

# Underpinnings of CP-violation @ the high-energy frontier

**PLANCK 2025**

Collider BSM session  
28/5/2025

**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)



# 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



# 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

...

In fact – its “a mess” !



# *We need a plan*

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

EFT extensions probably best ! use SMEFT basis...

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

**We need guiding principles ...**



# *We need a plan*

- Understanding the patterns of CPV @ TeV-scale

- Ignorance (regarding underlying heavy physics):

EFT extensions probably best ! use SMEFT basis...

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
- Where to look for the expected leading CPV effects?



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 !
- $SM_+$ : the  $SM_0$  with a massive top-quark has a reduced symmetry  $G_+ = U(3)^4 \times U(2) \times U(1) \subset G_0$  :

$$\mathcal{L}_{SM_t} = \mathcal{L}_{SM_0} + \left( y_t \bar{q}_3 t \tilde{\phi} + \text{H.c.} \right)$$



- 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 possess the  $G_0$  &  $G_t$  global symmetries of the  $SM_0$  and  $SM_t$  ; then

$$\begin{aligned}\mathcal{L}_{\mathcal{G}_0} &= \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} , \\ \mathcal{L}_{\mathcal{G}_t} &= \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}\end{aligned}$$



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

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} ,$$

$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}$$

## - CPV sectors of $SMEFT_0$ & $SMEFT_t$ :

$\mathcal{L}_{SMEFT_0}^{CPV}$	$\mathcal{L}_{SMEFT_t}^{CPV}$
$Q_{\tilde{G}} = f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{tG} = (\bar{q}_3 \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$
$Q_{\tilde{W}} = f^{IJK} \tilde{G}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{tW} = (\bar{q}_3 \sigma^{\mu\nu} t) \tau^I \tilde{\phi} W_{\mu\nu}^I$
$Q_{\phi\tilde{G}} = \phi^{\dagger} \phi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{tB} = (\bar{q}_3 \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}$
$Q_{\phi\tilde{W}} = \phi^{\dagger} \phi \tilde{W}_{\mu\nu}^I G^{I\mu\nu}$	$Q_{t\phi} = \phi^{\dagger} \phi (\bar{q}_3 t) \tilde{\phi}$
$Q_{\phi\tilde{B}} = \phi^{\dagger} \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	
$Q_{\phi\tilde{W}B} = \phi^{\dagger} \tau^I \phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	

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

$SMEFT_0 \times SM_0$  &  $SMEFT_t \times SM_t$



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

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} ,$$

$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}$$

## - CPV sectors of $SMEFT_0$ & $SMEFT_t$ :

Selection rules @ the UV

$\mathcal{L}_{SMEFT_0}^{CPV}$	$\mathcal{L}_{SMEFT_t}^{CPV}$
$\mathcal{L} Q_{\tilde{G}} = f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{tG} = (\bar{q}_3 \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$
$\mathcal{L} Q_{\tilde{W}} = f^{IJK} \tilde{G}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{tW} = (\bar{q}_3 \sigma^{\mu\nu} t) \tau^I \tilde{\phi} W_{\mu\nu}^I$
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$\mathcal{L} Q_{\phi\tilde{W}} = \phi^{\dagger} \phi \tilde{W}_{\mu\nu}^I G^{I\mu\nu}$	$Q_{t\phi} = \phi^{\dagger} \phi (\bar{q}_3 t) \tilde{\phi}$
$\mathcal{L} Q_{\phi\tilde{B}} = \phi^{\dagger} \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	
$\mathcal{L} Q_{\phi\tilde{W}B} = \phi^{\dagger} \tau^I \phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	

- 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



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

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} \text{ ,}$$
$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}$$

- CPV sectors of SMEFT<sub>0</sub> & SMEFT<sub>+</sub>:

$\mathcal{L}_{SMEFT_0}^{CPV}$	$\mathcal{L}_{SMEFT_t}^{CPV}$
$\mathcal{L}_{\tilde{G}} = f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{tG} = (\bar{q}_3 \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$
$\mathcal{L}_{\tilde{W}} = f^{IJK} \tilde{G}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{tW} = (\bar{q}_3 \sigma^{\mu\nu} t) \tau^I \tilde{\phi} W_{\mu\nu}^I$
$\mathcal{L}_{\phi\tilde{G}} = \phi^{\dagger} \phi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{L}_{tB} = (\bar{q}_3 \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}$
$\mathcal{L}_{\phi\tilde{W}} = \phi^{\dagger} \phi \tilde{W}_{\mu\nu}^I G^{I\mu\nu}$	$Q_{t\phi} = \phi^{\dagger} \phi (\bar{q}_3 t)$
$\mathcal{L}_{\phi\tilde{B}} = \phi^{\dagger} \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	
$\mathcal{L}_{\phi\tilde{W}B} = \phi^{\dagger} \tau^I \phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	

Selection rules @ the UV

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 (LC) underlying theory

expect corresponding ref:

$$\alpha_i \sim 1/(4\pi)^2$$

Arzt, Einhorn, Wudka, NPB(2013), arxiv:1307.0478 & Einhorn, Wudka, NPB(2013), arxiv:1307.0478



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

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} ,$$

$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}$$

## - CPV parts of $SMEFT_0$ & $SMEFT_t$ :

Selection rules @ the UV

$\mathcal{L}_{SMEFT_0}^{CPV}$	$\mathcal{L}_{SMEFT_t}^{CPV}$
$\text{✗ } Q_{\tilde{G}} = f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{tG} = (\bar{q}_3 \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$
$\text{✗ } Q_{\tilde{W}} = f^{IJK} \tilde{G}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$	$Q_{tW} = (\bar{q}_3 \sigma^{\mu\nu} t) \tau^I \tilde{\phi} W_{\mu\nu}^I$
$\text{✗ } Q_{\phi\tilde{G}} = \phi^{\dagger} \phi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\text{✗ } Q_{tB} = (\bar{q}_3 \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}$
$\text{✗ } Q_{\phi\tilde{W}} = \phi^{\dagger} \phi \tilde{W}_{\mu\nu}^I G^{I\mu\nu}$	<div style="border: 1px solid black; padding: 5px;"><math>\text{✔ } Q_{t\phi} = \phi^{\dagger} \phi (\bar{q}_3 t) \tilde{\phi}</math></div>
$\text{✗ } Q_{\phi\tilde{B}} = \phi^{\dagger} \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	
$\text{✗ } Q_{\phi\tilde{W}B} = \phi^{\dagger} \tau^I \phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	

- the only opt. that is Potentially Tree-Level Generated (PTG) !

✔ expect (naturalness) corresponding Wilson coef:  $\alpha_i = O(1)$

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



# CPV @ the high-energy frontier: guiding principles

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

$$\mathcal{L}_{\mathcal{G}_0} = \mathcal{L}_{SM_0} + \mathcal{L}_{SMEFT_0} ,$$

$$\mathcal{L}_{\mathcal{G}_t} = \mathcal{L}_{SM_t} + \mathcal{L}_{SMEFT_0} + \mathcal{L}_{SMEFT_t}$$

If SMEFT possesses  $\mathcal{G}_+$  ...

