

Fits of dimension-6 SMEFT in VBS and diboson

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Based on: [ph-hep 2101.03180 \(EPJC 81 560/2021\)](#)

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Introduction

A central goal of the pheno community: Global fit of LHC data

- ♦ SMEFT interpretation, parametrise deviations from the SM:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{d_j}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

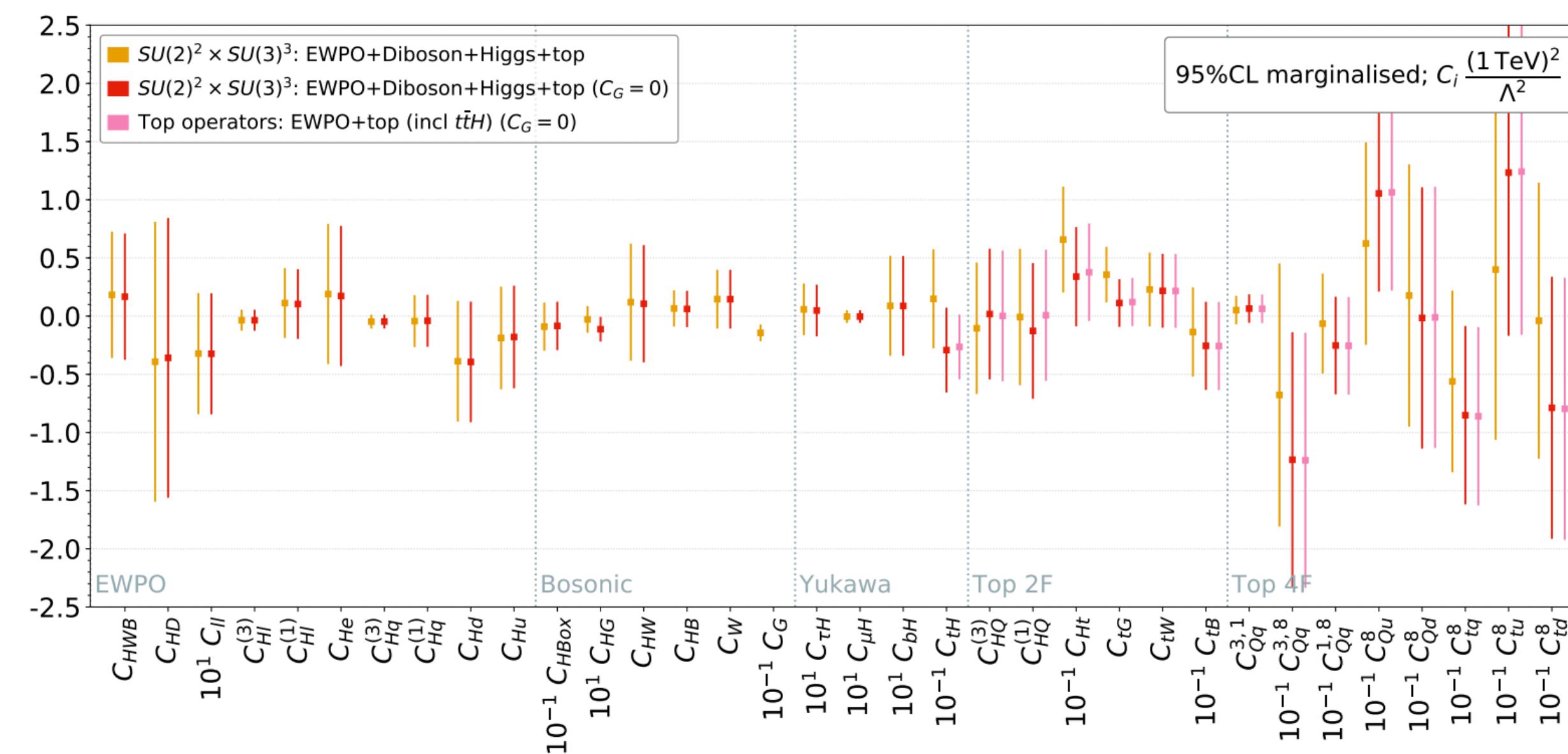
- ♦ Counterpart to direct searches (Dark Matter, exotic, light new physics, etc.)
- ♦ A global SMEFT fit will tell us:
 - If there is any deviation from the SM prediction in the LHC (i.e: where to look in the future)
 - If the SMEFT is a correct interpretation of such deviations or we need a more complex EFT

See opening talk by M. Trott

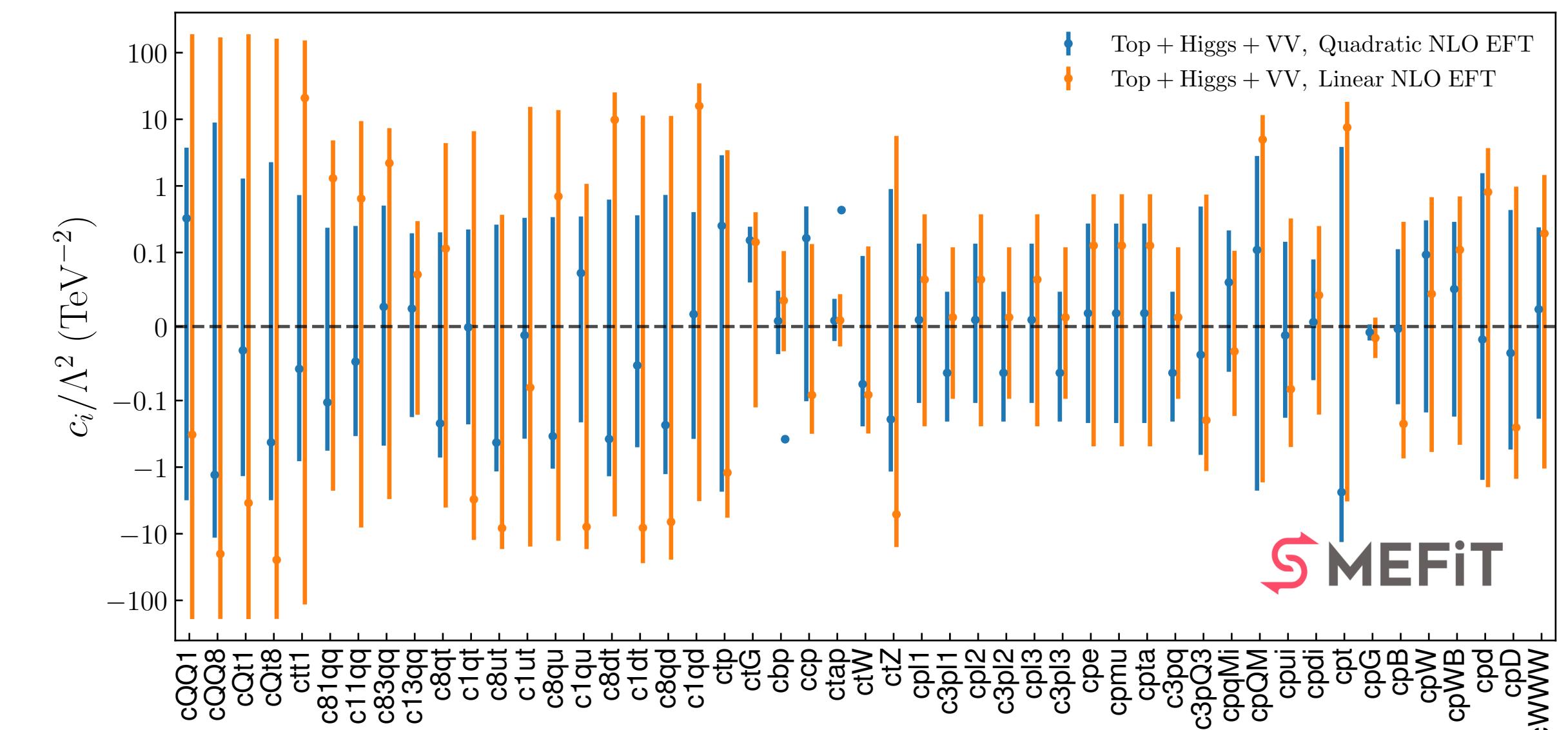
Introduction

Global fit of LHC data

- ♦ Recent studies produced fits of **Top + Higgs + VV + EWPO** measurements with **dim6 SMEFT**
- ♦ Warsaw basis as common choice, but various assumptions are possible regarding:
flavour assumptions, NLO corrections, EFT quadratics...



[FitMaker: 10.1007/JHEP04\(2021\)279](https://doi.org/10.1007/JHEP04(2021)279)



[SMEFiT: arXiv:2105.00006](https://arxiv.org/abs/2105.00006)

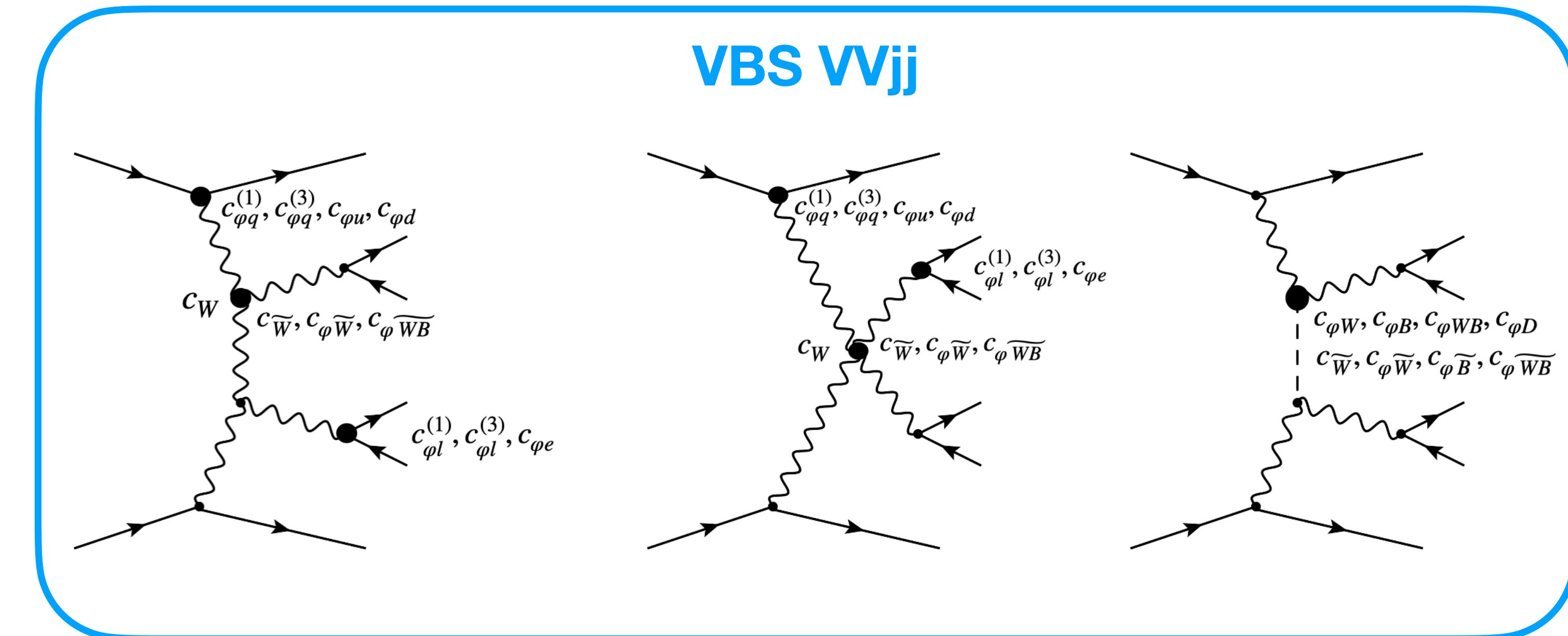
And other groups: Dawson, SFitter, ATLAS, ...

(See talk by G. Durieux)

Our contribution:

SMEFT interpretation of VBS and VV

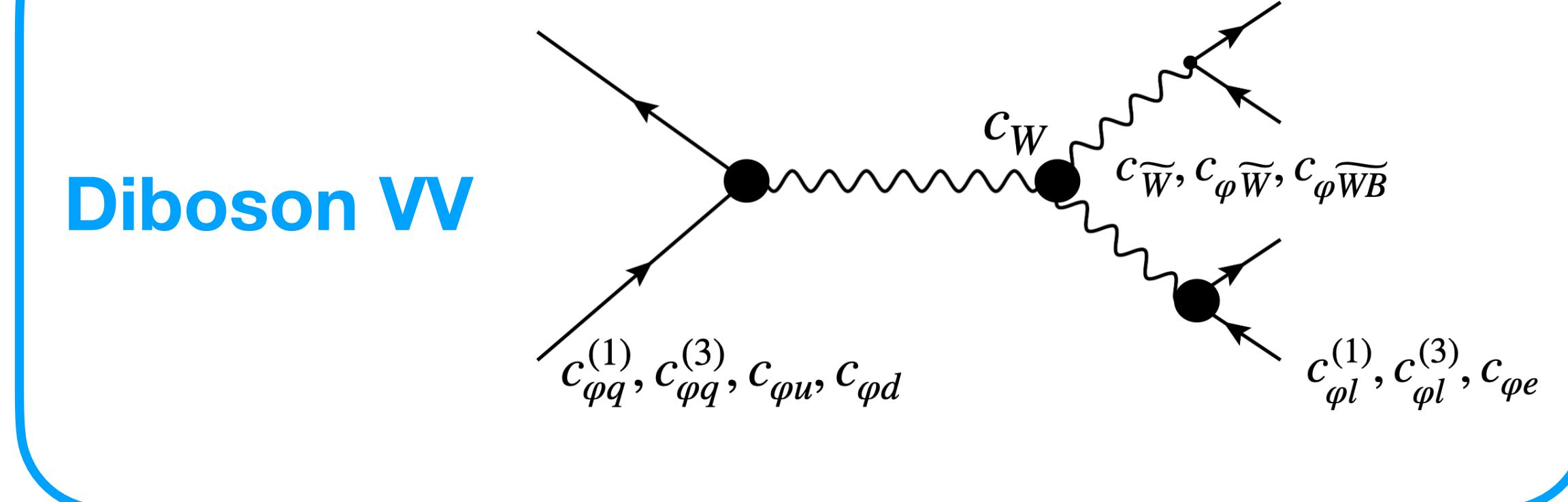
VBS gives direct access to Quartic Gauge couplings and t-channel Higgs exchange



The HVV and HHV couplings play a fundamental role on the EWSB mechanism. Understanding them we will know if we need SMEFT or HEFT

