Prospects of Higgs self-coupling measurements at the ILC using ILD detector

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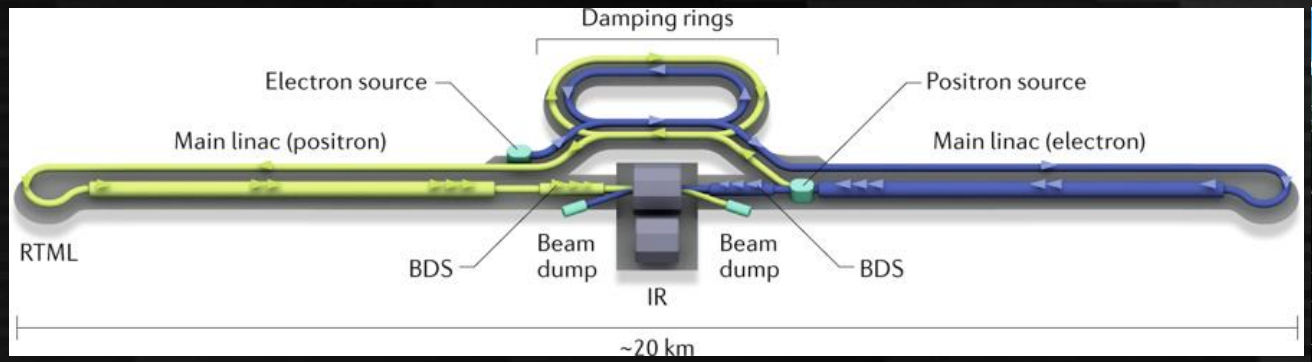
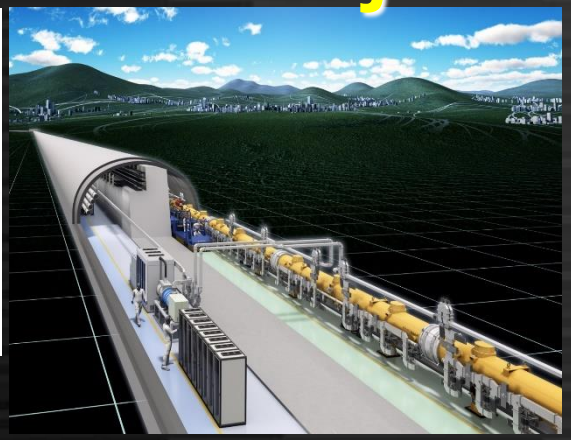
On behalf of ILD group

International Linear Collider Project



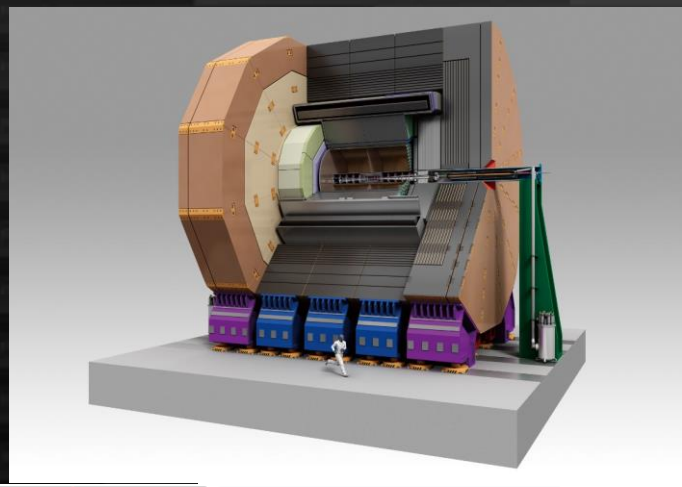


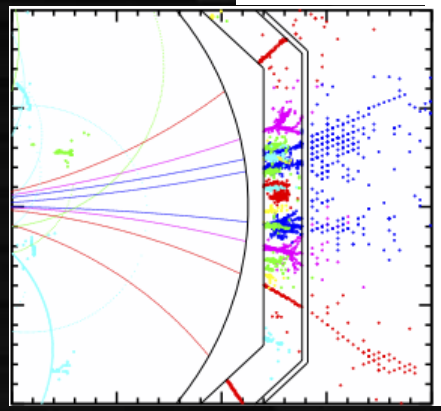
- e^+e^- linear collider to be built in Japan
- Higgs factory (250 GeV) starting at 2035-2040
  - Beam polarization (e^-: 80%, e^+: 30% expected)
  - 2 ab^{-1}, similar physics potential with FCCee (by polarization)
- Upgradable by increasing tunnel length and accelerating gradien

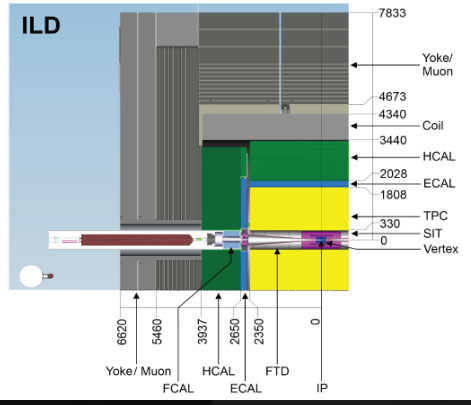
Energy	Physics	Technology
350 GeV	Top threshold	Better surface treatment (up to ~50 MV/m)
~500 GeV	Higgs self coupling (ZHH)	
~1 TeV	Higgs self coupling ($\nu\nu$HH)	Thin-film superconductor (up to ~100 MV/m)
Up to a few TeV	BSM search (eg. TeV Wino)	
30 TeV	?	Plasma accelerator? (~1 GV/m)

