A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC

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Motivation of the study

- EFT sensitivity reach of Vector Boson Scattering to dim6 SMEFT operators

- LHC moving towards global EFT combination → What's the expected interplay of VBS and WW in constraining dim6 SMEFT Wilson Coefficients?

  - Effects of including EFT in QCD induced backgrounds

  - Study optimal kinematic variables for each operator / channel

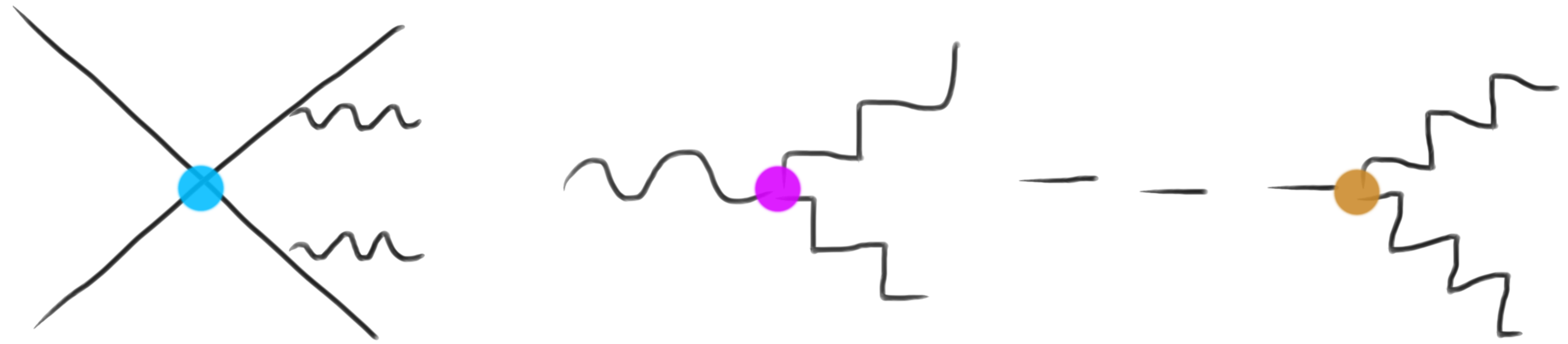
  - Perform profiled fits

SMEFT and MC Generations

- 14 dim-6 SMEFT operators with various field content from Warsaw basis [arXiv:1008.4884v3].
- Generated at LO with SMEFTsim [arXiv: 2012.11343] + MadGraph5_aMC@NLO (2.6.5).
- Insertion of one operator per diagram in production/decay.
- $U(3)^5$ flavour symmetry, $\{m_W, m_Z, G_F\}$ input scheme, CP-even, Λ = 1 TeV.

$Q_{qq}^{(1)} = (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r)$	$Q_{qq}^{(1,1)} = (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$
$Q_{qq}^{(3)} = (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r)$	$Q_{qq}^{(3,1)} = (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$
$Q_{ll}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$	$Q_W = \varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{HW} = (H^\dagger H) W_{\mu\nu}^i W^{i\mu\nu}$
$Q_{HWB} = (H^\dagger\sigma^i H) W_{\mu\nu}^i B^{\mu\nu}$	$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$
$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$	$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_p)$
$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$	$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_p)$

4-fermion, hVV, gauge, EW-input, Vff



$$N \propto \overbrace{|\mathscr{A}_{\mathrm{SM}}|^2}^{\text{SM}} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\Re(\mathscr{A}_{\mathrm{SM}}\mathscr{A}_{Q_\alpha}^\dagger)}_{\text{Lin}} + \frac{c_\alpha^2}{\Lambda^4} \cdot \overbrace{|\mathscr{A}_{Q_\alpha}|^2}^{\text{Quad}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\Re(\mathscr{A}_{Q_\alpha}\mathscr{A}_{Q_\beta}^\dagger)}_{\text{Mix}}$$

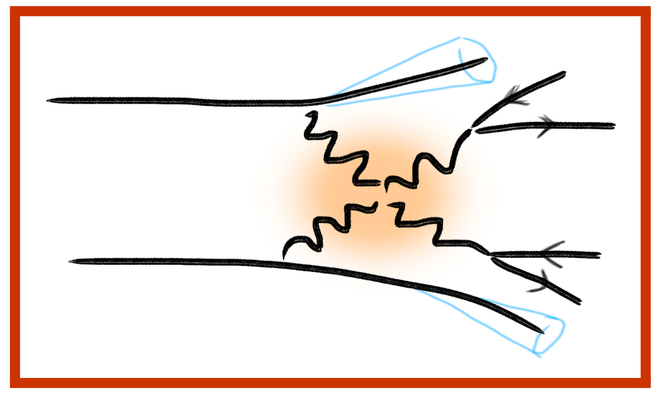
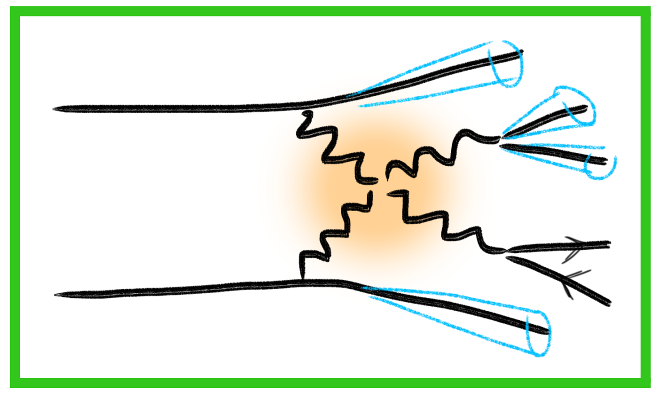
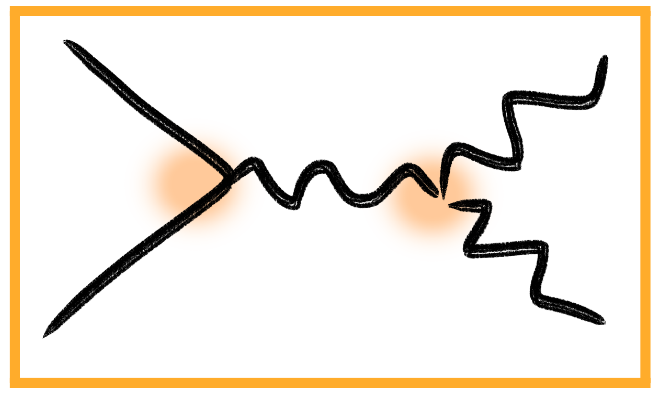
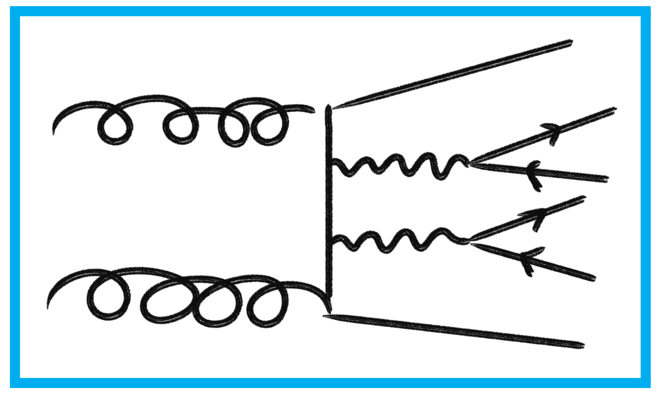
Two complementary approaches employed:

- Generate single components, $c_\alpha = 1 + n(n+3)/2 = 119 + 1$ (SM) $\forall$ processes
- Generate events once, LO MG re-weight to different Wilson coeff. Algebra to extract components.

