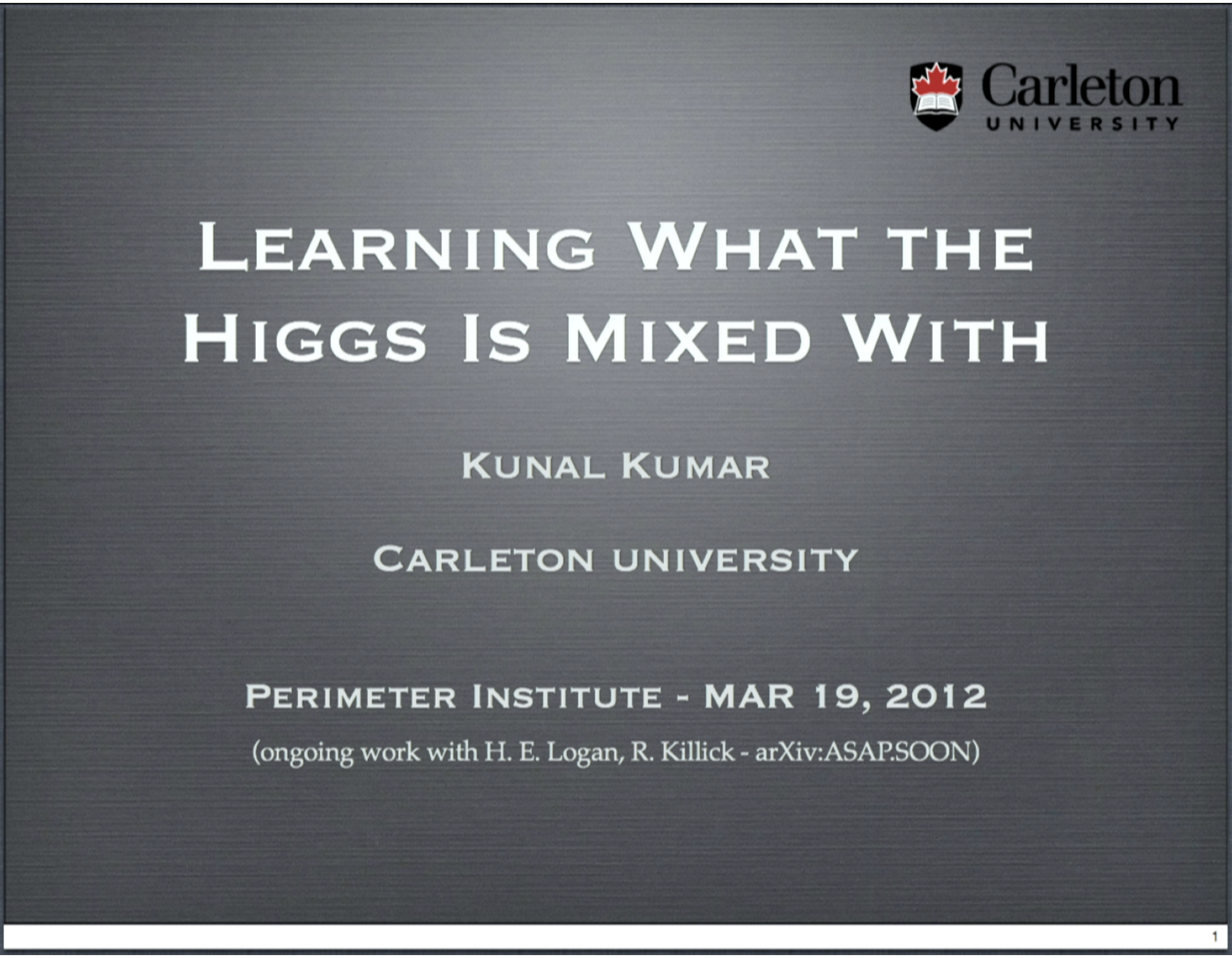
Title: Learning what the Higgs is mixed with

Date: Mar 19, 2013 01:00 PM

URL: http://pirsa.org/13030089

Abstract: The Standard Model Higgs boson may be mixed with another scalar that does not couple singly to gauge bosons or fermions. The electroweak quantum numbers of such an additional scalar can be determined by measuring the quartic Higgs-Higgs-vector-vector couplings, which contributeâ€”along with the coveted triple Higgs couplingâ€”to double Higgs production in e+eâˆ’ collisions. We show that simultaneous sensitivity to the quartic Higgs-Higgs-vector-vector coupling and the triple Higgs coupling can be obtained using measurements of the double Higgs production cross section at two different e+eâˆ’ center-of-mass energies. Kinematic distributions of the two Higgs bosons in the final state could provide additional discriminating power.


Carleton UNIVERSITY
LEARNING WHAT THE HIGGS IS MIXED WITH
KUNAL KUMAR
CARLETON UNIVERSITY
PERIMETER INSTITUTE - MAR 19, 2012
(ongoing work with H. E. Logan, R. Killick - arXiv:ASAP.SOON)
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OUTLINE

- Motivation for measuring *hhVV*
- Measuring Higgs Couplings - LHC, ILC
- Parametrization of Couplings
- 3 Benchmark Models (BMs)
- *hhVV* and *hhh* from di-Higgs rates at ILC
- M_{hh} as kinematic discriminant
- Caveats / Viability of BMs
- Conclusions

Motivation

- We've entered the stage of measuring the properties of the 125 GeV resonance more precisely
- Through a long-term experimental program we hope to find out more about the nature of this particle and EWSB
- Many extensions of the SM involve the Higgs mixing with another scalar
- This scenario can be tested by measuring coupling deviations or by direct searches
- We shall focus on the scenario where no new particles are observed

Motivation

With no new particles seen measuring coupling deviations is crucial

$$\mathcal{L} \supset M_V^2 V_\mu^* V^\mu \left[1 + a_V \frac{2h}{v} + b_V \frac{h^2}{v^2}\right] - m_f \bar{f} f \left[1 + c_f \frac{h}{v}\right]$$
$$-\frac{1}{2} M_h^2 h^2 \left[1 + d_3 \frac{h}{v} + d_4 \frac{h^2}{4v^2}\right]$$

- We assume the new scalar doesn't contribute to EWSB (has zero or tiny vev) and so doesn't couple singly to vector bosons
- We assume the new scalar doesn't couple singly to quarks or charged leptons to avoid stringent constraints from FCNCs

