Title: New CP violating observables for the LHC

Date: Nov 25, 2011 01:00 PM

URL: http://pirsa.org/11110142

Abstract: I discuss new types of CP violating observables that arise in three body decays that are dominated by an intermediate resonance. If two interfering diagrams with different orderings of the final state particles exist, the required CP even phase arises due to the different virtualities of the resonance in each of the two diagrams. Using momentum asymmetries, I demonstrate that CP violation can be seen in this way at the LHC and future colliders.

New $\not{CP}$ observables for the LHC

Joshua Berger

Cornell University

November 25, 2011

J.B., Monika Blanke, Yuval Grossman: 1105.0672

J.B., Monika Blanke, Yuval Grossman, Shamayita Ray: 1112.xxxx

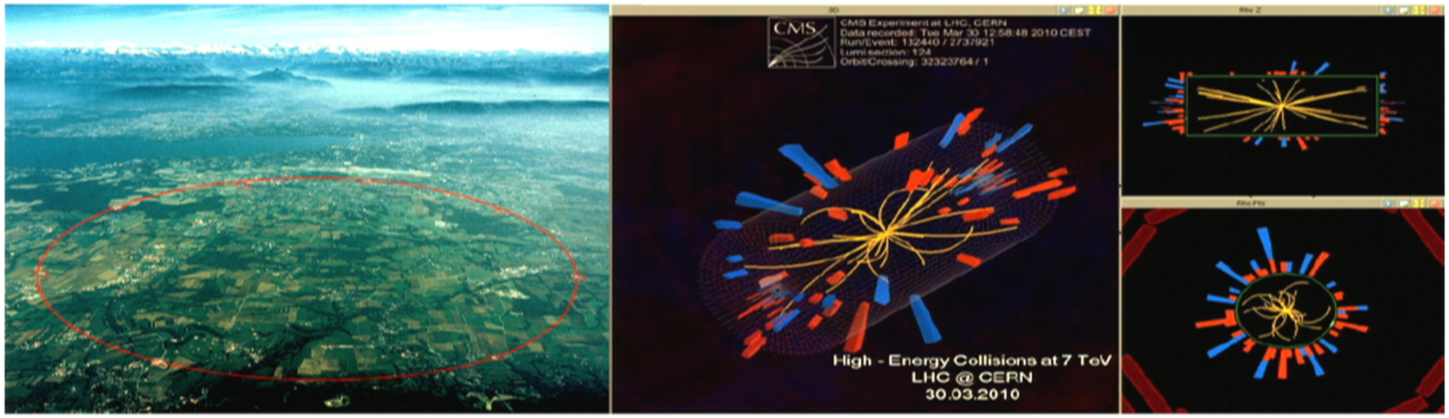
Today's menu

1. Motivation
2. *CP* violation without mixing
3. Exploiting phase space
4. A SUSY example
5. Conclusions

2

Motivation

Can we see $\not{CP}$ directly at the LHC?

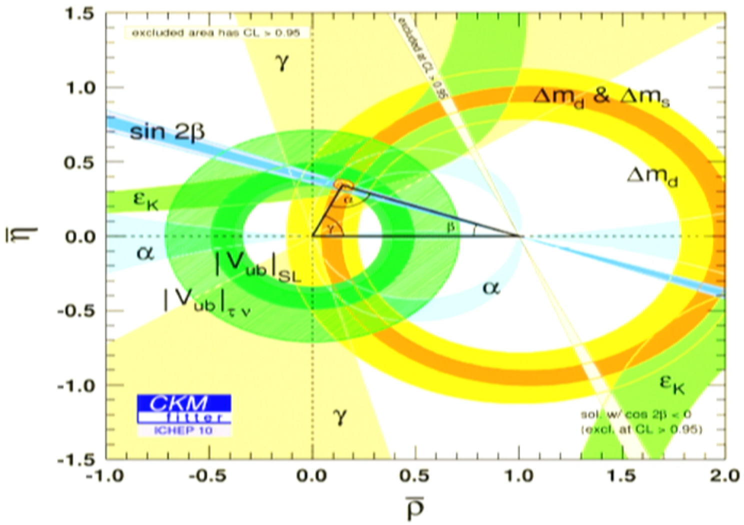


- Step 1: Discover new states
- Step 2: Measure masses and spins
- Step 3: Determine couplings, flavor, $\not{CP}$

4

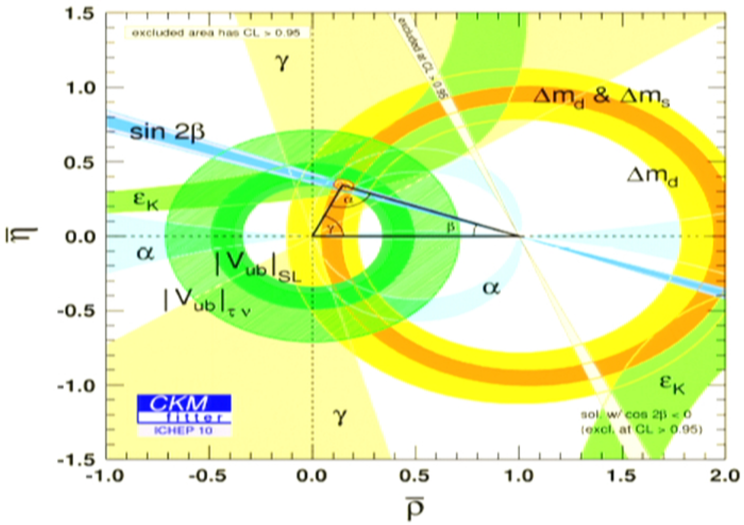
State of the art

- No significant deviations
- The SM works



State of the art

- No significant deviations yet
  - 3σ's in the B sector (Now D sector too!)
- The SM works too well
  - $\Lambda_{\mathrm{NP}} \gtrsim 10^5$ TeV



5

Why are there so many atoms?

