九州大学
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Z' search in 2f final states with ILC 500 GeV

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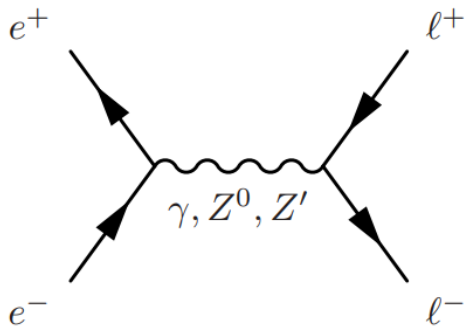
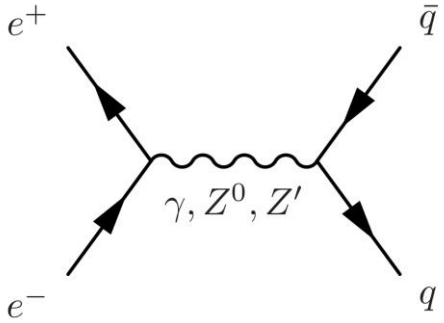
2-fermion $e^+e^- \rightarrow f^+f^-$ event

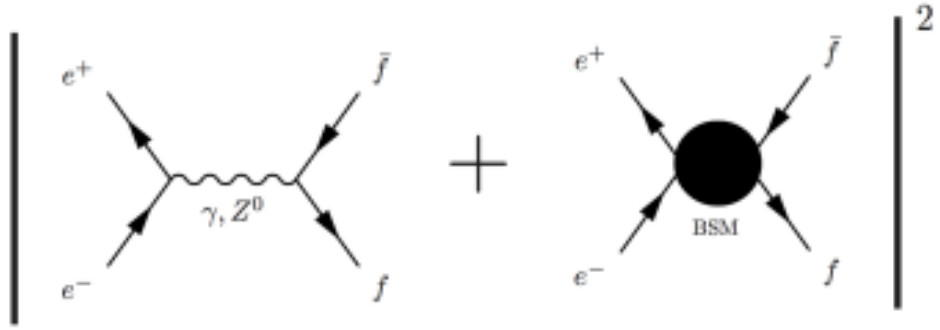
- $e^+e^- \rightarrow f^+f^-$: The production of fermionic pairs is sensitive to the production of heavy gauge bosons (Z'). In the presence of new physics mediated by new particles, total and differential cross section can be deviated from the standard model as shown in the interference diagram below.



2 lepton process

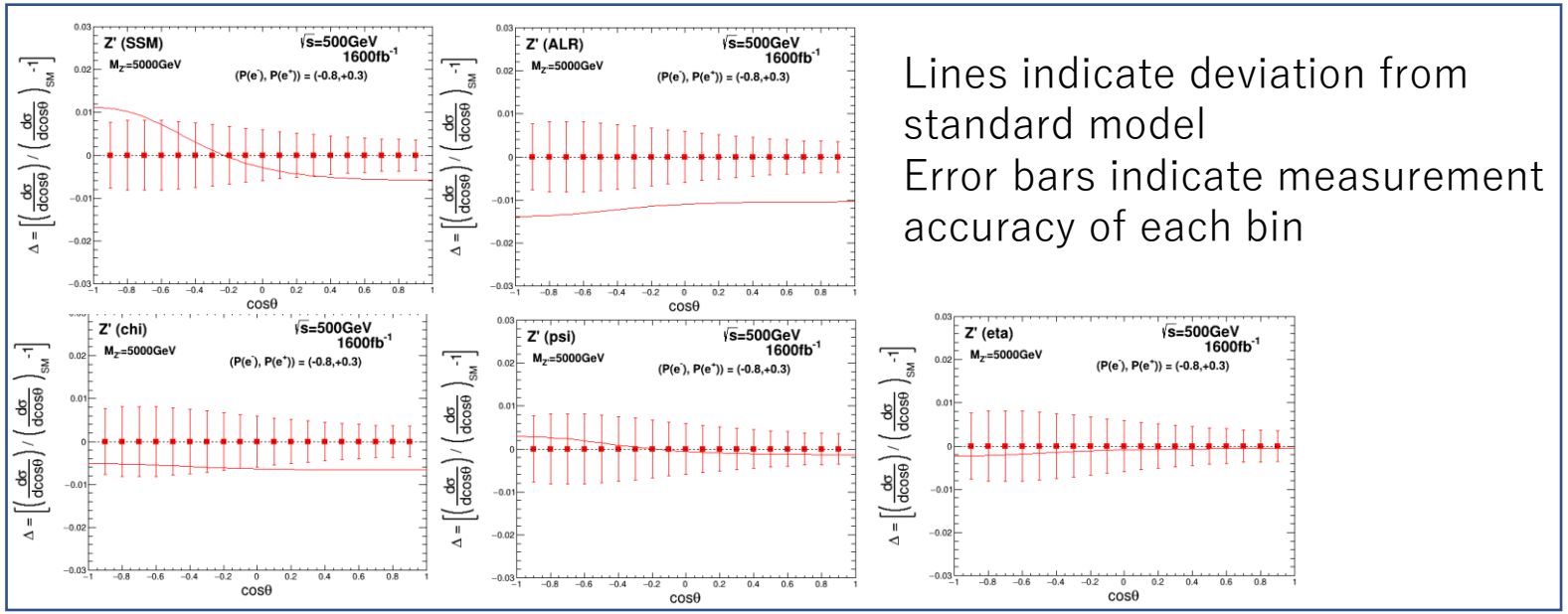


2 quark process



Feynman diagram of fermion pair production when the new physics (Beyond Standard Model : BSM) is included

previous result: Leptonic channel(mu&tau)



Lines indicate deviation from standard model
Error bars indicate measurement accuracy of each bin

<- for mu
(Z' mass 5TeV)

SSM: Sequential Standard Model
ALR : Alternative Left-Right symmetric
chi : $E_6\ \chi\ model\ (\beta = 0)$
psi : $E_6\ \psi\ model\ (\beta = \pi/2)$
eta : $E_6\ \eta\ model\ (\beta = \pi - \arctan\sqrt{5/3})$

Z'model	SSM	ALR	χ	ψ	η
5-sigma	6.24 TeV	8.35 TeV	6.08 TeV	3.16 TeV	3.53 TeV

5-sigma = discovery reach

Z'model	SSM	ALR	χ	ψ	η
2-sigma	9.84 TeV	13.18 TeV	9.60 TeV	4.96 TeV	5.55 TeV

2-sigma = 95% CL lower limit

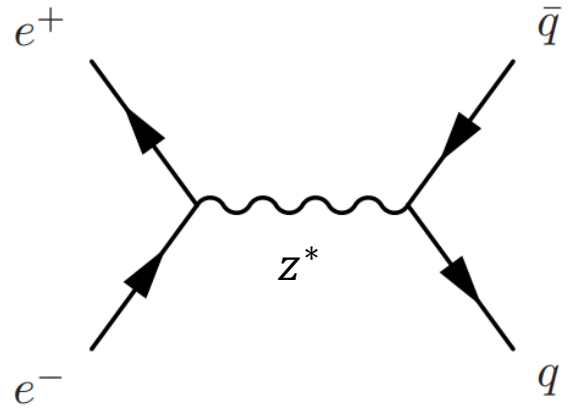
Additional channel

- I have conducted mu and tau event selection and have used the results to evaluate the Z' new physics search.

- In addition to these, I will include electron and quark events in this evaluation.
- However, I don’t yet have simulation data for electron event selection, so I only do quark event selection.

Use below events for qq event selection

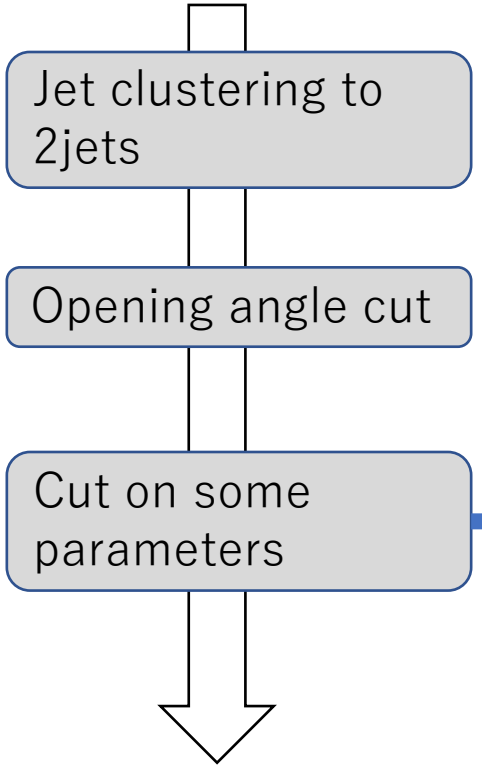
- $quark$ **event selection with the ILD 500 GeV full simulation.**
- **Signal Event**:
  - $e^+e^- \to qq(z^*$ true mass≥450 $GeV)$
- **Background Event**:
  - 2-fermion background
    $e^+e^- \to qq(z^*$ true mass<450 $GeV)$
  - 4-fermion background
    hadronic event(Mainly W/Z-derived)
    semileptonic event(Mainly W/Z-derived)



- **Polarization** **Luminosity**
- $e^-: -80\%\,, e^+: +30\%$ $1600\ \mathrm{fb}^{-1}$ each

qq event selection

the ILD 500 GeV full simulation data



Evaluation of Z' new physics search

- The best cut condition among several parameter combinations is

  mass(jet with higher energy) <= 80 & log10(y34)<=-3.0

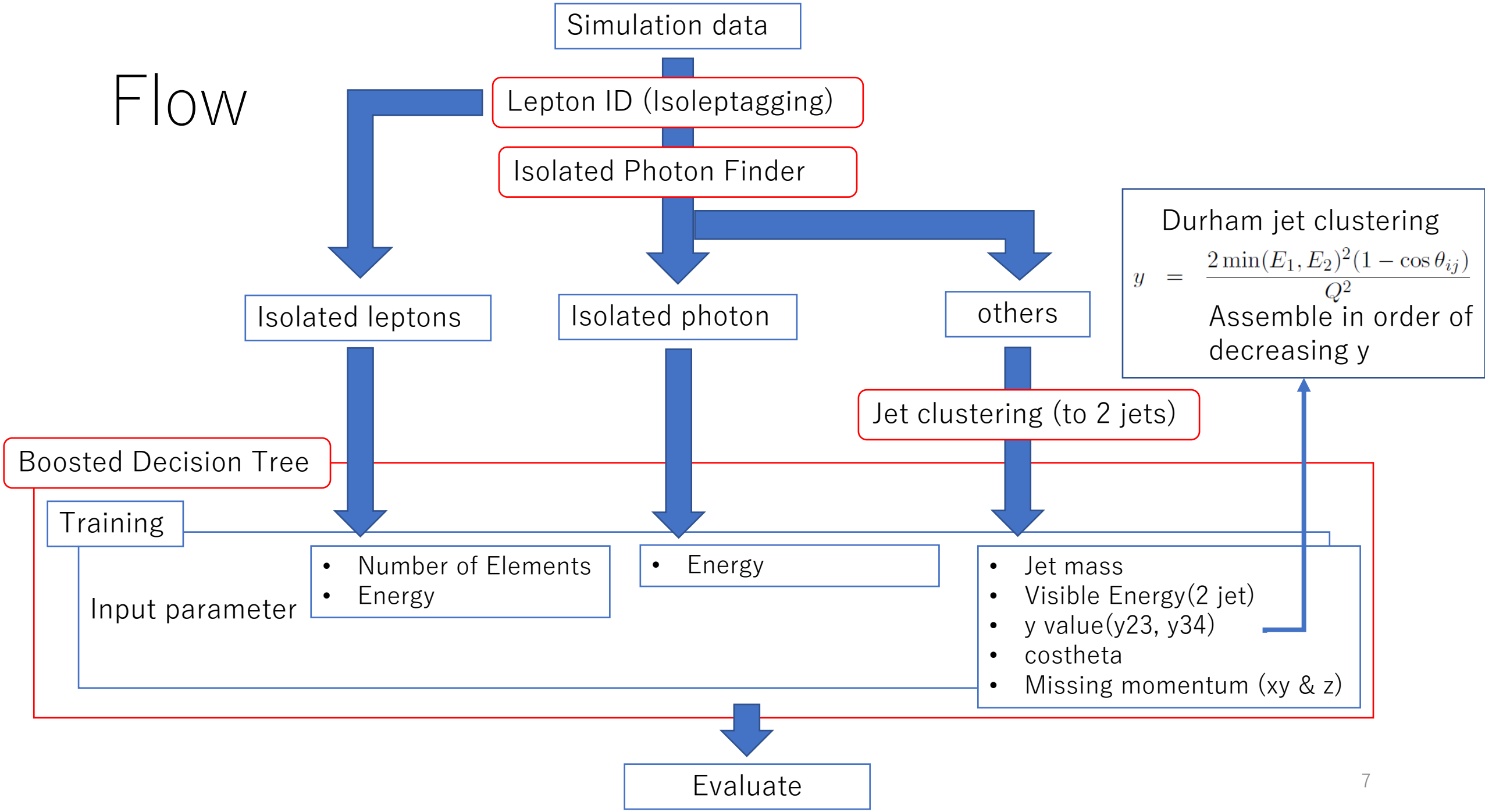
  cos(opening angle) <= -0.95

- but the number of 4f semileptonic BG events is still **too large**.

	signal	2f BG	4f hadronic BG	4f semileptonic BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With mass, OP angle cut	**1,329,022(62%)**	**747,675(8%)**	**701,049(6%)**	**3,614,268(18%)**

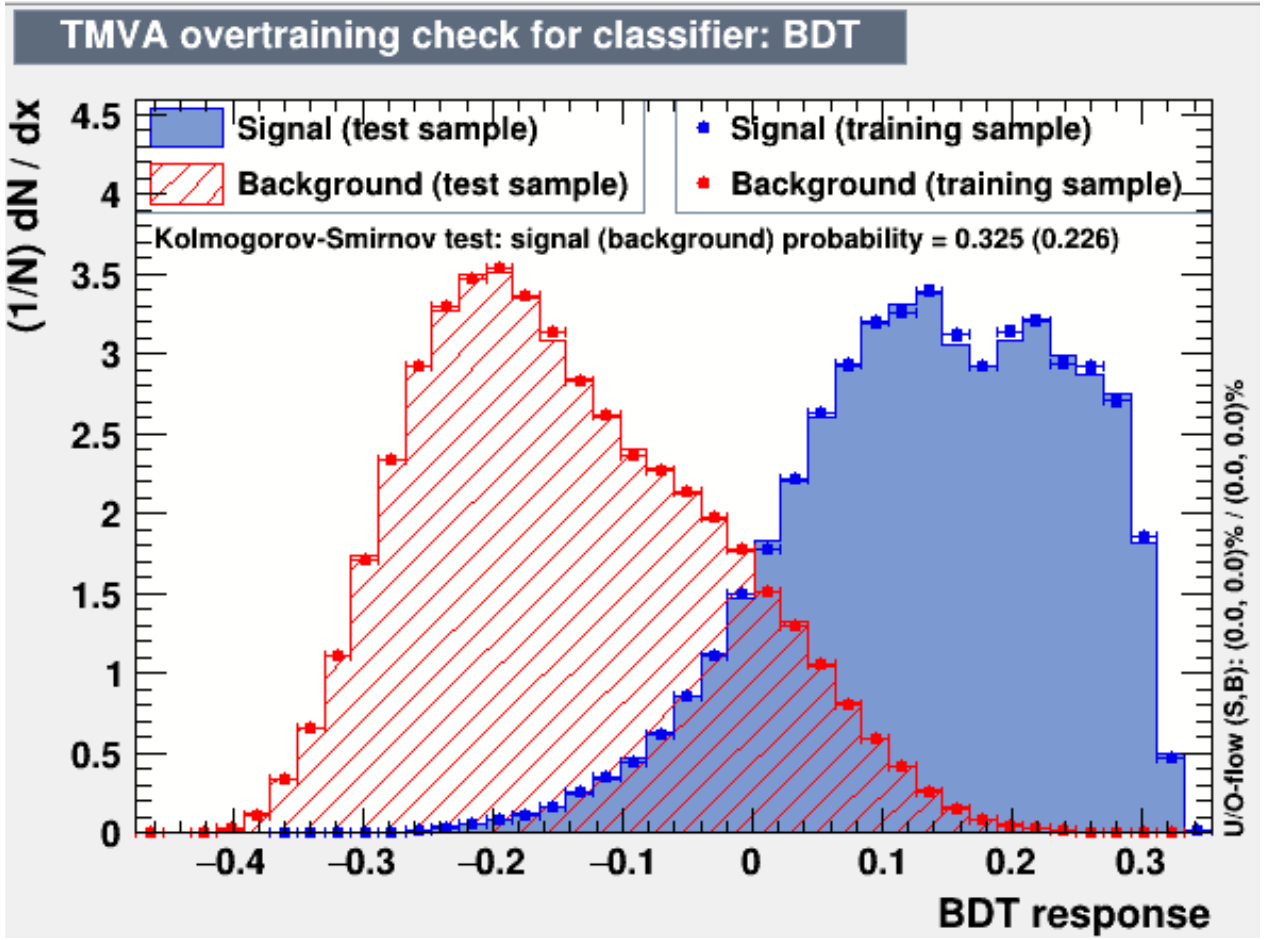
qq event selection was conducted, but the number of background events could not be reduced significantly, **so the multivariate analysis will be conducted.**

