Genuine CP-Odd Observables at the LHC and ZZH Coupling

Tao Han *
Univ. of Wisconsin–Madison

MCTP Spring Symposium on Higgs Boson Physics
Ann Arbor, May 14, 2010

*Collaborators: Neil Christensen and Y.-C. Li

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Concluding Remarks

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- Or, differential w.r.t. a *definitive* CP observable $PS \to PS'$:

$$dA_{CP} \propto \quad d_{PS}\Gamma(i^0 \to f) - d_{PS'}\Gamma(i^0 \to \bar{f}),$$
$$e.g.: \quad (p^+ \times p^-) \cdot p^0 \ \ldots$$

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With longitudinally polarized beams $\sigma_1\sigma_2$,

$$e^-(p_1)\ e^+(p_2) \to \ell^-(q_1)\ \ell^+(q_2)\ X^0$$

under CP:

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

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Eq. (2), CP eigenstate: construct angular FB asymmetries:

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

Simple examples include:

$$\begin{aligned} e^-(p_1)\ e^+(p_2) &\rightarrow W^+W^- \rightarrow \ell^-(q_1)\ell^+(q_2)\ \nu\bar{\nu}, \\ &\rightarrow \tau^+\tau^- \rightarrow \ell^-(q_1)\ell^+(q_2)\ 2\nu 2\bar{\nu}, \\ &\rightarrow t\bar{t} \rightarrow \ell^-(q_1)\ell^+(q_2)\ \nu\bar{\nu}\ \ b\bar{b}, \\ &\rightarrow Z\ H^0 \rightarrow \ell^-(q_1)\ell^+(q_2)\ H^0, \\ &\rightarrow \chi^+\chi^-,\ \chi_i^0\chi_j^0,\ \tilde{\ell}^+\tilde{\ell}^- \rightarrow \ell^-(q_1)\ell^+(q_2)\ X^0. \end{aligned}$$

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Such as CP-odd observables: $(\vec{q}_\pm = \vec{q}_1 \pm \vec{q}_2)$

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

CP-odd, $\hat{T}$-even:	CP-odd, $\hat{T}$-odd:
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Challenge: CP-odd observables at the LHC

Difficulties in choosing a state (process):

- pp is NOT a CP eigenstate (comparing with $\bar{p}\bar{p}$?)
  ⇒ Most of the subprocesses are NOT from CP eigen-states, $W^{\pm}$...

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(a). Stay in $\hat{T}$-odd observables: ‡
(wish the absence of a CP-conserving phase $\delta \approx 0$:)

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(b). Or start from a well-defined i^0: §
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- Transverse variables:

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- Modified triple-product variables:[‖]

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or its variations like:

$$((\vec{p}_f \times \vec{p}_{\bar{f}}) \cdot \hat{z})^{2m+1} \cdot (\vec{p}_{fT} \cdot \vec{p}_{\bar{f}T})^n \ \mathrm{sgn}((\vec{p}_f - \vec{p}_{\bar{f}}) \cdot \hat{z}),$$

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Example: General ZZH Vertex

(for EWSB sector**)

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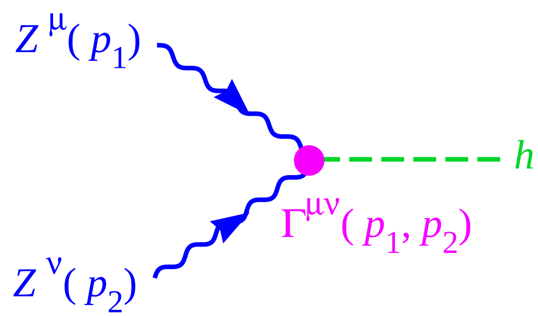
Most general vertex function for ZZh



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

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

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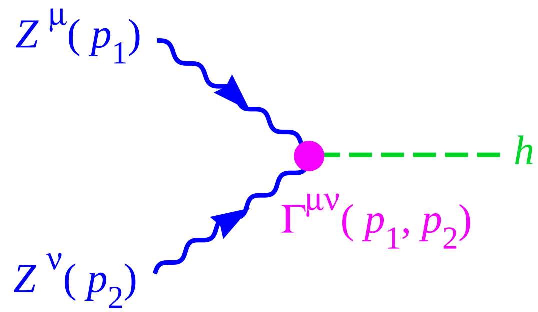

