Study of HγZ coupling using $e^+e^- \to \gamma H$ at the ILC

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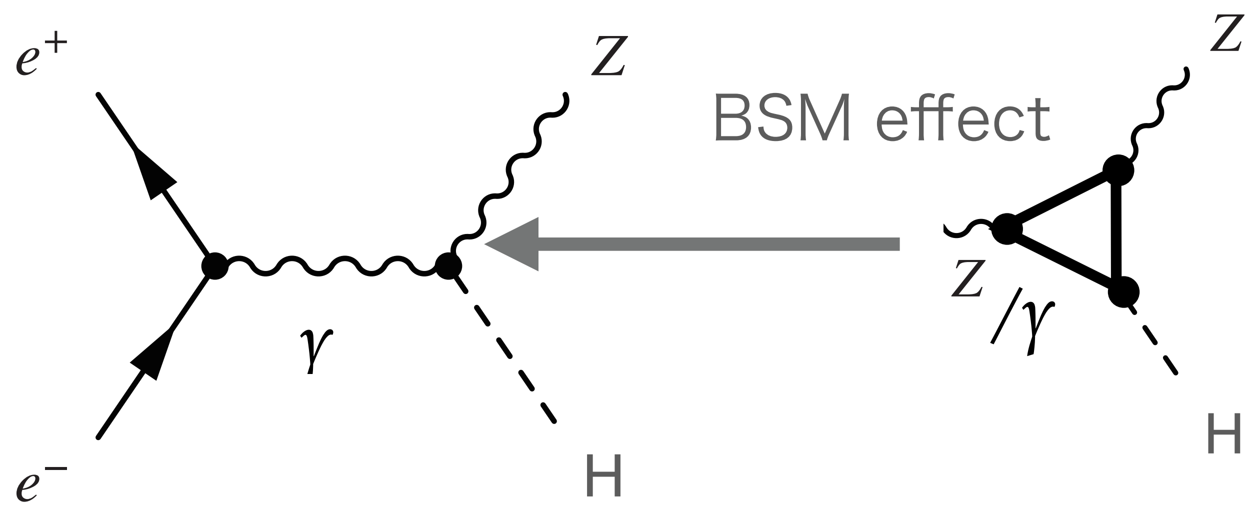
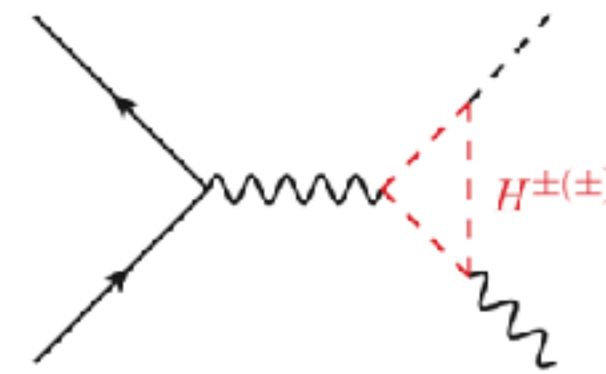
1.Motivation

To find new physics via Hγγ and HγZ couplings

Higgs to γZ coupling in the Standard Model (SM) is a loop induced coupling.
→We expect BSM amplitude can be larger than SM amplitude.



e.g. : Inert Triplet Model



Mawatari, et al, arXiv:1808.10268

This process can be also useful to constrain the dimension 6 EFT operators which can introduce effective anomalous hγZ and hγγ couplings.

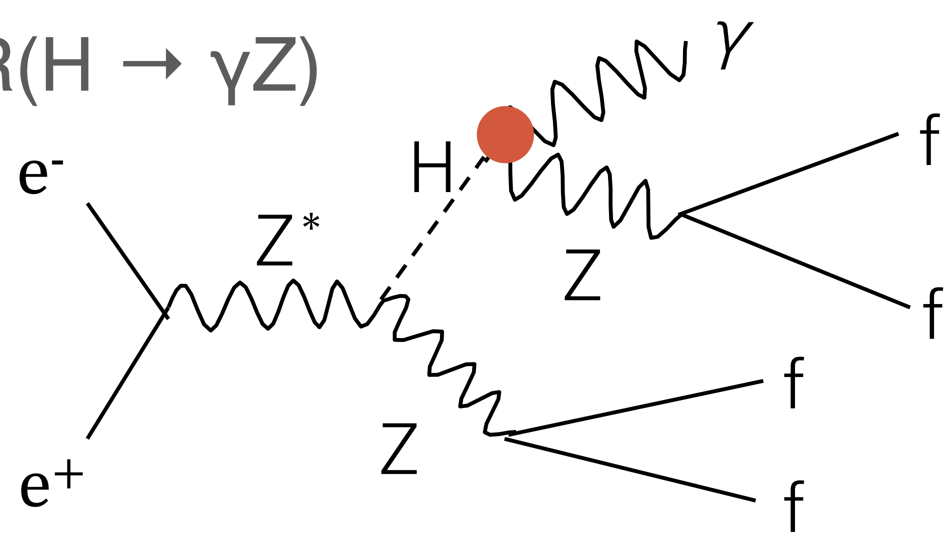
Q. H. Cao, et al, arXiv:1505.00654 [hep-ph]

Any deviation of the coupling constants from SM signals new physics.

2. Two ways to measure HγZ coupling

Higgs decay

BR(H → γZ)

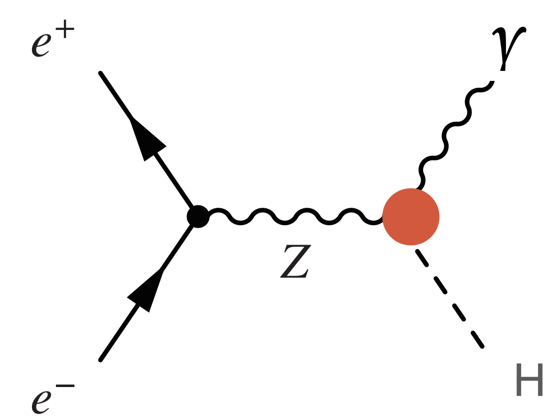


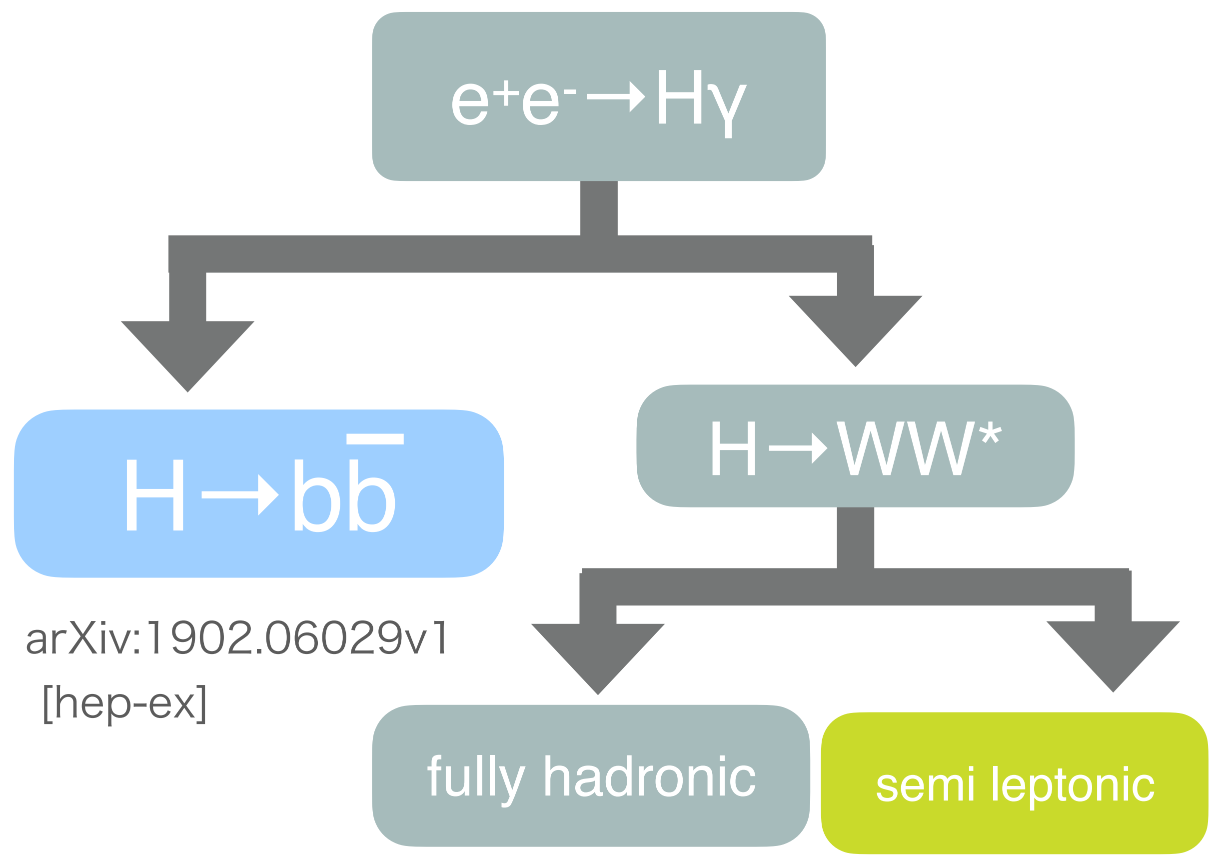
final state	BR
mmqqγ	4.7%
eeqqγ	4.7%
nnqqγ	28.0%
qqqqγ	48.9%
others	13.7%

by Kazuki Fujii at LCWS2018

Higgs production

σ (e+e- → Hγ)





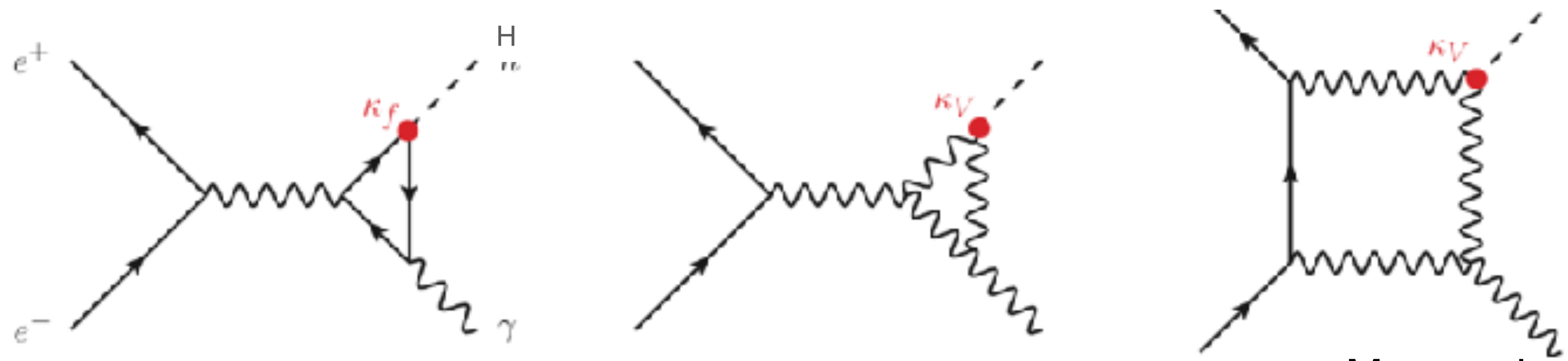
arXiv:1902.06029v1 [hep-ex]

arXiv:2002.07164 [hep-ex]

3. Theoretical framework for our analysis

SM one-loop predictions

The main Feynman diagrams



Mawatari, et al, arXiv:1808.10268

SM cross sections by one loop calculation:

e^- e^+

σ_{SM}=0.35 fb for (-100%,+100%)

