Di-Higgs production in e^+e^- Collisions and Measurement of the Higgs Self-Coupling

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Introduction

- This is a review talk, not much in the way of new material – more of an introduction to the subject
  - covering both ILC and CLIC results
- I'm coming at this from something of a hadron collider perspective (in my day job I do Higgs physics at ATLAS)
- Am personally working on prospects for the bbττ mode using SiD simulation

よろしくお願いします！

Motivation

- Measurements from LHC:
  - confirm picture that W, Z masses arise from Higgs interactions
  - confirm that Higgs interacts with fermions as expected
  - **do not yet** confirm that the Higgs field breaks its symmetry through self-interactions
- In SM the Higgs potential after EWSB reads

$$V(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

v = Higgs vev = 246 GeV; λ = 0.13

$\lambda v^2 = \frac{1}{2} m_H^2$

- Non-SM models can change the coefficients of the terms
  - enhanced H^3 coupling can lead to strong first-order EW phase transition → electroweak baryogenesis
  - ideally would have sensitivity to O(15-20%) difference from SM
- Measurement of the triple Higgs coupling one of the key measurements of a future energy frontier collider!
  - quartic seems beyond reach for the foreseeable future

Hadron Colliders

- Higgs self-coupling is a key target of the HL-LHC program
  - direct observation: search for di-Higgs production
  - one useful production mechanism: gluon-gluon fusion
  - heavy dependence on $bb\gamma\gamma$ and $bb\tau\tau$ signatures due to triggering, QCD backgrounds in bbbb
- Because of interference effects (more later) observation of HH production != observation of Higgs self-coupling
  - Extrapolations: 4σ evidence for HH production, $0.52 < \kappa_\lambda < 1.5$ @ 68% CL
- FCC-hh has much higher σ (> 30×) and luminosity (10×)
  - projections give precision on λ of 3-8%

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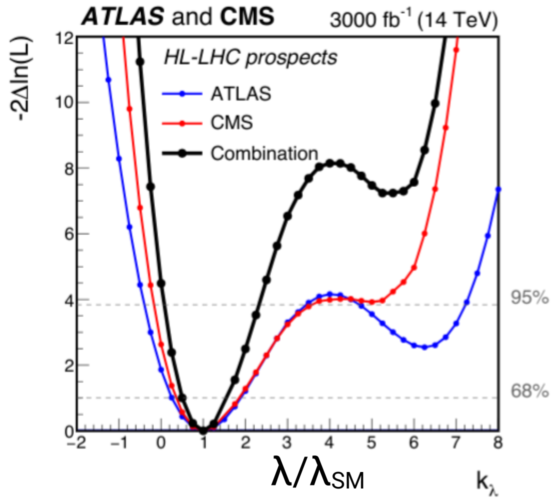

