THE OPERATOR OBSERVABLE MAP

Towards the ultimate differential SMEFT analysis

Scalars 2019, Warsaw

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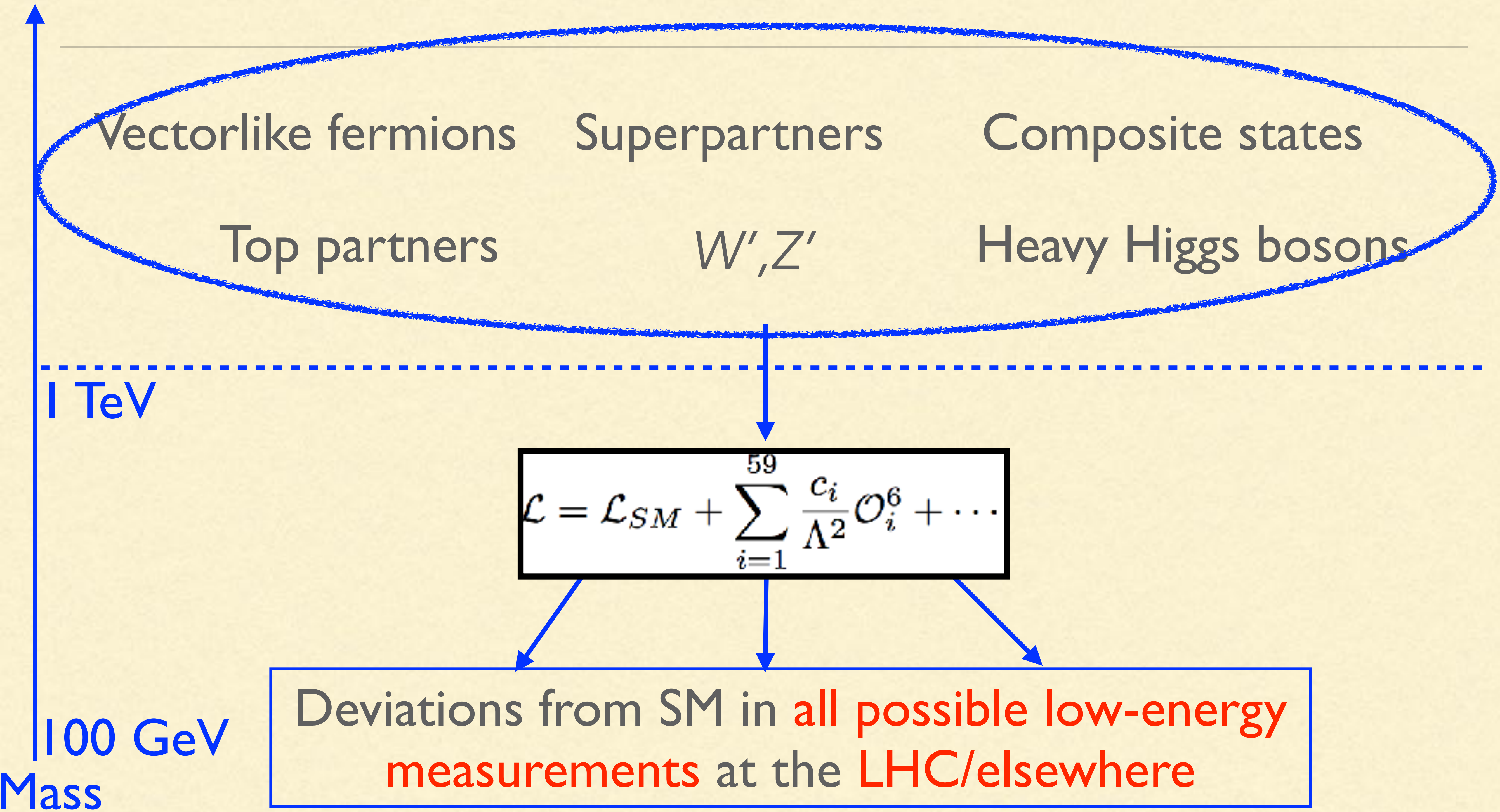
IPPP Durham, UK

Based on: Banerjee, RSG, Reines & Spannowsky (2018,2019, in prep.)

SMEFT: MODEL INDEPENDENT PARAMETRISATION



SMEFT: MODEL INDEPENDENT PARAMETRISATION

Vectorlike fermions   Superpartners   Composite states

To[...] ...bosons

But cannot see Lagrangian in a lab!

We see amplitudes

1 TeV

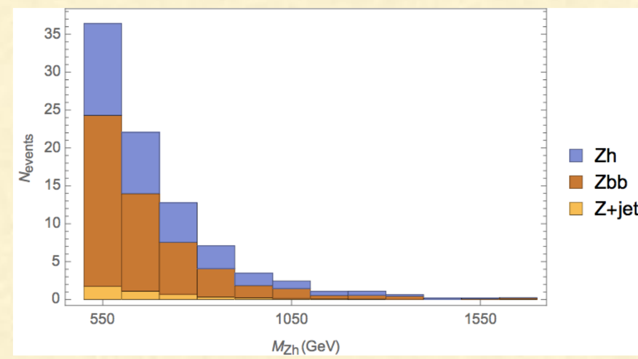
$i=1$

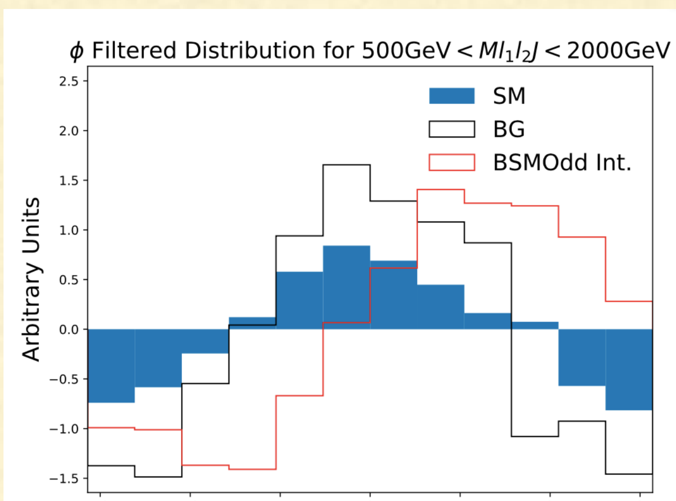
Deviations from SM in all possible low-energy measurements at the LHC/elsewhere

