HiggsCouplings 2018, Ryogoku, Tokyo

Studies of Dim-6 EFT in Vector Boson Scattering

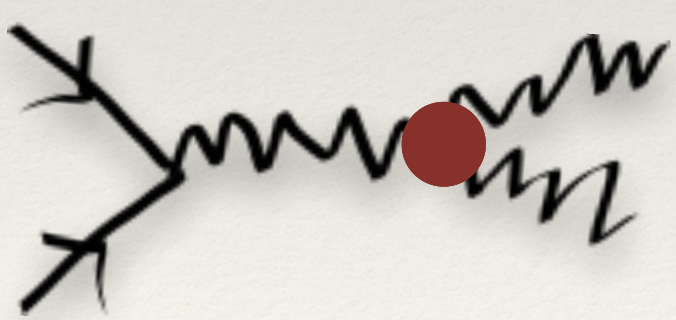
Raquel Gomez Ambrosio
(IPPP Durham)

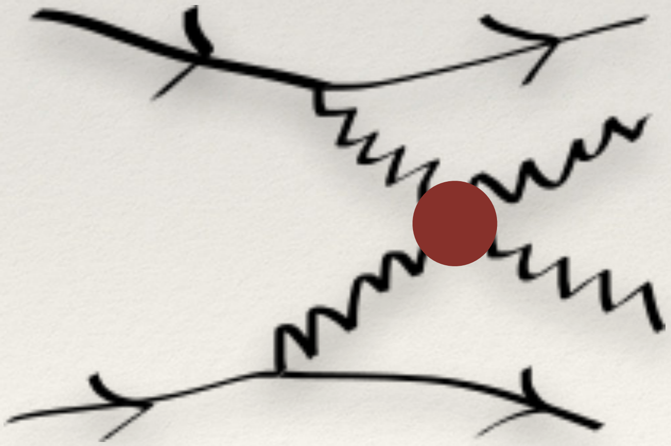
From 1809.04189, accepted for EPJC

Motivation: From LEP to LHC

From anomalous to effective

- LEP: TGCs (on-shell)
- LHC: QCGs (off shell)
- The anomalous coupling approach is good in a first approximation, for more complicated processes, like VBS we need a more robust formalism





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

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

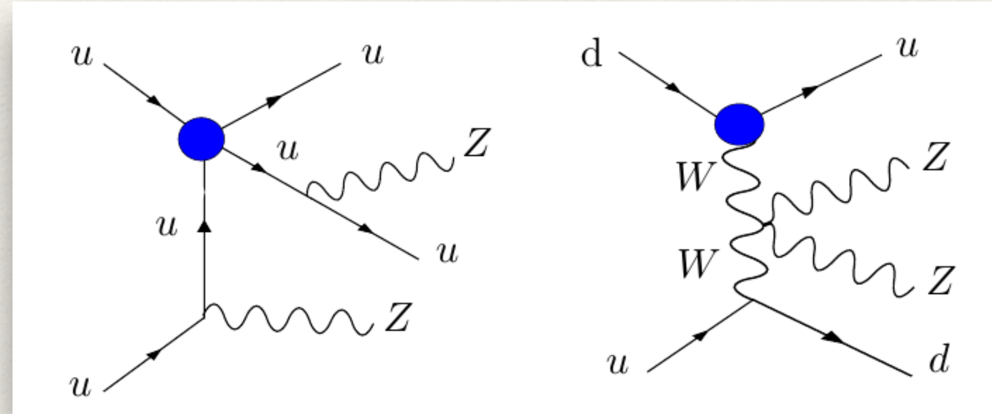
$$\sigma_{EFT} \sim |\mathcal{A}_{SM}|^2 + 2\frac{g'}{\Lambda^2}\mathcal{A}_{SM}\mathcal{A}_6 + \frac{g'2}{\Lambda^4}\left(2\mathcal{A}_{SM}\mathcal{A}_8 + |\mathcal{A}_6|^2\right) + \dots$$

