Stau NLSP Pair Production @ ILC 500GeV

Takuaki Mori, Ryo Katayama, Tomohiko Tanabe,
Satoru Yamashita (The University of Tokyo),
Sho Iwamoto, Norimi Yokozaki, Shigeki Matsumoto (Kavli IPMU),
Taikan Suehara (Kyushu University),
Keisuke Fujii (KEK)

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  - Constraints of mass & lifetime
  - Physics motivation of Stau pair production
- Analysis
  - Event selection
  - Cut variables in detail
- Results
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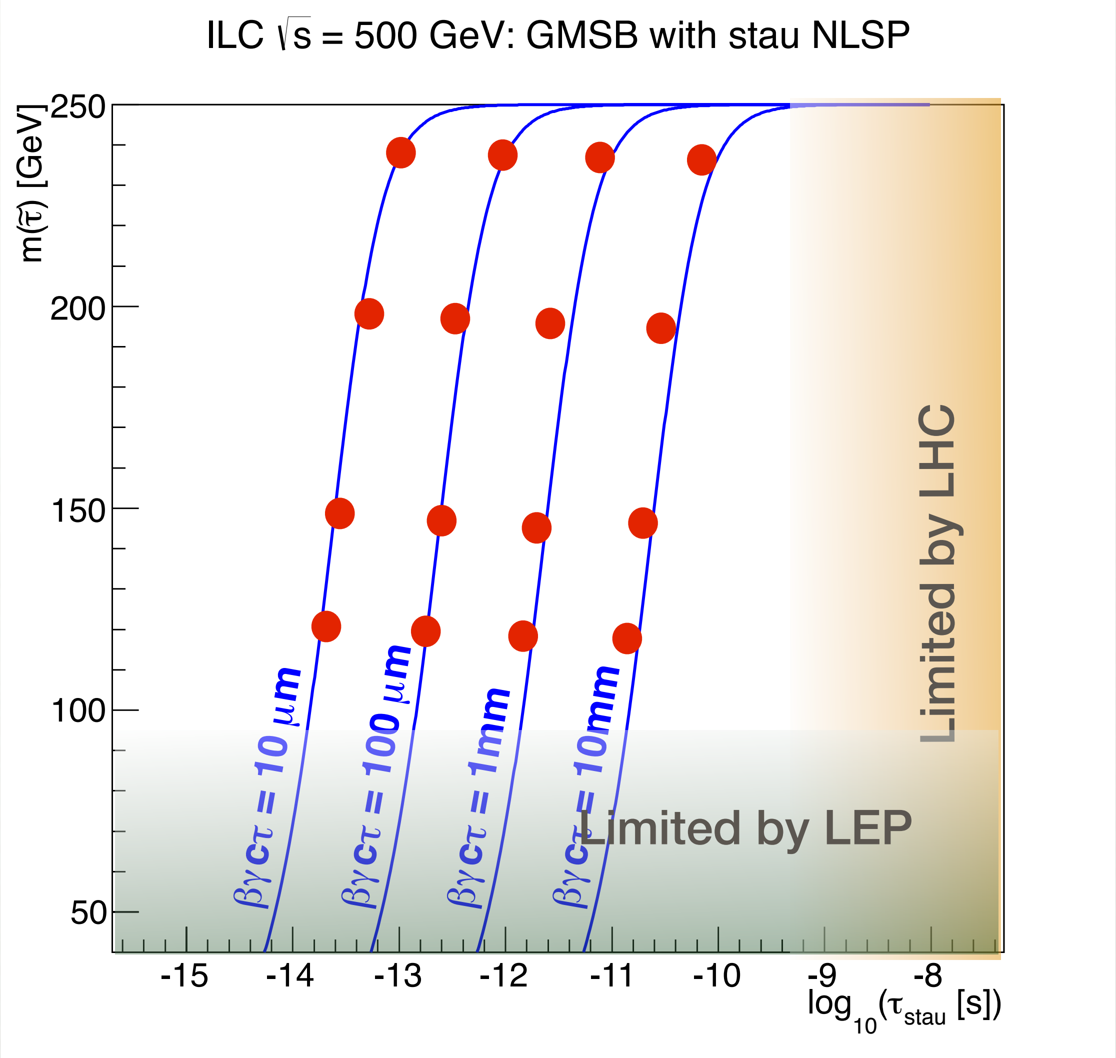
stau lifetime&mass

- **Lifetime upper limit @LHC**
  Squark , Gluino > 1TeV
  Stable stau < 360GeV is excluded
  -> Stau decays promptly

- **Mass lower limit @ LEP**
  stau < 90 GeV is excluded

Benchmark point

- Mass 120GeV~240GeV
- Lifetime 10μm~10mm



Supersymmetry Breaking

No Breaking $\longleftrightarrow$ $M_{\mathrm{SUSY}} \simeq M_{\mathrm{SM}}$

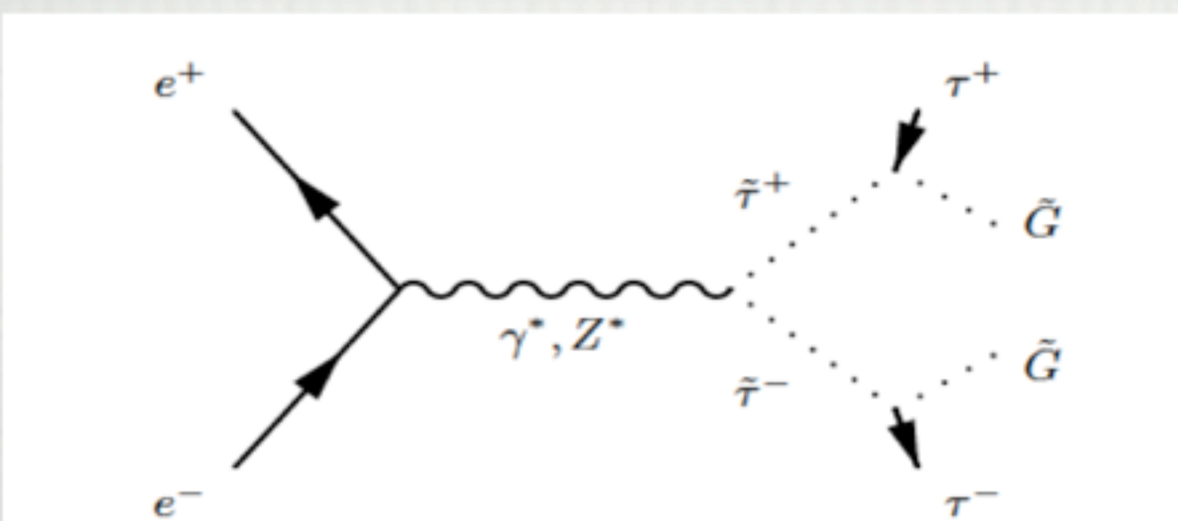
$\longrightarrow$ **Soft Breaking term**

Gauge Mediated Symmetry Breaking (GMSB)

⇒

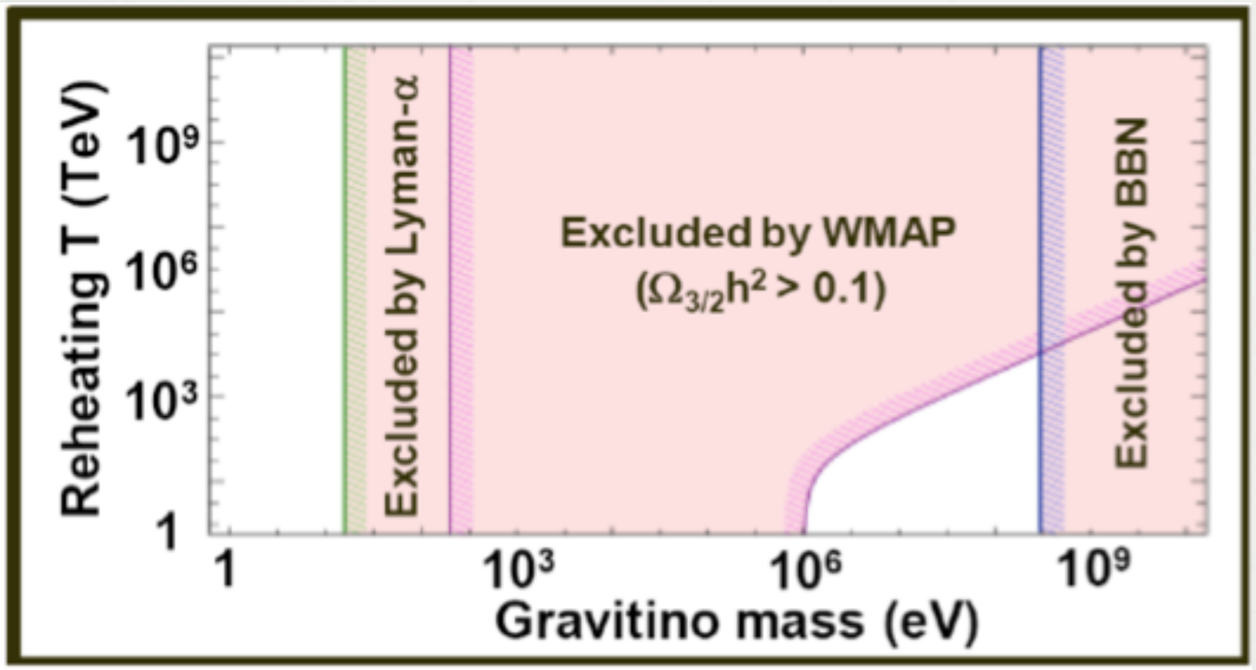
- ☐ Solve SUSY Flavor Problem
- ☐ Gravitino LSP

Decay mode : Stau->Tau+Gravitino



We observe particles decayed from tau lepton

Low Scale Gravitino mass $m_{3/2} \sim \mathcal{O}(10)\mathrm{eV}$



Free from constraints of
- ✻reheating Temperature
- ✻LHC experiment

In GMSB..

Stau lifetime and mass ⟶ Gravitino Mass

$$\tau_{\tilde{\tau}} = 48\pi M_{pl}^2 m_{3/2}^2 / m_{\tilde{\tau}}^5 \simeq 5.9 \times 10^{-12} \times (\frac{m_{3/2}}{10\mathrm{eV}})^2 (\frac{m_{\tilde{\tau}}}{100\mathrm{GeV}})^{-5}$$ [arXiv 1104.3624v1]

Sensitivity of Stau mass and lifetime is important for determination of susy breaking scale.

Other decay modes can be considered..

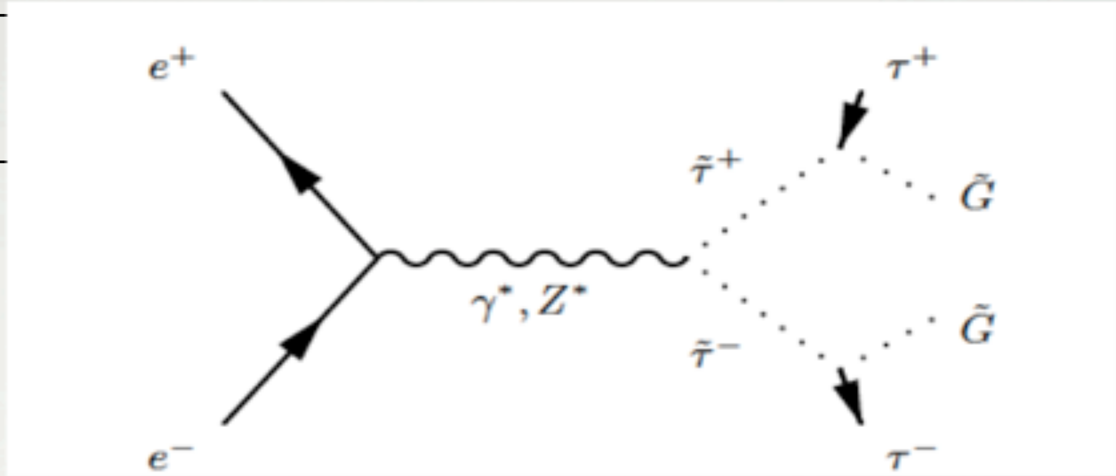
[Bhattacharyya Bhattacherjee, Yanagida, Yokozaki   arciv 1304.2508v2]

- **Stau ⟶ Tau + Axino** $\tilde{\tau} \to \tau \tilde{a}$
- **Stau ⟶ Tau + Neutrino (RPV)** $\tilde{\tau} \to \tau \nu_e, \tau \nu_\mu$

Stau Search strategy is applicable in these modes.

common signature : Tau + missing particle

EVENT SELECTION



- Signal $\tilde{\tau}^+\tilde{\tau}^- \to \tau^+\tau^-\tilde{G}\,\tilde{G}$
  - 1-prong decay (85%)

    $\tau \to e\nu\bar{\nu}(17.82\%)$ $\tau \to \mu\nu\bar{\nu}(17.39\%)$

    $\tau \to \pi\nu\nu(10.91\%)$ $\tau \to \pi\pi^o\nu(25.51\%)$
  - 3-prong decay (15%)
- Background
  - main background

    $e^+e^- \to W^+W^- \to l^+l^-\nu\bar{\nu}$ $e^+e^- \to Z\,Z \to l^+l^-\nu\bar{\nu}$

    $e^+e^- \to Z/\gamma \to l^+l^-$
  - large cross section

    $e\gamma \to el^+l^-$ $e^+e^- \to e^+e^-$ (bhabha) $\gamma\gamma \to l^-l^+$

Beam polarization (e,p)=(+0.8 , -0.3)

