Higgs self-coupling study at ILC

---based on the ILD full simulation

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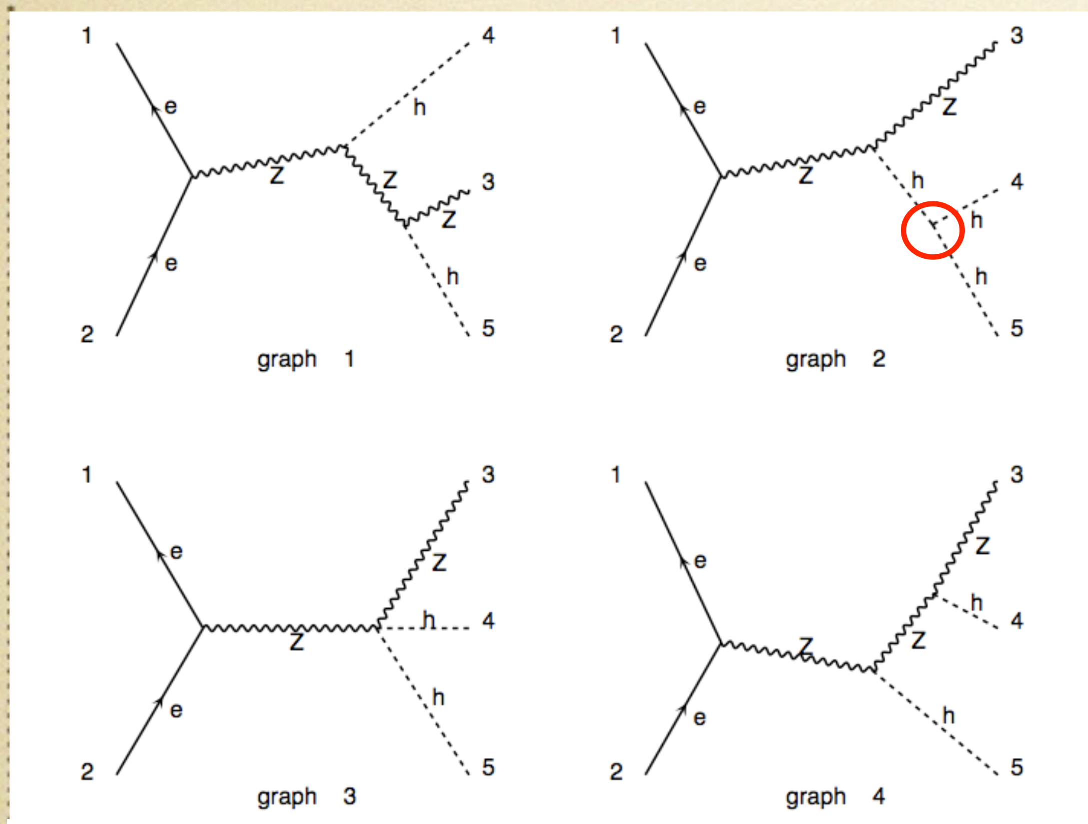
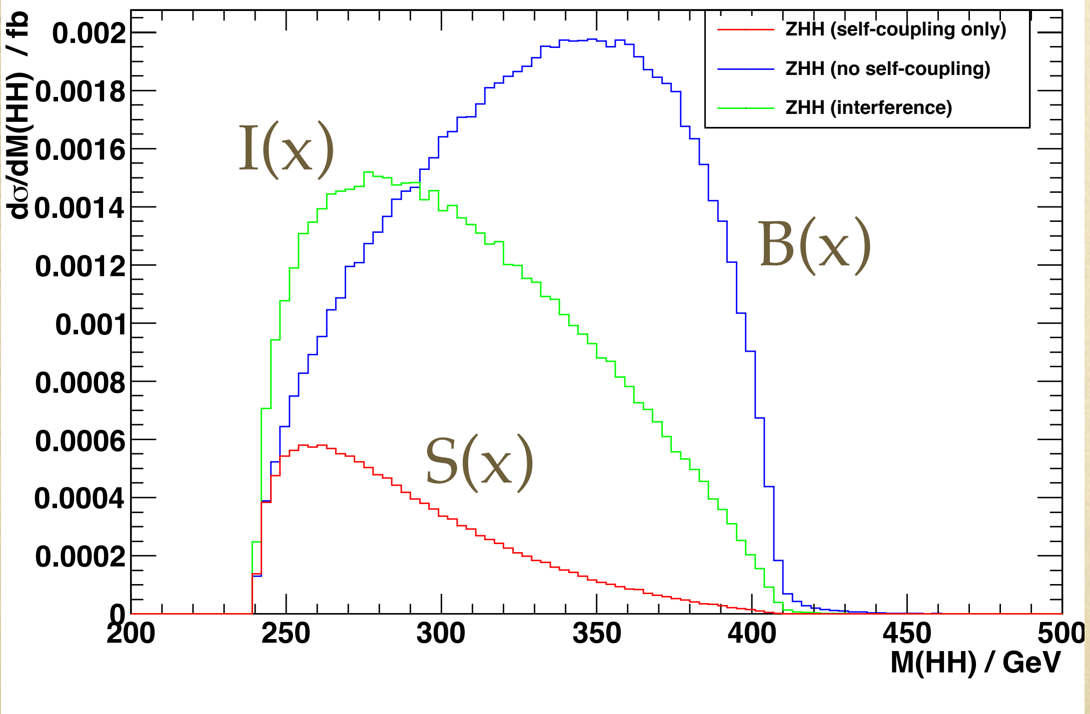
outline

- introduction
- new weighting method to enhance the sensitivity of coupling
- status of DBD analysis: ZHH @ 500 GeV
- vvHH (fusion) @ 1TeV based on SGV simulation
- summary and conclusion

new weighting method





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

irreducible — interference — self-coupling

find a weight function: w(x)

observable: weighted cross-section

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

$$= \underbrace{\int B(x)w(x)\mathrm{d}x}_{B_w} + \lambda \underbrace{\int I(x)w(x)\mathrm{d}x}_{I_w} + \lambda^2 \underbrace{\int S(x)w(x)\mathrm{d}x}_{S_w}$$

weighting

$$\lambda = -\frac{I_w}{2S_w} \pm \frac{\sqrt{I_w^2 - 4S_wB_w + 4S_w\sigma_w}}{2S_w}$$

$$\Delta\lambda|_{\lambda=\lambda_{SM}} = \frac{\Delta\sigma_w}{I_w + 2S_w} = \frac{\sqrt{\int \sigma(x)w^2(x)\mathrm{d}x}}{\int I(x)w(x)\mathrm{d}x + 2\int S(x)w(x)\mathrm{d}x}$$

→ **minimize the error of coupling** (variance principle)

equation of the optimal w(x):

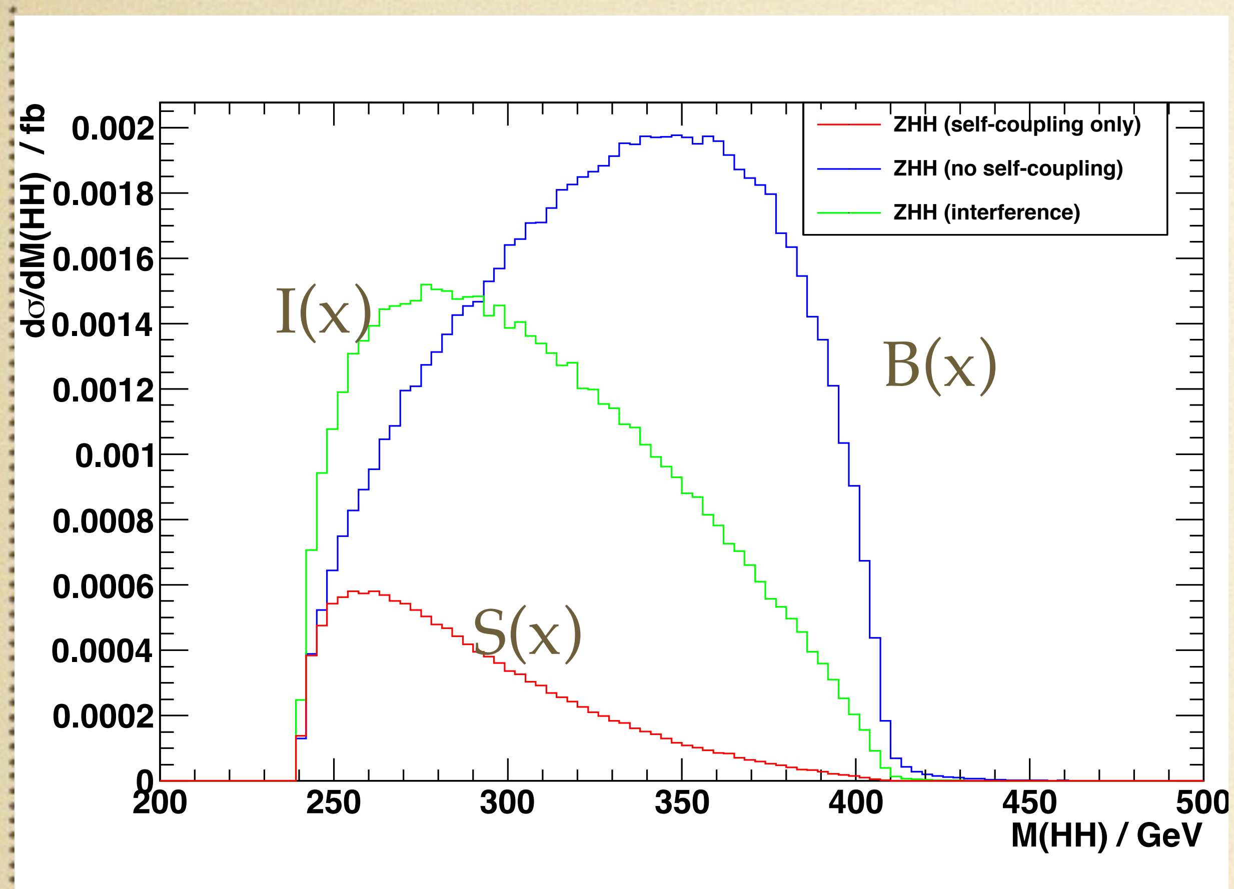
$$\sigma(x)w_0(x)\int(I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int\sigma(x)w_0^2(x)\mathrm{d}x$$

general solution:

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

c: arbitrary normalization factor

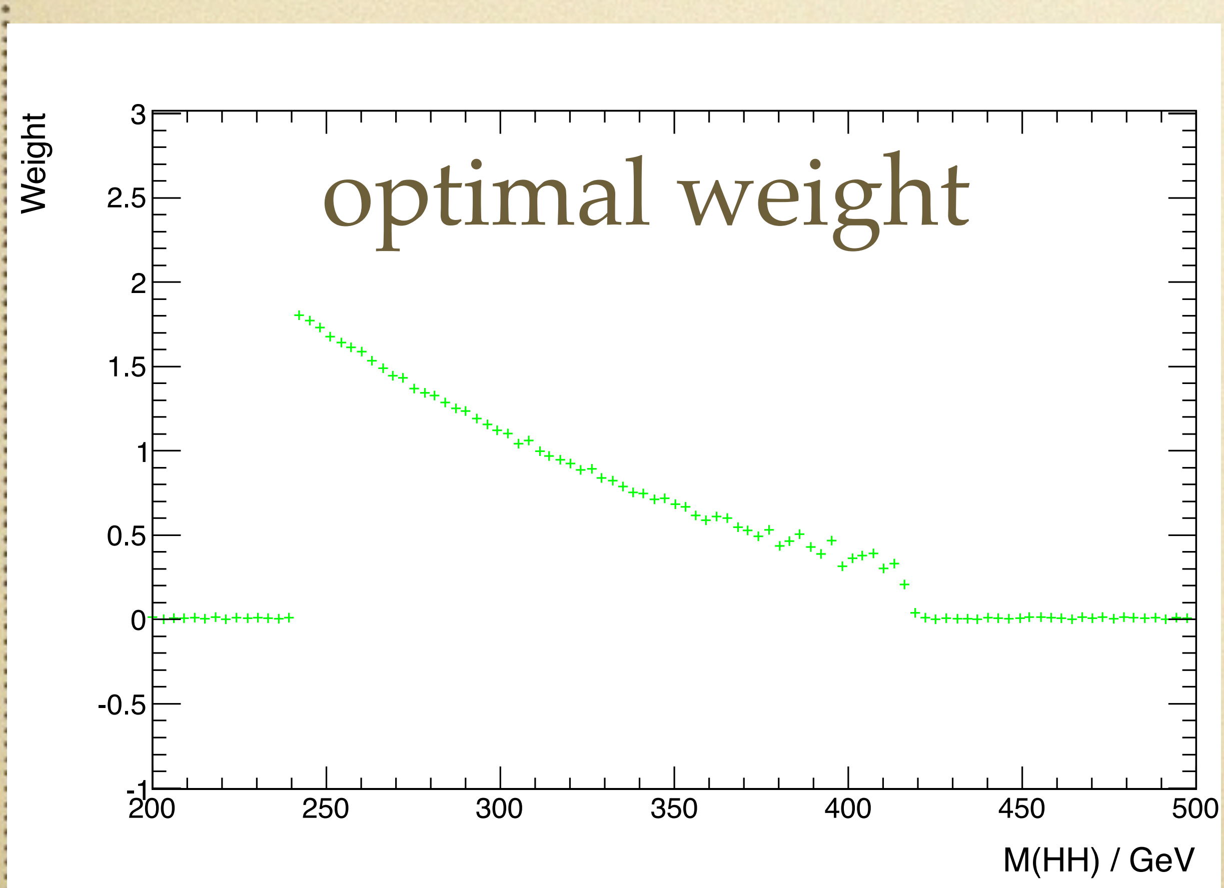
weighting functions

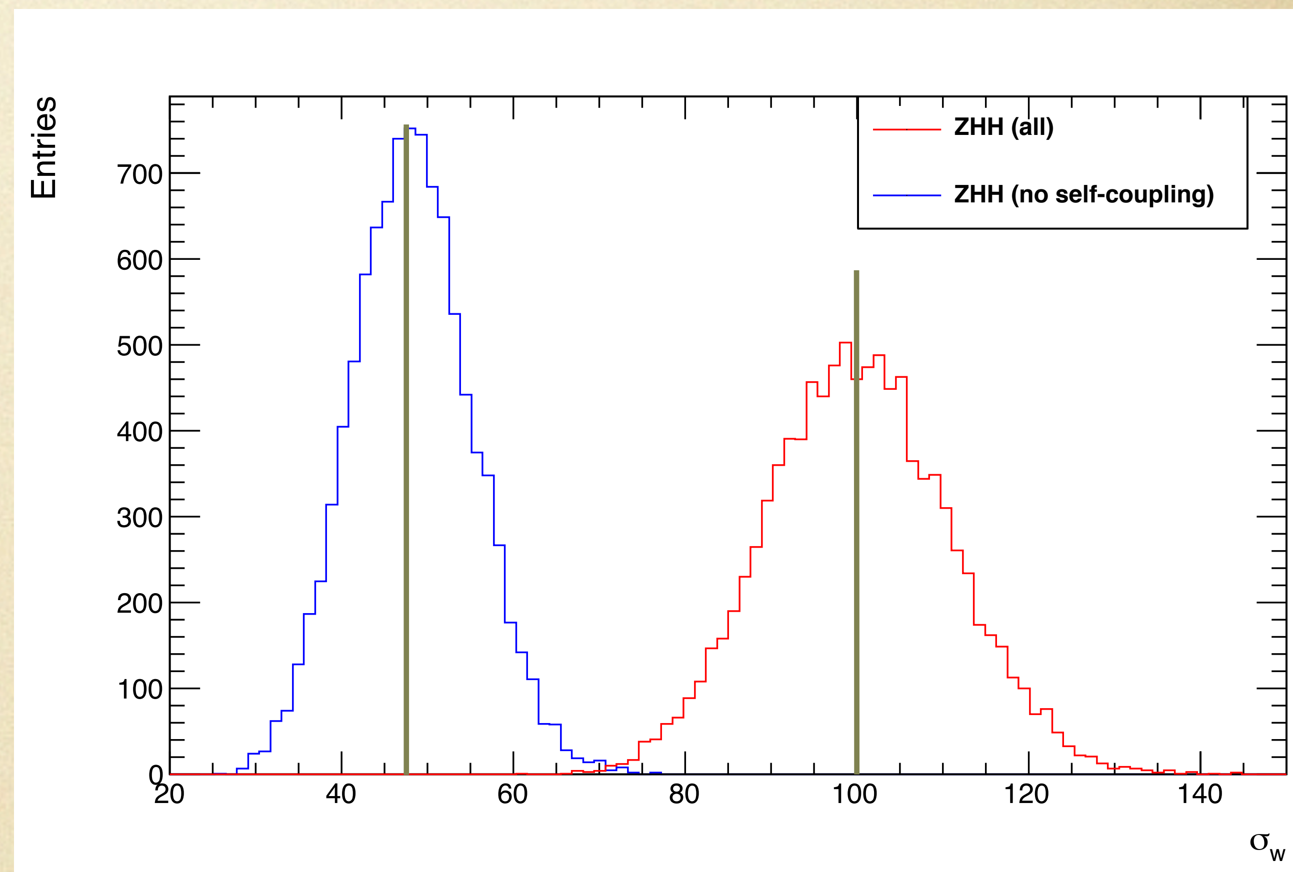


weighted cross section

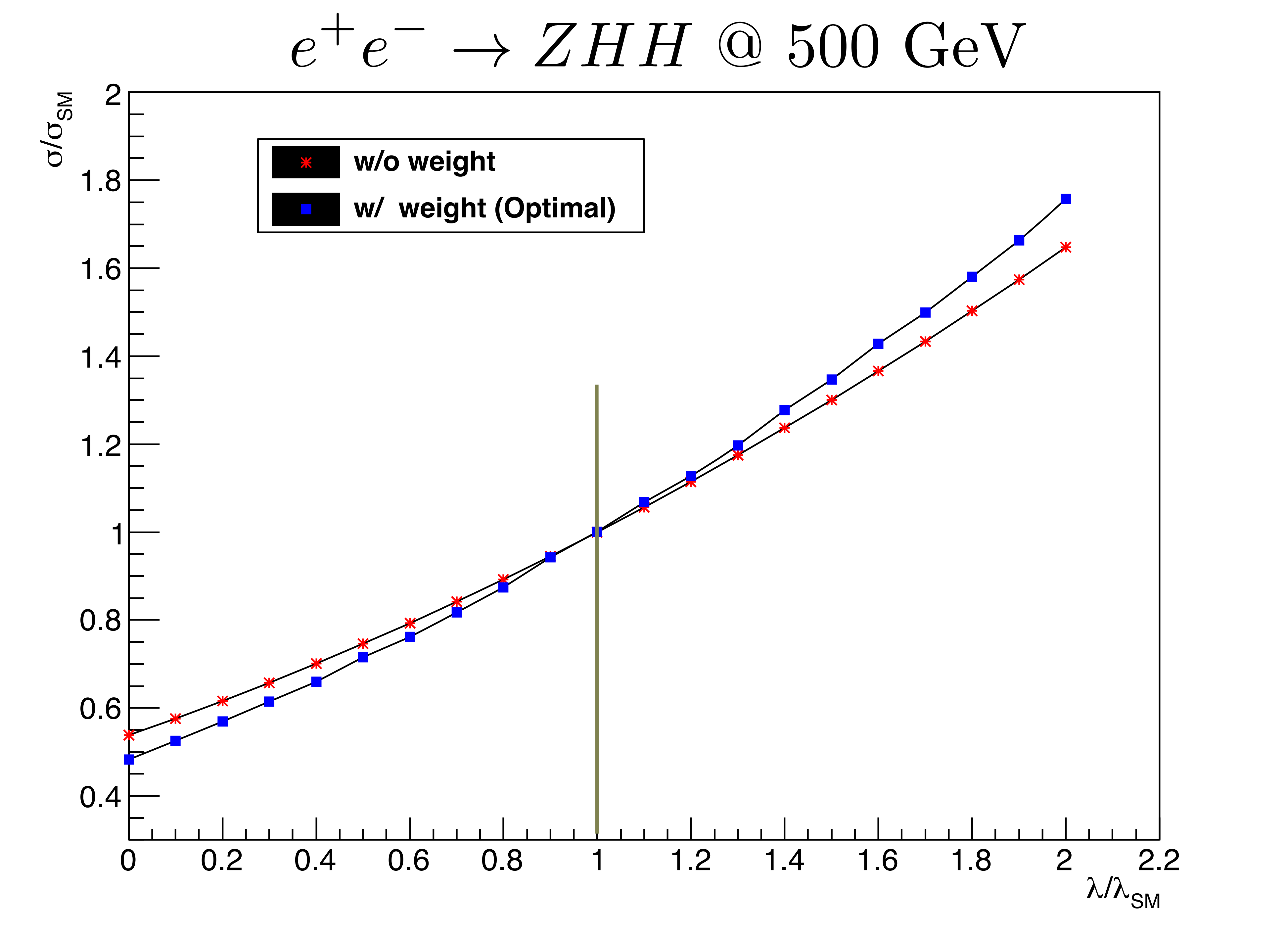
(from toy monte-carlo)

assuming 100 signal events
(~54 from non-self-coupling)





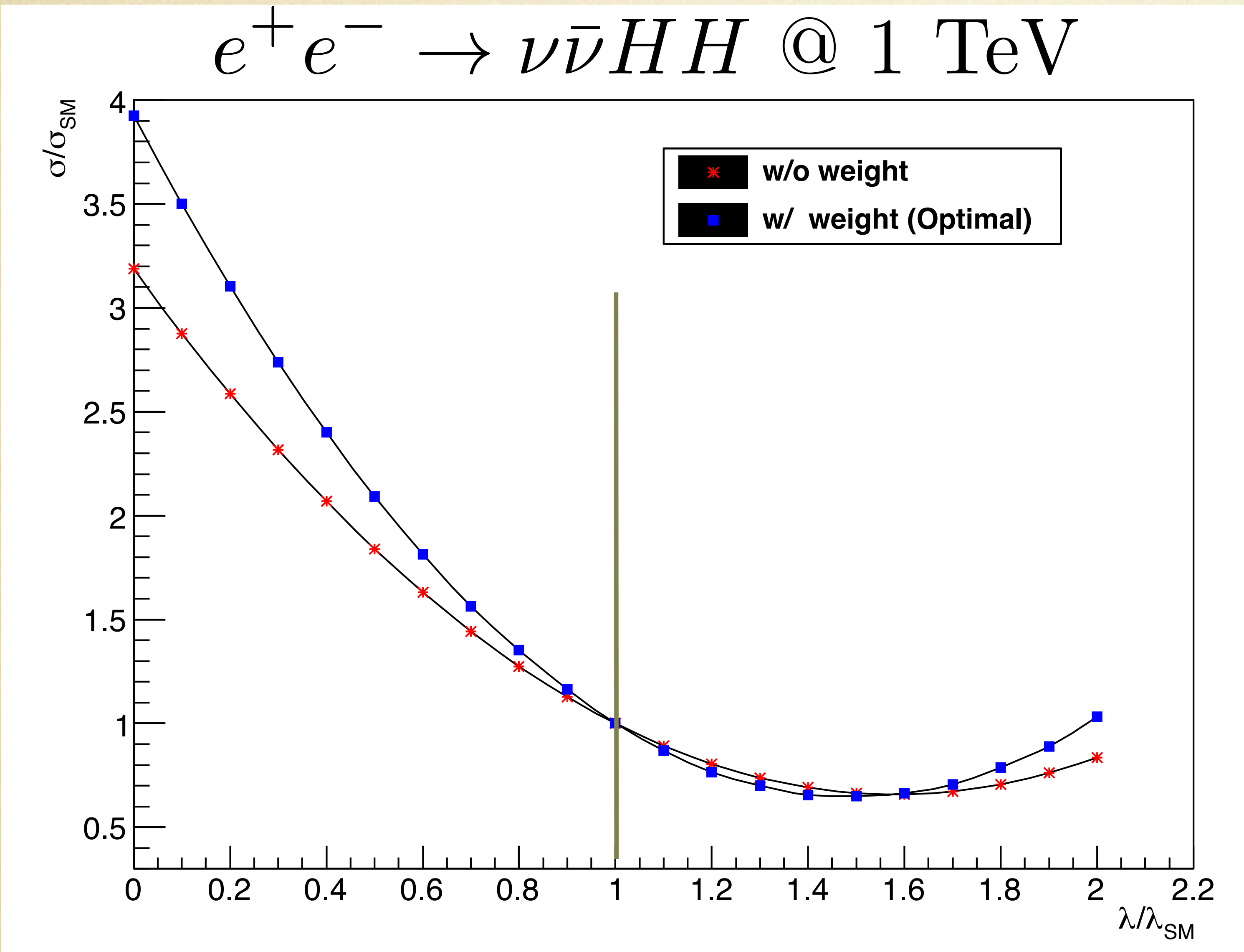
sensitivity

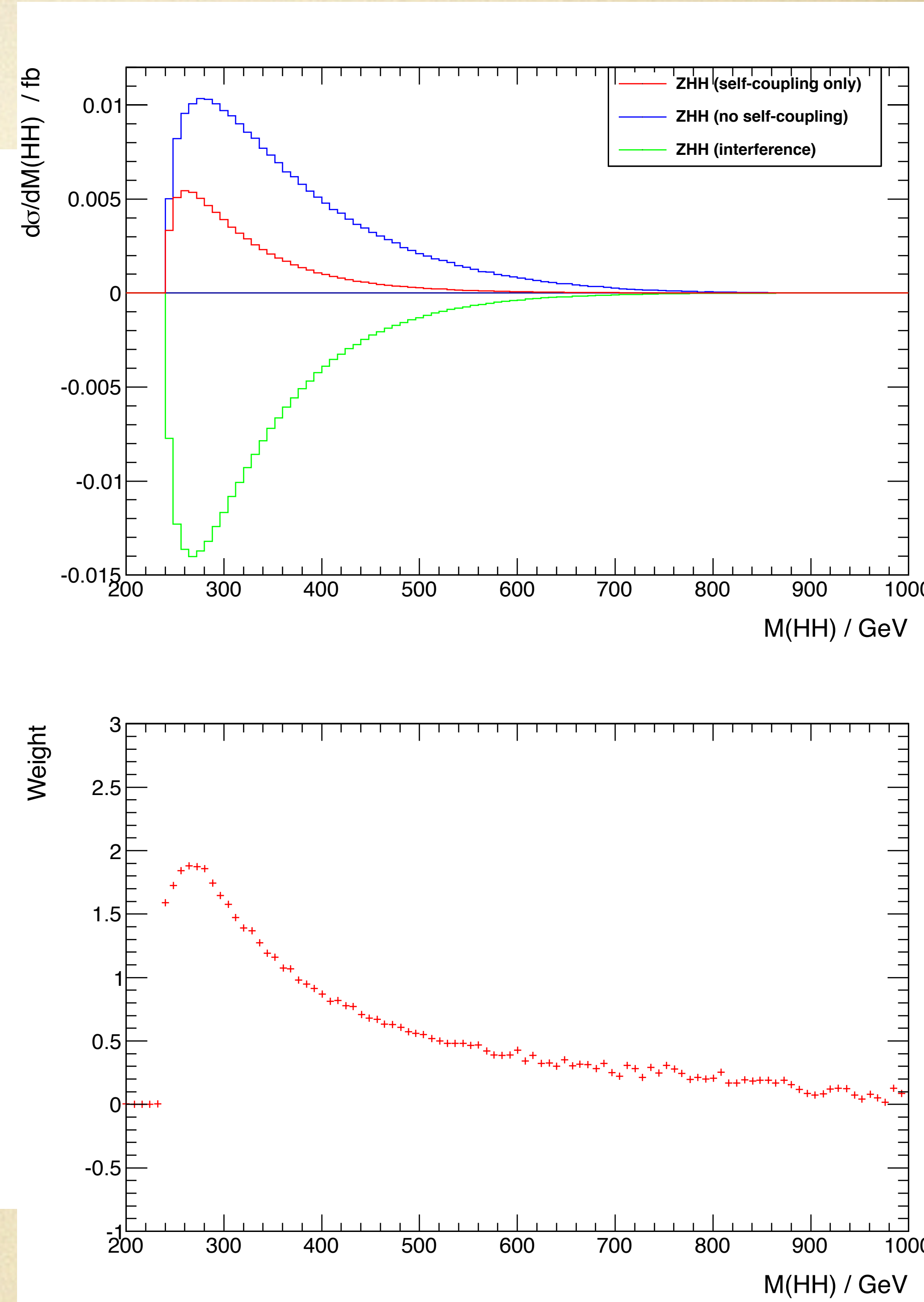


$$\frac{\Delta\lambda}{\lambda} = 1.80\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\lambda}{\lambda} = 1.57\frac{\Delta\sigma_w}{\sigma_w} = 1.66\frac{\Delta\sigma}{\sigma}$$

sensitivity





$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

$$\frac{\Delta\lambda}{\lambda} = 0.69\frac{\Delta\sigma_w}{\sigma_w} = 0.76\frac{\Delta\sigma}{\sigma}$$

Status of DBD analysis

$$e^{+} + e^{-} \rightarrow ZHH \text{ @ } 500\ GeV$$

main improvements to the LoI analysis: talk by T. Suehara

- better flavor tagging (tracking, PFA, LCFIPlus, B-baryon fixed)
- better lepton selection (muon detector, vertex constrained, bremsstrahlung and FSR recovered)

main backgrounds in each mode:

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

a neural-net is trained for each dominant background process (in total 9)

to make the result more stable, ~20 ab^{-1} statistics is needed (now ~10 ab^{-1} available)

$$e^+ + e^- \rightarrow ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b}) \rightarrow q\bar{q} + 4 \text{ bjets}$$

full simulation @ 500GeV

✦generator: Whizard 1.95
✦simulation: ilcsoft-v01-14-01
✦reconstruction: ilcsoft-v01-16
✦flavor tagging: LCFIPlus

pre-selection:

