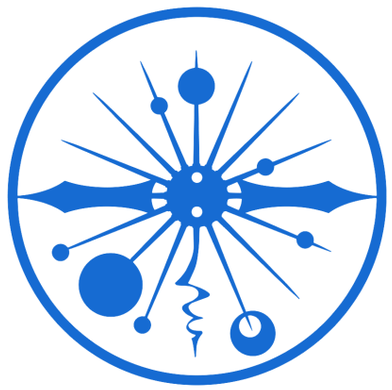
Higgs self-coupling projections at ILC

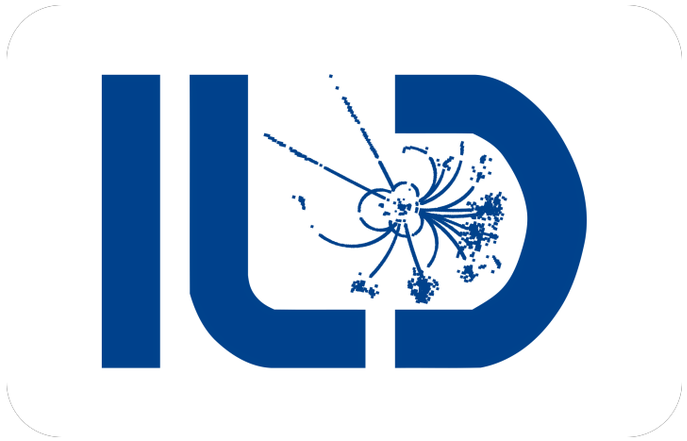
Junping Tian (U. Tokyo)

— on behalf of ILD

Higgs Coupling 2018, Nov. 26-30 @ Tokyo



ILC Supporters

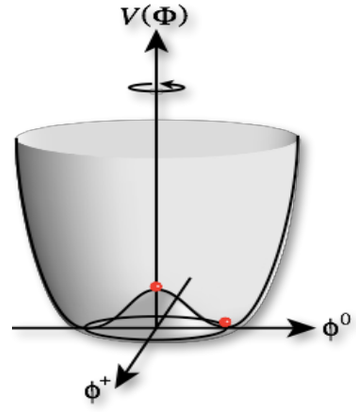


Motivation to measure the Higgs self-couplings

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

- direct probe of the Higgs potential

  —> decisive test of the Standard Model



- the structure of vacuum is crucial for
  - Baryogenesis models: strongly 1st order phase transition, $\delta\lambda_{HHH} > 20\%$
  - EWSB models with classical scale invariance, possibly only self-couplings are deviated: $\delta\lambda_{HHH} \sim 70\%$

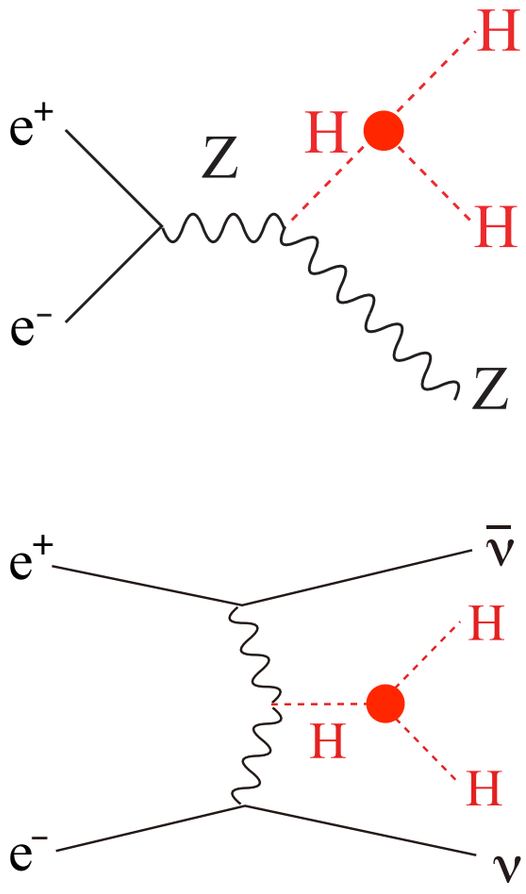
talk by E.Senaha

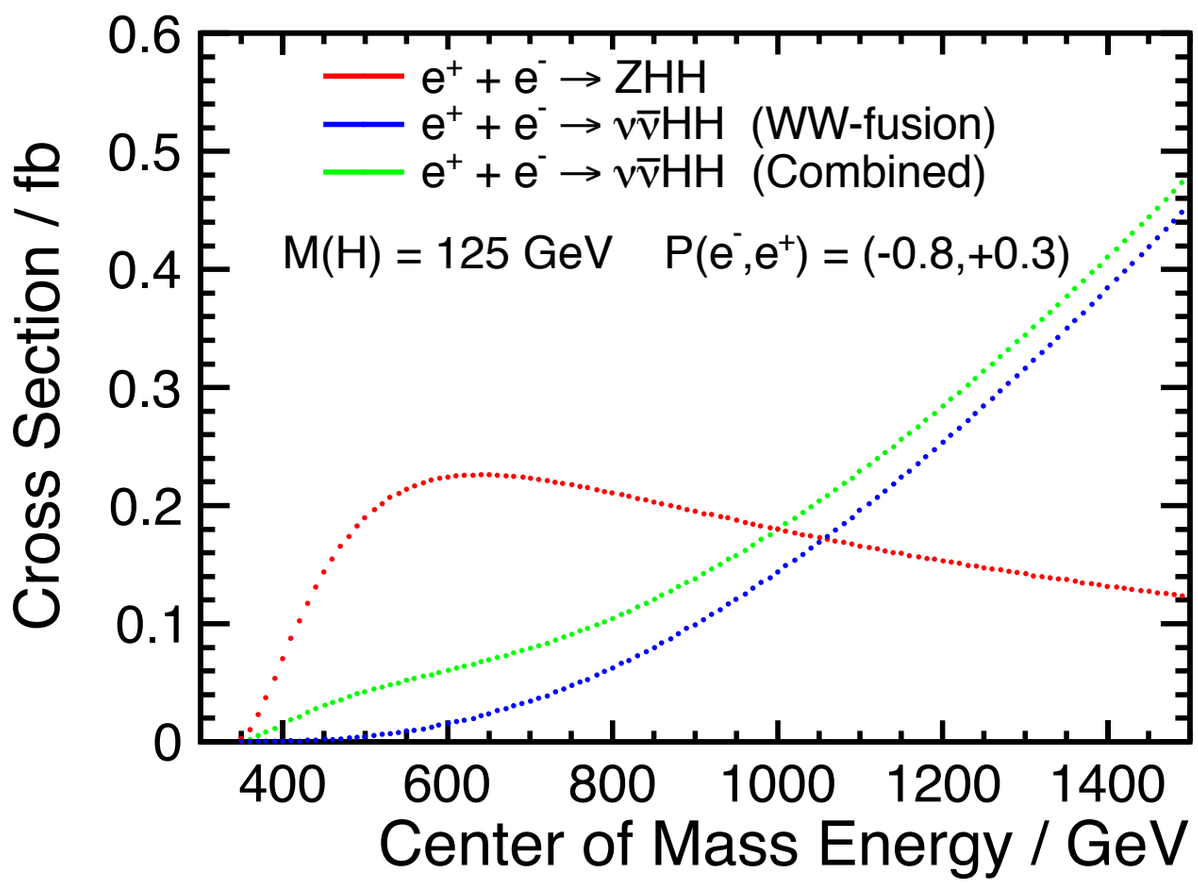
Grojean, et al., hep-ph/0407019
Senaha, et al., hep-ph/0411354