See talks by F. Llanes-Estrada,
and C. Quezada-Calonge

Diboson VV



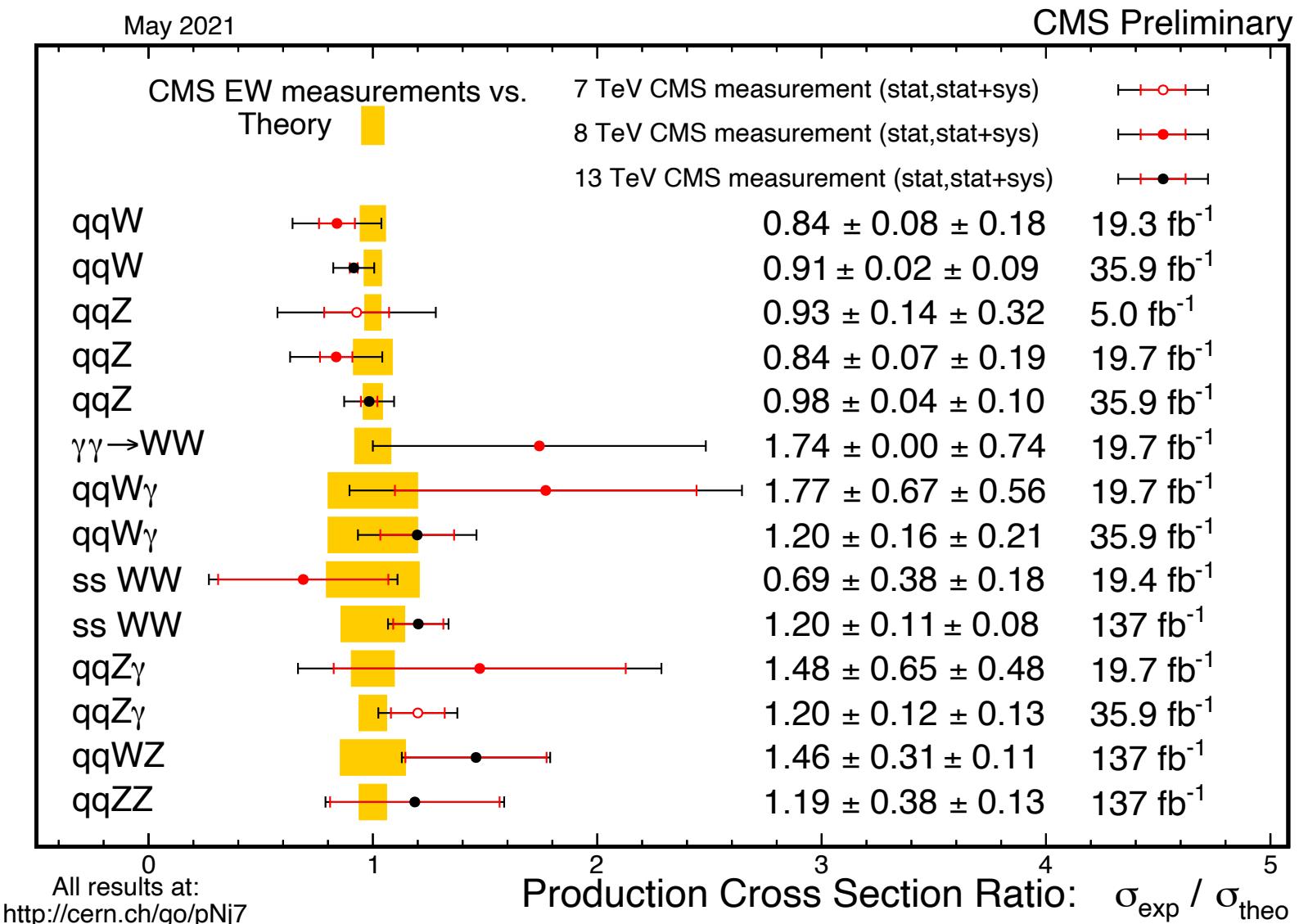
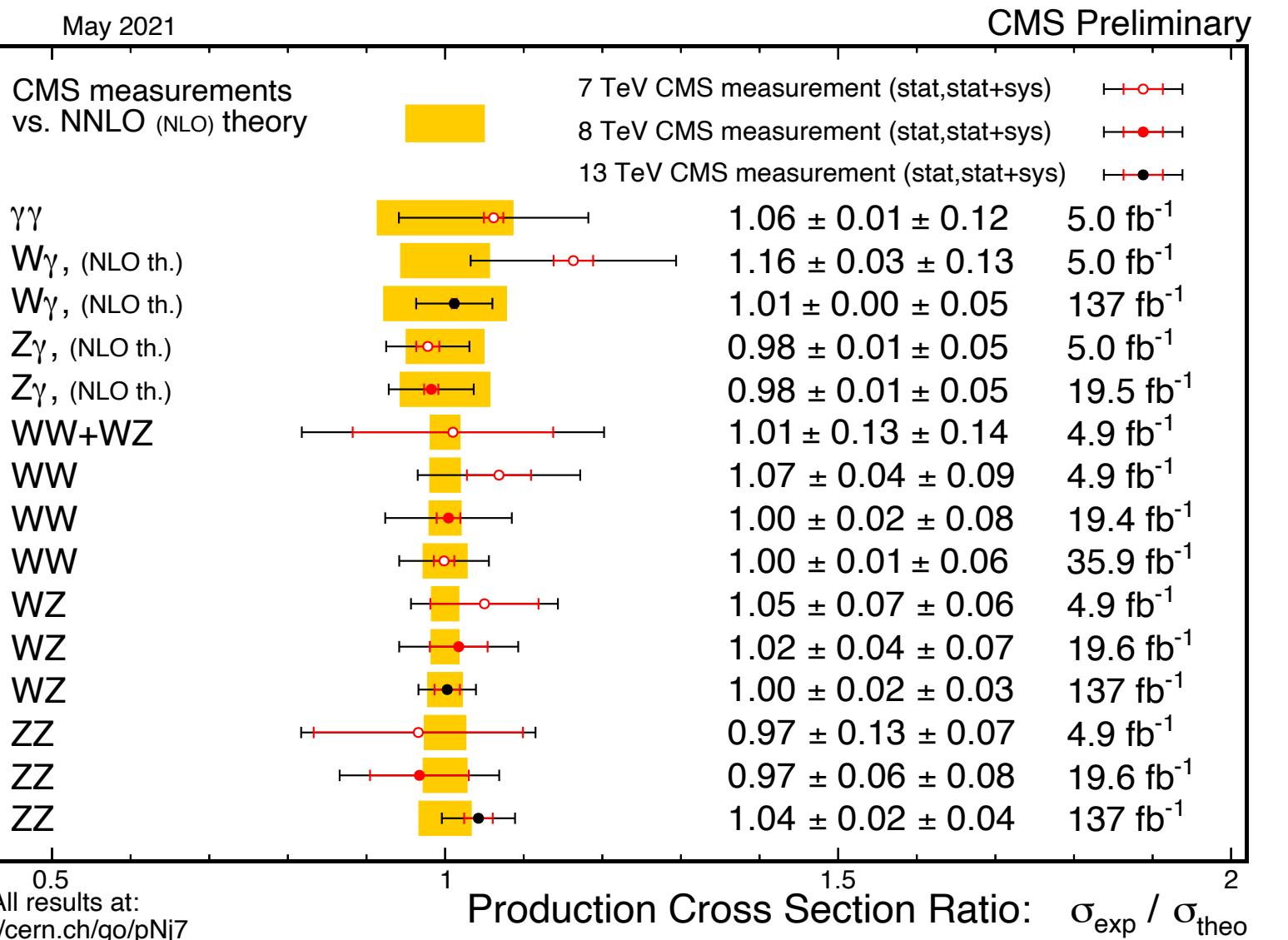
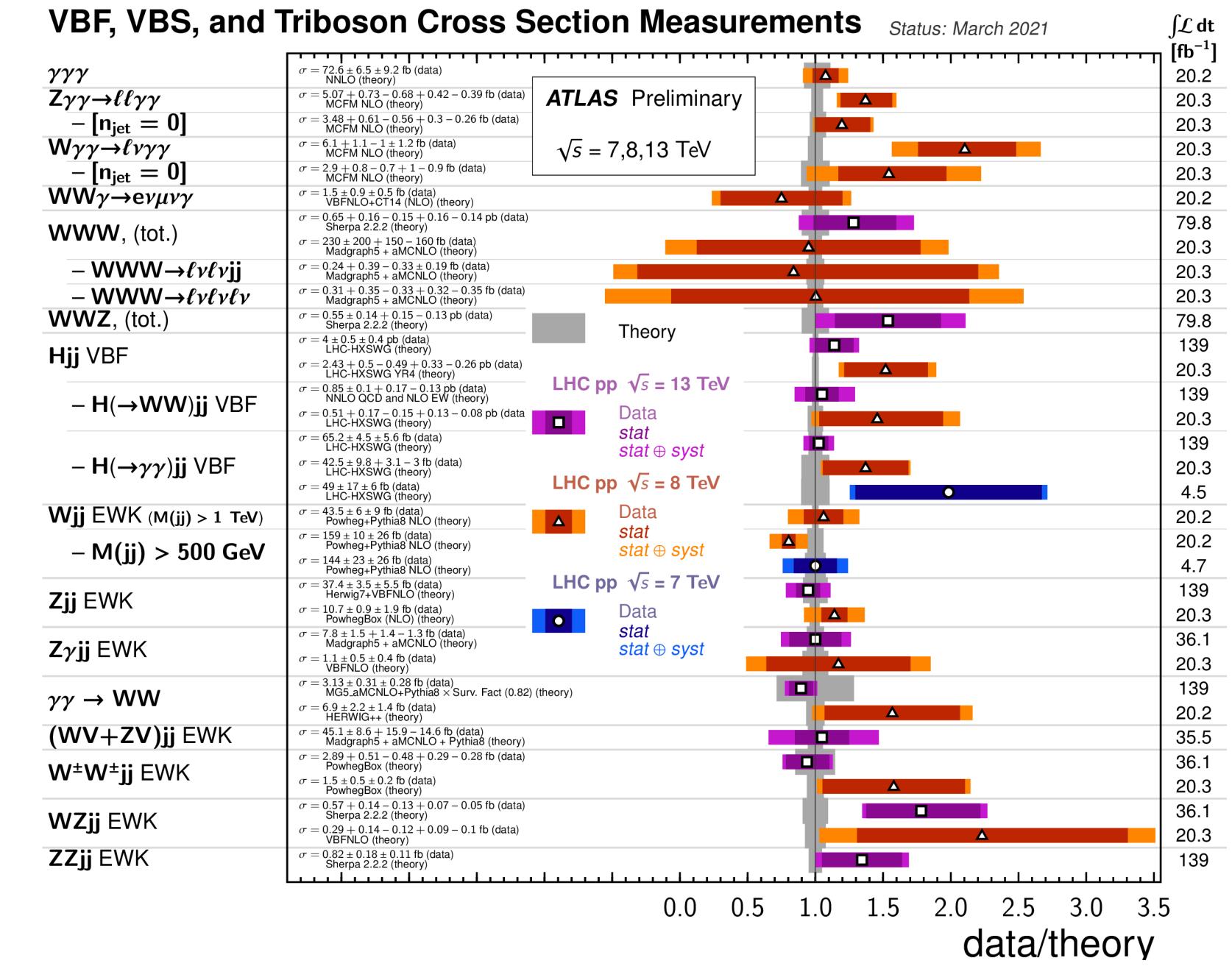
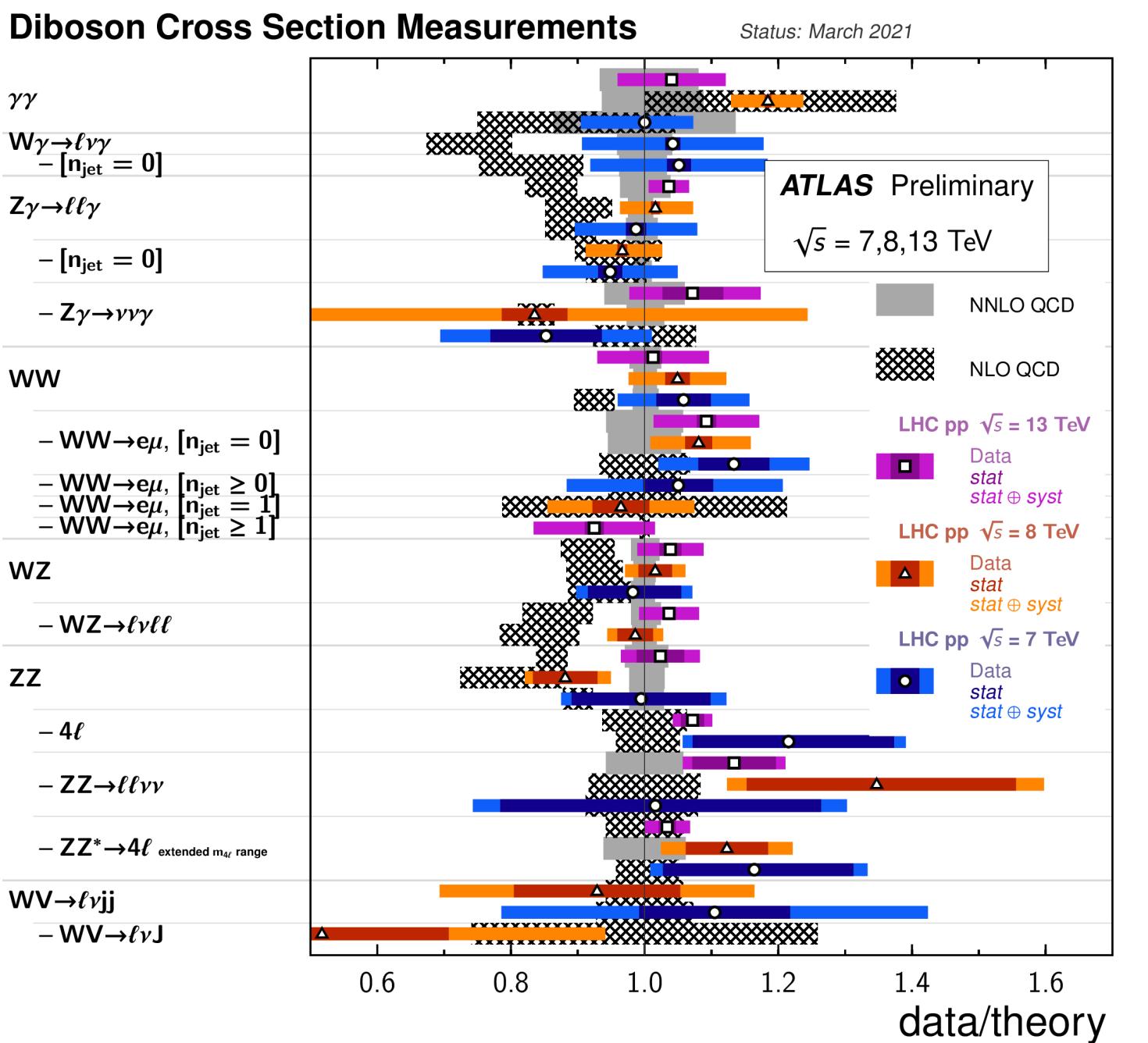
Experimental datasets

Several VBS results have recently been made available

See the CMS & ATLAS talks

However:

- ◆ Very challenging analysis
- ◆ VBS precision still far from Higgs and diboson



Experimental datasets

Dataset available by end of 2020

- ◆ Dataset from LHC Run II
- ◆ Unfolded fiducial and differential cross sections of VV and VBS
- ◆ All vectors decay into leptons
- ◆ EFT effects in “signal” region only

Final state	Selection	Observable	n_{dat}	$\mathcal{L} (\text{fb}^{-1})$	Label
$W^\pm W^\mp$	VV	$d\sigma/dm_{e\mu}$	13	36.1	ATLAS_WW_memu
		$d\sigma/dm_{e\mu}$	13	35.9	CMS_WW_memu
$W^\pm Z$	VV	$d\sigma/dp_{T_Z}$	7	36.1	ATLAS_WZ_ptz
		$d\sigma/dp_{T_Z}$	11	35.9	CMS_WZ_ptz
ZZ	VV	$d\sigma/dm_{ZZ}$	8	137	CMS_ZZ_mzz
Total diboson			52		

Final state	Selection	Observable	n_{dat}	$\mathcal{L} (\text{fb}^{-1})$	Label
$W^\pm W^\pm jj$	EW-only	σ_{fid}	1	36.1	ATLAS_WWjj_fid
	EW-only	σ_{fid}	4	137	CMS_WWjj_fid
	EW+QCD	$d\sigma/dm_{ll}^{(*)}$			CMS_WWjj_mll
$ZW^\pm jj$	EW+QCD	$d\sigma/dm_{T_{WZ}}$	5	36.1	ATLAS_WZjj_mwz
	EW-only	σ_{fid}	4	137	CMS_WZjj_fid
	EW+QCD	$d\sigma/dm_{jj}^{(*)}$			CMS_WZjj_mjj
$ZZjj$	EW+QCD	σ_{fid}	1	139	ATLAS_ZZjj_fid
	EW-only	σ_{fid}	1	139	CMS_ZZjj_fid
γZjj	EW-only	σ_{fid}	1	36.1	ATLAS_AZjj_fid
	EW-only	σ_{fid}	1	35.9	CMS_AZjj_fid
VBS total (unfolded)			18		
ZZjj	EW+QCD+Bkg	Events/ m_{ZZ}	4	139	CMS_ZZjj_mzz
γZjj	EW+QCD+Bkg	Events/ $p_{T_{\ell\ell\gamma}}$	11	36.1	ATLAS_AZjj_ptlla
VBS total (detector-level)			15		

