CP property of the Higgs in $e^+e^- \to t\bar{t}\Phi$.

- ♢ Introduction.
- ♢ Two issues:

  i Determination of CP for a Higgs which is a CP eigenstate.

  ii Determination of CP mixing in the Higgs sector for a Higgs with indeterminate CP.

R.G, S.Kraml, M.Krawczyk, D.J.Miller, P.Niezurawski and A.F.Zarnecki in (Phys. Rept. 426 (2006) 47 and hep-ph/0404024.); (hep-ph/0608079) CPNSH report.

R.M. Godbole,(Pramana **67** (2006) 835.)

Bhupal Dev,A.D.,R.G.,Muhelleitner, Rindani PRL **100**, 051801, arXiv:0707.2878 [hep-ph]. ILC, $e + e^-$, Model independent.

The phenomenon of $\not{C}\!P$ still lacks a fundamental understanding

- CKM description vindicated by measurements of CP mixing in the B_0 sector.

- Understanding of Baryon Asymmetry in the Universe seems to require physics beyond the SM.

- May be sources of CP violation beyond the CKM?

Note: if one thinks of leptogenesis things are quite different

CP Study in the Higgs sector

1. Determination of the CP properties of the Spin 0 particle(s) which we hope will be discovered at the future colliders.

2. Determination of the CP mixing if discovered scalars ($\simeq$ Higgses) **NOT** CP eignestates.

Establish tensor structure for $\phi_i f \bar{f}$, $\phi_i VV$ vertex.

ϕ_i : a generic Higgs.

Higgs Couplings with pair of gauge bosons (ZZ/WW) and the pair of heavy fermions (t/τ) are largest.

Study $\not{C}\not{P}$ in a model indpendent way (most studies so far)

$$
\begin{aligned}
\phi_i f\bar{f} &: -\bar{f}(a_f + i b_f \gamma_5)\frac{g m_f}{2 m_W}, \\
VV\phi_i &: c_V \frac{g m_V^2}{m_W} g_{\mu\nu} (\mathrm{V = W/Z\ \ tree}) \\
&: \eta \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma / m_Z^2 (\mathrm{loop\ level})
\end{aligned}
$$

General Strategy for CP determination:

1. SM: $a_f = c_V = 1, b_f = 0, \eta = 0$.

2. $a_f = c_V = 0$ and $b_f \neq 0$ for the CP odd Higgs, for general CP conserving multi-Higgs models.

3. Pseudoscalar $\epsilon^{\mu\nu\rho\sigma}$: only at loop level in MSSM and CP conserving 2HDM.

4. Generically CP mixing is a loop effect, hence small.

Collider	CP determination	Measurement of Mixing
ILC	$f\bar{f}$Higgs final state $VV, f\bar{f}$ final states	$f\bar{f}$ Higgs final state $VV, f\bar{f}$ final state
$\gamma\gamma$	VV final state VV fusion	Best for study of mixing

Some pioneering discussions for $\gamma\gamma$ collider: Gunion, Grzadkowski; Gunion, Kalinowski

VV and $f\bar{f}$ final state angular distributions show striking differences due to the differences in the tensor structure.

Most important advanatge for $t\bar{t}H$ final state and $\gamma\gamma$ colliders: Production channel treats both the scalar and the pseudscalar the same way. Then use all the same methods as at other colliders. The most unambigious way to measure CP mixing.

$\gamma\gamma$ colliders possible with backscattered lasers at a parent e^+e^- collider. Likely to be in the far future.

- Use kinematic distribution of the production process or the decay products of the Higgs: $H \to f\bar{f}(f = t, \tau)$, $H \to ZZ(Z^*) \to f\bar{f}f'\bar{f}'$.

