Angular observables

as a probe of new physics in the *Vh* sector

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Based on work with S Banerjee, R S Gupta & M Spannowsky

Arxiv: 1912.07628, 1905.02728

Motivation 1

The trajectory of particle physics:

- Going to higher *E* and *L*
- Time to move from total rates
- More sophisticated observables available

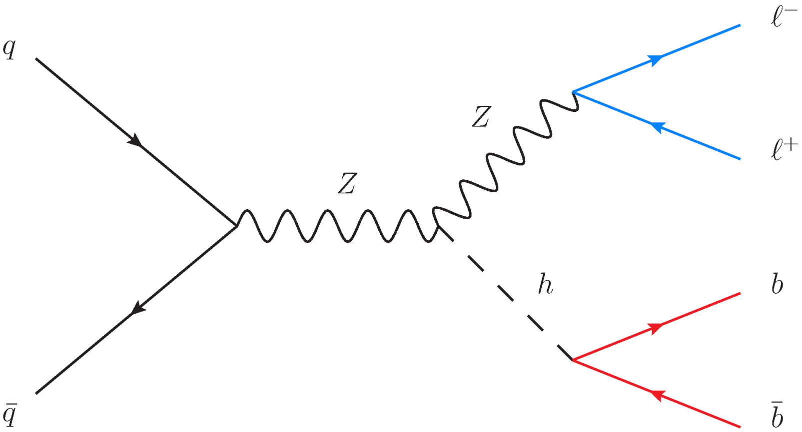
$$\sigma \quad \rightarrow \quad \frac{d\sigma}{dEd\varphi d\Theta d\theta}$$

Motivation 2

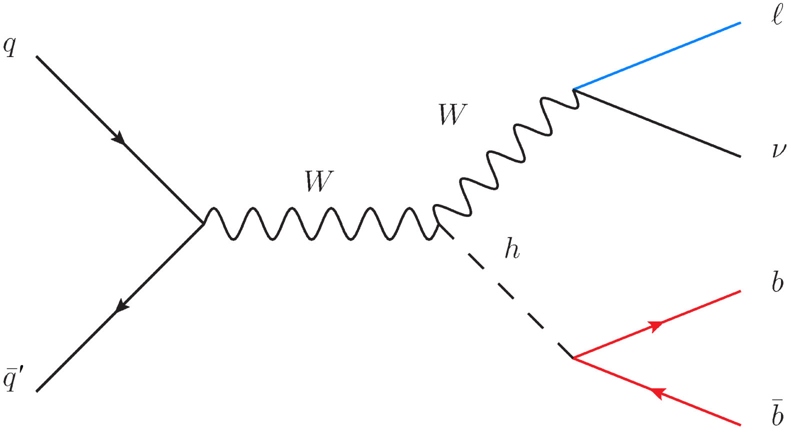
The aim:

- Can analytic knowledge instruct observables?
- Make smart choices of differential variables
- Increase sensitivity by capturing full angular info

Higgs-strahlung: **Z**



Higgs-strahlung: *W*



Roadmap

SMEFT operators in Warsaw basis

$$\mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

→

hVV*/hVff corrections

$\delta\hat{g}^h_{VV}$, g^h_{Vf}, $\hat{\kappa}_{VV}$, $\hat{\tilde{\kappa}}_{VV}$

→

Amplitude

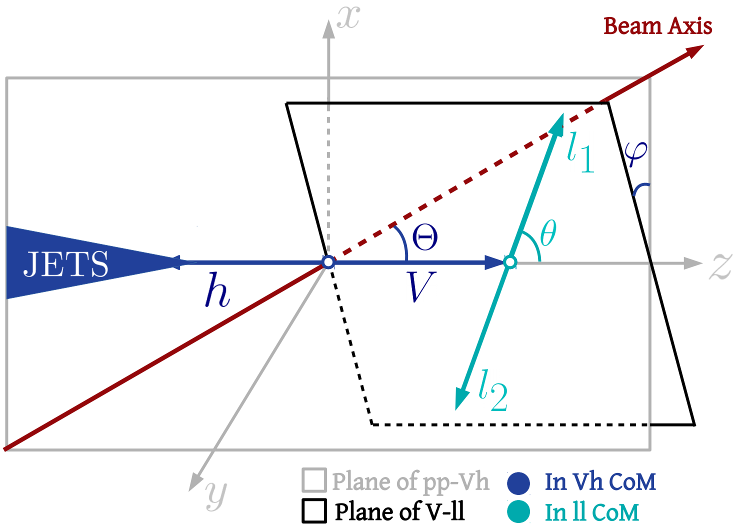
$$\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)$$

