Tests of CP violation in multi-lepton signals at the LHC

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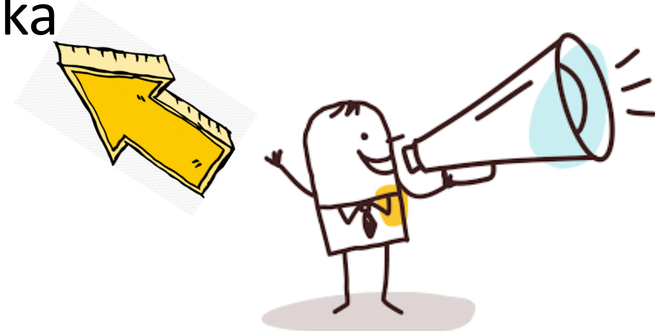

(presenter)

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CP violation & new physics

SM sources:

- CKM matrix.
- PMNS matrix.

small effects

… and the $\tilde{F} \cdot F$ term – apparently zero.

A good window into possible new physics (NP)

We 

stronger CPV: there's no us without it (BAoU)

Many forms of NP readily supply the need.

CP and T_N

- I assume CPT invariance holds.
- Unitarity of the $\mathcal{S}$ matrix:

$$\langle f|\mathcal{T}|i\rangle - \langle i|\mathcal{T}|f\rangle^* = i\underbrace{\sum_n \langle n|\mathcal{T}|f\rangle^* \langle n|\mathcal{T}|i\rangle}_{\text{Final state interactions (FSI)}} \qquad (\mathcal{S} = \mathbb{1} + i\mathcal{T})$$

$\mathcal{T}$ is Hermitian up-to FSI corrections.

useful for characterizing some CPV effects – no fundamental significance

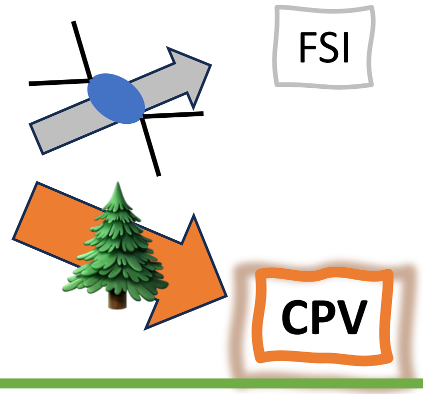
Define ‘naïve’ time reversal:

$$T_N : t \to -t$$

If

$$\mathcal{O} = \mathcal{O}(\underbrace{\mathbf{p}_f ,\, \mathbf{s}_f}_{\text{Final state momenta \& spin}}) \xrightarrow{T_N} -\mathcal{O}$$

$$\langle \mathcal{O} \rangle \neq 0$$



$$\langle \mathcal{O} \rangle = \frac{\int_R d\sigma\, \mathcal{O}}{\int_R d\sigma}$$

T_N – invariant phase-space region

A promising LHC process

Of the many final states,

$$p\,p \to n\,\ell + X$$

High p_T

are useful for measuring SM properties and NP searches.

Also useful in CPv searches. Will look at

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

$$(\ell,\, \ell' = e,\, \mu\ \tau)$$

δ_i: CP even (FSI)
ϕ_i: CP odd

CP

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

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

Parton-level amplitudes

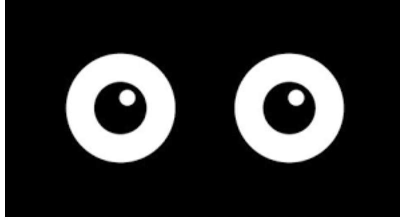
$$\Delta\delta = \delta_1 - \delta_2$$
$$\Delta\phi = \phi_2 - \phi_2$$

T_N even

T_N odd: $V' = V\,\mathcal{O}_{CP}$, $\overline{V}' = V\,\overline{\mathcal{O}_{CP}}$ (V: T_N-even)

Parton-level cross sections

$$d\hat\sigma_{ab\to\ell'^-\ell^+\ell^-} = W + U\cos(\Delta\delta+\Delta\phi) + V'\sin(\Delta\delta+\Delta\phi)$$
$$d\bar{\hat\sigma}_{\bar a\bar b\to\ell'^+\ell^-\ell^+} = W + U\cos(\Delta\delta-\Delta\phi) + \overline{V}'\sin(\Delta\delta-\Delta\phi)$$



