STUDIES OF ~~DIM-6~~ EFT IN VECTOR BOSON SCATTERING

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DIM-6 EFT AND VV PROCESSES

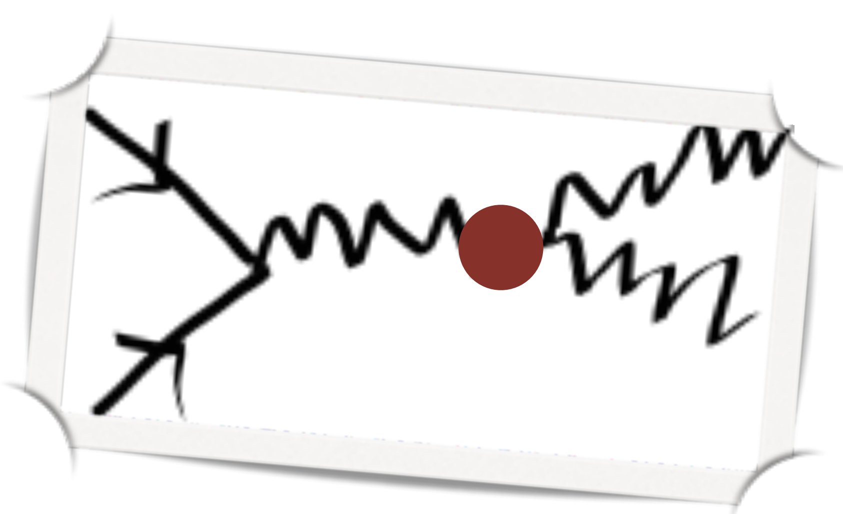
- Based on :
  - "Studies of Dimension-Six EFT effects in Vector Boson Scattering" **arXiv 1809.04189 (EPJC)**
  - "Higgs Physics at the HL-LHC and HE-LHC" **arXiv 1902.00134**
  - Work in progress **(within the EWWG)**

Comments and suggestions very welcome!

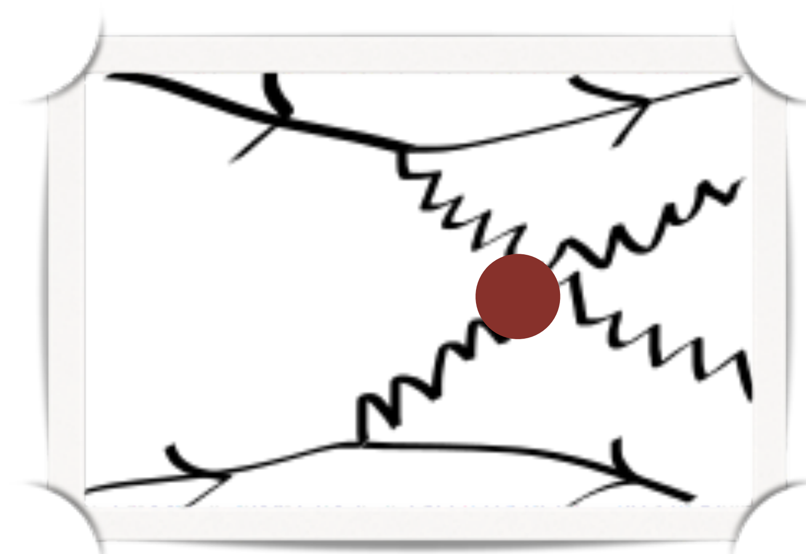
(Thanks already to R. Covarelli, J. Lindert, C. Degrande …)

MOTIVATION: FROM LEP TO LHC

- LEP: TGCs (on-shell) ← *Traditionally param. by form factors (aTGCs)*
- 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

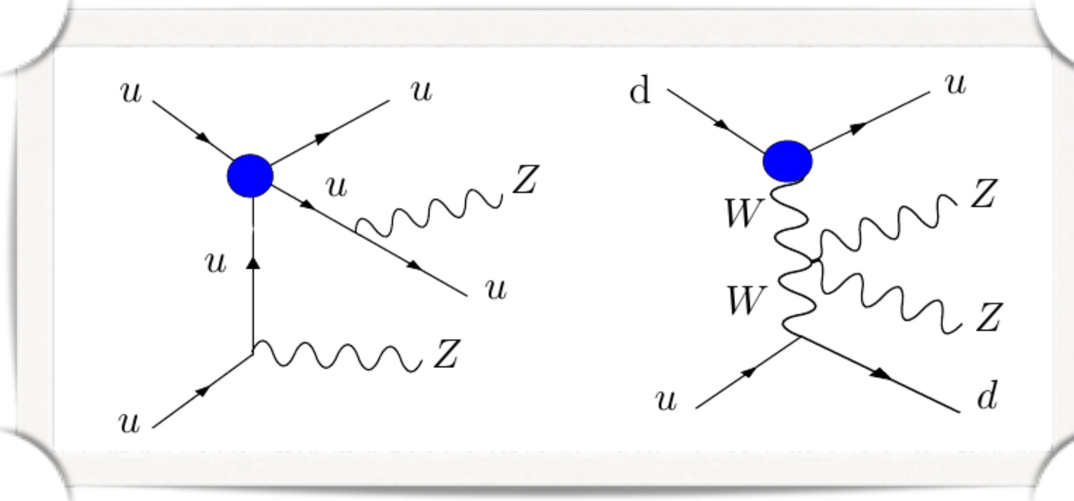
$$\mathcal{A}_{EFT} = \mathcal{A}_{SM} + \frac{g'}{\Lambda^2}\mathcal{A}_6 + \frac{g'^2}{\Lambda^4}\mathcal{A}_8 + \dots$$

