Study of Higgs self-coupling at 500 GeV and 1 TeV at ILC

---based on the ILD full simulation

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outline

- introduction
- sensitivity of coupling to cross section
- DBD analysis: ZHH @ 500 GeV
- DBD analysis: vvHH (fusion) @ 1TeV
- efforts ongoing and prospects
- summary

motivation of Higgs self-coupling measurement

Higgs Potential: $$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda \upsilon \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

physical Higgs field — mass term — trilinear coupling — quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

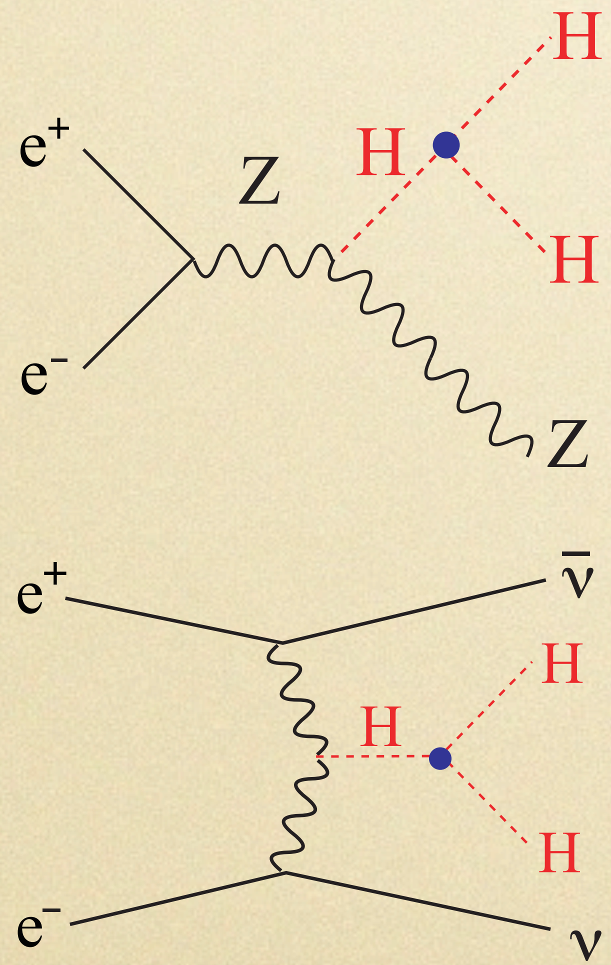
SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$ $\upsilon \sim 246$ GeV

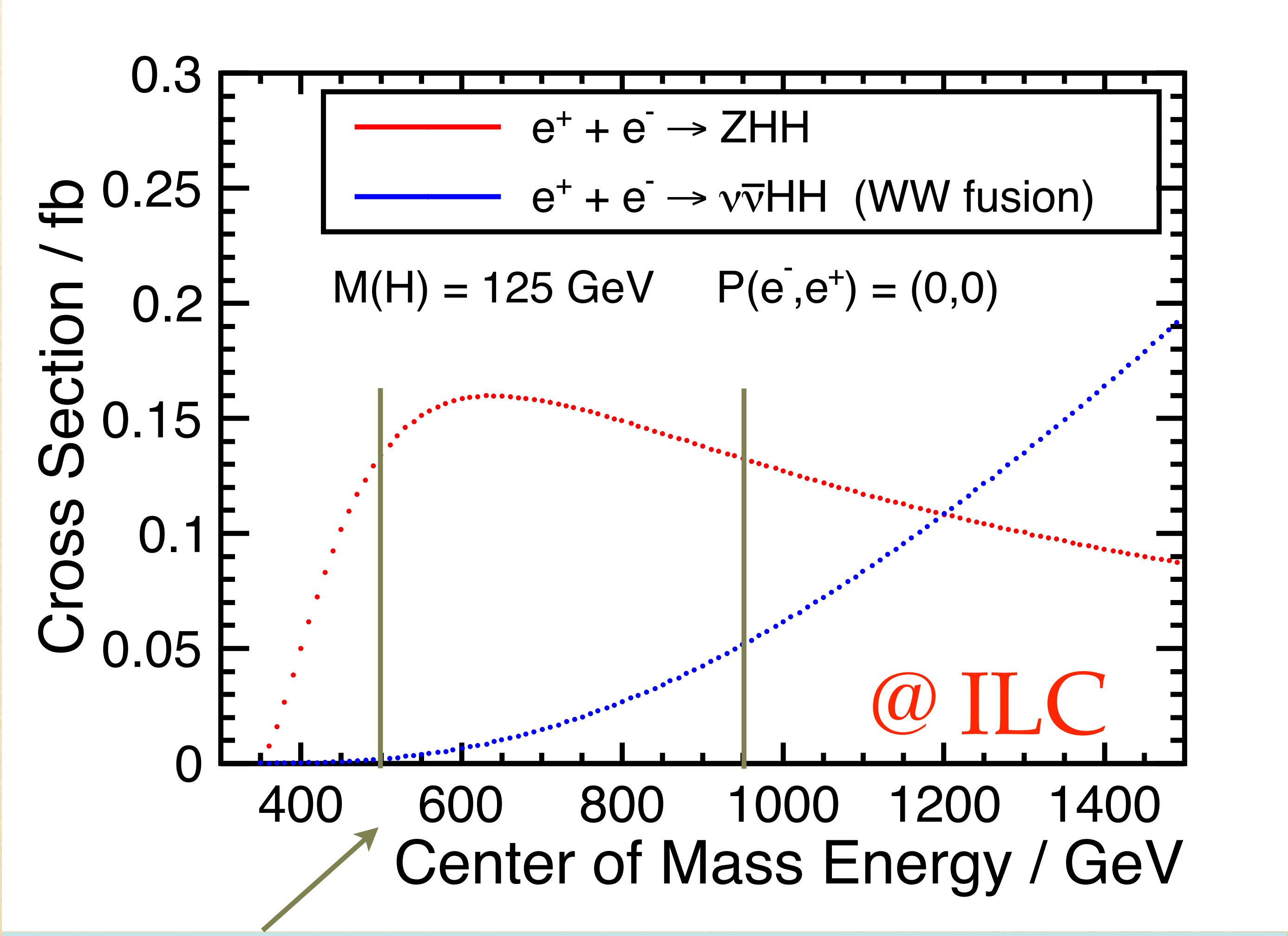
- just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).
- direct determination of the Higgs potential.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like THDM and SUSY.
- difficult to measure at LHC for a light Higgs.

Heidi Rzehak's talk	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$<$ 1%	3%	10%, 100%	2%, 15%

Measurement of the trilinear Higgs self-coupling @ ILC

- double Higgs-strahlung (dominate at lower energy)
- WW-fusion production (become important at higher energy)



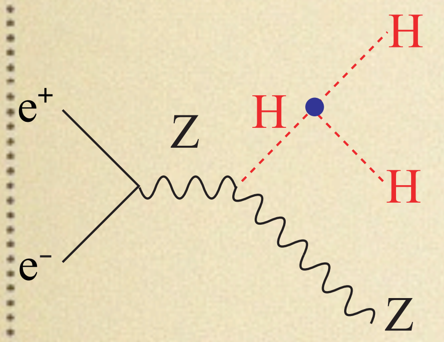


one of the reasons why 500 GeV

General issue: from cross section to the coupling

effect of irreducible diagrams

$$\sigma = a\lambda^2 + b\lambda + c$$



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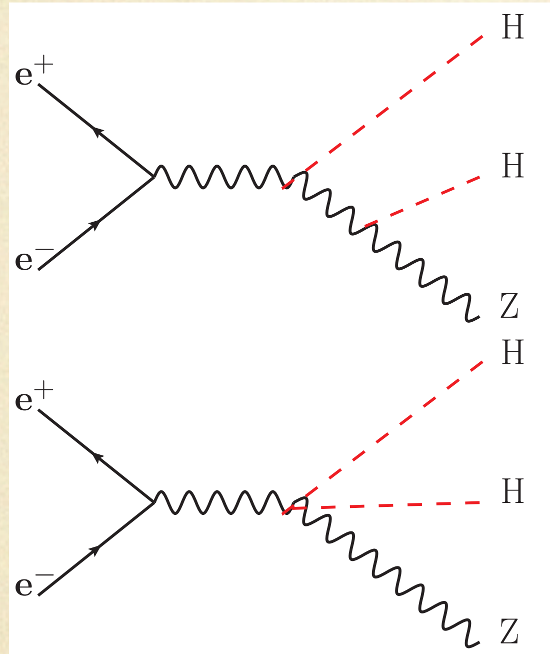

