GLOBAL SMEFT FITS FOR VBS

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SM@LHC 2019, ZÜRICH

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VBSCan COST

Dim-6 EFT and VV processes

- Outline:
  - Introduction and motivation
  - TGCs and QGCs in Dim-8 and Dim-6
  - The global Dim-6 picture: Differential distributions and fitting tools
  - Backgrounds
  - Future colliders

- Goals:
  - Focus on the less understood and/or controversial points
  - Introduce open questions on the topic:
    - Open questions and backup ★

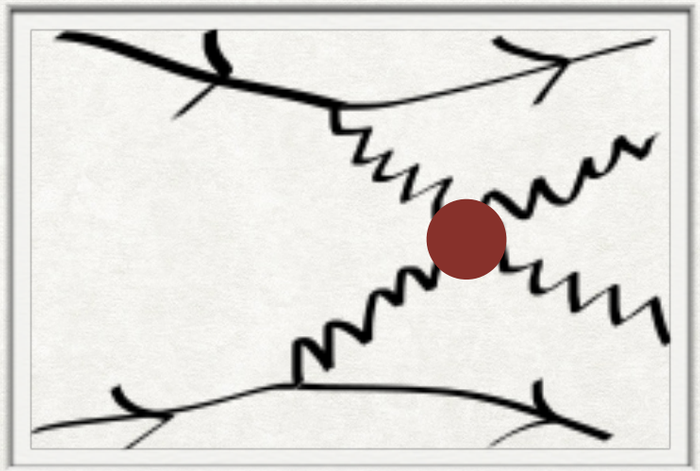
- Disclaimer: Won't cover ALL related topics (apologies!)

Vector Boson Scattering

- Family of processes of the type: $q_1\,\bar{q}_2 \to V\,V\,q_3\,\bar{q}_4$
  - Fundamental for tests of the EWSB mechanism
  - Only way to access Quartic Gauge Couplings (QGC) at LHC

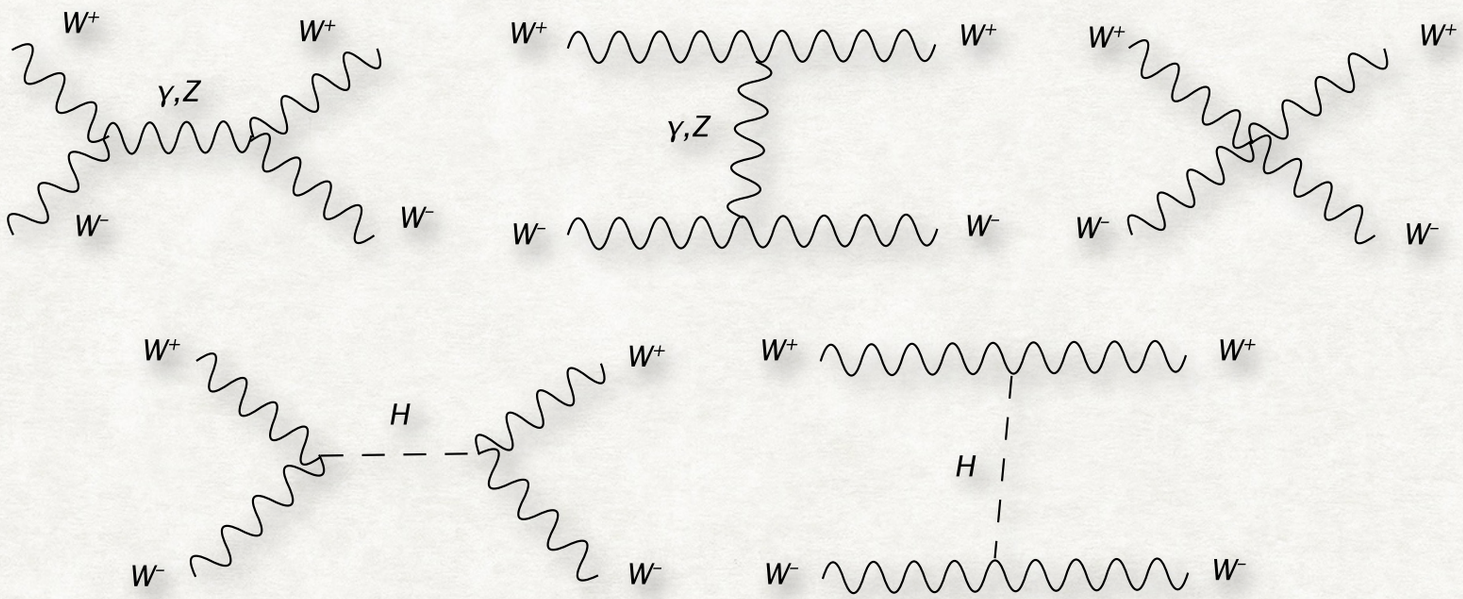
Why are TGC/QGC so attractive?

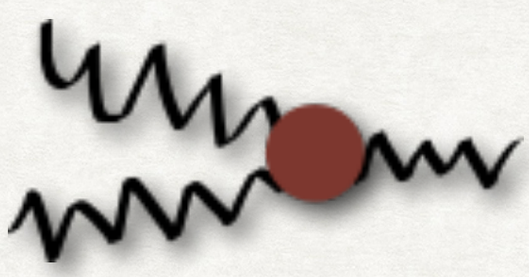
The VBS amplitudes violate unitarity at high energies.



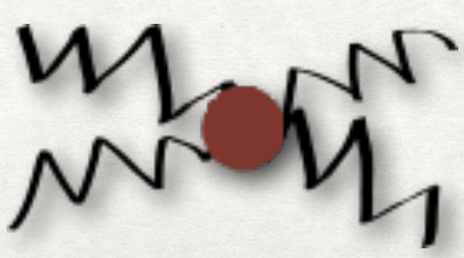
What makes VBS & the Gauge sector so interesting?

$W_L W_L \to W_L W_L$





$$\sim g\left(g^{\mu\nu}p_{12}^{\rho} + g^{\rho\nu}p_{23}^{\mu} + g^{\mu\rho}p_{13}^{\nu}\right)$$



