Higgs Recoil Studies

Shun Watanuki[A], J. Yan[B], T. Tomita[C]
H.Yamamoto[A], A.Ishikawa[A], J.Strube[A], T.Suehara[C], K.Fujii[D]
(A : Tohoku University, B : University of Tokyo, C : Kyushu University, D : KEK)

ILD meeting 2014.9.9

Outline

- Higgs recoil mass study
  - μμh, eeh @250GeV by S. Watanuki
  - μμh @350GeV by J. Yan
  - qqh @250GeV by T. Tomita
  - and comparison
- CP-mixture
  - Motivation
  - Current results
- Summary and plan

Target

One of the advantages of the ILC is model independent (MI) analysis of Higgs properties by recoil method.

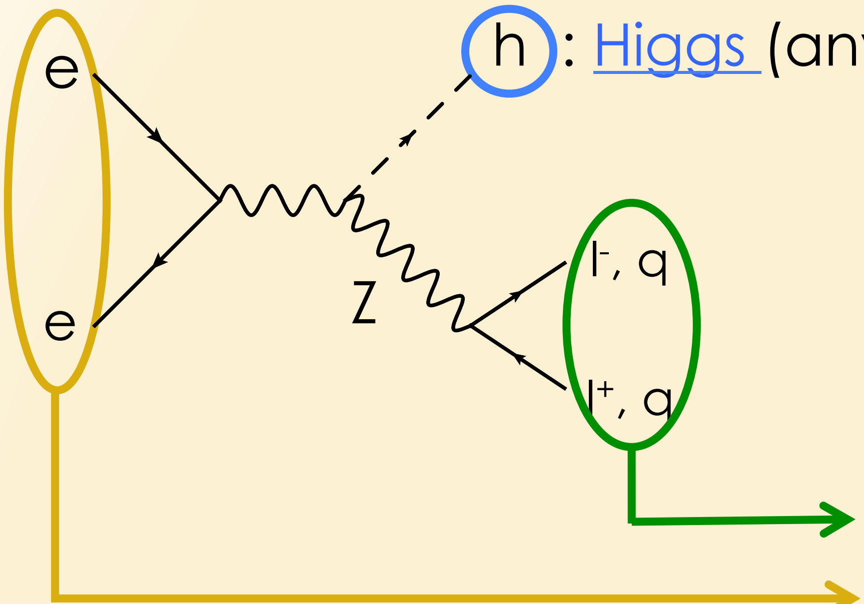
- How precise can we measure Higgs mass (only by llh) and cross section by this method?

The considered situations are …

Production Mode	Higgs mass (GeV)	E_{CM} (GeV)	Integrated Luminosity	Spin Polarization	Detector Simulation
$e^+e^- \to Zh \to \mu\mu h$, eeh	125	250	250 fb^{-1}	$P(e^-, e^+) = (\mp 0.8, \pm 0.3)$	ILD_01_v05 (DBD ver.)
$e^+e^- \to Zh \to \mu\mu h$	125	350	333 fb^{-1}	$P(e^-, e^+) = (\mp 0.8, \pm 0.3)$	ILD_01_v05 (DBD ver.)
$e^+e^- \to Zh \to qqh$	125	250	250 fb^{-1}	$P(e^-, e^+) = (\mp 0.8, \pm 0.3)$	ILD_01_v05 (DBD ver.)

What's the Recoil Method?

- ILC is a **lepton collider**
  = We already know initial state 4 momentum



h : Higgs (any decay mode is allowed)

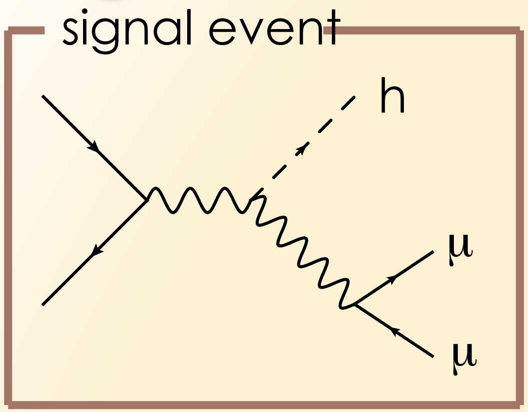
$p_h = p_{e-} + p_{e+} - p_Z$

✧ We can calculate the 4momentum of Higgs.

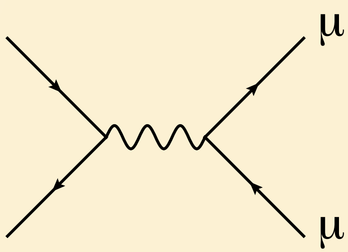
Aim for Higgs σ measurement

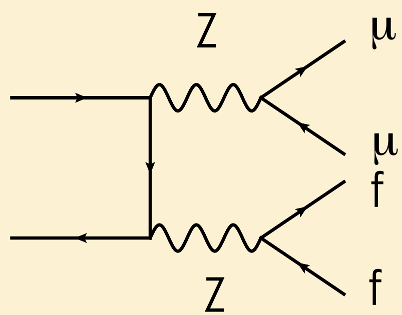
- **Directly** — It depends on the model of Higgs decay
- **Recoil method** — We can measure Higgs model independently

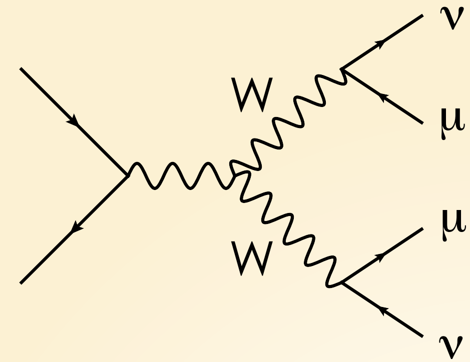
Signal and Background Events



- These are μμh channel signal & BGs.
- For eeh and qqh channel study, character of "μ" and "ν" are altered appropriately.







- Dominant Background is "μμ", "μμνν", "μμff" events, and other BG is rejected significantly.

Lepton Selection

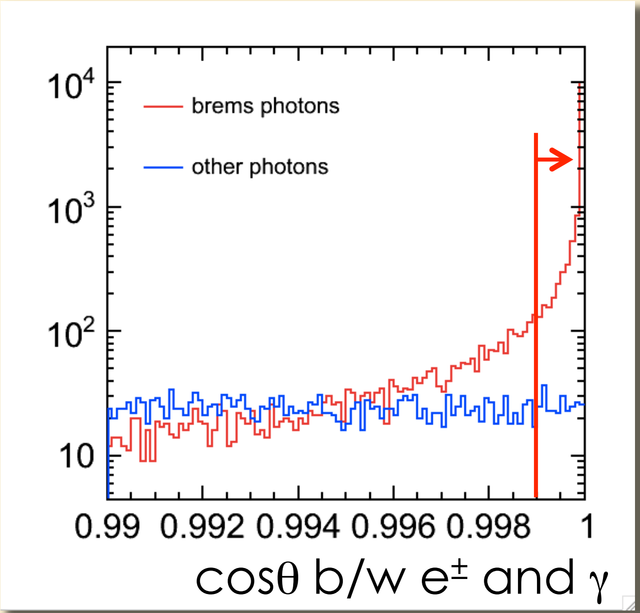
- Muon (electron) selection
  - based on deposited energy on calorimeter
- Good track selection
  - based on error in forward / barrel
- Impact parameter (only for muon)
  - To suppress muons from tau decays

