Generic tests of CP-violation for high-p_T multi-leptons

ICHEP 2024

BSM session
19/7/2024

Based on:

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

  PRL (2023), arxiv: 2212.09433, Afik(CERN), SBS(Technion), Pal(UCR), Soni(BNL), Wudka(UCR)

- "CP-Violation at the High-energy Frontier; guiding principles"

  SBS, Soni, Wudka, arxiv: 2407.XXXXX

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CPV @ the high-energy frontier

guiding principles

CPV @ the high-energy frontier: guiding principles

- 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

- NP that underlies the SM can be parameterized in general by higher dimensional, gauge-invariant effective operators:

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

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 parts of SMEFT_0 & SMEFT_t:

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

$O(1/\Lambda^2)$ 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

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

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- these opts are Loop Generated (LG) in the underlying theory
  - ☞ expect corresponding Wilson coef: $\alpha_i \sim 1/(4\pi)^2$

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

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- the only opt. that is Potentially Tree-Level Generated (PTG) in the underlying theory
  - ☞ expect (naturality) corresponding Wilson coef: $\alpha_i = O(1)$

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

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

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

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

- <u>Best bet:</u> CPV from interference of tree-level diagrams e.g., in $e^+e^- \to tth$, $pp \to tth$, $pp \to th + X$

CPV @ the high-energy frontier: guiding principles

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

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

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

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

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

CPV @ the high-energy frontier: guiding principles

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

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

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

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

▻ No CPV signal is expected from SMxEFT interreference if underlying NP obeys SM symmetries (G_0 & G_t)!

arxiv:2407.xxxxx, SBS, Soni, Wudka

CPV @ the high-energy frontier: guiding principles

- If flavor is violated in the underlying heavy theory

  then:

  all SMEFT opts containing flavor-violating

  combinations of fermion fields can violate CP !

Shaouly Bar-Shalom

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 !

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

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

$$|M_{\rm NP}|^2 \propto \frac{v_E^4}{\Lambda^4}$$

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

CPV @ the high-energy frontier: guiding principles

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

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

- CP asymmetry expected in this case:

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

CPV from flavor violating NP

Best bet: top-quark FV interactions (least constrained, heavy top …)

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 ☞ $Q_{lequ}^{(1)} = (\bar{l}^j e)\,\epsilon_{jk}\,(\bar{q}^k u)$ $Q_{lequ}^{(3)} = (\bar{l}^j \sigma_{\mu\nu} e)\,\epsilon_{jk}\,(\bar{q}^k \sigma^{\mu\nu} u)$

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

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

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

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

Scalar

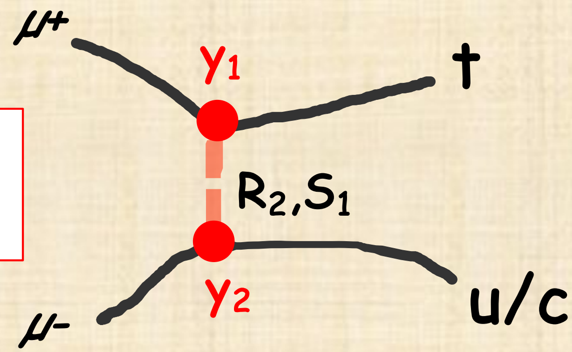
Tensor

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

- Matching to possible underlying BSM scenarios:

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

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



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

$$\text{Im}\,(\alpha_S \cdot \alpha_T^\star) = 0.25$$

CP test in high-p_T multi-leptons events

CPV ☞ multi-leptons events

PRL2023, Afik, SBS, Pal, Soni, Wudka (arxiv: 2212.09433)

- Constructing generic tests of CPV (BSM) in multi-lepton processes: focus on tri-lepton events

(applies also to 4-leptons events …)

$$pp \to \ell'^- \ell^+ \ell^- + X_3$$
$$pp \to \ell'^+ \ell^- \ell^+ + \bar{X}_3 \ ,$$
$$pp \to \ell'^+ \ell'^- \ell^+ \ell^- + X_4$$

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

- $\ell, \ell' = e, \mu, \tau$ (preferably $\ell \neq \ell'$)
- X_3, $\bar{X}_3$ and X_4: jets and missing energy