→

Angular observables

$$\frac{a_{LL}^2}{4} C_\varphi S_{2\theta} S_{2\Theta}$$

The 3 angles



x
Beam Axis
l_1
φ
Θ
θ
JETS
h
V
z
l_2
y
Plane of pp-Vh
Plane of V-ll
In Vh CoM
In ll CoM

New physics at higher energies

- No new resonances at LHC
- Still sensitive to higher-energy physics
- Effects from higher scales are suppressed

$\rightarrow$ show as perturbations to SM result

Social scale distancing

EFTs

- Effective Field Theories are handy
- Integrate out heavy physics for tower of higher-dimension operators

$$\mathcal{L}_L(\psi_L) + \mathcal{L}_H(\psi_L, \psi_H) \to \mathcal{L}_L(\psi_L) + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{\mathrm{dim}(\mathcal{O}_i)-4}}$$

- Can truncate series to dim 6 if $E \ll \Lambda_{\mathrm{NP}}$

SMEFT

Standard Model Effective Field Theory offers framework for parameterising effects of higher-energy physics

- Mostly model-independent
- Mass-dimension 6 operators
- Warsaw basis [1008.4844]
- Get 59 (2499) operators for 1 (3) gens

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^{(6)} + \ldots \qquad \mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}$$

The $hVV^* / hV\bar{f}f'$ vertex

We have 4 tensor structures of interest:

- $h\, V^\mu V_\mu$ [SM-like]
- $h\, V_\mu\, (\bar{f}\gamma^\mu f')$ [contact term]
- $h\, V^{\mu\nu} V_{\mu\nu}$ [CP even transverse]
- $h\, V^{\mu\nu} \tilde{V}_{\mu\nu}$ [CP odd transverse]

The hVV^* / $hV\bar{f}f'$ vertex

In the parameterisation of [1405.0181],

$$\Delta\mathcal{L}_6^{hV\bar{f}f} \supset \delta\hat{g}^h_{VV}\,\frac{2m_V^2}{v}h\frac{V^\mu V_\mu}{2} + \sum_f g^h_{Vf}\,\frac{h}{v}V_\mu\bar{f}\gamma^\mu f$$

$$+\,\kappa_{VV}\,\frac{h}{2v}V^{\mu\nu}V_{\mu\nu} + \tilde{\kappa}_{VV}\,\frac{h}{2v}V^{\mu\nu}\tilde{V}_{\mu\nu}$$

Other contributions

Operators that rescale the $hb\bar{b}$ and $V\bar{f}f'$ contribute

Also have to account for $Z\gamma$ terms

$$\kappa_{Z\gamma}\,\frac{h}{Z}A^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{Z\gamma}\,\frac{h}{Z}A^{\mu\nu}\tilde{Z}_{\mu\nu}$$

For $\hat{s} \gg m_Z^2$ just shifts parameters:

$$\kappa_{ZZ} \to \kappa_{ZZ} + 0.3\,\kappa_{Z\gamma} \qquad \tilde{\kappa}_{ZZ} \to \tilde{\kappa}_{ZZ} + 0.3\,\tilde{\kappa}_{Z\gamma}$$

The vertex in SMEFT

Which Warsaw basis SMEFT operators contribute to this vertex?

12 CP-even and 3 CP-odd (pre EWSB)

See [1008.4844] for operator notation.