Sakharov says:

- B-number violation
- C & CP violation
- Out-of-equilibrium dynamics

SM falls short $\Longrightarrow$ new sources of $\not{C}\not{P}$

$$\eta_{\rm obs} \sim 10^{-10} \qquad \text{vs.} \qquad \eta_{\rm SM} \sim 10^{-19}$$

6

Seeing $\not{CP}$

- $\not{CP}$ enters as CP-odd phases in Lagrangian
- TeV theories usually have new CP-oddd phases
- Observation requires CP-even (strong) phases
- Challenge: large, calculable CP-even phases

The CP challenge

$$\mathcal{A} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

First try

$$\mathcal{M} = ae^{i\phi} \qquad \overline{\mathcal{M}} = ae^{-i\phi}$$

$$|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 = 0$$

The CP challenge

$$\mathcal{A} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

Second try

$$\mathcal{M} = a_1 e^{i\phi_1} + a_2 e^{i\phi_2} \qquad \overline{\mathcal{M}} = a_1 e^{-i\phi_1} + a_2 e^{-i\phi_2}$$

$$|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 = 0$$

8

The CP challenge

$$\mathcal{A} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

$$\mathcal{M} = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2} \quad \overline{\mathcal{M}} = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}$$

$$|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 \propto a_1 a_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Three requirements:

1. Two contributing amplitudes
2. Different CP-odd phases:
3. Different CP-even phases

8

The CP challenge

$$\mathcal{A} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

$$\mathcal{M} = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2} \qquad \overline{\mathcal{M}} = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}$$

$$|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 \propto a_1 a_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

Three requirements:

1. Two contributing amplitudes
2. Different *CP*-odd phases:
3. Different *CP*-even phases

8

CP-even phases?

- Unstable state gives

$$e^{iEt-\Gamma t/2} \quad \text{or} \quad \frac{i}{q^2 - m^2 + im\Gamma}$$

  - Rescattering: Hard to calculate
  - Mixing: Requires mixing with $\Delta m \sim \Gamma$

- Triple product $\Longrightarrow$ $i\epsilon p_1 p_2 p_3 p_4$

9

The main ideas

A new CP-even phase from different q^2

$$\frac{i}{q^2 - m^2 + im\Gamma}$$

- When do we have this phase?
  - Three-body decays
  - Two different orderings
  - On-shell resonance
- How can we see this phase?
  - Use momentum asymmetries
  - Feasible at the LHC?

10

CP-even phases without mixing

The setup

- Three body decay via single resonance
  - No mixing
- Weak coupling
  - Breit-Wigner approximation
- Narrow, but not too narrow
  - Resonance can be slighly off-shell
  - Time dependence not an issue

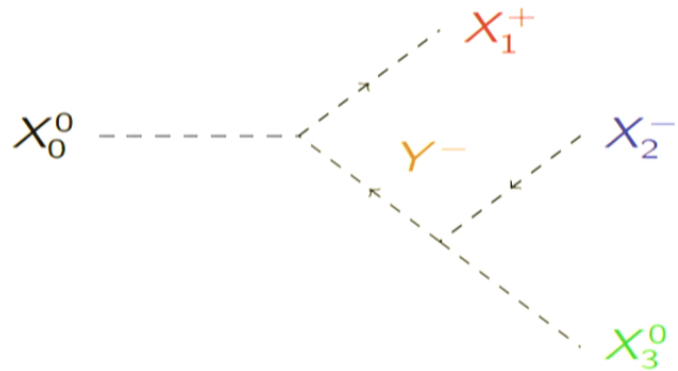
12

Toy model!

13

The roster

- Scalars are easy

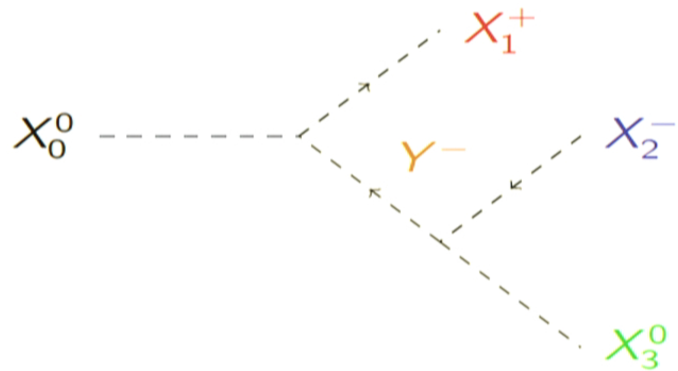


- Phase space $\Longrightarrow$ Scale hierarchy:

$$m_{X_0} > m_Y + m_{X_{1,2}}, \qquad m_Y > m_{X_{1,2}} + m_{X_3}$$

The roster

- Scalars are easy

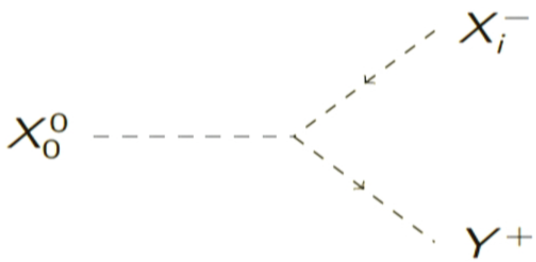


- Phase space $\implies$ Scale hierarchy:

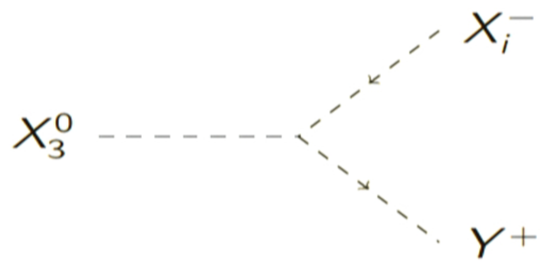
$$m_{X_0} > m_Y + m_{X_{1,2}}, \qquad m_Y > m_{X_{1,2}} + m_{X_3}$$

14

The interactions



$= -iae^{i\varphi_a}$

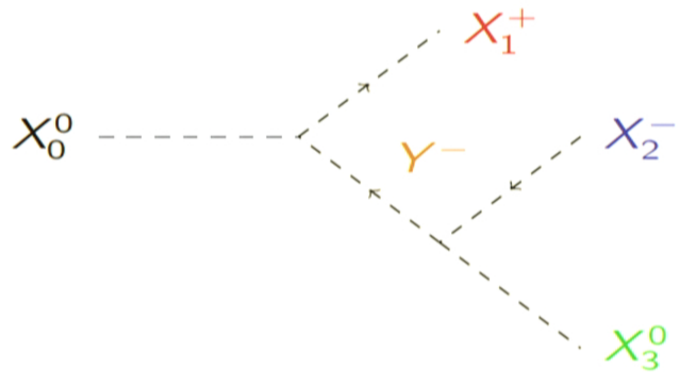


$= -ibe^{i\varphi_b}$

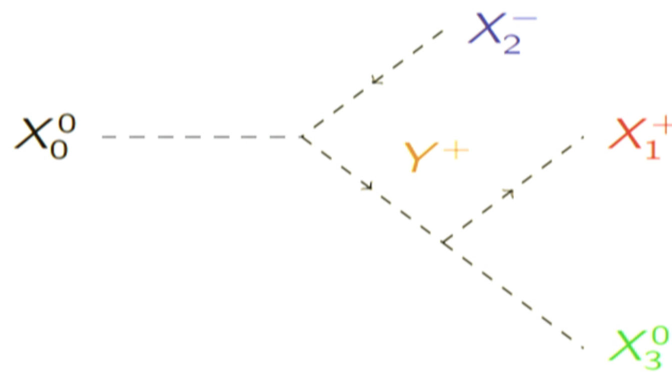
- One CP-odd phase: $\varphi = \varphi_b - \varphi_a$

15

The game plan



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

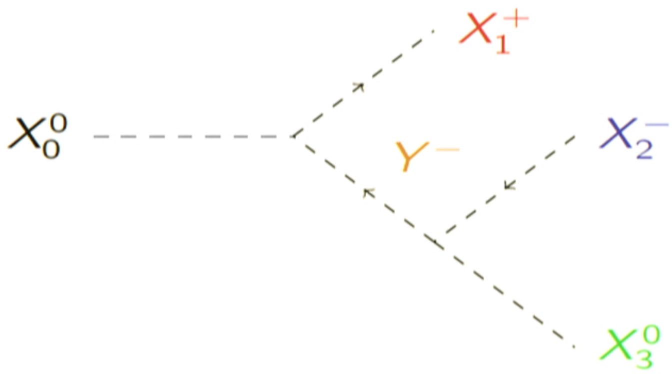


$$= \frac{|a||b|e^{-i\varphi}}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$$

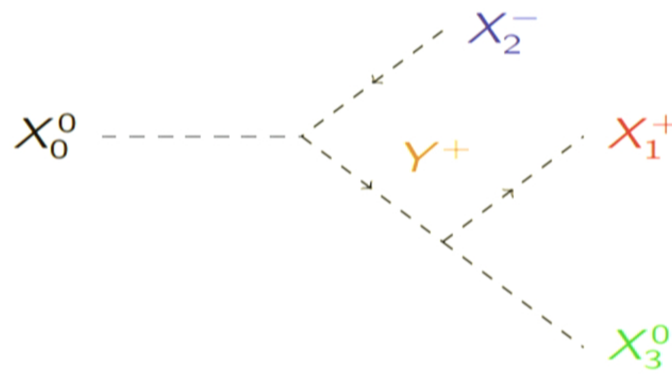
Different CP-odd phase, different CP-even phase