Sumino, et al, 1503.02819
Kanemura, et al, 1508.03245

Higgs self-coupling measurement @ ILC

- √s~500 GeV: e+e- —> ZHH
- √s~1 TeV: e+e- —> $\nu_e\nu_e$HH





C.Duerig, DESY-Thesis-2016-027 M. Kurata, LC-REP-2014-025 J. Tian, LC-REP-2013-003

full simulation studies @ ILC

- dominant channels covered

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%
$Z \to q\bar{q}$	$HH \to bbbb$	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- ->vvHH@1TeV: HH->bbbb/bbWW* are covered)

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

full simulation studies @ ILC

- results (example individual channels)

ZHH channel	s $(HH \to bbbb)$	b	σ_e	eff.
$eeHH$	3.9 ± 0.03 (2.6)	7 ± 0.6	1.29σ	59%
$\mu\mu HH$	5.1 ± 0.03 (2.8)	9 ± 0.5	1.48σ	55%
$\nu\nu HH$	5.6 ± 0.04 (5.5)	7 ± 1.0	1.78σ	19%
$bbHH$	8.5 ± 0.10 (8.0)	22 ± 1.3	1.75σ	29%
$qqHH$	12.6 ± 0.1 (10.9)	55 ± 2.0	1.65σ	15%

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%
vvHH @ 1 TeV	4 ab^{-1} (**)	15%	10%

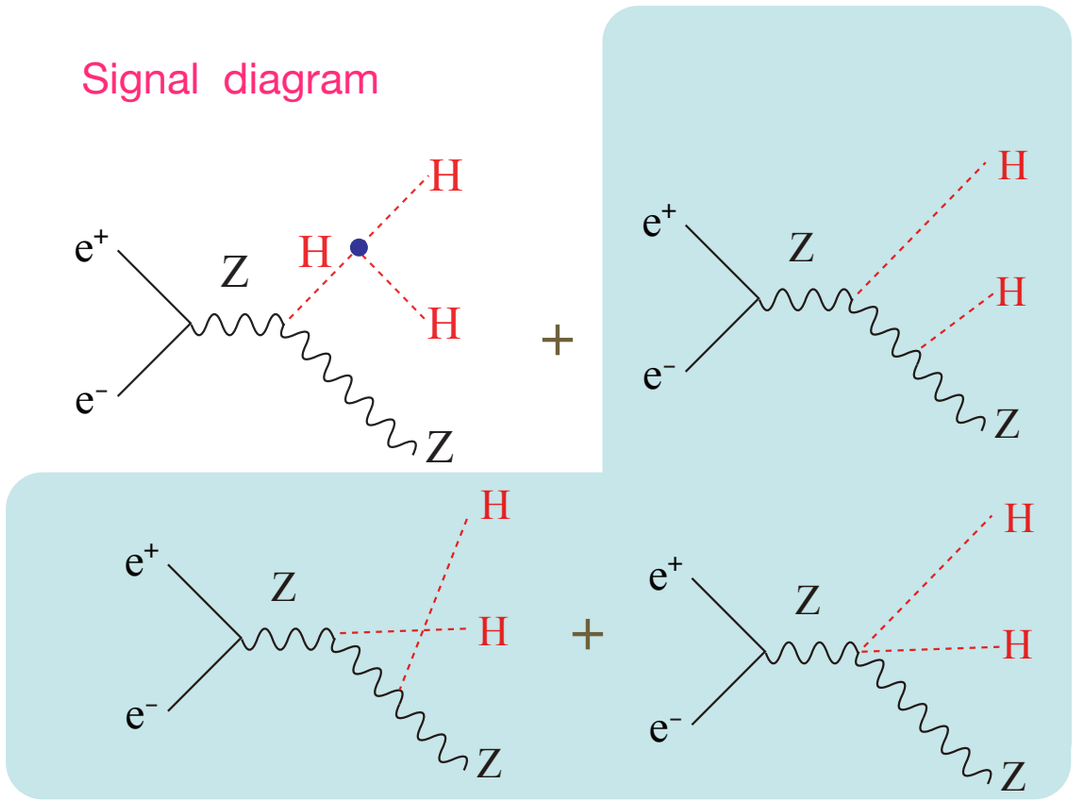
P(e+, e-) = *: equally shared by (-0.8,+0.3) and (+0.8,-0.3); **: (-0.8,+0.2)

from di-Higgs cross section to λ_{HHH}

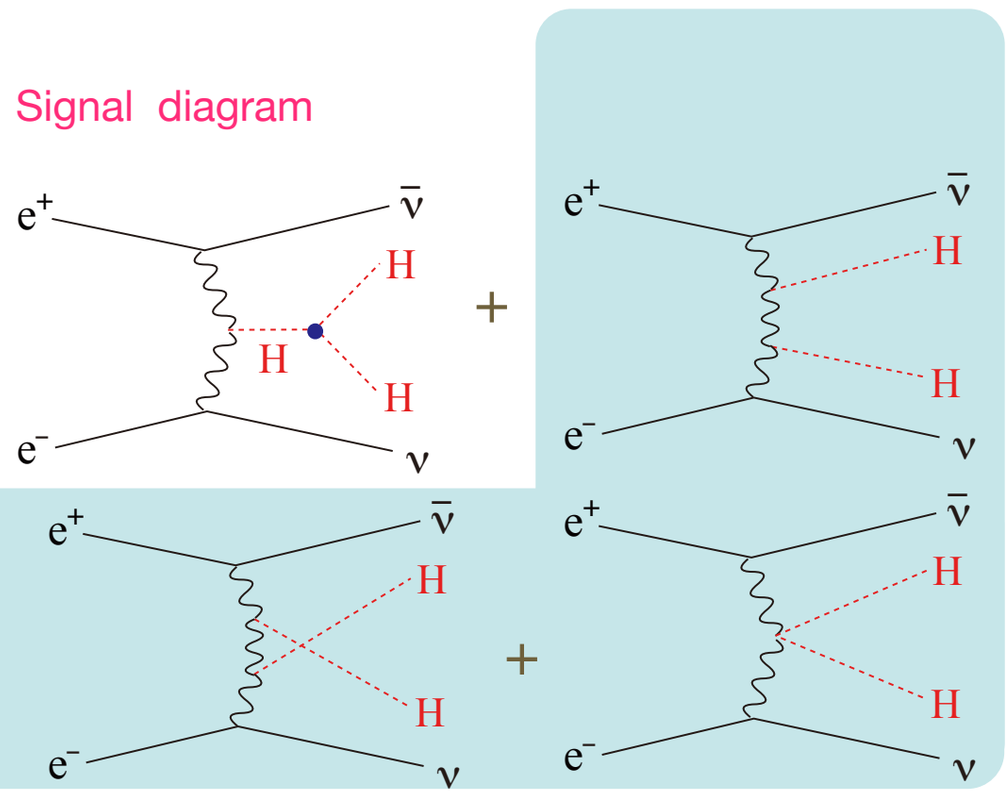
$$\sigma = S\lambda^2 + I\lambda + B$$

(signal diagram) (interference) (background diagram)

