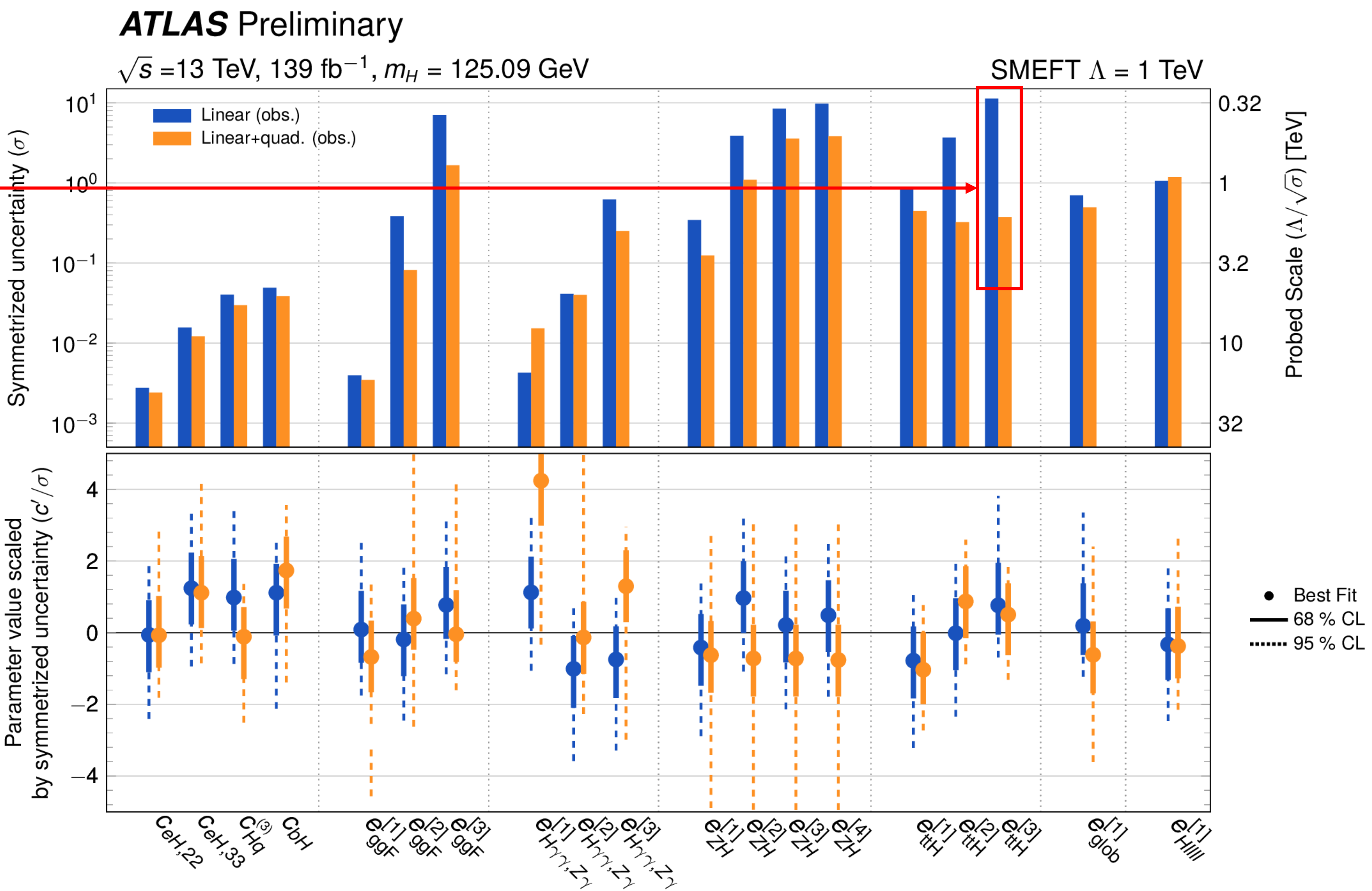
STXS: fit basis results: Lin vs Lin + Quad

Quad



STXS: fit basis results: Lin vs Lin + Quad

Quad



For some WC, a few orders of magnitude difference

Differential XS EFT interpretation

(and comparison to STXS)

$\frac{d\sigma}{dp_T^H}$: Overview

- Hyy & H4l (parametrised independently) combined for final results
- Observable: p_T^H

$\frac{d\sigma}{dp_T^H}$: Overview

- Hyy & H4l (parametrised independently) combined for final results
- Observable: p_T^H
  - cHG => Higgs-gluon direct coupling
  - ctH => Yukawa top-like
  - ctG => top-gluon coupling modifier

$\frac{d\sigma}{dp_T^H}$: Overview

- Hyy & H4l (parametrised independently) combined for final results
- Observable: p_T^H
  - cHG => Higgs-gluon direct coupling
  - ctH => Yukawa top-like
  - ctG => top-gluon coupling modifier

$$\frac{d\sigma}{dp_T^H} \propto \sigma \times \boxed{\mathrm{BR}} \times \boxed{\mathcal{A}}$$