- isolated-charged-leptons rejected
- 6-jets clustering (LCFIPlus, Durham)
- combine the six jets by minimizing, and require the b tagging

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_1}^2} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma_{H_2}^2} + \frac{(M(q,\bar{q}) - M_Z)^2}{\sigma_{Z_2}^2}$$

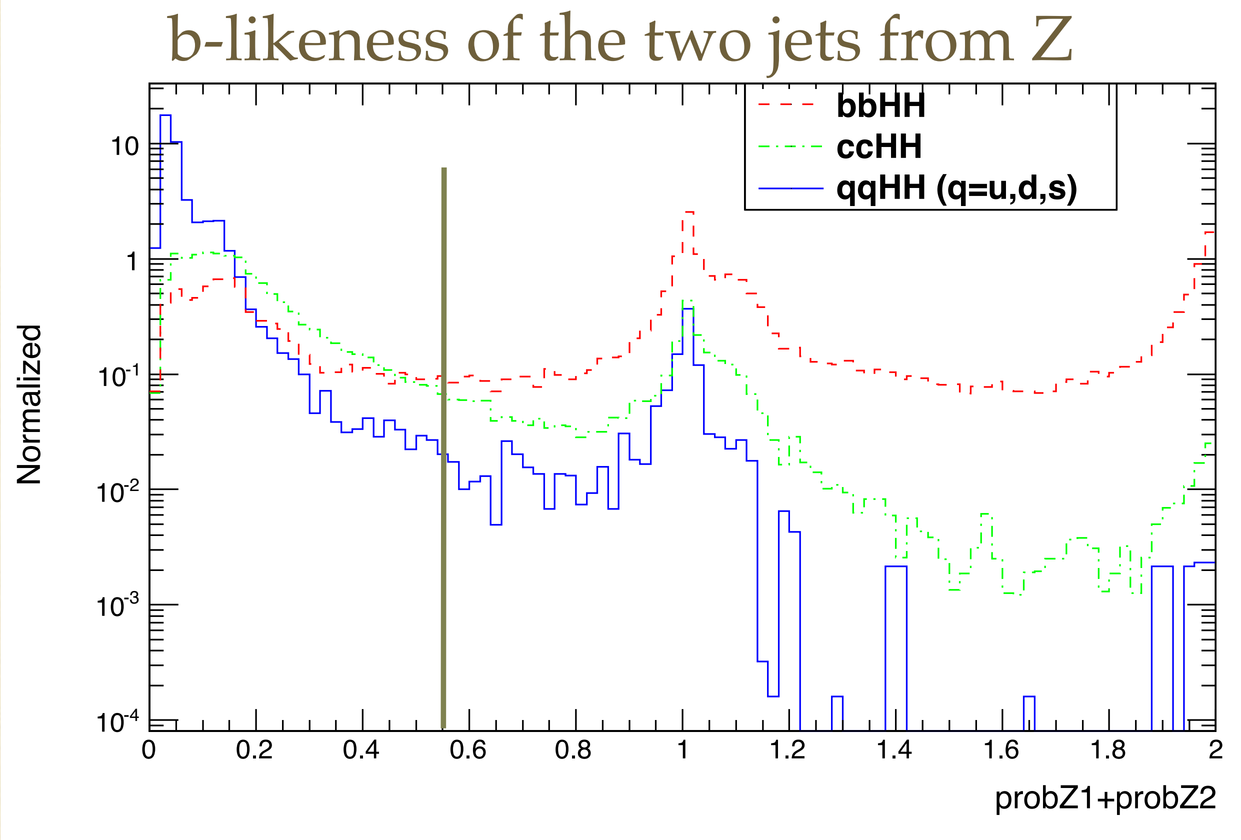
requirement implied in the pre-selection:

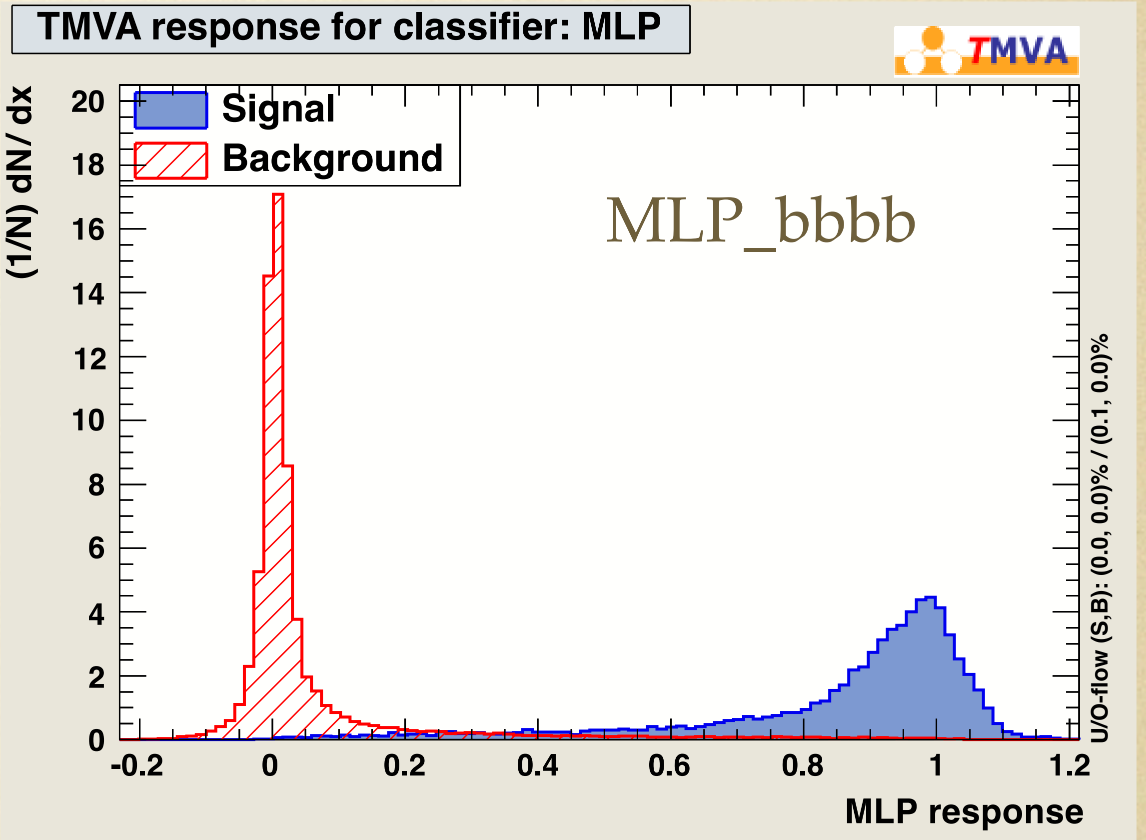
- b-tagged four jets from two Higgs (b-likeness > 0.16)

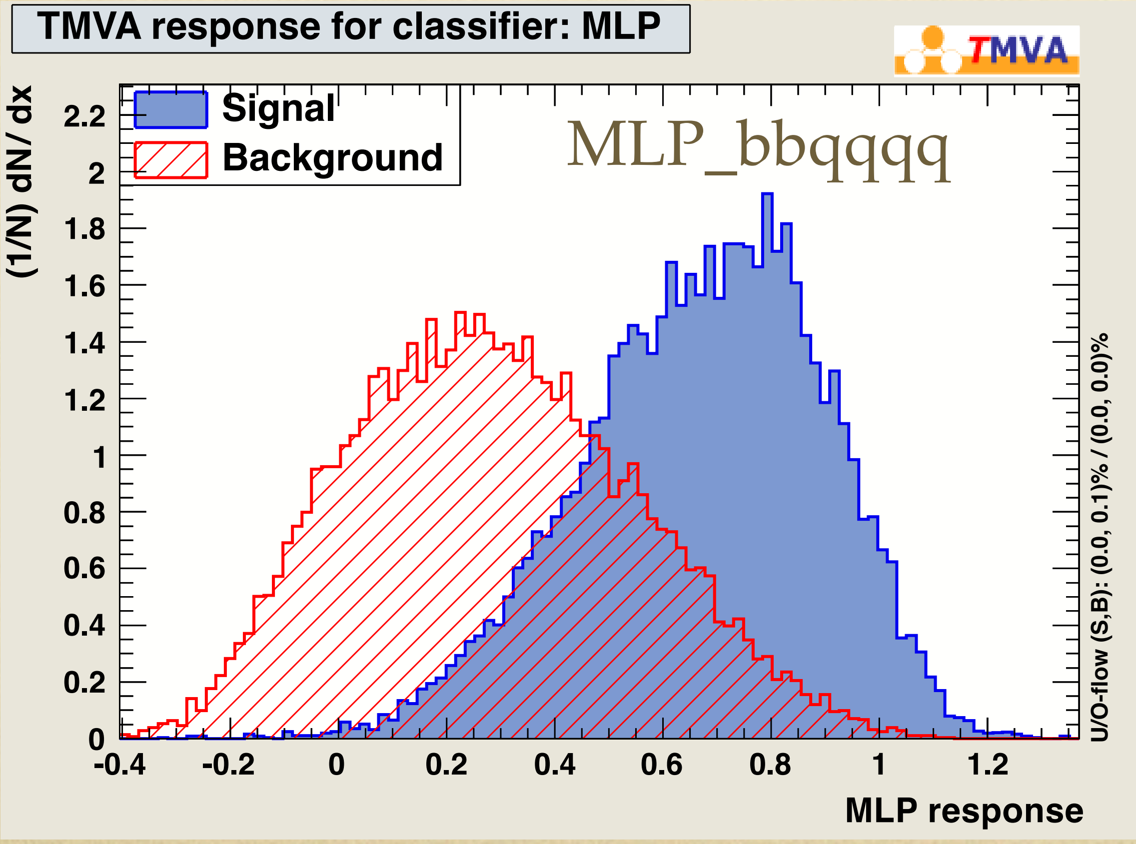
final selection:

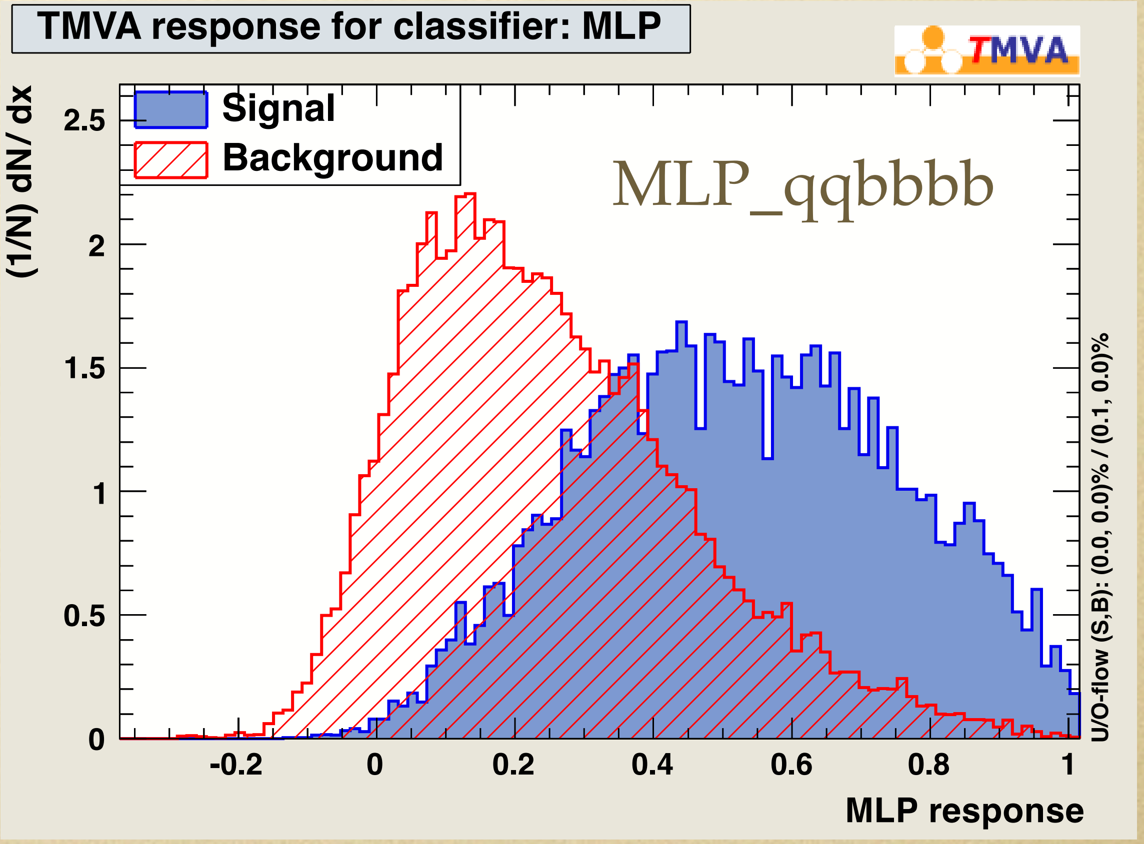
- separate to two categories: bbHH dominant and light qqHH dominant
- train the neural-nets, each event is also reconstructed as from ZZ, tt-bar, ZZZ and ZZH, and various variables are input to NN
- all cuts are optimized

some distributions









preliminary

P(e-,e+)=(-0.8,+0.3)

reduction table

(probZ1+probZ2 > 0.56)