Processes considered

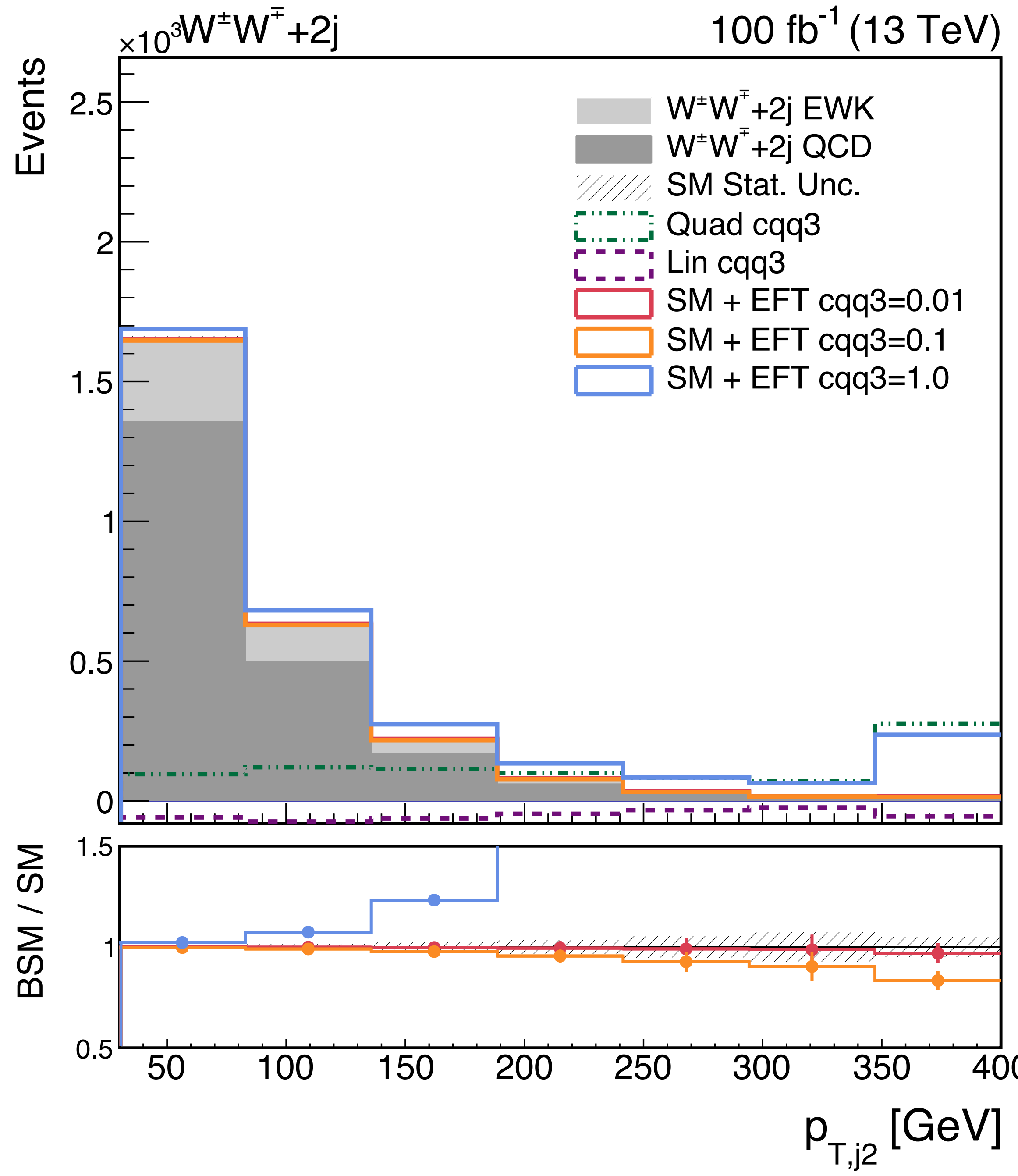
- **5 VBS Channels**: 4 fully leptonic 1 semi leptonic final state.
- **One diboson WW** channel.
- Different flavour category for all channels → highest sensitivity.
- **LHC-like selections performed**
- Full 2 → 6(4) VBS (diboson) processes including non-resonant diagrams.
- EW VBS phenomenology richer than diboson

proc / op	Q_{HD}	$Q_{H\square}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_{W}	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
SSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
ZV-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
OSWW-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ-QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ-QCD	✓		✓	✓	✓			✓	✓	✓					(✓)

Shape analysis

$$N \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2}(\text{Lin}^{EWK} + \text{Lin}^{QCD}) + \frac{c_\alpha^2}{\Lambda^4}(\text{Quad}^{EWK} + \text{Quad}^{QCD})$$



$$L = \prod_{bin=k} \text{Pois}(n_k \,|\, N_k(\mathbf{c})) \times \overbrace{\prod_{syst=j} \pi(\tilde{\theta} \,|\, \theta)}^{Nuisances}$$

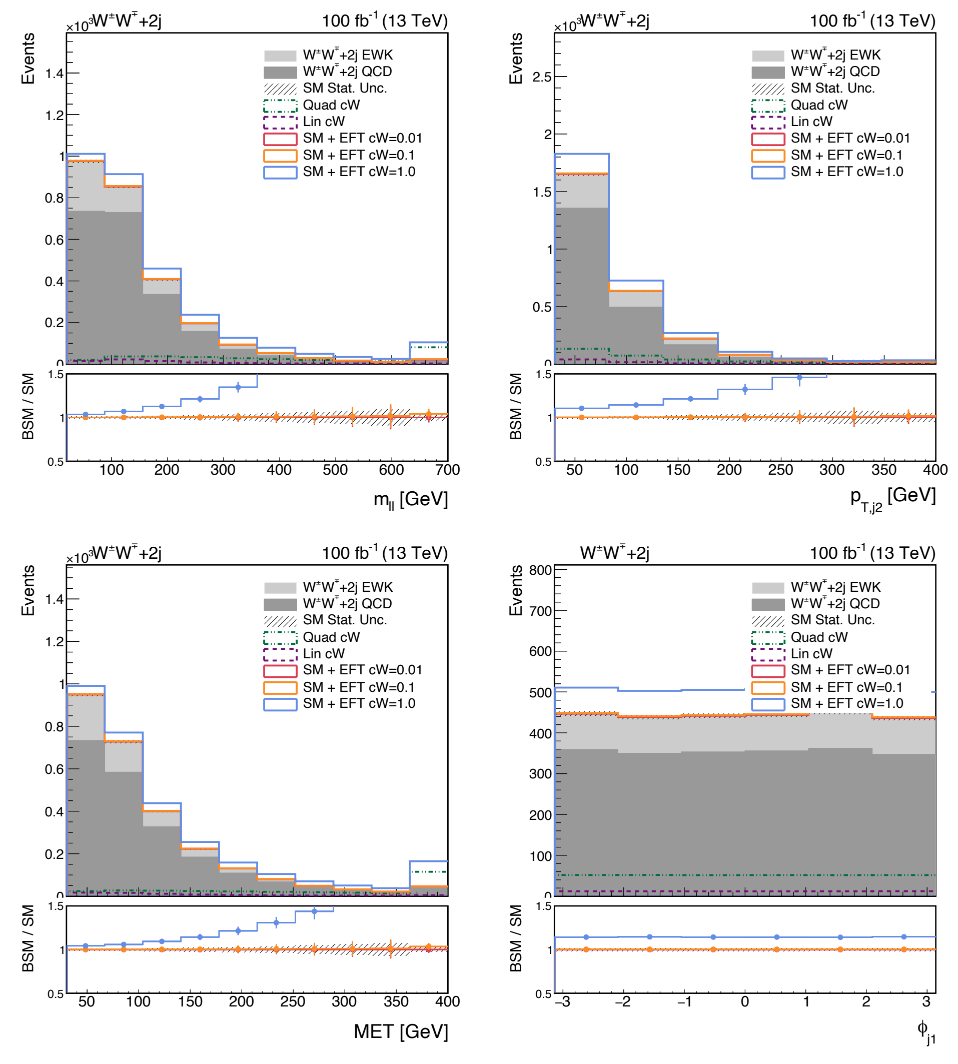
$$N(\mathbf{c}) = SM + \sum_{c_\alpha} c_\alpha \cdot Lin_\alpha + c_\alpha^2 \cdot Quad_\alpha + \sum_{\alpha,\beta} c_\alpha c_\beta Mix_{\alpha\beta}$$

