Genuine CP-Odd Observables and ZZH Coupling

Tao Han *
Univ. of Wisconsin–Madison
(LCWS 2010, March 28, 2010)

*Collaborators: Jing Jiang; Neil Christensen, Y.-C. Li

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General ZZH Vertex
CP-Odd Observables at ILC
CP-Odd Observables at LHC

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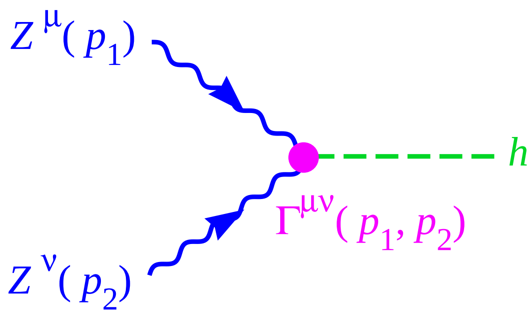

$$\Gamma^{\mu\nu}(p_1,p_2) = i\frac{2}{v}\, h[a\ M_Z^2 g^{\mu\nu} + b\ (p_1^\mu p_2^\nu - p_1\cdot p_2 g^{\mu\nu}) + \tilde{b}\ \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}]$$

$a = 1,\ b = \tilde{b} = 0$ for SM; $a,\ b$ terms: CP-even; $\tilde{b}$ term: CP-odd.

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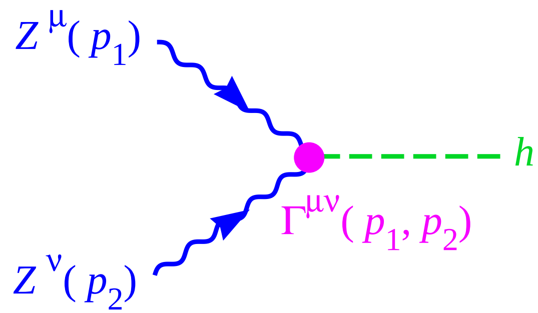

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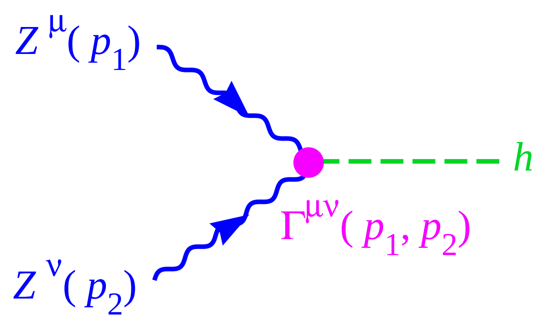

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In an “effective field theory”, operators $\frac{g^2}{\Lambda^2} HHW^{\mu\nu}W_{\mu\nu},\ \ \frac{g^2}{\Lambda^2} HHW^{\mu\nu}\tilde{W}_{\mu\nu}$,
natural size: $a,\ b,\ \tilde{b} \sim \mathcal{O}(\frac{1}{16\pi^2} \sim 1)$.

Consider direct production:

$$e^-(p_1)\ e^+(p_2) \to e^-(q_1)\ e^+(q_2)\ h(q_3)$$

via both Zh (Bjorken/Higgs-strahlung) and ZZ (Fusion).

