P-even, CP-violating Signals in Scalar-Mediated Processes

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Outline

1. Sources of CP violation in extended Higgs models
   - C and P symmetries in gauge theories of spin 0 and spin 1 fields
   - Example: J^{PC} assignments of bosons in the CP-conserving 2HDM

2. P-even, CP-violating processes of an extended Higgs sector in the exact Higgs alignment limit (a 2HDM example)

3. How to observe P-even, CP-violating scalar processes at lepton colliders

4. Brief comment on P-even, CP-violating signals via loop effects

This work is based on: H.E. Haber, V. Keus and R. Santos, Phys. Rev. D 106, 095038 (2022) [arXiv:2206.09643 [hep-ph]].

The source of CP violation in the Standard Model

1. In the Standard Model (SM), all observed CP-violating phenomena can be attributed to a nontrivial phase in the CKM mixing matrix.

2. So far, there is no evidence for a second source of CP violation that can arise in the SM if $\sin\theta_{\rm QCD} \neq 0$.

3. If the SM is extended to include massive neutrinos (e.g., the seesaw extended SM), three additional CP-violating phases arise in the PMNS mixing matrix.

If new physics beyond the SM (BSM) were discovered, new sources of CP-violation could be present. Given the nonminimal nature of the fermion and gauge sectors, perhaps the most natural expectation for BSM physics consists of a nonminimal Higgs scalar sector. Such a sector could provide sources of scalar-induced CP violation that do not exist in the SM or its seesaw extension.

Fundamentals of scalar sector CP violation

In an extended scalar sector, CP-violating phenomena can arise from two independent sources.

1. An explicit breaking of CP by the scalar potential or spontaneous CP violation due to a CP-noninvariant vacuum that arises when minimizing the scalar potential.

2. nontrivial phases in the CP-violating neutral Higgs–fermion Yukawa couplings.

3. nontrivial phases (beyond the CKM phase) in the CP-violating (singly) charged Higgs–fermion Yukawa couplings.

CP-violation arising from 1 above is qualitatively different from the CP-violation that originates from 2 and 3.

C and P symmetries in a gauge theory of spin-0 and spin-1 fields

Consider a theory of scalar fields (ϕ) and gauge fields (V).

- All kinetic energy terms (where derivatives are replaced by covariant derivatives) and mass terms of the Lagrangian separately conserve C, P and T. When scalar self-interactions are included, CP-violating interaction terms can arise.
- In the presence of (renormalizable) interactions,* P is conserved in all scattering processes.
- Gauge fields are assigned $P = -1$, since $\mathscr{L}_{\rm int} = -j^\mu A_\mu$ conserves P.
- All scalars can be consistently assigned $P = +1$.

*excluding the topological term $\theta F\widetilde{F}$, which is P-odd and C-even.

Example: Consider a gauge theory of scalar fields with CP-violating scalar self-interactions (but with no fermions). If ϕ is a mixed CP state, then the effective Lagrangian governing the $\phi \to VV$ decay, $\mathcal{L}_{\rm eff} \sim \phi F F$, arises at one-loop due to a loop of charged scalars, which is parity conserving. Since no $\epsilon_{\mu\nu\alpha\beta}$ will appear to all orders in perturbation theory, there is no loop-induced $\phi F\widetilde{F}$. Thus, CP violation must be interpreted as C violation.

> A theory with CP-violating scalar self-interactions provides an example of P-even CP violation.

In contrast, CP violation arising from $\theta F\widetilde{F}$ or from the Yukawa interactions of neutral scalars provide examples of P-odd CP violation, since FF, $F\widetilde{F}$, $\overline{\psi}\psi$, and $i\overline{\psi}\gamma_5\psi$ are C-even operators.

The CP-conserving two-Higgs doublet model (2HDM) provides an instructive example. Excluding the fermions, the $J^{\rm PC}$ quantum numbers of the bosonic fields of the 2HDM are shown below.

bosonic field	$J^{\rm PC}$	$J^{\rm P}$
γ, Z	1^{--}	
h, H	0^{++}	
A, G	0^{+-}	
$W^\pm$		1^-
$H^\pm, G^\pm$		0^+

Perhaps you were expecting the CP-odd neutral scalar A and the neutral Goldstone boson G to be 0^{-+} pseudoscalars. Such J^{PC} assignments arise in the context of the Yukawa interactions. But here, we are considering the bosonic sector alone.

The bosonic Lagrangian is separately C and P conserving. For example, there is no AZZ coupling due to C-invariance. If the scalar self-interactions violate CP, then C is no longer conserved.