- Only  $Q_{t\bar{t}}$  can potentially generate leading CPV effects @ high-energy colliders - **in top-quark systems ...**

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

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

e.g., in

$$e^+e^- \rightarrow t\bar{t}h$$

$$pp \rightarrow t\bar{t}h$$

$$pp \rightarrow t\bar{t}h + X$$



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

- However: CP asymmetry behaves as:

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

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

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



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

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

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

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

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

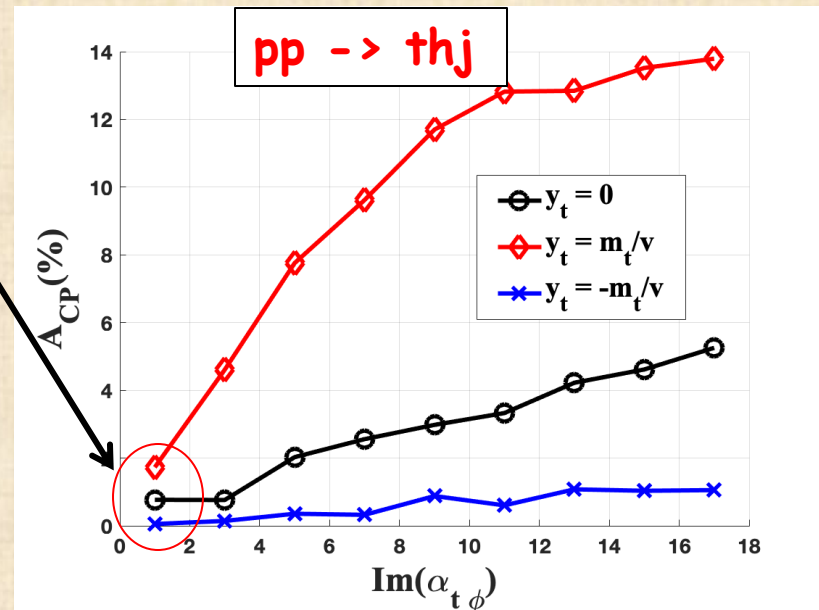
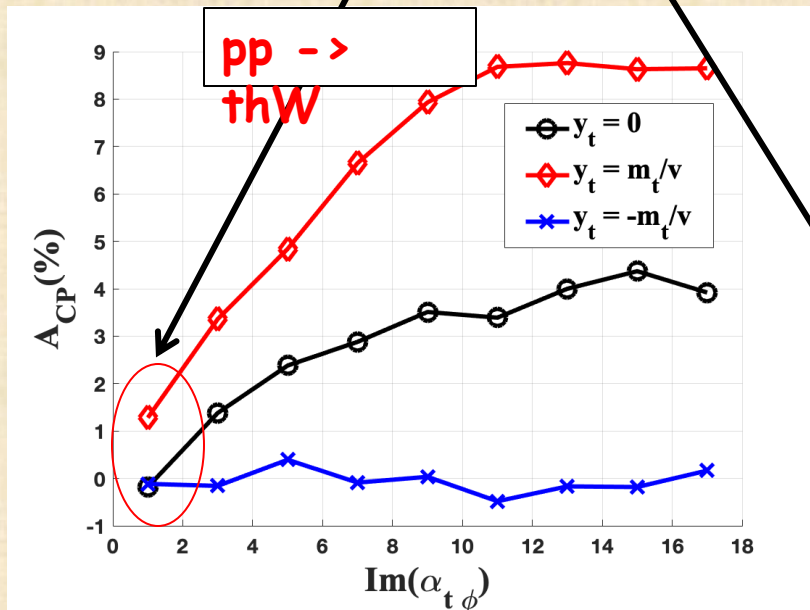
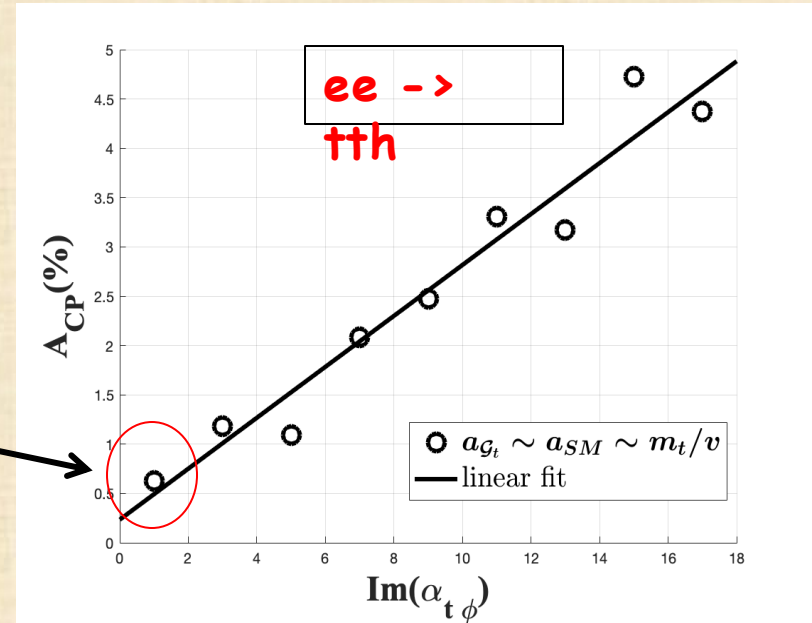




- Examples of tree-level CP asymmetry ( $A_{CP}$ ) from  $O_{t\phi}$

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

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





▷ No CPV signal is expected (e.g., @LHC)  
from SM X EFT interference if  
underlying heavy physics obeys the  
approximate SM flavor symmetries  
( $G_0$  &  $G_+$ )!

---



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

# HOWEVER

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

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

**then:**

**all SMEFT ops containing flavor-violating combinations of fermion fields can violate CP !**

$$\begin{aligned}
&(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r) \\
&(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r) \\
&(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r) \\
&(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r) \\
&(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r) \\
&(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r) \\
&(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r) \\
&i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)
\end{aligned}$$

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

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

$$\begin{aligned}
&(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi) \\
&(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi}) \\
&(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)
\end{aligned}$$



## CPV from flavor violating NP

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

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

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

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

$$v_E = v \text{ or } v_E = E \dots$$



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

$$v_E = v \text{ or } v_E = E \dots$$

- CP asymmetry expected in this case:

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



**Large ! CPV**

**From flavor-violating NP**

**in the top-quark sector ...**

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



# CPV from flavor violating NP

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

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

Scalar

Tensor

**SMEFT**  $\Rightarrow$

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

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



# CPV from flavor violating NP

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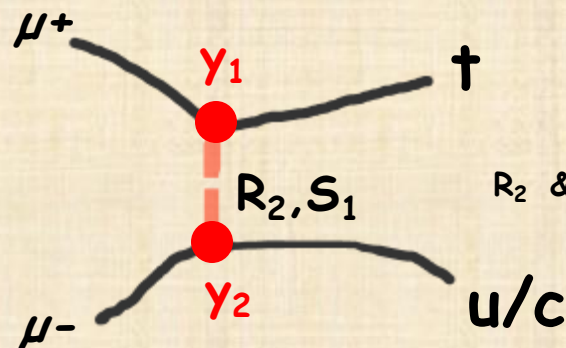


$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} [(\alpha_S Q_S + \alpha_T Q_T) + \text{H.c.}]$$



# - 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

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

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

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

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



# CP test in high- $p_T$ multi-leptons events

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

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

can only arise from EW processes at higher loop orders ...



