Study of spin correlations in Higgs boson decays to four leptons at CMS

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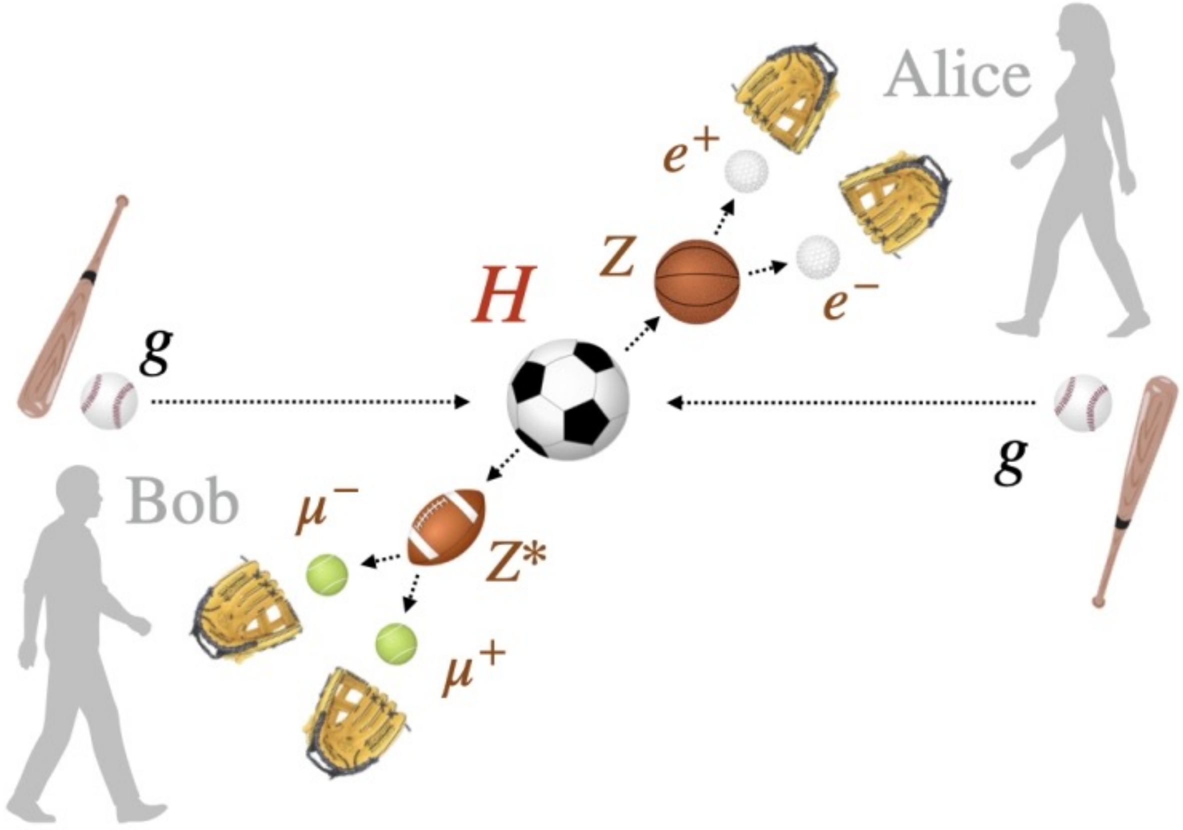
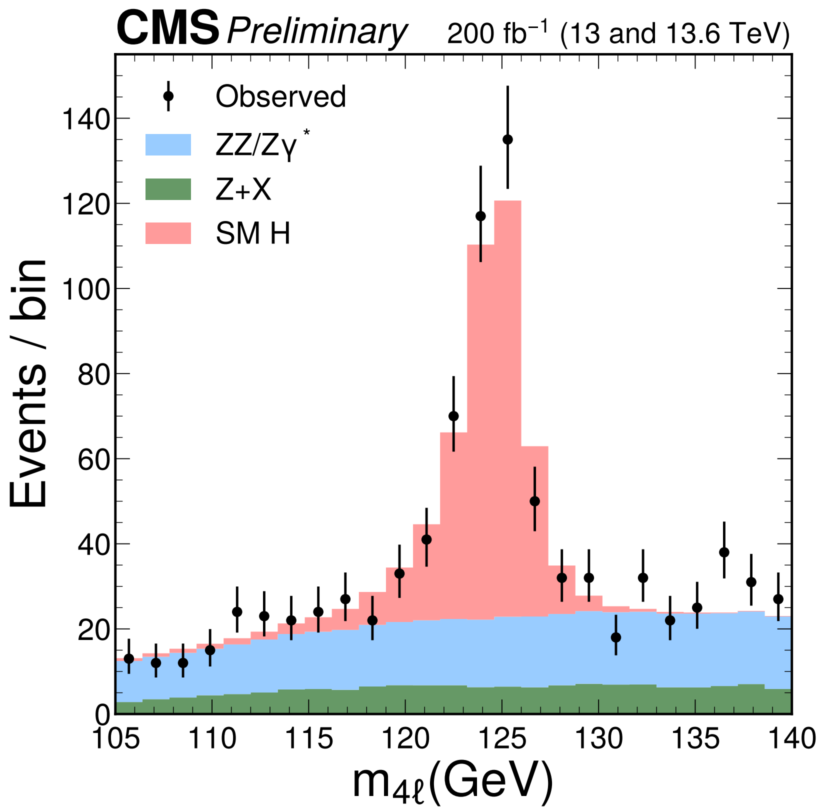


Overview

- Motivation
- General Formalism
- Spin Density Matrix
- Permutation of Identical Leptons
- Effective Field Theory
- (All plots shown come from CMS-PAS-HIG-25-011)

Motivation

- Small anomalous couplings to vector bosons permitted.
- Certain previous analyses performed by CMS assume $\mathrm{HZ}\gamma^*/\mathrm{H}\gamma^*\gamma^*$ couplings are constrained to 0 [CMS-HIG-19-009/arXiv:2104.12152].
- Can leverage clean reconstruction of $\mathrm{H} \rightarrow 4\ell$ final state.
  - Full incorporation of detector effects with anomalous couplings.
  - Can study $H \rightarrow \mathrm{ZZ}$ qutrit system to probe conditions for entanglement.



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General Formalism

- Most general Lorentz-Invariant Higgs to Vector Vector Amplitude:

$$A(\mathrm{HV_1V_2}) = \frac{1}{v}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1^{\mathrm{V_1V_2}}(q_1^2,q_2^2)g_{\mu\nu}m_H^2 + a_2^{\mathrm{V_1V_2}}(q_1^2,q_2^2)q_\mu q_\nu + a_3^{\mathrm{V_1V_2}}(q_1^2,q_2^2)\epsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta\right)$$

SM → $a_1 = \frac{2m_Z^2}{m_H^2}$

CP-Even

CP-Odd

- Two strategies within this analysis:
  - EFT Approach: Assume new physics at high mass scale Λ, expand $\mathrm{A(HVV)}$ in $\frac{q^2}{\Lambda^2}$.
    - Preserve $\mathrm{SU(2)\times U(1)}$.
  - Polarization approach: Parameterize polarization density matrix in terms of longitudinal and transverse components in HZZ decay.
    - Integrate over q_1^2, q_2^2 (masses of mediating vector bosons).