Flow


Simulation data
Lepton ID (Isoleptagging)
Isolated Photon Finder
Isolated leptons
Isolated photon
others
Durham jet clustering
$y = \frac{2\min(E_1, E_2)^2(1-\cos\theta_{ij})}{Q^2}$
Assemble in order of decreasing y
Jet clustering (to 2 jets)
Boosted Decision Tree
Training
Input parameter
• Number of Elements
• Energy
• Energy
• Jet mass
• Visible Energy(2 jet)
• y value(y23, y34)
• costheta
• Missing momentum (xy & z)
Evaluate

Training & Evaluate

- Cut condition
- Opening angle cut:
  - $\cos(angle) \leq -0.95$
- BDT_response >= 0.0



	signal	2f BG	4f hadronic BG	4f semileptonic BG
No cut	6,183,923(100%)	25,197,014(100%)	13,832,211(100%)	19,630,562(100%)
cut	**4,871,598(78%)**	**502,037(2%)**	**856,414(6%)**	**95,682(0.6%)**

quark flavor tagging

- To evaluate the new physics search, we make a cos theta distribution for each signal quark.
- To do this, I first conduct flavor tagging on the signals and separate them into b, c, and others.

		predicted flavor		
	qq(u,d,s)	cc	bb	others
true flavor qq(u,d,s)	2,438,521	30,904	5,305	665,024
cc	122,023	503,967	17,147	720,579
bb	9,703	7,887	619,293	248,343

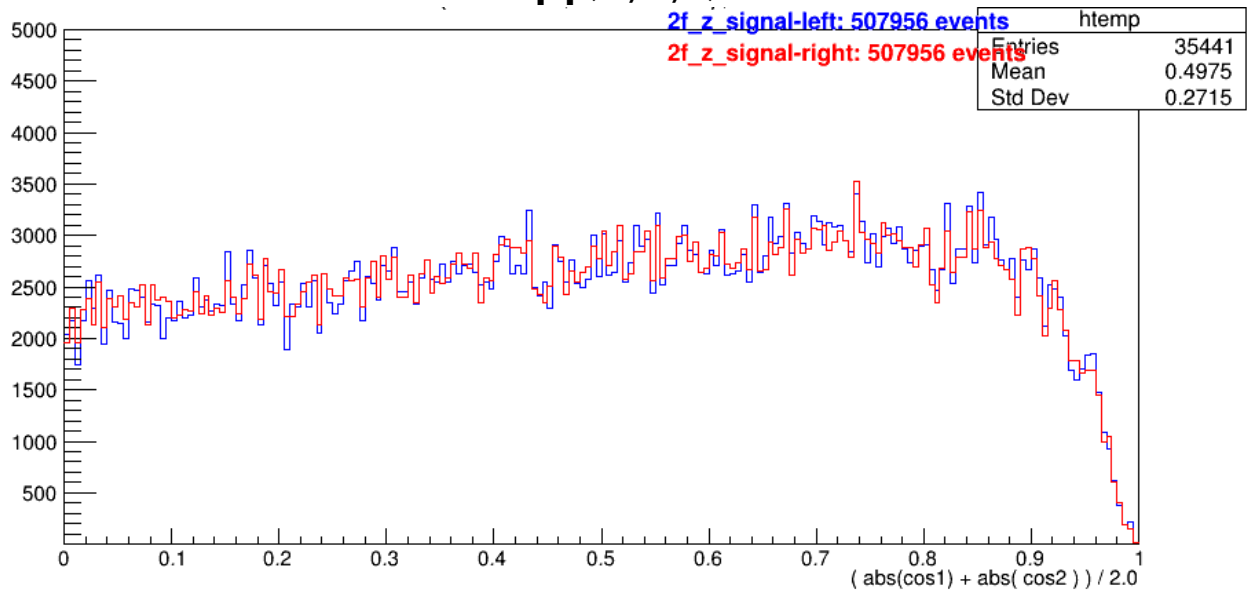
Flavor tagging is performed on the two jets of reconstituted particles
and events are used if the respective flavors match,
events that do not match are others.

costheta distribution for each predicted flavor

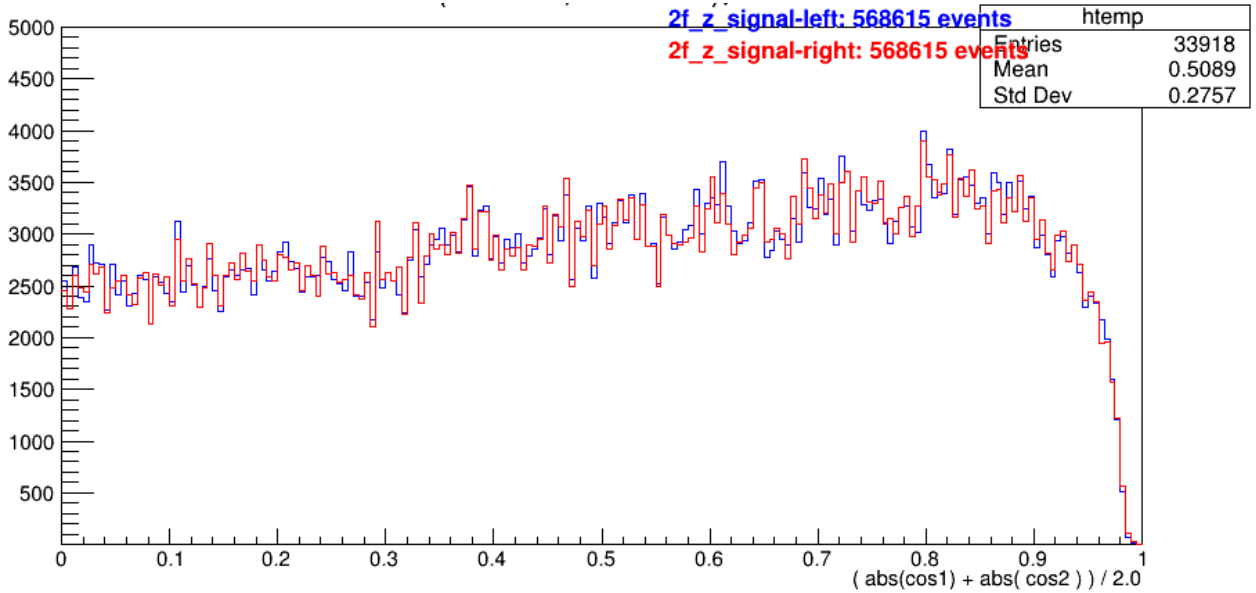
Blue: Left-handed (e^-, e^+)=(-80%,+30%)
Red : Right-handed (e^-, e^+)=(+80%,-30%)

Red scaled to match the number of events in blue

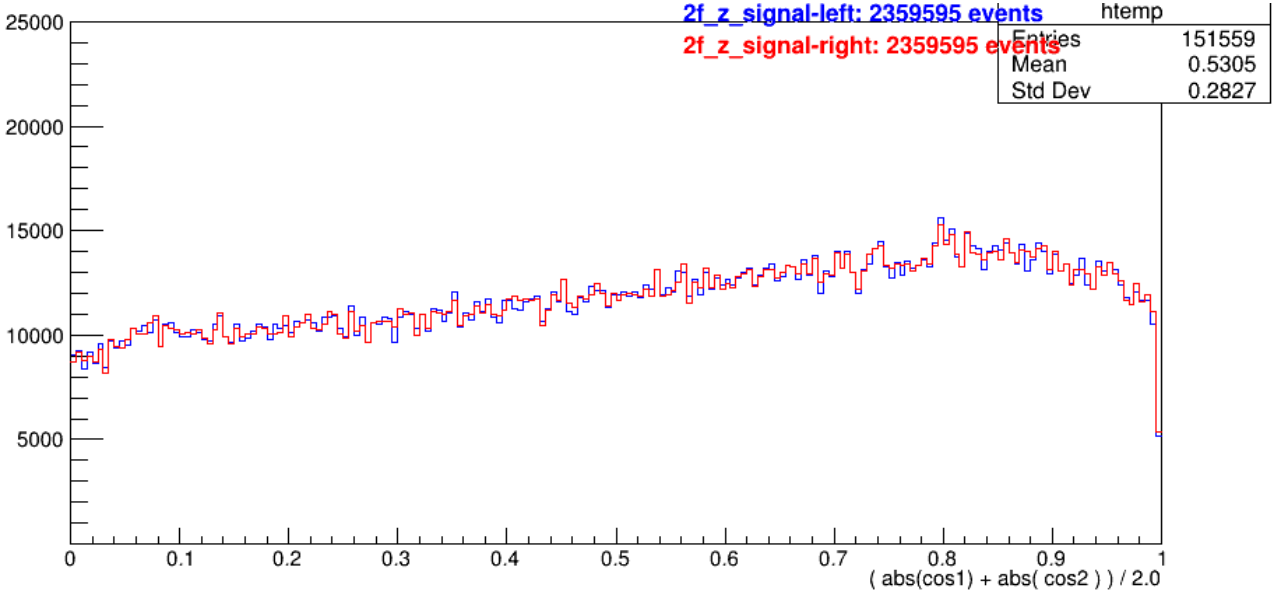
qq(u,d,s)



bb



cc



Procedures for evaluating each model search

- The accuracy $(\delta\sigma_i/\sigma_i(SM))$ in the ILC of the i-th bin of the angular distribution is evaluated as

$$\frac{\delta\sigma_i}{\sigma_i(SM)} = \sqrt{\left(\frac{\sqrt{S_i + N_i}}{S_i}\right)^2 + {\sigma_{syst}}^2}$$

S_i: the number of signal events
N_i: the number of background events **in each bin.**
In this evaluation, **systematic errors of 0.0 for b and 0.0 for c** are assumed.

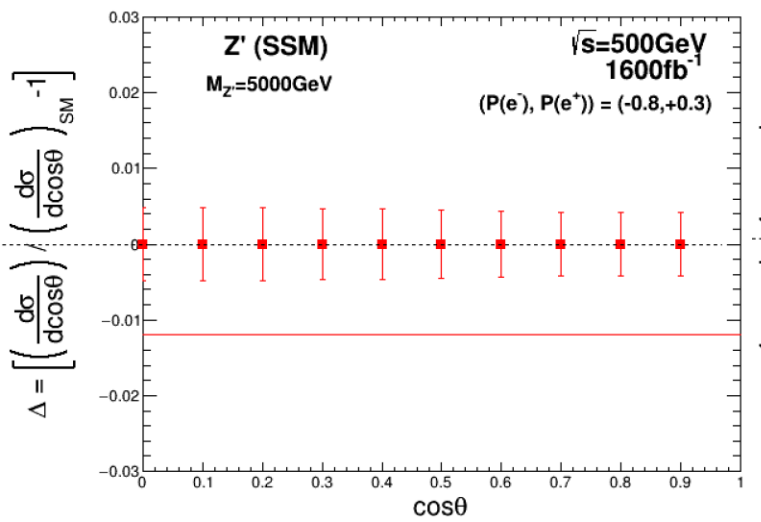
- The deviation of the differential cross section predicted by the standard model and each model for this i-th bin $(\delta\sigma_i(BSM)/\sigma_i(SM))$ is determined, and from

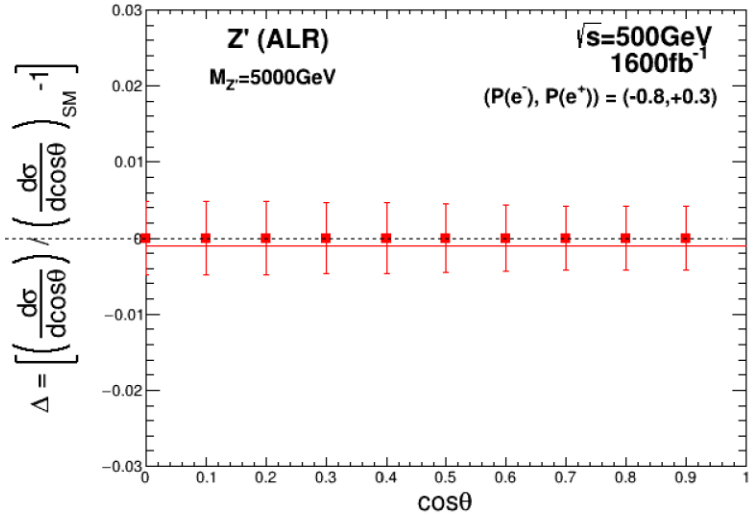
$$\chi^2(BSM) = \sum_i \left\{\left(\frac{\delta\sigma_i(BSM)}{\sigma_i(SM)} \Big/ \frac{\delta\sigma_i}{\sigma_i(SM)}\right)^2\right\},$$

the χ^2 is obtained.

For bb

Since the costheta distribution is taken in absolute values (0 to 1),
This plot is also calculated only in the range of 0 to 1
For example, if costheta=0.9, the average of the 0.9 and -0.9 results is used.





SSM: Sequential Standard Model
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psi : $E_6\ \psi\ model\ (\beta = \pi/2)$
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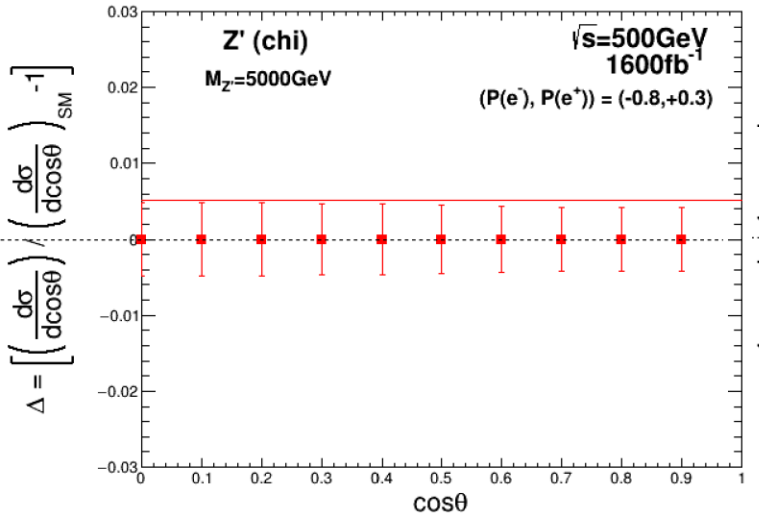
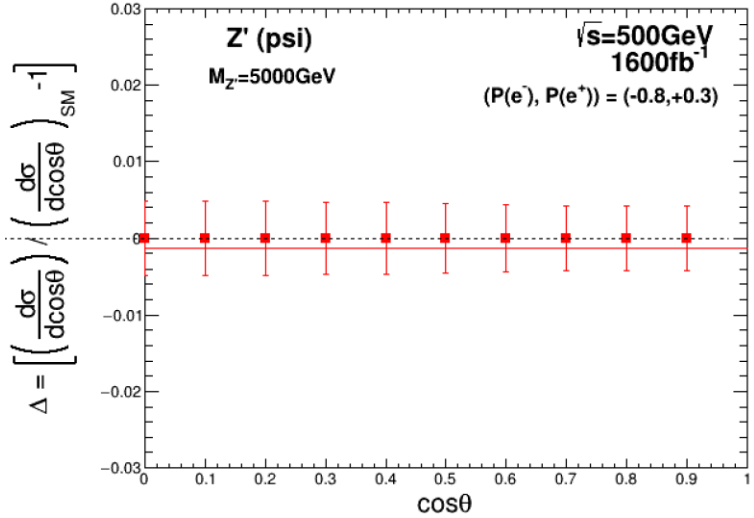
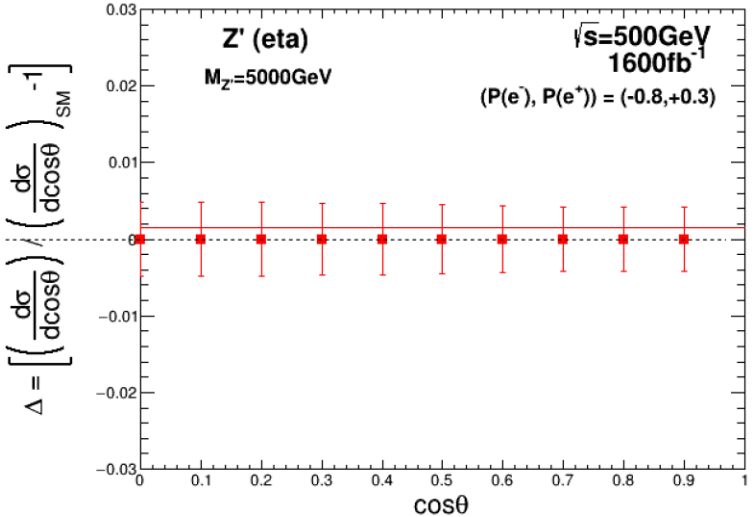
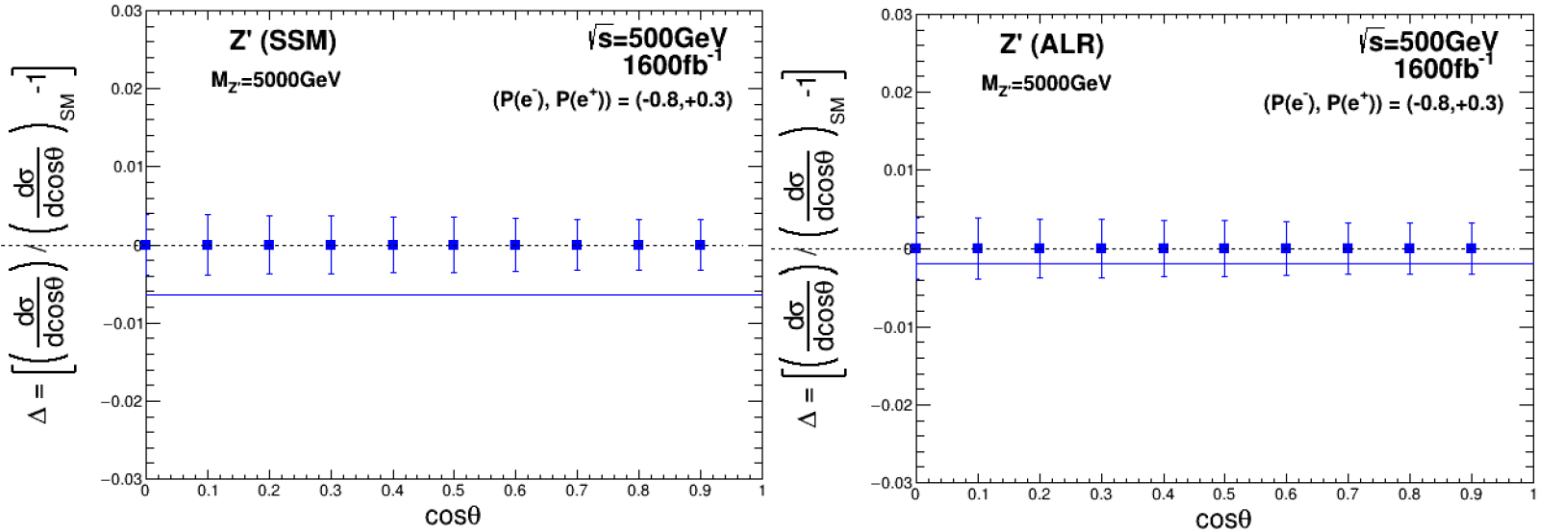






