update on Higgs self-coupling study @ ILC

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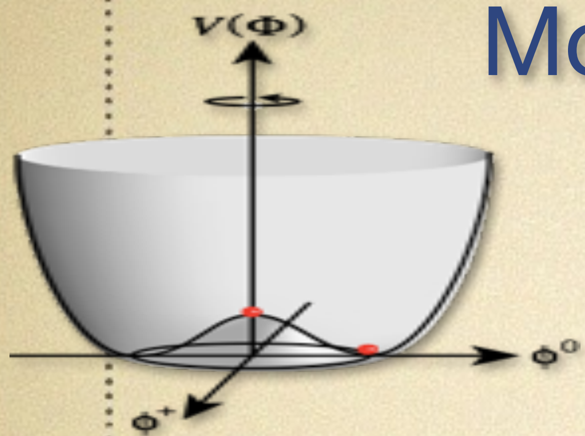
LCWS14, Oct. 6-10, 2014 @ Belgrade

Motivation to measure Higgs self-coupling

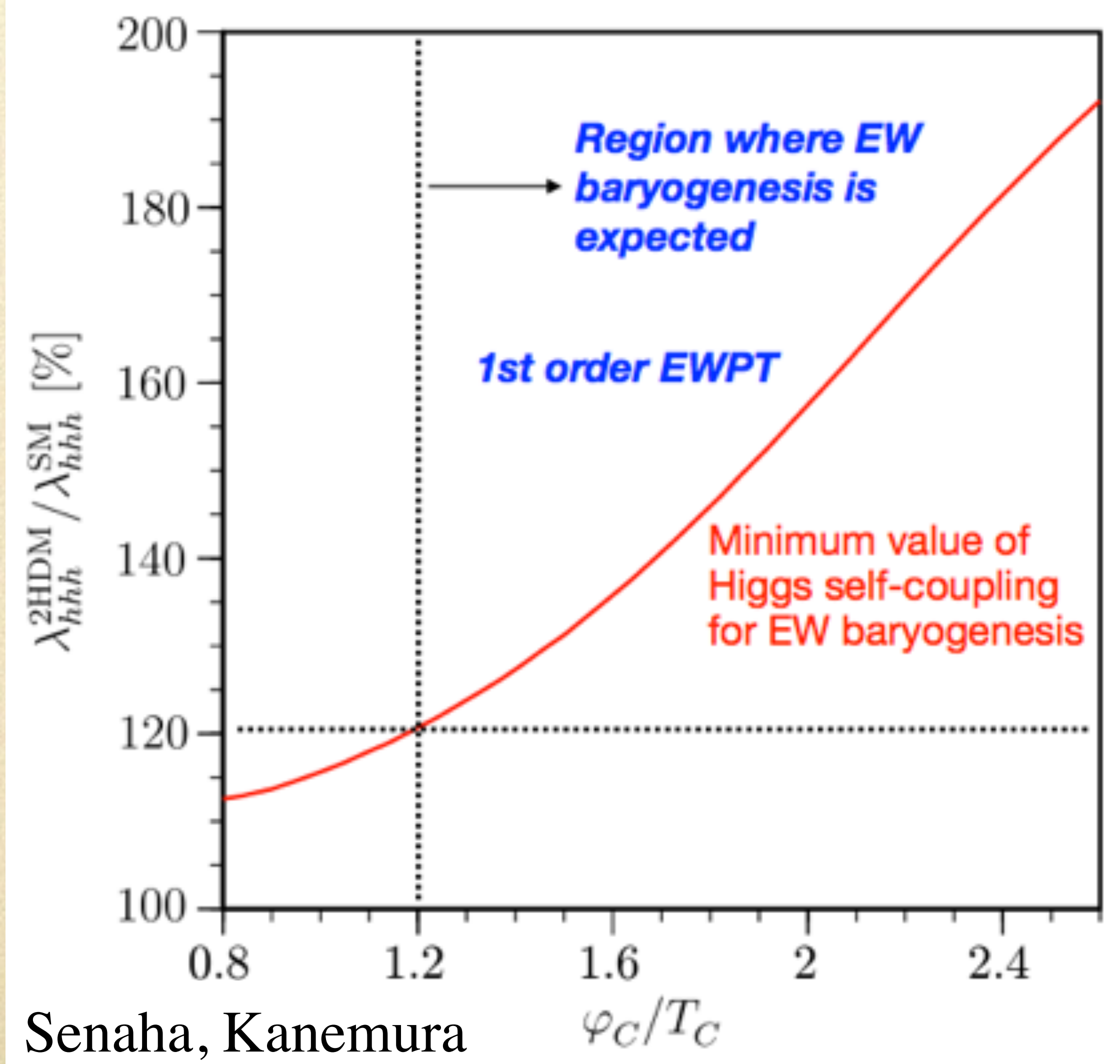


$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

- discover the force that makes Higgs condense in vacuum
- test extended Higgs sector
- test electroweak baryogenesis
- challenging at LHC

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$<$ 1%	3%	10%, 100%	2%, 15%

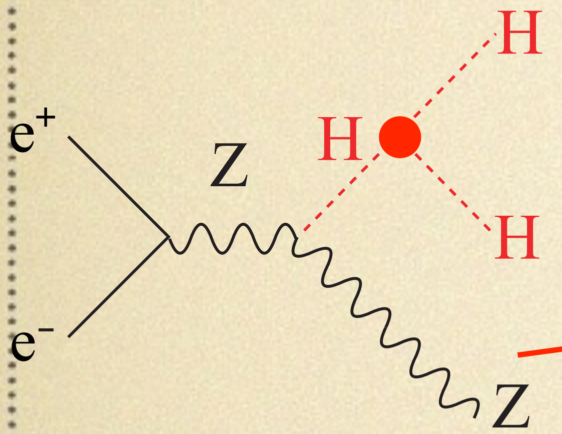
Gupta, Rzehak, Wells, arXiv:1206.3560

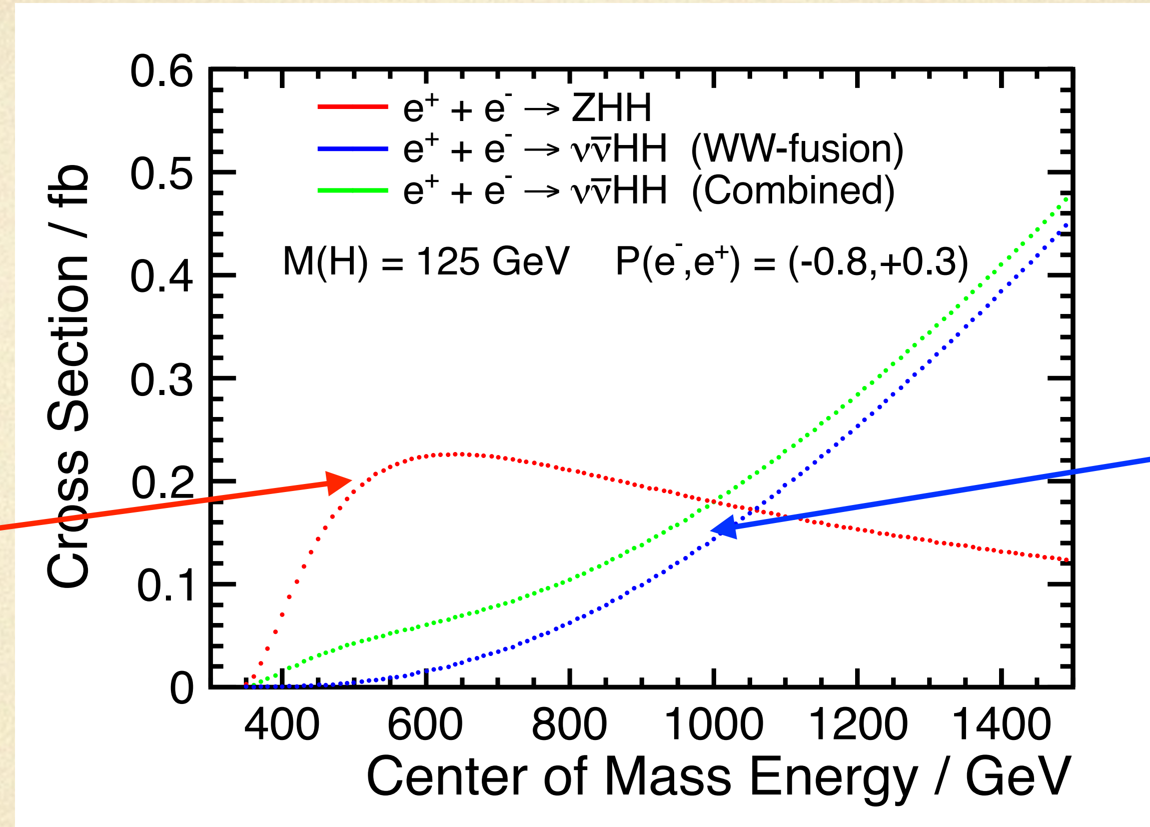


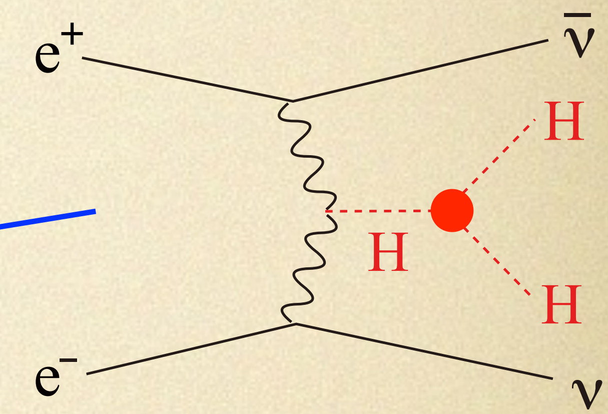
Senaha, Kanemura

yesterday's talk by K.Fujii

how we measure it at ILC and analysis strategy







searching mode and main backgrounds: $e^+ + e^- \rightarrow ZHH$ @ $500\ GeV$

- 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), bbqqq (tt-bar), qqbbbb (ZZZ/ZZH)

event selection:

B/S ~ $10^{3\text{-}4}$

- 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

status of analysis

500 GeV: 500 (1600) fb^{-1}
1 TeV: 1000 (2500) fb^{-1}

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

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Baseline	83%	21%
LumiUP	46%	13%

including HH—>bbWW*
(next talk by M. Kurata)

- 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

J. Tian, LC-REP-2013-003 C. Dürig @ AWLC14 M. Kurata @ ECFA2013

Preliminary results for 125 GeV without overlay

P(e-,e+) = (-0.8,+0.3), $\int L dt$ = 2 ab^{-1}

- m_H= 120 GeV results extrapolated to 125 GeV give a precision of 53% on Higgs self-coupling
- preliminary results without overlay

modes	signal	background	significance excess	significance measurement
$ZHH \to l^-l^+HH$	3.0	4.3	1.16σ	0.91σ
	3.3	6.0	1.12σ	0.91σ
$ZHH \to \nu\bar{\nu}HH$	5.2	6.9	1.63σ	1.37σ
$ZHH \to q\bar{q}HH$	9.2	20.9	1.82σ	1.64σ
	7.7	23.5	1.45σ	1.31σ

cross section: $\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}} = 32.6\%$

Higgs self-coupling: $\frac{\Delta\lambda}{\lambda} = 53\%$

	500 GeV at $\mathcal{L} = 2$ ab^{-1}		
scenario	A	B	C
extrapolated	53%	42%	34%
full analysis	53%	42%	34%

Extrapolation works, slightly conservative

Scenario A: $HH \to bbbb$

Scenario B: with $HH \to bbWW^*$, $\approx$ 20% improvement

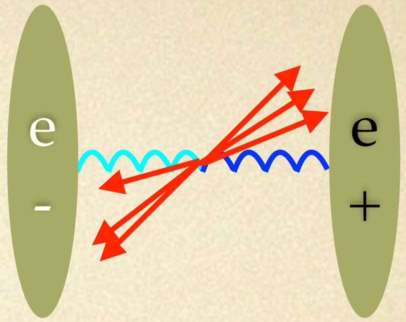
Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.), expect 20% improvement

We achieve a precision of 53% on the Higgs self-coupling for $m_H = 125$ GeV!

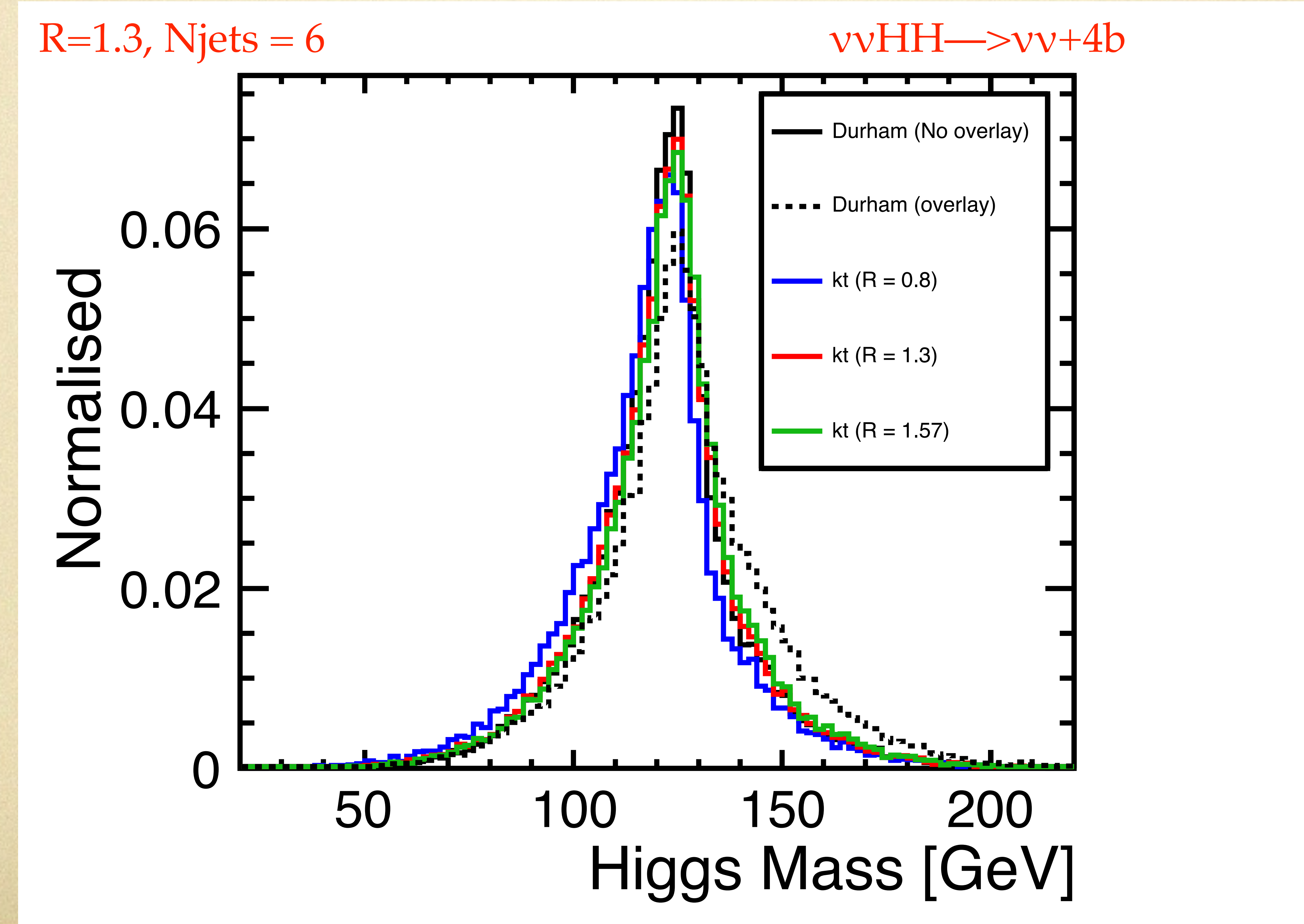
Effect of $\gamma\gamma$-overlay?