16

The game plan



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

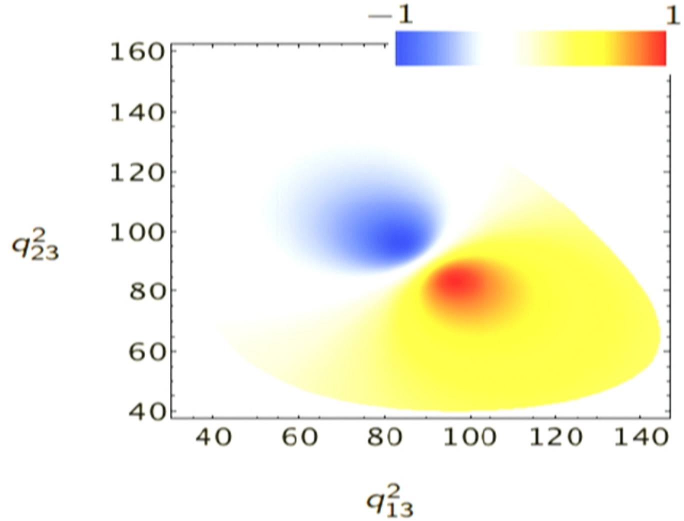


$$= \frac{|a||b|e^{-i\varphi}}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$$

Different CP-odd phase, different CP-even phase

What can we measure?

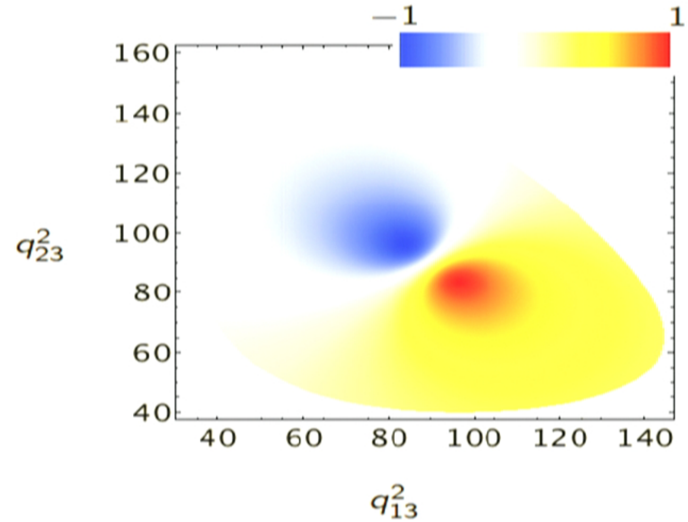
- $\mathcal{A}_{CP}^{\text{diff}} = \dfrac{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} - \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} + \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}$
- $\mathcal{A}_{CP}^{\text{int}} = \dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$
  - Suppressed by $\Delta m_{12}^2 / m_0^2$



17

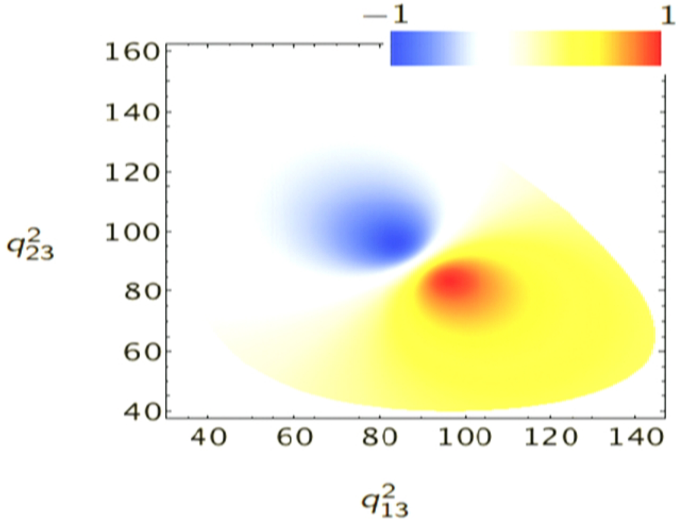
What can we measure?

- $\mathcal{A}_{CP}^{\text{diff}} = \dfrac{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} - \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} + \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}$
- $\mathcal{A}_{CP}^{\text{int}} = \dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$
  - Suppressed by $\Delta m_{12}^2 / m_0^2$



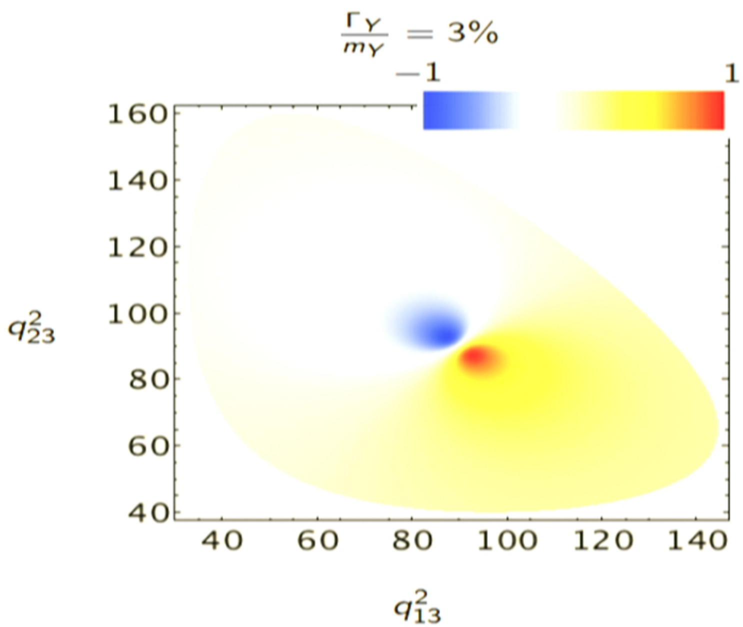
What can we measure?