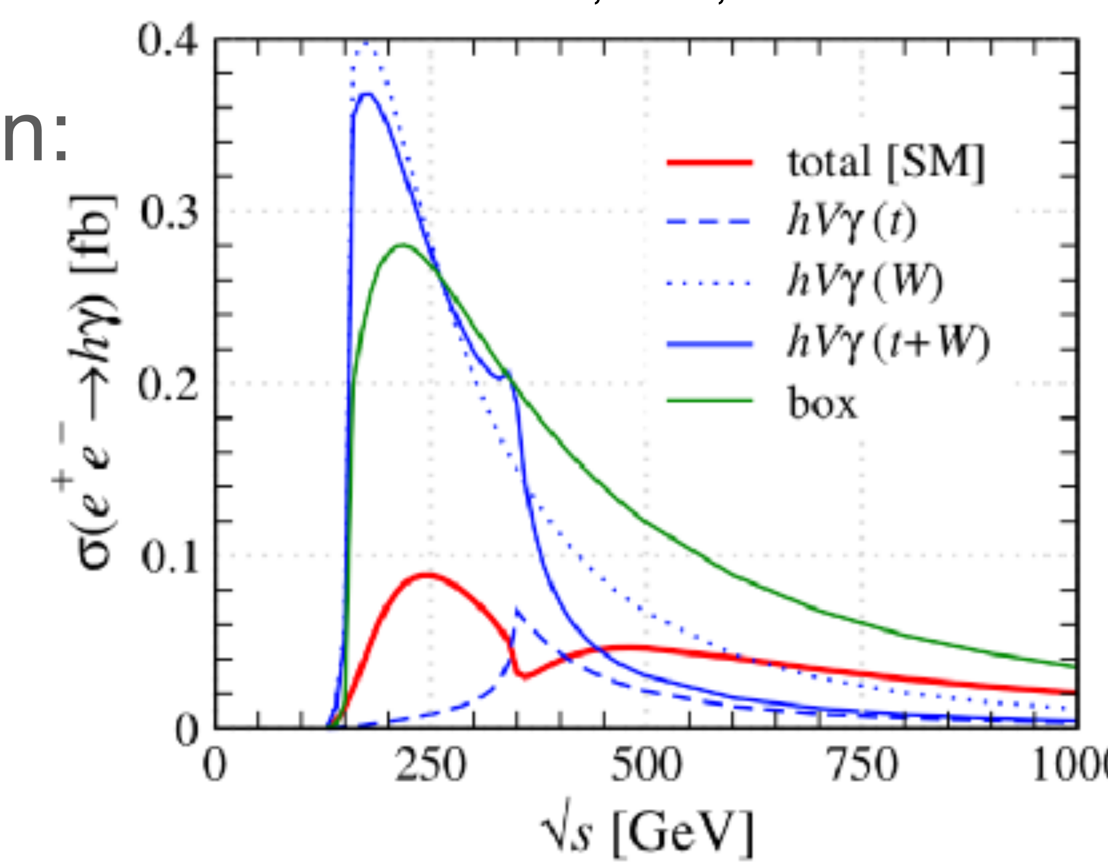
σ_{SM}=0.016 fb for (+100%,-100%)

σ_{SM}=**0.20 fb** for (-80%,+30%)

$\sqrt{s}$ = 250 GeV

Small !

This analysis is very challenging.



※For unpolarized beam

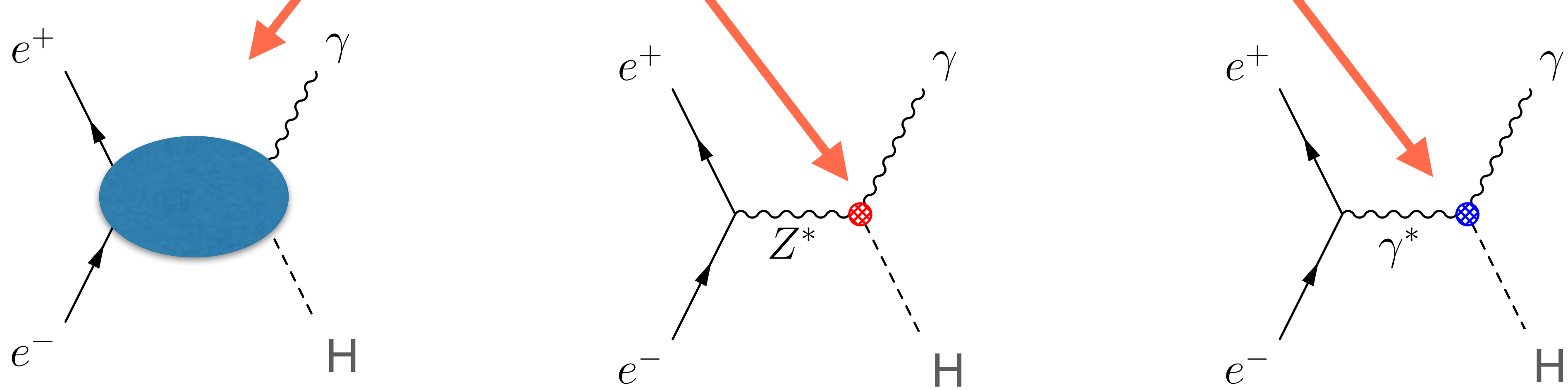
Destructive interference

3. Theoretical framework for our analysis

The effective field theory (EFT) Lagrangian to include new physics contributions to the $e^+e^- \to H\gamma$ cross section model-independently

effective hγZ coupling effective h$\gamma\gamma$ coupling

$$L_{\gamma H} = L_{\rm SM} + \frac{\zeta_{AZ}}{v} A_{\mu\nu} Z^{\mu\nu} H + \frac{\zeta_A}{2v} A_{\mu\nu} A^{\mu\nu} H$$



Phys.Rev. D94 (2016) 095015

$A_{\mu\nu}$, $Z_{\mu\nu}$: field strength tensors v: vacuum expectation value

Since ζ_A is already constrained by measurement of $H \to \gamma\gamma$ branching ratio at LHC, we can extract ζ_{AZ} parameter by just measuring cross section for a single beam polarization.

4. Simulation framework

Event generation

- $\sqrt{s}$=250 GeV
  Integrated Luminosity: 2000 fb^{-1}
  (900 fb^{-1} each for Left / Right handed pol.)
- background : 2f,4f (DBD sample)
- ISR and Beamstrahlung effects are included

Detector simulation

- ILD full simulation (Mokka)
- Geant4 based, realistic detailed detector model

Event reconstruction

- Full reconstruction chain from detector signals to 4-vectors
  (iLCSoft v01-16-02/ MarlinReco, PandoraPFA, LCFI+, Isolated photon finder, jet clustering)

Event selection

- $E_\gamma > 50$ GeV

4. Simulation framework - New Generator

Old

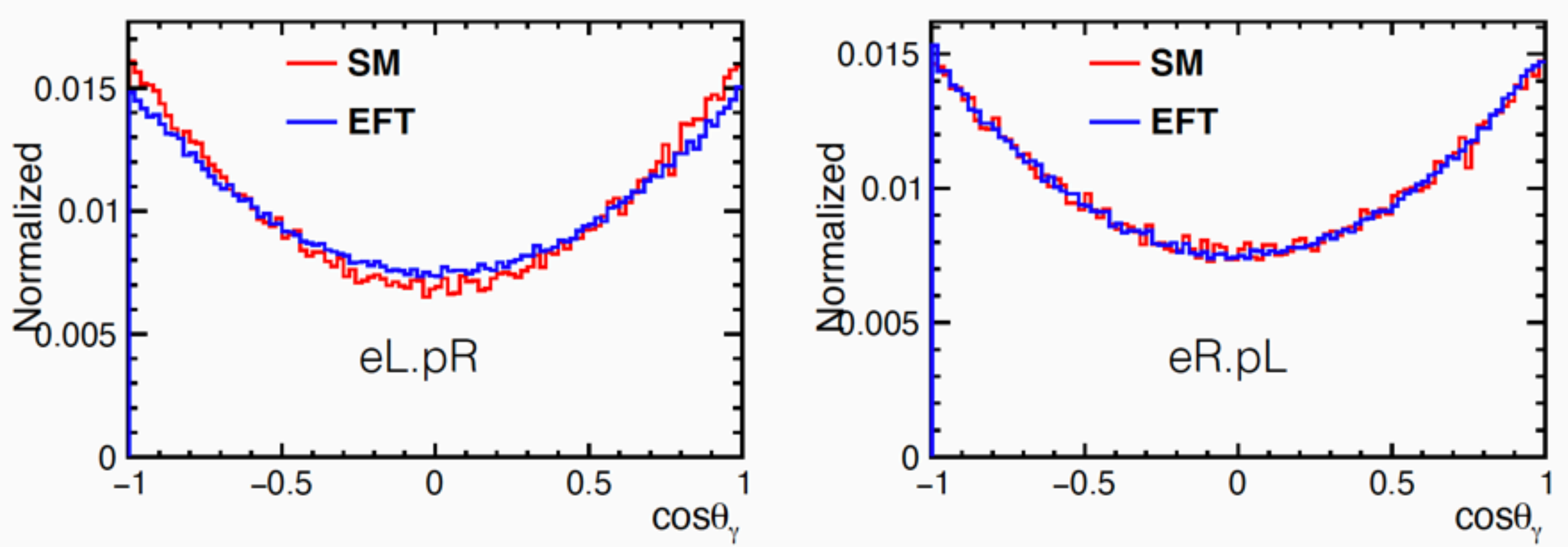
Implemented with EFT coefficients matched to SM h→γγ / γZ loop calculations

(without SM loop)

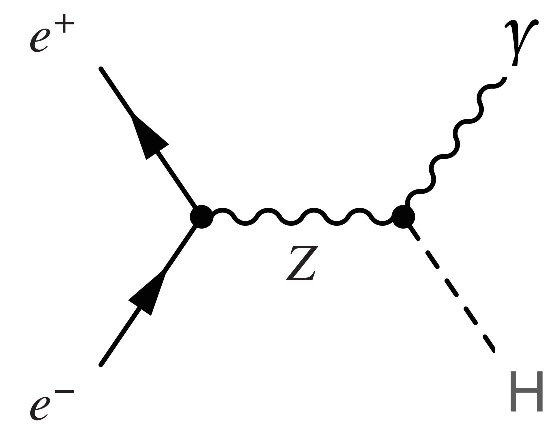
New

Implemented with full SM 1-loop calculations

angular distribution:



5. Analysis - Signal & Backgrounds



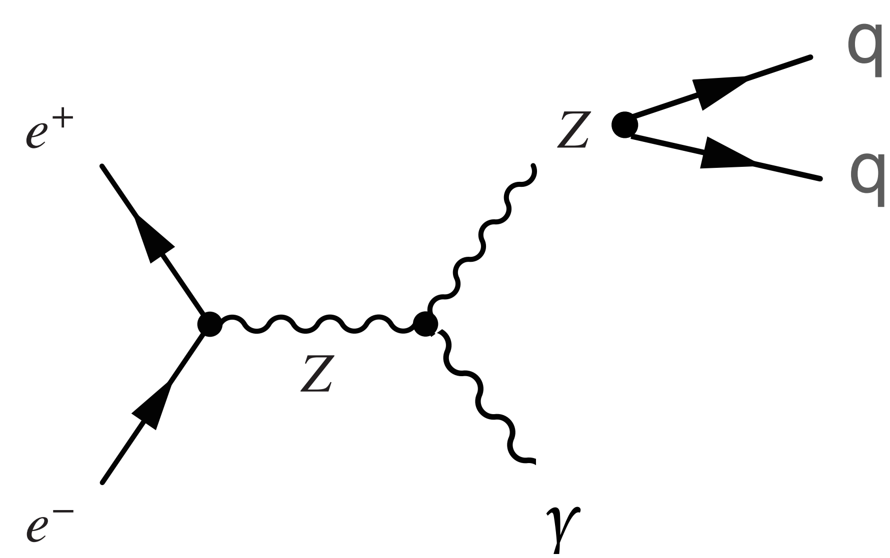
Signal: $e^+e^- \to \gamma H \to \gamma(b\bar{b})$

