Prospects of the Higgs self-coupling measurements @ the linear colliders

— focusing on the physics issues and impact of ecm

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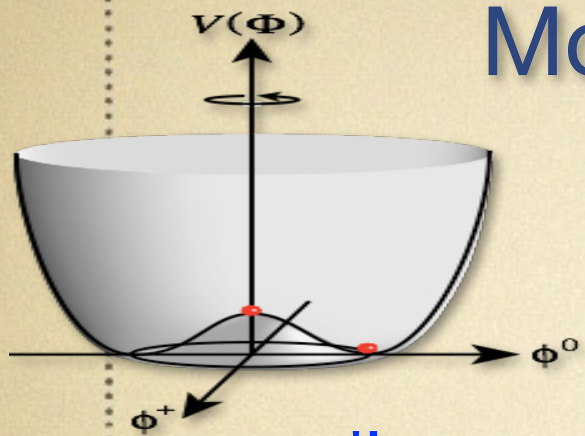
Motivation to measure Higgs self-coupling

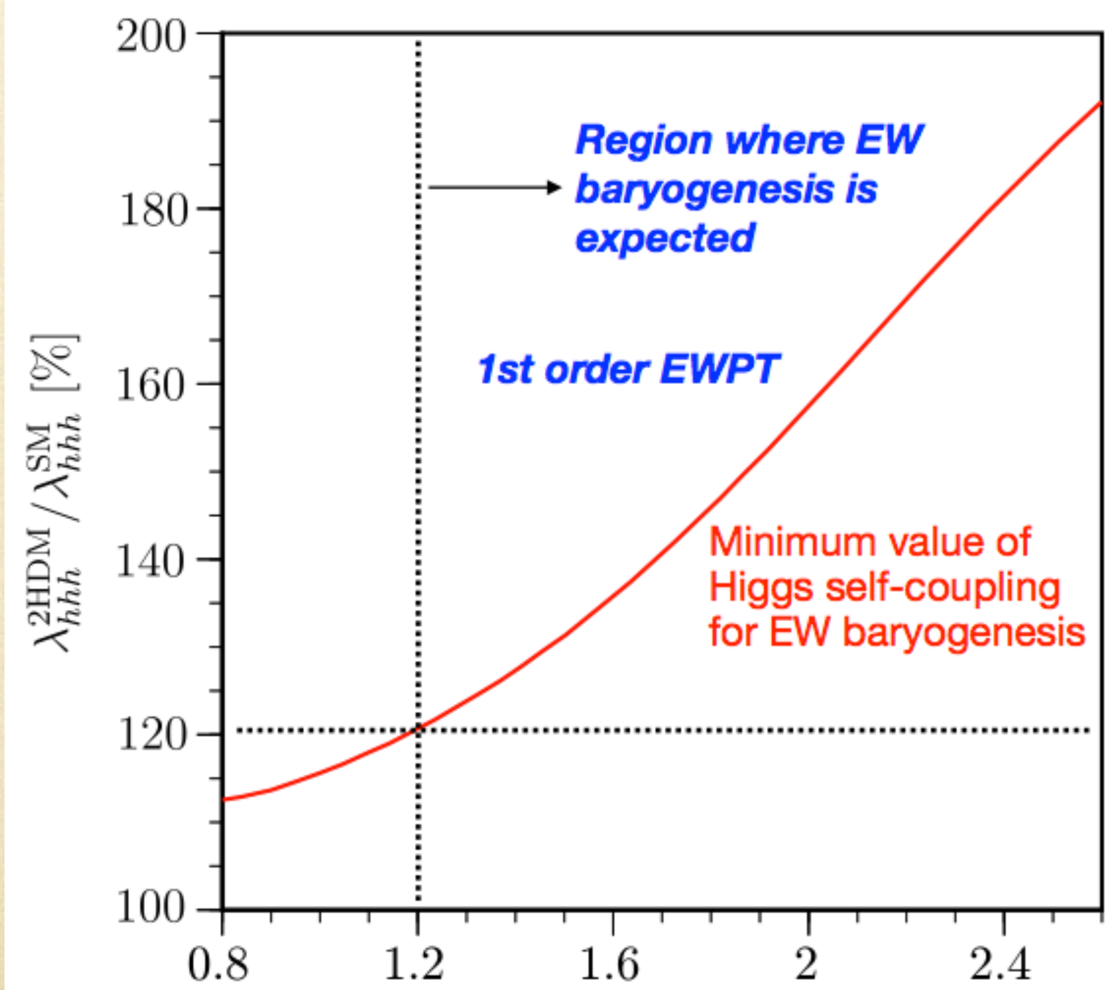


$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

- discover the force that makes Higgs condense in vacuum
- direct probe of the Higgs potential
- test the EWSB mechanism
- test extended Higgs sector
- test electroweak baryogenesis

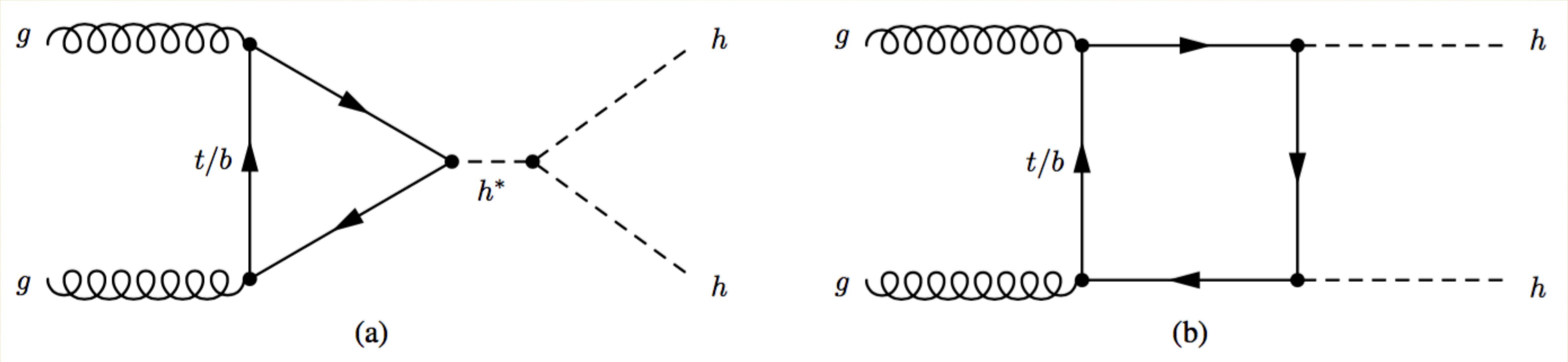
	$N=1$		
	(I)	(II)	(III)
$\lambda_{\rm hhh}/\lambda_{\rm hhh}^{\rm (SM)}$	1.7	1.8	1.8
$\lambda_{\rm hhhh}/\lambda_{\rm hhhh}^{\rm (SM)}$	3.7	4.3	4.5

Endo, Sumino, arXiv:1505.02819



Senaha, Kanemura

measurement of Higgs self-coupling @ LHC



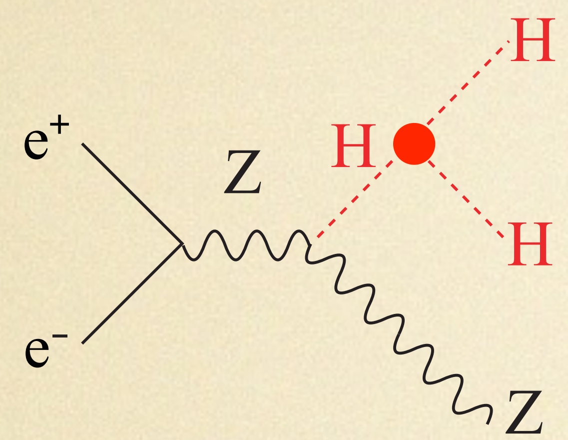
LHC Run1: pp—>hh @ ATLAS   95% C.L. upper limit: $\sigma/\sigma_{SM} < 70$ (48)

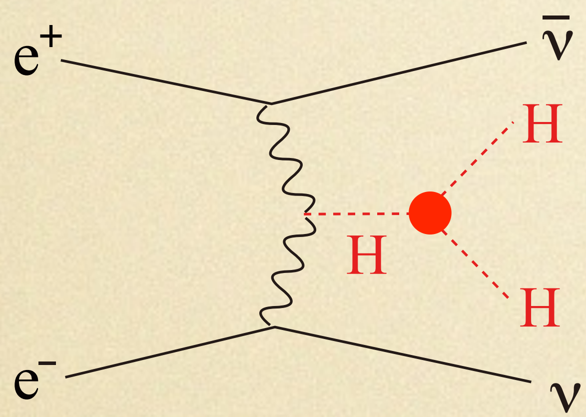
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