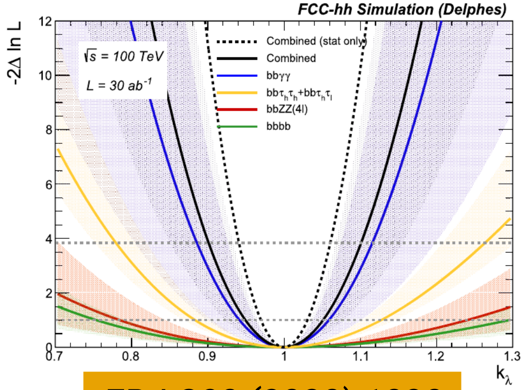

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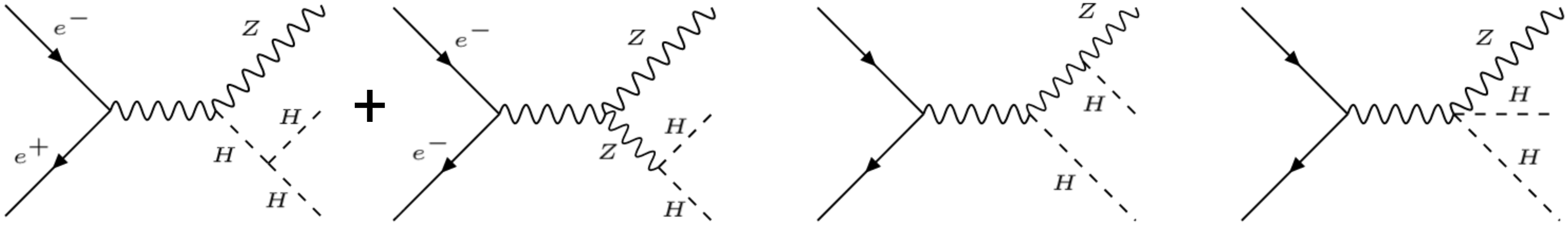
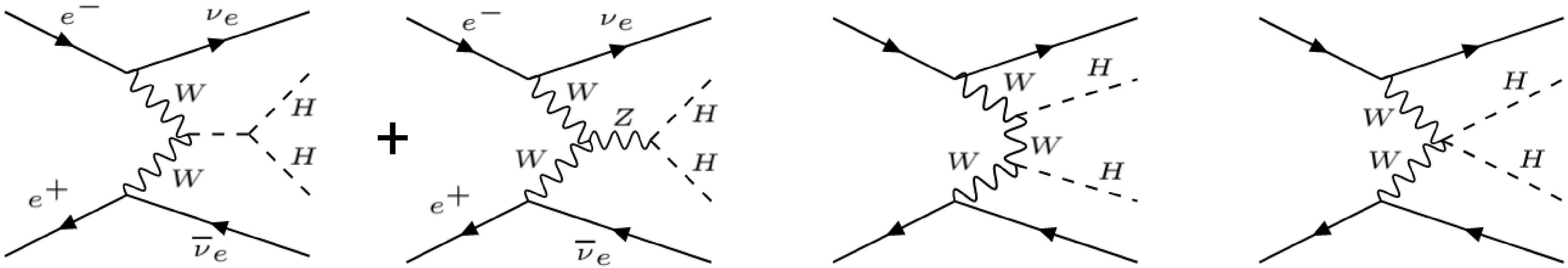
Processes

- ZHH: double Higgsstrahlung



- vvHH: WW fusion

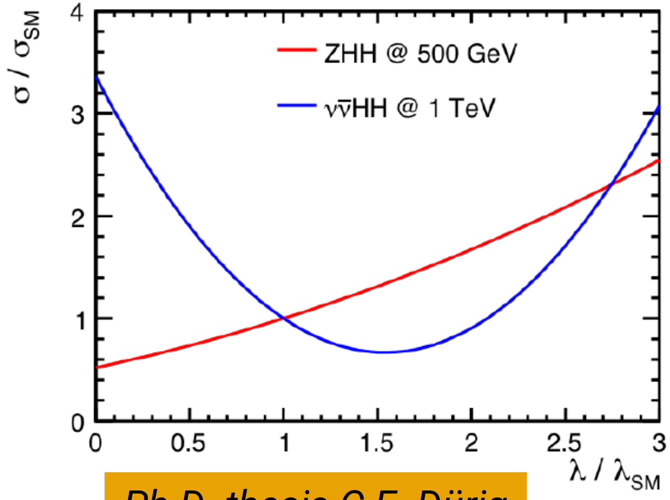


Effect of Interference

- Diagrams involving couplings other than HHH → HH cross section does not directly probe λ
- Describe sensitivity to λ via a "sensitivity factor" (smaller is better, ideal would be 0.5):

$$\frac{\Delta\lambda}{\lambda} = F\frac{\Delta\sigma}{\sigma} \qquad F_{\mathrm{ZHH}}(500\ \mathrm{GeV}) \sim 1.8 \qquad F_{\nu\nu\mathrm{HH}}(1\ \mathrm{TeV}) \sim 0.85$$

