Spin and CP of the Higgs at the Colliders (LHC).

- ♢ Introduction.
- ♢ Two issues:

  i Establishing that the spin and CP of the observed state assuming it to be a pure state

  ii Determination of amount of CP mixing assuming the state to have an indeterminate CP.

Methods for extracting information on spin and parity of the Higgs. Very rich subject.

A partial summary of the studies can be found:

Phys. Rept. 426 (2006) 47 , hep-ph/0404024, CPNSH report hep-ph/0608079.

2006–2010:

Many detailed studies (phenomenological and experimental) followed in the intervening years (will refer to them as we go along). Many of these studies indicated this to be high luminosity physics (30-100 fb^{-1} at 14 TeV) by identifying observables (angular distributions, invariant mass distributions) and studying the level to which the above two points could be addressed.

Recent development: How to obtain spin and parity information using *all* the kinematic distributions for the decay products of Z, and the correlations among different observables, including detector effects. This indicates that this may be possible even with the discovery sample.

hep-ph/1001.3396: Y. Gao et al; hep-ph/1001.5300 A De Rujula et al

Importance of Studies of Higgs CP and spin.

- Just the discovery of the Higgs boson is not sufficient to validate the minimal SM.
- In SM, the only fundamental neutral scalar is a $J^{PC} = 0^{++}$.
- Various extensions of the SM can have several Higgs bosons with different CP properties : e.g. MSSM has two CP-even and one CP-odd states.
- Therefore, should a neutral spin-0 particle be detected, a study of its CP-properties would be essential to establish it as *the* SM Higgs boson.

- To study the effects beyond SM, we need to establish the CP eigenvalues for the Higgs states if CP is conserved, and measure the mixing between CP-even and CP-odd states if it is not.

- One possible explanation of Baryon Asymmetry can be found in terms of CP violation in Higgs sector.

Spin and CP Study in the Higgs sector

1. Determine spin /consistency with spin 0.

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

3. Determination of the CP mixing if discovered scalars ($\simeq$ Higgses) are **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)

$$\phi_i f \bar{f} \; : \; -\bar{f}(a_f + i b_f \gamma_5) f \frac{g m_f}{2 m_W},$$

$$VV\phi_i \; : \; c_V \frac{g m_V^2}{m_W} g_{\mu\nu} (\mathrm{V = W/Z \;\; tree})$$

$$: \; \eta \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma / m_Z^2 (\mathrm{loop\ level})$$

In more detail:

$$V_{HVV}^{\mu\nu} = \frac{i g m_Z}{\cos\theta_W} \left[a\, g_{\mu\nu} + b \frac{p_\mu p_\nu}{m_V^2} + c\, \epsilon_{\mu\nu\alpha\beta} \frac{p^\alpha k^\beta}{m_V^2} \right],$$

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.

- 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.

Collider	CP determination and Measurement of Mixing
LHC	$t\bar{t}h$ **production: gg initial state.** Higgs + 2 jet : gg initial state.
	VV final state: initial state gg VV fusion : $f\bar{f}$ final state.
	$f\bar{f}$ final state : gg initial state.

ILC and $\gamma\gamma$ colliders are the best, but LHC is the only collider right now :-)

The best and most unambigious method to get complete information on Higgs CP is to use its $f\bar{f}$ or $\gamma\gamma$ coupling.

Why?

The scalar and the pseudoscalar couple democratically to $f\bar{f}$ and $\gamma\gamma$.

Whereas $VV\phi$ pseduoscalar tensor structure is always loop suppressed.

Thus,

to be produced in the VV channel the state either has to be a scalar (if it is a pure state) or it has to have a large scalar component if it is a mixed state.

WHY?

Since $c(\eta)$ is small, if the state has mixed CP, the CP even part is projected in VV mode. Hence agreement of an observed distribution with the expectation for CP even case would not prove anything about possible admixture.

Will come back to this later

The methods using VV coupling have been the most investigated for the LHC and hence will discuss them first.(methods indicated in blue)

But important to keep in mind the need of using/developing methods using the $t\bar{t}$ coupling. (methods indicated by red in the Table earlier)

A small example of the dependence on the CP property of the Higgs

$$\Gamma_{\text{Born}}(H \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f^3$$

$$\Gamma_{\text{Born}}(A \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f$$

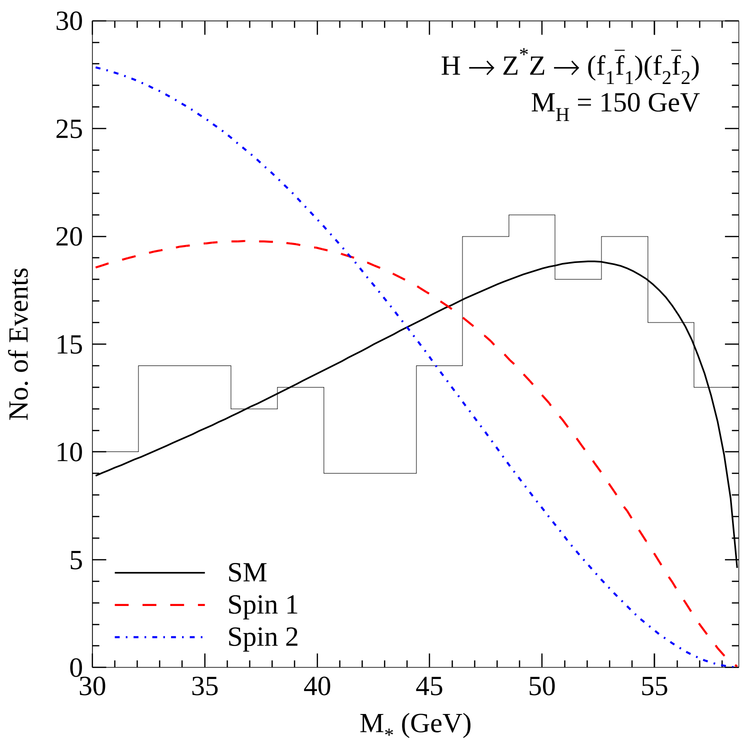
Surely one recalls $e^+e^- \to \gamma^* \to f\bar{f}(s\bar{s})$ have different energy dependence, near threshold, one proportional to one power of c.m. momentum and one to the third. Follows from angular momentum and parity conservation.

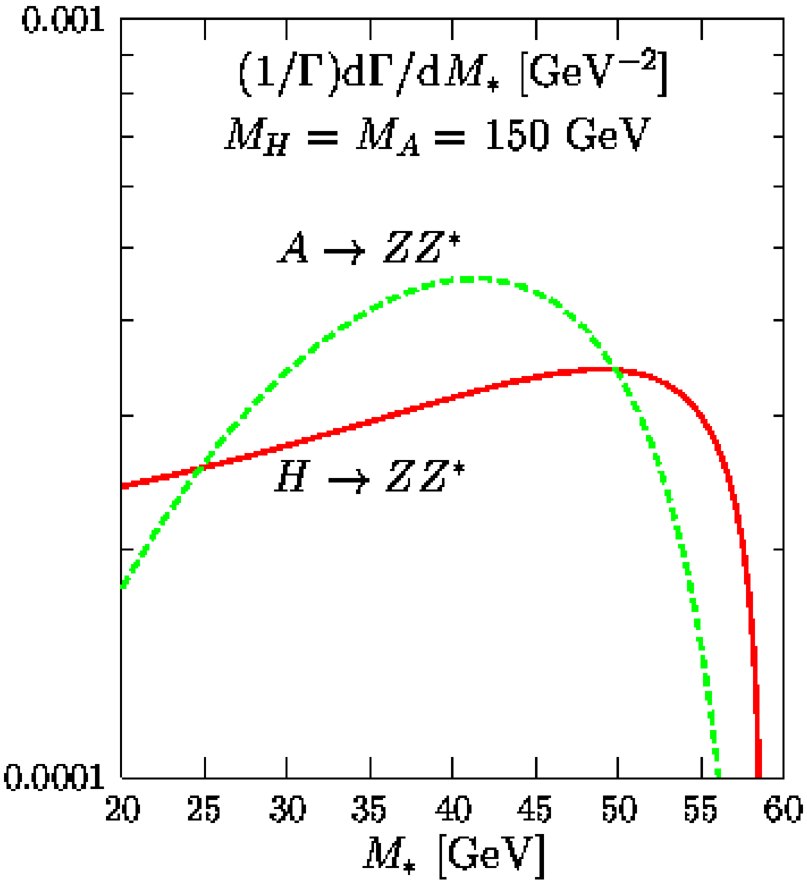
Similar things happen for Higgs production.

When observed in $\gamma\gamma$ final state spin 1 will be immediately ruled out (Yang's theorem)

Use of $\phi \to ZZ^{(*)} \to 4l$ Choi, D. Miller, Mühlleitner & Zerwas Below $\phi \to ZZ$ threshold, one Z is virtual $\to$ can examine threshold behaviour Choi et al, PLB 553 (2003) 61 to determine the spin, Barger et al, PRD 49 (1994)79 to determine the CP.

