

# Measurement Accuracies of Higgs Hadronic Branching Fractions in $v\bar{v}h$ at a 350GeV ILC

Felix Müller

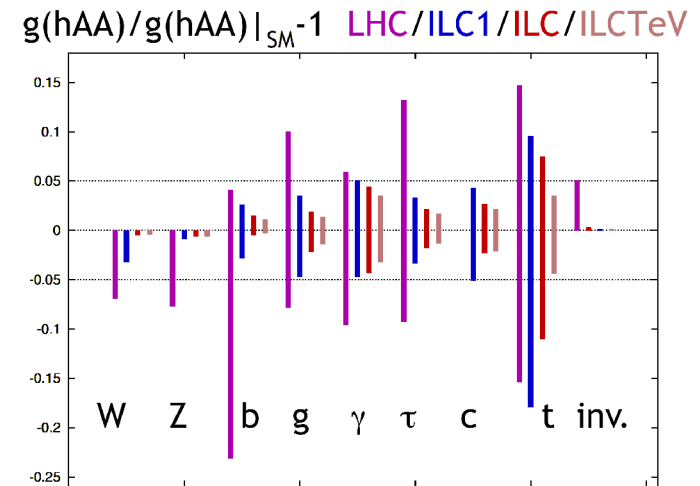
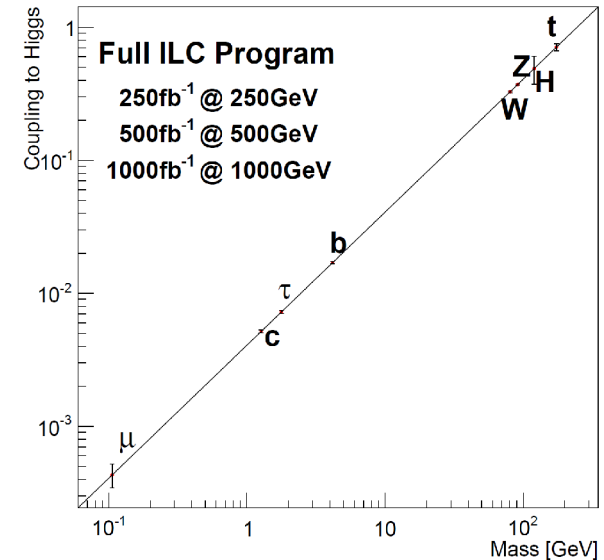
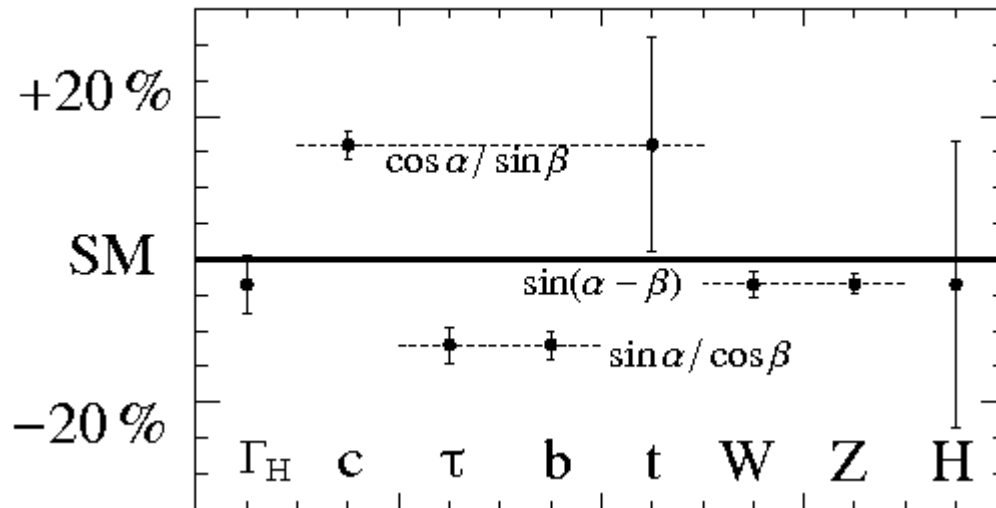
Terascale Alliance Meeting 2014

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Collaborators: Hiroaki Ono

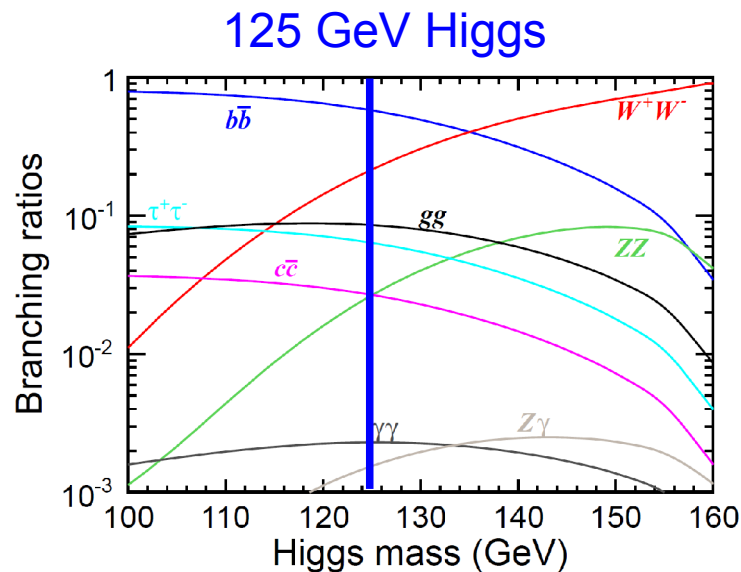
# Introduction and Motivation

- Measuring the Higgs BR is one of the key issues of the ILC after the discovery of the 125 GeV Higgs
- Any deviations in the Higgs coupling to mass relation is an indication of new physics
- Need precision measurements as predicted deviation are small



