CP-violating momentum asymmetries at the LHC

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Outline

1. CP violation - a quick overview
2. A calculable strong phase
3. CP violating momentum asymmetries
4. Conclusions

What’s so interesting about CP violation?

Think of CP symmetry as a mirror...
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This mirror is broken: Image does not match the original!
What’s so interesting about CP violation?

How does Dracula shave?

http://www.derbagger.org/files/14-vampir.jpg
CP violation - a quick overview

Observation of CP violation

\textbf{SM}: single source of CP violation ➤ phase $\delta$ of CKM matrix

- CP violation so far only observed in flavor violating $K$ and $B$ decays
- CKM picture works very well
- constraints on new physics (NP) up to scales $\mathcal{O}(10^5 \text{ TeV})$!
- however small tensions in UT fit ($\varepsilon_K$ vs. $S_{\psi K_S}$)

➤ Is the CKM phase the end of the story?
Cogito ergo sum

baryon asymmetry of the universe

\[ \eta = \frac{\eta_B - \eta_{\bar{B}}}{\eta_\gamma} \sim 6 \cdot 10^{-10} \]

Sakharov conditions for baryogenesis:

1. Baryon number violation
2. C and CP violation
3. Interactions out of thermal equilibrium

all three conditions fulfilled in the SM
however CP violating effects are too small!

➢ NP must introduce additional CP violation
The puzzle

New sources of CP violation must be well hidden from UT fit:

- large NP scale
- flavor alignment, such that effects are hidden from most dangerous observables
- CP violation “decoupled” from flavor sector
New sources of CP violation must be well hidden from UT fit:

- large NP scale ➢ *boring phenomenology*
- flavor alignment, such that effects are hidden from most dangerous observables ➢ *flavor symmetries?*
- CP violation “decoupled” from flavor sector ➢ *non-flavor tests needed!*

➢ different scenarios lead to very distinct signatures
Indirectly: NP contributions to low energy observables
- flavor and CP violating meson decays
- CP violation in the lepton sector
- electric dipole moments
- ...

➢ high precision required, NP effects often hidden by dominant SM contribution, QCD effects
Ways to access new sources of CP violation

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2 **directly:** CP violation at colliders
   - NP particle production cross-section
   - NP particle decays
   - high energies required, but SM background can often be reduced to a large extent
Ways to access new sources of CP violation

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Requirements for observing CP violation

CP symmetry relates particles and anti-particles
➢ CP violation can manifest itself through

\[ \Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f}) \]

necessary conditions:

1. two contributions of comparable size to decay amplitude \( A_f \)
2. different “weak” CP violating phases
3. different “strong” CP conserving phases
More explicitly...

\[ \mathcal{A}_f = |a_1|e^{i(\delta_1 + \phi_1)} + |a_2|e^{i(\delta_2 + \phi_2)} \]

\[ \bar{\mathcal{A}}_{\bar{f}} = |a_1|e^{i(\delta_1 - \phi_1)} + |a_2|e^{i(\delta_2 - \phi_2)} \]

- **CP violating phases** \( \phi_i \) result from complex parameters in the Lagrangian \( \Rightarrow \) appear with opposite sign in \( \mathcal{A}_f \) and \( \bar{\mathcal{A}}_{\bar{f}} \)

- **CP conserving phases** \( \delta_i \) stem from contributions of (strong) final state interactions or intermediate on-shell particles (propagator) \( \Rightarrow \) no sign change under CP conjugation

\[ a_{\text{CP}} = \frac{\Gamma(A \rightarrow f) - \Gamma(A \rightarrow \bar{f})}{\Gamma(A \rightarrow f) + \Gamma(A \rightarrow \bar{f})} \approx -\frac{2|a_1||a_2|}{|a_1|^2 + |a_2|^2} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]
Strong phase from intermediate state propagation

general structure:

\[ A = \mathcal{V}_1 \frac{1}{q^2 - m^2 + im\Gamma} \mathcal{V}_2 \]
A calculable strong phase

Strong phase from intermediate state propagation

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$$A = \mathcal{V}_1 \frac{1}{q^2 - m^2 + im\Gamma} \mathcal{V}_2$$