effect of overlay and strategy of removal: γγ—>hadrons

- exclusive kt algorithm.
- optimization: R-value and Njets



<N> = 1.7 (1.2) @ 500 GeV



impact of overlay on self-coupling

Preliminary results for 125 GeV with overlay

modes	signal	background	significance excess	significance measurement
ZHH → $l^- l^+$HH	2.7	5.9	0.91σ	0.72σ
	3.4	8.0	1.01σ	0.85σ
ZHH → $\nu\bar{\nu}$HH	5.6	9.0	1.45σ	1.23σ
ZHH → $q\bar{q}$HH	8.3	21.8	1.61σ	1.45σ
	8.7	38.2	1.31σ	1.21σ

cross section: $\frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}} = 35.4\%$

Higgs self-coupling: $\frac{\Delta\lambda}{\lambda} = 58.1\%$

	500 GeV at $\mathcal{L} = 2$ ab^{-1}		
scenario	A	B	C
w/o overlay	53%	42%	34%
w/ overlay	58%	47%	37%

Scenario A: HH → bbbb
Scenario B: with HH → bbWW*, ≈ 20% improvement
Scenario C: analysis improvement (kinematic fit, jet-clustering, etc.), expect 20% improvement

Considering $\gamma\gamma$-overlay, we achieve a precision of 58% on the Higgs self-coupling

1 TeV at $\mathcal{L} = 2.5$ ab^{-1}		
A	B	C
16%	13%	10%

arXiv:1310.0763v3[hep-ph]

Using additional WW-fusion data at 1 TeV we can achieve a precision of 10% on the Higgs self-coupling (w/o overlay)

it has a significant impact (8% worse); with few more overlaid particles, some background can be more like signal; we still need look into some detail to improve this; on the other hand, <N> of overlay is currently over estimated.

impact of beam polarisations

- standard polarisation used in analysis $P(e^-, e^+)=(-0.8, 0.3)$ with $\mathcal{L} = 2$ ab^{-1}
- rough estimation of Higgs self-coupling accuracy for other polarisations

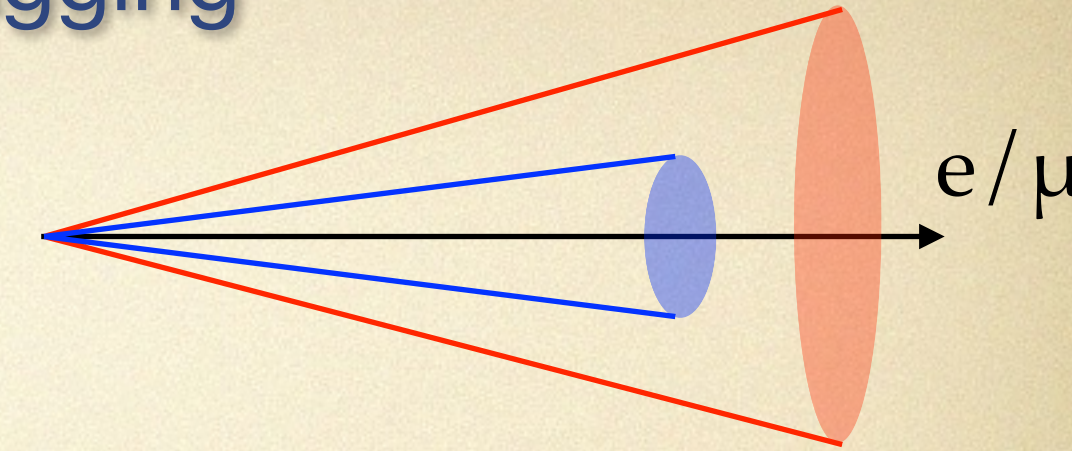
Polarisation	no overlay		overlay	
$P(e^-, e^+)$	cross section	self-coupling	cross section	self-coupling
(-0.8, 0.0)	36.7%	60.1%	40.7%	66.7%
(0.8, 0.0)	37.2%	61.1%	41.7%	68.4%
combined	26.2%	42.9%	29.1%	47.8%
(-0.8, 0.3)	**32.6%**	**53.5%**	**35.5%**	**58.1%**
(0.8, -0.3)	33.5%	54.9%	37.1%	60.8%
combined	23.4%	38.3%	25.6%	42.0%
(-0.8, 0.6)	29.9%	49.2%	33.6%	55.1%
(0.8, -0.6)	30.6%	50.2%	33.8%	55.4%
combined	21.4%	35.1%	23.8%	39.1%

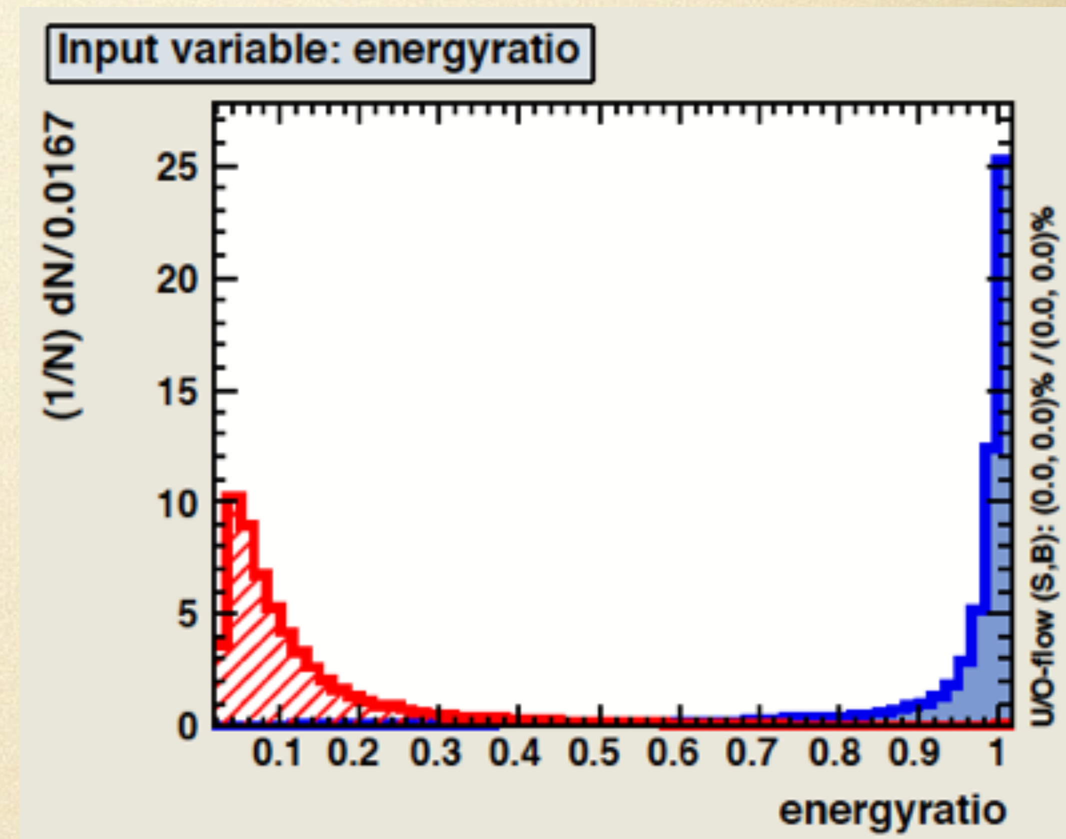
combined: $P(+) \cdot 2$ ab^{-1} + $P(-) \cdot 2$ ab^{-1}

- for $P(e^-)= -0.8$: increase $P(e^+) \rightarrow$ 10% improvement
  decrease $P(e^+) \rightarrow$ 10% worsening
- similar results for opposite polarisations

isolated lepton tagging

- ☑ general lepton identification: different fractions of energy deposited in ECAL, HCAL and Yoke.
- ☑ isolation requirement: effect of neighbour particles (now defined by two cones, one small, one large); from primary vertex.
- ☑ multivariate method is used to get the best efficiency / purity; output classifier (tagging) is kept for following optimization.
- ☐ shower shape not yet used (start point, lateral distribution), helpful for charged pion suppression.
- ☐ isolation still not ultimately optimized: infinity layers of cones (energy ratio .vs. cone angle).



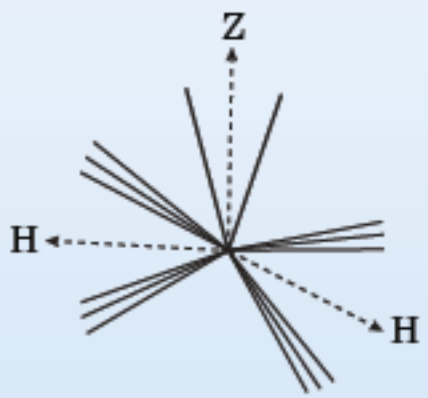


Eff (%)	eeHH	μμHH	bbbb	eνbbqq	μνbbqq
NEW	87.0	89.1	0.0017	0.32	0.020
DBD	85.7	88.4	0.028	1.44	0.10

kinematic fitting

Benjamin Hermberg (DESY)

Lepton channel



$$e^+e^- \to ZHH \to l\bar{l}HH$$

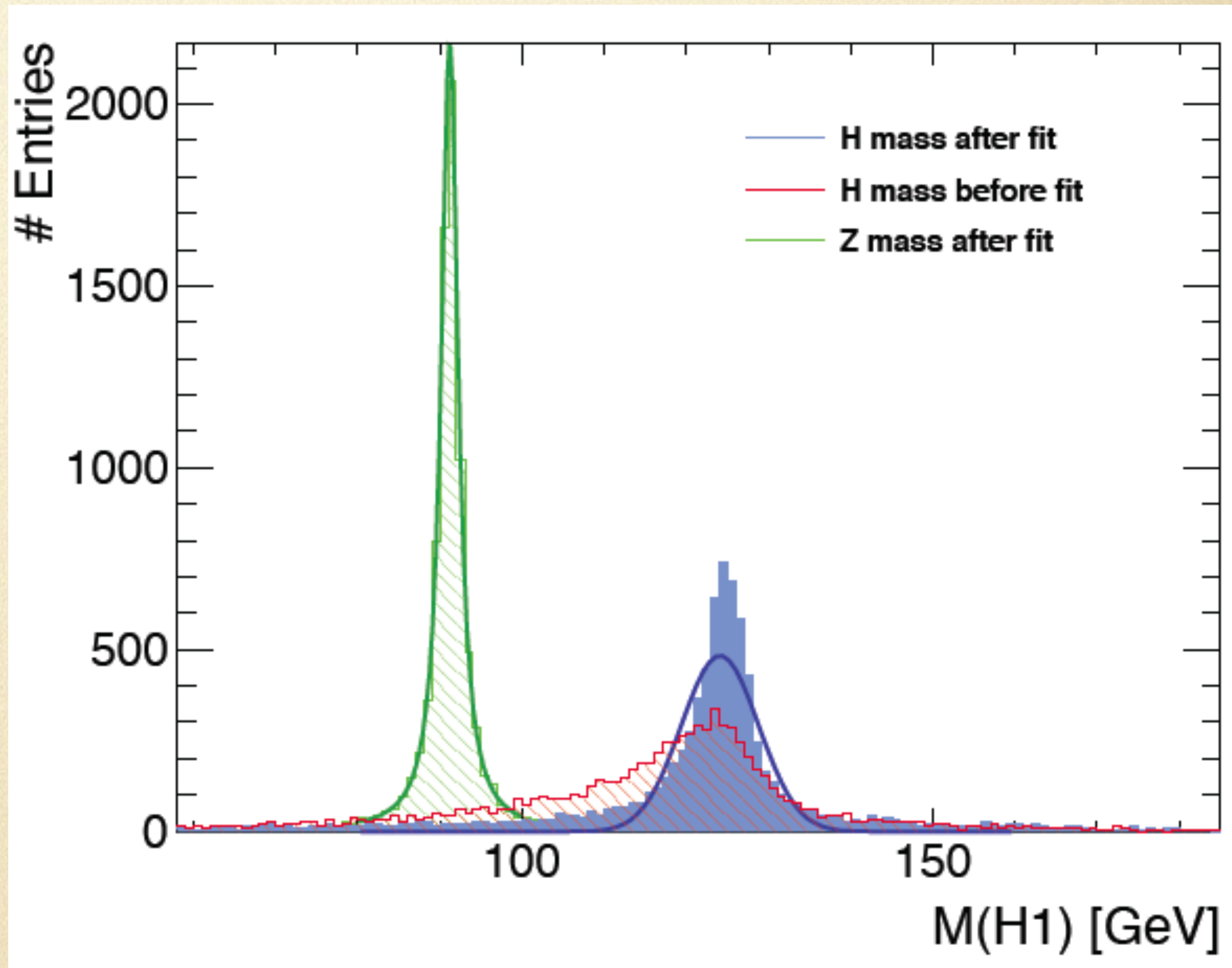
2 Leptons + 4 Jets

$$M_{ll} = M_Z$$

$$M_{j_1 j_2} = M_{j_3 j_4}$$

$$\sum E_J + \sum E_l = \sqrt{s}$$

$$\sum \vec{p} = 0$$

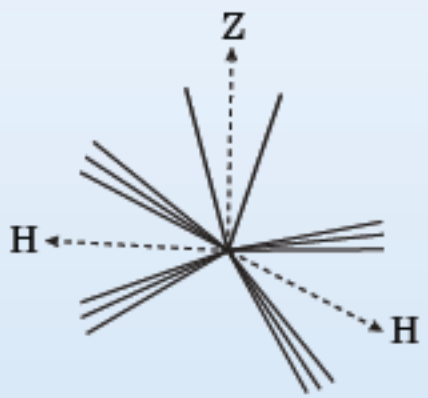


much narrower Higgs mass peak

kinematic fitting

Benjamin Hermberg (DESY)

