# ZHH cross section analysis

**— prospect of Higgs self-coupling measurement and impact of ecm**

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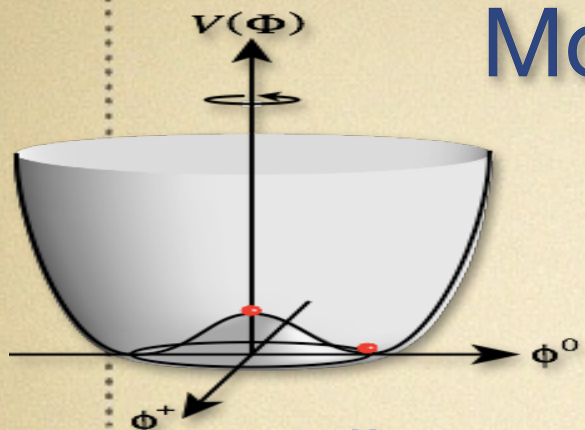
LCWS15, Nov. 2-6, 2015 @ Whistler, B.C., Canada

## outline

- introduction and current prospects at LHC and LCs
- cross section analysis and the impact of ecm
- prospects when $\lambda \neq \lambda_{SM}$
- weighting method to enhance sensitivity
- $\lambda_{HHH}$ analysis status at ILC

# 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 electroweak baryogenesis
- large deviation is expected

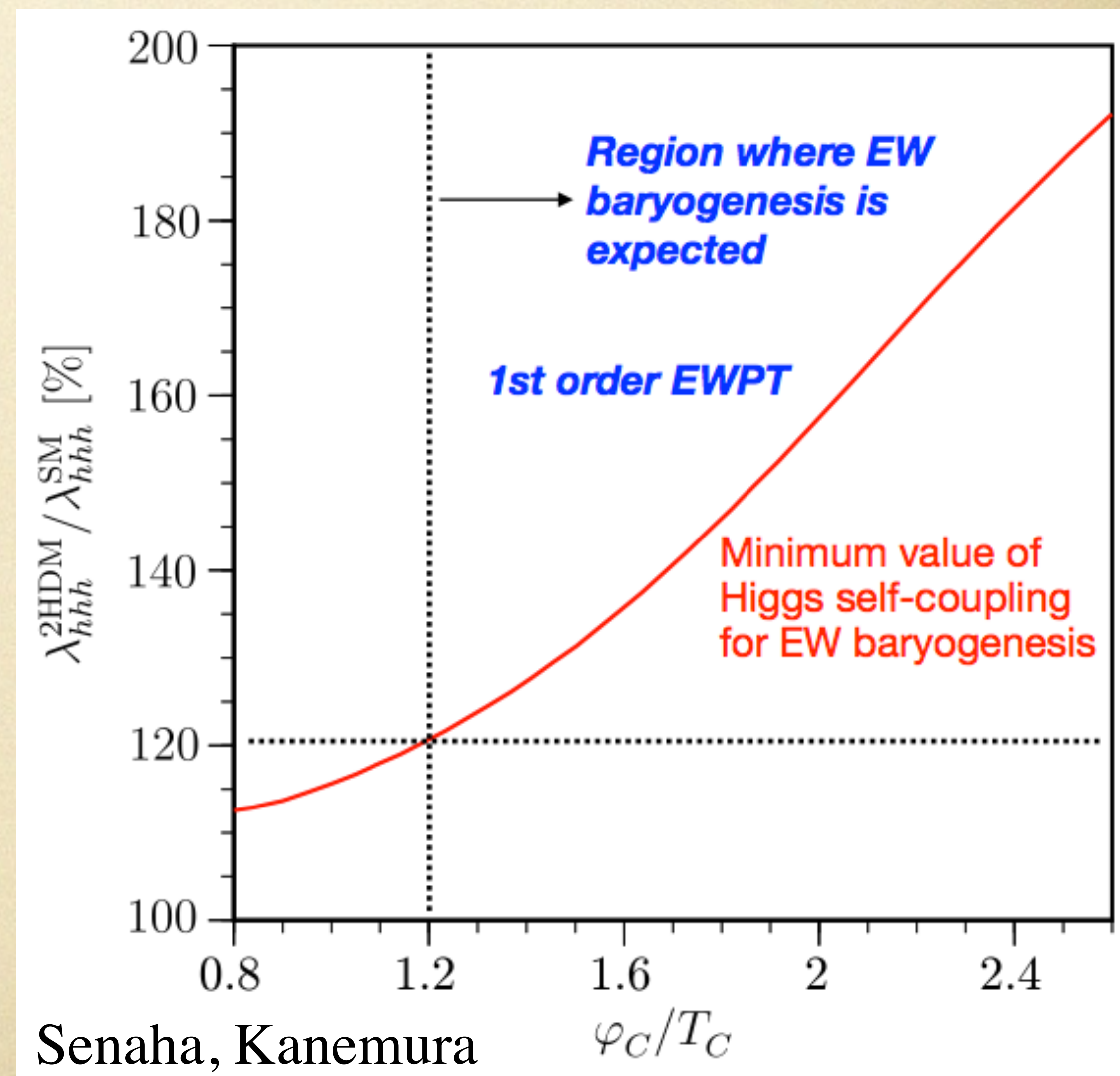
scale invariant models for EWSB

$$\Gamma_{hhh}^{\mathrm{CSI}} = \frac{5 m_h^2}{v} = \frac{5}{3} \times \Gamma_{hhh}^{\mathrm{SMtree}}.$$

Hashino,Kanemura,Orikasa, arXiv:1508.03245

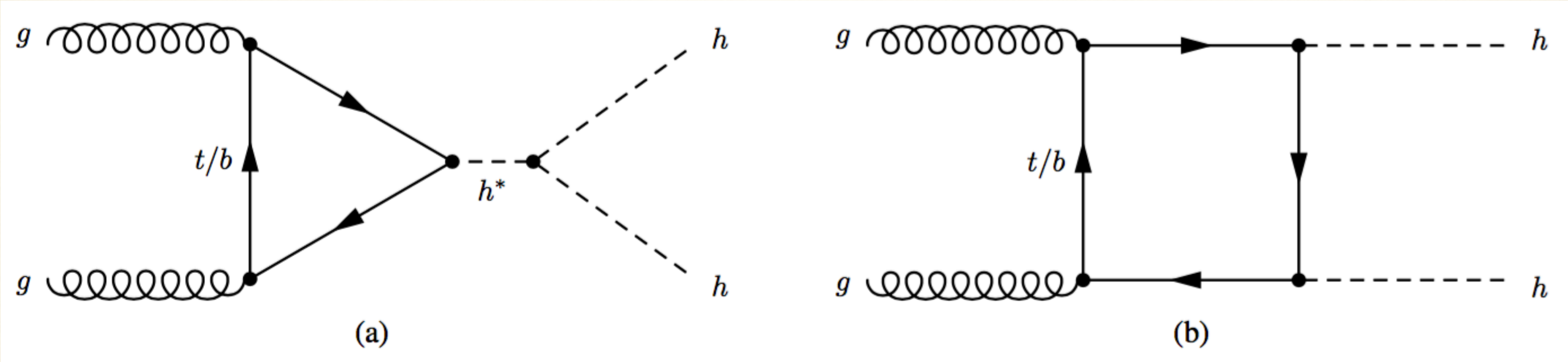
| | $N=1$ | | |
|---|---|---|---|
| | (I) | (II) | (III) |
| $\lambda_{\mathrm{hhh}}/\lambda_{\mathrm{hhh}}^{(\mathrm{SM})}$ | 1.7 | 1.8 | 1.8 |
| $\lambda_{\mathrm{hhhh}}/\lambda_{\mathrm{hhhh}}^{(\mathrm{SM})}$ | 3.7 | 4.3 | 4.5 |

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 |

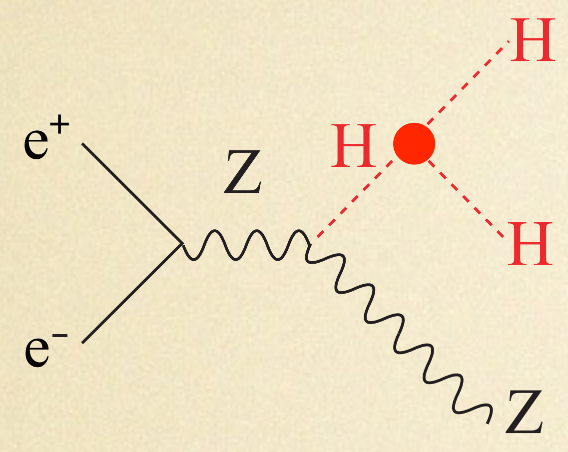
arXiv:1509.0467

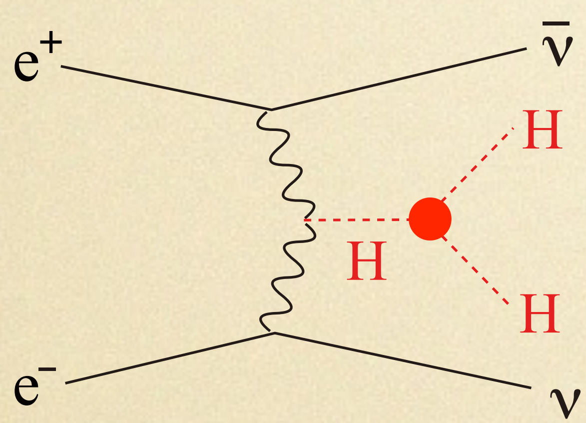
Snowmass Higgs working group:   $\delta\lambda_{HHH}/\lambda \sim 50\%$ @ 14 TeV, 3000 fb$^{-1}$

