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

Joshua Berger

Cornell University

October 24, 2011

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

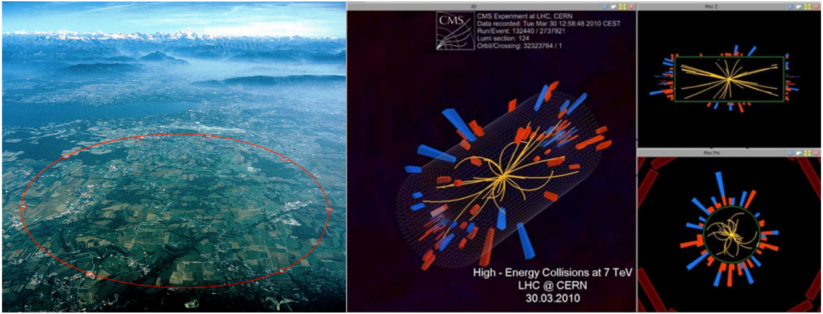
J.B., Monika Blanke, Yuval Grossman, Shamayita Ray: 1111.xxxx

Today's menu

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

Motivation

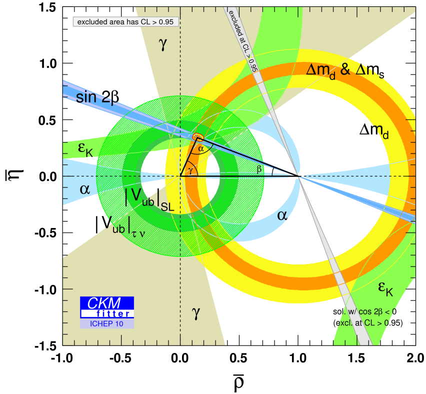
Can we see $\not{CP}$ directly at the LHC?



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

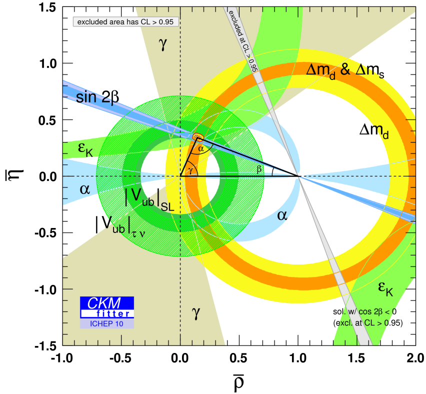
State of the art

- The SM works
- No significant deviations



State of the art

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



Why are there so many atoms?

Sakharov says:

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

SM falls short $\implies$ new sources of $\not{CP}$

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

Seeing $\not{CP}$

- TeV theories usually have new $\not{CP}$ 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

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

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

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

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 $\implies$ $i\epsilon p_1 p_2 p_3 p_4$

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?

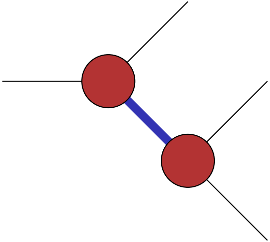
CP-even phases without mixing

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

CP-even phases in field theory

- Breit-Wigner gives us a phase:



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

Different CP-even phases

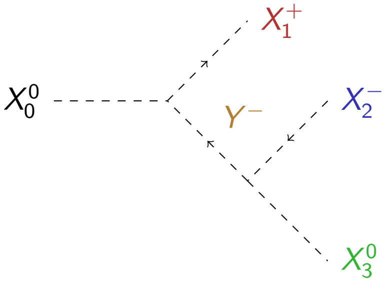
- CP-even phase from intermediate particle:
  1. Different particles $\leftrightarrow$ (Time-integrated) mixing
  2. Different virtuality $\rightarrow$ New!

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

Toy model!

