Operator Correlation in Electroweak Scattering at LHC

Jian-Nan Ding

Lanzhou University

July 12, 2021

PQCD @ Qingdao

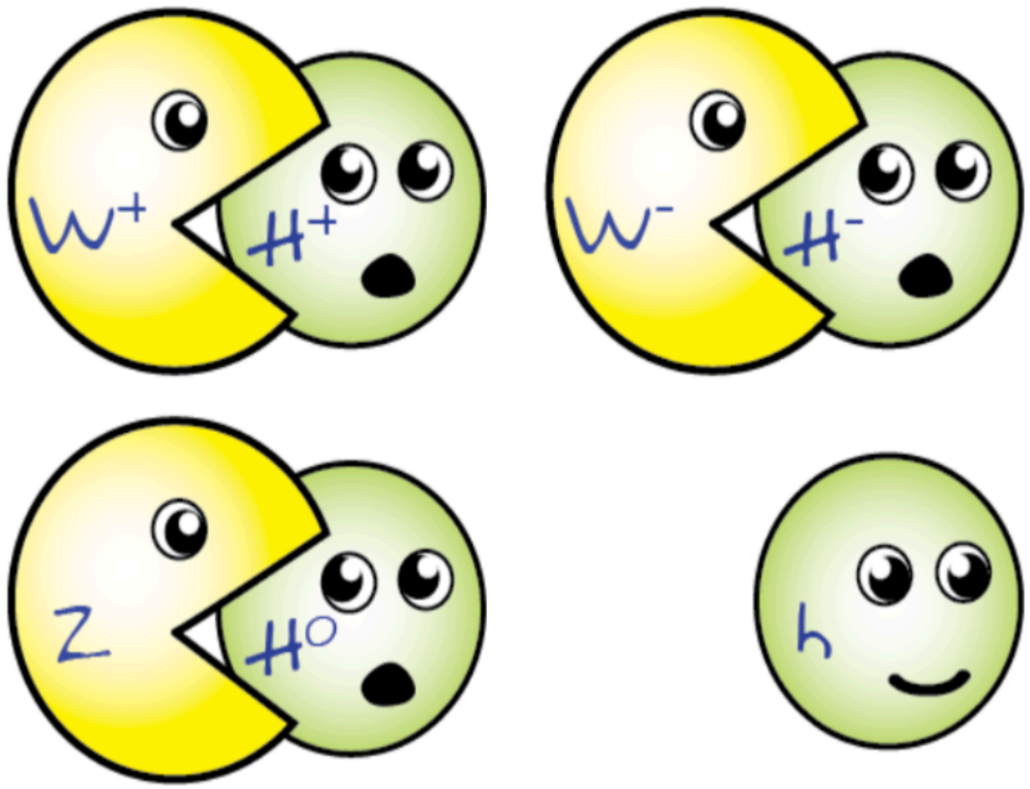
In collaboration with Qing-Hong Cao, Hao-Ran Jiang, Fu-Sheng Yu and Guo-Jin Zeng

Outline:

- Motivation
- Standard model effective field theory
- SMEFT in electroweak scattering
- Phenomenology analysis in electroweak scattering
- Results and discussion
- Summary

Why Higgs ?

- Without Higgs, gauge bosons are massless in Standard Model with gauge symmetry
- For electroweak sectors:
  - Massive vector bosons;
  - Transverse and longitudinal modes of polarization;
  - Adding new scalar sector: Higgs boson;
  - Prevent the unitarity violation in vector boson scattering;



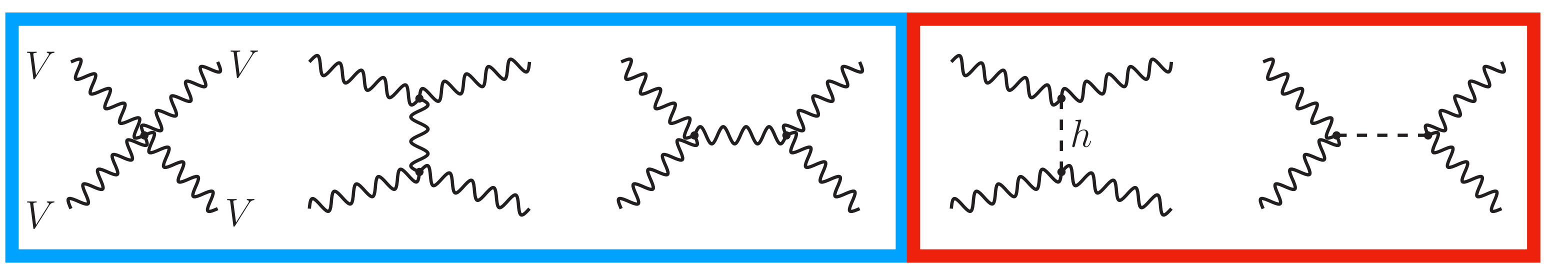
Vector Boson Scattering

- Quartic coupling is precisely predicted by Standard Model due to the gauge universality;

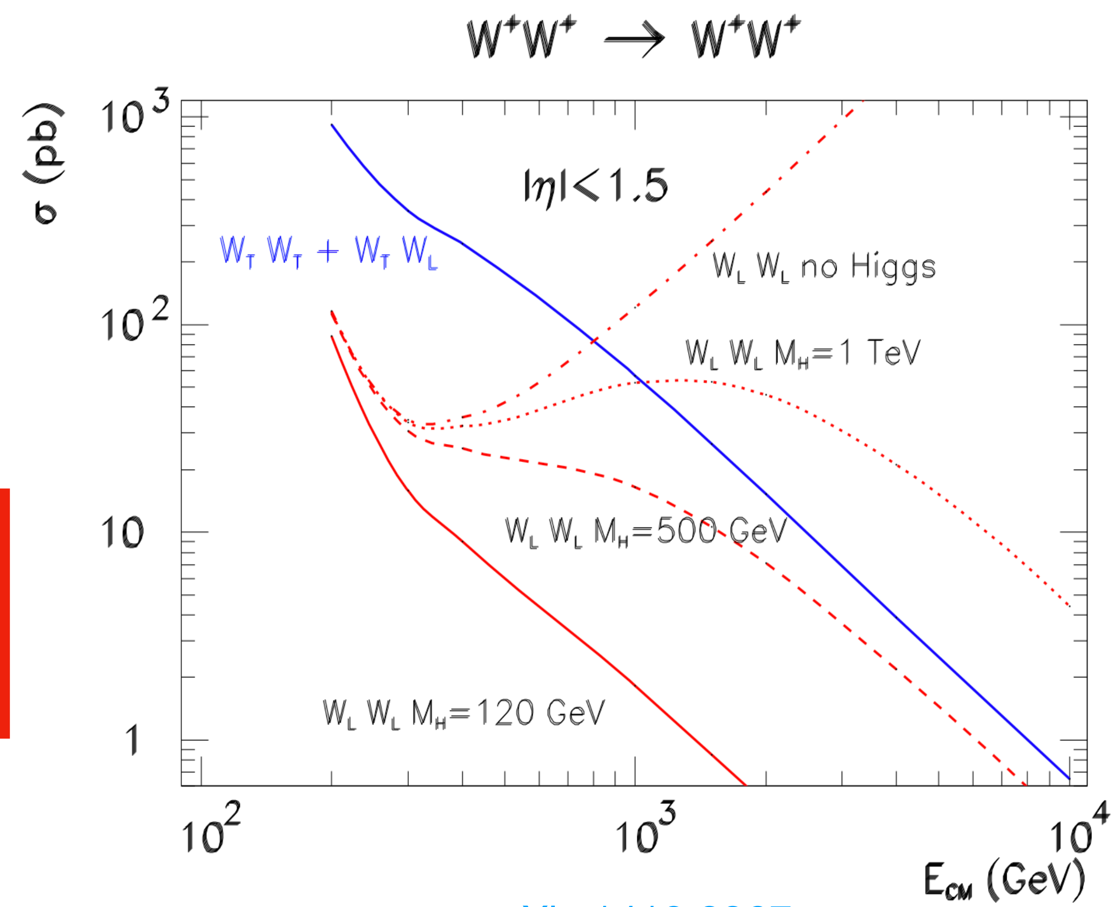
- Unitarity violation:

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

$$\sigma_l \leq 16\pi(2l+1)/s, \quad s = E_{cm}^2$$



Longitudinal: $a_J = A(E/M_W)^4 + B(E/M_W)^2 + C$

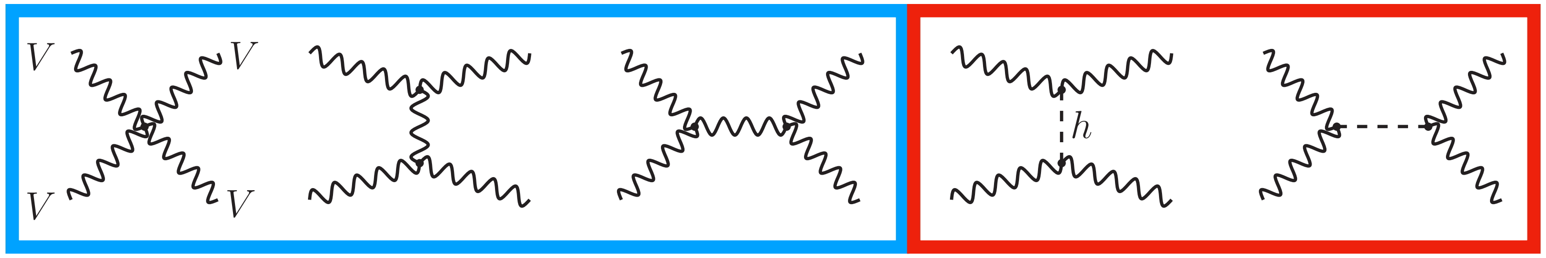


arXiv:1412.8367

- The unitarity will violate unless introduce the Higgs mediated processes.

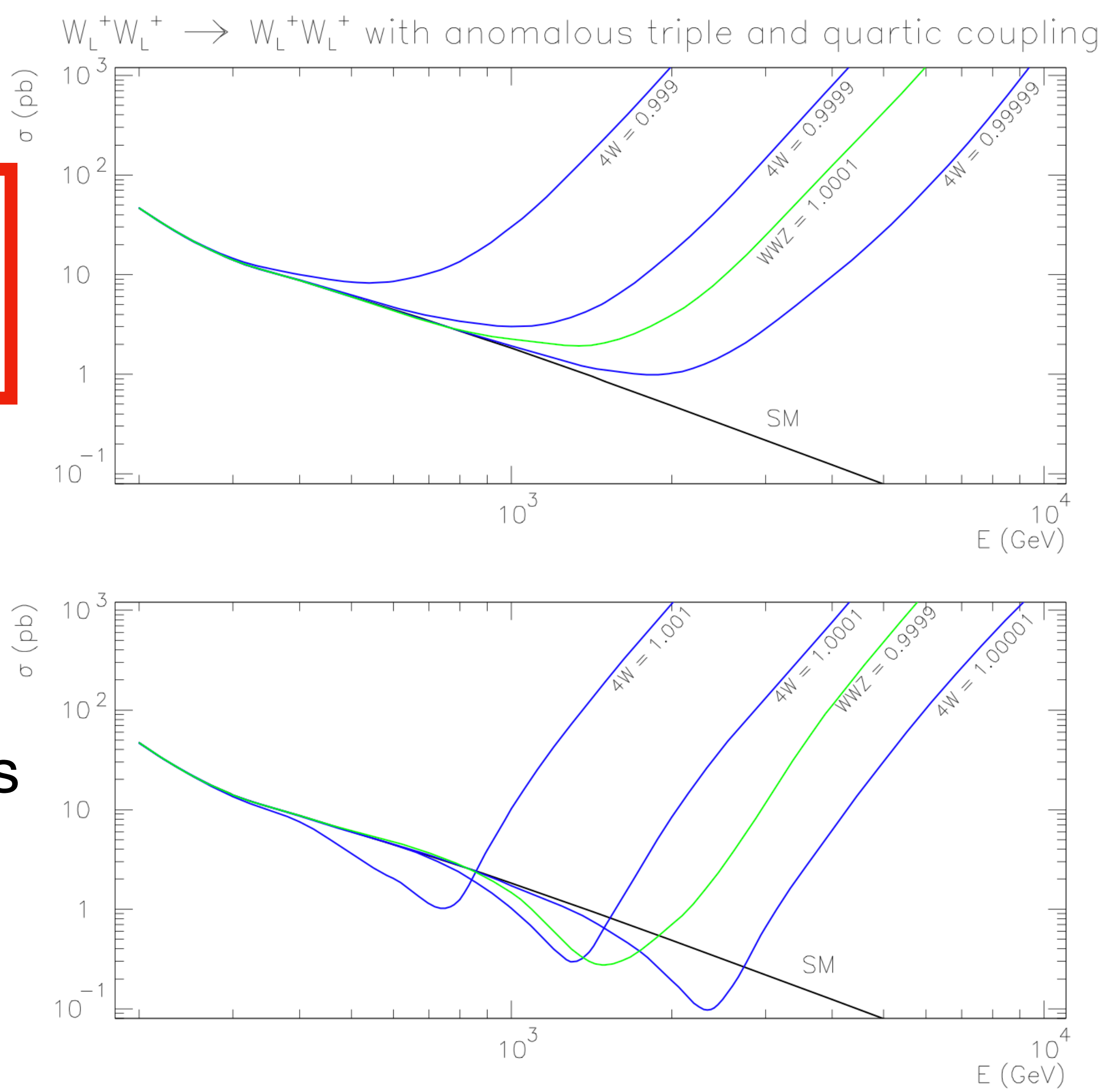
Vector Boson Scattering

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



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

- Vector boson scattering is very sensitive to slights shifts in the trilinear or quartic gauge couplings;

