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CP Properties of a Light Higgs Boson at the LHC

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Introduction

- **Light Higgs CP**
- **CP sensitive variables**

Parton Level Study

- **CP sensitive variables**
- **Likelihood**
- **Errors**
- **Results**

Detector Level Study

- **Event Selection**
- **Comparison of Parton Level and Detector Level**

Conclusions

Introduction

The search for the Higgs boson is one of the most important tasks for the LHC

Demonstrated for the TDR that ATLAS and CMS can cover the whole SM parameter space

Once the Higgs is discovered, we will need to study its properties

SM Higgs is spin 0 and CP-even

This may not be the case in models with extended Higgs sectors:

- **general 2HDM**
- **MSSM with complex parameters**

MSSM predicts 3 neutral Higgs particles. h, H (CP-even) A (CP-odd)

Presence of complex phases causes mixing and the mass eigenstates (h_1, h_2, h_3) then have mixed CP

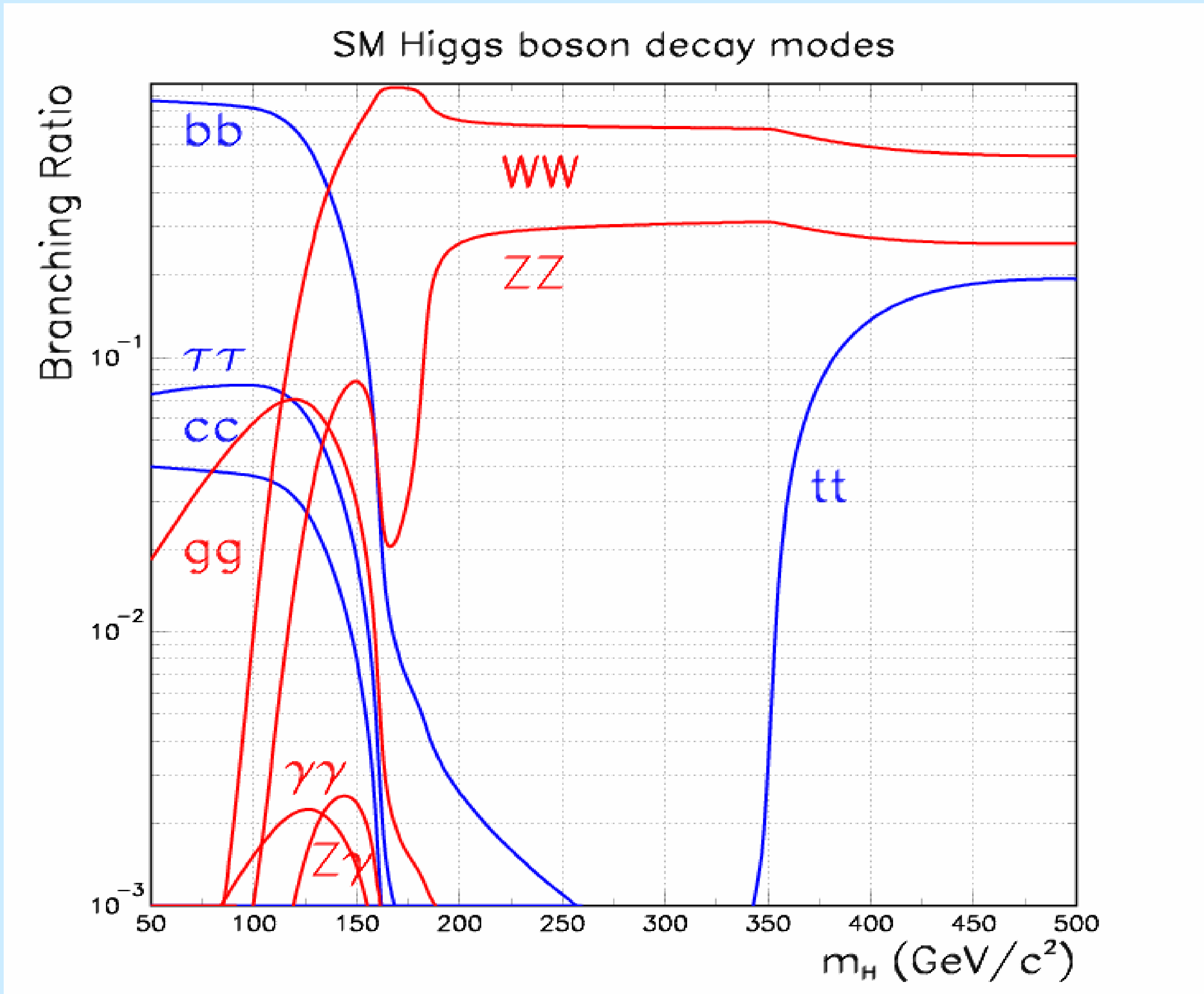
Carena, Ellis, Mrenna, Pilaftsis, Wagner. Nucl.Phys. B659 (2003) 145-178 - hep-ph/0211467

Experimental evidence that demonstrates the CP quantum numbers, would be very useful in constraining the range of allowed models