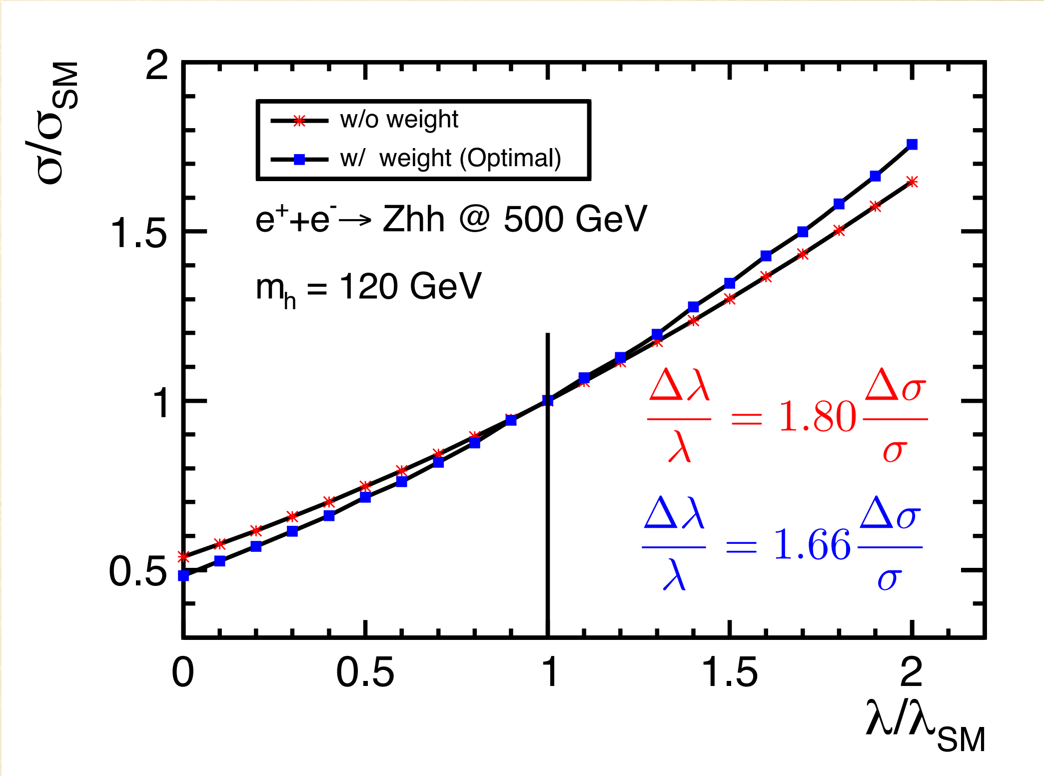

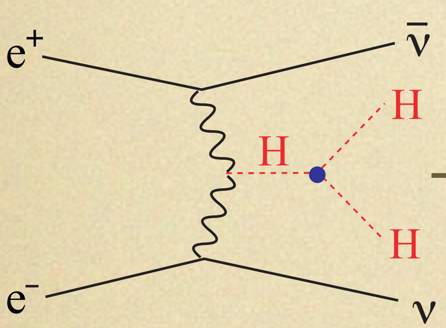

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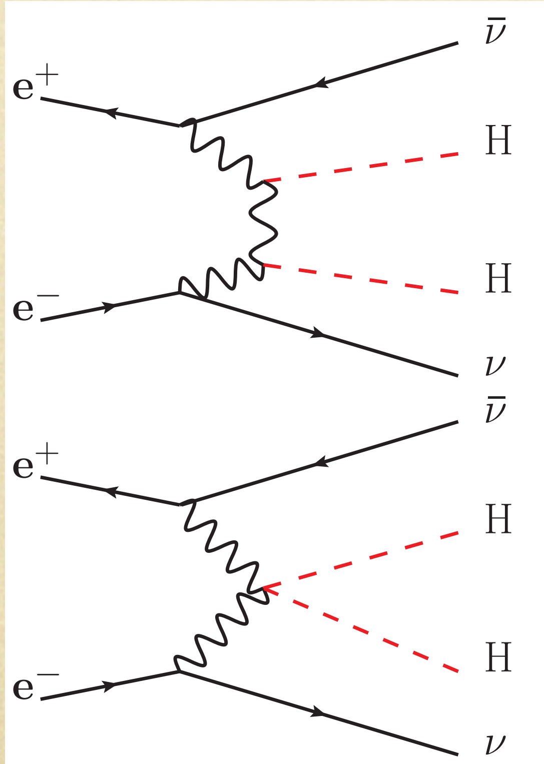
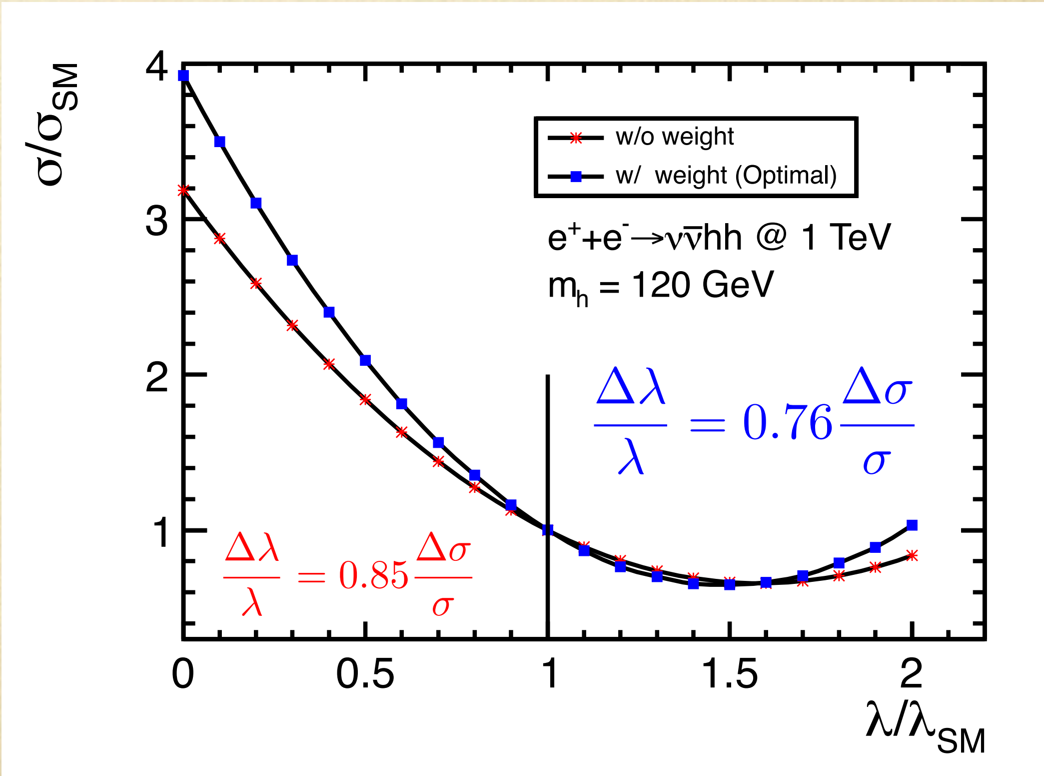
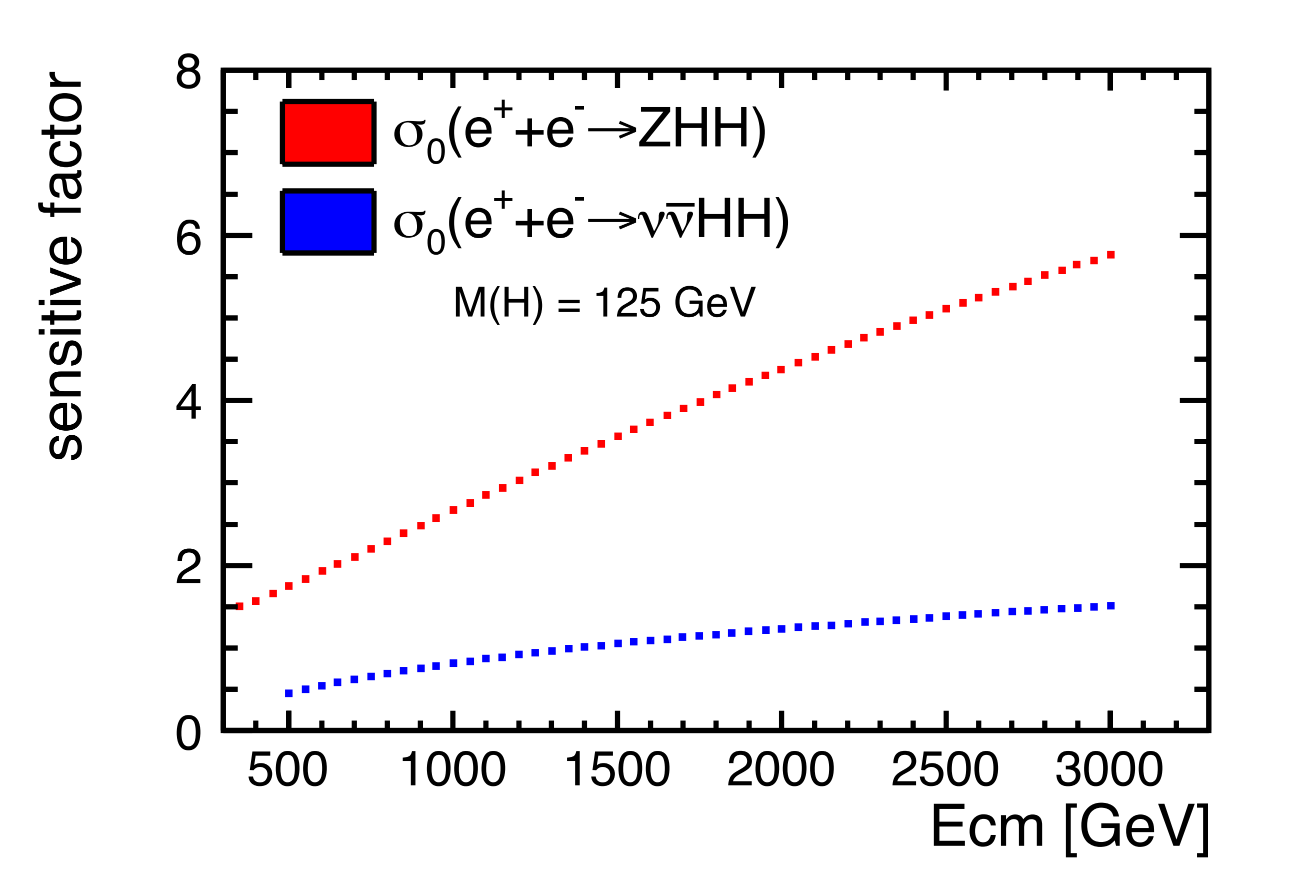