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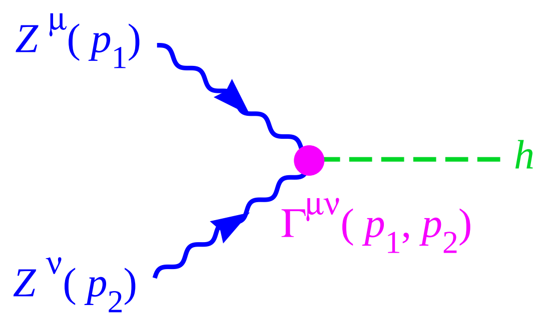

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In an "effective field theory", operators $\frac{g^2}{\Lambda^2}HHW^{\mu\nu}W_{\mu\nu},\ \ \frac{g^2}{\Lambda^2}HHW^{\mu\nu}\tilde{W}_{\mu\nu}$,
natural size: $a,\ b,\ \tilde{b} \sim \mathcal{O}(\frac{1}{16\pi^2} \sim 1)$.

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Search at the LHC

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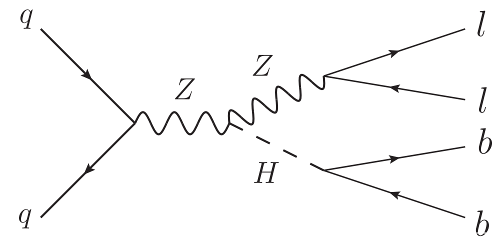

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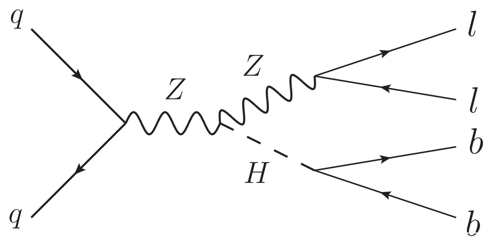

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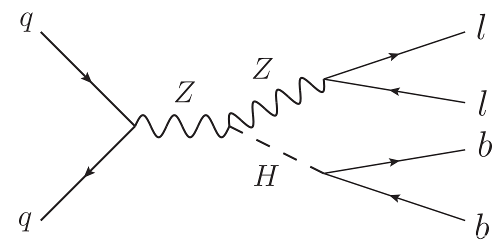

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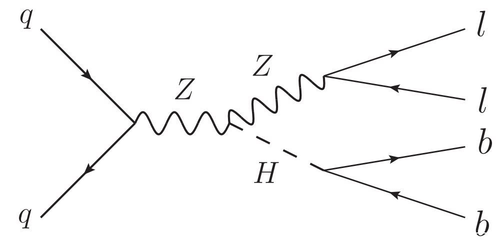

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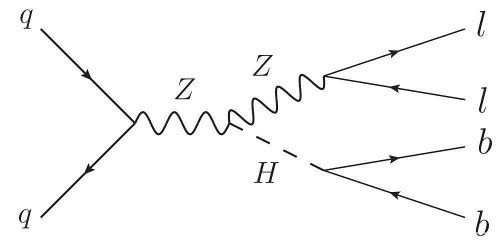

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- Vector-boson-fusion was exploited for ZZH, WWH:[‡‡]

