CP (mixing) in the Higgs sector in $t\bar{t}H$

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KAERU: Key Aspects in Exploring Roads to Unification

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The frog in the well knows nothing of the great ocean.
However, we will swim in the ocean in the future.

The frog in the well knows nothing of the great ocean ..However we all swim in the ocean of future!

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I dont have to make any apologies to make mention of collaborations with Kaoru. I had none!

I have a Kaoru number of 2!

I have collaborated with direct collaborators of Kaoru!!

But few things I have played with have been contained in the wide range of areas of his expertise!

Almost always I have come upon beautiful things he has done and have used them!

As a young graduate student I calculated Higgs production in $\nu + N \rightarrow \mu + X + h$

Phys. Rev. D 1978

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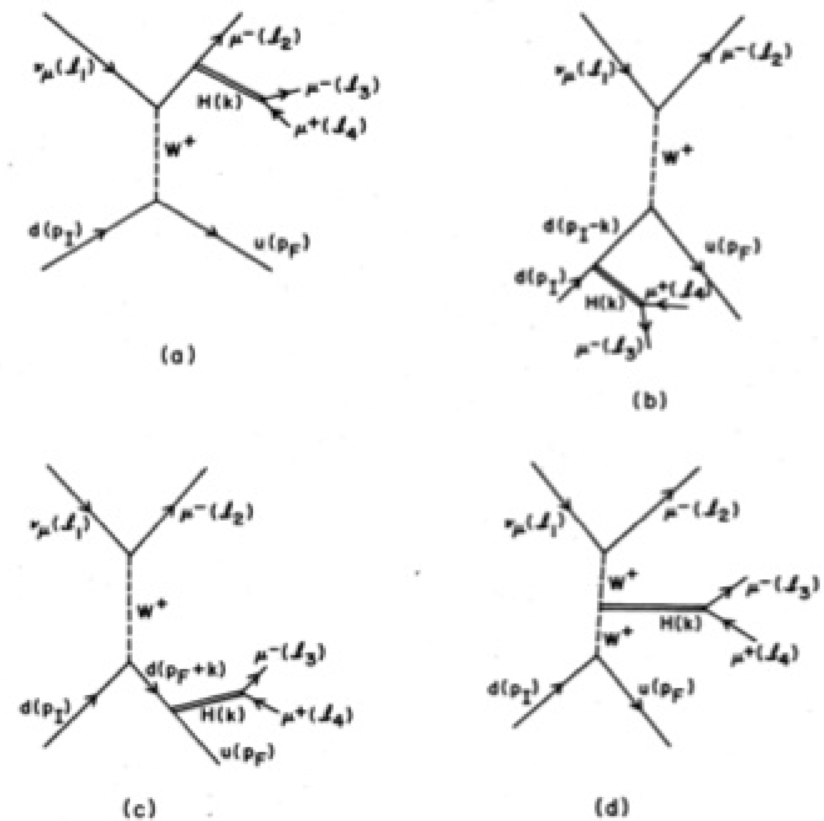


FIG. 3. Feynman diagrams for the production and decay of the Higgs boson.

But it took Kaoru and Dieter to convert the VBF into the work of art that it is today!

Introduction:

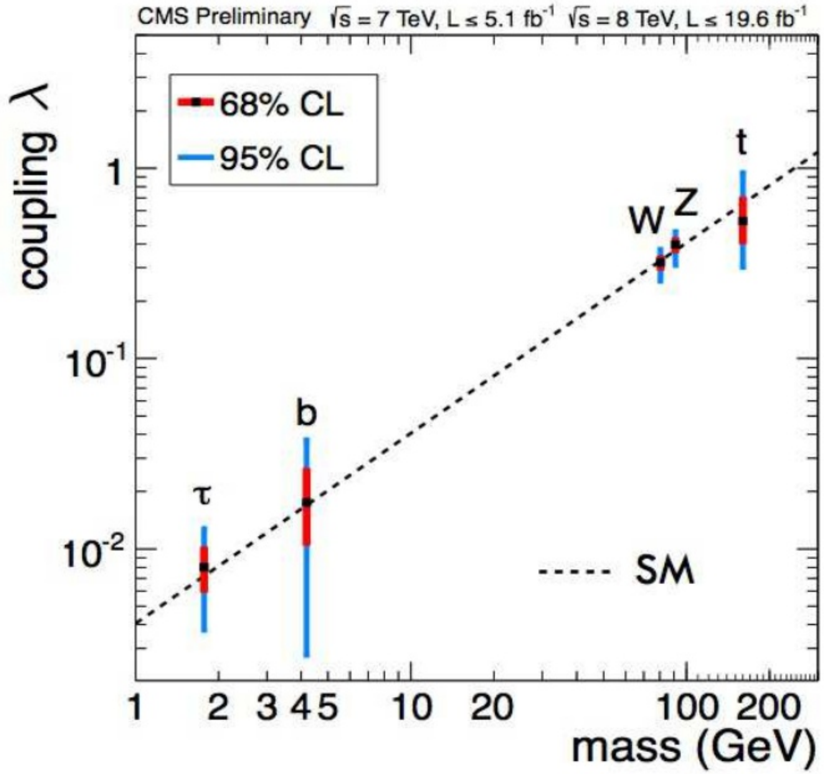
- **What do we do now that we have found the Higgs?**
- **One answer : study its couplings in detail.**
- **But then experimentalists show this great plot of couplings vs masses and tell us that we have the SM Higgs (almost!)**
- **SM predicts two things**
- **Coupling strengths of the Higgs to all the SM particles**

AND

- **Tensor structure of the coupling**

This is what we see all the time!

This is information on strengths of couplings, **obtained** USING the **SM tensor structure**.



What is meant by tensor structure?

- $\bar{f}fH$ coupling involves the bilinear $\bar{\mathbf{f}}\mathbf{f}$
- The VVH coupling involves $\mathbf{g}_{\mu\nu}$

Largest couplings of the Higgs to pair of vector bosons and the heaviest fermion the top quark.

- **If at all these will carry glimpses of BSM!**
- **Study these two couplings with a focus on CP violation.**
- **HVV coupling:**

  VBF, VH production

- $\mathrm{t\bar{t}H}$ coupling:

  Associated production of Higgs with a tt pair and inclusive production of Higgs.

- **Interesting studies by Bernereuther et al using higgs decay to a tau pair.**

References:
These studies were foreseen as the step after discovery!

1) (hep-ph/0608079) CPNSH report.

2) 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.)

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Workshop on CP Studies and Non-Standard Higgs Physics

May 2004 – December 2005

Edited by

Sabine Kraml[1], Georges Azuelos[2,3], Daniele Dominici[4], John Ellis[1], Gerald Grenier[5], Howard E. Haber[6], Jae Sik Lee[7], David J. Miller[8], Apostolos Pilaftsis[9] and Werner Porod[10]

References which I will use in this talk:

Anomalous $t\bar{t}H$ vertex at the LHC:

Contribution to Les Houches proceedings,

1) F. Boudjema, R.G, D. Guadagnoli and K. Mohan, 1408.5617,

2) A full fledged paper: arXiv:1501.03157

References which I will use in this talk.
Anom $t\bar{t}H$ vertex at the ILC:

1) Phys. Rev. Lett. 100 (2008) 051801
(Bhupal Dev, A.Djoaudi, R.G. et al)

2) EPJC, 71 (2011) 168,
(C. Hangst, R.G., Margarete Muehelleitner et al)

We need to establish the strength and the tensor structure of the Higgs couplings to all the matter and gauge particles.

To this end just using rates is not enough, but studying kinematic distributions and constructing variables that are sensitive to anomalous vertices, preferably linearly using INTERFERENCE EFFECTS.

Ways to probe the Tensor structure and CP violation:

0)Decay through ZZ to 4 lepton pairs.

0)Decay to a gamma gamma pair.
(happening now)

1) Production in WW fusion
2)Production of Higgs in association with a vector boson
(**Upcoming run**)

Completely unambiguious :
3)Associated production of a Higgs with a ttbar pair. **Low rates! Once we have seen the signal This will be the order of the day!**

CP violation in the Higgs couplings:

Generally of great interest as Baryogenesis requires additional source of CPV and Higgs couplings just might be it!

Decay through ZZ to 4 lepton pairs told us that it is CP even..so why should we still worry?

For VVh couplings CPV couplings are always loop induced and hence very small! Hence if h is NOT a CP eigenstate, hVV couplings project out CP even Part!

Fermion couplings the most unambigious place for probing the CPV !!

CP violation in the fermion couplings with the higgs can induce large edm's and hence imply very strong constraints. Why should we then worry again?

Reference: yesterdays talk by Kingman Cheung and various papers by him and collaborators.

