Operator Correlation in Electroweak Scattering at LHC

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Outline:

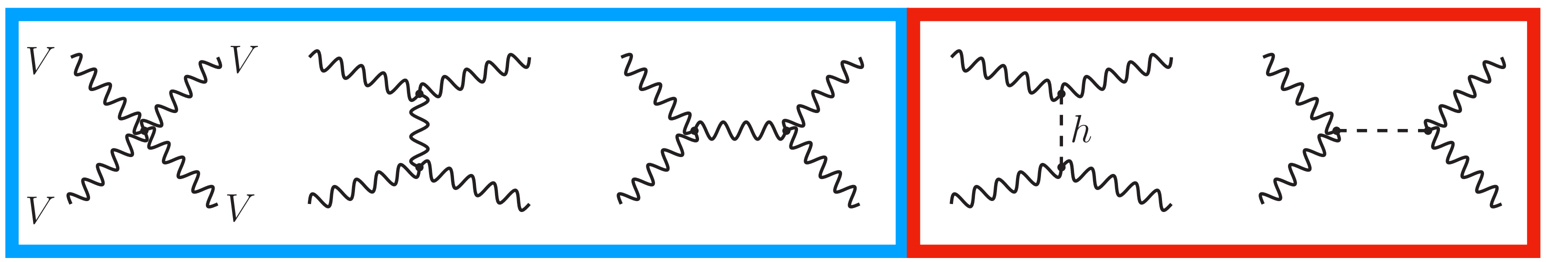
- Electroweak scattering and operator correlation
- Operators correlation in electroweak scattering
- Consistency of SMEFT
- Summary

Vector Boson Scattering

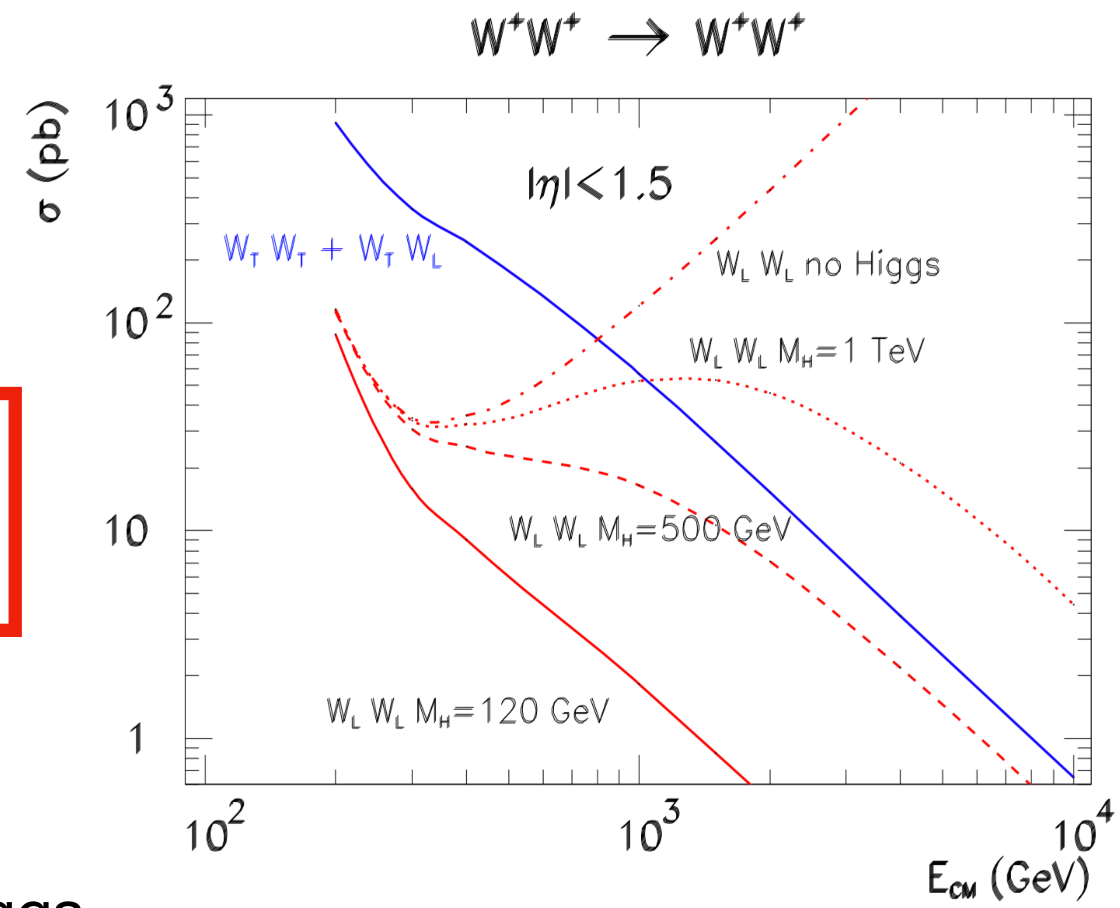
- Unitarity violation:

