

# Higgs CP properties

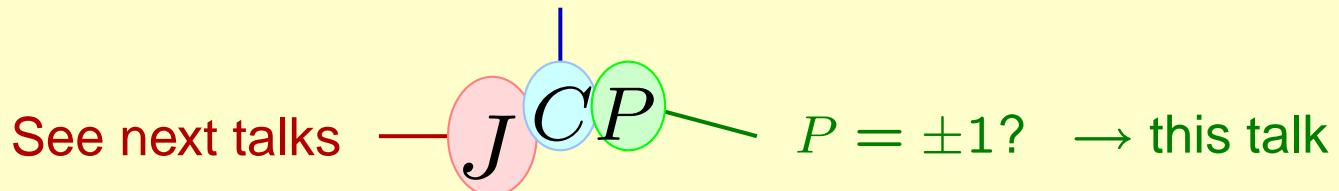
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- 1.** Reference scenario: Two Higgs Doublet Model
- 2.** Constraints from non-Higgs physics
- 3.** Signal rates
- 4.** Signal distributions
- 5.** Conclusions

# Higgs boson quantum numbers

$C = +1$  from observation of  $h \rightarrow \gamma\gamma$



## Two Higgs Doublet Model

Main sources of  $\mathcal{CP}$  violation in Higgs sector:

- Mixing between scalar and pseudoscalar from **scalar potential**
- Misalignment between fermion masses and **Yukawa couplings**

Minimal field content to achieve both: add second Higgs doublet

Scalar potential

$$\begin{aligned} V = & \frac{1}{2}m_{11}^2\Phi_1^\dagger\Phi_1 + \frac{1}{2}m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{1}{2}\left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \frac{1}{2}\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{1}{2}\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] \end{aligned}$$

$$v_1 = \langle\Phi_1\rangle = v \cos \beta, \quad v_2 = \langle\Phi_2\rangle = v \sin \beta e^{i\xi}$$

complex parameters, can be made real by redefining  $\Phi_{1,2}$

parameters with physical complex phase

## Scalar potential ct'd

$\mathbb{Z}_2$  symmetry to avoid FCNC:  $\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2$

→  $\Phi_1$  and  $\Phi_2$  cannot couple to the same fermion  $F$  ( $F = u, d, \ell$ )

May be **softly broken** by  $m_{12}^2$

## Scalar potential

$$\begin{aligned} V = & \frac{1}{2}m_{11}^2\Phi_1^\dagger\Phi_1 + \frac{1}{2}m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{1}{2}(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[ \frac{1}{2}\cancel{\lambda_5}(\Phi_1^\dagger\Phi_2)^2 + \frac{1}{2}\cancel{\lambda_6}(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{1}{2}\cancel{\lambda_7}(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.} \right] \end{aligned}$$

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## Scalar potential ct'd

Physical states:

- Goldstone bosons  $G^0, G^\pm$ , eaten by  $Z, W^\pm$
- Charged scalar  $H^\pm$
- Three neutral scalars  $H_1, H_2, H_3$  with mixed parity

Conditions for CP:

$$\text{Im } J_1 = \frac{1}{v^5} [m_1^2 e_1 (e_3 q_2 - e_2 q_3) + \text{cycl.}] \neq 0$$

$$\text{Im } J_2 = \frac{2e_1 e_2 e_3}{v^9} (m_1^2 - m_2^2)(m_2^2 - m_3^2)(m_3^2 - m_1^2) \neq 0$$

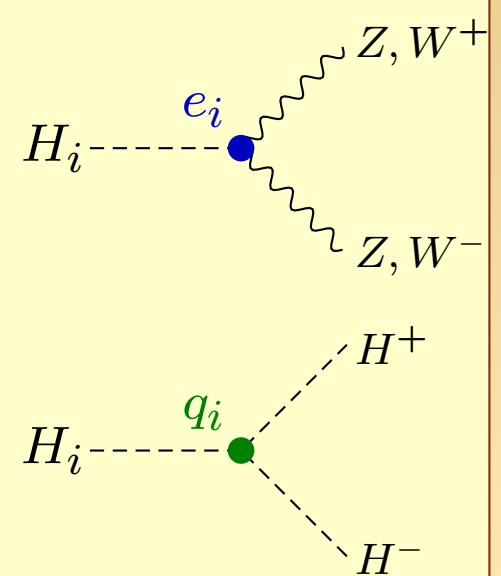
$$\text{Im } J_{30} = \frac{1}{v^5} [m_1^2 q_1 (e_2 q_3 - e_3 q_2) + \text{cycl.}] \neq 0$$