Signal signatures

1. Isolated monochromatic photon with energy 93 GeV
2. 2 b jets
3. m(bb) （invariant mass） = Higgs mass

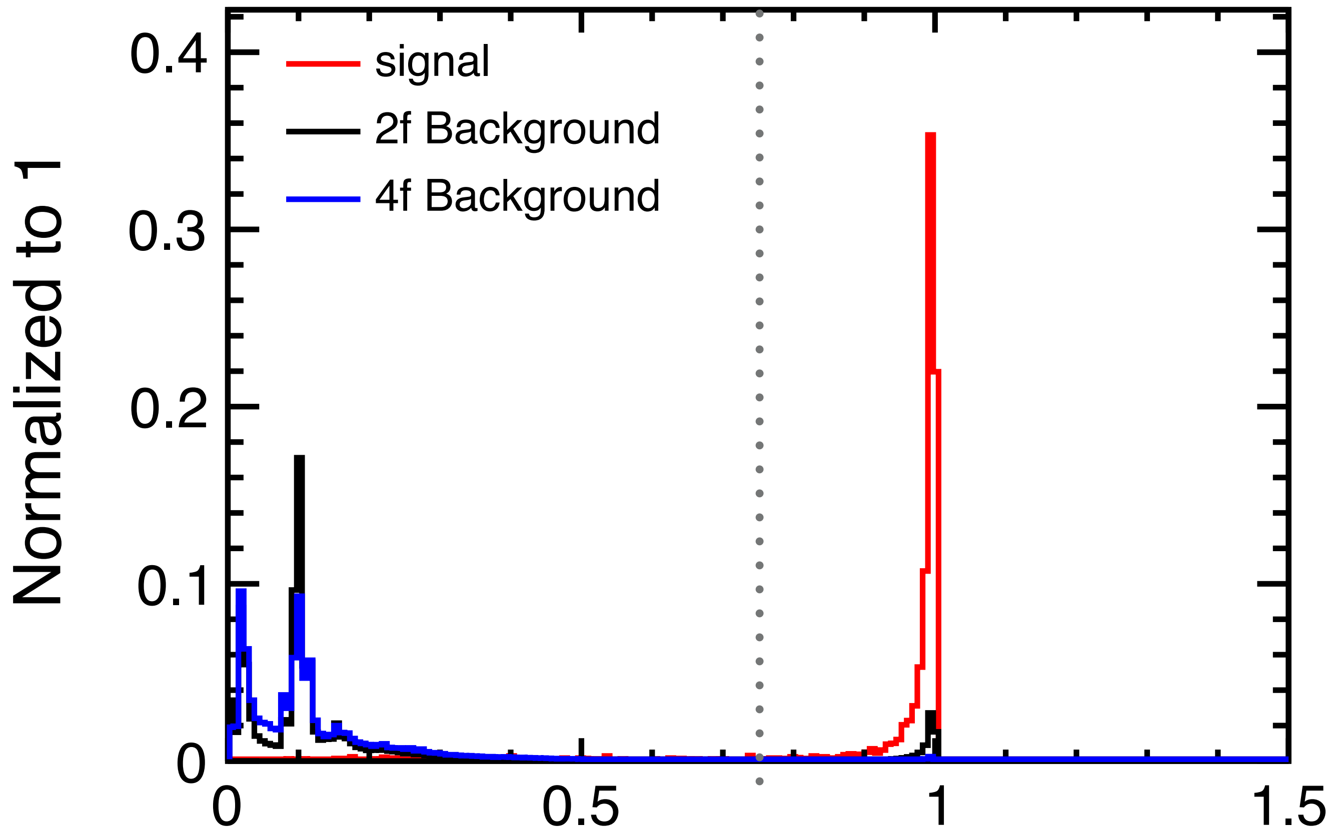
Main backgrounds

$e^+e^- \to \gamma Z \to \gamma qq$

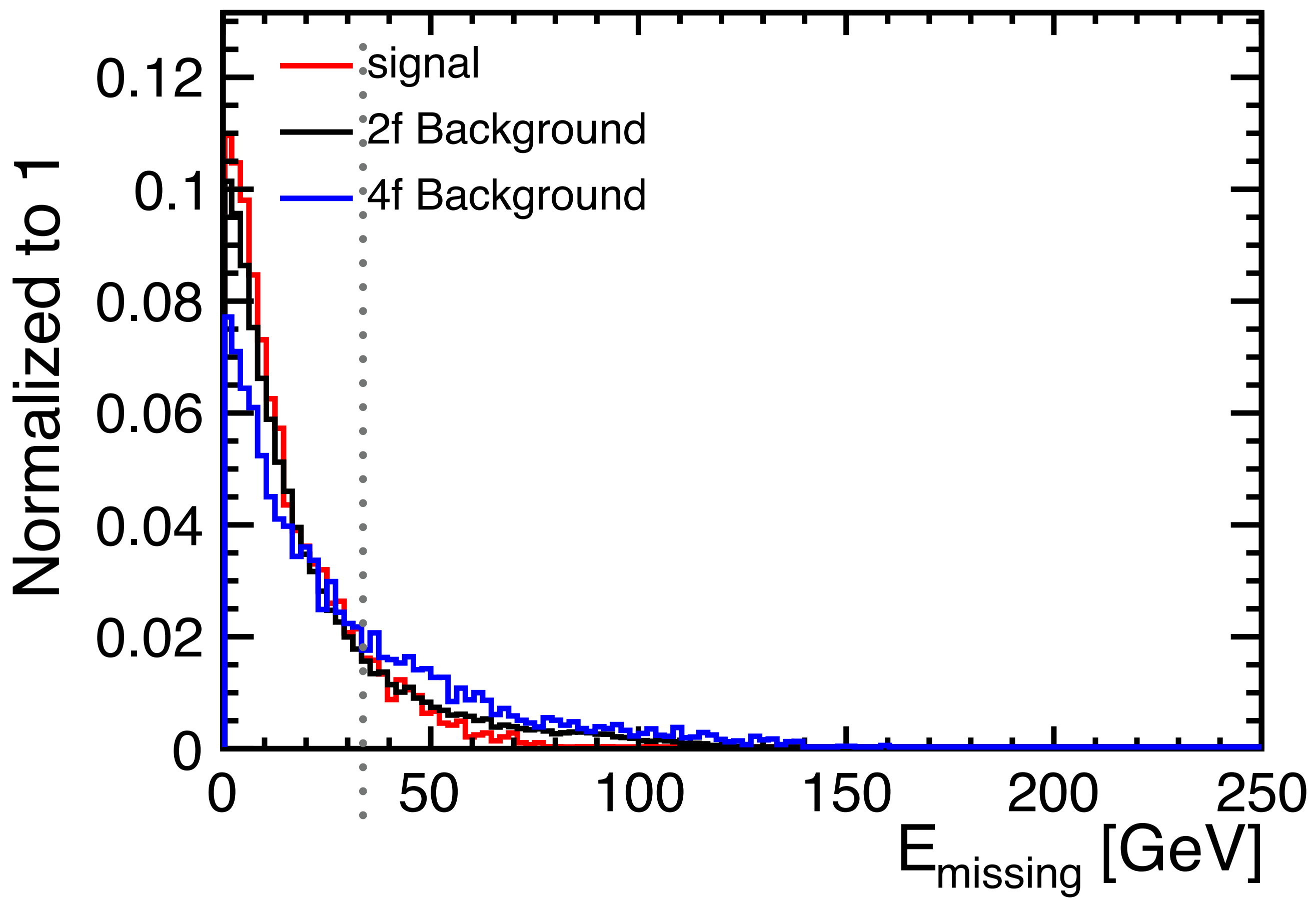


5. Analysis - Event selection

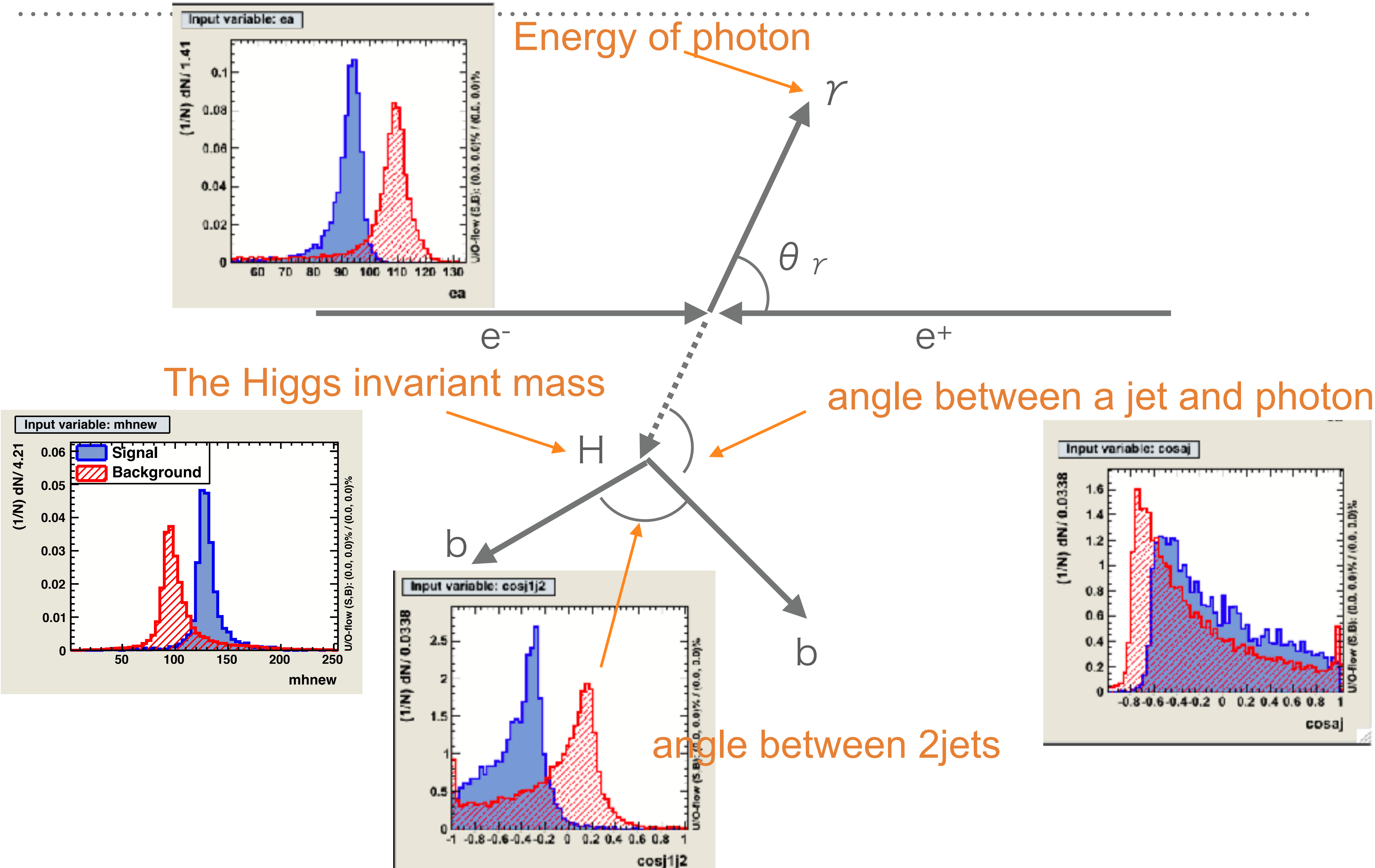
Cut 1: b likeliness1>0.77



Cut 2: missing energy<35 GeV

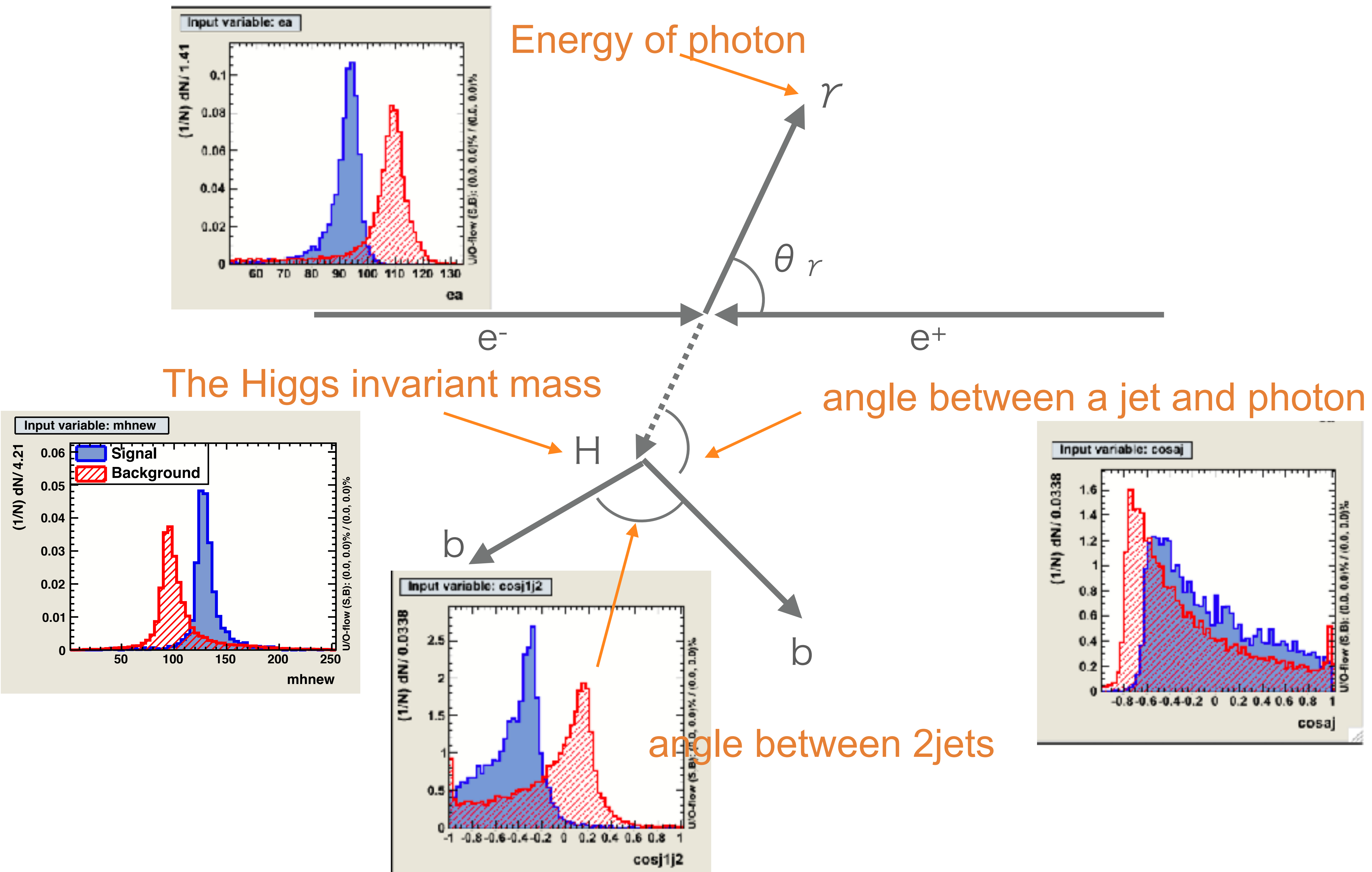


5. Analysis - Input variables for MVA



h→bb

h→WW* semi leptonic



5. Analysis - Signal & Backgrounds