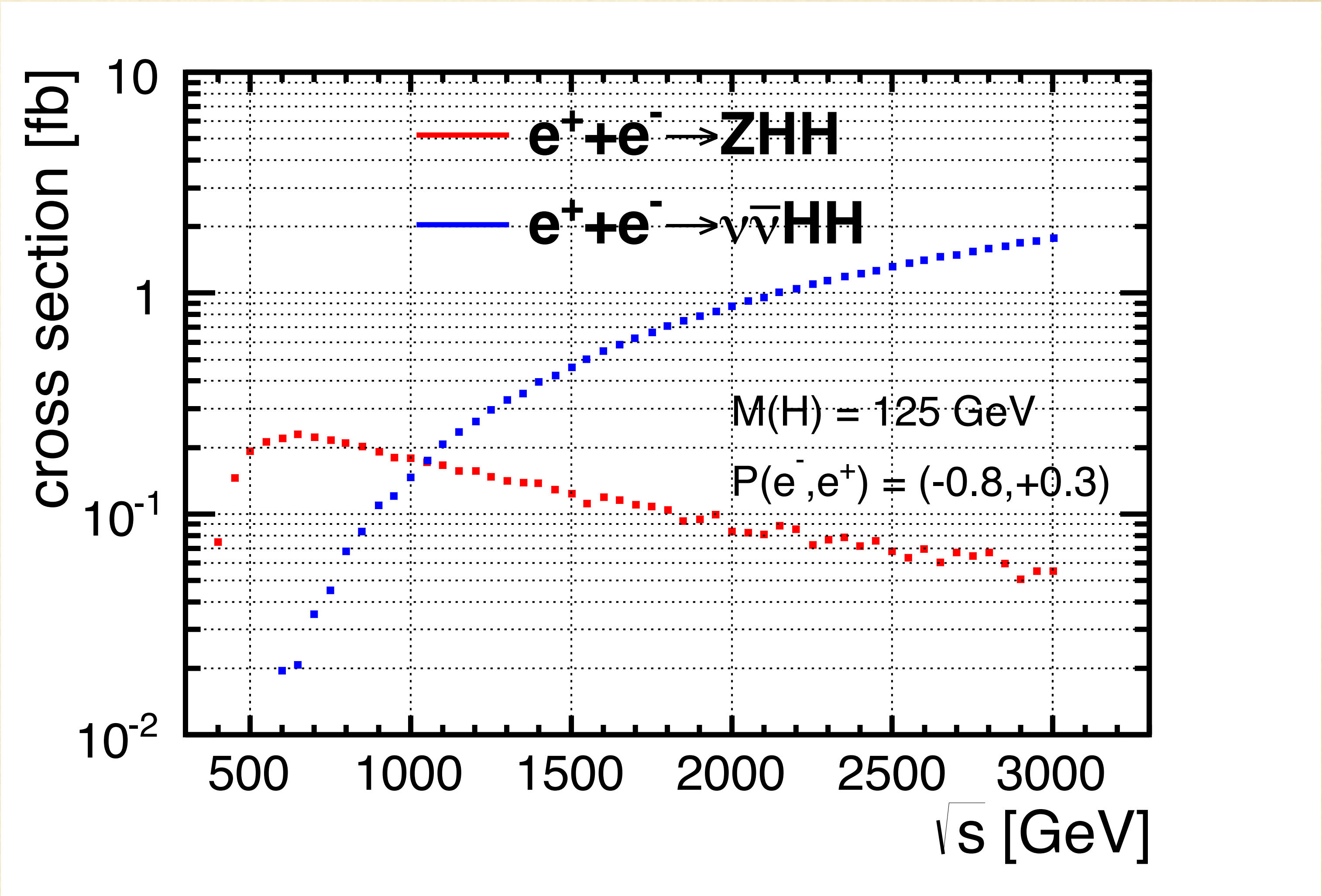
arXiv:1509.0467

Snowmass Higgs working group: $\delta\lambda_{HHH}/\lambda \sim 50\%$ @ 14 TeV, 3000 fb^{-1}
(arXiv: 1310.8361)

prospects of Higgs self-coupling @ linear colliders







prospects from full simulation studies:

ILC

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	29%	10%

CLIC

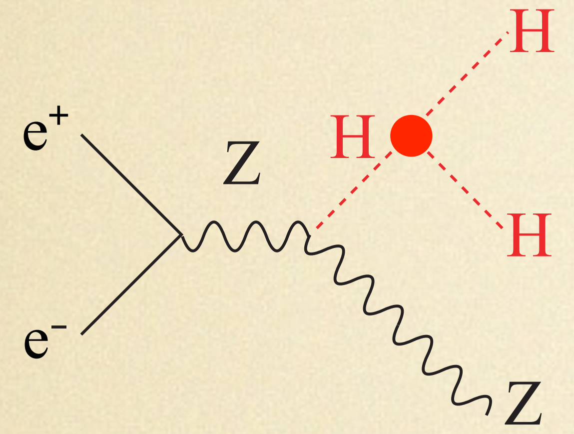
1.4 TeV	+3 TeV
21%	10%

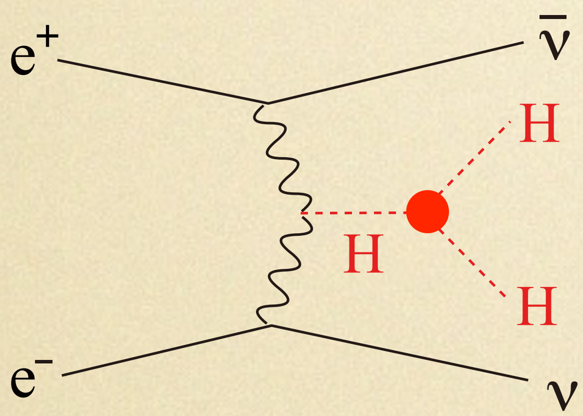
(ref. H20 arXiv: 1506.07870)

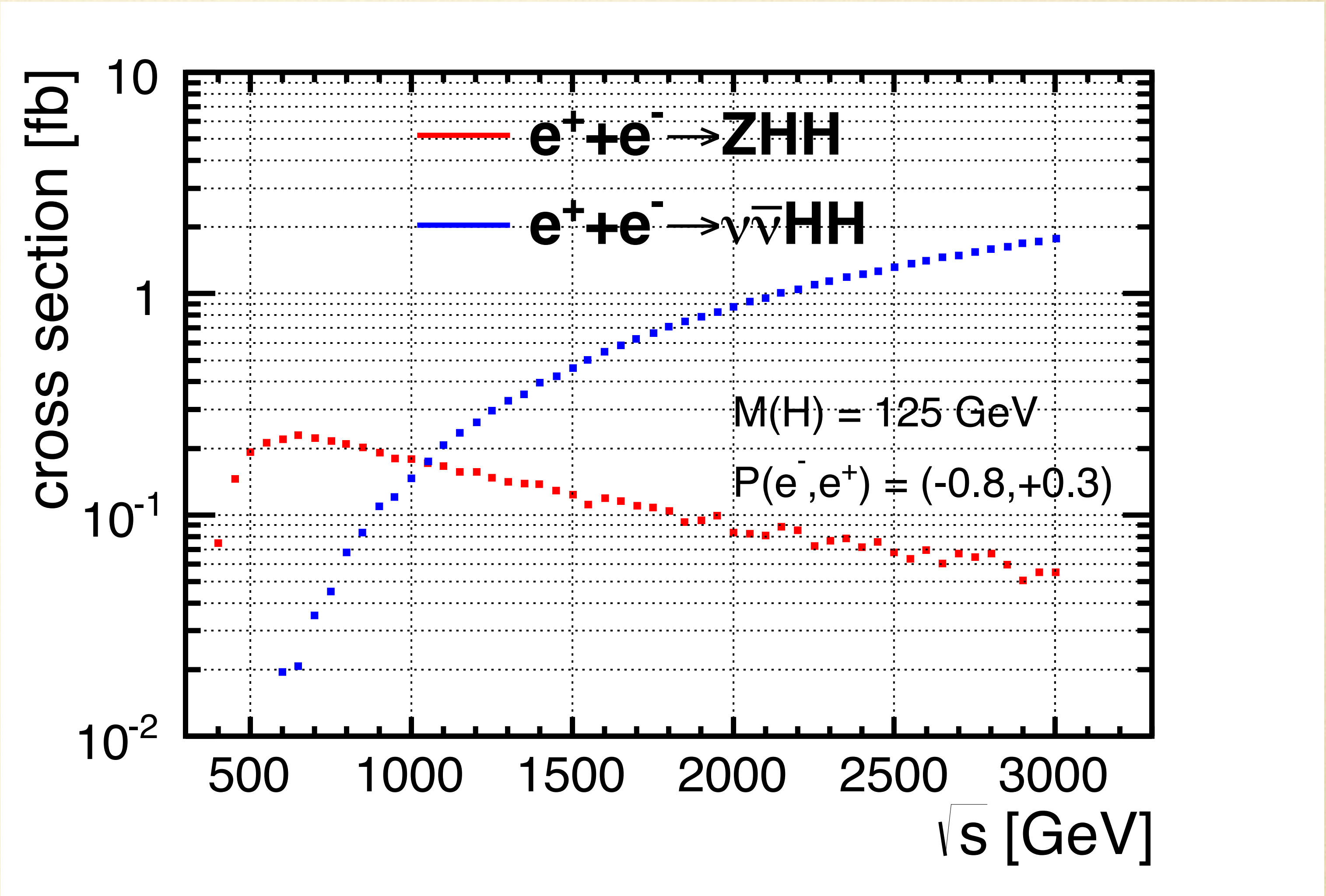
(arXiv: 1307.5288)

