December 2018 EWWG Meeting

Studies of Dim-6 EFT in Vector Boson Scattering

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Dim-6 EFT and VV processes

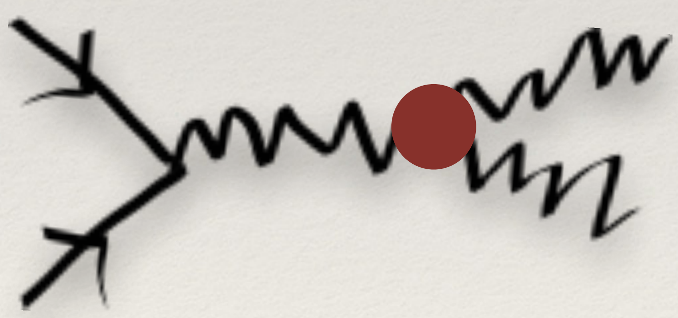
- Based on 1809.04189 , accepted for EPJC
- Work in progress, together with K. Lohwasser

Comments and suggestions very welcome!
(Thanks already to R. Covarelli, J. Lindert, C. Degrande …)

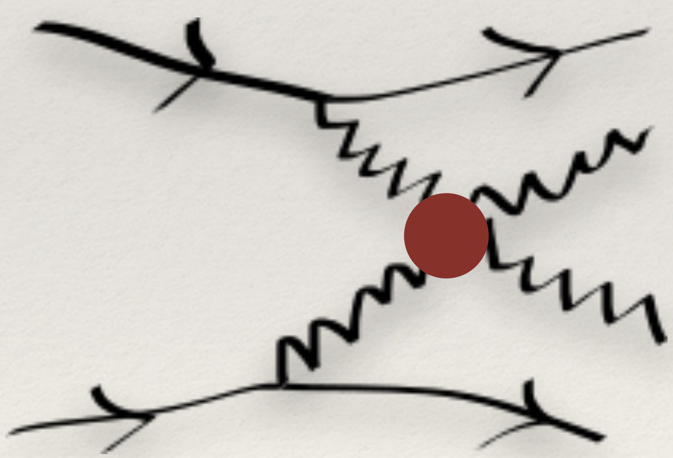
Motivation: From LEP to LHC

From anomalous to effective

- LEP: TGCs (on-shell) ← **Traditionally param. by (incomplete) Dim-6 EFT**
- LHC: QCGs (off shell) ← **Traditionally Dim-8 EFT**
- The anomalous coupling approach is good in a first approximation, for more complicated processes, like VBS we need a more robust formalism



$\mathcal{O}(1)$ diagram



$\mathcal{O}(10^4)$ diagrams

Bottom-Up EFT

- Assuming linear representation for the Higgs, no new light particles, SM symmetries, etc:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \sum_j\sum_k \frac{1}{\Lambda^{2+k}} c_j^{(6+k)}\mathcal{O}_j^{(6+k)}$$

- Amplitudes and cross-sections:

Quadratic + dim-8

$$\mathcal{A}_{EFT} = \mathcal{A}_{SM} + \frac{g'}{\Lambda^2}\mathcal{A}_6 + \frac{g'^2}{\Lambda^4}\mathcal{A}_8 + \ldots$$

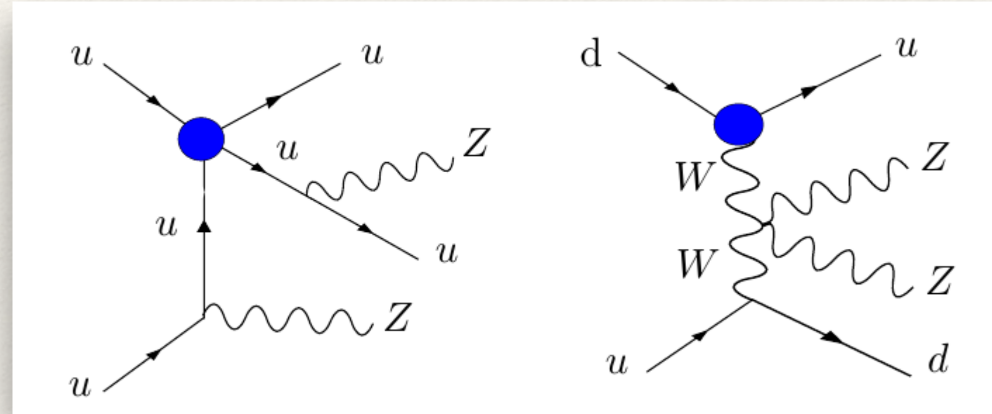
$$\sigma_{EFT} \sim |\mathcal{A}_{SM}|^2 + 2\frac{g'}{\Lambda^2}\mathcal{A}_{SM}\mathcal{A}_6 + \frac{g'2}{\Lambda^4}\left(2\mathcal{A}_{SM}\mathcal{A}_8 + |\mathcal{A}_6|^2\right) + \ldots$$

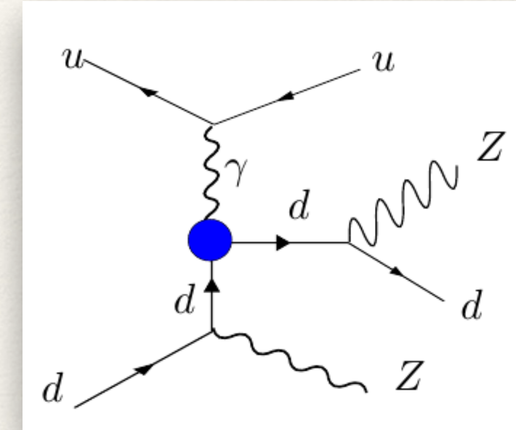
Linear EFT

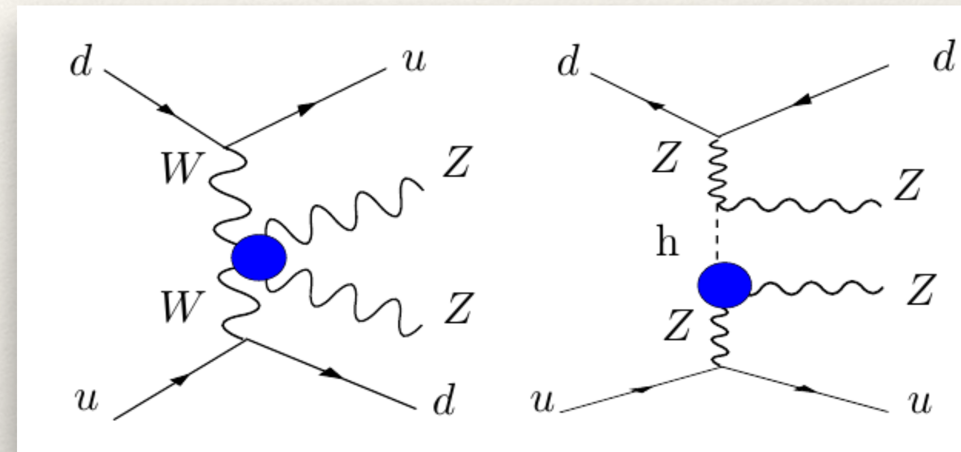
Obs: The larger Lambda is, the larger the difference between contributions….

