New physics search by precise measurements of 2-fermion final states at the ILC

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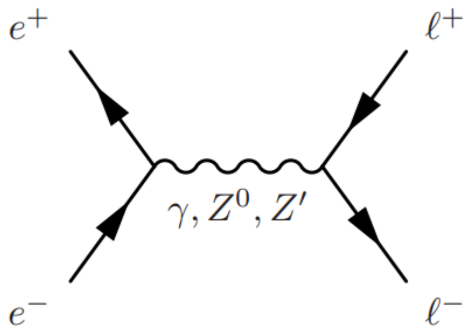
2-fermion $e^+e^- \to f\bar{f}$ event

- $e^+e^- \to f\bar{f}$ (f: charged lepton or quark)

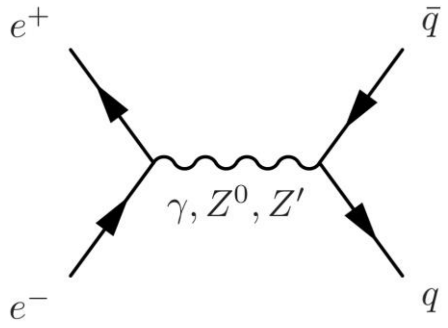
The production of fermion pairs is sensitive to a heavy gauge boson (Z').

If there are interactions mediated by Z', the total cross section and differential cross section will deviate from the predictions of the Standard Model.

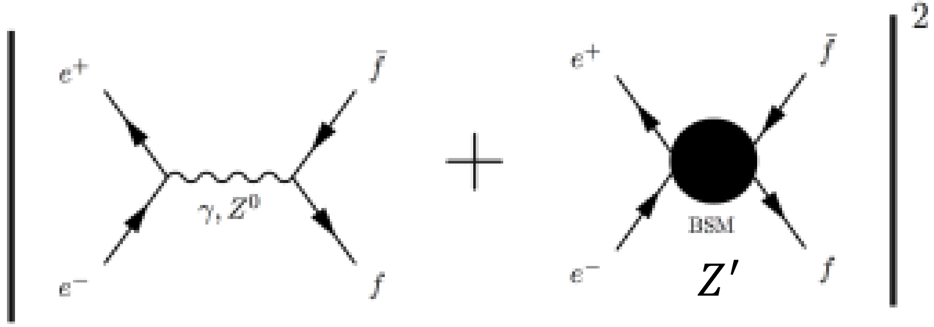
→Interference terms with Z and γ, and Z' can be observed.



2 lepton process



2 quark process



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

Conditions of the study

ILD full simulation (ilcsoft v02-00-01), $\sqrt{s} = 500$ GeV

Lepton channel ($\mu\mu$, $\tau\tau$ final states)

- Bhabha events to be done

- **Signal Events**:
  - $e^+e^- \to l^+l^-$ (Z^* true mass≥450 GeV)
- **Background Events**:
  - 2-fermion background
    $e^+e^- \to l^+l^-$ (Z^* true mass<450 GeV)
    other flavors
  - 4-fermion background
    leptonic events (mainly W/Z-derived)

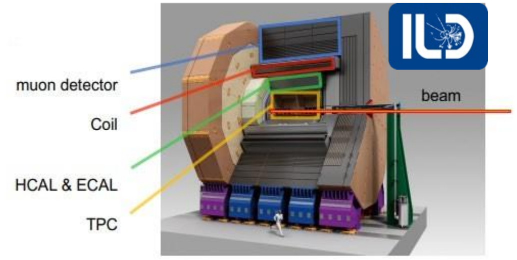
Quark channel (quark final states(w/o t))

- **Signal Events**:
  - $e^+e^- \to q\bar{q}$ (Z^* true mass≥450 GeV)
- **Background Events**:
  - 2-fermion background
    - $e^+e^- \to q\bar{q}$ (Z^* true mass<450 GeV) other flavors
  - 4-fermion background
    - hadronic events (mainly W/Z-derived)
      semileptonic events (mainly W/Z-derived)

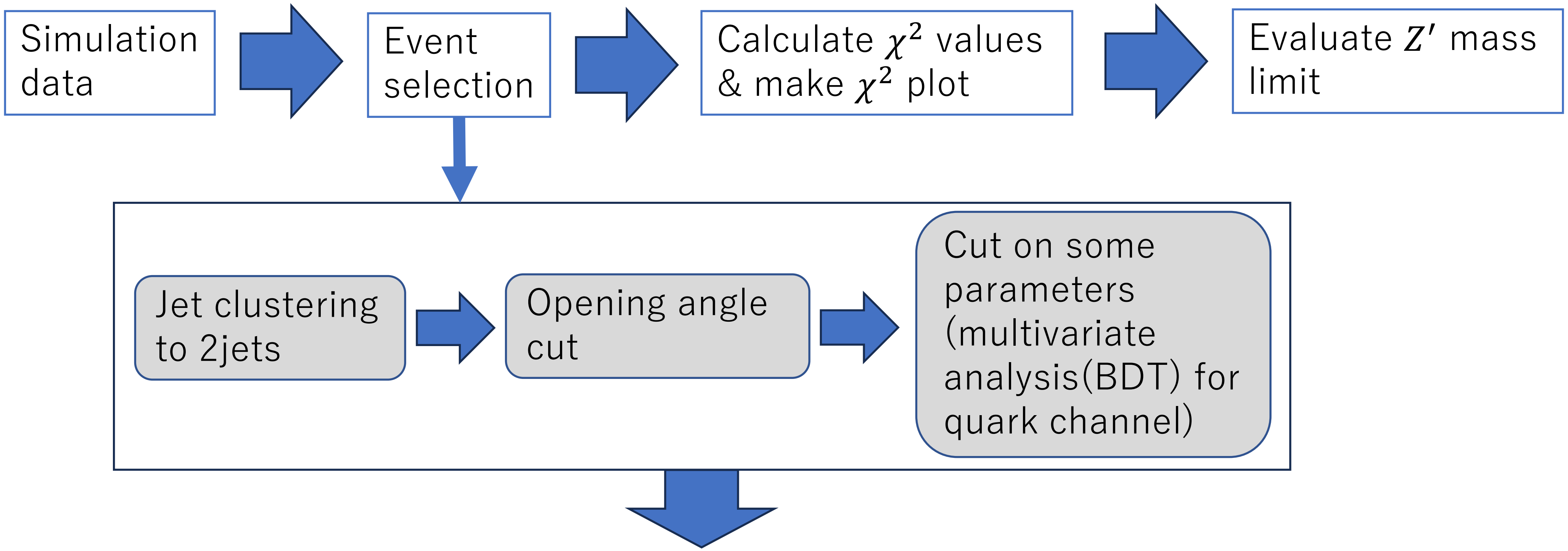
- **Polarization**
- e^-: $\mp 80\%$, e^+: $\pm 30\%$

Luminosity

1600 fb^{-1} each



Evaluation flow



The number of event in (e^-, e^+)=(−80%,+30%)

signal	$\boldsymbol{\mu^+\mu^-}$	$\boldsymbol{\tau^+\tau^-}$	**quark(u,d,s,c,b)**
Original	781,215(100%)	776,143(100%)	6,183,923(100%)
After event selection	716,569(92%)	559,438(72%)	4,871,598(78%)

efficiency in ()

Evaluation of Z' new physics search

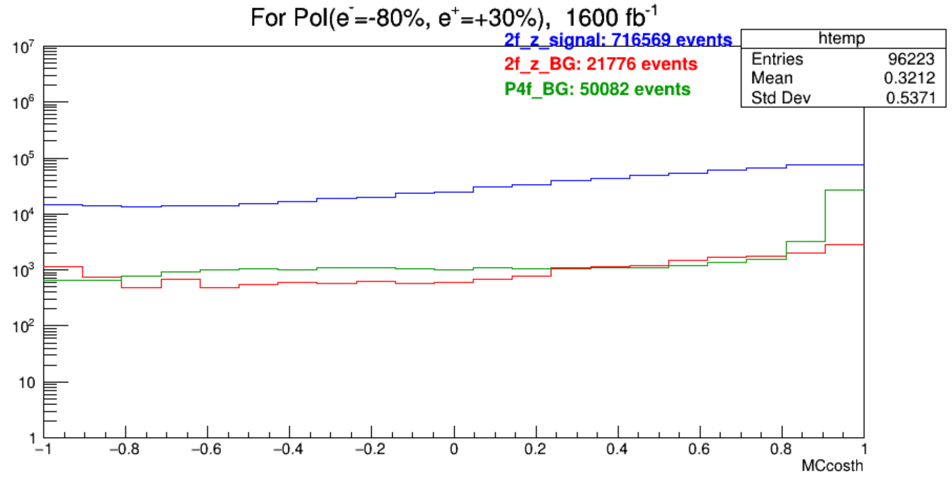
In the case of new physics

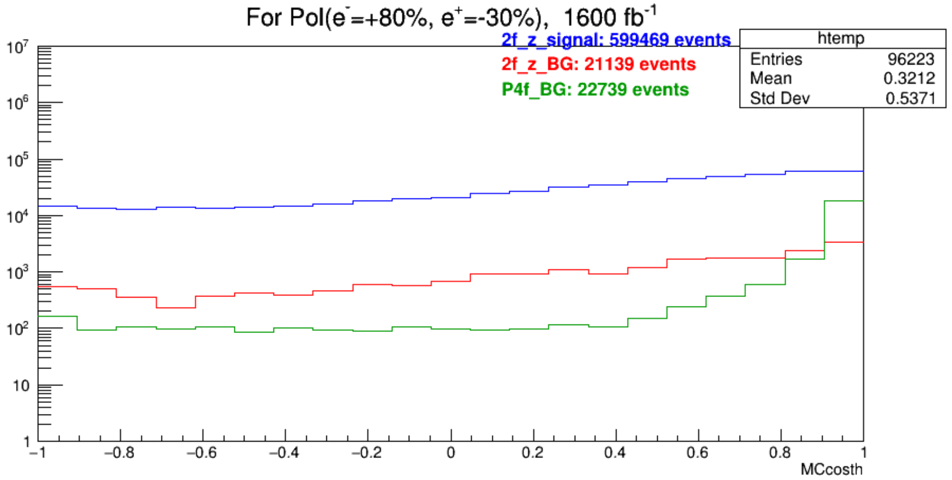
- angular distributions deviate due to the interference with Z'.