Kinematic Discriminants

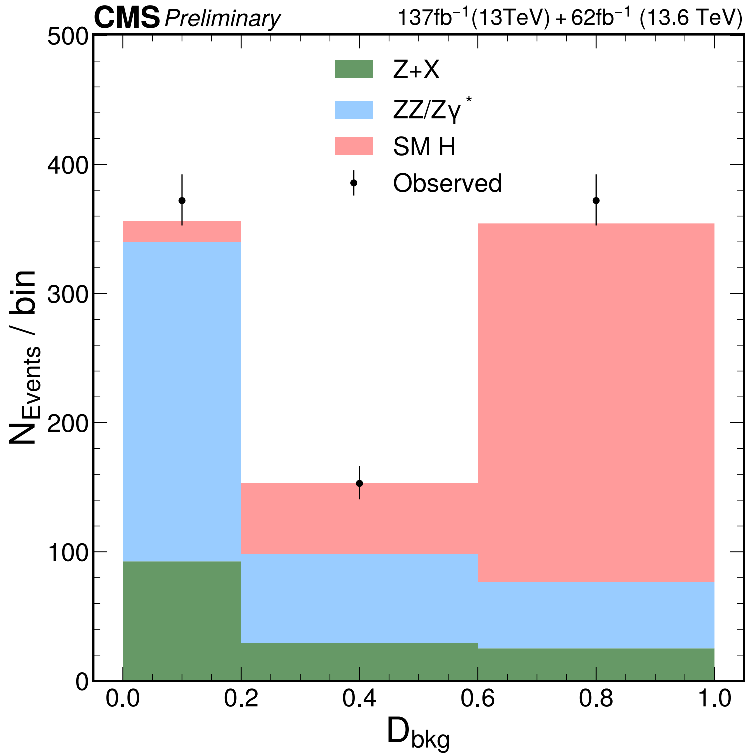
- Clean reconstruction in $\mathrm{H} \rightarrow 4\ell$ final state allows for use of matrix-element-based observables. CMS-PAS-HIG-25-011
- Use JHUGenMELA to generate observables.

2 Classes of Matrix Element Observable:

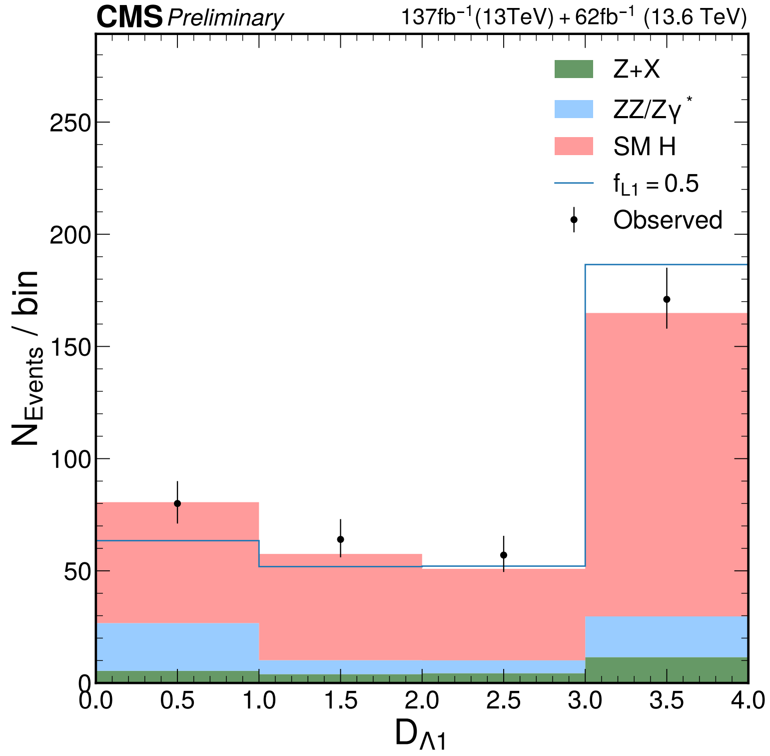
$$D_{alt} = \frac{P_{sig}(\Omega)}{P_{sig}(\Omega)+P_{alt}(\Omega)}$$

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

D_{int} optimal in the EFT limit for any anomalous coupling.



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



$$D_{\Lambda 1} = \frac{P_{\mathrm{SM}*\Lambda 1}(\Omega)}{P_{SM}(\Omega)}$$

*all discriminant projections have a cut of $D_{\mathrm{bkg}} > 0.6$

Polarization Measurements

- Can describe $\mathrm{H} \to \mathrm{ZZ}$ system as "qutrit" in terms of helicity amplitudes.
- A_{00}: Amplitude of longitudinal polarization.
- A_{++}: CP − even transverse polarization amplitude.
- A_{--}: CP − odd transverse polarization amplitude.
- Polarization defined in $2e2\mu$ channel.
  - Relate $4e/4\mu$ through amplitude.
- Integrate over m_1, m_2.
  - Assume SM mass spectrum.
  - Avoid dependence on mass.

$$\rho = \int \frac{dm_1 dm_2\, \mathcal{P}(m_1,m_2)}{|A_{++}|^2 + |A_{00}|^2 + |A_{--}|^2} \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{++}A_{++}^* & 0 & A_{++}A_{00}^* & 0 & A_{++}A_{--}^* & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{00}A_{++}^* & 0 & A_{00}A_{00}^* & 0 & A_{00}A_{--}^* & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{--}A_{++}^* & 0 & A_{--}A_{00}^* & 0 & A_{--}A_{--}^* & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Fractions of longitudinal and transverse polarization

$$f_L = \int dm_1 dm_2\, \mathcal{P}(m_1,m_2) \frac{|A_{00}|^2}{|A_{++}|^2 + |A_{--}|^2 + |A_{00}|^2}$$ = 0.61 in SM.

$$f_\perp = \int dm_1 dm_2\, \mathcal{P}(m_1,m_2) \frac{|A_\perp|^2}{|A_{++}|^2 + |A_{--}|^2 + |A_{00}|^2}$$ = 0 in SM.

Polarization Measurements

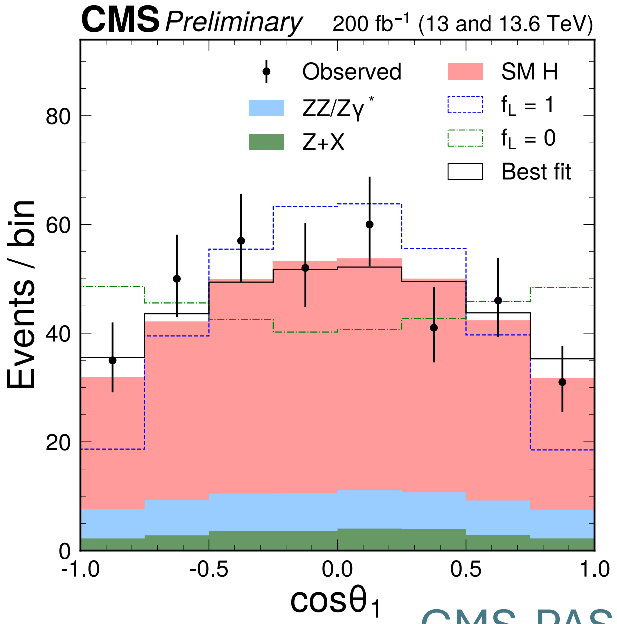
- Additional approach, assume CP-conservation, enforce $f_\perp = 0$.

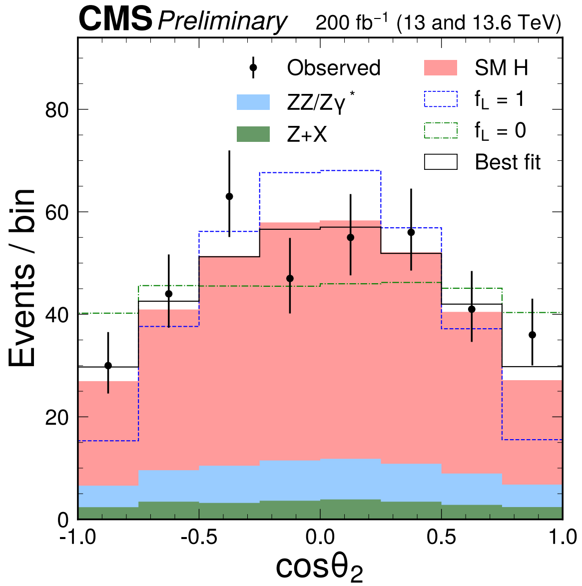
$$-C_\parallel \sqrt{f_L(1-f_L)} = \int dm_1 dm_2\, \mathcal{P}(m_1, m_2)\, \frac{A_\parallel(m_1, m_2) A_{00}(m_1, m_2)}{|A_\parallel|^2 + |A_{00}|^2}$$

- $C_\parallel$: Coherence parameter quantifying interference b/n CP-even longitudinal and transverse states.
  - 0.91 in SM.