# Introduction and Motivation

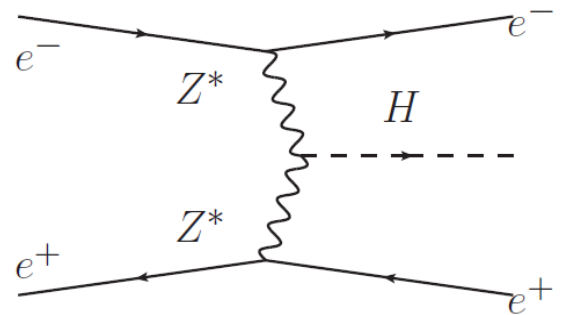
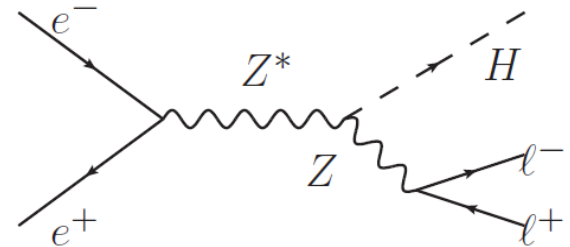
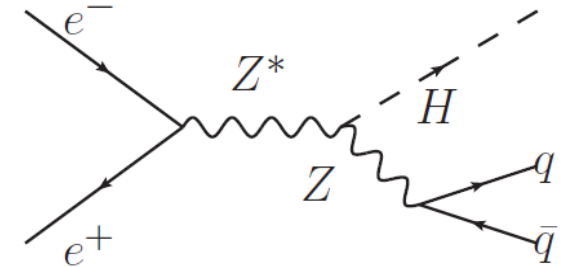
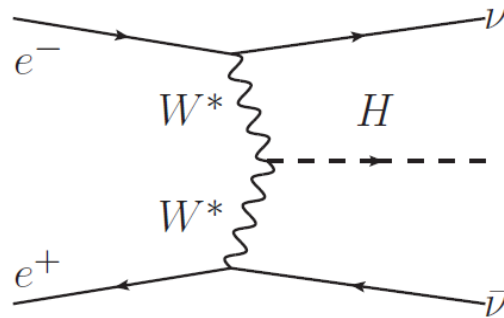
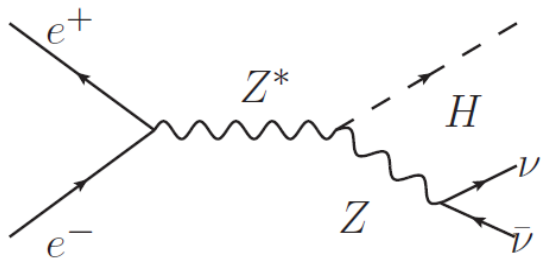
- All decay channels accessible for the ILC (even charm)
- High precision measurements of Higgs hadronic decay channels possible for a 125 GeV Higgs



| BR      | bb    | cc   | gg   | tt   | WW*   | ZZ*  | $\mu\mu$ |
|---------|-------|------|------|------|-------|------|----------|
| LHCHSWG | 57.8% | 2.7% | 8.6% | 6.4% | 21.6% | 2.7% | 0.2%     |

# Possible Final States for the ILC

- Nearly all final states from Higgs Strahlung and Vector Boson Fusion (VBF) accessible
- $Z \rightarrow qq$  possible due to tagging performance (b and c) and low QCD background
- $Z \rightarrow ee$  has very low VBF contribution and good reconstruction of the Z
- $Z \rightarrow \nu\nu$  possible due to the known initial state  
→ BUT more difficult to distinguish between VBF and Higgs Strahlung



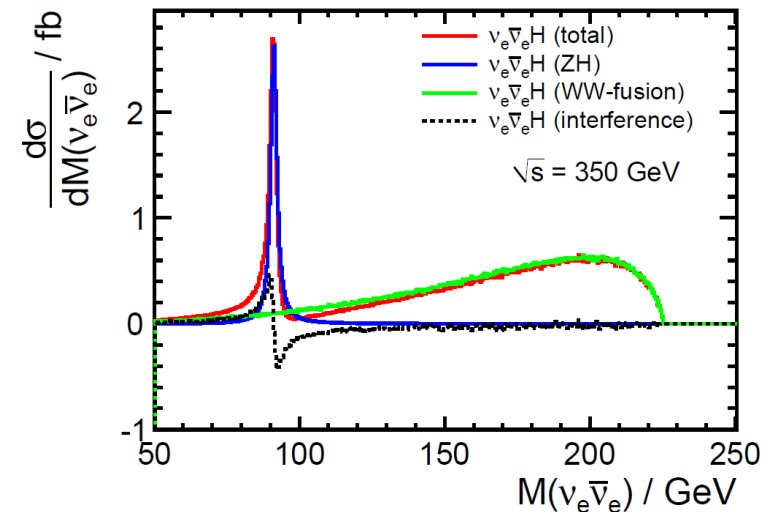
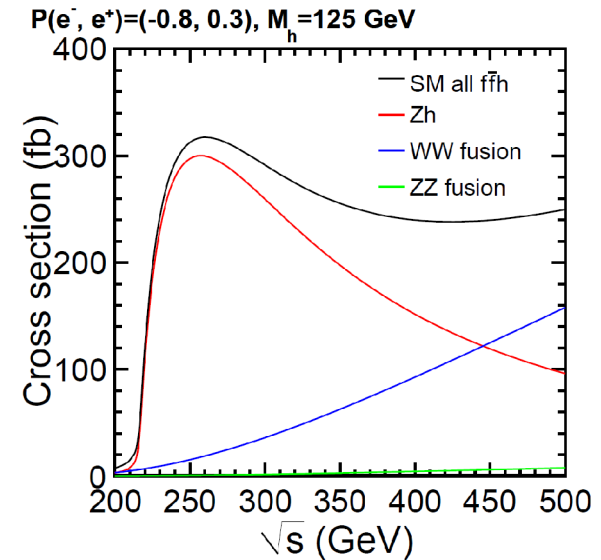
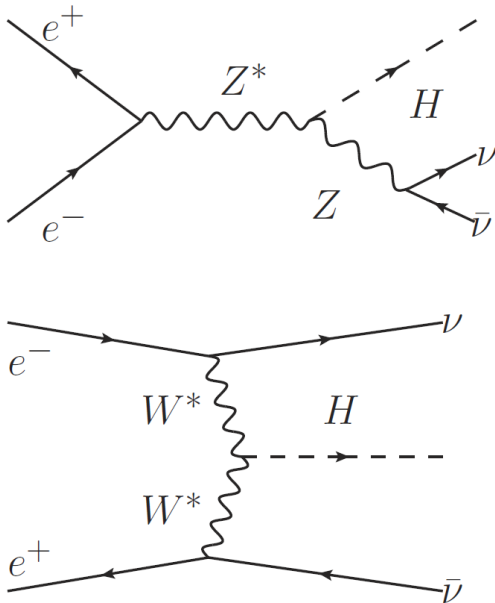
# Introduction and Motivation