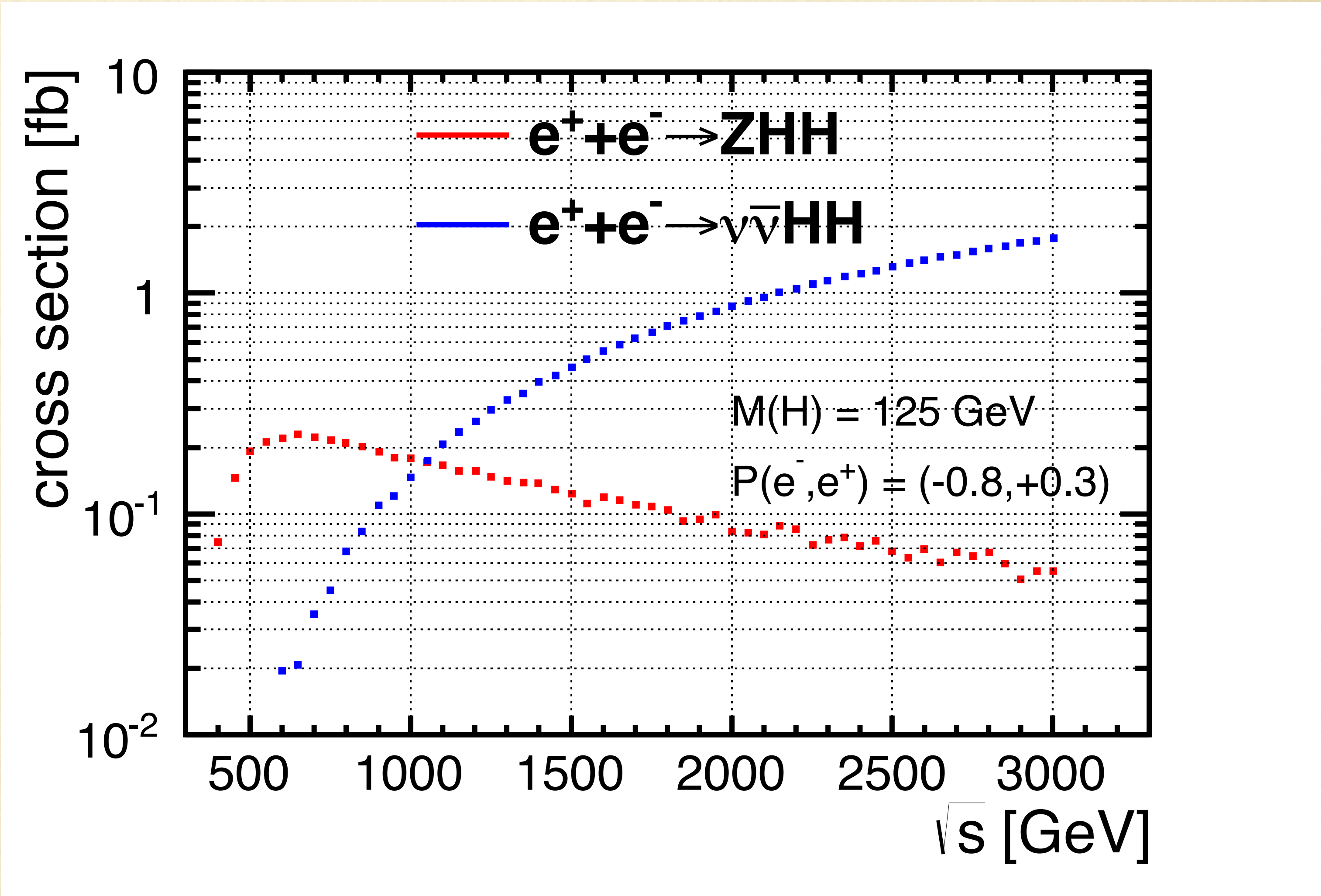
(arXiv: 1310.8361)

LHC talk by C.Vernieri:   HH production ~ $1.9\sigma$ @ 14 TeV, 3000 fb$^{-1}$

# 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 | 27% | 10% |

(ref. H20 arXiv: 1506.07870)

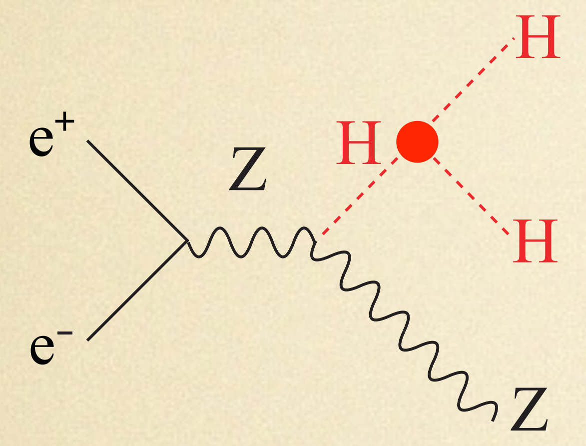
CLIC

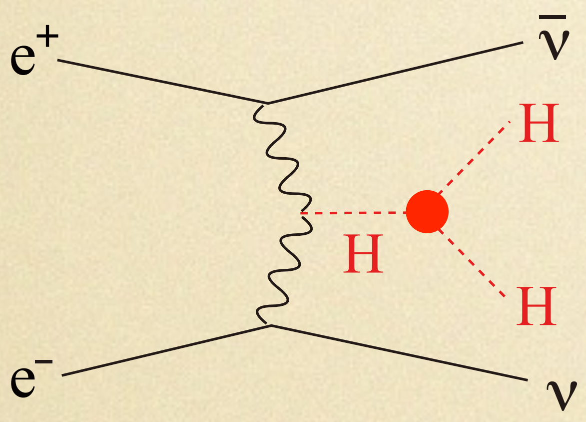
| 1.4 TeV (1.5 $ab^{-1}$) | +3 TeV (2 $ab^{-1}$) |
|---|---|
| 21% | 10% |

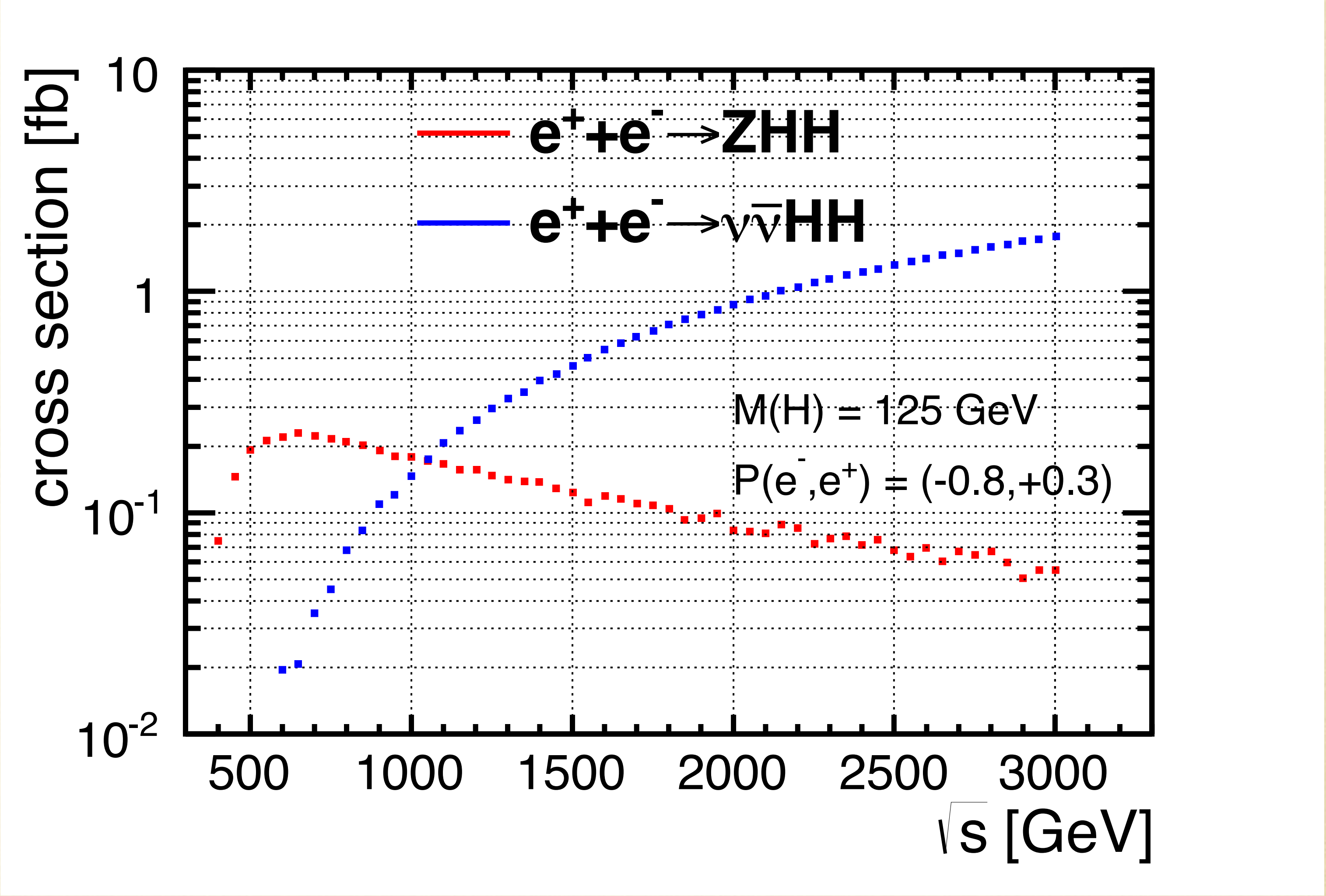
(arXiv: 1307.5288)

