Search for CP Violations at Colliders

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Outline

- CP violating phases in SUSY (MSSM)
- Constraints on SUSY CP phases : SUSY CP problem

  Solutions to SUSY CP problem
- CP violating Observables at collider

CP Violating Phases in the MSSM

- **First, consider only flavor-independent phases and neglect relative phases in the gaugino sector**

SUSY parameter $W = \mu H_u H_d$ Higgsino mass

soft SUSY breaking parameters

$$\mathcal{L} = -\frac{1}{2} m_\lambda \lambda\lambda - A \left(h_u Q H_u \bar{u} - h_d Q H_d \bar{d} - h_e L H_d \bar{e} \right) - \mu B H_u H_d \; + \; h.c.$$

Gaugino mass Trilinear soft mass term B term for Higgs

Naively there are four CP violating phases, but only two of them are physical!

- **In the absence of the parameters above, two additional flavor conserving global U(1)'s: $U(1)_{PQ}$ and $U(1)_{R\text{-}PQ}$**
- **We treat dimensionful parameters in non-gauge couplings which break the two U(1)'s as spurions with charges assigned to compensate those of fields. Dimopoulos and Thomas 1995**

$$W = \mu H_u H_d$$

$$\begin{aligned}\mathcal{L} &= -\frac{1}{2} m_\lambda \lambda\lambda - \mu B H_u H_d \\ &\quad -A\left(h_u Q H_u \bar{u} - h_d Q H_d \bar{d} - h_e L H_d \bar{e}\right) \;+\; h.c.\end{aligned}$$

	$U(1)_{PQ}$	$U(1)_{R-PQ}$
m_λ	0	-2
A	0	-2
μB	-2	0
μ	-2	2
H_u	1	0
H_d	1	0
$Q\bar{u}$	-1	2
$Q\bar{d}$	-1	2
$L\bar{e}$	-1	2

- **Physical phases should be invariant under reparametrization: linear combination of phases with zero total charge under both U(1)'s.**

$$m_\lambda \mu(\mu B)^*, \qquad A\mu(\mu B)^*, \qquad A^* m_\lambda$$

Only two of them are independent.

	$U(1)_{PQ}$	$U(1)_{R-PQ}$
m_λ	0	-2
A	0	-2
μB	-2	0
μ	-2	2
H_u	1	0
H_d	1	0
$Q\bar{u}$	-1	2
$Q\bar{d}$	-1	2
$L\bar{e}$	-1	2

Flavor dependent phases and phase in the gaugino sector,

Two relative phases between gaugino masses $m_\lambda^{i*} m_\lambda^j$

Flavor dependent phases, Lebedev 2002

E.g., relative phases between off-diagonal A terms;
For the squark sector, at most 28 independent phases

$$\phi_0 = \mathrm{Arg}\left[(Y^d Y^{d\dagger})_{12} (Y^d Y^{d\dagger})^*_{13} (Y^d Y^{d\dagger})_{23}\right] ,$$

$$\phi_i^a = \epsilon_{ijk} \mathrm{Arg}\left[(Y^d Y^{d\dagger})_{jk} (F^a)^*_{jk}\right] ,$$

$$\chi_i^a = \epsilon_{ijk} \mathrm{Arg}\left[(A^{u\dagger} Y^u + \mathrm{h.c.})_{jk} (G^a)^*_{jk}\right] ,$$

$$\xi_i^a = \epsilon_{ijk} \mathrm{Arg}\left[(A^{d\dagger} Y^d + \mathrm{h.c.})_{jk} (H^a)^*_{jk}\right] ,$$

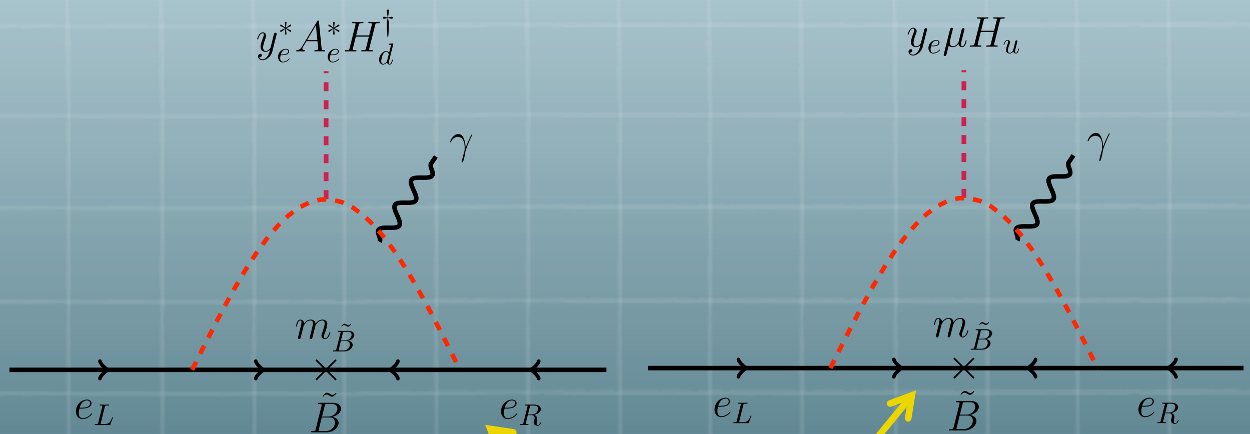
$$F^a = \{M^{2q_L}, A^u A^{u\dagger}, A^d A^{d\dagger}, A^u Y^{u\dagger} + \mathrm{h.c.}, A^d Y^{d\dagger} + \mathrm{h.c.}\} ,$$
$$G^a = \{M^{2u_R}, A^{u\dagger} A^u\} ,$$
$$H^a = \{M^{2d_R}, A^{d\dagger} A^d\} .$$

SUSY CP problem

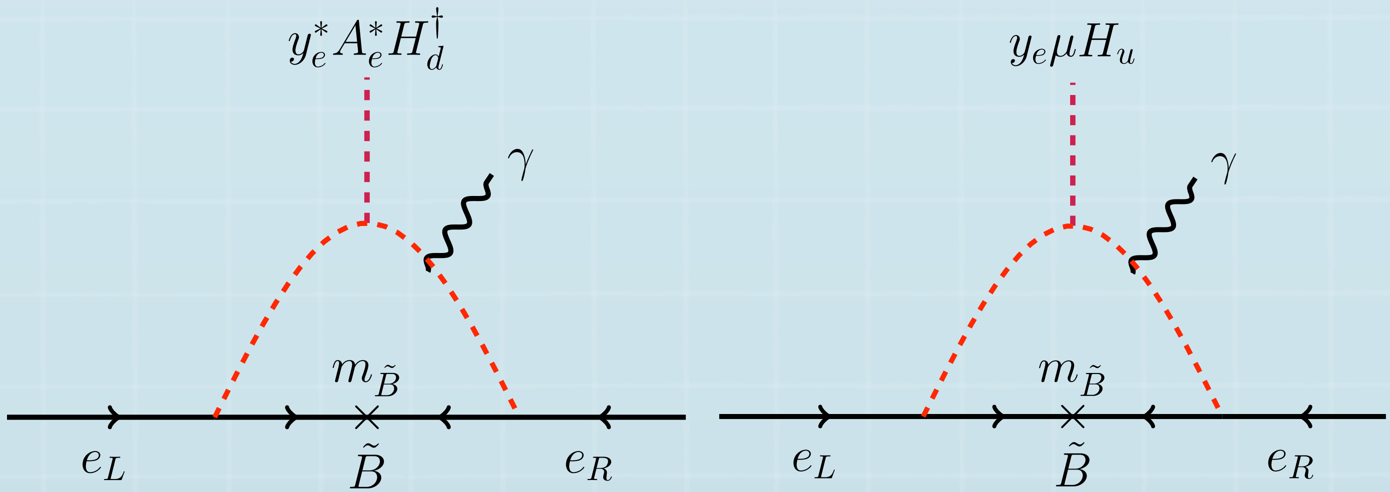
- **The fermion electric dipole moments receive one-loop contributions due to superpartner exchange which for generic phases can exceed the experimental bounds**

- **Phases that are constrained, e.g::**

For a review, Ellis, Lee and Pilaftsis 2008



$m_\lambda \mu (\mu B)^*, \qquad A^* m_\lambda$



$$m_\lambda \mu (\mu B)^*, \qquad A^* m_\lambda$$

$$\frac{d_f}{e} \sim 10^{-25}\,\phi \left(\frac{100\,\mathrm{GeV}}{\tilde{m}}\right)^2 \mathrm{cm}$$