For cc

Since the costheta distribution is taken in absolute values (0 to 1),
This plot is also calculated only in the range of 0 to 1
For example, if costheta=0.9, the average of the 0.9 and -0.9 results is used.



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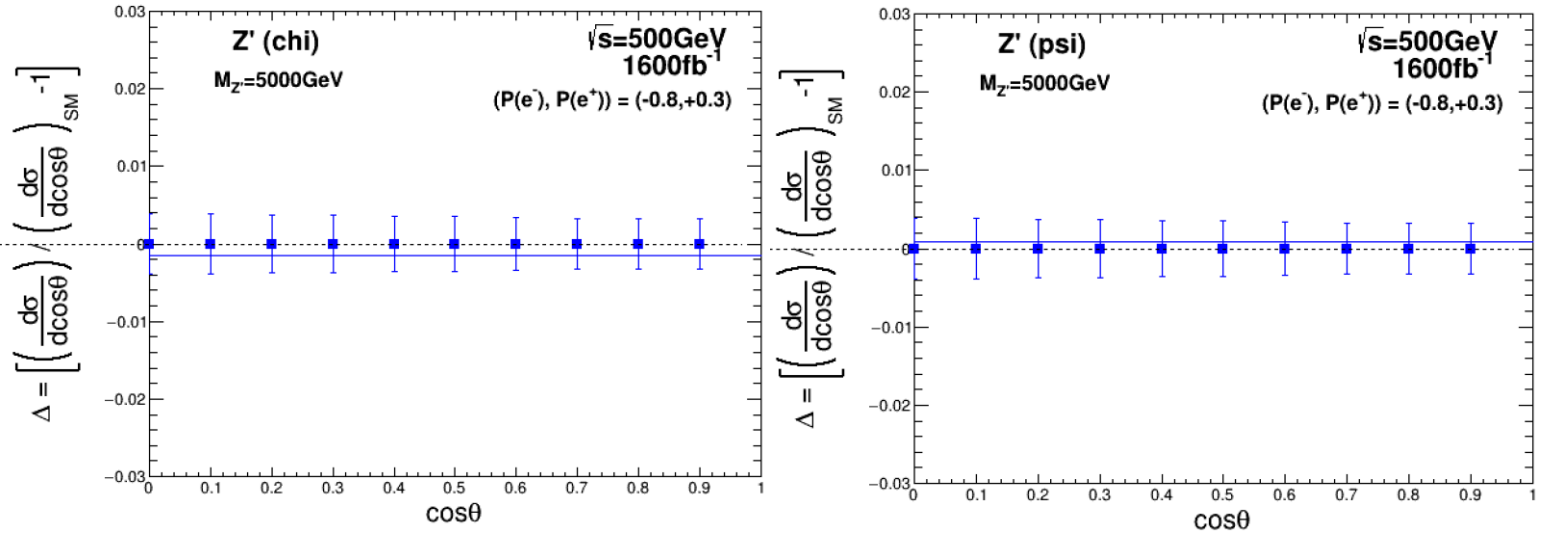
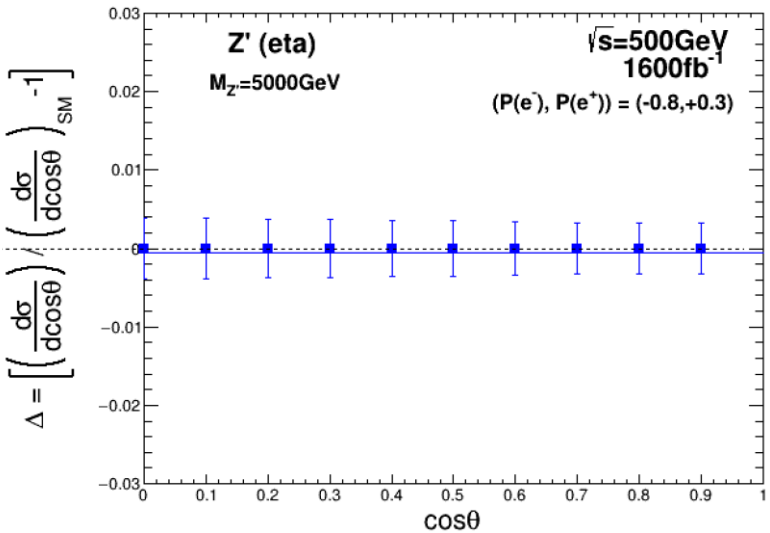
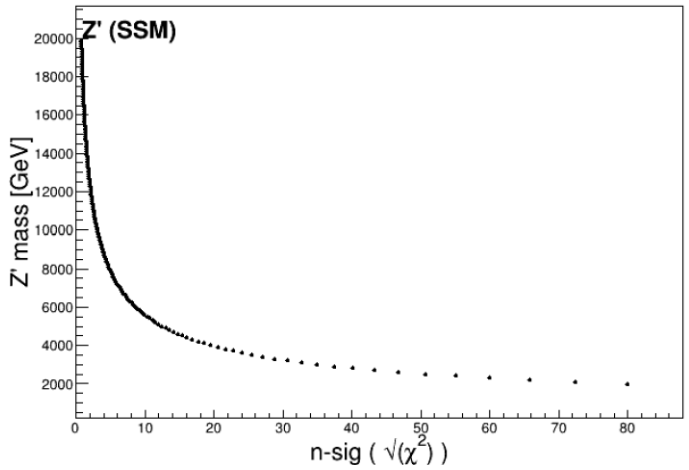
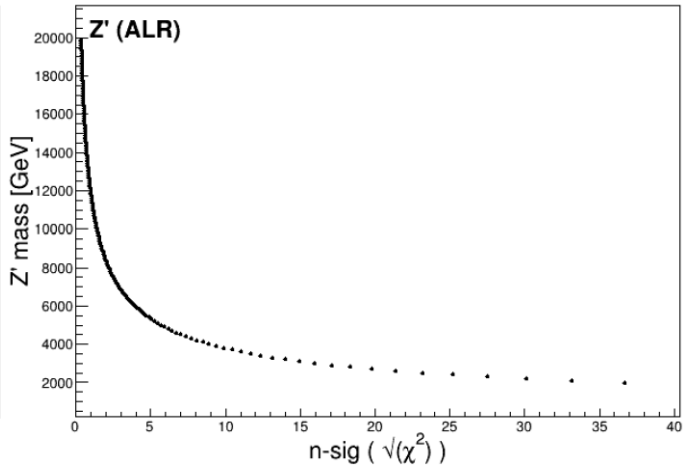
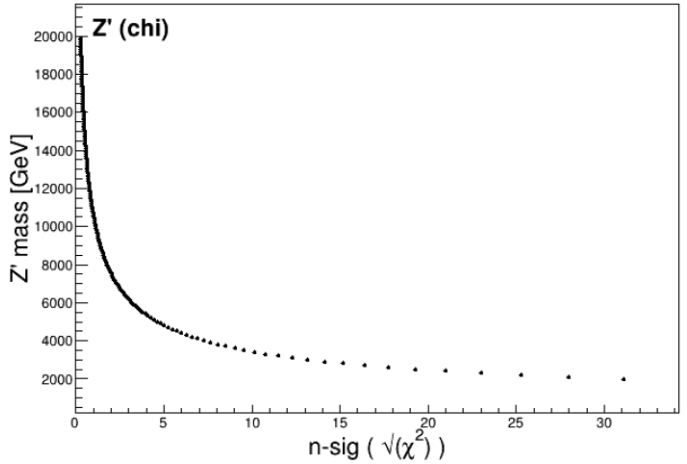


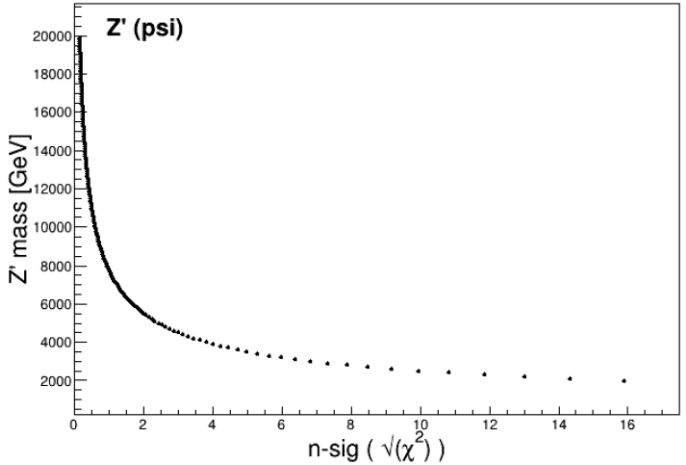


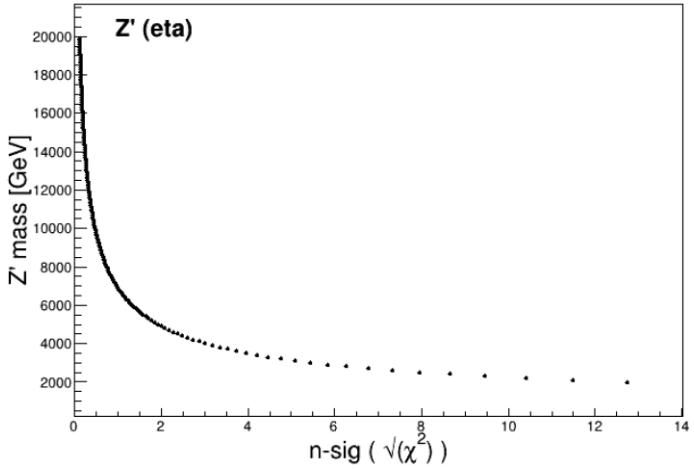
Chi square for b + c event











Z'model	SSM	ALR	χ	ψ	η
2-sigma	12TeV	8.4TeV	7.6TeV	5.5TeV	4.9TeV

2-sigma = 95% CL lower limit

Summary

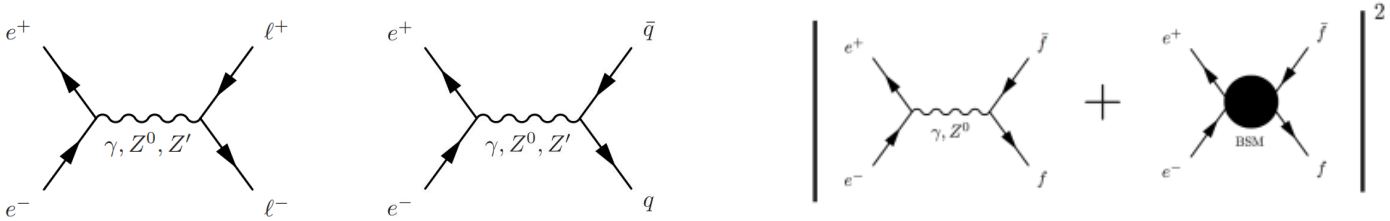
- b and c event selections are conducted for a full simulation of the ILC with a cms energy of 500 GeV and a mass limits of Z' are obtained based on angular distribution.
- The evaluation results show that the combined results of b and c has sensitivity for Z' mass of 5-12 TeV.

- As a next step, electron and lepton pair events will also be combined for evaluation.

backup

2-lepton $e^+e^- \rightarrow l^+l^-$ event

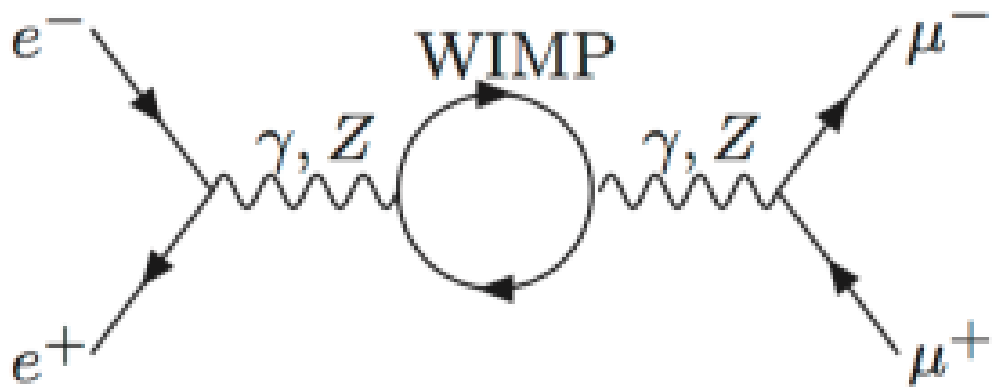
- $e^+e^- \rightarrow l^+l^-(l = \mu, \tau)$: The production of fermionic pairs is sensitive to the production of heavy gauge bosons (Z'). In the presence of new physics mediated by new particles, the first power term of the interference can be seen as a shift, as in right Figure.



- In the Gauge Higgs Unification (GHU) model, Higgs particles are part of an extra-dimensional component of the gauge potential, which is represented by a variation of the Aharonov-Bohm (AB) phase (θ_H) in the fifth dimension.

2-lepton $e^+e^- \rightarrow l^+l^-$ event

- There is a general method to investigate the $e^+e^- \rightarrow f\bar{f}$ misalignment due to WIMPs.
- If we introduce the WIMP(χ) into the 2-fermion final state process ($e^+e^- \rightarrow f\bar{f}$) analyzed so far and assume a diagram that includes the loop $Z \rightarrow \chi\chi \rightarrow Z$, the coupling constant changes.



Definition of signal events

- I separate signal events into signal and background by mass.
- This mass corresponds to the Z* mass in the Feynman diagram.
- If Z* mass is small, the contribution of heavy new particles such as Z' that interfere with Z* will be small.
- When calculating the Z' model, Z* is assumed to be 500 GeV (not including ISR and other effects), so if low Z* contribution is included, the result will be different from what we expect.

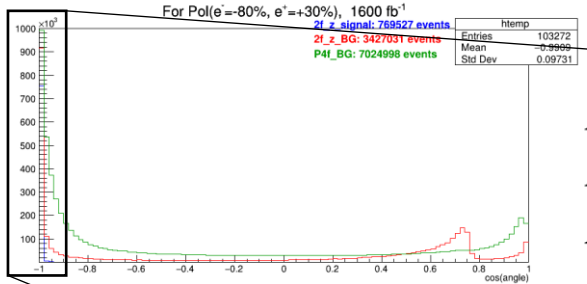
- So I drop the low mass events as background.

