Validity of SMEFT studies of VH and VV Production at NLO

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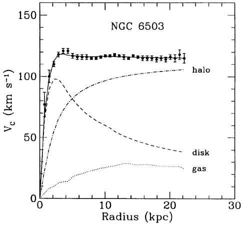
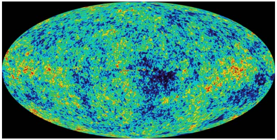
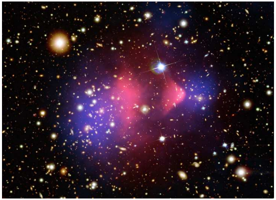
Open Questions in Particle Physics/Standard Model

- What is Dark Matter?
- What causes the Matter Antimatter Assymmetry?
- Why is there a mass hierarchy in the SM?
- ...

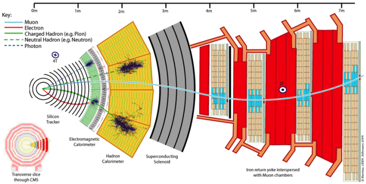






Beyond Standard Model (BSM)

- BSM physics can answer questions or solve problems with SM
- Everyone has their favorite BSM Model
- Lots of direct searches across many experiments.
- So far everything turns up Standard Model



EFT Basics

- There is a limit to the energy scales we can probe in every experiment.
- What to do if the new physics is not in this limit.
- Take some UV theory with particle χ corresponding to some scale Λ.
- Can approximate Lagrangian and action by integrating out χ

$$\mathcal{L}_{UV}[\chi] \approx \mathcal{L}_{IR} + \sum_{i,n>4} \frac{C_{i,n}}{\Lambda^{(n-4)}} O_{i,n}$$

Warsaw Basis (arXiv: 1008.4884v3)

- Includes all relevant Dimension-6 Operators involving SM fields

$$\mathcal{L}_{UV}[\chi] \approx \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)}$$

- Total of 59 Operators after using EOM (assuming Baryon Number Conservation)
- If only considering certain processes only certain operators contribute
- 10 operators relevant for our study of VH and VV production

$$O_{H\Box} = \varphi^\dagger \varphi \Box \varphi^\dagger \varphi \qquad O_{HD} = \varphi^\dagger D_\mu \varphi \varphi^\dagger D^\mu \varphi$$

$$O_W = \epsilon_{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu} \qquad O_{HWB} = \varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$$

$$O_{HW} = \varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu} \qquad O_{HB} = \varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$$

$$O_{Hu} = \varphi^\dagger \varphi \bar{q}_L u \tilde{\varphi} \qquad O_{Hd} = \varphi^\dagger \varphi \bar{q}_L d \varphi$$

$$O_{Hq}^{(1)} = \varphi^\dagger i \overleftrightarrow{D}_\mu \varphi \, \bar{q}_L \gamma^\mu q_L \qquad O_{Hq}^{(3)} = \varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi \, \bar{q}_L \tau^I \gamma^\mu q_L$$

Doing Calculations and Weak Couplings

- Amplitudes/Cross sections calculated by including new operators

$$A = A_{SM} + \Sigma_i \frac{C_i}{\Lambda^2} A_i^6 + \Sigma_{ij} \frac{C_i C_j}{\Lambda^4} A_{ij}^6$$

$$\sigma = \sigma_{\rm SM} + \Delta\sigma_{\Lambda^2} + \Delta\sigma_{\Lambda^4}$$

- The SMEFT couplings generically scale as

$$\alpha_{\rm EFT} \sim \frac{g_{\rm EFT}^2 v^2}{\Lambda^2} \text{ or } \frac{g_{\rm EFT}^2 \text{Energy}^2}{\Lambda^2}$$

$$\Delta\sigma_{\Lambda^2} \sim \alpha_{\rm EFT} \qquad \Delta\sigma_{\Lambda^4} \sim \alpha_{\rm EFT}^2$$

- For a weakly coupled theory

$$\alpha_{\rm EFT} < 1 \; (4\pi) \implies \Delta\sigma_{\Lambda^4} < (4\pi)\Delta\sigma_{\Lambda^2}$$

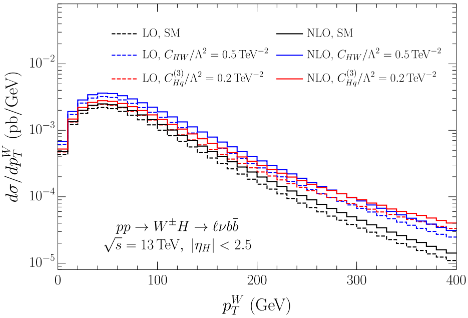
- This condition is more or less equivalent to cross section converging quickly.