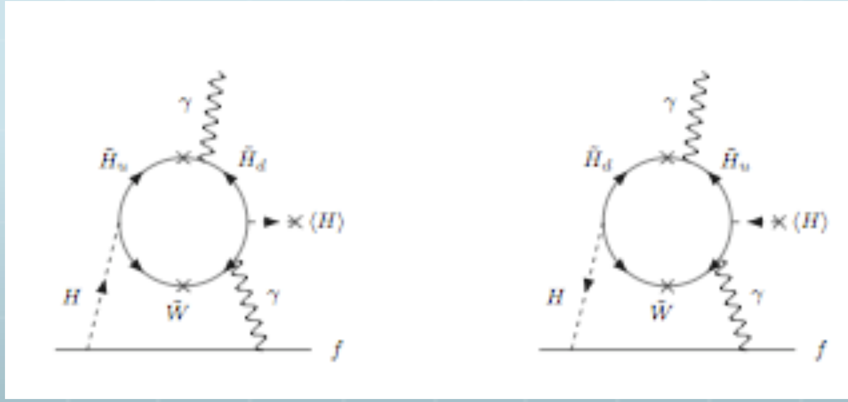
$$d_e/e < 1.05 \times 10^{-27}\,\mathrm{cm}$$
$$d_n/e < 2.9 \times 10^{-26}\,\mathrm{cm}\,(90\%)$$

$$\phi \leq 10^{-2}$$

- **Current EDM bounds are sensitive to two-loop processes**

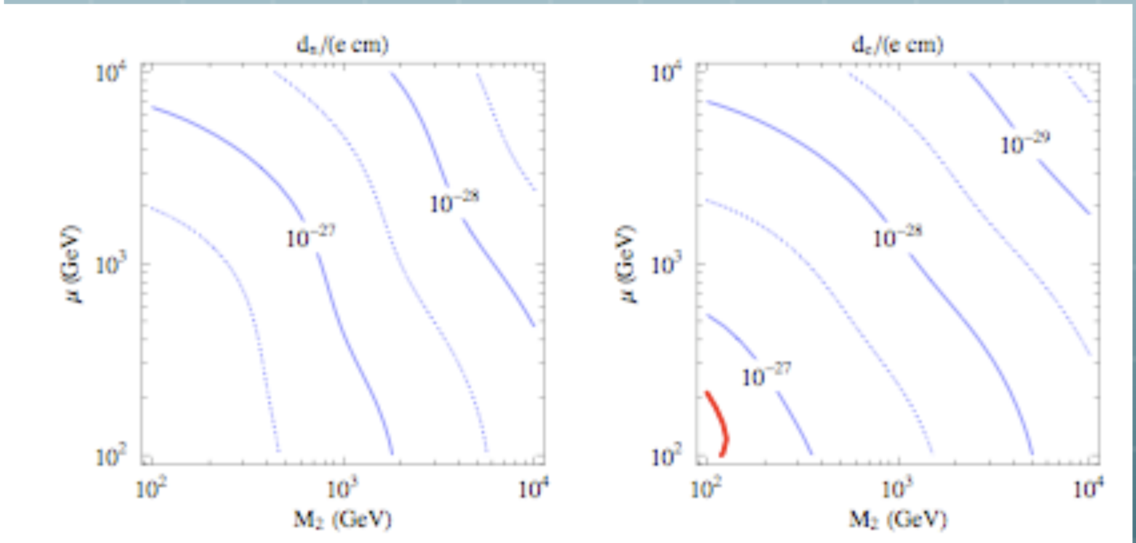
$m_\lambda \mu (\mu B)^*$

Chang, Keung , Pilaftsis, Keung; Arkani-Hamed, Dimopoulos, Giudice, Romanino; Li, Profumo, Ramsey-Musolf



$$\frac{c}{\Lambda^2} H^\dagger H F_{\mu\nu} \tilde{F}^{\mu\nu}$$

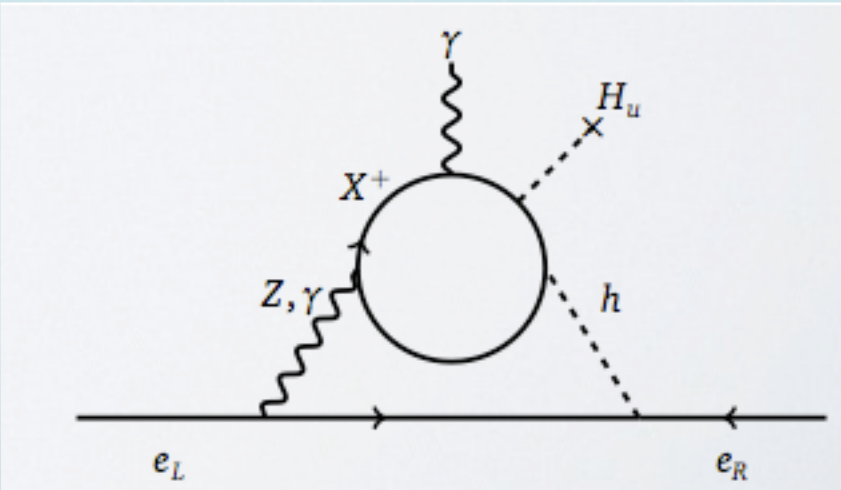
$$c = \frac{\alpha}{4\pi} g^2 \sin\beta \cos\beta \sin\phi; \Lambda^2 = M_2 \mu$$



$$\frac{d_f}{e} = -\frac{Q_f m_f c}{4\pi^2 \Lambda^2} \log \frac{\Lambda^2}{m_h^2}$$

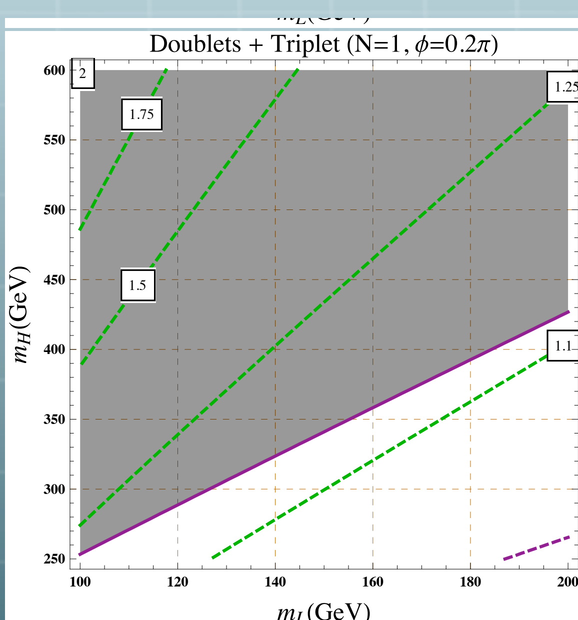
$$\frac{d_e}{e} < 10^{-27}\,\mathrm{cm} \rightarrow \Lambda \geq 700\mathrm{GeV}$$

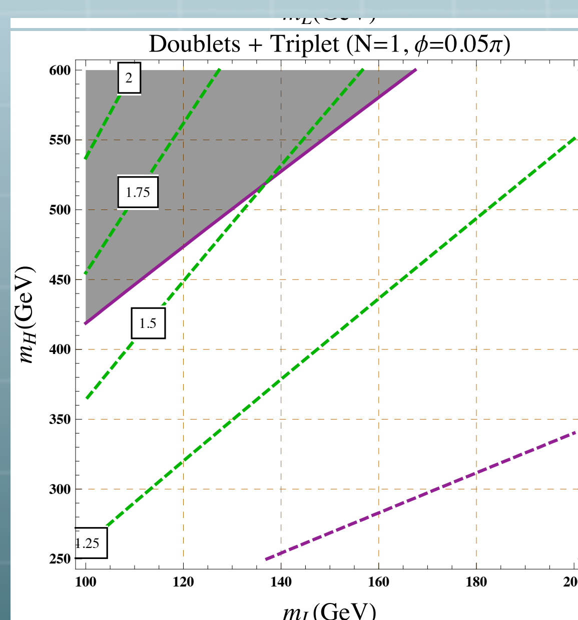
Interesting connection to a possible enhanced higgs diphoton rate:
(a possible Higgs CP problem?)



$$\mathcal{L}_M = -\left(\psi^{+Q}\ \chi^{+Q}\right)\begin{pmatrix} m_\psi & \frac{yv}{\sqrt{2}} \\ \frac{y^c v}{\sqrt{2}} & m_\chi \end{pmatrix}\begin{pmatrix} \psi^{-Q} \\ \chi^{-Q} \end{pmatrix} + cc,$$

$$\phi \;=\; \arg\left(m_\psi^* m_\chi^* y y^c\right)$$





Recently, McKeen, Pospelov and Ritz 2012;
Fan and Reece 2013;

Ways around SUSY CP problem

- Heavy SUSY scalars: suppress some EDM diagrams

a. First two generations are heavy but third generation, e.g., stops could be light

b. Split SUSY: all scalars are heavy;

There could still be two-loop chargino diagrams

Ways around SUSY CP problem

- Accidental cancelations (tuning)

  Cancelations exist between various one-loop diagrams contributing to EDMs. In other words, a tuning at 1% level is required.