$m_i$ : masses of neutral Higgs boson  $H_i$

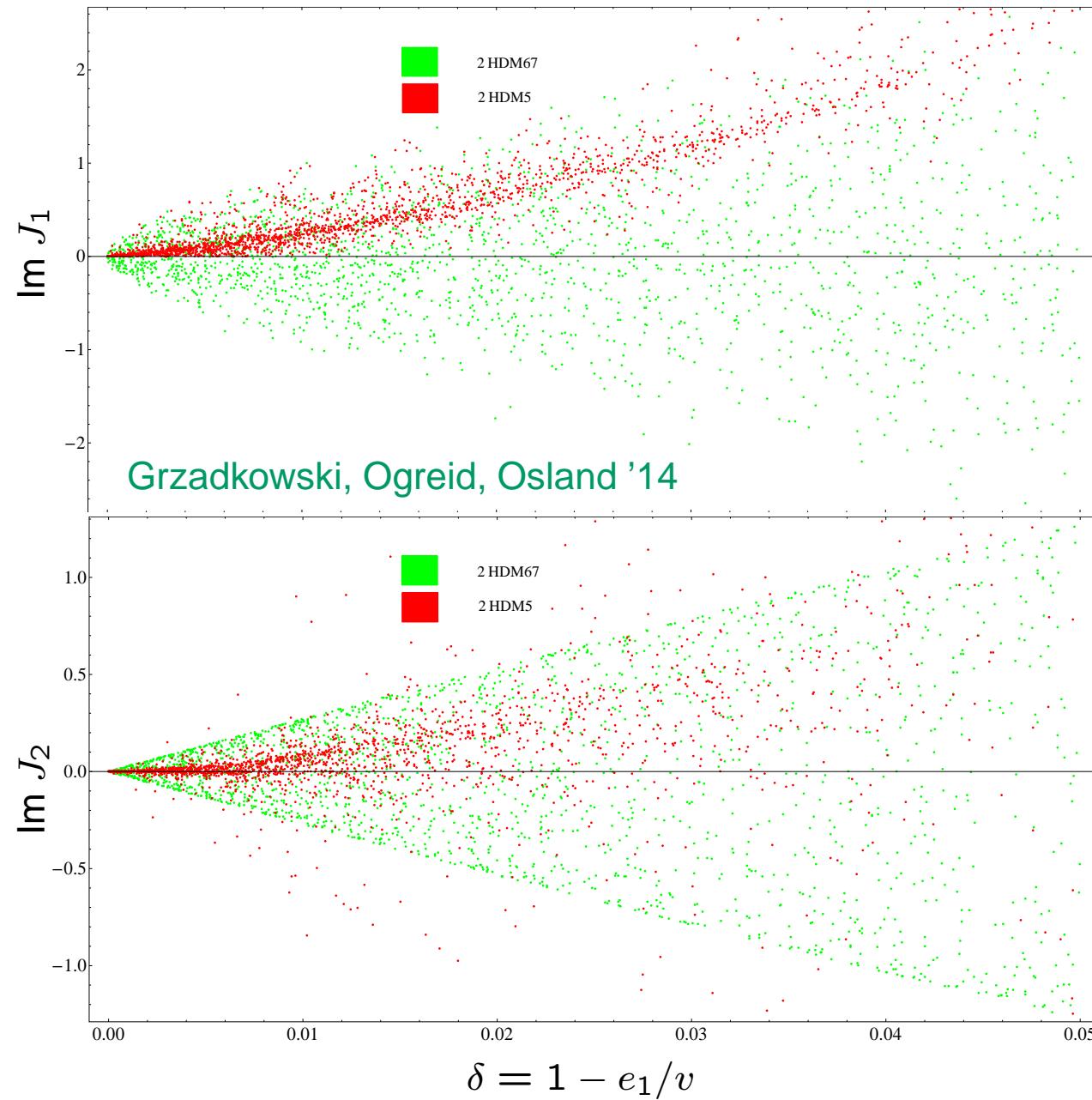
Branco, Rebelo, Silva-Marcos '05

Gunion, Haber '05

Grzadkowski, Ogreid, Osland '14



## Scalar potential ct'd



Red:  $\mathbb{Z}_2$  symmetry  
( $\lambda_{6,7} = 0$ )  
 $m_{H^\pm}, m_2, \beta$ ,  
Re  $m_{12}^2$  fixed  
( $m_1 = 125$  GeV)

Grn: General potential  
 $m_{H^\pm}, m_{2,3}, \beta$   
Re  $m_{12}^2$  fixed  
( $m_1 = 125$  GeV)

Large CP possible  
for  $\delta < 0.05$

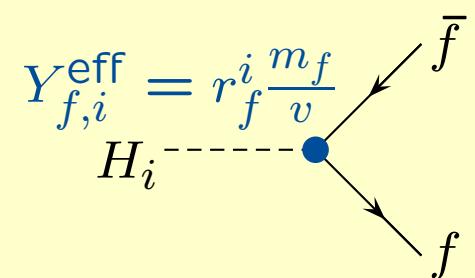
## Yukawa couplings

**Aligned THDM:** No  $\mathbb{Z}_2$  symmetry, but  $y_f^{\Phi_1} \propto y_f^{\Phi_2}$  ( $3 \times 3$  matrices in flavor space)  
to void FCNC

Pich, Tuzon '09

$$\mathcal{L}_{\text{Yuk}} = -\frac{1}{v} \sum_i \sum_f r_f^i m_f \bar{f}_L f_R H_i + \text{h.c.}$$

$$r_{r,d,\ell}^i = R_{i1} + (R_{i2} + iR_{i3}) \zeta_{u,d,\ell}$$



$R$  = mixing matrix of  $H_{1,2,3}$

$\zeta_{u,d,\ell}$  = complex  $\mathcal{O}(1)$  numbers

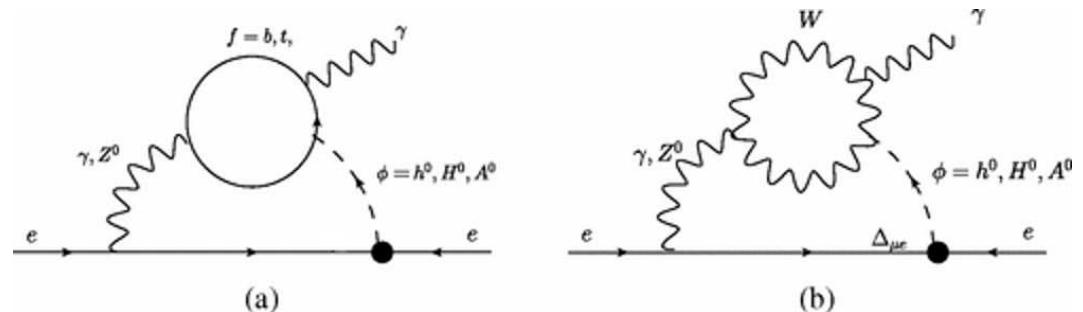
→ CP in  $H_1$  decays possible also if  $R_{13} = 0$  (no scalar–pseudoscalar mixing)

# Constraints from non-Higgs physics

Electric dipole moments (EDMs):

a) **Electron EDM:** Main contribution from 2-loop Barr-Zee diagrams:

Barr, Zee '90



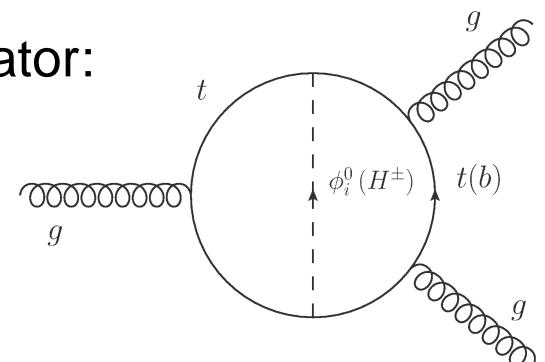
$$\left[ \frac{d_e}{e} \right]_t = \frac{\sqrt{2}\alpha G_F v}{6\pi^3} \sum_i \left[ f\left(\frac{m_t^2}{m_i^2}\right) \operatorname{Re} Y_{e,i}^{\text{eff}} \operatorname{Im} Y_{t,i}^{\text{eff}} + g\left(\frac{m_t^2}{m_i^2}\right) \operatorname{Im} Y_{e,i}^{\text{eff}} \operatorname{Re} Y_{t,i}^{\text{eff}} \right]$$

$$\left[ \frac{d_e}{e} \right]_W = -\frac{\sqrt{2}\alpha G_F}{16\pi^3} \sum_i \left[ 3f\left(\frac{M_W^2}{m_i^2}\right) + 5g\left(\frac{M_W^2}{m_i^2}\right) \right] \operatorname{Im} \{ Y_{e,i}^{\text{eff}} v_i \}$$

b) **Neutron EDM:** Main contribution from Weinberg operator:

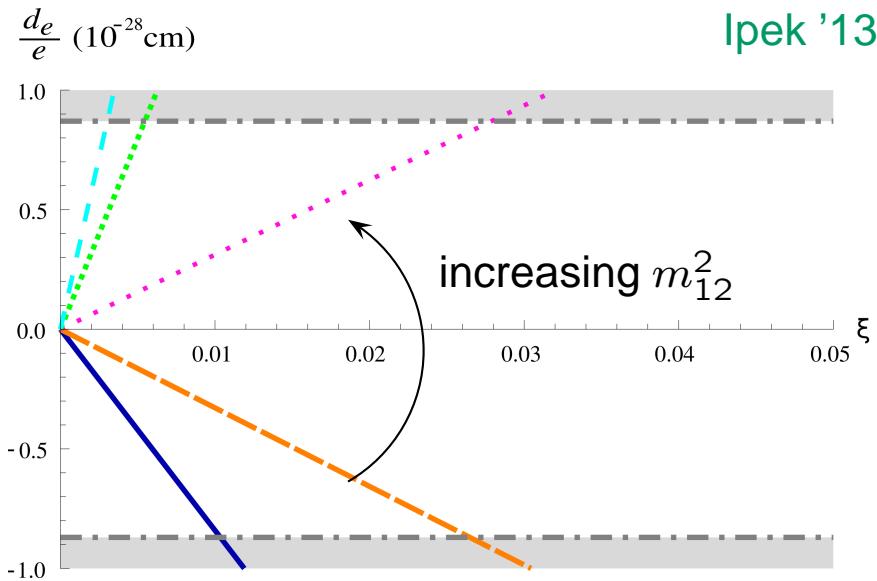
$$[d_n]_{H^\pm} \propto \operatorname{Im} \{ Y_{t,i}^{\text{eff}*} Y_{b,i}^{\text{eff}} \}$$

Weinberg '89



## EDM constraints

For  $\mathcal{CP}$  in scalar potential:

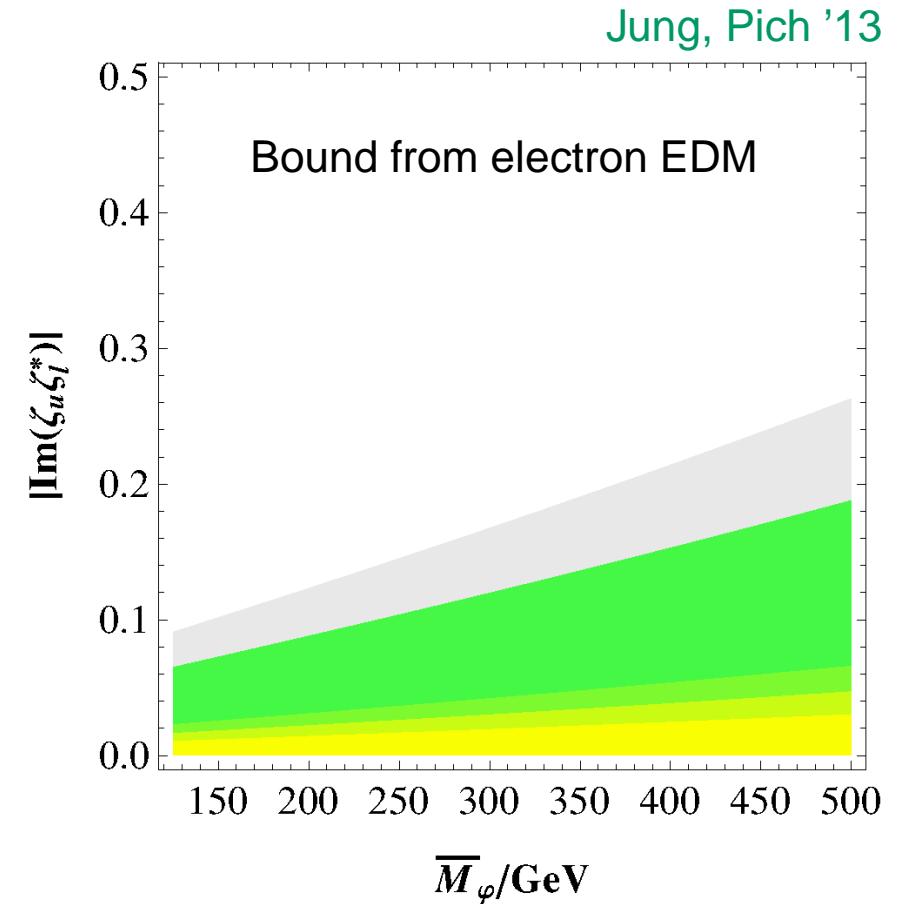


$$(m_{2,3} = 400\ldots 500 \text{ GeV}, t_\beta = 1, \lambda_6 = 5)$$

Cancellation between  $t$  and  $W$  loop

→  $\xi \sim 0.1$  allowed with mild tuning

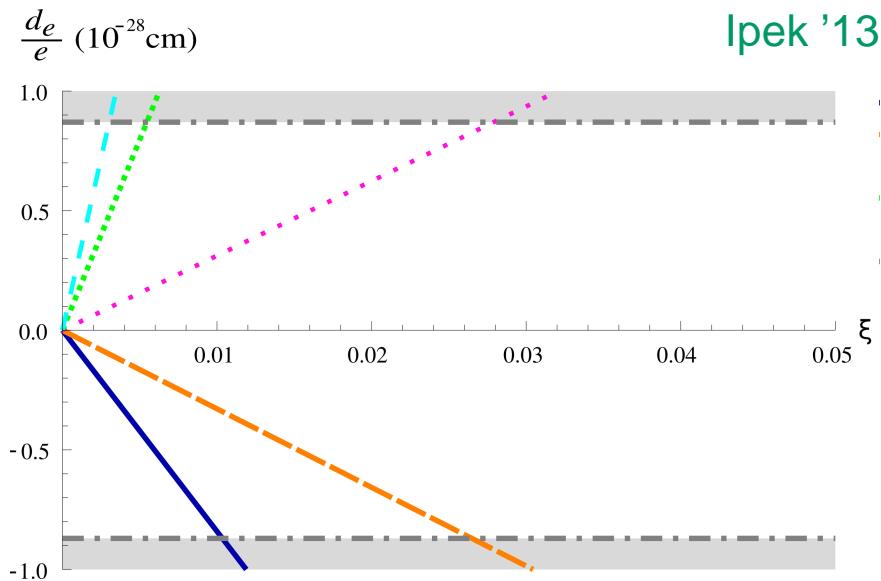
For  $\mathcal{CP}$  in Yukawa couplings:



→  $\mathcal{O}(0.1)$  CP phases allowed

## EDM constraints

For  $\mathcal{CP}$  in scalar potential:

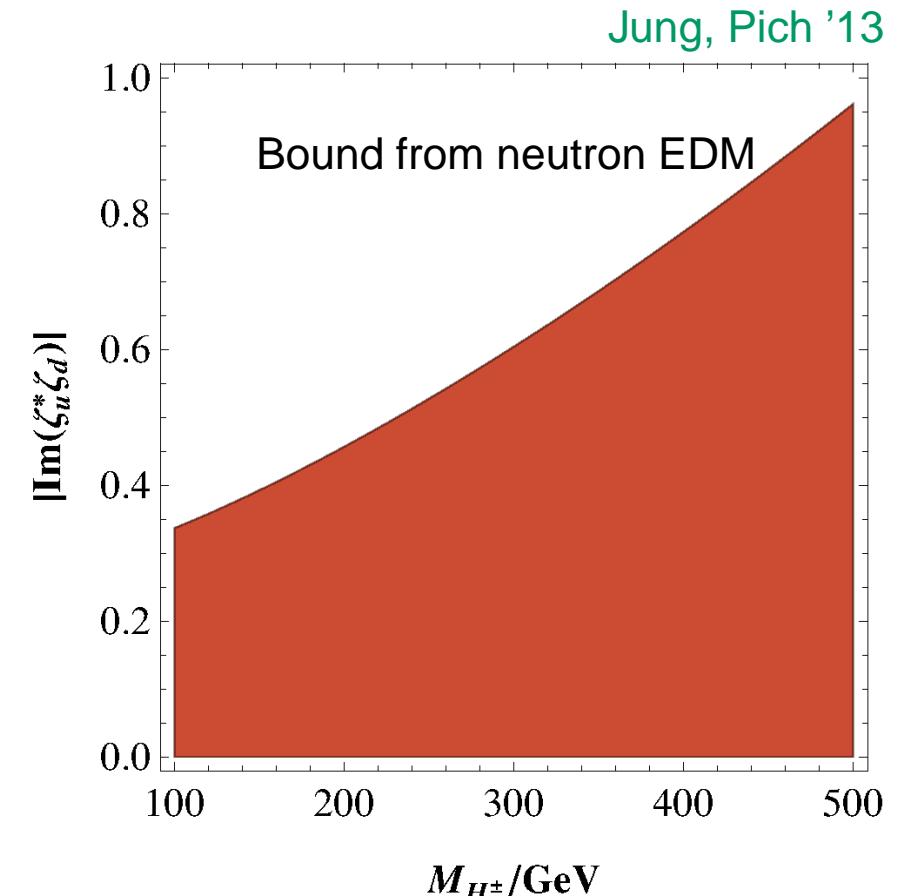


Curves for different  $m_{12}^2$   
( $m_{2,3} = 400\ldots 500 \text{ GeV}$ ,  $t_\beta = 1$ ,  $\lambda_6 = 5$ )

Cancellation between  $t$  and  $W$  loop

→  $\xi \sim 0.1$  allowed with mild tuning

For  $\mathcal{CP}$  in Yukawa couplings:



→  $\mathcal{O}(0.1)$  CP phases allowed

# Anomalous gauge boson couplings

Loop-induced triple- $Z$  coupling:

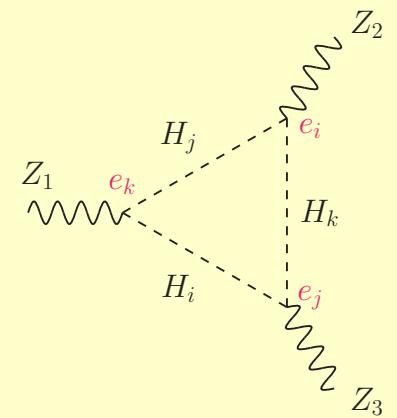
Contribution to  $Z_{\mu_1}^*(p_1) \rightarrow Z_{\mu_2}(p_2)Z_{\mu_3}(p_3)$

$$e\Gamma_{ZZZ}^{\mu_1\mu_2\mu_3} = ie f_4^Z \frac{p_1^2 - M_Z^2}{M_Z^2} (p_1^{\mu_2} g^{\mu_1\mu_3} + p_1^{\mu_3} g^{\mu_1\mu_2})$$

Grzadkowski, Ogreid, Osland '14

Loop suppressed, but strong LHC bounds:  $|f_4^Z| < 0.003$

CMS '13



## Signal rates

CP-odd scalar  $A$  does not have renormalizable tree-level couplings to  $ZZ$ ,  $WW$

→ Observation of these final states limits CP-odd component in

$$\phi = \cos \alpha H + \sin \alpha A$$

Burdman, Haluch, Matheus '11

Frandsen, Sannino '12; Coleppa, Kumar, Logan '12

Freitas, Schwaller '12; Djouadi, Moreau '13

$$\mathcal{L}_{HVV} = -gM_W H W_\mu^+ W^{-\mu} - \frac{1}{2c_W} g M_Z H Z_\mu Z^\mu$$

$$\mathcal{L}_{AVV} = \frac{1}{4(4\pi)^2 v} c_G AG_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{4(4\pi)^2 v} c_B AB_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{1}{4(4\pi)^2 v} c_W AW_{\mu\nu} \tilde{W}^{\mu\nu},$$

