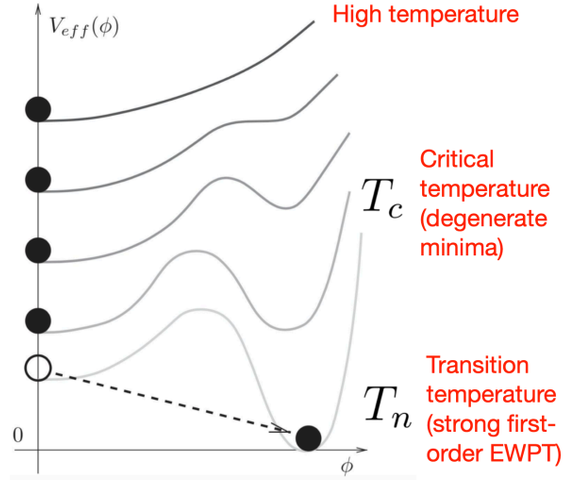
Focus Topic: ZHang - CP

- **Determination of ZH couplings**
- **Access to CP-properties of H**



Why important? Are there additional sources for CP violation in Higgs sector?

Baryogenesis: creation of the asymmetry between matter and anti- matter in the universe requires a strong first-order electroweak phase transition (EWPT)

First-order EWPT does not work in the SM
The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

First-order EWPT can be realised in extended Higgs sectors could give rise to detectable gravitational wave signal

⇒ Search for additional sources of CP violation

But: strong experimental constraints from limits on electric dipole moments (EDMs)

Focus Topic: ZHang - CP

What's the problem?

H → ZZ, WW,γγ

$$\mathcal{A}(X \to VV) = \frac{1}{v}\left(a_1 M_V^2 \varepsilon_1^* \varepsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

most cases: suppressed AVV coupling,
i.e. even if sizable CP-odd component
→'no' deviation from pure CP-even!

$$f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

H → tt,ττ, μμ

$$\mathcal{A}(X \to f\bar{f}) = \frac{m_f}{v} \bar{u}_2 \left(b_1 + i b_2 \gamma_5\right) u_1$$

Higg to fermions more democratic
CP-even and -odd may be similar
→ deviation 'easier' feasible

*2205.07715*2

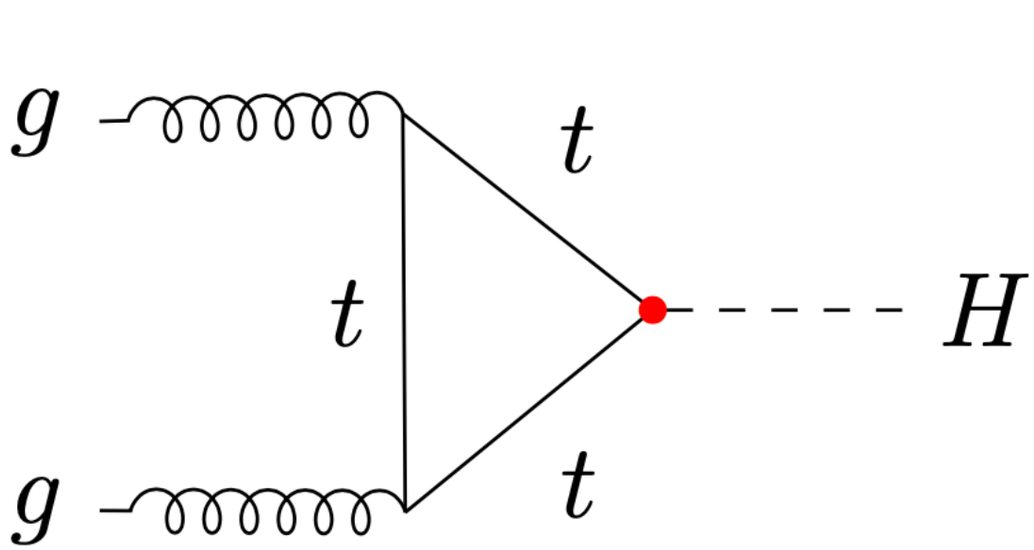
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	$\sim$1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

