

# Studies of kinematic-fit method for measurements of $H \rightarrow Z \gamma$ decay using ILD detector at ILC

Kazuki Fujii

# Purpose and Flow

- Purpose : Evaluation of  $H \rightarrow Z \gamma$  measurement in ILC
  - : To improve, apply kinematic fit
- Flow
  1. Evaluate photon and jet's resolution .
  2. With the resolution, apply kinematic fit to  $H \rightarrow Z \gamma$  process, and confirm improvement.
  3. Evaluate  $H \rightarrow Z \gamma$  measurement with all bkg.

# 研究の概要

## 測定器分解能評価

- 光子及びジェットの測定分解能を評価
- エネルギー & 角度依存性の精査

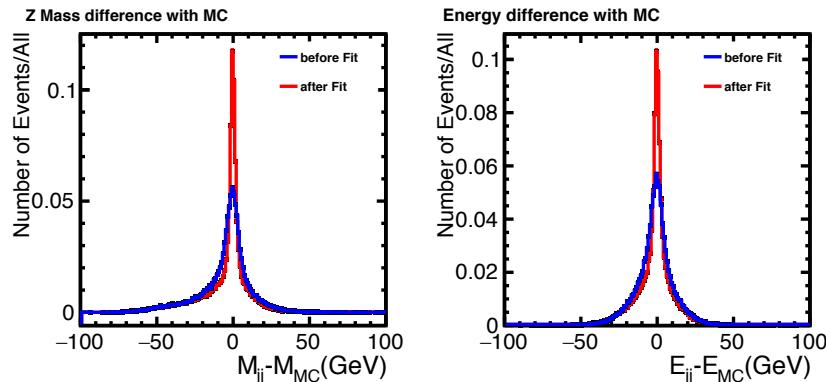
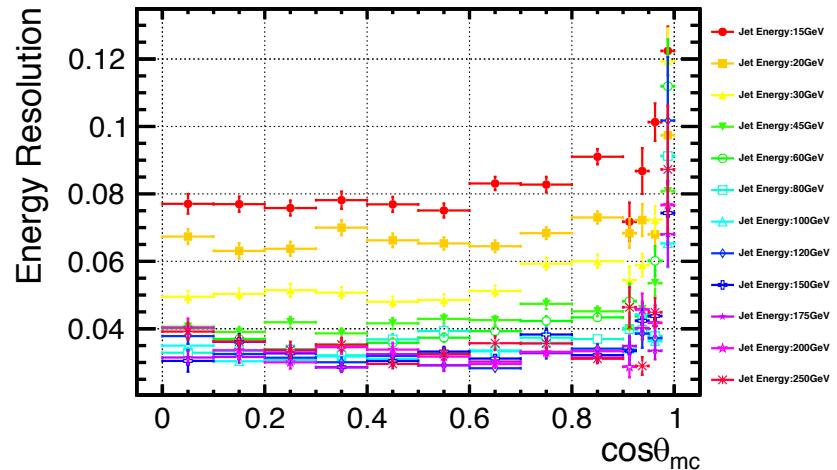
## kinematic fit 構築

- 測定分解能を実装したkinematic fitを構築した
- kinematic fitに必要なパラメータ誤差を測定分解能評価の結果↑から取得
- ZH $\rightarrow$ ZZ $\gamma$  $\rightarrow$ qqqqq $\gamma$ 及びvvqqq $\gamma$ 過程に適用、fit変数の精度向上を確認

## H $\rightarrow$ Z $\gamma$ 崩壊解析へ応用

ZH $\rightarrow$ ZZ $\gamma$  $\rightarrow$ qqqqq $\gamma$ 及びvvqqq $\gamma$ 過程を用いた崩壊分岐比の上限推定に応用し、kinematic fitによる効果を確認

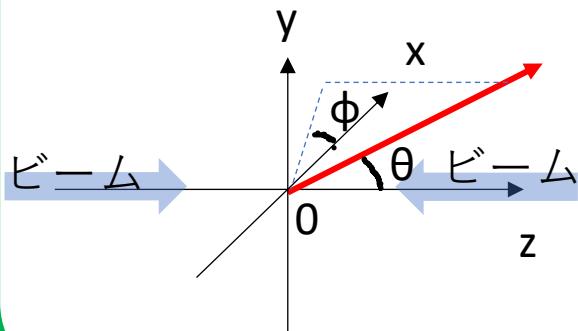
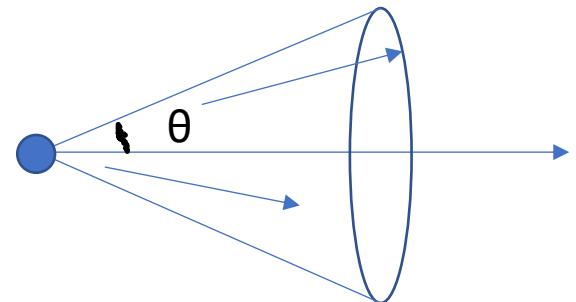
	w/o KF	w KF
Significance	$1.91 \pm 0.01$	$1.98 \pm 0.02$
Upper limit	0.287%	0.283%



# Evaluate photon's resolution

## Reconstructing method

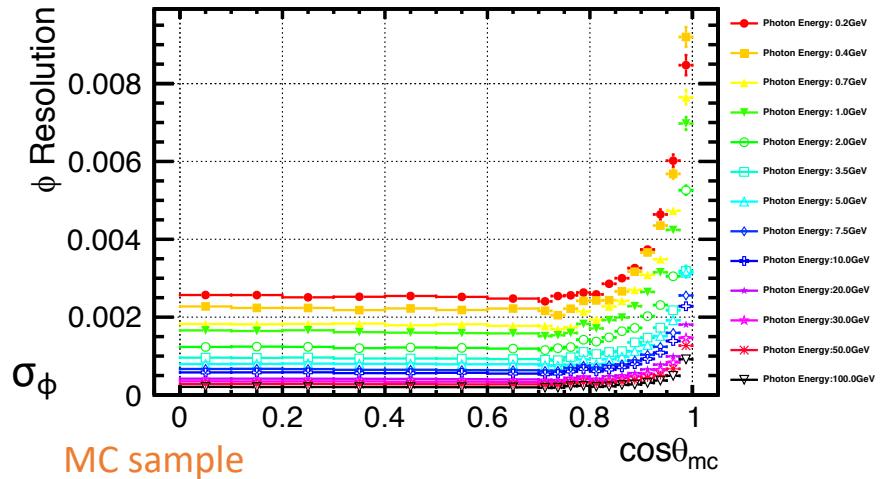
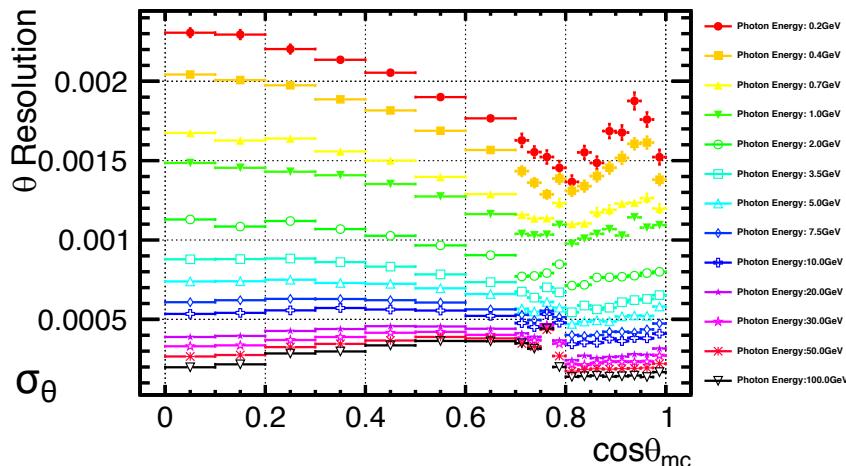
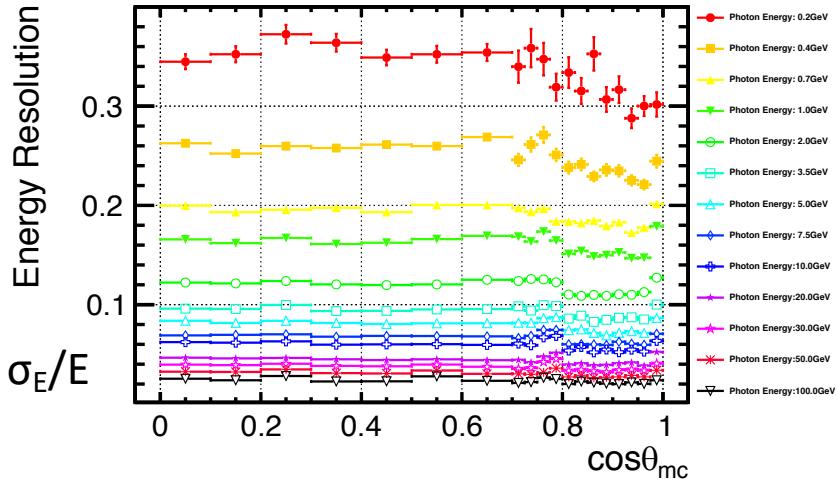
- PFA
- Recombine a max energy photon with photons in cone ( $\cos\theta=0.998$ )



## Evaluate resolution

- Classified by angle  $\theta$  and energy of MC particle
- Made histogram  
 $E_{\text{rec}} - E_{\text{mc}}, \theta_{\text{rec}} - \theta_{\text{mc}}, \phi_{\text{rec}} - \phi_{\text{mc}}$
- Gaussian Fitting → Resolution = standard deviation

# Evaluate photon's resolution



- Single photon event (no bkg v02-00-01)
  - (0.2, 0.4, 0.7, 1.0, 2.0, 3.5, 5.0, 7.5, 10, 20, 30, 50, 100 )GeV
  - 100000 events per energy classes
- ILD model : ILD\_I5\_v02 (DDsim)

Classified by angle  $\theta$   
 $(0 < \cos\theta < 0.7 : \text{per } 0.1, \quad 0.7 < \cos\theta < 1.0 : \text{per } 0.025)$

# Evaluate jet's resolution

## Reconstructing method

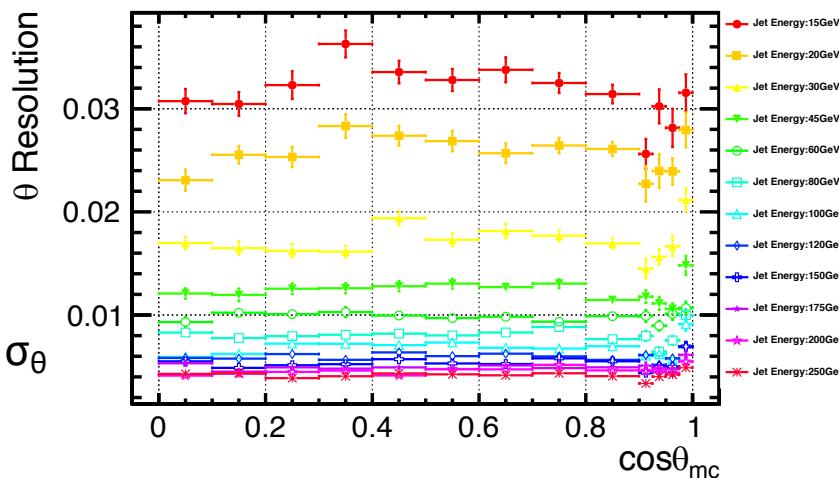
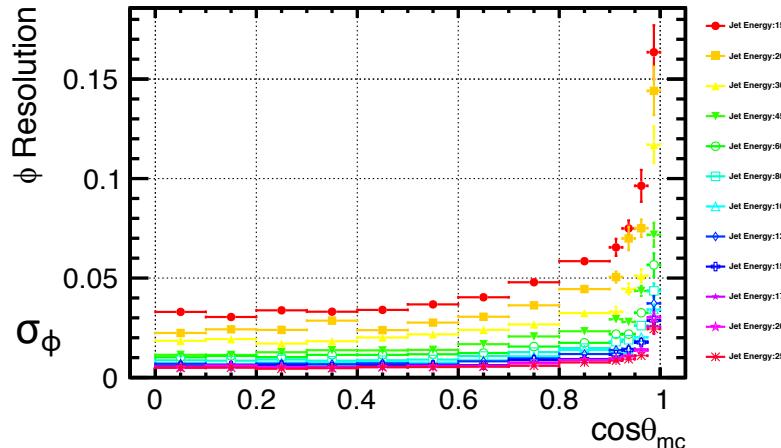
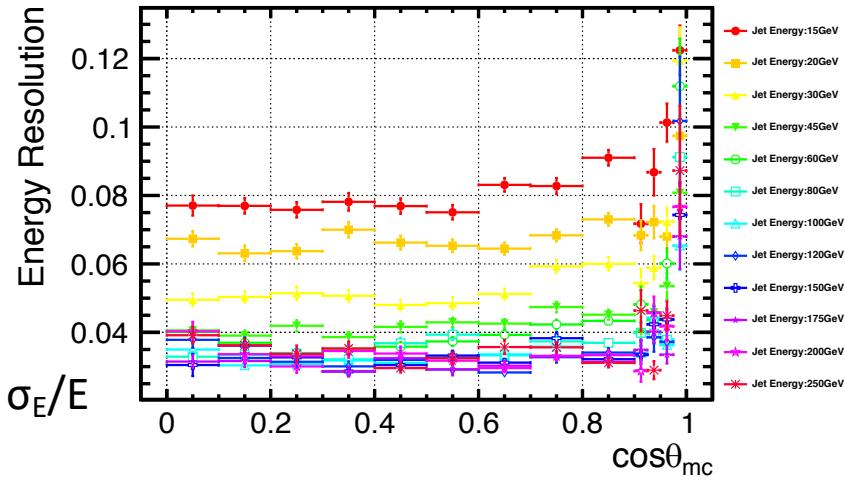
- PFA
- Jet clustering to MC particles and reconstructed particles with Durham

$$y \text{ 值} = \frac{2E_{min}^2(1 - \cos \theta_{ij})}{Q^2}$$

## Evaluate resolution

- Classified by angle  $\theta$  and energy of MC particle
- Made histogram  
 $E_{rec} - E_{mc}, \theta_{rec} - \theta_{mc}, \phi_{rec} - \phi_{mc}$
- Gaussian Fitting → Resolution = standard deviation

# Evaluate jet's resolution



## MC sample

- off-shell  $Z \rightarrow uds$  2 jets (no bkg v02-00-01)
- $\sqrt{s} = (30, 40, 60, 91, 120, 160, 200, 240, 300, 350, 400, 500) \text{ GeV}$
- 10000 events per energy

ILD model : ILD\_I5\_v02 (DDsim)

Classified by angle  $\theta$

( $0 < \cos\theta < 0.9$  : per 0.1,  $0.9 < \cos\theta < 1.0$  : per 0.025)

# Purpose and Flow

- Purpose : Evaluation of  $H \rightarrow Z \gamma$  measurement in ILC
  - : To improve, apply kinematic fit
- Flow
  1. Evaluate photon and jet's resolution .
  2. With the resolution, apply kinematic fit to  $H \rightarrow Z \gamma$  process, and confirm improvement.
  3. Evaluate  $H \rightarrow Z \gamma$  measurement with all bkg.

# Kinematic fitの原理

ラグランジュ未定乗数法を用いて  
測定量を運動学的制約の下で最適化

$$\begin{aligned}\chi_T^2(\vec{\eta}, \vec{\xi}, \vec{\lambda}) &= \chi^2(\vec{\eta}) + F_C(\vec{\eta}, \vec{\xi}, \vec{\lambda}) \\ \chi^2(\vec{\eta}) &= (\vec{\eta} - \vec{y})^T V^{-1} (\vec{\eta} - \vec{y}) \\ F_C(\vec{\eta}, \vec{\xi}, \vec{\lambda}) &= 2\vec{\lambda}^T \cdot \vec{f}(\vec{\eta}, \vec{\xi})\end{aligned}$$

$\chi_T^2(\vec{\eta}, \vec{\xi}, \vec{\lambda})$  を最小化する

$$\begin{aligned}\text{自由度: } N_{dof} &= N_m - \{N_f - (K - J)\} \\ &= K - J\end{aligned}$$

引用:18年修士論文:加藤悠

$\vec{y}$  : 実際の測定量 (N 次)

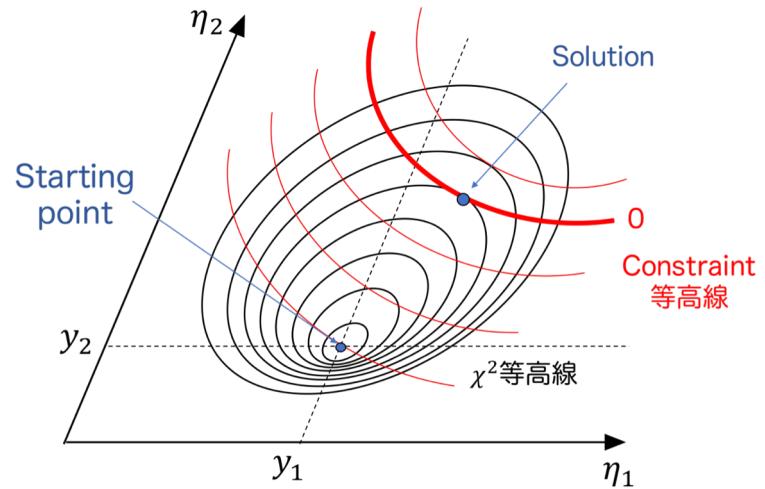
$\vec{\eta}$  : フィットパラメータ (N 次)

$\vec{\xi}$  : 非測定量パラメータ (J 次)

$\vec{\lambda}$  : ラグランジュ未定乗数パラメータ (K 次)

$\vec{f}(\vec{\eta}, \vec{\xi})$  : 制約条件関数 (K 次)

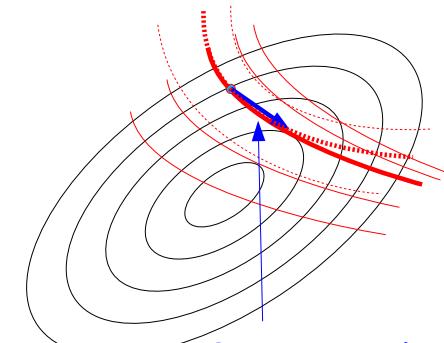
$V$  : 測定量の分散共分散対角行列 ( $N \times N$ )