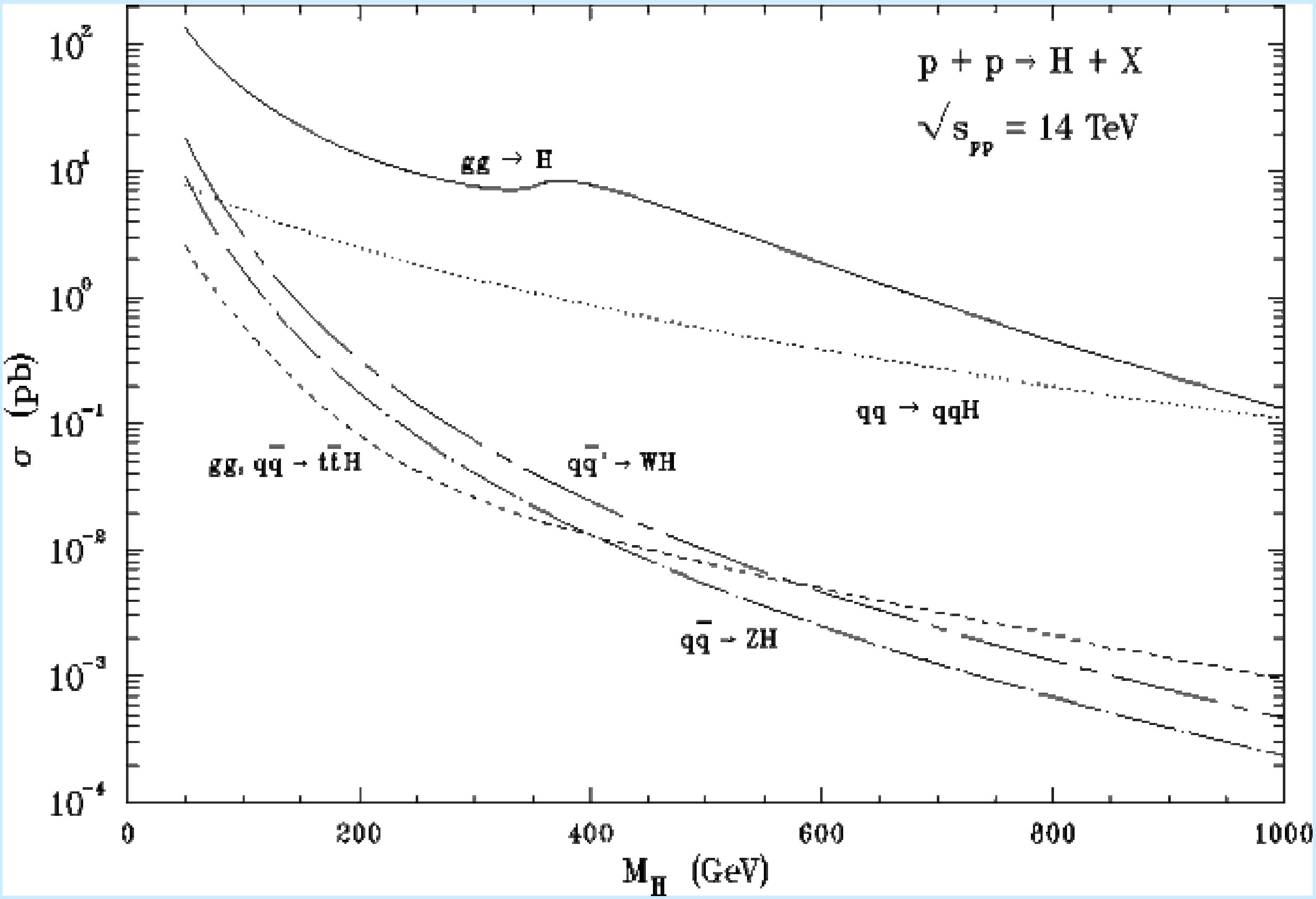
However …

Making a precision measurement such as this will be very difficult in the messy environment of the LHC

Higgs Decays



Higgs production



Light Higgs CP

For a light Higgs we can't use the $H \rightarrow ZZ^*$ decay mode.

Using ideas from Gunion, He (*PRL 76, 24, 4468 (1996)*)

Interaction Lagrangian

$$\mathcal{L} \equiv \bar{t}(c + id\gamma_5)th$$

c is the CP-even coupling and d is the CP-odd coupling

SM has c = 1 and d = 0

$$|\mathcal{M}|^2 \propto M_{Q^2}(c^2 - d^2)$$

Top quark will have greatest sensitivity to CP

Use this fact in the associated tth production channel

CP sensitive variables

$$a_1 = \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\bar{t}} \times \widehat{n})}{|(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\bar{t}} \times \widehat{n})|}$$

$$a_2 = \frac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|}$$

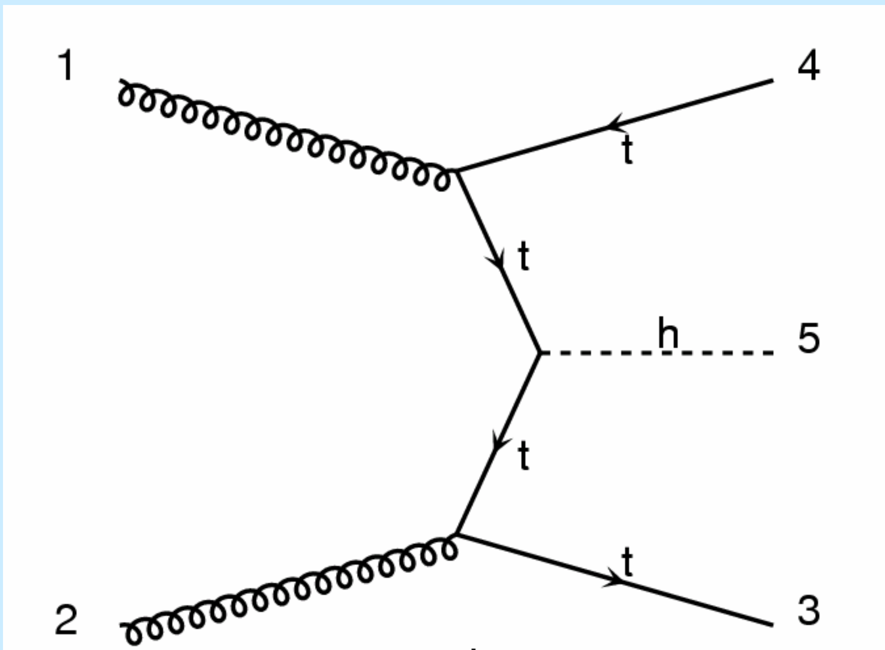
$$b_1 = \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\bar{t}} \times \widehat{n})}{p_t^T p_{\bar{t}}^T} \qquad b_2 = \frac{(\vec{p}_t \times \widehat{n}) \cdot (\vec{p}_{\bar{t}} \times \widehat{n})}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$

$$b_3 = \frac{p_t^x p_{\bar{t}}^x}{p_t^T p_{\bar{t}}^T} \qquad b_4 = \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$