- F can be improved by using kinematic variables to isolate more sensitive phase space
  - Higgs propagator favors low m(HH) events; weighting in m(HH) improves sensitivity ~ 10%



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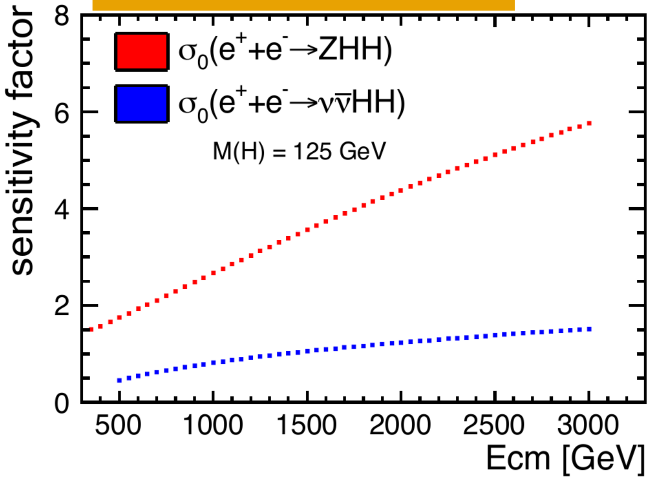
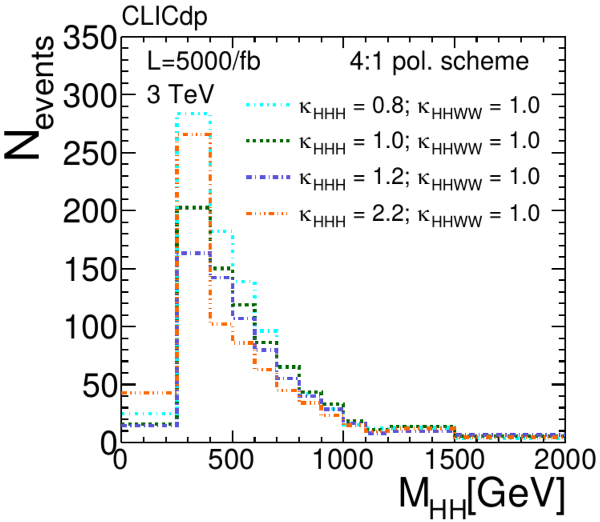
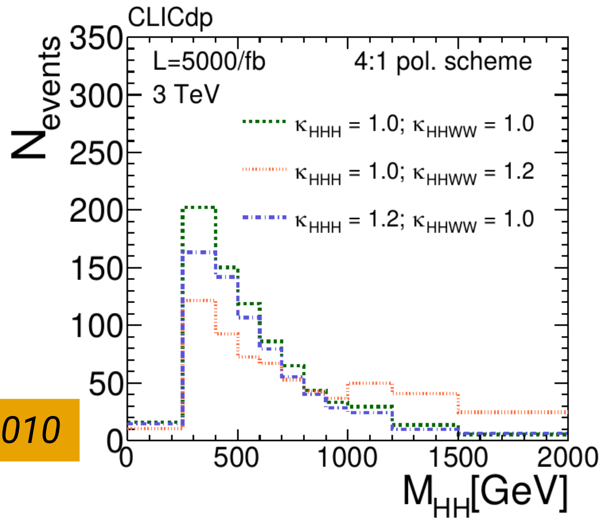


Differential Distributions

- CLIC study: can break degeneracy in λ in total cross section by using differential distributions in mass
- Differential distributions also give sensitivity to other couplings e.g. HHWW
  - in effective field theory contexts expect more than one operator to be changing …
- To do this effectively a long lever arm in m(HH) is needed