$$qq' \rightarrow qq'H,$$

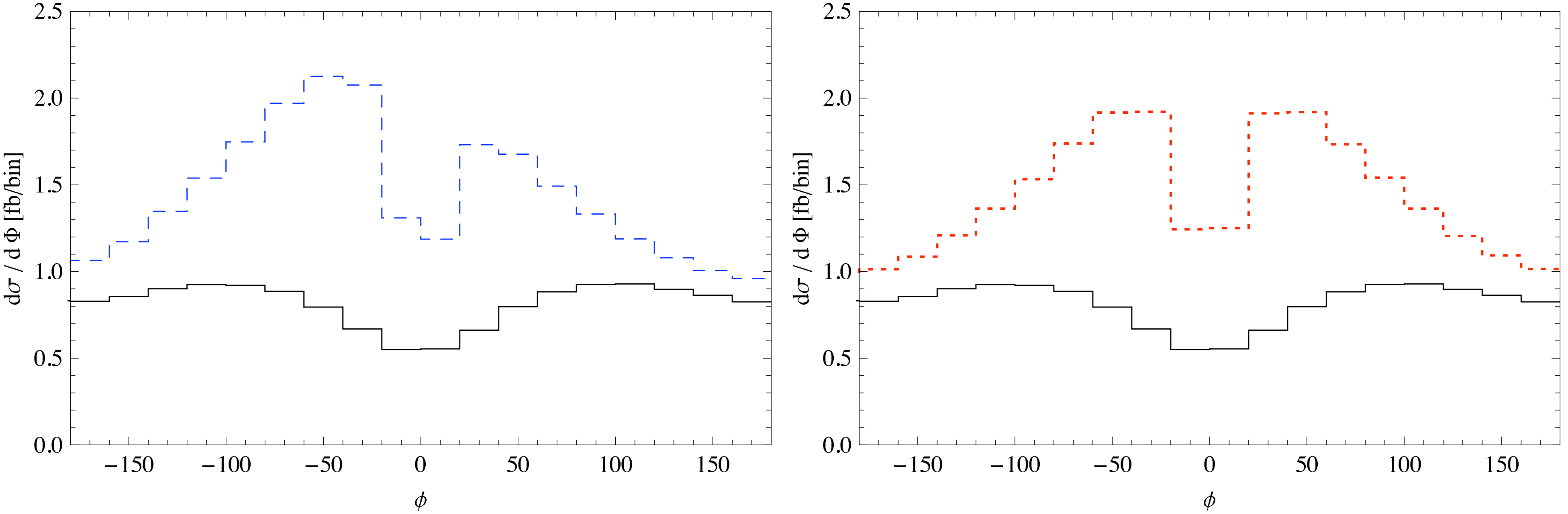
with distinctive distributions for a, b and $\tilde{b}$ terms,
but no charge info, no q versus $\bar{q}$,
thus not a test of CP violation (actually only P).

[††] Butterworth, Davison, Rubin, Salam (2008).
[‡‡] Plehn, Rainwater, Zeppenfeld (2002).

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

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

$$A_{\phi_{ll}} \equiv \frac{\sigma_{\phi_{ll}<0} - \sigma_{\phi_{ll}>0}}{\sigma_{\phi_{ll}<0} + \sigma_{\phi_{ll}>0}}$$