$$Im\mathscr{M}(p_1p_2 \to p_1p_2) \geq 2E_{cm}|p_2|\sigma_l(p_1p_2 \to k_1k_2)$$

$$\sigma_l \leq 16\pi(2l+1)/E_{\rm cm}^2$$

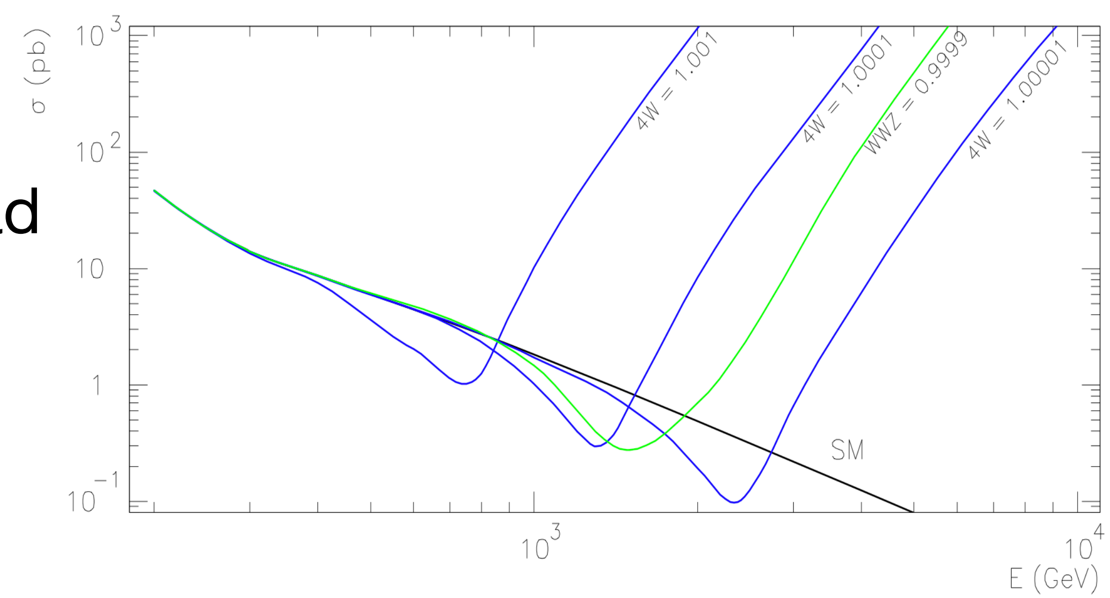


Longitudinal: $a_{\rm J} = A(E/M_W)^4 + B(E/M_W)^2 + C$



arXiv:1412.8367

- The unitarity will violate unless considering the Higgs mediated contribution.



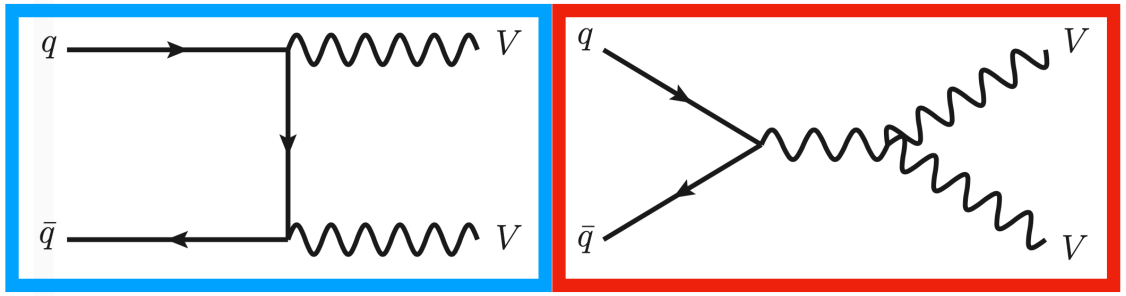
- Anomalous gauge/Higgs relevant couplings will lead to unitarity violation:

$$\mathscr{M}_{NP} = \mathcal{O}(E^2/\Lambda^2)\, Q_i^{(6)} \ldots$$

di-boson production

- Precise measurement of di-boson production can accurately examine electroweak gauge theory.