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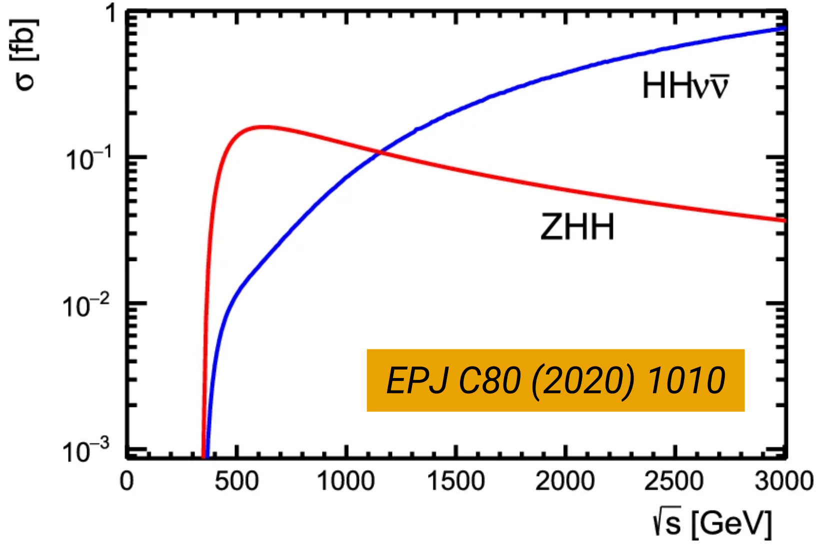
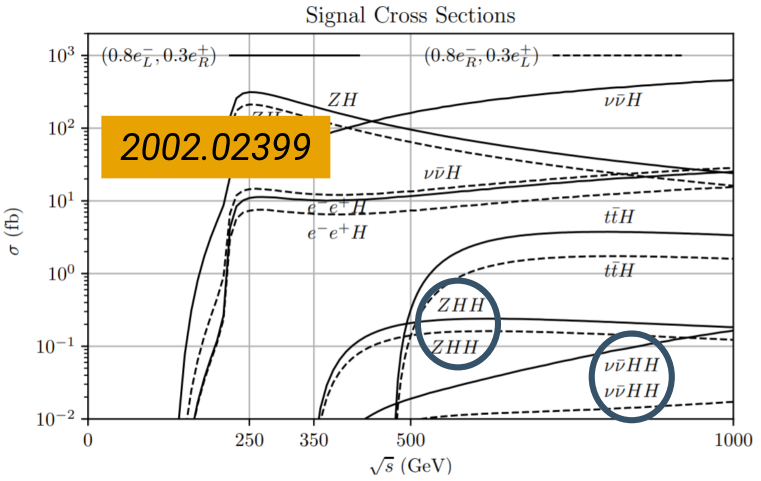
Cross Section vs √s

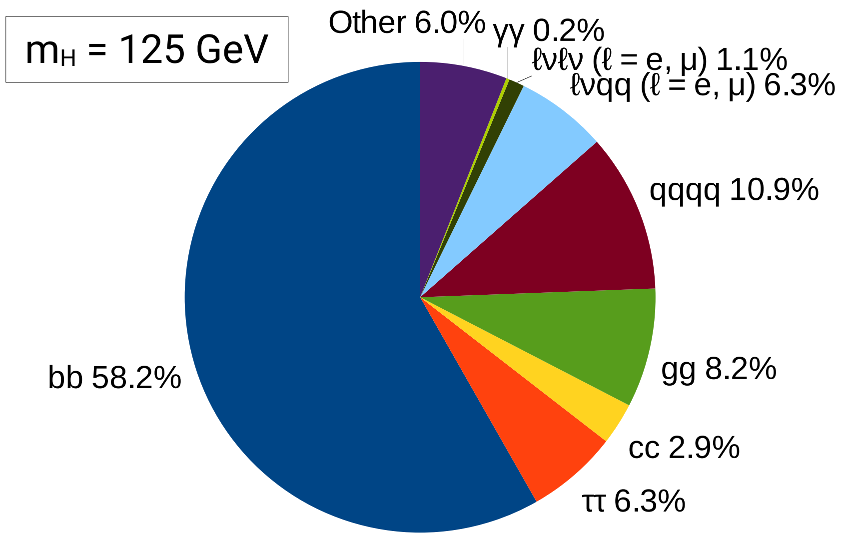
- Higgsstrahlung peaks ~ 500 GeV
  - important for ILC @ 500 GeV or 1 TeV
  - weak channel for CLIC @ 1.4 TeV, not relevant for 3 TeV
  - somewhat dependent on polarization
- WW-fusion rises with √s
  - negligible for ILC @ 500 GeV, important at 1 TeV
  - main channel for CLIC
  - very dependent on polarization (switches off for e_R)