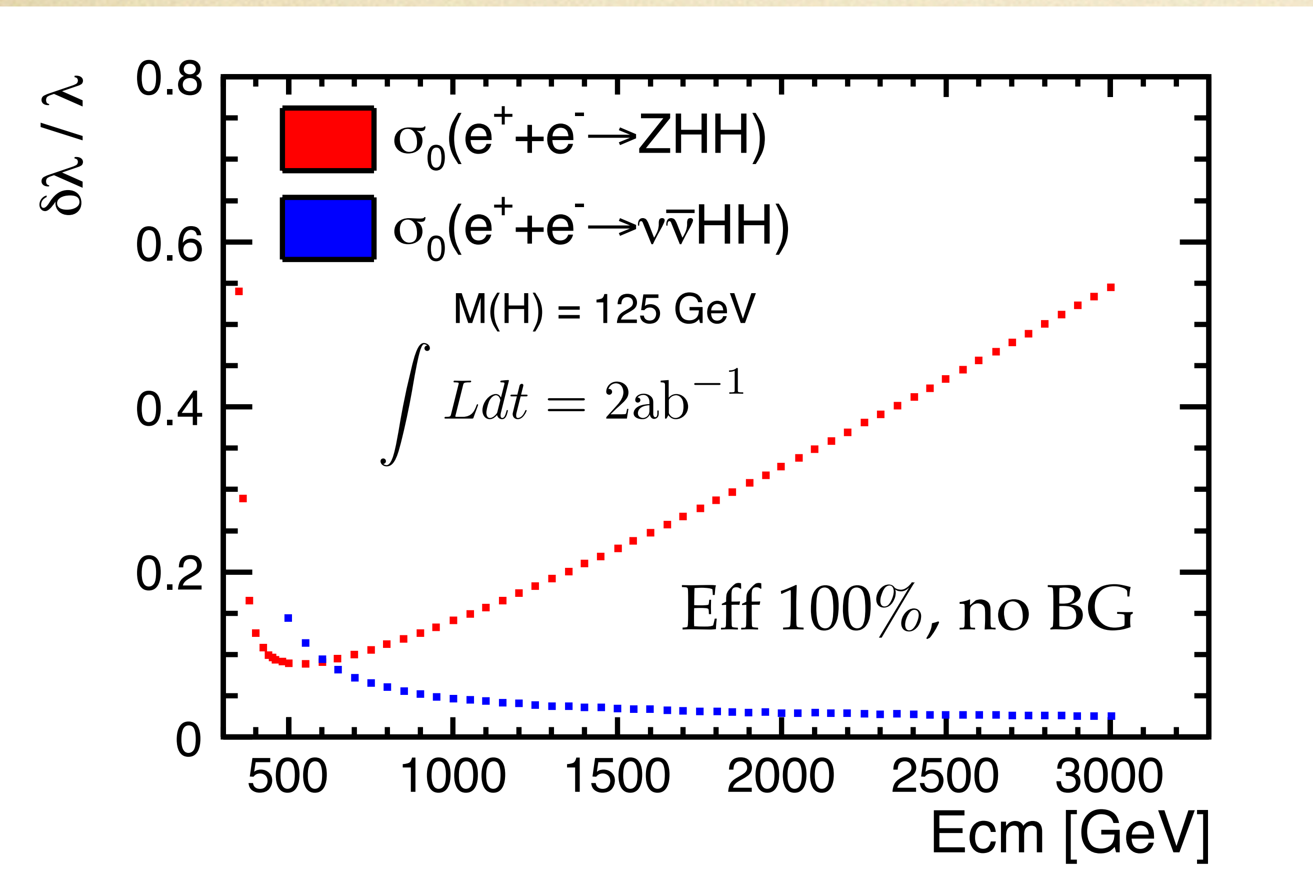
these diagrams significantly degraded the coupling sensitivity

General issue: running of the sensitive factor and expected coupling precision at different Ecm



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

Factor increases quickly as going to higher energy

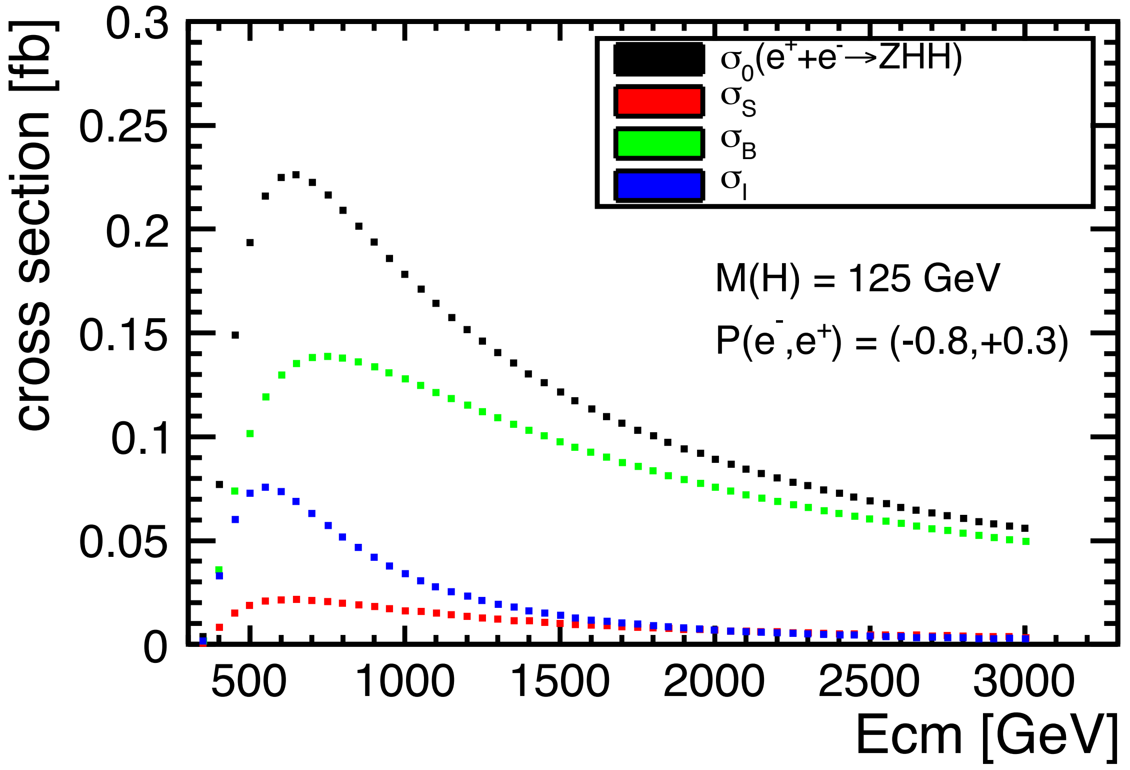


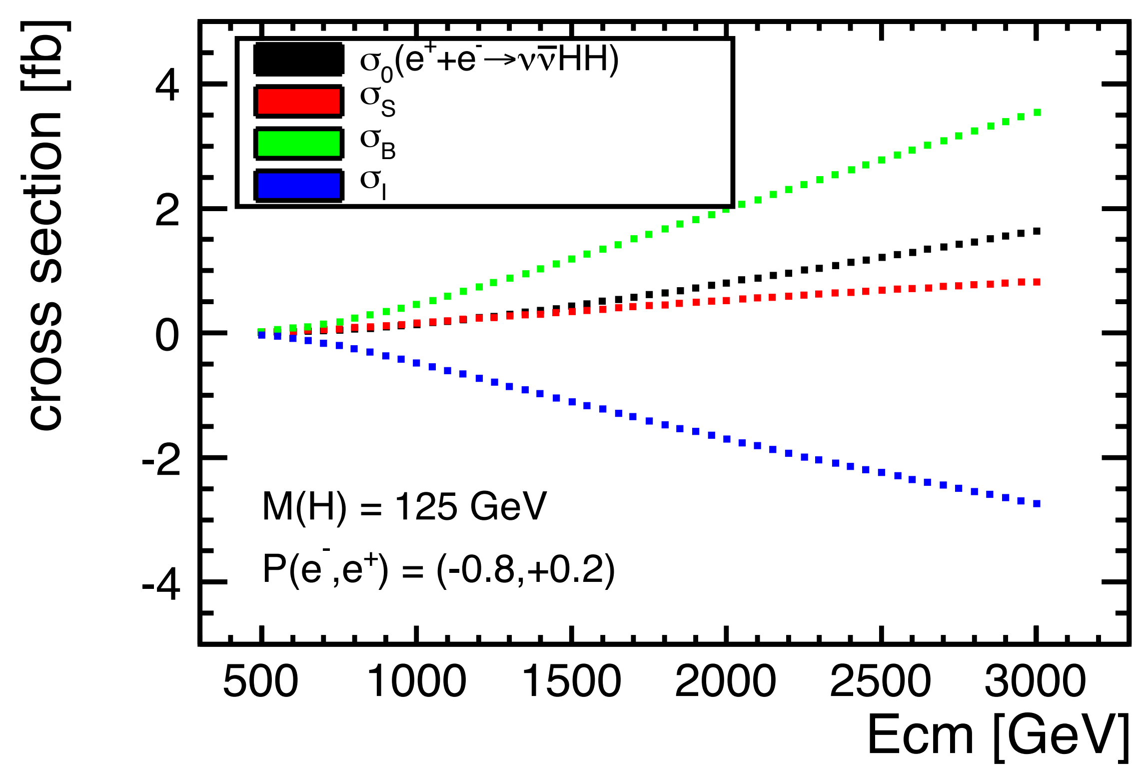
for ZHH, the expected optimal energy ~ 500 GeV (though cross section is maximum ~ 600 GeV)