$n = N(\mathbf{0})$ → assume SM

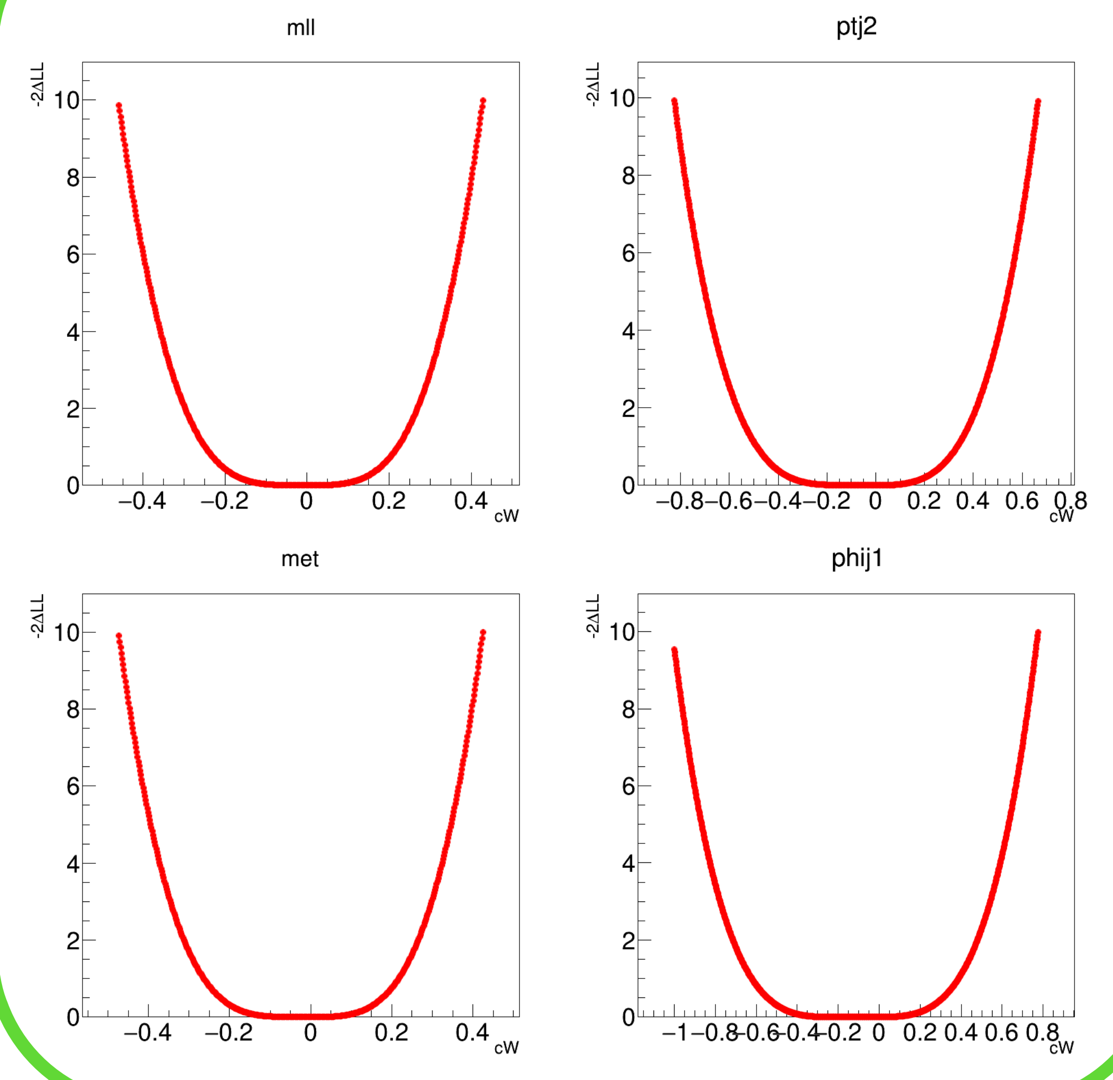
- Only one nuisance: correlated 2% between all yields, samples, and bins (proxy LHC lumi). Flat prior
- under SM, sensitivity estimated as $-2\Delta \log L < 1$ (2.30) and $-2\Delta \log L < 3.84$ (5.99) for 1(2) W.C.