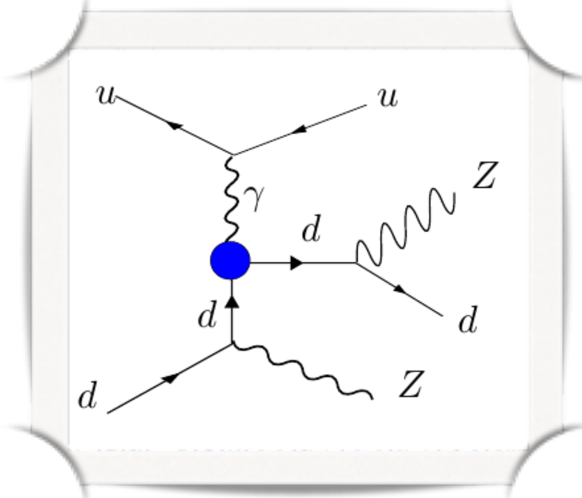
$$\sigma_{EFT} \sim |\mathcal{A}_{SM}|^2 + 2\frac{g'}{\Lambda^2}\mathcal{A}_{SM}\mathcal{A}_6 + \frac{g'^2}{\Lambda^4}\left(2\mathcal{A}_{SM}\mathcal{A}_8 + |\mathcal{A}_6|^2\right) + \dots$$

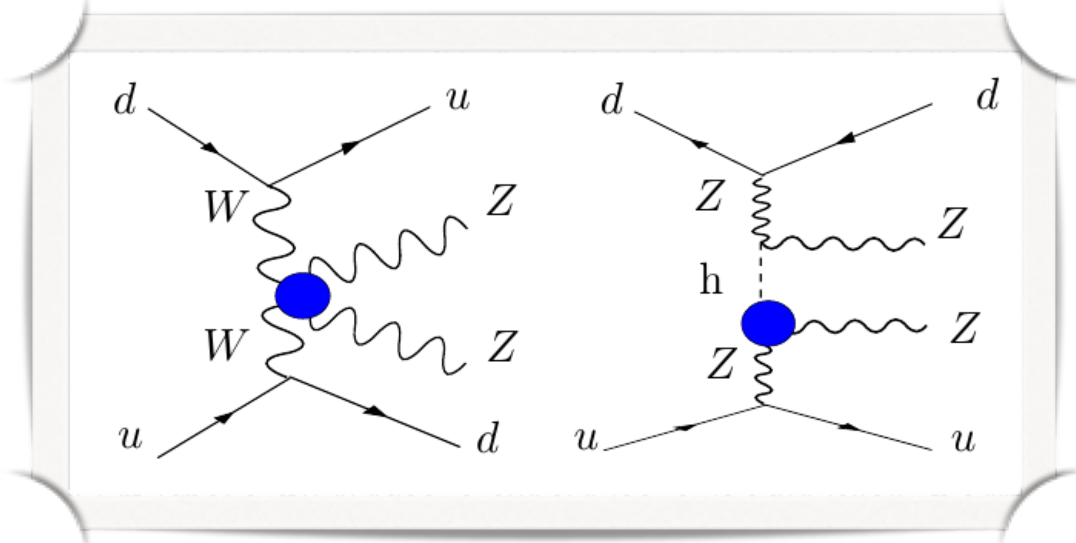
Linear EFT

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

VBS (ZZ)







- *Generate the purely electroweak process $p\,p \rightarrow z\,z\,j\,j$, 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….*

In progress:

- *Study fully leptonic final state*
- *Shower events*
- *Migrate to Rivet analyser*
- *Validate results with SHERPA**

**TBD*

UP-TO-NOW TOOLS

Everywhere: Linear EFT (LO) and MW IPS

- Monte Carlo:
  - SMEFTsim + Madgraph5 + Pythia8
- Event Analysis:
  - Madanalysis5 (partonic)
- Numerical analysis:
  - Mathematica + Python

NEAR-FUTURE TOOLS

Everywhere: ~~Linear EFT (LO)~~ and MW IPS

Linear +Quadratic + Dim 8

- Monte Carlo:
  - SMEFTsim* + Madgraph5 + Pythia8
  - SMEFTsim* + SHERPA
- Event Analysis:
  - ~~Madanalysis5 (partonic)~~ ⟶ Rivet (showered)
- Numerical analysis:
  - Mathematica + Python

**Possibility of validation against private UFO model*

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}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
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.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

VBS ZZ

VBS WW?