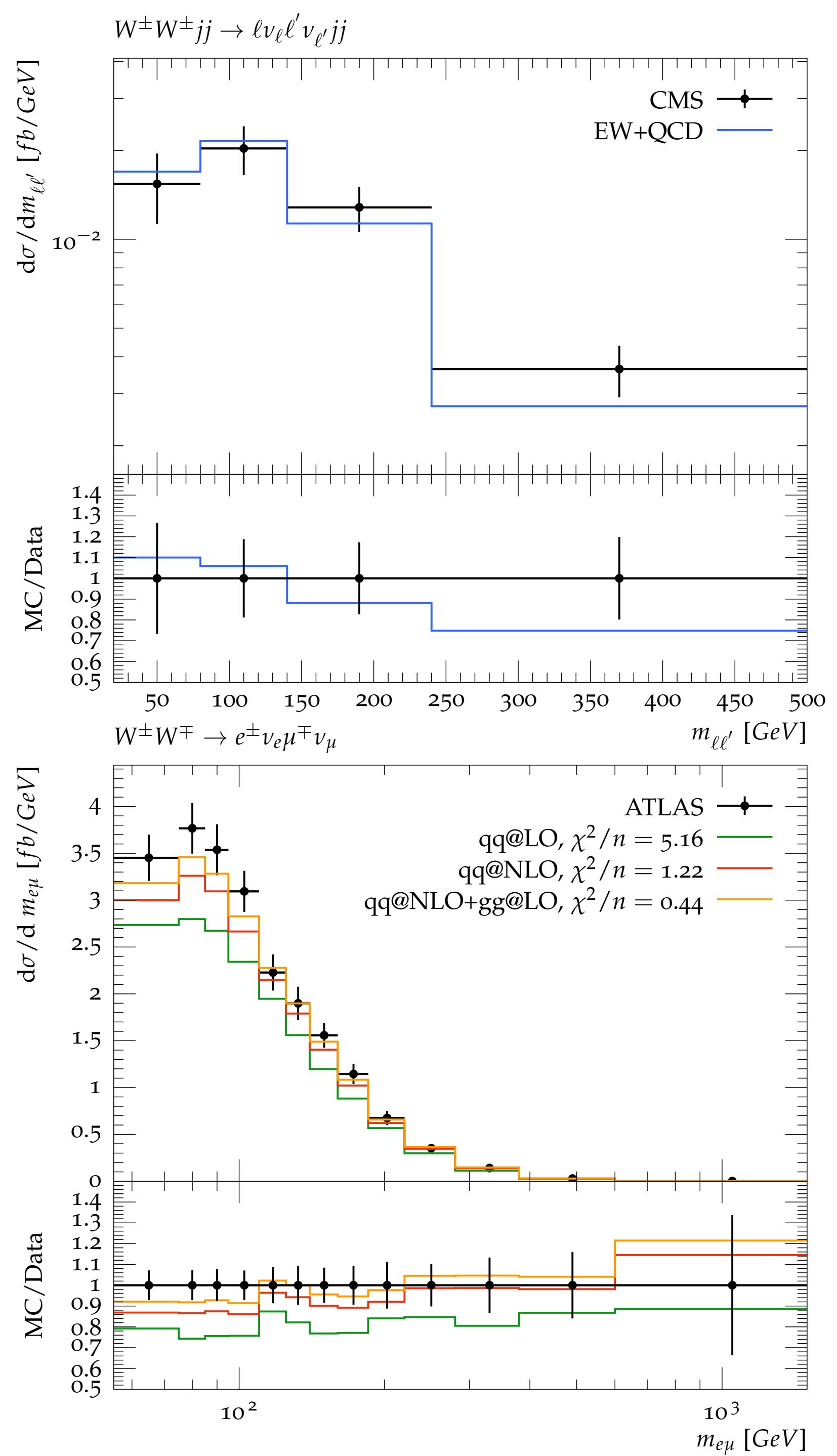
Other channels for future update:
 $Z\gamma$ CMS, $Zjj \dots$

Theoretical calculations

$$\sigma_{SMEFT} = \sigma_{SM} + \sum_{i=1}^{N_{dof}=16} \frac{c_i}{\Lambda^2} \sigma_i^{(int)}$$

Combining HEP tools to achieve good predictions:

1. **SM** MC event generation with *Madgraph* and/or *PowhegBox @ NLO*
2. **EFT linear** contribution @ LO with: *SmeftSim* UFO model ($SU(3)^5$ symmetry) *For Quadratics, see talk by G.Boldrini*
3. **Parton shower** using *Pythia8* and experimental phase space selection with ***ad-hoc Rivet*** analysis
4. Experimental data with corresponding uncertainties collected from *Hepdata* *Manage to reproduce experimental predictions accurately*

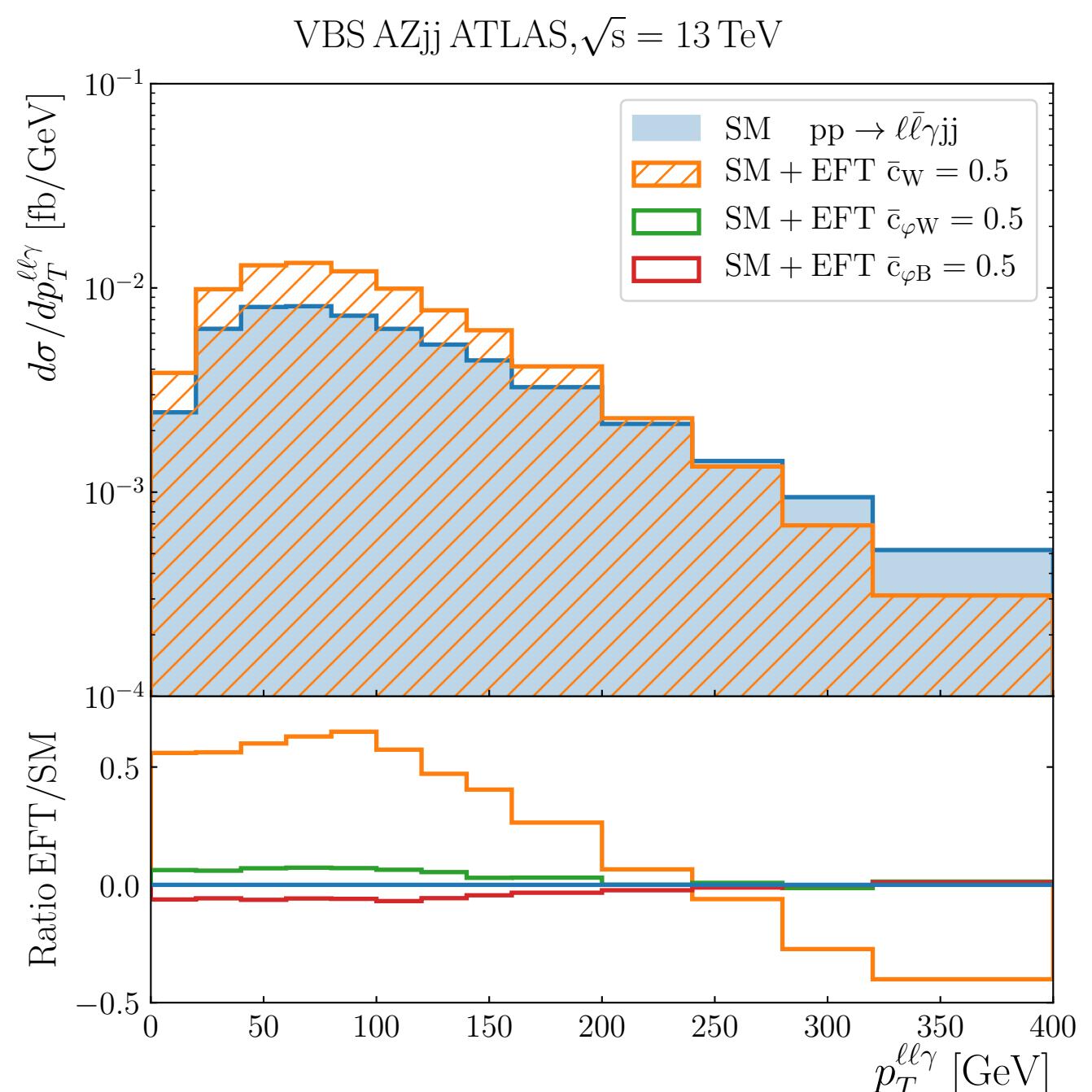
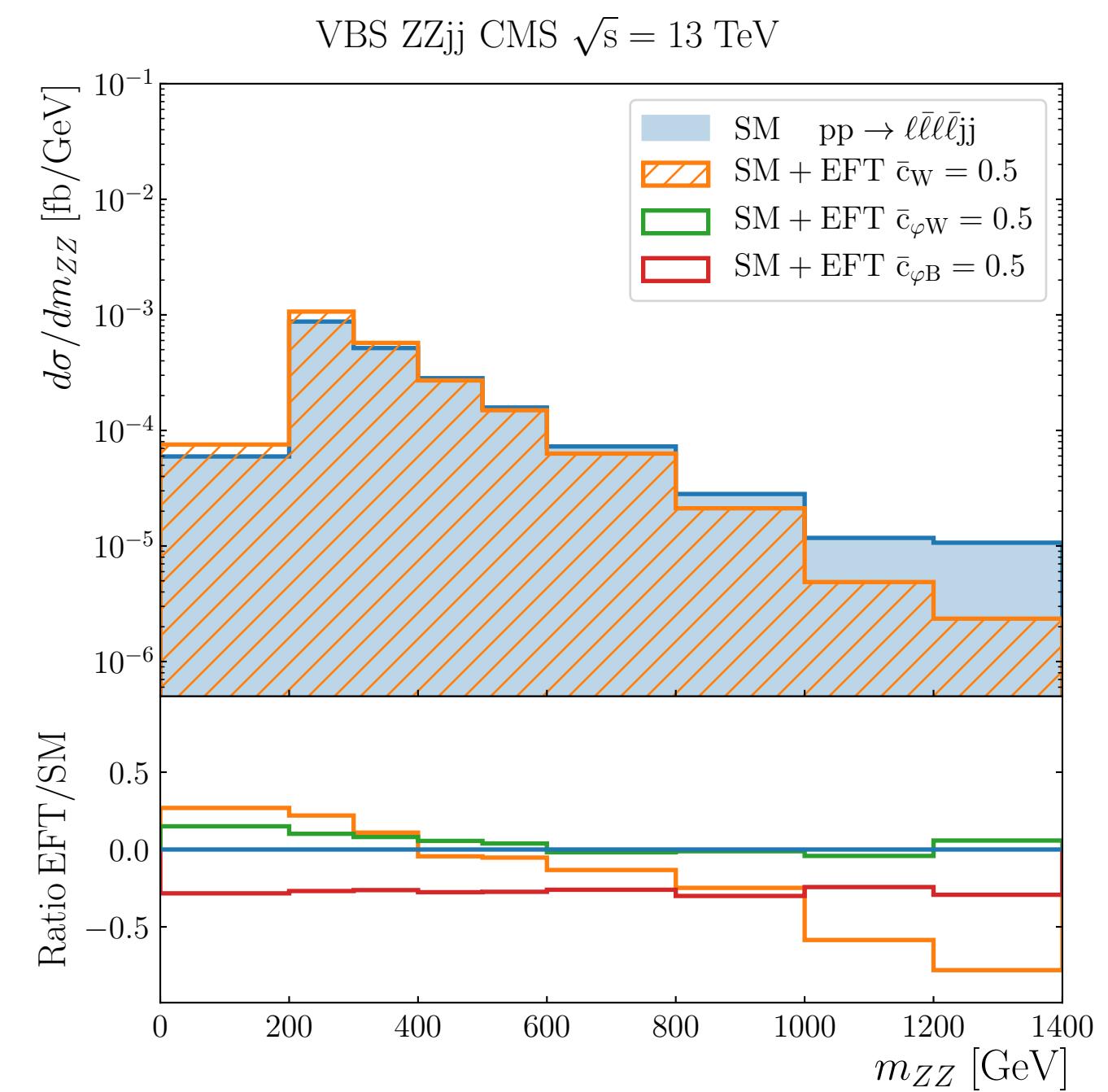
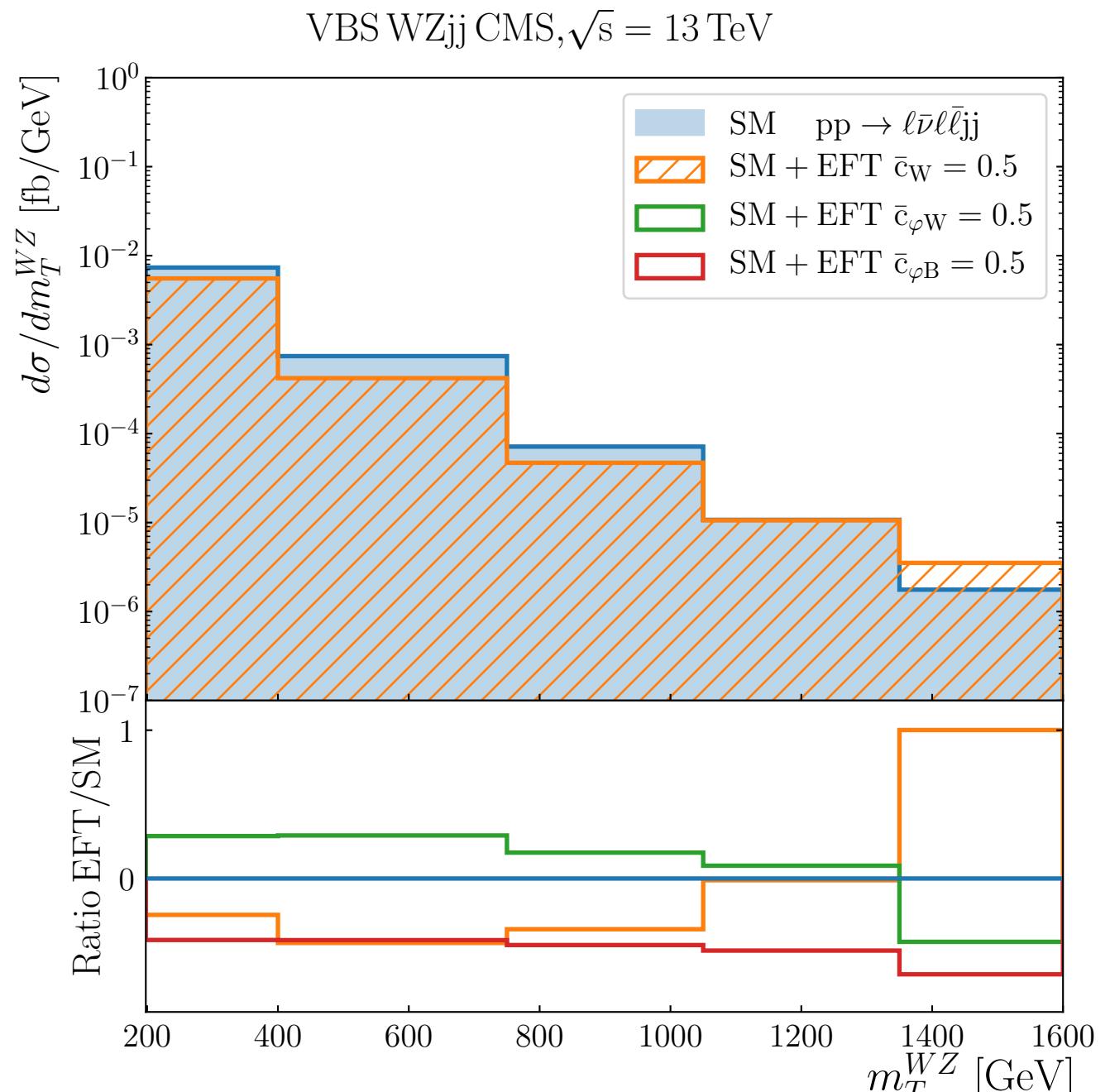
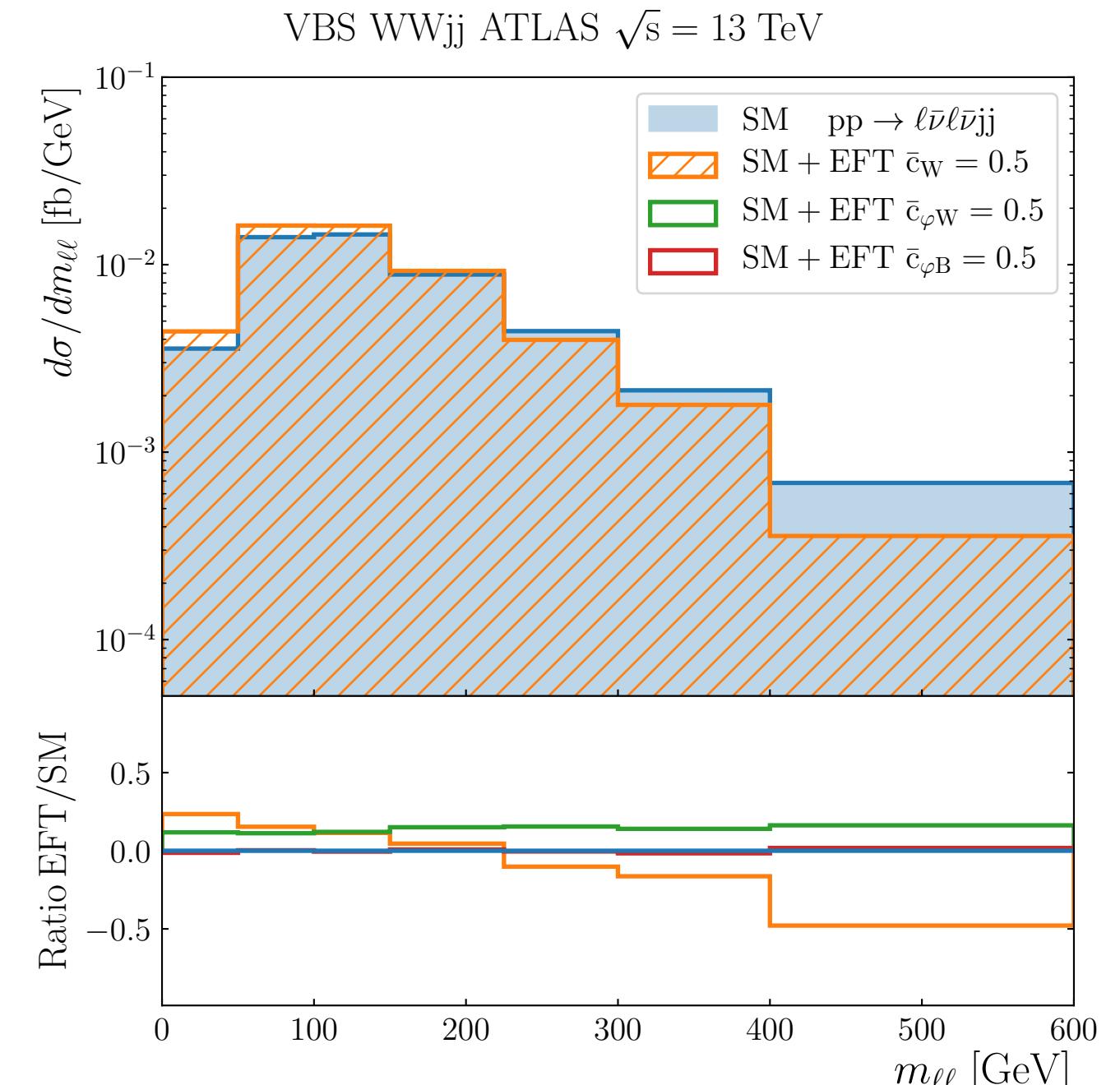


