CPV Searches @ COLLIDERS

Amarjit Soni BNL-HET Pheno 2023 5/9/23

Initial state is NOT selfconjugate

outline

Motivation

- Main new development: Formula that deals with a non-conjugate initial state, i.e. pp collider such as LHC e-Print: <u>2212.09433</u> [hep-ph]
- Application to multilepton FS
- Summary

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay Princeton University, Princeton, New Jersey
(Received 10 July 1964)

BNL'64

(Christenson) Cronin, Fitch (& Turlay), PRL'64

 KL => 3 pi, most of the time but once in a purple moon it also goes to 2 pi

- This is an example of indirect CPV
- Nevertheless it has the profound consequence that CP is not a symmetry of nature!
- => Weak shall "inherit the earth"

More on BNL '64 Expt

- BNL'64 Cronin+Fitch, Br (KL =>2 pi) => not eq 0; CP is not a symmetry of nature
- Naturalness arguments then suggest any new physics scenario to entail BSM CP-odd-phase(s)
- Explicit examples of popular BSM back that assertion: 2 Higss DMs, LRSM, warped XDIM, SUSY, r RPV-Susy or LQMs
- Moreover, SM-KM CP cannot seem to a/c for baryogenesis

Message for exptd faiends:

Only go after CP: surest way to see real NP& grab the NP and run!

Sample of previous attempts @ the EF

PHYSICAL REVIEW D

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1 FEBRUARY 1996

Large tree-level CP violation in $e^+e^- \to t\bar{t}H^0$ in the two-Higgs-doublet model

S. Bar-Shalom, D. Atwood, G. Eilam, R. R. Mendel, ** and A. Soni*

We find a large CP violation effect within the two-Higgs-doublet model for the reaction $e^+e^- \to t\bar{t}H^0$ at future linear colliders. The CP asymmetry arises already at the tree level as a result of interference between diagrams with H^0 emission from t (and \bar{t}) and its emission from a Z^0 and can be about 10–20%. In the best case one needs a few hundred $t\bar{t}H^0$ events to observe CP violation at the 3σ level.

Two problems with this:

- This is not for LHC (a pp machine)
- II. Moreover, we know now that we are in the alignment limit

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II. Example

PHYSICAL REVIEW D

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Probing CP violation via Higgs boson decays to four leptons

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Since decays to four leptons is widely considered a promising way to search for the Higgs particle, we show how the same final state can also be used to search for signals of CP nonconservation. Energy asymmetries and triple correlations are related to parameters in the underlying CP-violating effective interaction at the H^0 -W-W and H^0 -Z-Z vertices. It is argued that the expected size of the effects is extremely small in the standard model, and it is shown that the result also seems small to be observable in an extension of the standard model with an extra Higgs doublet.

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Rigorous formula dealing with initial state that is NOT self-conjugate as for pp colliders [LHC and hadron colliders for the future]

Generic tests of CP-violation in high- p_T multi-lepton signals at the LHC and beyond

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We introduce a modification to the standard expression for tree-level CP-violation in scattering processes at the LHC, which is important when the initial state in not self-conjugate. Based on that, we propose a generic and model-independent search strategy for probing tree-level CP-violation in inclusive multi-lepton signals. We then use TeV-scale 4-fermion operators of the form $tu\ell\ell$ and $tc\ell\ell$ with complex Wilson coefficients as an illustrative example and show that it may generate $\mathcal{O}(10\%)$ CP asymmetries that should be accessible at the LHC with an integrated luminosity of $\mathcal{O}(1000)$ fb⁻¹.