Higgs coupling to top quarks

$$\mathcal{L}_{tth} = g_{tth}\bar{t}(a + ib\gamma_5)\phi t$$

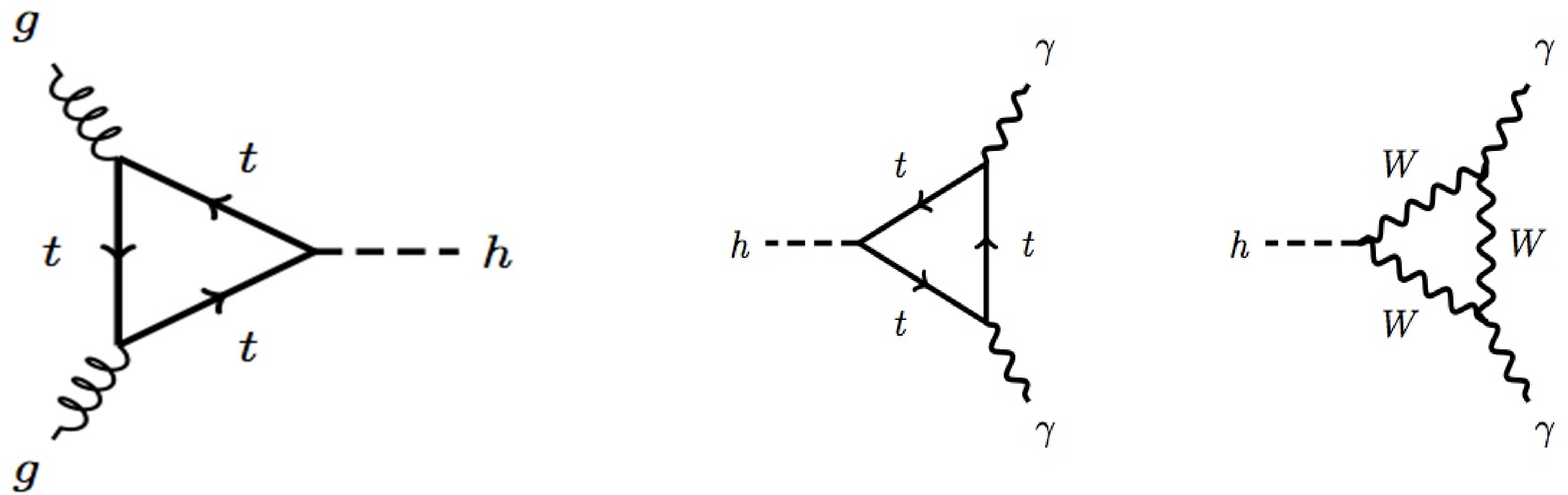
$$g_{tth} = m_t/v$$

In SM $a = 1$ and $b = 0$.

For a pure pseudoscalar $a = 0$ and $b \neq 0$.

Higgs of mixed CP properties $a \neq 0$ and $b \neq 0$.

Non-SM couplings will affect higgs production and decay rates



EDM's

- In principle edm's can put big constraints on ratios and products of $\mathbf{a_e, b_e}$ and hence also on $\mathbf{a_t, b_t}$ if we assume CP violation to be universal in all couplings.
- **This depends on the models for CPV in the fermion couplings**
- In SUSY based models where CPV phases allow mixing in the Higgs sector through loops one can satisfy all the edm constraints and still have CP violation in the $\mathbf{f\bar{f}h}$ couplings (for $\mathbf{f = t}, \tau$)

Arbey, Godbole, Ellis and Mahamoudi (arXiv:1410.4824: to appear in JHEP)

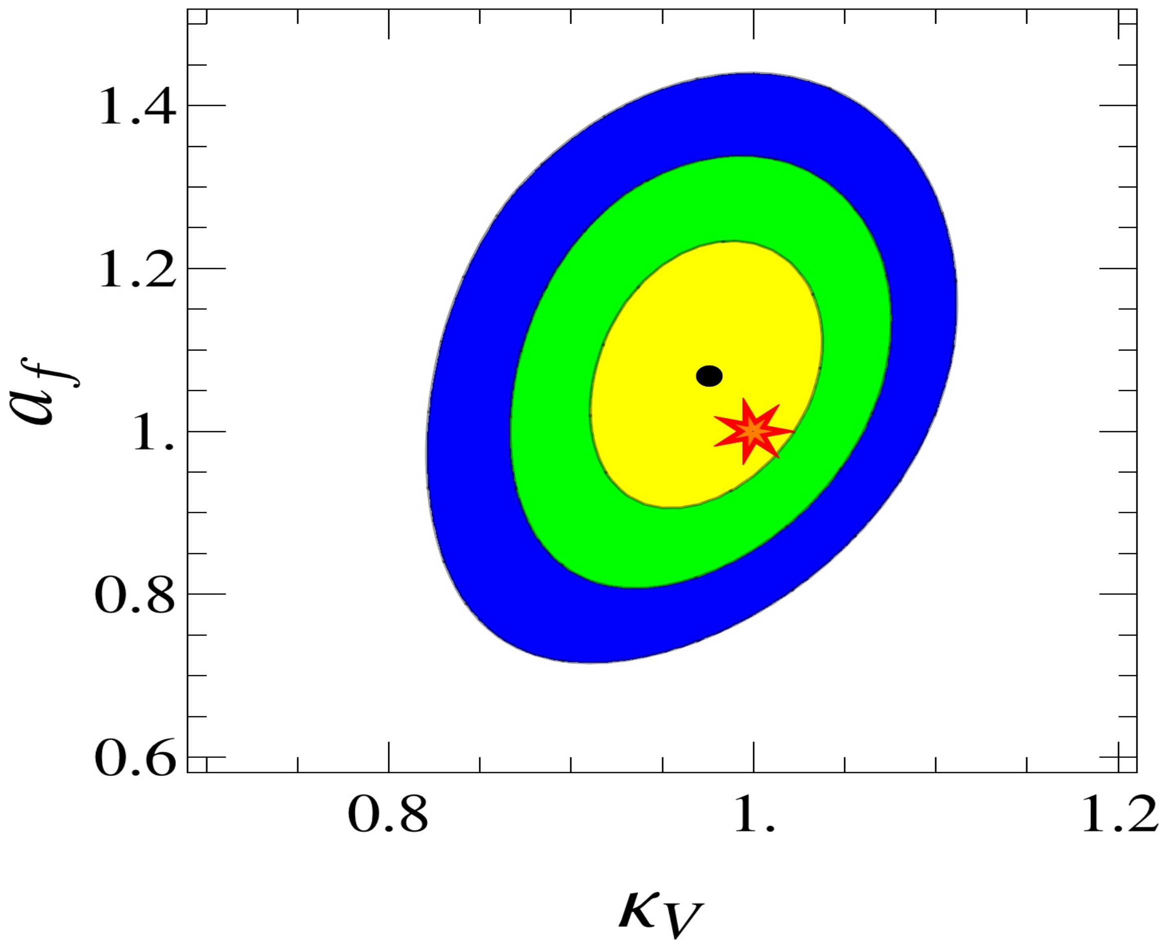
Higgs rates

- What if one allows for floating coupling strength with the vector bosons W/Z as well as a_f, but allowing only CP even couplings for fermions.

Yellow : 68%

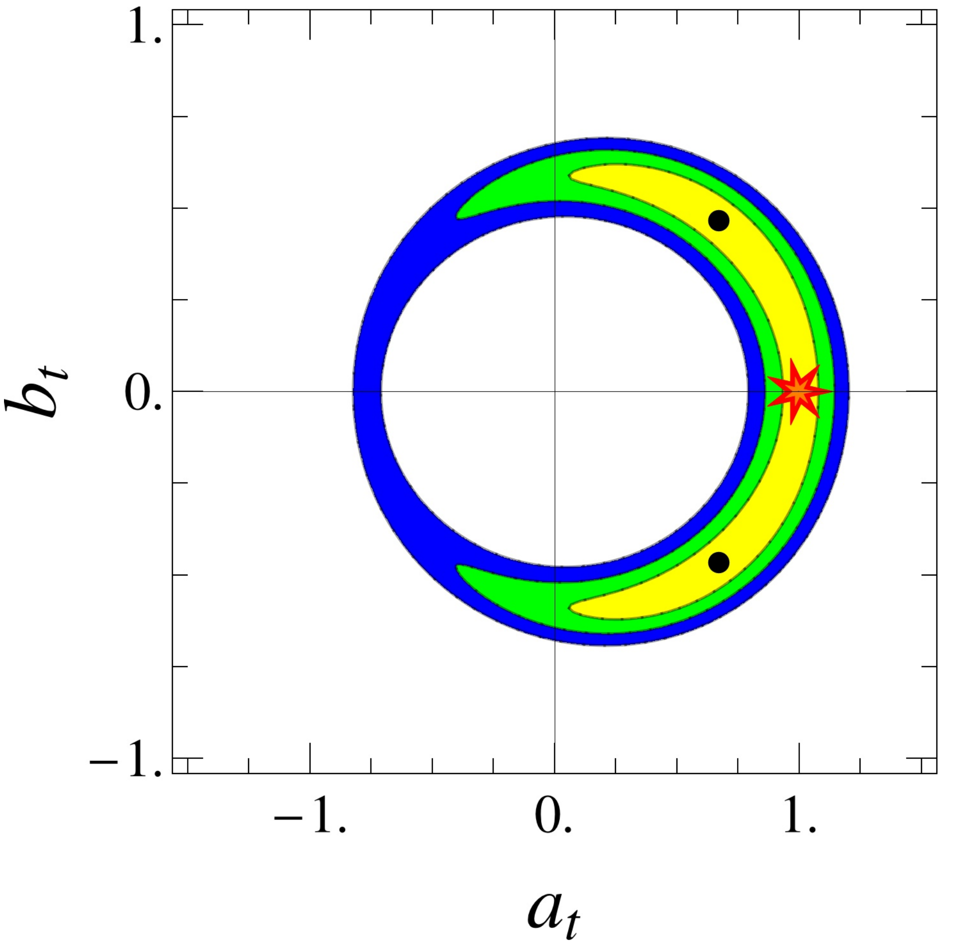
Green: 95%

Blue: 99.7%



Higgs rates

- Higgs production and decay rates can provide information about the strength of g_{tth}
- SM VVh couplings and for all f other than top.
- Unambiguous determination of the nature of the interaction requires a more direct probe
- Only a small difference from other similar analyses. We have included higher order effects in the branching ratios.