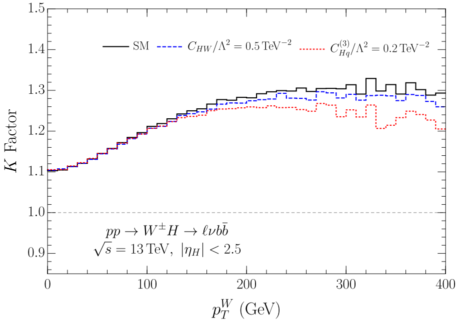
Data Simulation

- For each process ($W^+W^-, W^{\pm}Z, W^{\pm}H$, and ZH), we introduce anomalous couplings in the Warsaw basis and utilize existing implementations in the `POWHEG-BOX` framework[1]
- We make use of the `WWanomal`, `WZanomal`, `HW_smeft` and `HZ_smeft` user processes introduced in previous works.
- We do calculations so at LO and NLO QCD in the SMEFT.
- We can extract distributions at order $\mathcal{O}(1/\Lambda^2)$ or $\mathcal{O}(1/\Lambda^4)$
- We ignore dimension-8 operators. They could contribute to $\mathcal{O}(1/\Lambda^4)$
- We use a factorization and renormalization scale of $M_Z/2$

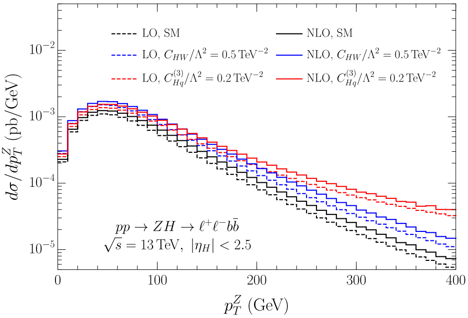
[1]This public tool can be found at http://powhegbox.mib.infn.it