Study strategy

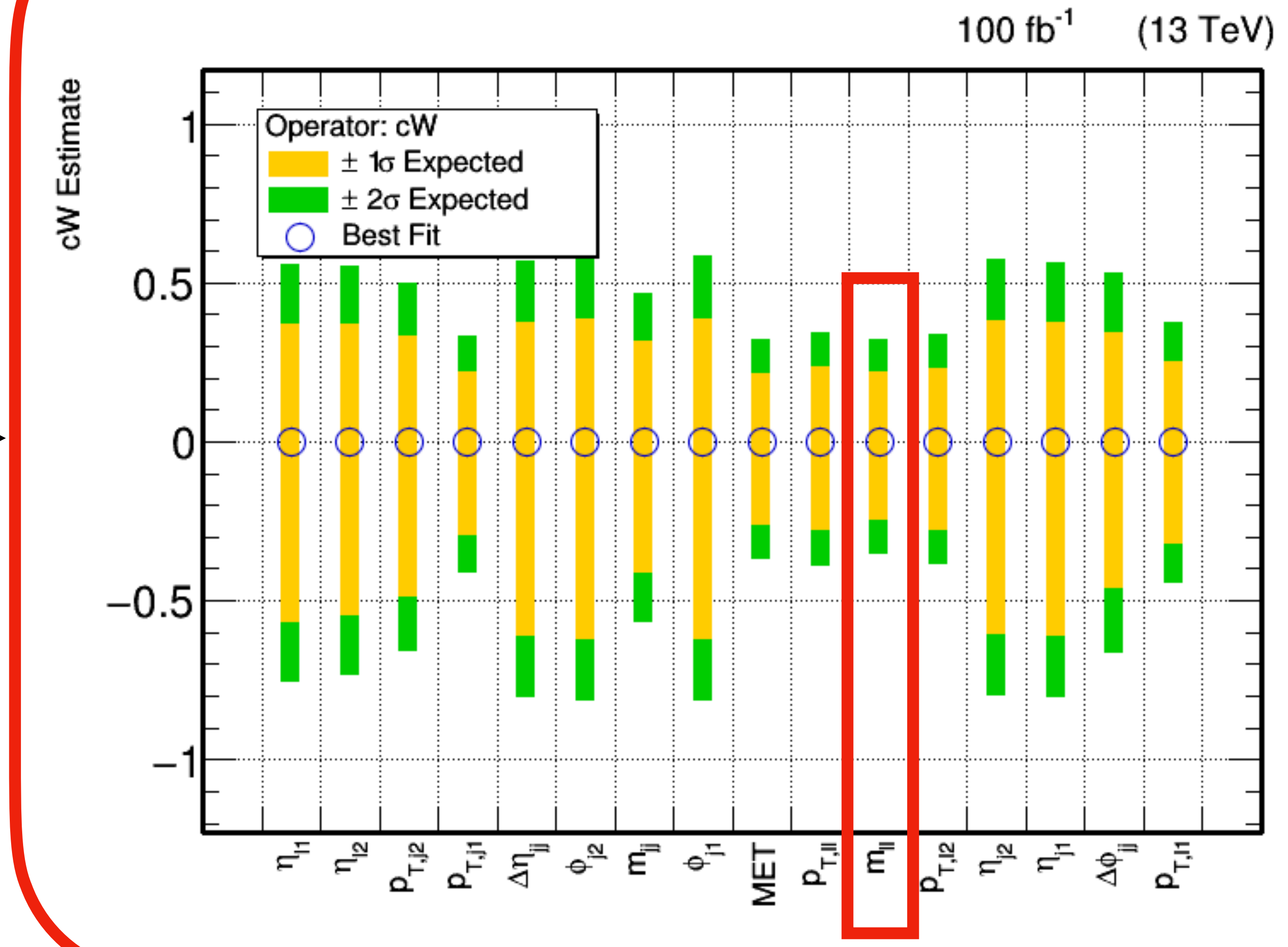
Templates



LL Scans

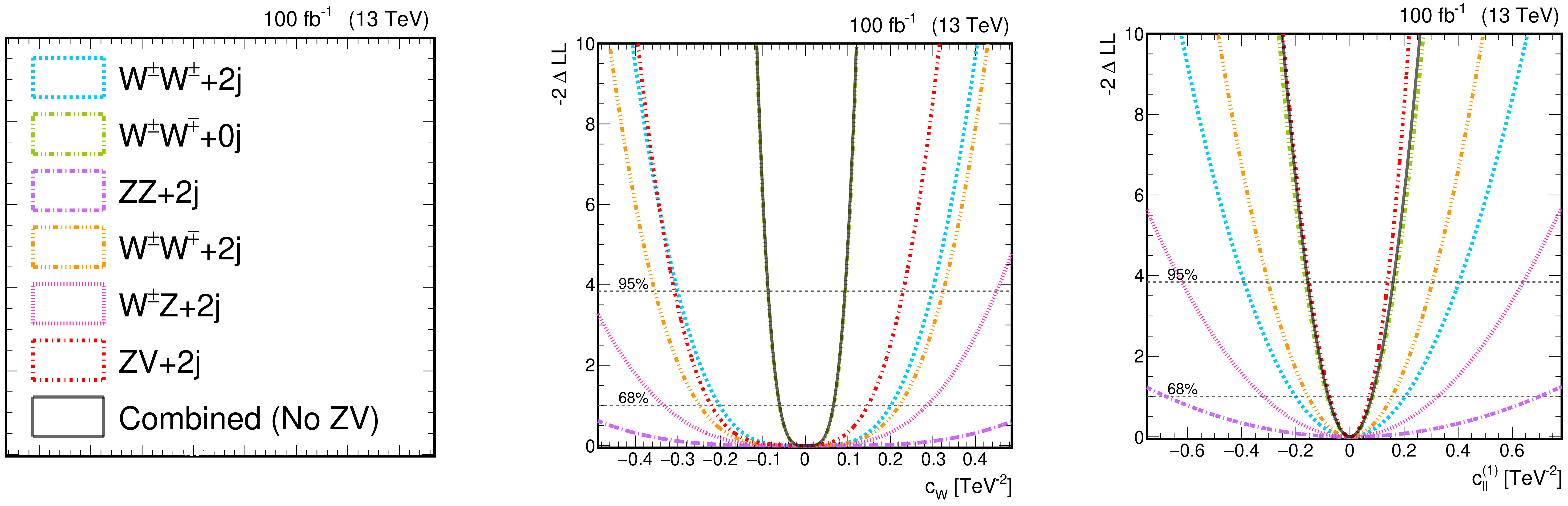


Ranking



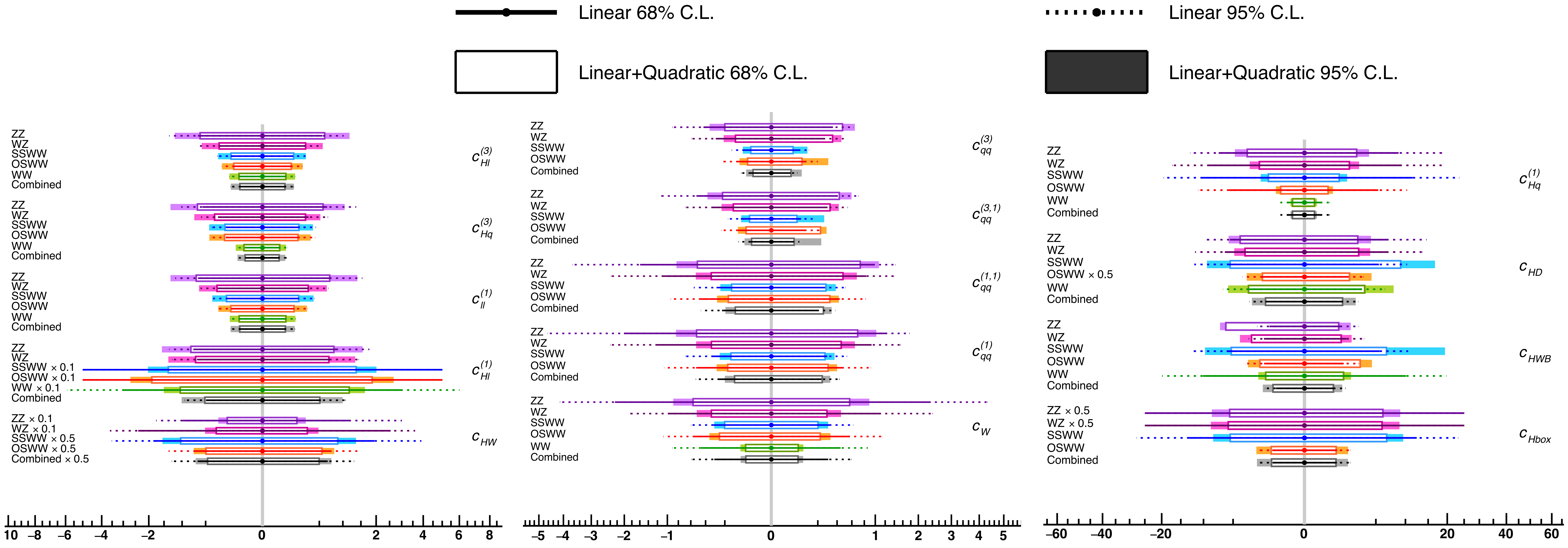
- **Parametrize EFT** dependence on c_i for observables of interest
- **Fit** each variable for each operator
- **Rank** variables based on 1σ range (1σ area in 2D).
- For every operator extract best variable for **combination**

Single constraints and Best variables



- Compare extracted one dimensional limits for each process using best variable
- Profiles of $-2\Delta \log L$ reported for individual channels and their combination (excluding ZV+2j)
- Likelihood was built using the most constraining variable for each process
- OSWW+2j, WZ+2j, ZZ+2j and ZV+2j channels include contributions from the QCD induced processes