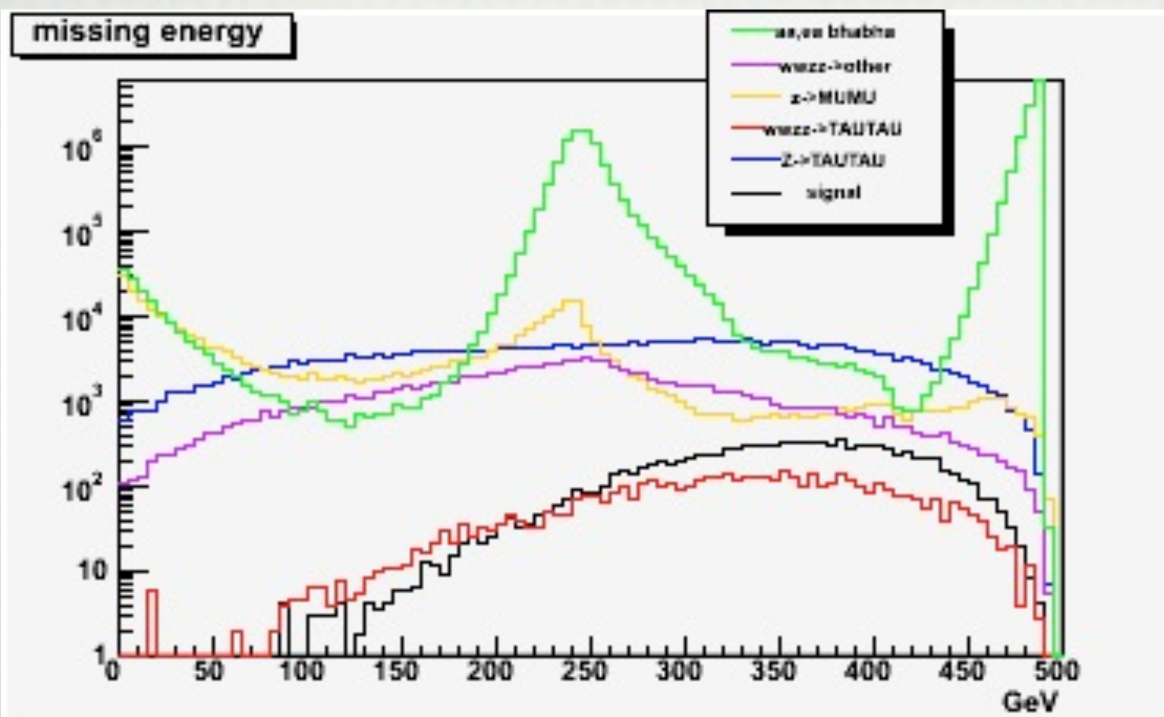
CUT FLOW (ex. 200GeV 100um)

- ☐ **0.** number of tracks==2 ⟶ **cut multi-prong decay**
- ☐ **1.** energy > 20GeV ⟶ **cut low energy γγ BG**
- ☐ **2.** Track Energy < 125GeV for each track ⟶ **cut Z->μμ**
- ☐ **3.** $-0.9 < \cos\theta_{-} < 0.8\ \&\ -0.8 < \cos\theta_{+} < 0.9$ ⟶ **cut t-channel BG**
- ☐ **4.** acoplanarity $-0.9 < \cos(\phi_{-} - \phi_{+})$ ⟶ **cut Z->ll**
- ☐ **5.** $|\cos\theta_{\mathrm{miss}}| < 0.9$ ⟶ **cut eγ, γγ BG**
- ■ **6.** missing energy >250GeV ⟶ **cut Z->ττ BG**
- ☐ **7.** Hcal Deposit > 3 % ⟶ **cut WWZZ->ee,μμ,eμ + νν BG**
- ☐ **8.** Track Energy / Calorimeter Deposit > 0.03 ⟶ **cut Z-> μμ**
- ☐ **9.** Cosine angle between two tracks > -0.9 ⟶ select signal
- ■ **10.** Impact parameter significance > 2.5 ⟶ **cut WWZZ-> llνν**

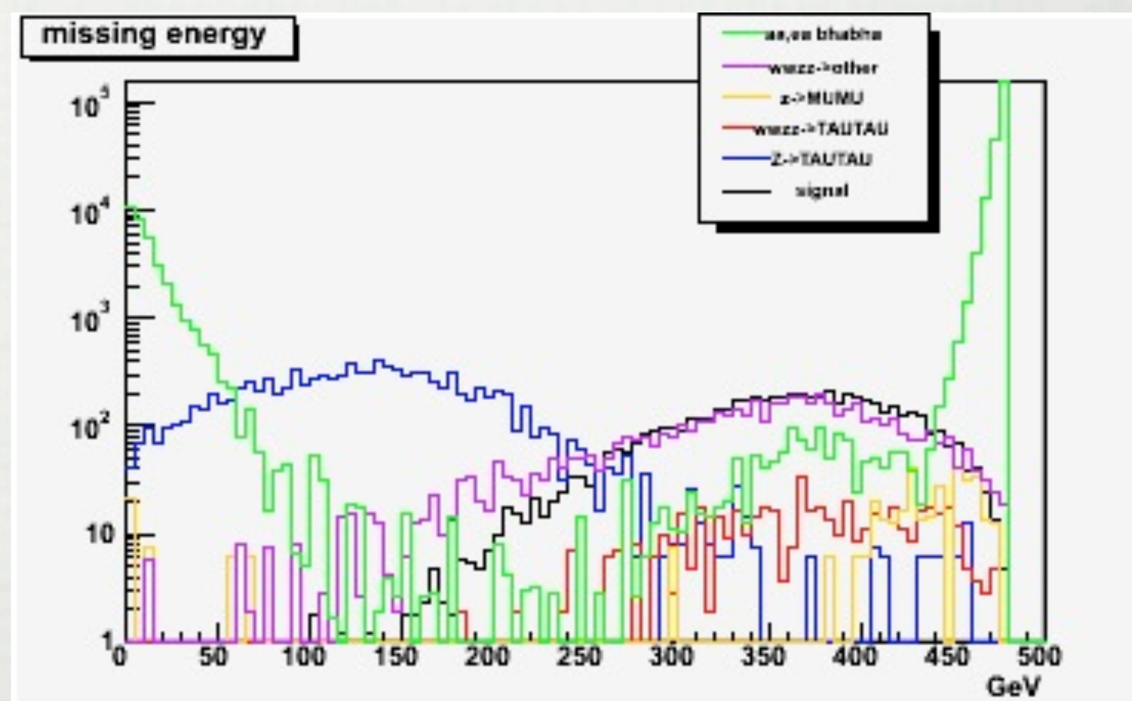
Cut Variable 6

MISSING ENERGY>250GEV

Reduce Z->tauTau process (blue line).
Gravitino has large missing energy (signal: black line)



number of tracks==2

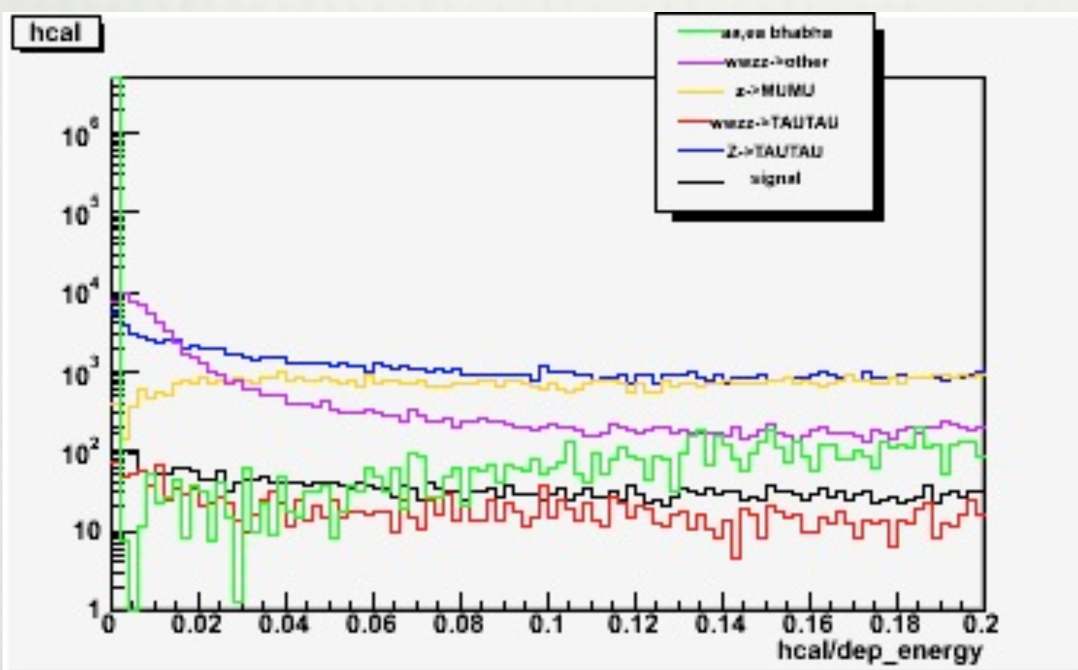


cut variable 0〜5

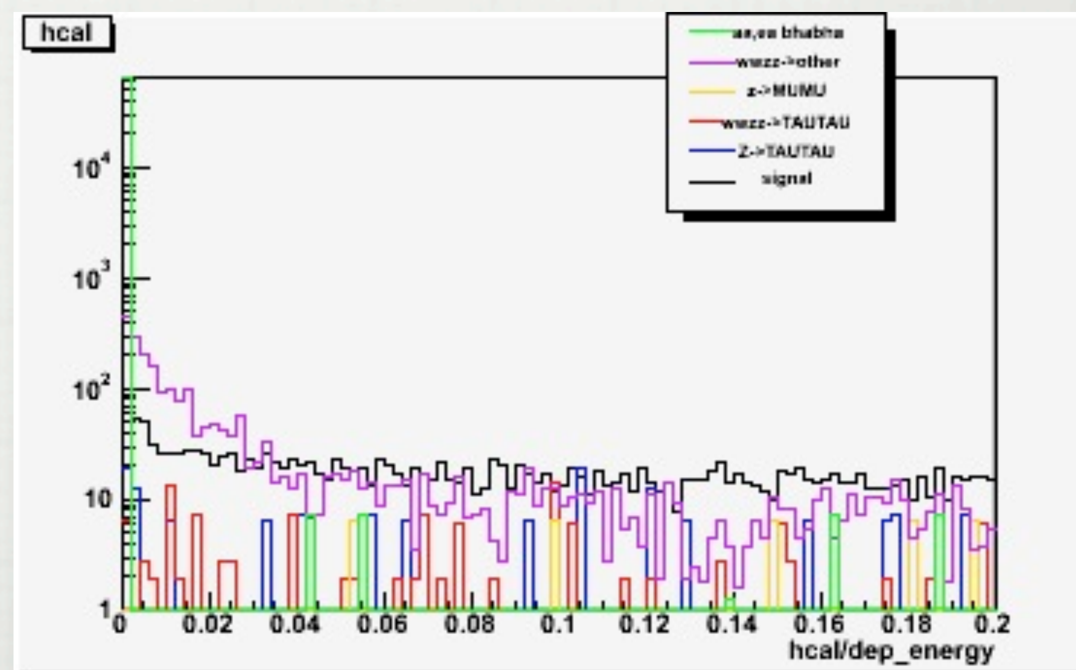
Cut Variable 7

HCAL Deposit / Energy Depotit > 0.03

$WW, ZZ \to \mu\mu\nu\nu, ee\nu\nu, e\mu\nu\nu$ is reduced for its low energy deposit in hadron calorimeter.(purple line)



number of tracks==2



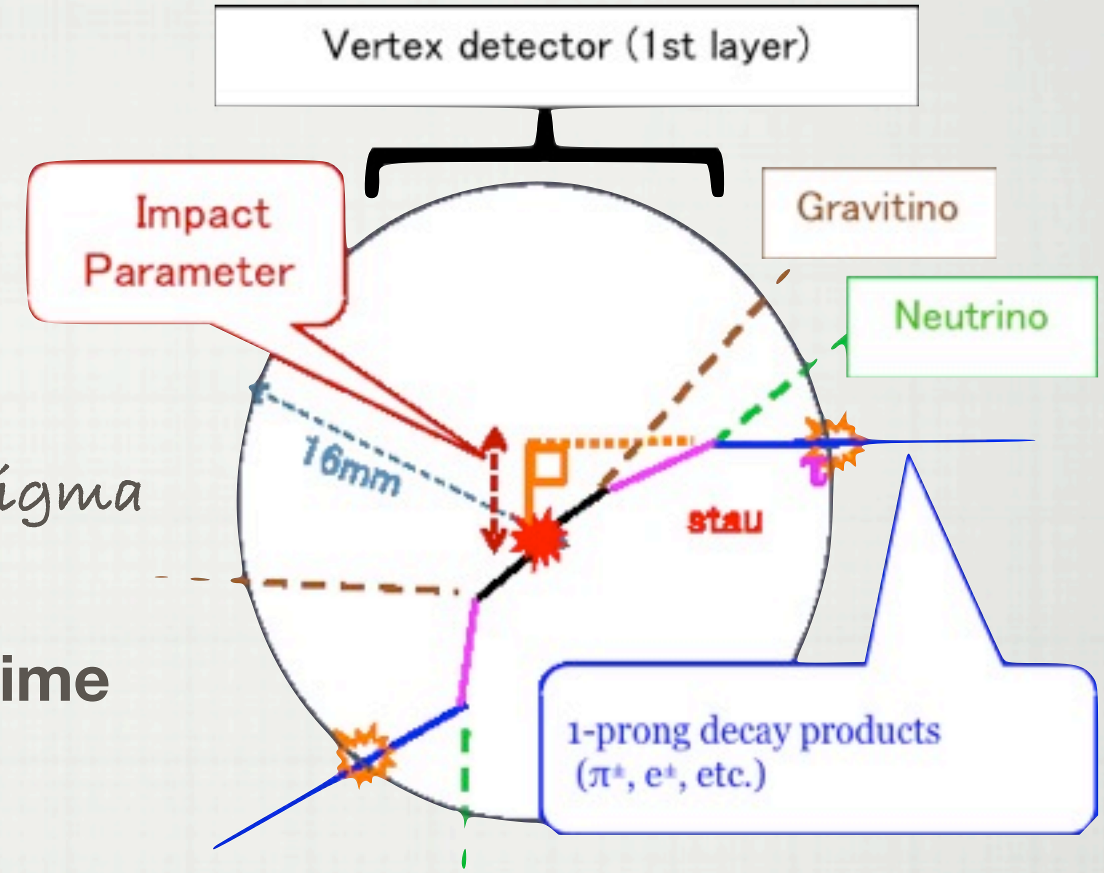
Cut Variable 0〜6

impact parameter cut (ex 200GeV , 100um)