J. Tian, LC-REP-2013-003 C. Dürig @ ALCW15 M. Kurata, LC-REP-2014-025

λ_{HHH} @LCs: impact of ecm



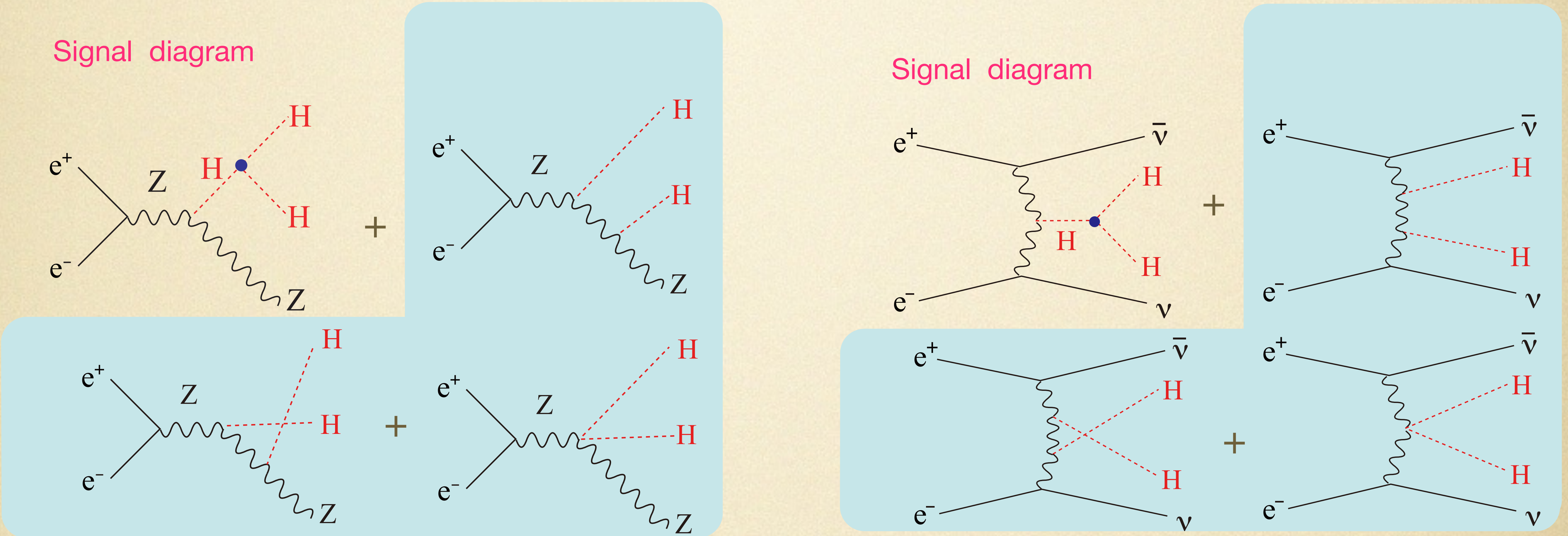




For ZHH: 500 GeV seems not the optimal energy?

For ννHH: isn't 3 TeV much better than 1 TeV?

physics issues: diagrams for double Higgs production



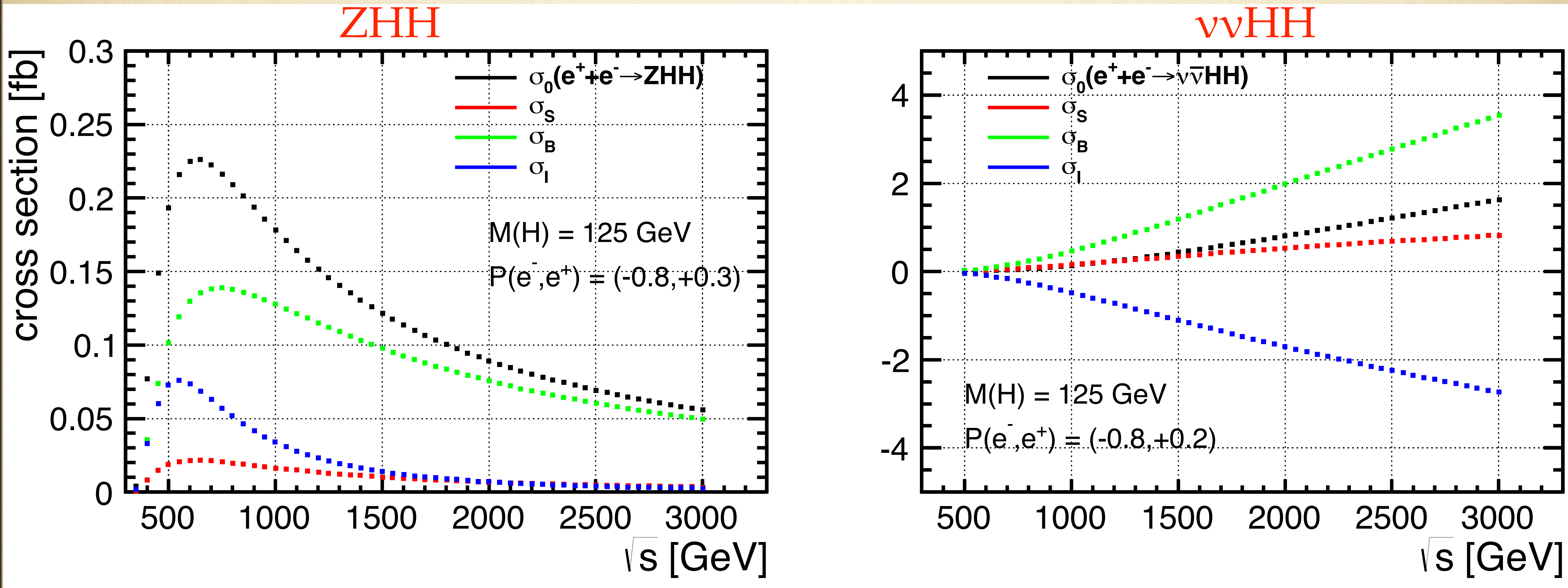
$$\sigma = S\lambda^2 + I\lambda + B$$

(signal diagram) (interference) (background diagram)

- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

breakdown of σ to *S*, *I* and *B* terms

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



- B term (green) >> S term (red) —> more difficult than expected
- interference I term (blue) plays an crucial role in both cases; larger I term for ννHH indicates potential better sensitivity in ννHH than ZHH
- For ZHH: clearly ~500-600 GeV is preferred; peak positions of I or S term are smaller than that of B term and the apparent total σ (black)
- For ννHH: dependence on ecm, S term < apparent σ < B term ≈ I term

sensitivity of λ to the direct measured σ

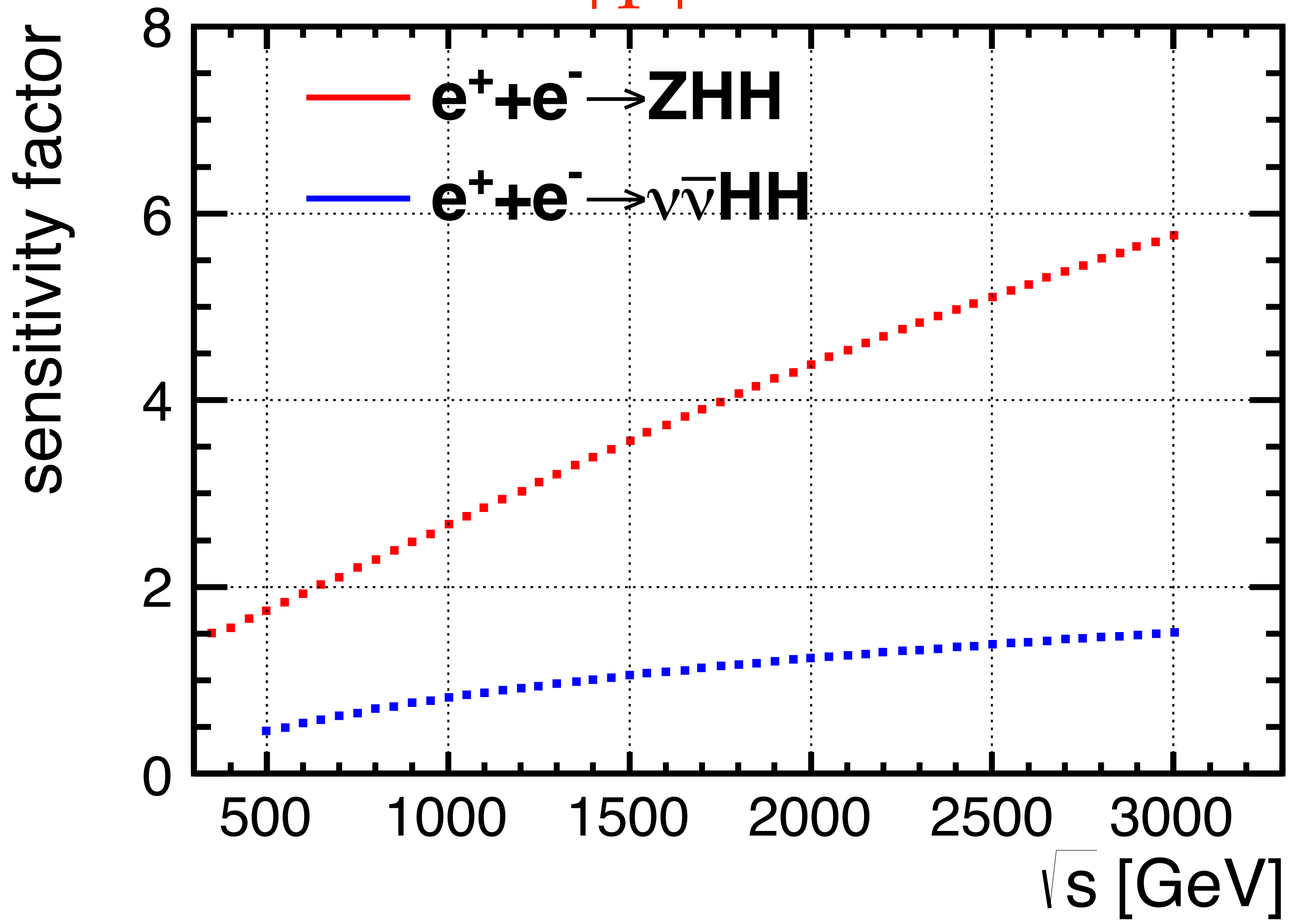
$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

