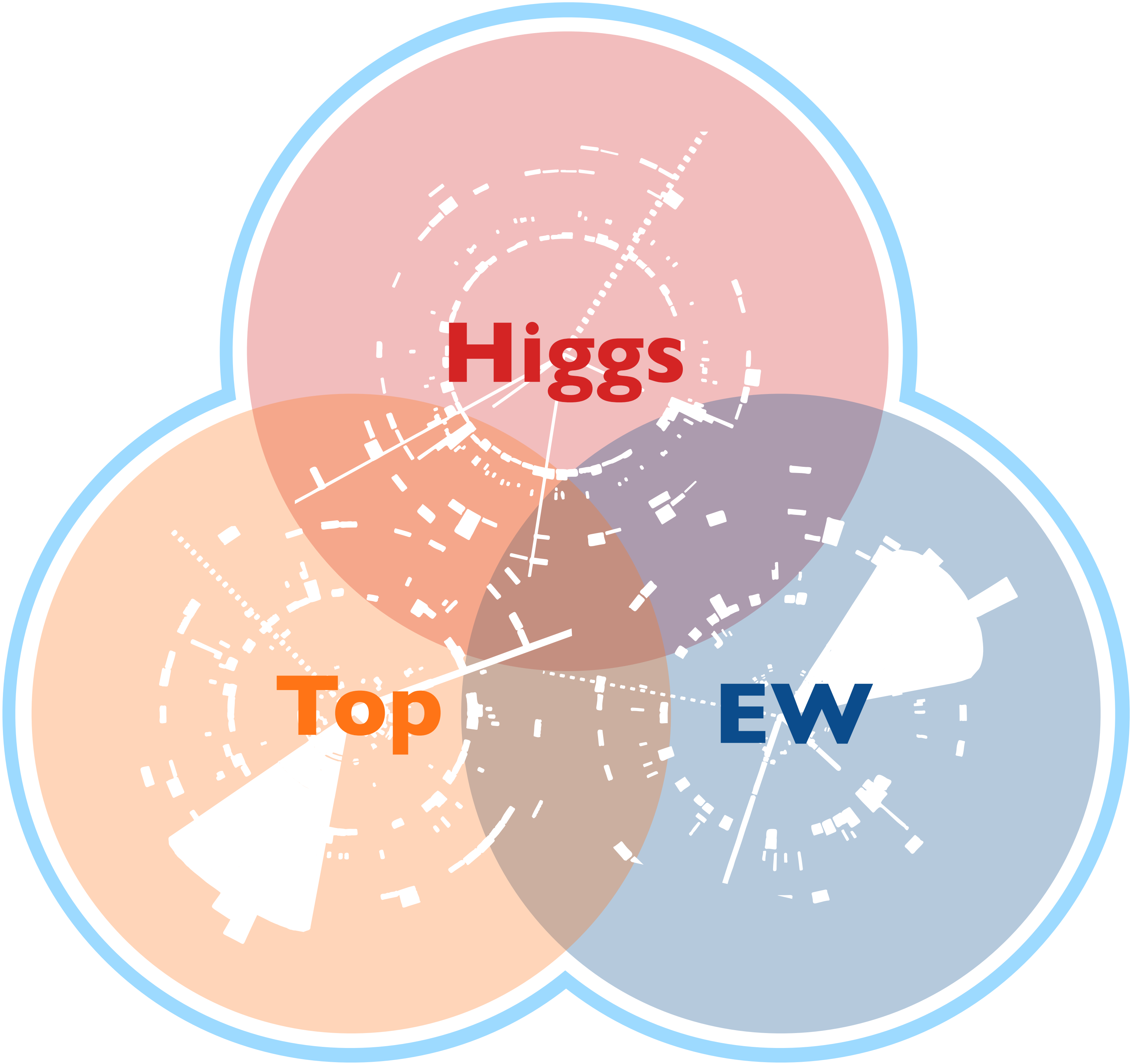

Combined SMEFT interpretation of Higgs and electroweak measurements

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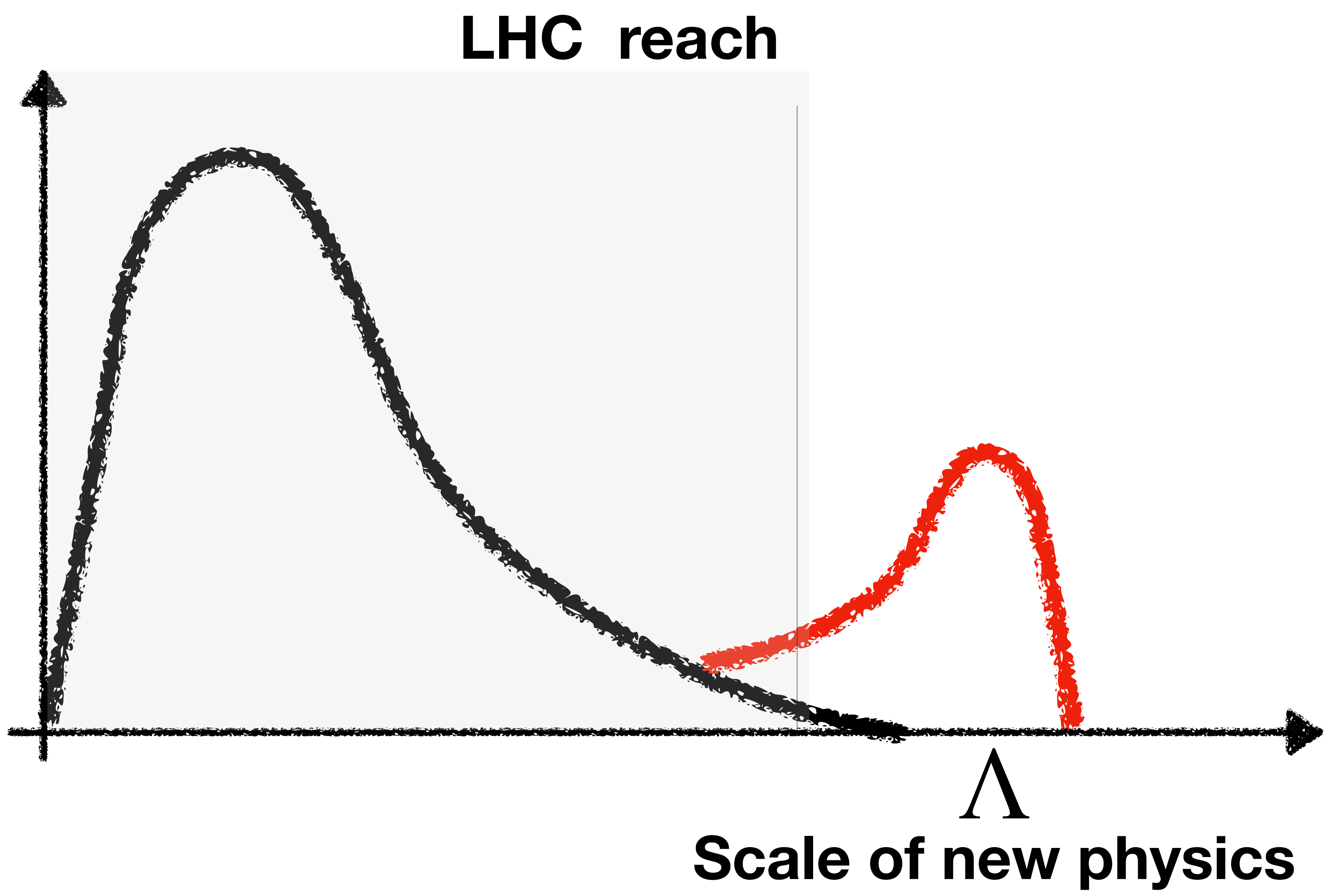
NNV Annual meeting, Lunteren, 4-11-2022