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

# $\lambda_{HHH}$ @LCs: impact of ecm



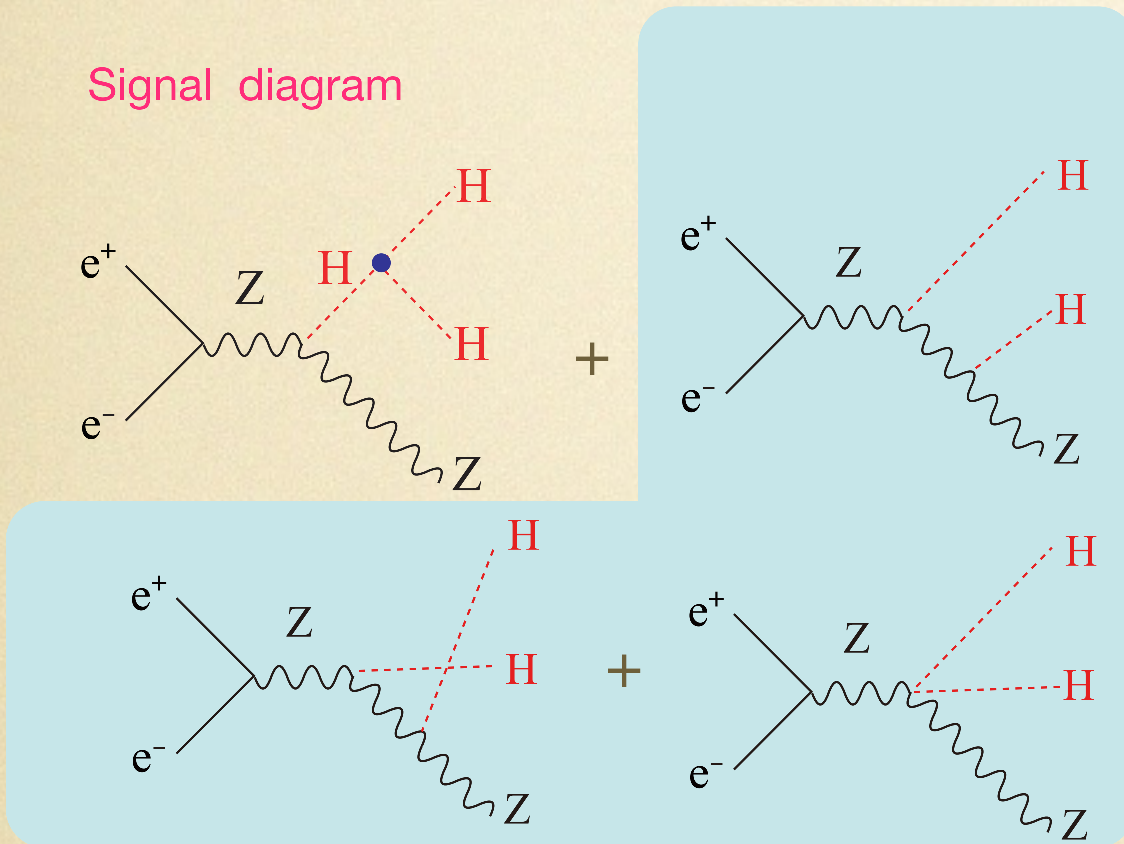



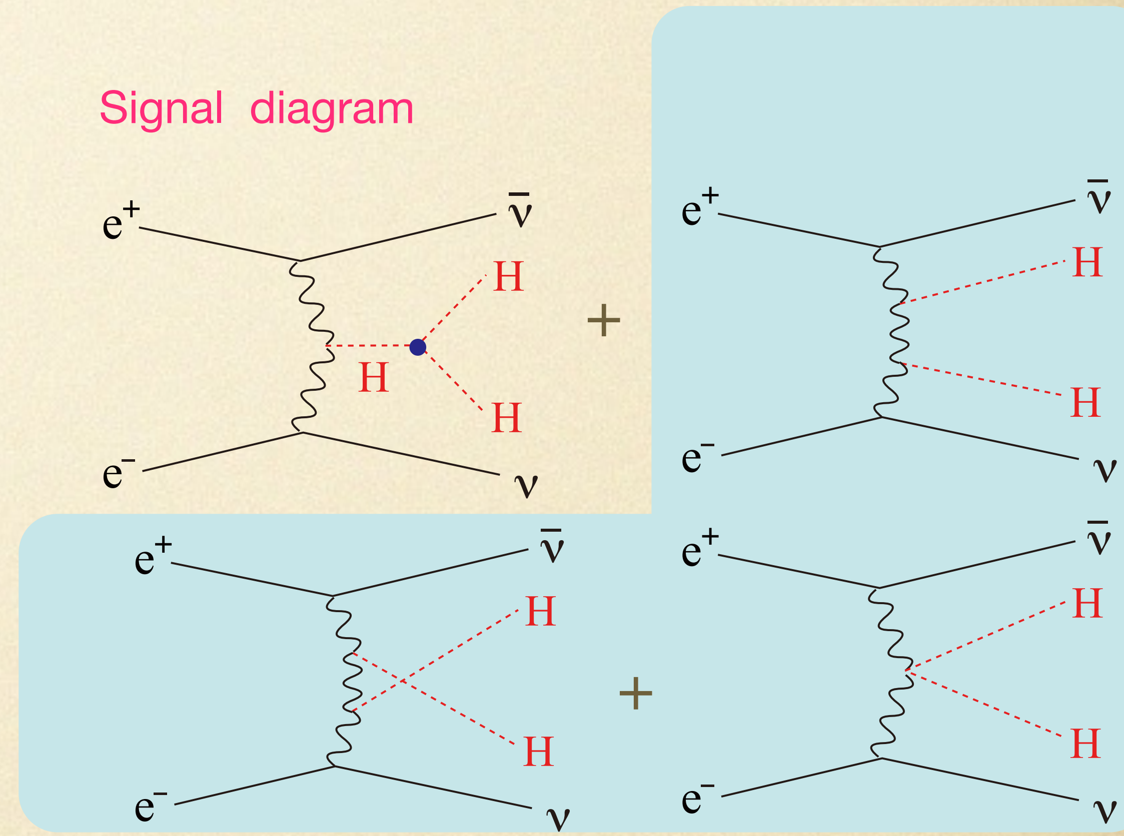




For ZHH: what would be the optimal energy?

For ννHH: how much improvement would be expected?

# physics issues: diagrams for double Higgs production




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

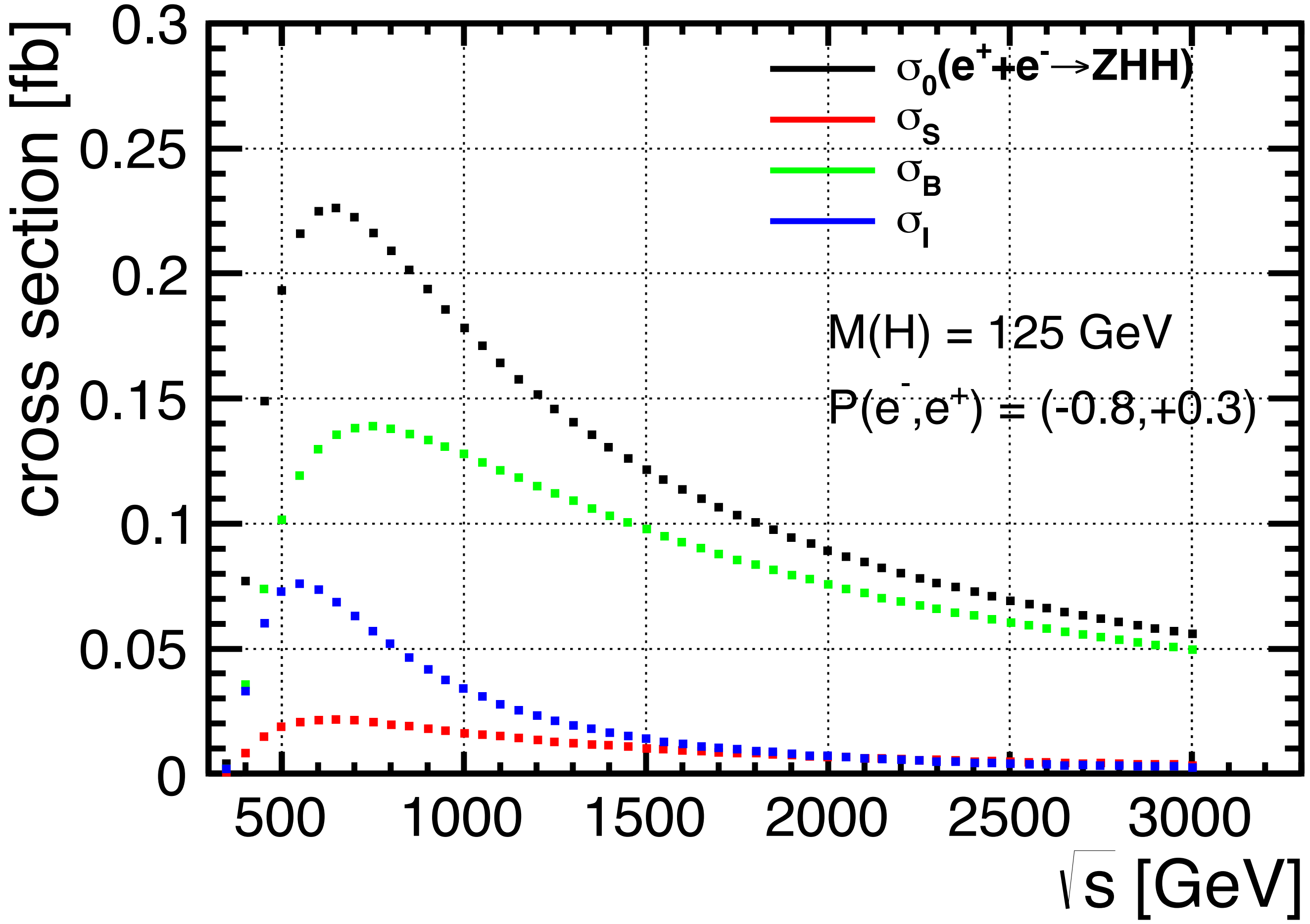
(signal diagram) (interference) (background diagram)

- the sensitivity of $\lambda$ 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

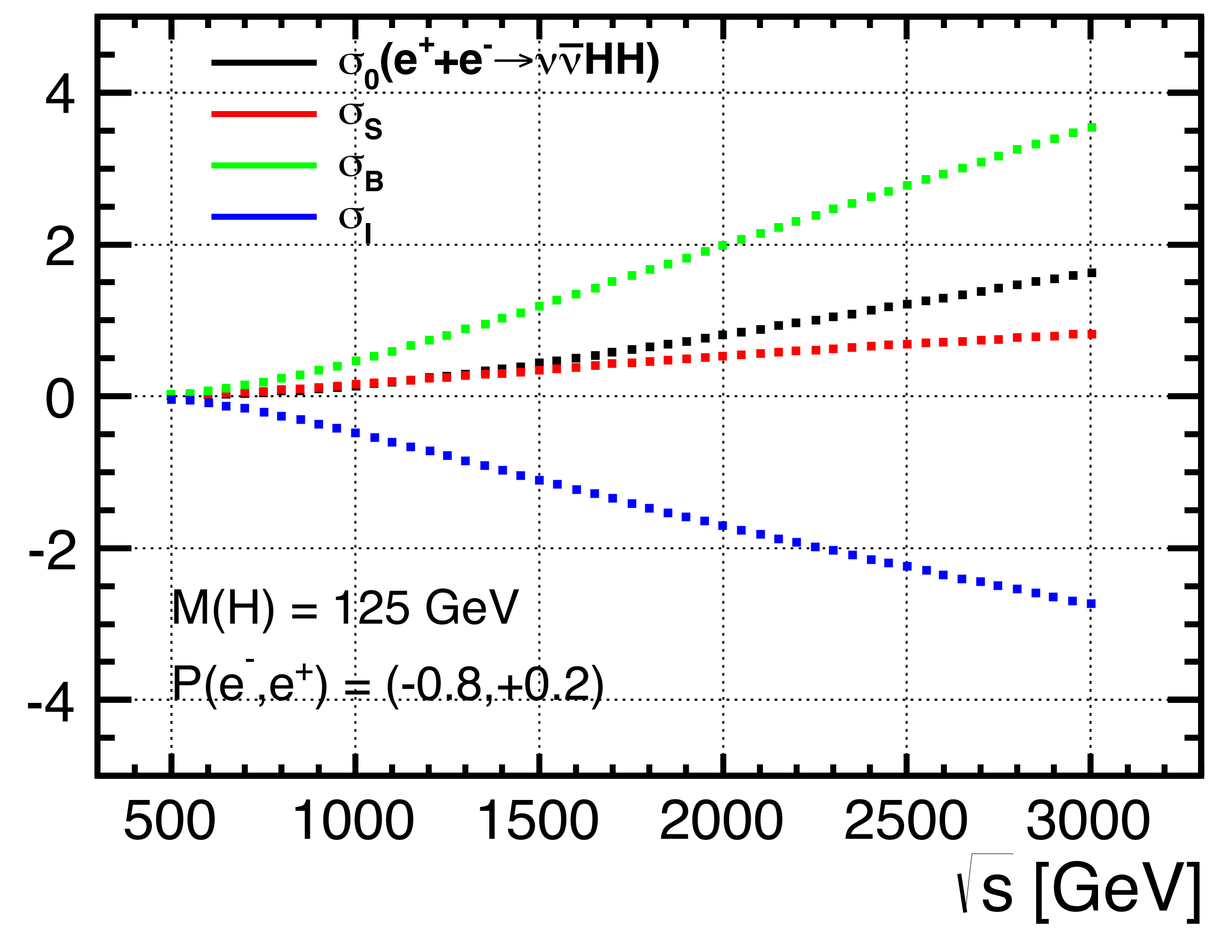
# breakdown of $\sigma$ to $S$, $I$ and $B$ terms