The distribution is sensitive to both the spin and parity of the resonance.





Has been used by ATLAS. Will show the results of their analysis later.

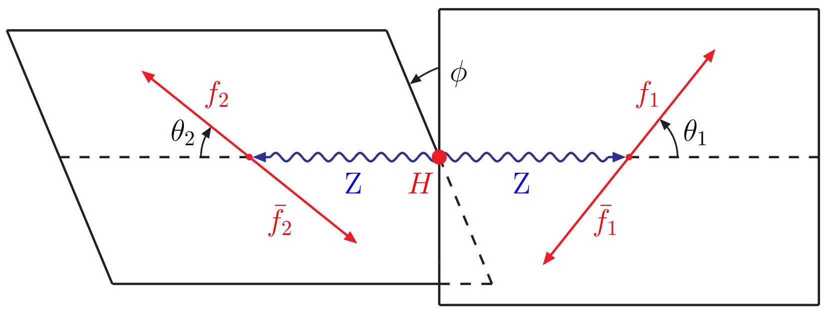
Determination of CP and CP mixing. Three types of studies.

Production of Higgs in gg fusion and decay through ZZ to 4 lepton pairs.

Production in WW fusion

Production of Higgs in association with two jets or heavy fermions

The definition of the polar angles θ_i $(i = 1, 2)$ and the azimuthal angle φ. In the rest frame of H.



Need to distinguish between f_1 and $\bar{f}_1$.

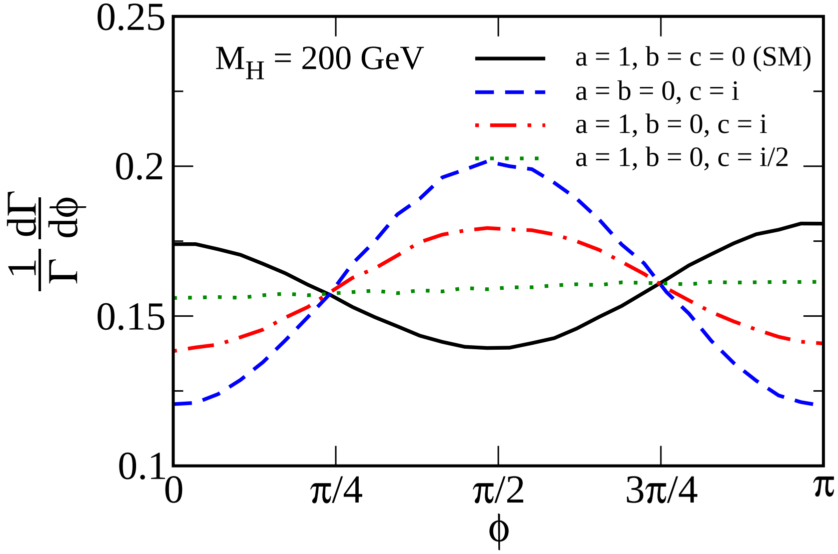
One Z decays to $f_1 \bar{f}_1$ and other two $f_2 \bar{f}_2$.

Available complete analytic expression for the triple diff. crosssection. (for example: RG, Miller and Muhlleitner : JHEP 0712 (2007) 31)

Gao et al, A De Rujula et al: for all spin/parity cases.

In the SM

Distribution in φ ; the angle between the planes of the fermion pairs coming from the Z boson decays.



RG, Miller, Muhlleitner (JHEP 0712 (2007) 31)

$$\frac{d\Gamma}{d\varphi} \sim 1 + A\cos\varphi + B\cos 2\varphi$$

A, B are functions of M_H, M_Z. the ϕ dependence will vanish for larger Higgs masses.

For CP odd case:

$$\frac{d\Gamma}{d\varphi} \sim 1 - \frac{1}{4}\cos 2\varphi$$

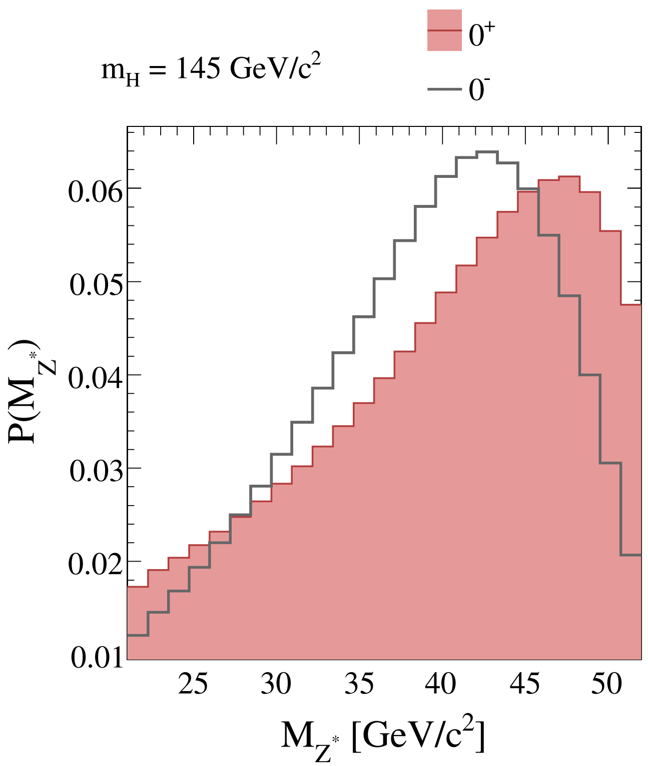
The ϕ distribution can be used to get the information on CP and CP mixing. Has been studied by a few authors. Buszello et al, EPJC32 (2004) 209, hep-ph/0406181, M. Bluj in CPNSH report. (show plots later)

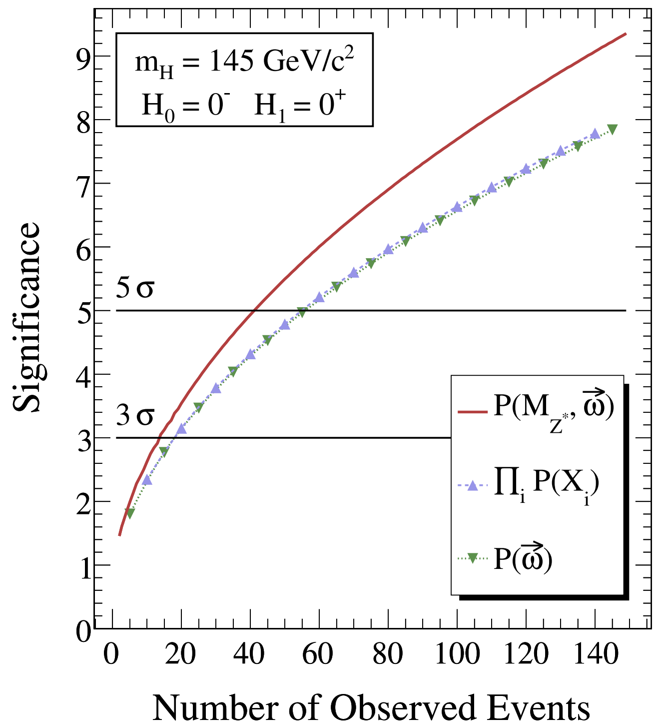
In all these studies the production angular distribution is basically integrated over and taken to be flat.

In most studies sensitivity of one particular angular or invariant mass distribution was used.

A De Rujula et al (hep-ph/1001.5300) and Gao et al (hep-ph/1001.3396) study all the kinematic variables and correlations among them.