Sensitivity plots

Study the impact of each operator in the experimental phase space region, fixing the Wilson coefficient to a reference value

We observe, a priori:

- ◆ Sizeable effects not only in the high energy tails
- ◆ The optimal observables to include in the fit are not always the available ones



Fisher information

A more systematic study of the EFT sensitivities

Defined as the trace of:

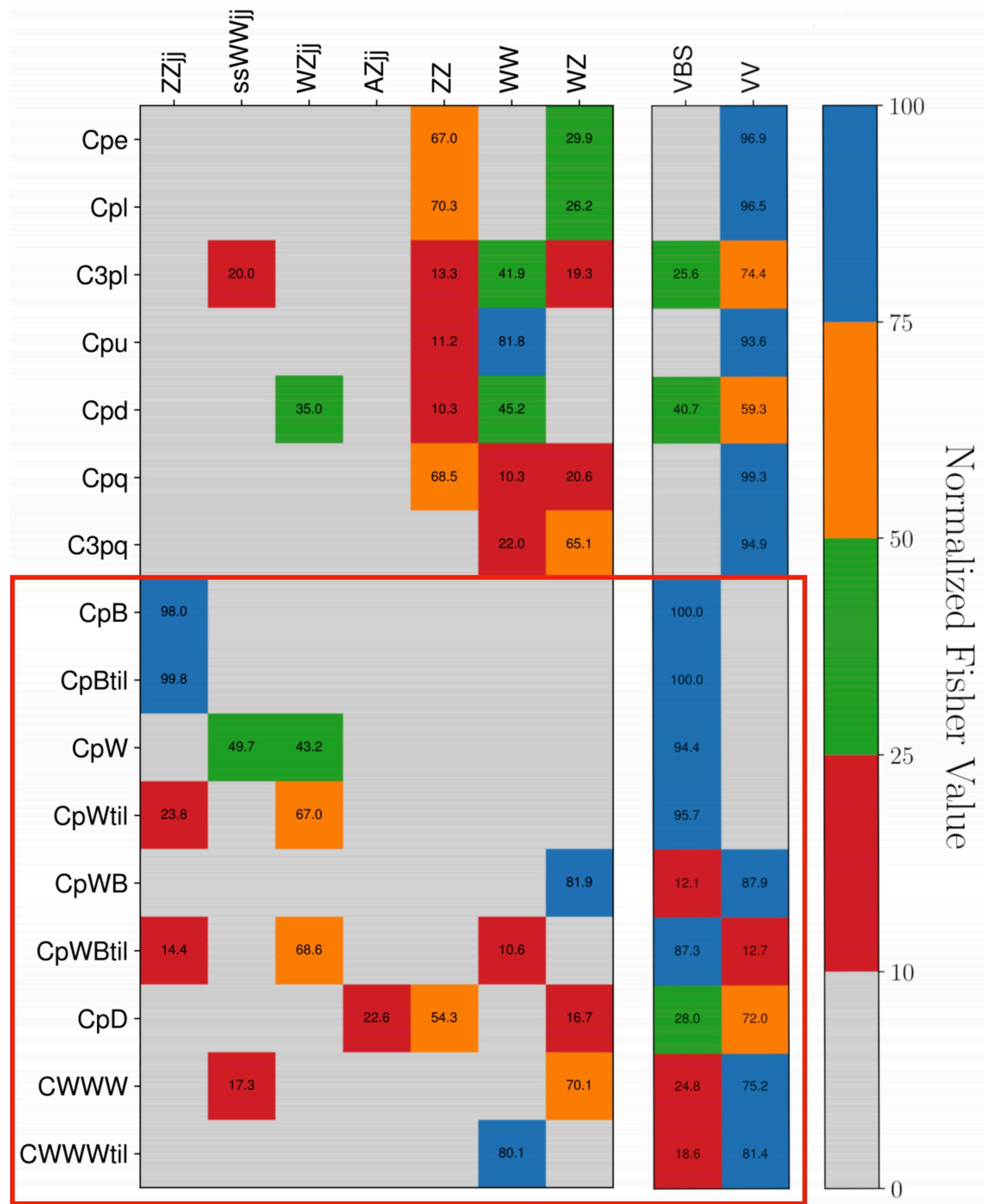
$$I_{i,j} = E\left[\frac{\partial^2 \ln f(\sigma_{exp} | c)}{\partial c_i \partial c_j}\right] = \sum_{m=1}^{n_{dat}} \frac{\sigma_{(m,i)}^{(eft)} \sigma_{m,j}^{(eft)}}{\delta_{exp,m}^2}, \quad i, j = 1 \dots n_{op}$$

And normalised per operator.

- ◆ It shows how each channel contribute to the fit result.
- ◆ Computed before fitting

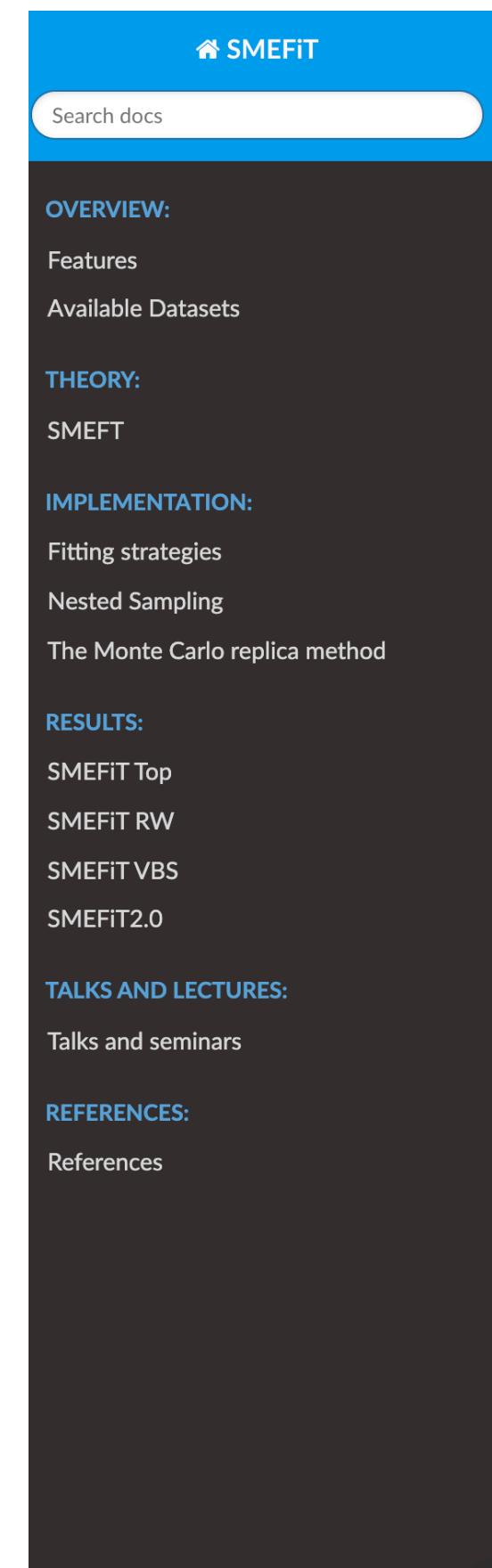
We observe:

- ◆ 2F2H operators dominated by VV
- ◆ VBS plays a role for purely boson operators:
 $HDH^2, 2H2V, 3V$



Fitting strategy

- ◆ SMEFiT is a novel framework to carry out global analyses of the SMEFT which exploits (but is independent from) ample expertise inherited from (NN)PDF fits
- ◆ Two independent fitting strategies based: frequentist and Bayesian approach
- ◆ Able to account for quadratic EFT corrections



» Welcome to the SMEFiT website!

[View page source](#)

SMEFiT

Welcome to the SMEFiT website!

SMEFiT is a Python package for global analyses of particle physics data in the framework of the Standard Model Effective Field Theory (SMEFT). The SMEFT represents a powerful model-independent framework to constrain, identify, and parametrise potential deviations with respect to the predictions of the Standard Model (SM). A particularly attractive feature of the SMEFT is its capability to systematically correlate deviations from the SM between different processes. The full exploitation of the SMEFT potential for indirect New Physics searches from precision measurements requires combining the information provided by the broadest possible dataset, namely carrying out extensive global analysis which is the main purpose of SMEFiT.

Project description

The SMEFiT framework has been used in the following scientific publications:

- *A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector*, N. P. Hartland, F. Maltoni, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang [[HMN+19](#)].
- *Constraining the SMEFT with Bayesian reweighting*, S. van Beek, E. R. Nocera, J. Rojo, and E. Slade [[vBNRS19](#)].
- *SMEFT analysis of vector boson scattering and diboson data from the LHC Run II*, J. Ethier, R. Gomez-Ambrosio, G. Magni, J. Rojo [[EGAMR21](#)].
- *Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC*, J. Ethier, G. Magni, F. Maltoni, L. Mantani, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang [[EMM+21](#)]

Results from these publications, including driver and analysis scripts, are available in the **Results** section.

Team description

The **SMEFiT collaboration** is currently composed by the following members:

- Jaco ter Hoeve, *VU Amsterdam and Nikhef Theory Group*
- Giacomo Magni, *VU Amsterdam and Nikhef Theory Group*
- Fabio Maltoni, *Centre for Cosmology, Particle Physics and Phenomenology Louvain and University of Bologna*
- Luca Mantani, *Centre for Cosmology, Particle Physics and Phenomenology Louvain*

Documentation and fit posterior distribution available:

[**Web Site**](#)

Fitting strategy



- ♦ Define the figure of merit to minimise as:

$$\chi^2(c_k) = \frac{1}{N_{data}} \sum (O_{exp,i} - O_{th,i})(cov^{-1})_{ij} O_{exp,j} - O_{th,j})$$

- ♦ Include available experimental uncertainties, correlations and theory uncertainties (*from MC and pdfs*).
- ♦ Use **NESTED SAMPLING** : sampling the posterior as :