  Yet combining electron, neutron and mercury EDMs, one gets a general bound of $O(10^{-2})$ on SUSY phases in certain models, e.g, mSUGRA and D-brane models. Abel, Khalil and Lebedev 2001 (Models with only two SUSY CP phases)

Ways around SUSY CP problem

- **CP symmetry** Dimopoulos and Thomas 1995

  An analogous SUSY PQ mechanism: SUSY phases are dynamical fields associated with spontaneous breakings of global symmetries at high energy in the SUSY breaking sector. The vacuum can then relax near a CP conserving point.

General gauge mediation: non-minimal messenger sector Carpenter, Dine, Festuccia and Mason 2008

- **Flavor off-diagonal CP violation**

Abel, Bailin, Khalil and Lebedev 2001

Flavor-independent phases are zero and flavor off-diagonal phases are non-zero;

EDMs are suppressed but non-zero off-diagonal phases affect K and B physics

Recap

- EDM experiments are sensitive to flavor-independent phases but could still be detectable at collider given tuning
- Phases that EDM experiments are not sensitive to: off-diagonal phases; but flavor physics observables are sensitive to them.

Detect CP Violation at Collider

Asymmetries of decay rates, cross sections

Necessary conditions for a non-zero asymmetry (e.g, in decay rates)

$$\mathcal{A}_{\mathrm{CP}} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}.$$

- **Interference: Amplitude of the physical processes must be composed of at least two terms**
- **The two terms must have different CP-even ("strong") phases**
- **The two terms must have different CP-odd ("weak") phases**

- **Derivation**

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}.$$

Two processes

$$\begin{aligned}\mathcal{M}(M \to f) &= |a_1| e^{i(\delta_1 + \phi_1)} + |a_2| e^{i(\delta_2 + \phi_2)}, \\ \mathcal{M}(\bar{M} \to \bar{f}) &= |a_1| e^{i(\delta_1 - \phi_1)} + |a_2| e^{i(\delta_2 - \phi_2)}.\end{aligned}$$

Strong phases weak phases

$$\Gamma(M \to f) \propto |M(M \to f)|^2 \quad \Gamma(\bar{M} \to \bar{f}) \propto |M(\bar{M} \to \bar{f})|^2$$

$$\mathcal{A}_{\rm CP} \propto |a_1||a_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2),$$

Weak phases: CKM phase in the SM; complex phases of the Lagrangian parameters in general;

Strong phases: arise from strong-interactions/electromagnetic interactions among the particles in the final state and thus not always calculable or small;
Other calculable cases: in $B \rightarrow \Psi K_S$, through the time evolution of the intermediate $B^0 - \overline{B^0}$ system;
in processes involving a propagating intermediate unstable particle

$$\mathcal{M} = \mathcal{M}_1 \frac{1}{q^2 - \underset{\substack{\uparrow \\ \text{CP even}}}{m^2} + i\Gamma m} \mathcal{M}_2,$$

A calculable strong phase $\quad \arg\left(\frac{1}{q^2 - m^2 + i\Gamma m}\right)$

Strong phases: in processes involving a propagating intermediate unstable particle

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

CP even

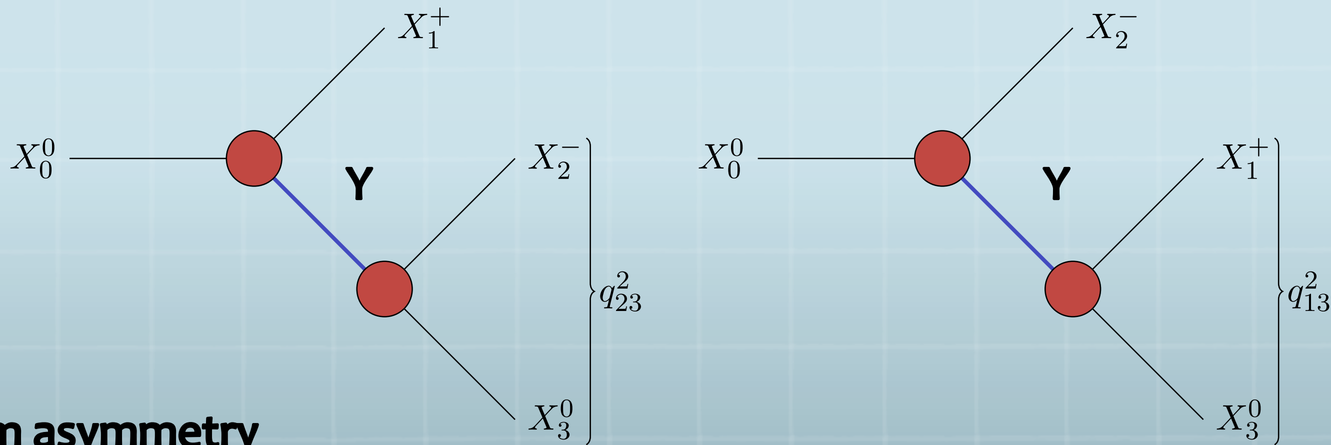
A calculable strong phase $\arg\left(\frac{1}{q^2 - m^2 + i\Gamma m}\right)$

Two ways to get different strong phases,

a. The propagating particles could be different, thus different mass/width (Eilam, Hewett, Soni 1991; Atwood, Eilam, Gronau, Soni 1994 in top, charged B decays)

b. The propagating particles could be the same, but off-shell by different amounts (Berger, Blanke, and Grossman and Ray 2011, 2012);

The propagating particles could be the same, but off-shell by different amounts (Berger, Blanke, and Grossman and Ray 2011, 2012):
Amplitudes with different orderings

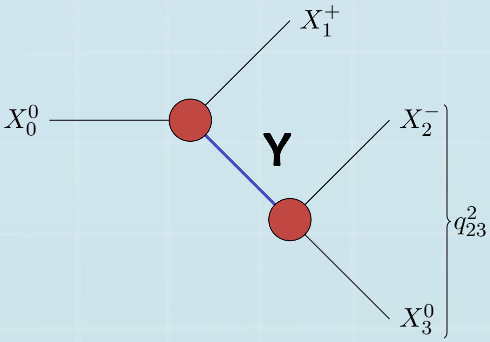


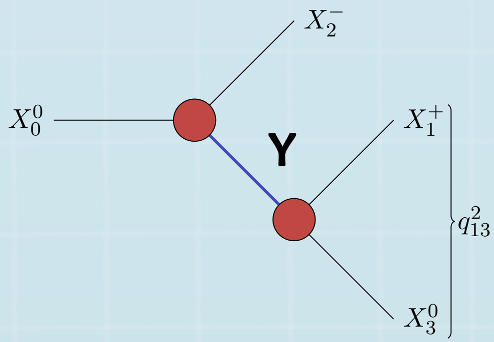
Momentum asymmetry

Differential asymmetry $$\mathcal{A}_{\rm CP}^{\rm diff} = \frac{d\Gamma/dq_{13}^2 dq_{23}^2 - d\overline{\Gamma}/dq_{13}^2 dq_{23}^2}{d\Gamma/dq_{13}^2 dq_{23}^2 + d\overline{\Gamma}/dq_{13}^2 dq_{23}^2}\,.$$