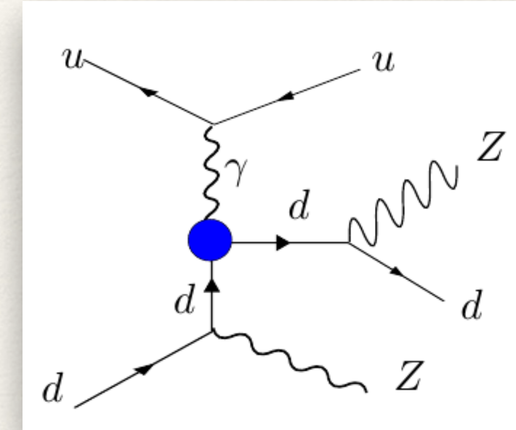
Linear EFT

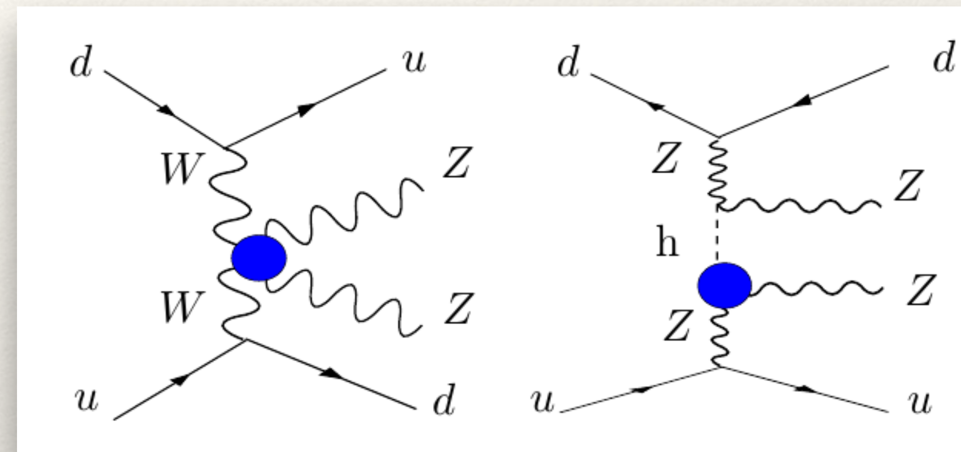
Obs: The larger Lambda is, the larger the difference between contributions….

The idea:

VBS (ZZ)







- Generate the purely electroweak process p p > zz jj , 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

Triple Vs Quartic:

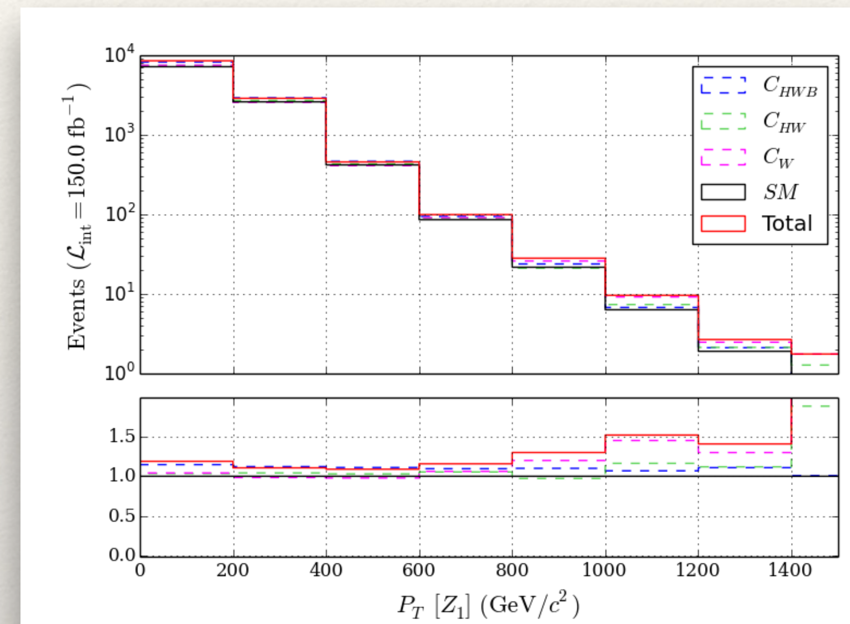
Dim-6 Vs Dim-8?

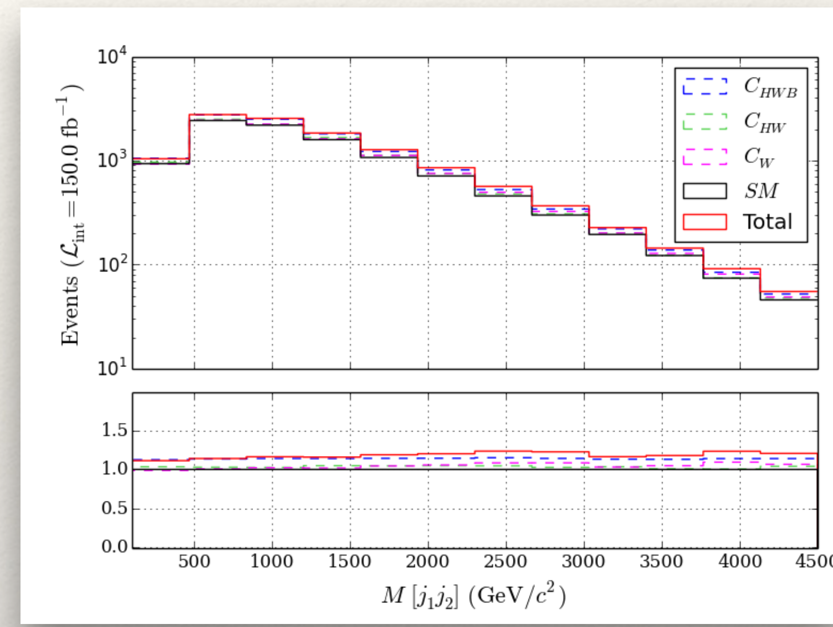
- Warsaw basis operators generating TGCs and QGCs

