Testing the Higgs Potential at e+e- and Hadron Colliders

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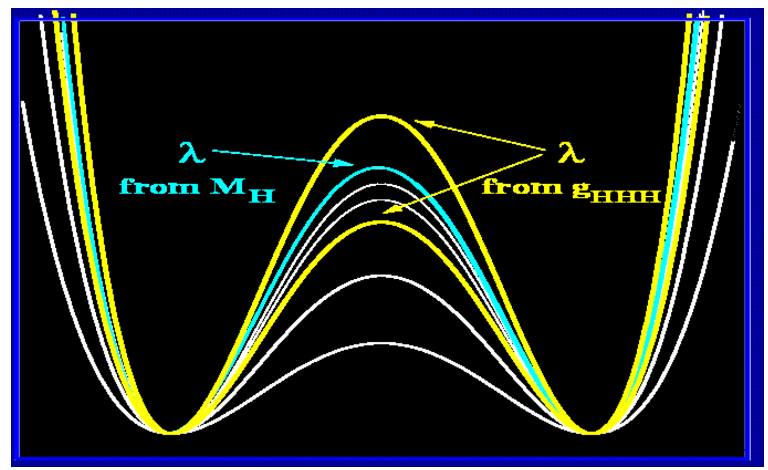
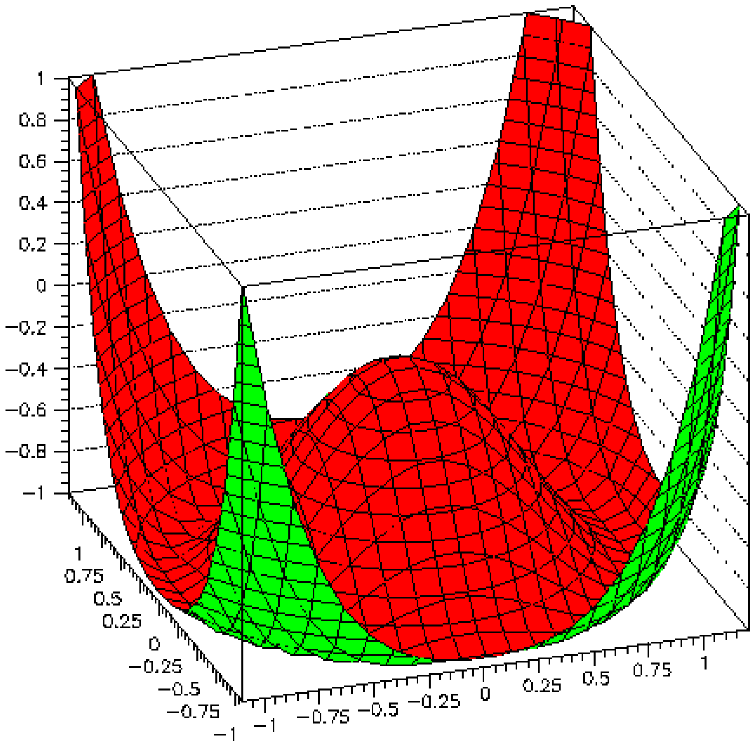


Thanks to M. Battaglia, U. Bauer, E. Boos, D. Rainwater

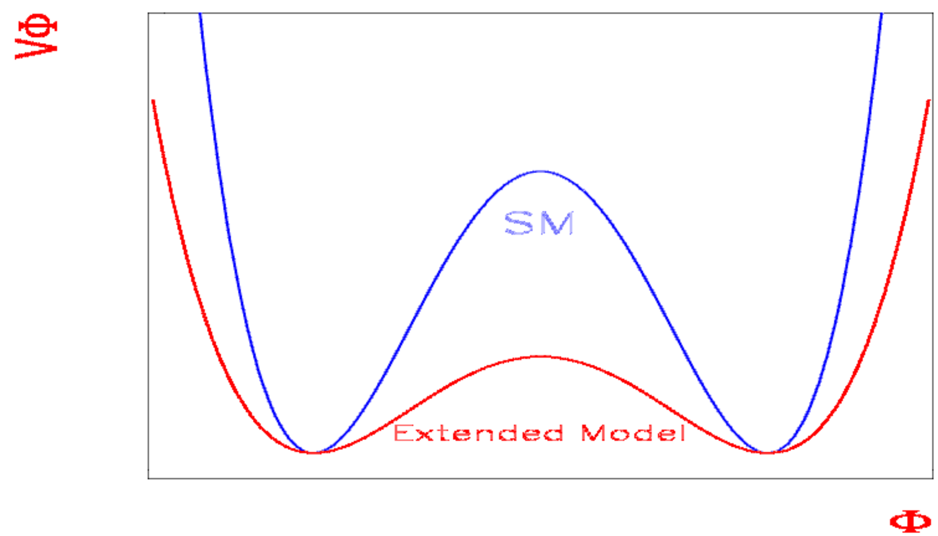
Reconstructing the Higgs Potential

The shape of the Higgs potential

Determination of the shape needed for the complete investigation of the Higgs profile and to obtain a direct proof of the mechanism of EW symmetry breaking



$$V(\Phi^*\Phi) = \lambda(\breve{\Phi}^*\Phi - \frac{1}{2}v^2)^2$$



Tests may reveal the extended Nature of the Higgs sector

Higgs potential

- Higgs potential can be expressed in terms of the Higgs field as:

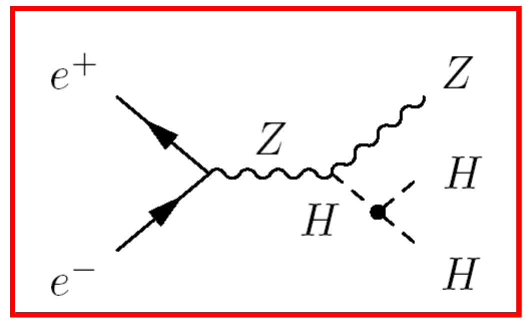
$$V_H = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^4}{8v^2} H^4$$

$$\lambda_{HHH} = 3m_H^2/v \; *$$

$$\lambda_{HHHH} = 3m_H^2/v^2$$

$$v = (\sqrt{2G_F})^{-1/2} \simeq 246GeV$$

Access to the potential via Higgs self coupling (triple Higgs coupling), i.e. via double Higgs production



Quartic Higgs self-coupling 2-3 orders of magnitude smaller than triple Higgs coupling → concentrate on λ_{HHH}

* Sometimes other notation used: $\lambda_{SM} = \frac{m_H^2}{2v^2}$ $\quad V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4$

Experimental prospects

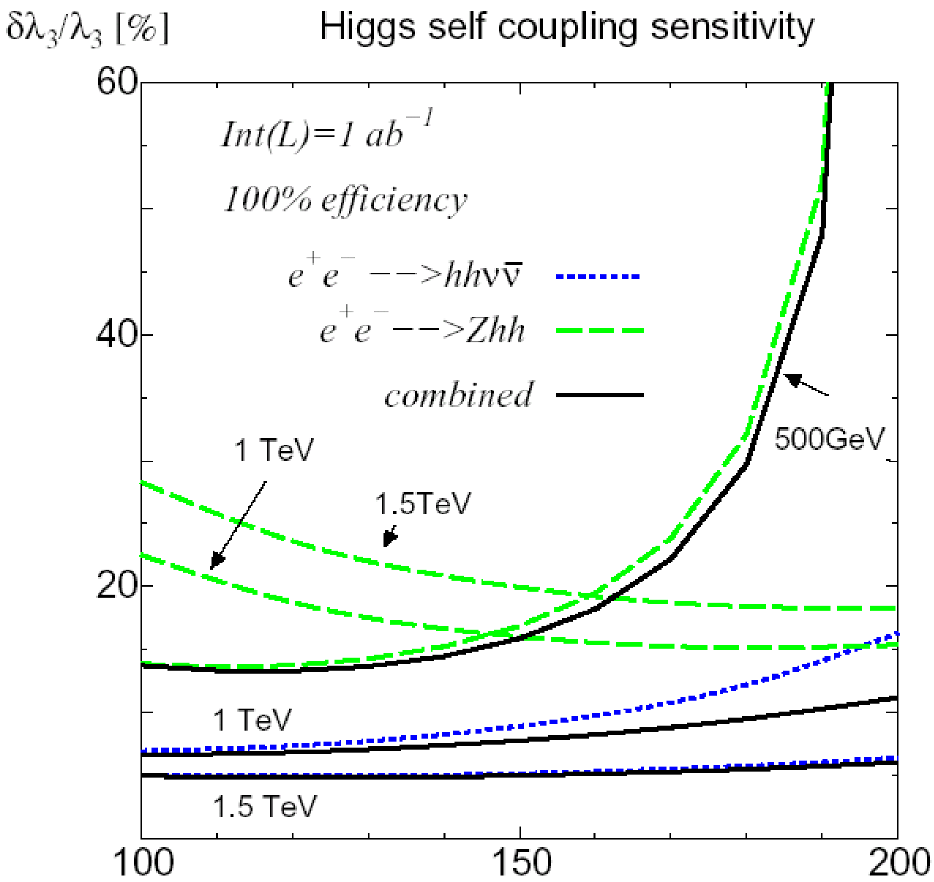
Colliders for which double Higgs production has been studied

- TeV Class Linear Collider (TESLA,NLC,JLC)
  e+e-, $\sqrt{s}$ = 500-1000 GeV (0.5-2) ab^{-1} $2\text{-}3 \cdot 10^{34} cm^{-2} s^{-1}$
- Photon collider
  e+e-, $\sqrt{s}$ = 500-1000 GeV (0.5-2) ab^{-1} $10^{34} cm^{-2} s^{-1}$
- Multi-TeV Linear Collider
  e+e-, $\sqrt{s}$ = 1-5 TeV (3-5) ab^{-1} $10^{35} cm^{-2} s^{-1}$
- LHC
  pp, $\sqrt{s}$ = 14 TeV 0.3-0.6 ab^{-1} $10^{34} cm^{-2} s^{-1}$
- SLHC
  pp, $\sqrt{s}$ = 14 TeV 3-6 ab^{-1} $10^{35} cm^{-2} s^{-1}$
- VLHC
  pp, $\sqrt{s}$ = 200 TeV 0.3-1.2 ab^{-1} $2 \cdot 10^{34} cm^{-2} s^{-1}$

λ_{HHH} at a LC

Processes: $e^+e^- \to hhZ$ $\quad e^+e^- \to (WW)\nu\bar{\nu} \to hh\nu\bar{\nu}$

