Tau and SUSY study in ILD

Taikan Suehara
ICEPP, The Univ. of Tokyo

Jenny List, Daniela Kaefer
DESY, for SUSY study

Thanks to all ILD people for various support.

Analysis notes supporting LOI

- Tau-pair

http://www.ilcild.org/documents/ild-loi-material/tau090316.pdf/at_download/file

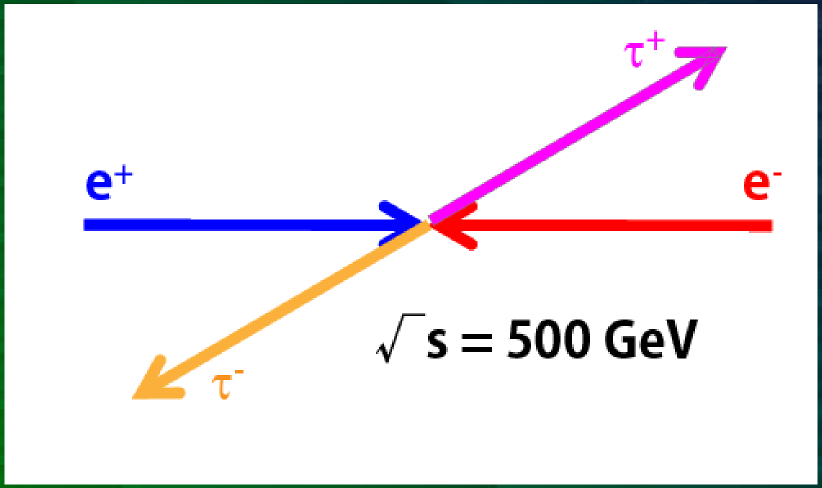
- SUSY point5

http://www.ilcild.org/documents/ild-loi-material/point5_090319_2.pdf/at_download/file

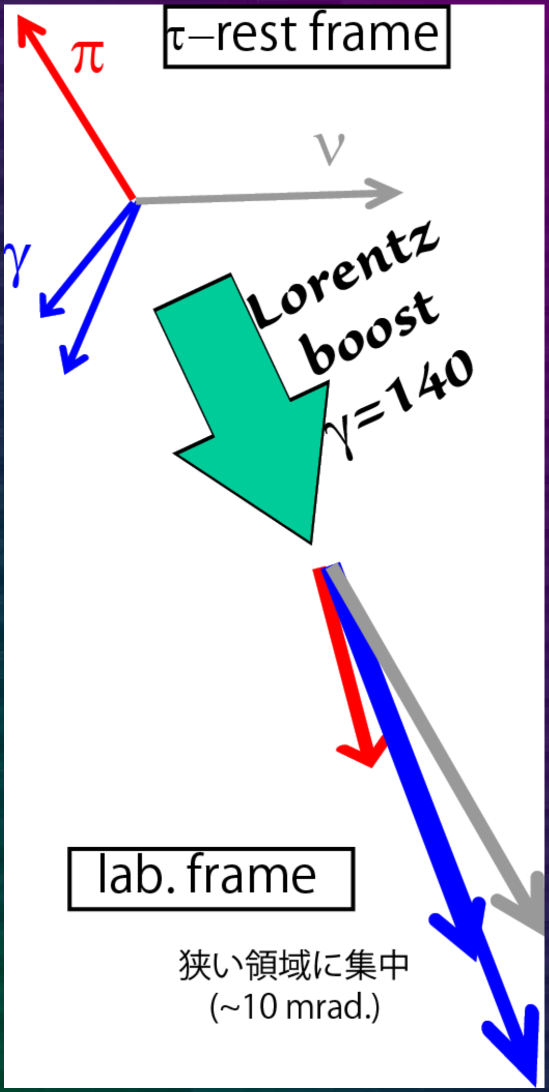
Please read them for details.

Tau-pair analysis

Tau-pair process



Difficulty on decay analysis



σ=2600 fb^{-1} ($e^-_L e^+_R$) σ=2000 fb^{-1} ($e^-_R e^+_L$)

radiative events: ~70%

[Observables]

P(e$^-$)=80%, P(e$^+$)=30%, 500 fb^{-1}

- σ, A_{FB} (bg suppression)
- Polarization P(τ)

  ↑Decay angle determination

Data Samples

- Signal events (tau-pair)
  - 500 fb^{-1} tau-pair events generated in DESY
    - Correct polarization treatment
    - 100% left/right e-/e+ samples.
      Event weighting applied for 80/30 polarization.
- SM events (mass production, ~10M events)
  - 20-50 fb^{-1} ee->2/4/6-jet(+lepton) events
  - 0.1 fb^{-1} $\gamma\gamma/e\gamma$ events
  - Preselected Bhabha events (~1 fb^{-1})
    - Back-to-back (opening angle > 165 deg)
    - $|\cos(\theta)| < 0.92$
- All ILD_00 geometry

BG suppression

BG suppression cuts

- # Track <=6
- 1(+)+1(-) clusters
- Opening angle >178 deg
- $|\cos\theta|_\tau$ < 0.9
- < 2 electrons, < 2 muons
- 40 < E_{vis} < 450 GeV
- 30 < MaxE(τ) < 240 GeV

Purity ~ 90% (almost bg free)

Cuts	Tau-pair	Bhabha	$\mu\mu$	$n\ell + n\nu$	$\gamma\gamma \to \ell\ell$	other $\gamma\gamma$, $e\gamma$	other
# tracks, # clusters	573140	1.24e+07	590712	1.15e+06	1.39e+09	4.07e+07	1.25e+06
Opening angle > 178 deg.	152758	7.78e+06	157407	7938	8.41e+06	59454	2673
$\lvert\cos\theta\rvert < 0.9$	129208	5.44e+06	133413	3278	6.39e+06	57534	447
ee, $\mu\mu$ veto	118557	38803	2616	2113	1.20e+06	50645	118
$40 < E_{vis} < 450$ GeV	114819	1861	491	1931	95365	10647	23
$30 <$ Max $E(\tau) < 240$ GeV	105369	16	61	1833	10133	0	16

(a) e^-_L (80%) e^+_R (30%)

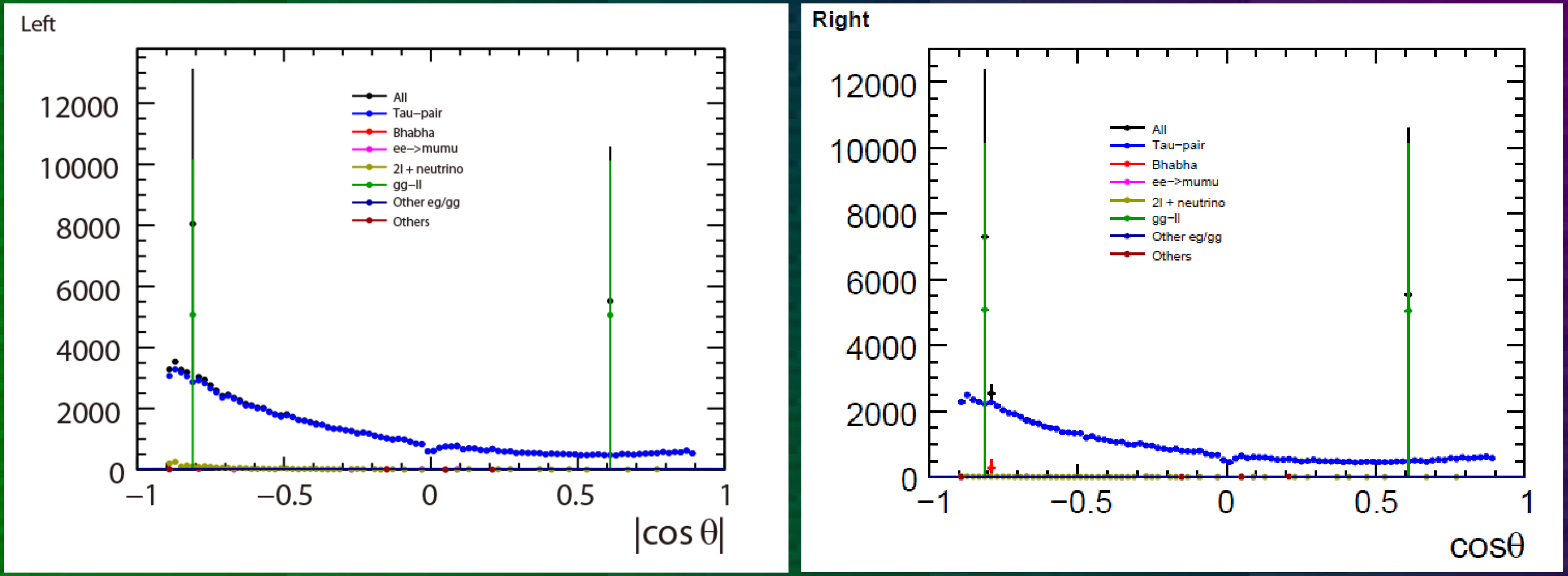
Cuts	Tau-pair	Bhabha	$\mu\mu$	$n\ell + n\nu$	$\gamma\gamma \to \ell\ell$	other $\gamma\gamma$, $e\gamma$	other
# tracks, # clusters	447002	1.13e+07	460889	116200	1.39e+09	4.69e+07	1.23e+06
Opening angle > 178 deg.	127061	6.97e+06	133628	519	8.41e+06	59920	2966
$\lvert\cos\theta\rvert < 0.9$	107489	4.82e+06	113785	218	6.39e+06	58596	433
ee, $\mu\mu$ veto	98886	42237	2078	132	1.20e+06	51196	101
$40 < E_{vis} < 450$ GeV	94181	3395	405	122	95365	11199	24
$30 <$ Max $E(\tau) < 240$ GeV	84051	269	49	116	10133	0	7

(b) e^-_R (80%) e^+_L (30%)

σ, A_{FB}

σ: 0.33% ($e^-_L e^+_R$), 0.37% ($e^-_R e^+_L$) stat. error (count based)

A_{FB}: 51.64 ± 0.29% ($e^-_L e^+_R$), 44.18 ± 0.37% ($e^-_R e^+_L$)

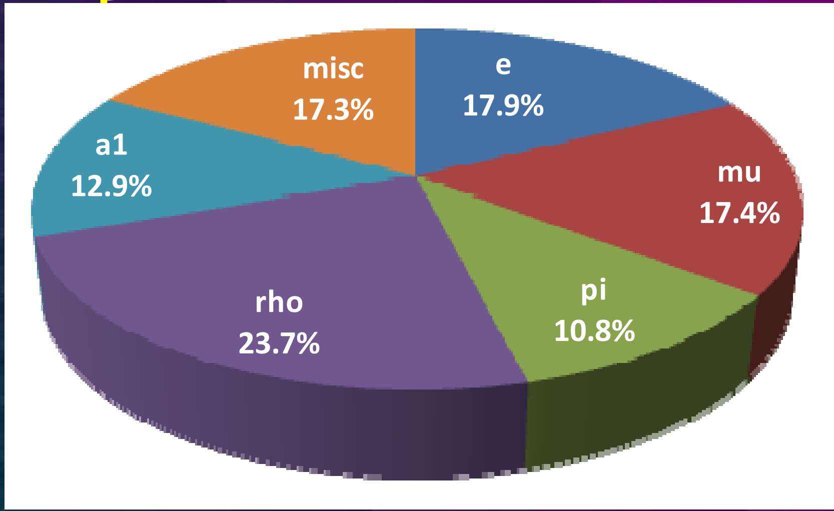


Green: γγ->ττ, more events will be processed.