Table 1 Transformation properties under T_N and CP and presence or absence of final state interactions (FSI). Here $Y \equiv FSI$ present and $N \equiv FSI$ absent

T_N	CP-violating	CP-conserving
even	Y	N
even odd	N	Y

Two interfering amplitudes

• As always for CPV to be observable, need (at least) two interfering amplitudes M1 and M2 with CP even (delta1 and delta2) and CP odd (phi1 and phi2) phases

Fon letails see 2212.09433

$$\mathcal{L}_{CP} = \frac{\mathcal{I}_{ab} + \mathcal{I}_{\bar{a}\bar{b}}}{2} \cos \Delta \delta \sin \Delta \phi + \frac{\mathcal{I}_{ab} - \mathcal{I}_{\bar{a}\bar{b}}}{2} \sin \Delta \delta \cos \Delta \phi$$

$$\mathcal{L}_{ab} \propto \frac{\int_{R} d\Phi \cdot f_{a} f_{b} \cdot V \cdot \operatorname{sign}(\mathcal{O}_{CP})}{\int_{R} d\Phi \cdot f_{a} f_{b} \cdot (W + U \cdot \cos(\Delta \delta + \Delta \phi))}, (13)$$

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where $d\Phi$ is the phase-space volume element, R is the phase-space region of integration and f_a , f_b are the PDF's of the incoming particles a, b; similarly, for the charge conjugate (CC) channel, $\mathcal{I}_{\bar{a}\bar{b}}$ is obtained by replacing $f_a f_b \to f_{\bar{a}} f_{\bar{b}}$ and $\mathcal{O}_{CP} \to \overline{\mathcal{O}}_{CP}$.

Simple observable to serve as an illustrative example

$$\begin{array}{lll} \mathcal{O}_{\text{CP}} &=& \vec{p}_{\ell'^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \ , \\ \overline{\mathcal{O}_{\text{CP}}} &=& \vec{p}_{\ell'^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}) \ , \end{array}$$

violating the term dynamics.

We will use an effective field theory (EFT) approach to describe the underlying NP responsible for CPV in tri-lepton production at the LHC, using the so-called SM Effective Field Theory (SMEFT) framework, which is defined by adding to the SM Lagrangian an infinite series of higher-dimensional, gauge-invariant operators, constructed using the SM fields [36–39]:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_{i} f_i O_i^{(n)} , \qquad (15)$$

where n is the mass dimension of the operator $O_i^{(n)}$, f_i are the (Wilson) coefficients which depend on the details of the underlying heavy theory and may carry a CP-odd phase if the underlying NP violates CP.

We will demonstrate our strategy for the CP-violating search in multi-lepton events using the following two scalar and tensor 4-Fermi operators:

$$\mathcal{O}_S(prst) = (\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t) , \qquad (16)$$

$$\mathcal{O}_T(prst) = (\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t) , \qquad (17)$$

where ℓ and q are left-handed SU(2) lepton and quark doublets, respectively, e and u are SU(2) singlets charged-leptons and up-quarks, respectively and p, r, s, t are flavor indices. These 4-Fermi interactions can be generated by tree-level exchanges of heavy scalars and ten-CPV@Colliders, Pheno2023; A. Soni

The scalar and tensor 4-Fermi operators in (16) and (17) (or equivalently, tree-level exchanges of the leptoquarks S_1 and R_2) generate $t\bar{t}\ell^+\ell^-$ as well as flavor-changing (FC) $t\bar{u}_i\ell^+\ell^-$ (and the CC $\bar{t}u_i\ell^+\ell^-$) contact terms, where $\ell=e,\mu,\tau$ stands for any one of the SM charged leptons and $u_i=u,c$. The $tt\ell\ell$ interaction modifies the process $pp \to t\bar{t}\ell^+\ell^-$, as discussed in detail in [4], and can thus give rise to tree-level CPV in both the trilepton and four-leptons production channels of (1)-(3), if the corresponding Wilson coefficients carry a CP-phase. In this case, our CP-asymmetries can be used for both the tri- and four-leptons signals.

