The VBS viewpoint on the EFT landscape

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Winter 2021 topical meeting on VBS: VBS at Snowmass

The VBS viewpoint on the EFT landscape

Introduction:

- No need no introduce VBS to this audience, excellent overview by Ansgar (here)
- Also excellent overview on the BSM sate-of-the-art, given by Marc (here)
- Latest experimental developments shown by Joanny (here) and Kenneth (here)
- This talk: dim6 EFT interpretation of the former

The VBS viewpoint on the EFT landscape

EFT has been "traditionally" a Higgs-Sector theory

$$\mathscr{L}_{SM} = \sum_i \mathcal{O}_i^{(4)}$$

$$\mathcal{O}^{(6)} = H^\dagger H \, \mathcal{O}^{(4)}$$

With some exceptions:

$$\mathcal{O}_W = \epsilon_{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$$

$$\mathcal{O}_{dip} = \bar{\ell} \sigma_{\mu\nu} e_R \, \varphi W_{\mu\nu}$$

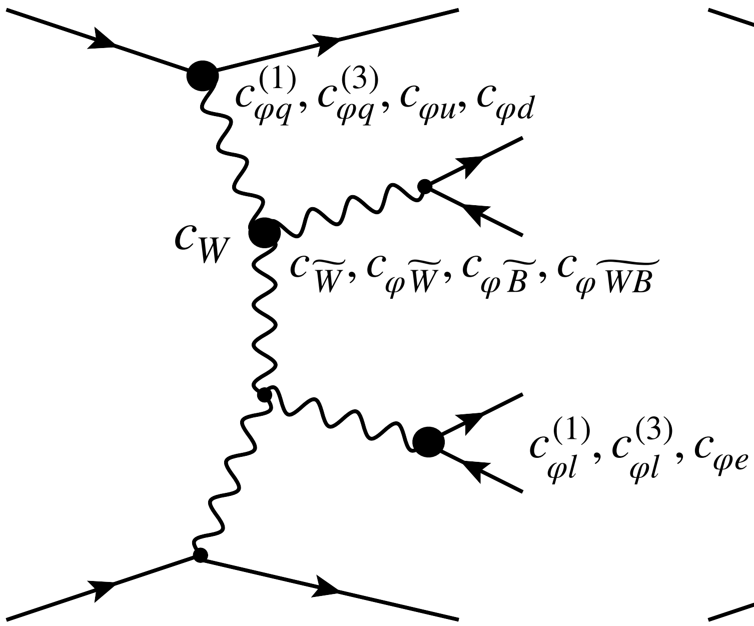
$$\mathcal{O}_8 = \bar{\ell}_1 \ell_1 \, \bar{\ell}_2 \ell_2$$

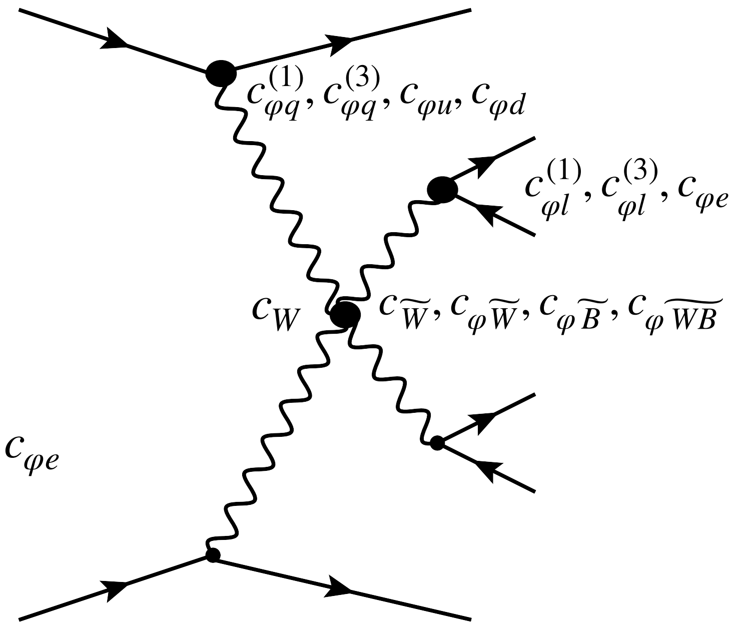
For completeness: the Warsaw basis (2010)

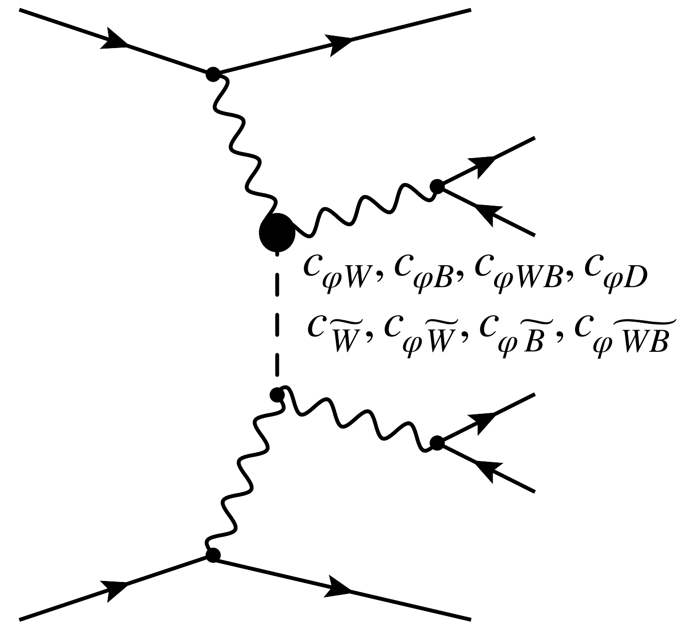
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

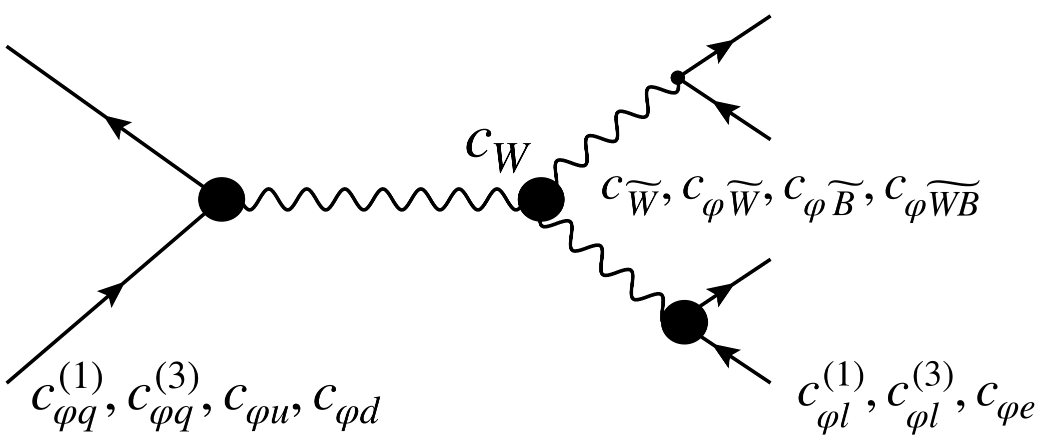
+ fermion operators (for future work)

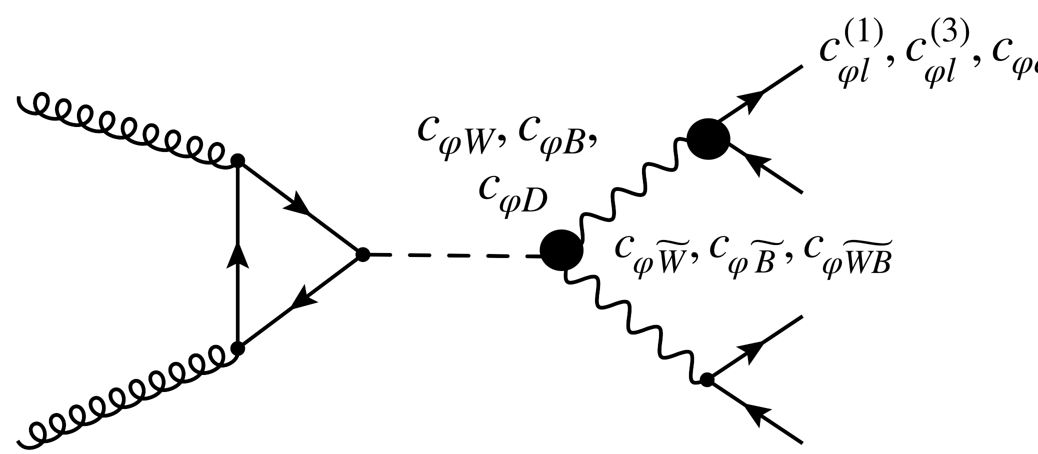
In practise:











TGC/QCG

$$\mathcal{O}_W = \epsilon_{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$$

Small Clarification:

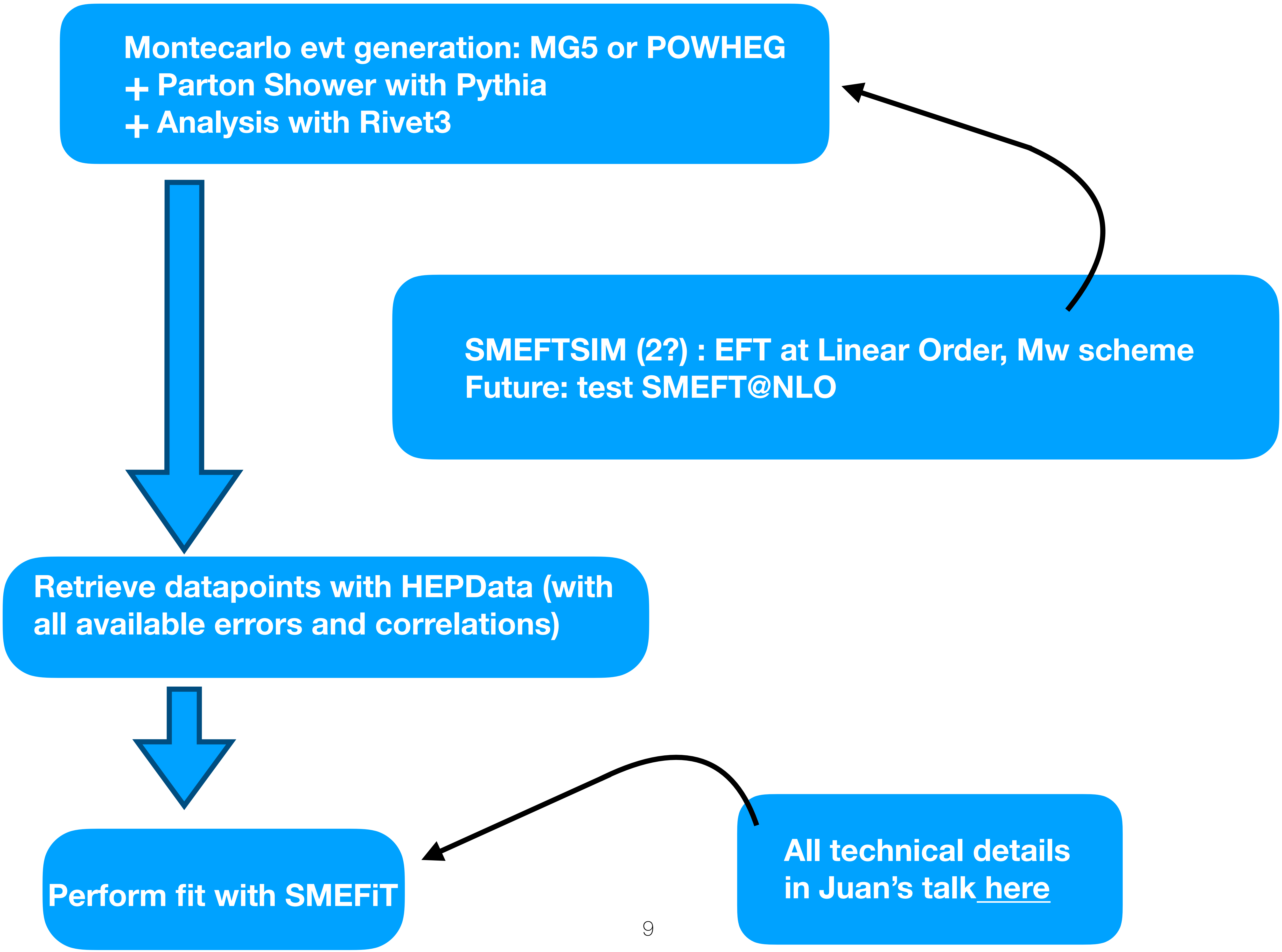
	Enters TGC/QGC	Enters VV/VBS
Warsaw cW	★	★
Warsaw cHW/cHB	X	★
SILH c3W	★	★
SILH cHW/cHB	★	★

“SMEFT analysis of vector boson scattering and diboson data from the LHC Run II ”

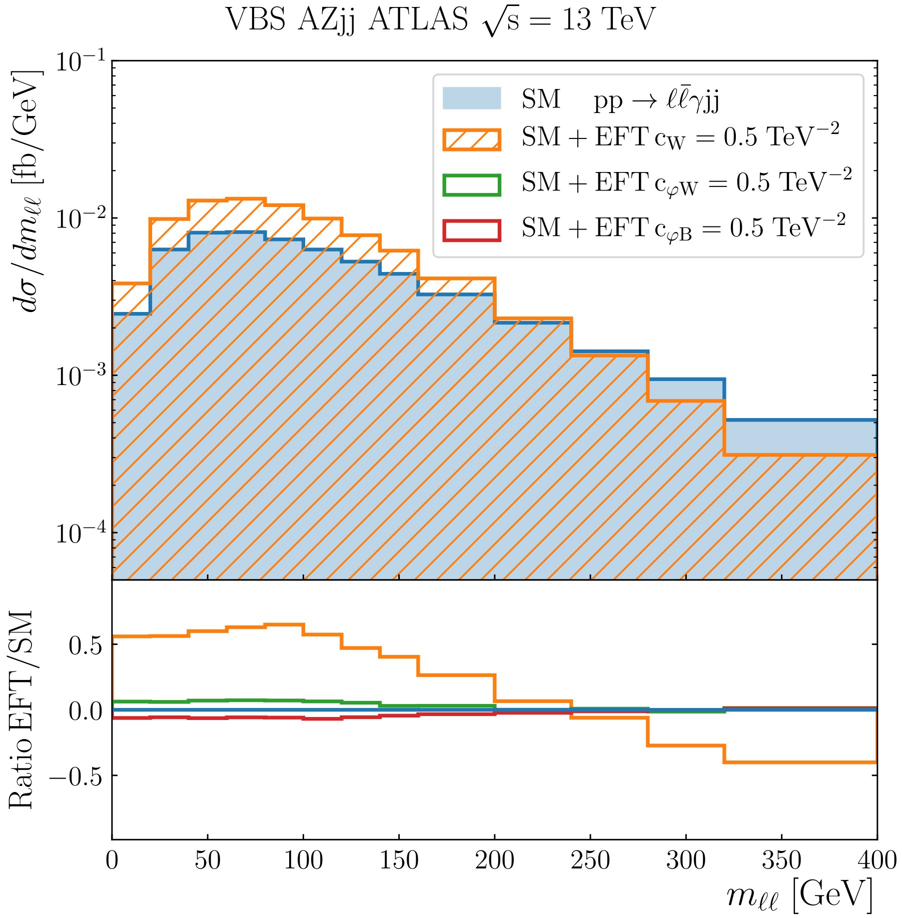
Jacob J. Ethier, Raquel Gomez-Ambrosio, Giacomo Magni, Juan Rojo,

