CP-violating momentum asymmetries at the LHC

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**"Understanding the TeV Scale
Through LHC Data, Dark Matter, and Other Experiments"**

Galileo Galilei Institute, Firenze

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Outline

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

   

Berger, MB, Grossman, JHEP 1108 (2011) 033, arXiv:1105.0672

Berger, MB, Grossman, Ray, JHEP 10 (2012) 181, arXiv:1206.1651

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?

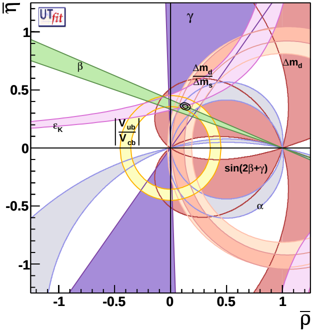
How does Dracula shave?

http://www.derbagger.org/files/14-vampir.jpg

Observation of CP violation

SM: single source of CP violation ➢ phase δ 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 (ε_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

The puzzle

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

Ways to access new sources of CP violation

1. **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

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   - NP particle production cross-section
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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 $\mathcal{A}_f$
2. different "weak" CP violating phases
3. different "strong" CP conserving phases

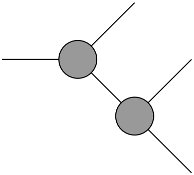
More explicitly...

$$\begin{aligned} \mathcal{A}_f &= |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)} \\ \bar{\mathcal{A}}_{\bar{f}} &= |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)} \end{aligned}$$

- **CP violating phases** ϕ_i result from complex parameters in the Lagrangian ➢ appear with opposite sign in $\mathcal{A}_f$ and $\bar{\mathcal{A}}_{\bar{f}}$
- **CP conserving phases** δ_i stem from contributions of (strong) final state interactions or intermediate on-shell particles (propagator) ➢ no sign change under CP conjugation

$$\begin{aligned} a_{\mathsf{CP}} &= \frac{\Gamma(A \to f) - \Gamma(\bar{A} \to \bar{f})}{\Gamma(A \to f) + \Gamma(\bar{A} \to \bar{f})} \\ &\sim -\frac{2|a_1||a_2|}{|a_1|^2 + |a_2|^2} \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \end{aligned}$$

Strong phase from intermediate state propagation



general structure:

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

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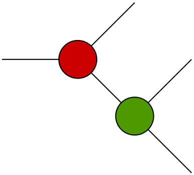

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- $\mathcal{V}_{1,2}$ contain Lagrangian parameters ➢ **weak phase**

$$\phi = \arg\left(\mathcal{V}_1 \mathcal{V}_2\right)$$

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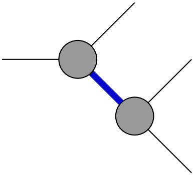

- $\mathcal{V}_{1,2}$ contain Lagrangian parameters ➢ **weak phase**

$$\phi = \arg\left(\mathcal{V}_1 \mathcal{V}_2\right)$$

- 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 ➢ two interfering diagrams

1. $|\mathcal{A}_1| \simeq |\mathcal{A}_2|$
2. different weak phases $\phi_1 \neq \phi_2$

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

Conditions for CP violation

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

$$\delta_i = \arg\left(\frac{1}{q_i^2 - m_i^2 + i m_i \Gamma_i}\right)$$

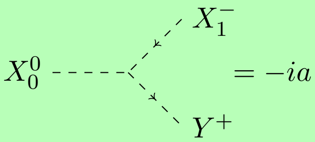
- different mass and/or width: distinct particles
  ➢ e. g. meson oscillations, several overlapping resonances
- different amount of virtuality: possible for identical particles
  ➢ case we focus on now!