## > 250 GeV: Higgs Strahlung dominant

- $\sigma_{ZH} \times \text{BR}$
- $\sigma_{ZH}$  from recoil measurement

## > 350 GeV: Higgs Strahlung + WW-fusion

- $(\sigma_{ZH} + \sigma_{WW}) \times \text{BR}$
- Need  $\sigma_{WW}$



# Goal of the Analysis

- Update the Letter Of Intent (LOI) analysis ( arXiv:1207.0300) with a full simulation study using Technical Design Report (TDR) data samples
  - Update Higgs Mass (from 120 GeV to 125 GeV)
    - Branching fractions depend on the mass of the Higgs
- Check the influence of  $\gamma\gamma$ -overlay
- Add missing mass in the fit to get cross section ratio of Higgs Strahlung and WW-fusion

| BR             | bb    | cc   | gg   | tt   | WW    | ZZ   | $\gamma\gamma$ | $Z\gamma$ |
|----------------|-------|------|------|------|-------|------|----------------|-----------|
| previous study | 65.7% | 3.6% | 5.5% | 8.0% | 15.0% | 1.7% | 0.3%           | 0.1%      |
| new study      | 57.8% | 2.7% | 8.6% | 6.4% | 21.6% | 2.7% | 0.2%           | 0.2%      |



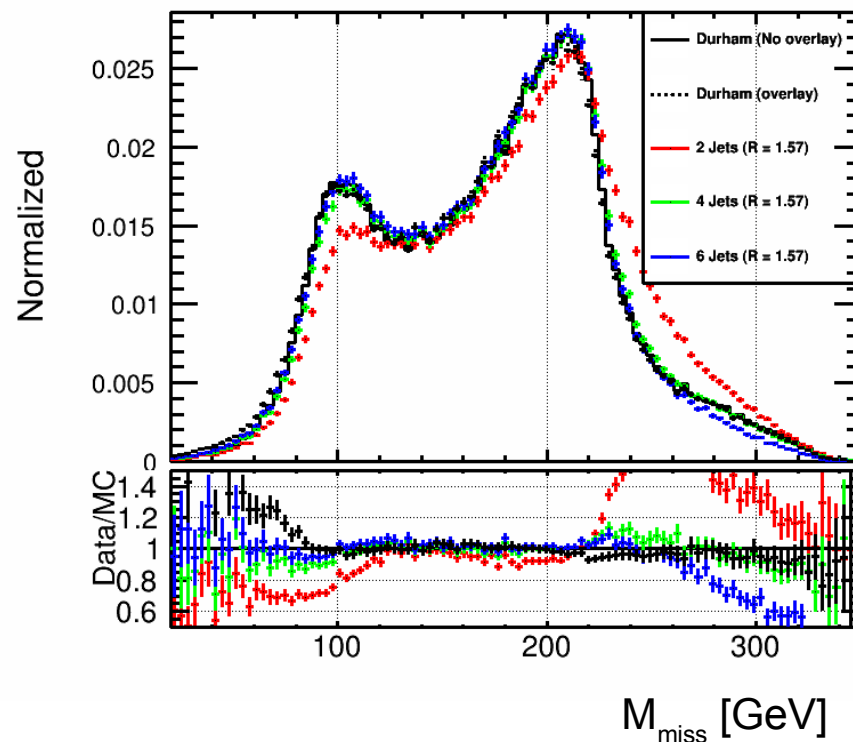
# Reconstruction Strategy

- $\nu\nu h \rightarrow 2 \text{ Jets} + \text{Missing Mass}$
- $\gamma\gamma$ -overlay removal
  - Low  $p_T$   $\gamma\gamma \rightarrow$  hadron background
  - Virtual photons get radiated off the primary beam  $e^-/e^+$
  - Real photons from bremsstrahlung and synchrotron radiation
- Jet clustering and flavor tagging (LCFIPlus)
- Event selection with cut analysis and BDT
- Log Likelihood Template fit to the flavor likeness of the Higgs di-jets



# $\gamma\gamma$ -Overlay Removal

- Overlaid background per event depends on beam energy :  
 $350 \text{ GeV} \rightarrow \langle N_{\gamma\gamma} \rangle = 0.33$
- Exclusive  $k_t$  algorithm to remove overlay
- By tuning the number of jets and  $r$  parameter the overlay can be removed
- Kinematic variables are correctly reconstructed in the relevant energy regime
- Getting more important for higher beam energies ( $500 \text{ GeV} \rightarrow \langle N_{\gamma\gamma} \rangle = 1.7$ )





# Binned Log Likelihood Template Fit

- Create 3D-Templates with b,c and bc likeness of the events
- LOI study used the fit function:

$$N_{ijk}^{Data} = \sum_{s=b,c,g,other} \frac{\sigma \cdot BR(h \rightarrow s)}{(\sigma \cdot BR(h \rightarrow s))^{SM}} \cdot N_{ijk}^{h \rightarrow s} + N_{ijk}^{bkg}$$

with  $N_{ijk}$  the number of events in the bin  $ijk$

- $h \rightarrow other$  was fixed
- $\sigma$  includes Higgs Strahlung and WW-fusion
  - Disentangling both processes done by hand
- Binned log likelihood fit ignoring zero entry bins
  - Zero entry bins do contain information
  - Bias of the fit results

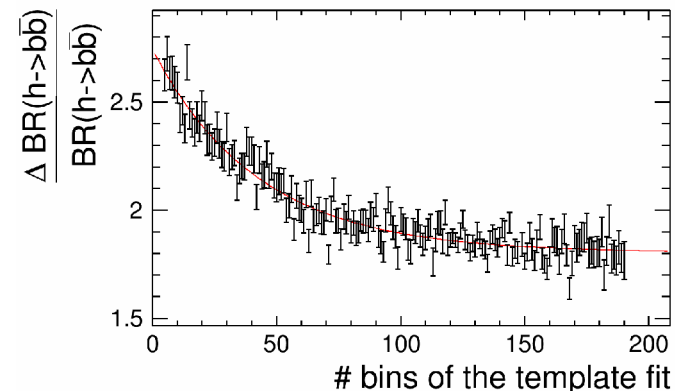
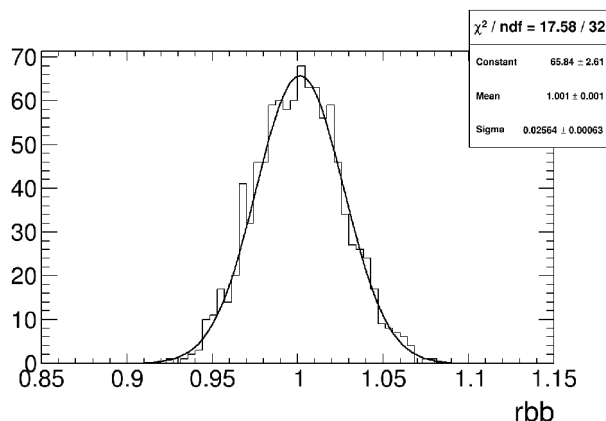