Higgs Decays + Signatures

- Need to find two Higgs decays
  - H → bb is so dominant that **one** of the two Higgs goes to bb in any plausible detection scenario
  - bbbb is first target of almost all searches; bbqqqq or bbℓνqq (via bbWW*) the second
  - possibly useful: bbττ (and bbgg ??)
- ZHH requires Z tagging as well – qq, ℓℓ, νν have been investigated



	bb	ττ	cc	gg	qqqq	ℓνqq	ℓνℓν	γγ
bb	33.92%							
ττ	7.31%	0.39%						
cc	3.37%	0.36%	0.08%					
gg	9.54%	1.03%	0.47%	0.67%				
qqqq	12.68%	1.37%	0.63%	1.78%	1.19%			
ℓνqq	7.30%	0.79%	0.36%	1.03%	1.36%	0.39%		
ℓνℓν	1.23%	0.13%	0.06%	0.17%	0.23%	0.78%	0.01%	
γγ	0.26%	0.03%	0.01%	0.04%	0.05%	0.13%	0.00%	0.00%

Statistics

- Signal events are very precious at ILC
  - H → bb+X: even without background, 2 ab^{-1} of 500 GeV data → stat error on λ ≳ 10%
- many more events at CLIC 3 TeV: higher σ(ννHH) and ∫ L dt

Total events

ZHH @ 500 GeV (σ = 0.2 fb), 2 ab^{-1}

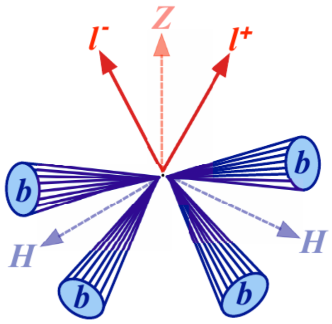
	bb	ττ	cc	gg	qqqq	ℓνqq	ℓνℓν
bb	135.7						
ττ	29.2	1.6					
cc	13.5	1.5	0.3				
gg	38.1	4.1	1.9	2.7			
qqqq	50.7	5.5	2.5	7.1	4.7		
ℓνqq	29.2	3.1	1.4	4.1	5.5	1.6	
ℓνℓν	4.9	0.5	0.2	0.7	0.9	3.1	0.0
γγ	1.1	0.1	0.1	0.1	0.2	0.5	0.0

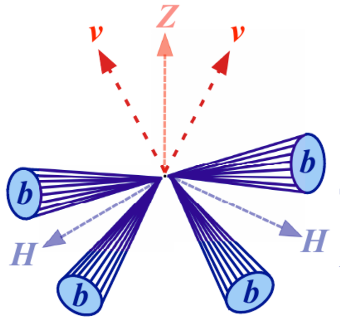
ννHH @ 3 TeV (σ = 0.6 fb), 5 ab^{-1}

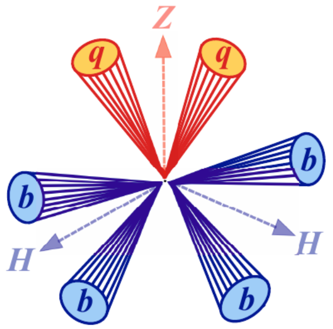
	bb	ττ	cc	gg	qqqq	ℓνqq	ℓνℓν
bb	1017.6						
ττ	219.2	11.8					
cc	101.0	10.9	2.5				
gg	286.1	30.8	14.2	20.1			
qqqq	380.5	41.0	18.9	53.5	35.6		
ℓνqq	218.9	23.6	10.9	30.8	40.9	11.8	
ℓνℓν	36.9	4.0	1.8	5.2	6.9	23.5	0.3
γγ	7.9	0.9	0.4	1.1	1.5	4.0	0.1