The idea:

VBS (ZZ)







- Generate the purely electroweak process p p → z z j j , with on-shell Zs
- Use ***numerical methods**** to find the relative contribution for each operator of the Warsaw basis to the total cross sections
- Observe the behaviour of different operators and combinations thereof, in a bin-by-bin, observable-by-observable basis
- Repeat for other VBS and VV channels….

Tools

Everywhere: Linear EFT (LO) and MW IPS

- Monte Carlo:
  - SMEFTsim + Madgraph5 + Pythia8
  - Plan to implement in SHERPA (SMEFTsim or private UFO)
- Event Analysis:
  - Madanalysis5 (for partonic) + Rivet (full process)
- Numerical analysis:
  - Mathematica + Python

The Warsaw Basis

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q^{(1)}_{\ell q}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q^{(3)}_{\ell q}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$

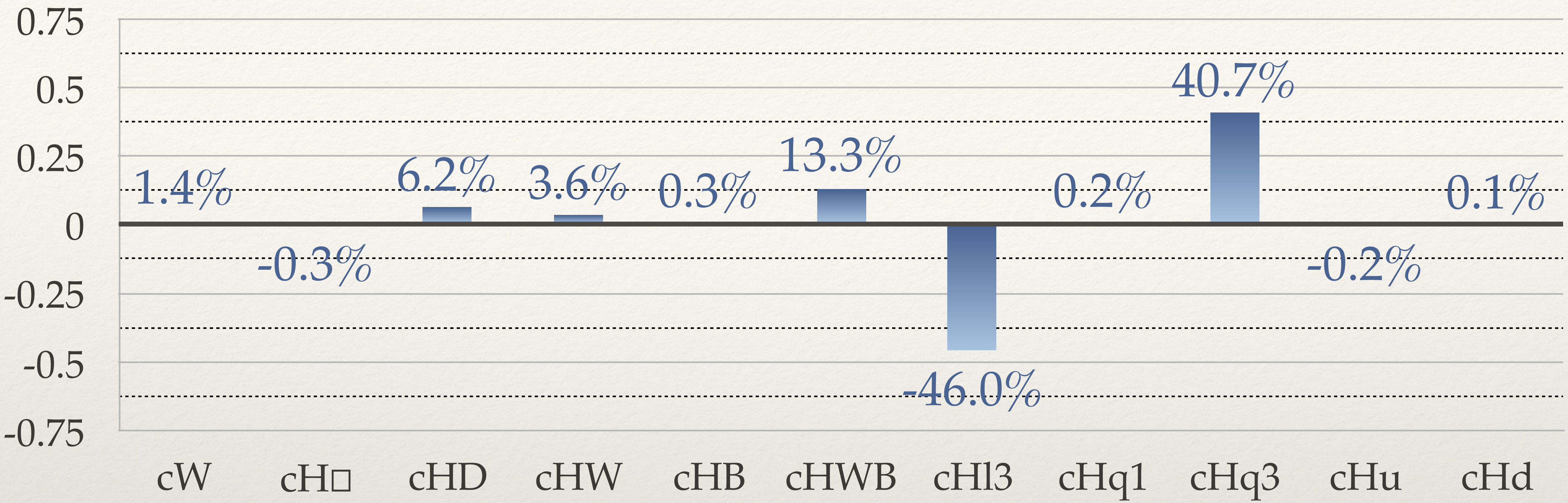
$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

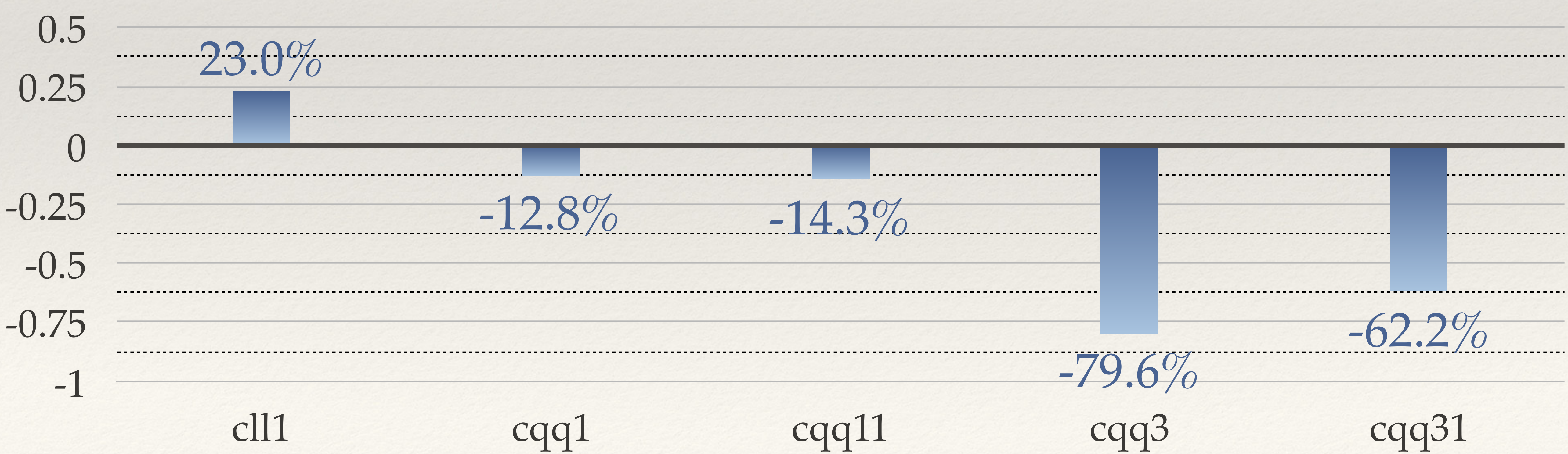
Grzadkowski et al. (basis) , Alonso et al. (representation)

Results:

"VBS region":

