CP tests for high-p_T multileptons

Moriond 2023

Electroweak Interactions & Unified Theories

Flavour Physics
20/3/2023

Based on:

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

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

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outline

Try to motivate an inclusive search for CP-violation (CPV) in multi-leptons events @ the LHC

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

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

-How to look for CPV ?
-Where to look for CPV ?
-What to look for ?

Emphasizing the subtleties …

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)
    - <u>Examples:</u>
      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, VV, VVV …):
  - 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)

CPV ☞ multi-leptons events

- Constructing generic tests of CPV (BSM) in multi-lepton processes: focus on tri-lepton events
  (applies also to 4-leptons events …)

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

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

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

- Note: Negligible (un-observed) SM Background to CP !

sizeable, say O(1%) 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)

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

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

CP studies @LHC are more complicated - initial state is NOT self-conjugate

We develop a rigorous formula for testing CPV in an LHC-like environment

i.e., provide a correction to the CP "master" formula

CPV ☞ multi-leptons events

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

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

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

- 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

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

CC channel

CPV ☞ multi-leptons events

based on CPT theorem
See e.g., "CP-violation in top physics"
Atwood, Bar-Shalom, Eilam, Soni, Phys.Rep. 347, 1 (2001)

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

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

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

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

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- required 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%)

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- 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

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

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 $t \to -t$):

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

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

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

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

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

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

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

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

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

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

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:

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

CPV ☞ multi-leptons events

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

- The resulting CP asymmetry:

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

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

PDF's

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

"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)

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

CPV ☞ multi-leptons events

- The resulting CP asymmetry:

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

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

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

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

CPV ☞ multi-leptons events

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:

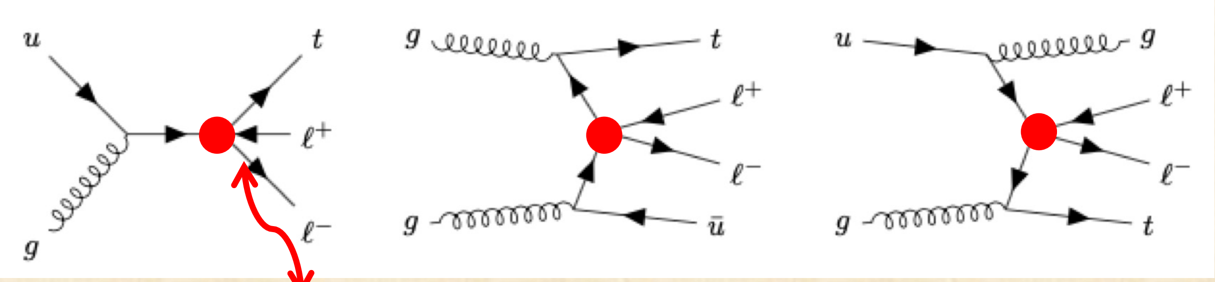
- "contamination" to the CPV measurement can arise if initial state is not self-conjugate
- at the tree-level: $\Delta\delta = 0$ (no FSI) $\Rightarrow$ regardless of initial state properties:

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

CPV in tri-lepton events from single top production

NP: a $tu_i ll$ 4-Fermi "toy model" from EFT framework

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



tull/tcll 4-Fermi

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

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

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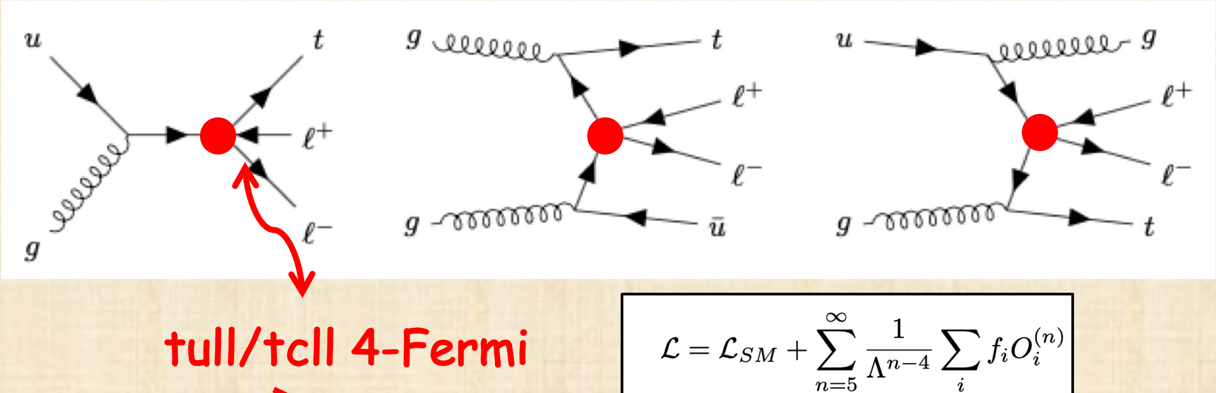