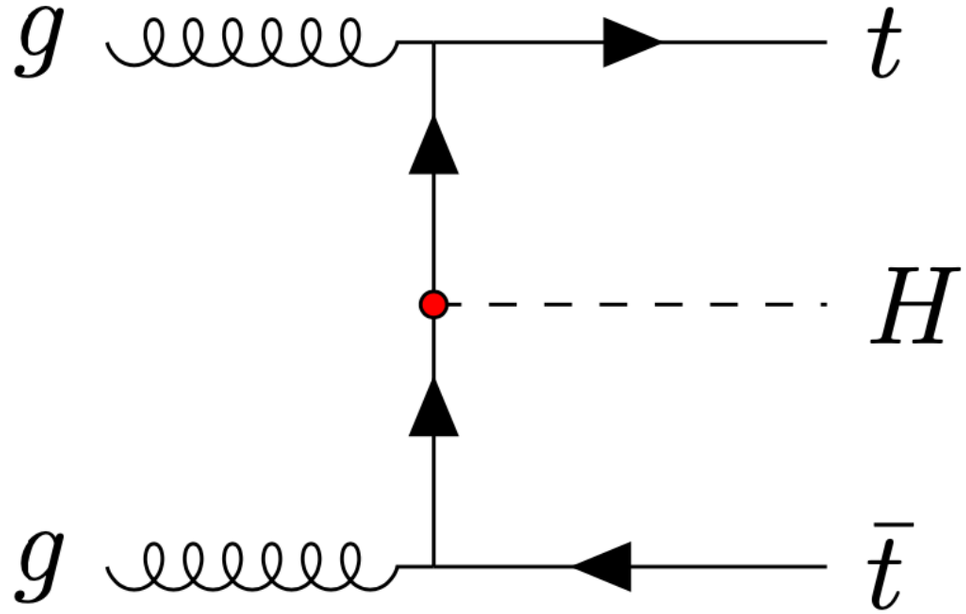
E (GeV)	$\mathcal{L}$ (fb^{-1})	f_{CP}^{HVV}	$f^{\gamma\gamma}$	$f^{Z\gamma}$	$f_{CP}^{\gamma\gamma}$	$f_{CP}^{Z\gamma}$
250	250	$\pm3.4\cdot10^{-4}$	< 0.144	< 0.234	–	–
250	2,500	$\pm3.9\cdot10^{-5}$	< 0.037	< 0.079	–	–
350	350	$\pm1.2\cdot10^{-4}$	< 0.058	< 0.088	–	–
350	3,500	$\pm2.9\cdot10^{-5}$	< 0.016	< 0.032	–	–
500	500	$\pm4.3\cdot10^{-5}$	< 0.028	< 0.039	–	–
500	5,000	$\pm1.3\cdot10^{-5}$	< 0.009	< 0.016	–	–
1,000	1,000	$\pm1.0\cdot10^{-5}$	< 0.009	< 0.014	–	–
1,000	10,000	$\pm3.0\cdot10^{-6}$	< 0.004	$0.0050^{+0.0026}_{-0.0028}$	–	±0.96

CP properties of h125

It has been experimentally verified that h125 is not a pure CP-odd state, but it is by no means clear that it is a pure CP-even state