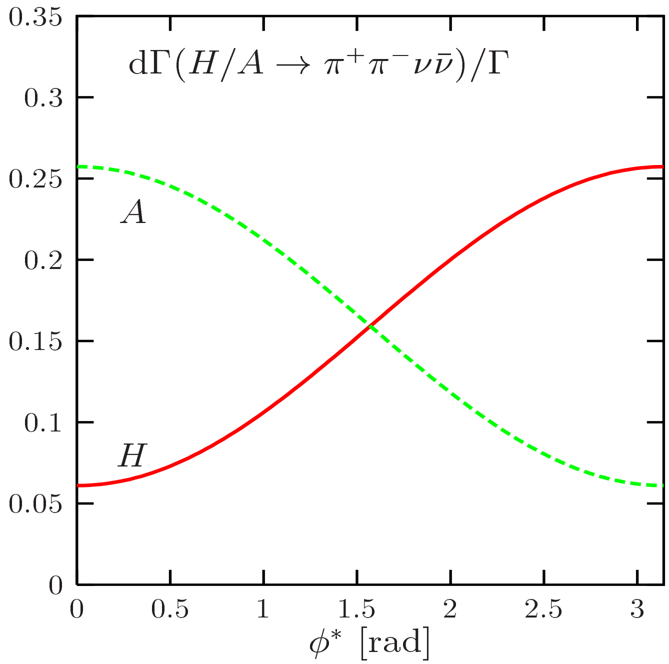
- What distributions: Angular distributions, invariant mass distributions, angular correlations.

- Kinematics of the production process, threshold rise.

- Spin information of the fermions produced in the decay of Higgs or the fermions which are produced in association with the Higgs.

- For the τ decay products carry the spin information of the decaying τ. Due to its large decay width ($\Gamma_t \sim 1.5$ GeV), top also decays much before hadronization; hence its spin information is translated to the decay distribution before being contaminated by hadronisation effects. Hence $\phi \to t\bar{t}, \phi \to \tau^+\tau^-$ and $e^+e^- \to t\bar{t}\phi$ carry information on CP character of Φ.

- The decay lepton angular distribution for the t is independent of any non-standard effects in the top decay vertex. Thus this distribution is a pure probe of new physics associated with the t-production [e.g. Godbole, Rindani, and Singh, *JHEP* **12**, 021 (2006)]. Lepton angular distribution a good polariometer. Measuring decay lepton angular distribution asymmetries can give information on produced top polarisation asymmetries.



ϕ angle between the decay planes of the $\tau^\pm$. Asymmetry is clearly visible.

The parity can be also determined by looking at the the distribution in the angle between the pions into which the $\tau^\pm$ decay. This in turn determined by the polarisation of the $\tau^\pm$ and that in turn by the CP.

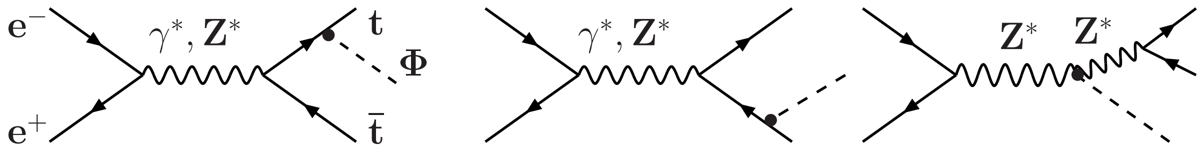
It was shown one could be sensitive to an angle of six degree.

$H \to t\bar{t}$ will offer information only for heavy Higgs.

Uses ϕZZ coupling for prooduction. Which means for a pseudoscalar the strength is necessarily small as loops are involved. For a state of mixed CP, only the CP-even part gets projected out in production. This is true of all the various studies suggested above.

$t\bar{t}\phi$ production interesting: $t, \bar{t}$ couples to both H/A democratically. There is no natural suppression of either a and b.

Gunion and collaborators studied optimal observable technique to study CP property of the Higgs and concluded that with a high luminosity it should be possible to measure even a mixing of a few degrees. Slice the phase space region and use the kinematical distributions of the particles expected for the signal in an optimal way.However, the physics is somewhat obscured by the optimal observable technique used.



The parity violating nature of the Z coupling means $t/\bar{t}$ can have nonzero polarisation and it will be different from H/A.

NB The cross-sections may also be enhanced by choosing e^+/e^- polarisation judiciously.