Y.Yasui et al LCWS02

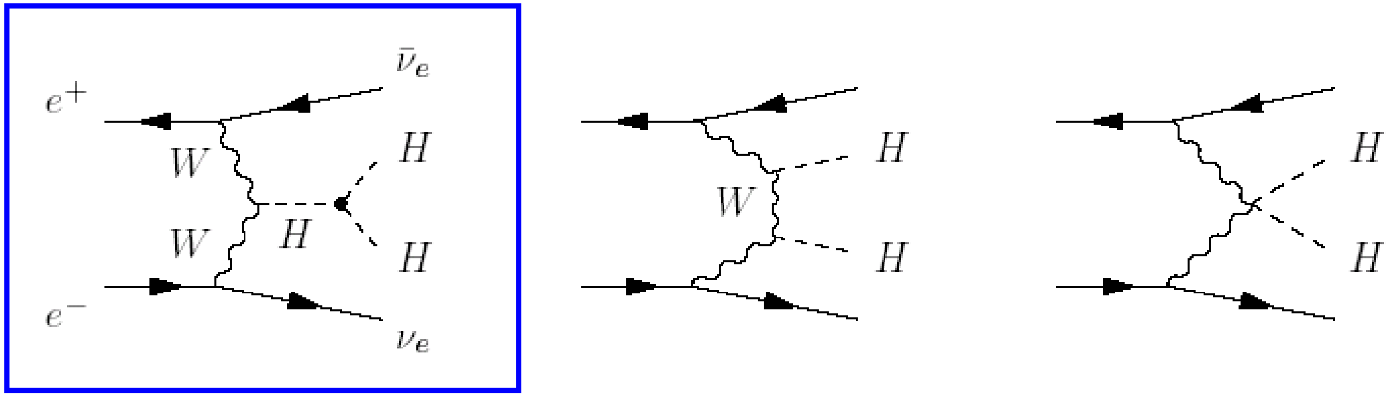


Parton level calculation
e- beams assumed polarized

HHZ mode dominant at
500 GeV
HH$\nu\nu$ mode dominant
at high beam energies

Promising sensitivity

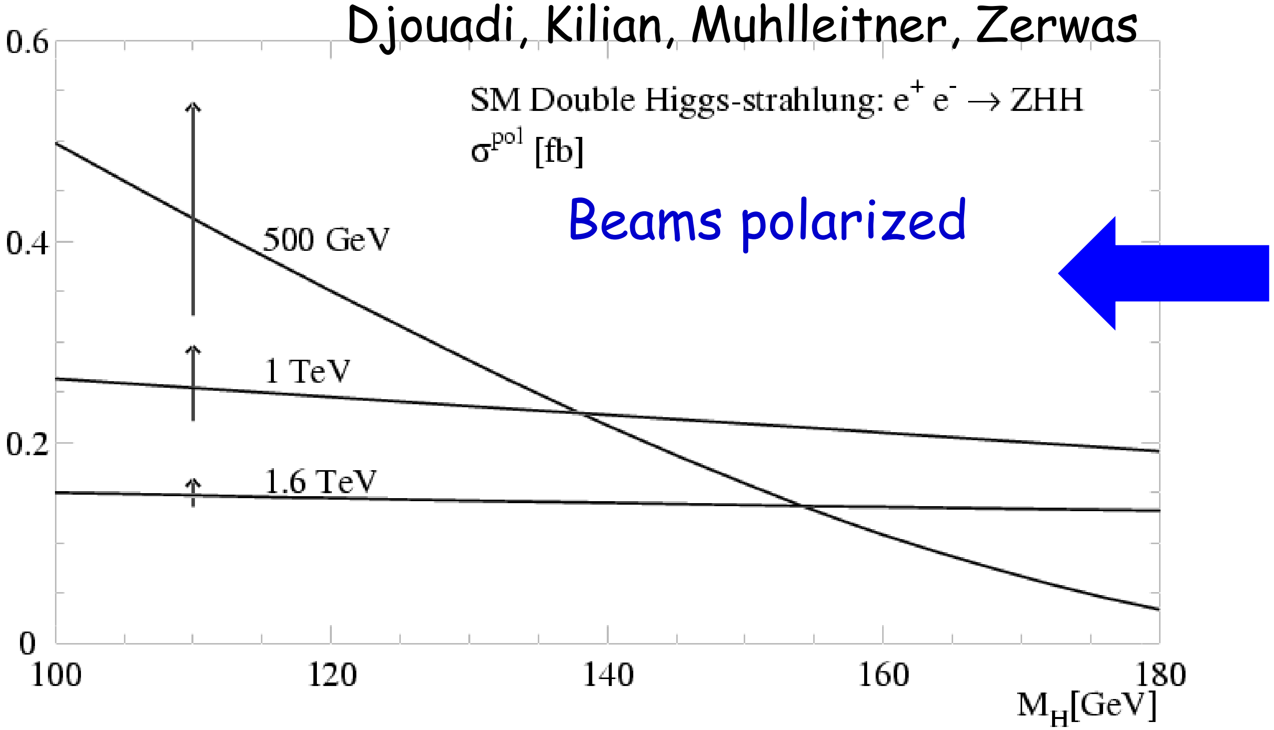
e+e-→ZHH



Only first diagram sensitive to λ_{HHH}

Other diagrams dilute the sensitivity

Djouadi, Kilian, Muhlleitner, Zerwas

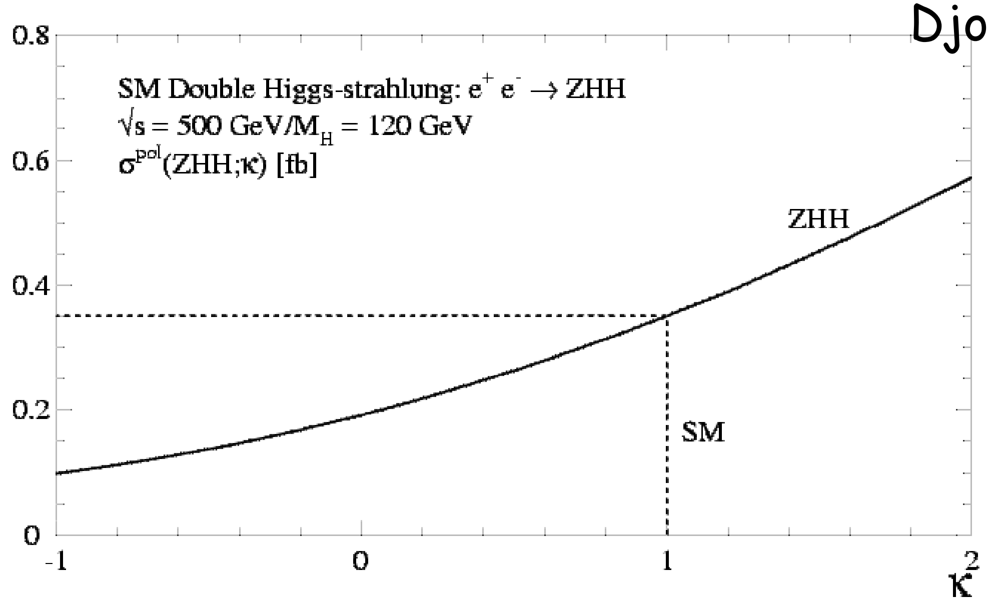


Cross sections for three collider energies. Small!

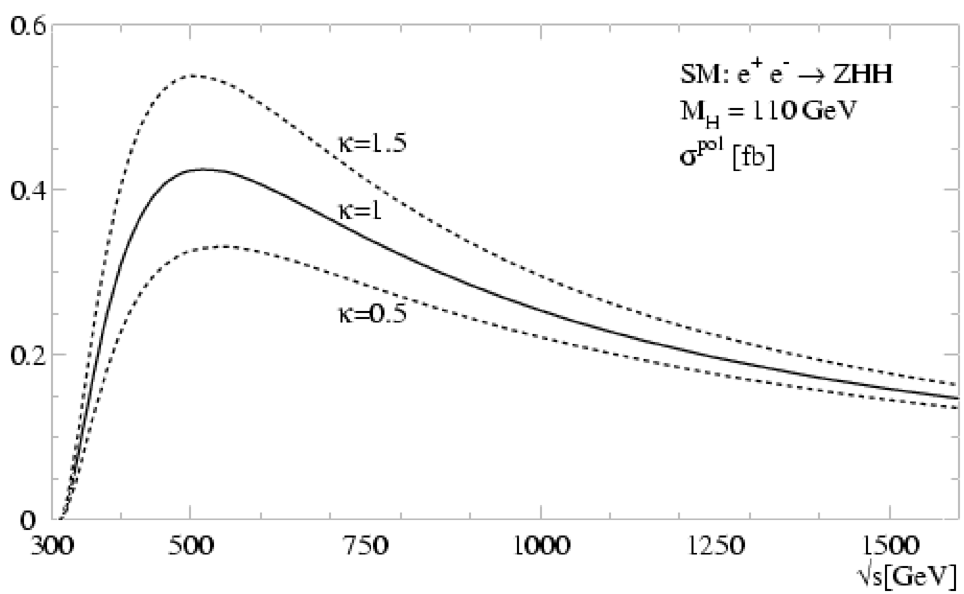
Arrows show variation of λ_{HHH} from 1/2 to 3/2 the SM value

e+e-→ZHH

Djouadi, Kilian, Muhlleitner, Zerwas



Variation of the cross section with the modified trilinear coupling $\kappa\lambda_{HHH}$



Energy dependence for a fixed Higgs mass with a modified trilinear coupling $\kappa\lambda_{HHH}$

Results: e+e-→ZHH @ 500 GeV

Castanier, Gay, Lutz, Oloff

$hhZ \rightarrow b\bar{b}b\bar{b}\ell^+\ell^-$ $hhZ \rightarrow b\bar{b}b\bar{b}q\bar{q}$ Final states

- Detector simulation (SIMDET fast simulation/TESLA Detector)
- 2 b-quarks identified/Neural Network
- Backgrounds (WW,Zγ,ZZ,WWZ,ZZZ,ttH,hZ…)

m_h(GeV/c^2)	σ_{hhZ}(fb)	N^{500}_{hhZ}	ϵ_{hhZ}	$\Delta\sigma/\sigma$		
				$\mathcal{L}$= 500fb^{-1}	1000fb^{-1}	2000fb^{-1}
120	0.186	93.	43%	24.1%	17.3%	11.6%
130	0.149	74.	43%	26.6%	19%	17.7%
140	0.115	57.	39%	32%	23%	17%

selection	variable	$\Delta\lambda/\lambda$		
		$\mathcal{L}$= 500fb^{-1}	1000fb^{-1}	2000fb^{-1}
B	$\mathcal{B}^{recoil}$	42.2%	30.3%	20.3 %
D	NN output	35.7%	22.6%	18.0%

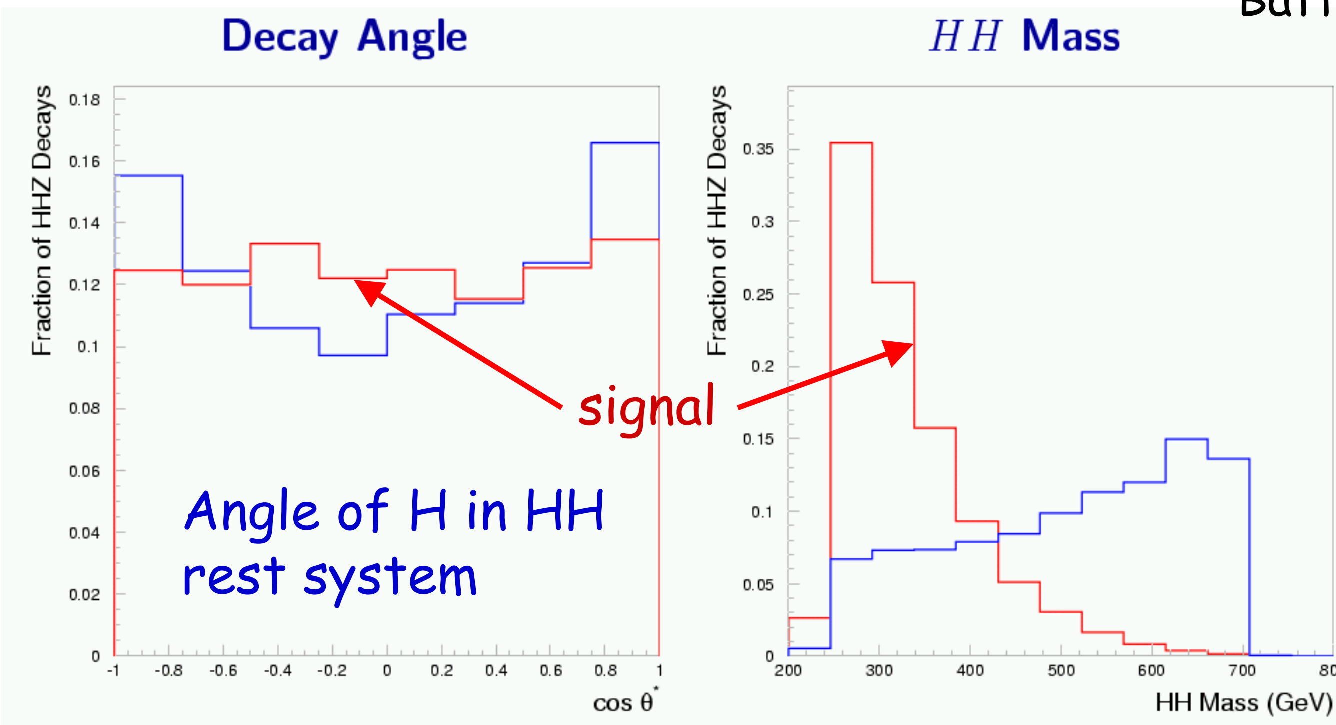
S/√B=4.2

23% (40%) Precision for 1 ab^{-1} at 500GeV for m_H=120(140) GeV

Results: e+e-→ZHH @ 500 GeV

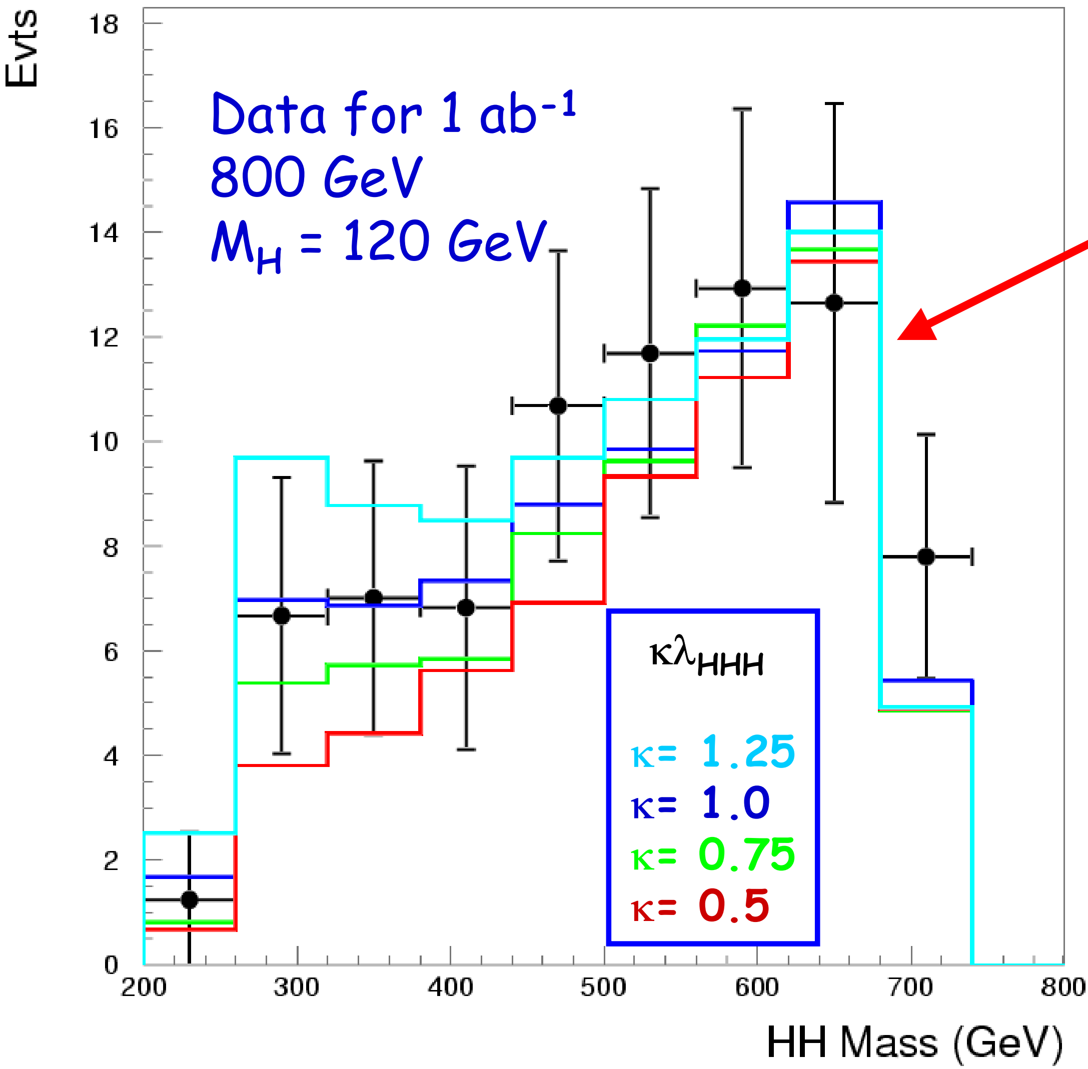
Additional diagrams dilute the λ_{HHH} sensitivity of the σ(e+e-→HHZ) measurement:
Try to exploit the scalar decay and phase space properties to enhance sensitivity to the HHH vertex contribution

