Exploring SMEFT operators through single top-quark production associated with the Higgs boson at the LHC

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Introduction

- The **SM has been successful**, compatible with all experimental measurements, and no evidence of light states are present till now
- This indicates **BSM physics** may reside at somewhat **higher scale**
- This motivates to interpret deviations from the dim=4 SM Lagrangian predictions in terms of an EFT:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_{i=1}^{N_{d6}} C_i^{(6)} \mathcal{O}_i^{(6)}$$

- There can be **59 independent set of operators** in dim=6 EFT expansion
- In this work, we focus on **operators related to the tHq process** and mainly **affecting top-quark interactions which can be a sensitive probe for new physics having close relation to EWSB**

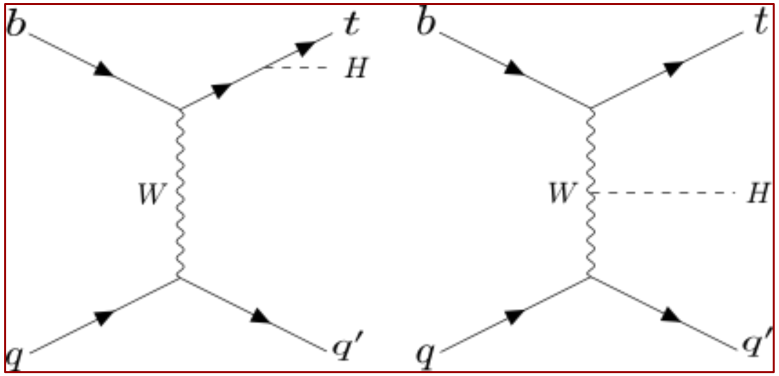
SMEFT operators affecting tHq production

- **Symmetry assumption**, to focus on top quark related operators

$$U(3)_l \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d \equiv U(2)^2 \times U(3)^3$$

- **Relevant operators** (Warsaw basis)

Operator	Coefficient	Definition	Vertex
$\mathcal{O}_{t\phi}$	$C_{t\phi}$	$(\phi^\dagger\phi - v^2/2)\bar{Q}t\tilde{\phi}$	$t\bar{t}H$
$\mathcal{O}_{\phi t}$	$C_{\phi t}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)\bar{t}\gamma^\mu t$	$t\bar{t}H$, $t\bar{t}V$
$\mathcal{O}^{(1)}_{\phi Q}$	$C^{(1)}_{\phi Q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)\bar{Q}\gamma^\mu Q$	$t\bar{t}H$,Wtb
$\mathcal{O}^{(3)}_{pQ}$	$C^{(3)}_{\phi Q}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)\bar{Q}\gamma^\mu \tau^I Q$	$t\bar{t}H$,Wtb
$\mathcal{O}_{tw}$	C_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t)\tilde{\phi}W^I_{\mu\nu}$	Wtb
$\mathcal{O}_{\phi W}$	$C_{\phi W}$	$(\phi^\dagger\phi - v^2/2)W^I_{\mu\nu}W^I_{\mu\nu}$	HWW
$\mathcal{O}_{\phi D}$	$C_{\phi D}$	$(\phi^\dagger D_\mu \phi)(\phi^\dagger D^\mu \phi)$	HWW



- The operators affecting HWW vertex are found not to be much sensitive and are constrained mainly by EW precision data
- **5 operators are relevant**

$$\mathcal{O}_{t\phi}, \mathcal{O}_{\phi t}, \mathcal{O}^{(3)}_{pQ}, \mathcal{O}_{tw}, \mathcal{O}^{(-)}_{\phi Q} \equiv \mathcal{O}^{(1)}_{\phi Q} - \mathcal{O}^{(3)}_{\phi Q}$$

Constraints on Wilson Coefficients

- There exists constraints from **global fits** of operators (*JHEP* 04 (2021) 279, *JHEP* 11 (2021) 089)
- Some recent measurements sensitive to the chosen operators are not included
- We try to find a **complementary approach of constraining with a subset of data** which are most relevant and recent

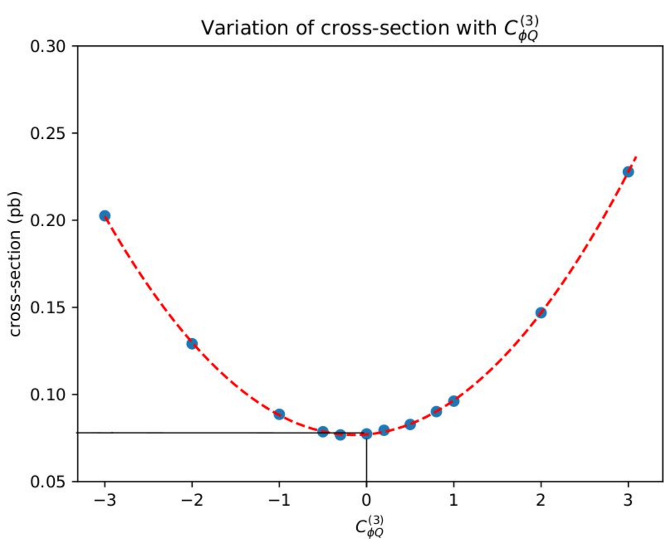
Most relevant experimental data

- Higgs data → $\mathrm{t\bar{t}H, tHq, tHW}$
- Top data → $\mathrm{single\ top, t\bar{t}Z, t\bar{t}W, tZq, tW}$

Calculation of expressions of observables

SMEFTatNLO → MadGraph+Madspin → Vary WCs to get list of cross-section → Polynomial Fit →

$$\sigma^{(tot)}(C) = \sigma^{(sm)} + \sum_{i=1}^{n} C_i\beta_i + \sum_{i<j}^{n} C_iC_j\gamma_{ij}$$