- We Point out a simple way to discriminate CP even and CP odd case.

- Specifically use $t\bar{t}\phi$ coupling is

$$g_{t\bar{t}\phi} = -ig_2 \frac{m_t}{2m_W}(a + ib\gamma_5) \ .$$

- We take the $ZZ\phi$ Coupling to be similar to the SM case:

$$(g_{ZZ\phi})_{\mu\nu} = -ic \frac{g_2 m_Z}{\cos\theta_W} g_{\mu\nu}$$

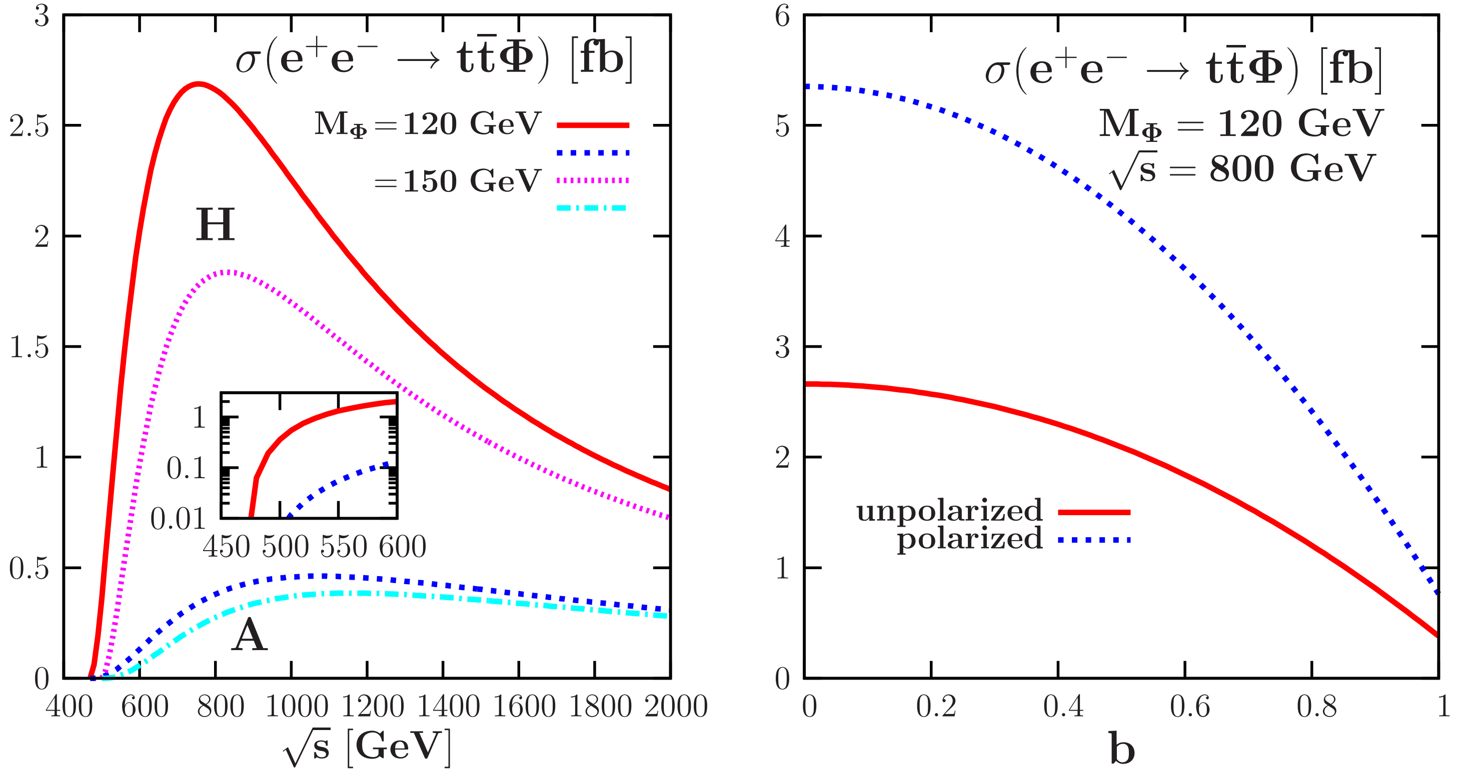
  we will see that the effect of this term will be negligible here. Can be probed using $e^+e^- \to Z\phi$ (eg. Phys. Rev. D 06, Biswal et al)