$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \simeq \frac{|\kappa_W A_W^a(\tau_W)+\frac{4}{3}a_t(1-\alpha_s/\pi)A_t^a(\tau_t)|^2+|\frac{4}{3}b_t A_t^b(\tau_t)|^2}{|A_W^a(\tau_W)+\frac{4}{3}(1-\alpha_s/\pi)A_t^a(\tau_t)|^2}$$

$$\simeq 1.6\left((\kappa_W-0.21a_t)^2+0.12b_t^2\right)$$

$$\frac{\sigma(gg\to h)}{\sigma(gg\to h)_{SM}} \simeq \frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}}$$

$$\simeq a_t^2+b_t^2\left(1+\frac{\alpha_s}{2\pi}\right)\frac{|A_t^b(\tau_t)|^2}{|A_t^a(\tau_t)|^2} \simeq a_t^2+2.29b_t^2$$

Difference from other analyses: we have used the NLO expressions.

Simpler form possible due to large values of top mass.

Higgs rates

Repeat:

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \simeq 1.6(\kappa_W - 0.21 a_t)^2 + (0.34 b_t)^2$$

$$\frac{\Gamma(gg \to h)}{\Gamma(gg \to h)_{SM}} \simeq a_t^2 + 2.29 b_t^2$$

For the loops the pseudoscalar contributes more.

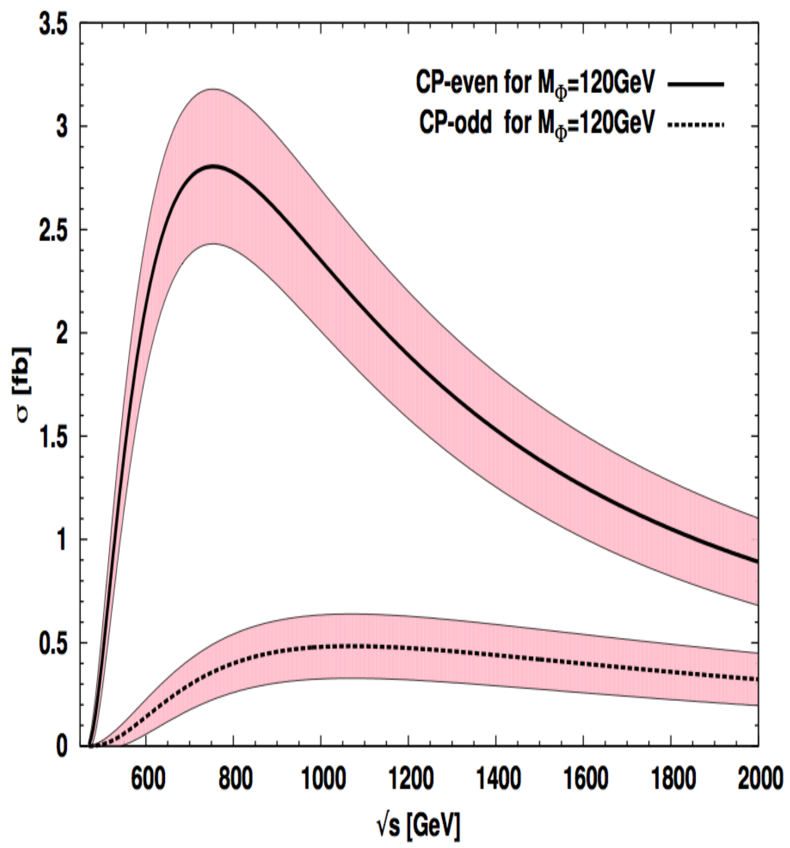
But the rates can not rule out zero value of bt and also can not lift the degeneracy between two values.

We will see later that for the ttH production the scalar contributes more.

Effect on kinematic distributions

- To probe directly the nature of the coupling scalar or pseudoscalar look at the kinematic distributions of decay products
- Also look at the spin spin correlations between the top and the anti-top.
- How to probe these correlations?

Reminder of a result from e+e-



The energy dependence of
cross-section depends on a and b

Top curve a =1, b=0, Pure Scalar
Bottom curve a=0, b=1, pure pseudoscalar.

Phys. Rev. Lett. 100 (2008) 051801
(Bhupal Dev, A.Djoaudi, R.G. et al)

and

EPJC, 71 (2011) 1681
(C. Hangst, R.G., Margarete Muehelleitner et al)

Threshold behaviour of tth production

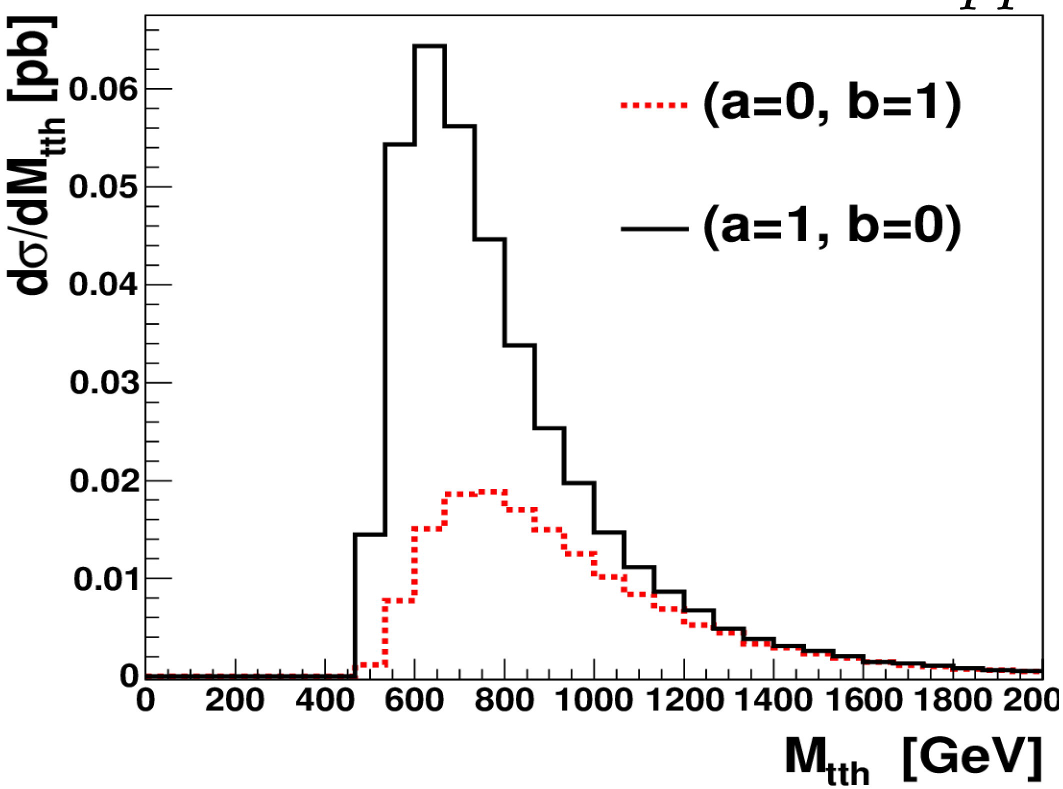
For qq initiated process angular momentum provide hints to origin of suppression.

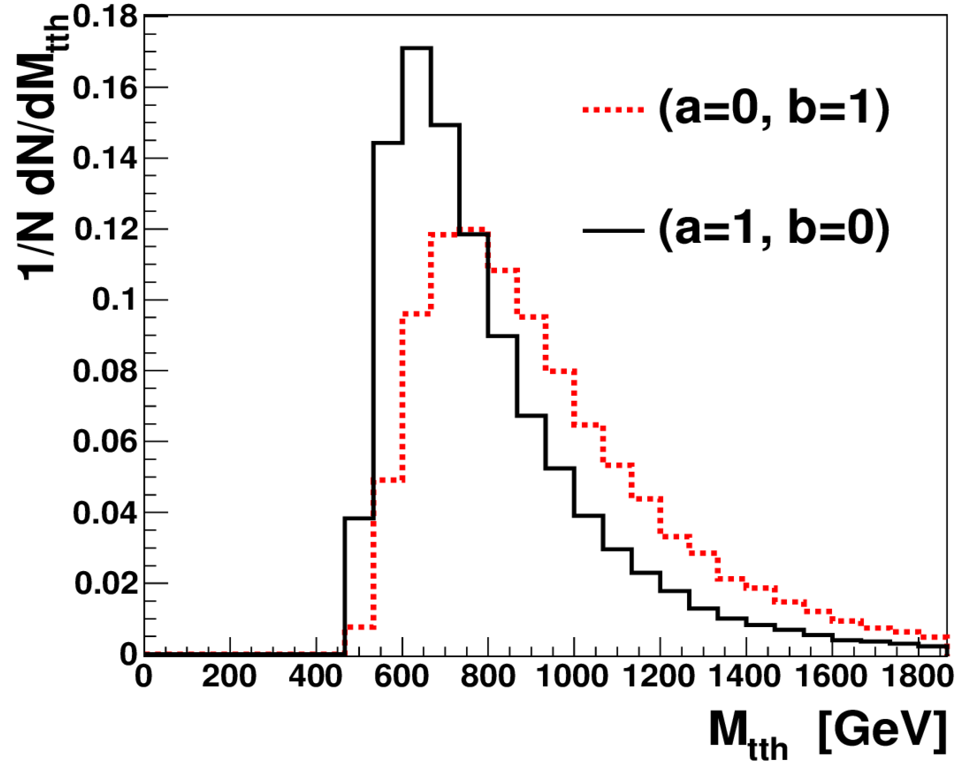
For scalar overall angular momentum of tth =0.

For pseudoscalar overall angular momentum of tth =1.

Dominant gg initiated process also suppressed but not as strongly.