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

ZHH




ννHH




- 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 directly measured σ

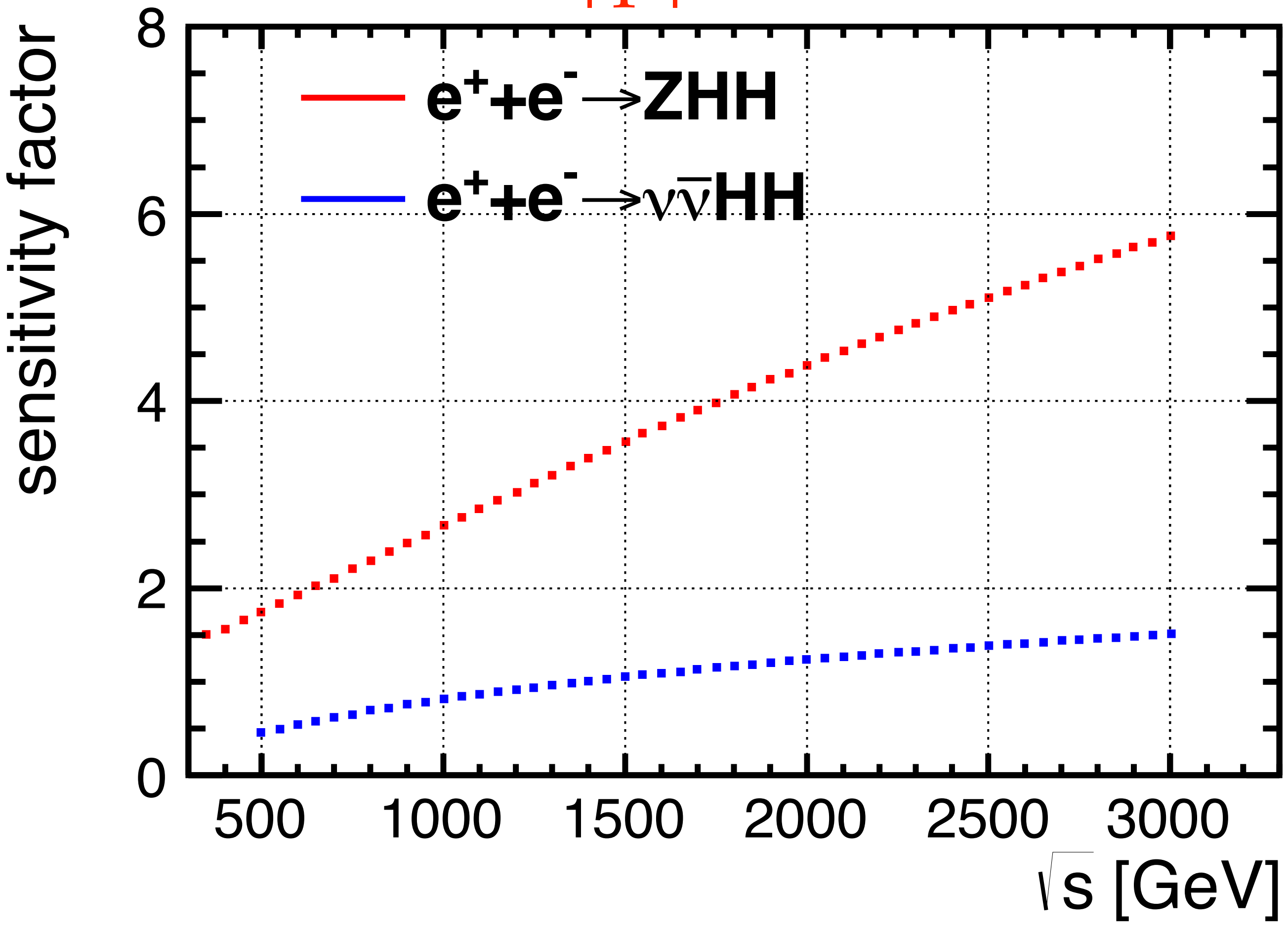
$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

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

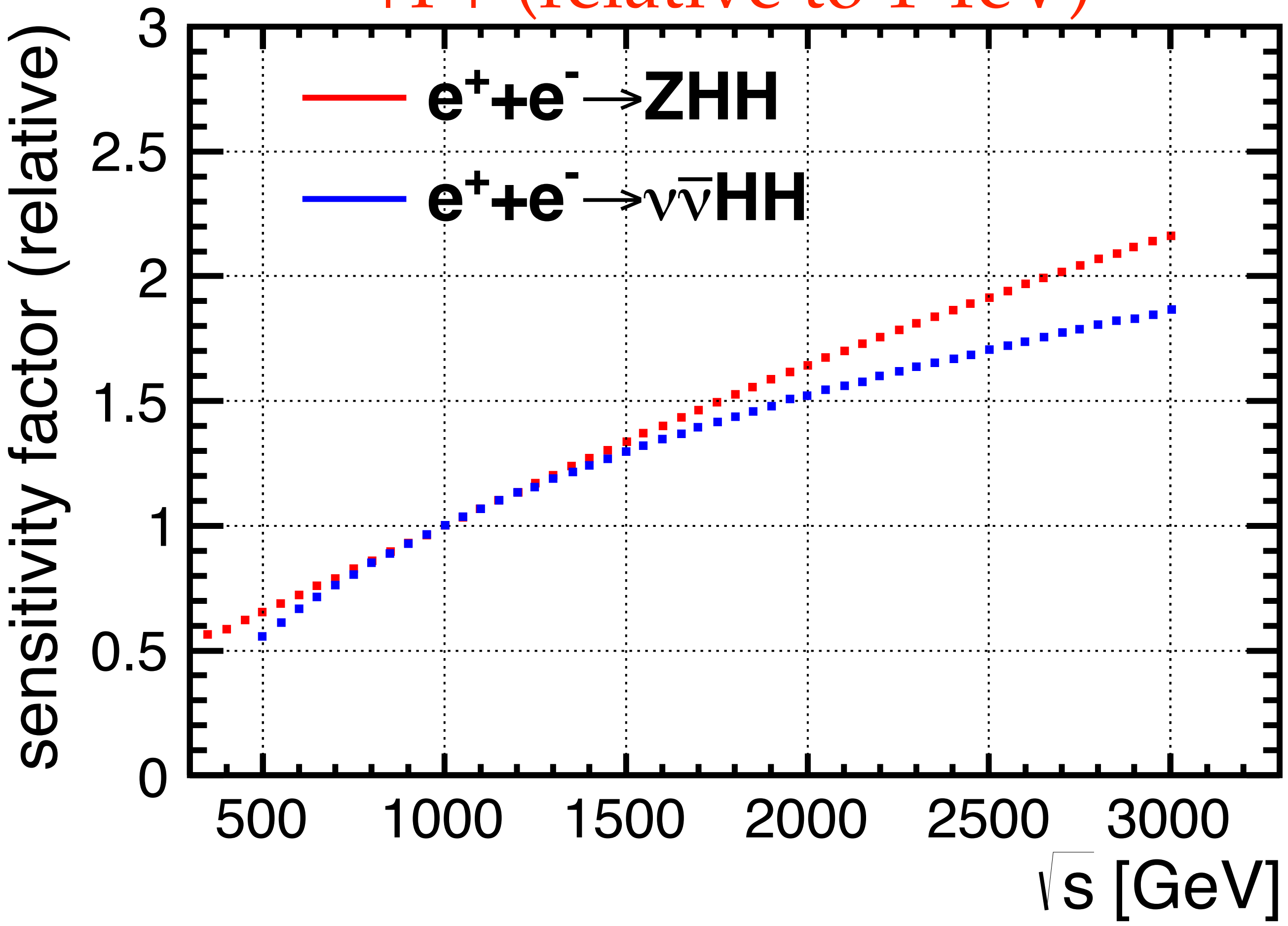
sensitivity factor

- 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|



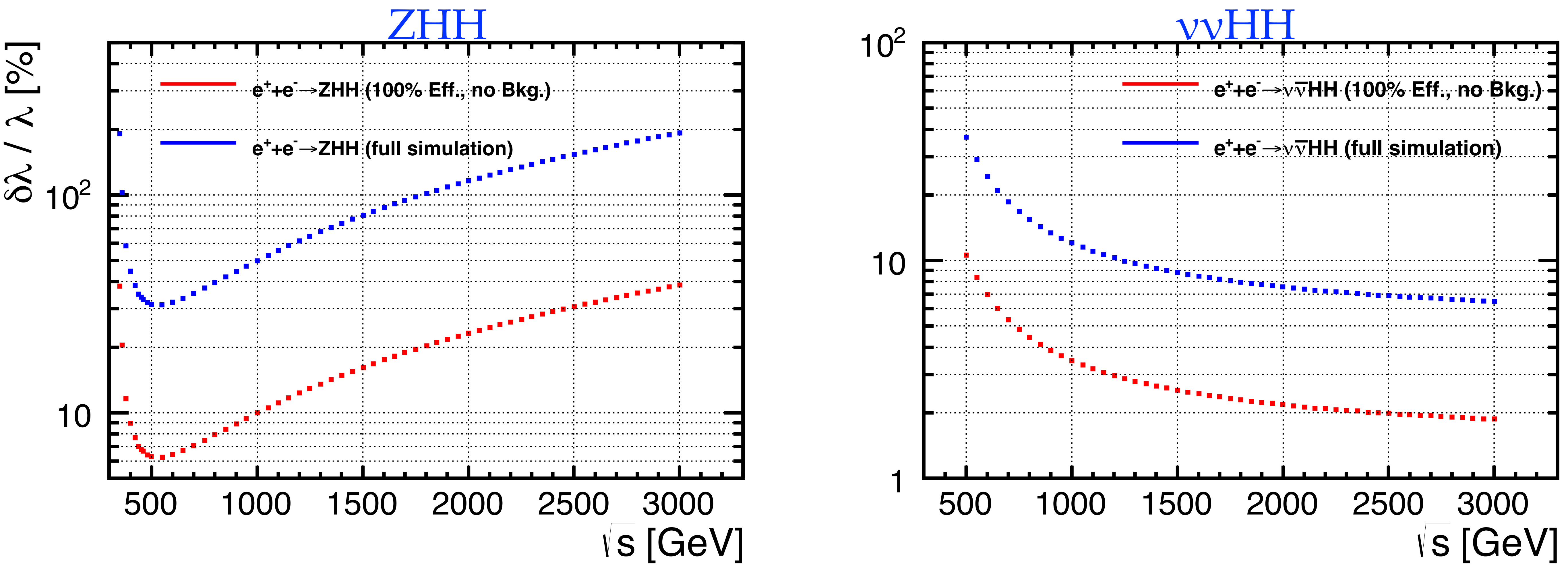

|F| (relative to 1 TeV)