- In the SM, $a = 1 = c$ and $b = 0$.
- A model-independent way of parametrization can be $|a|^2 + |b|^2 = 1$. We have taken $c = a$.
- Hence only one CP-violating term ab and only independent parameter b.
- In principle, in a specifc model we may have predictions for a, b, c: e.g. THDM and CP-violating MSSM.

- We have studied the sensitivity of b to simple observables such as cross section and polarization asymmetry, with and without polarized beams.

- The Polarization Asymmetry for top-quark is given by

$$P_t = \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)} \qquad \text{(with unpolarized initial beams).} \quad (1)$$



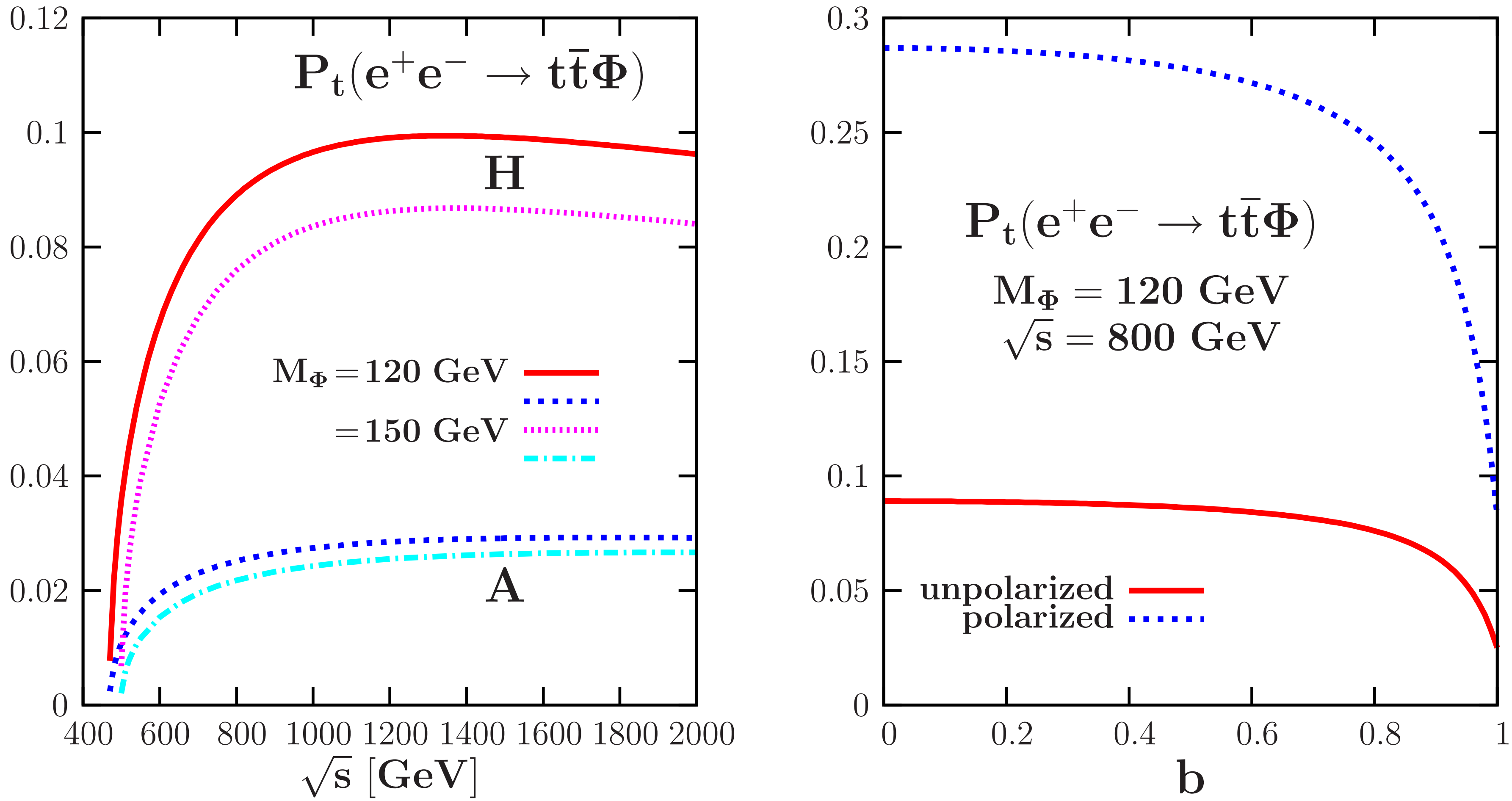
σ(e+e− → tt̄Φ) [fb]
MΦ = 120 GeV
= 150 GeV
H
A
√s [GeV]
σ(e+e− → tt̄Φ) [fb]
MΦ = 120 GeV
√s = 800 GeV
unpolarized
polarized
b