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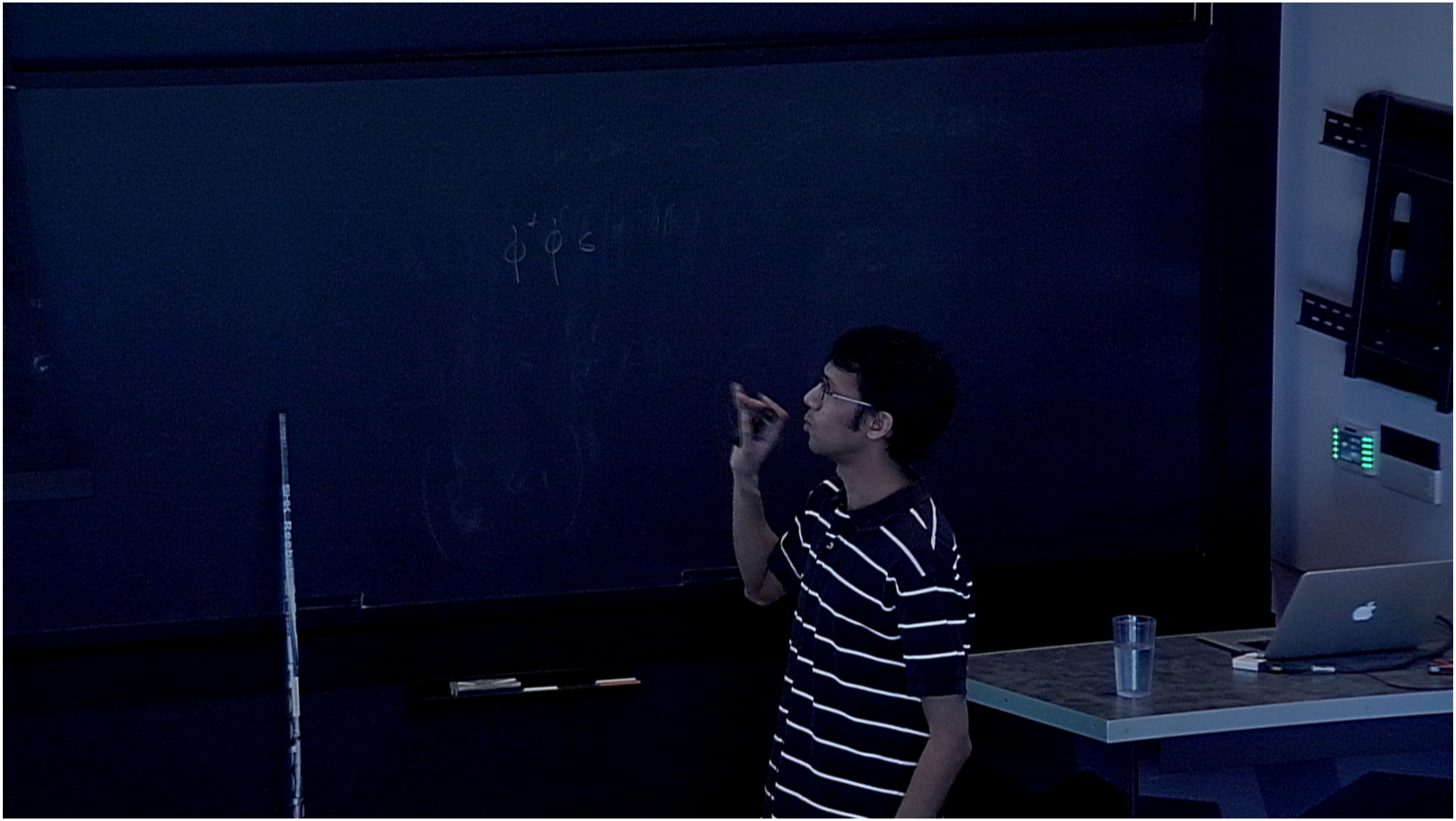
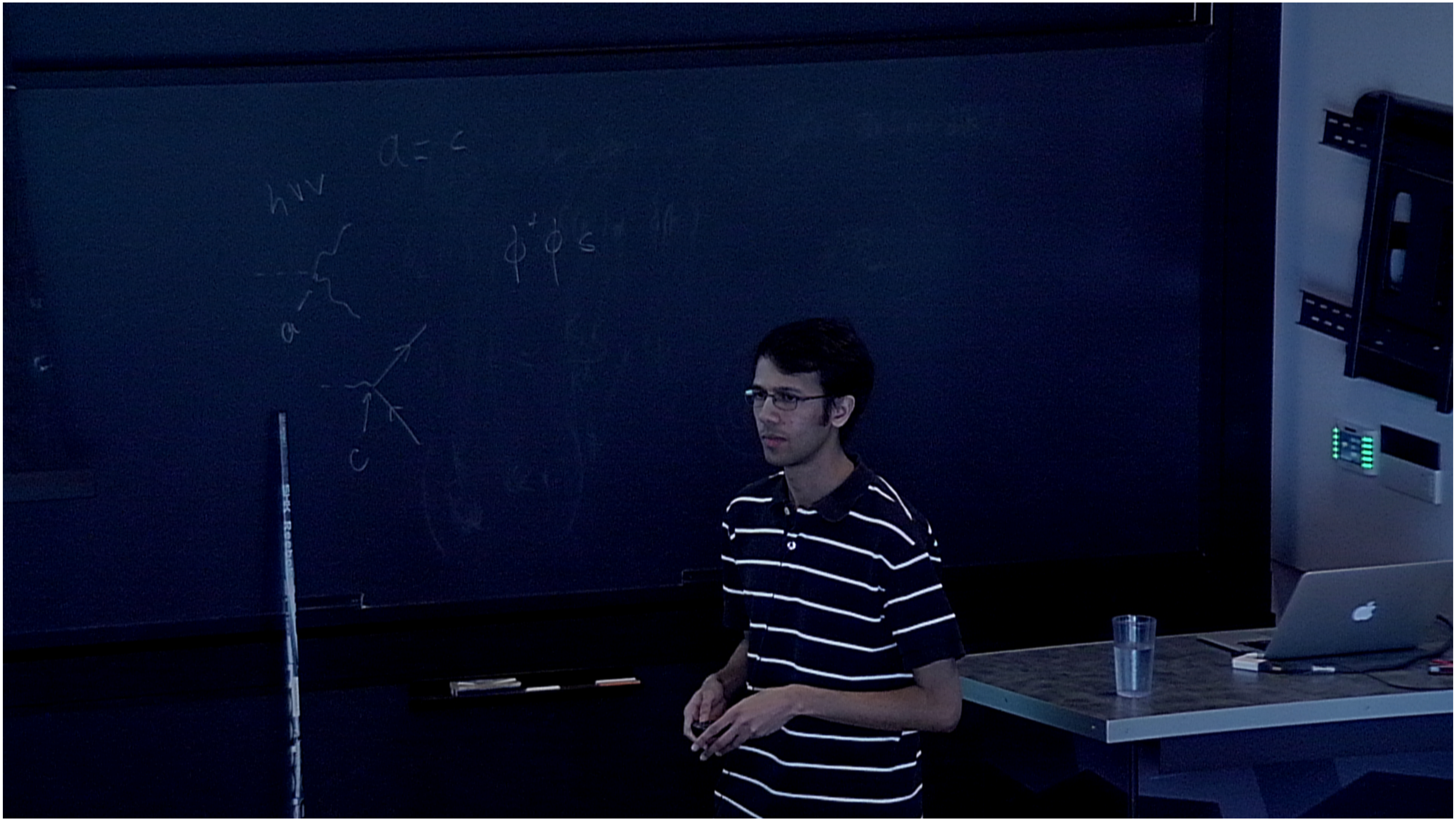
Motivation

- Measuring these at the LHC is extremely hard (details to follow)
- We propose to extract them from cross sections of $e^+e^- \to Zhh$ and $e^+e^- \to \nu\bar{\nu}hh$ at the proposed ILC
- These processes have been looked at in the past only to extract the Higgs self coupling
- So the main goal of this work is to make a case for doing this hard measurement at the ILC in order to find out more about the EW quantum numbers of the scalar the Higgs mixes with




hvv
a = c

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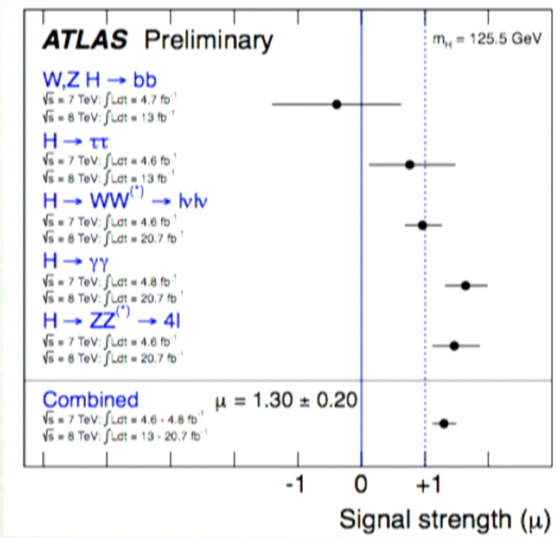
Measuring Higgs Couplings - LHC

- Extracting Higgs couplings in a model independent way from the signal strength require global fits (too many parameters vs model dependence)



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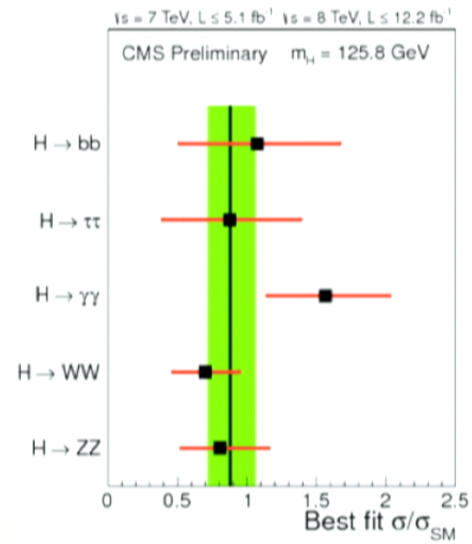