One plot from Higgs look alike (1001.5300)





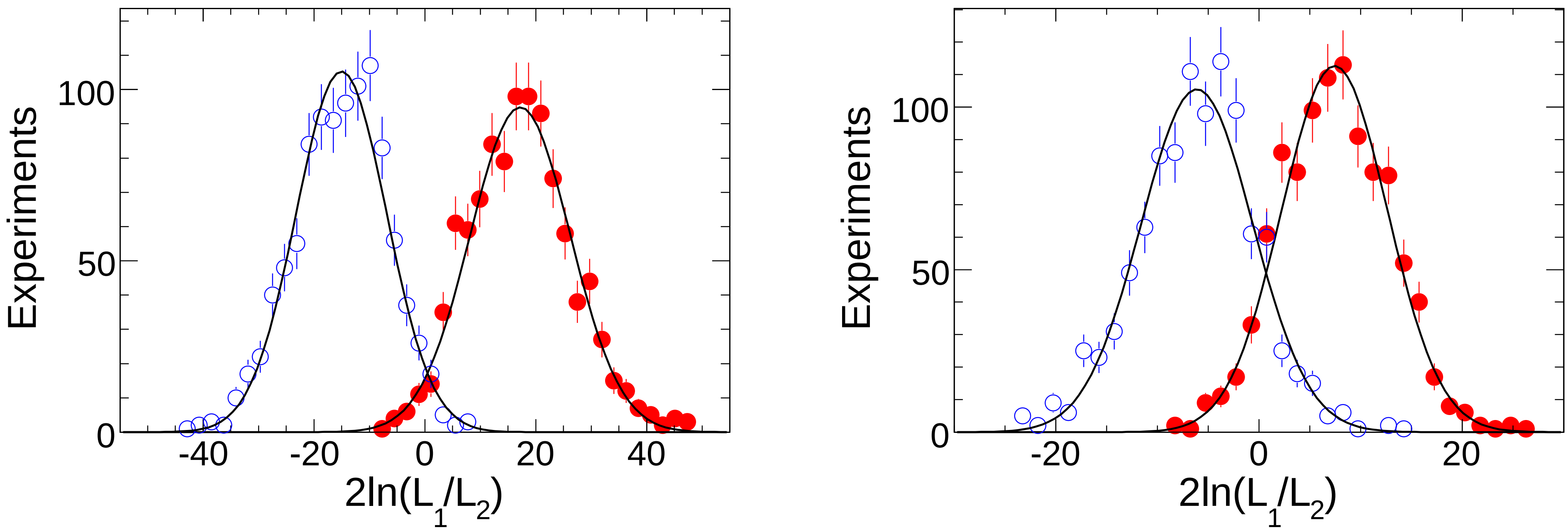
They construct likelihood ratios, take into account sculpting of disributions due to finite acceptance effects.

Plot shows median significance for rejecting 0^- in favour of 0^+.

Thus use of correlations can increase significance for a given number of events or decrease the number of events required for a given significance.

In general when one usese shapes more sensitive to effect of higher order corrections A. Bredenstein et al, PRD 74 (2006) 013004 So this can be important while considering mixed states.

Analysis for 10 TeV LHC.



Gao et al: hep-ph/1001.3396

1000 generated experiments, 30 signal events, 24 background events, $M_X = 250$ GeV ~ 5 fb^{-1} luminosity.

Effective signal hypothesis separation power 4.1 and 2.8 respectively.

Analysis for 14 TeV LHC.

Ask the question how well can one determine additional tensor structure in the ZZH vertex, if any is present.

Recall the new physics that modifies ZZH vertex will modify rates too. So that can be an independent effect on the phenomenology of the changed ZZH vertex. Here we will not consider that.

The form of the general ZZH vertex we use:

$$V^{\mu\nu}_{HZZ} = \frac{igm_Z}{\cos\theta_W}\left[a\, g_{\mu\nu} + b\,\frac{p_\mu p_\nu}{m_Z^2} + c\,\epsilon_{\mu\nu\alpha\beta}\frac{p^\alpha k^\beta}{m_Z^2}\right],$$

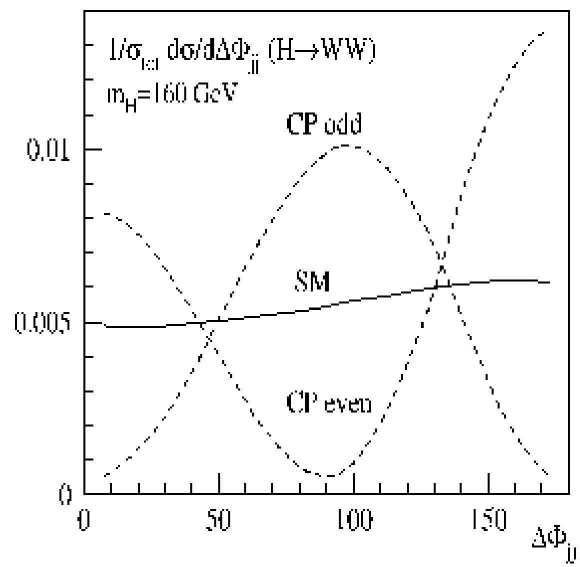
Can be related to difft. other forms used in literature using gauge invariance.

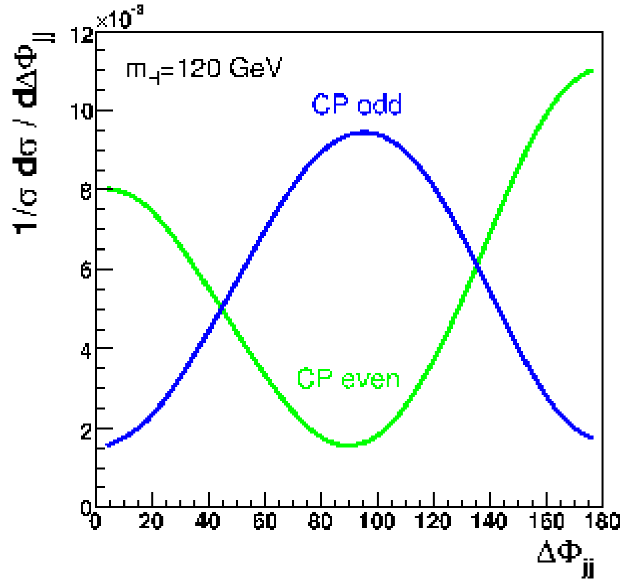
ϕ among jets produced through VV fusion, Angular distribution of the forward/backward jets distinguish a scalar and a pseudoscalar higher dimensional contribution. T.Plehn, D.Rainwater and D.Zeppenfeld, PRL **88** (2002) 051801

Same true for $gg \to \phi+$ 2 jets, QCD corrections?? V. Del Duca, et al arXiv:hep-ph/0109147, V. Hankele, et al, PRD 74 (2006) 095001,arXiv:hep-ph/0605117 K. Odagiri, JHEP 0303, 009 (2003)

The sensitivity of the observable stable against higher order corrections . Used hjj and $hjjj$ sample. J. Andersen, et al JHEP 1006,(2010) 091

higgs + 2jets: VBF and gluon fusion

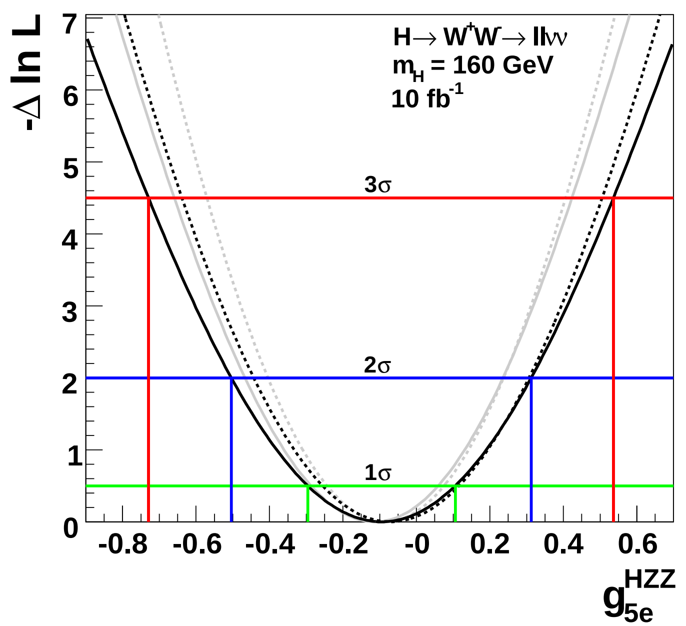


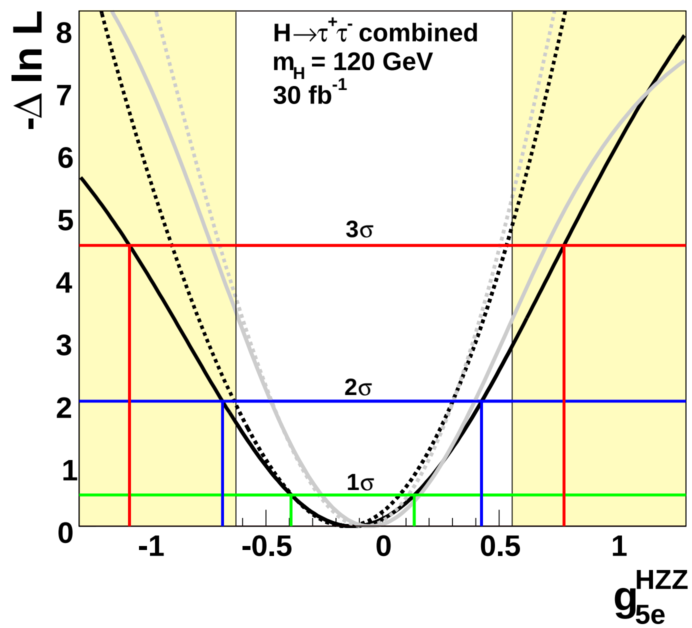


The distribution in the azimuthal angle between the two jets is different for the CP odd and CP even part of the anomalous couplings for the VBF and also from the SM.

