Experimental approaches to SMEFT in $H \to 4l$ decays

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LHCEFTWG Meeting

Introduction

- Presenting studies shown in arxiv:2601.10822

Maximizing Returns: Optimizing Experimental Observables at the LHC

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(Dated: January 15, 2026)

To download the packages used in this talk: https://spin.pha.jhu.edu/

Download MiLoMerge Python code, MiLoMerge Documentation, License, Notice,

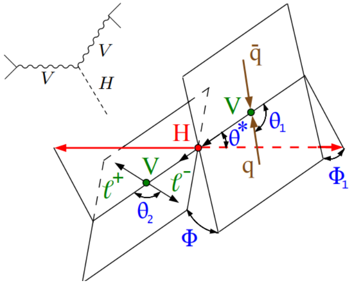
Note: Last version of the MiLoMerge package was released on January 15, 2026

Introduction

- Approaches in this paper are general to any EFT analysis

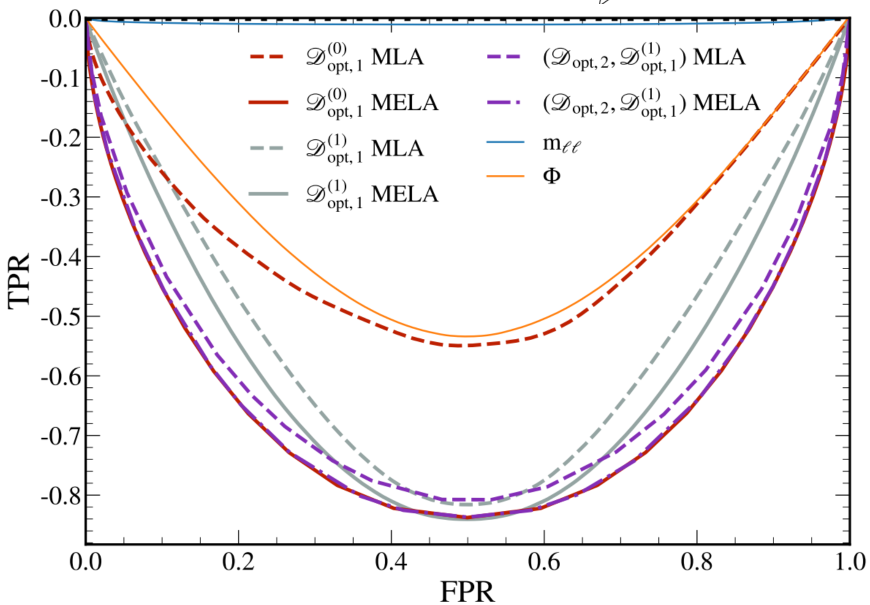
- We use matrix element based observables (MELA) in H→4l
- *Could just as well use Machine learning or analytical calculations*

- Example: Consider VH production: Target SM vs BSM

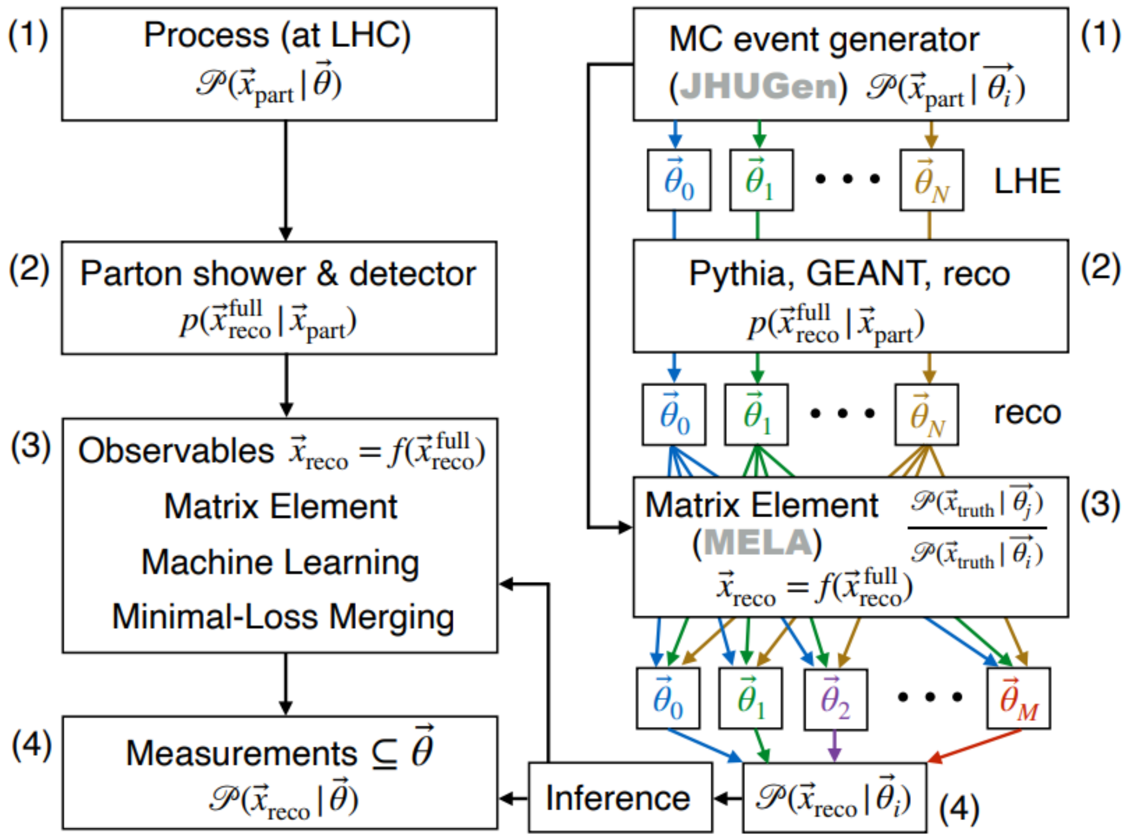


- ML (MLA) vs ME (MELA)
- *Construct Observables for:*
- SM vs Quadratic Dim-6 (Red)
- SM vs Linear Dim-6 (Grey)
- SM vs Linear + Quadratic (Purple)
- Kinematics (Blue/Orange)

- ML approximates the Analytic



SMEFT Analysis in H→4l decays



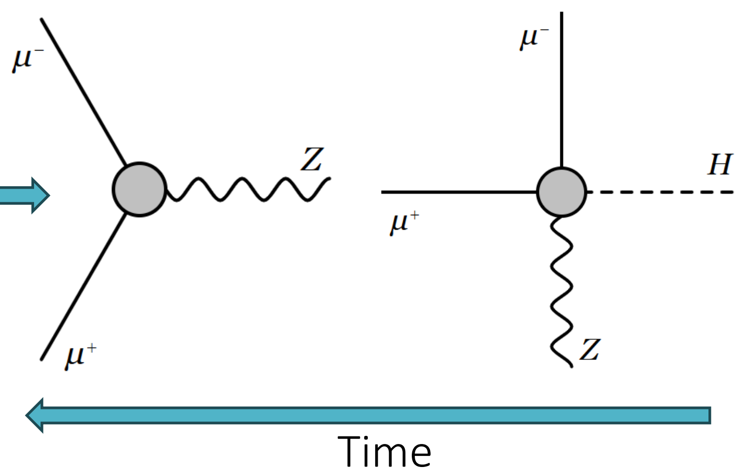
- In this presentation:
  - LHE level studies
  - Standard cuts for analysis-like selection
  - (Skip (2))