Decay modes in A_{pol} analysis

5 major decay modes

- Leptonic (35.3% in total)
  - 「Lepton ID」 (high eff.)
  - P=0.22 (lost power by 2 νs)
- Pinu decay (10.8%)
  - 「only one $\pi^{\pm}$」 (simplest)
  - P=0.58 (full)
- Rhonu decay (23.7%)
  - 「one $\pi^{\pm}+2\gamma$」 P=0.49 (almost full)
- A1nu decay (12.9%)
  - 「one $\pi^{\pm}+4\gamma$」 or 「three $\pi^{\pm}$」 (each 50%)
  - P=0.45, 3-prong is useful.



Branching ratio of tau

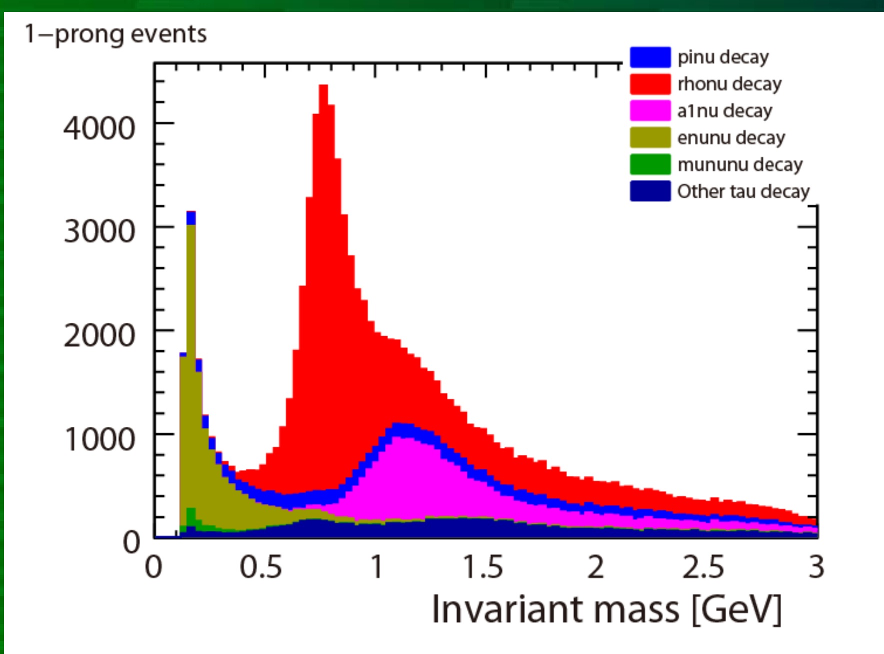
P = Sensitivity
M.Davier et al., PLB306 411 (1993)

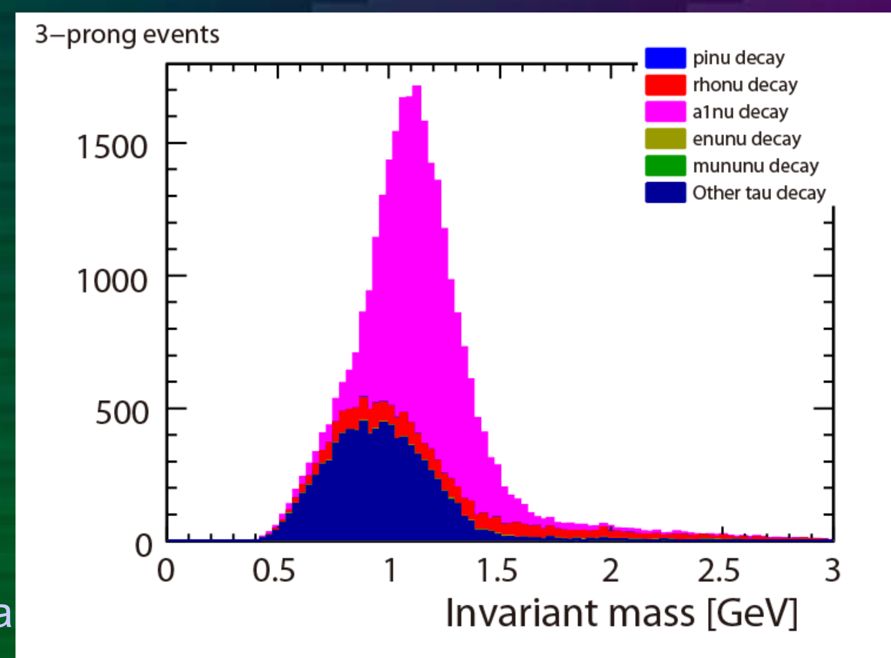
Minimize stat. error by combining decay modes

Mode selection

- Pure-leptonic decay – lepton ID
- Hadronic decay – composite selection
  - # prongs, # neutrals
  - Lepton veto
  - Invariant mass (ρ = 0.77 GeV, a_1 = 1.26 GeV)

Quite complicate cuts:
Details are in backup slides.





Mode selection – efficiency & purity

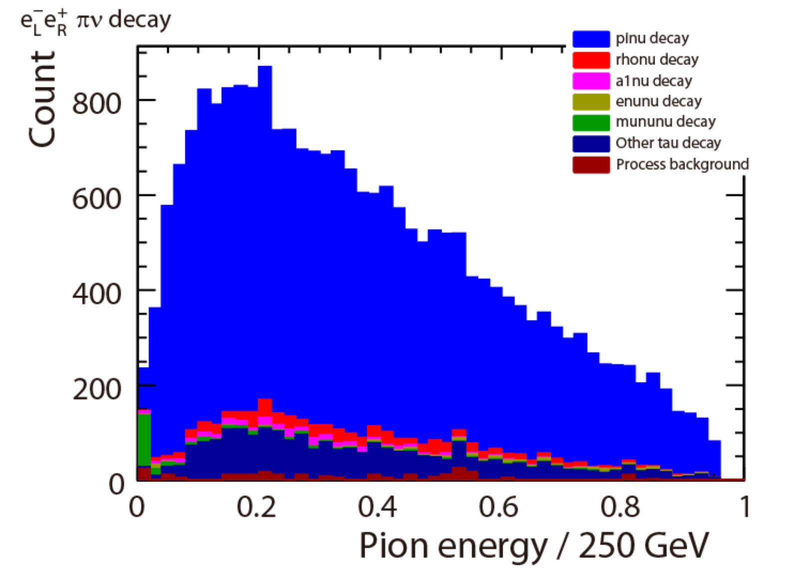
Mode	Signal	Background	Efficiency	Purity
$e\nu\nu$	32449	2374	95.2%	93.2%
$\mu\nu\nu$	30379	1694	86.1%	94.7%
$\pi\nu$	19565	9021	81.7%	68.4%
$\rho\nu$	39578	13604	67.2%	74.4%
$a_1\nu$ (3-prong)	13802	2297	78.5%	85.7%

- > 65% efficiency and purity are obtained.
  - Not yet for a1nu 1-prong mode
- Two issues:
  - Lepton ID is degraded in current samples
  - More # of neutrals in PFOs
    - Especially in high energy pions
    - Pandora is mainly for jets, not for single energetic pion

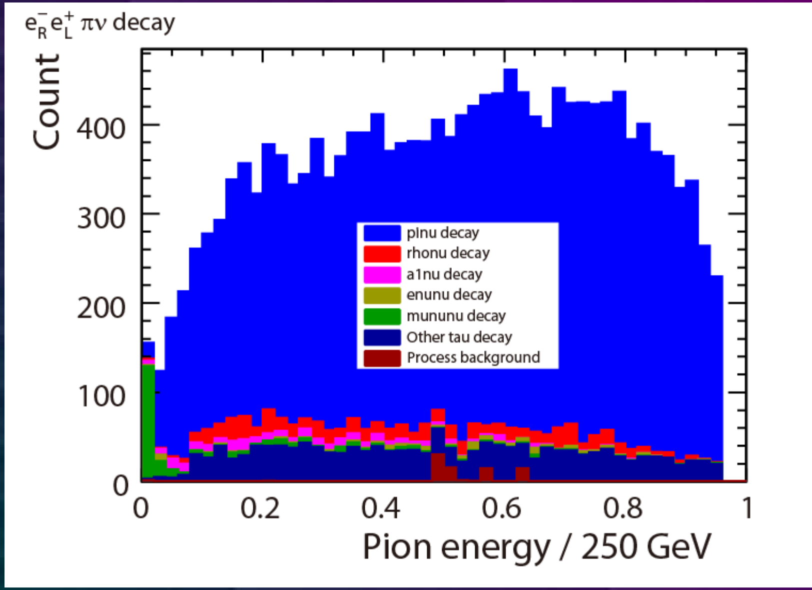
A_{pol} calculation ($\pi\nu$ mode)

