Underpinnings of CP-violation @ the high-energy frontier

BNL Forum 2025

22/10/2025

Based on:

- "**Generic tests of CP-violation in high-pT multi-lepton signals at the LHC and beyond**"
  Y. Afik, SBS, K. Pal, A. Soni, J. Wudka, PRL 131 (2023) 17, 171801 (arxiv: 2212.09433)

- "Theoretical underpinnings of CP-Violation at the High-energy Frontier"
  SBS, A. Soni, J. Wudka, PLB 860 (2025), 139135 (arxiv: 2407.19021)

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CP – Violation (CPV)

- We know that CP is not a symmetry of nature !
  (measured in K,D,B systems …)

unfortunately, CPV(SM) is not sufficient for explaining the observed baryon asymmetry of the universe

⊳ on general grounds, one expects any generic new physics to entail new BSM CP-odd phase(s):

many BSM models/interactions/particles with new CP-phases "on the market"

Supersymmetry

Leptoquarks

Vector-like fermions

Multi-Higgs models

…

and yet, !
no signal of CPV have been observed @ high-energy colliders …

CP – Violation (CPV)

- Why? What? Where? How? …
  - Why is CPV(BSM) from TeV-scale NP so illusive ?
  - What type of NP can potentially yield large/measurable CPV effects @ high-energy scattering processes?
  - Where & how should we look for such large/measurable CPV(BSM) effects?
  - Can an O(10%) or larger CPV(BSM) signal be detected @ the LHC ?

We need a plan

- Challenge: understanding the patterns of CPV @ TeV-scale
  - Ignorance (regarding underlying heavy physics):

EFT approach probably best !

SMEFT basis useful …

still a mess: SMEFT(dim.6) has O(1000) new CP-odd phases !

We need guiding principles …

We need a plan

- Challenge: understanding the patterns of CPV @ TeV-scale
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EFT approach probably best !

SMEFT basis useful …

still a mess: SMEFT(dim.6) has O(1000) new CP-odd phases !

We need guiding principles …

- Apply well motivated (flavor) underlying restrictions
- Use reasonable assumptions + "selection rules" for the UV
- Look for the expected leading CPV effects

CPV @ the high-energy frontier: guiding principles

2 well motivated limiting (flavor) cases to consider :

- **SM_0: SM has a G_0 = $U(3)^5$ flavor symmetry when all fermion masses are set to zero:**

  SM_0 is CP-conserving !

- **SM_t: the SM_0 with a massive top-quark has a reduced symmetry $G_t = U(3)^4 \times U(2) \times U(1) \subset G_0$:**

$$\mathcal{L}_{\mathrm{SM}_t} = \mathcal{L}_{\mathrm{SM}_0} + \left(y_t \bar{q}_3 t \tilde{\phi} + \mathrm{H.c.} \right)$$

CPV @ the high-energy frontier: guiding principles

- EFT parameterization of NP

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i Q_i^{(n)}$$

use the SMEFT framework (basis)

- SMEFT can likewise be segregated into the sectors that posses the G_0 & G_t global symmetries of the SM_0 and SM_t ; then

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{\mathrm{SM}_0} + \mathcal{L}_{\mathrm{SMEFT}_0} \ ,$$
$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{\mathrm{SM}_t} + \mathcal{L}_{\mathrm{SMEFT}_0} + \mathcal{L}_{\mathrm{SMEFT}_t}$$

CPV @ the high-energy frontier: guiding principles

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- **CPV sectors of SMEFT_0 & SMEFT_t:**

$\mathcal{L}^{\mathrm{CPV}}_{\mathrm{SMEFT}_0}$	$\mathcal{L}^{\mathrm{CPV}}_{\mathrm{SMEFT}_t}$
$Q_{\tilde{G}} = f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{tG} = \left(\bar{q}_3 \sigma^{\mu\nu} T^A t\right) \tilde{\phi} G^A_{\mu\nu}$
$Q_{\tilde{W}} = f^{IJK} \tilde{G}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{tW} = \left(\bar{q}_3 \sigma^{\mu\nu} t\right) \tau^I \tilde{\phi} W^I_{\mu\nu}$
$Q_{\phi\tilde{G}} = \phi^\dagger \phi \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$Q_{tB} = \left(\bar{q}_3 \sigma^{\mu\nu} t\right) \tilde{\phi} B_{\mu\nu}$
$Q_{\phi\tilde{W}} = \phi^\dagger \phi \tilde{W}^I_{\mu\nu} G^{I\mu\nu}$	$Q_{t\phi} = \phi^\dagger \phi \left(\bar{q}_3 t\right) \tilde{\phi}$
$Q_{\phi\tilde{B}} = \phi^\dagger \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	
$Q_{\phi\tilde{W}B} = \phi^\dagger \tau^I \phi \tilde{W}^I_{\mu\nu} B^{\mu\nu}$	

$O(1/\Lambda^2)$ interference effects (CPV) only from:

$\mathrm{SMEFT}_0 \times \mathrm{SM}_0$ & $\mathrm{SMEFT}_t \times \mathrm{SM}_t$

CPV @ the high-energy frontier: guiding principles

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$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{\mathrm{SM}_0} + \mathcal{L}_{\mathrm{SMEFT}_0} \ ,$$
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- **CPV sectors of SMEFT_0 & SMEFT_t:**

Selection rules @ the UV

$\mathcal{L}^{\mathrm{CPV}}_{\mathrm{SMEFT}_0}$	$\mathcal{L}^{\mathrm{CPV}}_{\mathrm{SMEFT}_t}$
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- these opts are Loop Generated (LG) in the underlying theory

  ☞ expect corresponding Wilson coef: $\alpha_i \sim O\left(\frac{1}{4\pi^2}\right)$

Arzt, Einhorn, Wudka, NPB(1995), hep-ph/9405214 & Einhorn, Wudka, NPB(2013), arxiv:1307.0478

CPV @ the high-energy frontier: guiding principles

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i \alpha_i Q_i^{(n)}$$

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{\mathrm{SM}_0} + \mathcal{L}_{\mathrm{SMEFT}_0} \; ,$$
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- CPV sectors of SMEFT_0 & SMEFT_t:

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Also: these opts are tightly constrained by lepton and neutron EDMs
Kley, Theil, Venturini, Weiler, EPJC(2022), arxiv:2109.15085

- these opts are Loop Generated (LG) … nderlying theory
  - ☞ expect correspond… coef: $\alpha_i \sim O\left(\frac{1}{4\pi^2}\right)$

Arzt, Einhorn, …ka, NPB(1995), hep-ph/9405214 & Einhorn, Wudka, NPB(2013), arxiv:1307.0478

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- CPV parts of SMEFT_0 & SMEFT_t:

Selection rules @ the UV

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- the only opt. that is Potentially Tree-Level Generated (PTG) !
  - ☞ expect (naturality) corresponding Wilson coef: $\alpha_{t\phi} \sim O(1)$

Arzt, Einhorn, Wudka, NPB(1995), hep-ph/9405214 & Einhorn, Wudka, NPB(2013), arxiv:1307.0478

CPV @ the high-energy frontier: guiding principles

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If SMEFT possesses G_t …

- Only $Q_{t\Phi}$ can potentially generate leading CPV effects @ high-energy colliders – in top-quark systems …

$$Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi} \quad \Longrightarrow \quad \mathcal{L}_{tth} = -h \bar{t} \, (a + i b \gamma_5) \, t$$

- **Best bet:** CPV from interference of tree-level diagrams

e.g., in

$e^+e^- \to tth$
$pp \to tth$
$pp \to th + X, \ tV + X$

CPV @ the high-energy frontier: guiding principles

$$Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi}$$

- **<u>However:</u> CP asymmetry behaves as:**

$$\mathcal{A}_{\rm CP} \propto \frac{d\sigma_{\rm CPV}}{d\sigma_{\rm CPC}}$$

$$d\sigma_{\rm CPV} \rightarrow \text{Im}\left(M_{SM} M_{NP}^\dagger\right) \propto \frac{v^2}{\Lambda^2}$$

$$d\sigma_{\rm CPC} \rightarrow \left|M_{\rm SM}\right|^2$$

CPV @ the high-energy frontier: guiding principles

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$$|M_{\rm SM}|^2$$

$$Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi}$$

$$\mathcal{A}_{CP} \sim O\left(\frac{v^2}{\Lambda^2}\right) \sim O(1\%)$$

- **Such CP effects are, unfortunately, too small to be detected**

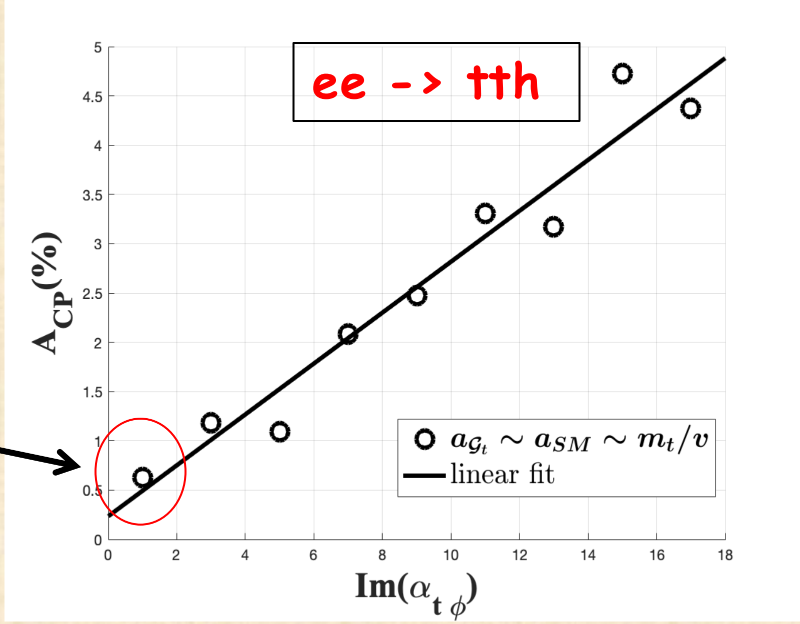
SBS, Soni, Wudka, PLB 2025 (arxiv:2407.19021)