Individual constraints



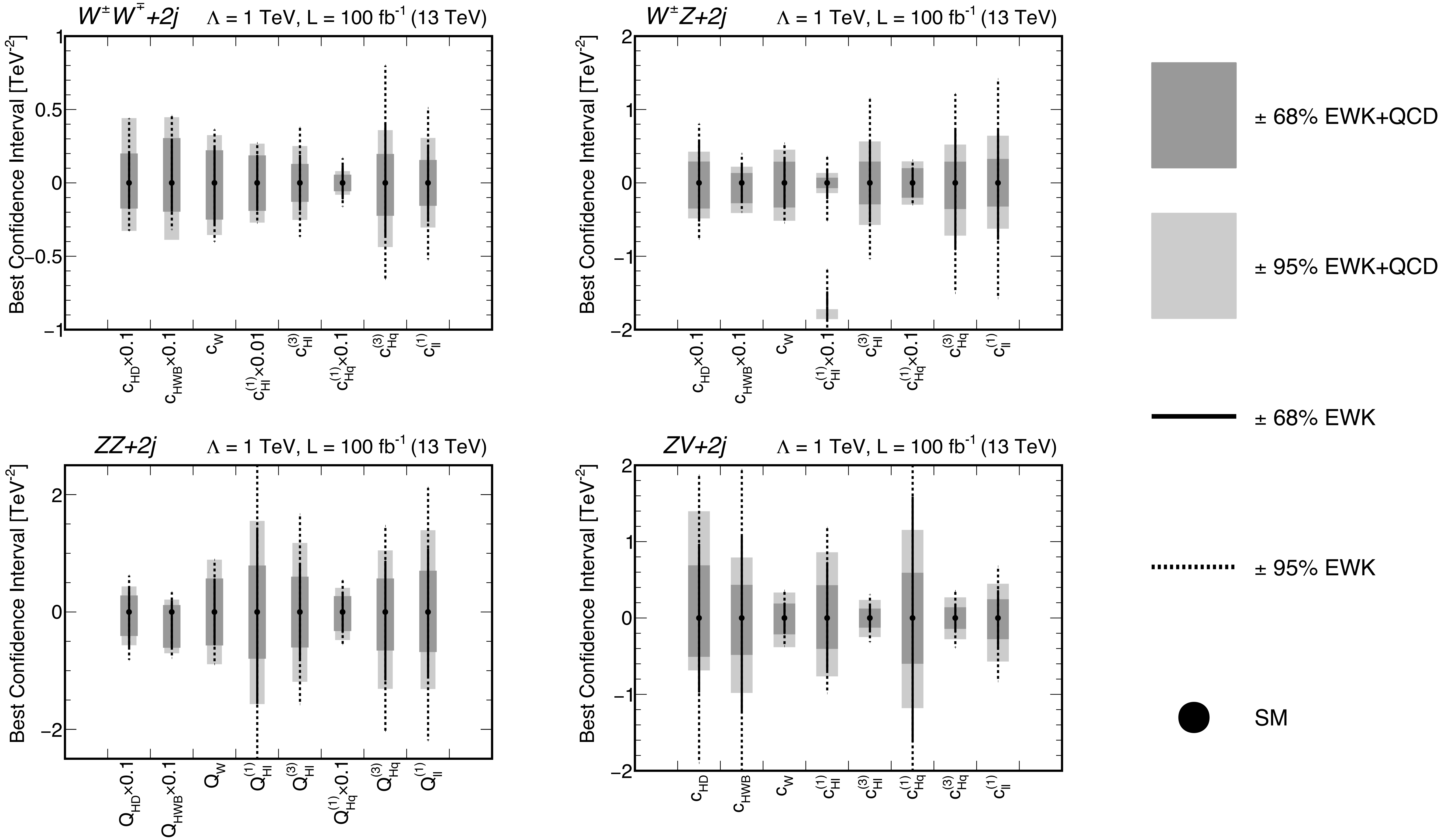
- Most stringent constraints from VBS to 4-fermion ops, agrees with previous studies
- Strong impact of fits including $O(\Lambda^{-4})$ terms for 1 / 2 operators. For the remaining, no difference observed
- Among VBS, SSWW, OSWW > WZ, ZZ due to higher cross-section
- $Q_{Hl}^{(1)}, Q_{HW}, Q_{H\Box}, Q_{HD}$ only constrained by VBS
- $Q_{Hl}^{(1)}$ mostly constrained by VBS WZ/ZZ

Impact of QCD EFT dependence

$$N(EWK+QCD) \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2}(\mathrm{Lin}^{EWK} + \mathrm{Lin}^{QCD}) + \frac{c_\alpha^2}{\Lambda^4}(\mathrm{Quad}^{EWK} + \mathrm{Quad}^{QCD})$$

$$N(EWK) \propto SM^{EWK} + \frac{c_\alpha}{\Lambda^2}\mathrm{Lin}^{EWK} + \frac{c_\alpha^2}{\Lambda^4}\mathrm{Quad}^{EWK}$$

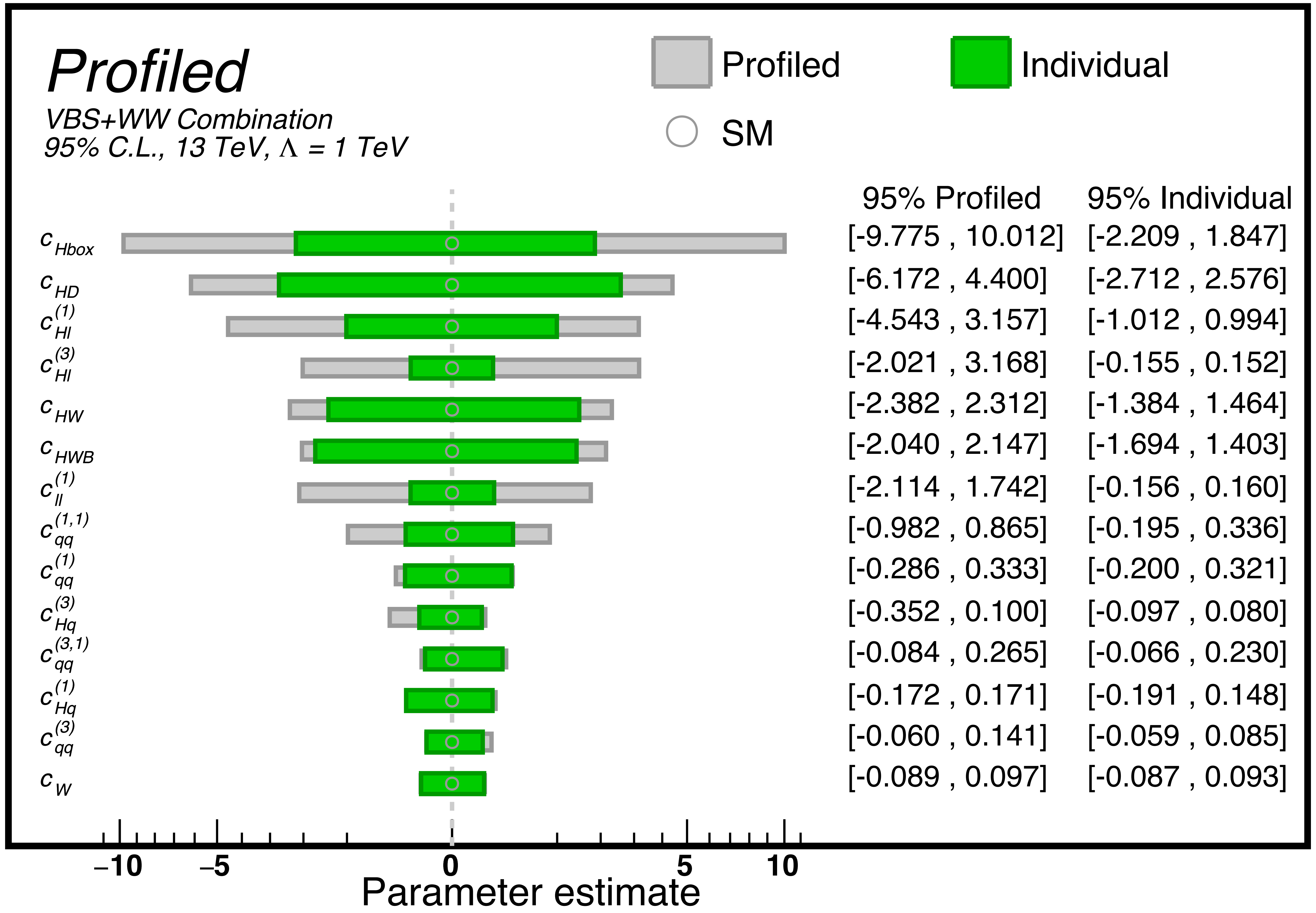
Including the background QCD dependence never weakens the sensitivity reach of all analyses.