$8: (\bar L L)(\bar L L)$	
$Q_{\ell\ell}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{\ell q}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{\ell q}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
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}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

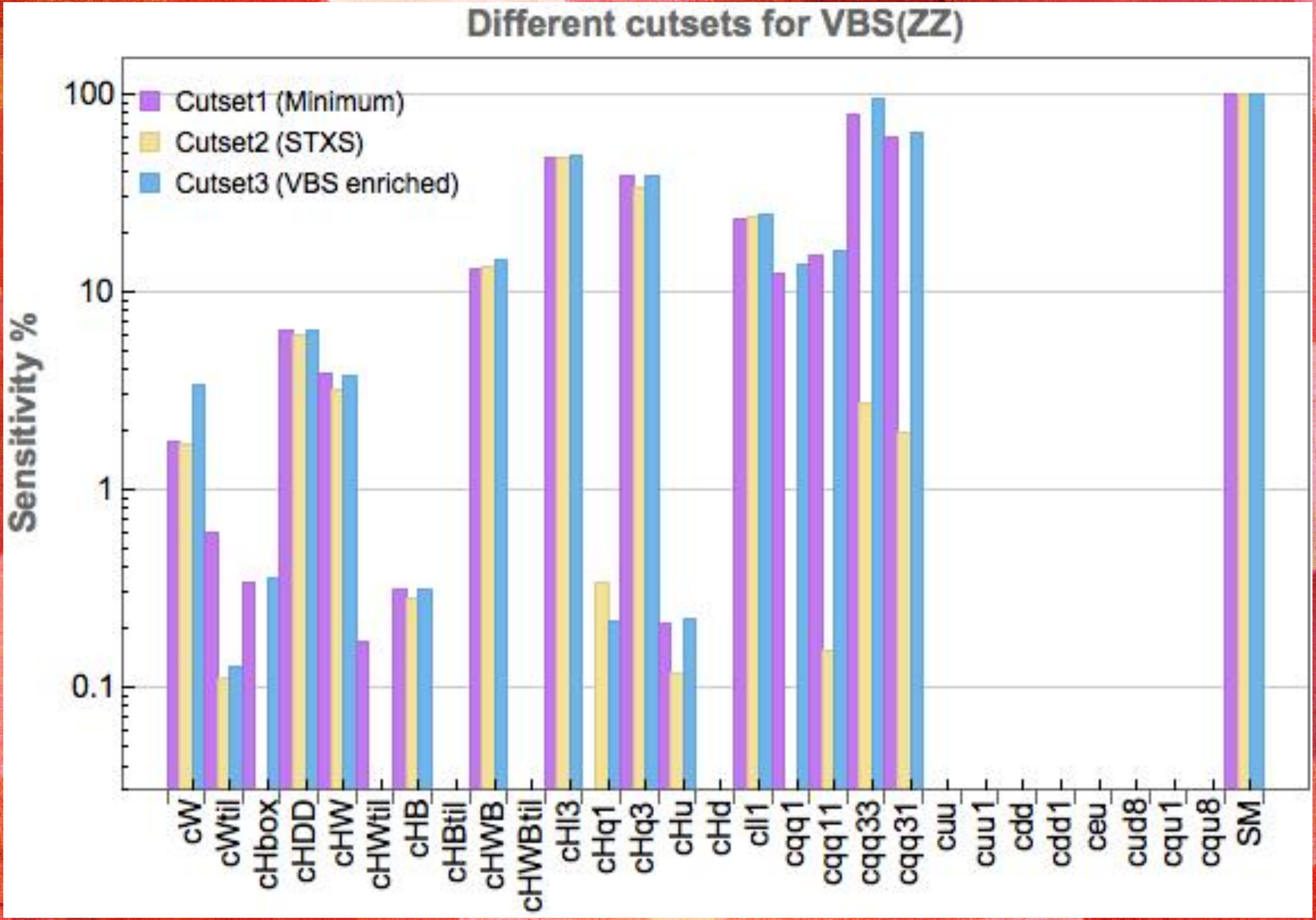
$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$

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

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

STEP 1: COMPARE DIFFERENT CUT SELECTIONS

- Selection 1:
  - Pt(j1) > 30 GeV & Pt(j2) > 30 GeV
  - Eta(j) > 4.5 & DeltaEta (jj) > 2.5
  - m(jj) > 100 GeV ← *Minimum Cut*
- Selection 2: *STXS Style region*
  - 100 GeV < m(jj) < 250 GeV
- Selection 3: *"Traditional" VBS region*
  - m(jj) > 400 GeV