for $\nu\nu$HH, expected precision improves slowly as going to higher energy

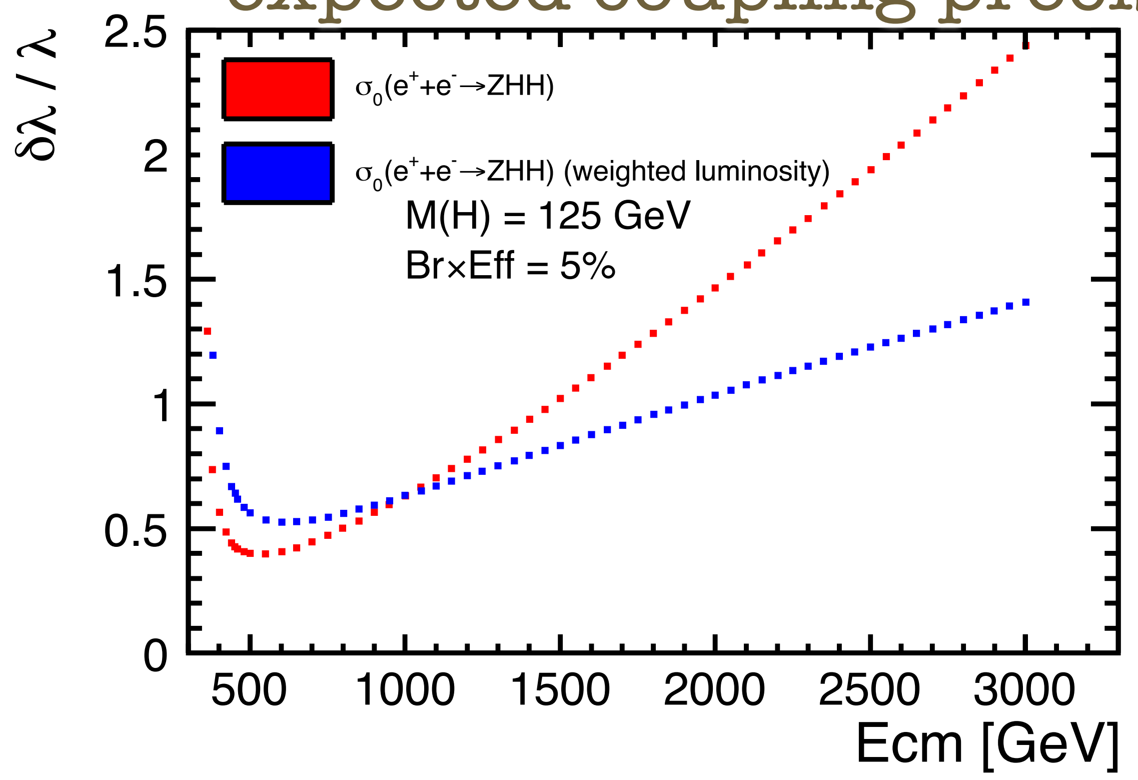
General issue: cross sections of each contribution

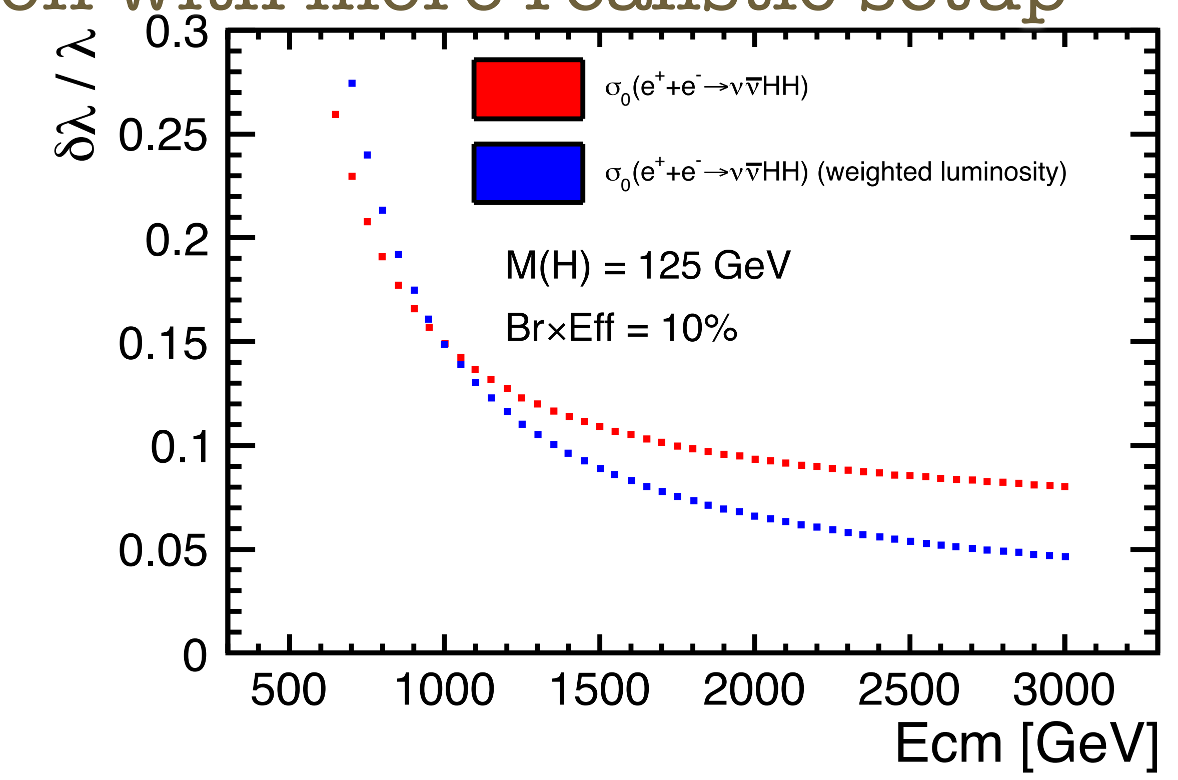
$$\sigma_0 = a\lambda^2 + b\lambda + c = \sigma_S + \sigma_I + \sigma_B$$





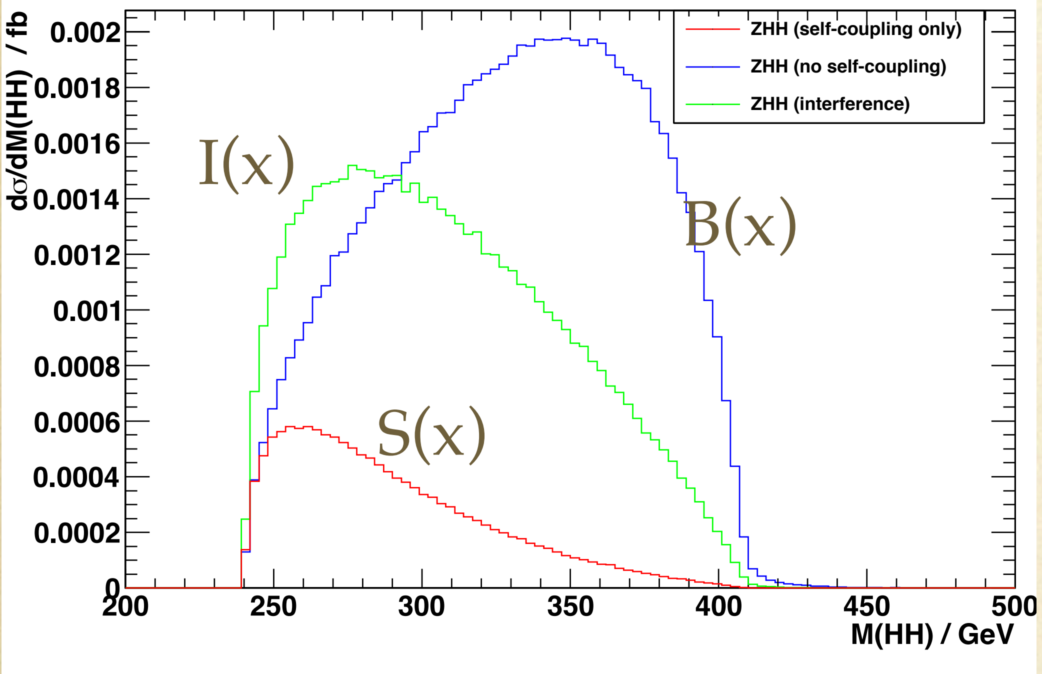
expected coupling precision with more realistic setup





new weighting method to enhance the coupling sensitivity

differential cross-section



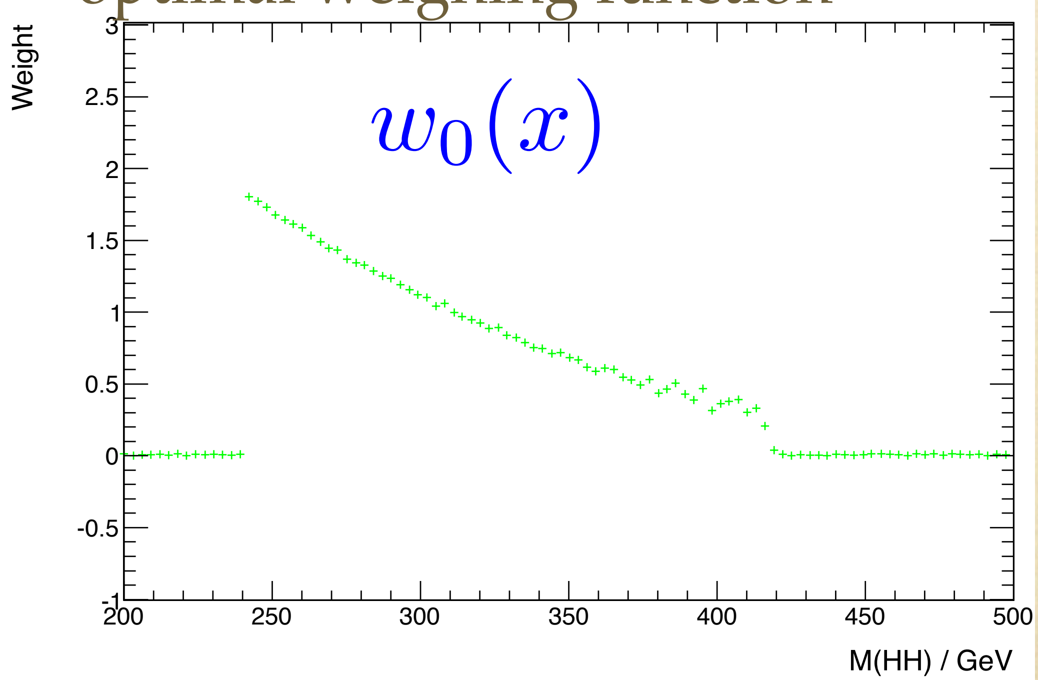
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