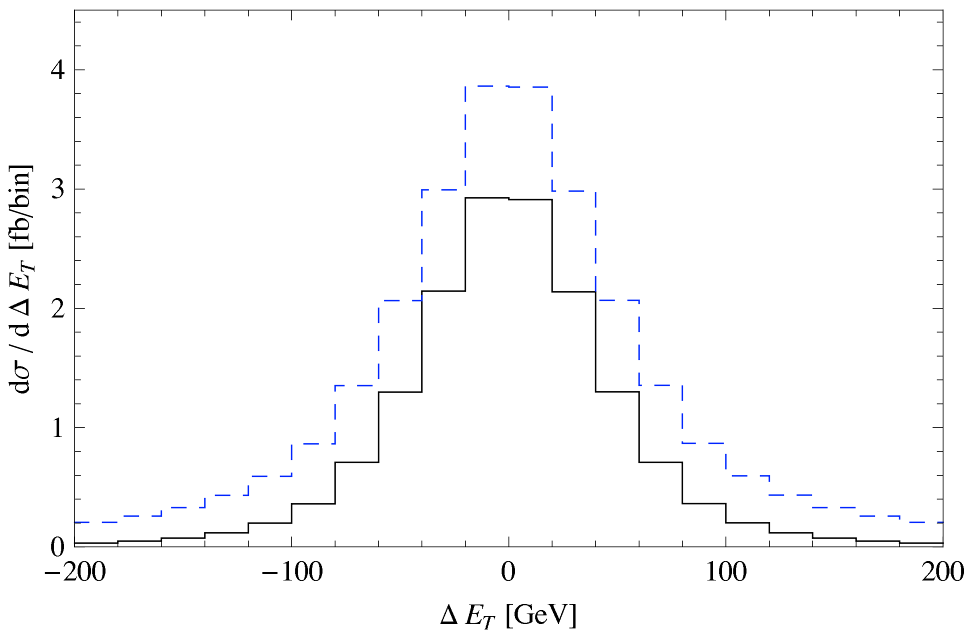


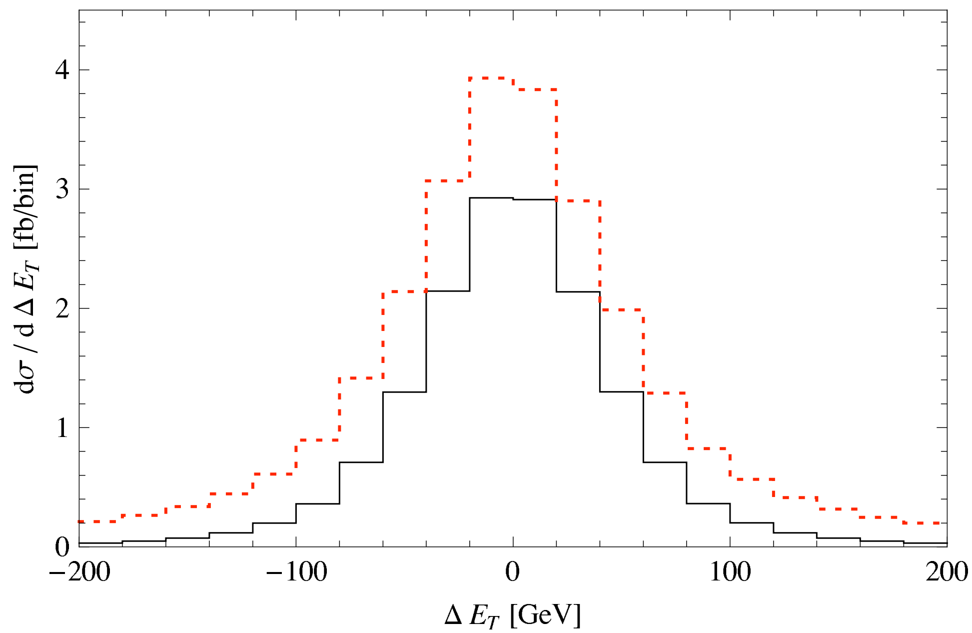
$$|\tilde{b}| = 0.25.$$

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

$$\Delta E_T \equiv E_T^+ - E_T^-$$

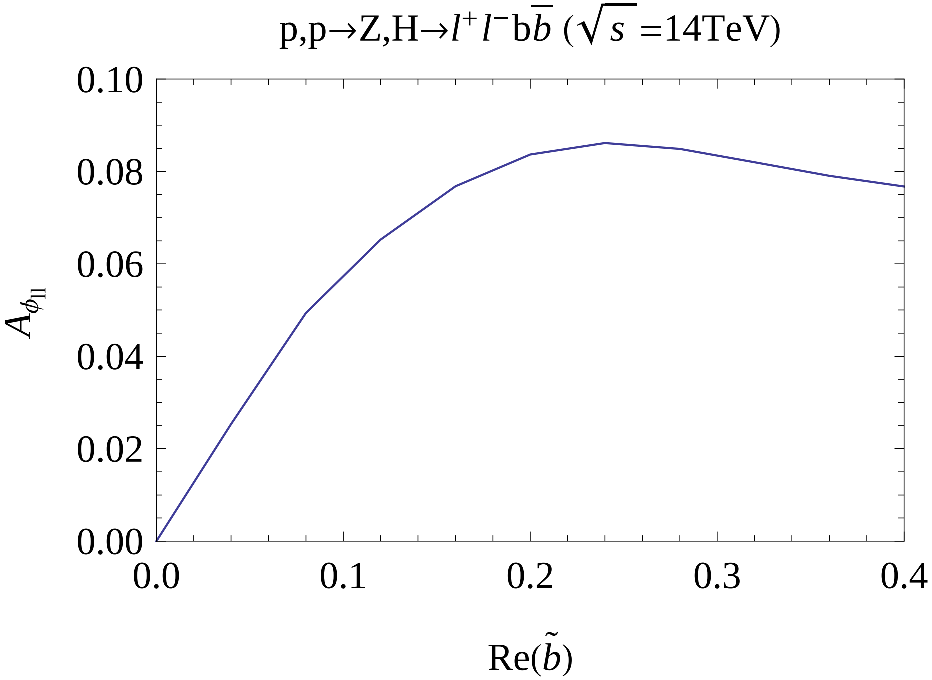
$$A_{\Delta E_T} \equiv \frac{\sigma_{\Delta E_T<0} - \sigma_{\Delta E_T>0}}{\sigma_{\Delta E_T<0} + \sigma_{\Delta E_T>0}}.$$