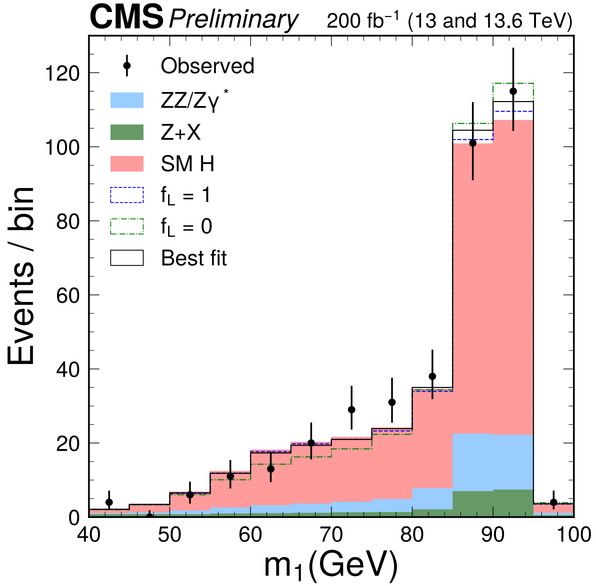
$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & (1-f_L)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & f_L & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & (1-f_L)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

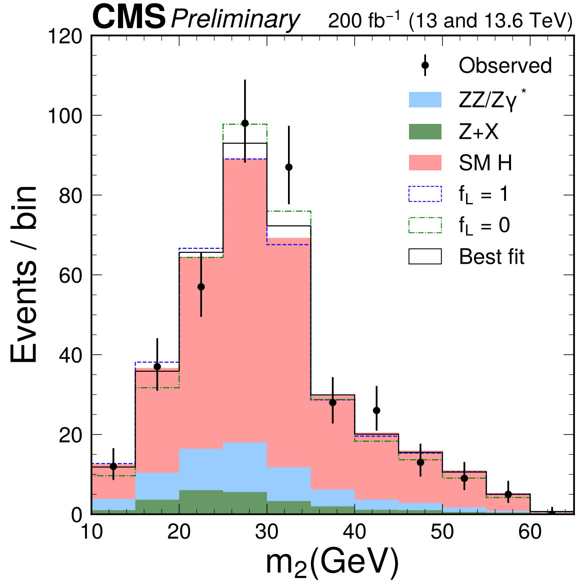
Polarization Measurements





Kinematics impacted, but mass distributions remain unchanged.





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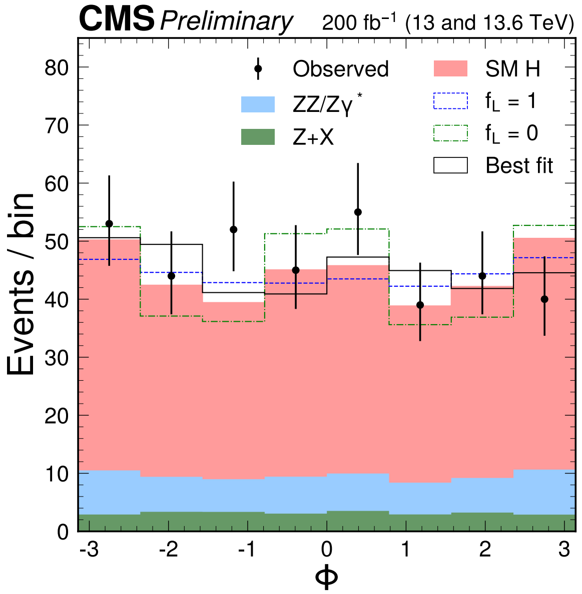
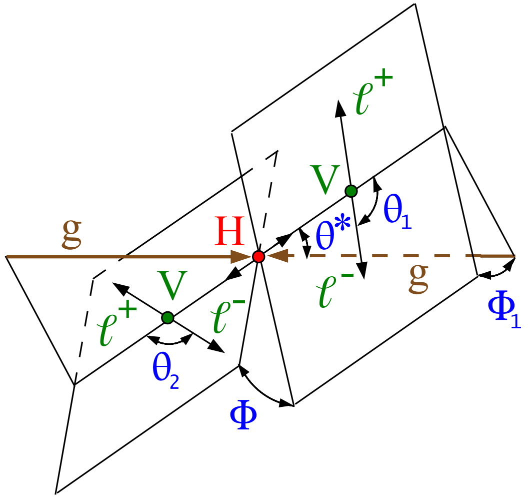
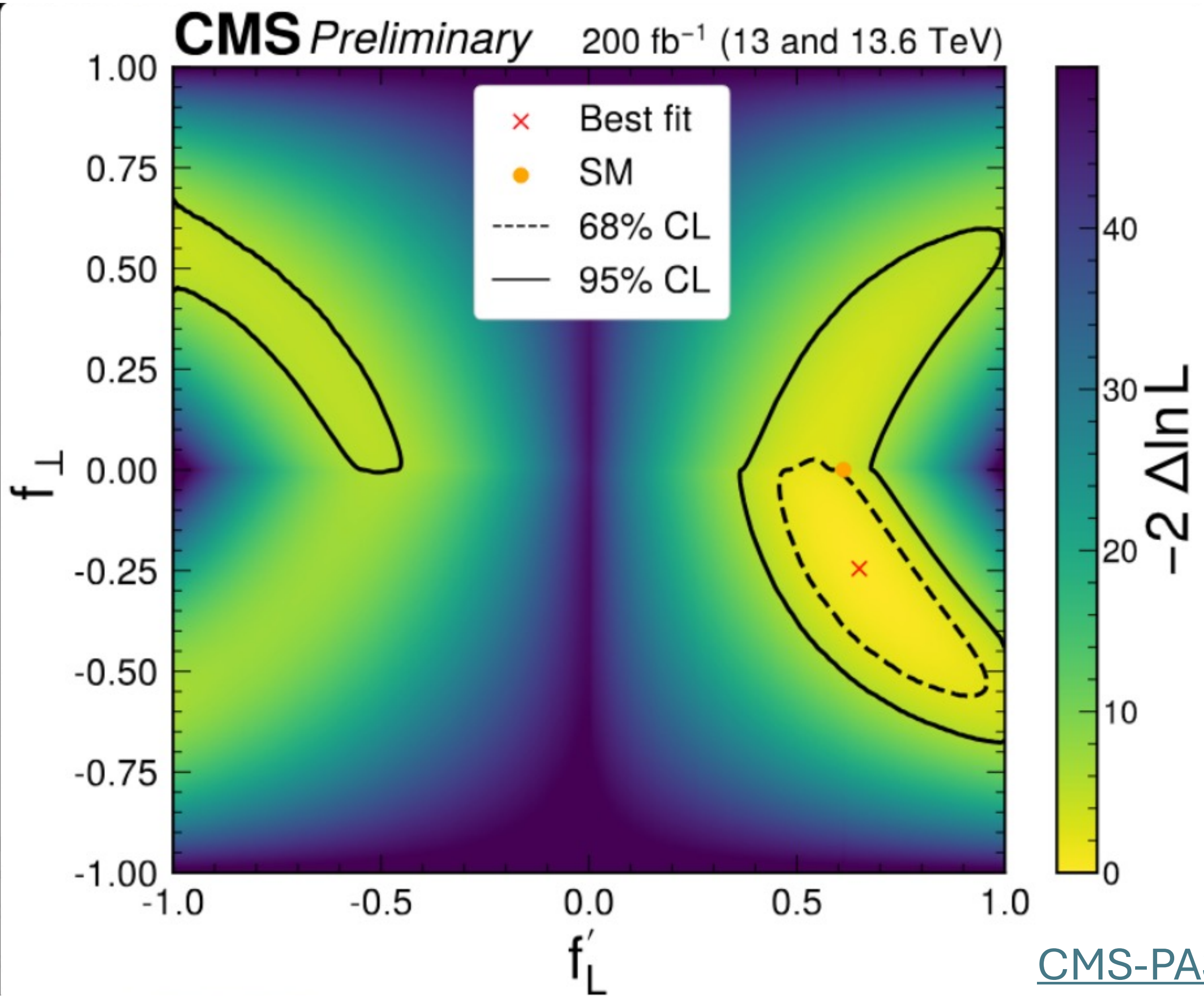
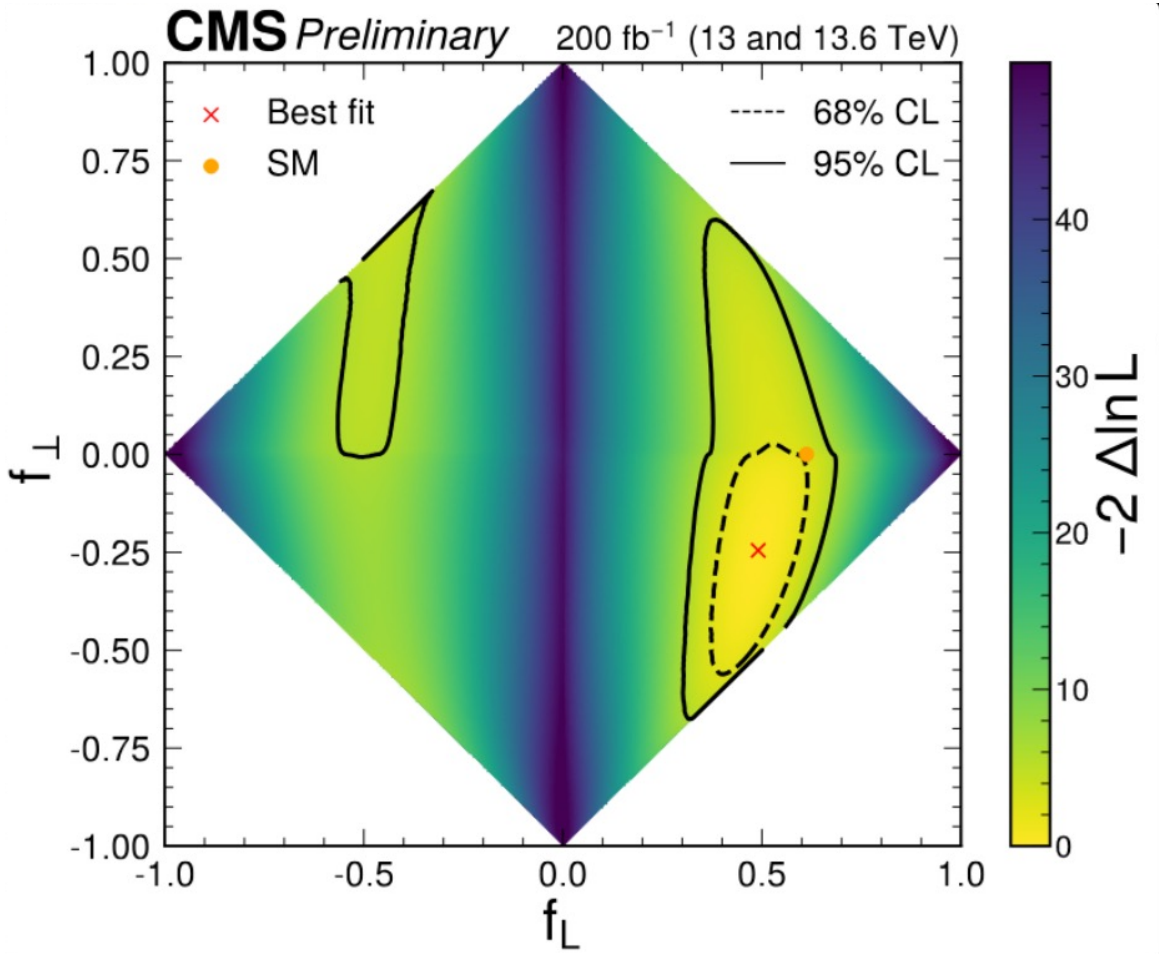