Operator Considerations

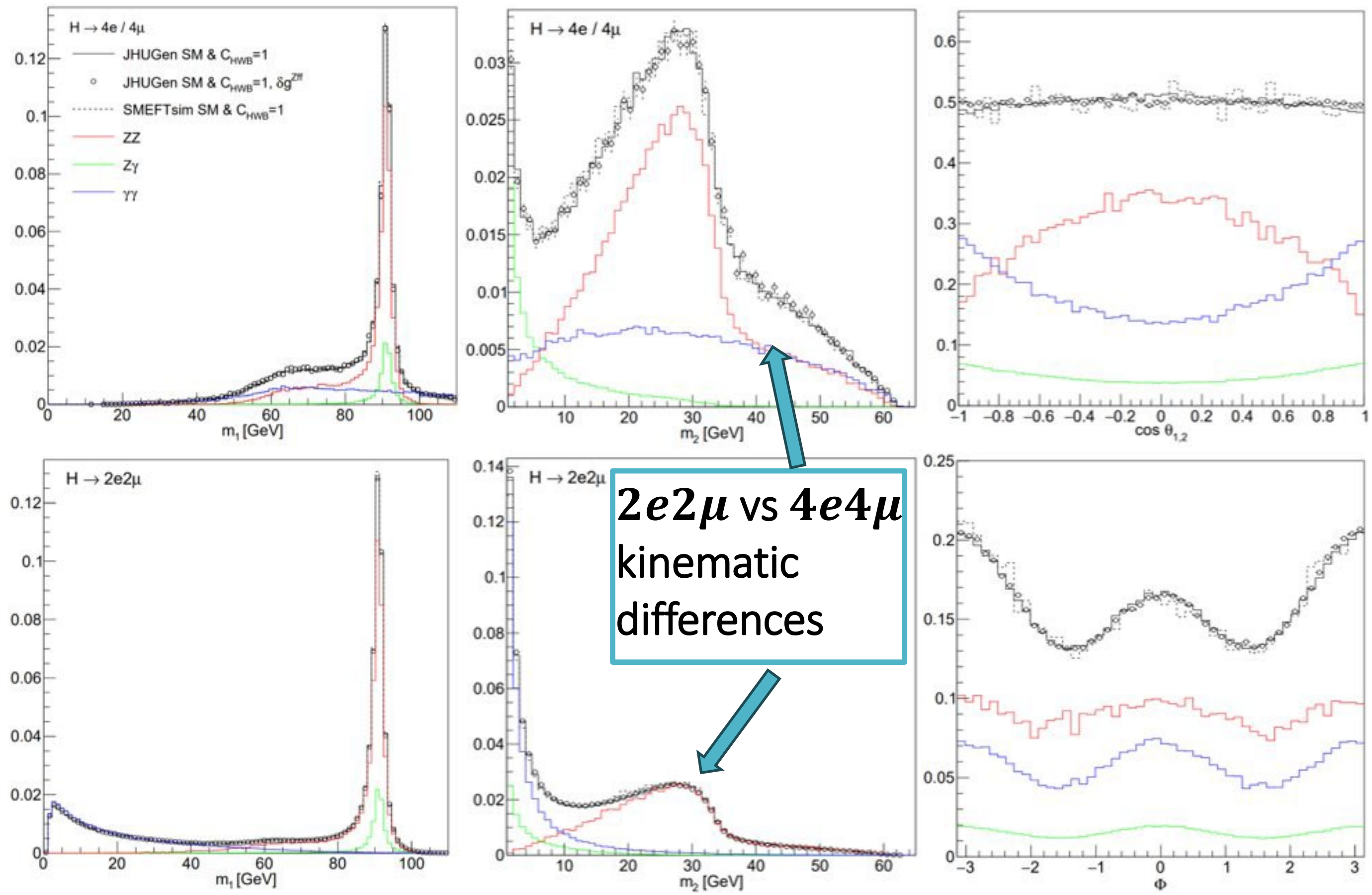
$$\mathcal{L} = -\frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D_\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{2}(\varphi^\dagger\varphi)^2$$
$$+C^{\varphi}(\varphi^\dagger\varphi)^3 + \boxed{C^{\varphi\Box}}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \boxed{C^{\varphi D}}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$$
$$+\boxed{C^{\varphi W}}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu} + \boxed{C^{\varphi B}}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu} + \boxed{C^{\varphi WB}}(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}$$
$$+\boxed{C^{\varphi\widetilde{W}}}(\varphi^\dagger\varphi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu} + \boxed{C^{\varphi\widetilde{B}}}(\varphi^\dagger\varphi)\widetilde{B}_{\mu\nu}B^{\mu\nu} + \boxed{C^{\varphi\widetilde{W}B}}(\varphi^\dagger\tau^I\varphi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$$
$$+\cdots$$

- Target the 8 Couplings that directly impact HVV vertex

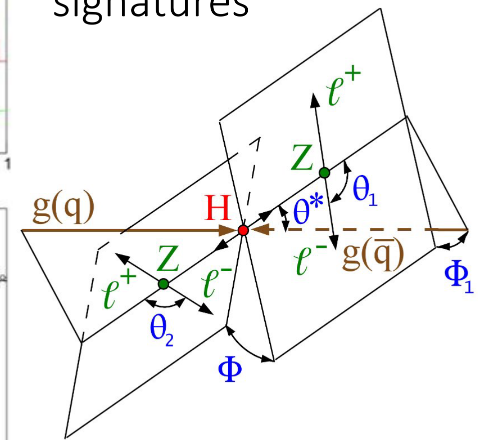
- Other Operators can generate 4l final state
- Ex: $C^{eW}_{f_1f_2}$, $C^{eB}_{f_1f_2}$ generates:
  - $H \rightarrow Z/\gamma^* l^+ l^-$
  - $Z/\gamma^* \rightarrow l^+ l^-$
- Better constrained in other processes



Operator Considerations



Mass eigenstates have more distinct experimental signatures



See:arxiv:2109.13363

- Consider kinematics of $C^{\phi WB}$ in $H \rightarrow 4\ell$
  - Anomalous HZZ, HZγ, Hγγ interactions
  - Also in $C^{\phi W}, C^{\phi B}$
- Rotate operators to align with mass-eigenstates: i.e single parameter for each interaction