BR: analytical expression

$\mathcal{A}$: Acceptance x efficiency

$\frac{d\sigma}{dp_T^H}$: Overview

- Hyy & H4l (parametrised independently) combined for final results
- Observable: p_T^H
  - cHG => Higgs-gluon direct coupling
  - ctH => Yukawa top-like
  - ctG => top-gluon coupling modifier

$$\frac{d\sigma}{dp_T^H} \propto \sigma \times \boxed{\mathrm{BR}} \times \boxed{\mathcal{A}}$$

BR: analytical expression

$\mathcal{A}$: Acceptance x efficiency

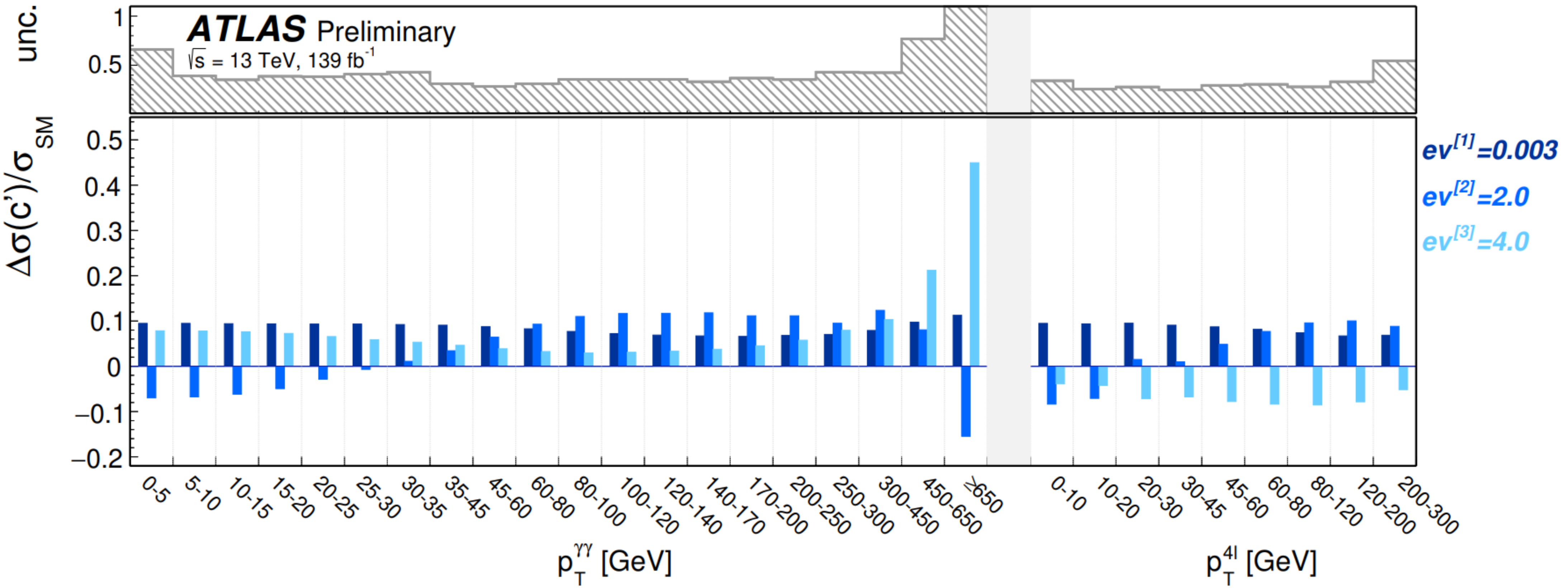
$$\mu_{bin} = \frac{1}{\sum_{i \in prod} \sigma_{i,bin}^{SM}} \left(\sum_{i \in prod} \frac{\sigma_{i,bin}^{SMEFT}(c)}{\sigma_{i,bin}^{SMEFT}(c=0)} \times \sigma_{i,bin}^{SM} \right)$$

$\sigma_{i,bin}^{SM}$: To benefit from accurate SM computations

$\frac{d\sigma}{dp_T^H}$: Principal Component Analysis

Define eigenvectors to absorb all correlations for the differential cross-section measurement.
Apply the same "rotation" to the STXS (Hyy + H4l) results.