Opening angle cut

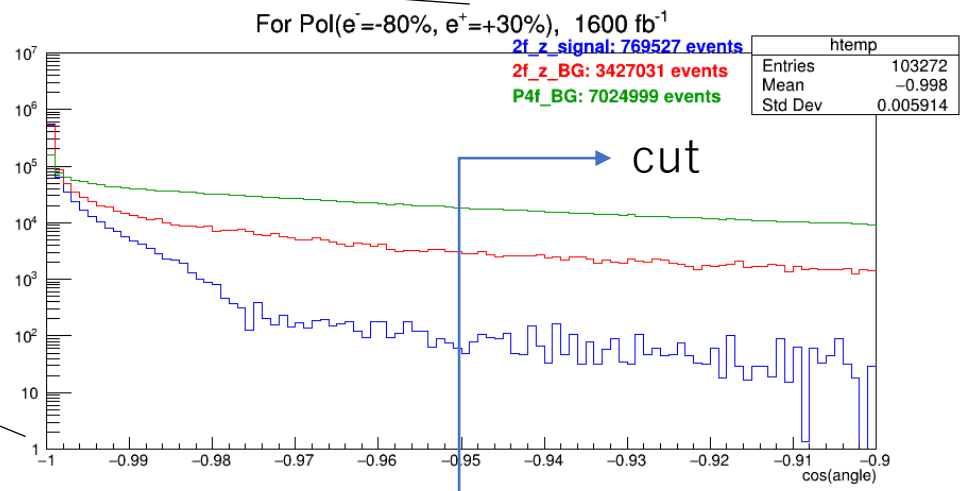
The angle between the signal jets is almost 180 degrees.
→An event near 180 degrees is considered a signal (2 fermion) event.

For mu event

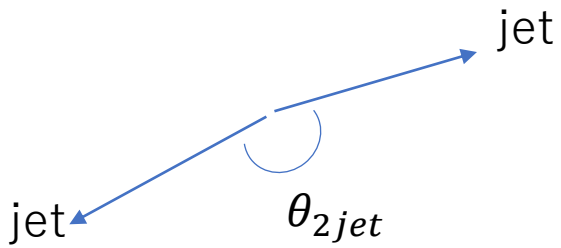
overall



Around 180°



Candidate -0.95

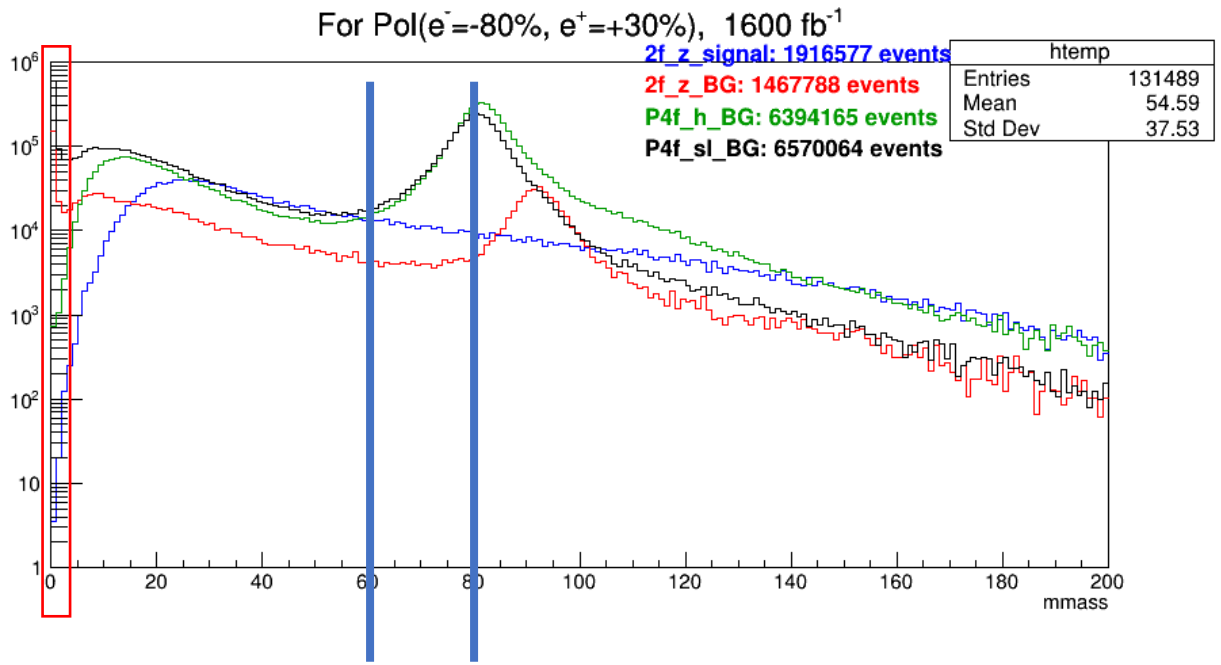


qq event selection

- With Opening angle: $\cos(angle) \leq -0.95$

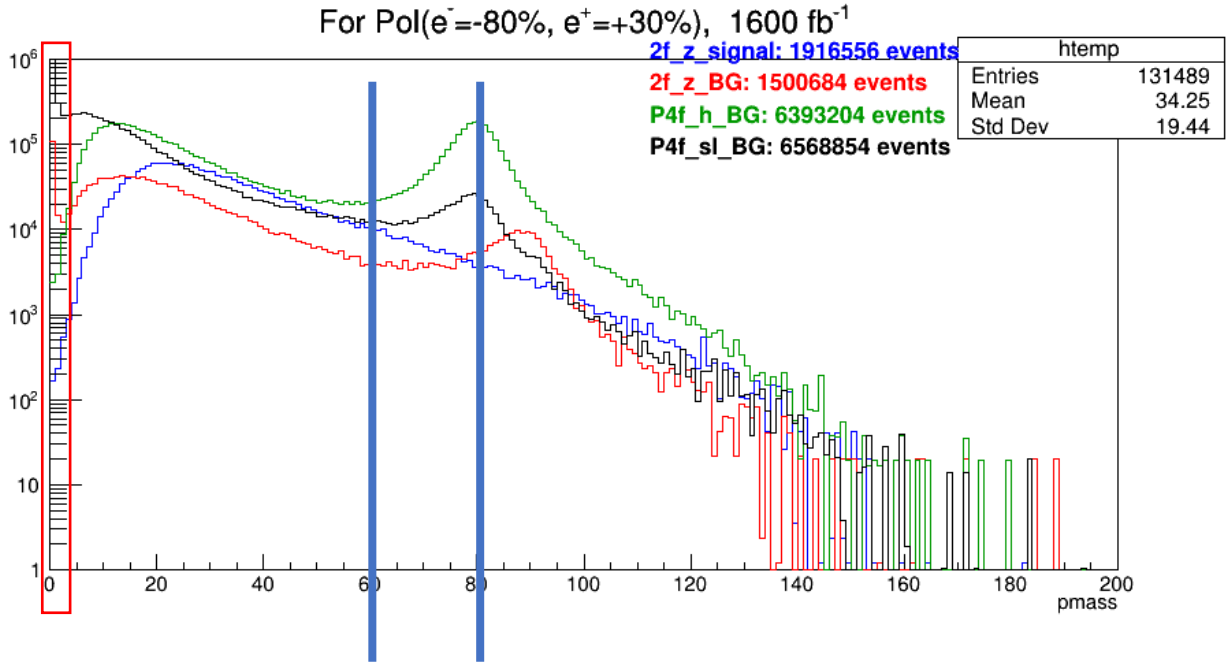
Jet mass plot

First jet



Cut condition
1 < mmass <= 60 or 80 GeV

Second jet

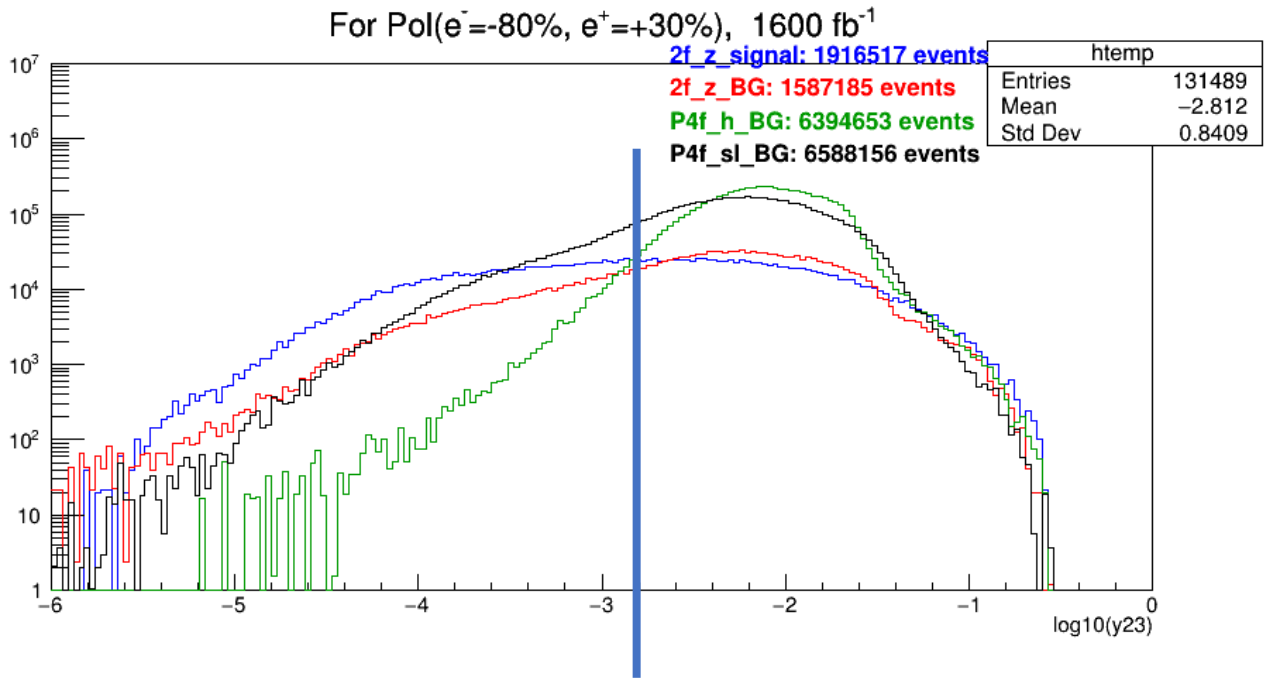


Cut condition
1 < pmass <= 60 or 80 GeV

qq event selection

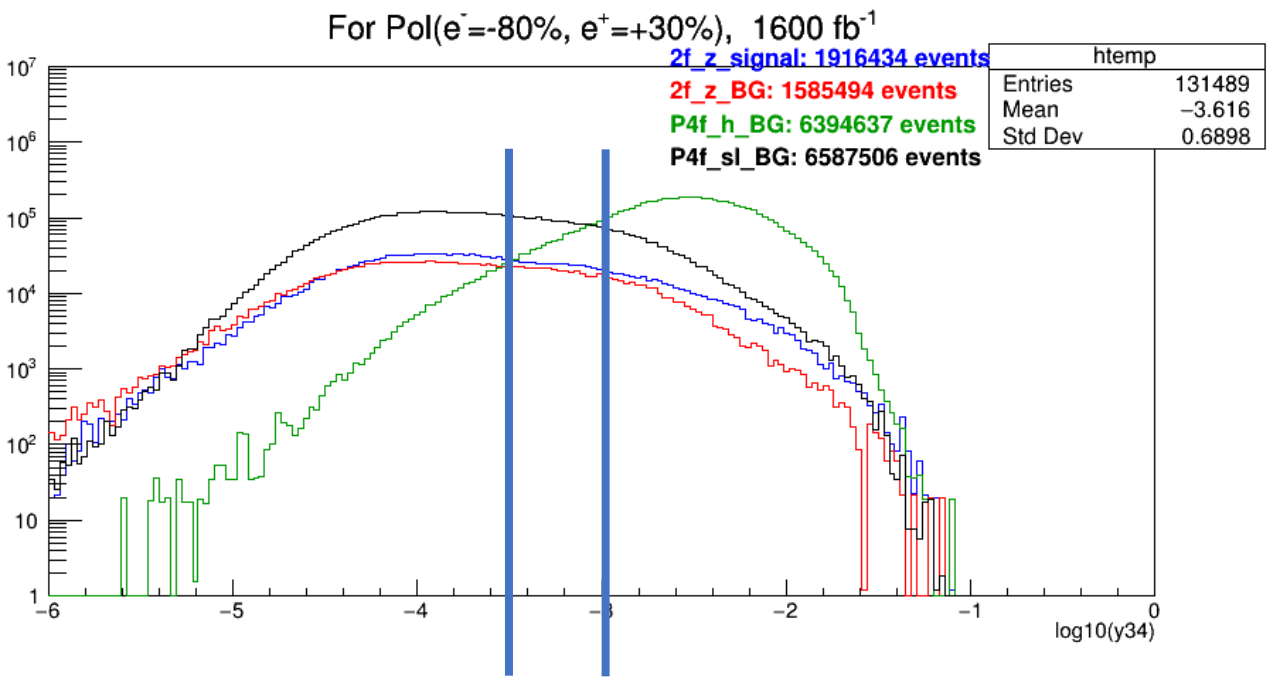
- With Opening angle: $\cos(angle) \leq -0.95$

y23



Cut condition
log10(y23) <= -2.8

y34



Cut condition
log10(y34) <= -3.0 or -3.5

y23, y34

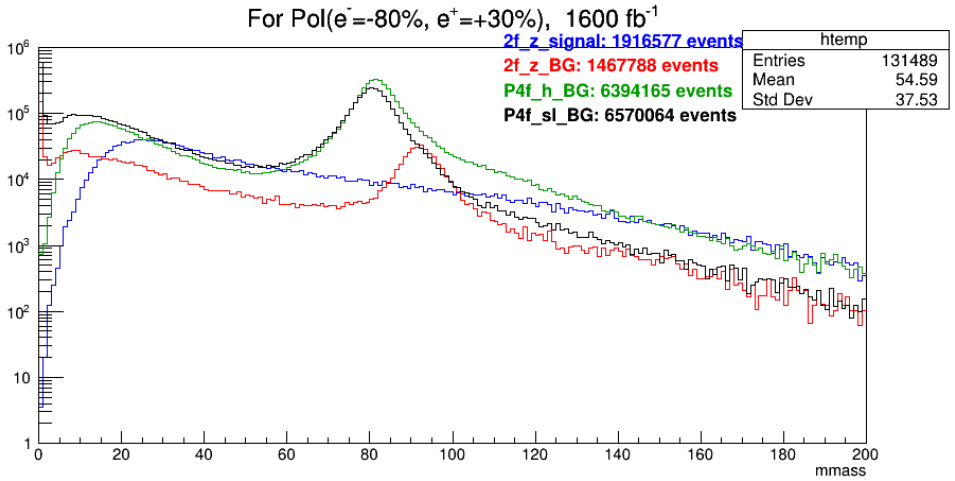
$$y = \frac{2\min(E_1, E_2)^2(1-\cos\theta_{ij})}{Q^2}$$

Cut on some parameters

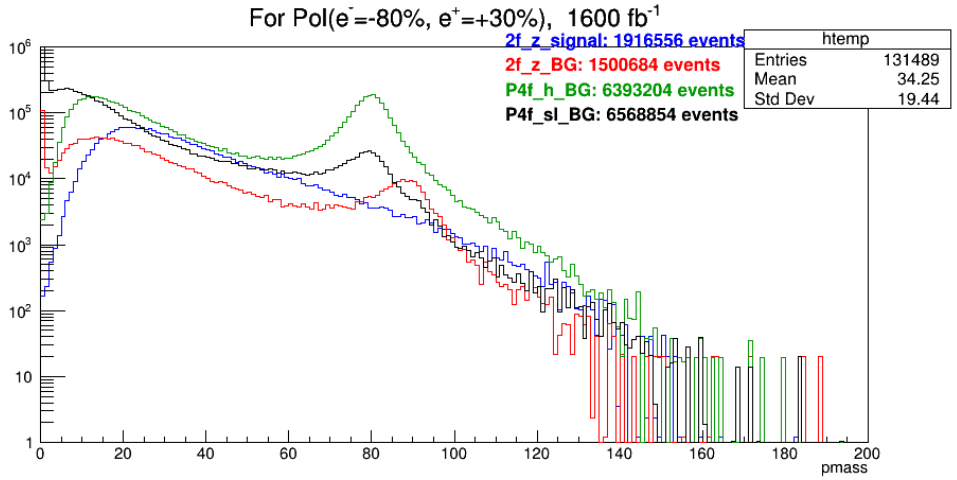
- Additional cut conditions: Mass (jet), y23, y34