Battaglia, Boos, Yao



Use in likelihood fit…

Results: e+e-→ZHH @ 500 GeV



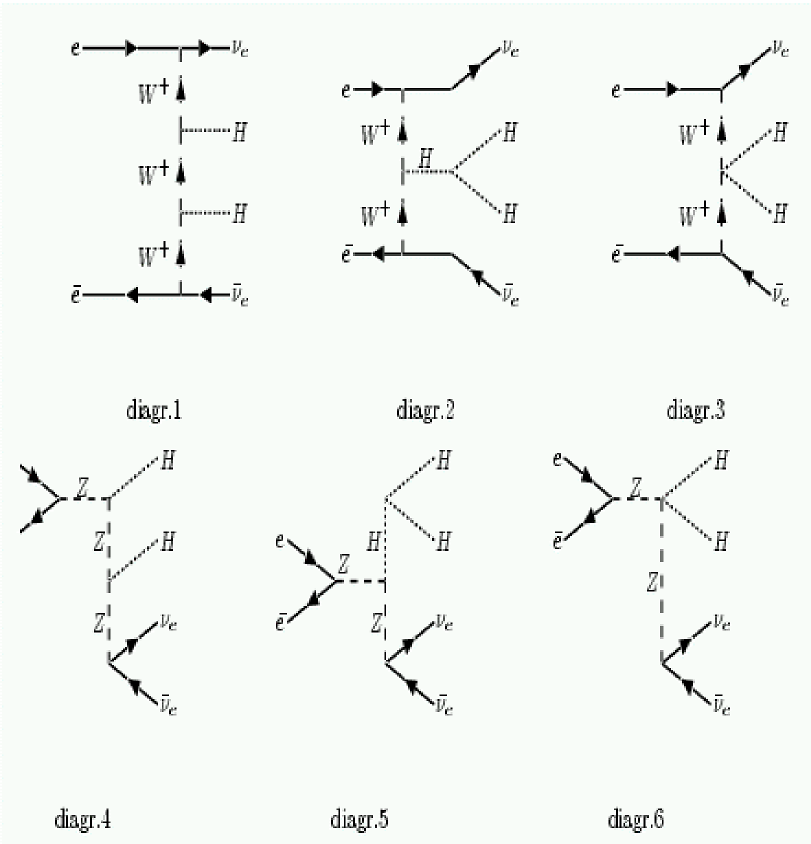
Results including a χ^2 fit to the M_{HH} distribution

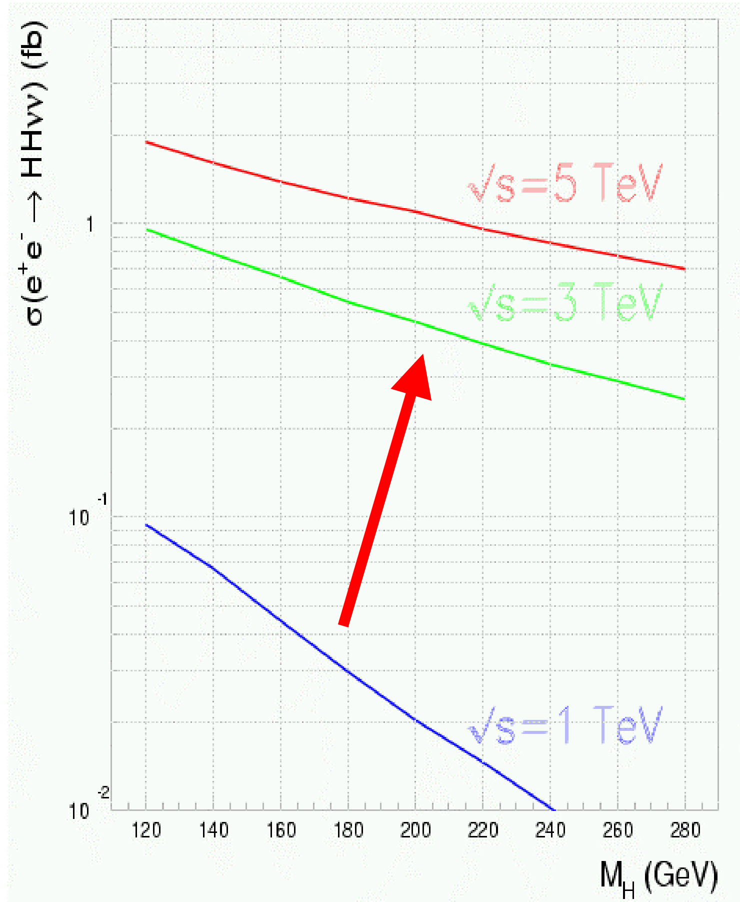
$\sqrt{s}$ (TeV)	σ_{HHZ} Only	M_{HH} Fit
0.5	± 0.23 (stat)	± 0.20 (stat)
0.8	± 0.35 (stat)	± 0.29 (stat)

20% precision for 1 ab^{-1} at 500 GeV
⇒Improvement O(15%)

e+e- $\rightarrow HH\nu\nu$

Higher energies: $HH\nu\nu$ significantly larger cross section than HHZ





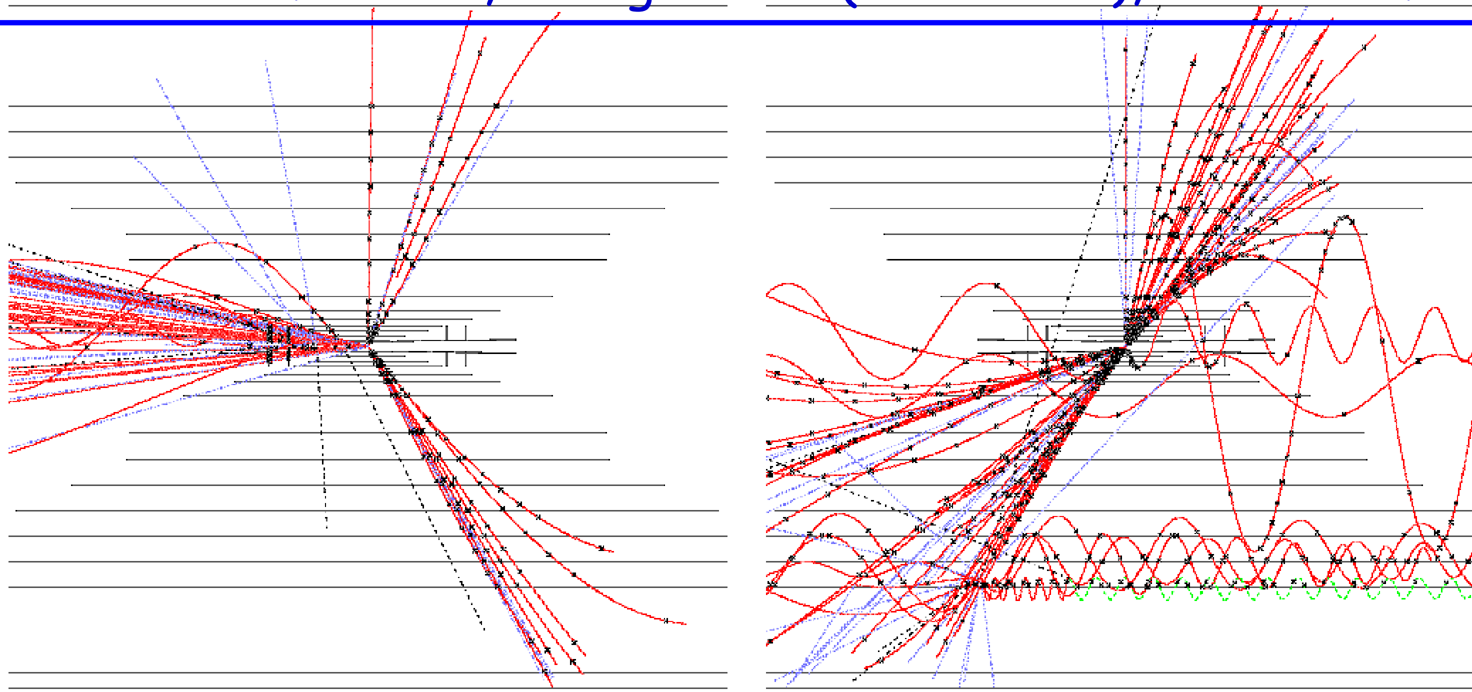
Study: $HH \rightarrow b\bar{b}b\bar{b},\ W^+W^-W^+W^-$

e+e- →HHνν (3 TeV)

Battaglia, Boos, Yao, ADR

$$e^+e^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}\ \ b\bar{b}\ +\ \ E_{missing}$$

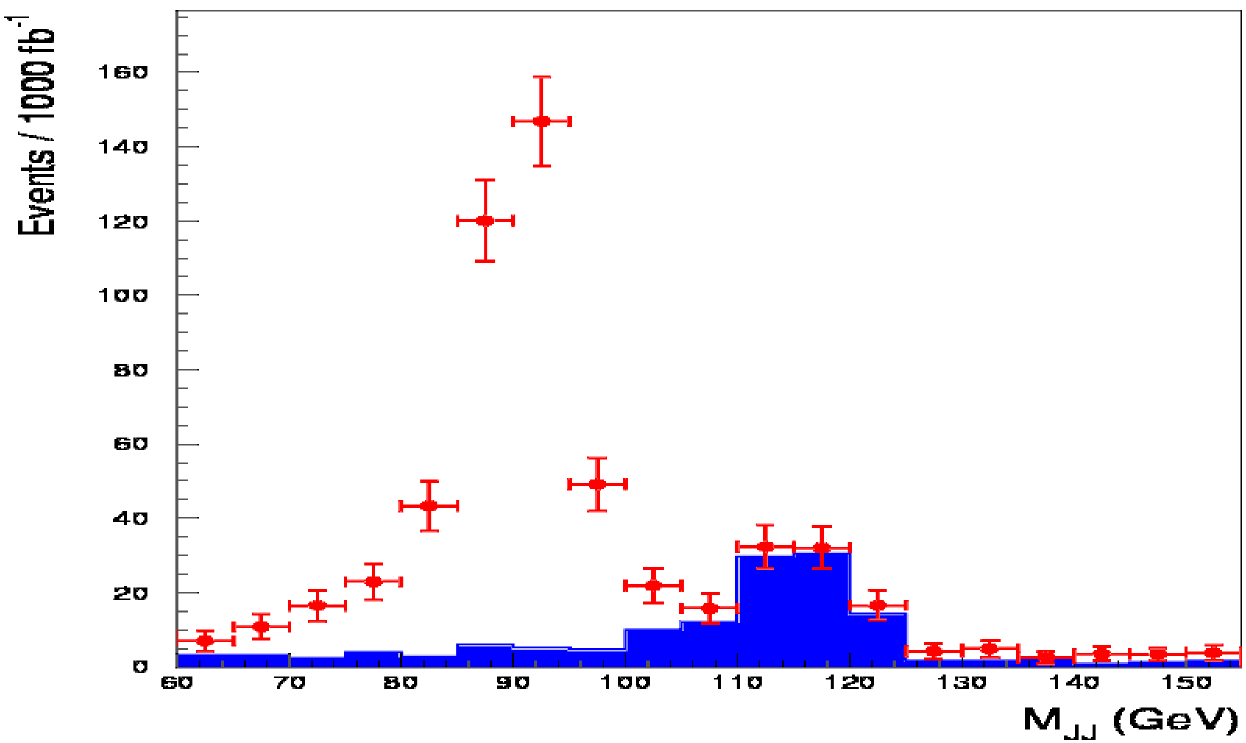
Include detector simulation, backgrounds (COMPHEP), CLIC beam spectra…