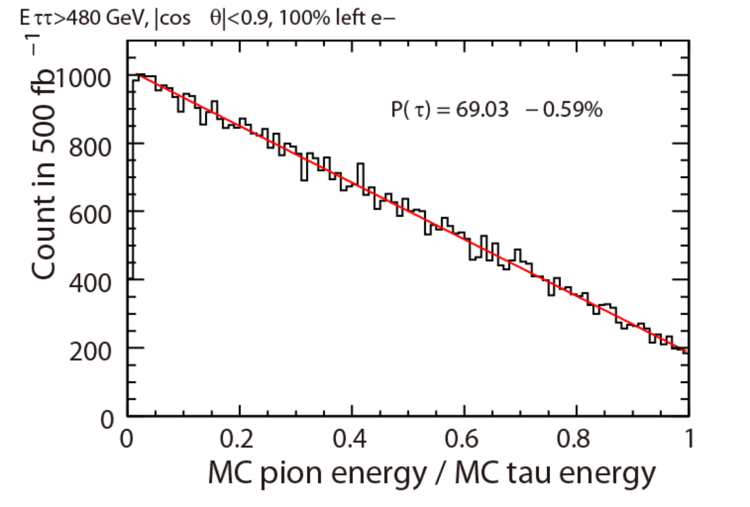
left

right

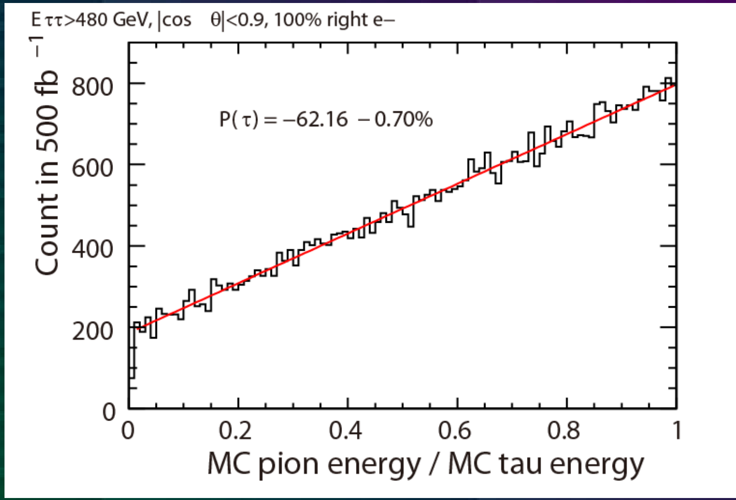


Reco dist
with
all cuts

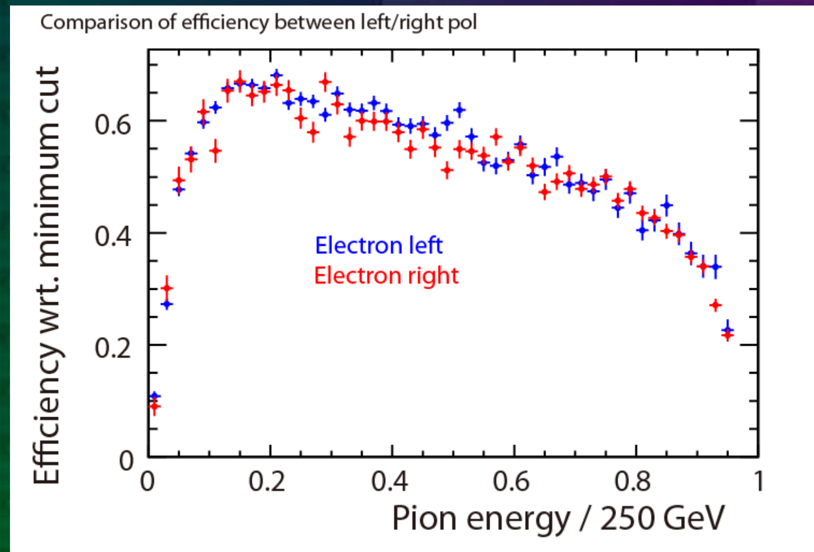




MC truth with
minimal cuts

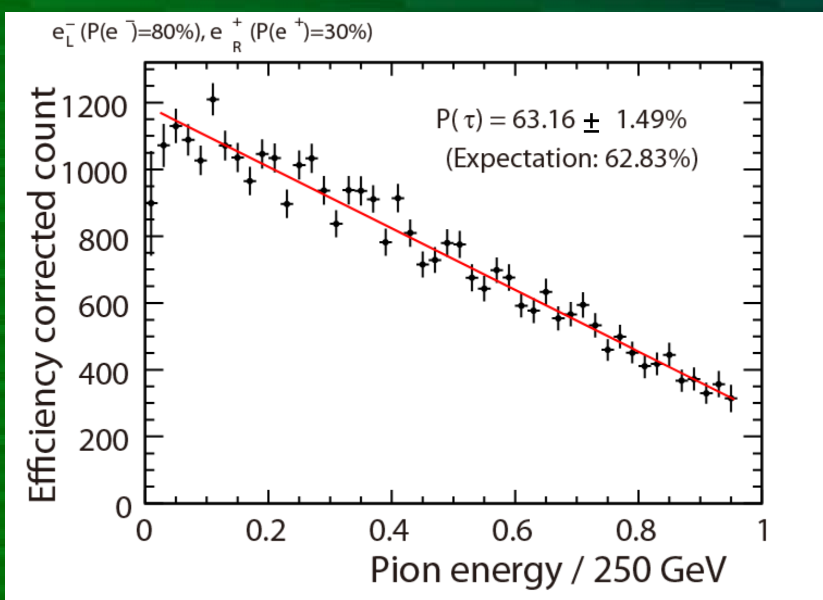


A_{pol} calculation ($\pi\nu$ mode) (cont.)

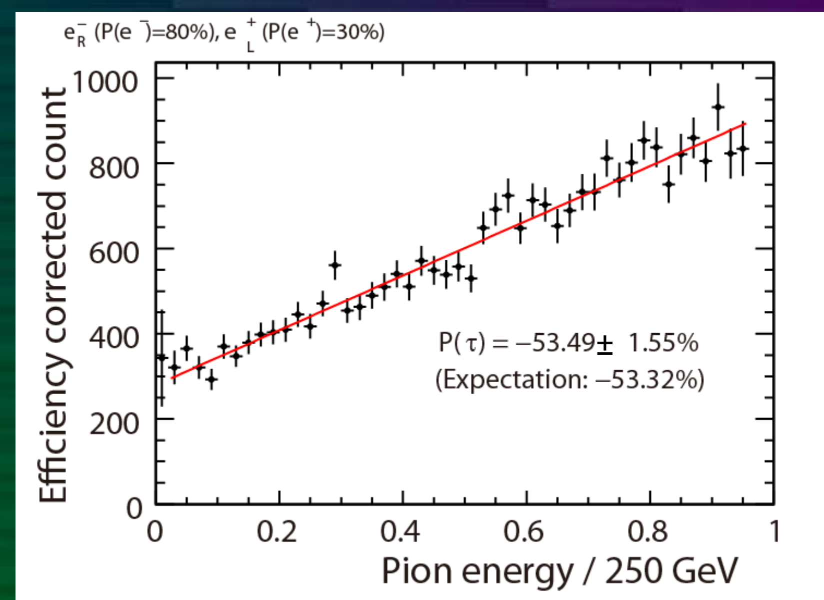


Efficiency of cut + reco (By comparison to MC dist.)

Corrected distribution (80% left e-)



Corrected distribution (80% right e-)



Estimation using analyzing power

Modes	# events after cut	Sensitivity	Analyzing power
$\pi\nu$	19565	0.58	11347
$\ell\nu\nu$	62828	0.22	13822
$\rho\nu$	39578	0.49	19393
$a_1\nu$ (3-prong only)	13802	0.45	6210
Total			50772

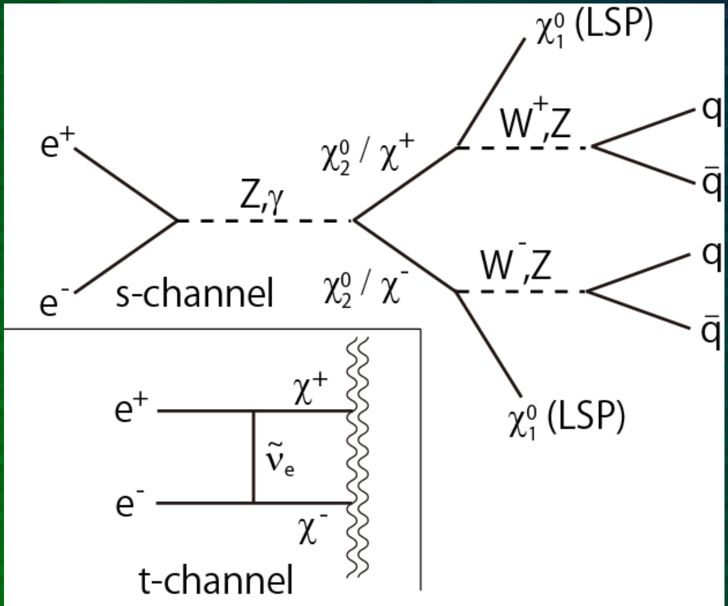
- Sensitivity: relative value expressing statistical power/event for each process.
- Pinu: 1.5% stat. error (previous plots)
- Analyzing power is 4.5 times larger if using all modes
  →Total stat. error estimation = 0.7%
- Dedicated analysis of every decay mode are in preparation.

Summary for Tau

- Backgroud is almost negligible.
- Excellent σ and A_{FB} resolution.
- > 65% purity / efficiency are obtained for polarization analysis of leptonic, pinu, rhonu and a1nu(3-prong) mode.
- Polarization resolution of pinu mode is 1.5%, which can be extrapolated to 0.7% error by combining all modes.
  - Dedicated analysis on rhonu, a1nu and leptonic mode are in preparation.