# expected precision of λ

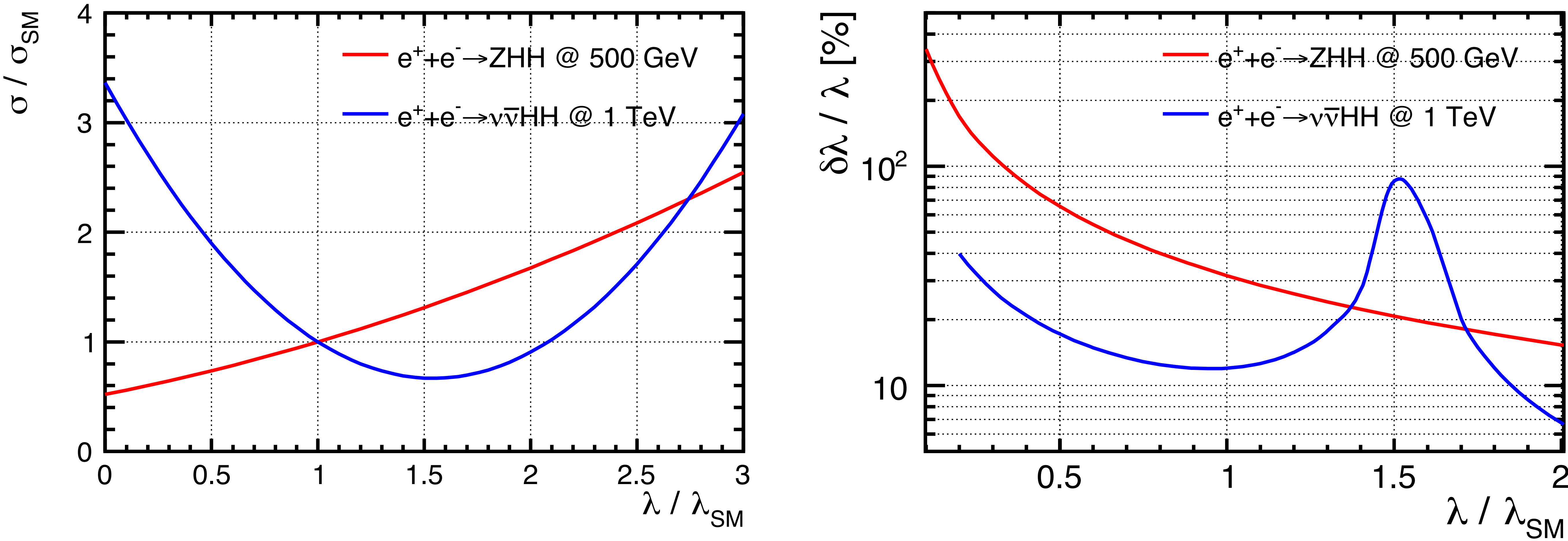
- based on the cross sections and sensitivity factors, give two types of expectations
- theoretical precision assuming 100% signal efficiency and no background;
- realistic precision extrapolated from the full detector simulation results at the ILC, ZHH @ 500 GeV and ννHH @ 1 TeV
- 4 ab-1 data is assumed; P(-0.8,+0.3) for ZHH; P(-0.8,+0.2) for ννHH

# expected precision of λ



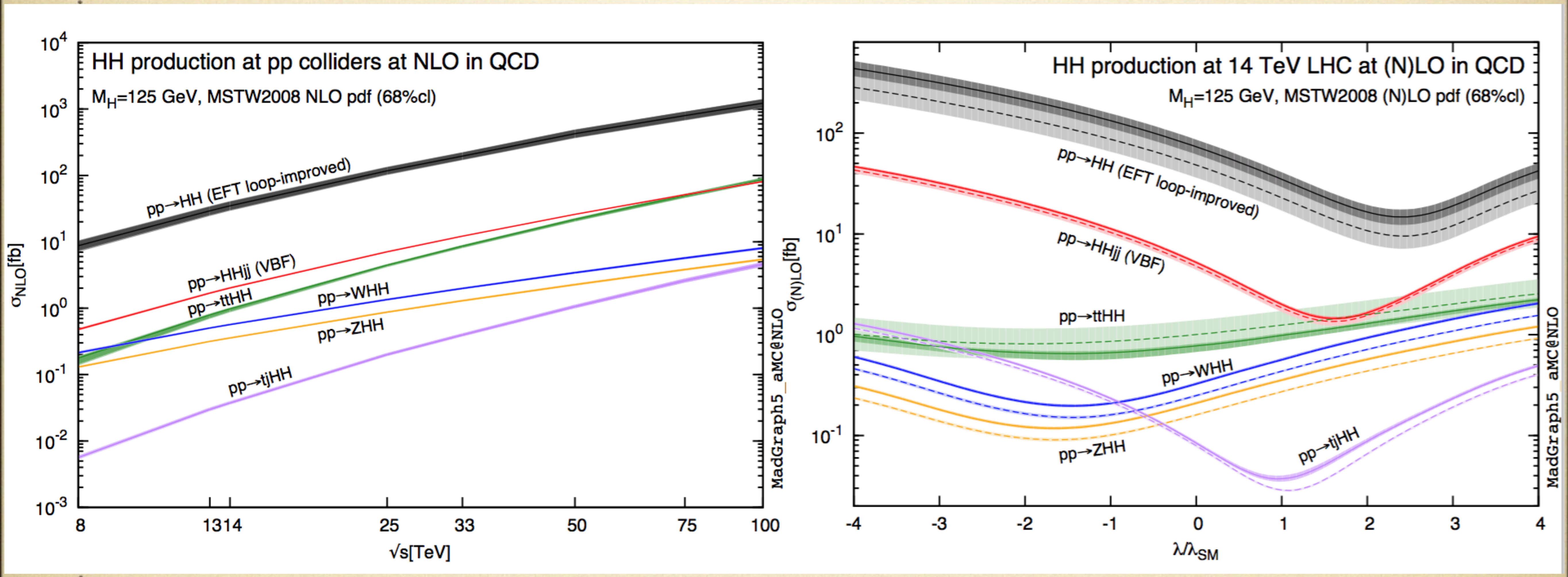

- gap of these two expectations —> room of improvement
- for ZHH: 500 GeV is the optimal energy, $\delta\lambda/\lambda$ ~ 6% : 30%, but rather mild dependence between around 500-600 GeV, significantly worse if much lower or higher than that
- for ννHH: significantly better going from 500 GeV to 1 TeV, $\delta\lambda/\lambda$~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 $\lambda$ will increase the total $\sigma$, and improve sensitive factor as well, e.g. if $\lambda = 2\lambda_{SM}$, $\sigma$ increase by 60%, F decease by half, $\delta\lambda/\lambda$ ~15%, —> we may finish the $\lambda$ story at 500 GeV ILC
- for ννHH, interference is destructive, enhanced $\lambda$ will decrease $\sigma$, minimum when $\lambda$~$1.5\lambda_{SM}$, $\delta\lambda/\lambda$ 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 $\lambda$ measurement in BSM

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

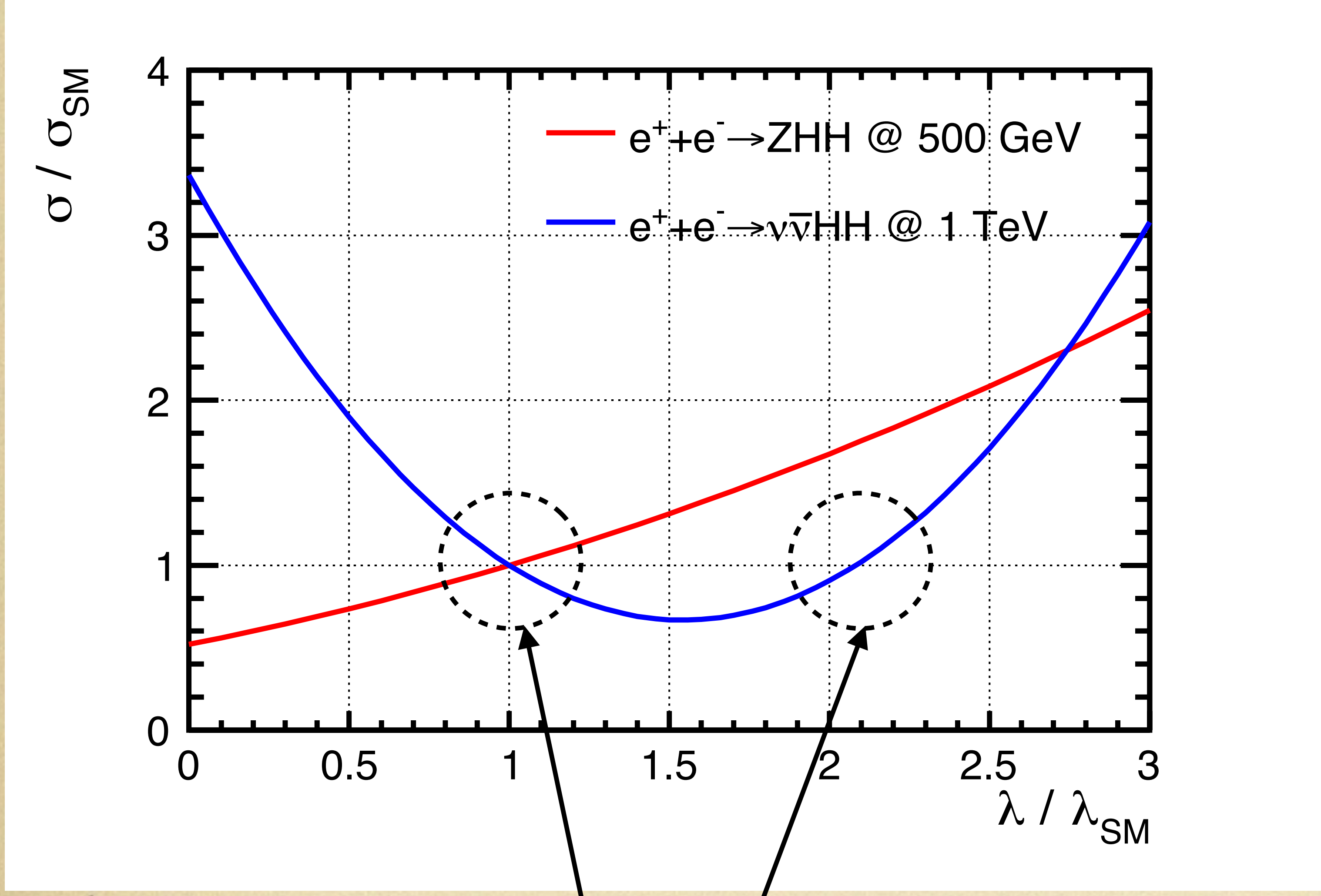



arXiv:1401.7304

- interference is destructive, $\sigma$ minimum at $\lambda \sim 2.5\lambda_{SM}$; if $\lambda$ 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 $\sim 2\sigma$, if cross section deceases by a fact of 2~3, very challenging to observe pp—>HH)