In contrast, consider a theory of neutral scalars and fermions with (dimension-4) Yukawa interactions. In the CP-conserving 2HDM,

$$\mathscr{L}_{\rm Yuk} = -g_{h\psi\psi}\overline{\psi}\psi h - g_{H\psi\psi}\overline{\psi}\psi H - i g_{A\psi\psi}\overline{\psi}\gamma_5\psi A\,,$$

which would imply that h and H are 0^{++} scalars and A is a 0^{-+} scalar. Given a theory of scalars and fermions (with renormalizable Yukawa interactions), one can consistently assign $C=+1$ to all neutral scalar fields. Thus, if ϕ is a scalar of indefinite CP, then

$$\mathscr{L}_{\rm Yuk} = -\overline{\psi}(g_1 + i g_2\gamma_5)\psi\phi\,,$$

which for $g_1 g_2 \neq 0$ violates P but conserves C. This is an example of C-even CP violation.

In summary, new sources of CP violation (CPV) can be present in extended Higgs sectors:

- P-even CPV via a CP-violating scalar potential (explicit CP violation) or vacuum (spontaneous CP violation).
- C-even CPV via CP-violating neutral scalar Yukawa couplings.
- P-odd CPV via CP-violating charged scalar Yukawa couplings.

CP-violating Yukawa couplings can be probed via P-violating asymmetries (which arise due to the presence of an $\epsilon_{\mu\nu\alpha\beta}$).

In this talk, the following question is posed:

How can we experimentally identify signals of P-even CP violation mediated by scalars?

For simplicity, proposed observables are presented in the context of the CP-violating 2HDM, with neutral scalars h_1, h_2 and h_3.

Initial Proposal:[†]

- Detect the three decays, $h_3 \to h_2 Z$, $h_3 \to h_1 Z$, and $h_2 \to h_1 Z$;

or

- Detect the three production processes, $Z^* \to h_3 h_2$, $h_3 h_1$, $h_2 h_1$.

If CP is conserved, then the J^{PC} assignments of the bosonic sector imply that the two final state scalars have opposite sign C.[‡] But it is not possible for h_i and h_j to have opposite sign C for all possible $i < j$.

[†] Based on Fontes, Romão, Santos and Silva: arXiv:1506.06755. See also: A. Mendez and A. Pomarol, Phys. Lett. B 272, 313 (1991) and G. Cvetic, M. Nowakowski and A. Pilaftsis, Phys. Lett. B 301, 77 (1993).

[‡] Note that P is conserved since combining two parity-even scalars in an angular momentum $L = 1$ state (corresponding to the Z boson) yields $P = (-1)^L = -1$.