$E_{\rm cm} = 500{\rm GeV}, M_H = 120{\rm GeV}$

$\int Ldt = 2{\rm ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2>0.56	MissPt < 60	MLP_bbbb>0.74	MLP_bbqqqq>0.34	MLP_qqbbbb>0.0	Bmax3>0.82 Bmax4>0.21
qqhh(qqbbbb)	310(129)	3.73×10^5	111(85.3)	26.7(23.0)	25.9(22.8)	20.6(18.8)	20.1(18.4)	20.0(18.3)	12.4(11.8)
bbbb	4.02×10^4	7.19×10^5	22889	2289	2253	9.04	8.06	7.94	3.32
lvbbqq	7.40×10^5	3.56×10^6	17240	357	172	8.47	6.69	6.69	0.03
qqbbbb	140	3.03×10^4	82.3	13.6	13.5	7.43	6.96	3.94	2.36
bbuddu	1.56×10^5	8.87×10^5	565	11.2	11.2	8.82	6.73	6.73	0.73
bbcsdu	3.12×10^5	1.26×10^6	6109	86.8	86.4	61.6	44.6	44.1	2.41
bbcssc	1.56×10^5	1.17×10^6	12456	256	254	177	126	125	4.71
qqqqH(ZZH)	381	not available yet							
ttqq	2169	not available yet							
BG			59342	3013	2790	273	199	197	11.0

bbHH dominant: nS = 12.4, nB = 11.0 ~ 2.7σ preliminary

P(e-,e+)=(-0.8,+0.3)

reduction table

$E_{cm} = 500\text{GeV}, M_H = 120\text{GeV}$

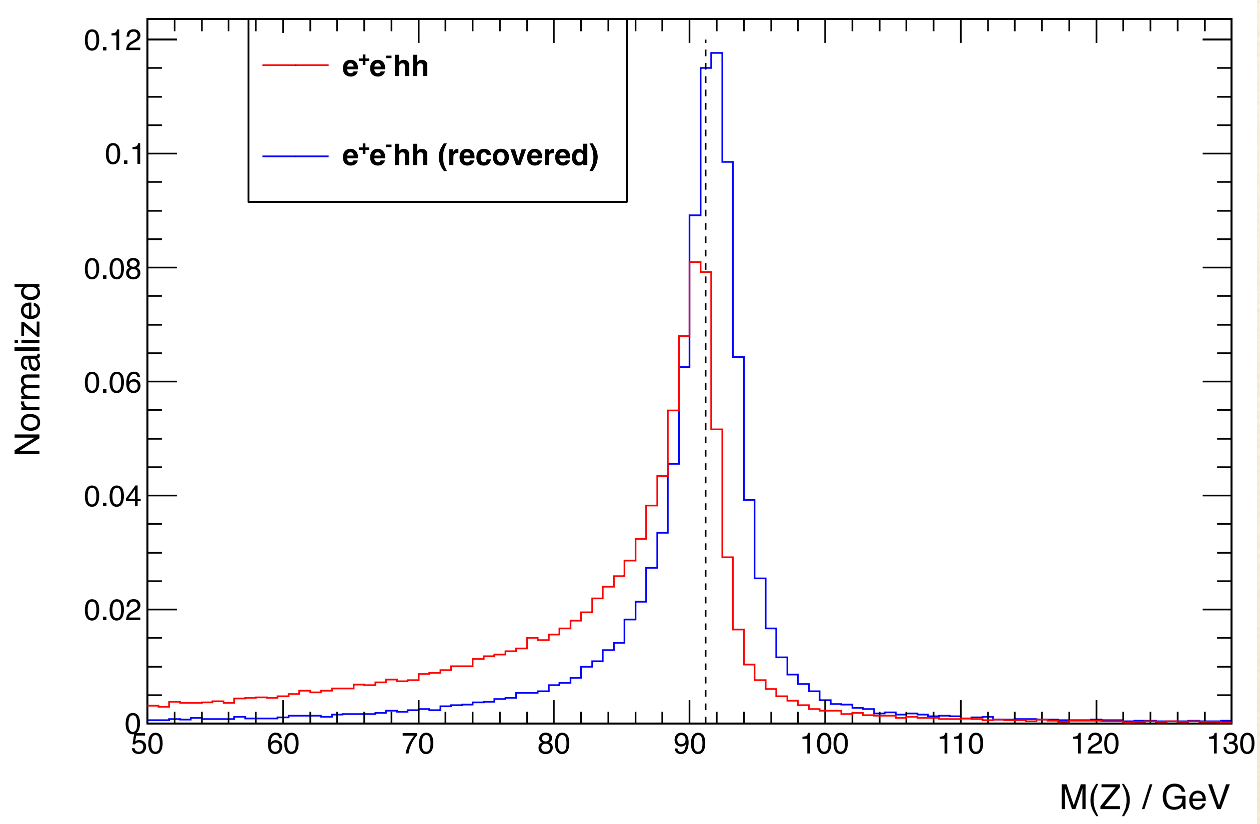
(probZ1+probZ2 < 0.56)

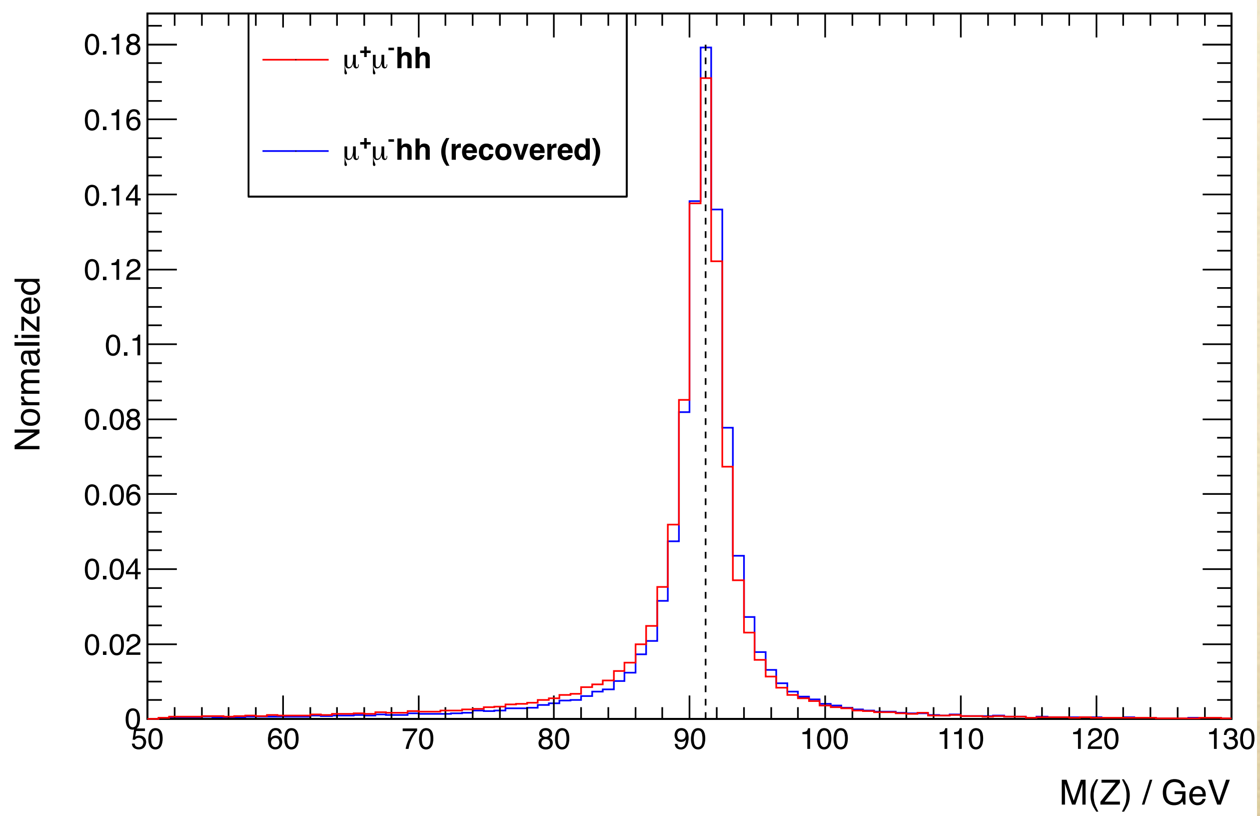
$\int Ldt = 2\text{ab}^{-1}$

normalized	expected	MC	pre-selection	probZ1+probZ2<0.56	MissPt < 60	MLP_bbbb>0.63	MLP_bbqqqq>0.55	MLP_qqbbbb>0.15	Bmax3>0.85 Bmax4>0.43
qqhh(qqbbbb)	310(129)	3.73×10^5	111(85.3)	84.3(62.3)	80.9(61.8)	66.9(53.5)	45.9(37.7)	44.5(36.6)	21.4(18.6)
bbbb	4.02×10^4	7.19×10^5	22889	20600	20282	152	62.9	53.5	25.6
lvbbqq	7.40×10^5	3.56×10^6	17240	16884	7937	536	115	105	1.36
qqbbbb	140	3.03×10^4	82.3	68.7	68.3	42.5	20.7	14.9	7.03
bbuddu	1.56×10^5	8.87×10^5	565	554	550	434	105	99.2	11.3
bbcsdu	3.12×10^5	1.26×10^6	6109	6022	5987	4559	977	917	25.4
bbcssc	1.56×10^5	1.17×10^6	12456	12200	12115	9181	1655	1556	19.2
qqqqH(ZZH)	381	not available yet							
ttqq	2169	not available yet							
BG			59342	56329	46939	14906	2936	2745	89.9

light qqHH dominant: nS = 21.4, nB = 89.9 ~ 2.0σ

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

analysis ongoing...

Expectation of DBD analysis

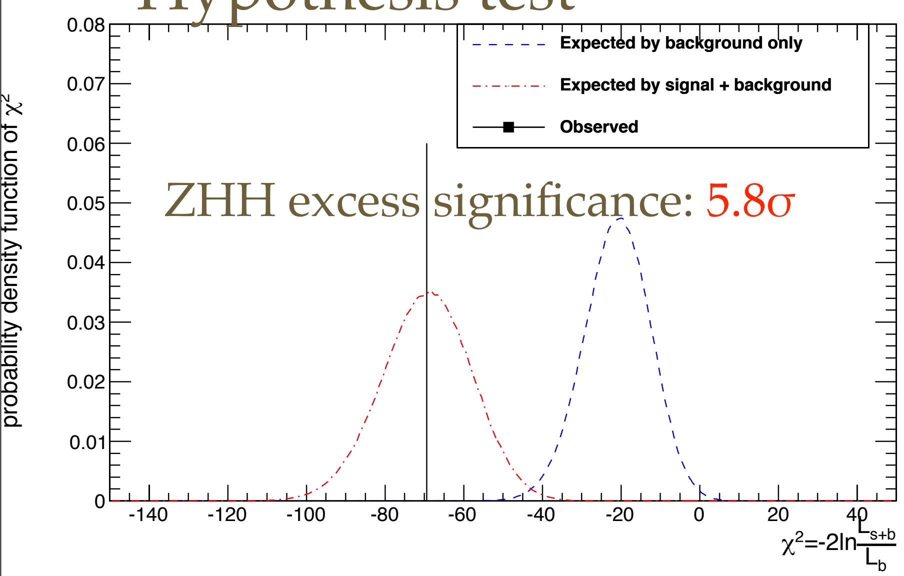
preliminary

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

Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	-	-	-	-
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	-	-	-	-
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	12.4	11.0	3.1σ	2.7σ
		21.4	89.9	2.2σ	2.0σ

- qqHH mode only, significance is already as same as using all modes in LoI
- similar improvement would be expected for llHH and ννHH modes (~20%)

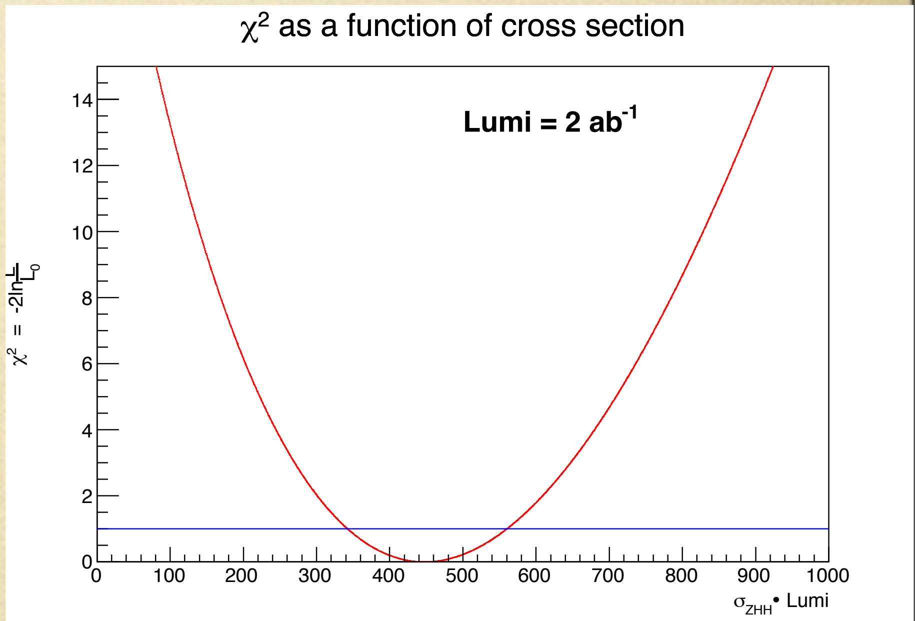
Hypothesis test



$$\sigma_{ZHH} = 0.22 \pm 0.05 \quad \text{fb}$$

precision of cross section: **24%**

Higgs self-coupling: **43%**



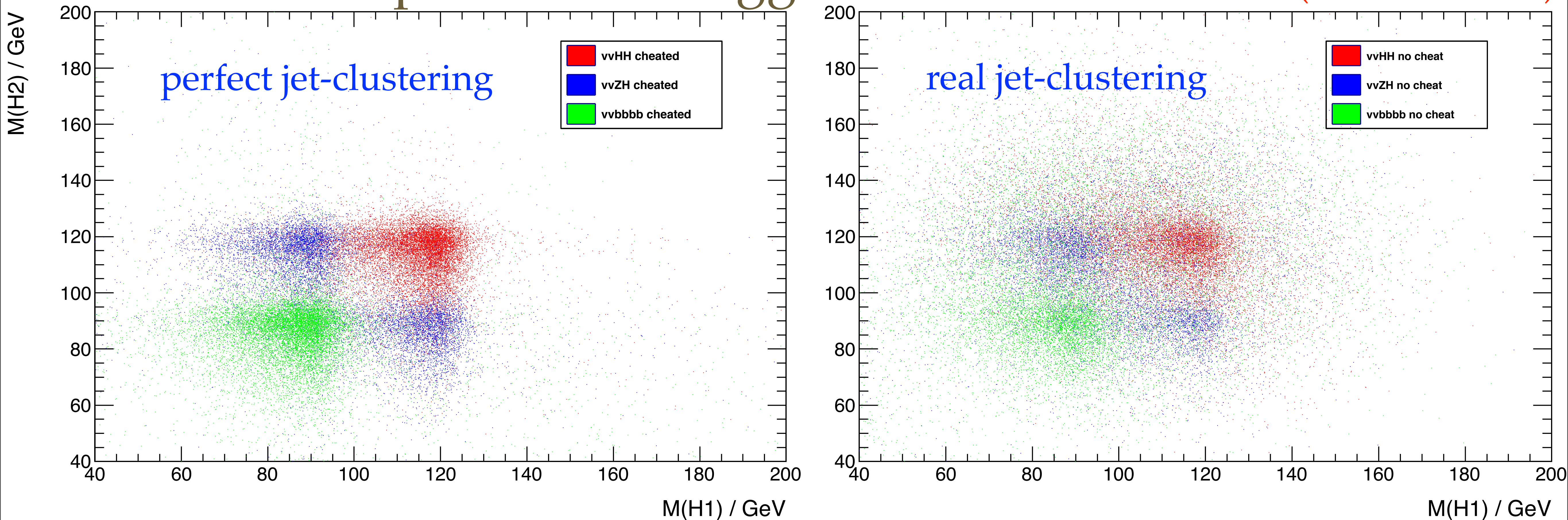
after using weighting, would be: $\frac{\delta\sigma}{\sigma} = 22\%$ $\frac{\delta\lambda}{\lambda} = 40\%$

Color-singlet Jet Finder

(project under developing)

- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda$ ~ 40%

scatter plot of two Higgs masses vvHH mode: (ZZH and ZZZ)



- 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)
- looks very challenging now...