T_N odd observables

$\mathcal{O}$

CP-odd $\Rightarrow$ $\langle \mathcal{O} \rangle \propto \cos\Delta\delta \sin\Delta\phi$

CP-even initial state

CP-even $\Rightarrow$ $\langle \mathcal{O} \rangle \propto \sin\Delta\delta \cos\Delta\phi$

Sensitive to **tree-level** CPv

O(10%) CP asymmetries

Requires CP-even phases (FSI)
→ higher-order effect
→ O(0.1%) CP asymmetries

Chose

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

that are T_N-odd, and

$$\mathcal{O}_{\text{CP}} \overset{\text{CP}}{\Longleftrightarrow} -\overline{\mathcal{O}_{\text{CP}}}$$

Construct the T_N-odd asymmetries

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

And an observable sensitive to CPv :

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

May be affected by CP-even contributions.

More explicitly:

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

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

$$\mathcal{I}_{ab} \propto \frac{\int_R d\Phi \cdot \overbrace{f_a f_b}^{\text{PDF's}} V\, |\mathcal{O}_{\rm CP}|}{\int_R d\Phi \cdot f_a f_b \cdot (W + U \cdot \cos(\Delta\delta + \Delta\phi))}$$

PDF's

T_N even phase-space region

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

'Bona fide' CPv contribution

Vanishes if $\Delta\phi = 0$

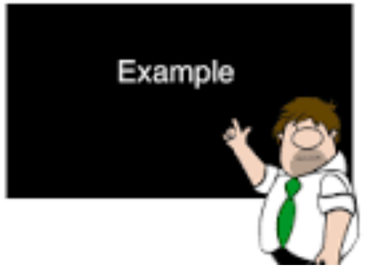
Insensitive to small CP-even phases $\Delta\delta$

Correction when initial state is not CP-even (*e.g.* LHC)

Survives even if $\Delta\phi = 0$

Suppressed for small CP-even phases $\Delta\delta$ (no resonances)

Example



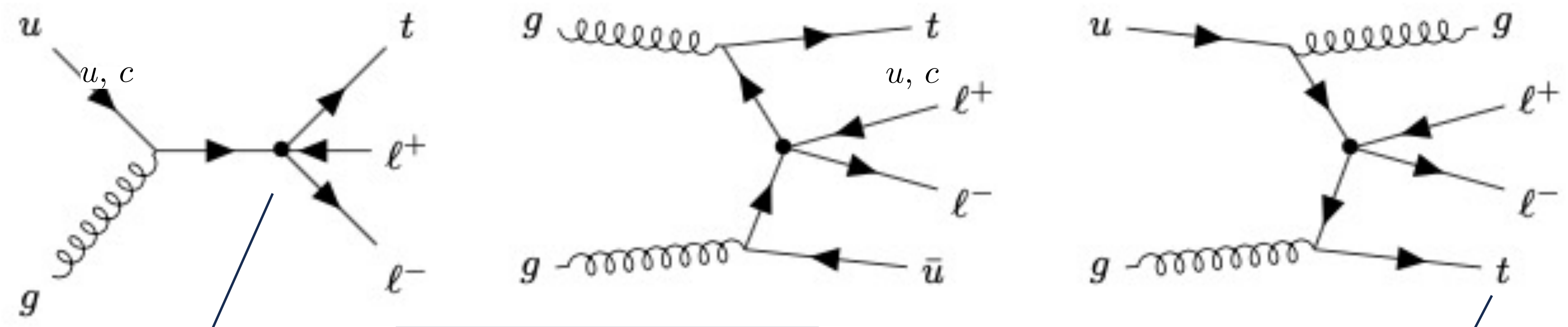
New physics:

- Decoupling
- Weakly coupled
- Not directly observed

Can be generated by
$S_1 \sim (3,1,-1/3)$
$R_2 \sim (3,2,7/6)$
leptoquarks, in which case
$| f_{\tt S} | = 4 \, | f_{\tt T} |$

$$\mathcal{L} = \mathcal{L}_{\tt SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i f_i O_i^{(n)} \subset \frac{f_{\tt S}}{\Lambda^2} (\bar{l}^j e) \epsilon_{jk} (\bar{q}^k u) + \frac{f_{\tt T}}{\Lambda^2} (\bar{l}^j \sigma_{\mu\nu} e) \epsilon_{jk} (\bar{q}^k \sigma^{\mu\nu} u) + \mathrm{H.c.}$$

Reaction of interest (representative diagrams):