Fit incorporates all angular observables + D_{bkg}.

Polarization Measurements: Results





$$f_L' = \frac{f_L}{1 - |f_\perp|}$$

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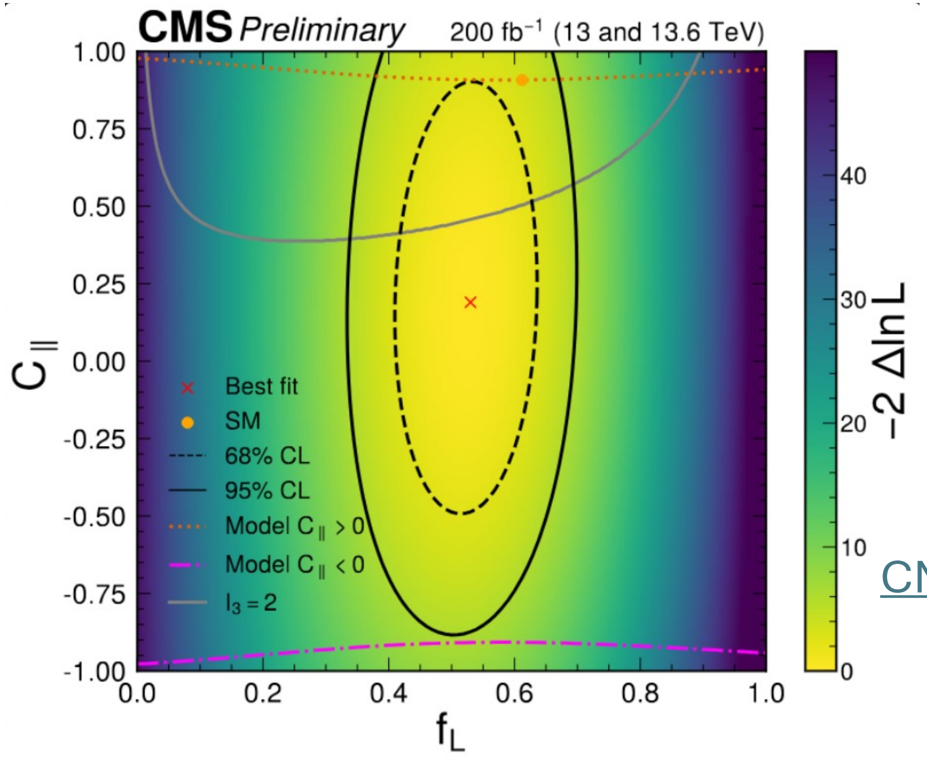
$f_L, f_\perp$ agree with SM within $\sim 1\,\sigma$.