These angular distributions will now be compared with various Z' models to evaluate the performance of the new physics search in the ILC at energy of 500 GeV.

- For quark events, flavour tagging is made and then Charge Identification is performed.

For mu





Procedures for evaluating each model search

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

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

$\boldsymbol{S_i}$: **the number of signal events**
$\boldsymbol{N_i}$: **the number of background events** **in each bin.**

In this evaluation,

systematic errors = $\begin{cases} \mathbf{0.001}\ \boldsymbol{for} & \boldsymbol{\mu\mu} \\ \mathbf{0.002}\ \boldsymbol{for} & \boldsymbol{\tau\tau} \\ \mathbf{0.002}\ \boldsymbol{for} & \boldsymbol{bb} \\ \mathbf{0.002}\ \boldsymbol{for} & \boldsymbol{cc} \\ \mathbf{0.002}\ \boldsymbol{for}\ \boldsymbol{qq}(\boldsymbol{uds}) \end{cases}$ are assumed.(preliminary)

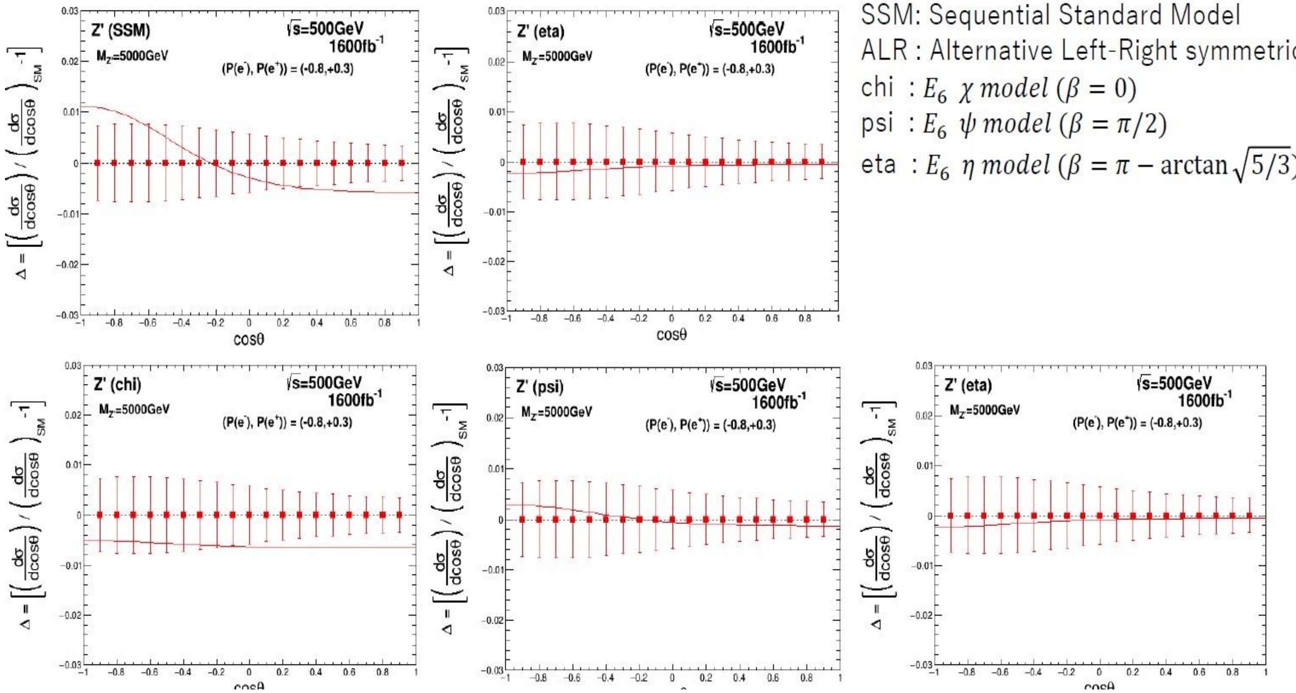
- The deviation of the differential cross section predicted by the standard model and each model for this i-th bin ($\delta\sigma_i(BSM)/\sigma_i(SM)$) is determined, and from

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

the χ^2 is obtained.

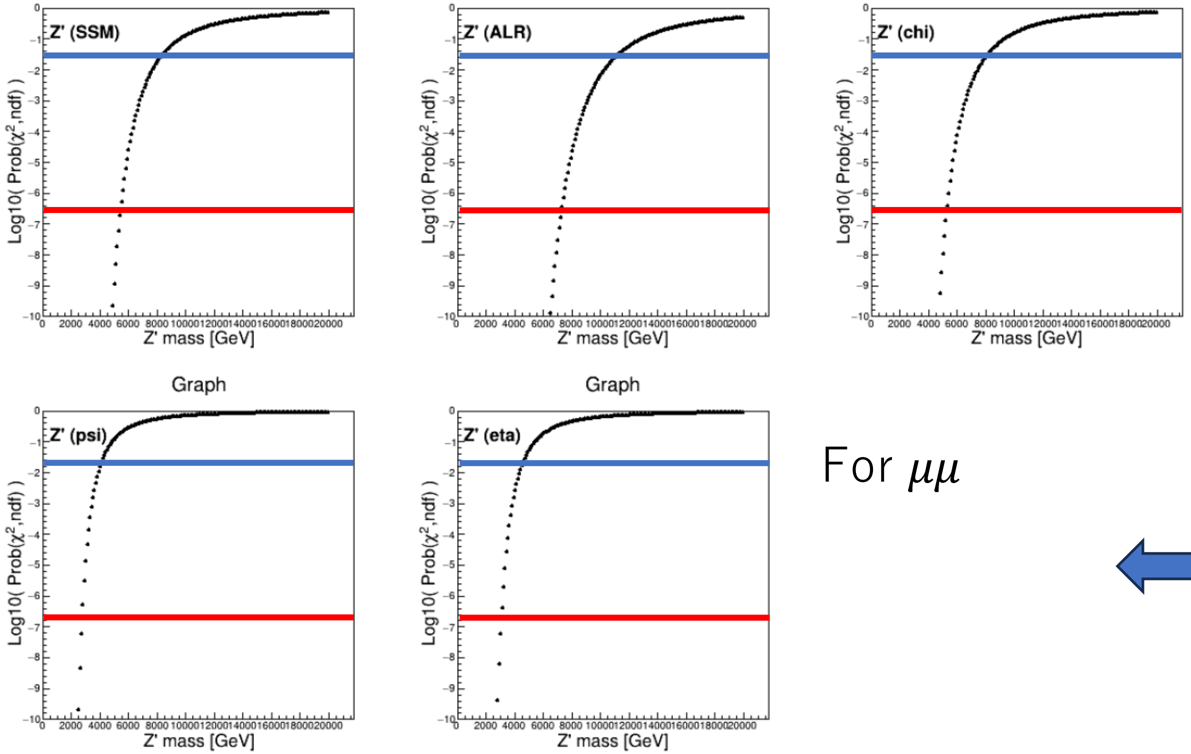
Deviation on angular distribution & mass limit

For $\mu\mu$



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 $model$ $(\beta = \pi - \arctan\sqrt{5/3})$

Deviation on angular distribution
Vertical Axis: Deviation of SM and BSM
horizontal axis: $\cos\theta$
line: BSM effect
error bars: error on each bin



For $\mu\mu$

Vertical axis: Log10(Probability at χ^2 for Z' mass)
Horizontal Axis: Z' mass[2 TeV~20 TeV]
5-sigma -> -6.52 (discovery reach)
2-sigma -> -1.3 (95% CL lower limit)

Mass limit for each 5 channel (preliminary)

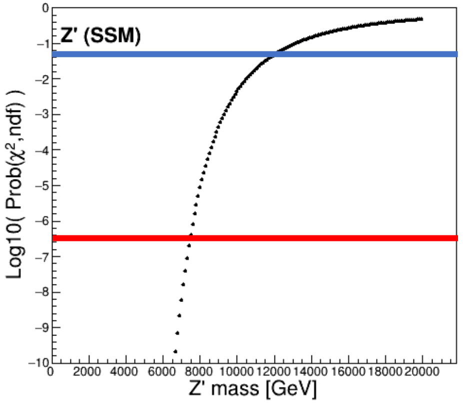
5-sigma

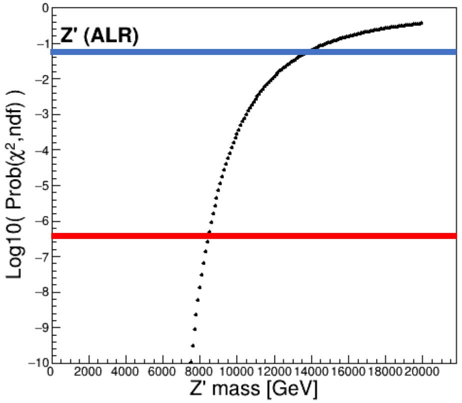
	SSM	ALR	χ	ψ	η
μ	5.4 TeV	7.3 TeV	5.3 TeV	2.8 TeV	3.1 TeV
τ	4.8 TeV	6.4 TeV	4.7 TeV	2.4 TeV	2.7 TeV
b	5.9 TeV	2.7 TeV	3.9 TeV	2.7 TeV	2.1 TeV
c	3.8 TeV	3.7 TeV	2.0 TeV	1.9 TeV	2.0 TeV
$q(u, d, s)$	4.0 TeV	4.1 TeV	2.0 TeV	2.0 TeV	2.2 TeV