In the following, we will focus instead on the FC $tu_i\ell\ell$ 4-Fermi interactions, which can modify (see also [3, 22]) and generate CPV in the tri-lepton signals of (1) and (2), via the underlying single-top hard processes $ug \to t\ell^+\ell^-$ and the CC channel (see Fig. 1), followed by the t and \bar{t} decays $t \to b\ell'^+\nu_\ell$ and $\bar{t} \to \bar{b}\ell'^-\bar{\nu}_\ell$.

Chosing

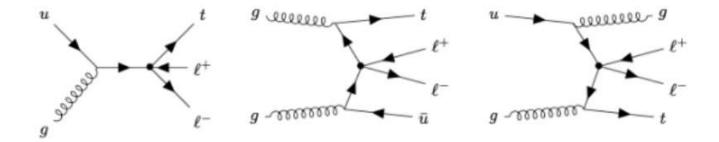


FIG. 1: Representative Feynman diagrams for the lowest order single top-quark + di-lepton production channels $pp \to t\ell^+\ell^-$ and $pp \to t\ell^+\ell^- + j$ (j is a light jet), via the $tu\ell^+\ell^-$ 4-Fermi interaction (marked by a heavy dot).

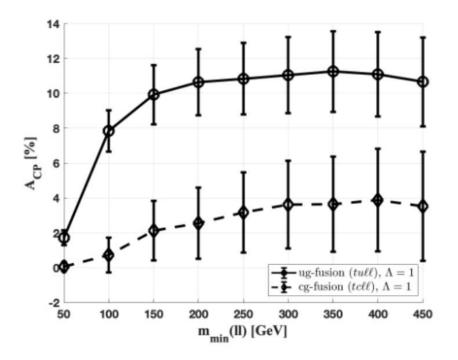


FIG. 2: The expected CP-asymmetry A_{CP} , as a function of the invariant mass cut on the same-flavor di-leptons, for the cases of NP considered, with $\Lambda=1$ TeV, Im $(f_S f_T^*)=0.25$ and including the SM background. The dependence of the asymmetry on Λ is given in the supplemental material. The error bars represent the expected statistical uncertainty with an integrated luminosity of 1000(3000) fb⁻¹ for the ug-fusion(cg-fusion) case. See also text.

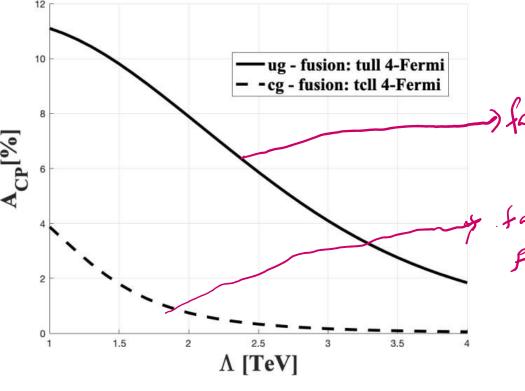


FIG. 3: The expected CP-asymmetry A_{CP} , as a function of the NP scale Λ , for $m_{min}(\ell\ell) = 400$ GeV and Im $(f_S f_T^*) = 0.25$. Results are shown for the cases of NP from ug and cg-fusion, which arise from the $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators, respectively. The SM background is calculated from $pp_{om} \to ZW^{\pm} + X$.

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Summary + Conclusion (p1 of 2)

- Naturalness arguments suggest existence of BSM phase
- Besides does not seem SM-KM phase is enough to a/c for baryogenesis
- In this regard it is important to keep in mind our past experience:
 Indirect CP epsilon_K ~10^-3; several experiments gave up too soon.

That era is similar to our current situation...We have no clue about the relevant energy scale...Patience and of course accuracy is essential

The search for new CP-odd phase(s) should continue on all frontiers

Summary + Conclusion p.2 of 2

- Presented a formula that deals with CPV when the initial state is not self-conjugate, for example, pp colliders.
- As an illustration studied final state with 3 leptons: CP asymmetry may be O(10%) for ug fusion or O(few %) from cg fusion for new physics scale of O(1 TeV)
- Falloff with scale for ug fusion is rather slow but rather fast for cg fusion