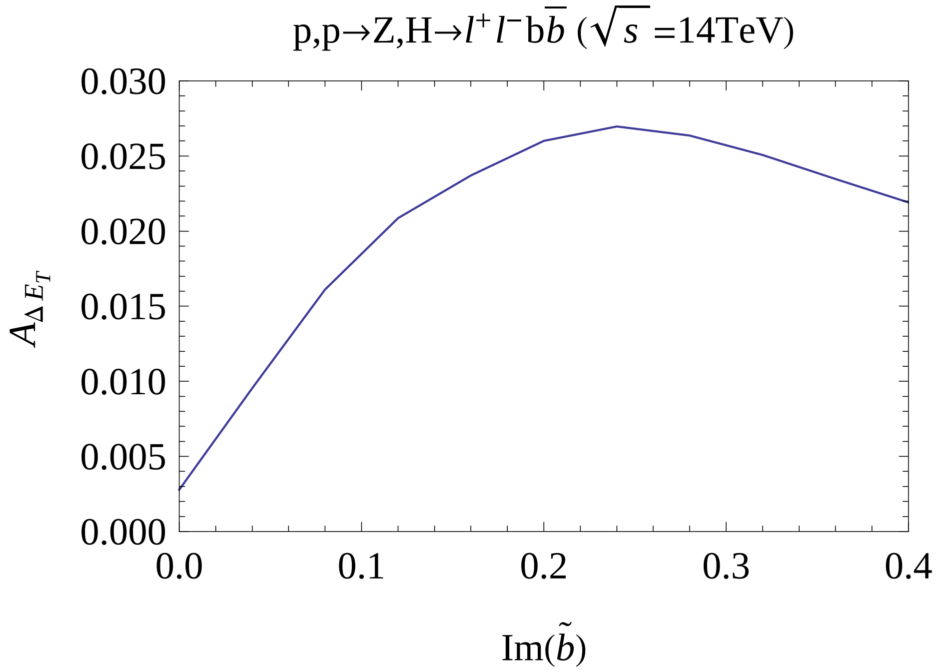




$$|\tilde{b}| = 0.25.$$

Possible size of asymmetries: Re($\tilde{b}$), Im($\tilde{b}$)