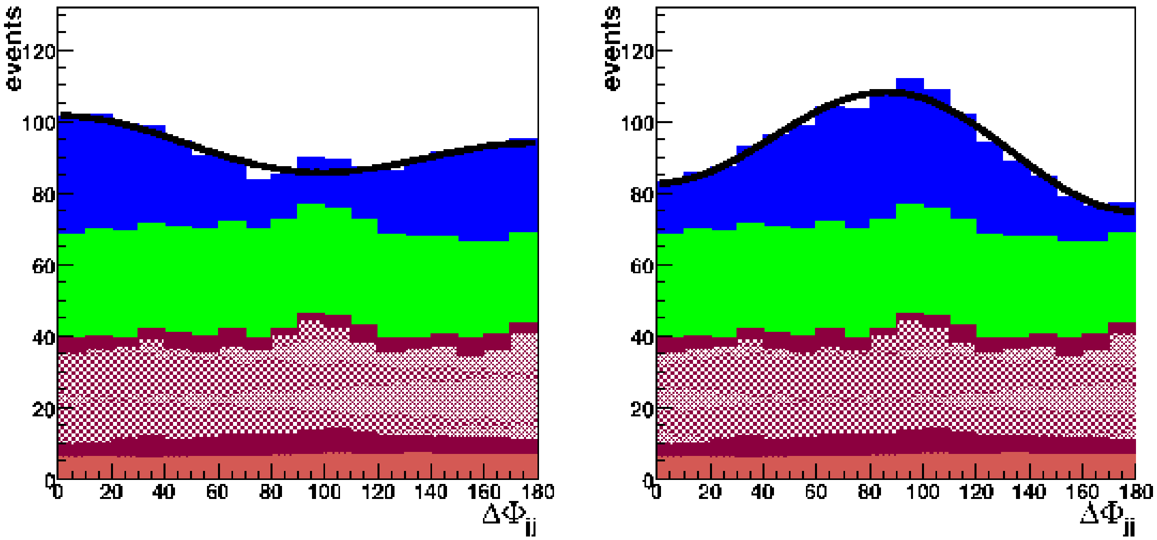
For gluon fusion the angular distribution is decided by the CP property of the $t\bar{t}H$ coupling.

VBF can probe the anomalous ZZH 5 dimensional vertex. With 10 fb^{-1} one can find good evidence for a purely anomalous CP even or CP odd operators. With 30 fb^{-1} good sensitivity to rule out. The limits on CP even and CP odd operators are corrleated.





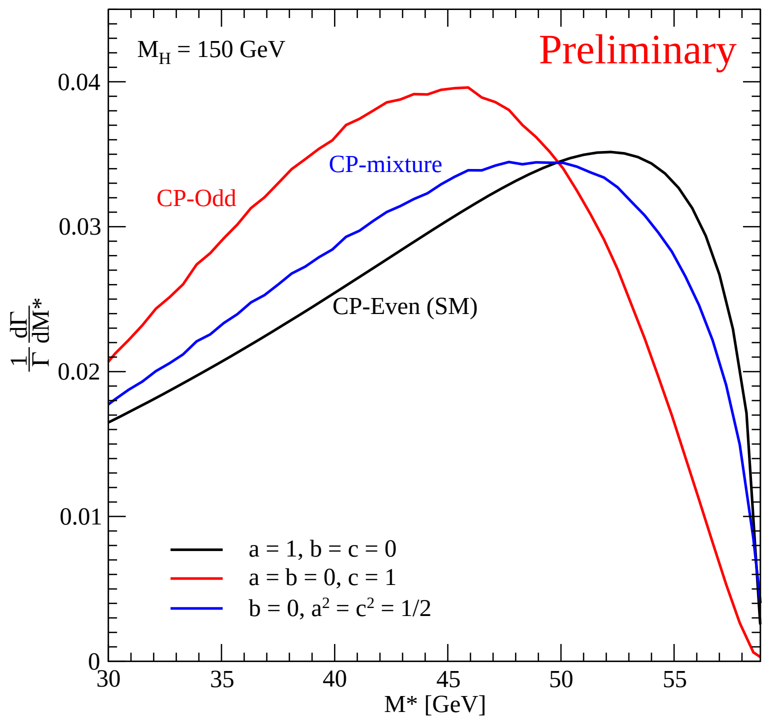
One can probe the additional couplings only upto moderate values, independent of H mass. C. Ruwiedel et al, EPJC 51 (2007) 385



The Hjj with gluon fusion can distinguish between the CP even and odd coupling of the t quark with 30 pb at 14 TeV.

Threshold behaviour (Zerwas, Miller, Choi..) to determine the spin. Can we determine Higgs CP parity also like this: (D. Miller, + Muhlleitner R.G) Same distribution used by Buszello et al (hep-ph/0406181)

Considered by Gao et al and A De Rujula et al

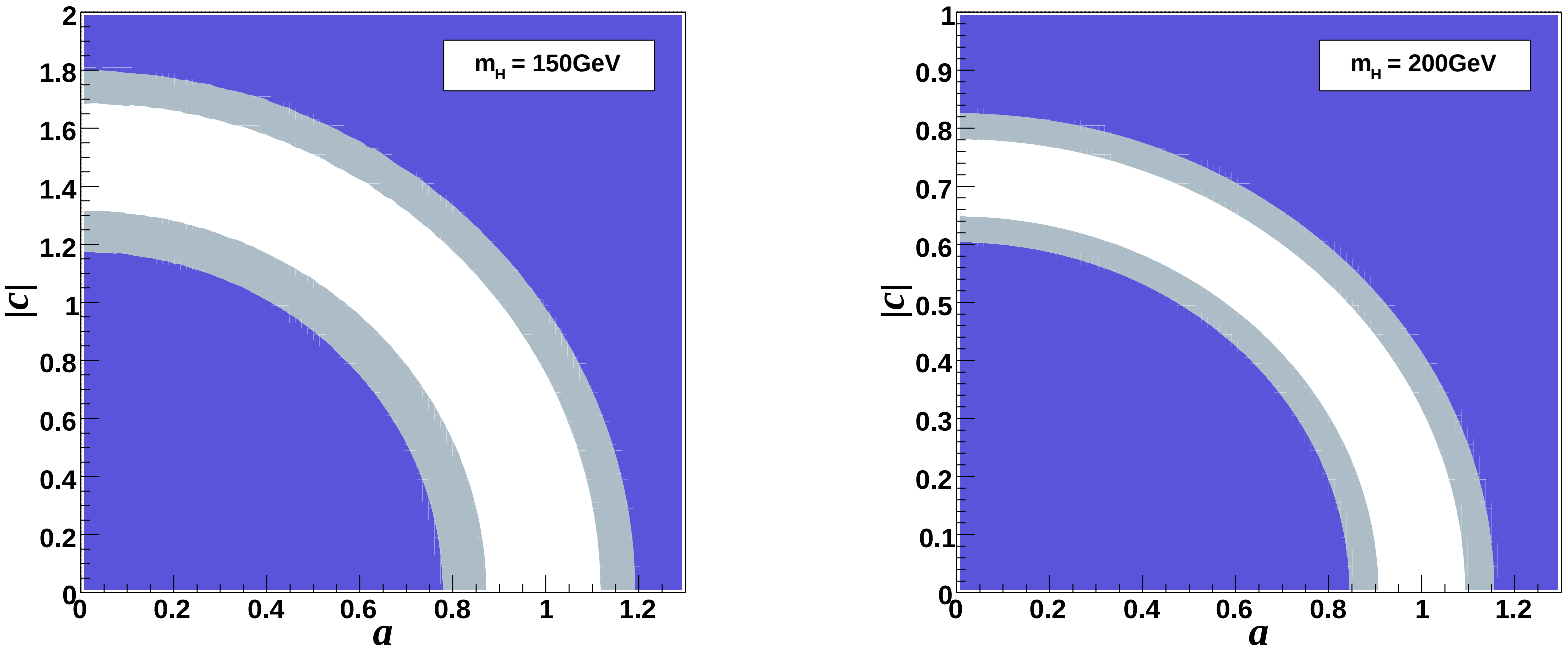


One can distinguish CP-odd from CP-even. How about mixtures?

Calculated $\Gamma(H \to ZZ^* \to f_1\bar{f}_1 f_2\bar{f}_2)$ Total rate CP even. Can not test the CP odd coupling Depends on the CP-even $a, \Re e(b), |b|$ and $|c|$.

Assume that the effect of the cuts on the observable cross-sections is the same as for the SM and take the expected numbers from an ATLAS study

Regions that can be excluded at 5 and 3 σ level using just rates alone.



All such studies look for difference caused by the different tensor structure to kinematical distributions.

CP-violating observables: constructed for ILC Gunion et al, Hagiwara et al, Han et al, Biswal et al.

For the PLC Gunion and collab., Hagiwara et al, Singh et al, Krawzyck et al.