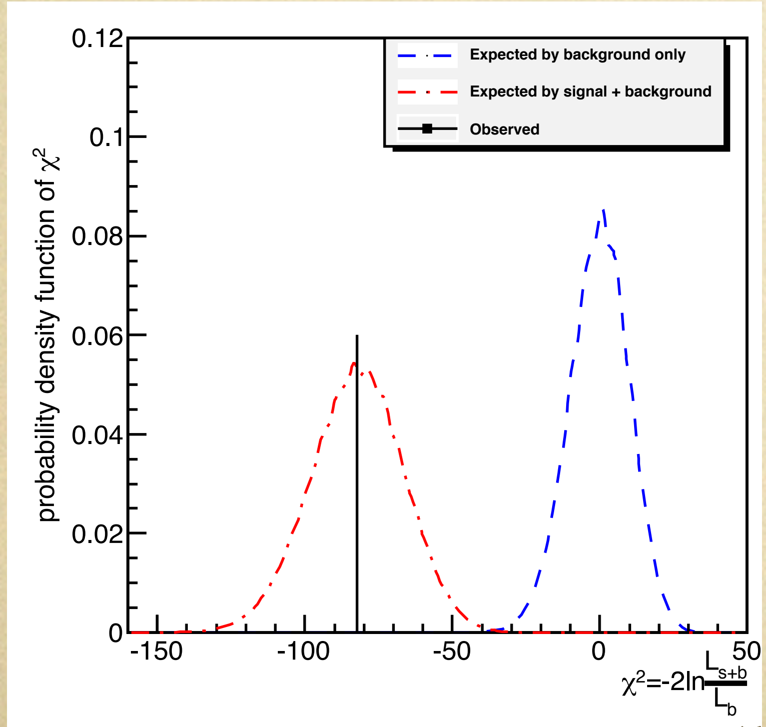
analysis using the perfect jet-clustering

preliminary — (similar strategy) — cheated analysis

Polarization: (e-,e+)=(-0.8,0.3)

$$e^+ + e^- \rightarrow ZHH \quad M(H) = 120\text{GeV} \quad \int Ldt = 2\text{ab}^{-1}$$

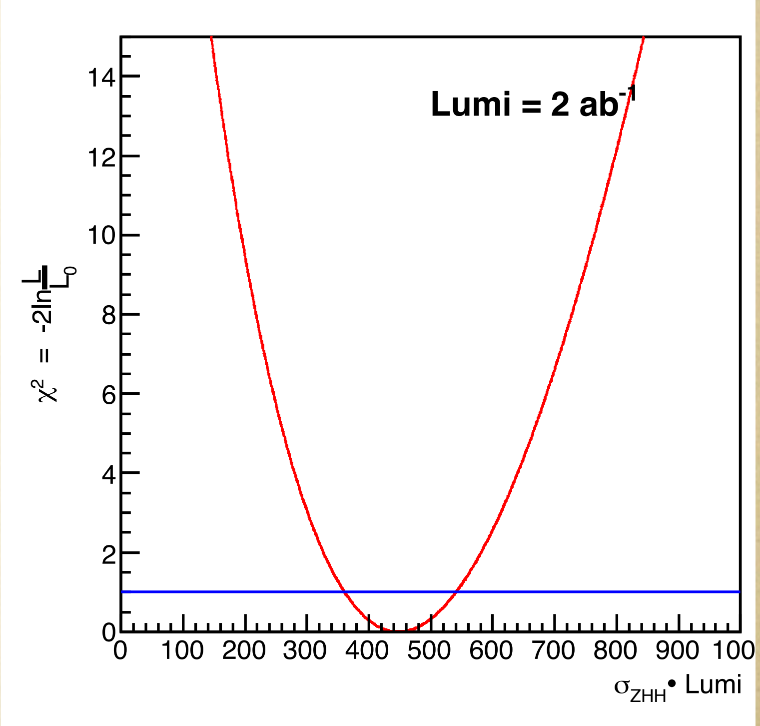
Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	9.8	3.9	3.7σ	2.8σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	12.6	8.1	3.6σ	2.9σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	12.2	11.9	3.0σ	2.6σ
		17.7	29.5	2.9σ	2.6σ
500	combined			8.1σ	5.2σ



$$\sigma_{ZHH} = 0.22 \pm 0.04 \;(0.07) \quad \text{fb}$$

$$\frac{\delta\sigma}{\sigma} = 20\% \quad (32\%)$$

$$\frac{\delta\lambda}{\lambda} = 36\% \quad (57\%)$$



(limited by the signal efficiency ~20%)

$$e^+ + e^- \to \nu\bar{\nu}HH \to \nu\bar{\nu}(b\bar{b})(b\bar{b})$$

SGV fast simulation @ 1 TeV

- ✦generator: Whizard 1.95 (DBD)
- ✦simulation: SGV (ILD_00)
- ✦reconstruction: ilcsoft-v01-15

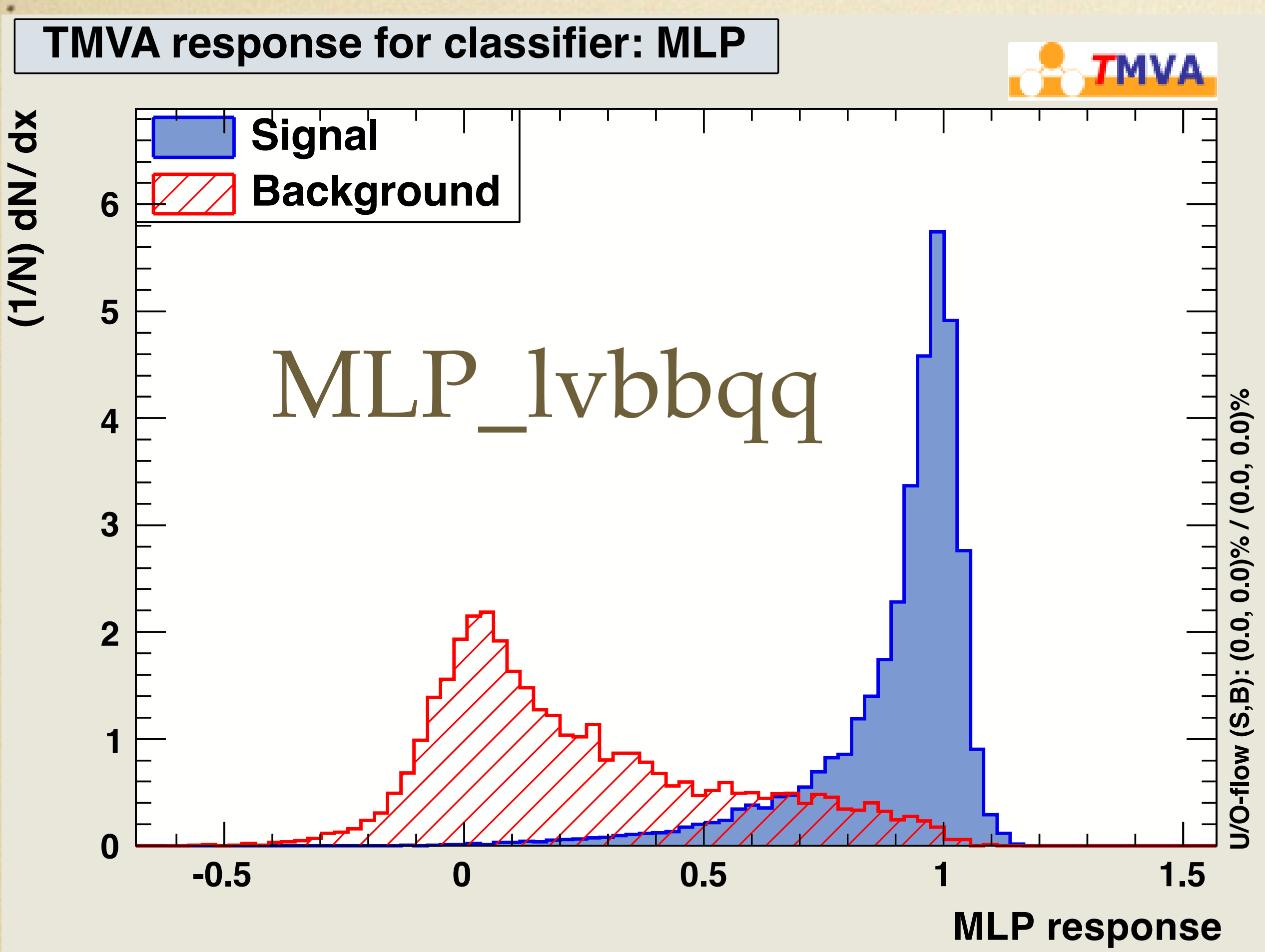
pre-selection:

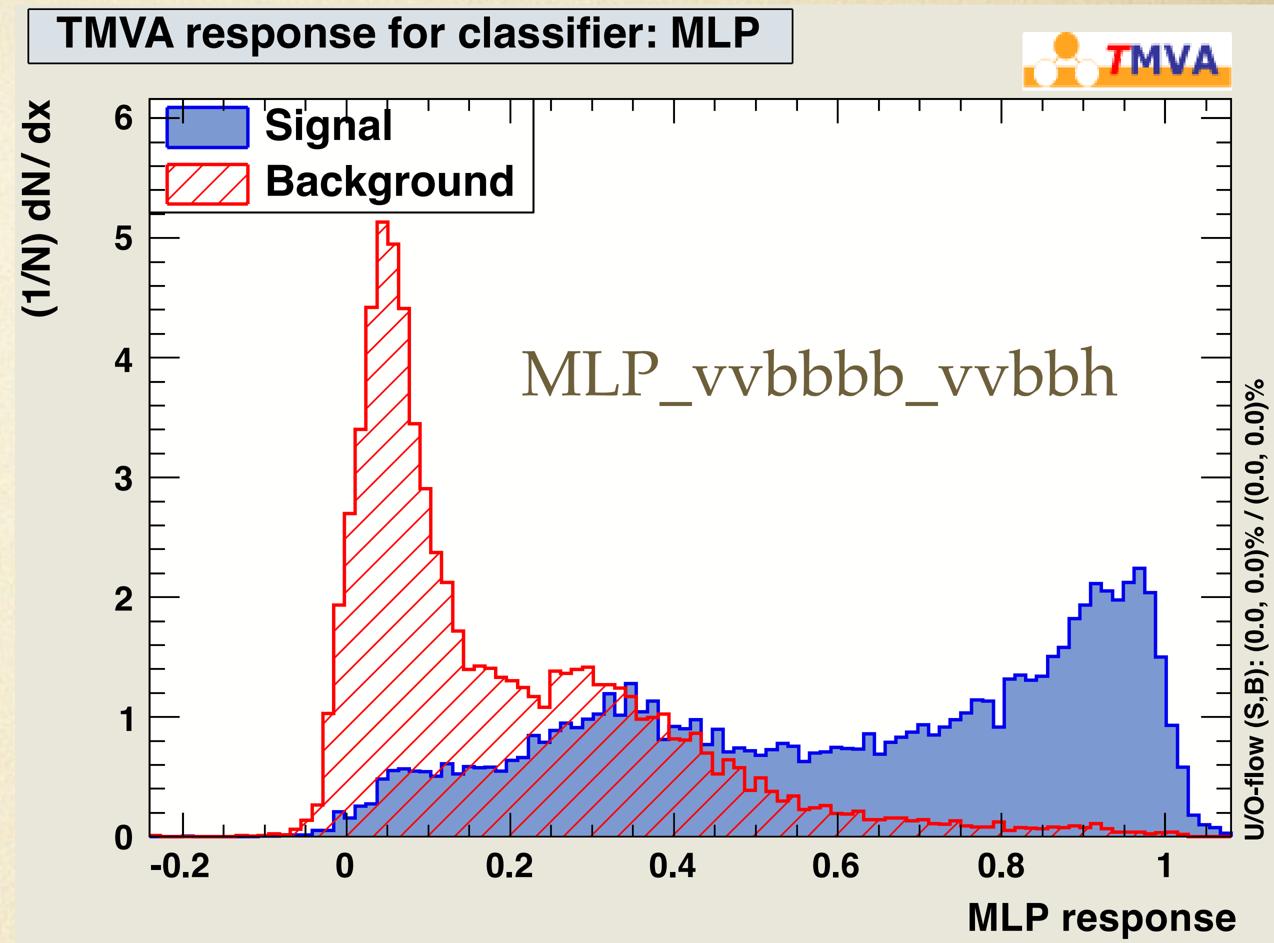
- no isolated lepton, ISR tag
- four jets, each with more than 8 particles, 3rd Btagging > 0.2

final-selection:

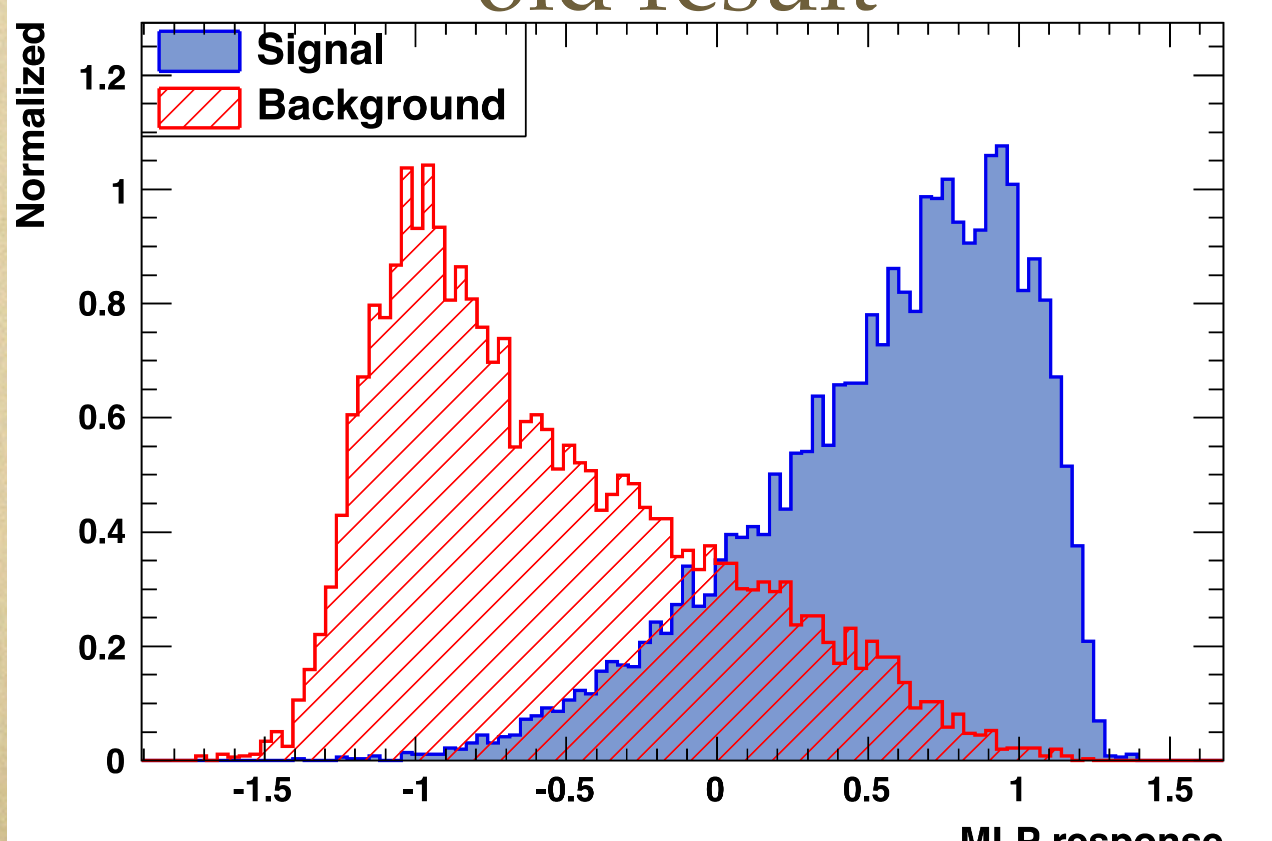
- Visible energy: Evis < 500 + 3*MissPt, Pt > 10 GeV (cut1)
- Missing mass (Z rejection): > 200 GeV (cut2)
- tt-bar suppression: MLP_lvbbqq > 0.82 (cut3)
- vvZZ and vvZH suppression: MLP_vvbbbb > 0.59 (cut4)
- B-tagging: Bmax3 > 0.49 (cut5)