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

difficulties for the analysis

fundamental:

- irreducible SM diagrams, significantly degrade the coupling sensitivity.
- very small cross section (σ_{ZHH}~0.22 fb with P_L) and we are only using ~40% of the signal (both H-->bb). large integrated luminosity needed. (high beam polarization helped a lot)
- huge SM background (tt/WWZ, ZZ/Zγ, ZZZ/ZZH), 3-4 orders higher.

strategic:

- Higgs mass reconstruction: mis-clustering, missing neutrinos, wrong pairing.
- flavor tagging and isolated-lepton selection: need very high efficiency and purity.
- neural-net training: separated neural-nets, huge statistics needed.

analysis strategy and status

$e^+ + e^- \rightarrow ZHH$ @ $500\ GeV$

searching mode and main backgrounds in each mode:

- llHH: llbb (ZZ, γZ, bbZ), lνbbqq (tt-bar), llbbbb (ZZZ/ZZH)
- ννHH: bbbb (ZZ, γZ, bbZ), τνbbqq (tt-bar), ννbbbb (ZZZ/ZZH)
- qqHH: bbbb (ZZ, γZ, bbZ), bbqqqq (tt-bar), qqbbbb (ZZZ/ZZH)

event selection:

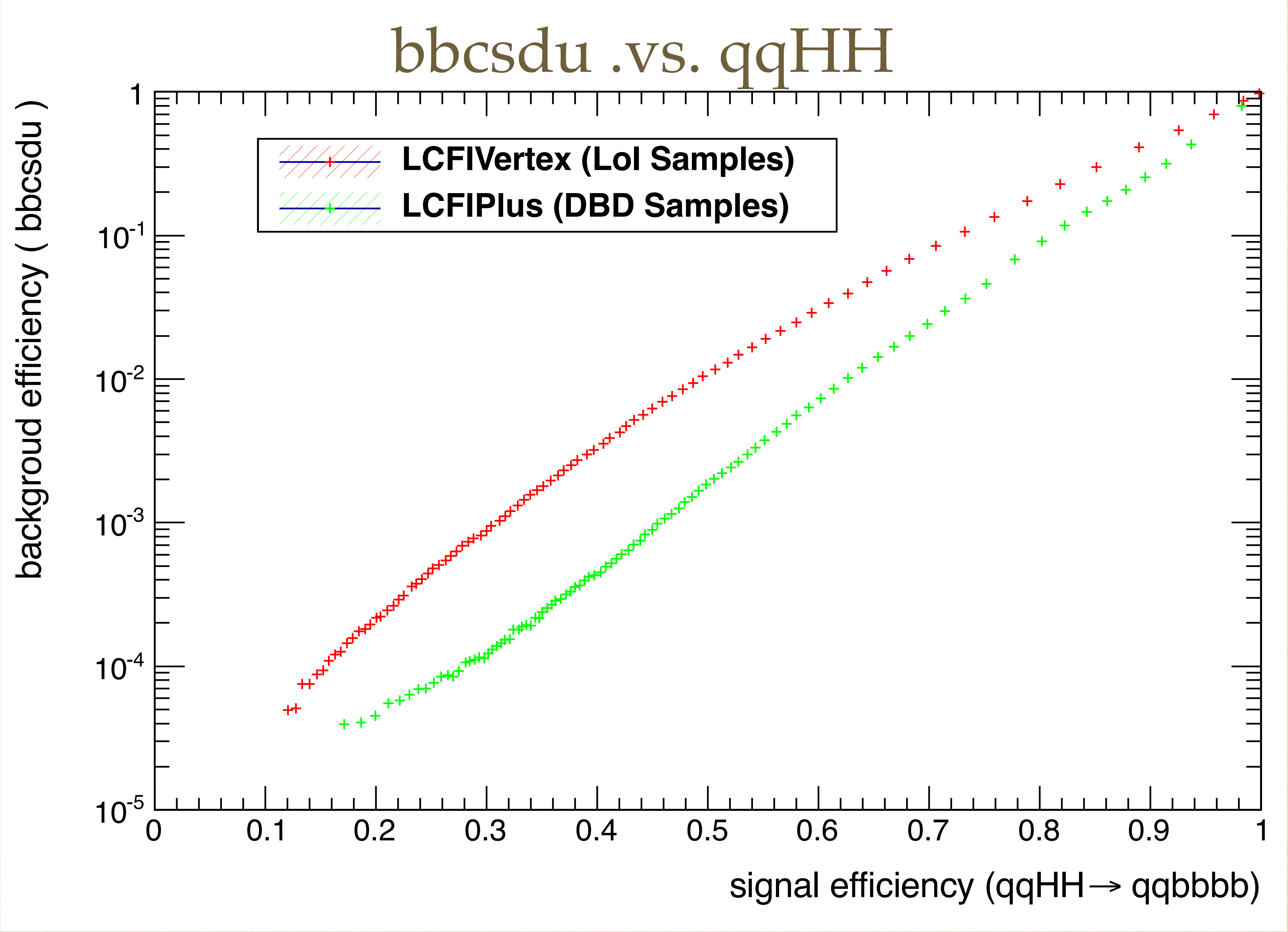
- isolated-lepton selection or rejection
- jet clustering and flavor tagging
- missing energy or visible energy requirement
- event reconstructed as from signal and dominant background
- each dominant background is suppressed by training a neural-net

to make the result stable, high statistics (~10 ab^{-1}) is used

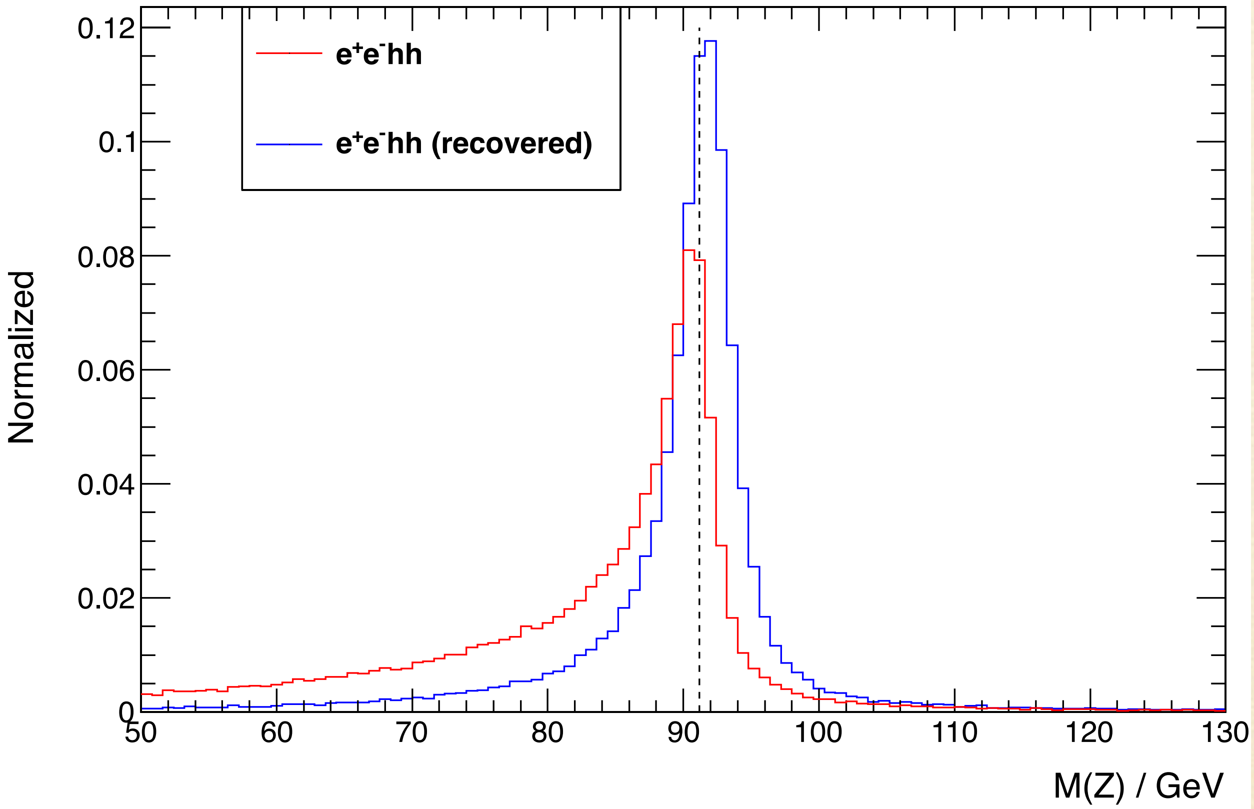
strategy for ννHH @ 1 TeV is quite similar