☐ + STAU IMPACT PARAMETER

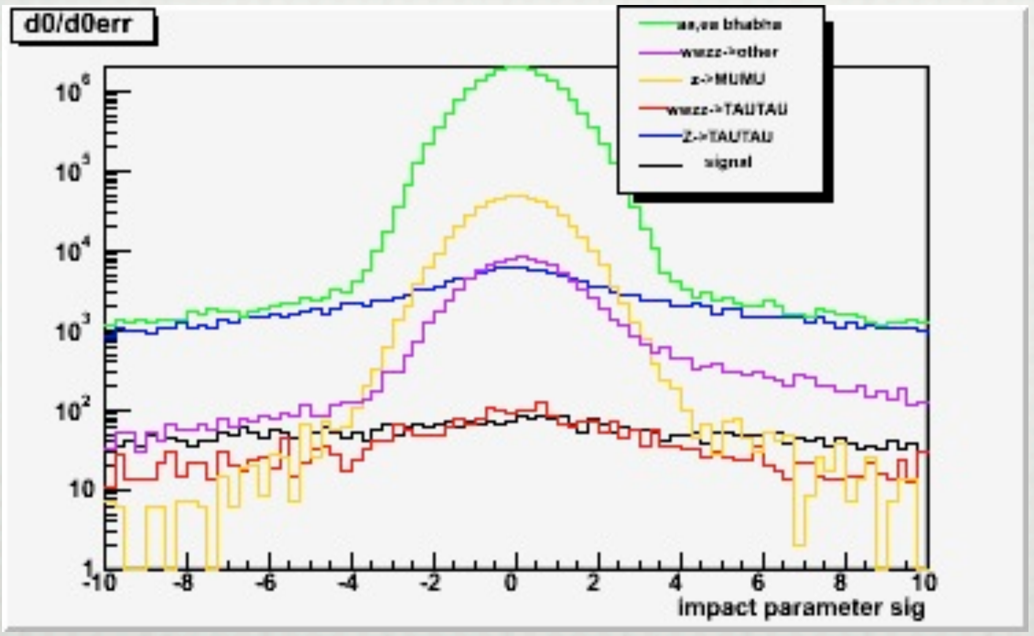
- |D0/D0_err| > 2.5

D0=impact parameter , D0_err = D0 sigma

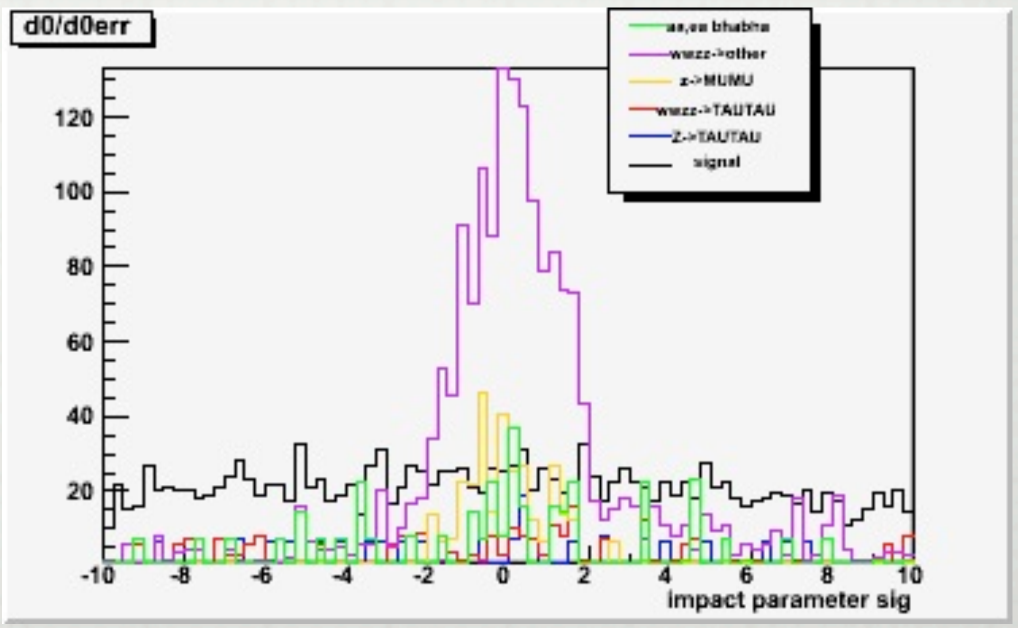


impact parameter related with stau lifetime

$\longrightarrow \quad WW, ZZ \to ll\nu\bar{\nu}$



number of tracks==2



Cut Variable 0〜9

Statistical Significance
Lifetime vs Mass RESULT

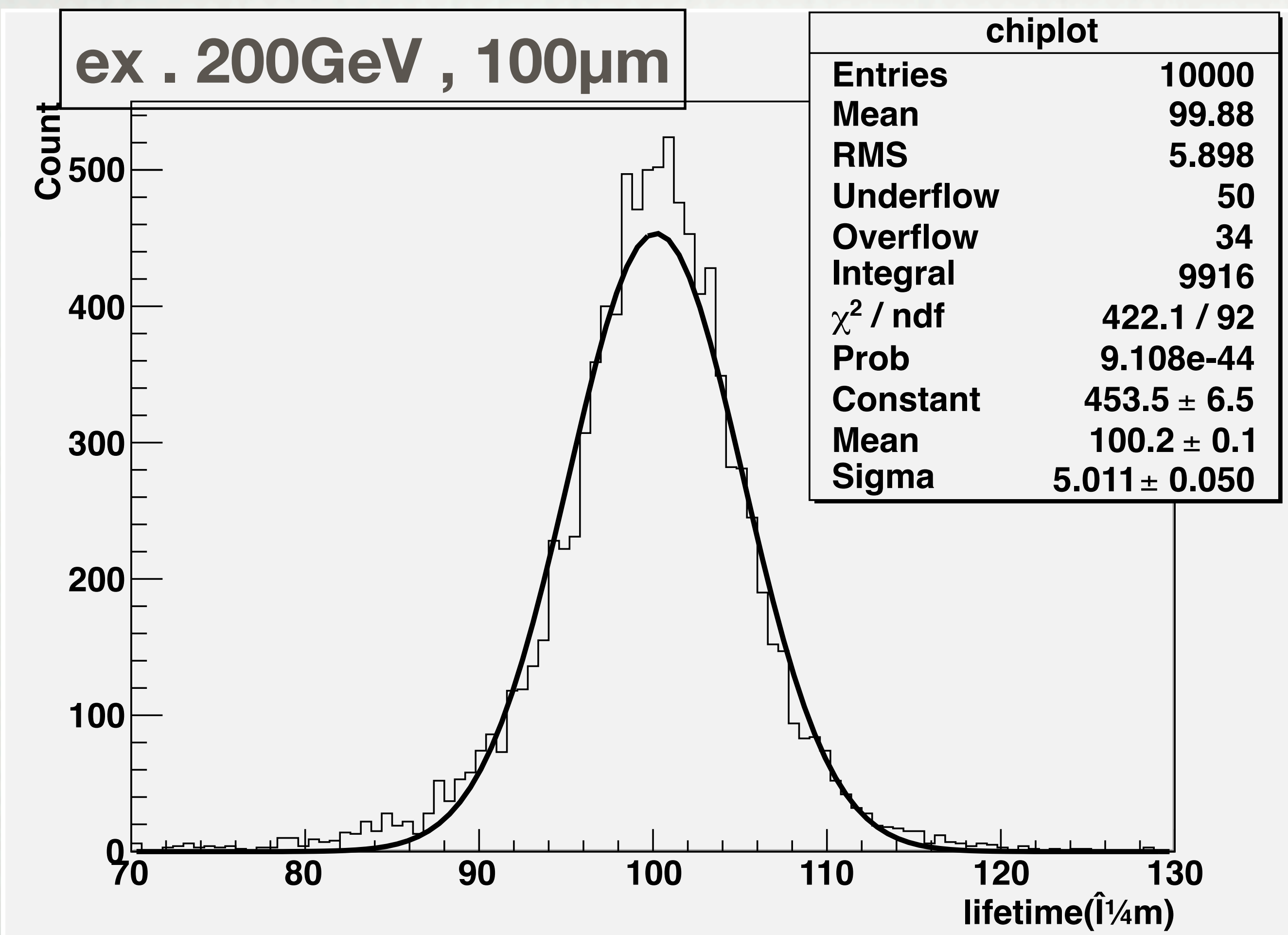
	120GeV	150GeV	200GeV	240GeV
10μm	113.2	98.6	53.4	6.05
100μm	117.1	101.5	55.3	6.00
1mm	121.5	105.3	59.1	8.14
10mm	123.1	109.5	62.4	12.3

$>5\,\sigma$ for all benchmark points

Lifetime Analysis

Perform the toy MC experiment with each experiment distribution with poisson statistics folded in , and compare with the high statistics samples with various lifetime by calculation of chi square quantity.

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{n_i^{exp} - n_i^{templ}}{\Delta n_i^{exp}} \right)^2$$