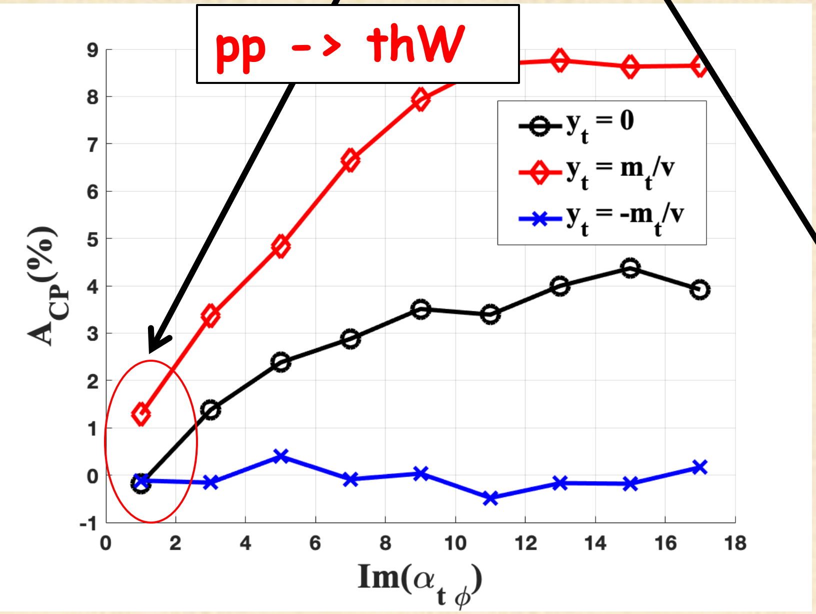
- **Examples of tree-level CP asymmetry (A_{CP}) from $O_{t\varphi}$**

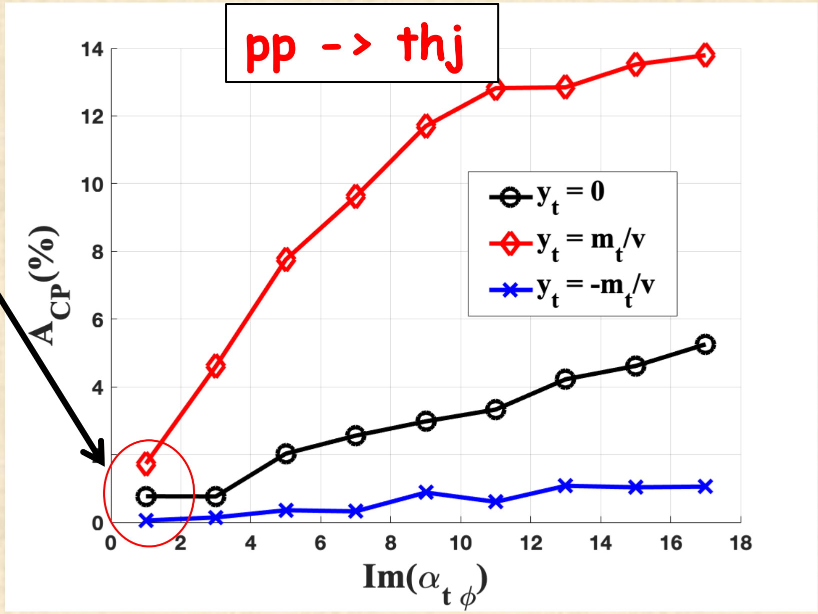
SBS, Soni, Wudka, PLB 2025 (arxiv:2407.19021)

$$Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi}$$

$$Im(\alpha_{t\phi}) \sim O(1)$$







- Examples of tree-level CP asymmetry (A_{CP}) from $O_{t\varphi}$

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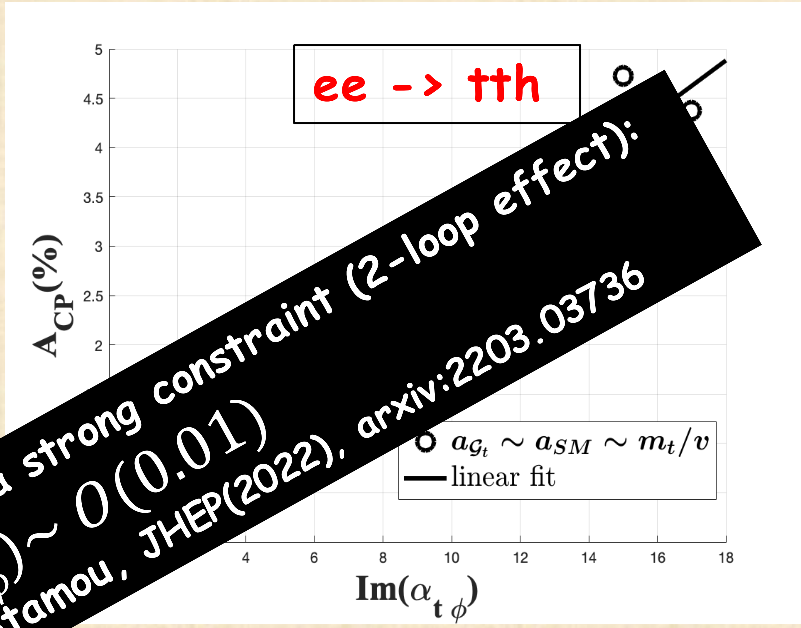
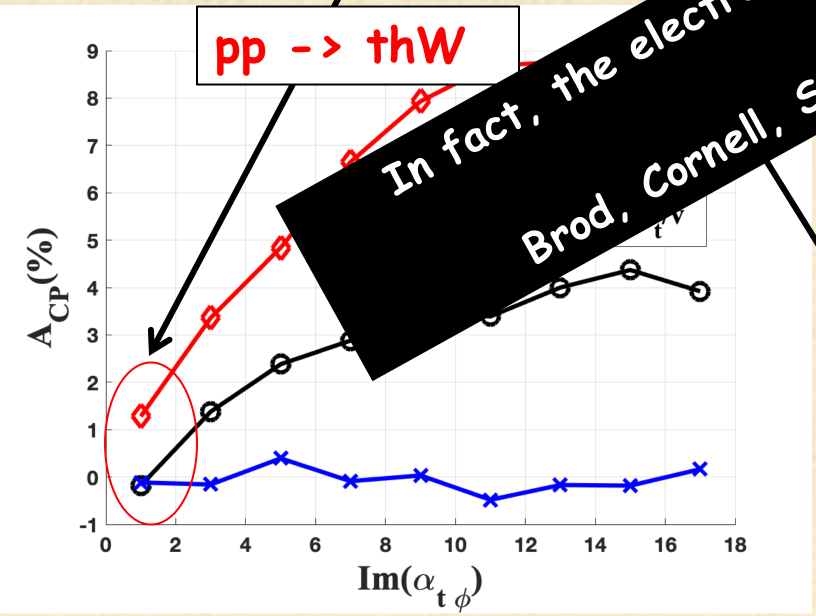
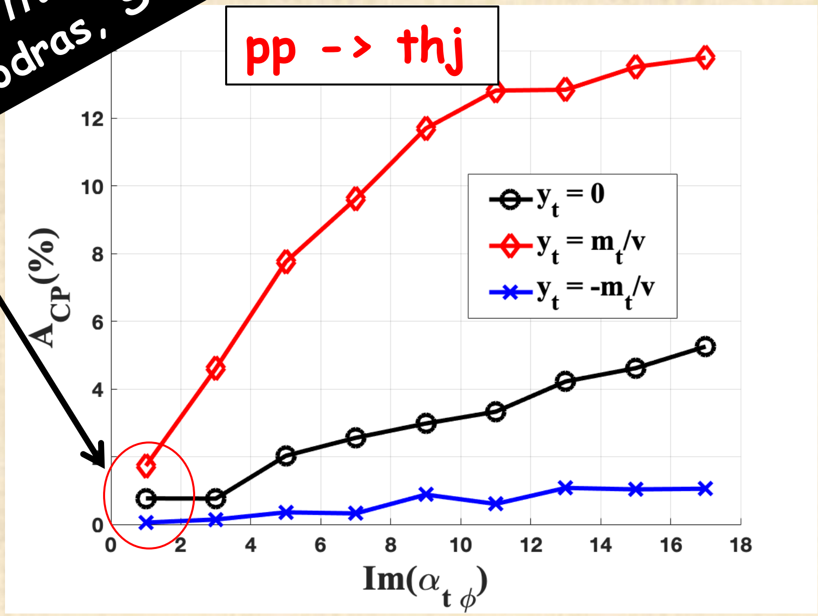


In fact, the electron EDM sets a strong constraint (2-loop effect):

$$Im(\alpha_{t\phi}) \sim O(0.01)$$

Brod, Cornell, Skodras, Stamou, JHEP(2022), arxiv:2203.03736





▻ No CPV signal is expected @ high-energy colliders (e.g., @LHC) from SM X EFT interreference if underlying heavy physics obeys the approximate SM flavor symmetries (G_0 & G_t)!

$$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$$
$$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$$
$$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$$
$$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$$
$$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$$
$$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$$
$$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$$
$$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$$

HOWEVER

$$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$$
$$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$$
$$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$$
$$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$$
$$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$$
$$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$$
$$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$$

- **If** flavor is violated in the underlying heavy theory

then:
all SMEFT opts containing flavor-violating combinations of fermion fields can violate CP !

$$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$$
$$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$$
$$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$$

$$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$$
$$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$$
$$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$$
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$$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$$

$$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$$
$$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$$
$$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$$
$$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$$
$$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$$

$$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$$
$$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$$
$$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$$

CPV @ the high-energy frontier: guiding principles

CPV from flavor violating NP

- **Leading CPV effects in this case from NPxNP' @ tree-level**
- **No SM contribution @ tree-level !**

$$\mathrm{Im}\left(M'_{NP}M^{\dagger}_{NP}\right) \propto \frac{v_E^4}{\Lambda^4}$$

$$d\sigma \equiv d\sigma_{\mathrm{CPC}} + d\sigma_{\mathrm{CPV}}$$

$$\left|M_{\mathrm{NP}}\right|^2 \propto \frac{v_E^4}{\Lambda^4}$$

$v_E = v$ or $v_E = E$ ...

CPV @ the high-energy frontier: guiding principles

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$v_E = v$ or $v_E = E$ ...

- CP asymmetry expected in this case:

$$\mathcal{A}_{\mathrm{CP}} \propto \frac{d\sigma_{\mathrm{CPV}}}{d\sigma_{\mathrm{CPC}}} \sim \mathcal{O}(1)$$

Large CPV !