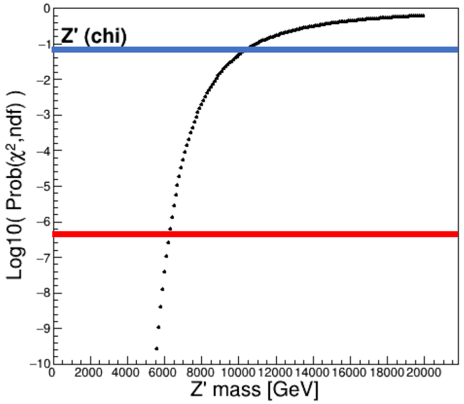
2-sigma

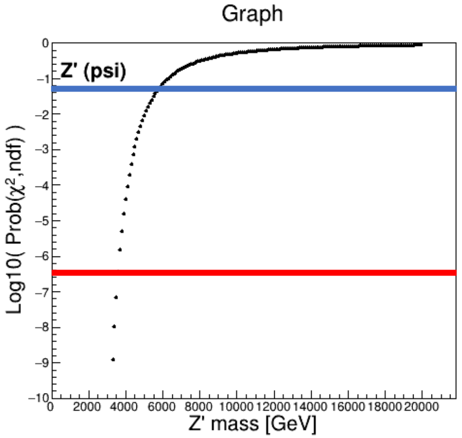
	SSM	ALR	χ	ψ	η
μ	8.8 TeV	11.8 TeV	8.5 TeV	4.4 TeV	4.9 TeV
τ	7.7 TeV	10.4 TeV	7.5 TeV	3.9 TeV	4.4 TeV
b	9.4 TeV	4.3 TeV	6.2 TeV	4.2 TeV	3.4 TeV
c	6.2 TeV	5.9 TeV	3.1 TeV	3.0 TeV	3.2 TeV
$q(u, d, s)$	6.5 TeV	6.6 TeV	3.2 TeV	3.2 TeV	3.6 TeV

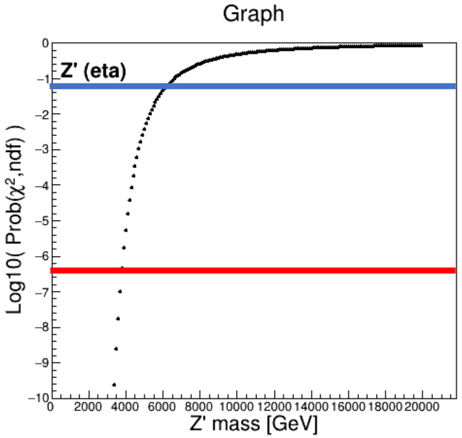
Mass limit for 5 channel combined (preliminary)











Vertical axis: Log10(Probability at χ^2 for Z' mass)
Horizontal Axis: Z' mass
5-sigma -> -6.52 (discovery reach)
2-sigma -> -1.3 (95% CL lower limit)

For μ+τ+b+c+q(uds)

Z'model	SSM	ALR	χ	ψ	η
5-sigma	7.5 TeV	8.4 TeV	6.2 TeV	3.6 TeV	3.8 TeV
2-sigma	12.0 TeV	13.6 TeV	10.0 TeV	5.8 TeV	6.1 TeV

Summary

- I performed the calculation for the mass limit when combining **$\mu\mu$, $\tau\tau$, bb, cc, and qq(uds) events**.
- An evaluation was conducted for five models, and when combining all event, it ranged from **3.6-8.4 TeV** at 5 sigma and **5.8-13.6 TeV** at 2 sigma (these results are not yet final).

- However, the systematic error setting is still insufficient and needs to be reexamined.
- Also, I will also incorporate lepton pair events and evaluate them interactively.

backup

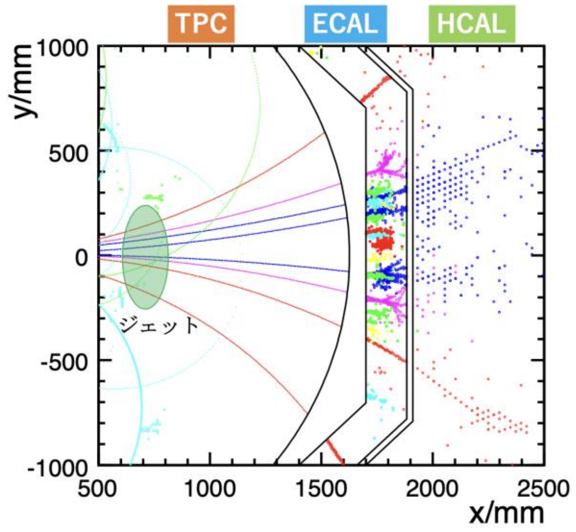
Particle Flow Algorithm (PFA)

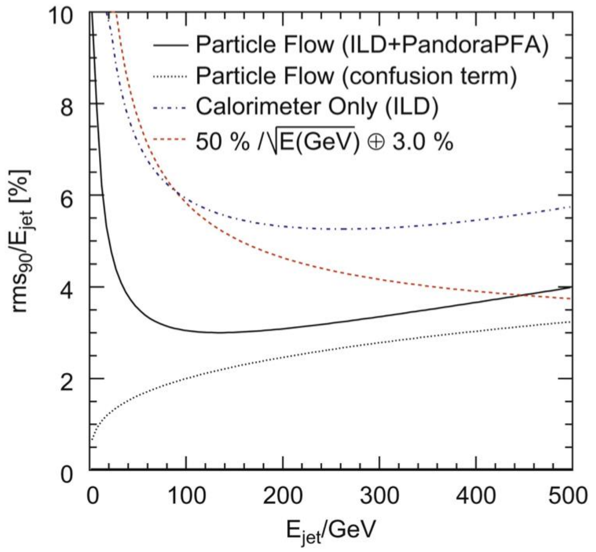
- A method to obtain higher jet energy resolution by reconstructing the particle trajectory for each type of particle in the jet.
- Charged particles: Tracker
- Photons: ECAL
- Neutral hadrons : HCAL
  → To separate the deterioration of resolution for neutral hadrons
- Resolution of a calorimeter for a single particle :