ILD detector

- International Large Detector (ILD)
  - One of two detector concepts for ILC
- Particle flow concept
  - Separate particles in jets by highly-segmented calorimeters
- Key subsystems
  - Monolithic vertex detector
  - TPC + silicon tracker
  - High granular calorimeter (silicon/scintillator ECAL, scintillator/RPC HCAL)



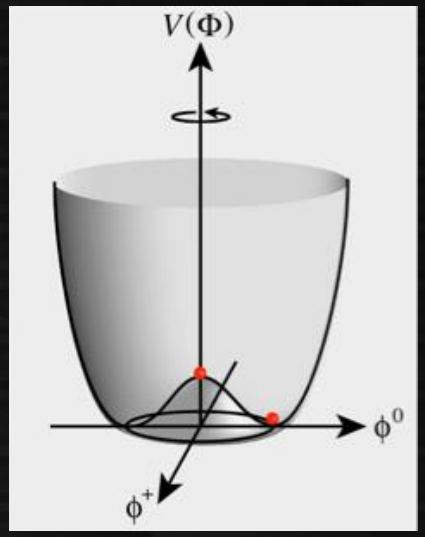




Unprecended performance by precise particle imaging

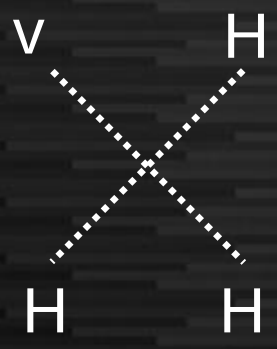
- b/c tagging, momentum resolution, jet energy resolution…

Higgs self coupling and baryogenesis

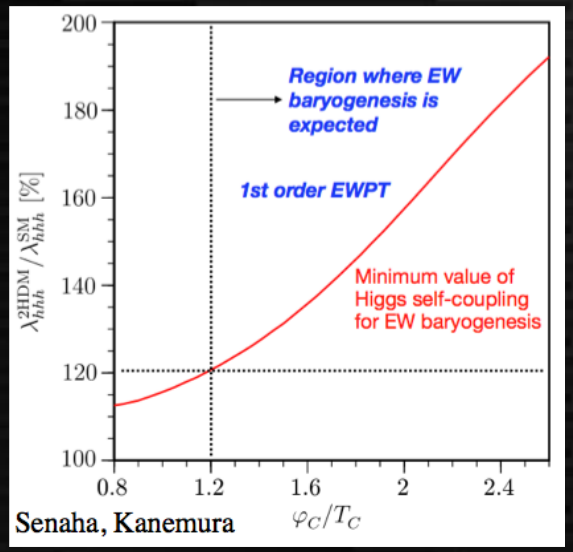


$$V(\eta_H) = \frac{1}{2}m_H^2\eta_H^2 + \lambda v\eta_H^3 + \frac{1}{4}\lambda\eta_H^4$$

λ determines the quadratic term of Higgs potential
→ Unique probe for structure of vacuum



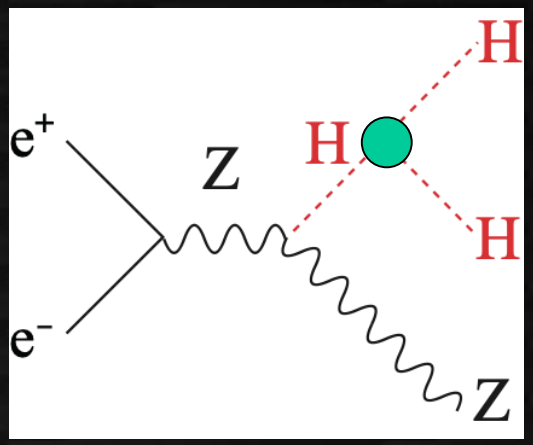
Electroweak baryogenesis requires strong 1st order EW transition
→ In the two-Higgs doublet models, λ positively deviates by >20%
→ should be an experimental target