- Unitarity violation:



$\mathscr{M} \propto g^2 E^2$

- Anomalous couplings may also lead to unitarity violation

Anomalous signal = new physics evidence

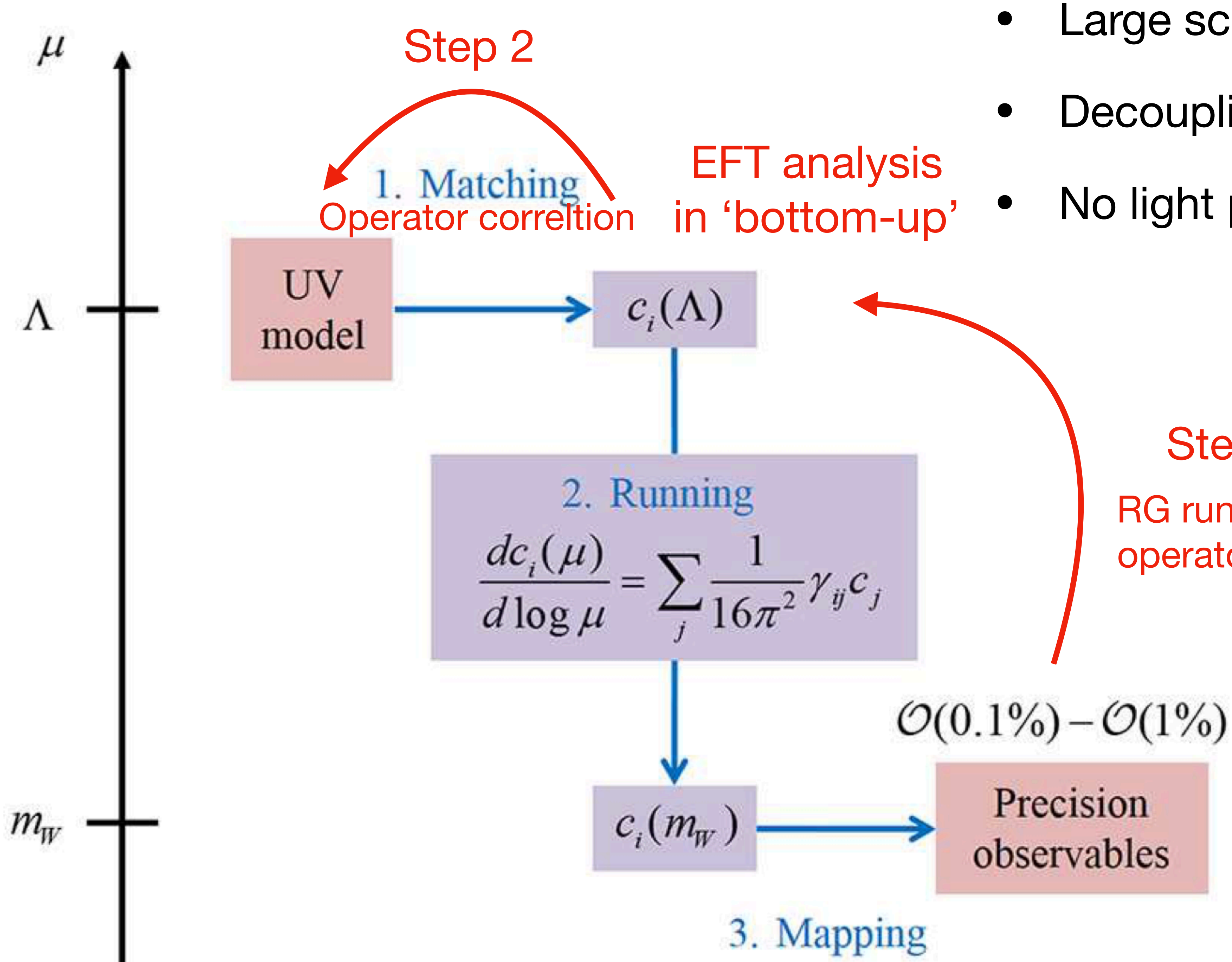
No deviation = No new physics ?

