九州大学
KYUSHU UNIVERSITY

New physics search by 2-fermion measurement at the ILC

2022/11/25

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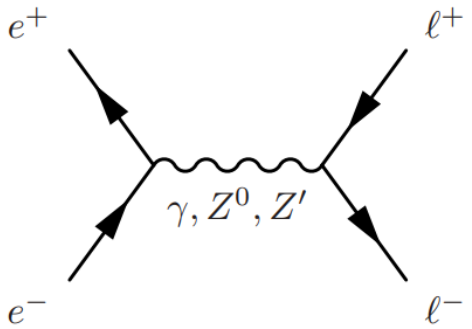
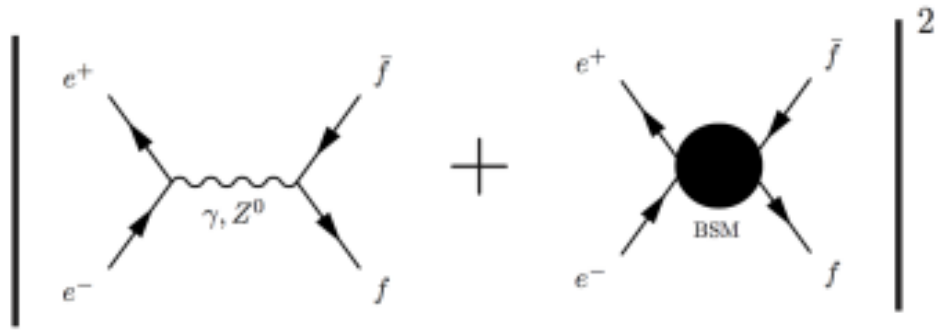
2-lepton $e^+e^- \rightarrow l^+l^-$ event

- $e^+e^- \rightarrow l^+l^-(l = \mu, \tau)$: 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, total and differential cross section can be deviated from the standard model as shown in the interference diagram below.

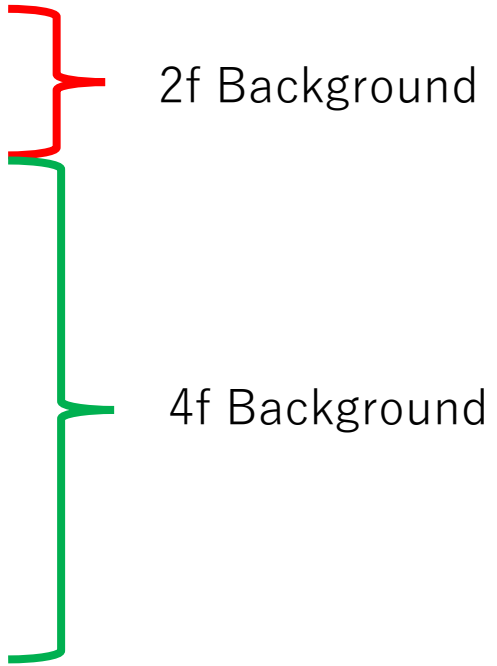




events

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

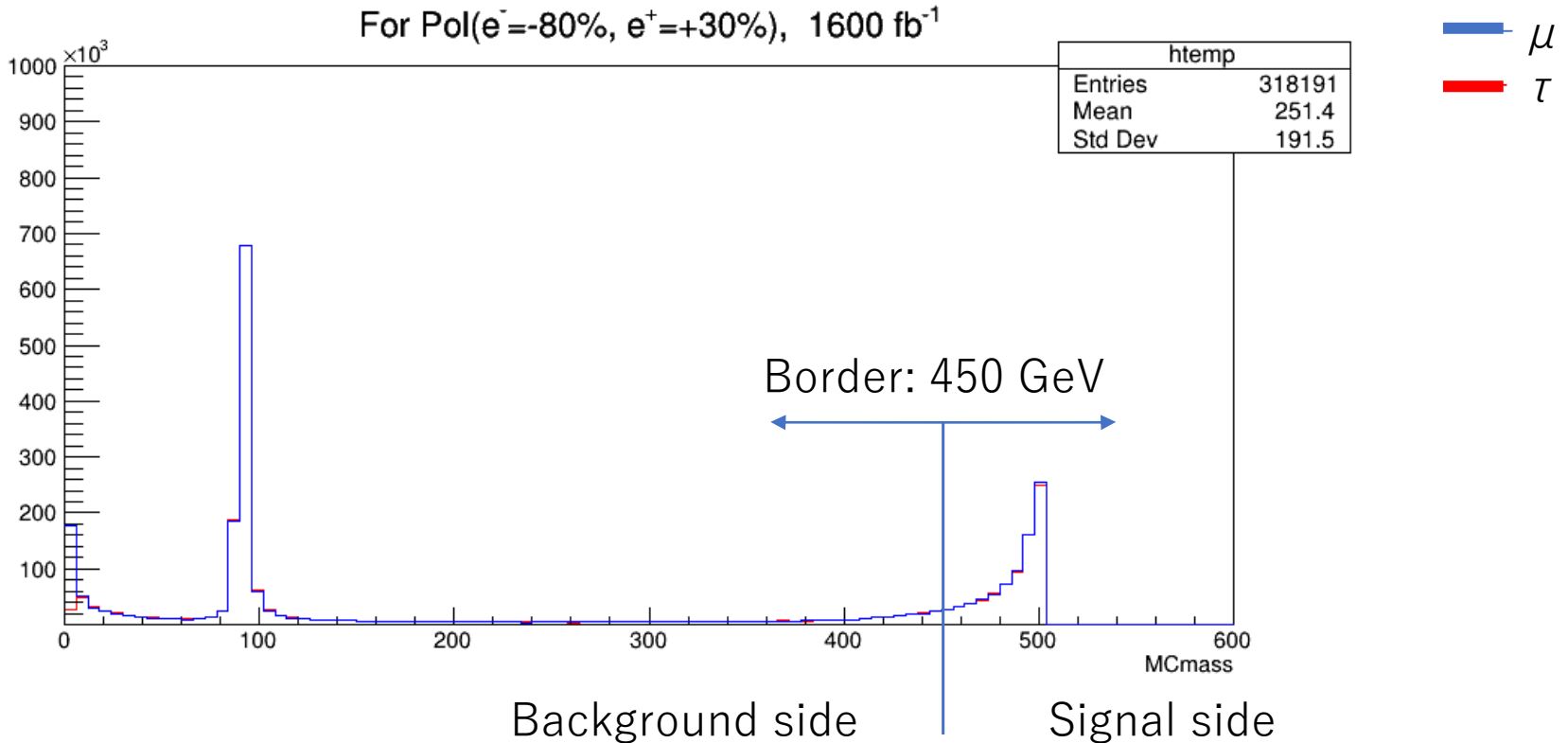
2f_Z_leptonic (signal $mass$ <450 GeV)
2f_Z_leptonic (If sig is mu then tau, if tau then mu.)
4f_WW_leptonic
4f_ZZ_leptonic
4f_singleZee_leptonic
4f_singleZsingleWMix_leptonic
4f_ZZWWMix_leptonic
4f_singleW_leptonic
4f_singleZnunu_leptonic



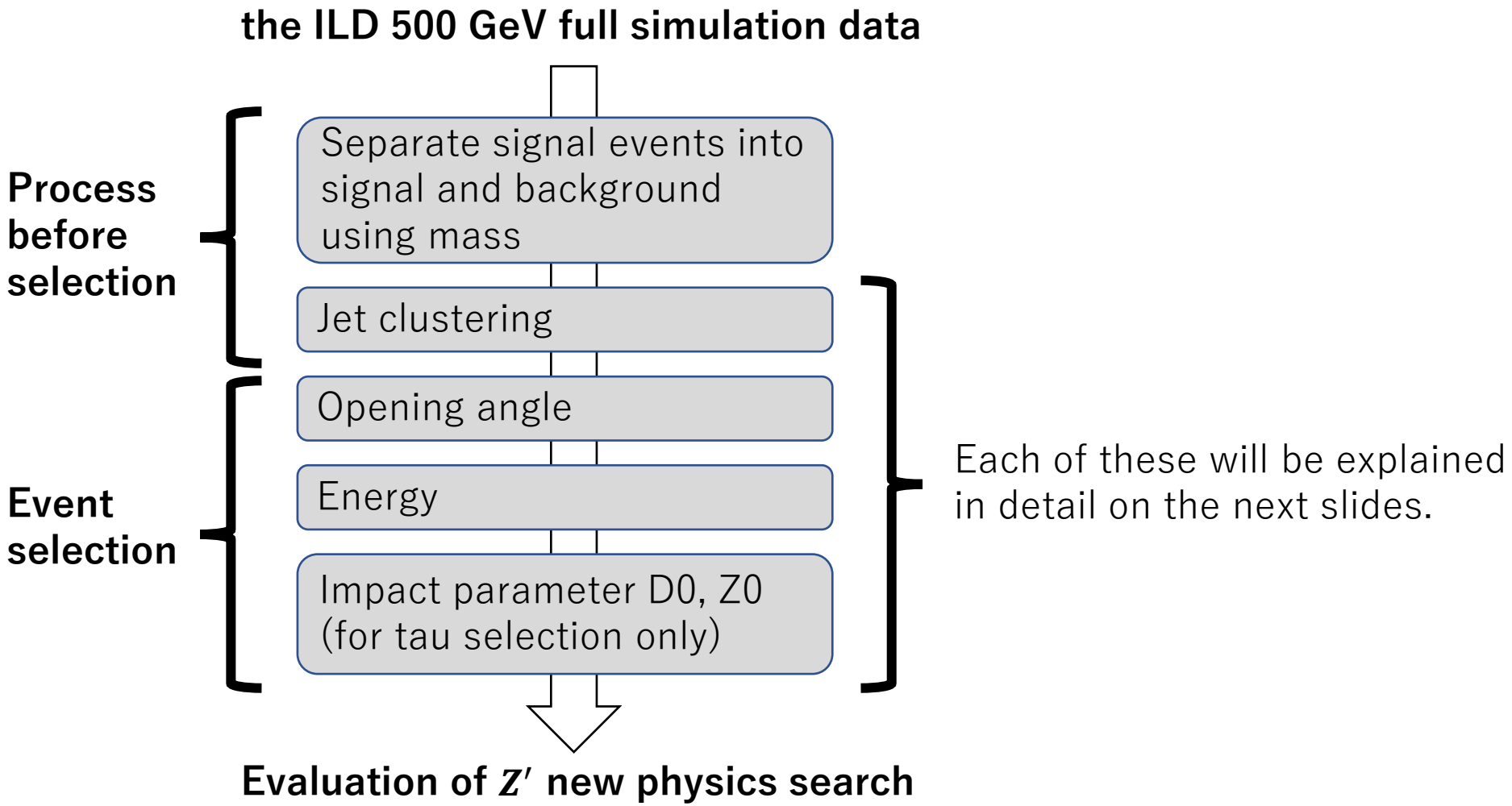
- **Polarization** **Luminosity**
- $e^-: \mp 80\%$, $e^+: \pm 30\%$ $1600\ \mathrm{fb}^{-1}$ each

Definition of signal events

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

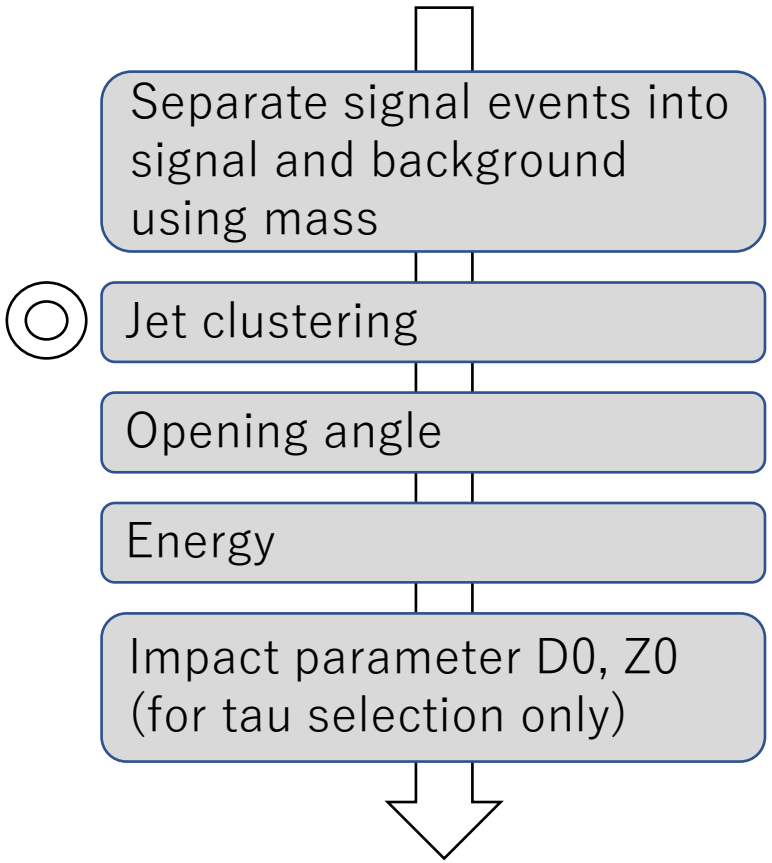


μ & τ event selection order



Jet clustering

the ILD 500 GeV full simulation data

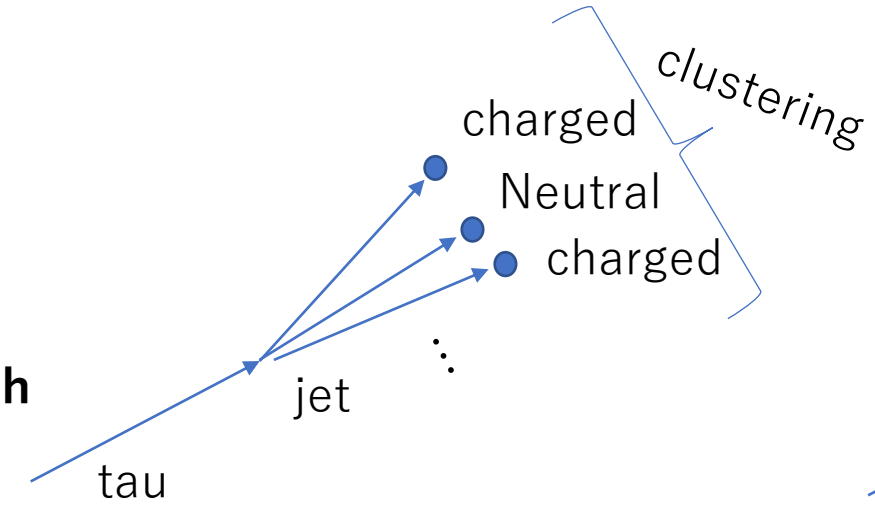


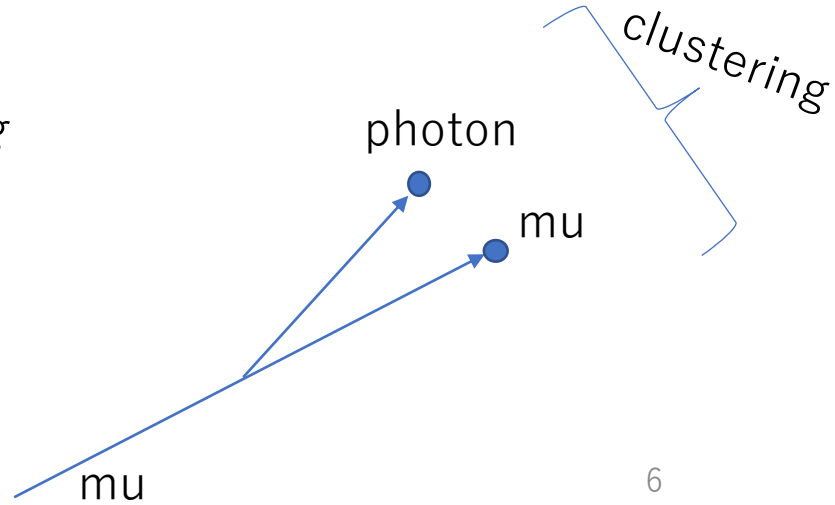
Evaluation of Z' new physics search

Tau particles produce jets when they decay into hadrons.