# Newton Fitter

$$\begin{cases} \nabla_{\eta} \chi_T^2 = \nabla_{\eta} \chi_A^2 + 2 \sum_{k=1}^K \lambda_k \nabla_{\eta} f_k = \vec{0} \\ \nabla_{\lambda} \chi_T^2 = \vec{f} = \vec{0} \end{cases}$$

In Newton Fitter, calculate an approximate solution with iteration of matrix calculation with second derivative term



One NewtonFitter iteration step

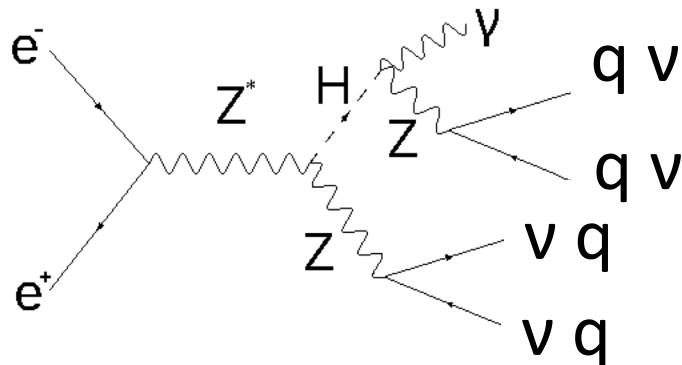
$$\left( \begin{array}{cccccc} \frac{\partial^2 \chi_A^2}{\partial \eta_1 \partial \eta_1} + \lambda_k \frac{\partial^2 f_k}{\partial \eta_1 \partial \eta_1} & \cdots & \frac{\partial^2 \chi_A^2}{\partial \eta_1 \partial \eta_N} + \lambda_k \frac{\partial^2 f_k}{\partial \eta_1 \partial \eta_N} & \frac{\partial f_1}{\partial \eta_1} & \cdots & \frac{\partial f_K}{\partial \eta_1} \\ \vdots & & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 \chi_A^2}{\partial \eta_N \partial \eta_1} + \lambda_k \frac{\partial^2 f_k}{\partial \eta_N \partial \eta_1} & \cdots & \frac{\partial^2 \chi_A^2}{\partial \eta_N \partial \eta_N} + \lambda_k \frac{\partial^2 f_k}{\partial \eta_N \partial \eta_N} & \frac{\partial f_1}{\partial \eta_N} & \cdots & \frac{\partial f_K}{\partial \eta_N} \\ \frac{\partial f_1}{\partial \eta_1} & \cdots & \frac{\partial f_1}{\partial \eta_N} & 0 & \cdots & 0 \\ \vdots & & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_K}{\partial \eta_1} & \cdots & \frac{\partial f_K}{\partial \eta_N} & 0 & \cdots & 0 \end{array} \right) \begin{pmatrix} \eta_1^\nu - \eta_1^{\nu+1} \\ \vdots \\ \eta_N^\nu - \eta_N^{\nu+1} \\ \lambda_1^\nu - \lambda_1^{\nu+1} \\ \vdots \\ \lambda_K^\nu - \lambda_K^{\nu+1} \end{pmatrix} = \begin{pmatrix} \frac{\partial \chi_A^2}{\partial \eta_1} + \lambda_k^\nu \frac{\partial f_k}{\partial \eta_1} \\ \vdots \\ \frac{\partial \chi_A^2}{\partial \eta_N} + \lambda_k^\nu \frac{\partial f_k}{\partial \eta_N} \\ f_1 \\ \vdots \\ f_K \end{pmatrix}$$

Using second derivative term,  
Convergence speed improve

## Convergence condition

- $\delta \chi^2_T < 0.001$
- $2 \sum (\lambda \nabla f) < 0.001$
- $2 \sum (\lambda \nabla f) < 10^{-6}$  or  $\delta \{2 \sum (\lambda \nabla f)\} < 0.2$

# Apply to $\nu\nu\bar{q}\bar{q}\gamma$

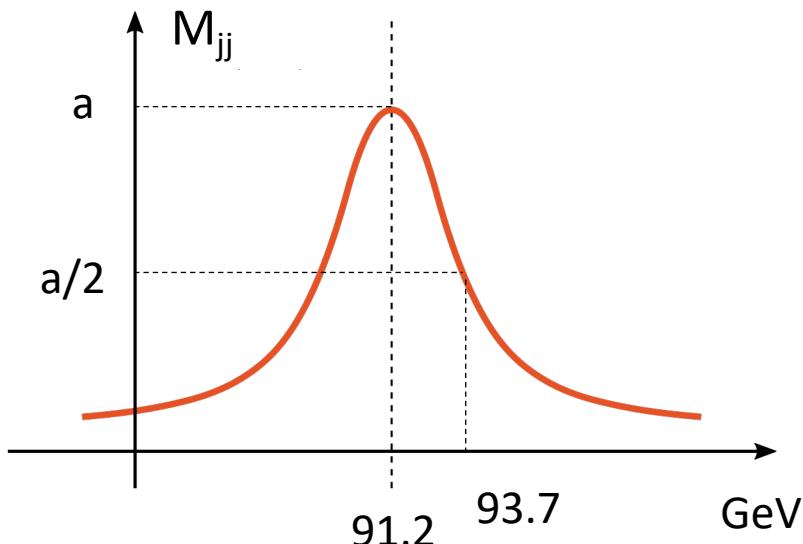


Fit object

- 2 jets( $E, \theta, \phi$ )

Constraint ( $N_{dof} = 1$ )

- 2jet mass =  $Z$  mass  
(mean = 91.2 GeV, width=2.5 GeV Breit-Wigner)



Two neutrino



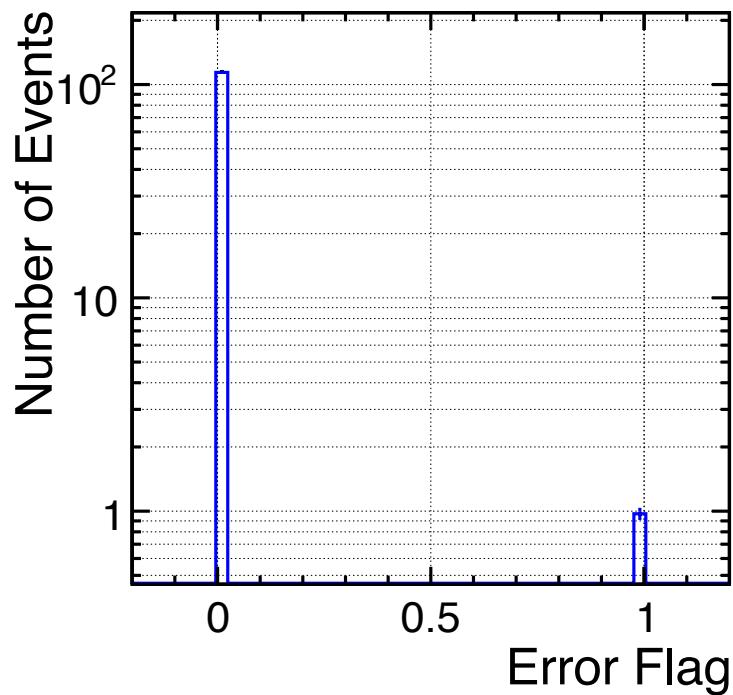
not use Energy constraint and Momentum constraint

# Apply to $\nu\nu\bar{q}\bar{q}\gamma$

Success rate

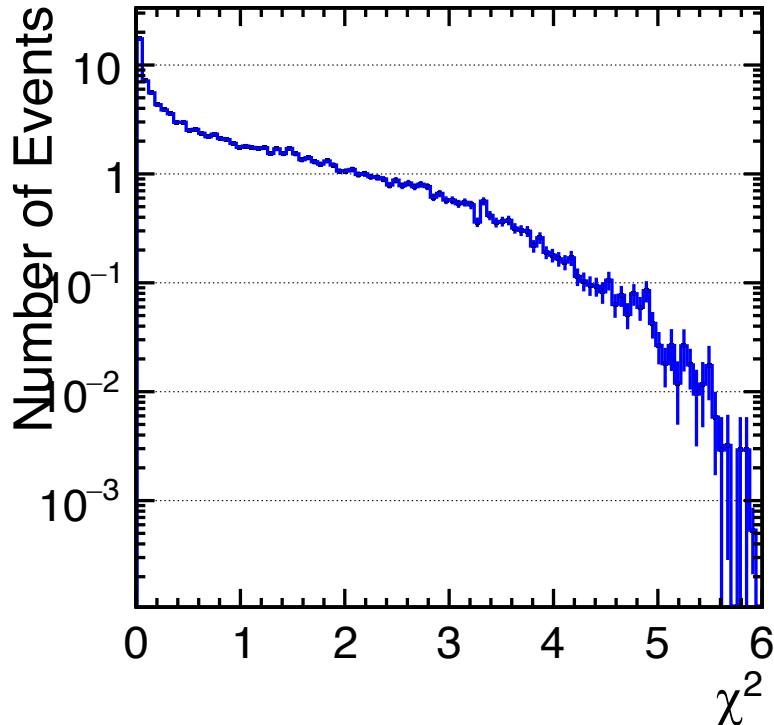
If

$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 0.9915

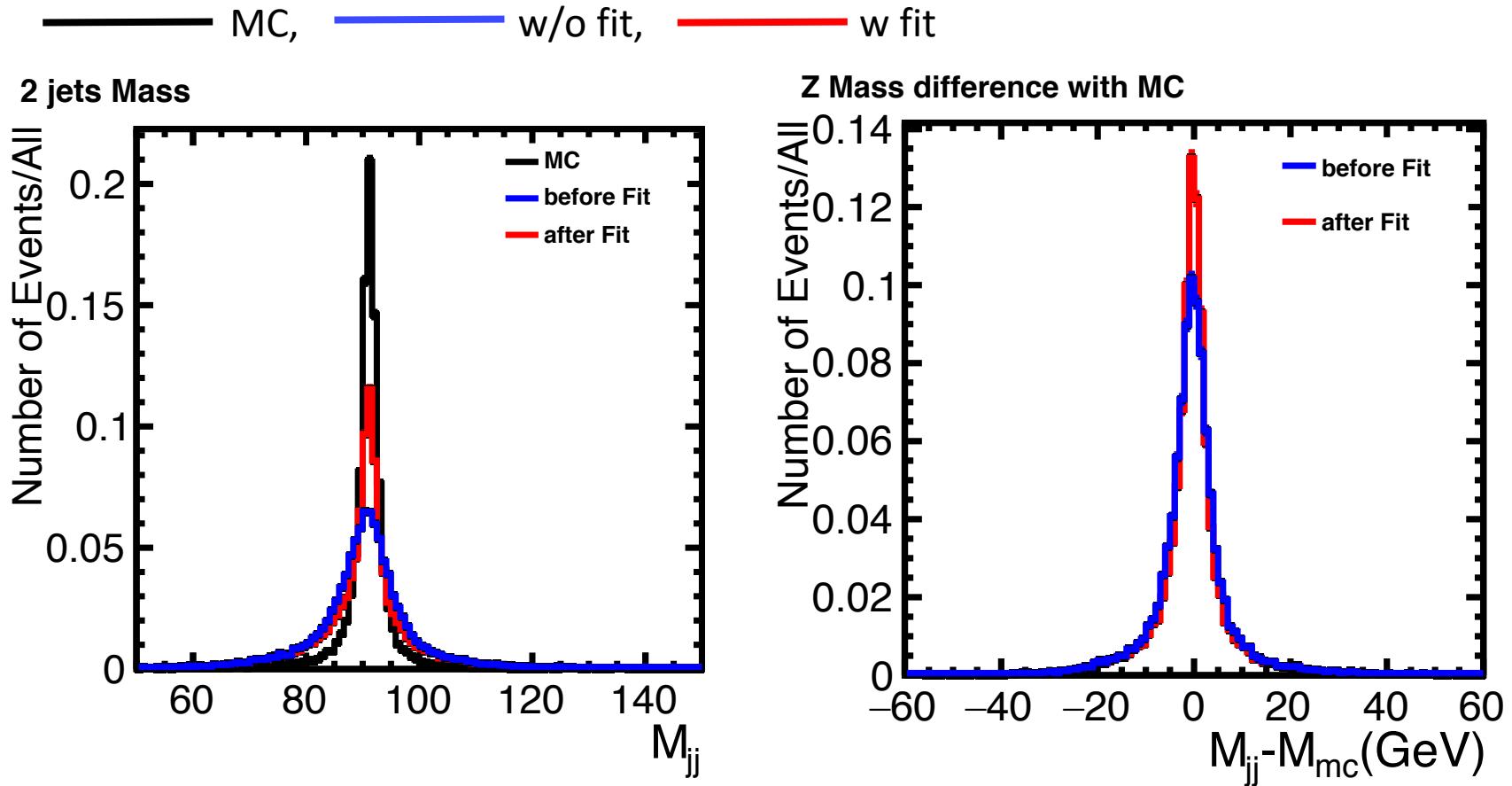


99%以上の収束率を達成

$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 0.9915

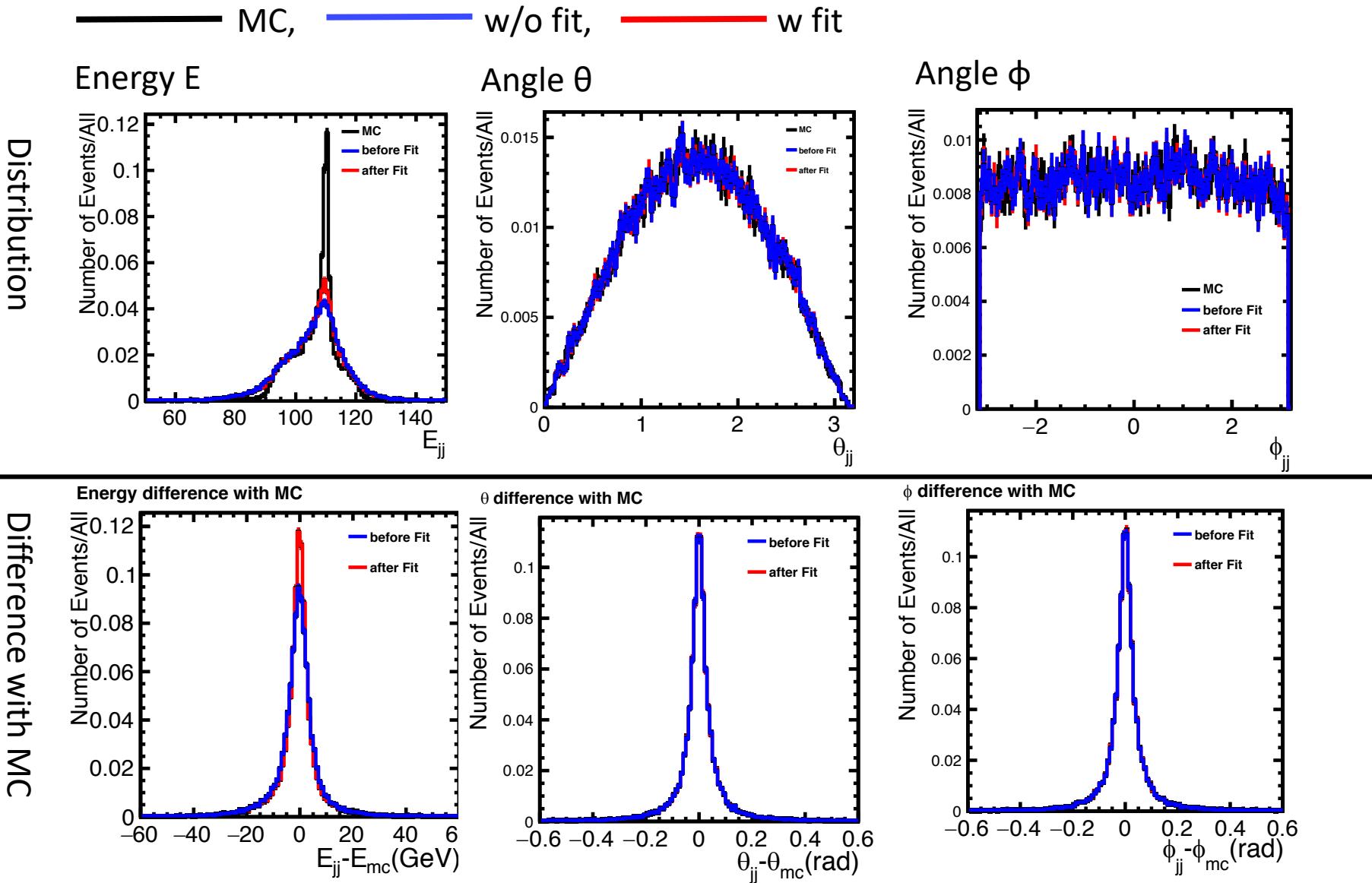


# Convergence of 2jet mass



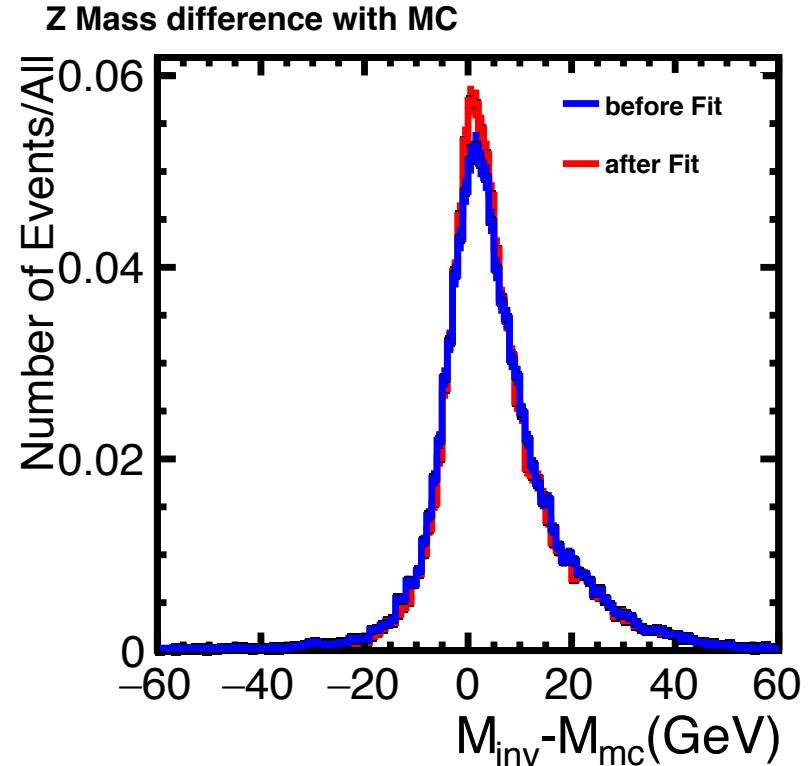
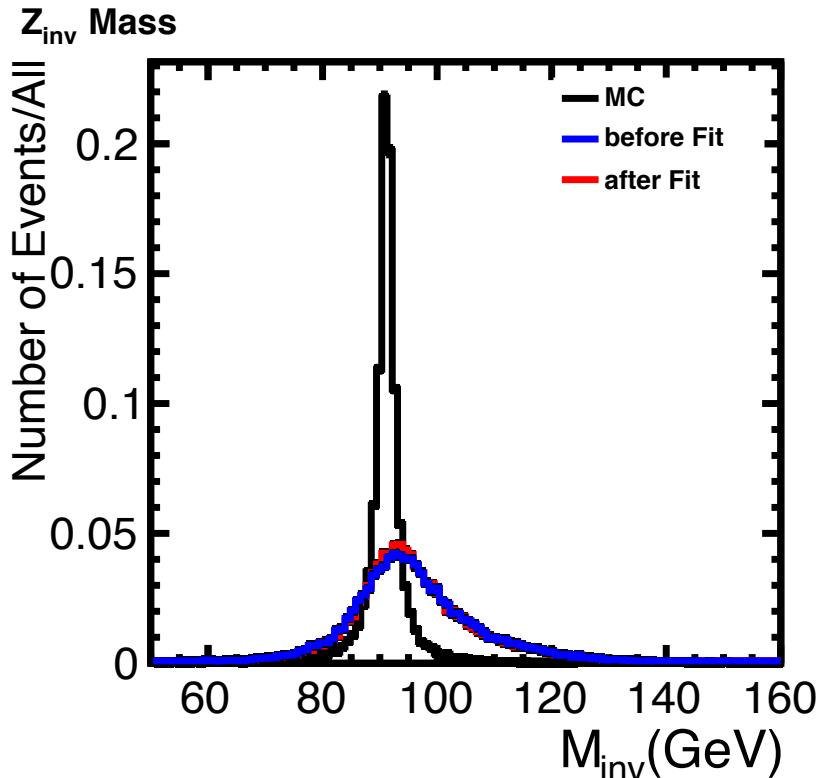
Confirm that the mass distribution become like the distribution of MC by fitting