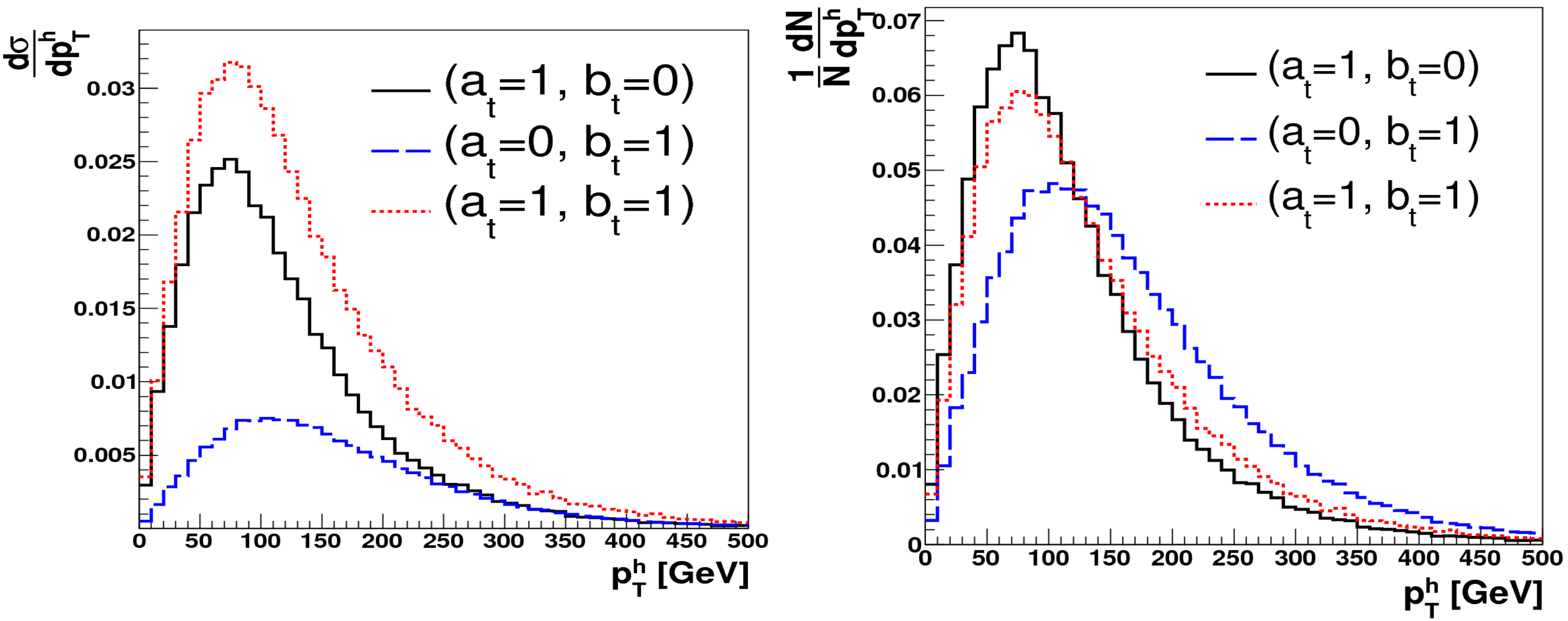
$pp \to tth$





Pt distribution of Higgs

Noticed also by Maltoni et al:



The gamma_5 in the vertex makes a difference in the momentum flow at the vertex. Difference seen even in normalised distributions.

Ratios of tth cross-sections

If we construct ratios of tth cross-sections using different pt cuts, for example, the a_t and b_t terms will contribute differently

So this can give information on CP violation (ie. Simultaneous presence of a_t and b_t !.

$$\frac{\sigma}{\sigma_{SM}} = a_t^2 + X b_t^2$$

Where X depends on the pt cut , invariant mass cut., beam energy.

Ratios of tth cross-sections

For example:

$$\left(\frac{\sigma}{\sigma_{SM}}\right)_{8TeV} = a_t^2 + 0.31 b_t^2$$

Where as for 14 TeV 0.31 will be 0.42

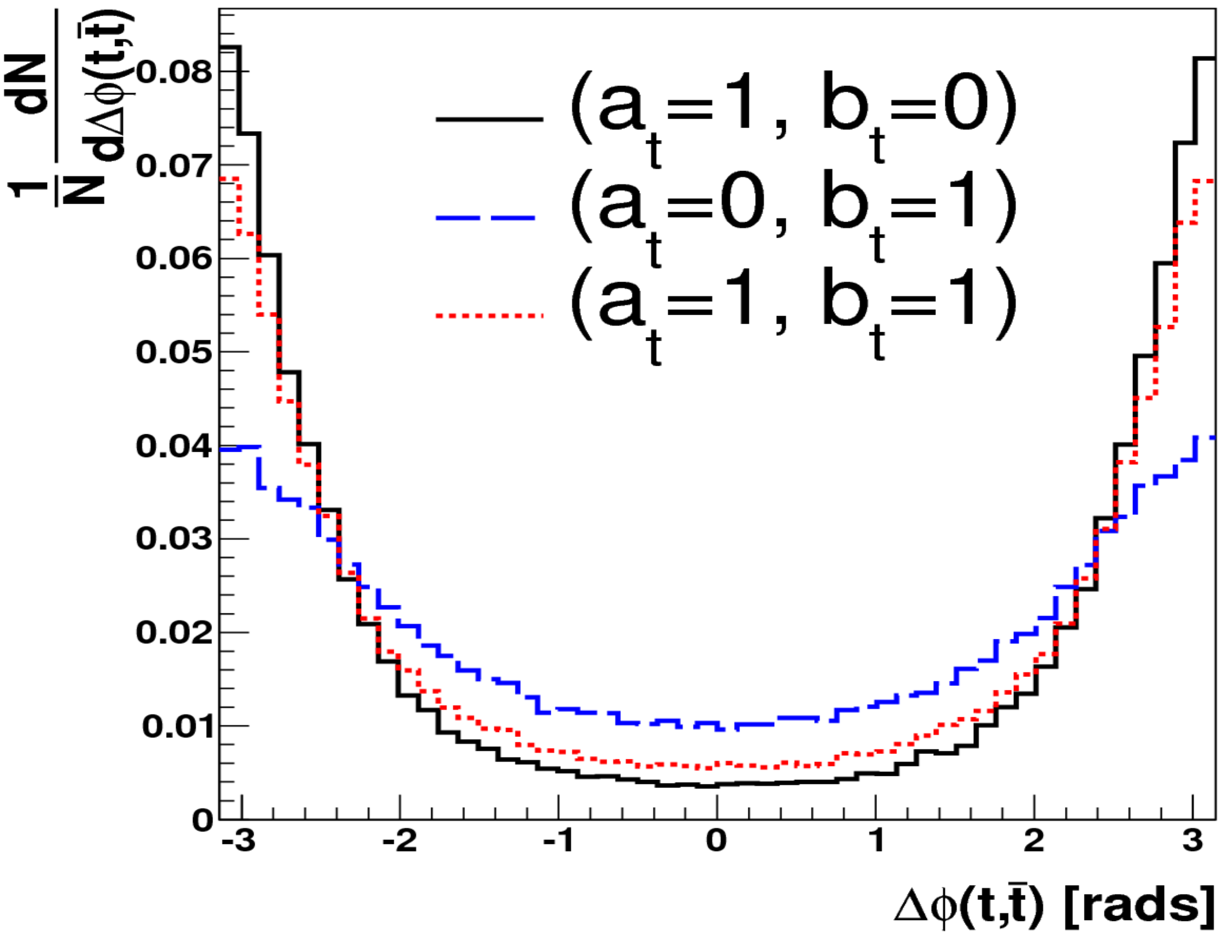
At 14 TeV with a cut on top transverse momentum

$P_T^t > 100 GeV$ the coeffeicent 0.42 will become 0.60

So we can detect simultaneous presence of a_t and b_t from rate measurements. But will require every accurate measruements and theoretical systematics in the rate prediction can also dominate

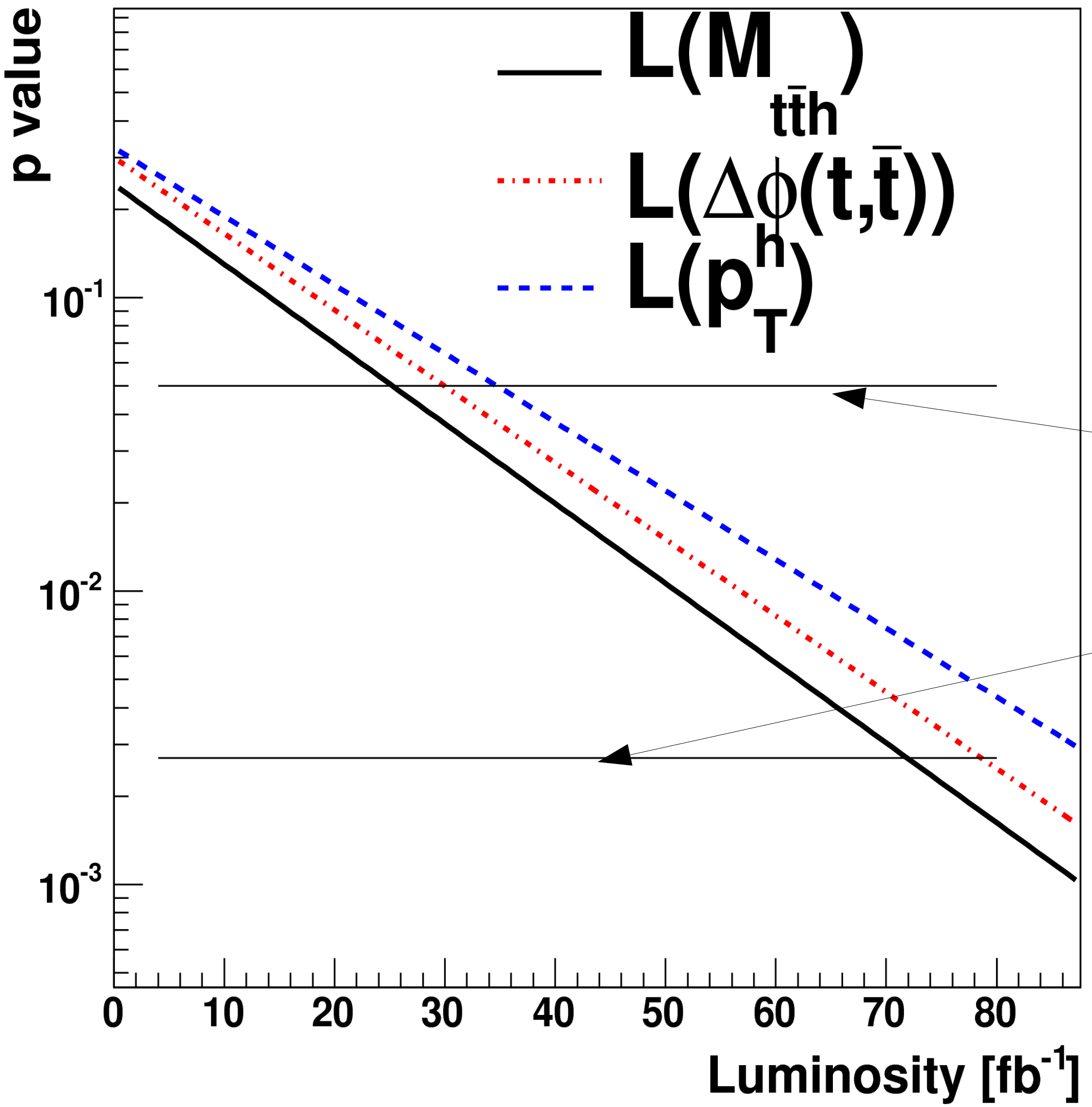
Djouadi, RG and Baglio : Phys. Lett. B. 716, 2012, 203.