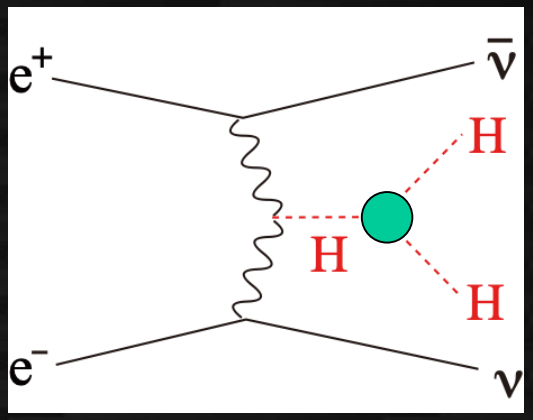


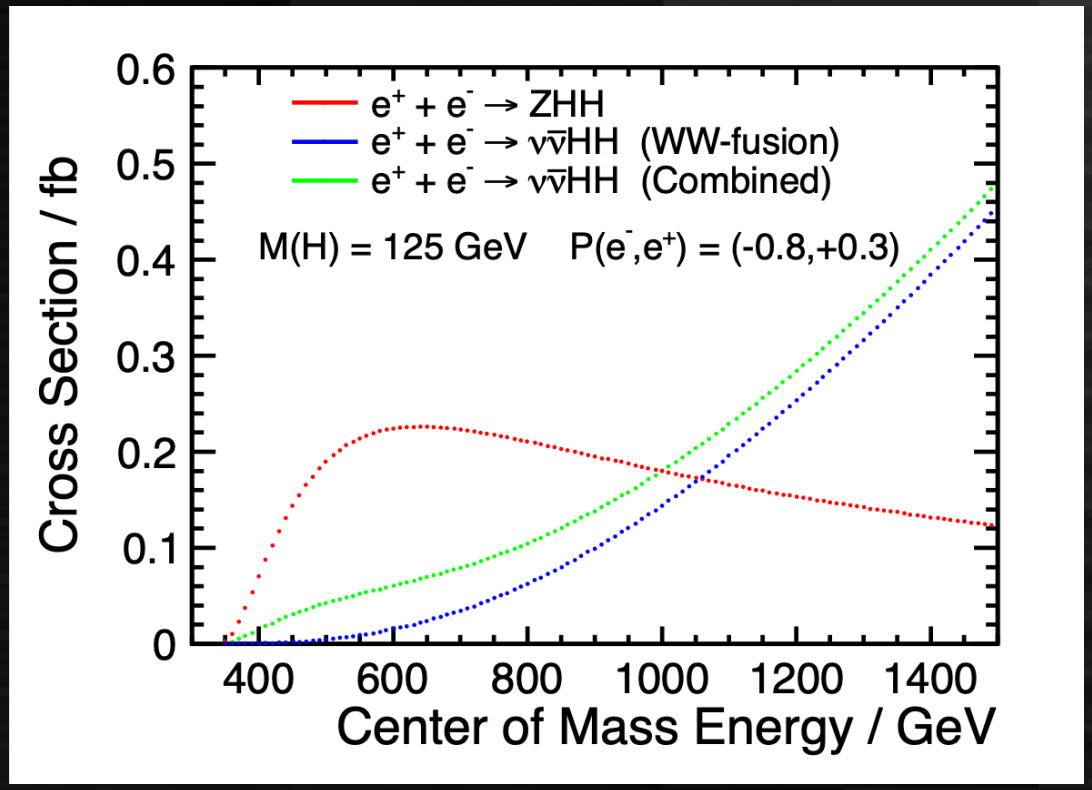
Higgs self-coupling at ILC

$\sqrt{s}$ = 500 GeV: $e^+e^- \rightarrow ZHH$

$\sqrt{s}$ >= 1 TeV: $e^+e^- \rightarrow \nu_e\nu_e HH$







Extremely low cross section: O(100 ab)

Decay channels

- dominant channels covered for ZHH @ 500 GeV

Z decay mode	HH decay mode	BranchingRatio
$Z \to e^+e^-$	$HH \to b\bar{b}b\bar{b}$	1.1%
$Z \to \mu^+\mu^-$	$HH \to b\bar{b}b\bar{b}$	1.1%
$Z \to \nu^+\bar{\nu}$	$HH \to b\bar{b}b\bar{b}$	6.7%
$Z \to b\bar{b}$	$HH \to b\bar{b}b\bar{b}$	5.0%
$Z \to q\bar{q}$	$HH \to b\bar{b}b\bar{b}$	17%
$Z \to b\bar{b}$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	1.7%
$Z \to c\bar{c}$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	1.4%
$Z \to b\bar{b}$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	1.1%
$Z \to c\bar{c}$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	0.92%
$Z \to l^+l^-$	$HH \to b\bar{b}WW^*, WW^* \to 4q$	0.76%
$Z \to l^+l^-$	$HH \to b\bar{b}WW^*, WW^* \to l\nu 2q$	0.50%

Table 1: signal channels analysed for $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV.

(for $e^+e^- \to \nu\nu HH$@1TeV: HH → bbbb/bbWW* are covered)

Result of full simulation studies

- results (example individual channels)

ZHH channel	s ($HH \to bbbb$)	b	σ_e
$eeHH$	3.9 ± 0.03 (2.6)	7 ± 0.6	1.29σ
$\mu\mu HH$	5.1 ± 0.03 (2.8)	9 ± 0.5	1.48σ
$\nu\nu HH$	5.6 ± 0.04 (5.5)	7 ± 1.0	1.78σ
$bbHH$	8.5 ± 0.10 (8.0)	22 ± 1.3	1.75σ
$qqHH$	12.6 ± 0.1 (10.9)	55 ± 2.0	1.65σ

Table 2: Results of the event selection of ZHH with $HH \to bbbb$ corresponding to an integrated luminosity of $\mathcal{L} = 2$ ab^{-1} and a beam polarisation of $P(e^+e^-) = (0.3, -0.8)$.