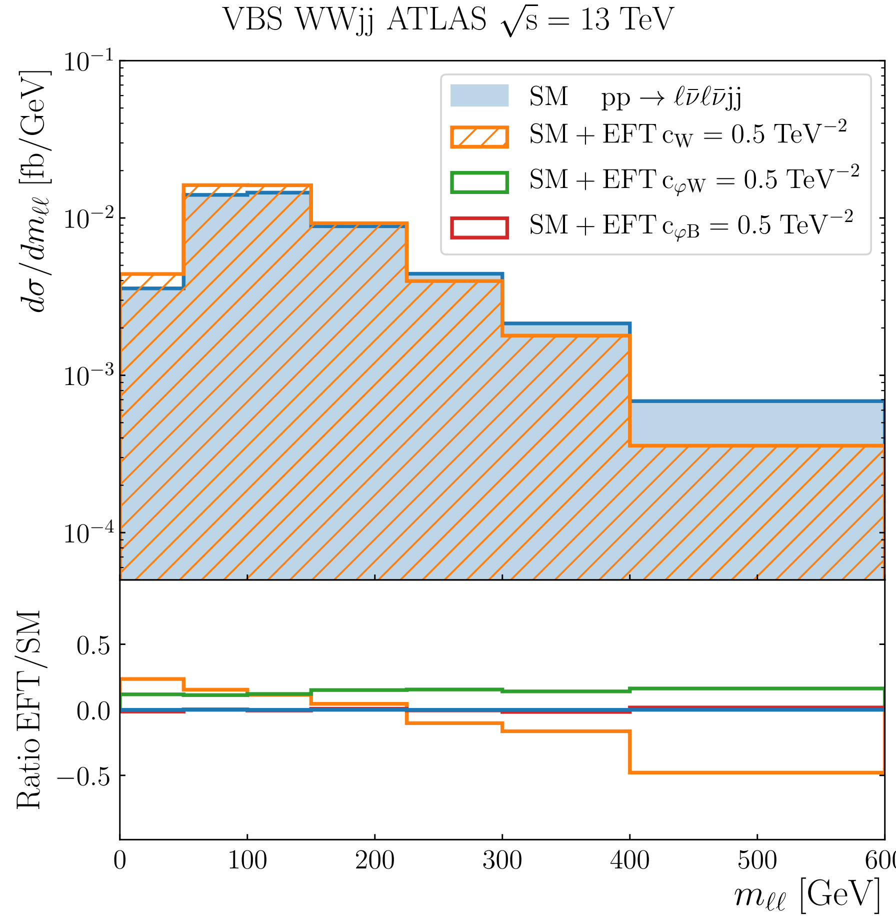
https://arxiv.org/abs/2101.03180

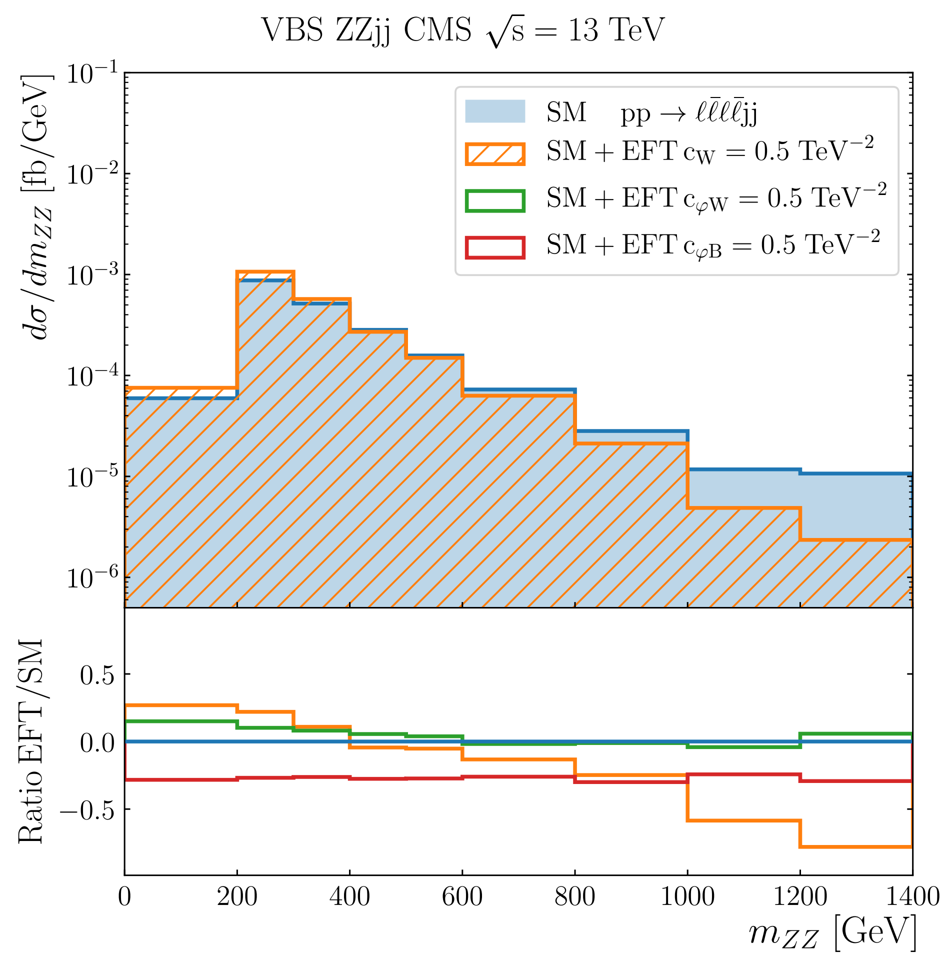
Final state	Selection	Observable	$n_{\rm dat}$	$\mathcal{L}$ (fb^{-1})	Label
$W^{\pm}W^{\pm}jj$	EW-only	$\sigma_{\rm fid}$	1	36.1	ATLAS_WWjj_fid
	EW-only	$\sigma_{\rm fid}$	4	137	CMS_WWjj_fid
	EW+QCD	$d\sigma/dm_{ll}$ $^{(*)}$			CMS_WWjj_mll
$ZW^{\pm}jj$	EW+QCD	$d\sigma/dm_{T_{WZ}}$	5	36.1	ATLAS_WZjj_mwz
	EW-only	$\sigma_{\rm fid}$	4	137	CMS_WZjj_fid
	EW+QCD	$d\sigma/dm_{jj}$ $^{(*)}$			CMS_WZjj_mjj
$ZZjj$	EW+QCD	$\sigma_{\rm fid}$	1	139	ATLAS_ZZjj_fid
	EW-only	$\sigma_{\rm fid}$	1	139	CMS_ZZjj_fid
γZjj	EW-only	$\sigma_{\rm fid}$	1	36.1	ATLAS_AZjj_fid
	EW-only	$\sigma_{\rm fid}$	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**		

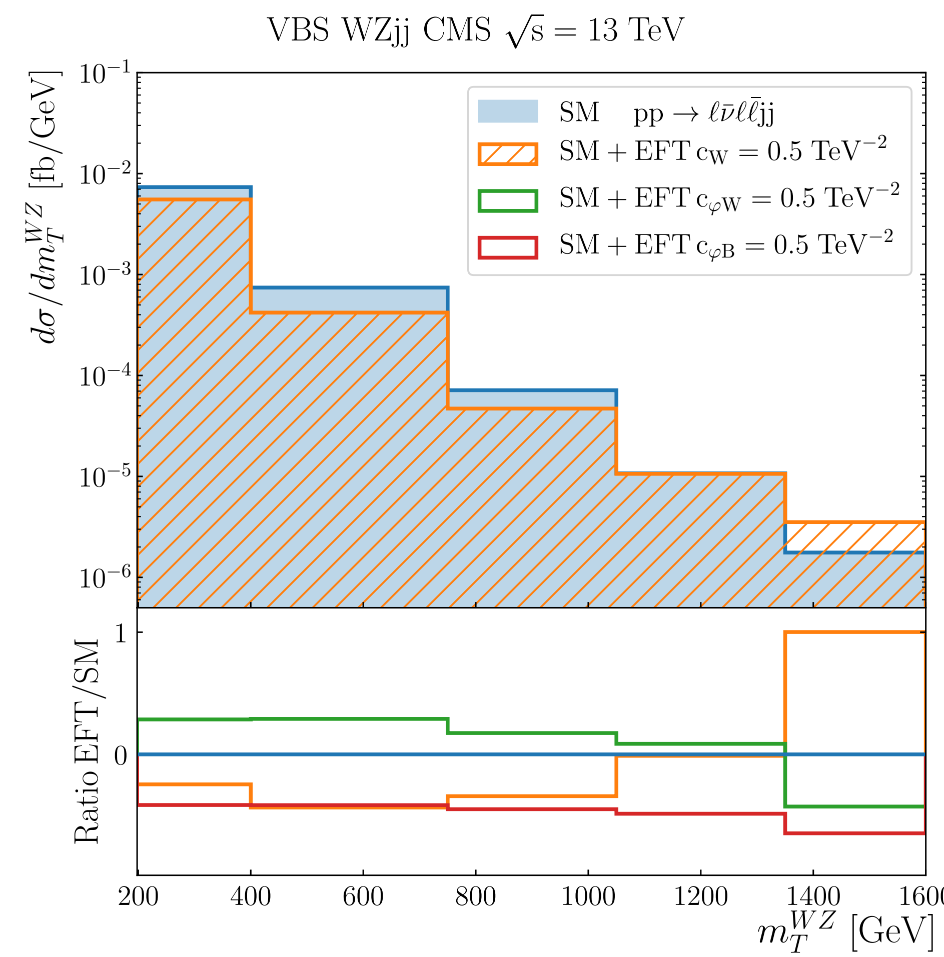

Montecarlo evt generation: MG5 or POWHEG
+ Parton Shower with Pythia
+ Analysis with Rivet3
SMEFTSIM (2?) : EFT at Linear Order, Mw scheme
Future: test SMEFT@NLO
Retrieve datapoints with HEPData (with all available errors and correlations)
Perform fit with SMEFiT
All technical details in Juan's talk here

RESULTS


VBS AZjj ATLAS $\sqrt{s} = 13$ TeV
SM pp → $\ell\bar{\ell}\gamma jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_{\ell\ell}$ [fb/GeV]
Ratio EFT/SM
$m_{\ell\ell}$ [GeV]


VBS WWjj ATLAS $\sqrt{s} = 13$ TeV
SM pp → $\ell\bar{\nu}\ell\bar{\nu}jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_{\ell\ell}$ [fb/GeV]
Ratio EFT/SM
$m_{\ell\ell}$ [GeV]