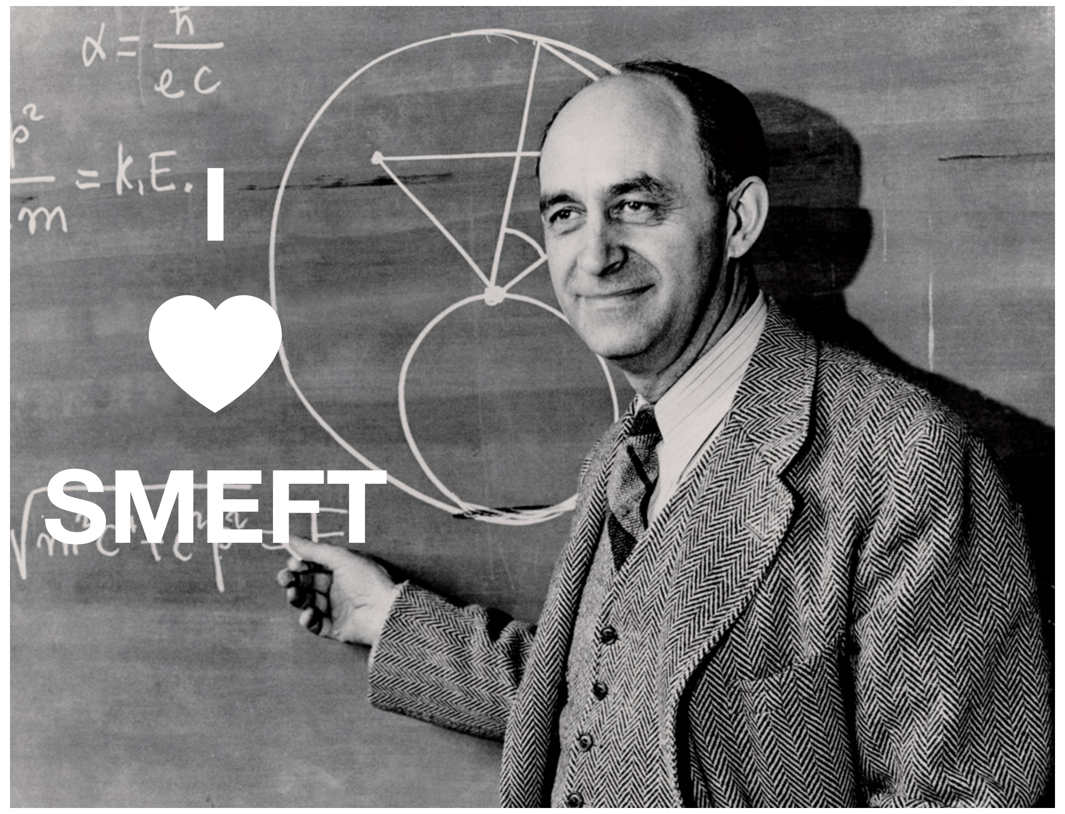
Standard Model Effective Field Theory (SMEFT)

Interpreting combined measurements without many assumptions on the nature of new physics!

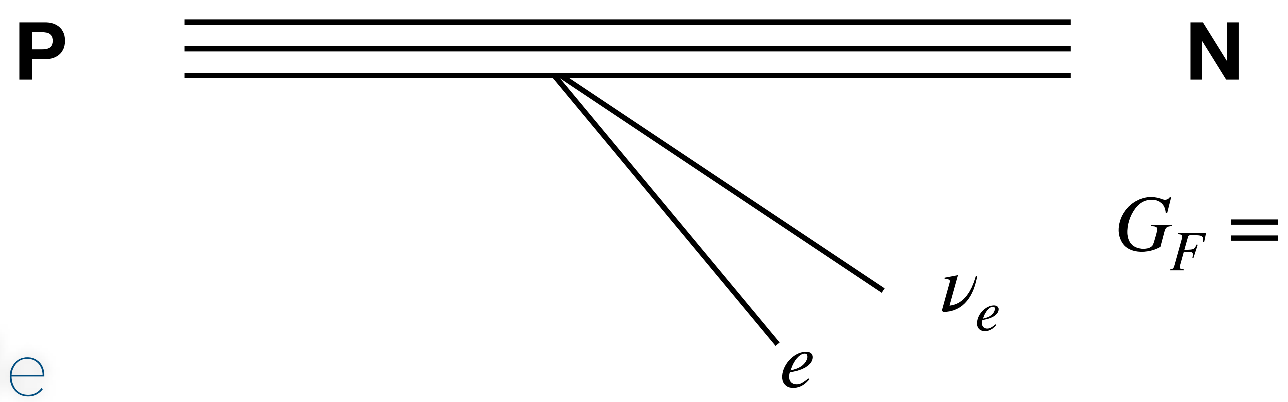
- Standard Model as a low energy approximation of a fundamental theory at high energy Λ
- All allowed deviations from SM parametrised in a **model independent** manner



Deviations in the high tails of observable distributions can show the presence of physics beyond the Standard Model!

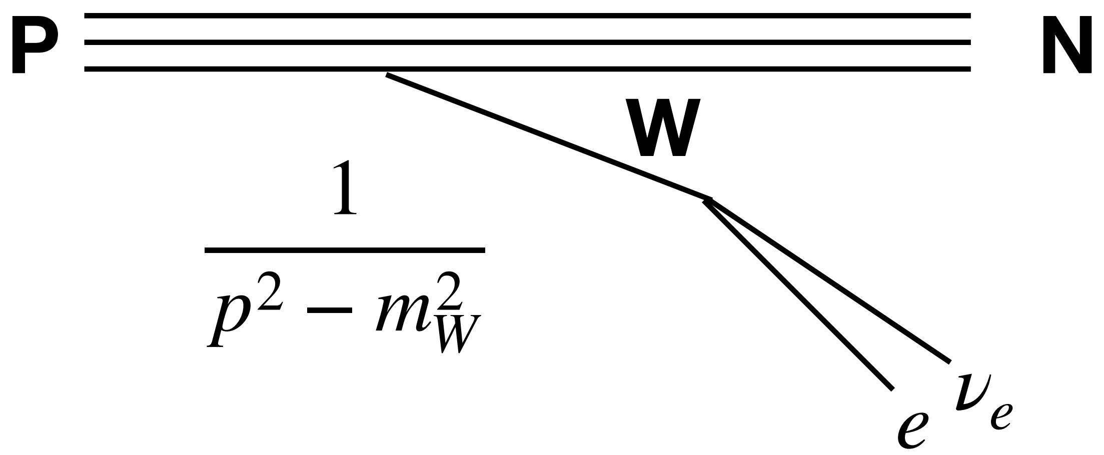


Fermi theory of β decay



$$G_F = \frac{1}{m_W^2}$$

Higher energies →



$$\frac{1}{p^2 - m_W^2}$$

Standard Model Effective Field Theory (SMEFT)

SMEFT Lagrangian

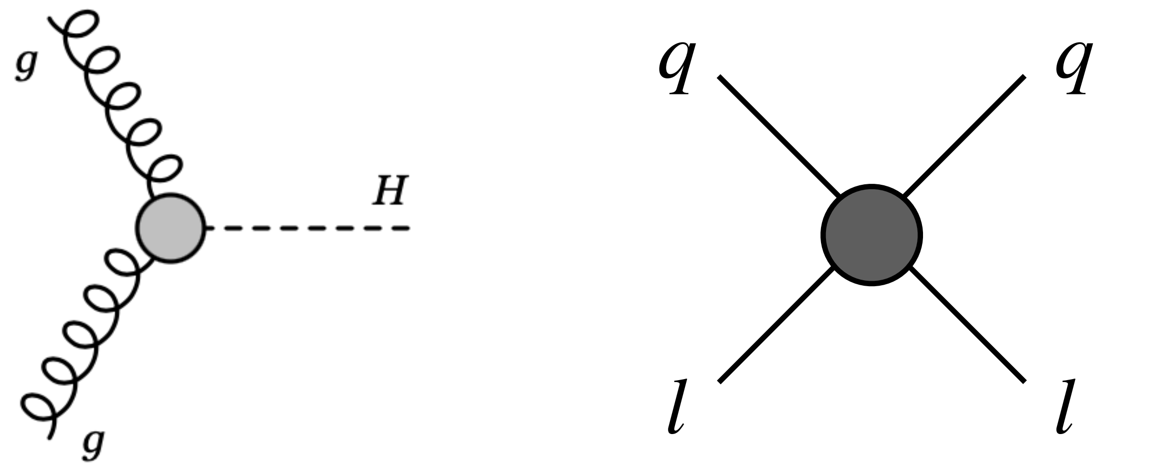
Current analysis

Future analyses

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i^{N_5} \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i^{N_6} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i^{N_7} \frac{c_i}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i^{N_8} \frac{c_i}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

Violate Lepton and Baryon number!
Not sensitive to them with the observables in our analysis

$\mathcal{O}_i^{(n)}$ $\rightarrow$ **Operators** - introduce new interaction vertices



c_i $\rightarrow$ **Wilson coefficients** - free parameters of the model, strength of the interaction!

Λ $\rightarrow$ **Energy scale of new physics** - assumed 1 TeV

Scaling down SMEFT complexity: flavour symmetry

SMEFT can be complex: 2499 operators in dim. 6!