Signal: $e^+e^- \to \gamma h \to \gamma(WW^*)$

one W decays hadronically (W_1), and another decays leptonically(W_2)

Signal signatures

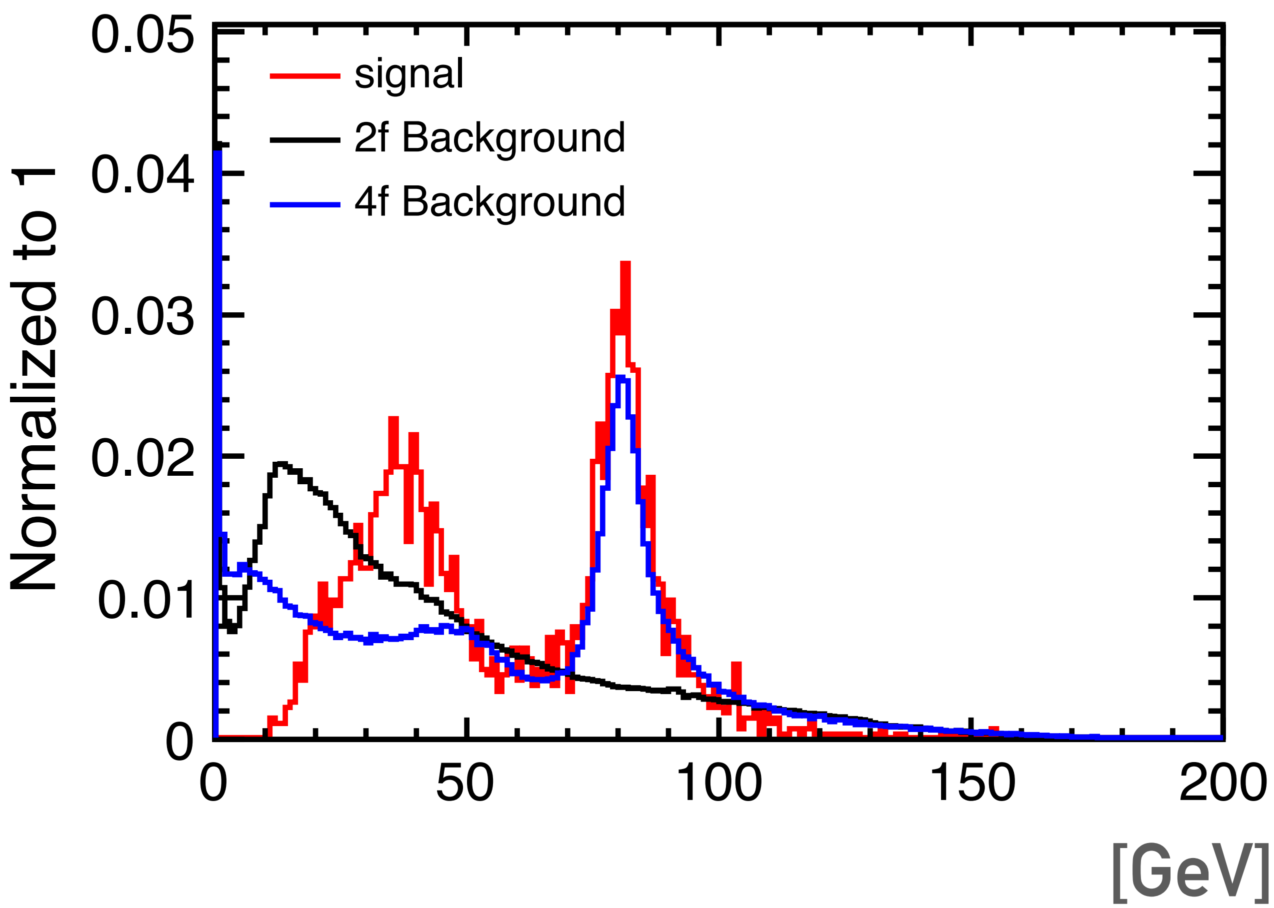
1. there is one isolated monochromatic photon with energy 93 GeV
2. there are 2 jets that originated from the hadronically decayed W
3. the sum of four momenta of the 2 jets, the lepton and leptin neutrino is consistent with Higgs hypothesis,
4. either one of the 2 jets or the lepton-neutrino systems has an invariant mass consistent with the on-sell W hypothesis
5. there are no b-quark jets