# Improved Fit Function

- Assuming the knowledge of  $\sigma(Zh)$  from recoil measurements

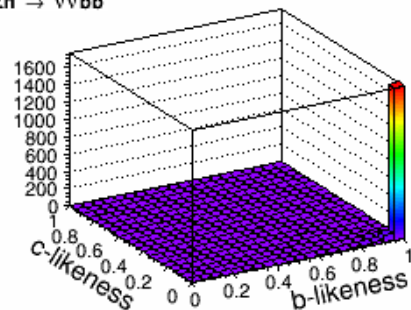
$$\frac{\sigma^{SM}(Zh)}{\sigma(Zh)} N_{ijk}^{Data} = \sum_{t=ZH, WWH} \sum_{s=b, c, g, other} \frac{\sigma^{SM}(Zh)}{\sigma(Zh)} \frac{\sigma(t)}{\sigma^{SM}(t)} \cdot \frac{BR(h \rightarrow s)}{BR^{SM}(h \rightarrow s)} \cdot N_{ijk}^{t \rightarrow s} + \frac{\sigma^{SM}(Zh)}{\sigma(Zh)} N_{ijk}^{bkg}$$

- One can fit the cross section ratio and the branching ratios directly
- Log likelihood fit which also takes zero bins into account
- Determination the error on the fit:
  - Fit 1000 toy MC samples from data
  - Study dependency on the binning (expect convergence)

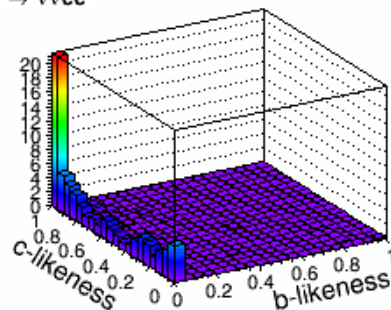


# 3D-Templates (Branching Ratio)

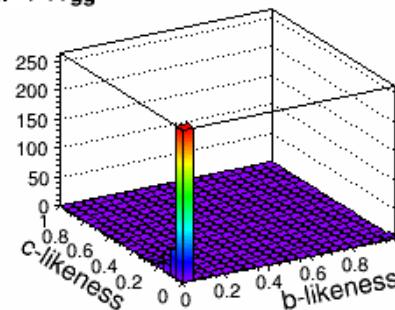
$Zh \rightarrow \nu\nu b\bar{b}$



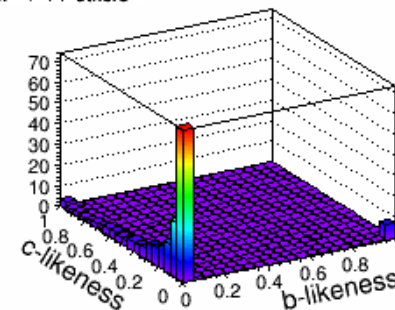
$Zh \rightarrow \nu\nu c\bar{c}$



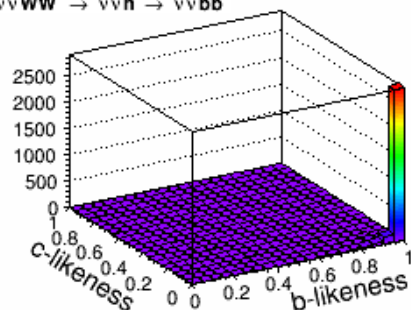
$Zh \rightarrow \nu\nu gg$



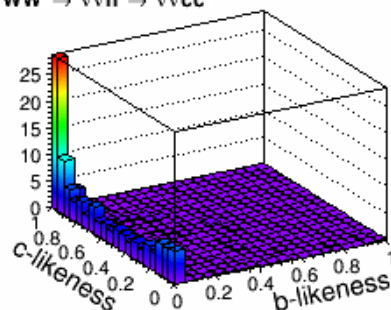
$Zh \rightarrow \nu\nu \text{ others}$



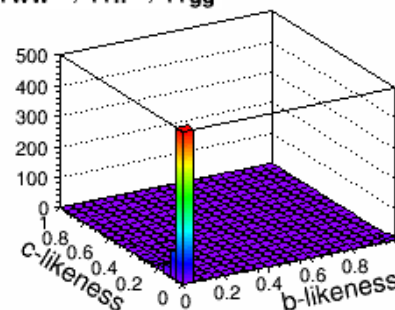
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu b\bar{b}$



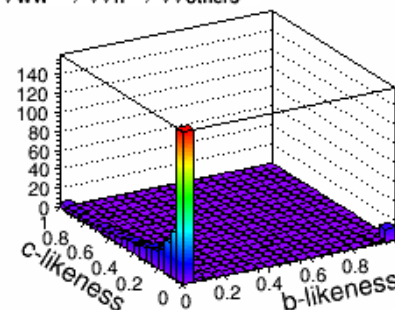
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu c\bar{c}$



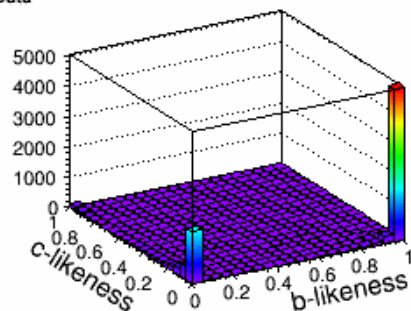
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu gg$



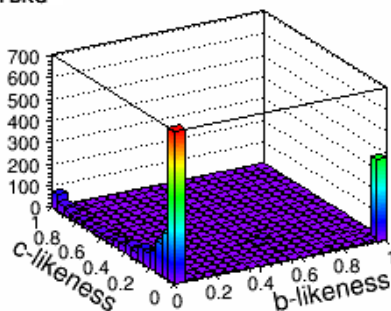
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu \text{ others}$