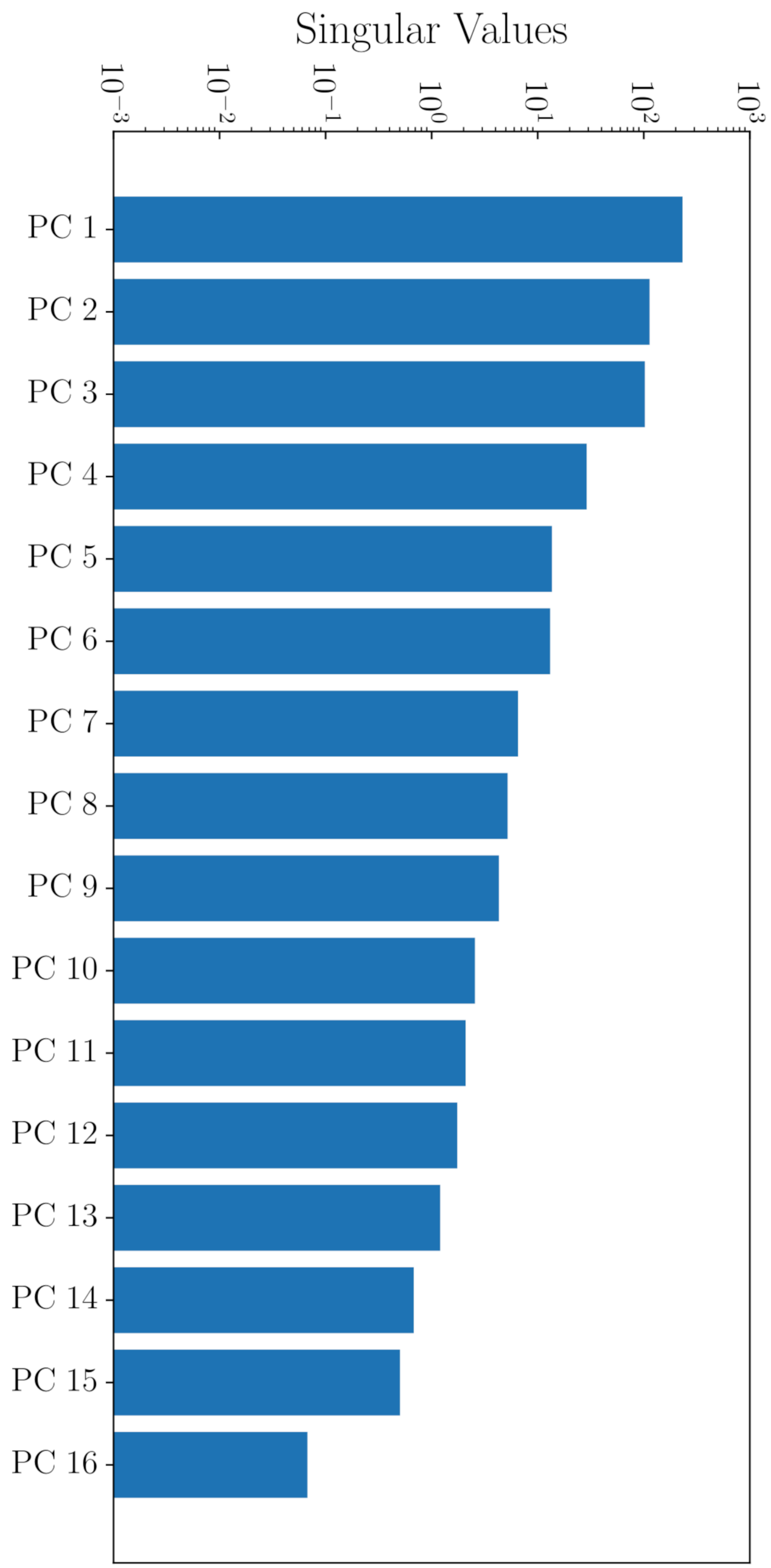

VBS ZZjj CMS $\sqrt{s} = 13$ TeV
SM pp → $\ell\bar{\ell}\ell\bar{\ell}jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_{ZZ}$ [fb/GeV]
Ratio EFT/SM
m_{ZZ} [GeV]


VBS WZjj CMS $\sqrt{s} = 13$ TeV
SM pp → $\ell\bar{\nu}\ell\bar{\ell}jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_T^{WZ}$ [fb/GeV]
Ratio EFT/SM
m_T^{WZ} [GeV]

Quality of the Dataset

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**

Principal Component Analysis



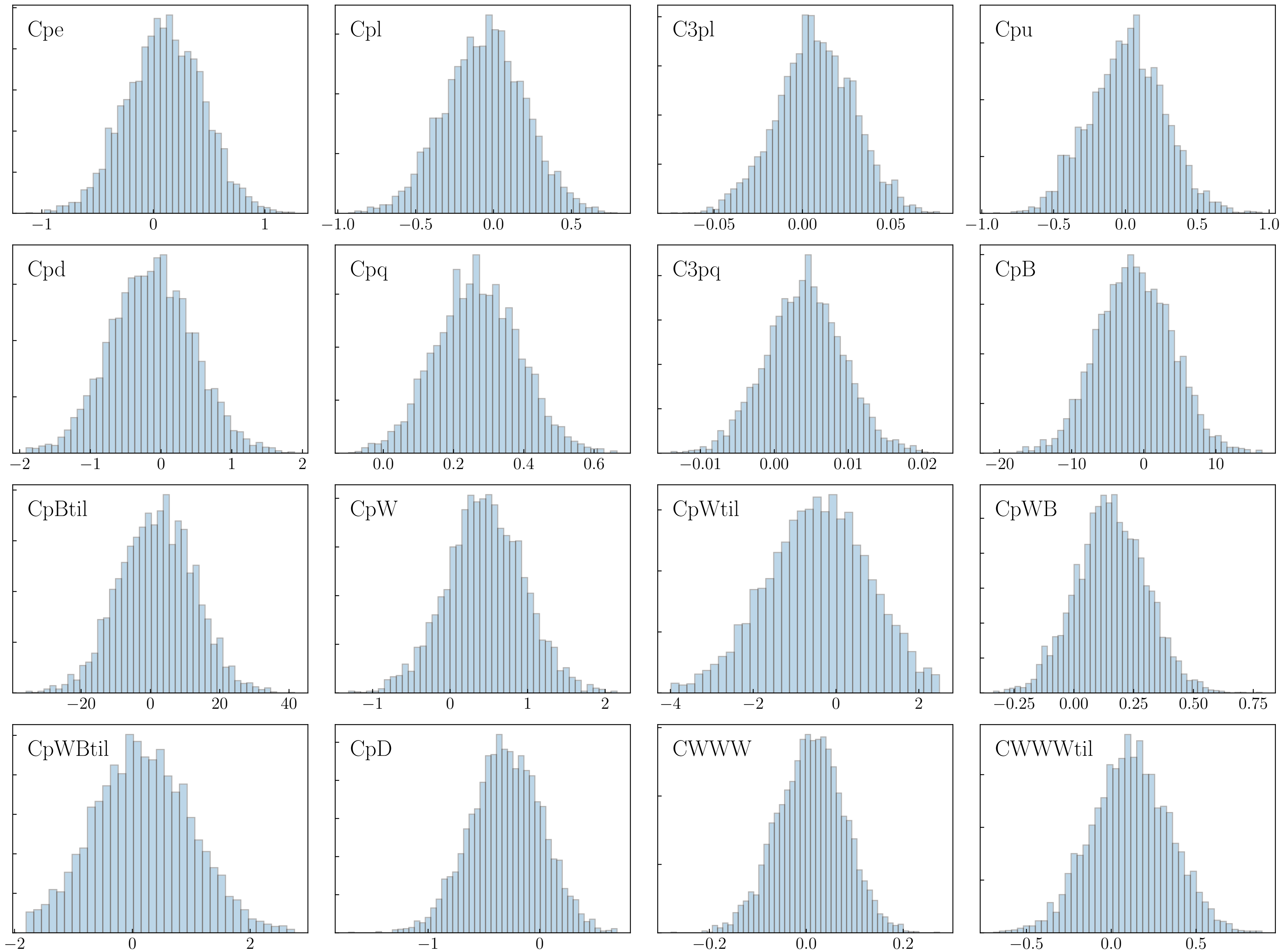
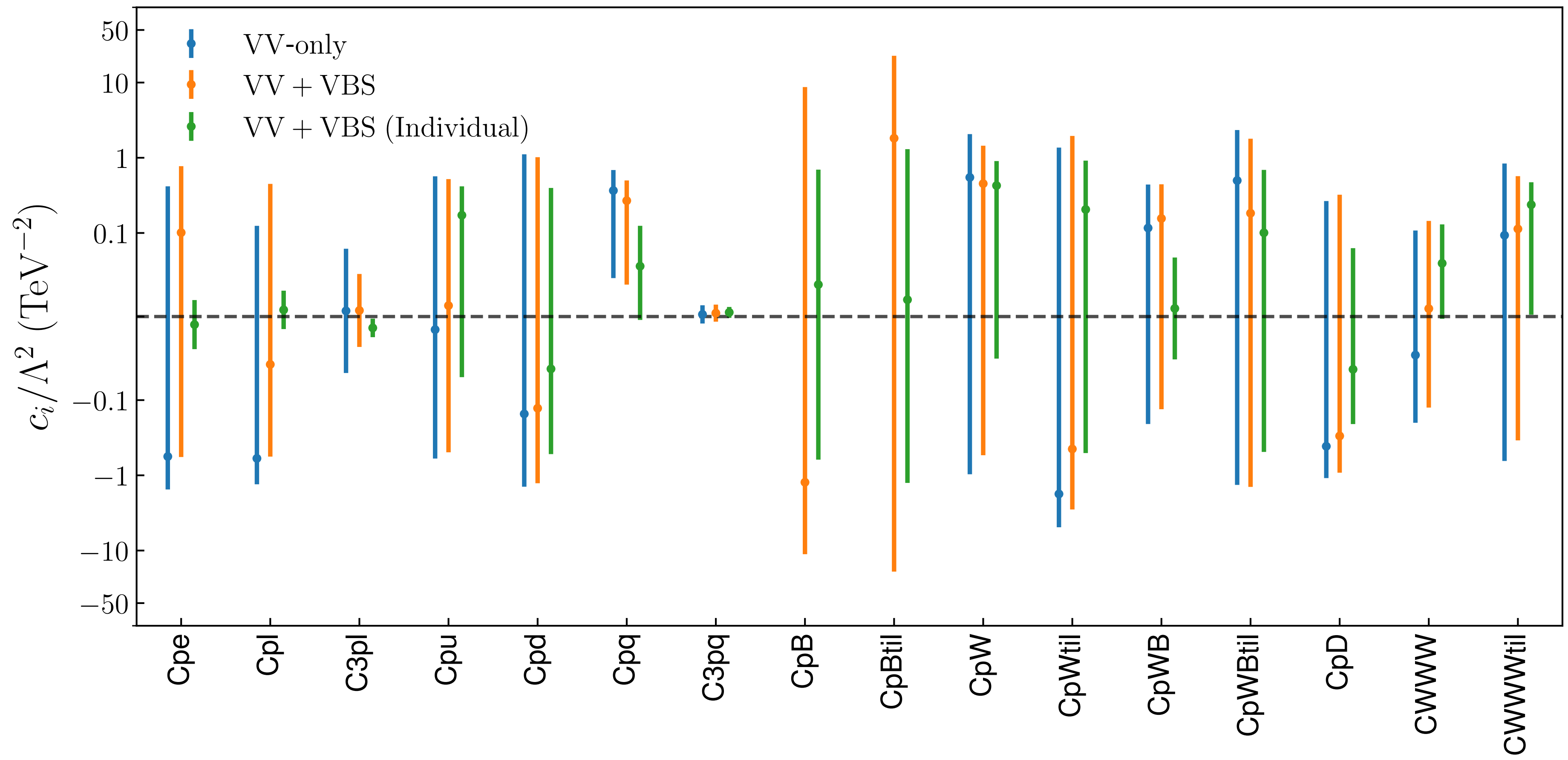
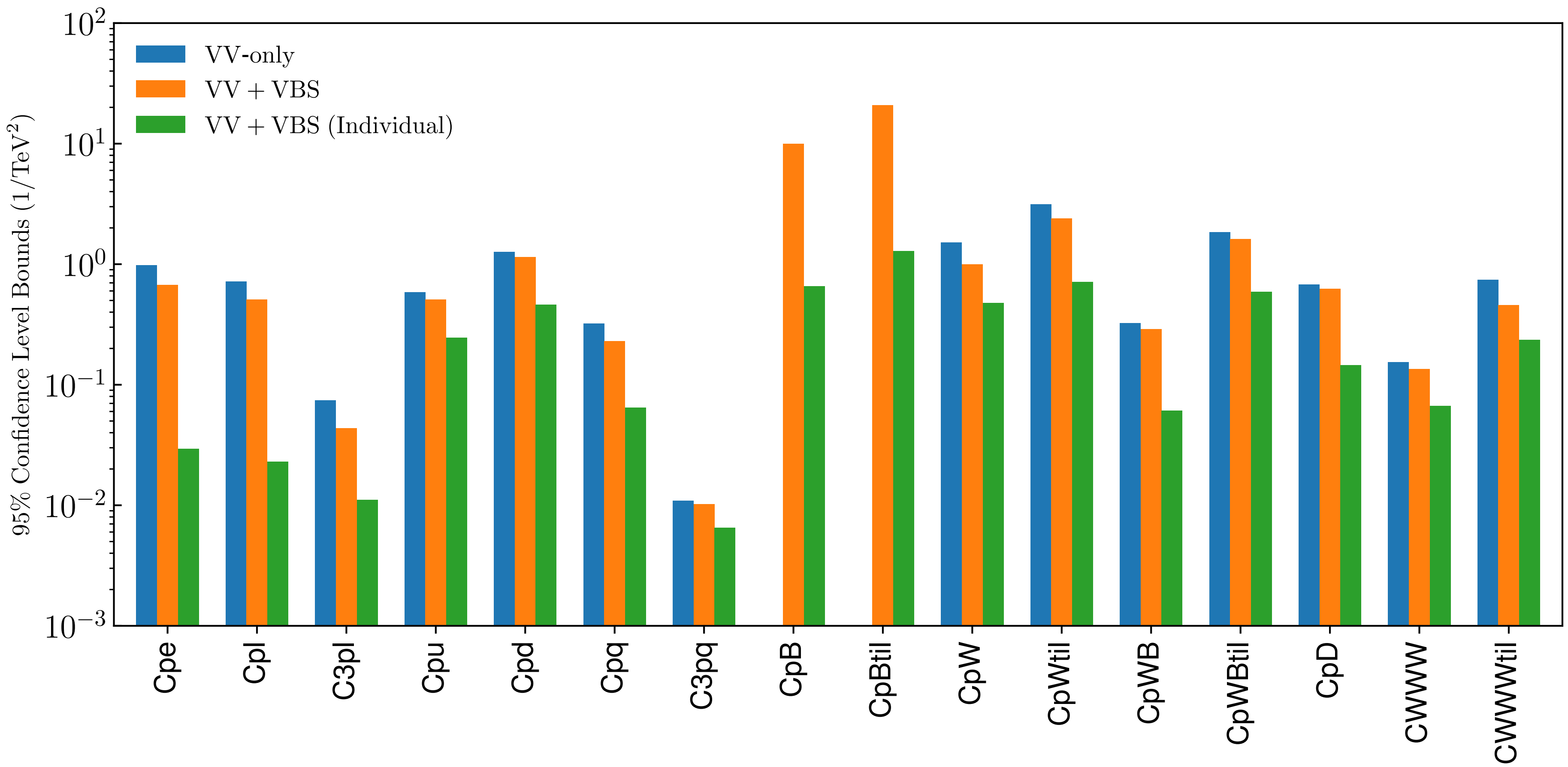