$$p(c_k | data) = \frac{1}{Z} \mathcal{L}(data | c_k) \Pi(c_k)$$

Multi Gaussian Likelihood

Prior, assumed flat

Fit Output

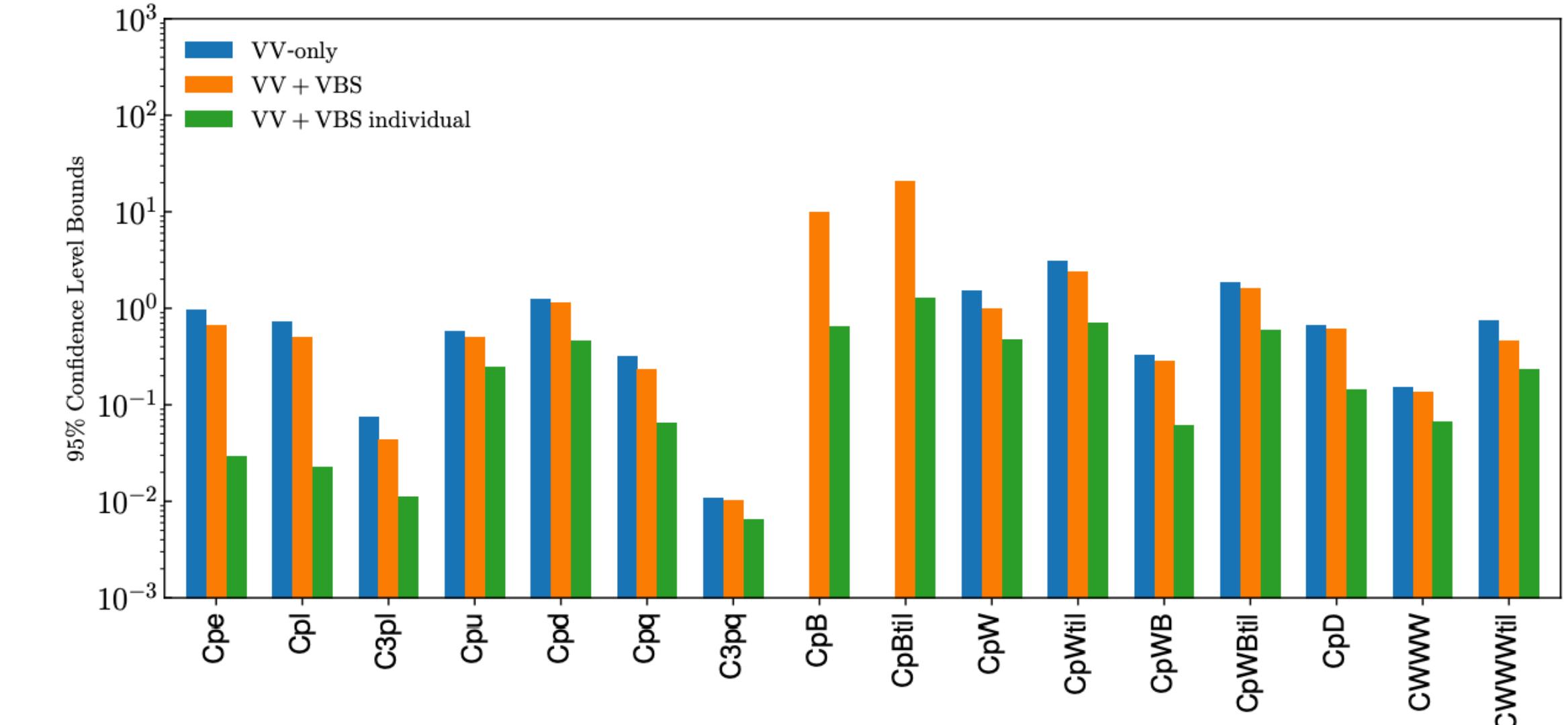
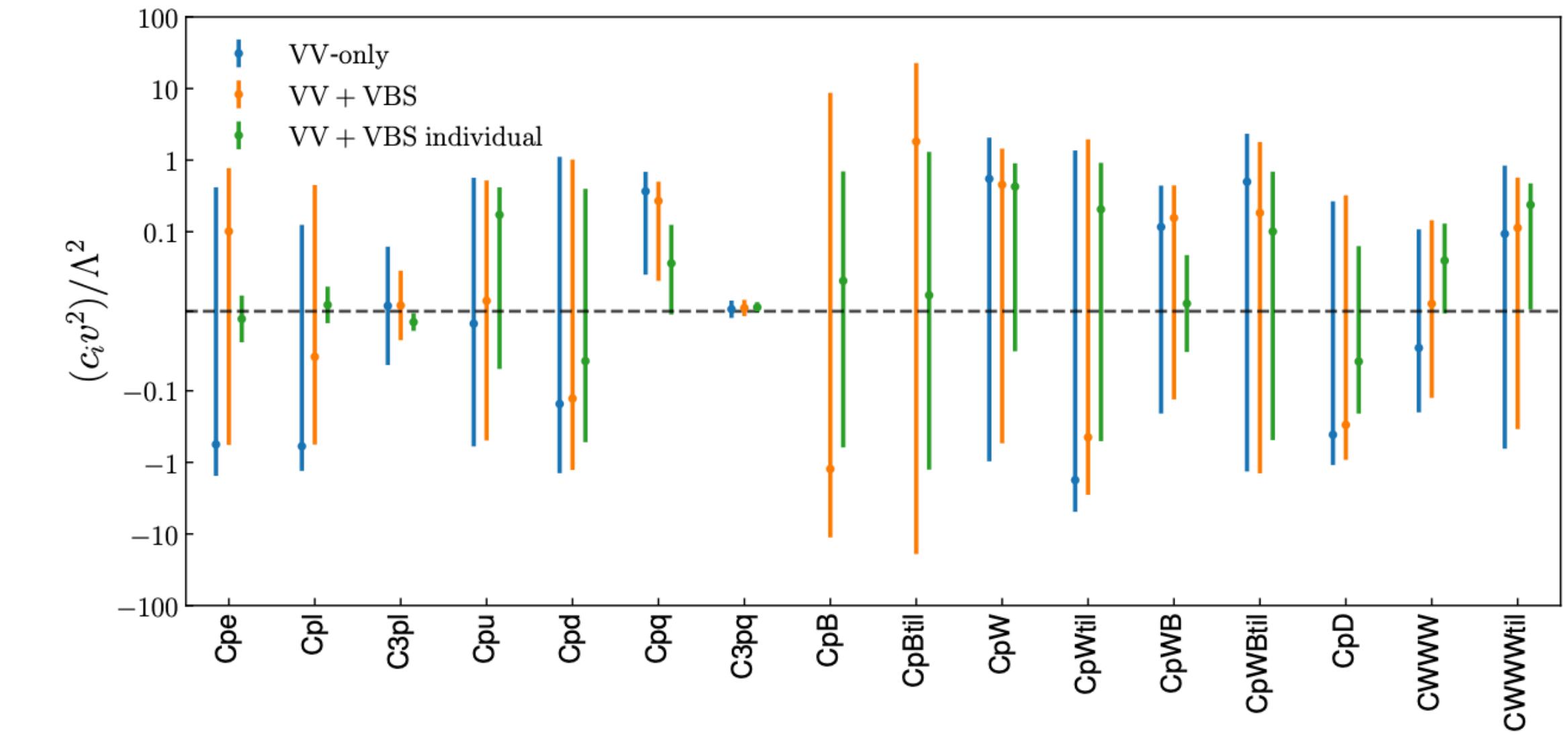
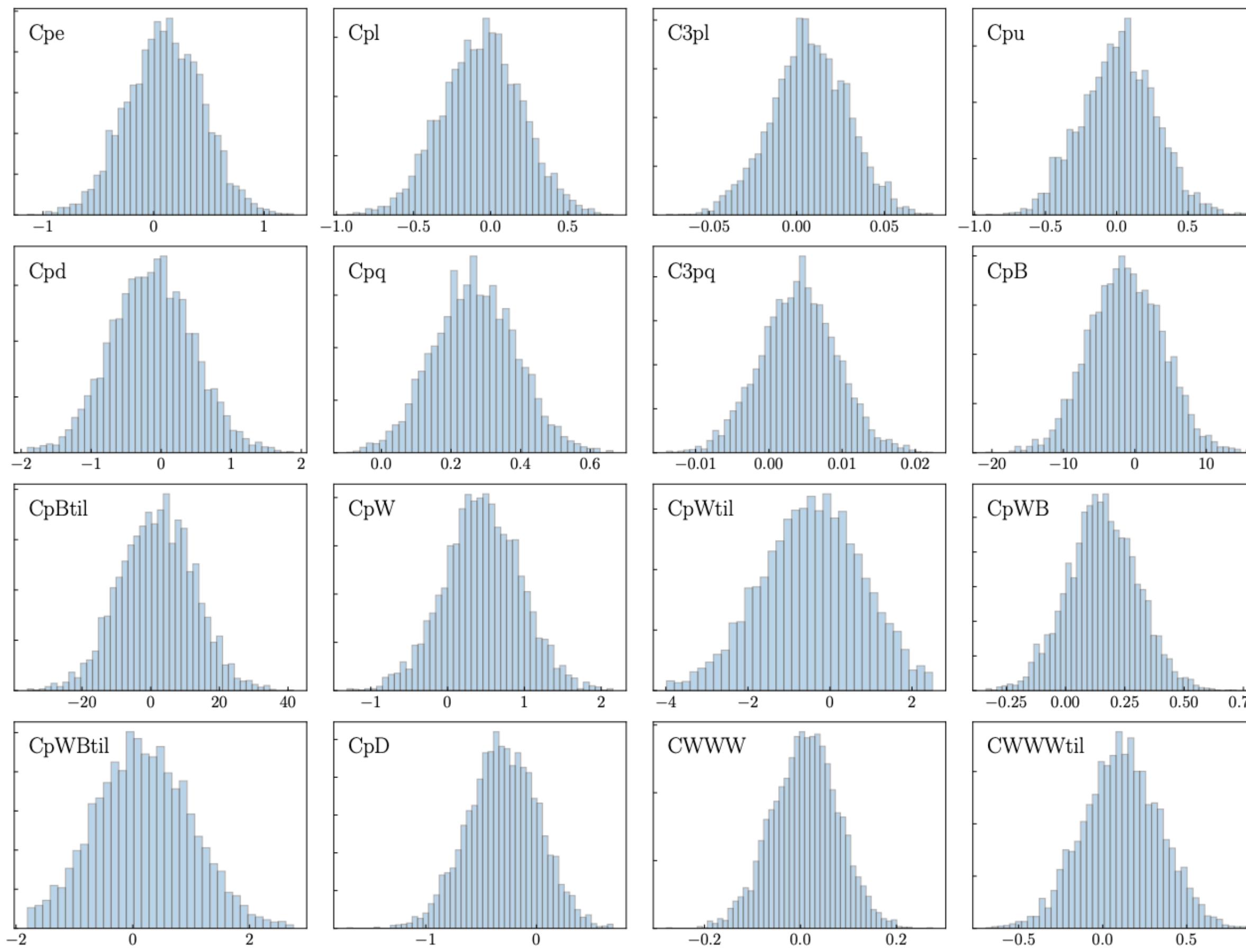
& dataset quality

- ◆ Some statistical fluctuations for individual VBS measurements
(should improve when more data points will be available)
- ◆ Global reduced chi2: $\chi^2 \approx 1$
- ◆ MHOU (SM and EFT) not included

Process	Dataset	n_{dat}	χ^2/n_{dat} (SM)	χ^2/n_{dat} (EFT)
Diboson	ATLAS_WW_memu	13	0.70	0.66
	CMS_WW_memu	13	1.28	1.32
	ATLAS_WZ_ptz	7	1.38	0.93
	CMS_WZ_ptz	11	1.48	1.14
	CMS_ZZ_mzz	8	1.17	0.74
	Total diboson	52	1.17	0.97
VBS	ATLAS_WWjj_fid	1	0.01	0.67
	CMS_WWjj_fid	1	2.17	0.15
	CMS_WWjj_mll	3	0.31	0.45
	ATLAS_WZjj_mwz	5	1.60	1.52
	CMS_WZjj_fid	1	0.38	0.79
	CMS_WZjj_mjj	3	1.10	0.73
	ATLAS_ZZjj_fid	1	0.09	0.15
	CMS_ZZjj_fid	1	0.02	0.02
	ATLAS_AZjj_fid	1	0.00	0.25
	CMS_AZjj_fid	1	0.03	0.38
Total VBS		18	0.83	0.75
	Total	70	1.084	0.917

Fit output

VV+VBS fit



Posterior distribution VV+VBS

Central values and 95 % CL

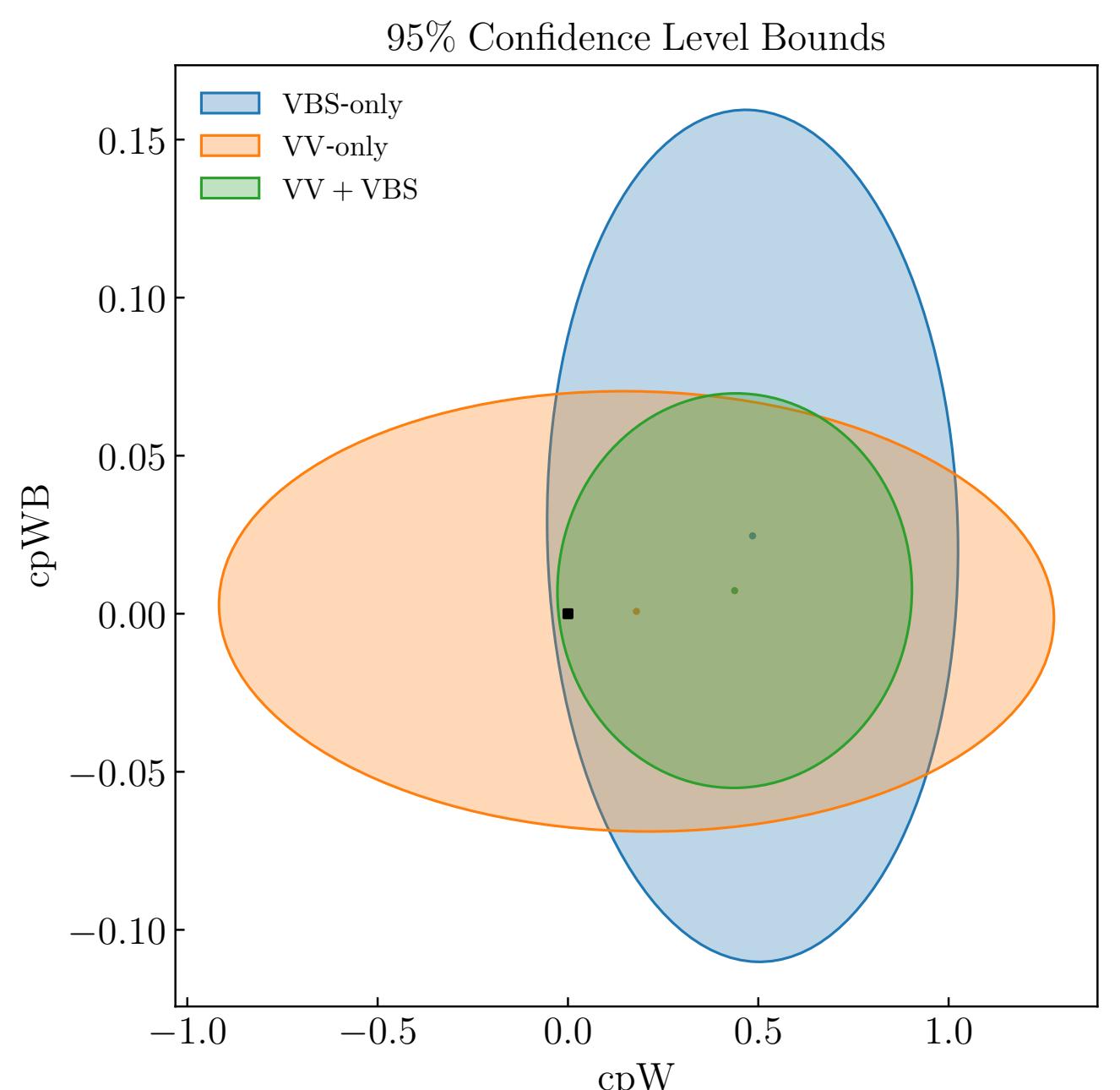
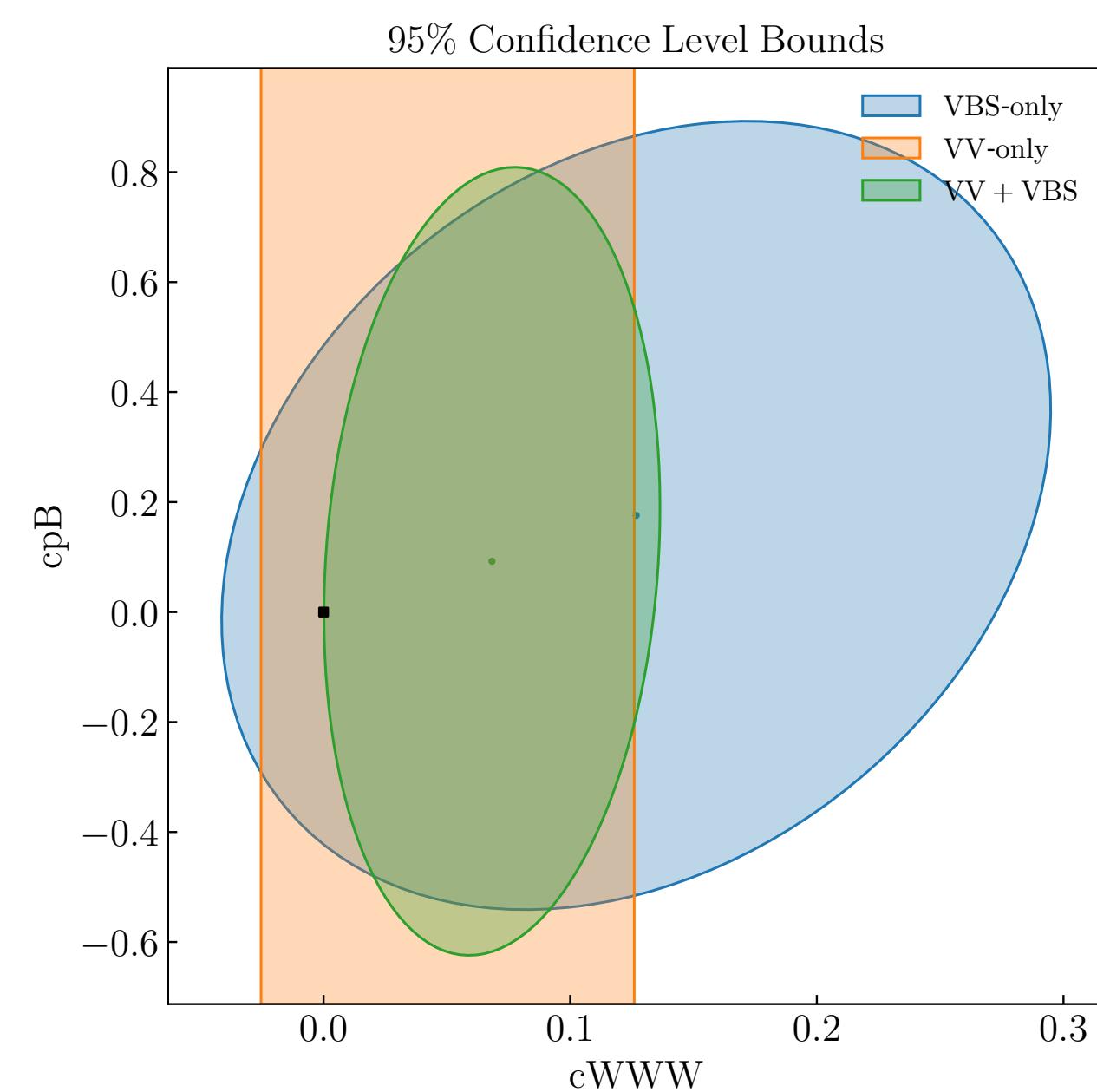
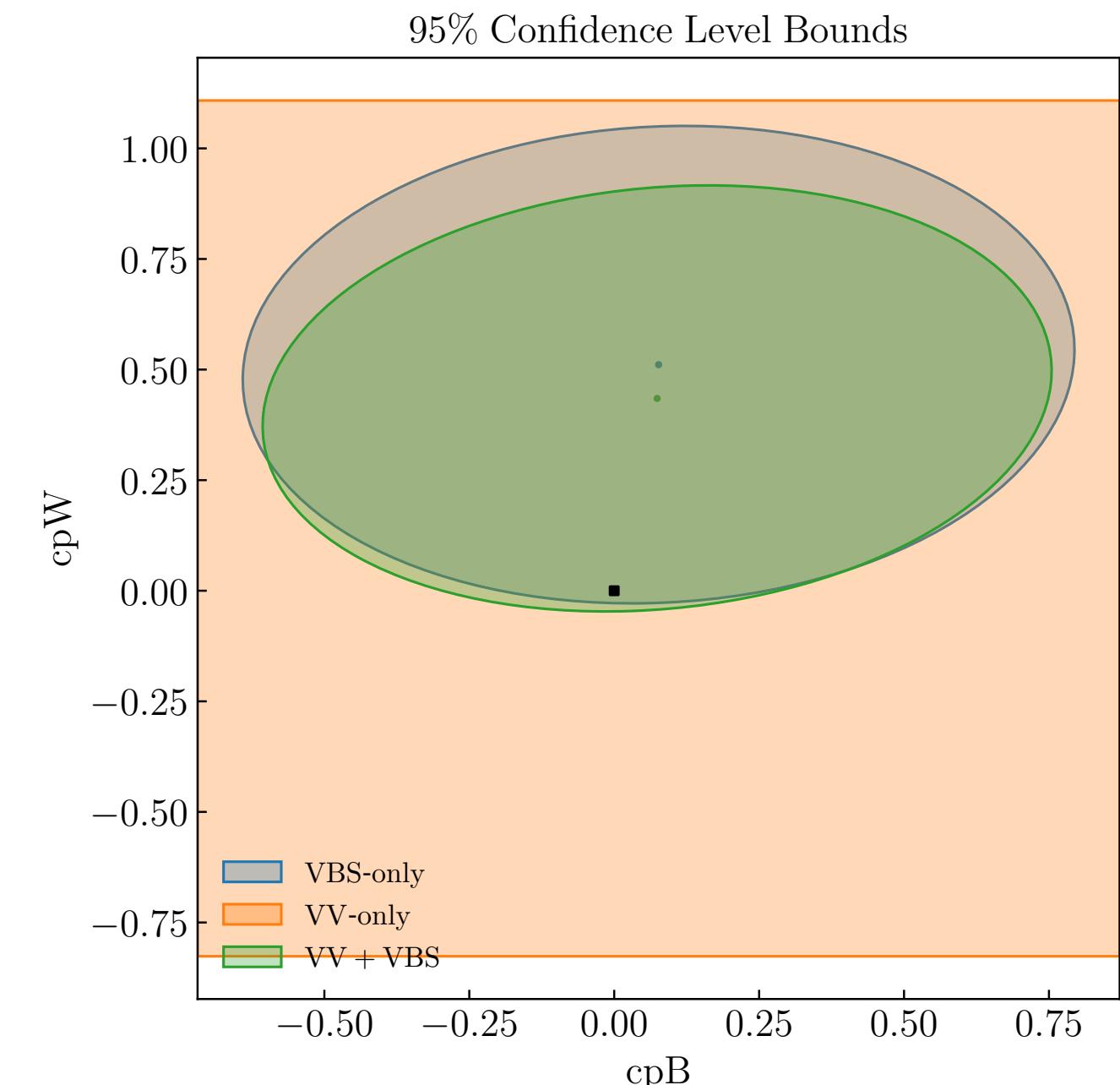
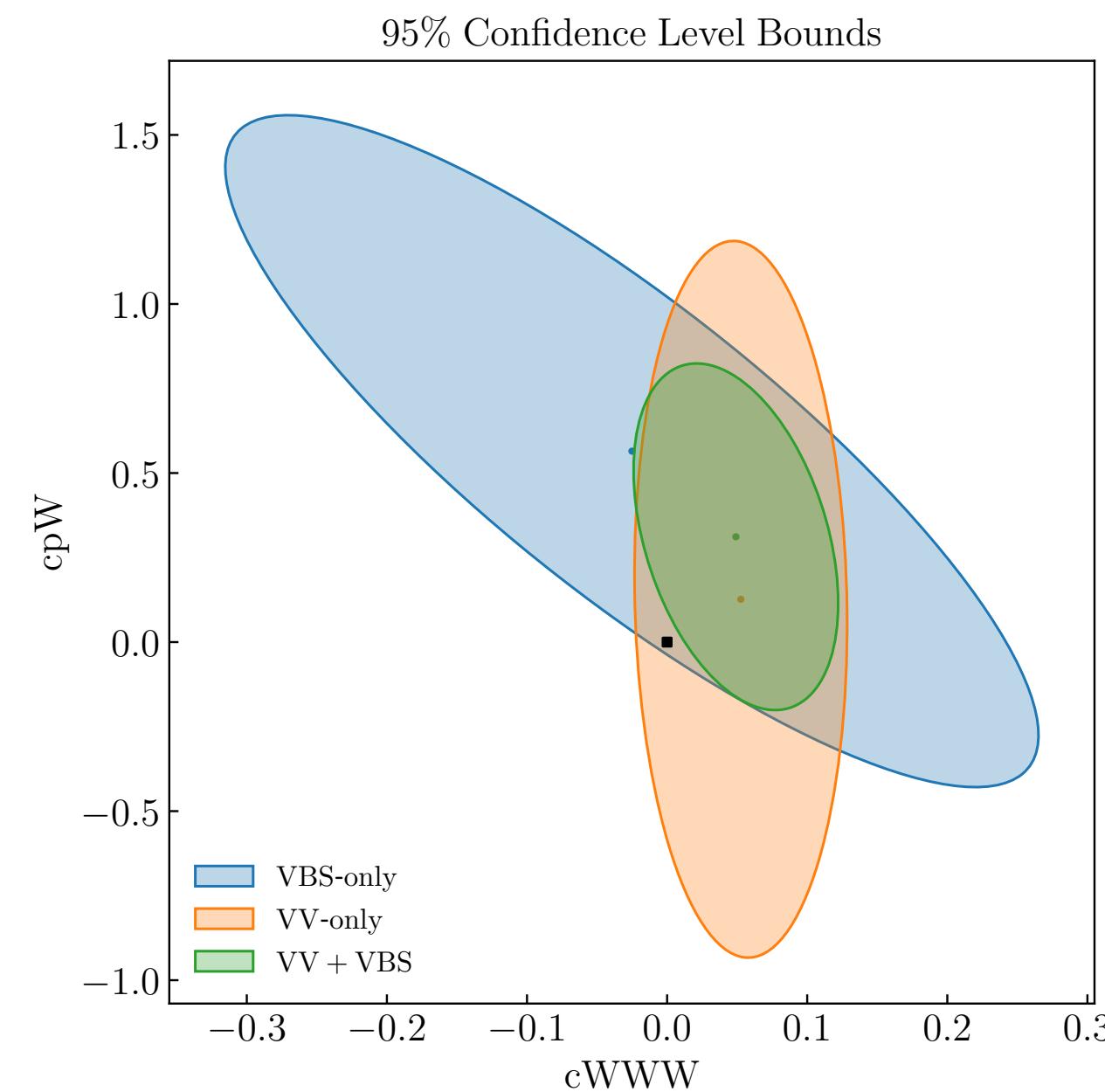
Fit output