TMINUIT with MIGRAD → **χ2 minimization** → **Best-Fit values**

$$\mathcal{C}_{t\phi} \rightarrow -0.79^{+1.7}_{-1.6}$$
$$\mathcal{C}_{\phi t} \rightarrow 0.9^{+1.1}_{-1.4}$$
$$\mathcal{C}_{\phi Q}^{(3)} \rightarrow 1.4^{+0.6}_{-0.9}$$
$$\mathcal{C}_{\phi Q}^{(-)} \rightarrow -3.7^{+1.9}_{-0.7}$$
$$\mathcal{C}_{tw} \rightarrow -1.36^{+1.5}_{-1.0}$$

Constraints on Wilson Coefficients (continued)

- Fits are carried out for both **linear and quadratic** order in WCs
- Both for **individual operator at a time or combined fit** of all operators
- **Quadratic fits** was seen to put **much stronger constraints**

Information Matrix $(\mathrm{I_{ij}})$

(Phys.Rev.D 95 (2017) 7, 073002)

$$I_{ij} = E\left[\sum_{m=1}^{N_{exp}} \frac{1}{\delta^2_{exp,m}} \left(\gamma_{m,ij}\left(\sigma_m^{(sm)} - \sigma_m^{(exp)}\right) + \left(\beta_{m,i}^{(eft)} + \sum_{l=1}^{N_{wc}} C_l \gamma_{m,il}^{(eft)}\right)\left(\beta_{m,j}^{(eft)} + \sum_{l'=1}^{N_{wc}} C_{l'} \gamma_{m,il'}^{(eft)}\right)\right)\right]$$

- Provides a **quantitative measurement** of the **information about the parameters that one can derive from a set of observations**

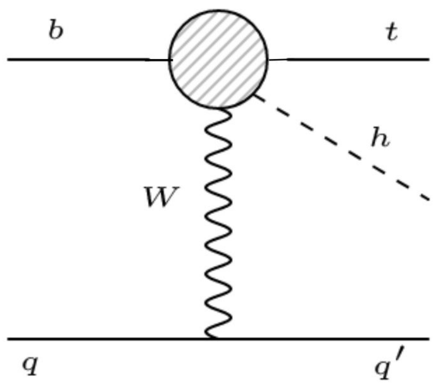
Relative size of normalised entries of diagonalised $\mathrm{I_{ij}}$ → Relative effect a given dataset puts on different operators

Diagonal entries for each dataset Normalized to 100

	$C_{pQ}^{(3)}$	$C_{pQ}^{(-)}$	$C_{\phi t}$	$C_{t\phi}$	C_{tw}
tH	15.7	15.6	16.4	33.4	18.5
ttH	2.4	0.4	3.7	92.1	1.2
tj	79.6	0.4	0.4	0.8	18.4
ttV	2.3	55.3	41.6	0.6	0.4
tZ	50.1	37.2	0.2	0.003	12.4
tW	64.0	0.7	0.1	0.002	35.1

What effects can we see in the distributions at the LHC?

- ➔ Unlike other processes like ttH, ggH etc., tHq poses the **bw→ tH scattering sub amplitude** **(*JHEP* 10 (2019) 004)**
- ➔ This results in an **energy growth** for specific operators
- ➔ We use **H→bb decay mode**
- ➔ We consider both **leptonic and hadronic** decay mode of Top-quark