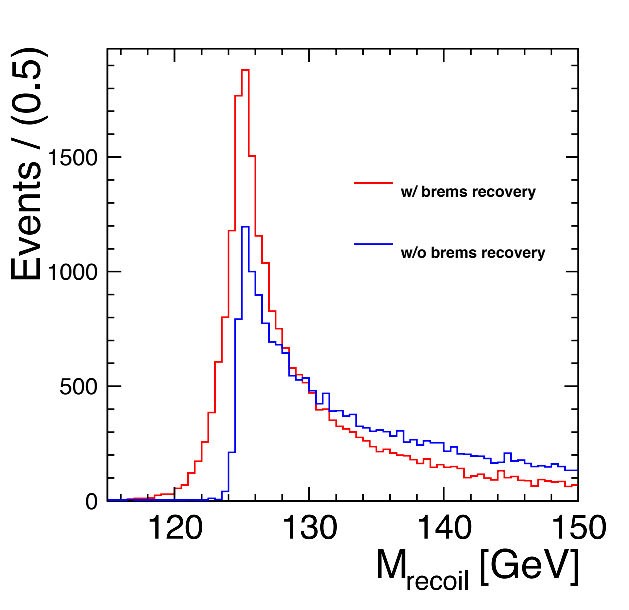
μμh, eeh @250GeV

By S. Watanuki from Tohoku University

Bremsstrahlung Recovery

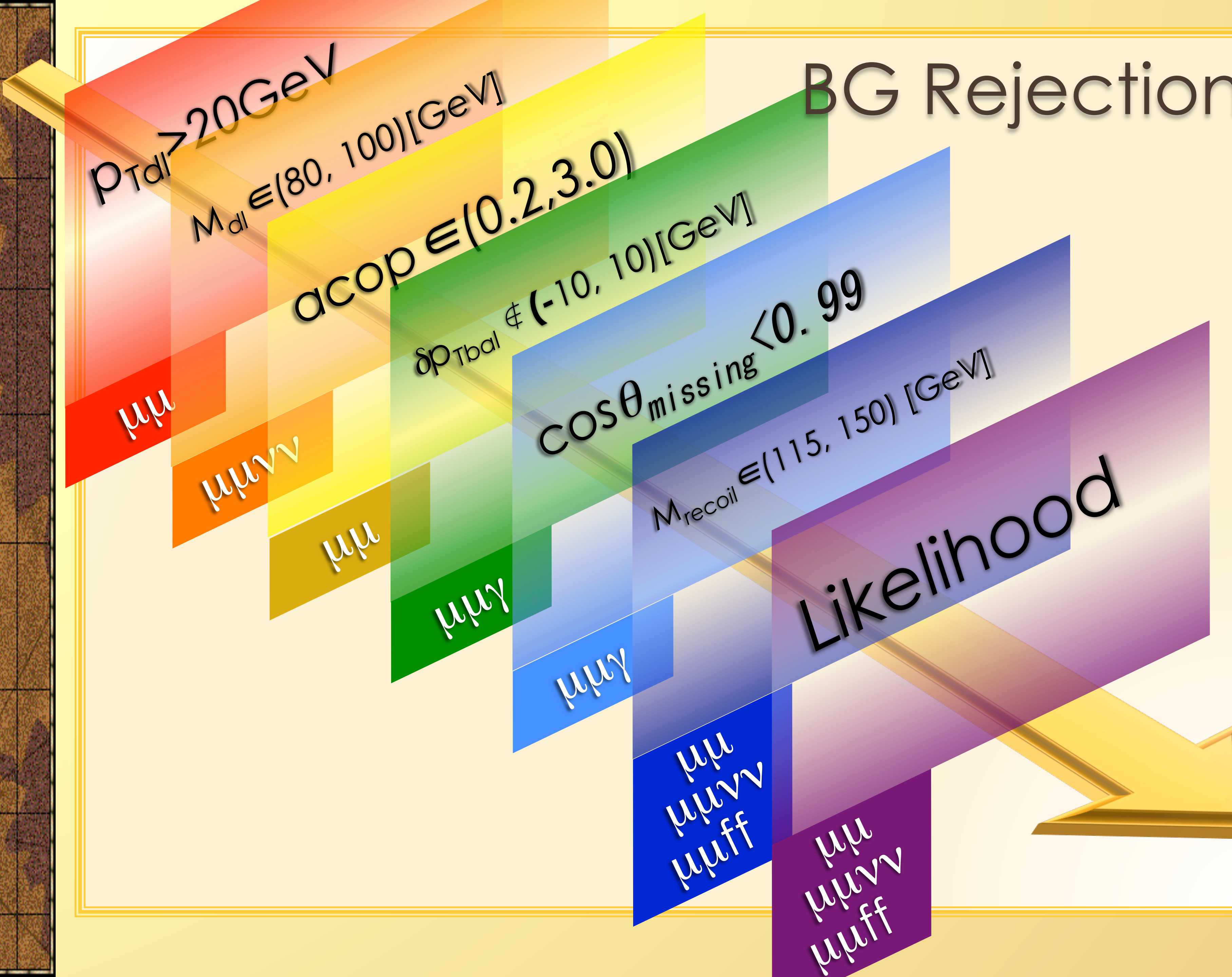
- Only for eeh channel, momentum of photon around final state electron is added to the electron.
  - $\cos\theta > 0.9995$
  - $\cos\theta > 0.999$ && $E_{photon}/E_{electron} > 0.03$
  - not split photon
- This process contributes to the distribution of recoil mass significantly.





※ For mass analysis, it is effective not to perform the recovery.

BG Rejection



BG Rejection

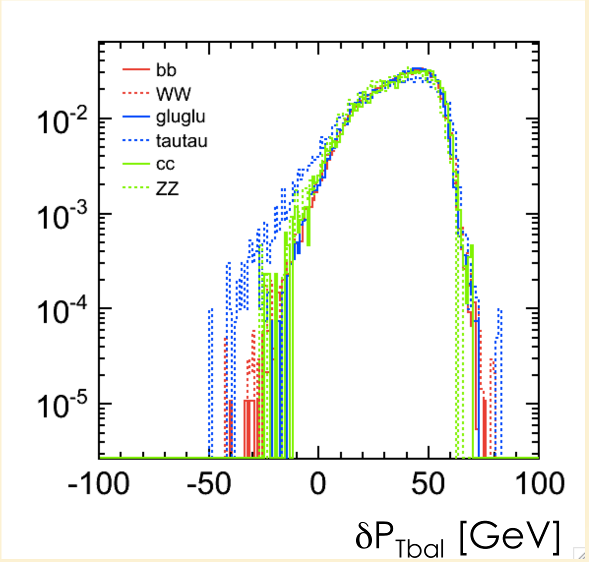
μμh	signal	ll	llνν	llff	others
No Cut	2603	3.2M	507166	390041	7.1M
After Cut	1386	322	1479	1054	3

eeh	signal	ll	llνν	llff	others
No Cut	2729	7.8M	520624	404279	2.5M
After Cut	1190	1496	2203	937	4

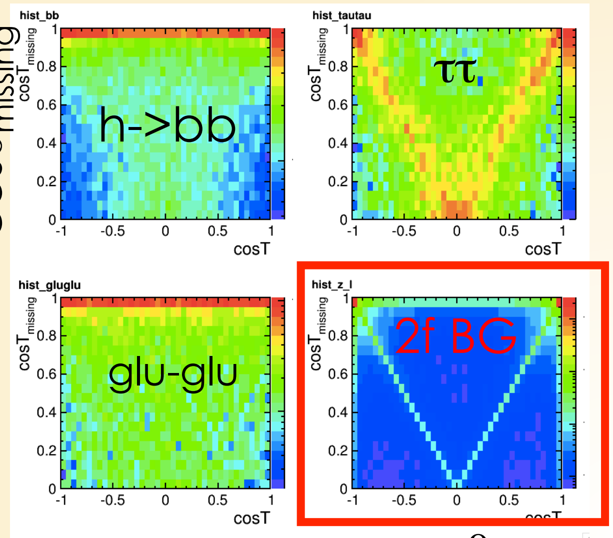
Unbiased Selection

- δP_{Tbal} and $\cos\theta_{missing}$ cut has bias for Higgs decay modes.
- To avoid this bias problem, some additional conditions are needed
- $\delta P_{Tbal} = P_{Tdl} - P_{T\ photon}$
  - photon should satisfy …
    - $m_{2\gamma} > 0.2$ [GeV]
    - or $E\gamma > 60$ [GeV]
- $\cos\theta_{missing}$: $\cos\theta$ of all PFOs
  - $|\cos\theta_{missing}| < 0.99$
  - or $|\cos\theta_{Z\ boson}| < 0.8$
- These additional condition avoid bias, but efficiency of BG rejection is sacrificed.

	bb	glu-glu	ττ	BG (ll)
$\cos\theta_{miss} < 0.99$	95.1%	92.8%	99.2%	41.1%
$\cos\theta_{miss} < 0.99$ or $|\cos\theta| < 0.8$	99.3%	99.1%	99.8%	74.6%