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$$

Operator Considerations

- Each Lagrangian basis should be equivalent
- Single operator per interaction

$$
\begin{aligned}
\delta c_z &= \frac{v^2}{\Lambda^2}\left(C^{\varphi\Box} - \frac{1}{4}C^{\varphi D} - 3\delta_v\right) \\
c_{z\Box} &= \frac{v^2}{\Lambda^2}\left(\frac{s_w^2}{2e^2}C^{\varphi D} + \frac{2s_w^2}{e^2}\delta_v\right) \\
c_{zz} &= \frac{v^2}{\Lambda^2}\left(\frac{4c_w^4 s_w^2}{e^2}C^{\varphi W} + \frac{4c_w^3 s_w^3}{e^2}C^{\varphi WB} + \frac{4c_w^2 s_w^4}{e^2}C^{\varphi B}\right) \\
c_{z\gamma} &= \frac{v^2}{\Lambda^2}\left(\frac{4c_w^2 s_w^2}{e^2}C^{\varphi W} - \frac{2c_w s_w(c_w^2 - s_w^2)}{e^2}C^{\varphi WB} - \frac{4c_w^2 s_w^2}{e^2}C^{\varphi B}\right) \\
c_{\gamma\gamma} &= \frac{v^2}{\Lambda^2}\left(\frac{4s_w^2}{e^2}C^{\varphi W} - \frac{4c_w s_w}{e^2}C^{\varphi WB} + \frac{4c_w^2}{e^2}C^{\varphi B}\right) \\
\tilde{c}_{zz} &= \frac{v^2}{\Lambda^2}\left(\frac{4c_w^4 s_w^2}{e^2}C^{\varphi\widetilde{W}} + \frac{4c_w^3 s_w^3}{e^2}C^{\varphi\widetilde{W}B} + \frac{4c_w^2 s_w^4}{e^2}C^{\varphi\tilde{B}}\right) \\
\tilde{c}_{z\gamma} &= \frac{v^2}{\Lambda^2}\left(\frac{4c_w^2 s_w^2}{e^2}C^{\varphi\widetilde{W}} - \frac{2c_w s_w(c_w^2 - s_w^2)}{e^2}C^{\varphi\widetilde{W}B} - \frac{4c_w^2 s_w^2}{e^2}C^{\varphi\tilde{B}}\right) \\
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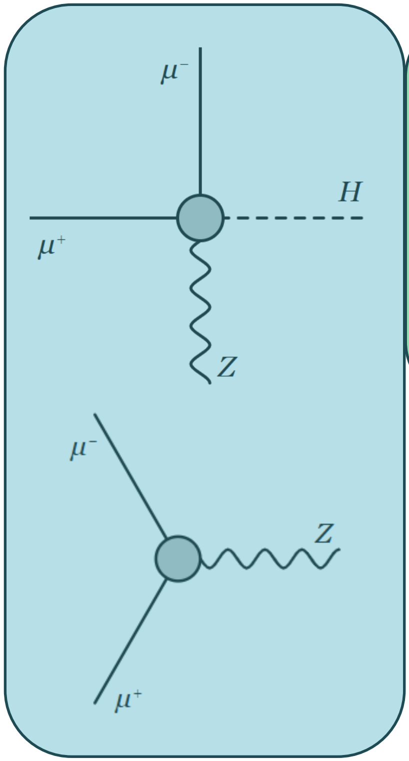
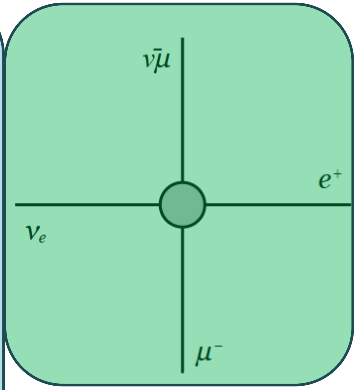
\delta c_w &= \frac{v^2}{\Lambda^2}\left(C^{\varphi\Box} + \frac{s_w c_w}{c_w^2 - s_w^2}C^{\varphi\widetilde{W}B} + \frac{s_w^2 - 2}{4(c_w^2 - s_w^2)}C^{\varphi D} - \frac{s_w^2}{c_w^2 - s_w^2}\delta_v\right)
\end{aligned}
$$

Other considerations:

$$\delta_v = \frac{1}{2}\left(C^{\phi l}_{11} + C^{\phi l}_{22}\right) - \frac{1}{4}C^{ll}_{1221}$$





Better constrained elsewhere

Analysis Strategy

- Tools allow for general anomalous couplings but we work in SMEFT
- General Analysis Strategy
  - $SU(2) \times U(1)$ (SMEFT)
  - 7 Independent AC, 1 Dependent

$$\mathcal{L}_{\mathrm{HVV}} = \frac{H}{v}\Big[m_Z^2(\delta c_z + 1) Z_\mu Z^\mu + \frac{m_Z^2}{v^2} c_{zz} Z_{\mu\nu}Z^{\mu\nu} + \frac{e^2}{s_w^2} c_{z\Box} Z_\mu \partial_\nu Z^{\mu\nu} + \frac{m_Z^2}{v^2}\tilde{c}_{zz} Z^{\mu\nu}\tilde{Z}_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A^{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A^{\mu\nu}\tilde{A}_{\mu\nu} + \frac{e^2}{2 s_w c_w} c_{z\gamma} Z_{\mu\nu}A^{\mu\nu} + \frac{e^2}{2 s_w c_w}\tilde{c}_{z\gamma} Z_{\mu\nu}\tilde{A}^{\mu\nu} + \frac{e^2}{s_w c_w} c_{\gamma\Box} Z_\mu \partial_\nu A^{\mu\nu} \Big],$$

Note: For this analysis we enforce the SMEFT relations at the template level!

Observable Classes

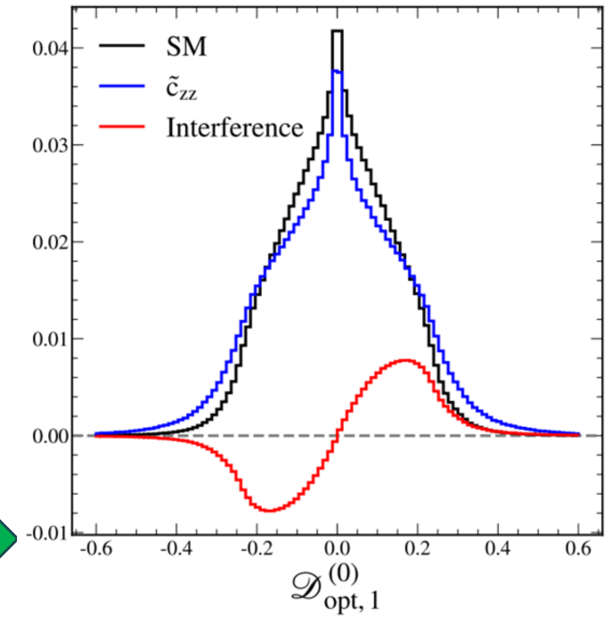
$$D_{bkg} = \frac{P_{sig}(\Omega)}{P_{sig}(\Omega) + P_{bkg}(\Omega)}$$