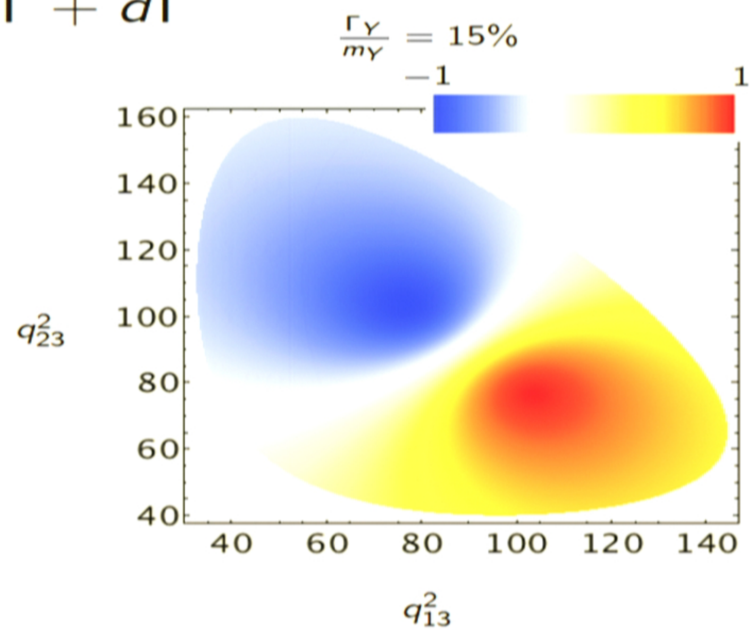
- $$\mathcal{A}_{CP}^{\text{diff}} = \frac{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} - \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}{\frac{d\Gamma}{dq_{13}^2 dq_{23}^2} + \frac{d\overline{\Gamma}}{dq_{13}^2 dq_{23}^2}}$$
- $$\mathcal{A}_{CP}^{\text{int}} = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$
  - Suppressed by $\Delta m_{12}^2 / m_0^2$



Width effects

$$\mathcal{A}_{CP}^{\text{diff}} = \frac{d\Gamma - d\overline{\Gamma}}{d\Gamma + d\overline{\Gamma}}$$





Lessons so far

- CP-even phase:
  - Three body decays
  - Different orderings
  - On-shell resonance
- Integrated asymmetry suppressed by mass splitting
- Next step: make this new source practical