$\hat{\mu} = 0.88 \pm 0.21$

HCP 2012

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Measuring Higgs Couplings - LHC

- *hhVV* and *hhh* couplings are hard to measure because the cross sections for di-Higgs production are small
- At 14 TeV LHC
  pp -->h ~ 50 pb (gluon fusion)
  pp --> h h ~ 20 fb (gluon fusion)
  pp --> h h ~ 2 fb (VBF)

A. Djouadi, W. Kilian, M. Muhlleitner and P. Zerwas, Eur. Phys. J. C10 (1999) 45

Building the ILC

- There are good reasons to do better even in channels that the LHC measures to ~10% precision
- A number of NP scenarios with a light Higgs and other particles (heavier than a TeV) can cause deviations smaller than that in one or more of the Higgs couplings (decoupling limit)
- In the absence of any other particles being discovered at the LHC, measuring the Higgs couplings more precisely is crucial
- Measuring these couplings more precisely is one of the main physics reasons to build a linear collider like the proposed ILC

Advantages

- e+ e- collisions have much smaller total cross sections (~100 nb as compared to ~100 mb)
- No pile up or hadrons from underlying event
- Z and W bosons are recognized easily even in hadronic decay modes
- Absolute branching ratios of the Higgs can be measured as the Higgs can be tagged when it recoils against the Z boson in $e^+e^- \to Zh$ at 250 GeV
- Combined with $\sigma(e^+e^- \to \nu\bar{\nu}h \to b\bar{b})$ at 500 GeV gives the Higgs width to 6% accuracy

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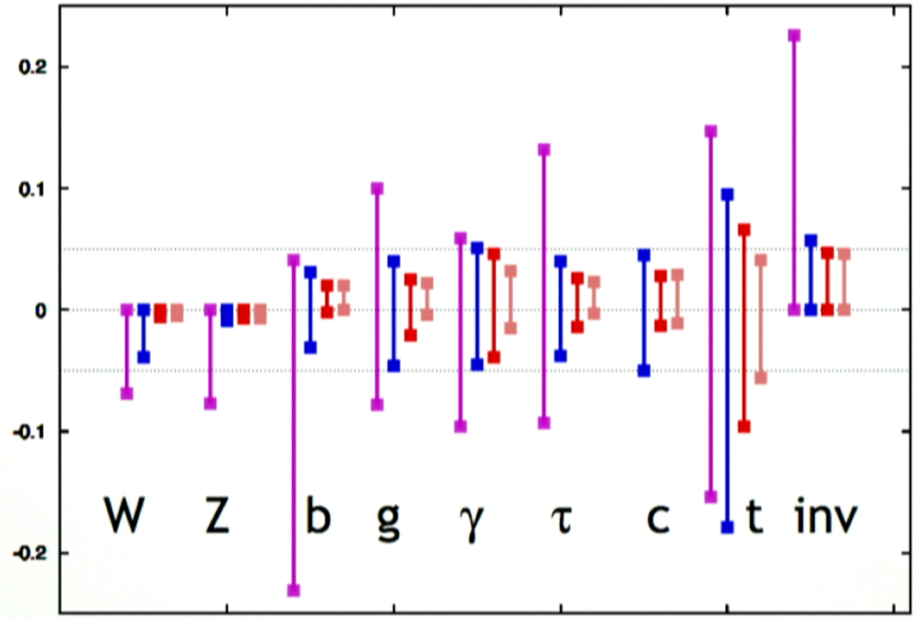
LHC-ILC comparison

g(hAA)/g(hAA)|$_{SM}$-1   LHC/ILC1/ILC/ILCTeV

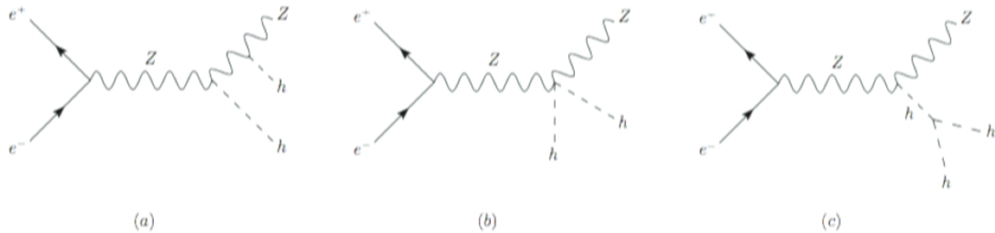


LHC - 14 TeV , 300 inv. fb
ILC1 - 250 GeV, 250 inv. fb
ILC - 500 GeV, 500 inv. fb
ILCTeV - 1 TeV, 1000 inv. fb

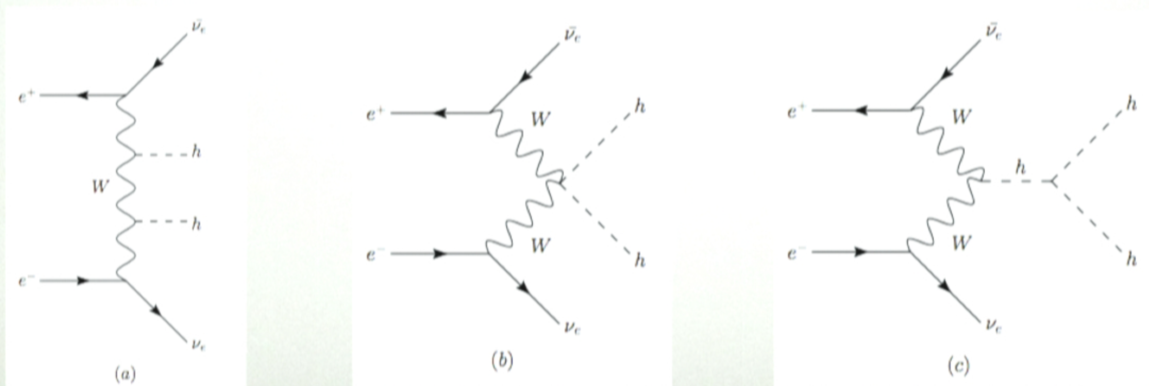
M. Peskin, arXiv : 1208.5152

Double Higgs production at ILC

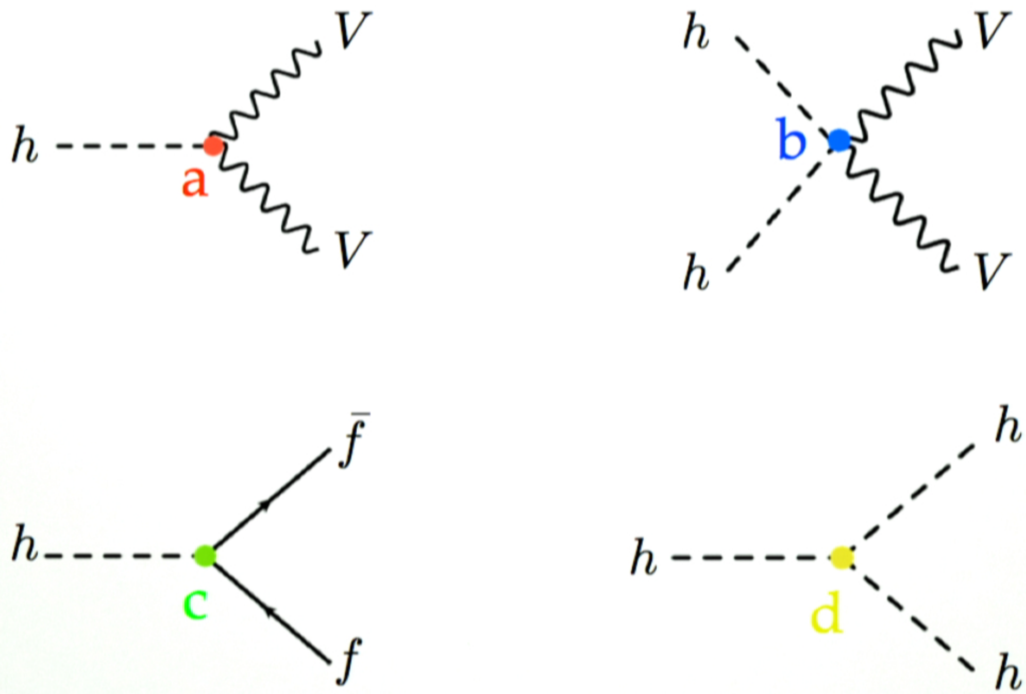
$$e^+e^- \to Zhh$$



$$e^+e^- \to \nu\bar{\nu}hh$$



Nomenclature



a,b,c,d are multiplicative factors by which the SM couplings are modified and V denotes the W or Z boson