- $\mathcal{V}_{1,2}$ contain Lagrangian parameters $\Rightarrow$ weak phase

$$\phi = \text{arg} (\mathcal{V}_1 \mathcal{V}_2)$$
A calculable strong phase

**Strong phase from intermediate state propagation**

**general structure:**

$$ A = V_1 \frac{1}{q^2 - m^2 + im\Gamma} V_2 $$

- $V_{1,2}$ contain Lagrangian parameters ➢ **weak phase**

$$ \phi = \arg (V_1 V_2) $$

- phase of Breit-Wigner denominator is CP even ➢ **strong phase**

$$ \delta = \arg \left( \frac{1}{q^2 - m^2 + im\Gamma} \right) $$
Conditions for CP violation

Observable CP violation \( \Rightarrow \) two interfering diagrams

1. \(|A_1| \sim |A_2|\)
2. different weak phases \(\phi_1 \neq \phi_2\)

\(\Rightarrow\) “easy” to obtain from different (combinations of) Lagrangian parameters
Conditions for CP violation

Observable CP violation ➞ two interfering diagrams

1. \( |A_1| \simeq |A_2| \)
2. different weak phases \( \phi_1 \neq \phi_2 \)

➢ “easy” to obtain from different (combinations of) Lagrangian parameters

1. different strong phases \( \delta_1 \neq \delta_2 \) from propagating particles with

\[
\delta_i = \arg \left( \frac{1}{q_i^2 - m_i^2 + im_i \Gamma_i} \right)
\]

- different mass and/or width: distinct particles
  ➢ e.g. meson oscillations, several overlapping resonances
- different amount of virtuality: possible for identical particles
  ➢ case we focus on now!
theory of scalar particles $X_{1}\pm$, $X_{0,3}^{0}$, $Y^{\pm}$ with interaction Lagrangian

$$\mathcal{L}_{\text{int}} = -aX_{0}^{0}X_{1}^{+}Y^{-} - bX_{3}^{0}X_{1}^{+}Y^{-} + \text{h.c.}$$

complex couplings $a, b$, universal for $X_{1}\pm$ and $X_{2}\pm$

one physical CP violating phase: $\varphi = \arg(ab^*)$

➢ any CP violating process must involve both couplings $a$ and $b$
A calculable strong phase

The decay $X_0^0 \rightarrow X_1^+ X_1^- X_3^0$

$A_1 = a^* b \frac{1}{q_{23}^2 - m_Y^2 + i m_Y \Gamma_Y}$

$A_2 = ab^* \frac{1}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$

- different weak and strong phases due to different orderings of final states!
- decay is its own CP conjugate $\Rightarrow$ integrated CP asymmetry vanishes trivially
A calculable strong phase

Differential decay rate – Dalitz plot

\[ X_0^0 \rightarrow X_1^+ X_1^- X_3^0 \]

\[ q_{13}^2 = (p_3 + p_+)^2 \]
\[ q_{23}^2 = (p_3 + p_-)^2 \]

**benchmark parameters**

\[ m_0 = 400 \text{ GeV} \]
\[ m_Y = 2/3m_0 \]
\[ \Gamma_Y = 1/10m_Y \]
\[ m_1, m_3 = 0 \]

**CP violation** = difference between \( X_1^+(p) \) and \( X_1^-(p) \)

\[ A_{\text{CP}} = \frac{N(q_{13}^2 > q_{23}^2) - N(q_{13}^2 < q_{23}^2)}{N} \]
The ideal asymmetry

\[ q_{13}^2 = (p_3 + p_+)^2 = (p_0 - p_-)^2 = m_0^2 - 2m_0 p_{RF} \]
\[ q_{23}^2 = m_0^2 - 2m_0 p_{RF} \]

Dalitz plot asymmetry can be reduced to momentum asymmetry in the rest frame of \( X_0 \)

\[ A_{CP}^{RF} = \frac{N(p_-^{RF} > p_+^{RF}) - N(p_+^{RF} > p_-^{RF})}{N} \]

Our benchmark parameter point: \( A_{CP}^{RF} = 0.405 \)

In a realistic hadron collider environment:
- loss of kinematic information (\( X_0 \) rest frame often unknown)
- combinatorics
- energy smearing effects
Survey of observables

Study three scenarios for $X_0$ production in $pp$ collisions

- resonant production
- pair production
- production via decay

and identify observables that best reproduce the ideal asymmetry

Technical details

- $pp$ collisions at $\sqrt{s} = 14$ TeV
- $10^5$ signal events simulated with MadGraph5
- parton level analysis with no cuts, no background
- energy smearing for $X_1^\pm$ like muons at CMS

$$\frac{\Delta p_T}{p_T} = 0.08 \frac{p_T}{1 \text{ TeV}} \oplus 0.01$$

- assume that $X_3^0$ escapes detection
Resonant production

\[ pp \rightarrow X_0^0 \rightarrow X_1^+ X_1^- X_3^0 \]