CP information contained in the momenta of the tops

Parton Level Study

Parton Level



Use HERWIG to generate the pure CP-even and pure CP-odd, tth and ttA channels

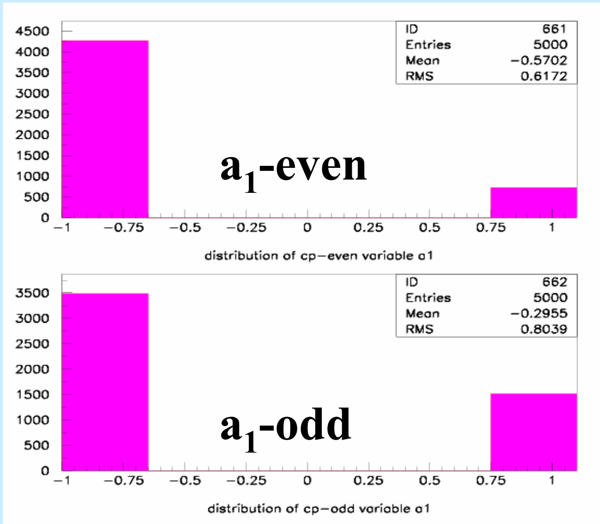
IPROC =3816

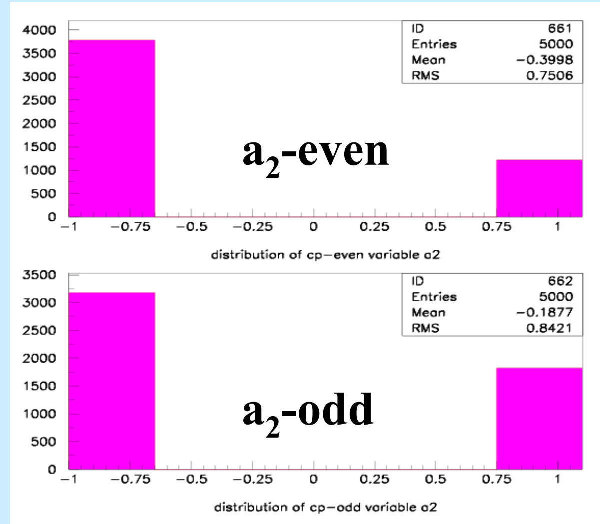
IPROC =3836

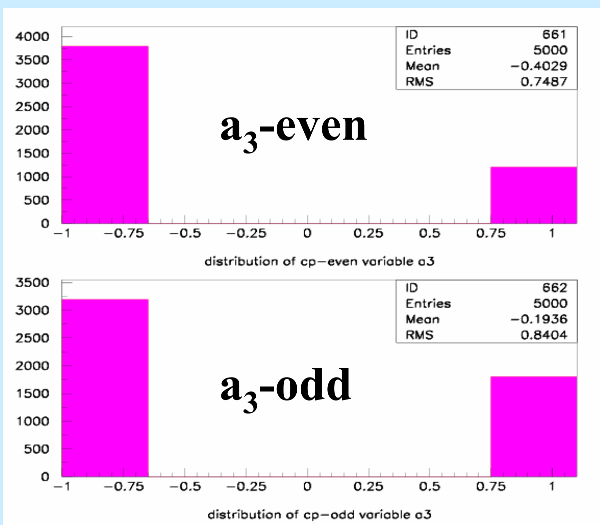
Calculate the CP sensitive variables

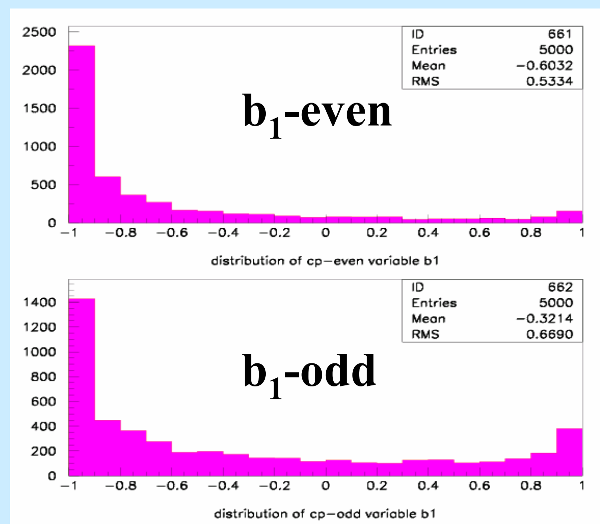
Obtain the PDF's for the variables

Distribution of variables I

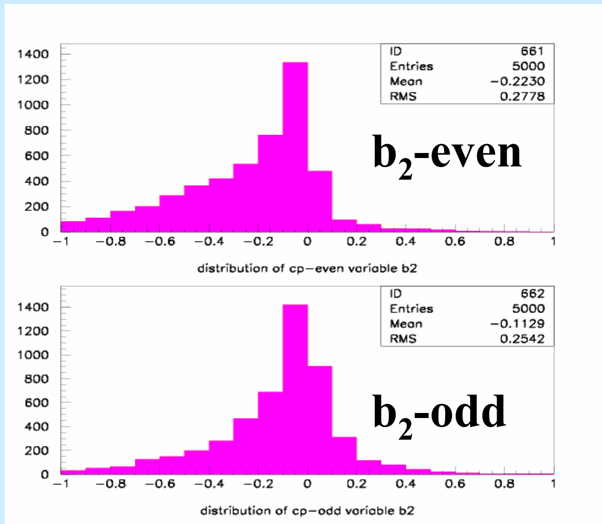


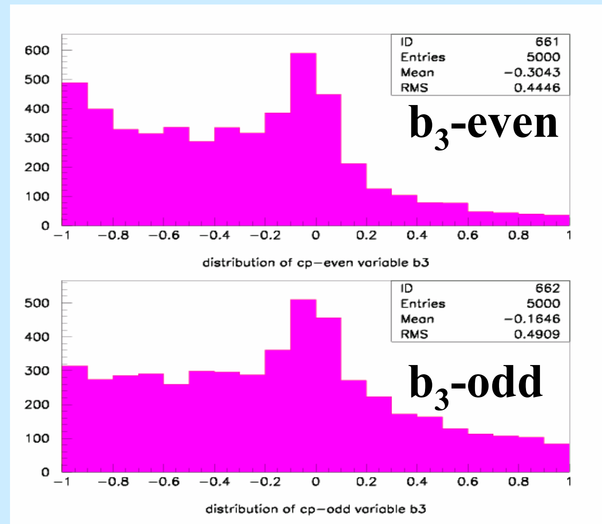


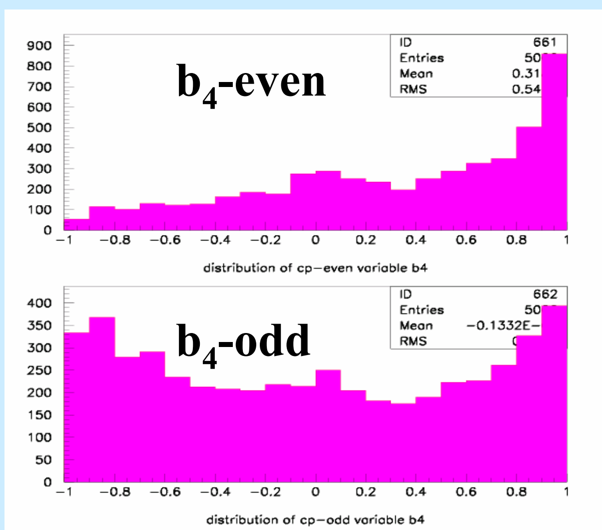


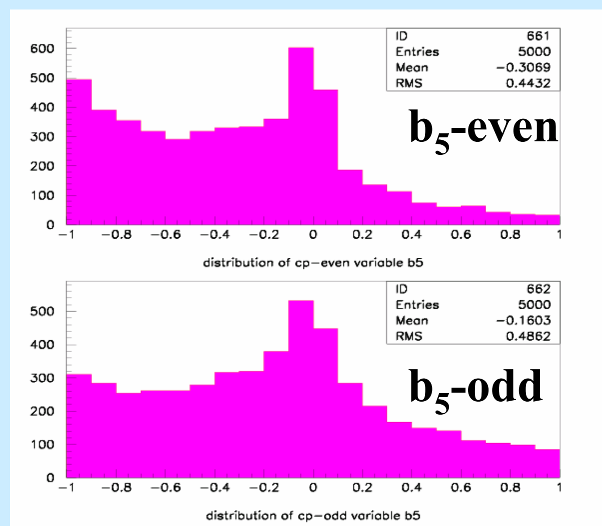


Distribution of variables II









Simulation

Generate sample data for a Higgs mass of 110GeV

Gunion and He use Signal = 130 events, Background = 21 events for a Higgs mass of 100GeV and 600fb^{-1} accumulated by ATLAS + CMS.

Here we consider ATLAS only situation and generated samples with 50 signal events.

Create a mixed CP state by combining the CP-even and CP-odd samples.

Maximum Likelihood

Use the method of maximum likelihood to try and determine the mixing parameter α.