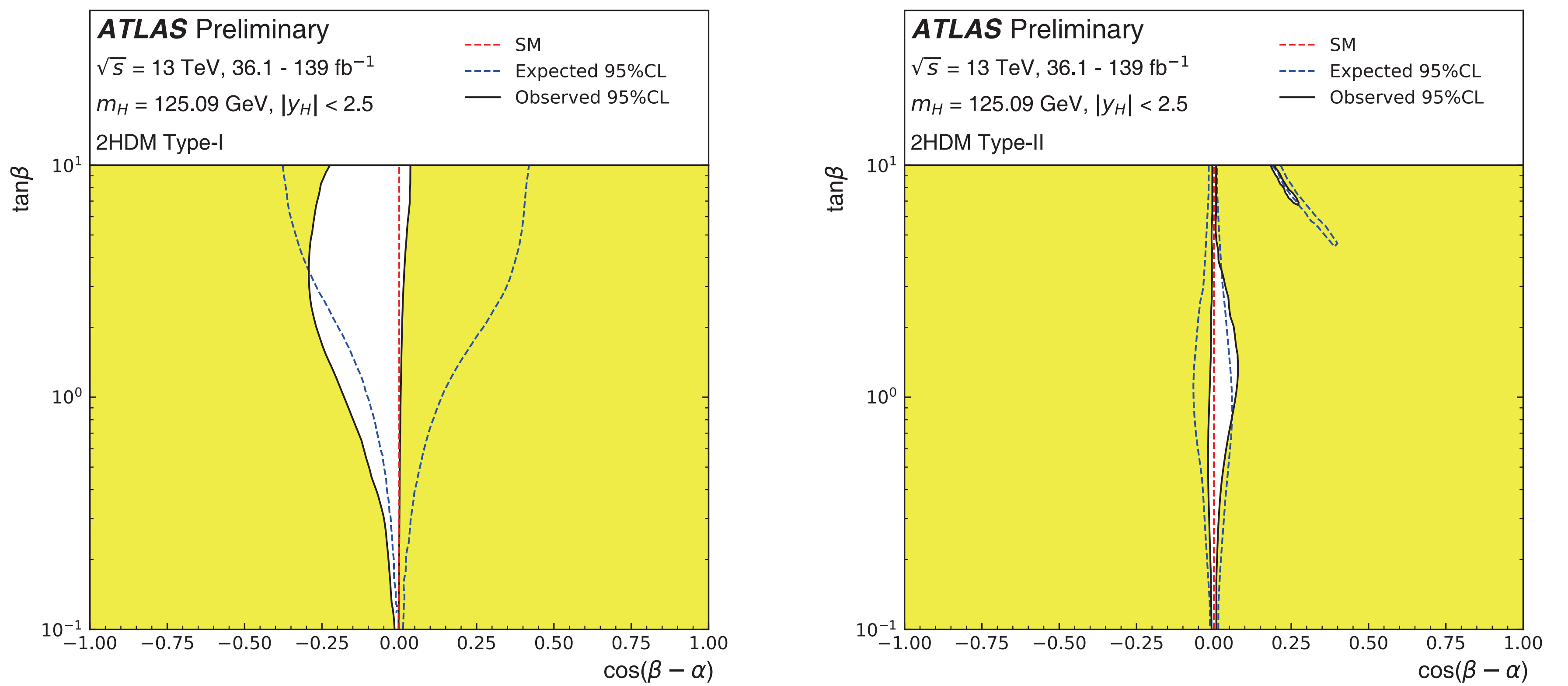
Why the initial proposal does not work

The LHC Higgs data suggests that the observed Higgs boson is very SM-like. Any extended Higgs sector must take this observation into account. In an extended Higgs sector, a SM-like Higgs boson (denoted by h_1 below) arises in the so-called *Higgs alignment limit*. In the exact alignment limit, the following Higgs boson–gauge boson interactions vanish:

1. hVV for $h \neq h_1$

2. $h_i h_j V$ $(i \neq j)$, for $i = 1$ or $j = 1$.

REMARK: Exact Higgs alignment in the CP-conserving 2HDM implies that $\cos(\beta - \alpha) = 0$.



Regions excluded (at 95% CL) by fits to the measured rates of the productions and decay of the Higgs boson (assumed to be h of the 2HDM), highlighted in yellow. The observed best fit values for $\cos(\beta - \alpha)$ are -0.006 for the Type-I 2HDM and 0.002 for the Type-II 2HDM. Taken from The ATLAS Collaboration, ATLAS-CONF-2021-053 (December 15, 2021).

In the exact Higgs alignment limit, the neutral Higgs bosons of the 2HDM arising at tree-level, $h_1 \equiv h_{\rm SM}$ (CP-even), h_2 (CP-even), and h_3 (CP-odd), are eigenstates of CP. If CP is broken (either explicitly or spontaneously) by the scalar potential or vacuum, then in the exact Higgs alignment limit, the only bosonic sources of CP violation are:

$$h_3h_3h_3\,,\;\; h_3h_2h_2\,,\;\; h_3H^+H^-\,,\;\; h_3h_3h_3h_1\,,\;\; h_3h_1h_2h_2\,,\;\; h_3h_1H^+H^-.$$

Our Proposal: We propose to find observables that are similar to the ones of the initial proposal in which all couplings are present in the exact Higgs alignment limit.

In the 2HDM, there are four classes of processes (involving trilinear couplings) whose simultaneous observation would constitute a detection of P-even CP violation.

1. $h_2H^+H^-\,, \quad h_3H^+H^-\,, \quad Zh_2h_3\,,$
2. $h_2h_kh_k\,, \quad h_3H^+H^-\,, \quad Zh_2h_3\,,$ (for $k=2$ or 3),
3. $h_3h_kh_k,\,, \quad h_2H^+H^-\,, \quad Zh_2h_3\,,$ (for $k=2$ or 3),
4. $h_2h_kh_k\,, \quad h_3h_\ell h_\ell\,, \qquad Zh_2h_3\,,$ (for $k,\ell=2$ or 3).

Note: If CP is conserved, then both H^+H^- and h_kh_k in an angular momentum zero state have $C=P=+1$.

P-even, CP-violating scalar processes at lepton colliders

We shall assume that the neutral scalars (beyond the SM-like h_1) and the charged scalars of the extended Higgs sector have been discovered (at the LHC or at some future collider facility).

Lepton colliders provide an ideal tool for exploring P-even, CP violation, since the relevant production processes involve tree-level purely bosonic interactions. (In contrast, the dominant production mechanism at the LHC is gluon-gluon fusion via a top quark loop.)

Since signals of P-even CP violation require the production of multiple scalars, sub-TeV lepton colliders are unlikely to provide the necessary production cross sections.

Thus, we shall focus on a number of TeV-scale lepton colliders that have been considered as the facility of choice to explore P-even CP-violating phenomena.

Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	10	10
Muon Collider	14	20

Accelerators used in the analysis with different CM energies proposed and the corresponding total integrated luminosity in a multiyear program (typically of order 10 years).

