Status Report: Muon g-2 anomaly + SUSY at the ILC

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Muon g-2 + SUSY: status report

- Produced SUSY MC samples at ILC500 with WHIZARD2.8.5
  - Included beam energy spread, ISR, PYTHIA6 with patch, and TAUOLA
  - Details in backup
- Run detector simulation: this time DELPHES used
  - PID performance depends on DELPHES PFA
  - Will improve (or be more realistic) when we use ILD full detector simulation in future
- Started physics analysis with SM background

arXiv:2104.03217

	BLR1	BLR2	BLR3	BLR4
M_1	100	100	150	150
$m_L = m_R$	150	150	200	200
$\tan\beta$	5	10	5	10
μ	1323	678	1922	973
$m_{\tilde{\mu}_1}$	154	154	202	202
$m_{\tilde{\mu}_2}$	159	159	207	208
$m_{\tilde{\tau}_1}$	113	113	159	158
$m_{\tilde{\tau}_2}$	190	191	242	243
$m_{\tilde{\nu}_{\mu,\tau}}$	137	136	190	190
$m_{\tilde{\chi}_1^0}$	99	99	150	149
$m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_1^\pm}$	1323–1324	678–680	1922–1923	973–975
$a_\mu^{\mathrm{SUSY}} \times 10^{10}$	27	27	17	17
$\Omega_{\mathrm{DM}} h^2$	0.120	0.120	0.120	0.120
$\sigma_p^{\mathrm{SI}} \times 10^{47}$ [cm^2]	1.7	3.7	0.8	1.9
$\mu_{\gamma\gamma}$	1.01	1.01	1.01	1.01

Units in GeV
So far, I am only working with BLR1 parametrization.

Produced events (1)

Process $e^+e^- \rightarrow$	Pol (e-, e+) (%)	Xsec (fb)	N = L*Xsec (Assume L = 4 ab^{-1})	N = L*Xsec (Assume L = 1.6 ab^{-1})	N_generated	process ID
$\tilde{e}_L^+ \tilde{e}_L^-$	-80/+30	28.7091 +- 0.0012	114836	45935	500K	1
$\tilde{e}_L^+ \tilde{e}_L^-$	+80/-30	22.30497 +- 0.00071	89220	35688	500K	2
$\tilde{e}_R^+ \tilde{e}_R^-$	-80/+30	53.5626 +- 0.0019	214250	85700	1M	3
$\tilde{e}_R^+ \tilde{e}_R^-$	+80/-30	54.6909 +- 0.022	218764	87505	1M	4
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$	-80/+30	99.1388 +- 0.0079	396555	158622	1.5M	5
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$	+80/-30	25.9426 +- 0.0021	103770	41508	500K	6
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$	-80/+30	26.9622 +- 0.0021	107849	43140	500K	7
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$	+80/-30	92.4999 +- 0.0072	370000	148000	1.5M	8

1.6 ab^{-1} is the integrated luminosity of ILC500 with -80/+30 and +80/-30

Produced events (2)

Process $e^+e^- \to$	Pol (e-, e+) (%)	Xsec (fb)	N = L*Xsec (Assume L = 4 ab^{-1})	N = L*Xsec (Assume L = 1.6 ab^{-1})	N_generated	process ID
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	-80/+30	92.9890 +- 0.0063	371956	148782	1.5M	9
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	+80/-30	86.6444 +- 0.0059	346578	138631	1.5M	10
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	-80/+30	29.0410 +- 0.0033	116164	46466	500K	11
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	+80/-30	26.3214 +- 0.0029	105286	42114	500K	12
$\tilde{\tau}_1^+\tilde{\tau}_2^-$	-80/+30	8.18989 +- 0.00062	32760	13104	200K	13
$\tilde{\tau}_1^+\tilde{\tau}_2^-$	+80/-30	6.48573 +- 0.00050	25943	10377	200K	14
$\tilde{\tau}_2^+\tilde{\tau}_1^-$	-80/+30	8.19128 +- 0.00062	32765	13106	200K	15
$\tilde{\tau}_2^+\tilde{\tau}_1^-$	+80/-30	6.48553 +- 0.00050	25942	10377	200K	16

1.6 ab^{-1} is the integrated luminosity of ILC500 with -80/+30 and +80/-30

Potential problem

- The spin information is not stored in stau events
  - This might affect to the decay products of tau
  - It is OK for SM world (e.g.: Keita’s study)
  - So far, no special treatment applied

Physics analysis

- Made everything luminosity-weighted
  - Considered MC statistics
  - eLpR/eRpL for (e-, e+) = (-80%, +30%)/(+80%, -30%)
  - 1.6 ab^{-1} for both polarization (ILC500 full statistics)

- Start analysis with smuon events to measure edges
  - $m_{\mathrm{SUSY}}^2 = (\sqrt{s})^2 \frac{E^+E^-}{(E^+ + E^-)^2}$
  - $m_{\chi}^2 = m_{\mathrm{SUSY}}^2 \left[1 - \frac{2(E^+ + E^-)}{\sqrt{s}}\right]$

SM background (1)

- Added available IDR samples
  - /gpfs/group/ilc/soft/samples/mc-opt-3/ild/dst-merged/500-TDR_ws/PROCESS/ILD_l5_o1_v02/v02-00-01/~~~~~.slcio
  - processes
    - 2f: bhabha(Bhabha), leptonic (2lepton)
    - 4f: XXX_leptonic (XXX = singleW($e\nu W$), singleZee(eeZ), singleZnunu($\nu\nu Z$), singleZsingleWMix($e\nu W/eeZ/\nu\nu Z$), WW(WW), ZZ(ZZ), ZZWWMix(WW/ZZ))
    - all aa_4f (AA4f)

SM background (2)

- Also added aa_2f (AAee, AAll) created by SGV
  - /ghi/fs02/orig_root_fs02/ilc/grid/storm/users/berggren/mc-dbd/sgv-dst_6/500-TDR_ws/aa_2f/~~~~~.slcio
  - ~8 years old samples (even used in my PhD thesis)
  - 4 types of processes: aa_ee, aa_ll, aa_xx, aa_yy
  - included only aa_ee and aa_ll for this analysis
- Since the cross-section is huge, there are no full simulation samples of aa_2f @ 500 GeV.
- SGV is pretty much faster, but not enough MC samples (event weight ~ 20, which means 1 MC event corresponds to ~20 real events)

eLpR analysis

Statistics (eLpR)

	$\widetilde{e}_L\widetilde{e}_L$	$\widetilde{e}_R\widetilde{e}_R$	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^+\widetilde{\tau}_1^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_1^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_1^-$
No cuts	$4.59*10^4$	$8.57*10^4$	$1.59*10^5$	$4.31*10^4$	$1.49*10^5$	$4.65*10^4$	$1.31*10^4$	$1.31*10^4$

SM bkg	Bhabha	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	$e\nu W/eeZ/\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
No cuts	$5.40*10^6$	$5.44*10^6$	$2.59*10^6$	$1.14*10^7$	$2.62*10^5$	$1.04*10^6$	$7.40*10^5$	$5.82*10^4$	$7.68*10^5$	$3.36*10^5$	$1.15*10^9$	$2.25*10^9$

precuts

$N_{\mu\text{-PFO}} == 2$

$N_{\text{chargedPFO}} == 2$

※These precuts might change when we switch to ILD full simulation because of different PFA performance and $\gamma\gamma \rightarrow$ low P_t hadron backgrounds.

※pfo->getType() does not work for SGV samples because it is always 0. Instead, getPDG() is used (this will pick up PDG value of detailed PID info) for SGV.