Neural-net output

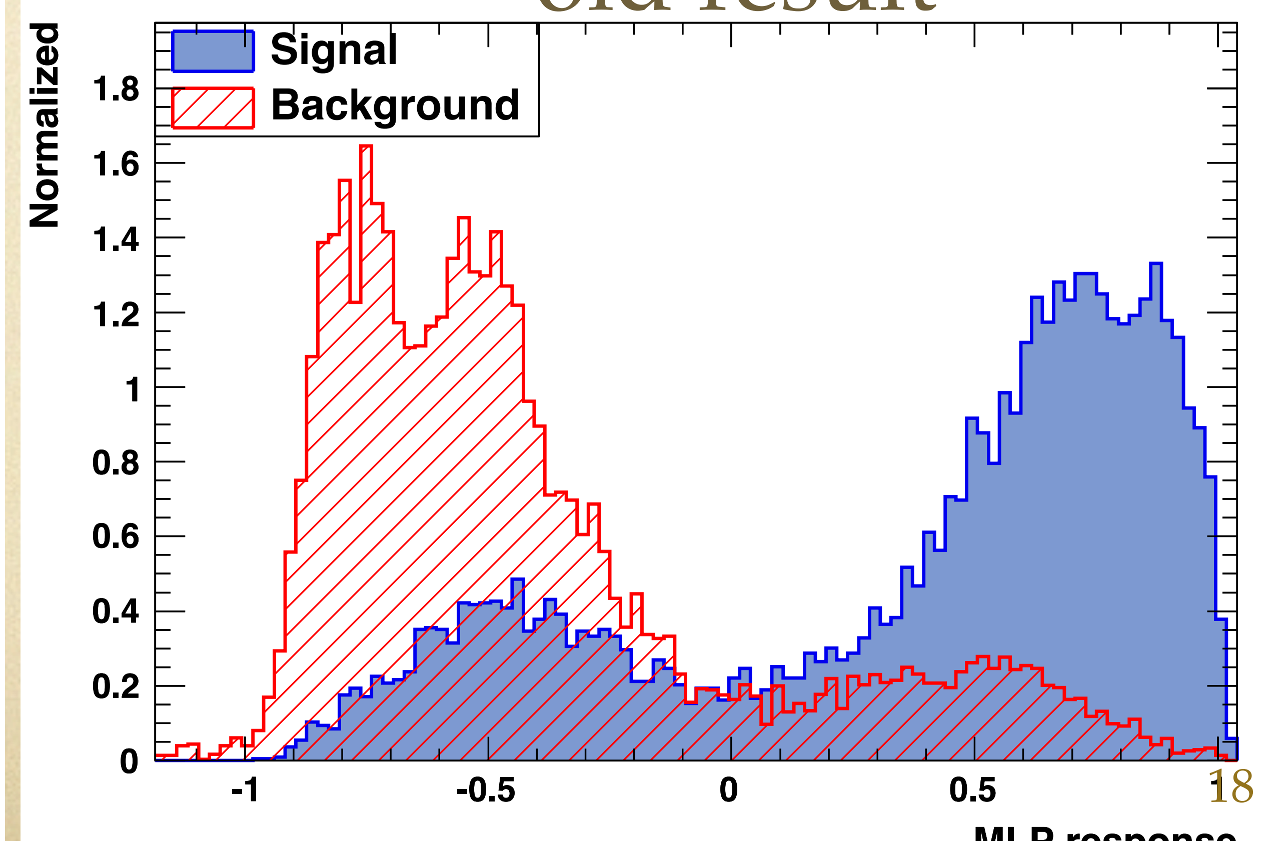




old result



old result



signal and backgrounds (reduction table)

preliminary

Polarization: (e-,e+)=(-0.8,+0.2) $E_{\rm cm} = 1$ TeV, $M_H = 120$ GeV $\int L = 2\ {\rm ab}^{-1}$

	Expected	Generated	pre-selction	cut1	cut2	cut3	cut4	cut5
ννhh (WW F)	272	9.20×10^4	104	97.9	96.5	75.8	44.8	35.6
ννhh (ZHH)	74.0	4.76×10^5	26.8	17.9	14.7	7.15	4.46	3.67
ννbbbb	650	4.43×10^5	481	466	459	162	4.18	3.28
ννccbb	1070	5.10×10^5	200	193.6	189	64.4	1.56	0.22
bbxyyx	2.92×10^5	1.05×10^6	14102	563	530	20.6	12.4	0.91
eνbbqq	1.16×10^5	6.22×10^5	620	462	353	34.6	6.42	0.83
μνbbqq	1.08×10^5	6.39×10^5	366	255	196	10.1	2.25	0.49
τνbbqq	1.08×10^5	6.37×10^5	3502	2184	1741	104	33.9	4.47
ννZH	3125	5.00×10^4	449	441	439	296	21.4	13.1
ttH	6952	1.00×10^5	88.6	59.7	55.1	1.40	0.96	0.68
BG	6.37×10^5		19835	4643	3978	701	87.4	27.6
significance	0.34		0.74	1.42	1.51	2.72	3.90	4.48

$$\frac{\Delta\sigma}{\sigma} \approx 22\% \quad (20\%) \qquad \frac{\Delta\lambda}{\lambda} \approx 19\% \quad (17\%)$$

conclusion

- a new general weighting method developed, ~10% improvement for coupling.
- better flavor tagging and lepton ID performance for DBD simulations and reconstruction, ~20% improvement for analysis.
- DBD full simulation: ZHH @ 500 GeV, P(e-,e+)=(-0.8,+0.3), 2 ab^{-1}, M(H)=120GeV, $\delta\sigma/\sigma \sim 22\%$, $\delta\lambda/\lambda \sim 40\%$.
- SGV fast simulation: $\nu\nu$HH @ 1 TeV, P(e-,e+)=(-0.8,+0.2), 2 ab^{-1}, M(H)=120GeV, $\delta\sigma/\sigma \sim 20\%$, $\delta\lambda/\lambda \sim 17\%$.
- similar result for M(H)=125GeV may be achieved by including HH-->bbWW* (Br. ~25%).
- jet-clustering could affect the performance very much, but it is very challenging to improve it in practice.

backup

motivation of Higgs self-coupling measurement

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

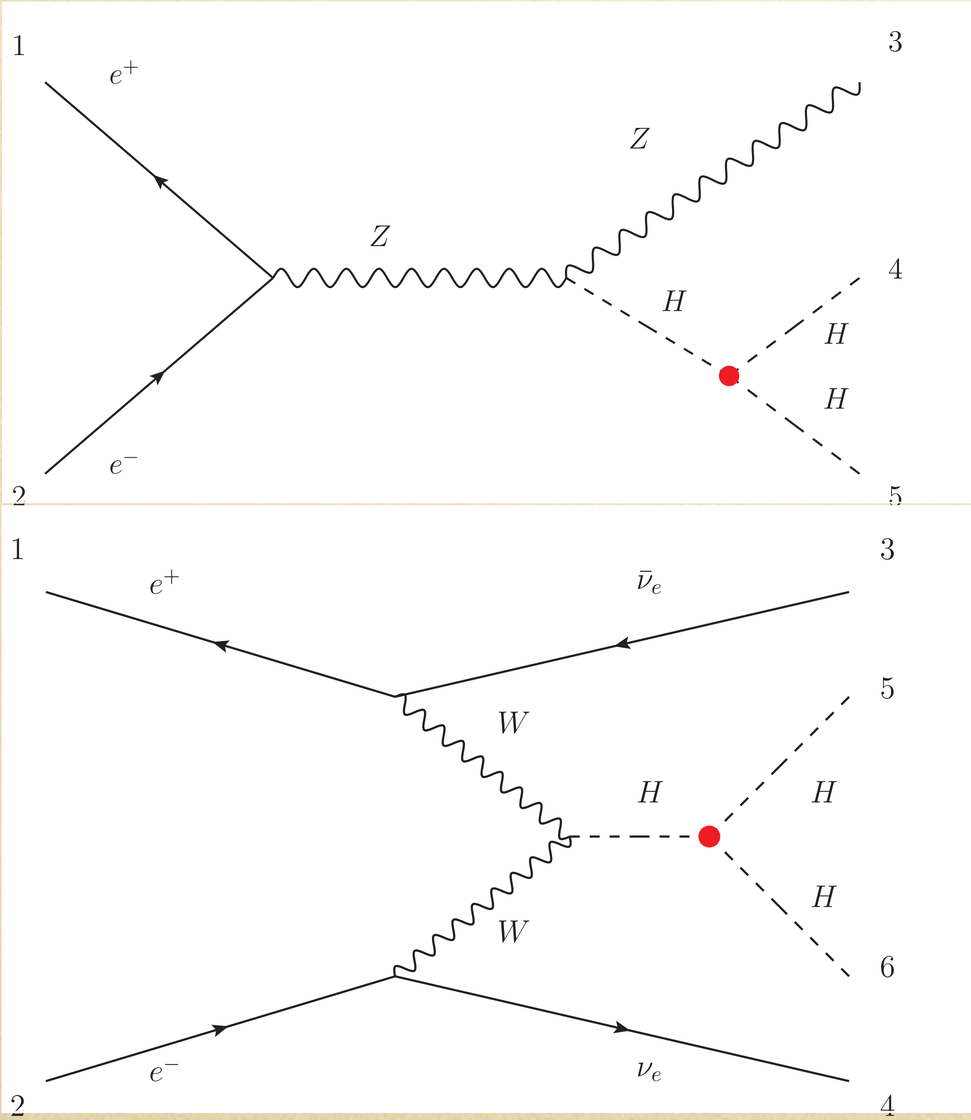
physical Higgs field — mass term — trilinear coupling — quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

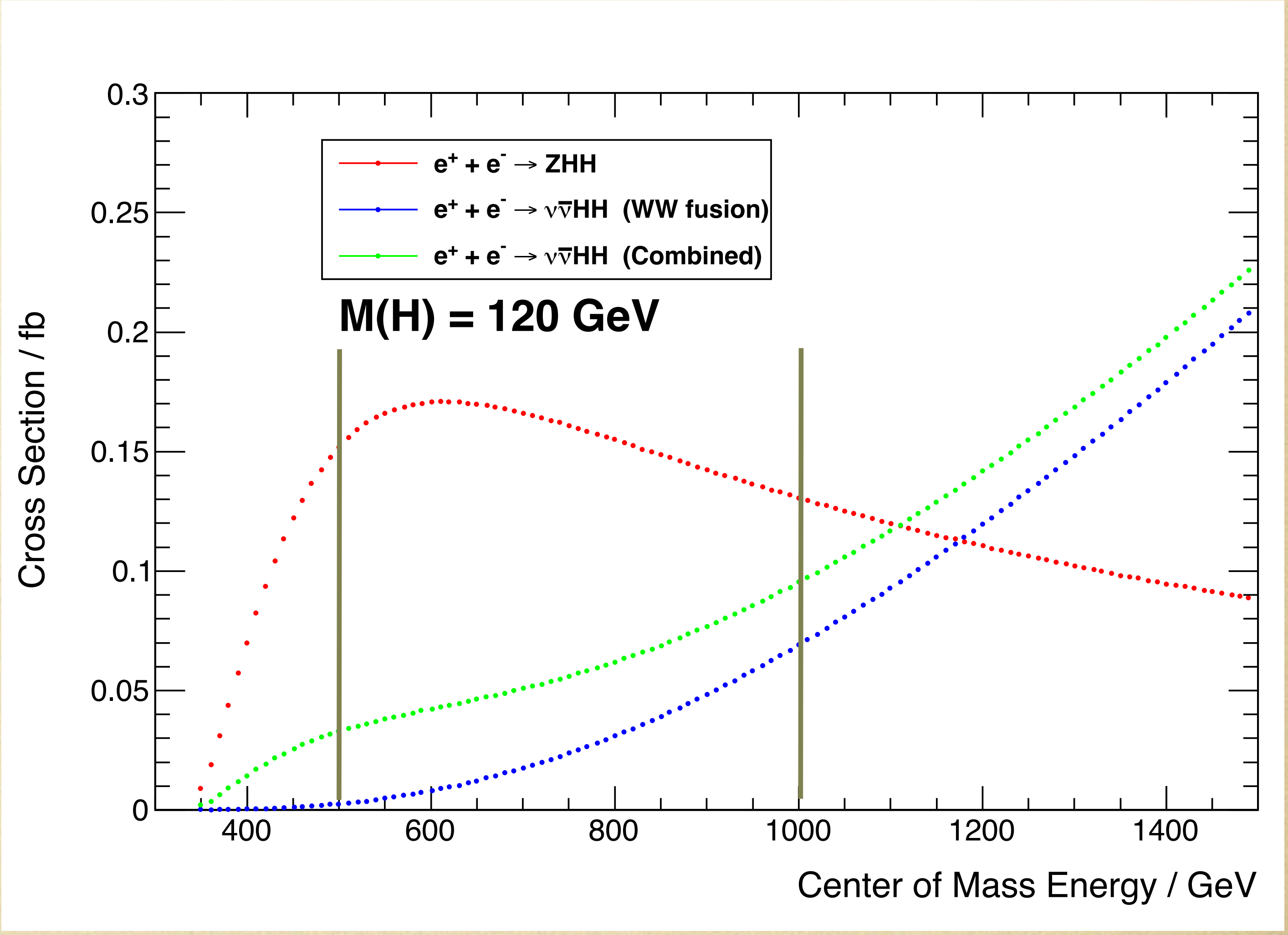
SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$ $\upsilon \sim 246$ GeV

- 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.