Stau Mass 200GeV

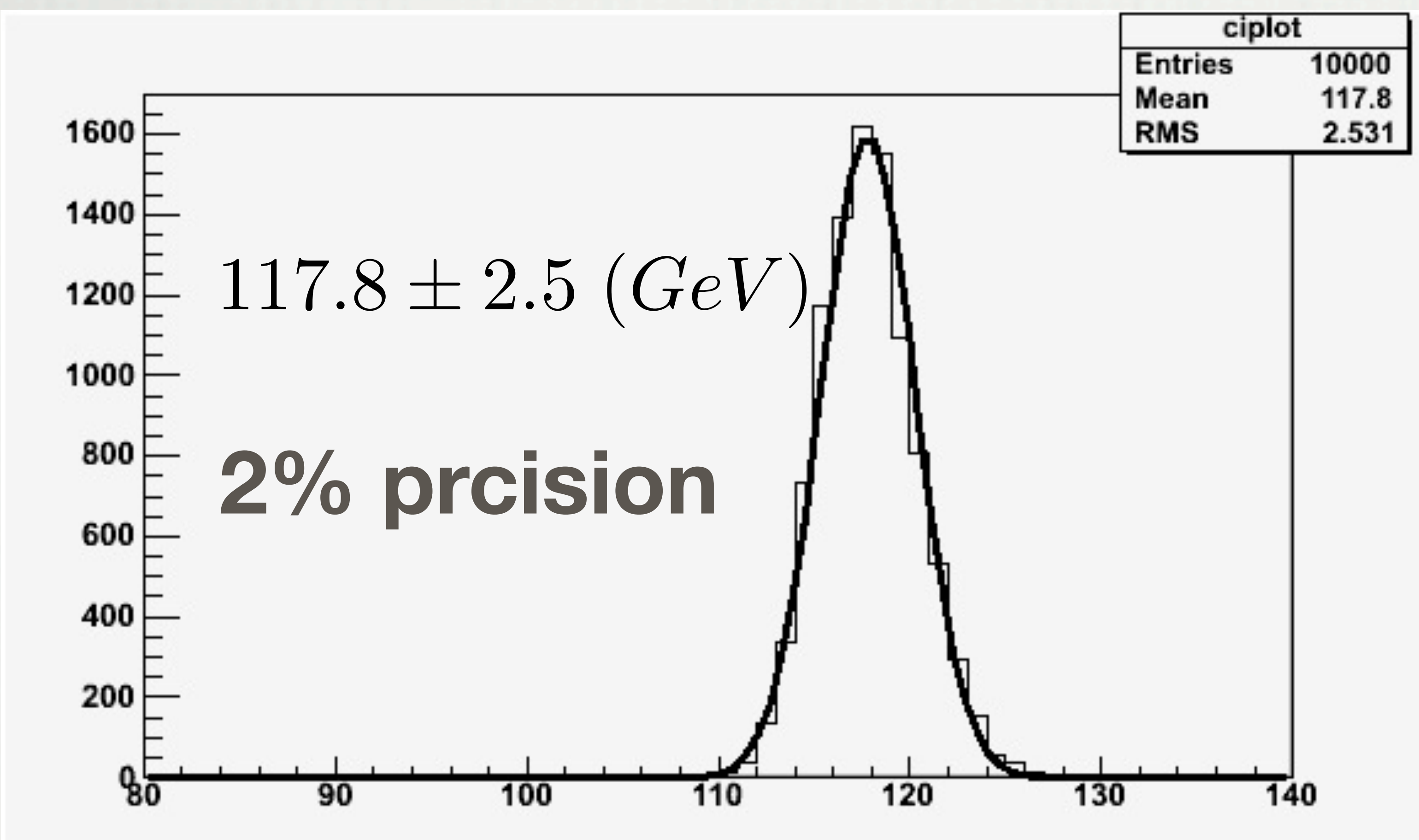
Stau Lifetime 100μm

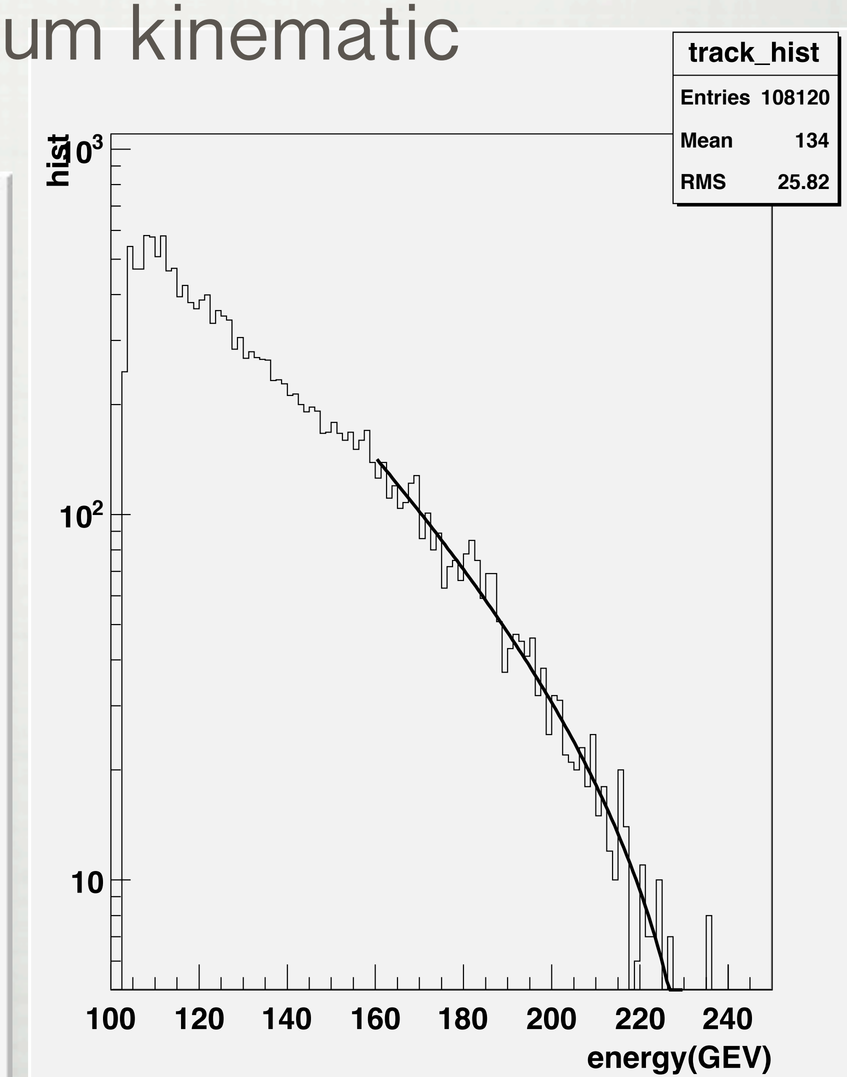
$$c\tau = 99.8 \pm 5.0 \ (\mu m)$$

5% precision

Mass Analysis (kinematic cut)

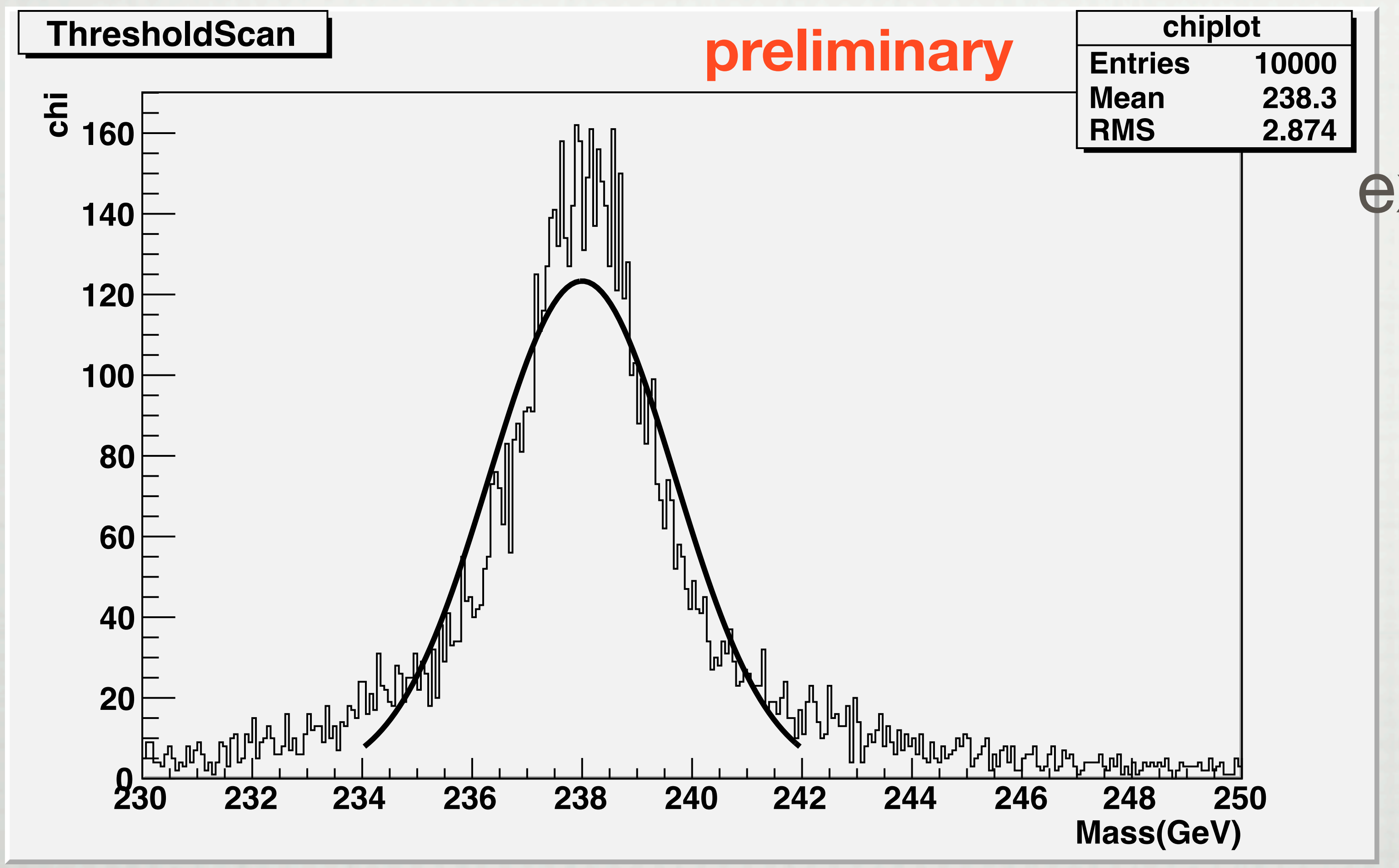
Kinematic cut is applied for measurement of stau mass via the maximum track energy.
Track energy distribution is modeled with the following function $f(x) = \alpha(\beta - x)exp(-\gamma x)\theta(\beta - x)$.
120GeV mass corresponds to the maximum kinematic energy of 234GeV.





Mass Analysis (Threshold Cut)

The technique of Threshold scan is used for heavy stau, for its low sensitivity of kinematic mass measurement.



ex. M=240GeV ct=100μm

$$238.3 \pm 2.8 \text{ (GeV)}$$

1.2 % precision

Conclusions & Future Plans

Conclusions

We studied the ILC sensitivity for measuring the wide range of benchmark points of stau mass and lifetime and obtain over 5 σ significance.
Mass and lifetime sensitivity are also studied, and for example we can obtain stau Mass with 5% precision at M=200GeV .

Future Plans

- Optimization of cut flow for kinematic mass measurement to improve its sensitivity.
- 3-prong decays are being studied.

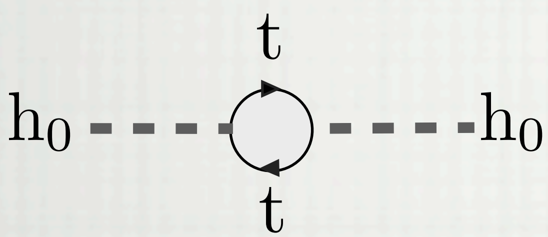
THANK YOU FOR YOUR ATTENTION .

BACKUP

physics motivation

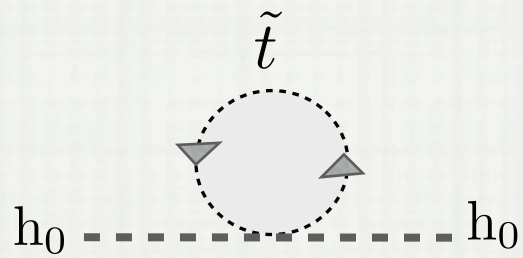
WHY SUSY ?

FINE TUNING



$\delta m_H^2 \sim -\lambda\Lambda^2$

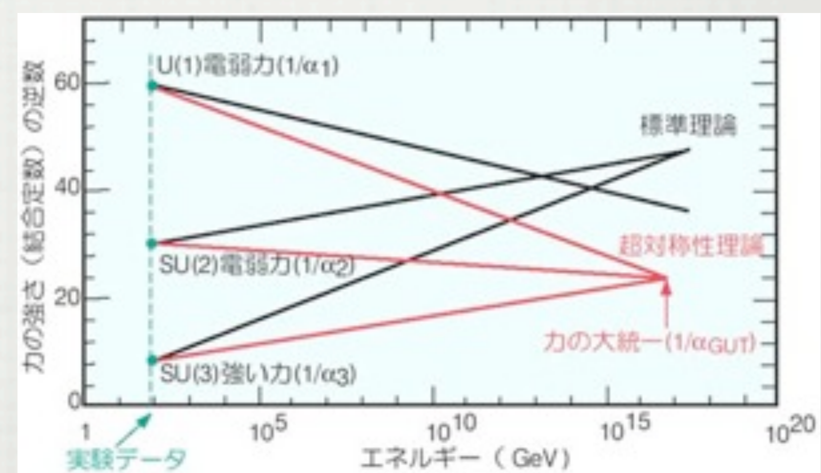
$+$



$\delta m_H^2 \sim \lambda[\Lambda^2 - 2m_s^2 \ln(\Lambda/m_s) + ..]$

quadric divergence
become
logarithmic
divergence

GUT SCALE UNIFICATION



Coupling constant unification
at high scale region .