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

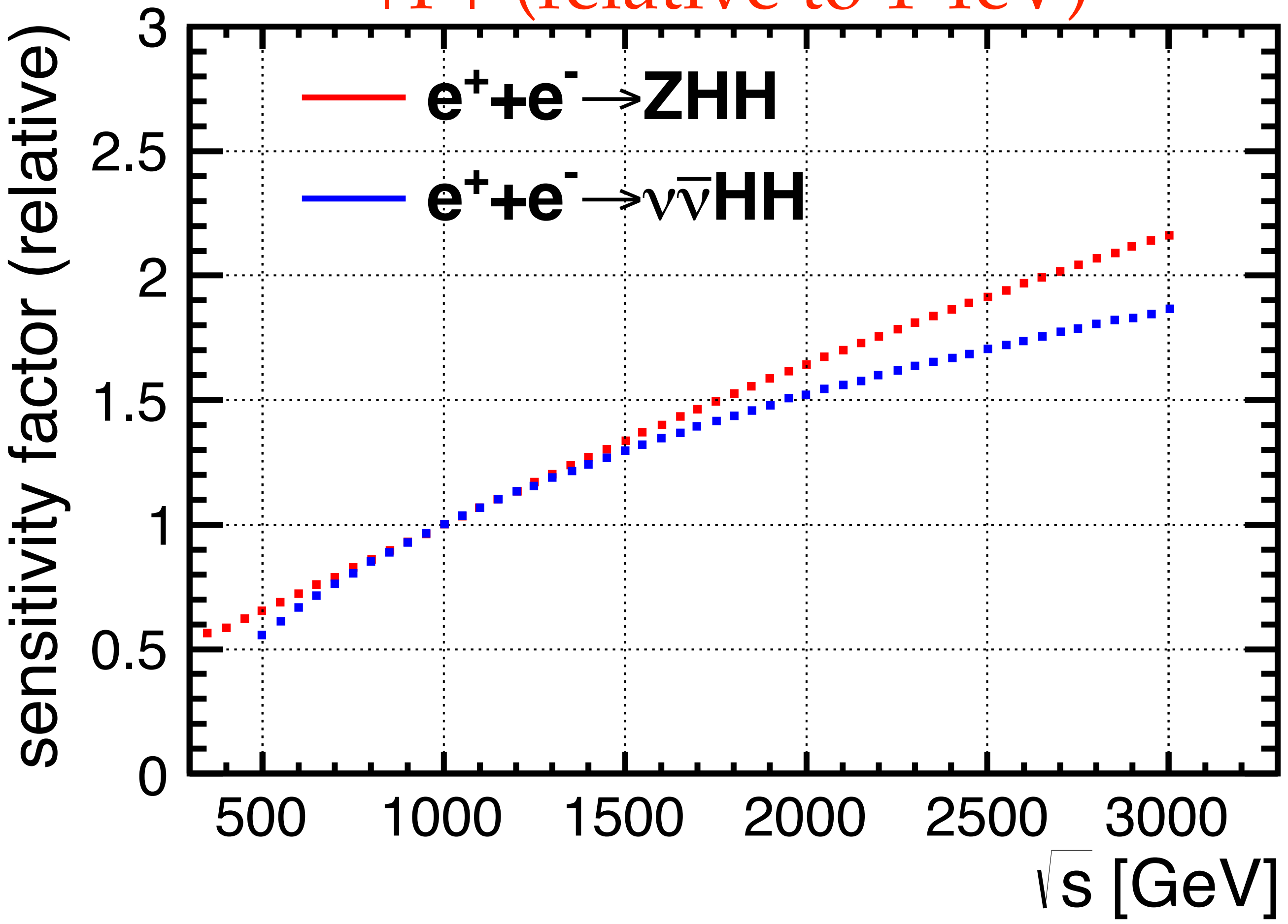
sensitivity factor

- smaller F means better sensitivity; if only signal diagram, F=0.5
- F in ZHH indeed much worse than F in ννHH
- in both cases F increases significantly when ecm increases