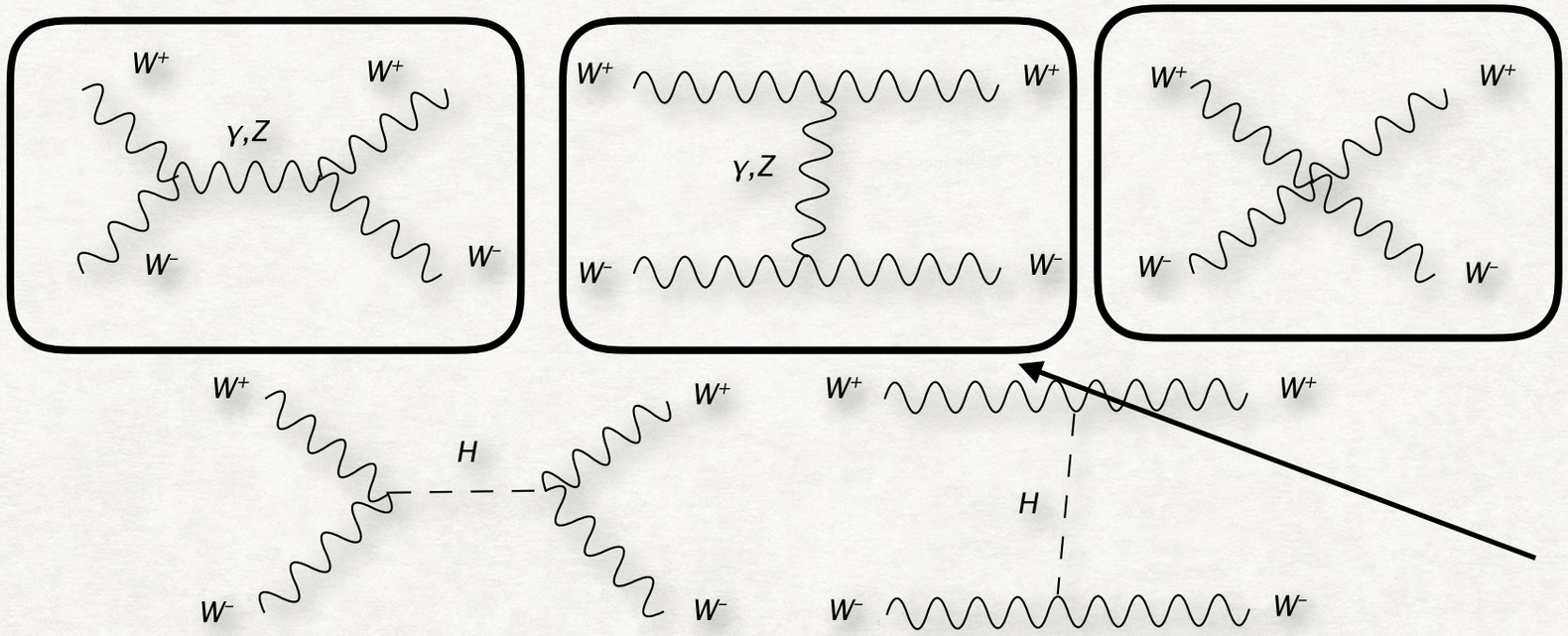
$$\sim g^2$$

$$\boxed{\epsilon_L^{\mu} \sim \frac{k^{\mu}}{M}}$$

At high energies, the longitudinal modes are dominating

What makes VBS & the Gauge sector so interesting?

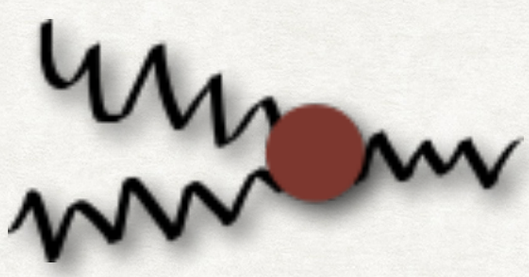
$W_L W_L \to W_L W_L$



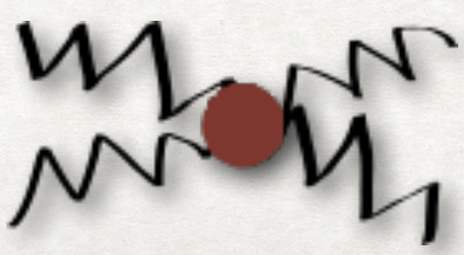
$$\sim \frac{s^2}{4M^2}$$

Need very precise cancellations …

1. *TGC/QGC*
2. *Higgs*



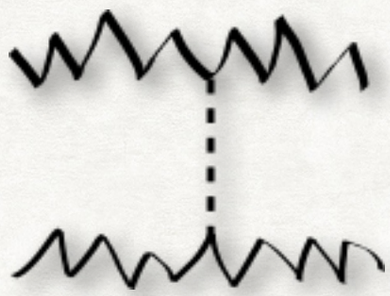
$$\sim g\left(g^{\mu\nu}p_{12}^{\rho} + g^{\rho\nu}p_{23}^{\mu} + g^{\mu\rho}p_{13}^{\nu}\right)$$

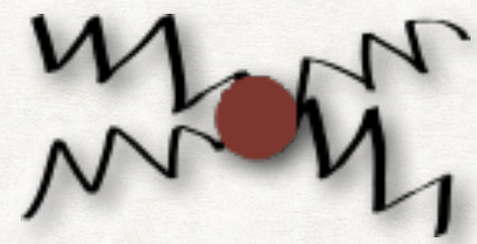


$$\sim g^2 \qquad \epsilon_L^{\mu} \sim \frac{k^{\mu}}{M}$$

SM Effective Field Theory (SMEFT)

- Effective field theory: Decoupling heavy states from the *light* energy regime





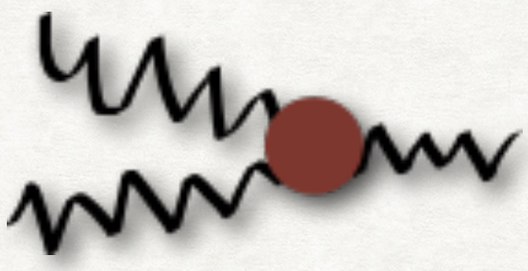
$$\sim \frac{1}{p^2 + M^2} \quad \rightarrow \quad M^2 \gg p^2 \quad \rightarrow \quad \frac{1}{M^2}\left(1 - \frac{p}{M^2} + \frac{1}{2}\left(\frac{p}{M^2}\right)^2 + \ldots\right)$$

- Assuming linear representation for the Higgs, no new light particles, and SM symmetries:
  - $\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$
  - The most general basis in dim-6 has 2499 Operators, 59 if we assume some flavour symmetries: Here we will use the so-called Warsaw Basis

Compatible with NLO corrections!
(unlike kappa/anomalous approach)

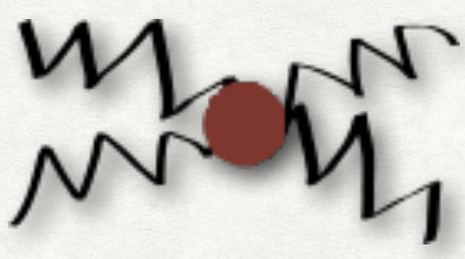
Higher DIM operators in TGC and QGC

The higher dimensional effects can be parametrised as:



$$\sim \underbrace{g^{\mu\nu}p^{\rho} + \ldots}_{dim-4} + \underbrace{\frac{1}{\Lambda^2}p^{\mu}p^{\nu}p^{\rho} + \ldots}_{dim-6} + \underbrace{\frac{M^2}{\Lambda^2}p^{\mu}p^{\nu}p^{\rho} + \ldots}_{dim-8} + \ldots$$

$Z_{\mu}W^{+}_{\nu}W^{-}_{\rho}$



$$\sim \underbrace{1}_{dim-4} + \underbrace{\frac{1}{\Lambda^2}p^{\mu}p^{\nu} + \ldots}_{dim-6} + \boxed{\underbrace{\frac{1}{\Lambda^2}p^{\mu}p^{\nu}p^{\rho}p^{\sigma} + \ldots}_{dim-8}} + \ldots$$

$Z_{\mu}Z_{\nu}W^{+}_{\rho}W^{-}_{\sigma}$

Grows very fast with energy:
Unitarity constraints on EFT

TRADITIONAL VBS INTERPRETATION: DIM 8

- VBS has traditionally been associated with Quartic Gauge Couplings, and the former have traditionally been described in terms of dim-8 operators only
- QGC can be parametrised in terms of "non-TGC EFT operators"