From flavor-violating NP

in the top-quark sector …

<u>Best "bet":</u> top-quark flavor changing interactions

(CPV effects typically α m_f …)

CPV from flavor violating NP

Interesting example: **tull/tcll 4-Fermi contact terms**

$$Q_S = \left(\bar{\ell}_R \ell_R\right)\left(\bar{t}_R u_R\right) \quad , \quad Q_T = \left(\bar{\ell}_R \sigma_{\mu\nu} \ell_R\right)\left(\bar{t}_R \sigma_{\mu\nu} u_R\right) \; ; \quad \ell = e,\, \mu$$

Scalar

Tensor

SMEFT ☞

$$Q_{\ell equ}^{(1)} = \left(\bar{\ell}^j e\right) \epsilon_{jk} \left(\bar{q}^k u\right)$$

$$Q_{\ell equ}^{(3)} = \left(\bar{\ell}^j \sigma_{\mu\nu} e\right) \epsilon_{jk} \left(\bar{q}^k \sigma^{\mu\nu} u\right)$$

CPV from flavor violating NP

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Scalar

Tensor

SMEFT ☞

$$Q^{(1)}_{\ell equ} = (\bar{\ell}^j e)\, \epsilon_{jk}\, (\bar{q}^k u)$$

$$Q^{(3)}_{\ell equ} = (\bar{\ell}^j \sigma_{\mu\nu} e)\, \epsilon_{jk}\, (\bar{q}^k \sigma^{\mu\nu} u)$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\left[\left(\alpha_S Q_S + \alpha_T Q_T\right) + \mathrm{H.c.}\right]$$

GENERIC (model-independent) tests of CPV(BSM) in inclusive multi-lepton processes

SM-CPV in multi-lepton signals @ LHC is negligible !

can only arise from EW processes at higher loop orders …

Afik, SBS, Pal, Soni, Wudka, PRL 2023 (arxiv: 2212.09433)

CPV ☞ multi-leptons events

- **Focused on tri-lepton events** (applies also to n-leptons events …)

$$pp \to \ell'^- \ell^+ \ell^- + X_3$$
$$pp \to \ell'^+ \ell^- \ell^+ + \bar{X}_3 \ ,$$

e.g., $\ell'^- \ell^+ \ell^- = e^\pm \mu^+ \mu^-, \ \mu^\pm e^+ e^-$

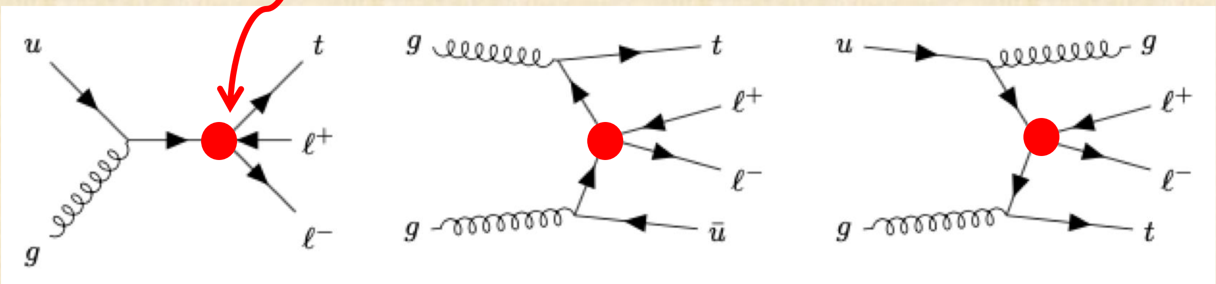
- $\ell, \ell' = e, \mu, \tau$ (preferably $\ell \neq \ell'$)
- $X_3, \bar{X}_3$ jets and missing energy

CPV in tri-lepton events from single top production

tull & tcll 4-Fermi is "injected" as an EFT toy model

tull/tcll 4-Fermi →

$$\text{dim.6 scalar}: \ \mathcal{O}_S = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$
$$\text{dim.6 tensor}: \ \mathcal{O}_T = (\bar{l}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$



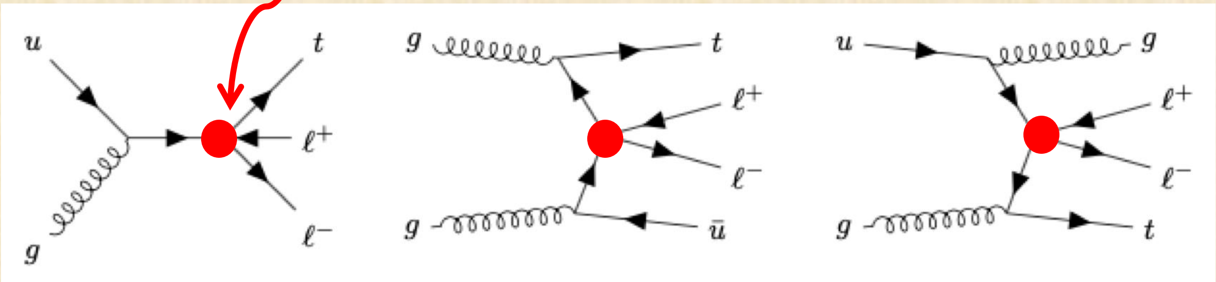
$$pp \to \ell^+\ell^- + t \ ,$$
$$pp \to \ell^+\ell^- + t + j$$

CPV in tri-lepton events from single top production

tull & tcll 4-Fermi is "injected" as an EFT toy model

tull/tcll 4-Fermi →

$$\text{dim.6 scalar}: \quad \mathcal{O}_S = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$
$$\text{dim.6 tensor}: \quad \mathcal{O}_T = (\bar{l}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$



$$pp \to \ell^+\ell^- + t \,,$$
$$pp \to \ell^+\ell^- + t + j$$

Signal (e.g.):

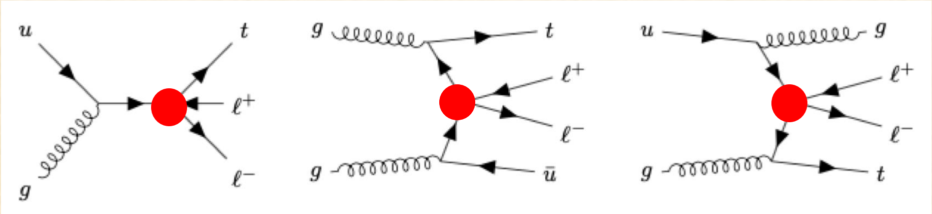
$pp \to t\ \mu+\ \mu-\ + X \to e+\ \mu+\ \mu-\ + X$ (+ CC channel)

This channel has interesting implications also for generic BSM searches of new heavy states around the TeV-scale which generate top-leptons 4-Fermi

PRD2021, (2101.05286), Afik, SBS, Soni, Wudka

Dominant SM backg.

NP signals



pp → WZ +X

followed by W & Z decays …

much smaller contribution from:

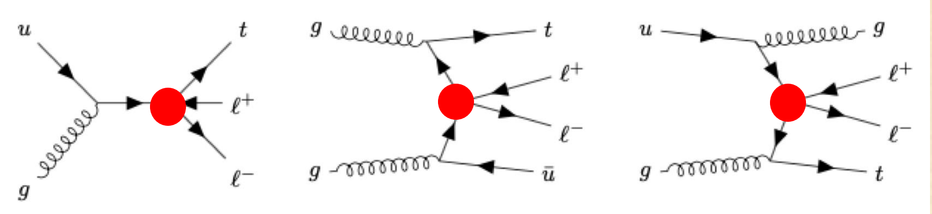
pp → ttW, ttZ, tVV, tt, Z+jets

followed by t and V decays …

Dominant SM backg.

NP signals

pp → WZ +X
followed by W & Z decays …



much smaller contribution from:
pp → ttW, ttZ, tVV, tt, Z+jets
followed by t and V decays …

CPV part

$$d\hat{\sigma}(CPV) \propto \epsilon\left(p_{u_i}, p_{\ell'^+}, p_{\ell^+}, p_{\ell^-}\right) \cdot \mathrm{Im}\left(f_S f_T^\star\right)$$

No interference with SM:

$$\sigma(m_{\ell\ell}^{\mathtt{min}}) = \sigma^{\mathrm{SM}}(m_{\ell\ell}^{\mathtt{min}}) + \frac{f^2}{\Lambda^4} \cdot \sigma^{\mathrm{NP}}(m_{\ell\ell}^{\mathtt{min}})$$

$$\sigma(m_{\ell\ell}^{\mathtt{min}}) \equiv \sigma(m_{\ell\ell} \geq m_{\ell\ell}^{\mathtt{min}}) = \int_{m_{\ell\ell} \geq m_{\ell\ell}^{\mathtt{min}}} dm_{\ell\ell} \frac{d\sigma}{dm_{\ell\ell}}$$

m_{ll}^{min} - useful discriminating parameter

Generic CP-asymmetries for tri-lepton events:

sensitive to tree-level CPV !

- P-violating & T_N-odd observables (odd under t → -t):

$pp \to e\,\mu\,\mu + X$

$$\mathcal{O}_{\rm CP} = \vec{p}_{e^-} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$$
$$\overline{\mathcal{O}_{\rm CP}} = \vec{p}_{e^+} \cdot (\vec{p}_{\mu^-} \times \vec{p}_{\mu^+})$$

- Divide into 2 "hemispheres" in O_{CP} space and define:

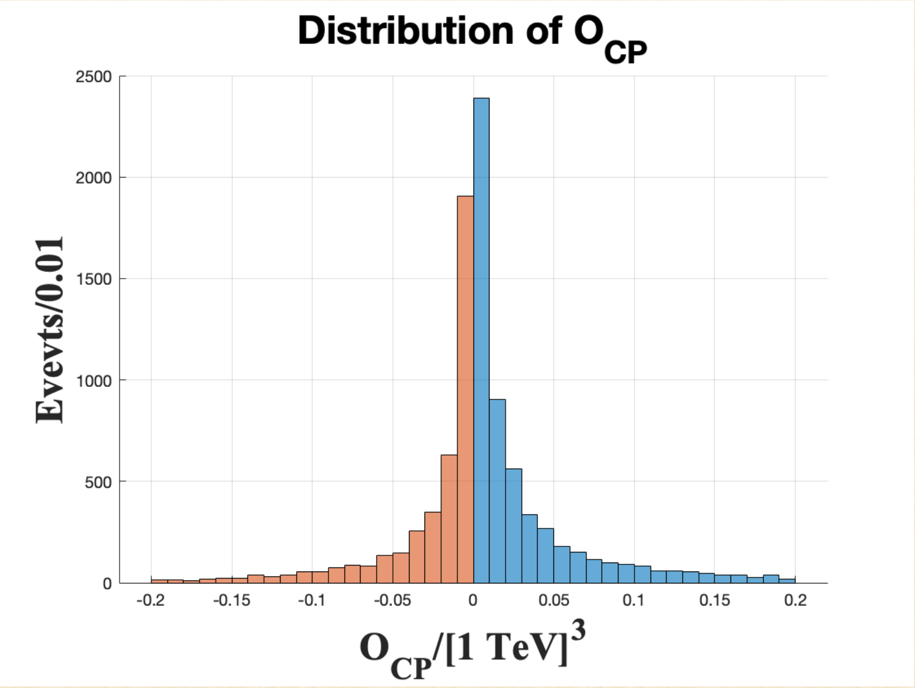
$$A_{CP} = \frac{1}{2}\left(A_T - \bar{A}_T\right)$$