# CPV multi-leptons events

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

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

$$pp \rightarrow \ell'^- \ell^+ \ell^- + X_3$$

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

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 multi-leptons events

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

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

tull 4-Fermi is “injected” as an EFT toy model

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

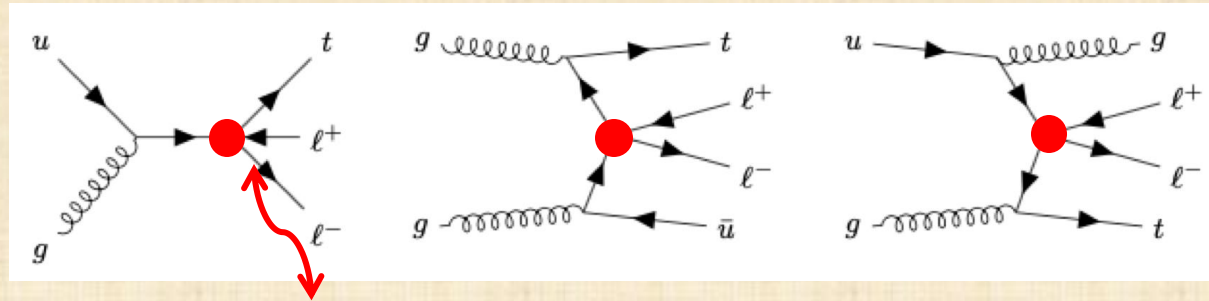
$$Q_{lequ}^{(3)} = (\bar{\ell}^j \sigma_{\mu\nu} e) \epsilon_{jk} (\bar{q}^k \sigma^{\mu\nu} u)$$



# CPV in tri-lepton events from single top production

$$pp \rightarrow \ell^+ \ell^- + t ,$$

$$pp \rightarrow \ell^+ \ell^- + t + j$$



tull/tcII 4-Fermi

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

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

**Signal (e.g.):**

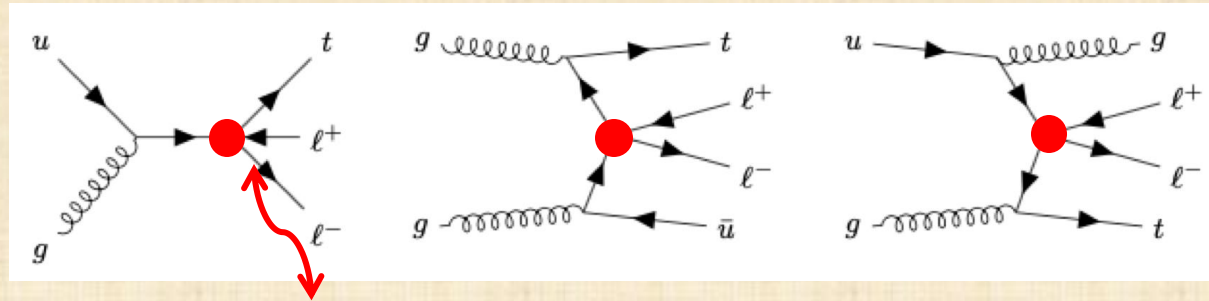
$$pp \rightarrow t \mu^+ \mu^- + X \rightarrow e^+ \mu^+ \mu^- + X \quad (\& \text{ CC channel})$$



# CPV in tri-lepton events from single top production

$$pp \rightarrow \ell^+ \ell^- + t ,$$

$$pp \rightarrow \ell^+ \ell^- + t + j$$



tull/tcII 4-Fermi

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

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

**Signal (e.g.):**

$$pp \rightarrow t \mu^+ \mu^- + X \rightarrow e^+ \mu^+ \mu^- + X \quad (\& \text{CC channel})$$

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

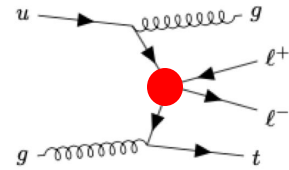
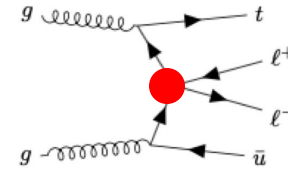
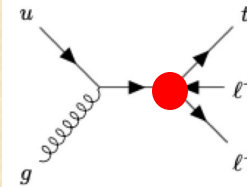


**Dominant SM backg.**

**$pp \rightarrow WZ + X$**   
**followed by W & Z decays ...**

**much smaller contribution from:**  
 **$pp \rightarrow ttW, ttZ, tVV, tt, Z+\text{jets}$**   
**followed by t and V decays ...**

**NP signals**

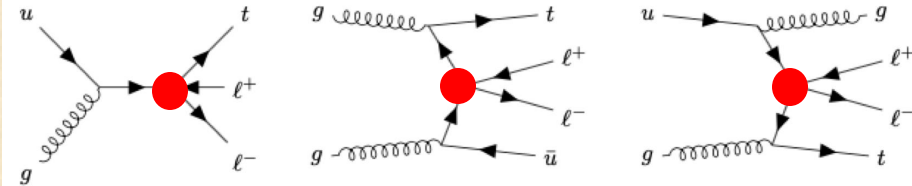




**Dominant SM backg.**

**NP signals**

**$pp \rightarrow WZ + X$**   
followed by W & Z decays ...



**much smaller contribution from:**  
 $pp \rightarrow ttW, ttZ, tVV, tt, Z+\text{jets}$   
followed by t and V decays ...

**CPV part**

$$d\hat{\sigma}(CPV) \propto \epsilon(p_{u_i}, p_{\ell^+}, p_{\ell^-}) \cdot \text{Im}(f_S f_T^*)$$

No interference with SM:

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

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

**$m_{\ell\ell}^{\min}$  - useful discriminating parameter**



# Generic CP-asymmetries for tri-lepton events:

sensitive to tree-level CPV !

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

$$pp \rightarrow e \mu \mu + X$$

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

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

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

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

- Divide into 2 “hemispheres” in  $\mathcal{O}_{CP}$  space and define the  
**P-violating &  $T_N$ -odd** observables (odd under  $t \rightarrow -t$ ):