Simulation

SMEFTatNLO → MadGraph → PYTHIA8 → Delphes

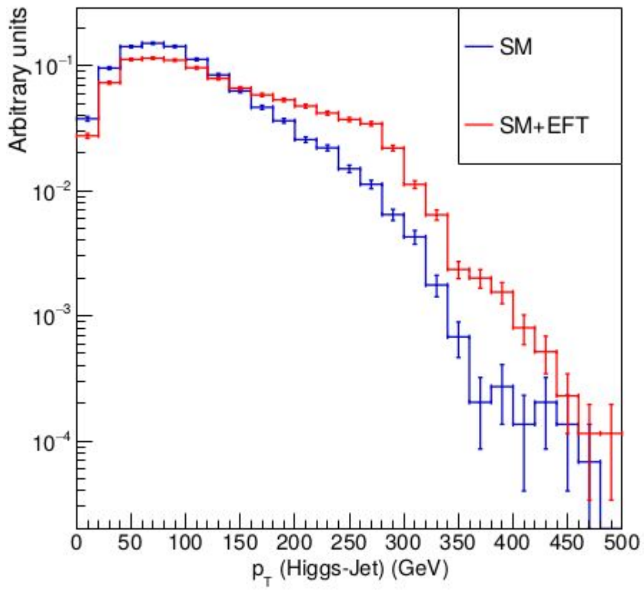
Event selection

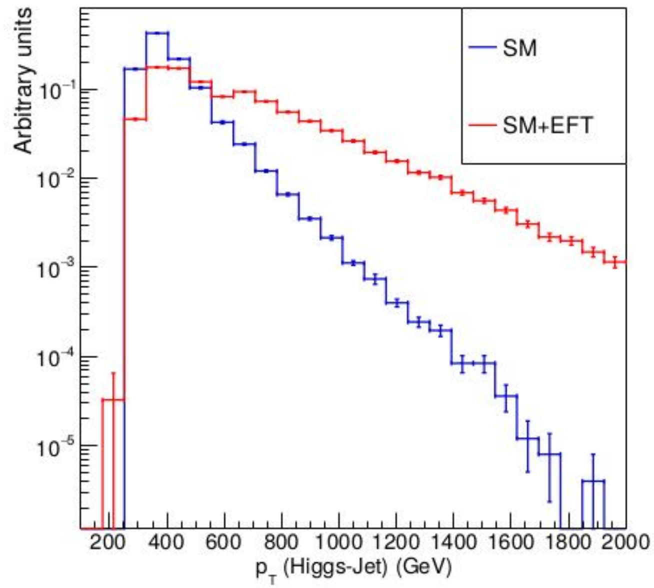
- ➔ One **reconstructed Higgs Jet**
  - For boosted region, tagging **CA8 fat-jets with two b-like subjects** and **[100,150]** mass window
  - For non-boosted region, using **combination of AK4 b-jets**
- ➔ One **isolated lepton (for leptonic final state)**
- ➔ One **reconstructed Top Jet (for hadronic final state)**
  - Using **HEPTopTagger,** in boosted region
- ➔ At least one **extra AK4 jet with pT>30 GeV**

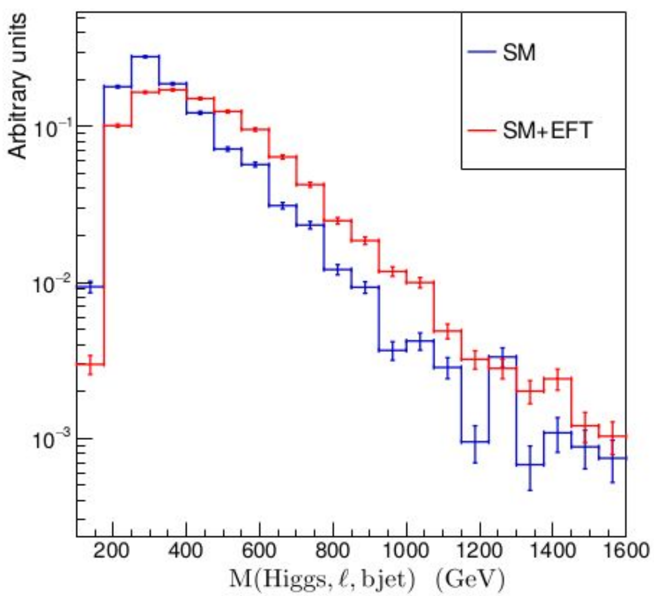
Distributions at reconstructed level (Leptonic final state)

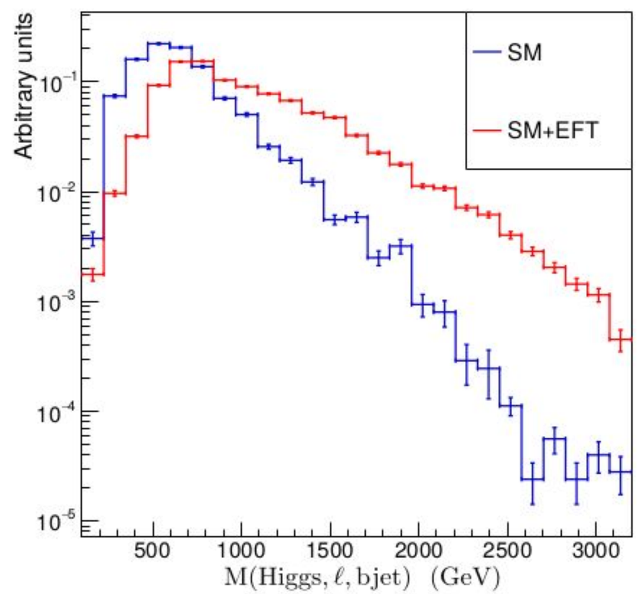
Non-boosted (pT(H) <300 GeV)

Boosted (pT(H) >300 GeV)









Selections

1 Higgs jet + 1 isolated lepton + extra bjet + extra jet

Transverse momentum of the reconstructed Higgs boson Jet

Invariant mass of reconstructed Higgs boson Jet, isolated lepton and b-jet

Distributions at reconstructed level (Hadronic final state)

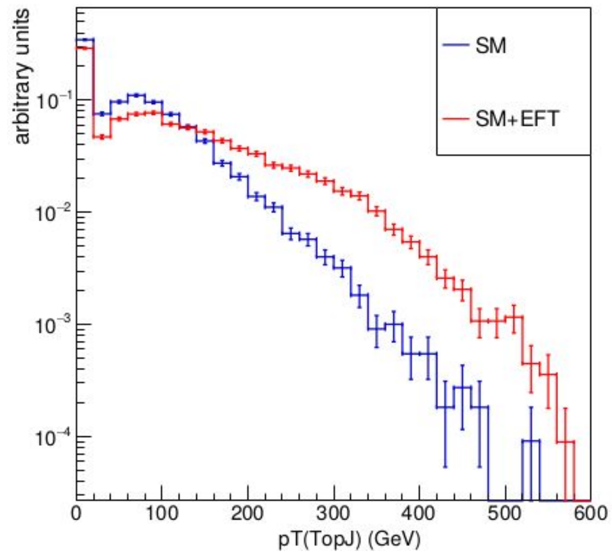
Selections

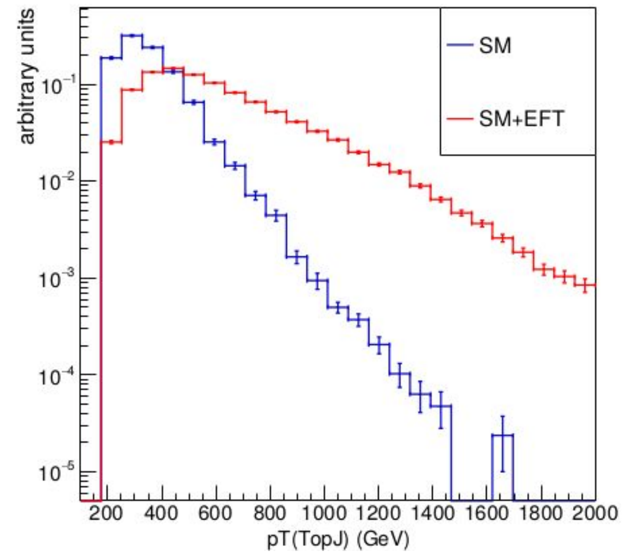
1 Higgs jet + 1 Top-jet +extra jet

Non-boosted (pT(H) <300 GeV)