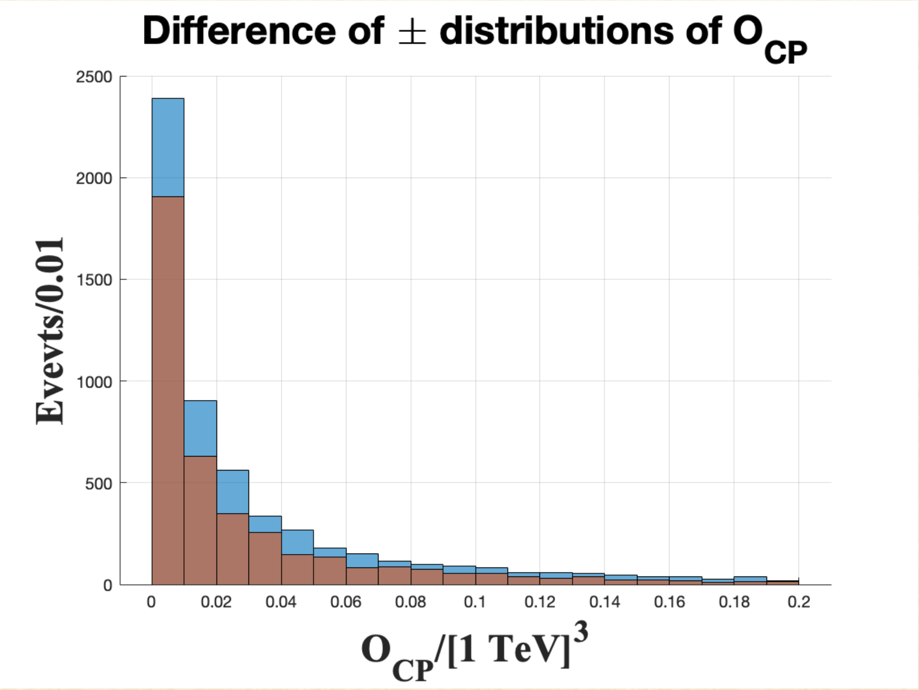
$$A_T \equiv \frac{N(\mathcal{O}_{\rm CP} > 0) - N(\mathcal{O}_{\rm CP} < 0)}{N(\mathcal{O}_{\rm CP} > 0) + N(\mathcal{O}_{\rm CP} < 0)} ,$$
$$\bar{A}_T \equiv \frac{N(-\overline{\mathcal{O}_{\rm CP}} > 0) - N(-\overline{\mathcal{O}_{\rm CP}} < 0)}{N(-\overline{\mathcal{O}_{\rm CP}} > 0) + N(-\overline{\mathcal{O}_{\rm CP}} < 0)}$$

we are looking for asymmetric distributions of O_{CP}

$$A_T \equiv \frac{N(\mathcal{O}_{\rm CP} > 0) - N(\mathcal{O}_{\rm CP} < 0)}{N(\mathcal{O}_{\rm CP} > 0) + N(\mathcal{O}_{\rm CP} < 0)},$$

$$\mathcal{O}_{\rm CP} = \vec{p}_{e^-} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$$

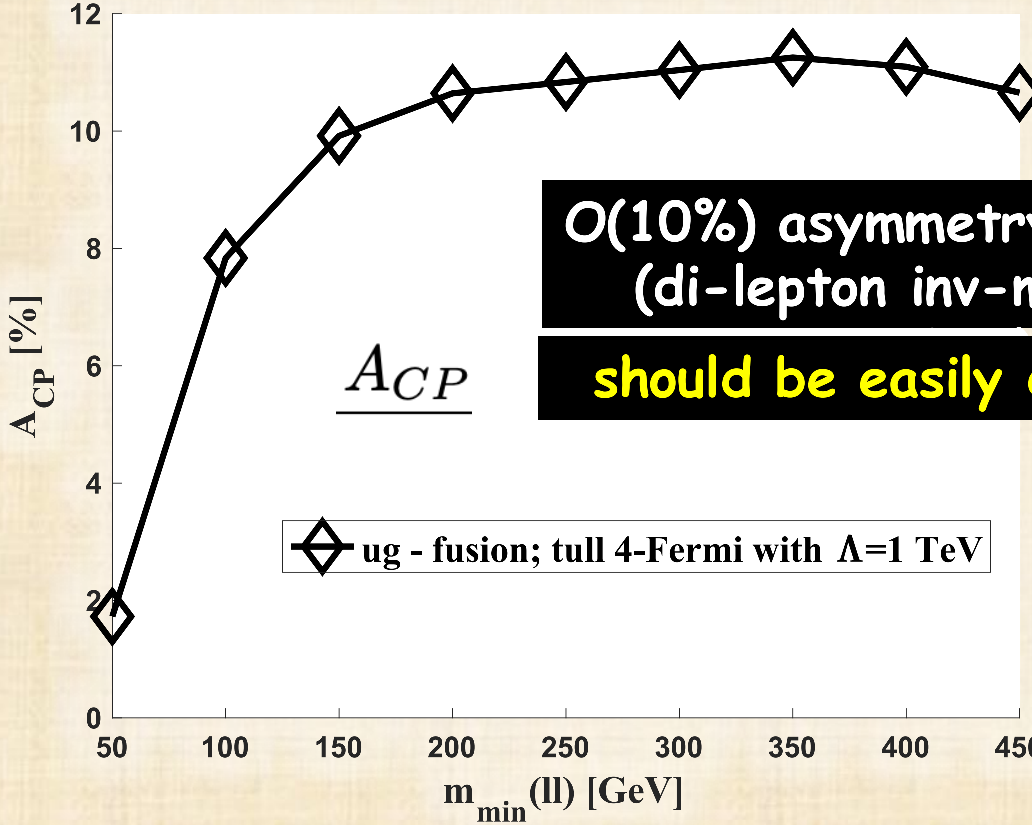




Results:

$u\,g \rightarrow t\,\mu\,\mu \rightarrow e\,\mu\,\mu$
($tu\mu\mu$ 4-Fermi)

	ug-fusion: $\Lambda = 1(2)$ TeV
A_{CP}	11.1(7.9)%
A_T	16.4(13.5)%
$\bar{A}_T$	-5.8(-2.3)%



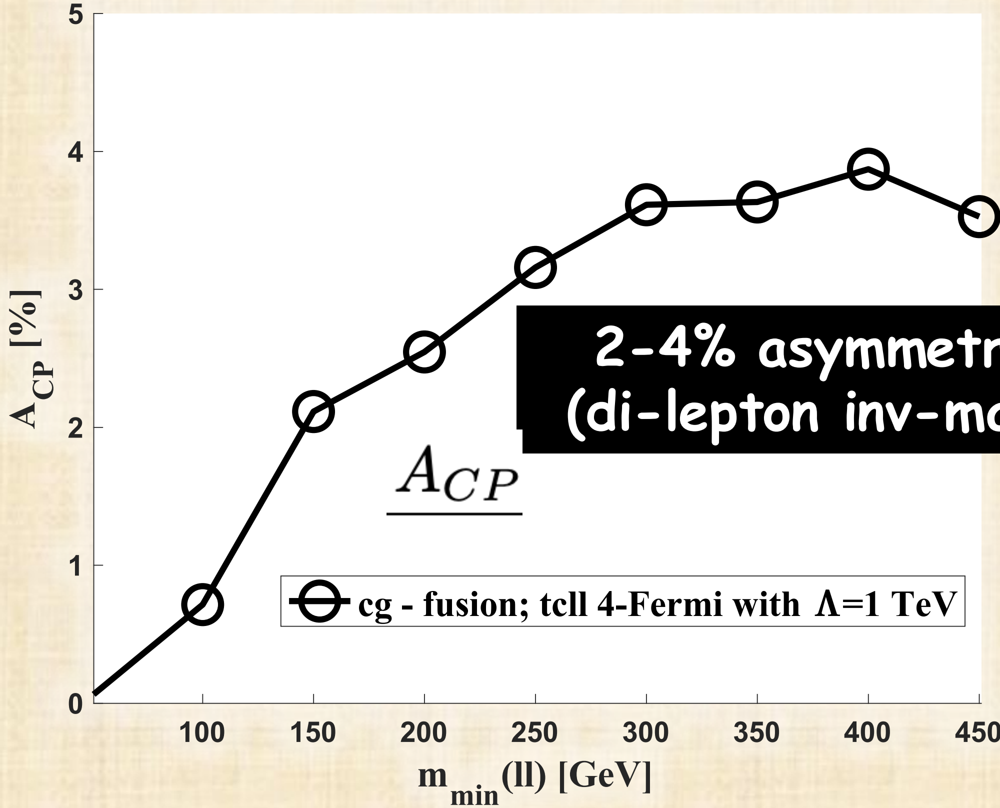
O(10%) asymmetry at high m_{ll} !
(di-lepton inv-mass > 150

should be easily detectible …

Results:

$c\,g \rightarrow t\,\mu\,\mu \rightarrow e\,\mu\,\mu$
($tc\mu\mu$ 4-Fermi)

	cg-fusion: $\Lambda = 1(2)$ TeV
A_{CP}	3.9(0.7)%
A_T	3.1(0.5)%
$\bar{A}_T$	-4.7(-1.0)%



2-4% asymmetry at high m_{ll} !
(di-lepton inv-mass > 150 GeV)

SUMMARY

CONCLUSION

- Take home message:

If the underlying heavy physics is weakly coupled …

CPV from (SMXNP) interference effects

is NOT accessible @ TeV-scale scattering processes !