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right] ,$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta} ,$$
$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha} ,$$

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] ,$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] ,$$
$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right] ,$$

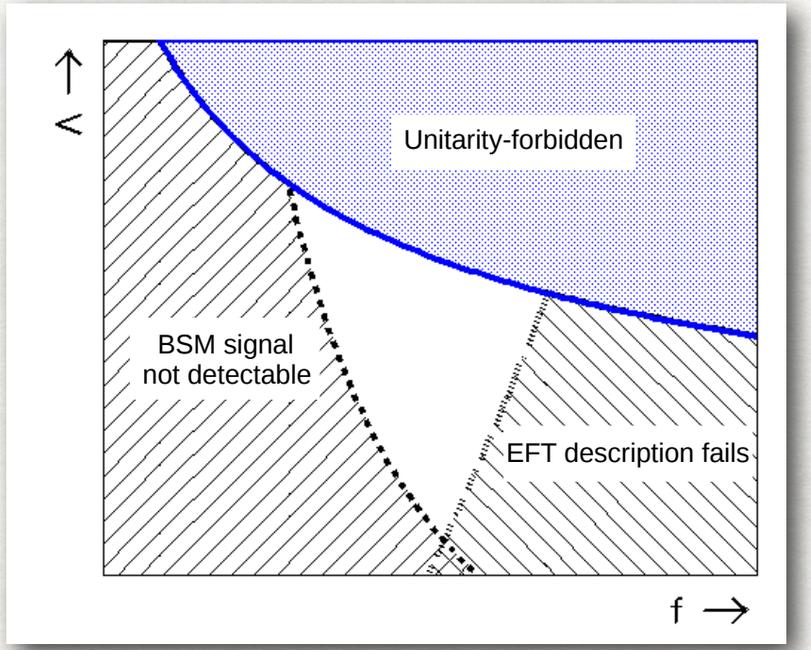
$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\mu\Phi\right] \times \widehat{B}^{\beta\nu} ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\nu\Phi\right] \times \widehat{B}^{\beta\mu} ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right] .$$

Approach adopted by ATLAS and CMS

- Basis from Eboli et al., Phys. Rev. D74, 073005 (2006),
- Complete Dim-8 basis in: (Henning et al. 2015)
  "2, 84, 30, 993, 560, 15456, 11962, 261485, ...: Higher dimension operators in the SM EFT"

TRADITIONAL APPROACH: DIM-8

"Same-sign WW scattering at the LHC: can we discover BSM effects before discovering new states?" (Kalinowski et al. 2018)



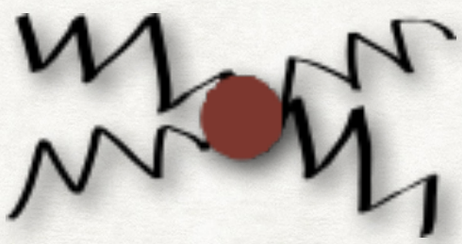
Apply BSM significance + Unitarity considerations to find the optimal search region

Coeff.	Lower limit (TeV^{-4})	Upper limit (TeV^{-4})	Coeff.	Lower limit (TeV^{-4})	Upper limit (TeV^{-4})
f_{S0}	1.3	2.0	$-f_{S0}$	1.2	2.0
f_{S1}	8.0	6.5	$-f_{S1}$	5.5	6.0
f_{T0}	0.08	0.13	$-f_{T0}$	0.05	0.12
f_{T1}	0.03	0.06	$-f_{T1}$	0.03	0.06
f_{T2}	0.20	0.25	$-f_{T2}$	0.10	0.20
f_{M0}	1.0	1.2	$-f_{M0}$	1.0	1.2
f_{M1}	1.0	1.9	$-f_{M1}$	0.9	1.8
f_{M6}	2.0	2.4	$-f_{M6}$	2.0	2.4
f_{M7}	1.1	2.8	$-f_{M7}$	1.3	2.8

Table 1: Estimated lower limits for BSM signal significance and upper limits for EFT consistency for each dimension-8 operator (positive and negative f values), for the case when Λ is equal to the unitarity bound, in the W^+W^+ scattering process at the LHC with 3 ab^{-1}.

DIM 6: TGC AND QGC IN THE WARSAW BASIS

For the previous reasons, a description in terms of Dim-6 is more general and consistent. In terms of dim-6 operators, QGCs and TGCs can be written as:

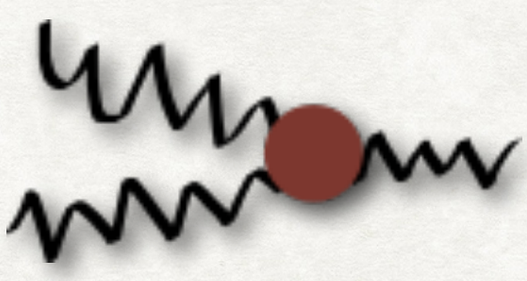


$Z_\mu Z_\nu W^+_\rho W^-_\sigma$

$$\mathrm{SM} + \frac{1}{\Lambda^2}\left(\mathscr{F}(C_{HD}, C_{HW}, C_{H\ell^{(3)}}, C'_{\ell\ell}) + \mathscr{F}(C_{HWB}, C_W, p_i)\right)$$

Field and parameter shifts

Vertex



$Z_\mu W^+_\nu W^-_\rho$

$$\mathcal{O}_{HD} = \left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{H\ell^{(3)}} = \left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\bar{\ell}_p \gamma_\mu \ell_r\right)$$

$$\mathcal{O}'_{\ell\ell} = \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right)$$

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

$$\mathcal{O}_W = \epsilon_{IJK} W^I_{\mu\nu} W^J_{\nu\rho} W^K_{\rho\mu}$$

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

THE WARSAW BASIS

THERE IS MORE TO VBS THAN GAUGE COUPLINGS

$1: X^3$	
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}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

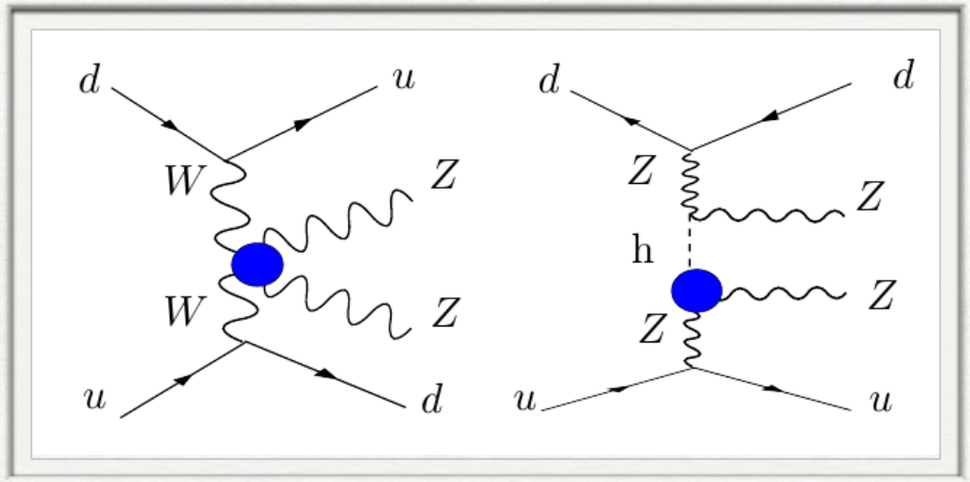
$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