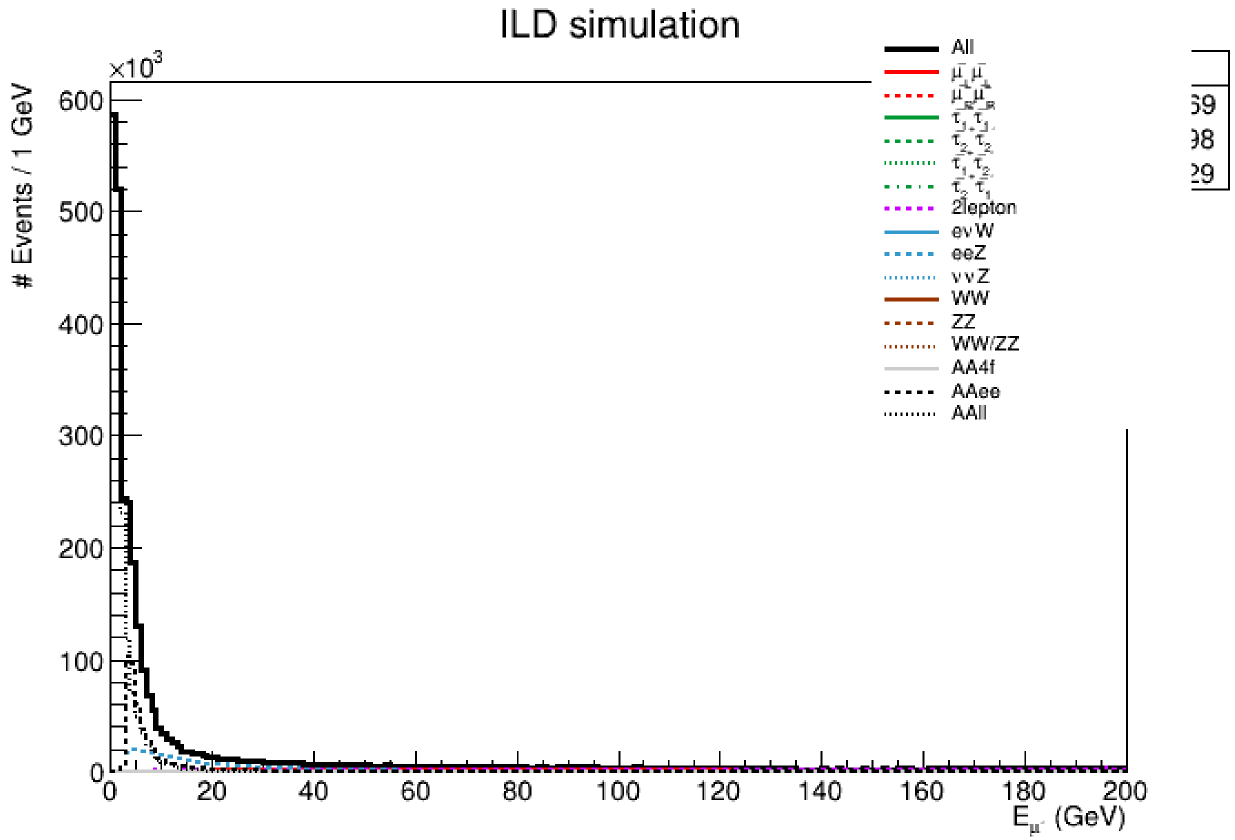
	$\widetilde{e}_L\widetilde{e}_L$	$\widetilde{e}_R\widetilde{e}_R$	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^+\widetilde{\tau}_1^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_1^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_1^-$
precuts	0	0	$1.38*10^5$	$3.77*10^4$	$2.71*10^3$	$1.11*10^3$	274	271

SM bkg	Bhabha	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	$e\nu W/eeZ/\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	0	$6.44*10^5$	22.0	$3.72*10^5$	$2.97*10^4$	0	$3.20*10^4$	$3.74*10^3$	$9.78*10^4$	858	$4.42*10^5$	$1.69*10^6$

Distribution of E_{μ^-} at precuts

Solid Black histogram is the sum up all processes and this is the histogram we can obtain from the real experiment.

Clearly, more background rejection is necessary to measure edges.
Dominant backgrounds:
AAll, AAee, 2lepton, eeZ(singleZee)



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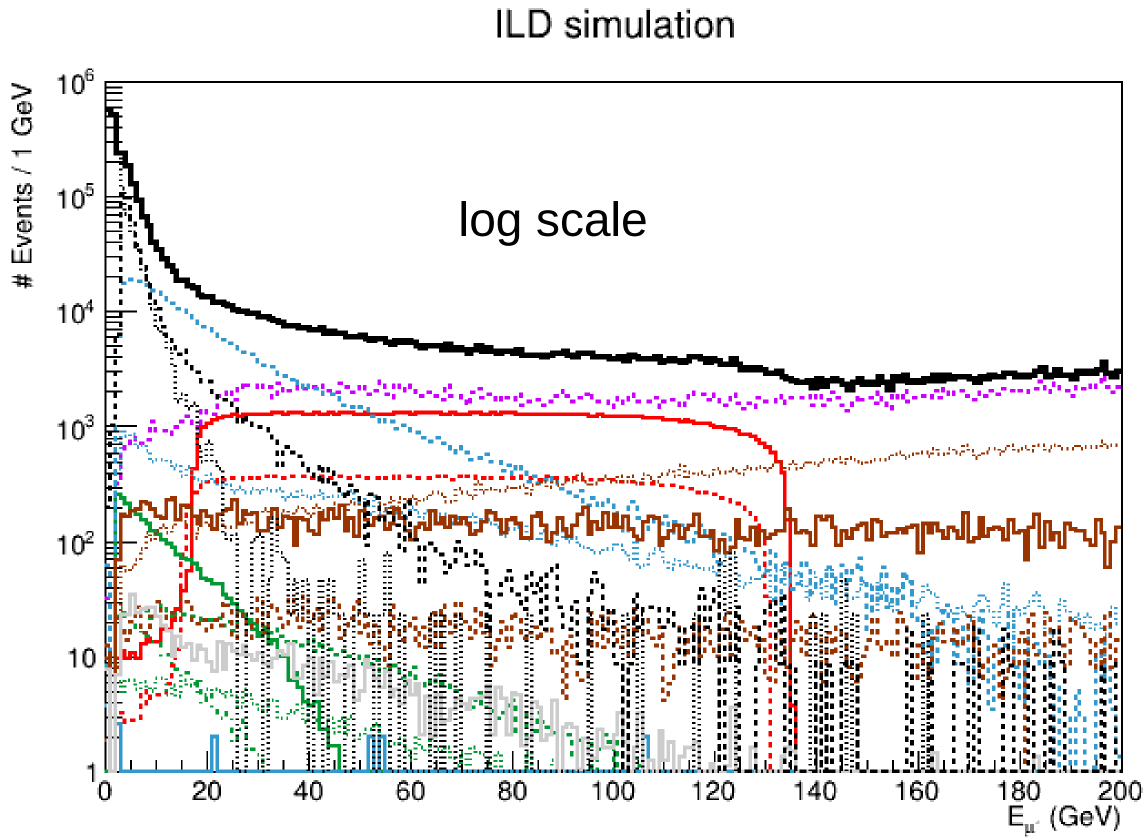


Signal signature & Cut design

- Process: $e^+e^- \to \tilde{\mu}\tilde{\mu} \to \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - 2 muons + large missing
  - missing energy level depends on neutralino mass, still we can assume some missing component
  - In refs.[arXiv:0902.2434, DESY-THESIS-09-004], 200 < E_{miss} < 430 GeV was applied.
- Cuts are work in progress
  - design cuts not to destroy flat and edge structure
  - look variables from visible component, then invisible component
  - working on 2 types of cuts
    - (1) Loose (less bias)
    - (2) Tight (increase bias)

Loose cuts (eLpR)