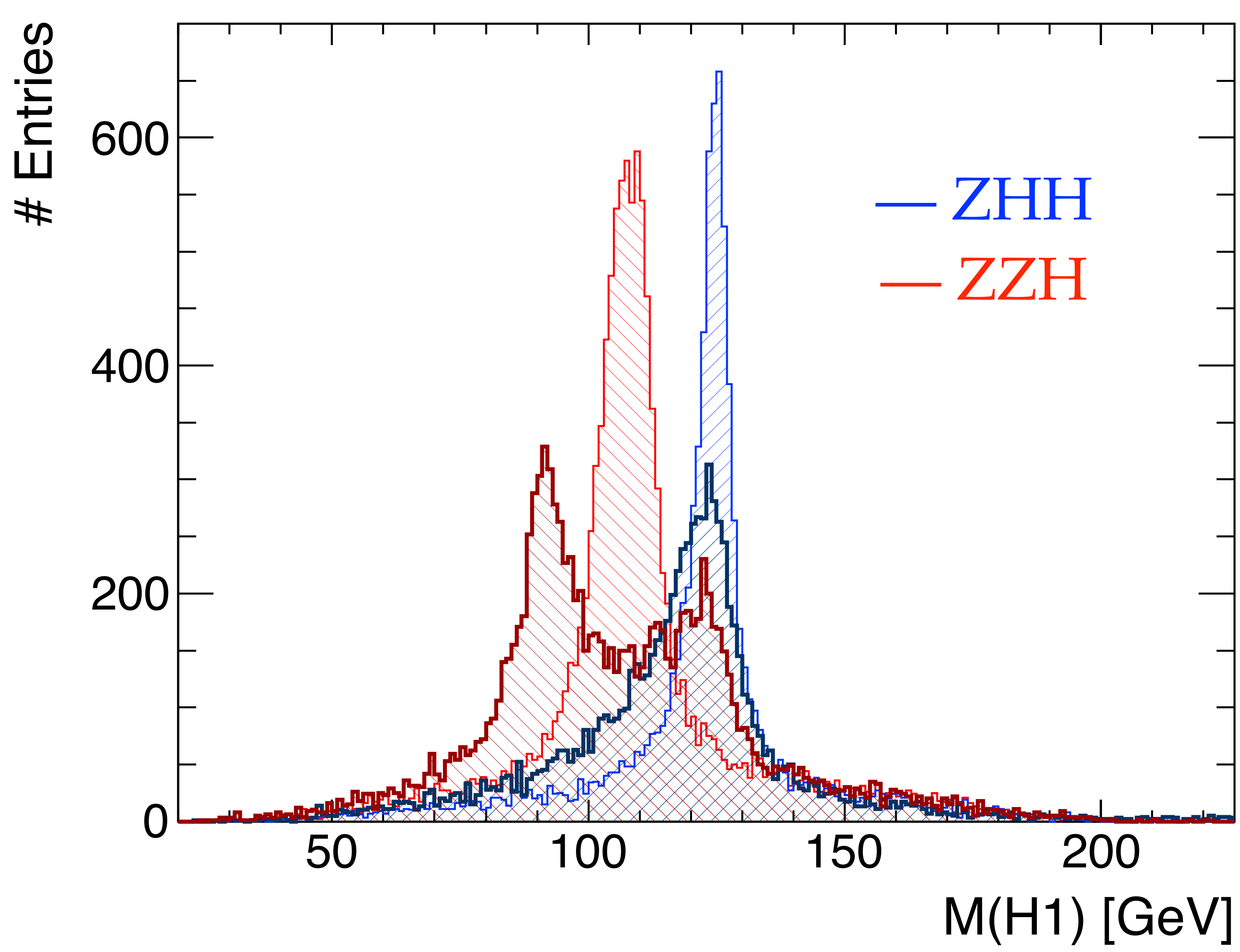
Lepton channel



$$e^+e^- \to ZHH \to l\bar{l}HH$$

2 Leptons + 4 Jets

$$M_{ll} = M_Z$$
$$M_{j_1j_2} = M_{j_3j_4}$$
$$\sum E_J + \sum E_l = \sqrt{s}$$
$$\sum \vec{p} = 0$$



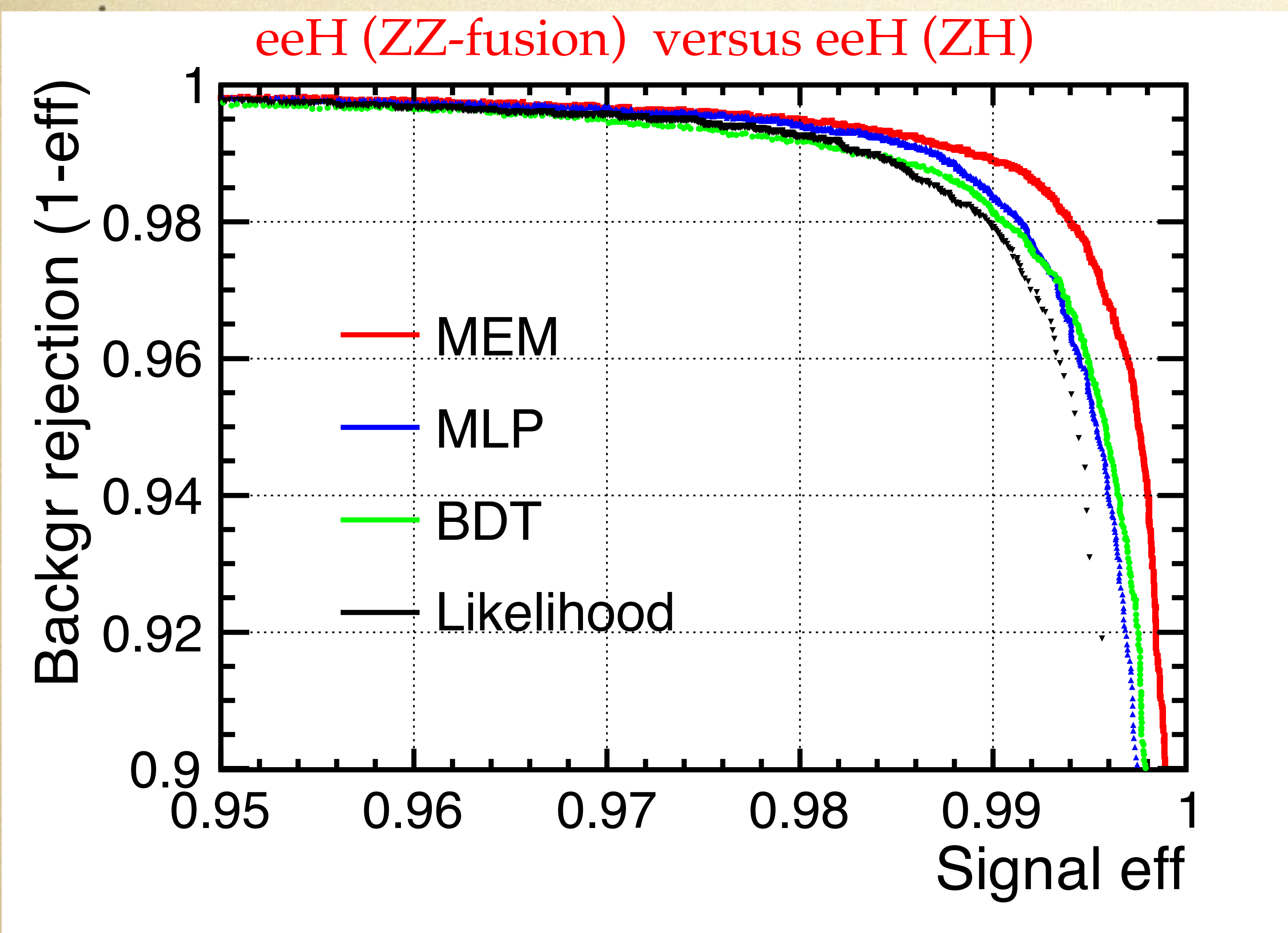
much narrower Higgs mass peak

very promising! going to check improvement on separation with ZZH

recent development of Matrix Element tools

(approach the true likelihood of each event)

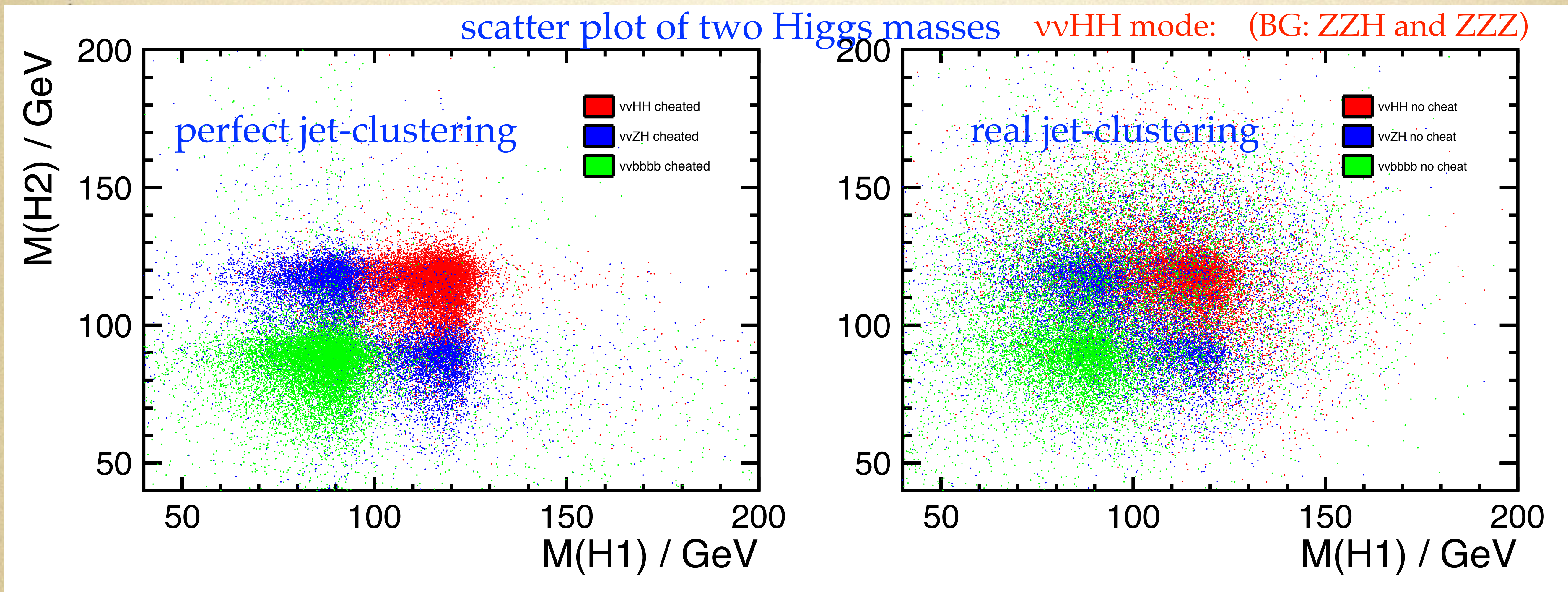
J. Tian@AWLC14



- showed very encouraging improvement in ZZ-fusion analysis.
- going to be applied to event weighting in ZHH analysis (to increase sensitivity from self-coupling diagram).
- would be really exciting if we can apply to color-singlet-jet-clustering (see following slides)

(developed for full detector simulation, available in latest ilcsoft release v01-17-06)

what's wrong with current jet-clustering?

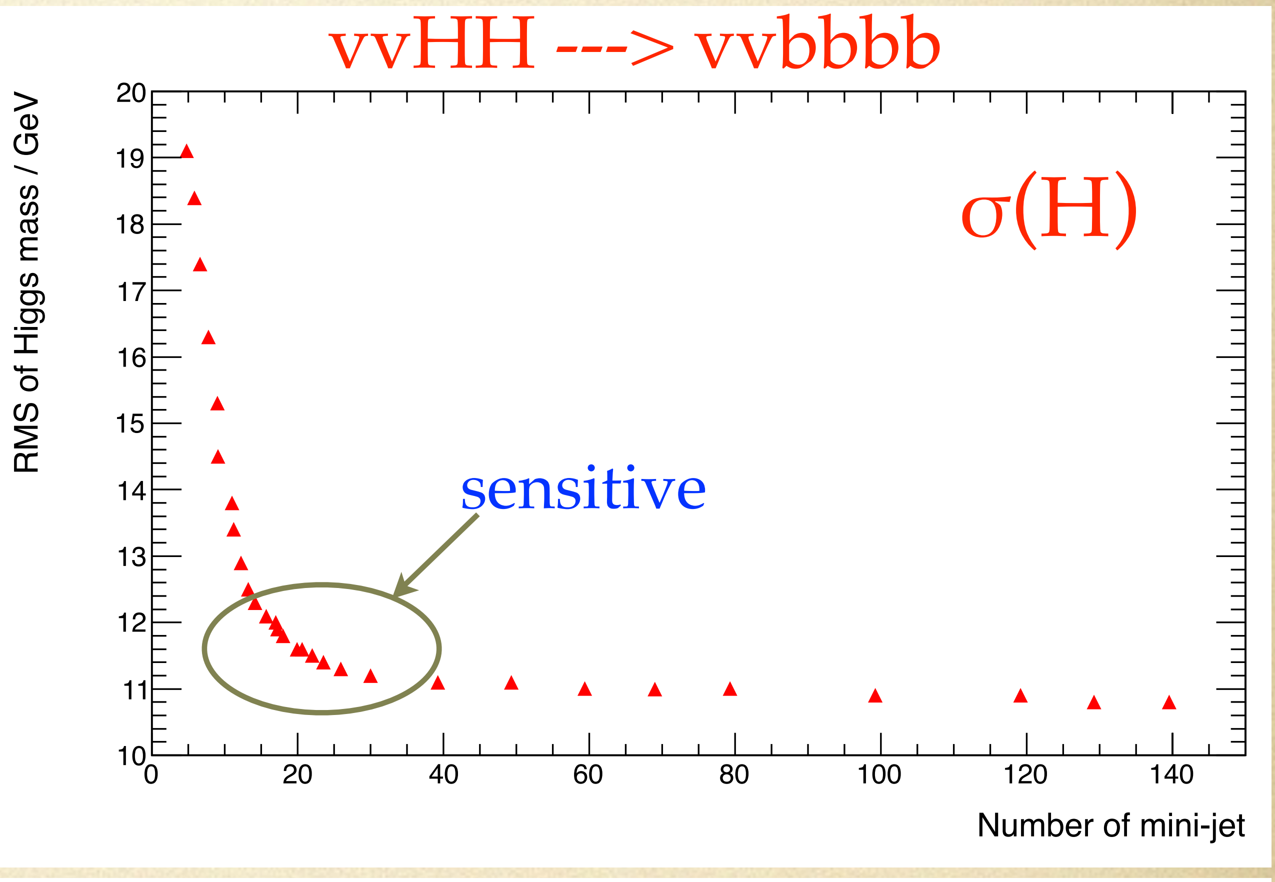


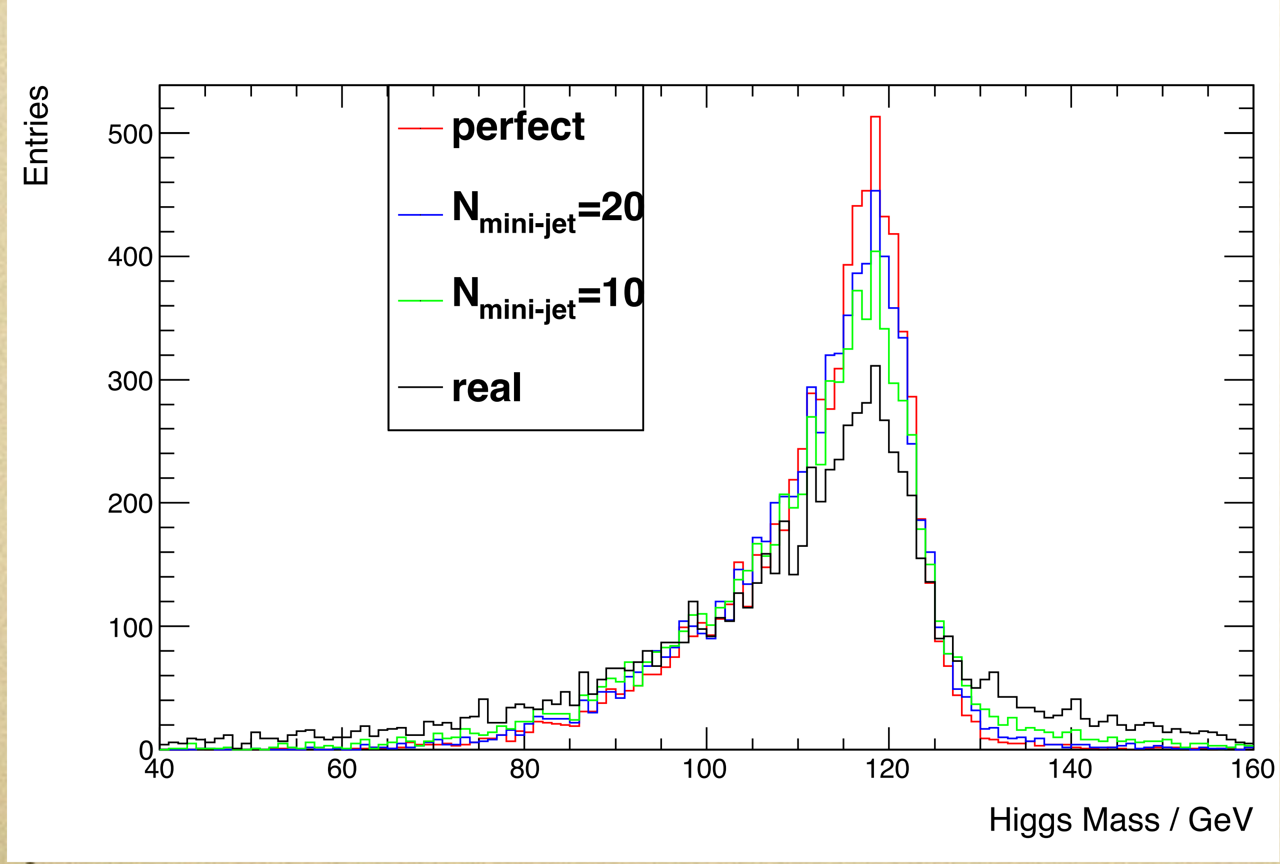
- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%!