Experimental challenge: Higgses often forward!
Require 4B's or 4W's

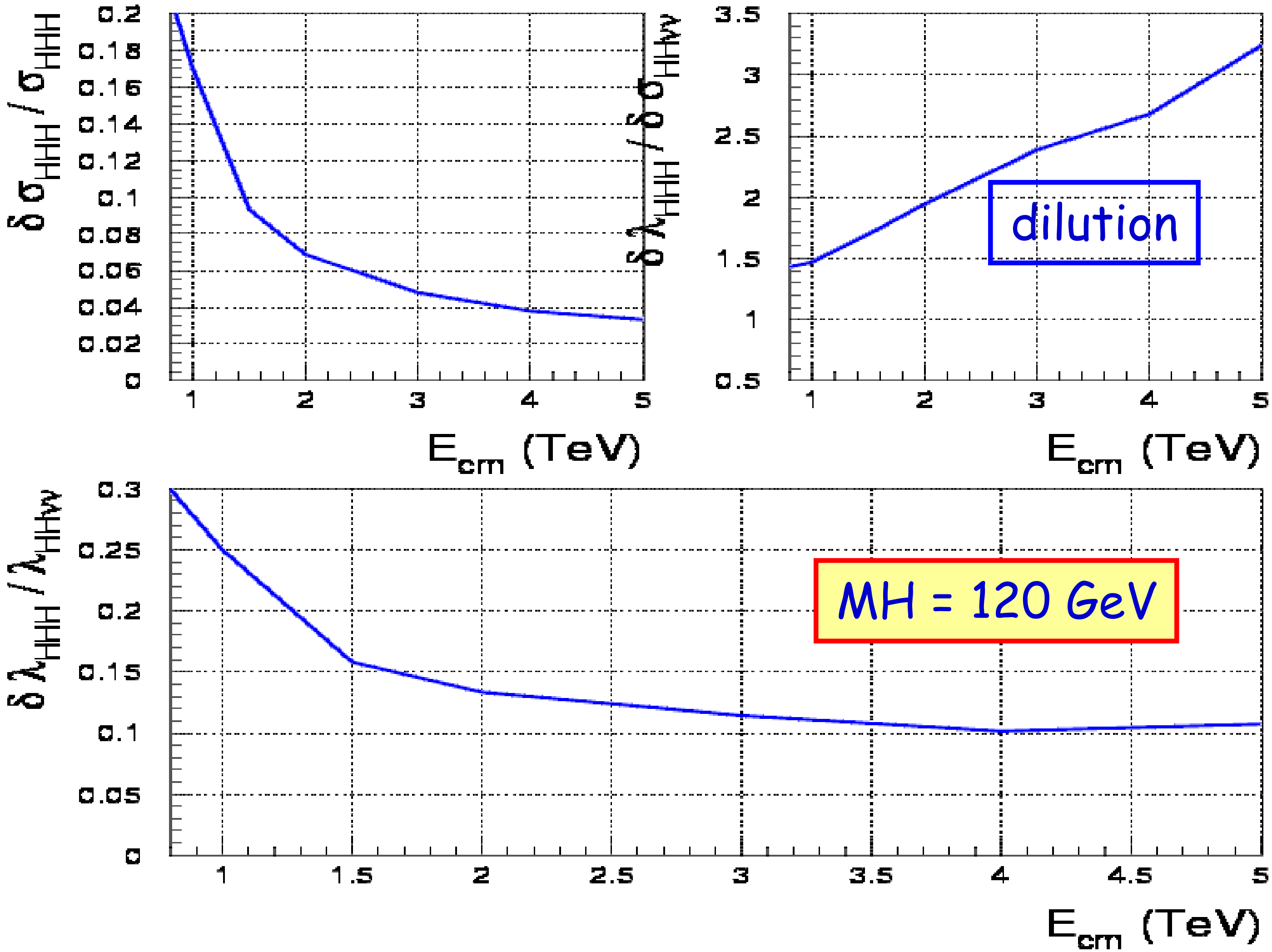
$e^+e^- \to HH\nu\nu \to bbbb\nu\nu$

Select b-tagged events with significant missing ET, force 4-jets
Studies include detector simulation, backgrounds…



$$\frac{\delta\sigma_{HH\nu\nu}}{\sigma_{HH\nu\nu}} \simeq 0.12\ \mathrm{ab}^{-1}$$

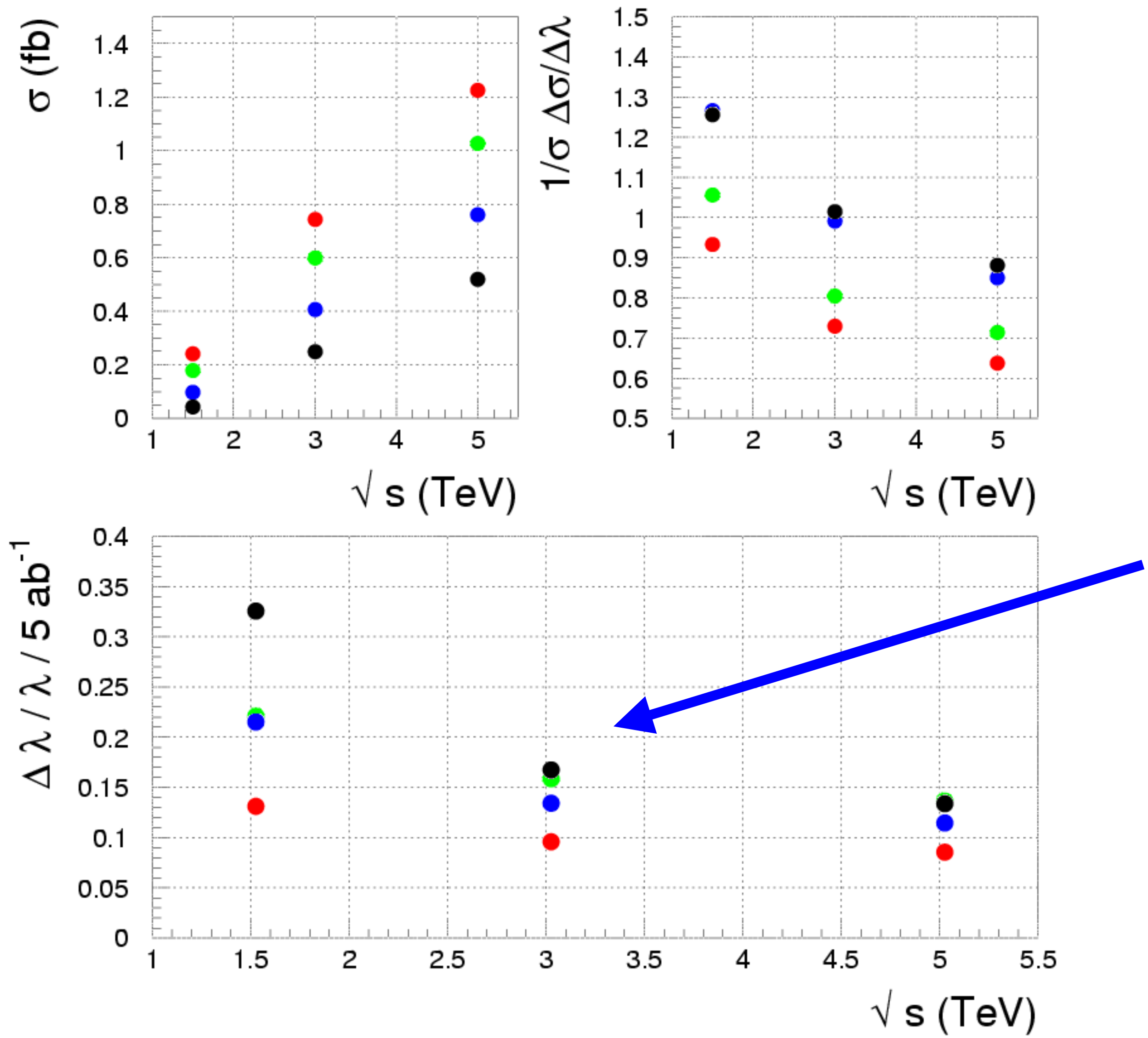
Results: e+e- →HHνν



12% precision for 3 ab^{-1} at 3 TeV

Results: e+e- →HHνν

New



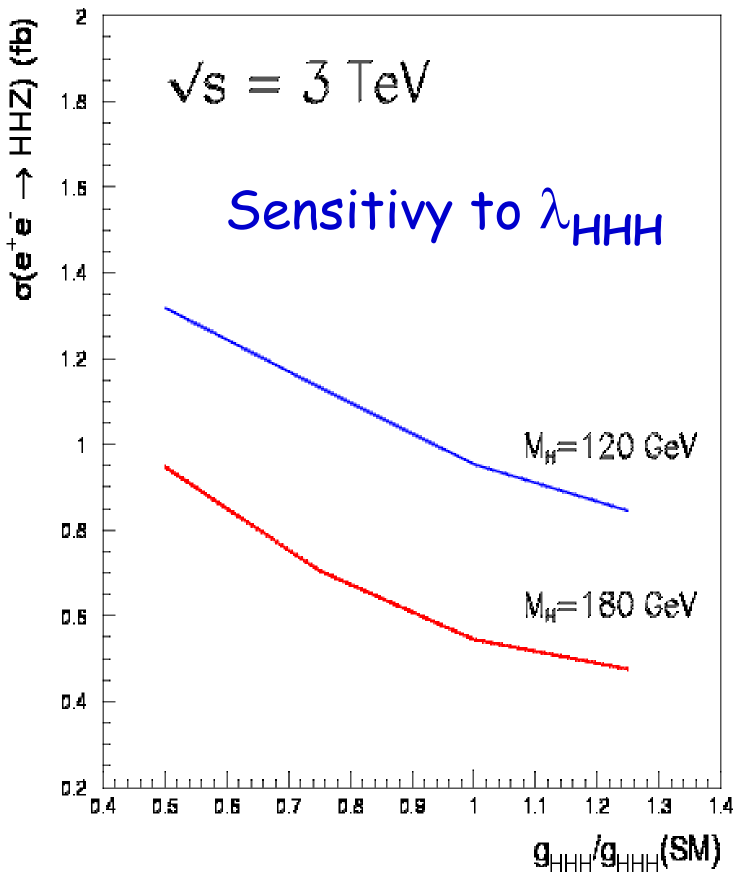
Precision on λ_{HHH} for Higgs masses in the range

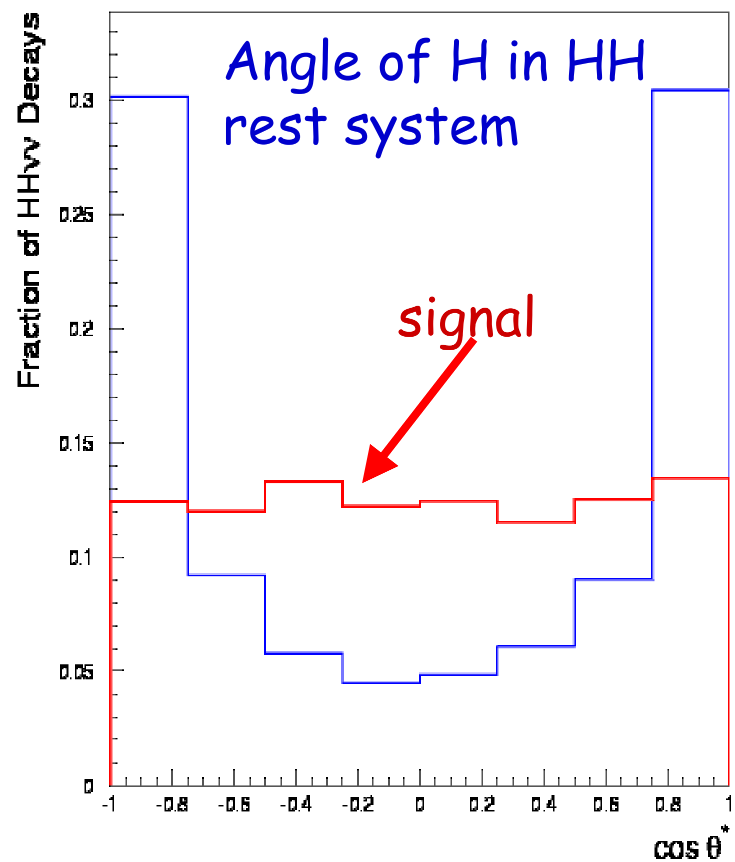
- m_H = 120 GeV
- m_H = 140 GeV
- m_H = 180 GeV
- m_H = 240 GeV

For 5 ab^{-1} of data

Results: e+e- $\rightarrow$HH$\nu\nu$

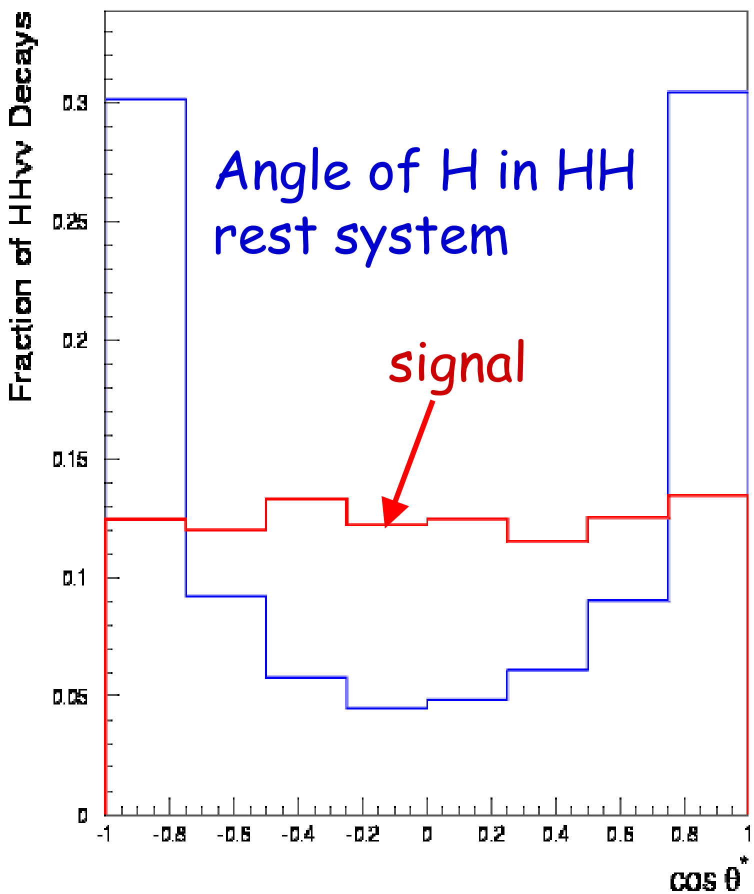
Improve further the results by using the scalar nature of the Higgs