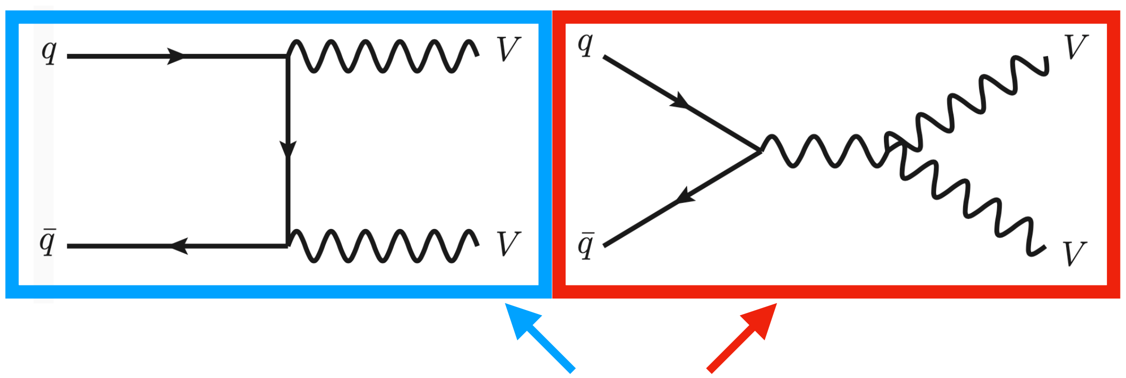


arXiv:1412.8367

di-boson production

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

- Unitarity violation:



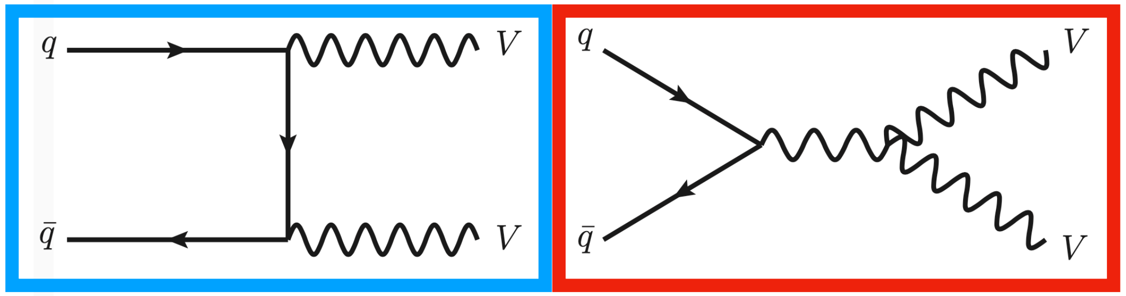
$\mathcal{M} \propto \boxed{g^2E^2}$

- Anomalous couplings may also lead to unitarity violation

di-boson production

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

- Unitarity violation:



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

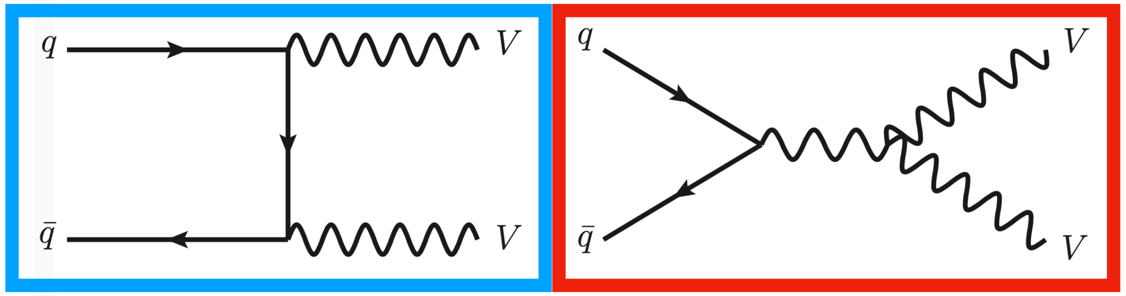
- Anomalous couplings may also lead to unitarity violation

Anomalous signal = new physics evidence

di-boson production

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

- Unitarity violation:



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

- Anomalous couplings may also lead to unitarity violation

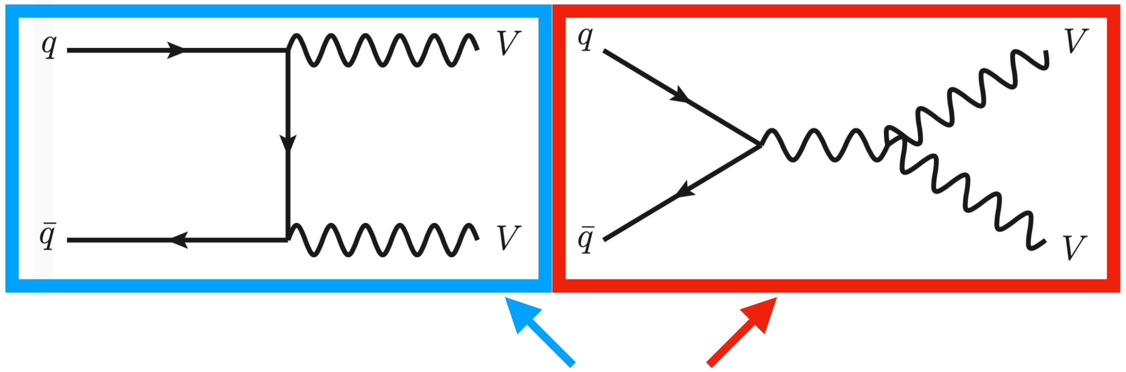
Anomalous signal = new physics evidence

No extra signal = No new physics ?

di-boson production

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

- Unitarity violation:



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

- Anomalous couplings may also lead to unitarity violation

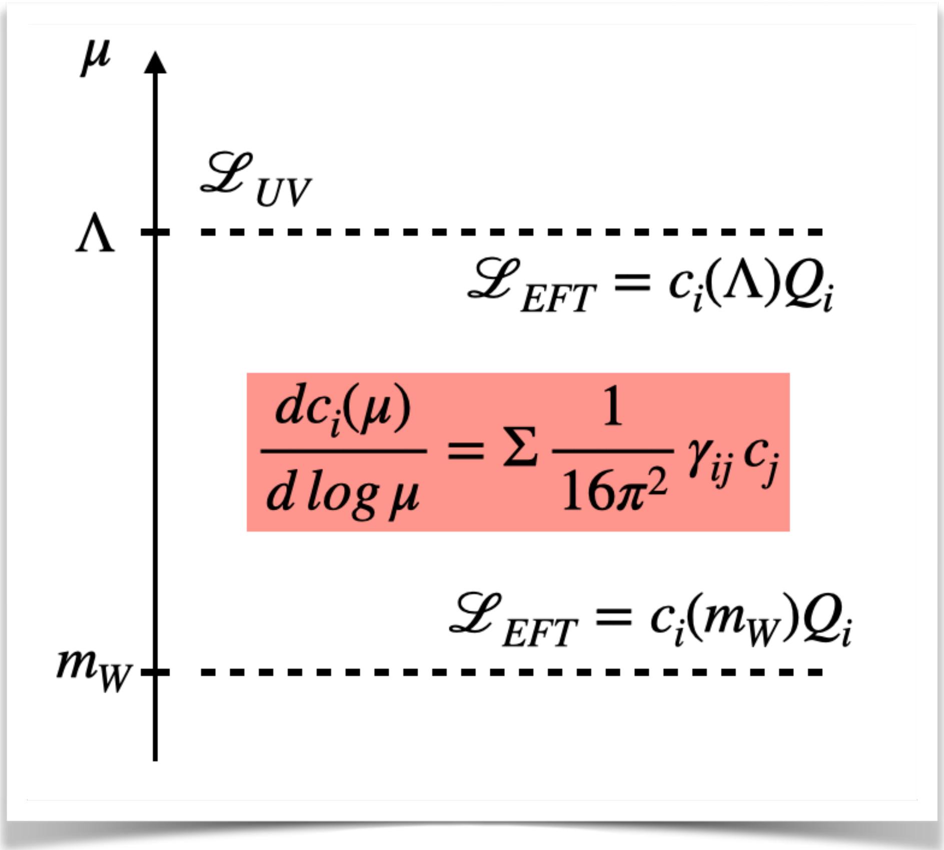
Anomalous signal = new physics evidence

No extra signal = No new physics ?