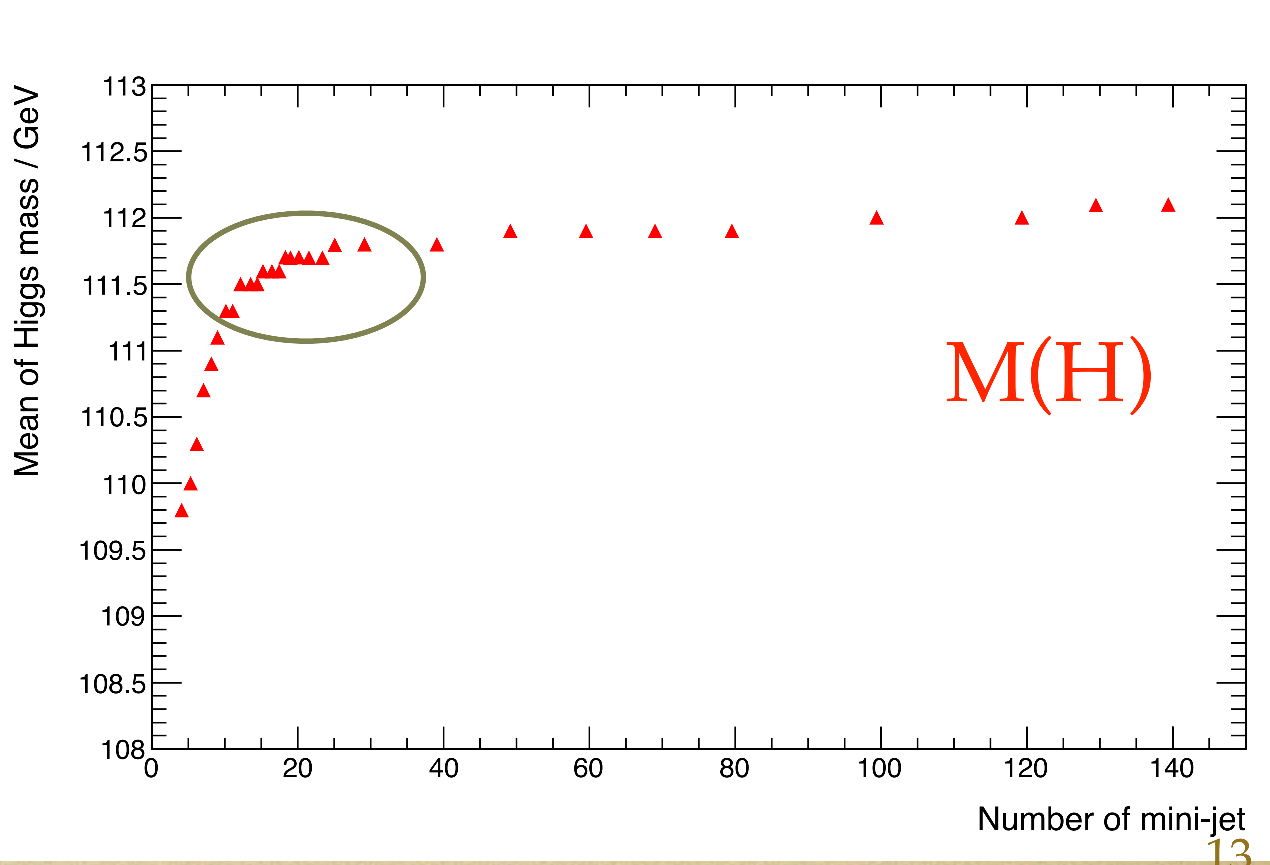
how to approach perfect jet-clustering?

(idea of a mini-jet based jet-clustering algorithm)

- find vertex before clustering then merge particles from same vertex (LCFI+)
- early stage of jet-clustering —> find all mini-jet : suppose the traditional clustering algorithm can work well with very small y-values.
- combine the mini-jets: ideally we need matrix element at parton shower level!







a new Georgi algorithm of jet-clustering

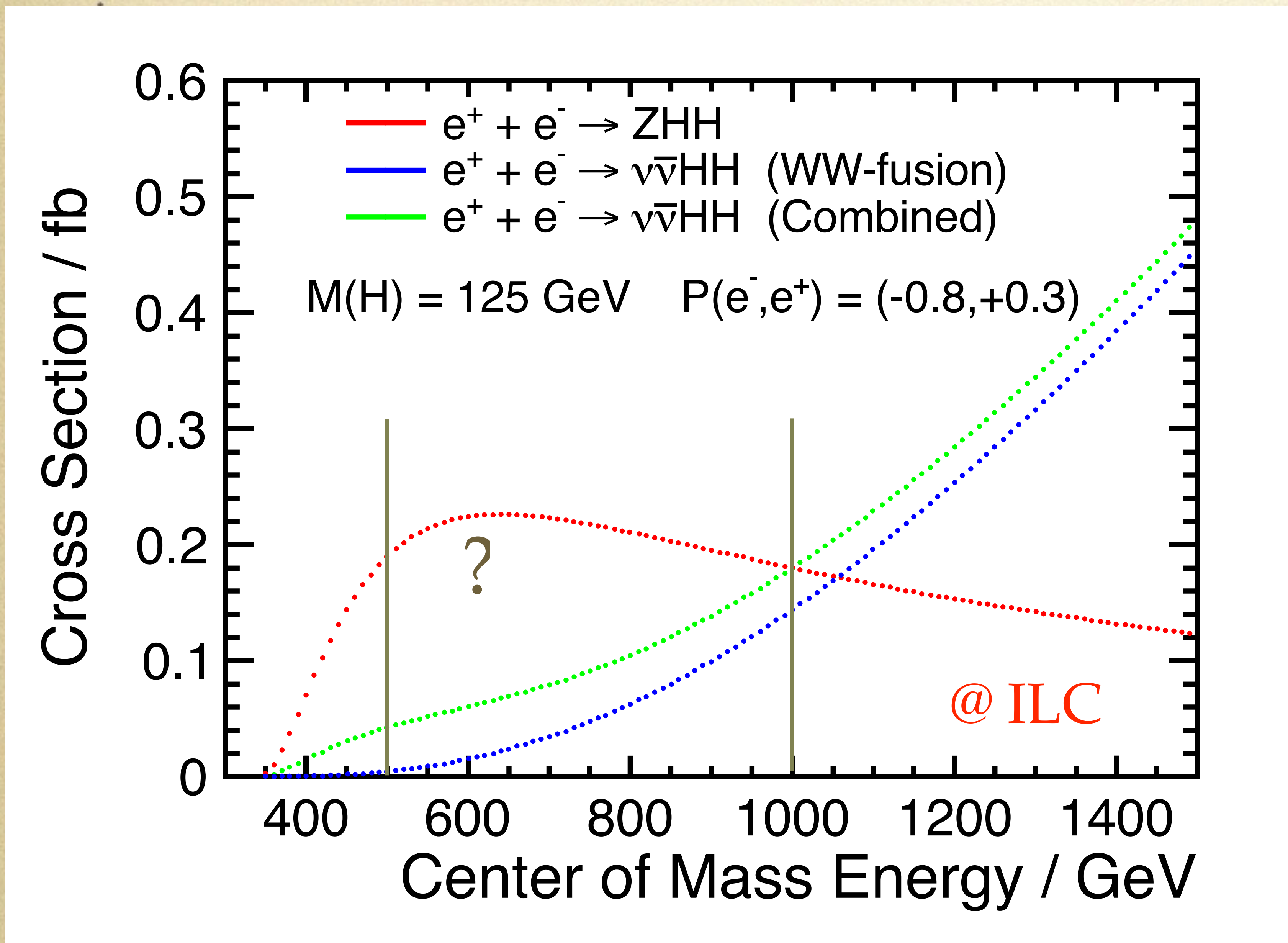
arXiv:1408.1161 / 1408.3823

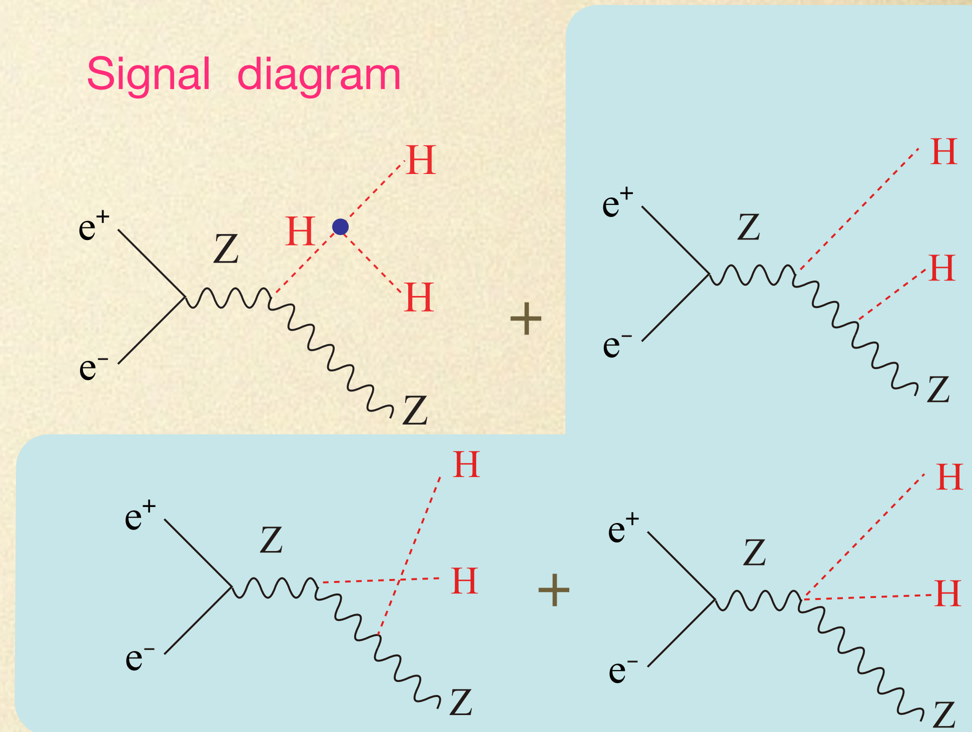
Jet function:

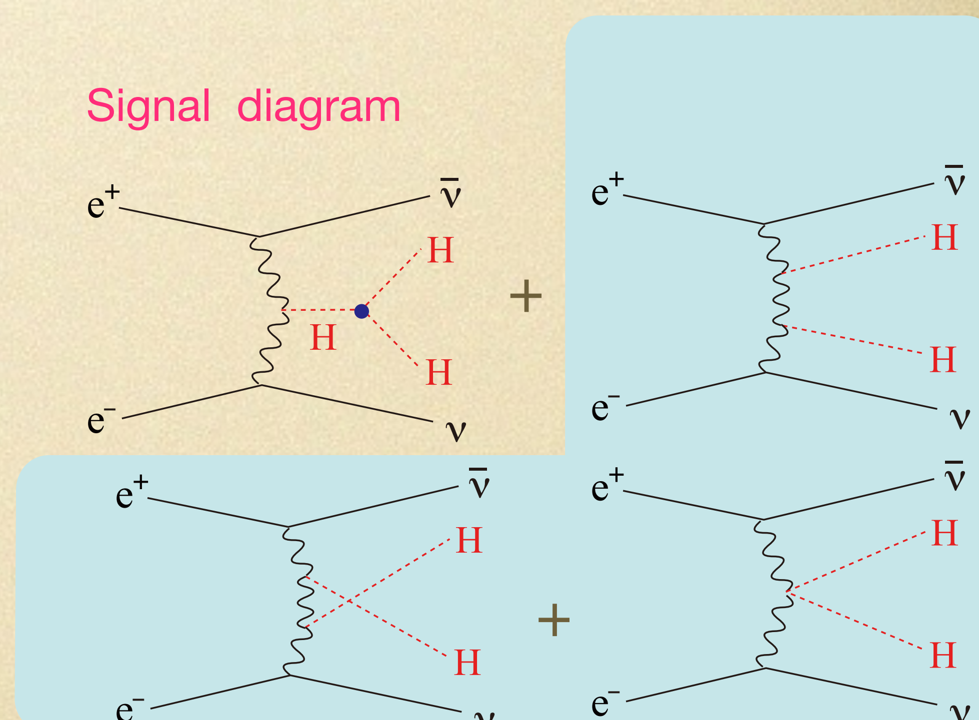
$$J_\beta(P_\alpha) \equiv E_\alpha - \beta \frac{P_\alpha^2}{E_\alpha} = E_\alpha \left[(1-\beta) + \beta v_\alpha^2\right] ,$$

- one interesting feature: jet-clustering can be done globally
- main procedure: find the set of particles (any #particle) with maximum jet function
- number of combinations = 2^N, where N is number of particles to be clustered
- in most jet processes, it almost impossible to start with this algorithm at the beginning, based on N= 100~150
- luckily, now we more or less know the real starting point, ~ 20 mini-jets, which means ~ 1 million combinations; ~0.3s / event
- most interestingly, Jet function *= Likelihood of color-singlet system