Jet mass plot

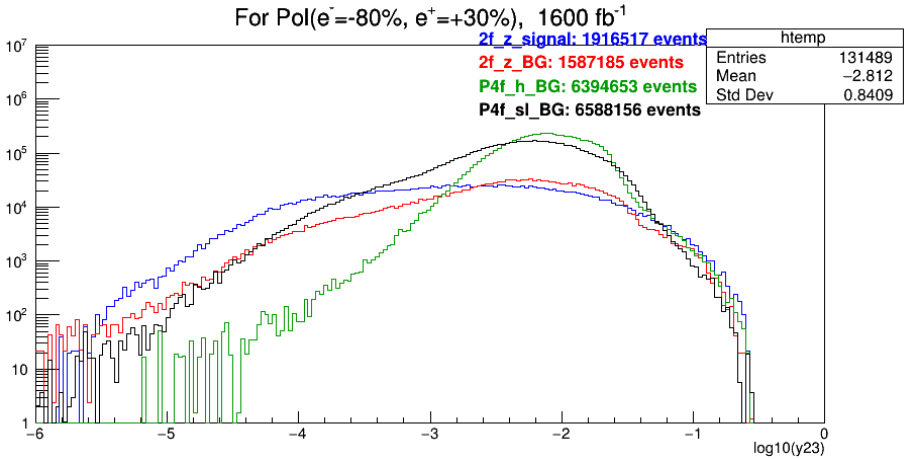
The first one



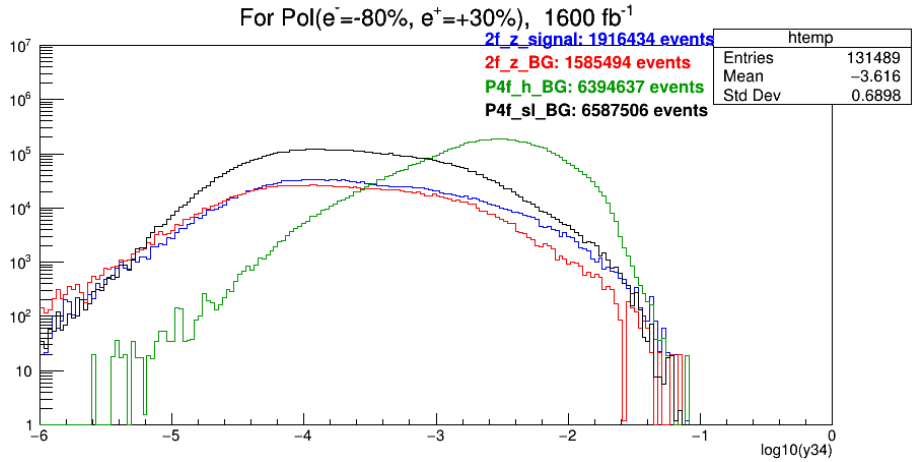
The second one



y23



y34



qq event selection

- Jet mass cut with Opening angle cut: $\cos(angle) \leq -0.95$

First jet

1 < mmass <= 60 GeV

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With mass, OP angle cut	1,272,931(59%)	786,796(9%)	1,865,450(17%)	2,751,771(14%)

1 < mmass <= 80 GeV

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With mass, OP angle cut	1,497,172(70%)	869,734(10%)	3,382,997(31%)	4,212,822(21%)

Second jet

1 < pmass <= 60 GeV

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With mass, OP angle cut	1,713,454(80%)	1,184,916(13%)	3,995,870(36%)	4,620,594(24%)

1 < pmass <= 80 GeV

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With mass, OP angle cut	1,846,892(86%)	1,264,701(14%)	5,321,984(48%)	4,938,367(25%)

qq event selection

- With Opening angle: $\cos(angle) \leq -0.95$

y23

log10(y23) <= -2.8

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With y23, OP angle cut	936,400(44%)	426,342(5%)	183,726(2%)	1,166,883(6%)

y34

log10(y34) <= -3.0

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With y34, OP angle cut	1,539,170(72%)	1,339,581(15%)	1,156,958(11%)	5,524,699(28%)

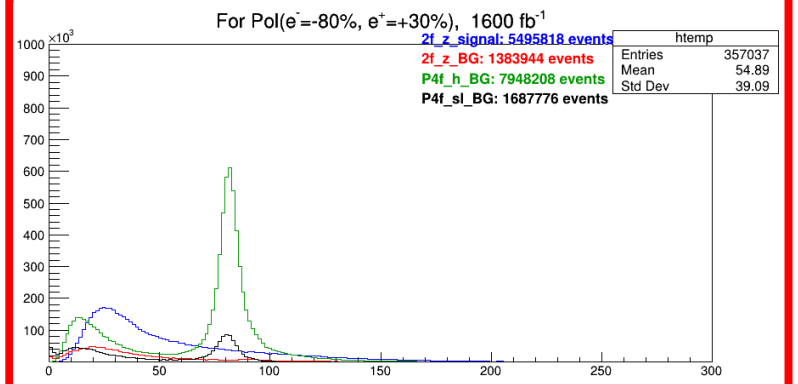
log10(y34) <= -3.5

	signal	2f BG	4f_h_BG	4f_sl_BG
No cut	2,151,356(100%)	8,800,899(100%)	11,016,453(100%)	19,630,562(100%)
With y34, OP angle cut	1,135,346(53%)	1,003,140(11%)	262,340(2%)	4,004,374(20%)

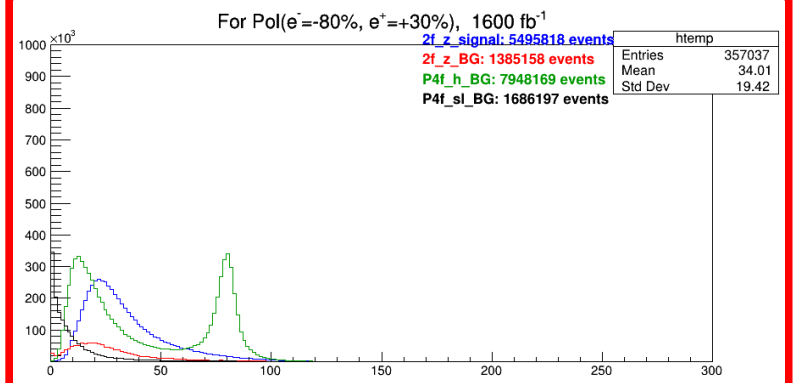
Input parameter 1

Isolated leptons
top: NumberOfElements
bottom: Energy of isolated leptons

Single Jet mass

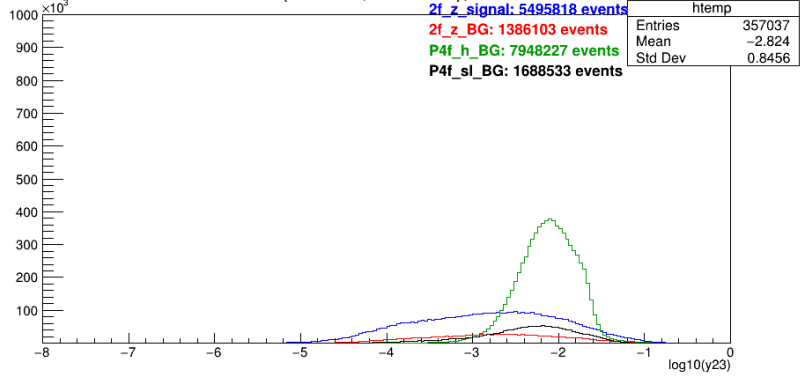


m_1st

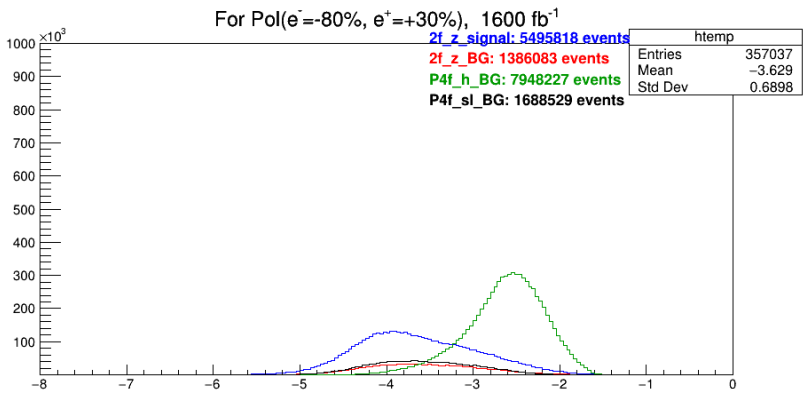


m_2nd

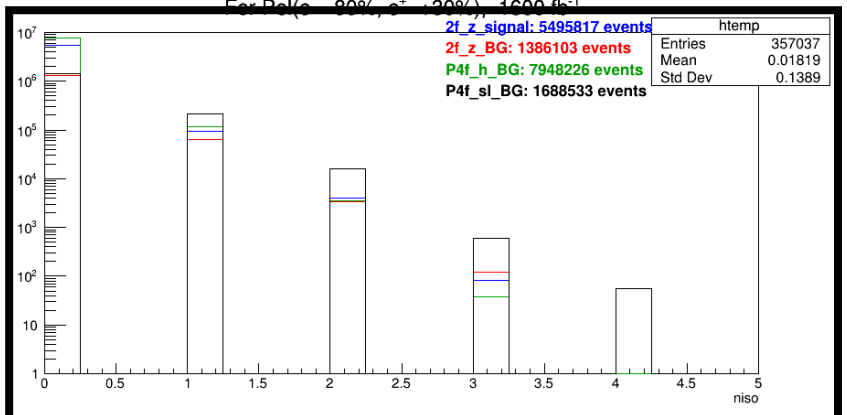
y value

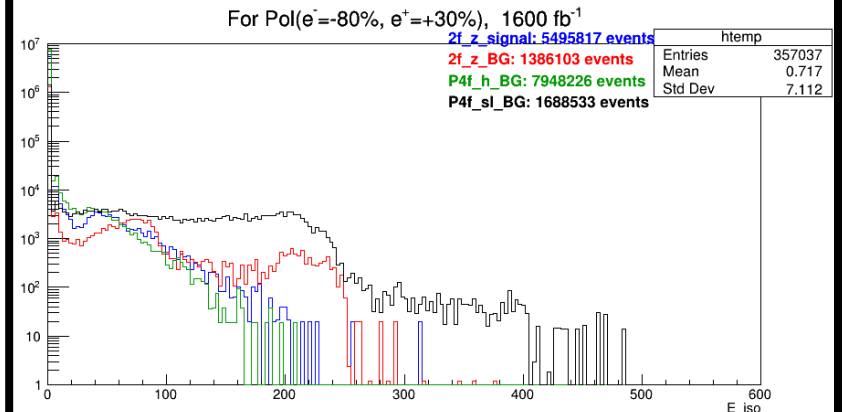


y23



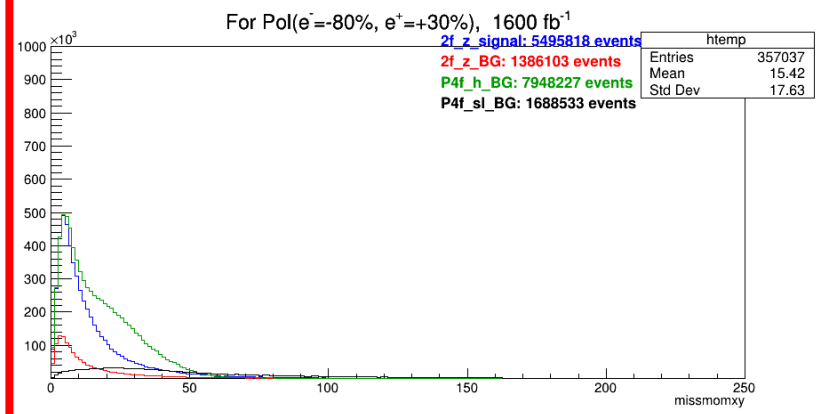
y34



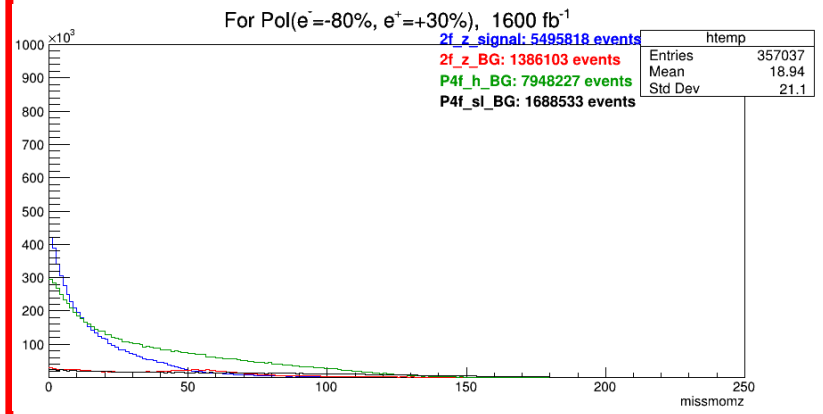


Input parameter 2

Missing momentum (2jet)

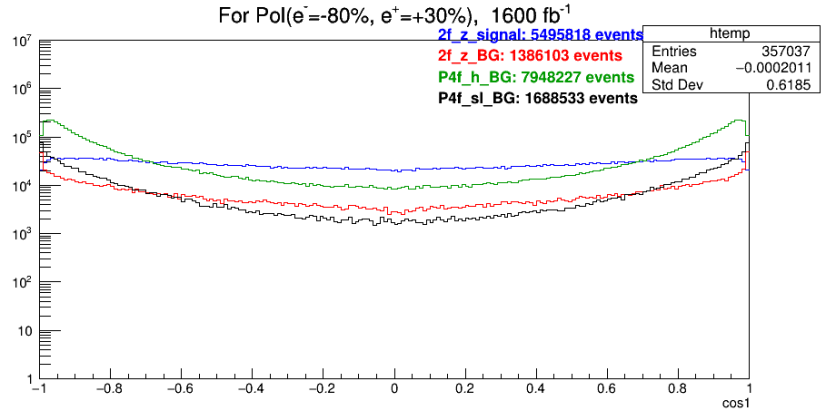


Missing momentum (xy)

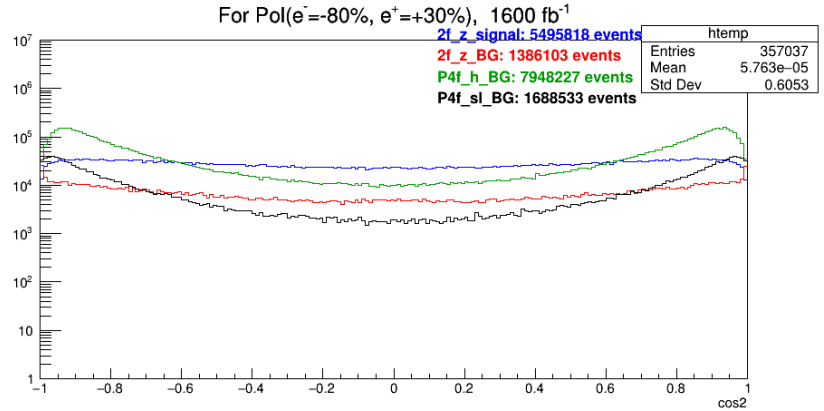


Missing momentum (z)

Costheta (jet)

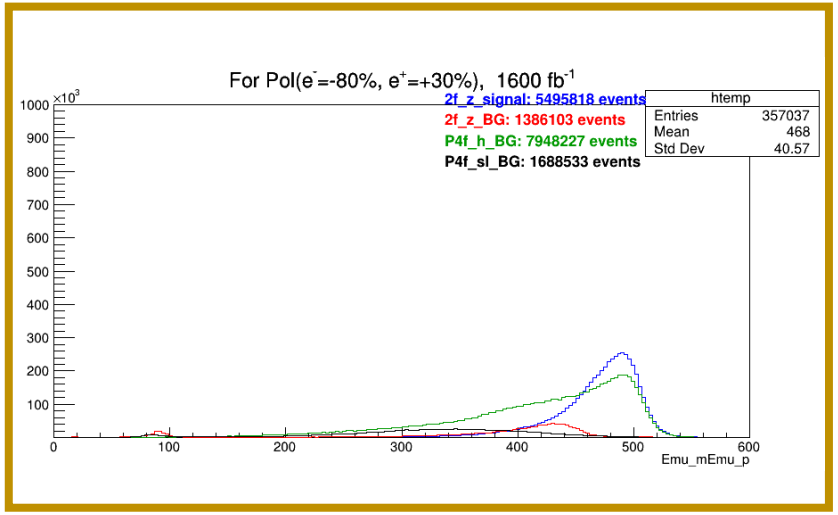


Costheta_1st

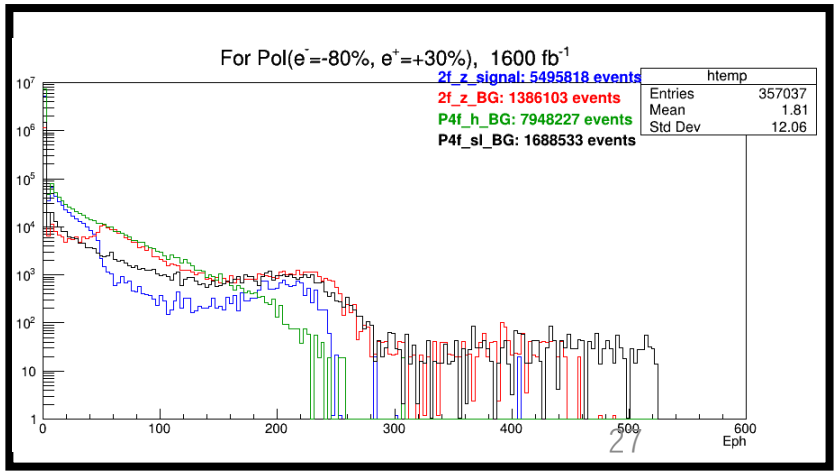


Costheta_2nd

Visible energy(2 jet)



Isolated photons: Energy



events

- μ & τ **event selection with the ILD 500 GeV full simulation.**
- **Signal Event**: 2f_Z_leptonic (mu or tau) ($mass$ ≥450 GeV)
- **Background Event**:

2f_Z_leptonic (signal $mass$ <450 GeV)
2f_Z_leptonic (If sig is mu then tau, if tau then mu.)
4f_WW_leptonic
4f_ZZ_leptonic
4f_singleZee_leptonic
4f_singleZsingleWMix_leptonic
4f_ZZWWMix_leptonic
4f_singleW_leptonic
4f_singleZnunu_leptonic

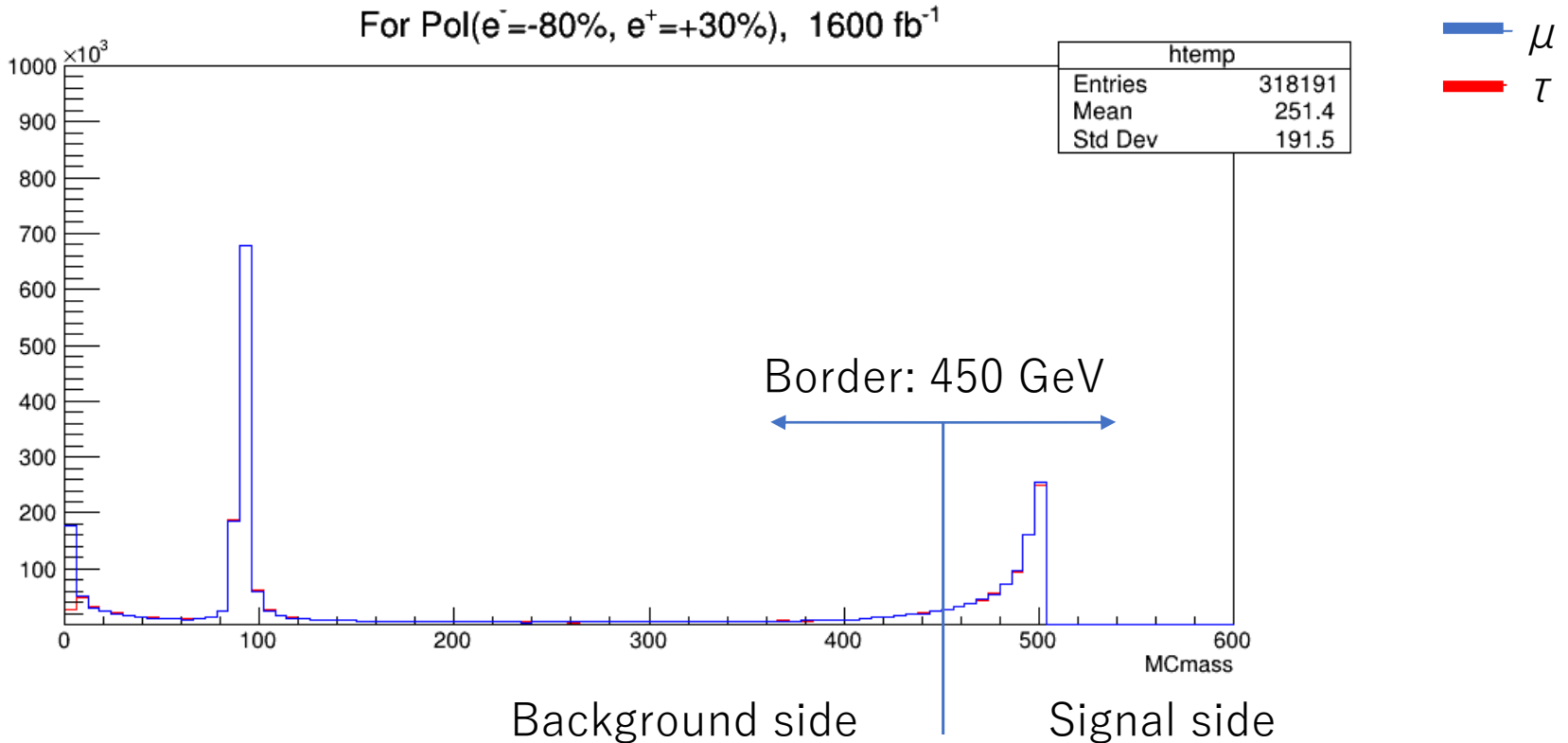
2f Background

4f Background

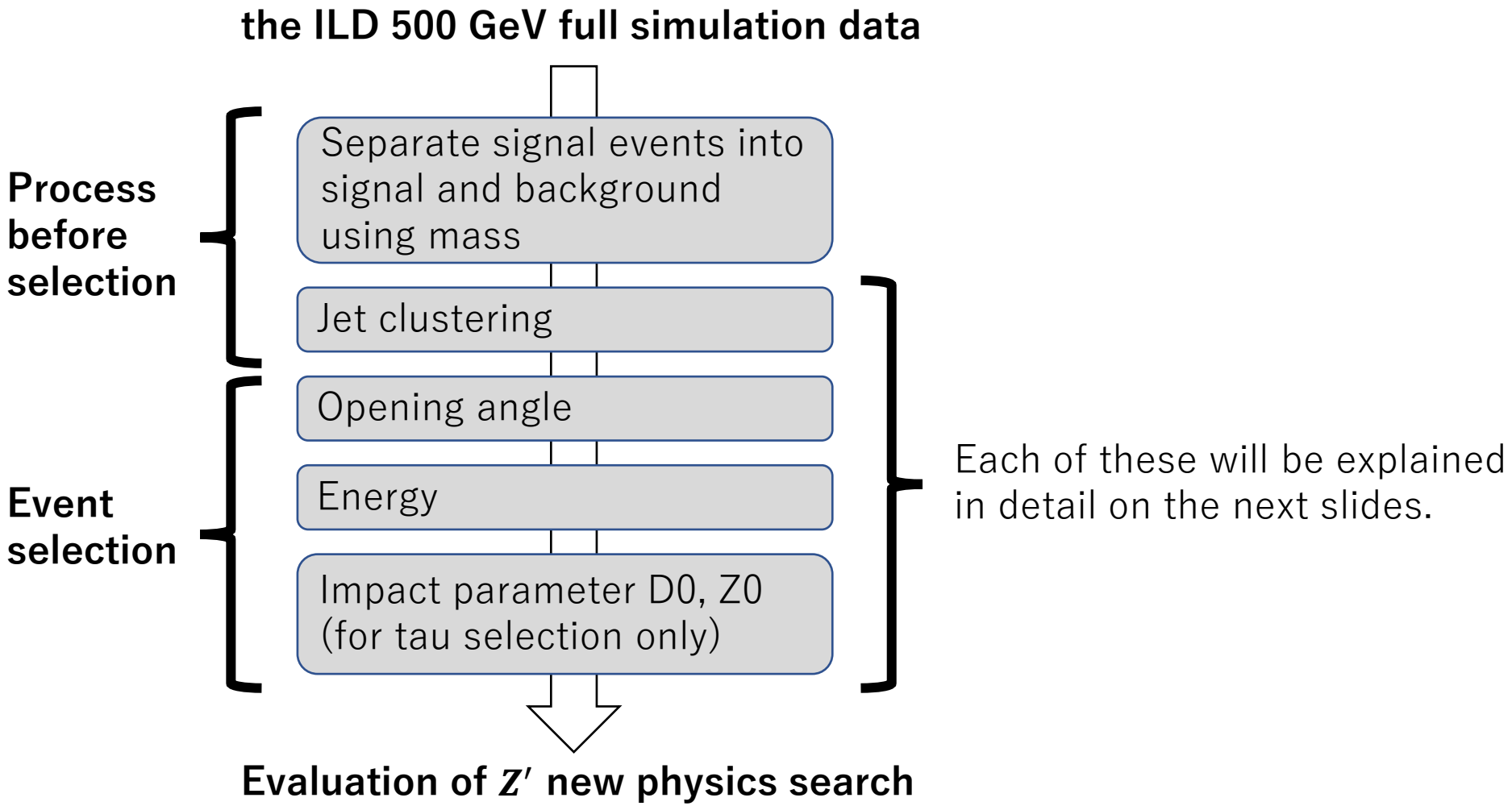
- **Polarization** **Luminosity**
- $e^-: \mp 80\%$, $e^+: \pm 30\%$ $1600\ \mathrm{fb}^{-1}$ each

Definition of signal events

- With 450 GeV as the border, the right side is the signal and the left side is the background.

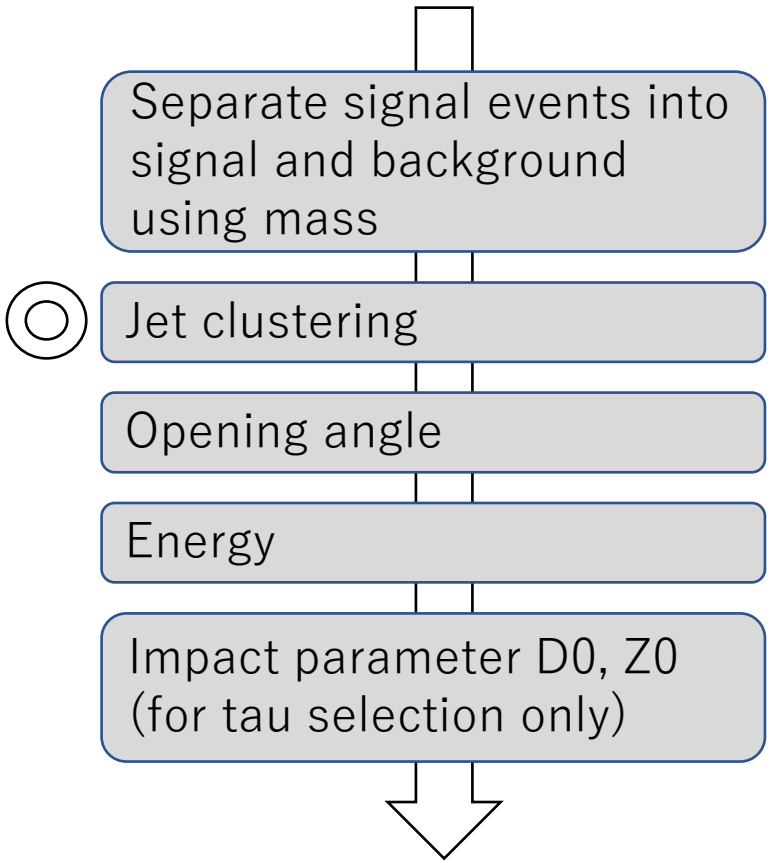


μ & τ event selection order



Jet clustering

the ILD 500 GeV full simulation data

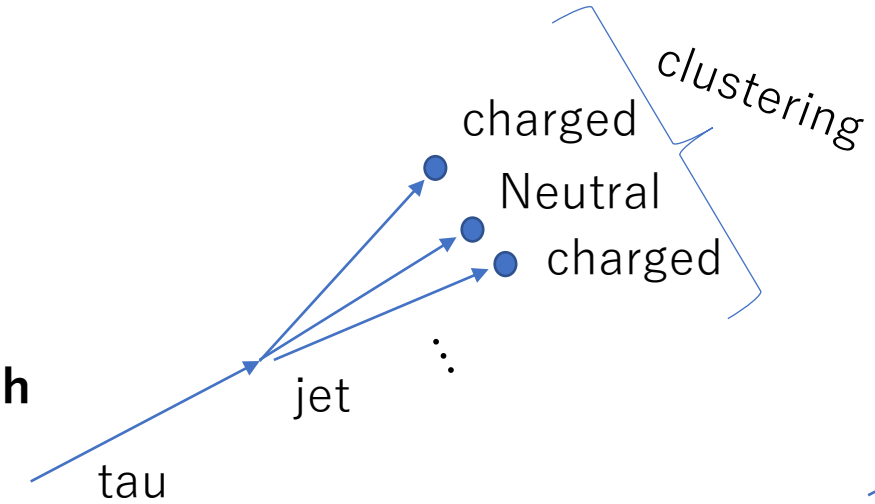


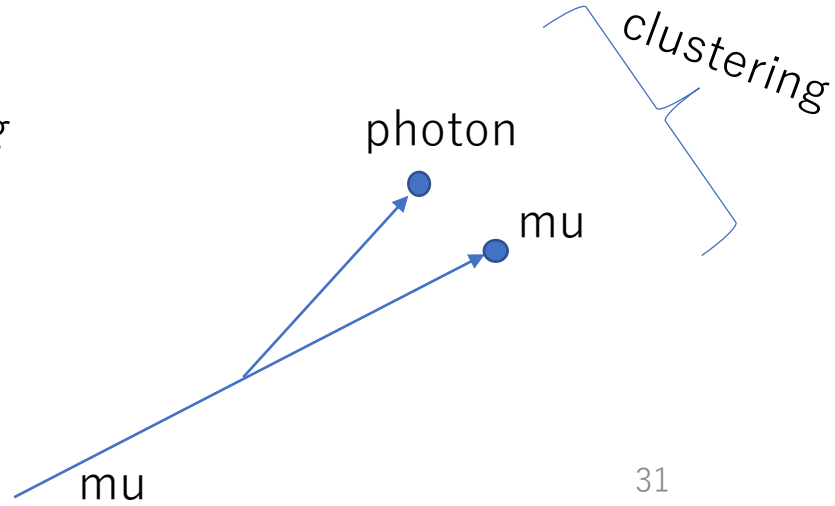
Evaluation of Z' new physics search

Tau particles produce jets when they decay into hadrons.

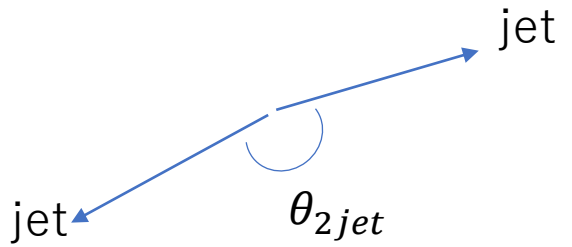
→ Clustering of nearby particles consistent to tau mass as a jet

→ In the case of mu, the photon of Final State Radiation is included in "jet", so energy of this "jet" is used for mu event selection.(**FSR recovery**)





Opening angle cut



the ILD 500 GeV full simulation data

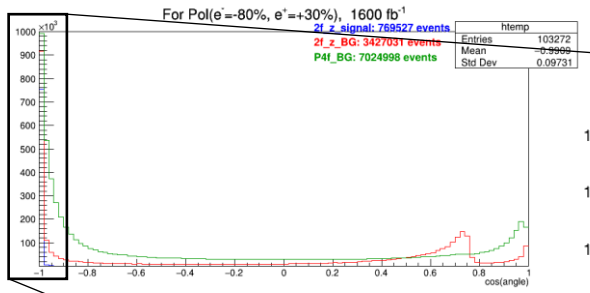
- Separate signal events into signal and background using mass
- Jet clustering
- Opening angle
- Energy
- Impact parameter D0, Z0 (for tau selection only)

Evaluation of Z' new physics search

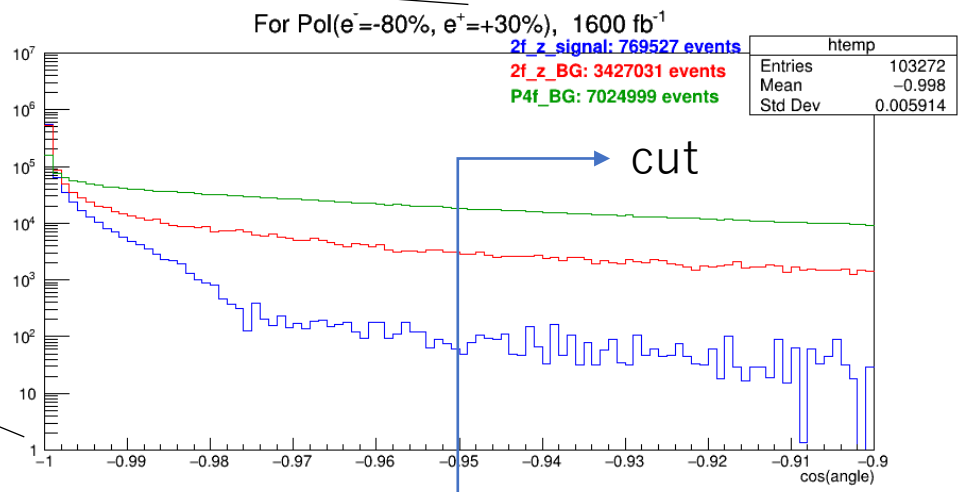
The angle between the signal jets is almost 180 degrees.
→An event near 180 degrees is considered a signal (tau & mu) event.