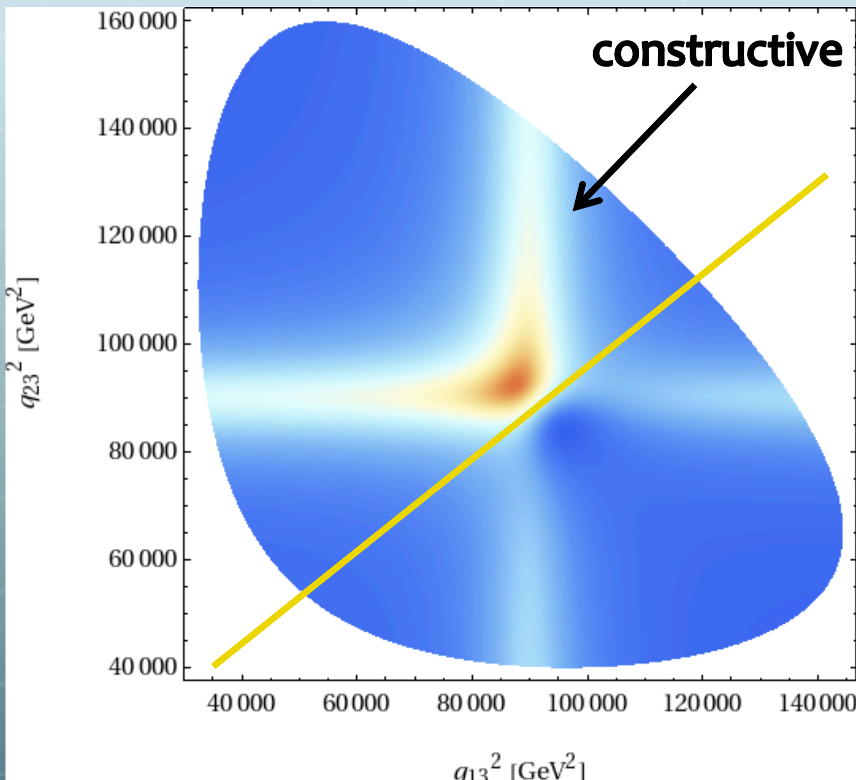
Weighted asymmetry: eliminate suppression when particles 1 and 2 are nearly degenerate

$$\mathcal{A}_{\rm CP}^{\rm PS\ wgt} = \frac{\Big(N(q_{13}^2 > q_{23}^2) - N(q_{13}^2 < q_{23}^2)\Big) - \Big(\overline{N}(q_{13}^2 > q_{23}^2) - \overline{N}(q_{13}^2 < q_{23}^2)\Big)}{N + \overline{N}}\,,$$

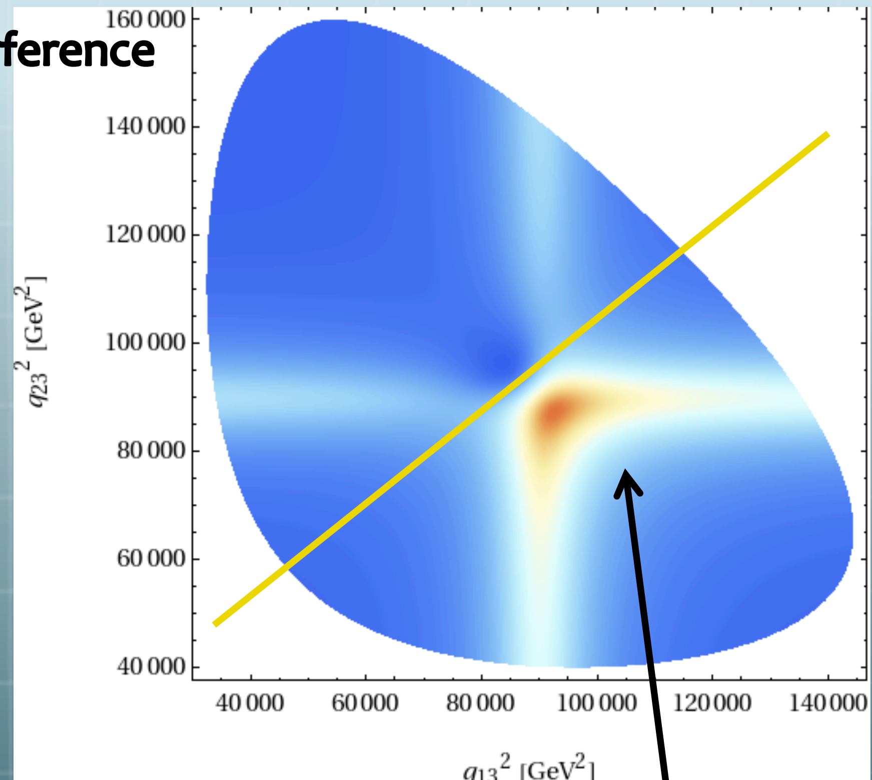




Dalitz plots for the differential rates of CP conjugate processes



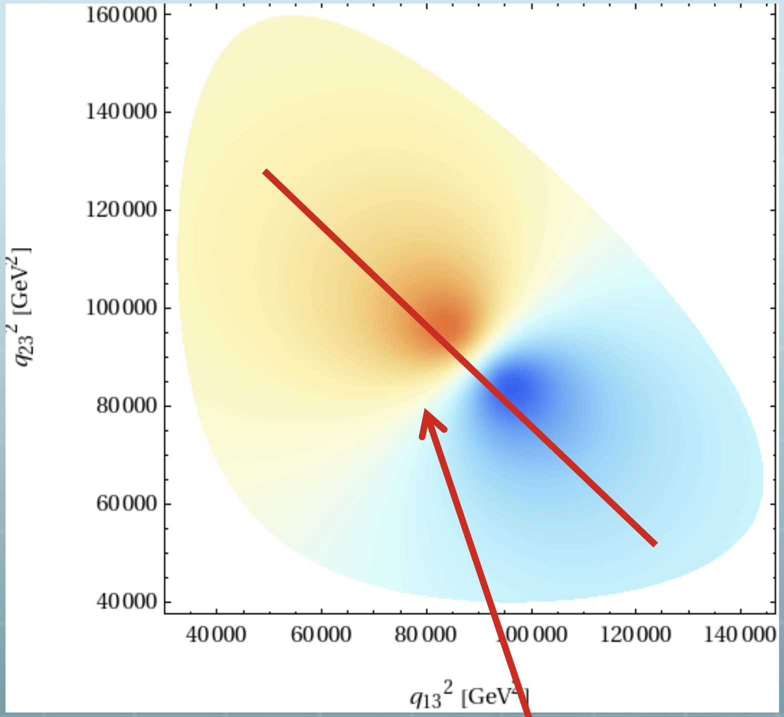
constructive interference

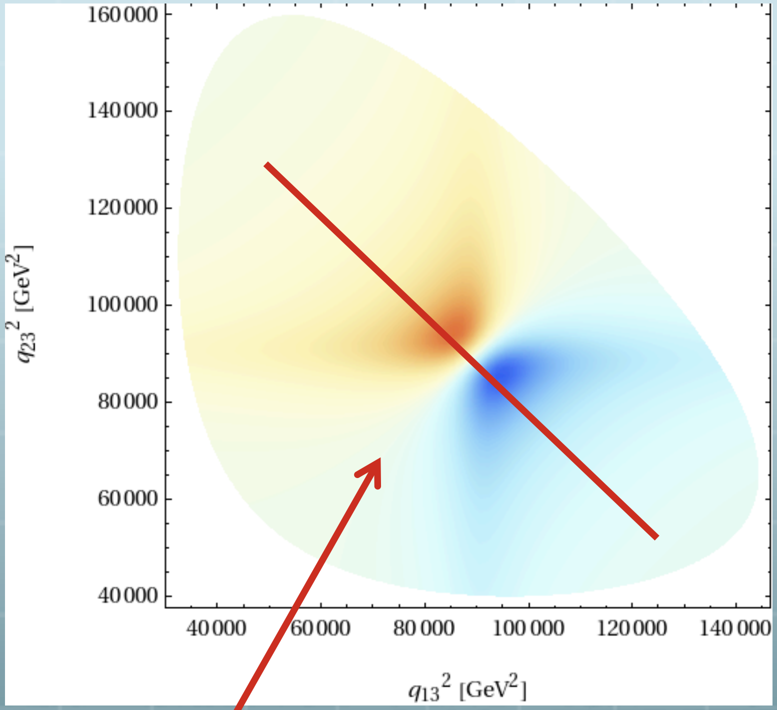


constructive interference

Asymmetry and differential asymmetry

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}. \qquad \mathcal{A}_{\rm CP}^{\rm diff} = \frac{d\Gamma/dq_{13}^2 dq_{23}^2 - d\overline{\Gamma}/dq_{13}^2 dq_{23}^2}{d\Gamma/dq_{13}^2 dq_{23}^2 + d\overline{\Gamma}/dq_{13}^2 dq_{23}^2} \;.$$