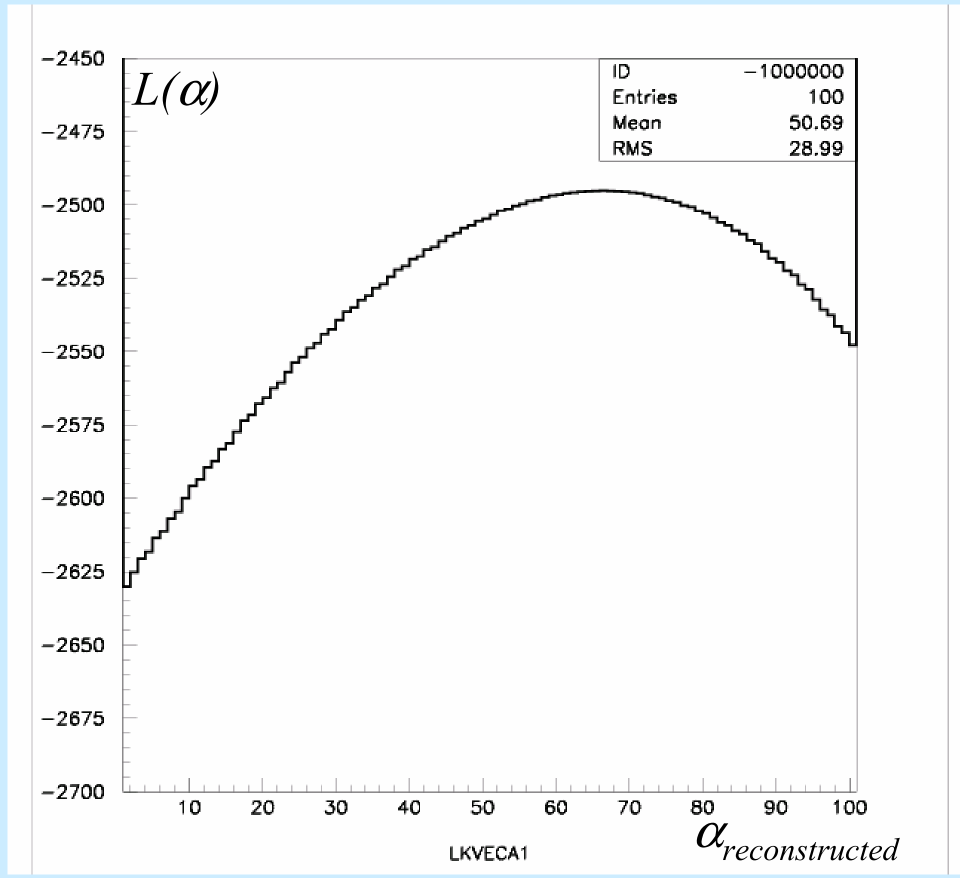
$$\mathcal{L}(\alpha) = \prod_{events} f(x;\alpha)_{mix}$$

$$f(x;\alpha)_{mix} = \alpha f(x)_{\mathrm{CP-even}} + (1-\alpha) f(x)_{\mathrm{CP-odd}}$$

Where *f(x)* are the PDF's for the test statistic, which in our case are just the individual variables (e.g. PDF for a_1, a_2, …)

Example Likelihood distribution

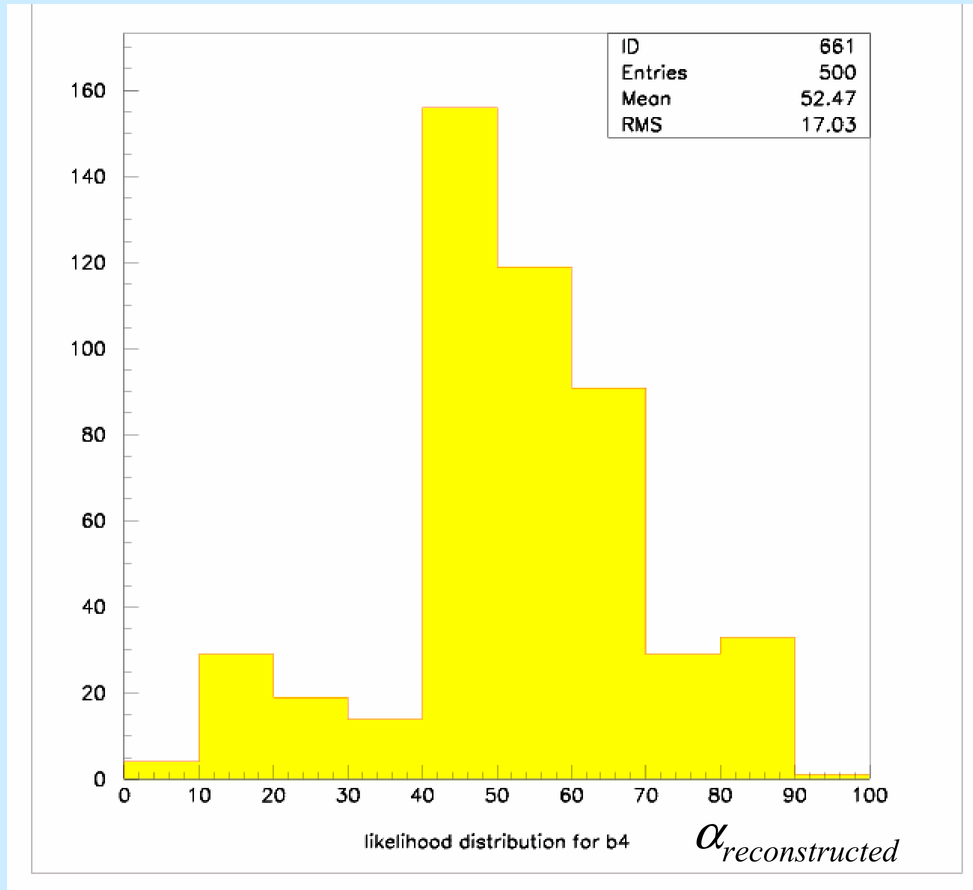
Distribution of the likelihood function for a_1 for $\alpha_{true} = 50\%$.
Here the maximum is at around 65%



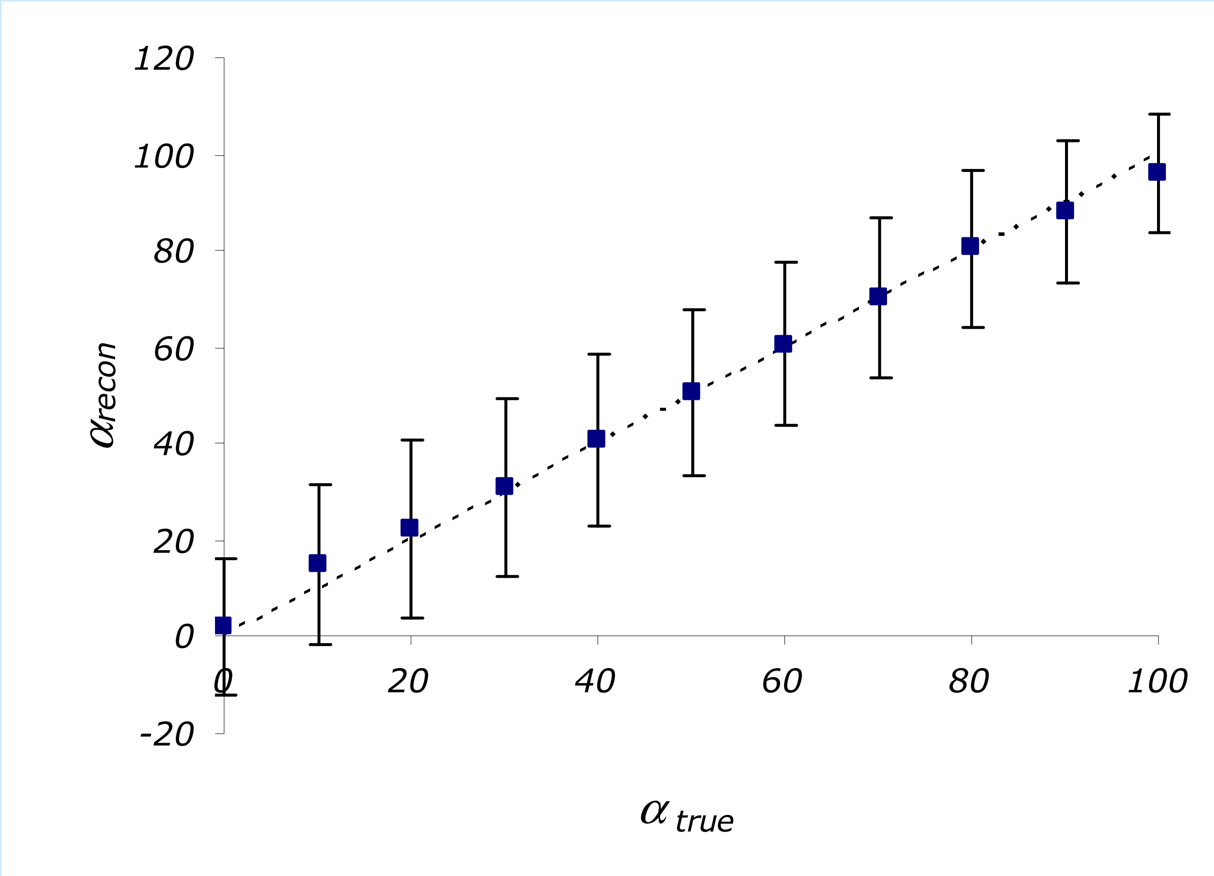
Errors

The uncertainty in using this method is given by the distribution of $\alpha_{reconstructed}$ for independent data samples