The roster

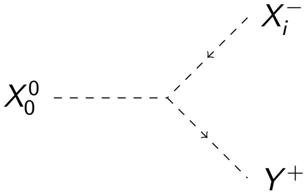
- Scalars are easy



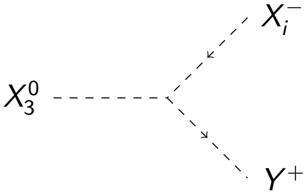
- Phase space $\Longrightarrow$ Scale hierarchy:

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

The interactions



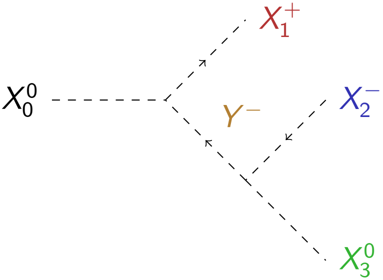
$$= -iae^{i\varphi_a}$$



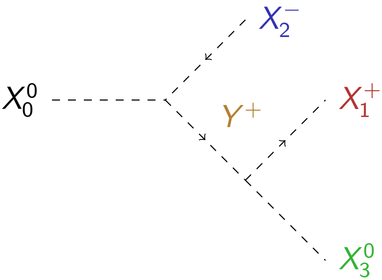
$$= -ibe^{i\varphi_b}$$

- One weak phase: $\varphi = \varphi_b - \varphi_a$

The game plan



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

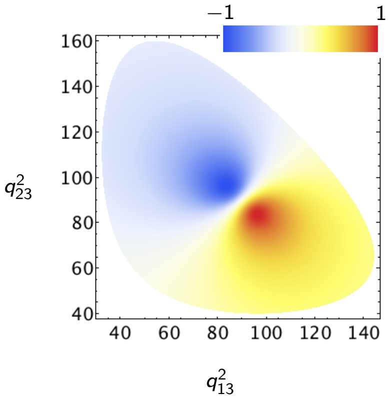


$$= \frac{|a||b|e^{-i\varphi}}{q_{13}^2 - m_Y^2 + i m_Y \Gamma_Y}$$

Different CP-odd phase, different strong phase

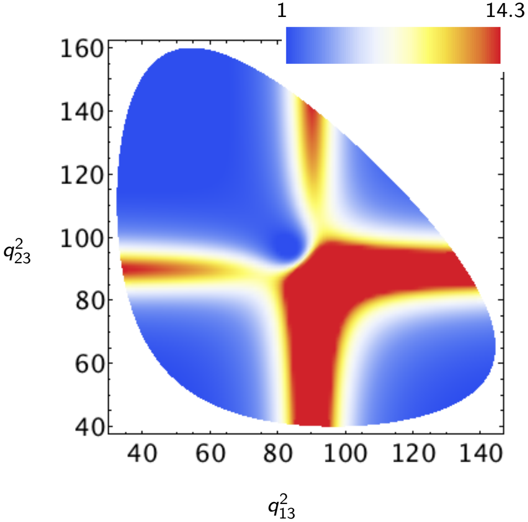
What can we measure?

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



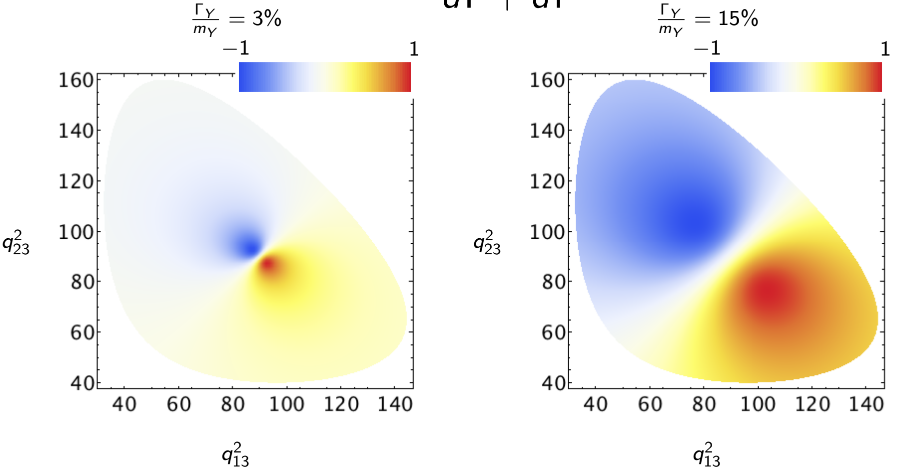
Dalitz plot: The rate

$$\frac{d\Gamma}{dq_{13}^2 dq_{23}^2}:$$



Width effects

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



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

Exploiting phase space

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

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?