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- $\ell, \ell' = e, \mu, \tau$ (preferably $\ell \neq \ell'$)
- X_3, $\bar{X}_3$ and X_4: jets and missing energy

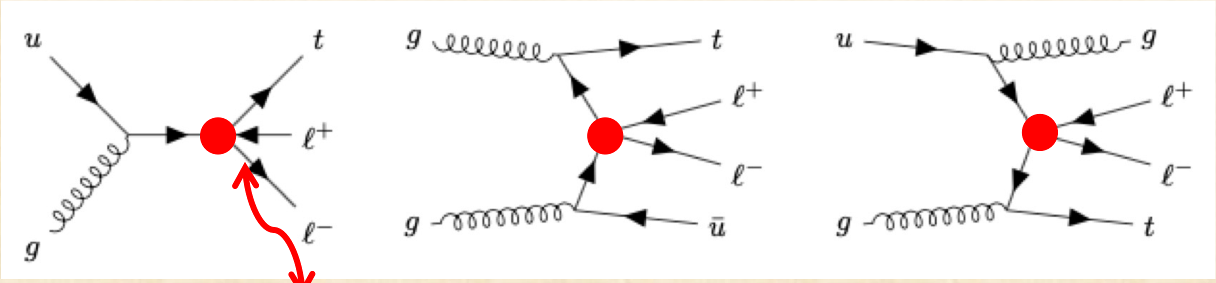
- Note: sizeable, say O(few%), manifestation of CPV in multi-leptons events of the type considered will be an unambiguous indication of NP, since the CP-odd CKM-phase of the SM is expected to yield negligible CP-violating effects in these processes

  (CPV@SM in multi-lepton signals can only arise from EW processes at higher loop orders)

CPV in tri-lepton events from single top production

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

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



tull/tcll 4-Fermi

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

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

e.g.,

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

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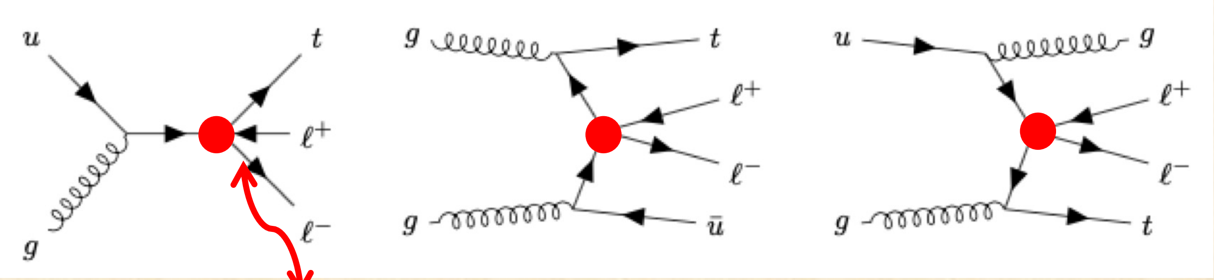

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e.g.,

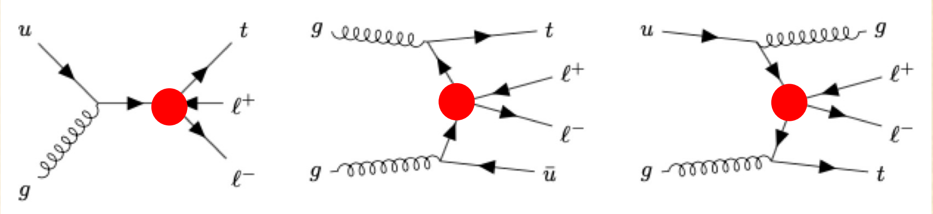
pp → t μ+ μ- → e+ μ+ μ- + X (& CC channel)

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.