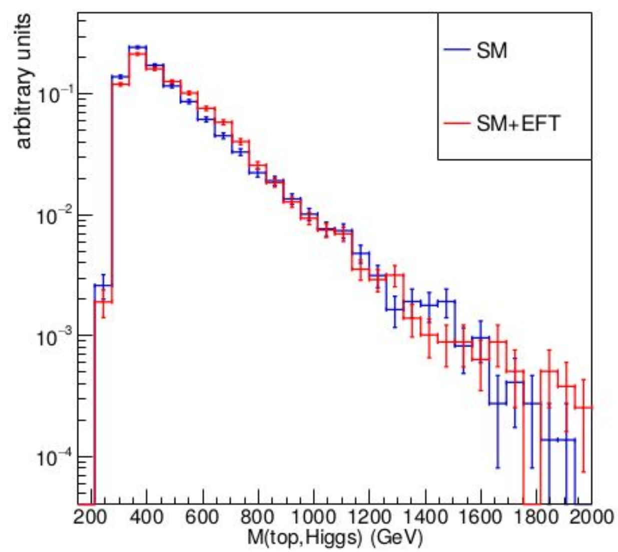
Boosted (pT(H) >300 GeV)

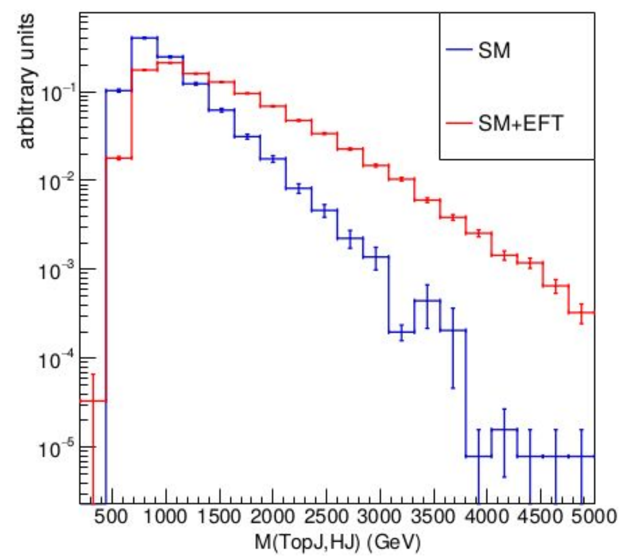
Transverse momentum of the reconstructed top-jet



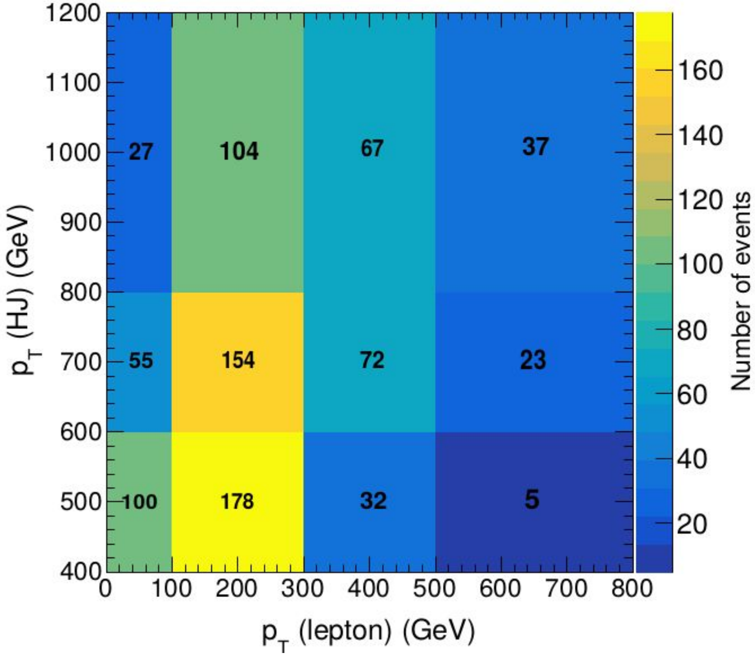


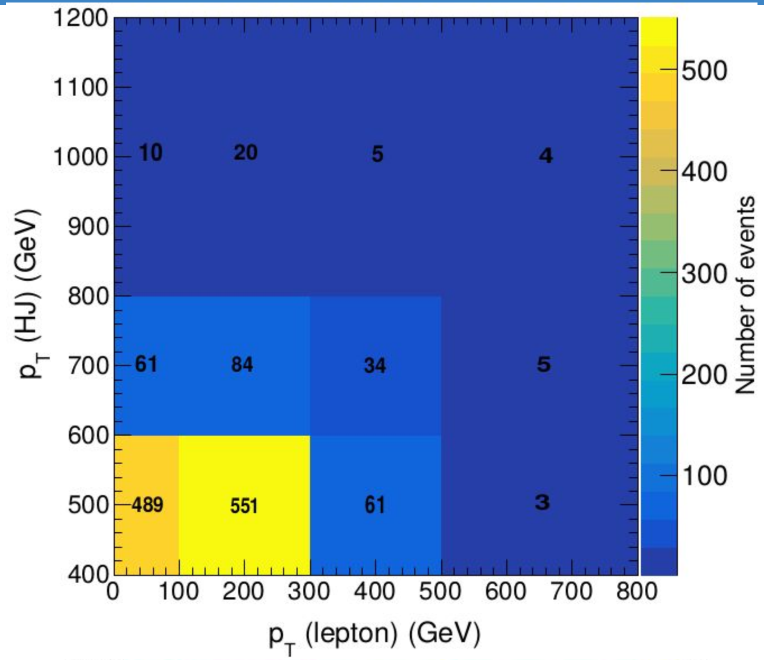
Invariant mass of reconstructed Higgs boson Jet and top-jet