Signal diagram



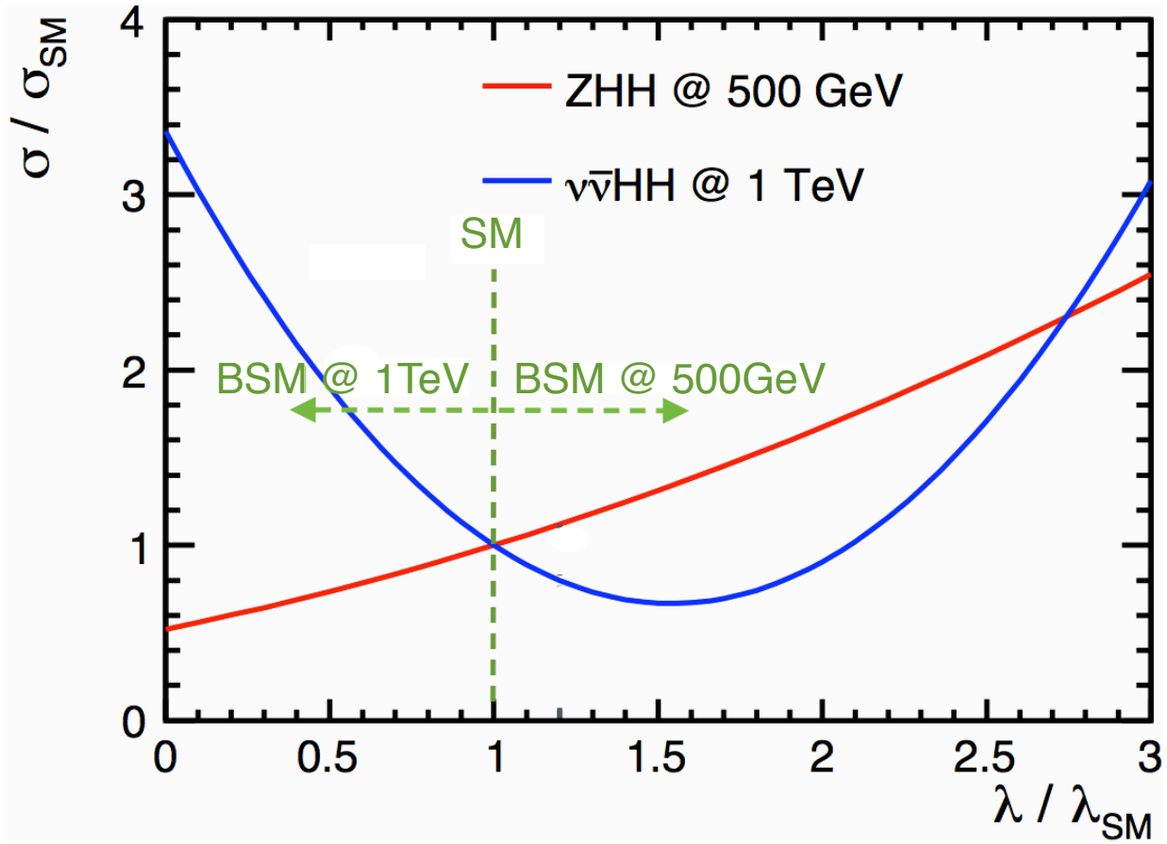
Signal diagram



interference: constructive in ZHH, destructive in vvHH

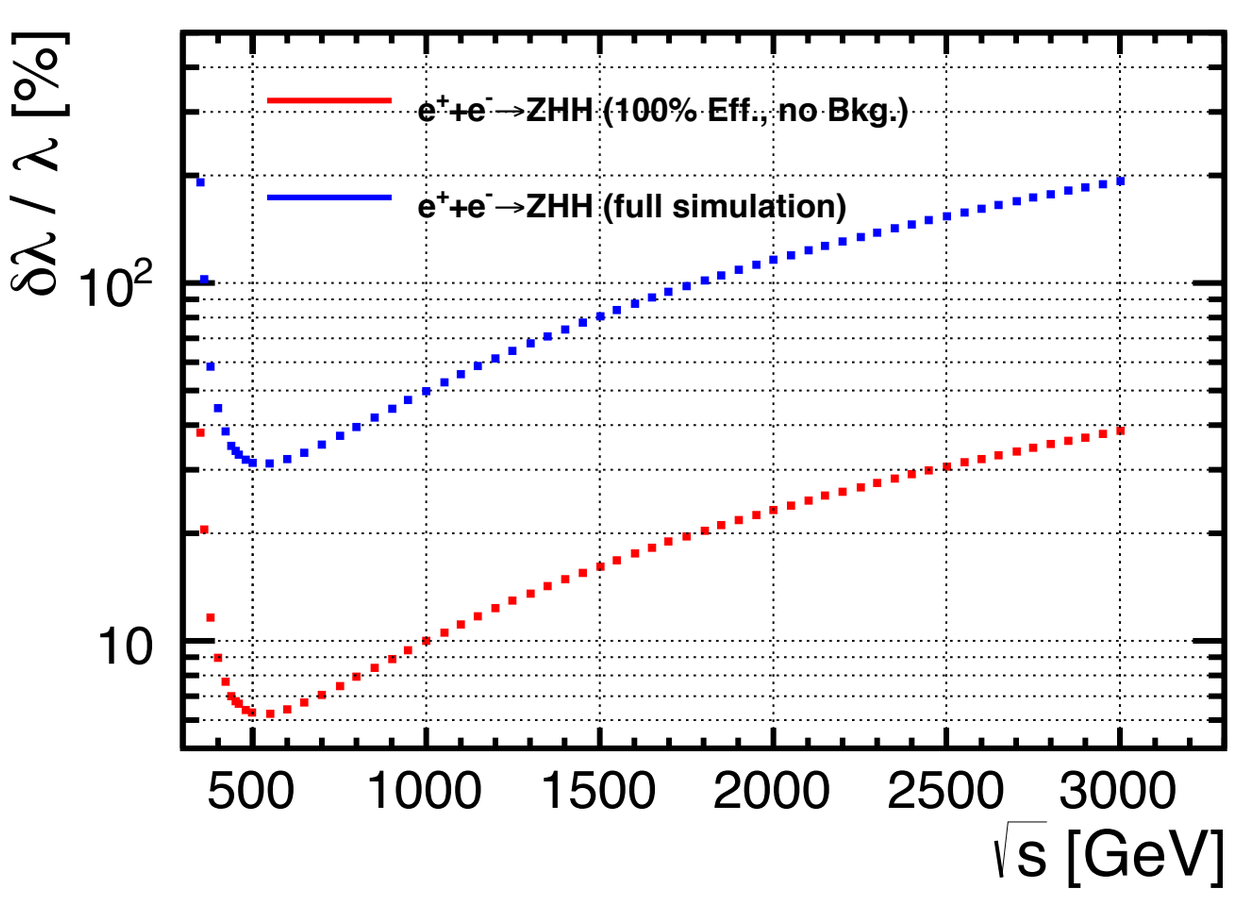
Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