ZHH @ 500 GeV

- Consider $Z \rightarrow \ell\ell$ (ℓ=e,μ), νν, qq | $H \rightarrow$ bb, qqqq, qqℓν
  - channels separated by missing energy, lepton requirements
  - dilepton has clean signature, automatically suppresses $t\bar{t}$, but low BR
  - neutrino mode is clean but allows contamination from lower-multiplicity processes
  - quark mode: 6 jet (qqbbbb) or 8 jet (qqbbqqqq) final states
    - at 500 GeV parent objects are not boosted; jets overlap & combinatorics can be hard to resolve
- Main backgrounds: ZZH, ZZZ, $t\bar{t}$
- Object reconstruction performance is critical
  - $HH \rightarrow 4b$: 5% per-jet improvement in b-tag efficiency for same purity gives 20% improvement in overall signal efficiency
  - jet energy resolution important to separate Z and H decaying to bb
  - $HH \rightarrow$ bbqqqq: quark/gluon tagging of jets improves rejection of top pairs
  - handling of hadronic τ decays important for vetoing $t\bar{t}$, W contributions
- Kinematic fits, MVAs can be used for signal/background discrimination







ZHH @ 500 GeV

- 4b mode
- Positive electron polarization reduces signal, but also reduces background; λ sensitivity is similar
- Biggest overall problem with ZHH is the bad sensitivity factor

$P(e^+, e^-)$	ZHH channel	s $(HH \to bbbb)$	b	σ_e	σ_m
(0.3, −0.8)	$eeHH$	3.9 (2.6)	7.0	1.29σ	1.07σ
	$\mu\mu HH$	5.1 (2.8)	8.9	1.48σ	1.26σ
	$\nu\nu HH$	5.6 (5.5)	6.9	1.78σ	1.50σ
	$bbHH$	8.5 (8.0)	21.9	1.75σ	1.57σ
	$qqHH$	12.6 (10.9)	55.0	1.65σ	1.55σ
				combined excess significance	3.5σ
				measurement precision on σ_{ZHH}	30.3%
(−0.3, 0.8)	$eeHH$	2.9 (1.9)	4.2	1.18σ	0.92σ
	$\mu\mu HH$	3.8 (2.0)	5.3	1.37σ	1.10σ
	$\nu\nu HH$	3.6 (3.5)	1.1	2.72σ	1.54σ
	$bbHH$	5.9 (5.6)	7.0	1.89σ	1.58σ
	$qqHH$	8.3 (7.8)	16.0	1.85σ	1.64σ
				combined excess significance	4.8σ
				measurement precision on σ_{ZHH}	29.4%

2 ab^{-1}

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$\Delta\lambda/\lambda \sim 50\%$ per 2 ab^{-1}