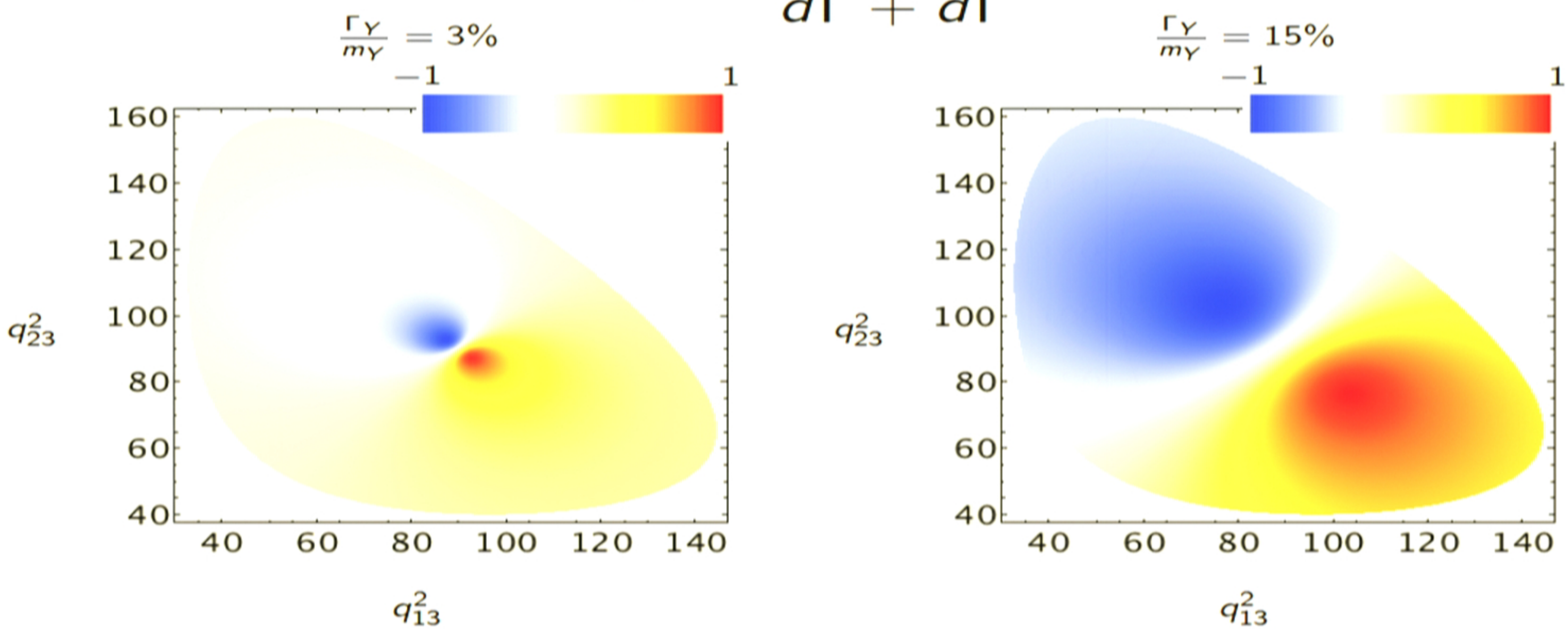
19

The best bang for your buck

- Integrated rate sensitive to mass splitting
  - Eliminate suppression using phase space weighting
- Extreme case: identical charged final state particles
  - Can get non-zero asymmetry
- Charged particle kinematics measured
  - Momentum asymmetries possible

Width effects

$$\mathcal{A}_{CP}^{\rm diff} = \frac{d\Gamma - d\overline{\Gamma}}{d\Gamma + d\overline{\Gamma}}$$



18

The best bang for your buck

- Integrated rate sensitive to mass splitting
  - Eliminate suppression using phase space weighting
- Extreme case: identical charged final state particles
  - Can get non-zero asymmetry
- Charged particle kinematics measured
  - Momentum asymmetries possible

21

The best bang for your buck

- Integrated rate sensitive to mass splitting
  - Eliminate suppression using phase space weighting
- Extreme case: identical charged final state particles
  - Can get non-zero asymmetry
- Charged particle kinematics measured
  - Momentum asymmetries possible

21

The observables

- Ideally: Rest-frame asymmetry

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

- Lepton collider pair production: p asymmetry

$$\mathcal{A}_{CP}^{p} \propto N(|\mathbf{p}_+| > |\mathbf{p}_-|) - N(|\mathbf{p}_-| > |\mathbf{p}_+|)$$

- Hadron collider pair production: p_T asymmetry

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

- Triple product asymmetries?

22

The observables

- Ideally: Rest-frame asymmetry

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

- Lepton collider pair production: p asymmetry

$$\mathcal{A}_{CP}^{p} \propto N(|\mathbf{p}_+| > |\mathbf{p}_-|) - N(|\mathbf{p}_-| > |\mathbf{p}_+|)$$

- Hadron collider pair production: p_T asymmetry

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

- Triple product asymmetries?

CP and kinematics

- Consider decay in rest frame of X_0^0
  - $\mathcal{P}(p_+, p_-) = X_0^0 \to X_1^+(p_+)X_1^-(p_-)X_3^0$
  - $\overline{\mathcal{P}}(p_+, p_-) = X_0^0 \to X_1^+(p_-)X_1^-(p_+)X_3^0$
- $\mathcal{P}(p_+ > p_-) \xrightarrow{CP} \mathcal{P}(p_- > p_+)$
  - Can construct a CP asymmetry $\mathcal{A}_{CP}^{RF}$

23

CP and kinematics

- Consider decay in rest frame of X_0^0
  - $\mathcal{P}(p_+, p_-) = X_0^0 \to X_1^+(p_+)X_1^-(p_-)X_3^0$
  - $\overline{\mathcal{P}}(p_+, p_-) = X_0^0 \to X_1^+(p_-)X_1^-(p_+)X_3^0$
- $\mathcal{P}(p_+ > p_-) \xrightarrow{CP} \mathcal{P}(p_- > p_+)$
  - Can construct a CP asymmetry $\mathcal{A}_{CP}^{RF}$

23

Choosing the parameters wisely

- Want large Γ_Y: limited by weak coupling
- Numerics: largest asymmetry for $m_Y/m_{X_0} \approx 2/3$
- Example: $\Gamma_Y/m_Y = 0.1$, $m_Y/m_{X_0} = 2/3$

$$\mathcal{A}_{CP}^{RF} = 0.4052$$

24

A dose of realism

- If full decay reconstructable, we're done
- More realistic: $pp \longrightarrow X_0^0 X_0^0$, with $X_0^0 \longrightarrow X_1^+ X_1^- X_3^0$
- X_3^0 could escape as MET
  - Best we can try: $\mathcal{A}_{CP}^{|\mathbf{p}|}$ and $\mathcal{A}_{CP}^{p_T}$

25

Taking stock

- Momentum asymmetries: practical $\not{C}\not{P}$ observables
- Even with MET, asymmetry survives
  - Washed out by $\sim 1/3$
- In what kinds of models is this relevant?