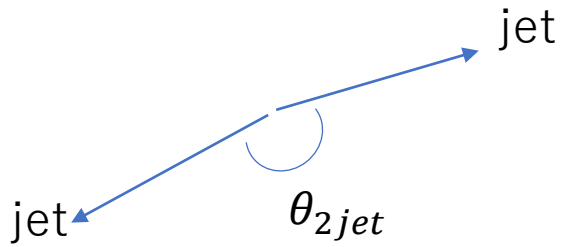
→ Clustering of nearby particles consistent to tau mass as a jet

→ 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

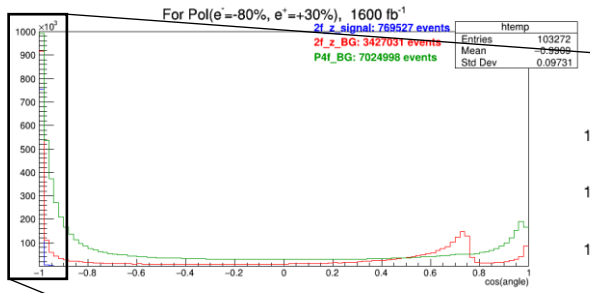
- Separate signal events into signal and background using mass
- Jet clustering
- Opening angle
- Energy
- Impact parameter D0, Z0 (for tau selection only)

Evaluation of Z' new physics search

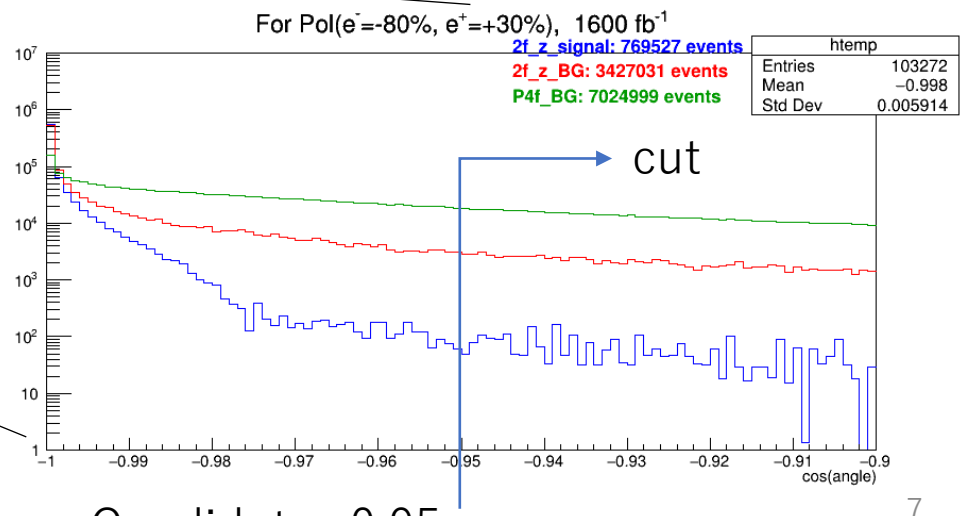
The angle between the signal jets is almost 180 degrees.
→An event near 180 degrees is considered a signal (tau & mu) event.

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

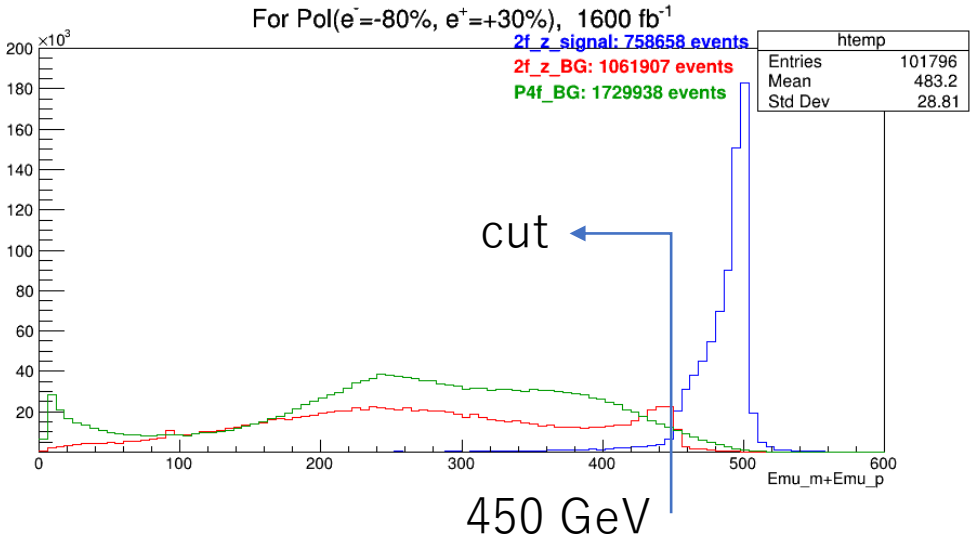
◎ Energy

Impact parameter D0, Z0 (for tau selection only)

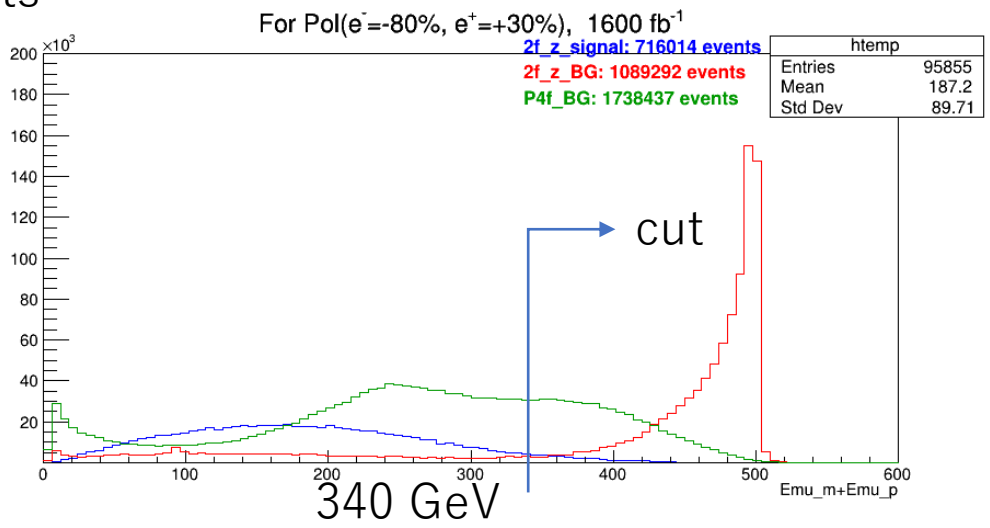
Evaluation of Z' new physics search

- $l^- Energy + l^+ Energy$ 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

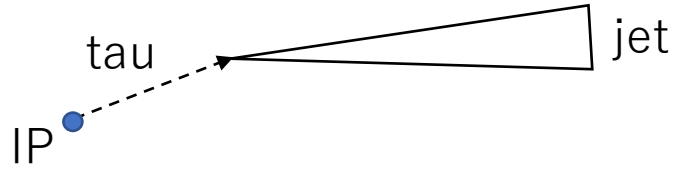
Opening angle

Energy

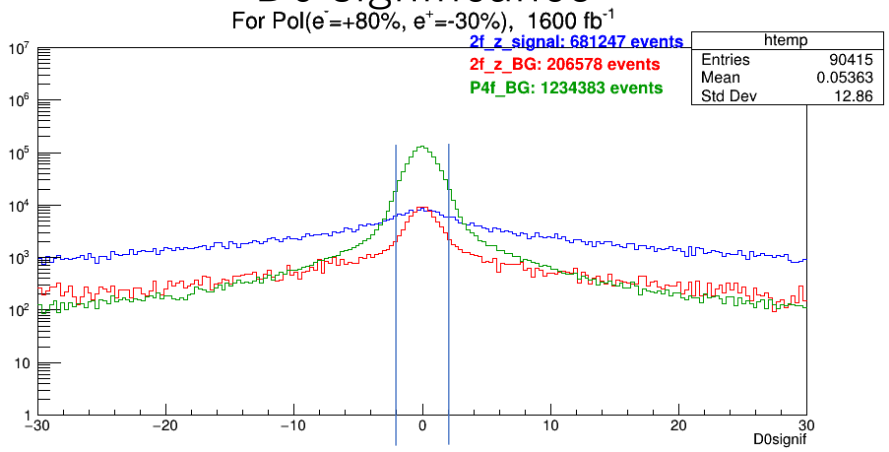
Impact parameter D0, Z0 (for tau selection only)

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.

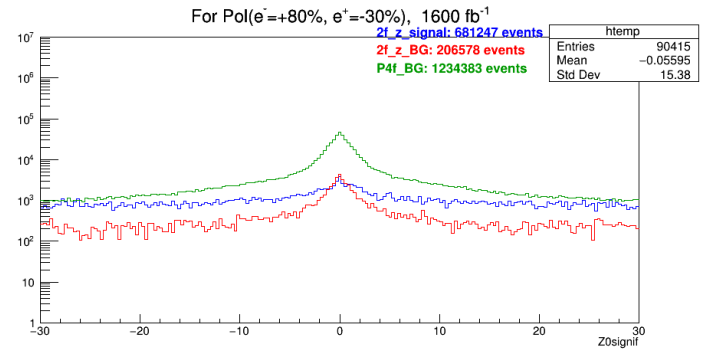


D0 significance



-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	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%)

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: $D0\ significance \geq |2.0|$

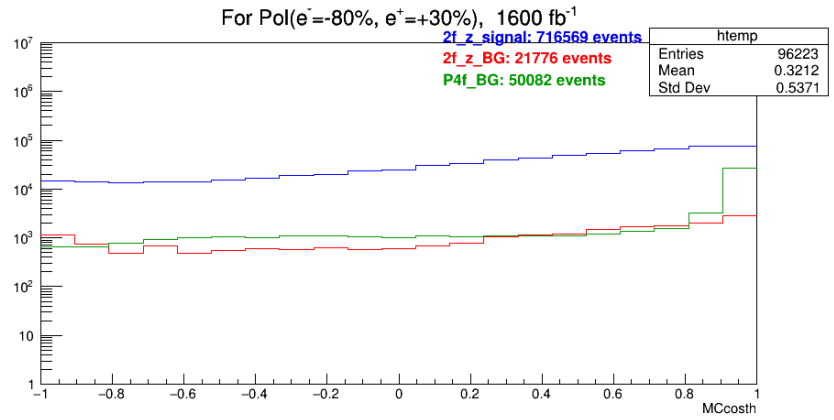
efficiency in ()

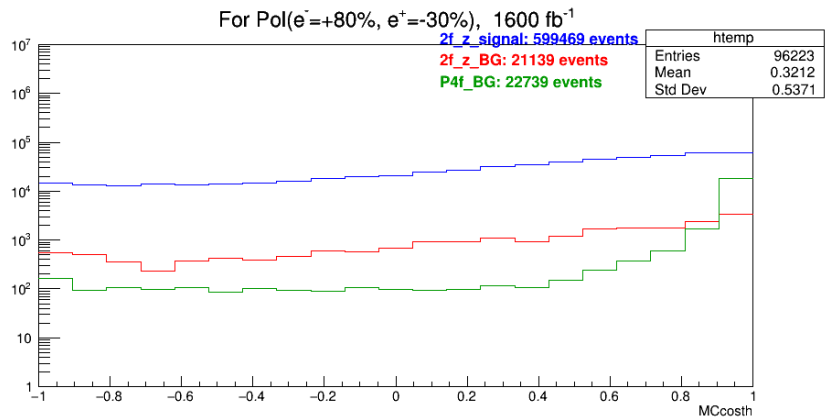
Tau Event	2f signal	2f BG	4f BG
Original	612,985(100.00%)	2,733,746(100.00%)	3,644,779(100.00%)
Opening angle	595,529(97.15%)	909,703(33.27%)	591,752(16.24%)
Energy	557,309(90.02%)	168,853(6.18%)	424,585(11.65%)
Impact parameter	457,204(74.59%)	100,404(3.67%)	53,115(1.46%)

Evaluation of Z' new physics search

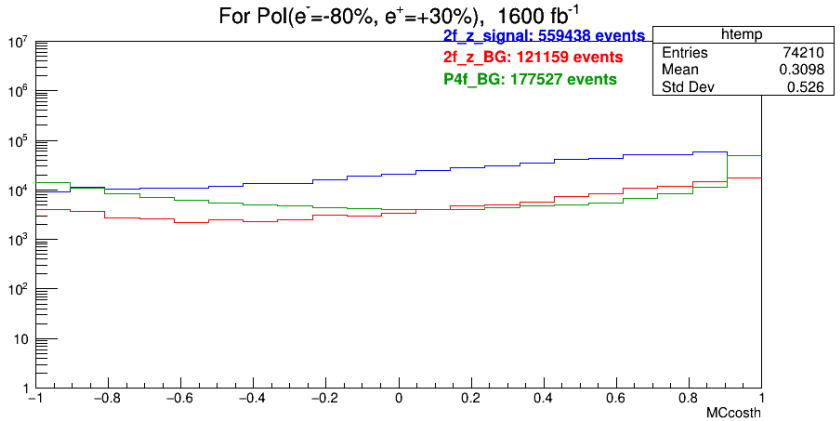
- In the case of new physics, these angular distributions also deviate due to the deviation of the reaction cross section values.
- These angular distributions will now be compared with the Z' model to evaluate the performance of the new physics search in the ILC at energy of 500 GeV.