U(3)^5 scheme

All quark generations treated similarly

All lepton generations treated similarly

Relax t,b →

“topU3l” scheme

First two quark generations treated similarly

All lepton generations treated similarly

topU3l : top & bottom treated differently

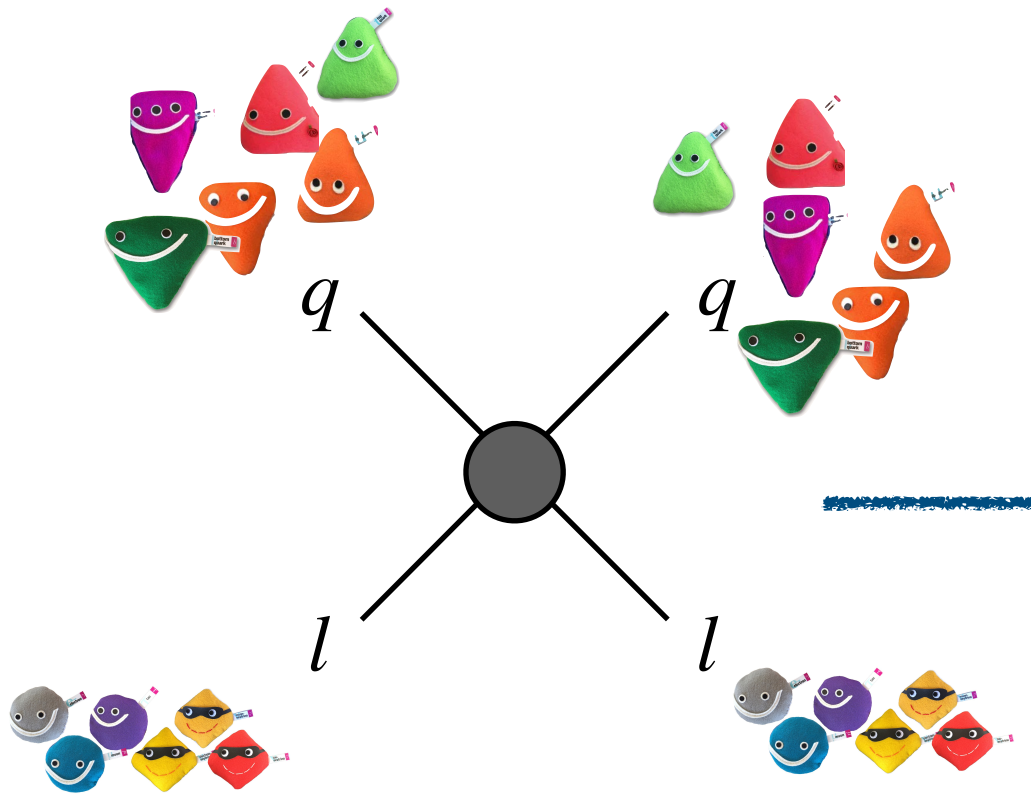
Relax leptons →

“top” scheme

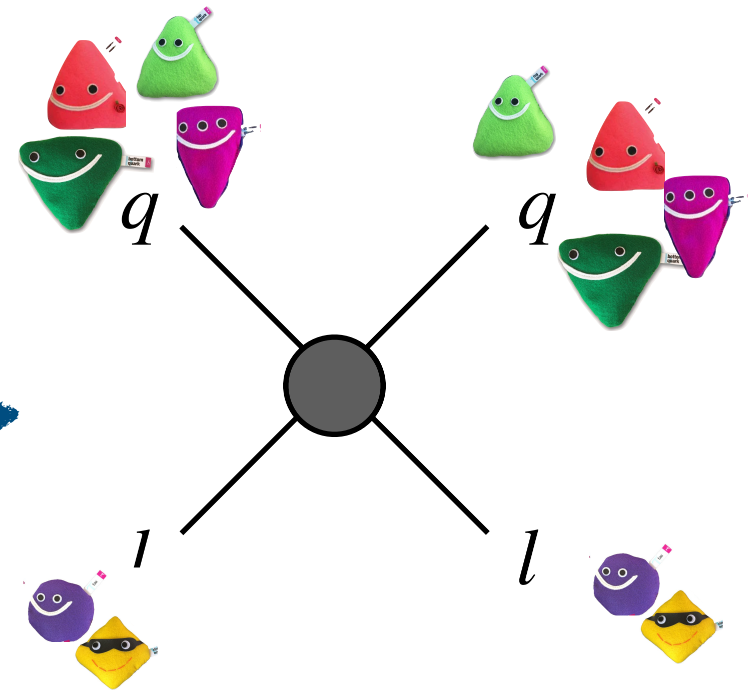
First two quark generations treated similarly

All leptons generations treated separately

No symmetry



TopU3l



We are using this!

182 operators

Symmetry that merges operators we cannot distinguish with our measurements!