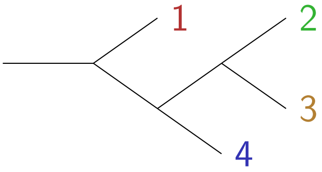

DETOUR

Triple products

- Requires non-trivial Lorentz structure
- Get terms $i\epsilon p_1 p_2 p_3 p_4$
  - Interference from P-even parts of amplitude
- In particular frame, becomes triple product:

$$\mathbf{p}_1 \cdot (\mathbf{p}_2 \times \mathbf{p}_3)$$

Pros and cons



- Pros:
  - Contributes $\pi/2$ CP-even phase
  - Generic in long decay chains
- Cons:
  - Requires lots of kinematic info: $\propto \epsilon p_1 p_2 p_3 p_4$
  - Doesn't work in 3 body decays without polarization


END
ROAD WORK

CP and kinematics

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

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: $\Gamma_Y/m_Y = 0.1$, $m_Y/m_{X_0} = 2/3$

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

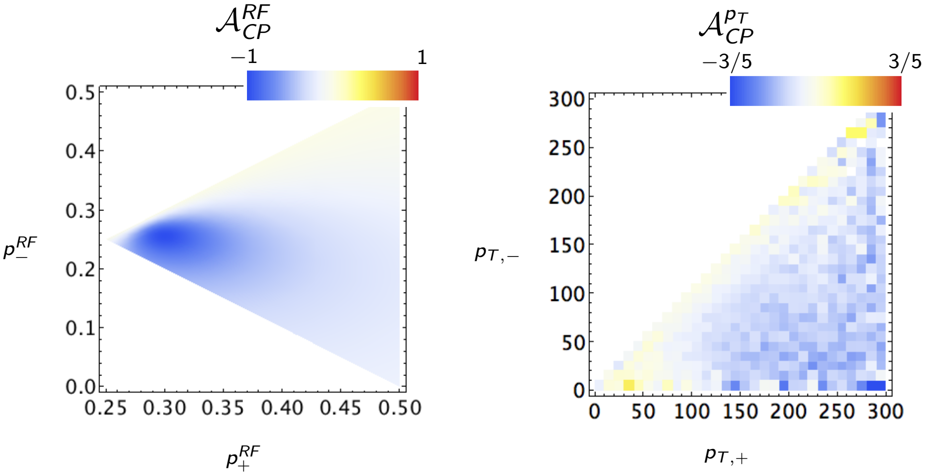
A dose of realism

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

Hadron colliders and you

- Proton rest frame is not parton rest frame
  - Only transverse variables are invariant
- Large z boost: $p_z \gg p_T$
  - Asymmetry in p_z washed out by $\sim p_T/p_z$
- $\mathcal{A}_{CP}^{|\mathbf{p}|} \approx \mathcal{A}_{CP}^{p_T}$

Reality's bite



Asymmetry still there

Asymmetry variable	Result
$\mathcal{A}_{CP}^{RF}$	0.4052
$\mathcal{A}_{CP}^{\vert\mathbf{p}\vert}$	0.1405
$\mathcal{A}_{CP}^{p_T}$	0.1412
$\mathcal{A}_{CP}^{T.P.}$	0.0008

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?

