

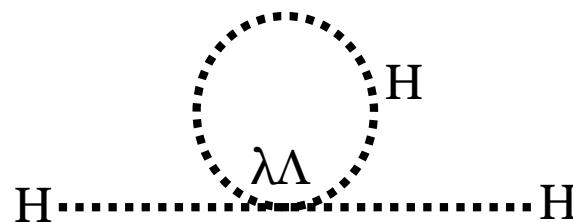
Measuring very light gravitino with stau NLSP at the ILC

Ryo Katayama^{*1}

T. Suehara^{*2}, T. Tanabe^{*2},
S. Yamashita^{*2}, S. Matsumoto^{*3},
T. Moroi^{*1}, K. Fujii^{*4}

*1: The University of Tokyo, *2: ICEPP
*3: Kavli IPMU, *4: KEK

Introduction



- Standard Model: Radiative correction due to the Higgs is too large to be natural (hierarchy problem)
example : at GUT scale , correction becomes $O(10^{19} \text{ GeV})$ for Higgs mass $O(10^2 \text{ GeV})$

→ Expected to be solved by constructing a new model

- Super symmetry model (SUSY): One of the most promising new models
- In case of gauge mediated SUSY breaking (GMSB), the gravitino appear as the lightest SUSY particle (LSP)
- GMSB doesn't have SUSY Flavor problem

Low Scale GMSB Model

< Cosmological Constraints >

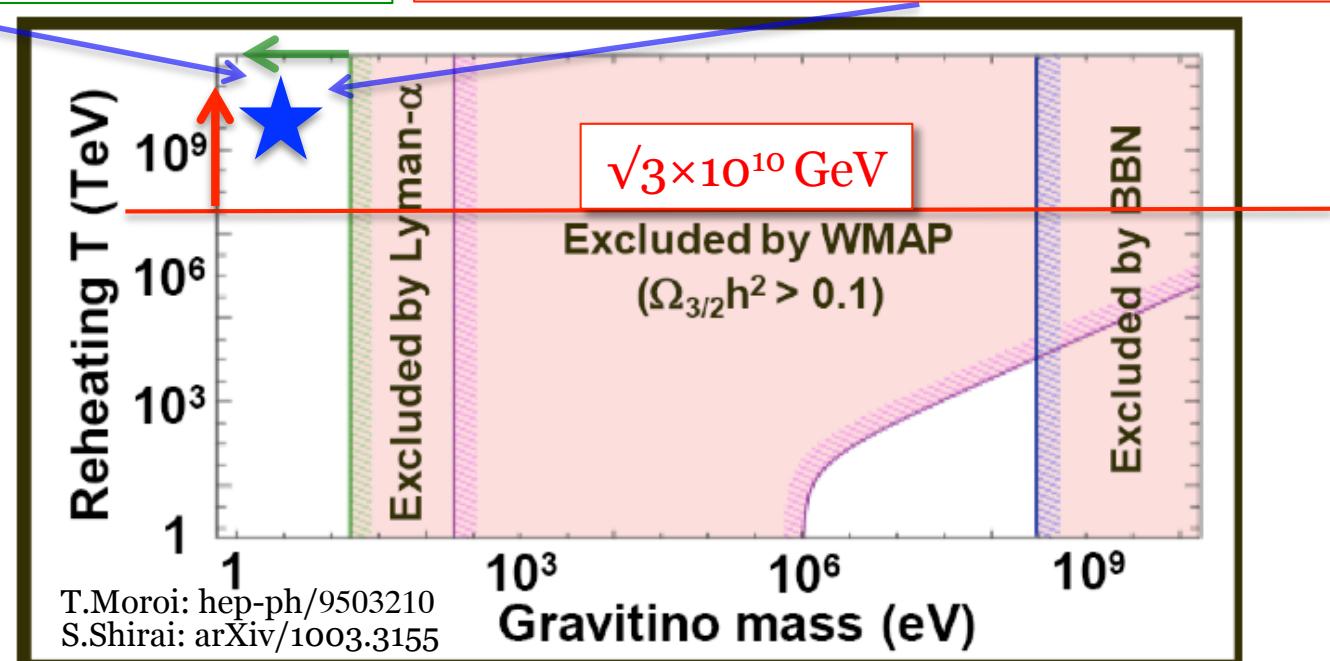
- Cosmological measurements constrain gravitino mass into two regions
- The constraint against reheating temperature doesn't exist for low scale GMSB which has $O(1 \text{ eV})$ Gravitino

< Thermal Leptogenesis >

- Baryogenesis is realized by assuming right handed neutrino was generated in the early universe and the sphaleron process which conserves $B - L$ (B : baryon number L : lepton number)
- Needs high reheating temperature to generate heavy right handed neutrino

The object of study is low scale GMSB which has very light Gravitino

*Low Scale GMSB can not be cold dark matter candidate because it is too light.
Expect its problem be solved by another model,
for example: axion and so on.



The Purpose and Significance of study

< Purpose >

- Low Scale GMSB is attractive because it can solve both hierarchy problem and baryon asymmetry problem
- In this study, we evaluate precision of gravitino mass determination at the ILC experiment

< Significance >

- High precision determination of gravitino mass
 - The mass of sparticles that appear in GMSB is a function of SUSY Breaking Scale
 - By combining results of other study, we can constrain the messenger mass

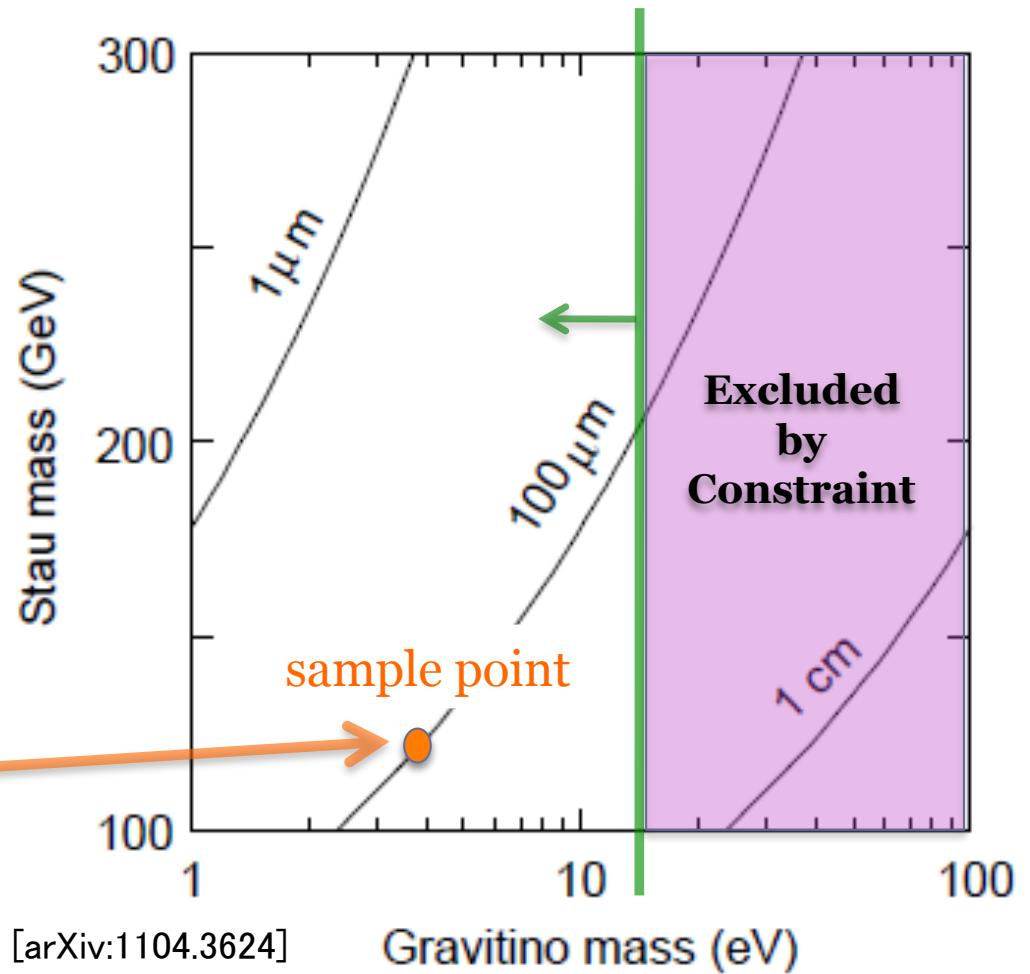
Stau NLSP properties in Low Scale GMSB

- Assume NLSP is the stau
 $\tilde{\tau} \rightarrow \tau \tilde{G}$
- Stau lifetime typically short