CP even

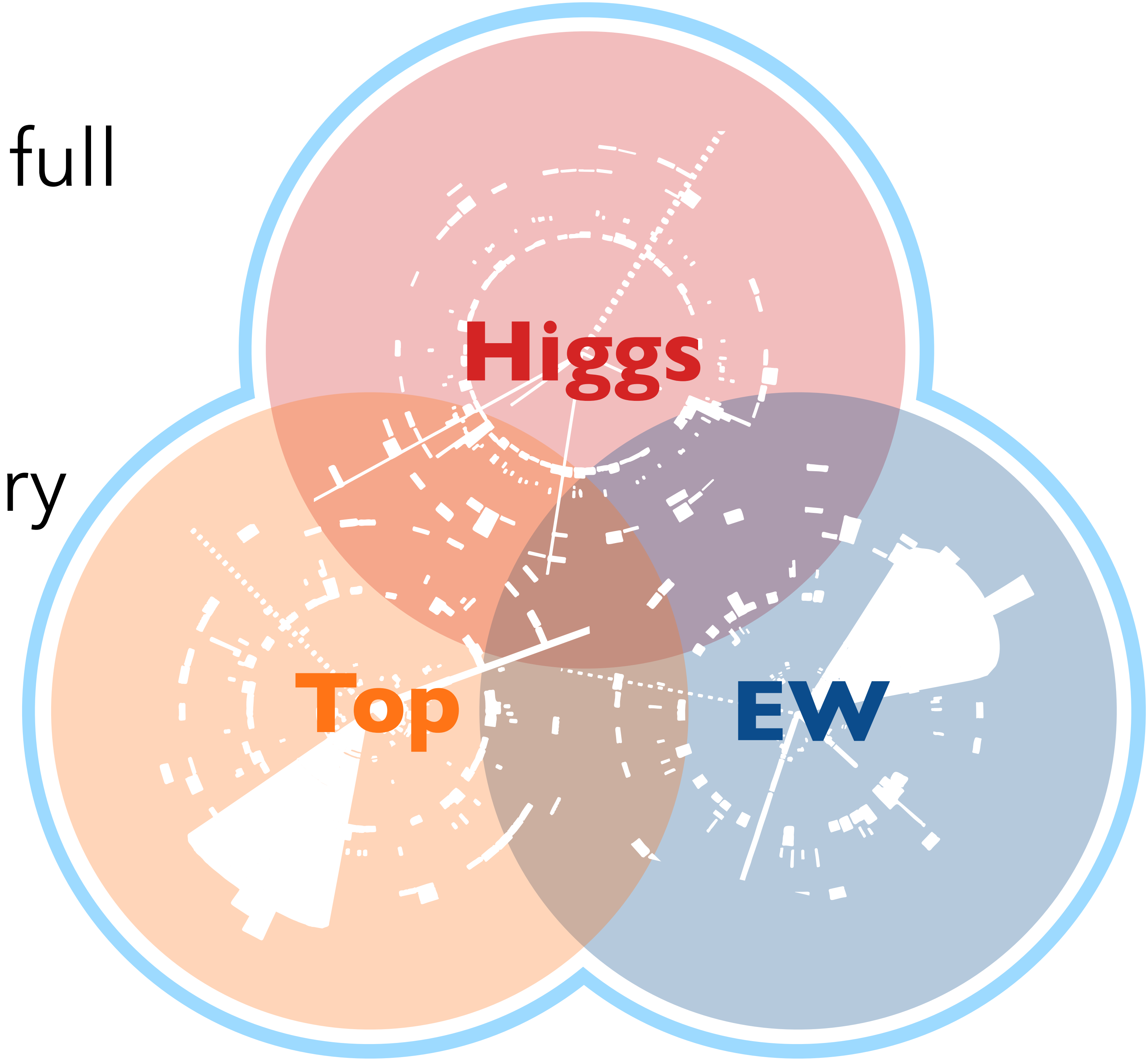
Consider CP-even only operators

129 operators

Global EFT fits in ATLAS

ATL-PHYS-PUB-2022-037

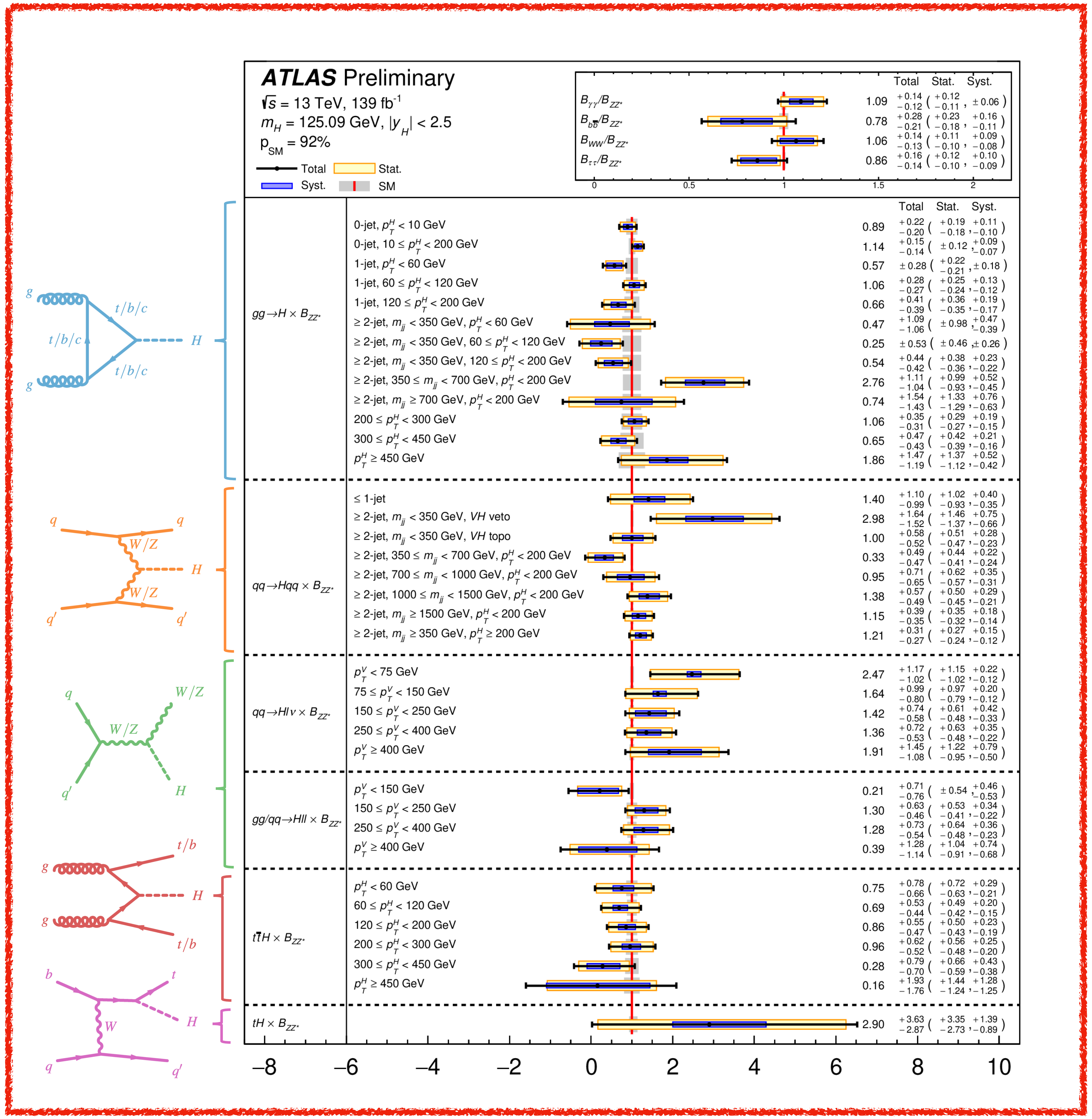
- This talk will present the results of the first combination of ATLAS Higgs and electroweak and LEP precision observables
- Combination within the ATLAS collaboration allows us to use the full statistical model used to perform the analyses
  - Precise modelling of systematic uncertainties, will be of primary importance with the increase of statistics at LHC



Inputs: Higgs sector

Higgs sector measurements are organised in the **Simplified Template Cross-Section (STXS)** framework:

- Higgs cross sections and decay ratios measured in 5 different decay channels, across different production modes
- From inclusive measurement to differential in various kinematic variables
- Kinematic regions help isolating BSM physics

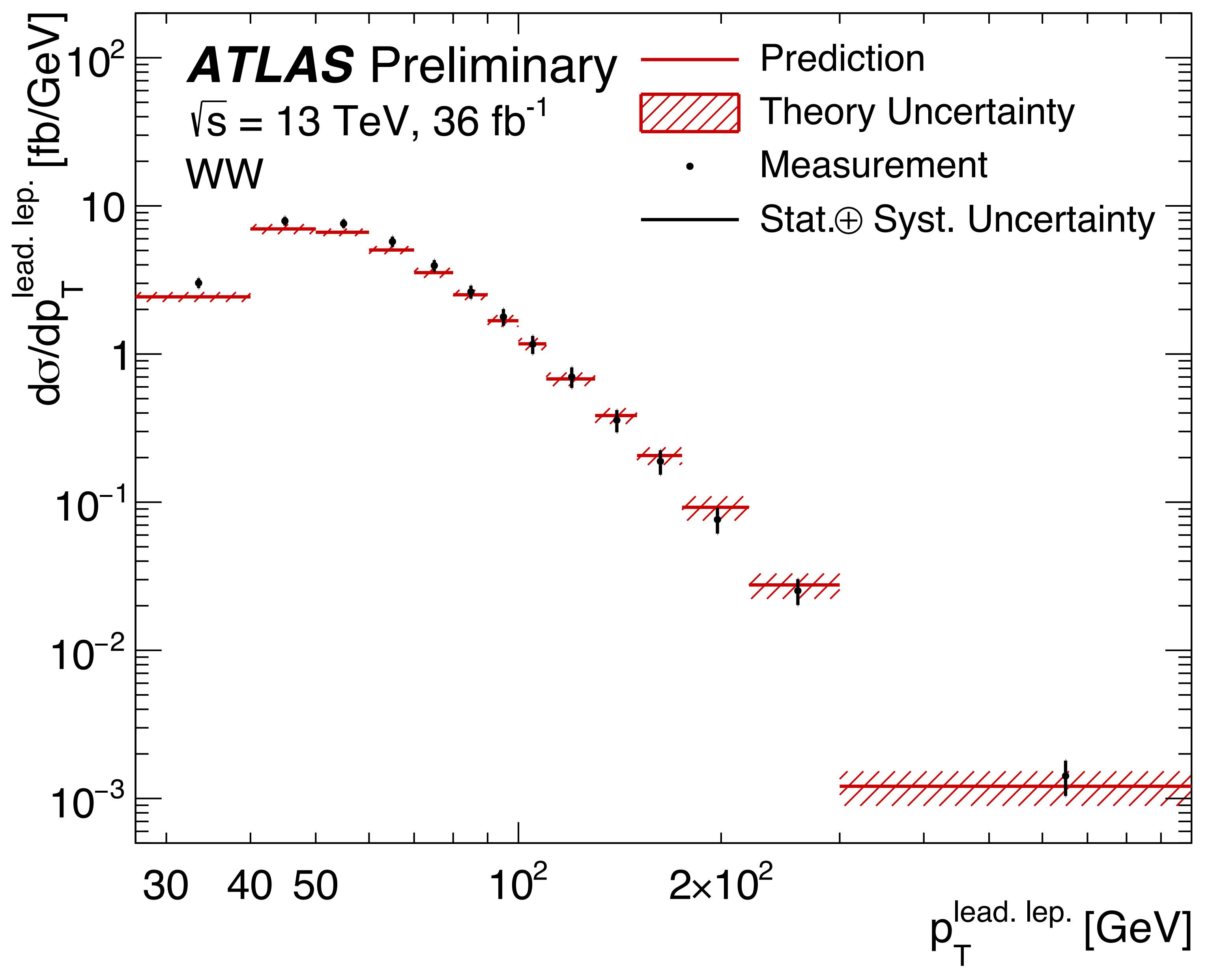


Inputs: Electroweak sector

Considering one **differential cross-section distribution** from WW, WZ, ZZ and Z+jets

Along with LHC measurements, eight precision observables from LEP have been included in the combination

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.003	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.07583 ± 0.00117	0.932 ± 0.048
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.10615 ± 0.00162	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019



One example of observable in the ATLAS EW sector

Statistical combination

Measurements can be combined performing statistical inference on the product of likelihoods of Higgs, EW and LEP:

Higgs

$$\mathcal{L}(\mu, \vec{\theta}, \vec{\gamma} = \prod_{i \,\epsilon\, \text{bins}} Poiss(N_i \,|\, \mu\, s_i(\vec{\theta}) + \gamma_i\, b_i(\vec{\theta})) \times \prod_{\theta \epsilon \vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i \,\epsilon\, \text{bins}} Gauss(\beta_i \,|\, \gamma_i\, \beta_i, \sqrt{\gamma_i\, \beta_i})$$

POI — Poissonian likelihood — Constraints on NPs — Constraints on MC statistics

EW

$$L\,(\boldsymbol{x}|\boldsymbol{c},\boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^{n_{\text{bins}}}\det(C)}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{x}^{\intercal}(\boldsymbol{c},\boldsymbol{\theta})\, C^{-1}\Delta\boldsymbol{x}(\boldsymbol{c},\boldsymbol{\theta})\right) \times \prod_{i}^{n_{\text{syst}}} f_i(\theta_i).$$

Stat-only covariance — Include impact of NP of expt. and theory unc — Gaussian constraint terms