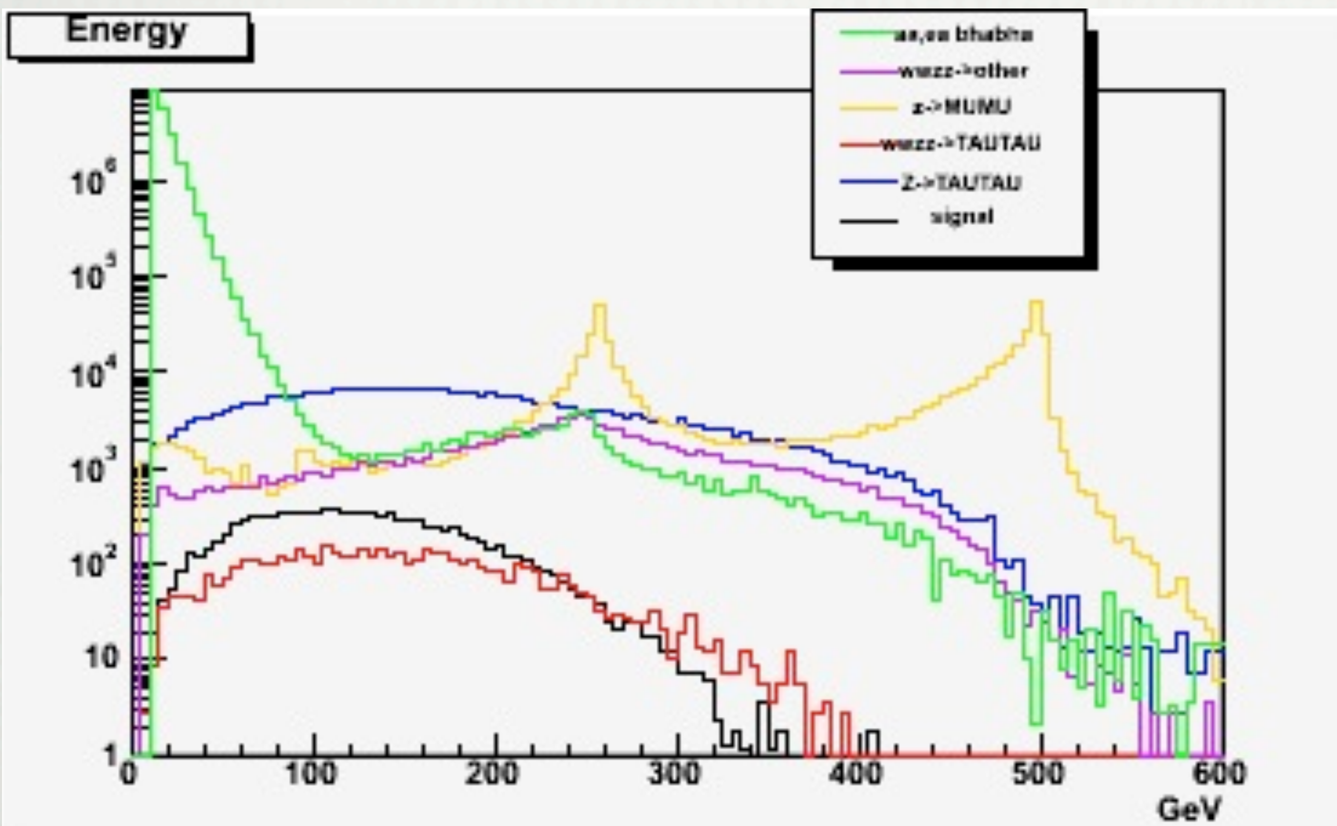
DARK MATTER

LSP(lightest supersymmetric particle) is a prominent candidate

Cut Variable 1

Energy >20GeV

Suppress low energy beam related $\gamma\gamma \to l^+l^-$ **process**



Signal

— $e^+e^- \to \tilde{\tau}^-\tilde{\tau}^+$

BackGround

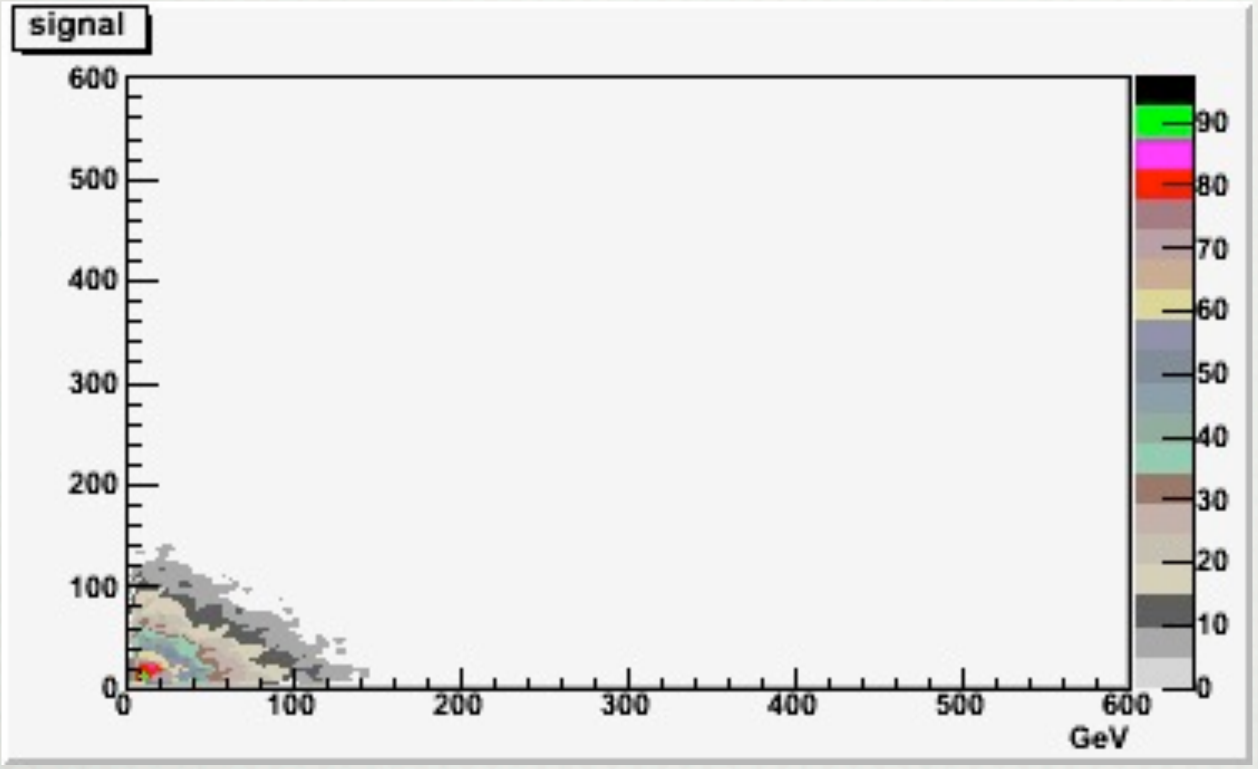
- $\gamma\gamma \to l^-l^+$, bhabha 散乱
- $WW, ZZ \to l^+l^-\nu\bar{\nu}$($\tau\tau\nu\bar{\tau}$ 除く)
- $Z \to \mu\mu$
- $WW, ZZ \to \tau^+\tau^-\nu\bar{\nu}$
- $Z \to \tau\tau$

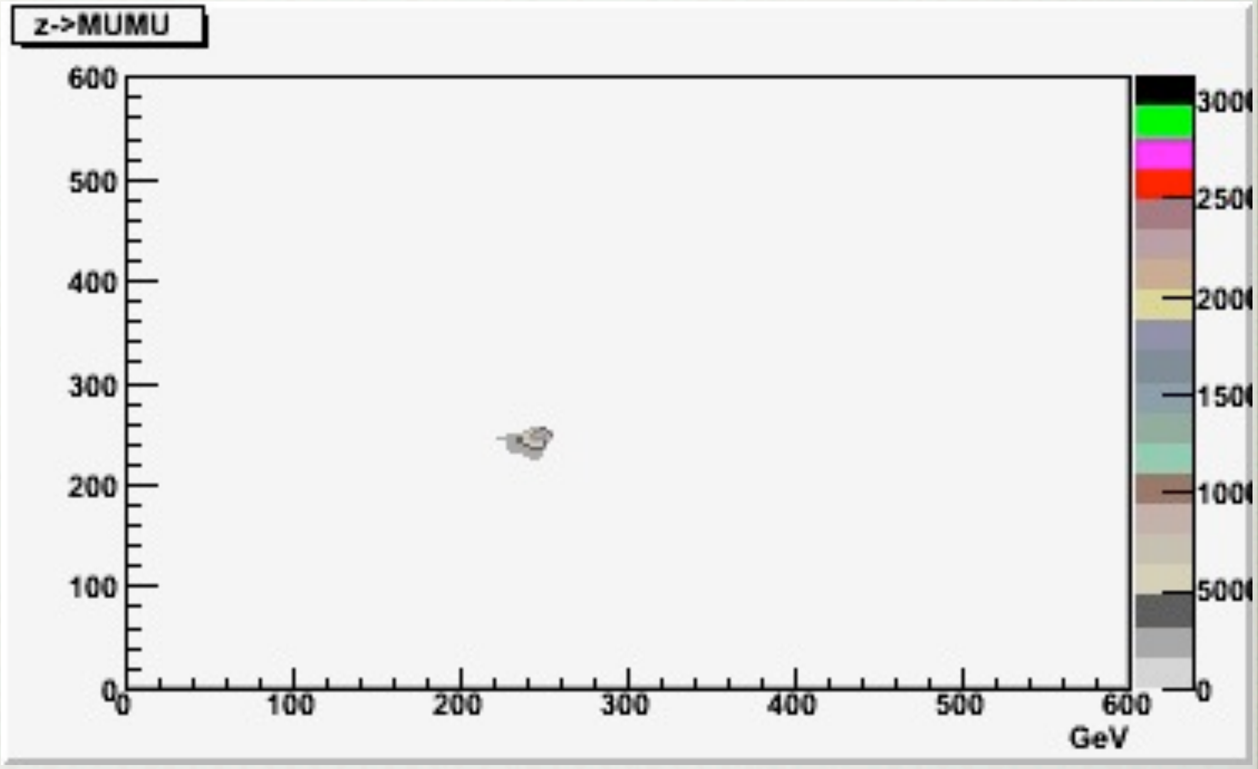
number of tracks==2

Cut variable 2

Track Energy < 125 GeV (for each track)

Supress high energy muon from $Z \to \mu\mu$.