Testing Conditions for Quantum Entanglement



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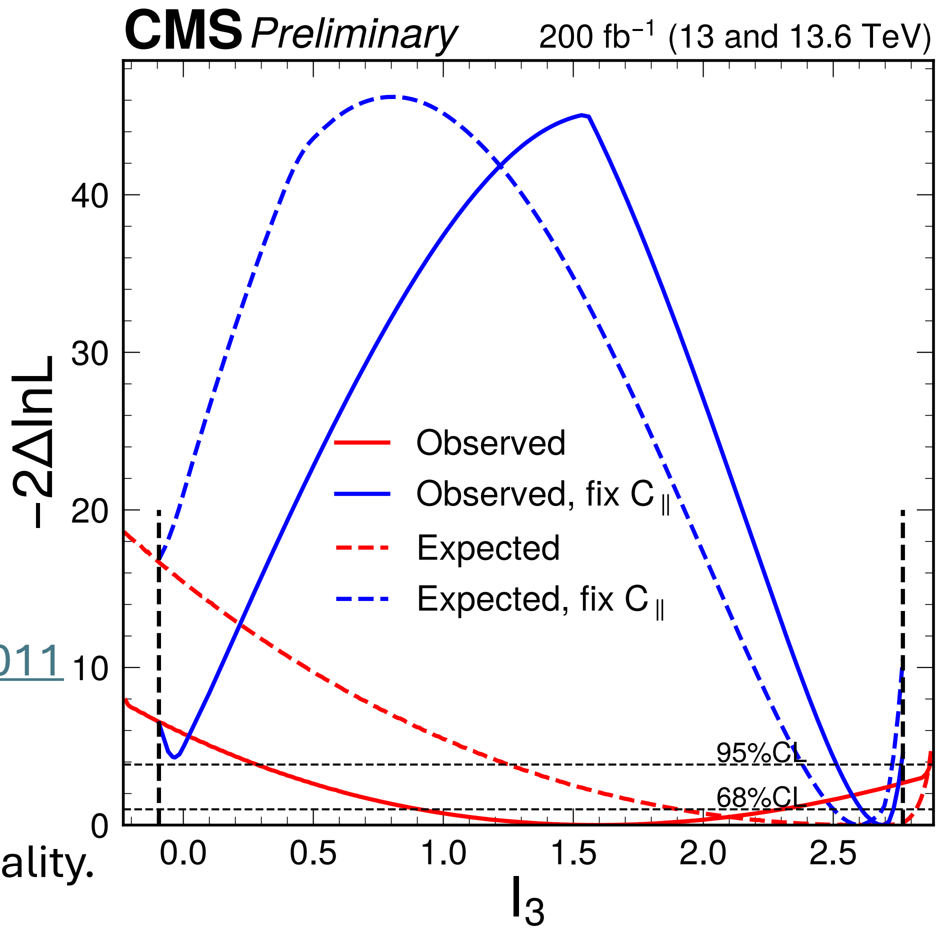
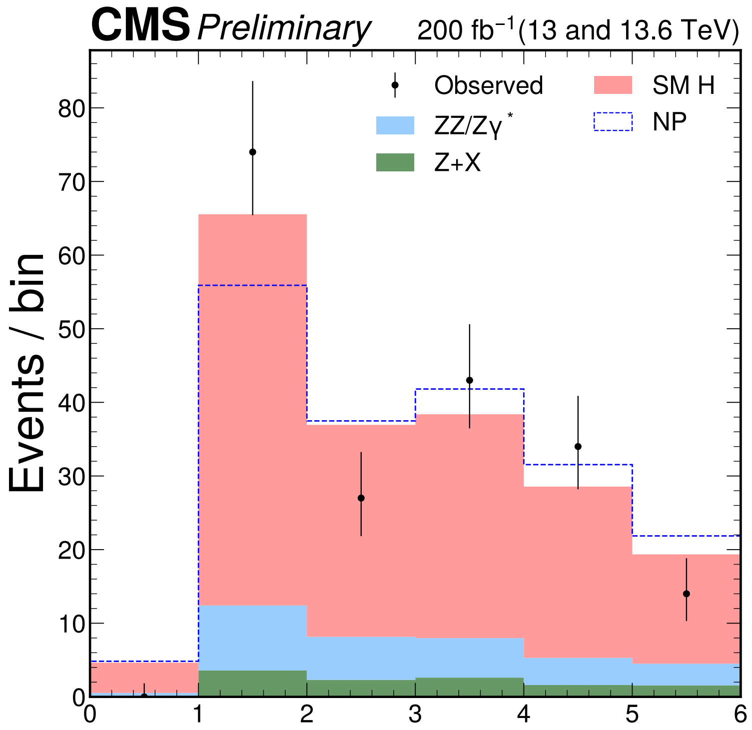


- Can test conditions for violation of GCLMP (Bell-Type) inequality.
- I_3: linear combination of density matrix elements. For more details, see [Aguilar-Saavedra et. al: arXiv:2209.13441].
  - Assuming no CP violation, $I_3 > 2 \rightarrow$ GCLMP inequality violated.
- Find $< \ 2\,\sigma$ deviation from standard model.

Permutation of Leptons

- In $\mathrm{H} \rightarrow 4\mathrm{e}$ / 4μ: Z_1, Z_2 are indistinguishable. Implies entanglement between the two.
- $Amp^2 \propto |H \rightarrow Z_1 Z_2 \rightarrow (\mu_1^+, \mu_2^-)(\mu_3^+, \mu_4^-) + H \rightarrow Z_1' Z_2' \rightarrow (\mu_3^+, \mu_2^-)(\mu_1^+, \mu_4^-)|^2$.
- Kinematics are sensitive to interference effects:
  - Use MELA tools to "turn off" interference (No Permutation), compare to SM.



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

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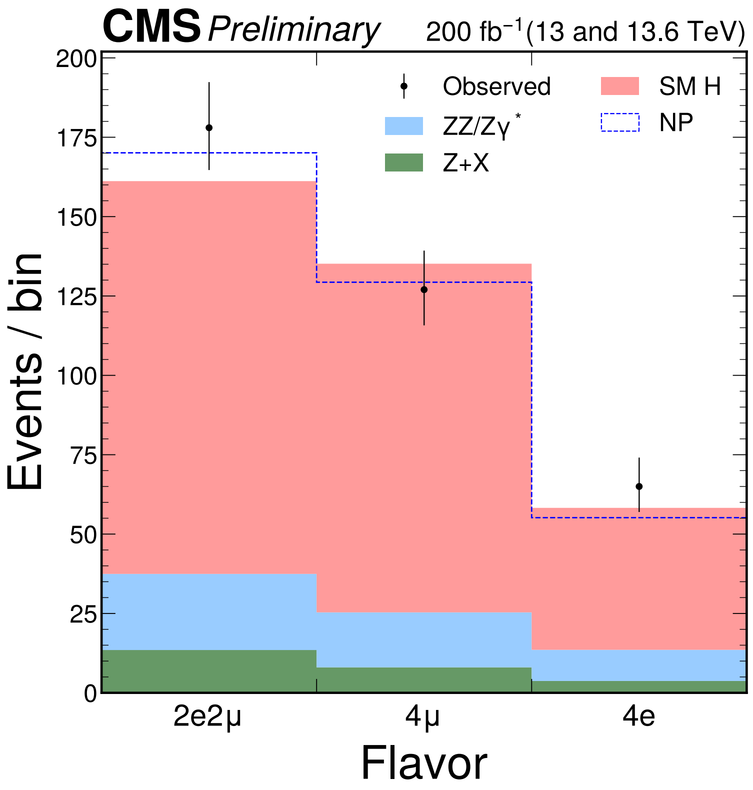
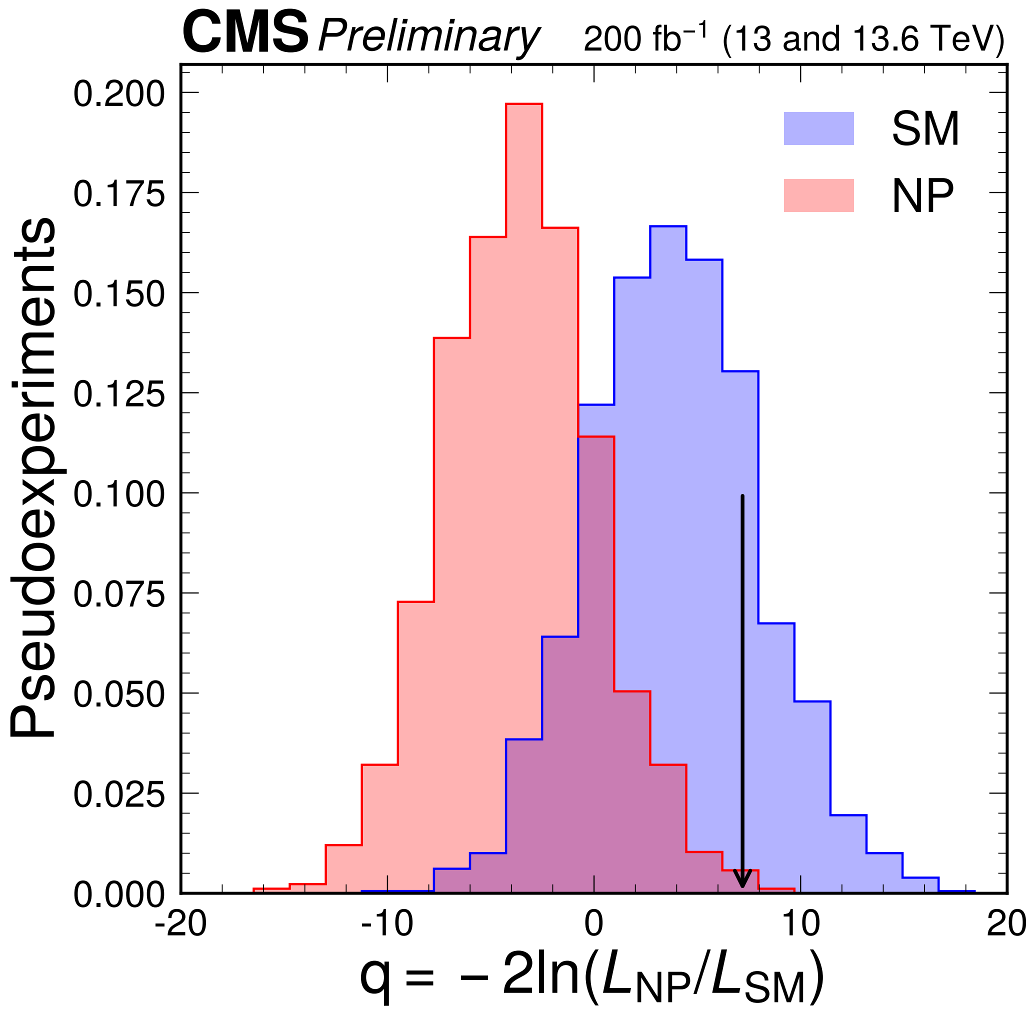