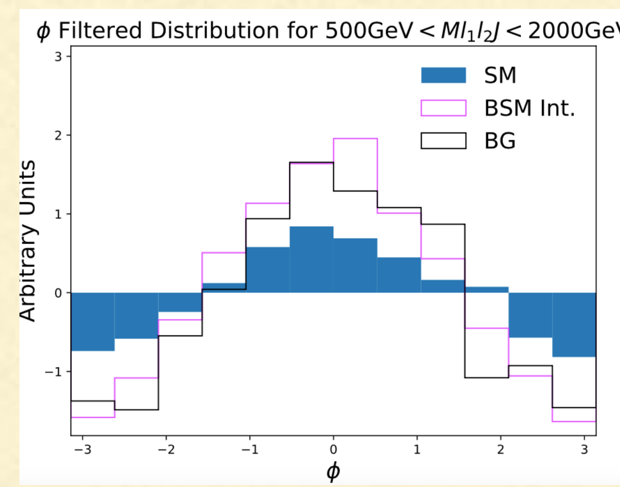
100 GeV

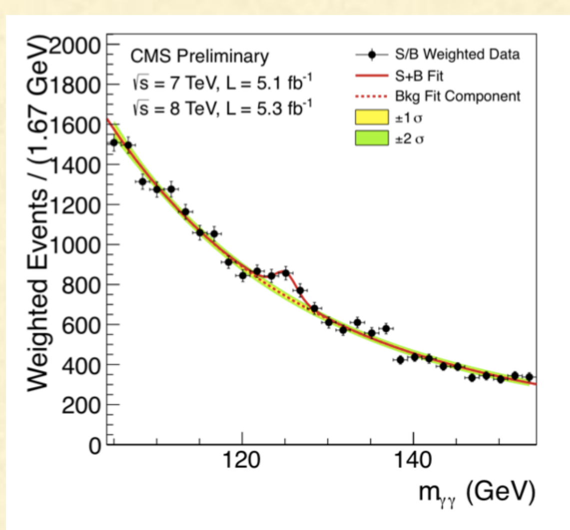
Mass

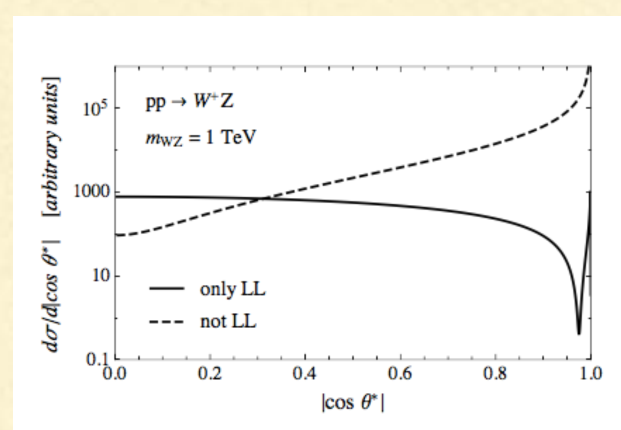
PLETHORA OF DATA AT LHC

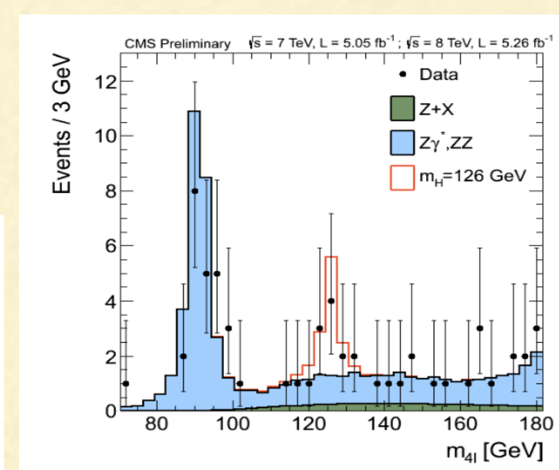






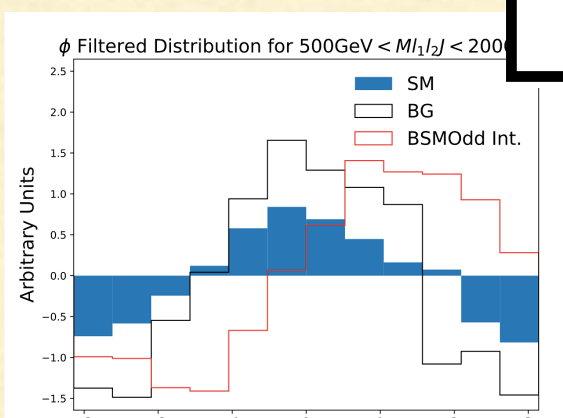


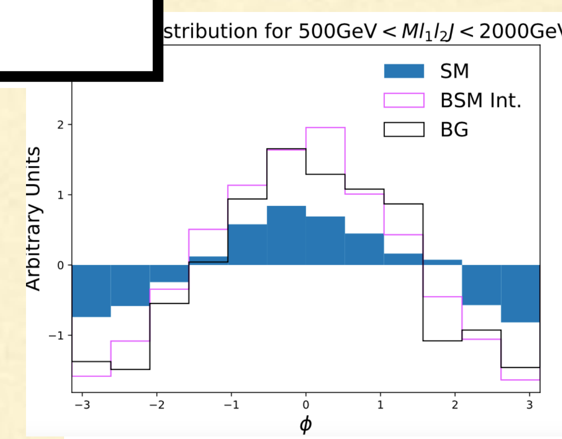


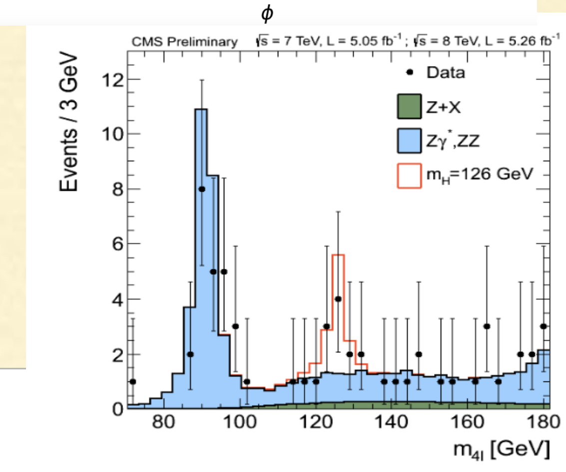


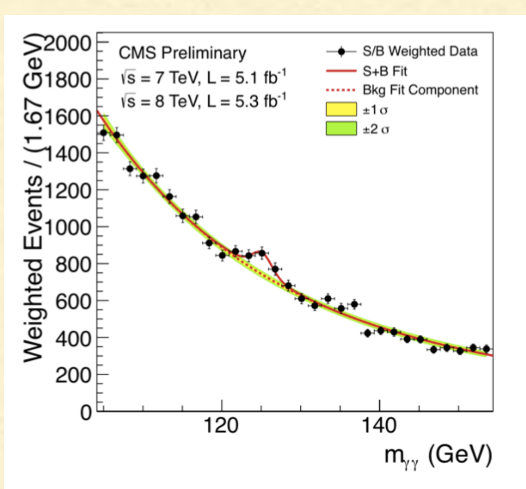
HOW TO RECONSTRUCT THE LAGRANGIAN?

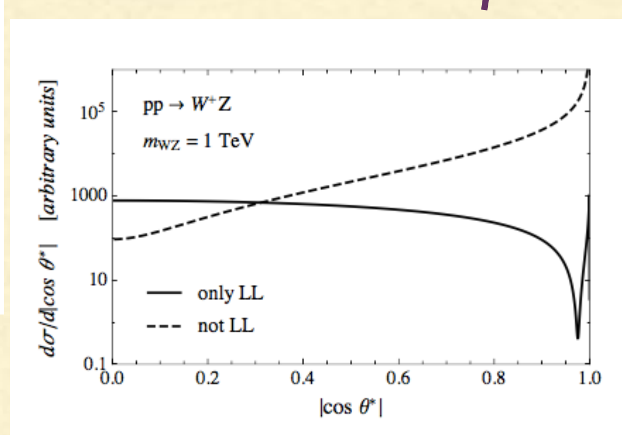
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{59} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \cdots$$