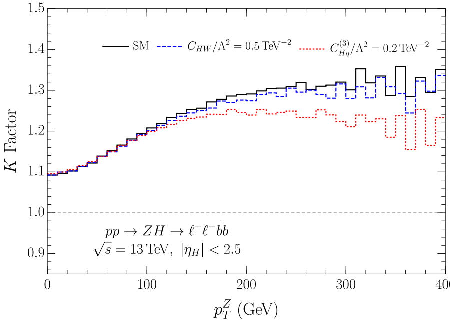
WH: p_t^W Distributions





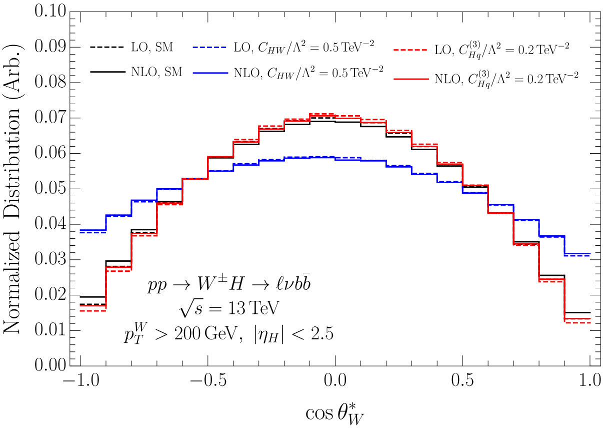
ZH: p_t^Z Distributions





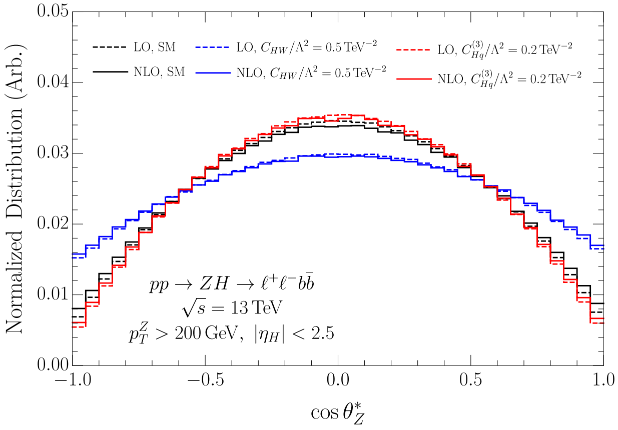
Angular Distributions

WH



Angular Distributions: Continued

ZH



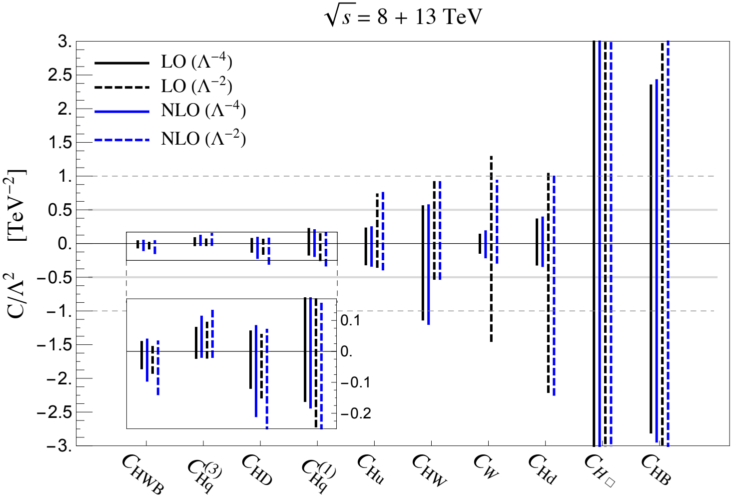
Fitting Procedure

We perform chi squared fits to the experimental data

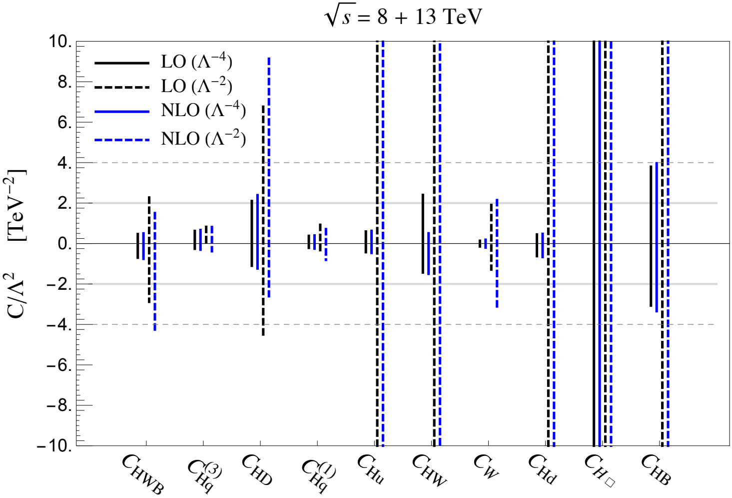
$$\chi^2(\vec{C}) = \sum_{\substack{WH,\, ZH \\ WW,\, WZ}}^{\text{processes}} \sum_{\alpha}^{\text{datasets}} \sum_{i}^{\text{bins}} \frac{(\epsilon_{i\alpha} \hat{O}(\vec{C})^{\text{theory}}_{i\alpha} - \hat{O}^{\text{exp}}_{i\alpha})^2}{(v^{\text{exp}}_{i\alpha})^2},$$

- $\hat{O}(\vec{C})^{\text{theory}}_{i\alpha}$ is the theoretical expected value
- $\hat{O}^{\text{exp}}_{i\alpha}$ is the experimental observation
- $v^{\text{exp}}_{i\alpha}$ is the estimated uncertainty
- $\epsilon_{i\alpha}$ is an efficiency factor between simulation and experiment

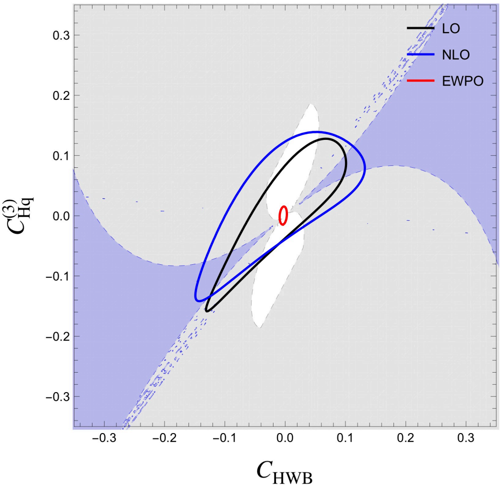
1D Fits Projected



1D Fits Profiled



2D Fits and Validity Regions



$$\sigma = \sigma_{\mathrm{SM}} + \Delta\sigma_{\Lambda^2} + \Delta\sigma_{\Lambda^4}$$

White $\implies \Delta\sigma_{\Lambda^4} < \Delta\sigma_{\Lambda^2}$

Grey $\implies \Delta\sigma_{\Lambda^4} > \Delta\sigma_{\Lambda^2}$

Blue $\implies \Delta\sigma_{\Lambda^4} < 4\pi\Delta\sigma_{\Lambda^2}$

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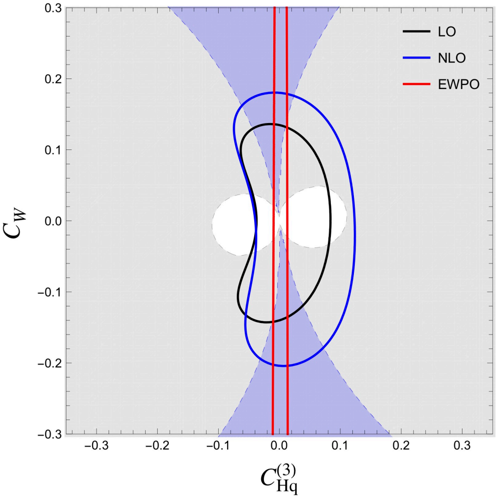

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Conclusion

- Including NLO QCD can have a significant effect on distributions
- This leads to order 20-30 % effects in the fits
- $\mathcal{O}(1/\Lambda^4)$ can significantly improve fits
- A lot of the 95 % confidence regions would not be explained by weakly coupled theories

Questions?