COUPLING MODIFICATIONS

$$h = \phi \cos\theta - \chi \sin\theta.$$

- χ - real neutral component of general electroweak multiplet X
- doesn't couple to fermions and since it doesn't acquire a vev it doesn't couple singly to VV.

$$a = \cos\theta, \qquad c = \cos\theta$$

- $hhVV$ couplings are modified by $\chi\chi^{VV}$ couplings

$$\chi\chi W^+_\mu W^-_\nu : ig^2 \left[T(T+1) - \frac{Y^2}{4}\right] g_{\mu\nu}$$

$$\chi\chi Z_\mu Z_\nu : i\frac{g^2}{2c_W^2} Y^2 g_{\mu\nu}$$

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BENCHMARK MODELS

- I : SM + Real Singlet Scalar

$$h = \phi \cos\theta - s \sin\theta$$

$$b_W = b_Z = \cos^2\theta = a^2$$

- II : SM + Inert Doublet

Consider a Type 1 2HDM where the doublet Φ_2 has small vev (fine-tuned)

$$h = \phi_1 \cos\theta - \phi_2 \sin\theta$$

$$b_W = b_Z = \cos^2\theta + \sin^2\theta = 1$$

BENCHMARK MODELS

- III : Georgi-Machacek model
- Contains the SM doublet along with a complex triplet (Y=2) and a real triplet (Y=0)
- Note that each of those triplets taken individually would violate custodial SU(2)
- Together they can be arranged so as to preserve it

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix} \qquad \chi = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & \xi^{-} & \chi^{0} \end{pmatrix}$$

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MEASURING THE $hhVV$ COUPLING

- Scenario : LHC + 250 GeV ILC data point to the Higgs mixing with another scalar that doesn't couple singly to gauge bosons or fermions

$$a = c = 0.9$$

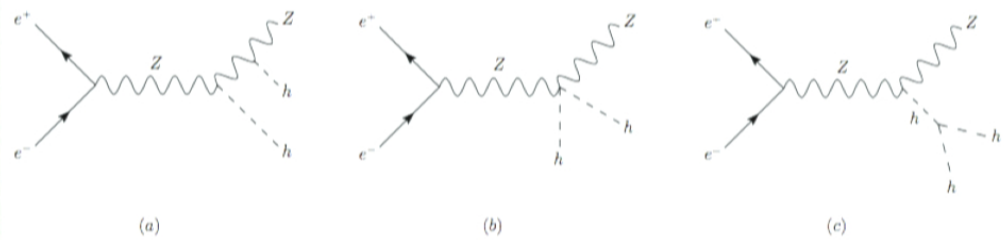
- The production rate would be scaled by a factor of 0.81 but all the BRs would stay the same
- The 250 GeV ILC measurement of $e^+e^- \to Zh$

  would yield *a* to a precision of $\Delta a/a = 1.3\%$

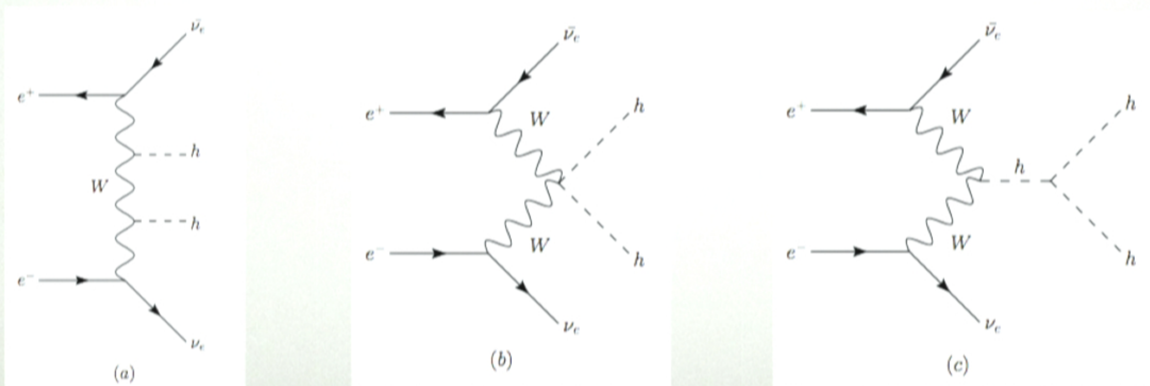
  with 250 inv. fb of data (~ 3 yrs)

Double Higgs production at ILC

$e^+e^- \to Zhh$



$e^+e^- \to \nu\bar{\nu}hh$



Double Higgs production at ILC

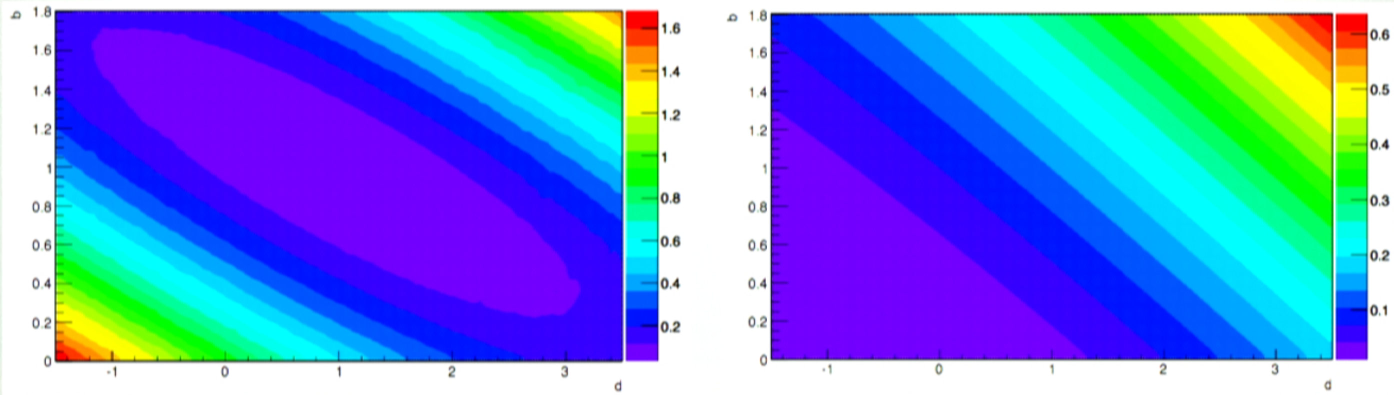
- We Z boson fusion because the cross section is much smaller than WBF
- We calculate the cross sections using CalcHEP and MG5 for di-higgs production for the SM and the three benchmark models assuming a = c = 0.9 and d = 1

Model	b	$\sigma^{500}(Zhh)$	$\sigma^{1000}(Zhh)$	$\sigma^{1000}(\mathrm{WBF})$
Singlet	0.81	0.109 fb	0.0815 fb	0.0411 fb
Doublet	1	0.136 fb	0.113 fb	0.0273 fb
GM	1.32	0.188 fb	0.183 fb	0.0901 fb
SM	1	0.157 fb	0.119 fb	0.0712 fb

Extracting b and d

- The cross sections for the two processes depend differently on b and d
- This dependence also varies with the CoM energy

$e^+e^- \to Zhh$ (500 GeV) $e^+e^- \to \nu\bar{\nu}hh$ (1 TeV)



Contour Plots of Cross sections (in fb)

Extracting b and d

- Measurements of $e^+e^- \to Zhh$ at 500 GeV and $e^+e^- \to \nu\bar{\nu}hh$ at 1 TeV can be used to fit for $\boldsymbol{b}$ and $\boldsymbol{d}$
- We can compute the two cross sections in terms of our effective lagrangian for $\boldsymbol{a} =$ 0.9 while varying $\boldsymbol{b}$ and $\boldsymbol{d}$
- Next we can plot 68% and 95% CL chi sq plots for each Benchmark Model

$$\chi^2(b,d) = \sum_{i=1,2} \frac{(\sigma_i(b,d) - \sigma_{BM,i})^2}{\Delta\sigma^2_{BM,i}}$$