Cut 1: $\frac{\theta_{\text{acop}}}{\pi} > 0.03$

Cut 2: $\frac{\theta_{\text{acol}}}{\pi} < 0.9$

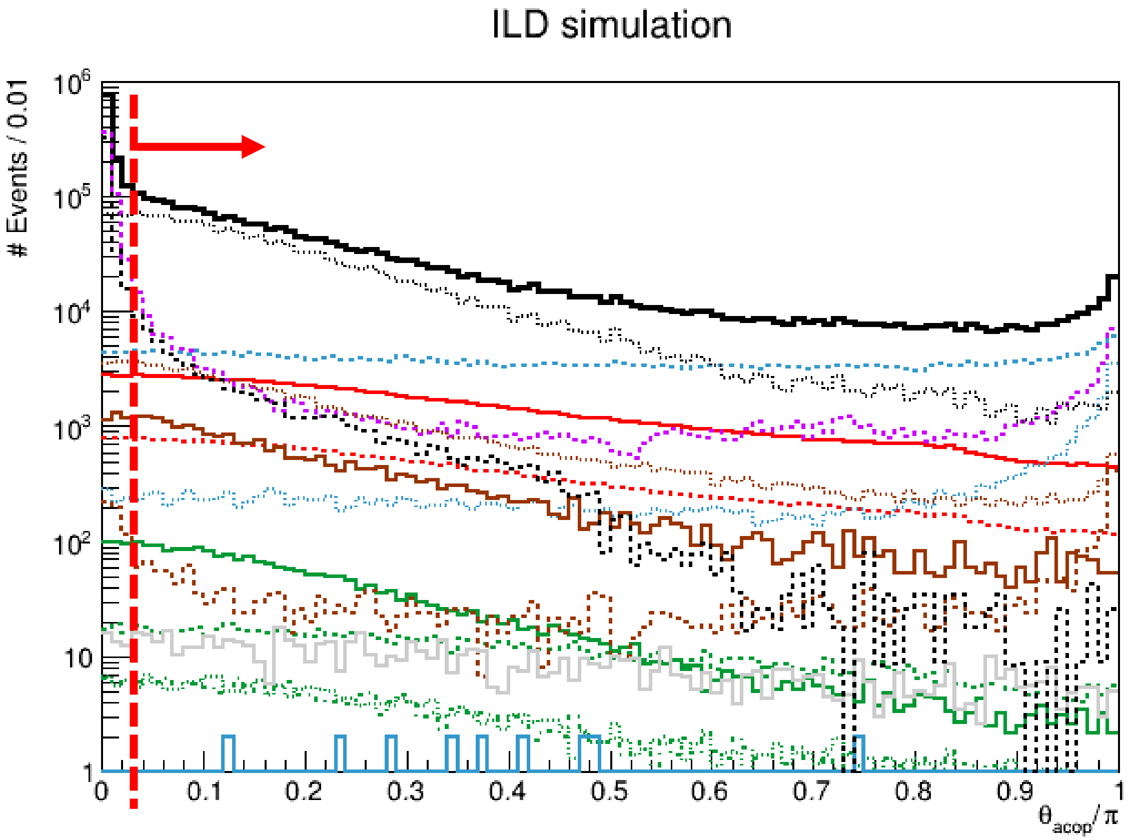
Cut 3: $M_{\mu\mu} > 15$ GeV

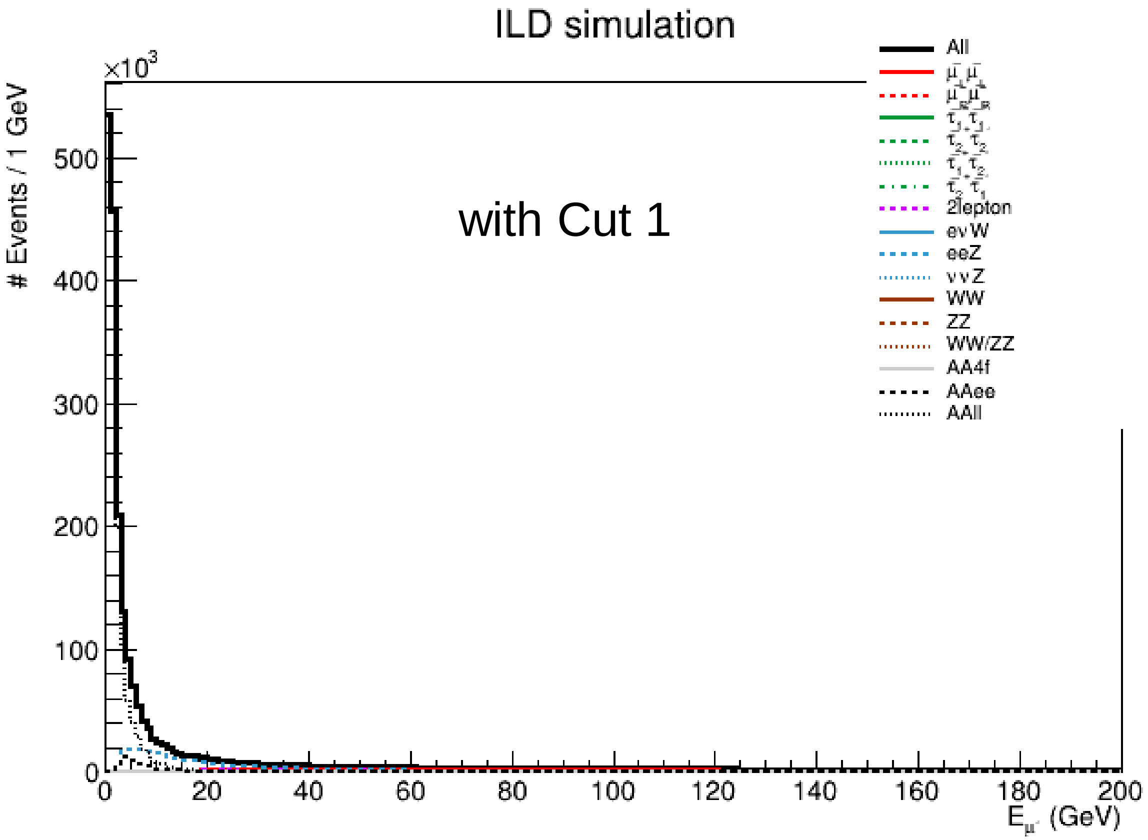
Cut 4: $E_{vis} < 490$ GeV

Cut 5: $|\cos\theta_{\text{miss}}| < 0.95$

Cut 6: missing $P_t > 5$ GeV

Cut on acoplanarity $\theta_{\text{acop}} = \pi - (\phi_1 - \phi_2)$



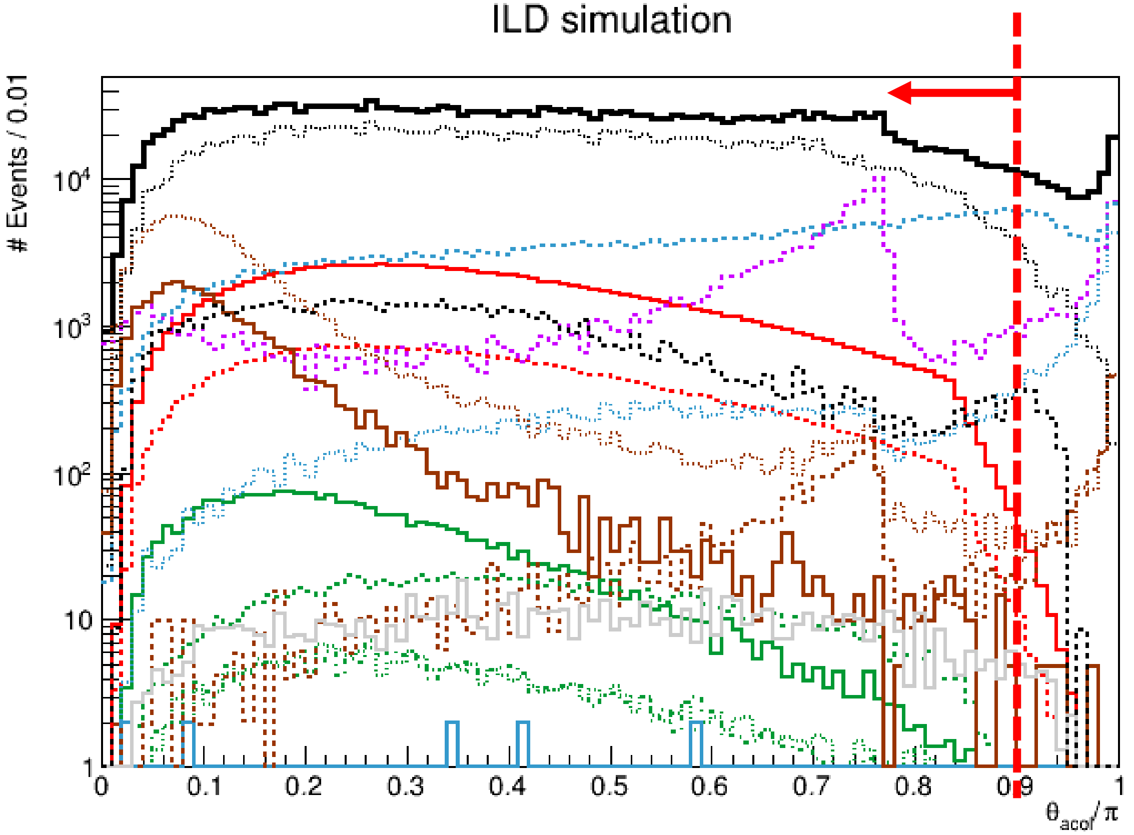


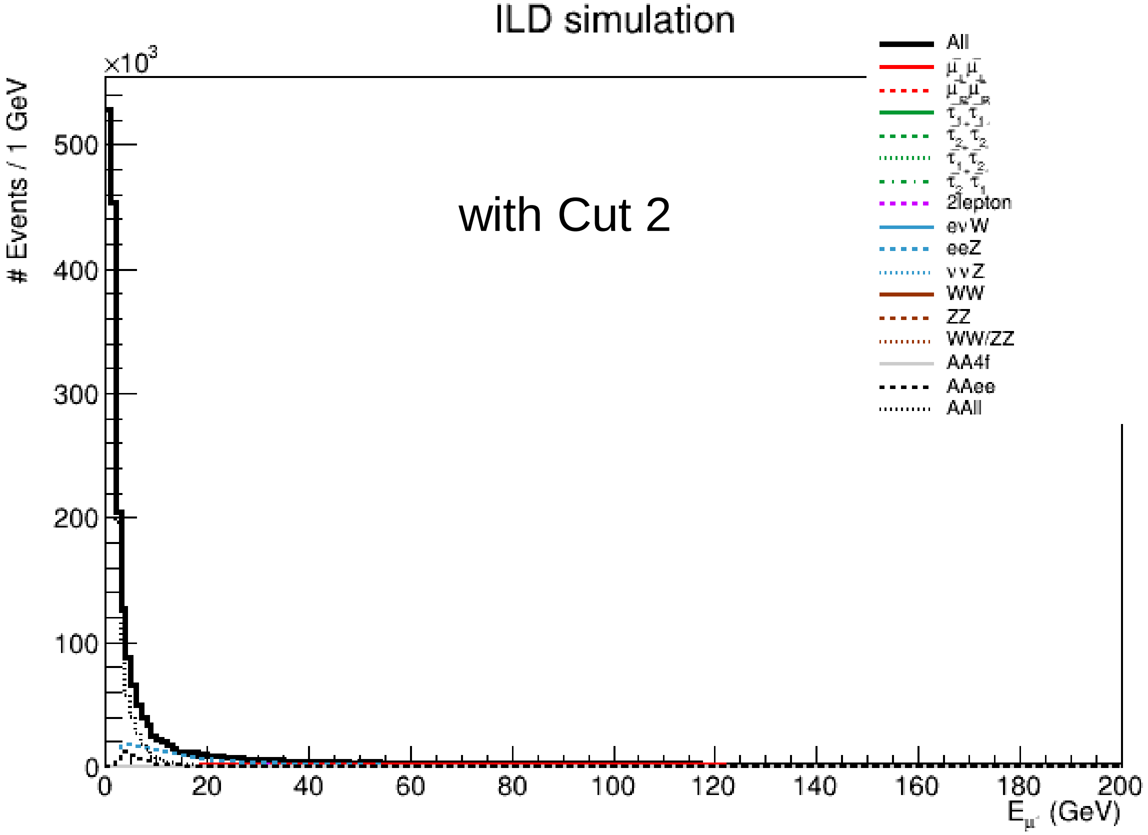