For the LHC Gunion et al., Buszello et al, Zhang et al, Zeppenfeld et al

Our analysis Miller, Moretti, Muhelleitner and R.G. in CPNSH report and in Les Houches proceedings (hep-ph/0608079 and hep-ph/0602198):

Miller, Muhlleitner and RG: JHEP 0712 (2007) 31

Construct variables such that each probes one part of the anomalous coupling; thus CP violating variables to probe CP mixing.

• $\tilde{T}$: Naive time reversal operation.

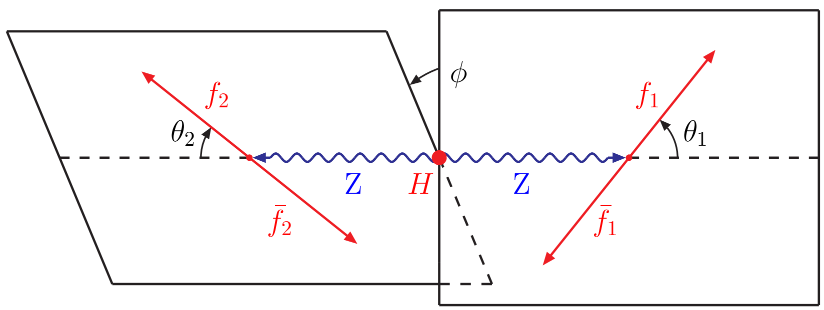
• Cross-sections integrated over $CP\tilde{T}$ symmetric phase space will probe only the $CP - even$, $\tilde{T}$–even couplings. in the approximation that the anomalous couplings are small.

• Partially integrated cross-sections will be able to probe these. for example to probe a P-odd cpupling we construct Forward-Backward asymmetry.

• Constructed different observables out of the available momenta such that they have specific CP and $\tilde{T}$ transformation properties.

• Look at expectaion value of 'sign' of these observables.These asymmetries, are proportional to the part of the anomalous coupling which has the **same** CP and $\tilde{T}$ transformation properties as the observable, to leading order in the anomalous coupling.

The definition of the polar angles θ_i $(i = 1,2)$ and the azimuthal angle φ. In the rest frame of H.



Need to distinguish between f_1 and $\bar{f}_1$.

One Z decays to $f_1\bar{f}_1$ and other two $f_2\bar{f}_2$.

Available complete analytic expression for the triple diff. crosssection

With these angles consruct observables:

$$O_1 \equiv \cos\theta_1 = \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}) \cdot (\vec{p}_{\bar{f}_2} + \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}||\vec{p}_{\bar{f}_2} + \vec{p}_{f_2}|}$$

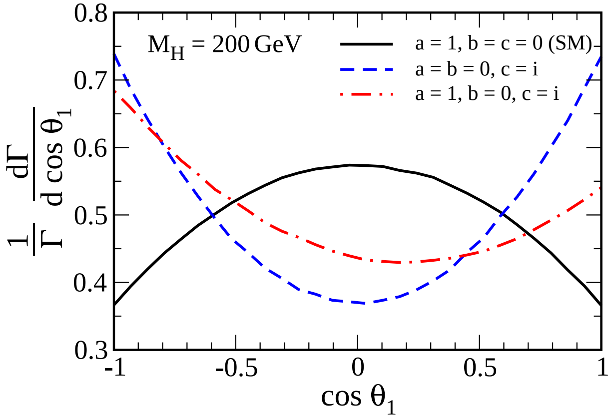
Calculate $< (sgn(\mathcal{O}_1)) >$

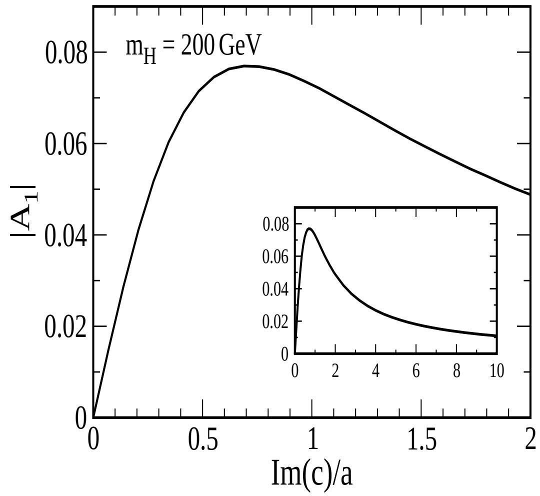
$$\mathcal{A}_1 = \frac{\Gamma(\cos\theta_1 > 0) - \Gamma(\cos\theta_1 < 0)}{\Gamma(\cos\theta_1 > 0) + \Gamma(\cos\theta_1 < 0)}.$$

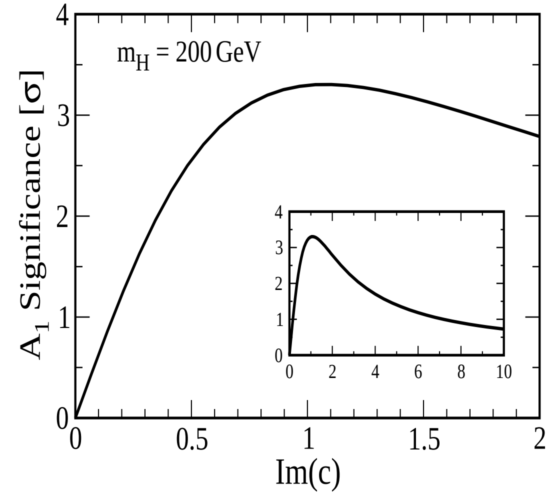
Expect this to be nonzero ONLY if $\Im m(c)$ is nonzero.

$\mathcal{A}_1 \propto \int d^2\mathcal{P}(-3\Im m(c))v_1 f_1$

If $\Im m(c) \neq 0$ this will mean $\mathcal{A}_1 \neq 0$.







The normalized differential width for $H \to ZZ \to (f_1\bar{f}_1)(f_2\bar{f}_2)$ The solid (black) curve: the SM ($a = 1$, $b = c = 0$), Dashed (blue) curve: pure CP-odd state ($a = b = 0$, $c = i$). The dot-dashed (red) curve is for a state with a CP violating coupling ($a = 1$, $b = 0$, $c = i$). One can clearly see an asymmetry about $\cos\theta_1 = 0$ for the CP violating case.

Corrected for change in the production rate due to our non-standard couplings as compared to the SM rate. For $100 fb^{-1}$

May be improved by using jets instead of f_2 as the asymmetry does not require charge determination. One essentially means 'b'-jets. ATLAS study demonstrates it is possible to see the signal in $Z \to b\bar{b}$.

One probe of $\Re e(c)$

$$O_3 = \cos\theta_1 \sin\theta_2 \cos\theta_2 \sin\phi \; .$$

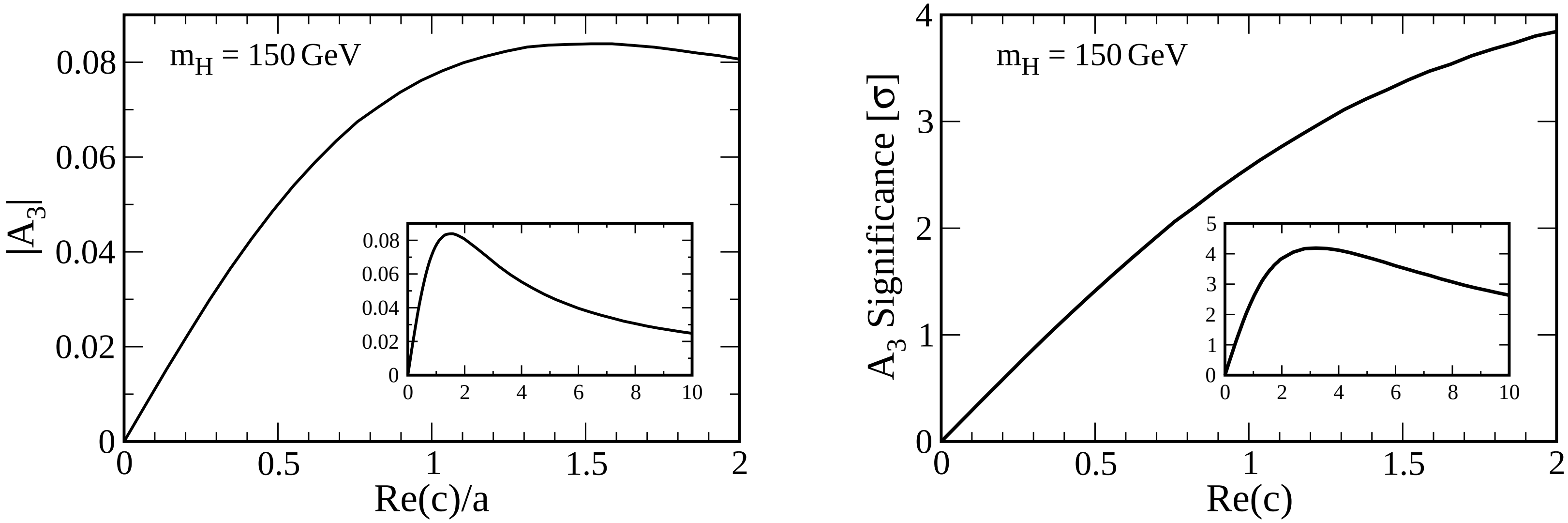
and

$$\mathcal{A}_3 = \frac{\Gamma(O_3 > 0) - \Gamma(O_3 < 0)}{\Gamma(O_3 > 0) + \Gamma(O_3 < 0)}.$$