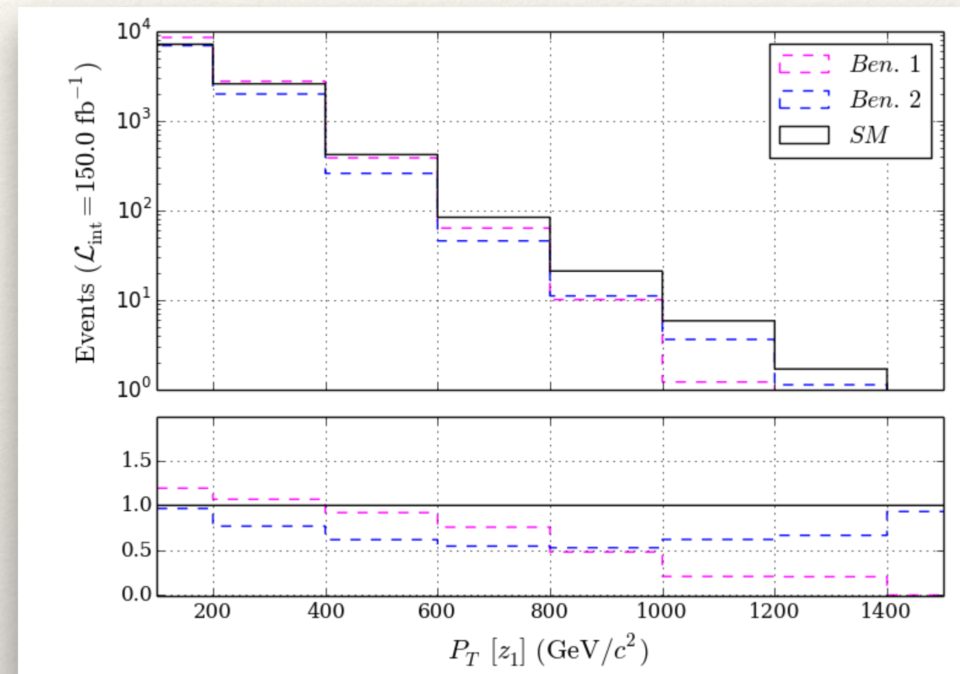
- $p_T(j) > 30$ GeV
- $m_{jj} > 100$ GeV
- $\Delta\eta(j_1 j_2) > 2.4$