$\cos\theta_{missing}$



$\cos\theta_{Z\ boson}$

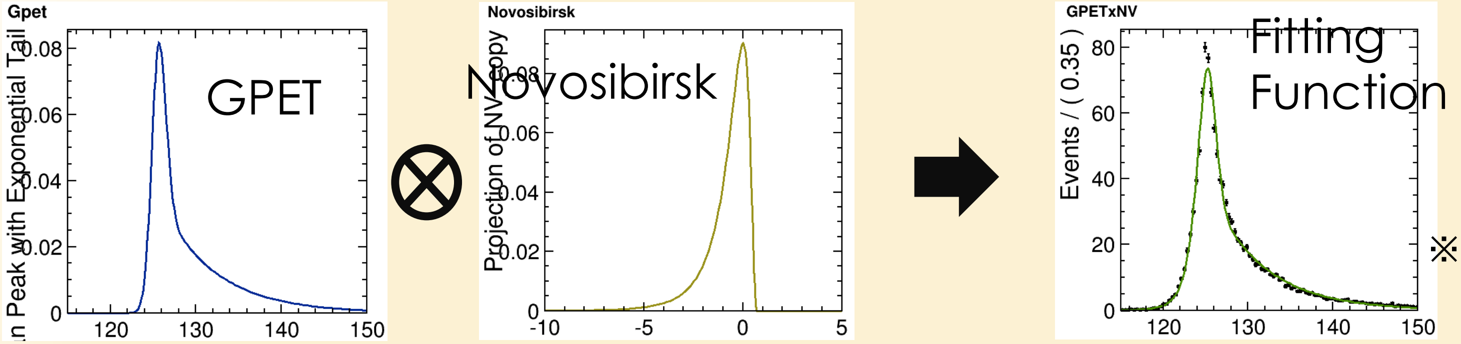
Signal Efficiency

- After that, bias of signal efficiency for Higgs decay is eliminated.

H decay mode	$\mu\mu h$ efficiency [%]	eeh efficiency [%]
bb	55.61	45.62
WW	55.39	44.95
gluglu	55.16	45.02
$\tau\tau$	55.42	44.49
cc	55.60	45.14
ZZ	54.04	45.51

- Systematic error due to efficiency in decay modes is 3%.
- (If we could use the information on measured cross section for higgs decay modes, the error should be much smaller)

Fitting Function



※eeh distribution

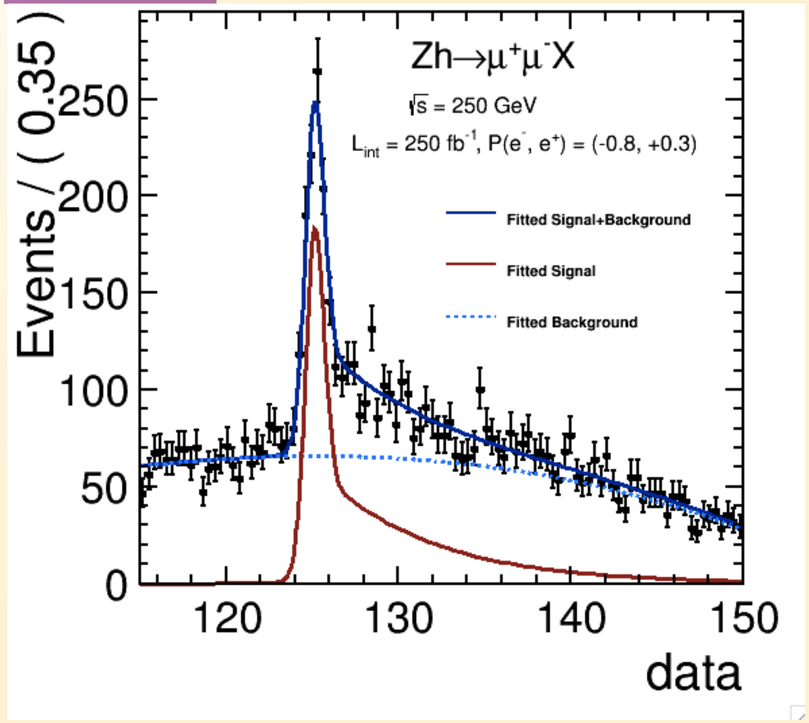
- GPET is constructed by Gaussian peak and exponential tail.
- Novosibirsk can express uncertainty of lepton detection.
  - For detail of Novosibirsk function, please check [Nuclear Instruments and Methods in Physics Research A 441 (2000) 401-426]
- For BG fitting, 3rd order polynomial is used. (BG shape is determined separately from signal shape determination)

	GPET (signal)					3rd order poly. (BG)			Yields	
	mean	width	k	b	NV	p1	p2	p3	Y_{sig}	Y_{BG}
Fitting	float	float	float	float	float	float	float	float	float	float
toyMC	float	fix	fix	fix	fix	fix	fix	fix	float	float

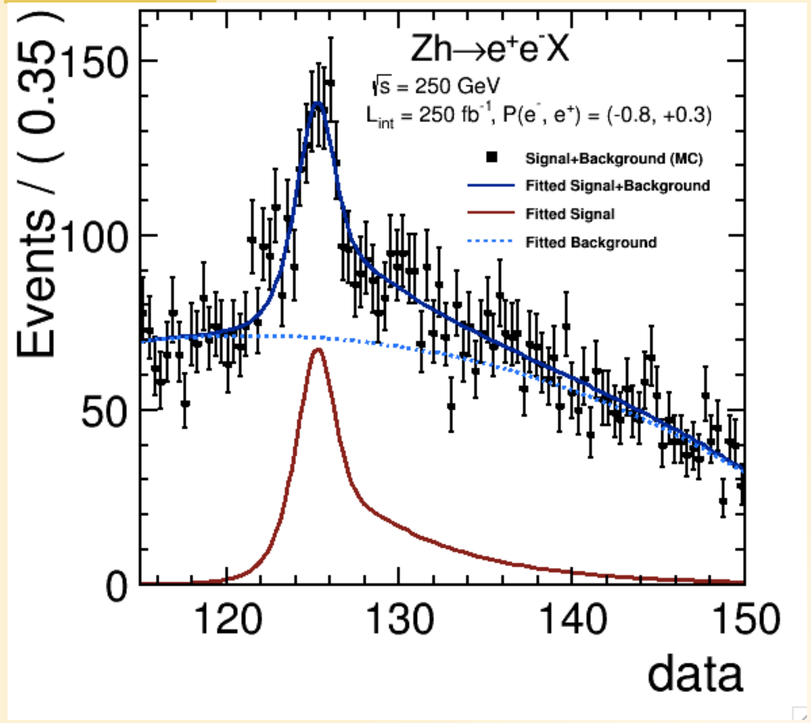
※ k : boundary, b : junction

Fitting Results

μμh



eeh

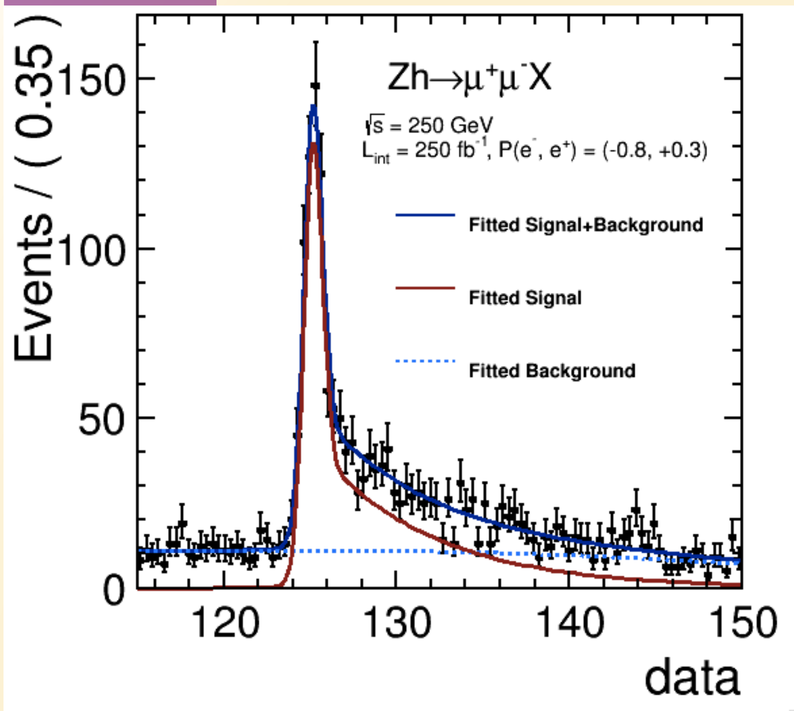


$L=250fb^{-1}$ P(e-,e+)=(-0.8,+0.3)	μμh		eeh		combined	
Δσ/σ	4.2%	3.8%	6.0%	5.6%	3.4%	3.1%
Δmass [MeV]	34	33	231	89	34	31