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



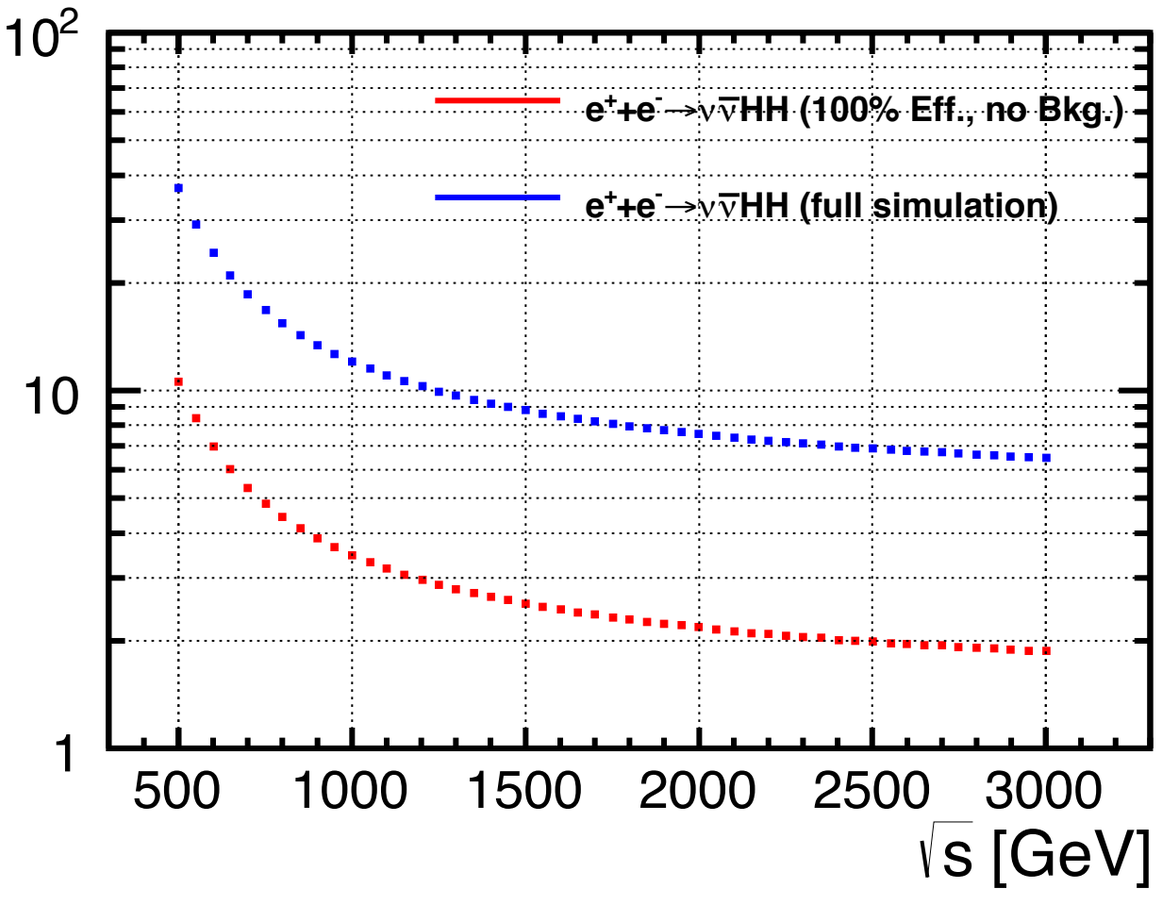
Higgs self-coupling: impact of ECM

ZHH



optimal $\sqrt{s}$~500-600 GeV

ννHH

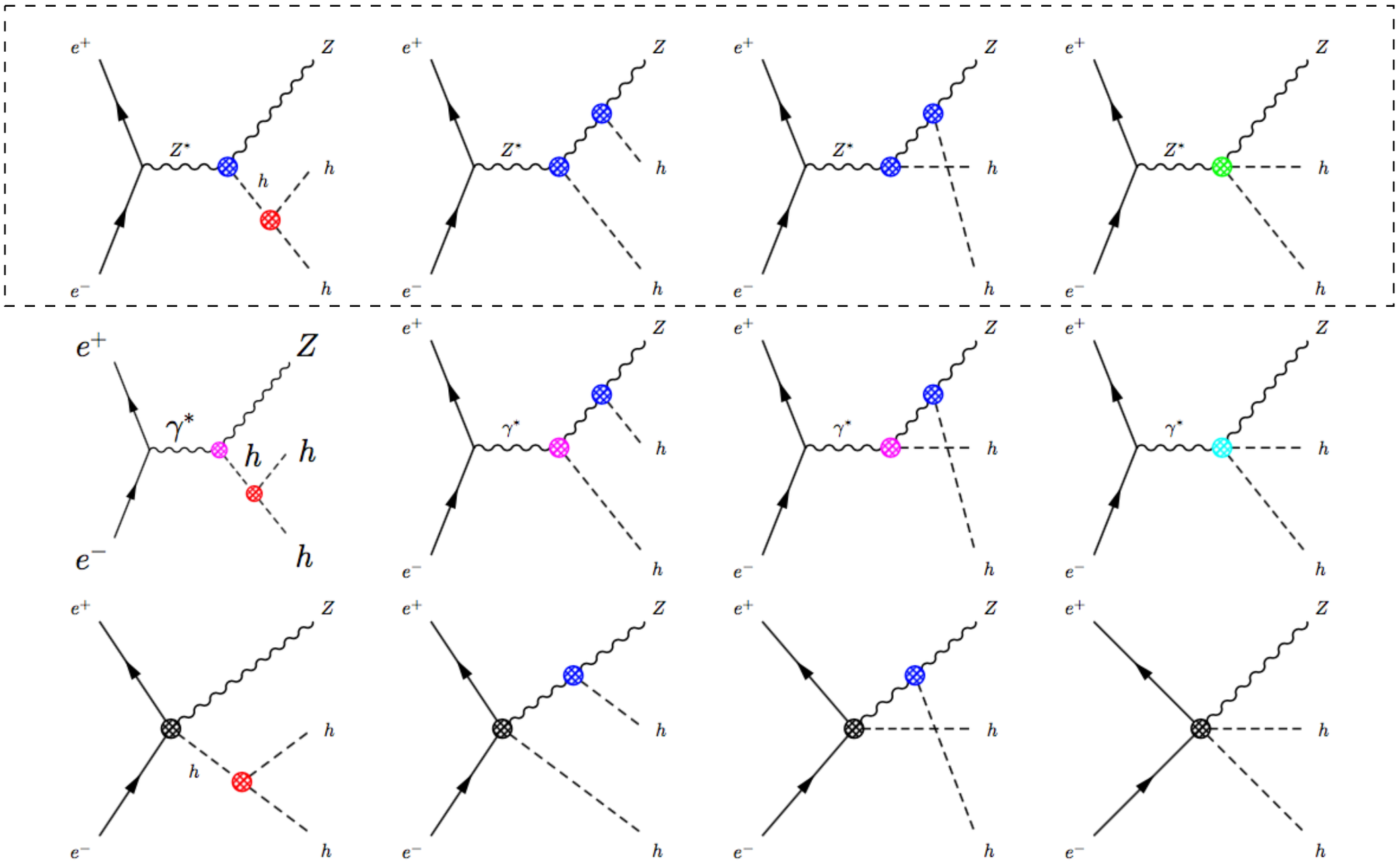


preferred $\sqrt{s}$ >=1 TeV

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



arXiv:1708.09079; arXiv:1708.08912

SM Effective Field Theory: full formalism (23 pars.)

("Warsaw" basis)

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\bar{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\bar{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\bar{e}\gamma_\mu e)\ .$$

10 operators (h,W,Z,γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4 SM parameters: g, g', v, λ

+ 5 operators modifying h couplings to b, c, τ, μ, g

+ 2 parameters for h->invisible and exotic

+ 2 operators for contact interactions with quarks

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

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

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

Barklow, et al
arXiv:1708.09079

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)

summary

- triple Higgs self-coupling can be determined model independently at e+e-
- projections at ILC in SM: 27% by ZHH@500GeV; 10% by vvHH@1TeV; based on full simulation, large room for improvement in future
- two channels are very complementary in BSM: ZHH can play a special role in particular when λ_{hhh} is largely enhanced

backup

Higgs couplings in EFT

$$\begin{aligned}\Delta\mathcal{L}_h = &\frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{2}m_h^2 h^2 - (1+\eta_h)\bar{\lambda} v h^3 + \frac{\theta_h}{v} h\partial_\mu h\partial^\mu h \\ &+(1+\eta_W)\frac{2m_W^2}{v}W_\mu^+ W^{-\mu}h + (1+\eta_{WW})\frac{m_W^2}{v^2}W_\mu^+ W^{-\mu}h^2 \\ &+(1+\eta_Z)\frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2}Z_\mu Z^\mu h^2 \\ &+\zeta_W \hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) \\ &+\frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v}+\frac{1}{2}\frac{h^2}{v^2}\right) .\end{aligned}$$