Need to look elsewhere …

SUMMARY

CONCLUSION

- **Look for:**

CPV signals in processes that may originate from FV dynamics in the underlying heavy physics

in this case: CPV from (NPXNP') interference !

Best bet:

processes in which top-quark FV interactions are involved
(CPV effects typically α m_f ...)

SUMMARY

CONCLUSION

- **An attractive example:**

CPV in inclusive tri-leptons signals @ the LHC

$pp \rightarrow t\, \mu^+ \mu^- + X \rightarrow e^+ \mu^+ \mu^- + X$ **(& CC channel)**

SUMMARY / CONCLUSION

- **An attractive example:**

CPV in inclusive tri-leptons signals @ the LHC

$$pp \to t\, \mu^+ \mu^- + X \to e^+ \mu^+ \mu^- + X \quad (\&\ CC\ channel)$$

- Resulting CP asymmetries:

O(10%) with new CPV TeV-scale NP

- SM backg. for CPV in multi-lepton events is at best sub-% level …

- Expect O(10000) high-p_T tri-lepton events @LHC

with L ~ O(1000) fb^{-1} & TeV scale NP (generating a tull 4-Fermi)

should be easily detectible !

Thank you!

Backups

CP – Violation (CPV)

- **CPV is of fundamental importance for our understanding of the laws of nature !**

  - CPV + CPT-invariance implies non-invariance of the microscopic EOM under time-reversal

  - CPV implies different physical properties of matter and anti-matter

  - CPV is inseparably linked to flavor physics

multi-leptons signals – a window to NP

$$(1\ell) : pp \to \ell^\pm + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(2\ell) : pp \to \ell'^+ \ell''^- + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(3\ell) : pp \to \ell'^\pm \ell^+ \ell^- + n \cdot j_b + m \cdot j + \not{E}_T + X \ ,$$
$$(4\ell) : pp \to \ell'^\pm \ell''^\mp \ell^+ \ell^- + n \cdot j_b + m \cdot j + \not{E}_T + X$$

- Rich & clean signals in the hadronic environment of the LHC

- Excellent test ground for NP (e.g., in pp → ttV, ttH, tV, tttt …):
  - Sensitive to many types of underlying NP

(lepton-flavor violation, lepton universality violation,
lepton-number violation - same sign leptons, CP violation …)

  - easy to construct observables with charged leptons

  - High-E/p_T (TeV energies …) leptons still relatively unexplored

- Correlated multi-lepton channels due to common underlying NP !

"Tri- and four-lepton events as a probe for new physics in ttll contact interactions"
NPB980 (2022), 115849 arxiv: 2111.13711, Afik(CERN), SBS(Technion), Pal(UCR), Soni(BNL), Wudka(UCR)

"New flavor physics in di- and trilepton events from single-top production at the LHC and beyond",
PRD103 (2021), 075031, arxiv: 2101.05286, Afik, SBS, Soni, Wudka

"High pT correlated tests of lepton universality in lepton(s) + jet(s) processes; An EFT analysis",
PLB811 (2020), 135908, arxiv: 2005.06457, Afik, SBS, Cohen(Technion), Soni, Wudka

"Searching for New Physics with bbll contact interactions",
PLB807 (2020), 135541, arxiv: 1912.00425, Afik, SBS, Cohen, Rozen(Technion)

- Our CP tests use multi-lepton final states as probes, which makes them experimentally highly distinctive

- They are based on simple kinematic observables that only require the reconstruction of the relatively easily-identifiable charged-lepton momenta

- They can be generated by tree-level CP-violating underlying physics, making them very sensitive to new physics

- They are generic, meaning they can probe a wide range of underlying new physics

- They include a new modification to the classic formula for CP-violation in scattering and decay processes, which takes into account the effect of an asymmetric initial state on the measurement of CP-violation

Non-Hermitian CPV opts:

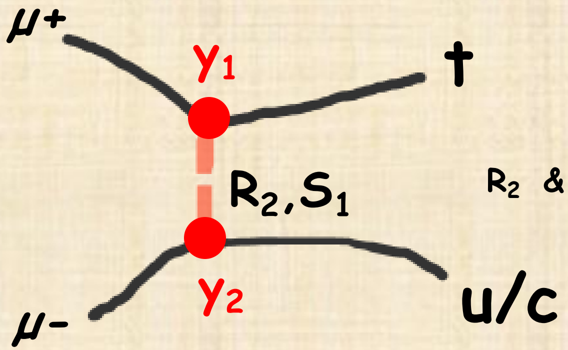
All non-Hermitian opts can in principle carry a CP-odd phase without FV in the underlying physics. These are the non-Hermitian PTG opts:

$$
\begin{aligned}
Q_{\phi ud} &= i\left(\tilde{\phi}^\dagger D_\mu \phi\right)\left(\bar{u}\gamma^\mu d\right) \ , \\
Q_{\ell edq} &= \left(\bar{\ell}^j e\right)\left(\bar{d} q_j\right) \ , \\
Q_{\ell equ}^{(1)} &= \left(\bar{\ell}^j e\right)\epsilon_{jk}\left(\bar{q}^k u\right) \ , \\
Q_{\ell equ}^{(3)} &= \left(\bar{\ell}^j \sigma_{\mu\nu} e\right)\epsilon_{jk}\left(\bar{q}^k \sigma^{\mu\nu} u\right) \ , \\
Q_{quqd}^{(1)} &= \left(\bar{q}^j u\right)\epsilon_{jk}\left(\bar{q}^k d\right) \ , \\
Q_{quqd}^{(8)} &= \left(\bar{q}^j T^a u\right)\epsilon_{jk}\left(\bar{q}^k T^a d\right) \ ,
\end{aligned}
$$

However, these opts do not conserve the G_0 & G_t sym. So that their interference effects with the SM are suppressed by powers of m(light fermion)/Lambda !

- Matching to possible underlying BSM scenarios:

Tree-level exchanges of the heavy R_2, S_1 LQ's



R_2 & S_1 can address R_{D^*} & muon g-2 anomalies

$$\alpha_S = 4\alpha_T = \frac{y_1 y_2^\star}{2M_{LQ}^2}$$

Specific proportion of Wilson coefficients used as benchmark from underlying UV physics

$$\mathrm{Im}\left(\alpha_S \cdot \alpha_T^\star\right) = 0.25$$

$$Q_S = \left(\bar{\ell}_R \ell_R\right)\left(\bar{t}_R u_R\right) \quad , \quad Q_T = \left(\bar{\ell}_R \sigma_{\mu\nu} \ell_R\right)\left(\bar{t}_R \sigma_{\mu\nu} u_R\right) \; ; \quad \ell = e, \mu$$

$$Q_S = (\bar{\ell}_R \ell_R)\,(\bar{t}_R u_R) \quad , \quad Q_T = (\bar{\ell}_R \sigma_{\mu\nu} \ell_R)\,(\bar{t}_R \sigma_{\mu\nu} u_R)\;; \quad \ell = e,\, \mu$$

Scalar **Tensor**

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\left[(\alpha_S Q_S + \alpha_T Q_T) + \text{H.c.}\right]$$

- ***Current sensitivities (bounds):***

Λ(tuμμ) , Λ(tuee) > ~ O(0.5 TeV) , Scalar
> ~ O(1 TeV) , Tensor

Current sensitivities (bounds …)

what do we know about the FC dim.6 (tu)(2l) opts

LEP: (ee → tu,tc):
Λ(tuee) > 0.5 – 1.5 TeV
(depending on Lorentz structure)

SBS,Wudka PRD1999
PLB2002 (0210041) ; EPJC2011 (1102.4455)

LHC (pp → tt followed by t → μμ + jet):
Λ(tuμμ) ~ Λ(tuee) > ~ 0.4 – 1 TeV
(depending on Lorentz structure)

Chala,Santiago,Spannowsky JHEP2019 (1809.09624)
also studied in:
Davidson,Mangano,Perries,Sordini EPJC2015 (1507.07163)
Durieux,Maltoni,Zhang PRD2015 (1412.7166)
Aguilar-Saavedra NPB2011 (1008.3562)
Boughezal,Chen,Petriello,Wiegand PRD2019 (1907.00997)

Constructing CP-asym. for tree-level CPV

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\cancel{\delta_1})} + M_2 e^{i(\phi_2+\cancel{\delta_2})}$$

$\phi_{1,2}$ are CP-odd phases & $\delta_{1,2}$ are CP-even phases (from FSI, loops ...)

CPV @ tree-level (no FSI phases: δ=0) !

- To probe tree-level CPV one needs T_N -odd observables (T_N : $t \to -t$)

=> T_N -odd observables do not vanish when FSI phases are zero (δ = 0)

T_N - odd

asymmetries based on triple-products (TP)

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

Recup:

$pp \to t\,\mu\,\mu \;\to e\,\mu\,\mu\; + X$

$$A_{CP} = \frac{1}{2}\left(A_T - \bar{A}_T\right)$$

$$A_T \equiv \frac{N\left(\mathcal{O}_{\rm CP} > 0\right) - N\left(\mathcal{O}_{\rm CP} < 0\right)}{N\left(\mathcal{O}_{\rm CP} > 0\right) + N\left(\mathcal{O}_{\rm CP} < 0\right)}\,,$$
$$\bar{A}_T \equiv \frac{N\left(-\overline{\mathcal{O}_{\rm CP}} > 0\right) - N\left(-\overline{\mathcal{O}_{\rm CP}} < 0\right)}{N\left(-\overline{\mathcal{O}_{\rm CP}} > 0\right) + N\left(-\overline{\mathcal{O}_{\rm CP}} < 0\right)}$$

NP (CPV)

$$Q_S = \left(\bar{\ell}_R \ell_R\right)\left(\bar{t}_R u_R\right) \quad , \quad Q_T = \left(\bar{\ell}_R \sigma_{\mu\nu} \ell_R\right)\left(\bar{t}_R \sigma_{\mu\nu} u_R\right)\;; \quad \ell = e,\,\mu$$

$$\mathcal{O}_{\rm CP} = \vec{p}_{e^-} \cdot \left(\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}\right)$$
$$\overline{\mathcal{O}_{\rm CP}} = \vec{p}_{e^+} \cdot \left(\vec{p}_{\mu^-} \times \vec{p}_{\mu^+}\right)$$

SM contributes to the denominators while NP(CPV) contributes to numerators !

