A new CP violating observable for the LHC

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The LHC era has begun!

1. Identify new states
2. Measure masses and spins
3. Measure couplings, flavor structure, CP-violation
Goal: Find calculable & measurable $\mathcal{CP}$ observables

- Requires interference & different strong phases
- So far: strong rescattering ($B \rightarrow K\pi$) and oscillation (meson mixing)
- Our result: new type of strong phase in 3-body decays with different orderings
Seeing CP-violation: Problem

- Looking for asymmetry:

\[ A_{\text{CP}} = \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} \neq 0 \]

\[ M = |a| e^{i\varphi} \]

\[ \bar{M} = |a| e^{-i\varphi} \]

then

\[ A_{\text{CP}} = 0 \]
Seeing CP-violation: Problem

• Looking for asymmetry:

\[
A_{\text{CP}} = \frac{\Gamma(i \rightarrow f) - \Gamma(i \rightarrow \bar{f})}{\Gamma(i \rightarrow f) + \Gamma(i \rightarrow \bar{f})} \neq 0
\]

\[
M = |a_1| e^{i\varphi_1} + |a_2| e^{i\varphi_2}
\]

\[
\overline{M} = |a_1| e^{-i\varphi_1} + |a_2| e^{-i\varphi_2}
\]

then

\[
A_{\text{CP}} = 0
\]
Looking for asymmetry:

\[ \mathcal{A}_{\text{CP}} = \frac{\Gamma(i \to f) - \Gamma(i \to \bar{f})}{\Gamma(i \to f) + \Gamma(i \to \bar{f})} \neq 0 \]

\[ \mathcal{M} = |a_1|e^{i\delta_1 + i\varphi_1} + |a_2|e^{i\delta_2 + i\varphi_2} \]

\[ \overline{\mathcal{M}} = |a_1|e^{i\delta_1 - i\varphi_1} + |a_2|e^{i\delta_2 - i\varphi_2} \]

then

\[ \mathcal{A}_{\text{CP}} \propto |a_1||a_2|\sin(\delta_1 - \delta_2)\sin(\varphi_1 - \varphi_2) \]
Seeing CP-violation: Solution

Requirements:

1. Two interfering amplitudes $a_1, a_2$
2. Different weak (CP-odd) phases $\varphi_1, \varphi_2$
3. Different strong (CP-even) phases $\delta_1, \delta_2$

\[ A_{\text{CP}} \propto |a_1| |a_2| \sin(\varphi_1 - \varphi_2) \sin(\delta_1 - \delta_2) \]
Strong phase?

- In general, comes from time evolution: $e^{iEt}$
- Basic case: oscillation of intermediate states - requires states with same quantum #’s
- More complicated: strong interaction rescattering - hard to calculate

Another way to get a calculable strong phase?
The Breit-Wigner Formula

Process with narrow-width virtual state:

\[ \mathcal{M} = \mathcal{M}_1 \frac{1}{q^2 - m^2 + i\Gamma m} \mathcal{M}_2 \]

- Breit-Wigner propagator contributes phase
- Momentum-space equivalent of \( e^{iEt} \)
Strong phase from the propagator

Strong phase from intermediate particle:

1. Different particles $\leftrightarrow$ Time-integrated oscillation
2. Different virtuality $\rightarrow$ New!

$$\delta = \arg \left( \frac{1}{q^2 - m^2 + im\Gamma} \right)$$
A new calculable strong phase

Requirements:

1. Three body decay
2. Two different orderings
3. On-shell resonance

Result:

CP-asymmetry in Dalitz plot
Toy model content

- All particles are scalars
- Heavy neutral particle: \( X_0 \)
- Charged resonance: \( Y^+ \)
- Lighter particles: \( X_{1,2}^+, X_3^0 \)
- Phase space \( \Rightarrow \) scale hierarchy:

\[
m_{X_0} > m_{Y^\pm} > m_{X_3^0} + m_{X_{1,2}^\pm}
\]
Feynman rules

\[ X_0^0 \rightarrow X_i^- \rightarrow Y^+ \]
\[ X_3^0 \rightarrow X_i^- \rightarrow Y^+ \]

\[ = -iae^{i\varphi_a} \]
\[ = -ibe^{i\varphi_b} \]

**One weak phase:** \( \varphi = \varphi_b - \varphi_a \)
Toy model decays

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

\[ = \frac{|a| |b| e^{i\varphi}}{q_{23}^2 - m_Y^2 + i m_Y \Gamma_Y} \]

Different weak phase, different strong phase
Asymmetry in the Dalitz plot

\[ A_{CP}^{\text{diff}} \propto \sin 2\varphi (q_{13}^2 - q_{23}^2) \Gamma_Y m_Y \]
Integrated asymmetries

\[ X_0^0 \rightarrow X_1^+ X_2^- X_3^0 \]

- Integrated rate suppressed:

\[ \mathcal{A}_{CP}^{\text{int}} \propto \frac{\Delta m_{12}^2}{m_0^2} \]

- Eliminate suppression by phase space weighting:

\[ \mathcal{A}_{CP}^{\text{wgt}} \equiv \frac{1}{\Gamma + \bar{\Gamma}} \int dq_{13}^2 dq_{23}^2 \ \text{sgn}(q_{23}^2 - q_{13}^2) \left( \frac{d\Gamma}{dq_{13}^2 dq_{23}^2} - \frac{d\bar{\Gamma}}{dq_{13}^2 dq_{23}^2} \right) \]
The relevant model

Electroweak sector of MSSM

- Heavy neutral particle: $\sim \tilde{B}$
- Intermediate charged resonance: $H^{\pm}$
- “Light” final states: lighter charginos and neutralinos
- Hierarchy of scales for maximal signal:

$$m_{\chi_4^0} \sim M_1 \gg m_{H^+} \gg m_{\chi_i^0}, m_{\chi_j^{\pm}} \sim \sqrt{\left|\mu M_2\right|} > m_Z$$
The Feynman diagrams

\[ \chi_4^0 \rightarrow \chi_2^- \rightarrow \chi_3^0 \rightarrow H^+ \]
\[ \chi_1^+ \rightarrow \chi_4^0 \rightarrow \chi_3^0 \rightarrow H^- \]

- One weak phase: \( \text{arg}(\mu b^* M_2) \)
Dalitz plot observables

\[ \log d\Gamma \]

\[ A_{\text{diff}}^{\text{CP}} \]
MSSM results

- Suppressed integrated asymmetry:

\[ A^\text{int}_{\text{CP}} = -3.5 \times 10^{-5} \]

- Using phase space weighting:

\[ A^\text{wgt}_{\text{CP}} = -6.5 \times 10^{-4} \]

Electroweak MSSM is challenging
The ingredients

Recipe for Dalitz plot asymmetry:

- Three body decay
- Two different orderings
- On-shell resonance