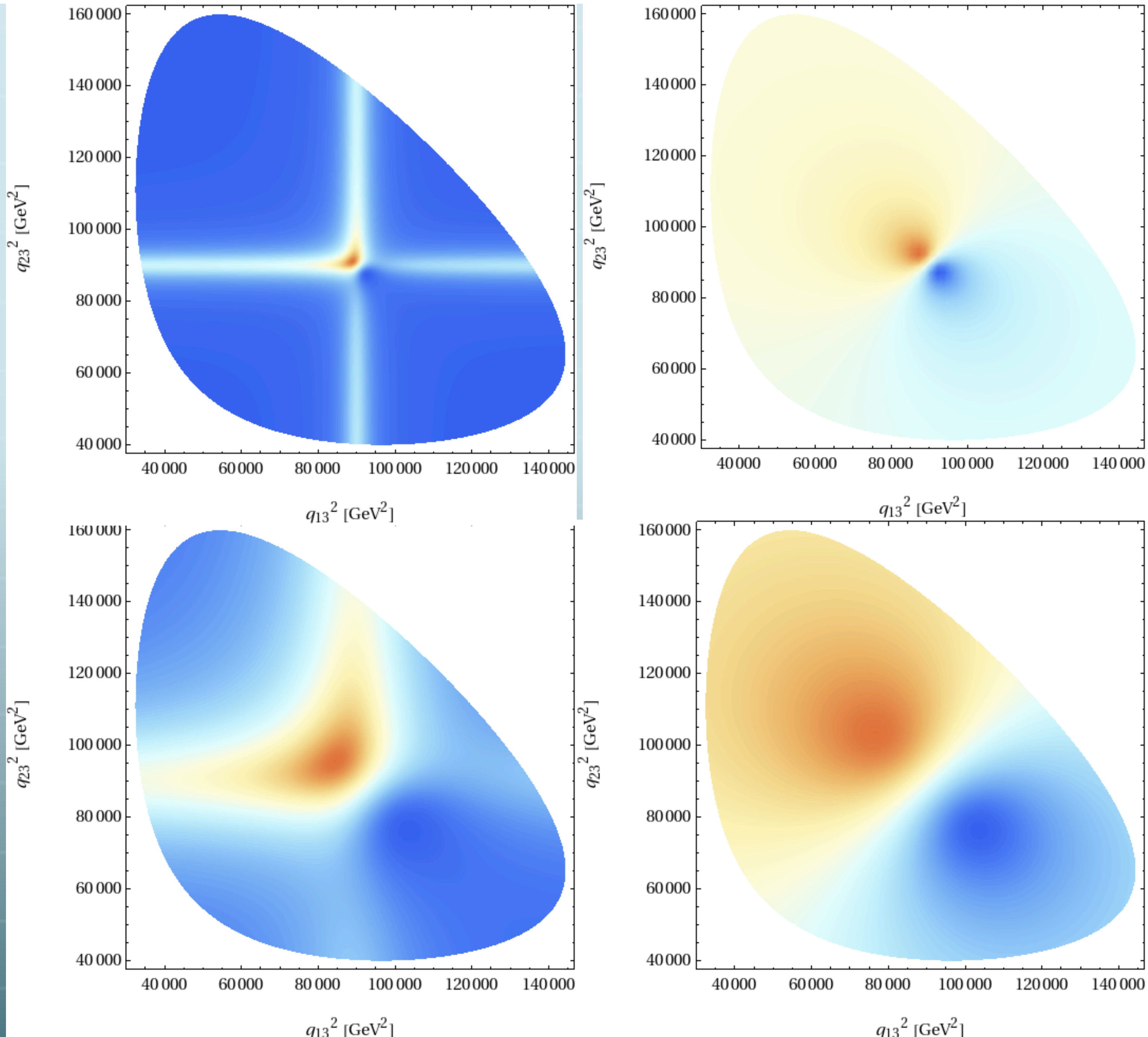




$$q_{13}^2 + q_{23}^2 = 2m_Y^2$$

$$\frac{\Gamma_Y}{m_Y} = 0.03$$

$$\frac{\Gamma_Y}{m_Y} = 0.15$$



Main problems:

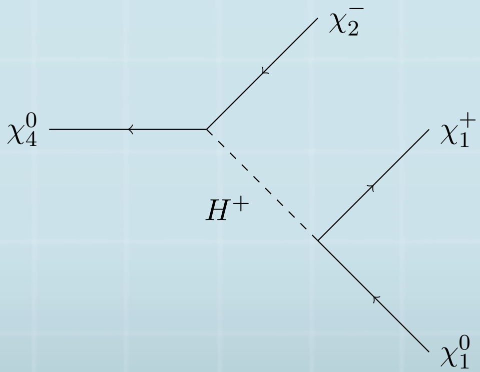
a. kinematics information is not all available, in particular, events with large boost and/or missing energy; solution: p_T asymmetries; $\mathcal{A}_{\mathrm{CP}}^{p_T} = \frac{N(p_{T,-} > p_{T,+}) - N(p_{T,+} > p_{T,-})}{N}$.

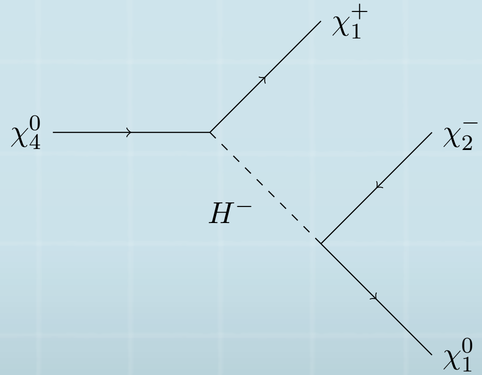
b. Energy smearing if the detector resolution is not sufficient to probe the width of the resonance;

c. Combinatorics: cannot correctly determine which particles came from the same mother particle; calculate observables using all possible combinations.

Momentum asymmetries mostly useful in cases where the CP violation occurs in a three-body decay where the final state is stable and momentum cannot be measured.

Example: $m_{\chi_4^0} \sim M_1 \gg m_{\chi_i^0}, m_{\chi_j^\pm} \sim \sqrt{|\mu M_2|} > m_Z$





$$M_1 \gtrsim 3\sqrt{|\mu M_2|}.$$

$$m_{H^\pm} \gtrsim 2\sqrt{|\mu M_2|}.$$

weak phase: $\mu(\mu B)^* m_2$

$$\mathcal{A}_{\rm CP}^{\rm PS\,wgt} \sim \frac{\Gamma_{H^\pm}|\mu m_2|}{m_{H^\pm} m_1^2}$$

Asymmetry is more evident with large width of charged Higgs and μ, M_2 close as possible to M_1 without cutting into phase space

- **Triple product asymmetries** **Valencia 1989; Kamionkowski 1990; Kayser 1990; Korner, Schilcher and Wu 1990**

$$\epsilon_{\mu\nu\alpha\beta} p_0^{\mu} p_1^{\nu} p_2^{\alpha} p_3^{\beta}$$

In the rest frame of a decaying particle $p_0 = (M, 0,0,0)$

$$\begin{aligned} \mathcal{T} &= -M \ \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3) \\ \overline{\mathcal{T}} &= -M \vec{p}_1^{\,c} \cdot (\vec{p}_2^{\,c} \times \vec{p}_3^{\,c}) \end{aligned}$$

$$\langle \mathcal{T} \rangle \sim \sin(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2) + \cos(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

<T> ≠ 0: a strong phase or CP violation

One could separate the CP violating term:

$$\langle \mathcal{T} \rangle + \langle \overline{\mathcal{T}} \rangle \sim \cos(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2).$$

- **Triple product asymmetries** **Valencia 1989; Kamionkowski 1990; Kayser 1990; Korner, Schilcher and Wu 1990**

$$\begin{aligned} \mathcal{T} &= -M\ \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3) \\ \overline{\mathcal{T}} &= -M\vec{p}_1^{\,c} \cdot (\vec{p}_2^{\,c} \times \vec{p}_3^{\,c}) \end{aligned}$$