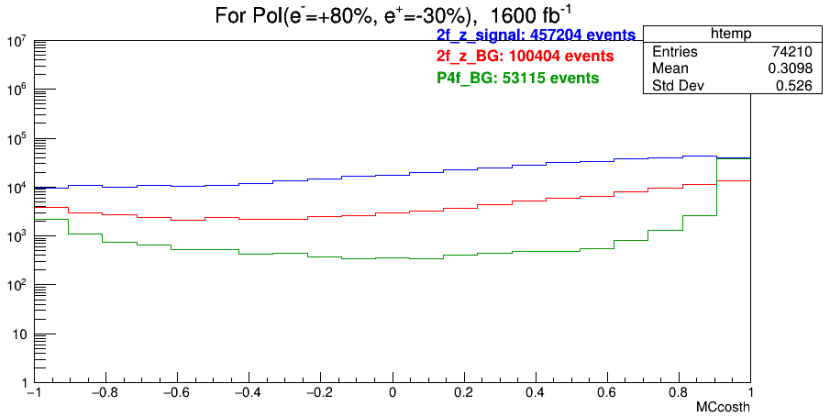
For mu





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

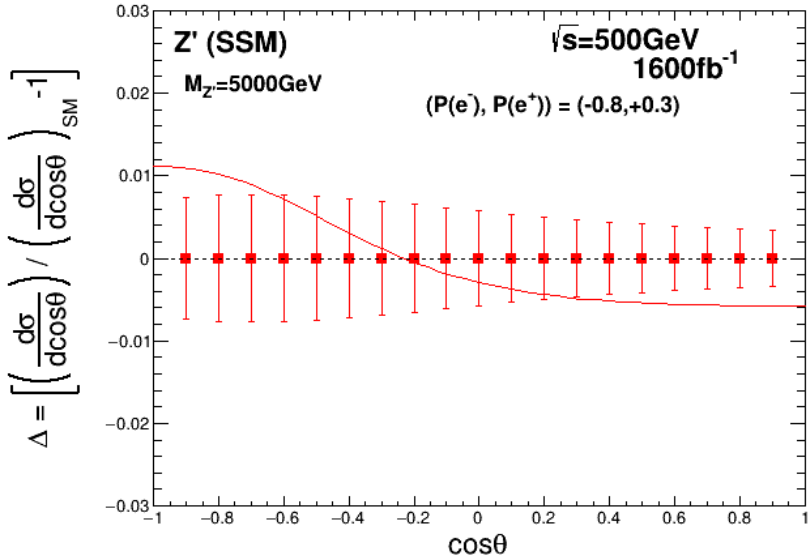
$$\frac{\delta\sigma_i}{\sigma_i(SM)} = \sqrt{\left(\frac{\sqrt{S_i + N_i}}{S_i}\right)^2 + {\sigma_{syst}}^2}$$

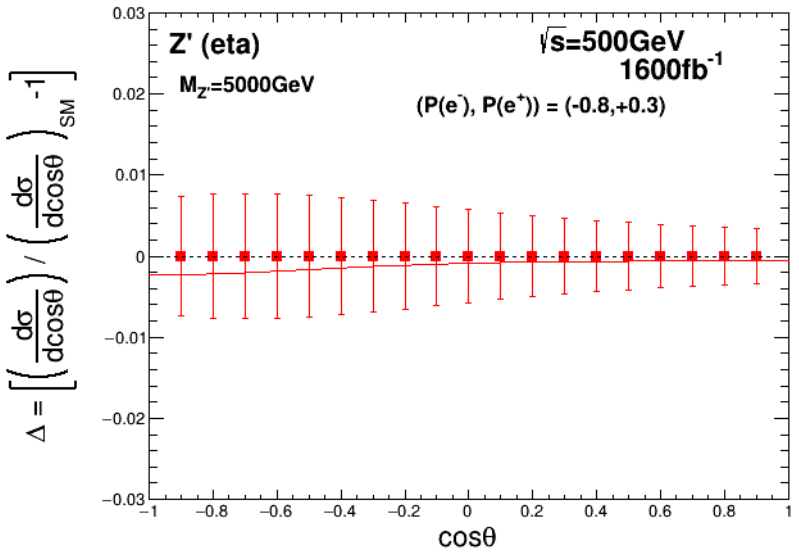
- S_i and N_i are the number of signal and background events in each bin.
- In this evaluation, systematic errors of 0.001 for mu and 0.002 for tau are assumed.
- The deviation of the differential cross section predicted by the standard model and each model for this i-th bin $(\delta\sigma_i(BSM)/\sigma_i(SM))$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

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

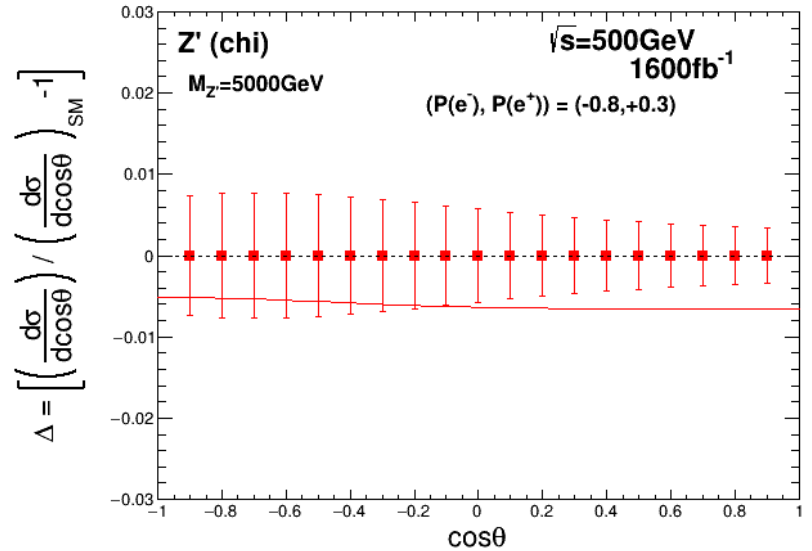
- the χ^2 is obtained. From this χ^2 value, we obtain the probability of being consistent with the standard model.

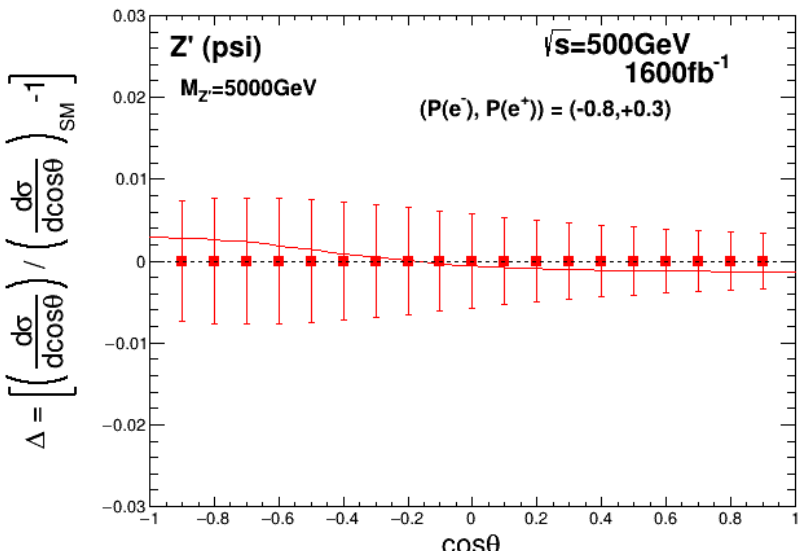
For mu

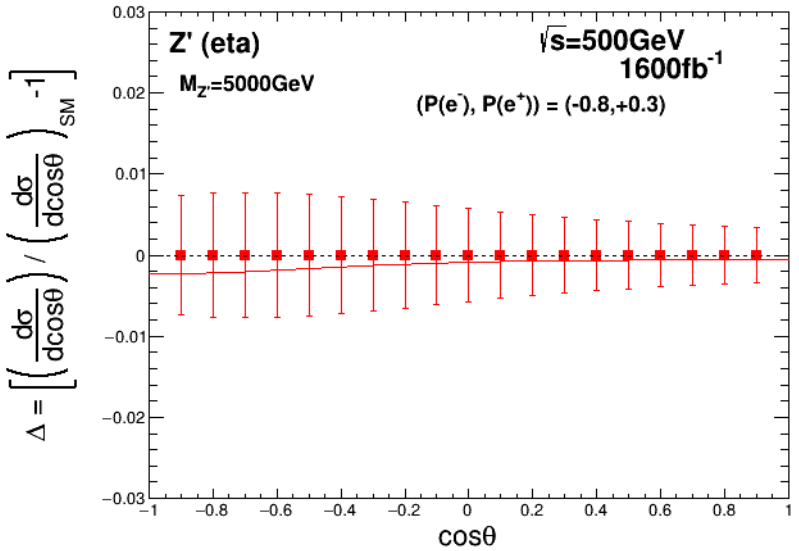




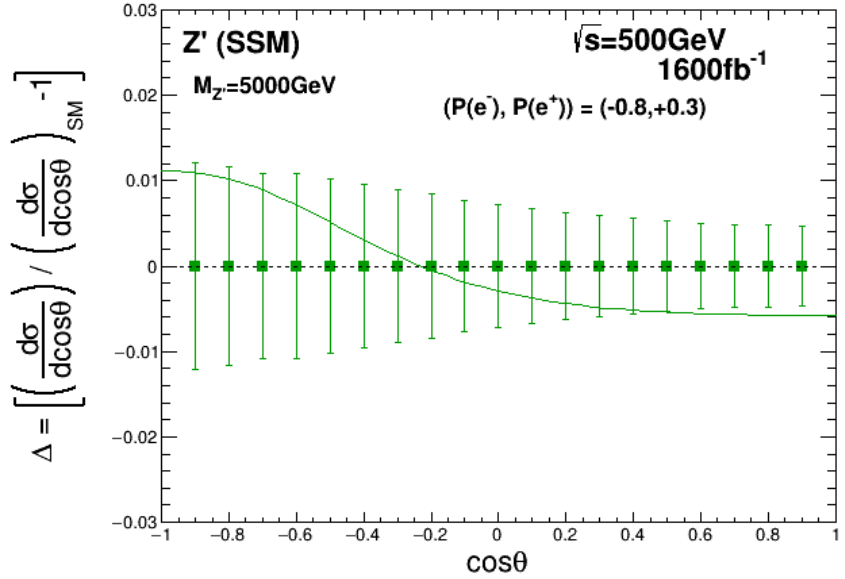
SSM: Sequential Standard Model
ALR : Alternative Left-Right symmetric
chi : E_6 χ *model* ($\beta = 0$)
psi : E_6 ψ *model* ($\beta = \pi/2$)
eta : E_6 η *model* ($\beta = \pi - \arctan\sqrt{5/3}$)