- Gravitino mass can be determined from the stau mass and lifetime:

$$\tau_{\tilde{\tau}} = 48\pi M_{pl} m_{\frac{3}{2}}^2 / m_{\tilde{\tau}}^5$$

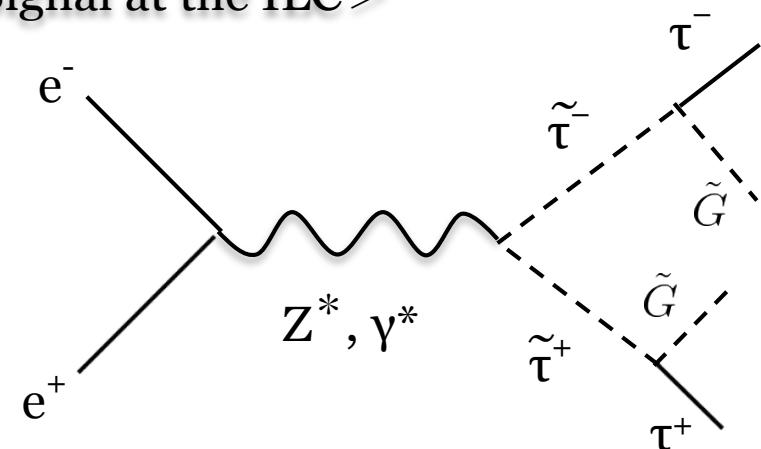
- In this study, we analyze the case of stau mass of 120 GeV and lifetime of 100 μ m



Stau pair event topology

- Decay lifetime of tau is $87\mu\text{m}$
→ Observe only the decay products
- Tau decay mode:
 - We limit to only the 1-prong mode in this study
 - Influence the stau lifetime determination method
- ✓ Indirect lifetime measurement from the impact parameter distribution
- ✓ Future plan:
we will include the 3-prong decay

<Signal at the ILC>



<Branching ratio of tau 1-prong decay>

- $\tau \rightarrow e\nu\bar{\nu}$ (17.82%)
- $\tau \rightarrow \mu\nu\bar{\nu}$ (17.39%)
- $\tau \rightarrow \pi\nu$ (10.91%)
- $\tau \rightarrow \pi\pi^0\nu$ (25.51%)
- $\tau \rightarrow \pi2\pi^0\nu$ (9.51%)

[PDG] 3 prong ratio (15.19%)

Analysis strategy

1. Determine the stau mass by using the following two methods
 - From the track energy distribution: $\sqrt{s} = 500 \text{ GeV}$
 - From the threshold scan : $\sqrt{s} \approx 250 \text{ GeV}$
2. Determine the stau lifetime by using below
 - From the impact parameter distribution: $\sqrt{s} = 500 \text{ GeV}$
3. Determine Gravitino mass precision by putting both stau mass and lifetime precision into the formula below

$$\frac{\Delta m_{\frac{3}{2}}}{m_{\frac{3}{2}}} = \sqrt{\left(\frac{5}{2} \frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}}\right)^2 + \left(\frac{1}{2} \frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}}\right)^2}$$

Simulation framework

- Event Generator
 - Signal : Physsim
 - Background : Whizard Ver.1.95
- Beam condition
 - Energy spectrum: include effects of Beamstrahlung
 - Beam polarization
 - Signal and background samples are generated with pure beam polarizations, then weighted to realistic polarizations
- Software tools
 - Mokka with ILD_00 for the detector simulation
 - LOI digitizer, tracking, PFA for event reconstruction

Signal and Background Processes

<Choice in this analysis>

- Signal: Only right handed stau
- Polarization: $(P_{e-}, P_{e+}) = (+0.8, -0.3)$
→ To suppress WW background

< Assumed E_{CM} and Luminosity >

	\sqrt{s} (GeV)	Luminosity (fb^{-1})
nominal analysis	500	500
threshold scan	250 ~ 261	100 /point

< Process and generated event number >

Process	Num event (nominal analysis)	Num event (threshold scan)
$[Signal] e^+ e^- \rightarrow \tilde{\tau}^+ \tilde{\tau}^-$	68078	969
$[\tau\tau - BG] e^+ e^- \rightarrow \tau^+ \tau^-$	634295	811753
$[WW - BG] e^+ e^- \rightarrow W^+ W^- \rightarrow l^+ l^- \nu \bar{\nu}$	207952	37081
$[ZZ - BG] e^+ e^- \rightarrow Z^0 Z^0 \rightarrow l^+ l^- \nu \bar{\nu}$		
$[\gamma\gamma BG] e^+ e^- \rightarrow e^+ e^- \gamma\gamma \rightarrow e^+ e^- l^+ l^- (q\bar{q})$	$\sim O(10^8)$	$3.5 * 10^9$
$[bhabha] e^+ e^- \rightarrow e^+ e^-$	$\sim O(10^9)$	/

Overview of event selection

< Main selection >

- Number of tracks = 2
- high P_T and energy
→ Suppress $\gamma\gamma$ background
- Tight cut on $|\cos(\theta)|$ → Suppress bhabha
- Acoplanarity cut → Suppress $\tau\tau$ background
- Analysis specific cut
 - ◆ $|do|/\sigma(do)$ (track energy, Threshold Scan)
 - ◆ require at least 1 hadron track (track energy, lifetime)

	Nominal analysis	Threshold Scan
Evis (GeV)	> 30	30 ~ 150
$ \cos(\theta) $	< 0.8	< 0.85
Acoplanarity	> -0.93	> -0.9

< Weighted event counts after all cuts > Signal Background

	stau-stau	$\tau\tau$	$\gamma\gamma$ BG, Bhabha	WW, ZZ -> l ₁ l ₂ v
Track energy fit (only 180 ~ 250 GeV)	219.5	1.1	0	6.1
Threshold scan (261 GeV)	467.5	49.7	20.0	211.8
Lifetime analysis	14565	563	1047	1859

Stau mass with track energy fit

Track Energy fit

The stau mass determines the maximum of the track energy

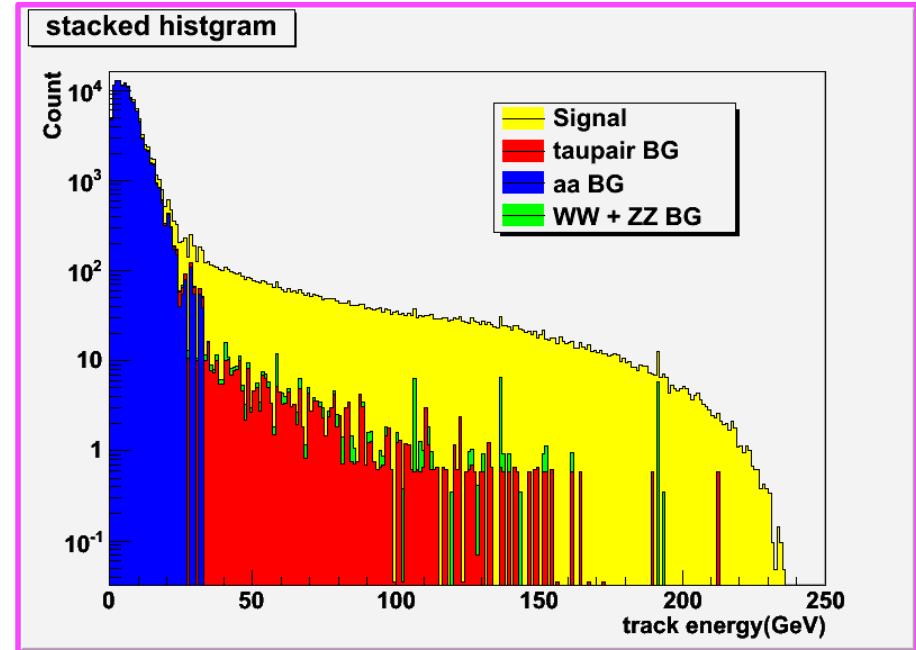
Procedure

- Acquire the edge of track energy distribution by the following fitting function (refer to right figure)

$$f(x) = \begin{cases} g(x) = \alpha(x - \beta) \exp(\gamma x) & (g(x) > 0) \\ 0 & (g(x) < 0) \end{cases}$$

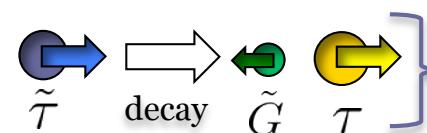
- Substitute the fitted value for the maximum energy in the kinematic formula (refer to right) to solve for the stau mass
- Repeat 1 – 2 above 10,000 times to evaluate expected precision of stau mass

$$\Rightarrow \frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 1.4 \%$$



$$E'_{\max} = \gamma_{\max} E + \sqrt{\gamma_{\max}^2 - 1} \sqrt{E^2 - m_{\tau}^2}$$

$$\gamma_{\max} = \frac{250(\text{GeV})}{m_{\tilde{\tau}}} \quad E = \frac{m_{\tilde{\tau}}^2 + m_{\tau}^2 - (m_{\frac{3}{2}})^2}{2m_{\tilde{\tau}}} \simeq 0$$