SUSY point5

SUSY chi1/ne2-pair process



SUSY parameters:
m_0 = 206 GeV, $m_{1/2}$ = 293 GeV,
tan β = 10, A = 0, μ = 375 GeV

Degenerate

$m(\chi^{\pm}_1)$ = 216.5 GeV, $m(\chi^0_2)$ = 216.7 GeV
$m(\chi^0_1)$ = 115.7 GeV, Others heavy

100 GeV diff.: decays W/Z + LSP (>95%)

$\sigma(e^+e^- \rightarrow \chi^+_1\chi^-_1)$ = 132.2 fb
$\sigma(e^+e^- \rightarrow \chi^0_2\chi^0_2)$ = 23.3 fb

5.7 times

- Analysis key: W/Z separation in 4j environment
- Observables
  - Cross section of chargino and neutralino: 1D/2D fit
  - SUSY mass determination

Data Samples

- SUSY point5 signal events generated with whizard (worked by DESY)
  - 500 fb^{-1} all-SUSY processes in point5
  - Another 500 fb^{-1} $\chi^{\pm}/\chi^{0}$ signal events for template

  NOTE: m_W = 79.8 GeV due to whizard's problem
- SM events (mass production, ~10M events)
  - 20-50 fb^{-1} ee->2/4/6-jet(+lepton) events
  - 0.1 fb^{-1} $\gamma\gamma/e\gamma$ events
  - Additional 500 fb^{-1} $\gamma\gamma$ -> WW events
- All ILD_00 geometry

Cuts for SM suppression

BG suppression cuts

"qqqq + missing"

- 4-jet clustering (Durham)
- # Track >= 20
- 100 < E_{vis} < 300 GeV
- each E_{jet} > 5GeV
- $|\cos\theta|_{jet}$ < 0.99
- unlike 3jet ($y_{th,3}$ > 0.001)
- each jet has >= 2tracks
- $|\cos\theta|_{miss}$ < 0.99
- no > 25 GeV leptons

Loose cut (efficiency ~ 90%)

	ch1 had	ne2 had	other SUSY	SM gg	SM 6f	SM 4f	SM2f	SM other
nocut	28529	5488	74650	3.66e+09	521610	1.48e+07	2.14e+07	4.75e+06
Total # of tracks $\geq$ 20	27897	5449	24305	3.03e+06	495605	6.68e+06	5.33e+06	0
$100 < E_{\rm vis} < 300$ GeV	27895	5449	22508	1.06e+06	44394	959805	1.56e+06	0
$E_{\rm jet} > 5$	27889	5446	20721	908492	44096	916507	1.47e+06	0
$\lvert\cos(\theta)_{\rm jets}\rvert < 0.99$	26560	5240	19200	350364	41098	678083	874907	0
$y_{34} > 0.001$	26416	5218	15255	202510	38638	423080	166305	0
# of tracks $\geq$ 2/jets	25717	5146	9559	162193	22740	255870	145270	0
$\lvert\cos(\theta)_{\rm miss}\rvert < 0.99$	25463	5099	9487	25087	22311	193706	4039	0
$E_l < 25$	25123	4981	6463	23133	14407	154927	3534	0

Kinematic fit & Jet pairing

- MarlinKinFit processor
  - (Essential) free parameters: Energy and opening angle for each jet(-pair)… NDF=6
  - Constraints:
    - Two di-jet masses are the same – 1C fit
    - Two di-jet masses are m_W / m_Z – 2C fit (W/Z)
  - Implemented in Desy (J.List et al) and shared
- Jet pairing
  - All pair
  - $$\chi^2_W(m_1,m_2) = \frac{(m_1-m_W)^2+(m_2-m_W)^2}{\sigma^2}$$ $$\chi^2_Z(m_1,m_2) = \frac{(m_1-m_Z)^2+(m_2-m_Z)^2}{\sigma^2}$$
  - Best kinematic fit

Obs.	KinFit	Pairing
σ(1D fit)	1C	KinFit
σ(2D fit)	No	All
mass	2C	χ^2 / KinFit

Cross section – 1D fit (1)

By J. List (DESY)

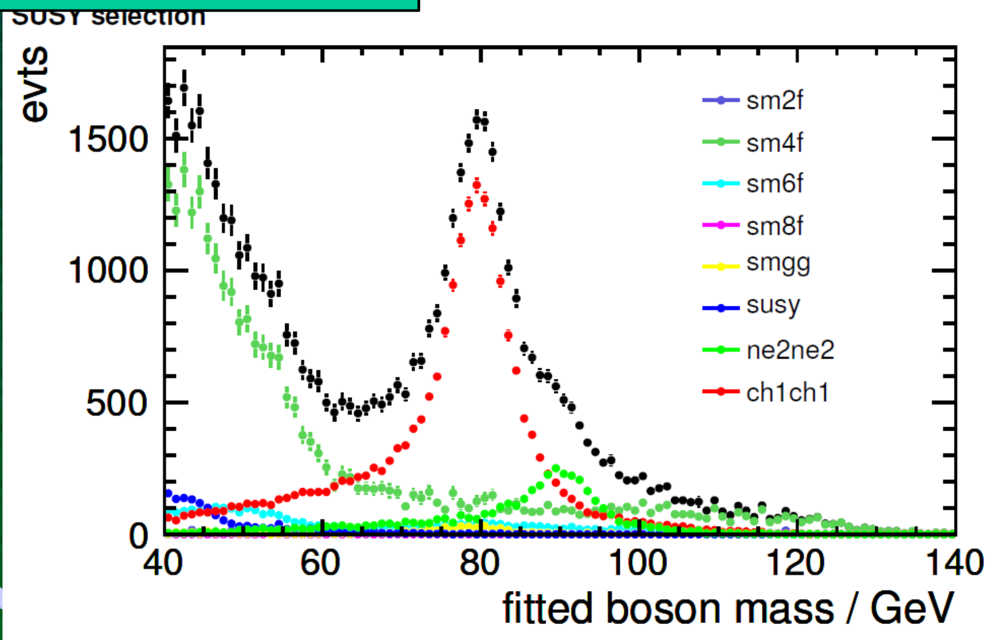
Additional cuts

	ch1 had	ne2 had	other SUSY	SM gg	SM 6f	SM 4f	SM2f
$E_l < 25$	25123	4981	6463	23133	14407	154927	3534
$N_{PFO} > 3$	25029	4975	6103	23014	13696	139429	3518
$\lvert\cos\theta_{pmiss}\rvert < 0.8$	20144	4079	5180	681	9950	62668	529
$M_{miss} > 220$ GeV	20139	4079	5180	630	3687	45867	389
kin. fit converged	20085	4068	4999	626	3649	44577	341

- Additional cuts
- 1C kinematic fit
- Pairing selection by the kinematic fit

gives good separation of W/Z peaks.

Mass spectrum



Cross section – 1D fit (2)

By J. List (DESY)

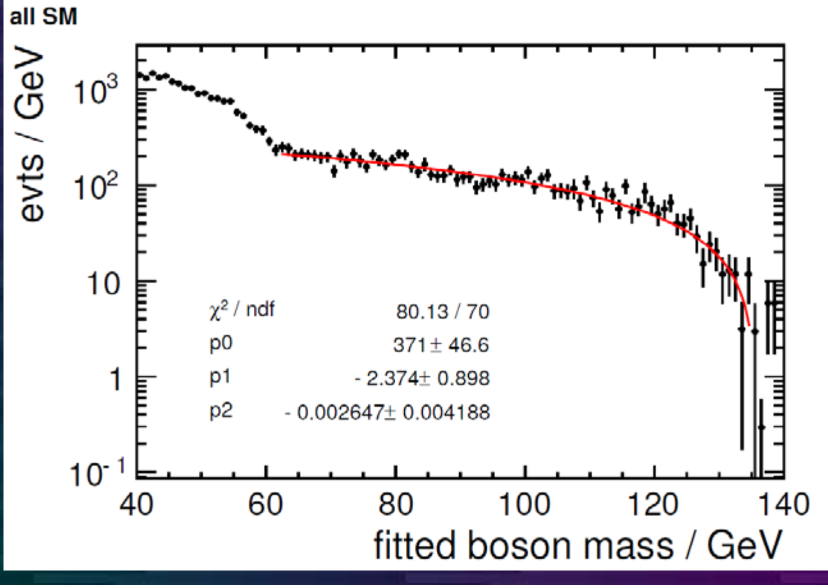
Cross section fitting procedure:

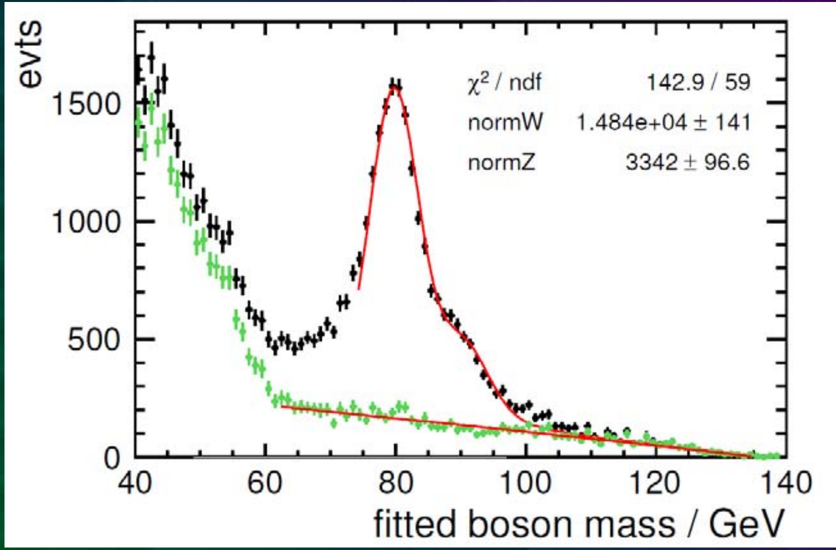
- SM background
  - 2^{nd} polynomial fitting separately
- SUSY + SM
  - Gaussian + BW for each W/Z
  - Width and center value fixed, normalization is the only free parameters
  - SM 2^{nd} polynomial fixed

Fit result (σ resolution):

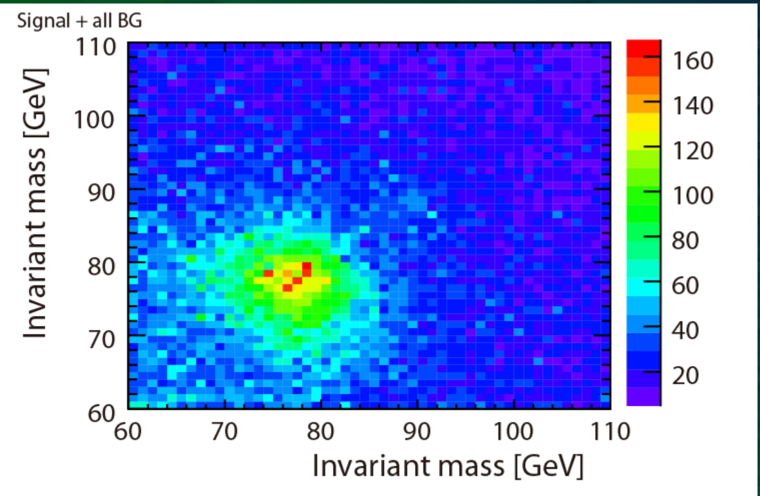
0.95% for $\chi^{\pm}$, 2.9% for χ^0_2.