Coupling parameters that govern the three-scalar interactions

In the exact Higgs alignment limit, the interaction vertices that contribute to the P-even, CP-violating observables of interest are:

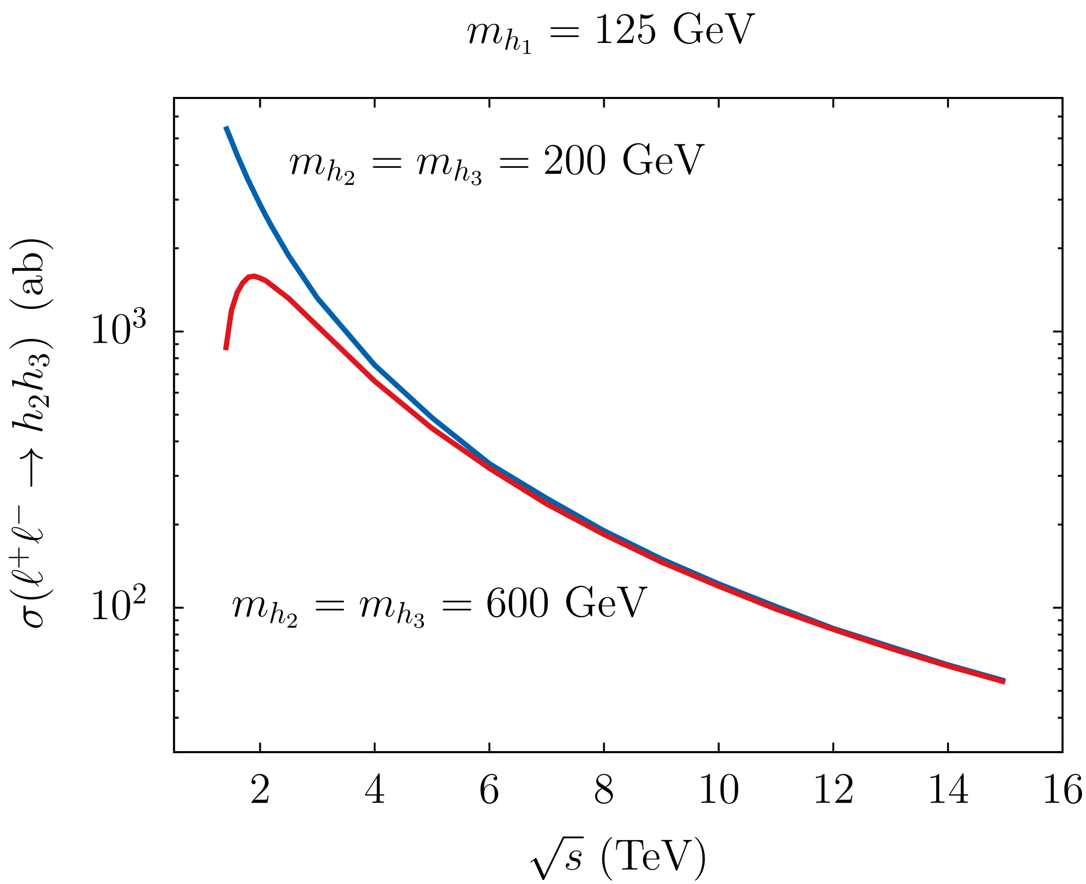
$$\lambda_{H^+H^-h_1} = vZ_3\,,$$
$$\lambda_{H^+H^-h_2} = \lambda_{h_3h_3h_2} = v\,\mathrm{Re}(Z_7e^{-i\eta})\,,$$
$$\lambda_{H^+H^-h_3} = \lambda_{h_2h_2h_3} = -v\,\mathrm{Im}(Z_7e^{-i\eta})\,.$$

For convenience, we shall denote:

$$\Lambda_1 \equiv Z_3, \qquad \Lambda_2 \equiv \mathrm{Re}(Z_7e^{-i\eta}), \qquad \Lambda_3 \equiv \mathrm{Im}(Z_7e^{-i\eta}).$$

Note: The parameters Z_3 and $Z_7e^{-i\eta}$ are coefficients of the $(\mathcal{H}_1^\dagger\mathcal{H}_1)(\mathcal{H}_2^\dagger\mathcal{H}_2)$ and $(\mathcal{H}_1^\dagger\mathcal{H}_2)(\mathcal{H}_2^\dagger\mathcal{H}_2) + \mathrm{h.c.}$ terms of the scalar potential in the so-called Higgs basis where $\langle\mathcal{H}_1^0\rangle = v/\sqrt{2}$ (with $v \simeq 246$ GeV) and $\langle\mathcal{H}_2^0\rangle = 0$. The phase angle η represents the freedom to rephase $\mathcal{H}_2$ in defining the Higgs basis.

An optimal case study: $\ell^+\ell^- \to Z^* \to h_2 h_3$



The sweet spot is $\sqrt{s} \simeq 3$ TeV, where at least 1000 events are produced at a lepton collider operating for roughly 10 years, for the scalar masses shown above.

The relevant h_2 and h_3 decay modes (if kinematically allowed):

$h_3 \to h_2 Z$, $h_3 \to h_2 h_2$, $h_{2,3} \to H^{\pm} W^{\mp}$, $h_{2,3} \to H^+ H^-$, $h_{2,3} \to \bar{t}t$, $h_{2,3} \to \bar{b}b$ and $h_{2,3} \to \tau^+\tau^-$.

