Effectively Exploring New Physics: EFT interpretation of ATLAS Run-2 data on the $WZ \rightarrow ll\nu l$ channel

WNPPC - 2025

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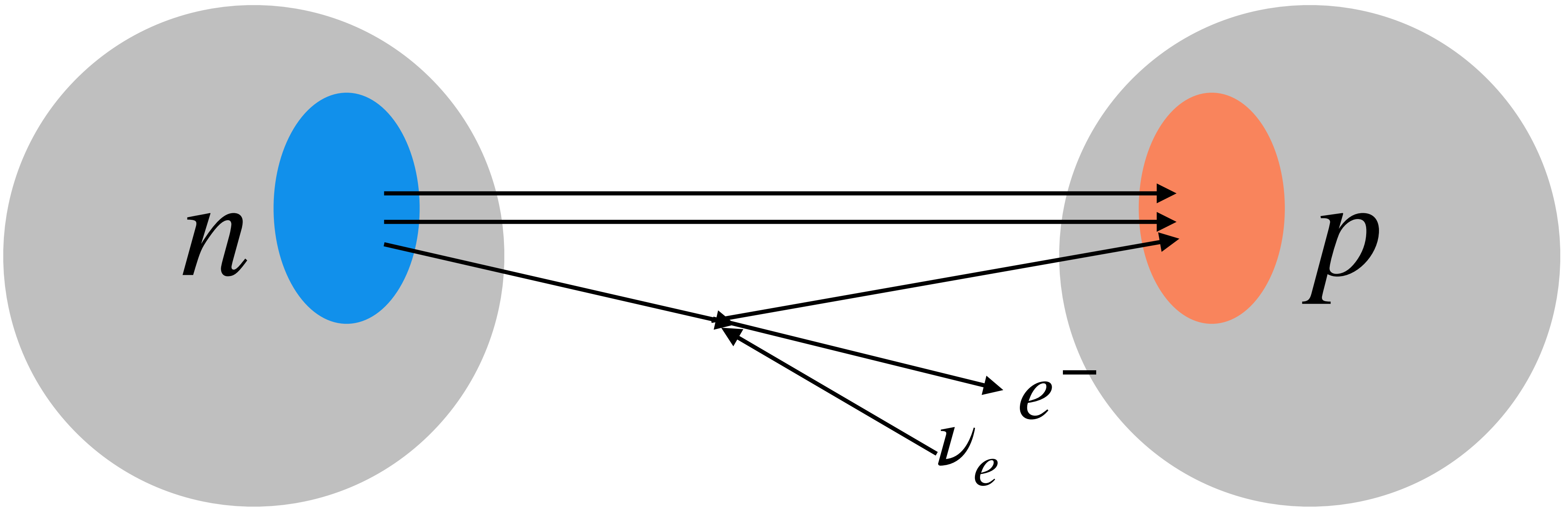
ATLAS EXPERIMENT

- The Standard Model is the most successful theory describing the fundamental interactions of particles at the highest energies probed in particle physics experiments
- Yet, we know that it is incomplete as it is still unable to explain several physical phenomena

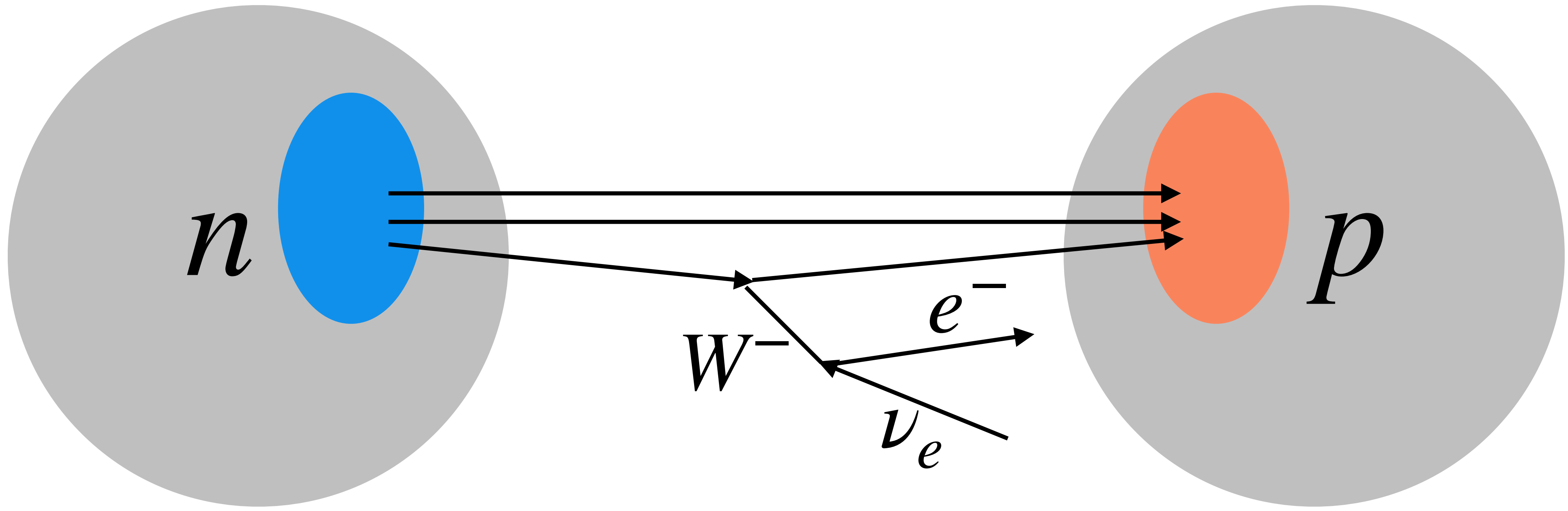
CRAZY IDEA:

What if the SM is a low energy approximation of a more fundamental theory at a higher energy scale Λ?

Fermi theory of β decay



$q^2 > (M_W)^2$



At high energies, the boson exchange reveals underlying physics, while at low energies, a four-point interaction explains the decay by effectively integrating out the massive boson

Standard Model Effective Field Theory (SMEFT)

- SMEFT is the framework that provides a systematic way to include the effects of unknown high-energy physics while preserving the fundamental gauge symmetries of the SM.
  - ➡ Given that we haven't seen any direct signs of new particles in colliders → New particles likely much heavier than our current energy scale.
  - ➡ We can integrate out heavy BSM particles → Capture effects model-independently.

