Probing CP-odd Higgs couplings

Michael Spannowsky

IPPP, Durham University

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"Everything has been said, but not yet by everybody"

[Karl Valentin]

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Existing experimental results in searches of CP violating effects in Higgs coupling measurements

[ATLAS 1602.04516]

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu}$$

$$+ \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

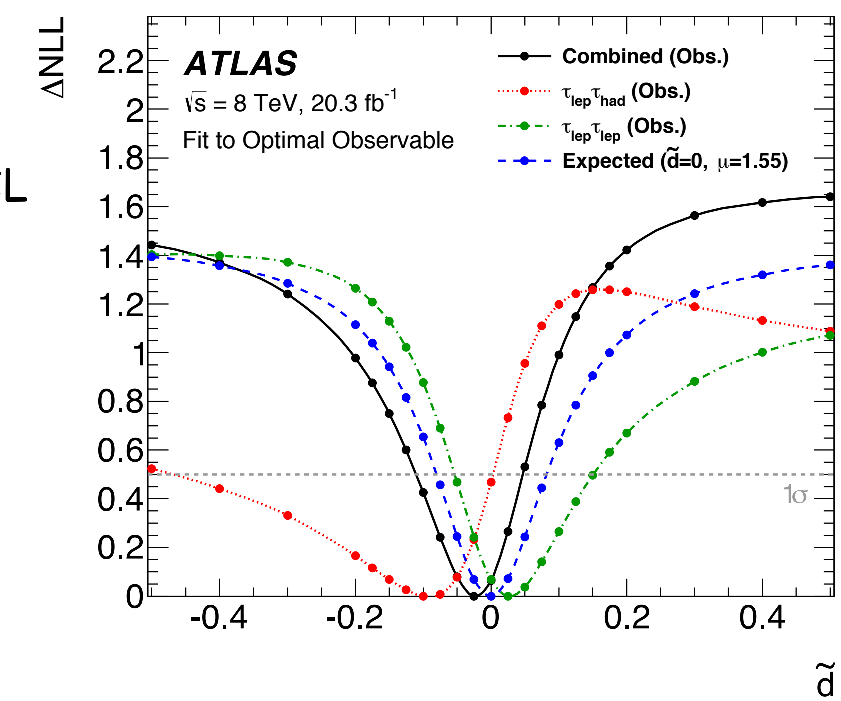
- Only 2 linearly indep. due to gauge invariance
- relate two parameters -> get $\tilde{d}$

In WBF H-> tautau

Excluded at 68% CL

$\tilde{d} < -0.11$

$\tilde{d} > 0.05$

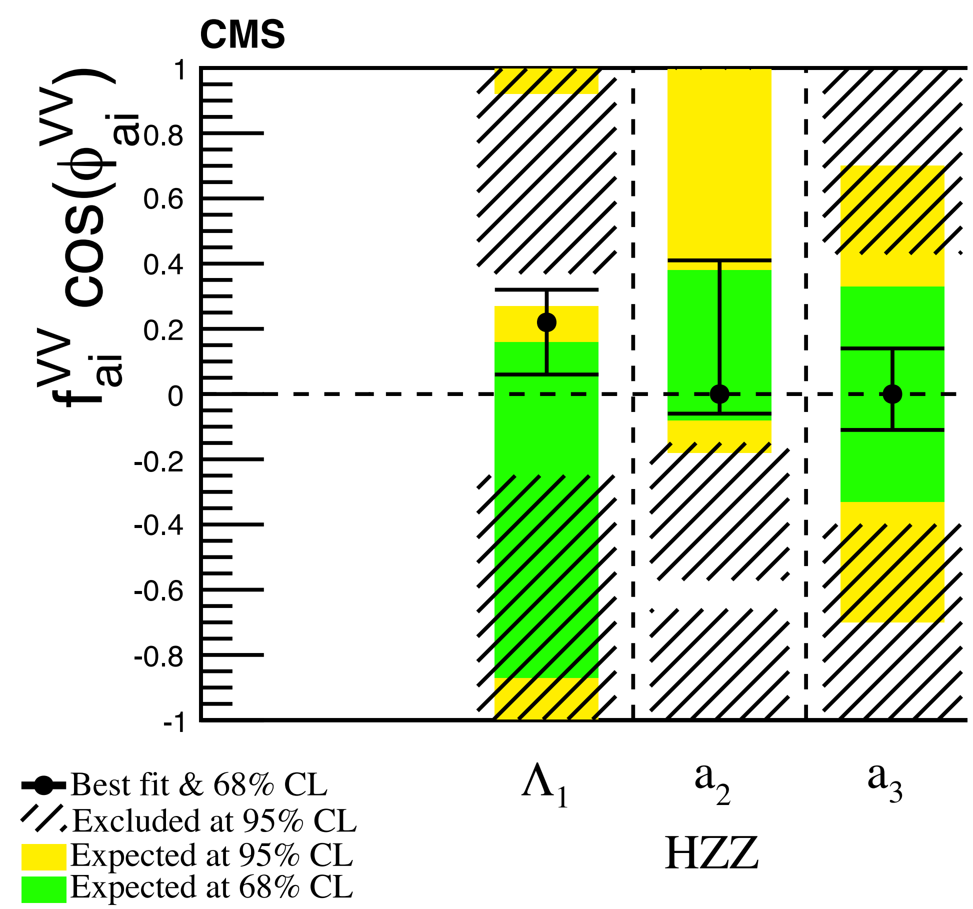


[CMS 1411.3441]

$$A(\mathrm{HVV}) \sim \left[a_1^{\rm VV} + \frac{\kappa_1^{\rm VV} q_{\rm V1}^2 + \kappa_2^{\rm VV} q_{\rm V2}^2}{\left(\Lambda_1^{\rm VV}\right)^2} \right] m_{\rm V1}^2 \epsilon_{\rm V1}^* \epsilon_{\rm V2}^*$$

$$+ a_2^{\rm VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\rm VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Measurement in H-> 4l



So, why do we look for CP-violation in the Higgs sector?

one reason: Matter-antimatter asymmetry

Baryon-to-photon ratio $Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ [Planck Data]

asymmetry parameter $\frac{\eta_B - \eta_{\bar{B}}}{\gamma} \simeq 10^{-9}$

Pre-inflation asymmetry would have been washed out

<u>Sakharov conditions:</u> (for dynamical generation of Baryon asymmetry)

- B violation
- CP violation
- Departure from thermal equilibrium

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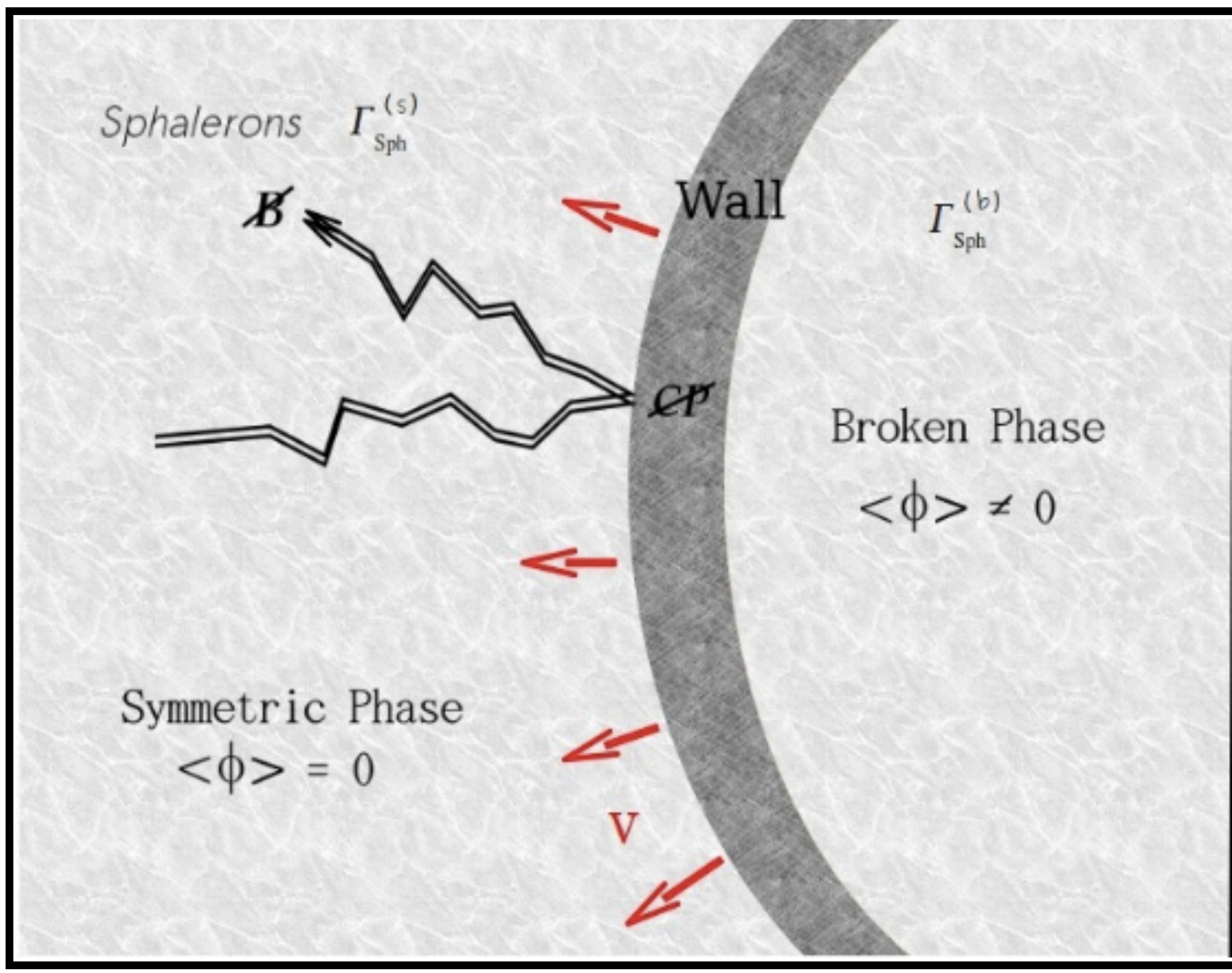
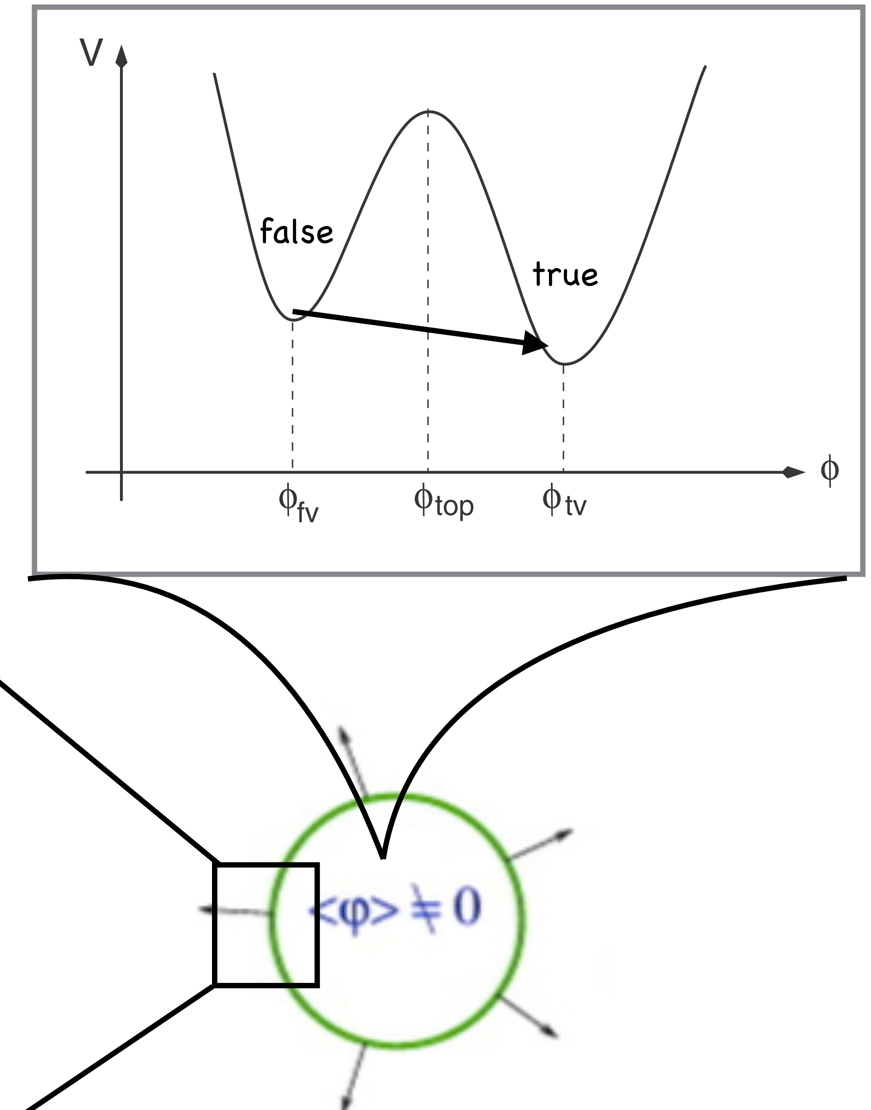
- CP violation ϟ not enough
- Departure from thermal equilibrium ϟ not enough