Tau energy is maximum when the stau and the tau are collinear

Stau mass with threshold scan

Threshold Scan

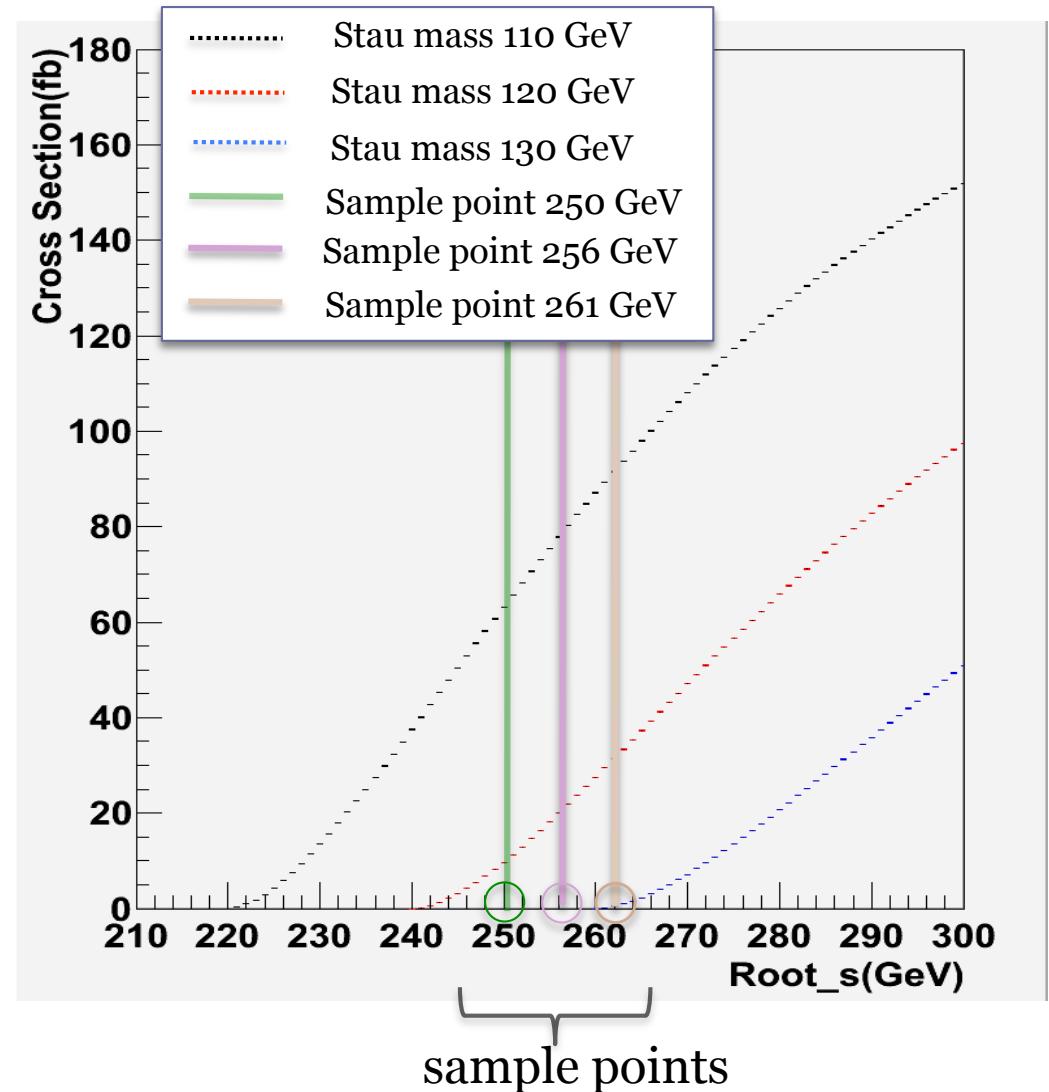
The stau mass can be also obtained from the rise of the cross section near the threshold

- Acquire the cross sections at several E_{CM} s to be compared with template samples of various stau masses

Procedure

1. Perform full simulation of signal samples at $\sqrt{s} = 250, 256, 261$ GeV and background samples at $\sqrt{s} = 250$ GeV, scaled to 256 and 261 GeV
2. Perform toy MC experiments on the signal yield to derive the cross sections considering S/N and cut efficiency

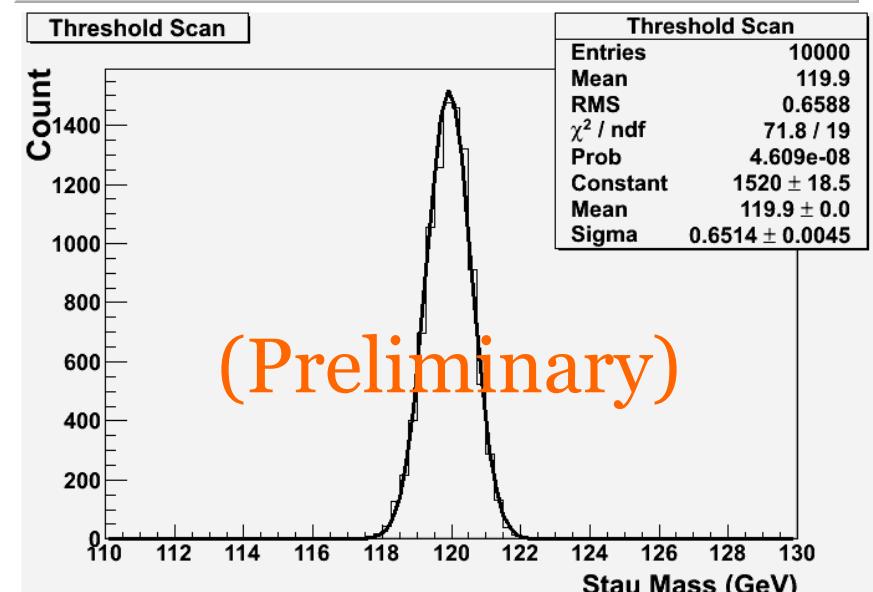
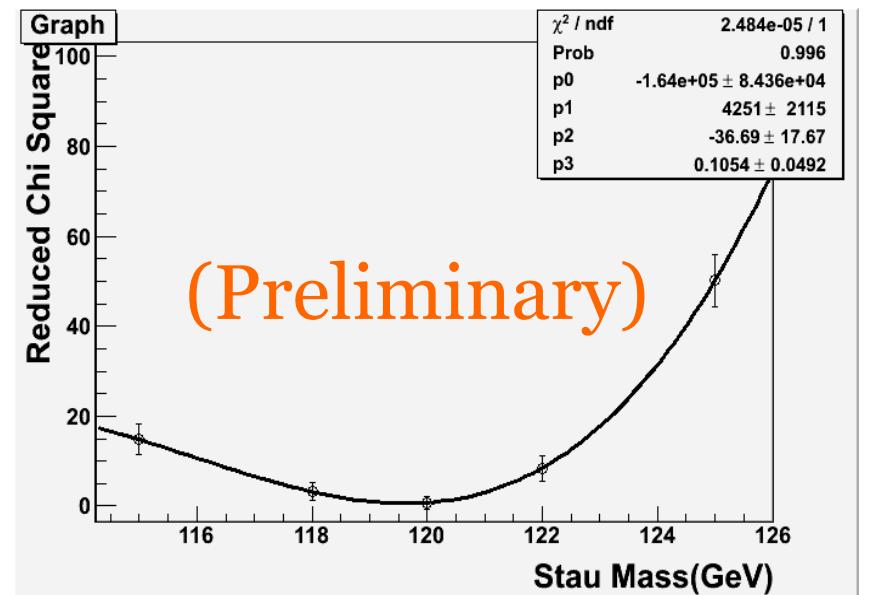
< The rise of the cross sections >



Stau mass with threshold scan

3. Compute the chi₂ against the expected cross section at five points (115 ,118 ,120 ,122, 125 GeV)
4. Compare the cross section with stau mass by fitting with a third polynomial function
→ Regard the chi₂ minimum as the measured stau mass
5. Repeat 2 – 4 above 10,000 times to evaluate the expected precision of stau mass

$$\rightarrow \boxed{\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 0.5\%}$$