Threshold dependence very different for scalar and pseudoscalar. Steep dependence (S vs P wave).

Define $\rho = 1 - 2m_t/\sqrt{s} - M_\Phi/\sqrt{s}$

$$F_1^H = -F_2^H \simeq 12 \left[m_t^2/(M_H\sqrt{s})\right]^{3/2} \rho^2 \quad F_1^A = -F_2^A \simeq 4 \left[m_t^4/(M_A s\sqrt{s})\right]^{1/2} \rho^3.$$

May be just two measurements, at 500 and (say) 800, would see the difference. For $M_\phi = 120$ GeV, the ratios for H and A are 7.5 and 63, as $\sqrt{s}$ changes from 500 to 800 GeV. Recall: radiative corrections are also substantial. So taking ratios is a good idea. Polarisation shows similar energy dependence and is again different for H(b=0) and A(b=1).


0.12
0.1
0.08
0.06
0.04
0.02
0
400 600 800 1000 1200 1400 1600 1800 2000
$\sqrt{s}$ [GeV]
$P_t(e^+e^- \to t\bar{t}\Phi)$
H
A
$M_\Phi = 120$ GeV
$= 150$ GeV
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.2 0.4 0.6 0.8 1
b
$P_t(e^+e^- \to t\bar{t}\Phi)$
$M_\Phi = 120$ GeV
$\sqrt{s} = 800$ GeV
unpolarized
polarized