Electroweak Baryogenesis

- Spontaneous symmetry breaking after temperature cooled down during expansion of early Universe

  → violent process, formation of bubbles





Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '91]

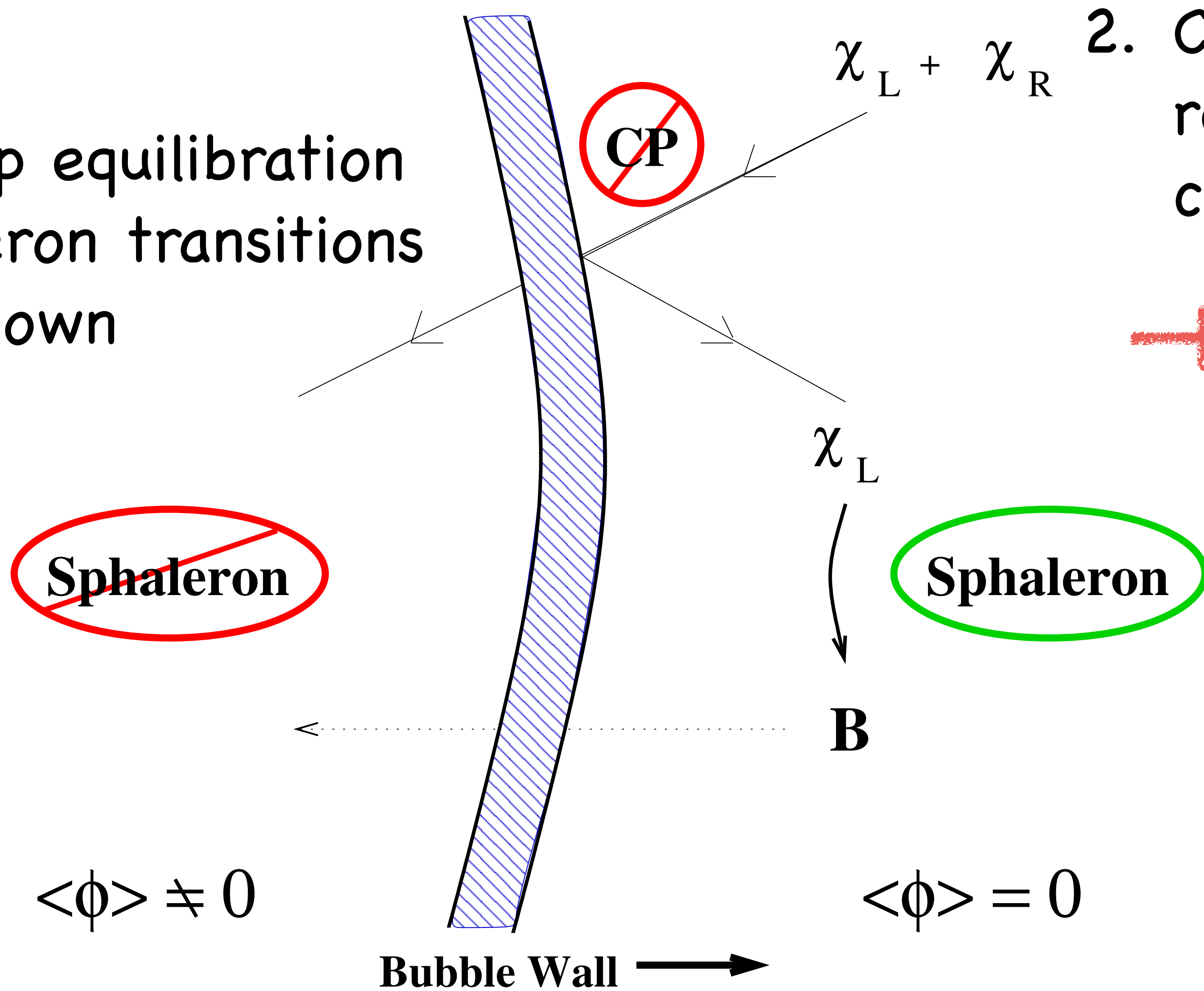
1. Nucleation and expansion of bubbles of broken phase

2. CP violation at phase interface responsible for mechanism of charge separation

→ chiral flux in front of wall

3. In symmetric phase, very active sphalerons convert chiral asymmetry into baryon asymmetry

4. To stop equilibration sphaleron transitions shut down



[Morrissey, Ramsey-Musolf '12]

CP violation during Electroweak Baryogenesis

$$Y_B = \frac{n_b}{s} = -\frac{3\Gamma_{\rm ws}}{2v_w s} \int_{-\infty}^{0} n_L(z)\, e^{z\, \mathcal{R}\Gamma_{\rm ws}/v_w}\, \mathrm{d}z$$

entropy density $s = 2\pi^2/(45) g_{*S} T^3$ sphaleron rate $\Gamma_{\rm ws} = 6\kappa\alpha_w^5 T$

$$Y_B \sim \frac{\Gamma_{ws}\ \delta_{CP}}{g_*\ L_w\ T^2} \sim \frac{10^{-6}\ \delta_{CP}}{g_*} \sim 10^{-8}\delta_{CP}$$

$\longrightarrow$ CPV needs to be order 1

Amount of CP violation in quark sector not sufficient. Thus need new sources of CP violation.

[Gavela, Hernandez, Orloff, Pene, Quimbay '94]

Simples gauge-invariant operator upon elw. sym. breaking

$$\mathcal{L}_{\rm eff} \supset -\left(\alpha + \beta \frac{H^\dagger H}{\Lambda^2}\right) H \ell^\dagger_{3\rm L} \tau_{\rm R} + {\rm c.c.}$$

with α and β complex parameters. After elw sym breaking

$$\mathcal{L}_{\rm eff} \supset -\left(\alpha + \beta \frac{v^2}{\Lambda^2}\right) v \tau^\dagger_{\rm L} \tau_{\rm R} - \left(\alpha + 3\beta \frac{v^2}{\Lambda^2}\right) \frac{h}{\sqrt{2}} \tau^\dagger_{\rm L} \tau_{\rm R} + {\rm c.c.}$$

$$\downarrow \quad \alpha + \beta \frac{v^2}{\Lambda^2} = y_\tau^{\rm SM} > 0$$

$$\mathcal{L} = m_f \bar{f}_L f_R + \frac{y_f}{\sqrt{2}} e^{i\Delta} h \bar{f}_L f_R + h.c.$$

$$\downarrow$$

$$\mathcal{L} = m_f \bar{f} f + \frac{y_f}{\sqrt{2}} \cos\Delta \; h \bar{f} f + i \frac{y_f}{\sqrt{2}} \sin\Delta \; h \bar{f} \gamma_5 f$$

New sources of CP-violation can be accommodated in several ways

(not exhaustive)

- Yukawa-Higgs coupling

CP-violating Yukawa-type interactions

$$|c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5 \sin\phi_f) f h_{\rm phys}$$

- gauge-Higgs coupling

CP-violating terms between scalar and gauge boson

$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma} h^2 \widetilde{F}_{\mu\nu} F^{\mu\nu}$$