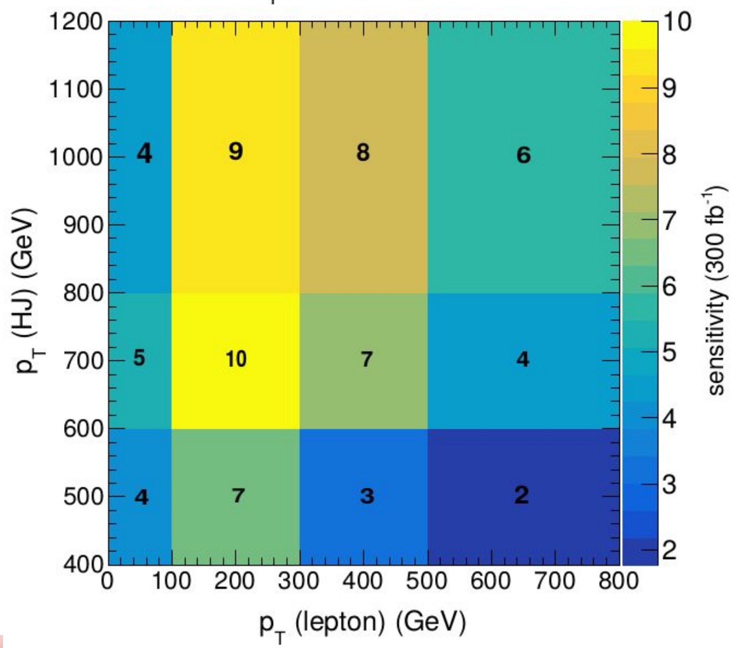




Estimation of backgrounds (Leptonic final state)







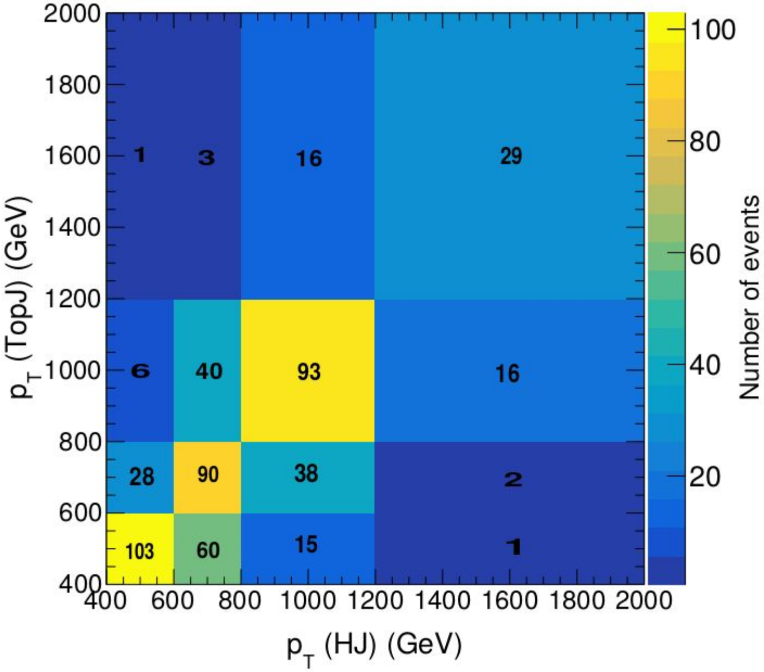
- We have considered the following backgrounds:

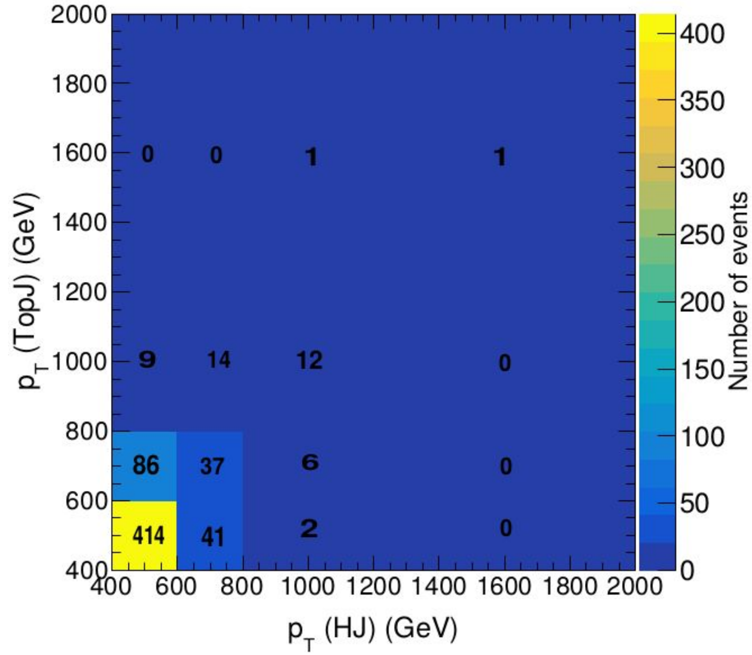
$$\mathrm{t\bar{t},\ t\bar{t}H,\ t\bar{t}Z,\ t\bar{t}b\bar{b},\ t\bar{t}W, WH}$$