$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{HL}^{(3)} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{L}\sigma^a\gamma^\mu L$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{HB} = \|H\|^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R\gamma^\mu d_R$	$\mathcal{O}_{HW} = \|H\|^2 W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R\gamma^\mu e_R$	$\mathcal{O}_{H\tilde{B}} = \|H\|^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{Q}\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}B} = H^\dagger \sigma^a H W^a_{\mu\nu} \tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(3)} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{Q}\sigma^a\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}} = \|H\|^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
$\mathcal{O}_{HL}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{L}\gamma^\mu L$	

The hVV^* / $hV\bar{f}f$ vertex

These contribute to the earlier parameters:

$$\delta\hat{g}^h_{VV} = \frac{v^2}{\Lambda^2}\left(c_{H\Box} + \frac{3c_{HD}}{4}\right)$$

$$g^h_{Vf} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T^f_3|c^{(1)}_{HF} - T^f_3 c^{(3)}_{HF} + (1/2 - |T^f_3|)c_{Hf})$$

$$\kappa_{VV} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{HW} + s^2_{\theta_W}c_{HB} + s_{\theta_W}c_{\theta_W}c_{HWB})$$

$$\tilde{\kappa}_{VV} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{H\tilde{W}} + s^2_{\theta_W}c_{H\tilde{B}} + s_{\theta_W}c_{\theta_W}c_{H\tilde{W}B})$$

The analytic amplitude

How do we extract information about these corrections?

By using knowledge of the amplitude’s analytic structure…

The analytic amplitude

Begin with $2 \to 2$ process $f(\sigma)\bar{f}(-\sigma) \to V(\lambda)h$ in the helicity amplitude formalism:

$$\mathcal{M}_\sigma^{\lambda=\pm} = \sigma \frac{1 + \sigma\lambda \cos\Theta}{2\sqrt{2}} \frac{g g_f^V}{c_{\theta_W}} \frac{1}{\gamma} \left[1 + 2\gamma^2 \left(\frac{g_{Vf}^h}{g_f^V} + \kappa_{VV} - i\lambda\tilde{\kappa}_{VV} \right) \right]$$

$$\mathcal{M}_\sigma^{\lambda=0} = -\sin\Theta \frac{g g_f^V}{2c_{\theta_W}} \left[1 + \delta\hat{g}_{VV}^h + 2\kappa_{VV} + \frac{g_{Vf}^h}{g_f^V} \left(-\frac{1}{2} + 2\gamma^2 \right) \right]$$

Neglect terms subdominant* in $\boxed{\gamma = \sqrt{\hat{s}}/(2m_V)}$

The analytic amplitude

Leading SM is **longitudinal** $(\lambda = 0)$

Leading effect of κ_{VV} and $\tilde{\kappa}_{VV}$ is in **transverse** $(\lambda = \pm 1)$

The LT interference term vanishes if we're not careful...

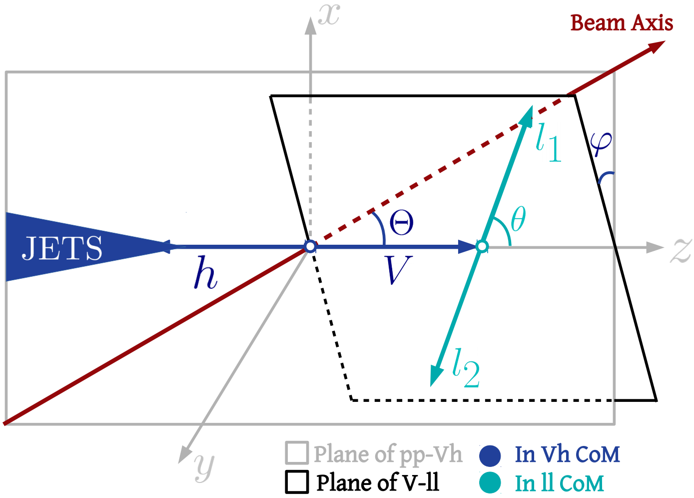
The analytic amplitude

Full amplitude can be written as:

$$\mathcal{A}_h(\hat{s},\Theta,\hat{\theta},\hat{\varphi}) = \frac{-i\sqrt{2}g_\ell^V}{\Gamma_V}\sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s},\Theta)\, d_{\lambda,1}^{J=1}(\hat{\theta})\, e^{i\lambda\hat{\varphi}}$$

Wigner functions $d_{\lambda,1}^{J=1}(\hat{\theta})$, hats indicate positive helicity leptons rather than positive charge [1708.07823].