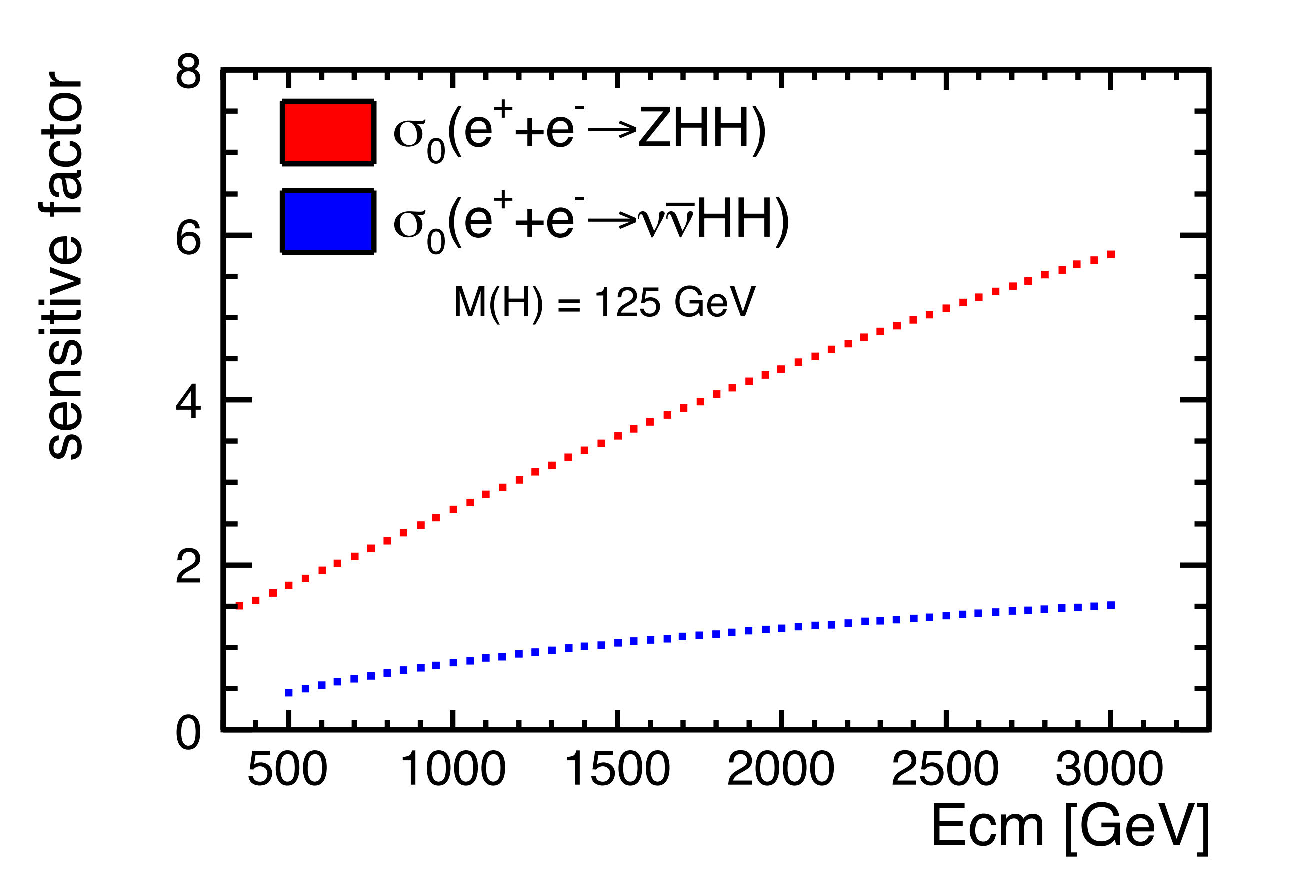
impact of centre-of-mass energies

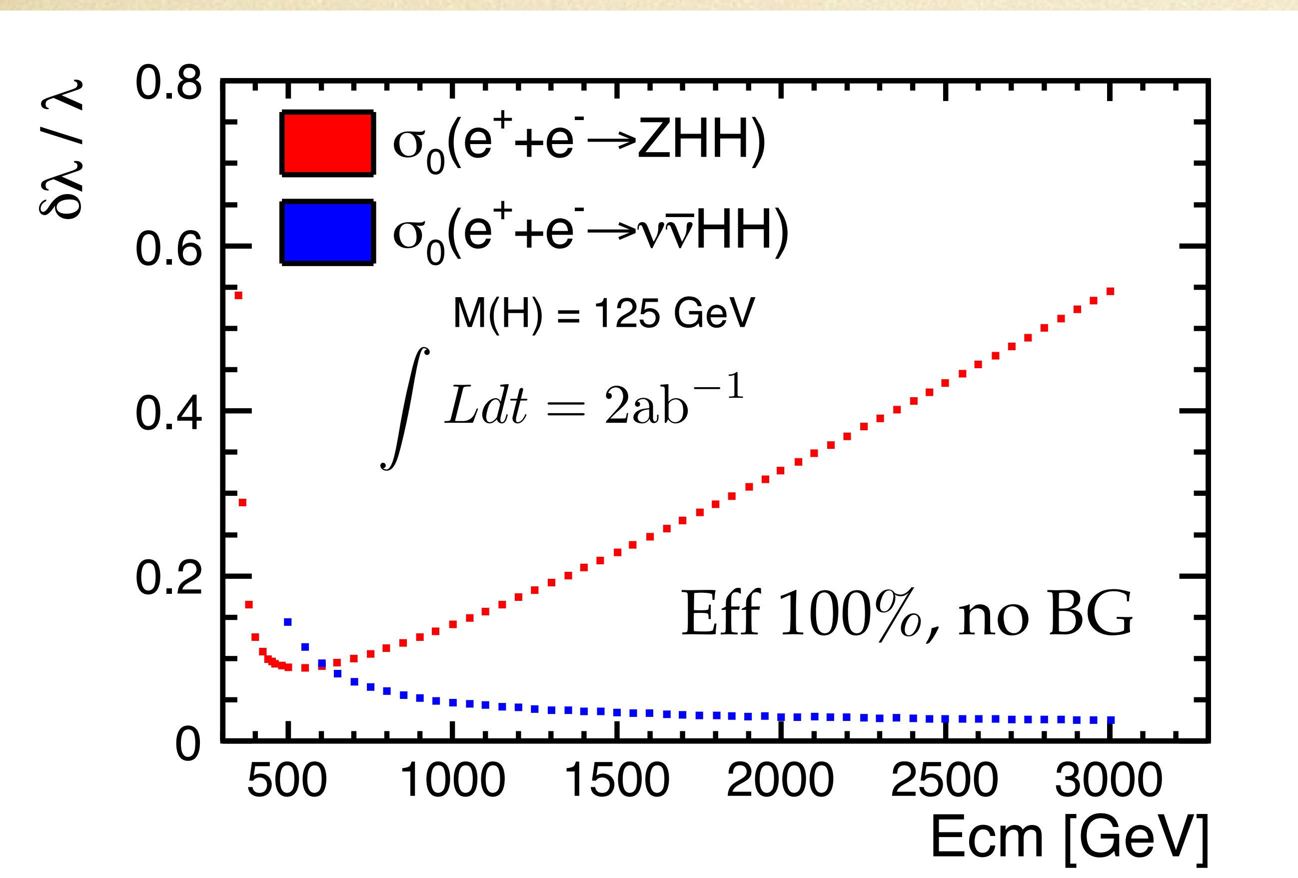






impact of centre-of-mass energies





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

Factor increases quickly as going to higher energy

for ZHH, the expected optimal energy ~ 500 GeV (rather flat at 500 — 600 GeV)

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

summary

- it is one of the fundamental tasks to measure λ_{HHH} at the future colliders; ultimate test/ingredient of SM/2HDM / EWPT; 10% precision is achievable at 1 TeV ILC.
- current focus is to improve analysis at 500 GeV: updated with mH=125 GeV and confirmed previous extrapolation, beam background included and has big impact; many ongoing efforts kinematic fitting, isolated lepton tagging, jet clustering and jet pairing, optimisation strategy, don't forget flavor tagging…
- it's challenging but that's why we're interested…

Backup

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	3.88
BG (tt/ννZH)	7.86×10	33.7
significance	0.3	4.29

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

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

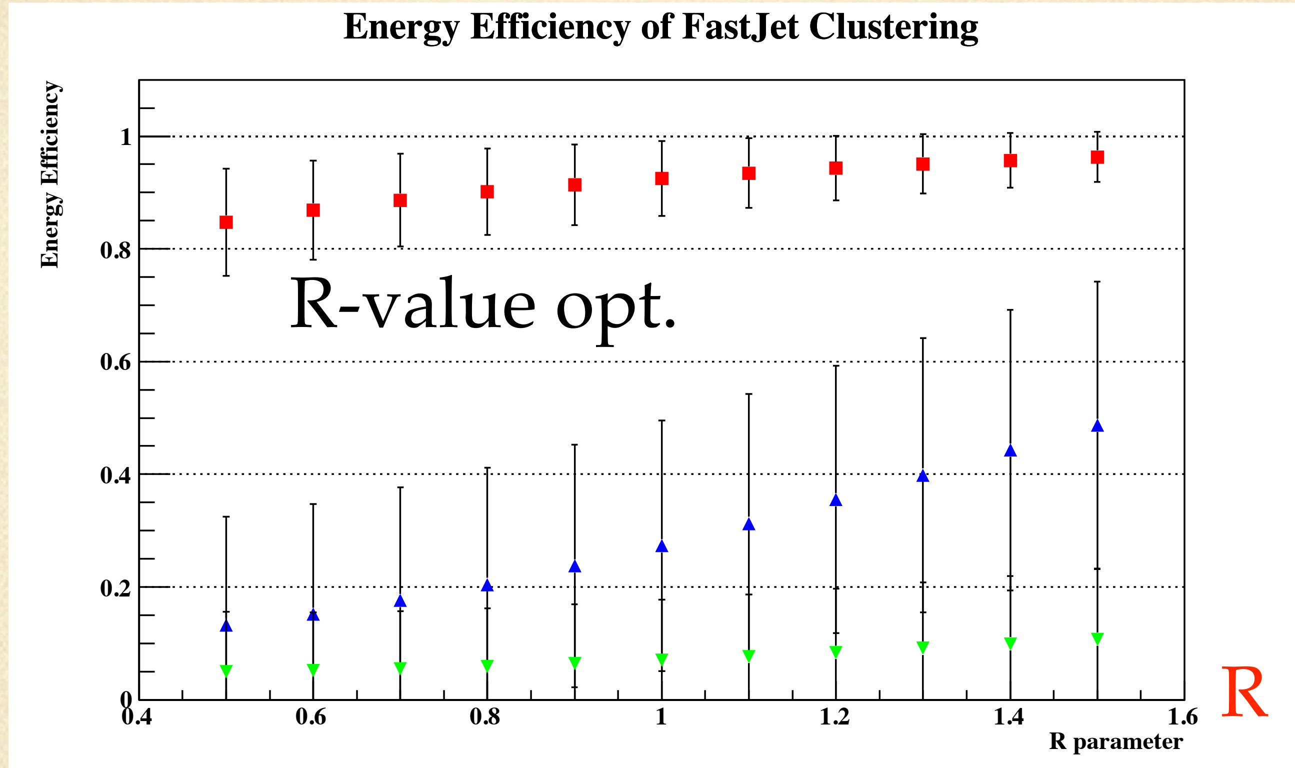
Double Higgs excess significance: $> 7\sigma$

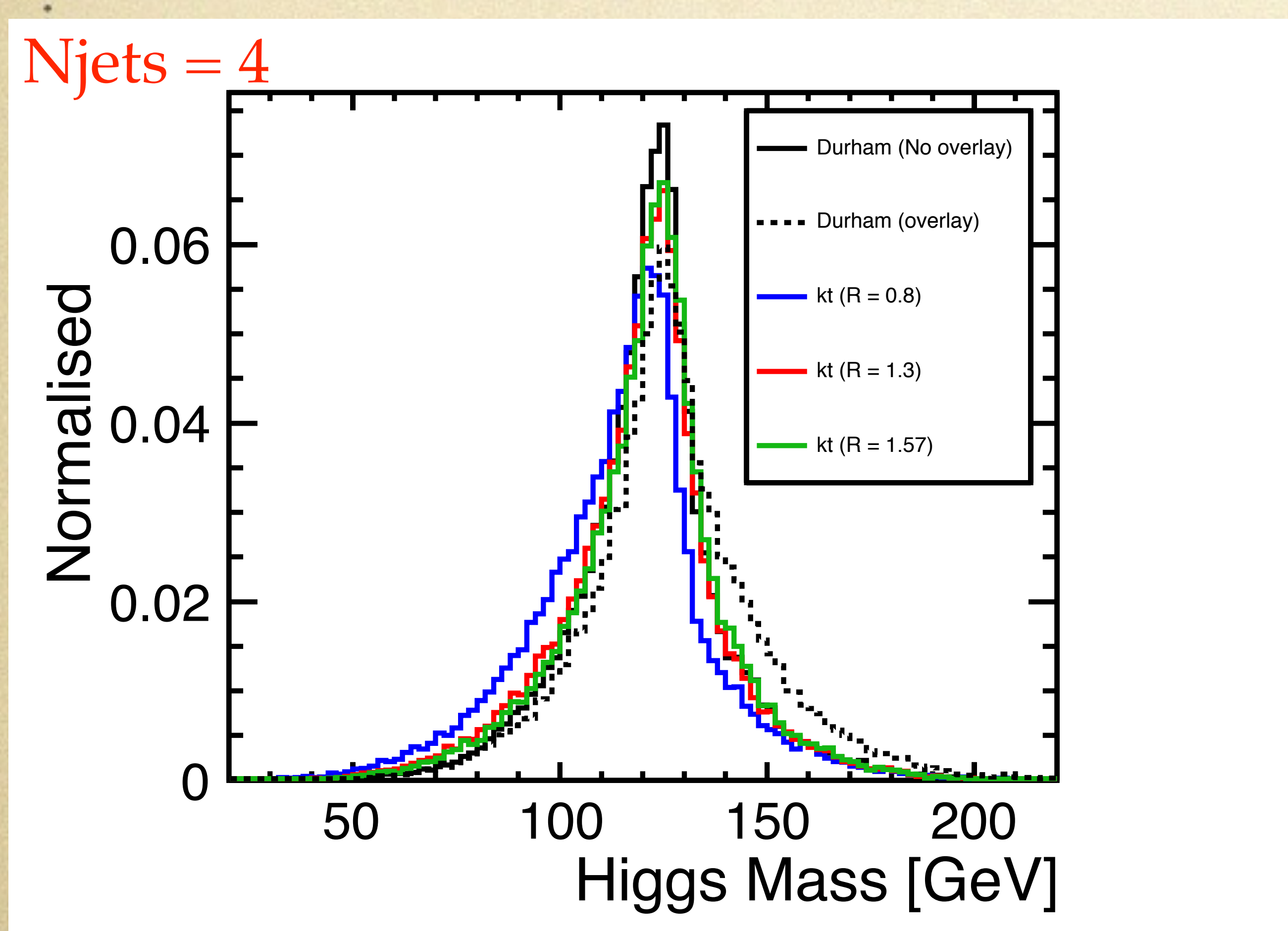
Higgs self-coupling significance: $> 5\sigma$