Distribution of maximum likelihood using b_4 as the test statistic for $\alpha_{true} = 50\%$



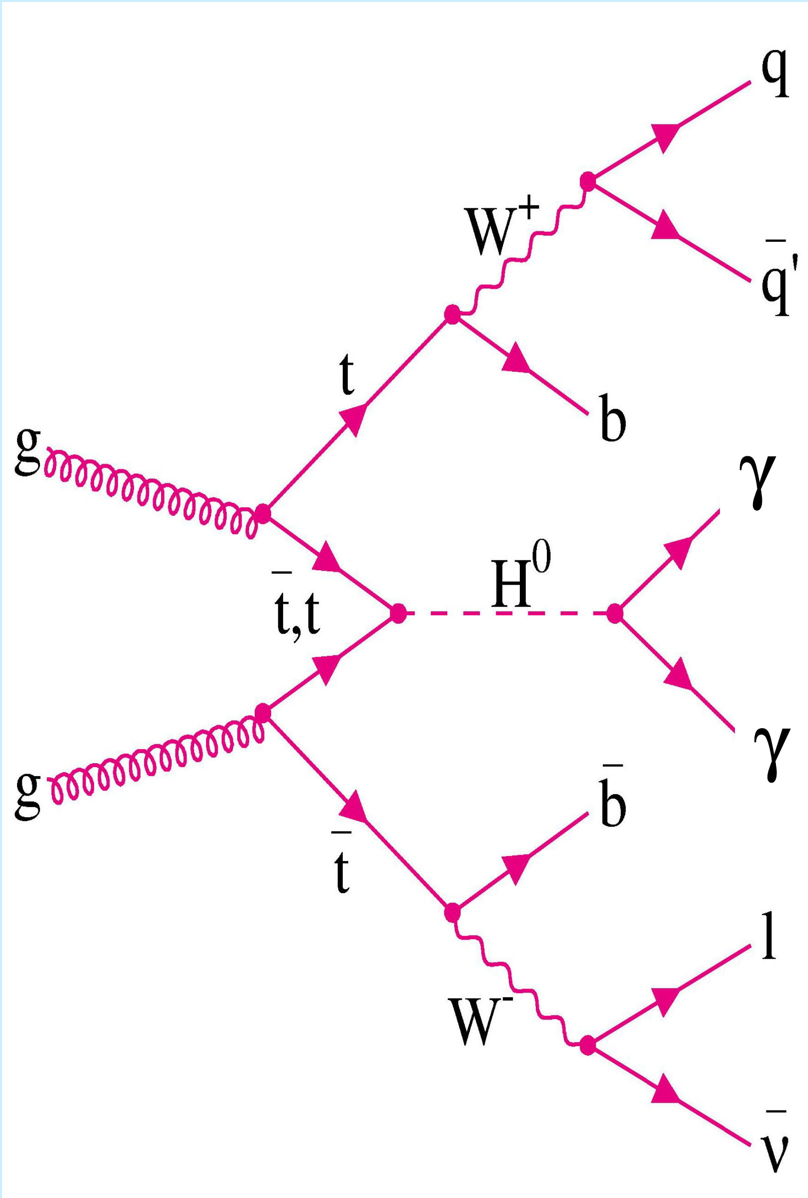
Results



Dashed line is $\alpha_{true} = \alpha_{recon}$

- **Means of the distributions are unbiased**
- **width of around 15-20%**

Detector Level Study



Selection Procedure

- ≥ 2 light jets
- 2 bjets
- 2 photons (pT ≥ 25 GeV)
- 1 electron or muon (pT ≥ 25 GeV)

For events which meet these requirements

- **Reconstruct a hadronic W from all jet-jet pairs**
- **Assume missing momentum is due to the neutrino, use W mass constraint to fully reconstruct the neutrino momentum.**
- **Reconstruct a leptonic W in events which have 1 or more neutrino solutions**
- **Reconstruct the top quarks by combining the b-jet's and W's 4-vectors**

Top Reconstruction

Reconstruct a top for all bjj and blν combinations.

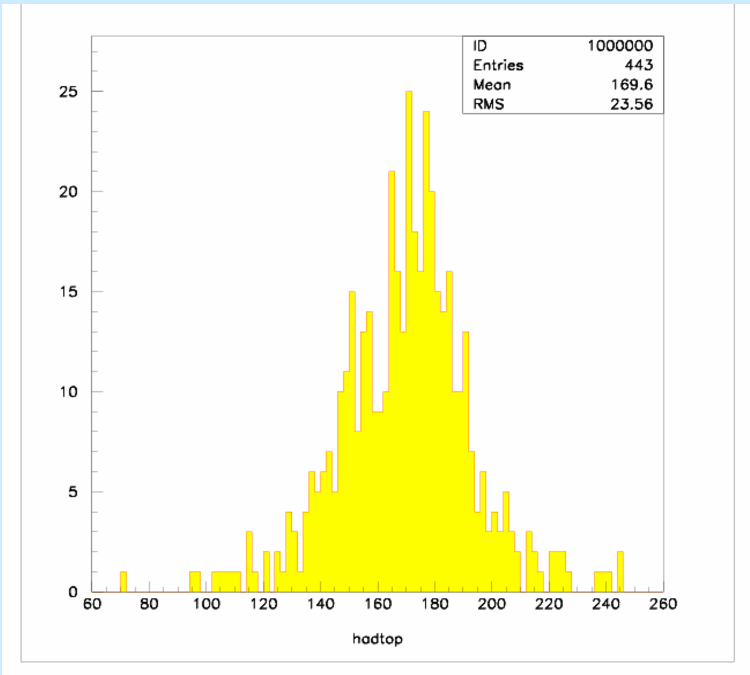
4-vectors of the two tops are found by selecting the combination which minimizes the χ^2