Measurement of the trilinear Higgs self-coupling @ ILC

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

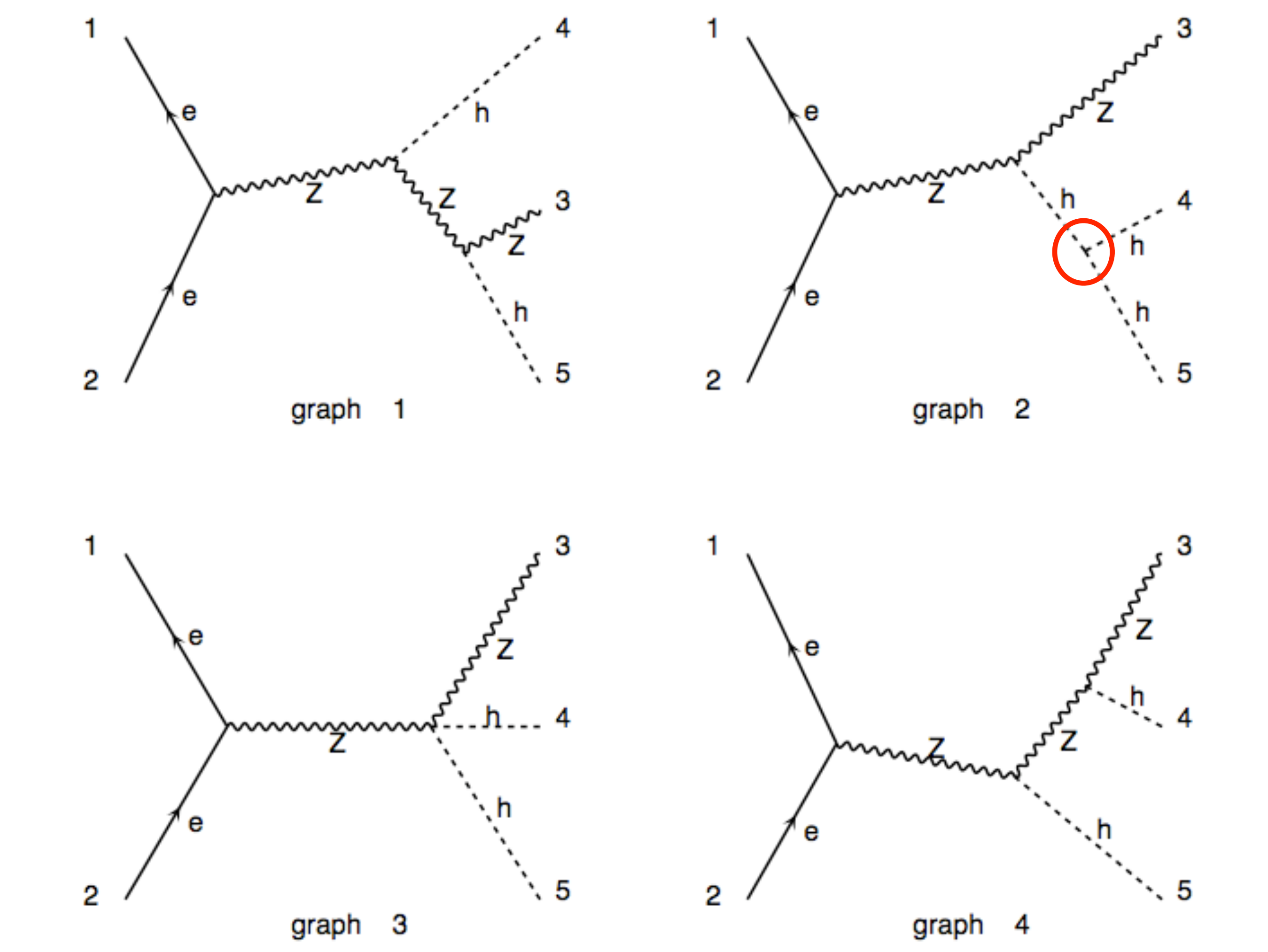




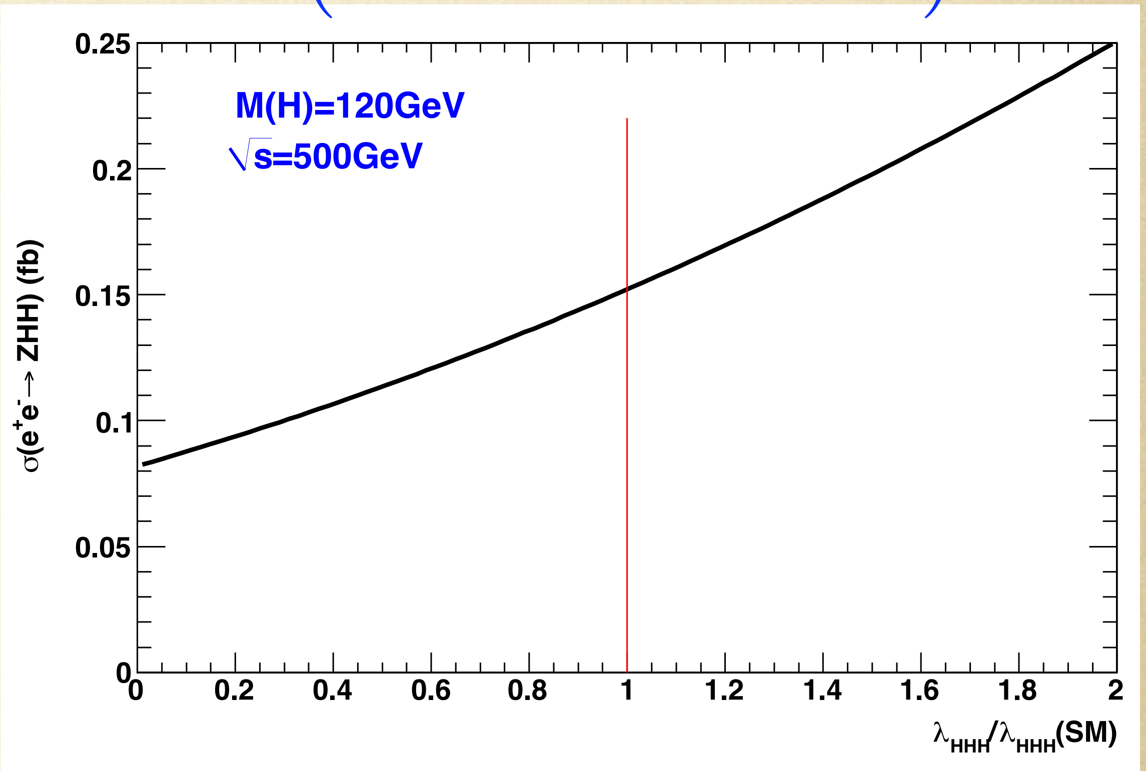
extraction of Higgs self-coupling from the cross section of ZHH

effect of irreducible diagram

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



$$\sigma(e^+e^- \to ZHH)$$



$$\frac{\Delta\lambda}{\lambda} = 1.8\frac{\Delta\sigma}{\sigma}$$

precision of self-coupling

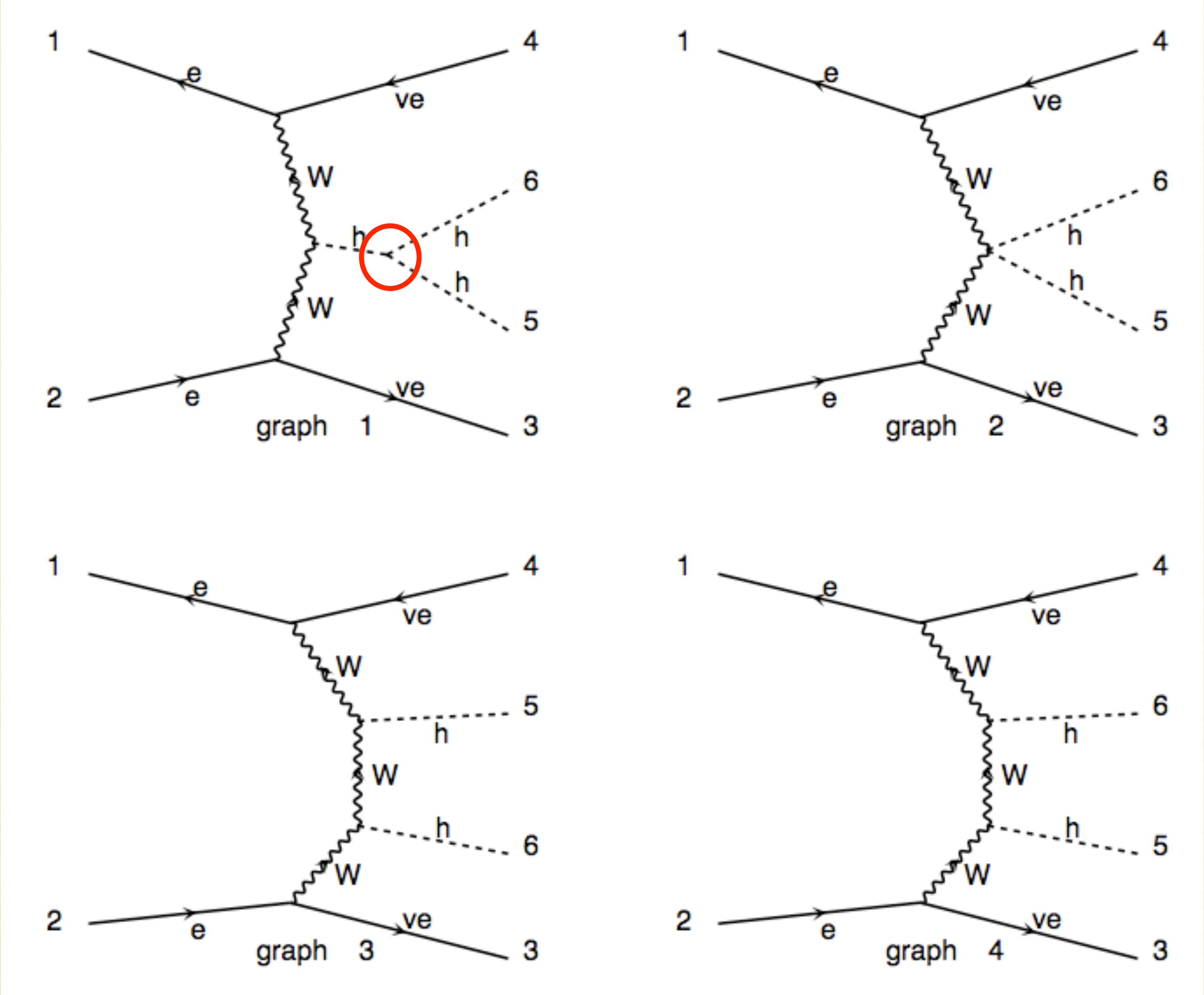
precision of cross-section

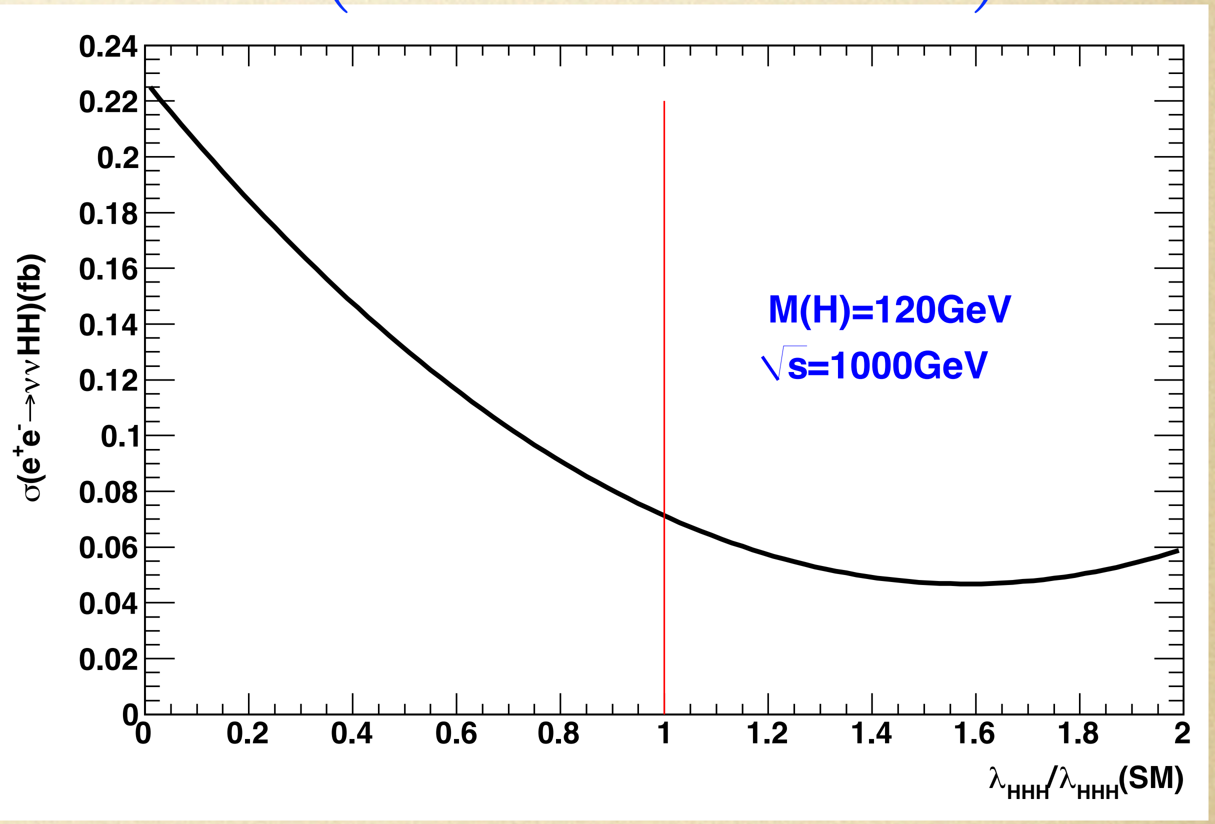
extraction of Higgs self-coupling from the cross section of $\upsilon\upsilon$HH

effect of irreducible diagram

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

$$\sigma(e^+e^- \to \nu\bar{\nu}\mathrm{HH})$$





$$\frac{\Delta\lambda}{\lambda} = 0.85\frac{\Delta\sigma}{\sigma}$$

precision of self-coupling

precision of cross-section

result of LoI analysis

@ALCPG11

- focus on the ZHH @ 500 GeV, M(H) = 120 GeV.
- three decay modes of ZHH (Z-->ll, vv, qq, H-->bb) are investigated, based on ILD full simulation.
- neural-net methods are used to improve the background suppression.
- effects of different beam polarizations are checked.