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\cancel{\sum_i c_i^{(5)}\mathscr{O}_i^{(5)}} + \boxed{\frac{1}{\Lambda^2}\sum_i^{2499} c_i^{(6)}\mathscr{O}_i^{(6)}} + \dots$$

Violates Lepton and Baryon number

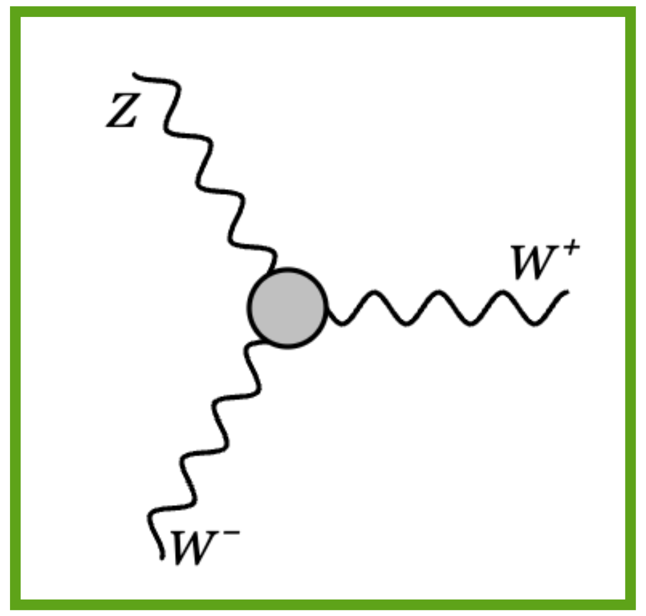
Studied in this analysis

$\mathscr{O}_i$: Higher order dimension **operators** which introduce new interaction vertices

c_i : **Wilson coefficients** parameterize the strength of these operators

Λ : **Scale of new physics** - assumed to be 1 TeV

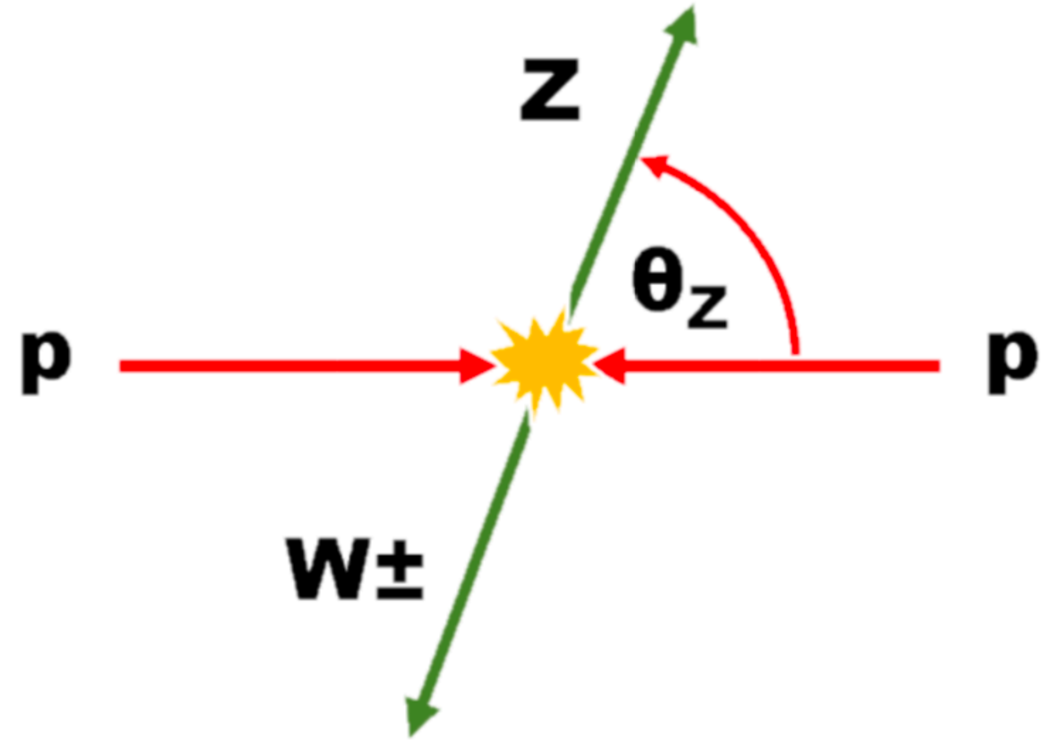
- Dimension-6 operators are particularly useful because they contribute to anomalous triple gauge couplings (aTGCs), modifying how electroweak bosons interact with each other and with fermions



- Since aTGCs are sensitive to $\sqrt{s}$, the LHC (highest energy collider) is ideal for studying them. General purpose detectors like ATLAS can measure these effects, offering indirect evidence of new physics.
- Triple gauge couplings manifest themselves naturally in WZ production. To avoid the more noisy signal from strong interactions, the leptonic decay (to e, μ) of the bosons is chosen to be studied.

What observables are studied:

- EFT analyses naturally look at kinematic observables (p_T, m_T), where new physics effects are possible in the higher bins.
- Information regarding the polarization of the bosons by studying angular distributions of the bosons and of their decay products



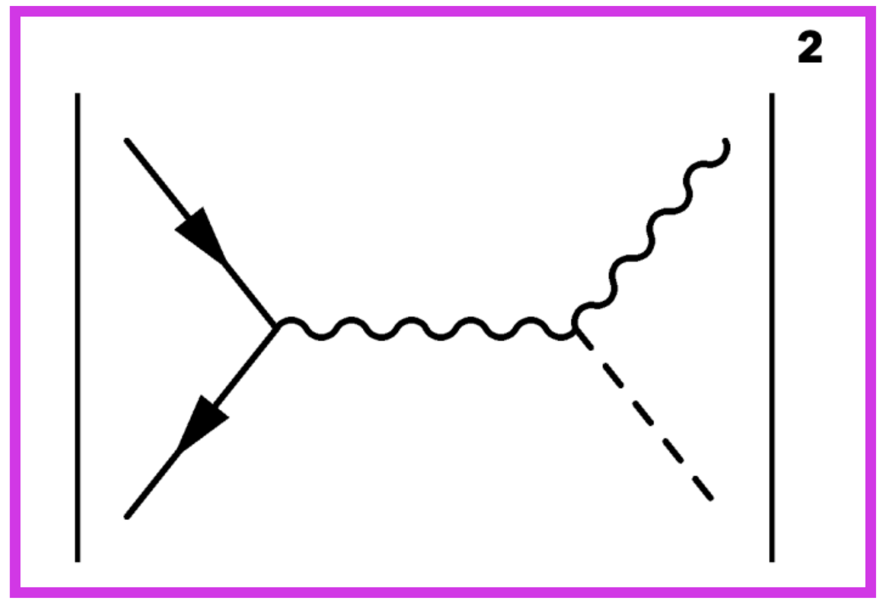
For this talk, the observable $|\cos(\theta_V)|$ is presented. This is the angle that the Z boson makes with the beam direction in the WZ rest frame