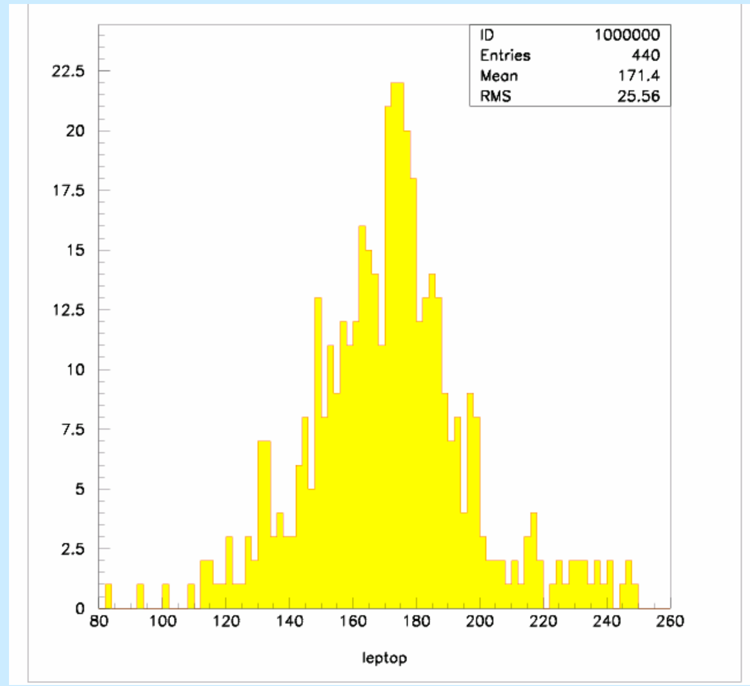
$$\chi^2 = \frac{(m_t - m_{bjj})^2}{\sigma_{bjj}^2} + \frac{(m_W - m_{jj})^2}{\sigma_{jj}^2} + \frac{(m_t - m_{bl\nu})^2}{\sigma_{bl\nu}^2}$$

m_t = 175 GeV, m_w = 80 GeV, σ from TDR

The selected tops are then used to determine the values of the CP sensitive variables