2D Fits

- ❖ Useful to spot correlation between operators.
- ❖ Understand how the combined fit behaves with respect to the VV-only or VBS-only



*Complementarity between
VBS and VV data
when looking at dim6 EFT effects !*



Toy model

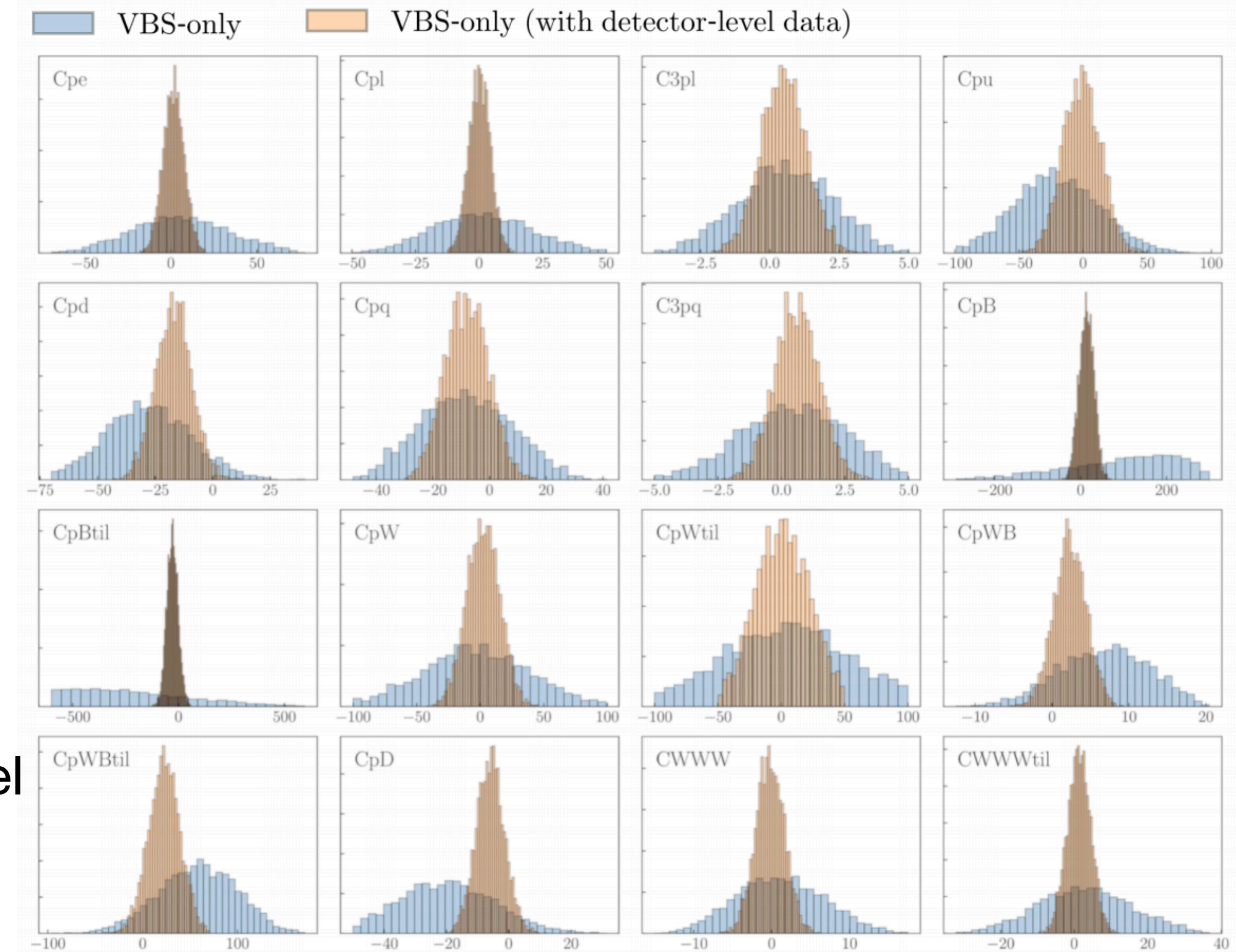
Dataset variation

Effect of differential $ZZjj$ and $Z\gamma jj$:

1. Break degeneracy on c_{pB} and $c_{p\widetilde{B}}$
2. Improve globally the VBS only fit.

$ZZjj$	EW+QCD+Bkg	Events/ m_{ZZ}	4	139	CMS_ZZjj_mzz
γZjj	EW+QCD+Bkg	Events/ $p_{T_{\ell\ell\gamma}}$	11	36.1	ATLAS_AZjj_ptll1a
VBS total (detector-level)			15		

To test this, add to our baseline two detector level distributions (only bins with high statistics)



Differential results make a big difference!

Posterior distribution

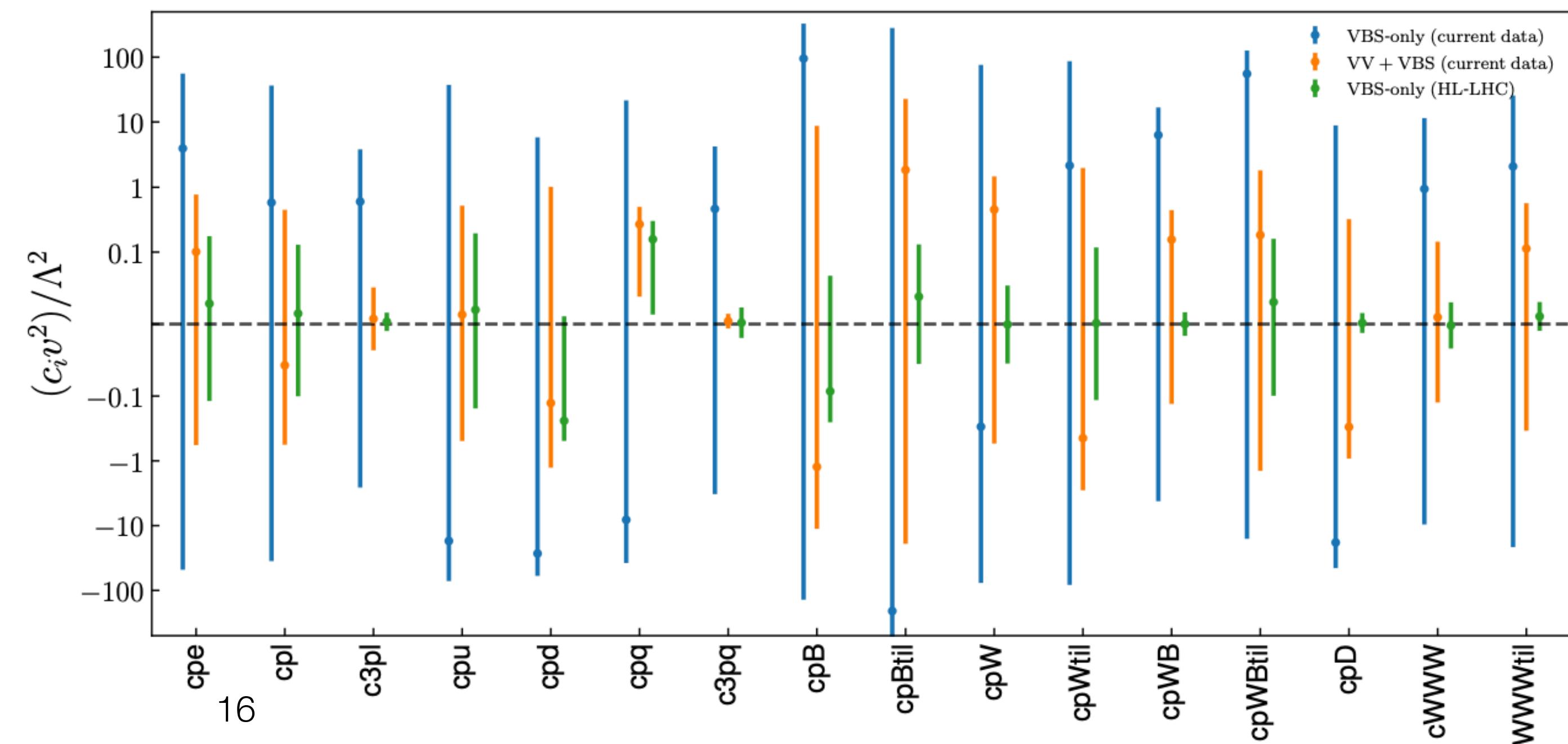
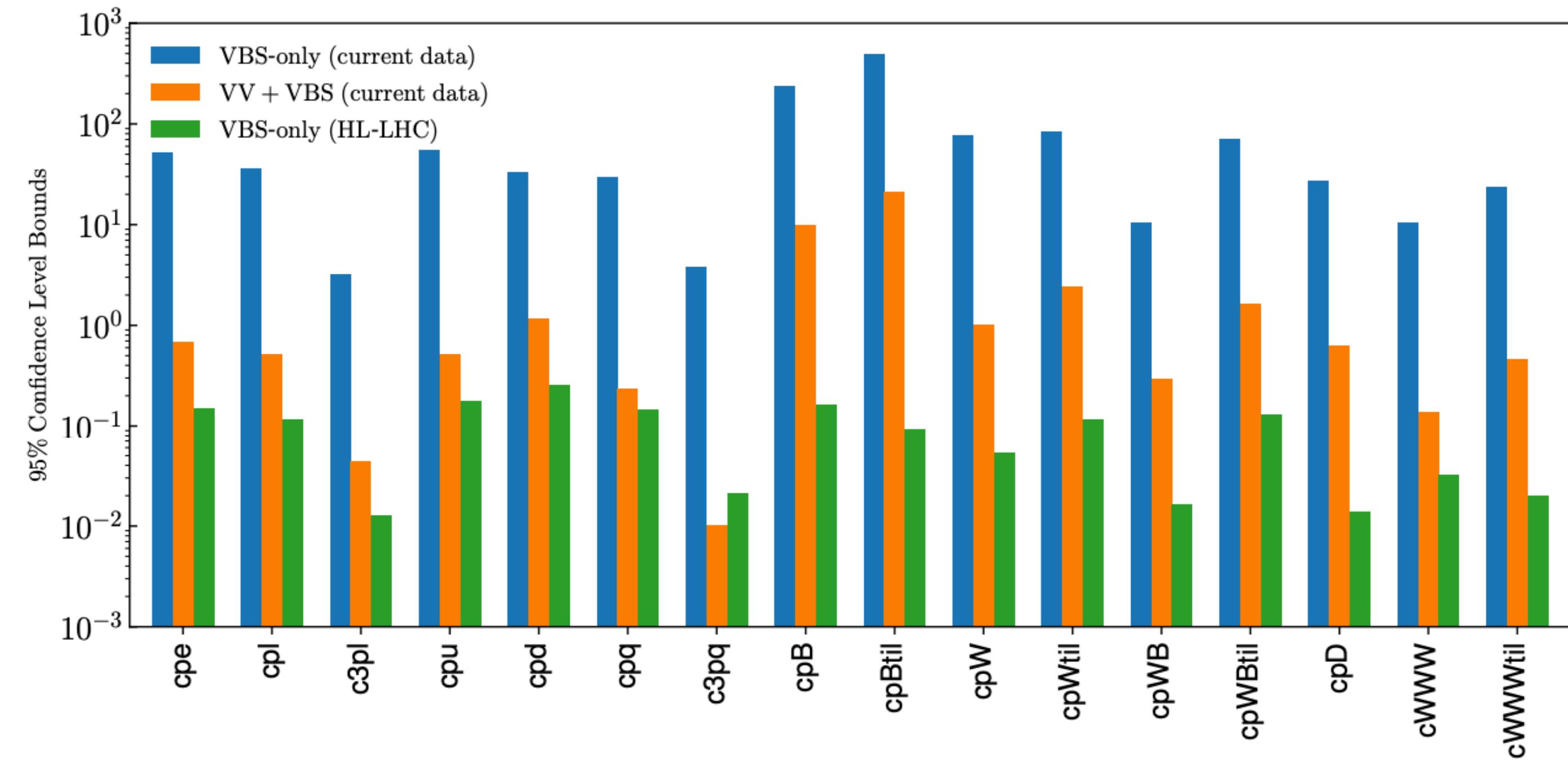
Toy model