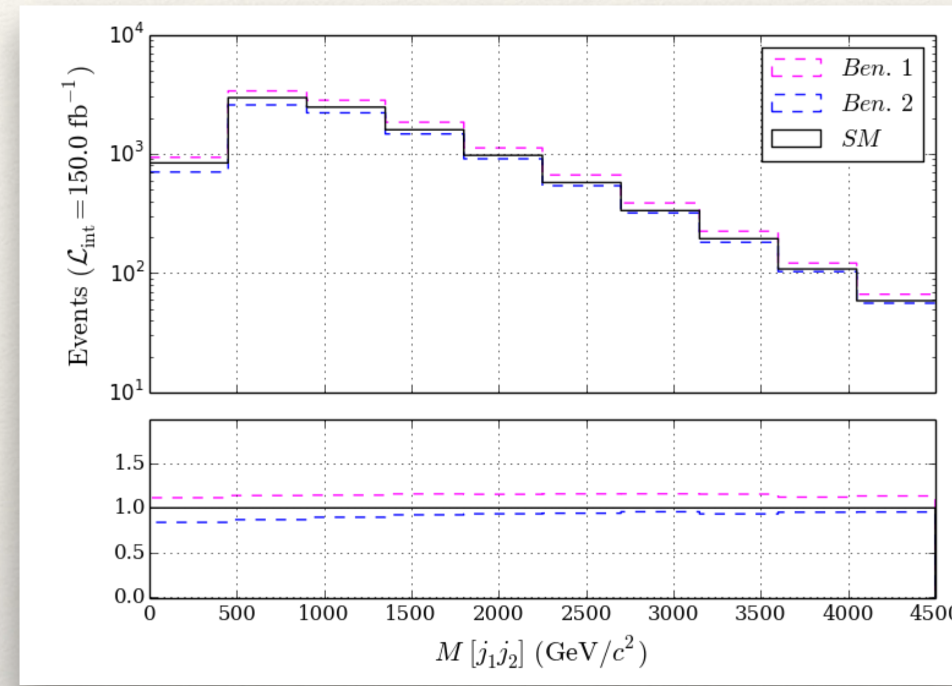




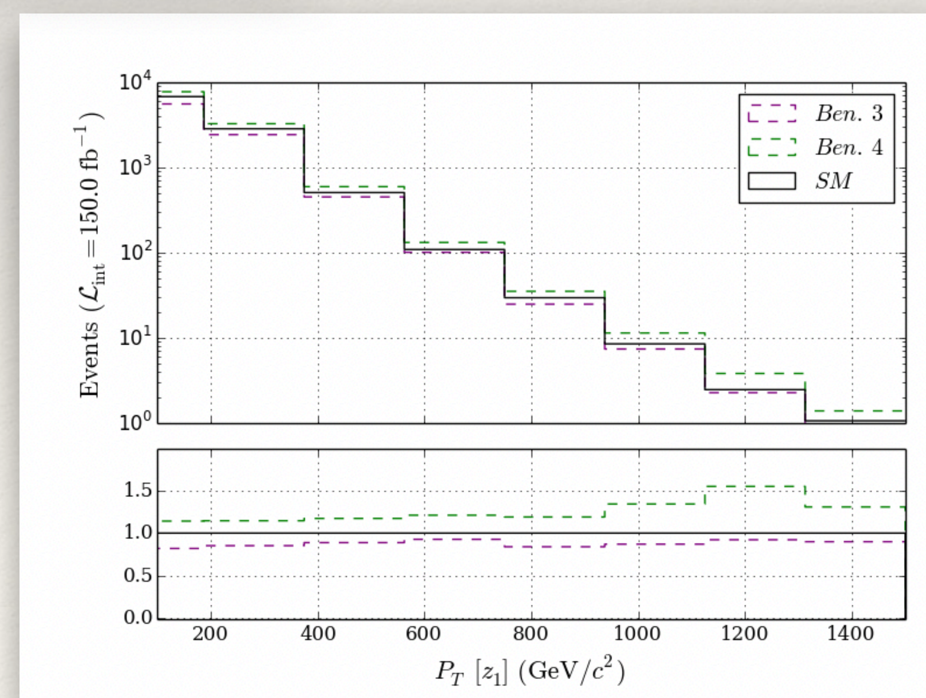
Differential Distributions

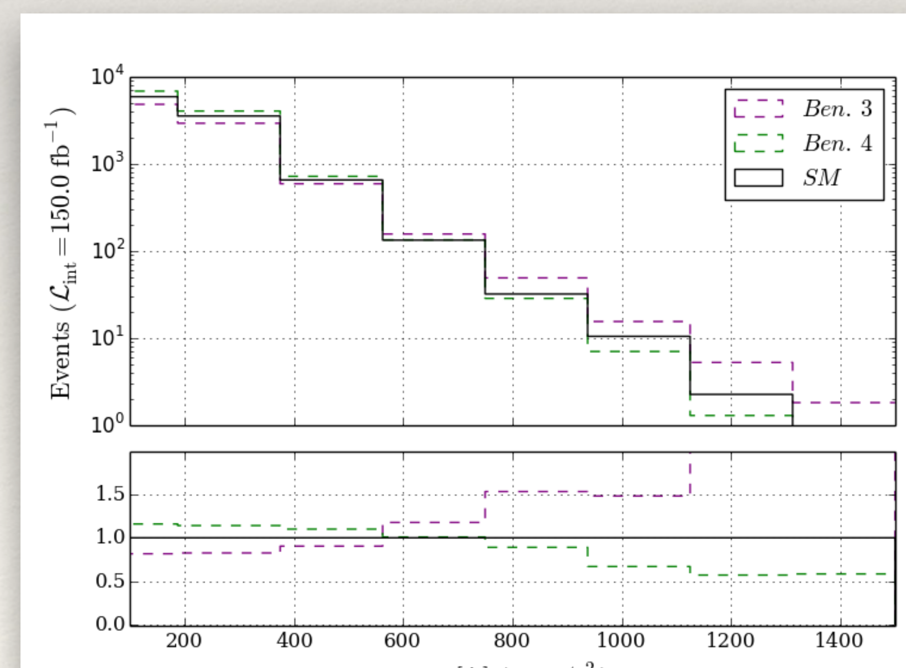
Bosonic benchmarks:





Fermionic benchmarks:

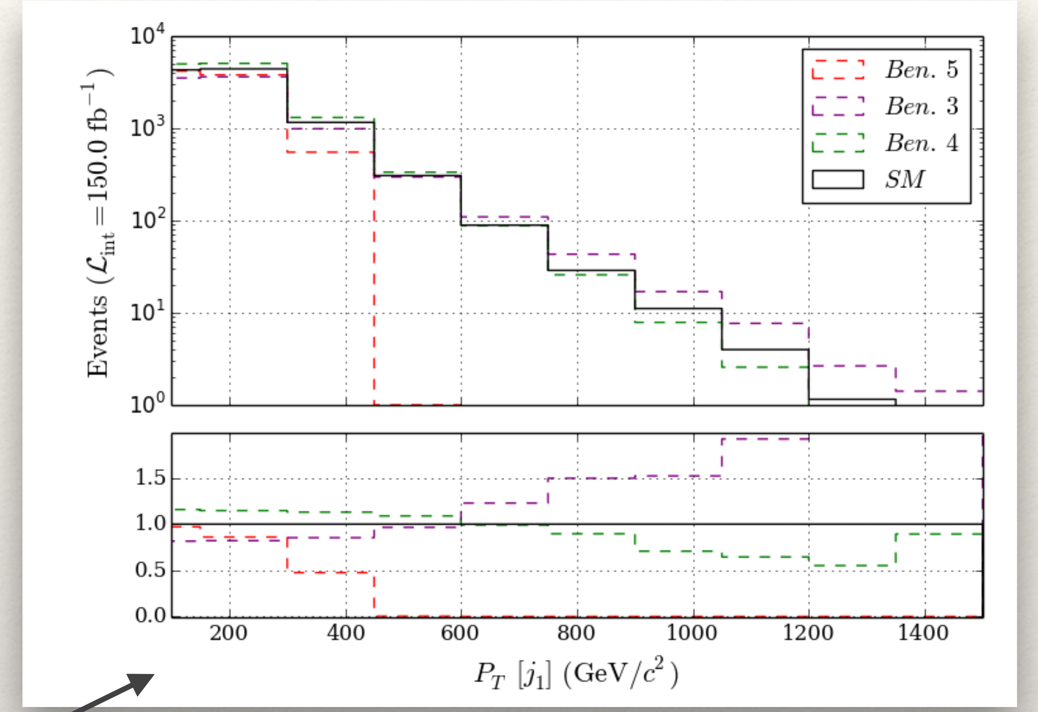




We choose different sets of the c_i values, enhancing or suppressing the xsec by 15%

An interesting observation:

- A study of differential distributions sheds much more light on the EFT behaviour. Not only at high energies



Use low energy bins to derive stronger bounds on the EFT coefficients (unitarity bounds)

Work in progress…

Proposal for the EWWG report

- Look at different kinematic regions to find the optimal ones. (in line with the STSX approach)
- Region 1: *"VBS region"*
  - $p_T(j) > 30$ GeV
  - $m_{jj} > 100$ GeV
  - $\Delta\eta(j_1 j_2) > 2.4$
- Region 2: *CMS analysis*
  - $p_T(j) > 30$ GeV
  - $m_{jj} > 100$ GeV
- Region 3: *"VBS enriched region"*
  - $p_T(j) > 30$ GeV
  - $m_{jj} > 400$ GeV
  - $\Delta\eta(j_1 j_2) > 2.4$

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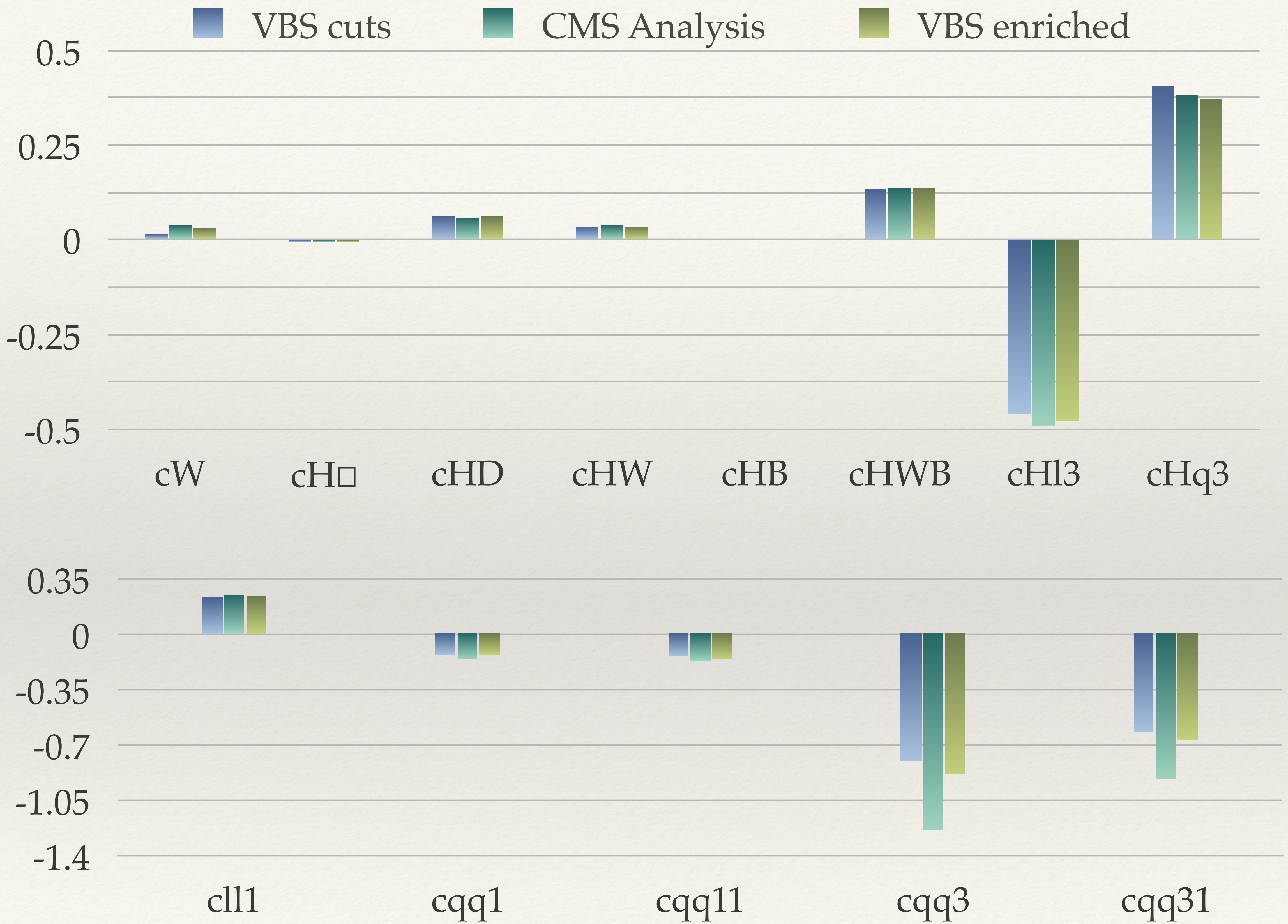
STXS-style analysis:



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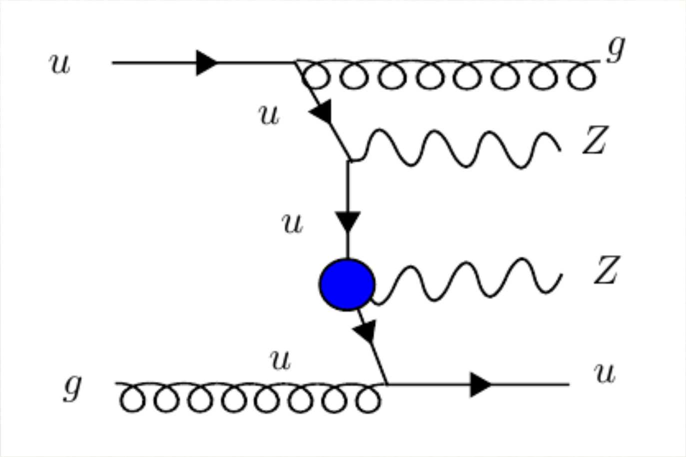
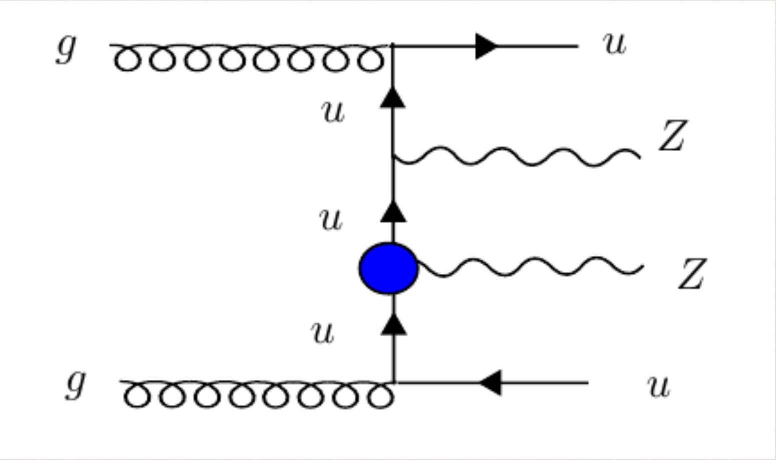
Next Steps:

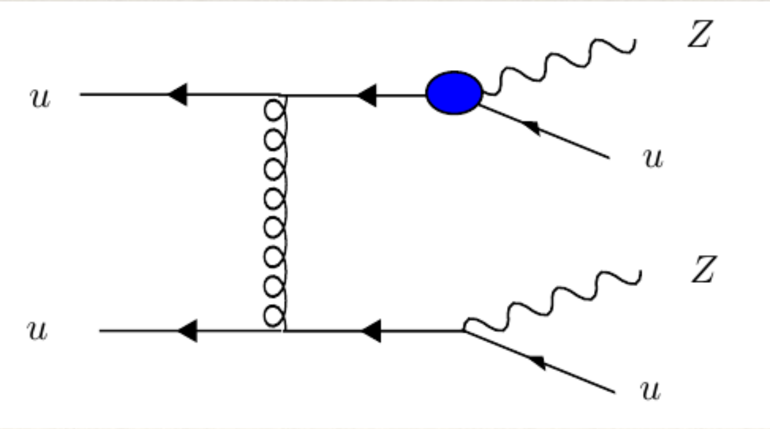
1. Study the Backgrounds
2. Extend to other VBS and VV processes
3. Projections for HL-LHC and future colliders
4. Study of Dim-8 linear and Dim-6 quadratic terms