The 3 angles



x
Beam Axis
l_1
φ
Θ
θ
JETS
h
V
z
l_2
y
Plane of pp-Vh
Plane of V-ll
In Vh CoM
In ll CoM

The analytic amplitude

Squared amplitude for *Vh* can be written as:

$$\sum_{L,R} |\mathcal{A}(\hat{s}, \Theta, \theta, \varphi)|^2 = \alpha_L |\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)|^2 + \alpha_R |\mathcal{A}_h(\hat{s}, \Theta, \pi - \theta, \pi + \varphi)|^2$$

with $\alpha_{L,R} = (g^V_{l_{L,R}})^2 / [(g^V_{l_L})^2 + (g^V_{l_R})^2]$

Also define $\epsilon_{LR} = \alpha_L - \alpha_R \approx 0.16,\ 1$ for Z, W

The analytic amplitude

We collect into 9 angular structures:

$$
\begin{aligned}
= \;& a_{LL}\sin^2\Theta\sin^2\theta \\
&+ a^1_{TT}\cos\Theta\cos\theta \\
&+ a^2_{TT}(1+\cos^2\Theta)(1+\cos^2\theta) \\
&+ \cos\varphi\sin\Theta\sin\theta(a^1_{LT} + a^2_{LT}\cos\theta\cos\Theta) \\
&+ \sin\varphi\sin\Theta\sin\theta(\tilde{a}^1_{LT} + \tilde{a}^2_{LT}\cos\theta\cos\Theta) \\
&+ a_{TT'}\cos 2\varphi\sin^2\Theta\sin^2\theta \\
&+ \tilde{a}_{TT'}\sin 2\varphi\sin^2\Theta\sin^2\theta
\end{aligned}
$$

and thus 9 angular observables.

Summary

SMEFT operators in Warsaw basis

$$\mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

→

hVV*/hVff corrections

$\delta\hat{g}^h_{VV}$, g^h_{Vf}, $\hat{\kappa}_{VV}$, $\hat{\tilde{\kappa}}_{VV}$

→

Amplitude

$$\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)$$

→

Angular observables

$$\frac{a^2_{LL}}{4} C_\varphi S_{2\theta} S_{2\Theta}$$

The analytic amplitude

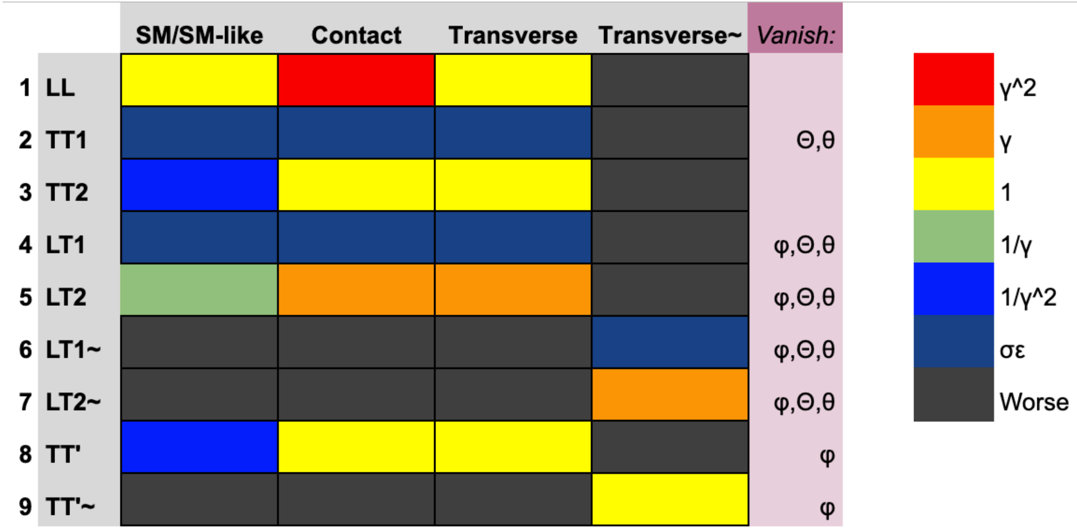
LT interference term dominated by:

$$\sim \frac{a_{LT}^2}{4} \cos\varphi \sin 2\theta \sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4} \sin\varphi \sin 2\theta \sin 2\Theta$$

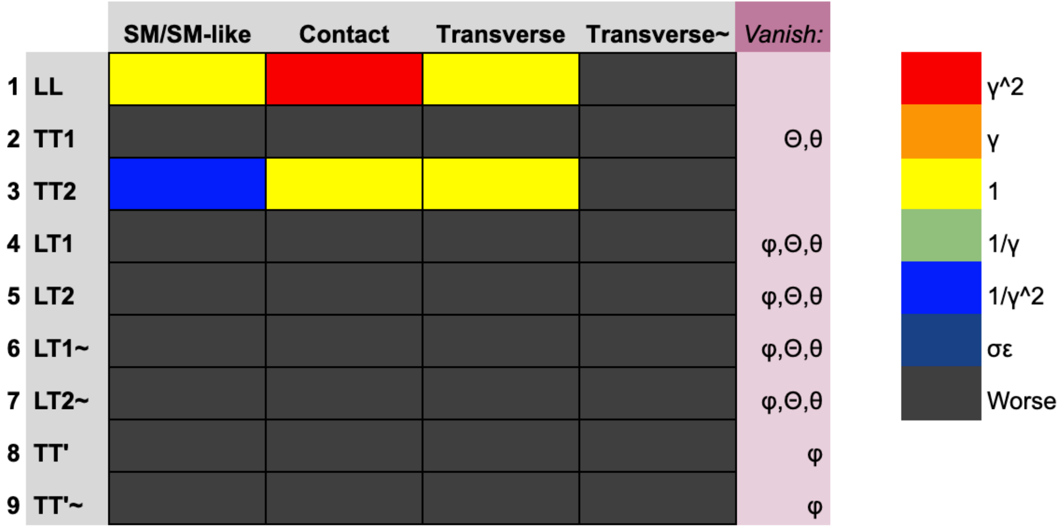
NB: these terms vanish on integration of ANY angle!

a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1+2\delta\hat{g}^h_{VV}+4\kappa_{VV}+\frac{g^h_{Vf}}{g^V_f}(-1+4\gamma^2)\right]$		
a^1_{TT}	$\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma^2}\left[1+4\left(\frac{g^h_{Vf}}{g^V_f}+\kappa_{VV}\right)\gamma^2\right]$		
a^2_{TT}	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Vf}}{g^V_f}+\kappa_{VV}\right)\gamma^2\right]$		
a^1_{LT}	$-\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma}\left[1+2\left(\frac{2g^h_{Vf}}{g^V_f}+\kappa_{VV}\right)\gamma^2\right]$	$\tilde{a}^1_{LT}$	$-\mathcal{G}^2\sigma\epsilon_{LR}\tilde{\kappa}_{VV}\gamma$
a^2_{LT}	$-\frac{\mathcal{G}^2}{2\gamma}\left[1+2\left(\frac{2g^h_{Vf}}{g^V_f}+\kappa_{VV}\right)\gamma^2\right]$	$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{VV}\gamma$
$a_{TT'}$	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Vf}}{g^V_f}+\kappa_{VV}\right)\gamma^2\right]$	$\tilde{a}_{TT'}$	$\frac{\mathcal{G}^2}{2}\tilde{\kappa}_{VV}$

Summary of sensitivity



Total rate sensitivity



Proposal

- Use MadGraph-Pythia-ROOT to generate and cut samples for SM (NLO) and EFT (NLO) and BGs (K-factor)

- Design angular method to extract a_i parameters
- Perform χ^2 tests to establish 1σ bounds

But are these angular structures kept in tact?