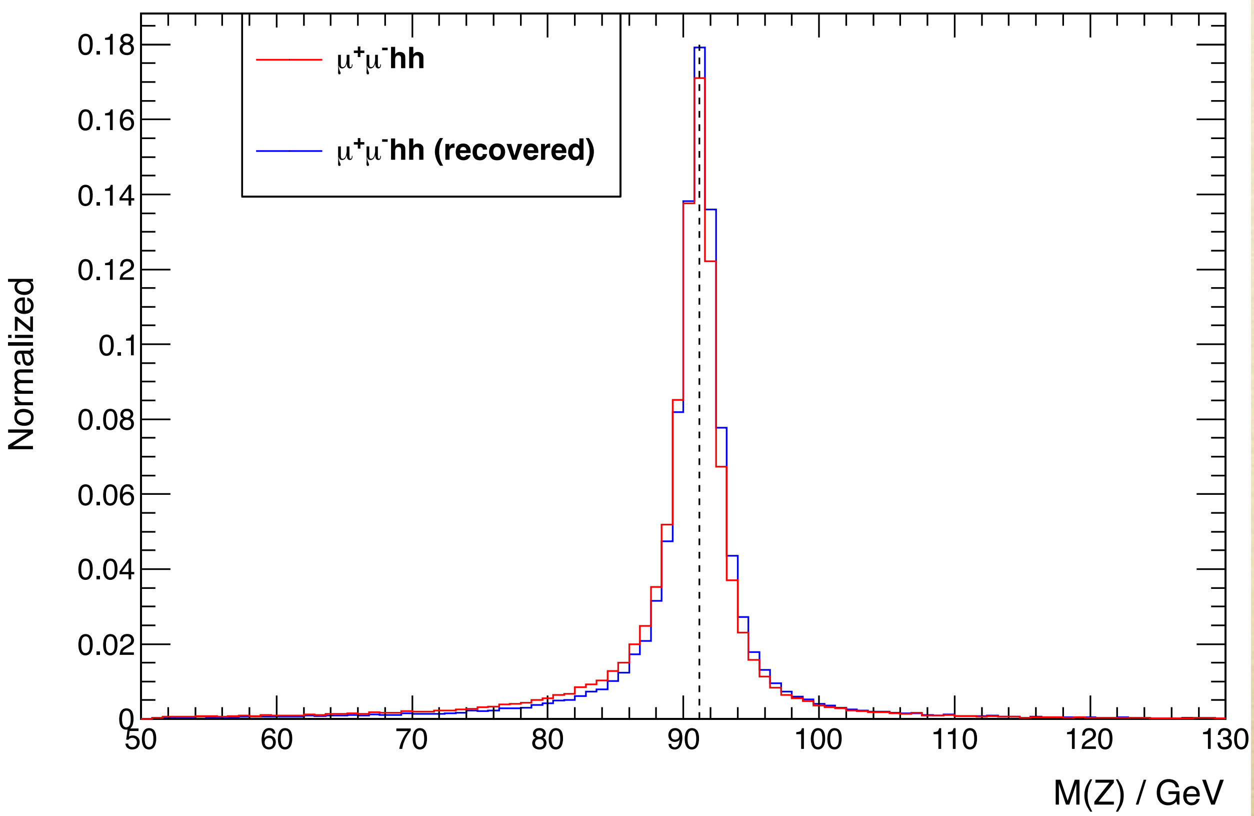
flavor tagging performance in qqHH mode

Thanks to developers of LCFIPlus (T. Tanabe and T. Suehara)



Isolated lepton selection (llHH)





(Etot = Eecal + Ehcal)

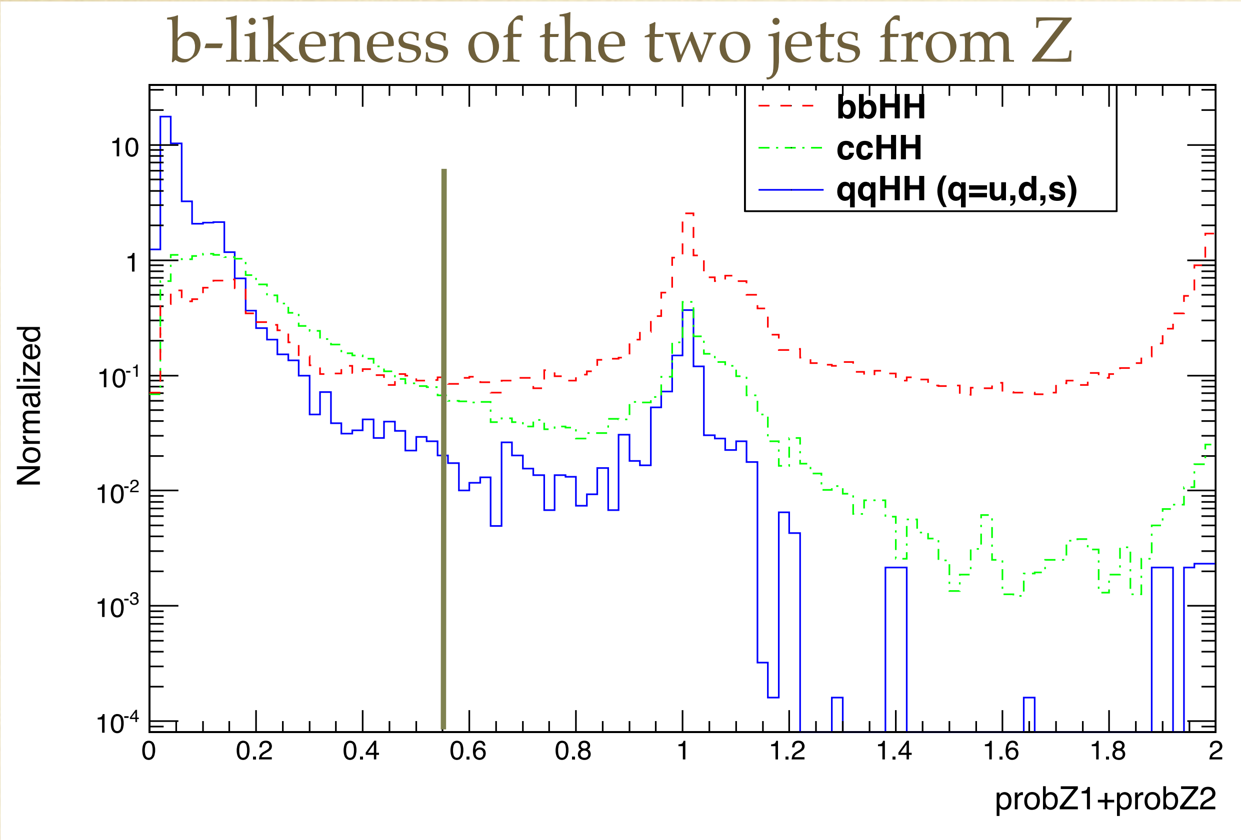
	electron ID	muon ID
✦	Eecal / Etot > 0.9	Eyoke > 1.2
✦	0.5 < Etot / P < 1.3	Etot / P < 0.3
✦	from primary vertex	from primary vertex
✦	P > 12.2 + 0.87Econe	P > 12.6 + 4.62Econe

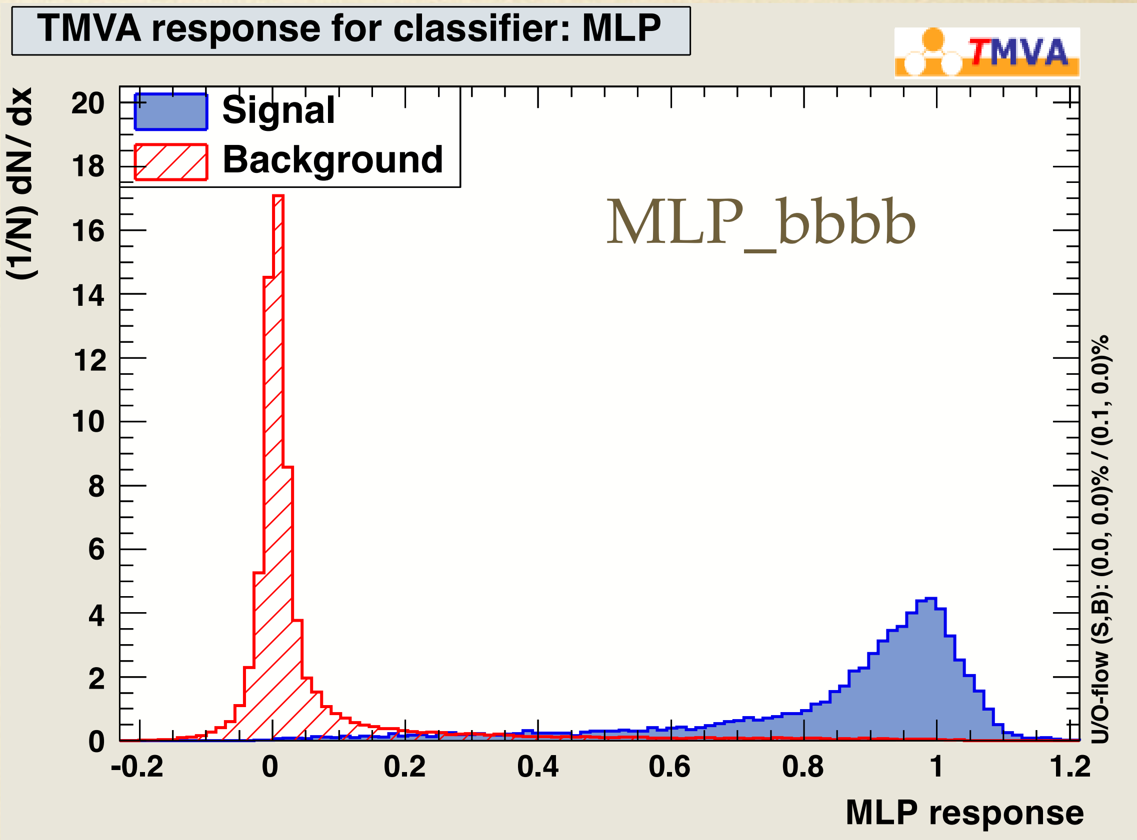
BS and FSR recovery adapted from ZFinder