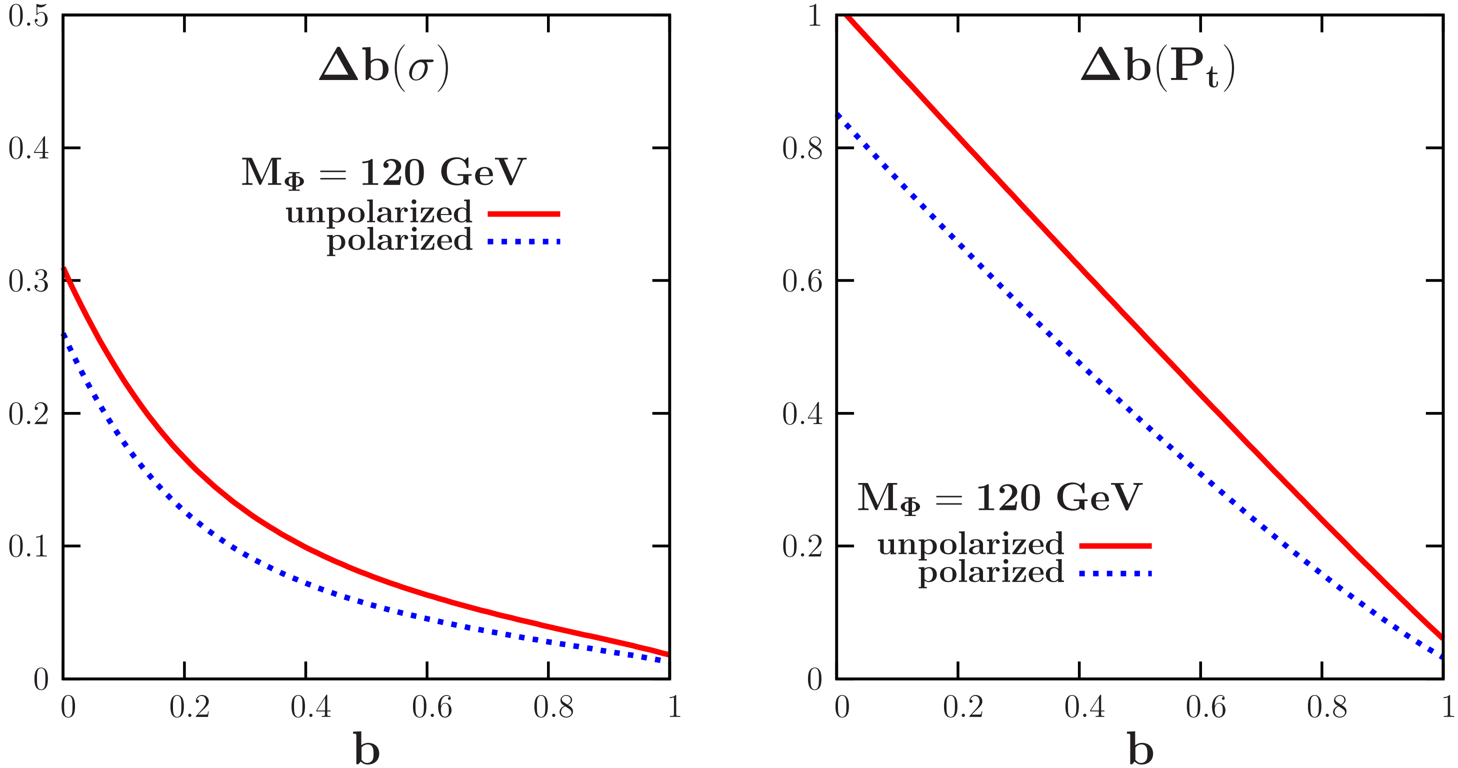
Δb is the sensitivity at $b = b_0$ if for an observable $O(b)$,

$$|O(b) - O(b_0)| = \Delta O(b_0) \quad \text{for } |b - b_0| < \Delta b$$

Apply to the observables σ and P_t, using the fact that at a luminosity L,

$$\Delta\sigma = f\sqrt{\frac{\sigma}{L}}\ , \qquad \Delta P_t = \frac{f}{\sqrt{\sigma L}}\sqrt{1 - P_t^2}$$

at a confidence level f (assuming no systematic error).



Polarisation of top not very sensitive to b except for b very close to 1. But the only unambigious one for the pseudoscalar state.

Nevertheless, both good observables to distinguish a purely CP-even state from a purely CP-odd one.

CP-odd observables to measure b?

- The up-down asymmetry of the $\bar{t}$ production w.r.t. the e^- - t plane ($\phi_4' = 0$) is given by