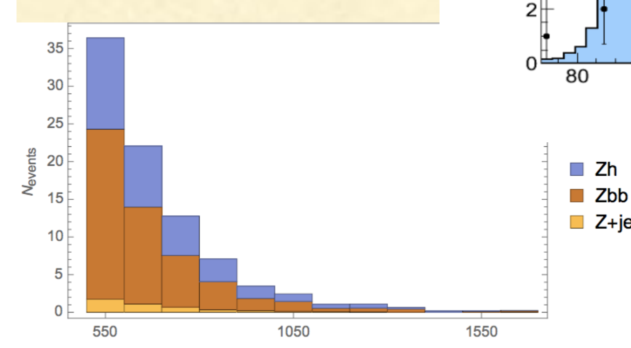






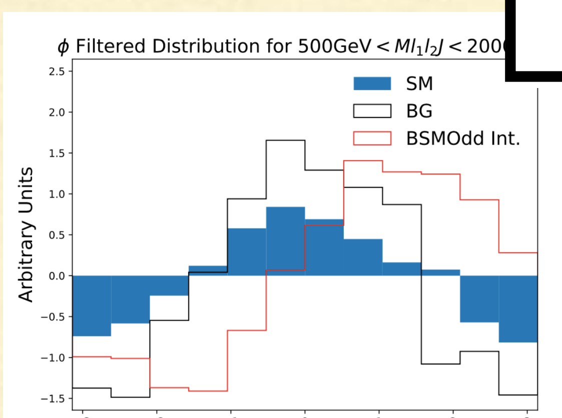


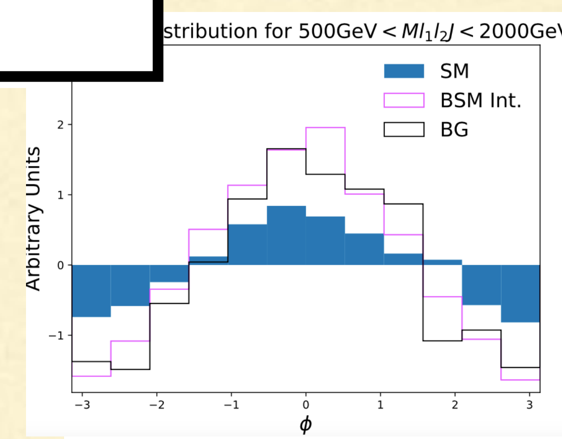


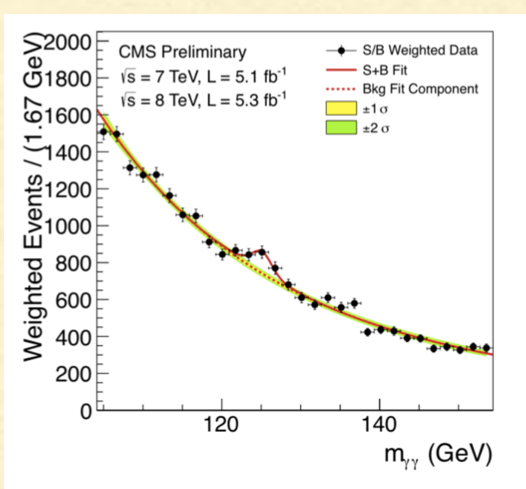


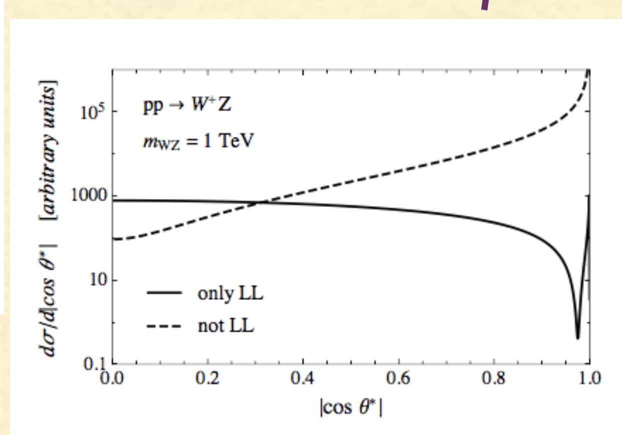
THE OPERATOR OBSERVABLE MAP

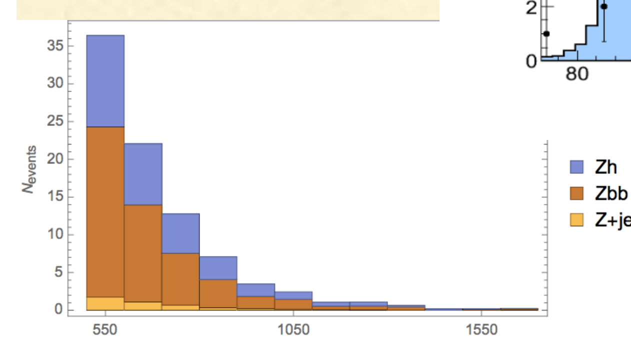
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{59} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \cdots$$

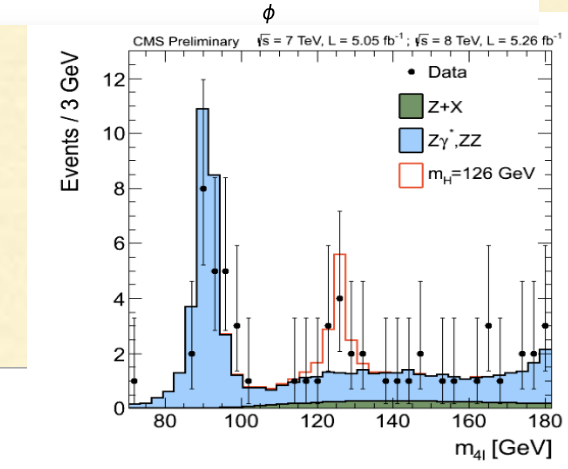










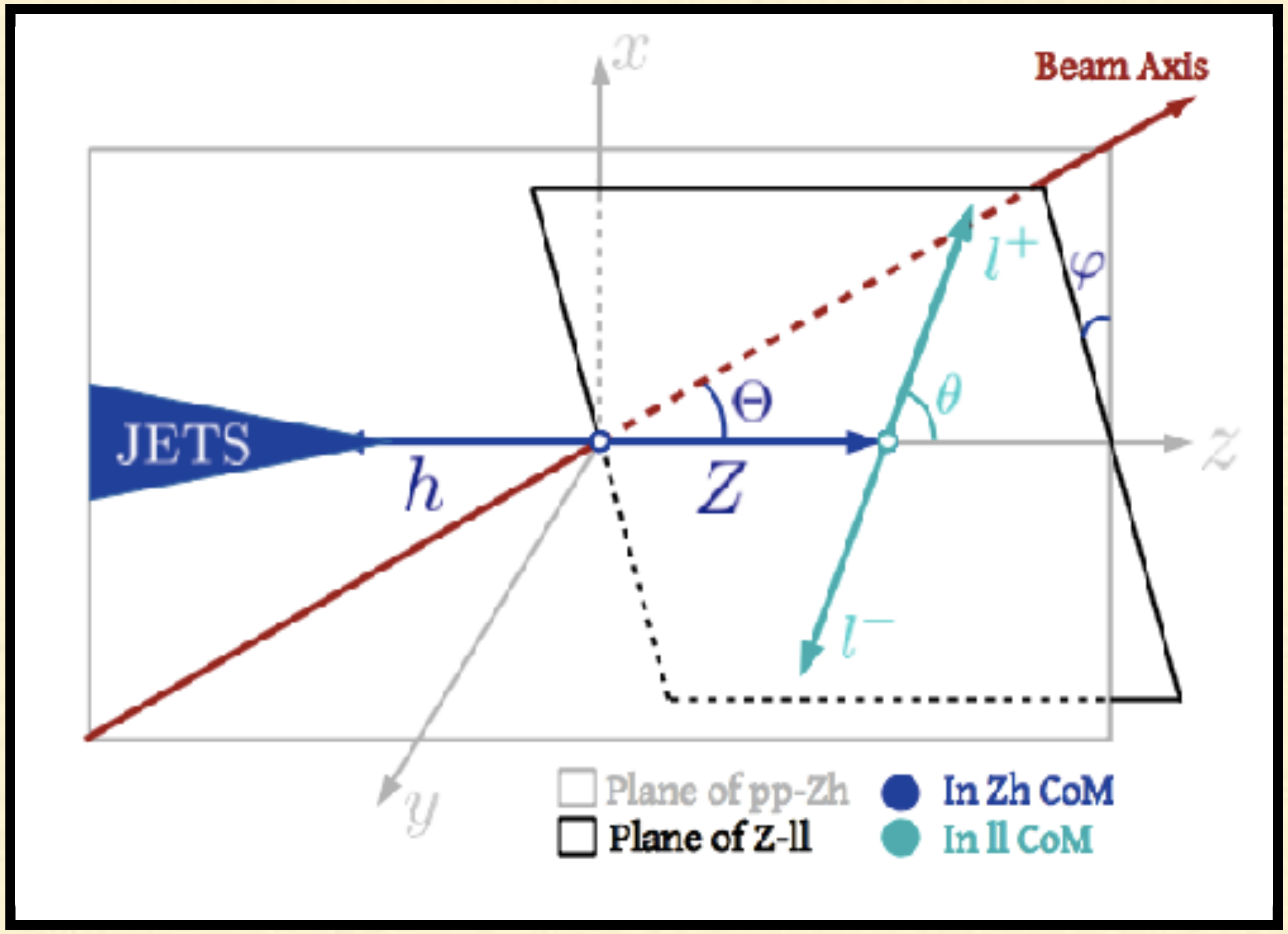


MAIN QUESTIONS

- New vertices in the EFT often show much more pronounced effect differentially in energy/angular variables
- How do we efficiently extract *all* the differential information in a process ?
- How do we prevent reduction of differential information in experimental analyses ?
- Such questions especially relevant as we enter era of high energies and luminosities