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

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

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

EXAMPLE: ZZ VBS AND WZ



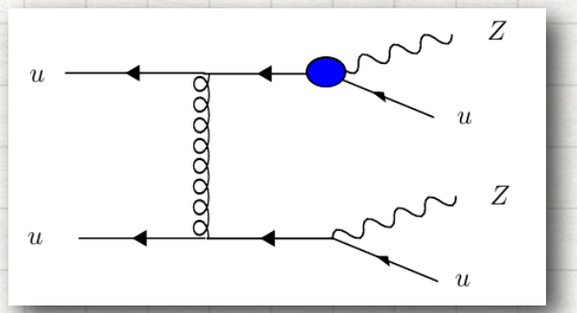
- Evidence/Measured at Run-2

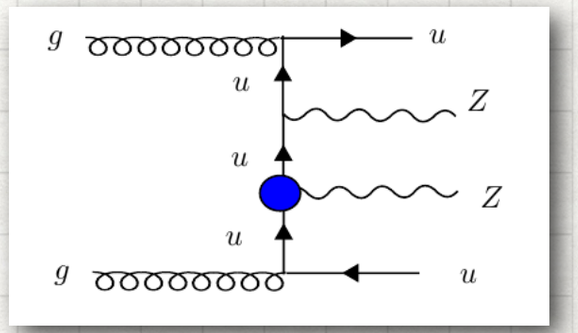
$$\frac{\sigma_{EFT,bosonic}}{\sigma_{SM}} \approx 1. + 0.047\ \bar{c}_{HB} - 0.053\ \bar{c}_{H\Box} - 0.0021\ \bar{c}_{\widetilde{HB}} + 0.010\ \bar{c}_{Hd} - 1.84\ \bar{c}_{HD} - 3.86\ \bar{c}_{Hl^{(3)}} - 0.017\ \bar{c}_{Hq^{(1)}} + 5.61\ \bar{c}_{Hq^{(3)}} - 0.033\ \bar{c}_{Hu} + 0.59\ \bar{c}_{HW} - 0.0041\ \bar{c}_{\widetilde{HW}} - 0.69\ \bar{c}_{HWB} - 0.022\ \bar{c}_{\widetilde{HWB}} + 0.23\ \bar{c}_{W} - 0.086\ \bar{c}_{\widetilde{W}}.$$

$$\frac{\sigma_{EFT,fermionic}}{\sigma_{SM}} \approx 1. - 3.23 \cdot 10^{-6}\ \bar{c}_{dd} - 2.89 \cdot 10^{-6}\ \bar{c}^{(1)}_{dd} - 3.86\ \bar{c}^{(1)}_{\ell\ell} + 0.0010\ \bar{c}^{(1)}_{qd} + 1.80 \cdot 10^{-20}\ \bar{c}^{(8)}_{qd} - 1.93\ \bar{c}^{(1)}_{qq} - 2.57\ \bar{c}^{(11)}_{qq} - 14.3\ \bar{c}^{(3)}_{qq} - 10.3\ \bar{c}^{(31)}_{qq} - 0.0049\ \bar{c}^{(1)}_{qu} - 2.51 \cdot 10^{-20}\ \bar{c}^{(8)}_{qu} + 0.00020\ \bar{c}^{(1)}_{ud} + 1.62 \cdot 10^{-21}\ \bar{c}^{(8)}_{ud} - 0.0010\ \bar{c}_{uu} - 0.00099\ \bar{c}^{(1)}_{uu}.$$

$$\frac{\sigma_{EFT,bkg}}{\sigma_{SM,bkg}} \approx 1. - 0.00073\ \bar{c}_{Hd} - 0.0036\ \bar{c}_{HD} + 0.044\ \bar{c}_{HG} - 0.00016\ \bar{c}_{\widetilde{HG}} - 0.077\ \bar{c}^{(3)}_{Hl} + 0.018\ \bar{c}^{(1)}_{Hq} + 0.17\ \bar{c}^{(3)}_{Hq} + 0.0065\ \bar{c}_{Hu} + 0.035\ \bar{c}_{HWB} - 0.077\ \bar{c}^{(1)}_{\ell\ell}$$

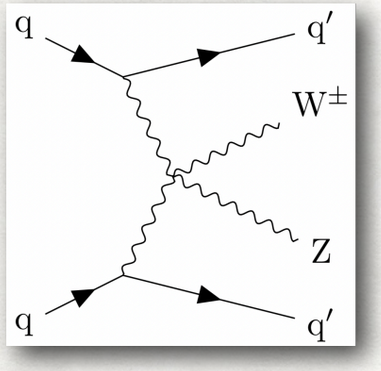
Background:

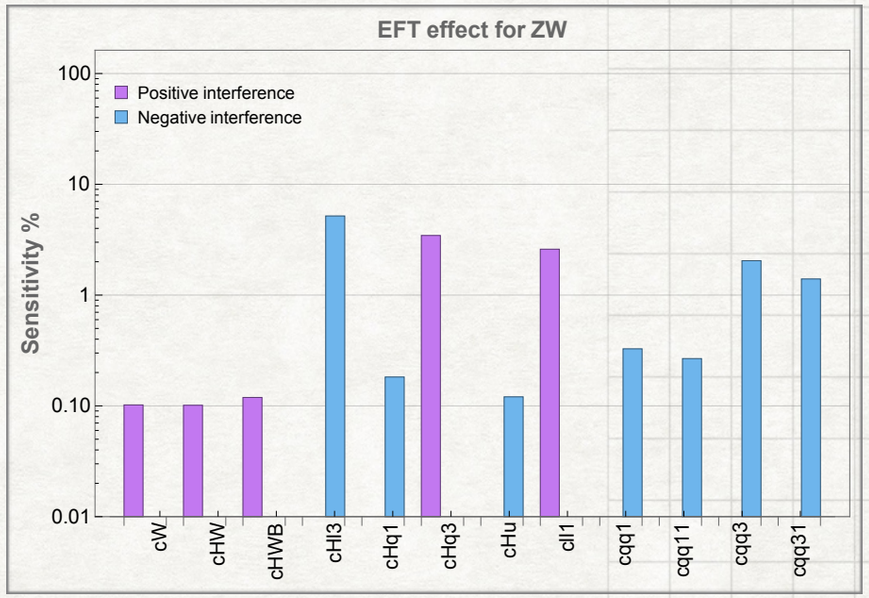


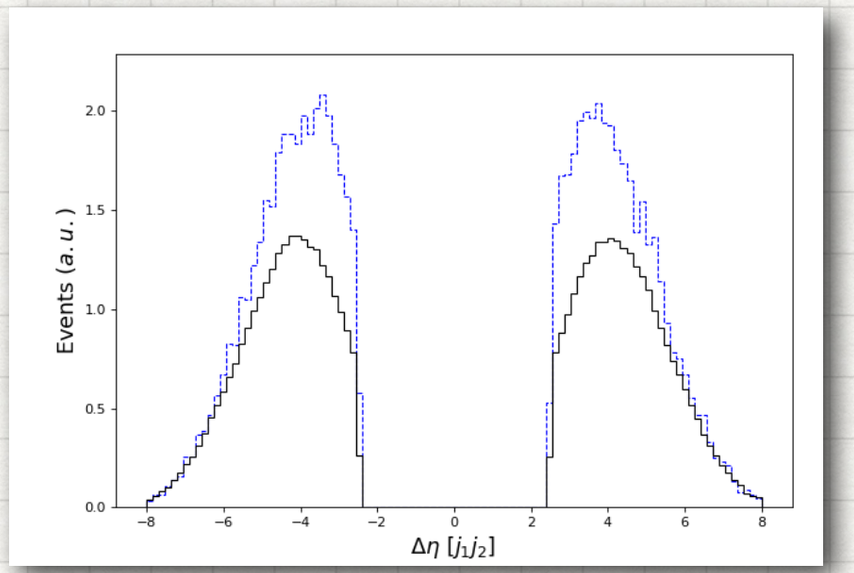


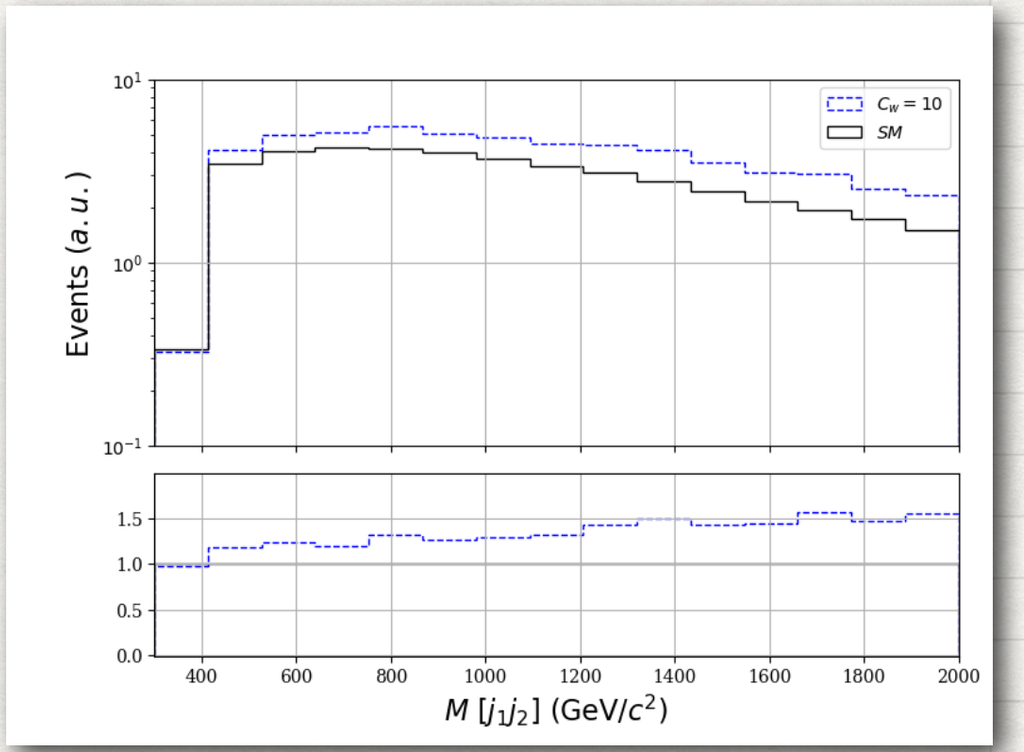
1809.04189

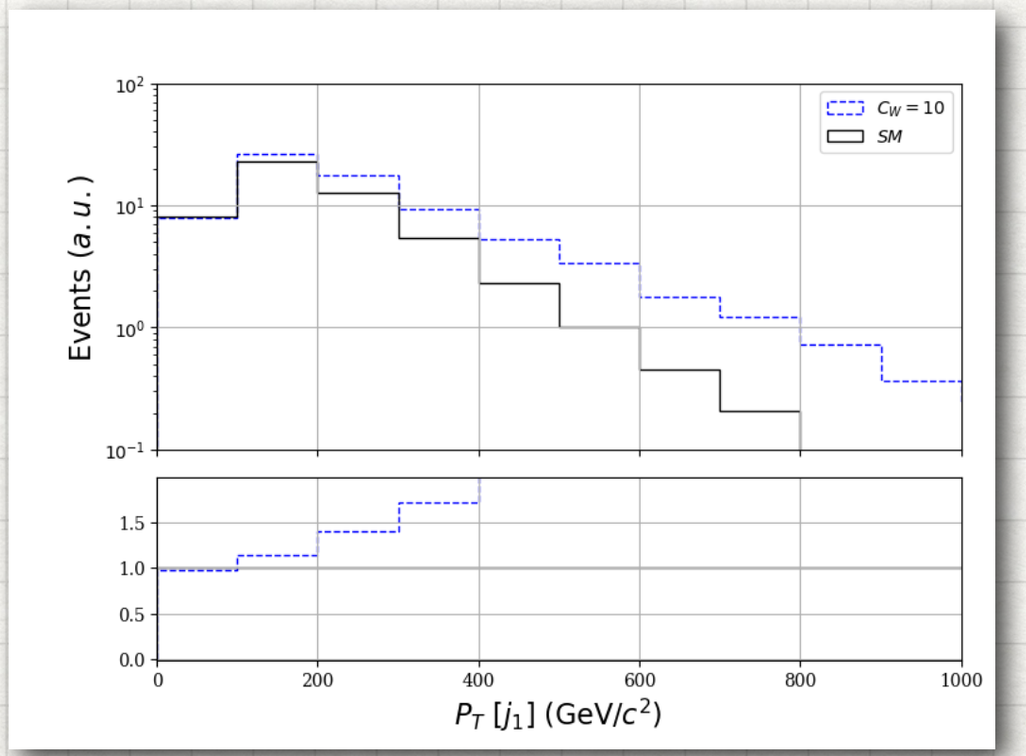
Not only total cross-sections… Differential observables shed light on the EFT effects











Important to understand TH and EXP correlations across observables, in order to choose wisely!

FITS: STRATEGY AND TOOLS

G fitter

HEPfit

flavio

NNPDF

CMS

Combine

User friendly, modular, many observables pre-implemented…. Not optimal when the number of parameters is large

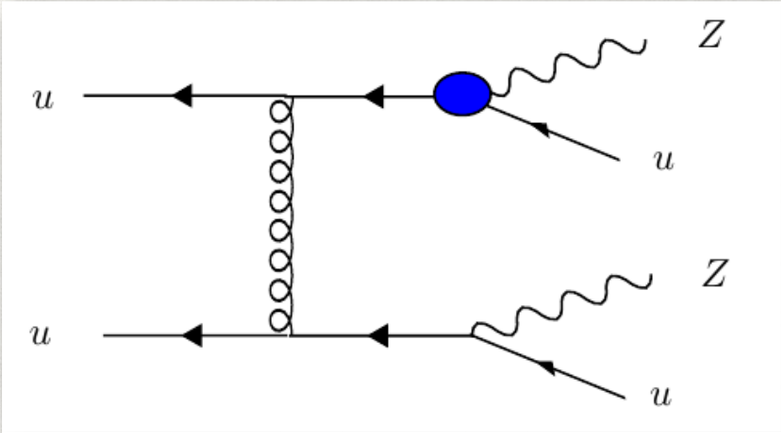
More robust, good at dealing with large number of parameters and nuisances. Not the most "user friendly"