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

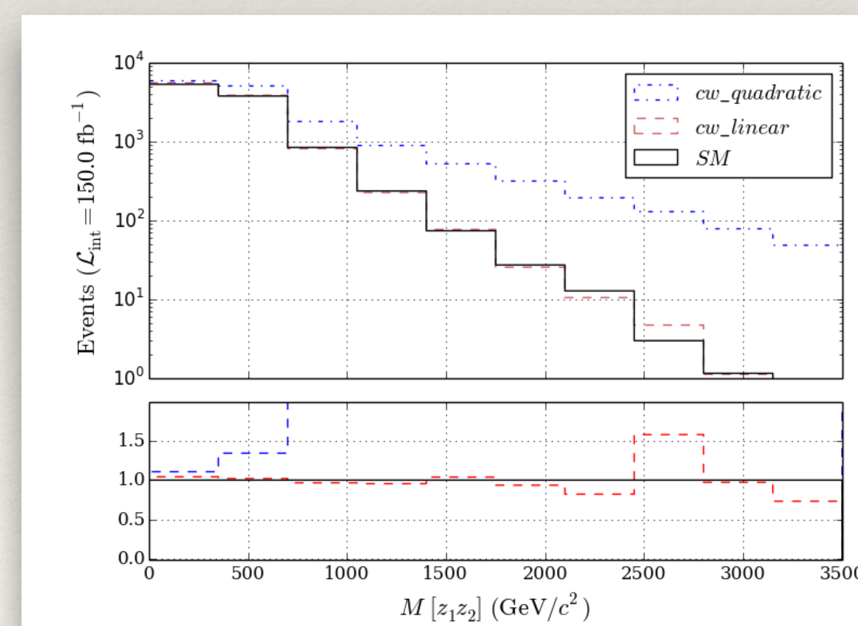
$$\mathcal{O}_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu I}$$

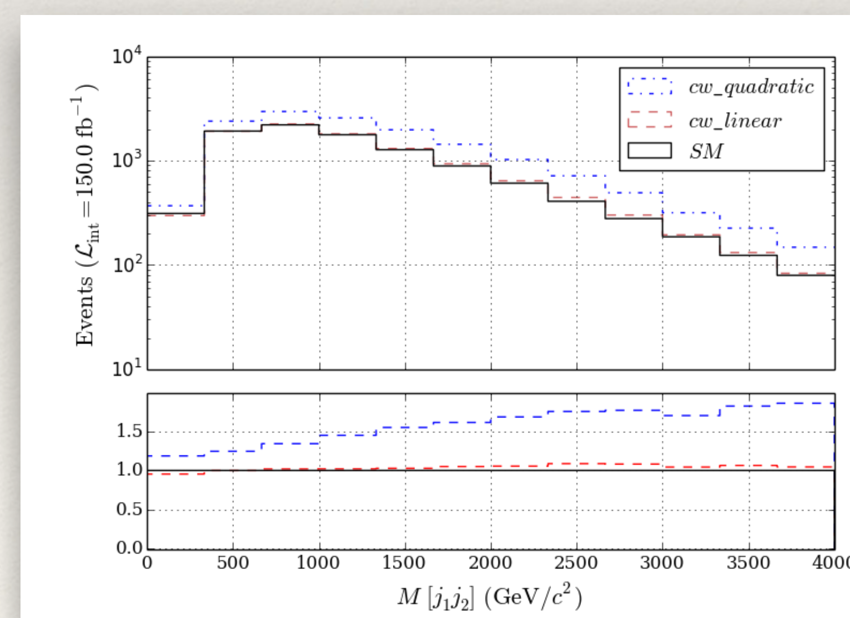
$$\mathcal{O}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$





Example of quadratic contributions:





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}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

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

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

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

$8 : (\bar{R}R)(\bar{R}R)$	
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}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}L)(\bar{R}R)$	
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}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

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

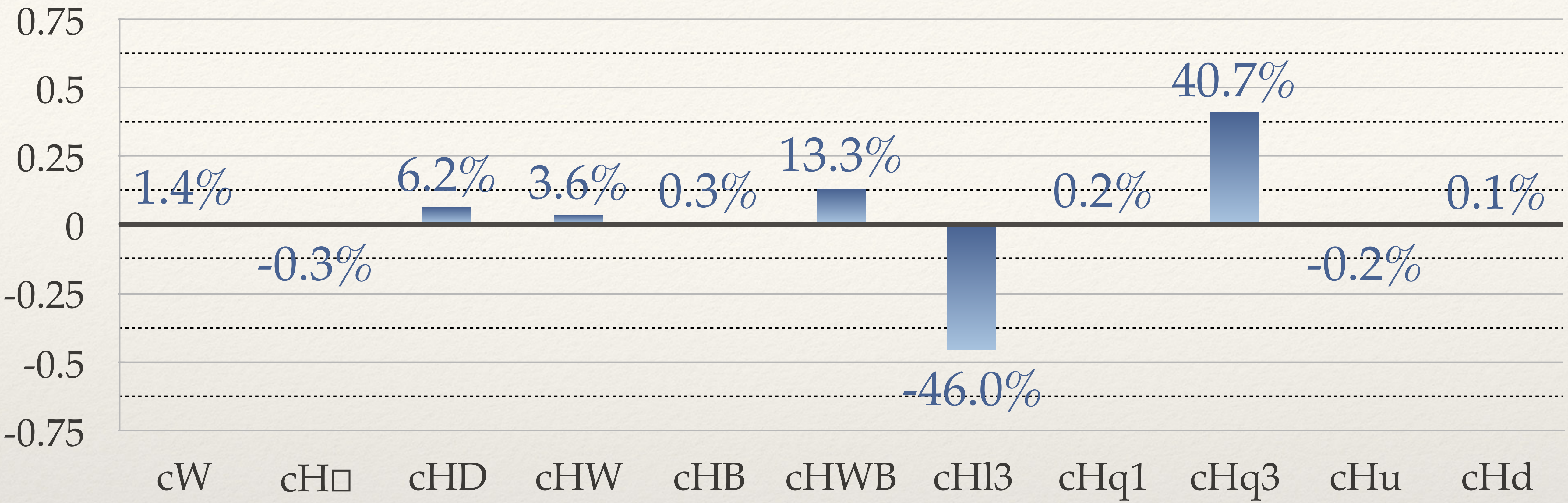
$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$

