A new CP violating observable for the LHC

Joshua Berger
Cornell University

with Monika Blanke and Yuval Grossman
arXiv:1105.0672

August 11, 2011
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 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

Looking for asymmetry:

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

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 \( \delta_1, \delta_2 \)

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

- In general, comes from time evolution: $e^{iEt}$
- Basic case: oscillation of intermediate states - requires states with same quantum numbers
- 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:

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

- Breit-Wigner propagator contributes phase

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

Strong phase from intermediate particle:

\[ \delta = \arg \left( \frac{1}{q^2 - m^2 + im\Gamma} \right) \]

- Different particles $\leftrightarrow$ Time-integrated oscillation
- Different virtuality $\rightarrow$ New!
A new calculable strong phase

Requirements:

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

Result:

CP-asymmetry in Dalitz plot
All particles are scalars

Heavy neutral particle: $X_0^0$

Charged resonance: $Y^+$

Lighter particles: $X_{1,2}^+, X_3^0$

Phase space $\Rightarrow$ scale hierarchy:

$$m_{X_0^0} > m_{Y^\pm} > m_{X_3^0} + m_{X_{1,2}^\pm}$$
One weak phase: $\varphi = \varphi_b - \varphi_a$
Toy model decays

\[ X_0^0 \rightarrow \begin{cases} X_1^+ \quad & X_2^- \quad & X_3^0 \end{cases} \]

\[ Y^- \]

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

\[ X_0^0 \rightarrow \begin{cases} X_1^+ \quad & X_2^- \quad & X_3^0 \end{cases} \]

\[ Y^+ \]

\[ = \frac{|a||b|e^{-i\varphi}}{q_{13}^2 - m_Y^2 + im_Y\Gamma_Y} \]

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

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

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

- **Integrated rate** suppressed:

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

- **Eliminate suppression by phase space weighting**:

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

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

$$m_{\chi^0_4} \sim M_1 \gg m_{H^+} \gg m_{\chi^0_i}, m_{\chi^\pm_j} \sim \sqrt{|\mu M_2|} > m_Z$$
The Feynman diagrams

\[ \chi_{-2} - 2 \chi_{0} + 4 \chi_{1} + 1 \chi_{0} - 4 \chi_{2} + 3 \chi_{0} + 1 \chi_{4} - H^{+} \]

One weak phase: \( \arg(\mu b^{*} M_{2}) \)
Dalitz plot observables

\[ \log d\Gamma \]

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

Josh Berger (Cornell University)
MSSM results

- Suppressed integrated asymmetry:

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

- Using phase space weighting:

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

Electroweak MSSM is challenging
The ingredients

Recipe for Dalitz plot asymmetry:

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