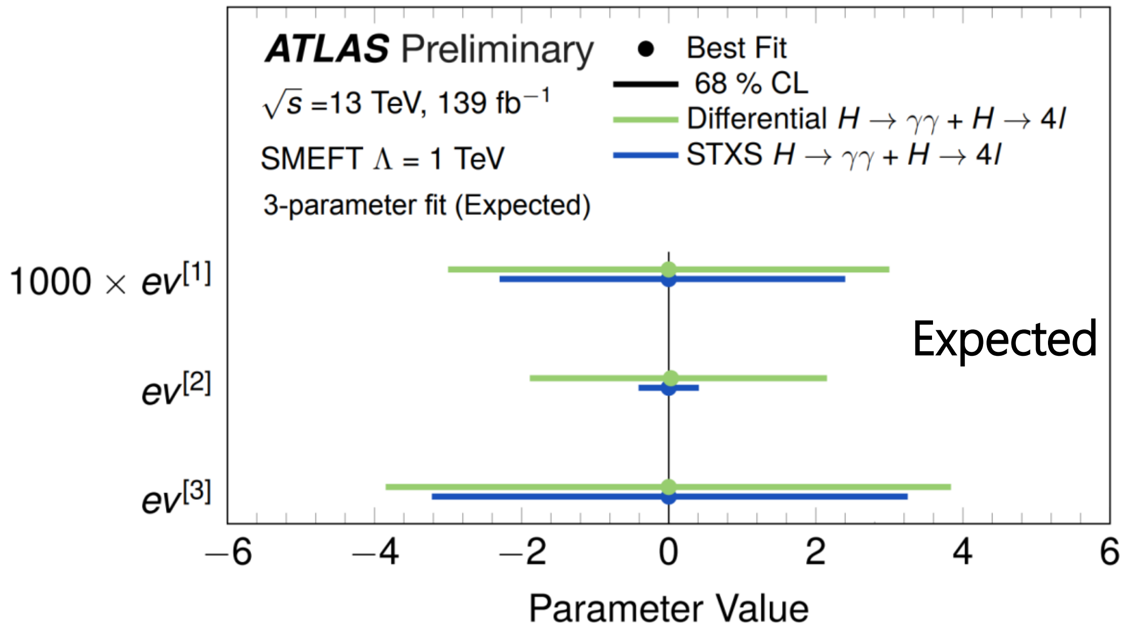
$$ev^{[1]} = 0.999c_{HG} - 0.035c_{tG} - 0.003c_{tH}$$
$$ev^{[2]} = 0.035c_{HG} + 0.978c_{tG} + 0.205c_{tH}$$
$$ev^{[3]} = -0.005c_{HG} - 0.205c_{tG} + 0.979c_{tH}$$

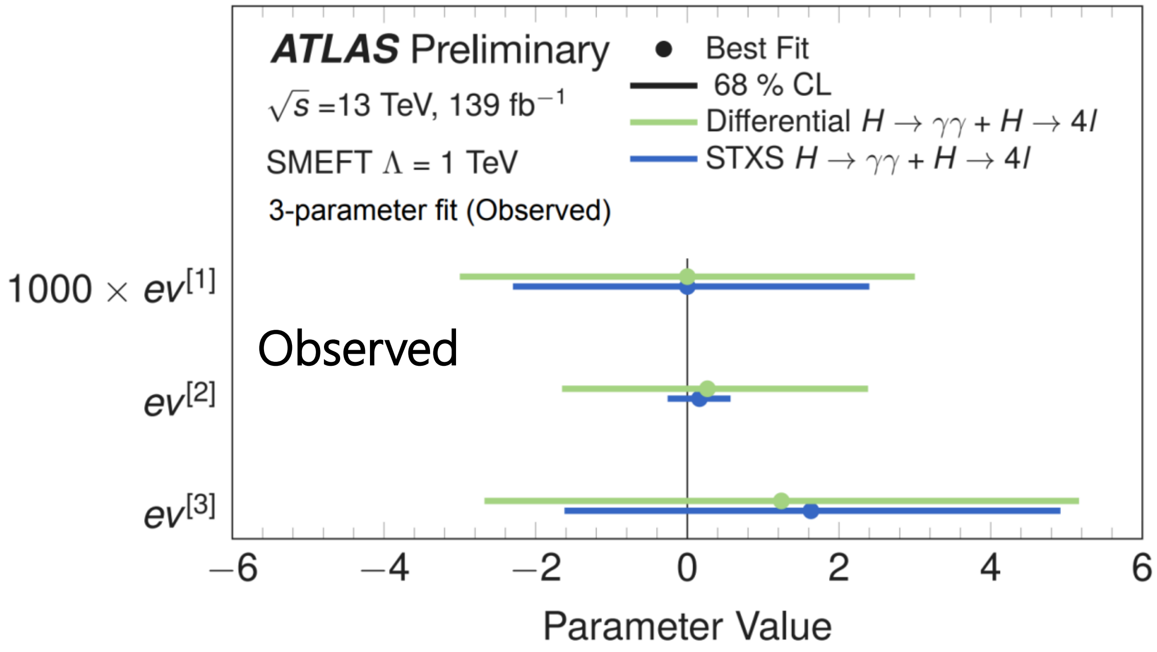


$\frac{d\sigma}{dp_T^H}$: PCA sensitivity (profiled case)

Compare performance of STXS and Diff XS => similar conditions required:

- same **dataset** yy + 4l
- same **basis**: Differential cross-section basis applied both to diff XS and STXS





- Comparable STXS and Differential performance for ev_01 (mainly constrained by ggH production mode)
- Much better STXS performance for ev_02 and ev_03 coming from the remaining production modes which can be probed separately in the STXS framework

Conclusion: results

- New SMEFT interpretation of the combined Higgs dataset
    - New channels included (Zy, mumu)
    - New linear & linear + quadratic results provided

Conclusion: results

- New SMEFT interpretation of the combined Higgs dataset
  - New channels included (Zy, mumu)
  - New linear & linear + quadratic results provided