VBS at HL-LHC

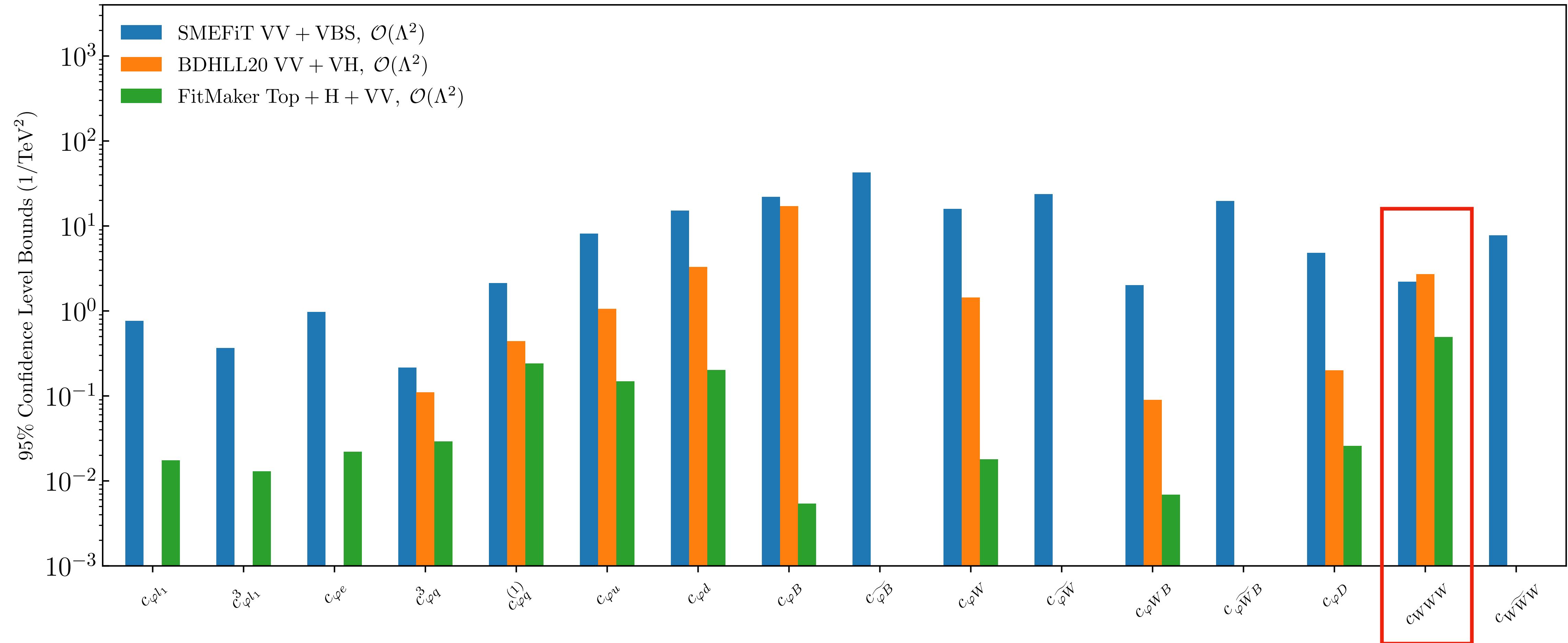
$$\sigma_i^{HL-LHC} = \sigma_i^{th}(1 + r_i \delta_{tot,i}^{exp})$$

- ◆ Assume the systematic errors reduce by 50% while statistical by 80 %
- ◆ Create gaussian dataset
- ◆ Keep LHC binning
- ◆ 61 data points from VBS

**Central values
and 95 % CL**



Comparison with the literature



█ [BDHLL: J. Baglio, S.Dawson, S.Homiller, S.Lane and I.Lewis](#)
█ [FitMaker: J.Ellis, M.Madigan,K.Mimasu,V.Sanz and T.You](#)

Our future plans within SMEFiT

- ◆ Inclusion of **new LHC observables** (including flavour)
- ◆ Also non-LHC processes (low-energy, neutrinos, EDMs)
- ◆ Keep stress-testing the fit methodology as it scales to a fit involving hundreds of coefficients
- ◆ Study of the **optimal observables** to maximise the EFT sensitivity
- ◆ Not discussed here:
 - **UV-motivated theory constraints**
 - Bayesian inference for very fast EFT projections,
 - Interplay with PDF fits,
 - Treatment of theory uncertainties,
 - Matching to UV scenarios
- ◆ **Benchmark** comparisons with other groups

Summary and outlook

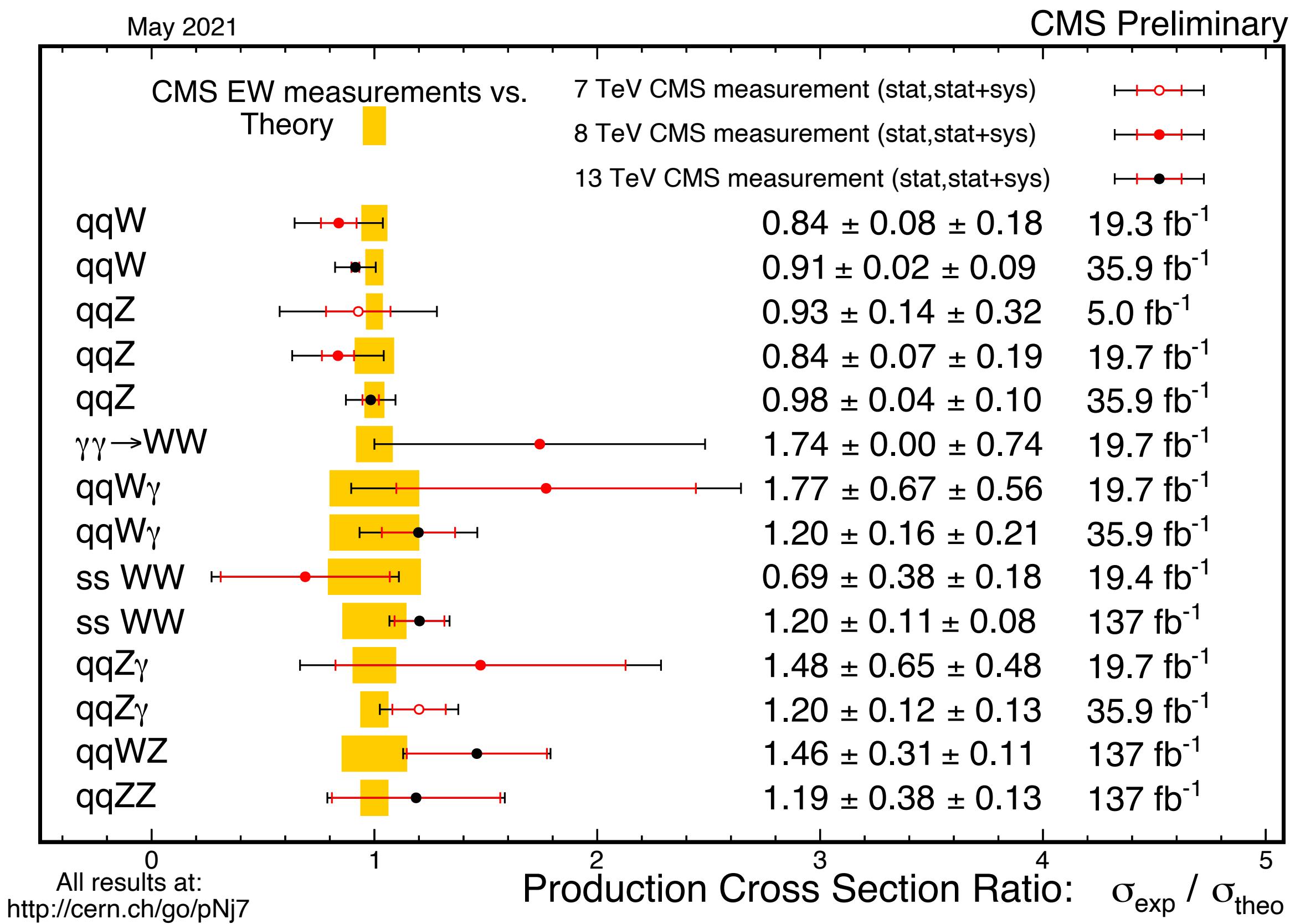
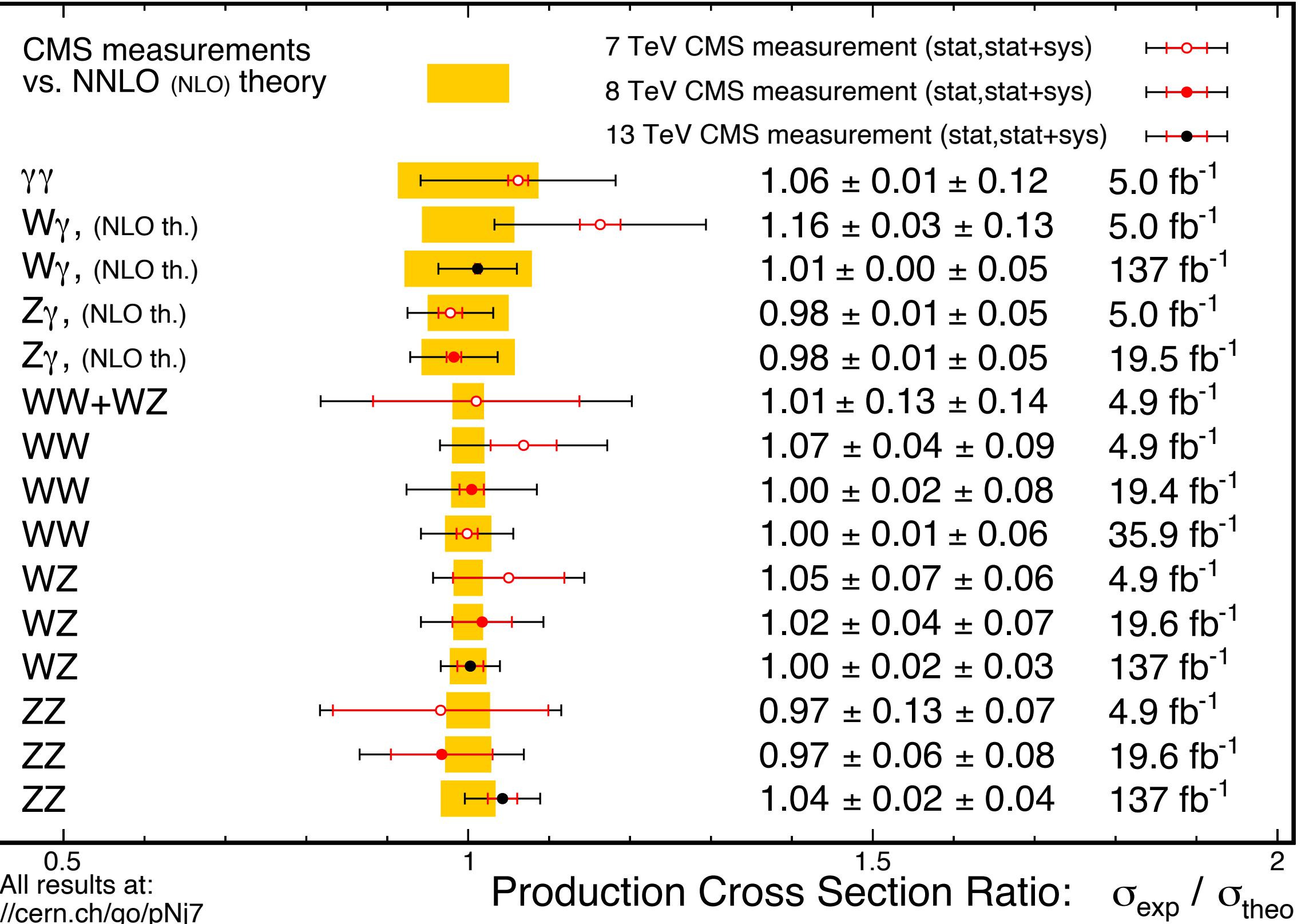
- ♦ VBS can be used to check TGC and QGC, but can validate also the Higgs sector*
- ♦ The different fitting groups are well on the way towards a global EFT fit of the LHC dataset
- ♦ Highly nontrivial: $Top + H + VV + VBS \approx \mathcal{O}(100)$ operators involved
- ♦ Include theory improvements:
 - Higher accuracy on the theory simulations (both SM and EFT)

Addressed in several of the theory talks (Lindert, Grazzini, Alioli, Melnikov...)

- Adding dim6 quadratic terms as well as dim8 interference terms to the EFT prediction
- Better understanding of the MHOU in the EFT is needed too

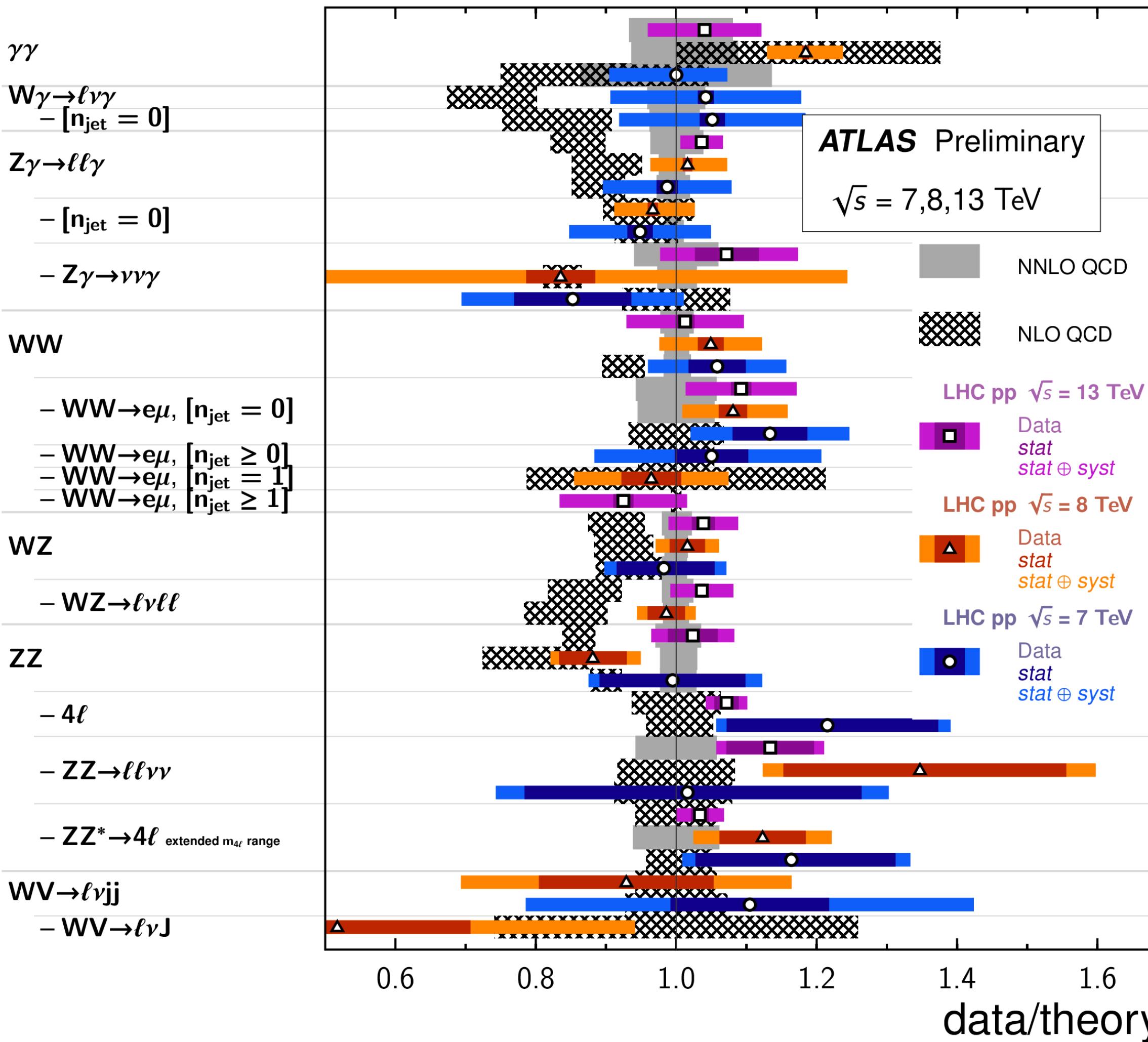
**Bonus: can VBS-EFT give us extra information
on the Higgs potential?*

Thanks for your attention!