Figure 4.4. The posterior probability distributions associated to each of the $n_{\rm op} = 16$ coefficients that are constrained in this analysis for the baseline dataset. Note that the x-axis ranges are different for each coefficient.

Results (qualitative)



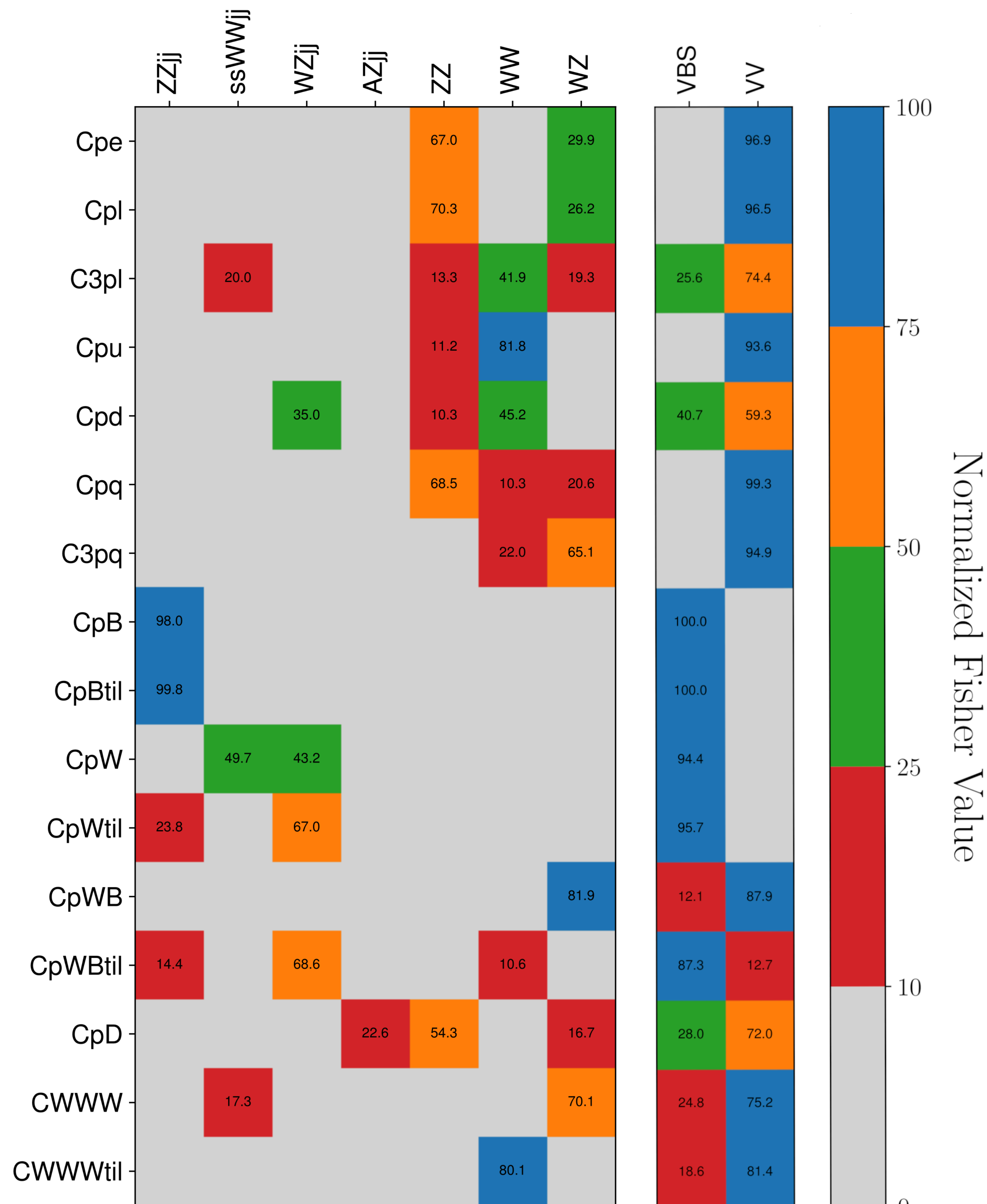


Results (quantitative)

