CP violation in (new physics) three body decays

A calculable strong phase

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The Role of Heavy Fermions in Fundamental Physics

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In a nutshell

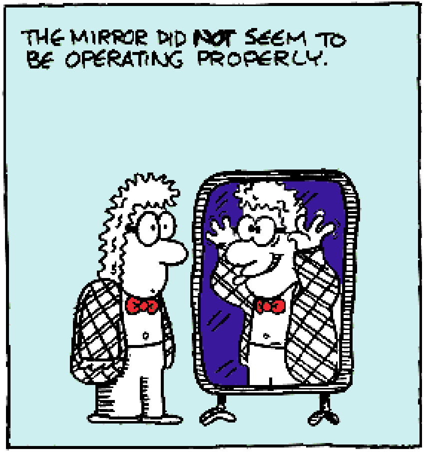
1. CP violation in heavy particle decays requires *two interfering amplitudes* with different weak and strong phases
2. a *calculable* strong phase can be obtained from the propagation of intermediate virtual particles

   ➢ NEW! possible with the *same* intermediate state having **different virtualities**

3. effect present in MSSM neutralino decay – but detection very challenging

J. Berger, MB, Y. Grossman, 1104.soon

What's so interesting about CP violation?



http://www.phy.bris.ac.uk/groups/particle/PUS/A-level/Pictures/CartoonCP.gif

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

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

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

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...

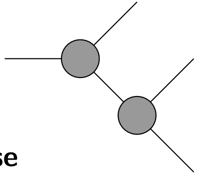
$$\begin{aligned} \mathcal{A}_f &= |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)} \\ \bar{\mathcal{A}}_{\bar{f}} &= |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)} \end{aligned}$$

- **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

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

Strong phase from intermediate state propagation

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



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

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

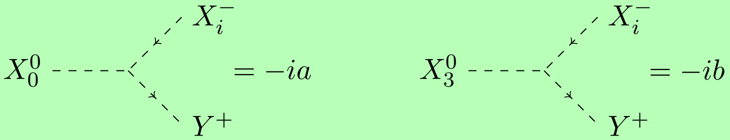
- Breit-Wigner denominator is CP even ➢ calculable **strong phase**

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

➢
- different mass and/or width: distinct particles
  ➢ e. g. meson oscillations, several resonances
- different amount of virtuality: possible for identical particles

Minimalistic CP violating toy model

- theory of scalar particles $X^{\pm}_{1,2}$, $X^0_{0,3}$, $Y^{\pm}$
- neutral particles $X^0_{0,3}$ are CP eigenstates
- complex couplings a, b, universal for $X^{\pm}_1$ and $X^{\pm}_2$

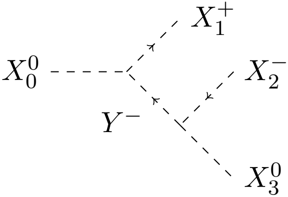


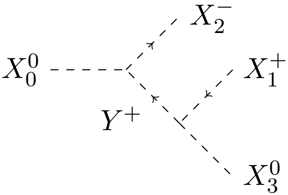
- one physical CP violating phase: $\varphi = \arg(ab^*)$

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

The decay $X_0^0 \to X_1^\pm X_2^\mp X_3^0$

two interfering diagrams:



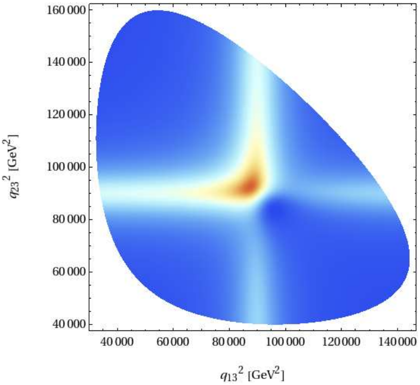


$$\mathcal{A}_1 = a^* b \frac{1}{q_{23}^2 - m_Y^2 + i m_Y \Gamma_Y} \qquad \mathcal{A}_2 = a b^* \frac{1}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$$

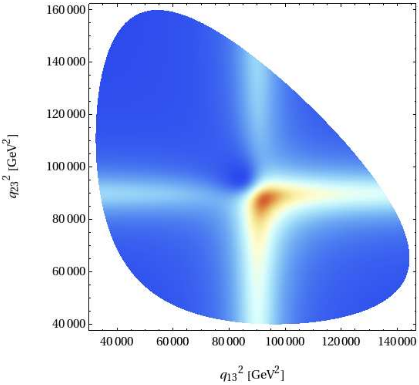
➢ different weak *and* strong phases!