1) Background

- QCD induced VV production

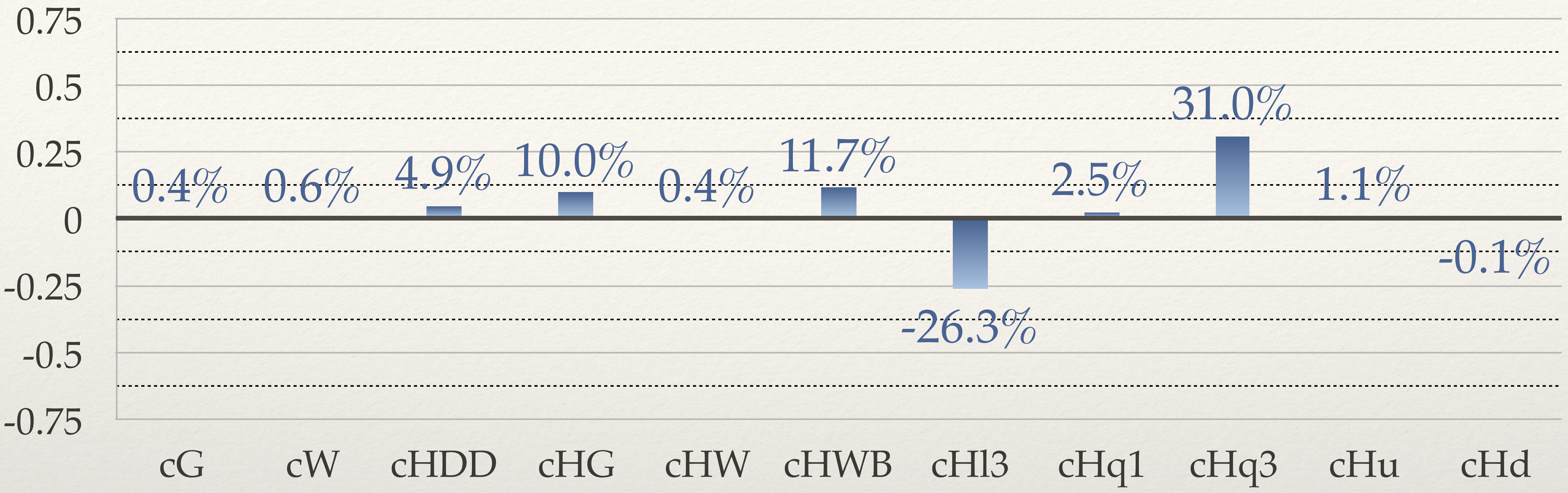


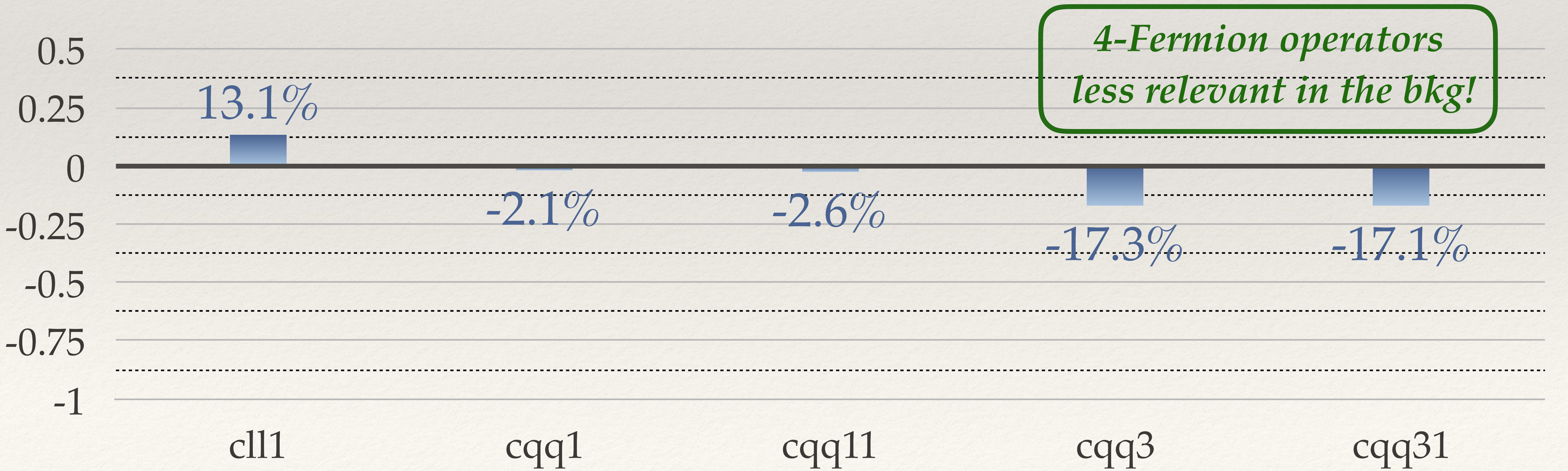




Results: VBS(ZZ)Background

"VBS region":
- $p_T(j) > 30$ GeV
- $m_{jj} > 100$ GeV
- $\Delta\eta(j_1 j_2) > 2.4$





2) Other Processes

- Other VBS: ssWW, ZA, WA
- Diboson: WW, WZ, ZZ
- VBF

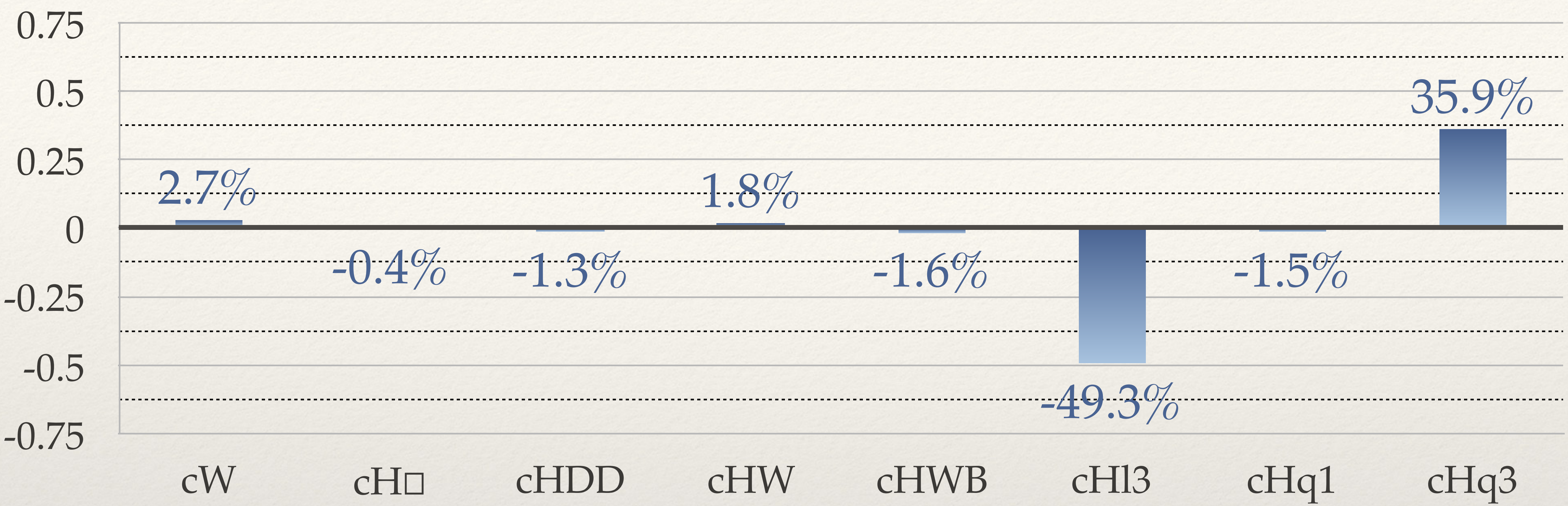
Find the optimal "EFT regions" for each process. In the spirit of the STXS