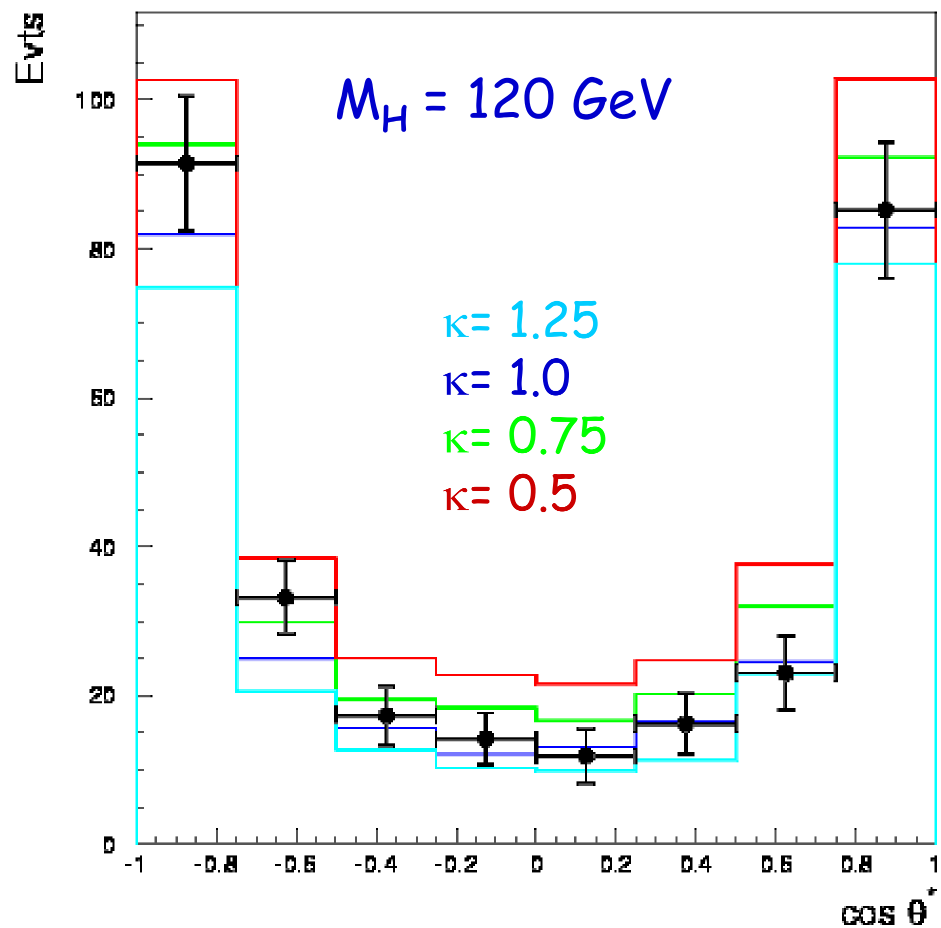




Results: e+e- →HHνν

Improve the results further by using the scalar nature of the Higgs





Fit to the cross sections and the normalized shape of the |cosθ| distribution

Results: e+e- $\rightarrow HH\nu\nu$

Results for 3 TeV and 5 ab^{-1}

M_H (GeV)	$\sigma_{HH\nu\bar{\nu}}$ Only	$\lvert\cos\theta^*\rvert$ Fit
120	$\pm$ 0.094 (stat)	$\pm$ 0.070 (stat)
180	$\pm$ 0.140 (stat)	$\pm$ 0.080 (stat)

Including a fit to the cosθ distribution improves the results with 25-30%
Further improvement using polarized beams is possible (x ~1.5)

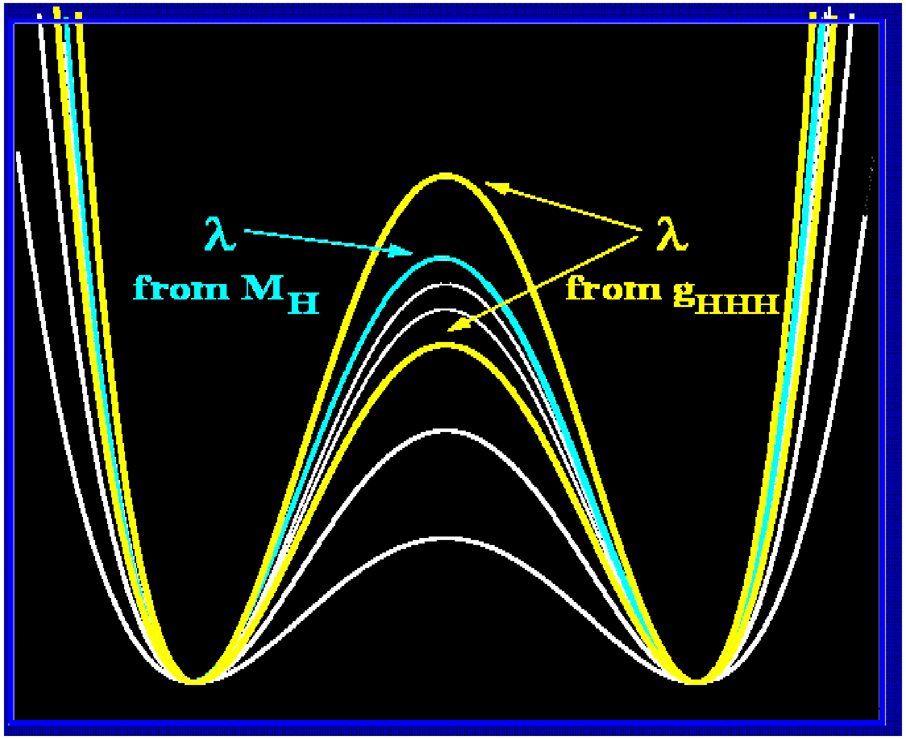
The quartic couplings will remain elusive:
The table below gives the cross section in atobarns
I.e. one expects 1-2 (5) events/year for CLIC at 5 (10) TeV

$\sqrt{s}$	$g_{HHHH}/g_{HHHH}^{SM} = 0.9$	$g_{HHHH}/g_{HHHH}^{SM} = 1.0$	$g_{HHHH}/g_{HHHH}^{SM} = 1.1$
3 TeV	0.400	0.390	0.383
5 TeV	1.385	1.357	1.321
10 TeV	4.999	4.972	4.970

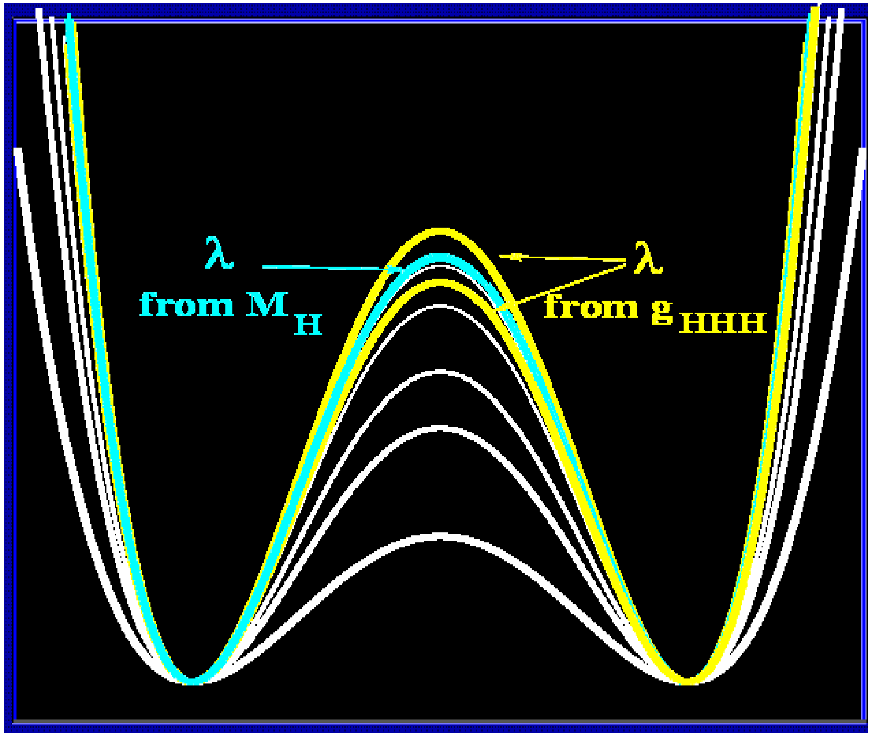
The Higgs potential

"Visual example": compare measurement from Higgs mass with results from λ_{HHH} measurements

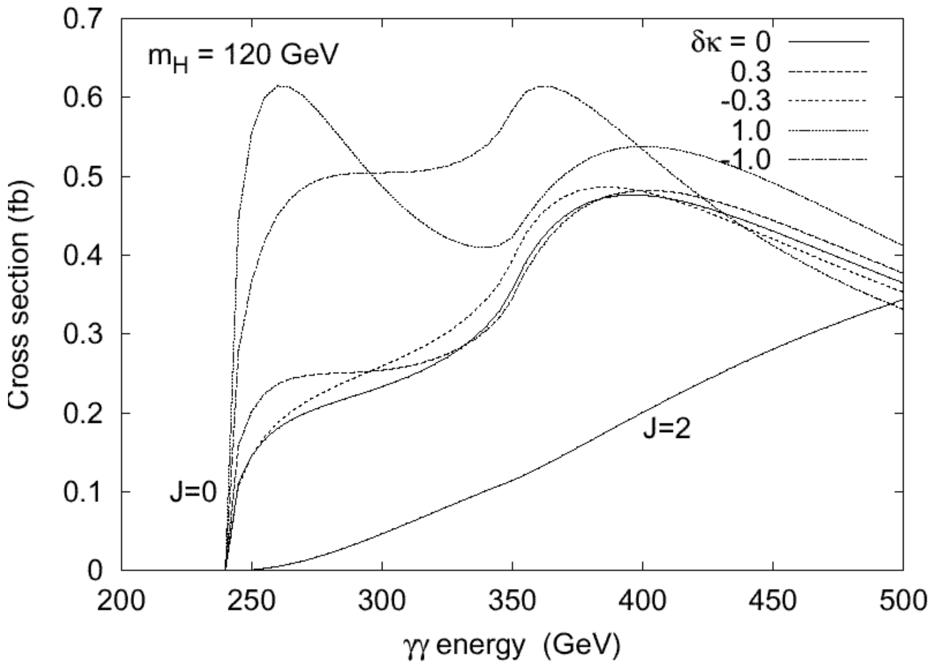
For 500 GeV e+e-



For 3 TeV e+e-



Photon Collider



D. Asner et al.

$$\delta\mathcal{L}_{\rm Higgs} = -\frac{\delta\kappa}{2}\frac{m_H^2}{v}\left[H^3 + \frac{3}{v}G^+G^-H^2\right] + \cdots,$$

e+e-→HHZ ⇔ γγ→ HH

Event rates similar

Final state cleaner (higher eficiency)?

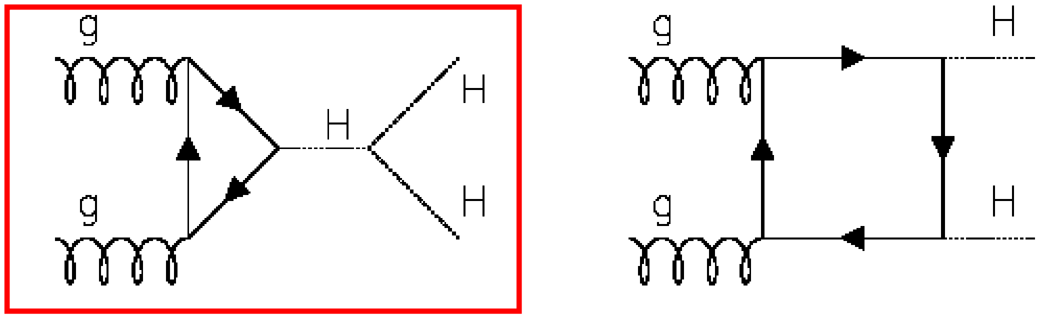
Parton level cross sections

	$\sqrt{s_{ee}} = 500$ GeV			$\sqrt{s_{ee}} = 800$ GeV		
	$\int \mathcal{L}_{th}$ (fb^{-1}/10^7 s)	σ (fb)	Event yield	$\int \mathcal{L}_{th}$ (fb^{-1}/10^7 s)	σ (fb)	Event yield
Spin-0	40	0.3	13	120	0.3	39
Spin-2	20	0.1	1-2	60	0.2	1-2
e^+e^-	160	0.2	32	250	0.15	38

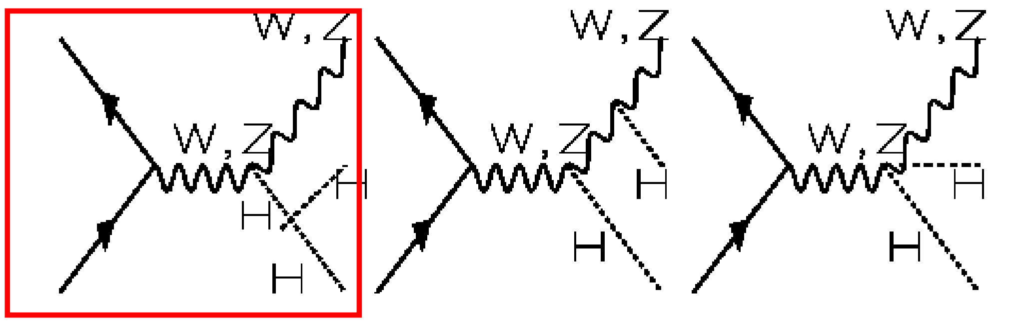
⇒ needs a study of the dilution, backgrounds, detector effects