Main backgrounds $e^+e^- \to W^+W^-(\gamma)$

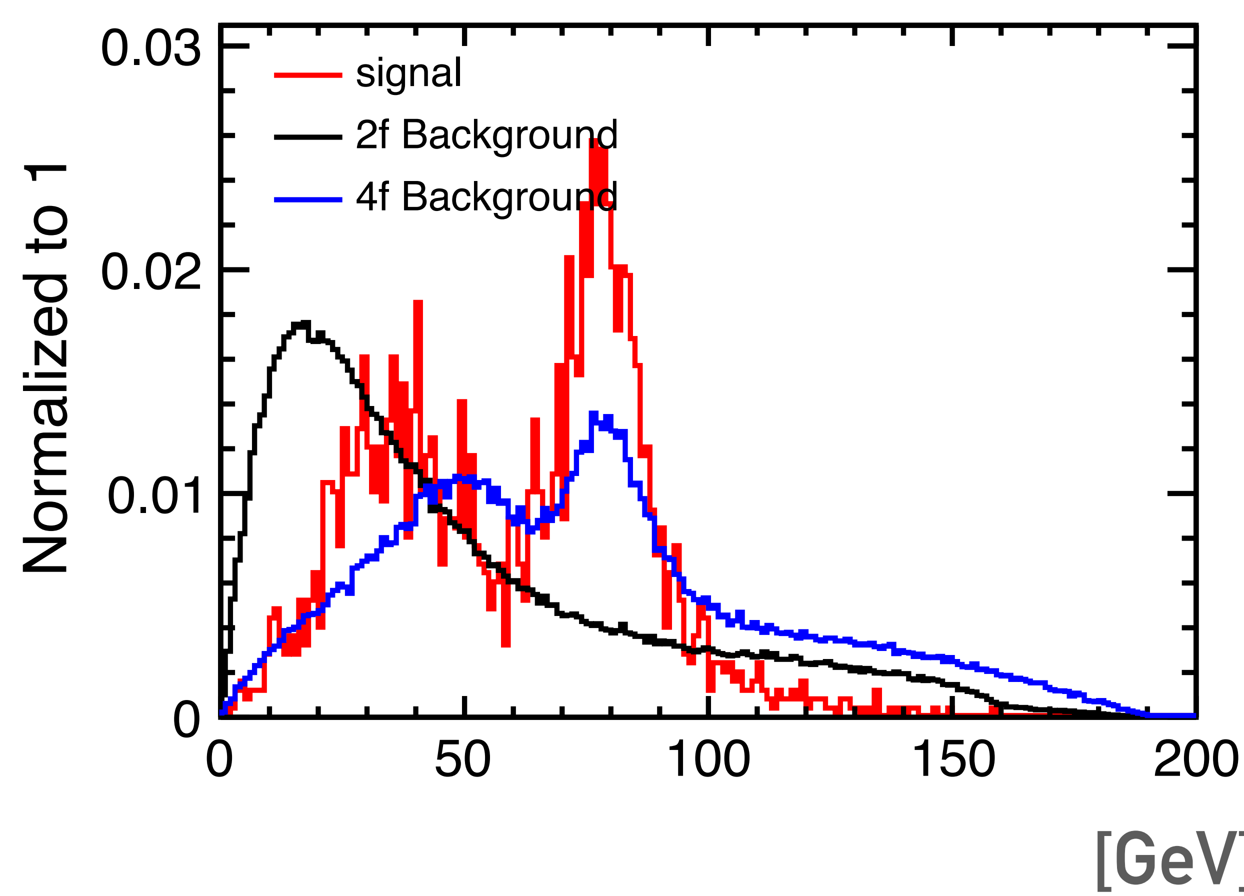
5. Analysis - Event selection

|mw1-80.4|<10 GeV or |mw2-80.4|<9.4 GeV

mw1

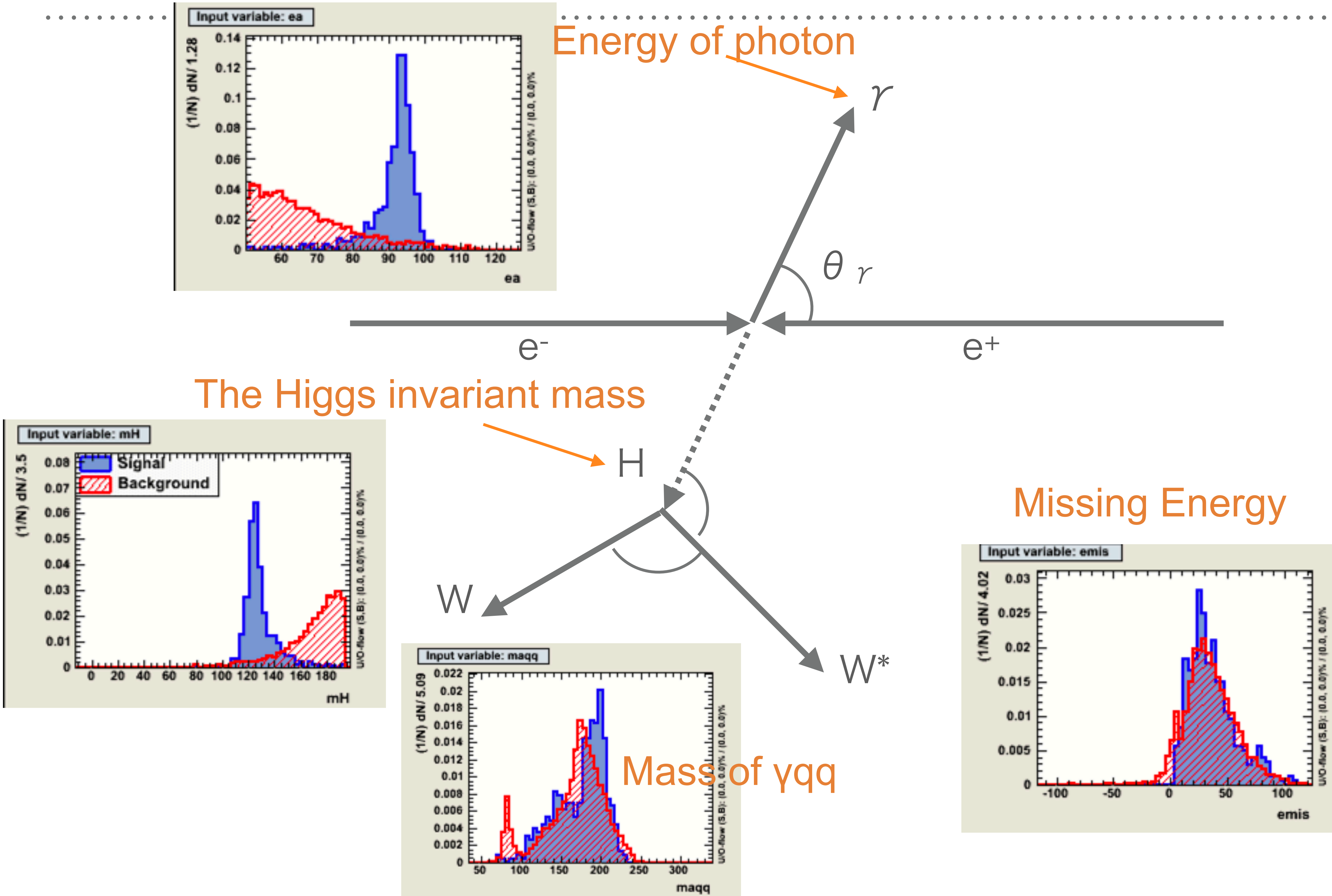


mw2



b likeliness<0.77 : to except overlap with bb

5. Analysis - Input variables for MVA



5. Analysis - Reduction table and upper limit(Left handed)

Reduction table

$$significance = \frac{N_s}{\sqrt{N_s + N_B}}$$

N_s:Number of signal N_B:Number of background

	total bg	Signal	Significance
Expected	1.4×10^8	107	0.01
Pre selection	2.9×10^7	100	0.02
b likeliness>0.77	2.2×10^6	90	0.06
E_{mis}<35	1.9×10^6	82	0.06
mvabdt > 0.025	19583	34	0.24
-0.92<$\cos\theta_\gamma$<0.92	12422	29	0.26

Preliminary

Dominant background : $e^+e^- \rightarrow \gamma Z \rightarrow \gamma qq$

→95% C.L upper limit $$\sigma_{\gamma H} = \sigma_{SM} + \frac{1.64}{\text{significance}}\sigma_{SM}$$

=2.6 [fb] (Left handed beam polarization case)

5. Analysis - Reduction table and upper limit(Right handed)

Reduction table

$$significance = \frac{N_s}{\sqrt{N_s + N_B}}$$

N_S:Number of signal N_B:Number of background

	total bg	Signal	Significance
Expected	7.8×10^7	11.2	0.001
Pre selection	2.3×10^7	10.3	0.002
b likeliness>0.77	1.5×10^6	9.4	0.008
$E_{mis}<35$	1.3×10^6	8.4	0.007
mvabdt > 0.025	1.0×10^4	3.4	0.034
$-0.92<\cos\theta_\gamma<0.92$	5.9×10^3	3.0	0.039

Preliminary

→95% C.L upper limit $$\sigma_{\gamma H} = \sigma_{SM} + \frac{1.64}{\text{significance}} \sigma_{SM}$$

= 0.7 [fb]   (Right handed beam polarization case)

5. Analysis - Reduction table and upper limit(Left handed)

	total bg	Signal	Significance
Expected	1.4×10^8	18.0	0.003
Pre selection	1.3×10^7	10.5	0.004
# of charged particle >3	3.1×10^5	5.4	0.010
|mw1-80.4|<10 GeV or |mw2-80.4|<9.4 GeV	1.9×10^5	3.7	0.009
b likeliness<0.77	1.8×10^5	3.7	0.009
mvabdt>0.1	41	1.0	0.16
$-0.93<\cos\theta_\gamma<0.93$	8	0.9	0.31

Preliminary

Dominant background : $e^+e^- \to W^+W^-$

→95% C.L upper limit (e-,e+=-100,+100)

$$\sigma_{\gamma H} = \sigma_{SM} + \frac{1.64}{\text{significance}}\sigma_{SM}$$

=2.2 [fb] (Left handed)

5. Analysis - Reduction table and upper limit(Right handed)

	total bg	Signal	Significance
Expected	7.8×10^{7}	1.9	0.000
Pre selection	1.2×10^{7}	2.0	0.000
# of charged particle >3	8.6×10^{4}	1.5	0.002
|mw1-80.4|<10 GeV or |mw2-80.4|<9.4 GeV	3.2×10^{4}	0.4	0.002
b likeliness<0.77	2.6×10^{5}	0.4	0.002
mvabdt>0.1	74	0.1	0.01
$-0.93<\cos\theta_\gamma<0.93$	5	0.1	0.04

Preliminary

→95% C.L upper limit $\sigma_{\gamma H} = \sigma_{SM} + \frac{1.64}{\text{significance}}\sigma_{SM}$

= 0.7 [fb] （Right handed）

5. Analysis - Uncertainty due to finite MC statistics (Left handed)

We conservatively re-estimated the numbers of remaining background events with high weights (= low statistics) and re-evaluated signal significance.

h→bb	total bg	Signal	Significance	95% C.L upper limit on σγH (fb)
Nominal	12422	29	0.29	2.6
Conservative	13488	29	0.25	2.7

Preliminary

h→WW	total bg	Signal	Significance	95% C.L upper limit on σγH (fb)
Nominal	8	0.9	0.31	2.2
Conservative	92	0.9	0.09	6.5

Preliminary

6. Combined result

Left handed

Preliminary

H→bb Significance = 0.26 for SM

H→WW (Semi-leptonic) Significance = 0.31 for SM

Combined Significance = 0.40 for SM

σγH < 1.8 fb (95% C.L upper limit)

Right handed

Preliminary

H→bb Significance = 0.039 for SM

H→WW (Semi-leptonic) Significance = 0.042 for SM

Combined Significance = 0.06 for SM

σγH < 0.5 fb (95% C.L upper limit)

7. Summary

We have performed a full simulation study of $e^+e^- \to H\gamma$ at 250 GeV ILC, using ILD detector and full 1-loop SM amplitudes.

- signal significance and upper limit of $\sigma_{\gamma H}$ for SM at $\sqrt{s}$=250 GeV, 900 fb^{-1}

(Left handed) Significance = 0.40 for SM

$\sigma_{\gamma H}$ < 1.8 fb (95% C.L upper limit)

(Right handed) Significance = 0.06 for SM

$\sigma_{\gamma H}$ < 0.5 fb (95% C.L upper limit)

- Estimated uncertainty due to finite MC statistics (Left handed)

Next step

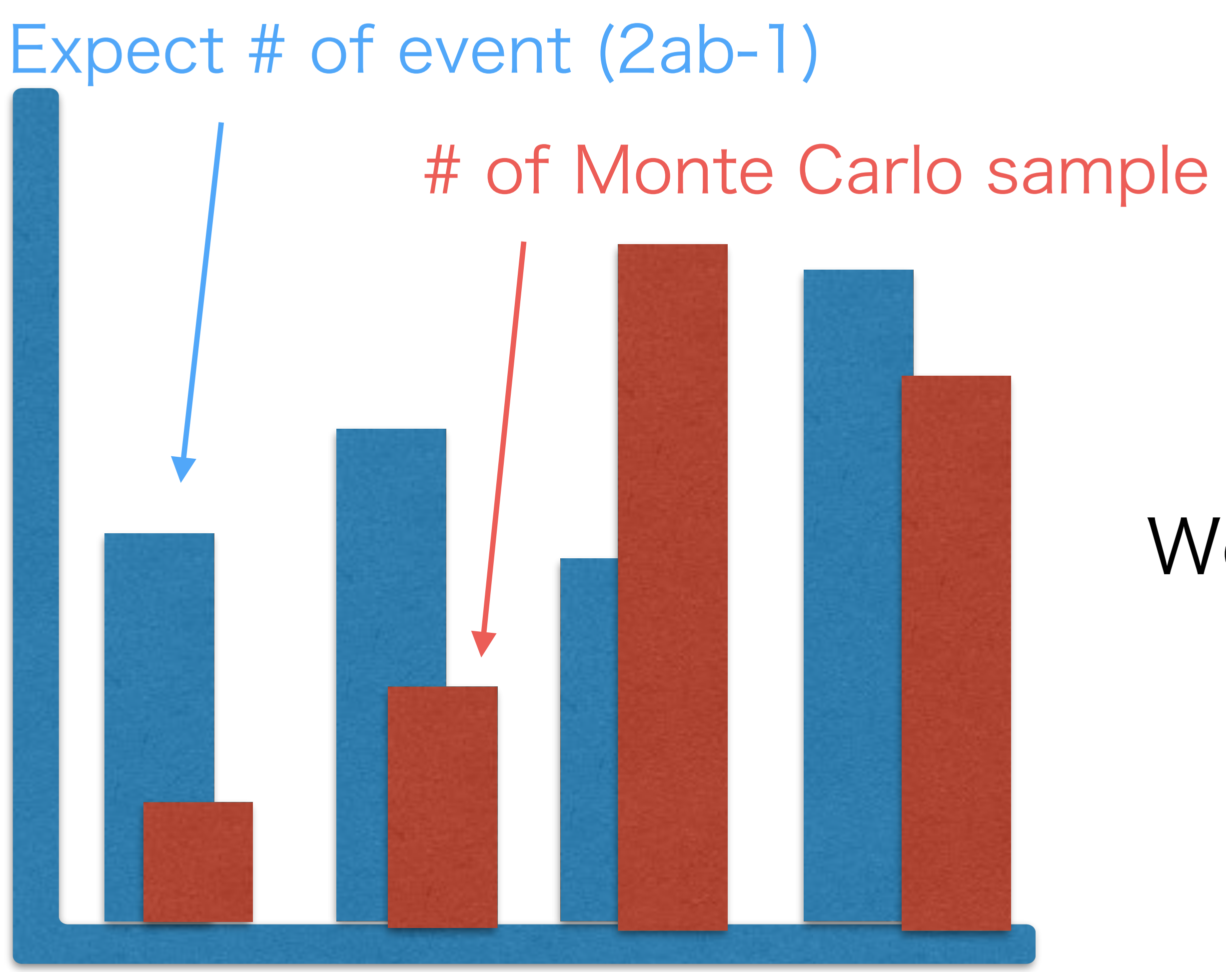
- Understand the role of this measurement in a global EFT analysis.