The main testing ground are processes involving only Higgs couplings to fermions





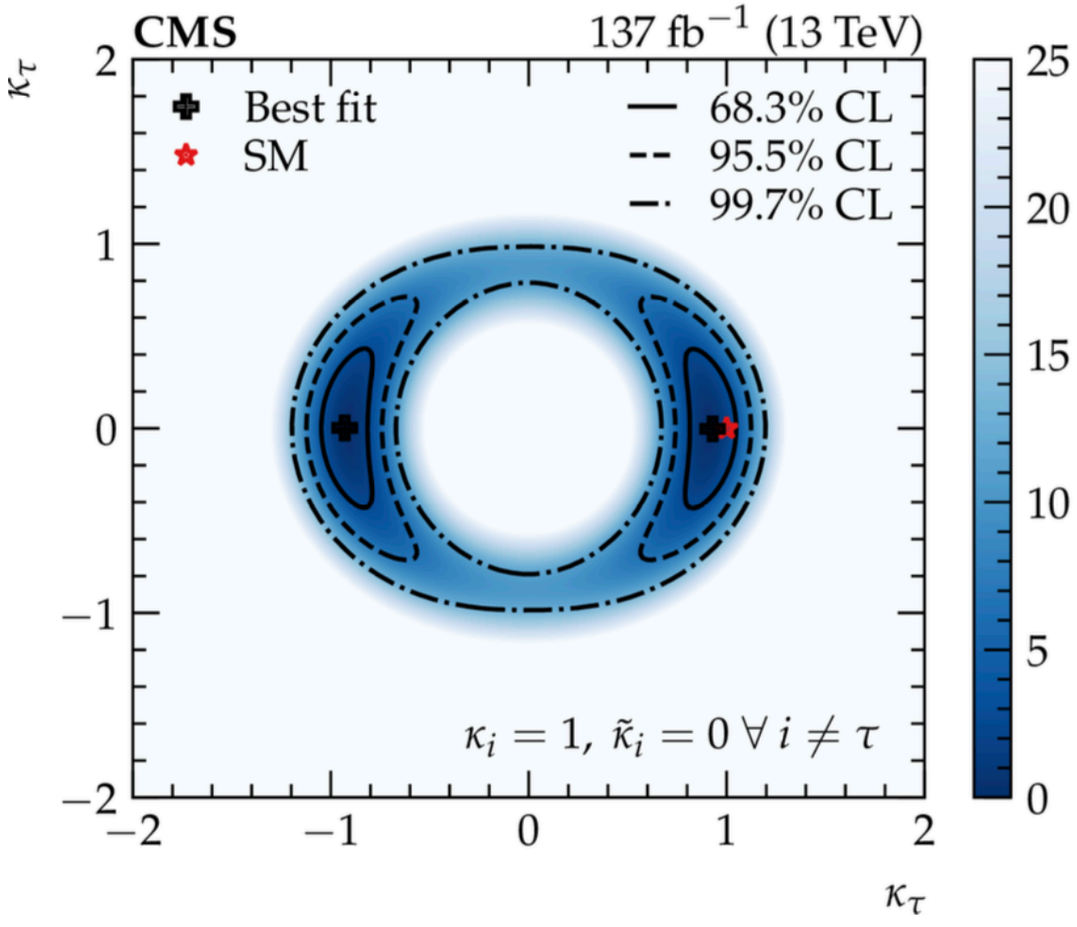
with H → ττ, bb, …

Focus Topic: ZHang - CP

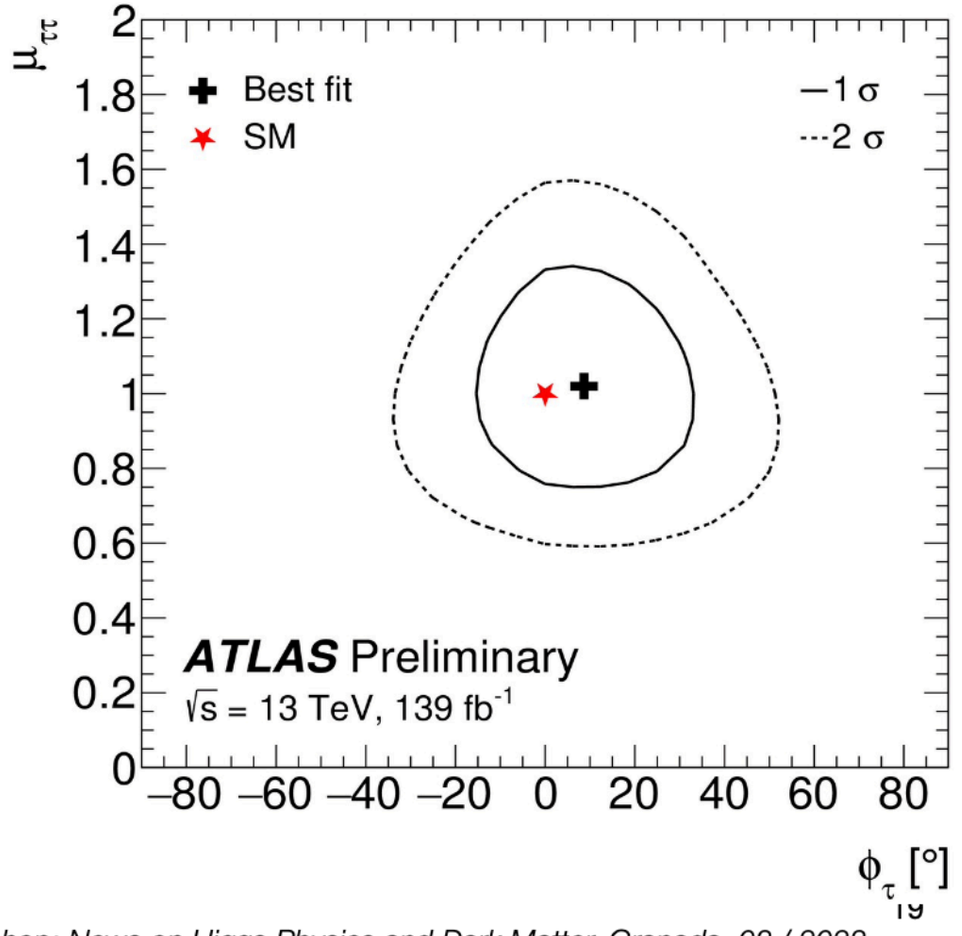
Test of CP violation in the tau Yukawa coupling