Correlated cancellation in new physics?

Electroweak scattering in SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_j}{\Lambda^2}\mathcal{O}_j^{(6)} + \ldots$$

- Large scale
- Decoupling
- No light particles



Henning, Lu, Murayama, 1214.1837

Electroweak scattering in SMEFT

Linear analysis in SMEFT

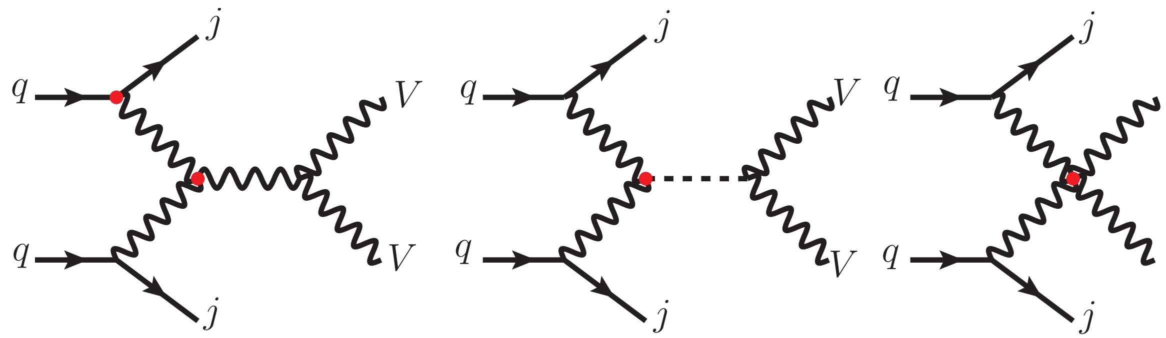


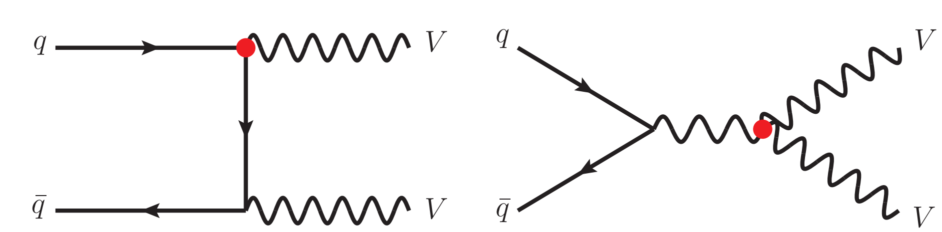
TABLE I: Operator formula in Warsaw basis[28] of SMEFT

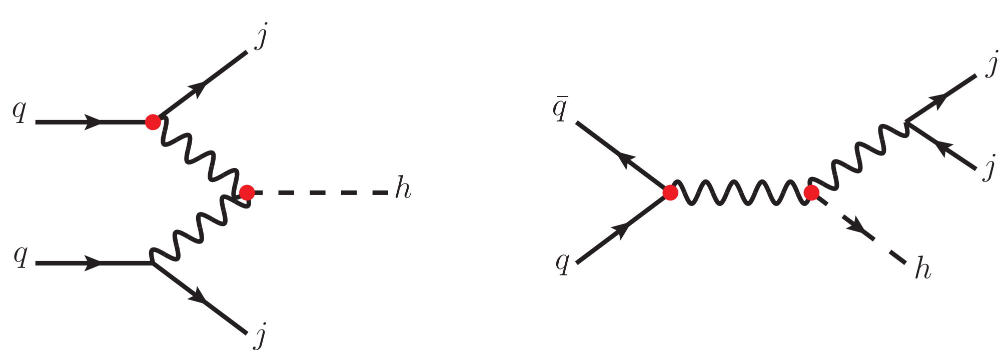
Operators	Q_W	$Q_{\varphi W}$	$Q_{\varphi B}$	$Q_{\varphi WB}$
Formula	$\epsilon^{IJK}W_\mu^{I\mu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$
Operators	$Q_{\varphi D}$ — EWPT —	$Q_{\varphi\Box}$	$Q^{(1)}_{\varphi q}$	$Q^{(3)}_{\varphi q}$
Formula	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Operators	$Q_{\varphi u}$	$Q_{\varphi d}$	Q_{uW}	Q_{uB}
Formula	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}W^I_{\mu\nu}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}B_{\mu\nu}$