Back up

6. Background study

Propose : Estimate Monte Calro fluctuation

We can't make Monte Calro samples amount of 2ab-1 because some sample is huge. → Define "Weight"



$$\text{Weight} = \frac{\text{Expect \# of event (2ab-1)}}{\text{\# of Monte Carlo sample}}$$

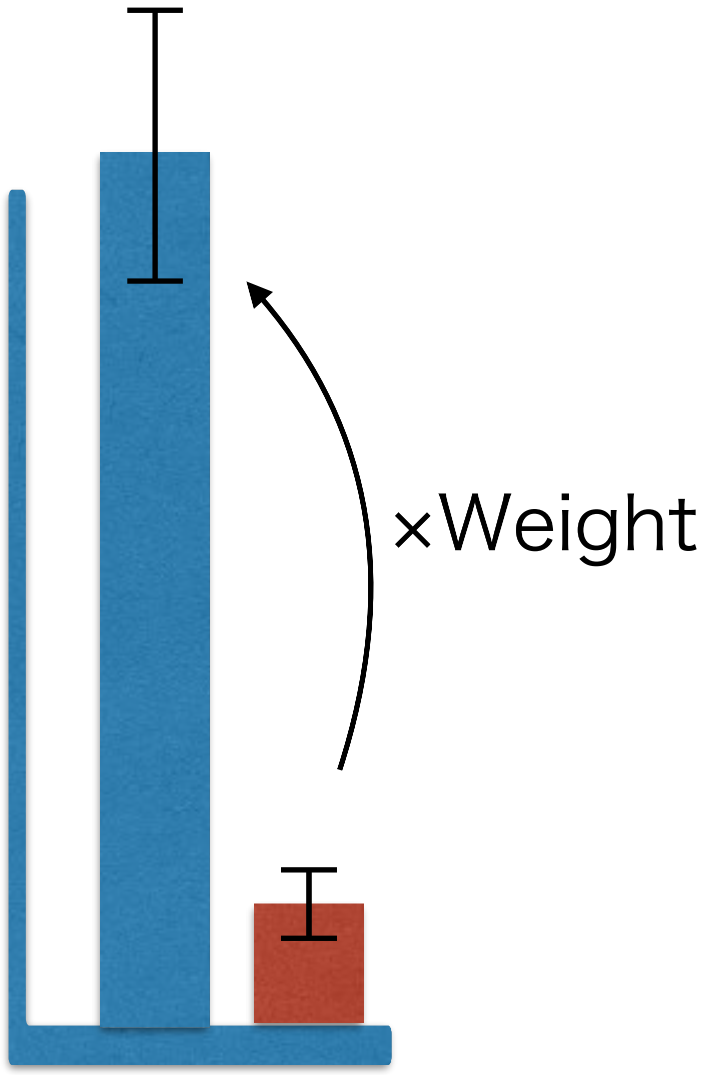
What is the problem?

Propose : Estimate Monte Calro fluctuation

$$\text{Weight} = \frac{\text{Expect \# of event (2ab-1)}}{\text{\# of Monte Carlo sample}}$$

If a sample has huge weight (few Monte Carlo samples), its error seems over estimated.

→ When we calculate the number of background at the worst case (upper limit), we should correct this effect.



For 0 or few background

Most background is suppressed by MVA and $\cos\theta_{\gamma}$,
so I estimate how MVA, $\cos\theta_{\gamma}$ suppress backgrounds

$$\text{MVA suppression ratio} = \frac{\text{\# of event when apply only MVA cut}}{\text{\# of event before cut}}$$

$$\text{MVA suppression ratio} = \frac{\text{\# of event when apply only } \cos\theta_{\gamma} \text{ cut}}{\text{\# of event before cut}}$$

conservative # of background = # of background just before MVA cut
×MVA suppression ratio
×$\cos\theta_{\gamma}$ suppression ratio

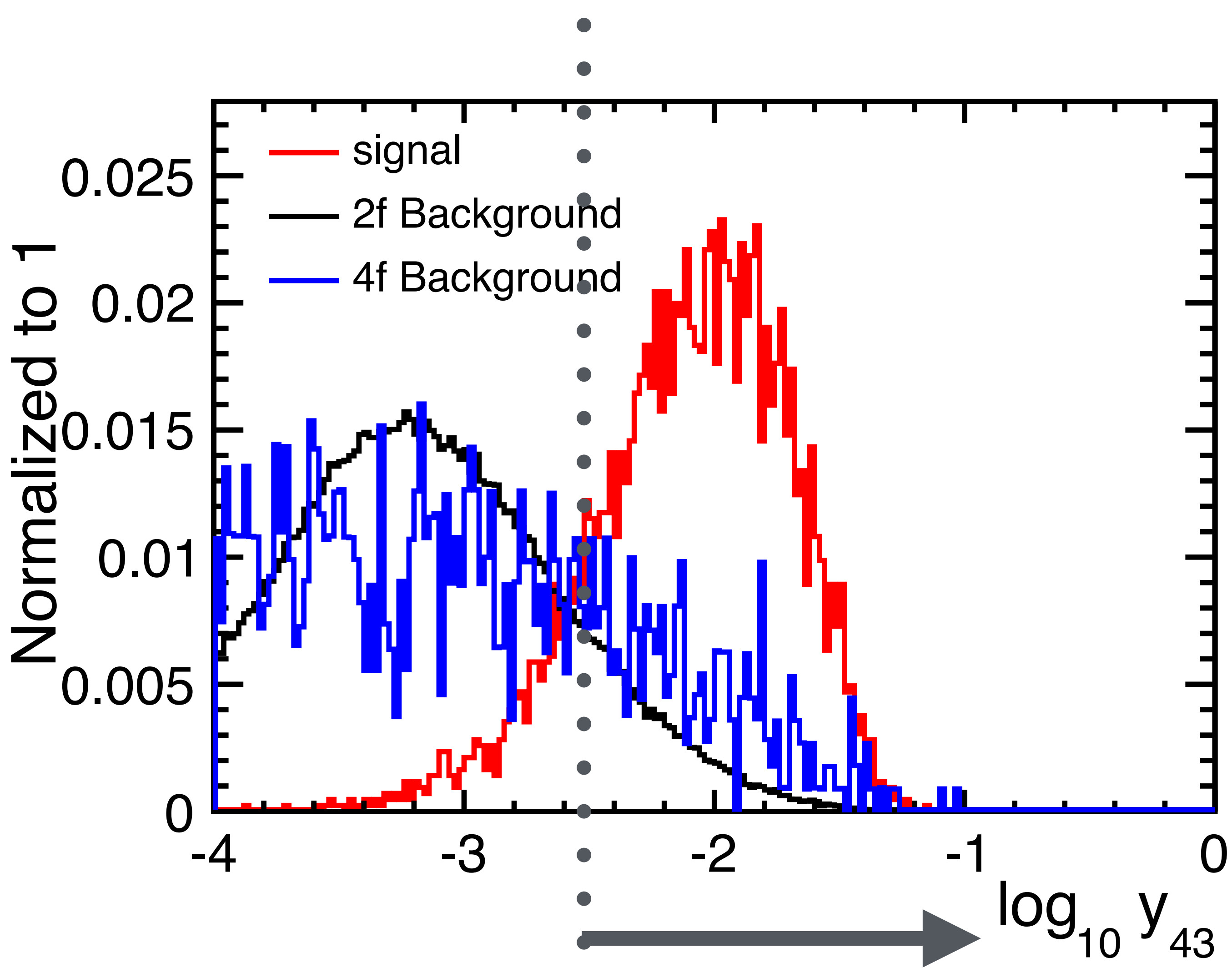
5. Analysis - Signal & Background (1)

$e^+e^- \to \gamma h \to \gamma(WW^*)$		e^+e^- -> 2f
number of particles in jet →many	# of particle>5	number of particles in jet →(l,ν)One
number of charged particles in jet →many	# of charged particle >1	number of charged particles in jet →One
y43, y32 →large	y43, y32	y43, y32 →relatively small