number of tracks==2

$$e^+e^- \to \tilde{\tau}^-\tilde{\tau}^+$$

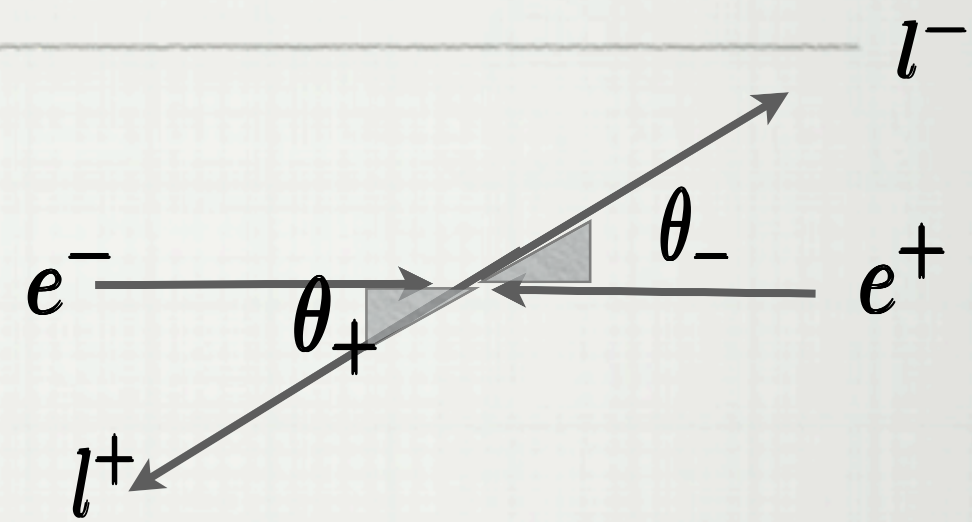
number of tracks==2

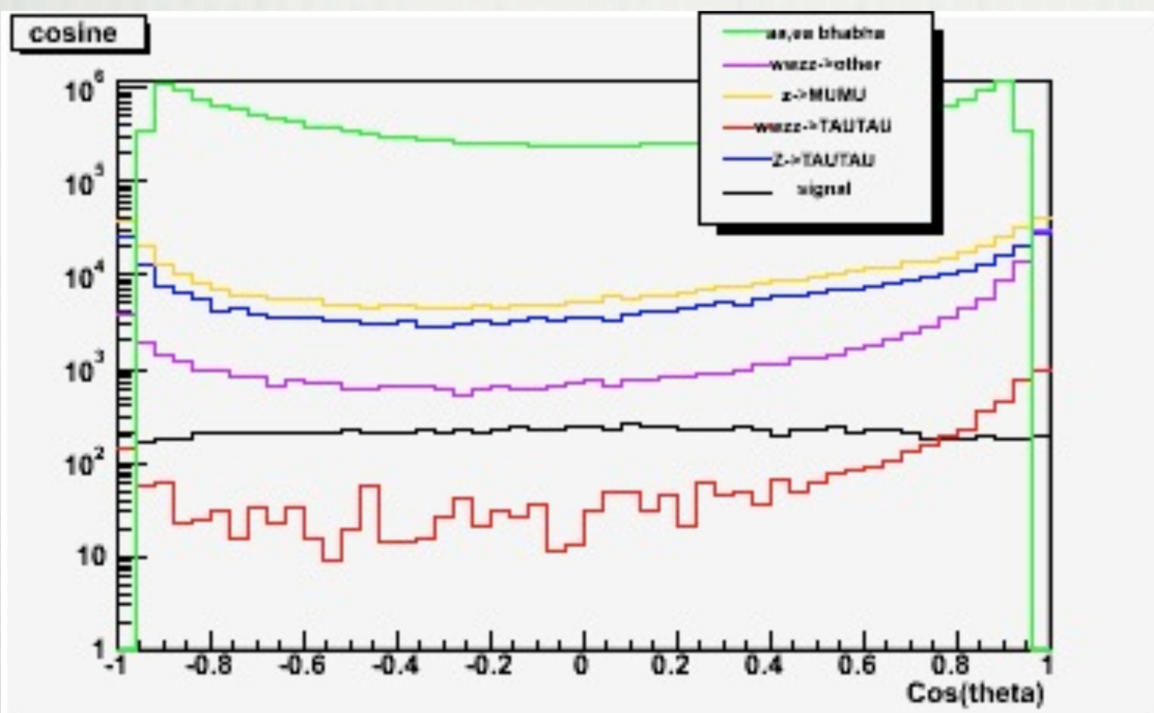
$$Z \to \mu^+\mu^-$$

Cut Variable 3

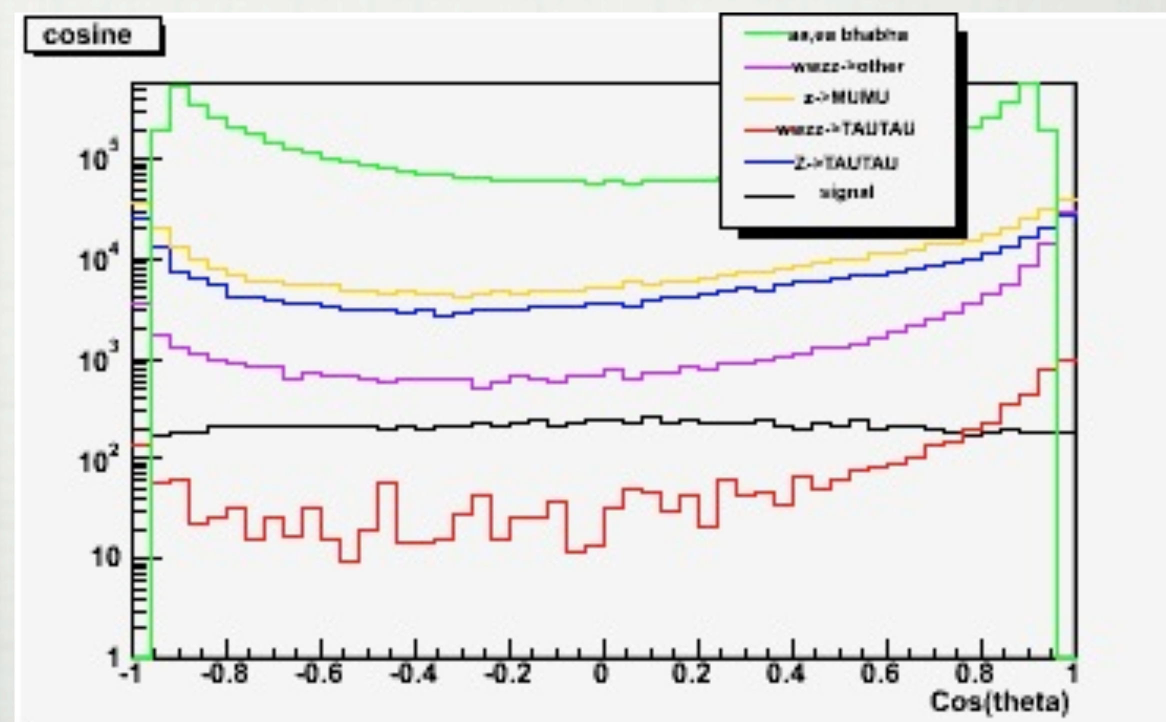
$$-0.9 < \cos\theta_- < 0.8 \ \ \& -0.8 < \cos\theta_+ < 0.9$$

Cut forward-backword dominant
W boson t-channel decays
(purple line)





number of tracks==2

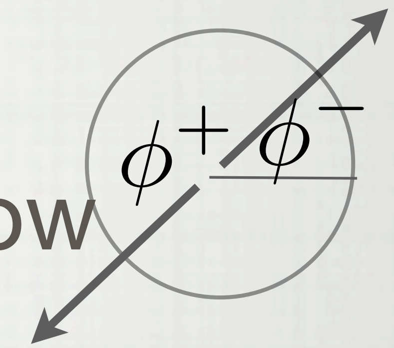


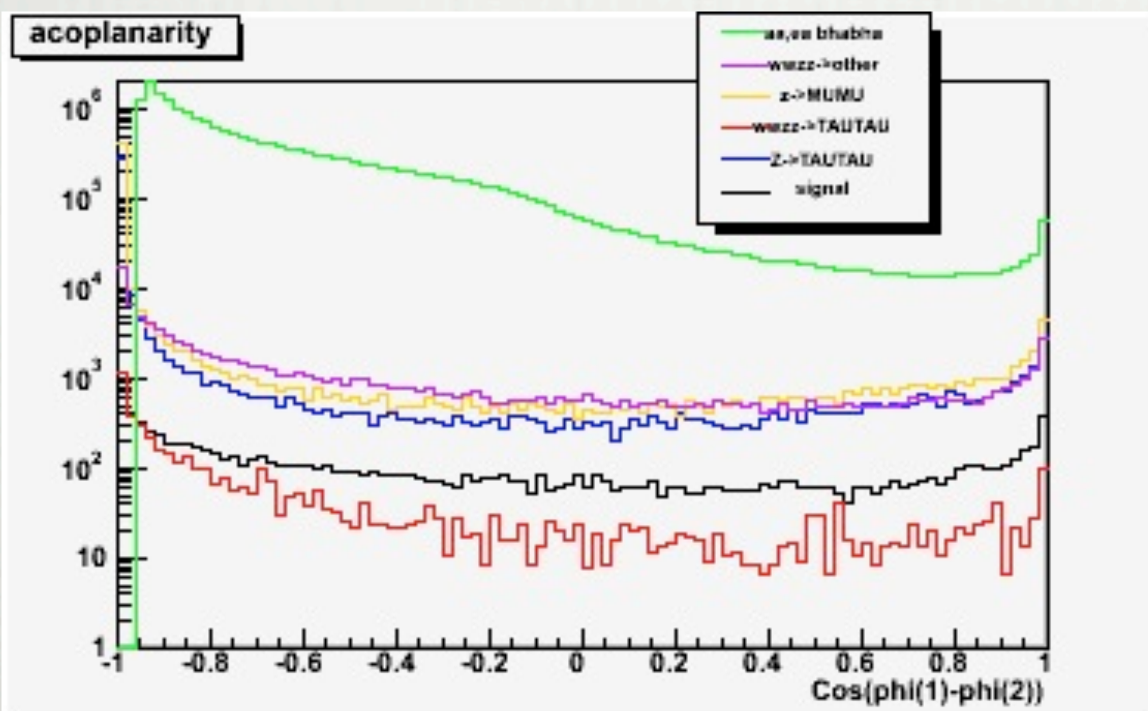
Cut Variable 0〜2

Cut Variable 4

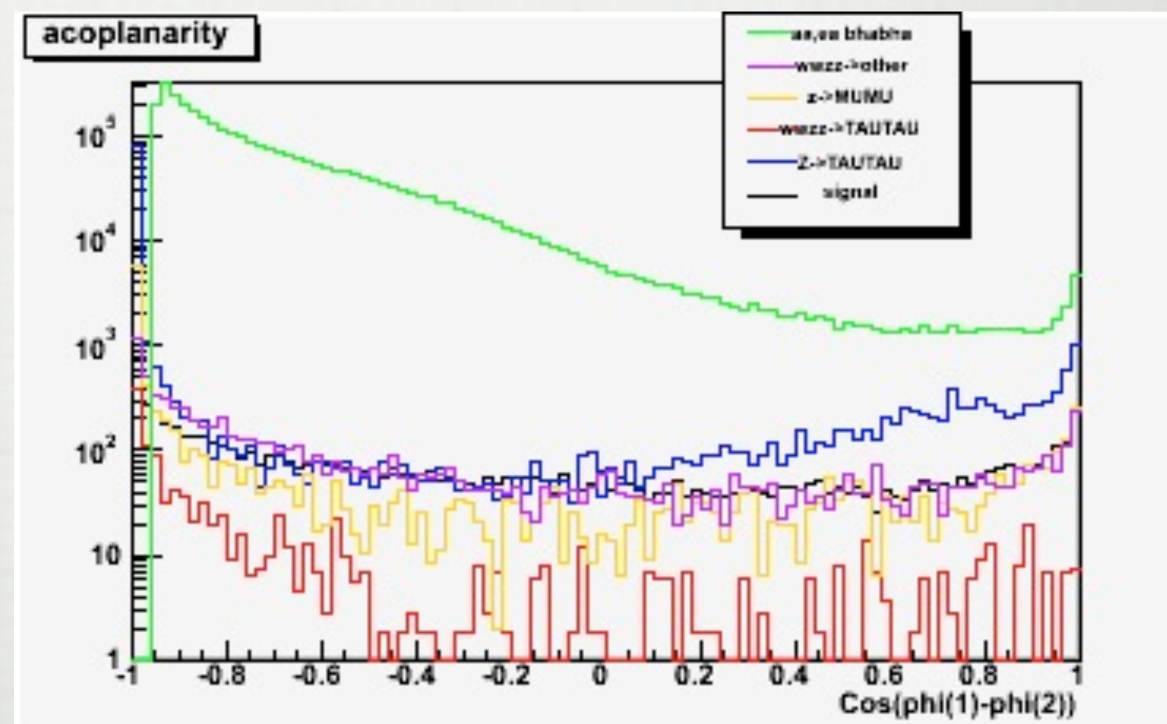
Acoplanarity $-0.9 < \cos(\phi_- - \phi_+)$

Cut tracks in opposite direction .
z->tautau background can be reduced for its low missing energy and highly boosted in opposite direction .





number of tracks==2

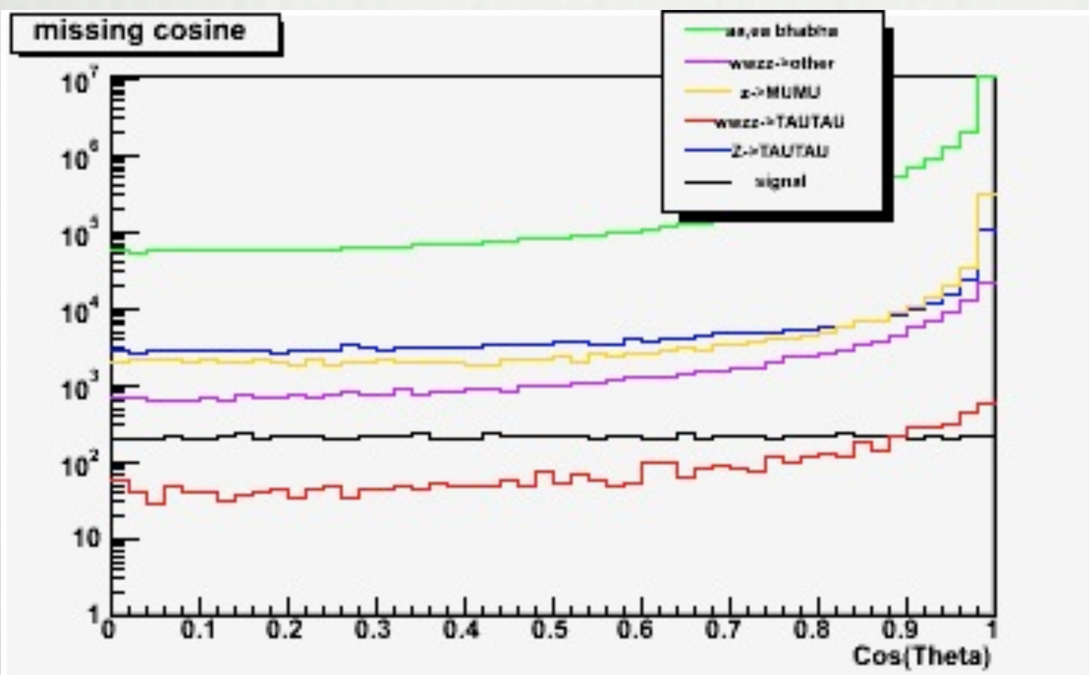


Cut Variable 0〜3

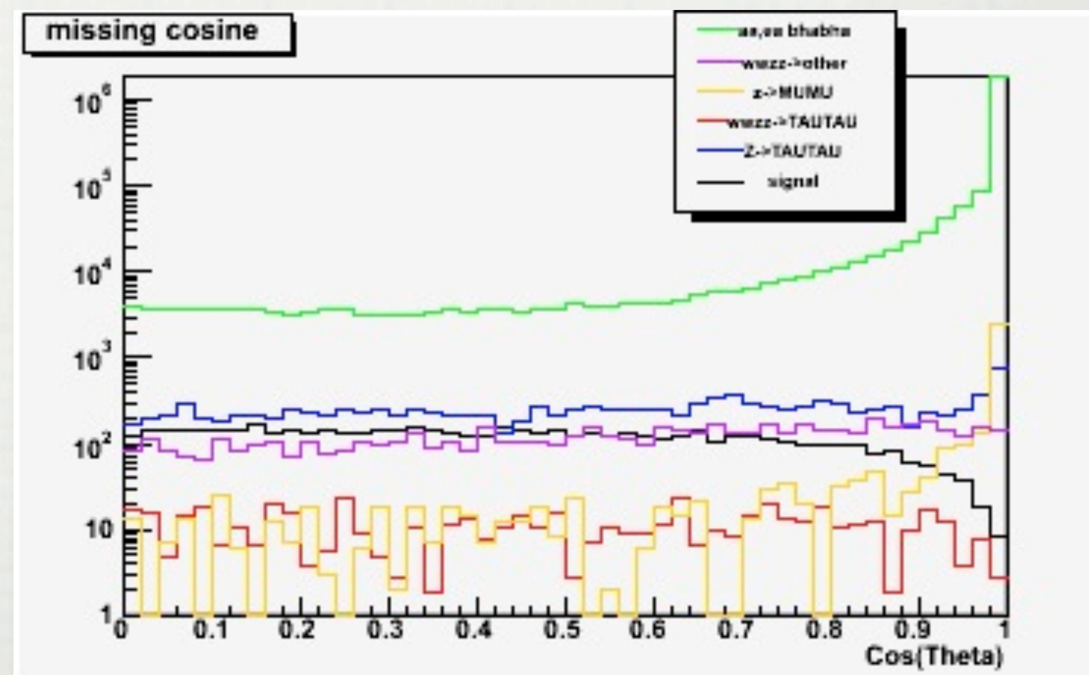
Cut Variable 5

$|\cos\theta_{\mathrm{miss}}| < 0.9$

Reduces beam-related background for bhabha scattering , each of whose tracks is towards the undetected beam pipe direction , and it appears as large missing energy towards forward-backward direction.