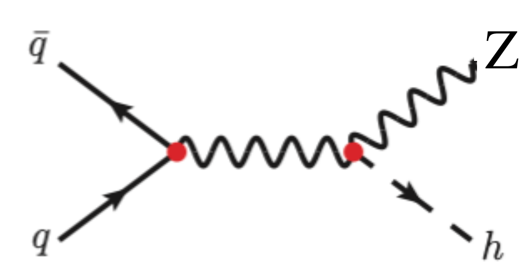
$$\sigma^{EW}_{pp\to jjZW^\pm} = \sigma_{SM} + 0.03557\,c_W + 0.01103\,c_{\varphi W} + 0.000349\,c_{\varphi B} + 0.04592\,c_{\varphi WB} + 0.019750\,c^{(1)}_{\varphi q} + 0.2538\,c^{(3)}_{\varphi q} + 0.004613\,c_{\varphi u} - 0.000118\,c_{\varphi d} - 0.1414\,c_{uW} - 0.002348\,c_{uB} \quad \text{(pb)}$$

Process \ Operator	Q_W	$Q_{\varphi W}$	$Q_{\varphi B}$	$Q_{\varphi WB}$	$Q^{(1)}_{\varphi q}$	$Q^{(3)}_{\varphi q}$	$Q_{\varphi u}$	$Q_{\varphi d}$	Q_{uW}	Q_{uB}
$pp\to jjW^\pm W^\pm$	⋆	⋆		⋆	⋆	⋆			⋆	
$pp\to jjZW^\pm$	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
$pp\to jjZZ$	⋆	⋆	⋆	⋆	⋆	⋆		⋆		
$pp\to W^\pm W^\mp$	⋆			⋆	⋆	⋆		⋆	⋆	
$pp\to ZZ$				⋆	⋆	⋆		⋆		
$pp\to ZW^\pm$	⋆			⋆	⋆	⋆				
$pp\to jjH$		⋆	⋆	⋆	⋆	⋆		⋆		
$pp\to ZH$		⋆	⋆	⋆	⋆	⋆		⋆		