27

A SUSY example

Motivating the MSSM

- MSSM remains a leading candidate for physics BSM
- Rich with important CP phases
  - Gaugino phases $\longrightarrow$ electroweak baryogenesis
- Flavor changing phases highly constrained

29

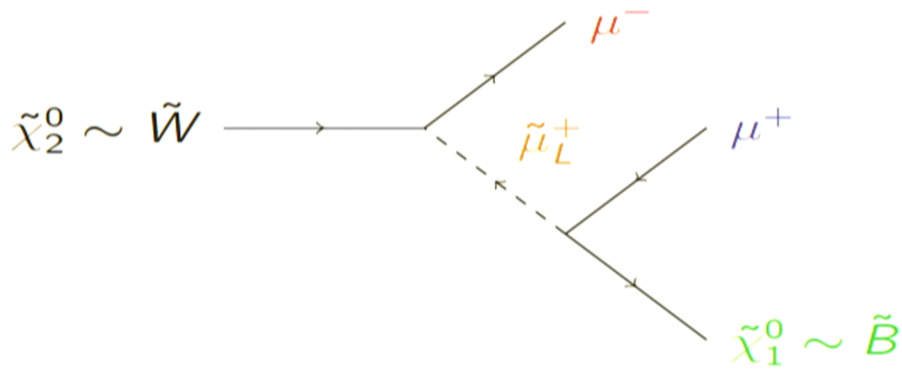
Motivating the MSSM

- MSSM remains a leading candidate for physics BSM
- Rich with important CP phases
  - Gaugino phases $\longrightarrow$ electroweak baryogenesis
- Flavor changing phases highly constrained

29

The relevant particles

- Leptons are easy



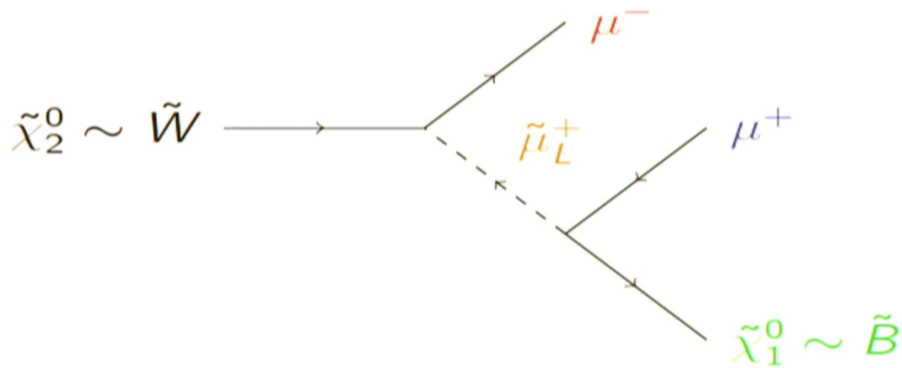
- Phase space $\implies$ Scale hierarchy:

$$m_{\chi_2^0} > m_{\tilde{\mu}_L} + m_\mu, \qquad m_{\tilde{\mu}_L} > m_\mu + m_{\chi_1^0}$$

30

The relevant particles

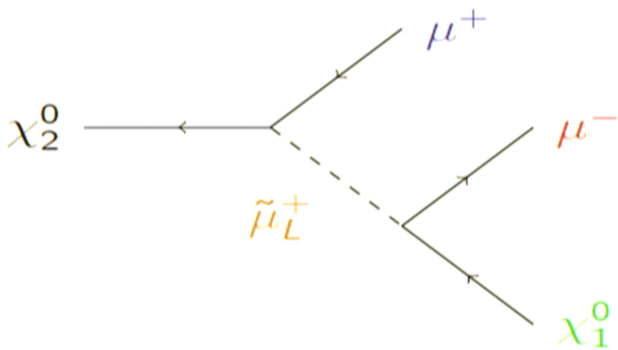
- Leptons are easy



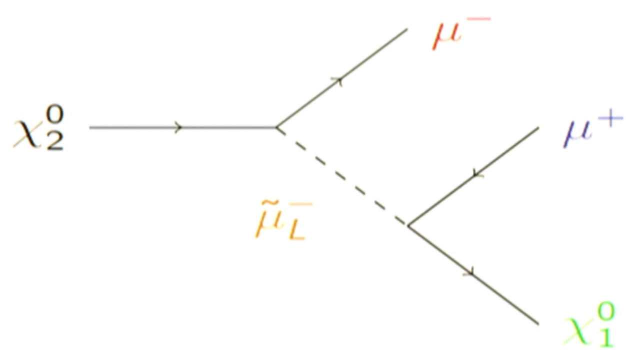
- Phase space $\implies$ Scale hierarchy:

$$m_{\chi_2^0} > m_{\tilde{\mu}_L} + m_\mu, \qquad m_{\tilde{\mu}_L} > m_\mu + m_{\chi_1^0}$$

The decay



$$\propto \frac{M_1 M_2^*}{q_{13}^2 - m_{\tilde{\mu}}^2 + i\Gamma_{\tilde{\mu}} m_{\tilde{\mu}}}$$



$$\propto \frac{M_1^* M_2}{q_{23}^2 - m_{\tilde{\mu}}^2 + i\Gamma_{\tilde{\mu}} m_{\tilde{\mu}}}$$

31

Narrow width issues

$$\mathcal{A}_{CP}^{\text{diff}} \approx \frac{m_{\chi_2}^2 m_{\chi_1}^2 m_{\tilde{\mu}} \Gamma_{\tilde{\mu}} (E_1 - E_2) \sin\delta}{f(E_1) + f(E_2)}$$

- Weakly interacting MSSM particles: $\Gamma \lesssim \alpha m$
  - $\Gamma/m \lesssim 1\%$
- Strongly interacting MSSM particles?
  - Stronger bounds
  - Tougher experimentally

32

Narrow width issues

$$\mathcal{A}_{CP}^{\text{diff}} \approx \frac{m_{\chi_2}^2 m_{\chi_1}^2 m_{\tilde{\mu}} \Gamma_{\tilde{\mu}} (E_1 - E_2) \sin\delta}{f(E_1) + f(E_2)}$$

- Weakly interacting MSSM particles: $\Gamma \lesssim \alpha m$
  - $\Gamma / m \lesssim 1\%$
- Strongly interacting MSSM particles?
  - Stronger bounds
  - Tougher experimentally

32

Is it feasible?