number of tracks==2

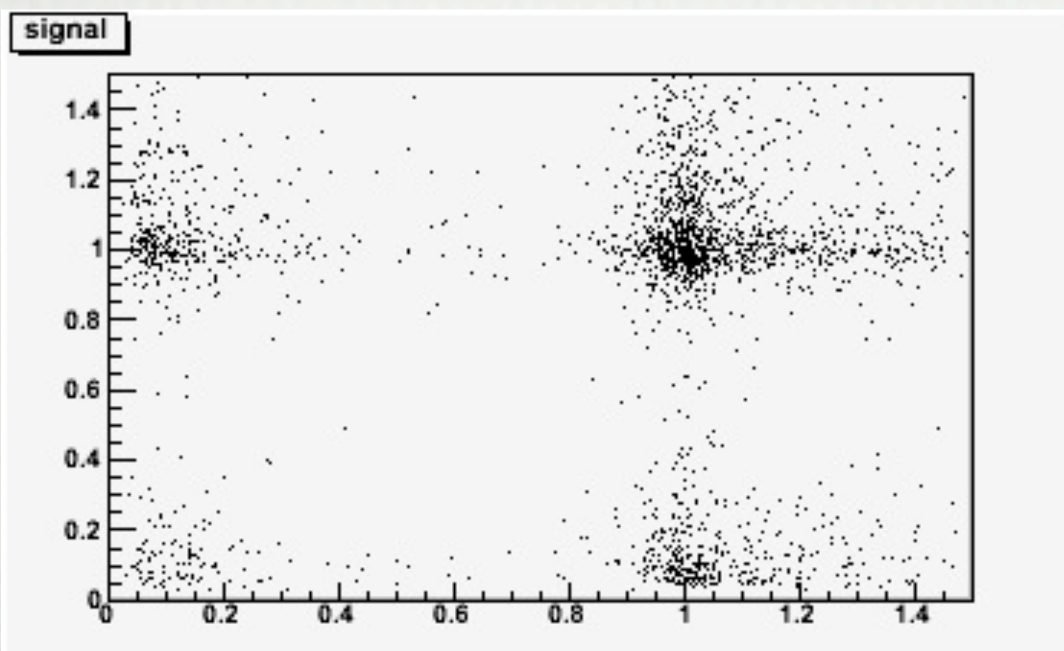


Cut Variable 0～4

Cut Variable 8

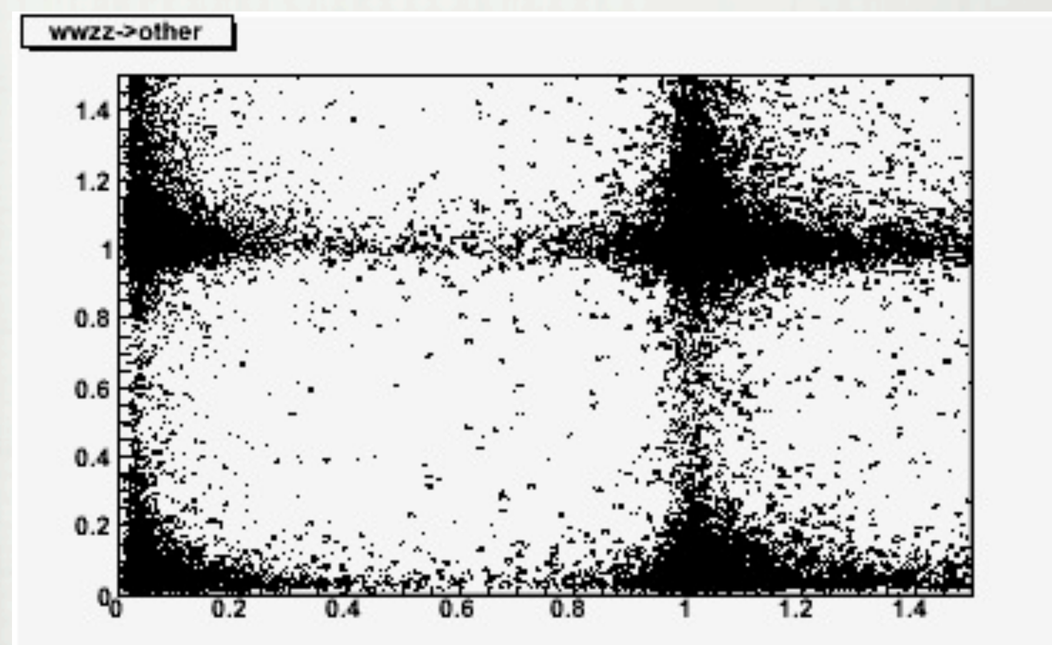
Energy deposit/Track energy > 0.3 for each track

Reduce $Z \to \mu\mu$ process for its low deposit in calorimeters and highly energetic track.



number of tracks==2

$e^+e^- \to \tilde{\tau}^-\tilde{\tau}^+$



number of tracks==2

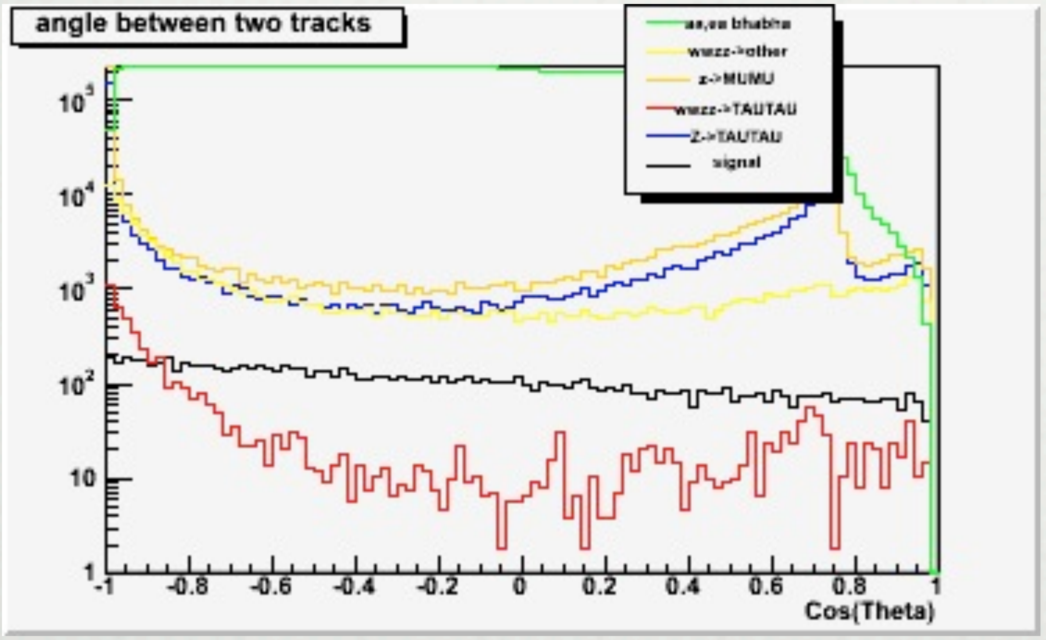
$WW, ZZ \to ll\nu\nu \; (l \neq \tau)$

Cut Variable 9

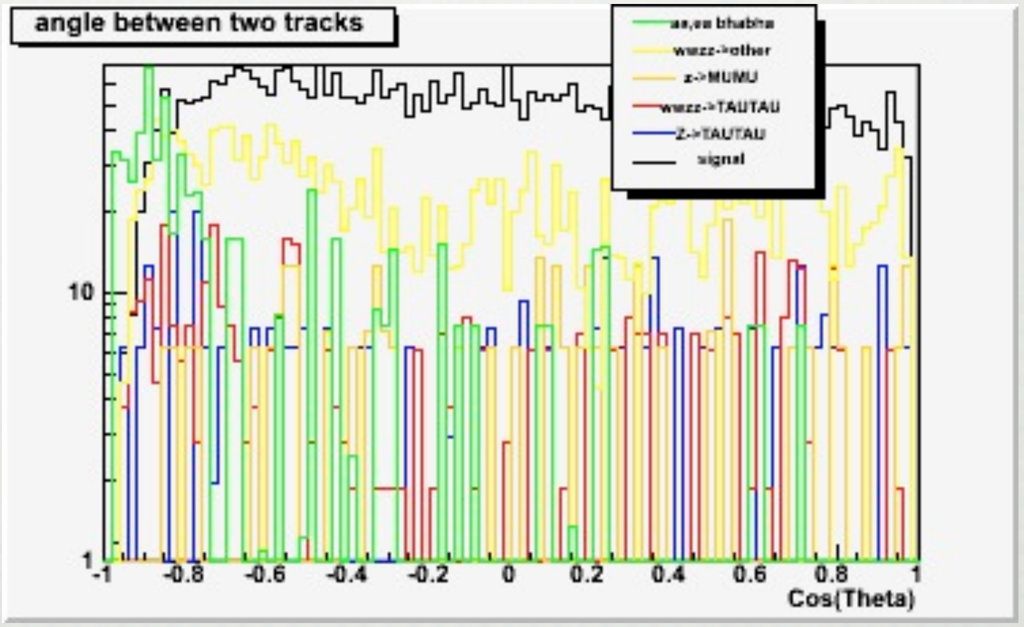
Cosine angle between two tracks > -0.9

$\tilde{\tau}$ の質量が重い場合ほぼ静止しているので、$\tilde{\tau} \to \tau\tilde{G}$ における τ は等方的に飛びやすい。

一方 $WW \to l\bar{l}\nu\bar{\nu}$ はブーストされ、正反対方向に飛びやすいため
カットされる。(黄色、赤線)



number of tracks==2



Cut Variable 0〜8

Friday, December 6, 13

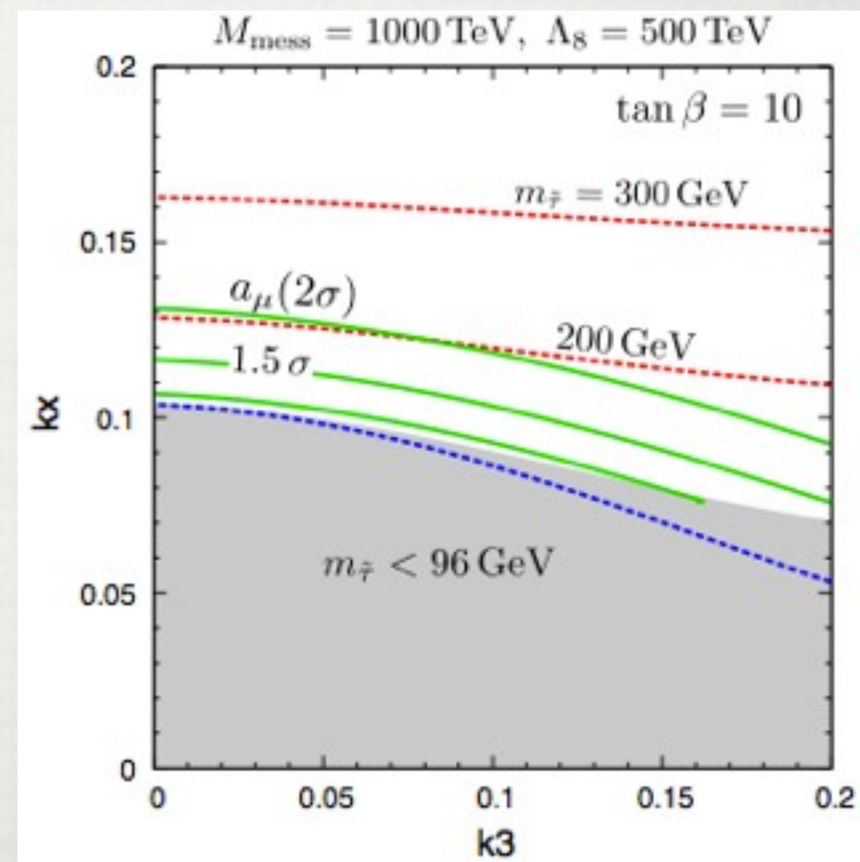
■ 重いSquark、軽いSlepton を示唆し、g-2の実験結果を説明する新たなモデル [Ibe, Matsumoto, Yanagida, Yokozaki　arxiv 1210.3122v2]

■GUT , GMSB -> no SUSY flavor/CP problem

■g-2 を説明可能

Stau mass = 200GeV で 実験値とのズレを2σで説明可能

(Stau mass = muon 150GeV の場合 1.5σ)



Stau -> Tau + Gravitino
の崩壊モード

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

SIGNAL

Mass (GeV)	Cross Section (fb)
120GeV	139
200GeV	33.3
150GeV	97.2
240GeV	3.22

BACKGROUND

Category	Cross Section (fb)
$WW, ZZ \to l^+l^-\nu\bar{\nu}$	445.9
$Z/\gamma \to \tau^+\tau^-$	1283.4
$\gamma\gamma \to l^+l^-$	1.41×10^6

PHYSICS MOTIVATION2

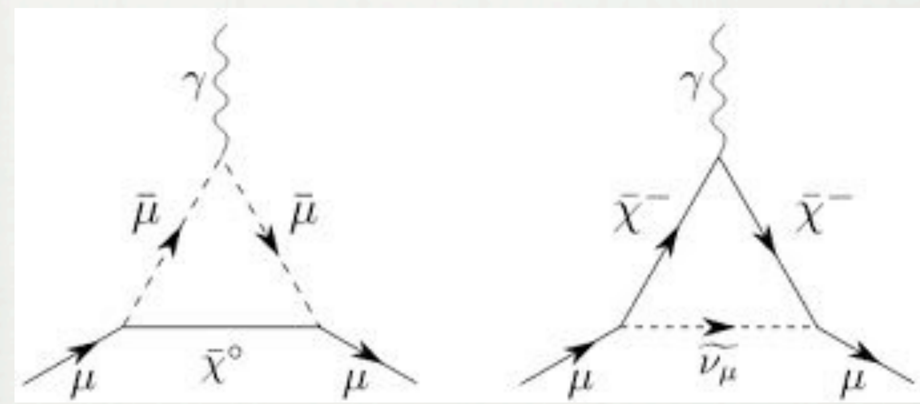
WHY STAU PRODUCTION?