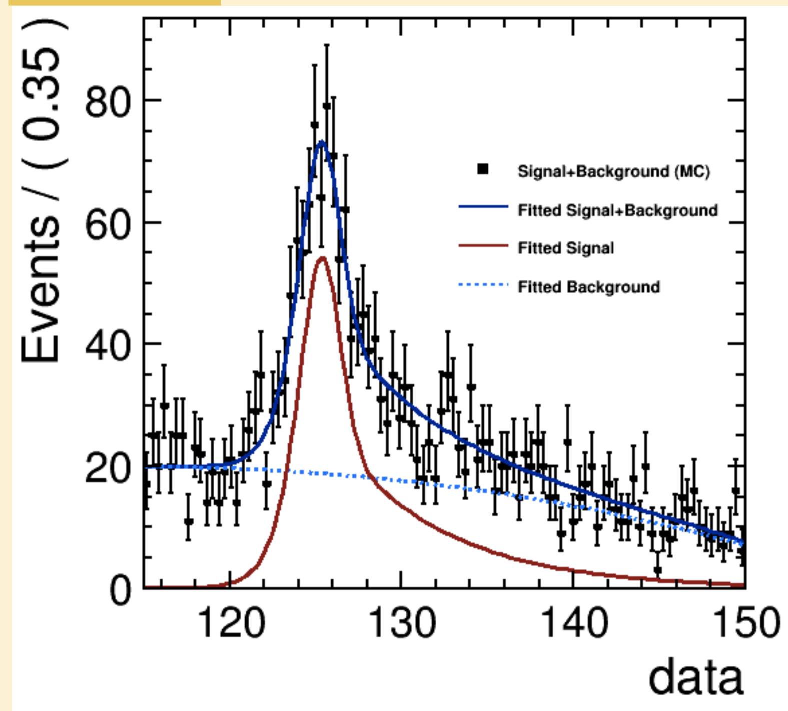
※ Red value means semi-MI analysis in which visible energy cut is performed.

Fitting Results (Right Handed)

μμh

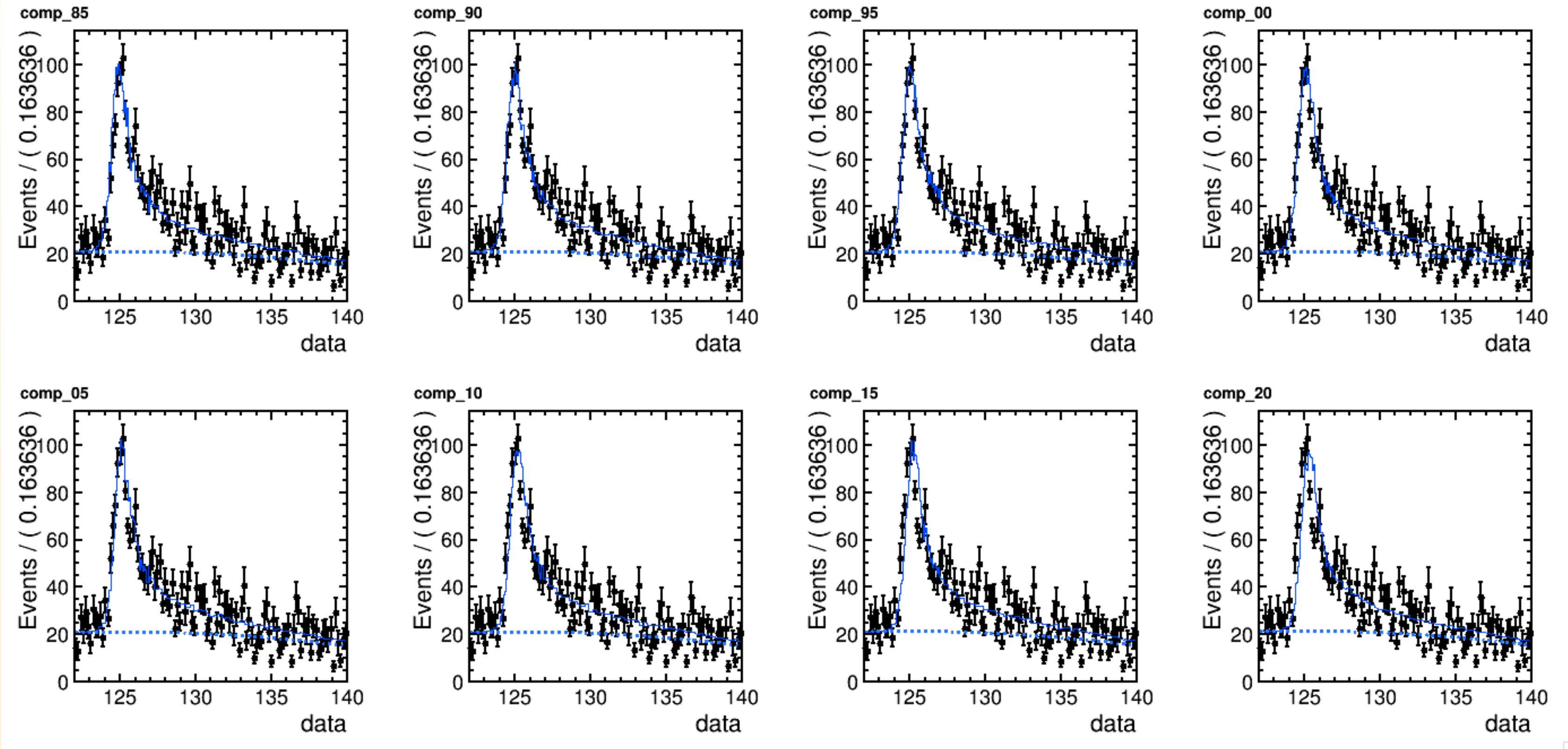


eeh



$L=250fb^{-1}$ P(e-,e+)=(-0.8,+0.3)	μμh	eeh	combined
Δσ/σ	3.8%	6.0%	3.2%
Δmass [MeV]	31	214	31

Mass Template Method



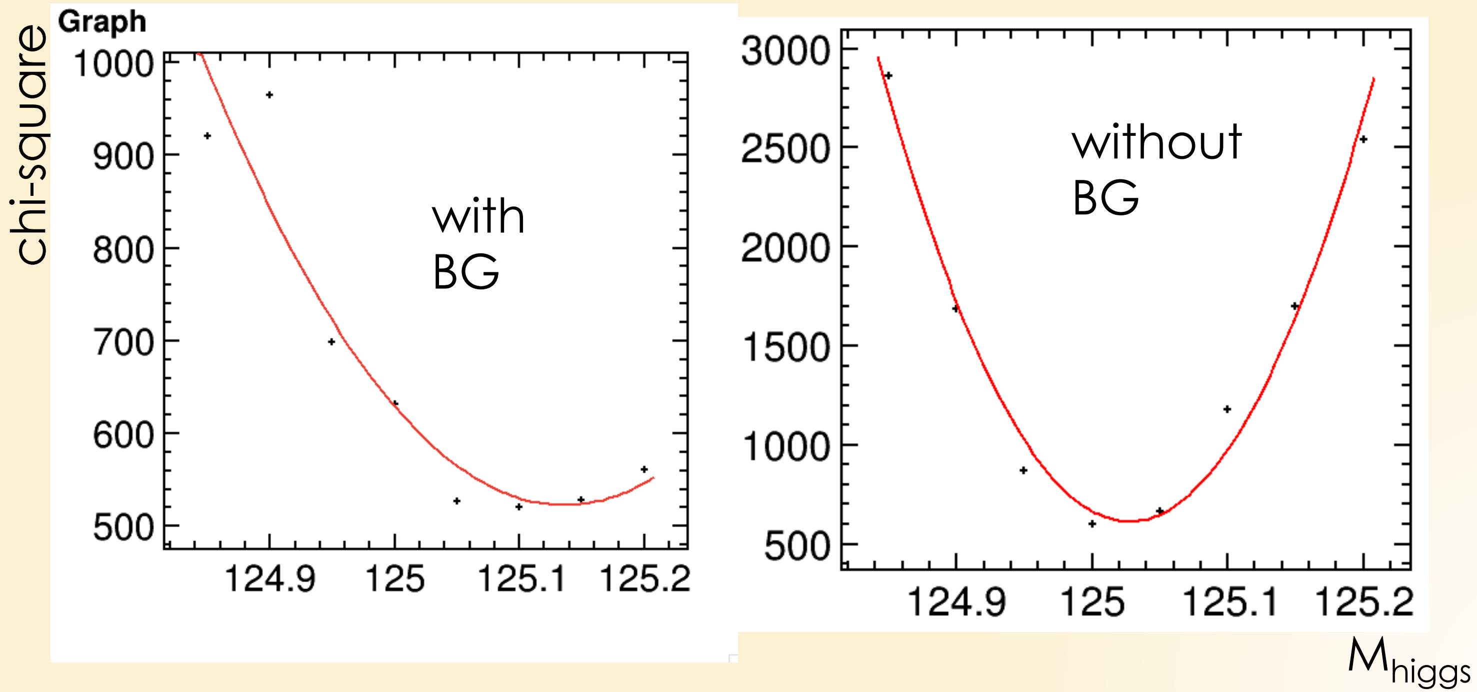
- For mass measurement, template method is also tried.
- Non-uniform binned histogram is used as PDF to fit.