# Change of 2jets fit variables



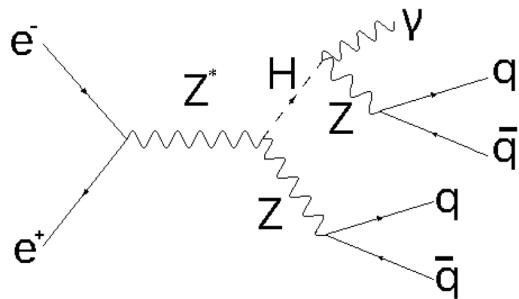
# Change of missing mass

— MC, — w/o fit, — w fit



Confirm that the distribution of mass improves although it is not as good as 2 jets  
Mass is shifting to high energy side due to influence of bkg

# Apply to $qqqq\gamma$

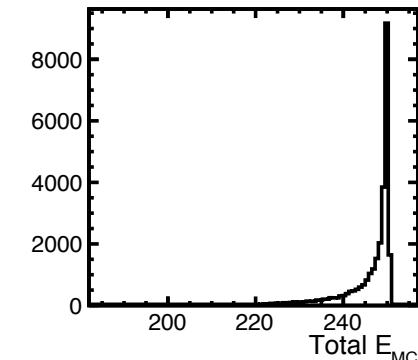
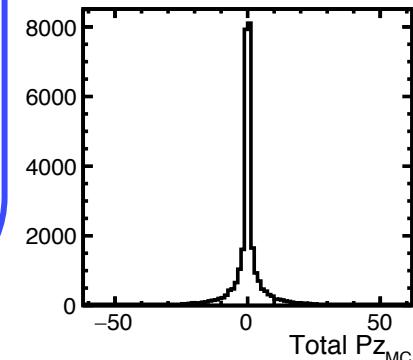
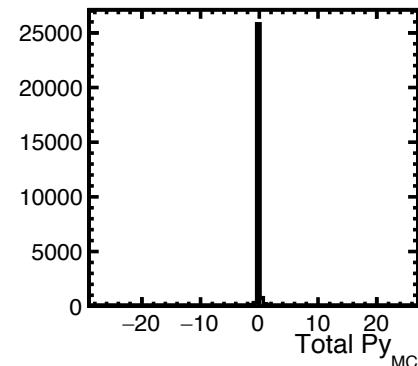
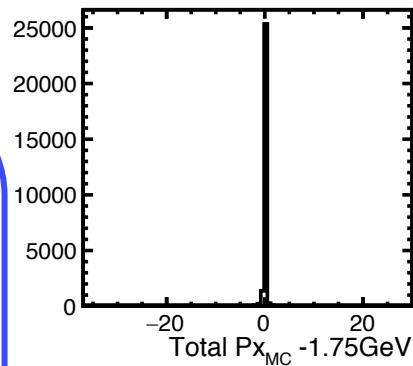


Constraint( $N_{\text{dof}} = 6$ )

- 2 jet mass =  $Z$  mass  
(mean = 91.2 GeV, width=2.5 GeV  
Breit-Wigner)
- 2 jet + photon mass =  $H$  mass  
(125 GeV:Hard constraint)
- $P_{x\text{tot}}=1,75$  GeV :Hard constraint)
- $P_{y\text{tot}}=0$  :Hard constraint)
- $P_{z\text{tot}}=0$  :  
 $\sigma = 2.3$  GeV Gaussian

Fit objects

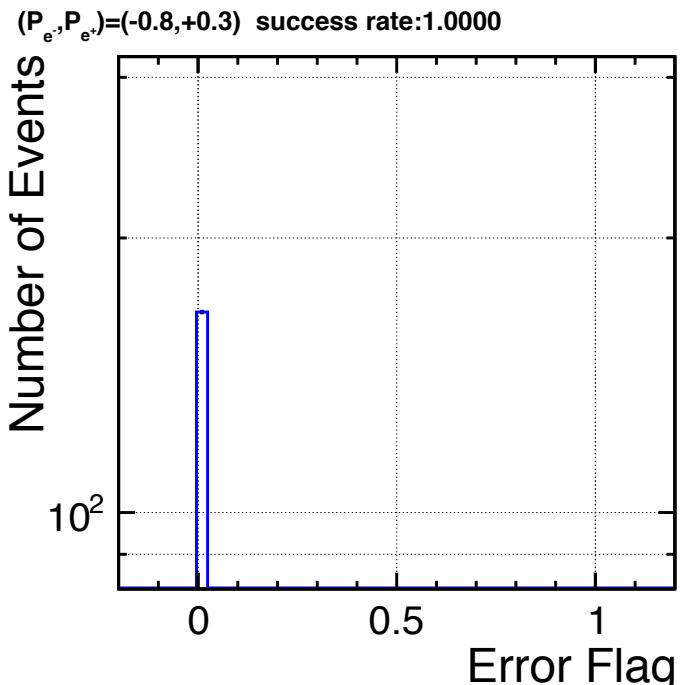
- 4 jets (with the resolution times 1.5)
- Isolated photon



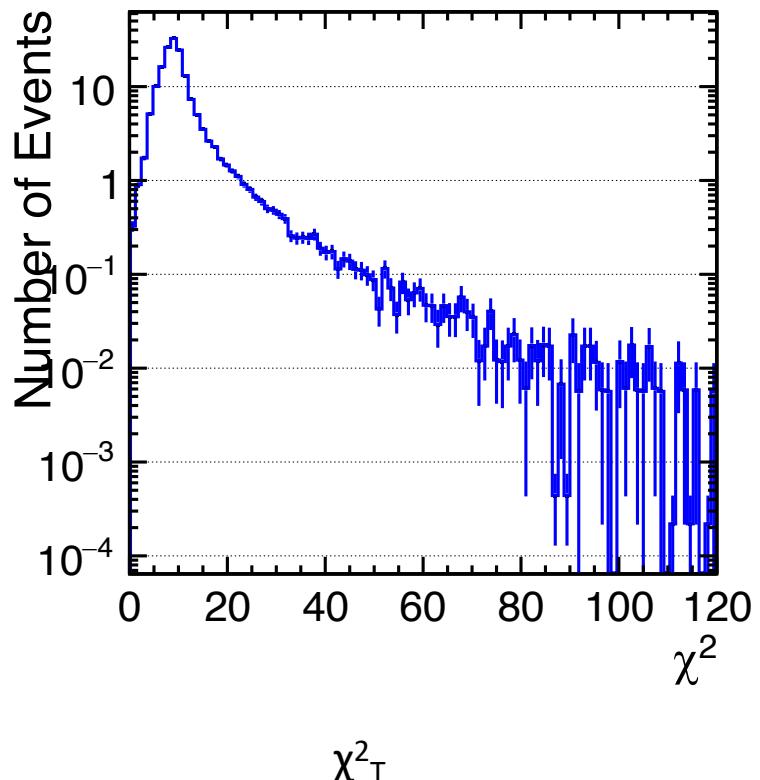
# Apply to $qqqq\gamma$

Success rate

If all 6 pairings don't converge, output error.

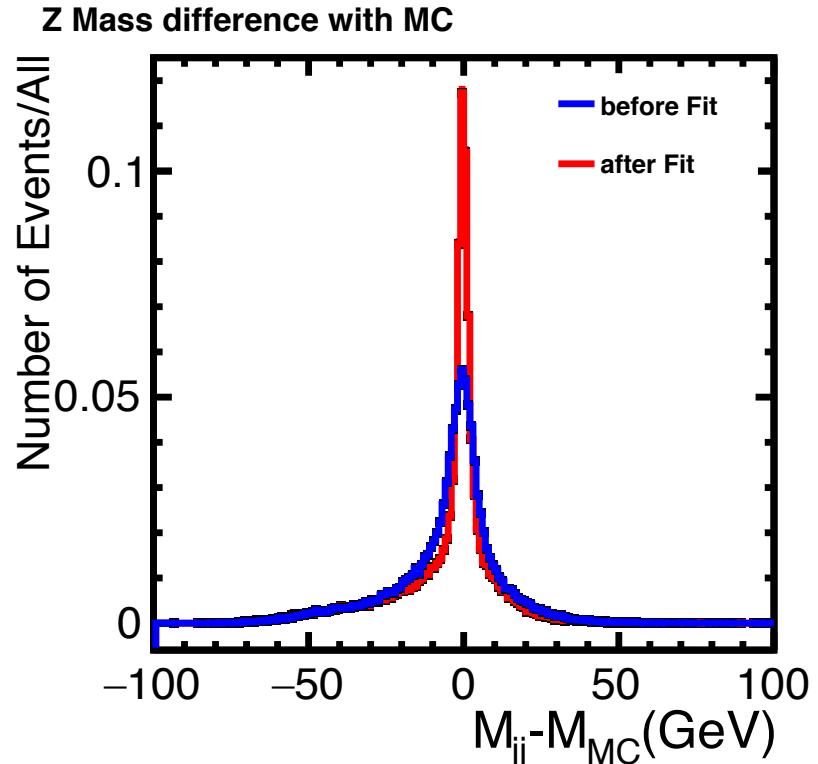
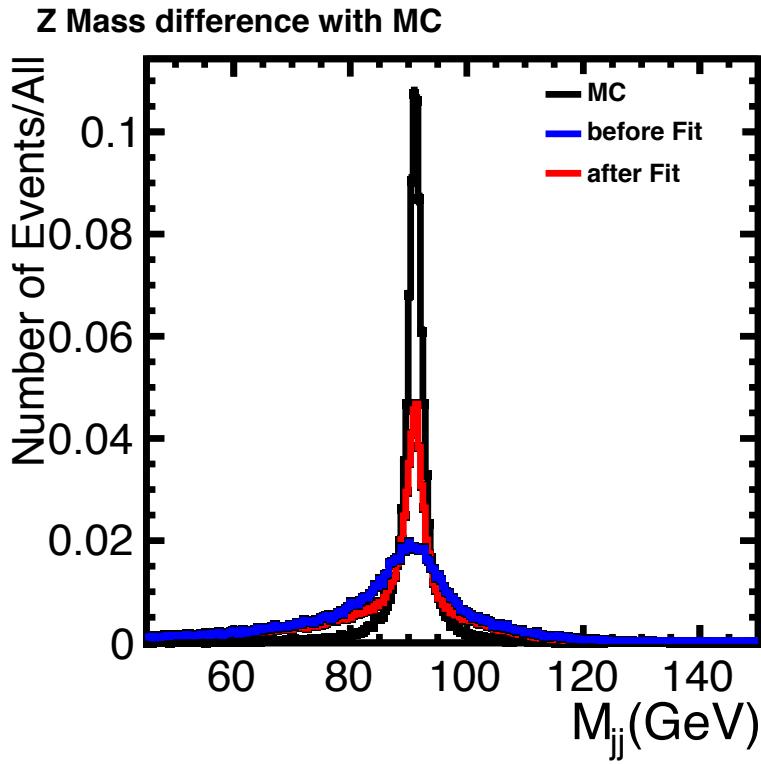


$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 1.0000



# Convergence of 2jet mass

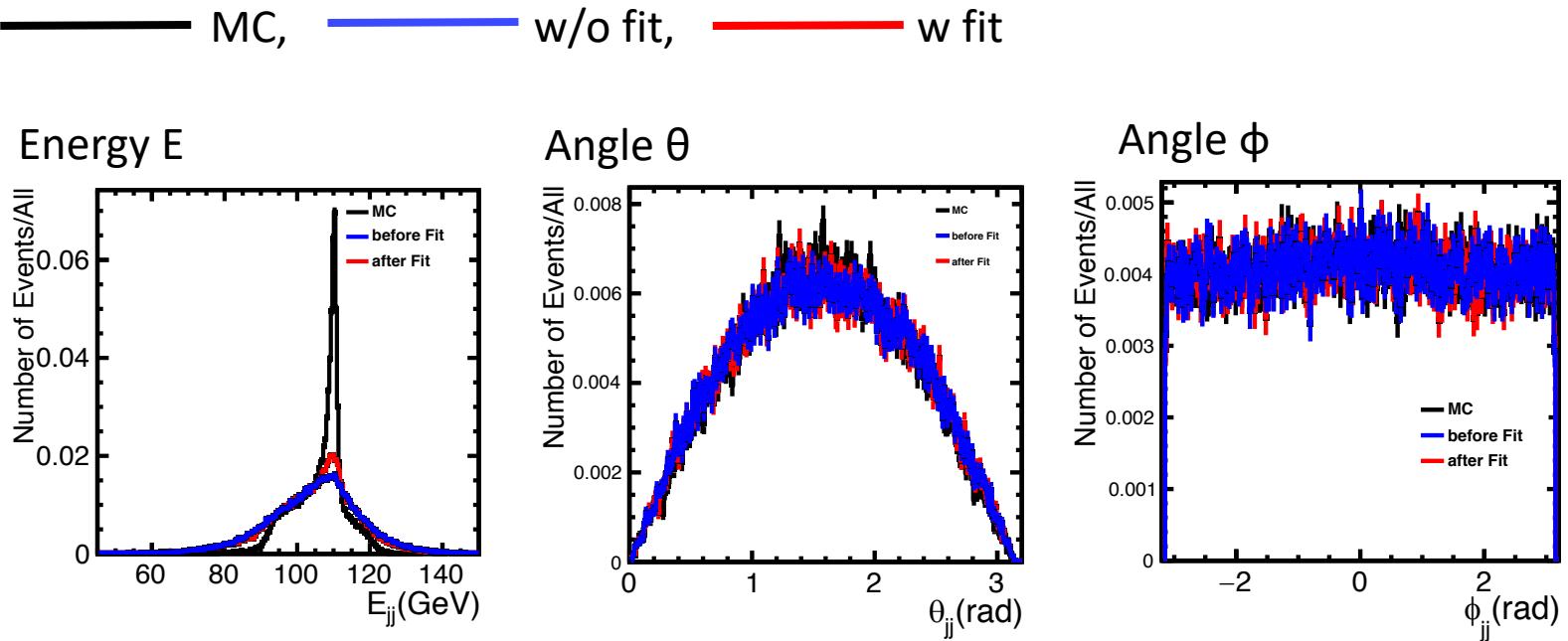
— MC, — w/o fit, — w fit



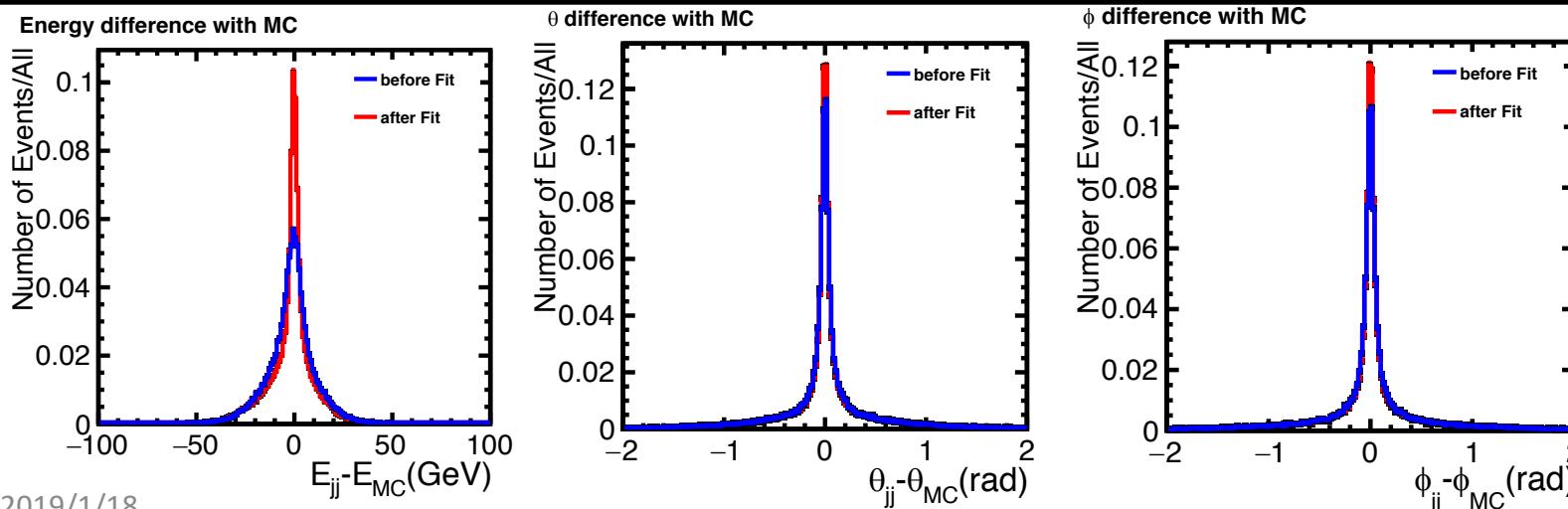
Confirm that the mass distribution become like the distribution of MC by fitting