Seeing SMEFT effects in cross-sections

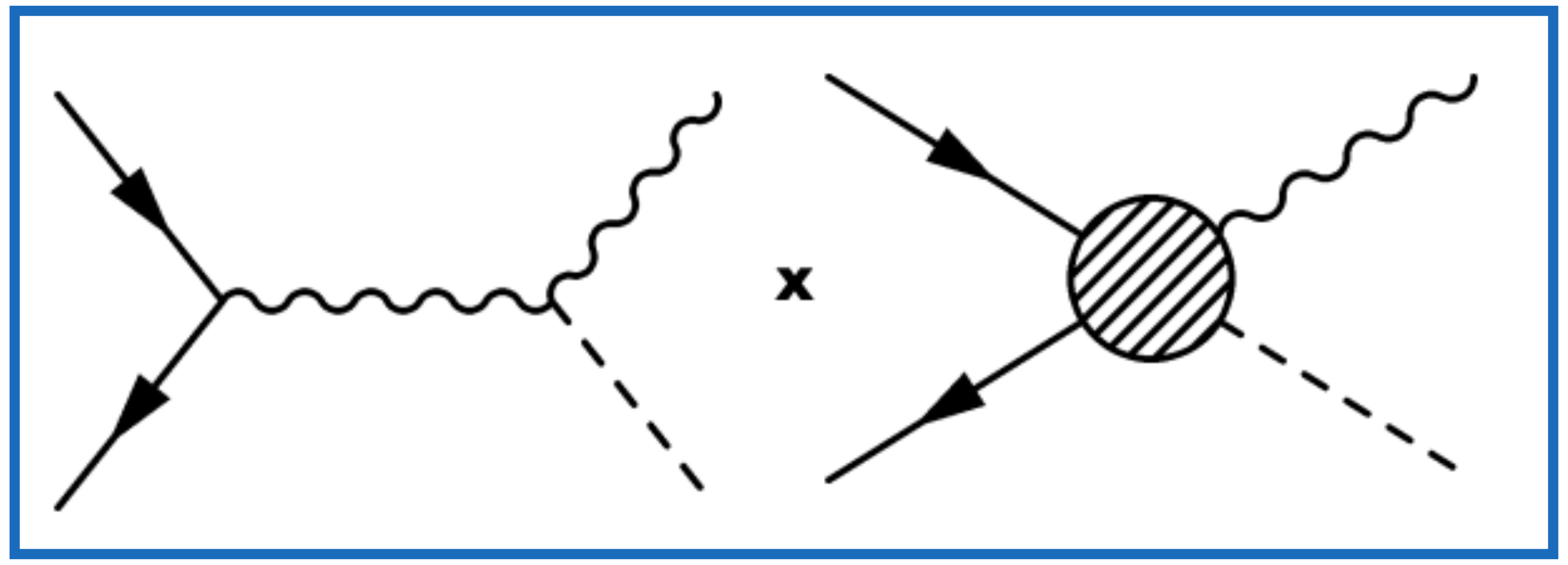
- Instead of only examining total cross-sections, we analyze how SMEFT causes event distributions to change across different bins → differential distributions.

- The dependence of SMEFT in the cross-section is parameterized as polynomials in Wilson coefficients:

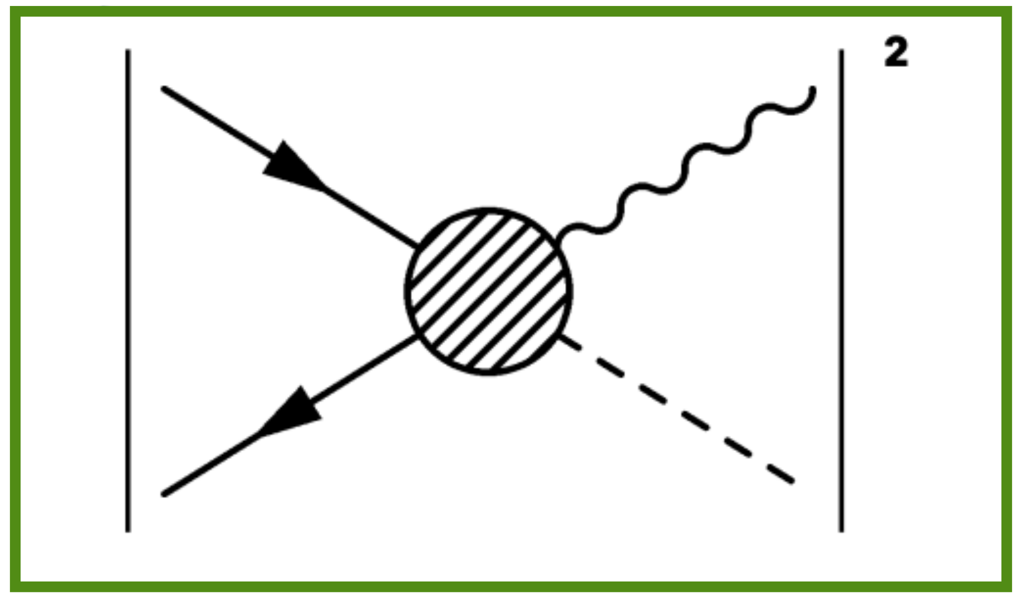
$$\sigma \propto |M_{\text{SMEFT}}|^2$$
$$= \boxed{|M_{\text{SM}}|^2} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\text{Re}\left(M_i^{(6)} M_{\text{SM}}^*\right)} + \boxed{\sum_i \frac{(c_i^{(6)})^2}{\Lambda^4} |M_i^{(6)}|^2} + \boxed{\sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(M_i^{(6)} M_j^{(6)*}\right)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