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- We use cross section uncertainties from the ILC Large Detector Study for the ILC Detailed Baseline Design (DBD) Report
- These uncertainties are scaled appropriately for the Benchmark Models as the cross section

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Measuring b and d

- Relative uncertainty increases for Singlet and Doublet Benchmark model and decreases for GM as one would expect from the table of cross sections

Model	b	$\Delta\sigma/\sigma(Zhh, 500\text{ GeV})$	$\Delta\sigma/\sigma(\nu\nu hh, 1\text{ TeV})$
Singlet	0.81	38%	32%
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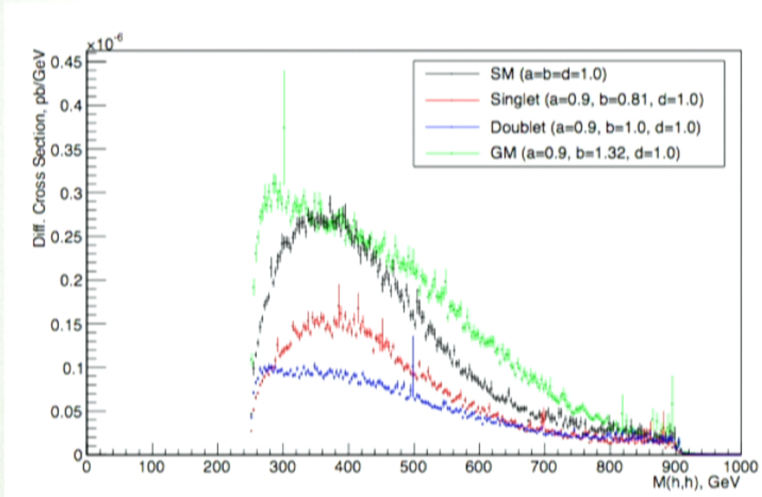
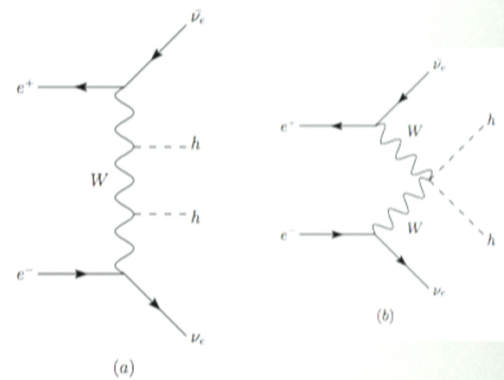
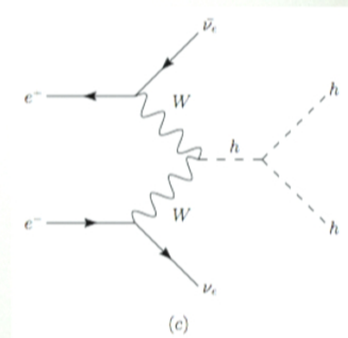
Measuring *b* and *d*

- The DBD report assumed a Higgs mass of 120 GeV and considered the channel where higgs decays to bottom quark pairs
- At 125 GeV this would reduce the cross sections by about 20%
- The lost precision can be regained by including the h h --> W+W- b b

WBF at 1 TeV







- Benchmark Models differ just in value of *b*
- Dig. (b) and (c) interfere constructively leading to enhancement at lower M_{hh} for larger *b* values (GM or Doublet model vs Singlet)

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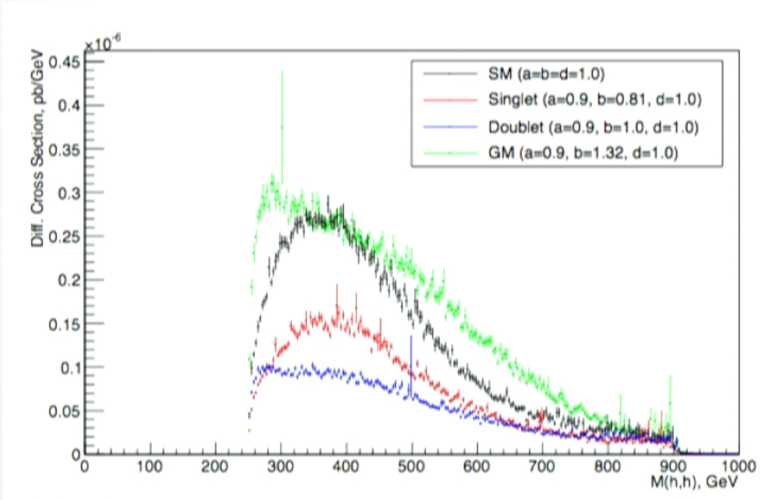

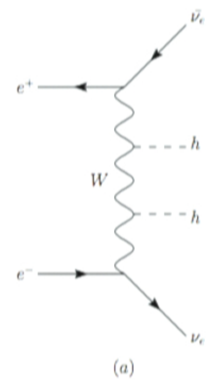

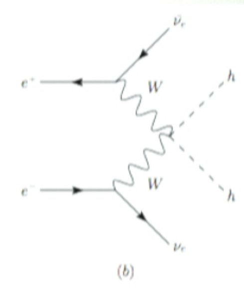

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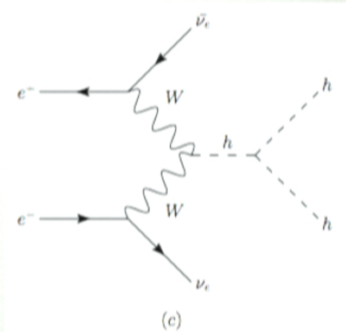

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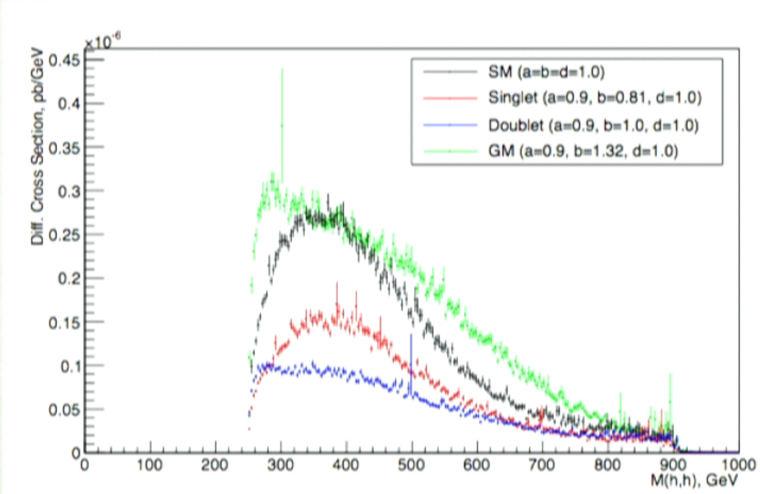

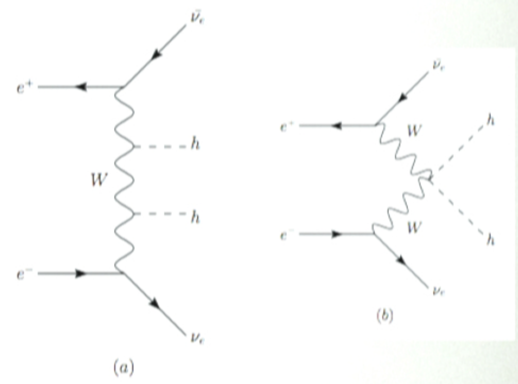

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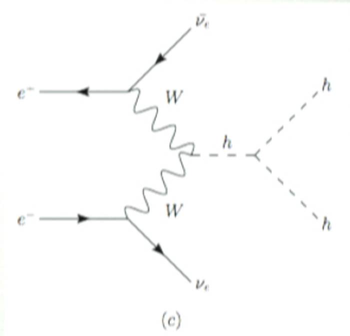