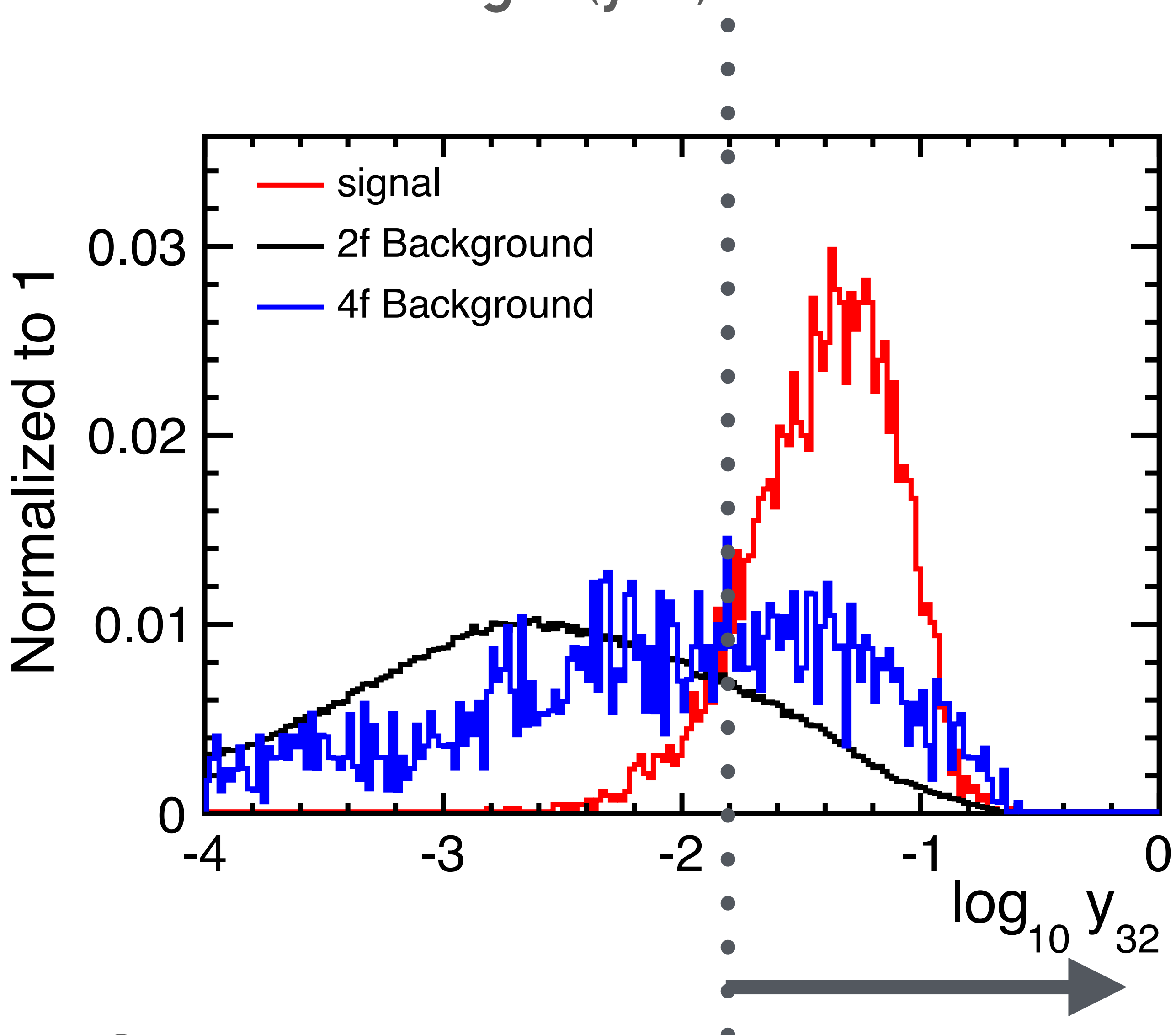
5. Analysis - Event selection

The distribution of y43 and y32 for signal and background events

log10(y43)>-2.5



log10(y32)>-1.8



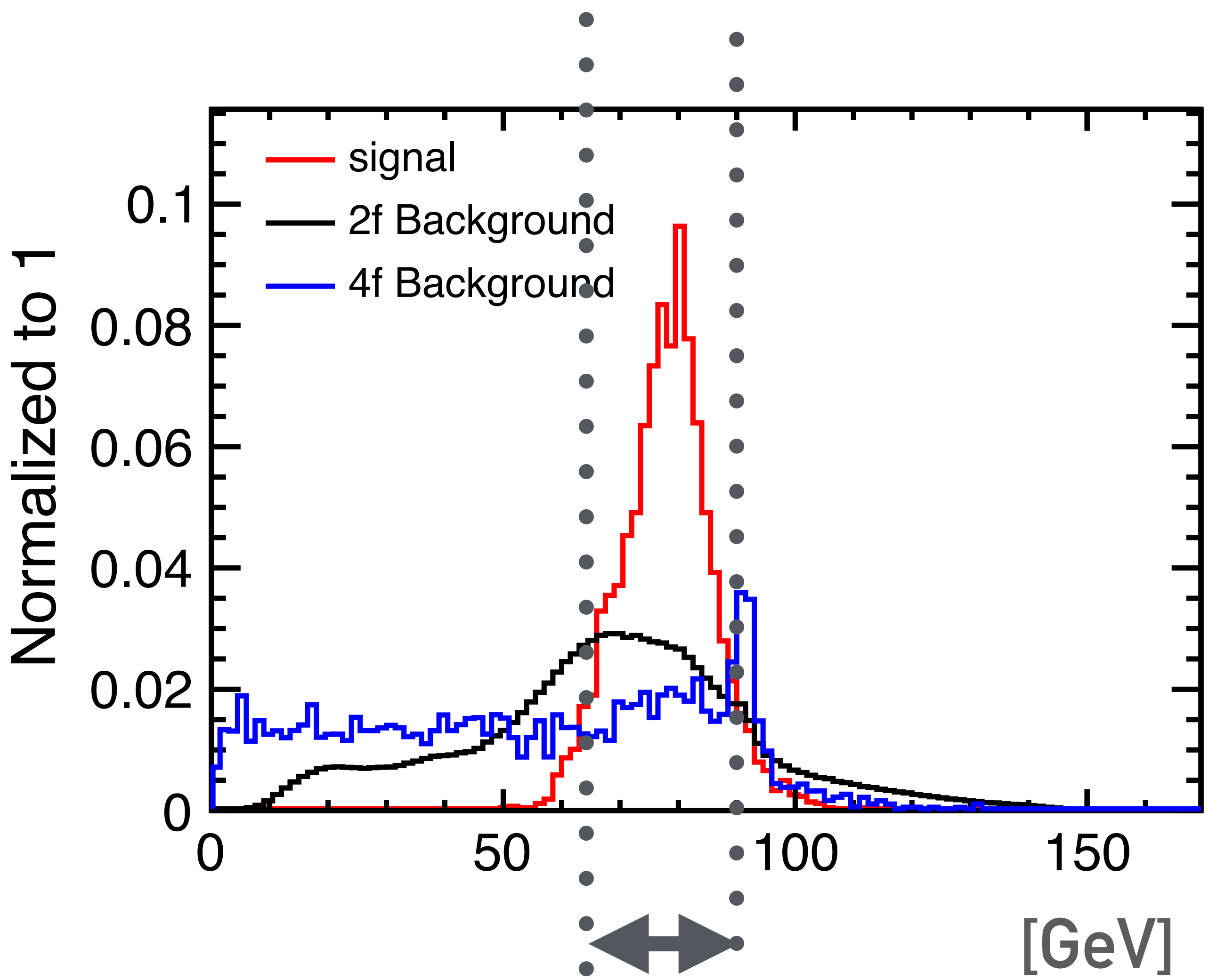
※ This plot is for events after the pre selection

5. Analysis - Signal & Background (2)

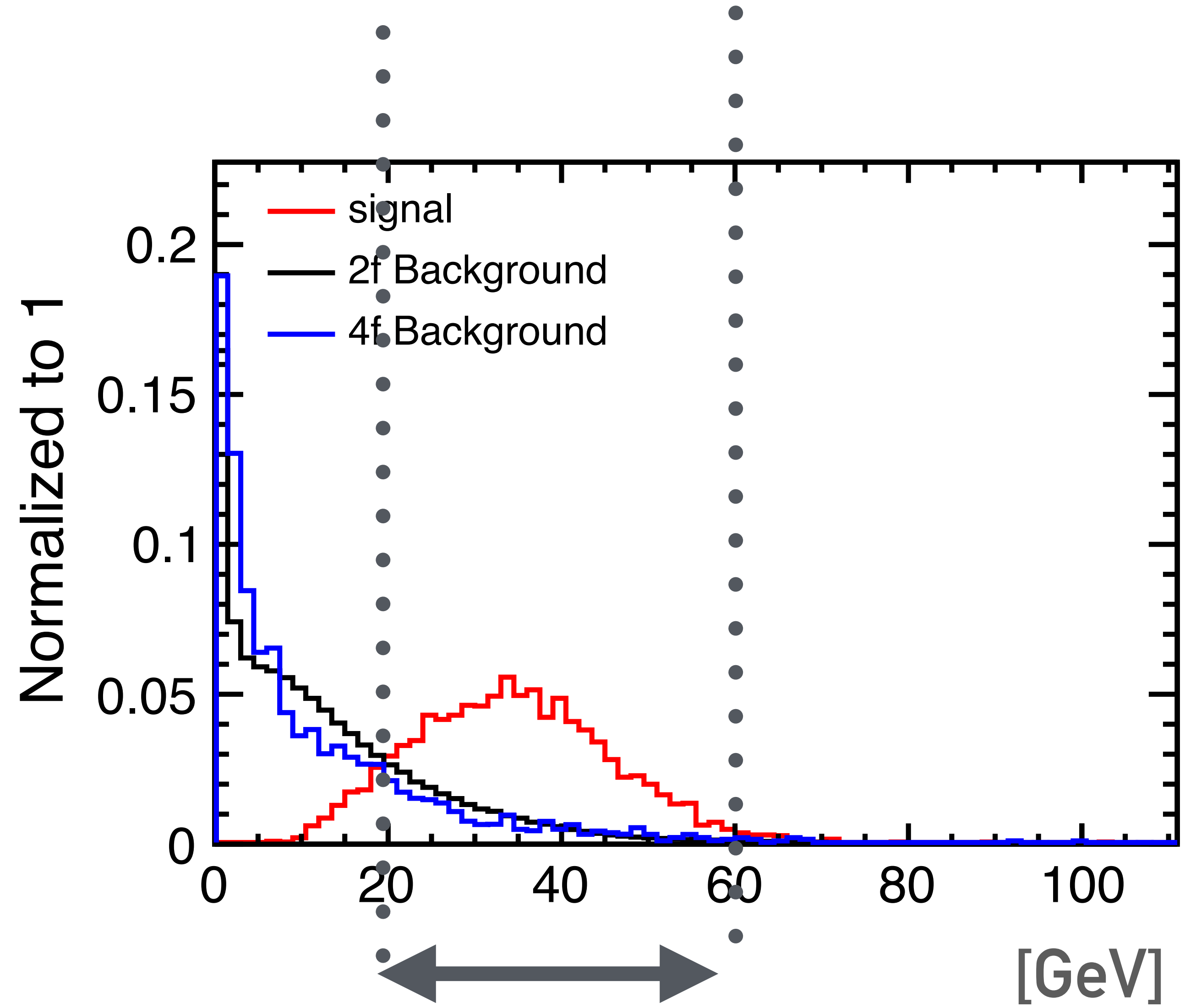
$e^+e^- \to \gamma h \to \gamma(WW^*)$		e^+e^- -> $W^+W^-(\gamma)$
mass other than real W < 50 GeV	m(W2)	mass other than real W ~80 GeV
m(4jets)= higgs mass	m(4jets)	m(4jets)= center mass energy
Energy of isolated monochromatic photon ~93 GeV	mγ	Energy of photon ~small