major bkg.: tt, ZZ, ZZZ, ZZH

- results (combined)

$\sqrt{s}$	$\int Ldt$	$\Delta\sigma/\sigma$	$\Delta\lambda_{HHH}/\lambda_{HHH}$
ZHH @ 500 GeV	4 ab^{-1} (*)	17%	27%
$\nu\ \nu$ HH @ 1 TeV	4 ab^{-1} (**)	15%	10%

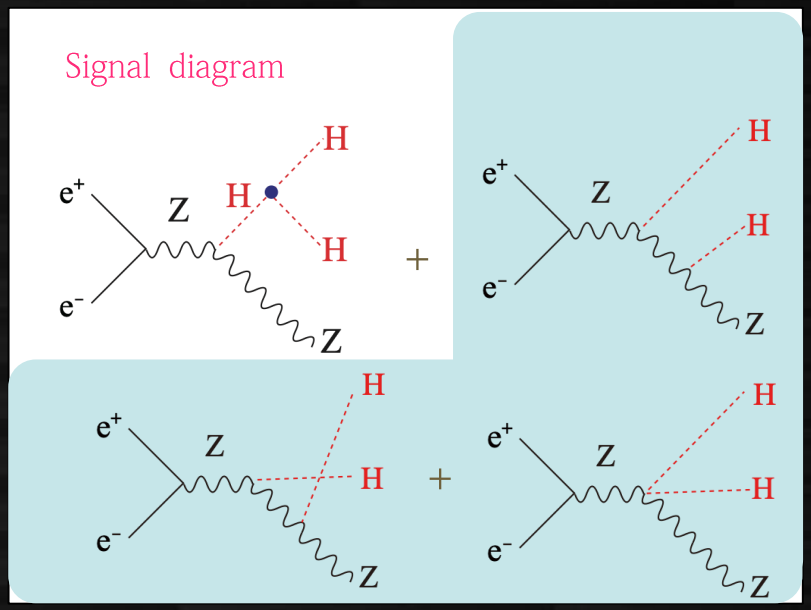
P(e+, e-) = *: equally shared by (-0.8,+0.3) and (+0.8,-0.3); **: (-0.8,+0.2)

from di-Higgs cross section to λ_{HHH}

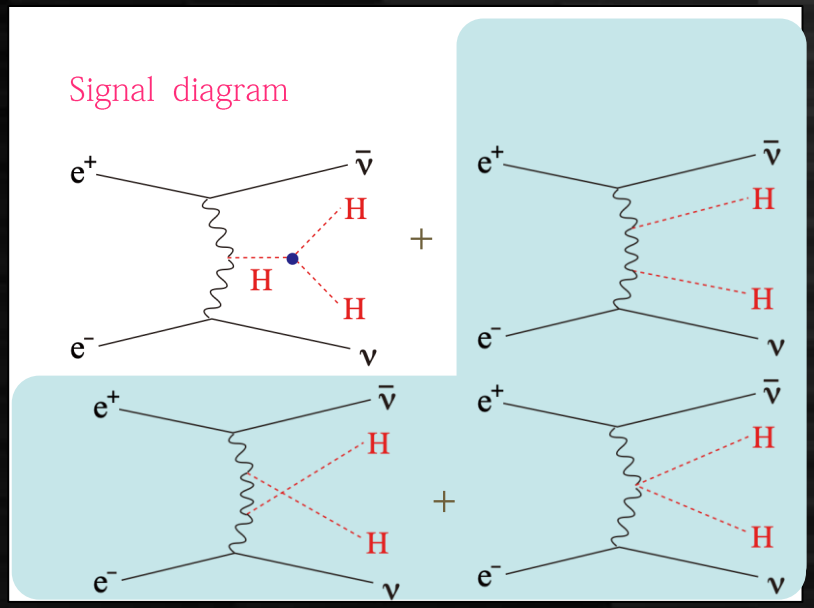
$$\sigma = S\lambda^2 + I\lambda + B$$

(signal diagram) (interference) (background diagram)

ZHH final states (500 GeV)



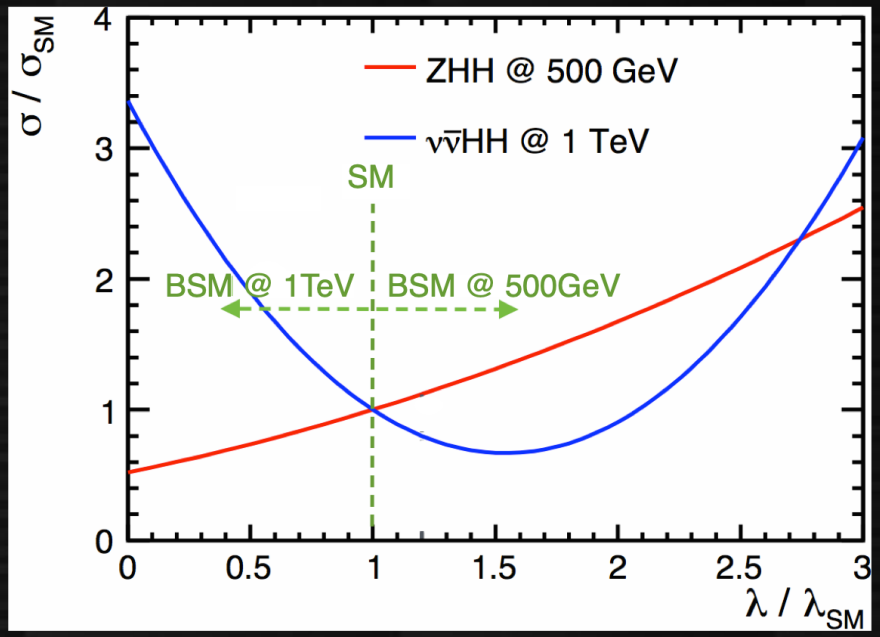
ννHH final states (>1 TeV)