Asymmetries sensitive to di-leptons invariant mass:

SM ∈ low m_{ll}

NP ∈ high m_{ll}

CSX's

TABLE I: The estimated cross-sections in [fb], for the NP tri-lepton signals and the SM tri-lepton background. Numbers are given for the NP parameters $\mathrm{Im}\,(f_S f_T^\star) = 0.25$, $\Lambda = 1$ TeV and for three values of $m_{min}(\ell\ell)$ as indicated. See also description in the paper.

$m_{min}(\ell\ell)[GeV] \Rightarrow$	200	300	400
$\sigma_{NP}(pp_{ug} \to \ell'^- \ell^+ \ell^- + X)$	12.43	11.65	10.84
$\sigma_{NP}(\bar{u}g \to \ell'^+ \ell^- \ell^+ + X)$	0.98	0.87	0.76
$\sigma_{NP}(pp_{cg} \to \ell'^- \ell^+ \ell^- + X)$	0.37	0.32	0.27
$\sigma_{NP}(pp_{\bar{c}g} \to \ell'^+ \ell^- \ell^+ + X)$	0.37	0.32	0.27
$\sigma_{SM}(pp \to \ell'^- \ell^+ \ell^- + X)$	0.33	0.11	0.05
$\sigma_{SM}(pp \to \ell'^+ \ell^- \ell^+ + X)$	0.56	0.21	0.10

Sensitivity to scale of NP

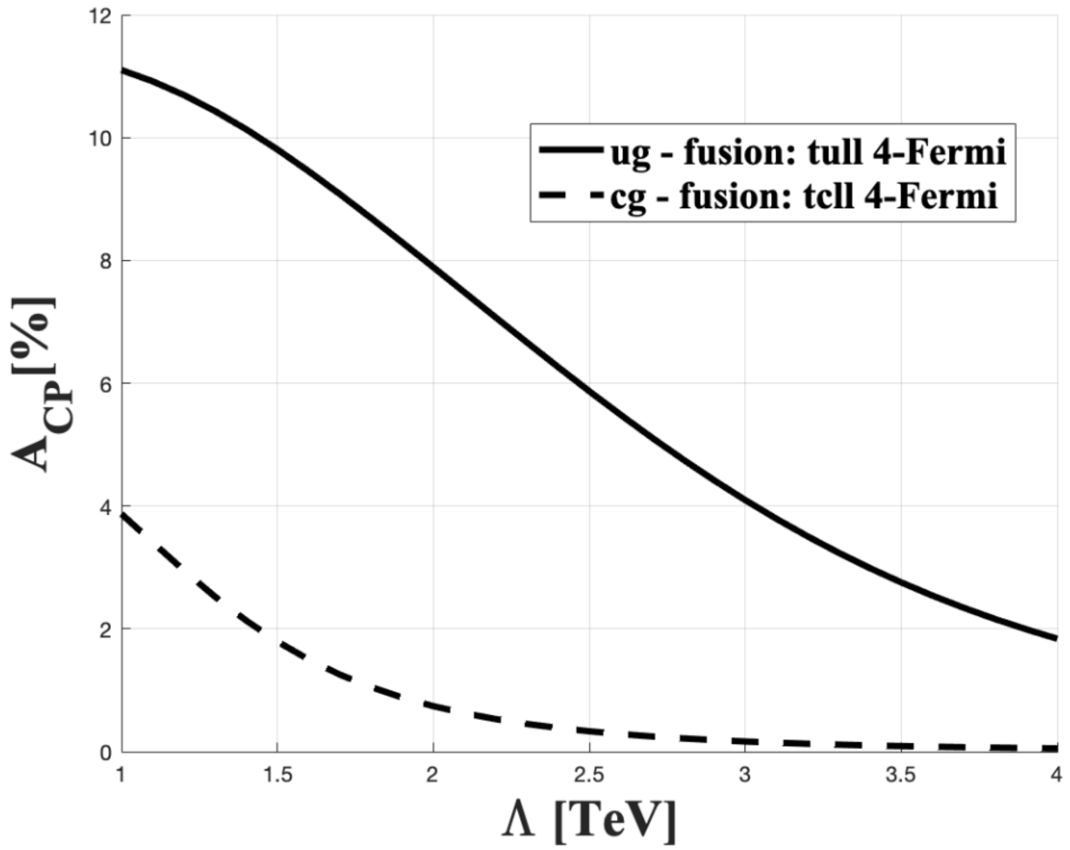


FIG. 1: The expected CP-asymmetry A_{CP}, as a function of the NP scale Λ, for $m_{min}(\ell\ell) = 400$ GeV and $\mathrm{Im}\,(f_S f_T^\star) = 0.25$. Results are shown for the cases of NP from ug and cg-fusion, which arise from the $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators, respectively. The SM background is calculated from $pp \to ZW^\pm + X$.

Sensitivity to scale of NP: uncertainties

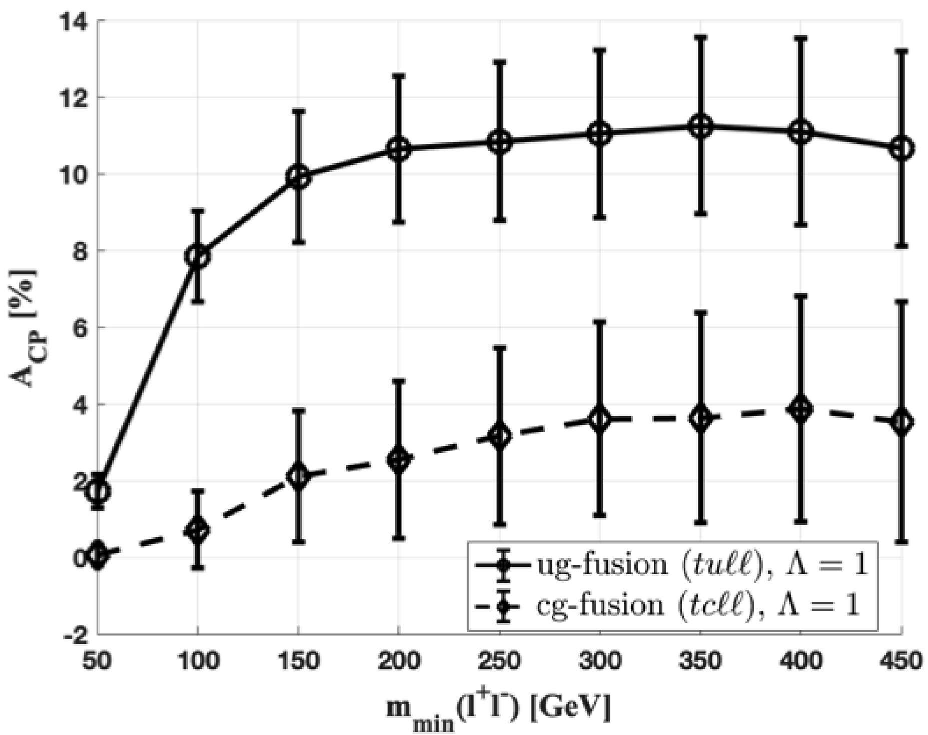


FIG. 2: A_{CP} as a function of $m_{min}(\ell^+\ell^-)$, for $\Lambda = 1$ TeV, $\mathrm{Im}\,(f_S f_T^\star) = 0.25$ and including the SM background. The dependence of the asymmetry on Λ is given in Appendix B. The error bars represent the expected statistical uncertainty with an integrated luminosity of 1000(3000) fb^{-1} for the ug-fusion(cg-fusion) case.

Axis dependent asymmetries

$$\mathcal{O}^i_{\rm CP} = p^i_a \cdot (\vec{p}_b \times \vec{p}_c)^i$$

$$A_{CP}^{x,y,z} = \frac{1}{2}\left(A_T^{x,y,z} - \bar{A}_T^{x,y,z}\right)$$

A measurement of the axis-dependent asymmetries can be used to distinguish between the different types of underlying NP: in our test case, between the tuℓℓ and the tcℓℓ CP-violating dynamics …

TABLE II: The expected T_N-odd and CP asymmetries A_T, $\bar{A}_T$, A_{CP} and the corresponding axis-dependent asymmetries A^i_T, $\bar{A}^i_T$, A^i_{CP} $(i = x, y, z)$, for the tri-lepton events $pp \to \ell'^{\pm}\ell^+\ell^- + X$ at the LHC with $m_{min}(\ell\ell) = 400$ GeV. Results are given for both the ug-fusion and cg-fusion production channels (and the CC ones). Numbers are presented for $\Lambda = 1$ TeV, $\mathrm{Im}\,(f_S f_T^\star) = 0.25$ and the dominant SM background from $pp \to ZW^\pm + X$ is included. The cases where an asymmetry is $\lesssim 0.5\%$ is marked by an X.

	A_{CP}	A^x_{CP}	A^y_{CP}	A^z_{CP}
ug-fusion:	11.1%	8.1%,	8.1%	X
cg-fusion:	3.9%	X	X	5.6%

	A_T	A^x_T	A^y_T	A^z_T
ug-fusion:	16.4%	11.3%,	10.7%	3.8%
cg-fusion:	3.1%	5.0	X	X

	$\bar{A}_T$	$\bar{A}^x_T$	$\bar{A}^y_T$	$\bar{A}^z_T$
ug-fusion:	-5.8%	-5.0%	-5.6%	3.1%
cg-fusion:	-4.7%	-6.3%	X	X

EFT-validity

Two "measures" to consider:

$$\sigma^{NP}(g,\Lambda,m_{\ell\ell}) = \frac{g^2}{\Lambda^2}\cdot\sigma^{SM\times NP}(m_{\ell\ell}) + \frac{g^4}{\Lambda^4}\cdot\sigma^{NP\times NP}(m_{\ell\ell})$$

$$\mathcal{R}_\Lambda \equiv \frac{\hat{s}}{\Lambda^2}$$

Addresses the validity of the specific calculation within the EFT framework – depends on the details of the underlying heavy physics and the process at hand

$$\mathcal{R}_{\Lambda/g} \equiv \frac{\hat{s}}{\Lambda^2/g^2}$$

The EFT expansion param – the expansion of the effective Lagrangian at leading order in g/Λ