- Comparison of the STXS and diff XS results (over Hyy + H4l)
  STXS is more sensitive

Conclusion: results

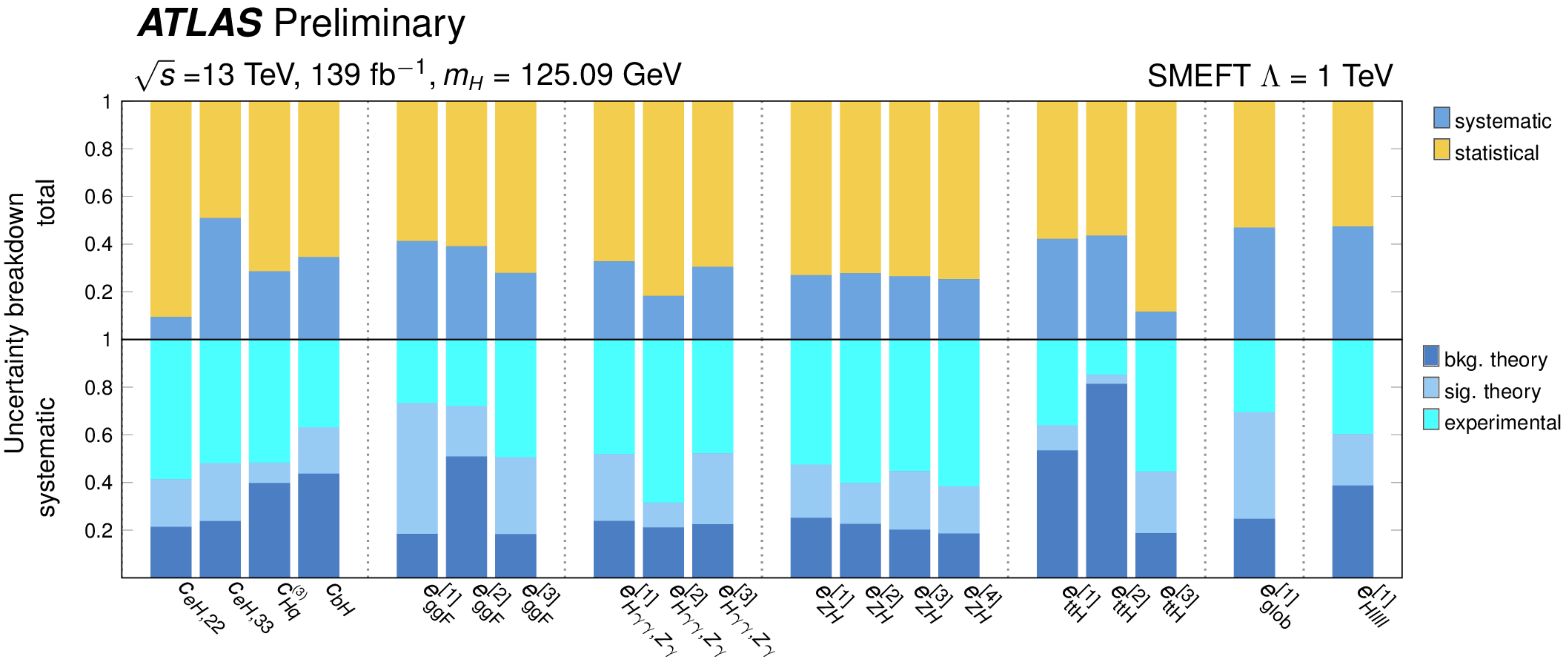
- New SMEFT interpretation of the combined Higgs dataset
  - New channels included (Zy, mumu)
  - New linear & linear + quadratic results provided

- Comparison of the STXS and diff XS results (over Hyy + H4l)
  STXS is more sensitive