Tree level correlation about same operators





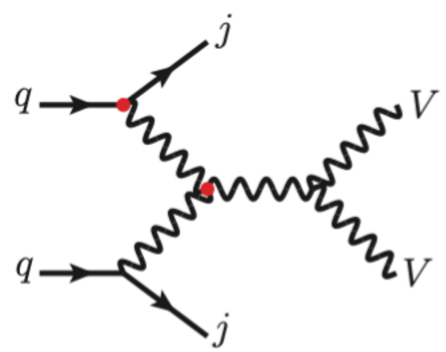


Operators correlation in electroweak scattering

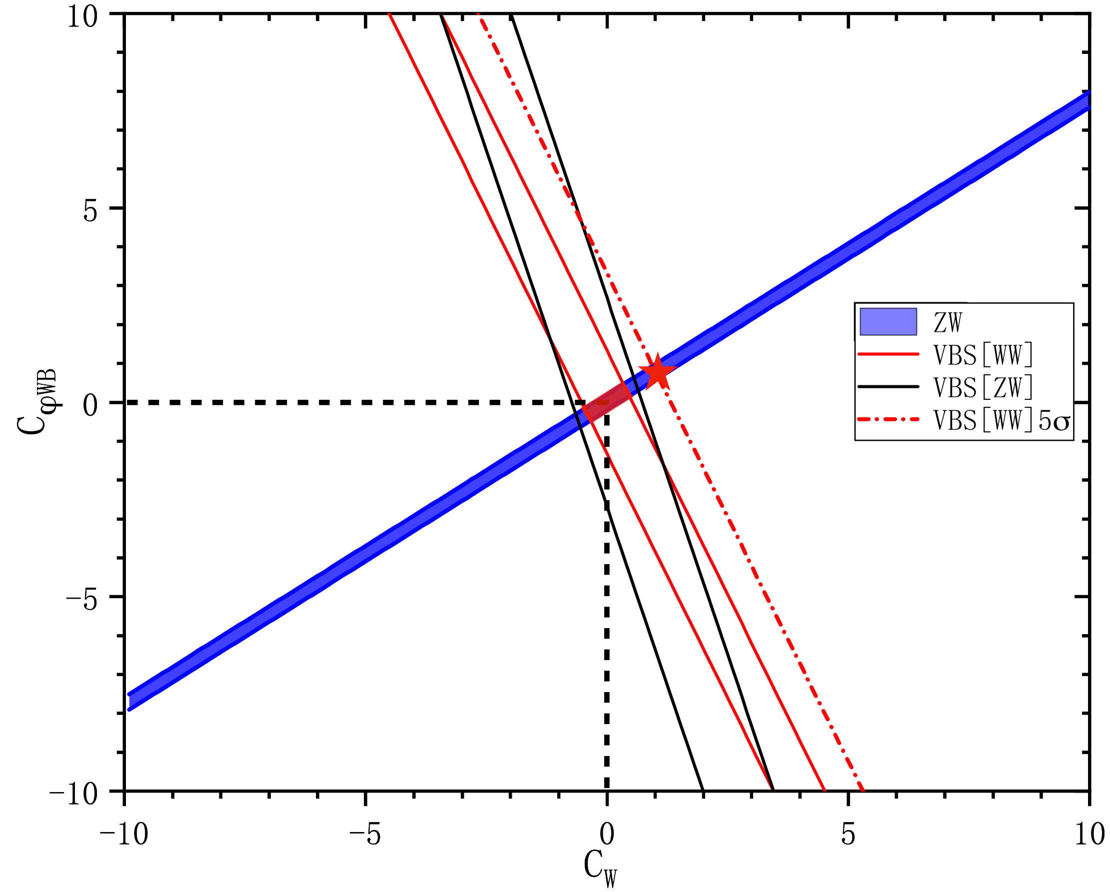
$$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

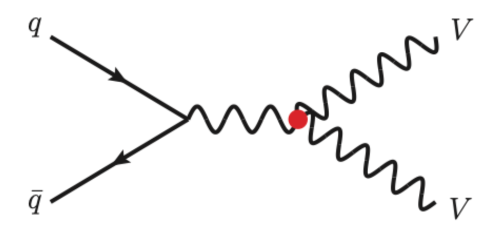
$$Q_{\varphi W} = \varphi^\dagger \varphi \, W_{\mu\nu}^I W^{I\mu\nu}$$

$$Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi \, W_{\mu\nu}^I B^{\mu\nu}$$