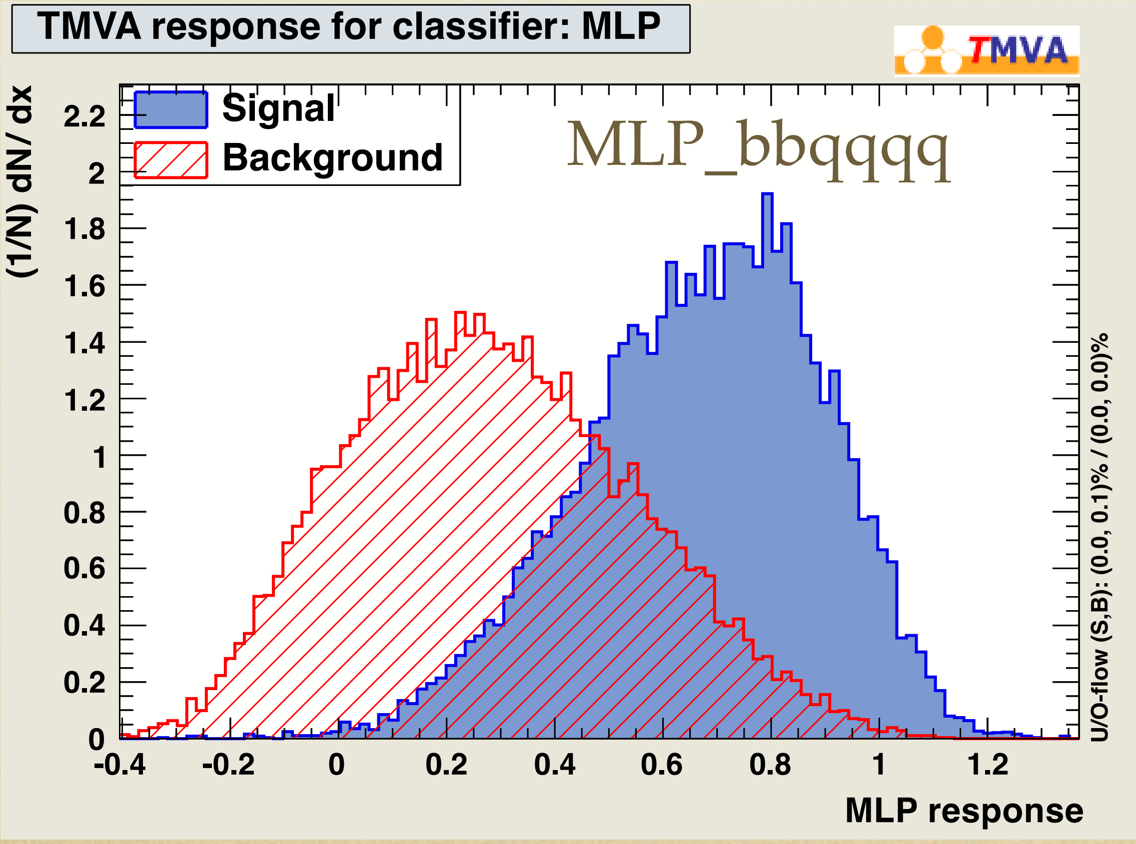
efficiency of two isolated lepton selection
(much better for DBD)

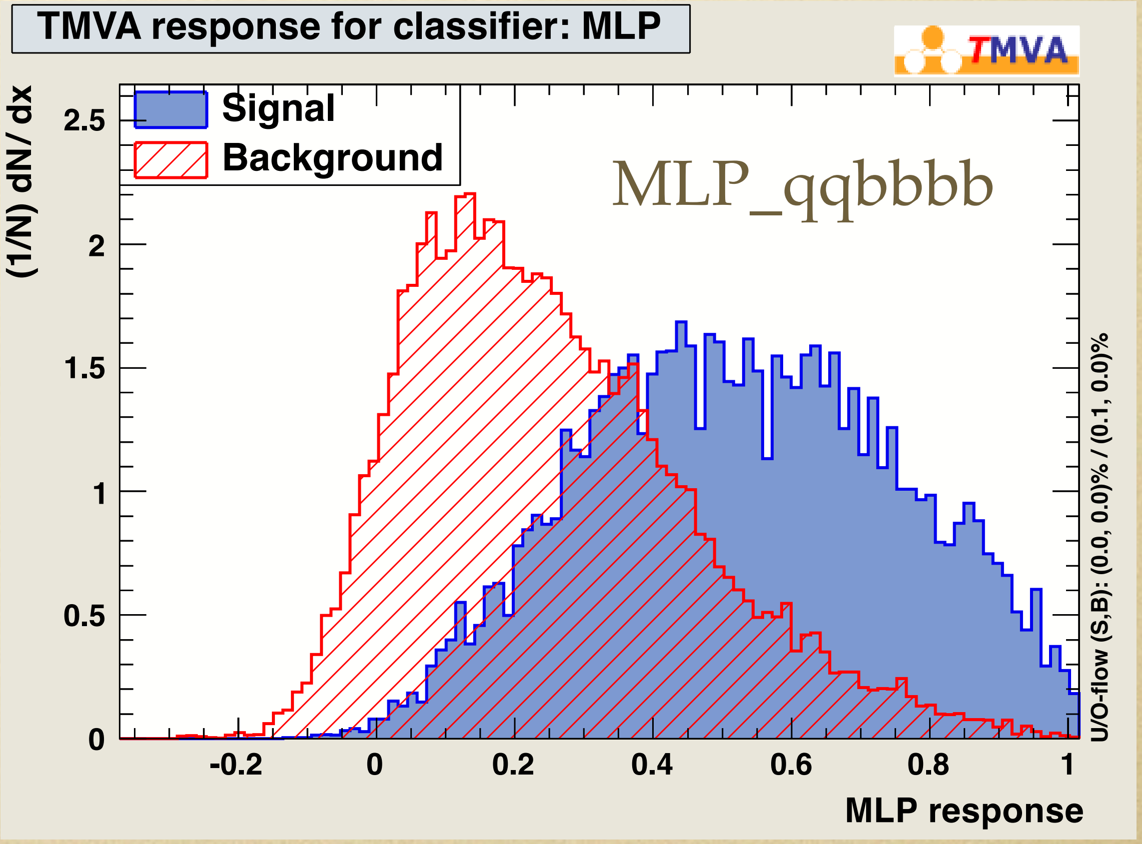
Eff (%)	eeHH	μμHH	bbbb	eνbbqq	μνbbqq
DBD	85.7	88.4	0.028	1.44	0.10
LoI	81.9	85.4	0.43	2.71	1.94

categorization and neural-net outputs in qqHH mode









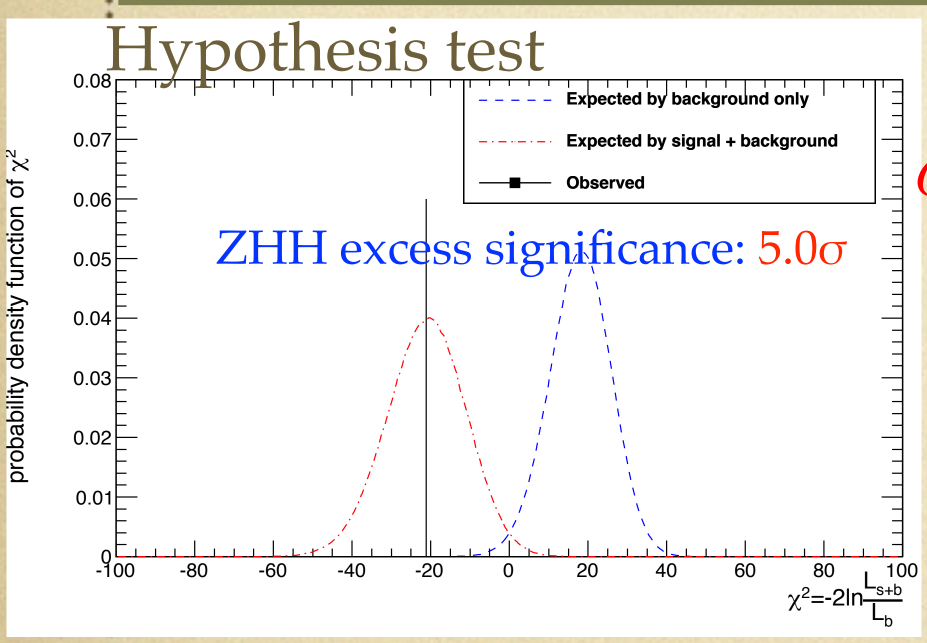
DBD full simulation

Higgs self-coupling @ 500 GeV (combined)

P(e-,e+)=(-0.8,+0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

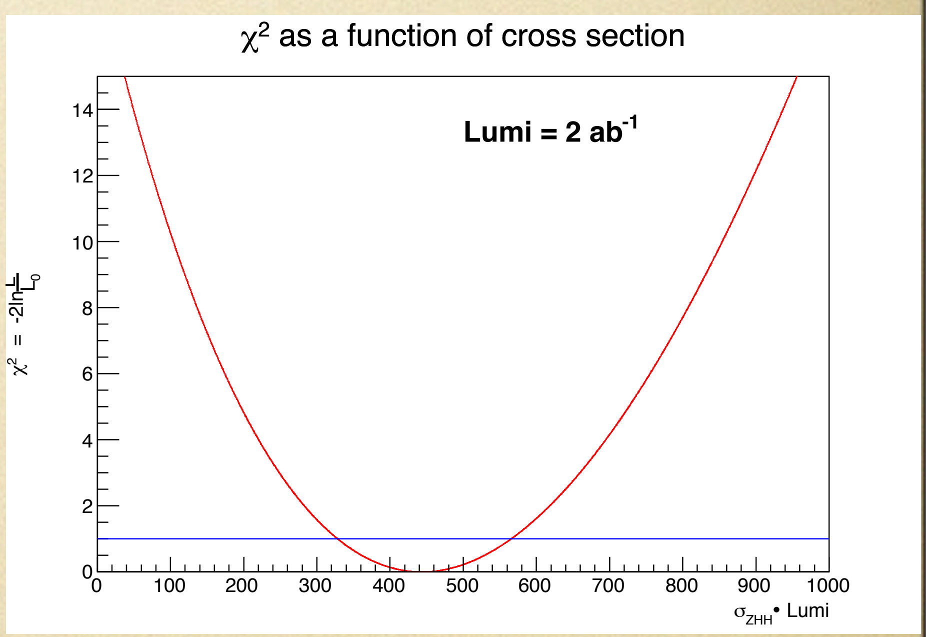
Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

Hypothesis test



$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

$$\frac{\delta\sigma}{\sigma} = 27\%$$



Higgs self-coupling: $\frac{\delta\lambda}{\lambda} = 44\%$

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^+ + e^- \to \nu\bar{\nu}HH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

	Expected	After Cut
ννhh (WW F)	272	35.7
ννhh (ZHH)	74.0	3.88
BG (tt/ννZH)	7.86×10^5	33.7
significance	0.30	4.29