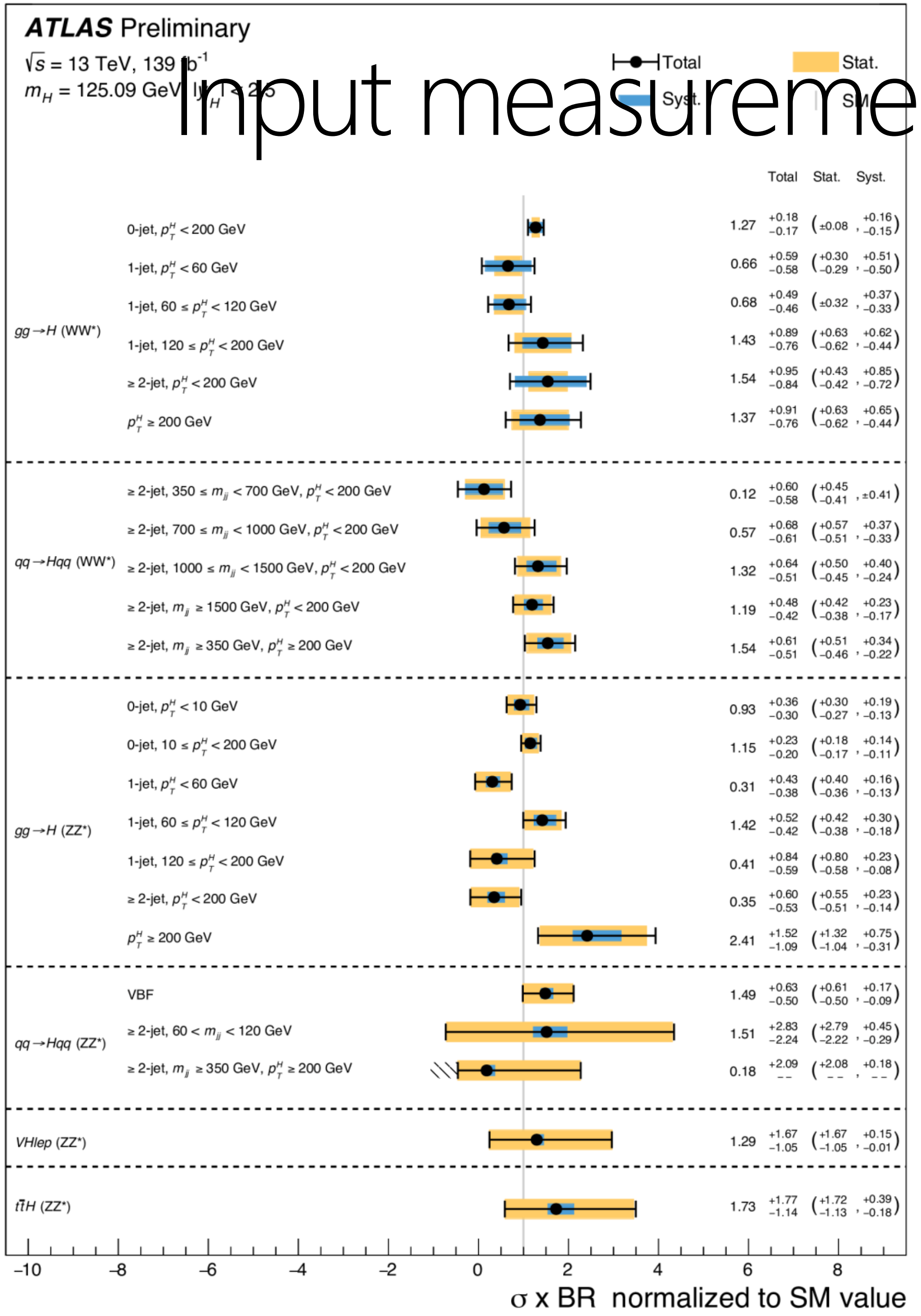
- No deviations wrt SM

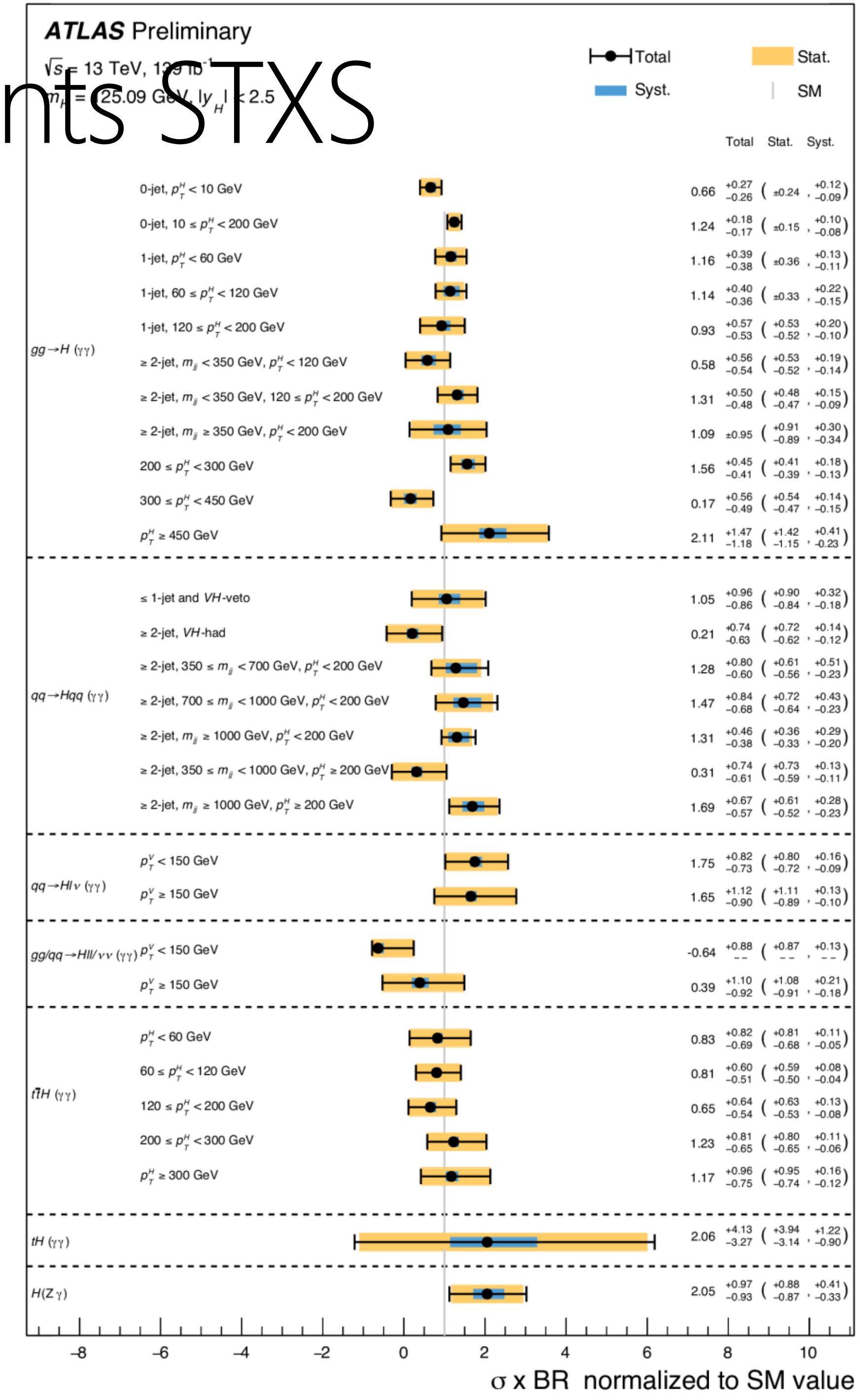
Back-up

Break-down of uncertainties

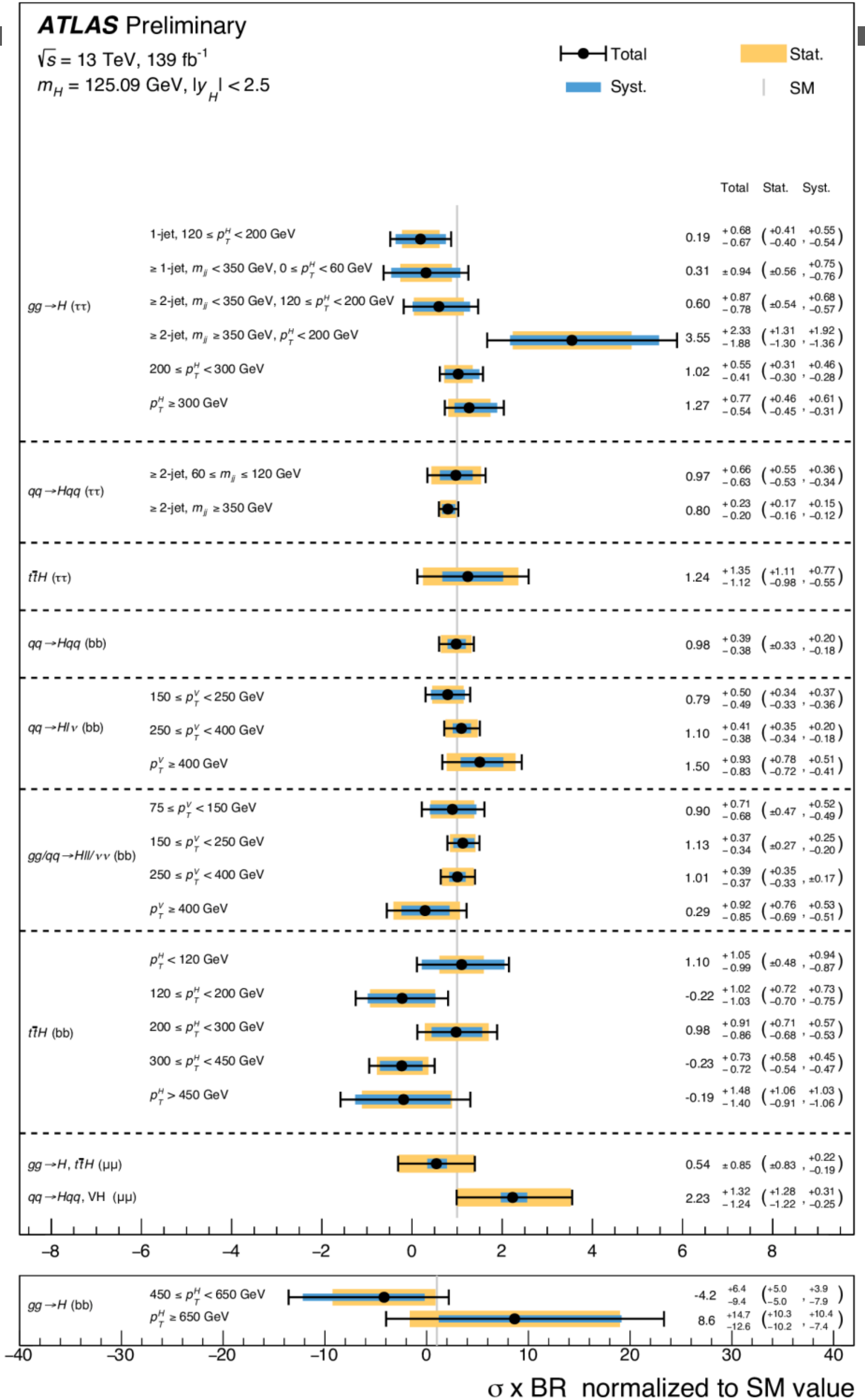


Input measurements STXS



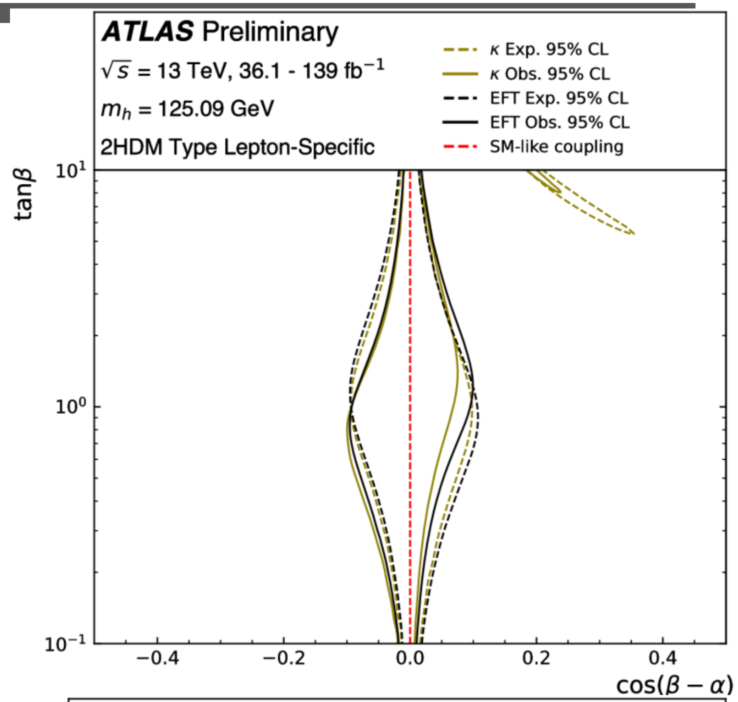


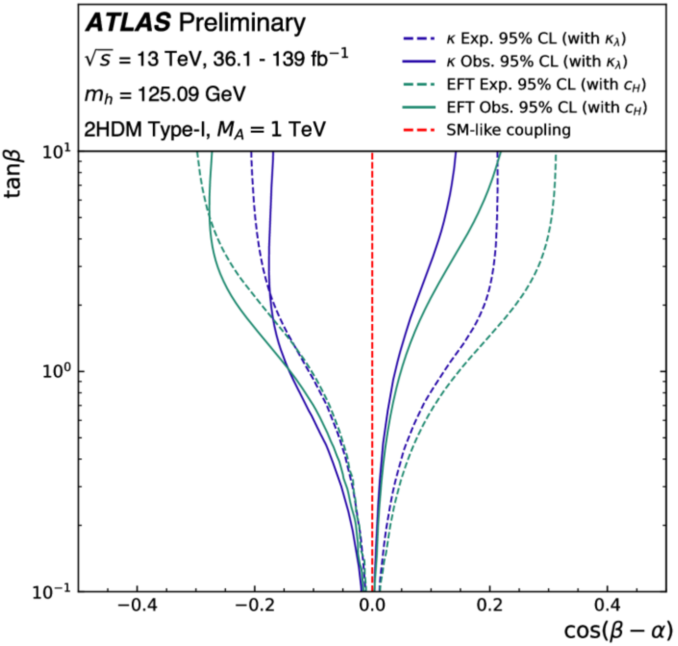