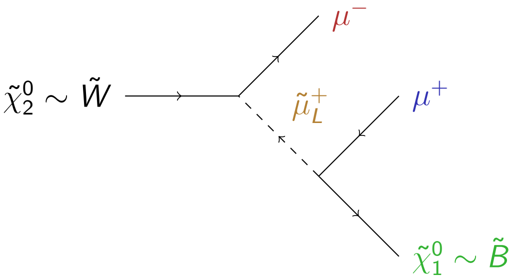
A SUSY example

Motivating the MSSM

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

The relevant particles

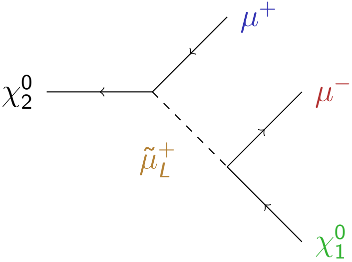
- Leptons are easy



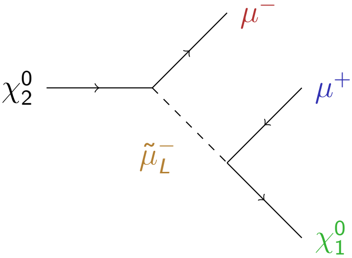
- Phase space $\implies$ Scale hierarchy:

$$m_{\chi^0_2} > m_{\tilde{\mu}_L} + m_{\mu}, \qquad m_{\tilde{\mu}_L} > m_{\mu} + m_{\chi^0_1}$$

The decay

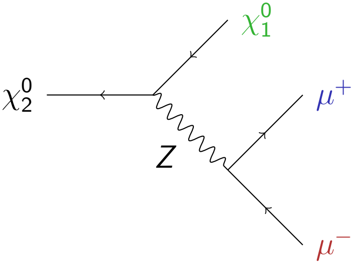


$$\propto \frac{M_1 M_2^*}{q_{13}^2 - m_{\tilde{\mu}}^2 + i\Gamma_{\tilde{\mu}} m_{\tilde{\mu}}}$$

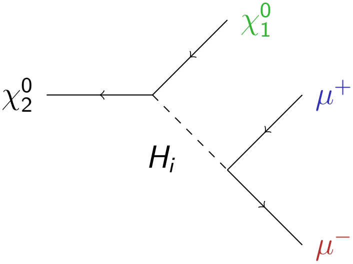


$$\propto \frac{M_1^* M_2}{q_{23}^2 - m_{\tilde{\mu}}^2 + i\Gamma_{\tilde{\mu}} m_{\tilde{\mu}}}$$

Real life is complicated



$$\propto N^*_{42} N_{41} - N^*_{32} N_{31}$$



$$\propto Y_\mu$$

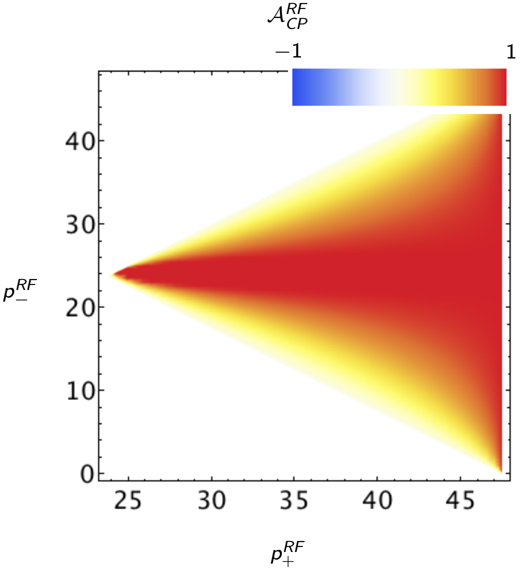
Narrow width issues

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

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

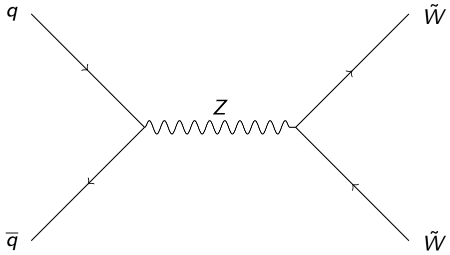
Asymmetry in phase space

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



Producing Neutralinos

- Pair production of neutralinos suppressed



$$\sim N^*_{42} N_{42} - N^*_{32} N_{32}$$

- Best bet: associated production $pp \to \tilde{\chi}^0_2 \tilde{\chi}^\pm_i$
- Somewhat small production cross section

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!

Conclusions

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

Future directions

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