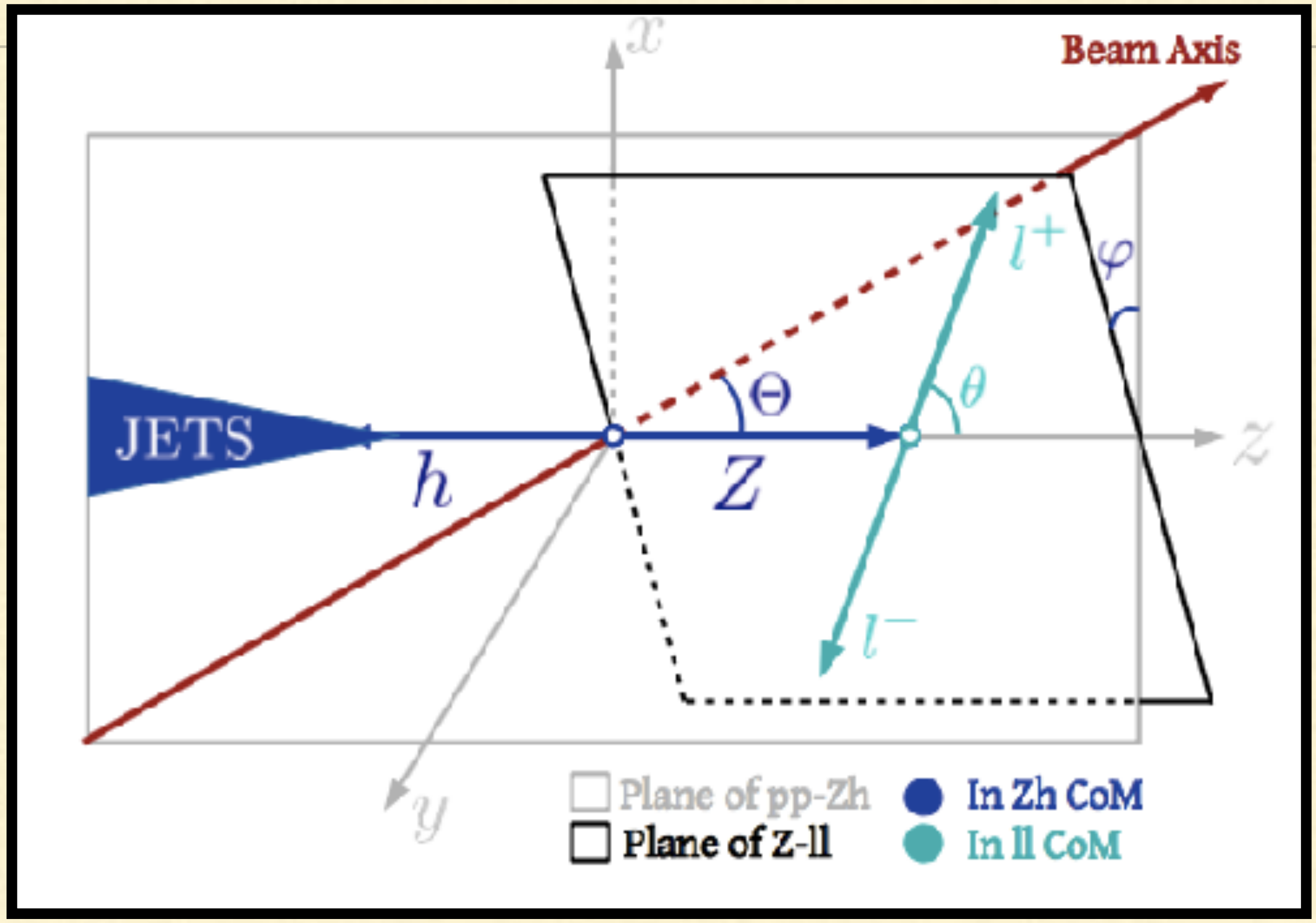
CASE STUDY: *pp> Z(ll)H(fat jet)*

- How much differential information in this process?
- Three body phase space so 3x3-4=5 kinematical variables completely define the final state



- Ignoring the boost there are 4: $\sqrt{s},\ \Theta,\ \theta,\ \varphi$

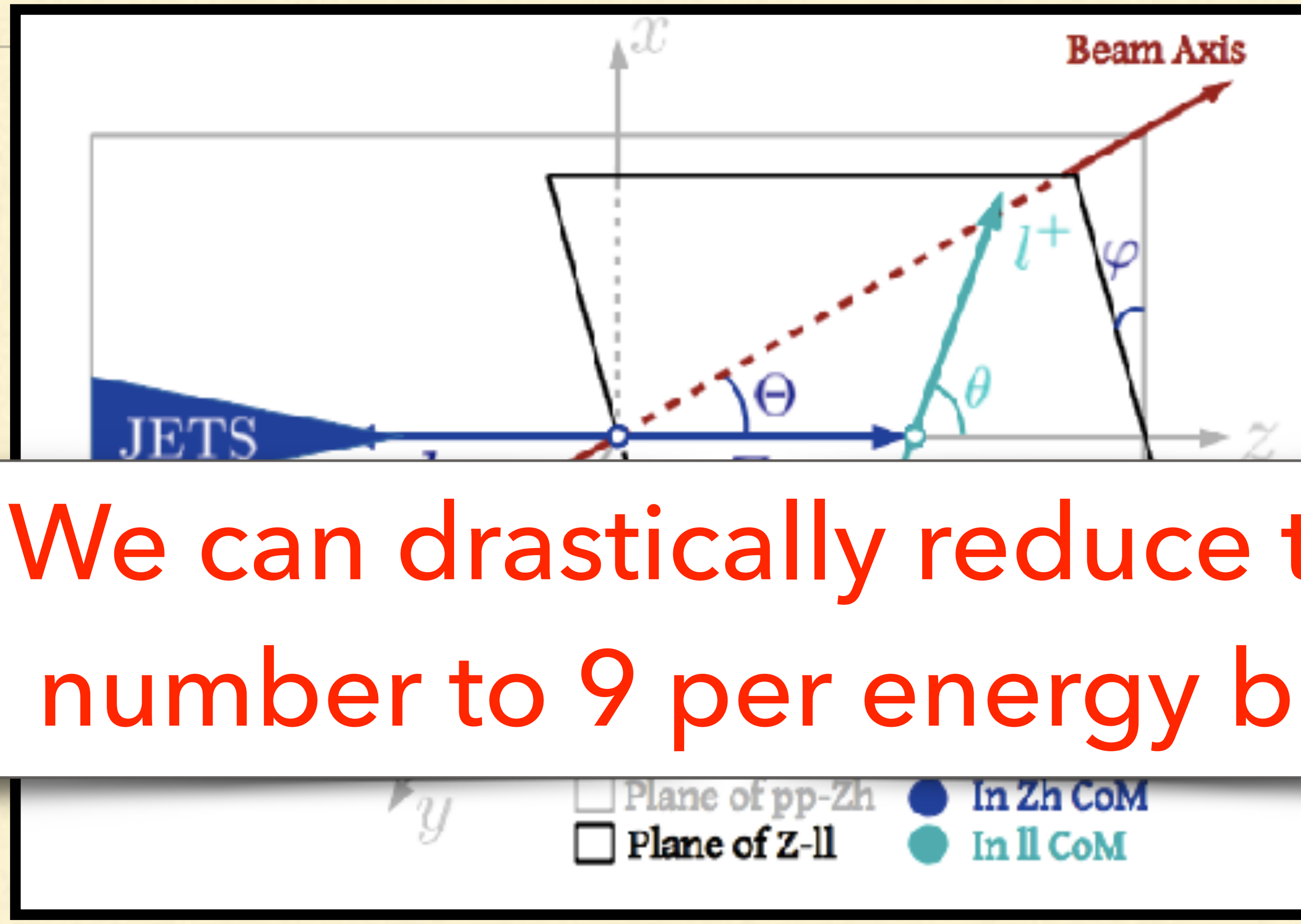
$pp > Z(ll)H(\text{fat jet})$:HOW MUCH INFORMATION ?



$$\sqrt{s},\ \Theta,\ \theta,\ \varphi$$

If we take 10 bins for each variable: 1000 numbers per energy bin to encapsulate full information

pp> Z(ll)H(fat jet) :HOW MUCH INFORMATION ?



We can drastically reduce this number to 9 per energy bin!

$$\sqrt{s},\ \ \Theta,\ \ \theta,\ \ \varphi$$

- If we take 10 bins for each variable: 10,000 numbers to encapsulate full information

HELICITY AMPLITUDES

$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}.$$

$$\mathcal{M}_\sigma^{\lambda=\pm} = \sigma\frac{1+\sigma\lambda\cos\Theta}{\sqrt{2}}\frac{gg_f^Z}{c_{\theta_W}}\frac{m_Z}{\sqrt{\hat{s}}}\left[1+\left(\frac{g^h_{Zf}}{g_f^Z}+\kappa_{ZZ}-i\lambda\tilde{\kappa}_{ZZ}\right)\frac{\hat{s}}{2m_Z^2}\right]$$

$$\mathcal{M}_\sigma^{\lambda=0} = -\sin\Theta\frac{gg_f^Z}{2c_{\theta_W}}\left[1+\delta\hat{g}^h_{ZZ}+2\kappa_{ZZ}+\frac{g^h_{Zf}}{g_f^Z}\left(-\frac{1}{2}+\frac{\hat{s}}{2m_Z^2}\right)\right],$$

- Three J=1 helicity amplitudes at 2 to 2 level. 4 SMEFT vertices contribute to these up to D6 level. No contributions to J>1

HELICITY AMPLITUDES

KEY POINT: Only a finite number of helicity amplitudes get corrections up to a given EFT order.

- Three J=1 helicity amplitudes at 2 to 2 level. 4 SMEFT vertices contribute to these up to D6 level. No contributions to J>1

HELICITY AMPLITUDES

$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}.$$

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

$$g^h_{Zf} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T_3^f|c^{(1)}_{HF} - T_3^f c^{(3)}_{HF} + (1/2 - |T_3^f|)c_{Hf})$$

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

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

Can be translated to Wilson coefficients (Warsaw Basis)

SQUARED AMPLITUDE AT THE 2 TO 3 LEVEL

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

Z to ll

QM says we must coherently sum over intermediate Z

$$\sum_{L,R}|\mathcal{A}(\hat{s},\Theta,\theta,\varphi)|^2$$ =3x3=9 terms

- We finally get 9 independent terms.
- Including 6 interference terms between different Z helicities contributions exist.

pp>Z(ll)H SQUARED AMPLITUDE IN SM & D6 SMEFT

$$
\begin{aligned}
\sum_{L,R} |\mathcal{A}(\hat{s},\Theta,\theta,\varphi)|^2 &= a_{LL}\sin^2\Theta\sin^2\theta + a^1_{TT}\cos\Theta\cos\theta \\
&+ a^2_{TT}(1+\cos^2\Theta)(1+\cos^2\theta) + \cos\varphi\sin\Theta\sin\theta \\
&\times (a^1_{LT} + a^2_{LT}\cos\theta\cos\Theta) + \sin\varphi\sin\Theta\sin\theta \\
&\times (\tilde{a}^1_{LT} + \tilde{a}^2_{LT}\cos\theta\cos\Theta) + a_{TT'}\cos 2\varphi\sin^2\Theta\sin^2\theta \\
&+ \tilde{a}_{TT'}\sin 2\varphi\sin^2\Theta\sin^2\theta.
\end{aligned}
$$

- The 9 coefficients above are the 9 angular moments for *pp>Z(ll)H*
- The angular moments can be used to reconstruct any possible kinematic distribution. The contain *all* the differential information.