region [GeV]	[122, 124]	[124, 127]	[127, 140]
# of bins	10	50	50

- BG PDF is used fitted 3rd order polynomial.

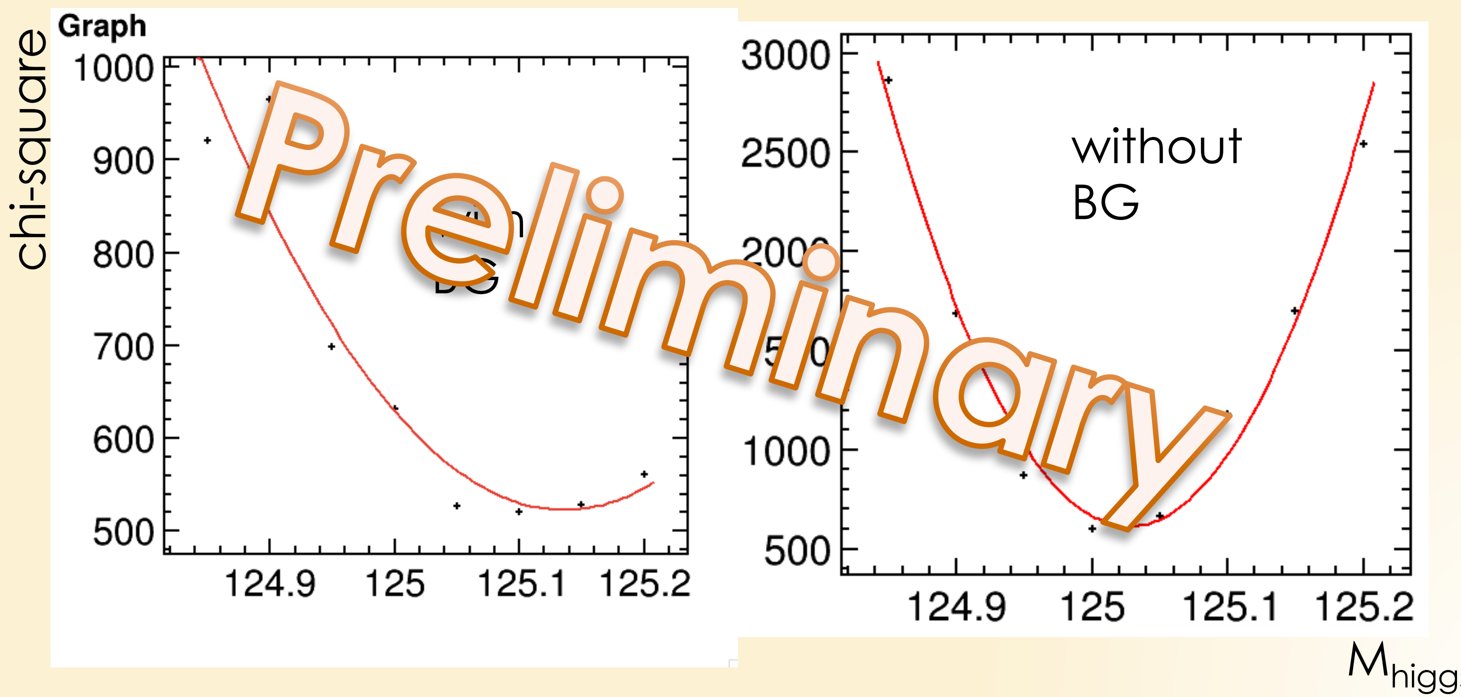
Chi-square Plot

- Chi2 of any fitting is plotted, and fitted by parabola.
- Minimum point :
  - x = 125.136 +- 0.013 [GeV]
  - x = 125.027 +- 0.003 [GeV] (w/o BG)



Chi-square Plot

- Chi2 of any fitting is plotted, and fitted by parabola.
- Minimum point :
  - x = 125.136 +- 0.013 [GeV]
  - x = 125.027 +- 0.003 [GeV] (w/o BG)



Next Plan

- Further investigation of mass template method is needed.
- Estimate sensitivity to Higgs CP-mixture, which is from anomalous coupling in 2HDM, by Z production angle.

μμh @350GeV

By J. Yan from University of Tokyo

Status

- Goal :
  - Precise measurement of Higgs cross section
  - Contribute to the decision for ILC run scenario
- BG : included all 2f, 4f, 6f processes
- Full ILD detector simulation
- Compare results between P(-0.8, +0.3) and P(+0.8, -0.3), between 350GeV and 250GeV
- Final selection for Ecm = 350GeV
  - $84 < M_{inv} < 98$ (GeV)
  - $10 < P_{Tdl} < 140$ (GeV)
  - dPTbal = $|P_{Tdl} - PT_{\gamma\_max}| > 10$ (GeV)
  - coplanarity < 3
  - $|\cos\theta Zpro| < 0.91$
- 120 < Mrecoil < 140 (GeV)

Cut Efficiency

	signal	BG	2f_Z_l	4f_WW_sl	4f_ZZ_sl
raw events	2288	32M	2M	2.7M	188087
best m pair	2254	2M	946129	236802	42345
D_0	2241	1.8M	925330	152599	39825
track angle	2205	1.6M	843738	136568	36073
M_{inv}	1826	313998	269446	5702	16365
P_{Tdl}	1819	111823	71877	5659	14934
δP_{Tbal}	1798	48694	10674	5505	14108
acop	1773	44735	9612	4578	13347
$\cos\theta_Z$	1698	30428	5709	2940	9147
M_{recoil}	1088	2700	276	405	1123

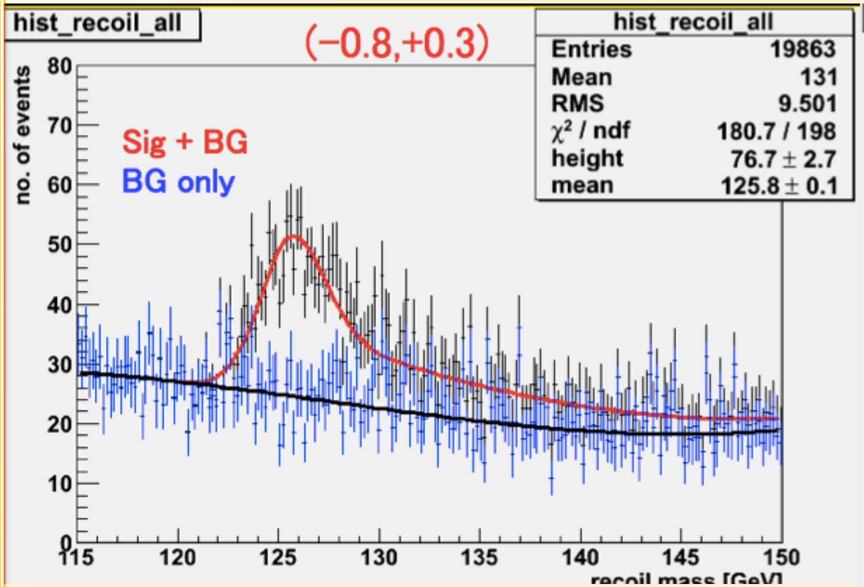
- After selection
  - signal efficiency = 47.6 +/- 0.5%
  - S/B = 0.40, significance = 17.2