Differential decay width and Dalitz plot

$$\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} = \frac{1}{(2\pi)^3}\frac{1}{32M_0^3}|\mathcal{A}|^2\,, \qquad \mathcal{A} = \mathcal{A}_1 + \mathcal{A}_2$$



$d\Gamma$

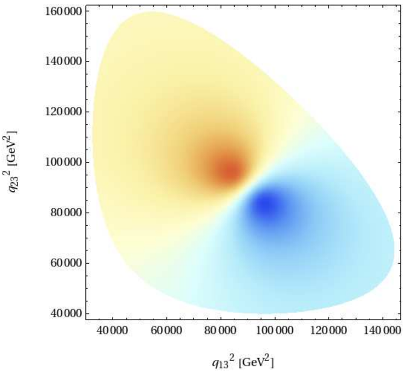


$d\Gamma_{\mathsf{CP}}$

Differential CP asymmetry

$$a_{\mathrm{CP}}^{\mathrm{diff}} = \frac{d\Gamma - d\Gamma_{\mathrm{CP}}}{d\Gamma + d\Gamma_{\mathrm{CP}}}$$

$$= \frac{2\sin 2\varphi\,(\Delta q_{13}^2 - \Delta q_{23}^2)\Gamma_Y m_Y}{2(1+\cos 2\varphi)m_Y^2\Gamma_Y^2 + (\Delta q_{13}^2)^2 + (\Delta q_{23}^2)^2 + 2\cos 2\varphi \Delta q_{13}^2 \Delta q_{23}^2}$$



$\Delta q_{i3}^2 = q_{i3}^2 - m_Y^2$: virtuality of Y

$a_{\mathrm{CP}}^{\mathrm{diff}} = 0$ for

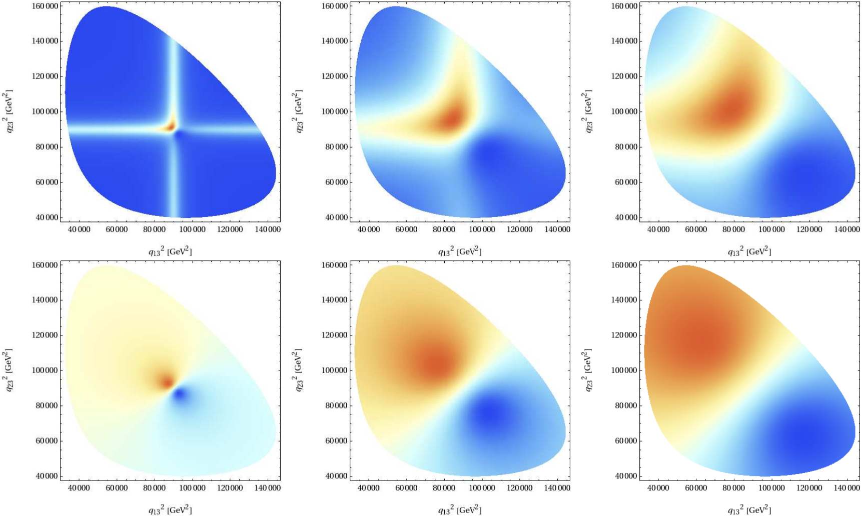
- $\varphi = 0$
- $m_Y = 0 \vee \Gamma_Y = 0$
  $\vee\, \Delta q_{13}^2 = \Delta q_{23}^2$

$|a_{\mathrm{CP}}^{\mathrm{diff}}|$ maximal for

$$\Delta q_{13}^2 = -\Delta q_{23}^2 = \pm \Gamma_Y m_Y \cot\varphi$$

Dependence on Γ_Y

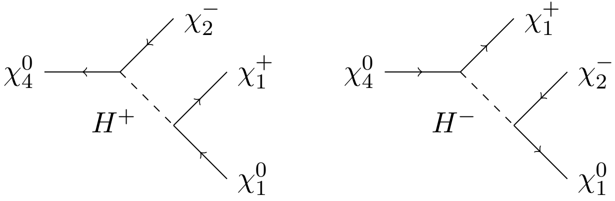
$\Gamma_Y/m_Y = 3\%$ $\Gamma_Y/m_Y = 15\%$ $\Gamma_Y/m_Y = 30\%$



CP violation in the MSSM electroweak sector

- gaugino masses $M_{1,2}$, μ and the b parameter in gerenal complex
- physical phases $\arg(\mu^* b M_2^*)$ and $\arg(M_1 M_2^*)$
- strong indirect constraints from electric dipole moments and flavor physics – but we would like to test these phases directly!