Perfect PFA: $\sim 20\%/\sqrt{E(GeV)}$

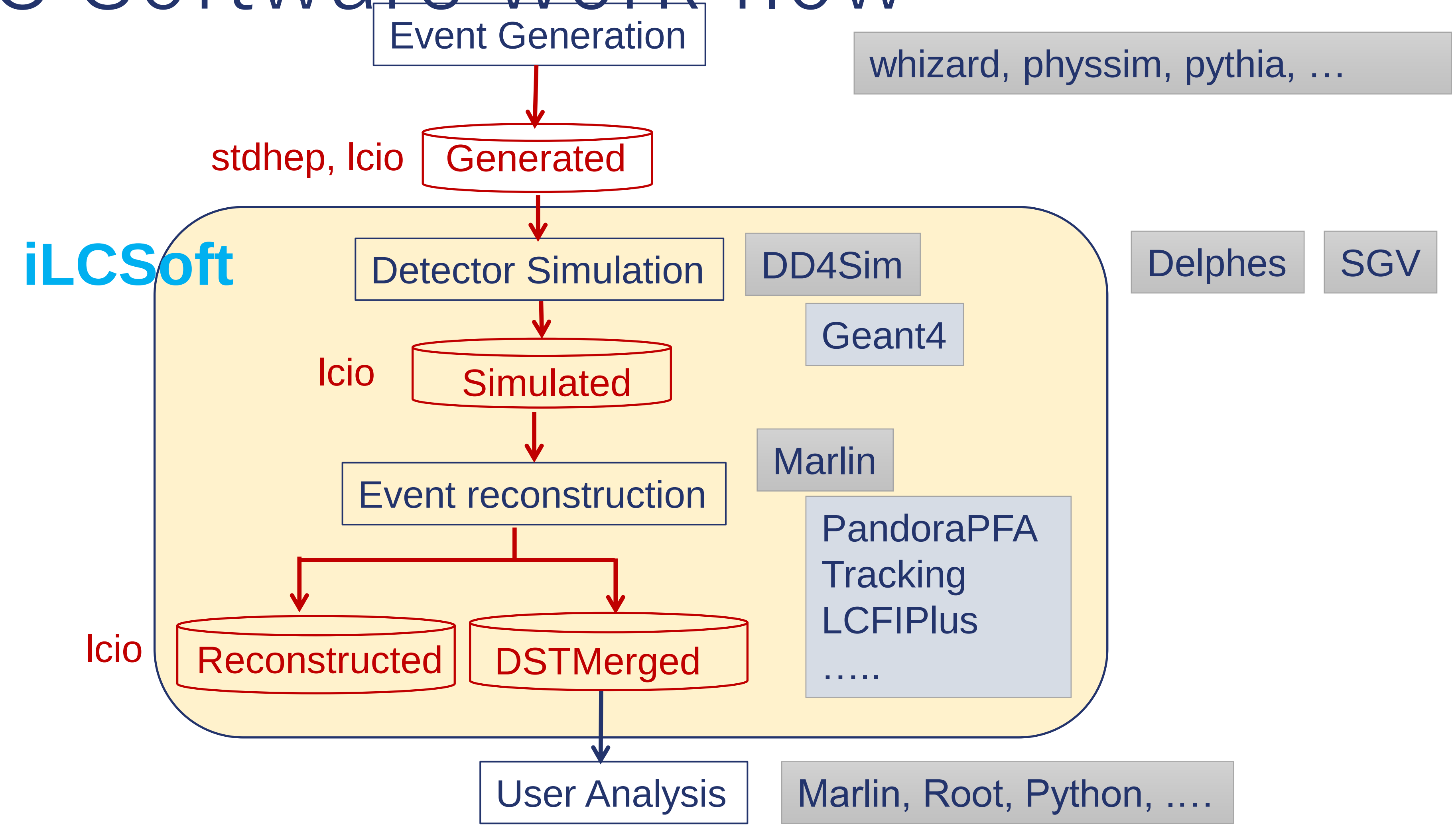
PandoraPFA : $\sim 30\%/\sqrt{E(GeV)}$

w/o PFA : $50 - 60\%/\sqrt{E(GeV)}$

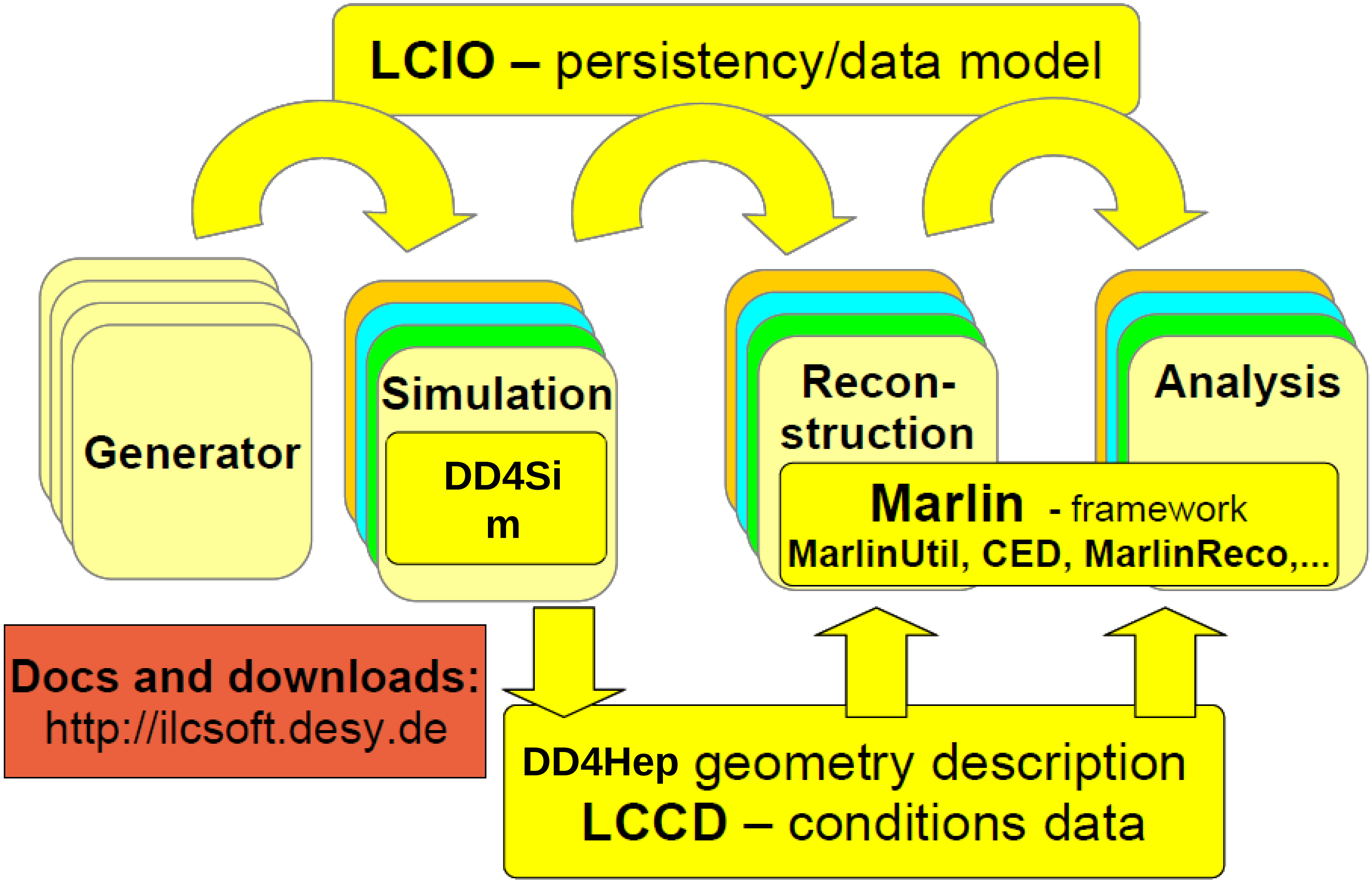




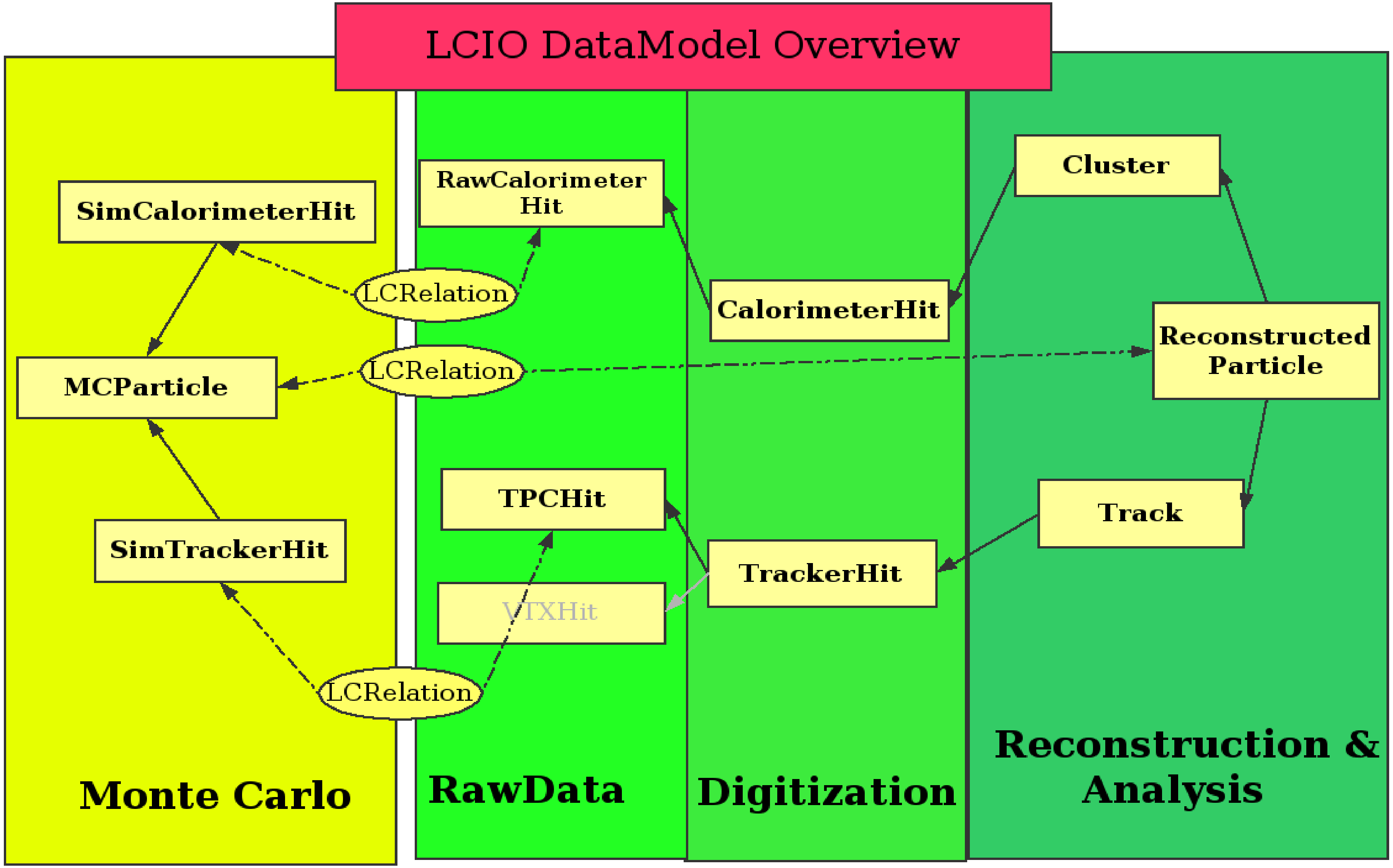
ILC Software work flow



Role of LCIO : persistency and data model



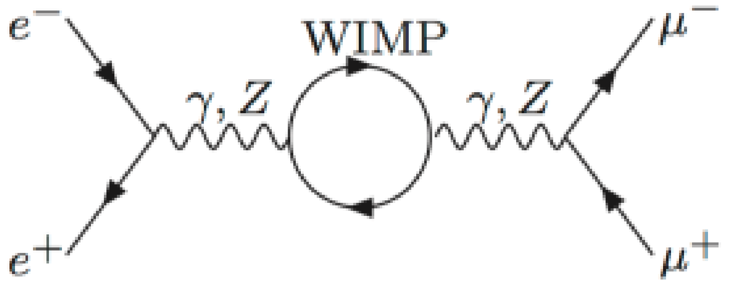
Data Model II



by Frank Gaede, DESY

2-fermion $e^+e^- \to f\bar{f}$ event

- $e^+e^- \to f\bar{f}$:
- ゲージヒッグス統一（GHU）モデルでは、ヒッグス粒子はゲージポテンシャルの余剰次元成分の一部であり、これは5次元におけるアハロノフ-ボーム（AB）相（ θ_H ）の変動として表されます。ILC において GHU モデルのずれを見ることができるかを判断することもできる。
- また、最近提案された新物理探索法として、WIMP(weakly-interacting massive particle) による $e^+e^- \to f\bar{f}$のずれを一般的に調べる方法がある。
- これまで解析してきた 2 フェルミオン終状態の過程 ($e^+e^- \to f\bar{f}$) に、WIMP(χ) を導入し $Z \to \chi\chi \to Z$のループを含んだダイアグラム を仮定すると、結合定数が変わってくる。この結合定数のずれは WIMP のスピンや質量によって異なり、WIMP モデルの詳細には依存しない。