- Scalar-Higgs coupling

CP-violating terms in the scalar potential

$$V_H \sim -\left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.}\right) + \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_1^\dagger \Phi_2\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + \text{H.c.}\right]$$

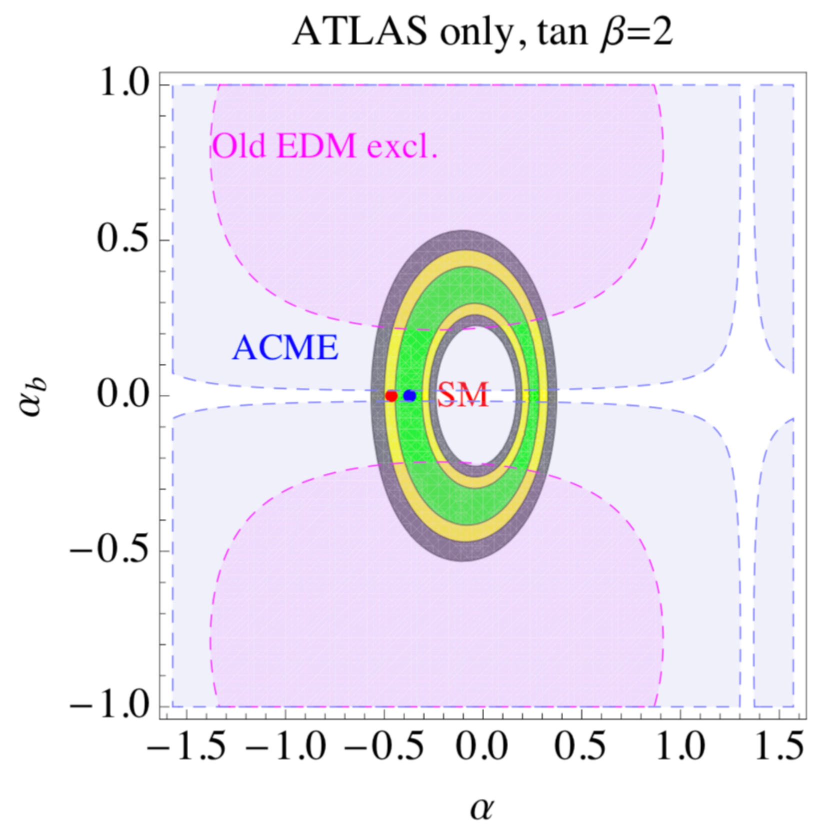
Relation between matter-antimatter asymmetry and CPV in a concrete model, i.e. 2HDM

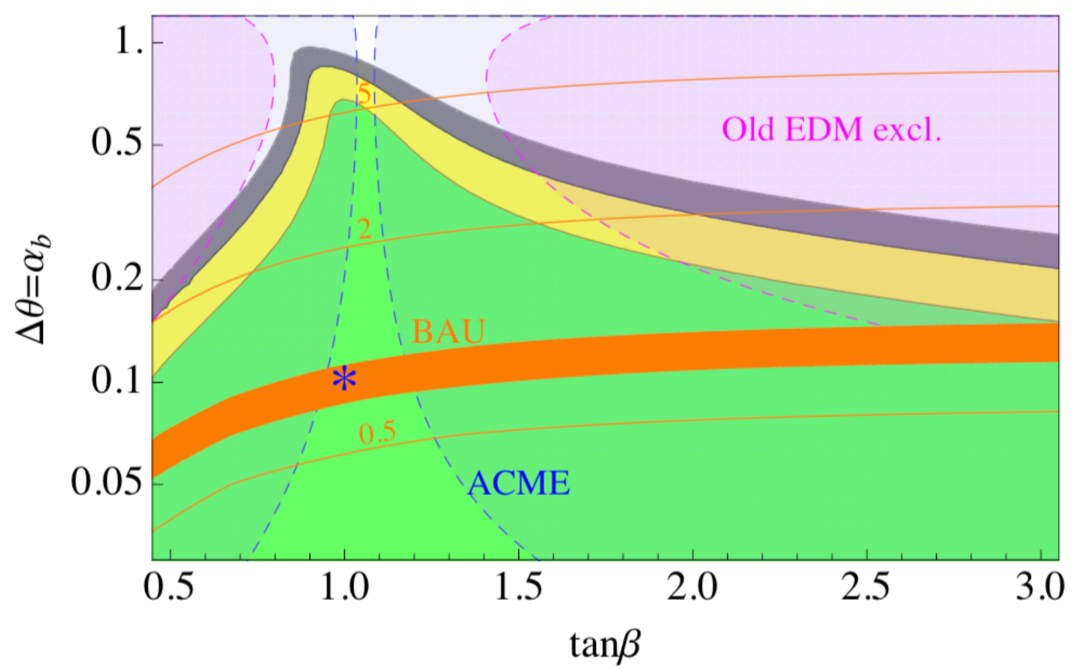
$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\},$$

[Shu and Zhang '13]

→ assumed all real but m_{12}^2

→ $$h_1 = -\sin\alpha\cos\alpha_b H_1^0 + \cos\alpha\cos\alpha_b H_2^0 + \sin\alpha_b A^0$$



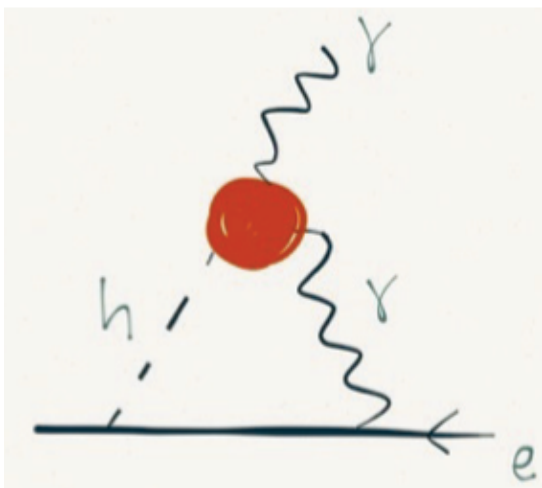


Higgs CP properties

eff. operators mediating CP-odd Higgs interactions:

indirect constraints

EDM



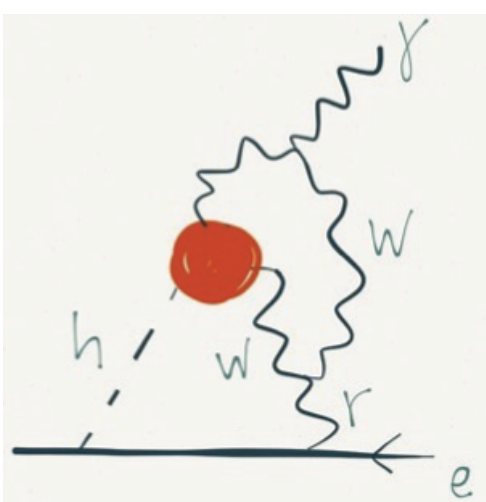
$\tilde{c}_{\gamma\gamma}^{-1/2} \geq 24 \text{ TeV}$

$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma}h^2\widetilde{F}_{\mu\nu}F^{\mu\nu}$$ photons

$$\frac{g_2^2}{2}\tilde{c}_{WW}h^2\widetilde{W}^{+}_{\mu\nu}W^{\mu\nu -}$$

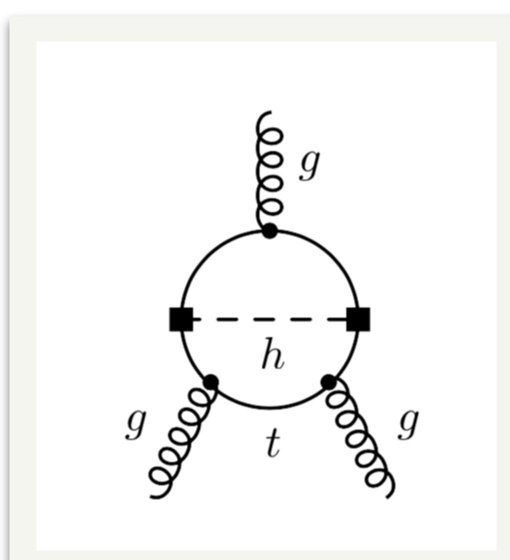
massive gauge bosons

$$\frac{g_Z^2}{2}\tilde{c}_{ZZ}h^2\widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$



$\tilde{c}_{WW}^{-1/2} \geq 600 \text{ GeV}$

$$\frac{g_s^2}{2}\tilde{c}_{gg}h^2\widetilde{G}_{\mu\nu}G^{\mu\nu}$$ gluons



$$\rightarrow |c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5\sin\phi_f)fh_{\text{phys}}$$ fermions

[McKeen, Pospelov, Ritz '12]

[Delaunay et al '14]

[Brod, Haisch, Zupan '13]

Higgs CP properties

eff. operators mediating CP-odd Higgs interactions:

<u>@ colliders:</u>

Look at interference effects between
h->ZZ*->4l and h->$\gamma^*\gamma^*$->4l

[Chen, Harnik, Vega Morales '14]

[Bolognesi et al '12]

tau phase in angular distributions of
$\tau^\pm \to \rho^\pm(\pi^\pm\pi^0)\nu$

[Harnik, Martin, Okui, Primulando, Yu '13]

Angular correlations in tth production

[Buckley, Goncalves '15]

$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma}h^2\widetilde{F}_{\mu\nu}F^{\mu\nu}$$ photons

$$\frac{g_2^2}{2}\tilde{c}_{WW}h^2\widetilde{W}^+_{\mu\nu}W^{\mu\nu-}$$

massive gauge bosons

$$\frac{g_Z^2}{2}\tilde{c}_{ZZ}h^2\widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$