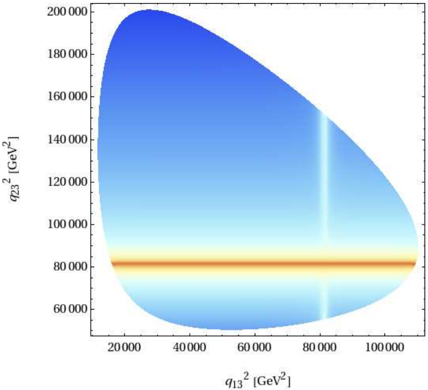
➢ **consider $\chi_4^0 \to \chi_1^\pm \chi_2^\mp \chi_1^0$**



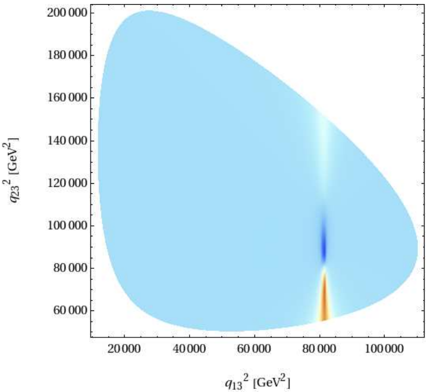
(neglect contributions of neutral Higgses, $W^\pm$, Z for the moment)

$\chi_4^0 \to \chi_1^\pm \chi_2^\mp \chi_1^0$ – decay width and CP asymmetry

$d\Gamma$



$a_{\text{CP}}^{\text{diff}}$



➢ visible asymmetry (up to 15%),
but only in very restricted region of phase space

The issue with R-parity

- R-parity conservation ➢ each decay products deays to SM particles and missing energy
- differential analysis (Dalitz plots...) not feasible – only integrated asymmetry can be accessed
- integrated asymmetry $a_{\text{CP}}^{\text{int}}$ suffers from various suppression factors

weak phase	$\propto \frac{\lvert\mu M_2\rvert}{M_1^2} \lesssim \mathcal{O}(10^{-1})$
finite $H^\pm$ width	$\propto \frac{\Gamma_{H^\pm}}{m_{H^\pm}} \sim \mathcal{O}(10^{-2})$
phase space asymmetry	$\propto \frac{\Delta m^2_{\chi^\pm}}{M_1^2} \lesssim \mathcal{O}(10^{-1})$

- for our benchmark point $a_{\text{CP}}^{\text{int}} = -3.5 \cdot 10^{-5}$

  ➢ bad news for the LHC... bad choice of example!

Conclusions

1. **heavy NP particle decays** are sensitive to **CP violation** if mediated by two interfering amplitudes with different weak *and* strong phases

2. **calculable strong phases** can be obtained from different virtualities of *identical* intermediate particles

3. very small effect in the MSSM – but **potentially significant in other new physics scenarios**

➢ new CP odd observables for the LHC!

Toy model parameters

$$
\begin{aligned}
a &= 20\,\text{GeV} \\
b &= 30\,\text{GeV} \cdot e^{i\pi/4} \\
m_0 &= 500\,\text{GeV} \\
m_1 &= 100\,\text{GeV} \\
m_2 &= 120\,\text{GeV} \\
m_3 &= 80\,\text{GeV} \\
m_Y &= 300\,\text{GeV} \\
\Gamma_Y &= 9, 21, 45, 90\,\text{GeV}
\end{aligned}
$$

MSSM parameters

$$\begin{aligned} M_1 &= 500\,\text{GeV} \\ M_2 &= 80\,\text{GeV} \\ m_{Hu}^2 &= -(120\,\text{GeV})^2 \\ m_{Hd}^2 &= (250\,\text{GeV})^2 \\ \tan\beta &= 5 \\ \phi_\mu &= \pi/2 \end{aligned}$$