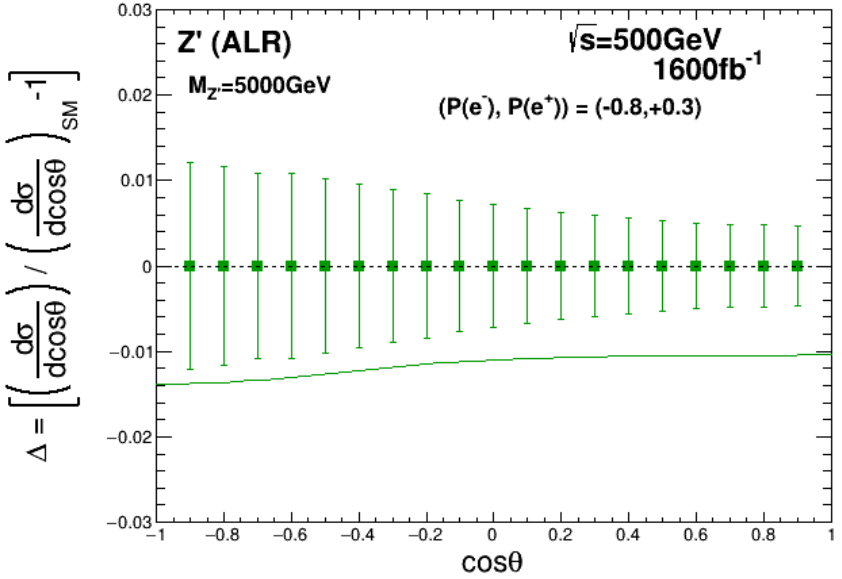






For tau





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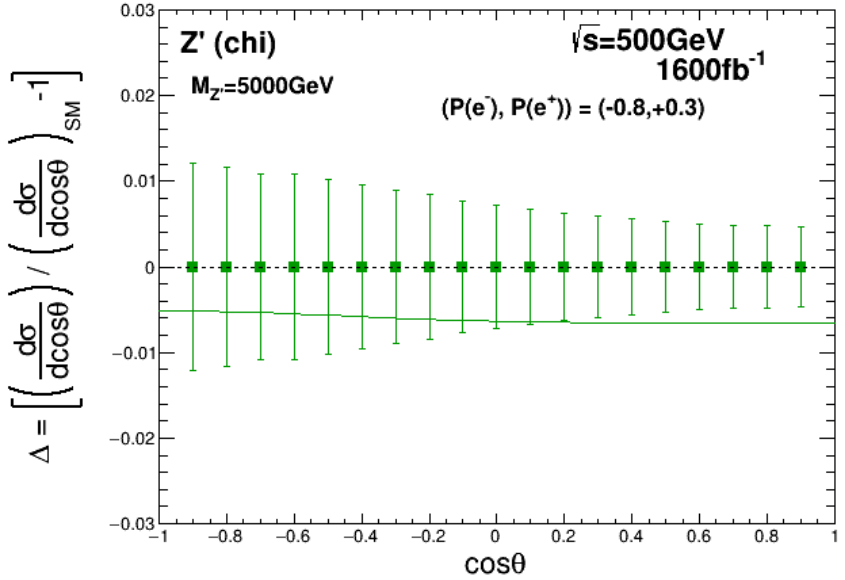
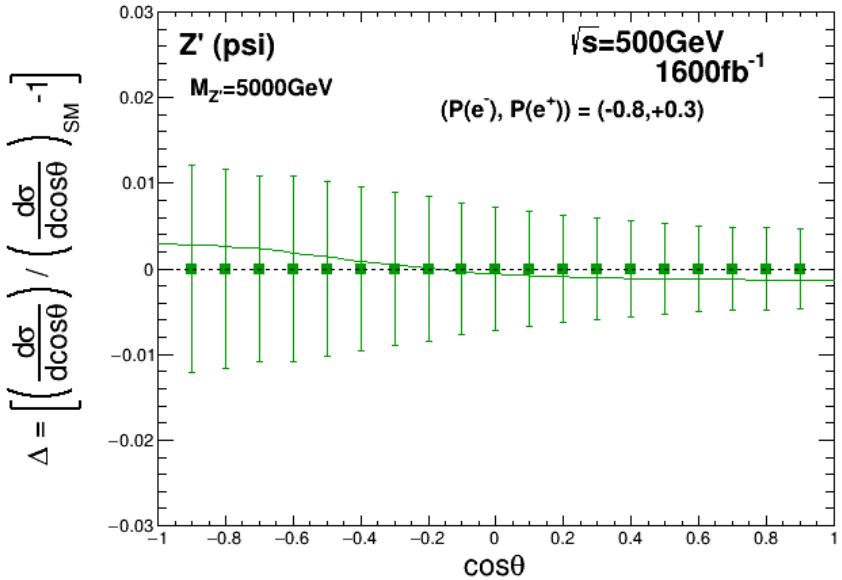
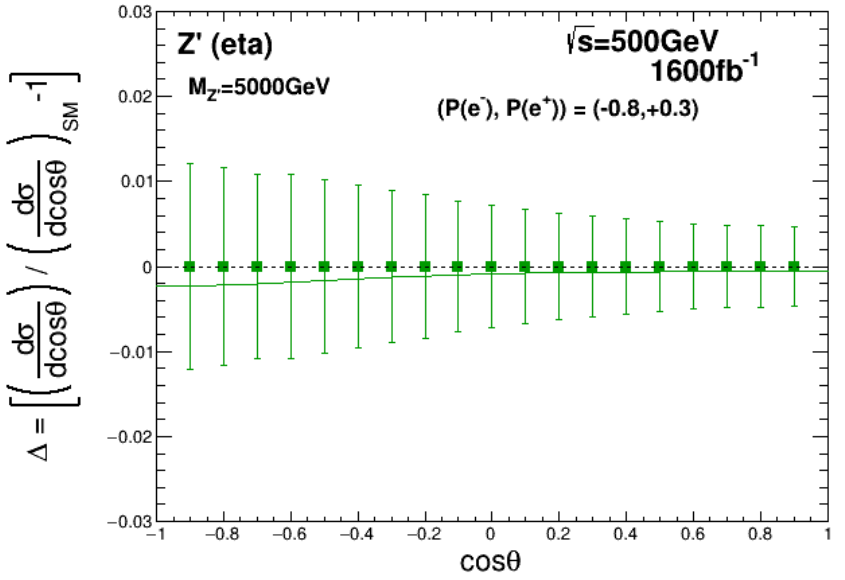
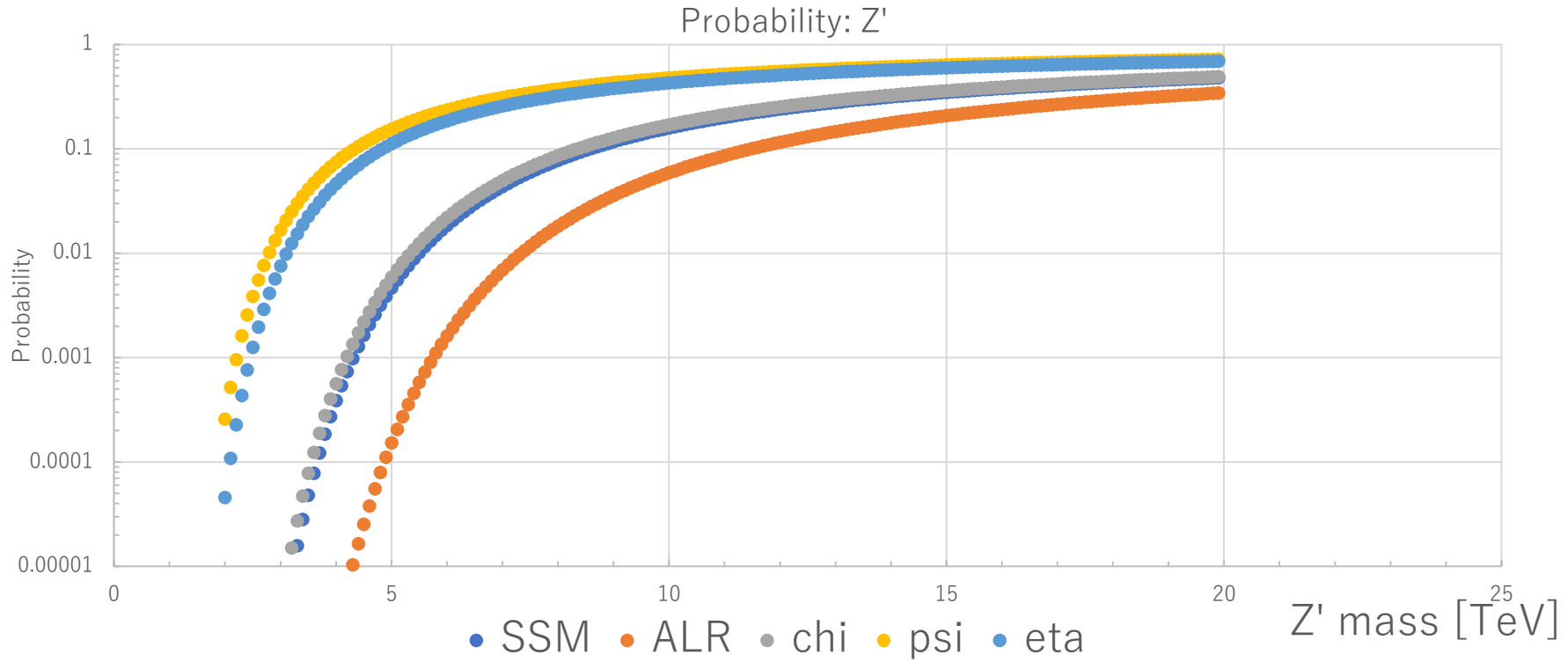






Probability



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

Conclusion

- mu and tau event selections are performed 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 mu and tau has sensitivity for Z' mass of 5.03 – 13.34 TeV.

- Combining electron and quark pairs will be done as next step, as well as investigating sensitivity of other interactions.

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.

• $e^+e^- \rightarrow l^+l^-(l = \mu, \tau)$: 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.

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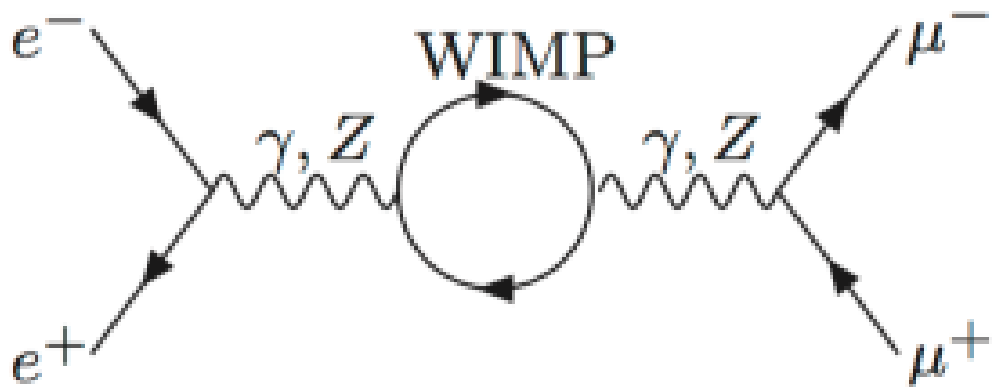
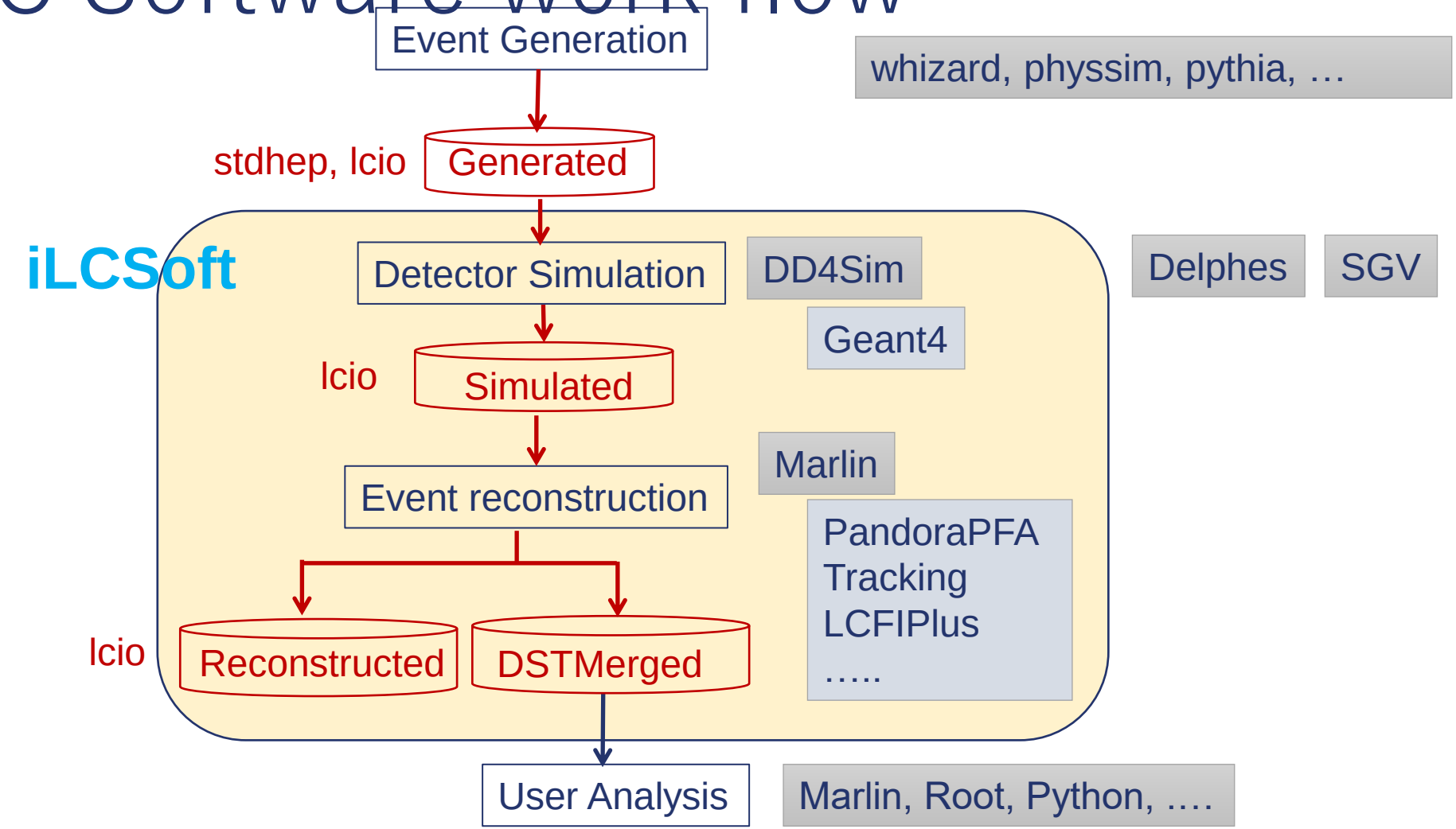
2-lepton $e^+e^- \rightarrow l^+l^-$ event