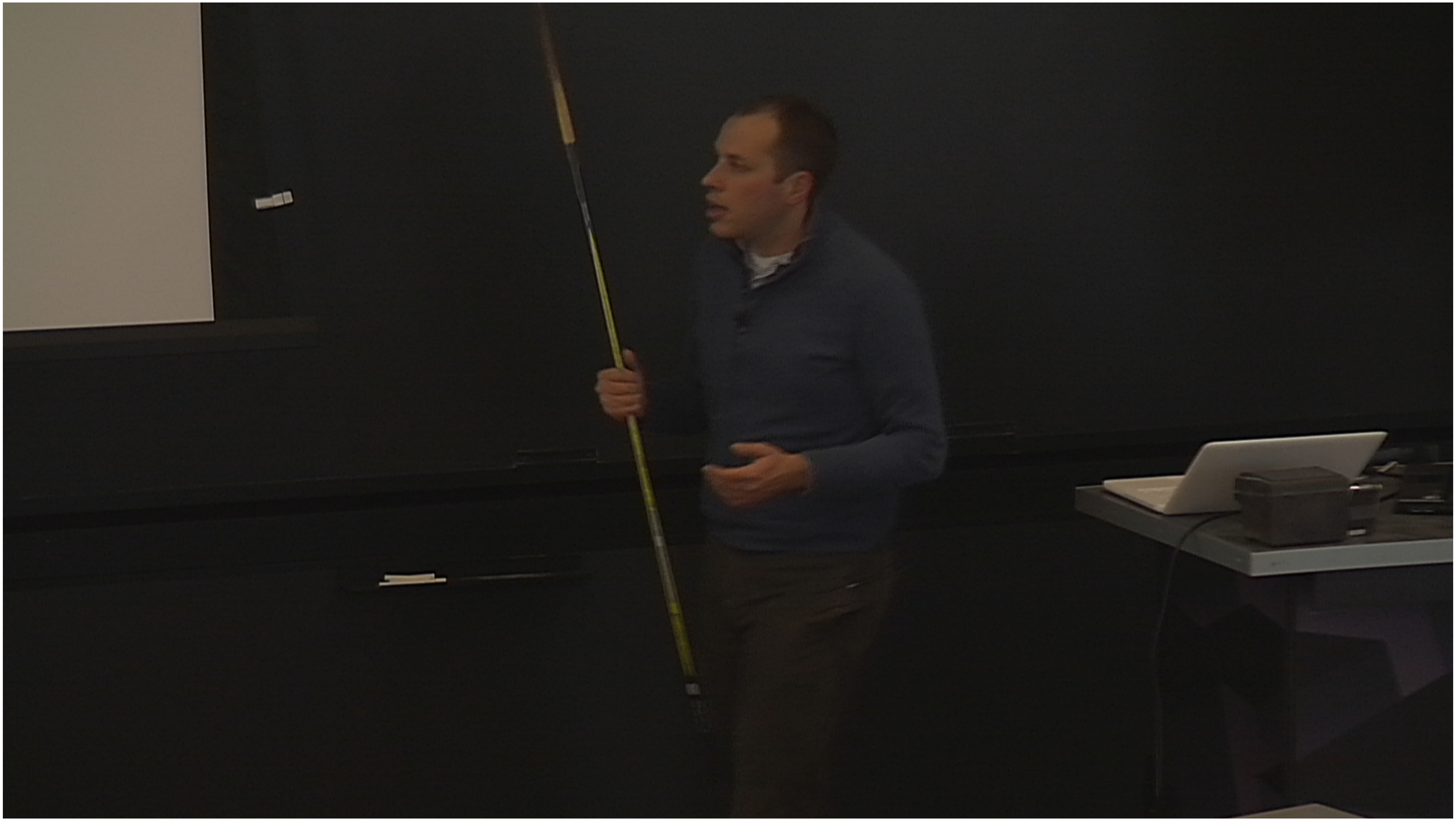
We're hopeful!

- Typically (but maybe not always) asymmetries $\lesssim 1\%$
- Small cross section poses a challenge
- Not all channels explored yet: work in progress!

Take home message

- Triple products aren't the only game in town
- New strong phase ingredients:
  - Three body decays
  - On-shell resonance
  - Different orderings
- Observation at the LHC could be possible:
  - Construct momentum asymmetry
  - Small kinematic requriements
  - Small suppressions due to lost info

35



Future directions

- Consider other processes (broader resonances?)
- Study spin dependence
- Full blown collider study

36