|F|

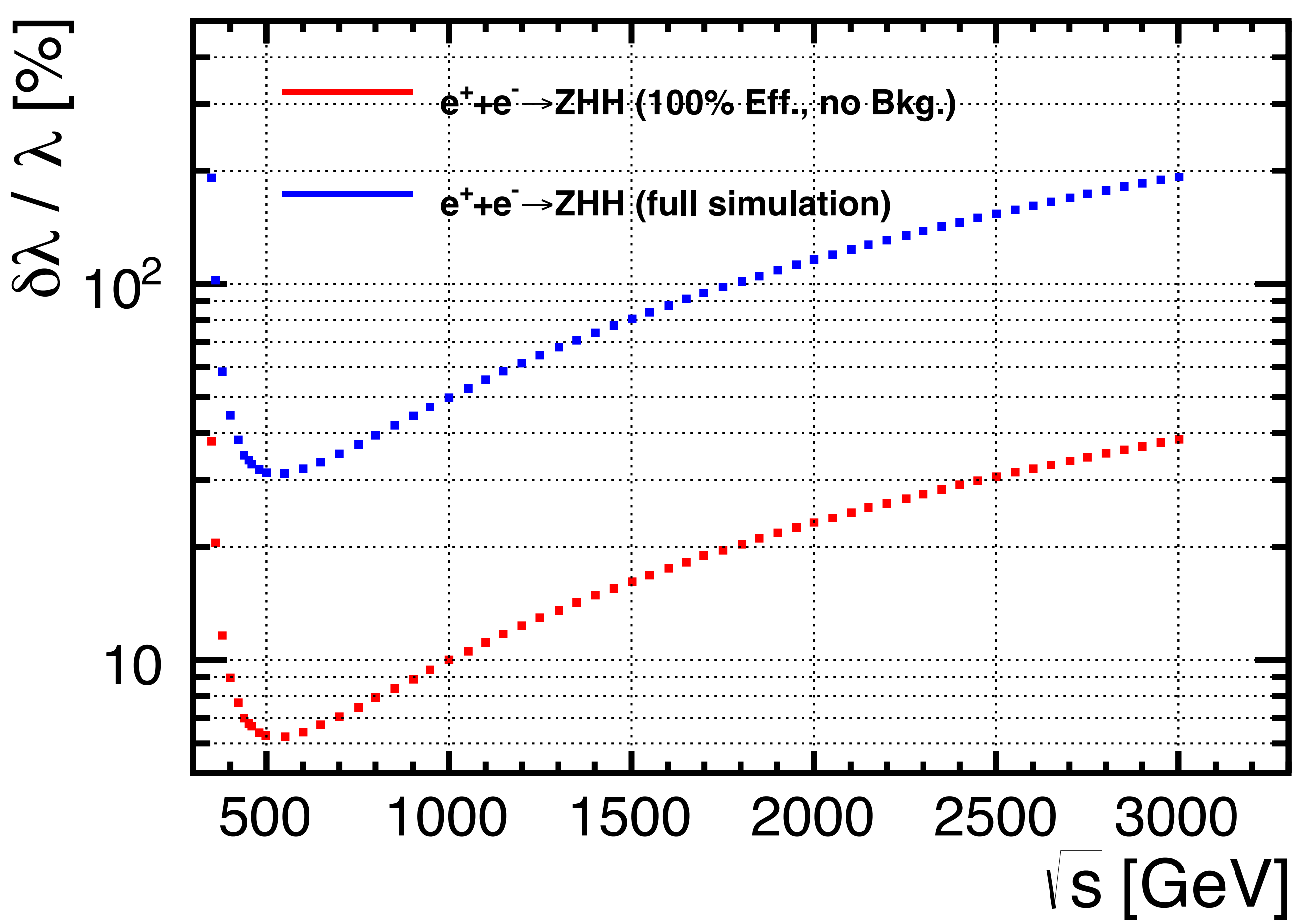


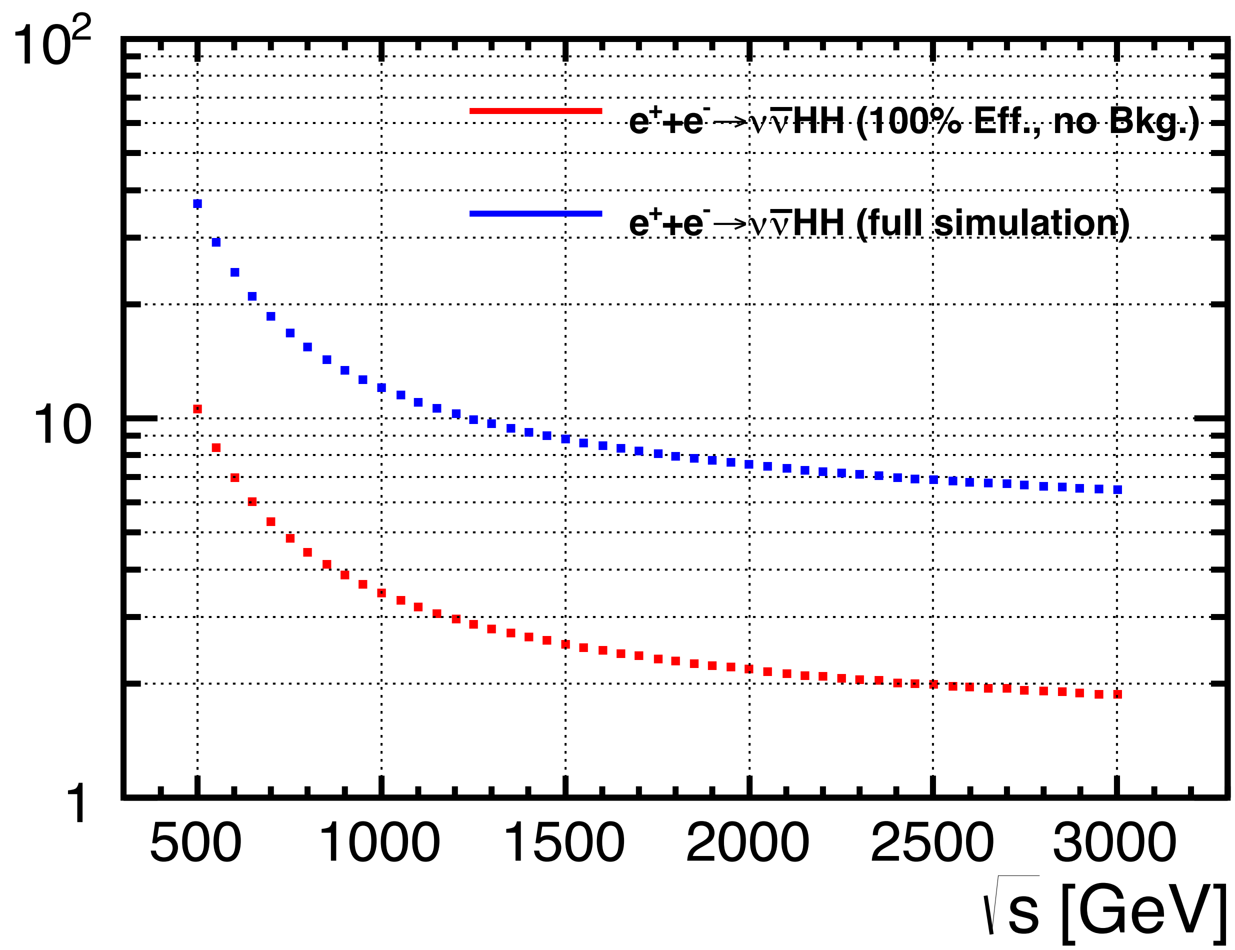
|F| (relative to 1 TeV)



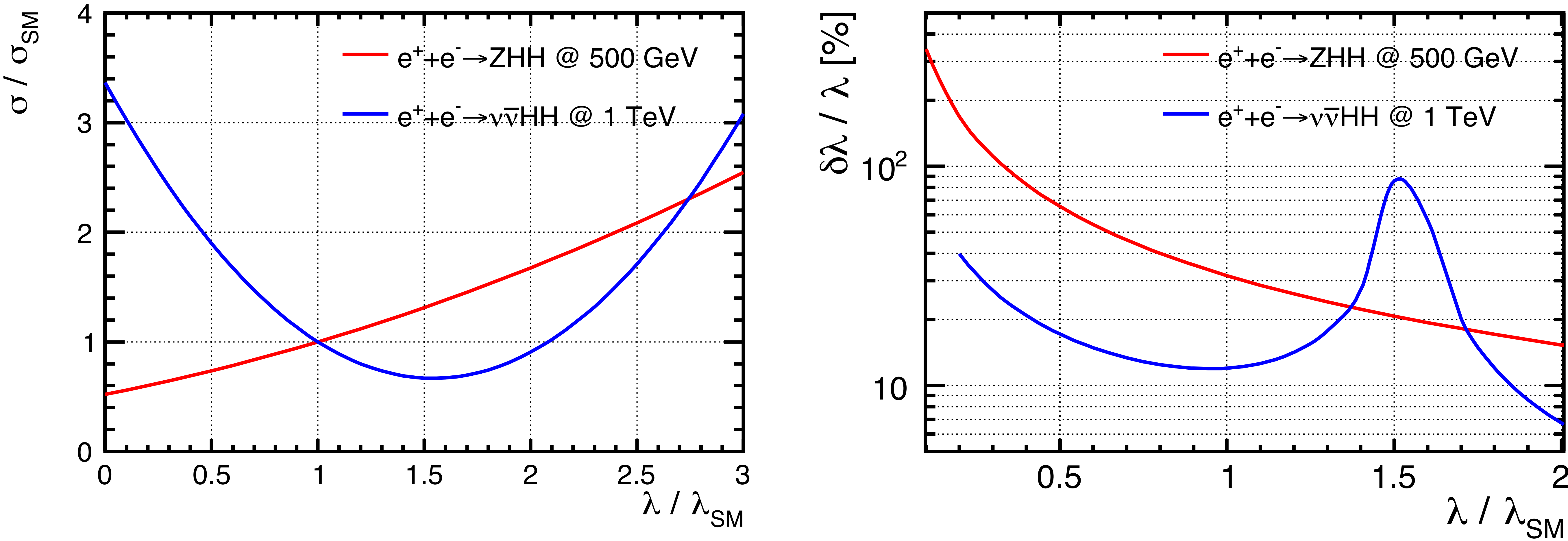
expected precision of λ

- two expectations: (red) theoretical precision assuming 100% signal efficiency and no background; (blue) realistic precision based on the state-of-the-art full detector simulation studies at the ILC
- in both cases at all energies, integrated luminosity of 4 ab^{-1} is assumed, which is reasonable according to H20 scenarios
- for ZHH: 500 GeV is the optimal energy, $\delta\lambda/\lambda$~30%, but rather mild dependence at around 500-600 GeV, significantly worse if much lower or higher than that
- for ννHH: $\delta\lambda/\lambda$~10% achievable when ecm > 1TeV; better precision at higher ecm, but not drastically, from 1 TeV to 3 TeV, improved by 50%