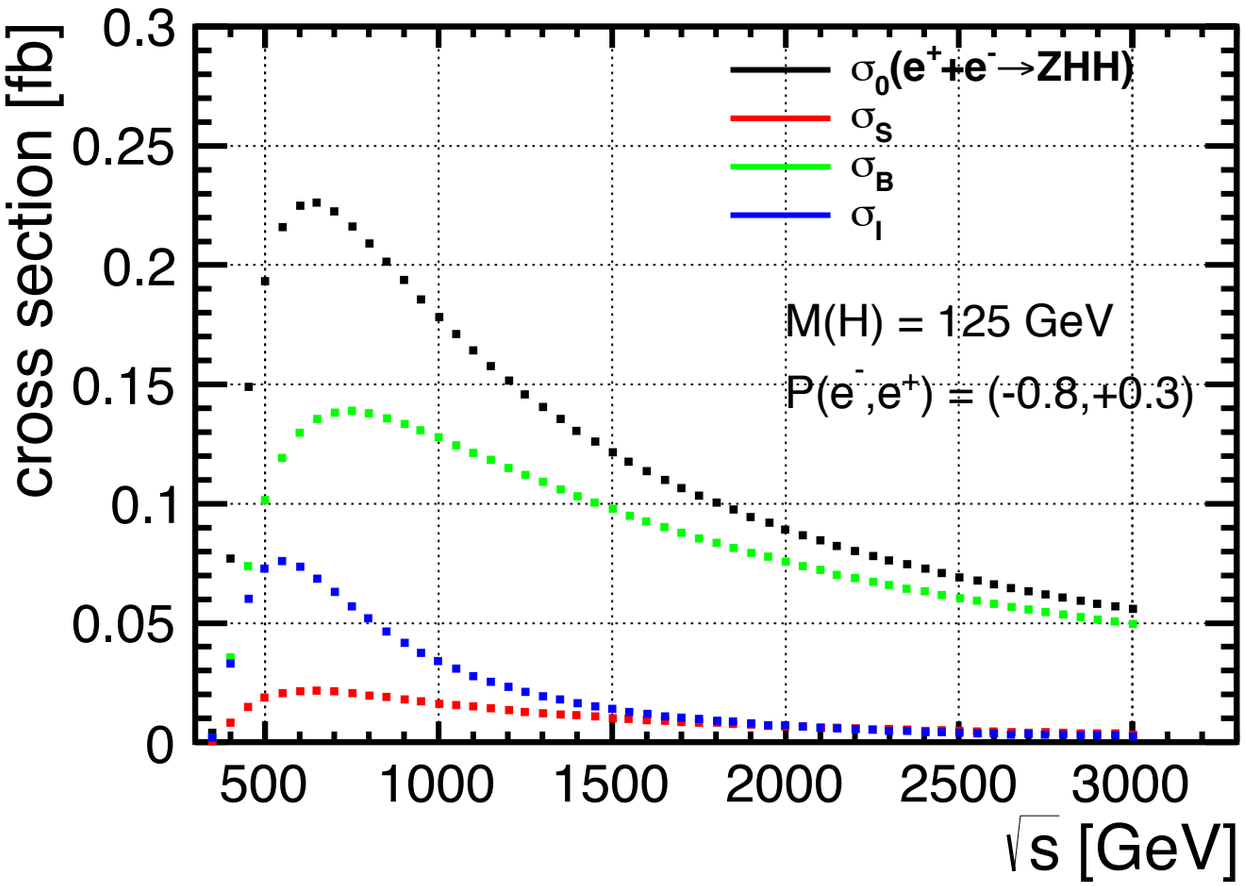
$$\begin{aligned}\eta_h &= \delta\bar{\lambda} + \delta v - \frac{3}{2}c_H + c_6 \\ \eta_W &= 2\delta m_W - \delta v - \frac{1}{2}c_H \\ \eta_{WW} &= 2\delta m_W - 2\delta v - c_H \\ \eta_Z &= 2\delta m_Z - \delta v - \frac{1}{2}c_H - c_T \\ \eta_{ZZ} &= 2\delta m_Z - 2\delta v - c_H - 5c_T\end{aligned}$$

$$\begin{aligned}\theta_h &= c_H \\ \zeta_W = \delta Z_W &= (8c_{WW}) \\ \zeta_Z = \delta Z_Z &= c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB}) \\ \zeta_A = \delta Z_A &= s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \\ \zeta_{AZ} = \delta Z_{AZ} &= s_w c_w\left((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\right)\end{aligned}$$