Banerjee, RSG, Reines & Spannowsky (2019)

OPERATOR-OBSERVABLE MAP

True observables

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

Banerjee, RSG, Reines & Spannowsky (2019)

MEASURING THE MOMENTS

- We can use analog of Fourier analysis to extract these angular moments

$$P(\Omega) = \sum_i a_i \times g_i(\Omega)$$

- Consider vector space spanned by angular moments. Find reciprocal vectors (weight functions)

$$w_i(\Omega) = \sum_i \lambda_{ij} g_j(\Omega) \longrightarrow \int d\Omega \; g_i(\Omega) w_j(\Omega) = \delta_{ij}$$

- Convoluting observed angular distribution with these weight functions gives us these angular moments $\longrightarrow$

$$a_i = \int d\Omega \; P(\Omega) w_i(\Omega)$$

Dunietz, Quinn, Snyder, Toki & Lipkin (1991)

MEASURING THE MOMENTS

- We can use analog of I ... these angular moments

$$g^1 = S_\Theta^2 S_\theta^2$$
$$g^2 = C_\Theta C_\theta$$
$$g^3 = (1 + C_\Theta^2)(1 + C_\theta^2)$$
$$g^4 = C_\varphi S_\Theta S_\theta$$
$$g^5 = C_\varphi S_\Theta S_\theta C_\Theta C_\theta$$
$$g^6 = S_\varphi S_\Theta S_\theta$$
$$g^7 = S_\varphi S_\Theta S_\theta C_\Theta C_\theta$$
$$g^8 = C_{2\varphi} S_\Theta^2 S_\theta^2$$
$$g^9 = S_{2\varphi} S_\Theta^2 S_\theta^2$$

- Consider vector space ... nts. Find reciprocal vectors (weight functio ...

$$w_i(\Omega) = \sum_i \lambda_{ij} \ldots$$

$$\ldots g_i(\Omega) w_j(\Omega) = \delta_{ij}$$

- Convoluting observed ... hese weight functions gives us these angular ...

$$a_i = \int d\Omega \; P(\Omega) w_i(\Omega)$$

Banerjee, RSG, Reines & Spannowsky (in prep.)

MEASURING THE MOMENTS

$$w_i(\Omega) = \sum_i \lambda_{ij} g_j(\Omega)$$

Inverse

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

Observed Distribution
In our case simulated using
MADGRAPH+PYTHIA

$$a_i = \int d\Omega \; P(\Omega) w_i(\Omega)$$

Banerjee, RSG, Reines & Spannowsky (in prep.)

ANGULAR MOMENTS

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

dominant at high energies

ENERGY GROWING EFFECTS

- At high energies the *LL* term is dominant a_{LL}

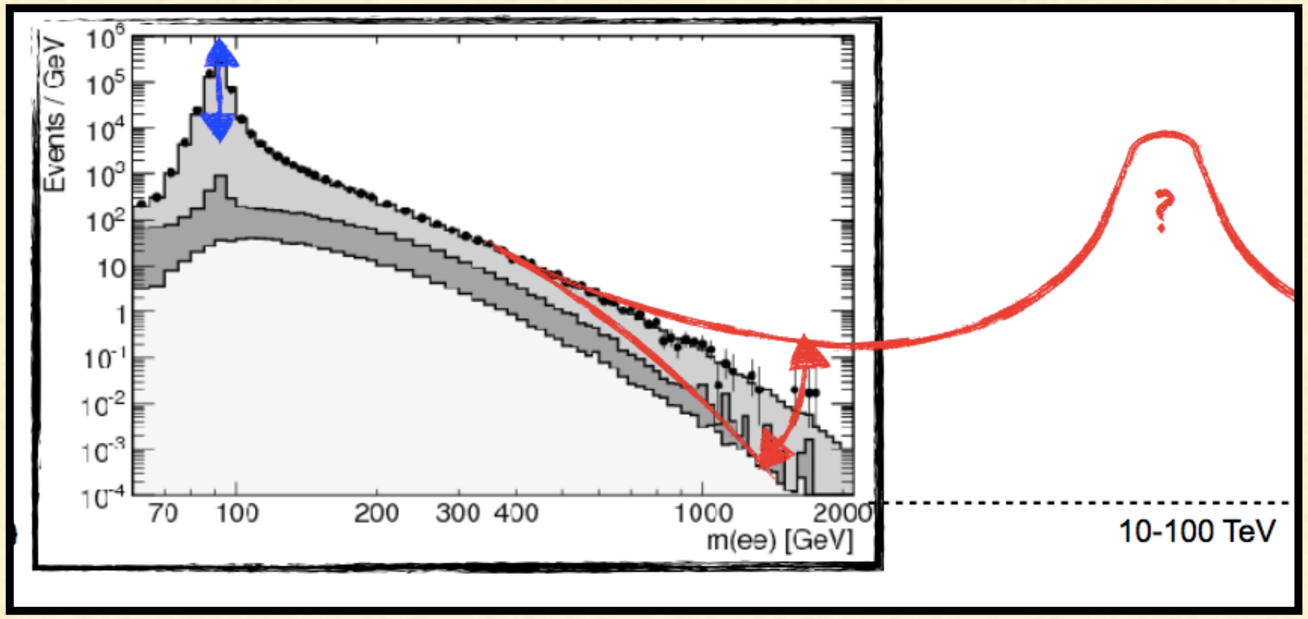
$$\sin\Theta \frac{g g_f^Z}{2c_{\theta_W}}\left[1+\delta\hat{g}^h_{ZZ}+2\kappa_{ZZ}+\frac{g^h_{Zf}}{g_f^Z}\left(-\frac{1}{2}+\frac{\hat{s}}{2m_Z^2}\right)\right] \times \sin\Theta \frac{g g_f^Z}{2c_{\theta_W}}\left[1+\delta\hat{g}^h_{ZZ}+2\kappa_{ZZ}+\frac{g^h_{Zf}}{g_f^Z}\left(-\frac{1}{2}+\frac{\hat{s}}{2m_Z^2}\right)\right]$$

- Interference term grows quadratically with energy with respect to SM

- This growth is driven by *hVff* contact term,

Banerjee, RSG, Reines & Spannowsky (2018)

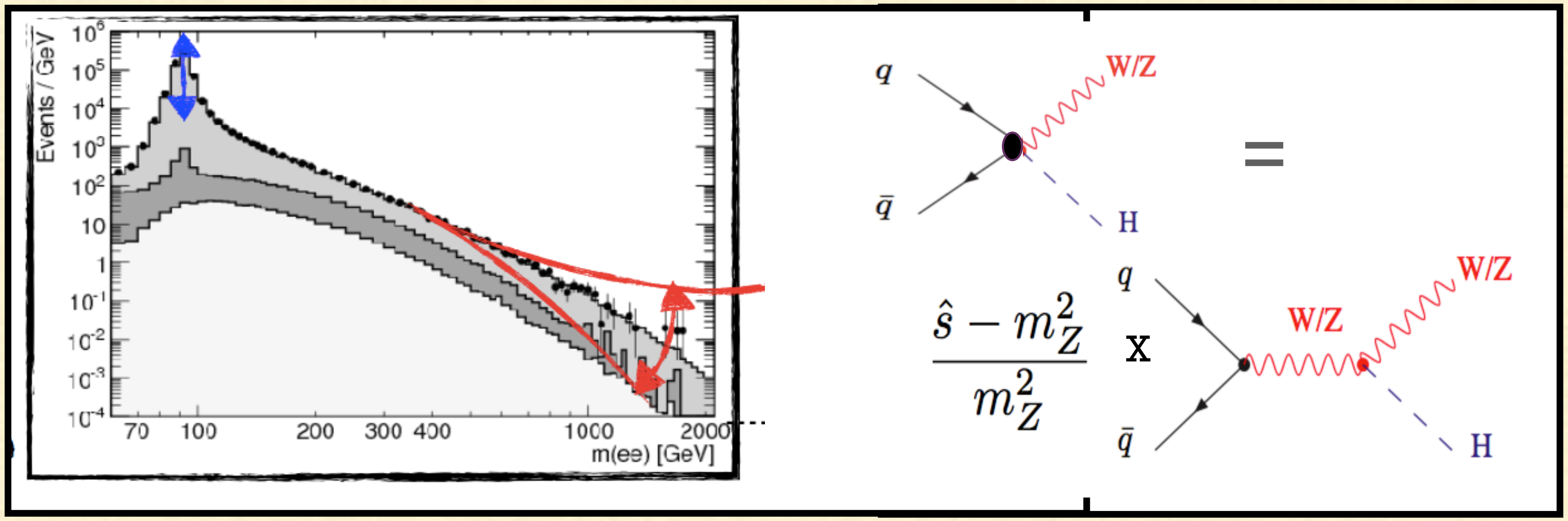
ENERGY GROWING EFFECTS



- Small anomalous coupling (*hVff*) can cause large relative deviation at high energies
- Precise measurement of such anomalous couplings possible