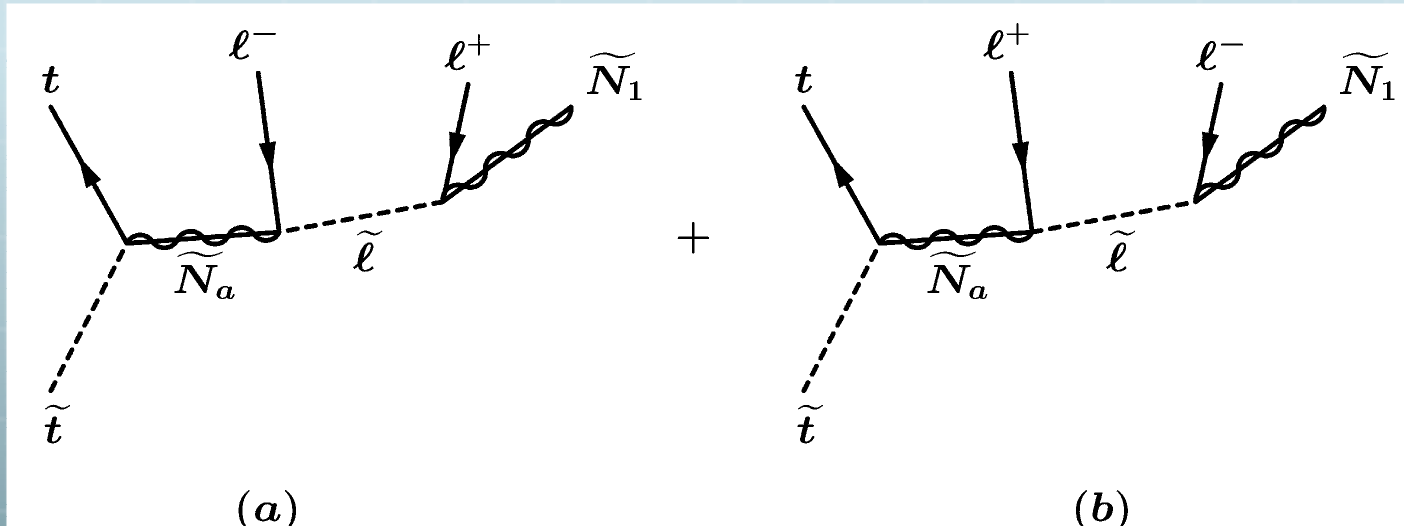
$$\langle \mathcal{T} \rangle \sim \sin(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2) + \cos(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

<T> ≠ 0: a strong phase or CP violation

Momentum asymmetries: presence of both strong and weak phases;
Triple product asymmetry: either strong phase or weak phase

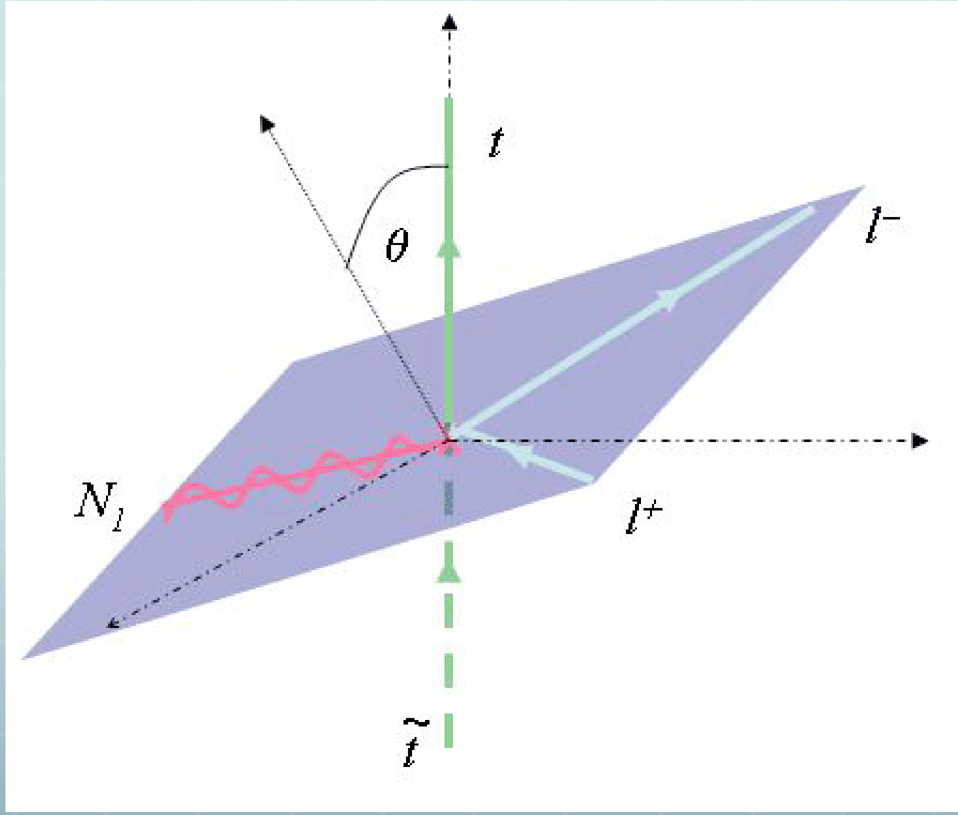
- **One example:** **Langacker, Paz, Wang and Yavin 2007; Moortgat-Pick, Rolbiecki, Tattersall and Wienemann 2009; Ellis, Moortgat, Moortgat – Pick, Smilie and Tattersall 2009, Deppisch, Kittel 2009**

$$\tilde{t} \to t + \tilde{N}_a \to t + l^+ + l^- + \tilde{N}_1$$

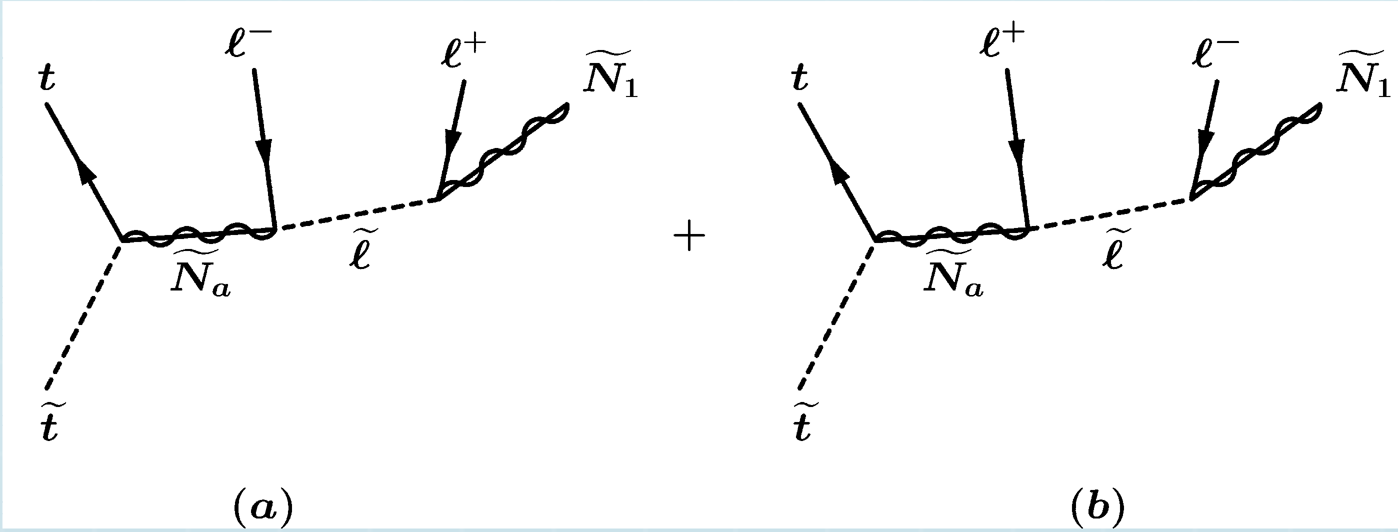


weak phase: $M_1^* M_2$, $A_t^* M_2$

$$\begin{aligned} \mathcal{T} &= -M_{\tilde{t}}\, \vec{p}_t \cdot (\vec{p}_{l^+} \times \vec{p}_{l^-}) \\ \overline{\mathcal{T}} &= -M_{\tilde{t}}\, \vec{p}_{t^c} \cdot (\vec{p}_{l^-} \times \vec{p}_{l^+}) \end{aligned}$$



$$\begin{aligned} \eta &= \frac{N_+ - N_-}{N_+ + N_-} = \frac{N_+ - N_-}{N_{total}}, \\ N_+ &= \int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta, \qquad N_- = \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta \end{aligned}$$