Azimuthal angle between t and tbar



Pseudoscalar case larger pt of Higgs makes the distribution flatter.

Which works better?



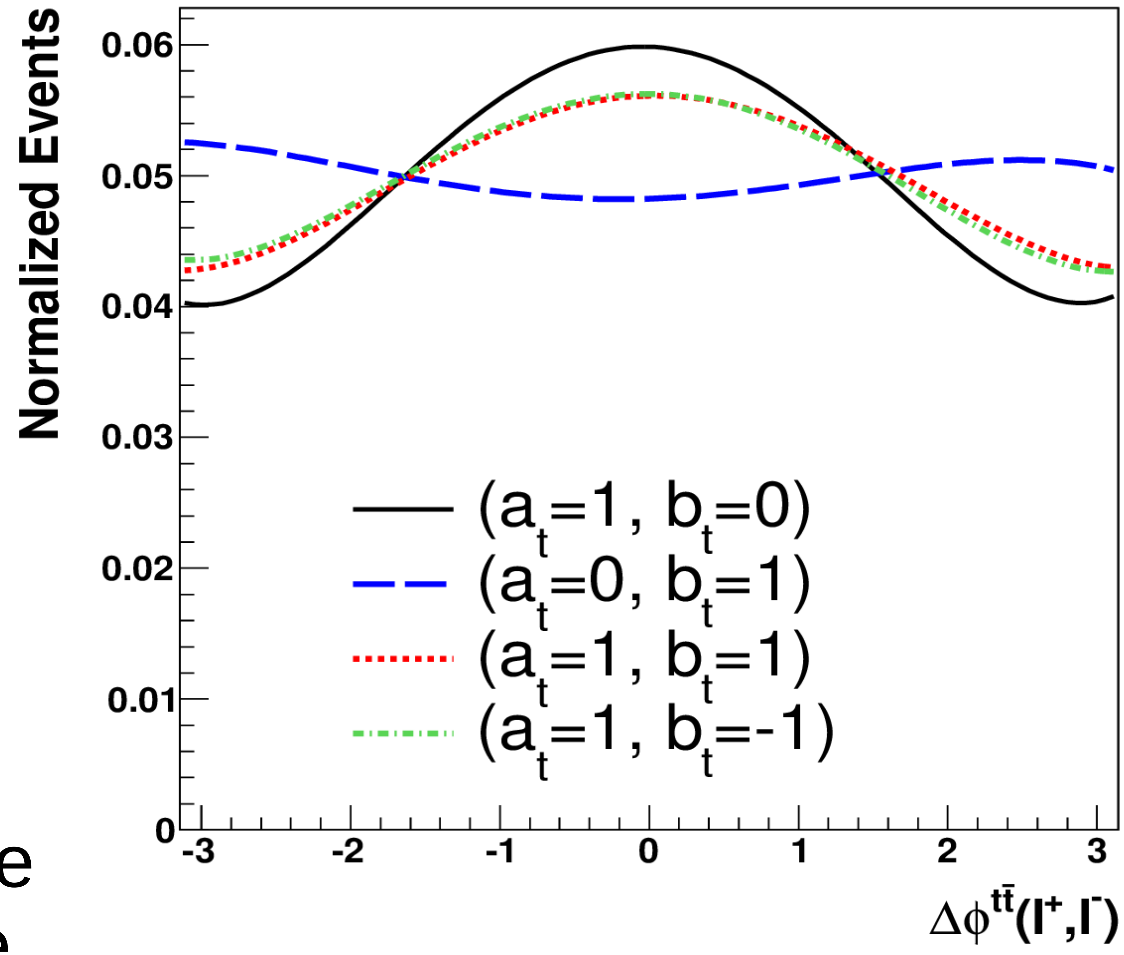
The observable m_{tth} seems to work best. The two lines are 2 σ and 3 σ

Simultaneous use of all distributions might do better.

Spin

Spin correlations of the top and anti-top affected by the nature of interaction.

Difficult angle to reconstruct at LHC.

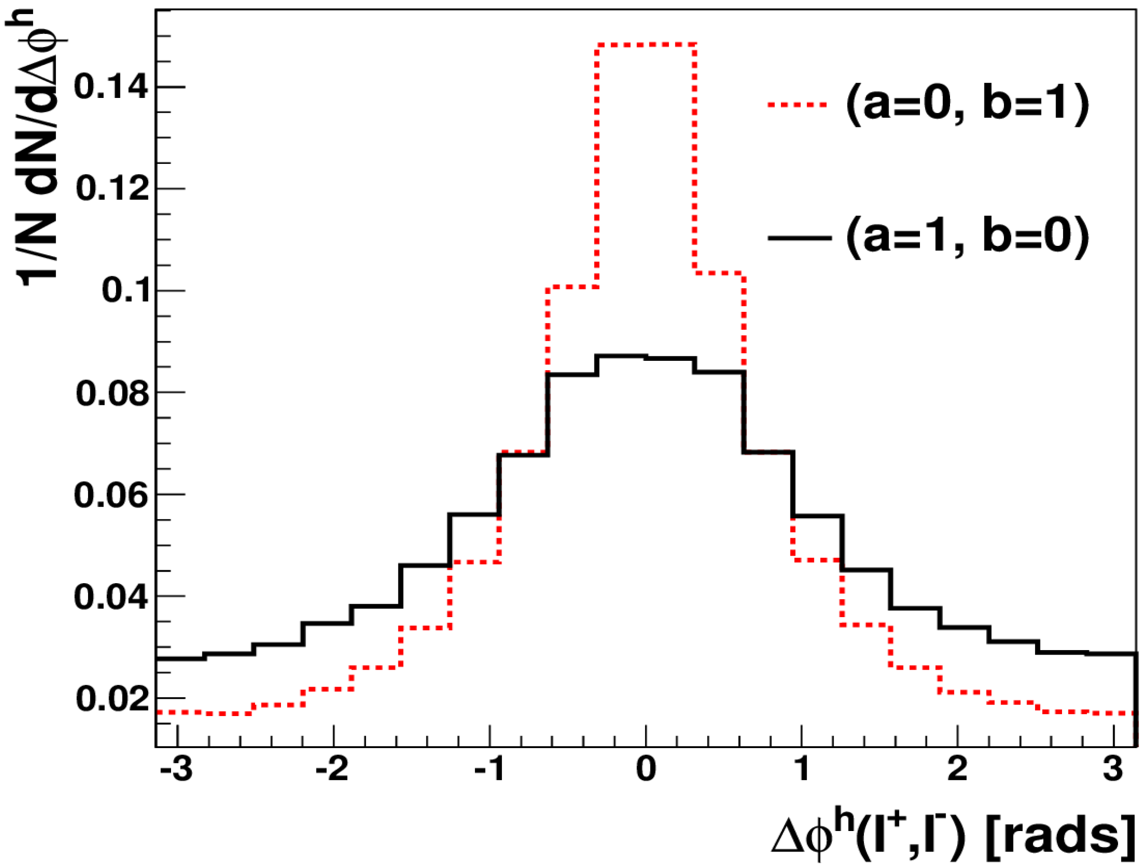


Azimuthal angle difference between the lepton in the t rest frame and anitlepton in the tbar rest frame!