Data

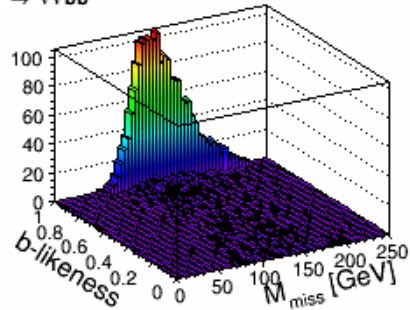


SM BKG

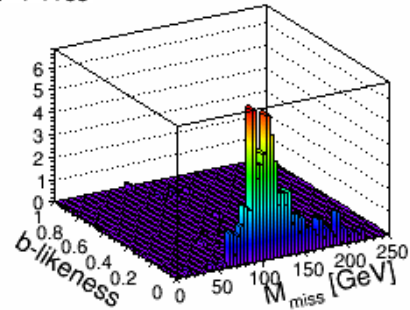


# 3D-Templates (Cross Section)

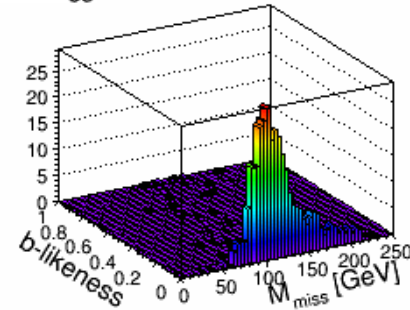
$Zh \rightarrow \nu\nu b\bar{b}$



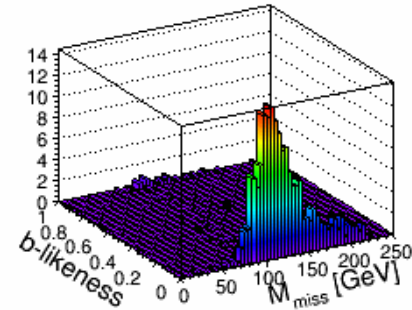
$Zh \rightarrow \nu\nu c\bar{c}$



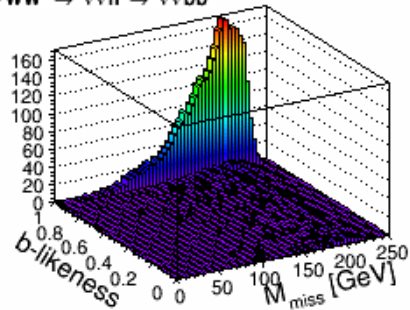
$Zh \rightarrow \nu\nu gg$



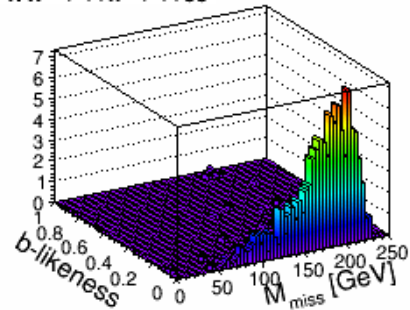
$Zh \rightarrow \nu\nu \text{ others}$



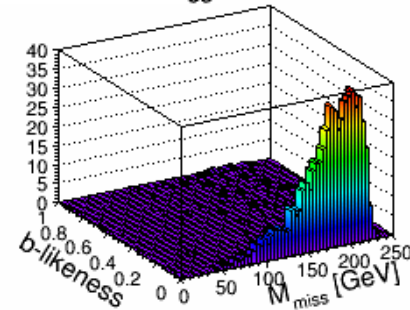
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu b\bar{b}$



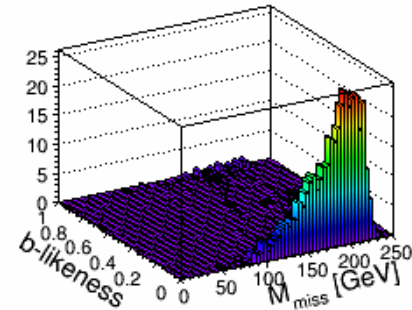
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu c\bar{c}$



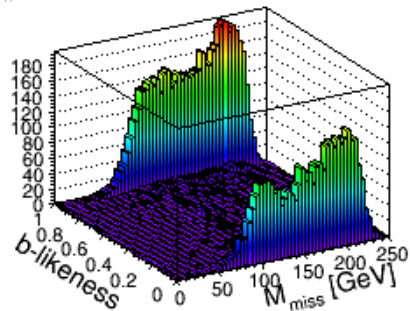
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu gg$



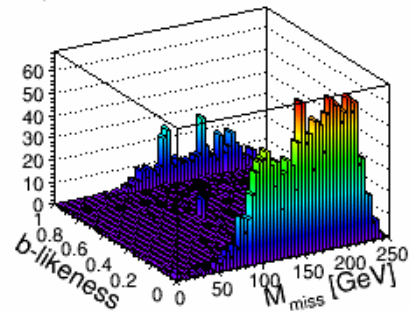
$\nu\nu WW \rightarrow \nu\nu h \rightarrow \nu\nu \text{ others}$



Data



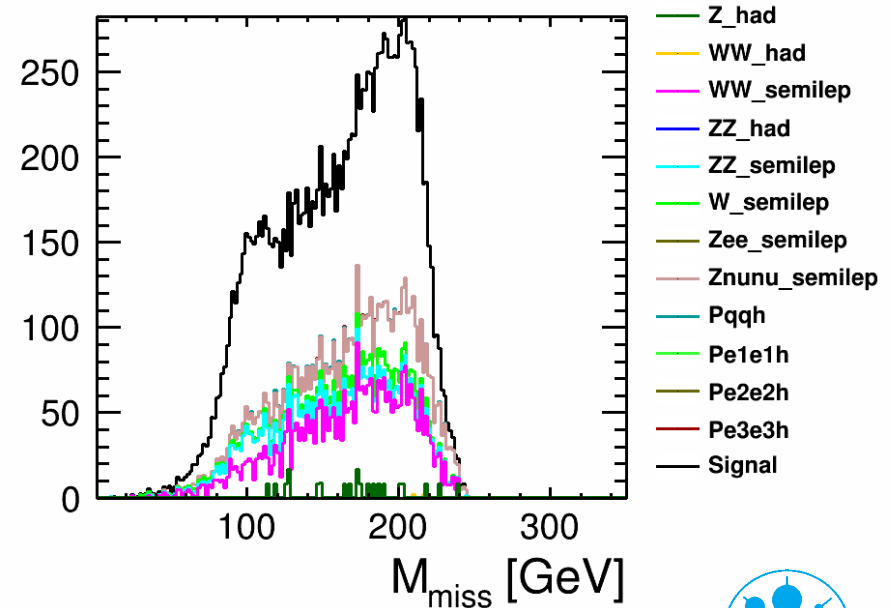
SM BKG



# Results

- Using the LOI fit function the obtained results worsen with the additional free parameter of  $h \rightarrow \text{other}$
- No cut on the missing mass as this seems difficult in the final missing mass spectrum  
→ assume knowledge of:  $\sigma = e_{Zh} \cdot \sigma(Zh) + e_{WWh} \cdot \sigma(WWh)$

| Relative Error on                                    | 3 par. Fit [%] | 4 par. Fit [%] |
|--|----------------|----------------|
| $\sigma \cdot \text{BR}(h \rightarrow bb)$           | 1.0            | 1.0            |
| $\sigma \cdot \text{BR}(h \rightarrow cc)$           | 5.9            | 5.9            |
| $\sigma \cdot \text{BR}(h \rightarrow gg)$           | 2.5            | 3.0            |
| $\sigma \cdot \text{BR}(h \rightarrow \text{other})$ | -              | 3.9            |