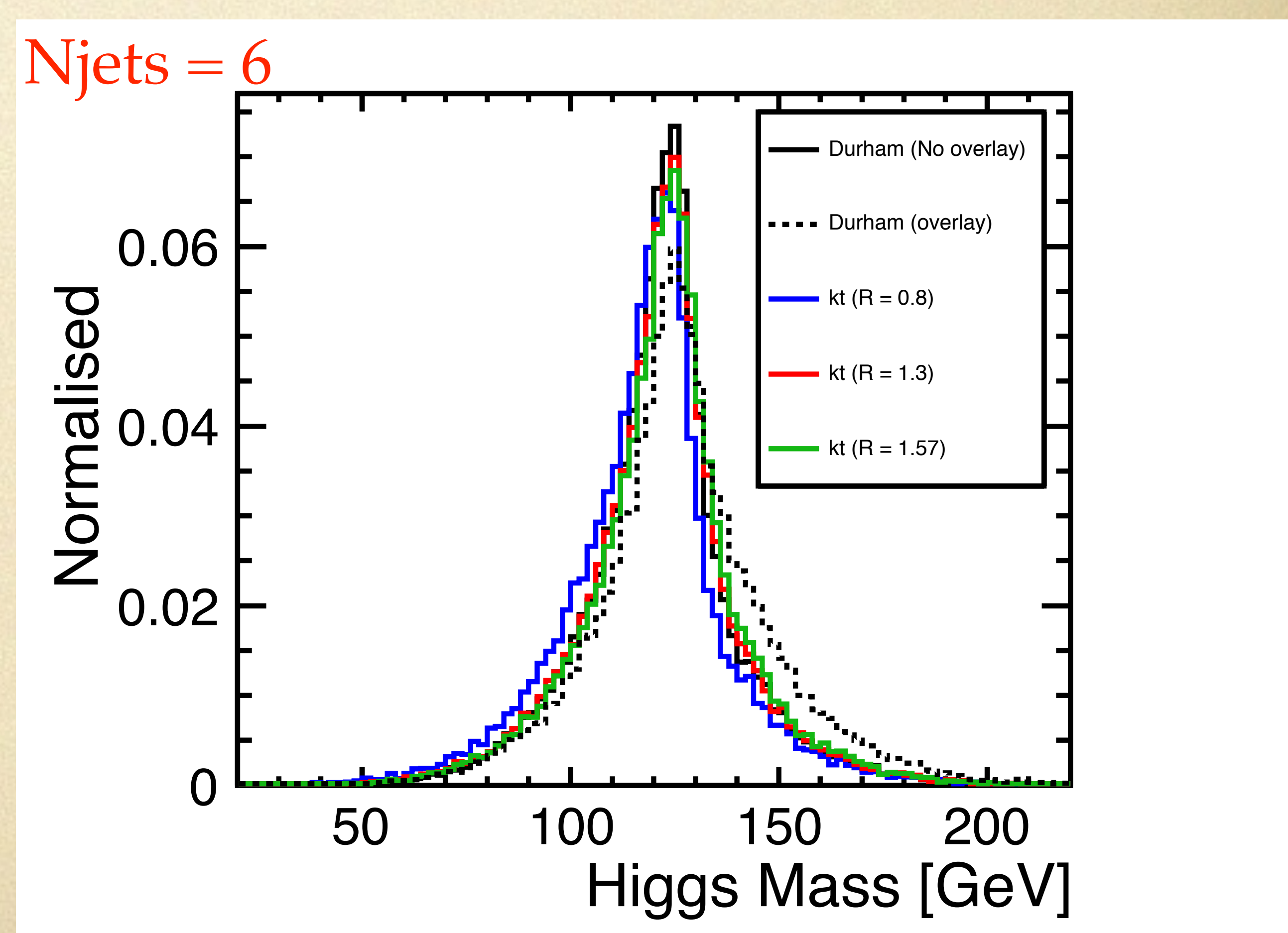
impact of centre-of-mass energies

- for ZHH process, 500 GeV is still the optimal energy.
- we do gain significantly from vvHH @ 1 TeV, where sensitivity factor is much smaller than that in ZHH.
- new baseline running scenario is up to 500 GeV, what would we expect?
- with 5500 fb^{-1} @ 500 GeV, we expect 25% precision on self-coupling based on already-done analyses; conservatively, 20% is achievable with improved techniques.
- reminder: 75% @ LoI —> 44% @ DBD (mH=120GeV, 2ab^{-1})
- with 1 TeV upgrade: $\delta\lambda/\lambda < 10\%$