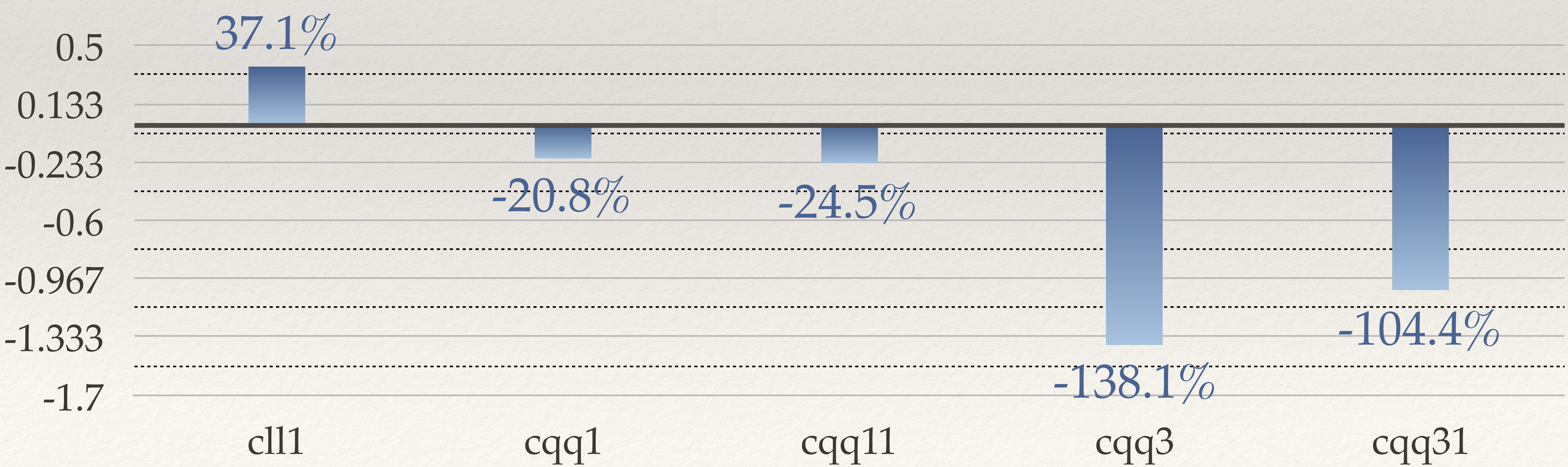
C. Degrande, R Gomez-Ambrosio, K Lohwasser

Results: ssWW VBS

"VBS region":

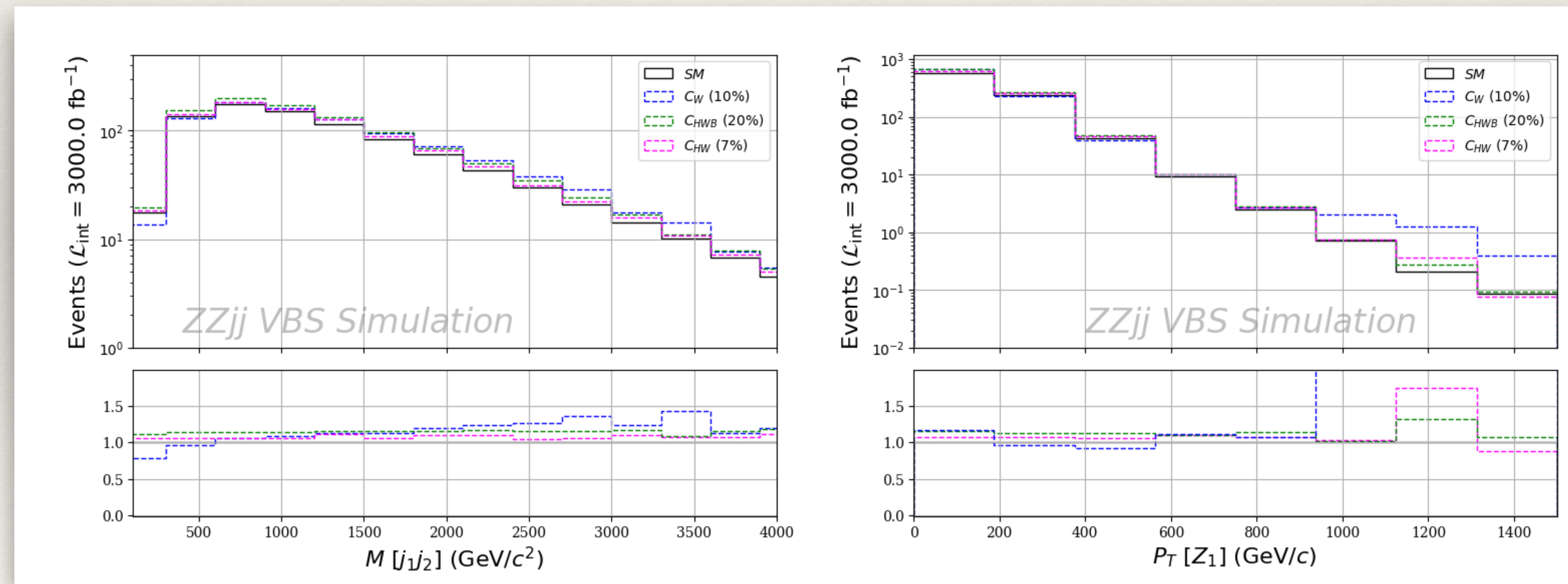
- $p_T(j) > 30$ GeV
- $m_{jj} > 100$ GeV
- $\Delta\eta(j_1 j_2) > 2.4$





3) Future (HL-LHC)

- VBS(ZZ) with leptonic decays: very good prospects for the future runs
- LHC Run-2: $\mathcal{O}(10)$ events $\longrightarrow$ HL-LHC: $\mathcal{O}(100)$ events



R. Covarelli, R. Gomez Ambrosio, for HL-LHC yellow report

4) Higher Order EFT

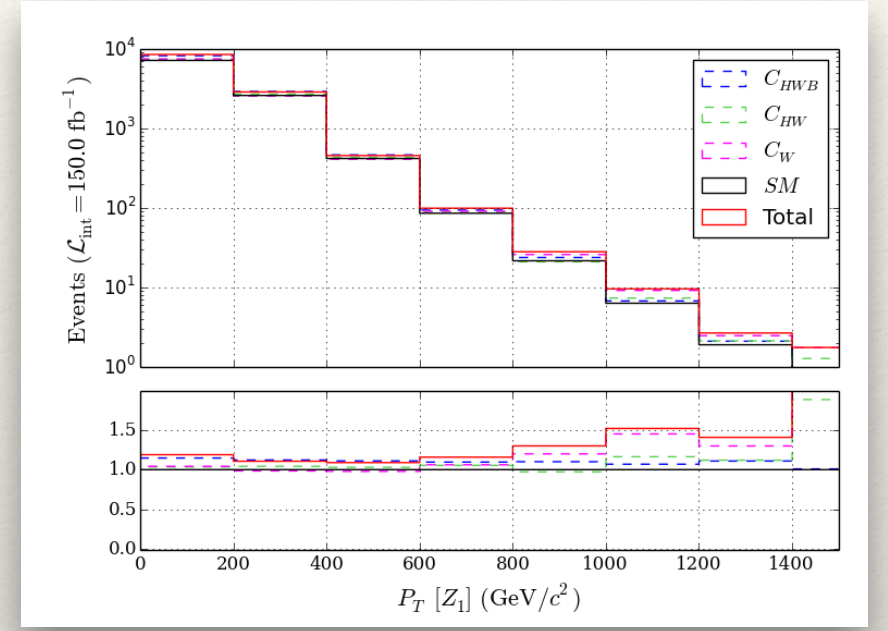
Triple Vs Quartic: Dim-6 Vs Dim-8?