Permutation of Leptons

- Performed hypothesis test performed between SM and NP.
- Exclude NP at 2.7σ.

Model	Observed		Expected	
	p-value	Z-score	p-value	Z-score
NP	3.4×10^{-3}	2.7	2.8×10^{-2}	1.9
SM	0.21	0.8	0.5	0



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Effective Field Theory: Strategy

- Simultaneous fit of 7 independent + 1 dependent anomalous couplings in $\mathrm{H} \rightarrow 4\ell$ decay:

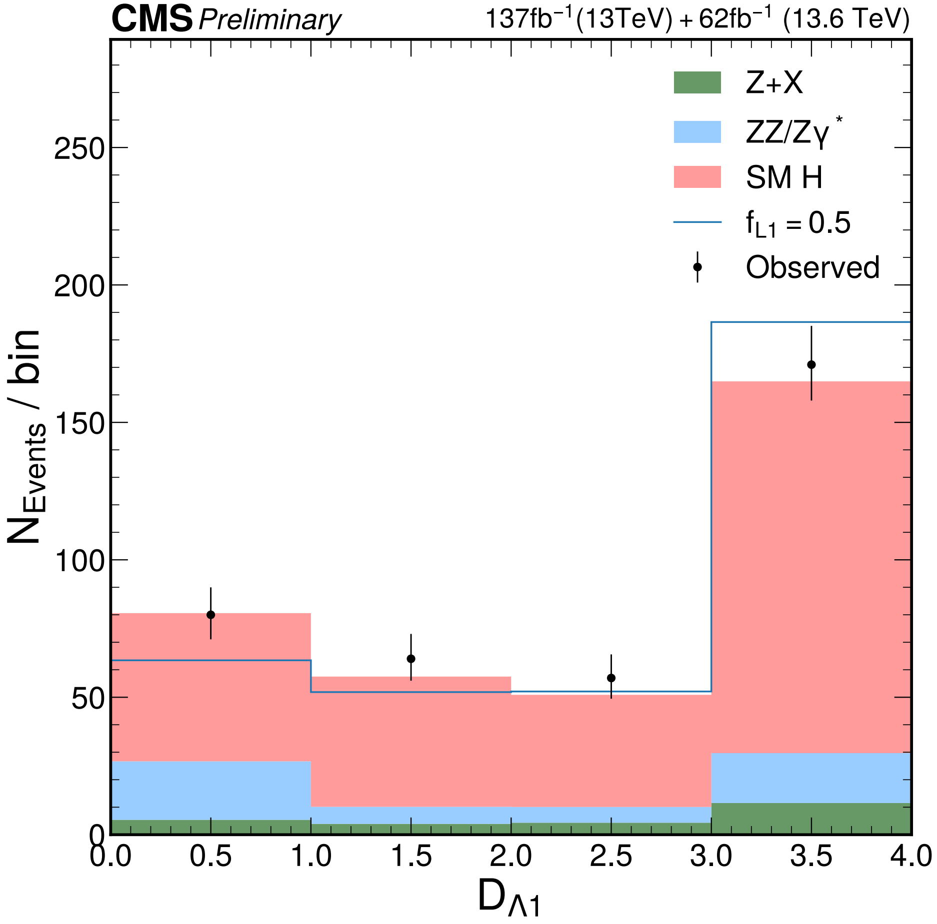
$$\mathcal{L}_{\mathrm{HVV}} = \frac{H}{v}\Big[m_Z^2\left(\delta c_z+1\right) Z_\mu Z^\mu + \frac{m_Z^2}{v^2} c_{zz} Z_{\mu\nu} Z^{\mu\nu} + \frac{e^2}{s_w^2} c_{z\Box} Z_\mu \partial_\nu Z^{\mu\nu} + \frac{m_Z^2}{v^2} \tilde{c}_{zz} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$
$$+ c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}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

- Report 7 $f_{ai} = \frac{|a_i|^2 \sigma_i}{\Sigma_j |a_j|^2 \sigma_j}\, sign\left(\frac{a_i}{a_1}\right)$.
  - Absorbs Γ_H, production couplings.
  - Systematic effects cancel in the ratio.

- Dedicated simulation of all anomalous couplings.
  - Fully incorporates detector / reconstruction effects.

- $\mathrm{SU(2)} \times \mathrm{U(1)}$ (SMEFT) relations enforced at the template level.

- Construct a 7D Histogram of EFT observables.
  - Dimensionality is reduced with minimal loss using MiLoMerge, see talk by Mohit Srivastav.