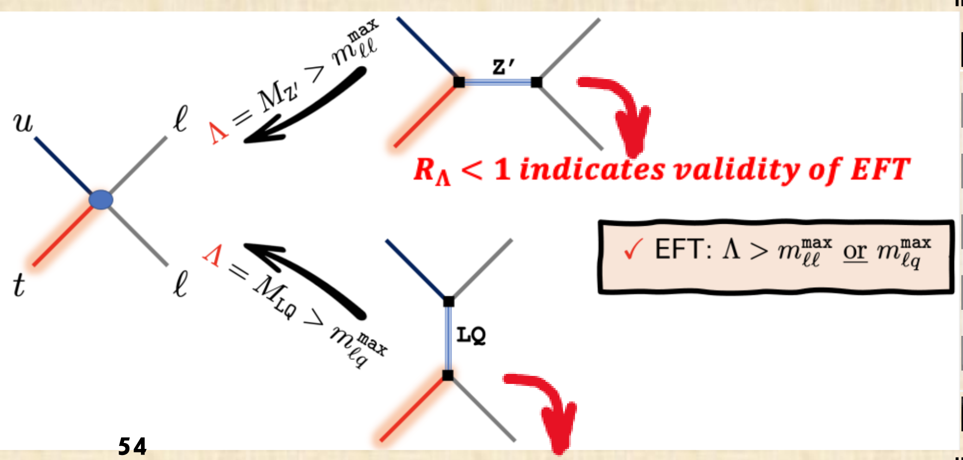
EFT-validity

Two "measures" to consider:

$$\sigma^{NP}(g,\Lambda,m_{\ell\ell}) = \frac{g^2}{\Lambda^2}\cdot\sigma^{SM\times NP}(m_{\ell\ell}) + \frac{g^4}{\Lambda^4}\cdot\sigma^{NP\times NP}(m_{\ell\ell})$$

$$\mathcal{R}_\Lambda \equiv \frac{\hat{s}}{\Lambda^2}$$

Addresses the validity of the specific calculation within the EFT framework – depends on the details of the underlying heavy physics and the process at hand



EFT may hold also when $R_\Lambda > 1$

$$\mathcal{R}_{\Lambda/g} \equiv \frac{\hat{s}}{\Lambda^2/g^2}$$

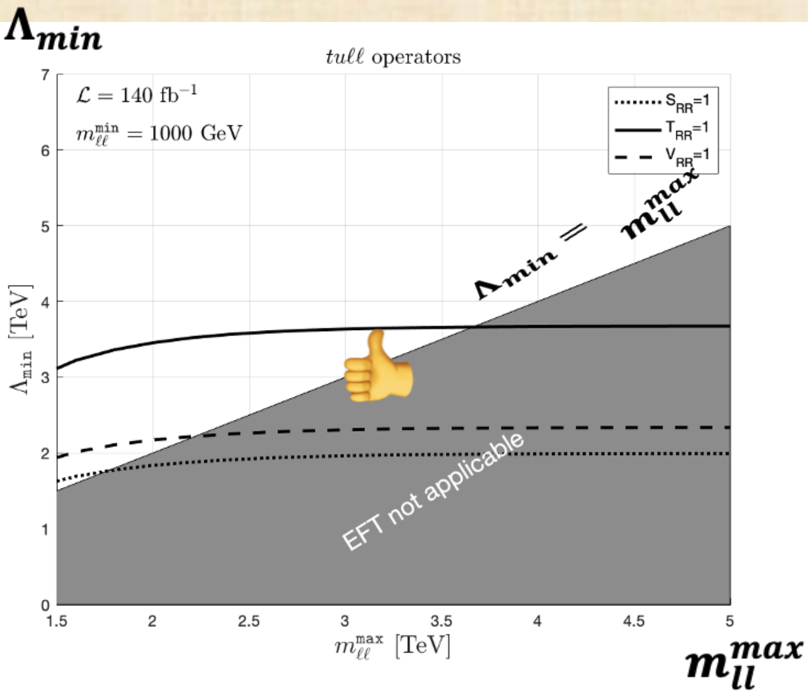
The EFT expansion param – the expansion of the effective Lagrangian at leading order in g/Λ

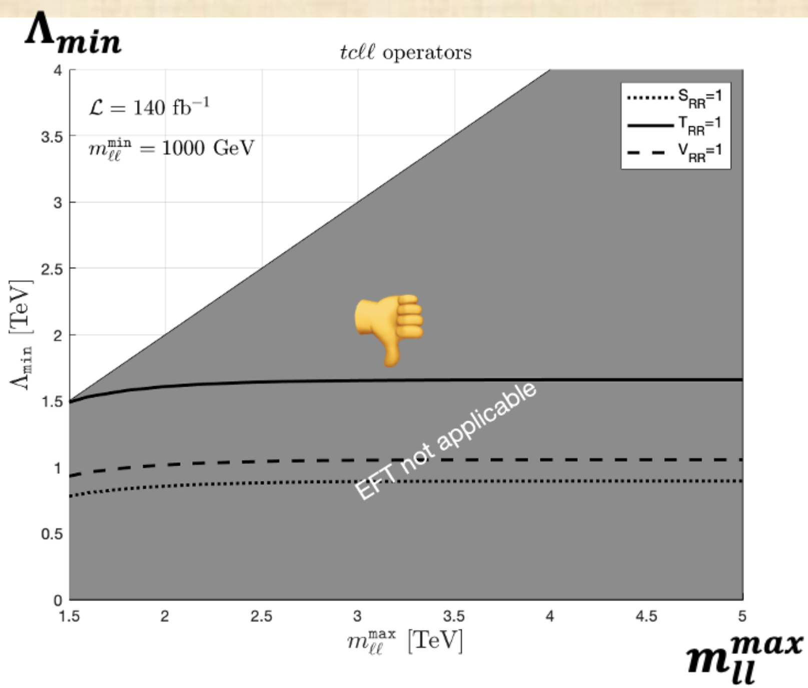
SMxNP interference term $\propto O(R_{\Lambda/g})$
NPxNP term $\propto O(R_{\Lambda/g}^2)$

$R_{\Lambda/g} < 1$ naively indicate the regime of validity of the EFT prescription & the potential effects from higher dim opts can be assessed from $R_{\Lambda/g}$

EFT-validity

Consider bounds (Λ_{min}) obtained on the scale Λ of an s-channel underlying NP pp $\rightarrow NP \rightarrow l^+l^-$; $\hat{s} = m_{ll}$





- **Consider the underlying hard processes for tri-leptons production:**

$$ab \to \ell'^- \ell^+ \ell^- \text{ and } \bar{a}\bar{b} \to \ell'^+ \ell^- \ell^+$$

- **CPV requires at least 2 amplitudes with different CP-odd phases:**

$$\mathcal{M}_{ab \to \ell'^- \ell^+ \ell^-} = M_1 e^{i(\phi_1 + \delta_1)} + M_2 e^{i(\phi_2 + \delta_2)}$$

$\phi_{1,2}$ are CP-odd phases & $\delta_{1,2}$ are CP-even phases

$$\bar{\mathcal{M}}_{\bar{a}\bar{b} \to \ell'^+ \ell^- \ell^+} = M_1 e^{i(-\phi_1 + \delta_1)} + M_2 e^{i(-\phi_2 + \delta_2)}$$

CC channel

- Classification of CP according to T_N transformation properties (T_N : $t \to -t$)

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}$$

- type:	T_N - odd	T_N - even
- CP asymmetry:	$A_{CP} \propto \cos\Delta\delta \sin\Delta\phi$	$A_{CP} \propto \sin\Delta\delta \sin\Delta\phi$

triple-products (TP) asymmetry

$$\mathcal{O}_{\rm CP} = \vec{p}_{\ell'^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$
$$\overline{\mathcal{O}_{\rm CP}} = \vec{p}_{\ell'^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})$$

odd under P & under T_N ($t \to -t$)

and

$$C(\mathcal{O}_{\rm CP}) = +\overline{\mathcal{O}_{\rm CP}} \;, \quad C(\overline{\mathcal{O}_{\rm CP}}) = +\mathcal{O}_{\rm CP} \;,$$
$$CP(\mathcal{O}_{\rm CP}) = -\overline{\mathcal{O}_{\rm CP}} \;, \quad CP(\overline{\mathcal{O}_{\rm CP}}) = -\mathcal{O}_{\rm CP}$$

A_{CP} function of $N\left(sign(\mathcal{O}_{\rm CP})\right)$ & $N\left(sign(\overline{\mathcal{O}_{\rm CP}})\right)$

dot-products

$$\mathcal{O}_{\rm CP} = \vec{p}_{\ell'^-} \cdot (\vec{p}_{\ell^+} - \vec{p}_{\ell^-})$$
$$\overline{\mathcal{O}_{\rm CP}} = \vec{p}_{\ell'^+} \cdot (\vec{p}_{\ell^+} - \vec{p}_{\ell^-})$$

or rate asymmetry

$$A_{CP} = \frac{N(\ell'^-\ell^+\ell^-) - N(\ell'^+\ell^-\ell^+)}{N(\ell'^-\ell^+\ell^-) + N(\ell'^+\ell^-\ell^+)}$$

- Classification of CP according to T_N transformation properties (T_N : t → - t)

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}$$

- type:	T_N - odd	T_N - even
- CP asymmetry:	$A_{CP} \propto \cos\Delta\delta \sin\Delta\phi$	$A_{CP} \propto \sin\Delta\delta \sin\Delta\phi$
- phases:	Only CP-odd	Both CP-odd & CP-even (strong phase)
- Sensitivity:	tree-level CPV	strong phase from FSI typically higher order effect ...
- Expected size:	O(10%)	O(0.1%)

$$\Delta\phi = \phi_1 - \phi_2,\ \Delta\delta = \delta_1 - \delta_2$$

Constructing CP-asym. For tree-level CPV

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}$$

$\phi_{1,2}$ are CP-odd phases & $\delta_{1,2}$ are CP-even phases (from FSI, loops ...)

- Classification of CP according to T_N transformation properties (T_N : t → - t)

- type:	T_N - odd	T_N - even
- CP asymmetry:	$A_{CP} \propto \cos\Delta\delta \sin\Delta\phi$	$A_{CP} \propto \sin\Delta\delta \sin\Delta\phi$
- requires:	Only CP-odd phase	Both CP-odd & CP-even phases

CPV @ tree-level (no FSI phases: Δδ=0) !