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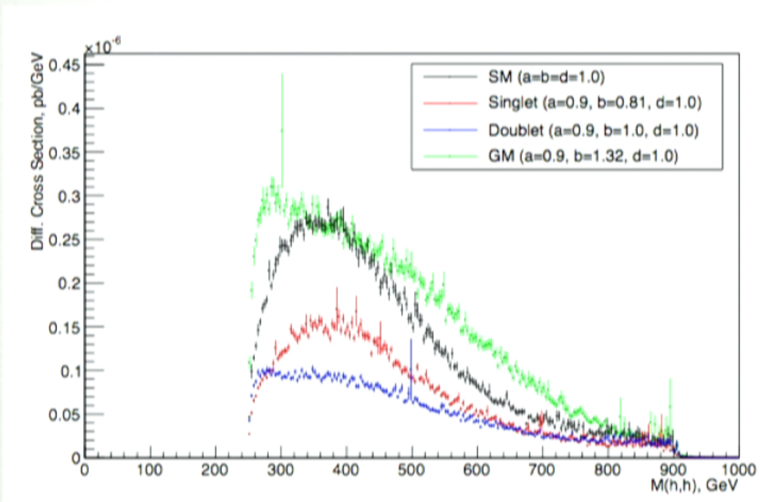

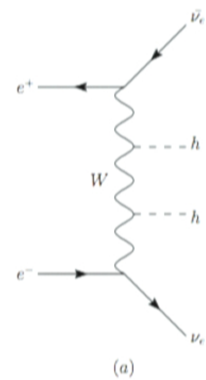

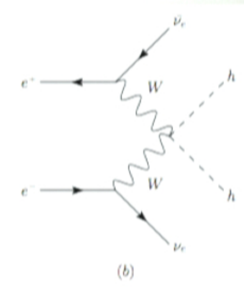

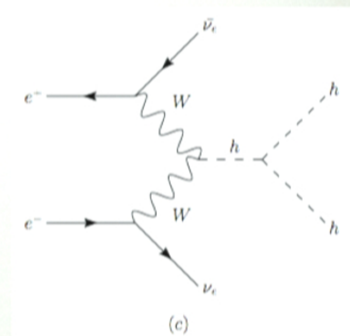

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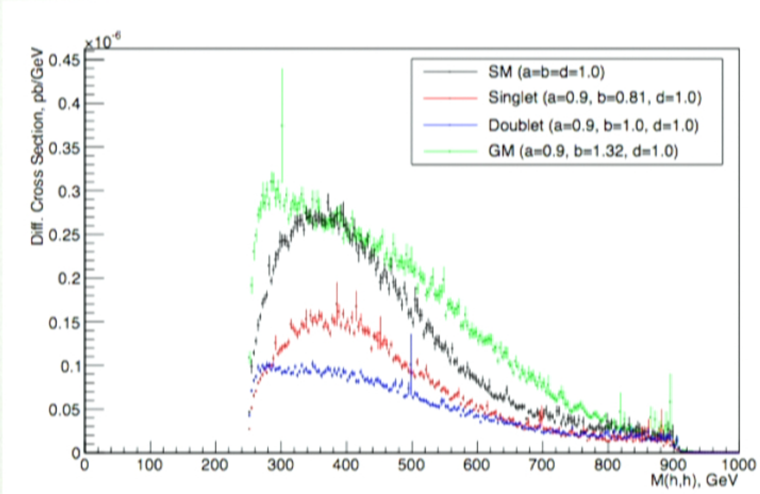
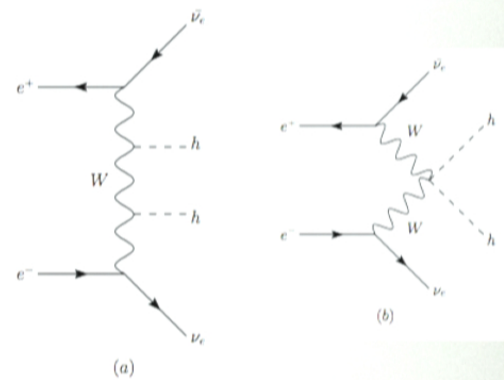
WBF at 1 TeV





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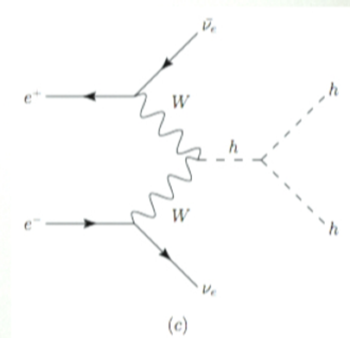
- Leads to a flatter spectrum at intermediate M_{hh} for large b values (Doublet vs Singlet model)



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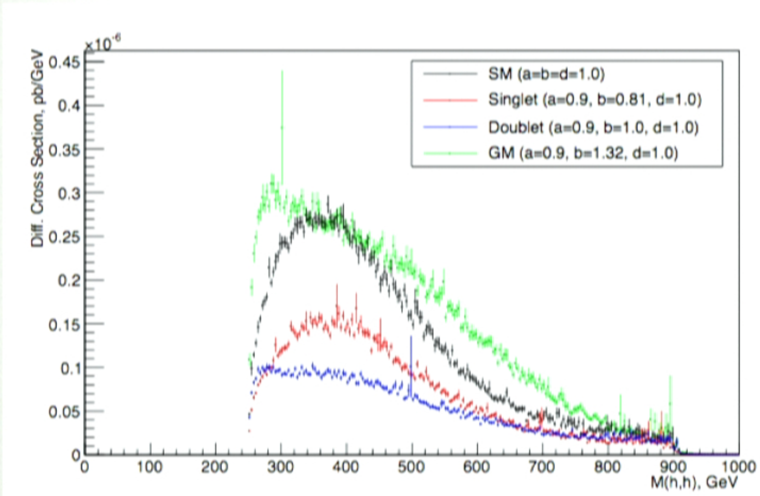

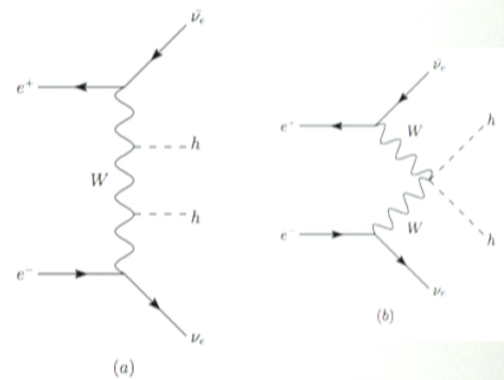

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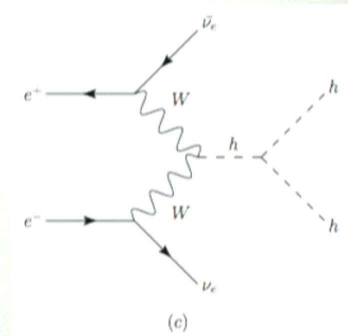
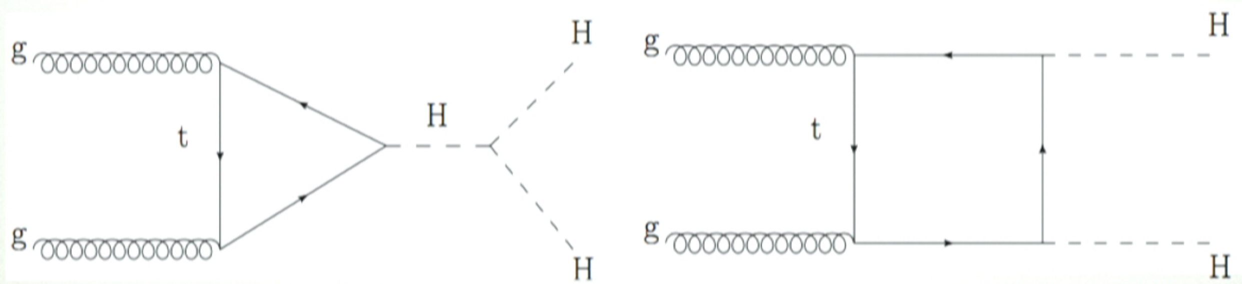


Constraints on *d* from LHC

- Accessed via di-Higgs production through gluon fusion
- Depends on top Yukawa coupling as well as new particles in the gluon-fusion loop



figs. from F. Goertz, A. Papaefstathiou, L.L.Yang, J. Zurita [arXiv : 1301.3492]