ZHH → (bb)(bb)(lvjj), 2 ab^{-1}

Category	Signal	Background	Significance
Lepton+ 6jets	1.72	14.55	$0.43\,\sigma$

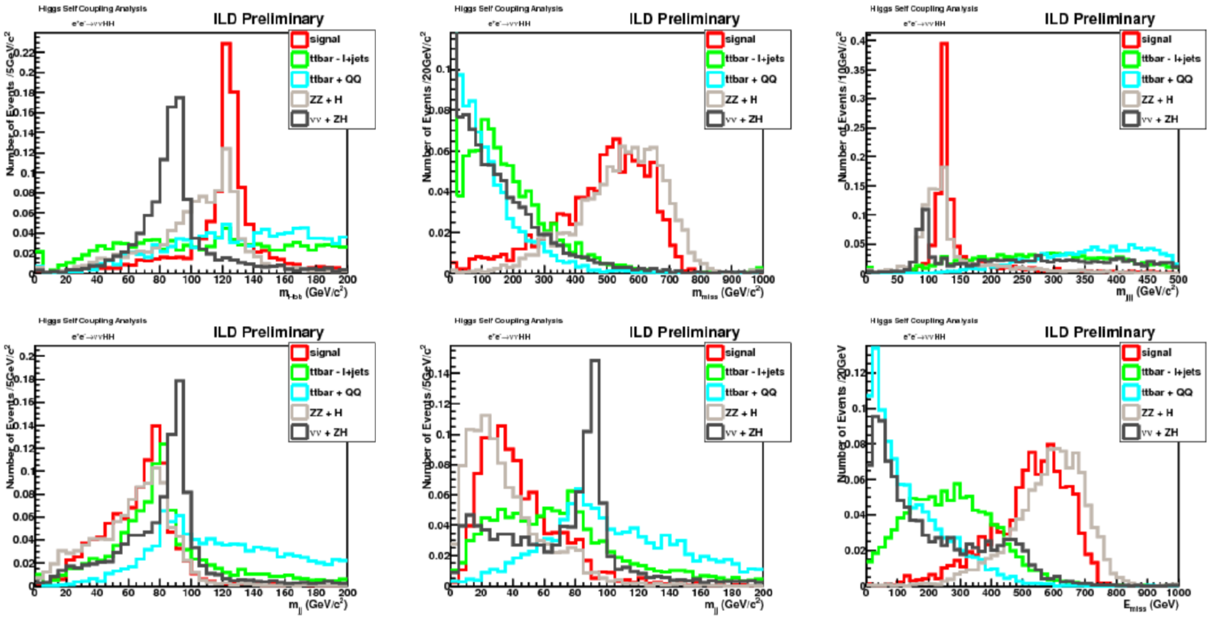
Kurata, ALCW15, ILD full sim

Combined 4 ab^{-1}: $\Delta\lambda/\lambda \sim 27\%$
(about 2× better than HL-LHC)

WW Fusion @ 1 TeV

- Channel includes WW fusion (dominant) & Z(→νν)HH
- Main backgrounds are $t\bar{t}$ and ννZH
  - unlike in ZHH, S/B ≳ 1 for H → 4b here
- 2 ab^{-1} of (-0.8, 0.2) polarization → Δλ/λ ~ 16%
  - some question about impact of γγ overlay