# Change of 4jets fit variables

Distribution



Difference with MC



# Purpose and Flow

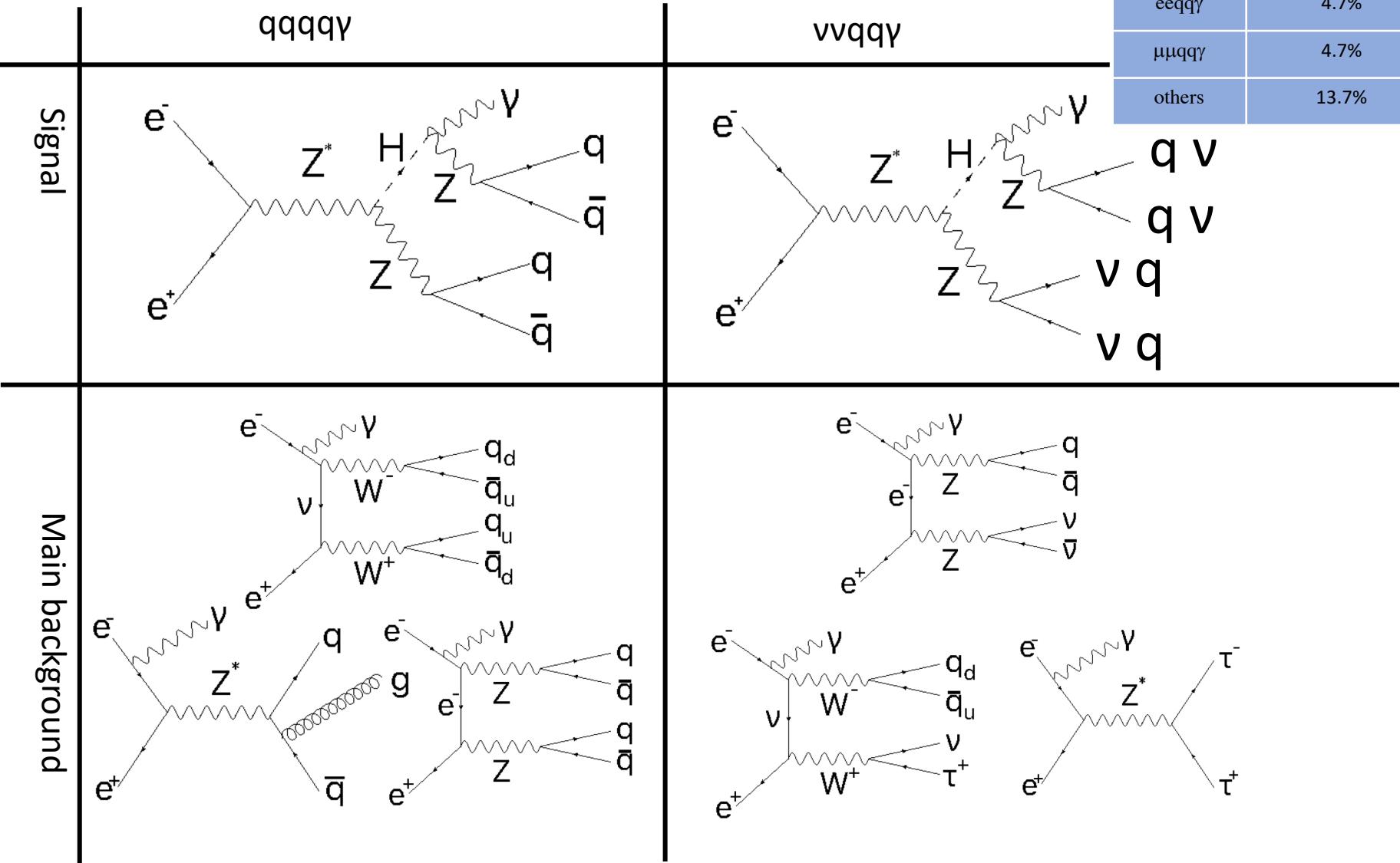
- Purpose : Evaluation of  $H \rightarrow Z \gamma$  measurement in ILC
  - : To improve, apply kinematic fit
- Flow
  1. Evaluate photon and jet's resolution .
  2. With the resolution, apply kinematic fit to  $H \rightarrow Z \gamma$  process, and confirm improvement.
  3. Evaluate  $H \rightarrow Z \gamma$  measurement with all bkg.

# Simulation set up

- ▶ Simulation set up
  - ▶ iLCSoft : v02\_00\_01
  - ▶ Generator : WHIZARD 1.95
  - ▶ Samples: Mass production sample(2012 DBD)
    - + Signal sample( $e^+e^- \rightarrow ZH, H \rightarrow Z\gamma$ )
  - ▶ Detector: ILD full simulation (Mokka)

# Signal processes

終状態	BR
qqqq $\gamma$	48.9%
vvqq $\gamma$	28.0%
eeqq $\gamma$	4.7%
$\mu\mu qq\gamma$	4.7%
others	13.7%



# Analysis flow ( $\nu\nu\text{qq}\gamma$ )

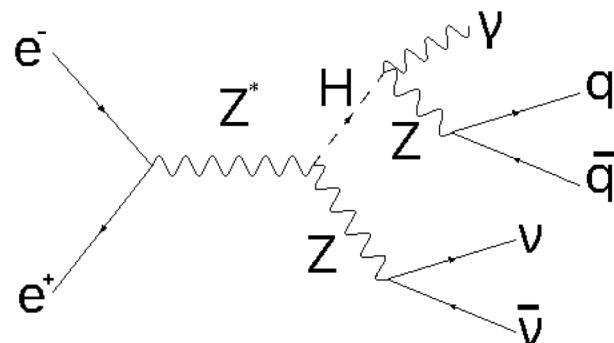
1. Reconstruction (Pandora PFA)
2. Isolated lepton veto
3. Isolated photon selection
4. 2 jet clustering : Durham
5. Kinematic-fit ( $M_{jj} = M_Z$ )
6. Variable cuts

## I. Pre-cut

1.  $\chi^2_T < 5.0$
2.  $\log_{10}(y_{23}) = (-4.2, 0)$
3.  $E_{jj} = (60, 150) \text{ [GeV]}$
4.  $M_{inv} = (60, 150) \text{ [GeV]}$
5.  $|\cos\theta_\gamma| = (0, 0.96), |\cos\theta_{jj}| = (0, 0.96), |\cos\theta_{inv}| = (0, 0.98)$
6.  $M_{jj\gamma} = (80, 170) \text{ [GeV]}$
7.  $M_{rec} = (70, 190) \text{ [GeV]}$

## II. MVA(BDTG) :

Pre-cut variables +  $E_\gamma$ , Energy ratio (Isolated photon)



# Result( $\nu\nu qq\gamma$ )

$$Significance = \frac{N_S}{\sqrt{N_S + N_B}}$$

$\ln(P_{e-}, P_{e+})=(-0.8, +0.3)$

Cut condition	Signal	2f_z_l	4f_sznu_sl	4f_ww_sl	4f_zz_sl	other bkg	all bkg	Significance
No cut	164.39	11694500	244625	9893620	771234	118768000	141372000	0.00909658
Particle selection	$114.97 \pm 0.55$	279259	6841	220108	20975	2398370	$2925550 \pm 8420$	$0.0672 \pm 0.0003$
Success kinematic-fit	$114.00 \pm 0.55$	277420	6811	219262	20878	2375320	$2899700 \pm 8384$	$0.0669 \pm 0.0003$
$\chi^2_T < 5.0$	$113.82 \pm 0.55$	174138	6348	193956	16168	1050320	$1440930 \pm 6069$	$0.0948 \pm 0.0005$
$-4.2 < \log 10(y_{23}) < 0$	$113.69 \pm 0.55$	92201	6338	193936	16157	1012220	$1320850 \pm 5984$	$0.0989 \pm 0.0005$
$60 \text{ GeV} < E_{jj} < 150 \text{ GeV}$	$113.21 \pm 0.55$	65612	6142	171961	14121	931584	$1189420 \pm 5752$	$0.1038 \pm 0.0006$
$60 \text{ GeV} < M_{inv} < 150 \text{ GeV}$	$111.59 \pm 0.55$	53456	5975	123220	11683	230380	$424714 \pm 2925$	$0.171 \pm 0.001$
$ \cos \theta_\gamma  < 0.96$								
$ \cos \theta_{jj}  < 0.96$	$102.31 \pm 0.53$	32244	4307	85598	7857	24125	$154131 \pm 1044$	$0.261 \pm 0.002$
$ \cos \theta_{inv}  < 0.98$								
$80 \text{ GeV} < M_{jj\gamma} < 170 \text{ GeV}$	$101.91 \pm 0.53$	27735	4244	73974	7423	20551	$133927 \pm 955$	$0.278 \pm 0.002$
$70 \text{ GeV} < M_{rec} < 190 \text{ GeV}$	$101.86 \pm 0.53$	27589	4240	72041	7390	20438	$131700 \pm 948$	$0.281 \pm 0.002$
$BDTG \text{ Cut} < 0.8250$	$51.44 \pm 0.41$	192	532	676	847	112	$2358 \pm 87$	$1.05 \pm 0.02$

w/o Kinematic-fit: $1.03 \pm 0.02$  → with Kinematic-fit: $1.05 \pm 0.02$

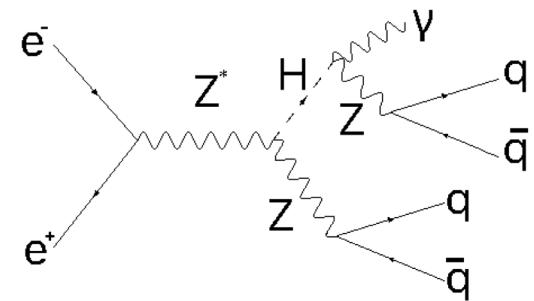
$\ln(P_{e-}, P_{e+})=(+0.8, -0.3)$

w/o Kinematic-fit: $1.10 \pm 0.02$  → with Kinematic-fit : $1.17 \pm 0.03$

# Analysis flow(qqqq $\gamma$ )

1. Reconstruction (PandoraPFA)
2. Isolated lepton veto
3. Isolated photon selection
4. 4 jet clustering: Durham
5. Kinematic-fit
6. Event selection
  - I. Pre-cuts

$$\begin{aligned} M_{jj} &= M_Z, M_{jj\gamma} = M_H, \\ P_{x_{tot}} &= 1.75, P_{y_{tot}} = 0, \\ P_{z_{tot}} &= 0 \end{aligned}$$



1.  $\chi^2_T < 60$
2.  $\log_{10}(y_{45}) = (-4.4, 0)$ ,  $\log_{10}(y_{23}) = (-2.4, 0)$
3.  $E_{jj1} = (60, 150) \text{ [GeV]}$ ,  $E_{jj2} = (40, 150) \text{ [GeV]}$
4.  $|\cos\theta_\gamma| = (0, 0.96)$ ,  $|\cos\theta_{jj1}| = (0, 0.96)$ ,  $|\cos\theta_{jj2}| = (0, 0.98)$
5.  $E_{jj\gamma} = (126, 170) \text{ [GeV]}$
6.  $M_{rec} = (50, 180) \text{ [GeV]}$

## II. MVA(BDTG):

Precut variables +  $E_\gamma$ , Energy ratio(Iso photon), btag2

# Result(qqqq $\gamma$ )

$$Significance = \frac{N_S}{\sqrt{N_S + N_B}}$$

$\ln(P_{e-}, P_{e+})=(-0.8, +0.3)$

Cut condition	Signal	2f_z_h	4f_ww_h	4f_zzorww_h	4f_zz_h	other bkg	all bkg	Significance
No cut	205.45	70241800	7835600	6526890	757239	56010200	141372000	0.0246602
Particle selection	$165.88 \pm 0.63$	1941710	253826	211670	24267	376985	$2808460 \pm 8363$	$0.0990 \pm 0.0004$
Success kinematic-fit	$165.88 \pm 0.63$	1679350	253760	211584	24252	333194	$2502140 \pm 7817$	$0.1049 \pm 0.0004$
$\chi_T^2 < 60$	$163.91 \pm 0.63$	783947	242115	201690	23249	81450	$1332450 \pm 5698$	$0.1420 \pm 0.0006$
$-4.4 < \log 10(y45) < 0$	$163.91 \pm 0.63$	751258	242100	201672	23223	13084	$1231340 \pm 5524$	$0.1477 \pm 0.0007$
$-2.4 < \log 10(y23) < 0$	$163.78 \pm 0.63$	487761	241510	201198	23126	9156	$962751 \pm 4542$	$0.1669 \pm 0.0008$
$65 \text{ GeV} < E_{jj1} < 150 \text{ GeV}$	$163.29 \pm 0.63$	432052	237805	198154	22918	5671	$896599 \pm 4335$	$0.1724 \pm 0.0008$
$40 \text{ GeV} < E_{jj2} < 150 \text{ GeV}$								
$ \cos \theta_\gamma  < 0.96$								
$ \cos \theta_{jj1}  < 0.98$	$151.91 \pm 0.63$	287558	177027	147812	17357	3990	$633744 \pm 3569$	$0.191 \pm 0.001$
$ \cos \theta_{jj2}  < 0.98$								
$126 \text{ GeV} < E_{jj\gamma} < 170 \text{ GeV}$	$151.14 \pm 0.63$	283939	175524	146343	17217	3891	$626913 \pm 3549$	$0.191 \pm 0.001$
$50 \text{ GeV} < M_{rec} < 180 \text{ GeV}$	$150.55 \pm 0.63$	266015	168392	140367	16836	3801	$595411 \pm 3441$	$0.195 \pm 0.001$
$BDTG \text{ Cut} < 0.8951$	$48.00 \pm 0.47$	1153	1007	858	1338	45	$4400 \pm 244$	$0.72 \pm 0.02$

w/o Kinematic-fit: $0.69 \pm 0.02$  → with Kinematic-fit : $0.72 \pm 0.02$

$\ln(P_{e-}, P_{e+})=(+0.8, -0.3)$

w/o Kinematic-fit: $0.94 \pm 0.02$  → with Kinematic-fit : $0.96 \pm 0.02$

# Total result

## Total significance

w/o Kinematic fit :  $1.91 \pm 0.01$  → with Kinematic fit :  $1.98 \pm 0.02$

When  $H \rightarrow Z\gamma$  BR=0.154%,

	w/o Kinematic fit	w Kinematic fit
Significance	$1.91 \pm 0.01$	$1.98 \pm 0.02$
$\Delta BR$	0.081%	0.078%
$\Delta BR / BR_{SM}$	52.4%	50.5%
Upper limit(95% C.L.)	0.287%	0.283%
UL/ $BR_{SM}$	1.52	1.51

# Plan

## kinematic fit

- Add new distribution for energy and momentum
- Add new object for invisible Z

## $H \rightarrow Z\gamma$ analysis

- Write thesis draft without kinematic fit

# backup

# まとめ

## 測定器分解能評価

- 光子及びジェットの測定分解能を評価
- エネルギー & 角度依存性の精査

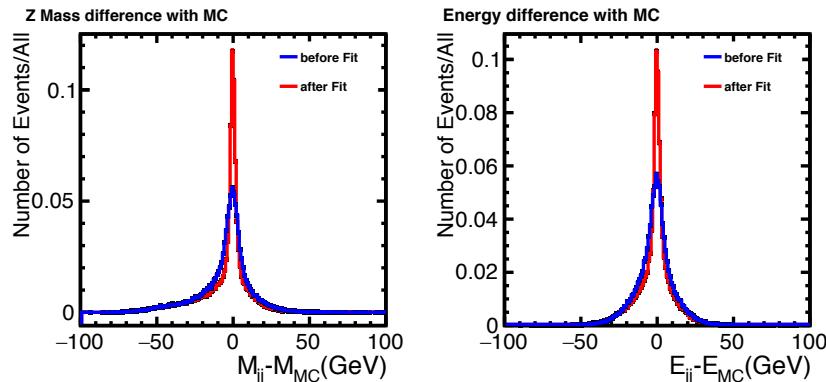
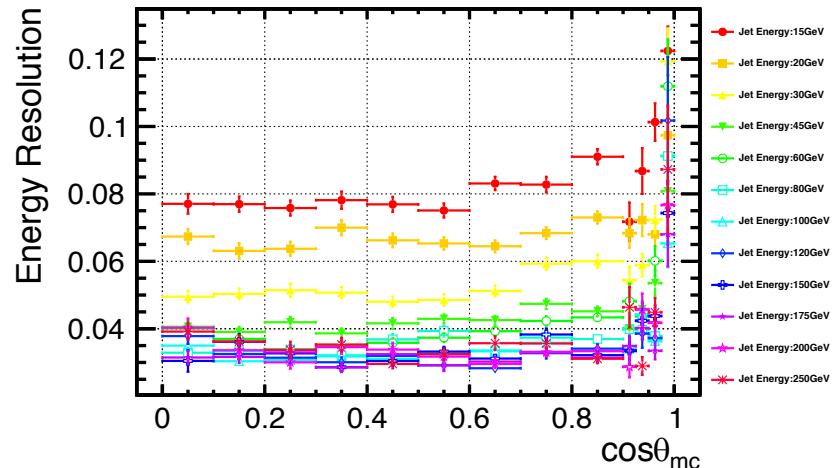
## kinematic fit 構築

- 測定分解能を実装したkinematic fitを構築した
- kinematic fitに必要なパラメータ誤差を測定分解能評価の結果↑から取得
- ZH $\rightarrow$ ZZ $\gamma$  $\rightarrow$ qqqqq $\gamma$ 及びvvqqq $\gamma$ 過程に適用、fit変数の精度向上を確認