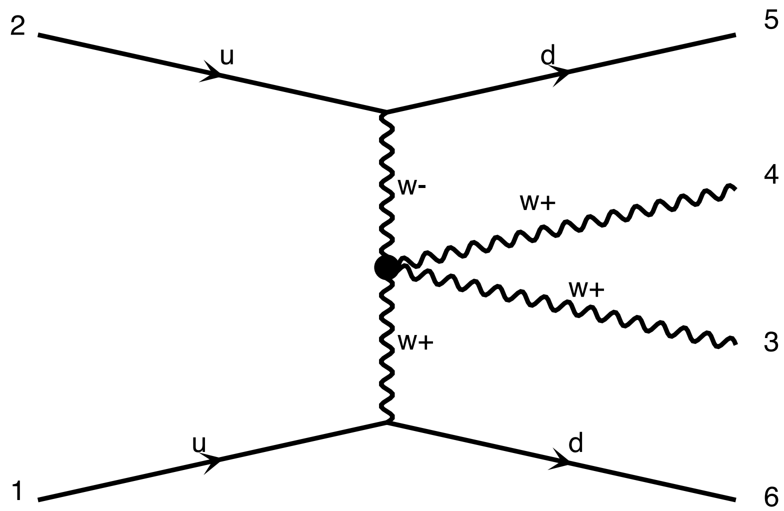


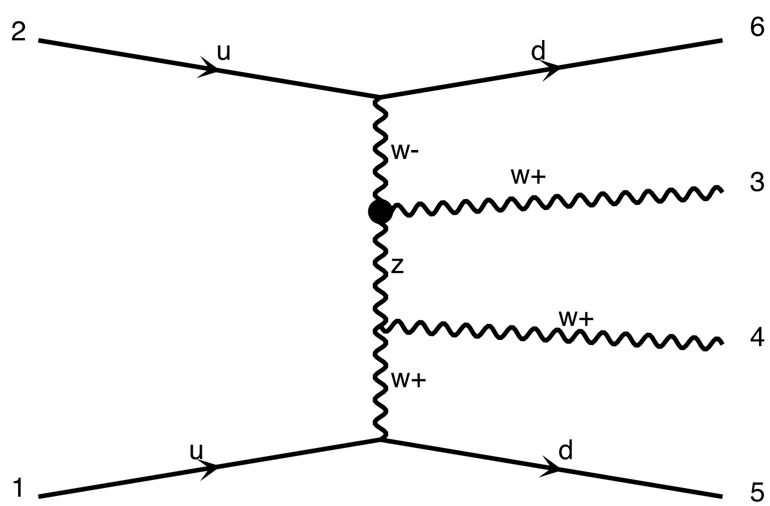
Different cutsets for VBS(ZZ)
Cutset1 (Minimum)
Cutset2 (STXS)
Cutset3 (VBS enriched)
Sensitivity %
100
10
1
0.1
cW
cWtil
cHbox
cHDD
cHW
cHWtil
cHB
cHBtil
cHWB
cHWBtil
cHl3
cHq1
cHq3
cHu
cHd
cll1
cqq1
cqq11
cqq33
cqq31
cuu
cuu1
cdd
cdd1
ceu
cud8
cqu1
cqu8
SM

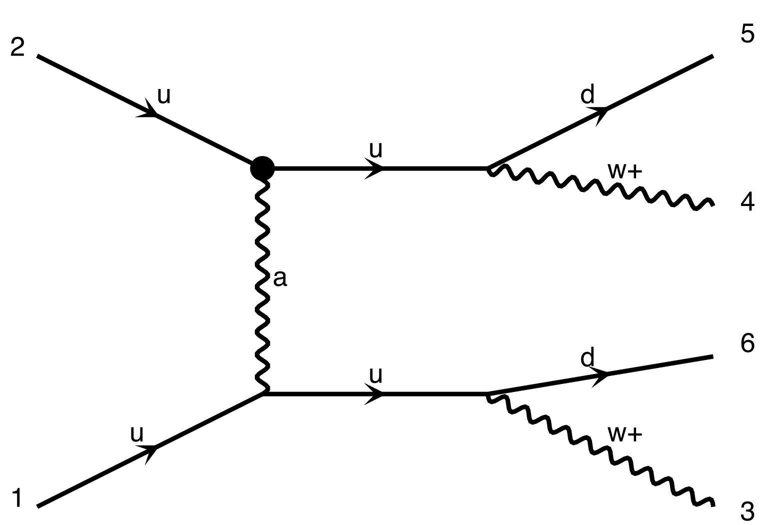
STEP 2: COMPARE DIFFERENT CHANNELS

- VBS Channels:
  - ZZ, ssWW, WZ…
- VBF Channels
  - Hjj, Zjj, Wjj …
- Diboson Channels:
  - QCD induced ZZjj, osWW, …