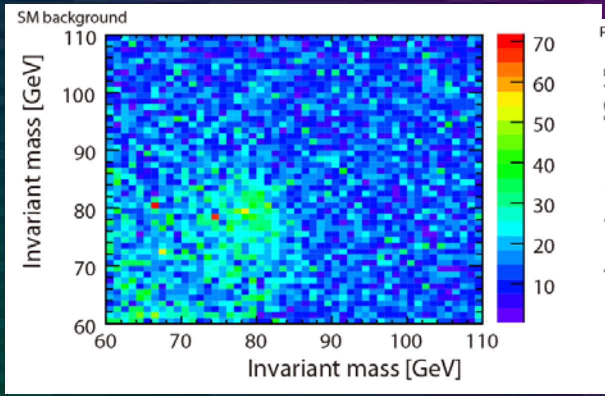
Resolution is a little worse, but less MC info required than 2D fit.

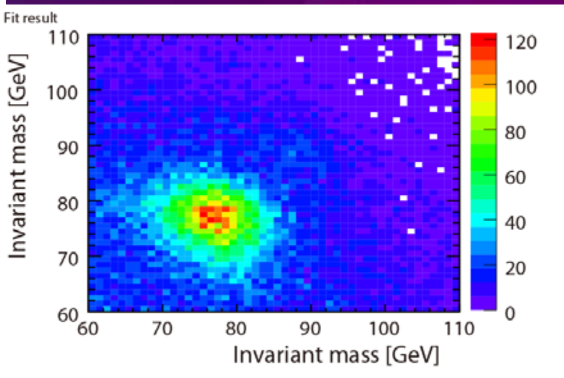




Cross section – 2D fit







↑SM background

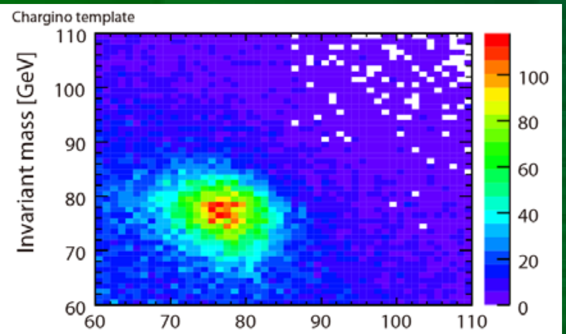
↑Fit result

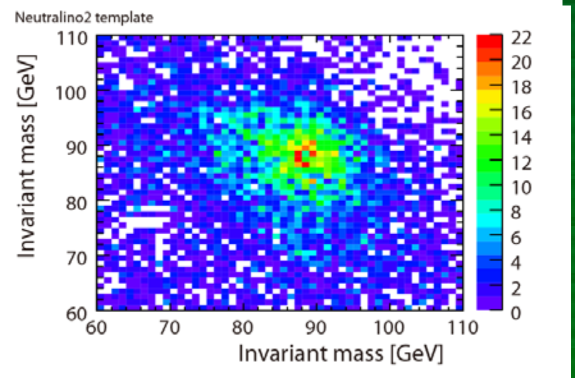
↓$\chi^\pm$ template

↑all events

Procedure

1. Make di-jet-mass-pair distribution.
2. SM background is subtracted considering statistical fluctuation.
3. $\chi^\pm$ and χ^0 distributions are created from independent samples (templates).
4. Fit normalization factor for templates.





← χ^0 template

Taikan Suehara et al., TILC09

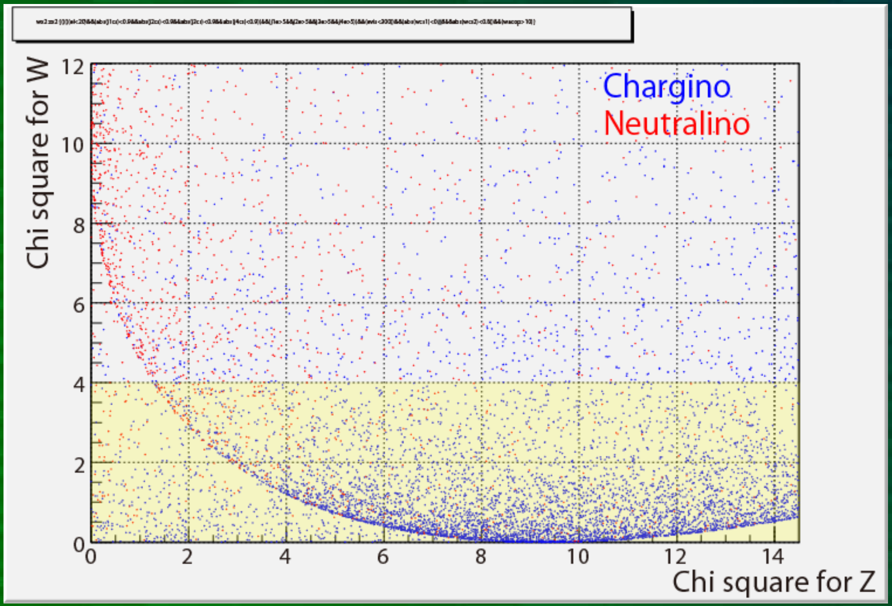
$\chi^\pm$: 0.64% resolution
χ^0 : 2.1% resolution

W/Z separation for mass fit

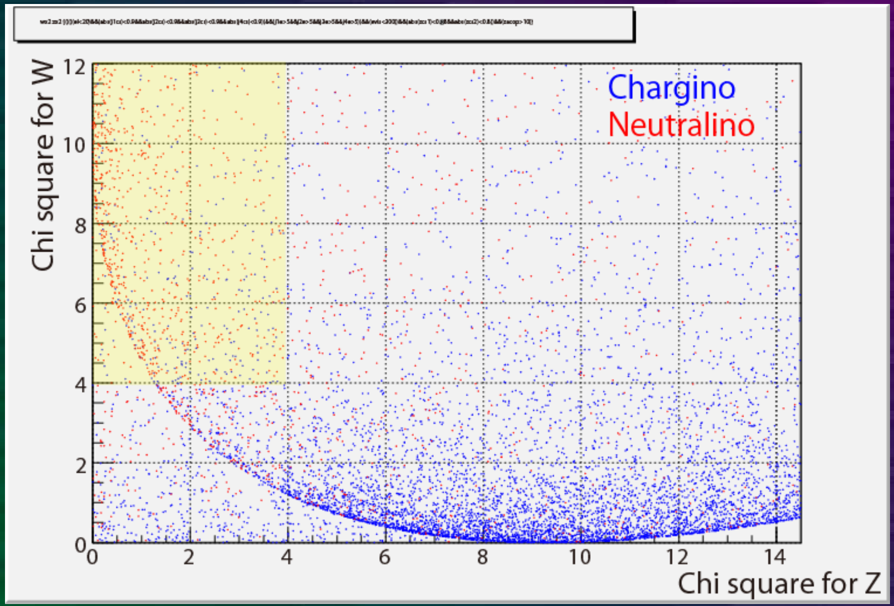
$$\chi^2_W(m_1, m_2) = \frac{(m_1 - m_W)^2 + (m_2 - m_W)^2}{\sigma^2}$$

$$\chi^2_Z(m_1, m_2) = \frac{(m_1 - m_Z)^2 + (m_2 - m_Z)^2}{\sigma^2}$$

- $\chi^2_W < 4$ for $\tilde{\chi}^\pm_1$ mass fit.
- $\chi^2_W > 4$ & $\chi^2_Z < 4$ for $\tilde{\chi}^0_2$ mass fit.