Proof of concept: *Zh*

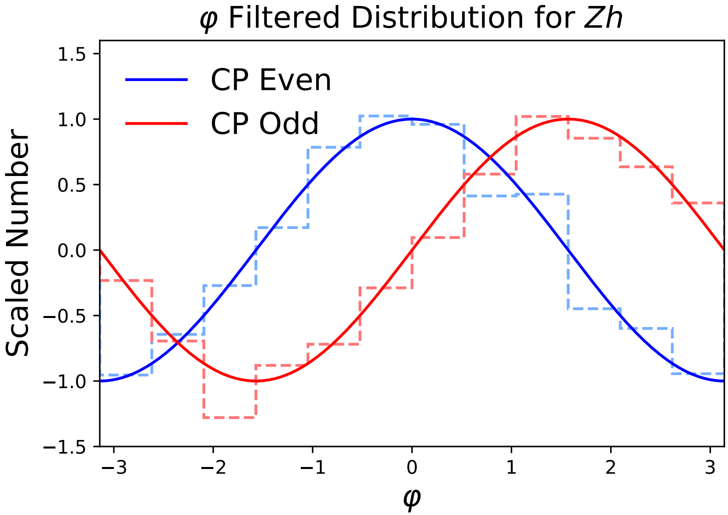
How to probe κ_{ZZ} and $\tilde{\kappa}_{ZZ}$?

Flip signs in regions to maintain positive $\sin 2\theta \sin 2\Theta$

$$\sim \frac{a_{LT}^2}{4} \cos\varphi \sin 2\theta \sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4} \sin\varphi \sin 2\theta \sin 2\Theta$$

$\rightarrow$ expect $\cos\varphi$ distribution for CP even
$\rightarrow$ expect $\sin\varphi$ distribution for CP odd

Proof of concept: ***Zh***

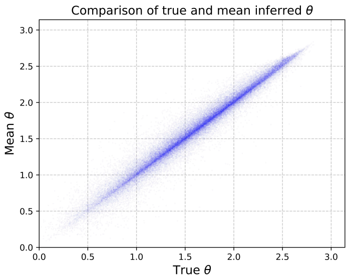


Wh angles

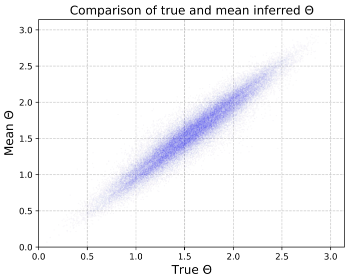
In *Wh* we have to deal with ambiguity in leptonic geometry

Comes from ambiguity in sign of neutrino's p_z

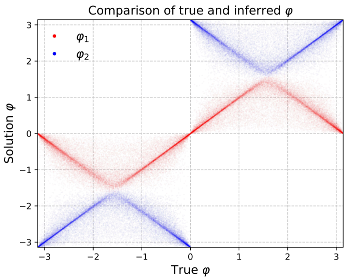
Wh angles



Comparison of true and mean inferred θ
Mean θ
True θ
0.0
0.5
1.0
1.5
2.0
2.5
3.0



Comparison of true and mean inferred Θ
Mean Θ
True Θ
0.0
0.5
1.0
1.5
2.0
2.5
3.0



Comparison of true and inferred φ
φ1
φ2
Solution φ
True φ
−3
−2
−1
0
1
2
3

Method of moments 1

We have a square amplitude $|\mathcal{A}|^2 = \sum_i a_i(E) f_i(\varphi, \Theta, \theta)$