See Kristin's part…



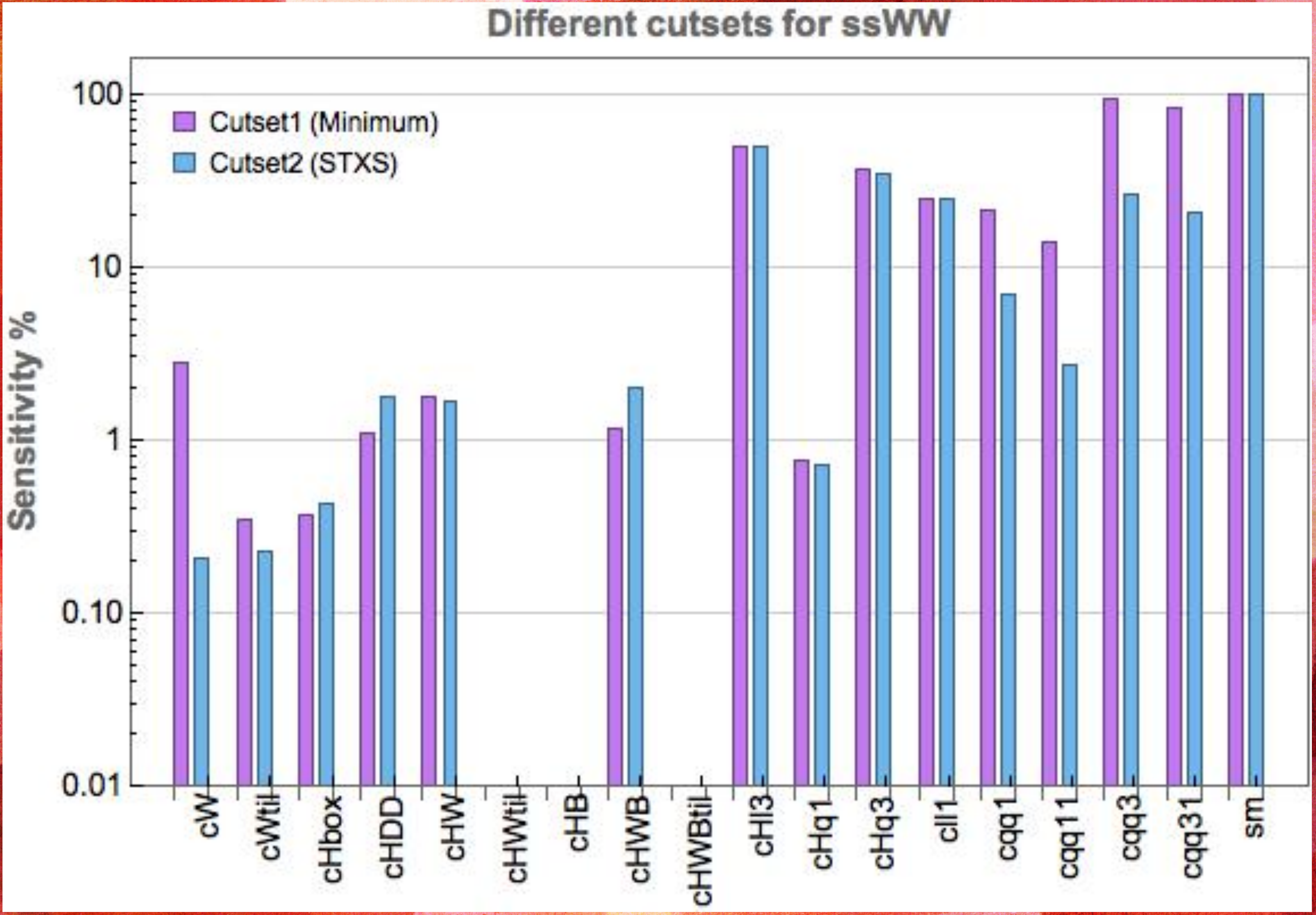




VBS (WW)

- For now: semileptonic decays
- Interesting news in this channel:
  - *"Precise predictions for same-sign W-boson scattering at the LHC"*

    1803.07943 (Ballestrero et. al)
  - *NLO EW+QCD corrections can amount up to -16%* **190X.XXXX (Pellen et. al)**



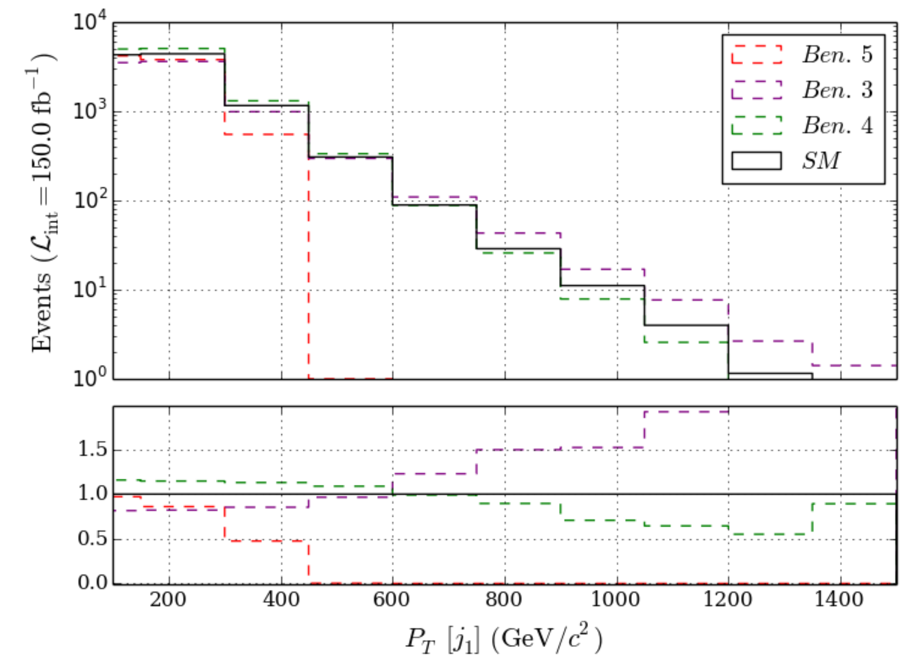
Different cutsets for ssWW
Cutset1 (Minimum)
Cutset2 (STXS)
Sensitivity %
100
10
1
0.10
0.01
cW
cWtil
cHbox
cHDD
cHW
cHWtil
cHB
cHWB
cHWBtil
cHl3
cHq1
cHq3
cll1
cqq1
cqq11
cqq3
cqq31
sm