Hadron Colliders: PP →HHX

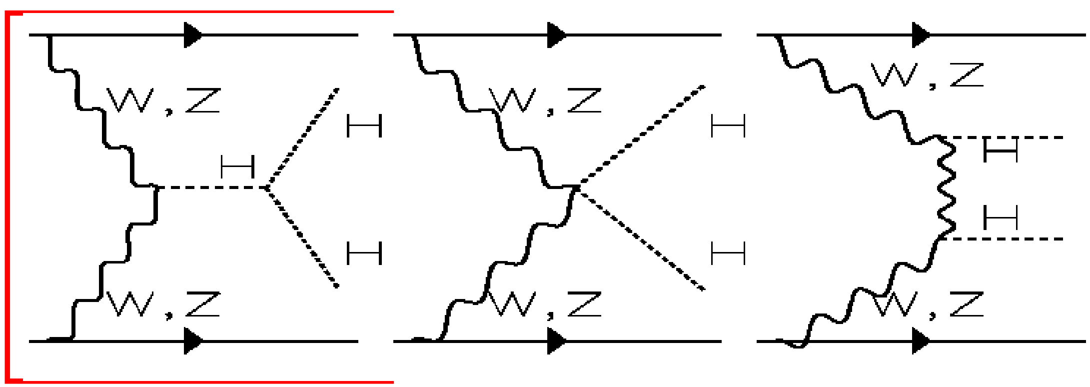
Contributing diagrams



gluon-gluon fusion



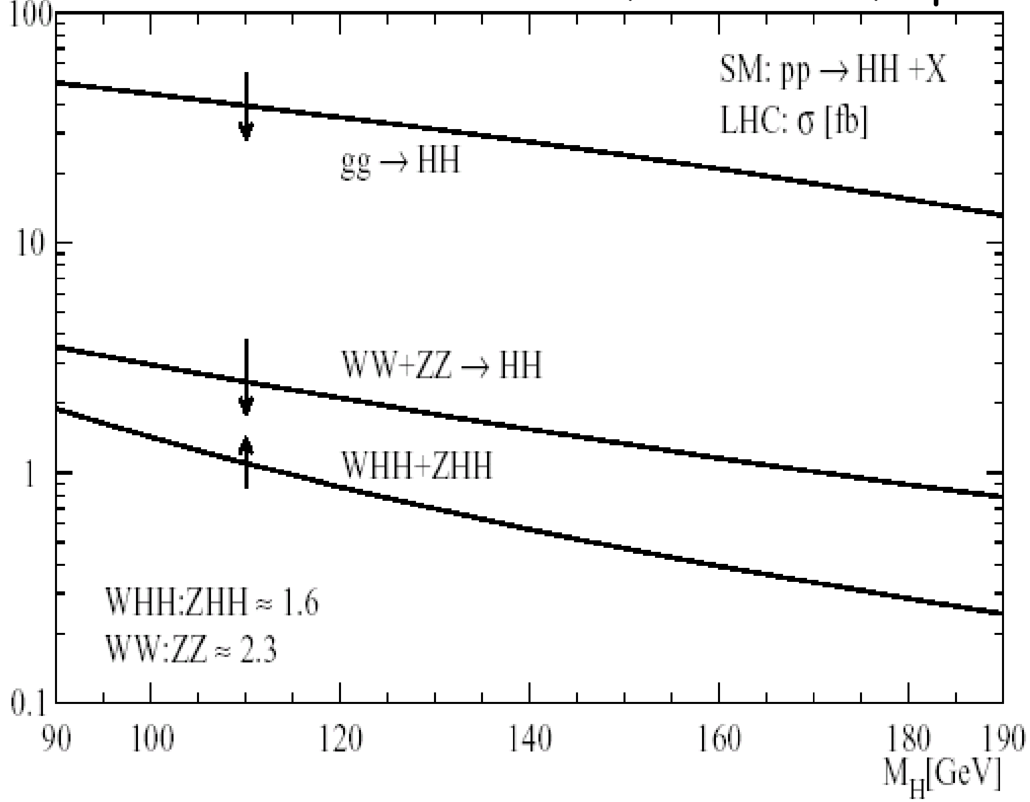
W or Z strahlung



WW and ZZ fusion

PP →HHX

NLO calculations: Dawson, Dittmaier, Spira



Blondel, Clark, Mazzucato (ATLAS)

Cross sections
for three processes
Small!

Arrows show
variation of λ_{HHH}
from 1/2 to 3/2
the SM value

ATLAS Study: study decay modes: H→WW and H→ZZ 150<M_H<200 GeV
LO (!) cross sections. K factor for signal in range 1.5-2
Detector simulation, backgrounds

Results: PP →HHX (LHC)

$pp \to HH \to WWWW \to l\nu qql\nu qq \; (\sigma * BR \simeq 0.24 fb^{-1} \text{ for } m_H = 200 GeV)$

$pp \to HH \to WWWW \to l\nu l\nu qqqq \; (\sigma * BR \simeq 0.12 fb^{-1} \text{ for } m_H = 200 GeV)$

$pp \to HH \to WWWW \to l\nu l\nu l\nu qq \; (\sigma * BR \simeq 0.072 fb^{-1} \text{ for } m_H = 200 GeV)$

$pp \to HH \to WWWW \to l\nu l\nu l\nu l\nu \; (\sigma * BR \simeq 0.006 fb^{-1} \text{ for } m_H = 200 GeV)$

$pp \to HH \to WWZZ \to qqqqllqq \; (\sigma * BR \simeq 0.09 fb^{-1} \text{ for } m_H = 200 GeV)$

$pp \to HH \to WWZZ \to l\nu qqllqq \; (\sigma * BR \simeq 0.055 fb^{-1} \text{ for } m_H = 200 GeV)$

Channels studied

600 fb^{-1}

	$l\nu qql\nu qq$	$l\nu qql\nu qq$	$l\nu l\nu l\nu qq$	$l\nu l\nu l\nu l\nu$	$llqqqqqq$	$l\nu qqllqq$
HH $m_H = 200$ GeV	22	58	5.8	1.	16	6.0
$t\bar{t}$	9	33678	79.	15.	665	17
WW	0	122	0.	0.	0	0
ZZ	0	1240	0.3	0	288	1.8
WZ	6	10	16.0	0	0	33.7
WWW all processes	150	-	-	-	-	-
WH only	37	183	7.1	1.9	50	12.4
ZH	6	322	14.1	11.	98	33.2
Wtt	159	0	0.	0	0	0
$Zb\bar{b}$	0	104	0.	0	28	0
$t\bar{t}t\bar{t}$	3	-	-	-	-	-
Total B	333	35659	117.	27.9	1129	98.4
S/B	0.07	$2 * 10^{-3}$	0.05	0.04	0.01	0.06
$S/\sqrt{B}$	1.2	0.3	0.53	0.19	0.5	0.61

Pretty hopeless for LHC…

Results: PP →HHX (SLHC)

For SLHC (6000 fb^{-1}) λ_{HHH} becomes accessible!

	$lvqqlvqq$	$lvqqlvqq$	$lvlvlvqq$	$lvlvlvlv$	$llqqqqqq$	$lvqqllqq$
HH $m_H = 200$ GeV	220	580	58	11.	160	60
$t\bar{t}$	90	336780	790.	150.	6650	170
WW	0	1225	0.	0.	0	0
ZZ	0	12404	3.5	0	2883	17
WZ	60	971	160	0	0	337
WH	374	1831	71	19	505	124
WWW	1500	-	-	-	-	-
ZH	59	3223	141	111.	977	332
Wtt	1594	0	3	0	0	0
$Zb\bar{b}$	0	1045	0.	0	285	0
$t\bar{t}t\bar{t}$	30	-	-	-	-	-
Total B	3333	356595	1169	279	11300	984
S/B	0.07	$2 * 10^{-3}$	0.05	0.04	0.01	0.06
$S/\sqrt{B}$	3.1	1.	1.7	0.7	1.5	1.9

Mass (GeV)	200	200 (fit)	170
$\frac{d\sigma}{\sigma}$	27%	17%	20%
$\frac{d\lambda}{\lambda}$	25%	15%	19%

Results: PP $\rightarrow$HHX

Baur, Plehn, Rainwater

- Studied signals at LHC, SLHC and VLHC (and LC),
- No detector simulation, but acceptance cuts, efficiencies
- NLO through K-factors
- Use minimum jet distance and M_{vis} quantities to improve S/B

For $M_H > 150$, examine $4W \rightarrow$ multipleptons.

$\ell^{\pm}\ell^{\pm} + 4j \quad , \qquad \ell^{\pm}\ell^{\pm}\ell^{\mp} + 2j$

$\rightarrow$ LHC can confirm $\lambda \neq 0$ (3-pt. Higgs coupling)

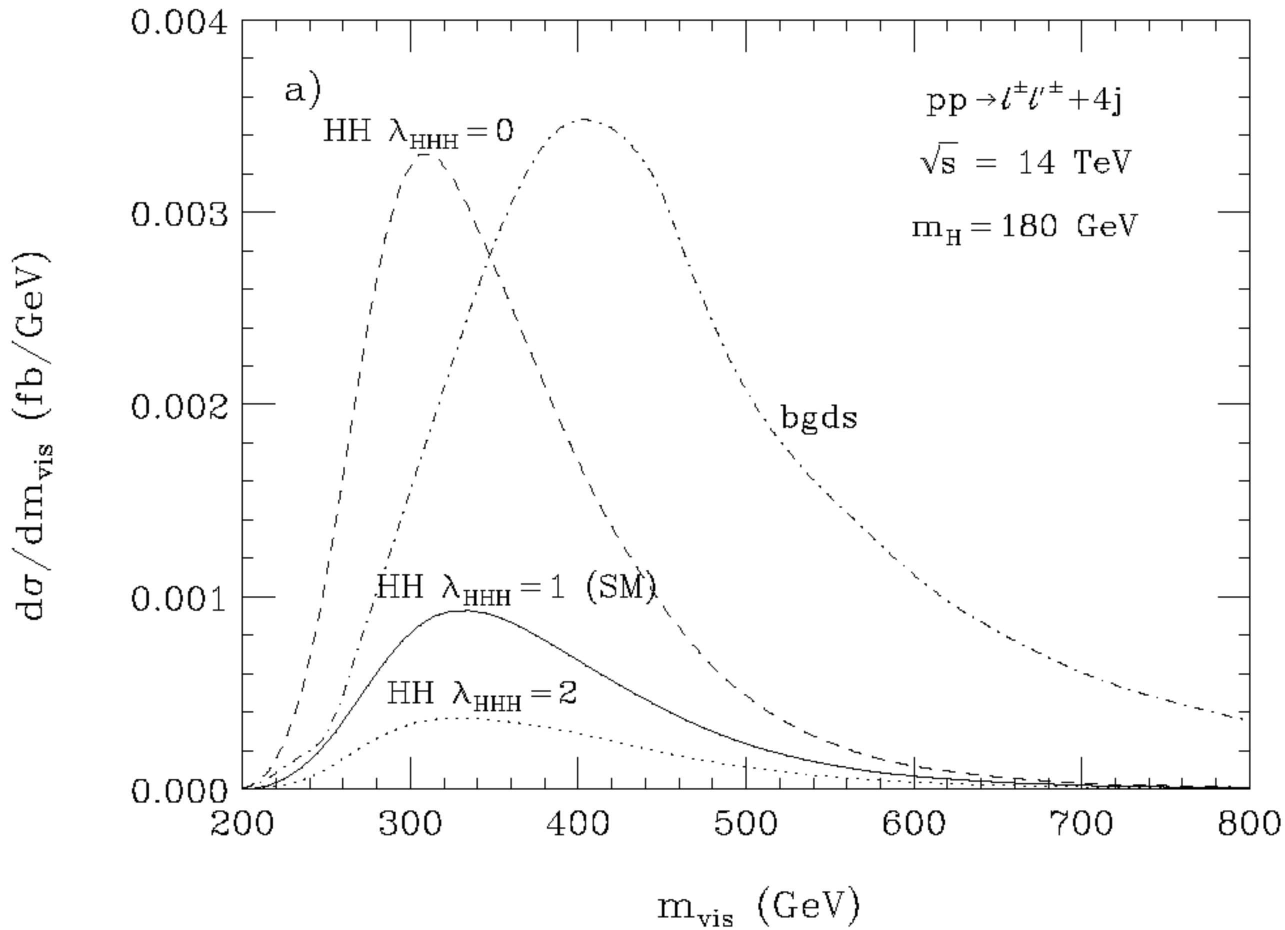
for $150 < M_H < 200$ GeV.

For $M_H < 150$, look for $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$.

$\rightarrow$ totally hopeless at LHC, SLHC,

1st measurement at VLHC if no TESLA.