Picture Courtesy: F. Riva

ENERGY GROWING EFFECTS



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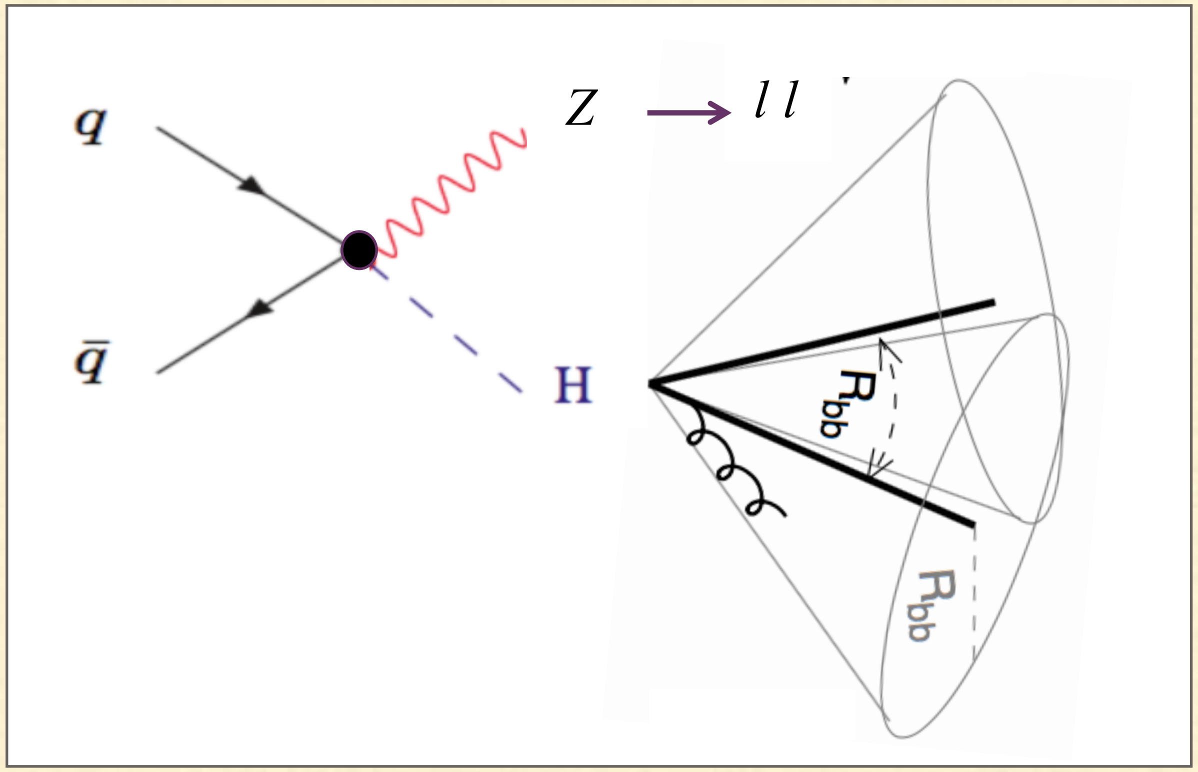
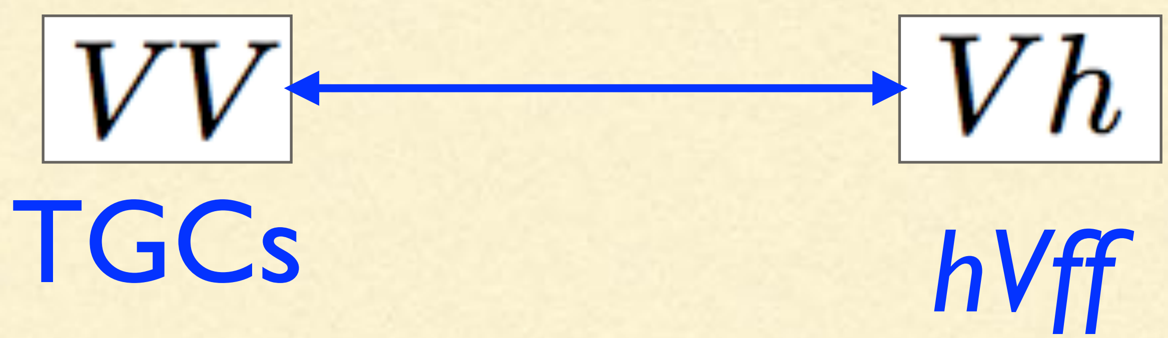
ENERGY GROWING EFFECTS



- We studied *Z(ll)H(bb)* at high energies using boosted Higgs reconstruction techniques to obtain per-mille level bounds on *hVff* couplings: $|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$

Banerjee, RSG, Reines & Spannowsky (2018)

ENERGY GROWING EFFECTS

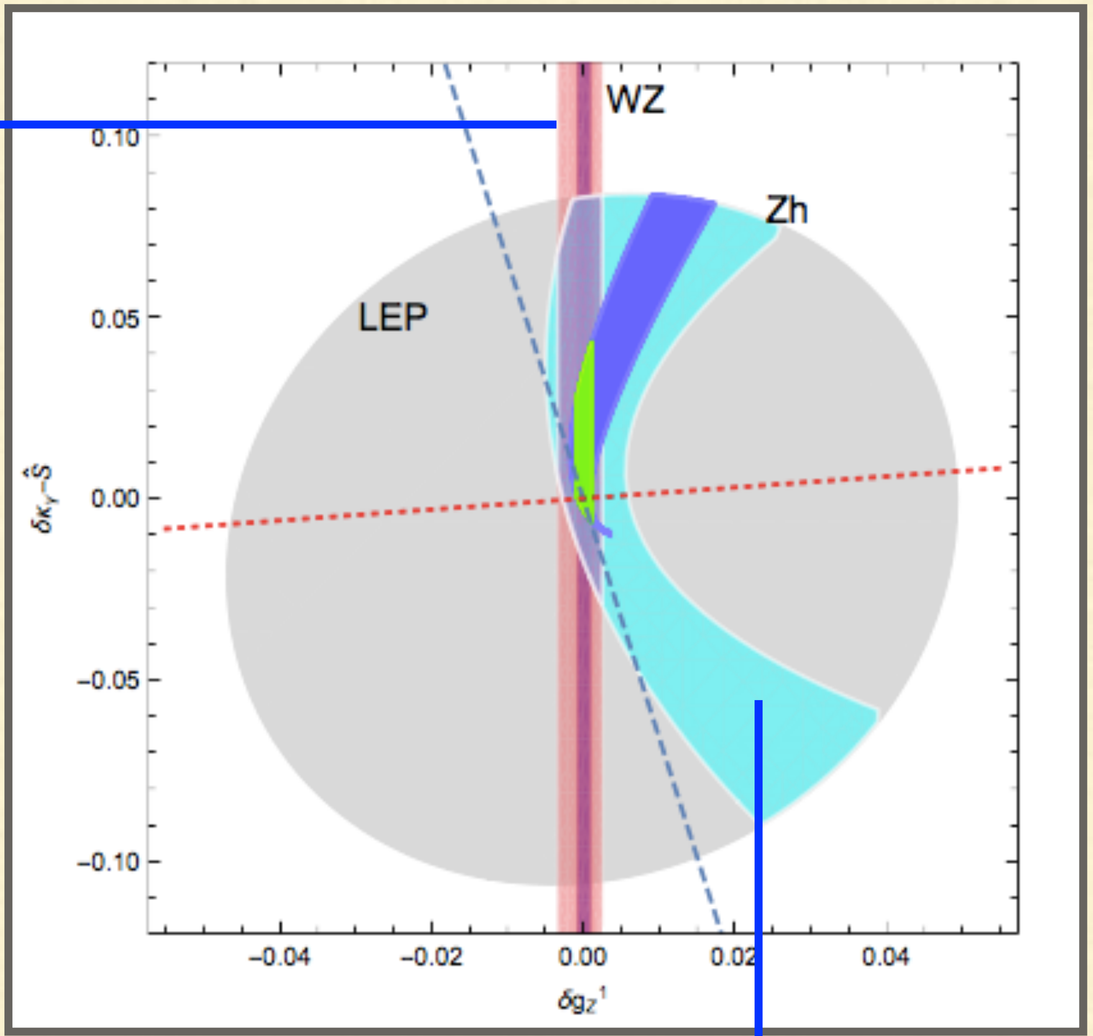


- Related by Goldstone Boson Equivalence
- Operators that generate *hVff* terms also generate V^3 terms i.e. Triple Gauge Couplings (TGC)

Franceschini, Panico, Pomarol, Riva & Wulzer (2017)

RESULTS: LARGE IMPROVEMENT OVER LEP

Franceschini, Panico, Pomarol, Riva & Wulzer (2017)



Banerjee, Englert, RSG & Spannowsky (2018)

ANGULAR MOMENTS

dominant at high energies
low-hanging fruit

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ANGULAR MOMENTS

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a^2 [illegible]	$\mathcal{G}^2$ [illegible]
[illegible]	[illegible]
a_{LT}	[illegible] $\frac{}{2\gamma}$ [illegible] $\frac{}{g^Z_f}+\kappa_{ZZ}\big)\gamma$ [illegible]
$\tilde{a}^1_{LT}$	$-\mathcal{G}^2\sigma\epsilon_{LR}\tilde{\kappa}_{ZZ}\gamma$
$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{ZZ}\gamma$
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dominant at high
low-hanging f

What information do other moments carry ?