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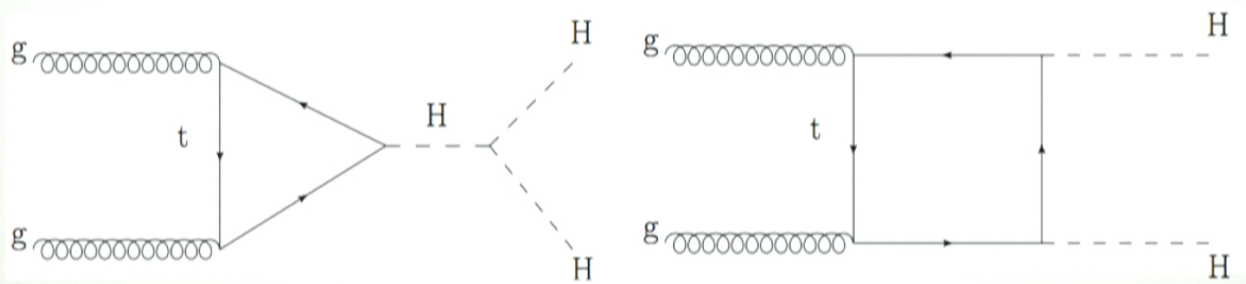
- Depends on top Yukawa coupling as well as new particles in the gluon-fusion loop



figs. from F. Goertz, A. Papaefstathiou, L.L.Yang, J. Zurita [arXiv : 1301.3492]

Constraints on d from LHC

- di-Higgs production at LHC is not very sensitive to b (the hhVV coupling modification)
- d can be constrained to be +ve at 96% CL using 600 inv. fb at 14 TeV LHC F. Goertz et al. [arXiv : 1301.3492]
- With 3000 inv. fb the 1 sigma uncertainty is reduced to +30% and -20%
- The study assumed $c = 1$ and no new particles in the loop
- A joint analysis from LHC and ILC data can thus be used to constrain b, d and new colored particles

Double Higgs production at ILC

- The approach we used to calculate di-Higgs rates doesn't account for contribution from t- and u-channel exchange of SU(2) triplet states in the doublet and GM model
- Doesn't include H -> h h where H is the heavier custodial singlet
- We assume these states are heavy enough to be kinematically forbidden at the 1 TeV ILC

$M_H \gtrsim 910$ GeV $\qquad e^+e^- \to Z(H \to hh)$

$M_{H^\pm, A^0} \gtrsim 875$ GeV $\qquad e^+e^- \to h(A^0 \to Zh)$

For the Inert Doublet case including these states increases the di-Higgs cross section by less than 3% if the states are heavier than 1 TeV

Unitarity limits

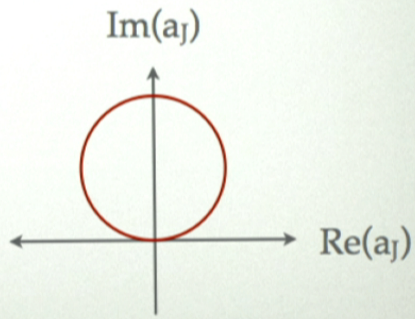
The amplitude for a scattering process can be written in terms of partial wave amplitudes of definite angular momentum

$$\mathcal{M} = 16\pi \sum_J (2J+1) a_J P_J(\cos\theta)$$

The cross section in each partial wave is limited

Since this is a result of the unitarity of the S-matrix the bounds on the partial wave amplitudes are called unitarity limits

$$|\mathrm{Re}(a_J)| \leq \frac{1}{2}$$



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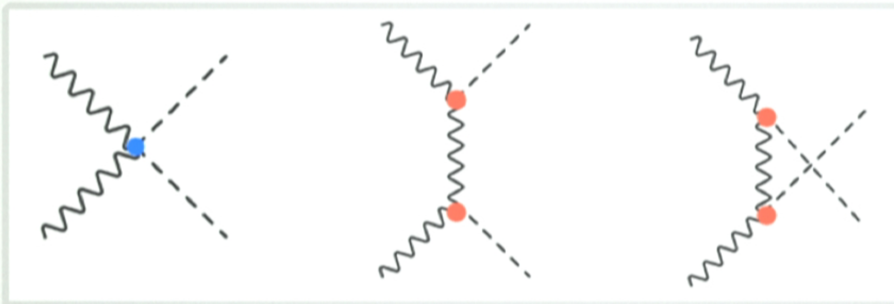
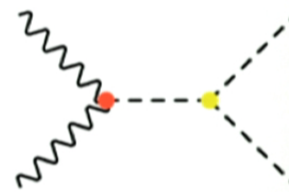
$V_L V_L \to hh$



$$\mathcal{O}\left(\frac{E^2}{v^2}\right)$$



$$\mathcal{O}\left(E^0\right)$$

- Clearly the t- and u-channel exchange is required to restore unitarity when $b - a^2 \neq 0$

$a \neq c$

- Benchmark Models assumed Higgs mixing with a scalar that doesn't participate in EWSB or break custodial SU(2)
- There are well motivated models for which these assumptions do not hold
- If new scalar participates in EWSB then $a \neq c$
- This can be determined from the high precision measurements of single Higgs couplings at the ILC

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$a \neq c$

- Considering the G-M model. We can still solve for the mixing angle.

$$c = \frac{\cos\theta}{v_\phi / v_{SM}}$$

$$v_\phi^2 + 8v_\chi^2 = v_{SM}^2$$

$$a = \cos\theta \frac{v_\phi}{v_{SM}} - \sin\theta \frac{8}{\sqrt{3}} \frac{v_\chi}{v_{SM}}$$