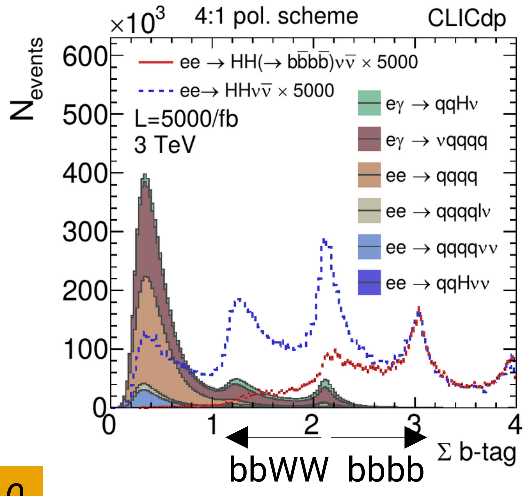
Kinematics for H → bbWW → bbqqqq

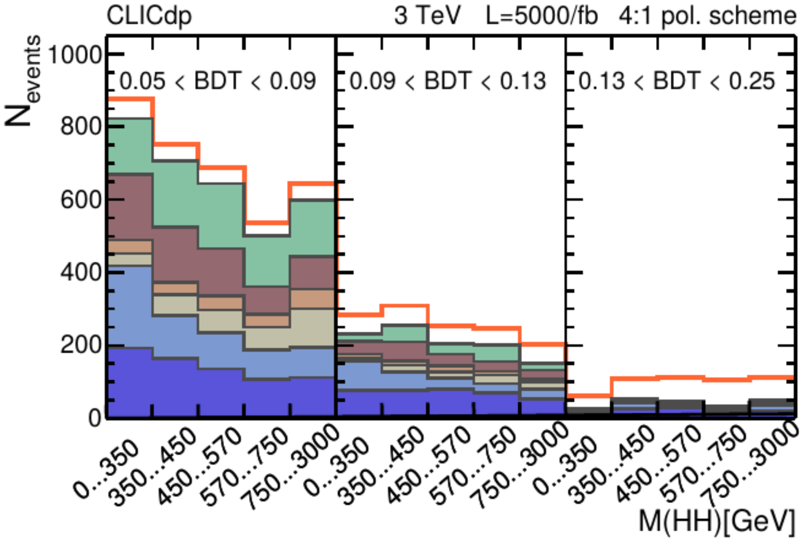


LC-REP-2013-003, Dürig ALCW 2015, Kurata ALCW 2015

vvHH @ 3 TeV

- CLIC study of capabilities
- Initial selection by # of b-jet, followed by grouping of jets & BDT application to reject backgrounds
- HH → 4b is quite clean; HH → bbWW has a rather large contribution of eγ → νqqqq and νqqH
- 3 TeV differential analysis gives Δλ/λ ~ 10%





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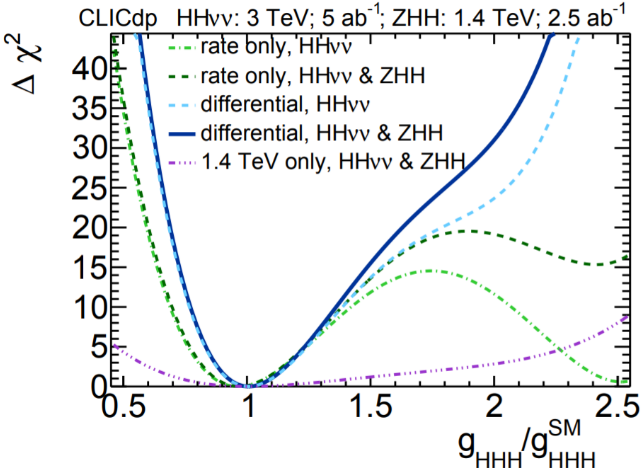

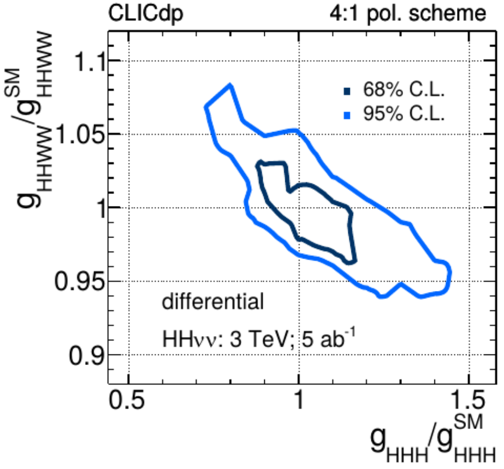

Summary

- Higgs self-coupling measurement is a key element of a future collider program
- Measurement of inclusive cross sections σ(ZHH), σ(ννHH) gives coupling through theoretical relations
  - ννHH is more powerful than ZHH for the same # of events
- Increasing σ(ννHH) with √s means highest energy stages dominate
  - ILC competitiveness requires long 500 GeV program (> LumiUP) or (better) 1 TeV upgrade
- ILC:
  - considering all aspects 500 GeV is probably close to a local optimum for ZHH, but worth checking if 10-20 GeV makes any appreciable difference
  - 1 TeV upgrade should be very careful about its polarization choices
- FCC-hh projections for λ sensitivity better than either ILC or CLIC by x1.2-4 depending on assumptions
  - LC estimates probably more robust