Stau lifetime determination

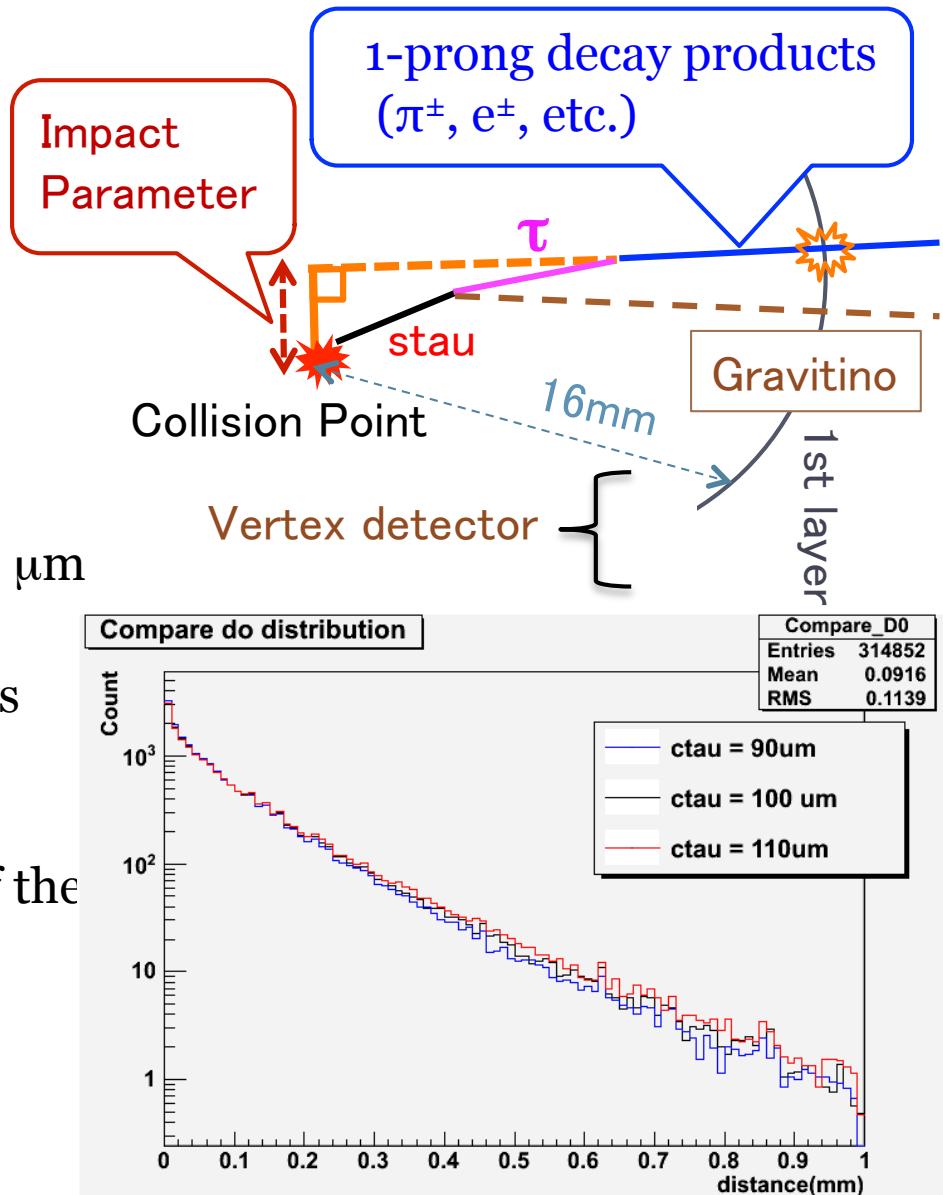
Impact parameter

- Impact parameter distribution is sensitive to the stau lifetime
- ⇒ Use the d_o component because its uncertain is small

Procedure

1. Perform toy MC experiments to compare d_o distribution against the template samples at $c\tau = 90, 100, 110 \mu\text{m}$
2. Fit the chi₂ at the three points by a parabola and regard the minimum as lifetime
3. Repeat 1 – 2 above 10,000 times to evaluate the expected precision of the stau lifetime

$$\Rightarrow \frac{\Delta\tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \simeq 2.1\%$$



Determination of the gravitino mass

- Substitute stau lifetime and mass precision into gravitino mass formula, we get the following result

$$\frac{\Delta m_{\frac{3}{2}}}{m_{\frac{3}{2}}} = \sqrt{\left(\frac{5}{2} \frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}}\right)^2 + \left(\frac{1}{2} \frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}}\right)^2}$$

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 1.4\% \text{ (track energy)}$$

$$\frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \simeq 2.1\%$$

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 0.5\% \text{ (threshold scan)}$$

$$\frac{\Delta m_{\frac{3}{2}}}{m_{\frac{3}{2}}} \simeq 4\% \text{ (track energy + lifetime)}$$

$$\frac{\Delta m_{\frac{3}{2}}}{m_{\frac{3}{2}}} \simeq 2\% \text{ (threshold scan + lifetime)}$$

- Reminder: Prefactors $5/2$ and $1/2$ come from the power in the gravitino mass formula

Summary

- Assuming Low Scale GMSB and stau NLSP with 120 GeV mass and $c\tau = 100 \mu\text{m}$ lifetime, we obtain the following results

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 1.4\%$$

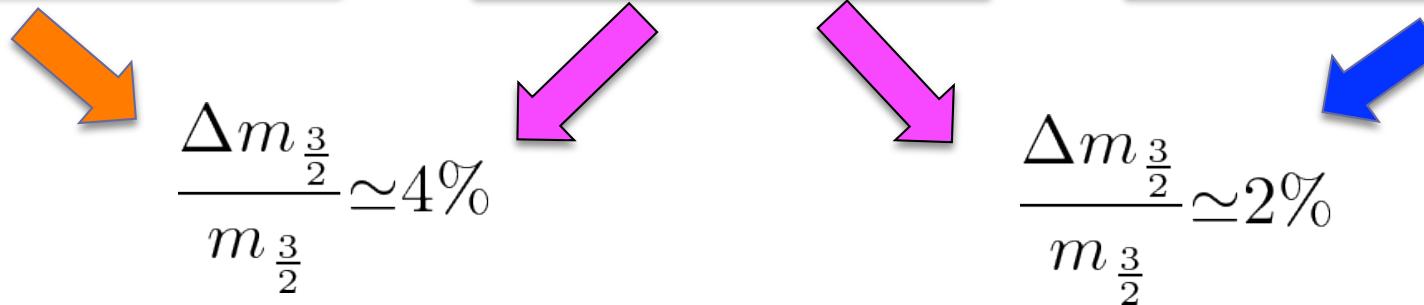
(track energy)

$$\frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \simeq 2.1\%$$

(lifetime result)

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 0.5\%$$

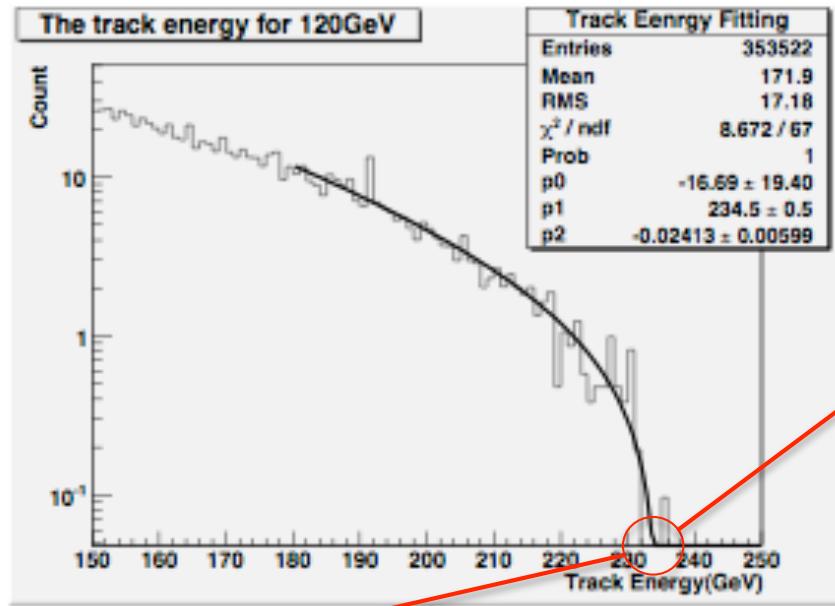
(threshold scan)



- The lifetime precision should be evaluated including three prong tau decays in the future

Back Up

stauの質量決定法



1. 実験結果のtrack energy分布のedgeを以下のFitting関数で取得(左上図参照)

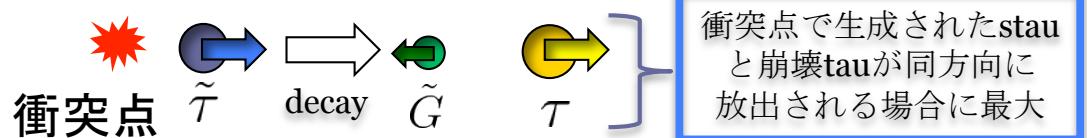
$$f(x) = \begin{cases} g(x) = \alpha(x - \beta) \exp(\gamma x) & (g(x) > 0) \\ 0 & (g(x) < 0) \end{cases}$$

2. 1の値をstauから崩壊するtauの持つ最大エネルギーの解析式へ代入し([左式参照](#))、stau質量の解を持つ関数を作る

$$E'_{\max} = (250(\text{GeV})/m_{\tilde{\tau}})E + \sqrt{(250(\text{GeV})/m_{\tilde{\tau}})^2 - 1}\sqrt{E^2 - m_{\tau}^2}$$

$$\gamma_{\max} = 250(\text{GeV})/m_{\tilde{\tau}}$$

$$E = \frac{m_{\tilde{\tau}}^2 + m_{\tau}^2 - \left(m_{\frac{3}{2}}\right)^2}{2m_{\tilde{\tau}}} \simeq 0$$