$$b = \cos^2\theta + \frac{8}{3}\sin^2\theta$$

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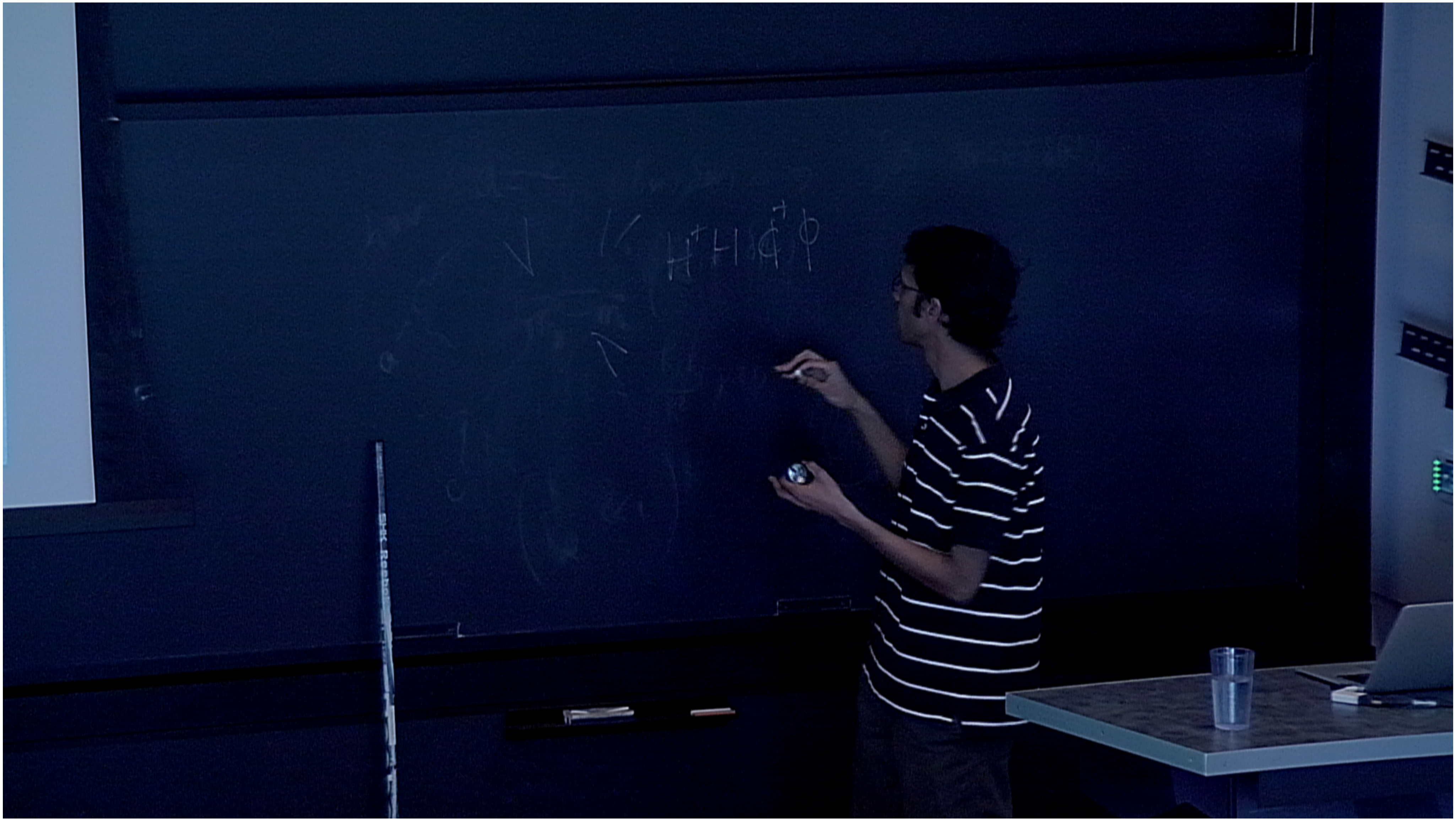
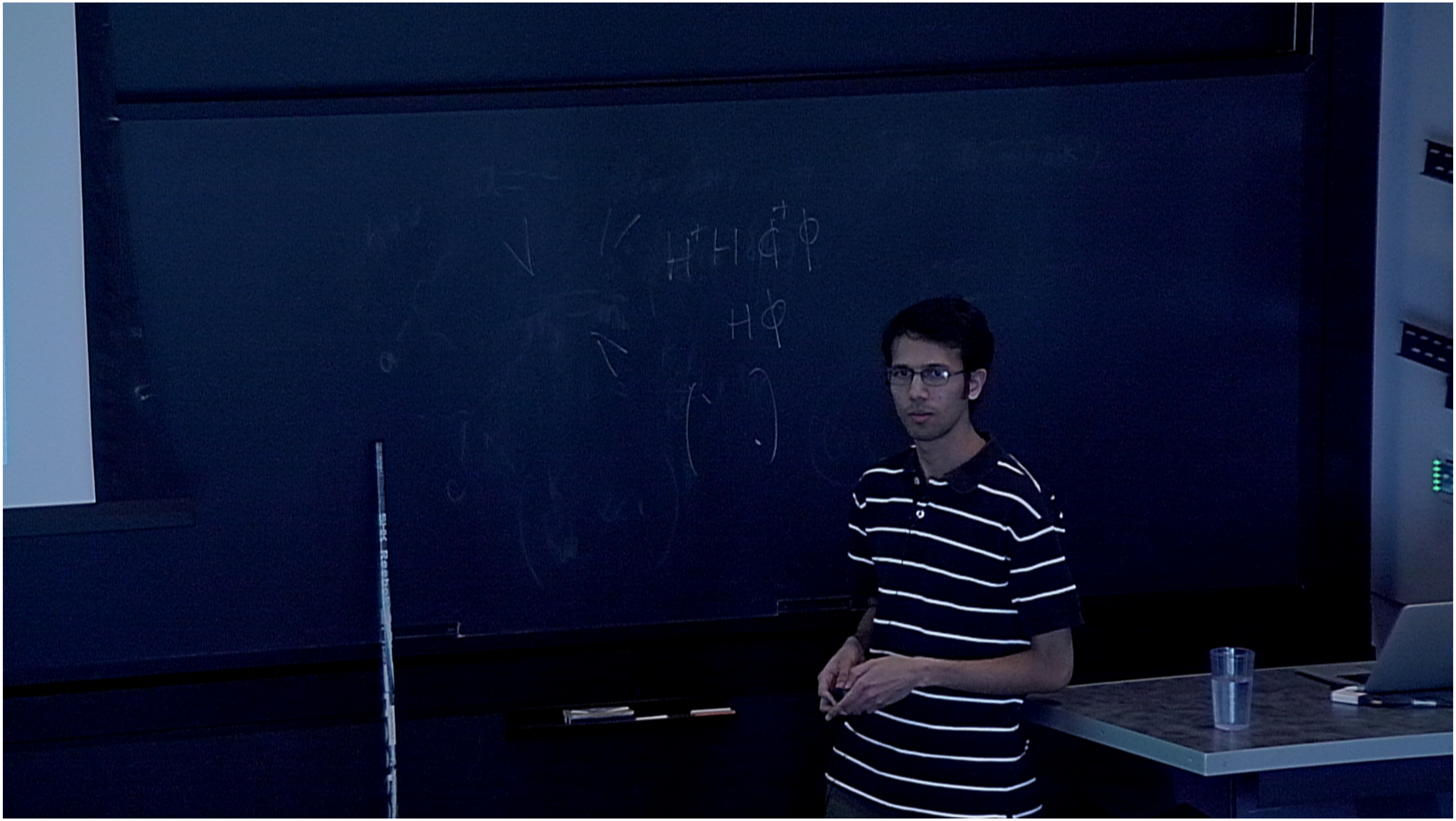
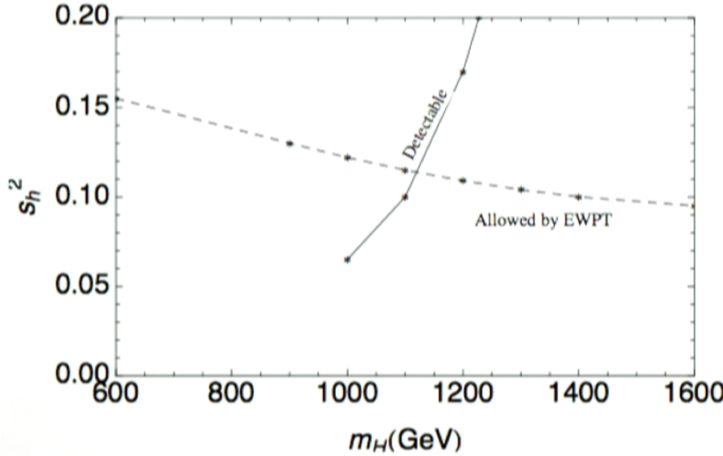




H†H φ†φ
Hφ

Electroweak Precision Constraints

- For a mixed-in scalar



R. Gupta, J.Wells, H. Rhezhak, arXiv : 1206.3560

- Additional new physics could compensate for a = 0.9
- At the very least a = 0.95 is safe for the mH range we are interested in

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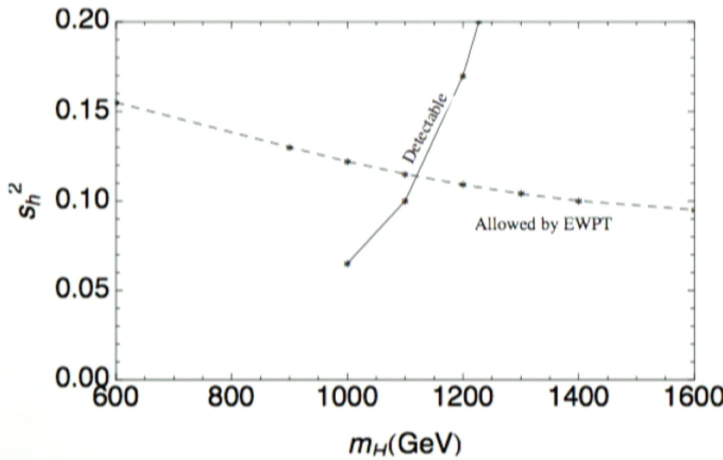
Electroweak Precision Constraints

- For a mixed-in scalar



R. Gupta, J.Wells, H. Rhezhak, arXiv : 1206.3560

- Additional new physics could compensate for a = 0.9
- At the very least a = 0.95 is safe for the mH range we are interested in

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Conclusions

- The $hhVV$ can be separated from the hhh coupling with rate measurements at two different centre of mass energies
- In addition LHC measurements can constrain the hhh independently