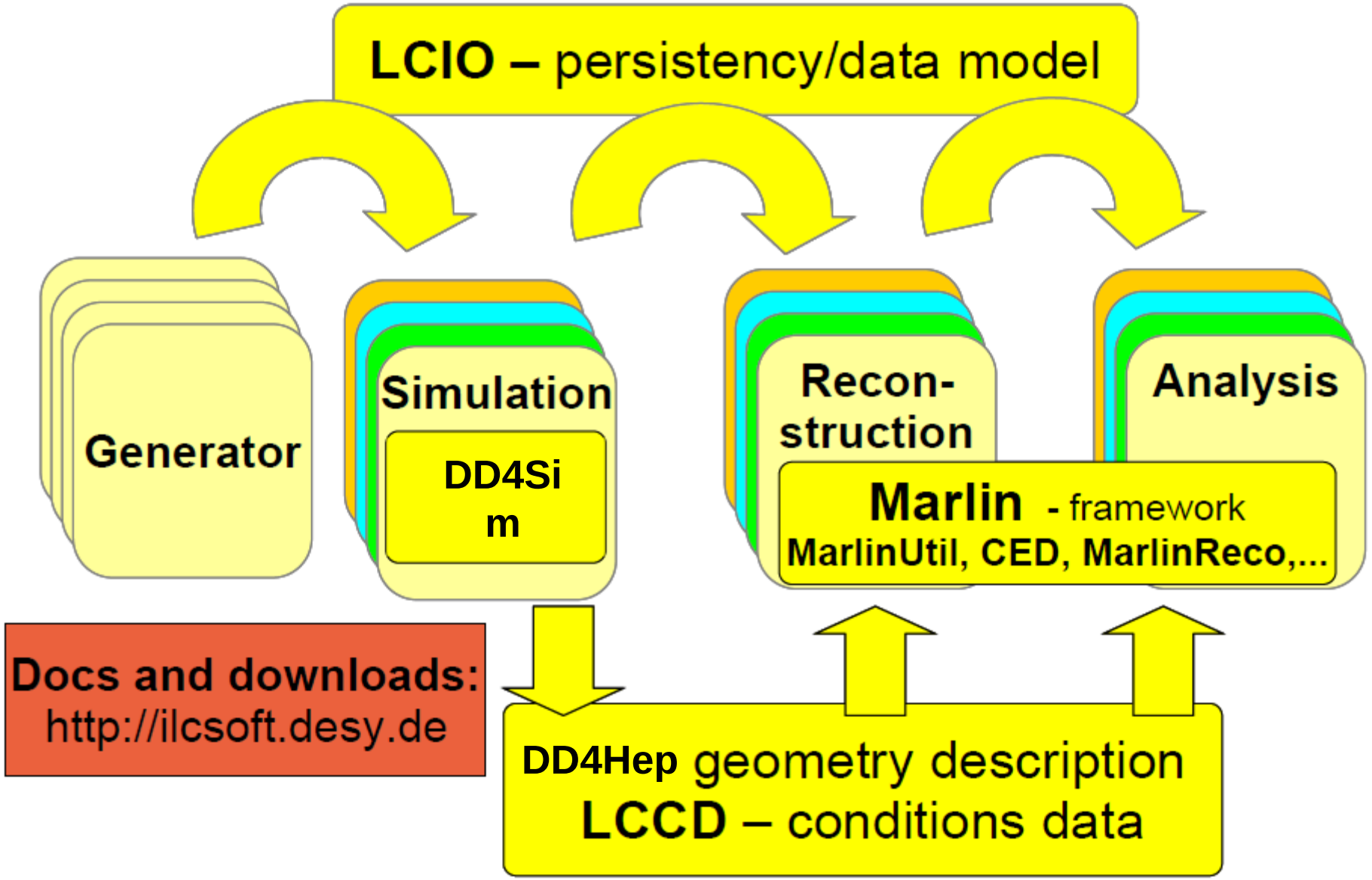
- There is a general method to investigate the $e^+e^- \rightarrow f\bar{f}$ misalignment due to WIMPs.
- If we introduce the WIMP(χ) into the 2-fermion final state process ($e^+e^- \rightarrow f\bar{f}$) analyzed so far and assume a diagram that includes the loop $Z \rightarrow \chi\chi \rightarrow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



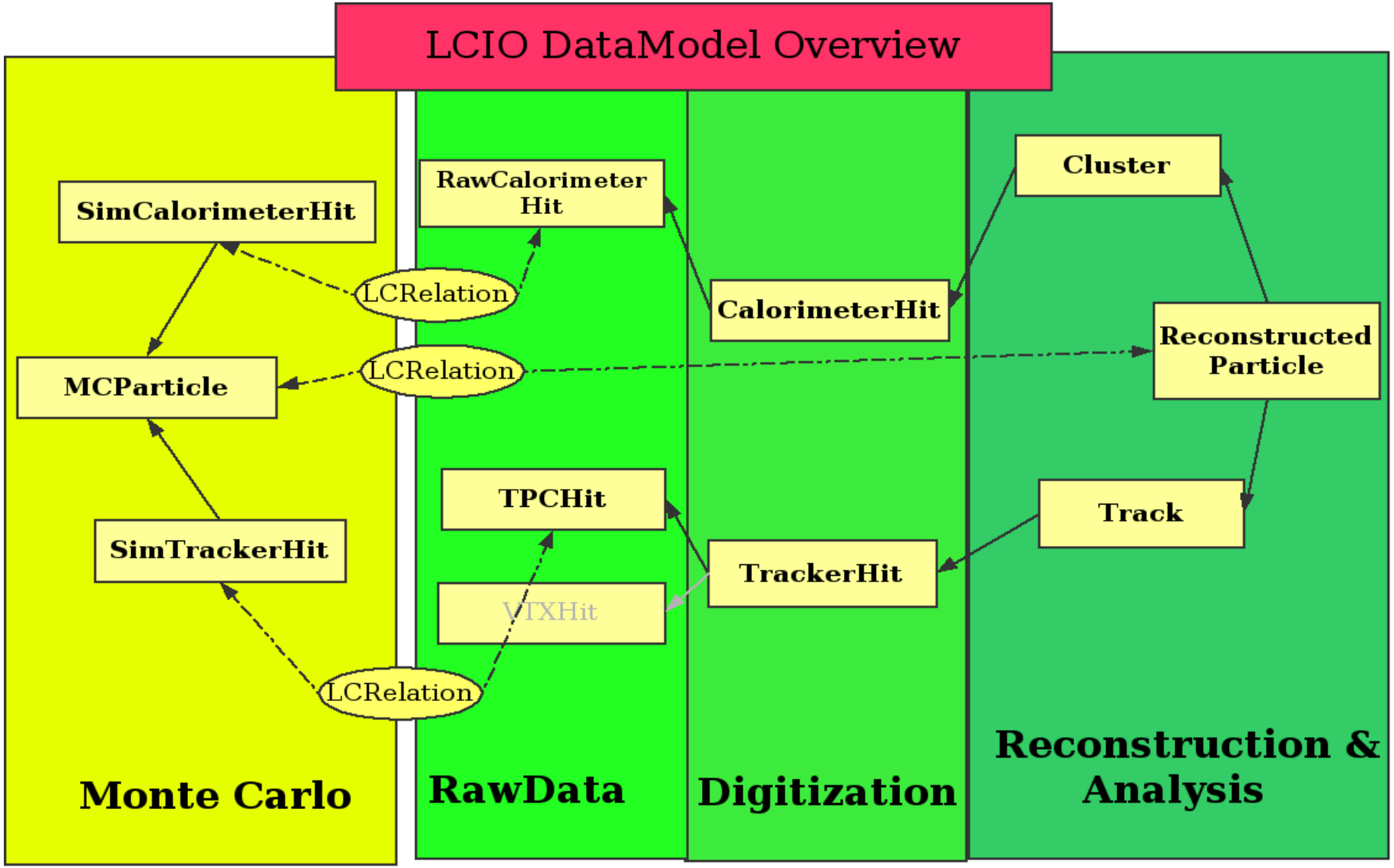
ILC Software work flow



Role of LCIO : persistency and data model



Data Model II



by Frank Gaede, DESY

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.

Impact parameter: D0, Z0

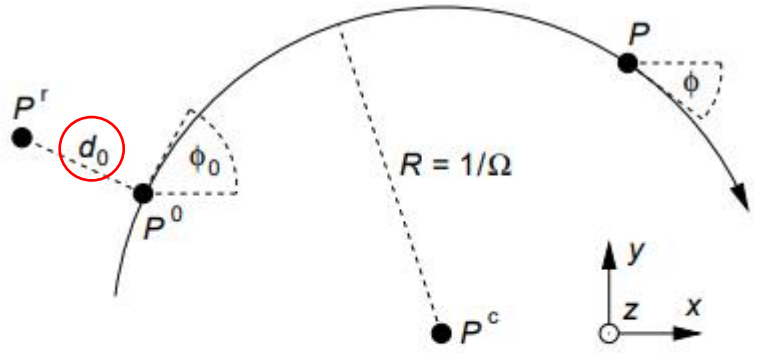


Figure 1: The projection of a helix segment in the xy plane is a part of an arc with centre $\boldsymbol{P}^c$ and radius R. The direction of the particle is shown with the arrow at the arc. All track parameters are given relative to the reference point $\boldsymbol{P}^r$.

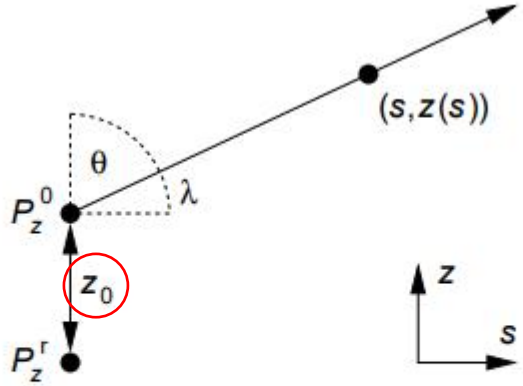
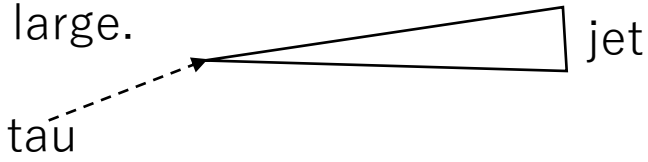


Figure 2: The projection of a helix in the sz plane is a straight line (see Eq. 10). The variable s at a point $\boldsymbol{P}$ is the arc length in the xy plane from $\boldsymbol{P}^0$ to $\boldsymbol{P}$. This also implies that $s = 0$, if $z = z_0$.

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.



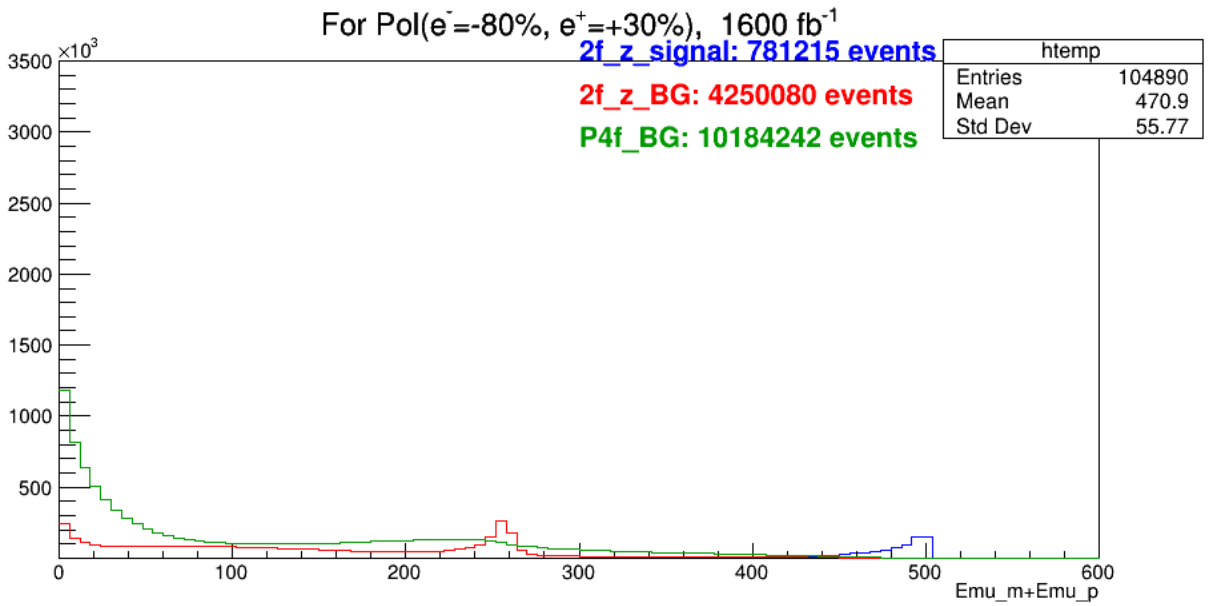
In addition to d0 and z0, d0 z0 significances divided by their respective errors are also candidates.