We get,

$$\mathcal{A}_3 = \frac{1}{\Gamma} \int d\mathcal{P} (\frac{-256}{9}) m_1^3 m_2^3 (v^2 + a^2)^2 \gamma_a \gamma_b (a \Re e(c) - \Re e(bc^*) m_1 m_2 \frac{\gamma_b^2}{\gamma_a})$$

The asymmetry is proportional to $a\Re e(c)$ and $\Re e(bc^*)$. In linear approximation for anomalous coupling it is then a probe of $\Re e(c)$. **Does not have the suppression that $\mathcal{A}_2$ has.**

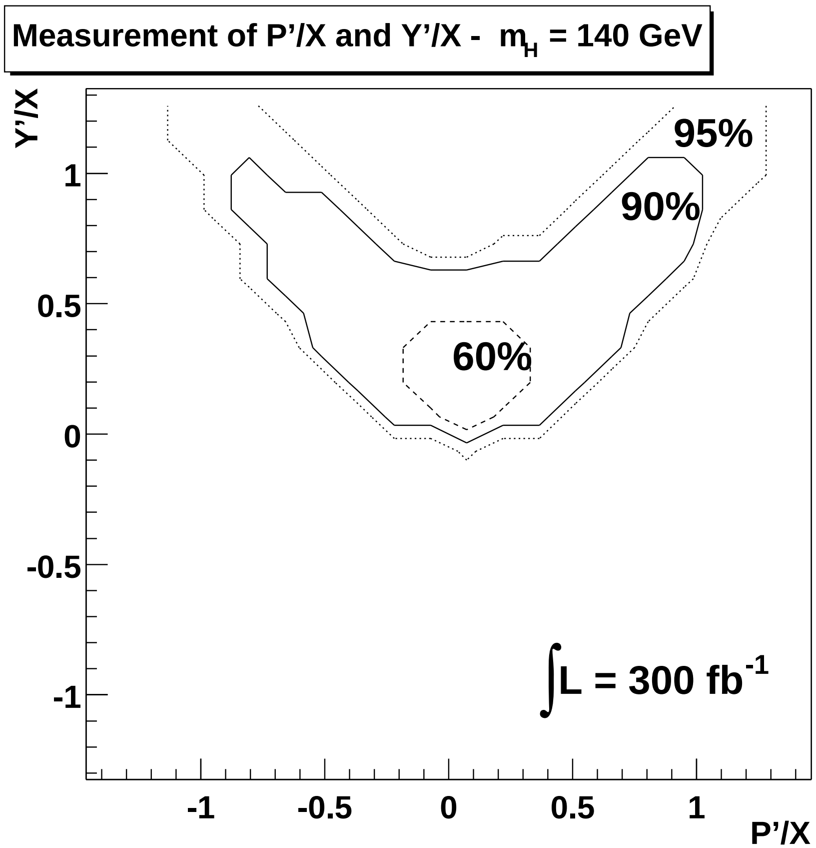


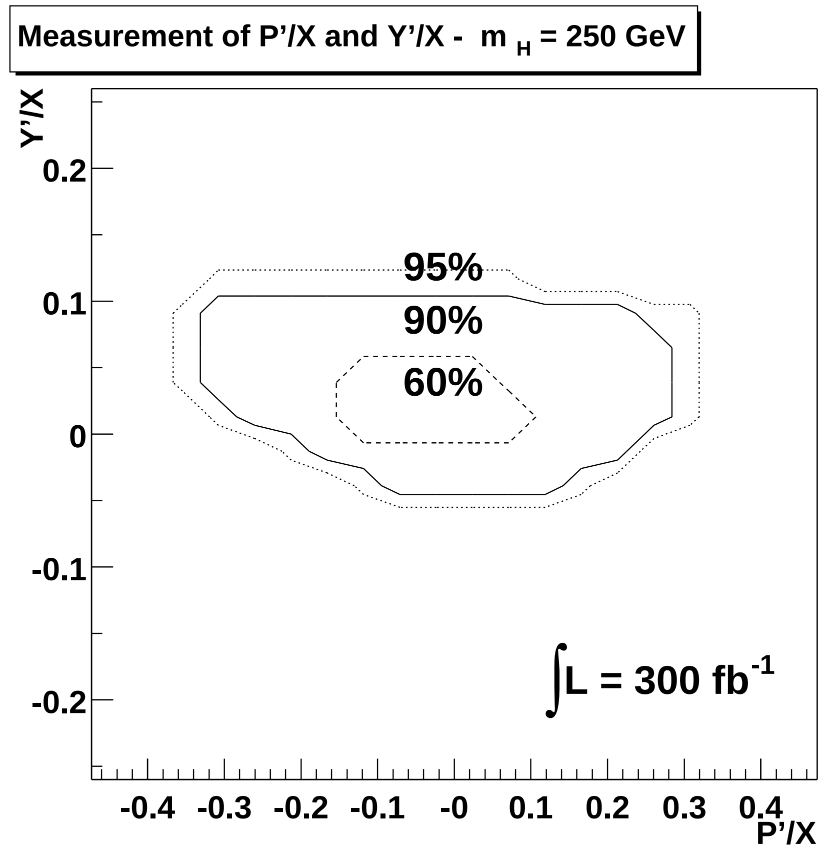
Expected signficance for 100 fb^{-1} not bad!

Asymmetry/form factor	a	$\Re e(b)$	$\Im m(b)$	$\Re e(c)$	$\Im m(c)$
$\mathcal{A}_1$	x				x
$\mathcal{A}_3$	x	(x)	(x)	x	(x)
$\mathcal{A}_4$	x			x	
$\mathcal{A}_5$	x	(x)	(x)	x	(x)
$\mathcal{A}_6$	x		x		

The dependence of the asymmetries $\mathcal{A}_1$ and $\mathcal{A}_3$ to $\mathcal{A}_6$ on the form factors a, b, c of the general HZZ coupling.

Buszello et al..slightly different formulation of the additional coupling
The earlier $Re(c)$ and $Im(b)$ become P, X, Y.





Warning: If we use ϕZZ coupling for production. it 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.

$t\bar{t}\phi$ production treats the scalar and the pseudoscalar democratically.

$\gamma\gamma$ colliders have the same good feature. But we may never have it!

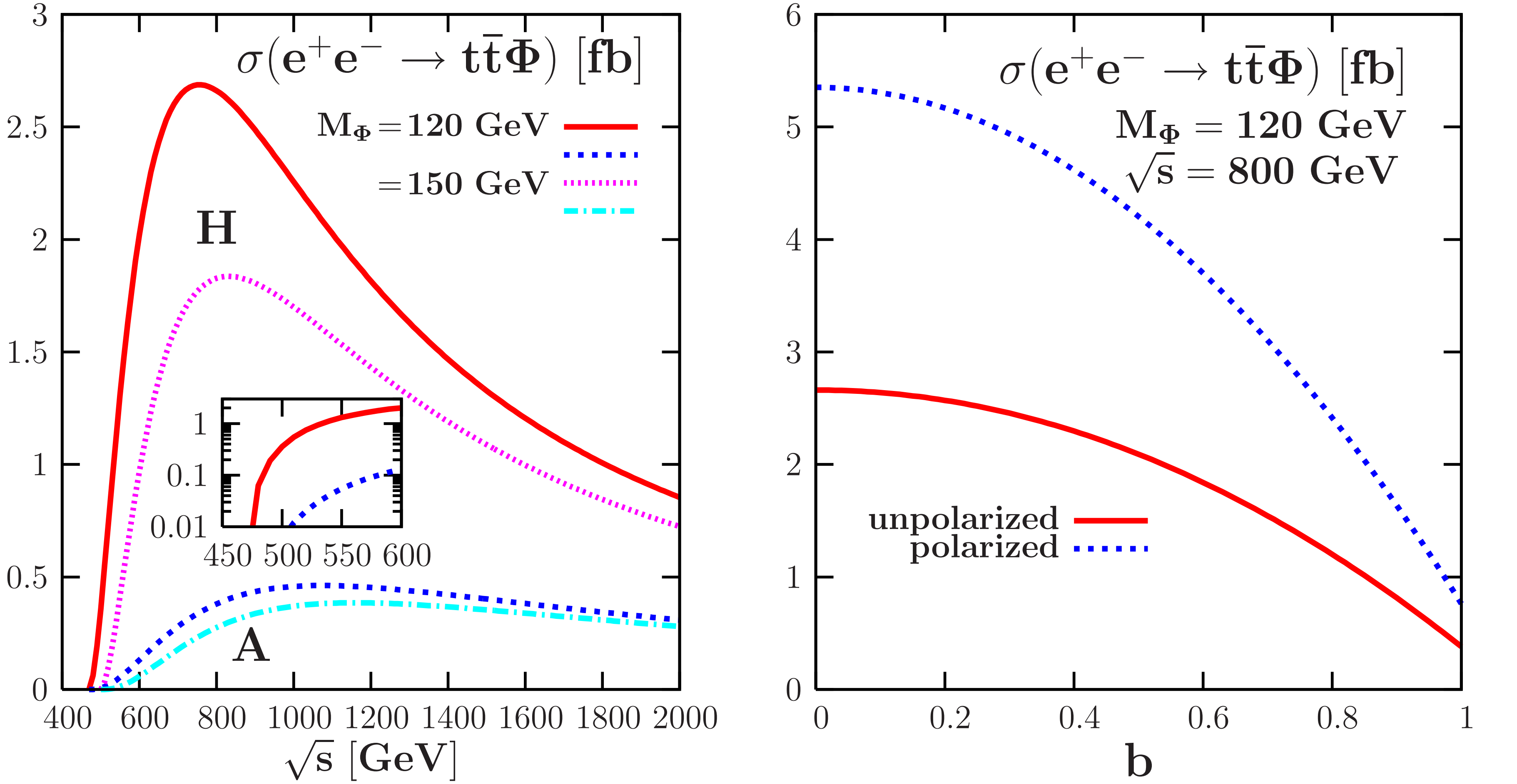
Can LHC do something? $t\bar{t}H$ needed!!!!!