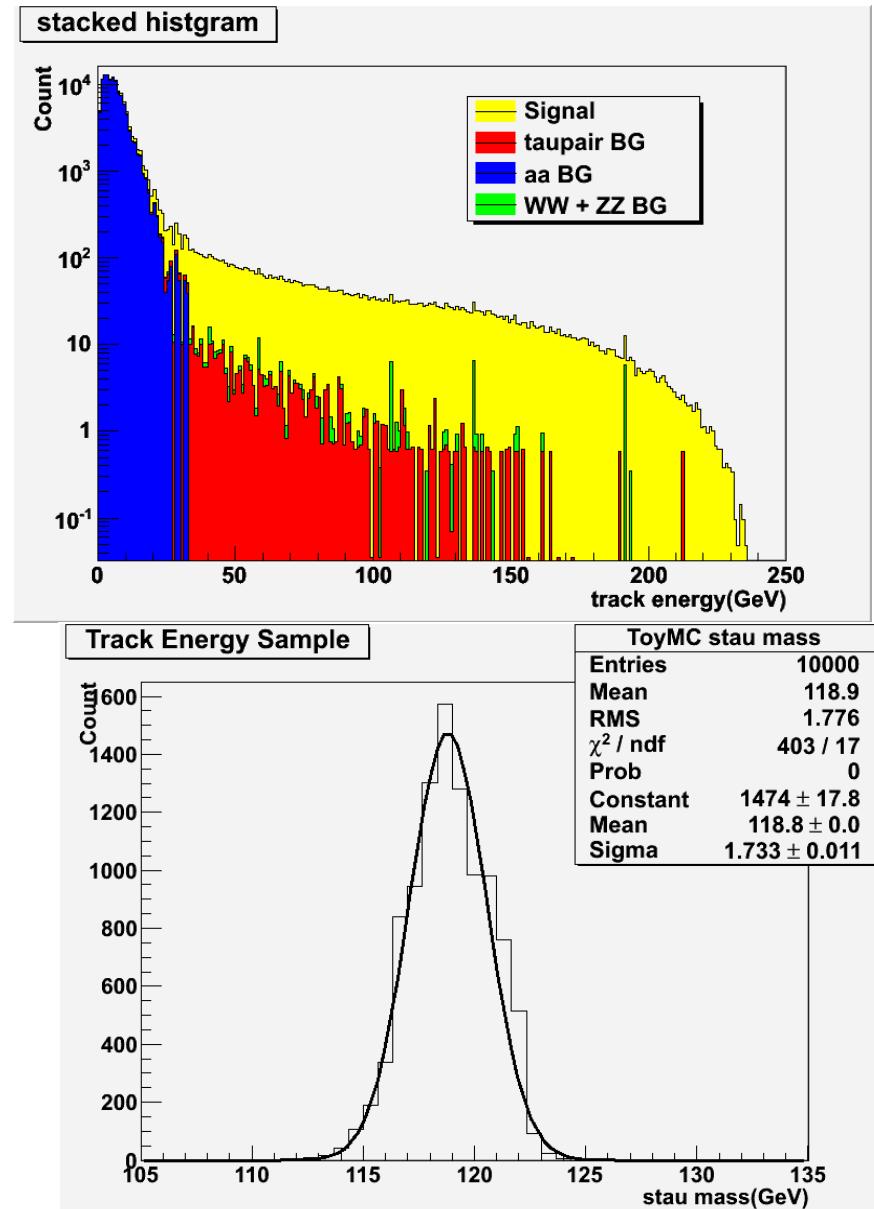


3. 2で得られた関数の解を数値計算で求める

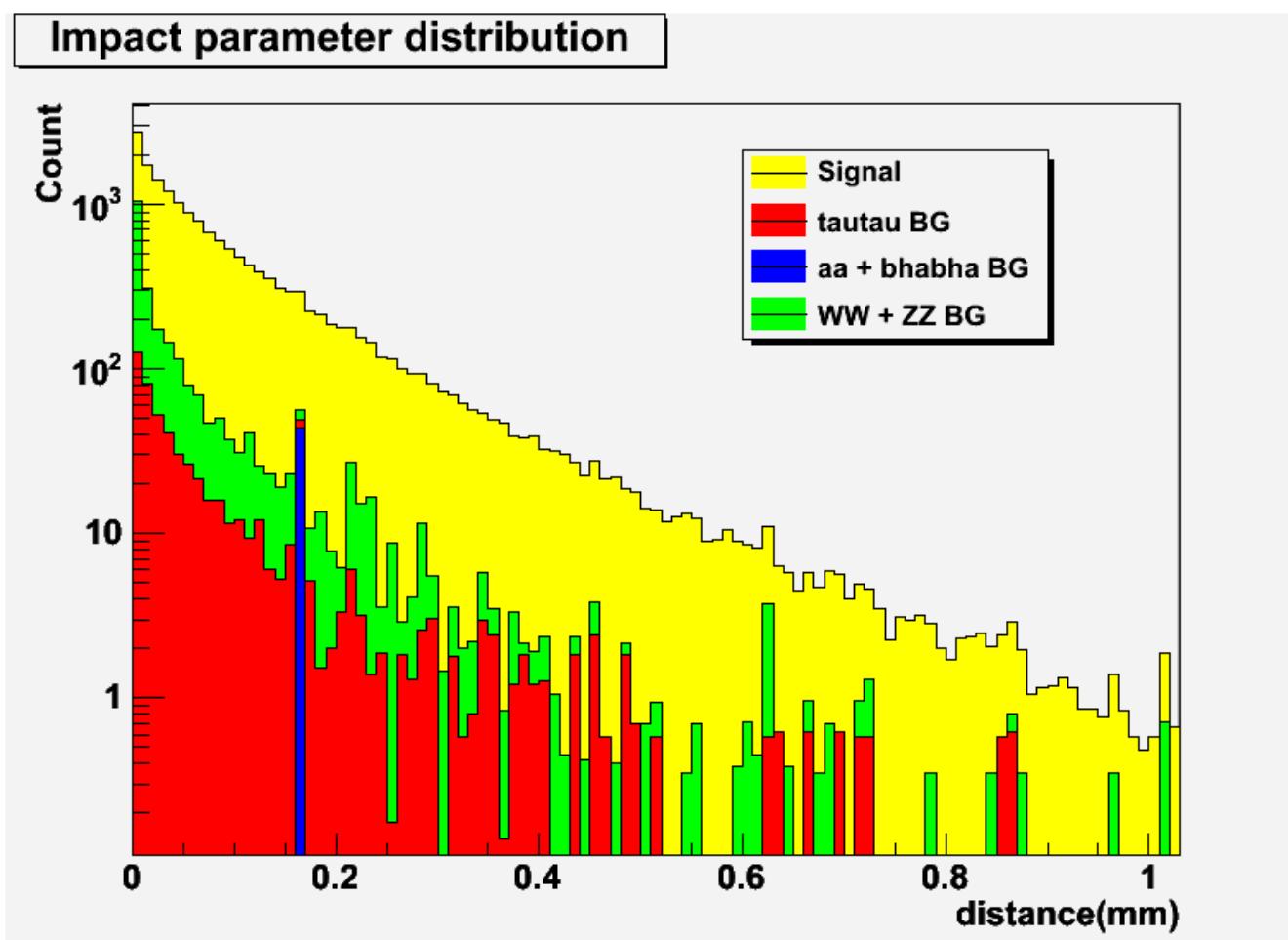
stau質量決定精度の評価

- signalの高統計サンプルを使って作った実験結果のtrack energy分布から、各BinをPoisson統計で振った『1実験』を生成(Toy MC)
- Toy MCでmass fitを1万回試行し、得られた結果の分布を用いてmass決定の誤差を見積もり以下の値を得た

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} \simeq 1.4 \%$$



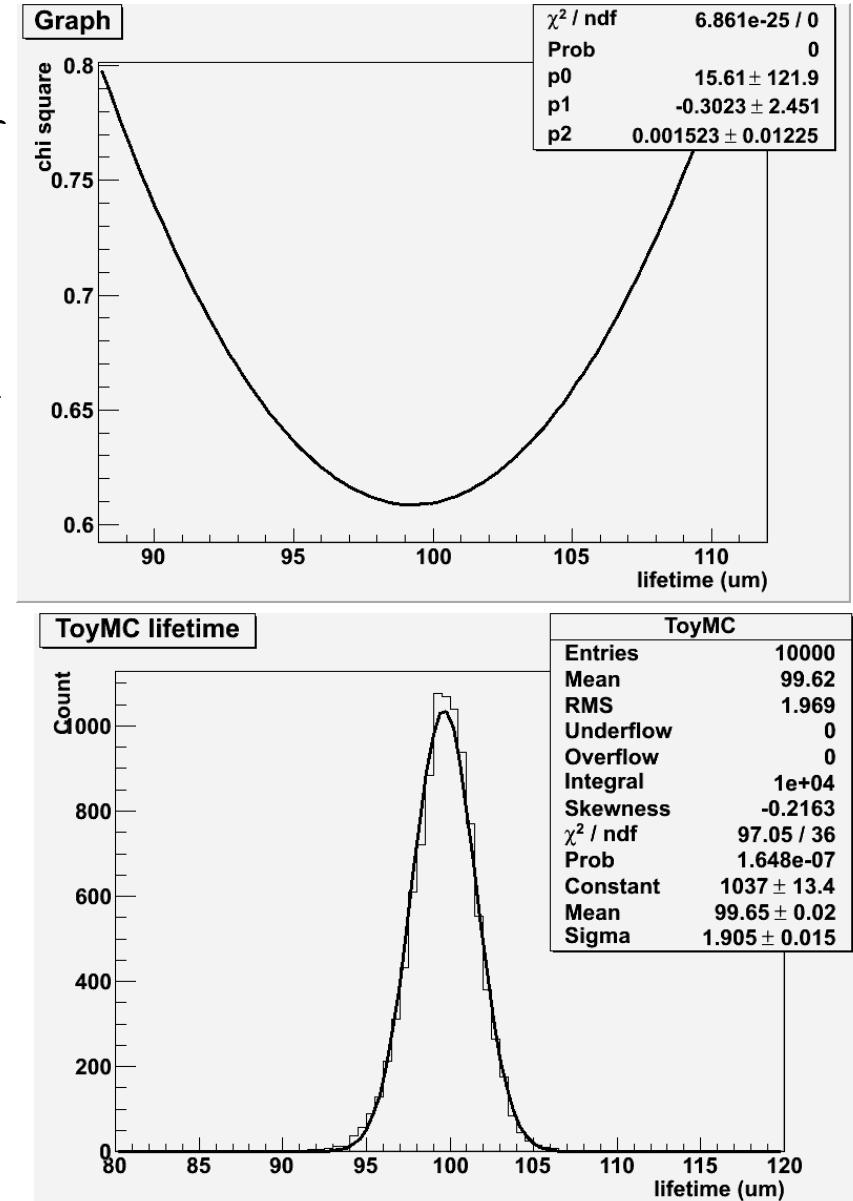
The signal and noise ratio for lifetime analysis