- better sensitive factor
- benefit more from beam polarisation
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: $>7\sigma$

Higgs self-coupling significance: $>5\sigma$

efforts going on

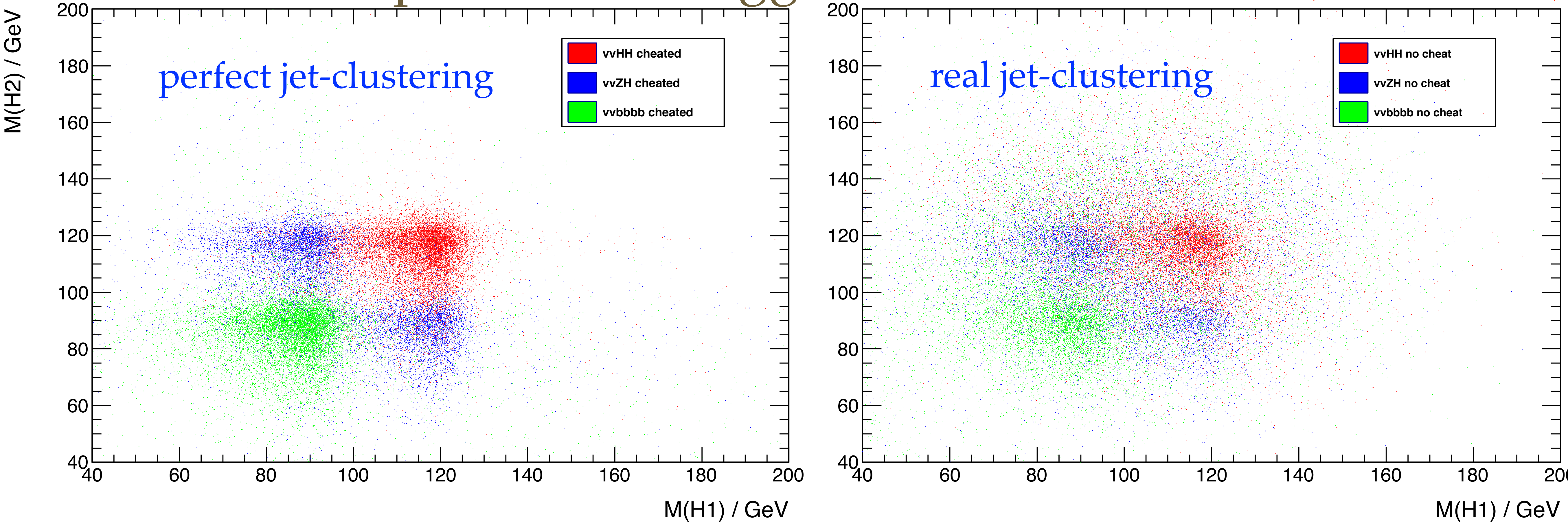
- include the H-->WW* mode (see next talk by Masakazu).
- investigate the kinematic fitting (DESY group, Claude and Jenny).
- re-optimize the analysis strategy (current selections are optimized for ZHH or ννHH, not for the self-coupling diagram).
- consider the beam background overlay.
- new signal samples with Higgs mass of 125 GeV.
- new color-singlet jet-clustering to improve the mass resolution

Color-singlet Jet-clustering

(challenging)

scatter plot of two Higgs masses

vvHH mode: (ZZH and ZZZ)



- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda \sim 40\%$
- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such as color-singlet dynamics: rapidity gap, coplanarity, energy pdf)
- looks very challenging now...

prospects

effect of positron polarisations

P(e^-) = -0.8

P(e^+)	0	+0.3 (+0.2)	+0.6 (+0.4)
ZHH @ 500 GeV	50%	44%	40%
ννHH @ 1 TeV	20%	18%	16%

ILC Luminosity Upgrade

Tim Barklow's talk

3.2 ab^{-1} ~ 6 years @ 500 GeV; 5 ab^{-1} ~ 6 years @ 1 TeV

	TDR-Upgrade
ZHH @ 500 GeV	44%--> 35%
ννHH @ 1 TeV	18%--> 11%

Summary

- measuring Higgs self-coupling is one of the fundamental task for the next generation Linear Collider.
- results from DBD full simulation:

  $\delta\lambda/\lambda$ ~ 44% by ZHH @ 500 GeV, P(e-,e+)=(-0.8,+0.3), 2 ab^{-1}

  $\delta\lambda/\lambda$ ~ 18% by ννHH @ 1 TeV, P(e-,e+)=(-0.8,+0.2), 2 ab^{-1}

  Double Higgs excess significance: 5.0σ @ 500 GeV, 7.2σ @ 1TeV.
- effect of irreducible diagrams degraded the coupling sensitivity. a new general weighting method developed, ~10% improvement for coupling.
- key algorithms: b-tag, lepton-finder, jet-finder.
- lots of efforts are ongoing for the further improvement.

backup

P value and Significance

large statistics

excess: assuming there is no signal, the probability of observing events equal or more than the expected number of events (S+B).

$$p = \int_{S+B}^{+\infty} f(x, B, \sqrt{B})\mathrm{dx} \qquad \frac{S}{\sqrt{B}}$$

measure: assuming signal exists, the probability of observing events equal or less than the expected number of background events (B).

$$p = \int_{-\infty}^{B} f(x, S+B, \sqrt{S+B})\mathrm{dx} \qquad \frac{S}{\sqrt{S+B}}$$

convert to gaussian significance (s):

$$1 - p = \int_{-\infty}^{\mathrm{s}\sigma} N(x; 0, 1)\mathrm{dx}$$

Higgs self-coupling measurement at LHC

for a low mass Higgs: M(H) < 140 GeV

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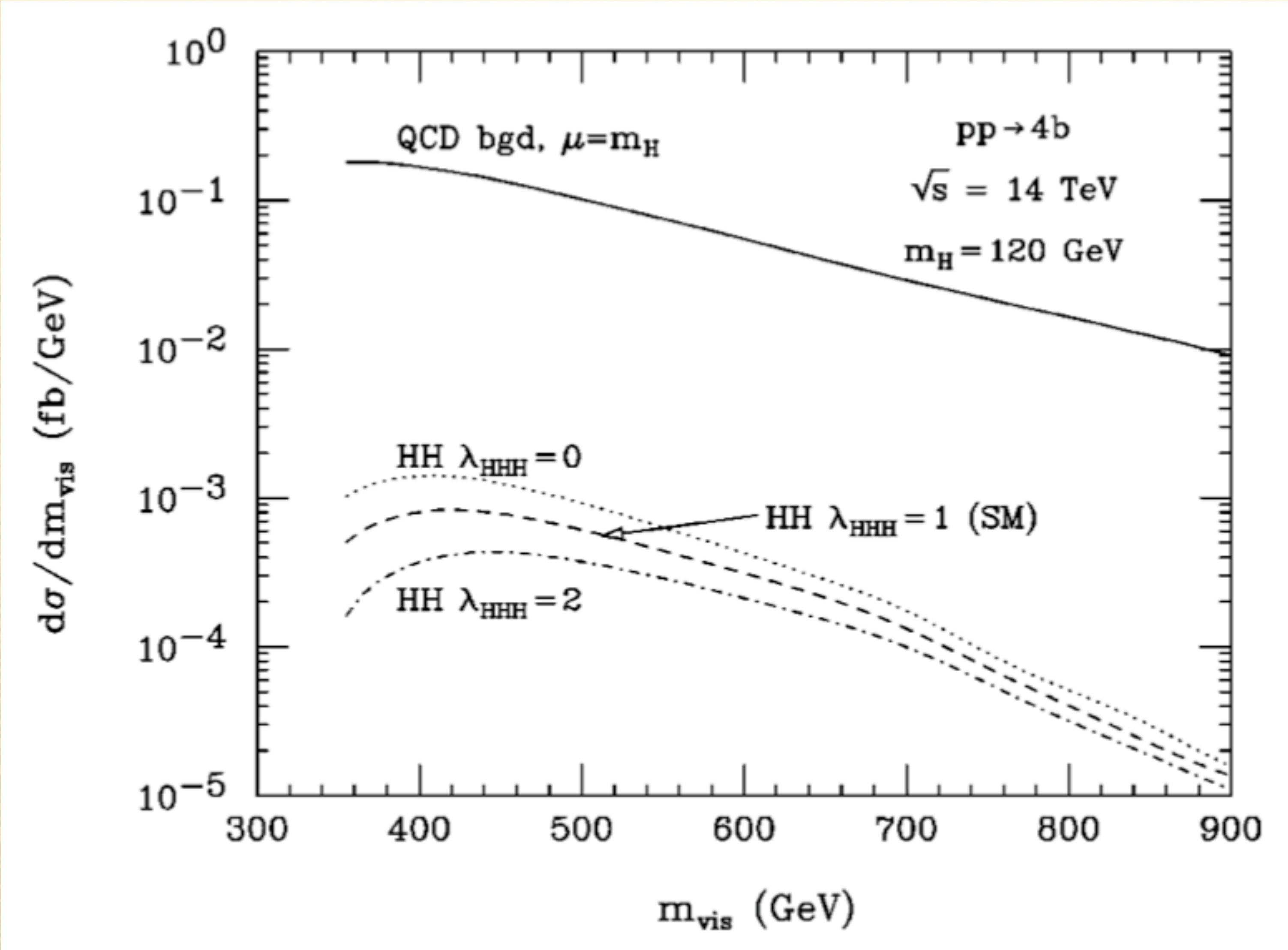
$$p + p \rightarrow HH \rightarrow b\bar{b}b\bar{b}$$

cross-section



Invariant mass of visible particles

solid: QCD 4b background
dashed: SM signal
dotted and dotted-dashed:
signal with different Higgs self-coupling

two orders overwhelmed by QCD 4b background!

$$-6.8 < \Delta\lambda_{HHH} < 10.1 \qquad (\Delta\lambda_{HHH} = \frac{\lambda}{\lambda_{SM}} - 1)$$