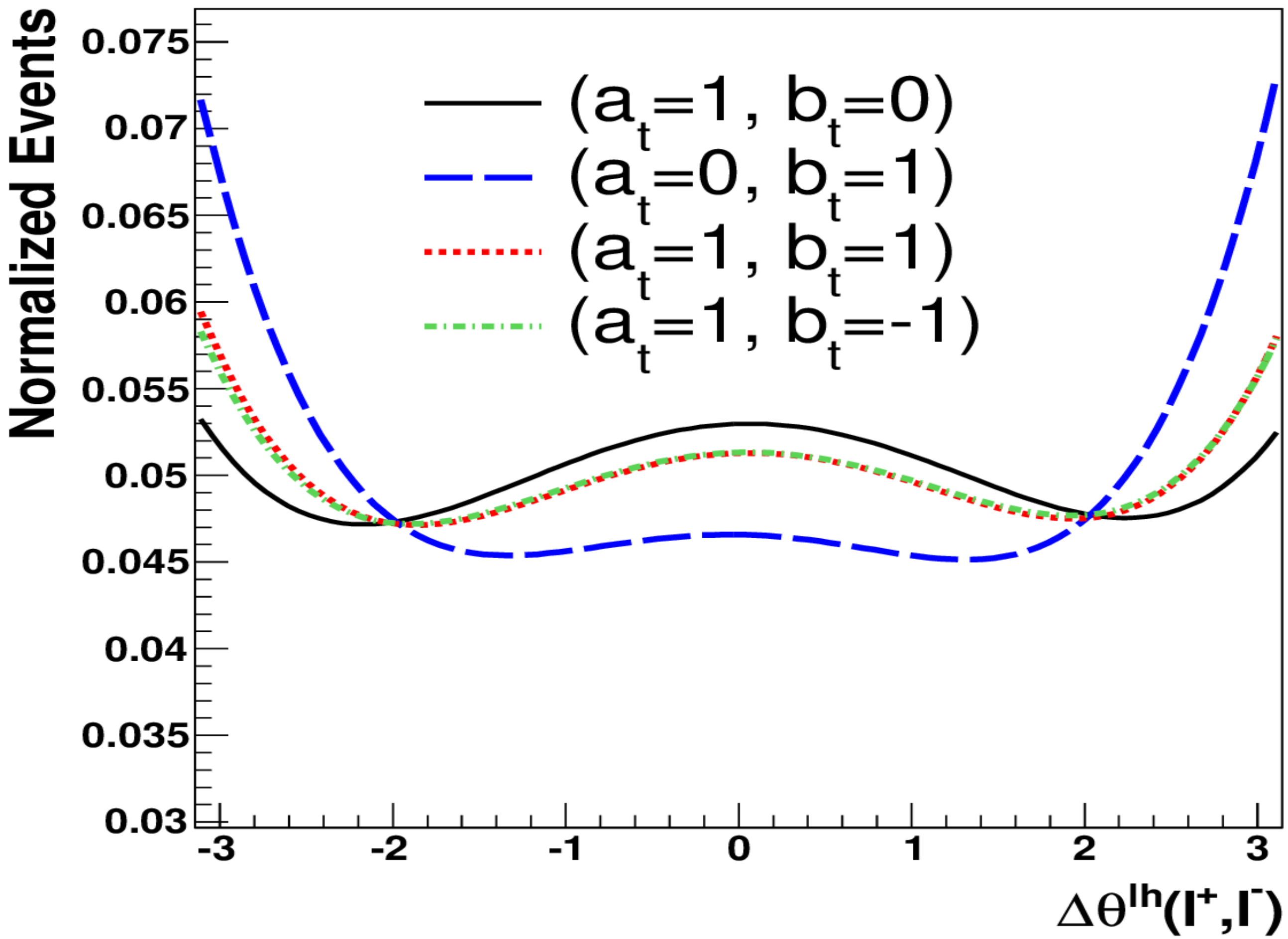
$$\cos(\Delta\phi^{t\bar{t}}(\ell^+,\ell^-)) = \frac{(\hat{z}\times\vec{p}^{\,\bar{t}}_{\ell-})\cdot(\hat{z}\times\vec{p}^{\,t}_{\ell+})}{|\vec{p}^{\,\bar{t}}_{\ell-}||\vec{p}^{\,t}_{\ell+}|},$$

Simpler Alternatives

- Difference in azimuthal angle of the leptons in the rest frame of the higgs.



Another angle: in terms of lab obs.



$$\cos(\Delta\theta^{\ell h}(\ell^-,\ell^+)) = \frac{(\vec{p}_h \times \vec{p}_{\ell-}) \cdot (\vec{p}_h \times \vec{p}_{\ell+})}{|\vec{p}_h \times \vec{p}_{\ell-}||\vec{p}_h \times \vec{p}_{\ell+}|} \,.$$

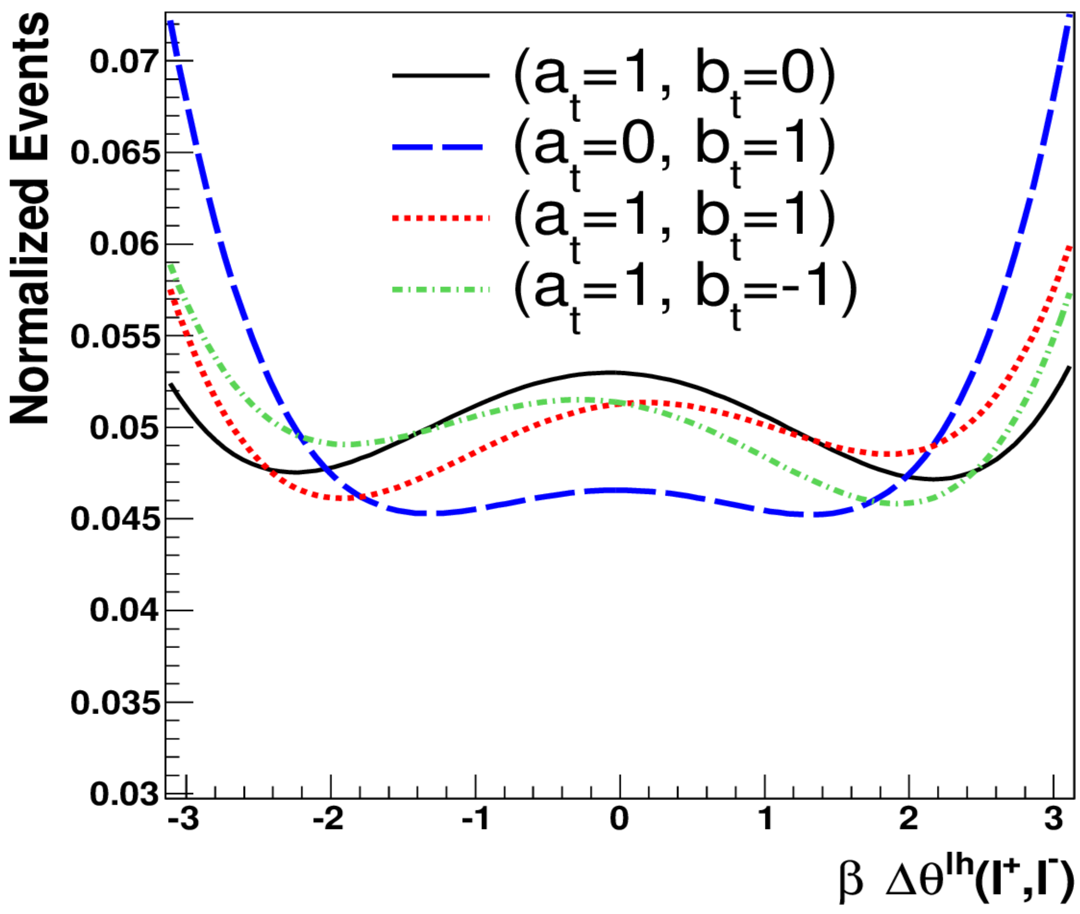
Similar observables using W momenta

They can discriminate well but...

- These distributions can discriminate well but do not work so well for determination of CP violation if there is mixing between CP even and CP odd state.
- The overall order of magnitude agreement WW ZZ and gamma gamma rates clearly says that the dominant part of the observed Higgs is certainly CP even
- Need observables sensitive to mixing and also CP violating in character!**Observables shown so far NOT LINEAR in b!**

One observable Linear in b

$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}) \right).$$



The red and blue have different behaviour wrt sign of beta.

Indeed an effect linear in b

Completely in terms of lab observables.

No need to construct any particular frame

Other studies

- Pt spectrum dependency on the CP even nature noticed by Maltoni and collaborators. PLB701 (2011) 427-433 AND 1407.5089

  Concentrated on using the distribution shapes to establish the CP property of the Higgs and used AMC @ NLO.

- Using the spin spin correlations for the ttHiggs signal: Gabrielli and collaborators.: 1403.1790.

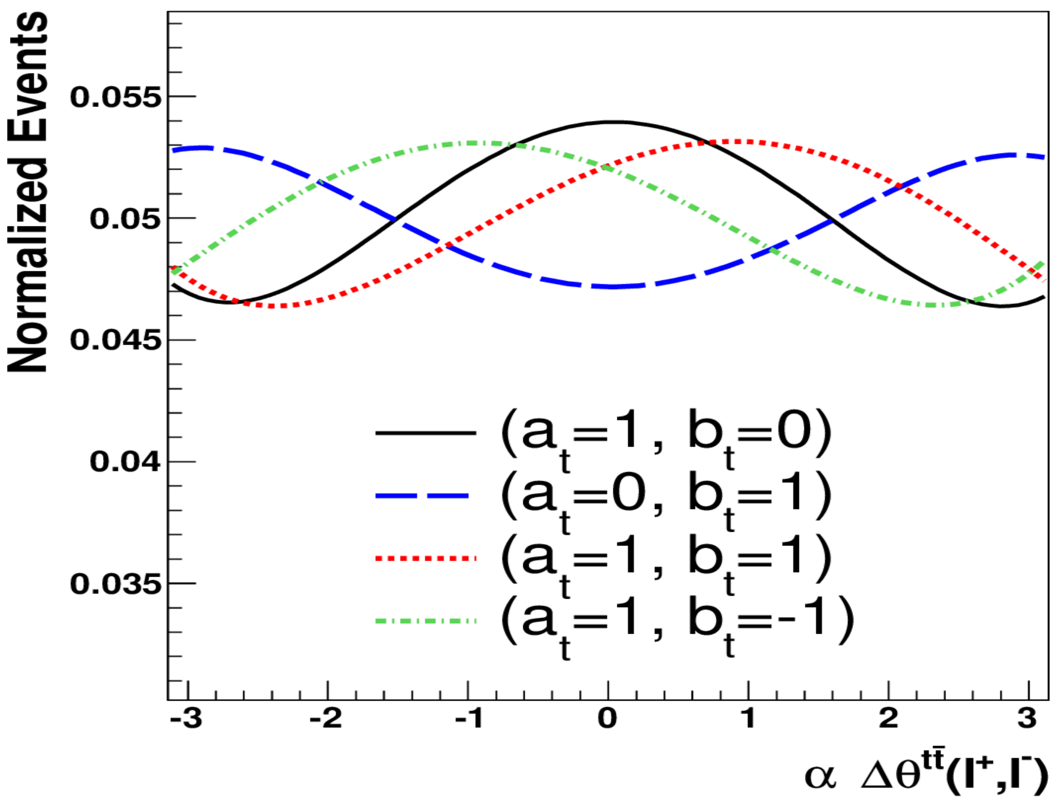
  Concentrated on using the spin spin correlations for getting the background under control

- CP violation studies : Ellis and collaborators

  1312.5736 .