Constraints on the CP structure of the tau Yukawa coupling from h125 → $\tau\tau$ decays using angular correlation between decay products:

[CMS Collaboration '21]



[ATLAS Collaboration '22]



Higgs physics and the evolution of the early universe, Georg Weiglein, 2023 Mini workshop: News on Higgs Physics and Dark Matter, Granada, 03 / 2023

Focus Topic: ZHang - CP

Effect on global CP analysis of Higgs-fermion couplings

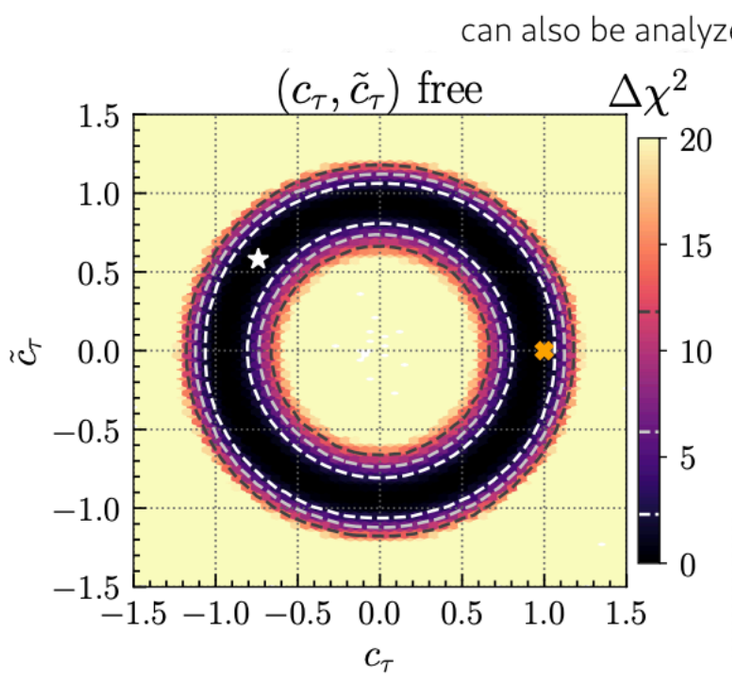
[H. Bahl et al. '22]

Incorporation of recent CMS result on the CP structure of the tau Yukawa coupling from h125 → ττ decays using angular correlation between the decay products