stauの崩壊寿命の決定精度の評価 1

- $c\tau = 90 \mu\text{m}, 100 \mu\text{m}, 110 \mu\text{m}$ の高統計テンプレートサンプルと Signal の高統計サンプルを使って作った do 分布から、各 Bin を Poisson 統計で振った『1実験』を各々用意する
- Toy MC 試行と各テンプレートとの reduced χ^2 を縦軸に、テンプレートの崩壊寿命 $c\tau$ を横軸に取る
- χ^2 の $(\text{Error})^2$ をテンプレートの統計の総和と実験結果の統計の総和の二乗の平方和で定義する
- 上記 reduced χ^2 の三点を放物線でフィットする
- Toy MC で放物線フィットを 1 万回試行し、得られた最小値の分布を用いて寿命決定の誤差を見積もり以下の値を得た

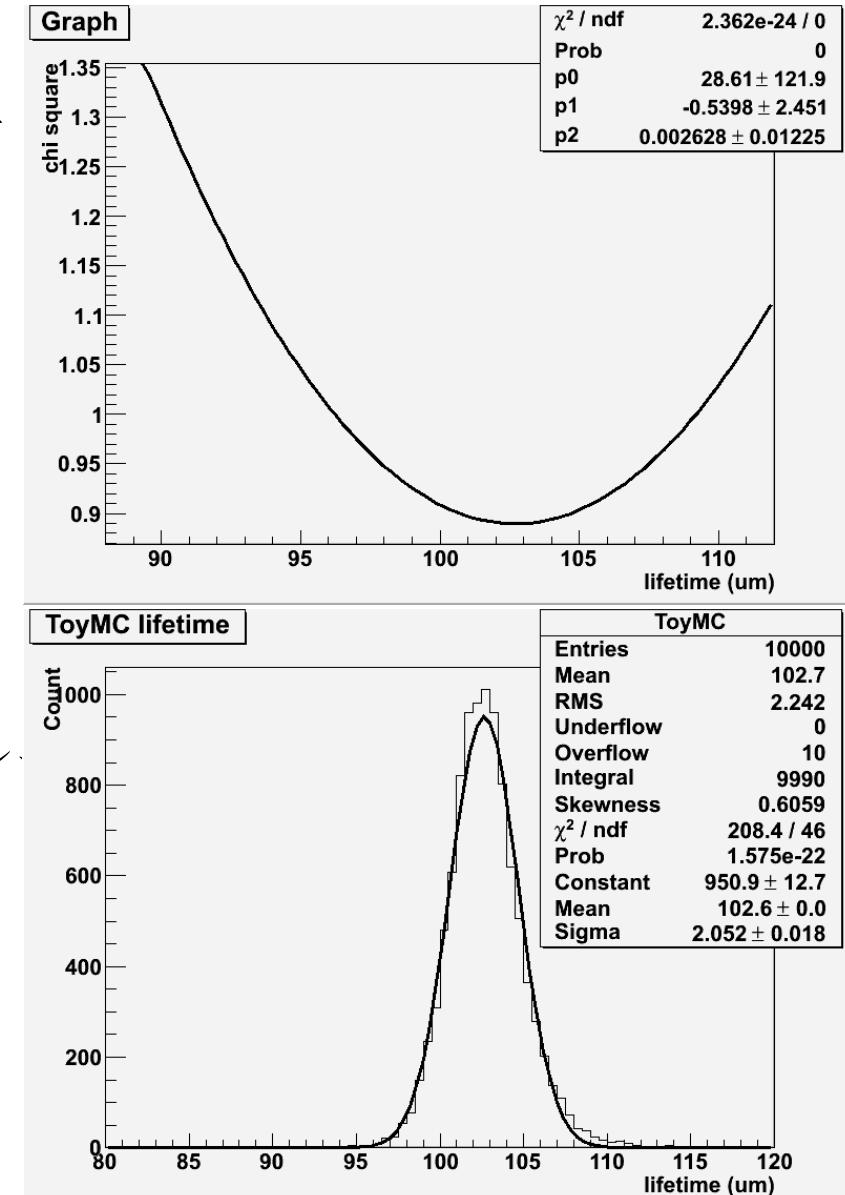
$$\frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \simeq 1.9\%$$



stauの崩壊寿命の決定精度の評価 2

- $c\tau = 90 \mu\text{m}, 100 \mu\text{m}, 110 \mu\text{m}$ の高統計テンプレートサンプルと Signal の高統計サンプルを使って作った do 分布から、各 Bin を Poisson 統計で振った『1実験』を各々用意する
- Toy MC 試行と各テンプレートとの reduced χ^2 を縦軸に、テンプレートの崩壊寿命 $c\tau$ を横軸に取る
- χ^2 の $(\text{Error})^2$ をテンプレートの統計の総和で定義する
- 上記 reduced χ^2 の三点を放物線でフィットする
- Toy MC で放物線フィットを 1 万回試行し、得られた最小値の分布を用いて寿命決定の誤差を見積もり以下の値を得た

$$\frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \simeq 2.1\%$$



GMSB模型検証とgravitino質量の関係

$$\mathcal{L}_{MSSM} \longleftrightarrow \mathcal{L}_{mess} \longleftrightarrow W_{SUSY}$$

- 見える超対称性粒子がメッセンジャー粒子のゲージ相互作用を介して超対称性ポテンシャルと相互作用し、超対称性の破れが伝わる模型
- メッセンジャースケールで超対称性粒子の質量が決まり、ほかのエネルギー階級へは繰り込み群方程式を発展させて決める
- 超対称性粒子の質量はメッセンジャースケールで以下である。

$$M_i = \left(\frac{\alpha_i}{4\pi}\right) \Lambda_G \quad m_f^2 = 2 \sum_r C_r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_s \quad m_{3/2} = \frac{F}{\sqrt{3} M_{pl}}$$

$$\Lambda_G = \frac{NF}{M_{mess} C_{grav}} \quad \Lambda_s = N \left(\frac{F}{M_{mess} C_{grav}} \right)^2 \quad C_r = \frac{4}{3} \text{ or } \frac{3}{4} \text{ or } 0 \text{ or } \frac{5}{4} Y^2$$

M_i : ゲージーノ質量 m_f : sfermion質量 $m_{3/2}$: gravitino質量

参考文献(1,(2,(3

N : メッセンジャー粒子の数 M_{mess} : メッセンジャースケール C_{grav} : 無次元定数

F : SUSY Breaking のスケール M_{pl} : プランク質量 = 2.44×10^{18} (GeV)

- GMSBモデルはパラメータ Λ 、 M_{mess} 、 N 、 C_{grav} で構築され、決定に gravitino質量取得によるSUSY Breakingのスケール F が必要