$\frac{\theta_{\text{acop}}}{\pi} \sim 0$: two muons are back-to-back in xy-plane

mostly for SM background rejection, some signals rejected as well

Cut 1: $\frac{\theta_{\text{acop}}}{\pi} > 0.03$

Cut on acolinearity $\theta_{\mathrm{acol}} = \pi - (\theta_1 - \theta_2)$



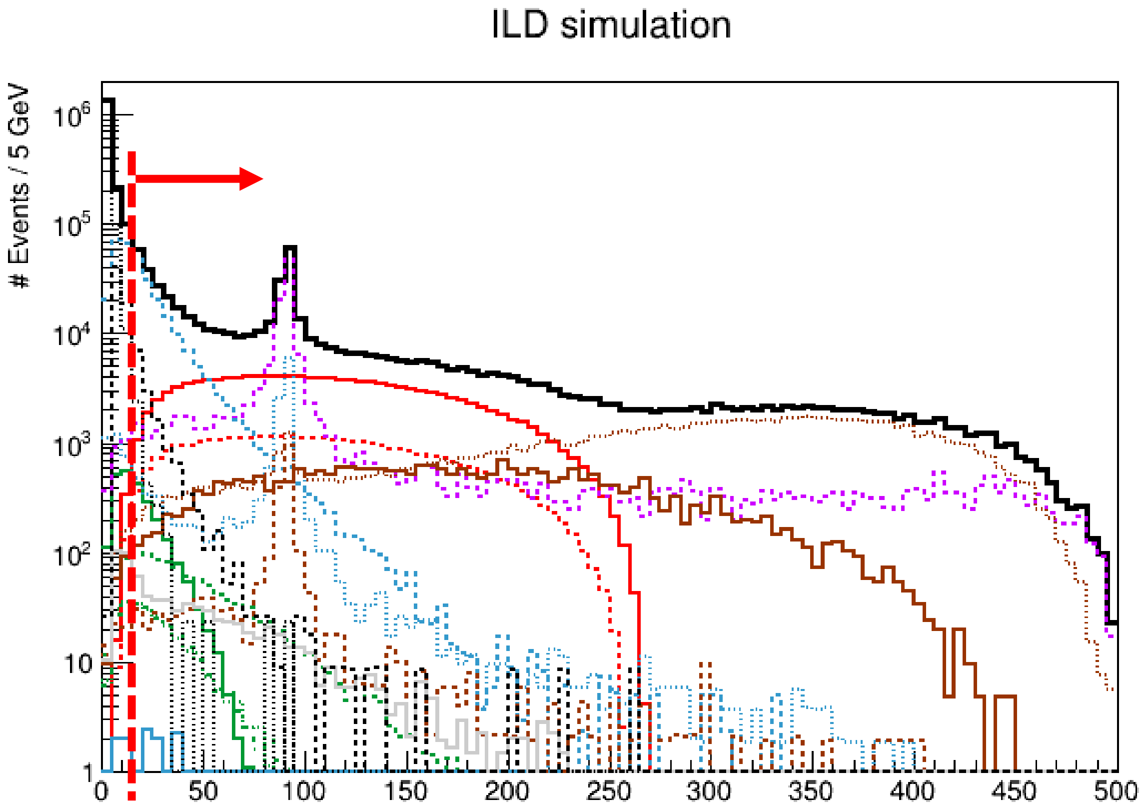


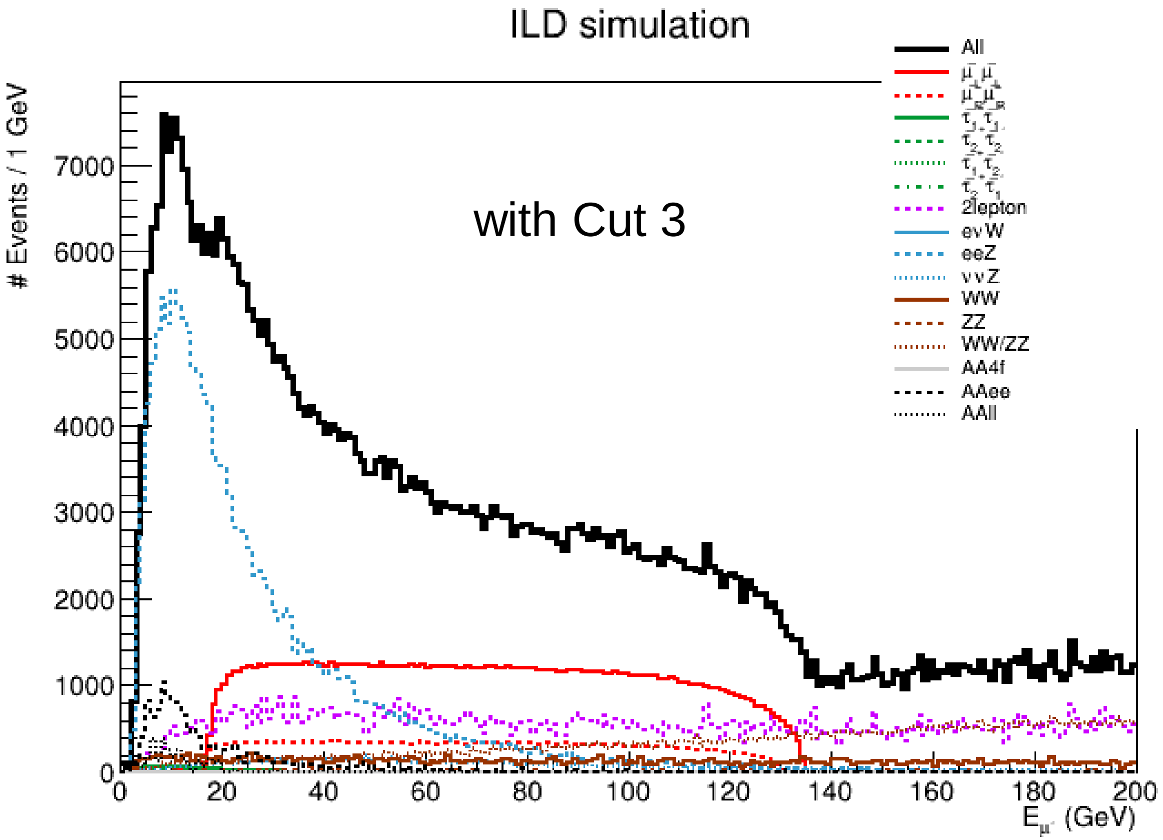
$\frac{\theta_{\mathrm{acol}}}{\pi} \sim 1$: two muons flying the same direction