$$D_{int} = \frac{P_{int}(\Omega)}{P_{SM}(\Omega)}$$

In EFT limit this is the most optimal observable for any anomalous coupling

2 Matrix Element based observables
- D_{sig}: SM Signal vs Bkg
- D_{int}: Dim-6 x SM

D_{int} for $\widetilde{c_{ZZ}}$

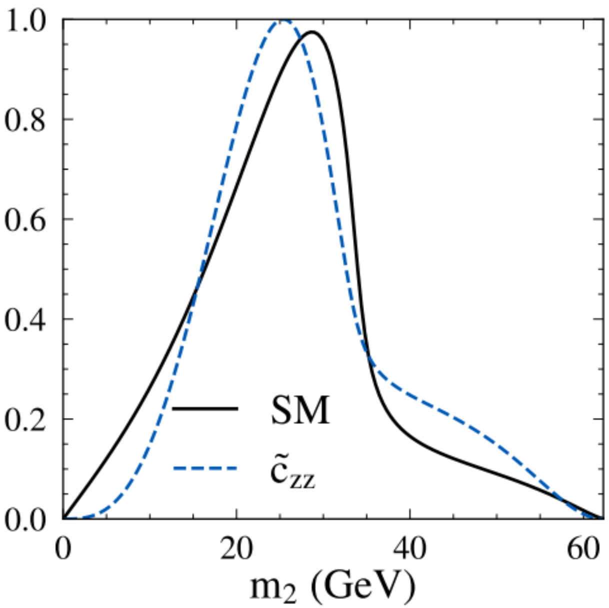


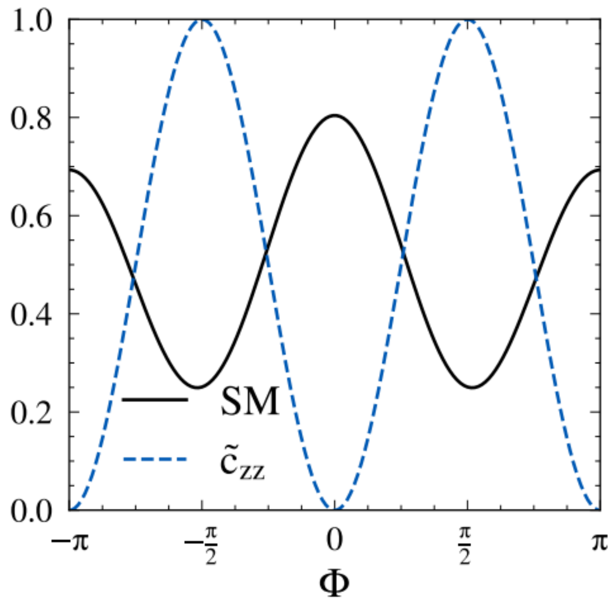
Experimental Considerations

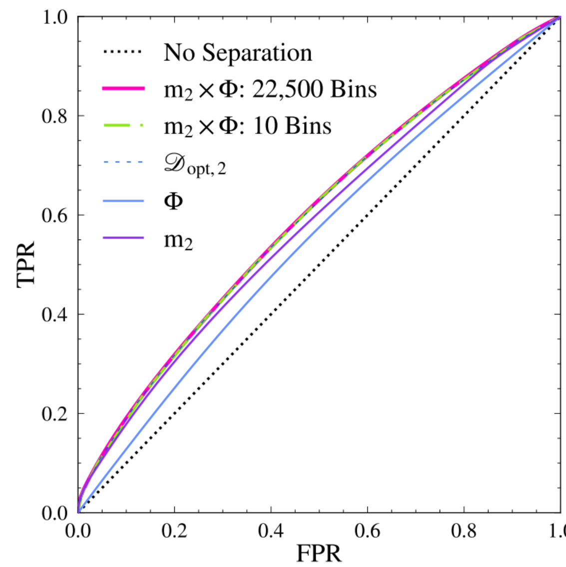
- Problem for EFT analysis! How to construct observables from 7 dimensional space?
- In EFT limit there are 7 optimal observables for interference
- Even with 4 bins in each observable → 16,384 bins!
- Must reduce the binning in order for analysis to be feasible
- Minimize information lost in going from O(10k) → O(100)

ROC curves

- ROC curve typically used to quantify performance of observables
- AUC measures separability of two hypothesis





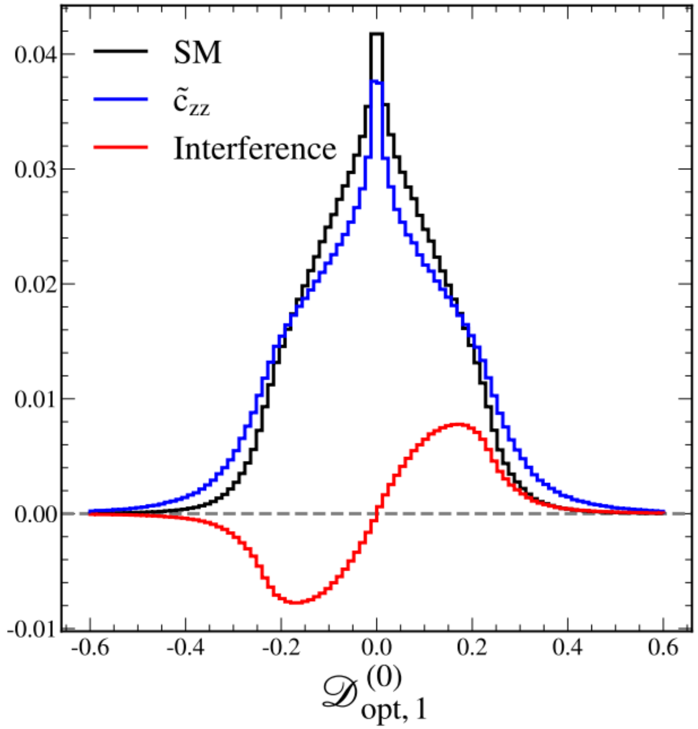


$$\mathrm{TPR}(t) = \frac{1}{|B|} \sum_{x \in B} \mathbb{I}[s(x) > t]$$

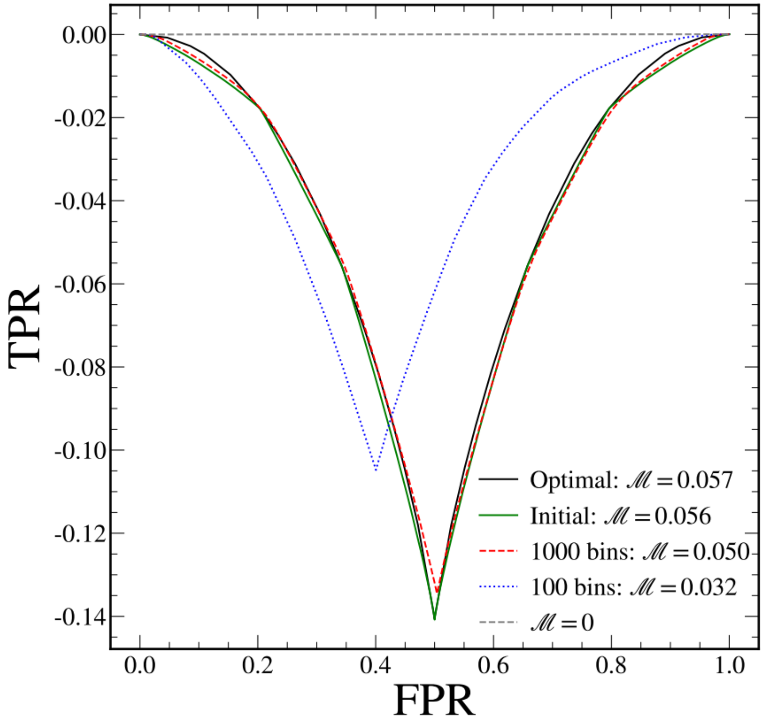
$$\mathrm{FPR}(t) = \frac{1}{|A|} \sum_{x \in A} \mathbb{I}[s(x) > t]$$

- What do we do in EFT limit where interference is the leading term?