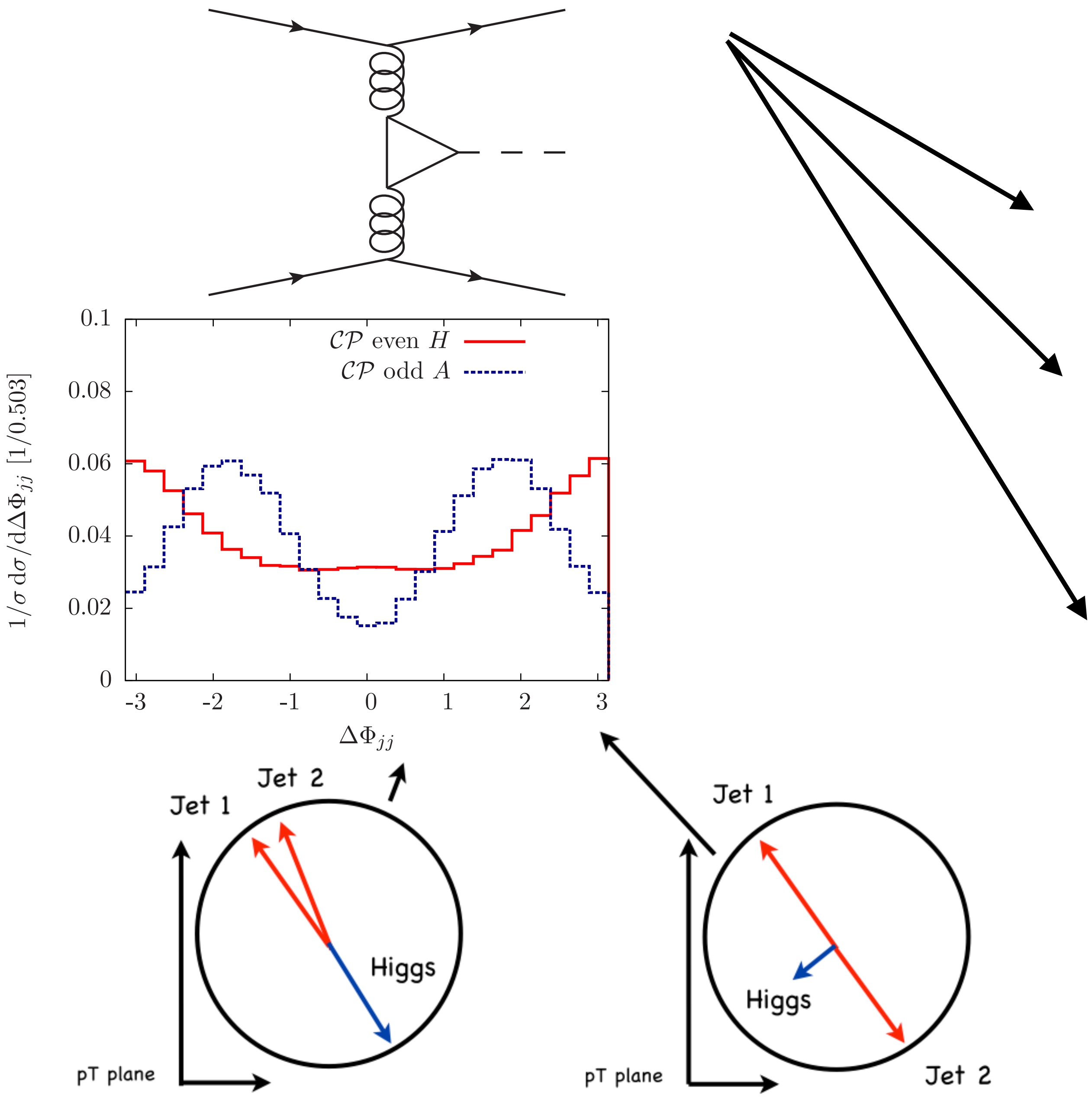
$$\frac{g_s^2}{2}\tilde{c}_{gg}h^2\widetilde{G}_{\mu\nu}G^{\mu\nu}$$ gluons

$$|c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5\sin\phi_f)f h_{\rm phys}$$ fermions

Higgs CP properties

eff. operators mediating CP-odd Higgs interactions:

Weak-boson and gluon fusion



$$\frac{e^2}{2}\tilde{c}_{\gamma\gamma}h^2\widetilde{F}_{\mu\nu}F^{\mu\nu}$$ photons

$$\frac{g_2^2}{2}\tilde{c}_{WW}h^2\widetilde{W}^+_{\mu\nu}W^{\mu\nu -}$$

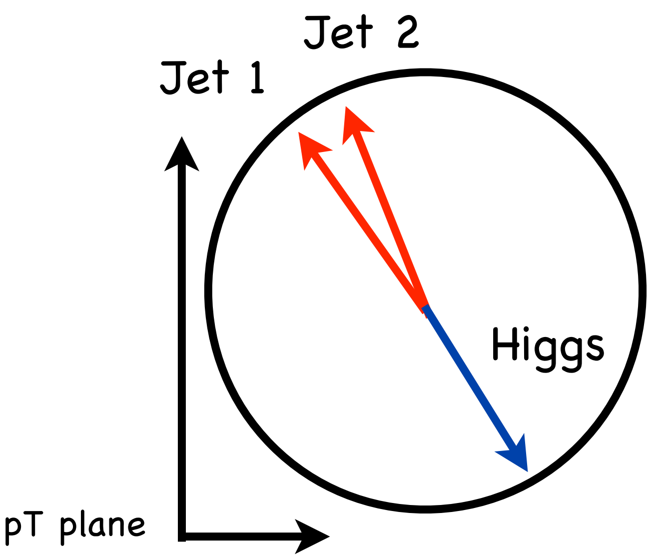
$$\frac{g_Z^2}{2}\tilde{c}_{ZZ}h^2\widetilde{Z}_{\mu\nu}Z^{\mu\nu}$$ massive gauge bosons

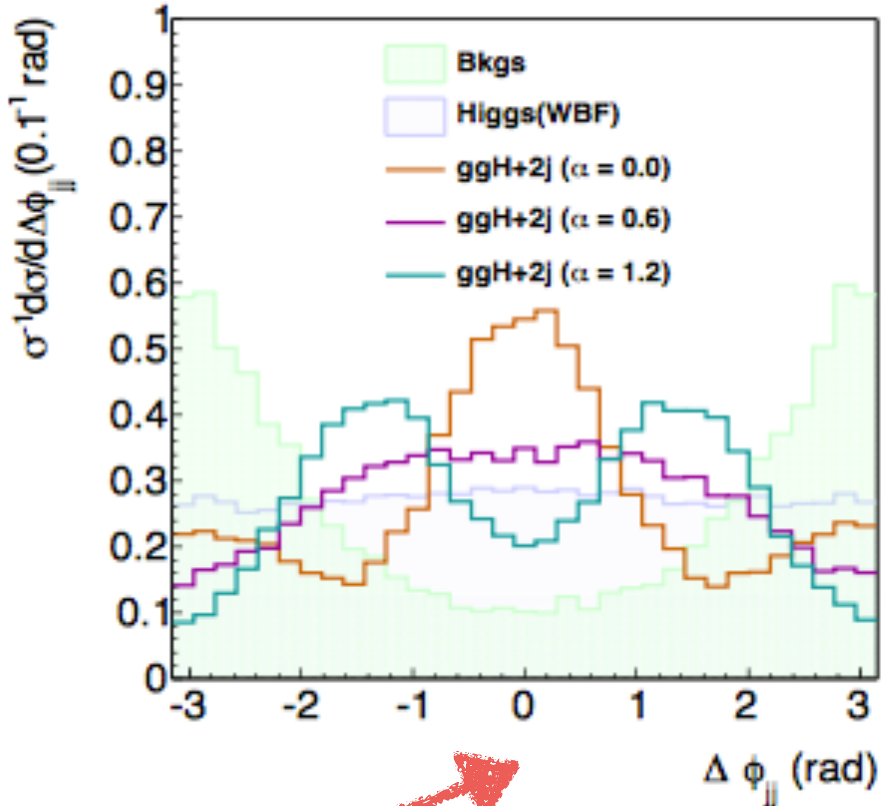
$$\frac{g_s^2}{2}\tilde{c}_{gg}h^2\widetilde{G}_{\mu\nu}G^{\mu\nu}$$ gluons

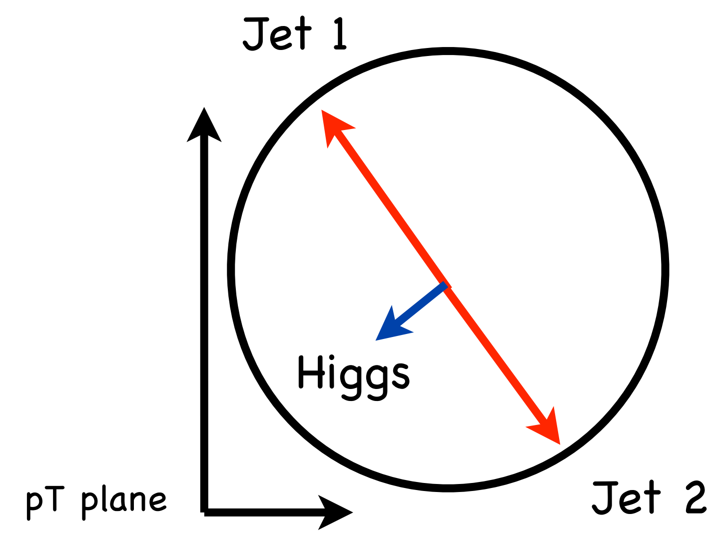
$$|c_f|\frac{m_f}{v}\bar{f}(\cos\phi_f + i\gamma_5\sin\phi_f)f h_{\text{phys}}$$ fermions

[Plehn, Rainwater, Zeppenfeld '01][Klamke, Zeppenfeld '07]

Mixed physical state: $$\mathcal{L}_{hgg} = \cos\alpha \frac{\alpha_S}{12\pi v} h G^a_{\mu\nu} G^{a,\mu\nu} + \sin\alpha \frac{\alpha_S}{4\pi v} h G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$