Because the couplings of h_2 and h_3 to other scalars can be large, $\ell^+\ell^- \to Z^* \to h_2 h_3$ alone could signal P-even CP violation in the exact Higgs alignment limit.

For example, if the following two-body decays are observed,

$$h_3 \to h_2 h_2 \quad \text{and} \quad h_2 \to H^+ H^-,$$

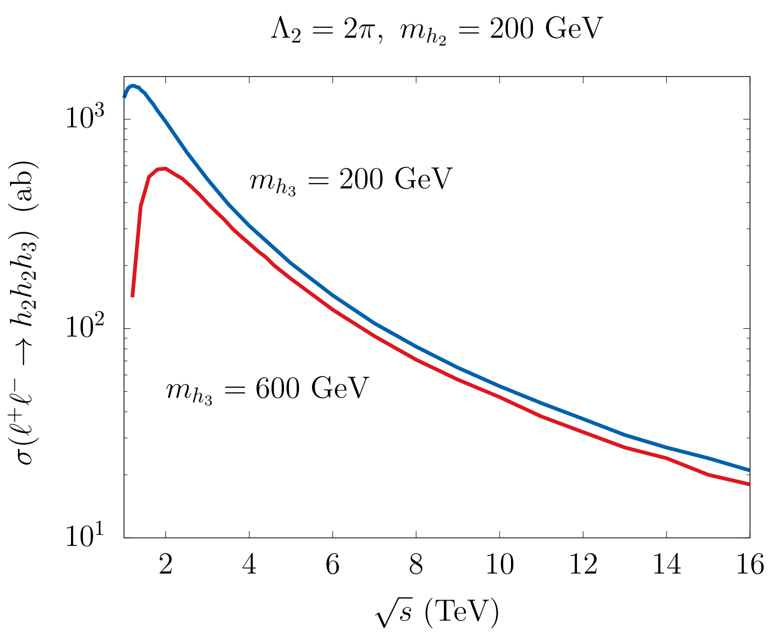
then $\ell^+\ell^- \to Z^* \to h_2 h_3$ would provide evidence for the simultaneous observation of the $h_3 h_2 h_2$, $h_2 H^+ H^-$ and $Z h_2 h_3$ vertices, which is a signal of P-even CP violation.

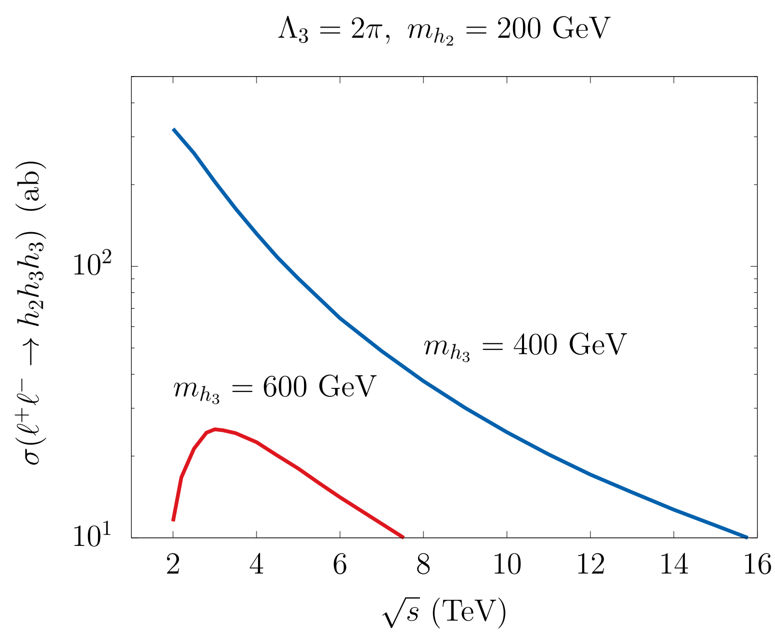
If the two-body decays of h_2 and h_3 into bosonic final states are kinematically forbidden, then

- consider separately the three production processes governed by one of the sets of bosonic interactions previously mentioned.

Advantage: only constrained by the collider energy.