Mu event

Signal events and BG events

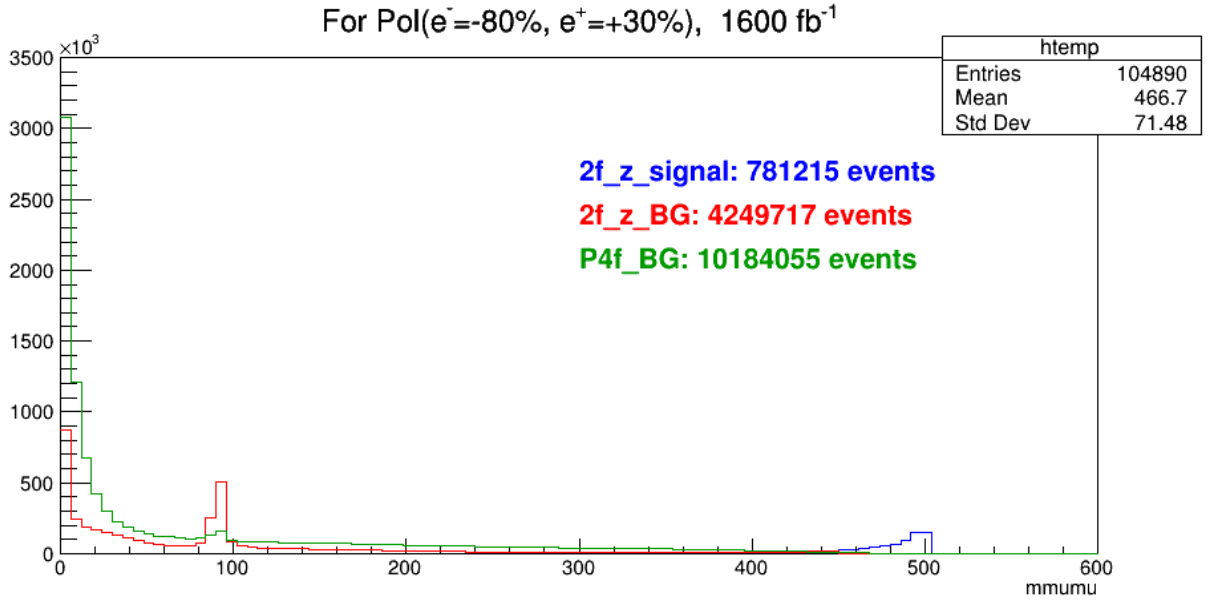
- No clustering & cuts : Original

2 jets' highest energy



Energy GeV

mass

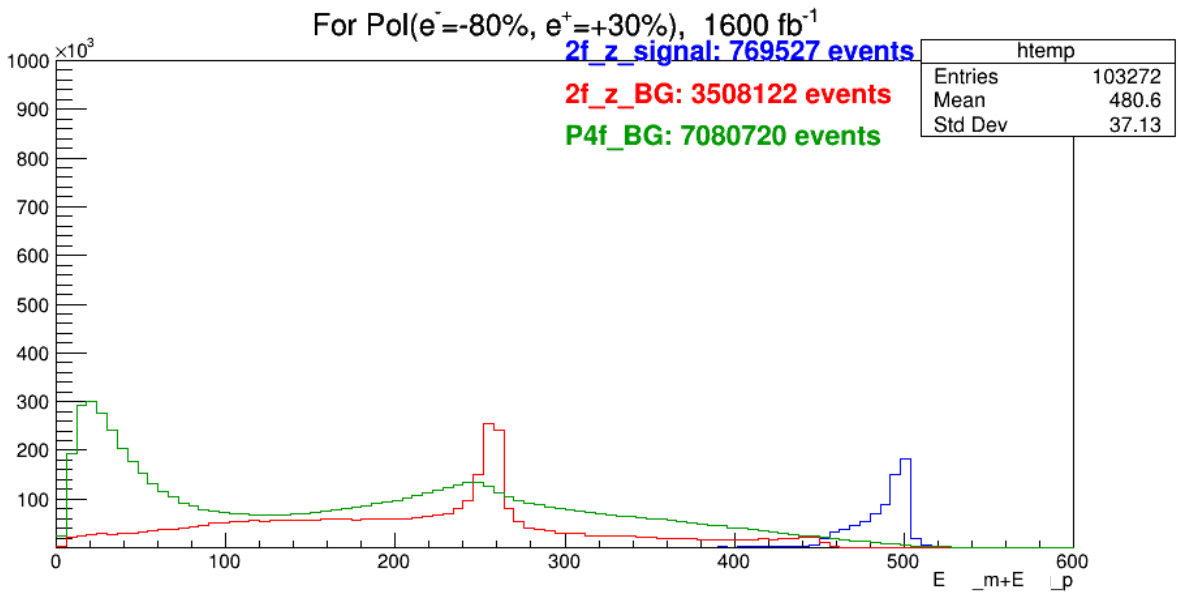


mass GeV

Clustering

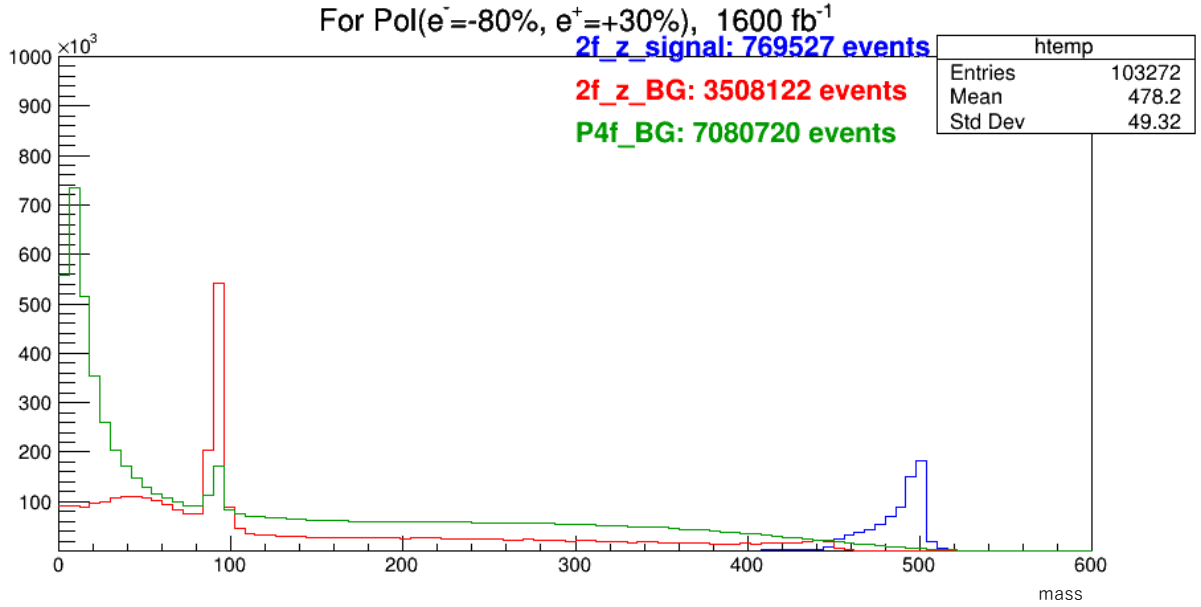
- After clustering

$l^- + l^+$ $Energy$ (highest):