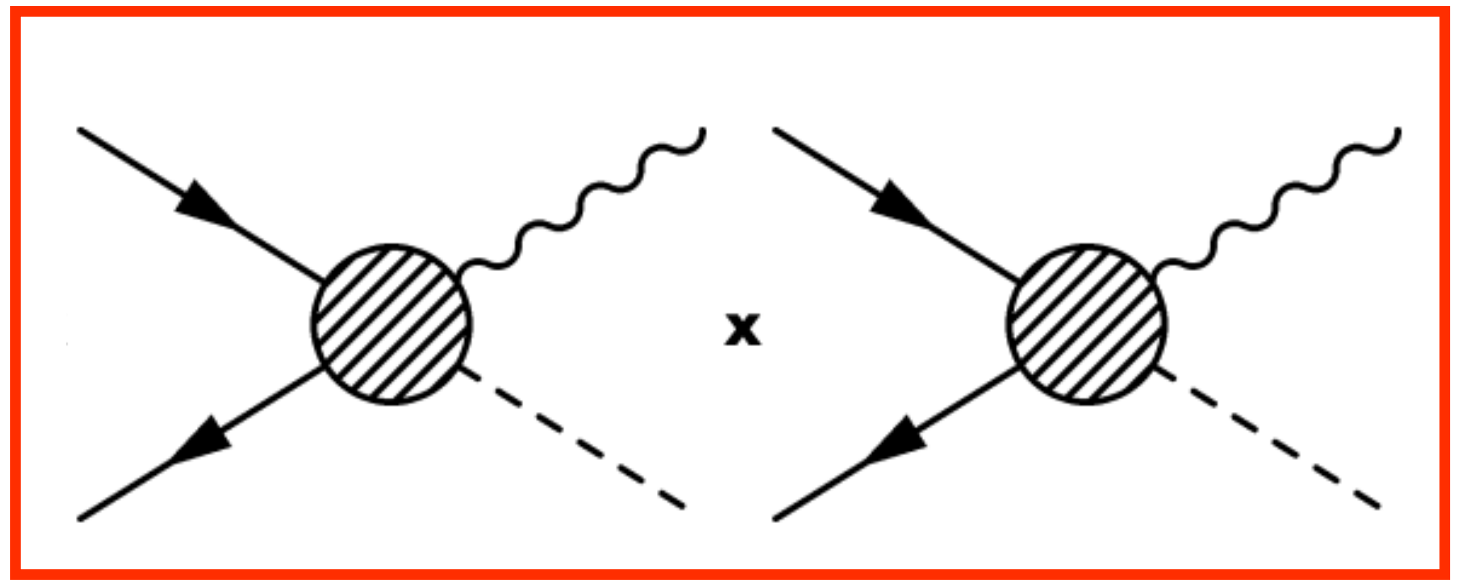
SM term



interference of dim 6 operators with SM: **Linear term**



dim 6 operators squared: **Quadratic term**

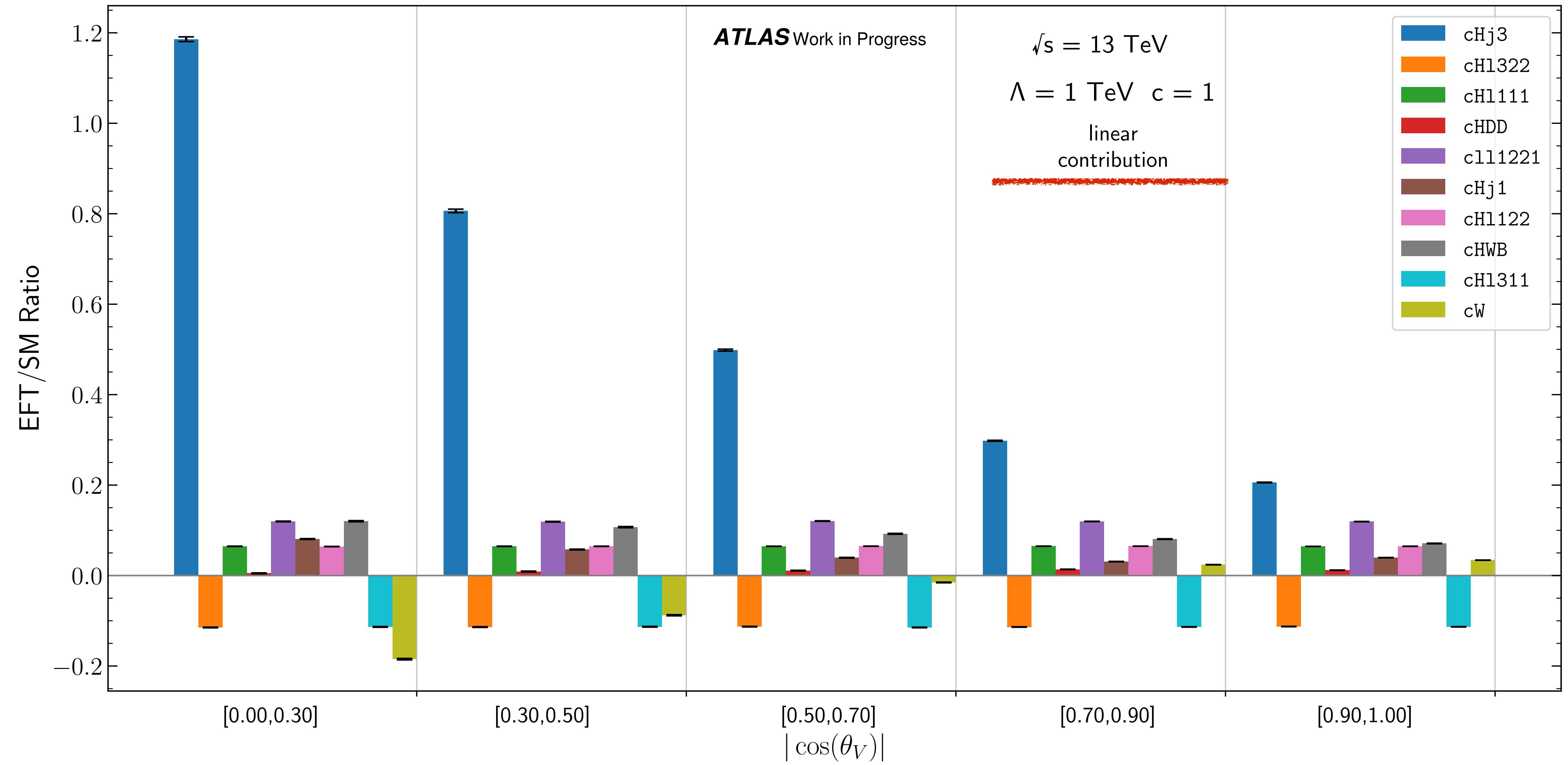


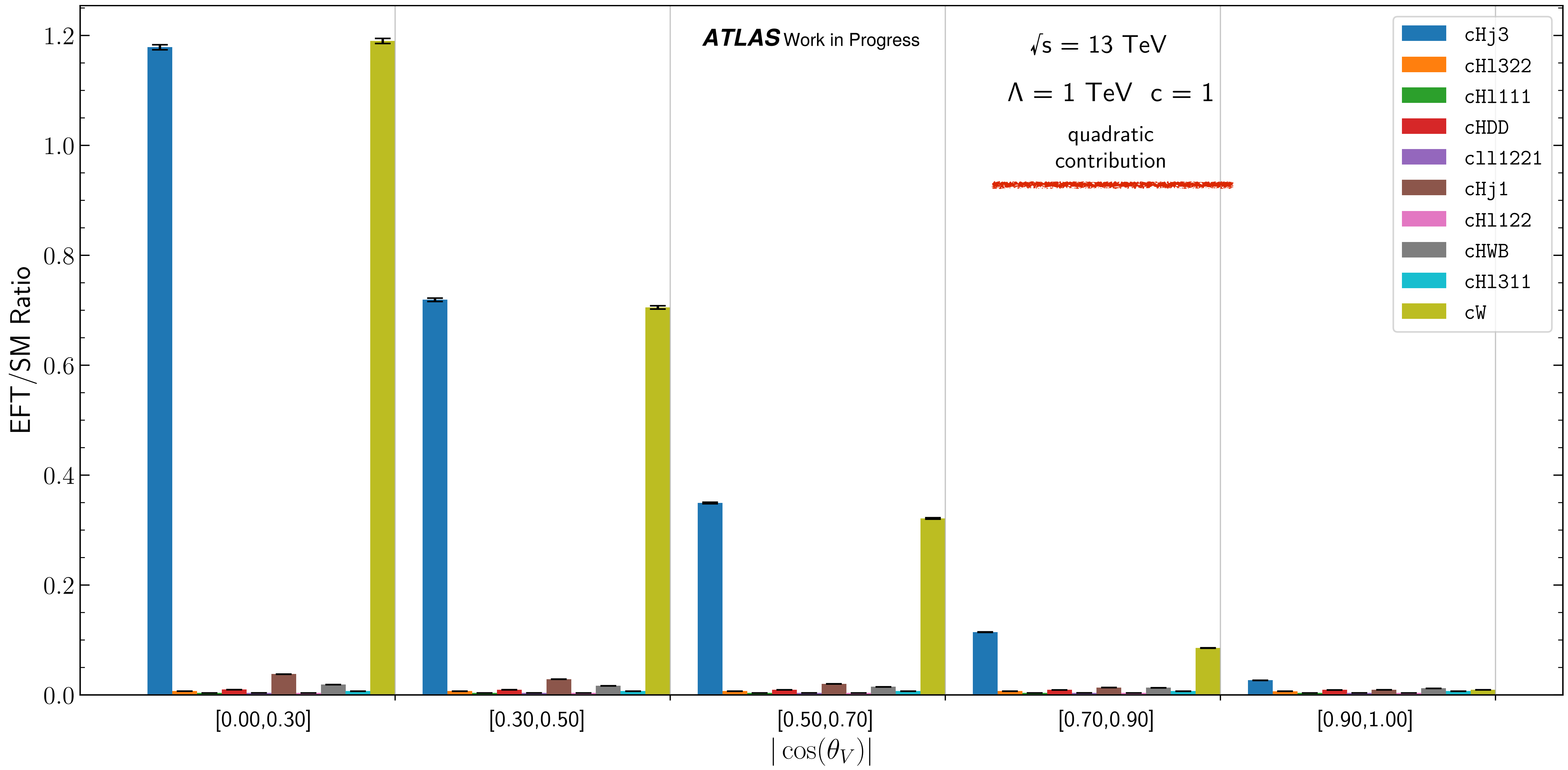
interference of two different dim 6 operators: **Cross term**

- SMEFT effects can be decomposed to a **linear**, a **quadratic** and uniquely in this analysis, a **cross-term** component.