$c_{G,B,W} \sim \mathcal{O}(1)$  from one-loop contributions

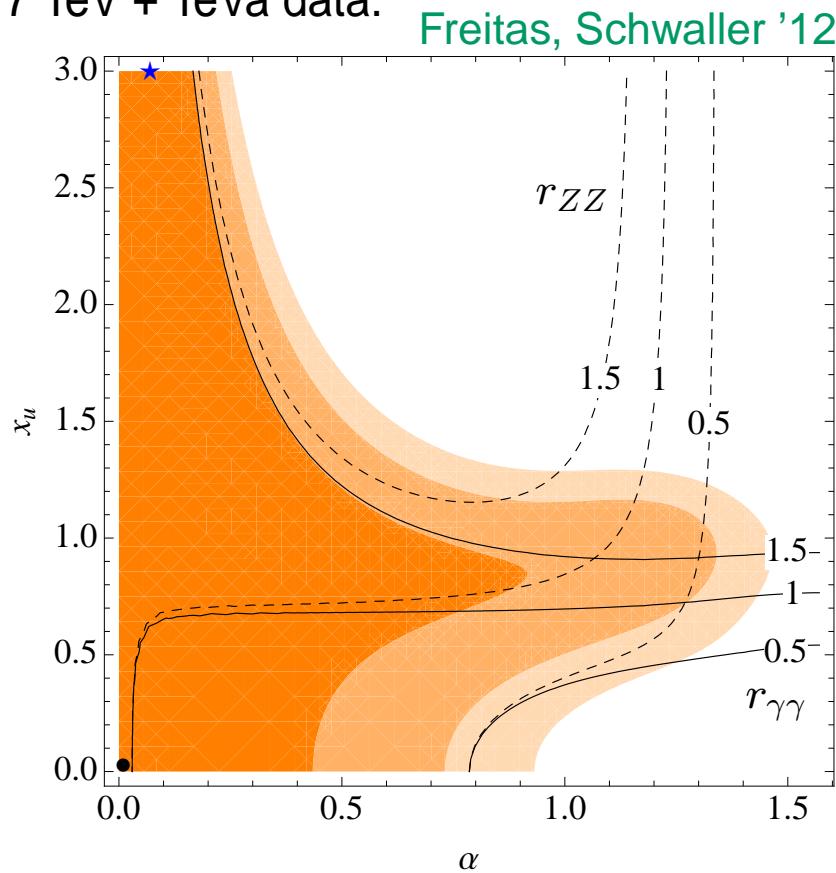
Also allow rescaling of Yukawa couplings relative to SM:

$$\begin{aligned} \mathcal{L}_{Yuk} = & -y_u Y_{ij}^u \bar{u}_i u_j H - y_d Y_{ij}^d \bar{d}_i d_j H - y_d Y_{ij}^\ell \bar{\ell}_i \ell_j H \\ & - i x_u Y_{ij}^u \bar{u}_i u_j A - i x_d Y_{ij}^d \bar{d}_i d_j A - i x_d Y_{ij}^\ell \bar{\ell}_i \ell_j A + \text{h.c.}, \end{aligned}$$

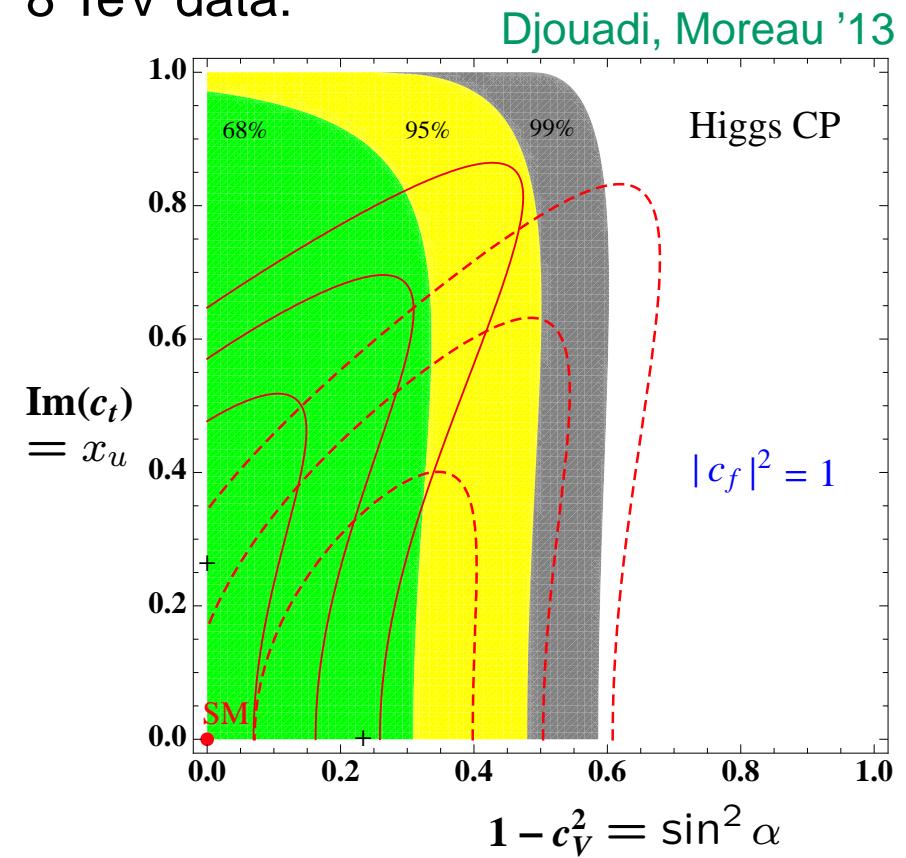
## Signal rates

If dim-5 operators are negligible ( $c_{G,B,W} \ll 1$ ):