ANGULAR MOMENTS

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

parametrically suppressed

ANGULAR MOMENTS

Only sensitive to these if Z inclusively treated

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

Cross-helicity terms. Vanish upon inclusive integration over lepton phase space

Differential analysis a must

ANGULAR MOMENTS

Only sensitive to these if Z inclusively treated

$$g^1 = S_\Theta^2 S_\theta^2$$

$$g^2 = C_\Theta C_\theta$$

$$g^3 = (1 + C_\Theta^2)(1 + C_\theta^2)$$

$$g^4 = C_\varphi S_\Theta S_\theta$$

$$g^5 = C_\varphi S_\Theta S_\theta C_\Theta C_\theta$$

$$g^6 = S_\varphi S_\Theta S_\theta$$

$$g^7 = S_\varphi S_\Theta S_\theta C_\Theta C_\theta$$

$$g^8 = C_{2\varphi} S_\Theta^2 S_\theta^2$$

$$g^9 = S_{2\varphi} S_\Theta^2 S_\theta^2$$

Cross-helicity terms. Vanish upon inclusive integration over lepton phase space

Differential analysis a must

ANGULAR MOMENTS

Only sensitive to these if Z inclusively treated

$$\delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}\,h\,\frac{Z^\mu Z_\mu}{2} + \kappa_{ZZ}\,\frac{h}{2v}\,Z^{\mu\nu}Z_{\mu\nu}$$

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

$$|g^h_{Z\mathbf{p}}| < 5\times10^{-4}$$

ANGULAR MOMENTS

$\lvert g^h_{Z\mathbf{p}}\rvert < 5\times 10^{-4}$

a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1+2\delta\hat{g}^h_{ZZ}+4\kappa_{ZZ}+\frac{g^h_{Zf}}{g^Z_f}(-1+4\gamma^2)\right]$
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$a_{TT'}$	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}_{TT'}$	$\frac{\mathcal{G}^2}{2}\tilde{\kappa}_{ZZ}$

CP-odd moments probe

$\tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$

Cross-helicity terms. Vanish upon inclusive integration over lepton phase space

Differential analysis a must

ANGULAR MOMENTS

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

$$|g^h_{Z\mathbf{p}}| < 5\times 10^{-4}$$

CP-even moments probe

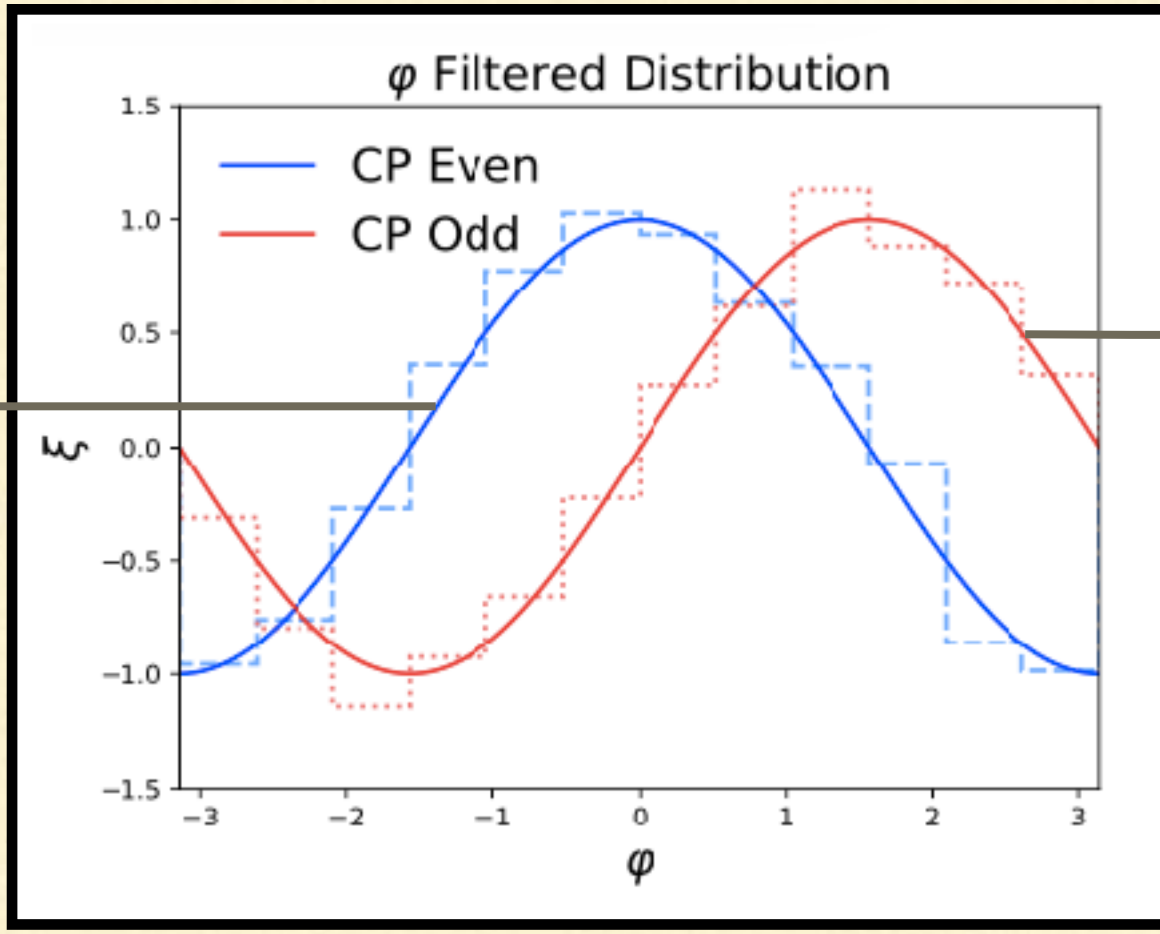
$$\kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}$$

Cross-helicity terms. Vanish upon inclusive integration over lepton phase space

Differential analysis a must

A TRIPLE DIFFERENTIAL OBSERVABLE

$$\kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}$$

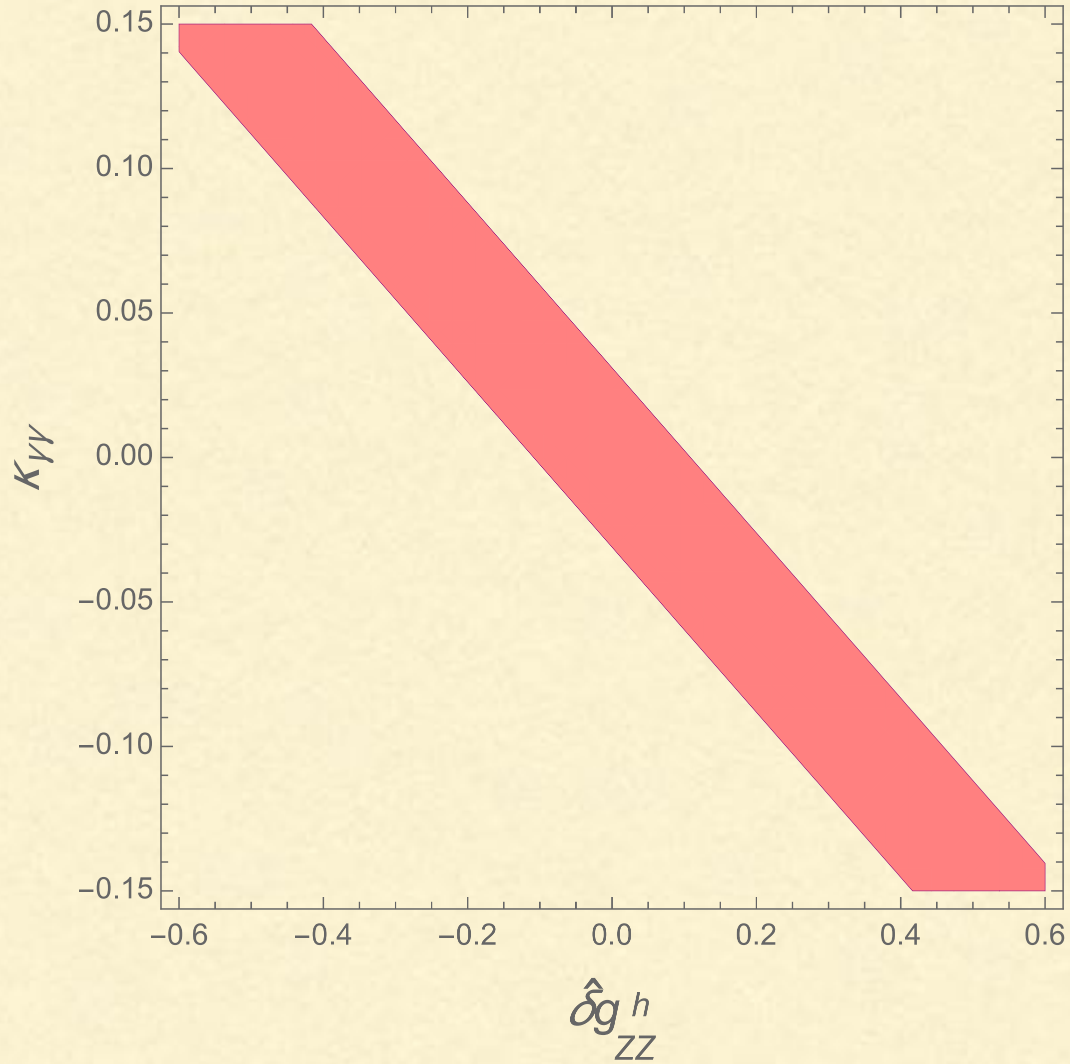


$$\tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}.$$

Dominant cross-helicity CP even & odd angular moment

Banerjee, RSG, Reines & Spannowsky (2019)