Profiled constraints

Global fit guarantees SMEFT model and basis independence. **VBS + WW profiled constraints** including all Λ^{-4} terms.

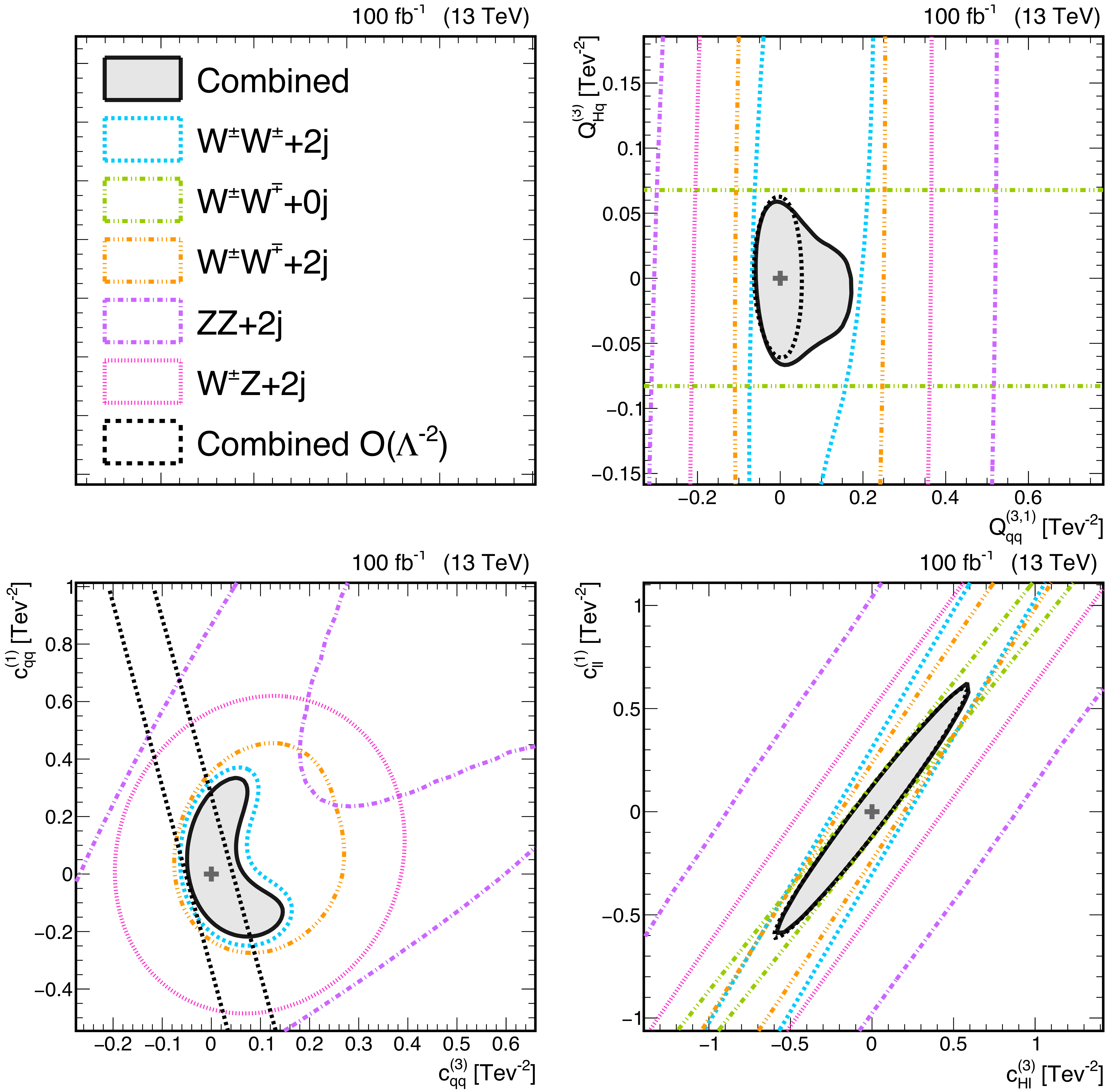
- All parameters free to float in likelihood maximization
- Individual limits on operators obtained by **profiling** uninteresting W.C (free to float in the fit)
- **Profiled ~ 1 − 20 × Individual**



Bidimensional constraints

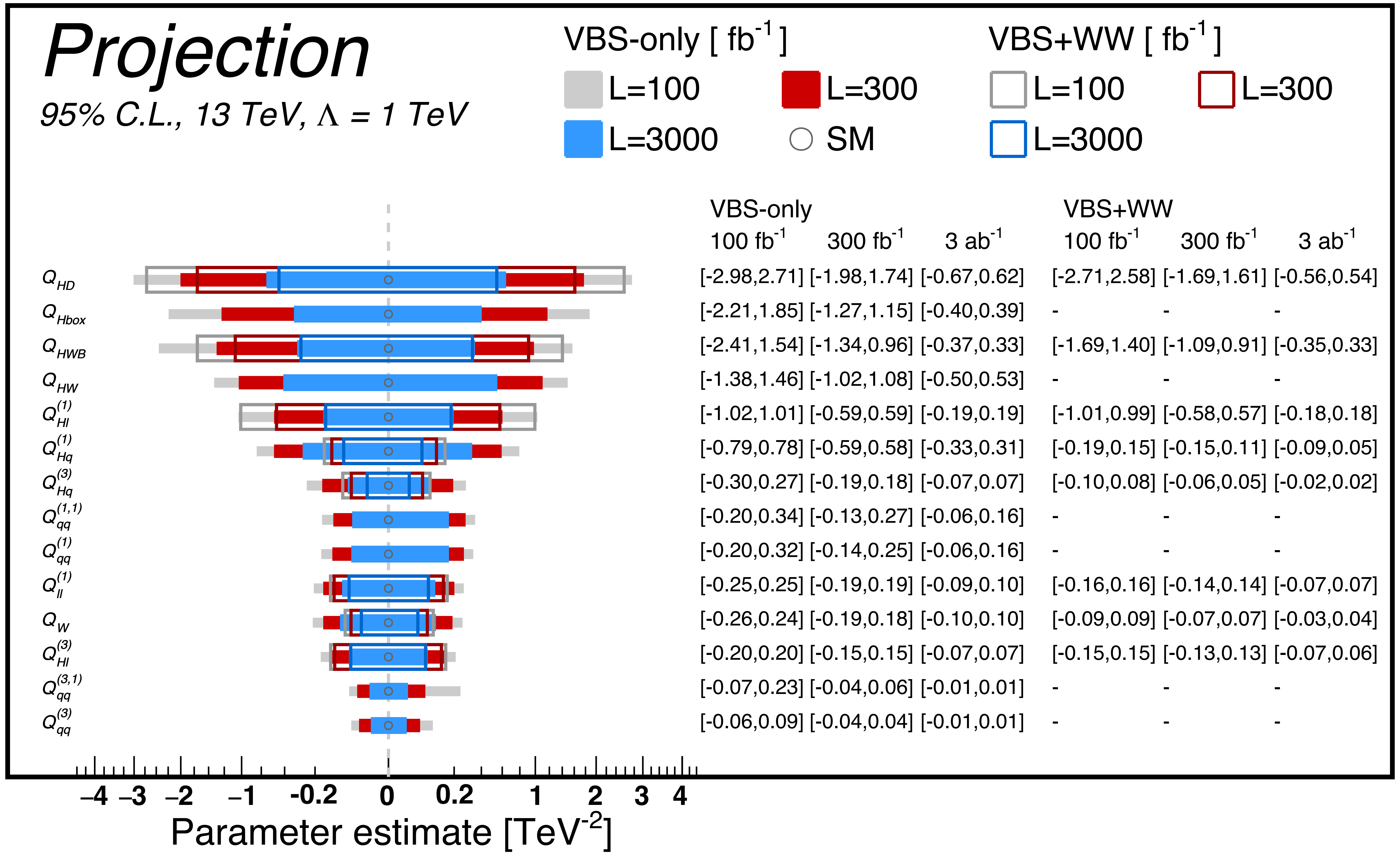
Complementarity of VBS and diboson measurements:

- Q_{qq} operators only constrained by VBS
- $Q_{H\Box}$, Q_{HW} operators only constrained by VBS
- Degeneracy on $Q_{ll}^{(1)}$, $Q_{Hl}^{(3)}$ resolved by VBS ZZ/WZ
- Flat directions resolved thanks to combination.



Projection of expected constraints

- **Projection of individual constraints to future LHC phases** Integrated luminosities: LHC Run II ~ 100fb^{-1}, LHC Run III > 300fb^{-1}, HL-LHC ~ 3 ab^{-1}. No scaling of the nuisance constraint involved.
- At the HL-LHC, the VBS-only combination is expected to constrain all operators to less than [-1,1], including diboson lowers the range to [-0.5,0.5]. Roughly a factor ~ 5 improvement expected from LHC Run II to HL-LHC.



Summary and outlook

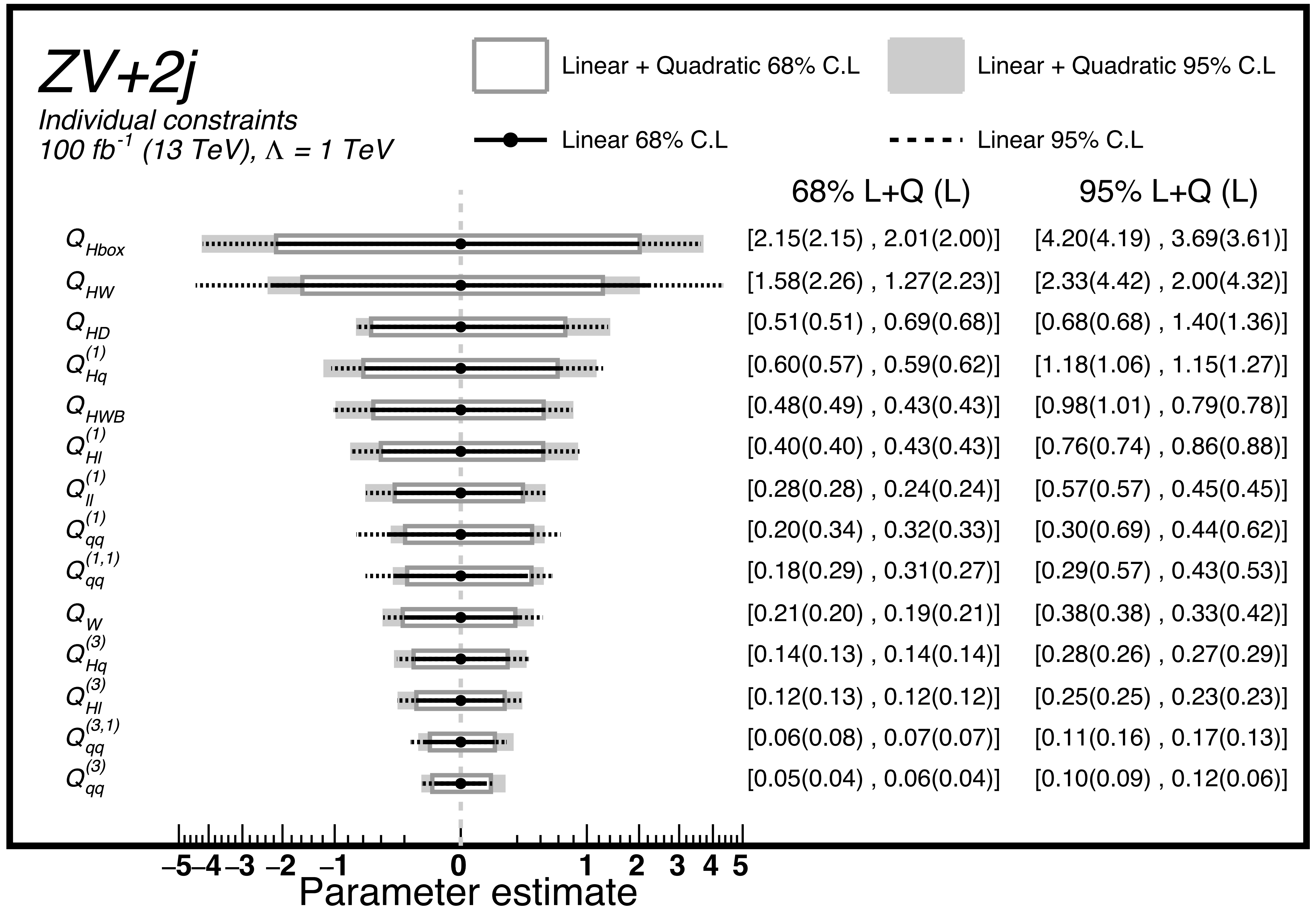
In this work we presented **a comprehensive study at parton level of EFT dimension-6 effects on VBS and diboson W^+W^-**

- Including **EFT quadratic terms** of order $O(\Lambda^{-4})$ has significant impact on the sensitivity
- $O(\Lambda^{-4})$ terms help in **reducing flat directions**
- **EFT dependence of the QCD** induced sample ($\alpha_s^2 \alpha_{EW}^4$) never weakens the sensitivity
- Addressed sensitivity reach of **ZV+2j (semileptonic)** for the first time
- Shown **orthogonality of VBS and diboson** measurements in more dimensions