- Look for weight functions $w_i(\varphi, \Theta, \theta)$ such that:

$$\langle w_i | f_j \rangle = \int d(\varphi, \Theta, \theta)\, w_i f_j = \delta_{ij}$$

- Can then pick out angular moments a_i:

$$\int d(\varphi, \Theta, \theta)\, w_i |\mathcal{A}|^2 = a_i$$

Method of moments 2

Look at matrix $M_{ij} = \langle f_i | f_j \rangle$:

$$M = \begin{pmatrix} \frac{512\pi}{225} & 0 & \frac{128\pi}{25} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{8\pi}{9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{128\pi}{25} & 0 & \frac{6272\pi}{225} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{16\pi}{9} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{16\pi}{225} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{16\pi}{9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{16\pi}{225} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} \end{pmatrix}$$

Method of moments 3

- Find that $w_i \propto f_i$ for all except $i = 1, 3$
- Rotate the (1,3) system to an orthogonal basis
- We just use discrete method:

$$a_i = \frac{\hat{N}}{N} \sum_{n=1}^{N} W_i(\Theta_n, \theta_n, \varphi_n)$$

Results 1

- Limit to interference terms
- Contact term constrained by quadratic *E*-dependence
- Implement method of moments to constrain other couplings
- All results for int. luminosity 3 ab^{-1} (HL-LHC)

Summary of sensitivity

		SM/SM-like	Contact	Transverse	Transverse~	*Vanish:*
1	LL					
2	TT1					Θ,θ
3	TT2					
4	LT1					φ,Θ,θ
5	LT2					φ,Θ,θ
6	LT1~					φ,Θ,θ
7	LT2~					φ,Θ,θ
8	TT'					φ
9	TT'~					φ

γ^2
γ
1
1/γ
1/γ^2
σε
Worse

Results: contact

Bounds on contact terms:

- Quadratic EFT contact term in a_{LL} dominates at high E
- Need to use highest-energy bins: too sparse for MoM
- Ensure EFT validity
- Get bounds:

$$|g^h_{WQ}| < 6 \times 10^{-4}, \qquad |g^h_{Z\mathbf{p}}| < 4 \times 10^{-4}.$$

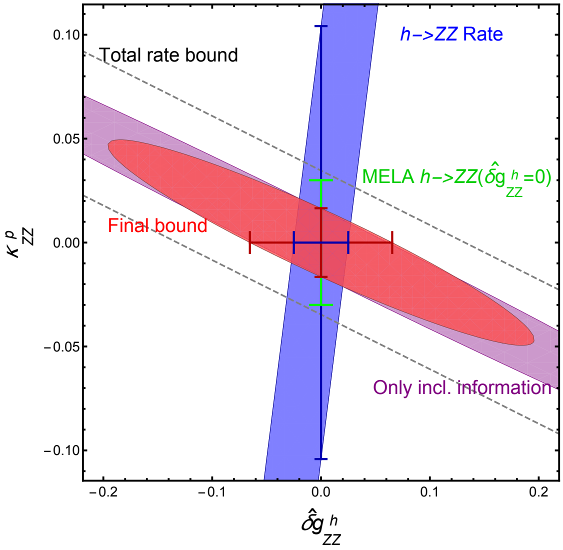
Results: *Zh*

Bounds on other *Zh* couplings:

- Use method of moments
- Get percent-level bounds on κ_{ZZ} in $(\kappa_{ZZ}, \delta g^h_{ZZ})$ plane
- Bounds are competitive and complimentary
- For independent CP odd coupling get bound:

$$|\tilde{\kappa}^{\mathbf{p}}_{ZZ}| < 0.03.$$

Results: ***Zh***



h->ZZ Rate
Total rate bound
MELA h->ZZ($\hat{\delta g}^{h}_{ZZ}$=0)
Final bound
Only incl. information
0.10
0.05
0.00
−0.05
−0.10
−0.2
−0.1
0.0
0.1
0.2
κ^{p}_{ZZ}
$\hat{\delta g}^{h}_{ZZ}$