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

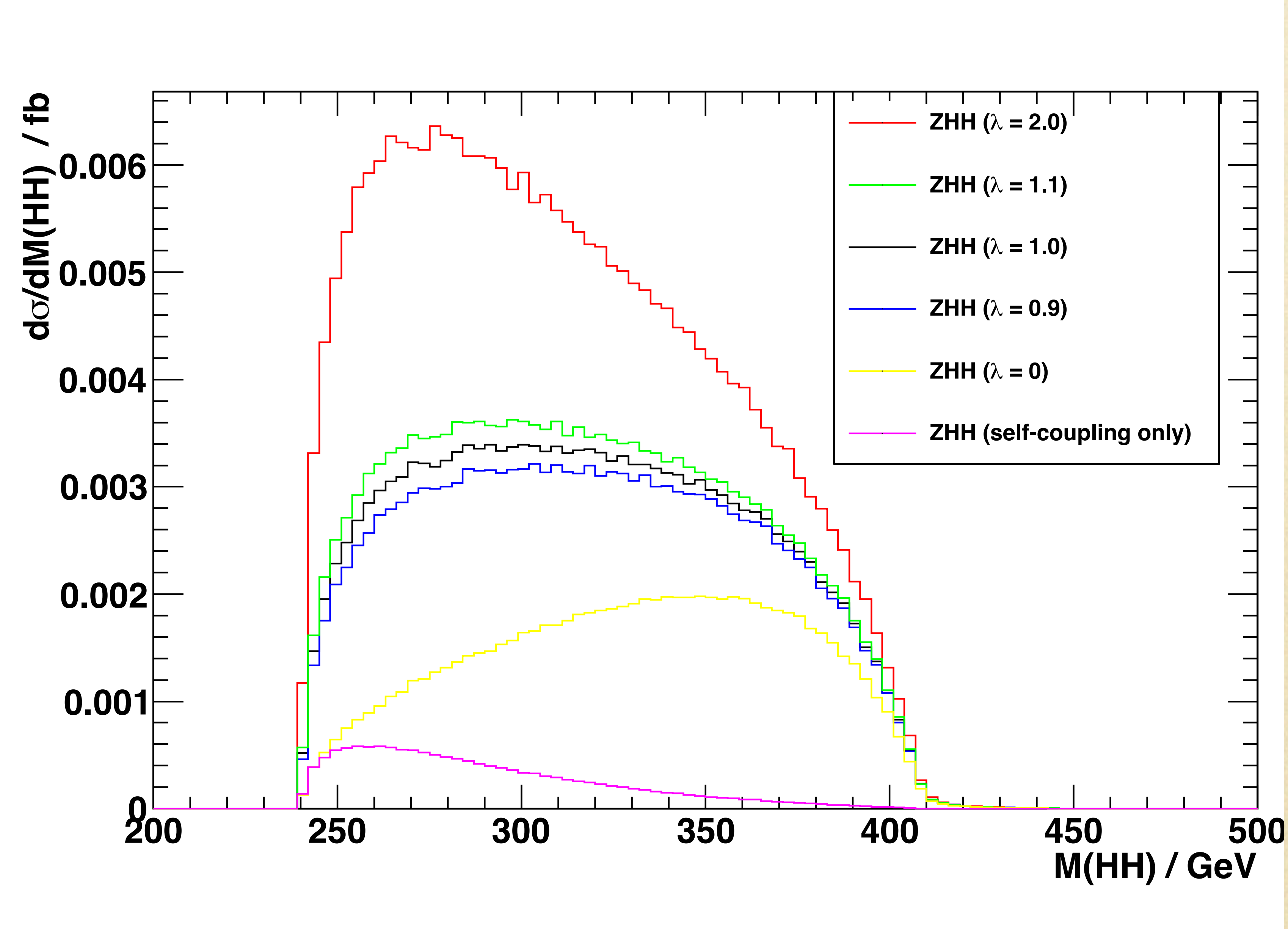
Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	6.4	6.7	2.1σ	1.7σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2	7.0	1.7σ	1.4σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	8.5	11.7	2.2σ	1.9σ
		16.6	129	1.4σ	1.3σ

$$\sigma_{ZHH} = 0.22 \pm 0.07 \quad \text{fb}$$

precision of cross section: **32%**
precision of Higgs self-coupling: **57%**

idea of weighting

- different spectrum of M(HH) for ZHH from Higgs self-coupling and non-self-coupling



at first ...

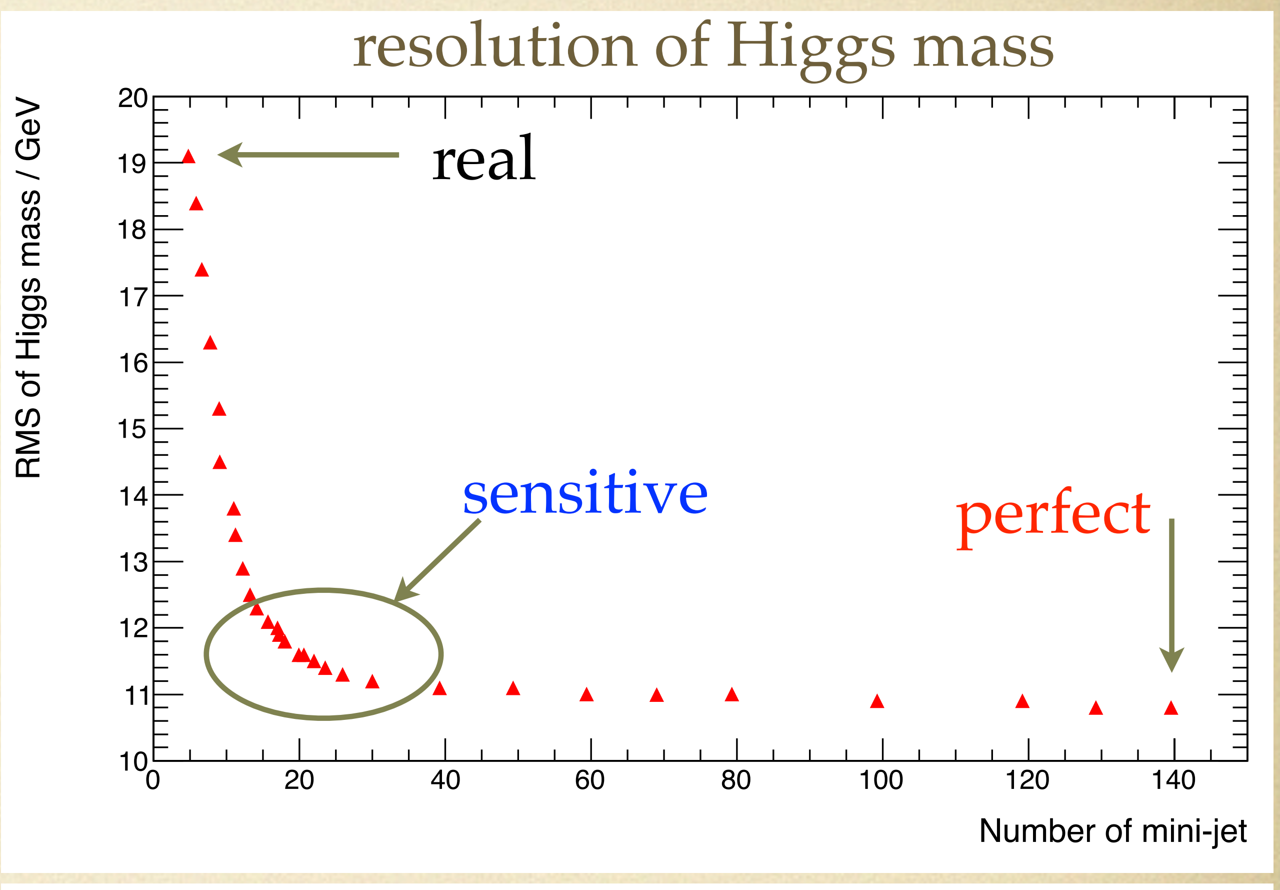
- ✦ Would the mini-jet be pure enough?
- ✦ When would the mini-jet clustering appropriately stop?

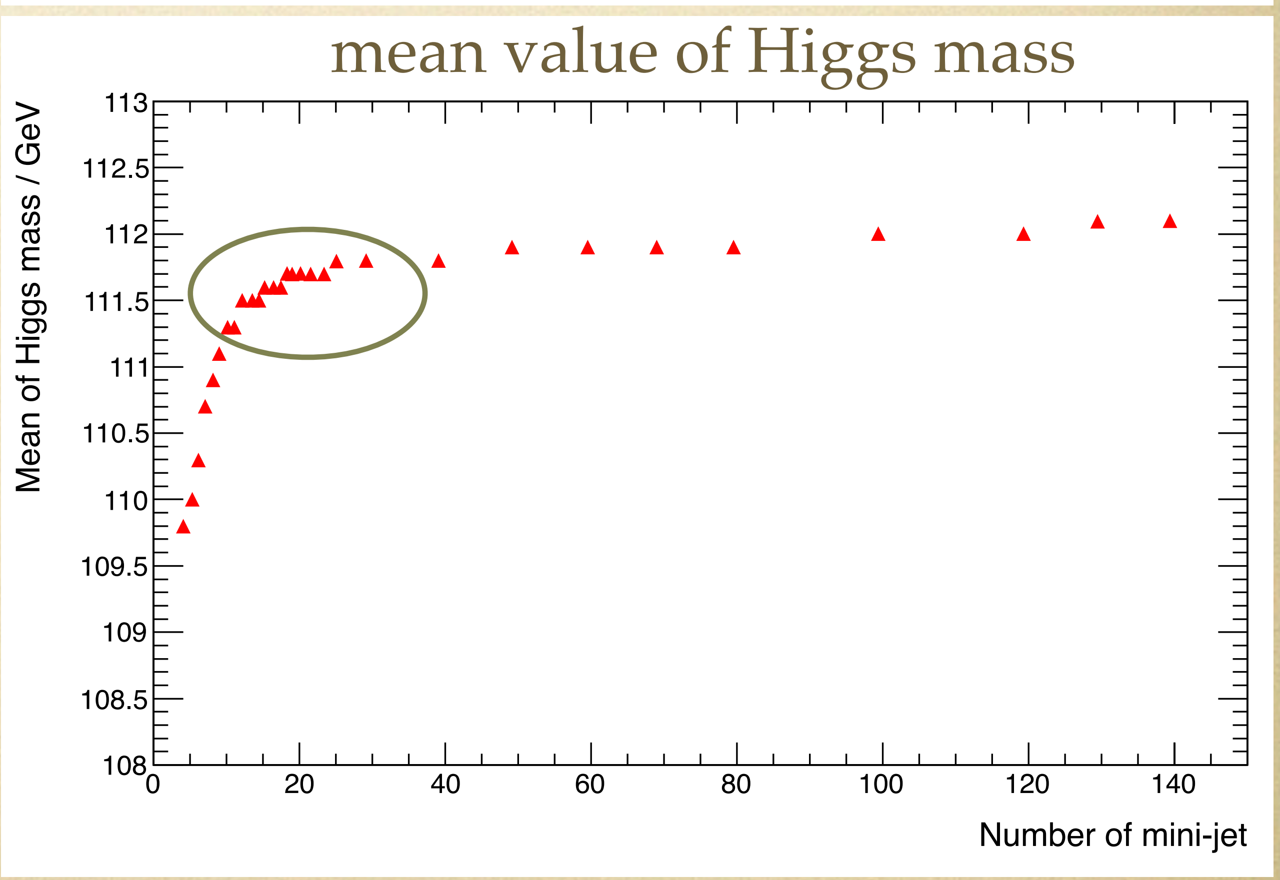
these can be tested supposing we can combine the mini-jets perfectly

vvHH ---> vvbbbb

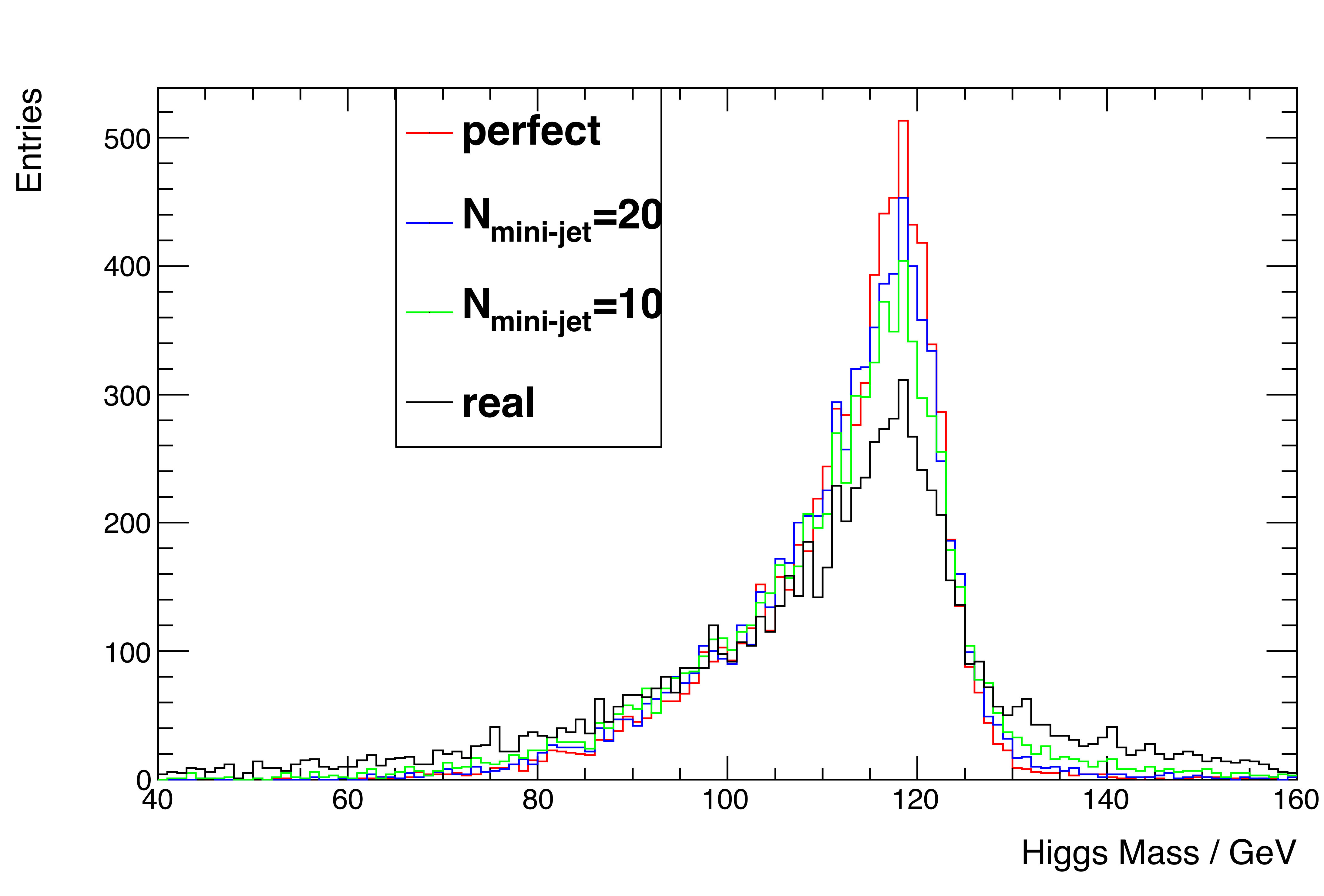
- using the realistic Duhram algorithm for the mini-jet clustering, stop when there are fixed number of mini-jets left.
- combine the mini-jets with cheated information, check the performance of Higgs reconstruction

(two Higgs masses are merged)





at first ...



Entries
500
400
300
200
100
0
40
60
80
100
120
140
160
Higgs Mass / GeV
perfect
N$_{mini\text{-}jet}$=20
N$_{mini\text{-}jet}$=10
real