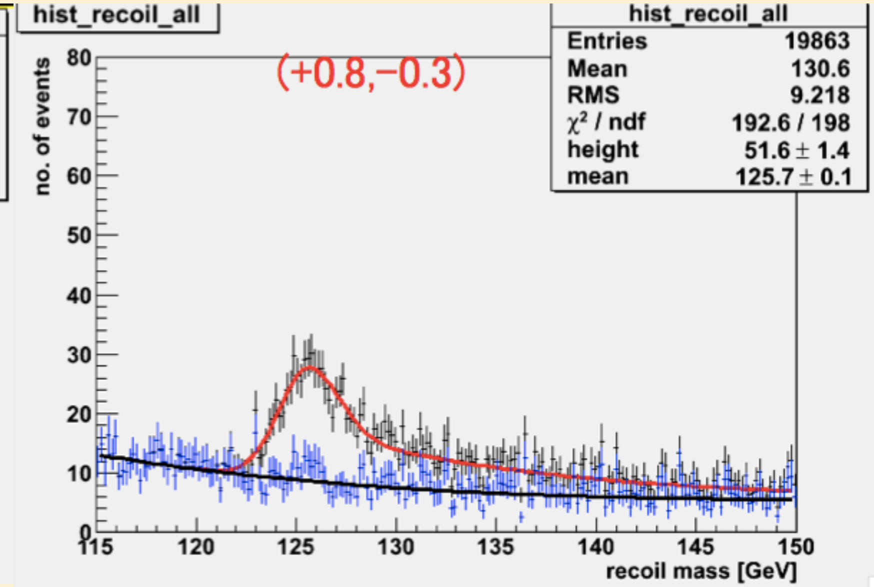
Fitting

- Signal is fitted by GPET
- BG is fitted by 3rd order polynomial
- Float only height and mean of GPET
- Fix BG function and remaining GPET pars from 1st time fitting

- Toy-MC study is done to estimate statistical error of cross section measurement

Results





E_{cm}	$P(e^-,e^+)$	eff	$\Delta\sigma/\sigma$	S/B
350	(-0.8, +0.3)	47.6±0.5%	4.9±0.2%	~0.40
	(+0.8, -0.3)	47.8±0.5%	5.0±0.2%	~0.75
250	(-0.8, +0.3)	66.4±0.5%	3.6±0.1%	~0.37
	(+0.8, -0.3)	64.4±0.5%	3.3±0.1%	~0.81

Plans

- Cut more BG without losing too much signal?
  - Improvement data selection : Implement isolation and likelihood cut?
- Study precision of fitted recoil mass M_h
- Study alternative polarization scenarios e.g. (-0.8, 0), (+0.8, 0) …etc

qqh @250GeV

By T. Tomita from Kyushu University

Motivation

- In recoil mass study, leptonic channel such as Z->ee, mm has very good signal/BG ratio.
- But the branching ratio of Z->leptonic is ~3.5% for each generation.

- In contrast, the branching ratio of **Z->hadronic is ~70%**.
- However, analysis is challenging due to a large amount of BG and worse Z mass resolution.

Cut

- Box cut – targeted ZZ/WW hadronic event
  - Using 4 jet clustering
- Mass cut – targeted semi-leptonic event
  - Using 2 jet clustering
- Z like jet pt cut – targeted back to back Z event
- dijet mass cut – selected Z
  - Using y value clusetering

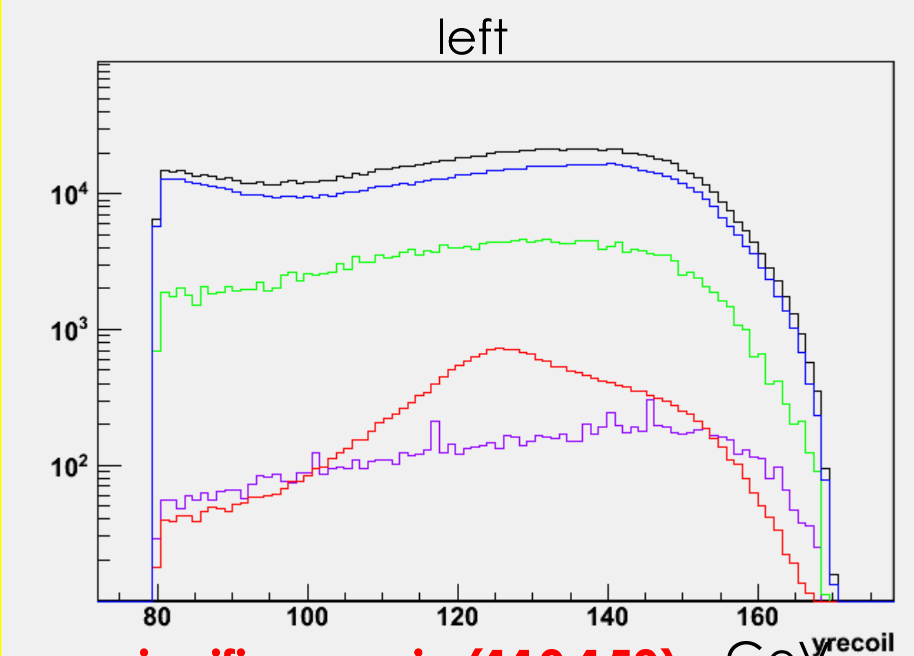
$$y = \frac{2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{Q^2}$$

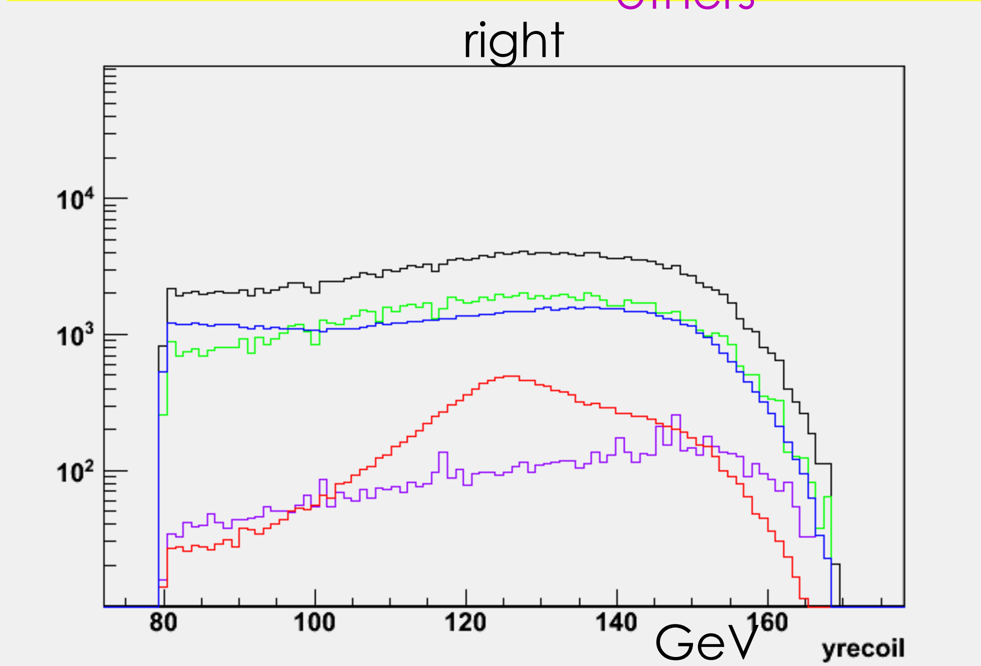
Cut Table

cut	qqH	4 fermion	2 fermion	others
left	490,370	6M	16M	21M
right	331,118	798,363	10M	21M
Box cut (81,101) ZZ, (70,90) WW	82.7%	83.9%	99.0%	99.9%
Z like Jet pt > 20	70.6%	60.9%	30.3%	2.4%
dijet mass (76,106)	54.7%	36.2%	10.0%	0.7%
recoil mass (110,150)	43.1%	10.8%	2.7%	0.3%
Sphericity > 0.1	39.1%	6.7%	0.7%	0.2%
Thrust cut major>0.3, minor>0.1	36.9%	5.2%	0.4%	0.05%

results

2-fermion
4-fermion
signal(qqH)
others





significance in (110,150) GeV

polarization	significance	$\Delta\sigma/\sigma$
left (-0.8, +0.3)	20.5 σ	4.8%
right (+0.8, -0.3)	31.1 σ	3.2%

Summary & Prospects

- Right handed polarization shows better significance than left handed one.
- Especially in left handed polarization, 4 fermion background should be reduced much more.
- We plan to categorize the events to analyze qqH channel model independently.
- We are preparing ISR finder and Tau tagger for categorization.