Correlated cancellation in new physics?

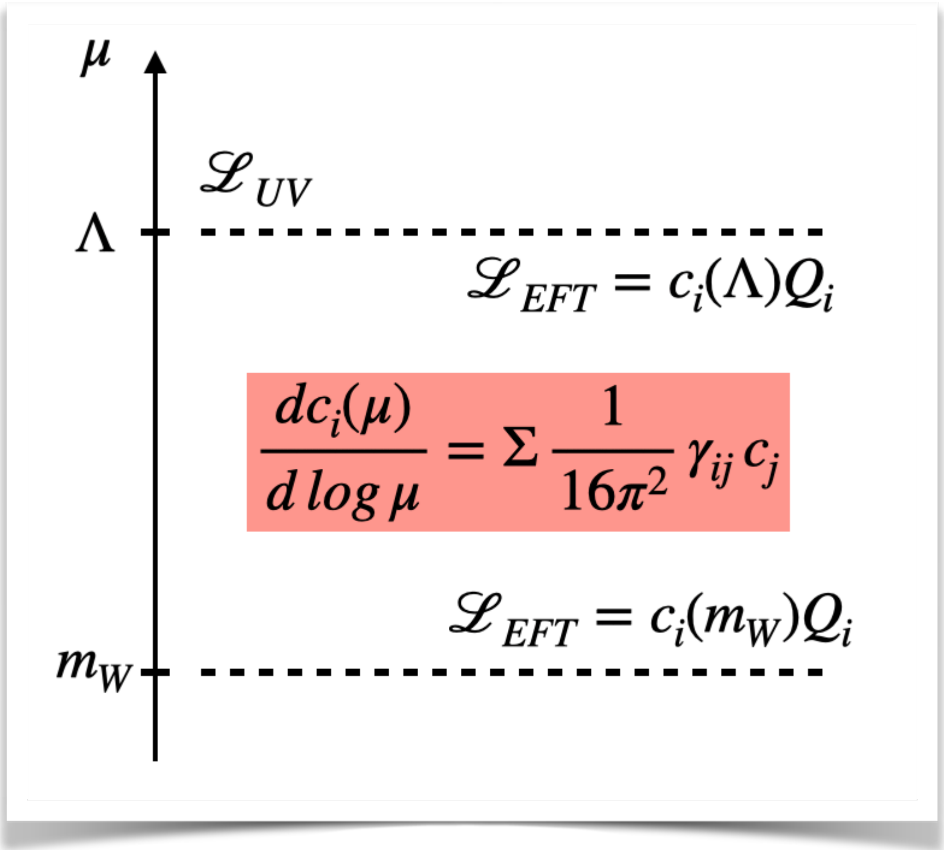
$$\sigma_{tot} = \sigma_{SM} + \sigma_{NP}^{(1)} - \sigma_{NP}^{(2)} \sim \sigma_{SM}$$