effect of overlay and strategy of removal: γγ—>hadrons



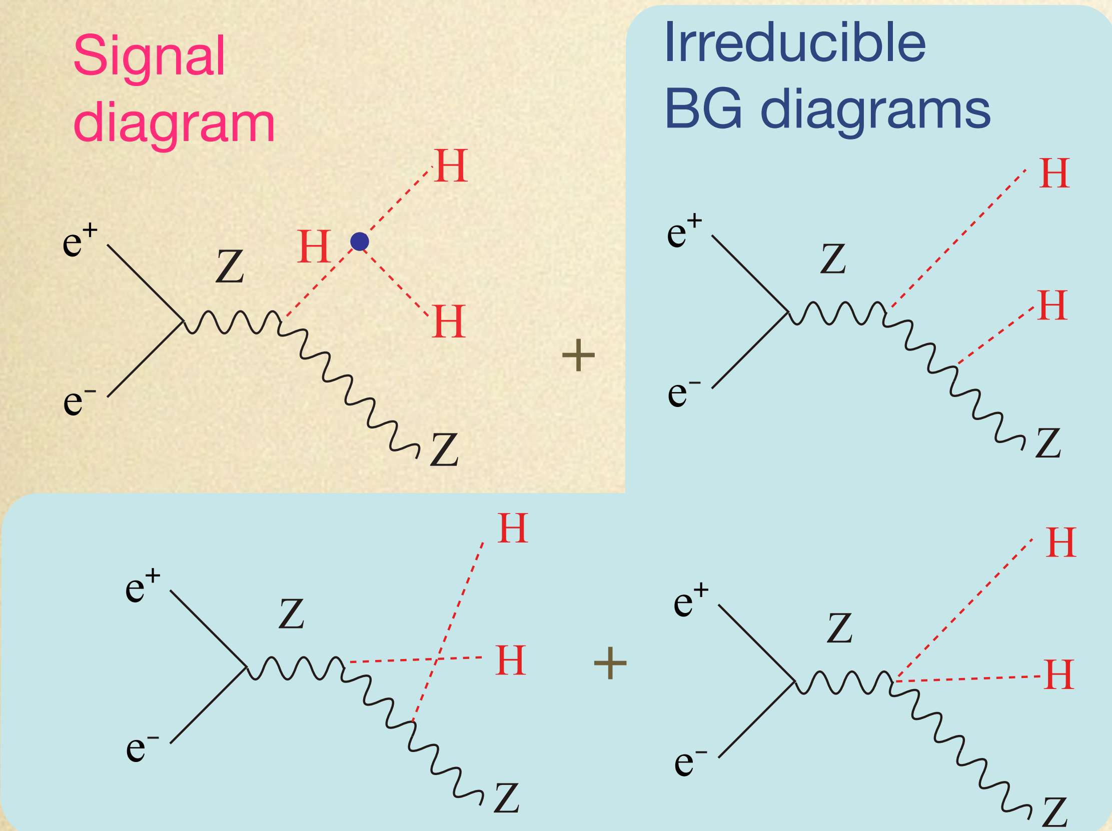


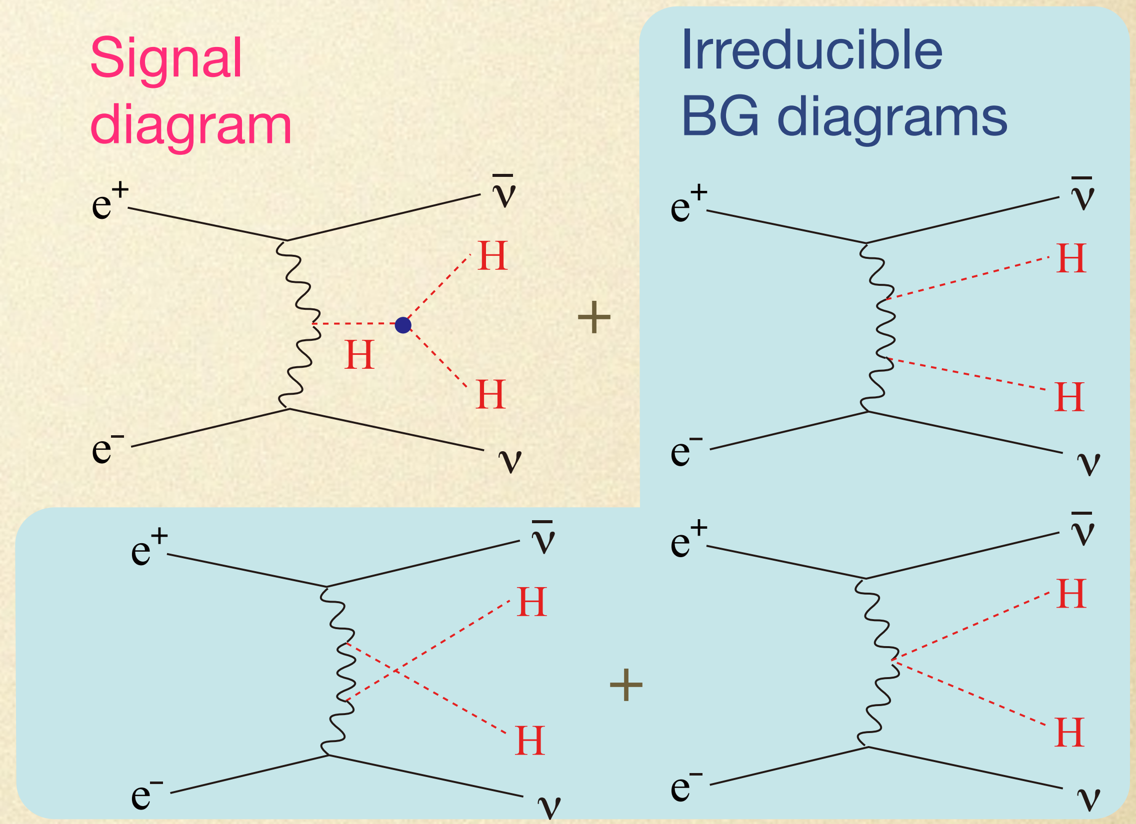


key issue: interference

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

~~$\frac{\Delta\lambda}{\lambda} = 0.5 \cdot \frac{\Delta\sigma}{\sigma}$~~





~~$\sigma_{ZHH} \sim 0.018$ fb~~

$\sigma_{ZHH} \sim 0.19$ fb

$$\frac{\Delta\lambda}{\lambda} = 1.7 \cdot \frac{\Delta\sigma}{\sigma}$$

@ 500 GeV

~~$\sigma_{\nu\nu HH} \sim 0.16$ fb~~

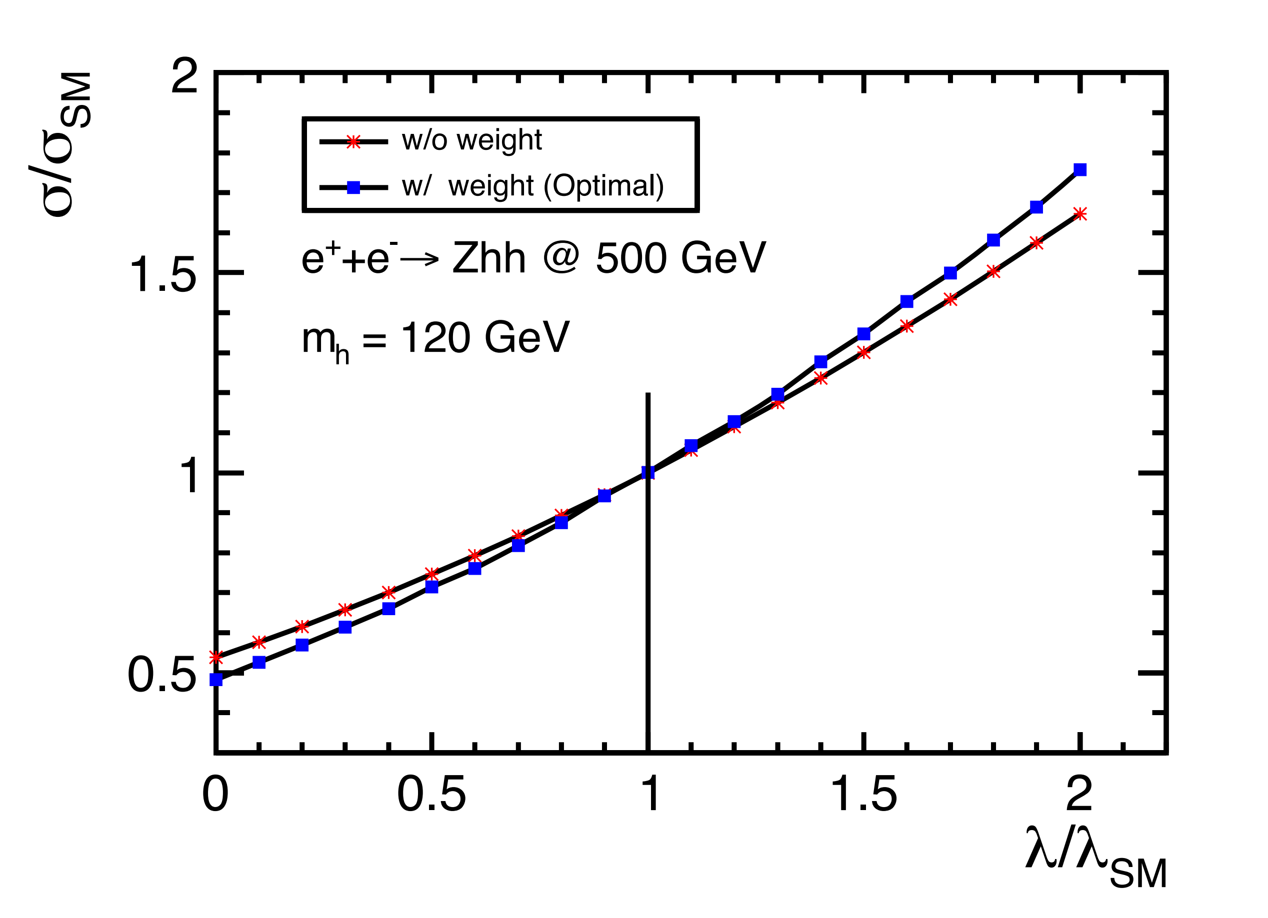
$\sigma_{\nu\nu HH} \sim 0.14$ fb

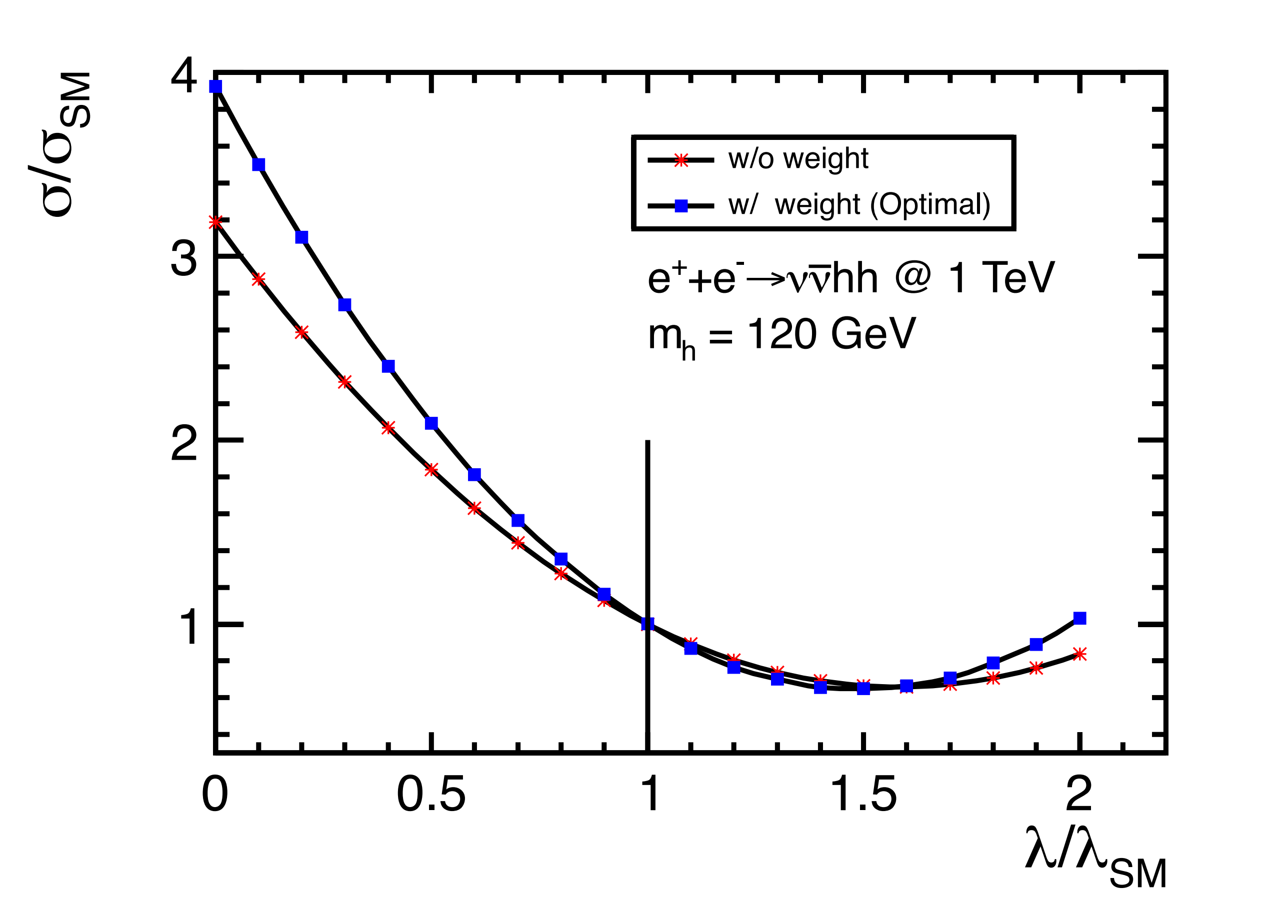
$$\frac{\Delta\lambda}{\lambda} = 0.8 \cdot \frac{\Delta\sigma}{\sigma}$$

@ 1 TeV

key issue: interference

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

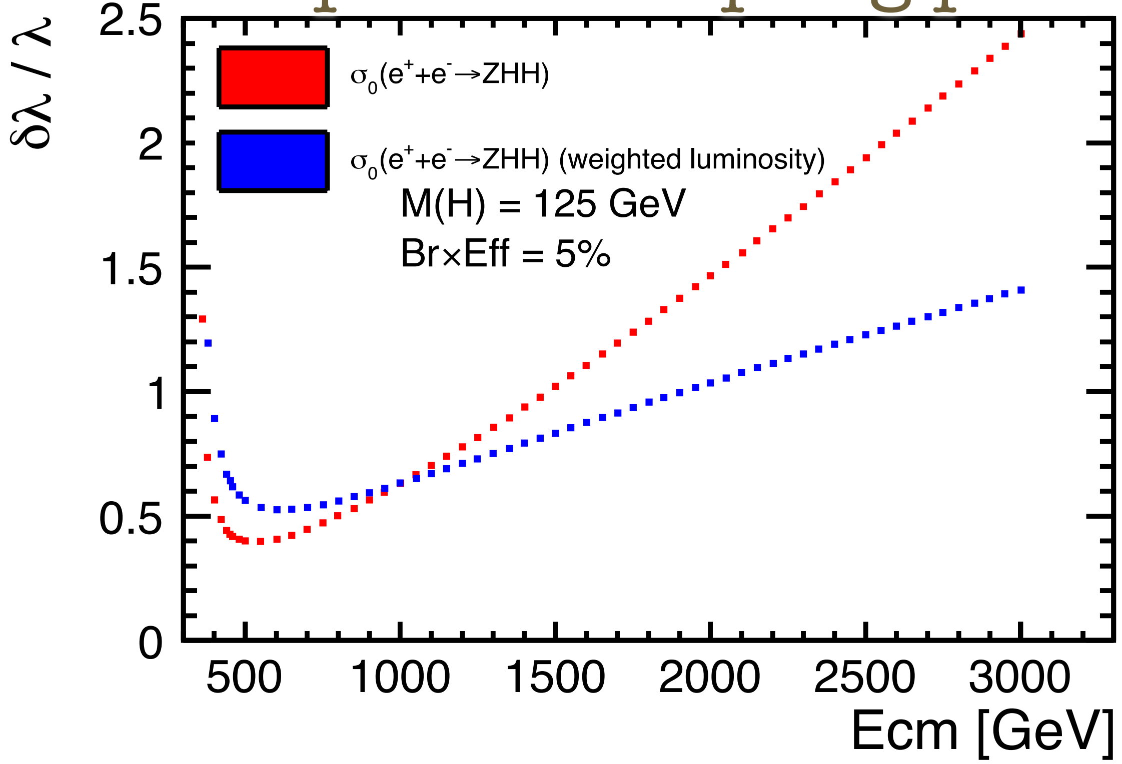


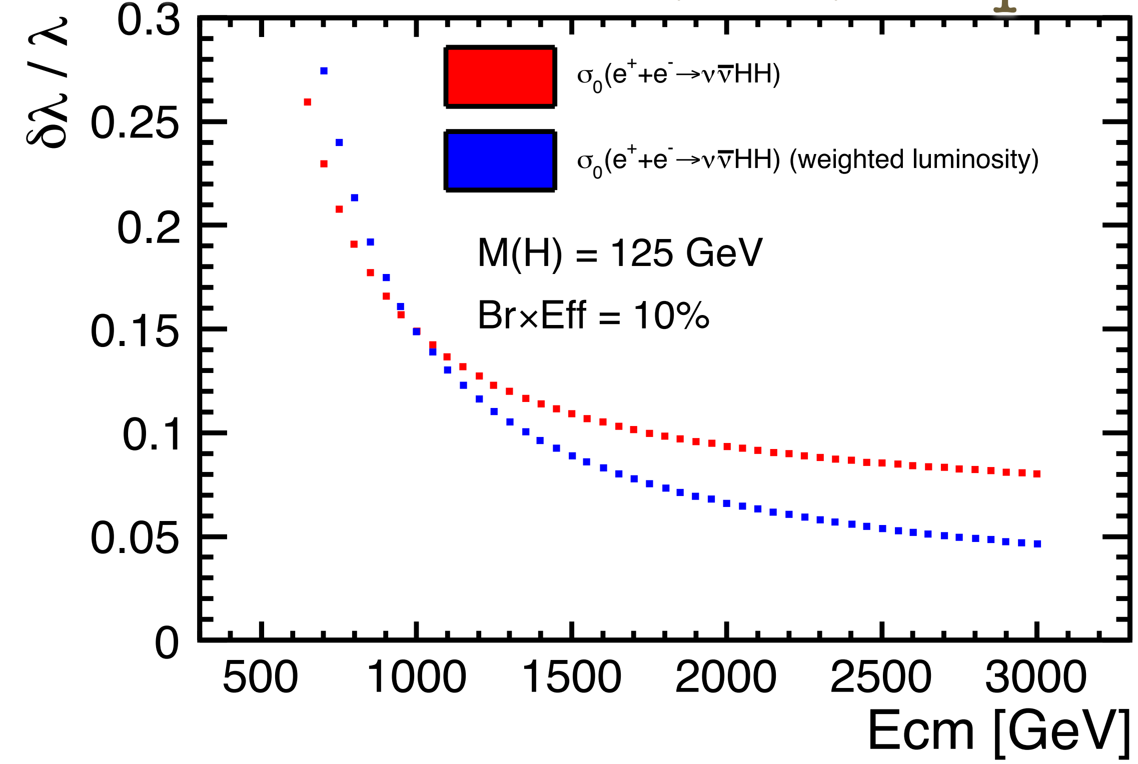


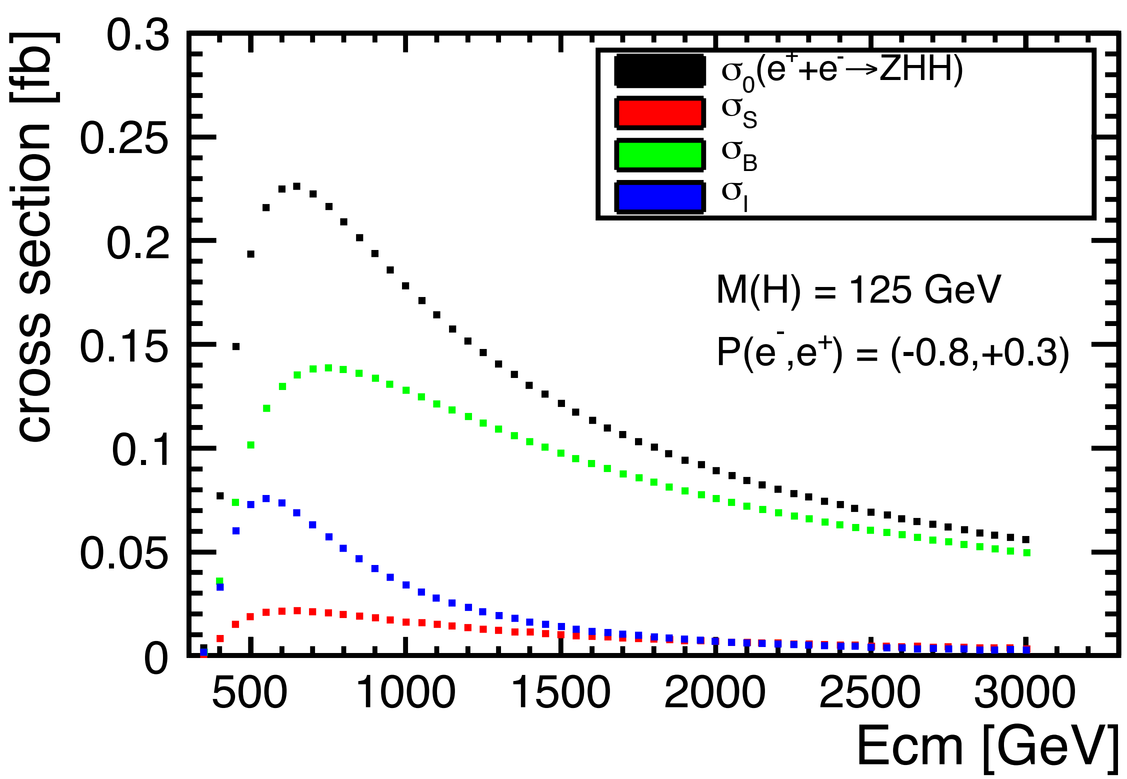
(with proper weighting sensitivity factor can be improved by ~10%)