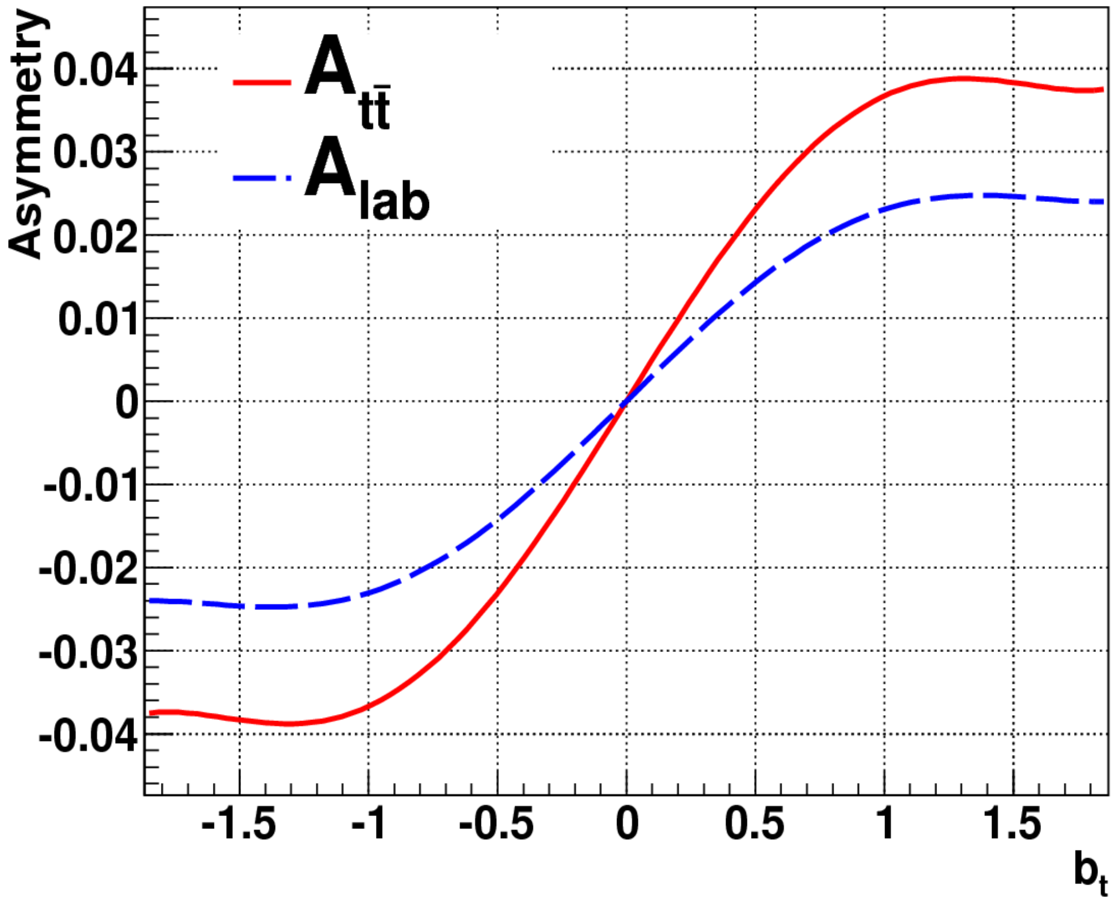
  Observables defined for lab frame in our anlaysis. Ellis et al defined similar observable but in the ttbar rest frame.

CPV observable in ttbar rest frame



$$\alpha \equiv \text{sgn}\left(\vec{p}_t^{\,t\bar{t}} \cdot (\vec{p}_{\ell^-}^{\,t\bar{t}} \times \vec{p}_{\ell^+}^{\,t\bar{t}})\right).$$

Asymmetries



Asymmetry: Linear behaiour in b, Uniquely CP violating.

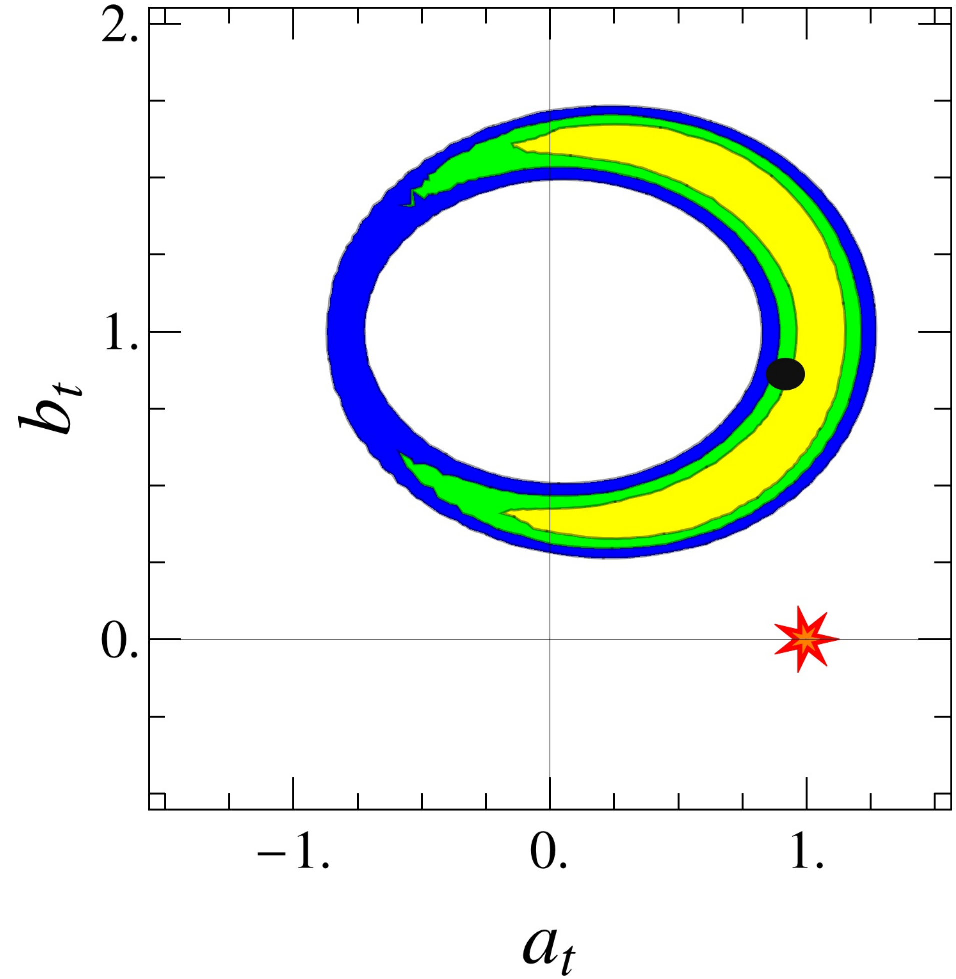
Asymmetry of lab variables (blue) is smaller but easier to construct. Less systematic uncertainties.

Summary

- The order of the day to analyse the CP structure of the HVV and Htt vertices, and hence probe the BSM, study of both rates and interference effects is necessary.
- The next round will be able to probe the WWH vertex separately in VBF and VH production and add to our knowledge
- Htt production and study of spin, spin correlations are the next order
- Electron positron colliders are really great for many of these studies.

Higgs rates

- Additional CP even or CP odd contribution to gamma gamma width coming from higher dimensional operators.
- For example terms due to (say) additional (s)particles in the loop!
- Follow JHEP 1303 (2013) 029, Deandrea et al



$$\mathbf{a} \to (\mathbf{a} + \kappa_{\gamma\gamma})$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)^{SM}} = \frac{|\kappa_W A_W^a(\tau_W) + a\frac{4}{3}A_t^a(\tau_t)|^2 + |b\frac{4}{3}A_t^b(\tau_t)|^2}{|A_W^a(\tau_W) + \frac{4}{3}A_t^a(\tau_t)|^2} .$$

$$\mathbf{b} \to (\mathbf{b} + \tilde{\kappa}_{\gamma\gamma})$$

Similary for gg. Figure corresponds to:

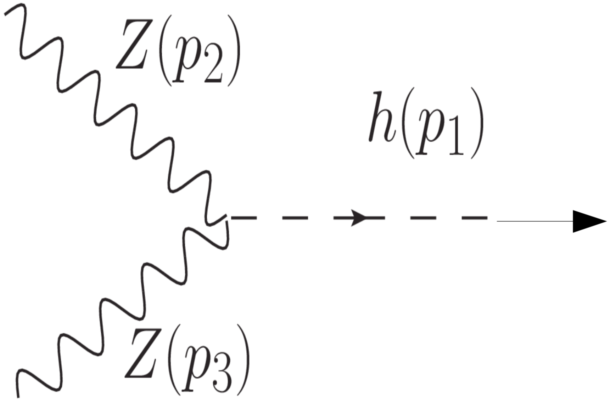
$\kappa_{\gamma\gamma} = 0, \tilde{\kappa}_{\gamma\gamma} = -1$ and $\tilde{\kappa}_{gg} = -1, \kappa_{gg} = 0$

What has been done?