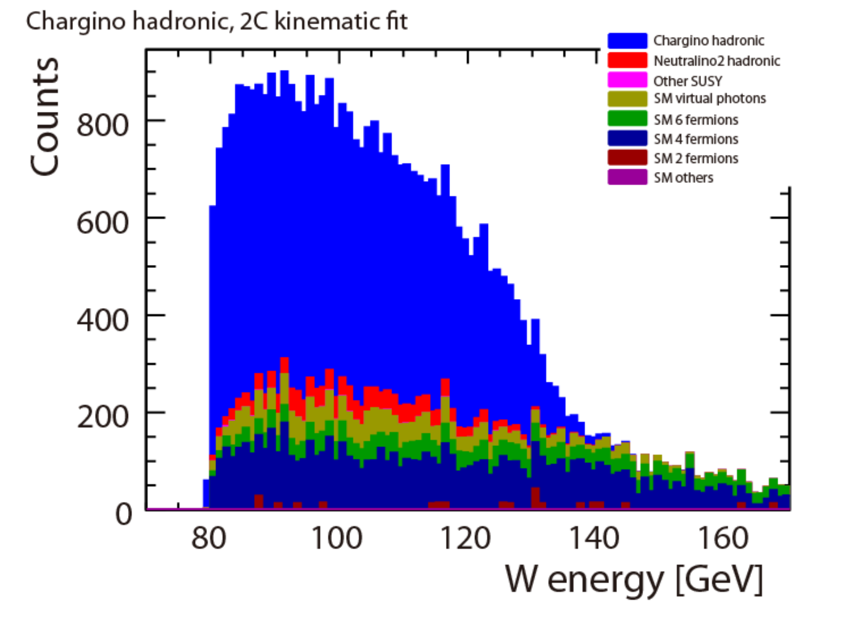


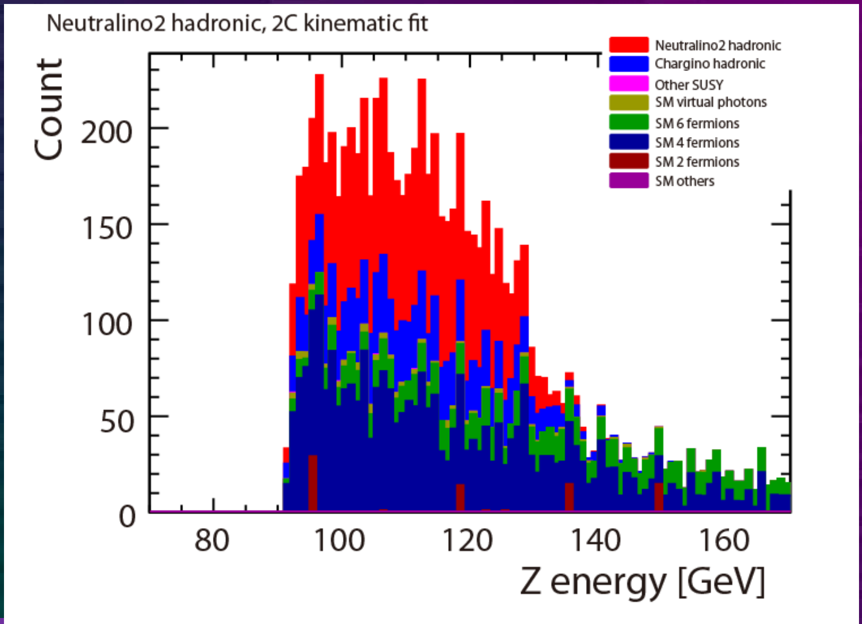
Chargino selection (no SM)

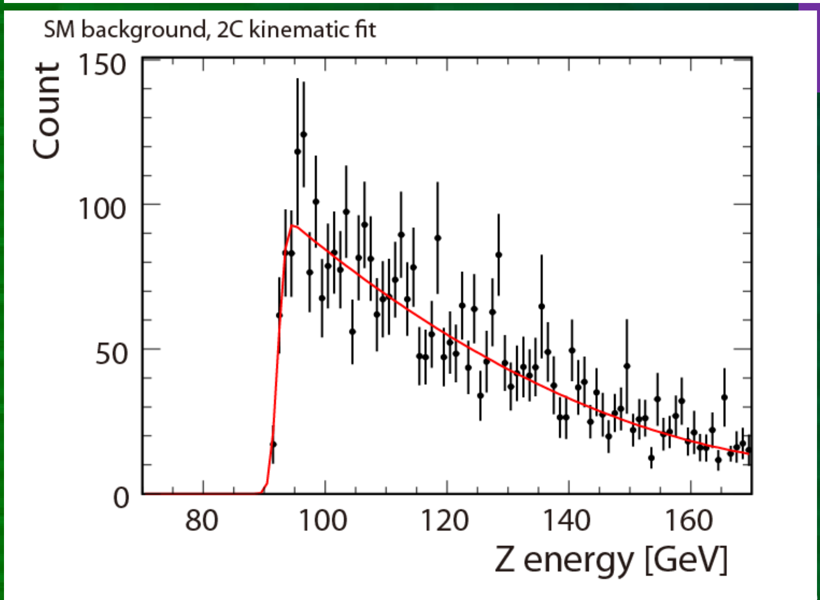


Neutralino selection (no SM)

Mass fit procedures



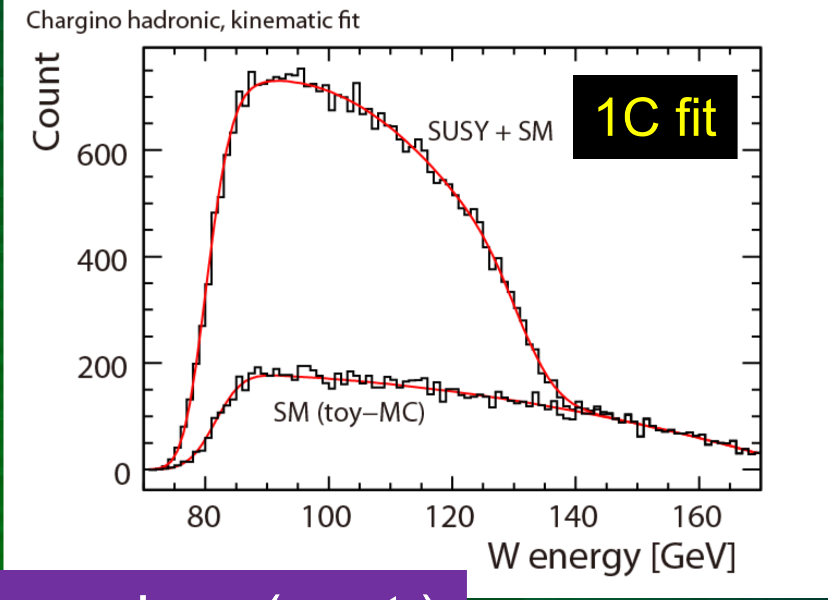


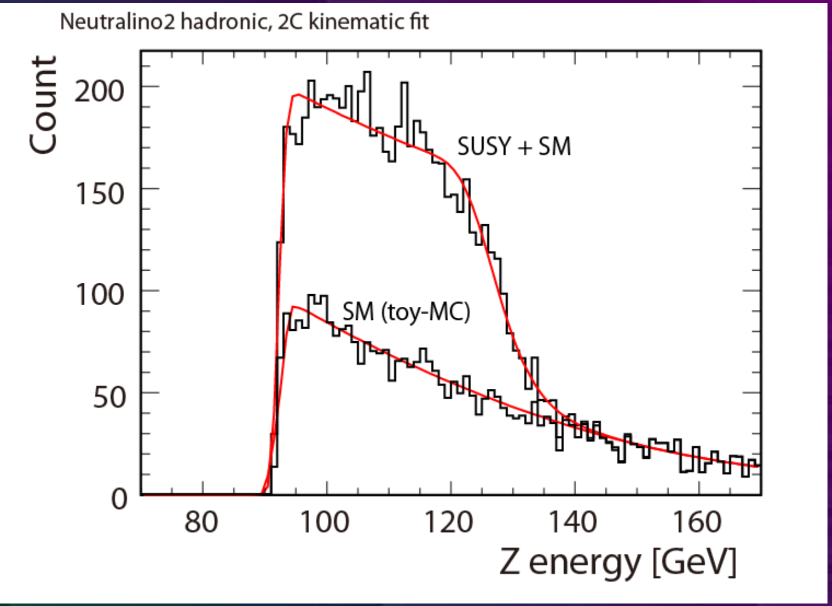


Procedure

1. 2C Kinematic fit
   after W/Z separation
   →upper plots
2. SM background parametrization
   2nd polynomial x Gaussian
   →left plot

Mass fit procedures (2)





Procedure (cont.)

3. Create SM distribution by toy-MC.
4. SUSY+SM fit (8 free param.)
   Convolution of 2nd pol. & Voigt func. + SM(fixed)
   integration range of convolution represents edges.
5. Mass calculation by kinematics.
   W low edge is just at m_W (no info for masses).
   Other 3 edges are used for the calculation.

Result and comments for the fit

Edge position resolution

W low: 0.07 GeV, W high: 0.62 GeV
Z low: 0.23 GeV, Z high: 0.71 GeV

Gaugino masses

$m(\chi^{\pm}_1) = 221.7 \pm 2.4$ GeV
$m(\chi^0_2) = 219.9 \pm 0.9$ GeV
$m(\chi^0_1) = 118.5 \pm 0.8$ GeV

- All SUSY masses are float at the fit. Correlation between SUSY masses is included.
- Edge positions are only used for mass determination.
  - Cross section dependence on SUSY masses is not used because it should have model uncertainty.
  - 2^{nd} pol and Voigt width are also not fixed.
- Error on $\chi^{\pm}$ mass is large.
  - Since W low edge cannot be used, LSP mass error on χ^0_2 fit is propagated to $\chi^{\pm}$ mass error.

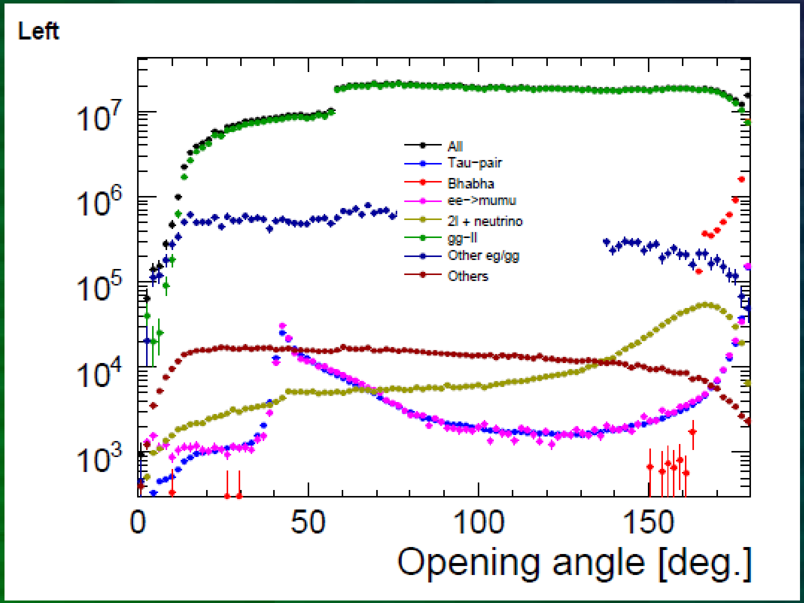
Summary for SUSY-point5

- ILD has sufficient power to separate chargino/neutralino events in point5 SUSY.
- < 1% ($\chi^{\pm}$) and 2-3% (χ^0_2) pair production cross section resolution is obtained.
- With 2C kinematic fit, < 1 GeV (χ^0_2) and 2.4 GeV ($\chi^{\pm}$) mass resolution is obtained.
- Although mass fit includes some conservative assumptions, it should be a good first estimate of real analyses.
  - Of course having a room to improve analysis…