$$\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f\right) f h,$$

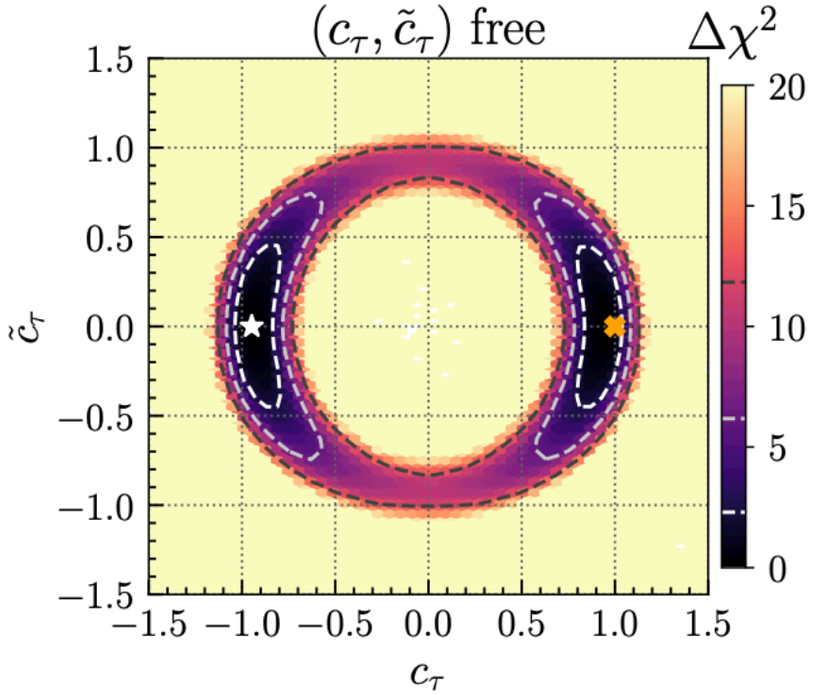
Global fit using **HiggsSignals** + recent analyses

can also be analyzed in EFT



CMS 2110.04836
h→ ττ CPV analysis

$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$



Ring-structure from upper/lower bound on BR

CMS analysis excludes large $\tilde{c}_\tau$

20

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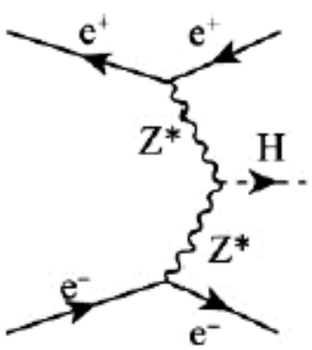
Focus Topic: ZHang - CP

work in progress

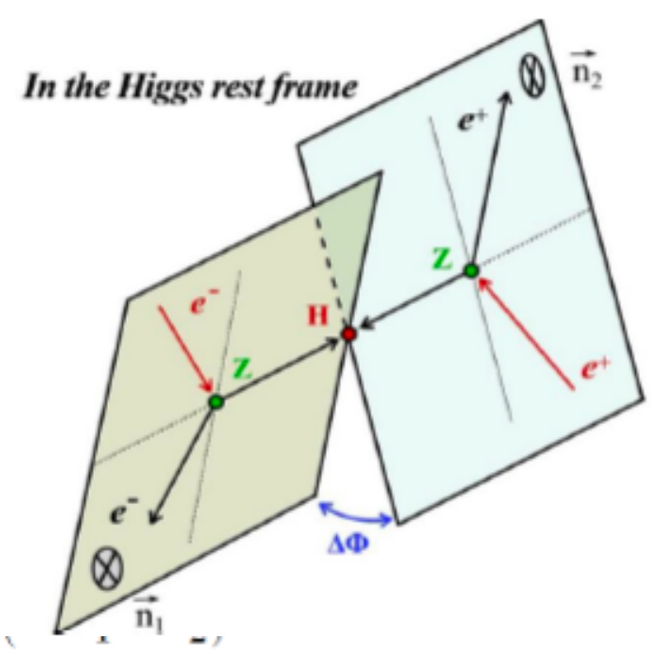
Strategy to work on CP-measurements in HZ and ZZ-fusion: Define CP-odd quantities

a few examples just as teasers …

unpolarized beams: ZZ-fusion



	√s	beam polarisation	∫Ldt (baseline)
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab-1 @ 250 GeV 0.2 ab-1 @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV



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E (GeV)	14,000	14,000	100,000	250	350	500	**1 TeV**	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	**8 ab-1**	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	**1.6 ·10-5**	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

$$sgn\ (\sin \Phi): \frac{q_1 \cdot (\hat{n}_1 \times \hat{n}_2)}{|q_1 \cdot (\hat{n}_1 \times \hat{n}_2)|} \qquad \hat{n}_1 = \frac{q_{e_i^-} \times q_{e_f^-}}{|q_{e_i^-} \times q_{e_f^-}|} \qquad \hat{n}_2 = \frac{q_{e_i^+} \times q_{e_f^+}}{|q_{e_i^+} \times q_{e_f^+}|}$$