such probability is expected to be small in signal

Cut 2: $\frac{\theta_{\mathrm{acol}}}{\pi} < 0.9$

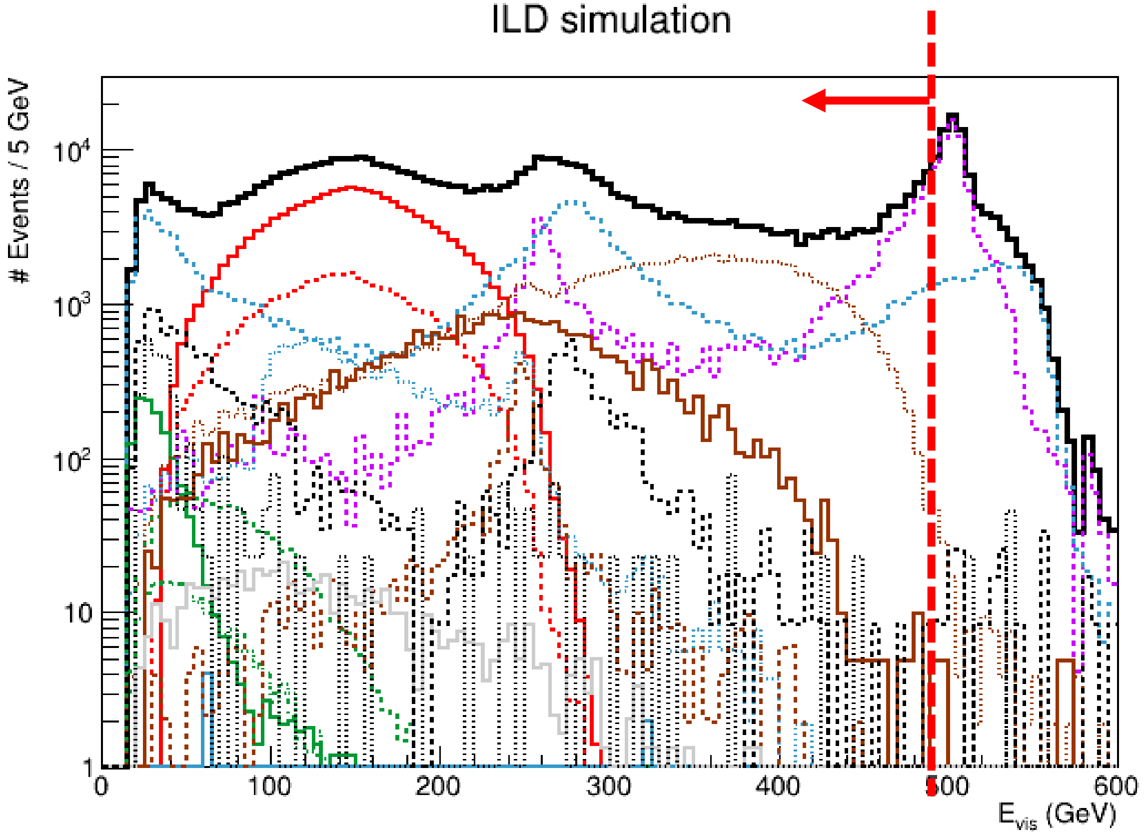
Cut on $M_{\mu\mu}$

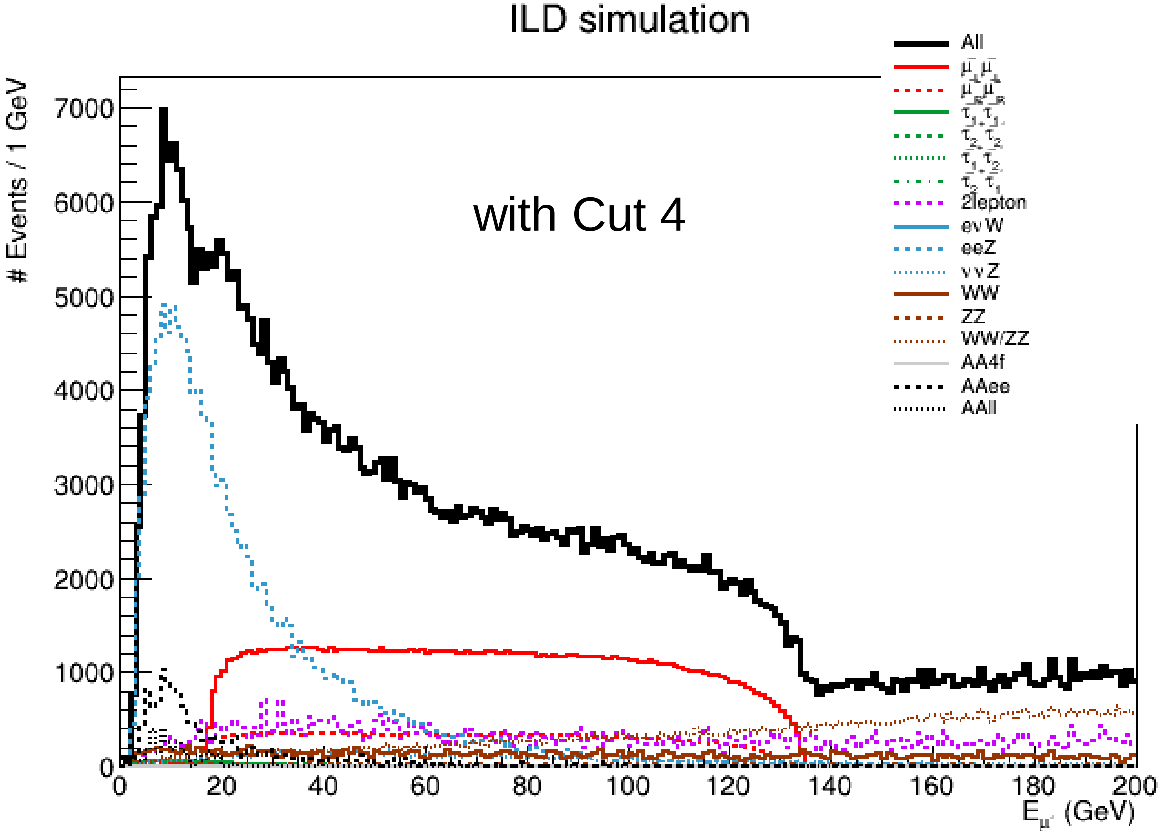




$M_{\mu\mu} \sim 0$ GeV: two muons produced by photon
expect no peaks around that region for signal
Cut 3: $M_{\mu\mu} > 15$ GeV