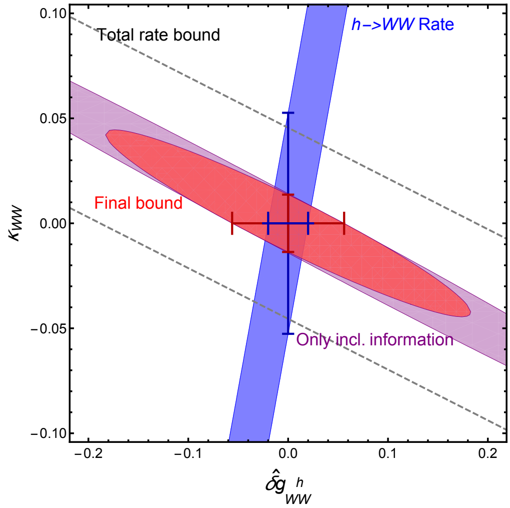
Results: *Wh*

Bounds on other *Wh* couplings:

- Use method of moments
- Get percent-level bounds on κ_{WW} in $(\kappa_{WW}, \delta g^h_{WW})$ plane
- Bounds are competitive and complimentary
- For independent CP odd coupling get bound:

$$|\tilde{\kappa}_{WW}| < 0.04.$$

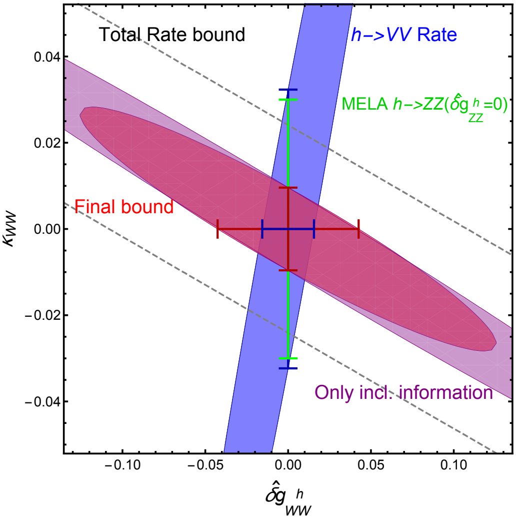
Results: *Wh*


Total rate bound
h->WW Rate
Final bound
Only incl. information
0.10
0.05
0.00
−0.05
−0.10
−0.2
−0.1
0.0
0.1
0.2
κ_{WW}
$\hat{\delta g}^{h}_{WW}$

Results: combination

- Can combine *Zh* and *Wh* results
- This assumes EW symmetry is linearly-realised
- Use correlations
- Get tighter bounds

Results: combination



Note: *WW* and *WZ*

- If EW is linearly-realised, can probe this plane with WW/WZ
- For more details see paper and refs therein
- Can use the relations as a test of EW realisation

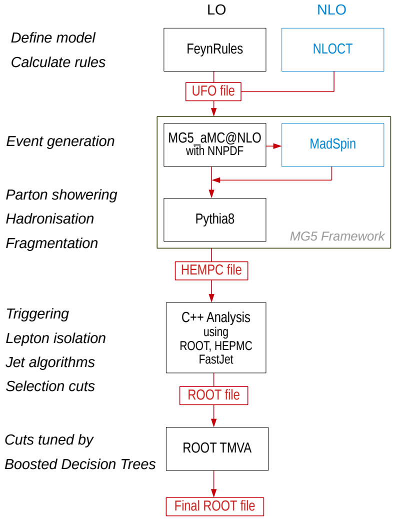
Conclusions

- Move to more sophisticated observables
- Use full differential information to resurrect elusive effects
- Rely on preservation of structures
- Get competitive and complimentary bounds
- Future: extend to more processes $\to$ global fit

For more, see [1912.07628, 1905.02728]

Stay home, stay safe, stay positive

Back up: simulation



Back up: backgrounds

Zh:

- Zbb
- ggF-h-ZZ
- ggBox-Zh
- Z+jets

Wh:

- Wbb
- tt-WWbb SL
- tt-WWbb FL
- W+jets