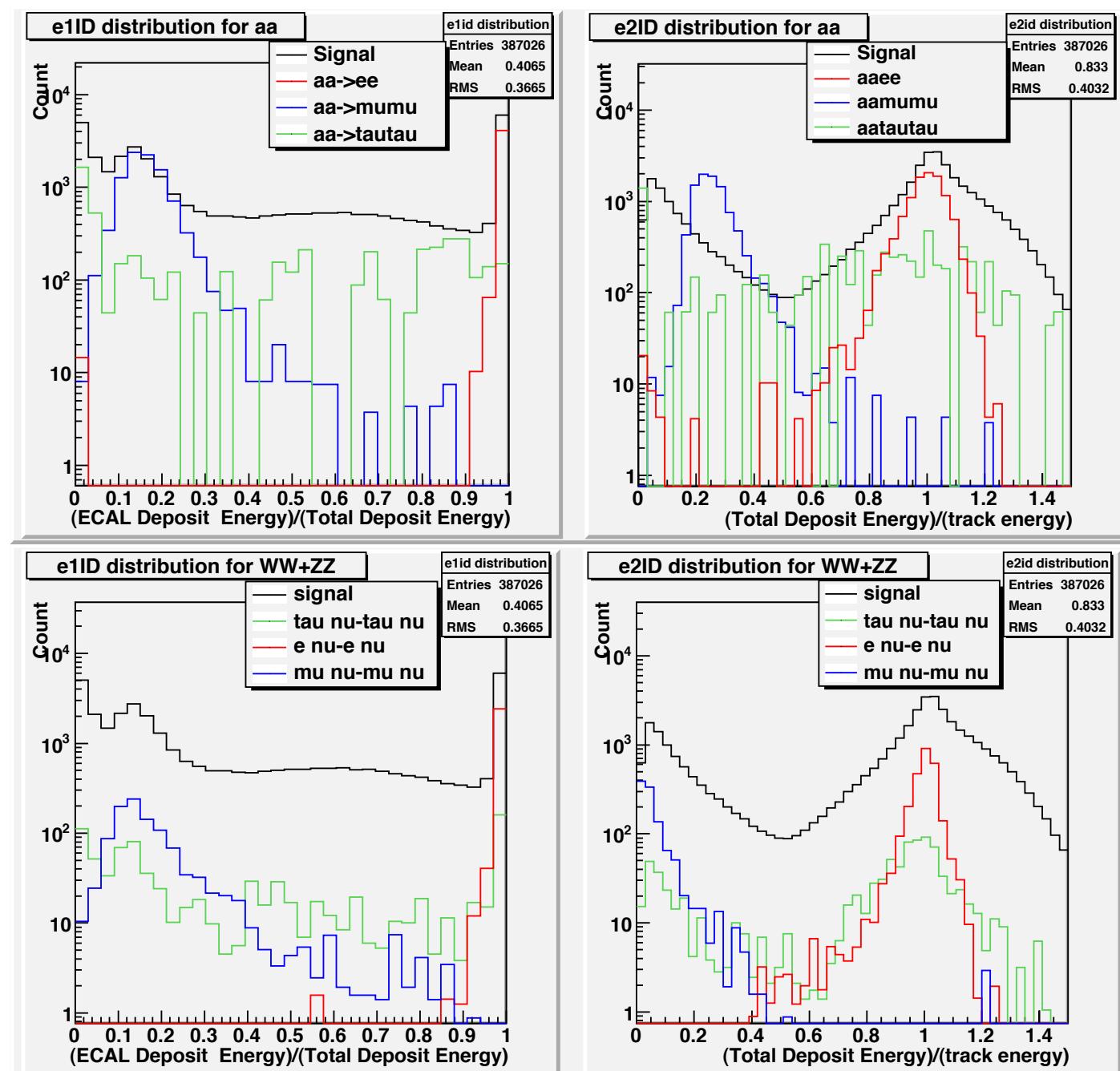


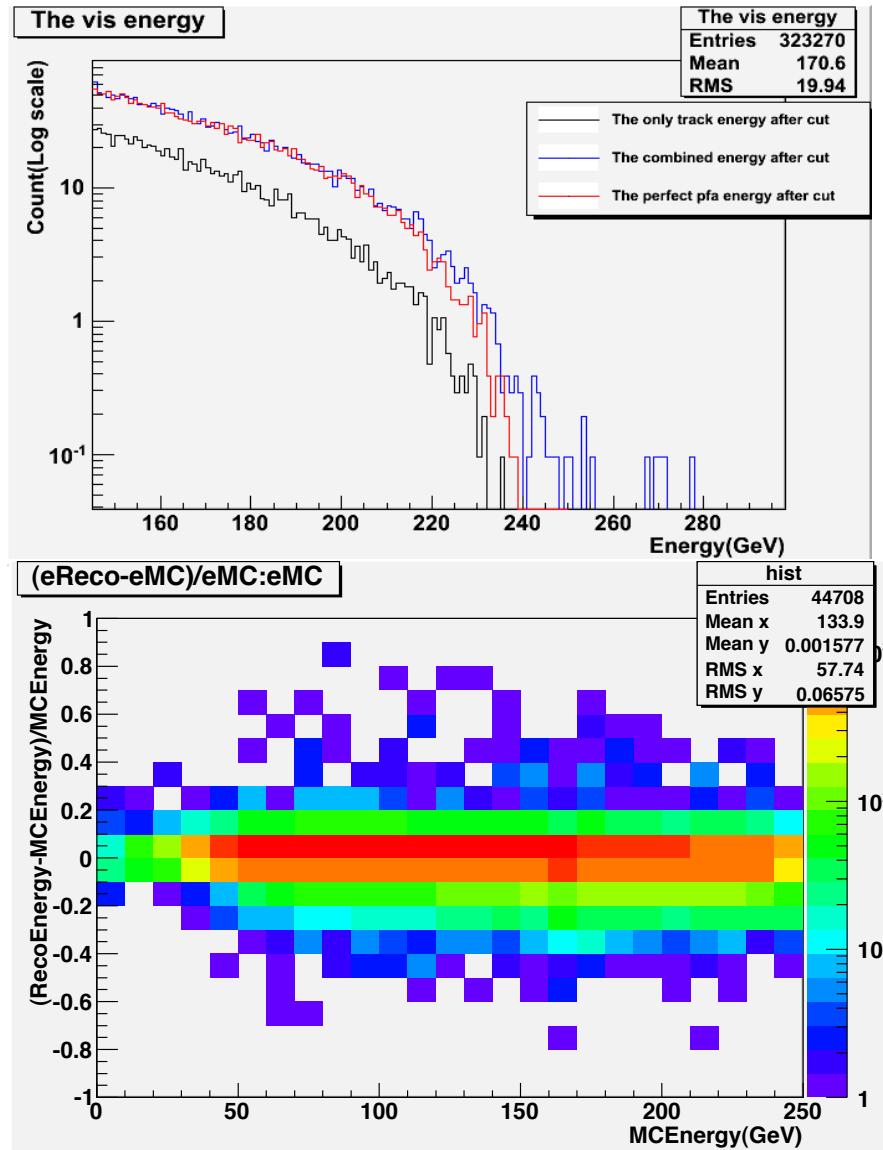
gravitino質量の取得精度はGMSB模型検証の根幹に関わる問題であり、高精度決定を目指す

前項の参考文献

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京都大学基礎物理学研究所
- 2) 高エネルギー物理学の発展 (著)長島順清(版)
朝倉書店
- 3) **Study of GMSB models with photon final states using the ATLAS detector**
[http://www-atlas.desy.de/theses/
Terwort_phd.pdf](http://www-atlas.desy.de/theses/Terwort_phd.pdf)

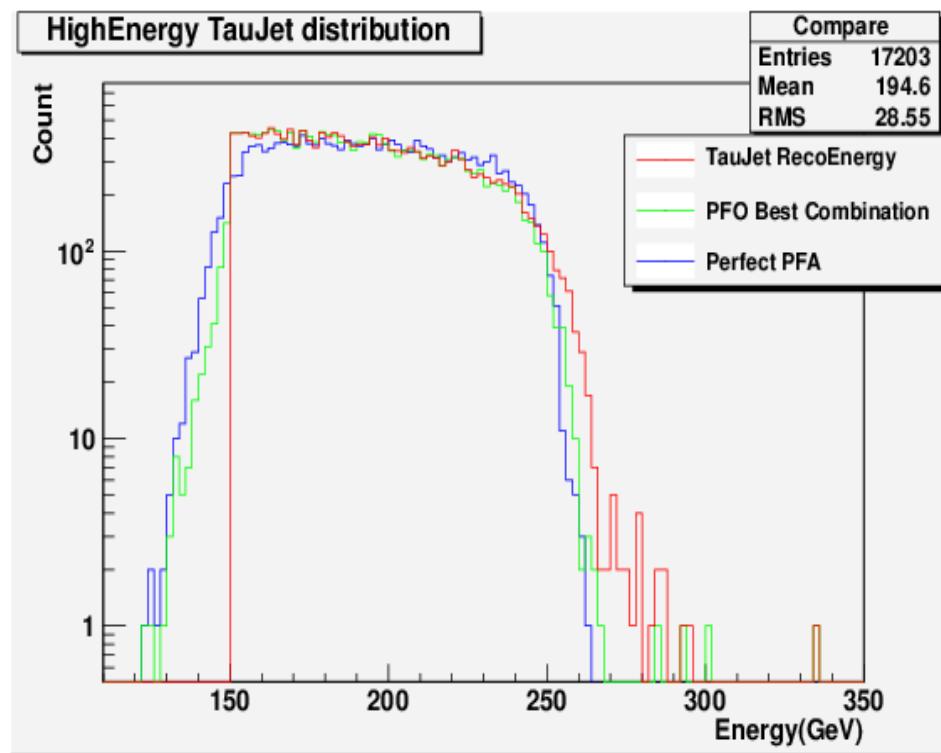
Lepton id distribution





- stau質量決定にtrack + neutral energyを用いればedge付近の統計が増大し結果も更に改善
 - 現在の再構成アルゴリズムには edgeにexcessが存在しFittingが不可能
高エネルギーTau Jetに対する PFAの失敗が疑われる
- ⇒ 重心系エネルギー500GeVで $e^+e^- \rightarrow \tau^+\tau^-$ を用いて以下を解析
 - $\tau^- \rightarrow \nu + \pi^- + \pi^0$
 - $\tau^- \rightarrow \nu + \pi^- + 2\pi^0$
- ⇒ エネルギー分解能が悪い結果は正負同程度存在
- 本研究では負の場合の補正に成功した