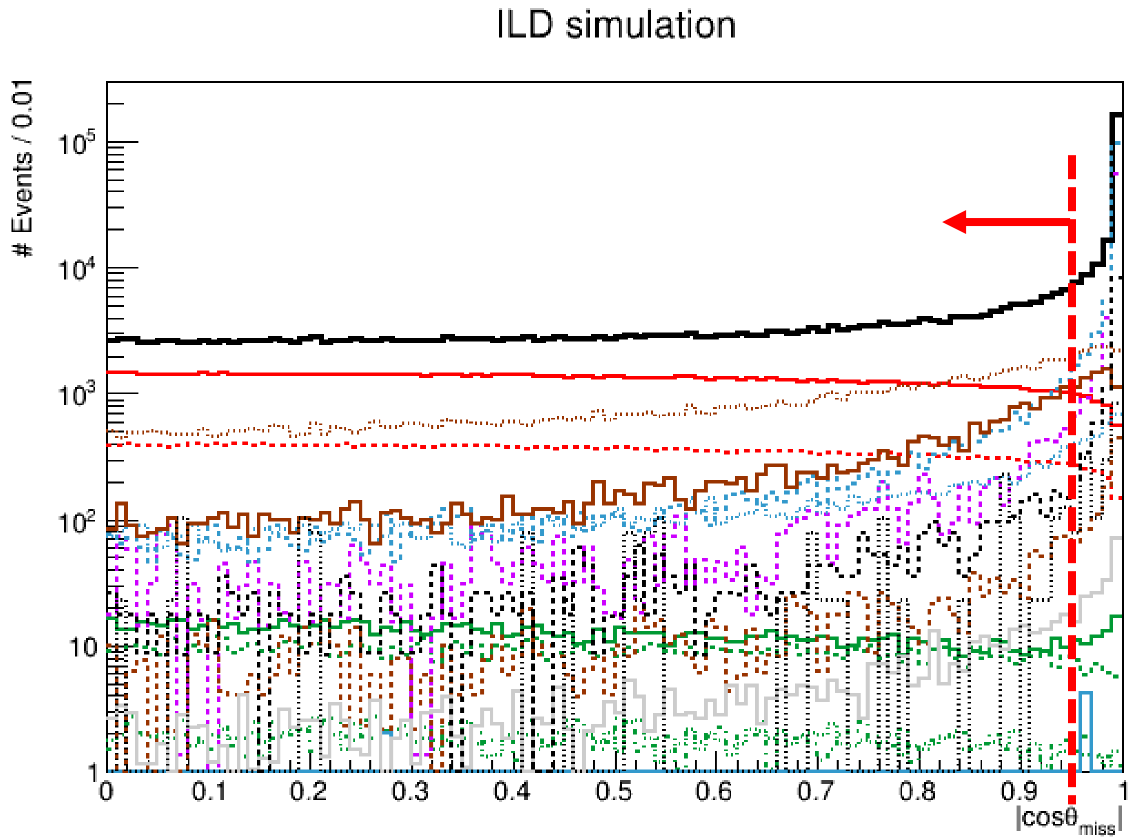
Cut on E_{vis}

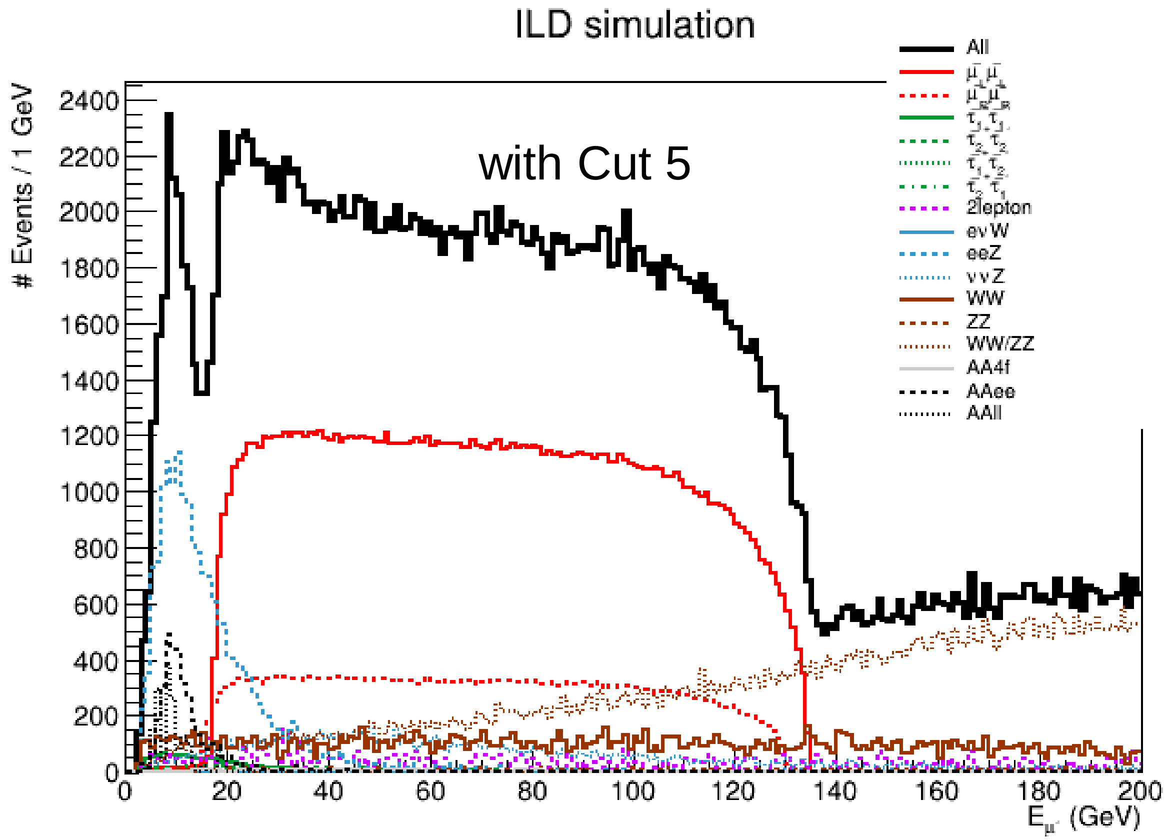




E_{vis} ~ 500 GeV: almost no missing component
signal have large missing component
Cut 4: E_{vis} < 490 GeV

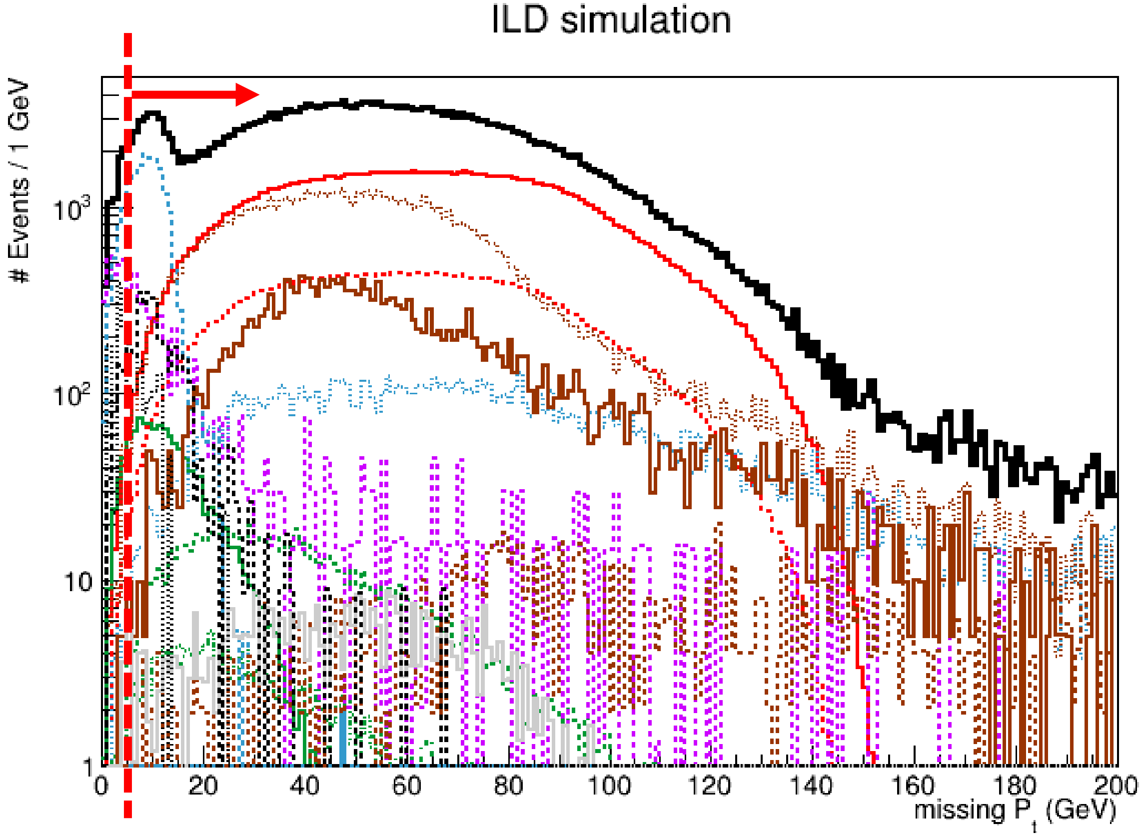
Cut on $\cos\theta_{\mathrm{miss}}$

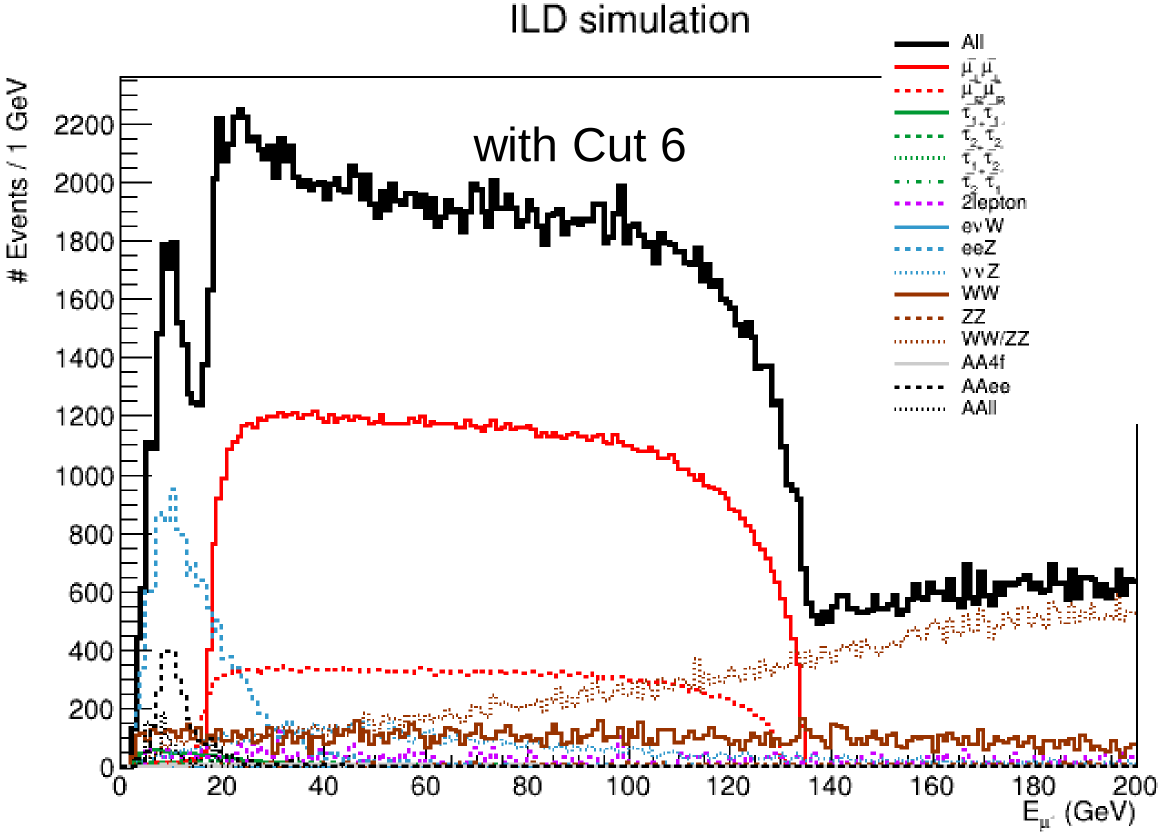




$|\cos\theta_{\mathrm{miss}}| \sim 1$: almost no missing component
signal have large missing component
Cut 5: $|\cos\theta_{\mathrm{miss}}| < 0.95$