Results: PP →HHX



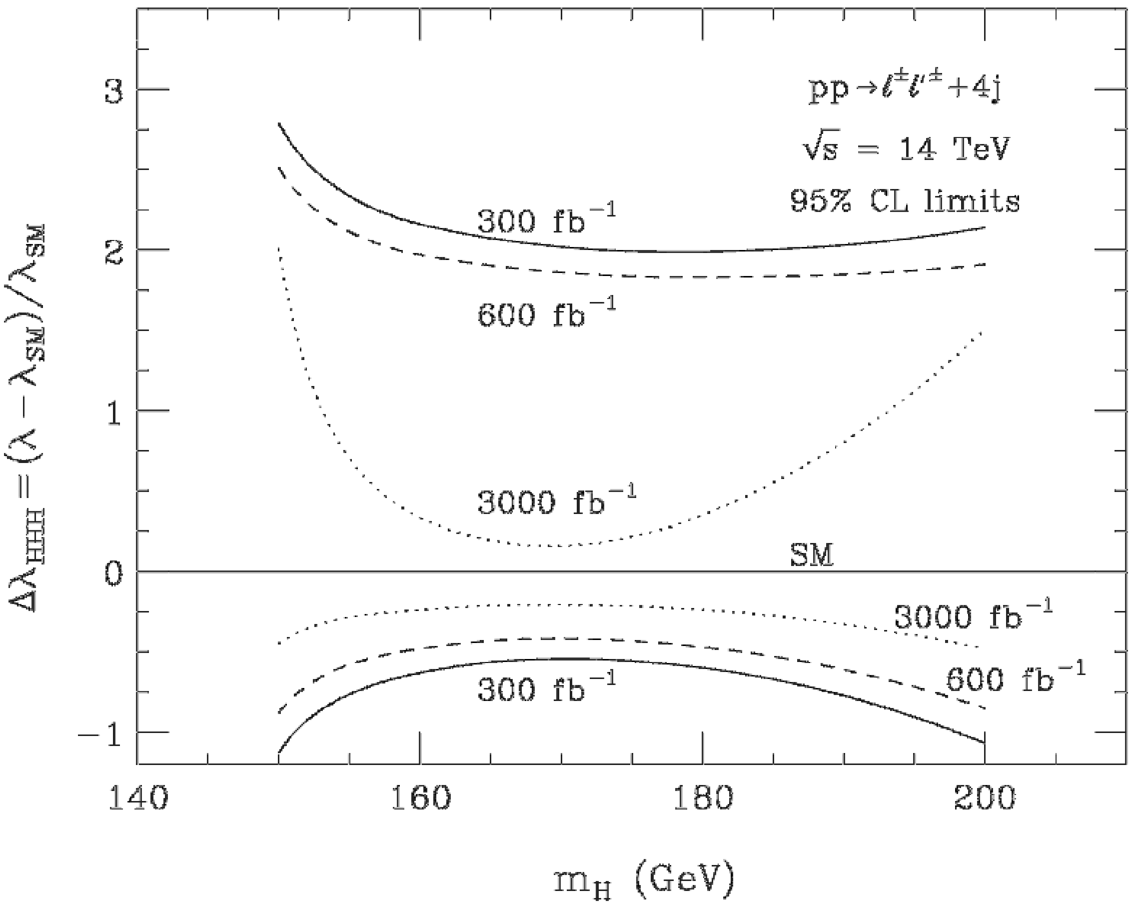
$$m_{vis}^2 = \left[\sum_{i=\ell,\ell',\mathrm{jets}} E_i\right]^2 - \left[\sum_{i=\ell,\ell',\mathrm{jets}} \mathbf{p}_i\right]^2$$

Shape of the M_{vis} distribution used to derive sensitivity bounds

Results: $PP \rightarrow HHX$

Baur, Plehn, Rainwater

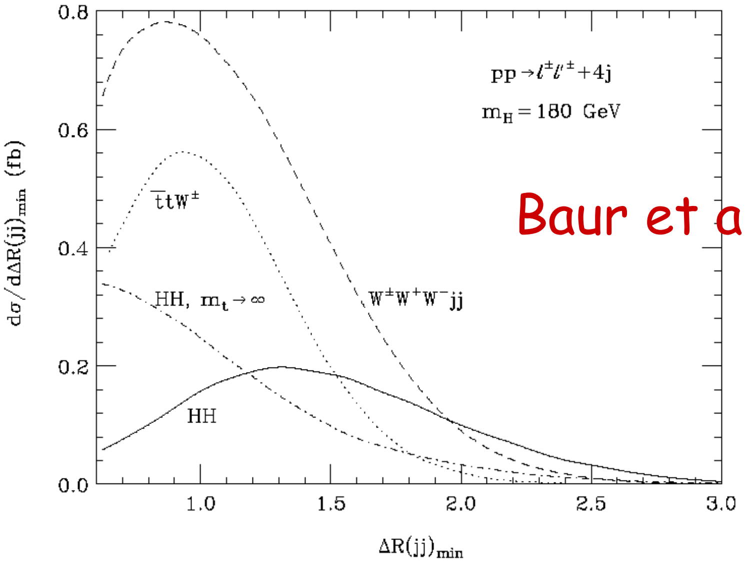
Limits achievable at the 95% CL. for $\Delta\lambda=(\lambda-\lambda_{SM})/\lambda_{SM}$

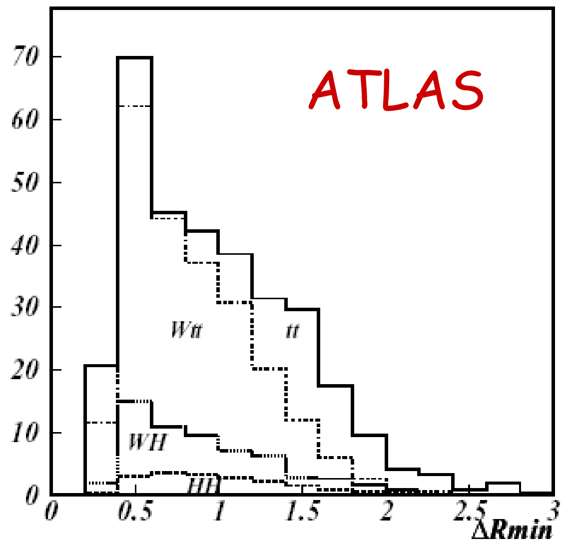


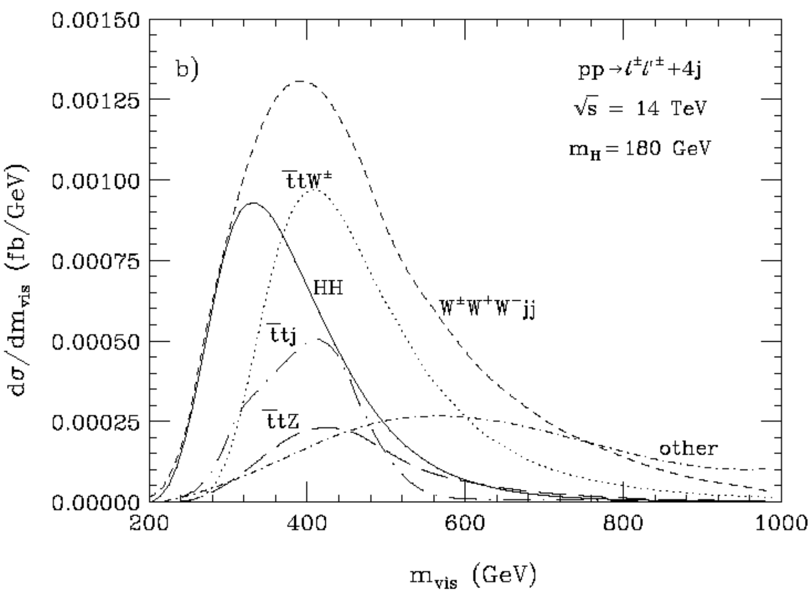
λ= 0 can be excluded at 95% CL.

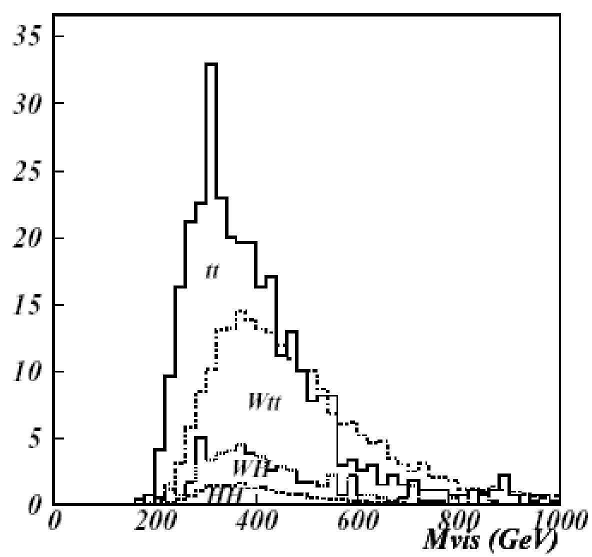
λ can be determined to 20-30% with SLHC

PP →HHX









Possible reasons for differences

Parton level ⇔ Detector Level

ATLAS includes parton showers

HO effects

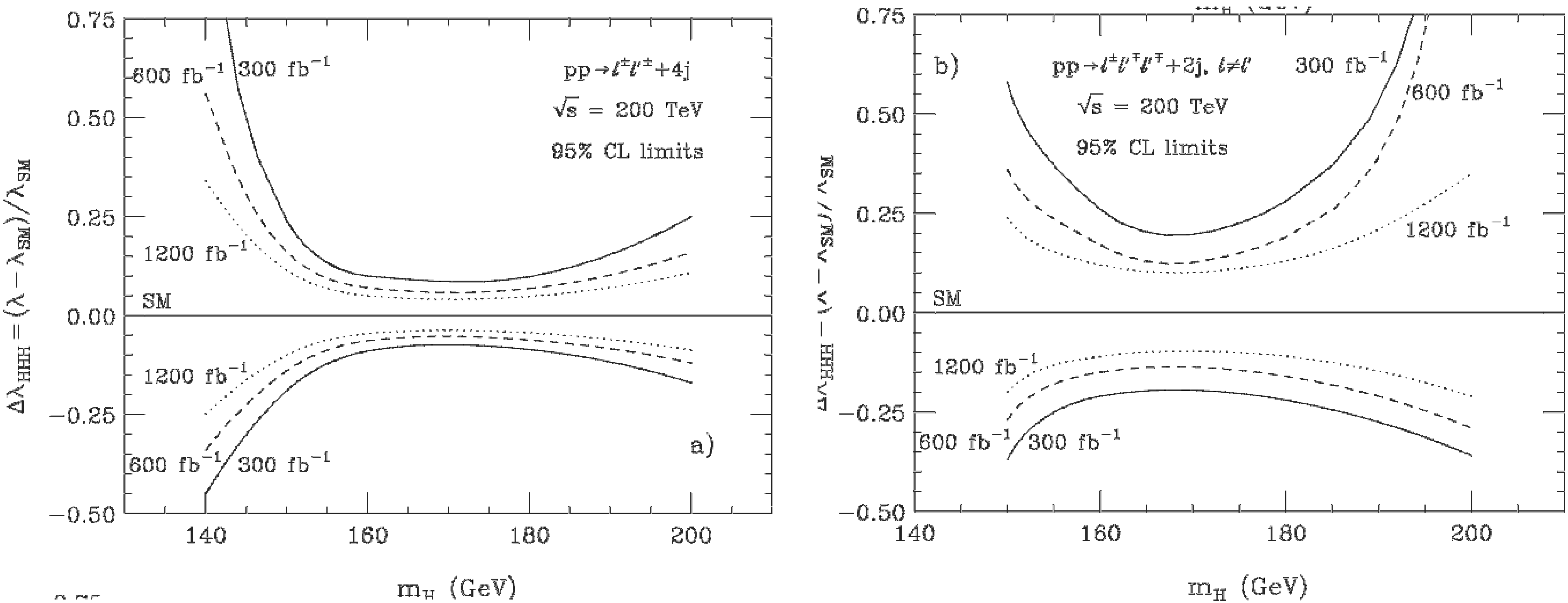
Incorrect simulation ttj of background (ATLAS)? (D.R.)

Jury still out…
CMS starting

Results: PP →HHX (VLHC)

Baur, Plehn, Rainwater

VLHC √s=200 GeV



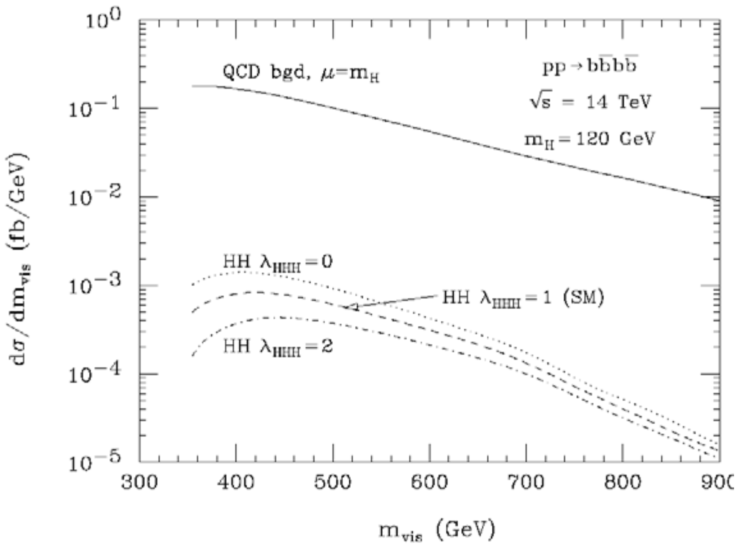
Can reach an accuracy of 8-30% (95% CL) for M_H 140-200 GeV

Lower M_H at pp colliders?

$HH \to 4b$ AT LHC

What about $HH \to b\bar{b}b\bar{b}$ for lower M_H @ LHC?

Unfortunately, QCD $b\bar{b}b\bar{b}$ is factor 1000 larger...



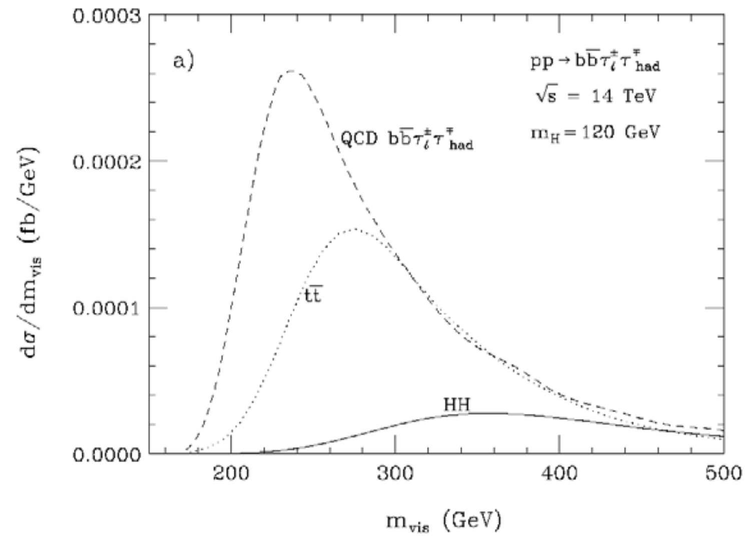
$M_H = 120$ GeV, ϵ_{ID} and QCD bkg
(in terms of λ_{SM}):

lumi	1σ upper	1σ lower
LHC, 300 fb^{-1}	+10	-7
SLHC, 3000 fb^{-1}	+ 6	-3

Difficult…

$HH \to b\bar{b}\tau^+\tau^-$ AT LHC

What about $HH \to b\bar{b}\tau^+\tau^-$ @ LHC instead?