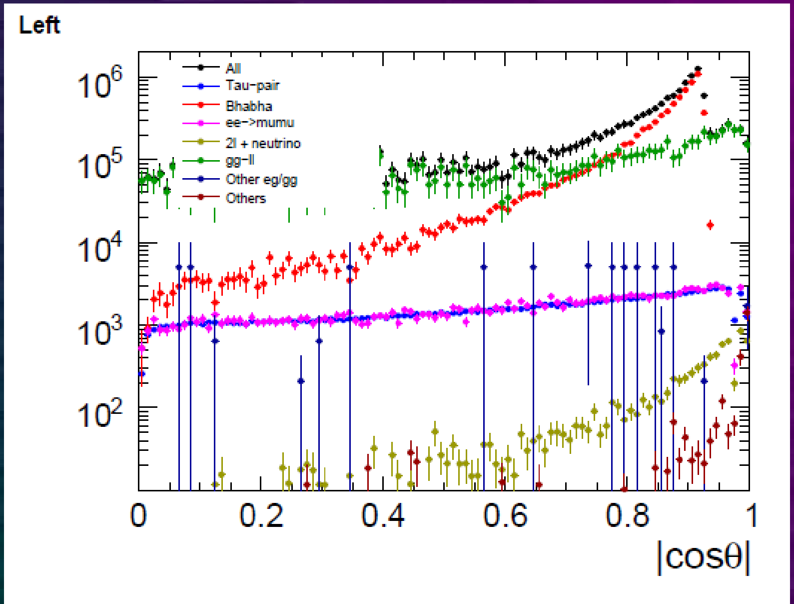
The end

Backup - Tau

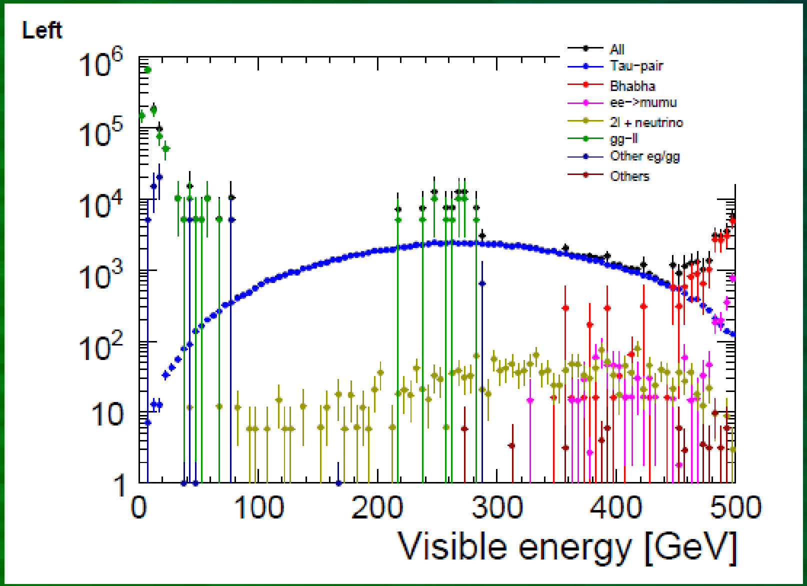
Cut plots



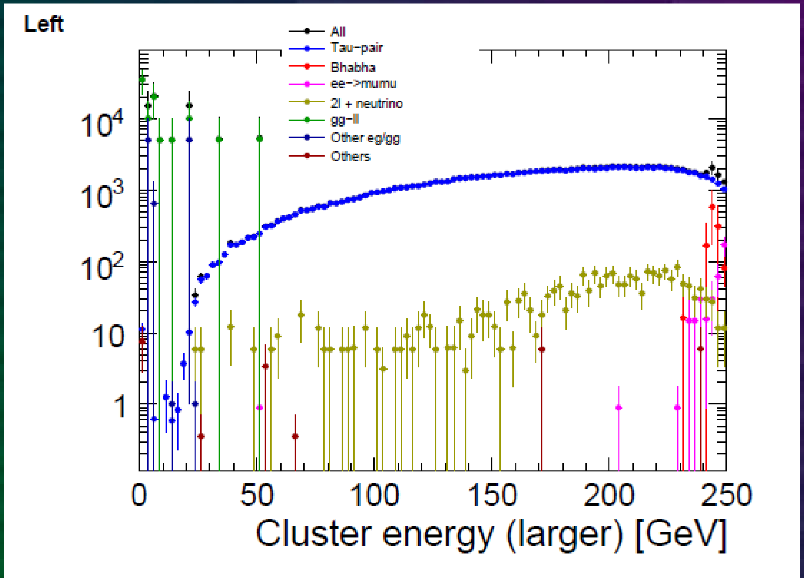
Left
All
Tau-pair
Bhabha
ee->mumu
2l + neutrino
gg-ll
Other eg/gg
Others
Opening angle [deg.]



Left
All
Tau-pair
Bhabha
ee->mumu
2l + neutrino
gg-ll
Other eg/gg
Others
|cosθ|



Left
All
Tau-pair
Bhabha
ee->mumu
2l + neutrino
gg-ll
Other eg/gg
Others
Visible energy [GeV]



Left
All
Tau-pair
Bhabha
ee->mumu
2l + neutrino
gg-ll
Other eg/gg
Others
Cluster energy (larger) [GeV]

Mode selection (1)

Leptonic mode

Cuts	$\pi\mu$	$\rho\nu$	$a_1\nu$	$e\nu\nu$	$\mu\nu\nu$	other tau	Process bg.
A_{FB} cut	23951	58897	37155	34089	35273	23649	25396
1-prong	23870	55090	18646	33855	35230	10956	19977
electron-ID (likelihood > 0.997)	156	779	339	32449	2	144	954
cluster energy cut	251	572	194	186	34706	126	2635
muon-ID	47	55	12	0	30379	12	1568

Pinu mode

Cuts	$\pi\mu$	$\rho\nu$	$a_1\nu$	$e\nu\nu$	$\mu\nu\nu$	other tau	Process bg.
A_{FB} cut	23951	58897	37155	34089	35273	23649	25396
1-prong	23870	55090	18646	33855	35230	10956	19977
lepton veto	23201	52636	17469	228	279	10526	16185
neutral energy	17363	133	7	127	261	1412	5273
1 neutral & mass outside ρ	2202	566	261	19	23	841	98
Sum of upper two rows	19565	699	268	146	284	2253	5371

Mode selection (2)

Rhonu mode

Cuts	$\pi\mu$	$\rho\nu$	$a_1\nu$	$e\nu\nu$	$\mu\nu\nu$	other tau	Process bg.
1-lepton veto	6532	5450	495	79	248	2027	319
1-neutral energy > 40 GeV	92	4611	448	13	33	1147	22
2-lepton veto	2115	17416	1166	52	49	1695	10437
2-neutral energy > 5 GeV	957	16938	1165	24	42	1556	5292
2-invariant mass (0.4 to 1.5 GeV)	235	15365	819	14	11	980	5225
3-lepton veto	636	14298	2509	27	16	1491	226
3-neutral energy > 5 GeV	223	13951	2501	9	15	1430	196
3-$E_{n3} < 5$ GeV (3-1)	221	12857	1783	9	15	1126	184
3-$E_{n3} < 1$ GeV (3-2)	182	8003	773	6	15	654	136
3-$0.47 < m < 0.87, 1.5 < m < 3$ GeV (3-1)	137	8067	467	4	5	670	71
3-$0.87 < m < 1.5$ GeV (3-2)	22	2691	496	0	1	184	67
3-total	159	10758	963	4	6	854	138
$\geq$4-lepton veto	550	15897	13691	49	11	4414	389
$\geq$4-neutral energy > 5 GeV (4-0)	182	15696	13667	24	10	4365	355
$\geq$4-$E_{n3} < 5$ GeV (4-1)	147	11042	2821	22	10	1079	191
$\geq$4-$E_{n3} < 2$ GeV (4-2)	96	5335	758	12	6	428	85
$\geq$4-$m < 0.87$ GeV (4-0)	8	4150	271	10	8	197	68
$\geq$4-$1.6 < m < 3$ GeV (4-1)	62	2718	629	2	1	445	17
$\geq$4-$0.87 < m < 1.6$ GeV (4-2)	20	1976	517	3	0	135	52
$\geq$4-total	86	8844	1417	15	9	777	137
all-total	572	39578	3647	46	59	3758	5522

Mode selection (3)

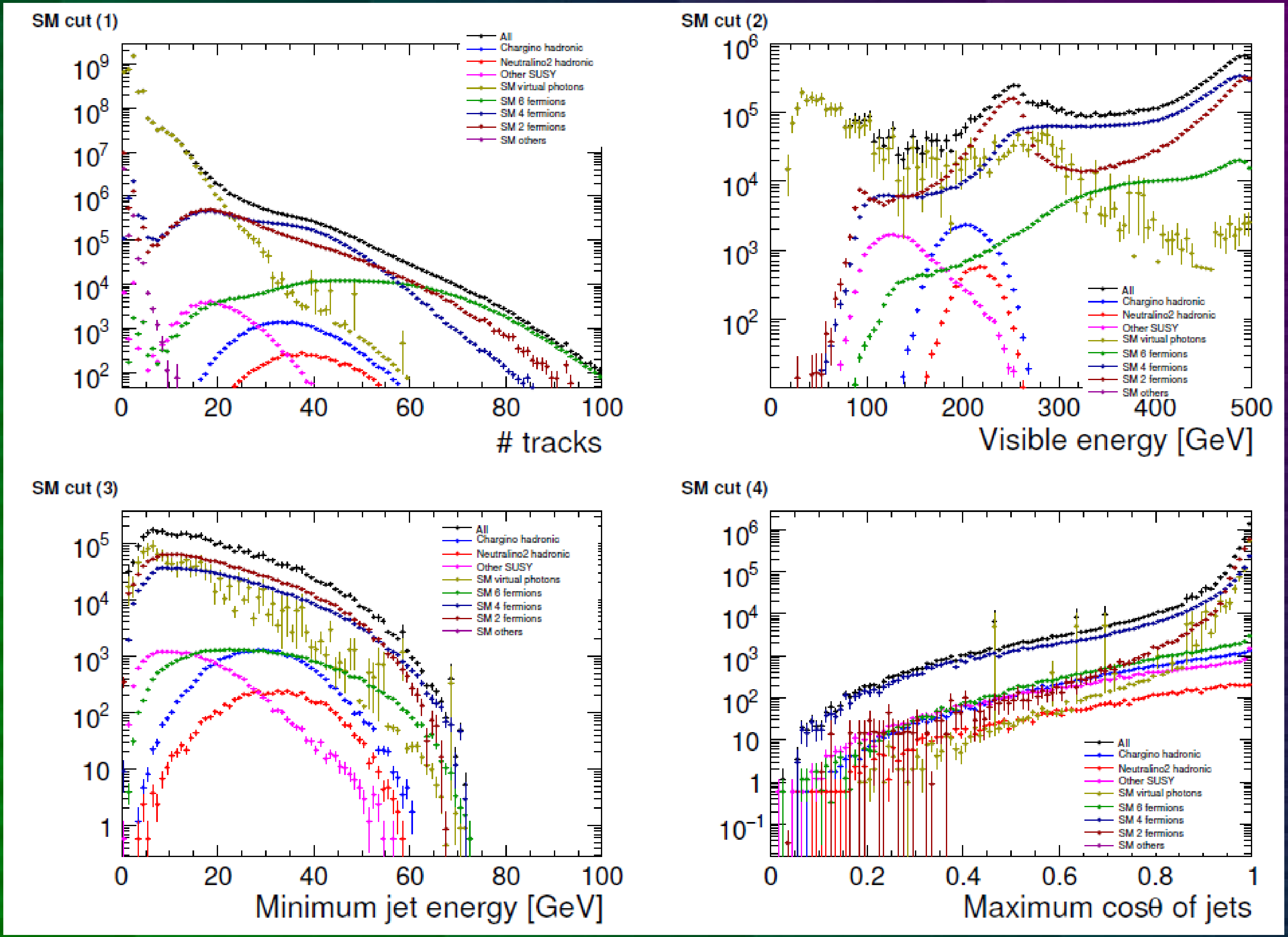
A1 mode (3prong)