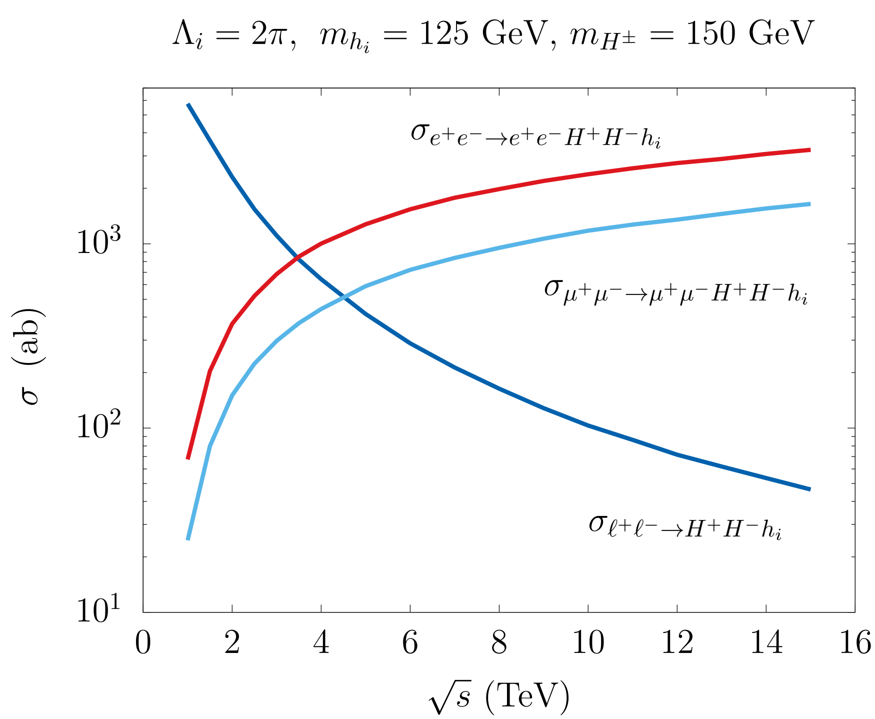
Disadvantage: requires the observation of 3-body processes with smaller cross sections. To ensure at least 100 events before cuts requires $\sigma \gtrsim 10$–100 ab.