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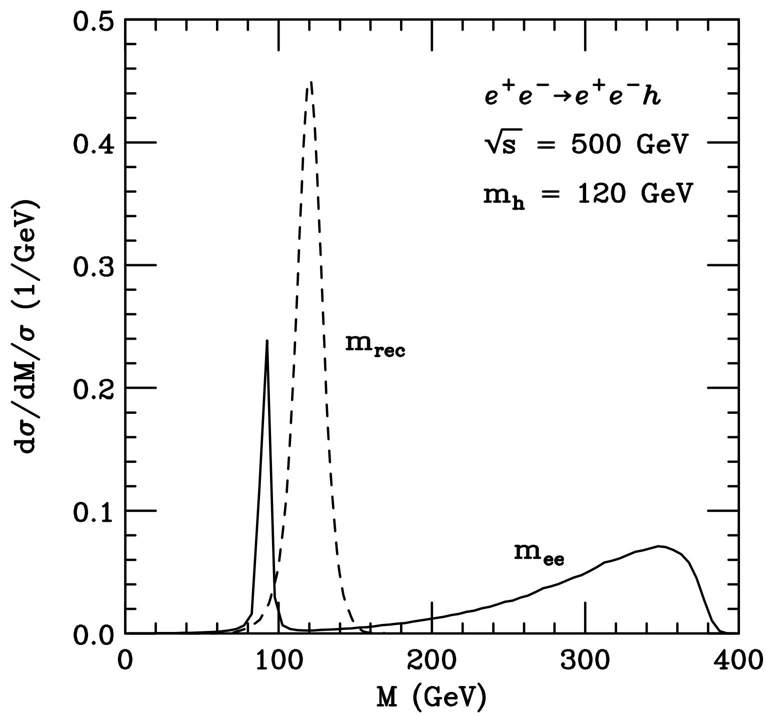
- Recoil mass, regardless the Higgs decay mode:
  $(p_1 + p_2 - q_1 - q_2)^2 = m_h^2$
- Distinctive $m_{e^+e^-}$ spectrum:

Bjorken process and Fusion can be separated.



Cross section rates:

Zh Bjorken process:* $\sigma \propto \frac{1}{s}$; ZZ fusion:† $\sigma \propto log^2(\frac{s}{M_Z^2})$.

*K. Hagiwara and M. Stong; V. Barger et al.; A. Skjold and P. Osland; ...

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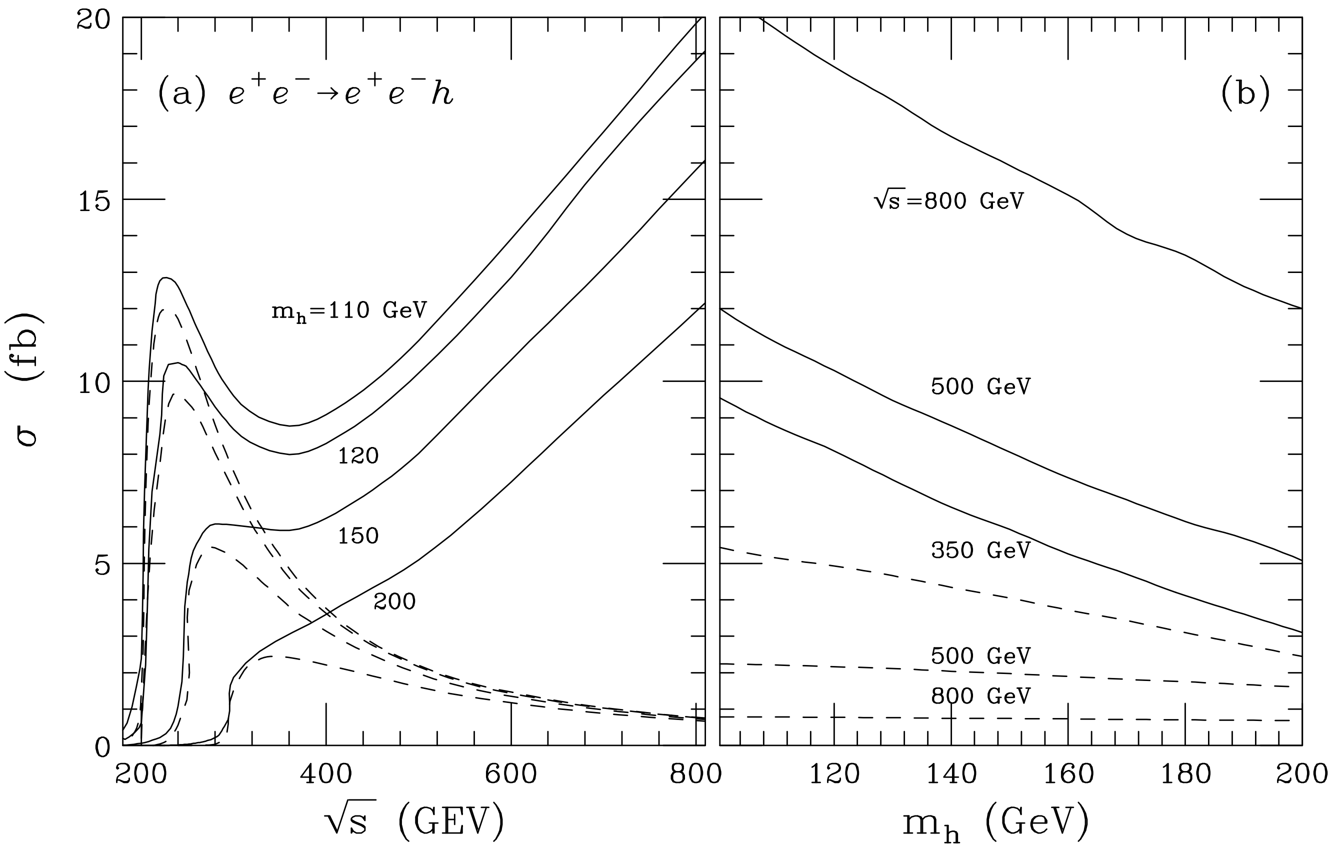
For instance: for $\sqrt{s} = 500$ GeV, $m_h = 120$ GeV:

$\sigma(fusion) > 2\sigma(Bjorken,\ e^+e^- + \mu^+\mu^-) \approx 10$ fb^{-1}.



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CP-odd observables at ILC

$$e^-(p_1)\ e^+(p_2) \to e^-(q_1)\ e^+(q_2)\ h(q_3)$$

With longitudinally polarized beams, under CP:

$$\mathcal{M}_{--}(\vec{p}_1,\vec{p}_2;\ \vec{q}_1,\vec{q}_2) \Rightarrow \mathcal{M}_{++}(\vec{p}_1,\vec{p}_2;\ -\vec{q}_2,-\vec{q}_1), \quad (1)$$

$$\mathcal{M}_{-+}(\vec{p}_1,\vec{p}_2;\ \vec{q}_1,\vec{q}_2) \Rightarrow \mathcal{M}_{-+}(\vec{p}_1,\vec{p}_2;\ -\vec{q}_2,-\vec{q}_1). \quad (2)$$

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Based on Eq. (1), construct a LR asymmetry:

$$\mathcal{A}_{hel} = \sigma_{--} - \sigma_{++}$$

Based on Eq. (2), construct angular FB asymmetries:

$$\mathcal{A}_{FB} = \sigma^F_{-+} - \sigma^B_{-+}.$$

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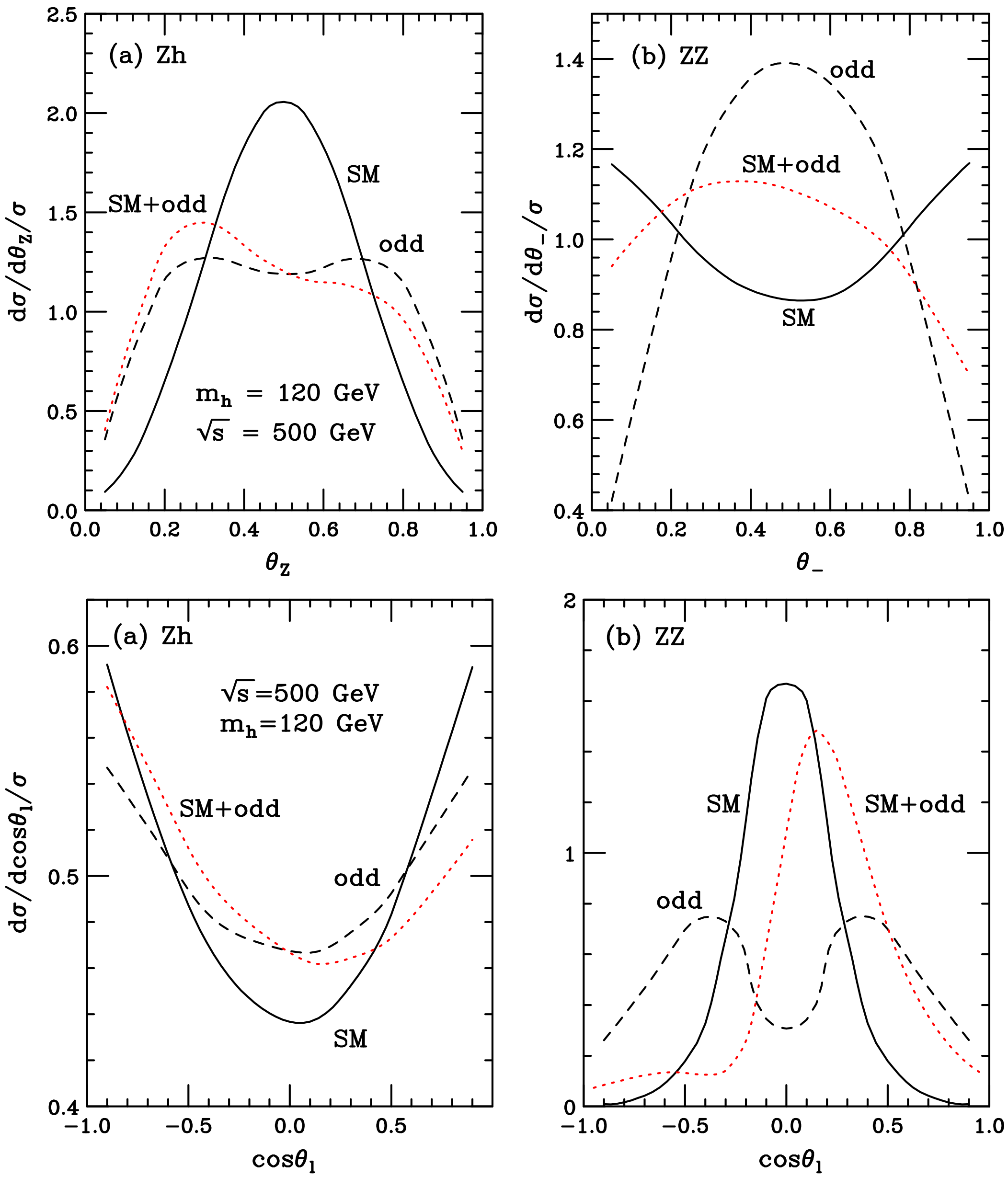
Such as CP-odd observables:

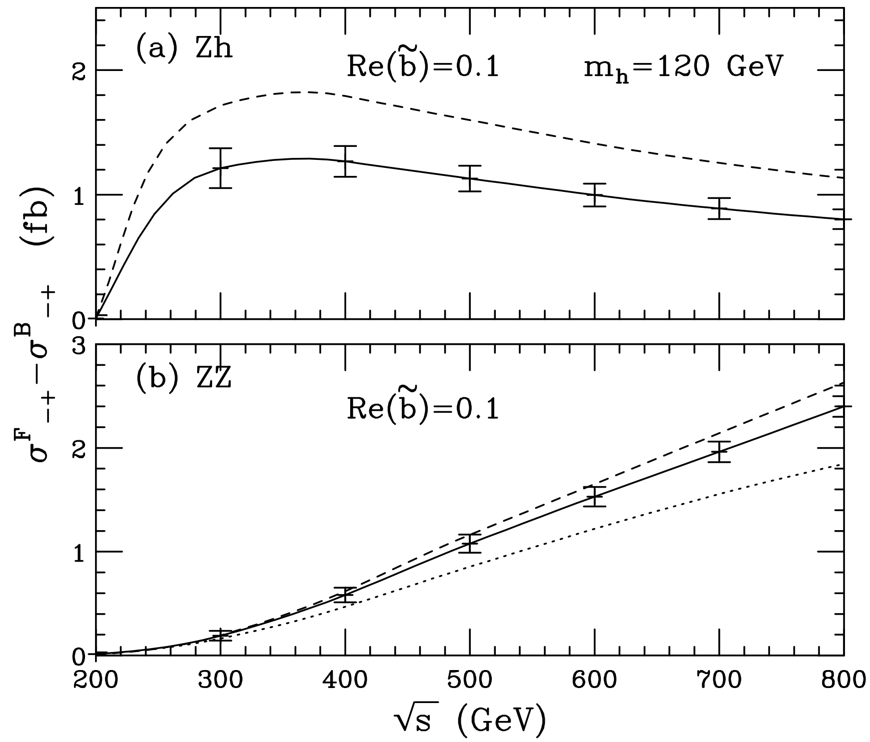
$\cos\theta_Z \sim \hat{z}\cdot\vec{q}_+$, $\cos\theta_\ell \sim \hat{z}\cdot(\vec{q}_1\times\vec{q}_2)$, $\sin\theta_- \sim (\hat{z}\times\vec{q}_-)\cdot(\vec{q}_1\times\vec{q}_2)$,