7 TeV + TeVa data:



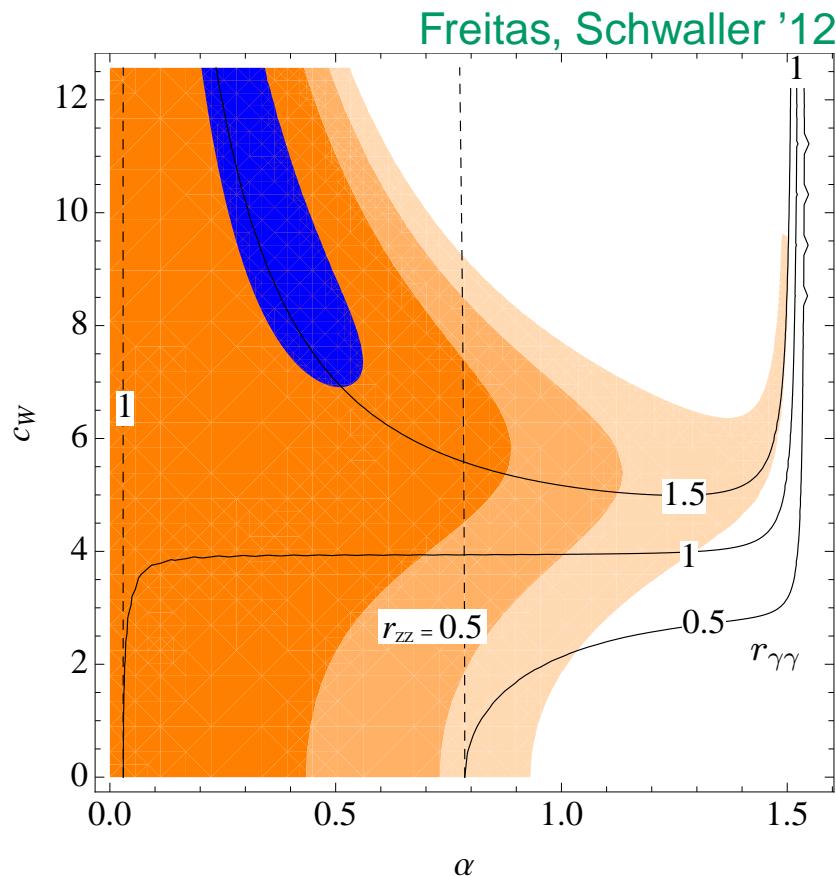
8 TeV data:



→ Pure CP-odd 125-GeV scalar excluded at  $\sim 4\sigma$ !

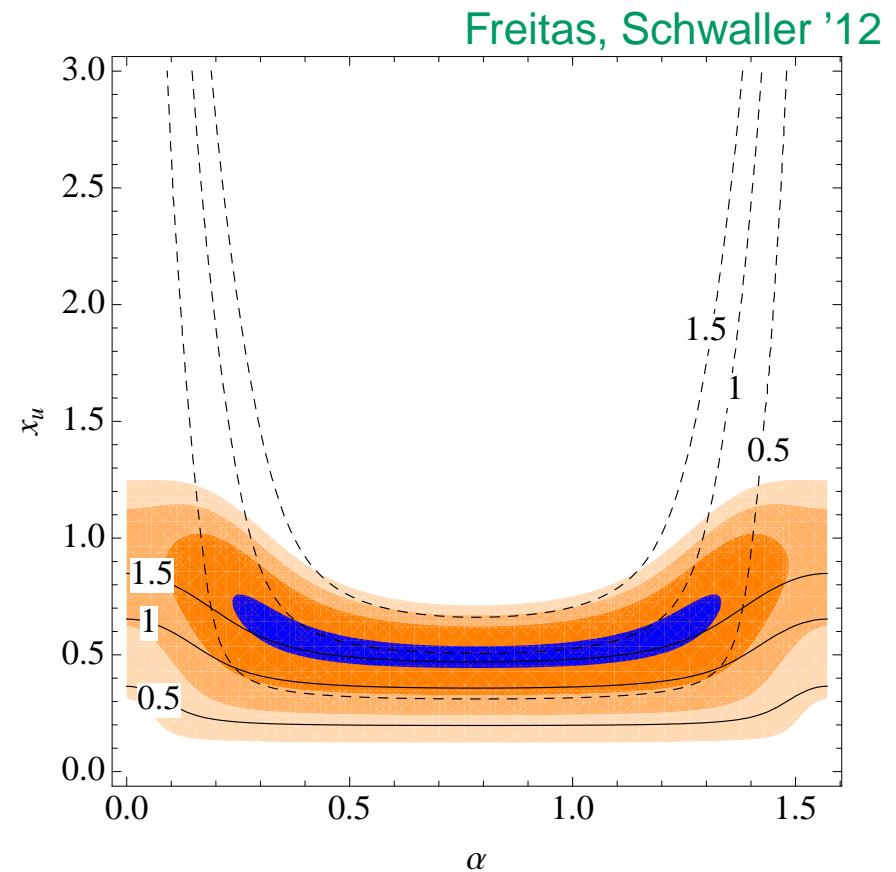
## Signal rates

With floating dim-5 coefficients  
(7 TeV + TeVa data):



Cannot increase  $r_{ZZ}$  significantly

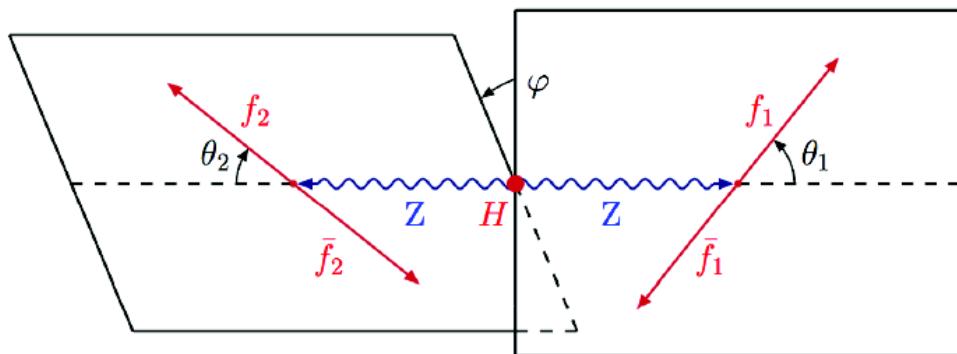
Two mixed resonances with  
 $m_{1,2} \approx 125$  GeV (7 TeV + TeVa):



$\alpha=0$  disfavored because reduced Yukawa couplings ( $y_u \approx 0$ )