Right now not clear we can handle the background in $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ channel.

Situation improves somewhat with the use of fat jets: T. Plehn et al PRL, 104,11801 (2010)

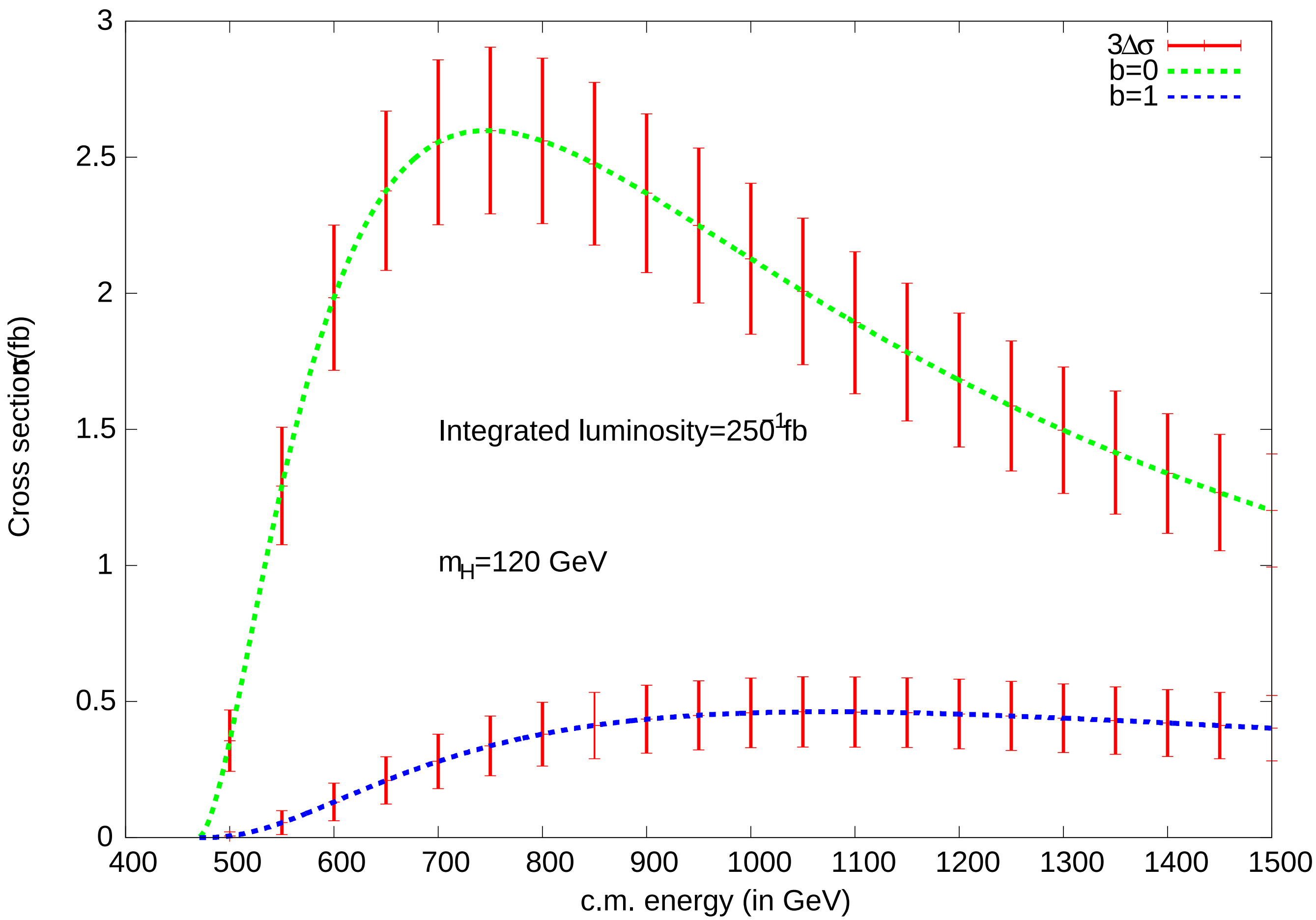
Pioneering study by Gunion and He PRL 76 (1996) 4468 Optimal observable analysis (a bit like the analysis presented for ZZ final state)

Experimental analysis in CPNSH report (Justin Albert et al, CPNSH report, hep-ph/0608079.) Require large luminosity, 300 fb^{-1}.



$$b = p_t, a_t = \sqrt{(1 - p_t^2)} = \sqrt{(1 - b^2)}.$$

PRL08 : B. Dev. RG, A. Djouadi, Rindani, Muhelleitner



Pankaj Sharma, RG. S.D. Rindani

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

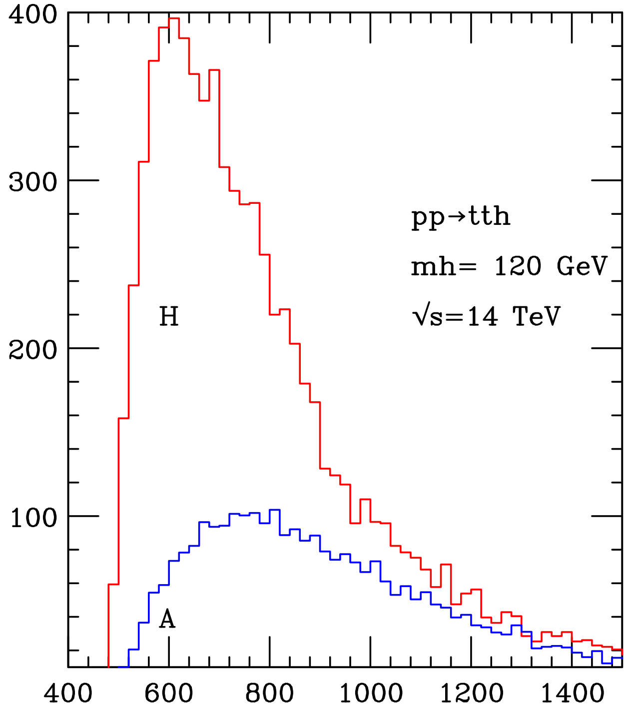
Define $\rho = 1 - 2m_t/\sqrt{s} - M_\Phi/\sqrt{s}$

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

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.

What does it have to with LHC?