# Results

- With the new fit function, one directly receives the branching ratios
- Slightly worse performance expected due to a new free parameter, but we don't need to get the BR out of  $\sigma \cdot \text{BR}$
- The error on  $\sigma(\text{Zh})$  is not yet included

| Relative Error on                      | %   |
|--|-----|
| BR (h->bb)                             | 1.8 |
| BR (h->cc)                             | 6.0 |
| BR (h->gg)                             | 3.2 |
| BR (h->other)                          | 4.0 |
| $\sigma(\text{WWh})/\sigma(\text{Zh})$ | 2.3 |



# Combining Results

- Combining  $\nu\nu h$  with other final state analysis
- Extrapolated results from scaling signal and background with the effective cross sections with the current beam parameter and by using LHC recommended Higgs BR
- The fitting procedure was changed which improved the results compared to the extrapolated results

| Updated results                         | 250 GeV                           |       |       | 350 GeV                           |       |       |
|---|-----------------------------------|-------|-------|-----------------------------------|-------|-------|
| $L(\text{fb}^{-1})$                     | 250 $\text{fb}^{-1}$ P(-0.8,+0.3) |       |       | 330 $\text{fb}^{-1}$ P(-0.8,+0.3) |       |       |
| $\Delta\sigma\text{BR}/\sigma\text{BR}$ | bb                                | cc    | gg    | bb                                | cc    | gg    |
| $\nu\nu h$ (WW and ZH)                  | 1.6%                              | 14.8% | 9.7%  | 1.1%                              | 5.9%  | 2.5%  |
| qqh (ZH)                                | 1.6%                              | 24.0% | 18.4% | 1.5%                              | 15.0% | 13.2% |
| eeh (ZH)                                | 4.4%                              | 57.4% | 36.3% | 6.5%                              | >100% | >100% |
| $\mu\mu h$ (ZH)                         | 3.4%                              | 34.0% | 22.3% | 4.6%                              | 65.7% | 30.9% |
| Combined                                | 1.0%                              | 11.6% | 7.8%  | 0.8%                              | 5.5%  | 2.5%  |
| Extrapolated                            | 1.1%                              | 8.0%  | 6.8%  | 0.9%                              | 6.5%  | 5.2%  |

All ZH only studies performed by Hiroaki Ono



# Summary and Outlook

- Higgs hadronic branching ratios were studied in the  $v\bar{v}h$  final state for a 350 GeV ILC
- $\gamma\gamma$ -overlay not an issue for a center of mass energy of 350 GeV
- New method to extract the branching fractions and cross section ratio was introduced
  - More model independent
- Qualitative and quantitative improvement of the existing analysis
- Incorporate in global Higgs coupling fit
- Exploit opposite polarization → different polarization dependence of the two signal processes





# Backup



- Study was performed for the LOI with a 120 GeV Higgs

| $E_{\text{cm}}$ (GeV)  | 250  | 350  | 500   |
|--|------|------|-------|
| Lumi ( $\text{fb}^{-1}$ )  | 250  | 250  | 500   |
| $M_{\text{H}}$ (GeV)   | 120  | 120  | 120   |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow b\bar{b}$ ) | 1.0% | 1.0% | 0.57% |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow c\bar{c}$ ) | 6.9% | 6.2% | 5.2%  |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow g\bar{g}$ ) | 8.5% | 7.3% | 5.0%  |

- Extrapolate results by scaling signal and background with the effective cross sections with the current beam parameter and by using LHC recommended Higgs BR

| $E_{\text{cm}}$ (GeV)  | 250  | 350  | 500   |
|--|------|------|-------|
| Lumi ( $\text{fb}^{-1}$ )  | 250  | 330  | 500   |
| $M_{\text{H}}$ (GeV)   | 125  | 125  | 125   |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow b\bar{b}$ ) | 1.1% | 0.9% | 0.66% |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow c\bar{c}$ ) | 8.0% | 6.5% | 6.2%  |
| $\Delta\sigma_{\text{BR}}/\sigma_{\text{BR}}$ ( $h \rightarrow g\bar{g}$ ) | 6.8% | 5.2% | 4.1%  |



# Jet Clustering and Flavor Tagging

- Decluster the 4 Jets from the  $\gamma\gamma$ -overlay and cluster the particles into 2 jets using Durham algorithm
- Determine the flavor tag from LCFIPlus
- Evaluate flavor likeness  $X_i$  of the event ( $i=b,c,bc$ )

$$X_i = \frac{x_{i1} x_{i2}}{x_{i1} x_{i2} + (1 - x_{i1})(1 - x_{i2})}$$

with  $x_i$  the flavor tag of the single jets

- LOI study: LCFIVertex  $\rightarrow$  bc-tag = c-tag trained with b-jets as background only
- TDR study: LCFIPlus  $\rightarrow$   $x_{bc} = \frac{x_c}{x_c + x_b}$



# Cut Optimization

- Cuts optimized for significance and for equal sensitivity to Higgs strahlung and WW fusion (~39% signal left for both processes)
- BDT variables:
  - All cut parameters, Longitudinal momentum, global  $\cos(\Theta)$ , thrust, thrust axis, jet masses, jet momenta, jet angles