# resolve the two solutions of λ

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

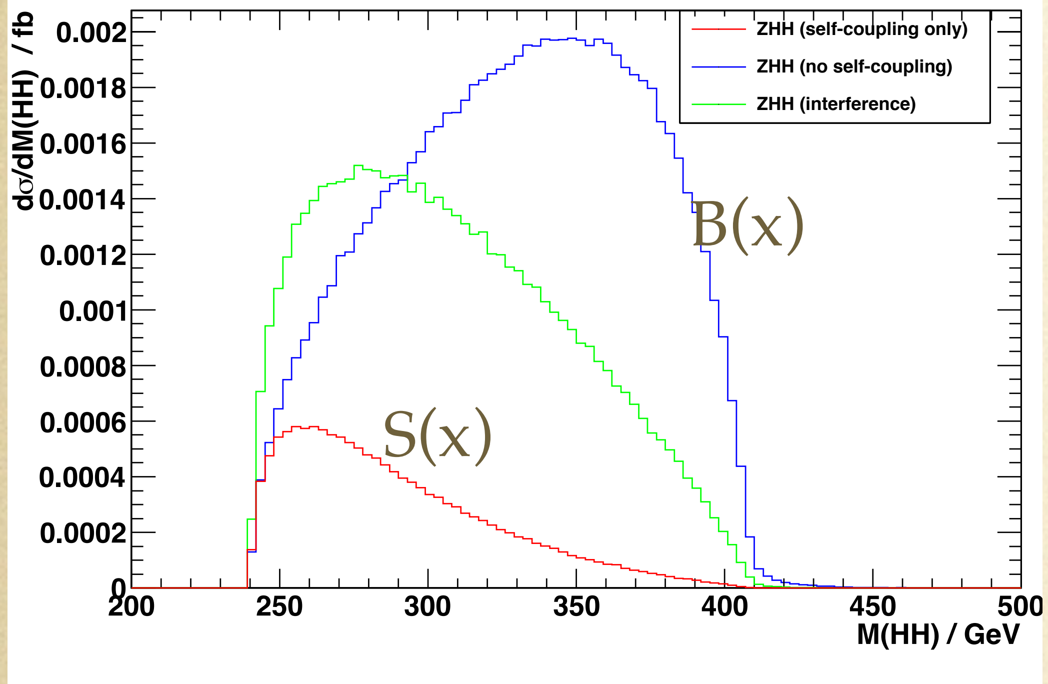



which one is the correct solution?

- $\lambda < 0$ 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, $\lambda$ by ZHH is actually very important (e.g. by 500 GeV data); these two channels are again complementary

# a new general method to improve the sensitivity of λ

differential cross-section



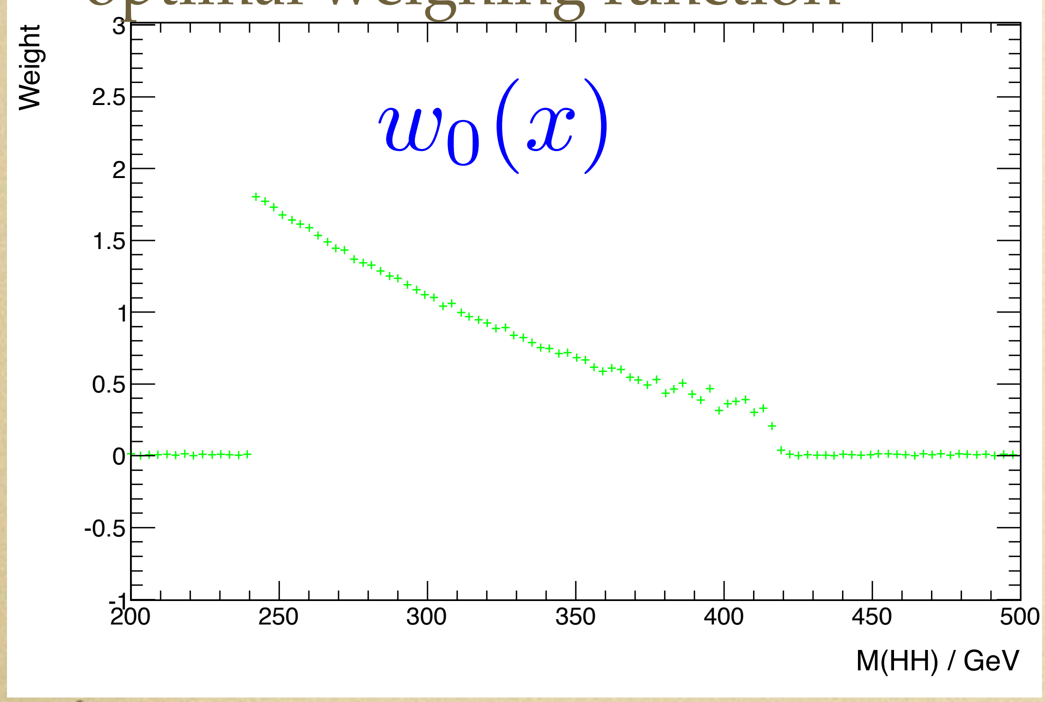

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible interference self-coupling

**observable:** weighted cross-section

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

optimal weighing function




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

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

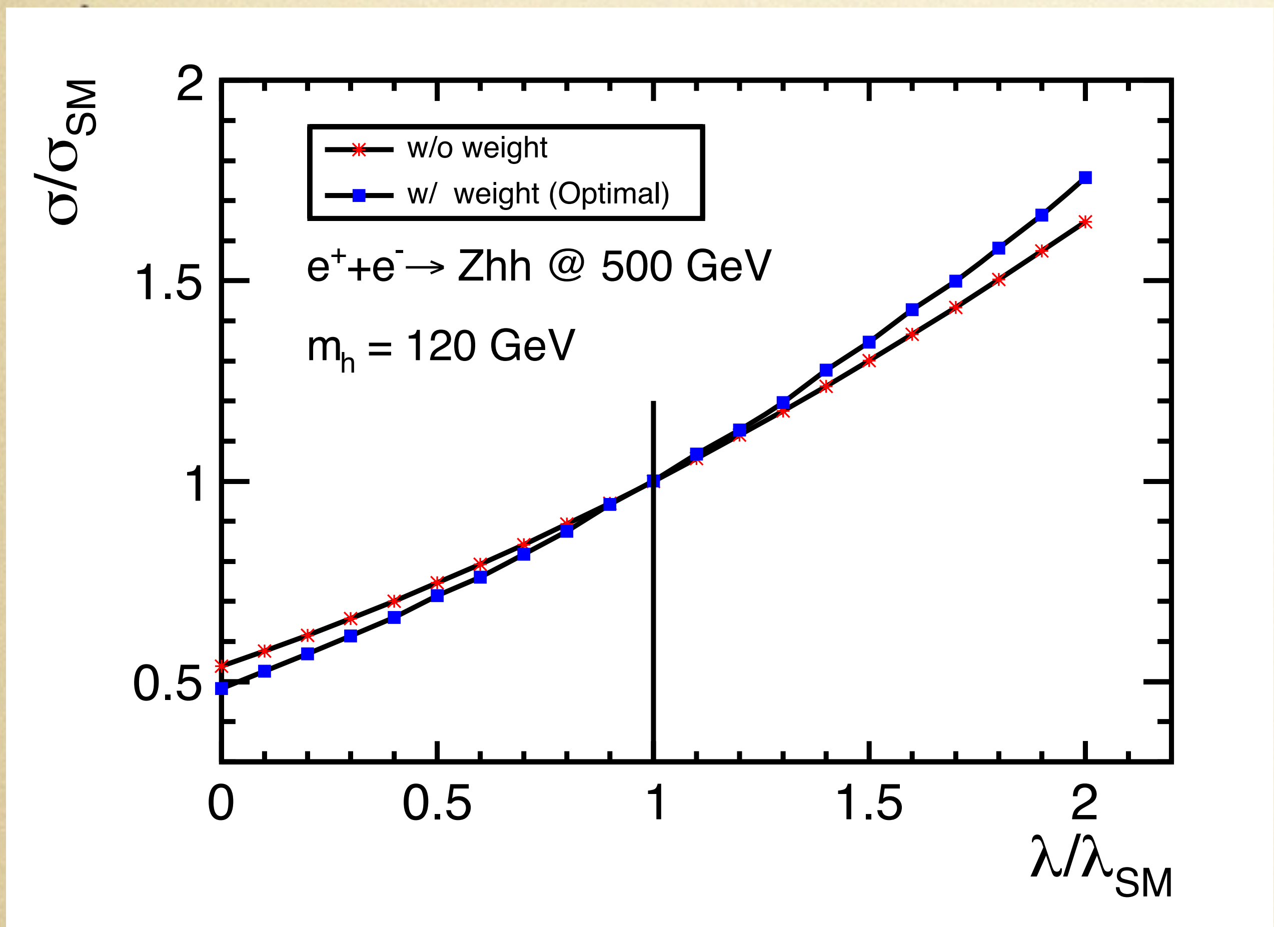
**general solution:**

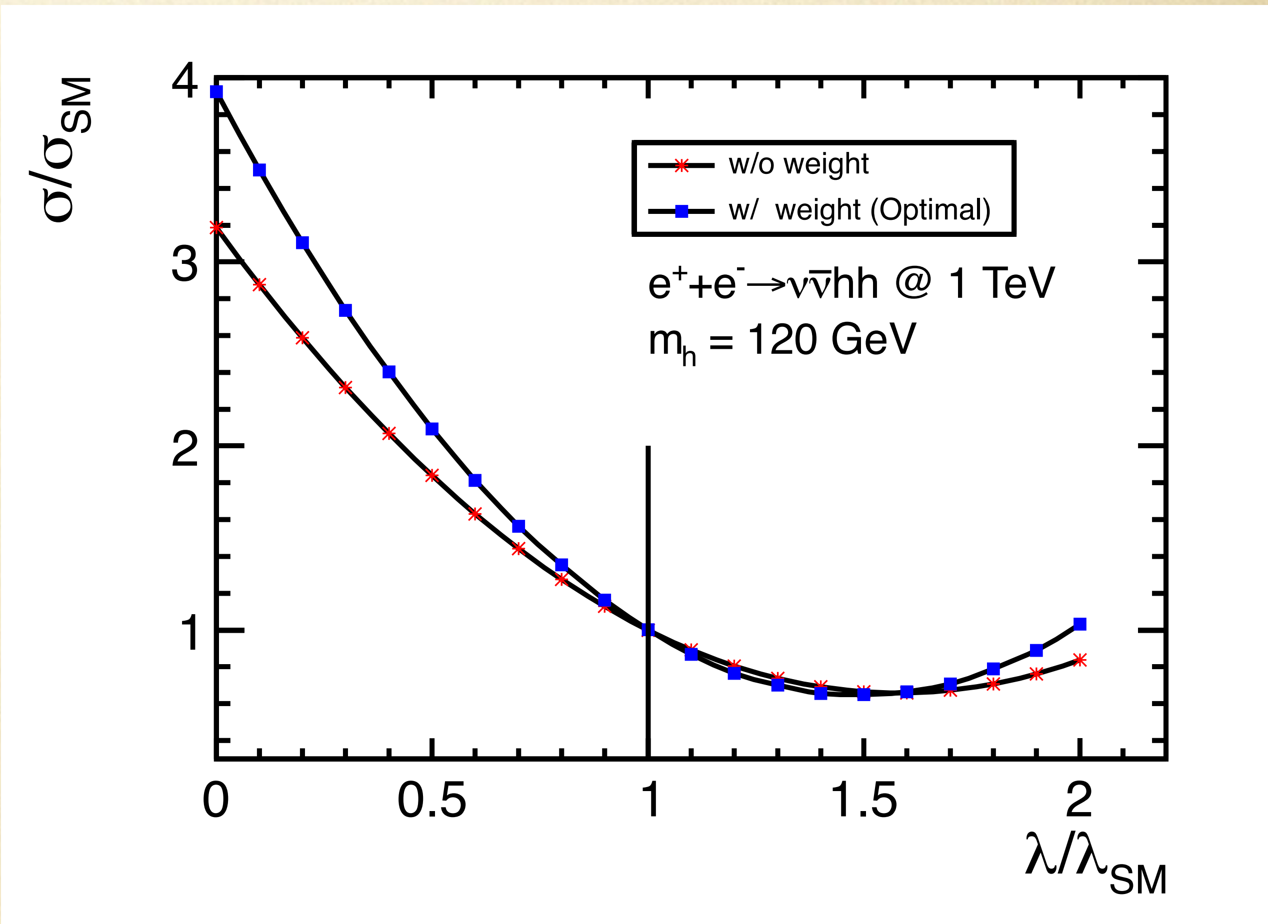
$$w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}$$