## H $\rightarrow$ Z $\gamma$ 崩壊解析へ応用

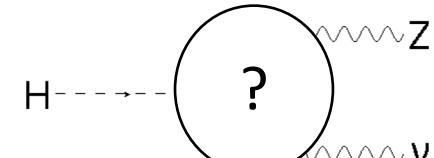
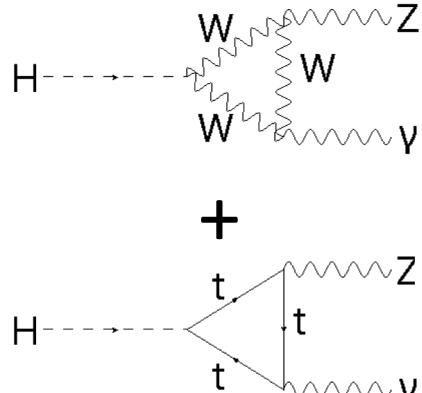
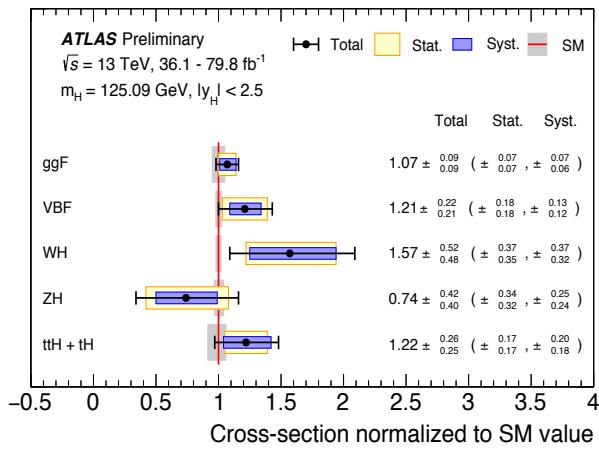
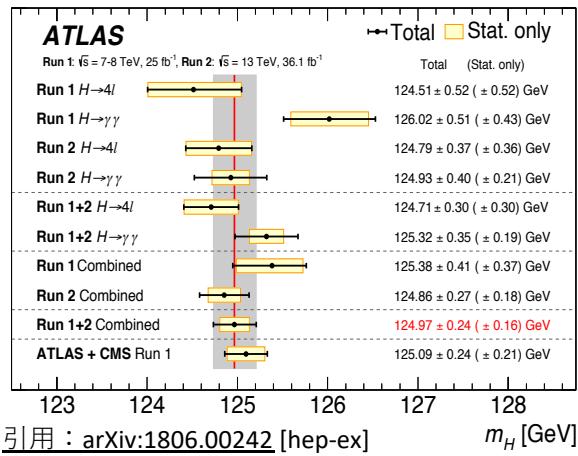
ZH $\rightarrow$ ZZ $\gamma$  $\rightarrow$ qqqqq $\gamma$ 及びvvqqq $\gamma$ 過程を用いた崩壊分岐比の上限推定に応用し、kinematic fitによる効果を確認

	w/o KF	w KF
Significance	$1.91 \pm 0.01$	$1.98 \pm 0.02$
Upper limit	0.287%	0.283%



# 背景 : Higgsの精密測定と $H \rightarrow Z\gamma$ 過程

## LHCによる測定結果



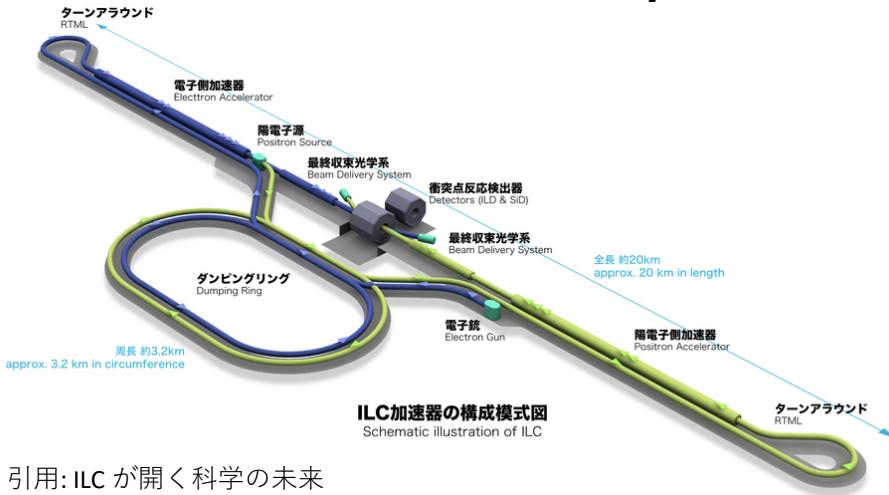
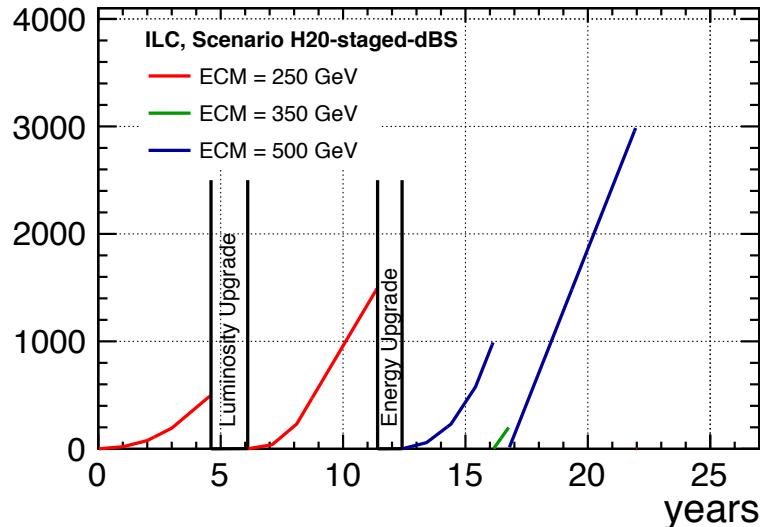
BSM過程  
(複合Higgsモデル、新粒子)

SM : BR = 0.154%

- 現在ヒッグス粒子の測定はLHCのみ
- 現状  $p\bar{p} \rightarrow H \rightarrow Z\gamma$  過程の反応断面積 × 崩壊分岐比のUpper limit(CL95%)はSMの6.6倍( $31.6 \text{ fb}^{-1}$ )
- ILCにて新物理に感度がある  $H \rightarrow Z\gamma$  過程の崩壊分岐比の測定が可能
- ILCではヒッグスの純粋な崩壊分岐比の測定が可能

# ILC計画

Integrated Luminosities [ $\text{fb}^{-1}$ ] 引用: [arXiv:1710.07621 \[hep-ex\]](https://arxiv.org/abs/1710.07621)



引用: ILC が開く科学の未来

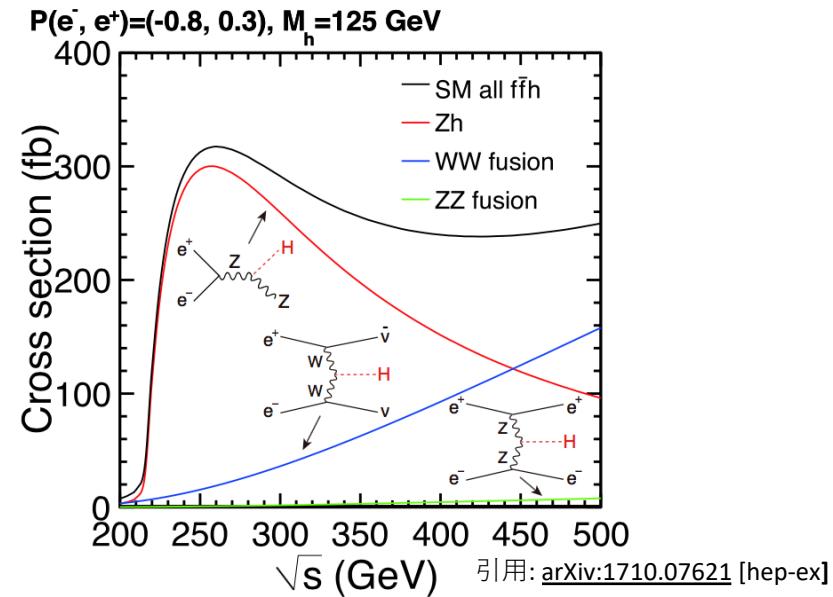
2019/1/18

## 特徴

- 次世代型電子陽電子線形加速器
- 重心系エネルギー250 GeVから運転開始
- 加速粒子の偏極率を調整可能



- 精密測定が可能
- ヒッグスファクトリーとして期待

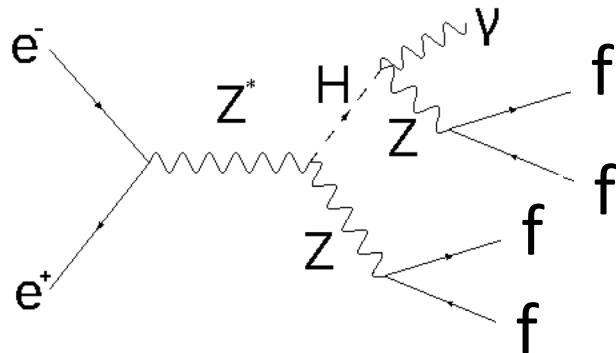


master thesis

32

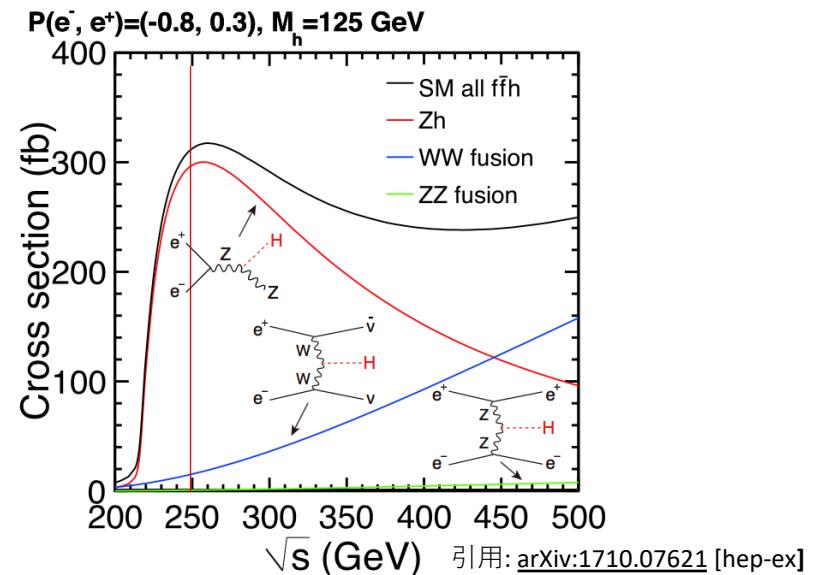
# 解析対象の過程

$$P = \frac{N_R - N_L}{N_R + N_L}$$

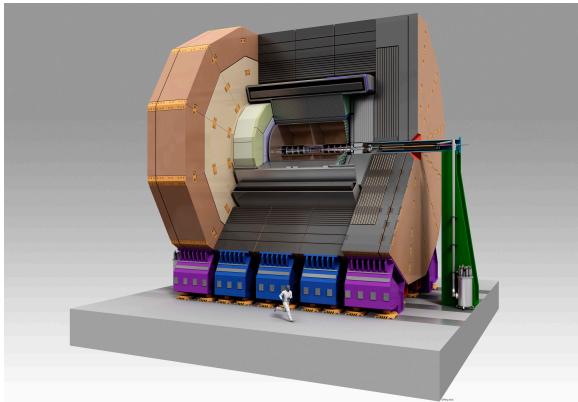


$E_{cm} = 250 \text{ GeV}$ ,  
 $\int L dt = 900 \text{ fb}^{-1}, (P_{e^-}, P_{e^+}) = (-0.8, +0.3)$   
 $\int L dt = 900 \text{ fb}^{-1}, (P_{e^-}, P_{e^+}) = (+0.8, -0.3)$

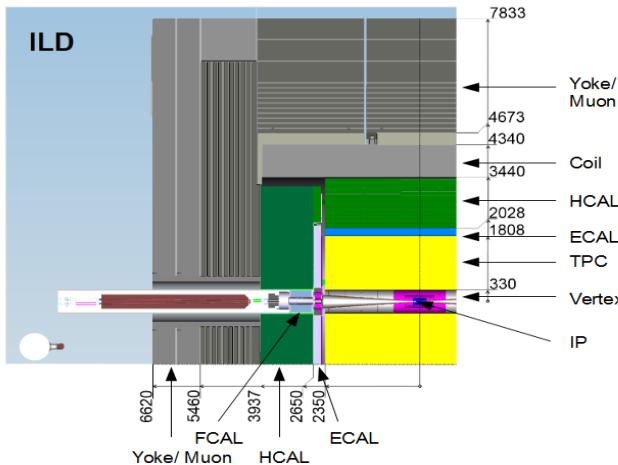
Final state	Branching ratio
qqqqγ	48.9%
ννqqqγ	28.0%
eeqqqγ	4.7%
μμqqqγ	4.7%
others	13.7%



# ILD測定器



引用 : arXiv:1306.6329 [physics.ins-det]

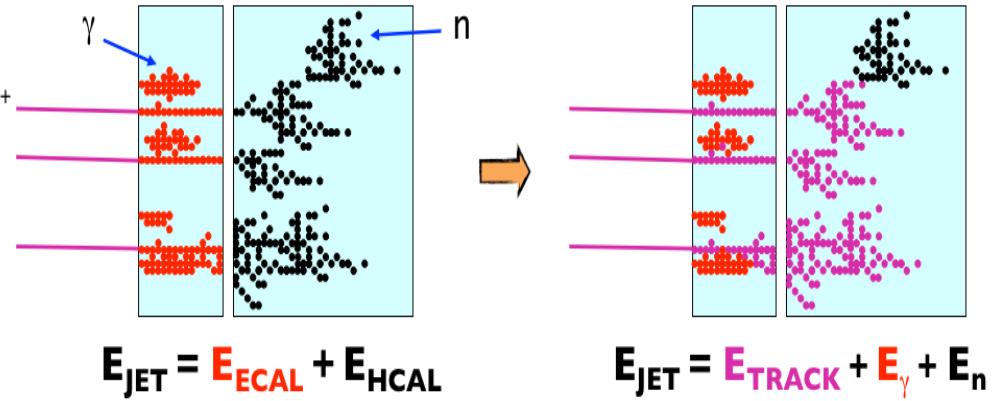


引用 : arXiv:1306.6329 [physics.ins-det]

本研究で想定する測定器 :

International Large Detector (ILD)

- 飛跡検出器、カロリメーター、ソレノイド(3.5T)、ミューオン検出器で構成
- Particle Flow Algorithm (PFA)を用いて一粒子ごとのより正確な再構成が可能



引用 : arXiv:1308.4537 [physics.ins-det]

★ In a typical jet :

- ♦ 60 % of jet energy in charged hadrons
- ♦ 30 % in photons (mainly from  $\pi^0 \rightarrow \gamma\gamma$  )
- ♦ 10 % in neutral hadrons (mainly  $n$  and  $K_L$  )

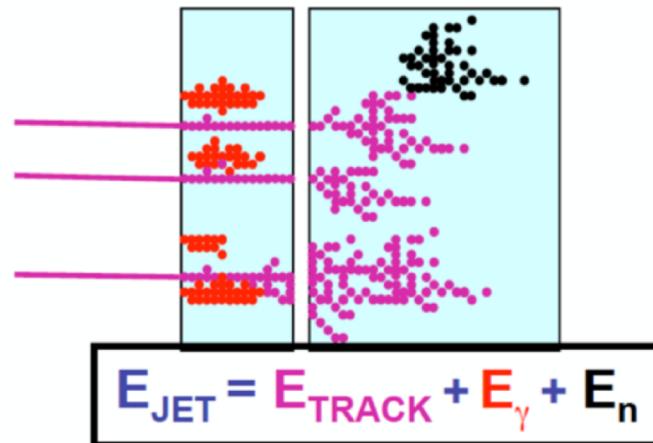
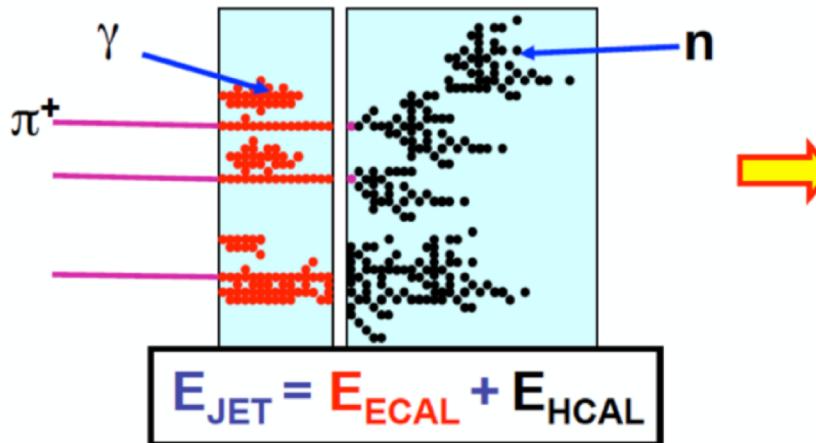
引用：

<https://indico.desy.de/indico/event/14235/session/1/contribution/18/material/slides/0.pdf>



★ Traditional calorimetric approach:

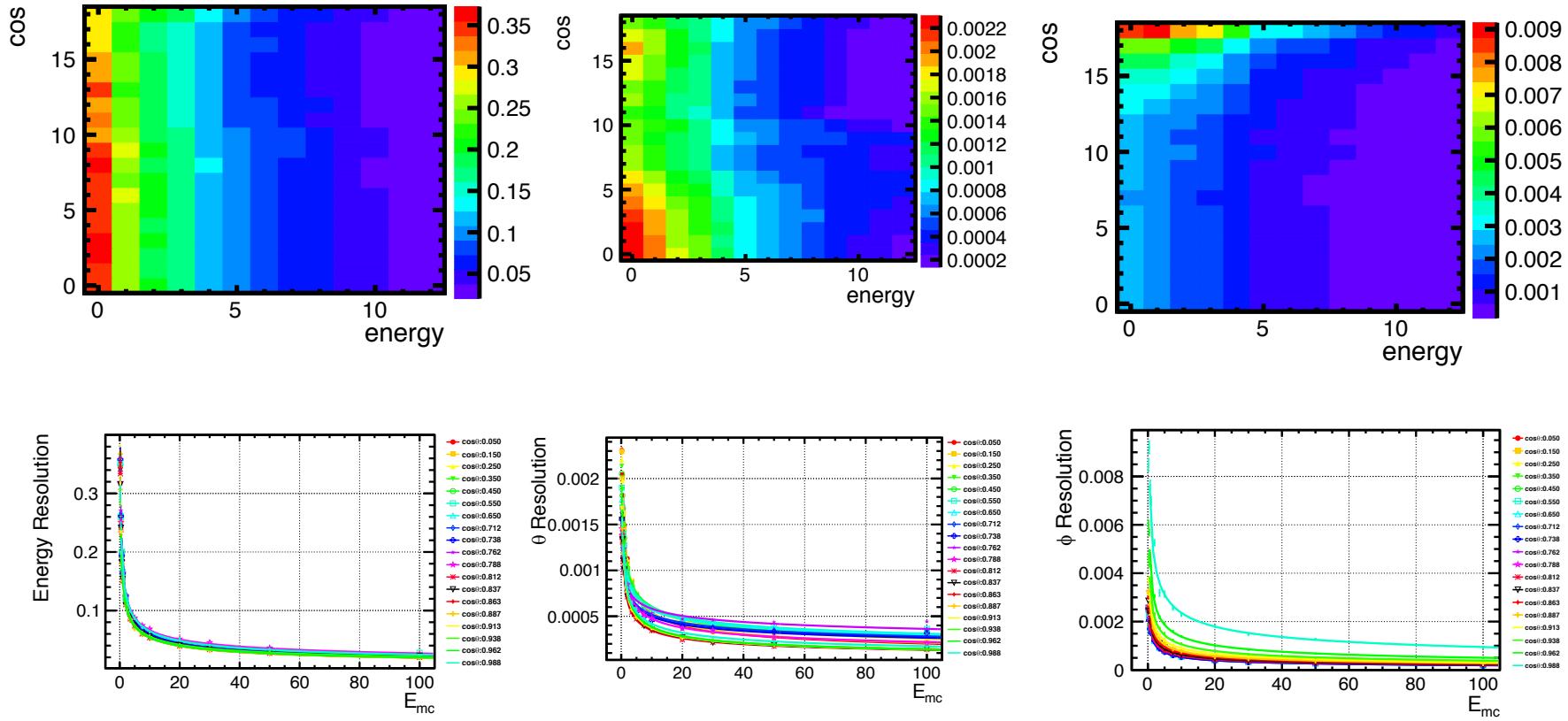
- ♦ Measure all components of jet energy in ECAL/HCAL !
- ♦ ~70 % of energy measured in HCAL:  $\sigma_E/E \approx 60\%/\sqrt{E(\text{GeV})}$
- ♦ Intrinsically “poor” HCAL resolution limits jet energy resolution



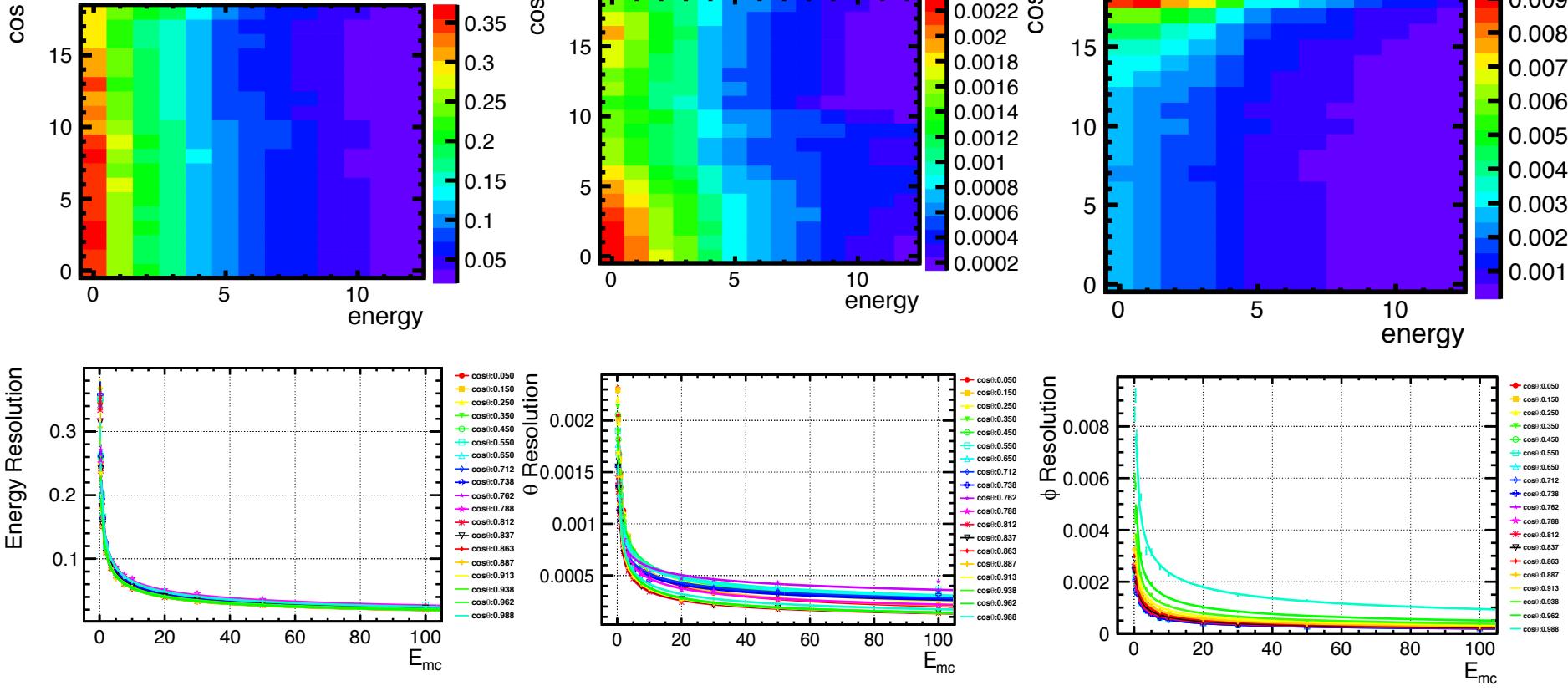
★ Particle Flow Calorimetry paradigm:

- ♦ charged particles measured in tracker (essentially perfectly)
- ♦ Photons in ECAL:  $\sigma_E/E < 20\%/\sqrt{E(\text{GeV})}$
- ♦ Neutral hadrons (ONLY) in HCAL
- ♦ Only 10 % of jet energy from HCAL → much improved resolution

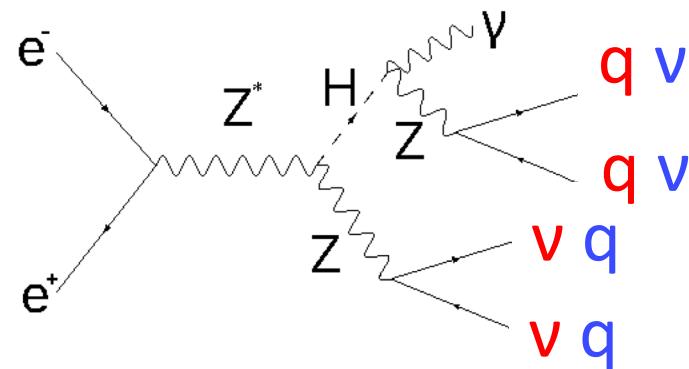
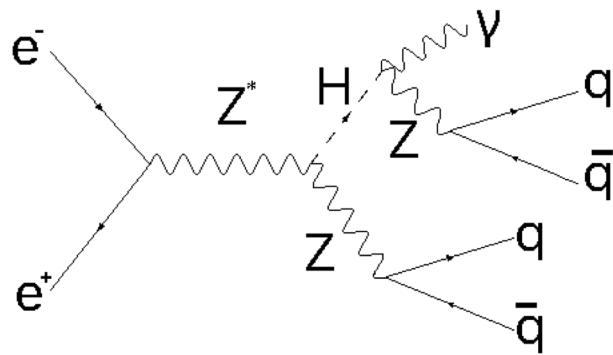
# 測定分解能評価(光子)



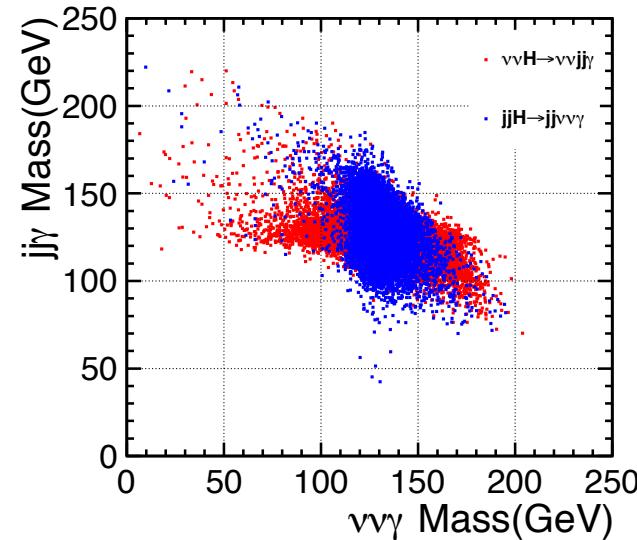
# 測定分解能評価(ジエット)



# 解析対象の過程



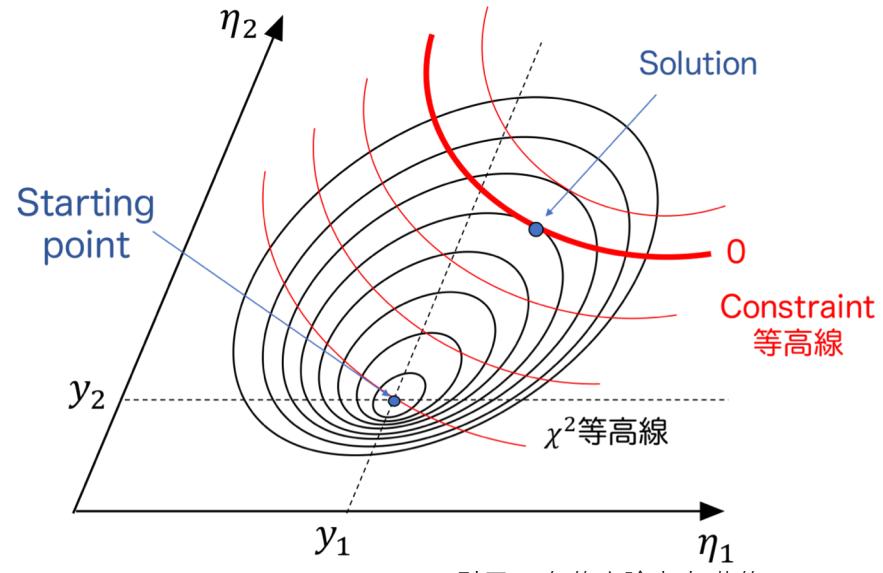
Final state	Branching ratio
qqqqgamma	48.9%
nu nu q q gamma	28.0%
ee qq gamma	4.7%
mu mu qq gamma	4.7%
others	13.7%



# Kinematic-fit

## Kinematic-fit

- 測定値に対し、運動学的条件（エネルギー、運動量保存 etc）を課し、Fitを行うことにより正しい物理量を得る手法

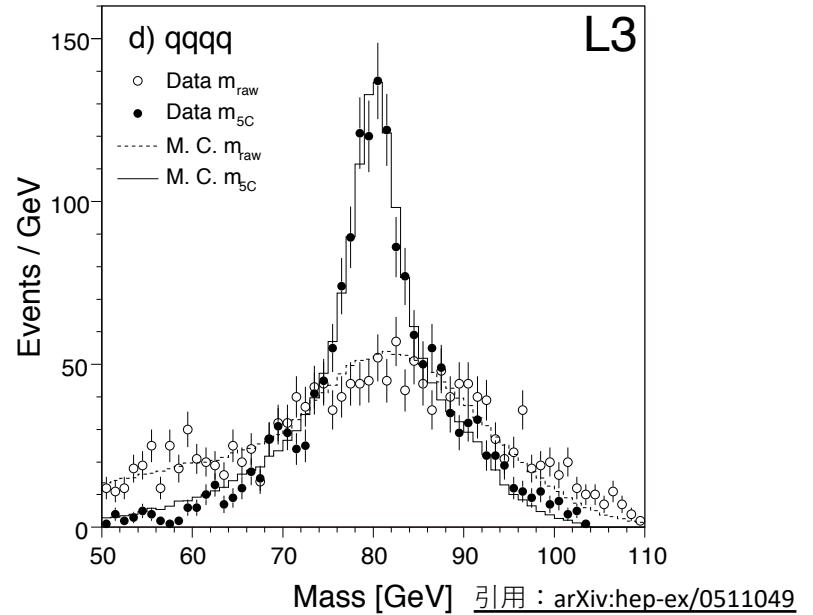


引用:18年修士論文:加藤悠

- LEP実験では測定精度の改善に大幅に貢献



- 本解析にも活用し、精度改善を目指す



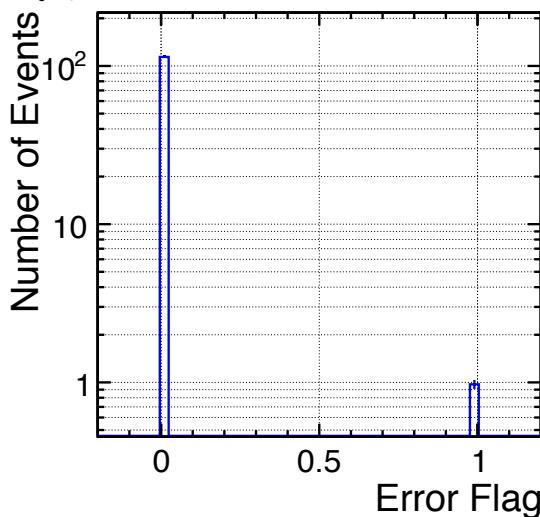
引用 : arXiv:hep-ex/0511049

# Kinematic-fitを終状態 $\nu\nu q\bar{q}\gamma$ へ適応

収束率

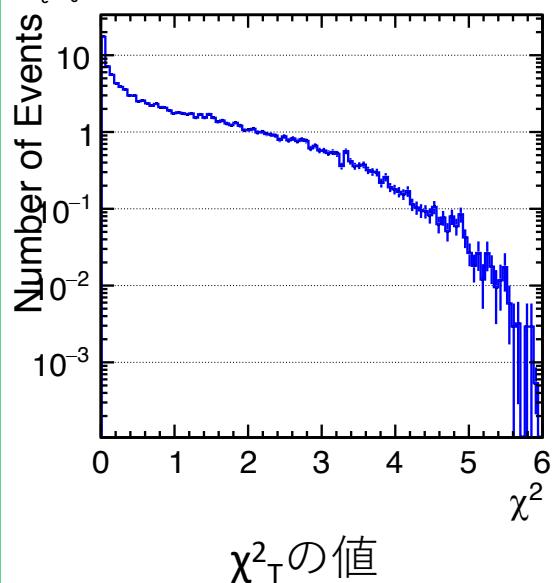
200回の反復計算時に収束条件が満たされなければエラー出力

$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 0.9915



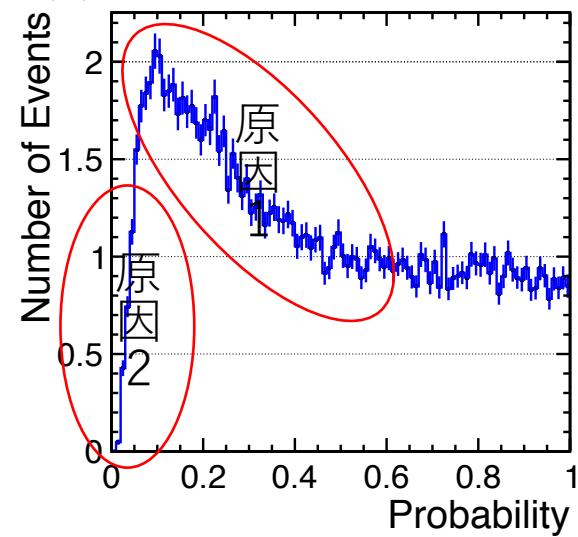
99%以上の収束率を達成

$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 0.9915



$$probability = \int_{\chi^2_T}^{\infty} f_{\chi^2}(x; N_{dof}) dx$$

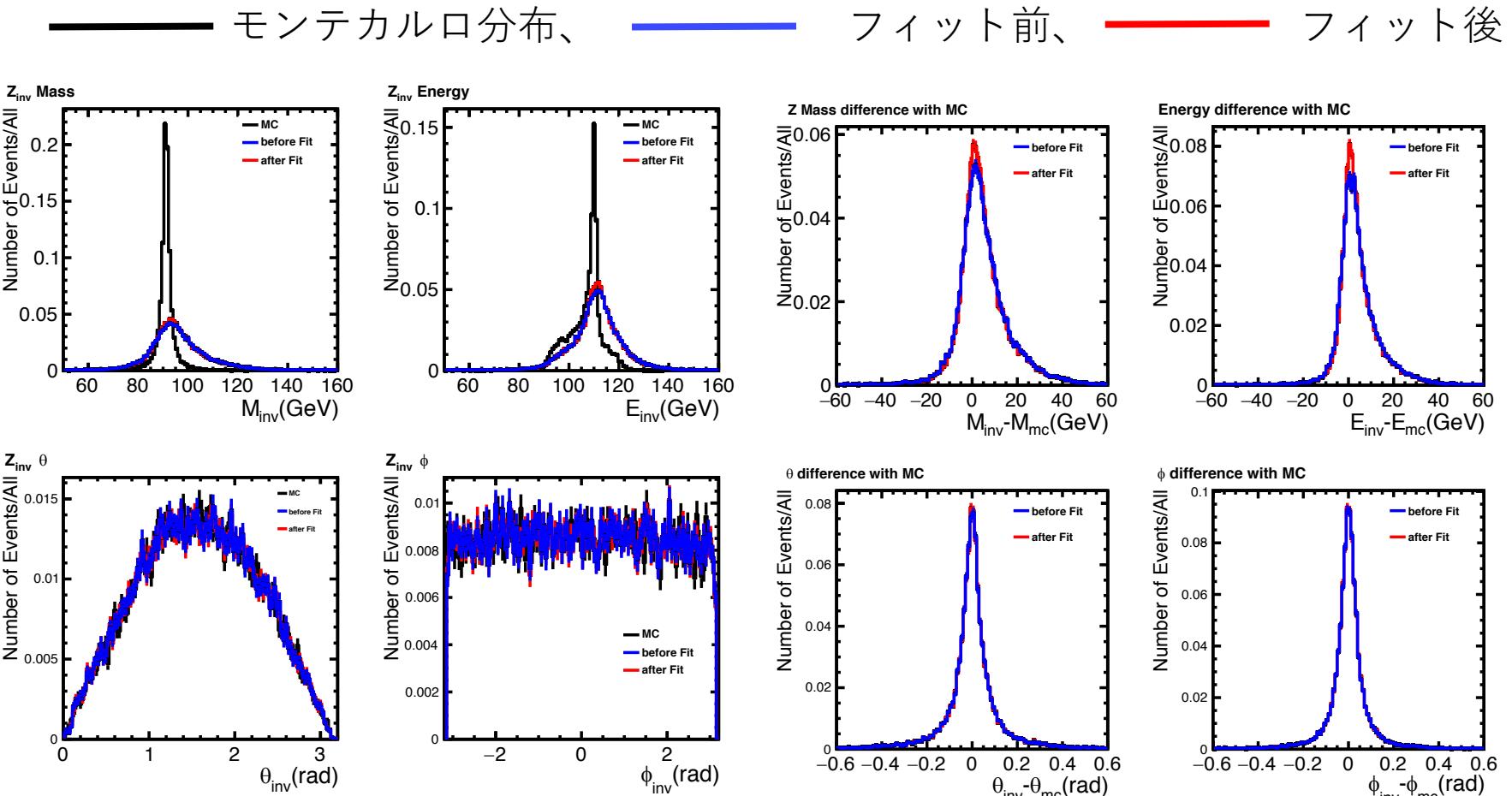
$(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$  success rate: 0.9915