Correlation between Q_W and $Q_{\varphi WB}$

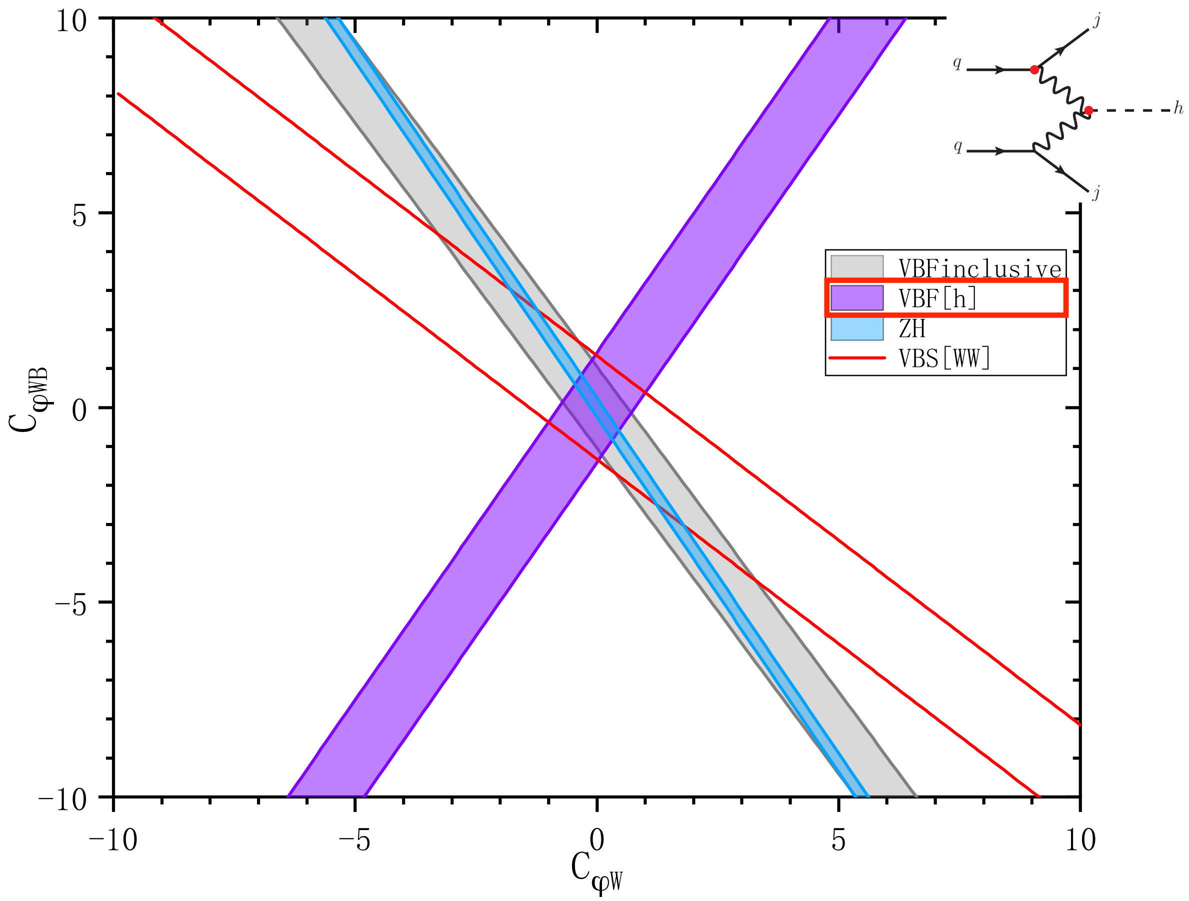




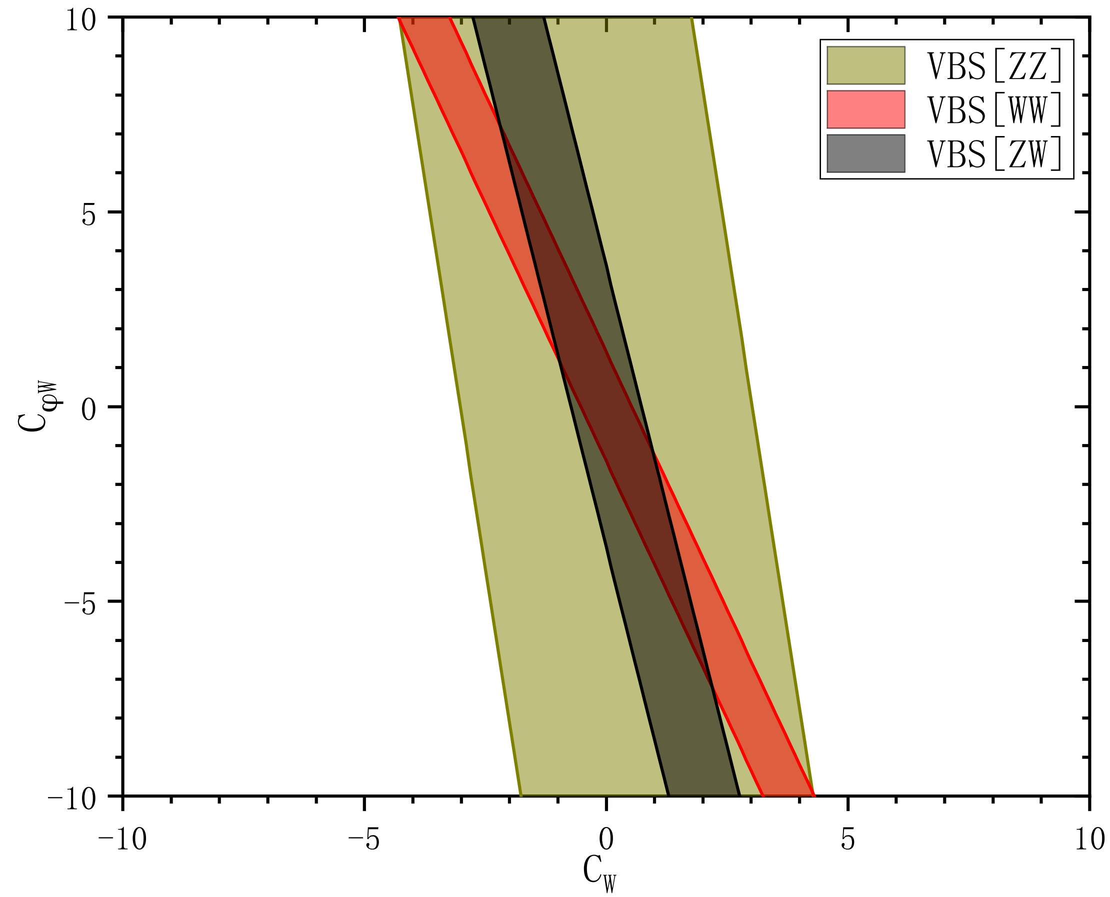
- In single channel, contribution from different operators may cancel with each other.
- Large deviation in VBS[WW] will uniquely determine Wilson coefficients value and correlated structure.
- No deviation in future measurements, Wilson coefficients will be constrained in a very small region.