Mixing 1st &2nd generations with the 3rd

With t → b ν ℓ

There is no NP-SM interference → CPv is purely NP-generated

$$A_{CP} \sim \frac{\epsilon\left(p_u, p_{\ell'^+}, p_{\ell^+}, p_{\ell^-}\right) \cdot \frac{1}{\Lambda^4}\mathbf{Im}\left(f_{\mathtt{S}} f_{\mathtt{T}}^{\star}\right)}{(\mathrm{SM}) + \frac{1}{\Lambda^4}\left[\mathrm{terms} \propto |f_S|^2,\ |f_T|^2,\ \mathbf{Re}(f_S \cdot f_T^{\star})\right]}$$

Levi-Civita product

Mainly (inclusive): $pp \to WZ + X$

Subdominant (important when b tagging): $pp \to t\bar{t}Z,\ t\bar{t}W,\ t\bar{t}t\bar{t}$

Simulation

Looked at (as an example)

$$pp \to e^{\pm}\,\mu^{+}\,\mu^{-}\ + X$$

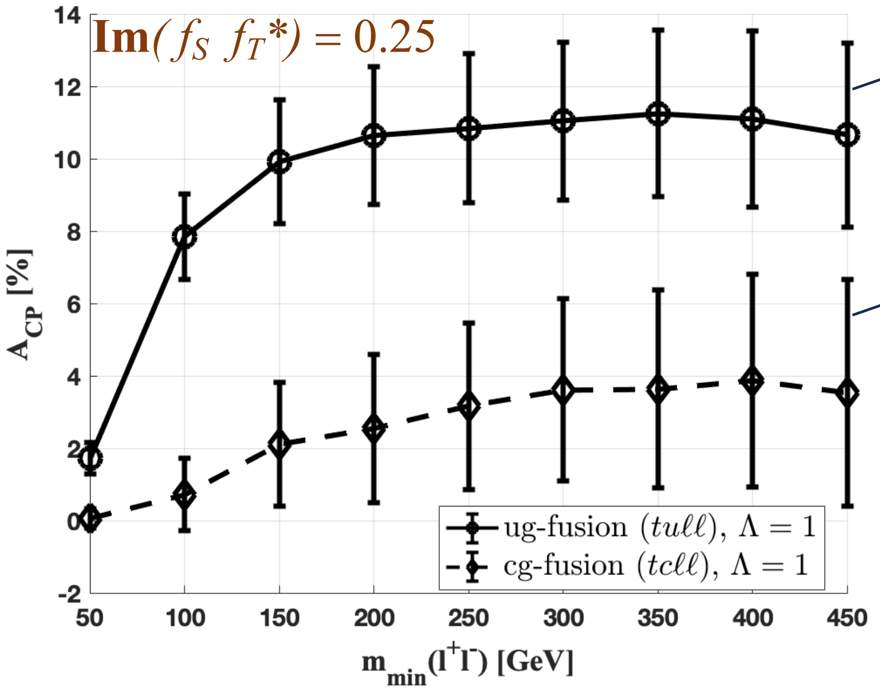
Selection:

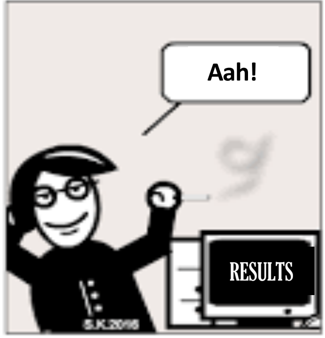
$$m(\mu^{+}\,\mu^{-}) > m_{\mathtt{min}}(\mu^{+}\,\mu^{-})$$

… plus minimal acceptance and threshold restrictions (no detector modeling)

(No b-tagging, though it can suppress the main SM background.)

Results





Stat. uncertainty only ($\mathcal{L}$ = 1000 fb^{-1})

Stat. uncertainty only ($\mathcal{L}$ = 3000 fb^{-1})

	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)%

- $m_{\mathtt{min}}\,(\mu^+\,\mu^-)$ = 400 GeV
- $\mathcal{L}$ = 1000 fb^{-1}
- Λ = 1 TeV

~100 SM trilepton events
~10^4 NP trilepton events

Summary

- Trilepton final states provide an O(10%) CPv asymmetry
- A challenging probe of CPv @ LHC
- Other T_N – odd observables can improve the asymmetry, *e.g.*

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

… but not dramatically.


THANK
YOU