Cuts	$\pi\mu$	$\rho\nu$	$a_1\nu$	$e\nu\nu$	$\mu\nu\nu$	other tau	Process bg.
3-prong events	36	3201	17576	139	14	8620	5400
0-no cut	0	83	6216	79	11	366	79
1-no cut	1	1205	5267	35	1	1065	62
1-lepton veto	1	59	4694	0	0	968	35
$\geq$2-no cut	35	1913	6092	23	0	7189	5258
$\geq$2-lepton veto	24	182	4074	0	0	6246	112
$\geq$2-neutral energy $<$ 10 GeV	3	25	2892	0	0	523	65
all-total	4	167	13802	79	11	1857	179

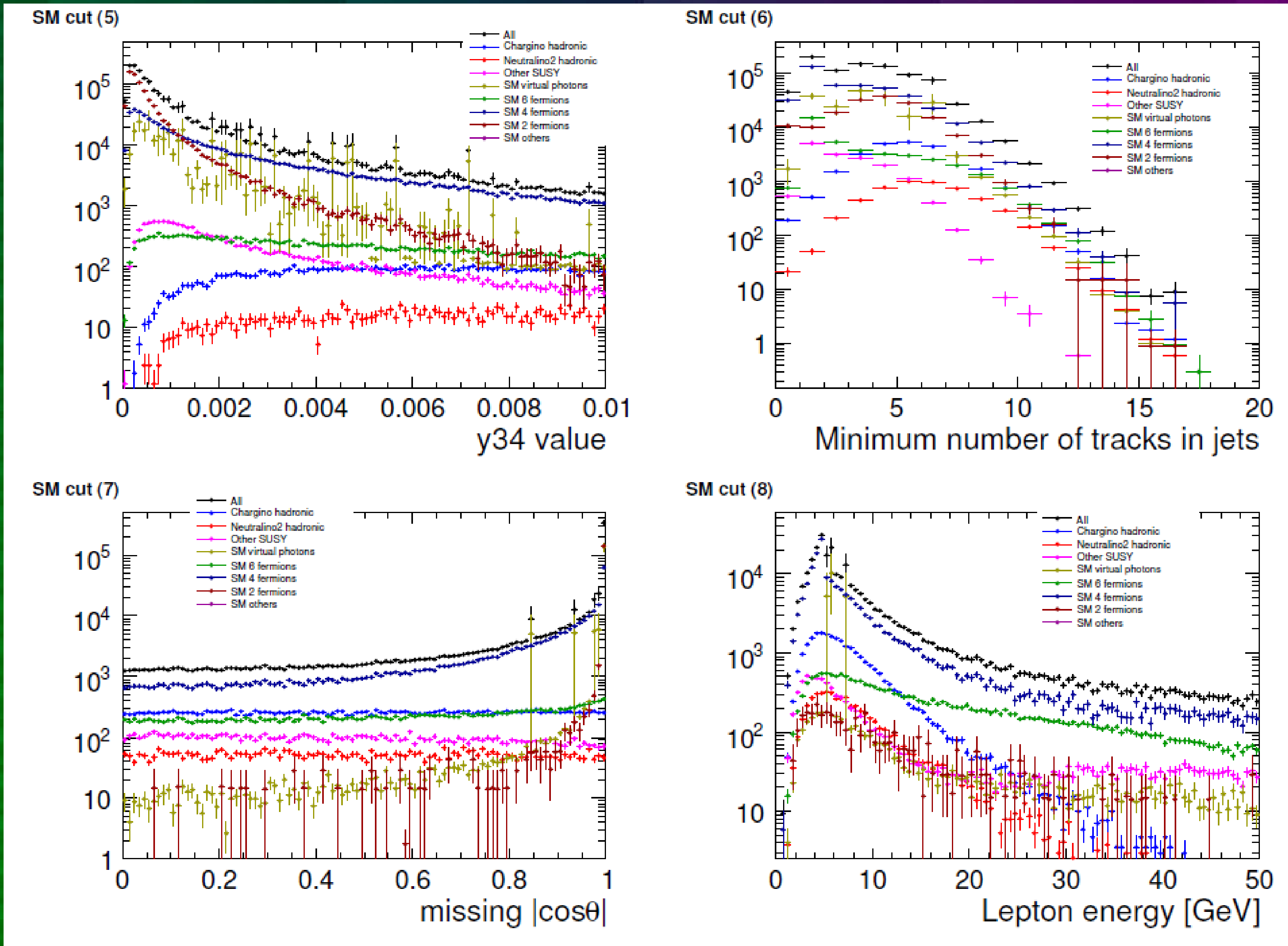
Mode	Signal	Background	Efficiency	Purity
$e\nu\nu$	32449	2374	95.2%	93.2%
$\mu\nu\nu$	30379	1694	86.1%	94.7%
$\pi\nu$	19565	9021	81.7%	68.4%
$\rho\nu$	39578	13604	67.2%	74.4%
$a_1\nu$ (3-prong)	13802	2297	78.5%	85.7%

Backup – SUSYp5

Cut plots(1)


SM cut (1)
All
Chargino hadronic
Neutralino2 hadronic
Other SUSY
SM virtual photons
SM 6 fermions
SM 4 fermions
SM 2 fermions
SM others
tracks
SM cut (2)
Visible energy [GeV]
SM cut (3)
Minimum jet energy [GeV]
SM cut (4)
Maximum cosθ of jets

Cut plots(2)



SM cut (5)
All
Chargino hadronic
Neutralino2 hadronic
Other SUSY
SM virtual photons
SM 6 fermions
SM 4 fermions
SM 2 fermions
SM others
y34 value
SM cut (6)
All
Chargino hadronic
Neutralino2 hadronic
Other SUSY
SM virtual photons
SM 6 fermions
SM 4 fermions
SM 2 fermions
SM others
Minimum number of tracks in jets
SM cut (7)
All
Chargino hadronic
Neutralino2 hadronic
Other SUSY
SM virtual photons
SM 6 fermions
SM 4 fermions
SM 2 fermions
SM others
missing |cosθ|
SM cut (8)
All
Chargino hadronic
Neutralino2 hadronic
Other SUSY
SM virtual photons
SM 6 fermions
SM 4 fermions
SM 2 fermions
SM others
Lepton energy [GeV]

Cut statistics

	ch1 had	ne2 had	other SUSY	SM gg	SM 6f	SM 4f	SM2f	SM other
nocut	28529	5488	74650	3.66e+09	521610	1.48e+07	2.14e+07	4.75e+06
Total # of tracks $\geq$ 20	27897	5449	24305	3.03e+06	495605	6.68e+06	5.33e+06	0
$100 < E_{vis} < 300$ GeV	27895	5449	22508	1.06e+06	44394	959805	1.56e+06	0
$E_{jet} > 5$	27889	5446	20721	908492	44096	916507	1.47e+06	0
$\lvert\cos(\theta)_{jets}\rvert < 0.99$	26560	5240	19200	350364	41098	678083	874907	0
$y_{34} > 0.001$	26416	5218	15255	202510	38638	423080	166305	0
# of tracks $\geq$ 2/jets	25717	5146	9559	162193	22740	255870	145270	0
$\lvert\cos(\theta)_{miss}\rvert < 0.99$	25463	5099	9487	25087	22311	193706	4039	0
$E_l < 25$	25123	4981	6463	23133	14407	154927	3534	0

Processes	No cut	SM all cut	Occupancy	Acceptance
Chargino hadronic	28529	25123	10.80%	88.06%
Neutralino2 hadronic	5488	4981	2.14%	90.76%
Other SUSY point5	74650	6463	2.78%	8.66%
qqqq (WW, ZZ)	4.29e+06	89779	38.60%	2.09%
qq$\nu\nu$ (ZZ)	367779	39411	16.95%	10.72%
qq$\ell\nu$ (WW)	5.19e+06	25291	10.87%	0.49%
$\gamma\gamma \rightarrow$qq	2.49e+08	19992*	8.60%	0.01%
qqqq$\ell\nu$ (tt)	216996	7252	3.12%	3.34%
qqqq$\nu\nu$ (WWZ)	9262	4763	2.05%	51.43%
qq	9.77e+06	3533	1.52%	0.04%
$\gamma\gamma \rightarrow$qqqq	26356	2624	1.13%	9.96%
Other background	3.43e+09	3357	1.44%	0.00%

* Number of events is 4 in 0.1 fb^{-1} MC statstics.