where $\vec{q}_\pm = \vec{q}_1 \pm \vec{q}_2$.

Angular distributions for the asymmetries: $\mathrm{Im}(\tilde{b}) \sim 1$



Asymmetries versus c.m. energy:



	$\sqrt{s}$ (GeV)	500	500	800	800
	$\mathcal{L}$ (fb^{-1})	500	1000	500	1000
$Im(\tilde{b})$	$\mathcal{A}^{FB}_{\theta_Z}(Zh)$ [−+]	0.0028	0.0022	0.0043	0.0032
	$\mathcal{A}^{FB}_{\theta_Z}(Zh)$ [unpol.]	0.019	0.013	0.025	0.019
	$\mathcal{A}^{FB}_{\theta_-}(ZZ)$ [−+]	0.21	0.16	0.19	0.13
	$\mathcal{A}_{LR}(ZZ)$	0.071	0.045	0.065	0.041
$Re(\tilde{b})$	$\mathcal{A}^{FB}_{\theta_\ell}(Zh)$ [−+]	0.023	0.018	0.019	0.014
	$\mathcal{A}^{FB}_{\theta_\ell}(ZZ)$ [−+]	0.021	0.017	0.014	0.009
	$\mathcal{A}^{FB}_{\theta_\ell}(ZZ)$ [unpol.]	0.024	0.018	0.016	0.010

CP-odd observables at LHC

$$\begin{aligned} pp &\rightarrow \ell^- \ \ell^+ \ H \ X \\ or \quad q\bar{q} &\rightarrow ZH \rightarrow \ell^- \ \ell^+ \ H. \end{aligned}$$

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$$pp \rightarrow \ell^- \ell^+ H X$$
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Problems:

- pp is NOT a CP eigen-state (comparing with $\bar{p}\bar{p}$?)
  $\Rightarrow$ Most of the subprocesses are NOT from CP eigen-states, $W^{\pm}$...
- Even $q\bar{q}$, gg only CP eigen-state in c.m. frame
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The naive triplet product variables:

$$(\vec{p}_f \times \vec{p}_{\bar{f}}) \cdot \hat{z}$$

will NOT work, because the above • • •

Must find new variables suitable to LHC!

$$\mathcal{O}_1 \equiv p_T^+ - p_T^- \quad \text{or} \quad E_T^+ - E_T^-,$$
$$p_T = \sqrt{p_x^2 + p_y^2}, \quad E_T = \sqrt{p_T^2 + m_f^2}.$$