Sensitivity to Wilson Coefficients

- Sensitivity studies help us narrow down which Wilson coefficients impact the $WZ \to ll\nu l$ channel the most.
- Monte Carlo generators such as MadGraph pipelined with SMEFT models (e.g SMEFTsim) can predict EFT effects at LO.

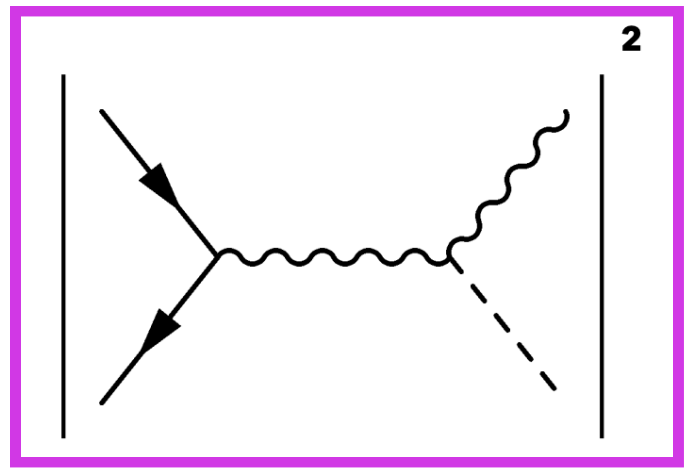




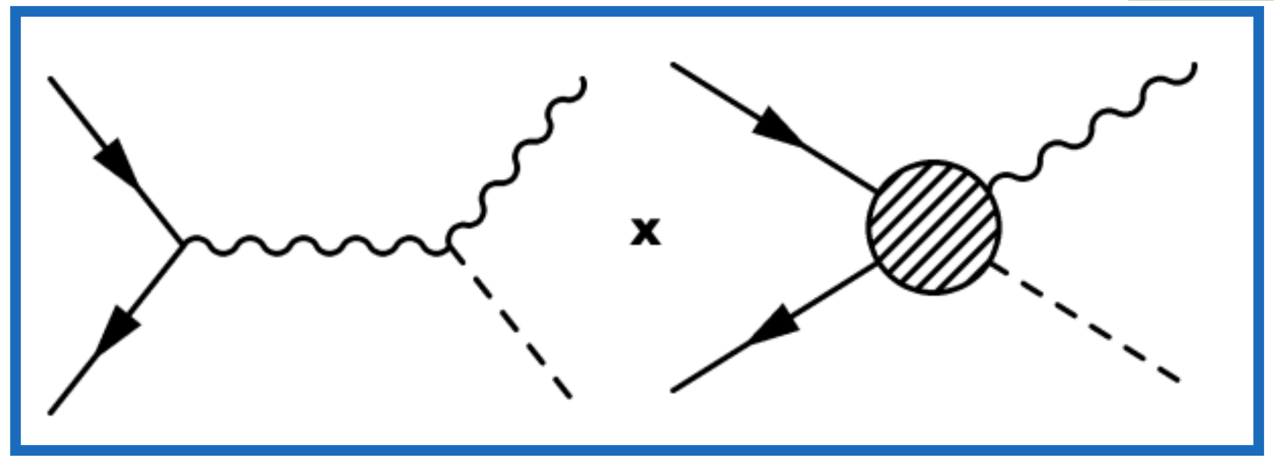
- Shown above are the 10 most sensitive operators out of the dim6 list.
  Sensitivity studied in all observables (only $|\cos(\theta_V)|$ shown). cW, cHj3 most impactful ops.

A case for cross-terms

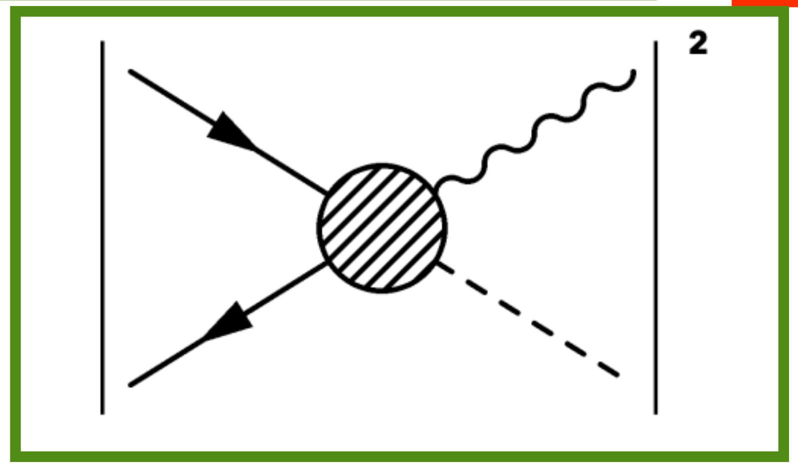
$$\sigma \propto |M_{\text{SMEFT}}|^2$$
$$= \boxed{|M_{\text{SM}}|^2} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\text{Re}\left(M_i^{(6)} M_{\text{SM}}^*\right)} + \boxed{\sum_i \frac{(c_i^{(6)})^2}{\Lambda^4} |M_i^{(6)}|^2} + \boxed{\sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(M_i^{(6)} M_j^{(6)*}\right)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