Reconstructed top quark mass

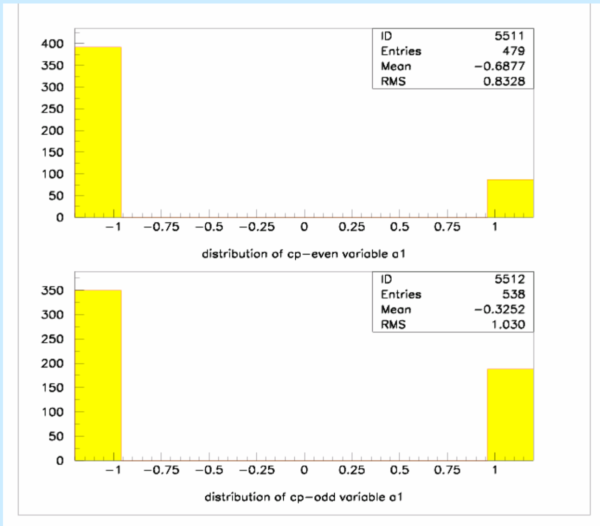


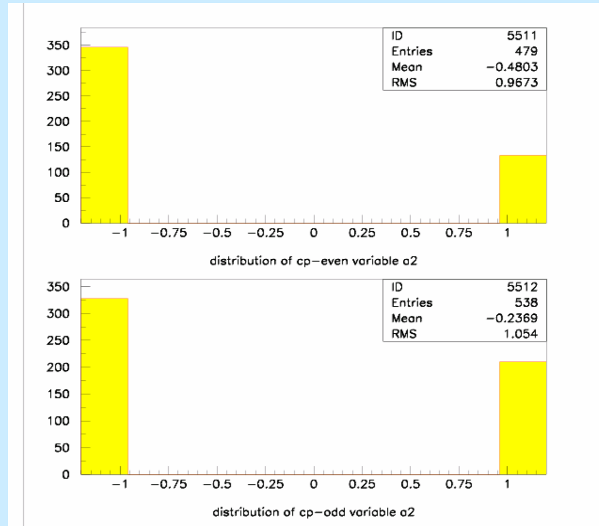


Hadronic top

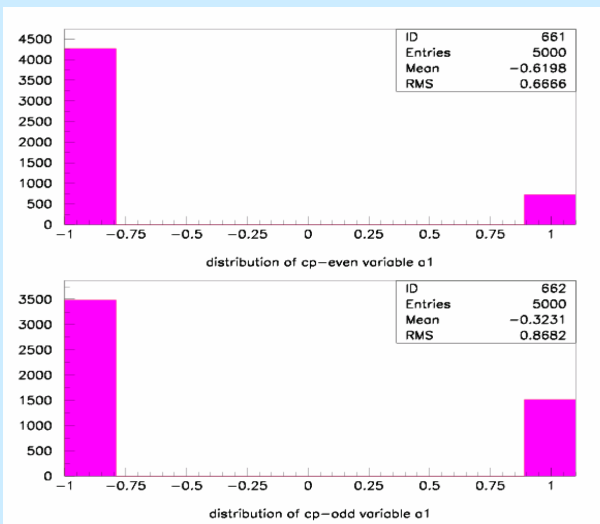
Semi-leptonic top

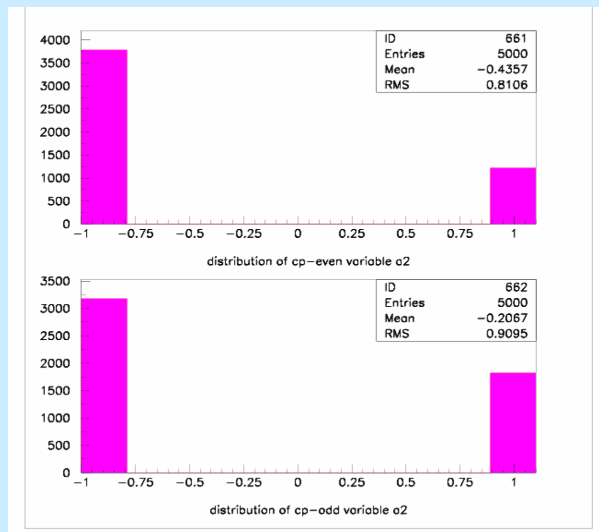
CP sensitive variables: a_1 , a_2





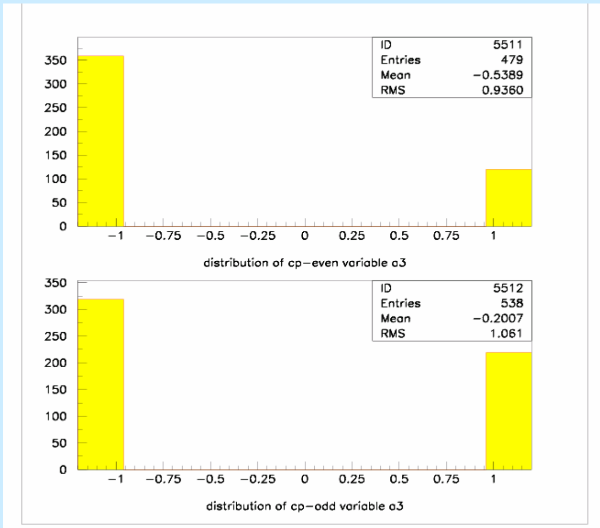
ATLFAST LEVEL

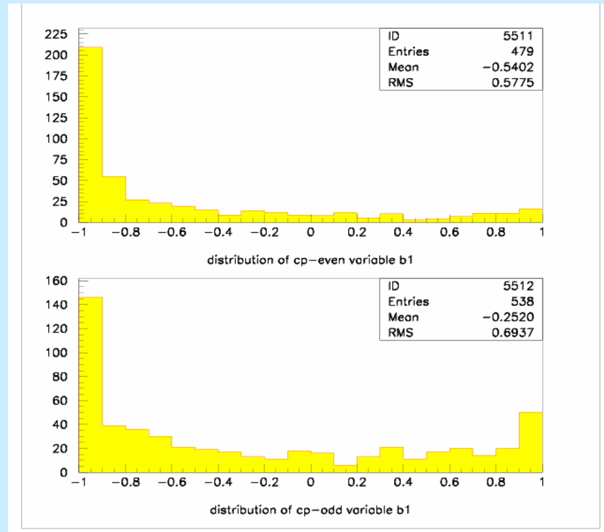




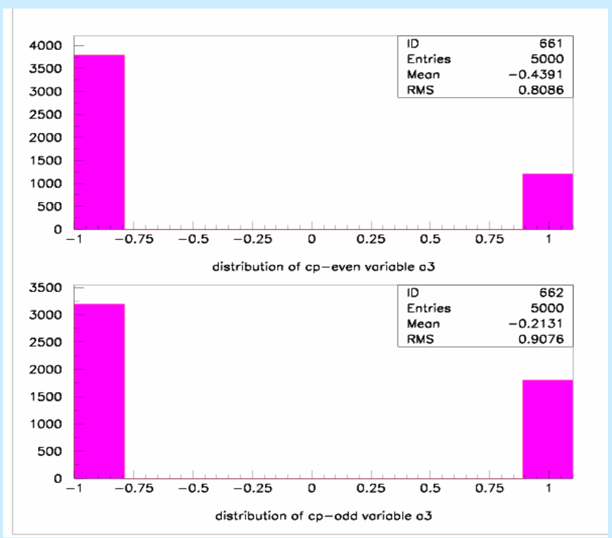
PARTON LEVEL

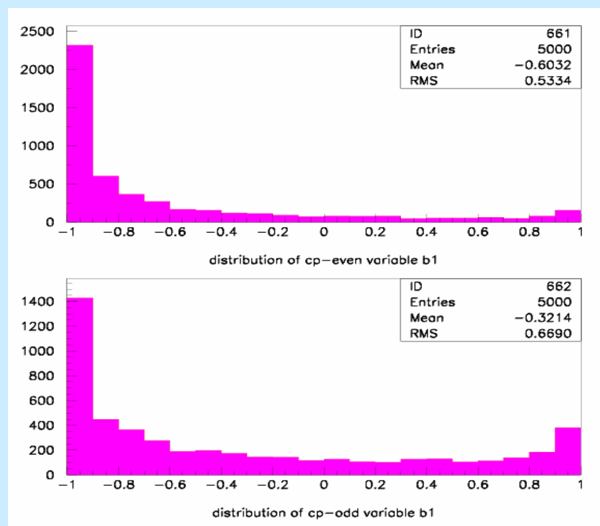
CP sensitive variables: a_3 , b_1





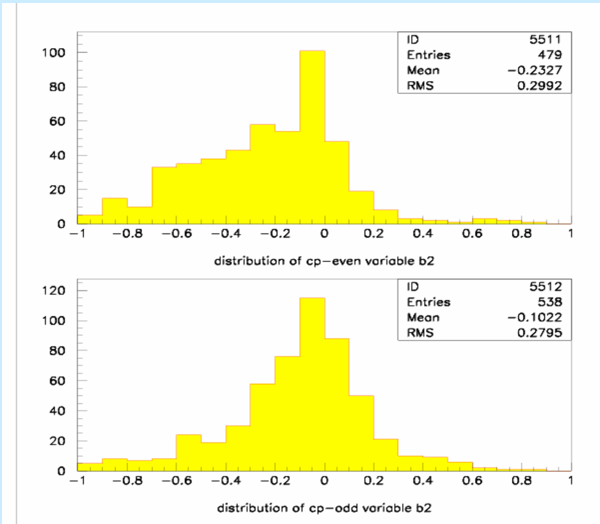
ATLFAST
LEVEL

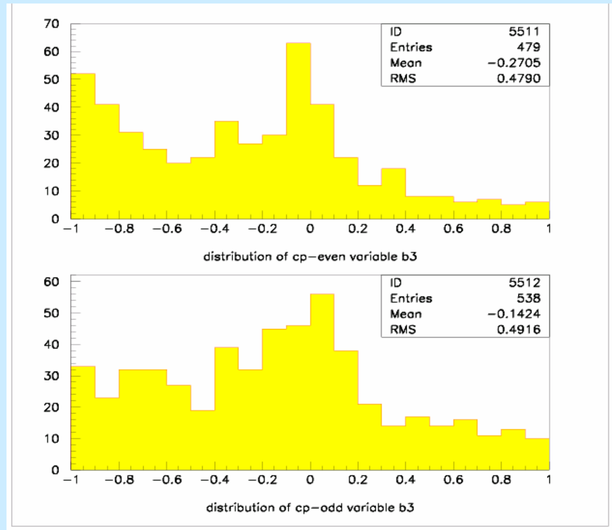




PARTON
LEVEL

CP sensitive variables: b_2 , b_3





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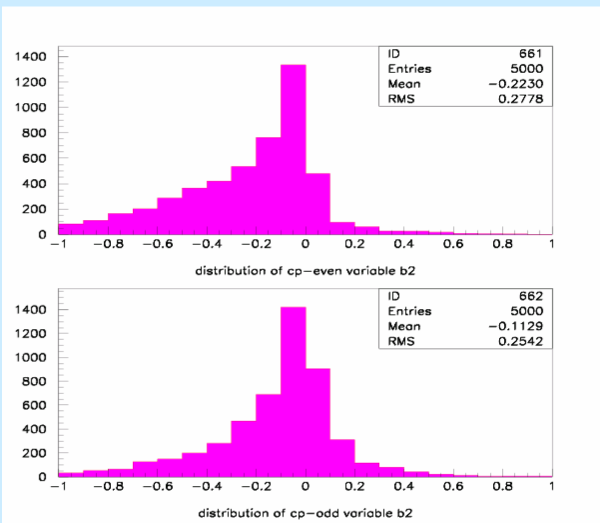
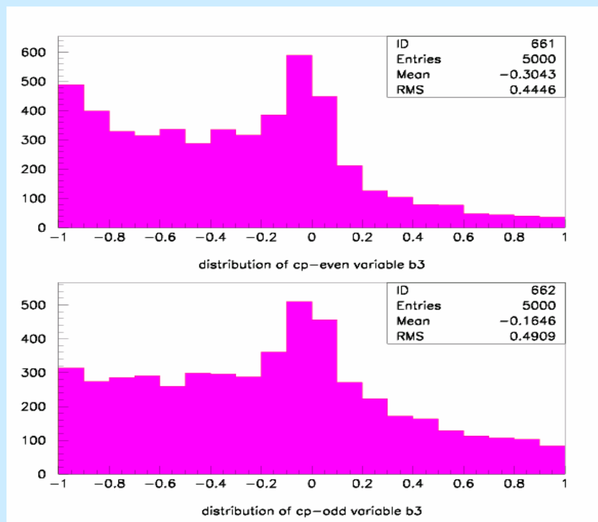
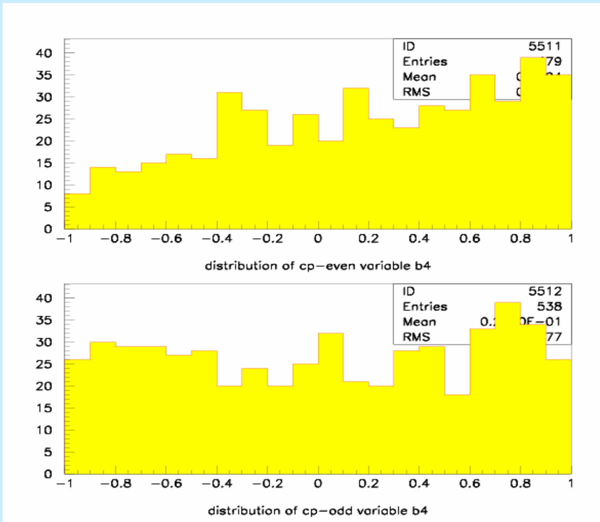
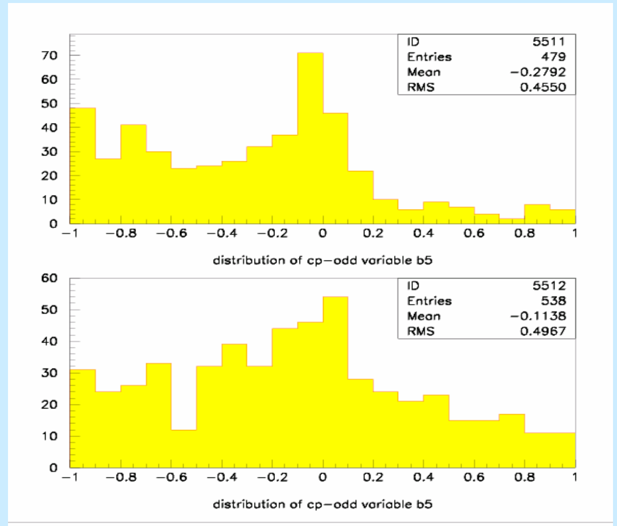