Standard model effective field theory



- Large scale
- No light particles
- Decoupling

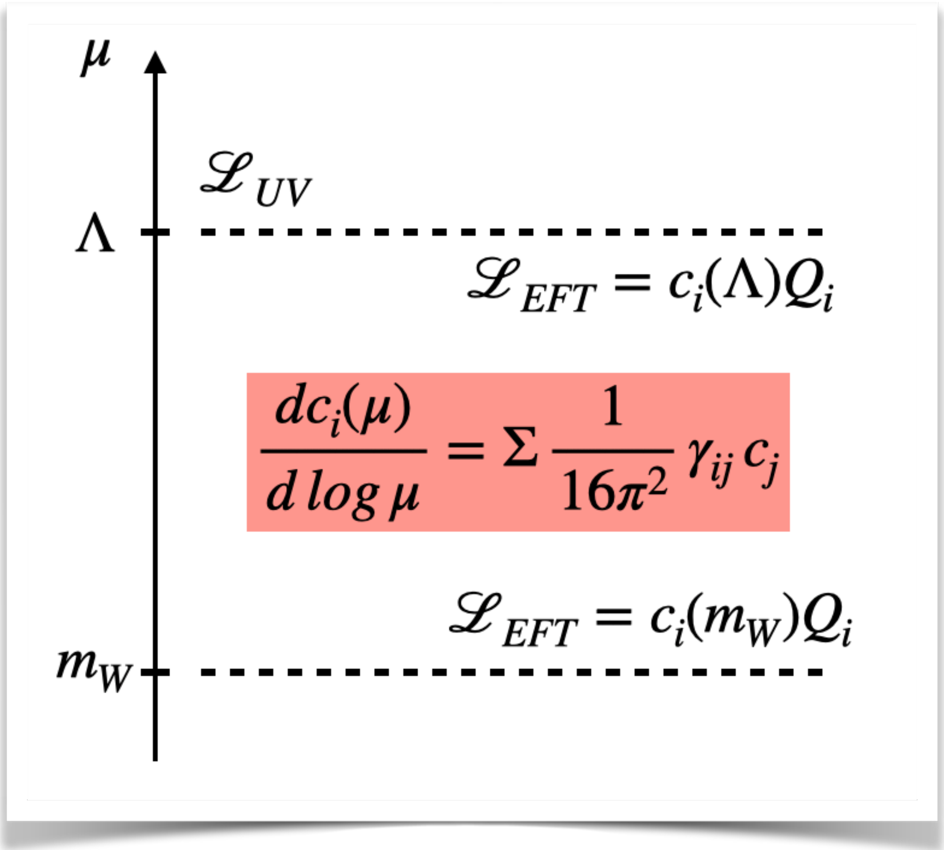
Standard model effective field theory



- Large scale
- No light particles
- Decoupling

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

Standard model effective field theory



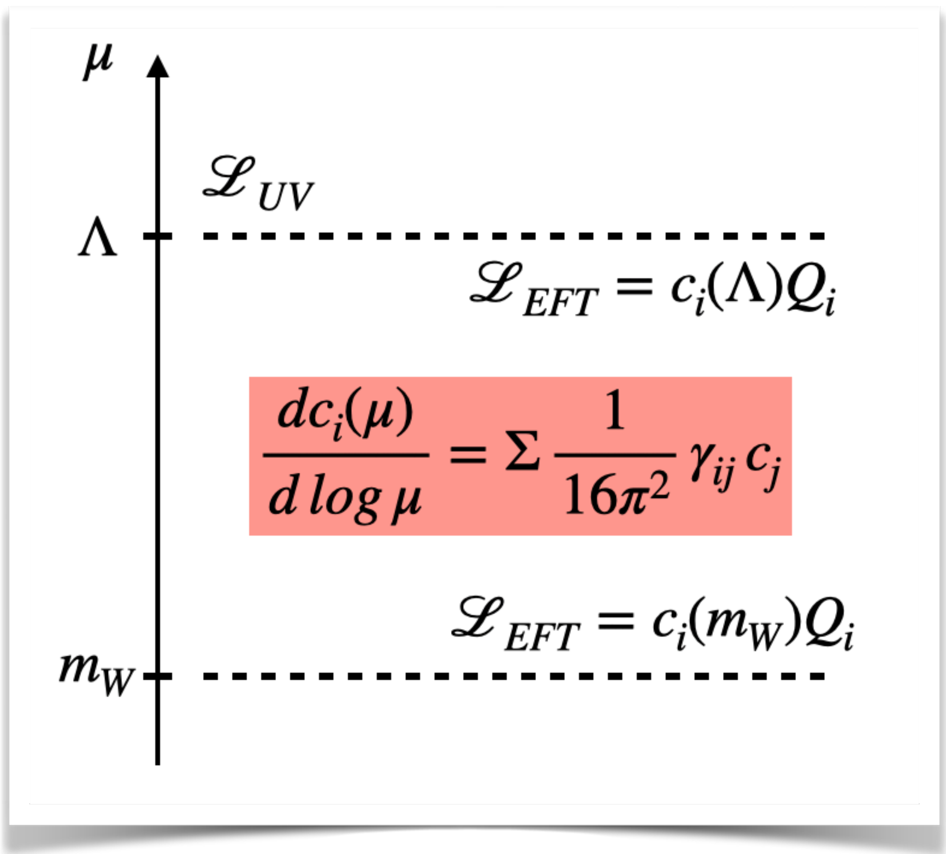
- Large scale
- No light particles
- Decoupling

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

- Operator correlation:

$$\sigma_{tot} = \sigma_{SM} + c_i\,\sigma_{NP}^i + c_k\,\sigma_{NP}^k$$

Standard model effective field theory



- Large scale
- No light particles
- Decoupling

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

- Operator correlation:

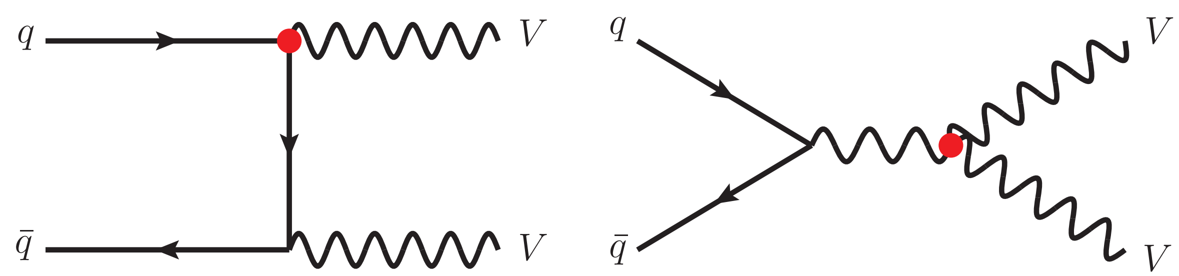
$$\sigma_{tot} = \sigma_{SM} + c_i\,\sigma_{NP}^{i} + c_k\,\sigma_{NP}^{k}$$

Only one cutoff

RGE insensitive

SMEFT in di-boson production

- In di-boson production, the Feynman diagram are shown as:



- Assuming that the new physics in quark sector only occur in the third generation.

- When considering the interference effects of new physics:

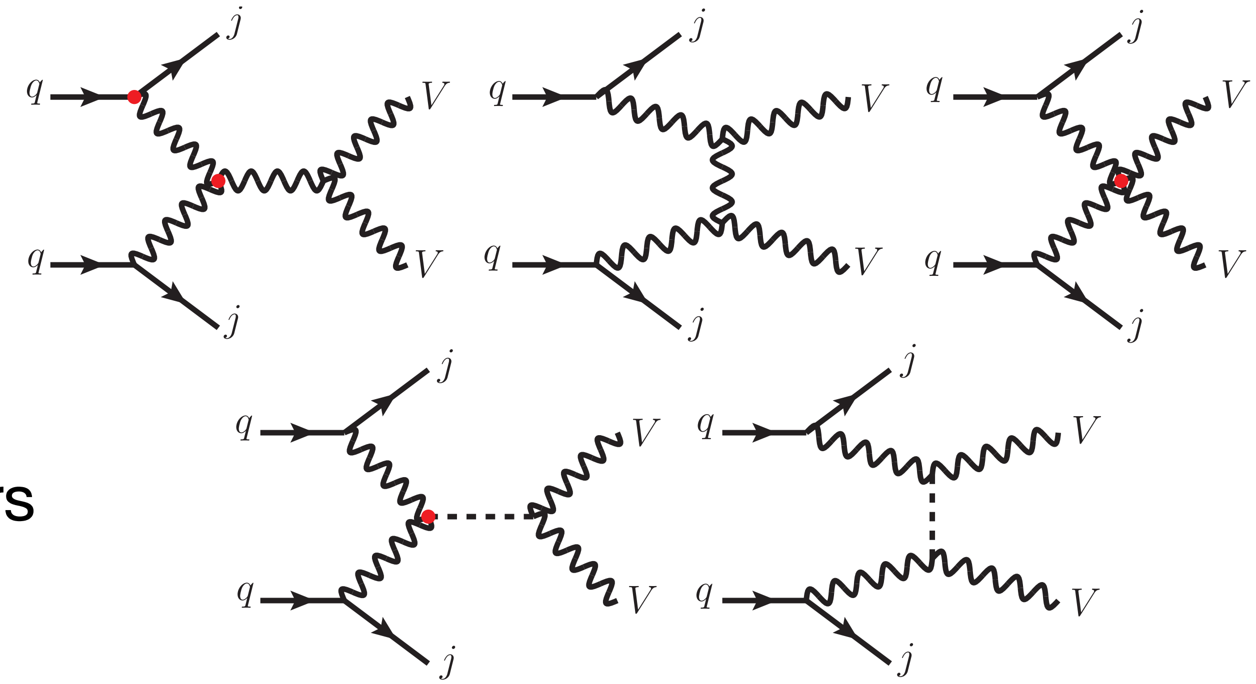
Process \ Operator	Q_W	$Q_{\varphi W}$	$Q_{\varphi B}$	$Q_{\varphi WB}$	$Q_{\varphi D}$	$Q_{\varphi\Box}$	$Q_{\varphi q}^{(1)}$	$Q_{\varphi q}^{(3)}$	$Q_{\varphi u}$	$Q_{\varphi d}$	Q_{uW}	Q_{uB}
$pp \to W^\pm W^\mp$	⋆			⋆			⋆	⋆		⋆	⋆	
$pp \to ZZ$				⋆			⋆	⋆		⋆		
$pp \to ZW^\pm$	⋆			⋆			⋆	⋆				

$$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu} \qquad Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu} \qquad Q_{\varphi q}^{(1)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$$

$$Q_{\varphi q}^{(3)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r) \qquad Q_{\varphi d} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r) \qquad Q_{uW} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\varphi} W_{\mu\nu}^I$$

SMEFT in vector boson scattering

- In vector boson scattering, the initial gauge boson comes from the radiation of quarks, the signal is set as:



$$pp \to VVjj\ , \quad V = Z, W^{\pm}$$

In this case, the fermion relevant operators should be contained in consideration.

- Although the four-fermion operators will influence these processes indirectly, we ignore the corresponding contribution.