Operators correlation in electroweak scattering

Correlation between $Q_{\varphi W}$ and $Q_{\varphi WB}$



Correlation between Q_W and $Q_{\varphi W}$



- Precise measurement of vector boson fusion (VBF[h]) is important to probe the direction of new physics.
- Since there are strict constraints in two projection plane of operator correlation, any deviation in electroweak scattering will determine all relevant Wilson coefficients.

Correlation and consistency of SMEFT

$$\begin{aligned}
\text{VBS[WW]}: \quad & C_W\,\sigma_W^{\text{VBS}} + C_{\varphi W}\,\sigma_{\varphi W}^{\text{VBS}} + C_{\varphi WB}\,\sigma_{\varphi WB}^{\text{VBS}} &= 0 \\
ZW - \text{production}: \quad & C_W\,\sigma_W^{ZW} + C_{\varphi WB}\,\sigma_{\varphi WB}^{ZW} &= 0 \\
\text{VBF[h]}: \quad & C_{\varphi W}\,\sigma_{\varphi W}^{\text{VBF}} + C_{\varphi WB}\,\sigma_{\varphi WB}^{\text{VBF}} &= 5\Delta\sigma
\end{aligned}$$

$$C_W = 0.7955; \quad C_{\varphi W} = -2.7599; \quad C_{\varphi WB} = 0.6190$$

- If RGE of these operators are insensitive, such Wilson coefficients are useful to look for the direction of new physics.

Correlation and consistency of SMEFT

$$\begin{aligned}
\text{VBS[WW]}: \quad & C_{\varphi W}\,\sigma^{\text{VBS}}_{\varphi W} + C_{\varphi WB}\,\sigma^{\text{VBS}}_{\varphi WB} &= 0 \\
ZW - \text{production}: \quad & + C_{\varphi WB}\,\sigma^{ZW}_{\varphi WB} &= 0 \\
\text{VBF[h]}: \quad & C_{\varphi W}\,\sigma^{\text{VBF}}_{\varphi W} + C_{\varphi WB}\,\sigma^{\text{VBF}}_{\varphi WB} &= 5\Delta\sigma
\end{aligned}$$

- When contribution from Q_W can be excluded by precise measurement in high energy tails of di-jet invariant mass in VBS, an over-constrained system appear.
- **Precise measurement in electroweak scattering is important to check the consistency of SMEFT.**

No deviation in ZW production: modification between VBS[WW] and VBF will be set as a fixed ratio.

↓ deviation in observables

Non-trivial enhancement of suppressed operators.

Summary

- Operator correlation might be important in searching for new physics in a ‘bottom-up’ framework.

- Precise measurement of electroweak scattering is important to check the consistency of SEMFT and probe new physics.

Thanks for your attention !