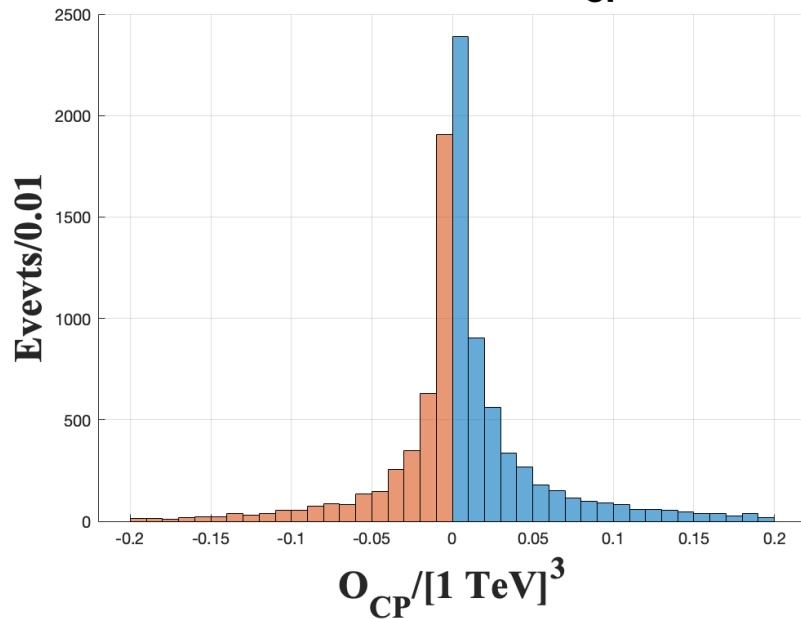


*we are looking for asymmetric  
distributions of  $\mathcal{O}_{CP}$*

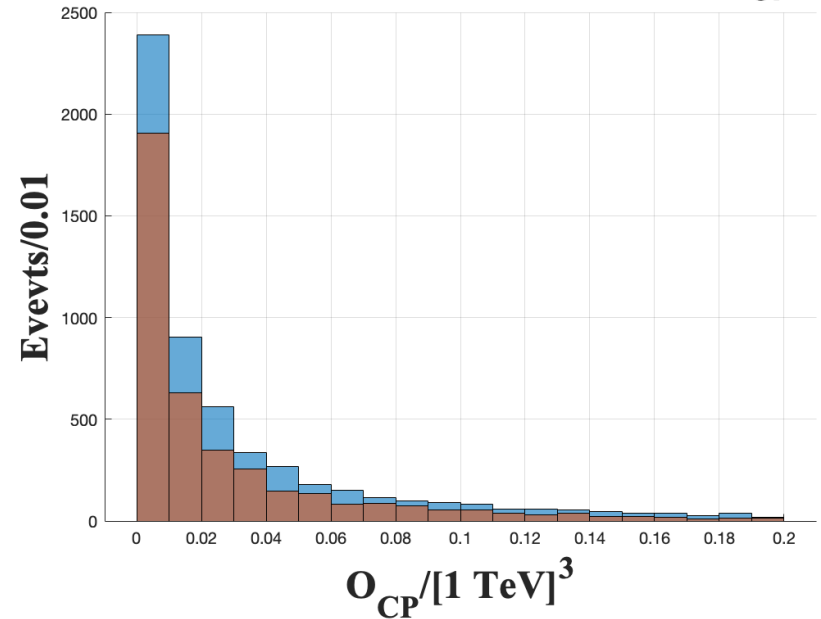
$$A_T \equiv \frac{N(\mathcal{O}_{CP} > 0) - N(\mathcal{O}_{CP} < 0)}{N(\mathcal{O}_{CP} > 0) + N(\mathcal{O}_{CP} < 0)} ,$$

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

**Distribution of  $\mathcal{O}_{CP}$**



**Difference of  $\pm$  distributions of  $\mathcal{O}_{CP}$**



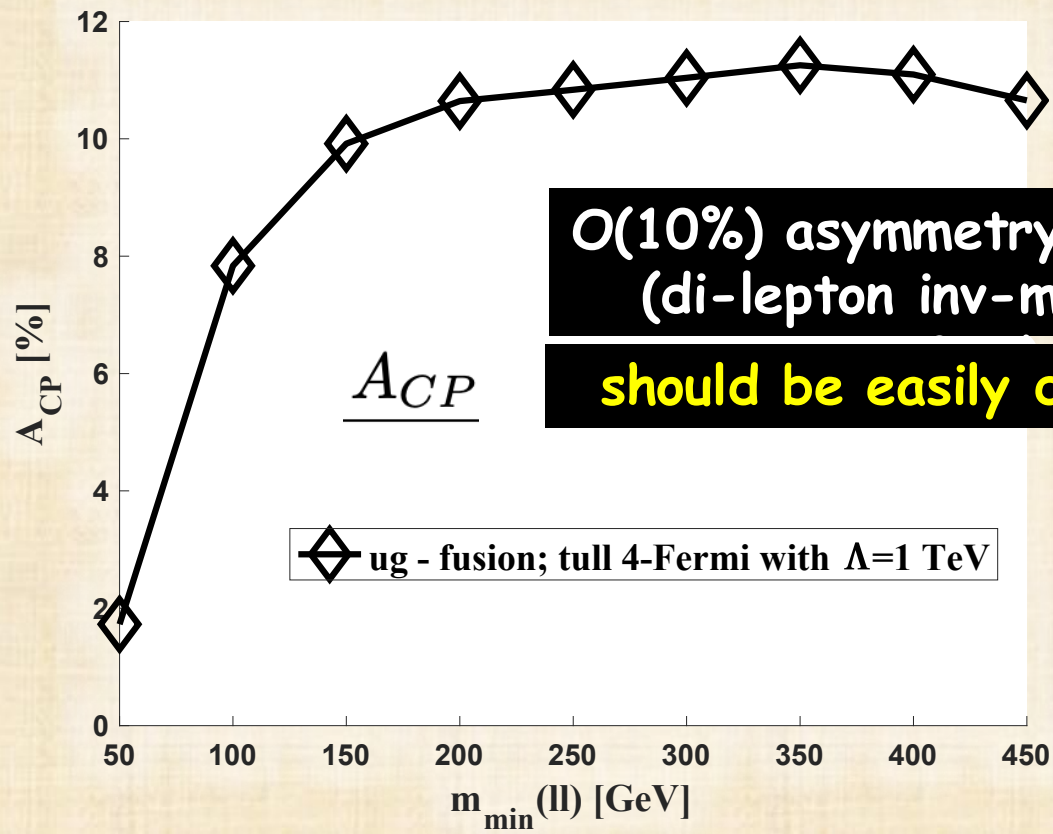


# Results:

$$u g \rightarrow t \mu \mu \rightarrow \mu \mu e$$

( $t\mu\mu\mu$  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)%

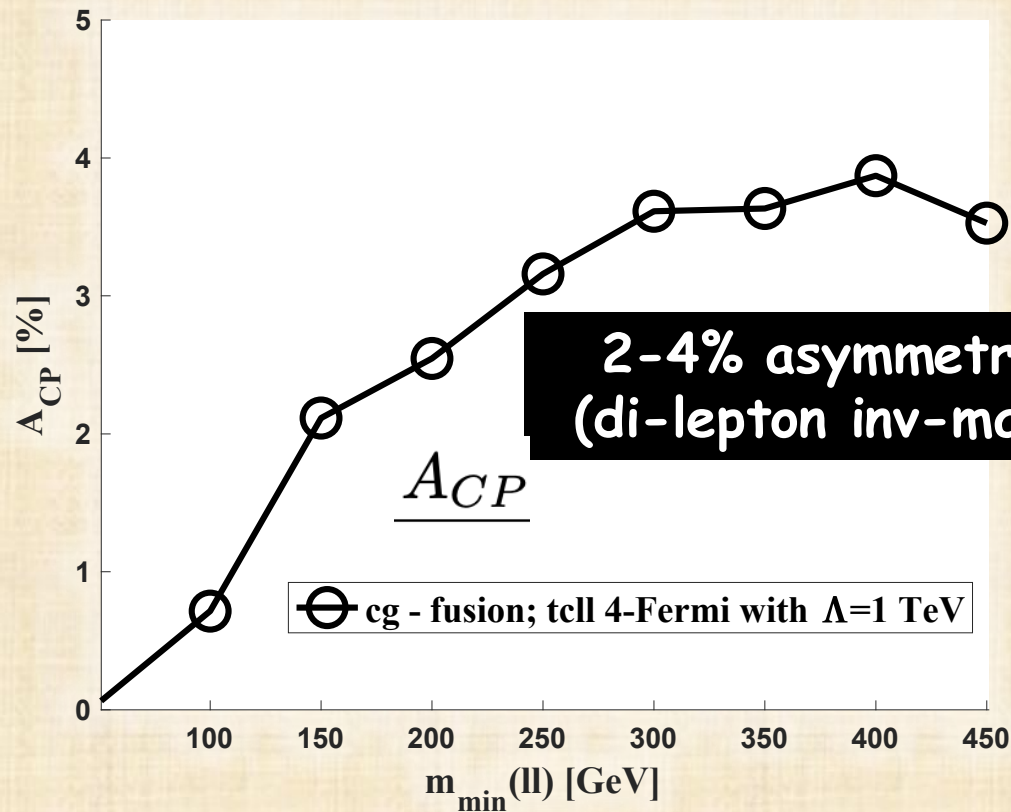




Results:

$c g \rightarrow t \mu \mu \rightarrow \mu \mu e$   
( $t c \mu \mu$  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)%







- Take home message:

If the underlying heavy physics is weakly coupled ...

CPV from interference effects  
(SMXNP)

is NOT accessible @ TeV-scale scattering processes !

Need to look elsewhere ...





- 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  $\propto m_f$  ...)**





- An attractive example:

CPV in inclusive tri-leptons signals @ the LHC

$$pp \rightarrow t \mu^+ \mu^- + X \rightarrow e^+ \mu^+ \mu^- + X \quad (\& \text{ } CC \text{ channel})$$





- An attractive example:

CPV in inclusive tri-leptons signals @ the LHC

$$pp \rightarrow t \mu^+ \mu^- + X \rightarrow e^+ \mu^+ \mu^- + X \quad (\& \text{ } CC \text{ channel})$$

- 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  $L \sim O(1000) \text{ fb}^{-1}$  & TeV scale NP (generating a full 4-Fermi)

should be easily detectable !



Thank you!



# Backups





- 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 bbl 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



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

Scalar

Tensor

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

- *Current sensitivities (bounds):*

$$\Lambda(\text{t}\mu\mu) , \Lambda(\text{t}uee) > \sim \text{O}(0.5 \text{ TeV}) , \text{ Scalar} \\ > \sim \text{O}(1 \text{ TeV}) , \text{ Tensor}$$



# Current sensitivities (bounds ...)

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

**LEP: ( $ee \rightarrow tu, tc$ ):**

**$\Lambda(tuee) > 0.5 - 1.5 \text{ TeV}$**

**(depending on Lorentz structure)**

SBS, Wudka PRD1999

PLB2002 (0210041) ; EPJC2011 (1102.4455)

**LHC ( $pp \rightarrow tt$  followed by  $t \rightarrow \mu\mu + \text{jet}$ ):**

**$\Lambda(tu\mu\mu) \sim \Lambda(tuee) > \sim 0.4 - 1 \text{ TeV}$**

**(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)



# multi-leptons signals - a window to NP

$$\begin{aligned}
 (1\ell) : & pp \rightarrow \ell^\pm + n \cdot j_b + m \cdot j + \cancel{E}_T + X , \\
 (2\ell) : & pp \rightarrow \ell'^+ \ell''^- + n \cdot j_b + m \cdot j + \cancel{E}_T + X , \\
 (3\ell) : & pp \rightarrow \ell'^\pm \ell^+ \ell^- + n \cdot j_b + m \cdot j + \cancel{E}_T + X , \\
 (4\ell) : & pp \rightarrow \ell'^\pm \ell''^\mp \ell^+ \ell^- + n \cdot j_b + m \cdot j + \cancel{E}_T + X
 \end{aligned}$$

- Rich & clean signals in the hadronic environment of the LHC
- Excellent test ground for NP (e.g., in  $pp \rightarrow t\bar{t}V, t\bar{t}H, t\bar{t}V, t\bar{t}t\bar{t} \dots$ ):
  - 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  $t\bar{t}l\bar{l}$  contact interactions”  
NPB980 (2022), 115849 [arxiv: 2111.13711](#), Afik(CERN), SBS(Technion), Pal(UCR), Soni(BNL),  
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“New flavor physics in di- and trilepton events from single-top production at the LHC and beyond”,  
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“Searching for New Physics with  $b\bar{b}l\bar{l}$  contact interactions”,  
PLB807 (2020), 135541, [arxiv: 1912.00425](#), Afik, SBS, Cohen, Rozen(Technion)



# Constructing CP-asym. for tree-level CPV

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

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

## CPV @ tree-level (no FSI phases: $\delta=0$ ) !

- To probe tree-level CPV one needs  $T_N$ -odd observables (  $T_N : \dagger \rightarrow -\dagger$  )  
=>  $T_N$ -odd observables do not vanish when FSI phases are zero ( $\delta = 0$ )

$T_N$ -

asymmetries based on triple-products (TP)

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



# CPV ~~BF~~ multi-leptons events: Constructing CP-asym from TP's

- Divide into 2 "hemispheres" in  $\mathcal{O}_{\text{CP}}$  space and define the **P-violating &  $T_N$ -odd** observables (odd under  $\dagger \rightarrow -\dagger$ ):

Recall:

$pp \rightarrow t \mu^+ \mu^- \rightarrow e^+ \mu^+ \mu^- + X$  & CC channel

$$\begin{aligned} \mathcal{O}_{\text{CP}} &= \vec{p}_{\ell'^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \\ \overline{\mathcal{O}_{\text{CP}}} &= \vec{p}_{\ell'^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}) \end{aligned} \quad (l' = e, l = \mu)$$

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



# CP ~~is~~ multi-leptons events: Constructing CP-asym from TP's

- Divide into 2 "hemispheres" in  $\mathcal{O}_{\text{CP}}$  space and define the **P-violating &  $T_N$ -odd** observables (odd under  $\dagger \rightarrow -\dagger$ ):

Recall:

$pp \rightarrow t \mu^+ \mu^- \rightarrow e^+ \mu^+ \mu^- + X$  & CC channel

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

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

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:

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



Recup:

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

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

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

NP (CPV)

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

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

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



## 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:

$$Q_{\phi ud} = i \left( \tilde{\phi}^\dagger D_\mu \phi \right) (\bar{u} \gamma^\mu d) ,$$

$$Q_{\ell edq} = (\bar{\ell}^j e) (\bar{d} q_j) ,$$

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

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

$$Q_{quqd}^{(1)} = (\bar{q}^j u) \epsilon_{jk} (\bar{q}^k d) ,$$

$$Q_{quqd}^{(8)} = (\bar{q}^j T^a u) \epsilon_{jk} (\bar{q}^k T^a d) ,$$

However, these opts do not conserve the  $G_0$  &  $G_t$  sym. So that there interference effects with the SM are suppressed by powers of  $m/\Lambda$  ! ...