STEP 3: DIFFERENTIAL DISTRIBUTIONS

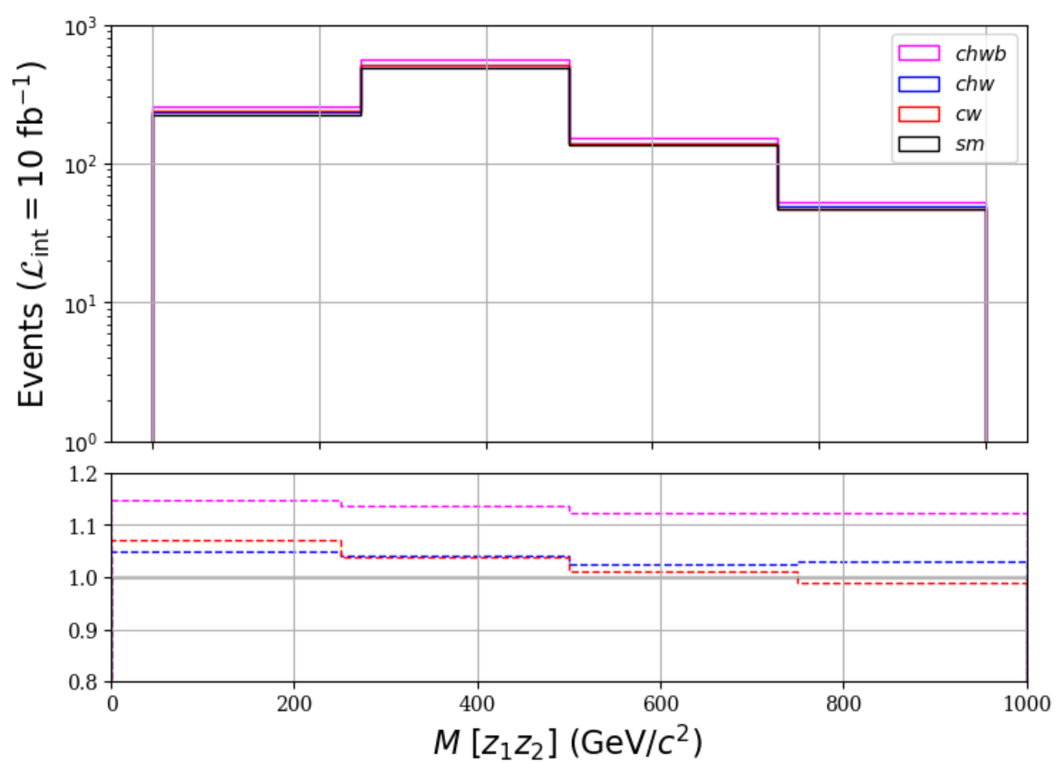
- The advantages of differential distributions are several:

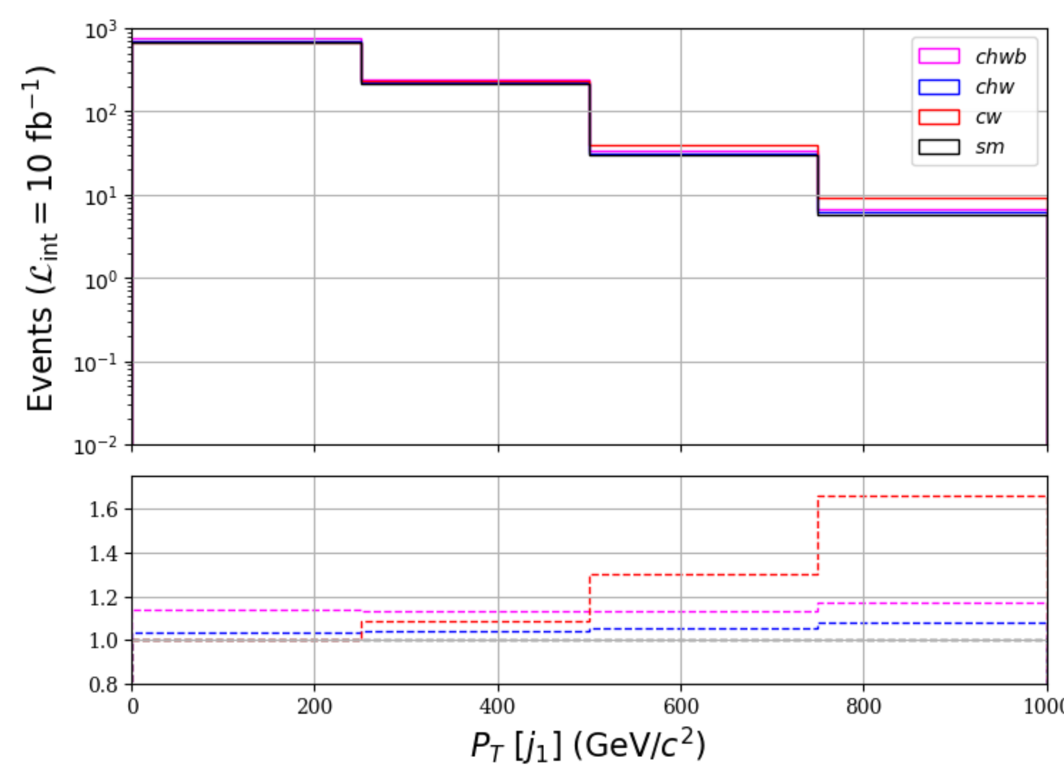
1. Provide with extra 'observables' to study (bins)
2. Provide with extra discrimination power

2.



1.