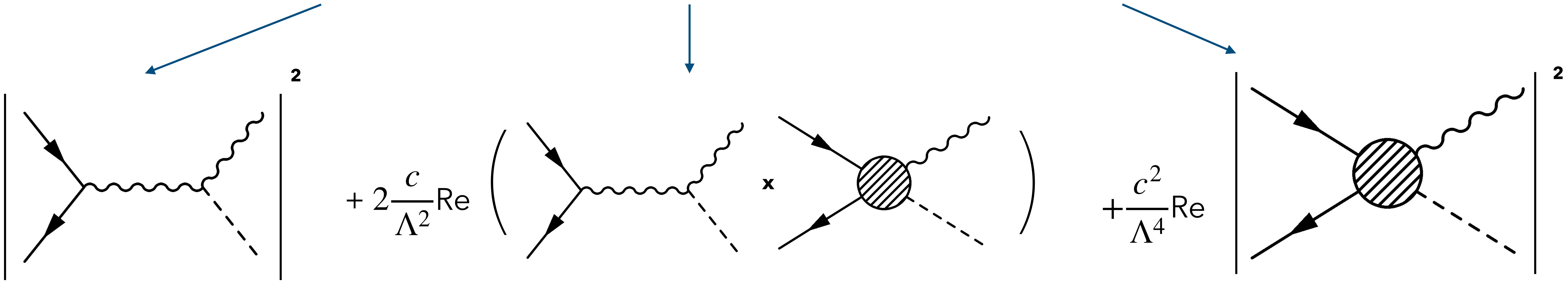
LEP

$$\exp\left(-\frac{1}{2}(\mu - \hat{\mu})^T C^{-1}(\mu - \hat{\mu})\right)$$

Parameterising cross sections

SMEFT dependence parameterised as **polynomials in Wilson coefficients**:

$$\sigma_{\text{SMEFT}} \sim |M_{SMEFT}|^2 = |M_{SM}|^2 + 2\text{Re}(M_{SM}M^*{}_{EFT}) + |M_{EFT}|^2 =$$



SM

Linear : SM, d=6 interference

Quadratic : (d=6)

$$\mathcal{O}_{SMEFT,b} = \mathcal{O}_b(1 + \sum_i A_{bi}c_i + \sum_i B_{bi}c_i^2 + \sum_{i,j} C_{bij}c_ic_j)$$

SMEFT effect on the SM predictions can be factored out in a **linear** and **quadratic** component.

Generating parameterisation

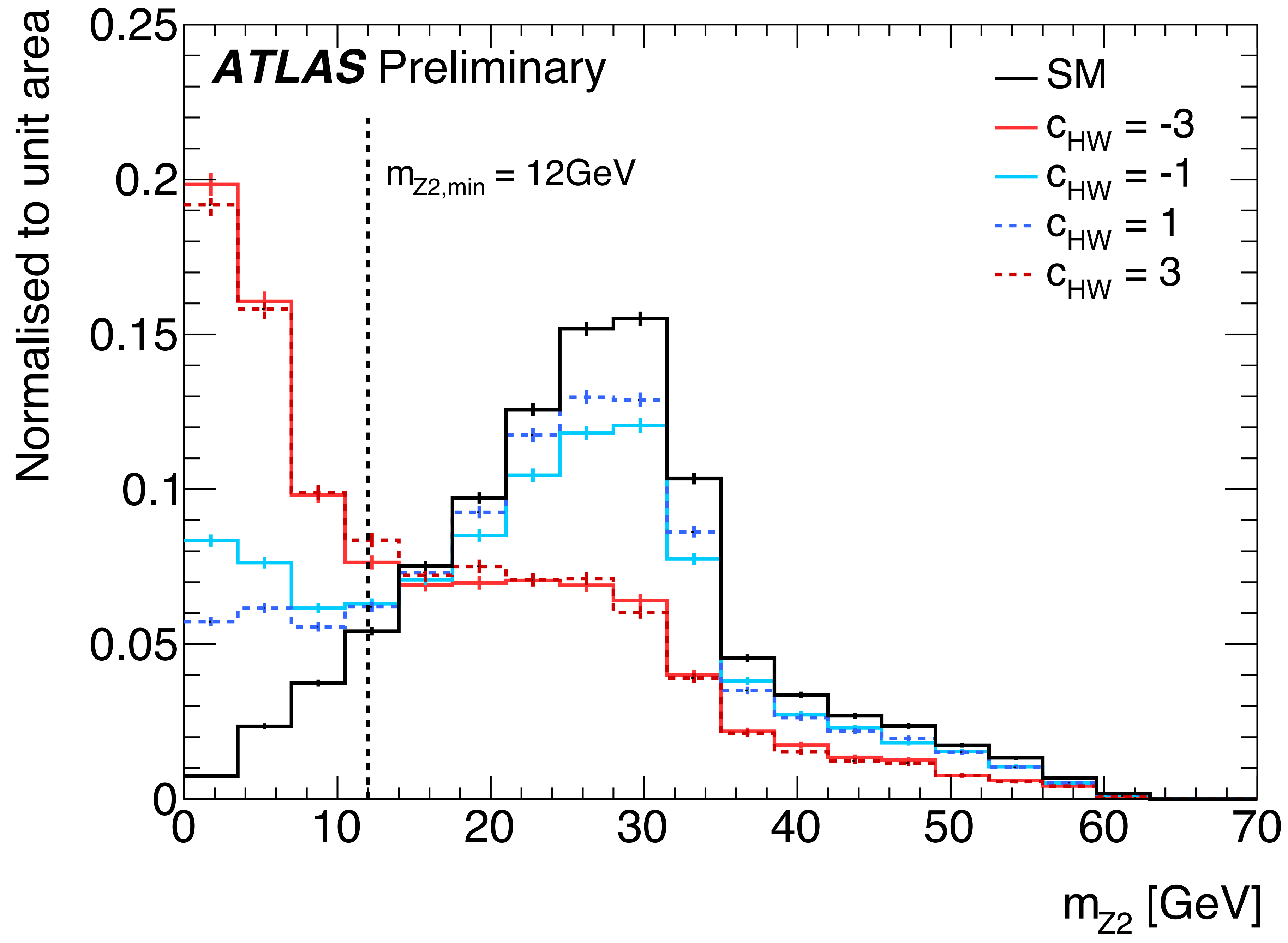
How to go from the measurement space to the EFT space?

Statistical model re-parametrised as function of the Wilson coefficients

through a parameterisation of the form:

$$f(\mu) -> f(\mu(EFT)) \text{ where}$$

$$\mu(EFT) = \mu_{SM}(1 + a_1c_1 + a_2c_2 + \ldots a_nc_n)$$

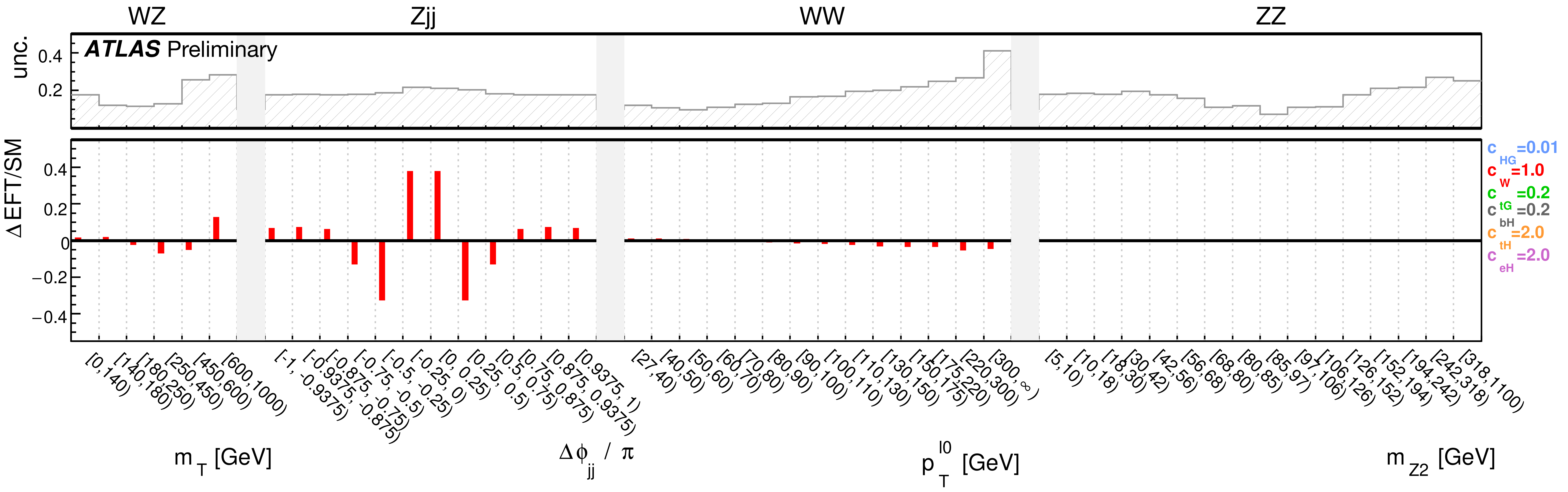


How is the parameterisation obtained?