Previous results

- muイベントとtauイベントの場合のZ‘新物理探索の評価の結果

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

$\boldsymbol{Z'}$**model**	**SSM**	**ALR**	$\boldsymbol{\chi}$	$\boldsymbol{\psi}$	$\boldsymbol{\eta}$
5-sigma	4.7 TeV	6.4 TeV	4.6 TeV	2.4 TeV	2.7 TeV

5-sigma = discovery reach

$\boldsymbol{Z'}$**model**	**SSM**	**ALR**	$\boldsymbol{\chi}$	$\boldsymbol{\psi}$	$\boldsymbol{\eta}$
2-sigma	6.6 TeV	8.8 TeV	6.4 TeV	3.3 TeV	3.7 TeV

2-sigma = 95% CL lower limit

Previous results: 山城さん

重心系エネルギー 250 GeV の ILC の $e^+e^- \to \ell^+\ell^-$ の測定で 3σ 以上のずれで検出可能な Z' の質量の上限。チャンネルを追加して質量の上限が下がる場合は、追加前の上限の値を用いている。これは χ^2 の値が 1 のまま bin 数が増えると確率が上がるためである。

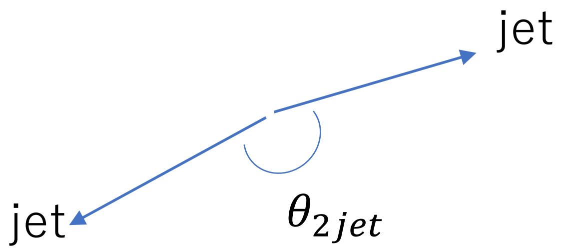
Z' model	ℓ	b	c	$\ell + b$	$\ell + b + c$
SSM	2.8 TeV	4.5 TeV	2.7 TeV	4.5 TeV	4.5 TeV
ALR	4.0 TeV	2.9 TeV	2.8 TeV	4.0 TeV	4.0 TeV
χ	2.9 TeV	2.4 TeV	1.4 TeV	2.9 TeV	2.9 TeV
ψ	1.4 TeV	2.1 TeV	1.4 TeV	2.1 TeV	2.1 TeV
η	1.8 TeV	2.3 TeV	1.4 TeV	2.3 TeV	2.3 TeV

シグナルイベントの定義

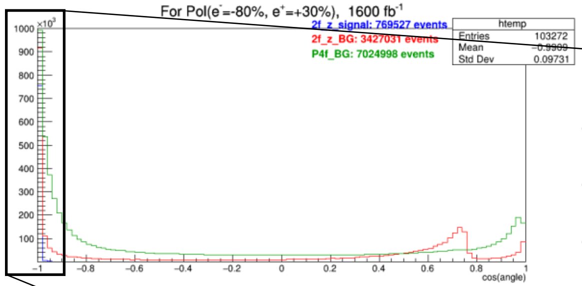
- シグナルイベントデータを質量に基づいてシグナルとバックグラウンドに分割。
- この質量はファインマンダイアグラムのZ*質量に対応
- もしZ*の質量が小さい場合、Z*と干渉する重い新しい粒子、例えばZ’の寄与は小さくなります。
- Z’モデルを計算する際、Z*は500 GeV（ISRやその他の効果を含まない）と仮定されているので、低いZ*の寄与が含まれている場合、結果は私たちが期待するものとは異なる。
- したがって、低質量のイベントをバックグラウンドとして除外

オープニングアングル

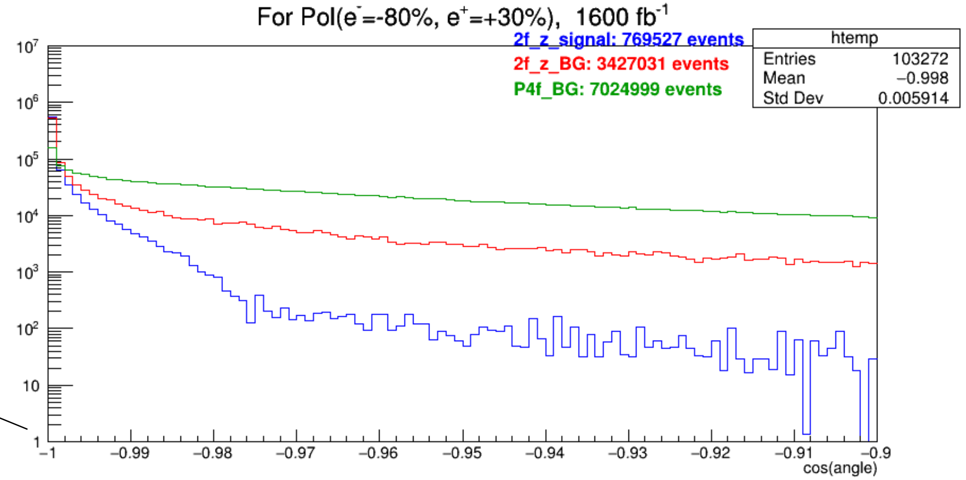
信号ジェット間の角度はほぼ180度
→180度付近のイベントは、シグナル（2フェルミオン）イベントと考えられる