Focus Topic: ZHang - CP

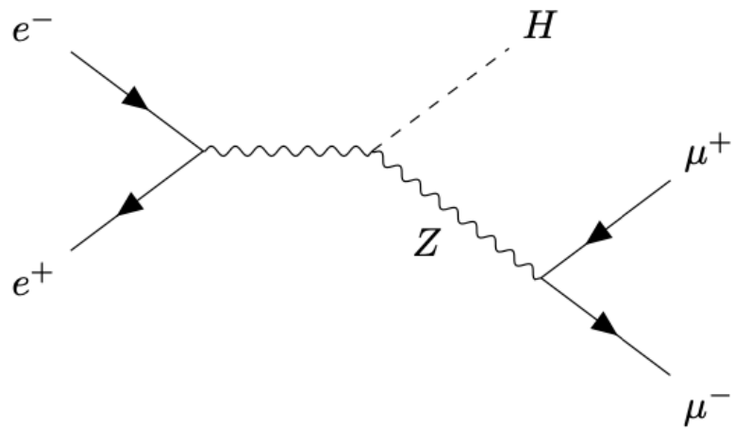
work in progress

Strategy to work on CP-measurements in HZ and ZZ-fusion: Define CP-odd quantities

a few examples just as teasers …

transversely-polarized beams: HZ

$$|\mathcal{M}|^2 = (1 - P^3_- P^3_+)(\cos^2\alpha\,\mathcal{A}_{\text{CP-even}} + \sin 2\alpha\,\mathcal{A}_{\text{CP-mix}} + \sin^2\alpha\,\mathcal{A}_{\text{CP-odd}})$$
$$+ (P^3_- - P^3_+)(\cos^2\alpha\,\mathcal{B}_{\text{CP-even}} + \sin 2\alpha\,\mathcal{B}_{\text{CP-mix}} + \sin^2\alpha\,\mathcal{B}_{\text{CP-odd}})$$
$$+ \sum^{1,2}_{mn} P^m_- P^n_+ \left(\cos^2\alpha\,\mathcal{C}^{mn}_{\text{CP-even}} + \sin 2\alpha\,\mathcal{C}^{mn}_{\text{CP-mix}} + \sin^2\alpha\,\mathcal{C}^{mn}_{\text{CP-odd}}\right)$$



$e^+e^- \to HZ, Z \to \mu^+\mu^-$

$(P^T_{e^-}, P^T_{e^+})$	Luminosity [fb^{-1}]	sin 2α limit	c_{AZZ} limit
(80%, 30%)	2000	-	[-0.31,0.31]
(80%, 30%)	5000	[-0.62,0.62]	[-0.12,0.12]
(90%, 40%)	2000	[-0.79,0.79]	[-0.15,0.15]
(90%, 40%)	5000	[-0.39,0.39]	[-0.09,0.09]

so far only $\sqrt{s}$=250 GeV….
not yet exploited at higher energies
not yet exploited ZZ-fusion

…..work in progress…..

you are welcome!

Working document

2 ZHang – ZH anglular distributions and CP studies

Expert Team: Cheng Li, Chris Hays, Gudrid Moortgat-Pick, Ivanka Bozovic, Jorge de Blas, Ken Mimasu, Markus Klute, Sandra Kortner

Sections:

ZHang - $e^+e^- \to Zh$: recontruction of production and decay angles ($\sqrt{s}$ = 240/250 GeV)

ZHang - CPV in Higgs to Z bosons coupling

ZHang - Higgs couplings in HZ

ZHang - CP-odd Observables

ZHang - global context, CP-conserving SMEFT

just ongoing,….please feel welcome to join!

Working document

Open Topics, working areas, summary so far:

- **Pheno area:** *CP-odd quantities in HZ, VV-fusion, HVV couplings, trilinear couplings etc., detailed model specific studies versus EFT studies, optimal observables versus ang/kin observables, impact of ISR and FSR, ……*

- **MC area:** *non-zero CPV mixing not yet included, detector-specific issues cc, full spin &polarization information, ISR, FSR,….*

- **Target areas:** *τ reconstruction including polarization, in general q, qbar separation, angular reconstruction, (electron tracking) to small polar angles, hermeticity, b-tagging efficiency uncertainty, triple product reconstruction, inclusion of systematic uncertainties in global analyses,….*

CP properties of Higgs crucial and requires both high luminosities and energies from 250 GeV - 1 TeV!

AND NOW YOUR IDEAS !