For mu

overall



Around 180°



Candidate -0.95

Energy cut

the ILD 500 GeV full simulation data

Separate signal events into signal and background using mass

Jet clustering

Opening angle

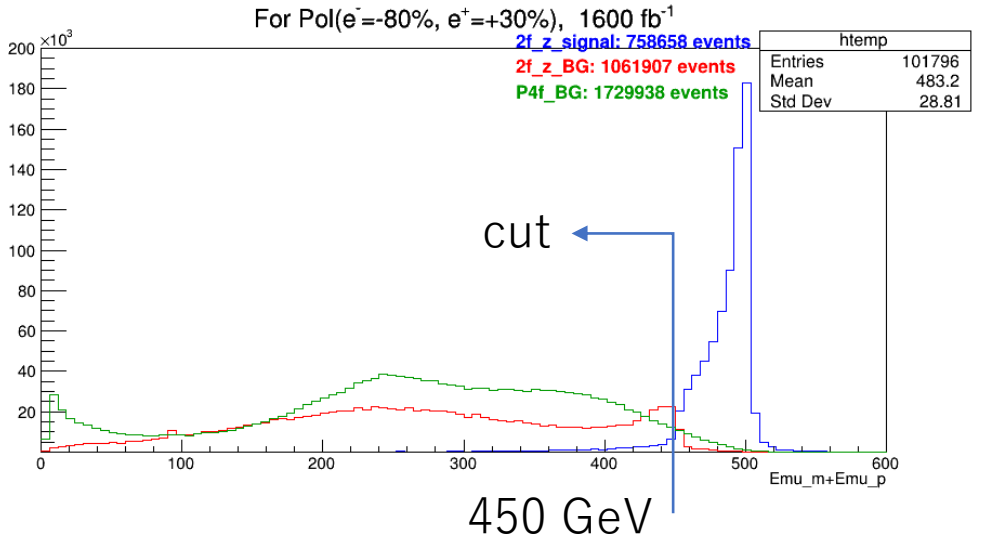
◎ Energy

Impact parameter D0, Z0 (for tau selection only)

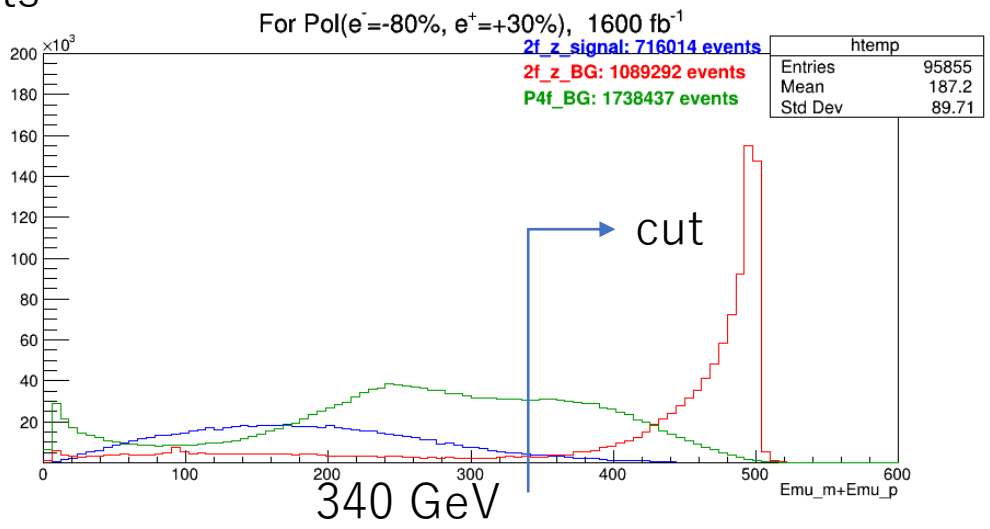
Evaluation of Z' new physics search

- $l^- Energy + l^+ Energy$ after opening angle cut

mu events



tau events



Impact parameter: D0, Z0

the ILD 500 GeV full simulation data

Separate signal events into signal and background using mass

Jet clustering

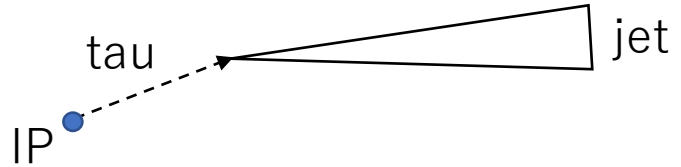
Opening angle

Energy

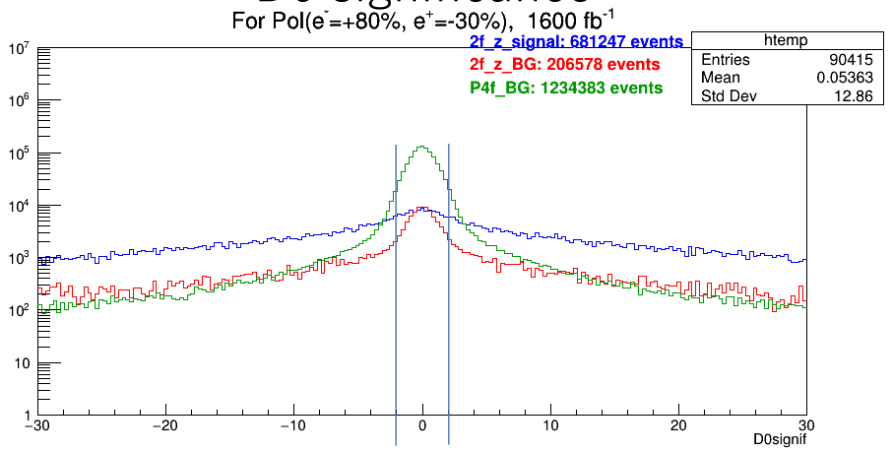
Impact parameter D0, Z0 (for tau selection only)

Evaluation of Z' new physics search

The Impact parameter indicates the distance from the track's Interaction point. (D0: r-phi direction, Z0: the z direction)
Since tau has a finite lifetime (ctau = 87 um), particles generated by tau decay fly a short distance from the IP.
-> D0, Z0 will be large.

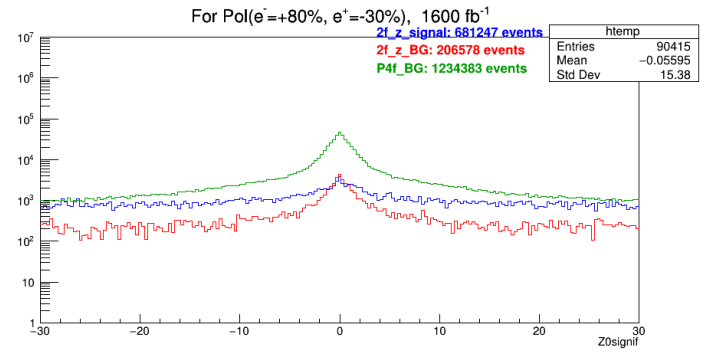


D0 significance



-2.0 2.0

Z0 significance



Result of event selection for (e-,e+)=(+80%,-30%)

For mu

- Opening angle: $\cos(angle) \leq -0.95$
- Energy: $Energy \geq 450\ GeV$

efficiency in ()

Mu Event	2f signal	2f BG	4f BG
Original	643,034(100.00%)	2,764,803(100.00%)	2,713,429(100.00%)
Opening angle	633,746(98.56%)	870,728(31.49%)	449,695(16.57%)
Energy	599,469(93.23%)	21,139(0.76%)	22,739(0.84%)

For tau

- Opening angle: $\cos(angle) \leq -0.95$
- Energy: $Energy \leq 340\ GeV$
- Impact parameter: $D0\ significance \geq |2.0|$

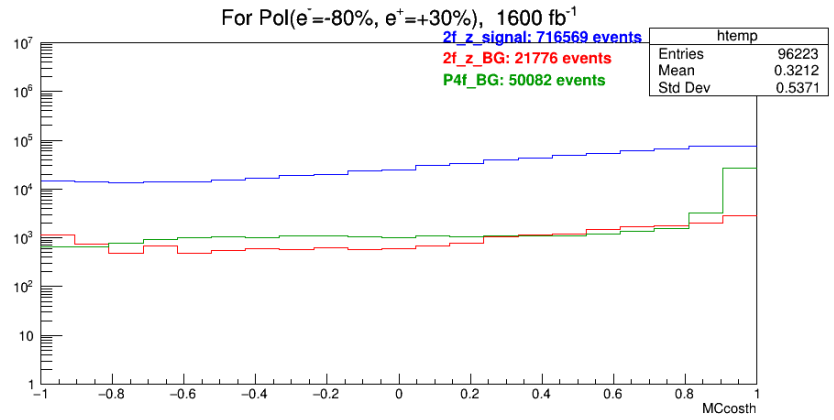
efficiency in ()

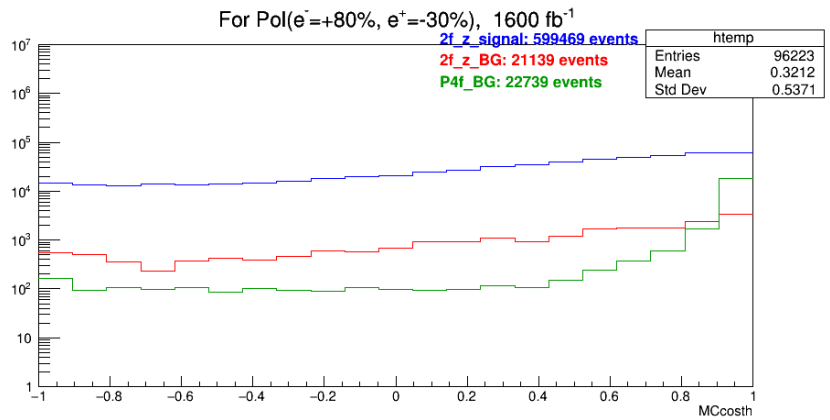
Tau Event	2f signal	2f BG	4f BG
Original	612,985(100.00%)	2,733,746(100.00%)	3,644,779(100.00%)
Opening angle	595,529(97.15%)	909,703(33.27%)	591,752(16.24%)
Energy	557,309(90.02%)	168,853(6.18%)	424,585(11.65%)
Impact parameter	457,204(74.59%)	100,404(3.67%)	53,115(1.46%)

Evaluation of Z' new physics search

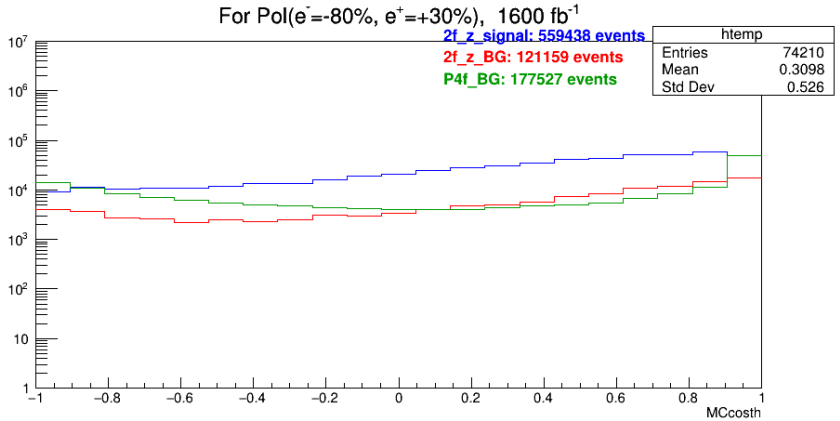
- In the case of new physics, these angular distributions also deviate due to the deviation of the reaction cross section values.
- These angular distributions will now be compared with the Z' model to evaluate the performance of the new physics search in the ILC at energy of 500 GeV.

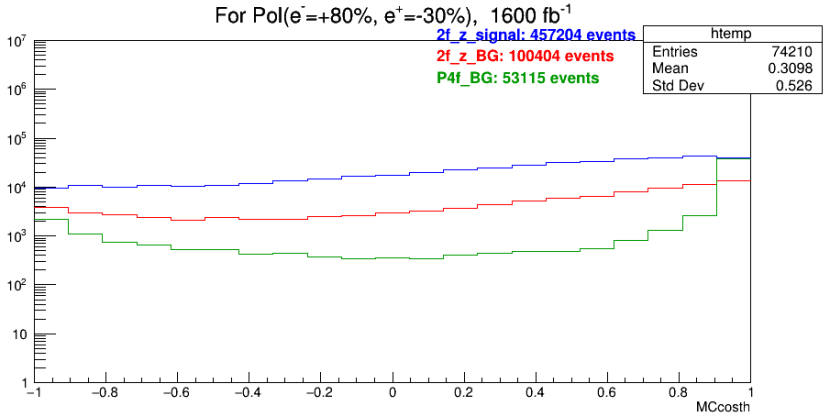
For mu





For tau





Procedures for evaluating each model search

- The accuracy $(\delta\sigma_i/\sigma_i(SM))$ in the ILC of the i-th bin of the angular distribution is evaluated as

$$\frac{\delta\sigma_i}{\sigma_i(SM)} = \sqrt{\left(\frac{\sqrt{S_i + N_i}}{S_i}\right)^2 + {\sigma_{syst}}^2}$$

- S_i and N_i are the number of signal and background events in each bin.
- In this evaluation, systematic errors of 0.001 for mu and 0.002 for tau are assumed.
- The deviation of the differential cross section predicted by the standard model and each model for this i-th bin $(\delta\sigma_i(BSM)/\sigma_i(SM))$ is determined, and from

$$\chi^2(BSM) = \sum_i \left\{ \left(\frac{\delta\sigma_i(BSM)}{\sigma_i(SM)} \Big/ \frac{\delta\sigma_i}{\sigma_i(SM)} \right)^2 \right\},$$

- the χ^2 is obtained. From this χ^2 value, we obtain the probability of being consistent with the standard model.

Result of event selection for (e-,e+)=(-80%,+30%)

For mu

- Opening angle: $\cos(angle) \leq -0.95$
- Energy: $Energy \geq 450\ GeV$

efficiency in ()

Mu Event	2f signal	2f BG	4f BG
Original	781,215(100.00%)	4,249,717(100.00%)	10,089,686(100.00%)
Opening angle	758,658(97.11%)	1,061,907(24.99%)	1,729,938(17.15%)
Energy	716,569(91.72%)	21,776(0.51%)	50,082(0.50%)

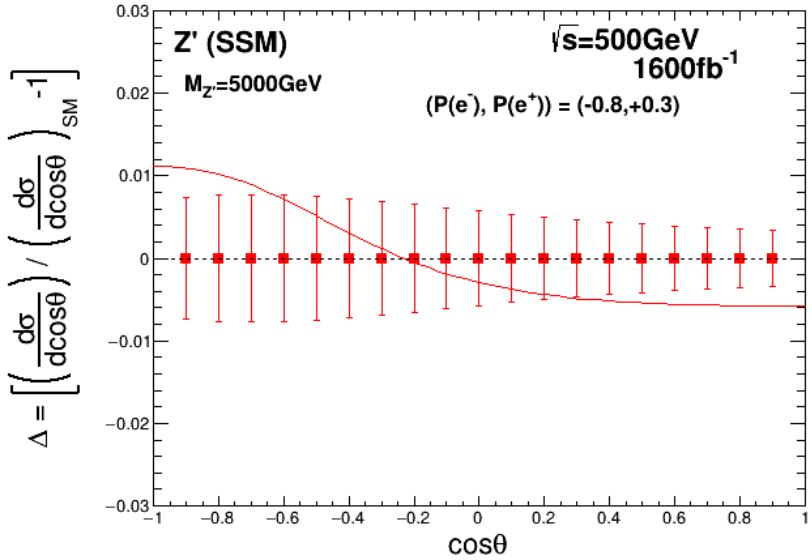
For tau

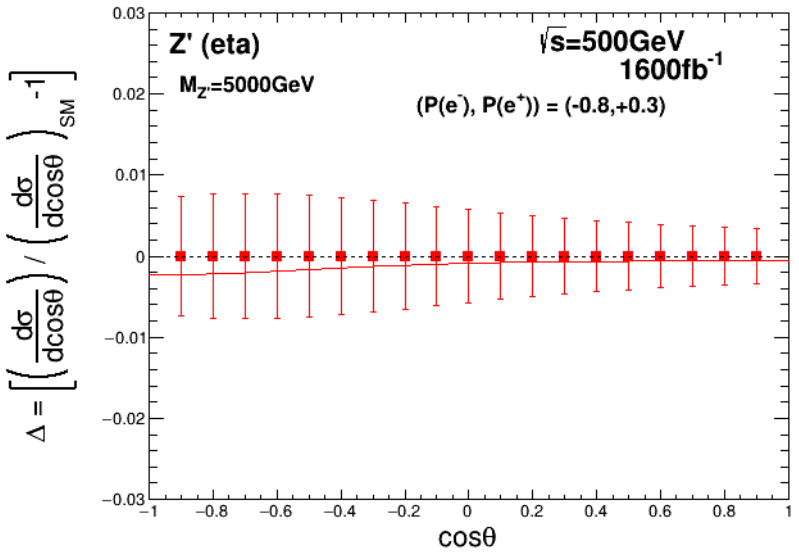
- Opening angle: $\cos(angle) \leq -0.95$
- Energy: $Energy \leq 340\ GeV$
- Impact parameter: $D0\ significance \geq |2.0|$

efficiency in ()