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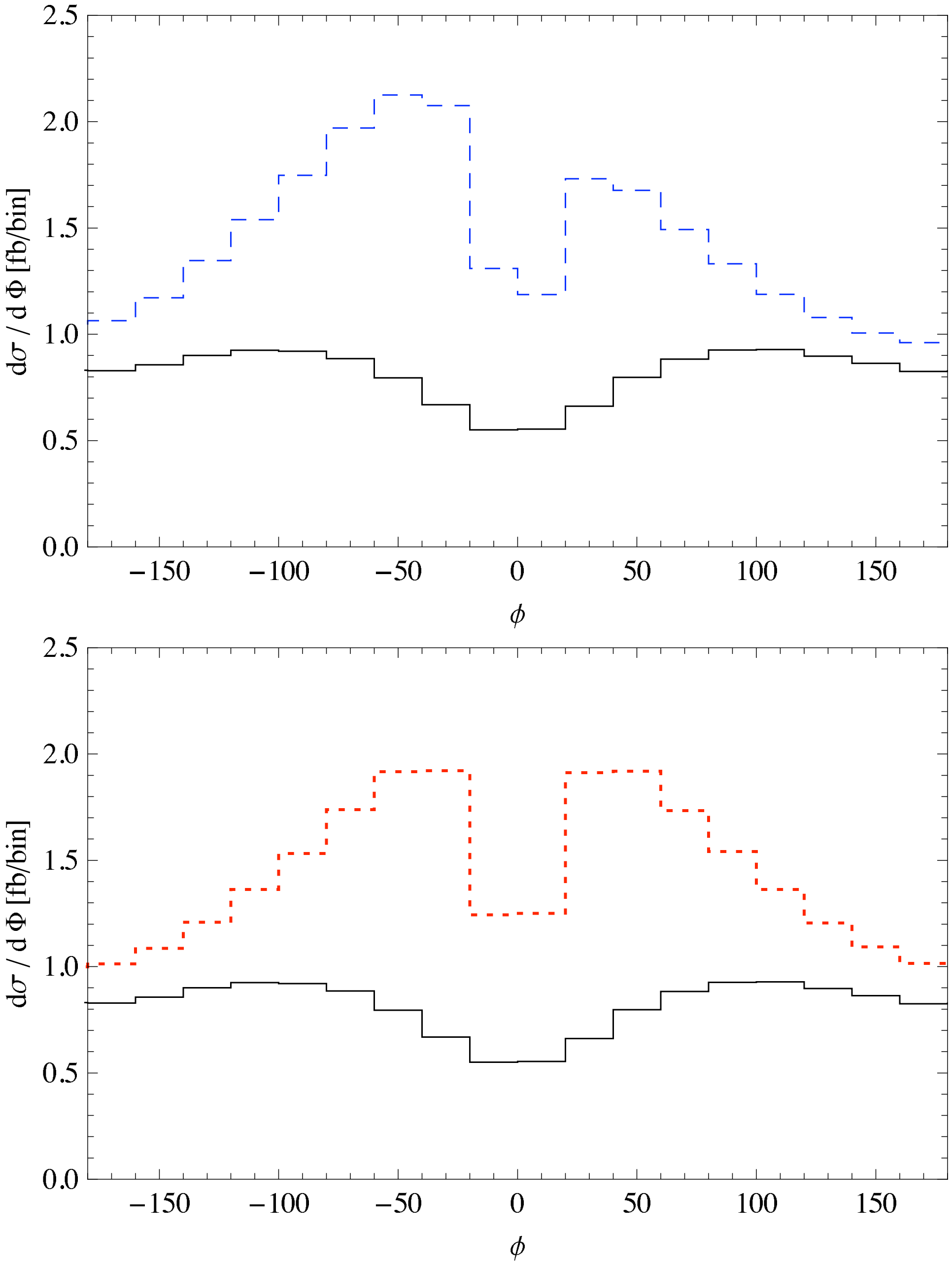
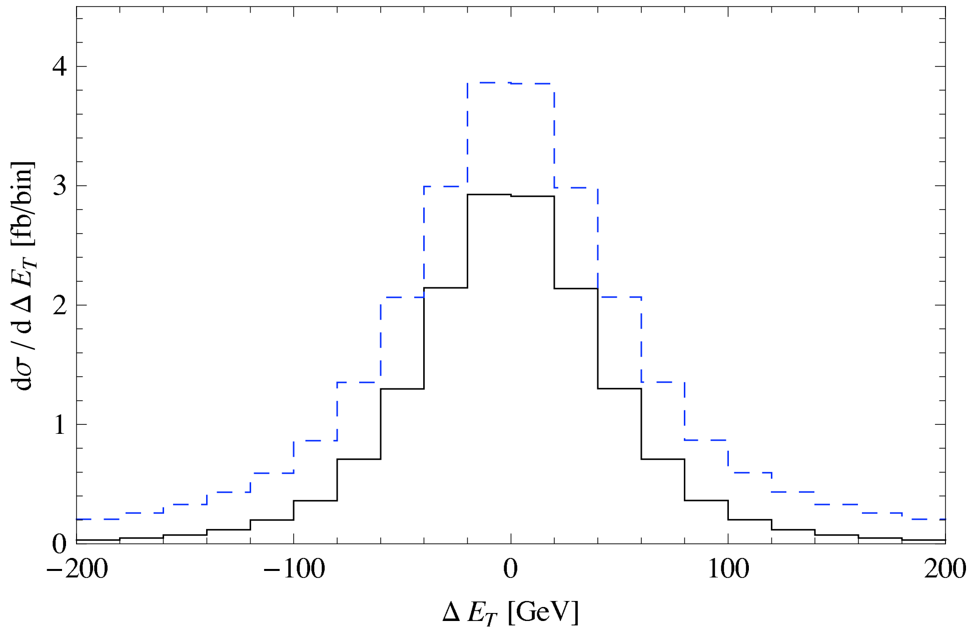
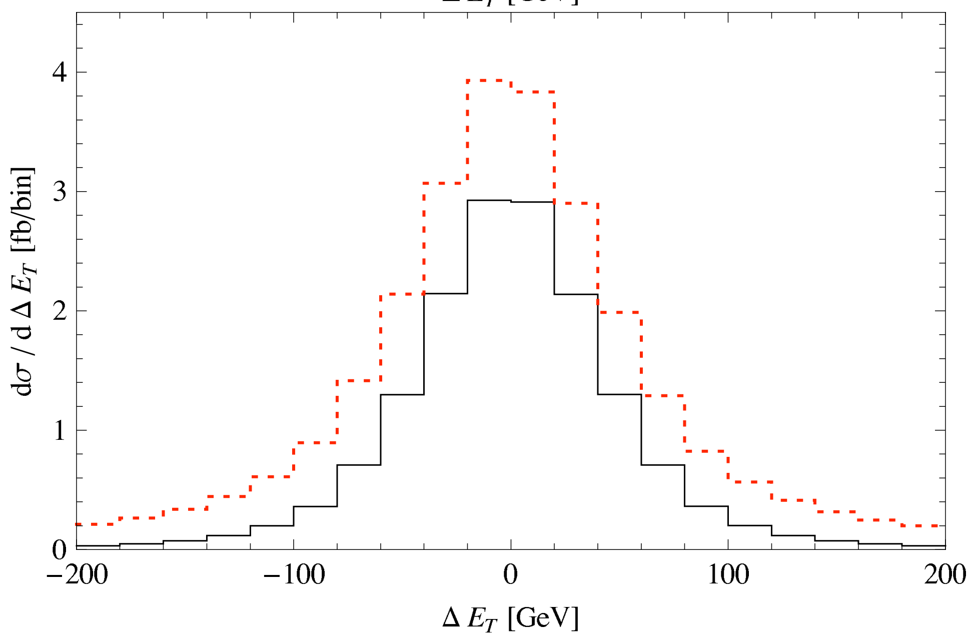
Note that a CP-odd+$\widehat{T}$-even $\sim \sin\delta$ (a CP-conserving strong phase);
while a CP-odd+$\widehat{T}$-odd $\sim \cos\delta$.