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  $\text{Im}(f_S f_T^*) = 0.25$ ,  $\Lambda = 1$  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
$\sigma_{NP}(pp_{ug} \rightarrow \ell'^- \ell^+ \ell^- + X)$	12.43	11.65	10.84
$\sigma_{NP}(\bar{u}g \rightarrow \ell'^+ \ell^- \ell^+ + X)$	0.98	0.87	0.76
$\sigma_{NP}(pp_{cg} \rightarrow \ell'^- \ell^+ \ell^- + X)$	0.37	0.32	0.27
$\sigma_{NP}(pp_{\bar{c}g} \rightarrow \ell'^+ \ell^- \ell^+ + X)$	0.37	0.32	0.27
$\sigma_{SM}(pp \rightarrow \ell'^- \ell^+ \ell^- + X)$	0.33	0.11	0.05
$\sigma_{SM}(pp \rightarrow \ell'^+ \ell^- \ell^+ + X)$	0.56	0.21	0.10



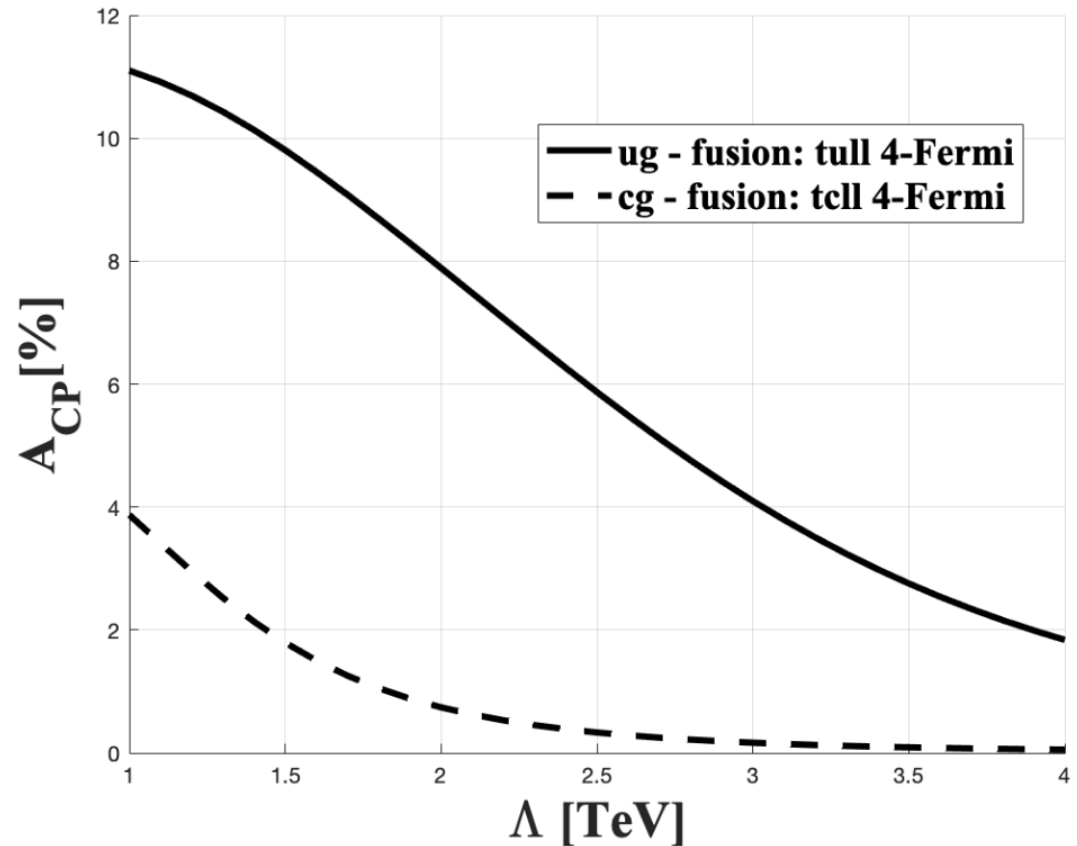


FIG. 1: The expected CP-asymmetry  $A_{CP}$ , as a function of the NP scale  $\Lambda$ , for  $m_{min}(\ell\ell) = 400$  GeV and  $\text{Im}(f_S f_T^*) = 0.25$ . Results are shown for the cases of NP from  $ug$  and  $cg$ -fusion, which arise from the *tull* and *tccl* 4-Fermi operators, respectively.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



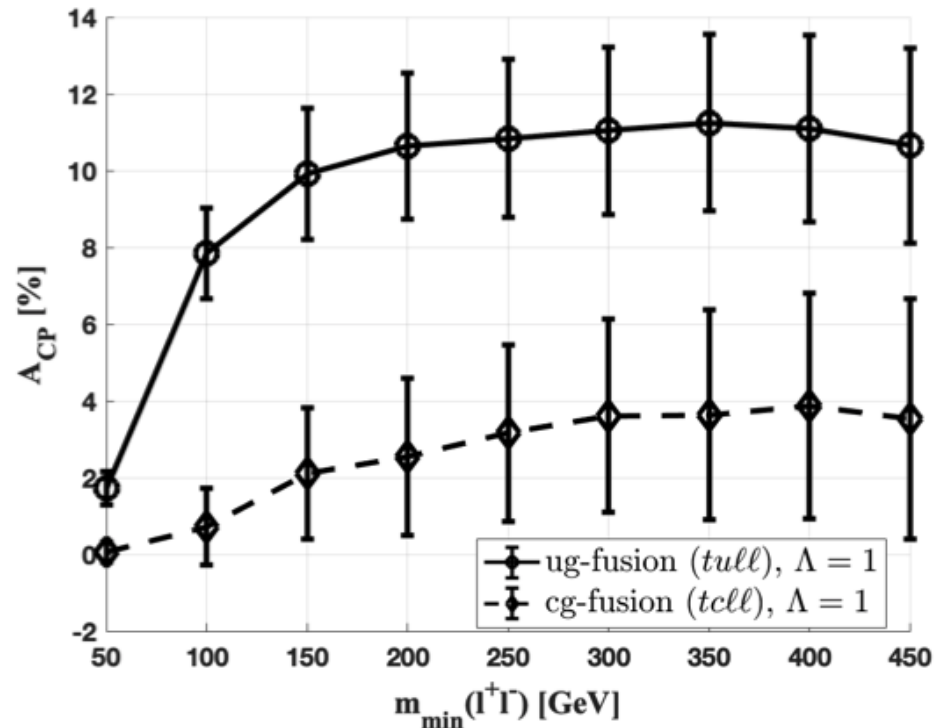


FIG. 2:  $A_{CP}$  as a function of  $m_{\min}(\ell^+\ell^-)$ , for  $\Lambda = 1$  TeV,  $\text{Im}(f_S f_T^*) = 0.25$  and including the SM background. The dependence of the asymmetry on  $\Lambda$  is given in Appendix B. The error bars represent the expected statistical uncertainty with an integrated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



# Axis dependent asymmetries

$$\mathcal{O}_{\text{CP}}^i = p_a^i \cdot (\vec{p}_b \times \vec{p}_c)^i$$



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

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  $t\ell\ell$  and the  $t\bar{c}\ell\ell$  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  $A_T^i$ ,  $\bar{A}_T^i$ ,  $A_{CP}^i$  ( $i = x, y, z$ ), for the tri-lepton events  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- + X$  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,  $\text{Im}(f_S f_T^*) = 0.25$  and the dominant SM background from  $pp \rightarrow ZW^{\pm} + X$  is included. The cases where an asymmetry is  $\lesssim 0.5\%$  is marked by an X.