- **The plot is only to illustrate a point about indirect effects.**
- **In these plots it is assumed that all the signal measurements are exactly equal to the SM rates and we have anticipated 14 TeV.**
- **Hence assumed that information all the channels, including** $\mathbf{h \rightarrow Z\gamma}$ & $\mathbf{t\bar{t}h}$ **will be available**

Higgs-Gauge Boson Coupling

- The most general Lorentz structure of the hVV vertex:



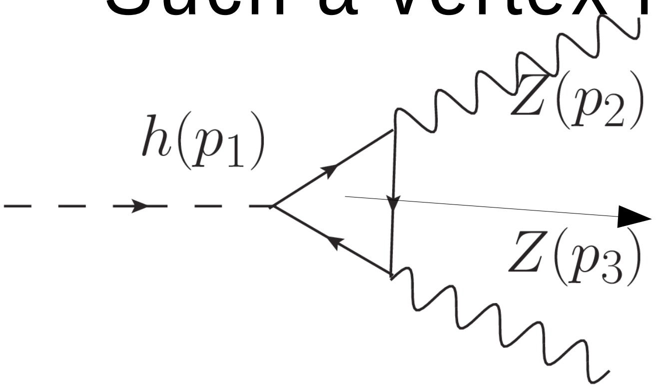
(α_Z) (β_Z) (γ_Z)

$p = p_1 + p_2$

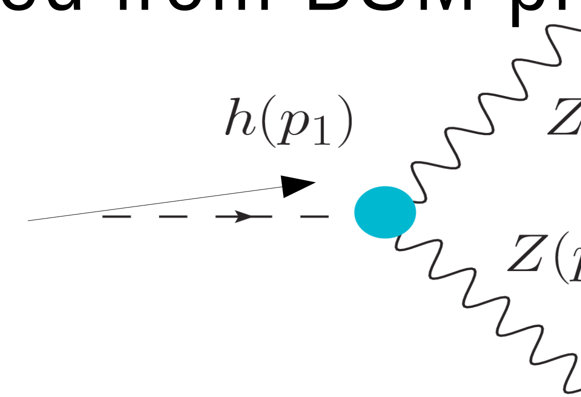
$q = p_1 - p_2$

$$i\Gamma^{\mu\nu} = i\frac{gM_Z}{c_W}\left[\underbrace{A\eta^{\mu\nu} + B\left(p^\mu q^\nu\right)}_{\text{CP even}} + \underbrace{C\epsilon^{\mu\nu\rho\sigma}p_\rho q_\sigma}_{\text{CP odd}}\right]$$

- A,B,C are momentum dependent form factors.
- In SM A=1, B=0=C.
- Such a vertex may be generated from BSM physics:

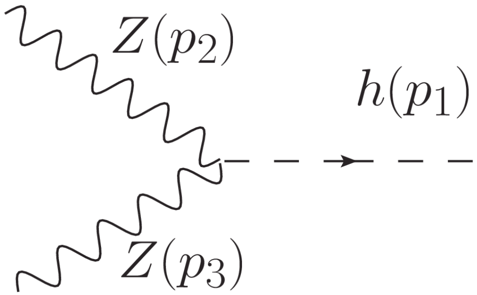


$h\bar{t}\gamma_5 t$ $\quad h\tilde{Z}^{\mu\nu}Z_{\mu\nu}$



Effective Lagrangian

- Supplement the SM lagrangian with th higher dimensional operators.
- This gives rise to a vertex of the form



$$\alpha_Z = 1 + a_Z - \frac{2b_{WW} m_W^2 \cos\theta_w^2}{\Lambda^2 m_Z^2}(k_2 \cdot k_3) + \frac{2b_{hW} m_W^2 (1+\cos\theta_w^2)}{\Lambda^2 m_Z^2}(k_2^2 + k_3^2),$$

$$\beta_Z = \frac{2b_{WW} m_W^2 \cos\theta_w^2}{\Lambda^2},$$

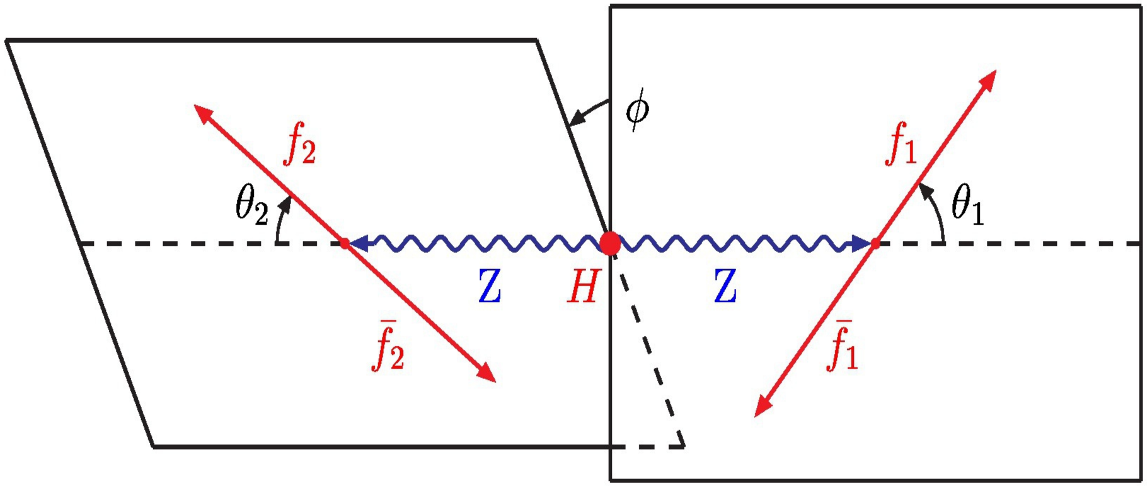
$$\gamma_Z = \frac{c_{WW} m_W^2 \cos\theta_w^2}{\Lambda^2}$$

$(\alpha_V, \beta_V, \gamma_V)$ are just the A,B, and C of the earlier slide.

a_z or a_w need not be suppressed by high scale

C (γV) is always small.

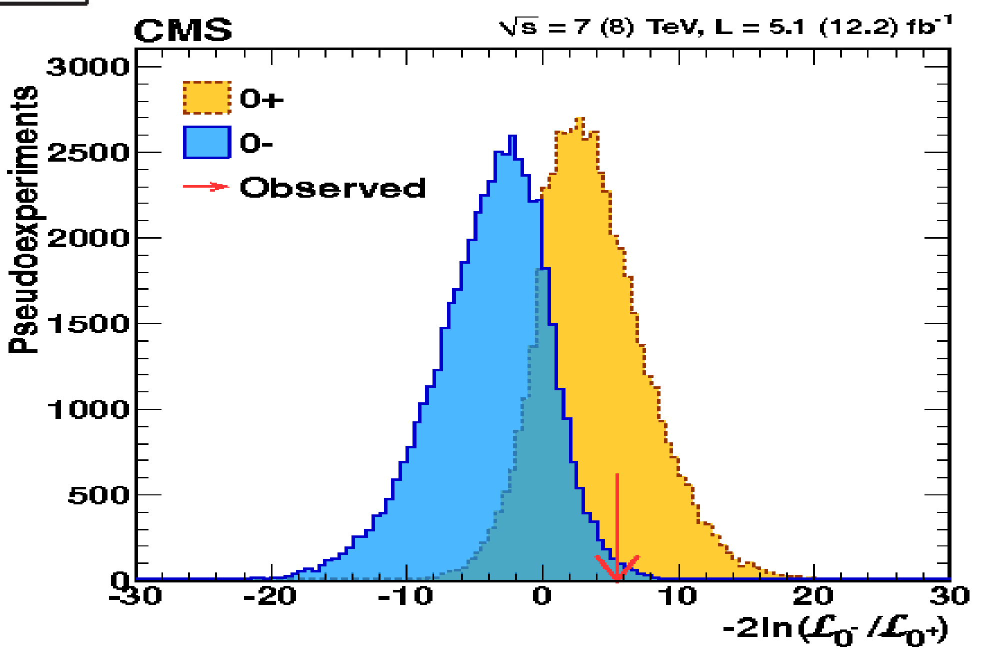
h → ZZ*(4l) decays



$$\cos(\theta_1),\ \cos(\theta_2),\ \cos(\theta^*),\ \cos(\phi),\ M^*_{Z2}$$

- Use observables to discriminate between the various vertex structures
- CMS & ATLAS use a likelihood constructed out of these.

CMS-HIG-12-041



Choi, Miller, Muhlleitner, Zerwas (2007) for spin determination., AND Godbole, Miller, Muhlleitner, 2007 for anomalous, CPC and CPV vertices.

pp → Higgs → ZZ not enough for hWW!

- Study associated production of W and h, h decaying to $b\bar{b}$ pair.
- Use substructure of jets to determine the direction of h and construct angles to get information on tensor structure of hWW vertex as well.
- In fact we showed that one could use this to study CP violation as well.

I) R.G., K. Mohan, D. Miller, C. White: PLB 730 (2014) 275

II) R.G., K. Mohan, D.Miller, C. White :1409.5549, To appear in JHEP.

- But when it comes to studies of CP violation all these measurements suffer from the ambiguity mentioned above.