New Metric for separability



Redefine: $$\text{TPR}_h(t) = \frac{1}{|A|} \sum_{x \in B_h} \mathbb{I}[s(x) > t]$$



With interference, AUC is no longer a good metric! For some interference AUC evaluates to 0!

$$\mathcal{M} = \text{LoC} - \text{LoC}_{\text{min}}$$

$$\text{LoC} = \sum_i \sqrt{\left(H_i^{(A)}\right)^2 + \left(H_i^{(B)}\right)^2}$$

Merging Procedure

- If I am limited experimentally by the number of bins, how can I ensure that I do not lose information when making my histograms?
- Take advantage of properties of the new LoC metric

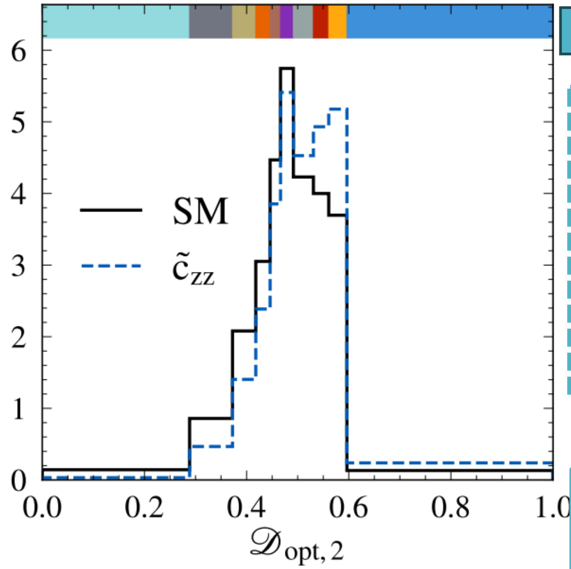
$$\text{LoC} = \sum_i \sqrt{\sum_h \left(H_i^{(h)}\right)^2}$$

- Invariant under exchange of label or bin!

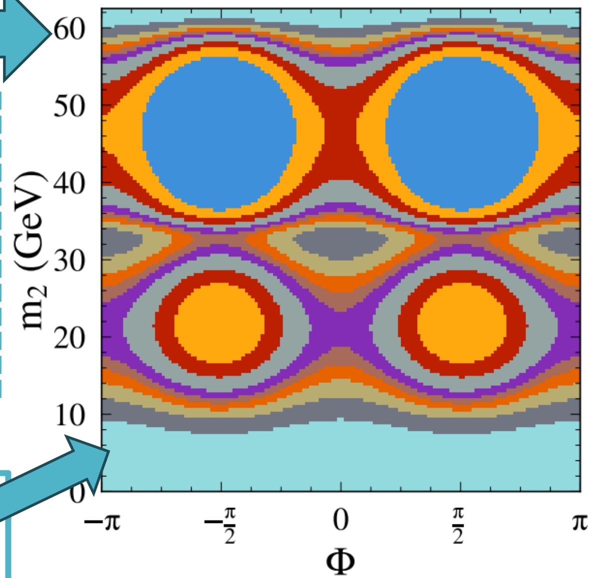
$$\mathbb{D}_{ij} = \sum_h \sum_{h'>h} w_{hh'} \left(H_i^{(h)} H_j^{(h')} - H_j^{(h)} H_i^{(h')}\right)^2$$

- Smallest score determines bin minimizes loss
  - *Minimal Loss Merging (MiLoMerge)*

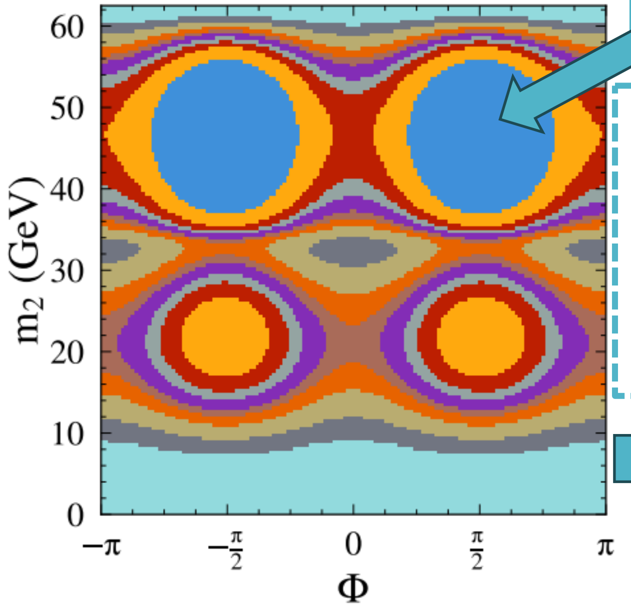
Generalized Example



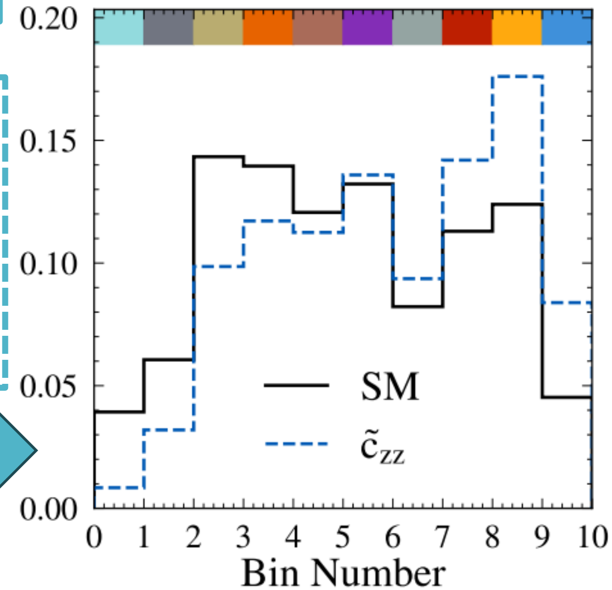
MAP Discriminant space to Observable space