RESULTS

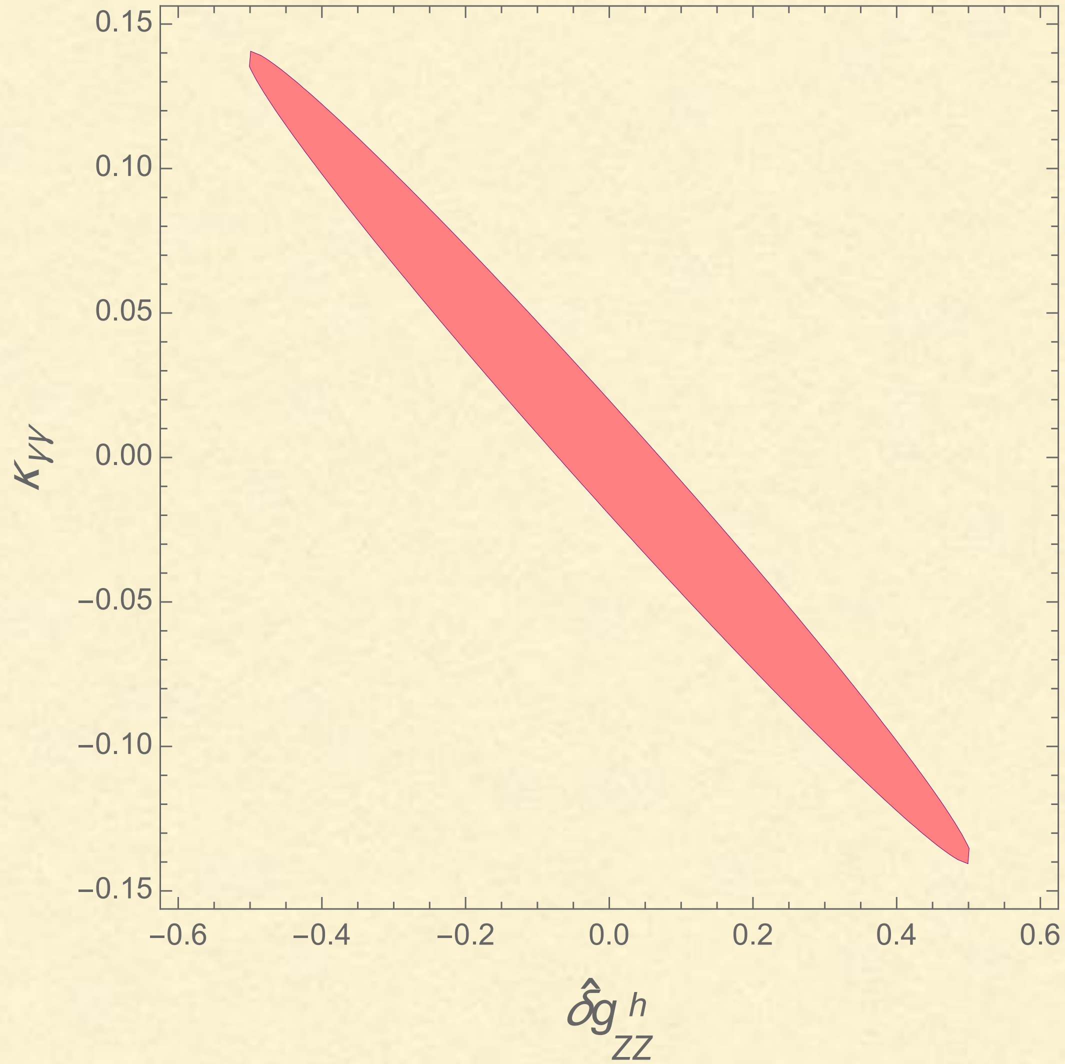


$$|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$$

Total Rate

Banerjee, RSG, Reines & Spannowsky (in prep.)

RESULTS



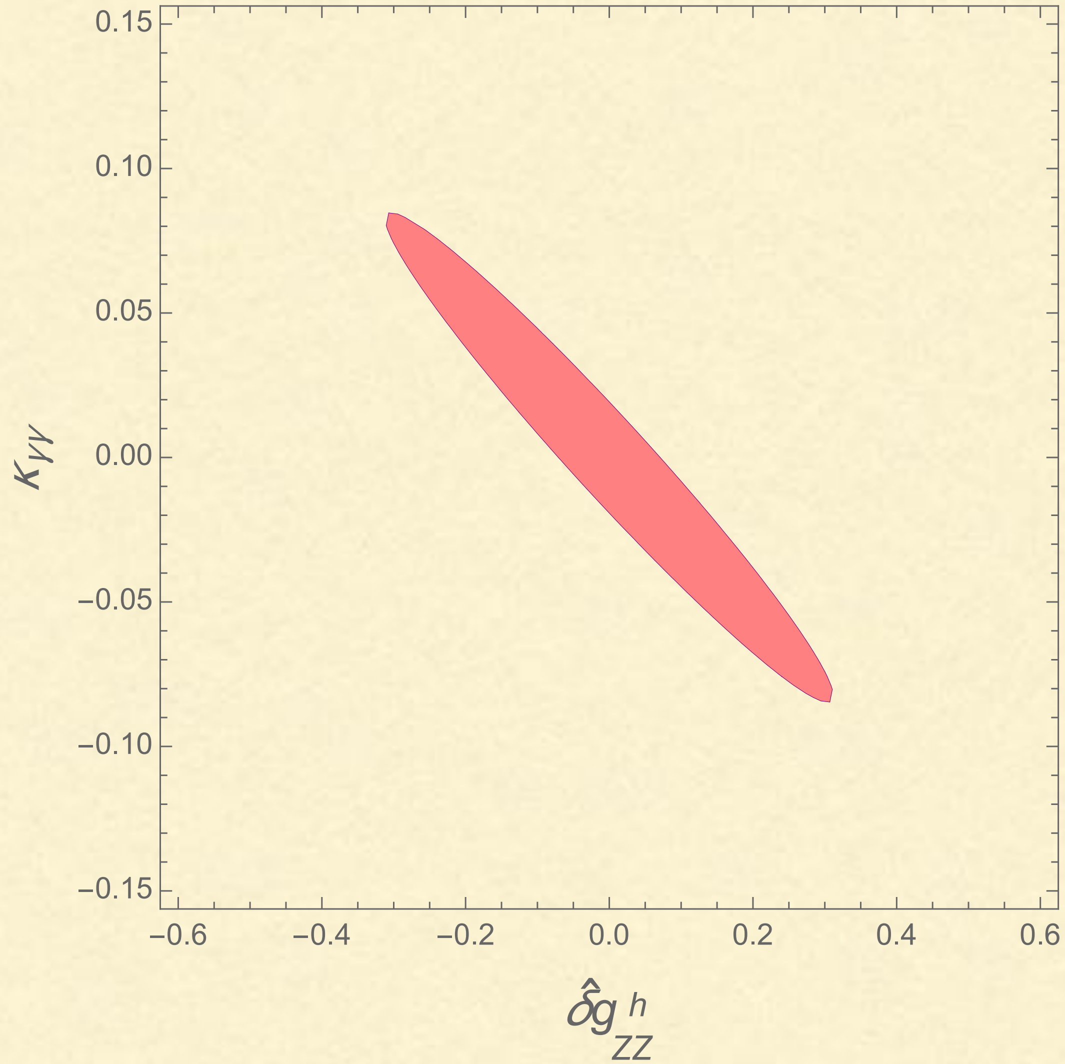
$$|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$$

Inclusive angular moments

Banerjee, RSG, Reines & Spannowsky (in prep.)

RESULTS

CP-even:



$|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$.

CP-odd:

$|\tilde{\kappa}_{ZZ}| < 0.05$

All angular moments

FUTURE DIRECTIONS

- We presented a way to extract all the differential data in *pp>Z(ll)h*
- This was only a case study. This method can be extended to all the standard electroweak processes: *pp >VV, VV > h, h>Z(ll)Z(ll)*
- Can this be a more transparent alternative to machine learning methods that also aim to prevent reduction of differential data?