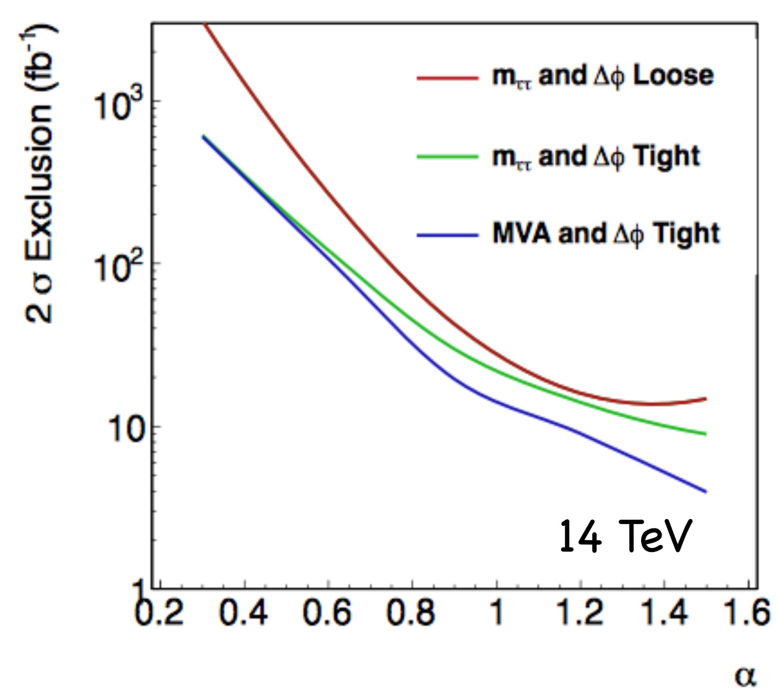




Can constrain/exclude mixed CP-states

to

$\alpha < 0.3$ with $500\ \mathrm{fb}^{-1}$



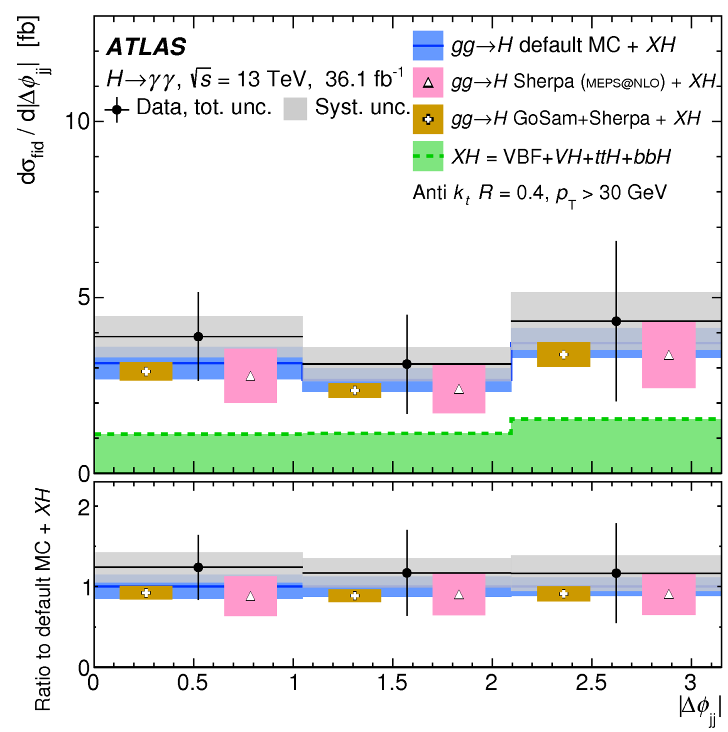
[Dolan, Harris, Jankowiak, MS '14]

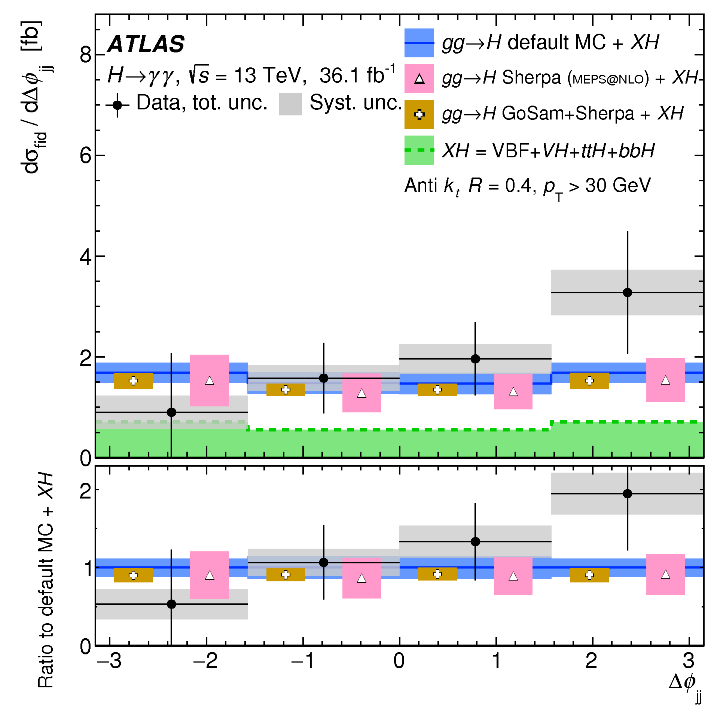
CP violating interactions of the Higgs boson

[Bernlochner et al '18]

$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$
$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu}\tilde{W}^a_{\mu\nu}\,,$$
$$O_{H\tilde{B}} = H^\dagger H B^{\mu\nu}\tilde{B}_{\mu\nu}\,,$$
$$O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu}\tilde{W}^{a\mu\nu}\,,$$

cp-violating tth interactions degenerate with $O_{H\tilde{G}}$ for our observables (blind direction)





Use recent ATLAS measurements in $h\to\gamma\gamma$ and $h\to ZZ^*\to 4\ell$

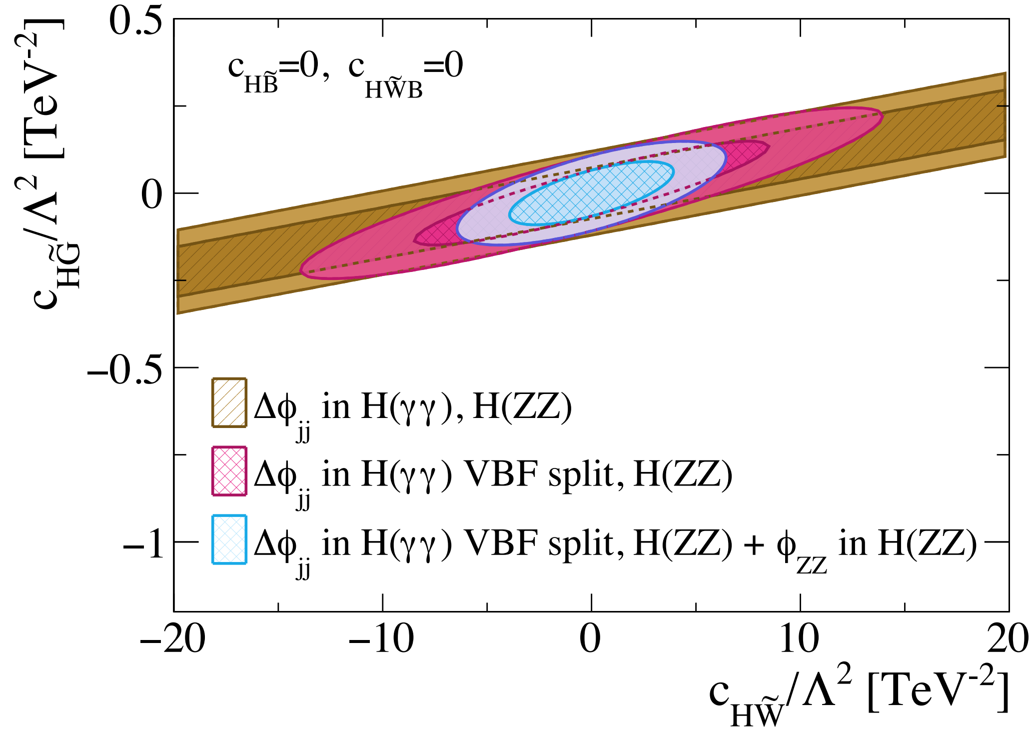
Need to construct CP sensitive observables in linearised framework $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2{\rm Re}\,(\mathcal{M}^\star_{\rm SM}\mathcal{M}_{\rm d6}) + \mathcal{O}(\Lambda^{-4}).$

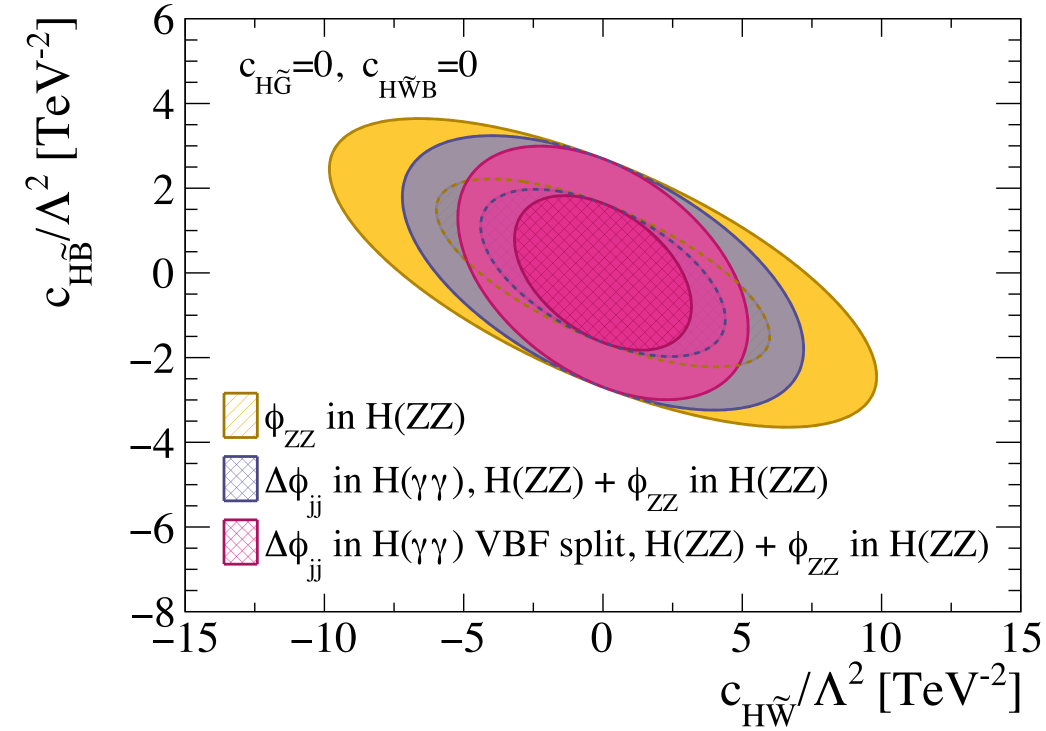
for example: $\Delta\phi_{jj} = \phi_1 - \phi_2,$ in Hjj → $A = \dfrac{\sigma(0<\Delta\phi_{jj}<\pi) - \sigma(-\pi<\Delta\phi_{jj}<0)}{\sigma(0<\Delta\phi_{jj}<\pi) + \sigma(-\pi<\Delta\phi_{jj}<0)}$

with ATLAS data one finds → $A = 0.3 \pm 0.2$

Future sensitivity can be improved by separating enriched regions of GF and WBF and by studying H->4l decay angles, e.g.