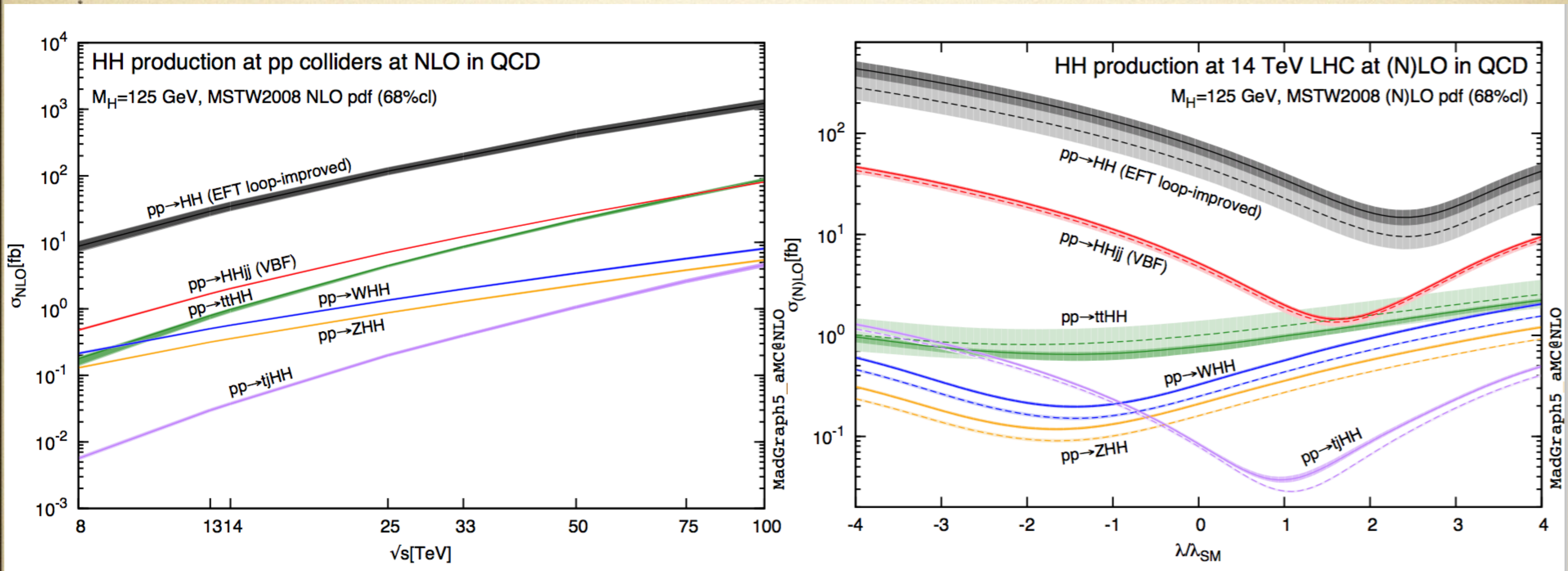


what's the expectation if $\lambda \neq \lambda_{SM}$? @ LCs



- for ZHH, interference is constructive, enhanced λ will increase the total σ, and improve sensitive factor as well, e.g. if $\lambda = 2\lambda_{SM}$, σ increase by 60%, F decease by half, $\delta\lambda/\lambda$ ~15%, —> we may finish the λ story at 500 GeV ILC
- for ννHH, interference is destructive, enhanced λ will decrease σ, minimum when λ~$1.5\lambda_{SM}$, $\delta\lambda/\lambda$ degrade significantly if $\lambda/\lambda_{SM} \in (1.3, 1.7)$
- but if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely on more on ννHH
- two channels are complementary in terms of λ measurement in BSM

what's the expectation if $\lambda \neq \lambda_{SM}$? @ LHC

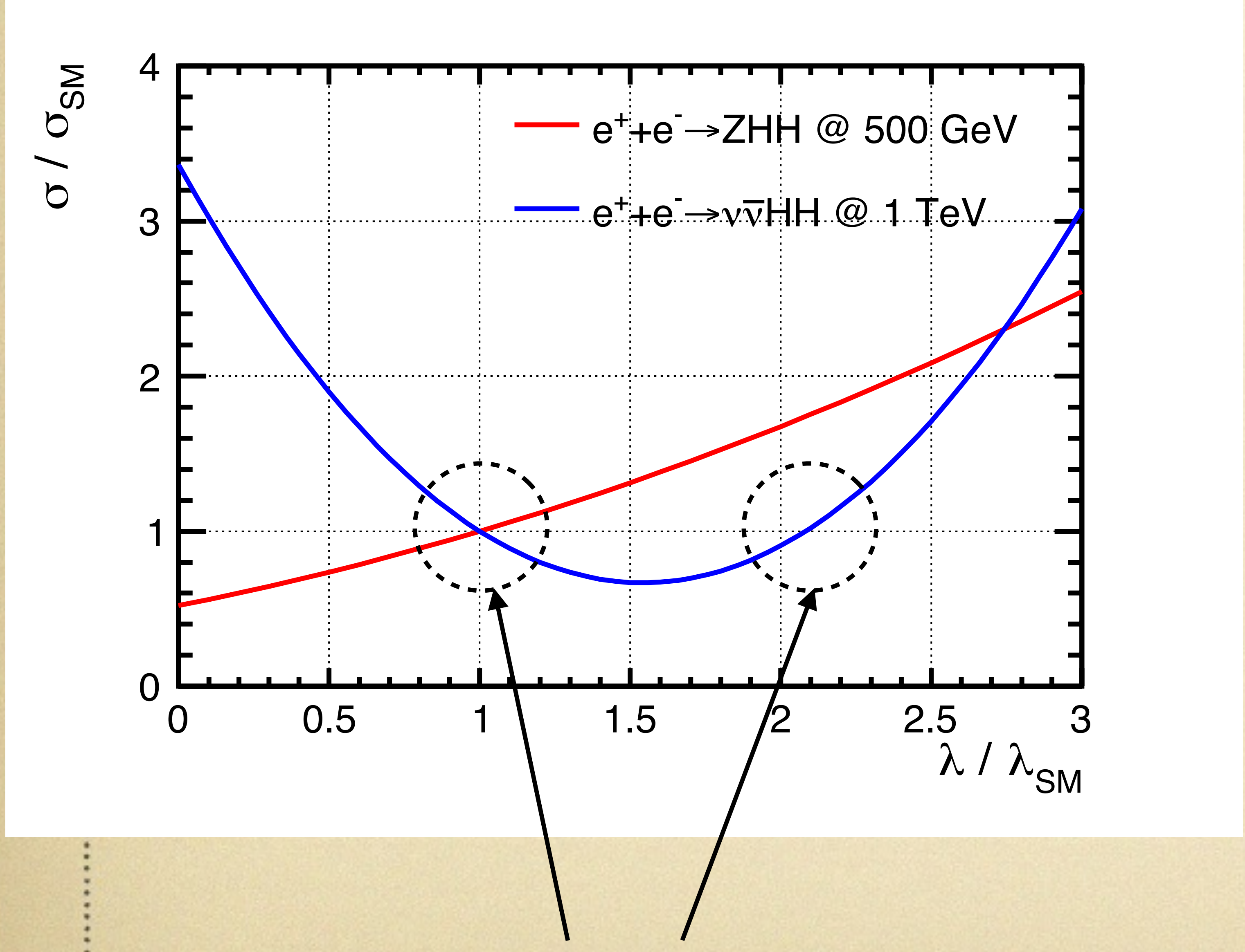


arXiv:1401.7304

- interference is destructive, σ minimum at $\lambda \sim 2.5\lambda_{SM}$; if λ is enhanced, it's going to be very difficult (from snowmass study by 3000 fb-1 @ 14 TeV, significance of double Higgs production is only ~ 2σ, if cross section deceases by a fact of 2~3, very challenging to observe pp—>HH)

resolve the two solutions of λ

$$\sigma = S\lambda^2 + I\lambda + B \longrightarrow \lambda = \frac{-I \pm \sqrt{I^2 - 4SB + 4S\sigma}}{2S}$$



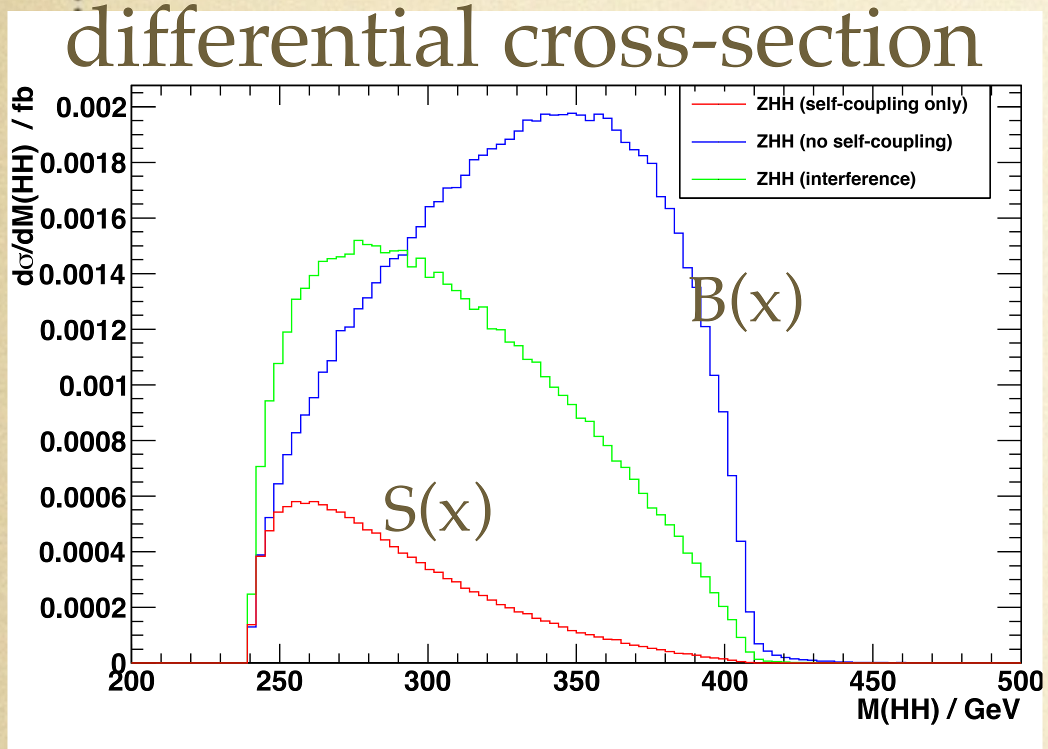
which one is the correct solution?