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

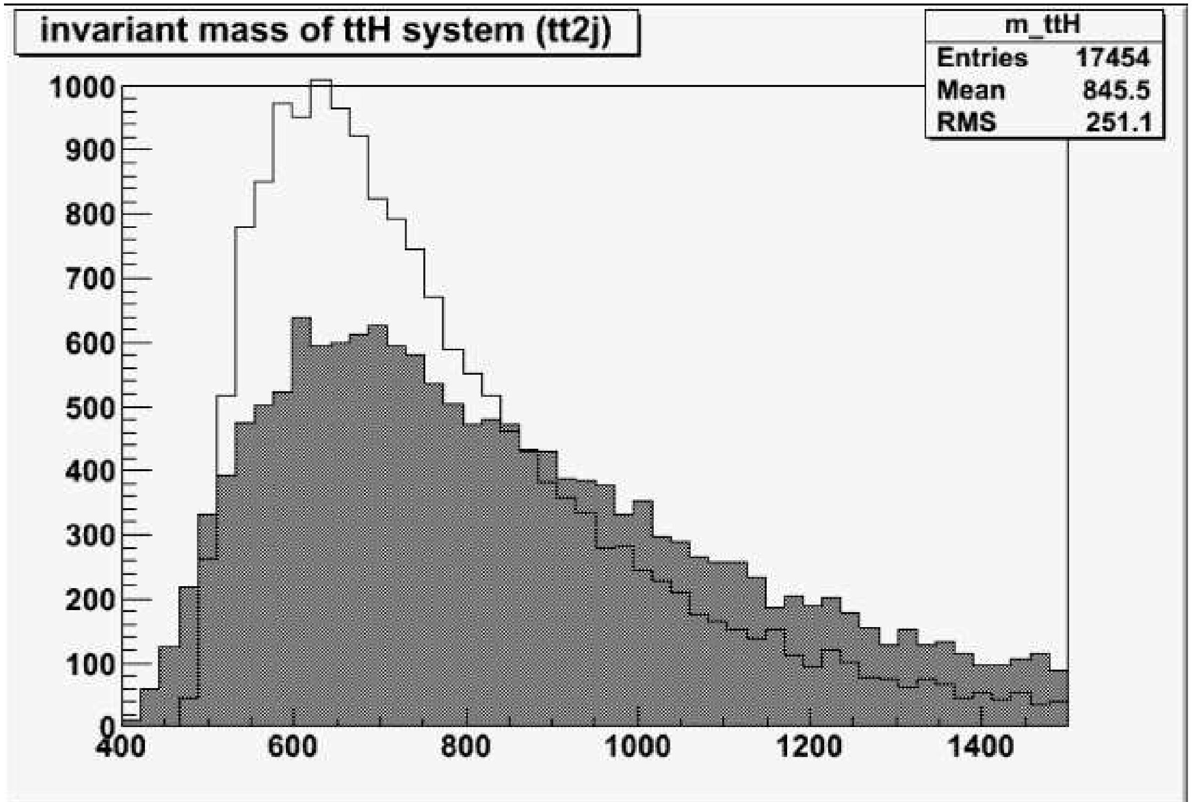


Djouadi, RG(Review for INSA jubilee issue: hep-ph/0901.2030)

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.

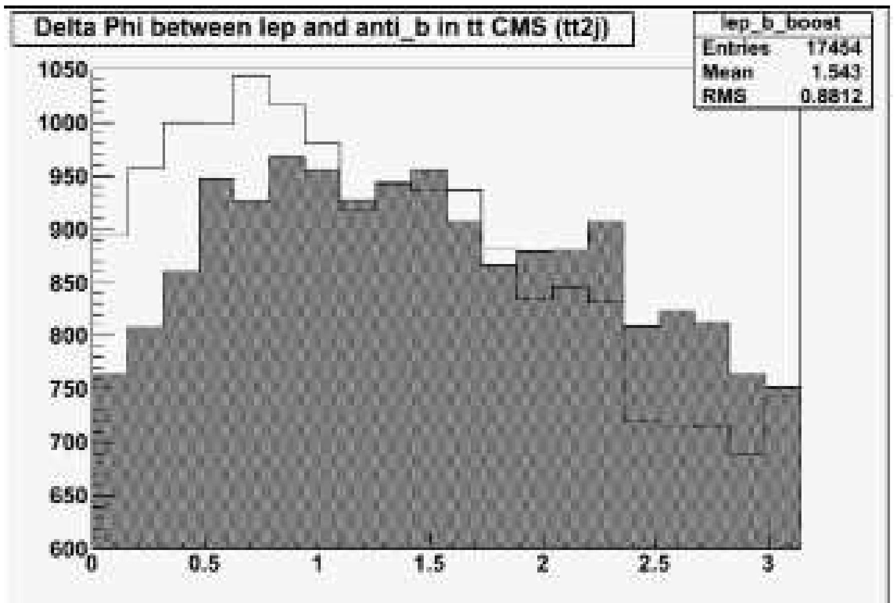
1) Clean variable to decide the CP at large luninosity

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

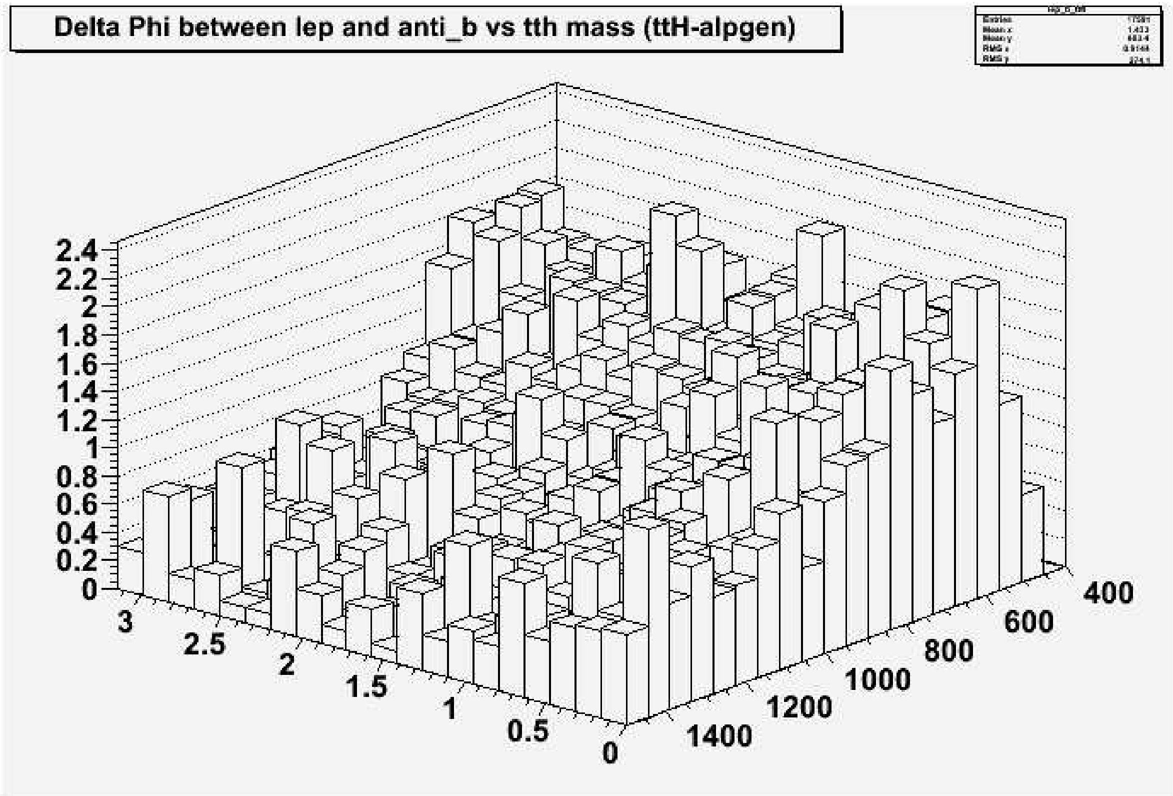


RG, Djouadi, Ferrag, Piccinnini, Rindani The shapes of the signal and background are quite different.

In addition the different spin-spin correlations between background and signal too



Distribution in the azimuthal angle between the decay lepton from one t and the b from the other. This is different for the two cases as the spin-spin correlation between the t and $\bar{t}$ are different for signal and background. RG, Djouadi, Ferrag, Picinnini,Rindani



The ratio of signal to background as a function of the $t\bar{t}b\bar{b}$ invariant mass and Δphi. Ratio can be maximised by cuts.

RG, Djouadi, Ferrag, Piccinnini,Rindani Can the differences in shape be utilized effectively to distinguish signal from the background?

- Nontrivial information on the spin and parity of the Higgs may be obtained at the LHC with a few femtobarns (5-10), over a wide range of higgs masses, by looking at all the angular and invariant mass distributions for the $H \to ZZ(^*) \to f_1 \bar{f}_1 f_2 \bar{f}_2$ and seems to afford a rejection of alternate to 0^{++} hypothesis at a high level of signficance. With 100 fb^{-1} data, it can afford a measurement of individual anamolous parts of the ZZH vertex. An experiemental study of this is lacking.

- The VBF offers possibility of distinguishing between CP even and CP odd couplings, for the anomalous couplings, independent of the decay mode, ie , independent of the mass.

- The azimuthal angular distributions for the two jets in $H + 2$ jets production, can also carry information on the CP mixing through the $t\bar{t}H$ coupling and requires about 30 fb^{-1} data at 14 TeV.

- The invariant mass distribution of the $t\bar{t}H$ system and the azimuthal angle between the decay products of the t and $\bar{t}$ in the laboratory frame (ie.the spin spin corelations) carry an imprint of the CP and spin of the Higgs. May be used either to increase the signal to background ratio or to determine the CP property of the Higgs. More investigations are necessary.