$$\cos\Phi = \frac{(\mathbf{p}_{l^-} \times \mathbf{p}_{l^+}) \cdot (\mathbf{p}_{l'^-} \times \mathbf{p}_{l'^+})}{\sqrt{(\mathbf{p}_{l^-} \times \mathbf{p}_{l^+})^2 \, (\mathbf{p}_{l'^-} \times \mathbf{p}_{l'^+})^2}}\Bigg|_h$$





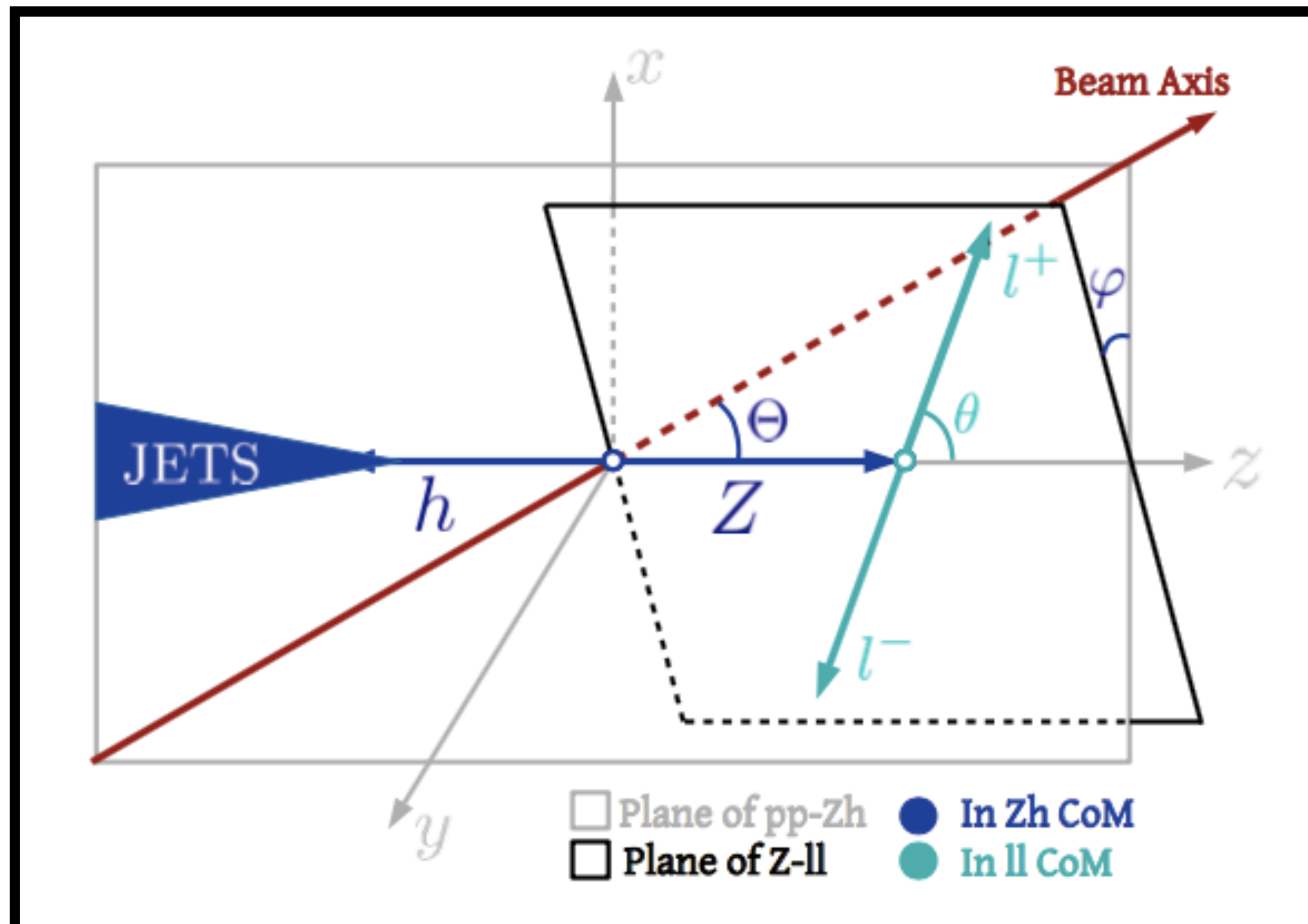
Coefficient [TeV^{-2}]	36.1 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$c_{H\tilde{G}}/\Lambda^2$	$[-0.19, 0.19]$	$[-0.067, 0.067]$	$[-0.021, 0.021]$
$c_{H\tilde{W}}/\Lambda^2$	$[-11, 11]$	$[-3.8, 3.8]$	$[-1.2, 1.2]$
$c_{H\tilde{B}}/\Lambda^2$	$[-5.9, 5.9]$	$[-2.1, 2.1]$	$[-0.65, 0.65]$
$c_{H\tilde{W}B}/\Lambda^2$	$[-14, 14]$	$[-4.9, 4.9]$	$[-1.5, 1.5]$

Marginalised over other coefficients

CPV in HZZ - a case study

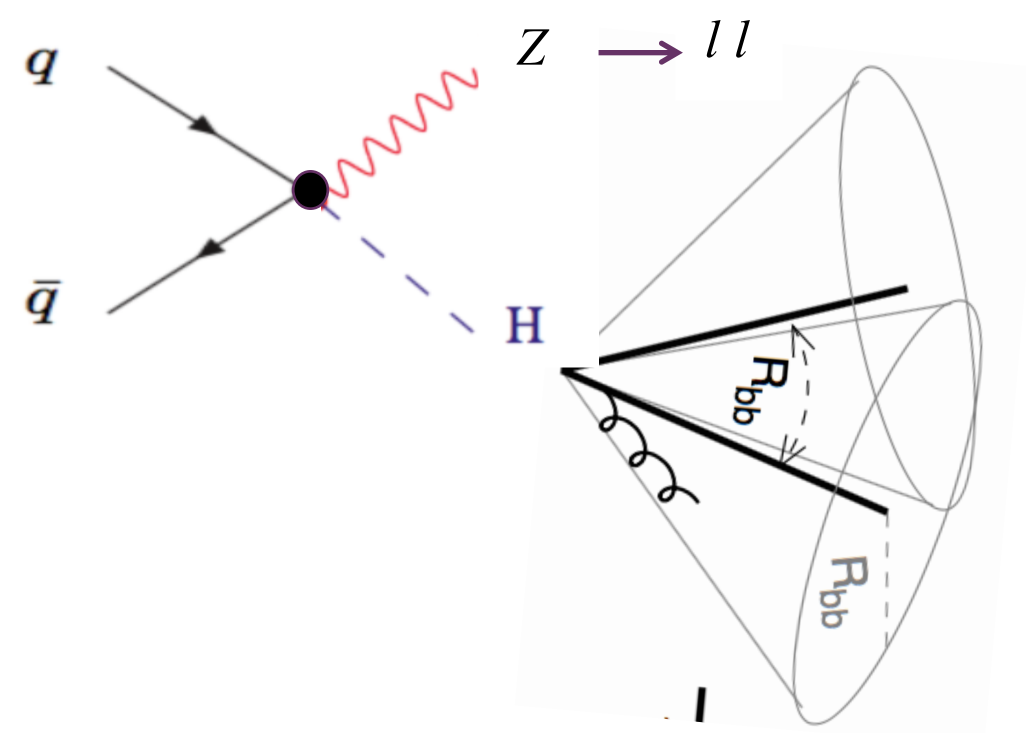
- H->ZZ-> 4l standard candle to search for CPV in Higgs sector
- New physics unlikely to induce only one new operator
- Easier to disentangle EFT operators in the production, rather than decay
- Three body phase space so 3x3-4=5 kinematical variables completely define the final state
- Ignoring the boost there are 4:

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



HZ boosted, reconstructed with fat jet

How much information does process provide differentially?



Free kinematic parameters

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

If we separate each variable into 10 bins:

1000 numbers per energy bin to encapsulate full information

Reconstruction: BDRS, ...

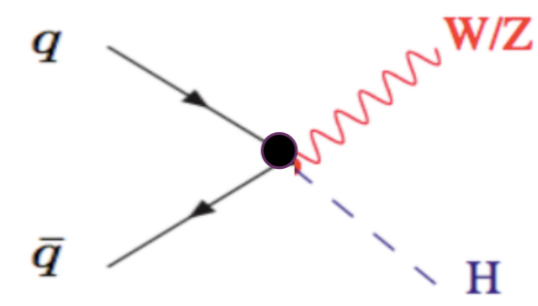
[Butterworth, Davidson, Rubin, Salam '08]

[Banerjee, Englert, Gupta, MS '18]

→ With some analysis, we can reduce that number to 9 per energy bin

The ff->HZ interactions are defined by

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



Process in terms of helicity amplitudes:

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

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

Only a finite number of helicity amplitudes receive corrections up to Dim-6 order

$$\mathcal{A}_h(\hat{s},\Theta,\hat{\theta},\hat{\varphi}) = \frac{-i\sqrt{2}g_\ell^Z}{\Gamma_Z}\sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s},\Theta)d^{J=1}_{\lambda,1}(\hat{\theta})e^{i\lambda\hat{\varphi}} \rightarrow \sum_{L,R}|\mathcal{A}(\hat{s},\Theta,\theta,\varphi)|^2 = 3 \times 3 = 9$$

Finally, 9 terms including 6 interference terms between different Z helicities

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

- 9 coefficient are 9 angular moments for pp > H(Z>ll)
- They contain all kinematic information of the process

To extract use analog to Fourier analysis $$P(\Omega) = \sum_i a_i \times g_i(\Omega)$$

Find reciprocal vector (weight function)

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

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

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

$$\sum_{L,R} |\mathcal{A}(\hat{s},\Theta,\theta,\phi)|^2 = a_{LL}\sin^2\Theta\sin^2\theta + a^1_{TT}\cos\Theta\cos\theta$$

$$+ a^2_{TT}(1+\cos^2\Theta)(1+\cos^2\theta) + \cos\varphi\sin\Theta\sin\theta$$

$$\times (a^1_{LT} + a^2_{LT}\cos\theta\cos\Theta) + \sin\varphi\sin\Theta\sin\theta$$

$$\times (\tilde{a}^1_{LT} + \tilde{a}^2_{L} \ldots \Theta\sin^2\theta$$

$$+ \tilde{a}_{TT'}\sin 2\varphi \ldots$$

$$g^1 = S^2_\Theta S^2_\theta$$

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

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

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

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

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

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

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

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

- 9 coefficient ... pp > H(Z>ll)
- They contain ... f the process

To extract use ar...