Summary of Recoil Study

- The recoil mass technique is important feature at the ILC to measure Higgs mass and cross section of Zh event.

μμh, eeh @250GeV		μμh		eeh		combined	
		Left	Right	Left	Right	Left	Right
MI	cross section	4.2%	3.8%	6.0%	6.0%	3.4%	3.2%
	mass [MeV]	34	31	231	214	34	31
semi-MI	cross section	3.8%		5.6%		3.1%	
	mass [MeV]	33		89		31	

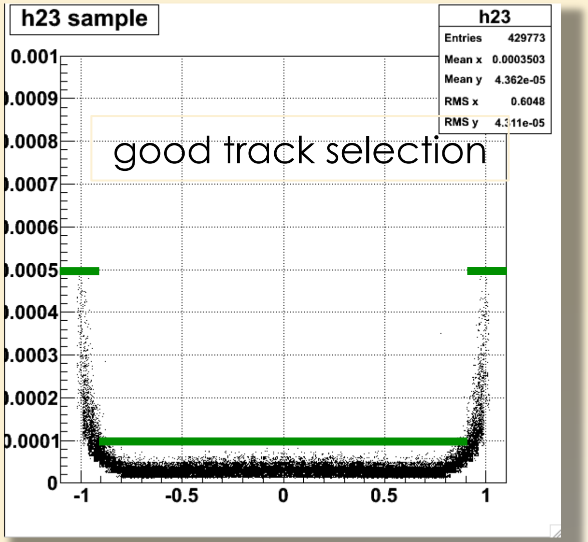
μμh @350GeV	Left handed	Right handed
cross section	4.9%	5.0%
cross section (250GeV)	3.6%	3.3%

qqh @250GeV	Left handed	Right handed
cross section	4.8%	3.2%

Backup Slides

Lepton Selection

- Muon (electron) selection
  - Momentum p > 15 [GeV]
  - Small (Large) energy deposited in calorimeters
    - $E_{ecal} / E_{total} < 0.5$ (> 0.6)
    - $E_{total} / p_{track} < 0.3$ (> 0.9)
- Good track selection
  - Track with small error (different selections between polar angle of tracks, barrel or end cap)
    $dp / p^2 < 2.5 \times 10^{-5} \oplus 8 \times 10^{-4} / p$
    (for $\cos\theta < 0.78$)
    $dp / p^2 < 5 \times 10^{-4}$
    (for $\cos\theta > 0.78$)



dp / p^2

- Impact parameter (only for muon)
  - To suppress muons from tau decays which tend to have large impact parameters.
    $D_0 / dD_0 < 5$

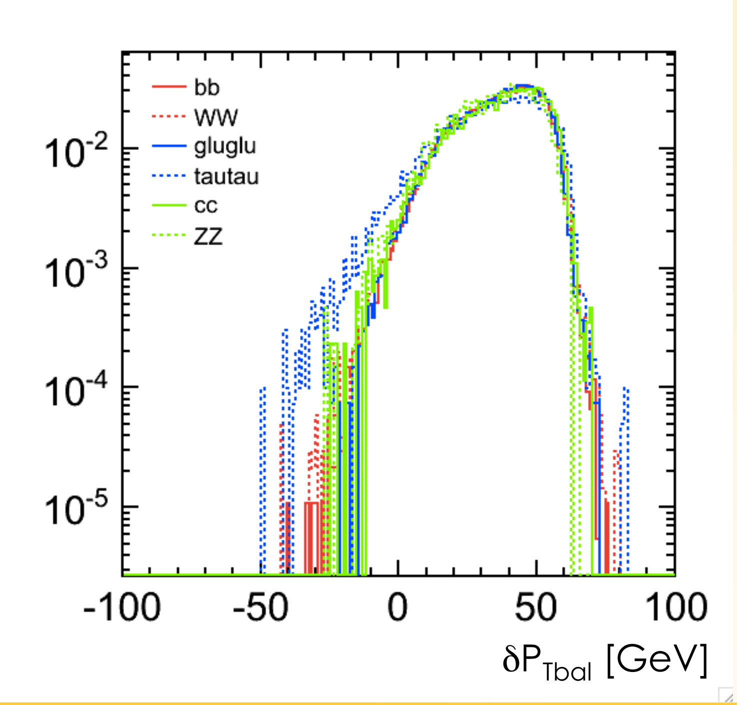
BG Rejection and Cut Table

$\mu\mu h$	signal	ll	$ll\nu\nu$	llff	others
No Cut	2603	3.2M	507166	390041	7.1M
selection	2278	17200	16286	7874	70
P_{Tdl}	2161	9965	14095	6852	59
M_{dl}	2036	7891	8147	5808	37
acop	1903	6825	7659	5306	33
dP_{Tbal}	1894	1751	7518	5189	33
$\cos\theta_{missing}$	1882	1257	7517	4815	30
M_{recoil}	1730	536	3116	1575	12
Likelihood	1386	322	1479	1054	3

eeh	signal	ll	llnn	llff	others
No Cut	2729	7.8M	520624	404279	2.5M
After Cut	1190	1496	2203	937	4

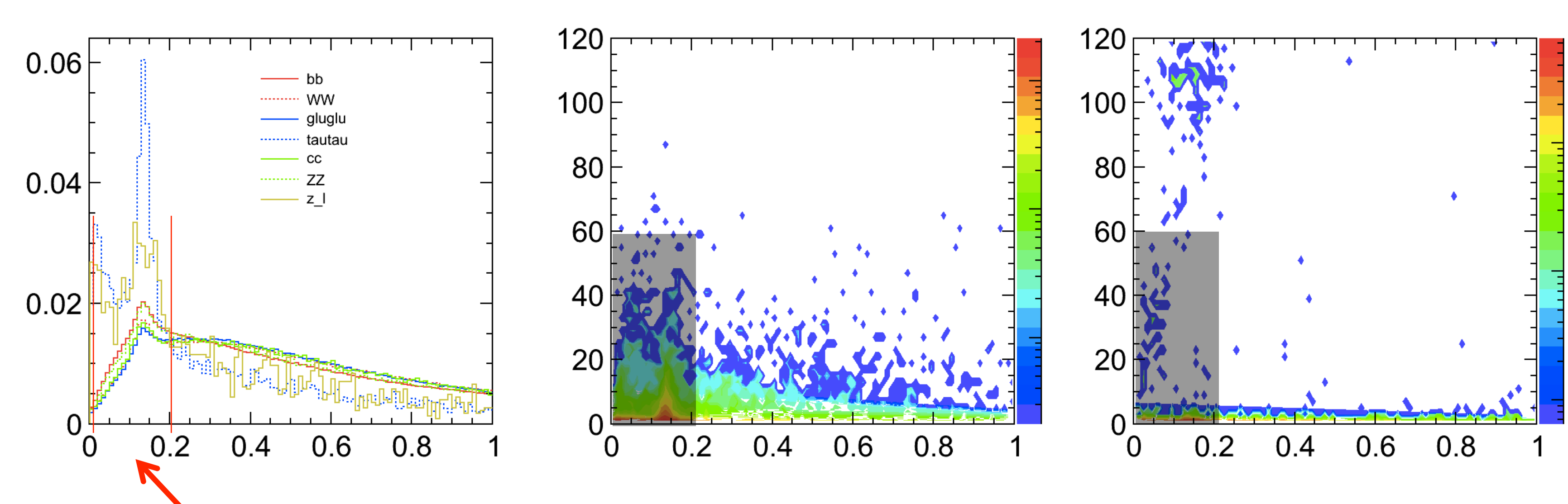
Bias Suppression (for δP_{Tbal})

- In δP_{Tbal} selection, we look at other particles (photon) besides di-lepton :
  $\delta P_{Tbal} \equiv PT_{dl} - PT_{\gamma}$
- So there is bias for some Higgs decay mode ($h \rightarrow \tau\tau$ mode).