例: μ イベント
全体

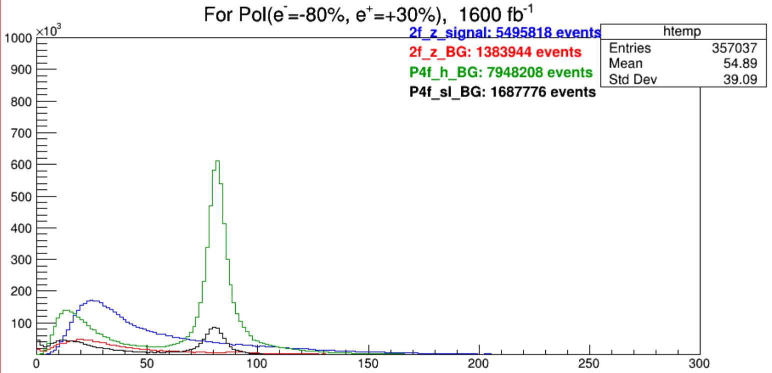


180°付近

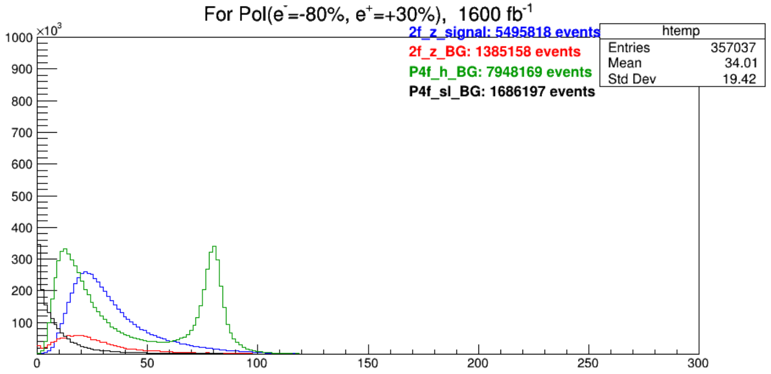


Input parameter 1

Single Jet mass

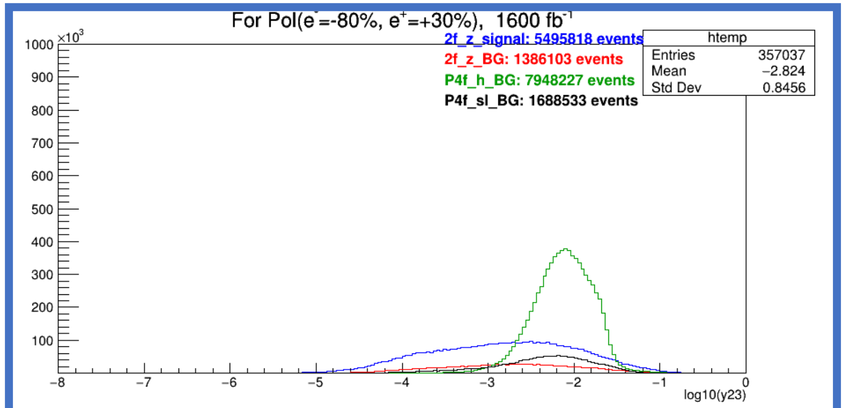


m_1st

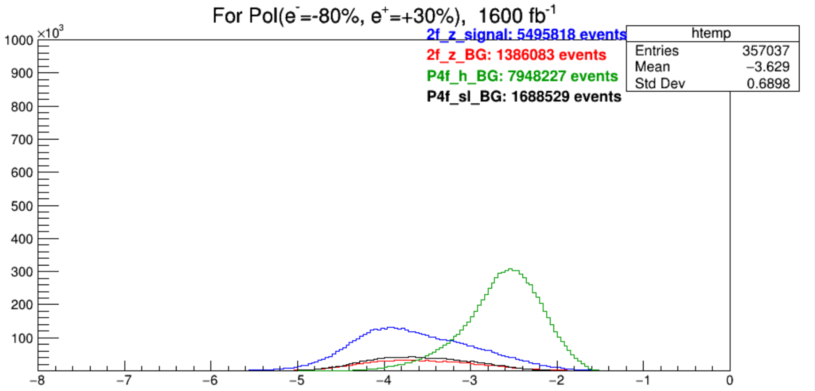


m_2nd

y value

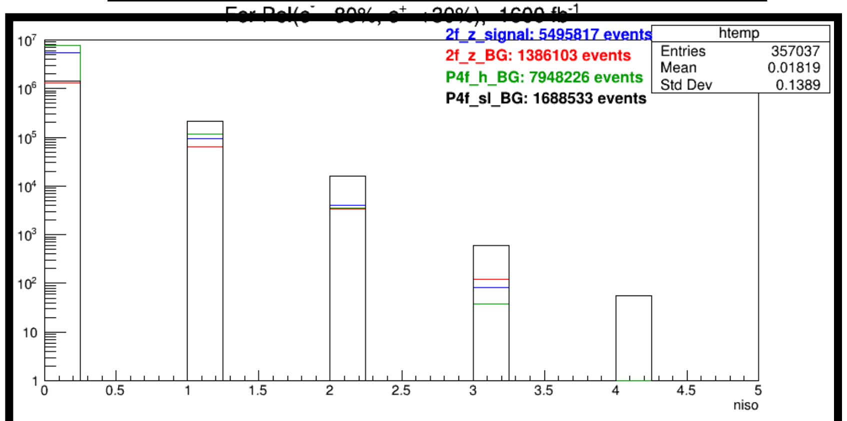


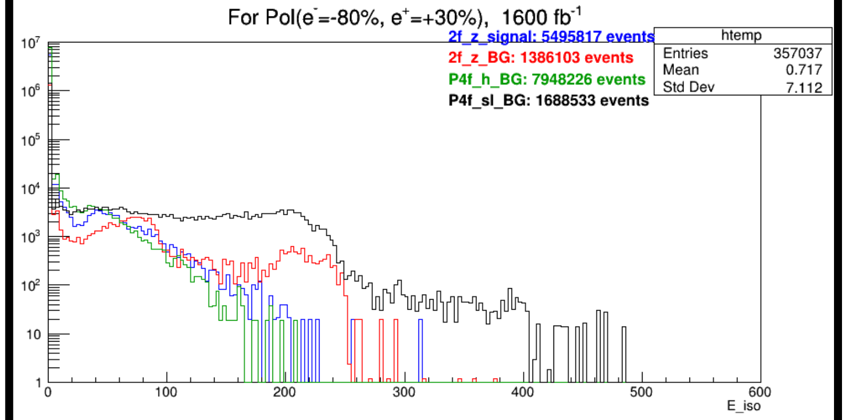
y23



y34

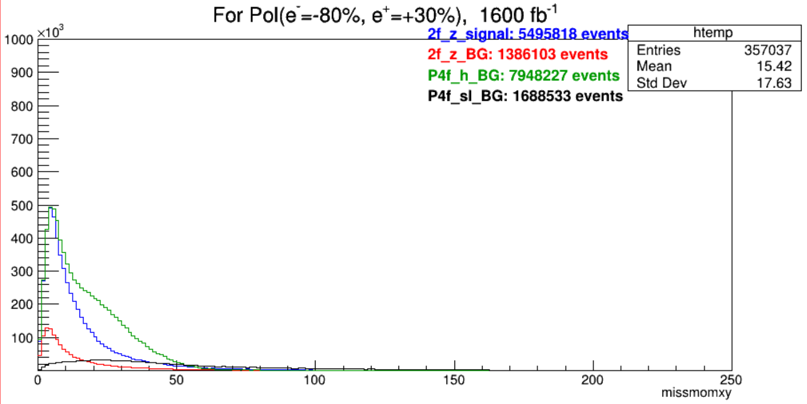
Isolated leptons
top: NumberOfElements
bottom: Energy of isolated leptons



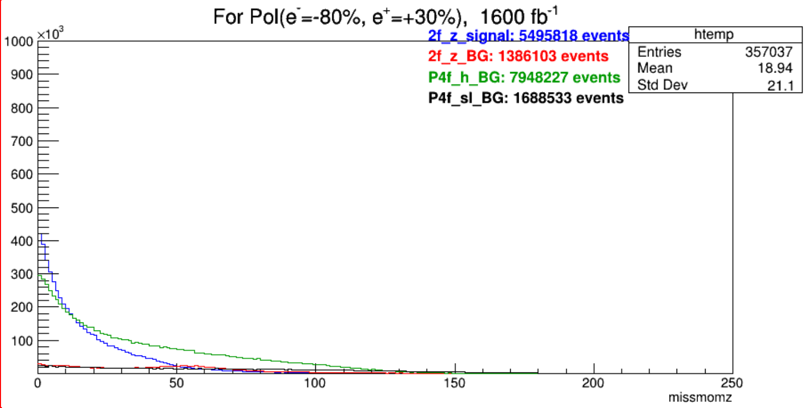


Input parameter 2

Missing momentum (2jet)

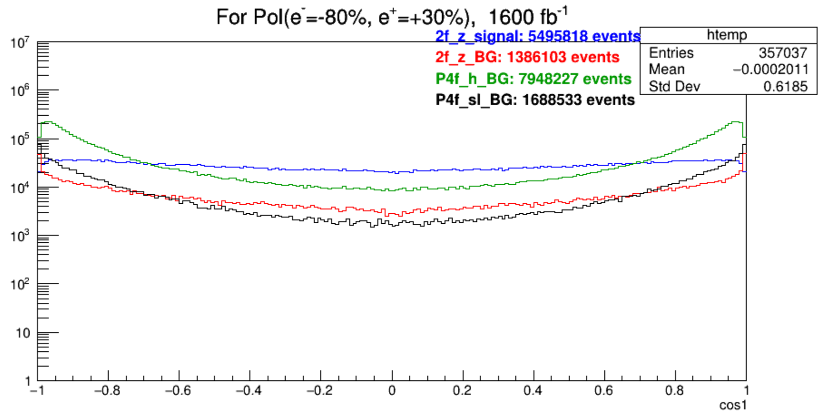


Missing momentum (xy)

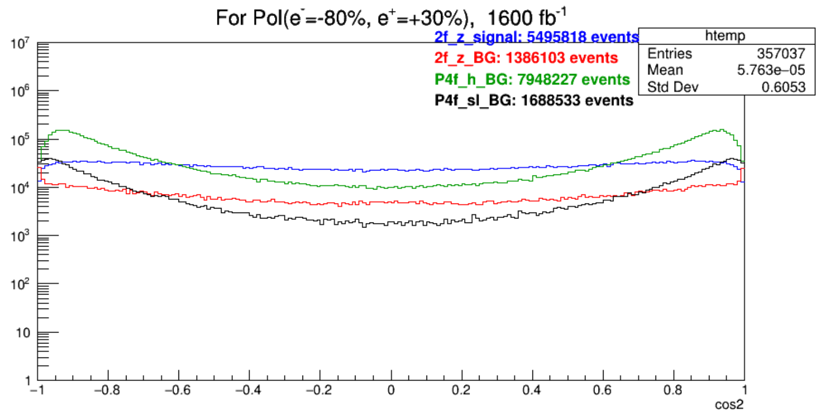


Missing momentum (z)

Costheta (jet)