**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=120 GeV): ZHH @ 500 GeV, ννHH @ 1 TeV
- ☑ SGV fast simulation analysis: ννHH @ 1 TeV (consistent with full simulation)

- task force: C.Duerig, M.Kurata, J.Tian, K.Fujii, J.List
- update analysis with mH=125 GeV
- study impact of beam background from γγ->hadrons
- study impact of beam polarisations
- improving analysis technique / strategy
  - isolated lepton tagging
  - kinematic fitting (see talk by M.Kurata)
  - optimize cuts for coupling instead of cross section
  - matrix element method and color-singlet-jet-clustering

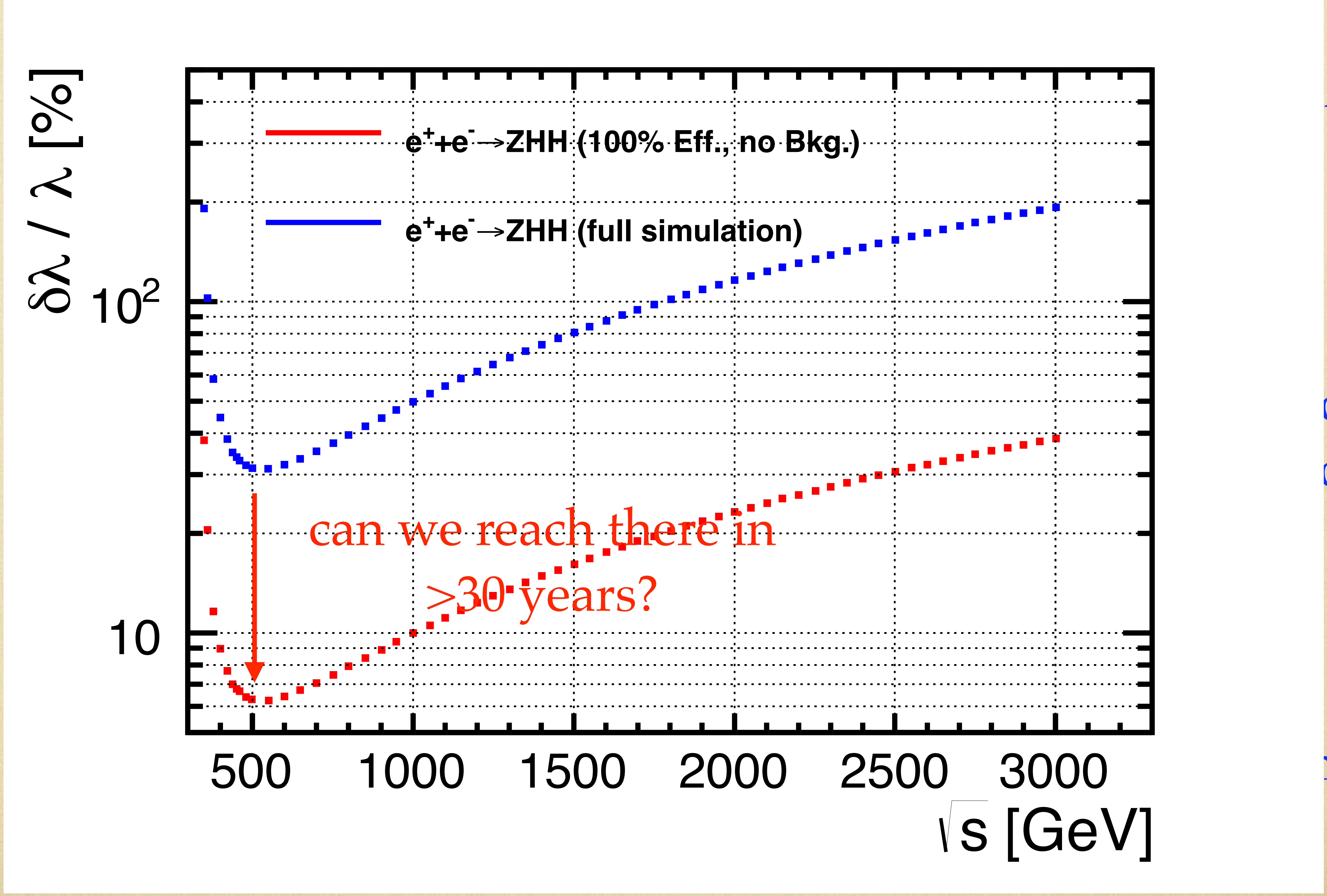
J. Tian, LC-REP-2013-003 M. Kurata, LC-REP-2014-025

# summary

- $\lambda_{HHH}$ is very important to measure, however challenging at both LHC and LCs
- the best expectation we have now, in SM case, $\delta\lambda/\lambda$~27% at 500 GeV, 10% at 1 TeV at the ILC
- two channels ZHH and $\nu\nu$HH are complementary; interference is crucial to determine $\lambda$ in both channels
- 500 GeV is optimal energy for ZHH; >=1TeV is important for $\nu\nu$HH, 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
- improvement of analysis is continuously pursued to fill some gap to the theoretical expectations

# summary

- $\lambda_{HHH}$ is very important to measure, however challenging at



back up

# ongoing: investigation of how to see colour correlation

**Seeing in Color: Jet Superstructure**

arXiv:1001.5027

Jason Gallicchio and Matthew D. Schwartz

*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

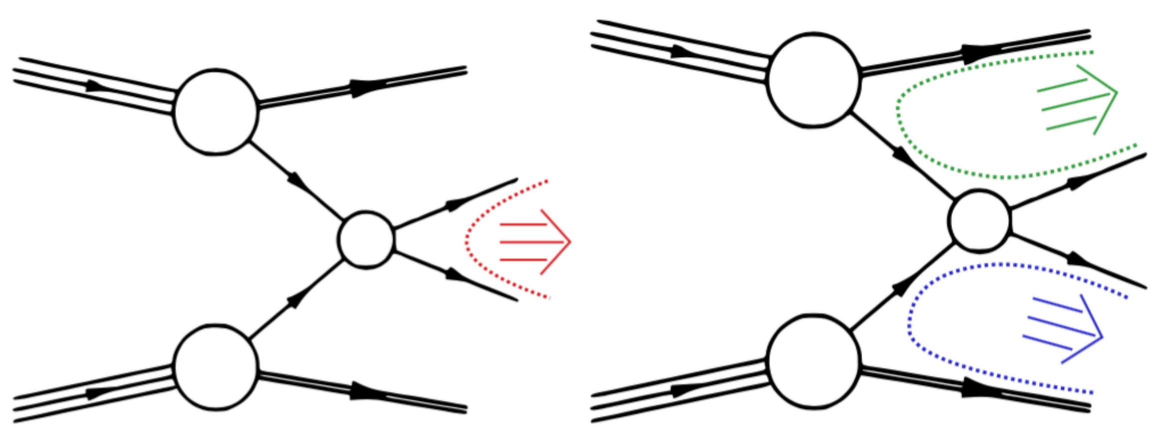
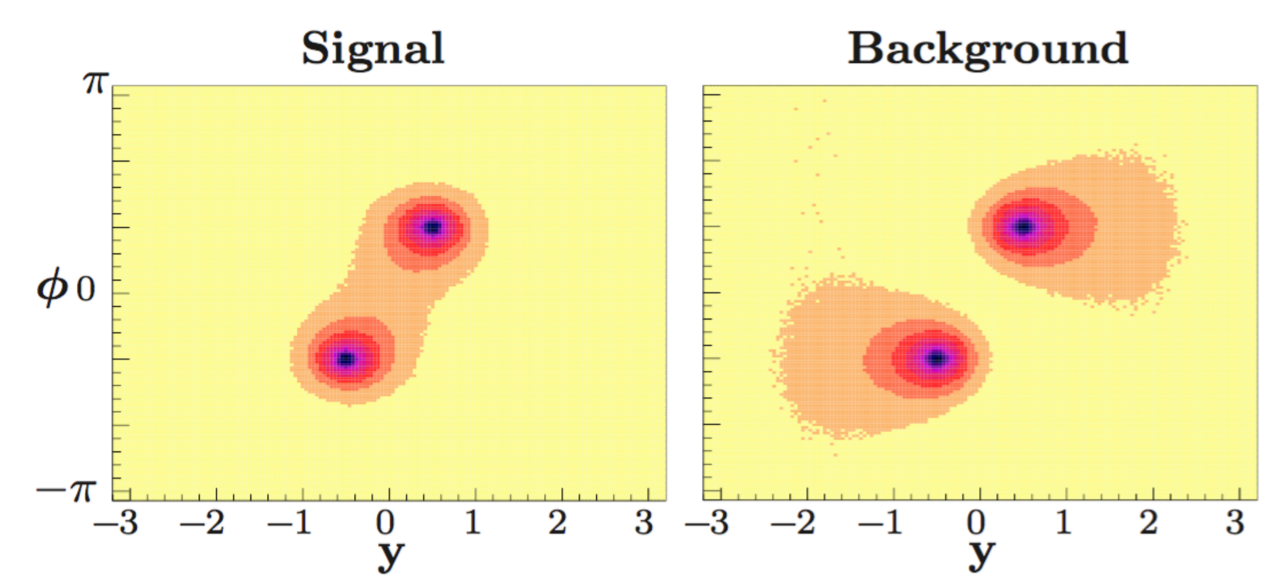


FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to g \to b\bar{b}$).