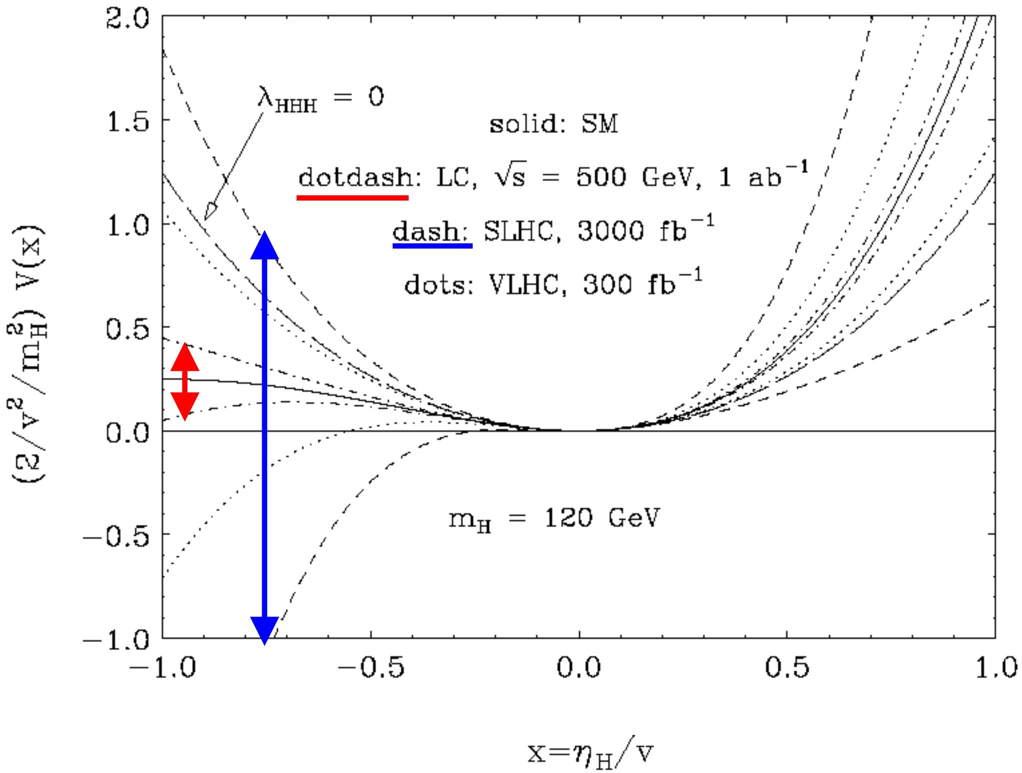
$M_H = 120$ GeV, ϵ_{ID} and QCD $Zb\bar{b}$ bkg
(in terms of λ_{SM}):

lumi	1σ upper	1σ lower
SLHC, 3000 fb^{-1}	+3.1	-1.6
VLHC, 300 fb^{-1}	+1.0	-0.86

Pretty grim, unless no TESLA...

Comparison for M_H=120 GeV

Baur, Plehn, Rainwater



Precise information from a Linear Collider

Hadron colliders can not contribute much (VLHC?)

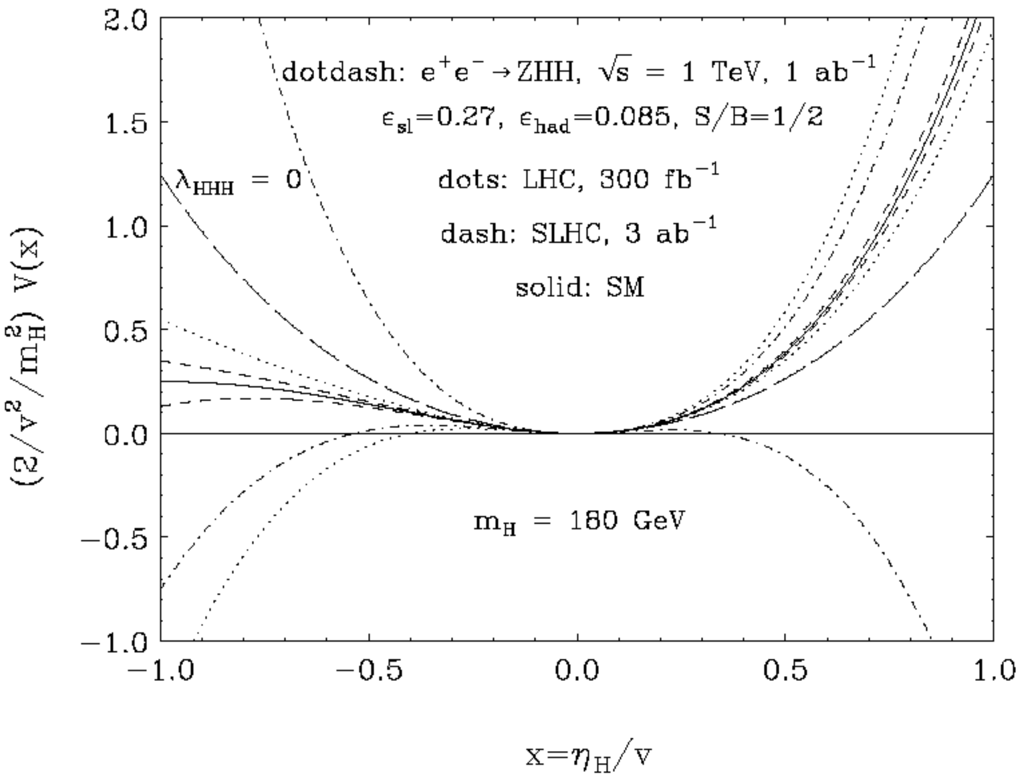
Scaled Higgs potential: $$\frac{2}{v^2 m_H^2} V(x) = x^2 + \lambda_{HHH} x^3 + \frac{1}{4} \tilde{\lambda}_{4H} x^4$$

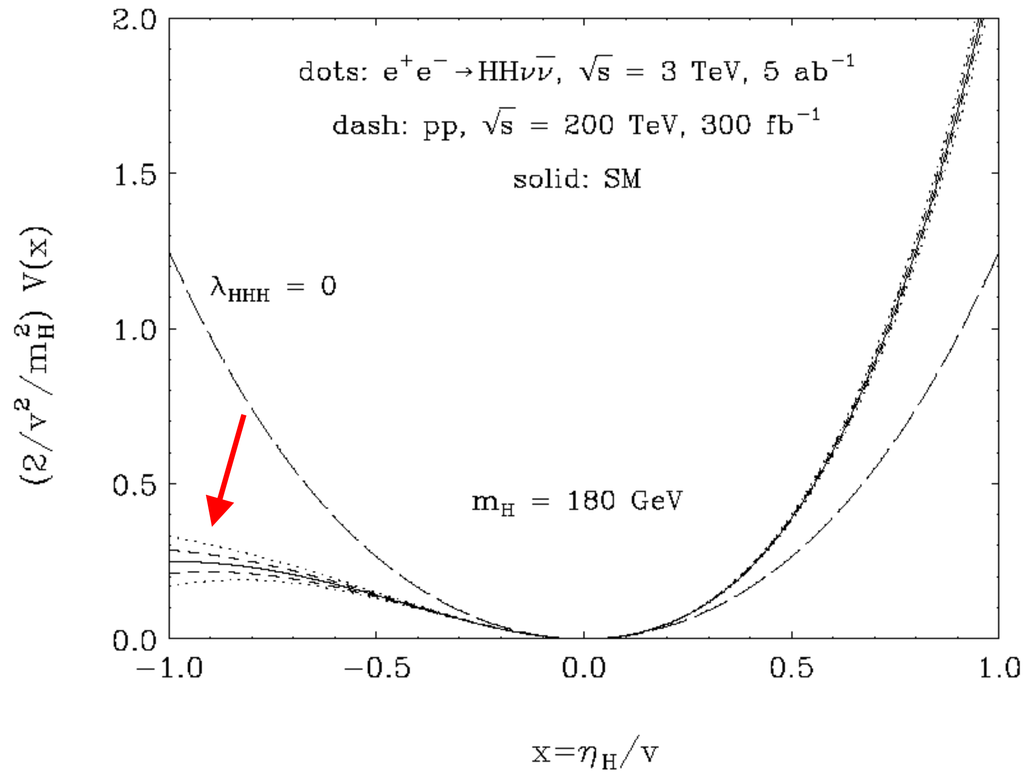
$x = \frac{\eta_H}{v}$ η_H = Higgs field

$\tilde{\lambda}_{4H} = \tilde{\lambda}/\lambda_{SM}$

assume $\tilde{\lambda}_{4H} = 1$

Comparison for M_H=180 GeV

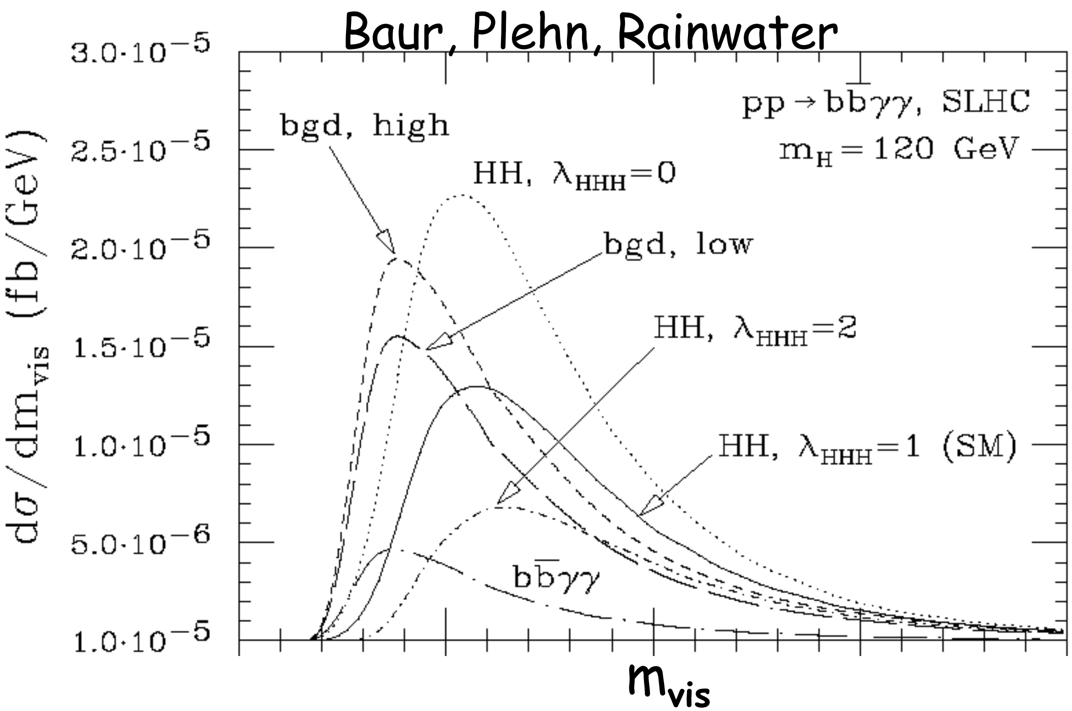




- First hint possible from LHC
- Measurement at SLHC
- LC (<~ 1 TeV) no information

Both Multi-TeV collider and VLHC can provide very precise measurements

pp→bbγγ and pp→bbμμ



pp→bbμμ not useable

pp→bbγγ promising

- Apply photon-photon and photon-b separation cuts
  - For m_H=120 GeV and 600 fb^{-1} expect 6 events at the LHC with S/B~ 2 (single b tag)
- Interesting measurement at the SLHC (double b tag)

	$m_H = 120$ GeV			$m_H = 140$ GeV		
machine	"hi"	"lo"	bkg. sub.	"hi"	"lo"	bkg. sub.
LHC, 600 fb^{-1}	$^{+1.9}_{-1.1}$	$^{+1.6}_{-1.1}$	$^{+0.94}_{-0.74}$	–	–	–
SLHC, 6000 fb^{-1}	$^{+0.82}_{-0.66}$	$^{+0.74}_{-0.62}$	$^{+0.52}_{-0.46}$	$^{+1.7}_{-0.9}$	$^{+1.4}_{-0.8}$	$^{+0.76}_{-0.58}$
VLHC, 600 fb^{-1}	$^{+0.44}_{-0.42}$	$^{+0.42}_{-0.40}$	$^{+0.32}_{-0.30}$	$^{+0.82}_{-0.62}$	$^{+0.66}_{-0.54}$	$^{+0.38}_{-0.34}$
VLHC, 1200 fb^{-1}	$^{+0.32}_{-0.30}$	$^{+0.30}_{-0.28}$	$^{+0.26}_{-0.22}$	$^{+0.76}_{-0.58}$	$^{+0.62}_{-0.50}$	$^{+0.36}_{-0.32}$

New

Needs accurate prediction of the bbγγ background rate

Summary

- LHC
  - Will have a hard time to measure say something on λ_{HHH}
  - Can possibly establish that $\lambda_{HHH} \neq 0$ if $150<M_H<200$ GeV
- SLHC
  - Can measure λ_{HHH} to 20-30% if $150<M_H<200$ GeV
  - Can measure λ_{HHH} to 50-80% if $120<M_H<140$ GeV
- LC (0.5-1 TeV)
  - Can measure λ_{HHH} to 20-35% if $M_H<140$ GeV
- CLIC (1-5 TeV)
  - Can measure λ_{HHH} to 7-15% for M_H up to 240 GeV
- VLHC
  - Can measure λ_{HHH} to 4-15% for $140<M_H<200$ GeV
  - Can measure λ_{HHH} to 20-40% for $120<M_H<140$ GeV

LC results can improve by factor up to 1.3-1.7 when polarised beams are used
VLHC (SLHC) may need LC to get precise (top Yukawa coupling, HWW…)