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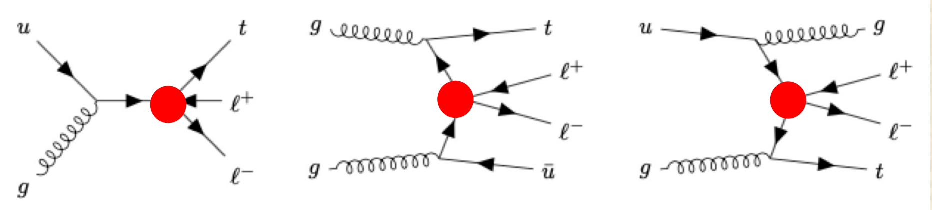

$$d\hat{\sigma}(CPV) \propto \epsilon\left(p_{u_i}, p_{\ell'^+}, p_{\ell^+}, p_{\ell^-}\right) \cdot \mathrm{Im}\left(f_S f_T^\star\right)$$

CPV

No interference with SM:

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

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

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

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 ...)

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

- To probe tree-level CPV one needs T_N-odd observables (T_N : t → -t)
  => T_N-odd observables do not vanish when FSI phases are zero (δ = 0)

T_N - odd

asymmetries based on triple-products (TP)

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

CPV ☞ multi-leptons events: Constructing CP-asym from TP's

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

Recall:
$pp \to t\, \mu^+ \mu^- \to e^+ \mu^+ \mu^- + X$ & CC channel

($l' = e$, $l = \mu$)

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

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

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

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

In general: $A_T \neq 0$ & $\bar{A}_T \neq 0$ may also be a signal of some strong or generic CP-even phase (FSI...) even if the underlying dynamics are CP-conserving !

- Isolating the pure CPV effect:

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

Recup:

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

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

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

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

NP (CPV)

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

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

Recup:

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

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

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

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

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 $\in$ low m_{ll}

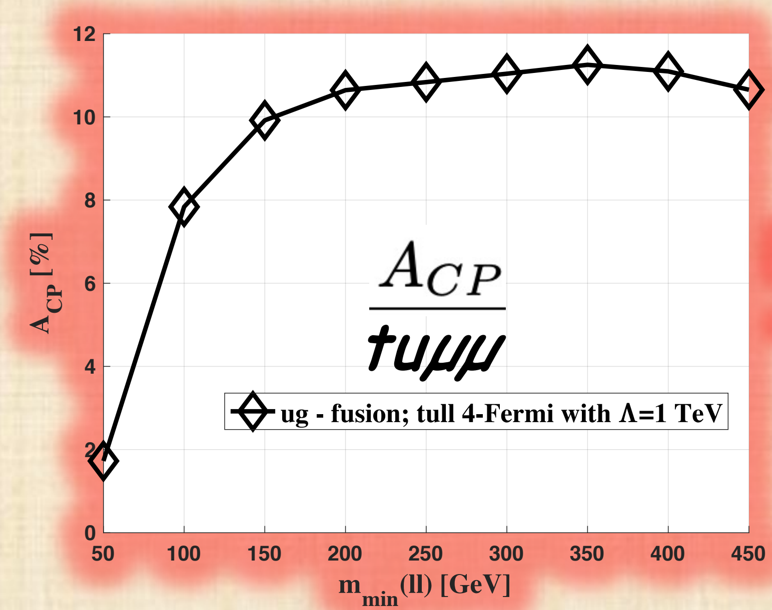
NP $\in$ high m_{ll}

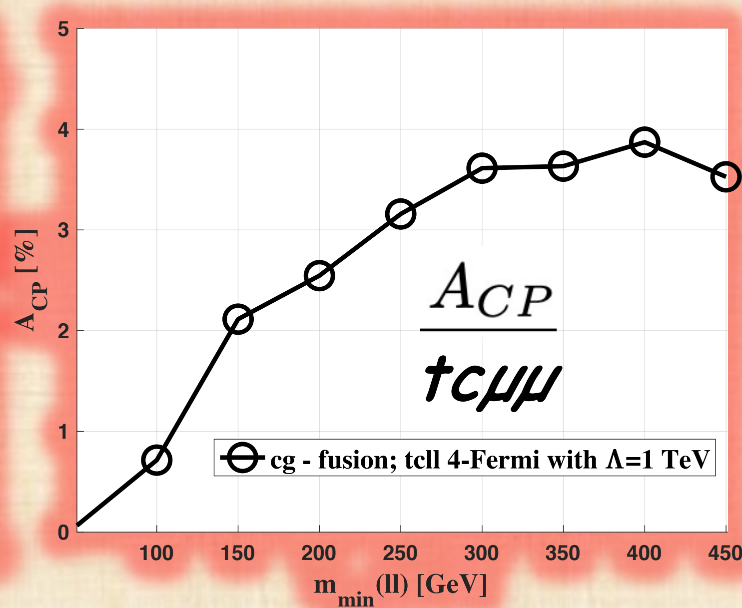
Results:

$u\,g \to t\,\mu\mu \to \mu\mu e$ (*tuμμ* 4-Fermi)

$c\,g \to t\,\mu\mu \to \mu\mu e$ (*tcμμ* 4-Fermi)

	ug-fusion: $\Lambda = 1(2)$ TeV	cg-fusion: $\Lambda = 1(2)$ TeV
A_{CP}	11.1(7.9)%	3.9(0.7)%
A_T	16.4(13.5)%	3.1(0.5)%
$\bar{A}_T$	-5.8(-2.3)%	-4.7(-1.0)%





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

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

SUMMARY – CONCLUSION

- Under naturality arguments of the underlying heavy NP & in the absence of flavor-changing interactions,

  only a single operator $Q_{t\phi} = \phi^\dagger \phi \, (\bar{q}_3 t) \, \tilde{\phi}$ can generate non-vanishing CPV from SMxNP interference !

- $Q_{t\varphi}$ modifies the top-Yukawa coupling:

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

- Unfortunately, CPV effects in top-quark systems, from $Q_{t\varphi}$, are too small … !

SUMMARY

CONCLUSION

- If flavor is violated @ TeV-scale in the top-quark sector, then large CPV effects might be manifested in multi-leptons signals at the LHC
  - Besides: multi-leptons signals provide an excellent & rich testing ground of NP:
    flavor physics, lepton flavor universality, CP-Violation …

"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)

- We have constructed useful CP asymmetries for measuring CP-violation in multi-lepton events
- These asymmetries have several new & unique features, that make them particularly useful for searching for CP-violation at high-energy colliders

SUMMARY

CONCLUSION

- 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

SUMMARY

CONCLUSION

- Resulting CP asymmetries:

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

- SM backg. For CPV in multi-lepton events is at the sub-% level …

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

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

Thank you!

Backups

CP – Violation (CPV)

- CPV may be the key to a deeper understanding of particle physics and the evolution of the universe; it has far-reaching implications for cosmology …

  - CPV is needed to explain the observed baryon asymmetry of the universe (BAU)

  - CPV@SM is insufficient to explain the BAU

  - CP is not a symmetry of nature

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

      - Examples:
        SUSY, Mutli-Higgs models, Leptoquarks, Vector-like fermions …

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)

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PLB807 (2020), 135541, arxiv: 1912.00425, Afik, SBS, Cohen, Rozen(Technion)

CPV ☞ multi-leptons events

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

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

- 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

CPV ☞ multi-leptons events

- 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:	$A_{CP} \propto \cos\Delta\delta \sin\Delta\phi$	$A_{CP} \propto \sin\Delta\delta \sin\Delta\phi$
- 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%)

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

CPV ☞ multi-leptons events

- 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	**Rate asymmetry**

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

Rate asymmetry

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

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 ($T_N : t \rightarrow -t$)

- 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

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- requires:	Only CP-odd phase	Both CP-odd & CP-even phases

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

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)

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 $\mathrm{Im}\left(f_S f_T^\star\right) = 0.25$, $\Lambda = 1$ 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