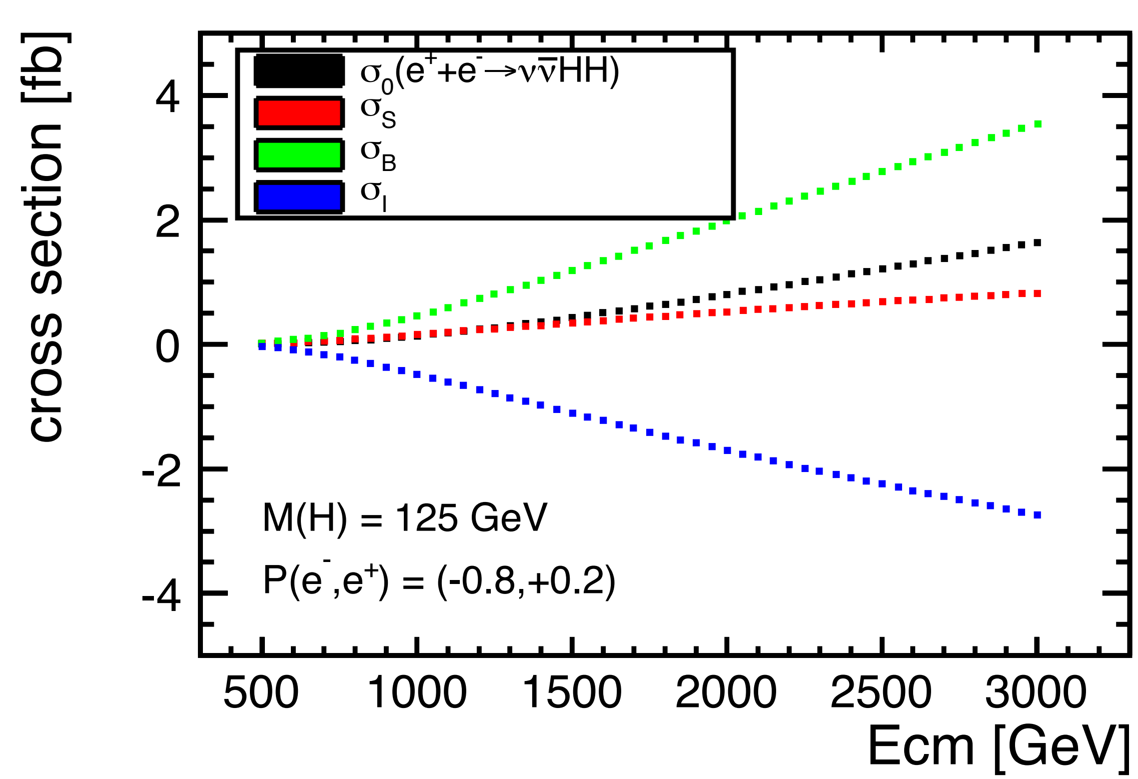
impact of centre-of-mass energies

expected coupling precision with more realistic setup



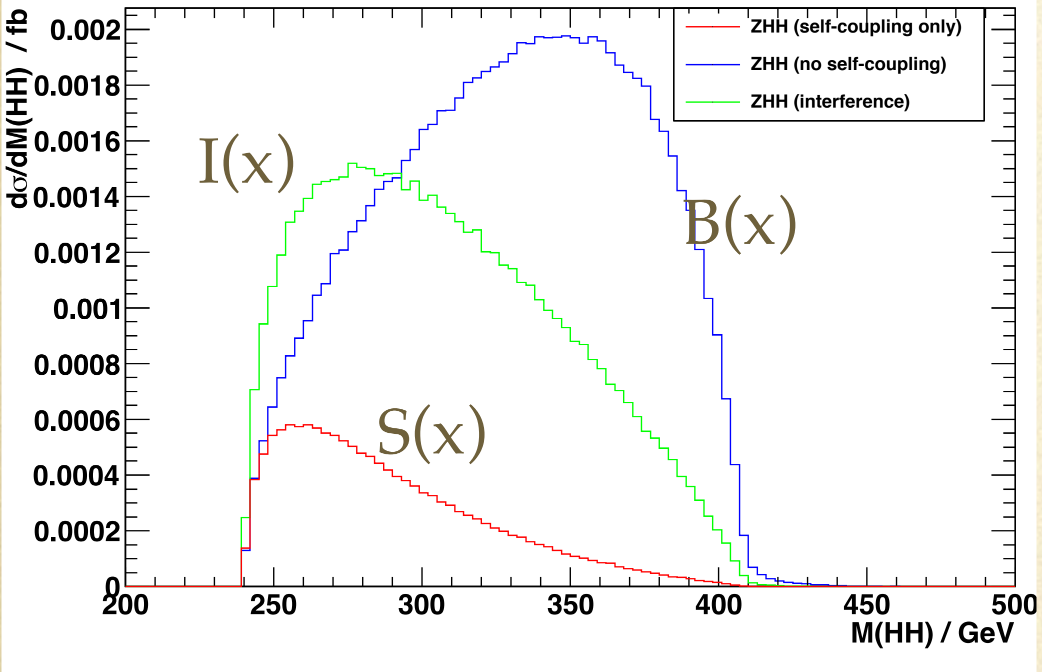






new weighting method to enhance the coupling sensitivity

differential cross-section



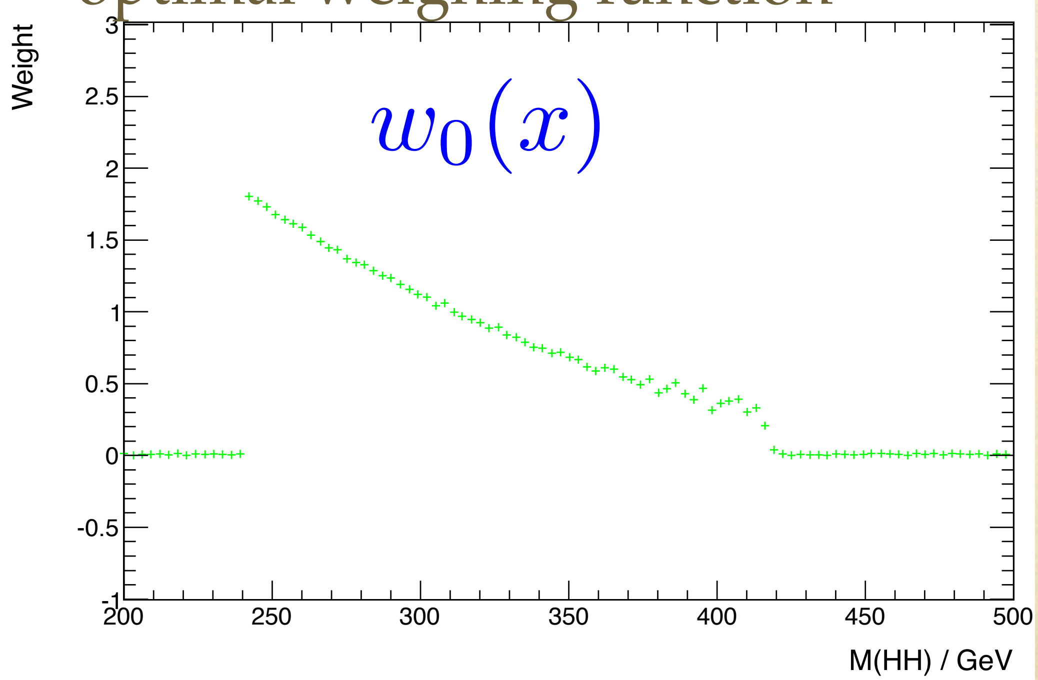
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

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):

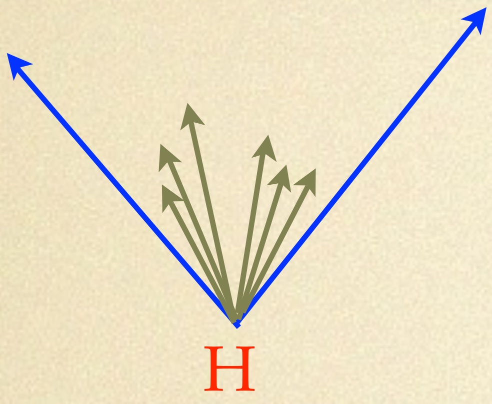
$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

general solution:

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

c: arbitrary normalization factor

decay plane



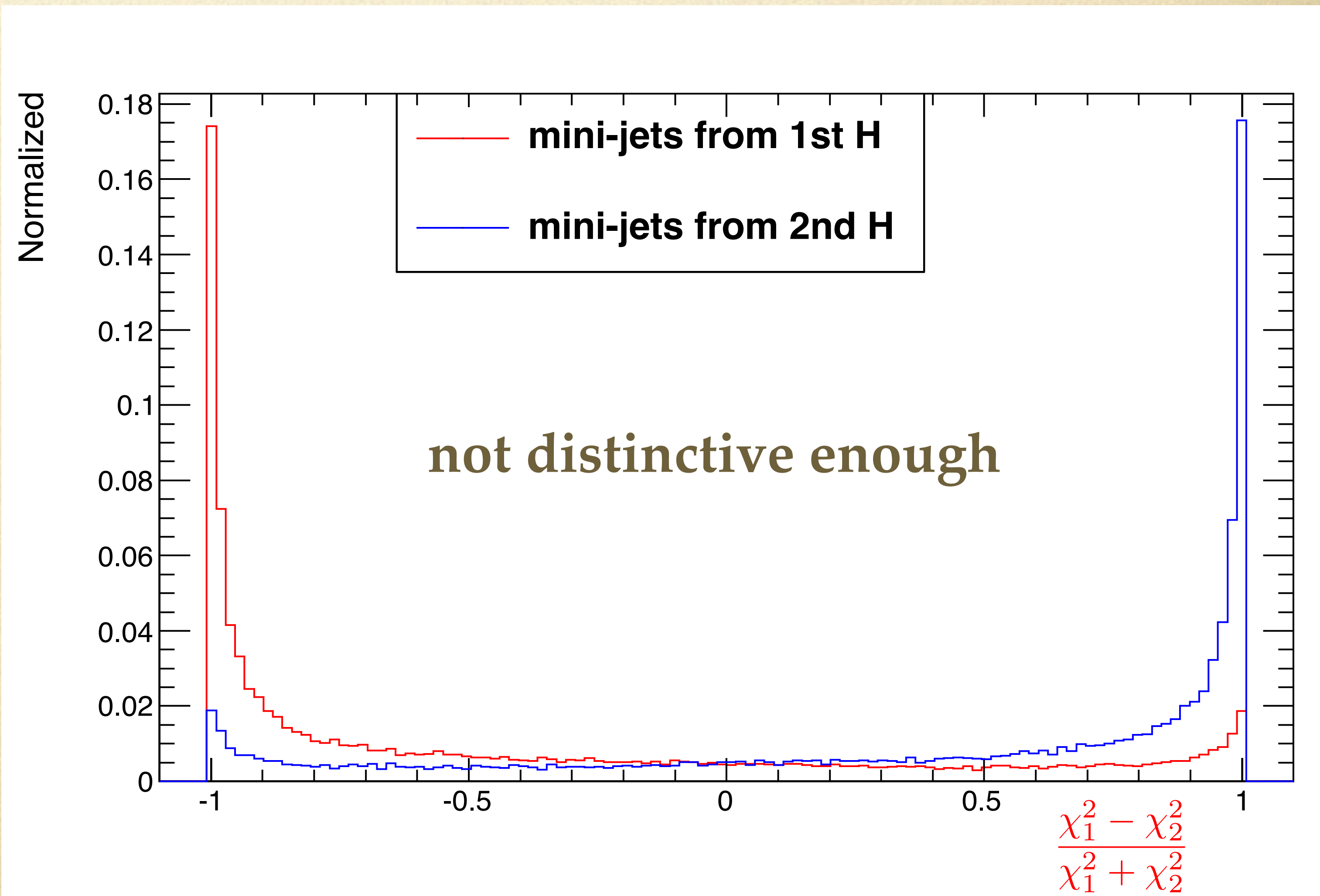
particles from one same color singlet should be around the decay plane

$$\chi^2 = P_t^2$$

transverse momentum relative to the decay plane

vvHH ---> vvbbbb

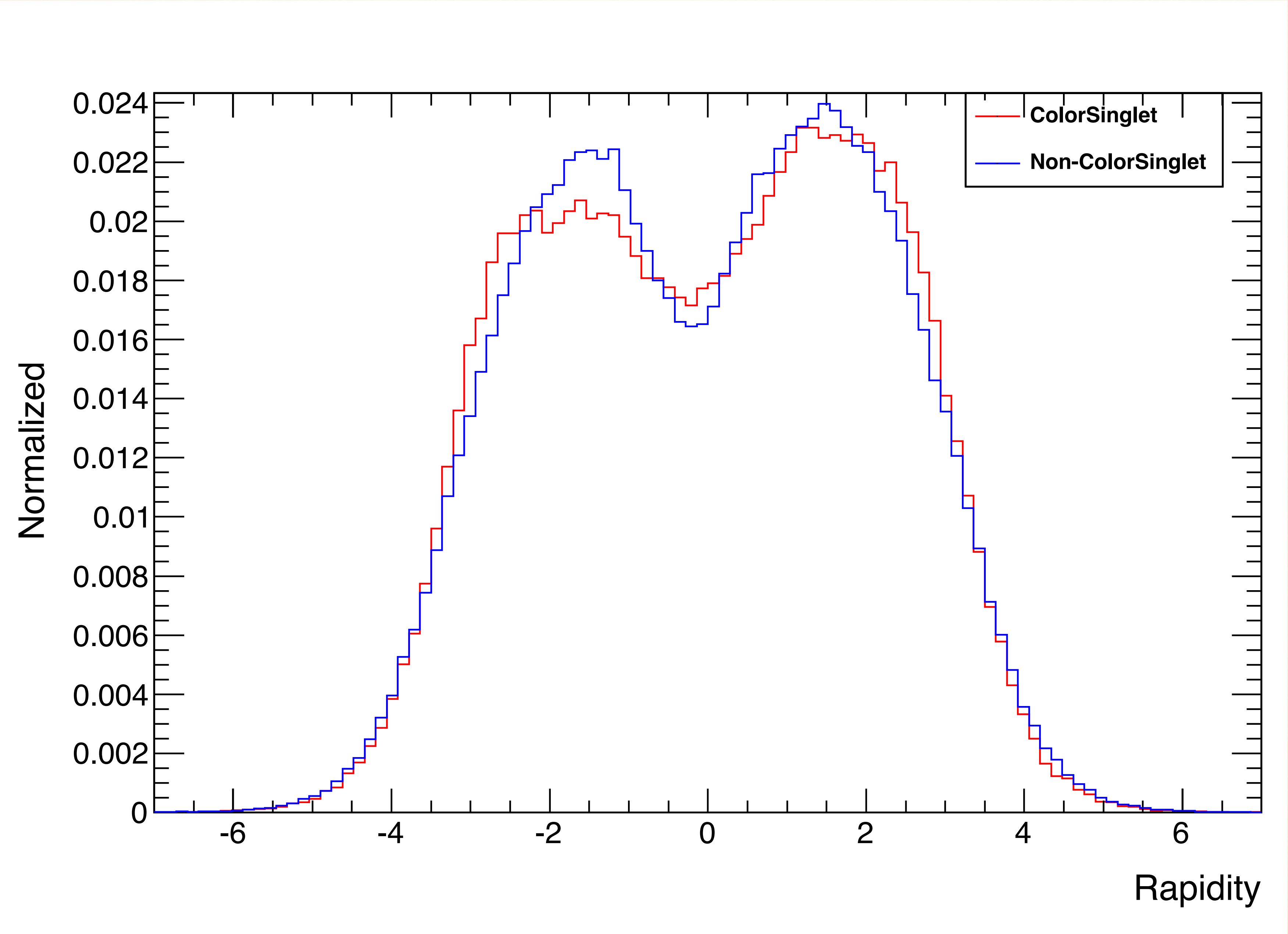
- using the realistic Duhram algorithm for the mini-jet clustering, stop when there are 20 mini-jets left.
- calculate the chi2 for each mini-jet, there are two decay planes, we get two chi2 for each mini-jet. (currently the two decay planes are decided by cheating)



not distinctive enough

rapidity gap? (reconstructed)

decay frame (one of the b momentum as z-axis)



- perfect jet-clustering for vvHH events
- rapidity of every particle in the jet pair

Summary

$$J_\beta^{(n)}(P_\alpha) \equiv E_\alpha^n \left[(1-\beta) + \beta v_\alpha^2\right] .$$

- J_β **increases** when clustering:
  - E_α increases due to energy conservation;
  - Jet virtuality P_α^2 doesn't increase that much.
- Not only **pair-wise**, but also can be defined **globally**.
- **Cone** implemented implicitly:

$$J_\beta^{(n)}(P_\alpha + p_j) = (E_\alpha + E_j)^n \left[\bar{\beta} + \beta \frac{|\mathbf{P}_\alpha|^2 + 2|\mathbf{P}_\alpha||\mathbf{p}_j|\cos\boldsymbol{\theta} + |\mathbf{p}_j|^2}{(E_\alpha + E_j)^2}\right]$$

- **Kinematic Properties**:
  - Cone shouldn't shrink;
  - Larger cone for smaller z;
  - Cone is bounded from above.
- **Parameter space**: $\mathbf{1 \leq n \leq 2}$, $\boldsymbol{\beta > 4/n(5-n)}$.
- Lorentz invariance.

Link to Parton Shower

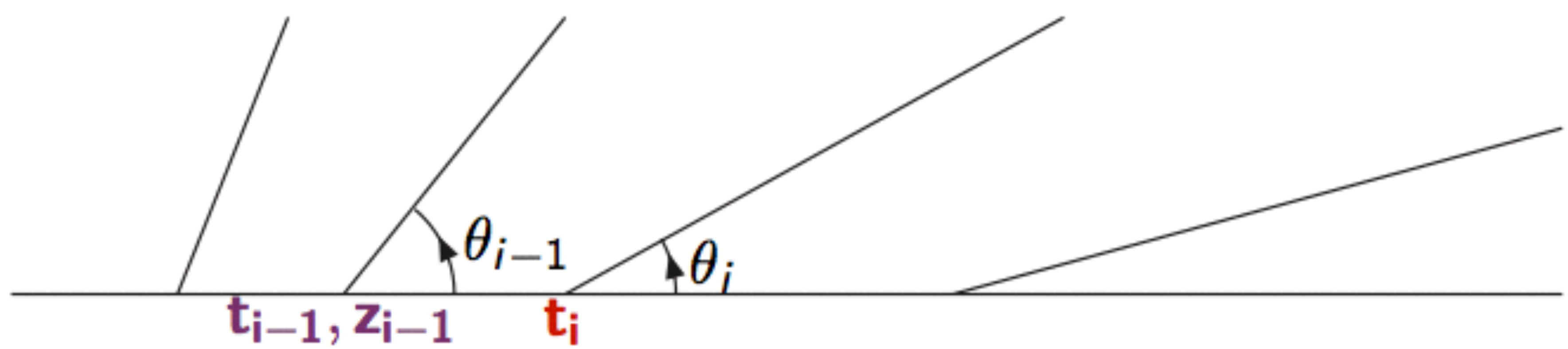
- Tends to emit one **soft parton**,

$$z \to 0\,.$$

- Soft parton takes **less fraction of energy @ higher scale**.

$$\frac{1}{2} - \sqrt{\frac{1}{4} - \frac{\Lambda}{\sqrt{t}}} < z < \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\Lambda}{\sqrt{t}}}\,.$$

- **Angular ordering**



$$\theta_i \approx \frac{t_i}{2\alpha_i^2} = \frac{t_i}{2z_i^2\alpha_{i-1}^2}, \quad \theta_i < \theta_{i-1} \quad \Rightarrow \quad t_i < (1 - z_{i-1})^2 t_{i-1}\,.$$