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

Find reciprocal ve...

$$w_i(\Omega) = \sum_i \lambda_i \ldots$$

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

Calcu...

...unietz, Quinn, Snyder, Toki & Lipkin (1991)

Comparison of amplitude coefficients and their respective 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}	$-\frac{\mathcal{G}^2}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}^1_{LT}$	$-\mathcal{G}^2\sigma\epsilon_{LR}\tilde{\kappa}_{ZZ}\gamma$
$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{ZZ}\gamma$
$a_{TT'}$	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}_{TT'}$	$\frac{\mathcal{G}^2}{2}\tilde{\kappa}_{ZZ}$

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

$\gamma = \sqrt{\hat{s}}/(2m_Z)$ and $\epsilon_{LR} = \alpha_L - \alpha_R$

↑ growth with energy (for γ)

↑ small, accidental cancellation (for ϵ_{LR})

Comparison of amplitude coefficients and their respective moments

Only sensitive to these if Z decay inclusively treated

Epsilon suppressed

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

Differential analysis a must

Comparison of amplitude coefficients and their respective moments

Only sensitive to these if Z decay inclusively treated

Epsilon suppressed

CP-even moments probe

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

CP-odd moments probe

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

a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1+2\delta\hat{g}^h_{ZZ}+4\kappa_{ZZ}+\frac{g^h_{Zf}}{g^Z_f}(-1+4\gamma^2)\right]$
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}	$-\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
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$\gamma = \sqrt{\hat{s}}/(2m_Z)$ and $\epsilon_{LR} = \alpha_L - \alpha_R$

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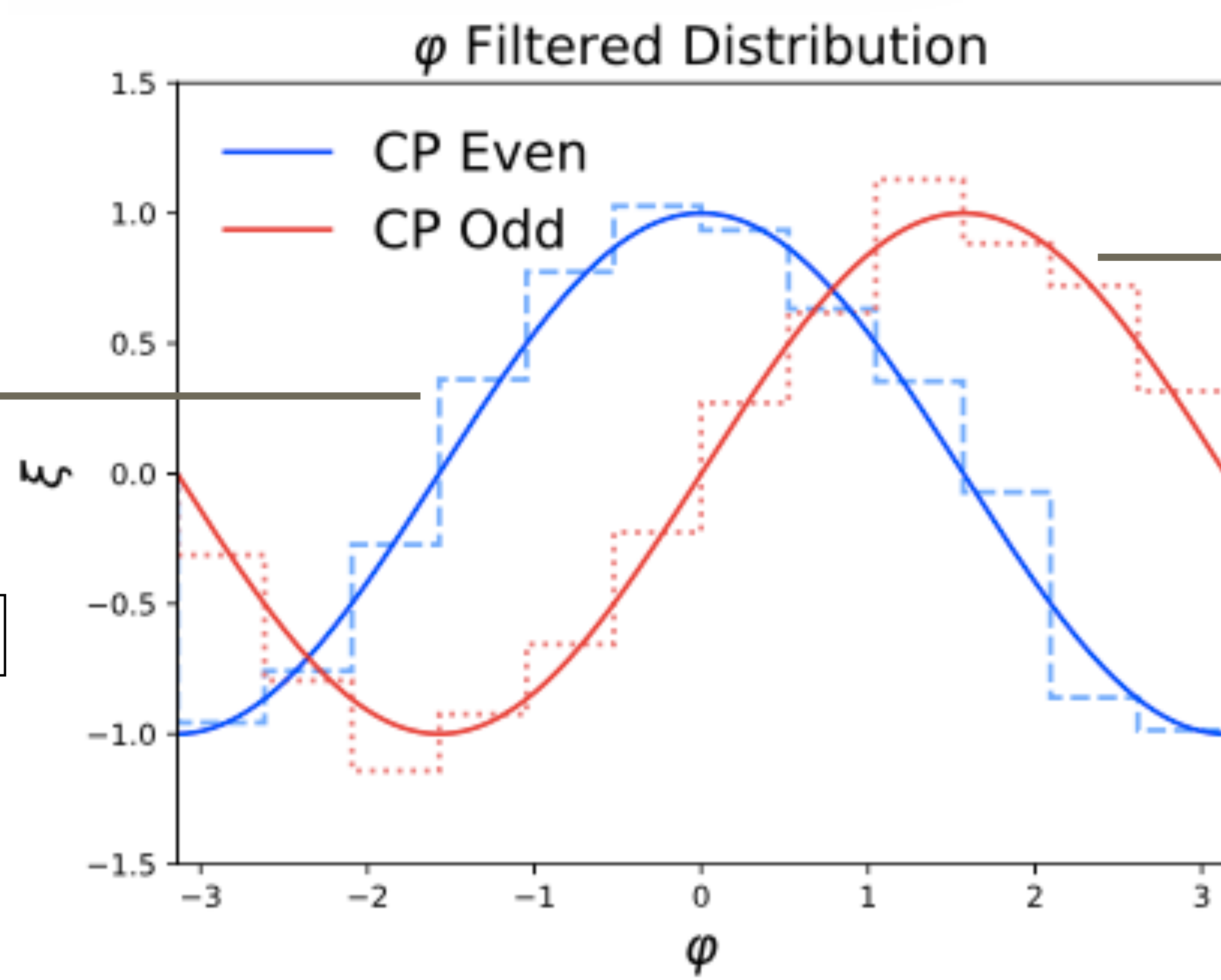
Cross-helicity terms. Vanish upon inclusive integration over lepton phase space

Differential analysis a must

A Triple Differential observable

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

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



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

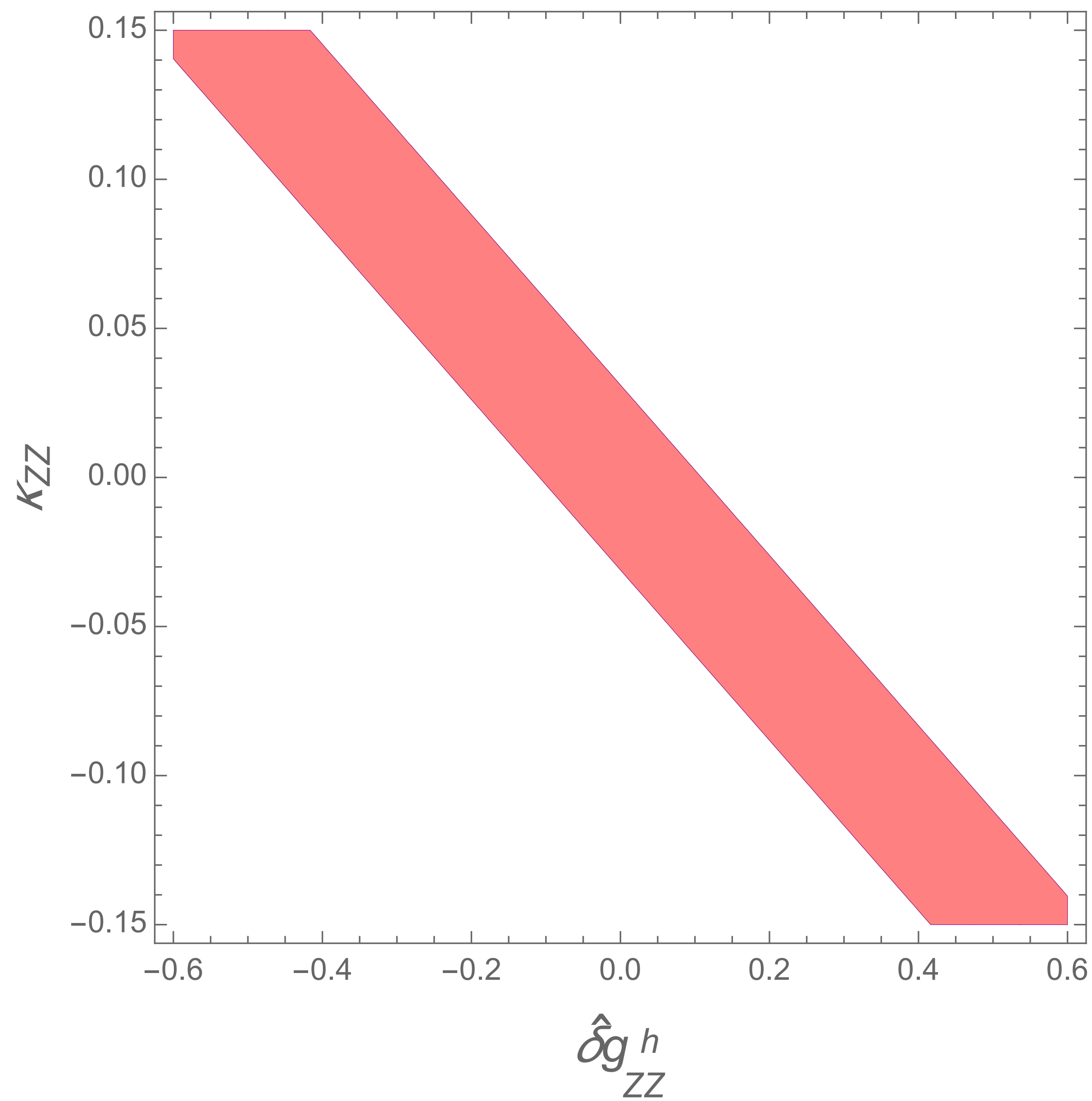
$$g^7 = S_\varphi S_\Theta S_\theta C_\Theta C_\theta$$