Minimalistic CP violating toy model

- theory of scalar particles $X_1^\pm$, $X_{0,3}^0$, $Y^\pm$ with interaction Lagrangian

$$\mathcal{L}_{\text{int}} = -aX_0^0 X_1^+ Y^- - bX_3^0 X_1^+ Y^- + \text{h.c.}$$

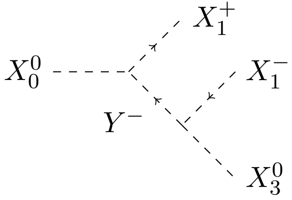
- complex couplings a, b, universal for $X_1^\pm$ and $X_2^\pm$

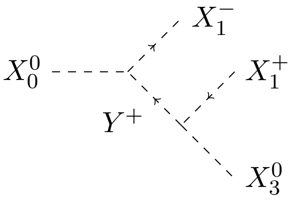


- one physical CP violating phase: $\varphi = \arg(ab^*)$

➢ **any CP violating process must involve both couplings a and b**

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

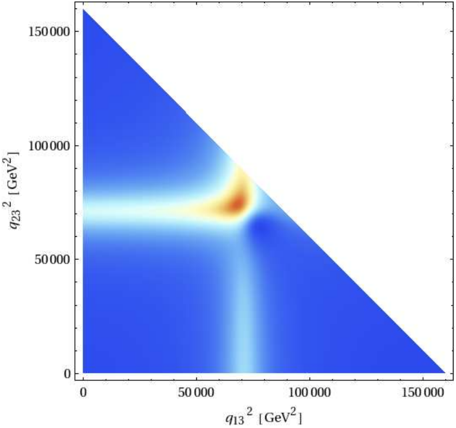




$$\mathcal{A}_1 = a^* b \frac{1}{q_{23}^2 - m_Y^2 + i m_Y \Gamma_Y} \qquad \mathcal{A}_2 = a b^* \frac{1}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$$

- different weak *and* strong phases due to different **orderings** of final states!
- decay is its own CP conjugate ➢ integrated CP asymmetry vanishes trivially

Differential decay rate – Dalitz plot



$X_0^0 \to X_1^+ X_1^- X_3^0$

$$q_{13}^2 = (p_3 + p_+)^2$$
$$q_{23}^2 = (p_3 + p_-)^2$$

benchmark parameters

$m_0 = 400$ GeV

$m_Y = 2/3 m_0$

$\Gamma_Y = 1/10 m_Y$

$m_1, m_3 = 0$

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

$$\mathcal{A}_{\rm CP} = \frac{N(q_{13}^2 > q_{23}^2) - N(q_{13}^2 < q_{23}^2)}{N}$$

The ideal asymmetry

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

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

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{RF}} = \frac{N(p_-^{\mathrm{RF}} > p_+^{\mathrm{RF}}) - N(p_+^{\mathrm{RF}} > p_-^{\mathrm{RF}})}{N}$$

Our benchmark parameter point: $\mathcal{A}_{\mathrm{CP}}^{\mathrm{RF}} = 0.405$

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 $\sqrt{s} = 14\,\text{TeV}$
- 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

$$pp \to X_0^0 \to X_1^+ X_1^- X_3^0$$

X_0 rest frame unknown due to longitudinal boosts ➢ p_T asymmetry

$$\mathcal{A}_{\rm CP}^{p_T} = \frac{N(p_{T,-} > p_{T,+}) - N(p_{T,+} > p_{T,-})}{N}$$

For our benchmark point:

- $\mathcal{A}_{\rm CP}^{p_T} = 0.209$ (compared to $\mathcal{A}_{\rm CP}^{\rm RF} = 0.405$)
- no significant suppression by energy smearing effects

Note that triple product asymmetries vanish trivially!