- Due to the large QCD background from $gg \to t\bar{t}(\to W^+W^-jj)$, we ignore the different-sign WW vector boson scattering channel:

~~$pp \to W^+W^-jj$~~

SMEFT in vector boson scattering

- When considering the interference effects of new physics:

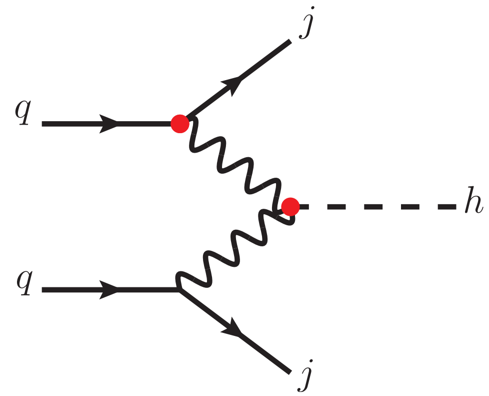
Process \ Operator	Q_W	$Q_{\varphi W}$	$Q_{\varphi B}$	$Q_{\varphi WB}$	$Q_{\varphi D}$	$Q_{\varphi\Box}$	$Q_{\varphi q}^{(1)}$	$Q_{\varphi q}^{(3)}$	$Q_{\varphi u}$	$Q_{\varphi d}$	Q_{uW}	Q_{uB}
$pp \to jjW^\pm W^\pm$	$\star$	$\star$		$\star$	$\star$	$\star$	$\star$	$\star$			$\star$	
$pp \to jjZW^\pm$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
$pp \to jjZZ$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	–	$\star$	–	–

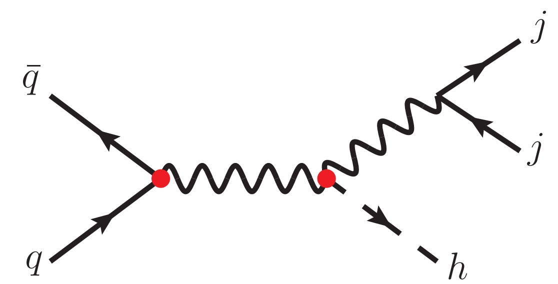
TABLE I: Operator formula in Warsaw basis[26] of SMEFT

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

- In order to give a more precise prediction in operator correlations, the Higgs production from vector boson fusion have to be included, since it is sensitive to Higgs relevant operators.

- When we choose the signal as $pp \to jjh$, not only the vector boson fusion channel will contribute to the signal, the Vh associated production will have non-vanishing contribution.





- In VBF, operator contribution are shown as:

Operator / Process	Q_W	$Q_{\varphi W}$	$Q_{\varphi B}$	$Q_{\varphi WB}$	$Q_{\varphi D}$	$Q_{\varphi\Box}$	$Q_{\varphi q}^{(1)}$	$Q_{\varphi q}^{(3)}$	$Q_{\varphi u}$	$Q_{\varphi d}$	Q_{uW}	Q_{uB}
$pp \to jjH$		⋆	⋆	⋆	⋆	⋆	⋆	⋆		⋆		

Phenomenology analysis in electroweak scattering

- In VBS and VBF channels, the two jet in electroweak processes will have very high energy and large pseudo-rapidity due to the pole in amplitude corresponding to $q_1(p_1)q_2(p_2) \to q_3(p_3)q_4(p_4)VV$:

$$|\mathcal{M}|^2 \propto \frac{p_1 \cdot p_2 \; p_3 \cdot p_4}{(q_1^2 - M_{V*}^2)^2 (q_2^2 - M_{V*}^2)^2}$$

  Therefore, the two hard jets can significantly distinguish the electroweak signal from QCD background.

CMS Collaboration, 2009,01186
CMS Collaboration, 2005,01173

- In order to compare with the experiments, we consider the cut similar to CMS Collaboration:

EW-VBS[ZZ]

- $p_T(\ell_1) > 20\text{GeV}$, $p_T(\ell_2) > 10\text{GeV}$, $p_T(\ell) > 5\text{GeV}$, $|\eta(\ell)| < 2.5$;
- $p_T(j) > 30\text{GeV}$, $|\eta(j)| < 4.7$, $\Delta R(\ell, j) > 0.4$;
- $60 < m(\ell\ell) < 120\text{GeV}$, $m(4\ell) > 180\text{GeV}$;
- $m_{jj} > 400\text{GeV}$, $|\Delta\eta(jj)| > 2.4$;

EW-VBS[ZW]

- $p_T(\ell) > 20\text{GeV}$, $|\eta(\ell)| < 2.5$, $m_{\ell\ell} > 20\text{GeV}$;
- $p_T(j) > 50\text{GeV}$, $|\eta(j)| < 4.7$, $\Delta R(\ell, j) > 0.4$;
- $m_{jj} > 500\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$;

EW-VBS[WW]

- $p_T(\ell) > 20\text{GeV}$, $|\eta(\ell)| < 2.5$, $|m_{\ell\ell} - m_Z| < 15\text{GeV}$;
- $p_T(j) > 50\text{GeV}$, $|\eta(j)| < 4.7$, $\Delta R(\ell, j) > 0.4$;
- $m_{jj} > 500\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$;

Phenomenology analysis in electroweak scattering

- In VBS and VBF channels, the two jet in electroweak processes will have very high energy and large pseudo-rapidity due to the pole in amplitude corresponding to $q_1(p_1)q_2(p_2) \to q_3(p_3)q_4(p_4)VV$:

$$|\mathcal{M}|^2 \propto \frac{p_1 \cdot p_2 \; p_3 \cdot p_4}{(q_1^2 - M_{V*}^2)^2 (q_2^2 - M_{V*}^2)^2}$$

  Therefore, the two hard jets can significantly distinguish the electroweak signal from QCD background.

CMS Collaboration, 2009,01186
CMS Collaboration, 2005,01173

- In order to compare with the experiments, we consider the cut similar to CMS Collaboration:

EW-VBS[ZZ]

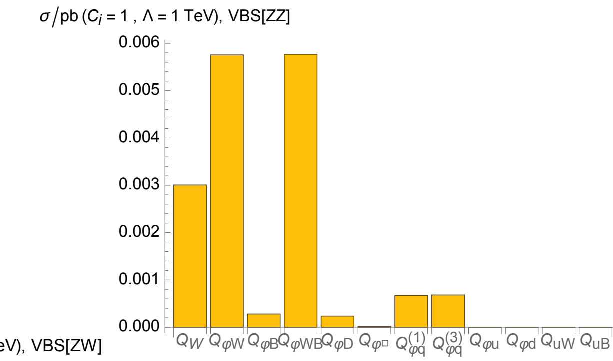
- $p_T(\ell_1) > 20\text{GeV},\ p_T(\ell_2) > 10\text{GeV},\ p_T(\ell) > 5\text{GeV},\ |\eta(\ell)| < 2.5;$
- $p_T(j) > 30\text{GeV},\ |\eta(j)| < 4.7,\ \Delta R(\ell, j) > 0.4;$
- $60 < m(\ell\ell) < 120\text{GeV},\ m(4\ell) > 180\text{GeV};$
- $m_{jj} > 400\text{GeV},\ |\Delta\eta(jj)| > 2.4;$