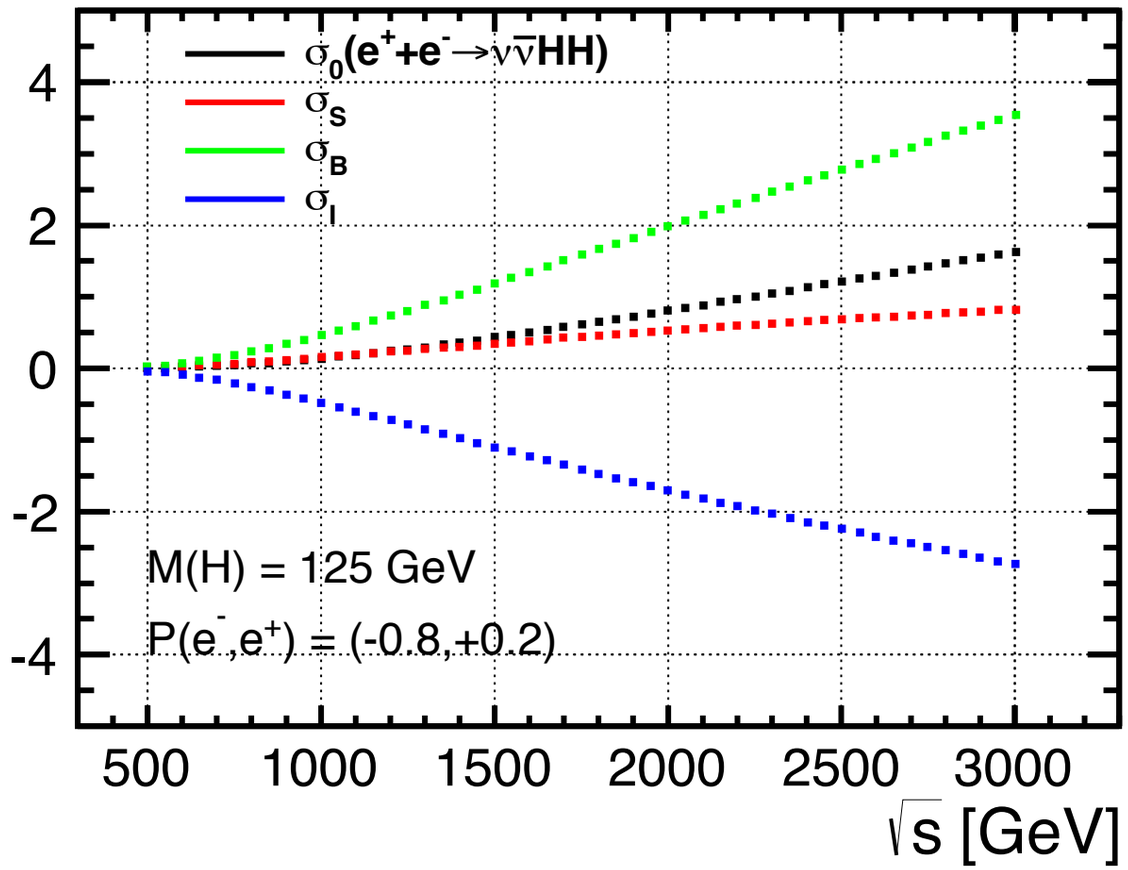
Higgs self-coupling: impact of ECM

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

ZHH



ννHH

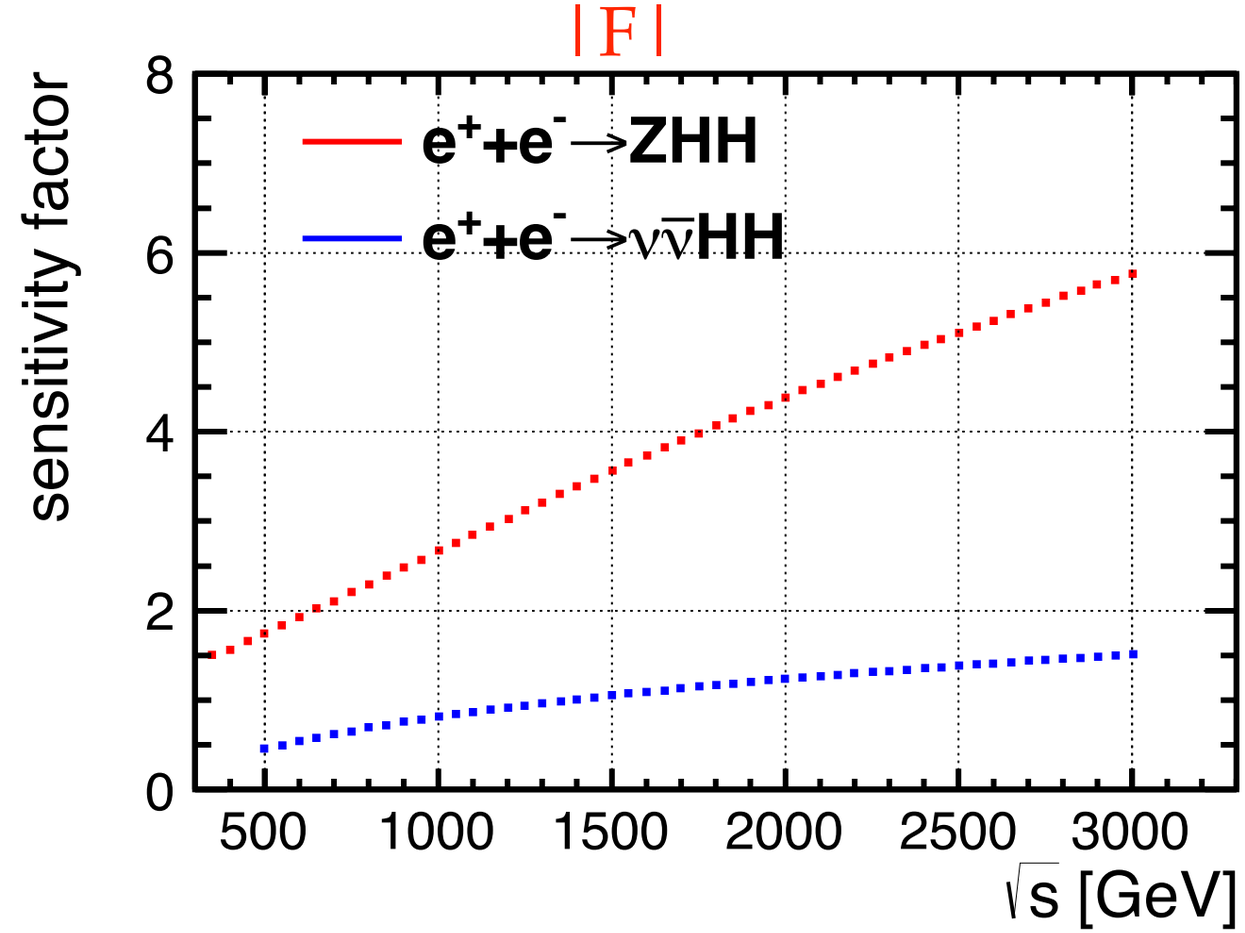


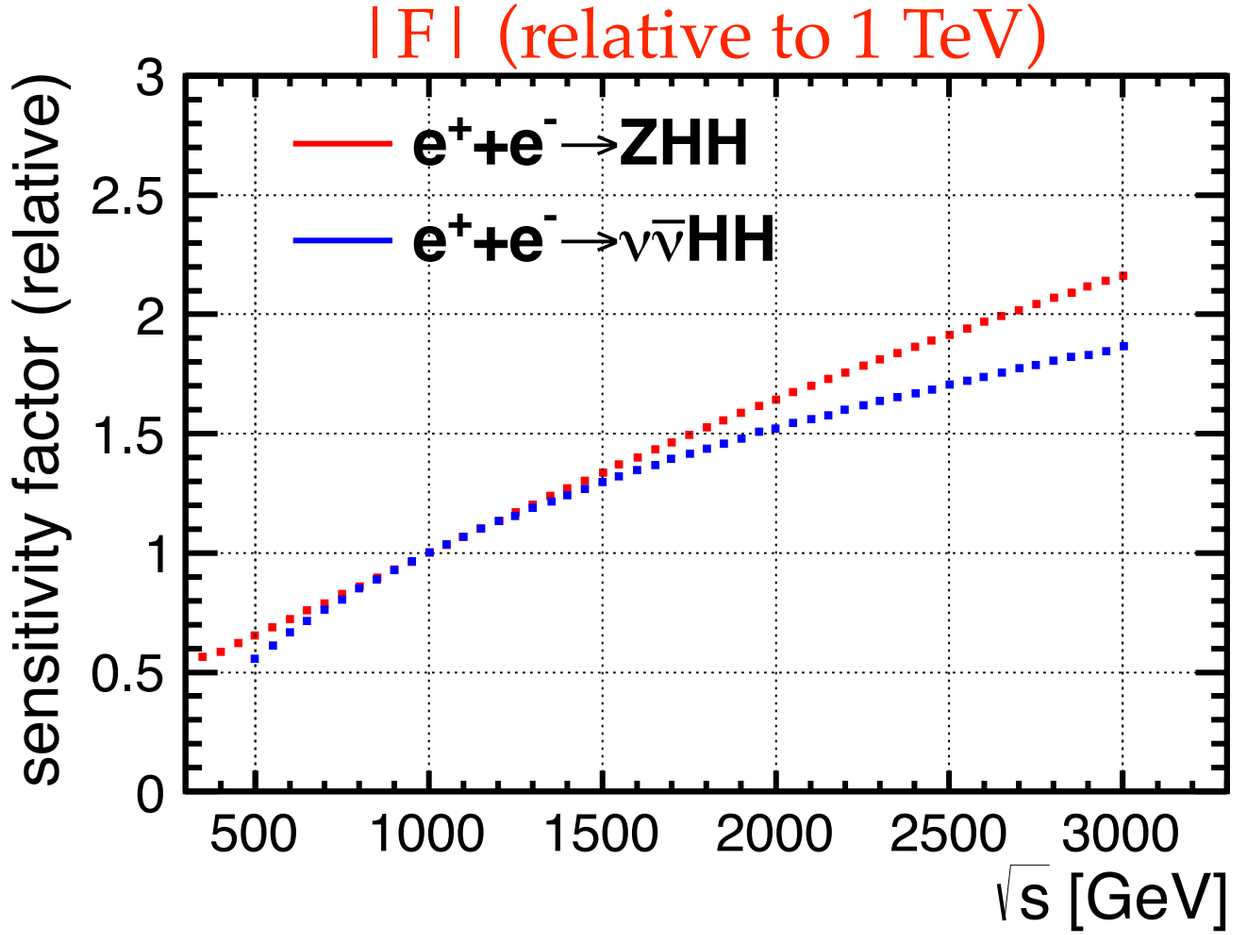
Higgs self-coupling: impact of ECM

$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

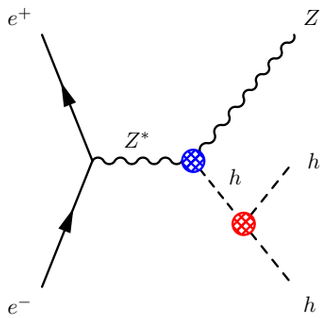
$$F = \frac{\sigma}{2S\lambda^2 + I\lambda}$$

sensitivity factor

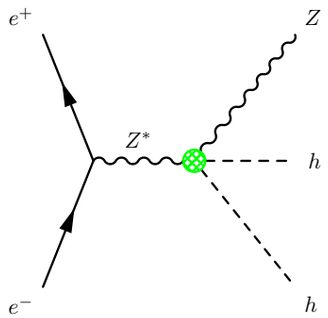




hhVV, hVV and λ_{hhh} in e+e- —> Zhh



(S)



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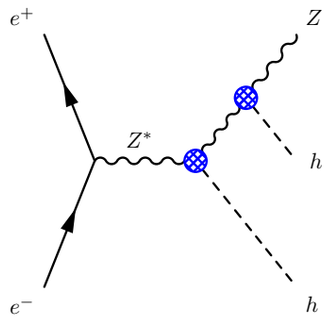