	$A_{CP}$	$A_{CP}^x$	$A_{CP}^y$	$A_{CP}^z$
$ug$ -fusion:	11.1%	8.1%,	8.1%	X
$cg$ -fusion:	3.9%	X	X	5.6%

	$A_T$	$A_T^x$	$A_T^y$	$A_T^z$
$ug$ -fusion:	16.4%	11.3%,	10.7%	3.8%
$cg$ -fusion:	3.1%	5.0	X	X

	$\bar{A}_T$	$\bar{A}_T^x$	$\bar{A}_T^y$	$\bar{A}_T^z$
$ug$ -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  $g/\Lambda$



# EFT-validity

Two “measures” to consider:

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

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

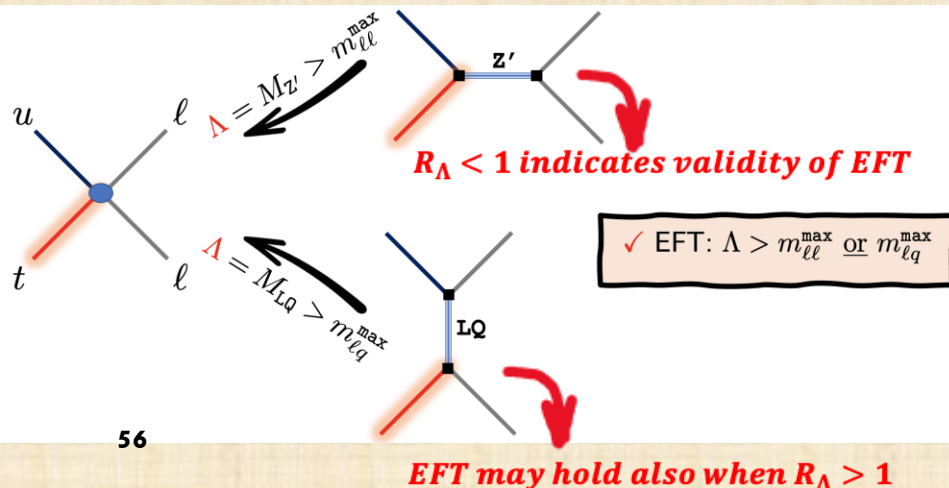
Addresses the validity of the specific calculation within the EFT framework – depends on the details of the underlying heavy physics and the process at hand

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

The EFT expansion param – the expansion of the effective Lagrangian at leading order in  $g/\Lambda$

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

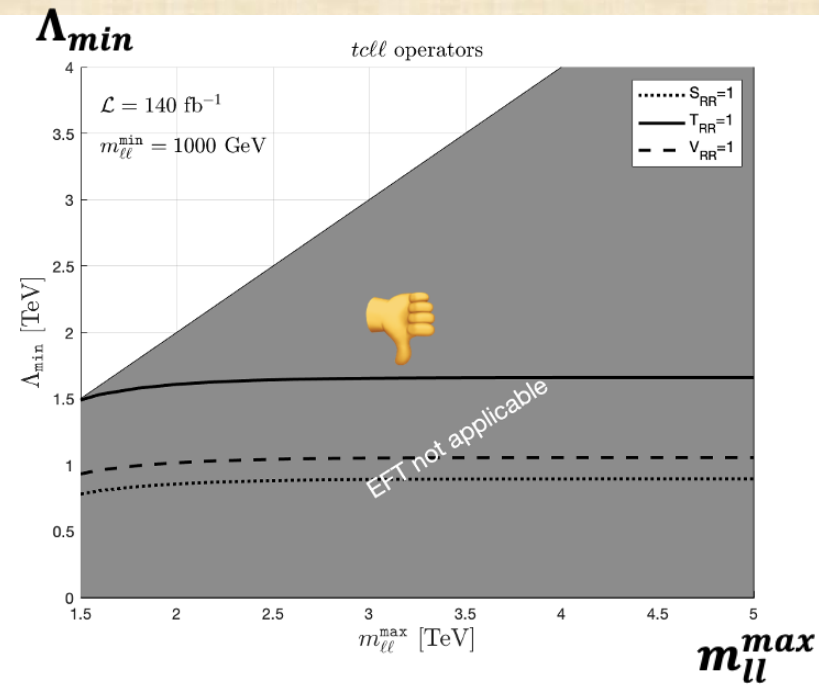
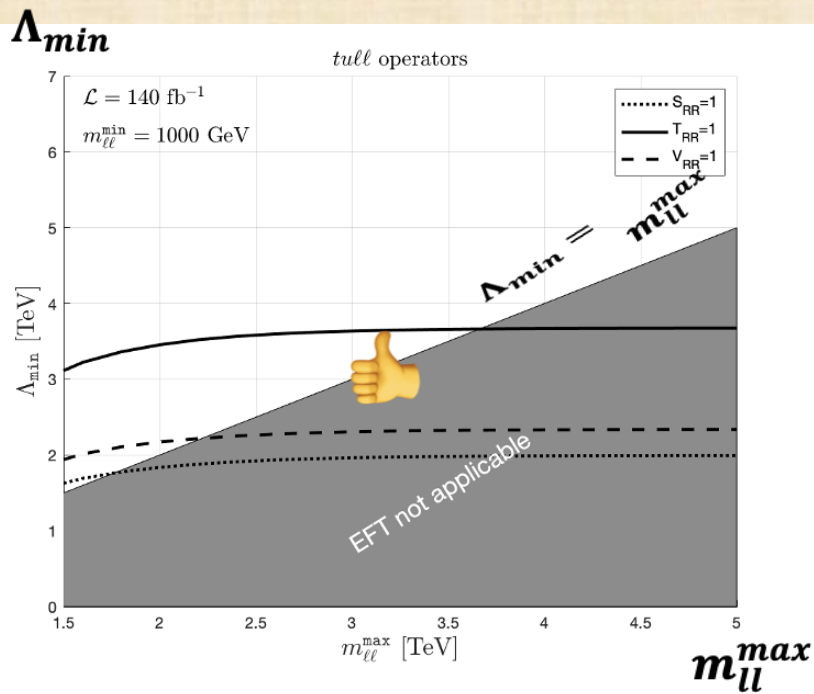
$R_{\Lambda/g} < 1$  naively indicate the **regime of validity** of the EFT prescription & the potential effects from higher dim opts can be assessed from  $R_{\Lambda/g}$





# EFT-validity

Consider bounds ( $\Lambda_{min}$ ) obtained on the scale  $\Lambda$  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:

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

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

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

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

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

CC channel



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

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

- 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

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

odd under P & under  $T_N (\dagger \rightarrow -\dagger)$

and

$$\begin{aligned} C(\mathcal{O}_{CP}) &= +\overline{\mathcal{O}_{CP}}, & C(\overline{\mathcal{O}_{CP}}) &= +\mathcal{O}_{CP}, \\ CP(\mathcal{O}_{CP}) &= -\overline{\mathcal{O}_{CP}}, & CP(\overline{\mathcal{O}_{CP}}) &= -\mathcal{O}_{CP} \end{aligned}$$

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

dot-products

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

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 ( $T_N : \dagger \rightarrow -\dagger$ )

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

- type:

$T_N -$

odd

$T_N -$

even

- CP asymmetry:

$$A_{CP} \propto \cos \Delta\delta \sin \Delta\phi$$

$$A_{CP} \propto \sin \Delta\delta \sin \Delta\phi$$

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

- phases:

Only CP-odd

Both CP-odd & CP-even  
(strong

- Sensitivity:

tree-level CPV

phase)  
strong phase from FSI  
typically higher order effect ...