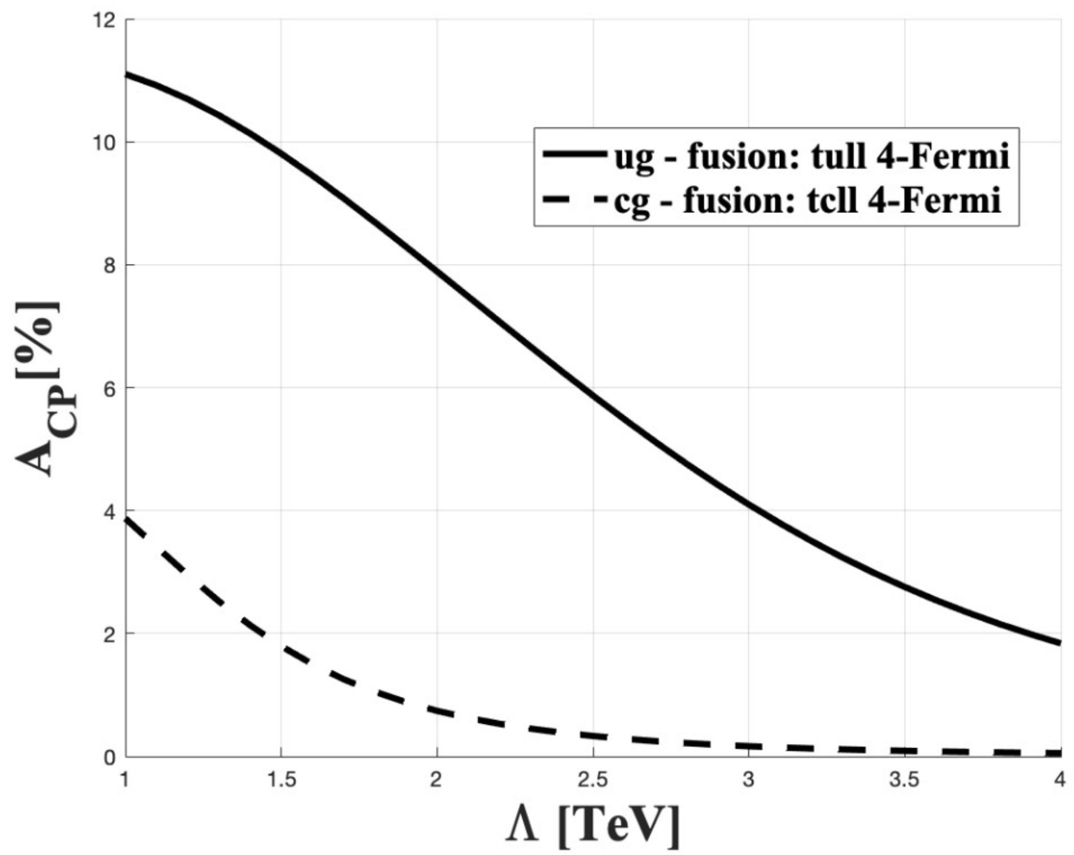


FIG. 1: The expected CP-asymmetry A_{CP}, as a function of the NP scale Λ, for $m_{min}(\ell\ell) = 400$ GeV and $\text{Im}\,(f_S f_T^\star) = 0.25$. Results are shown for the cases of NP from ug and cg-fusion, which arise from the $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators, respectively. The SM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