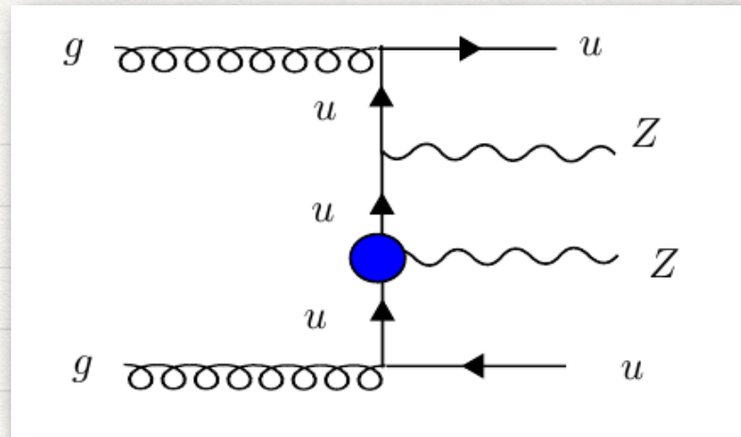
"Combination WG" (contact R. Covarelli, Magdalena Slawinska, Despoina Sampsonidou)

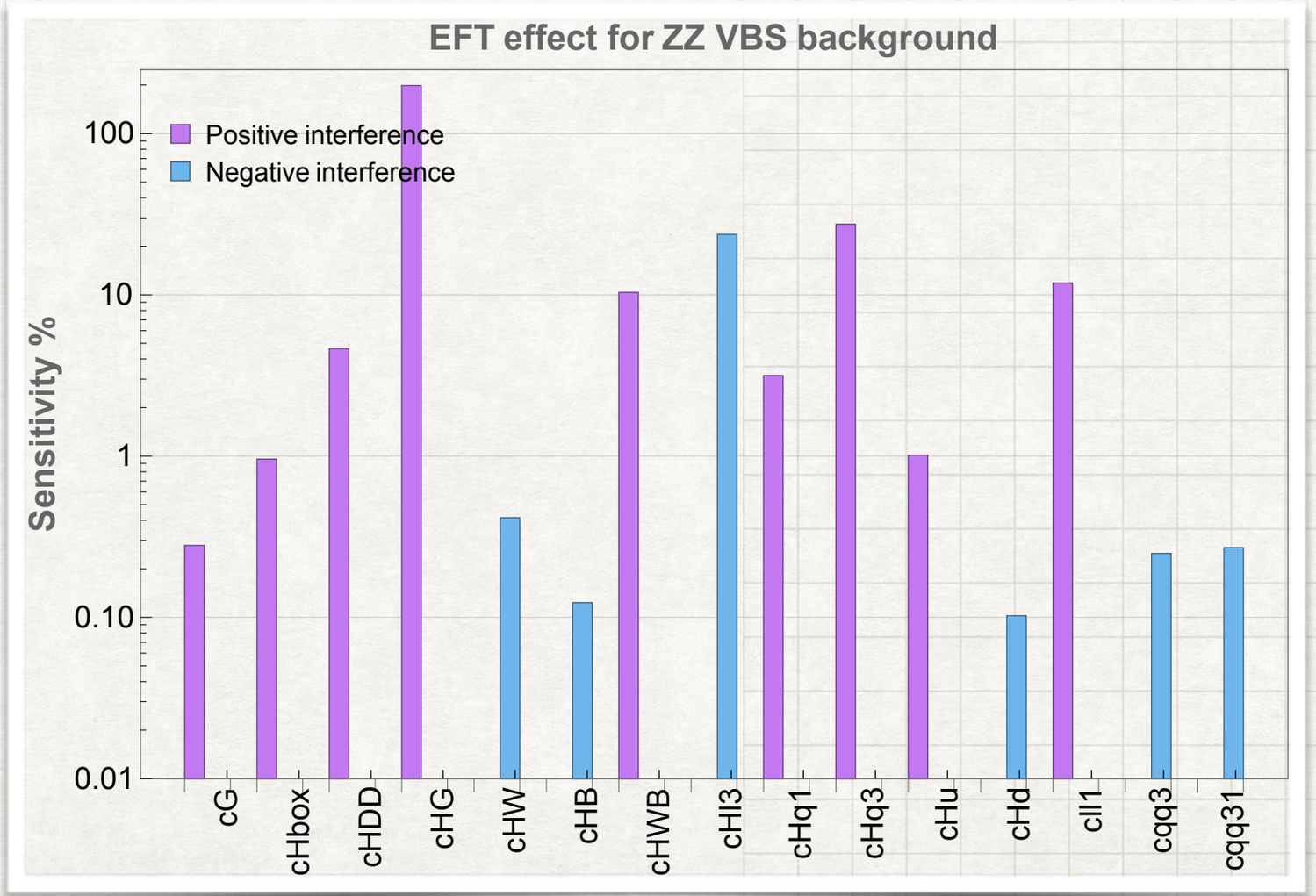
VBSCan COST

VBS ZZ BACKGROUND

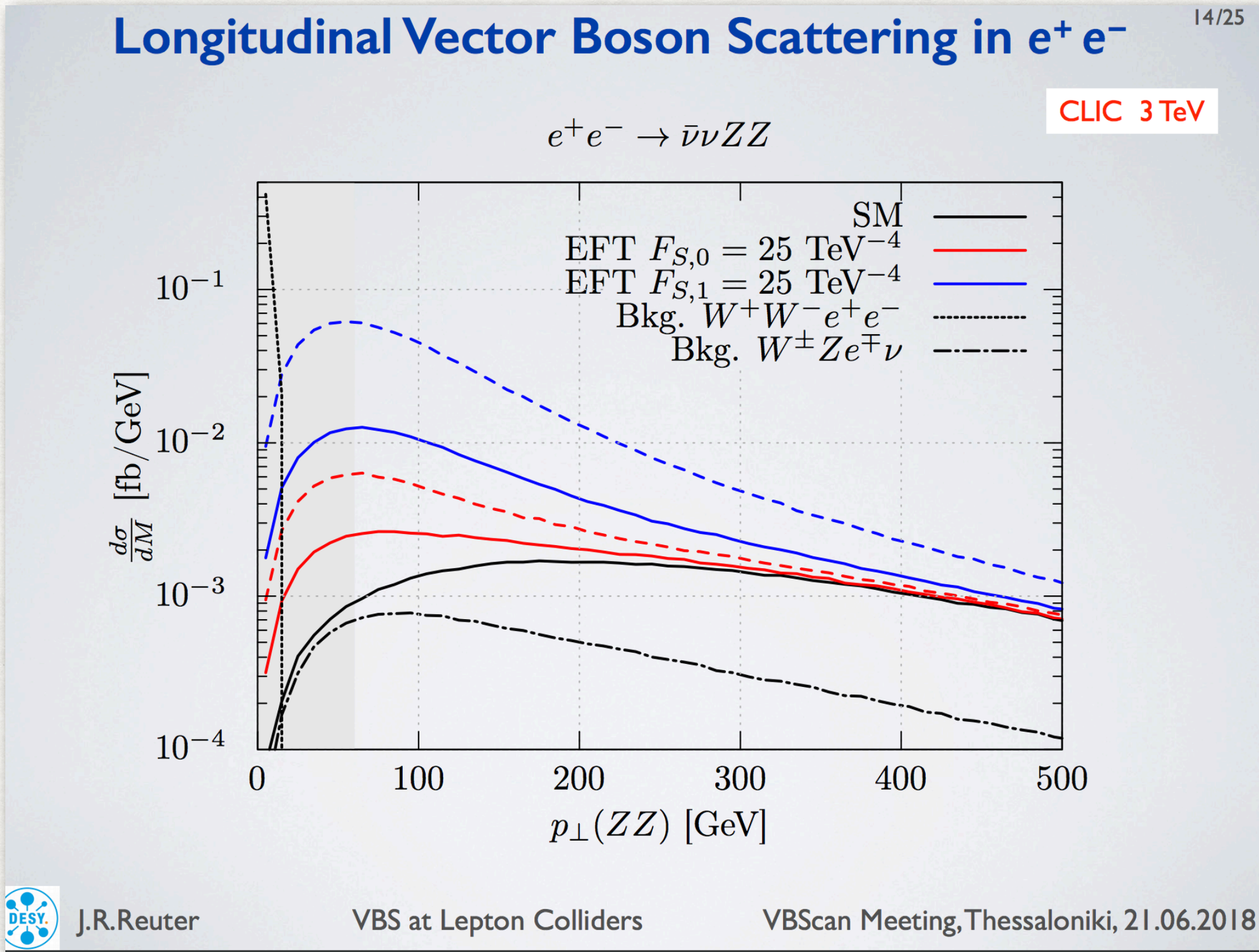
- QCD induced VV:







STATE OF THE ART: FUTURE COLLIDERS



(see refs. in the backup slides)

OPEN QUESTIONS

1. Is it enough to fit signal strengths as we do in f.ex Higgs physics?

   A. First problem: jet smearing

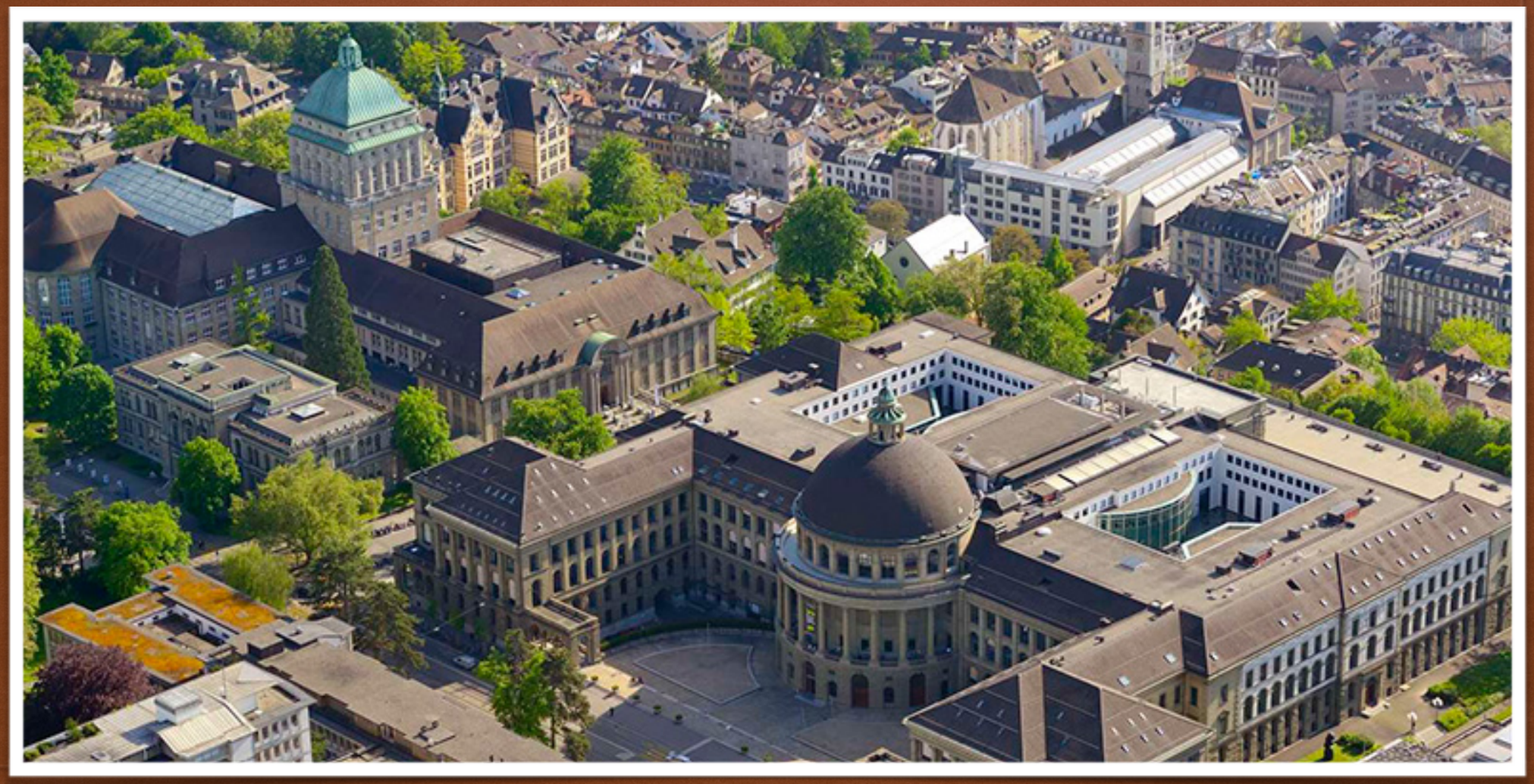
2. Why do the collaborations look for these “anomalous Dim-8” operators? Is there hope for Dim-6 in the current analyses?

3. Optimal observables for the fit (cover most of the NP space/avoid flat directions & correlations)?

4. …. ?

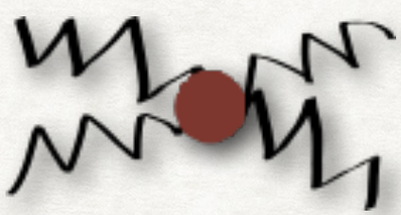
THANKS!