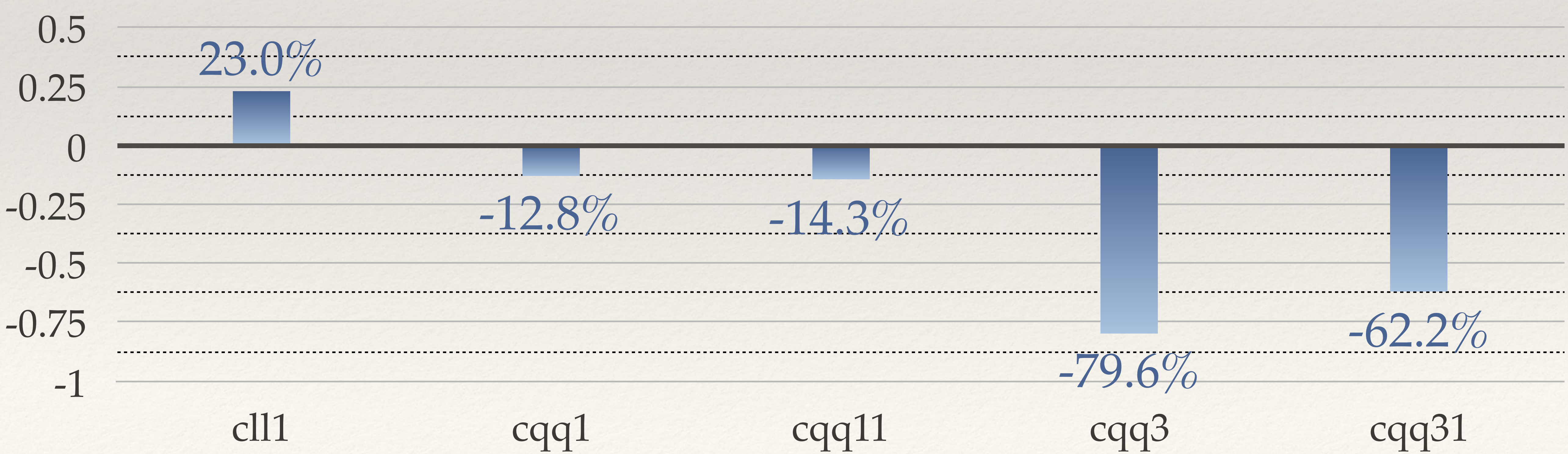
$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

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

Results:

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



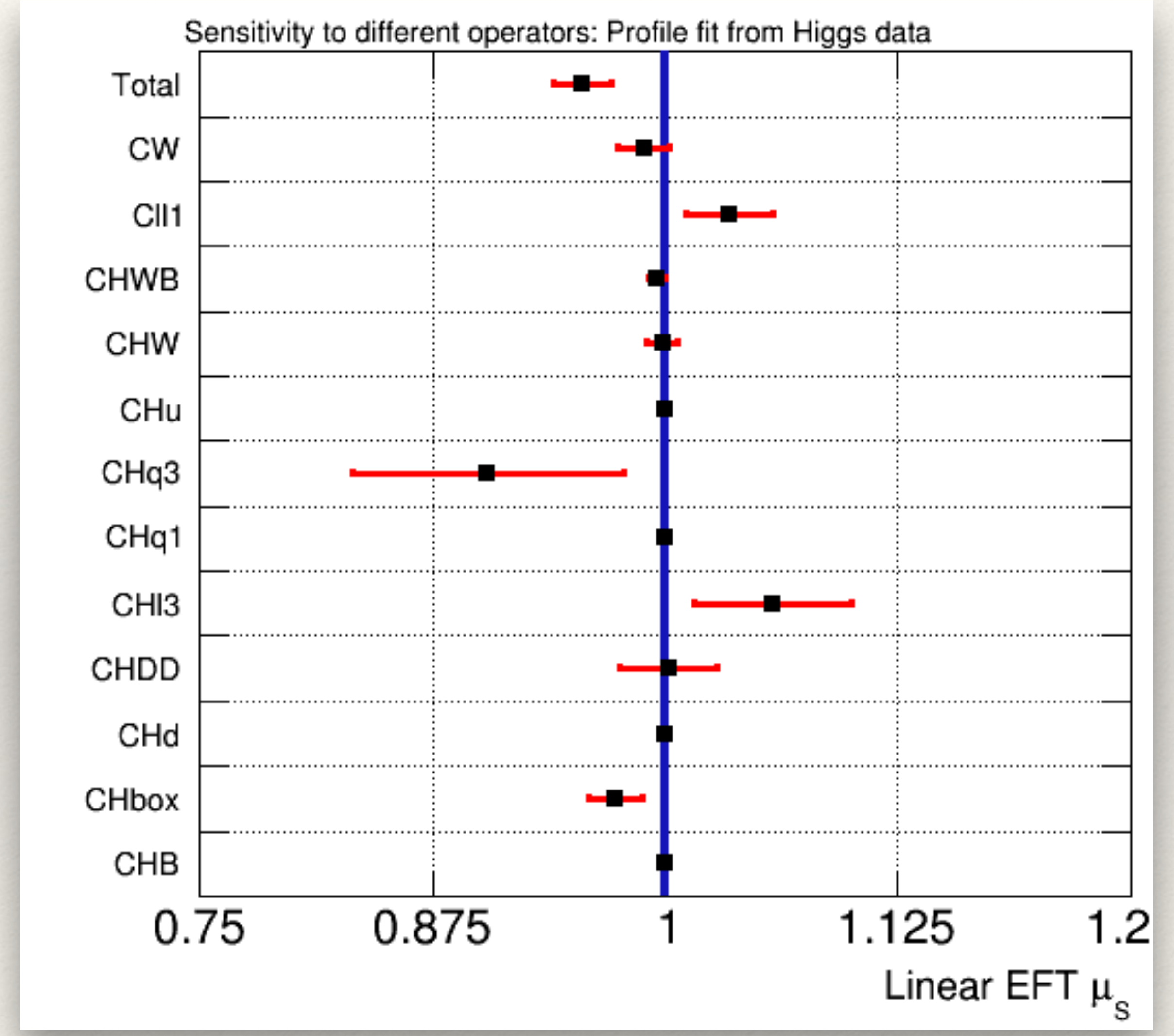


First interesting observation:

- If we look at signal strengths:

$$\mu = \frac{\sigma_{EFT}}{\sigma_{SM}}$$

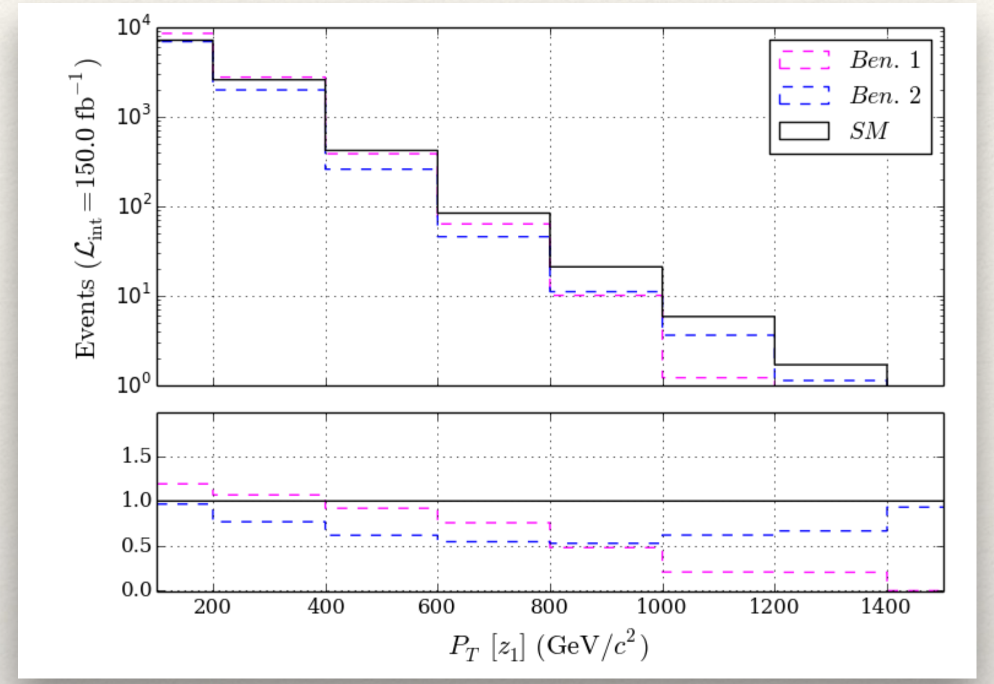
- Some existing bounds can be improved with VBS predictions
- In black: best fit values from the literature*, in red, $\pm 1\sigma$ CL region