introduce a new variable, *jet pull*

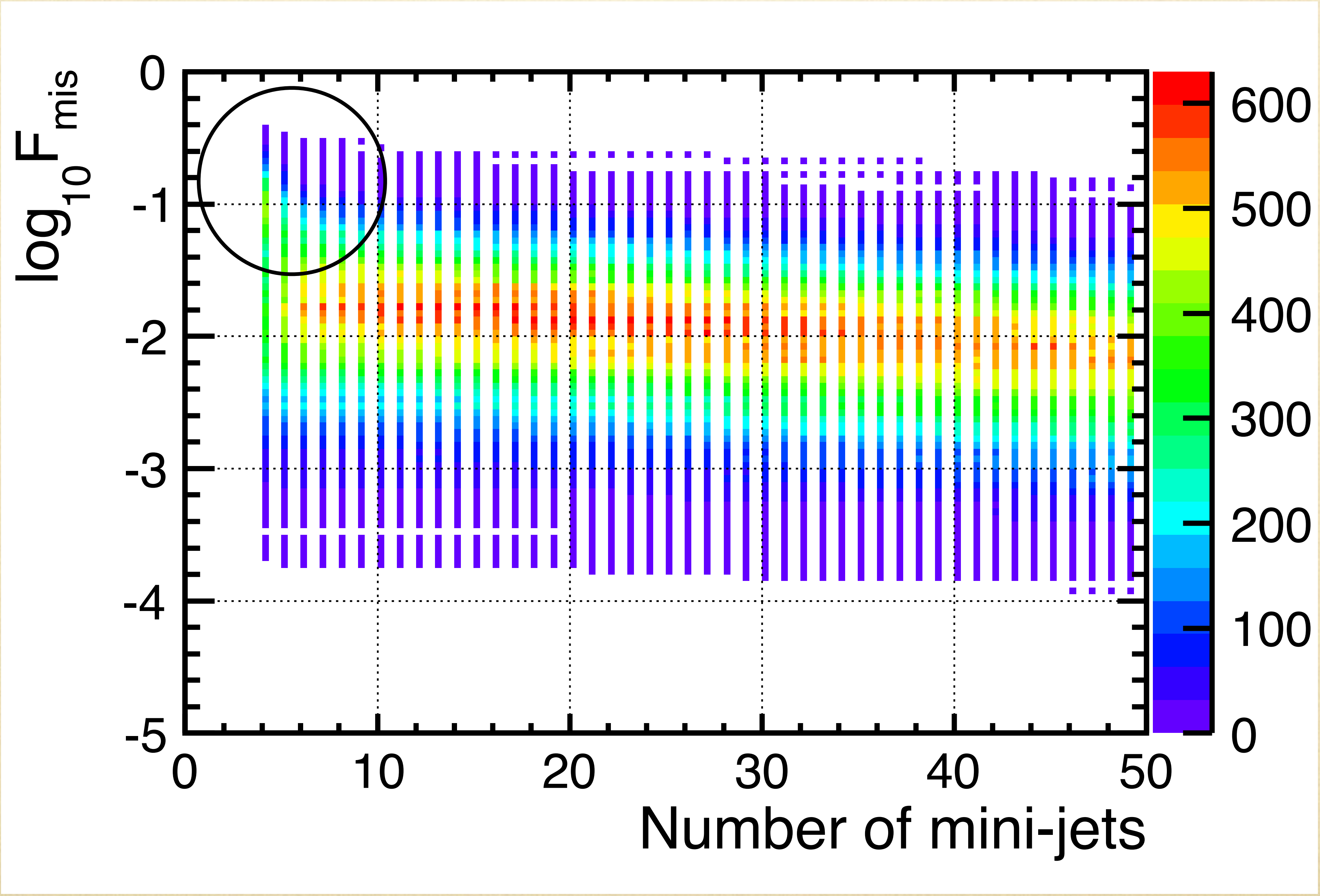
$$\vec{t} = \sum_{i \in \text{jet}} \frac{p_T^i \, |r_i|}{p_T^{\text{jet}}} \, \vec{r}_i \, .$$

i stands for constituents of jet; ri is vector from jet axis to particle i in (rapidity, phi) plane

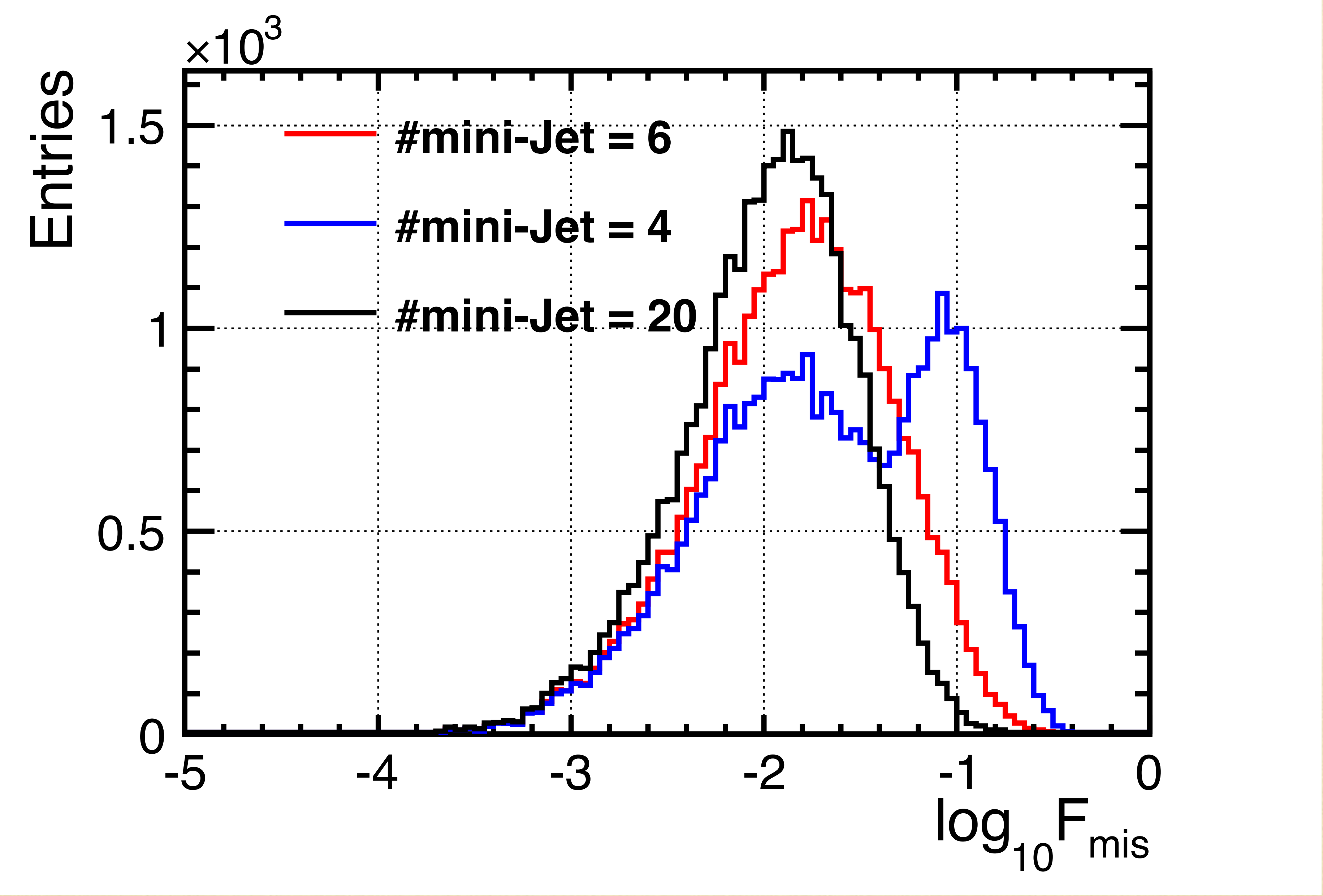
## new measure to evaluate jet clustering performance

$F_{mis}$: the fraction of energies which get mis-clustered

dependence of Fmis on number of mini-jet (fixed Njet clustering)



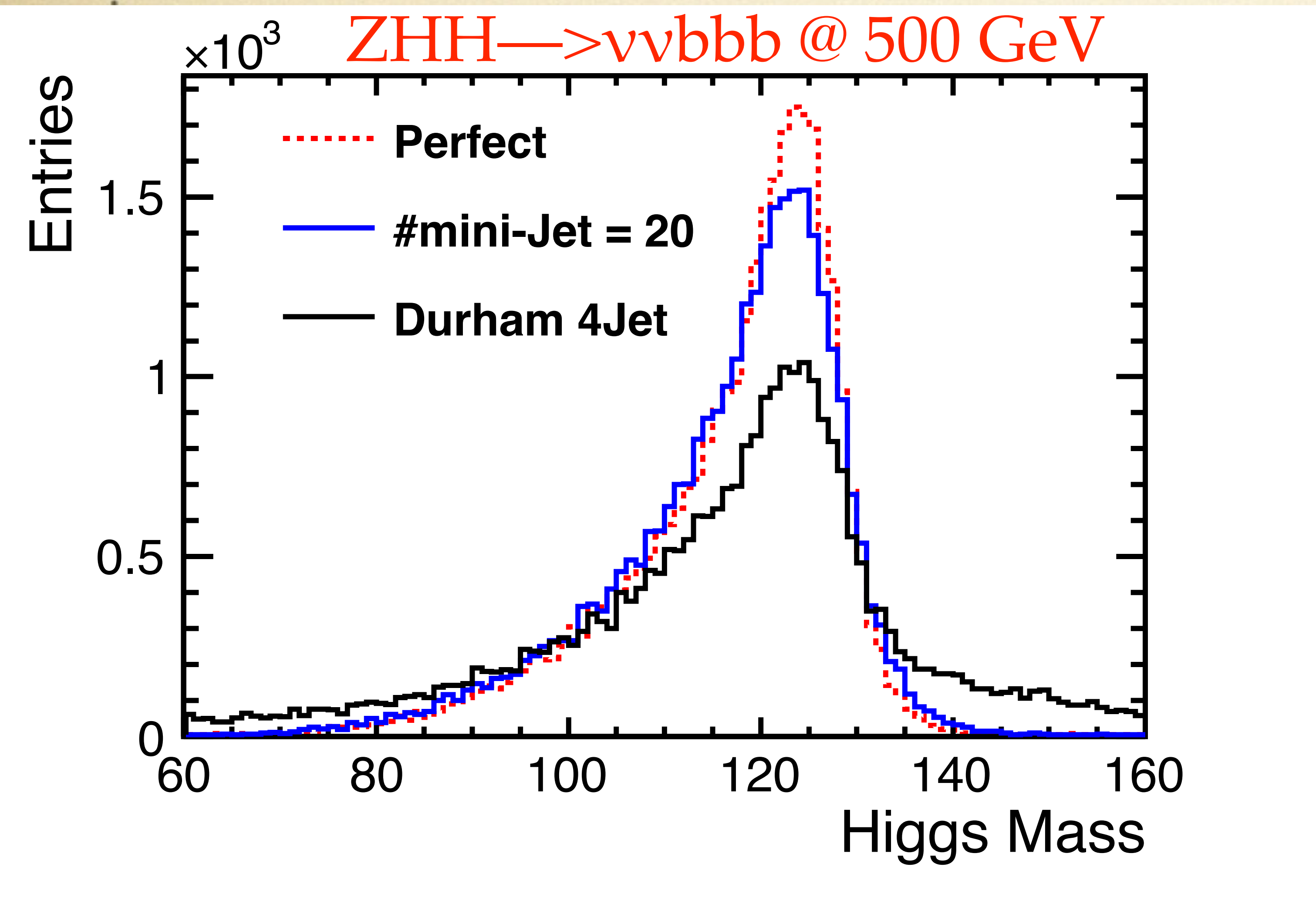
## a detailed look into Fmis




most severe mis-clustering happened from 6—>4

# development of new color-singlet jet clustering

ZHH—>ννbbb @ 500 GeV




- 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

parton = mini-jet?