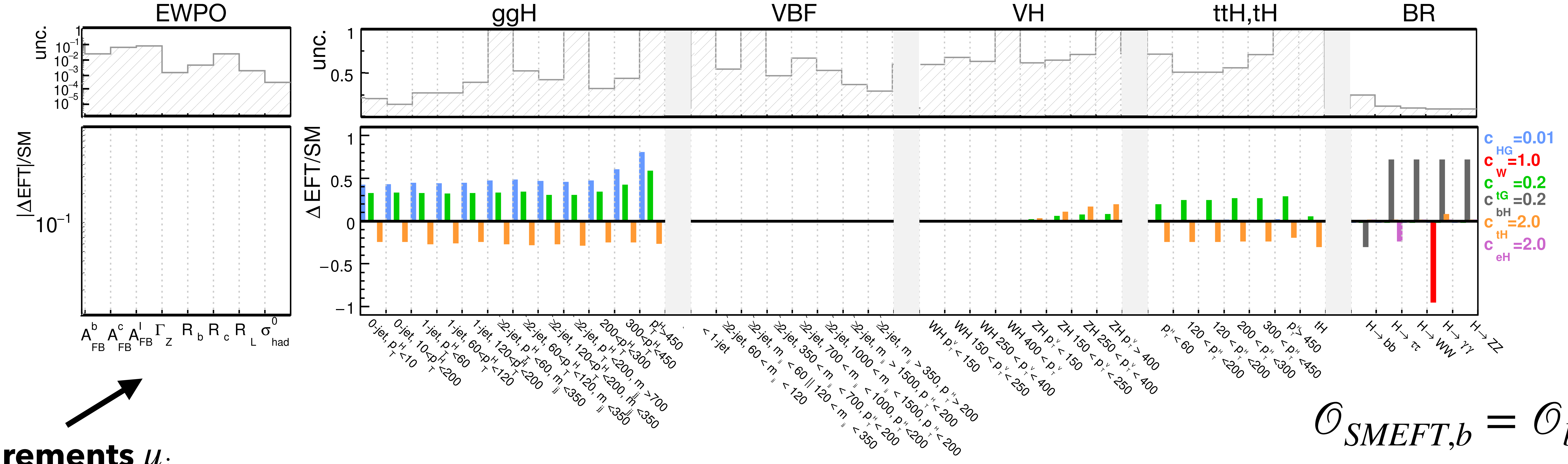
Madgraph Monte-Carlo predictions

SMEFTsim SMEFT@NLO MADGRAPH5 aMC@NLO

Visualising the parameterisation



Relative value of the correction



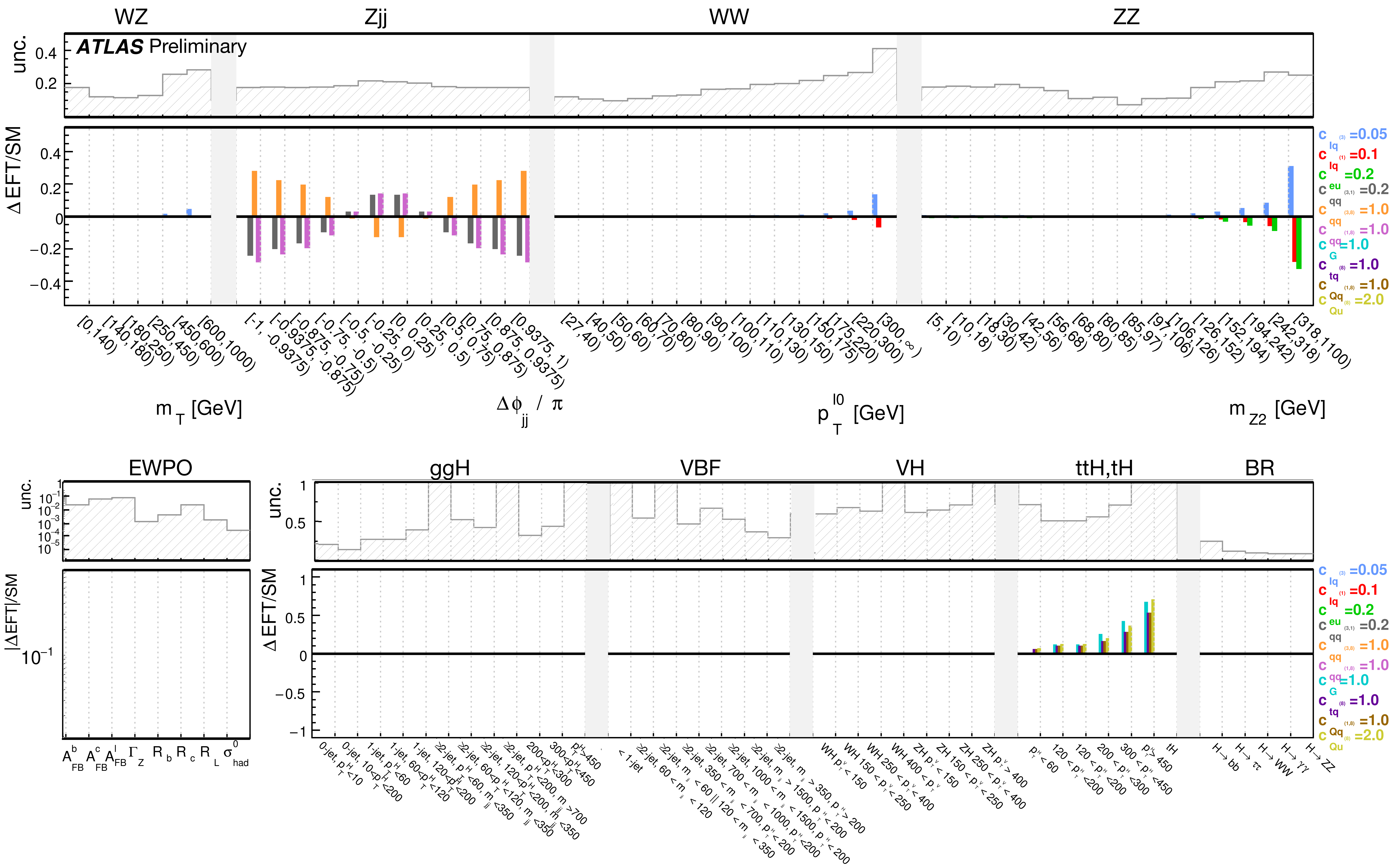
EFT operators c_i

Physics measurements μ_j

$$\mathcal{O}_{SMEFT,b} = \mathcal{O}_b(1 + \sum_i A_{bi}c_i)$$

Operators mainly sensitive to ggH and ttH

Visualising the parameterisation



- O_{c2ql} operators mainly sensitive to tails of WW and ZZ distributions
- O_{4q} leading sensitivity from VBF Z $\Delta\phi_{jj}$ measurement

Identifying sensitive directions

Linear fit with all Wilson coefficients is not possible!

We cannot tell apart every individual coefficient due to degeneracies in their effect on our set of measurements

Sensitivity study: identify the sensitive directions

Information matrix

$$I_{\text{EFT}} = P^T C_{\text{meas}}^{-1} P$$

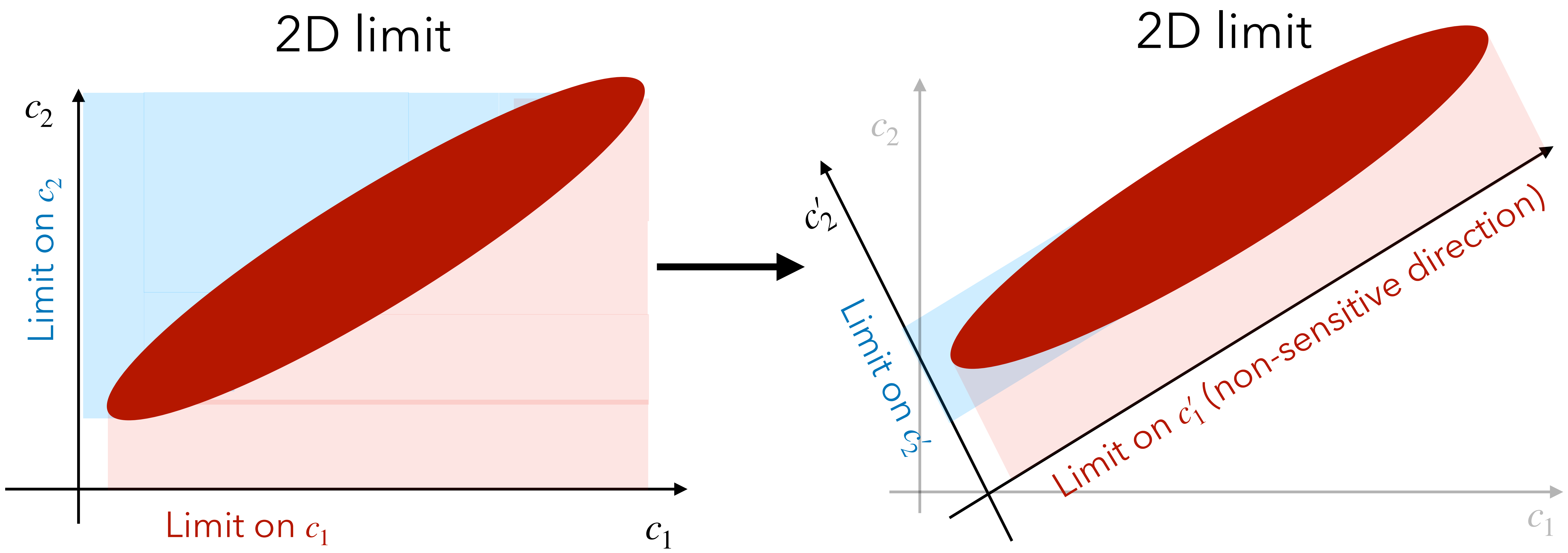
Principal component analysis on information matrix