- **MUON g-2 3.6 sigma deviation between SM theory**

SUSY particles 1-loop correction

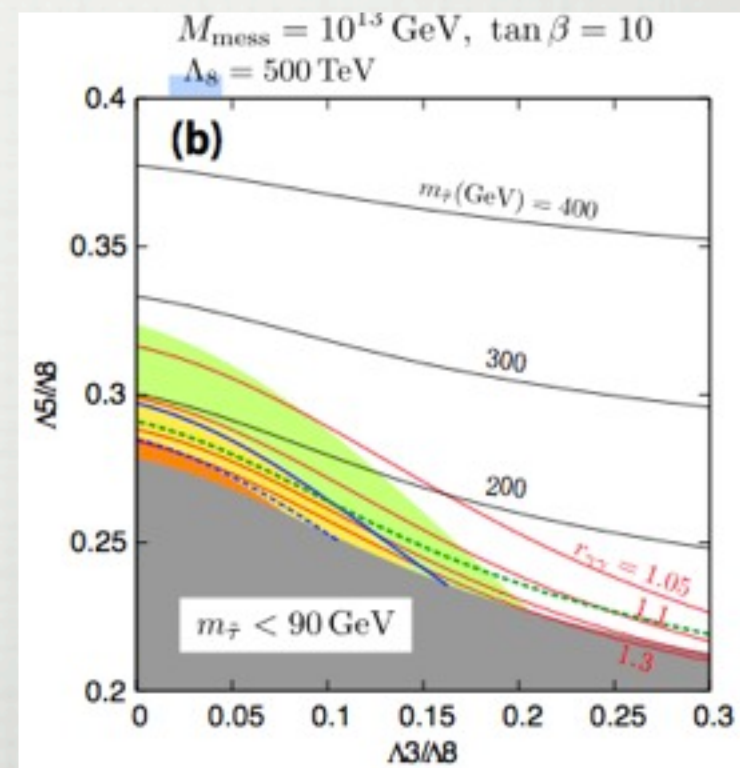
$$\delta a_\mu \sim \frac{3}{5}\frac{g_1}{8\pi^2}\frac{m_\mu^2 \mu tan\beta}{m_{\rm soft}^3}F_b$$

$m_{\rm soft}$ = loop sparticle mass
g is SU(2), Y(1) coupling const. $a_\mu \equiv \frac{g-2}{2}$



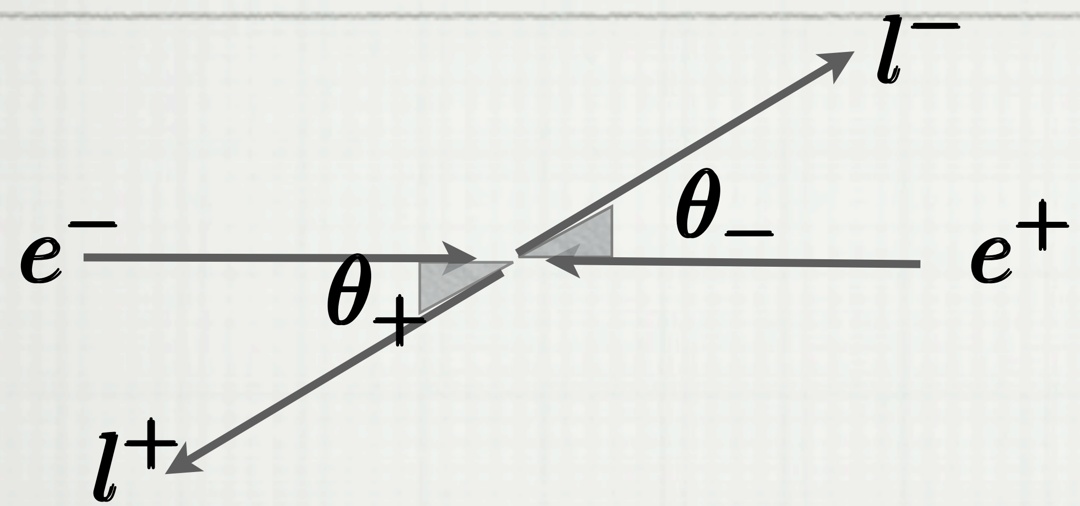
3.6 sigma deviation is explain with assumption of
Sfermion exist in the region of 100GeV

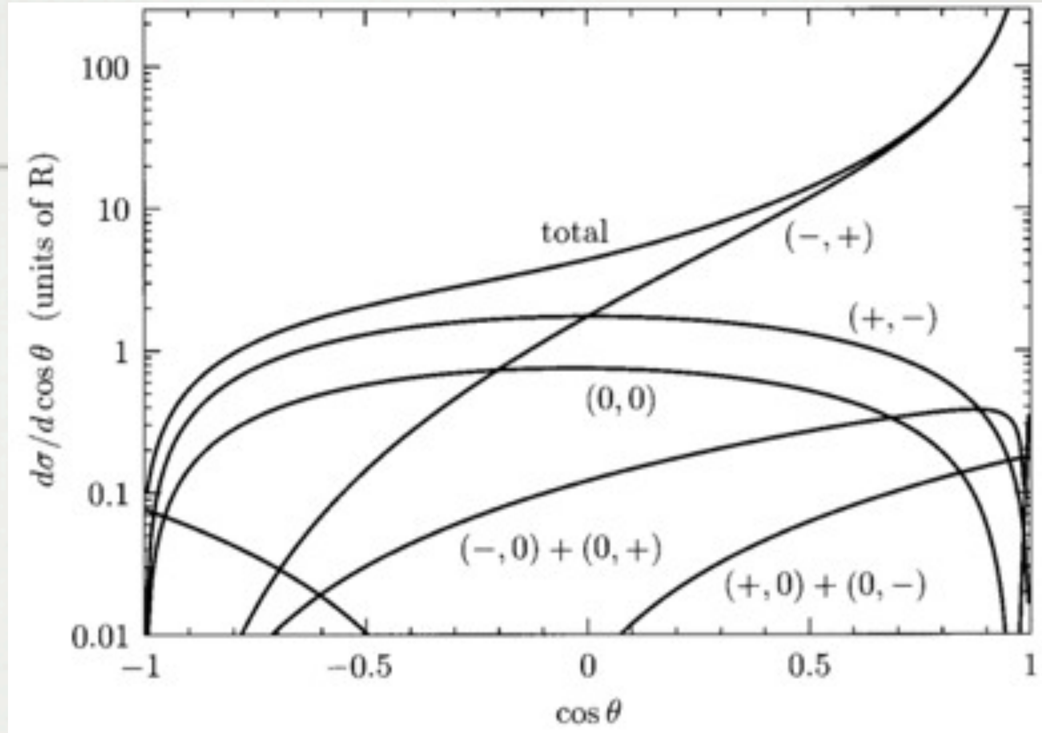
$$\mu\tan\beta \sim 4\mathrm{TeV}$$

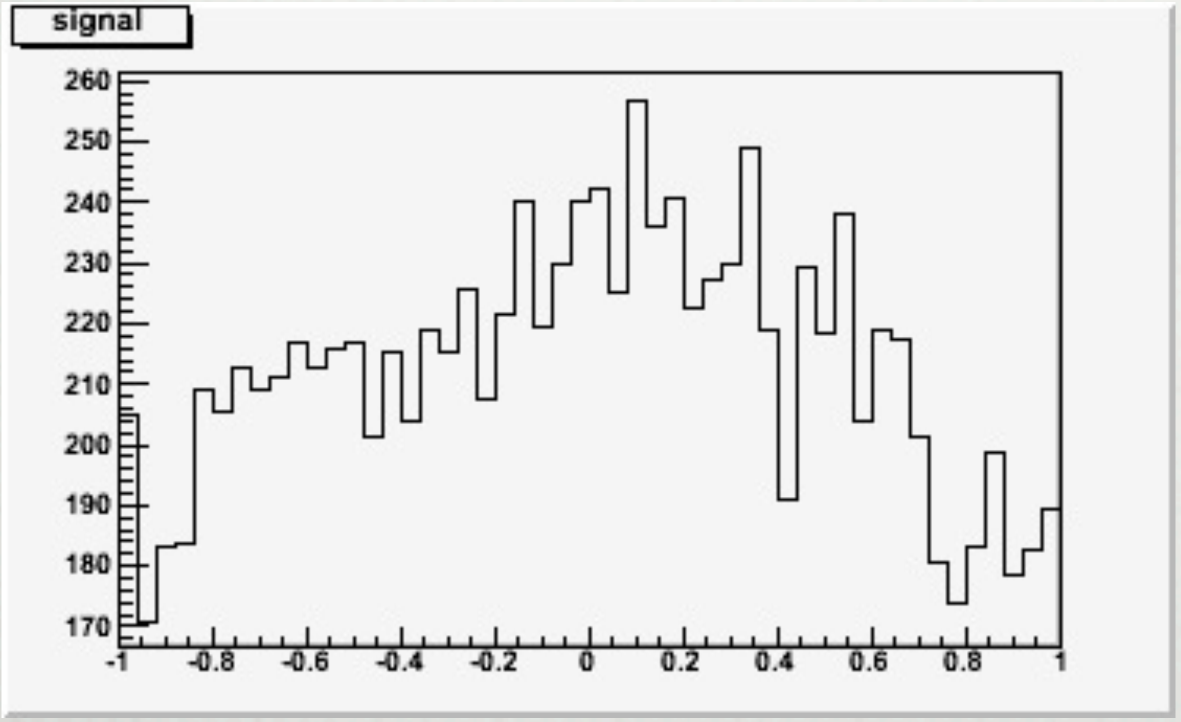


μtanβ~4TeV ⟶ large stau left-right mixing
⟶ stau is NLSP
⟶ FOR $a_\mu \sim 1.5\sigma \rightarrow m_{\tilde{\tau}} \sim 200GeV$

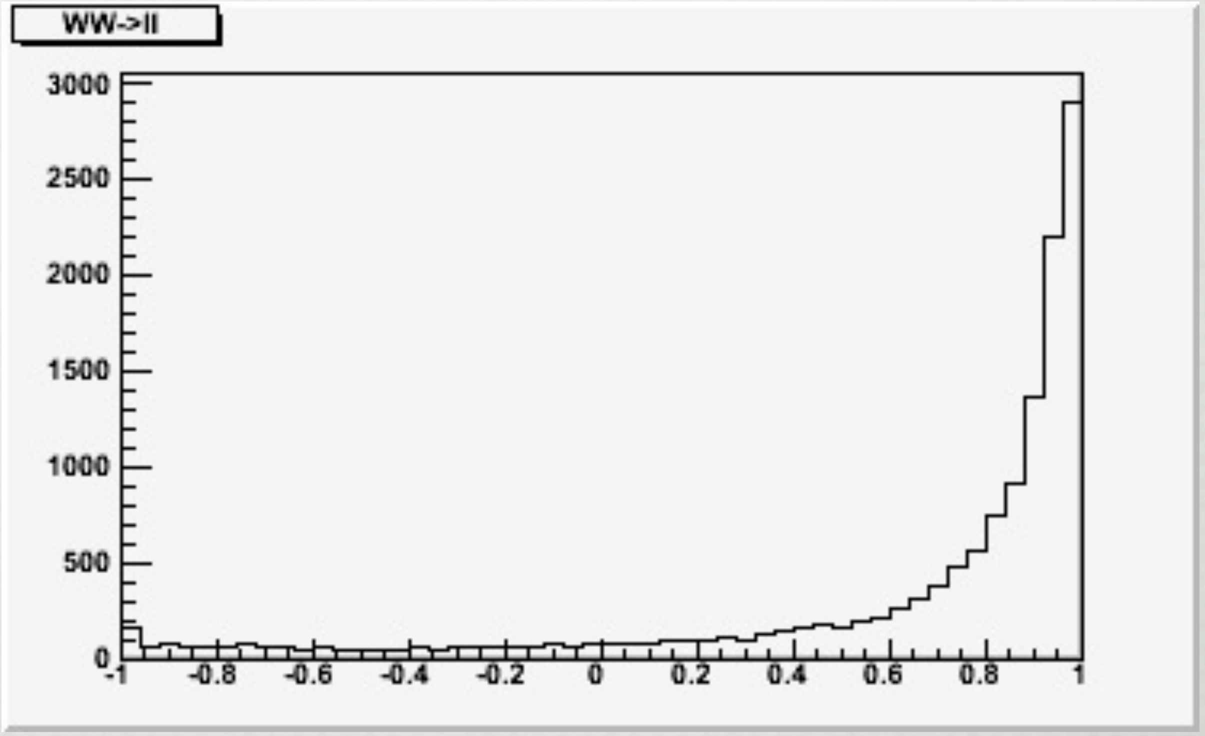
$$e_L^- e_R^+ \to W^- W^+$$ **CrossSection**







SIGNAL



WW

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

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

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