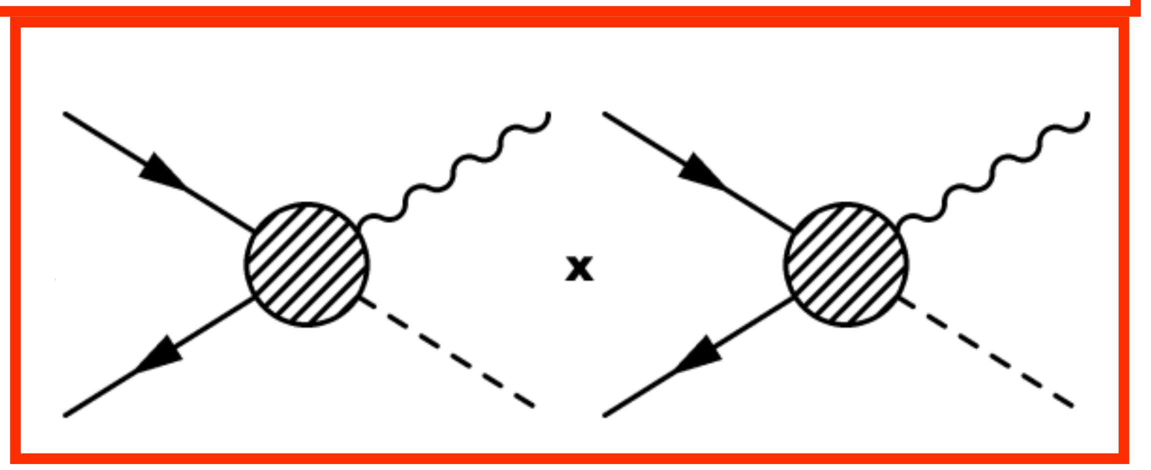
SM term



Linear term



Quadratic term



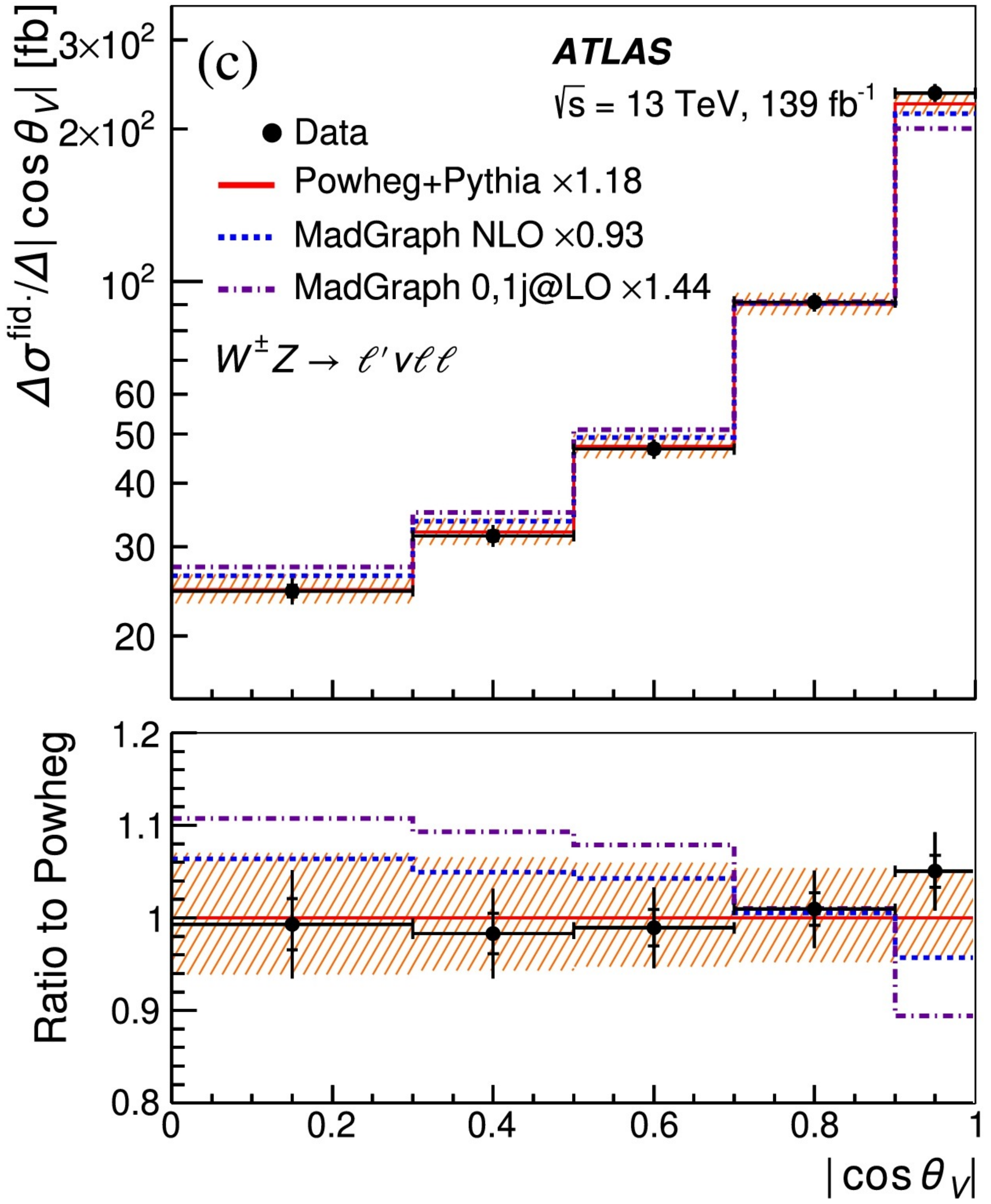
interference of two different dim 6 operators: **Cross term**

- Traditionally, most EFT analyses focus on lin+quad term, neglecting the effect of the smaller cross-term.
- **Problem**: Limits are usually placed on one Wilson coefficient at a time. Inherently assuming the other dim6 operators to be 0. Which is not the case in reality.

IDEA: **We can use the cross-term to constrain 2 Wilson coefficients simultaneously, offering more insight to how dim6 operators interact with each other**

- Given the data collected from ATLAS (unfolded to the particle level) and the MC simulations of particular dim6 operators.
- We construct a likelihood function that quantifies how well different parameter values in the model explain the observed data. By maximizing this likelihood, we determine the best-fit values.

Collected ATLAS Run-2 Data



10.1016/Phys. Lett. B 843 (2023) 137895 ATLAS

$$L(x\,|\,c,\theta) = \frac{1}{\sqrt{(2\pi)^{n_{\mathrm{bins}}}\det(C)}}\exp\left(-\frac{1}{2}\Delta x^{\mathsf{T}}(c,\theta)\, C^{-1}\,\Delta x(c,\theta)\right)\prod_{i=1}^{n_{\mathrm{syst}}} f_i(\theta_i)$$

$$\Delta x(c,\theta) = x^{\mathbf{meas}} - x^{\mathbf{pred}}(c,\theta)$$

C = unfolded measurement covariance matrix (stat, experimental systematics uncertainties)

$$x^{\mathbf{pred}}(c,\theta) = (x_{SM} + c x_{lin} + c^2 x_{quad} + c_1 c_2 x_{cross})$$

f_i = Gaussian constraints on Nuisance parameters θ (eg model systematics)

- A profile likelihood test statistic is defined using ln(L), confidence intervals are obtained from this

Expected Results - 2D limits

- Pending an Internal ATLAS review, the analysis has not yet been unblinded. Expected results however can still be obtained using Asimov (SM) data.

- Several interesting shapes observed, showing the effect of correlations and interferences between different dimension-6 operators.

- For the most sensitive Wilson coefficients, cW and cHj3, stringent limits are expected.

Conclusions

- Despite LHC's maturity, no new discoveries have been made in a while —BSM particles may lie beyond current kinematic reach.

- SMEFT provides a model-independent way to constrain new physics at the current energy scale
- The $WZ \to ll\nu l$ channel at the ATLAS experiment is a clean probe of electroweak boson interactions (to themselves or to fermions)

- Kinematic and angular observables offer unique sensitivity to dim-6 operators.
- One of the first analysis leveraging cross-terms to constrain two Wilson coefficients simultaneously (effort led by Canadian institutes).

- Expected 1D and 2D limits obtained. (1D limits in backup slides). Unblinding forecasted soon.
- **The Big Picture**: These limits feed into a global combination machinery, where other physics channels are probed, allowing for even better constraints on New Physics parameters.

Thank you!