# Signal distributions

**Golden channel:**  $H \rightarrow ZZ^* \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$

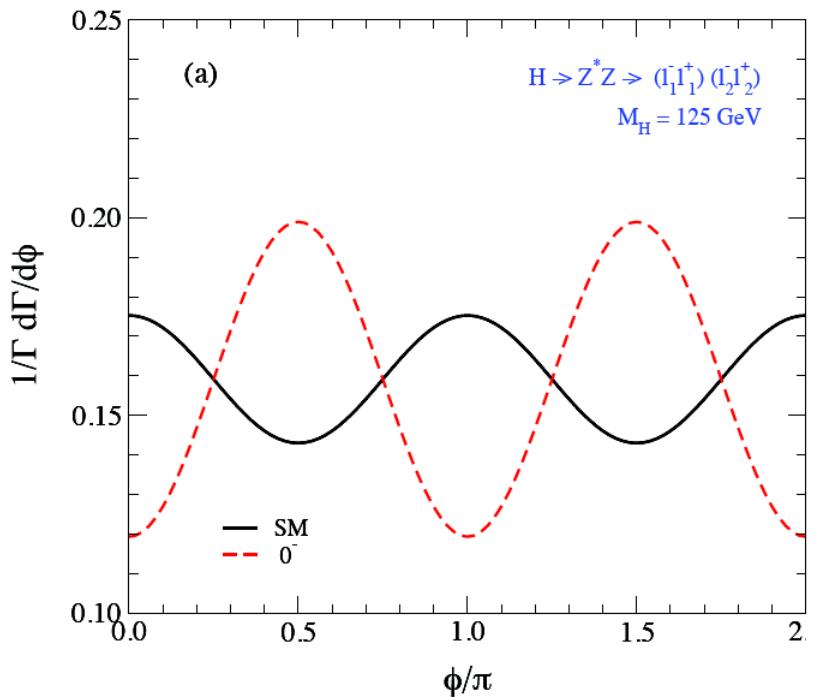


$\phi$  distribution directly distinguishes  
0<sup>+</sup> vs. 0<sup>-</sup> options

Yang '49; Dell'Aquila, Nelson '86

Djouadi et al. '94

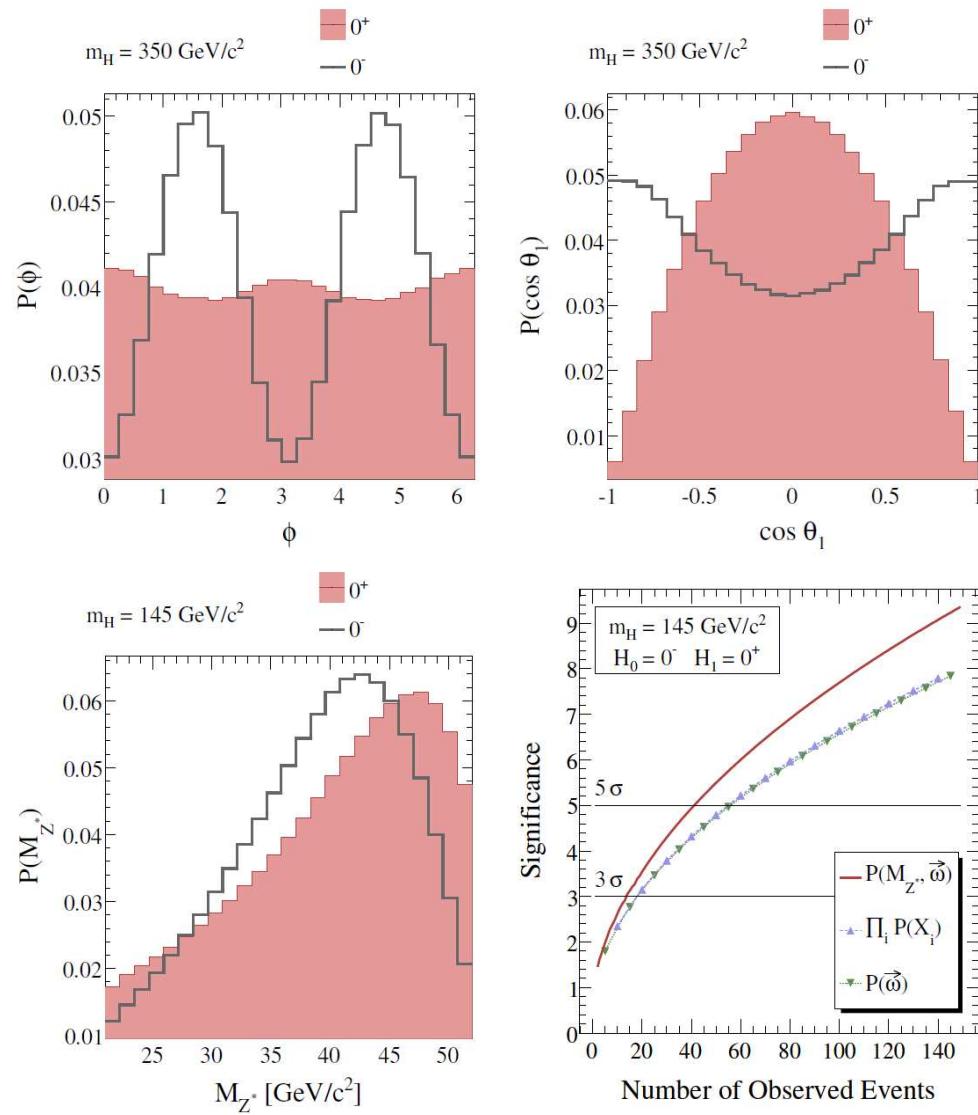
Choi, Miller, Mühlleitner, Zerwas '02



# Signal distributions: ZZ

Other variables also sensitive to  $J^P$

De Rújula, Lykken, Pierini, Rogan, Spiropulu '10



Combined likelihood improves significance (**Matrix Element Likelihood Analysis**)  
(approach taken by ATLAS/CMS)

See also:  
Bolognesi et al. '12  
Avery et al. '12 (MEKD)

## Signal distributions: $\tau^+\tau^-$

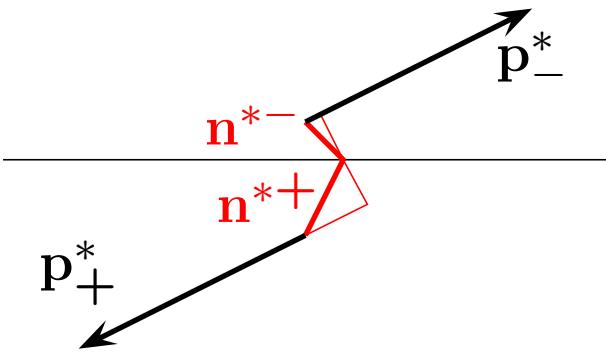
- Strong constraints from LHC Higgs data on  $\mathcal{CP}$  in scalar/gauge sector
- Little known about fermion/Yukawa sector

$\mathcal{CP}$  in  $H \rightarrow \tau\tau$  can be probed through  $\tau$  polarization