Sensitivity to scale of NP: uncertainties

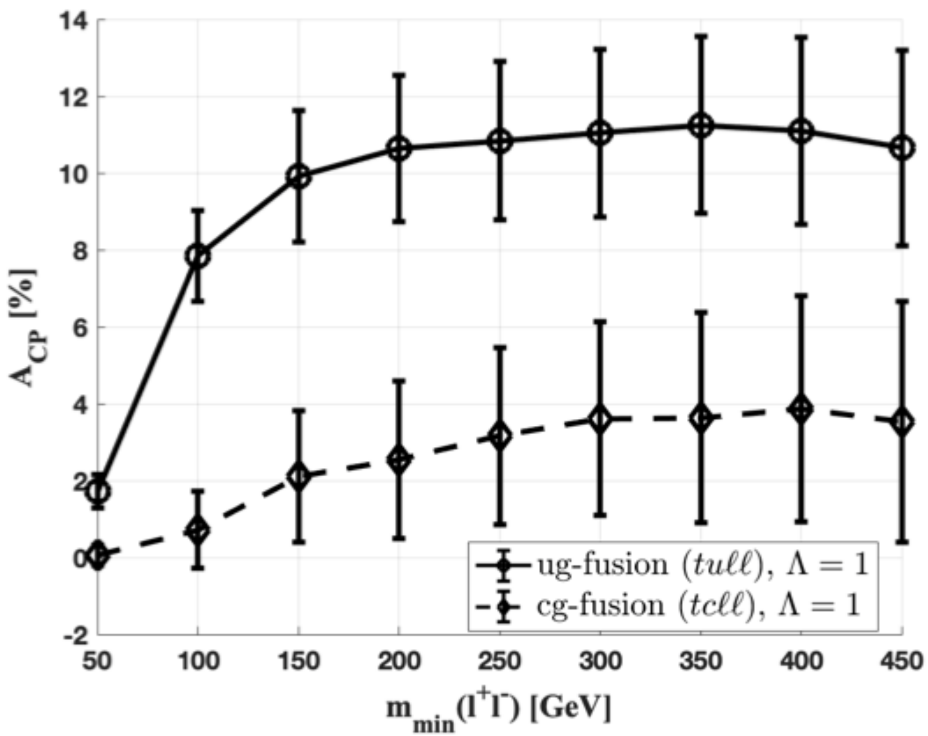


FIG. 2: A_{CP} as a function of $m_{min}(\ell^+\ell^-)$, for $\Lambda = 1$ TeV, $\mathrm{Im}\,(f_S f_T^\star) = 0.25$ and including the SM background. The dependence of the asymmetry on Λ is given in Appendix B. The error bars represent the expected statistical uncertainty with an integrated luminosity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

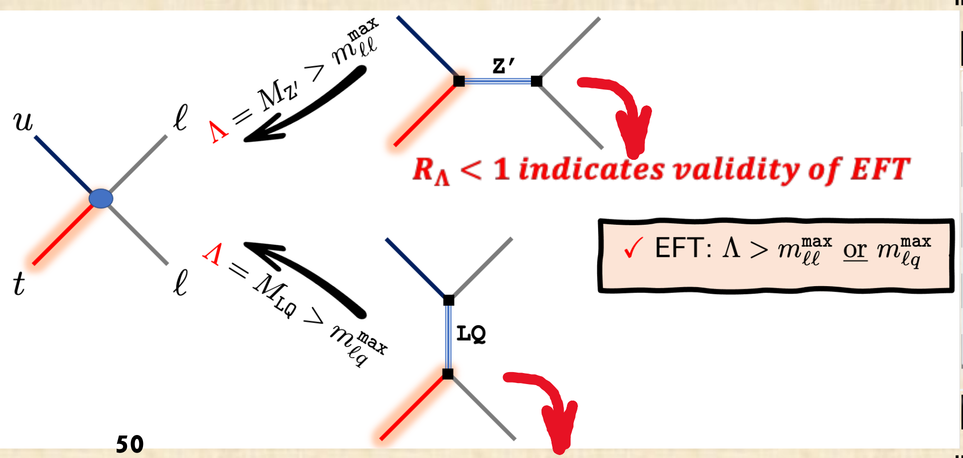
EFT-validity

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 $R_\Lambda > 1$

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

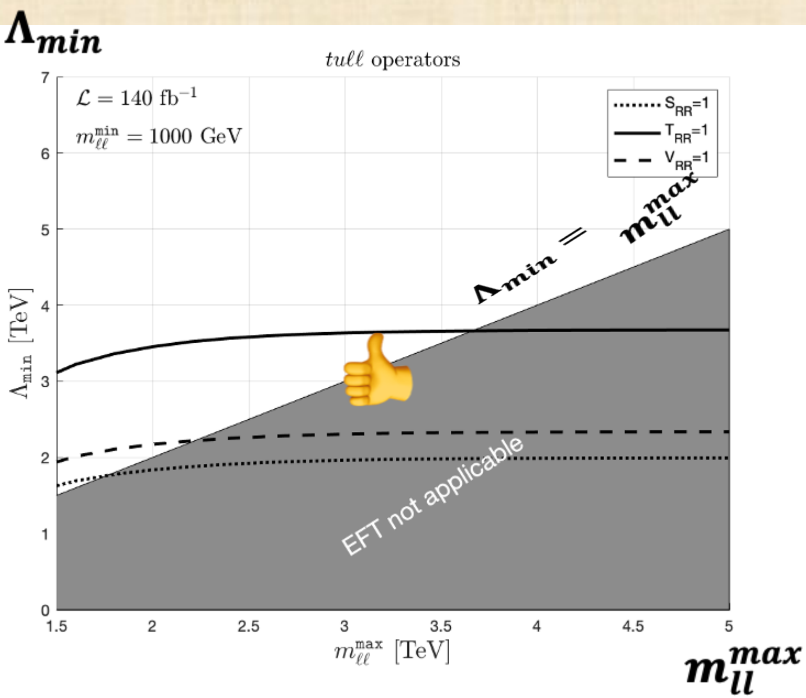
The EFT expansion param – the expansion of the effective Lagrangian at leading order in g/Λ