↓

Eigenvector basis

↓

Fixing non-sensitive directions



Here both parameters are loosely constraint

After rotation, the sensitive direction is identified and the insensitive direction is fixed to zero

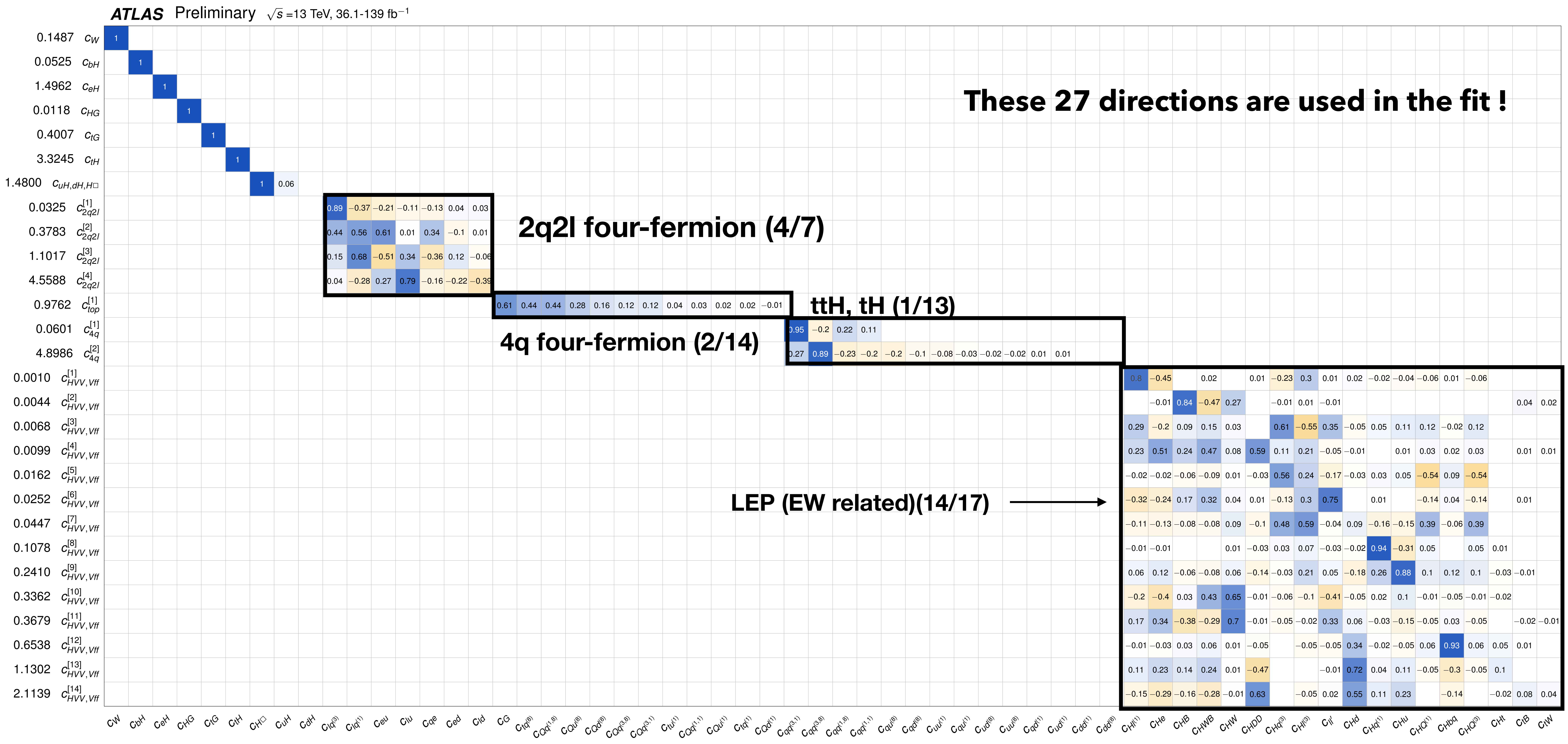
Among our parameters we identify 27 sensitive directions!

These directions are difficult to interpret because of mixing of very different operators!

A compromise

Coefficients can be grouped following a physical meaning!

This has a price: residual correlation! Compromise between physical meaning and correlation!



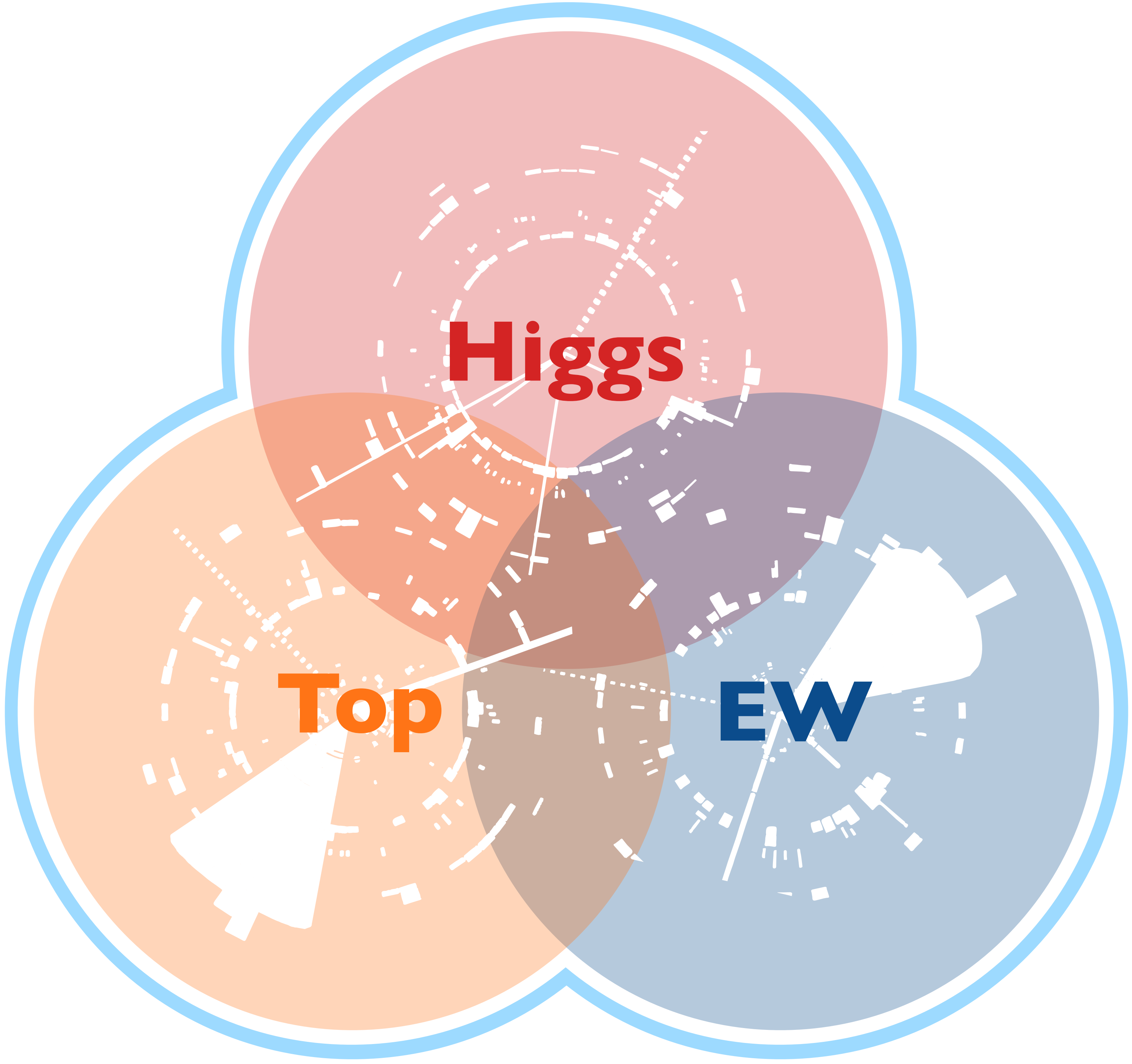
Linear fit results

Important to visualise our results along with an indication of what is their physical meaning!