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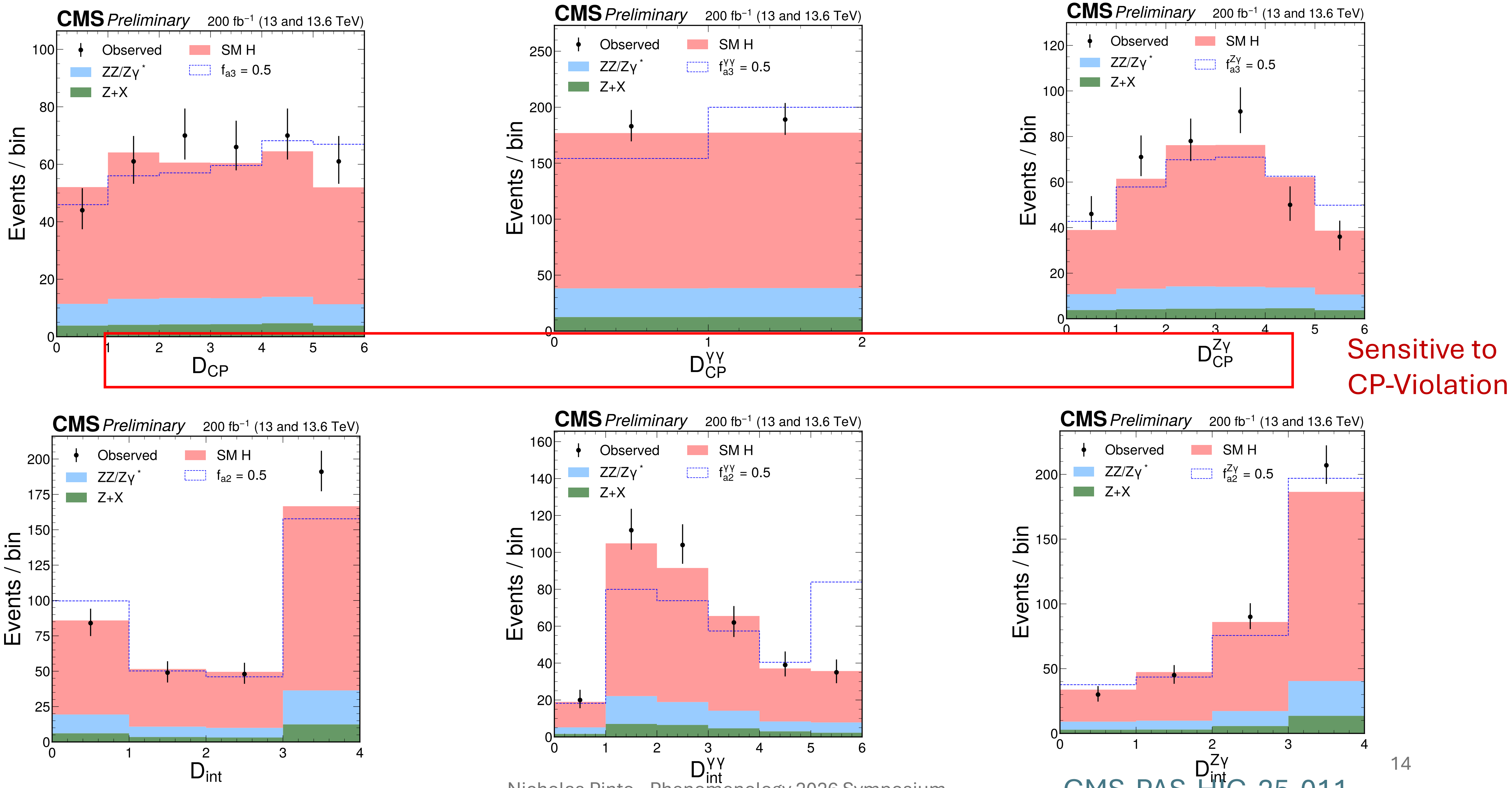
Effective Field Theory: Observables

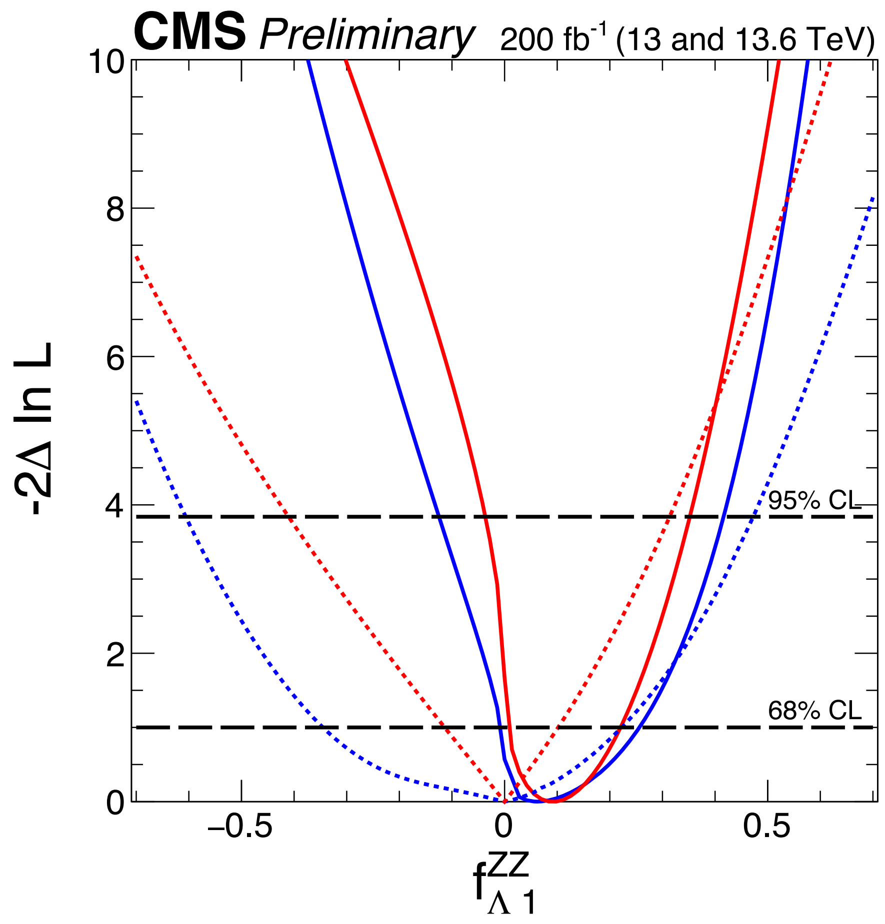


Effective Field Theory: Results

- Perform maximum-likelihood scan of all 7 anomalous couplings.

- Scans performed with all other AC simultaneously floated (blue), and all other AC fixed (red).

- Dashed = Expectation from Monte Carlo.
- Solid = Observation from CMS Data.



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Effective Field Theory: Results

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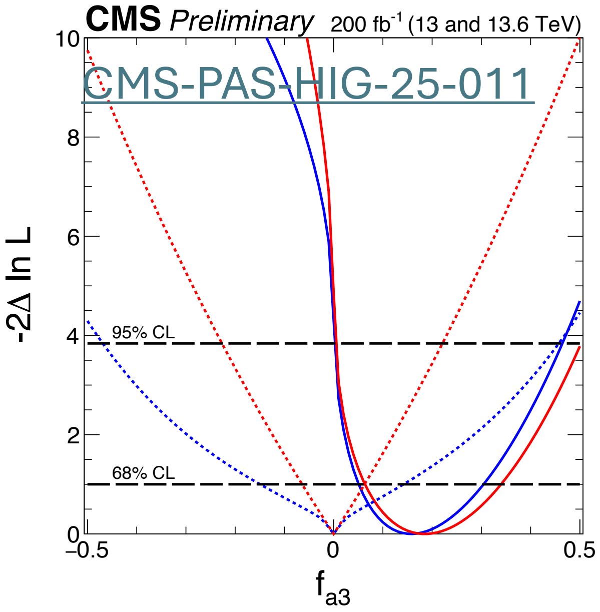