Same information



MiLoMerge Observable space to discriminant space

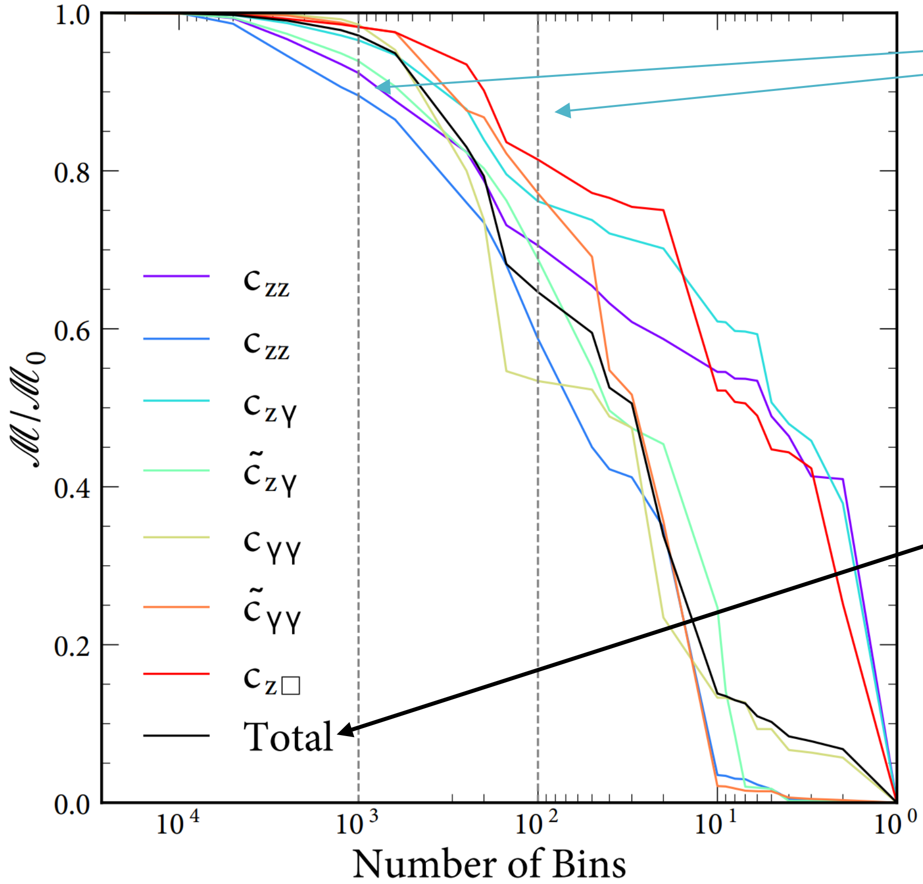


Procedure

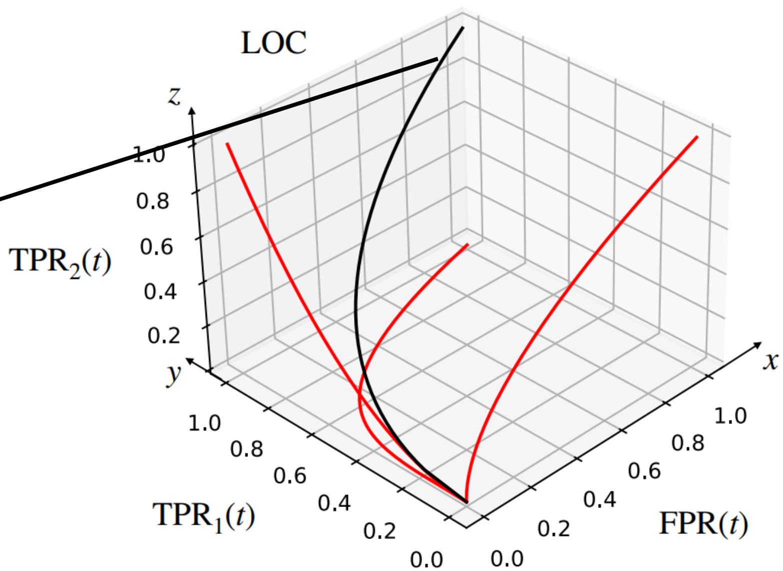
- Starting with LHE H → 4l events
- *Apply Analysis level cuts:*
- $p_T^l > 5GeV$
- $|\eta^l| < 2.5GeV$
- $12GeV < M_z < 120GeV$
- Determine optimal binning for 1D discriminant projections
- Construct 7D observable using optimal binning along each discriminant axis
- Merge bins to minimize information loss

- **Goal: Characterize the full H → 4l decay using only 100 bins!**

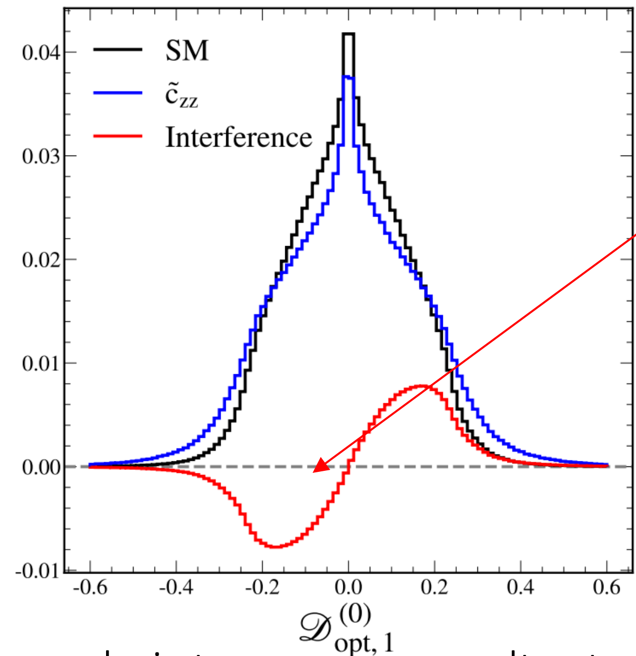
Merging multidimensional space



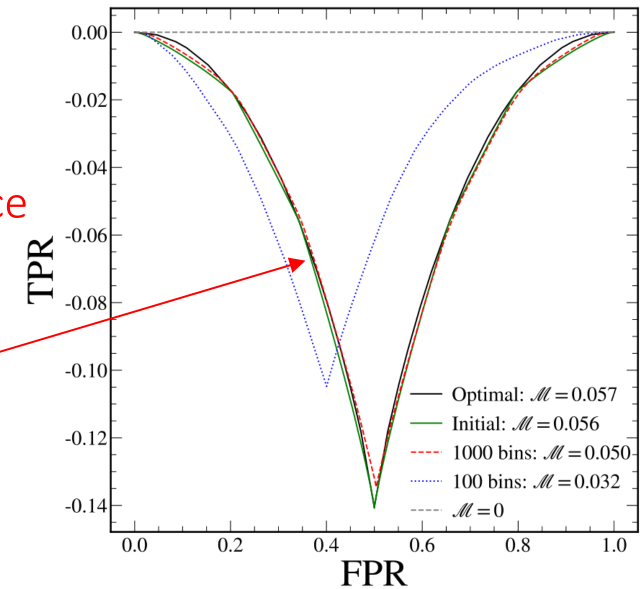
- Working points chosen at 1000 and 100 bins
- Performance for each coupling hypothesis parameterized as fractional change in initial LOC