Amount of asymmetry depends on the spectrum. Here consider two limits:

$$a. \quad \tilde{N}_a : \text{wino}; \quad \tilde{N}_1 : \text{bino}, \quad M^2_{\tilde{l}} < M^2_{\tilde{N}_a}$$

$$\langle \epsilon_{\mu\nu\alpha\beta}\, p^{\mu}_{\tilde{t}}\, p^{\nu}_{t}\, p^{\alpha}_{l^+}\, p^{\beta}_{l^-} \rangle = \frac{1}{24} M^2_{\tilde{t}} M^2_{\tilde{N}_a} \left(\frac{1}{\pi}\frac{\Gamma_{\tilde{l}}}{M_{\tilde{l}}}\right) \sqrt{\mu_1} \int dx_+ dx_- f(x_+, x_-)$$
$$\times \quad \sin\left(2\varphi^{l1}_L - 2\varphi^{la}_L\right)$$

Suppression from width of slepton ~ 1/300

Weak phase: $M_1^* M_2$

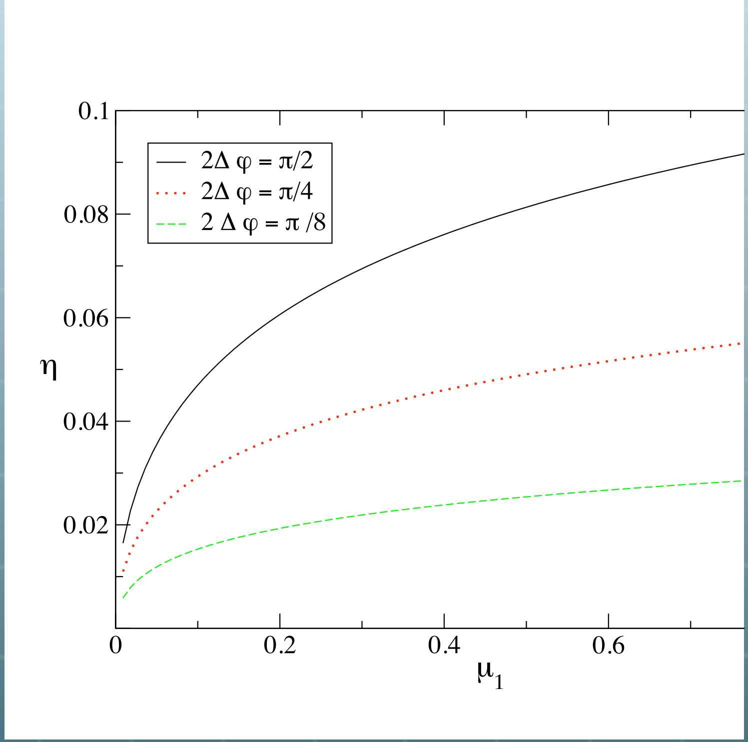
Asymmetry comes from the ratio of an off-shell process to an on-shell one; when both processes are on-shell, no interferences!

$$b. \quad \tilde{N}_a : \text{ wino}; \quad \tilde{N}_1 : \text{ bino}, \quad M^2_{\tilde{l}} \gg M^2_{\tilde{N}_a}$$

$$\eta = \frac{\sqrt{\mu_1}}{2} \left(\frac{F(\mu_1)}{G_1(\mu_1) + G_2(\mu_1)\cos(2\Delta\varphi)} \right) \sin(2\Delta\varphi)$$

$$\mu_1 = \frac{M^2_{\tilde{N}_1}}{M^2_{\tilde{N}_a}}$$

η is an O(0.1) number for decays through off-shell sleptons!



Ignoring experimental limitations, assuming Gaussian statistics, the number of events needed

$$N \sim \frac{100}{\sin^2(2\Delta\varphi)}$$

~ Arg ($M_1^* M_2$)

$$g_L^{la} = |g_L^{la}| \ \exp(i\varphi_L^{la})$$
$$\Delta\varphi = \varphi_L^{l1} - \varphi_L^{la}$$

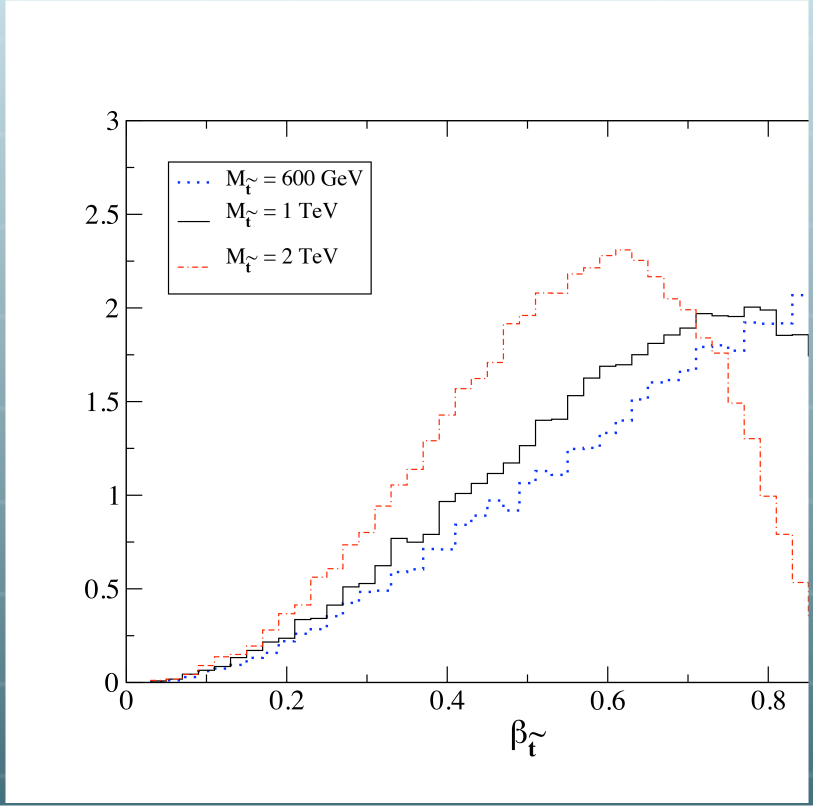
$M_{\tilde{t}_L}$	$\sigma\ (fb)$	$N[t\ell^+\ell^-]$ $\mathcal{L} = 300 fb^{-1}\ (1\ ab^{-1})$
500 GeV	300	7300 (24000)
800 GeV	20	560 (1800)
1 TeV	4	120 (400)
1.2 TeV	1	30 (100)

Table 1. The production cross-section for $\tilde{t}_L \tilde{t}_L^c$ is shown in the middle column. The branching ratio for the reaction $\tilde{t} \to t + \tilde{N}_a \to t + l^+ + l^- + \tilde{N}_1$ was calculated using $M_{\tilde{l}} = 300$ GeV, $M_{\tilde{N}_2} = 140$ GeV, $M_{\tilde{N}_1} = 100$ GeV, and assuming that the gluino and squarks are sufficiently heavy to have little effect. (Under these assumptions and wino/bino dominated $\tilde{N}_{2,1}$ the branching ratio for $\tilde{t} \to t\tilde{N}_2$ is slightly less then 1/3 because of the top's mass, and those for $\tilde{N}_2 \to e^+e^-\tilde{N}_1$ or $\mu^+\mu^-\tilde{N}_1$ are about 1/6 each.)

Experimental limitations:

a. Impossible to reconstruct the rest frame of the decaying particle due to the missing energy;

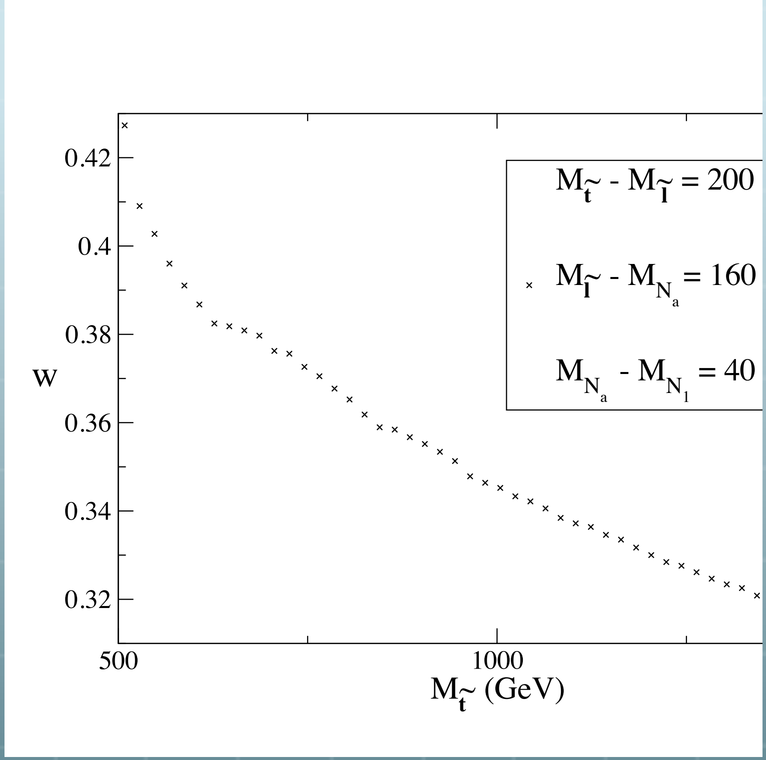
The decaying particles are produced very close to the threshold; thus could flip the sign of p_t or change the transverse orientation of the leptons