Backup

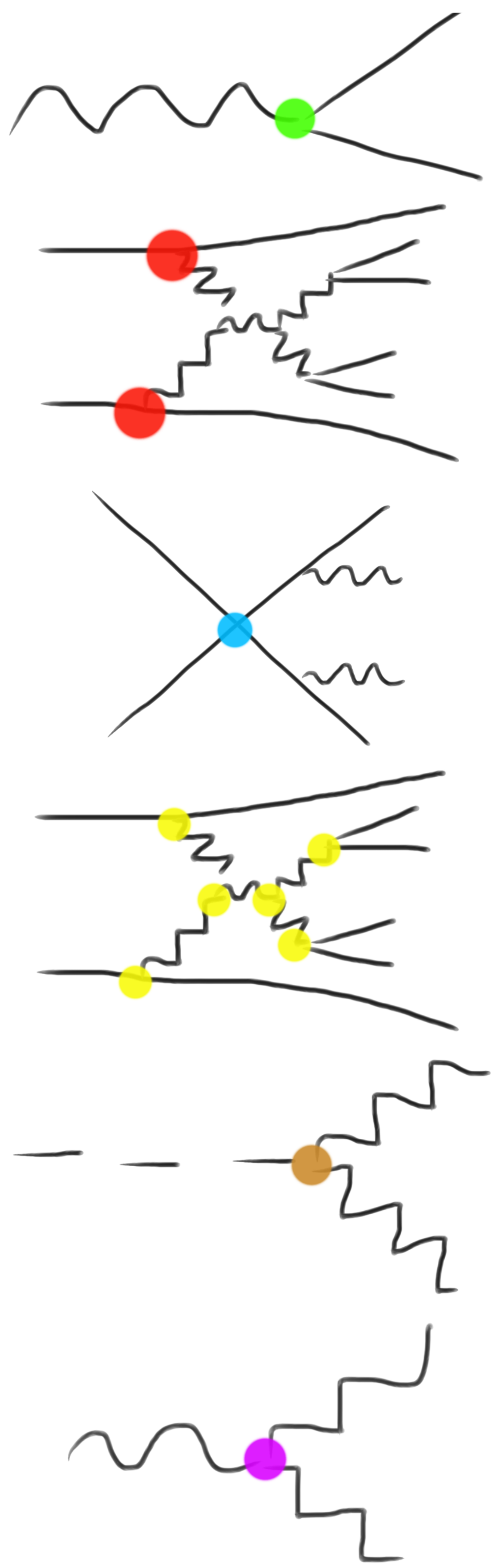
Individual constraints - VBS semi-leptonic

- Lack of Z+jets background $\alpha_s^4\alpha_{EW}^2$(dominant in ZV semi-leptonic) → not included in the combination.
- **Constraints competitive with diboson** W^+W^- and slightly better than any other VBS channel considered, especially for $Q_{Hl}^{(1)}$
- Impact of $O(\Lambda^{-4})$ less prominent w.r.t. other channels.



Individual constraints - Best variables

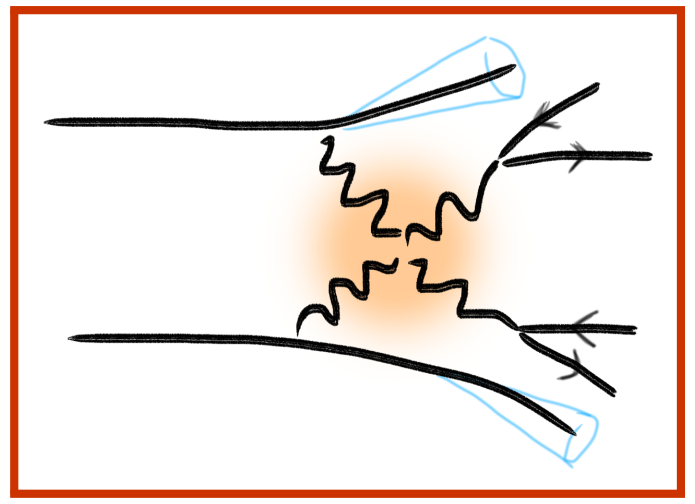
- Observables ranking by using only linear (L) or linear and quadratic (L+Q)

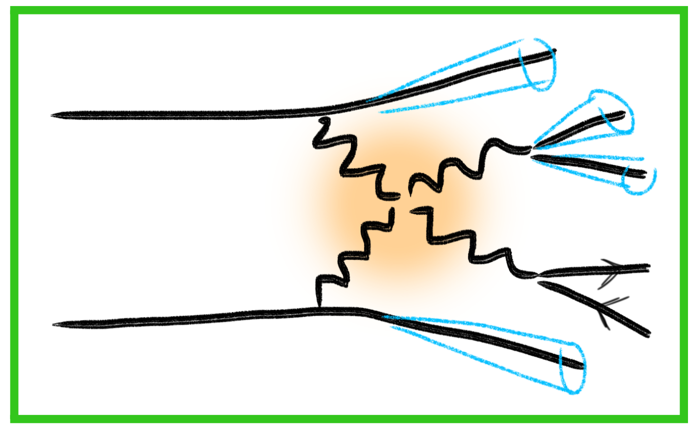


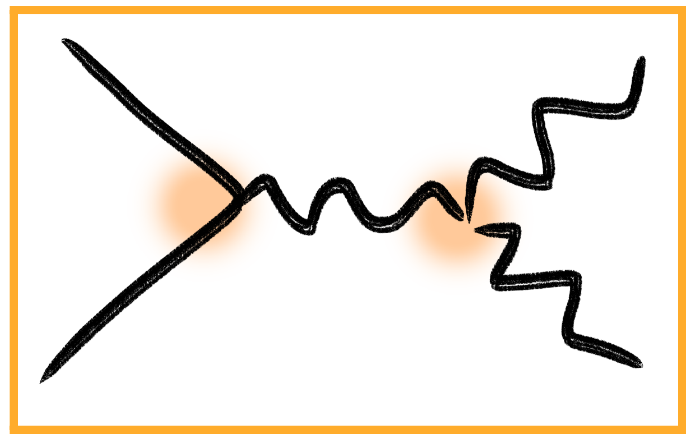
Op.	SSWW+2j		OSWW+2j		WZ+2j		ZZ+2j		ZV+2j		WW	
	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}^{\dagger}$	$p_{T,e^-\mu^-}^{\dagger}$	p^V_{T,j_1}	p^V_{T,j_1}	p_{T,l^1}	MET
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m^{VBS}_{jj}	m^{VBS}_{jj}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}^{\dagger}$	$\Delta\phi^{VBS}_{jj}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta^{V\dagger}_{jj}$	$\Delta\phi^{VBS}_{jj}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi^{VBS}_{jj}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi^{VBS}_{jj}$	p^{VBS}_{T,j_1}	-	-
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}^{\dagger}$	$\Delta\eta_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	m_{jj}	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$\Delta\eta^V_{jj}$	$\Delta\eta^V_{jj}$	$m_{ll}^{\dagger}$	$m_{ll}^{\dagger}$
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{ll}^{(1)}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	m_{jj}	$m_{jj}^{\dagger}$	$m_{jj}^{\dagger}$	$\Delta\eta^{V\dagger}_{jj}$	$\Delta\eta^{V\dagger}_{jj}$	$p_{T,ll}^{\dagger}$	p_{T,l^2}
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta^V_{jj}$	$\Delta\eta^V_{jj}$	p_{T,l^1}	MET
$c_{H\Box}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^V_{T,j_2}	p^V_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^V_{T,j_2}	-	-
c_W	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi^{VBS\dagger}_{jj}$	$\Delta\phi^{VBS\dagger}_{jj}$	MET	MET

Process of interest

- Same-signWW: pp > $e^+ \nu_e \mu^+ \nu_\mu jj$
- Opposite-sign WW (QCD): p p > $e^+ \nu_e \mu^- \bar{\nu}_\mu$ j j
- WZ+2j(QCD): pp > $e^+ e^- \mu^+ \nu_\mu jj$
- ZZ+2j(QCD): pp > $e^+ e^- \mu^+ \mu^-$
- ZV+2j(QCD): pp > $zw^+(w^-, z)$ > $l^+ l^- jjjj$
- WW: p p > $e^+ \nu_e \mu^- \bar{\nu}_\mu$







SMEFT corrections in propagators

- Mass terms and decay widths of the SM particles generally receive corrections from $\mathscr{L}_6$ operators.
- $\{m_W, m_Z, G_F\} \rightarrow \delta m_W = 0,\ \delta m_Z = 0,\ \Gamma \neq 0$
- Propagator corrections relevant only if close to the mass shell
- Corrections for different ops share the same shape except for normalization
  - **Propagator corrections** at $O(\Lambda^{-2})$ provide sensitive contributions up to a factor 5