Checking performance in analysis



Negative Interference = Negative TPR

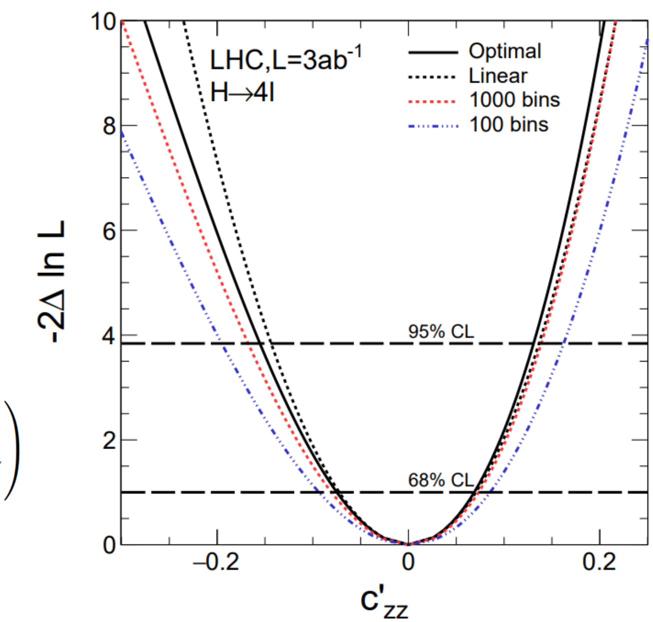


Metric M decreases with bins

- Toy analysis to compare results at various working points
  - **Optimal:** $\mathscr{D}^{(0)}_{\mathrm{opt},1}$ used for templates
  - Initial: 27648 bins before merging
  - 1000 bins
  - 100 bins

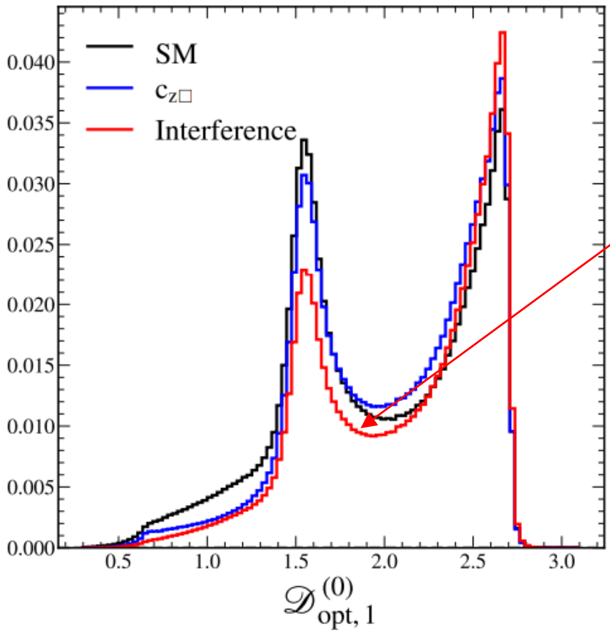
$$\frac{d\sigma(\vec{x})}{d\vec{x}} = \left[\frac{\sum \gamma_{jk}^{\mathrm{prod}} b_j b_k}{\Gamma_{\mathrm{tot}}(\vec{c})}(1+\delta c_z)^2\right]\left(\gamma_{00}^{\mathrm{dec}}(\vec{x}) + \sum_{1\leq m}\gamma_{0m}^{\mathrm{dec}}(\vec{x})c'_m + \sum_{1\leq m\leq l}\gamma_{lm}^{\mathrm{dec}}(\vec{x})c'_l c'_m\right)$$

$$c'_m = c_m/(1+\delta c_z)$$

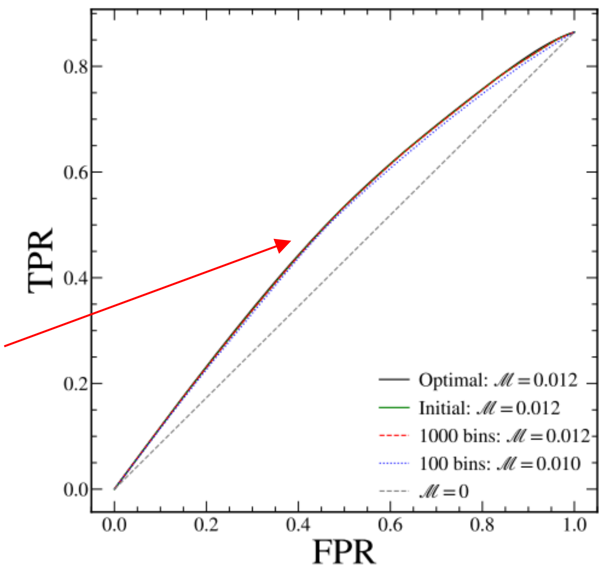


Sensitivity decreases in analysis

Checking performance in analysis



Positive
Interference
=
Positive TPR
(Reduced to
standard
ROC curve)



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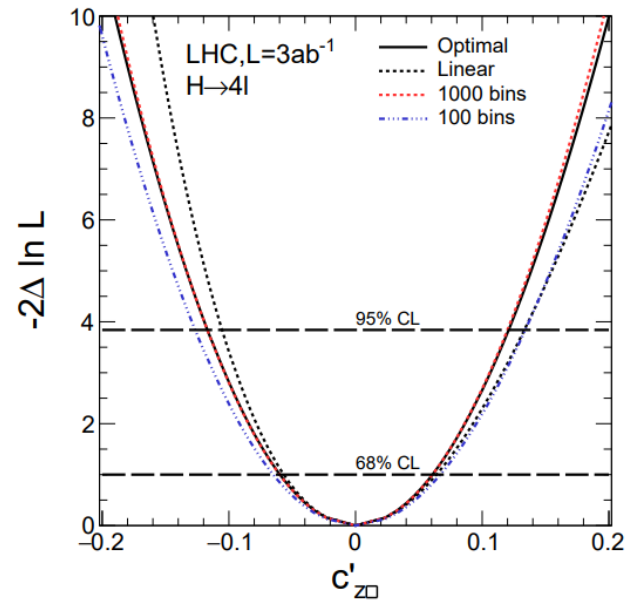
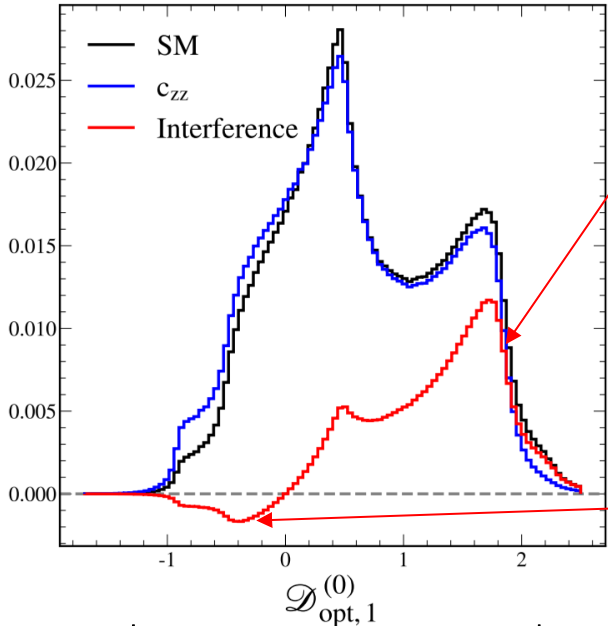