Dominant cross-helicity CP even & odd angular moment

[Banerjee, Gupta, Reines, MS '19]

Sensitivity result

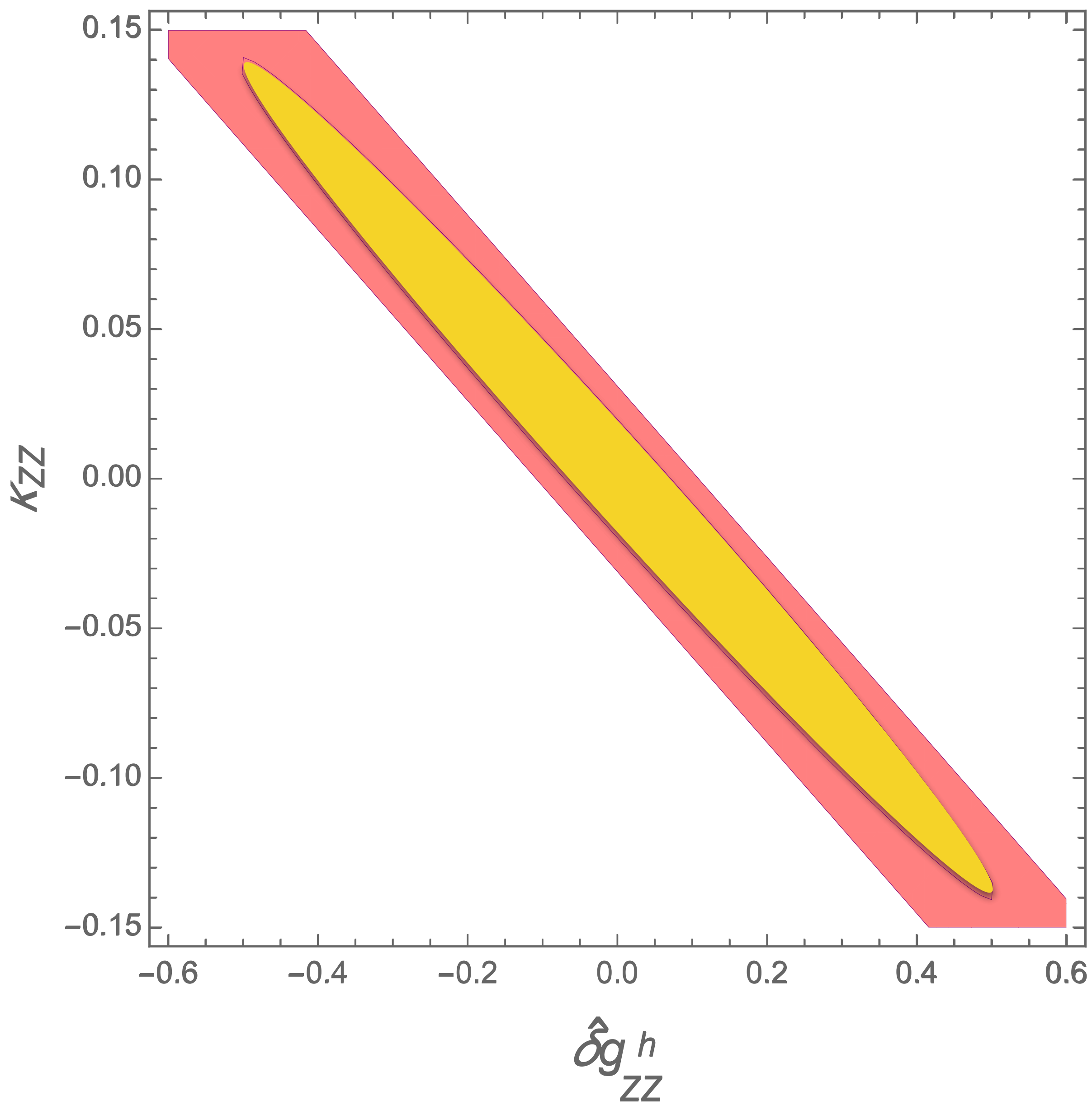
rates only



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

Sensitivity result

Inclusive angular moments



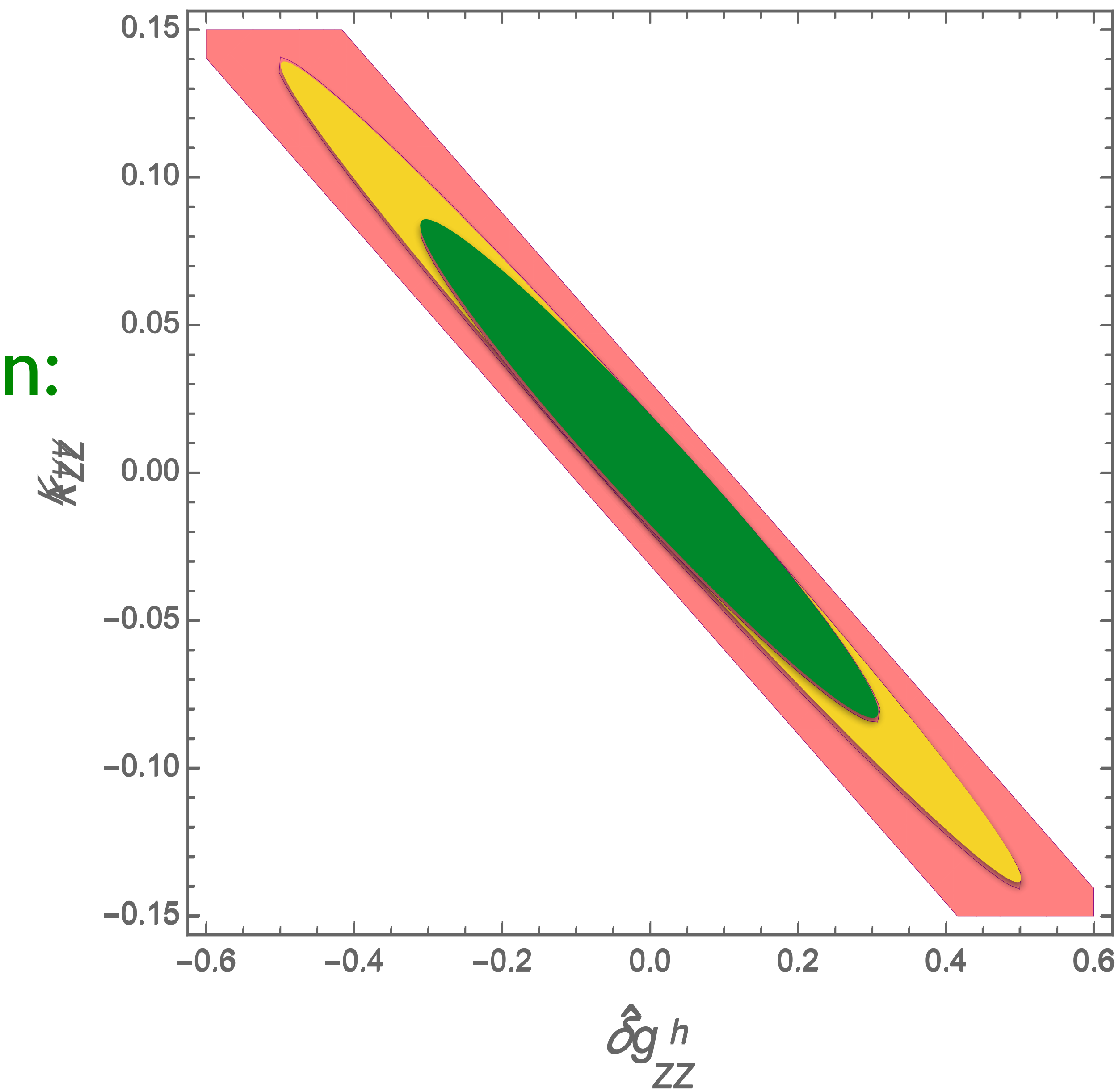
$$|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}.$$

Inclusive moments not sensitive to CP-odd coupling

Sensitivity result

All angular moments

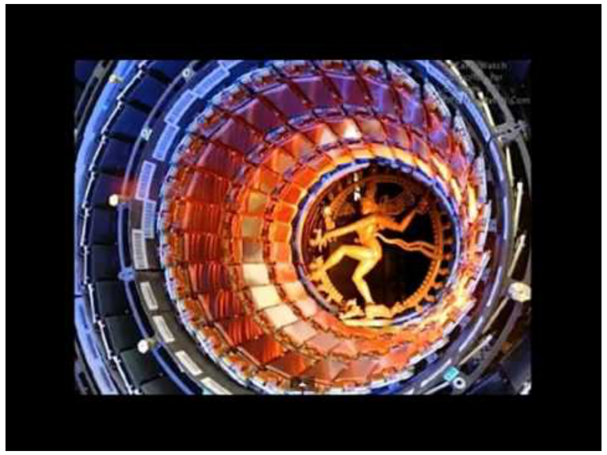
CP-even:



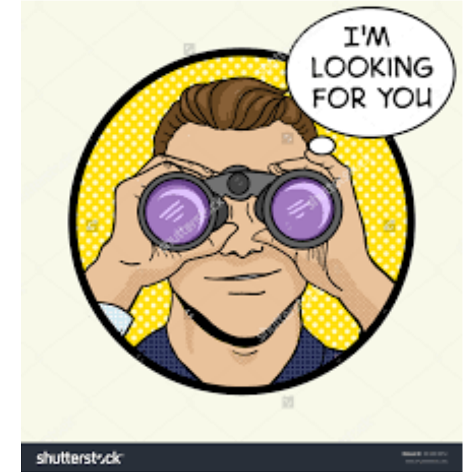
$|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$.

CP-odd:

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



Summary



CP violation in the Higgs sector a likely ingredient for electroweak baryogenesis
-> with reasonably large phases

Necessary to exploit all channels simultaneously

It can be beneficial to project onto maximum set of kinematically independent moments to obtain optimal sensitivity