Fit probabilityが一様分布でないこと原因

1. ジェットの分解能の過小評価
2. Fit自由度の過大評価

# Kinematic-fitを終状態 $vvqq\gamma$ へ適応



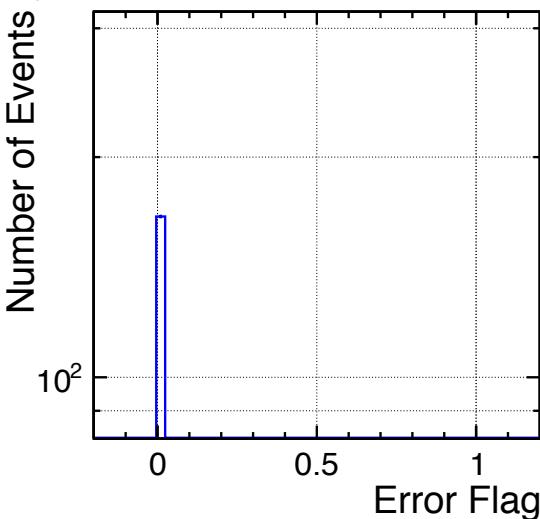
2ジェットほどではないが質量とエネルギーの分布が改善することを確認  
ISRの影響により質量とエネルギーが高エネルギー側へシフトしている

# Kinematic-fitを終状態 $qqqq\gamma$ へ適応

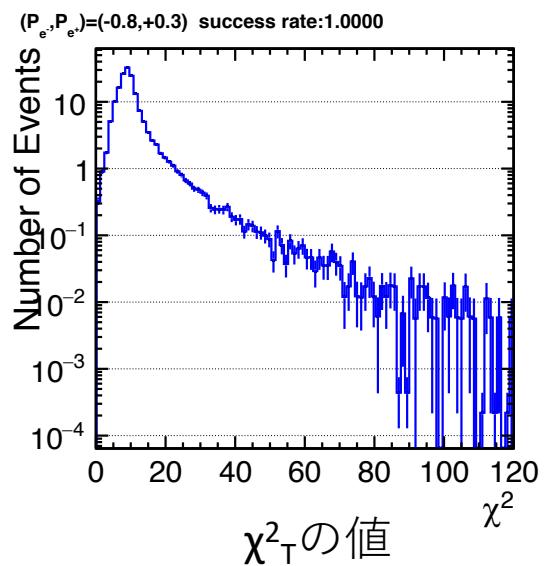
収束率

6通りの $jj\gamma$ のペアリングの全てが  
エラーの場合にエラー出力

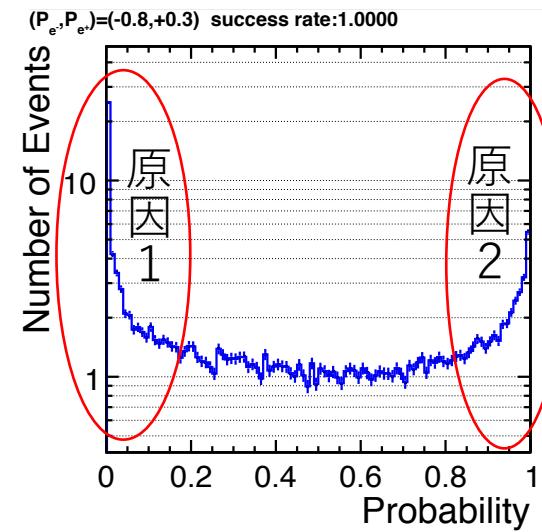
$(P_{e^+}, P_{e^-})=(-0.8, +0.3)$  success rate:1.0000



100%の収束率を達成



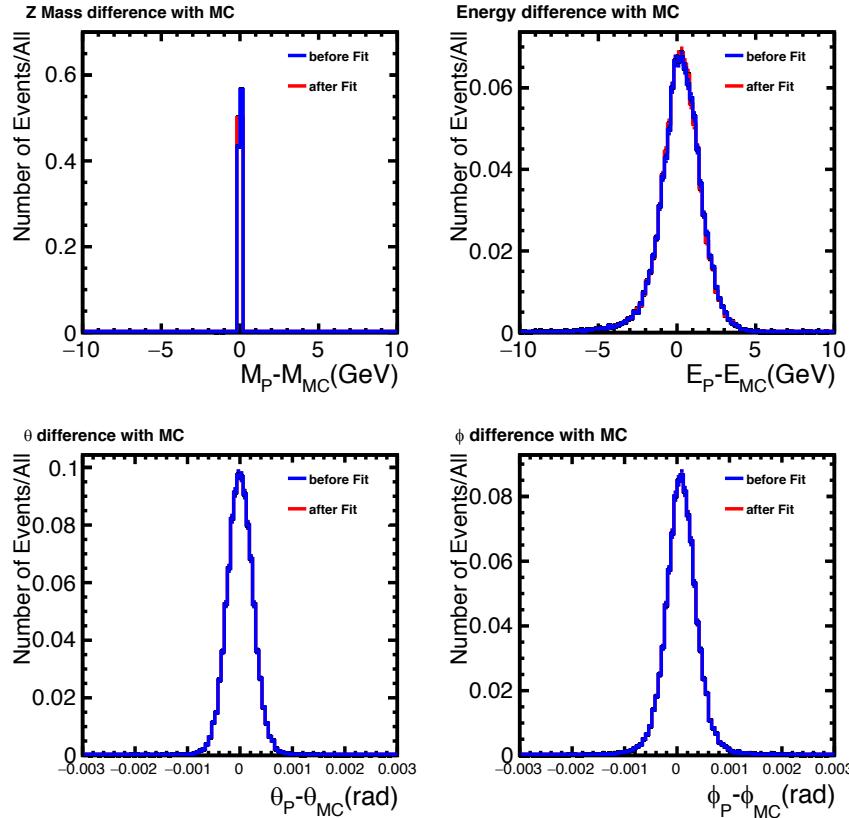
$$probability = \int_{\chi_T^2}^{\infty} f_{\chi^2}(x; N_{dof}) dx$$



Fit probabilityが一様分布でないこと原因

1. ジェットの分解能の過小評価
2. Fit自由度の過大評価

# Kinematic-fitを終状態 $qqqq\gamma$ へ適応

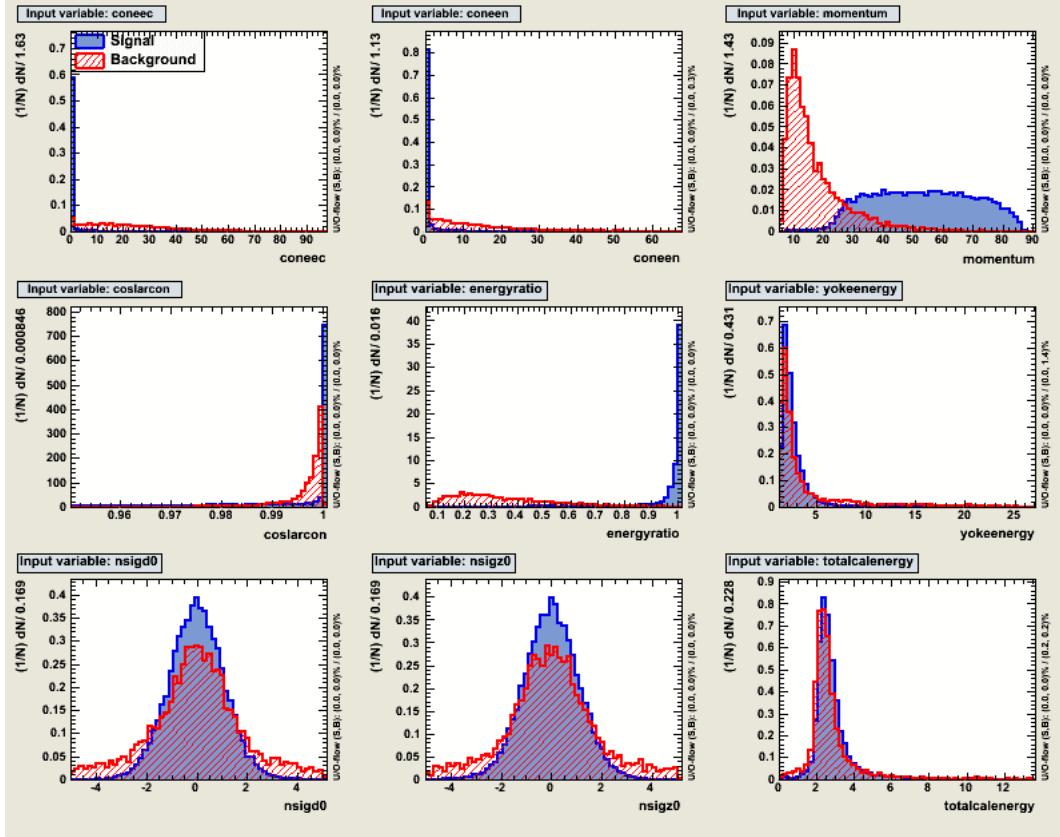


光子については大きな変化が見られなかった

ジェットの分解能に比べて制約条件が少なく、測定時からMCとの大きな差が見られないことによると考えられる。

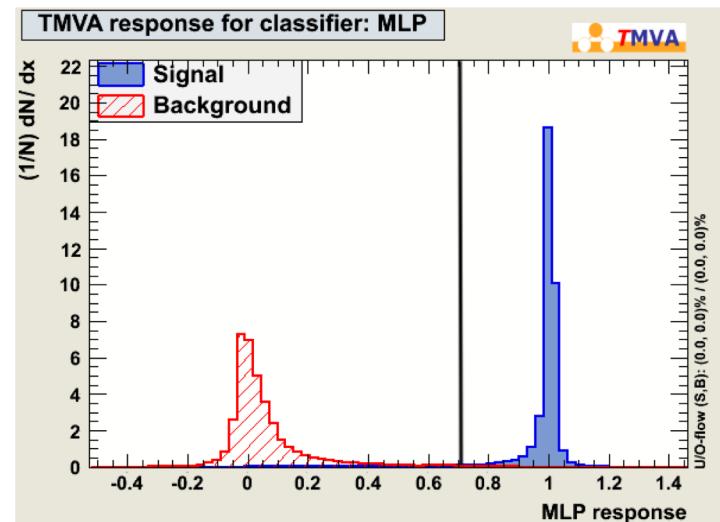
# 孤立レプトン選定

## 入力変数分布

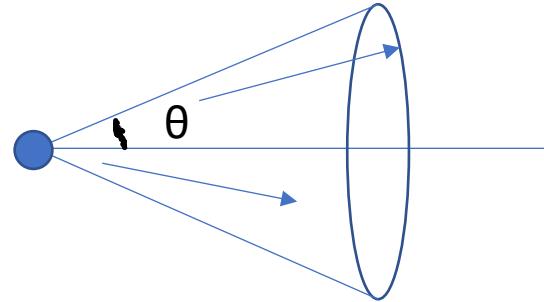


## 出力変数分布

TMVAのMulti-Layer Perceptron (MLP)を使用し、多変量解析を行なった。



# 孤立光子選定



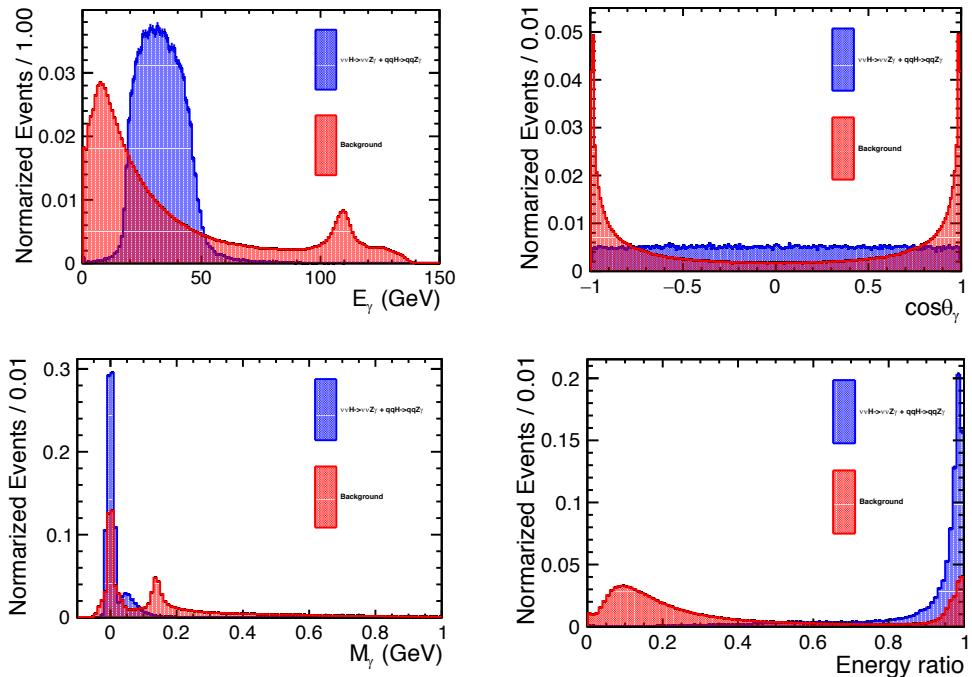
再構成粒子のうち、エネルギーが最大の光子を孤立光子とする(正答率約90%)

孤立光子らしい事象を選定

- $E_\gamma = (10, 70) \text{ [GeV]}$
- $|\cos\theta_\gamma| = (0, 0.99)$
- $M_\gamma < 0.1 \text{ GeV}$
- Energy ratio  $> 0.7$

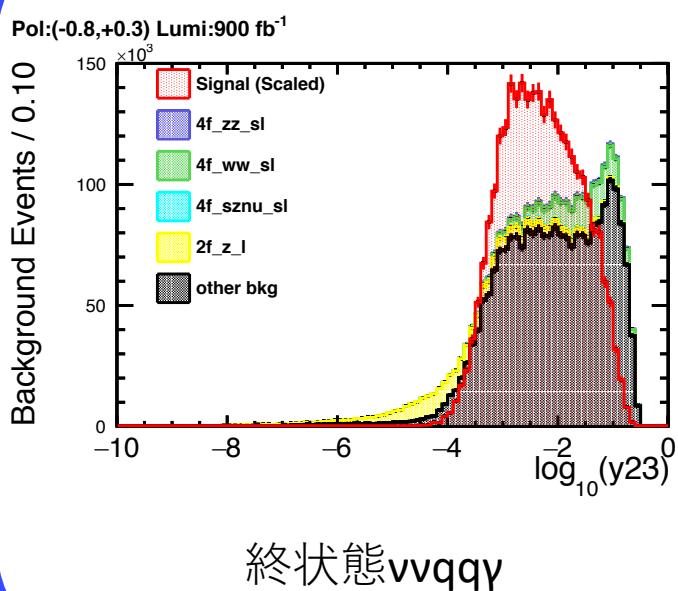
Energy ratioの定義  
 $E_\gamma / (E_\gamma + E_{\text{largecone}})$