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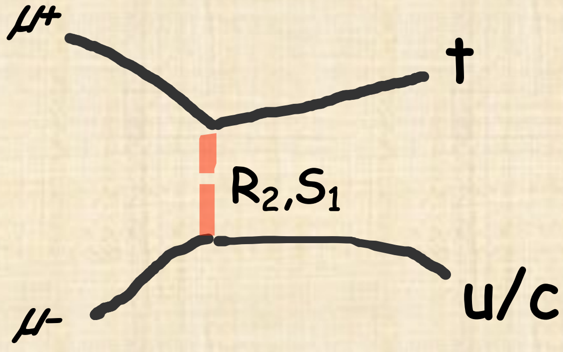
This channel has interesting implications also for generic BSM searches of new heavy states around the TeV-scale which generate top-leptons 4-Fermi

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

Matching – possible underlying BSM scenarios

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



4-Fermi contact terms:
(tu)(μ+ μ-) and/or (tc)(μ+ μ-)

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

$$\mathcal{L}^{\rm dim.6}_{tu\mu\mu} = \frac{1}{\Lambda^2}\left[f_S\left(\bar{\mu}_R \mu_R\right)\left(\bar{t}_R u_R\right) + f_T\left(\bar{\mu}_R \sigma_{\mu\nu} \mu_R\right)\left(\bar{t}_R \sigma_{\mu\nu} u_R\right)\right] + h.c$$

LQ's underlying UV physics yields specific proportion of Wilson coefficients, which we used as a benchmark for the CP study …

Collider signals of CPV in tri-lepton events

underlying CPV process:

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

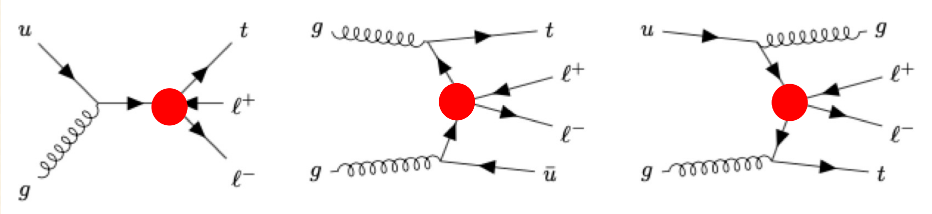
(& CC channel)

NP & CPV-phases:

$tu\mu\mu/tc\mu\mu$ 4-Fermi contact terms

Dominant SM backg.

NP signals



$pp \to WZ + X$

followed by W & Z decays …

much smaller contribution from:

$pp \to ttW, ttZ, tVV, tt, Z$+jets

followed by t and V decays …

Dominant SM backg.

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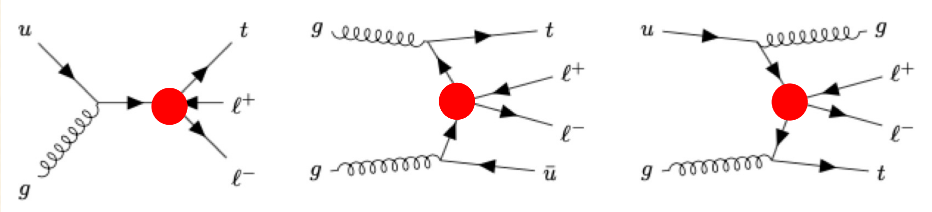
NP signals



guided by TeV-scale LQ's: $\mathrm{Im}\left(f_S \cdot f_T^\star\right) = 0.25$

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

CPV

No interference with SM:

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

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

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

Results:

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

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

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

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

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

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}

Use m_{ll} dependence to gain sensitivity to CP ...

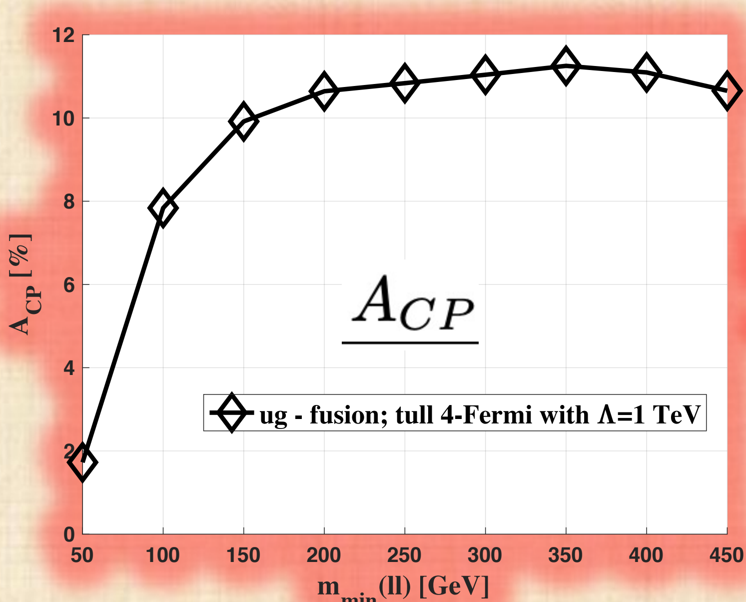
Results:

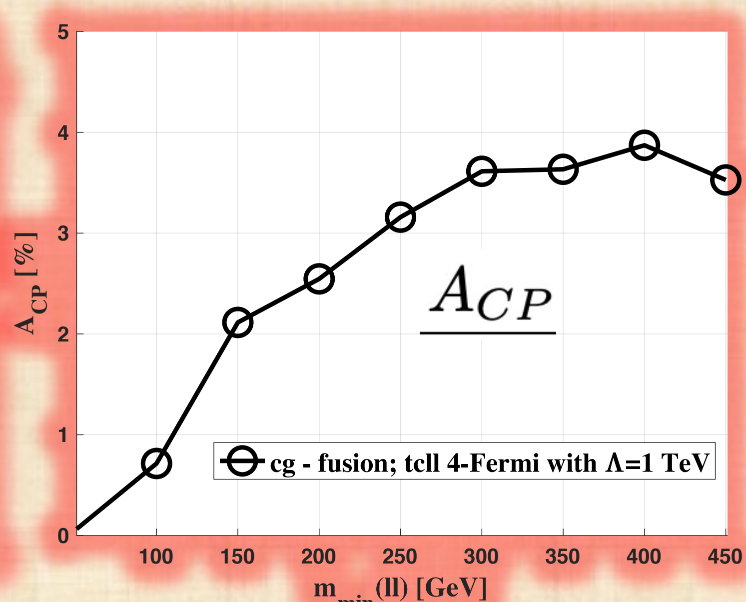
$u\,g \to t\,\mu\mu \to \mu\mu e$ (tu$\mu\mu$ 4-Fermi)	$c\,g \to t\,\mu\mu \to \mu\mu e$ (tc$\mu\mu$ 4-Fermi)

	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

- Multi-leptons signals provide an excellent & rich testing ground of NP:

  flavor physics, lepton flavor universality, CP-Violation …

- We have constructed useful CP asymmetries for measuring CP-violation in multi-lepton events:

  introducing 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

  (particularly useful for CP studies @LHC …)

SUMMARY / CONCLUSION

- These asymmetries have also several new & unique features, that make them particularly useful for searching for CP-violation at high-energy colliders

  - Our CP tests use <u>only</u> 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

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 tull 4-Fermi

Thank you

Backups

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)

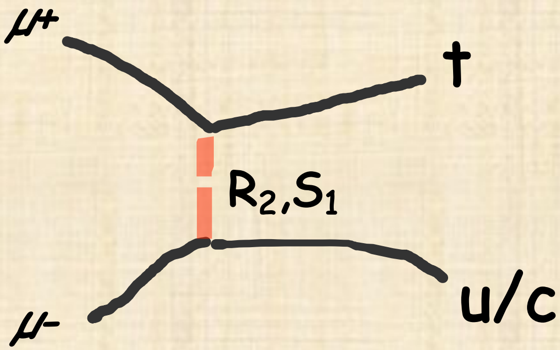
LHC (pp → tt followed by t → μμ + jet):
Λ(tuμμ) ~ Λ(tuee) > ~ 0.4 – 1 TeV
(depending on Lorentz structure)

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)

Matching – possible underlying BSM scenarios

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

Yukawa-like couplings to quark-lepton pair:



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

$$\mathcal{L}^{\rm dim.6}_{tu\mu\mu} = \frac{1}{\Lambda^2}\left[f_S\left(\bar{\mu}_R\mu_R\right)\left(\bar{t}_R u_R\right) + f_T\left(\bar{\mu}_R\sigma_{\mu\nu}\mu_R\right)\left(\bar{t}_R\sigma_{\mu\nu}u_R\right)\right] + h.c$$

4-Fermi contact terms:
$(tu)(\mu^+\mu^-)$ and/or $(tc)(\mu^+\mu^-)$

Matching – possible underlying BSM scenarios

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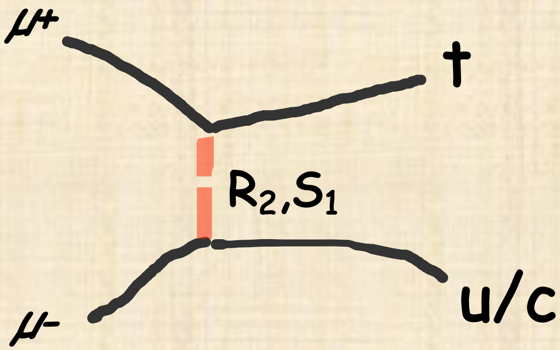