Pair production

Extend toy model by a neutral scalar S

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

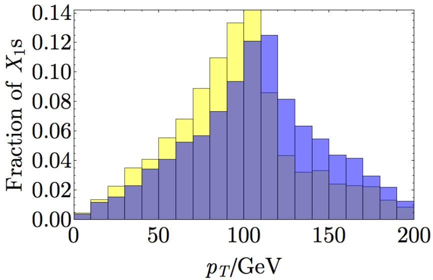
Cross section largest near X_0^0 threshold ➢ small $p_T(X_0^0)$ expected

Monte Carlo: average $p_T(X_0^0) \sim 200\,\mathrm{GeV}$

Consider again p_T asymmetry

$$\mathcal{A}_{\mathrm{CP}}^{p_T} = 0.127$$

no significant suppression by combinatoric effects



Production via decay

$$pp \to S \to \Phi\Phi \,, \qquad \Phi \to \phi X_0^0 \to \phi X_1^+ X_1^- X_3^0$$

enhanced cross-section possible, as Φ, ϕ may be colored

If Φ is boosted, its momentum is aligned with ϕ and X_0^0

➢ define CP asymmetry transverse to the direction of ϕ

$$\mathcal{A}_{\rm CP}^{\phi_T} = \frac{N(p_{T,-\phi} > p_{T,+\phi}) - N(p_{T,+\phi} > p_{T,-\phi})}{N} \,, \qquad p_{T,ij} \equiv \frac{|p_i \times p_j|}{|p_j|}$$

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

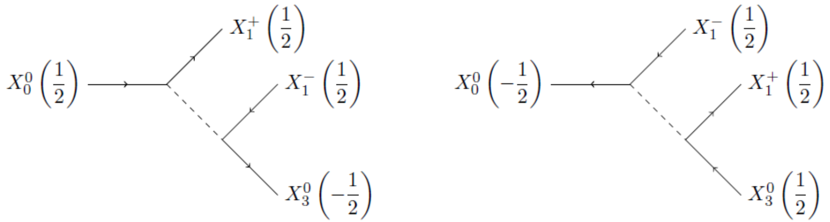
$$\mathcal{A}_{\rm CP}^{\phi_T} = 0.122$$

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?

$$\mathcal{L}_{\text{int}} = -\lambda_1 Y^+ \overline{X}_0^0 P_L X_1^- - \lambda_2 Y^+ \overline{X}_3^0 P_L X_1^- + \text{h.c.}$$

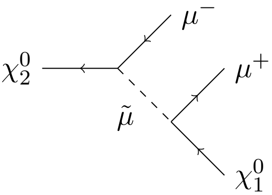


helicity flip on the X_0 and X_3 line required

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

A supersymmetric example

$\chi_2^0 \to \mu^+\mu^-\chi_1^0$ sensitive to relative phase of the gaugino masses M_1 and M_1 (relevant for MSSM baryogenesis)

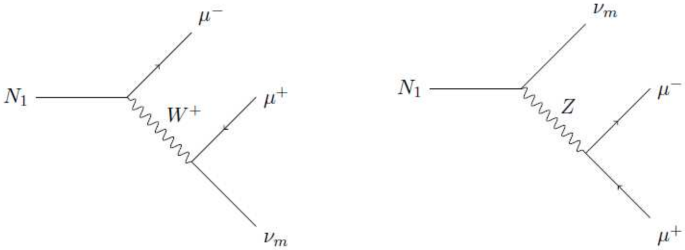


ideal asymmetry $\mathcal{A}_{\mathrm{CP}}^{\mathrm{RF}} \lesssim 1\%$ even in favored region of parameter space (chiral suppression and small smuon width...)

Majorana neutrino decay

Type-I seesaw model with weak scale RH neutrino

$$\mathcal{L}_{N_1} = i\overline{N}_1 \not{D} N_1 - \left(\frac{1}{2}\overline{N}_1 m_{N_1} N_1^C + \text{h.c.}\right) - \left(Y_\nu \overline{N}_1 \widetilde{\phi}^\dagger l_L + \text{h.c.}\right)$$



similar pattern, but with different intermediate resonances

- no chiral suppression
- $\mathcal{A}_{\text{CP}}^{\text{RF}} \lesssim 5\%$ for $m_{N1} = 90\,\text{GeV}$
- decreases quickly for larger m_{N1}

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