Angular asymmetries at the LHC: Re($\tilde{b}$), Im($\tilde{b}$)



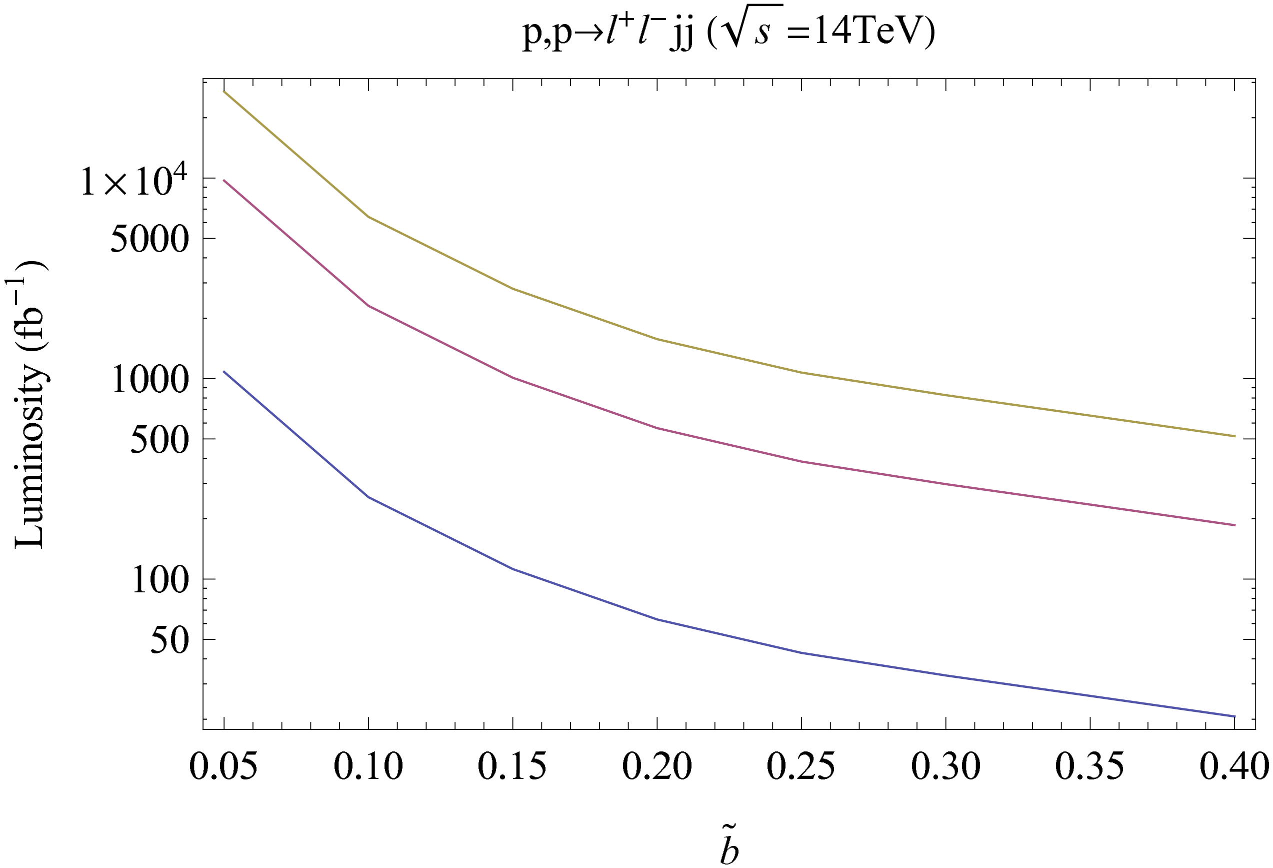
Energy asymmetries at the LHC: Re($\tilde{b}$), Im($\tilde{b}$)





Integrated luminosity needed for 1, 3, 5σ

$$pp \to ZH \to \ell^+\ell^- \; b\bar{b}$$



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- ILC: Good opportunity to search for CPv,
  reaching $\tilde{b} \sim 10^{-3}$.

- LHC: Very challenging, but possible (only recently),
  reaching $\tilde{b} \sim 0.25$.