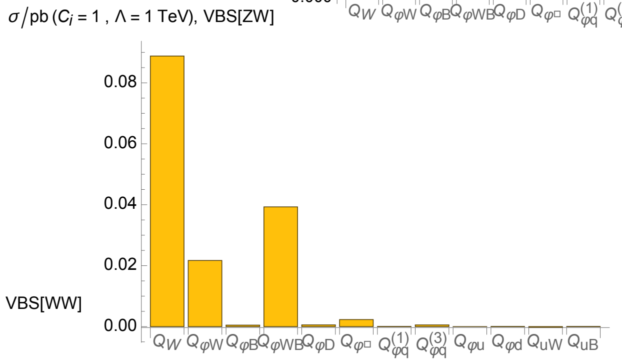
EW-VBS[ZW]

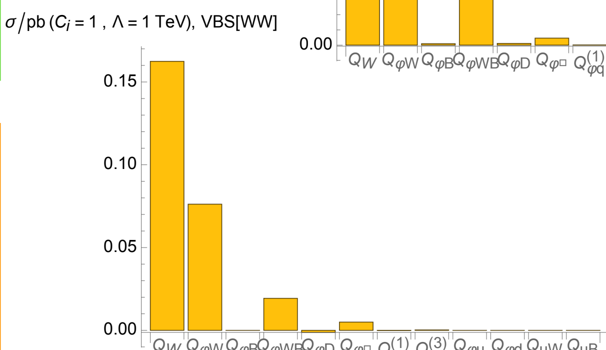
- $p_T(\ell) > 20\text{GeV},\ |\eta(\ell)| < 2.5,\ m_{\ell\ell} > 20\text{GeV};$
- $p_T(j) > 50\text{GeV},\ |\eta(j)| < 4.7,\ \Delta R(\ell, j) > 0.4;$
- $m_{jj} > 500\text{GeV},\ |\Delta\eta_{jj}| > 2.5;$

EW-VBS[WW]

- $p_T(\ell) > 20\text{GeV},\ |\eta(\ell)| < 2.5,\ |m_{\ell\ell} - m_Z| < 15\text{GeV};$
- $p_T(j) > 50\text{GeV},\ |\eta(j)| < 4.7,\ \Delta R(\ell, j) > 0.4;$
- $m_{jj} > 500\text{GeV},\ |\Delta\eta_{jj}| > 2.5;$







Phenomenology analysis in electroweak scattering

- In di-boson production and VBF, total cross section of experimental measurement is respected to the NNLO QCD + NLO EW theoretical prediction precisely.

ATLAS '17, CMS '20, ATLAS '19, ATLAS '20; Gehrmann et al '14, Grazzini et al '16, Cascioli et al '14, de Florian et al '16;

- In our analysis, we only consider the leading order contribution since the higher order corrections are absorbed into K factor.

- In order to estimate the operator correlation, we define the significance of vector boson scattering as:

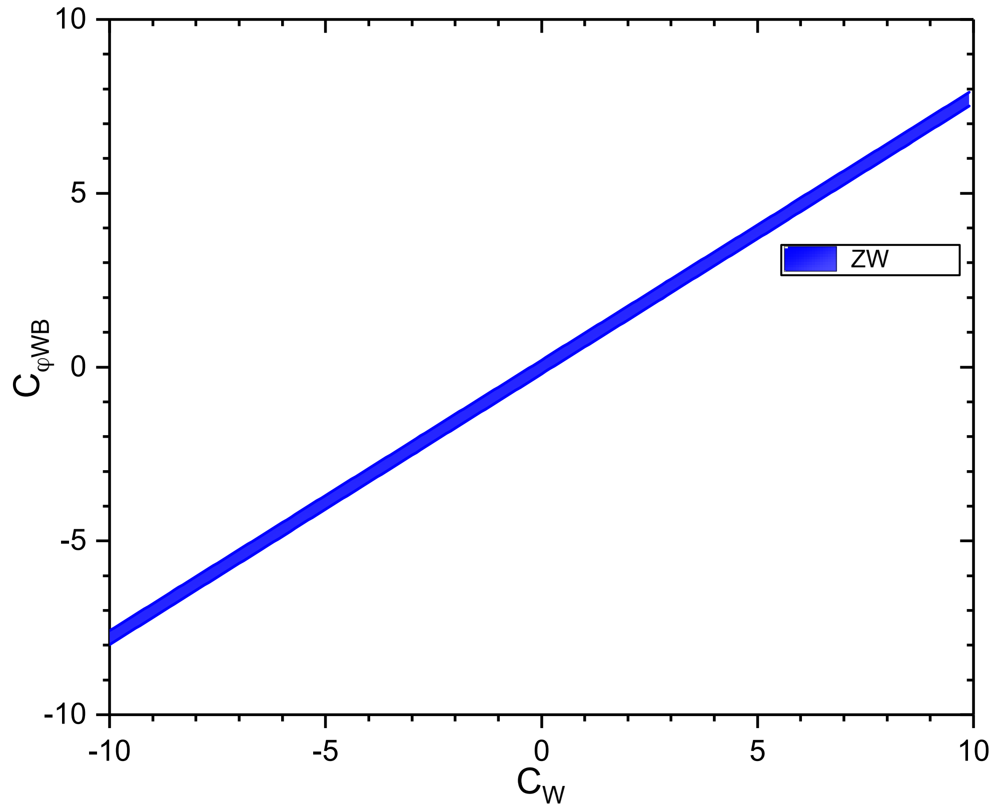
$$s = \frac{n_s}{\sqrt{n_s + n_B}} = 2.0$$

where $n_s\,, n_B$ denote the number of signal and background events.

- For di-boson production and VBF, we consider the corresponding relative uncertainty at HL-LHC.

Results and discussion

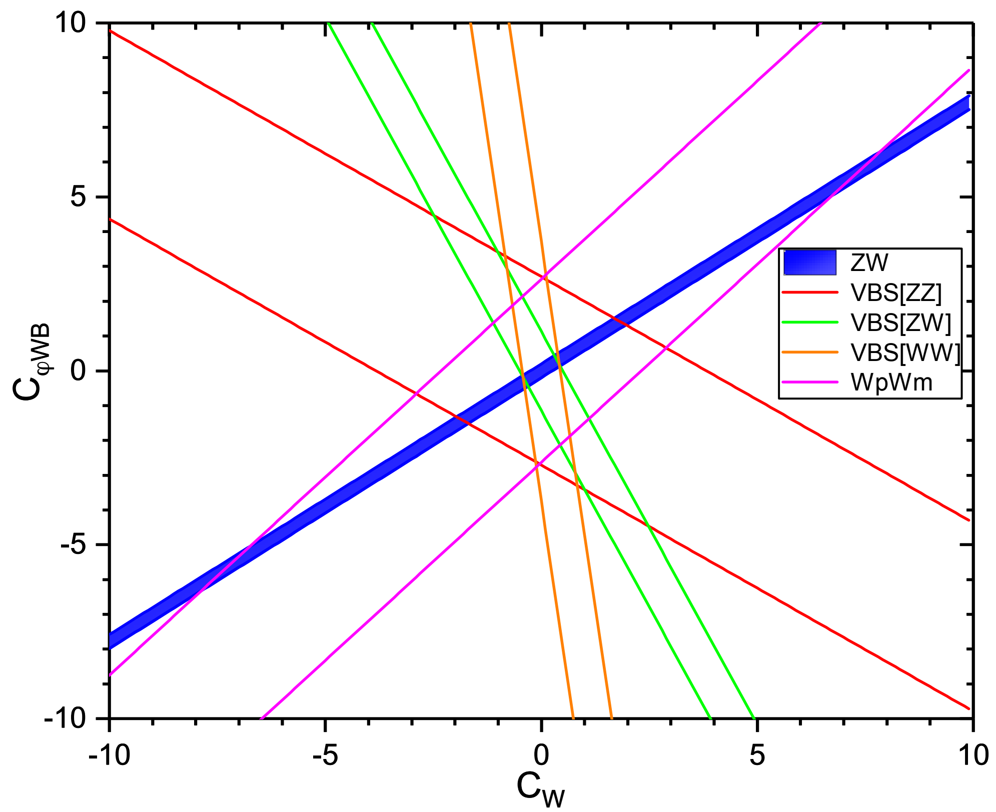
Operator correlation in Q_W - $Q_{\varphi WB}$



- Interference of Q_W will decrease the total cross section while $Q_{\varphi WB}$ is still contribute to enhancement.