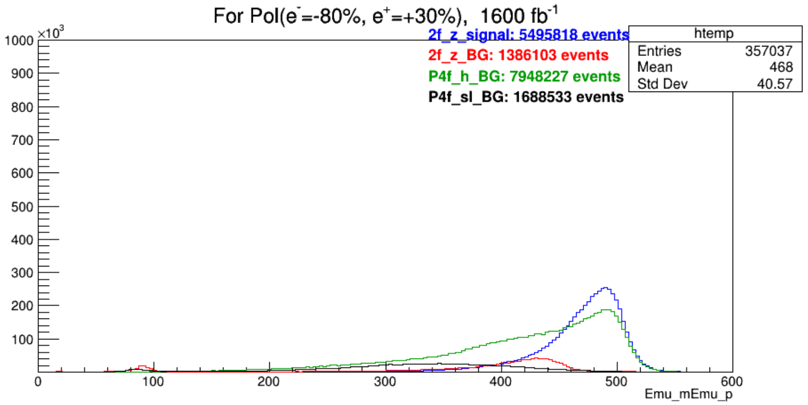


Costheta_1st

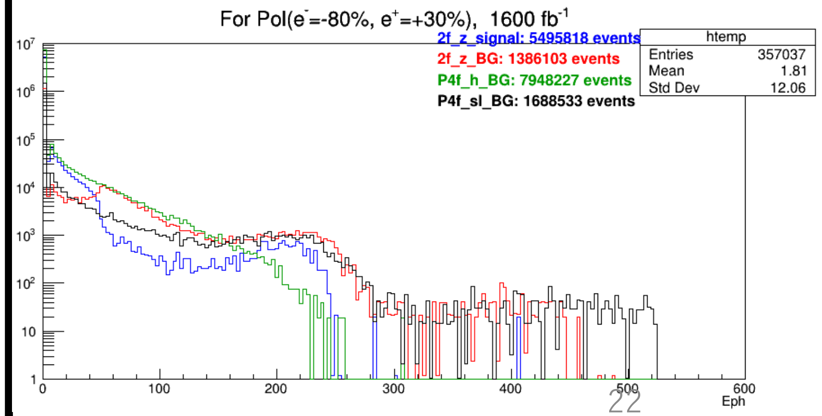


Costheta_2nd

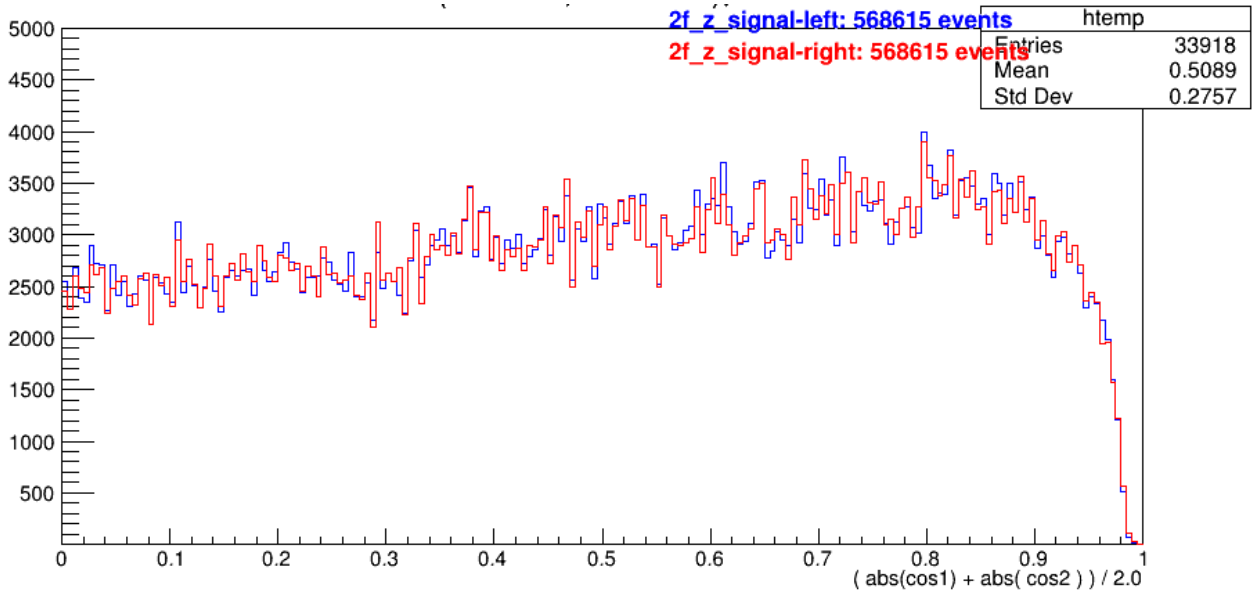
Visible energy(2 jet)



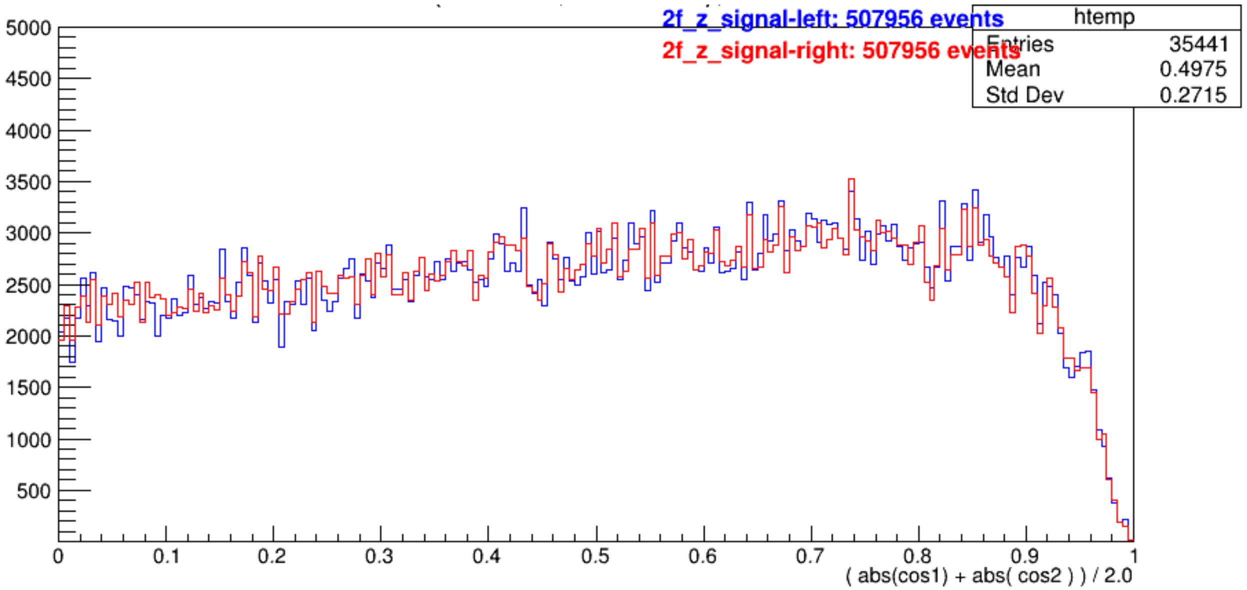
Isolated photons: Energy



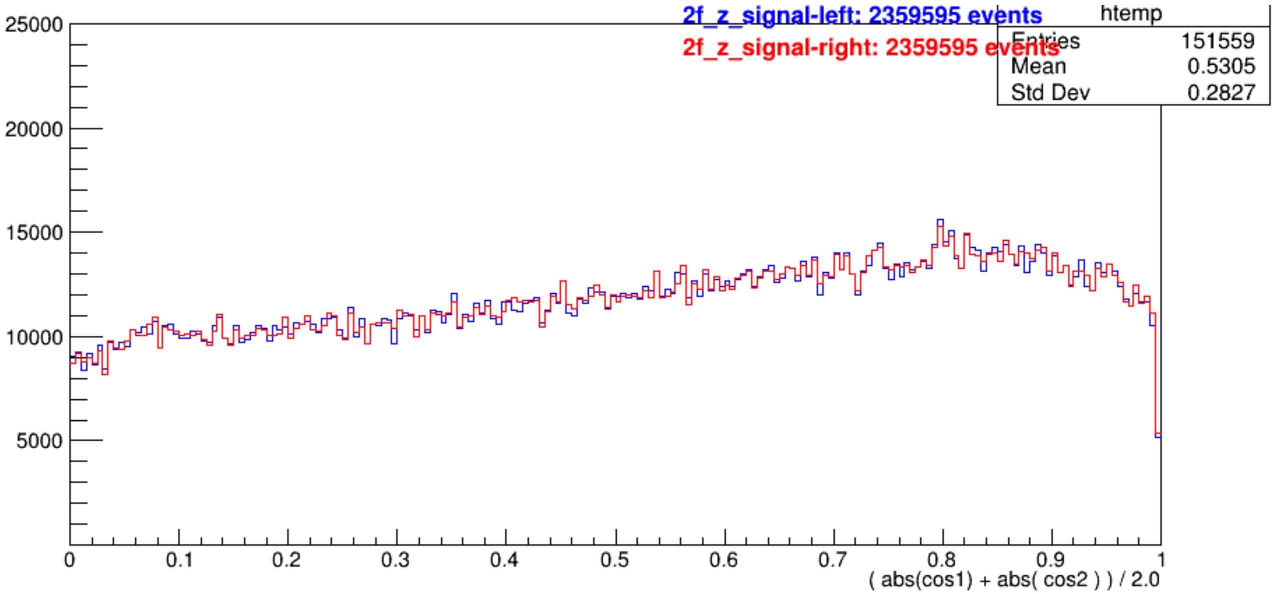
bb



cc



qq(u,d,s)



予測されたフレーバーごとのcos θ 分布（event selection後）

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

赤は、青のイベント数に合わせてスケーリングされています。

Z' モデル

- Z'は、標準理論のフェルミオンに結合する新しい中性ゲージボソンです。 Z'の結合定数はモデルによって異なり、この研究ではSequential Standard Model（以下、SSMモデル）とE_6モデルを使用します。
- **Sequential Standard Model (SSMモデル)**: このモデルでは、 Z'という粒子は、すでに知られているZ粒子と同じような性質を持っていると考える
- **E_6モデル**: このモデルは少し複雑で、新しい粒子Z'は、2つの他の粒子（ Z_ψとZ_χ ）の組み合わせとして表される

$$Z' = Z_\chi \cos\beta + Z_\psi \sin\beta$$

ここで、βはE_6の自発的な破れを定義する混合角です。この評価では、βの3つの値が使用され、**χモデル**（β=0）、**ψモデル**（β=π/2）、および**ηモデル**（$\beta = \pi - \arctan\sqrt{5/3}$）として参照される

- **Alternative Left-Right symmetric (ALRモデル)**: このモデルもE_6モデルから派生しており、新しい粒子Z'の性質を考えるためのものです。ただし、このモデルではZ'の性質が標準モデルのZ粒子とは少し異なると考えられている

quark flavor tagging

To evaluate the search for new physics, it is necessary to determine the cross-section for each flavor.

To do this, flavor tagging is performed, dividing events into b, c, q(u,d,s), and others.