$E_{\text{largecone}}$ :光子の進行方向に角度  $\cos\theta = 0.95$  の円錐を張り、円錐内の粒子の合計エネルギー



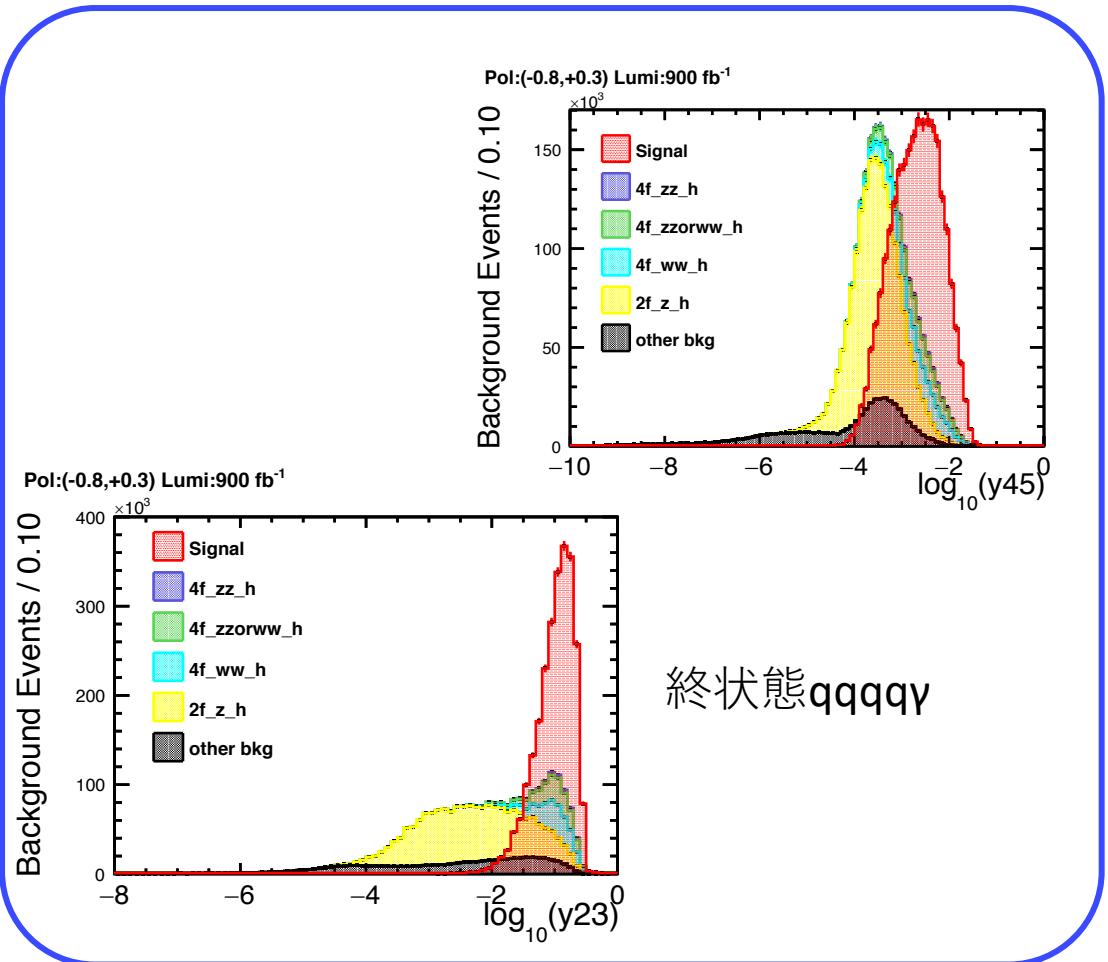
y' 値

$$y \text{ 値} = \frac{2E_{min}^2(1 - \cos \theta_{ij})}{Q^2}$$

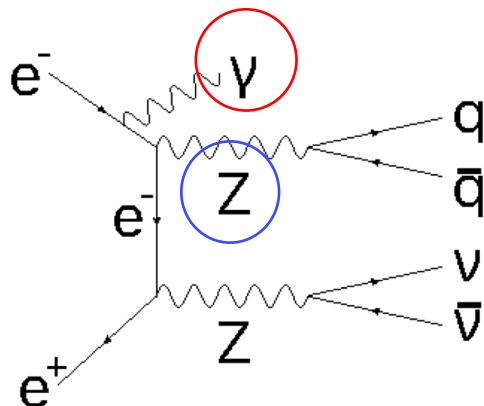


$y_{23}$ : 3つのジェットを2つにクラスタリングした際のy' 値

$y_{45}$ : 5つのジェットを4つにクラスタリングした際のy' 値

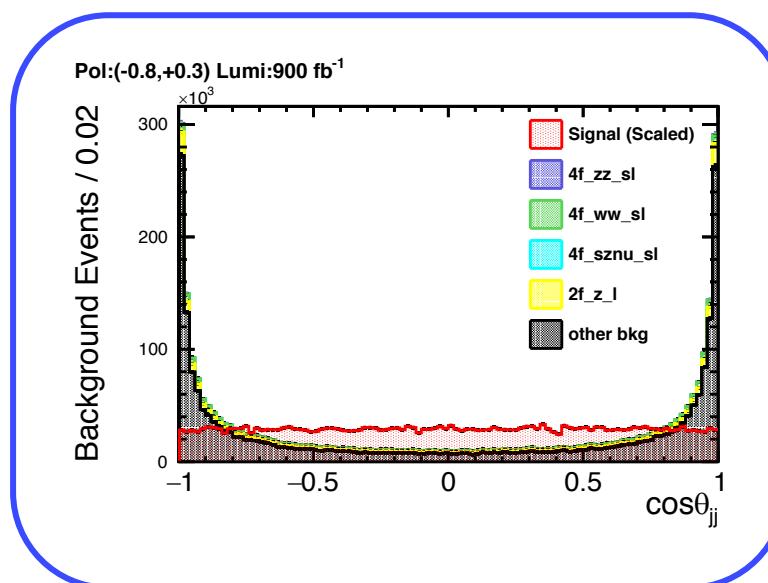
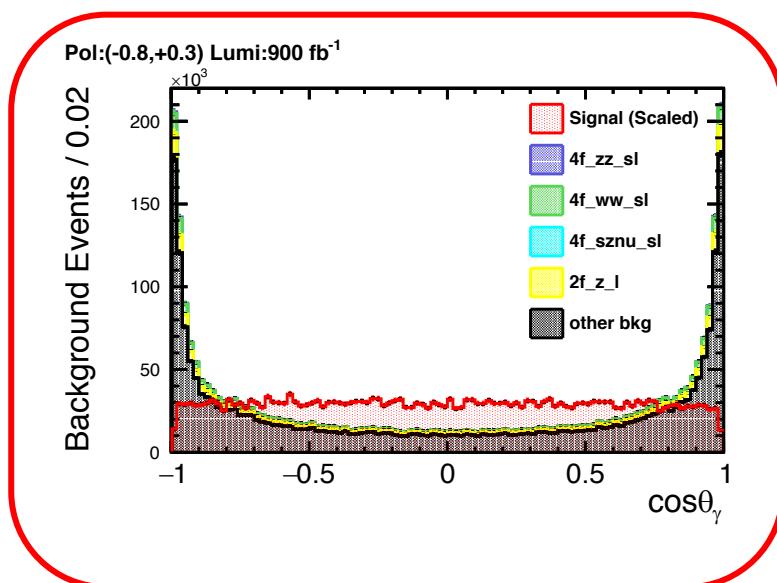


# 角度方向 $\cos\theta$



光子：ISR等のビーム軸方向に放出される背景事象が多く存在する

$Z$ 粒子：t-channelイベントは粒子がビーム軸方向に飛ぶ



# w/o KF nnqq $\gamma$ \_LR

```

Cut 0
OBJ: TCut
Cut 1
OBJ: TCut
Cut 2
OBJ: TCut
Cut 3
OBJ: TCut
Cut 4
OBJ: TCut
Cut 5
OBJ: TCut
Cut 6
OBJ: TCut
Cut 7
OBJ: TCut
Cut 8
OBJ: TCut
log10(ylepton) > -4.2 & log10(ylepton) < 0
lrzZJet.M() > 50 & lrzZJet.M() < 130
lrzZneu.M() > 30 & lrzZneu.M() < 150
abs(lrzPhoton.CosTheta()) < 0.96 & abs(lrzZJet.CosTheta()) < 0.98 & abs(lrzZneu.CosTheta()) < 0.98
lrzAZJet.M() > 70 & lrzAZJet.M() < 175
lrzRZJet.M() > 70 & lrzRZJet.M() < 190
MVABDTG_LR > 0.8523

```

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

Reduction Table

Process	:	other bkg	2f_z_1	4f_sznu_sl	4f_ww_sl	4f_zz_sl	all bkg	allbkg err	nnh	qqh	Signal	Sig error	efficiency	Signf	SignfErr
Cross Section	:	0	131964	12993.9	271.806	10992.9	856.927	157080	0.120176	0.325788	0.182654				
Generated	:	0	1.33926e+07	3.77276e+06	147517	1.96265e+06	535103		68862	99274	168136				
Expected	:	0	1.18768e+08	1.16945e+07	244625	9.89362e+06	771234	1.41372e+08	108.158	293.209	164.389		0.00909658		
Cut0	:	0	2.39837e+06	279259	6840.92	220108	20974.6	2.92555e+06	8419.53	64.8065	50.166	114.973	0.548405	0.699394	0.0672174 0.000334884
Cut1	:	0	2.32821e+06	147996	6819.92	220087	20952.1	2.72406e+06	8313.48	64.7257	50.1116	114.837	0.548273	0.698571	0.0695769 0.00034873
Cut2	:	0	899559	54540	5827.32	159523	13324.7	1.13277e+06	5640.69	64.0063	49.6381	113.644	0.547064	0.691315	0.106771 0.000578621
Cut3	:	0	391481	46767.3	5704.88	142456	11725.3	598135	3762.03	63.4431	49.4125	112.856	0.546591	0.686516	0.145909 0.000842477
Cut4	:	0	35721	30463.3	4166.37	104545	7949.24	182845	1148.48	59.2684	46.1748	105.443	0.537108	0.641426	0.24652 0.00147468
Cut5	:	0	29941.1	27172.5	4162.05	87635.6	7479.8	156391	1041.83	59.2597	46.0912	105.351	0.536824	0.640864	0.266309 0.00162049
Cut6	:	0	29358.6	25889.2	4144.87	81828.8	7363.82	148585	1018.12	59.0706	46.0912	105.162	0.536872	0.639714	0.27272 0.00167597
Cut7	:	0	29358.6	25889.2	4144.87	81828.8	7363.82	148585	1018.12	59.0706	46.0912	105.162	0.536872	0.639714	0.27272 0.00167597
Cut8	:	0	105.663	196.487	505.128	629.841	876.335	2313.45	85.6471	30.6508	19.2109	49.8617	0.400272	0.303316	1.02567 0.0202924

# w/o KF nnqq $\gamma$ \_RL

```

Cut 0
OBJ: TCut
Cut 1
OBJ: TCut          log10(yplus)>-4.2&&log10(yplus)<0
Cut 2
OBJ: TCut          lrzzJet.M(>50&&lrzzJet.M(<130
Cut 3
OBJ: TCut          lrzzneu.M(>30&&lrzzneu.M(<150
Cut 4
OBJ: TCut          abs(lrzPhoton.CosTheta())<0.96&&abs(lrzZJet.CosTheta())<0.98&&abs(lrzZneu.CosTheta())<0.98
Cut 5
OBJ: TCut          lrzAZZJet.M(>70&&lrzAZZJet.M(<175
Cut 6
OBJ: TCut          lrzRZZJet.M(>70&&lrzRZZJet.M(<190
Cut 7
OBJ: TCut
Cut 8
OBJ: TCut          MVABDTG_RL > 0.7898

```

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

-Reduction Table-

Process	:	other bkg	2f_z_l	4f_sznu_sl	4f_ww_sl	4f_zz_sl	all bkg	allbkg err	nnh	qqh	Signal	Sig error	efficiency	Signf	SignfErr
Cross Section	:	0	74578.6	10377.9	92.4997	758.383	467.188	86274.5	0.0660065	0.220026	0.113589				
Generated	:	0	1.33926e+07	3.77276e+06	147517	1.96265e+06	535103		68862	99274	168136				
Expected	:	0	6.71207e+07	9.34009e+06	83249.7	682544	420469	7.76471e+07	59.4059	198.023	102.23			0.00674165	
Cut0	:	0	1.07975e+06	224417	2658.99	15279	11487	1.3336e+06	4950.37	35.6633	33.6938	69.357	0.339722	0.678443	0.0600575 0.000314573
Cut1	:	0	1.02598e+06	113467	2657.74	15277.8	11460.5	1.16884e+06	4794.44	35.6263	33.632	69.2583	0.339527	0.677477	0.0640591 0.000340402
Cut2	:	0	567713	41990.4	2261.52	11264.8	7112.89	630343	3678.72	35.2827	33.3515	68.6342	0.338754	0.671372	0.0864427 0.000495604
Cut3	:	0	249855	36042.4	2243.8	10037.5	6093.1	304272	2462.84	35.114	33.1625	68.2765	0.338177	0.667874	0.123763 0.000791494
Cut4	:	0	13159.7	24247.8	1642.34	7504.69	3954.04	50508.6	632.098	32.8342	30.7903	63.6246	0.330713	0.622369	0.282923 0.00229917
Cut5	:	0	10800.2	20897.6	1640	6336.8	3664.02	43338.5	574.086	32.8337	30.7122	63.5459	0.33043	0.621599	0.305023 0.00256543
Cut6	:	0	10467.4	19934	1632.74	5903.98	3579.55	41517.7	563.239	32.7886	30.7122	63.5009	0.330439	0.621159	0.311409 0.00265899
Cut7	:	0	10467.4	19934	1632.74	5903.98	3579.55	41517.7	563.239	32.7886	30.7122	63.5009	0.330439	0.621159	0.311409 0.00265899
Cut8	:	0	14.3162	103.67	235.477	146.448	550.509	1050.42	45.1067	19.7065	16.4683	36.1748	0.265286	0.353858	1.09742 0.0241136

# w/o KF qqqq $\gamma$ \_LR

```

Cut 0
OBJ: TCut
Cut 1
OBJ: TCut
Cut 2
OBJ: TCut
Cut 3
OBJ: TCut
Cut 4
OBJ: TCut
Cut 5
OBJ: TCut
Cut 6
OBJ: TCut
Cut 7
OBJ: TCut
Cut 8
OBJ: TCut
Cut 9
OBJ: TCut

log10(yplus4)>-4.4&&log10(yplus4)<0&&log10(yplus)>-2.4&&log10(yplus)<0
BHLrzZ1.M(>30&&BHLrzZ1.M(<140
BHLrzZ2.M(>16
abs(lrzPhoton.CosTheta())<0.98&&abs(BHLrzZ1.CosTheta())<0.98&&abs(BHLrzZ2.CosTheta())<0.98
BHLrzAZ.M(>80&&BHLrzAZ.M(<170
BHLrzRZ.M(>100&&BHLrzRZ.M(<210
MVA_BDTG_LR > 0.9238

```

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

Reduction Table

Process	:	other bkg	2f_z_h	4f_ww_h	4f_zorw_h	4f_zz_h	all bkg	allbkg err	qqh	Sig error	efficiency	Signf	SignfErr
Cross Section	:	0	62233.5	78046.5	8706.23	7252.1	841.376	157080	0.228282				
Generated	:	0	1.38953e+07	3.17329e+06	1.10906e+06	1.13101e+06	501975		99274				
Expected	:	0	5.60102e+07	7.02418e+07	7.8356e+06	6.52689e+06	757239	1.41372e+08	205.454		0.0246602		
Cut0	:	0	376985	1.94171e+06	253826	211670	24266.7	2.80846e+06	8363.34	165.883	0.627021	0.8074	0.0989819 0.000402109
Cut1	:	0	76702.9	1.08378e+06	253126	211111	24127.8	1.64885e+06	6138.08	165.742	0.627101	0.806711	0.129068 0.000544205
Cut2	:	0	41303.9	753541	249349	207914	23704.5	1.27581e+06	5201.09	164.884	0.627575	0.802535	0.145968 0.000630182
Cut3	:	0	27209.2	620390	249094	207725	23617.4	1.12803e+06	4813.27	164.848	0.627594	0.802362	0.1552 0.000677254
Cut4	:	0	21063.8	470223	209472	175807	20148	896714	4190.45	156.678	0.631024	0.762593	0.165441 0.000770246
Cut5	:	0	16082.1	406937	207131	173403	19955.5	823509	3982.91	156.45	0.63109	0.761486	0.172385 0.000810656
Cut6	:	0	15206.9	394939	205411	172036	19837.3	807430	3935.81	156.308	0.63113	0.760794	0.173935 0.000820229
Cut7	:	0	15206.9	394939	205411	172036	19837.3	807430	3935.81	156.308	0.63113	0.760794	0.173935 0.000820229
Cut8	:	0	28.8189	706.855	715.14	632.828	1213.85	3297.49	197.132	39.8869	0.433596	0.19414	0.690442 0.0217135
Cut9	:	0	28.8189	706.855	715.14	632.828	1213.85	3297.49	197.132	39.8869	0.433596	0.19414	0.690442 0.0217135

# w/o KF qqqq $\gamma$ \_RL

```

Cut 0
OBJ: TCut
Cut 1
OBJ: TCut
Cut 2
OBJ: TCut
Cut 3
OBJ: TCut
Cut 4
OBJ: TCut
Cut 5
OBJ: TCut
Cut 6
OBJ: TCut
Cut 7
OBJ: TCut
Cut 8
OBJ: TCut
Cut 9
OBJ: TCut
log10(plus4)>-4.4&&log10(plus4)<0&&log10(plus)>-2.4&&log10(plus)<0
BHLrzZ1.M(>30&&BHLrzZ1.M(<140
BHLrzZ2.M(>16
abs(lrzPhoton.CosTheta())<0.98&&abs(BHLrzZ1.CosTheta())<0.98&&abs(BHLrzZ2.CosTheta())<0.98
BHLrzAZ.M(>80&&BHLrzAZ.M(<170
BHLrzRZ.M(>100&&BHLrzRZ.M(<210
MVABDTG_RL > 0.8914

```

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

-----Reduction Table-----

Process :	other bkg	2f_z_h	4f_ww_h	4f_zorw_h	4f_zz_h	all bkg	allbkg err	qgh	Sig error	efficiency	Signf	SignfErr
Cross Section :	0	38491.5	46214.8	600.369	564.949	402.98	86274.5		0.154085			
Generated :	0	1.38953e+07	3.17329e+06	1.10906e+06	1.13101e+06	501975			99274			
Expected :	0	3.46423e+07	4.15933e+07	540332	508454	362682	7.76471e+07		138.677		0.0224726	
Cut0 :	0	239337	955524	17571.6	16586.7	11936.2	1.24095e+06	4862.79	111.677	0.405969	0.805305	0.100246 0.000413951
Cut1 :	0	25217.7	494471	17529.8	16536.6	11858.6	565614	3379.71	111.573	0.406024	0.804559	0.14834 0.000698344
Cut2 :	0	12943	313667	17274.8	16255.6	11655	371795	2680.45	110.901	0.406373	0.799708	0.181852 0.000934539
Cut3 :	0	7968.75	247512	17255.4	16229.7	11601.6	300568	2374.94	110.873	0.406387	0.799508	0.202197 0.00108936
Cut4 :	0	5812.39	172748	14611.8	13723.7	9781.22	216677	1972.14	105.406	0.40847	0.760084	0.226388 0.00135266
Cut5 :	0	4718.92	149502	14461.4	13559	9683.71	191925	1837.75	105.184	0.408529	0.758484	0.24003 0.00147913
Cut6 :	0	4501.48	145425	14348.1	13450.1	9636.79	187362	1813.27	105.069	0.408559	0.757658	0.242669 0.00150574
Cut7 :	0	4501.48	145425	14348.1	13450.1	9636.79	187362	1813.27	105.069	0.408559	0.757658	0.242669 0.00150574
Cut8 :	0	28.918	315.275	399.367	454.709	989.788	2188.06	91.765	44.2664	0.341176	0.319206	0.936906 0.0205412
Cut9 :	0	28.918	315.275	399.367	454.709	989.788	2188.06	91.765	44.2664	0.341176	0.319206	0.936906 0.0205412

# カット後のヒストグラム