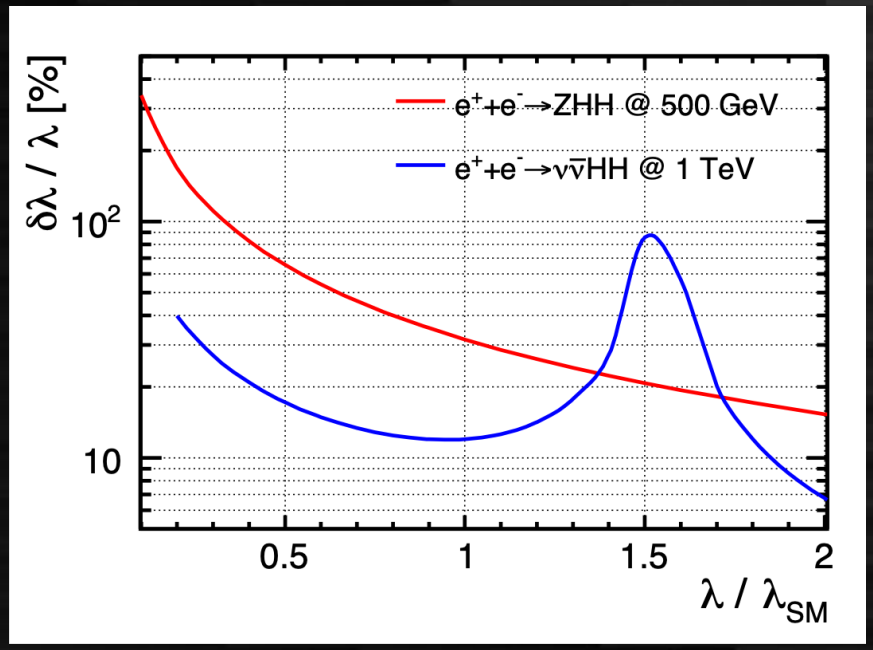


interference: constructive in ZHH, destructive in ννHH

Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

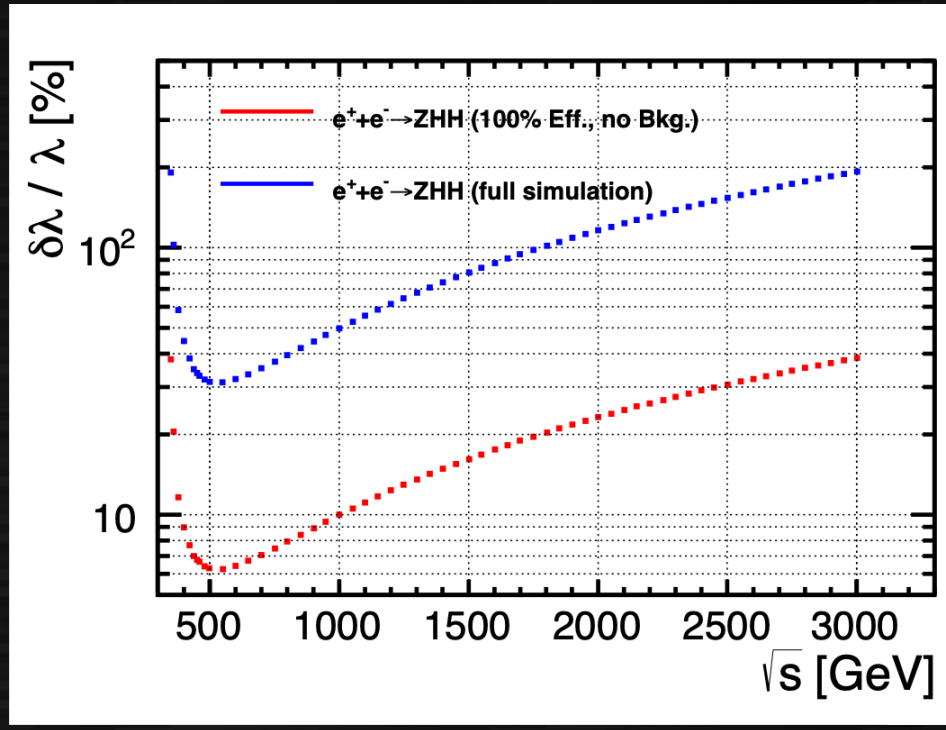
- λ_{HHH} can be enhanced significantly in BSM
- complementarity between ZHH & ννHH (& LHC): interference nature
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~13% using ZHH at 500 GeV e^+e^-
  A strong probe for electroweak baryogenesis