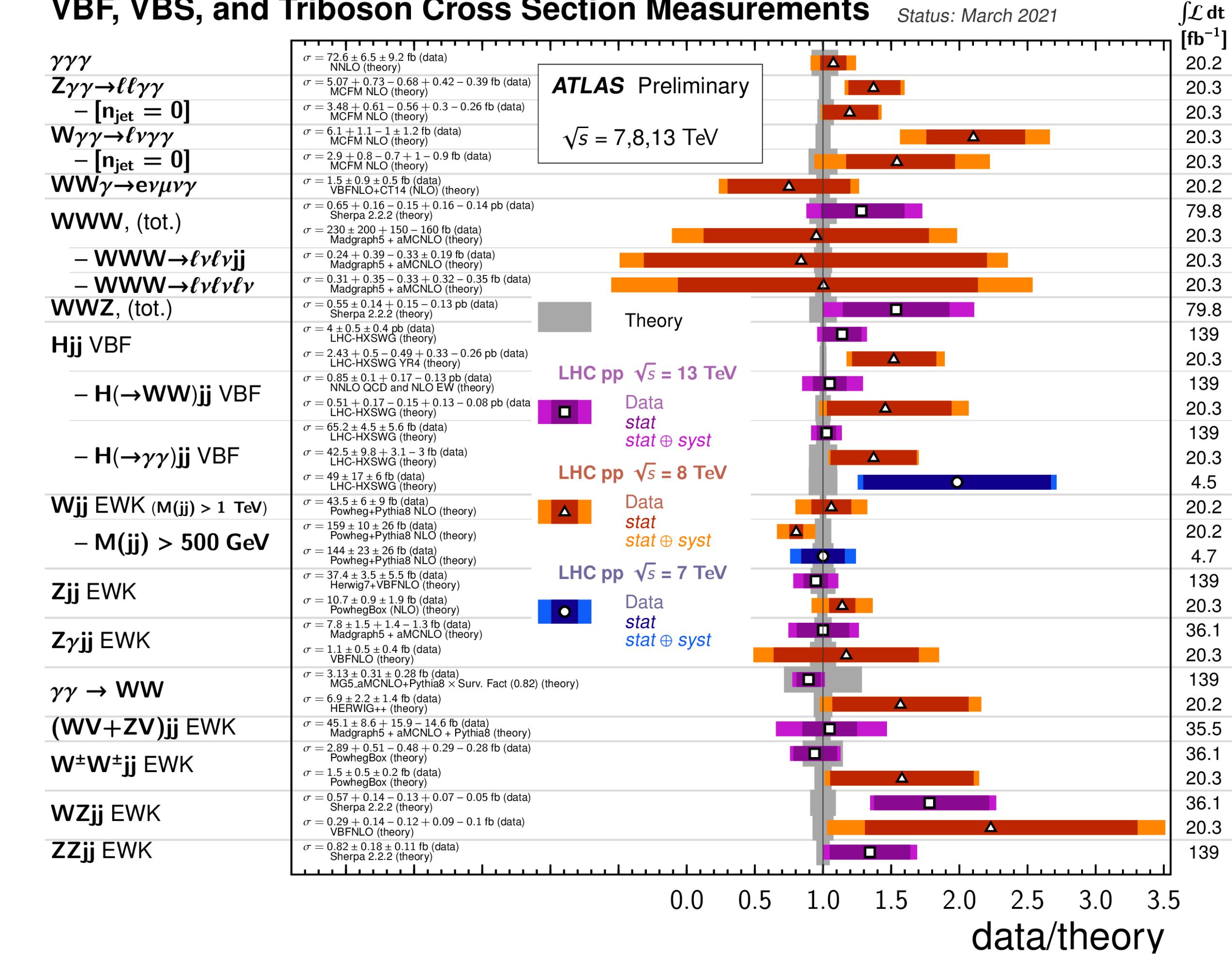
Diboson Cross Section Measurements

Status: March 2021



VBF, VBS, and Triboson Cross Section Measurements

Status: March 2021



Fitting methodology

MCfit generate a large sample of **Monte Carlo replicas** to construct the **probability distribution** in the space of experimental data accounting for all uncertainties

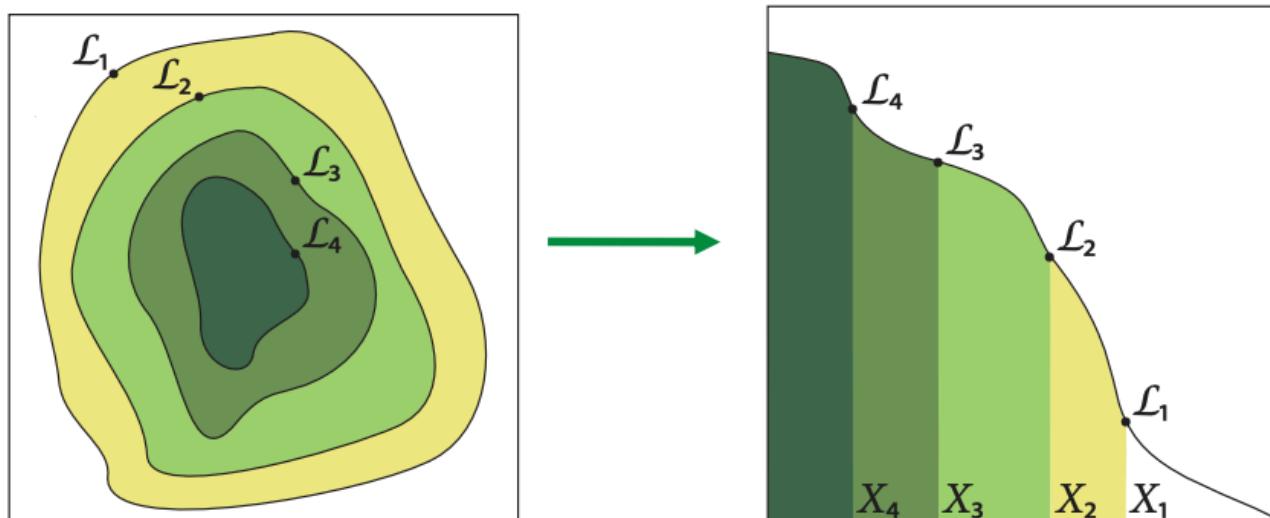
Determine the SMEFT coefficients **replica-by-replica** by minimising a cost function

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\text{dat}}} \sum_{i,j=1}^{N_{\text{dat}}} \left(\mathcal{O}_i^{\text{(th)}} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_i^{\text{(art)(k)}} \right) (\text{cov}^{-1})_{ij} \left(\mathcal{O}_j^{\text{(th)}} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_j^{\text{(art)(k)}} \right)$$

where covariance matrix includes **all sources of experimental + theory errors**

Nested Sampling statistical mapping of the N -dimensional likelihood profile to 1D

$$Z = \int d^N c \mathcal{L}(\text{data} | \vec{c}) \pi(\vec{c}) = \int_0^1 dX \mathcal{L}(X)$$



- Samples directly from prior space to locate **regions of maximum likelihood**
- Main advantage: **no need for optimiser** (fitting)
- Exponential increase in runtime as prior volume increases

Fit output

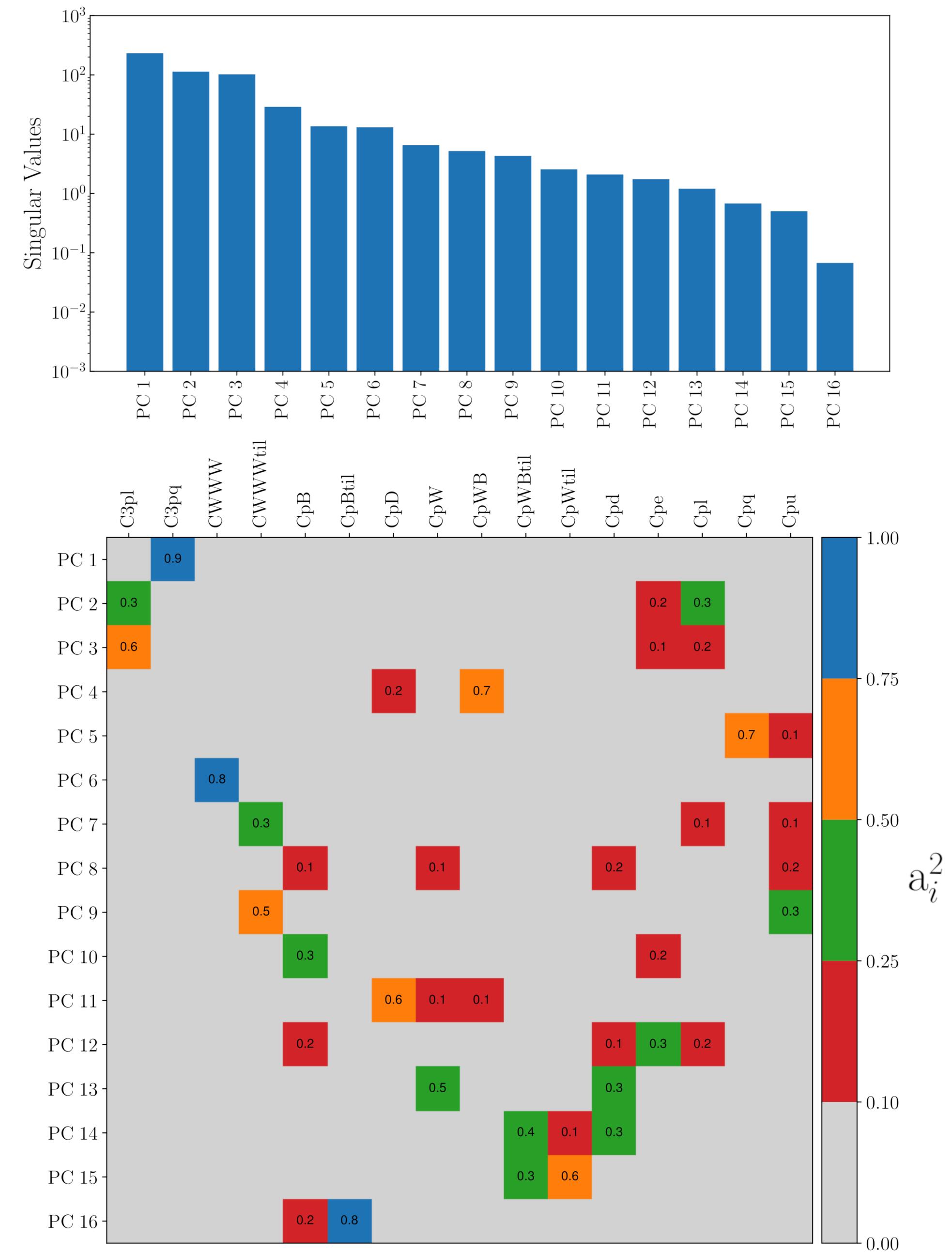
Principal Components Analysis

Trace of:

$$PC_k = \sum_{i=1}^{n_{op}} = a_{k,i}c_i \quad k = 1, \dots n_{op}$$

And normalised per operator.

- ◆ There are NO flat directions in a VV + VBS fit
 - ◆ First PCs contains 2F2H operators.



Fit output

CP EVEN only fit

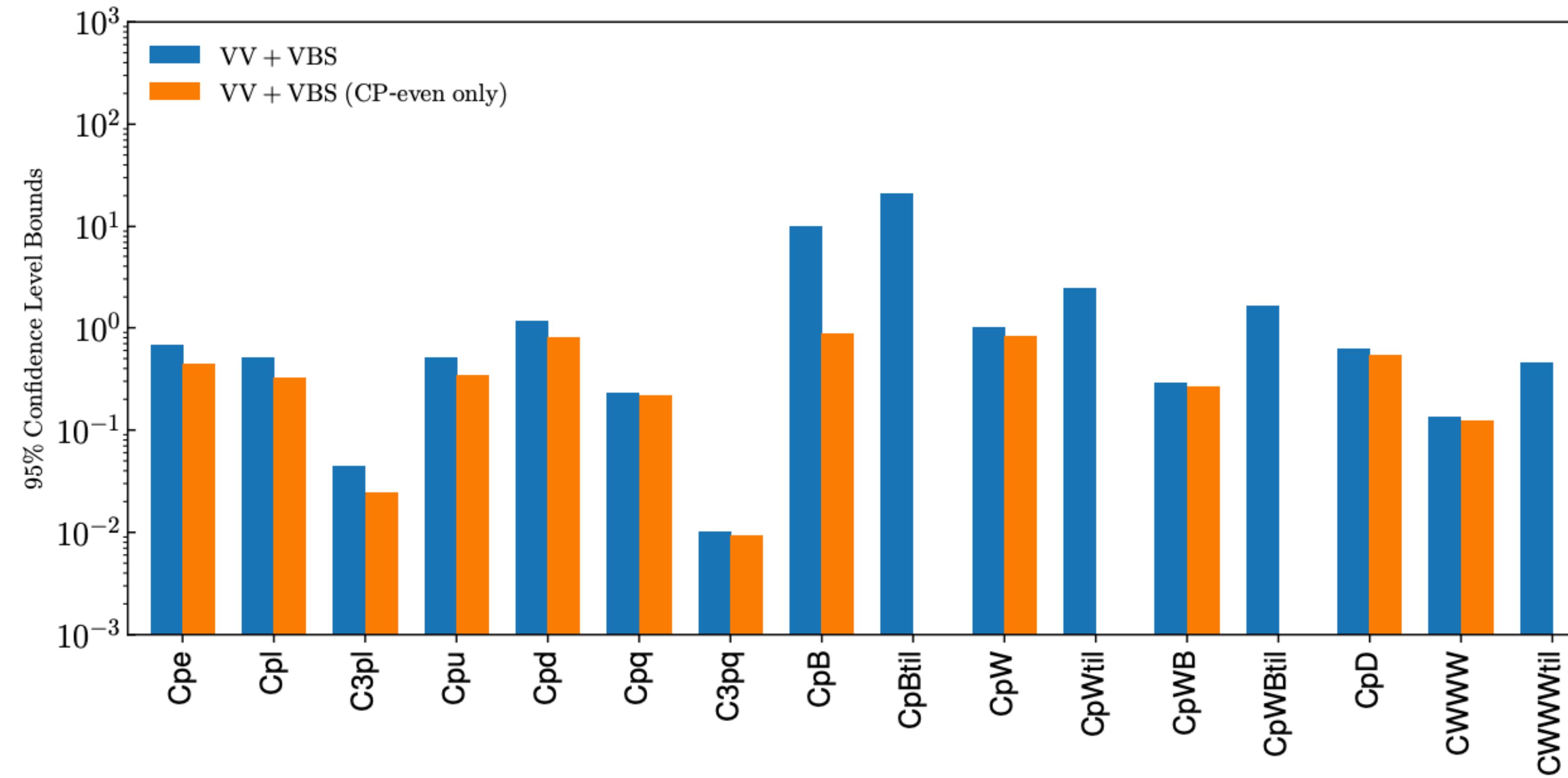


Figure 4.12. Comparing the results of the baseline fit with those of the same fit where the CP-odd operators have been set to zero, such that only the CP-even ones remain.