PARTON LEVEL

CP sensitive variables: b_4 , b_5





ATLFAST
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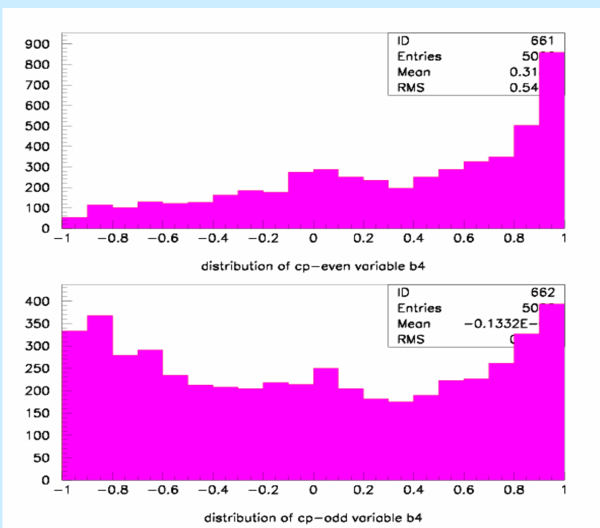
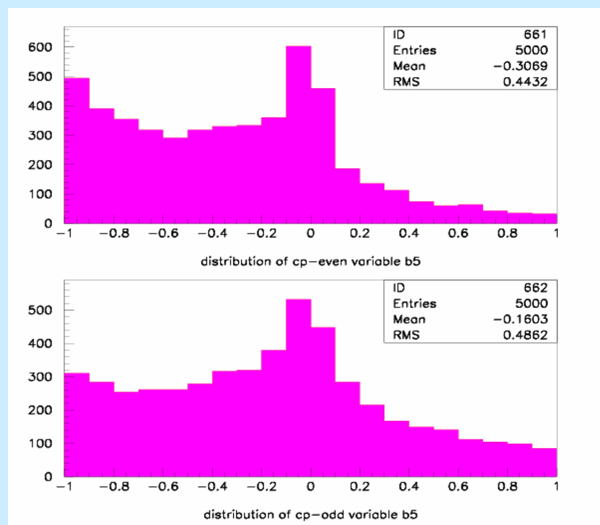




PARTON
LEVEL

Future Plans

- Finish detector level work – generate large numbers of toy experiments and carry out likelihood analysis

- Backgrounds, $tt\gamma\gamma$, $ttj\gamma$, $ttjj$

- Improved test statistic with greater sensitivity to CP – how best to combine the variables?

- Other Decay channels
  - $ttH \rightarrow \gamma\gamma$, both tops hadronic
  - $ttH \rightarrow bb$
  - $ttH \rightarrow \tau^+\tau^-$???
  - Combined analysis of the different channels

Conclusions

The LHC will have some sensitivity to the CP properties of a light Higgs using this method.

Can the TDR analysis for ttH $\rightarrow \gamma\gamma$ channel be improved? How have the latest MC improvements and NLO cross-sections changed things?

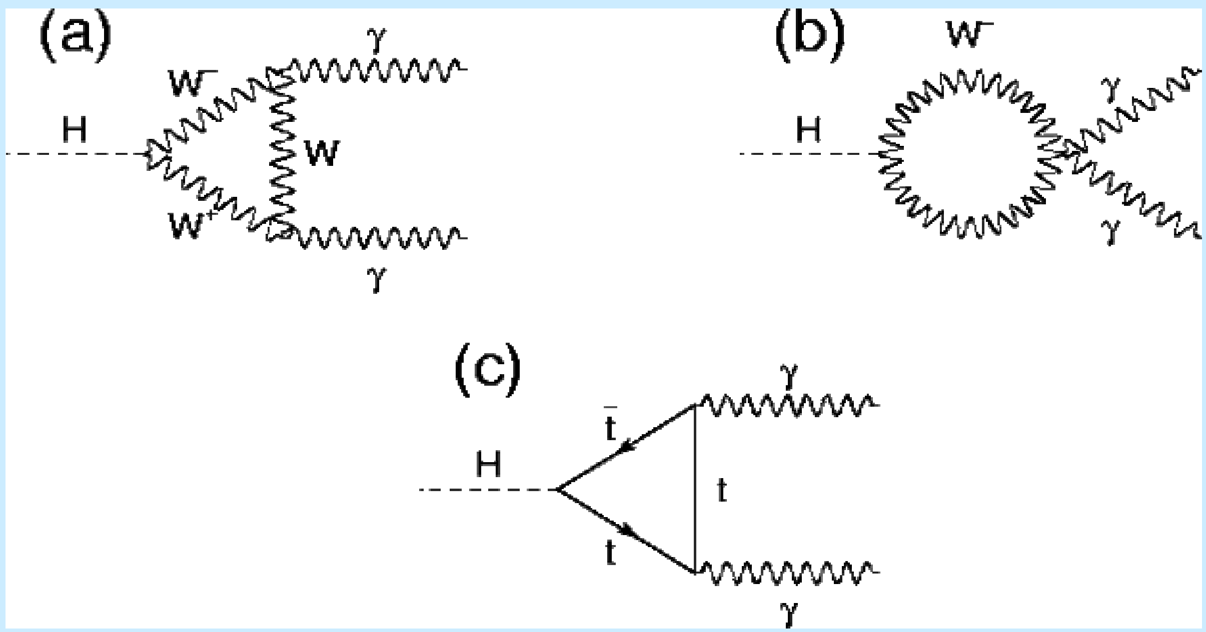
Precision measurements like this will benefit from a combined ATLAS/CMS analysis.

Extra Slides

Comment

The ttH → γγ will may not be the best channel in which to measure CP in MSSM

- Very small event rate
- In the context of the MSSM, the HVV coupling is absent



Comment II

the ttH → bb, $\tau^+\tau^-$ channels have advantages and disadvantages.

Much higher signal rate, much higher backgrounds

Couplings

$$\tau\tau A^0 \, , \; b\bar{b}A^0 \quad \propto \; \tan\beta$$

$$t\bar{t}A^0 \propto \; \cot\beta$$

Branching fractions increase

production cross-section decreases

Confidence Levels

The plot shows the 68% confidence levels

The errors do not differ significantly from the standard deviation error shown earlier.