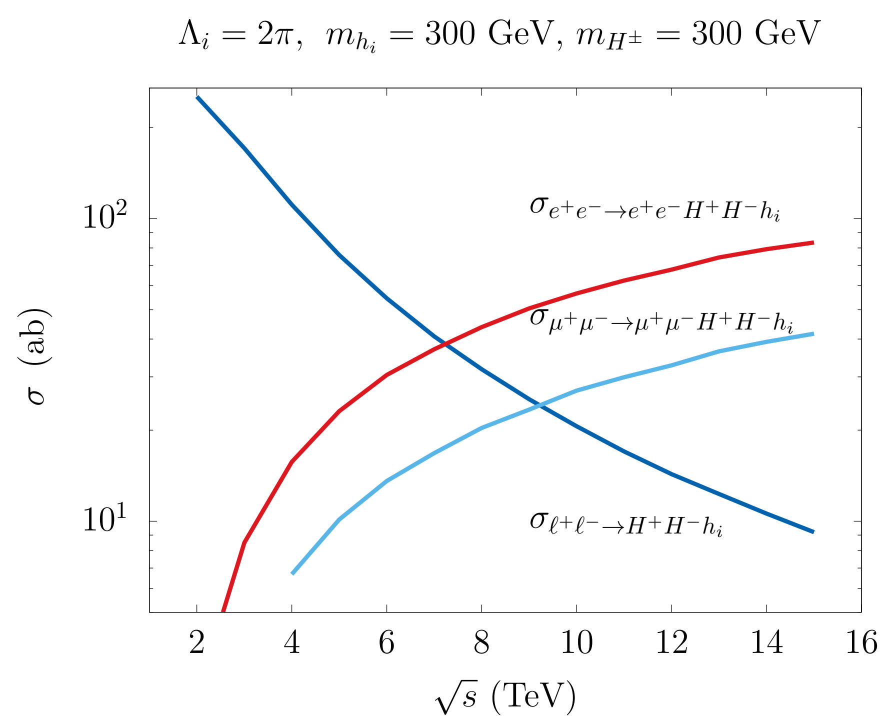




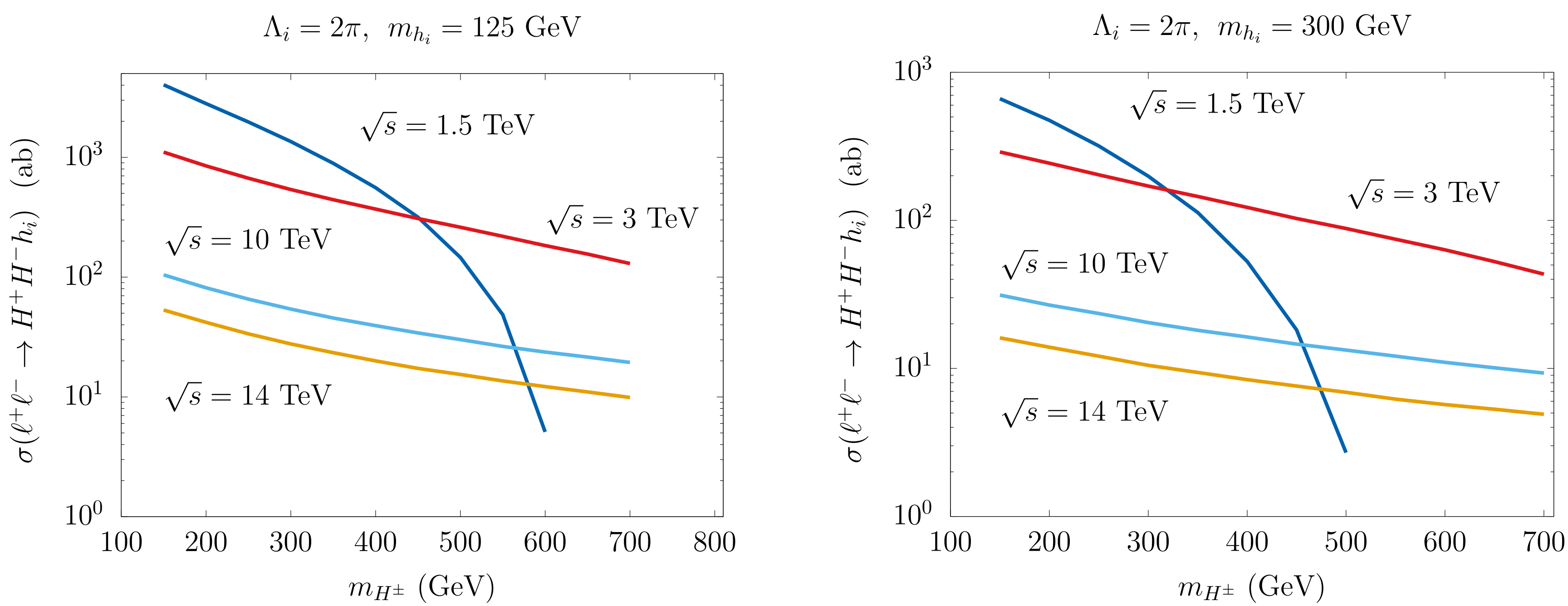
Production of charged Higgs bosons at lepton colliders

Instead of $h_i h_j h_j$ production via s-channel Z exchange, one can consider final state charged Higgs bosons, which can be produced either via s-channel γ/Z exchange, $\ell^+\ell^- \to H^+H^-h_i$, or via the t-channel $\gamma\gamma$ fusion process, $\ell^+\ell^- \to \ell^+\ell^- H^+H^-h_i$.