- $\lambda < 0$ can be excluded by LHC with 600 fb-1 @ 14 TeV (arxiv: 1301.3492)
- if we don't have constraints by ZHH, the two solutions from ννHH are still possible
- in this sense, λ by ZHH is actually very important (e.g. by 500 GeV data); these two channels are again complementary

impact of beam polarisations

- at ILC TDR: P(80%,30%) @ 500 GeV and P(80%,20%) @ 1 TeV promised for electron and positron beams; 60% for positron beam is sometimes mentioned possible
- at CLIC CDR: nominal studies assume no beam polarisations, but 80% is achievable for electron beam, not very clear about positron polarisation
- clearly beam polarisation is helpful for both ZHH and $\nu\nu$HH, σ(ZHH) increase by a factor of 1.4 at 500 GeV; σ($\nu\nu$HH) increase by a factor of 2.2 @ 1 TeV
- for fair comparison, throughout this talk, I assumed same polarisation at all energies: P(-80%,+30%) for ZHH processes, P(-80%,+20%) for $\nu\nu$HH process.

a new general method to improve the sensitivity of λ

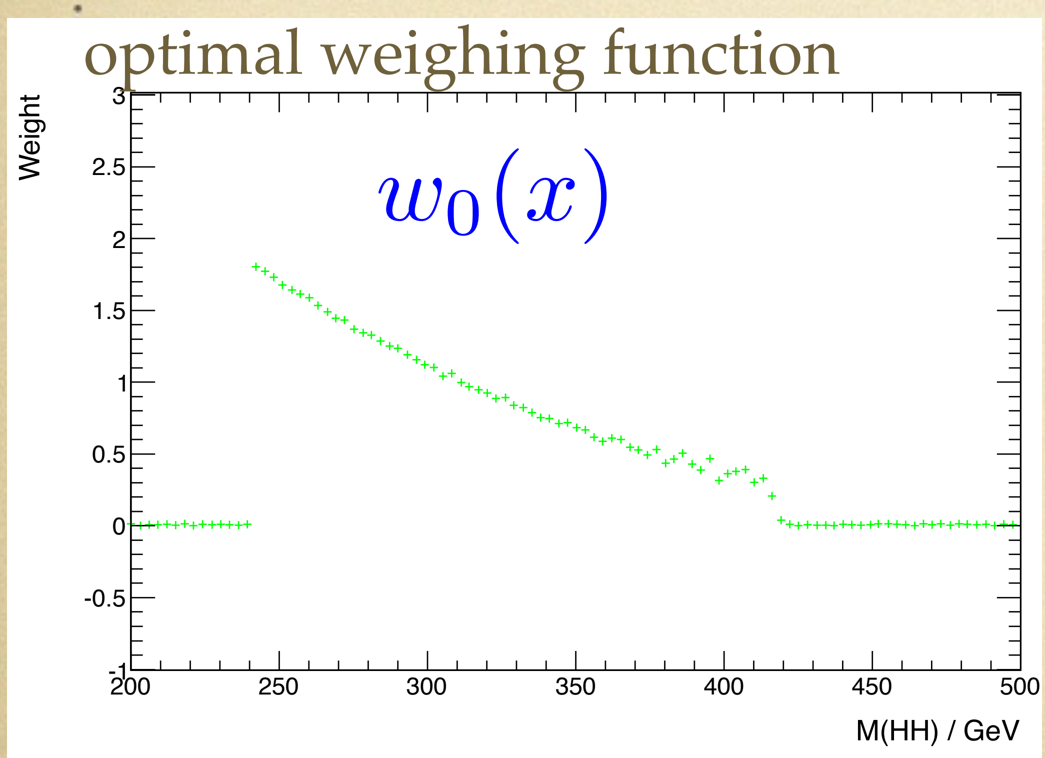


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x) \mathrm{d}x$$



equation of the optimal w(x) (variance principle):

$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

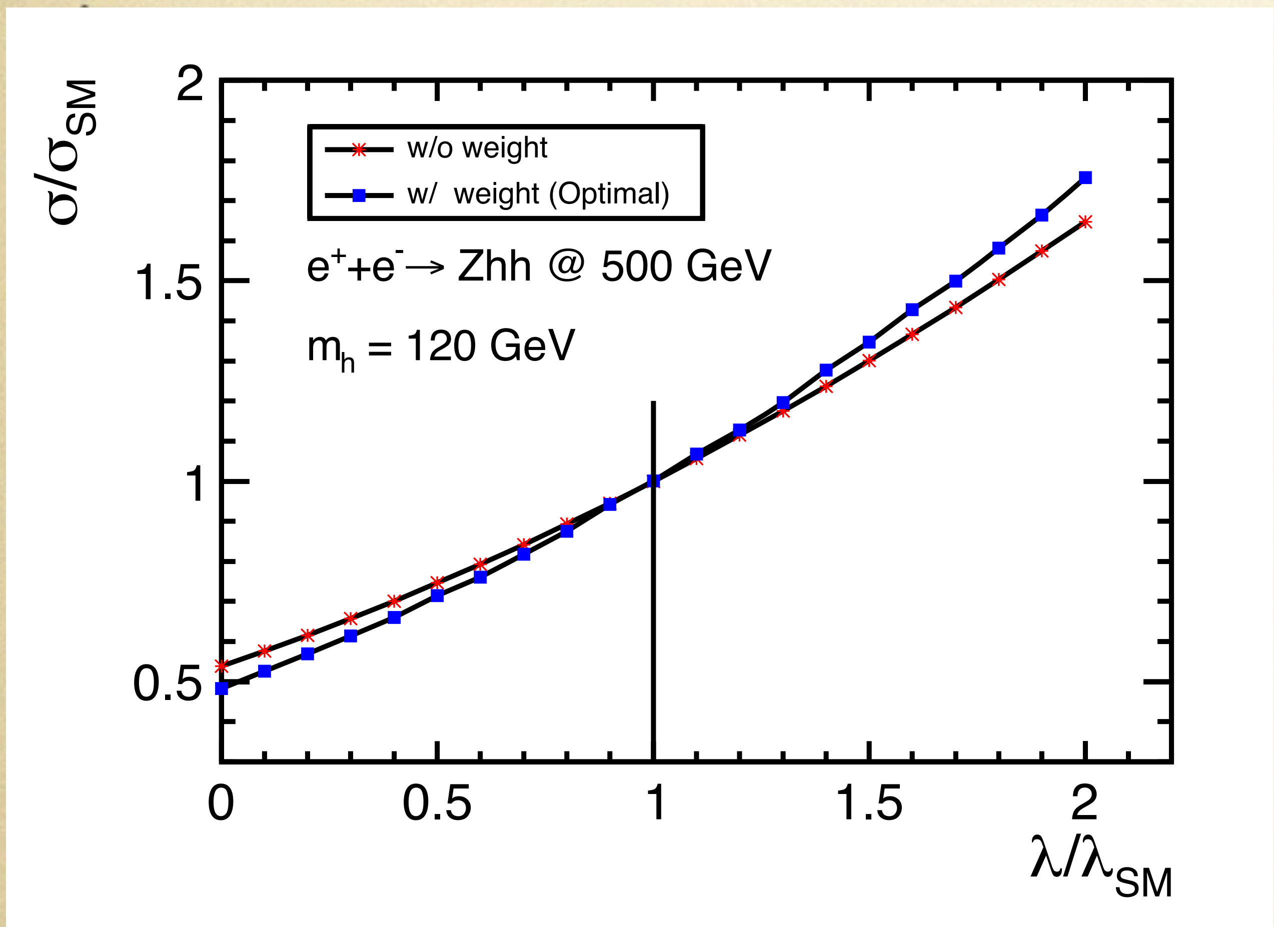
general solution:

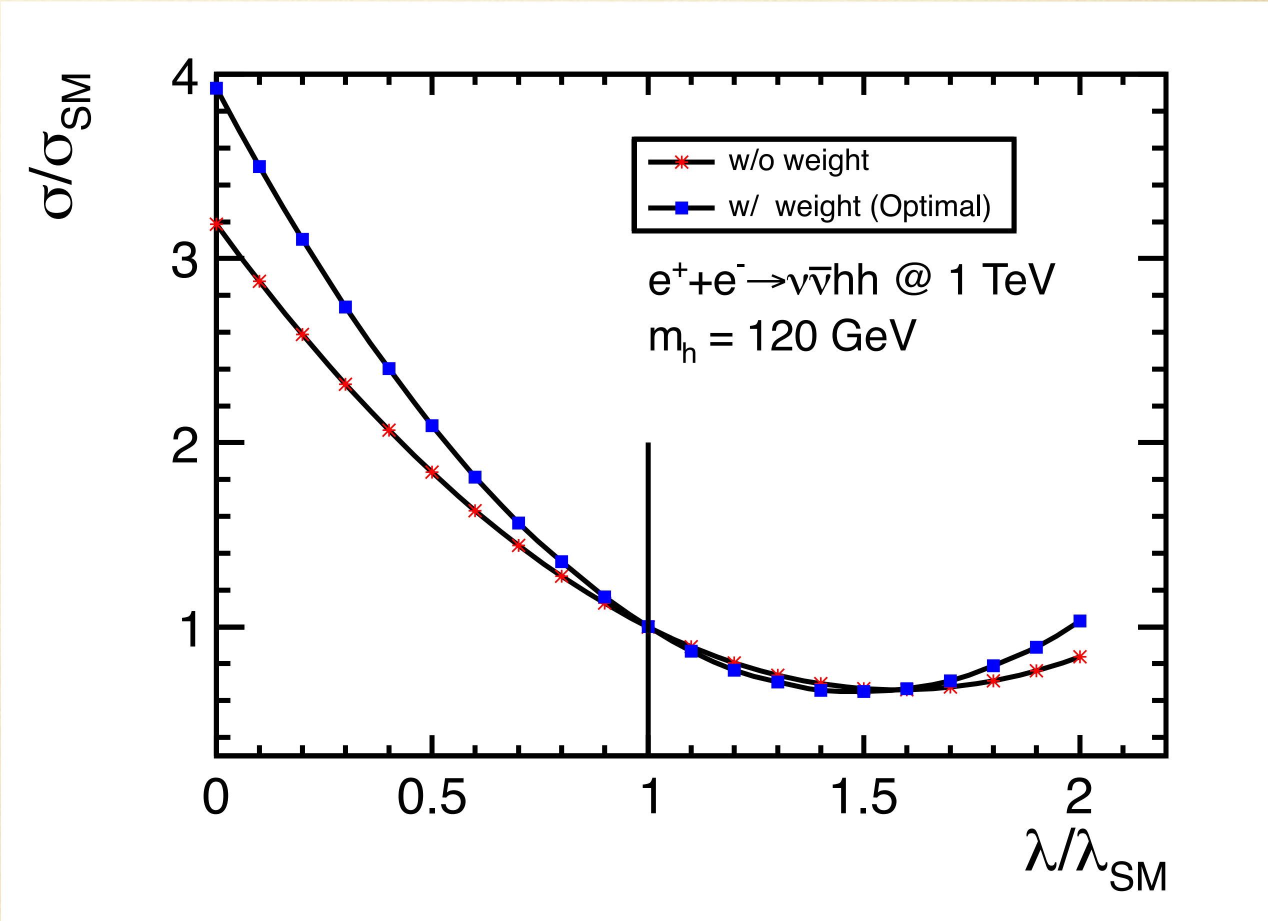
$$w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