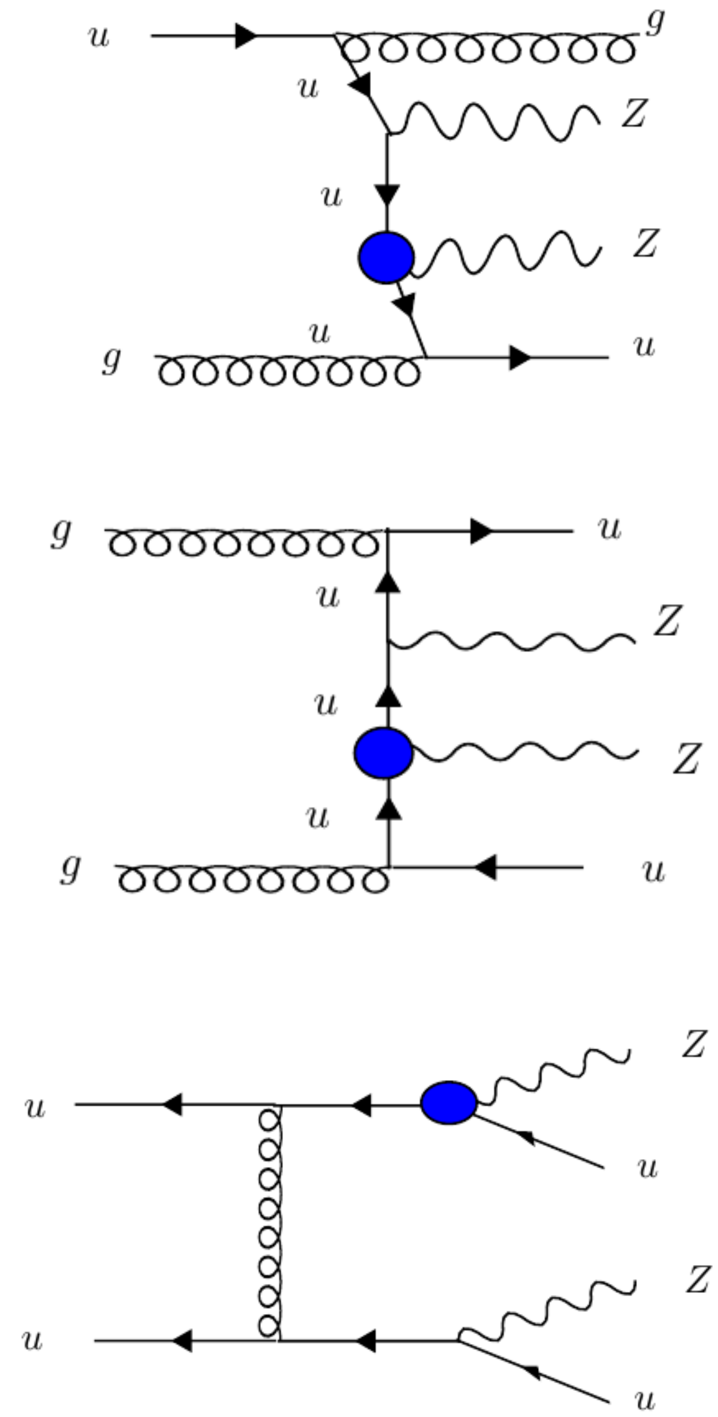


NEXT STEPS:

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

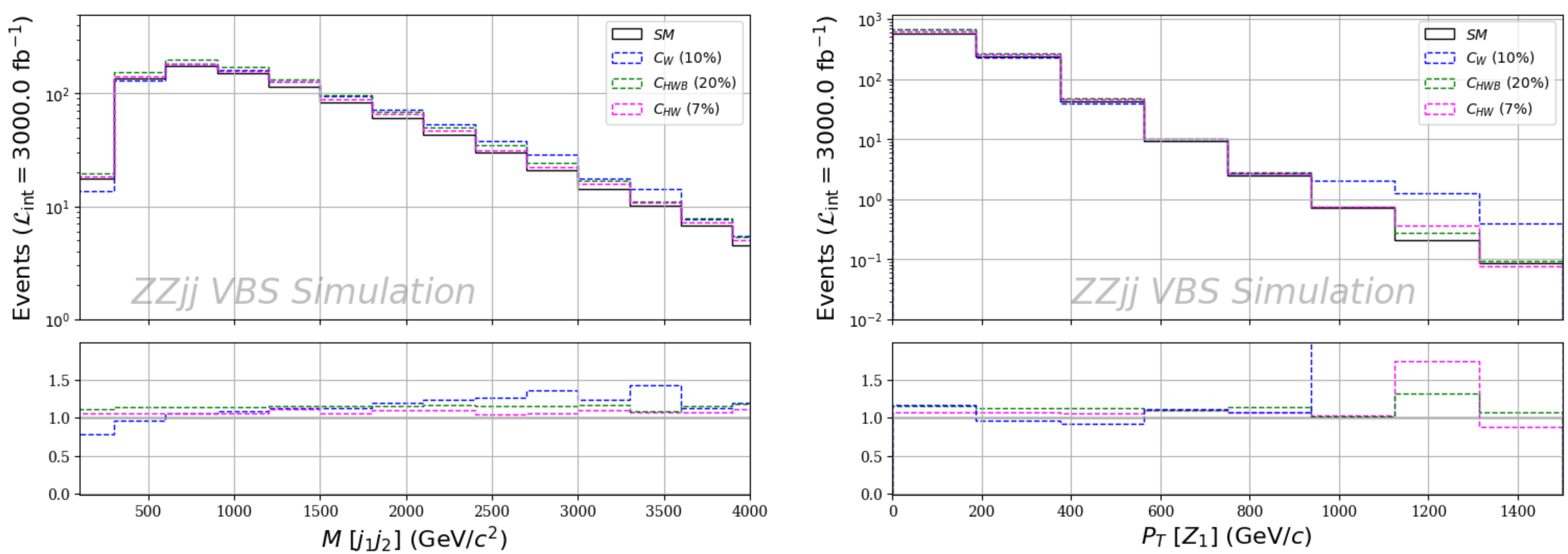
BACKGROUND

- QCD induced VV production



FUTURE (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

HIGHER ORDER EFT: QUADRATIC & DIM-8

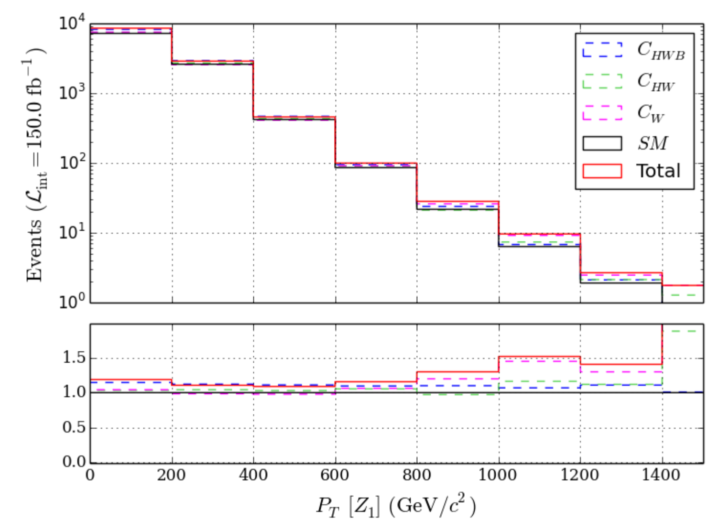
Suggestions for Dim-8 implementations welcome!

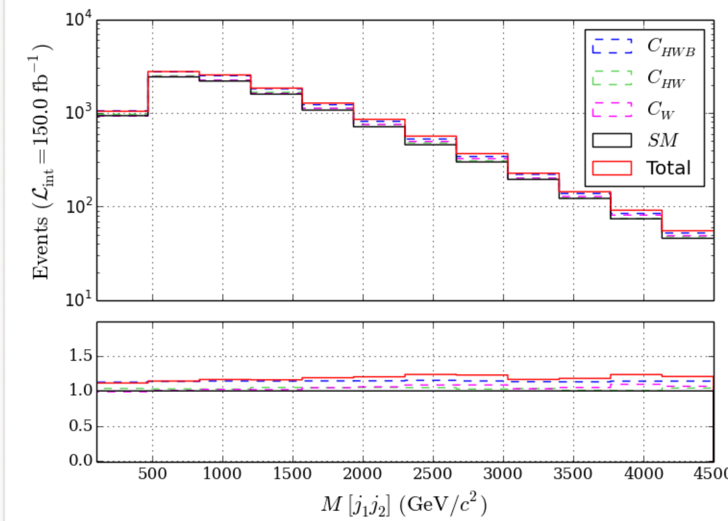
- Warsaw basis operators generating TGCs and QGCs

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

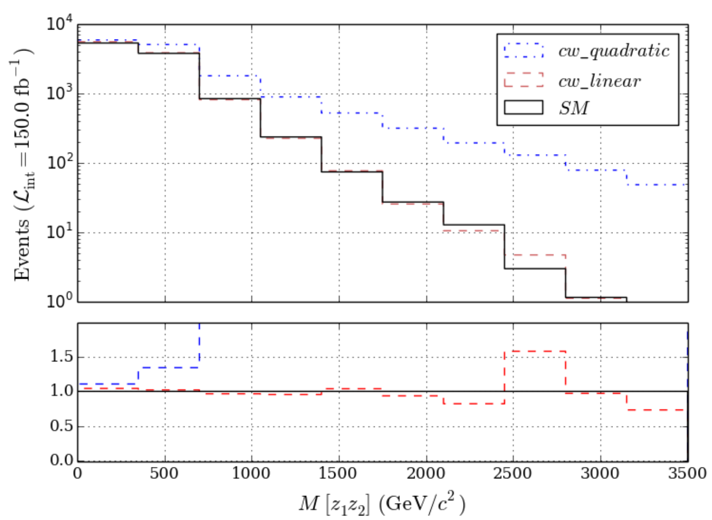
$$\mathcal{O}_{HW} = H^\dagger H W^I_{\mu\nu} W^{\mu\nu I}$$

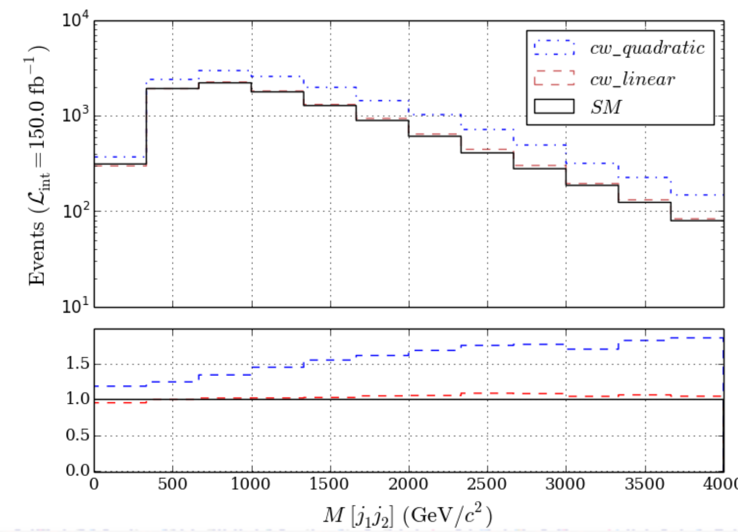
$$\mathcal{O}_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$





Example of quadratic contributions:





CONCLUSIONS AND OUTLOOK

- Precise VBS and Diboson EFT predictions are useful both on their own and as part of the global-fit agenda for EFT at LHC

- For this predictions to be useful, more VBS (signal and background) measurements are needed. In particular unfolded measurements for differential distributions would be a big boost to the programme.

Thanks for your attention!