After event selection

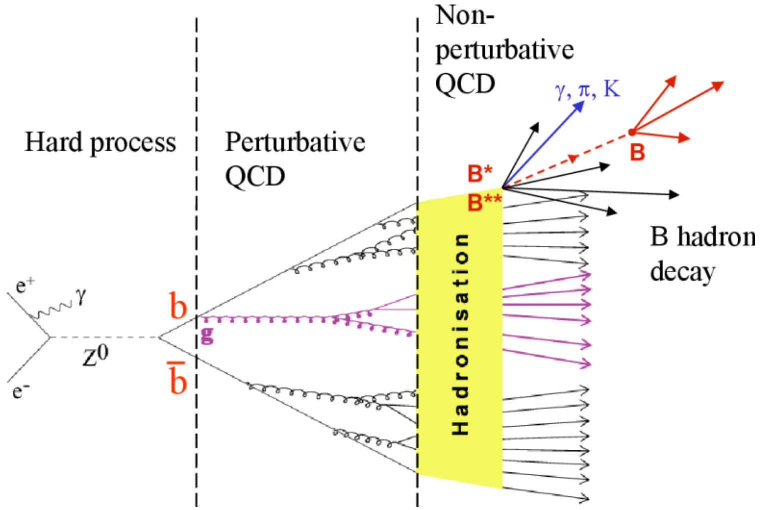
true flavor \ predicted flavor	q (u,d,s)	c	b	others
q (u,d,s)	**2,661,403**	83,956	36,887	34,311
c	266,296	**834,452**	89,949	10,348
b	13,535	21,423	**705,974**	5,104

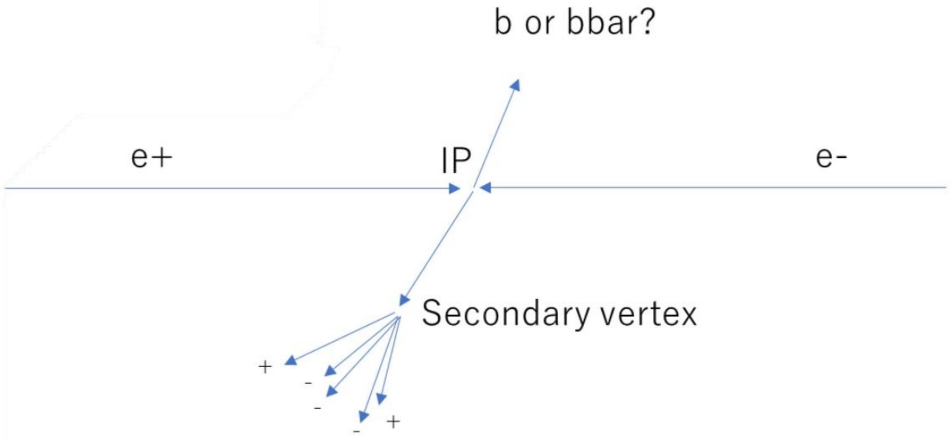
Flavor tagging is applied to the two reconstructed jets.

- **If the flavors of both jets match, that event is classified as the tagged quark.**
- **Events that do not match are classified as the quark with the higher score.**
- **Events where the tagging fails for both jets are classified as 'others'.**

Charge ID: Method for measuring jet charge

For reconstructed 2-jet events of quarks, we want to determine which one is q and which one is $\bar{q}$.
→ It's necessary to cross-reference the simulation data with the charge of particles within the jet to match them up.

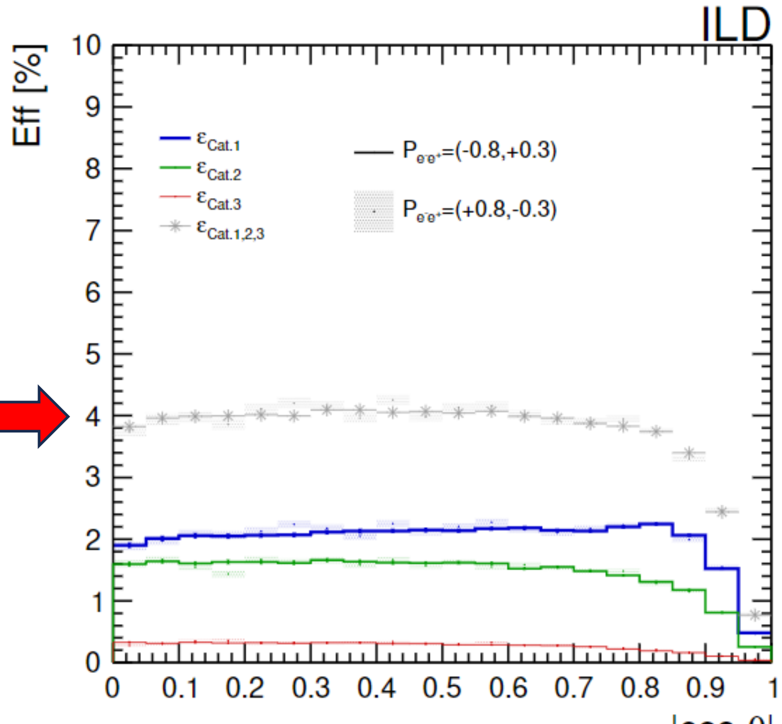




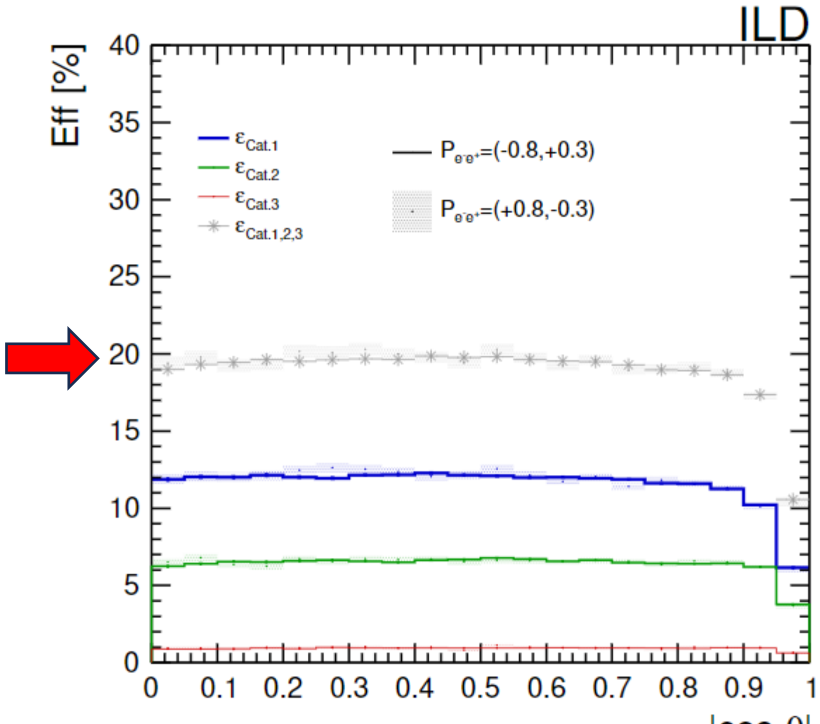
Method for measuring jet charge	vertex charge Vtx-method	$K^{\pm}$ charge K-method
Target charge	**the charge of the vertex**, defined as **the sum of the charges of all tracks in the secondary vertices in the jet.**	**the sum of all the identified $K^{\pm}$ reconstructed in secondary vertices inside the jet.**

reference.
ILD-PHYS-PUB-2023-001, June 2023,
"Experimental methods and prospects on the measurement of electroweak b and c-quark observables at the ILC operating at 250 GeV"

Charge ID: Method for measuring jet charge



$e^-e^+ \to c\bar{c}$



$e^-e^+ \to b\bar{b}$

- For $c\bar{c}$
  - Cat.1 ->K-method
  - Cat.2 ->Vtx-method
  - Cat.3 ->One jet used K-method and the other used Vtx-method

- For $b\bar{b}$
  - Cat.1 ->Vtx-method
  - Cat.2 ->K-method
  - Cat.3->One jet used Vtx-method and the other used K-method

This time, rather than evaluating whether charge ID could be done on an event-by-event basis, we used the efficiency from previous research.

reference.
ILD-PHYS-PUB-2023-001, June 2023

Efficiency($\mathbf{cos\theta}$)

- The number of signal events S_i for each $b\bar{b}$ and $c\bar{c}$ events is

$$S_i = cross\ section \times luminocity \times efficiecny$$

Efficiency depends on cosθ and is calculated, including the feasibility of Charge ID.

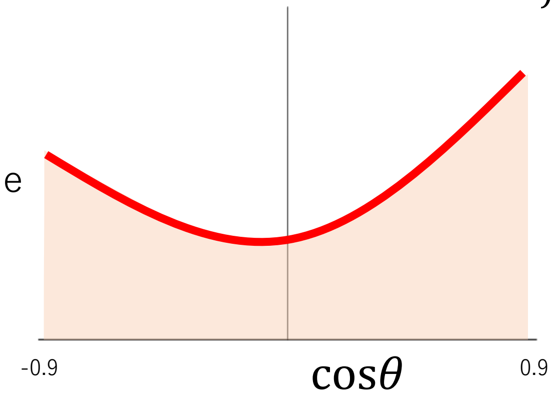
For $b\bar{b}$(The same applies for the $c\bar{c}$):

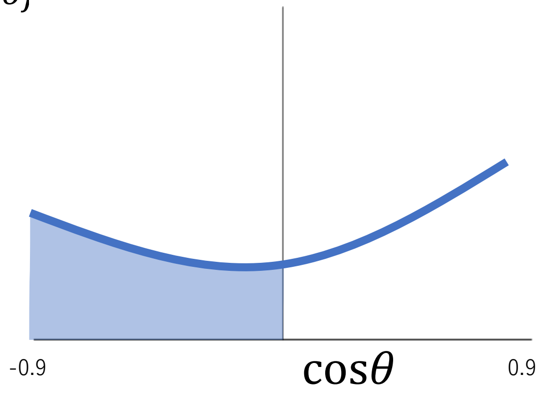
$$efficiency\_angle = \frac{\#\ of\ (true\ b\bar{b})\ w/\ eventcut}{\#\ of\ (true\ b\bar{b})\ w/o\ eventcut} \times \frac{\#\ of\ predicted\ b\bar{b}}{\#\ of\ predicted\ total} \times Charge\ ID\ efficiency$$

For events that were not identified by Charge ID, use the following equation for efficiency relative to the total cross section.

$$efficiency\_noChargeID = \frac{\#\ of\ (true\ b\bar{b}) w/\ eventcut}{\#\ of\ (true\ b\bar{b})\ w/o\ eventcut} \times \frac{\#\ of\ predicted\ b\bar{b}}{\#\ of\ predicted\ total} \times (1 - Charge\ ID\ efficiency)$$

In cases where Charge ID was not achieved, the total cross section for each polarization was used.





In cases where Charge ID was achieved, evaluations were made separately for costheta>0 and costheta<0.