Results and discussion

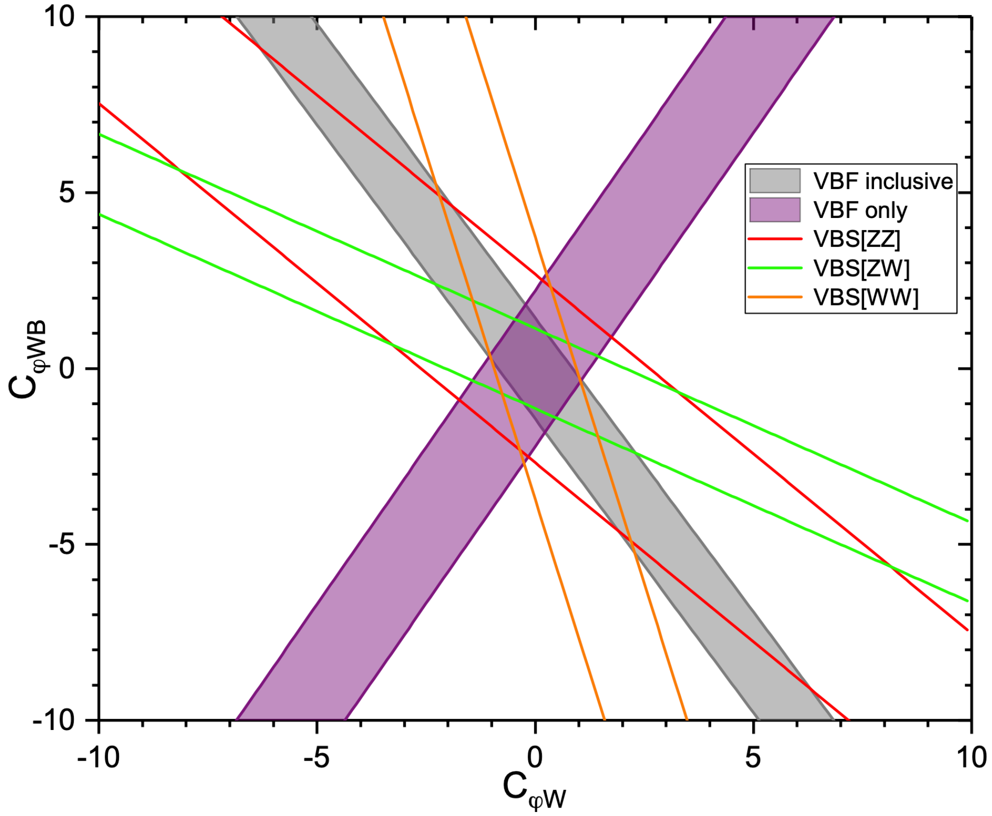
Operator correlation in Q_W - $Q_{\varphi WB}$



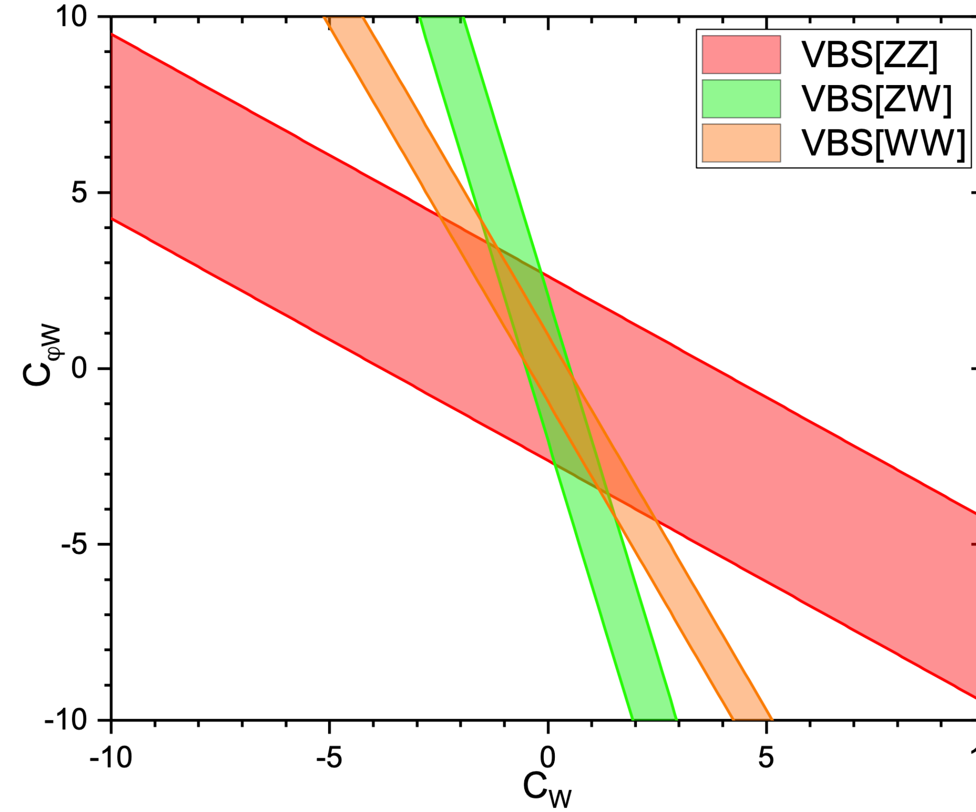
- Interference of Q_W will decrease the total cross section while $Q_{\varphi WB}$ is still contribute to enhancement.
- If the cross section of vector boson scattering has a large deviation at HL-LHC, we can uniquely determine the Wilson coefficient of these two operators.
- If no direct new physics evidence in future observation, new physics will be fixed in a small region.

Results and discussion

$Q_{\varphi W}$ - $Q_{\varphi WB}$



Q_W - $Q_{\varphi W}$



- In vector boson fusion, if we can veto the on-shell contribution from Vh , the correlated direction of VBF will converse to other processes, which will give a precise prediction to operator correlation.

- In Q_W - $Q_{\varphi W}$ correlation, although we can't have an accurate constrain to the corresponding Wilson coefficients, the precise measurement of vector boson scattering is necessary.

Summary

- Single operator dominant approximation sometimes can not reflect the true of natures, operator correlation may give us some hints about the physics beyond standard model.
- If we can find a deviation of cross section in electroweak scattering at HL-LHC, we can uniquely determine the Wilson coefficient, which will show us some information about the completed theories.
- If new physics can not be found in HL-LHC, its Wilson coefficient and correlated structure will be fixed in a small region.

Thanks for your attention !