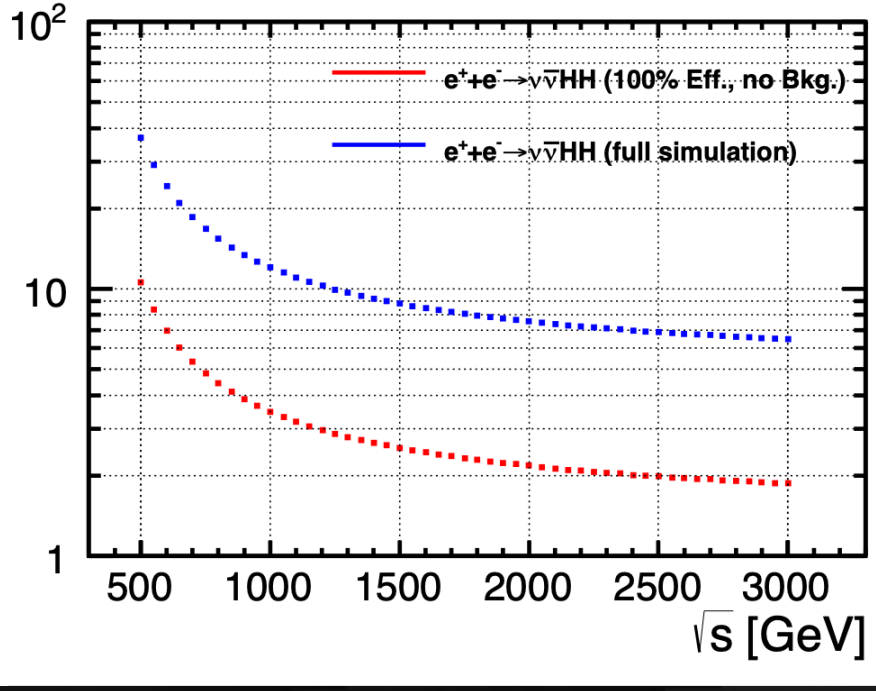
Higgs self-coupling: impact of ECM

ZHH



optimal √s~500-600 GeV

νν̄HH

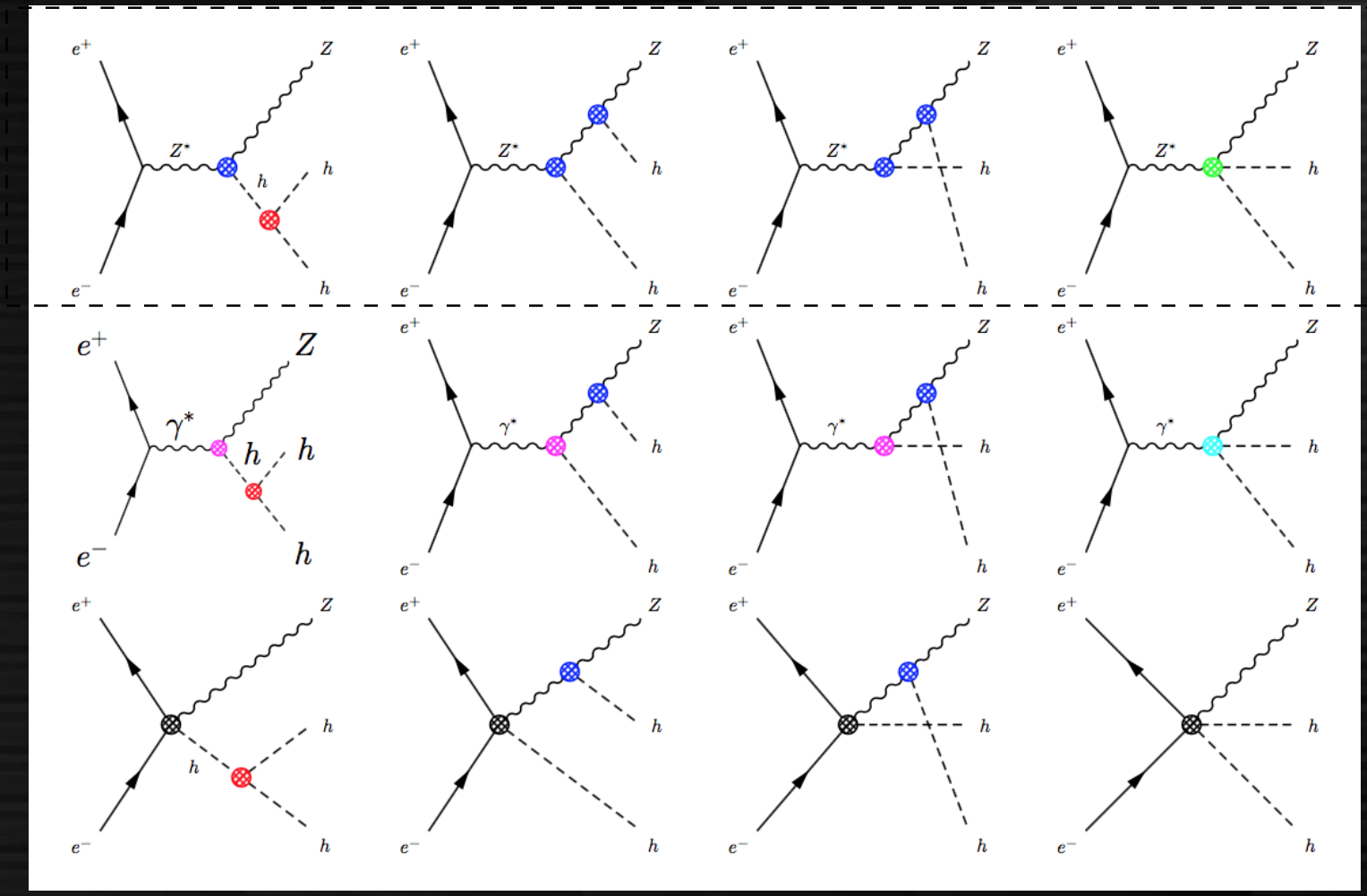


preferred √s >=1 TeV

large room for improving full simulation results in future

λ_{hhh}: can we really determine it mode independently?

σ_{HHX} depends on many other couplings



in a general model by SMEFT

λ_{hhh}: can we really determine it mode independently? yes!

$$\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 = 0.565c_6 - 3.58c_H + 16.0(8c_{WW}) + 8.40(8c_{WB}) + 1.26(8c_{BB})$$
$$-6.48c_T - 65.1c'_{HL} + 61.1c_{HL} + 52.6c_{HE},$$

all parameters determined simultaneously: EWPOs + TGCs + Higgs @ HL-LHC & ILC

Barklow, et al
arXiv:1708.09079

$$c_6 = \frac{1}{0.565}\left[\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 - \sum_i a_i c_i\right]$$

$$\frac{\Delta\lambda_{hhh}}{\lambda_{SM}} = \Delta c_6 = \frac{1}{0.565}\left[\left(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}}\right)^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