Cut on missing P_t





missing P_t ~ 0 GeV: almost no missing component
signal have large missing component
Cut 6: missing P_t > 5 GeV

Cut table (Loose)

signal efficiency: ~79%

significance $= \frac{1.59\times10^5}{\sqrt{1.59\times10^5+1.70\times10^5}} = 277\sigma$

overall dominant backgrounds:
WW/ZZ, WW, eeZ, nunuZ

affects E^- edge detection:
eeZ, AAll

	$\widetilde{\mu_L}\widetilde{\mu_L}$	$\widetilde{\mu_R}\widetilde{\mu_R}$	$\widetilde{\tau_1^+}\widetilde{\tau_1^-}$	$\widetilde{\tau_2^+}\widetilde{\tau_2^-}$	$\widetilde{\tau_1^+}\widetilde{\tau_2^-}$	$\widetilde{\tau_2^+}\widetilde{\tau_1^-}$
precuts	$1.38*10^5$	$3.77*10^4$	$2.71*10^3$	$1.11*10^3$	274	271
Cut 1	$1.30*10^5$	$3.53*10^4$	$2.42*10^3$	$1.06*10^3$	256	253
Cut 2	$1.30*10^5$	$3.53*10^4$	$2.42*10^3$	$1.06*10^3$	256	253
Cut 3	$1.30*10^5$	$3.52*10^4$	$1.24*10^3$	900	183	184
Cut 4	$1.30*10^5$	$3.52*10^4$	$1.24*10^3$	900	183	184
Cut 5	$1.26*10^5$	$3.41*10^4$	$1.18*10^3$	868	176	177
Cut 6	$1.25*10^5$	$3.40*10^4$	$1.07*10^3$	863	173	174

SM bkg	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	$6.44*10^5$	22.0	$3.72*10^5$	$2.97*10^4$	$3.20*10^4$	$3.74*10^3$	$9.78*10^4$	858	$4.42*10^5$	$1.69*10^6$
Cut 1	$1.56*10^5$	22.0	$3.58*10^5$	$2.89*10^4$	$2.83*10^4$	$3.20*10^3$	$8.69*10^4$	817	$7.45*10^4$	$1.48*10^6$
Cut 2	$1.35*10^5$	12.8	$3.08*10^5$	$1.66*10^4$	$2.83*10^4$	$2.22*10^3$	$8.60*10^4$	782	$7.28*10^4$	$1.46*10^6$
Cut 3	$1.33*10^5$	8.84	$1.49*10^5$	$1.36*10^4$	$2.81*10^4$	$2.16*10^3$	$8.57*10^4$	572	$1.42*10^4$	$3.32*10^3$
Cut 4	$6.99*10^4$	8.84	$1.27*10^5$	$1.36*10^4$	$2.81*10^4$	$2.16*10^3$	$8.55*10^4$	571	$1.39*10^4$	$3.23*10^3$
Cut 5	$7.54*10^3$	4.22	$1.78*10^4$	$1.10*10^4$	$2.15*10^4$	$1.29*10^3$	$7.44*10^4$	402	$3.52*10^3$	$1.62*10^3$
Cut 6	$5.27*10^3$	4.22	$1.51*10^4$	$1.10*10^4$	$2.15*10^4$	$1.29*10^3$	$7.43*10^4$	396	$3.14*10^3$	814

Tight cuts (eLpR)

Cut 1: $25 < E_{vis} < 300$ GeV

Cut 2: $15 < M_{\mu\mu} < 250$ GeV

Cut 3: $\frac{\theta_{\mathrm{acop}}}{\pi} > 0.03$

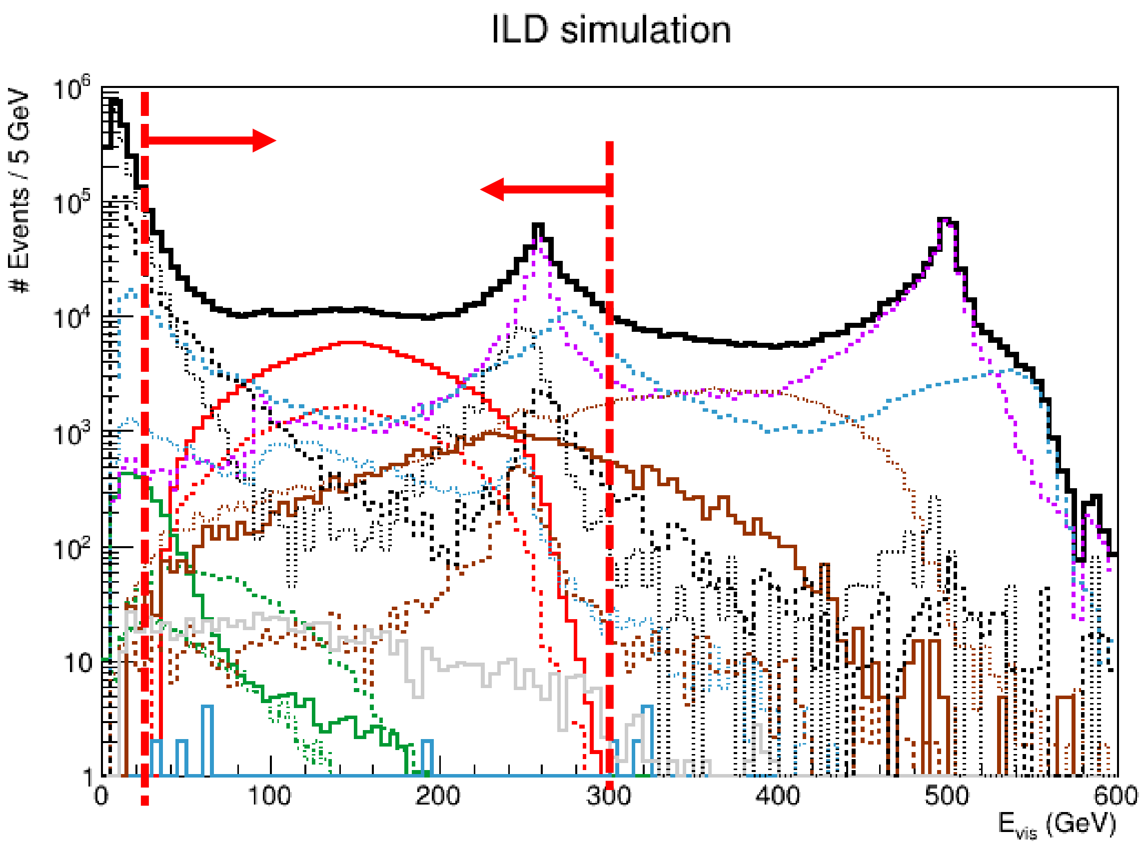
Cut 4: $\frac{\theta_{\mathrm{acol}}}{\pi} < 0.9$