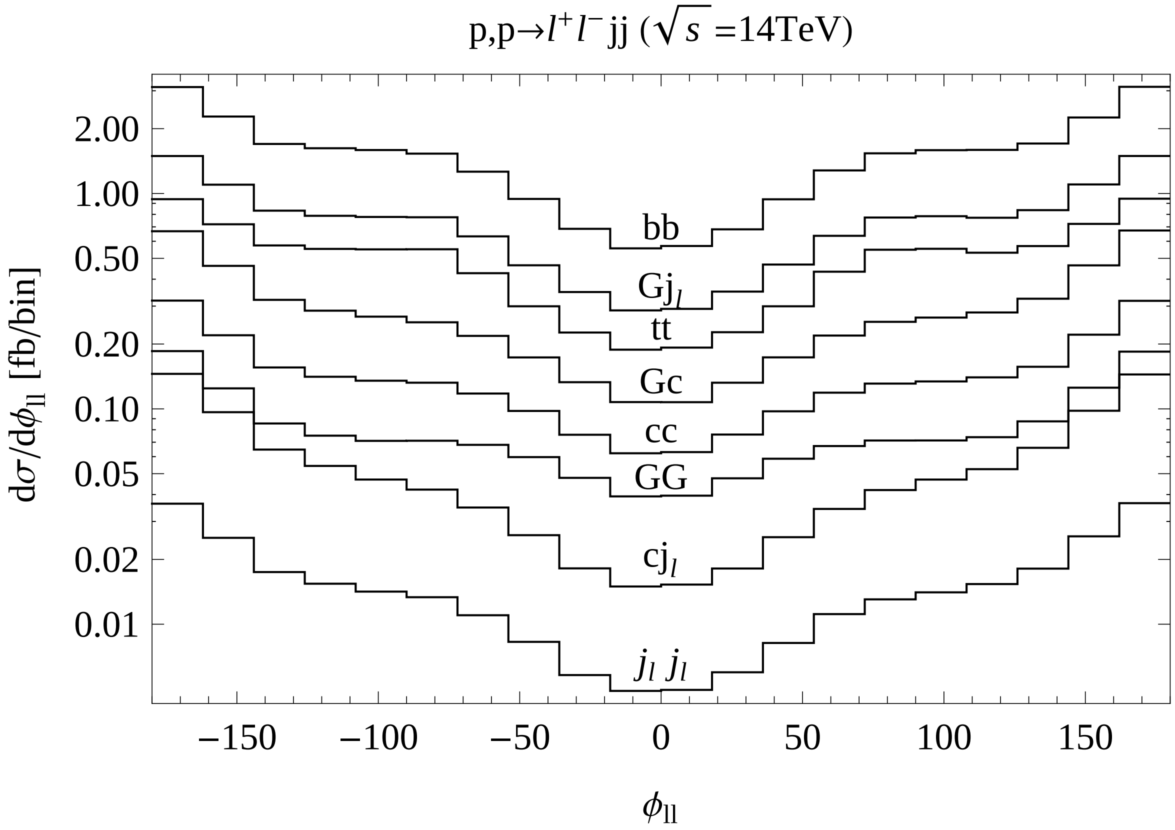


Around $|\tilde{b}| = 0.25$, linear approximation becomes a concern.

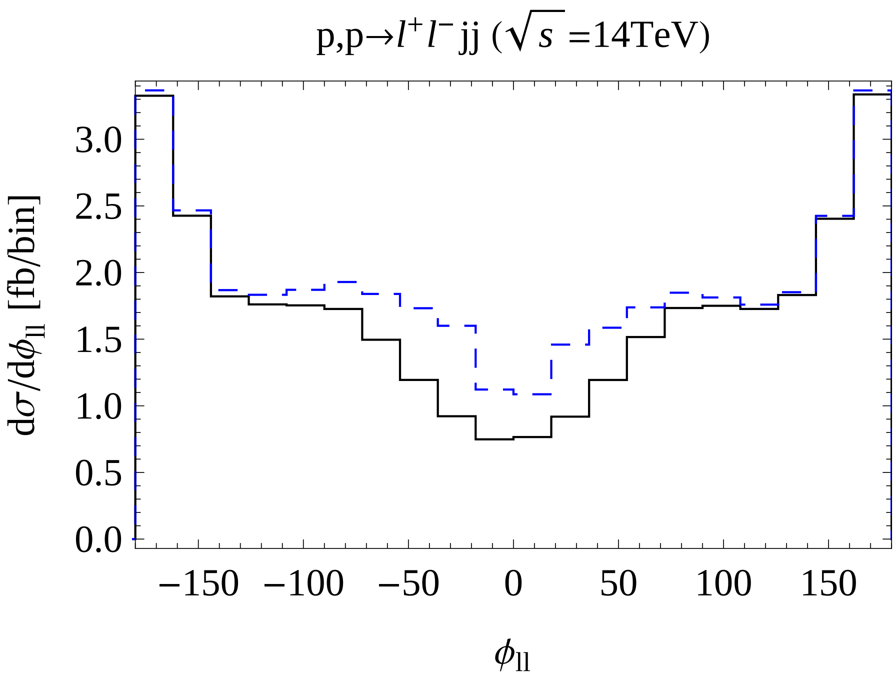
$\ell^+\ell^-\ b\bar{b}$ backgrounds:

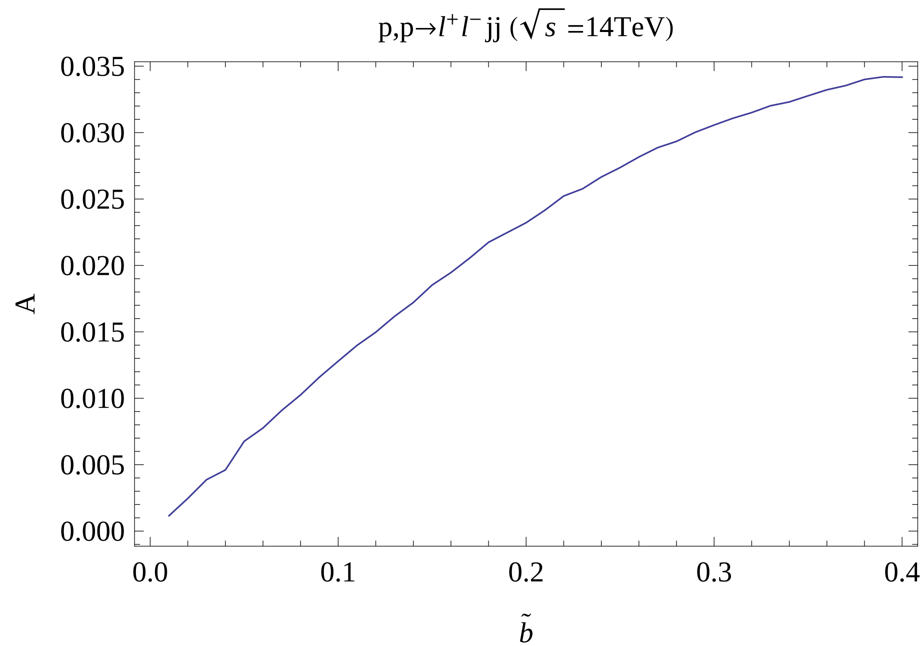
Jet tagging/mistagging rates (CMS TDR Figure 12.30):

b-quark jet	0.4
c-quark jet	0.03
Gluon jet	0.006
light jet	0.001



Including the backgrounds:

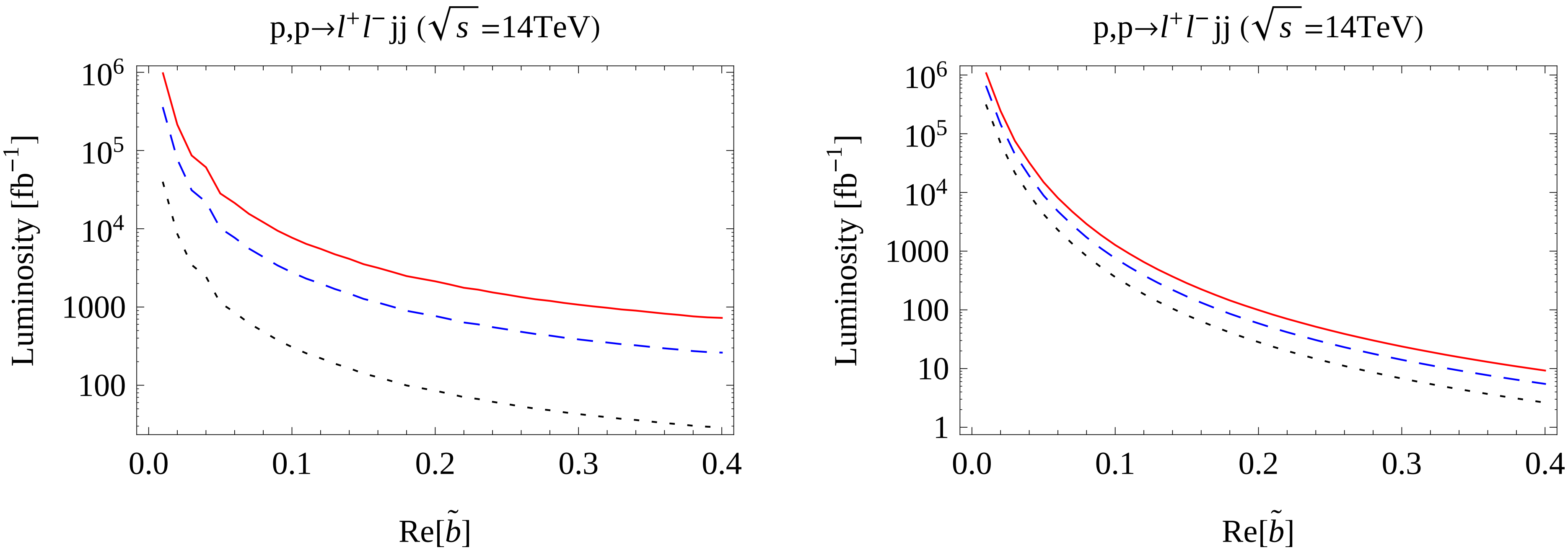




$|\tilde{b}| = 0.25.$

Integrated luminosity needed for 1, 3, 5σ

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



$A \pm \sqrt{N}$

Hypothesis test: Log likelihood $LL(\tilde{b}\ vs\ 0)$

Concluding Remarks

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LHC to open up new physics era,
and find "most wanted" new CP violation sources.