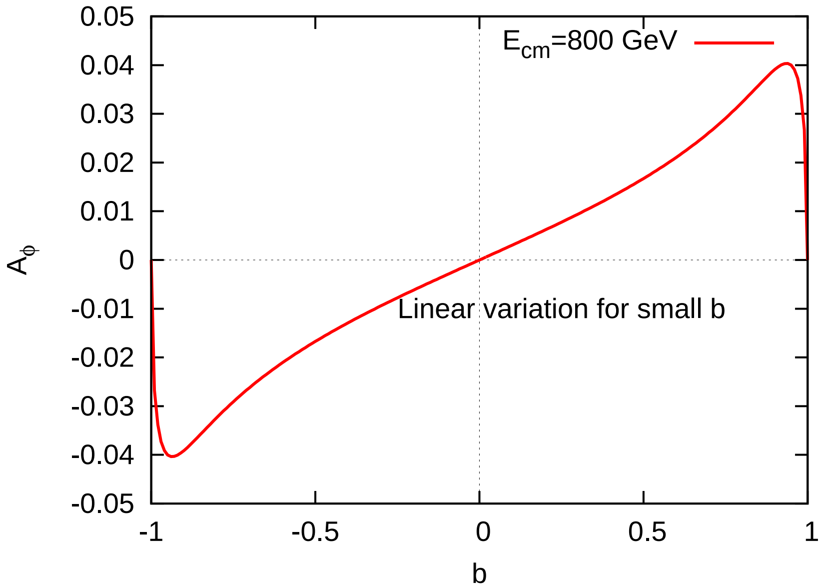
$$A_\phi = \frac{\sigma_{\text{partial}}(0 \le \phi_4' < \pi) - \sigma_{\text{partial}}(\pi \le \phi_4' < 2\pi)}{\sigma_{\text{partial}}(0 \le \phi_4' < \pi) + \sigma_{\text{partial}}(\pi \le \phi_4' < 2\pi)},$$

$$\text{with } \sin\phi_4' = \frac{\vec{P}\cdot(\vec{p}_3 \times \vec{p'}_4)}{|\vec{P}|\cdot|\vec{p}_3 \times \vec{p'}_4|} \qquad (\vec{P} \equiv \vec{p}_1 - \vec{p}_2)$$

$\vec{p}_4'$ is the $\bar{t}$ momentum in the $\bar{t}$ - Higgs rest-frame.

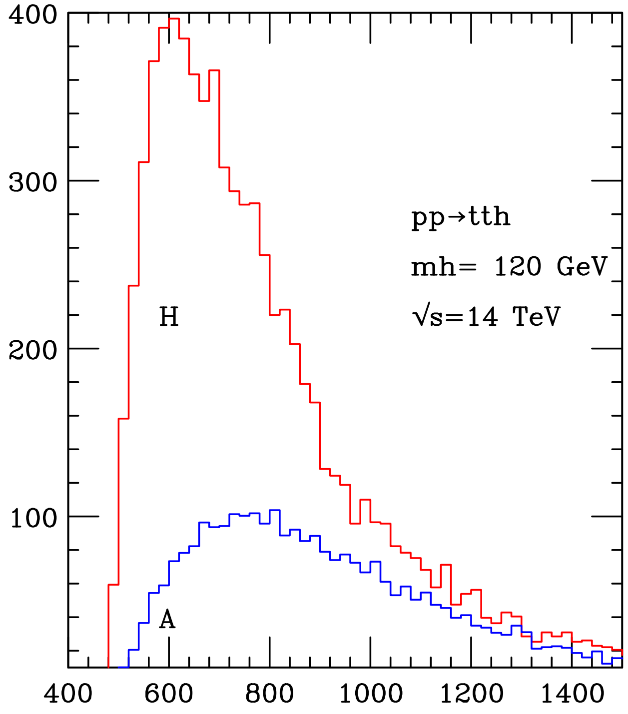
- In terms of a and b, this asymmetry has the structure

$$A_\phi = \frac{x_\phi\ ab}{x_t - y_t\ b^2} = c x_\phi\ ab\sigma_{\text{tot}}$$



The asymmetry can be be as high as 5%. Thus can offer good sensitivity to b.

Interesting: The $pp \to t\bar{t}\phi$ shows the same behaviour!



Idea: can one use this feature to control the bkgd? The $b\bar{b}$ in the $t\bar{t}b\bar{b}$ QCd background is produced from a spin 1 gluon.

Djouadi, RG, Fabio Maltoni (in progress).

1) Clean variable to decide the CP at large luninosity

2)Perhaps use this feature to help clean up the signal?

$\diamondsuit$ $e^+e^- \to t\bar{t}\Phi$ offers the best probe of CP violation in the Higgs sector. The energy dependence and the polarisaiton of the top quark can be utilised.

$\diamondsuit$ The threshold rise of the cross-section may be used at the LHC too! Study in progress.