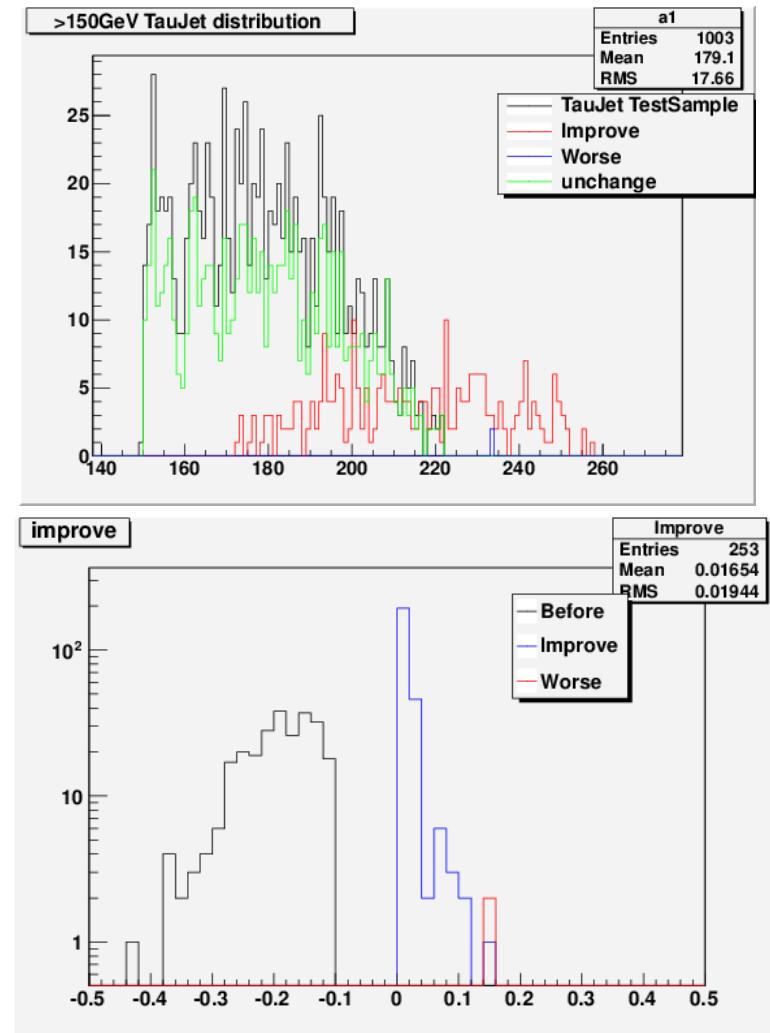
クラスター組み替えの試行



- 仮説: クラスターの組み間違え
 - エネルギー分解能の悪いイベントをEvent displayで確認した
- MCでの確認
 - MCの情報を見ながら、中性HCAL Clusterと荷電ECAL Clusterを組み替え、
 - 1.精度が改善した場合はそれを採用
 - 2.精度が悪化した場合はそれを採用しない
 - として新分布を生成
 - 結果はほぼ全てのexcessが消滅
 - 仮説を示唆する結果

PFAの改善

以下のprocedureで150GeV以上のtau jetのPFAの改善を確認した



1. trackで測ったエネルギーより荷電パイオンクラスターのエネルギーが**20%**以上大きいものを選び出す
2. フォトンクラスターのエネルギーより荷電パイオンクラスターのエネルギーが**40%**以上あるイベントを選び出す
3. 1,2を満たす場合に、ECALにあるエネルギー全てを $\text{pi}0 \rightarrow 2\gamma$ の寄与と見なし、不変質量を組んで、真の値 $m \sim 770\text{MeV}$ と 1GeV 以内のイベントを選ぶ
4. 3を満たすイベントに対しては ECAL全てのエネルギーをフォトンクラスターの寄与と見なしてエネルギー再構成を行う

結果、150GeV以上のTau Jetで Reco EnergyがMC Truthより-10%より悪い サンプル数1003のうち、253のイベントを改善できた

Cut table(lifftime analysis)

	stau-stau	$\tau\tau$	$\gamma\gamma \rightarrow ll, qq$	WW, ZZ $\rightarrow l\bar{l}l\bar{l}$
No cut	68078	634295	$4.6 \times 10^{+07}$	207952
Track数=2	45636	307758	$2.1 \times 10^{+07}$	96712
$p_T > 5$ GeV for each track	38698	271367	$1.1 \times 10^{+07}$	89460
$ \cos \theta_{\text{miss}} < 0.9$	35685	152974	$3.3 \times 10^{+06}$	50282
$E_{\text{vis}} > 30$ GeV	34824	152698	$1.0 \times 10^{+06}$	50146
$ \cos \theta < 0.8$ for each track	28606	118889	747386	18664
Acoplanarity > -0.93	18661	12151	566519	10716
$\theta_{12} / E_{\text{vis}} > 3.0/400$	18049	814	21799	6777

注) $\gamma\gamma \rightarrow ll, qq$ はPreselection後のイベント数

最終サンプル(lifetime analysis)

	stau-stau	$\tau\tau$	$\gamma\gamma \rightarrow ll$ +bhabha	WW, ZZ $\rightarrow l\bar{l}l\bar{l}$
前ページCut + Lepton ID CUT (stau lifetime 解析用)	14565	563	1047	1859

- Lepton ID Cut : 以下のelectron id Cutと muon id Cutを少なくとも一本のトラックが満たす事を要求
 - electron id cut:
 - ECAL deposit energy/Total deposit energy < 0.92
 - muon id cut:
 - Total deposit energy/Track energy > 0.5

Cut table(track energy)

	stau-stau	$\tau\tau$	$\gamma\gamma \rightarrow ll, qq$	WW, ZZ $\rightarrow l\bar{l}l\bar{l}$
No cut	68078	634295	$4.6 \times 10^{+07}$	207952
Track数=2	45636	307758	$2.11 \times 10^{+07}$	96712
$p_T > 5$ GeV for each track	38698	271367	$1.1 \times 10^{+07}$	89460
$E_{vis} > 30$ GeV	37800	270948	$6.4 \times 10^{+06}$	89316
$ \cos \theta < 0.8$ for each track	30036	129937	$4.5 \times 10^{+06}$	25118
Acoplanarity > -0.93	18856	13243	$2.9 \times 10^{+06}$	11423
$\theta_{12} / E_{vis} > 3.0/500$	18506	2172	$1.3 \times 10^{+06}$	8613
$ do /\sigma(do) > 1$ for each track	17537	1538	382615	1319

注) $\gamma\gamma \rightarrow ll, qq$ はPreselection後のイベント数

最終サンプル(track energy)

	stau-stau	$\tau\tau$	$\gamma\gamma \rightarrow ll$ +bhabha	WW, ZZ $\rightarrow l\bar{l}l\bar{l}\nu\nu$
前ページCut + Strong Lepton ID CUT (track fit解析用)	8301	829	78473	166

- Lepton ID Cut : 以下のelectron id Cutとmuon id Cutを少なくとも一本のトラックが満たす
 - electron id cut:
 - ECAL deposit energy/Total deposit energy<0.92
 - muon id cut:
 - Total deposit energy/Track energy>0.5
- Strong Lepton ID Cut : 以下のstrong electron id Cutとstrong muon id Cutを一本のトラックが満たす
 - electron id cut:
 - ECAL deposit energy/Total deposit energy<0.95
 - muon id cut:
 - Total deposit energy/Track energy>0.2

Cut Table for Threshold Scan (Preliminary)

	Signal-1 (250 GeV)	Signal-2 (256 GeV)	Signal-3 (261 GeV)	ee->ττ	γγ->l,l,qq eγ->l,l,qq	WW,ZZ ->v l l v
Before cut	969.6	1995.0	2943.7	811753	3.5*10+09	37081.6
track = 2	640.9	1342.3	1935.9	417522	1.8*10+09	27236.9
Pt > 5 GeV for each track	511.1	1078.5	1545.1	325647	9.5*10+07	24362.6
cos θ _{miss} < 0.8	410.5	872.0	1245.0	109289	2.0*10+06	16659.5
30 < E _{vis} < 150 (GeV)	392.4	834.0	1180.3	70297.5	321686.0	11505.6
cos θ < 0.85 for each track	328.1	689.9	991.3	62562.5	246379.0	8074.9
Acoplanarity > -0.9	287.6	614.2	874.1	2100	6147.3	6265.9
d ₀ /σ(d ₀) > 3.5	194.2	432.1	626.8	1003	183.1	319.3
Final cut	150.5	314.6	467.5	49.7	20.0	211.8

Final Cut = (Missing mass)² / |cos θ_{miss}| > 300e3 GeV²