$$\left[\sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}} = 0.04 \quad \ll \quad \frac{\Delta\sigma_{Zhh}}{\sigma_{SM}} = 0.168$$

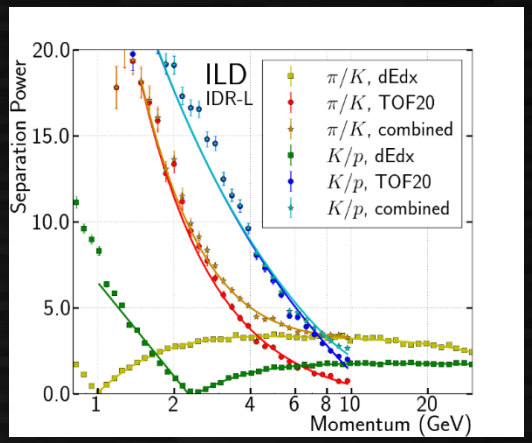
(systematic error) (statistical error)

Prospects of improvements

- Current result on λ_{HHH}
  - 27%: ZHH 500 GeV 4 ab^{-1}
  - 10%: $\nu\nu$HH 1 TeV 4 ab^{-1}
- Performance drivers
  - b-tagging: separation of ttbar background
  - Jet clustering: selection of Z and H
  - Analysis method (event selection)
- Possible improvements
  - K/π/p separation by dE/dx and ToF
  - Pattern recognition by deep learning

Possible improvements

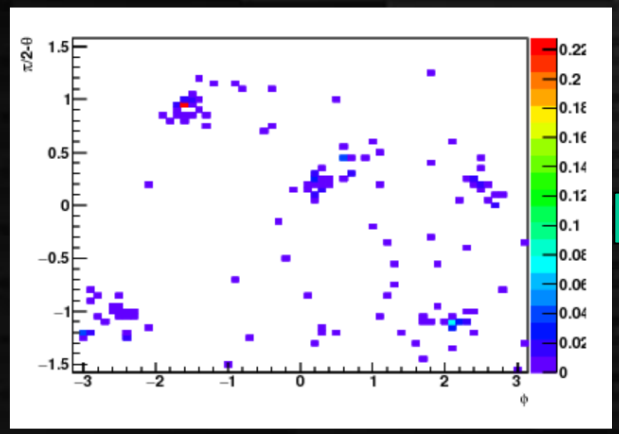
Pico-sec ToF

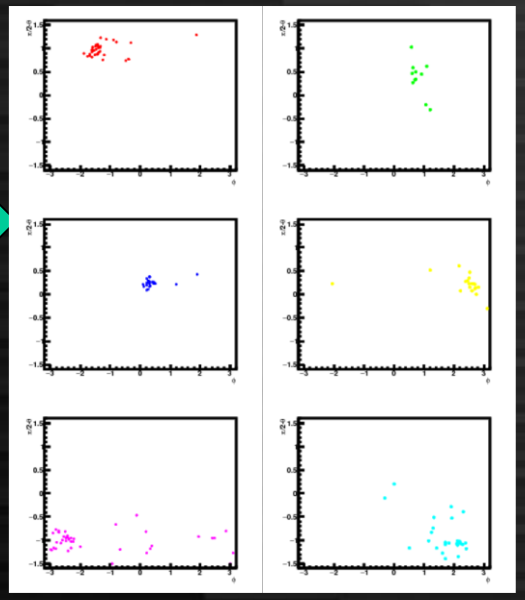


K/π/p separation by combining dE/dx at TPC and timing at ECAL

Hardware:
Fast silicon detector (LGAD)
Software:
Precise timing reconstruction
Flavor tagging with PID
Particle flow with timing