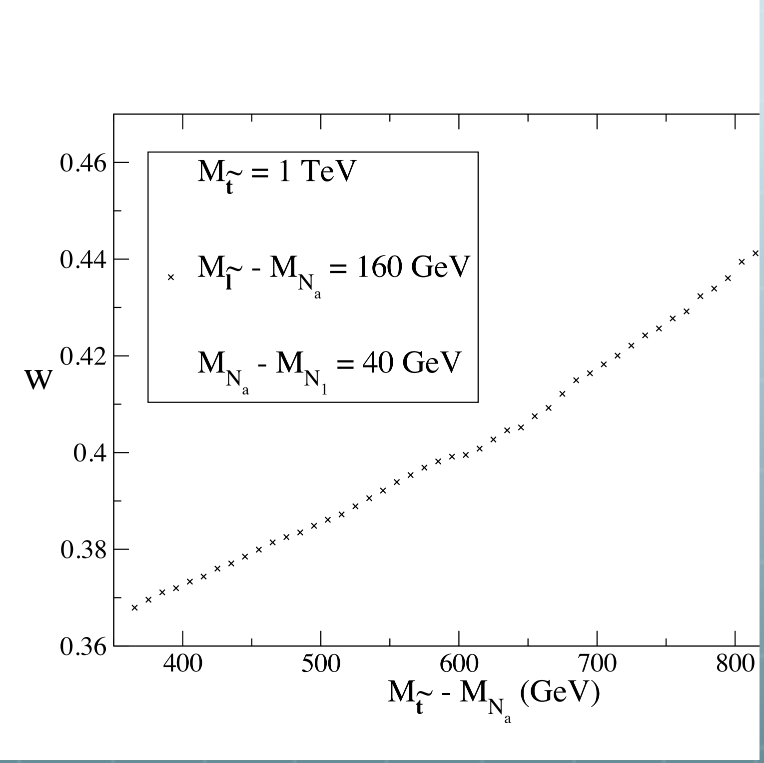


$$\eta_{lab} = \frac{N_+^{(lab)} - N_-^{(lab)}}{N_+^{(lab)} + N_-^{(lab)}} = \mathcal{D}\left(\frac{N_+^{(\tilde{N})} - N_-^{(\tilde{N})}}{N_+^{(\tilde{N})} + N_-^{(\tilde{N})}}\right)$$

$$\mathcal{D} = 1 - 2w$$

Dilution factor





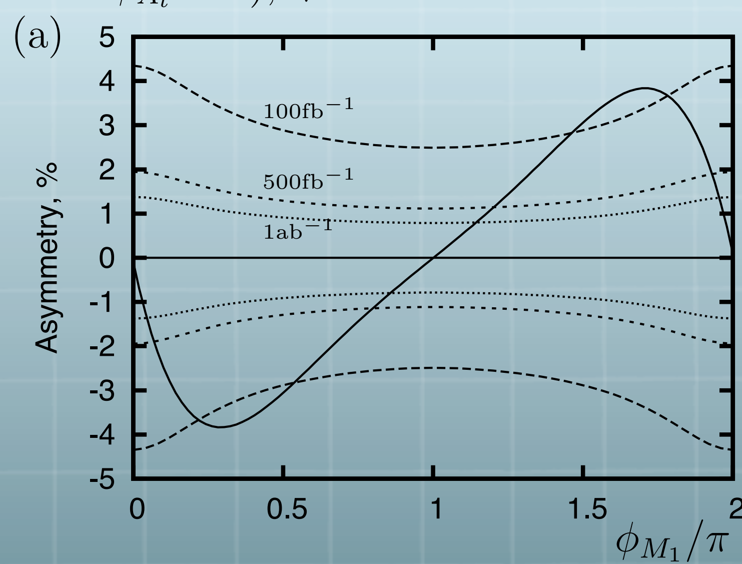
fix $M_{\tilde{t}} - M_{\tilde{N}_a}$ $M_{\tilde{t}} \uparrow w \downarrow D \uparrow$ fix $M_{\tilde{t}}$ $M_{\tilde{t}} - M_{\tilde{N}_a} \downarrow w \downarrow D \uparrow$

Other observables: $\mathcal{T}_b \sim \vec{p}_b \cdot (\vec{p}_{l^+} \times \vec{p}_{l^-})$

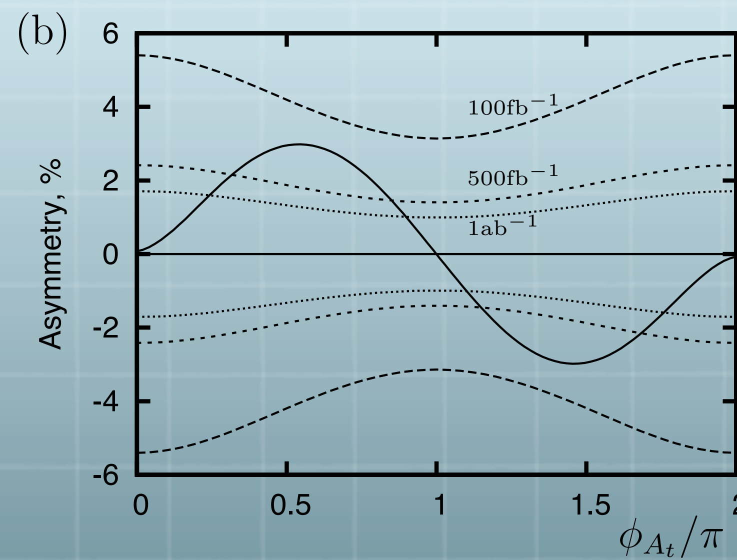
$$\mathcal{T}_{tb} \sim \vec{p}_b \cdot (\vec{p}_t \times \vec{p}_{l^\pm})$$

Include PDF (MRST 2004LO), Ellis, Moortgat, Moortgat – Pick, Smilie and Tattersall 2009

$\mathcal{A}_{\mathcal{T}_t}$, Scenario A ($M_1 = 130$ GeV, $\phi_{A_t} = 0$), $\sqrt{\hat{s}} = 14$ TeV



$\mathcal{A}_{\mathcal{T}_{tb}}$, Scenario A ($\phi_{M_1} = 0$), $\sqrt{\hat{s}} = 14$ TeV



$$m_{\tilde{t}_1} = 396.5\,\mathrm{GeV}, m_{\tilde{t}_2} = 595\,\mathrm{GeV}$$

A measurement of an asymmetry with an accuracy of a few % might be possible with 100 fb^{-1} data

b. Efficiency of identifying the top or anti-top, determining its charge and momentum, combinatorics (which pair of leptons come from top or anti-top)….

c. Strong phase contribution: electromagnetic interaction among leptons in the final state, of order $O(\alpha/\pi)$; finite width of sleptons, negligible for the more interesting off-shell slepton case.

CP-odd triple gauge couplings

Dim-6 operators contributing to CP-odd TGCs also contribute to EDMs;
EDM constraints are much stronger than constraints from CP-odd TGCs without tuning

Collider study: Han and Li 2009;

$$pp \to W^+W^- \to l^+l^-\nu\bar{\nu}$$

$$\Phi \equiv \mathrm{sgn}((\vec{\ell}^+ - \vec{\ell}^-)\cdot\hat{z})\ \sin^{-1}(\hat{\ell}^+ \times \hat{\ell}^-)\cdot\hat{z},$$

$$\mathcal{A}_\Phi \equiv \frac{N_{\Phi>0} - N_{\Phi<0}}{N_{\Phi>0} + N_{\Phi<0}},$$

With 100 fb^{-1} data at 14 TeV LHC, one could see ~ 5 σ signal if the CP-odd couplings ~ 0.1

Conclusions

- EDM impose strong constraints on SUSY CP phases
- Still with tuning, one could still hope to explore CP violation directly at the colliders
- Quite a few challenges for measuring CP violating observables at the colliders: requires more theoretical and experimental inputs !