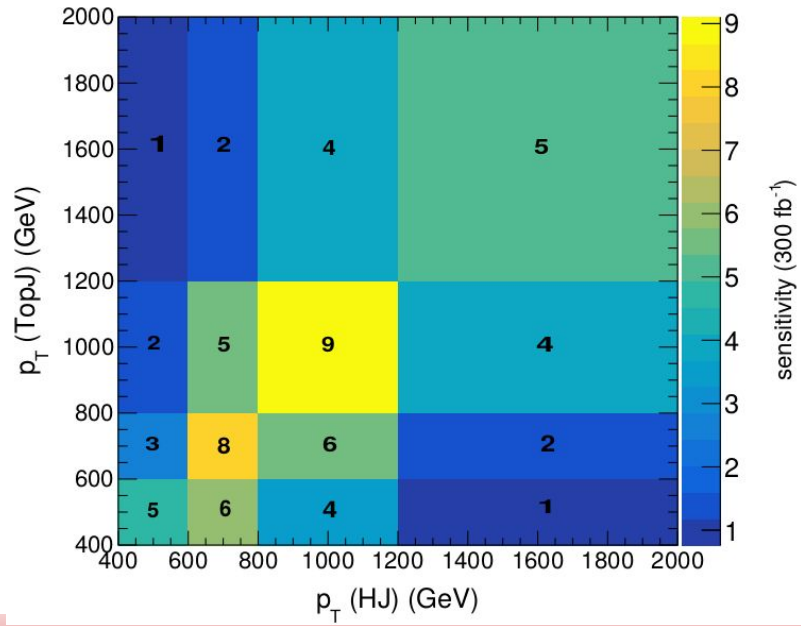
- Following selections were imposed

$$\mathrm{1\ HJ + 1\ lepton + \geq b-jet + \geq 1\ Other\ jets}$$

- Significant excess of events can be observed at 300 fb^{-1} luminosity







- We have considered the following backgrounds:

$$t\bar{t}H, t\bar{t}, t\bar{t}b\bar{b}, t\bar{t}Z, t\bar{t}W$$

- Following selections were imposed

$$1\ \mathrm{HJ} + 1\ \mathrm{Top-J} + \geq 1\ \mathrm{Other\ jets}$$

- Significant excess of events can be observed at 300 fb^{-1} luminosity

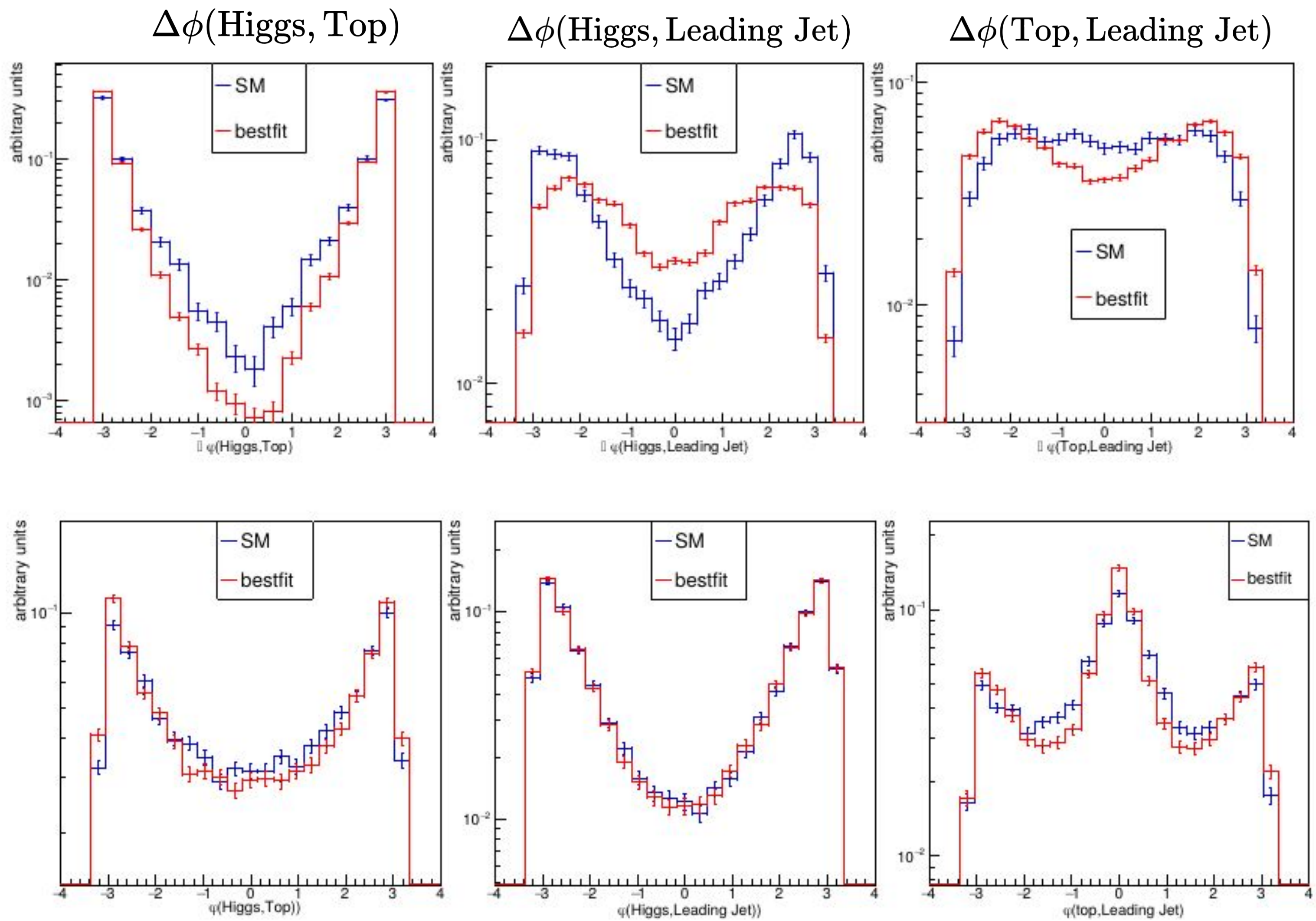
Summary

- **Top quark interactions** have important footprints of **EWSB**
- Within SMEFT framework, **these interaction can be probed through tHq process**
- Using various relevant and recent measurements, the **set of operators are constrained**
- **The implications at the collider are studied** using the best-fit values
- **Distinguishable deviations from SM** can be visible
- A signal background simulation shows **promising signal significance in pT-binned analysis 300 fb^{-1}**

Back Up

Boosted region

Non-boosted region



ttH, tHq measurements used in fit

	Process	observable	$\mathcal{L}$ (fb^{-1})	Value	Ref.
ATLAS	$t\bar{t}H, H \to b\bar{b}$	μ	79.8	$0.79^{+0.61}_{-0.60}$	Phys. Lett. B 784 (2018) 173
	$t\bar{t}H, H \to ZZ(4\ell)$	μ	79.8	< 1.77 at 68% CL	Phys. Lett. B 784 (2018) 173
	$t\bar{t}H, H \to$ Multilepton	μ	79.8	$1.56^{+0.42}_{-0.40}$	Phys. Lett. B 784 (2018) 173
CMS	$t\bar{t}H, H \to b\bar{b}$	μ	35.9	$0.72^{+0.45}_{-0.45}$	JHEP 03 (2019) 026
	$t\bar{t}H, H \to ZZ(4\ell)$	μ	137	$0.16^{+0.98}_{-0.16}$	Eur. Phys. J. C 81 (2021) 488
	$t\bar{t}H, H \to$ Multilepton	μ	35.9	$1.23^{+0.45}_{-0.43}$	JHEP 08 (2018) 066
	$tHq + thW$, combined	σ	35.9	0.9 pb	Phys. Rev. D 99, 092005 (2019)

- **Dedicated ttH, tHq measurements** are not generally used in previous fits
- Important for operators related to top-Higgs coupling

Singletop measurements used in fit

	Process	observable	$\mathcal{L}$ (fb^{-1})	Value	
CMS	tj (t-channel)	$\sigma_{\rm tot}(\rm t)$	35.9	130±19 pb	Phys. Lett. B 800 (2019) 135042
	tj (t-channel)	$\sigma_{\rm tot}(\bar{\rm t})$	35.9	77±12 pb	
	tj (t-channel)	$(1/\sigma)d\sigma/d\|y^{t+\bar{t}}\|$	2.3	0.64 ± 0.14(bin 1)	CMS-PAS-TOP-16-004
				0.55 ± 0.12(bin 2)	
				0.50 ± 0.12(bin 3)	
				0.18 ± 0.08(bin 4)	
		$(1/\sigma)d\sigma/d\|y^{t}\|$	35.9	0.58 ± 0.15(bin 5)	Eur. Phys. J. C 80 (2020) 370
				0.53 ± 0.08(bin 6)	
				0.5 ± 0.09(bin 7)	
				0.47 ± 0.09(bin 8)	
				0.26 ± 0.02(bin 9)	
ATLAS	tj (t-channel)	$\sigma_{\rm tot}(\rm t)$	3.2	156±28 pb	*JHEP* 04 (2017) 086
	tj (t-channel)	$\sigma_{\rm tot}(\bar{\rm t})$	3.2	91±19 pb	

ttV measurements used in fit

	Process	observable	$\mathcal{L}$ (fb^{-1})	Value	Reference
ATLAS	$t\bar{t}Z$	$\sigma_{\rm tot}$	36.1	0.95±0.13 pb	Phys. Rev. D 99, 072009 (2019)
	$t\bar{t}W$	$\sigma_{\rm tot}$	36.1	0.87±0.19 pb	
	$t\bar{t}Z$	$(1/\sigma)d\sigma/dp_T^Z$	139	0.0018 ± 0.0013(bin 1)	**Eur. Phys. J. C 81 (2021) 737**
				0.0055 ± 0.0025(bin 2)	
				0.0053 ± 0.002(bin 3)	
				0.0057 ± 0.0015(bin 4)	
				0.0022 ± 0.00085(bin 5)	
				0.0006 ± 0.0004(bin 6)	
				0.0006 ± 0.00025(bin 7))	
CMS	$t\bar{t}Z$	$\sigma_{\rm tot}$	35.9	0.99±0.14 pb	JHEP 08 (2018) 011
	$t\bar{t}W$	$\sigma_{\rm tot}$	35.9	0.77±0.17 pb	JHEP 08 (2018) 011
	$t\bar{t}Z$	$\sigma_{\rm tot}$	77.5	0.95±0.08 pb	JHEP 03 (2020) 056
	$t\bar{t}Z$	$(1/\sigma)d\sigma/dp_T^Z$	77.5	0.004 ± 0.001(bin 1)	JHEP 03 (2020) 056
				0.005 ± 0.0009(bin 2)	
				0.0022 ± 0.0005(bin 3)	
				0.0003 ± 0.0001(bin 4)	