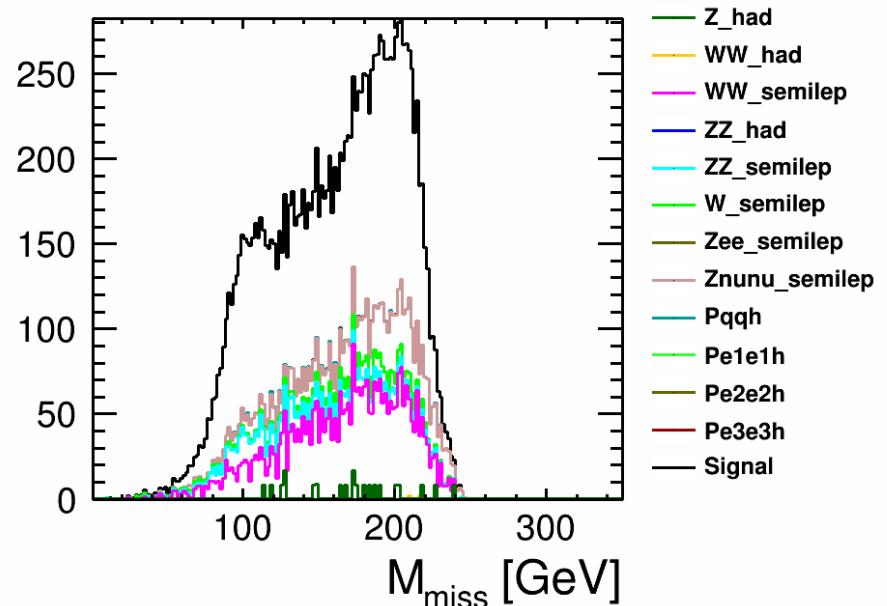
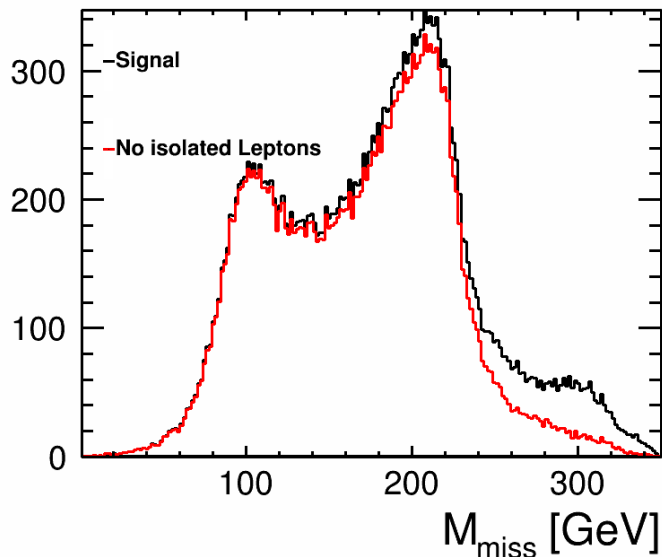
|                    | condition              | BG         | Signal  | Signf |
|--------------------|------------------------|------------|---------|-------|
| Expected           |                        | 19856532.5 | 32555.3 | 7.3   |
| isolated leptons   | #iso lep = 0           | 16605973.9 | 28922.8 | 7.0   |
| Transverse P       | $240 > P_{t,vis} > 30$ | 1171943.3  | 24423.1 | 22.3  |
| Visible Mass       | $135 > m_{vis}$        | 366041.9   | 23242.9 | 37.2  |
| Angle between jets | $0.27 > \cos a$        | 194536.1   | 21636.8 | 46.5  |
| # tracks > 1GeV    | $N_{chd} > 26$         | 58945.0    | 14903.7 | 54.8  |
| max. jet mass      | $135 > M_{j,max} > 40$ | 34911.1    | 13375.9 | 60.9  |
| Durham minus       | $Y_{12} > 0.05$        | 32837.3    | 13318.7 | 62.0  |
| BDT                | $BDT > -0.02$          | 3103.2     | 10478.6 | 89.9  |
| LOI Study          |                        | 11092.0    | 9543.0  | 66.4  |



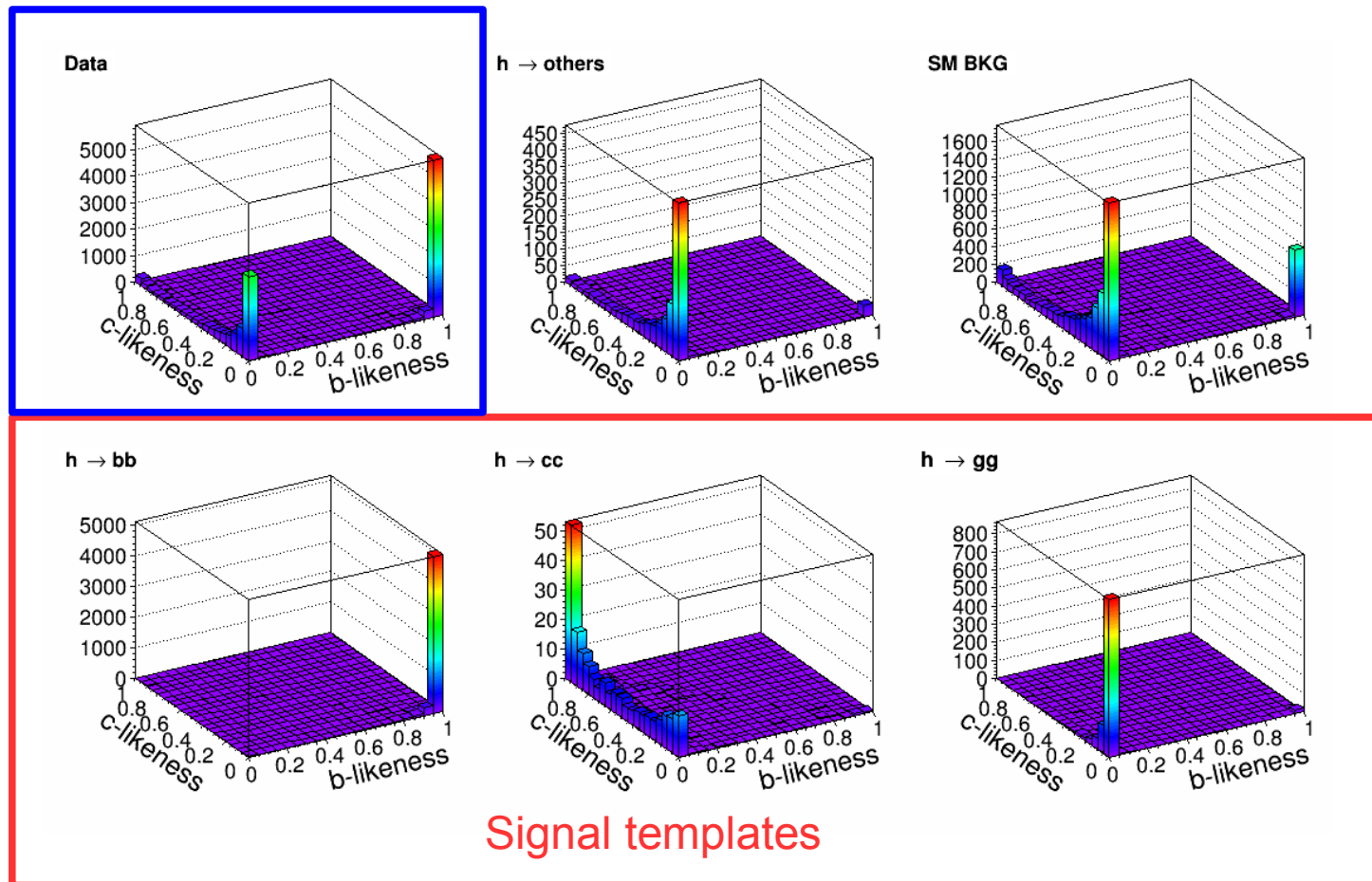
$$\begin{aligned}
 \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} N_{ijk}^{Data} = & \frac{BR(h \rightarrow bb)}{BR^{SM}(h \rightarrow bb)} \cdot N_{ijk}^{Zh \rightarrow bb} \\
 & + \frac{BR(h \rightarrow cc)}{BR^{SM}(h \rightarrow cc)} \cdot N_{ijk}^{Zh \rightarrow cc} \textcolor{red}{!} \\
 & + \frac{BR(h \rightarrow gg)}{BR^{SM}(h \rightarrow gg)} \cdot N_{ijk}^{Zh \rightarrow gg} \\
 & + \frac{BR(h \rightarrow oth)}{BR^{SM}(h \rightarrow oth)} \cdot N_{ijk}^{Zh \rightarrow oth} \\
 & + \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} \frac{\sigma(WWH)}{\sigma^{SM}(WWH)} \cdot \frac{BR(h \rightarrow bb)}{BR^{SM}(h \rightarrow bb)} \cdot N_{ijk}^{WWh \rightarrow bb} \\
 & + \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} \frac{\sigma(WWH)}{\sigma^{SM}(WWH)} \cdot \frac{BR(h \rightarrow cc)}{BR^{SM}(h \rightarrow cc)} \cdot N_{ijk}^{WWh \rightarrow cc} \\
 & + \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} \frac{\sigma(WWH)}{\sigma^{SM}(WWH)} \cdot \frac{BR(h \rightarrow gg)}{BR^{SM}(h \rightarrow gg)} \cdot N_{ijk}^{WWh \rightarrow gg} \\
 & + \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} \frac{\sigma(WWH)}{\sigma^{SM}(WWH)} \cdot \frac{BR(h \rightarrow oth)}{BR^{SM}(h \rightarrow oth)} \cdot N_{ijk}^{WWh \rightarrow oth} \\
 & + \frac{\sigma^{SM}(ZH)}{\sigma(ZH)} N_{ijk}^{bkg}
 \end{aligned}$$