Constructing CP-asym. For tree-level CPV

- Divide into 2 "hemispheres" in O_{CP} space and define the P-violating & T_N-odd observables (odd under t → -t):

$$ab \to \ell'^- \ell^+ \ell^- \text{ and } \bar{a}\bar{b} \to \ell'^+ \ell^- \ell^+$$

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}$$

$$\Delta\phi = \phi_1 - \phi_2, \; \Delta\delta = \delta_1 - \delta_2,$$

$$A_T \equiv \frac{N(\mathcal{O}_{\rm CP} > 0) - N(\mathcal{O}_{\rm CP} < 0)}{N(\mathcal{O}_{\rm CP} > 0) + N(\mathcal{O}_{\rm CP} < 0)},$$

$$\bar{A}_T \equiv \frac{N(-\overline{\mathcal{O}_{\rm CP}} > 0) - N(-\overline{\mathcal{O}_{\rm CP}} < 0)}{N(-\overline{\mathcal{O}_{\rm CP}} > 0) + N(-\overline{\mathcal{O}_{\rm CP}} < 0)}$$

$$A_T \propto \sin(\Delta\delta + \Delta\phi)$$
$$\bar{A}_T \propto \sin(\Delta\delta - \Delta\phi)$$

in general: $A_T \neq 0$ and/or $\bar{A}_T \neq 0$ could be generated without CPV (i.e., $\Delta\phi = 0$ & $\Delta\delta \neq 0$)

These are sensitive to the CP-odd phase BUT are NOT proper CP-asymmetries !

since: $CP(A_T) = \bar{A}_T$

Constructing CP-asym. For tree-level CPV

- Divide into 2 "hemispheres" in O_{CP} space and define the P-violating & T_N-odd observables (odd under $t \to -t$):

$$ab \to \ell'^- \ell^+ \ell^- \text{ and } \bar{a}\bar{b} \to \ell'^+ \ell^- \ell^+$$

$$\mathcal{M}_{ab\to\ell'^-\ell^+\ell^-} = M_1 e^{i(\phi_1+\delta_1)} + M_2 e^{i(\phi_2+\delta_2)}$$

$$\Delta\phi = \phi_1 - \phi_2, \; \Delta\delta = \delta_1 - \delta_2,$$

$$A_T \equiv \frac{N(\mathcal{O}_{\rm CP} > 0) - N(\mathcal{O}_{\rm CP} < 0)}{N(\mathcal{O}_{\rm CP} > 0) + N(\mathcal{O}_{\rm CP} < 0)},$$

$$\bar{A}_T \equiv \frac{N(-\overline{\mathcal{O}}_{\rm CP} > 0) - N(-\overline{\mathcal{O}}_{\rm CP} < 0)}{N(-\overline{\mathcal{O}}_{\rm CP} > 0) + N(-\overline{\mathcal{O}}_{\rm CP} < 0)}$$

$$A_T \propto \sin(\Delta\delta + \Delta\phi)$$
$$\bar{A}_T \propto \sin(\Delta\delta - \Delta\phi)$$

in general: $A_T \neq 0$ and/or $\bar{A}_T \neq 0$
could be generated without CPV
(i.e., $\Delta\phi = 0$ & $\Delta\delta \neq 0$)

- Isolating the "pure" CPV effect: $A_{CP} = \frac{1}{2}\left(A_T - \bar{A}_T\right)$

a modification to the classic formula for CP-violation in scattering and decay processes
takes into account the effect of an asymmetric initial state on the measurement of CP-violation

- **The resulting CP asymmetry:**

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

"conventional" CPV term:
CP-odd & T_N-odd
($CPT_N = CPT$)

initial state not self-conjugate:
CP-even & T_N-odd
($CPT_N \neq CPT$)

Recap: 3 asymmetries

$$A_T = \mathcal{I}_{ab} \sin(\Delta\phi + \Delta\delta)$$

$$\bar{A}_T = \mathcal{I}_{\bar{a}\bar{b}} \sin(-\Delta\phi + \Delta\delta)$$

CP-odd & T_N-odd

CP-even & T_N-odd

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

$$A_{CP}^{(\Delta\phi)}$$

$$A_{CP}^{(\text{"fake"})}$$

Key points:

- "contamination" to the CPV measurement can arise if initial state is not self-conjugate
- at the tree-level: $\Delta\delta = 0$ (no FSI) $\Rightarrow$ regardless of initial state properties:

  all 3 asymmetries are $\propto$ CP-odd phase & thus are good measures of CPV !

CPV ☞ multi-leptons events

Recap:

$$A_T = \mathcal{I}_{ab} \sin(\Delta\phi + \Delta\delta) \qquad \bar{A}_T = \mathcal{I}_{\bar{a}\bar{b}} \sin(-\Delta\phi + \Delta\delta)$$

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

- $A_T \neq 0$ and/or $\bar{A}_T \neq 0$ can be observed even in the absence of CP-violation (i.e., $\Delta\phi = 0$) due to the presence of CP-even phases $\Delta\delta \neq 0$ ...
- $|A_T| \neq |\bar{A}_T|$ is possible at the LHC even with $\Delta\delta = 0$ (if different PDF's are different: $f_a, f_b \neq f_{\bar{a}}, f_{\bar{b}}$) due to CP-asymmetric nature of the initial state at the LHC ...
- $A_{CP} \propto \sin\Delta\phi$ (maximal when $\Delta\delta \to 0$) if same PDF's of incoming particles ($f_a f_b = f_{\bar{a}} f_{\bar{b}}$)
- $A_{CP} \propto \sin\Delta\phi$ when $\Delta\delta \to 0$, even when $f_a f_b \neq f_{\bar{a}} f_{\bar{b}}$
- Thus, when $\Delta\delta << \Delta\phi$, A_{CP} is essentially probing the underlying CP-violating dynamics !

the case, in general, for the scattering processes at the LHC if there are no resonances involved, since then CP-even phases can only come from FSI, which occur at higher loop orders, whereas A_{CP} probes tree-level CPV effects !

- Considering only tree-level effects (no CP-even phases from FSI)

- general form of the amp. in presence of dim.6 SMEFT (α_k = Wilson coef. & ϕ_k = CPV phases)

$$\mathcal{M}_{i\to f} = M_{\rm SM} + \sum_k \frac{|\alpha_k|}{\Lambda^2} M_k e^{i\phi_k} + \cdots$$

- Then, 3 types of tree-level CPV effects (NP=SMEFT) :

  - TL-CPVI: CPV from SMxNP interference

  - TL-CPVII: CPV from NPxNP' interference;
    no SMxNP interference, but with a SM contribution

  - TL-CPVIII: CPV from NPxNP' interference;
    no SMxNP interference, and without a SM contribution

- **TL-CPVI: SMxNP interference**

$$Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi}$$

$$d\sigma_{\rm CPC} \propto |M_{\tt SM}|^2 + \frac{|\alpha_{t\phi}|}{\Lambda^2} {\rm Re}\left(M_{\tt SM} M_{t\phi}^\dagger\right) \cos\phi_{t\phi} + \cdots$$

$$d\sigma_{\rm CPV} \propto \frac{|\alpha_{t\phi}|}{\Lambda^2} {\rm Im}\left(M_{\tt SM} M_{t\phi}^\dagger\right) \sin\phi_{t\phi} + \cdots$$

- **TL-CPVII: NPxNP' interference,**

no SMxNP interference, with a SM contribution

$$d\sigma_{\rm CPC} \propto |M_{\tt SM}|^2 + \sum_k \frac{|\alpha_k|^2}{\Lambda^4} |M_k|^2 + \sum_{k<l} \frac{|\alpha_k \alpha_l|}{\Lambda^4} {\rm Re}\left(M_k M_l^\dagger\right) \cos\Delta\phi_{kl} + \cdots$$

$$d\sigma_{\rm CPV} \propto \sum_{k<l} \frac{|\alpha_k \alpha_l|}{\Lambda^4} {\rm Im}\left(M_k M_l^\dagger\right) \sin\Delta\phi_{kl} + \cdots$$

$$\Delta\phi_{kl} = \phi_k - \phi_l$$

- **TL-CPVIII: NPxNP' interference,**

no SMxNP interference, without a SM contribution

$$d\sigma_{\rm CPC} \propto |M_{\tt SM}|^2 + \sum_k \frac{|\alpha_k|^2}{\Lambda^4} |M_k|^2 + \sum_{k<l} \frac{|\alpha_k \alpha_l|}{\Lambda^4} {\rm Re}\left(M_k M_l^\dagger\right) \cos\Delta\phi_{kl} + \cdots$$

$$d\sigma_{\rm CPV} \propto \sum_{k<l} \frac{|\alpha_k \alpha_l|}{\Lambda^4} {\rm Im}\left(M_k M_l^\dagger\right) \sin\Delta\phi_{kl} + \cdots$$

- Then, for 3 types of tree-level CPV effects:
  - TL-CPVI: SMxNP' interference
  - TL-CPVII: NPxNP' interference, with a SM contribution
  - TL-CPVIII: NPxNP' interference, without a SM contribution

	CPV source in σ	Leading CPC term in σ	$\mathcal{A}_{CP}$	$N_{SD}(\mathcal{A}_{CP})$
TLCPV-I	$\mathrm{Im}\left(M_{SM}M_{NP}^\dagger\right) \propto \frac{v^2}{\Lambda^2}$	$\lvert M_{\mathrm{SM}}\rvert^2$	$\frac{v^2}{\Lambda^2}$	$\frac{v^2}{\Lambda^2}$
TLCPV-II	$\mathrm{Im}\left(M_{NP'}M_{NP}^\dagger\right) \propto \frac{v_E^4}{\Lambda^4}$	$\lvert M_{\mathrm{SM}}\rvert^2$	$\frac{v_E^4}{\Lambda^4}$	$\frac{v_E^4}{\Lambda^4}$
TLCPV-III	$\mathrm{Im}\left(M'_{NP}M_{NP}^\dagger\right) \propto \frac{v_E^4}{\Lambda^4}$	$\lvert M_{\mathrm{NP}}\rvert^2 \propto \frac{v_E^4}{\Lambda^4}$	1	$\frac{v_E^2}{\Lambda^2}$

$v_E = v$ or $v_E = E$

CPT = CPT_N if no FSI

…

- S-matrix unitarity ($SS^+=1$) in term of scattering amp:

$$\tau_{fi} - \tau_{if}^* = i\sum_n \tau_{nf}^*\tau_{ni}$$

* If no FSI (τ Hermitian), then: $\tau_{if} = \tau_{fi}^*$

If CP is conserved then T-reversal also conserved, and:

$$\tau_{if} = \tau_{f_T i_T} = \tau_{i_T f_T}^* \;(no\;FSI)$$

⬇

$$|\tau_{if}|^2 = |\tau_{i_T f_T}|^2$$

Modulus of τ_{if} is invariant under T_N !