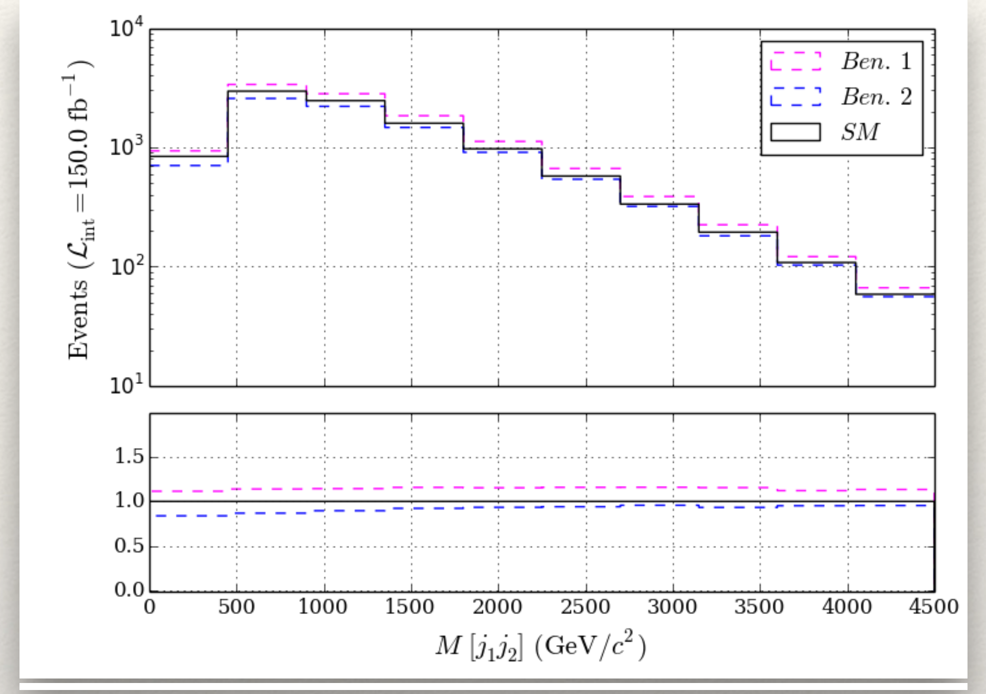


Ellis, Murphy, Sanz, You, 1803.03252

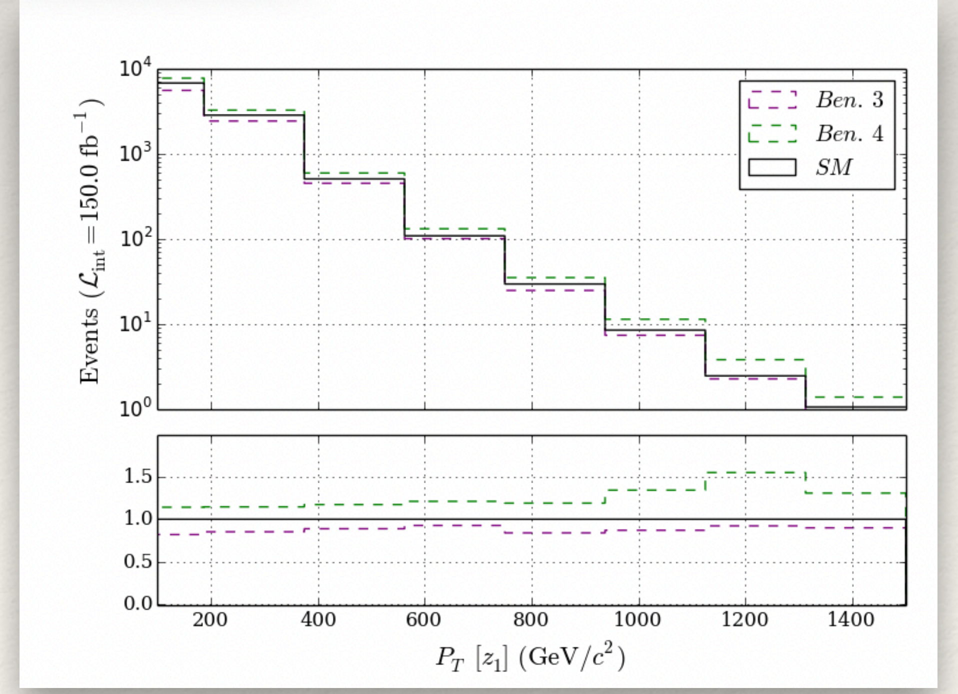
Differential Distributions

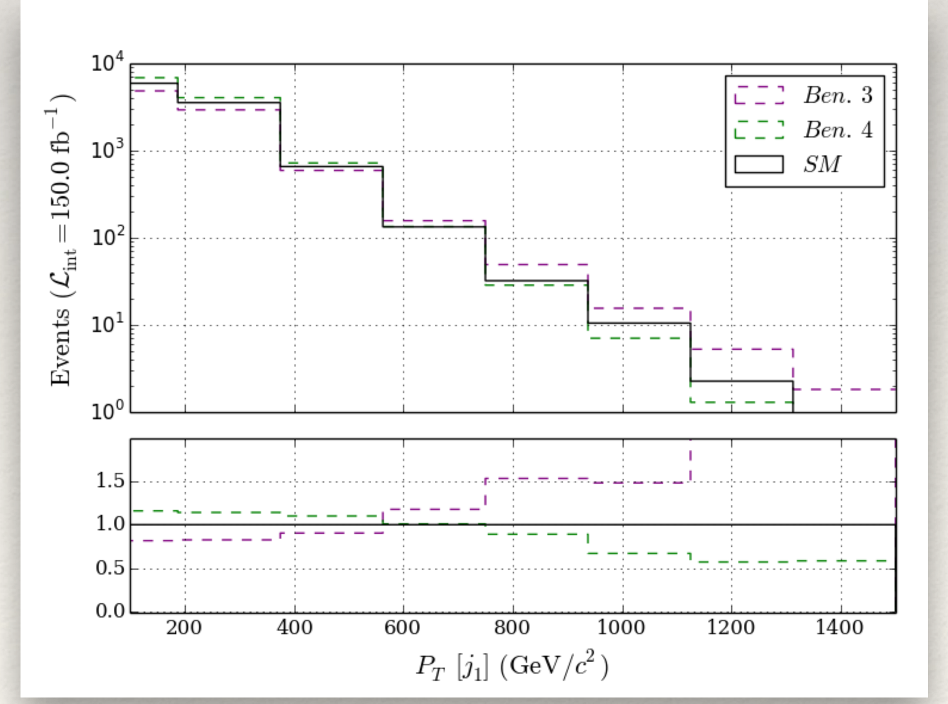
Bosonic benchmarks:





Fermionic benchmarks:

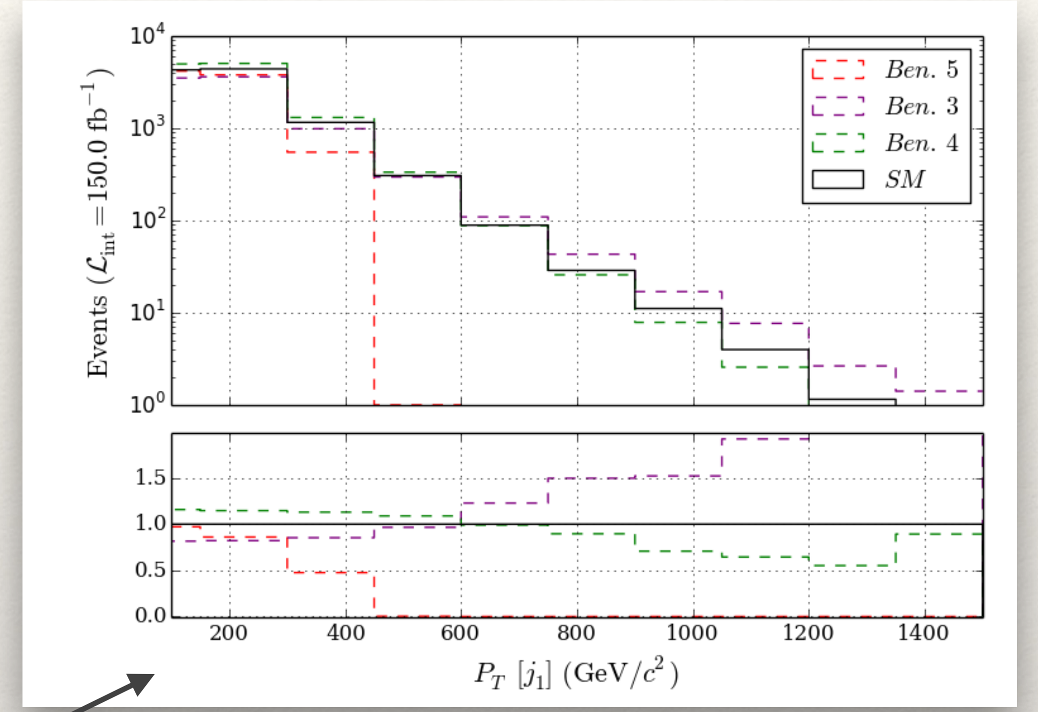




We choose different sets of the c_i values, enhancing or suppressing the xsec by 15%

Second interesting observation:

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

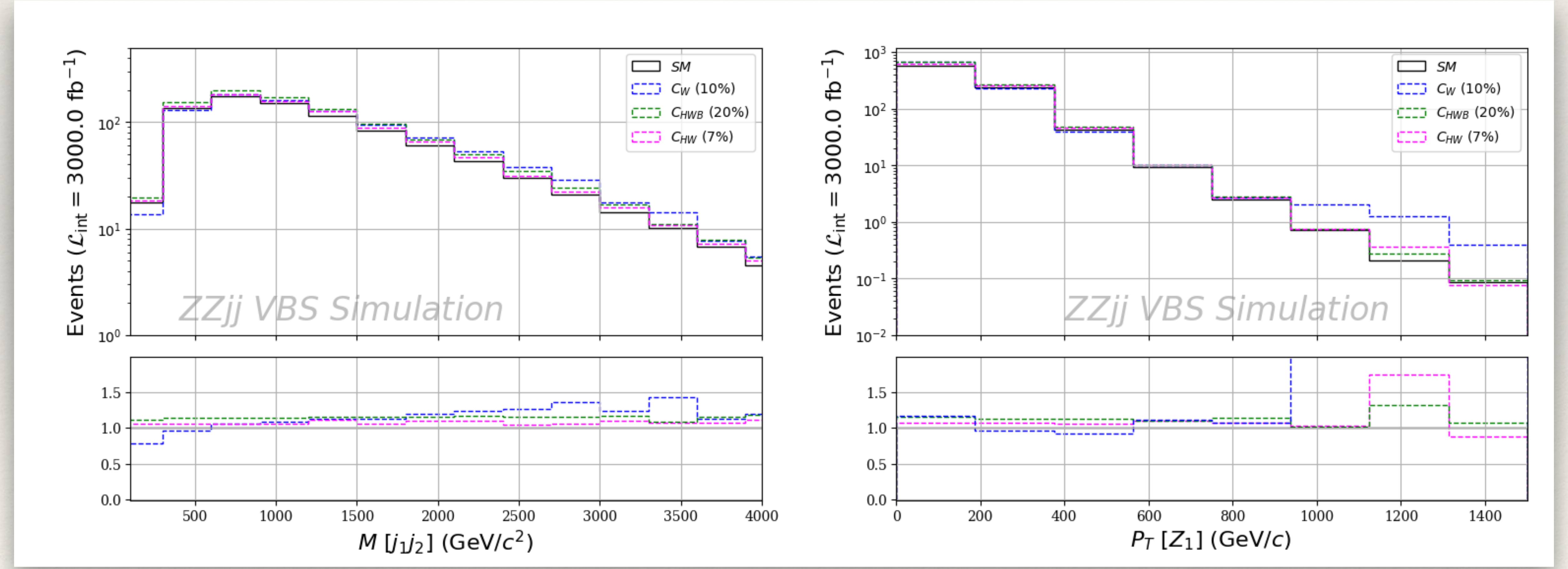


Use low energy bins to derive stronger bounds on the EFT coefficients (unitarity bounds)

Work in progress…

Future Prospects (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



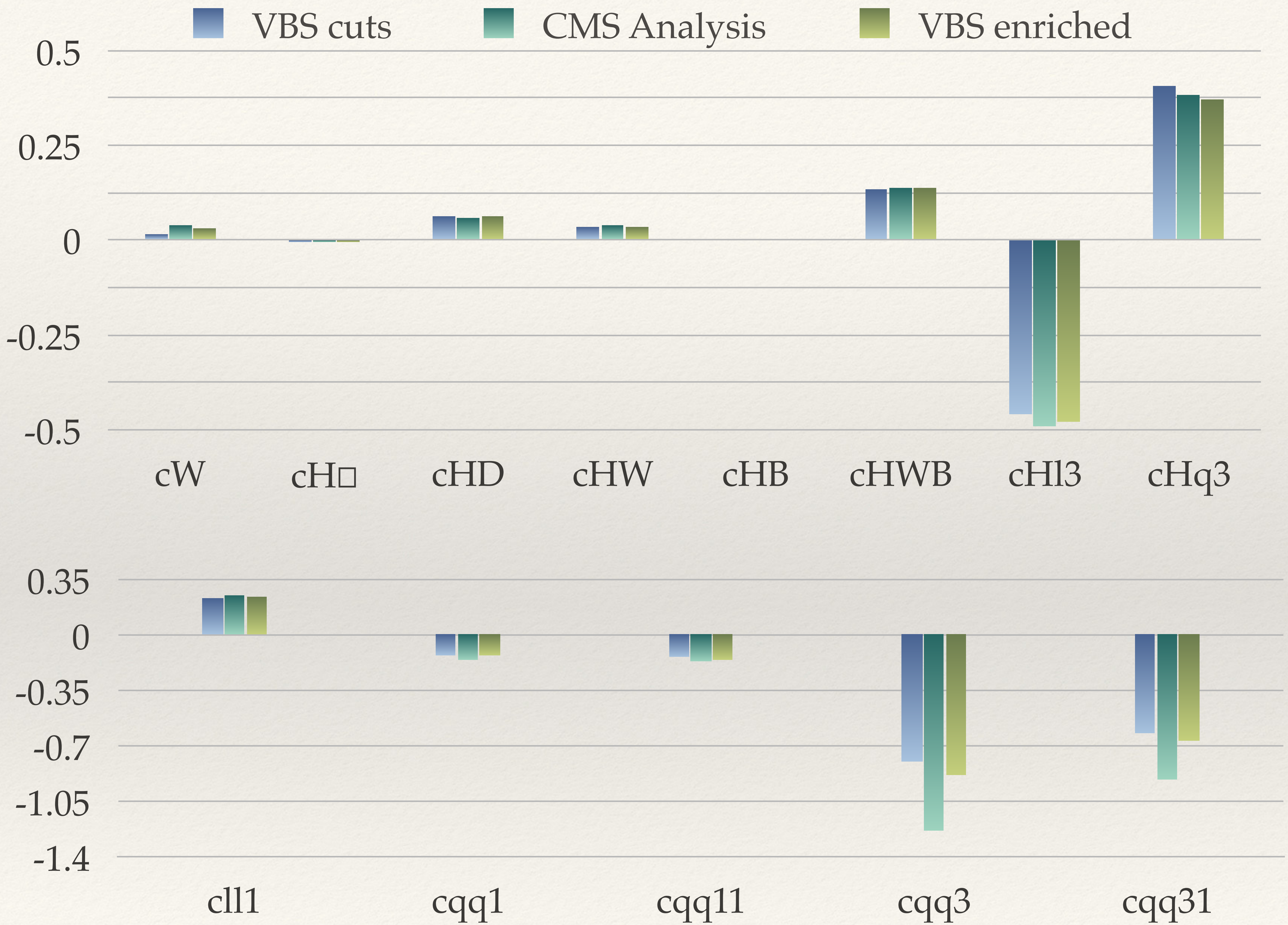
R. Covarelli, R. Gomez Ambrosio, for HL-LHC yellow report

More work in progress…

- 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
  - $\Delta\eta(j_1 j_2) > 2.4$

R Gomez-Ambrosio, K Lohwasser

STXS-style analysis:



R Gomez-Ambrosio, K Lohwasser

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

Thanks for your attention

"All of physics is either impossible or trivial. It is impossible until you understand it, and then it becomes trivial."

– Ernest Rutherford