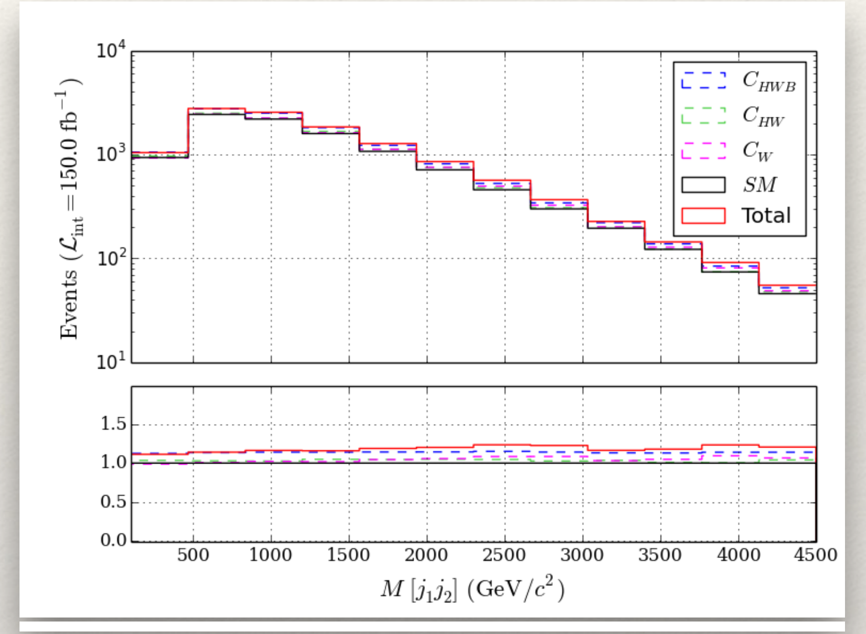
- Warsaw basis operators generating TGCs and QGCs

$$\mathcal{O}_W = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

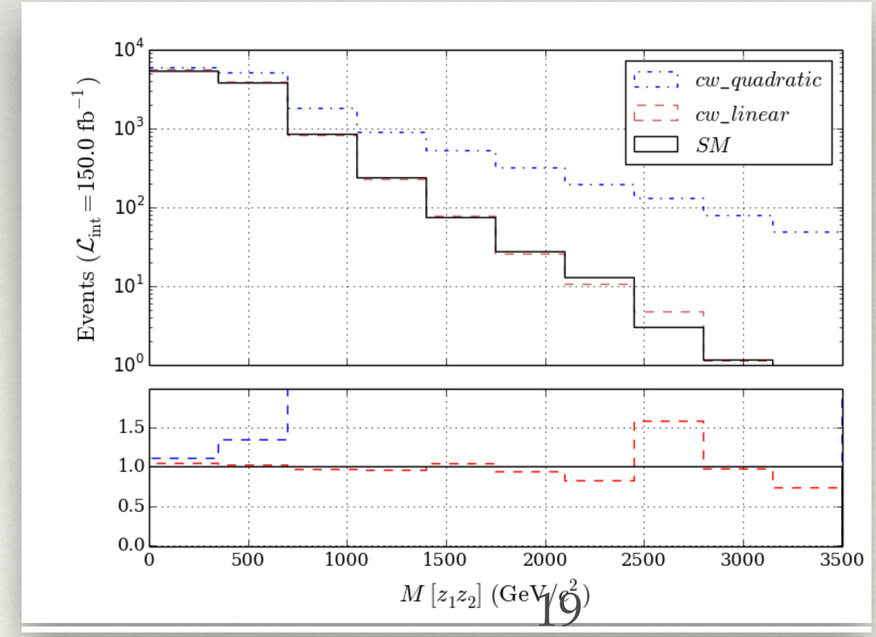
$$\mathcal{O}_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu I}$$

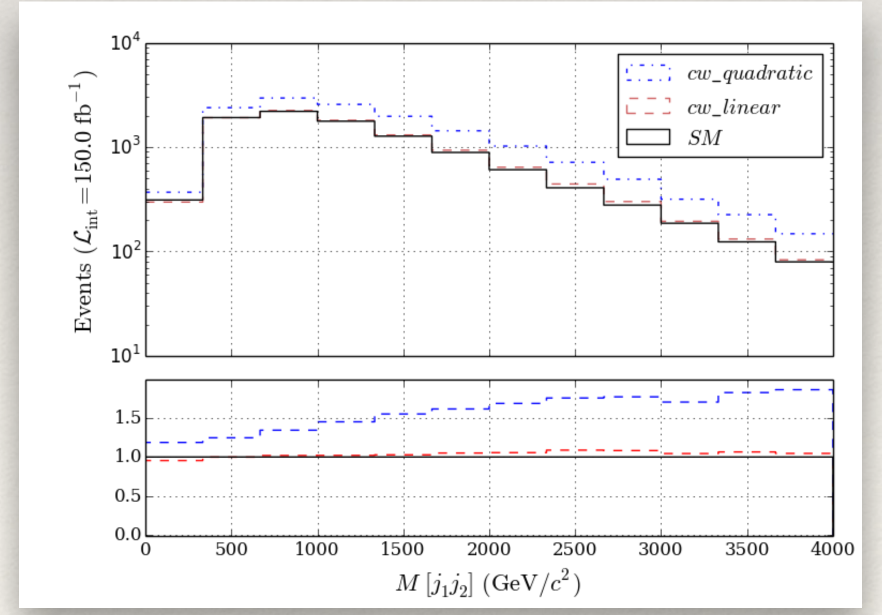
$$\mathcal{O}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$





Example of quadratic contributions:





Conclusions and outlook

- Goal: global fit of EFT coefficients
- Ingredients:
  - From the TH side:
    - Precise EFT predictions (SIG and BKG)
    - Control of MHOU (NLO EFT and higher dim operators)
  - From the EX side:
    - Measurements for cross sections and differential distributions
- From both:
  - See the big picture rather than fitting each channel individually