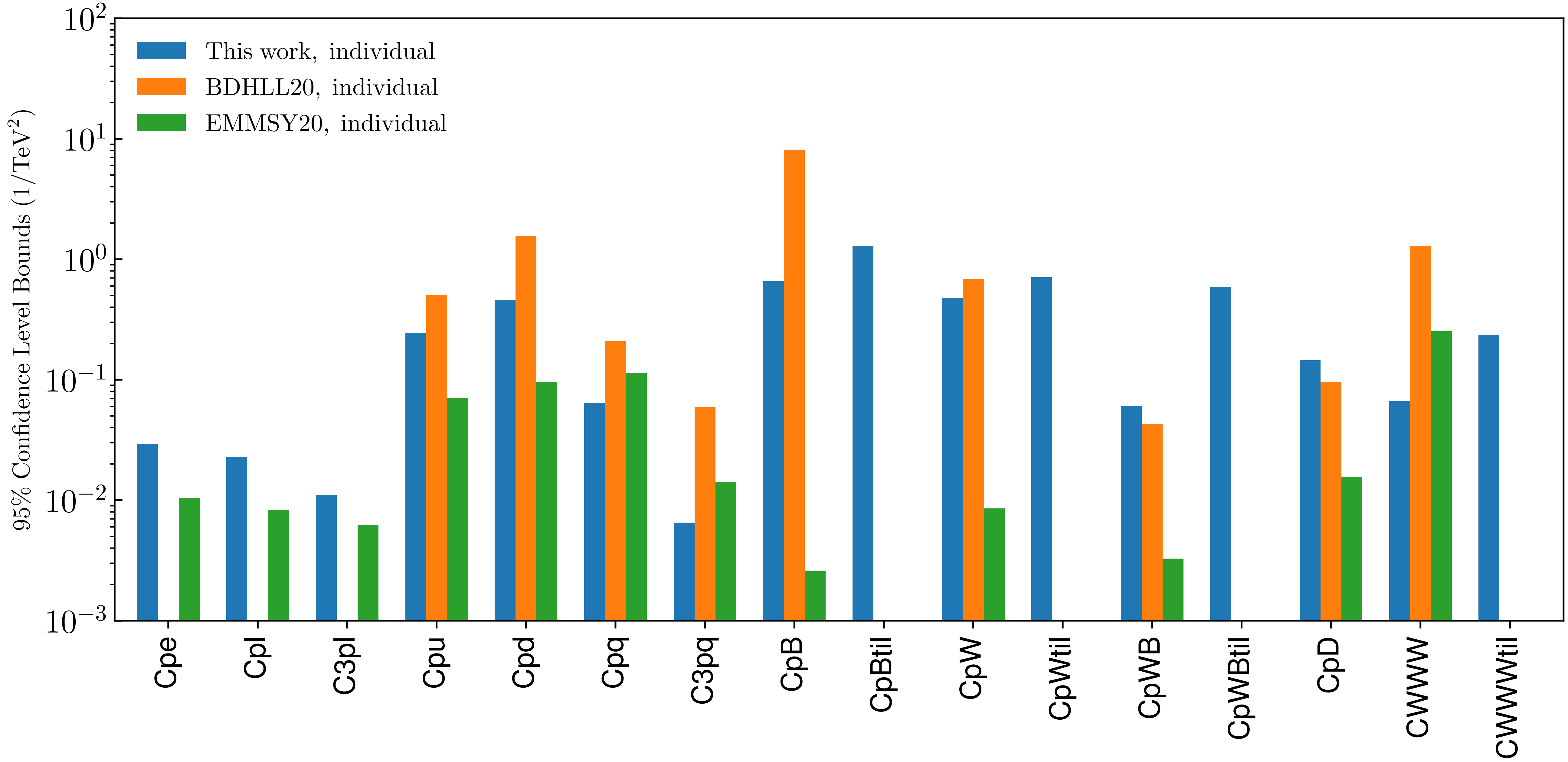
Class	Coefficient	VBS+diboson (marginalised)	VBS+diboson (individual)	Diboson-only (marginalised)
purely bosonic (CP-even)	c_W	[-0.13, 0.14]	[-0.001, 0.13]	[-0.20, 0.11]
	$c_{\varphi W}$	[-0.55, 1.4]	[-0.048, 0.91]	[-0.97, 2.1]
	$c_{\varphi B}$	[-11, 8.8]	[-0.62, 0.69]	—
	$c_{\varphi WB}$	[-0.13, 0.44]	[-0.050, 0.071]	[-0.20, 0.44]
	$c_{\varphi D}$	[-0.93, 0.32]	[-0.21, 0.08]	[-1.09, 0.26]
purely bosonic (CP-odd)	$c_{\widetilde{W}}$	[-0.35, 0.57]	[-0.008, 0.46]	[-0.63, 0.85]
	$c_{\varphi \widetilde{W}}$	[-2.9, 1.8]	[-0.49, 0.93]	[-4.9, 1.3]
	$c_{\varphi \widetilde{W} B}$	[-1.4, 1.8]	[-0.49, 0.69]	[-1.3, 2.4]
	$c_{\varphi \widetilde{B}}$	[-19, 23]	[-1.2, 1.4]	—
two-fermion	$c_{\varphi l}^{(1)}$	[-0.56, 0.45]	[-0.015, 0.031]	[-1.3, 0.12]
	$c_{\varphi l}^{(3)}$	[-0.037, 0.051]	[-0.024, -0.002]	[-0.068, 0.081]
	$c_{\varphi q}^{(1)}$	[0.043, 0.50]	[-0.007, 0.12]	[0.038, 0.68]
	$c_{\varphi q}^{(3)}$	[-0.002, 0.011]	[-0.006, 0.014]	[-0.008, 0.013]
	$c_{\varphi e}$	[-0.58, 0.77]	[-0.038, 0.021]	[-1.5, 0.41]
	$c_{\varphi u}$	[-0.49, 0.53]	[-0.073, 0.42]	[-0.59, 0.58]
	$c_{\varphi d}$	[-1.3, 1.0]	[-0.53, 0.39]	[-1.4, 1.2]

Table 4.2 of 2101.03180

Fisher information



Comparison with Higgs fits



J. Baglio, S. Dawson, S. Homiller, S. D. Lane, and I. M. Lewis, *Validity of standard model EFT studies of VH and VV production at NLO*, *Phys. Rev. D* **101** (2020), no. 11 115004, [arXiv:2003.07862].

J. Ellis, M. Madigan, K. Mimasu, V. Sanz, and T. You, *Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory*, arXiv:2012.02779.