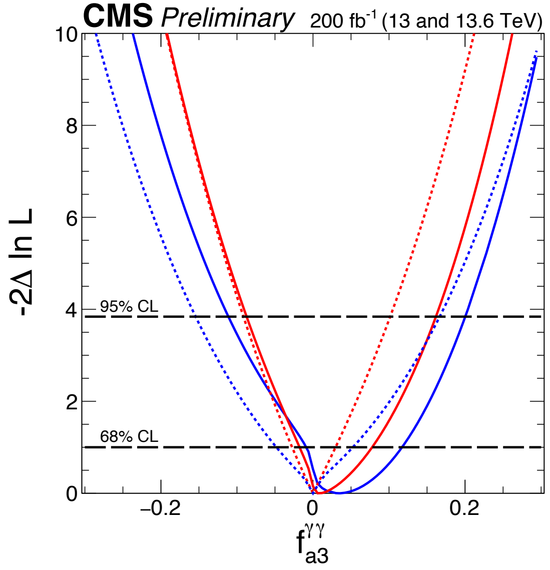

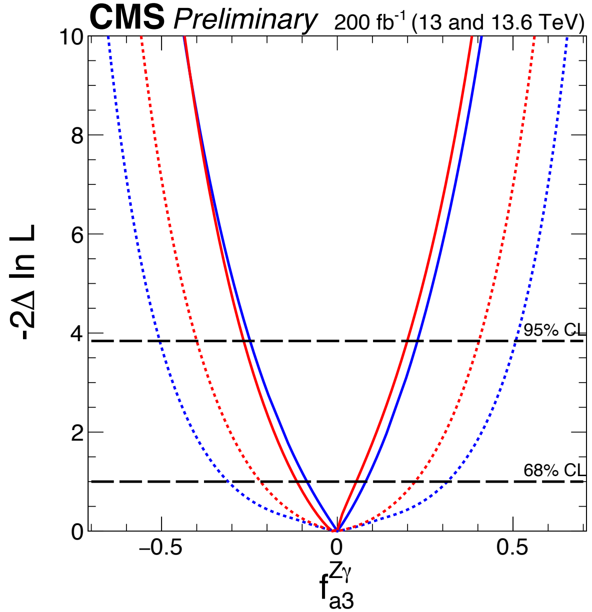

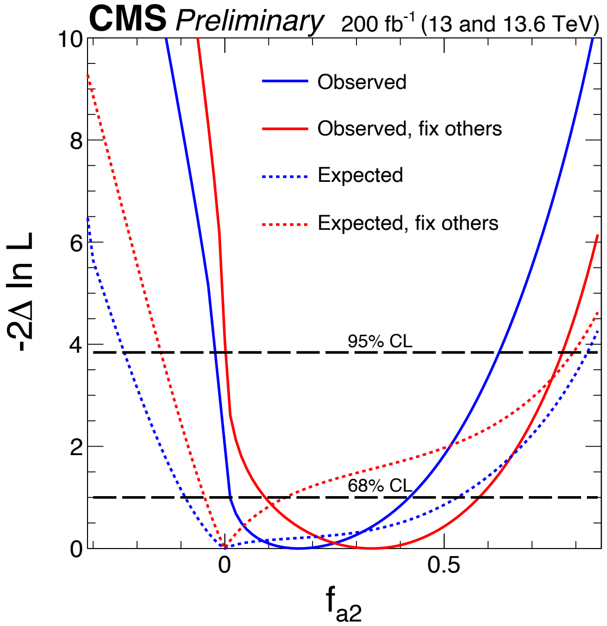

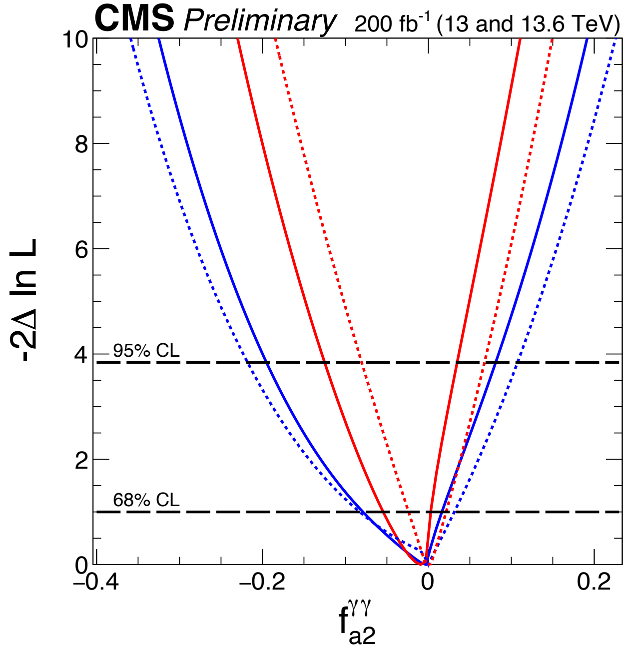

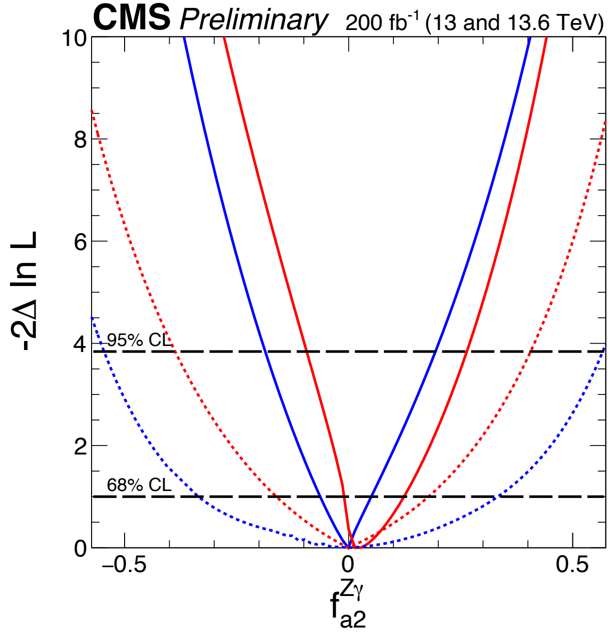

Summary

- Performed interpretation of spin correlations in $H \to 4\ell$ decay channel in various contexts.
- Set constraints on 7 anomalous HVV couplings in the context of SMEFT, floating all simultaneously.
- Tested conditions for quantum entanglement in multiple ways:
  - Permutation of leptons, GCLMP inequality generally agree with standard model.
- Measured polarization fractions, introducing no assumptions about the mass distribution of the Z boson mediators.

Backup: Numeric EFT Results

$\vec{f}$	Scenario	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
f_{a3}	float all	$0.16^{+0.15}_{-0.11}$	$[0.01, 0.46]$	$0.00^{+0.14}_{-0.15}$	$[-0.47, 0.46]$
	fix others	$0.18^{+0.16}_{-0.12}$	$[0.01, 0.50]$	$0.00^{+0.06}_{-0.06}$	$[-0.23, 0.22]$
$f_{a3}^{Z\gamma}$	float all	$0.00^{+0.08}_{-0.08}$	$[-0.25, 0.23]$	$0.00^{+0.31}_{-0.30}$	$[-0.49, 0.51]$
	fix others	$0.00^{+0.06}_{-0.11}$	$[-0.27, 0.20]$	$0.00^{+0.22}_{-0.22}$	$[-0.40, 0.40]$
$f_{a3}^{\gamma\gamma}$	float all	$0.03^{+0.08}_{-0.05}$	$[-0.11, 0.20]$	$0.00^{+0.05}_{-0.05}$	$[-0.15, 0.17]$
	fix others	$0.01^{+0.07}_{-0.03}$	$[-0.09, 0.16]$	$0.00^{+0.03}_{-0.03}$	$[-0.09, 0.10]$
f_{a2}	float all	$0.17^{+0.25}_{-0.15}$	$[-0.03, 0.63]$	$0.00^{+0.53}_{-0.08}$	$[-0.23, 0.83]$
	fix others	$0.33^{+0.25}_{-0.24}$	$[0.00, 0.77]$	$0.00^{+0.14}_{-0.05}$	$[-0.15, 0.79]$
$f_{a2}^{Z\gamma}$	float all	$0.00^{+0.05}_{-0.06}$	$[-0.18, 0.19]$	$0.00^{+0.33}_{-0.34}$	$[-0.54, 0.57]$
	fix others	$0.02^{+0.10}_{-0.03}$	$[-0.09, 0.26]$	$0.00^{+0.18}_{-0.16}$	$[-0.39, 0.41]$
$f_{a2}^{\gamma\gamma}$	float all	$0.00^{+0.02}_{-0.07}$	$[-0.19, 0.08]$	$0.00^{+0.03}_{-0.08}$	$[-0.22, 0.11]$
	fix others	$-0.01^{+0.01}_{-0.05}$	$[-0.13, 0.03]$	$0.00^{+0.02}_{-0.02}$	$[-0.08, 0.07]$
$f_{\Lambda 1}$	float all	$0.06^{+0.19}_{-0.05}$	$[-0.13, 0.42]$	$0.00^{+0.22}_{-0.34}$	$[-0.60, 0.47]$
	fix others	$0.09^{+0.13}_{-0.08}$	$[-0.04, 0.35]$	$0.00^{+0.10}_{-0.11}$	$[-0.41, 0.31]$

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