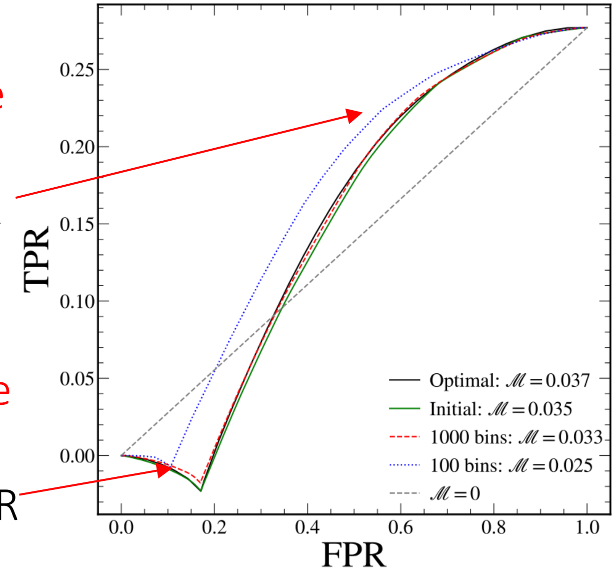
Sensitivity decreases in analysis

Checking performance in analysis



Positive Interference = Positive TPR

Negative Interference = Negative TPR



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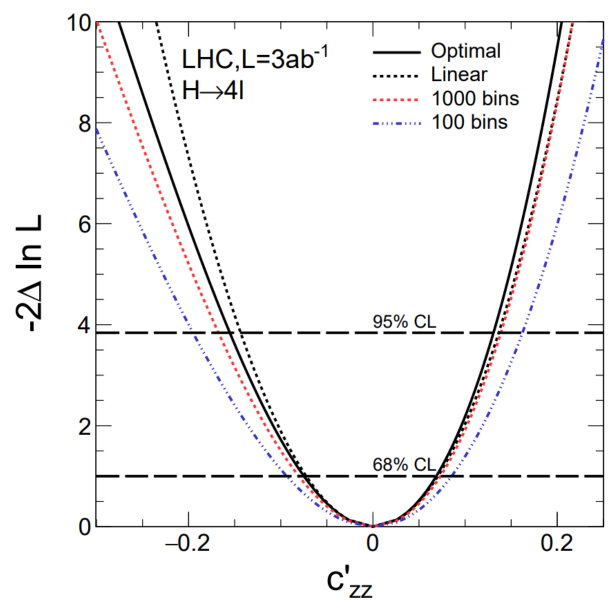
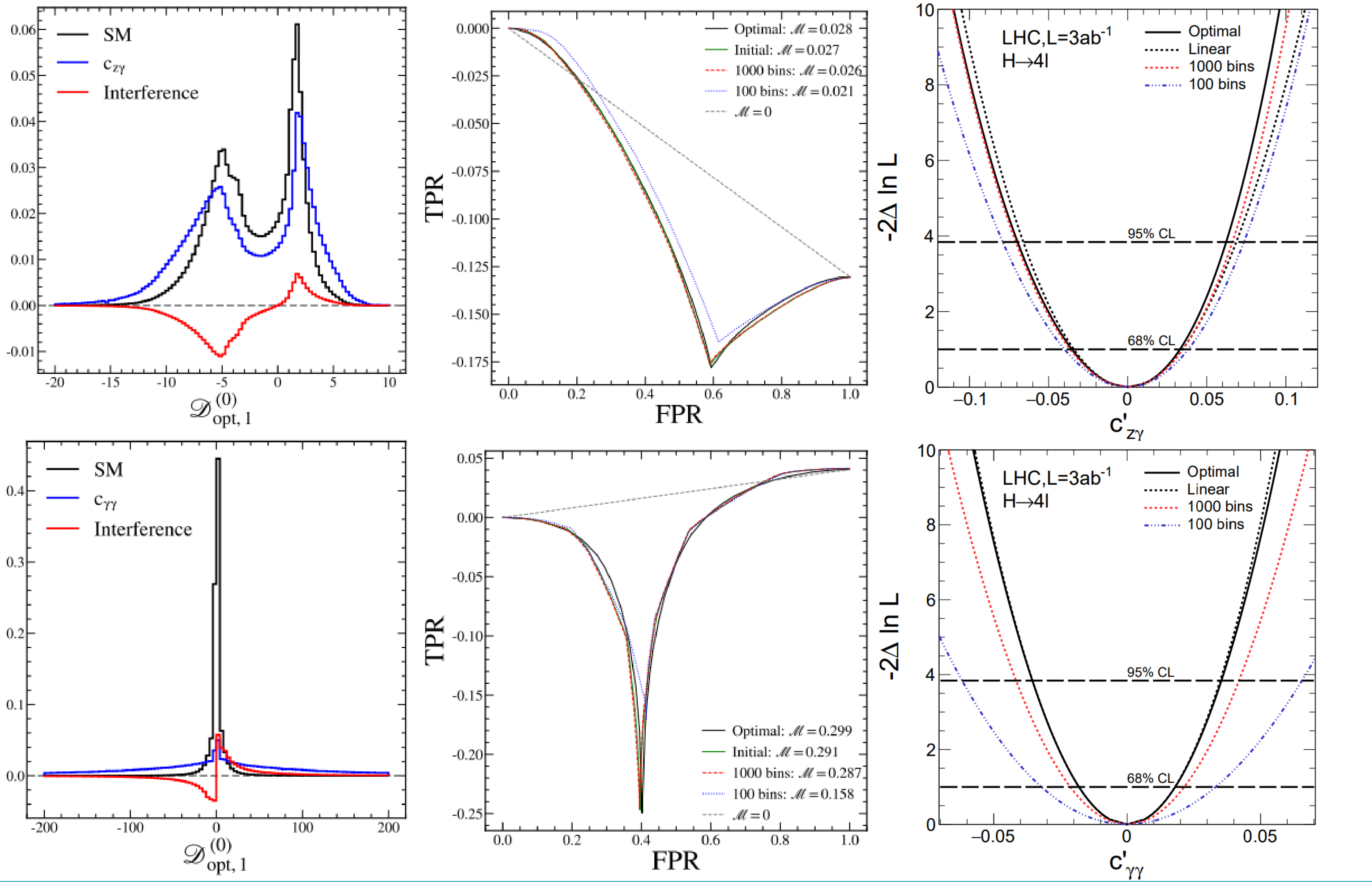


Sensitivity decreases in analysis

More comparisons



Conclusion

- Outline general phenomenological procedure for SMEFT analysis
- Discuss Operator Considerations in $\mathrm{H} \rightarrow 4\ell$ decays
- Establish method for constructing optimal observables out of complex multidimensional spaces:
- *(1) use either analytical or ML tools to construct most optimal EFT observables*
- *(2) novel MiLoMerge approach to create optimal binning*
- *(3) new LOC technique for validation and optimization*

Advertisement

- Link to Indico: https://indico.cern.ch/event/1659508/
- Wide Range of Topics:
  - LHC results
  - Beyond-LHC connections
    - Low energy experiment
    - Neutrino and flavor
    - Asto/cosmological
  - Standard Model EFT phenomenology
- Deadline for Abstract Submission: April 15!
- Registration open through May 15^{th}
- Nice stop before USCMS (June 3 – 5 at UMD)
- EFT tutorials geared towards CMS students