improvement of sensitivity by weighting method

(improved sensitivity factor)





|F|	ZHH @ 500 GeV	ZHH @ 1 TeV	ννHH @ 1TeV
default	1.73	2.62	0.8
by weighting	1.62	1.84	0.73

status of full simulation analysis @ ILC

- ☑ DBD full simulation analyses (mH=125 GeV): ZHH @ 500 GeV, $\nu\nu$HH @ 1 TeV
- ☑ SGV fast simulation analysis: $\nu\nu$HH @ 1 TeV (consistent with full simulation)

- updating analysis with mH=125 GeV
- impact of beam background from $\gamma\gamma$->hadrons
- impact of beam polarisations
- improving analysis technique / strategy
  - isolated lepton tagging
  - kinematic fitting
  - optimize cuts for coupling instead of cross section
  - matrix element method and color-singlet-jet-clustering

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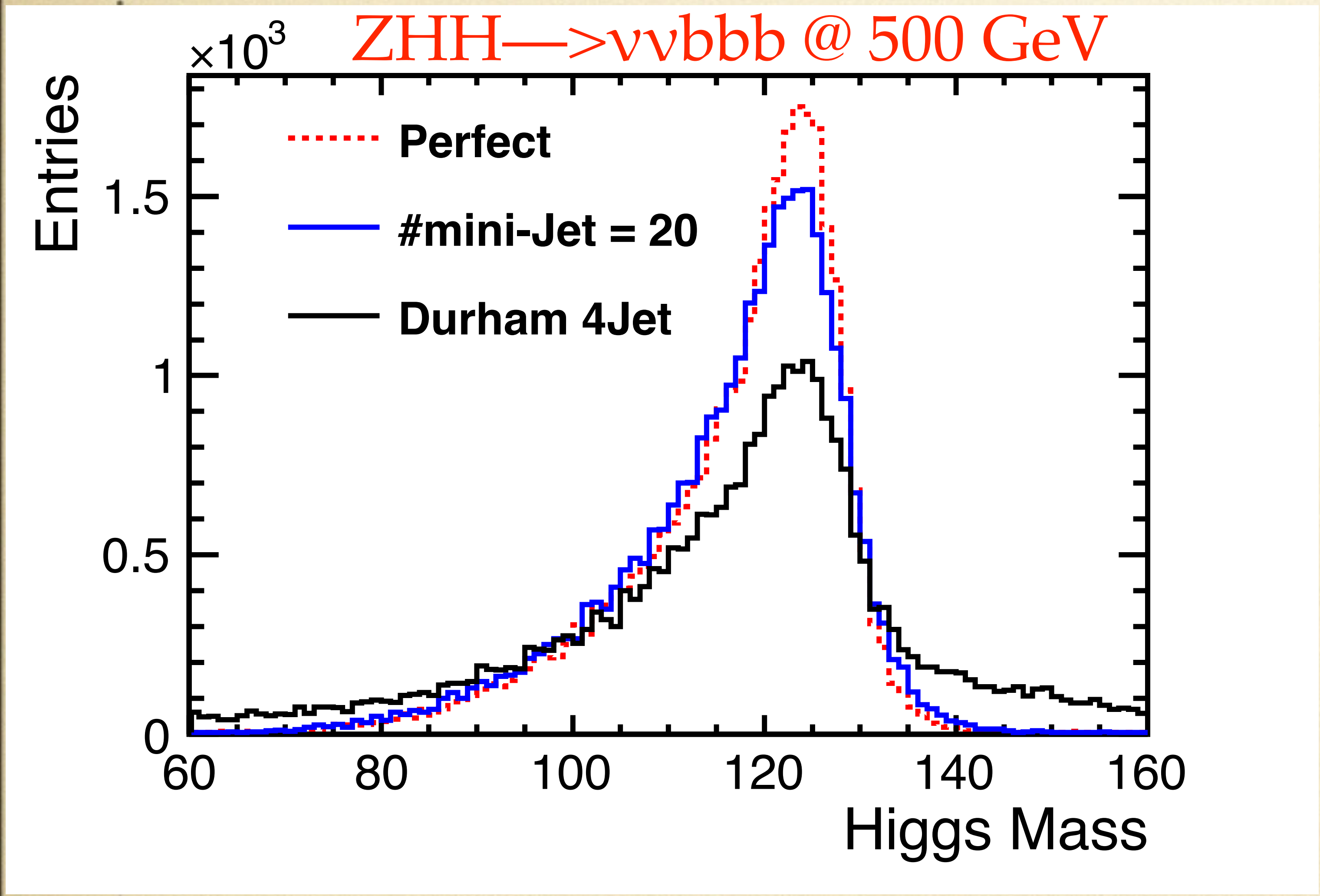
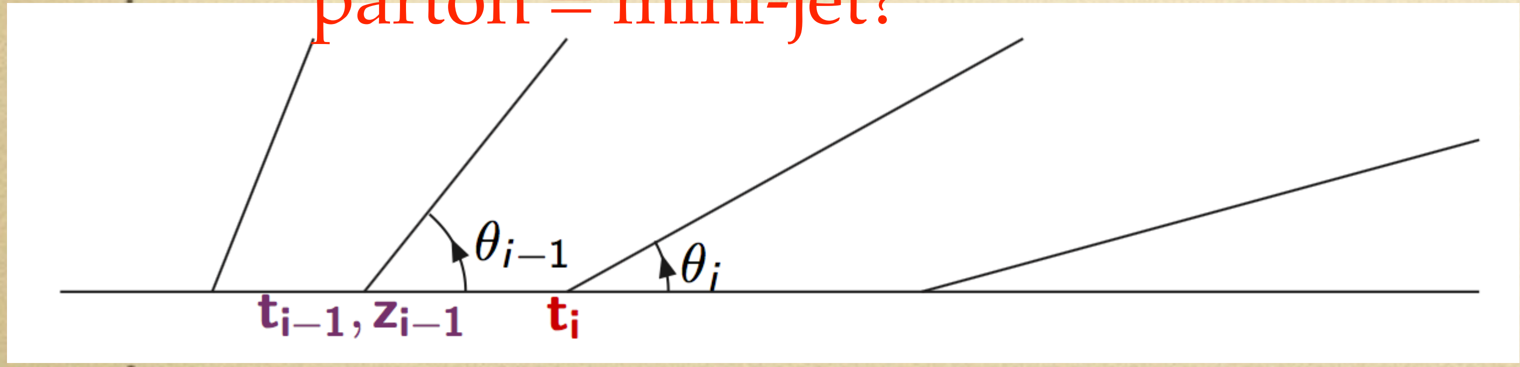
development of new color-singlet jet clustering



parton = mini-jet?



- mis-clustering is one of the major limiting factor
- $\delta\lambda/\lambda$ could be improved by 40% if we could achieve perfect clustering
- but it's very difficult to improve general jet clustering algorithm
- so far we only know mis-clustering starts mainly at the step when #mini-jet = 20
- need better algorithm to combine those mini-jets
- idea: deconstruct the who parton shower history, find the combination with largest probability

summary

- λ is very important to measure, however challenging at both LHC and LCs
- the best expectation we have now, in SM case, $\delta\lambda/\lambda$~29% at 500 GeV, 10% at 1 TeV at the ILC; further potential improvement at CLIC
- two channels ZHH and ννHH are complementary; interference is crucial to determine λ in both channels
- 500 GeV is optimal energy for ZHH; the improvement by ecm>1TeV is rather mild due to the increased sensitivity factor
- in some BSM scenario, $\delta\lambda/\lambda$ can be already well determined just at 500 GeV ILC
- analysis is very challenging and improvement being pursued