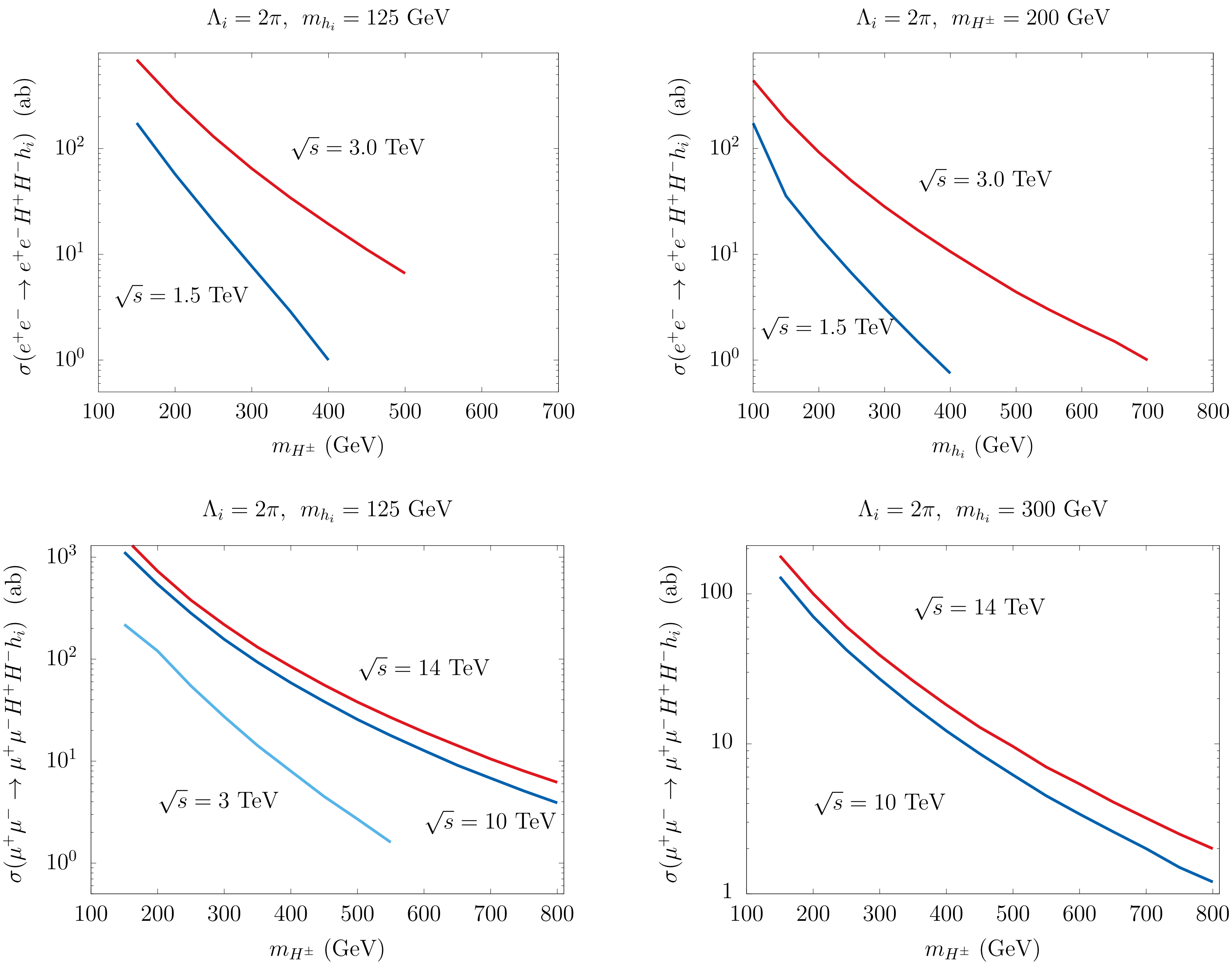




In more detail, we show below the s-channel cross section, $\sigma(\ell^+\ell^- \to H^+H^-h_i)$, as a function of the charged Higgs mass for four CM energies of $\sqrt{s} = 1.5$, 3, 10 and 14 TeV. The scalar potential parameters are chosen such that $\Lambda_i = 2\pi$.



The corresponding results for the t-channel $\gamma\gamma$ fusion processes for CLIC and the muon collider, respectively, are shown below.



$\Lambda_i = 2\pi,\ m_{h_i} = 125$ GeV
$\sigma(e^+e^- \to e^+e^- H^+H^- h_i)$ (ab)
$m_{H^\pm}$ (GeV)
$\sqrt{s} = 3.0$ TeV
$\sqrt{s} = 1.5$ TeV
$\Lambda_i = 2\pi,\ m_{H^\pm} = 200$ GeV
$\sigma(e^+e^- \to e^+e^- H^+H^- h_i)$ (ab)
m_{h_i} (GeV)
$\sqrt{s} = 3.0$ TeV
$\sqrt{s} = 1.5$ TeV
$\Lambda_i = 2\pi,\ m_{h_i} = 125$ GeV
$\sigma(\mu^+\mu^- \to \mu^+\mu^- H^+H^- h_i)$ (ab)
$m_{H^\pm}$ (GeV)
$\sqrt{s} = 14$ TeV
$\sqrt{s} = 3$ TeV
$\sqrt{s} = 10$ TeV
$\Lambda_i = 2\pi,\ m_{h_i} = 300$ GeV
$\sigma(\mu^+\mu^- \to \mu^+\mu^- H^+H^- h_i)$ (ab)
$m_{H^\pm}$ (GeV)
$\sqrt{s} = 14$ TeV
$\sqrt{s} = 10$ TeV

P-even, CP-violating signals via loop effects

One can indirectly probe the P-even, CP-violating phenomena via loop contributions to the ZZZ and ZW^+W^-form factors.[§]

$$\Gamma_V^{\alpha\beta\mu}(q,\bar{q},P) = f_1^V(\bar{q}-q)^\mu g^{\alpha\beta} - \frac{f_2^V}{m_W^2}(\bar{q}-q)^\mu P^\alpha P^\beta + f_3^V\left(P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}\right)$$
$$+ i f_4^V\left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right) + i f_5^V \epsilon^{\mu\alpha\beta\rho}(\bar{q}-q)_\rho$$
$$- f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho - \frac{f_7^V}{m_W^2}(\bar{q}-q)^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho (\bar{q}-q)_\sigma .$$

The form factor f_4^V is the unique form factor that is P-conserving and CP-violating. In the exact Higgs alignment limit, a nonzero scalar contribution to f_4 requires at least three neutral scalars beyond the SM-like Higgs boson.[¶]

[§]Applications to the CP-violating 2HDM can be found in Grzadkowski, Ogreid and Osland, arXiv:1603.01388.

[¶]Note that there are two triangle diagrams with internal scalars that contribute at one loop order to the ZW^+W^- form factors, consisting of an $H^+H^-h_j$ and an $h_jh_kH^+$ loop, with corresponding ZH^+H^- and Zh_jh_k vertices, respectively. Only the latter can contribute to the P-even, CP-violating form factor f_4.

Conclusions

- P-even CP violation can arise in extended Higgs sectors.
- The physics of P-even CP violation is distinct from CP-violating phenomena that originate from the Yukawa sector.
- If new sources of CP violation are present in an extended Higgs sector, then an important task of future Higgs studies will be to determine their origins.
- To discover and probe P-even CP violation of an extended Higgs sector, our initial studies suggest that a multi-TeV lepton collider will be required.[‖]

[‖] Although not discussed in this talk, a multi-TeV $\gamma\gamma$ collider (which could be obtained using an e^+e^- collider by converting the electrons to photons via Compton backscattering of laser light) can also be employed to identify P-even CP-violating signals.