Summary

This year is the **10th anniversary of the Higgs discovery!**
In ten years we moved from discovery to differential measurements and EFT interpretation!

- **First SMEFT interpretation of a combination of Higgs, electroweak and LEP measurements** in ATLAS has been presented
- **27 directions in the Wilson coefficient space can be constrained** and the origin of the sensitivity in terms of measurements has been investigated and shown
- Next steps: **including top** measurements into the combination



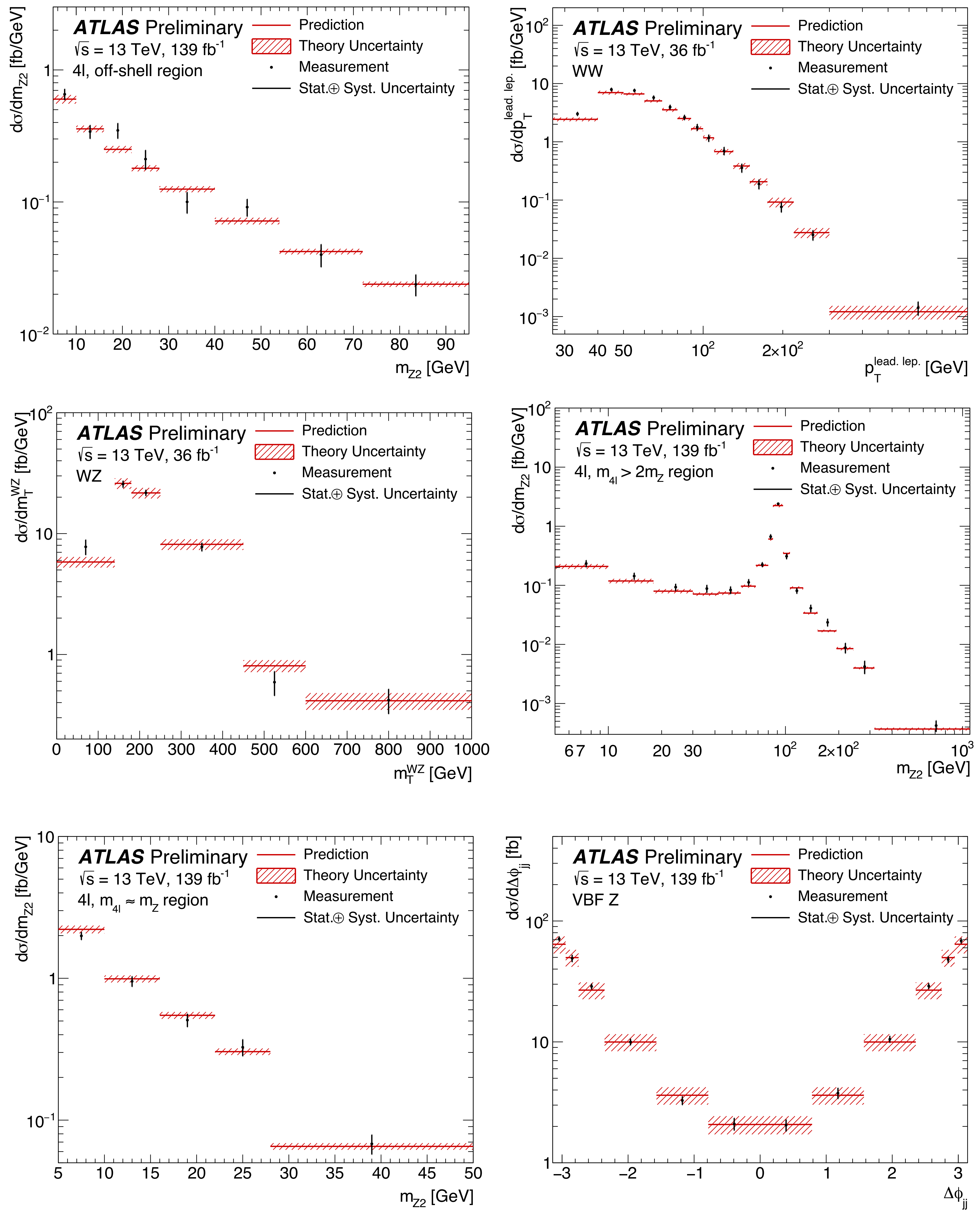
Thank you!

Back-up

ATLAS electroweak observables

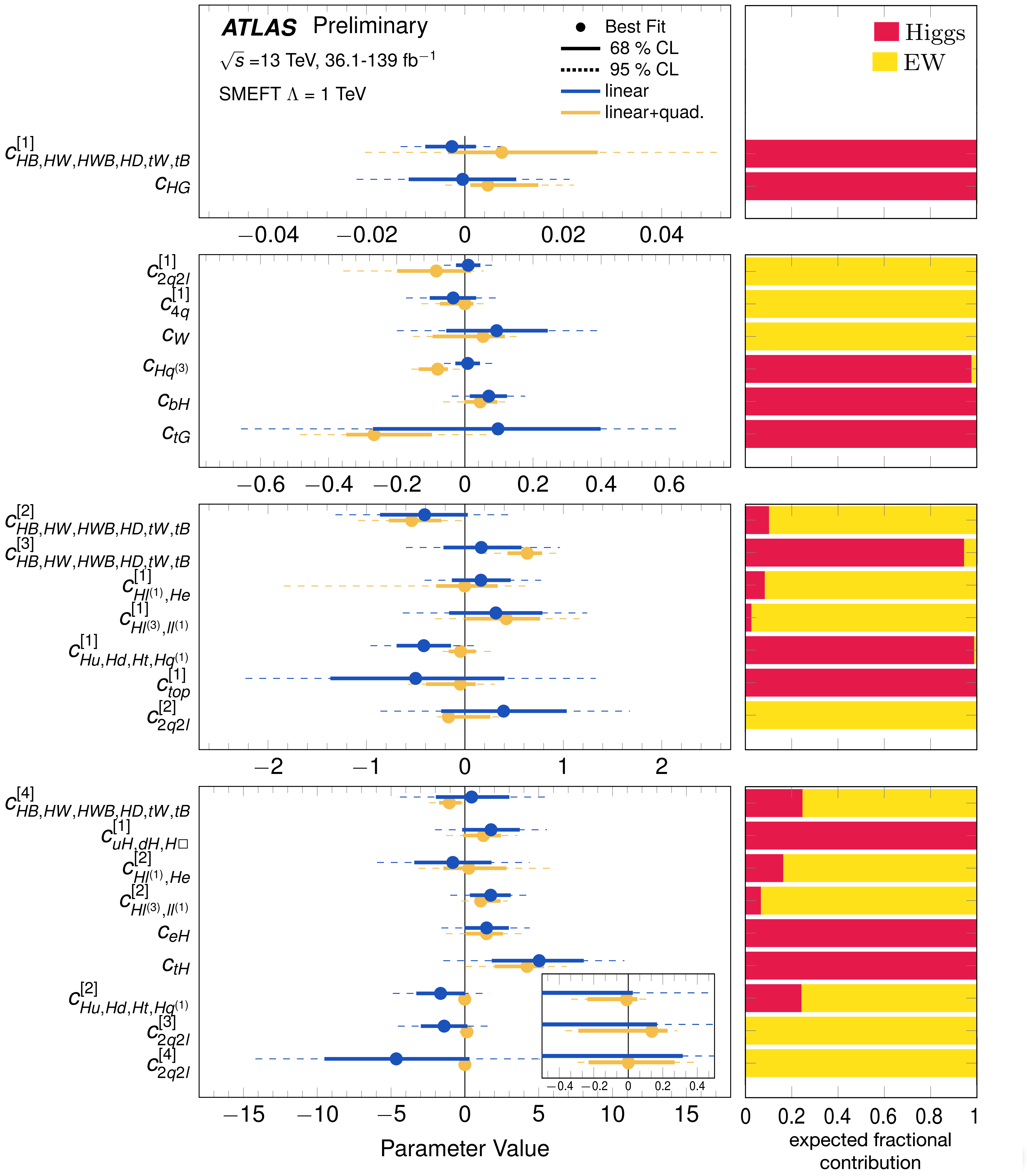
Considering one **differential cross-section distribution** from individual analysis of WW, WZ, ZZ and Z+jets: chosen the one most sensitive to EFT

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV$, $p_T^{\text{jet}} < 35\,GeV$	$p_T^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_T^{WZ}	36	[20]
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139	[21]
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139	[22]



Linear + quadratic fits

- Quadratic terms available for LHC measurements only
- **24 directions in the Wilson coefficient space** can be constrained with LHC only observables



Andrea Visibile