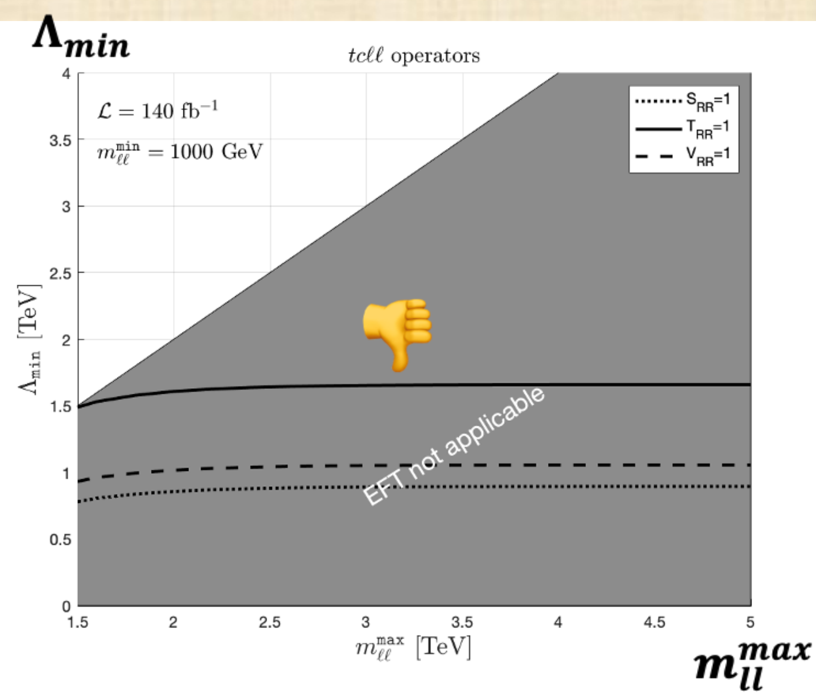
SMxNP interference term $\propto O(R_{\Lambda/g})$
NPxNP term $\propto O(R_{\Lambda/g}^2)$

*$R_{\Lambda/g} < 1$ 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 $\rightarrow NP \rightarrow l^+l^-$; $\hat{s} = m_{ll}$





CPV ☞ multi-leptons events: Constructing CP-asym from TP's

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

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

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

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

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

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

A measurement of $A_T \neq 0$ and/or $\bar{A}_T \neq 0$ may indicate the presence of CP-violation (CP-odd phase), but may also be a signal of some strong or generic CP-even phase, e.g., from final state interaction (FSI), even if the underlying dynamics that drives the processes under consideration is CP-conserving.

- Isolating the pure CPV effect:

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

CPV ☞ multi-leptons events

- The resulting asymmetries:

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

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

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

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

"conventional" CPV term

initial state not self-conjugate

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

$$V \propto \mathrm{Im}\left(M_1 M_2^\dagger\right)$$

$$\mathcal{I}_{ab(\bar{a}\bar{b})} = \frac{\int_R d\Phi f_{a(\bar{a})} f_{b(\bar{b})} V \cdot \mathtt{sign}(\mathcal{O}_{\mathrm{CP}})}{\int_R d\Phi f_{a(\bar{a})} f_{b(\bar{b})} U}$$

PDF's

CPV ☞ multi-leptons events

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

- The resulting asymmetries:

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

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

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

"conventional" CPV term

initial state not self-conjugate

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

a 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

$$V \propto \mathrm{Im}\left(M_1 M_2^\dagger\right)$$

$$\mathcal{I}_{ab(\bar{a}\bar{b})} = \frac{\int_R d\Phi f_{a(\bar{a})} f_{b(\bar{b})} V \cdot \mathtt{sign}(\mathcal{O}_{\rm CP})}{\int_R d\Phi f_{a(\bar{a})} f_{b(\bar{b})} U}$$

PDF's

CPV ☞ multi-leptons events

Recap:

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

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

- $A_T \neq 0$ 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 !