Bias Suppression (for δP_{Tbal})

- We can suppress this bias using Energy of photon and invariant mass of each photon

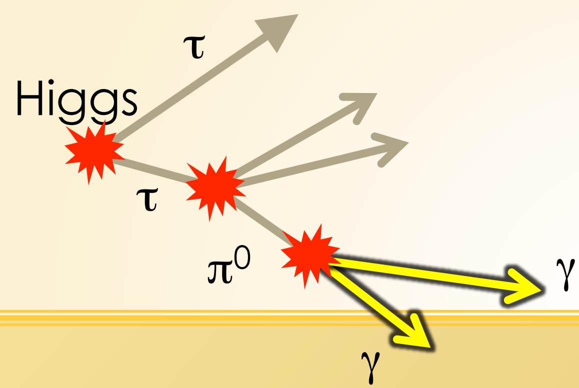


h->ττ signal

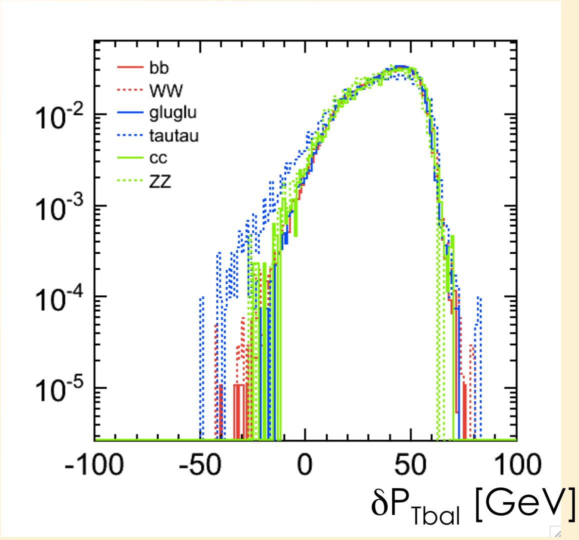
llγ BG

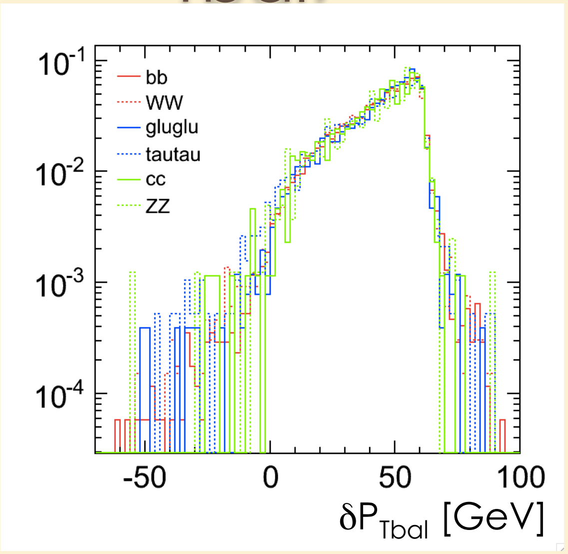
In h→ττ, there is a peak at $m_{2\gamma} \sim m_\pi$

condition of used γ
$m_{2\gamma} > 0.2$ [GeV]
or $E_\gamma > 60$ [GeV]



Bias Suppression (for δP_{Tbal})





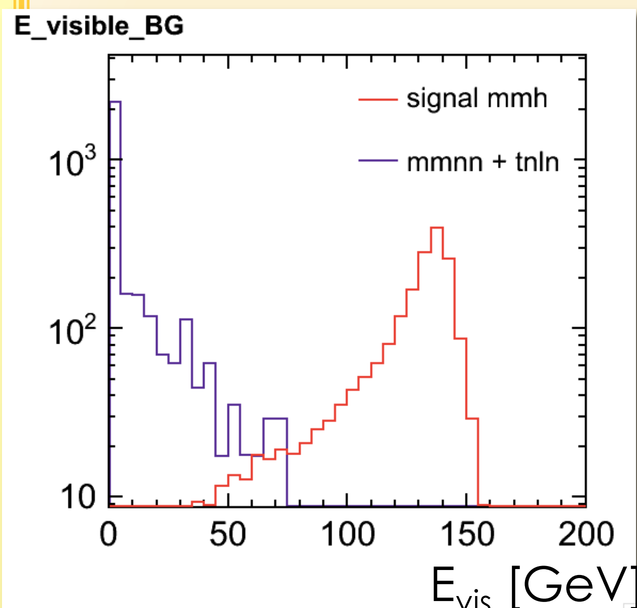
Comparison old&new	**efficiency of dPT_{bal} cut**			
	bb	ττ	cc	z_l (BG)
Simple calc.	99.4%	95.3%	99.0%	14.5%
My calc.	99.8%	97.8%	99.6%	22.2%

- In new calculation of δP_{Tbal}, bias will decrease.

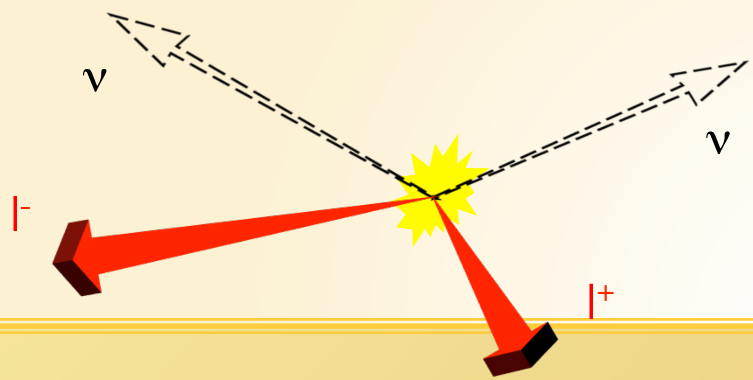
Semi-MI Analysis

μμh	signal	ll	llnn	llff	others
After Cut	1386	322	1479	1054	3
			llnn	llff	others
		1496	2203	937	4

There seems to be large number of remaining llνν BG.



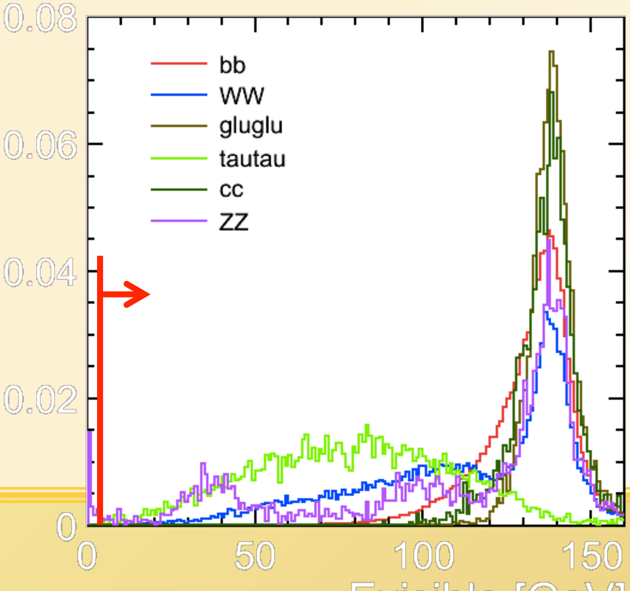
- Since contribution from Higgs invisible decays can be calibrated with data, visible energy selection is effective for reducing these BG.
- $E_{vis} := E_{PFOs} - E_{di\text{-}lepton} > 5$ [GeV]
- Loose selection is applied to avoid bias in signal selection.



Efficiency of $E_{visible}$

H decay mode	$\mu\mu h$ (E_{vis} eff.)	After all cut	eeh (E_{vis} eff.)	After all cut
bb	100%	66.31%	98.68%	39.14%
WW	100%	66.00%	98.31%	38.67%
gluglu	100%	65.40%	98.67%	38.82%
$\tau\tau$	99.94%	65.66%	98.43%	37.82%
cc	100%	66.32%	98.25%	39.43%
ZZ	96.64%	63.98%	94.84%	37.90%

- Bias as expected from SM.



qqh Cut Table

cut	qqH	4 fermion	2 fermion	others (aa, 1f_3f, etc..)
left	490,370	6,255,904	16,267,218	21,274,095
right	331,118	798,363	10,355,564	21,274,095
Box cut (81,101) ZZ (70,90) WW	82.7%	83.9%	99.0%	99.9%
Z like Jet pt cut pt > 20	70.6%	60.9%	30.3%	2.4%
dijet mass cut (76,106)	54.7%	36.2%	10.0%	0.7%
recoil mass cut (110,150)	43.1%	10.8%	2.7%	0.3%
Sphericity cut > 0.1	39.1%	6.7%	0.7%	0.2%
Thrust cut major>0.3 minor>0.1	36.9%	5.2%	0.4%	0.05%