Input measurements STXS

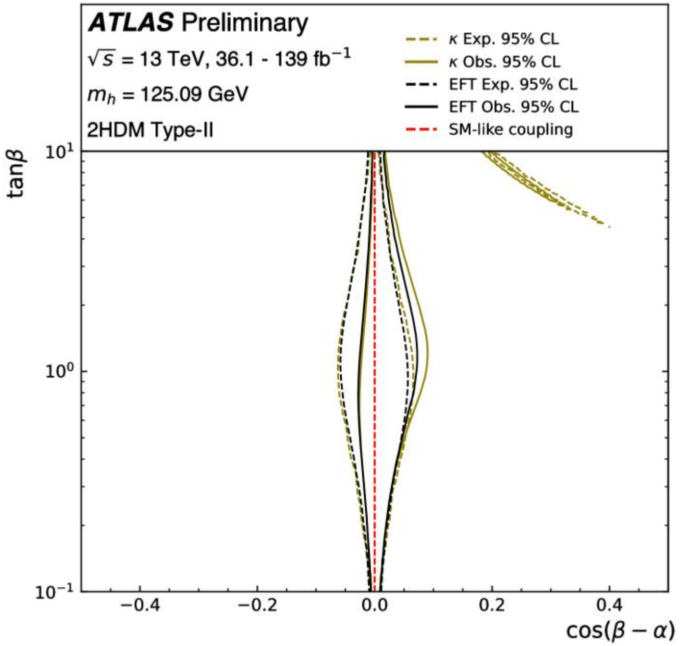


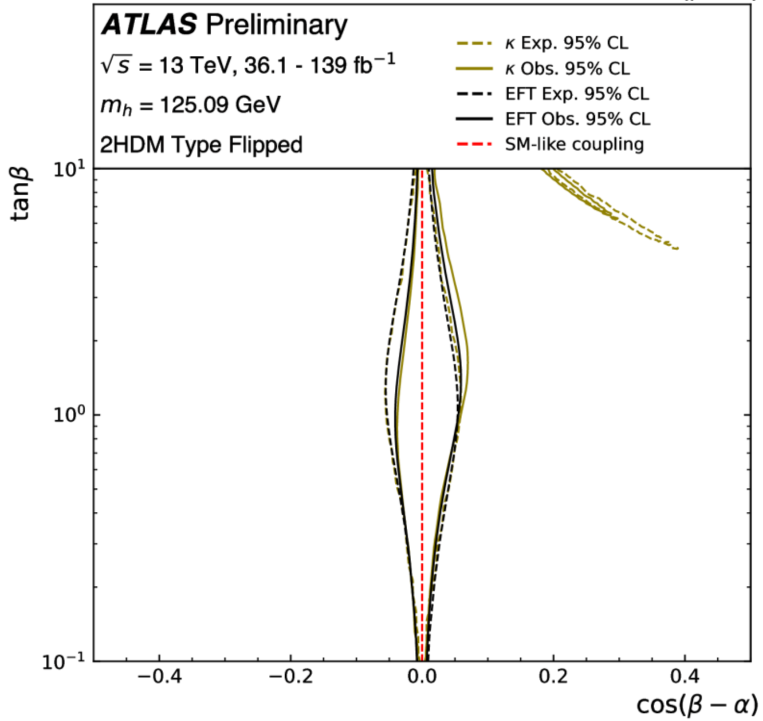
EFT matching

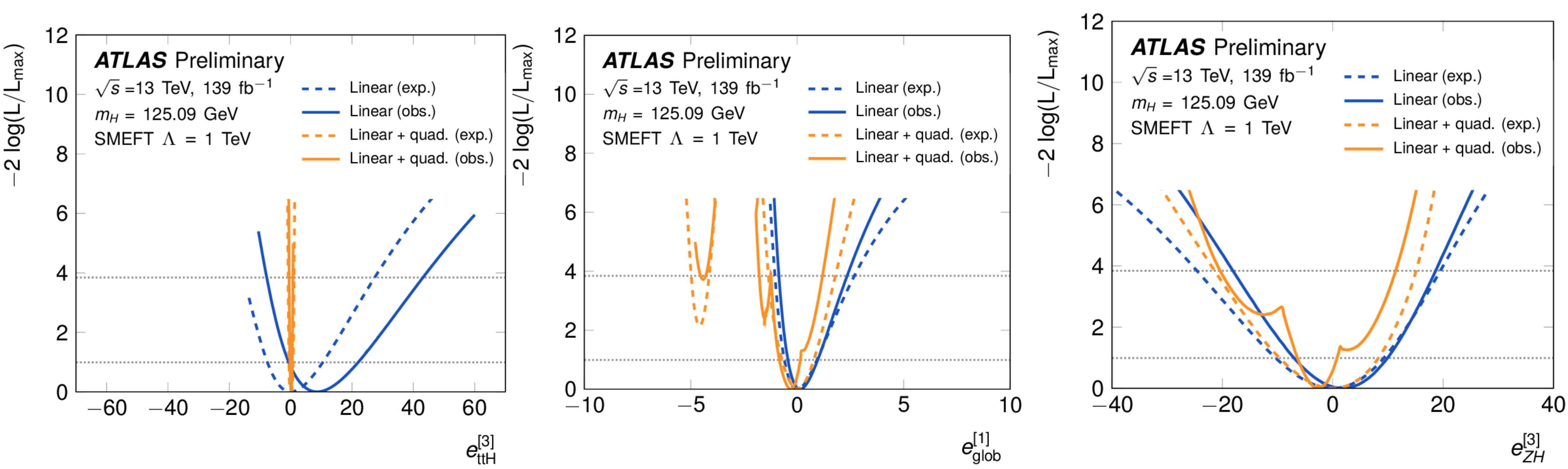
Coupling	Type I	Type II	Lepton-specific	Flipped
$u,\ c,\ t$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$			
$d,\ s,\ b$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$
$e,\ \mu,\ \tau$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
$W,\ Z$	$s_{\beta-\alpha}$			
H	$s^3_{\beta-\alpha} + \left(3 - 2\frac{\bar{m}^2}{m_h^2}\right) c^2_{\beta-\alpha} s_{\beta-\alpha} + 2\cot(2\beta)\left(1 - \frac{\bar{m}^2}{m_h^2}\right) c^3_{\beta-\alpha}$			










ATLAS Preliminary
√s =13 TeV, 139 fb−1
mH = 125.09 GeV
SMEFT Λ = 1 TeV
Linear (exp.)
Linear (obs.)
Linear + quad. (exp.)
Linear + quad. (obs.)
−2 log(L/Lmax)
e[3]ttH
e[1]glob
e[3]ZH