Energy GeV

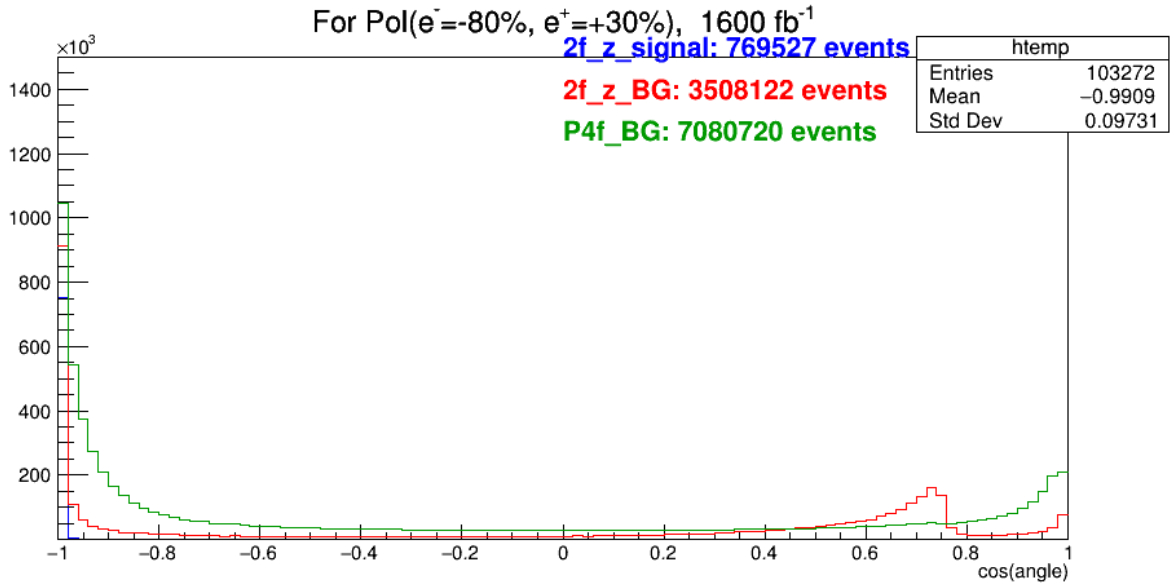
mass



mass GeV

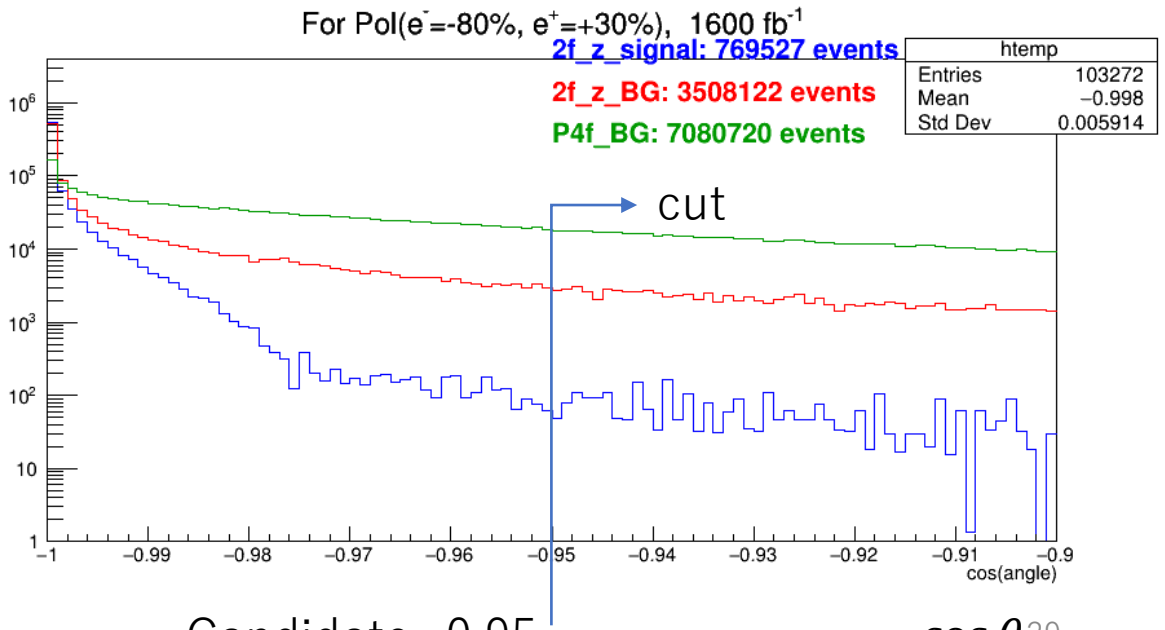
Opening angle cut

overall



$\cos\theta_{2jet}$

Around 180°

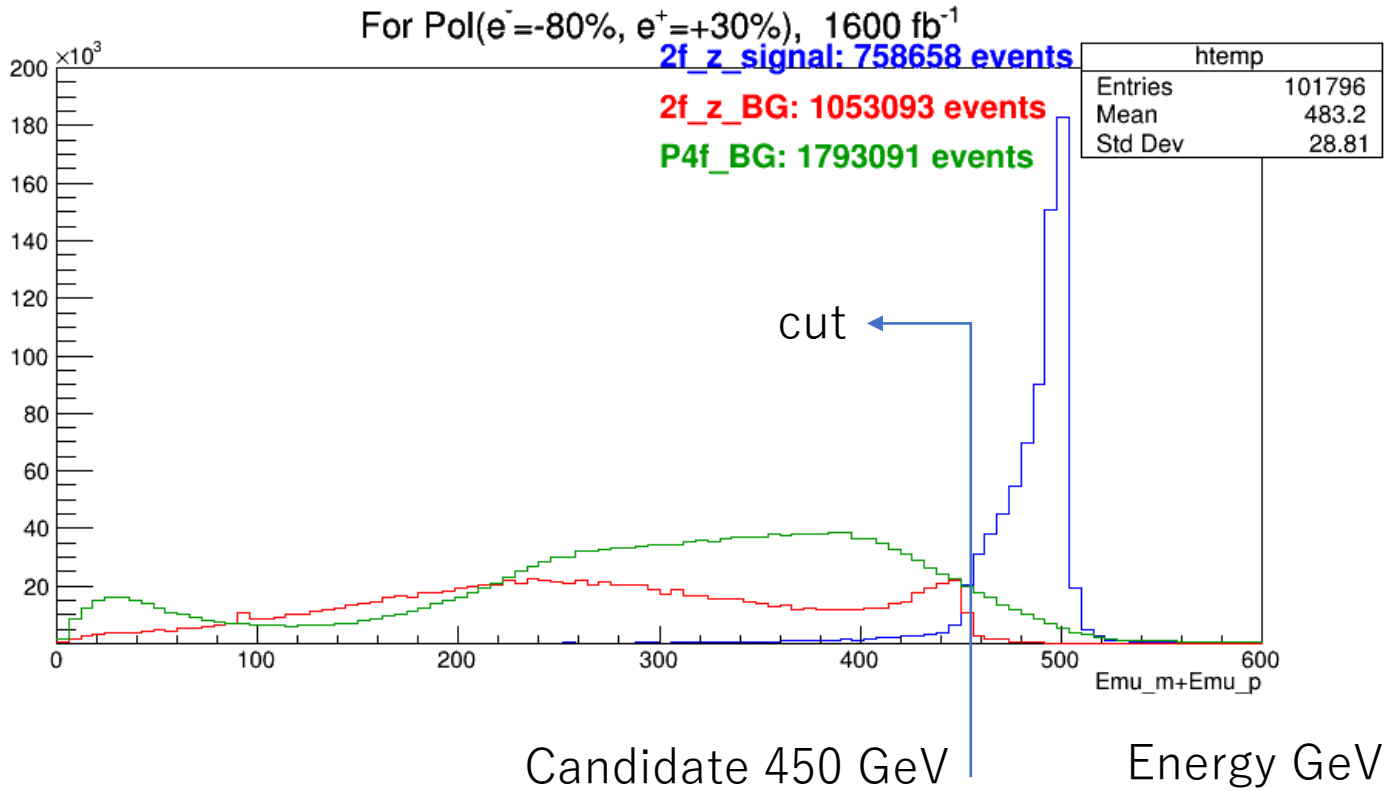


Candidate -0.95

$\cos\theta_{2jet}$

Energy cut

- Energy cut : 2 jets' highest energy
  - $l^- \, Energy + l^+ \, Energy$

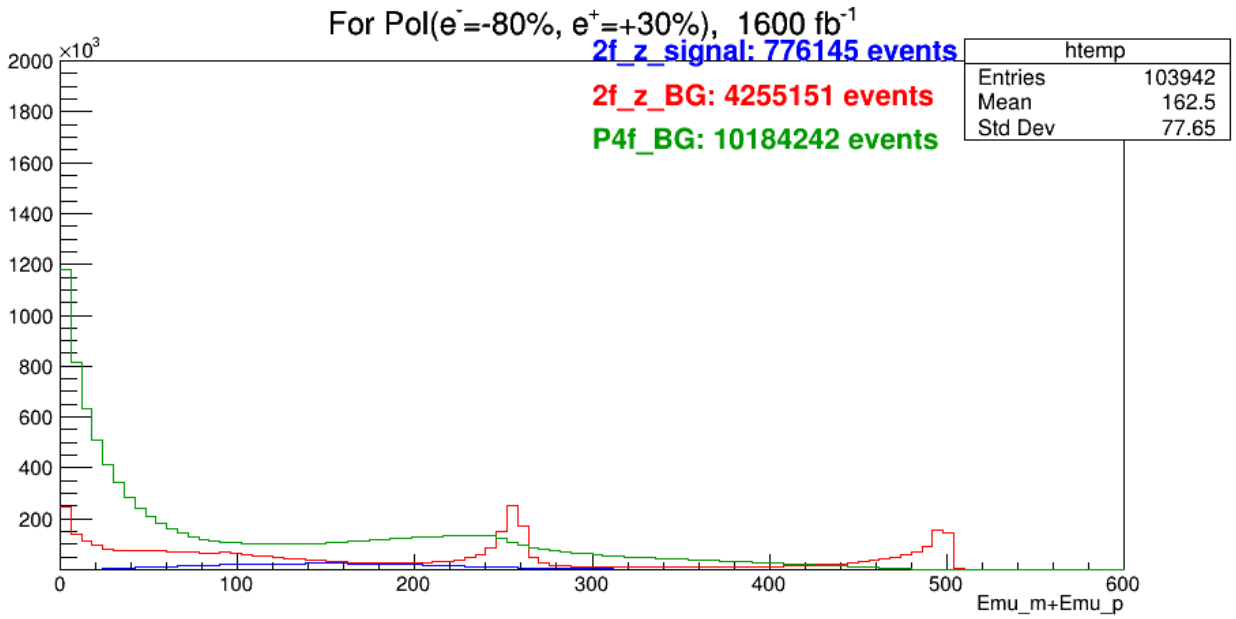


Tau event

Signal events and BG events

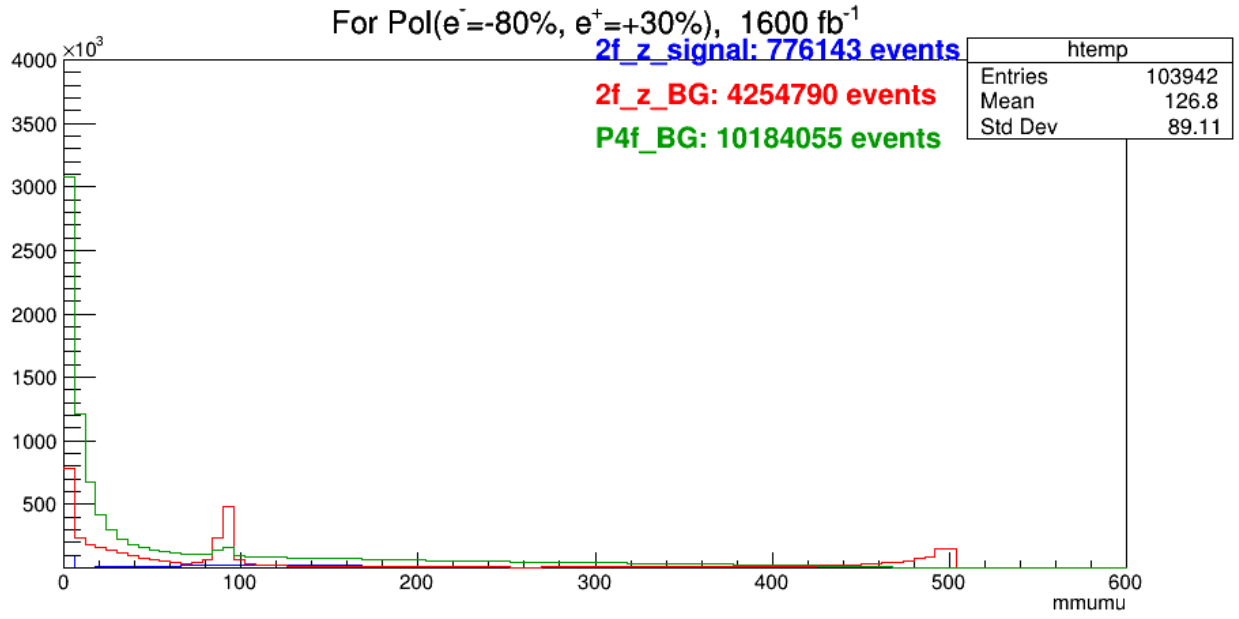
- No clustering & cuts : Original

$l^- + l^+$ $Energy$
highest energy



Energy GeV

mass

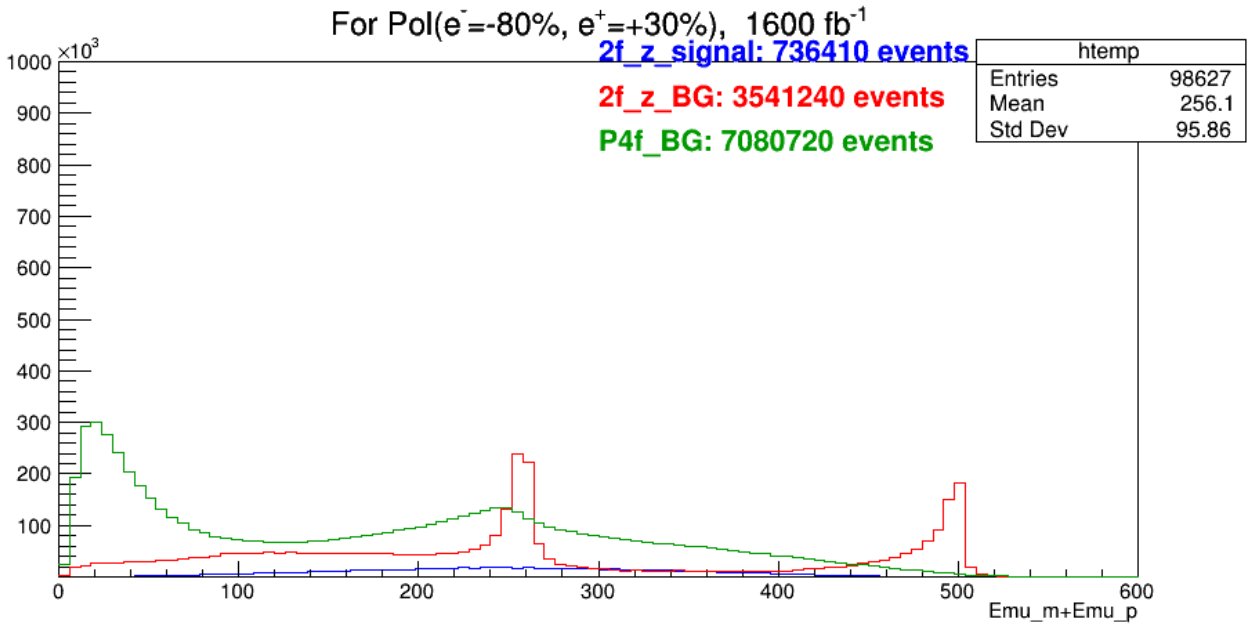


mass GeV

Tau jet clustering

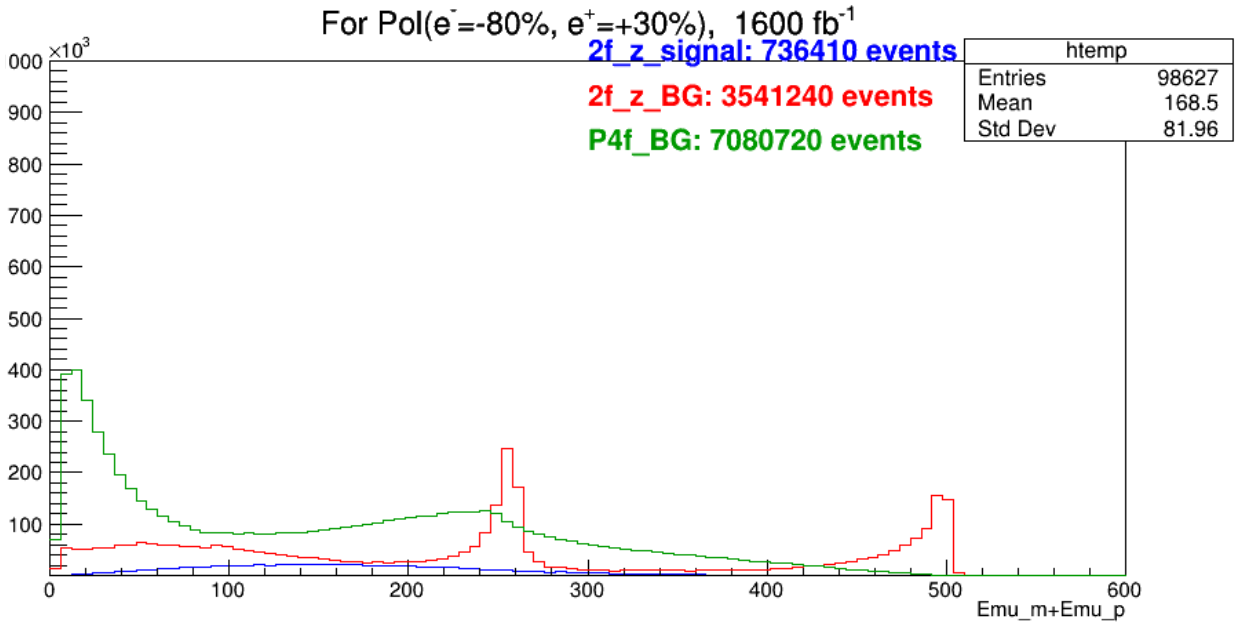
- Tau jet clustering　Use TauFinder/TaJetClustering.cc