tV measurements used in fit

	Process	observable	$\mathcal{L}$ (fb^{-1})	Value	
CMS	tZq(l$^+$, 2ℓ)	σ_{tot}	138	$62.2^{+7.4}_{-6.8}$ fb	**JHEP 02 (2022) 107**
	tZq(l$^-$, 2ℓ)	σ_{tot}	138	$26.1^{+5.6}_{-5.4}$ fb	**JHEP 02 (2022) 107**
	tW	σ_{tot}	36	89±13 pb	**JHEP 11 (2021) 111**
	tW	σ_{tot}	35.9	63±7 pb	JHEP 10 (2018) 117
	tZ	$1/\sigma d\sigma/dp_T^Z$	138	0.1 ± 0.035(bin 1)	**JHEP 02 (2022) 107**
				0.1 ± 0.03(bin 2)	
				0.035 ± 0.015(bin 3)	
				0.01 ± 0.0075(bin 4)	
ATLAS	tZ	σ_{tot}	139	97±15 pb	JHEP 07 (2020) 124
	tW	σ_{tot}	3.2	94^{+30}_{-24} pb	JHEP 01 (2018) 63

Fisher Information Matrix

(*Phys.Rev.D* 95 (2017) 7, 073002)

$$I_{ij}(\vec{C}) = -E\left[\frac{\partial^2 f(X|\vec{C})}{\partial c_i \partial c_j}\right]$$

→ $f(X|\vec{C})$ is the distribution of the experimental measurements X given the true values of WCs C

➔ The smallest achievable uncertainty can be obtained by the Cramer-Rao bound

$$C_{ij} \geq I_{ij}^{-1}$$

➔ Considering $f(X|\vec{C})$ a Gaussian distribution, the FIM can be expressed as.

$$I_{ij} = E\left[\sum_{m=1}^{N_{exp}} \frac{1}{\delta^2_{exp,m}} \left(\gamma_{m,ij}\left(\sigma_m^{(sm)} - \sigma_m^{(exp)}\right) + \left(\beta_{m,i}^{(eft)} + \sum_{l=1}^{N_{wc}} C_l \gamma_{m,il}^{(eft)}\right)\left(\beta_{m,j}^{(eft)} + \sum_{l'=1}^{N_{wc}} C_{l'} \gamma_{m,il'}^{(eft)}\right)\right)\right]$$

$$\vec{C} = \begin{bmatrix} C_{\phi Q}^{(3)} \\ C_{\phi Q}^{(-)} \\ C_{\phi t} \\ C_{t\phi} \\ C_{tW} \end{bmatrix} \quad \begin{bmatrix} 212.4 & -1.9 & -1.8 & 1.0 & 55.5 \\ -1.9 & 0.02 & -1.5 & -1.6 & -0.9 \\ -1.8 & -1.5 & -0.03 & 1.1 & -0.8 \\ -1.0 & -1.6 & 1.1 & 0.12 & -0.8 \\ 55.5 & -0.9 & -0.8 & -0.8 & -40.1 \end{bmatrix} \quad \begin{pmatrix} 223.5 \\ -1.1 \\ -1.2 \\ 2.3 \\ -51.5 \end{pmatrix}$$

Basis | **FIM** | **Eigen-values**

Example: Results for single-top data

➔ Single-top data mostly affects $C_{\phi Q}^{(3)}$ and C_{tW}

Higgs-Jet reconstruction

❖ **Fat jet reconstruction**

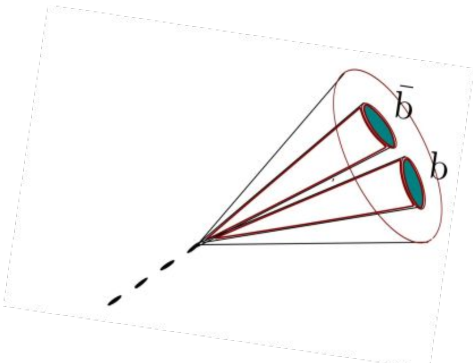
- Used **Fastjet3.3.4** and Delphes **e-flow objects**
- CA algorithm, R=0.8
- pT (jet) > 300 GeV, |η| <4.0

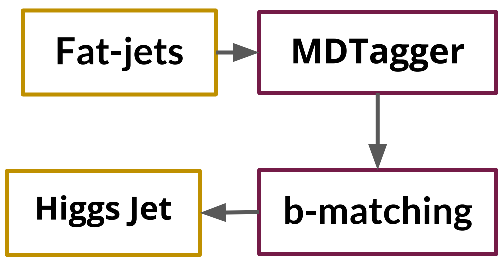
❖ **Ordinary jet reconstruction**

- Anti-KT algorithm, R=0.4
- pT (jet) > 30 GeV, |η| <4.0

Higgs jet reconstruction

❖ For the **non-resolved category**, Higgs bosons can be reconstructed as a fat jet





- In **resolved category**, pair of b-jets giving invariant mass closest to 125 GeV are identified
- If **100 GeV < m(bb) <150 GeV**, assign the resultant 4-momentum to Higgs-Jet

❑ **For b-matching,** sub-jets are matched with b-quarks of the event

- ❑ Used ΔR <0.3, |η|<2.5
- ❑ Also cross-checked the procedure by **confirming presence of b-hadrons** inside the tagged b-jets

***JHEP* 10 (2010) 085**

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Warsaw Basis - II

***JHEP* 10 (2010) 085**

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		