A TOY MODEL FOR HL-LHC

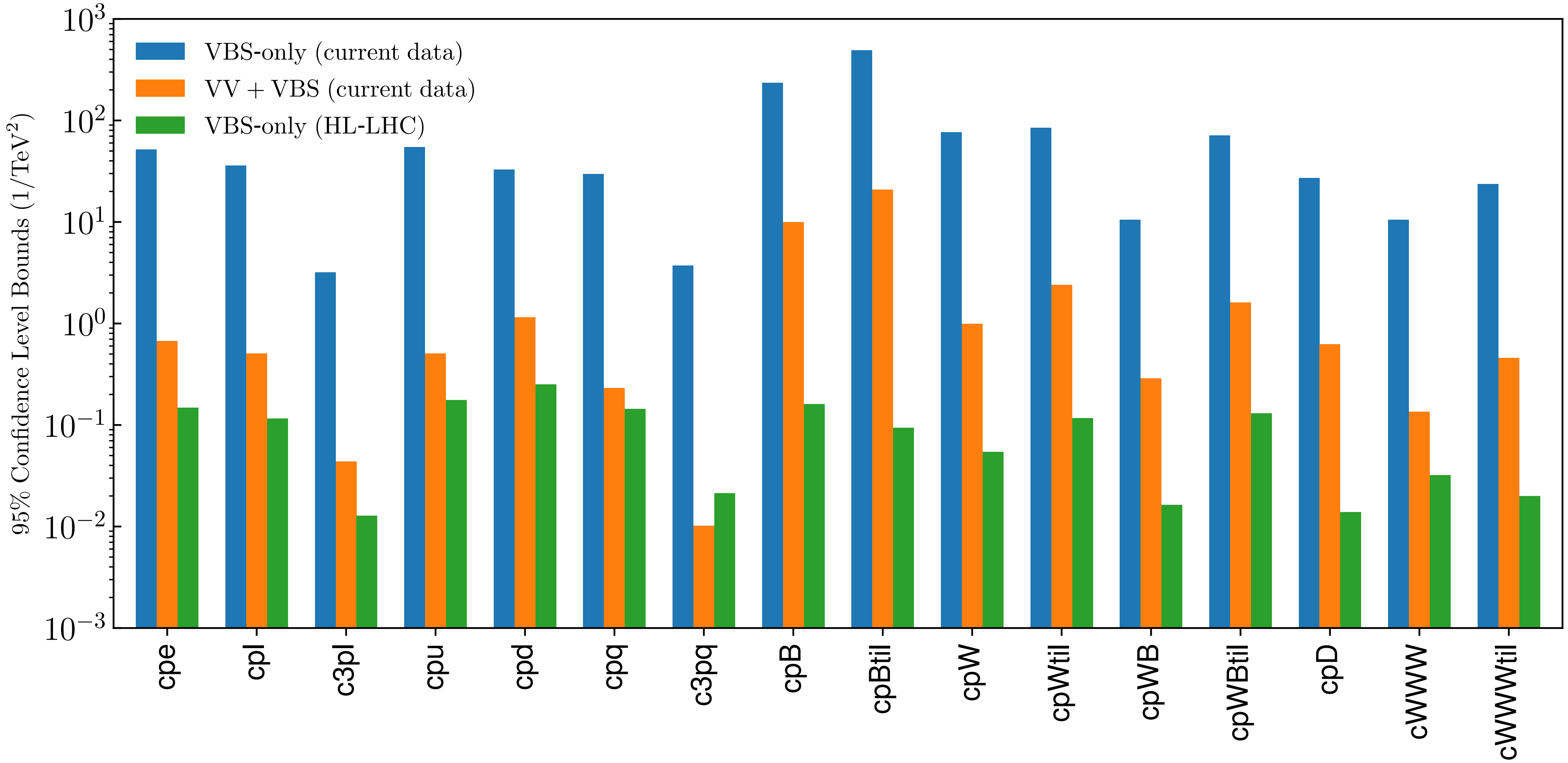
See previous talks for HL-LHC prospects

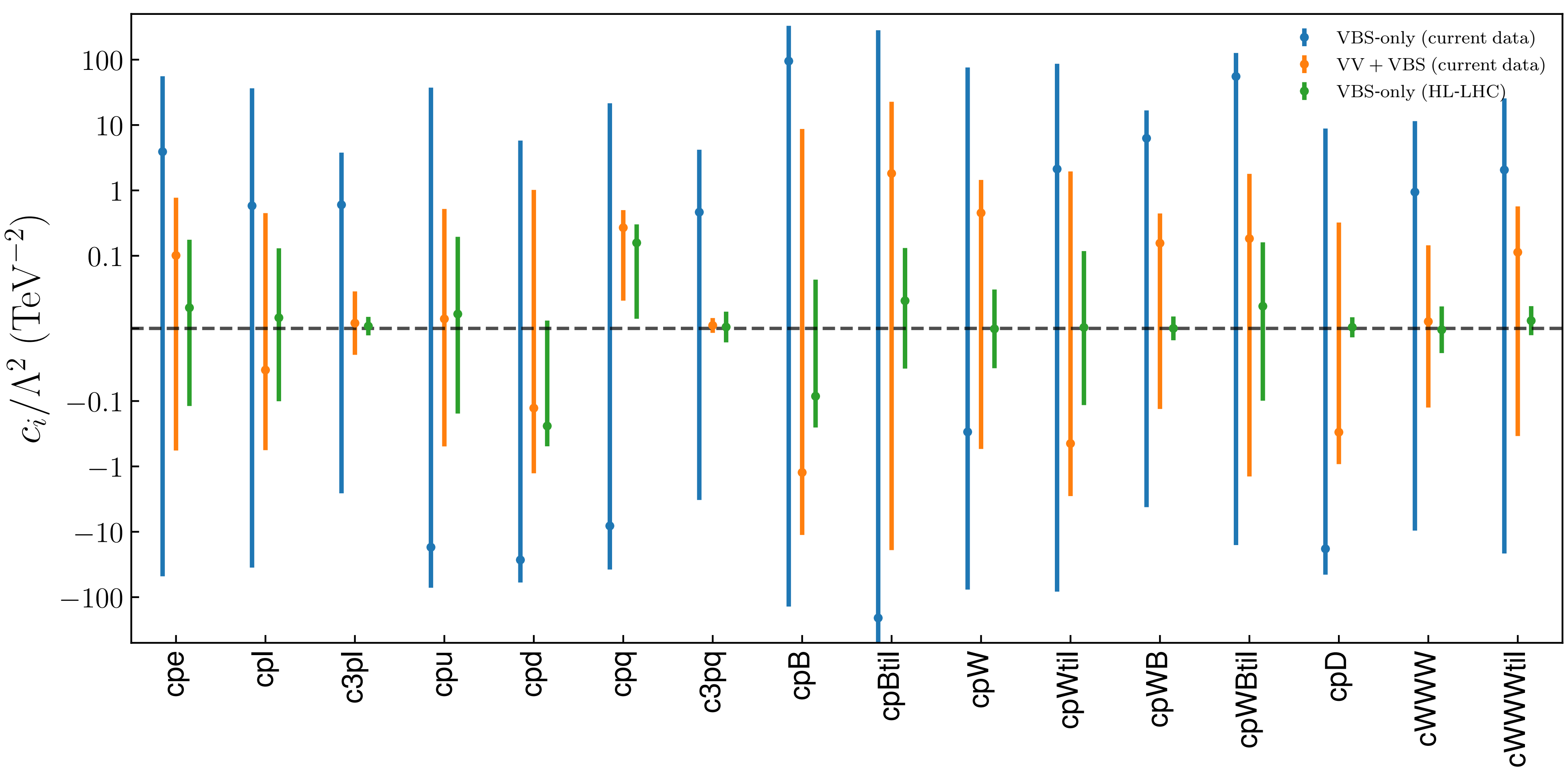
Generate *pseudodata*, assuming SM as hypothesis

$$\sigma_i^{\mathrm{hllhc}} \equiv \sigma_i^{\mathrm{th}}\left(1 + r_i \delta_{\mathrm{tot},i}^{\mathrm{exp}}\right) , \qquad i = 1, \ldots , n_{\mathrm{bin}} ,$$

Keep same binning as LHC, assume clean extraction of the signal. Systematic errors reduced by 50% (inline with projections) , stat error reduced to 20% (based on lumi), gaussian shape

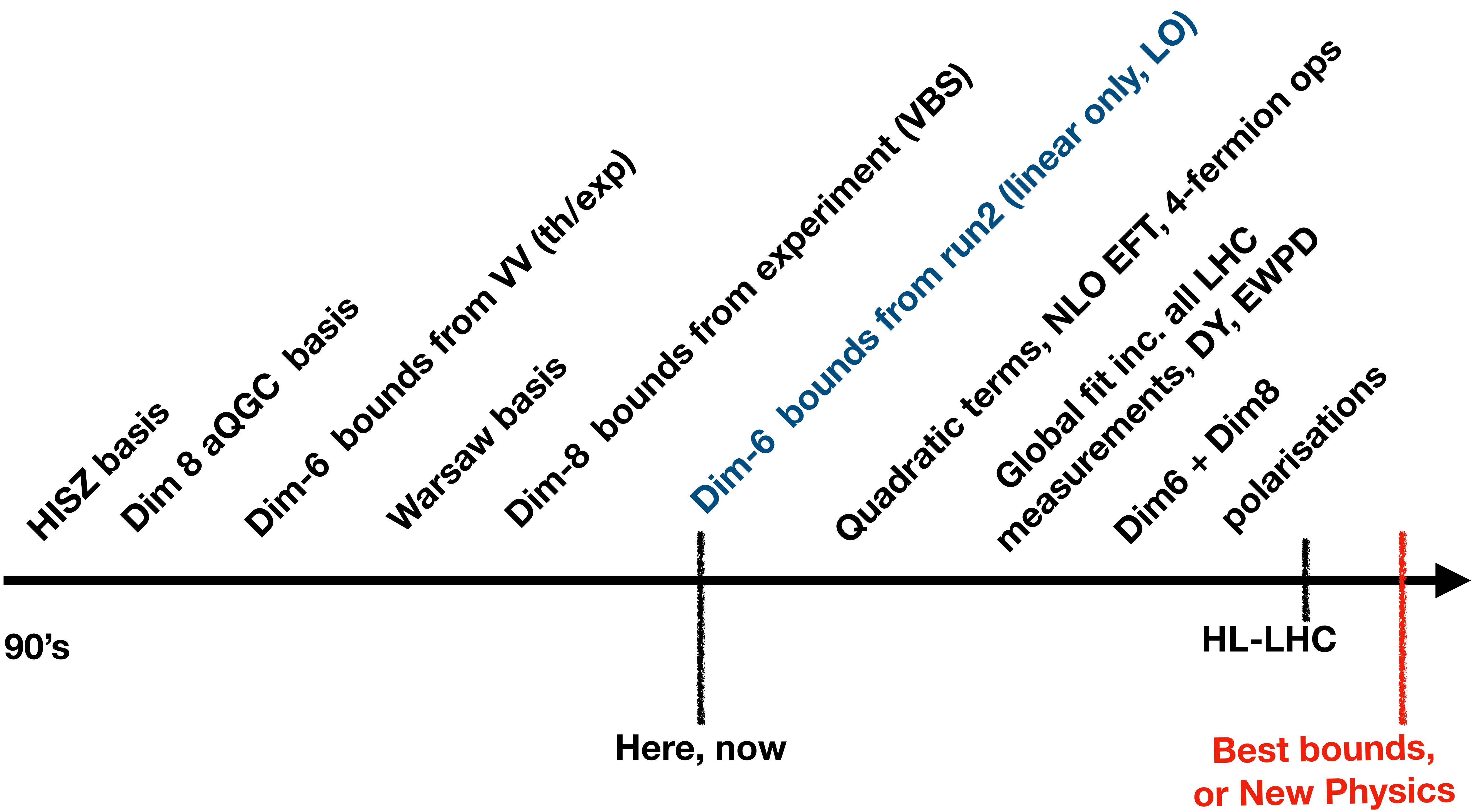
Final state	Selection	Observable	n_{dat}	$\mathcal{L}$ (ab^{-1})
$W^\pm W^\pm jj$	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_{ll}$	7	3
	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_{ll}$	4	3
$ZW^\pm jj$	EW-induced	$\mathrm{d}\sigma/\mathrm{d}p_{T_{\ell\ell\ell}}$	5	3
	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_T^{WZ}$	5	3
$ZZjj$	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_{ZZ}$	9	3
	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_{ZZ}$	9	3
γZjj	EW-induced	$\mathrm{d}\sigma/\mathrm{d}p_T^{\gamma\ell\ell}$	13	3
	EW-induced	$\mathrm{d}\sigma/\mathrm{d}m_{\gamma Z}$	9	3
HL-LHC VBS total			**61**	


VBS-only (current data)
VV + VBS (current data)
VBS-only (HL-LHC)
95% Confidence Level Bounds (1/TeV^2)
cpe
cpl
c3pl
cpu
cpd
cpq
c3pq
cpB
cpBtil
cpW
cpWtil
cpWB
cpWBtil
cpD
cWWW
cWWWtil


VBS-only (current data)
VV + VBS (current data)
VBS-only (HL-LHC)
c_i/Λ^2 (TeV^{-2})
cpe
cpl
c3pl
cpu
cpd
cpq
c3pq
cpB
cpBtil
cpW
cpWtil
cpWB
cpWBtil
cpD
cWWW
cWWWtil

NEXT STEPS

This project in context



The TO-DO list is very substantial…

- (quoting Ansgar) we need to establish priorities:
  - Quadratic + NLO EFT (NLO QCD, EW?)
  - Dim 6 + Dim 8 VBS interpretation
  - Global fit of LHC data
  - Polarisation studies
  - Other HL-LHC projections, BSM regions?