4-Fermi contact terms:
(tu)(μ+ μ-) and/or (tc)(μ+ μ-)

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$$\mathcal{L}^{\text{dim.6}}_{tu\mu\mu} = \frac{1}{\Lambda^2}\left[f_S\,(\bar{\mu}_R\mu_R)\,(\bar{t}_R u_R) + f_T\,(\bar{\mu}_R\sigma_{\mu\nu}\mu_R)\,(\bar{t}_R\sigma_{\mu\nu}u_R)\right] + h.c$$

$$f_S = 4 f_T = \frac{y_1 y_2^\star}{2M_{LP}^2}$$

Scalar Tensor

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

$$\mathrm{Im}\,(f_S \cdot f_T^\star) = 0.25$$

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

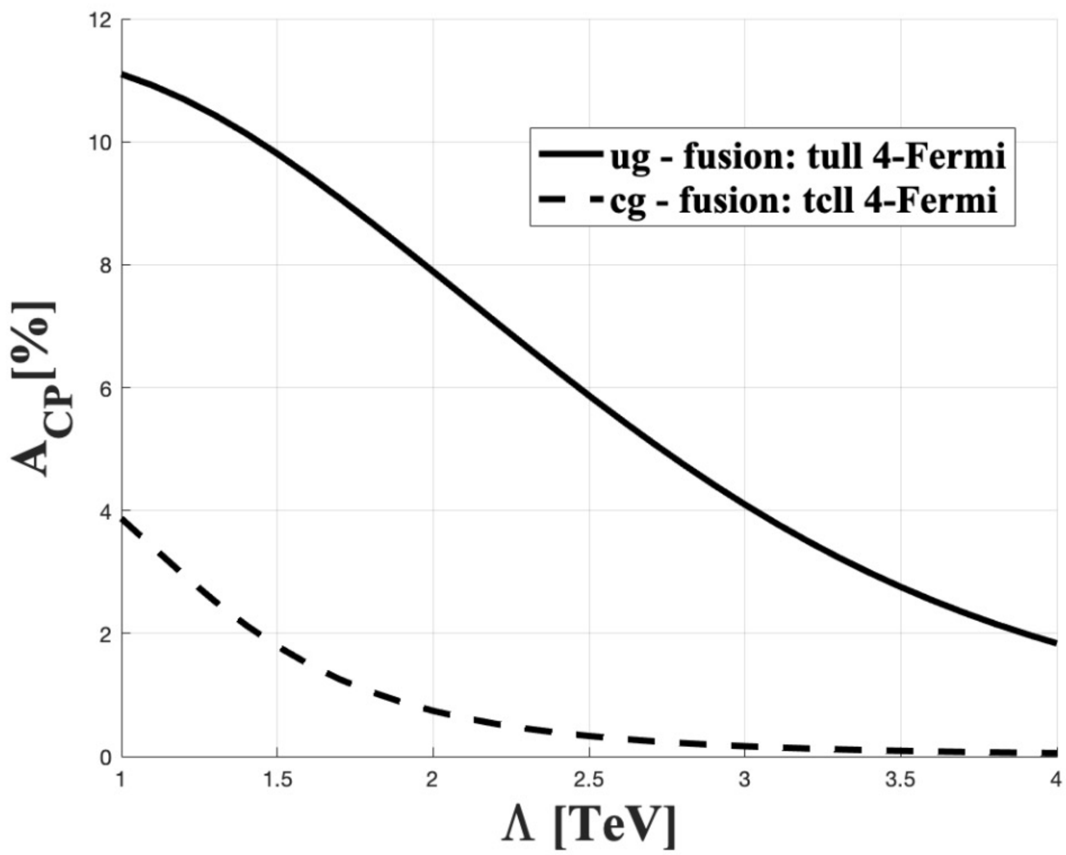

FIG. 1: The expected CP-asymmetry A_{CP}, as a function of the NP scale Λ, for $m_{min}(\ell\ell) = 400$ GeV and $\mathrm{Im}\,(f_S f_T^\star) = 0.25$. Results are shown for the cases of NP from ug and cg-fusion, which arise from the $tu\ell\ell$ and $tc\ell\ell$ 4-Fermi operators, respectively. The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

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

CPV ☞ multi-leptons events

- Consider CPV in tri-leptons production:

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

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

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

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

CC channel

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

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

- Differential CSX's:

$$d\hat{\sigma} = U + V \cdot \mathcal{O}_{\rm CP} \cdot \sin(\Delta\delta + \Delta\phi)$$
$$d\hat{\sigma} = U + V \cdot \overline{\mathcal{O}_{\rm CP}} \cdot \sin(\Delta\delta - \Delta\phi)$$