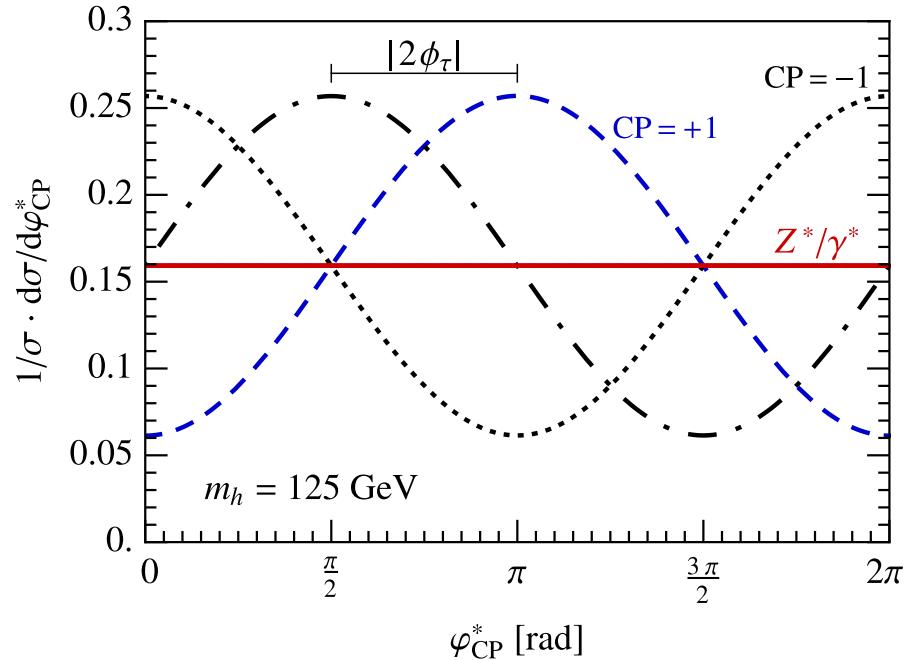
Berge, Bernreuther '08

Berge, Bernreuther, Kirchner '14

Charged prong momenta in prong-prong ( $\pi^+\pi^-$ ,  $\rho^+\rho^-$ , ...) rest frame:



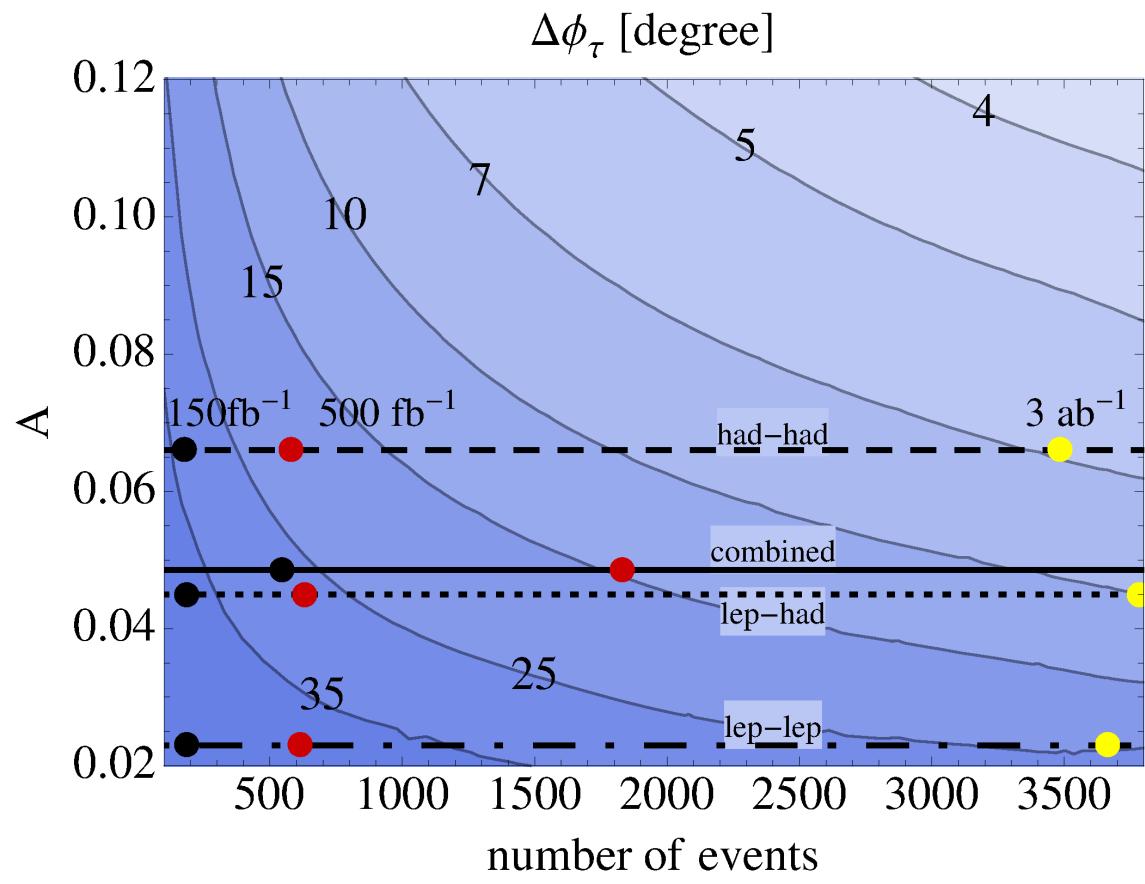
$$\cos \varphi_{\mathcal{CP}}^* = \mathbf{n}_{\perp}^{*+} \cdot \mathbf{n}_{\perp}^{*-}$$



## Signal distributions: $\tau^+ \tau^-$

Projected precision for CP in  $H \rightarrow \tau\tau$  with Drell-Yan background and cuts:

Berge, Bernreuther, Kirchner '14



CP phase  $\phi_\tau$  can be determined with  $15^\circ$  precision with  $500 \text{ fb}^{-1}$  (14 TeV)

## Conclusions

- Sizeable CP violation in Higgs sector still allowed by

- Electric dipole moments
  - Higgs rate data

Simple model framework: Two Higgs Doublet Model

- CP violation is/can be probed through

- $\sigma \times \text{BR}$  Higgs rates
  - $H \rightarrow ZZ \rightarrow 4\ell$  kinematical distributions
  - $H \rightarrow \tau\tau$  polarization distributions
  - Anomalous gauge-boson couplings?