- Expected size:

$O(10\%)$

$O(0.1\%)$



Constructing CP-asym. For tree-level CPV

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

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

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

- 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:  $\Delta\delta=0$ )



# Constructing CP-asym. For tree-level CPV

- Divide into 2 "hemispheres" in  $\mathcal{O}_{\text{CP}}$  space and define the **P-violating &  $T_N$ -odd** observables (odd under  $\dagger \rightarrow -\dagger$ ):

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

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

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

$$A_T \propto \sin(\Delta\delta + \Delta\phi)$$

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

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

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

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



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

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



# Constructing CP-asym. For tree-level CPV

- Divide into 2 "hemispheres" in  $\mathcal{O}_{\text{CP}}$  space and define the **P-violating &  $T_N$ -odd** observables (odd under  $\dagger \rightarrow -\dagger$ ):

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

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

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

$$A_T \propto \sin(\Delta\delta + \Delta\phi)$$

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

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

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

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:

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



$$\mathbf{V} \propto \text{Im}(M_1 M_2^*)$$

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

PDF's

$$\mathbf{U} \propto \text{Re}(M_1 M_2^*)$$

- The resulting CP asymmetry:

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

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

"conventional" CPV term:  
CP-odd &  $\mathcal{T}_N$ -odd  
( $\text{CPT}_N = \text{CPT}$ )

initial state not self conjugate:  
CP-even &  $\mathcal{T}_N$ -odd  
( $\text{CPT}_N \neq \text{CPT}$ )

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



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 &  $\mathcal{T}_N$ -odd

CP-even &  $\mathcal{T}_N$ -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: Constructing CP-asym from TP's

- Divide into 2 "hemispheres" in  $\mathcal{O}_{\text{CP}}$  space and define the **P-violating &  $T_N$ -odd** observables (odd under  $\dagger \rightarrow -\dagger$ ):

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

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

$$A_T \propto \sin(\Delta\delta + \Delta\phi)$$

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

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

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

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

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:

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



# CPV multi-leptons events

- The resulting asymmetries:

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

“conventional” CPV term

initial state not self-conjugate

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

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

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

PDF's



# CPV multi-leptons events

- The resulting asymmetries:

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

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

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

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

"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

$$V \propto \text{Im} (M_1 M_2^\dagger)$$

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

PDF's



## 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  $\Delta\delta \rightarrow 0$ ) if same PDF's of incoming particles ( $f_a f_b = f_{\bar{a}} f_{\bar{b}}$ )
- $A_{CP} \propto \sin \Delta\phi$  when  $\Delta\delta \rightarrow 0$ , even when  $f_a f_b \neq f_{\bar{a}} f_{\bar{b}}$
- Thus, when  $\Delta\delta \ll \Delta\phi$ ,  $A_{CP}$  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  
( $\alpha_k$  = Wilson coef. &  $\phi_k$  = CPV phases)

$$\mathcal{M}_{i \rightarrow f} = M_{\text{SM}} + \sum_k \frac{|\alpha_k|}{\Lambda^2} M_k e^{i\phi_k} + \dots$$

- 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**

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

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

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

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

no SMxNP interference, **with** a SM contribution

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

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

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

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

no SMxNP interference, **without** a SM contribution

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

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



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

$$v_E = v \text{ or } v_E = E$$



$$CPT = CPT_N \text{ if no FSI}$$

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

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

\* If no FSI ( $\tau$  Hermitian),  
then:

$$\tau_{if} = \tau_{fi}^*$$

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

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



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

**Modulus of  $\tau_{if}$  is invariant under  $T_N$  !**

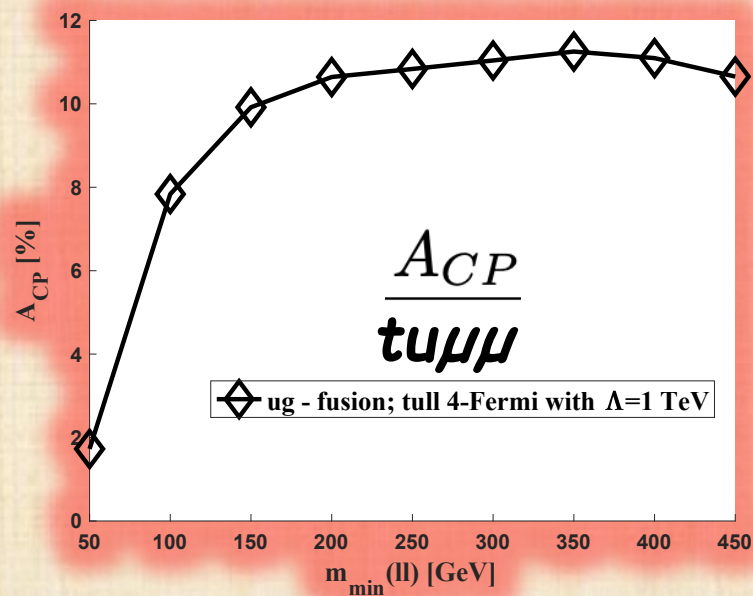


Results:

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

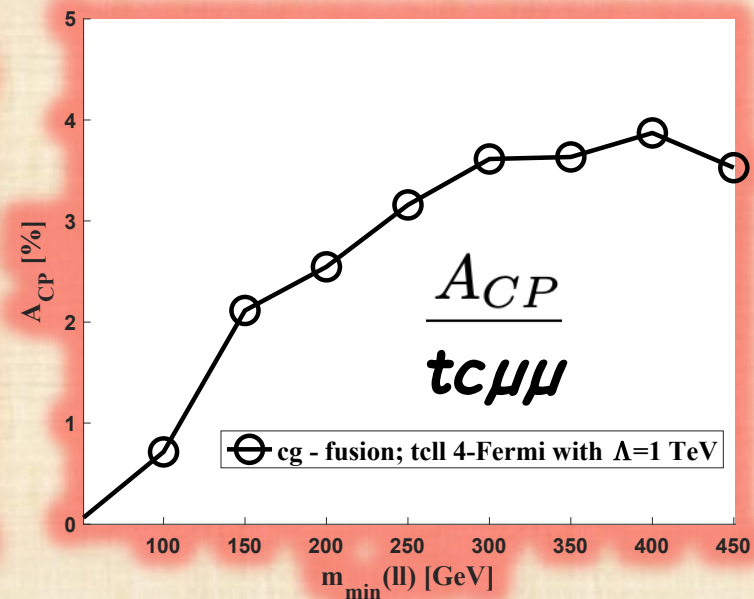
$c g \rightarrow t \mu \mu \rightarrow \mu \mu e$   
( $t c \mu \mu$  4-Fermi)

	$u g$ -fusion: $\Lambda = 1(2)$ TeV	$c g$ -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  $m_{\parallel}$  !**

(di-lepton inv-mass > 150 GeV)



**2-4% asymmetry at high  $m_{\parallel}$  !**

(GeV)