\( X_0 \) rest frame unknown due to longitudinal boosts \( \geq p_T \) asymmetry

\[
A_{CP}^{p_T} = \frac{N(p_T, - > p_T, +) - N(p_T, + > p_T, -)}{N}
\]

For our benchmark point:

- \( A_{CP}^{p_T} = 0.209 \) (compared to \( A_{CP}^{RF} = 0.405 \))
- no significant suppression by energy smearing effects

Note that triple product asymmetries vanish trivially!
Pair production

Extend toy model by a neutral scalar $S$

$$pp \rightarrow S \rightarrow X_0^0 X_0^0 \rightarrow (X_1^+ X_1^- X_3^0)(X_1^+ X_1^- X_3^0)$$

Cross section largest near $X_0^0$ threshold $\Rightarrow$ small $p_T(X_0^0)$ expected

Monte Carlo: average $p_T(X_0^0) \sim 200$ GeV

Consider again $p_T$ asymmetry

$$A_{CP}^{p_T} = 0.127$$

no significant suppression by combinatoric effects
Production via decay

\[ pp \rightarrow S \rightarrow \Phi\Phi \, , \quad \Phi \rightarrow \phi X_0^0 \rightarrow \phi X_1^+ X_1^- X_3^0 \]

enhanced cross-section possible, as \( \Phi, \phi \) may be colored

If \( \Phi \) is boosted, its momentum is aligned with \( \phi \) and \( X_0^0 \)

\( \begin{align*}
\mathcal{A}_{\text{CP}}^{\phi_T} &= \frac{N(p_T, -\phi > p_T, +\phi) - N(p_T, +\phi > p_T, -\phi)}{N}, \\
p_{T,ij} &\equiv \frac{|p_i \times p_j|}{|p_j|}
\end{align*} \)

With \( m_\Phi = 1 \text{ TeV}, m_\phi = 0 \) and CMS jet energy smearing for \( \phi \):

\[ \mathcal{A}_{\text{CP}}^{\phi_T} = 0.122 \]

close to the pair production case!
The impact of spin

What if $X_0^0$, $X_1^\pm$ and $X_3^0$ were chiral fermions?

$$L_{\text{int}} = -\lambda_1 Y^+ \bar{X}_0^0 P_L X_1^- - \lambda_2 Y^+ \bar{X}_3^0 P_L X_1^- + \text{h.c.}$$

helicity flip on the $X_0$ and $X_3$ line required

➢ chiral suppression of asymmetry by $\frac{m_3}{m_0}$
A supersymmetric example

\[ \chi_2^0 \rightarrow \mu^+ \mu^- \chi_1^0 \] sensitive to relative phase of the gaugino masses \( M_1 \) and \( \tilde{M}_1 \) (relevant for MSSM baryogenesis)

Ideal asymmetry \( A_{\text{CP}}^{\text{RF}} \lesssim 1\% \) even in favored region of parameter space (chiral suppression and small smuon width...)

\begin{align*}
\chi_2^0 & \rightarrow \mu^- \mu^+ \chi_1^0 \\
\tilde{\mu} & \rightarrow \mu^+ \mu^- \chi_1^0 \\
\chi_2^0 & \rightarrow \mu^- \mu^+ \chi_1^0 \\
\tilde{\mu} & \rightarrow \mu^- \mu^+ \chi_1^0
\end{align*}
Majorana neutrino decay

Type-I seesaw model with weak scale RH neutrino

\[ \mathcal{L}_{N_1} = i \bar{N}_1 \phi N_1 - \left( \frac{1}{2} \bar{N}_1 m_{N_1} N_1^C + \text{h.c.} \right) - \left( Y_\nu \bar{N}_1 \tilde{\phi}^\dagger l_L + \text{h.c.} \right) \]

similar pattern, but with different intermediate resonances

- no chiral suppression
- \( A_{\text{CP}}^{RF} \lesssim 5\% \) for \( m_{N_1} = 90 \text{ GeV} \)
- decreases quickly for larger \( m_{N_1} \)
Summary

1. new physics at the TeV scale generally introduces new sources of CP violation

2. momentum asymmetries provide an alternative tool to access CP violation at the LHC
   - identify direction in which parent particle is boosted
   - construct momentum asymmetry transverse to that direction

3. depending on the NP scenario and the production mechanism, sizable effects are possible