Jet clustering by deep learning





Jet coloring by convolutional network (under development)

Jet clustering as well as flavor tagging and event selection should be improved by deep learning techniques (convolutional network, recurrent network, graph network…) various trials ongoing

Target: 20-30% improvement in a few years

Summary

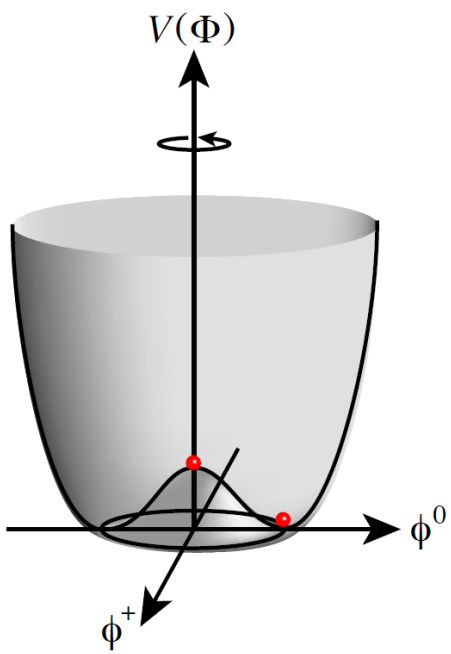
- Higgs self-coupling measurement is an essential probe for vacuum structure
  - Also essential for EW baryogenesis
- ILC gives powerful probe to the self coupling
  - 27%: ZHH 500 GeV 4 ab^{-1}
    Positive interference: preferred for $\lambda > 1$
  - 10%: $\nu\nu$HH 1 TeV 4 ab^{-1}
    Negative interference (as LHC): better for $\lambda < 1$
- Various hardware/software efforts ongoing for improvements: results in a few years

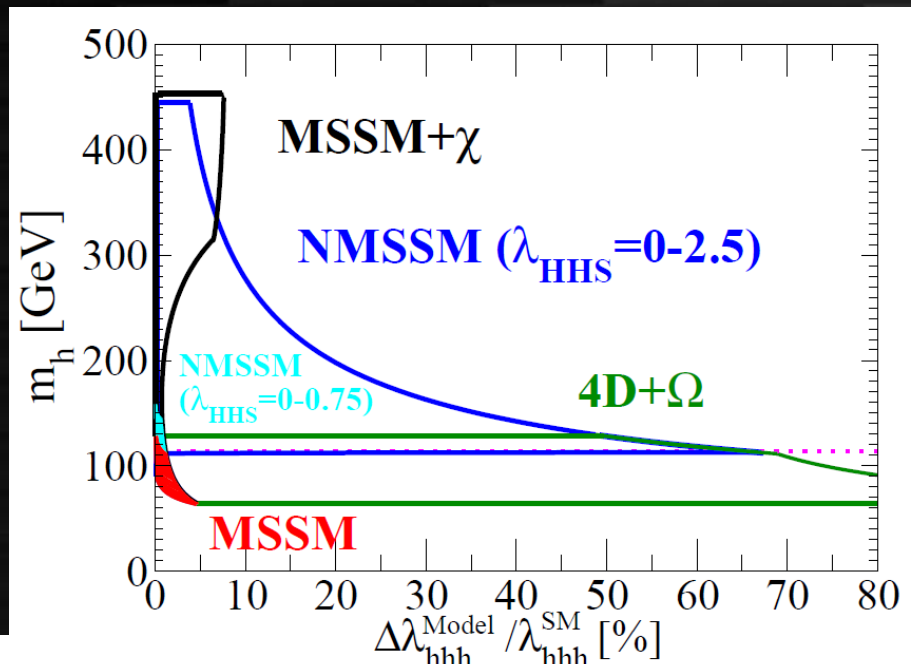
The only probe for Higgs potential: self coupling

SM force

Lagrangian term	example
Gauge force	QCD, electroweak
Yukawa force	Higgs-fermion
Higgs force	Higgs self-coupling

- The last force in SM
- A good probe for BSM with ~30% accuracy





$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{h.c.}, \qquad \mu^2 < 0, \lambda > 0$$

a, H SUSY case: Kanemura et al. (2011)

full simulation studies @ ILC

- generator: Whizard 1.95, Physsim (realistic beamsstrahlung, ISR, pile-up)
- parton shower & hadronization: Pythia 6
- detector model: ILD (as realistic as possible material budget, blind areas)
- simulation & reconstruction: Geant 4, iLCSoft (realistic algorithms for tracking, particle flow, flavor tagging, jet-clustering, etc)
- event selection: full SM background, realistic cuts, careful categorization, kinematic fitting, multivariate method