THANKS

BACKUP

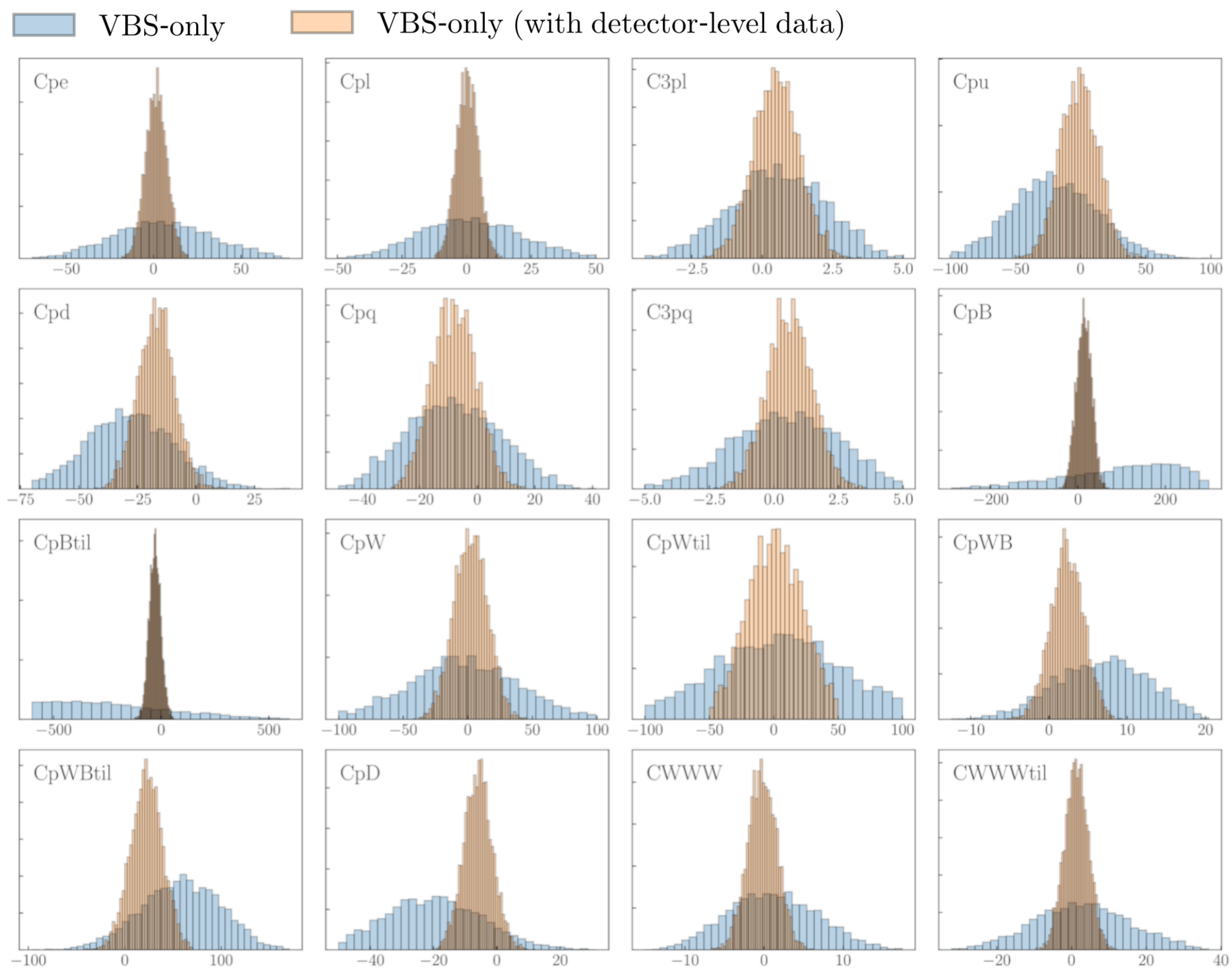
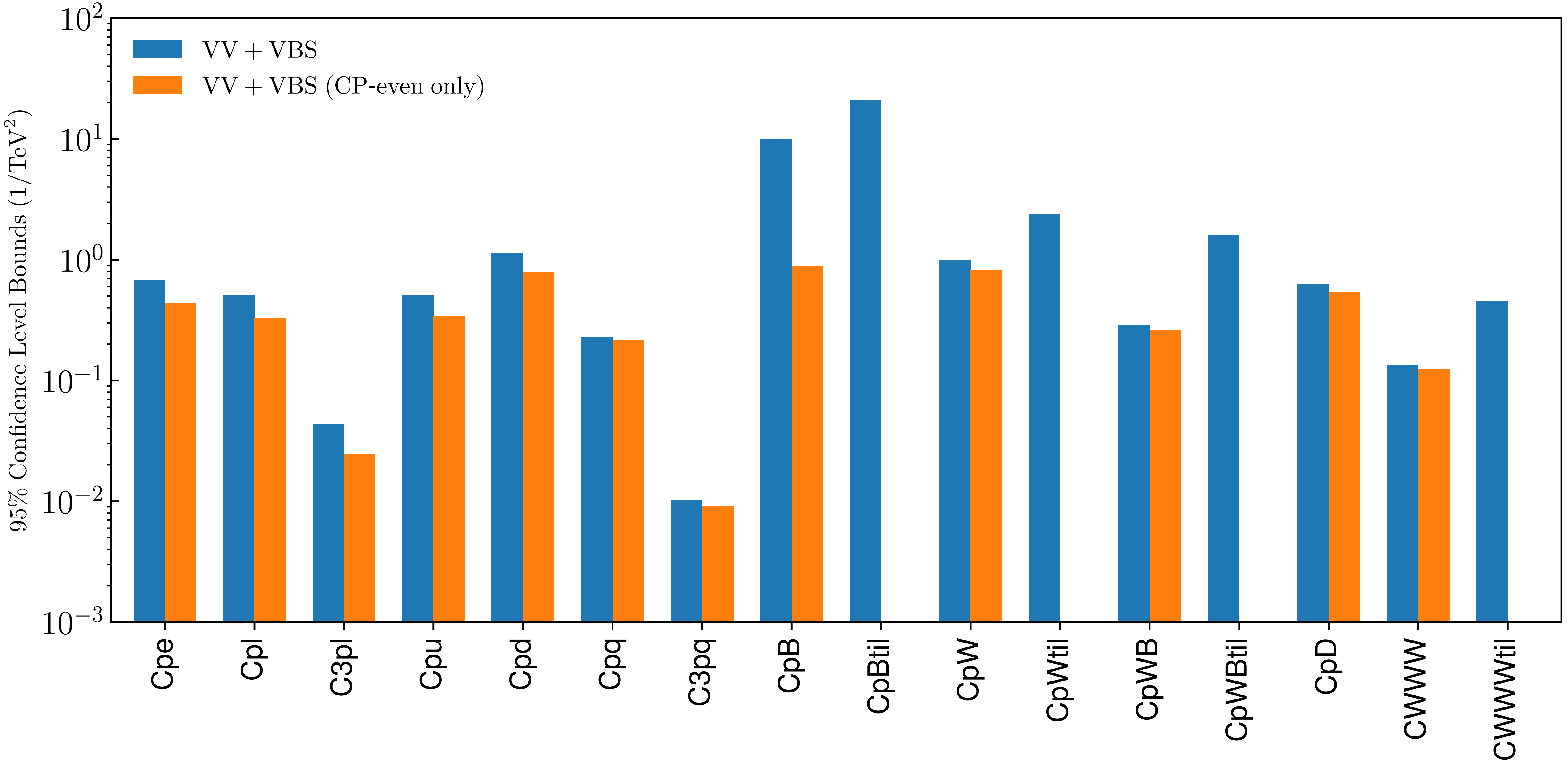


Figure 4.10. Posterior distributions associated to the VBS-only fits that include only unfolded cross-sections (blue) and also the detector-level distributions (orange).

BACKUP


VV + VBS
VV + VBS (CP-even only)
95% Confidence Level Bounds (1/TeV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Cpe
Cpl
C3pl
Cpu
Cpd
Cpq
C3pq
CpB
CpBtil
CpW
CpWtil
CpWB
CpWBtil
CpD
CWWW
CWWWtil