5. Analysis - Event selection

65<mw1<90



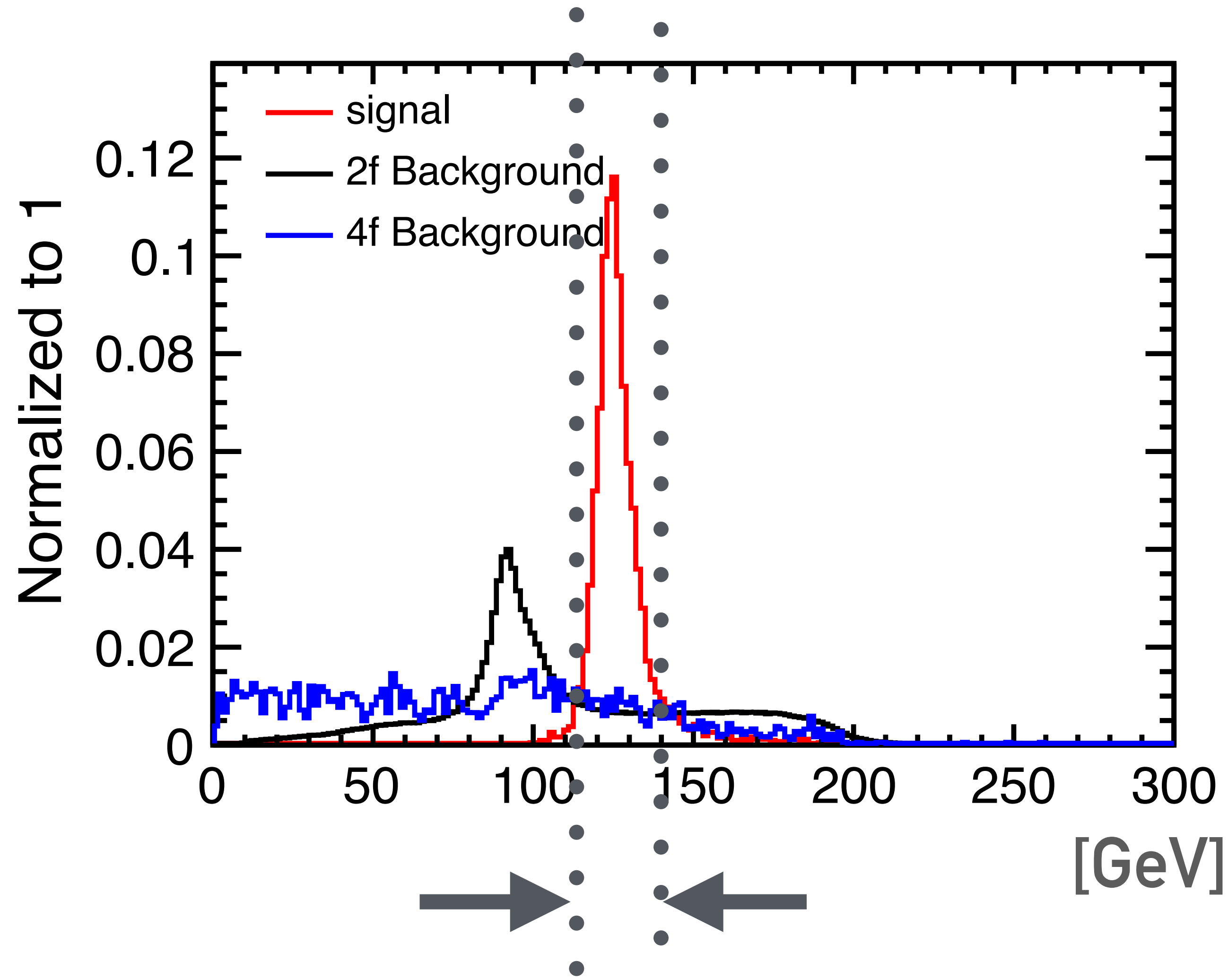
20<mw2<60



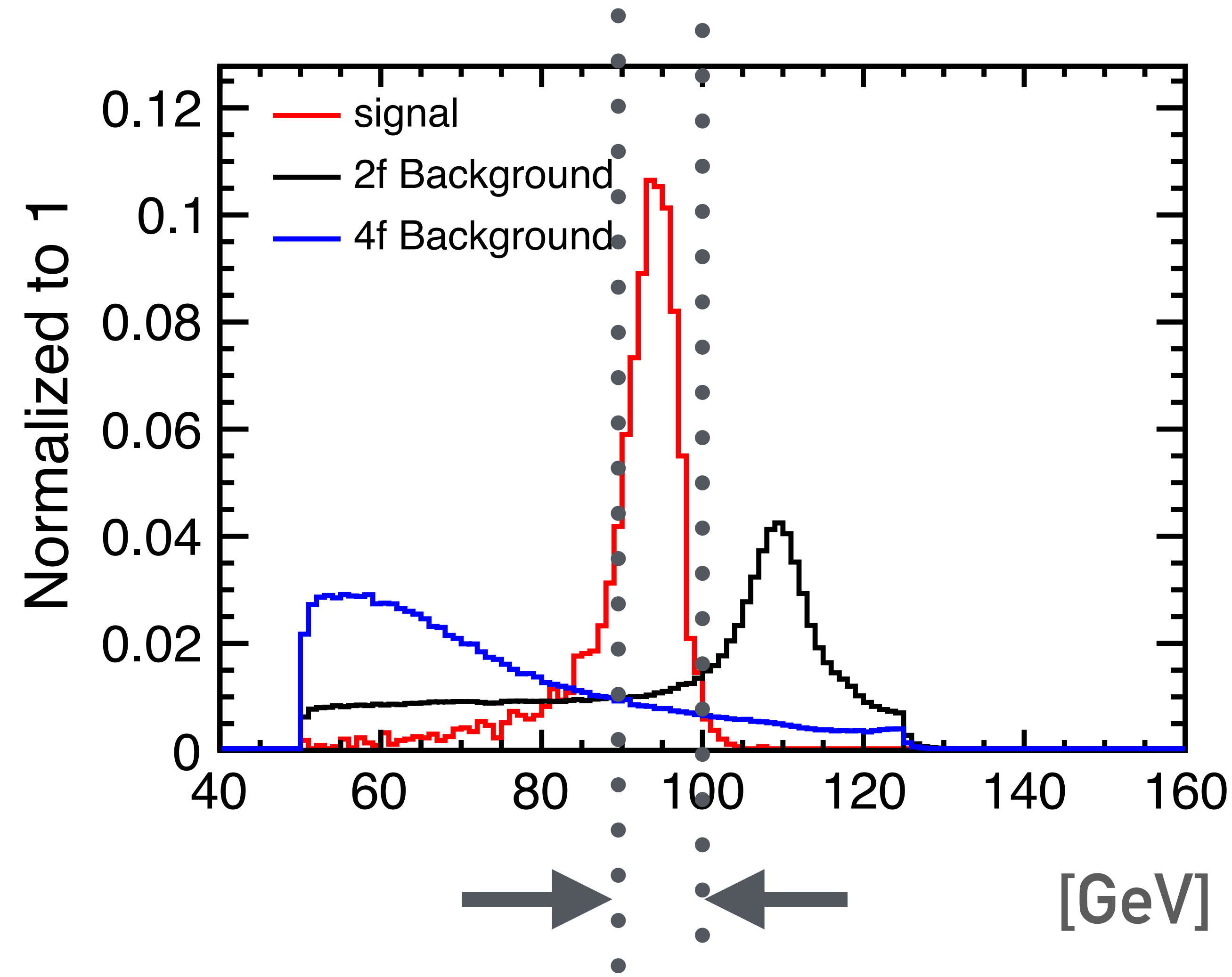
5. Analysis - Event selection

➤ mx

115<m(4jets)<135

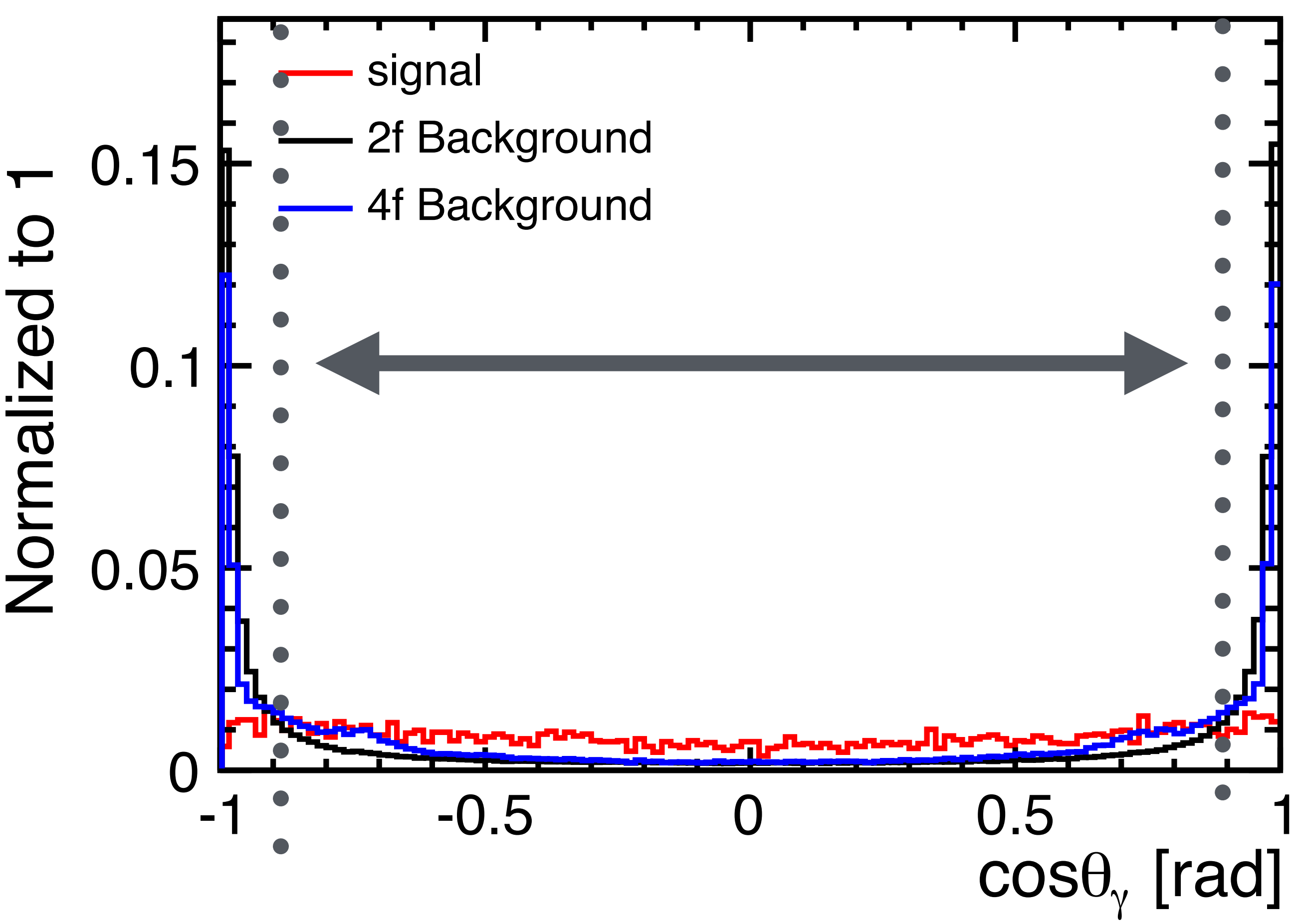


90<Eγ<100

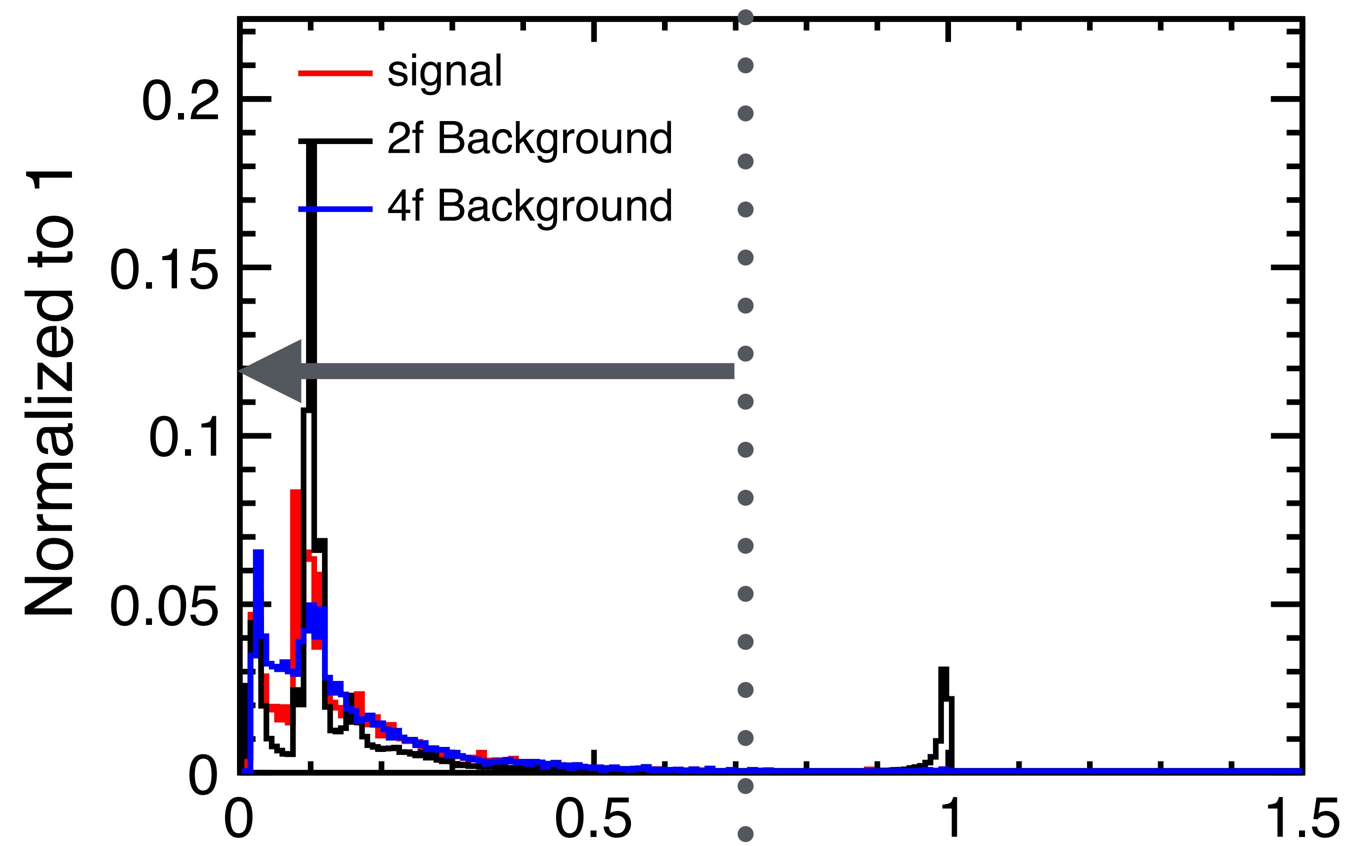


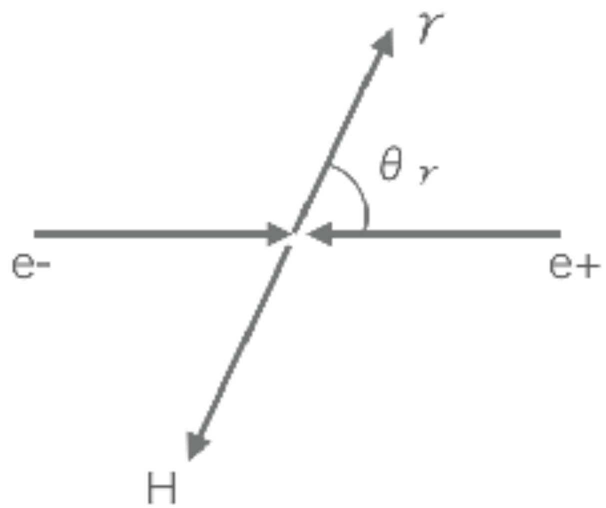
5. Analysis - Event selection

$-0.9<\cos\theta_\gamma<0.9$



b likelyness<0.7





5. Analysis - Reduction table

	2f_h	4f_h	total bg	Signal	Signal hadronic	Significance
Expected	156093000	33599400	314154000	88.5	40.2	0.005
Pre selection	27978300	760090	61010200	80.5	37.7	0.01
# of particle>5	10295600	681904	11233500	36.5	32.0	0.01
# of charged particle >1	5940470	591493	6646540	28.0	25.9	0.01
log10(y43)>-2.5 log10(y32)>-1.8	951914	527681	1515780	21.8	20.9	0.02
65<mw1<90	348875	495465	860262	19.2	18.9	0.02
20<mw2<60	235286	311623	559275	17.6	17.4	0.02
115<mx<135	53738	15634	74447	15.7	15.6	0.06
90<Eγ<100	21447	5494	27290	11.8	11.8	0.07
-0.9<cosθ<0.9	10636	3758	14525	10.3	10.3	0.09
bmax1<0.7	9746	3696	13558	10.0	10.0	0.09

5. Analysis - Result

→95% C.L upper limit $$\sigma_{\gamma H} = \sigma_{SM} + \frac{1.64}{\text{significance}} \sigma_{SM}$$

= 19.2 × 0.35 [fb] Significance = 0.09 for SM

=6.72 [fb] (Left handed)

19.2> $\frac{\sigma_{\gamma H}}{\sigma_{SM}} = 1 - 201\zeta_A - 273\zeta_{AZ}$ >0

asume ζ_A =0

-0.066> ζ_{AZ} >0.0037