# Event Preselection

- The expected behavior is visible in the missing mass distribution
  - A peak at the Z mass from the Higgs strahlung events
  - A sharp cutoff at  $350 \text{ GeV} - M_H$  from the WW fusion events
- Access in the missing mass distribution above 250 GeV
- The access in the missing mass distribution comes from  $H \rightarrow WW, \tau\tau$ 
  - Leptonic decays cause the problem
  - Use Isolated lepton finder to remove these events



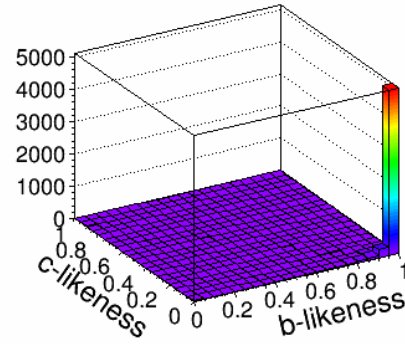
# Old 3-D Template Fit



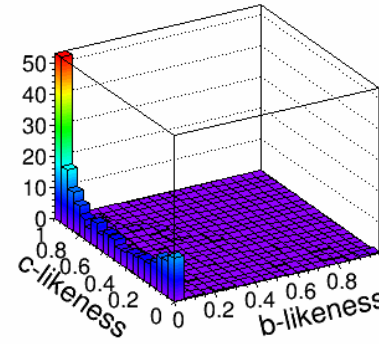
# Different Flavor Likeness Definitions

$$\frac{x_{i1} x_{i2}}{x_{i1} x_{i2} + (1 - x_{i1})(1 - x_{i2})}$$

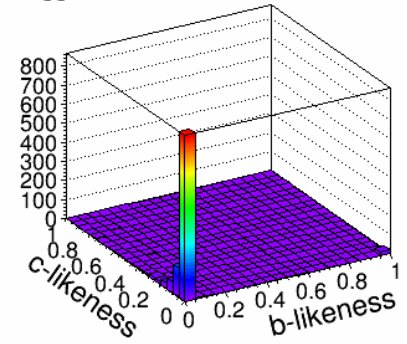
h → bb



h → cc

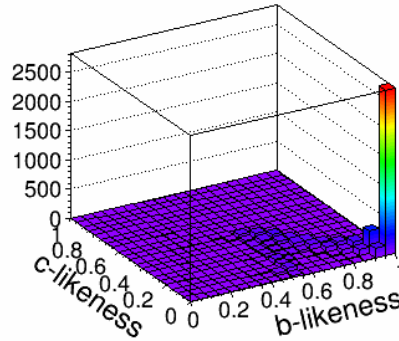


h → gg

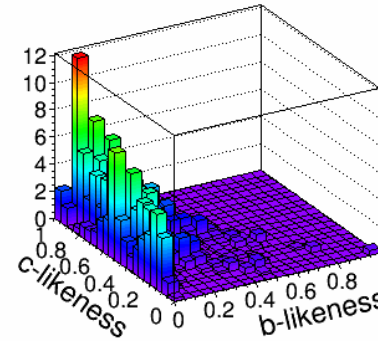


$$\frac{x_{i1} + x_{i2}}{2}$$

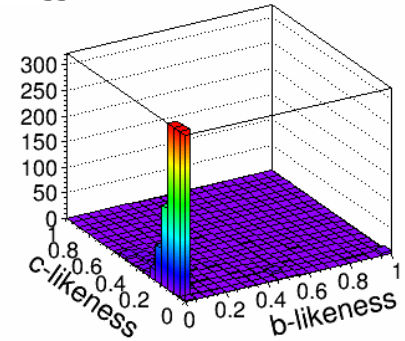
h → bb



h → cc



h → gg



Simple mean tag value gives better results than the standard likeness definition

| h-> | Standard likeness | (x <sub>1</sub> +x <sub>2</sub> )/2 |
|-----|-------------------|-------------------------------------|
| bb  | 1.148+-0.013      | 1.135+-0.013                        |
| cc  | 15.35+-0.16       | 14.56+-0.16                         |
| gg  | 4.758+-0.052      | 4.694+-0.049                        |