2 jets' highest energy for all particles in tau jet



Energy GeV

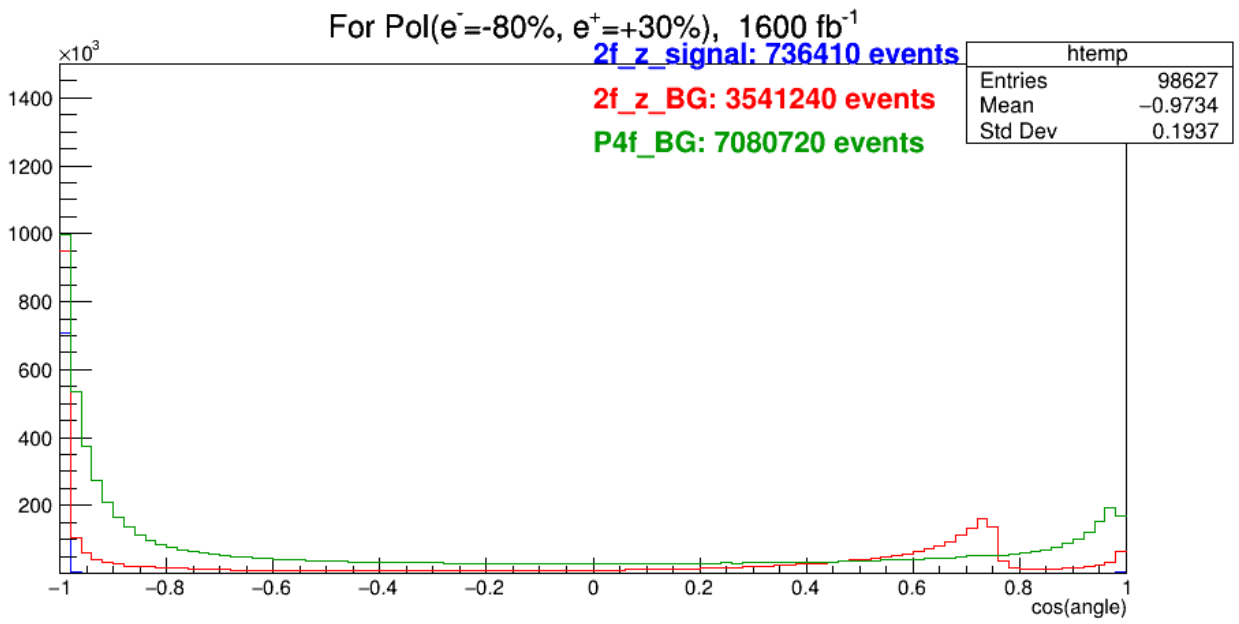
For charged particles in tau jet



Energy GeV

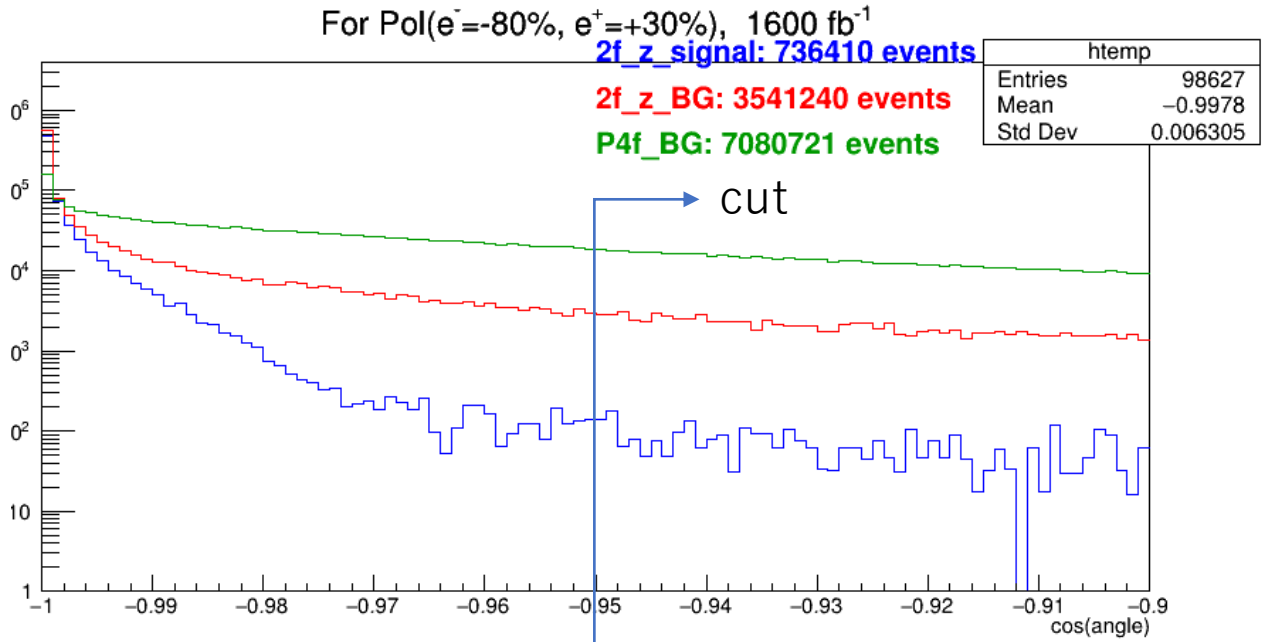
Opening angle cut

overall



$\cos\theta_{2jet}$

Around 180°

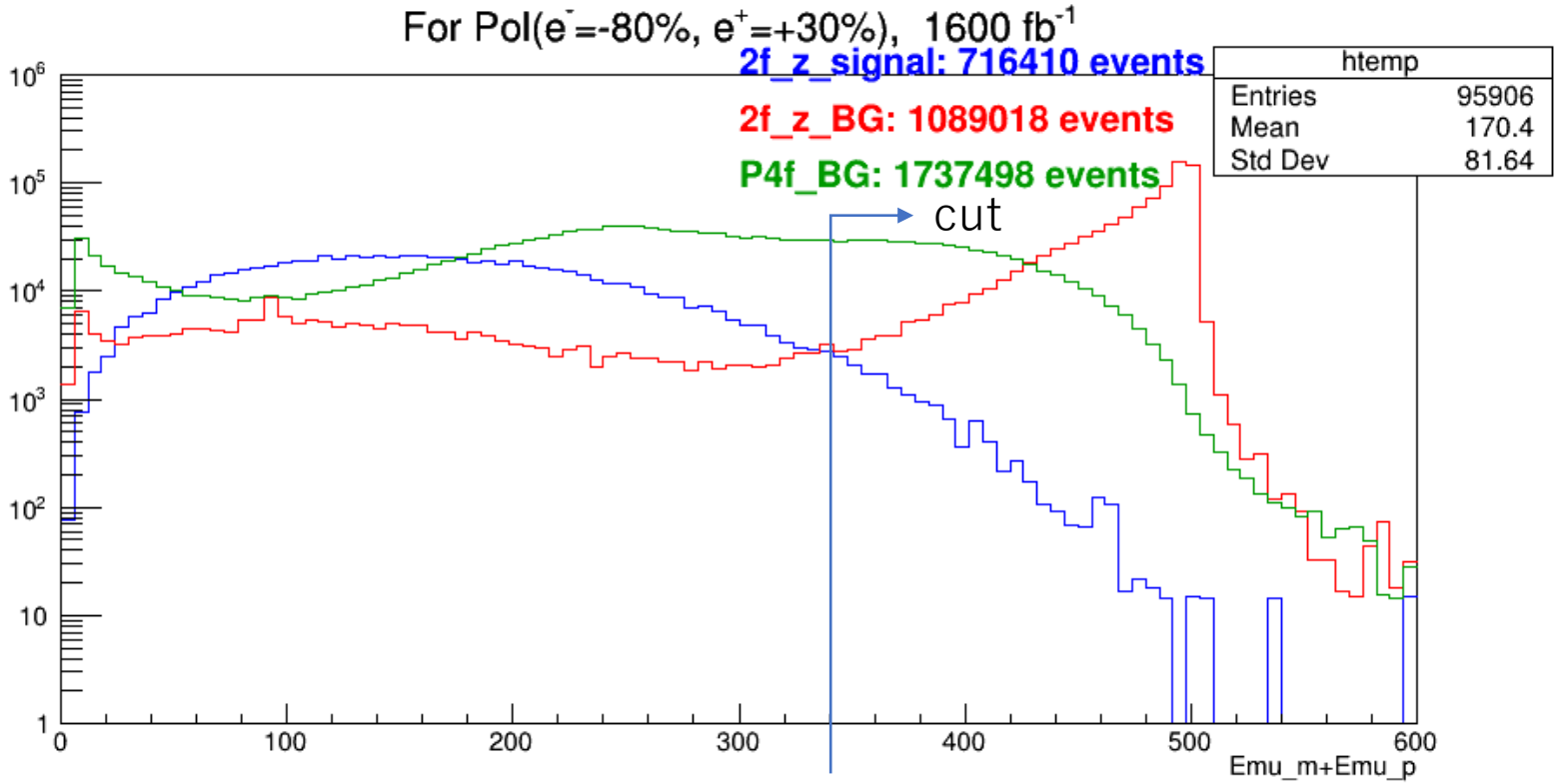


Candidate -0.95

$\cos\theta_{2jet}$

Energy cut

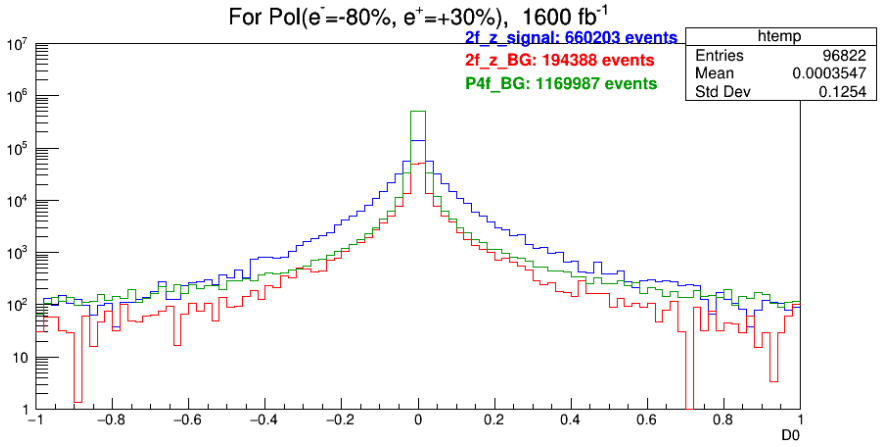
- Energy cut : 2 jets' highest energy
  - $l^- \, Energy + l^+ \, Energy$



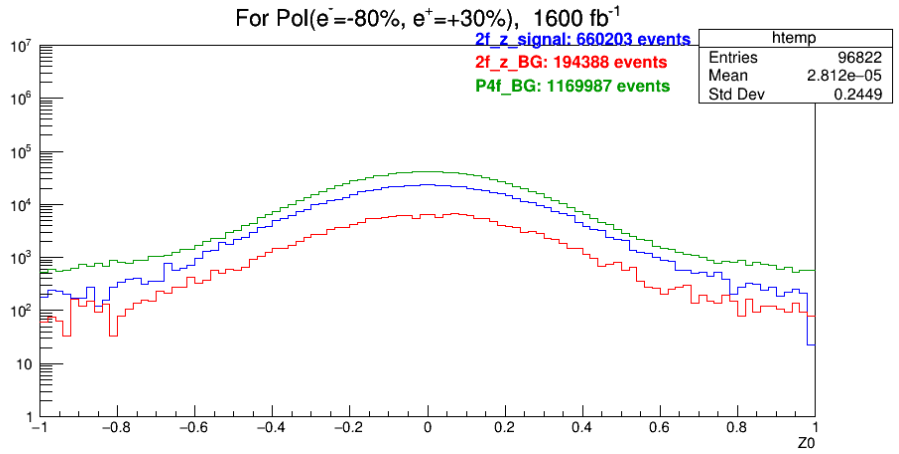
Candidate 340 GeV Energy GeV

Impact parameter plot after opening angle & energy cuts

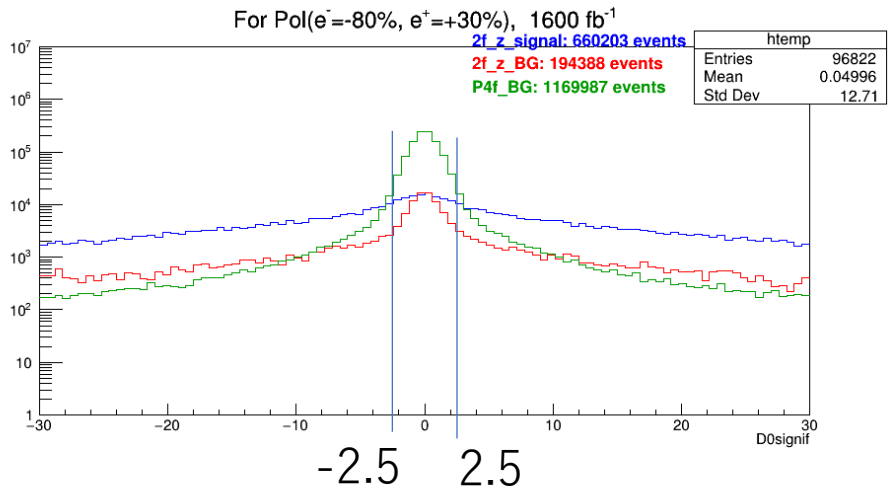
D0



Z0

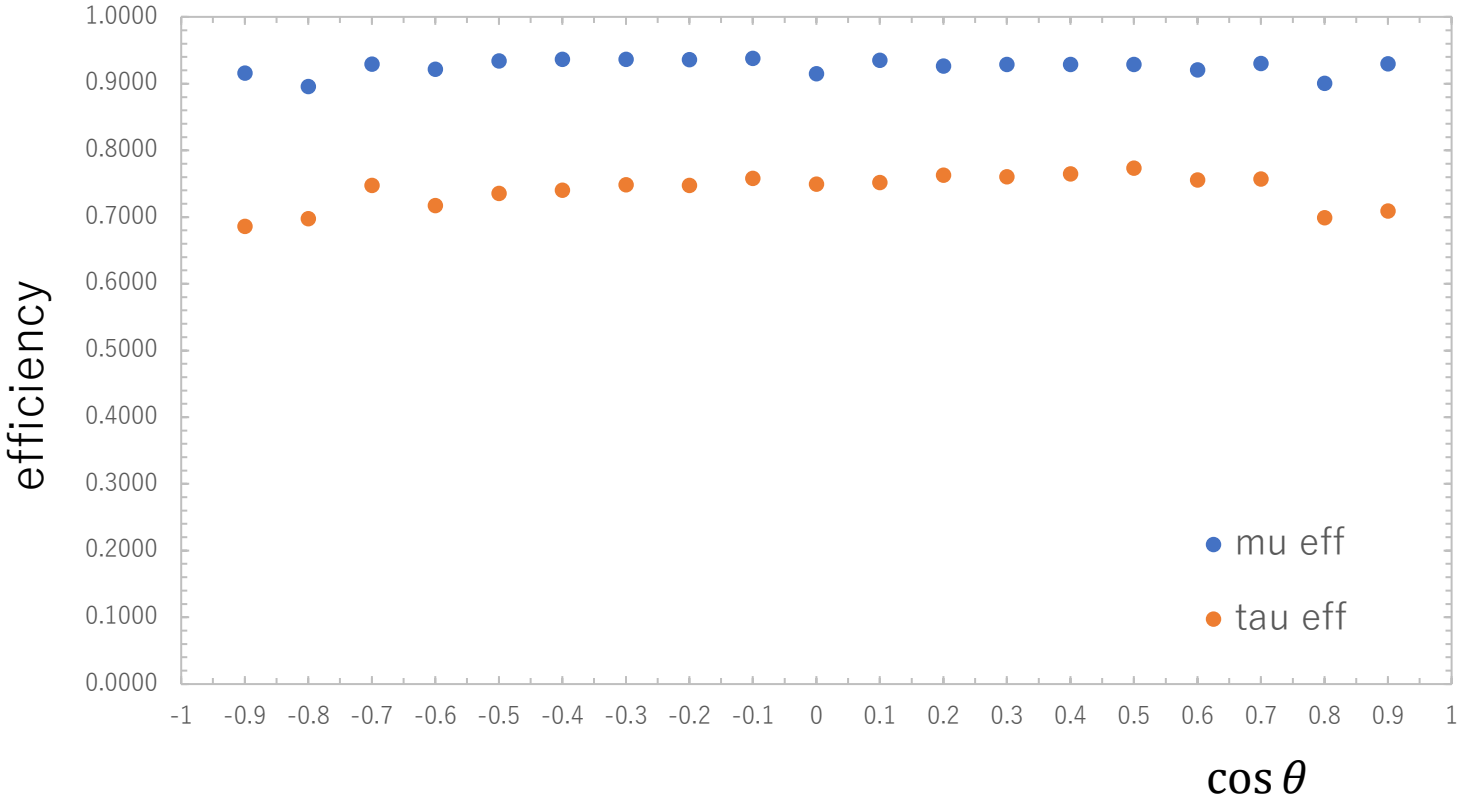


D0 significance



-2.5 2.5

mu & tau efficiency for costheta



Procedures for evaluating each model search

- The Z' is a new neutral gauge boson coupled to fermions in the standard theory. The coupling constants of Z' differ from model to model, and in this study we use the Sequential Standard Model (hereafter SSM model) and the E_6 model.
- In the SSM model, Z' has the same coupling constant as the standard theory gauge boson Z and fermions.
- The E_6 model, on the other hand, focuses on the special $U(1)$ that arises by decomposing E_6 such that $E_6 \rightarrow SO(10) \times U(1)_\psi \; and \; SO(10) \rightarrow SU(5) \times U(1)_\chi$. Z' is represented by a linear combination (Equation 5.6) of two special $U(1)$ gauge bosons (Z_ψ, Z_χ)
- $Z' = Z\chi \cos\beta + Z\psi \sin\beta$
- where β is the mixing angle defining the spontaneous breaking of E_6 . In this evaluation, three values of β were used, referred to as the χ model $(\beta = 0)$, the ψ model $(\beta = \pi/2)$, and the η model $(\beta = \pi - \arctan\sqrt{5/3})$.
- The Alternative Left-Right symmetric (ALR model) is derived from the E_6 model, which adds $SU(2)_R$ to $SU(2)_L$ in the Standard Model. The Z_R particle derived from this model is regarded as a Z' particle. This Z' particle behaves like Z_0 in the Standard Model, but the coupling constants are different from those in the Standard Model.