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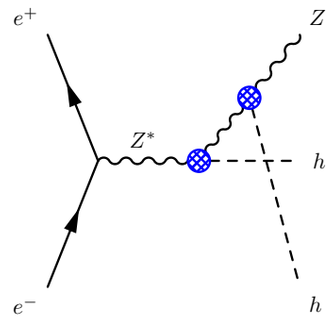
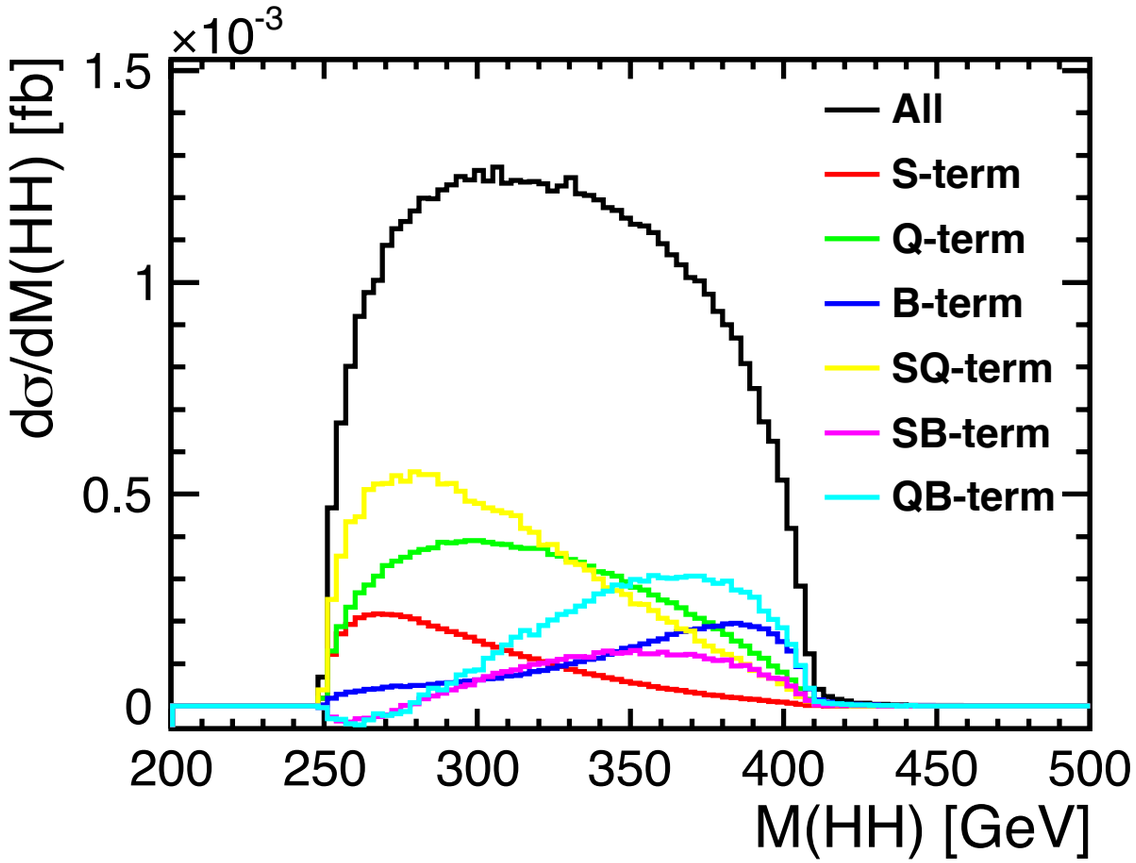
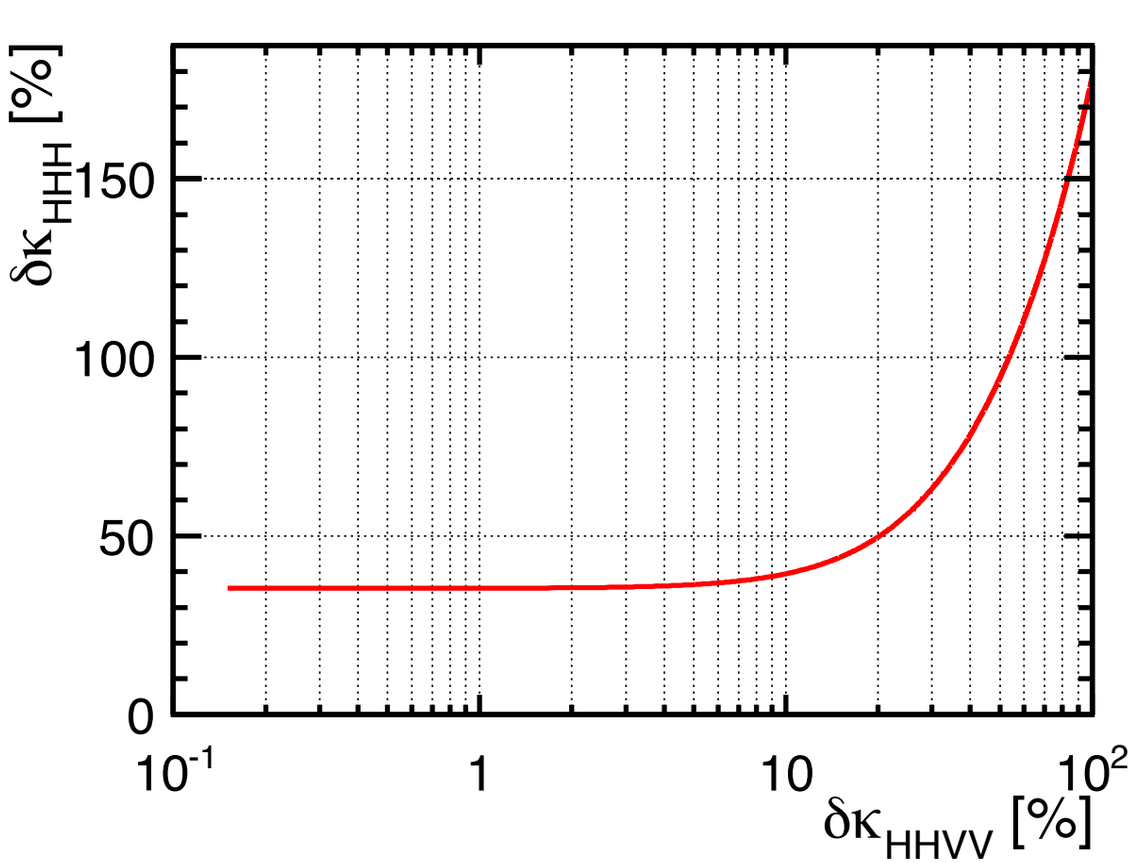


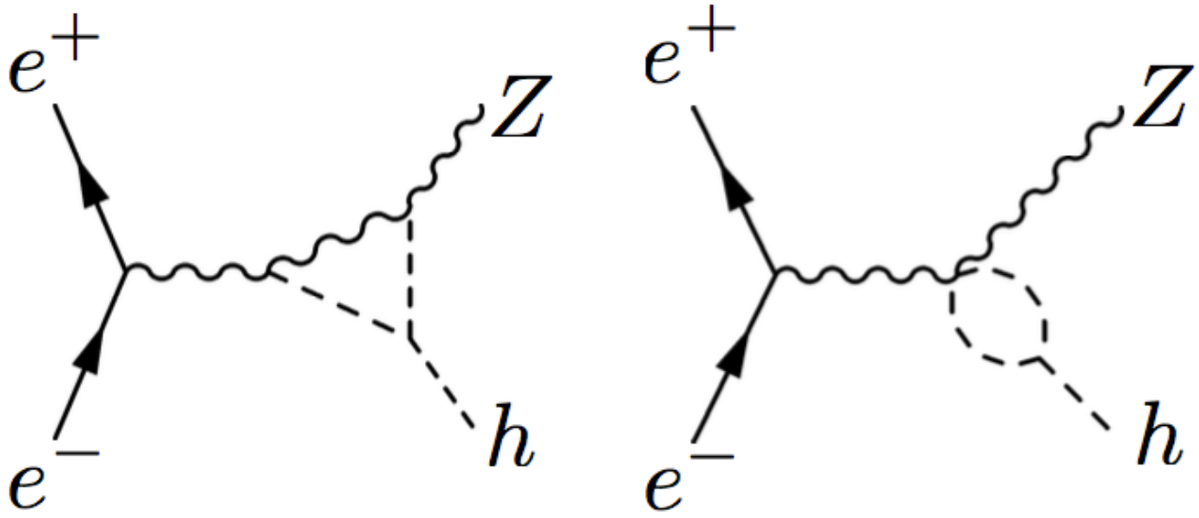
(B)