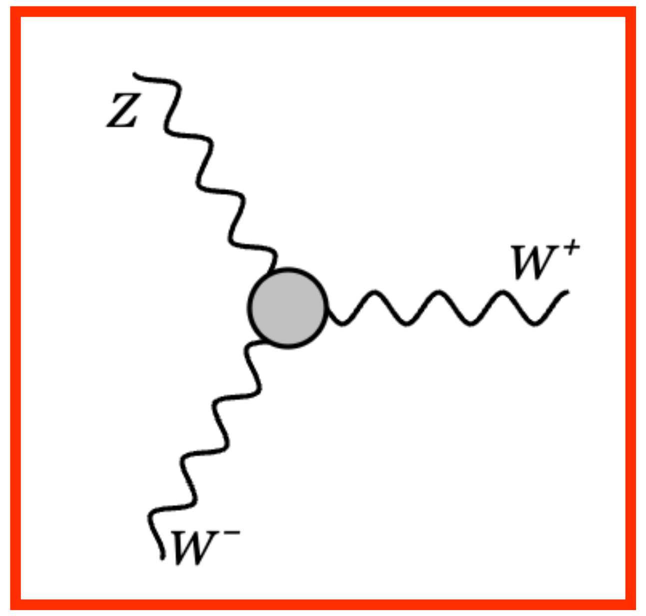

THANK YOU!
YOUR QUESTIONS AND COMMENTS
ARE MOST APPRECIATED

BACKUP SLIDE: Dimensional 6 operators in SMEFT

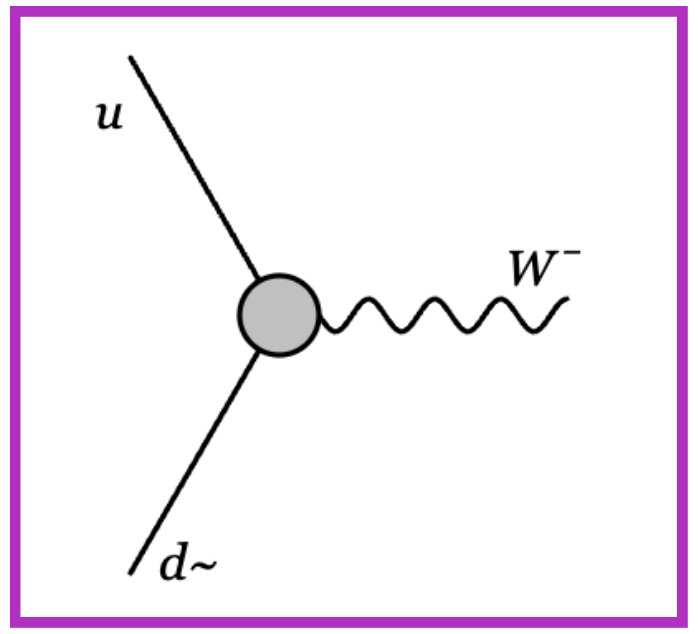
- SMEFT can be complex with 2499 operators in dim. 6!
- The Warsaw basis reduces these to 59 independent dimension-six operators (not including flavour indices) by having requirements to avoid redundant terms and to respect known symmetries
- Dim 6 operators are especially dominant in anomalous Triple Gauge Couplings (aTGCs) as well as couplings of EWK bosons to fermions.

$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i H W_{\mu\nu}^i$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^a u_r)\widetilde{H}\,G_{\mu\nu}^a$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^i\widetilde{H}\,W_{\mu\nu}^i$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^a d_r)H\,G_{\mu\nu}^a$	$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4D^2$		Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\sigma^i H\,W_{\mu\nu}^i$	$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^a u_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\,B_{\mu\nu}$		
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$				
$\mathcal{L}_6^{(4)} - X^2H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\,G_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\,W_{\mu\nu}^i W^{I\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{u}_s\gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger\sigma^i H\,W_{\mu\nu}^i B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\,\widetilde{W}_{\mu\nu}^i B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
		$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

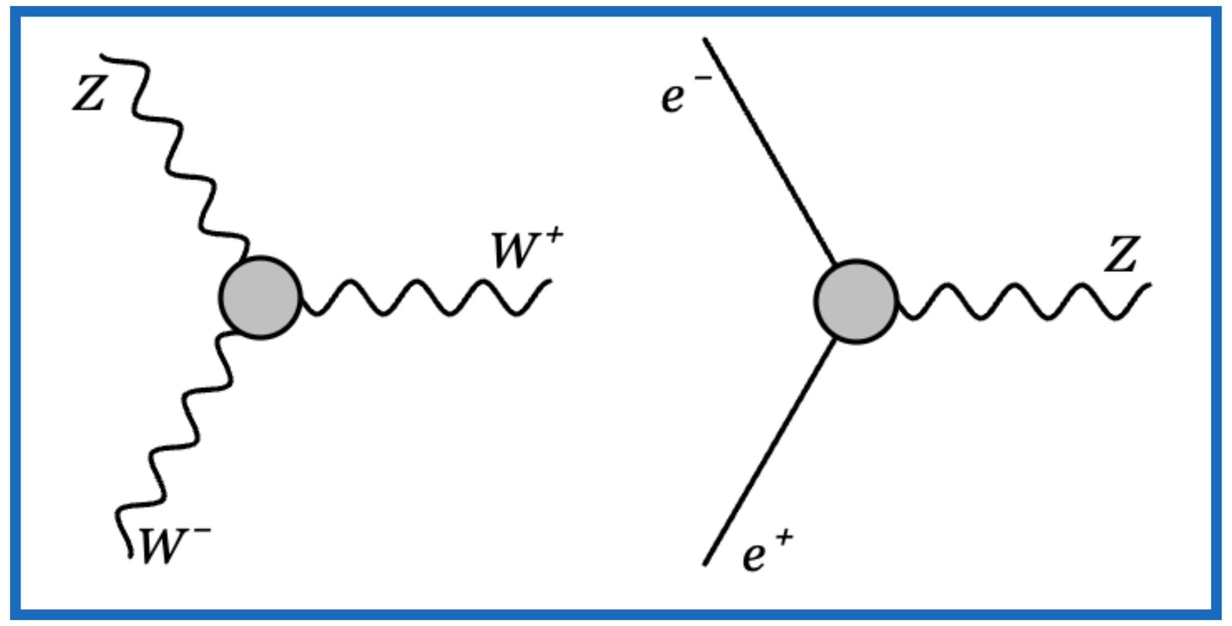
10.1007/JHEP 04 (2021) 073 Brivio



Q_W (Boson self-coupling operators)



$Q_{Hq}^{(3)}$ (Higgs-Fermion operators)