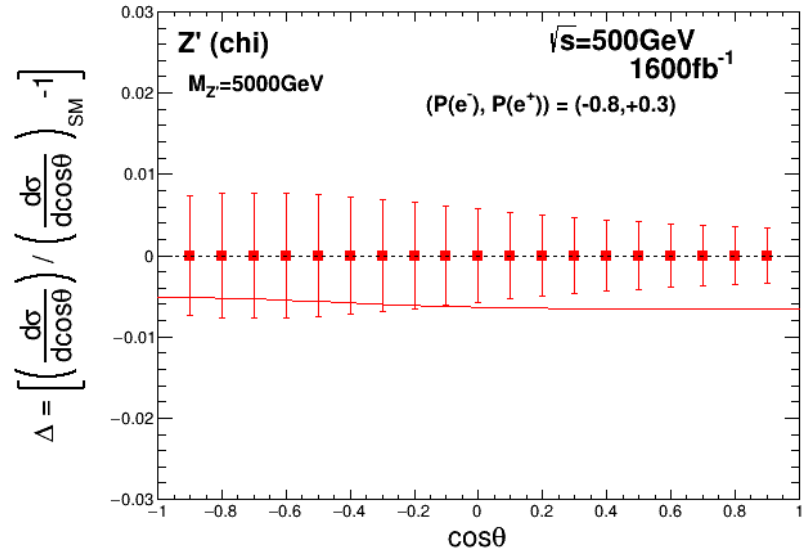
Tau Event	2f signal	2f BG	4f BG
Original	776,143(100.00%)	4,254,790(100.00%)	10,089,686(100.00%)
Opening angle	716,014(92.25%)	1,089,292(25.60%)	1,738,437(17.23%)
Energy	681,247(87.77%)	206,578(4.86%)	1,234,383(12.23%)
Impact parameter	559,438(72.08%)	121,159(2.85%)	177,527(1.74%)

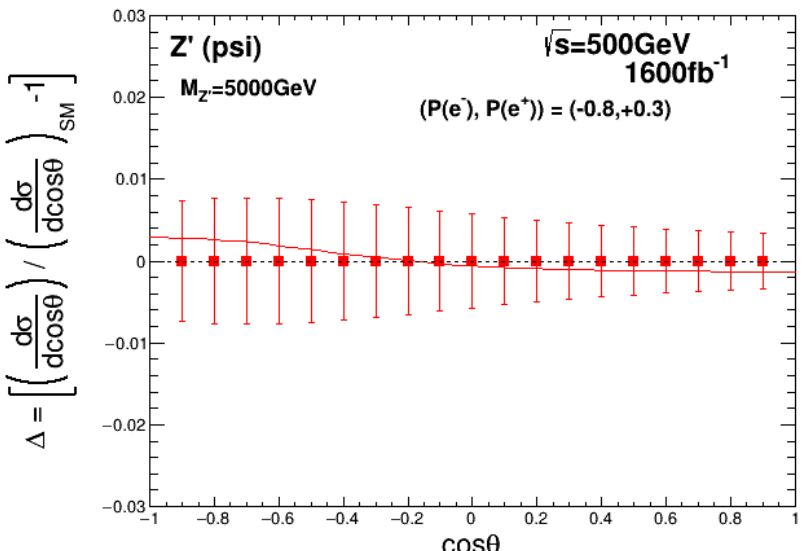
For mu

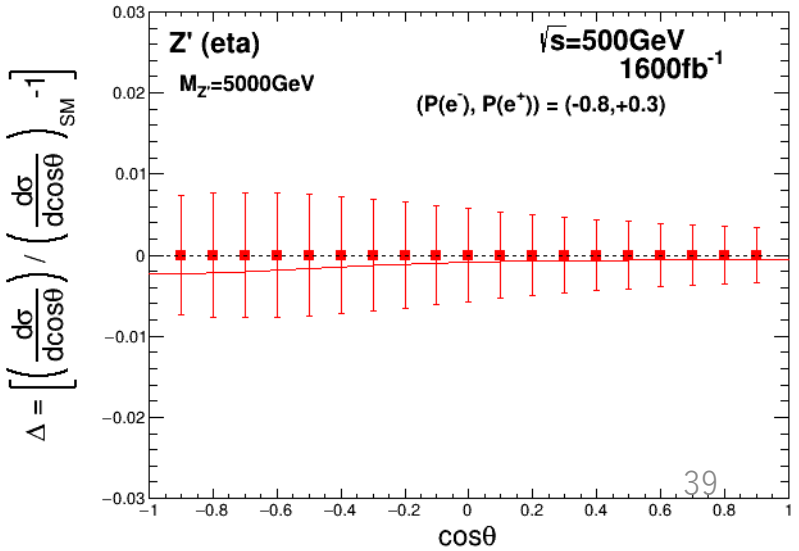




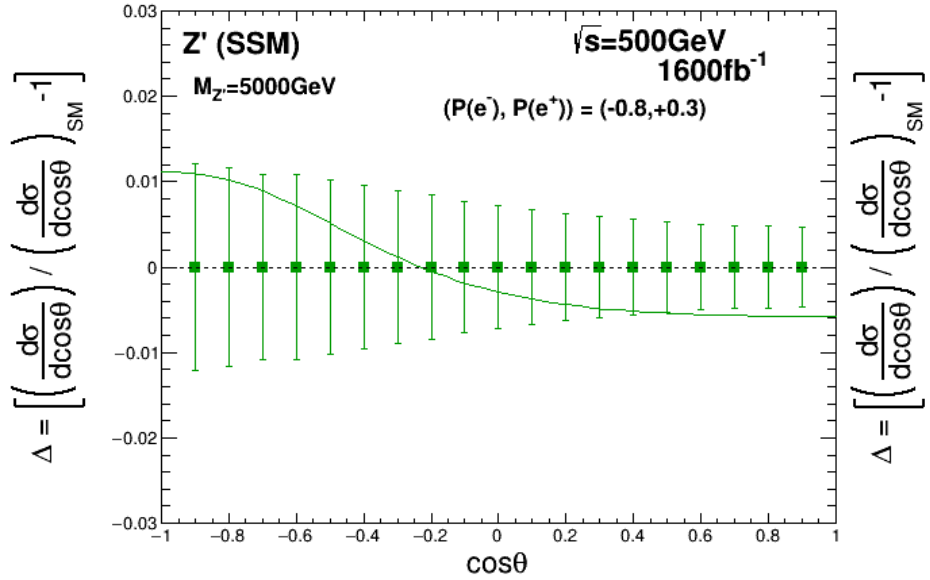
SSM: Sequential Standard Model
ALR : Alternative Left-Right symmetric
chi : E_6 χ *model* ($\beta = 0$)
psi : E_6 ψ *model* ($\beta = \pi/2$)
eta : E_6 η *model* ($\beta = \pi - \arctan\sqrt{5/3}$)

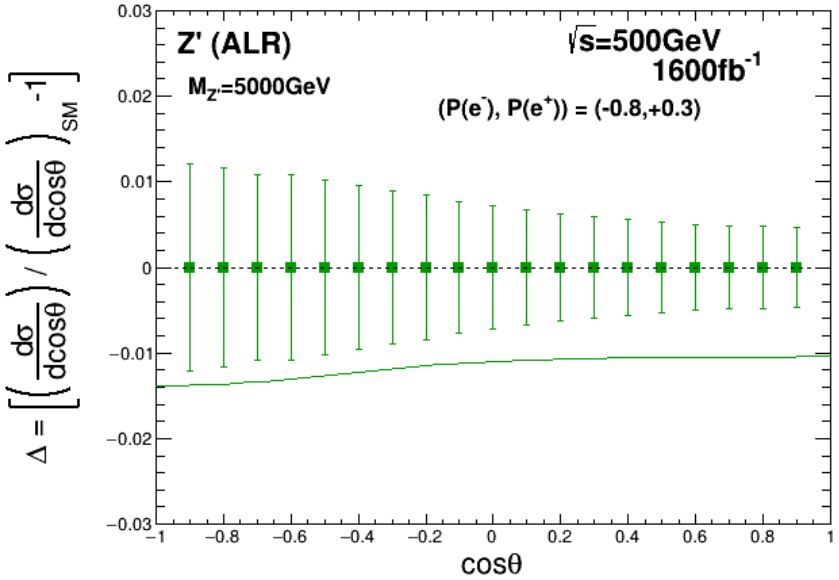




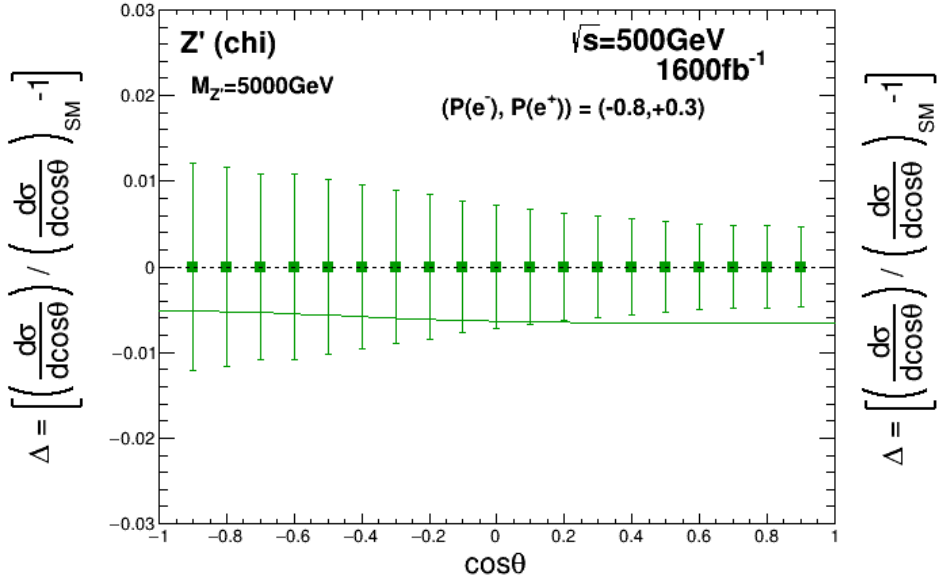


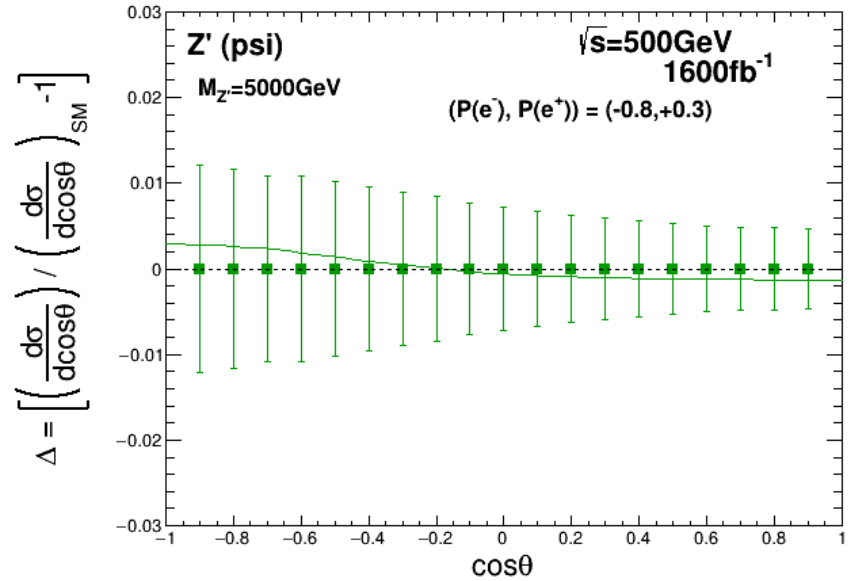
For tau

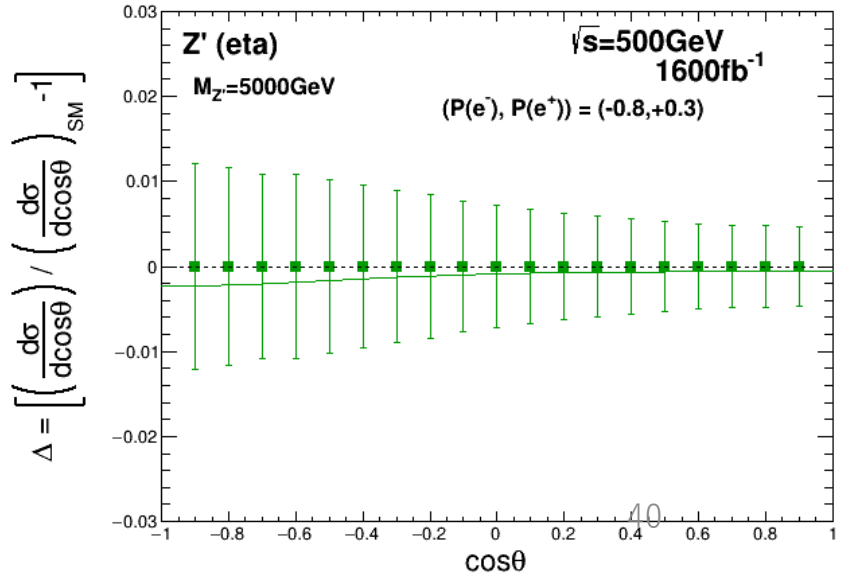




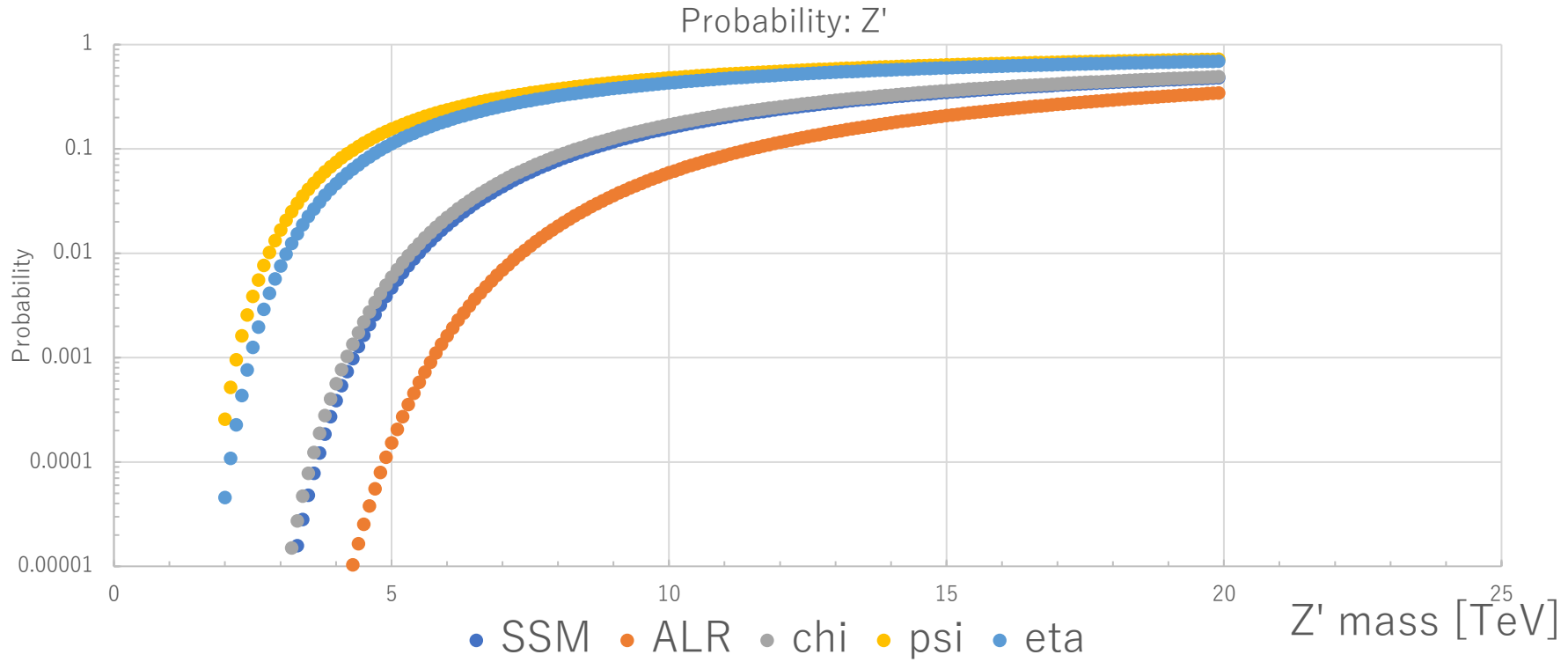
SSM: Sequential Standard Model
ALR : Alternative Left-Right symmetric
chi : $E_6\ \chi\ model\ (\beta = 0)$
psi : $E_6\ \psi\ model\ (\beta = \pi/2)$
eta : $E_6\ \eta\ model\ (\beta = \pi - \arctan\sqrt{5/3})$







Probability



Z'model	SSM	ALR	χ	ψ	η
5-sigma	6.31 TeV	8.45 TeV	6.15 TeV	3.21 TeV	3.57 TeV

5-sigma discovery reach

Z'model	SSM	ALR	χ	ψ	η
2-sigma	9.97 TeV	13.34 TeV	9.80 TeV	5.03 TeV	5.61 TeV

2-sigma = 95% CL lower limit

Previous results

- I have conducted mu and tau event selection without Bhabha events and have used the results to evaluate the Z' new physics search.

Evaluation of Z' new physics search by mu & tau event

Z'model	SSM	ALR	χ	ψ	η
5-sigma	6.24 TeV	8.35 TeV	6.08 TeV	3.16 TeV	3.53 TeV

5-sigma = discovery reach

Z'model	SSM	ALR	χ	ψ	η
2-sigma	9.84 TeV	13.18 TeV	9.60 TeV	4.96 TeV	5.55 TeV

2-sigma = 95% CL lower limit