$\delta\kappa_{hhVV}$ < 5% would be needed —> challenging by shape

Higgs self-coupling: indirect determination



McCullough, arXiv:1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources

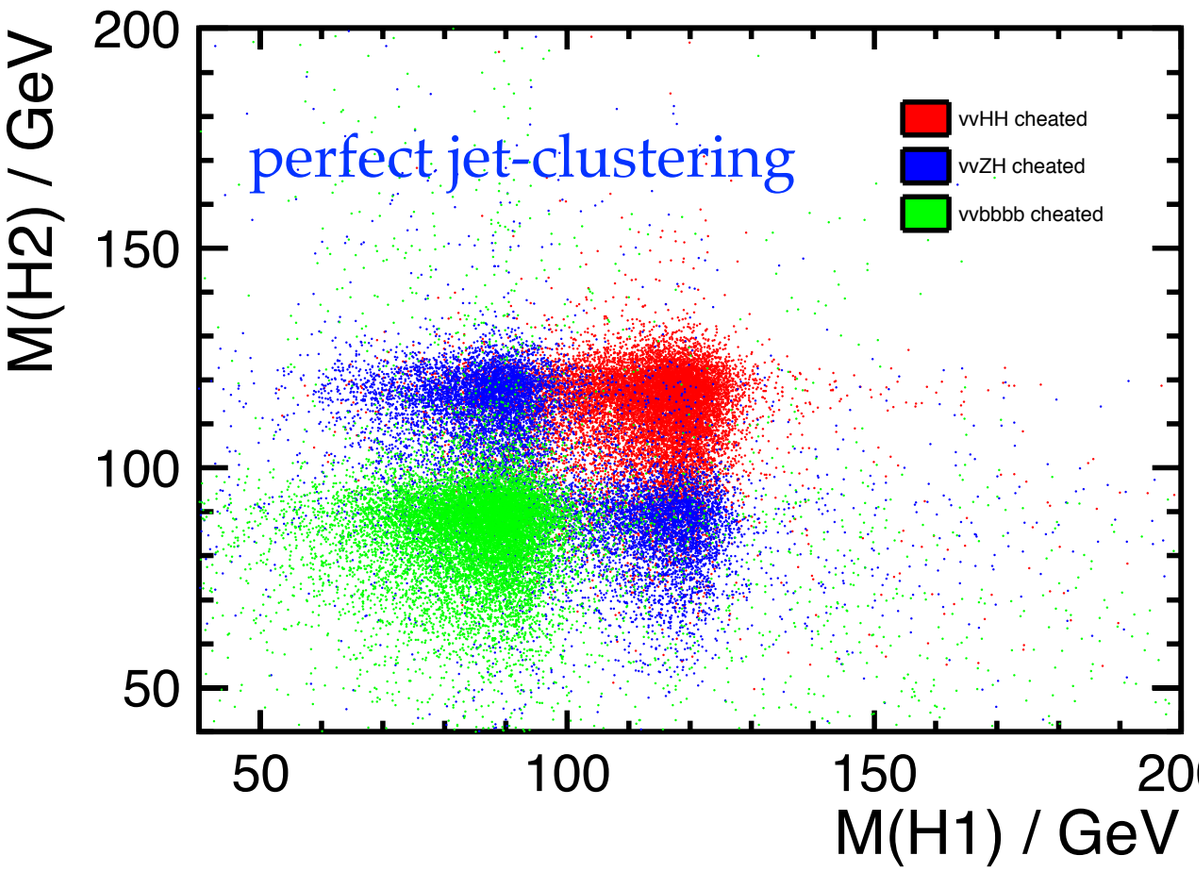
  —> **δh ~ 500%** at 250GeV only; Gu, Liu, et al, arXiv:1711.03978

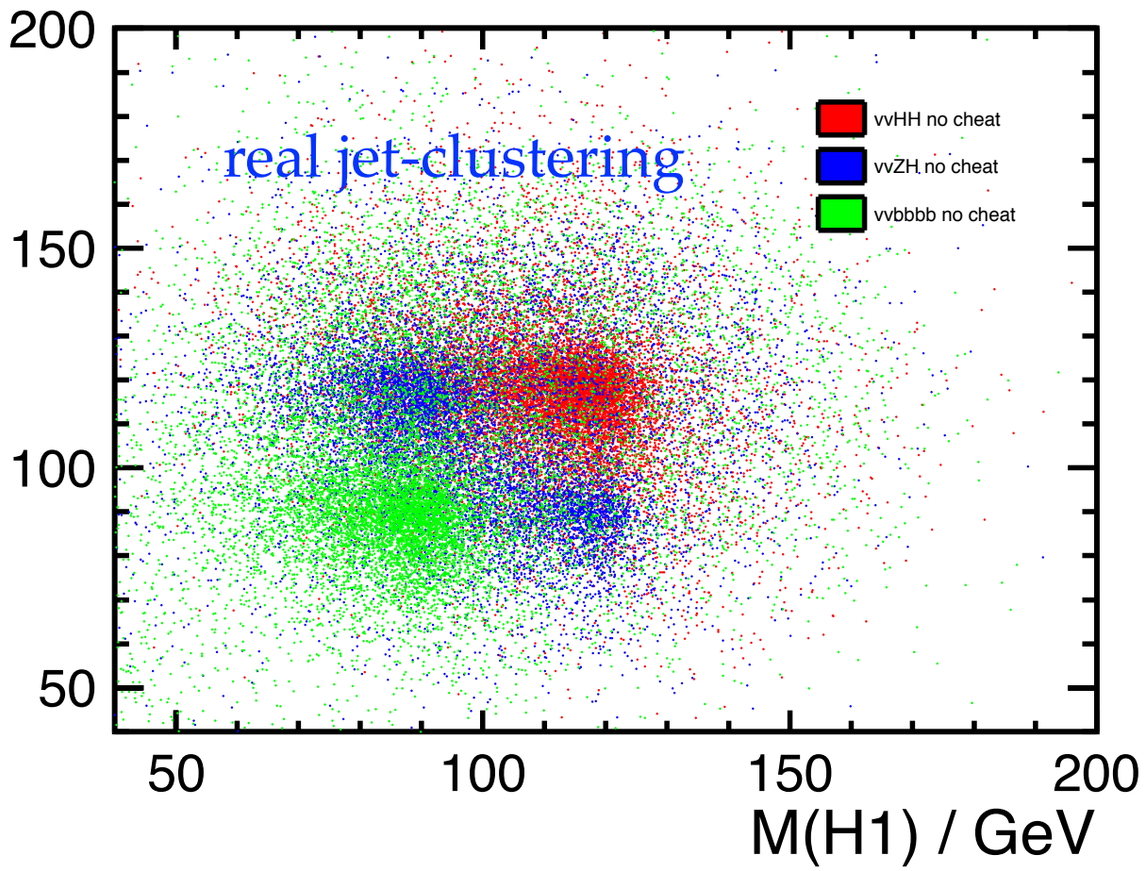
- what if we also include other NLO effects as well?

impact of jet-clustering algorithm

ννHH mode: (BG: ZZH and ZZZ)

scatter plot of two Higgs masses





- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%!