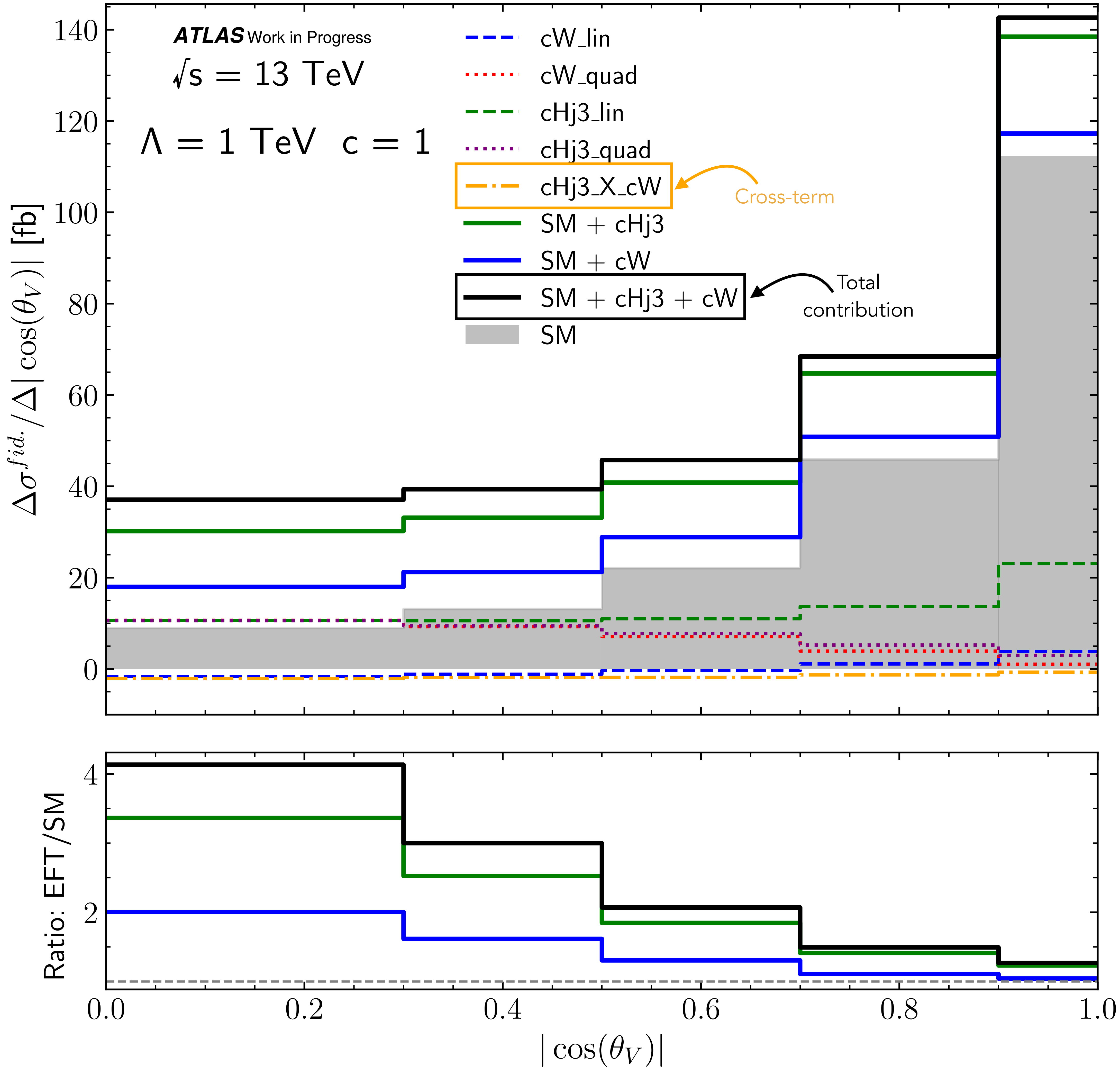


Q_{HWB} (Higgs gauge operators)

BACKUP SLIDE: A case-ier case for cross-terms

- Traditionally, most EFT analyses focus on lin+quad term, neglecting the effect of the smaller cross-term.

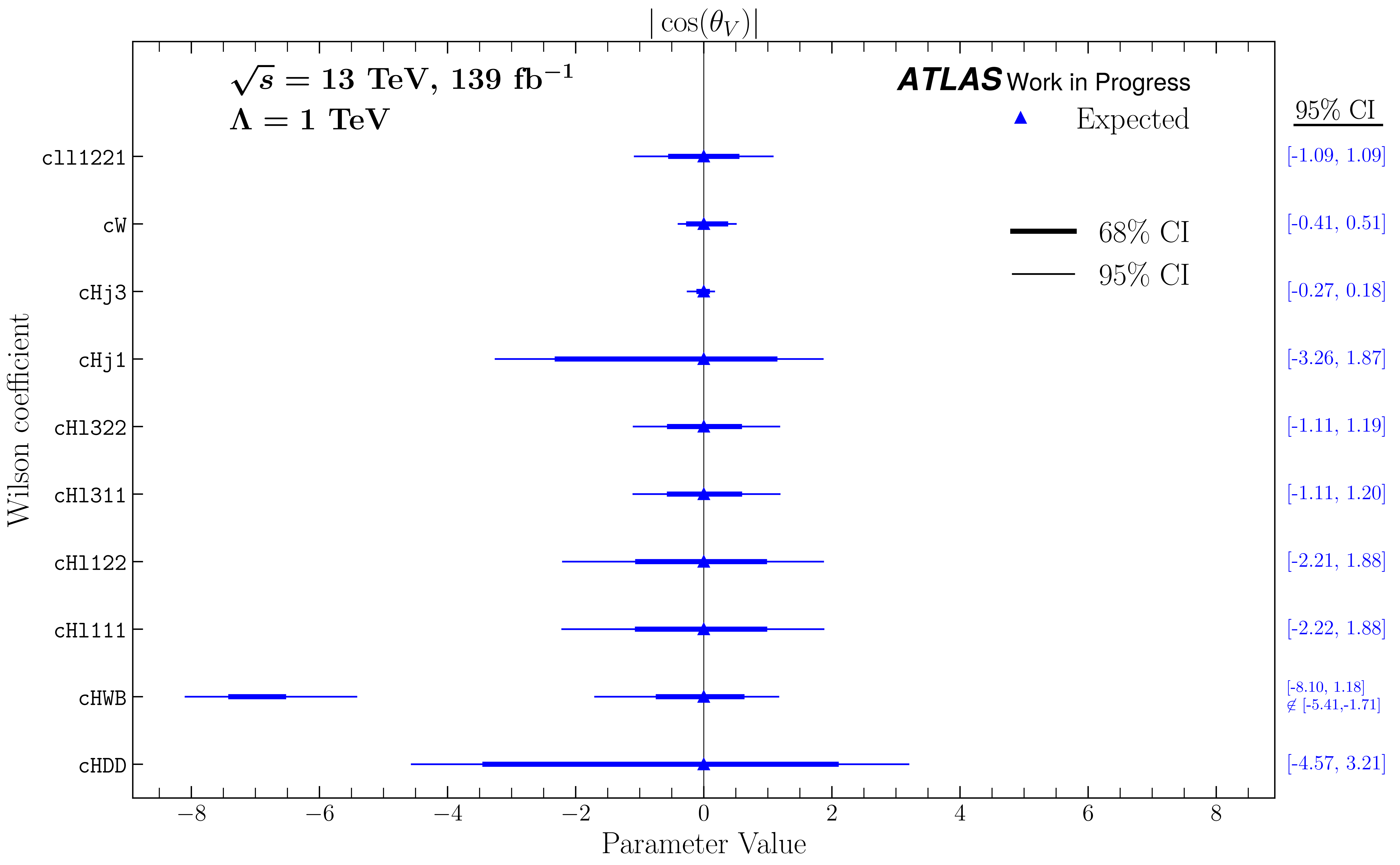
- Additionally, by including the cross-term (orange dashed line), the linear and quadratic terms for two operators add, improving sensitivity.



IDEA: **One can use the cross-term to constrain 2 Wilson coefficients simultaneously, offering more insight to how dim6 operators interact with each other**

BACKUP SLIDE: Expected Results - 1D limits

- Pending an Internal ATLAS review, the analysis has not yet been unblinded. Expected results however can still be obtained using Asimov (SM) data.



- For the most sensitive Wilson coefficients, cW and cHj3, stringent limits are expected, competitive with other analyses
- Having more angular and kinematic observables offers the opportunity to constraint certain coefficients better.