BACKUP



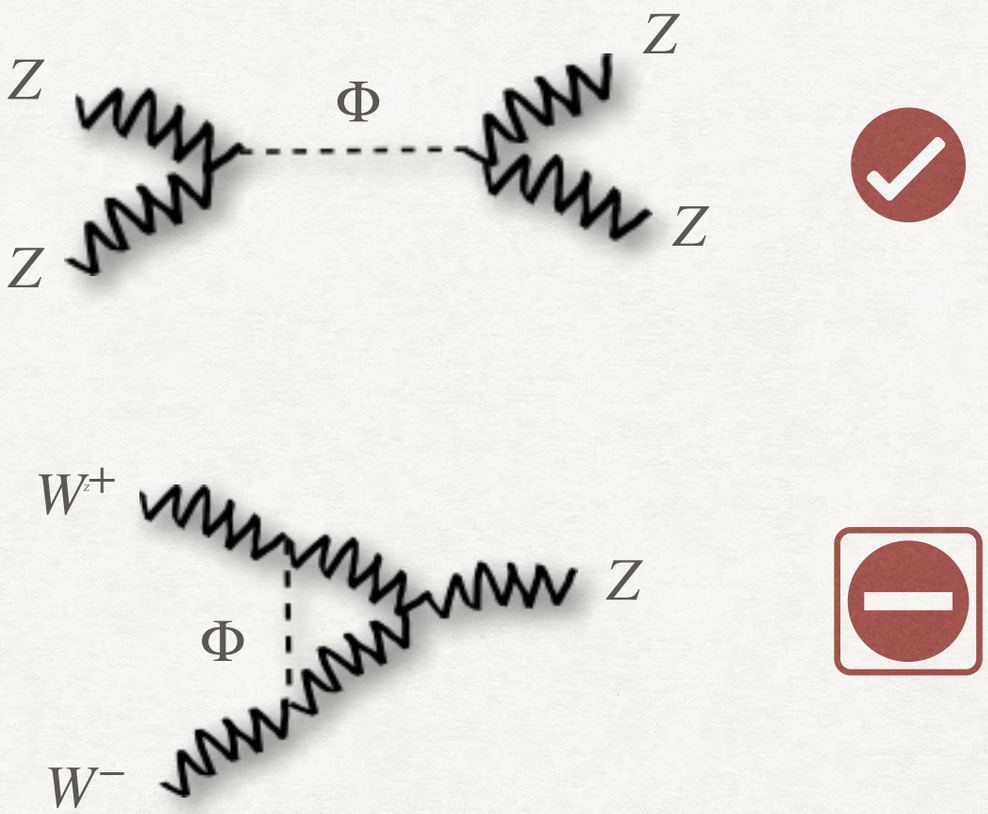
TRADITIONAL VBS INTERPRETATION: DIM 8

- One has to think which UV completion is compatible with this behaviour: only generating QGC and not TGC, predicting ZZZZ interactions….



$Z_\mu Z_\nu Z_\rho Z_\sigma$

If we assume the Higgs is a Doublet in a linear representation, we are implicitly assuming EWSB, where TGC and QGC are generated simultaneously



Possible UV completion.. not very model independent

SMEFT: LINEAR VS QUADRATIC

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

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

Quadratic + dim-8

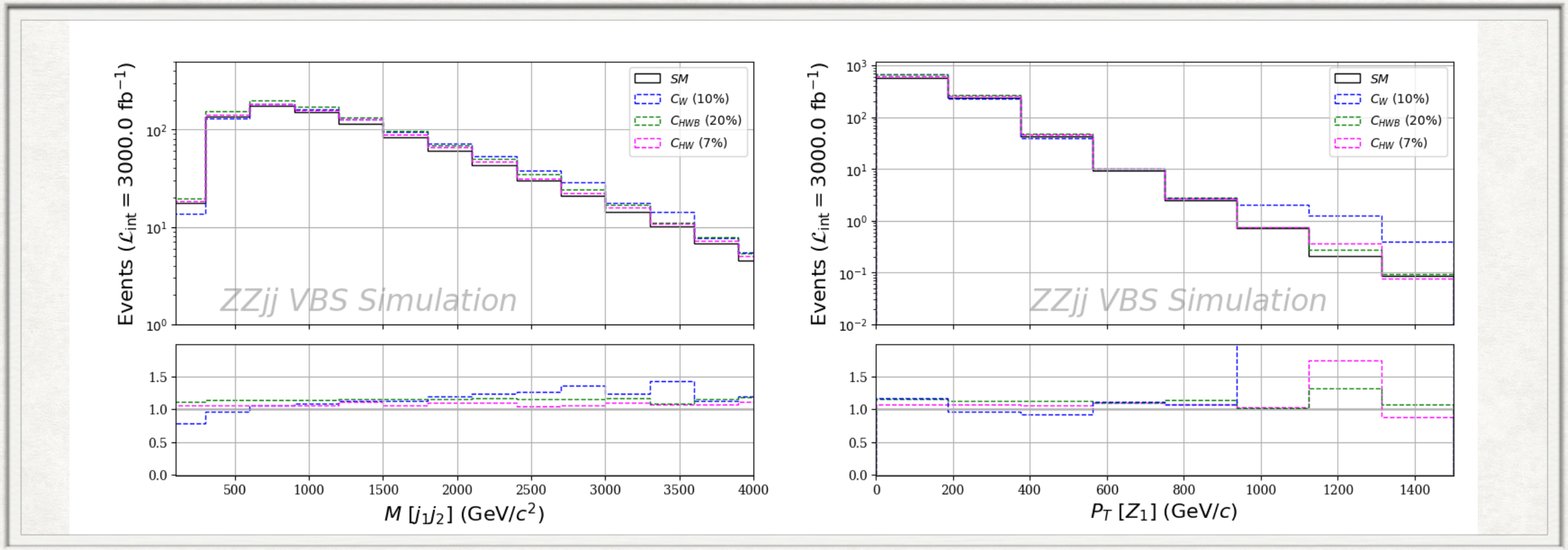
$$\mathcal{A}_{EFT} = \mathcal{A}_{SM} + \frac{g'}{\Lambda^2}\mathcal{A}_6 + \frac{g'^2}{\Lambda^4}\mathcal{A}_8 + \dots$$

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

Linear EFT

FUTURE PROSPECTS (HL-LHC)

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



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

Overview Literatur: VBS in $e^+ e^-$ / $e^- e^-$

- Gunion/Tofighi-Niaki, PRD36 (1987) 2671: full MEs for VBS (*WW*) and heavy Higgs production [0.5, 1, 2 TeV]
- Gunion/Tofighi-Niaki, PRD38 (1988) 1433: same for *ZZ* final states [0.5, 1, 2 TeV]
- Barger/Cheung/Han/Phillips, PRD52 (1995) 3815: measurements of *WW*/*ZZ* ratios [1.5 – 2 TeV]
- Dominici, Riv.Nuo.Cim.20 (1997) 1: access to parameters of EW chiral Lagrangian in *WW* VBS [1.5 TeV]
- Denner/Dittmaier/Hahn, PRD56 (1997) 117: EW corrections to $ZZ \to ZZ$
- Denner/Hahn, NPB525 (1998) 27: EW corrections to $WW \to WW$
- Han/He/Yuan, PLB422 (1998) 294: interplay of *WW* VBS and *WWZ*/*ZZZ* production [0.5, 0.8, 1, 1.6 TeV]
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD57 (1998) 1553: EW chiral Lagrangian (strong EW) [1.6 TeV]
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD61 (2000) 077901: strong EW: *ZZ*/W^-W^- channels [1.6 TeV]
- Kilian, Int.J.Mod.Phys.A15 (2000) 2387: strong EW in e^-e^- [1 TeV]
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- Chierici/Rosati/Kobel, LC-PHSM-2001-038 : experimental study for strong EW [0.18–0.8 TeV]
- Rosati, CERN-THESIS-2002-083 : experimental study for strong EW [0.18–0.8 TeV]
- Beyer/Kilian/Krstonošić/Mönig/JRR/Schmidt/Schröder, EPJC48 (2006) 353: α parameters, VBS+VVV [1 TeV]
- Accomando/Denner/Pozzorini, JHEP 0703 (2007) 078: EW Sudakov logarithms in VBS [3 TeV]
- Liebler/Moortgat-Pick/Weiglein, JHEP 1506 (2015) 093: moff-shell Higgs effects in $ee \to \nu\nu VV$ [0.25 – 1 TeV]
- Fleper/Kilian/JRR/Sekulla, EPJC77.2 (2017) 120: VBS for SMEFT with dim 8 / simplified models [1, 1.4, 3 TeV]