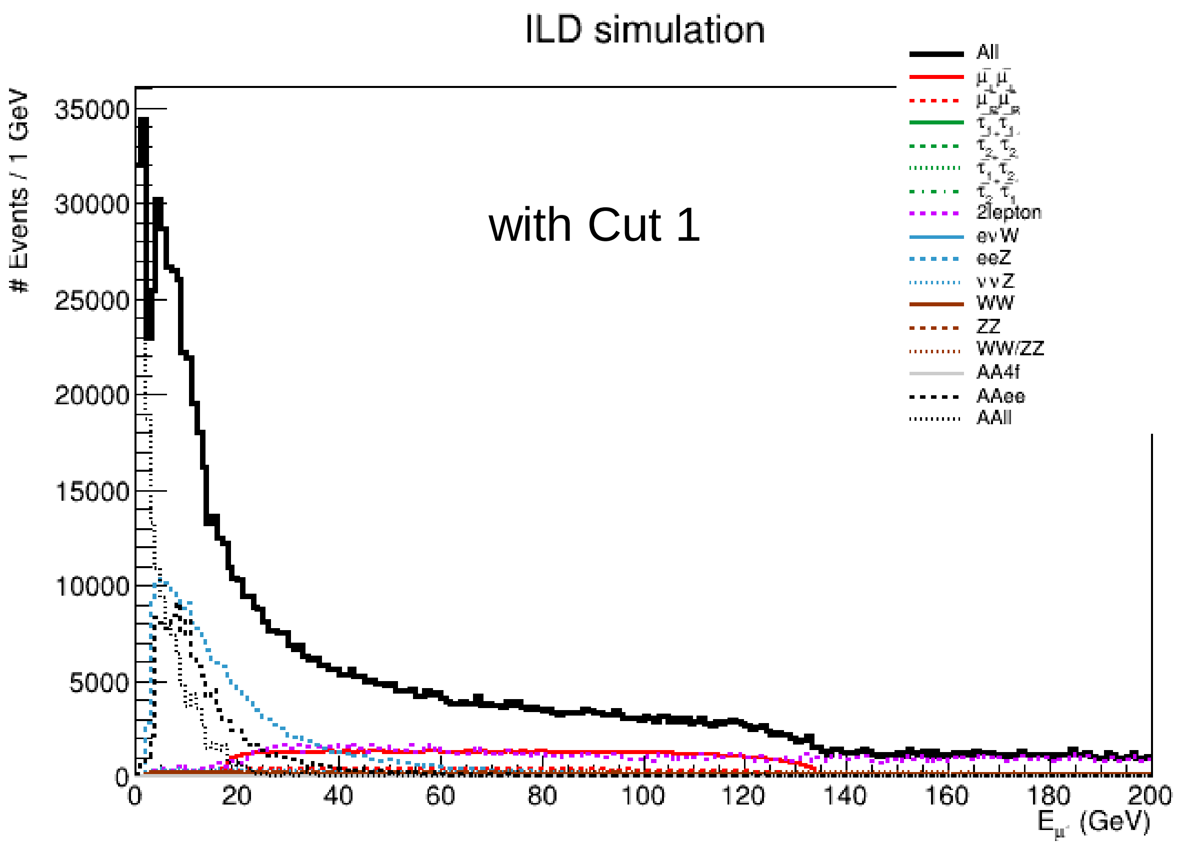
Cut 5: $|\cos\theta_{\mathrm{miss}}| < 0.95$

Cut 6: $10 <$ missing $P_t < 150$ GeV

Cut 7: $200 < M_{inv} < 470$ GeV

Cut on E_{vis}



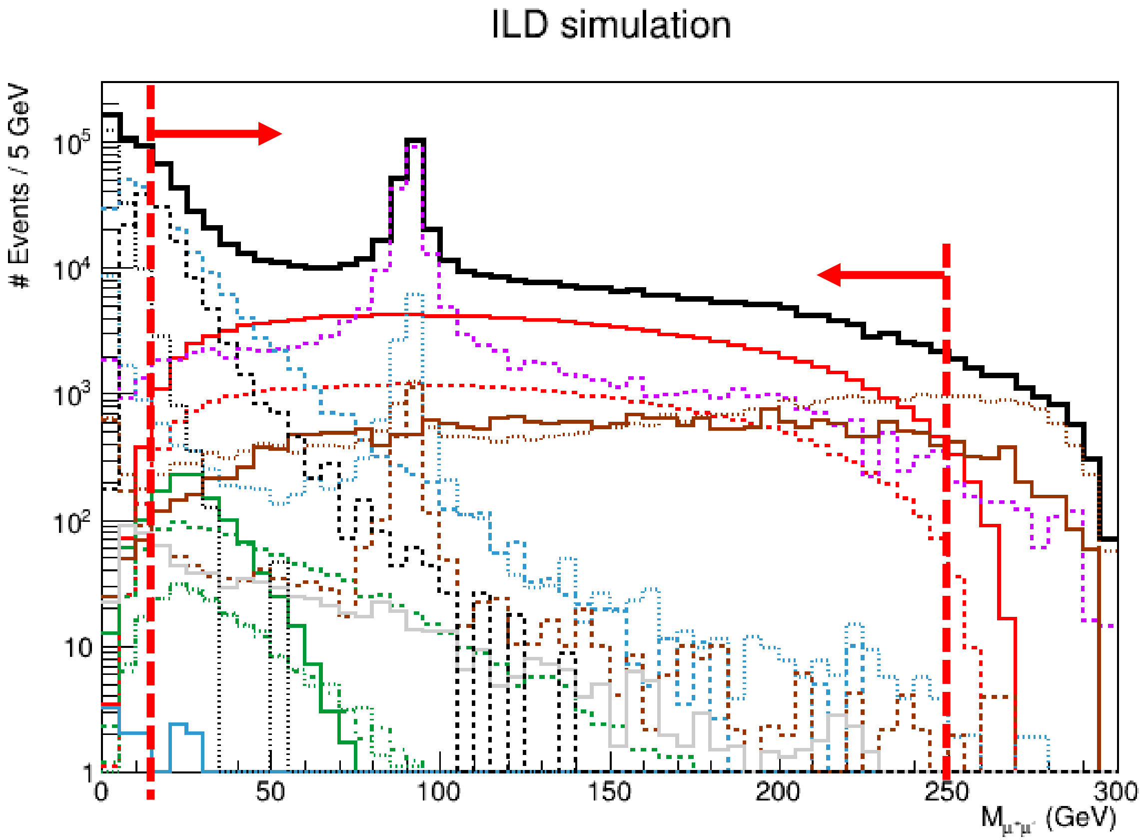


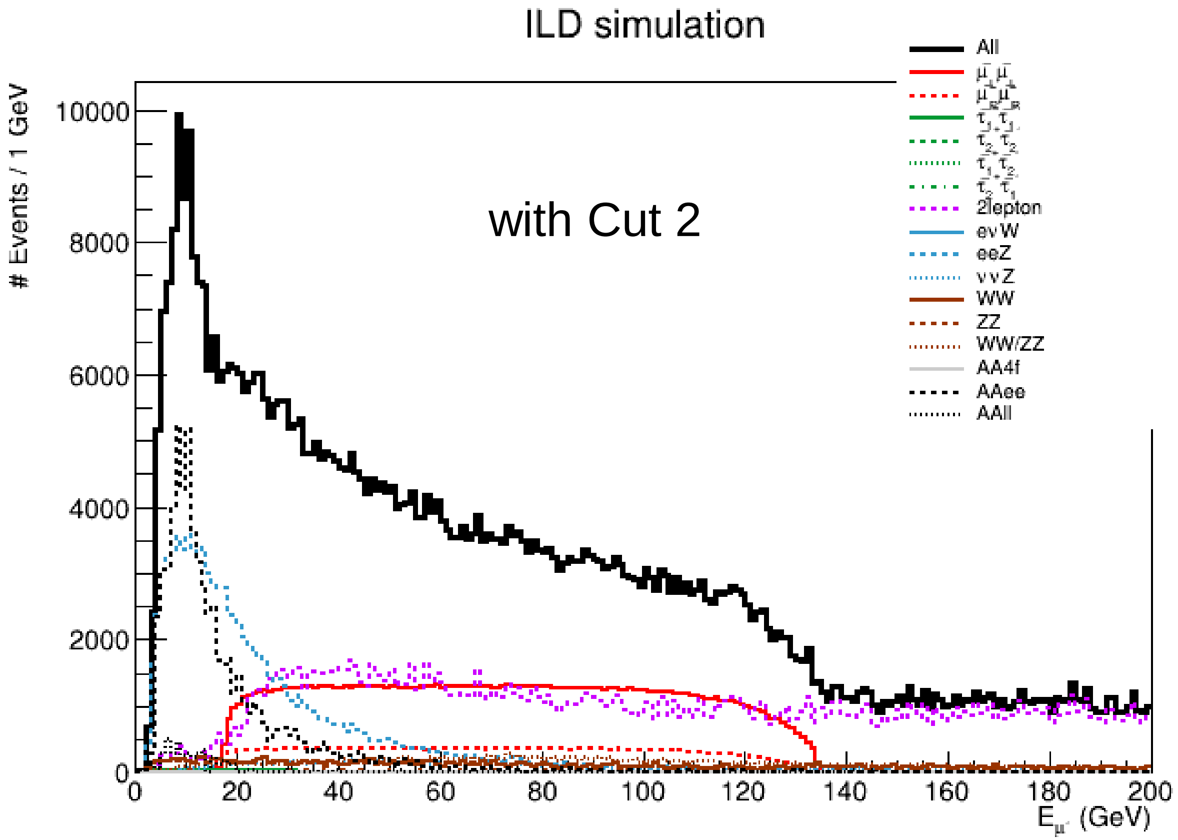
E_{vis} ~ 500 GeV: almost no missing component

E_{vis} ~ 0 GeV: almost all missing component

Cut 1: 25 < E_{vis} < 300 GeV

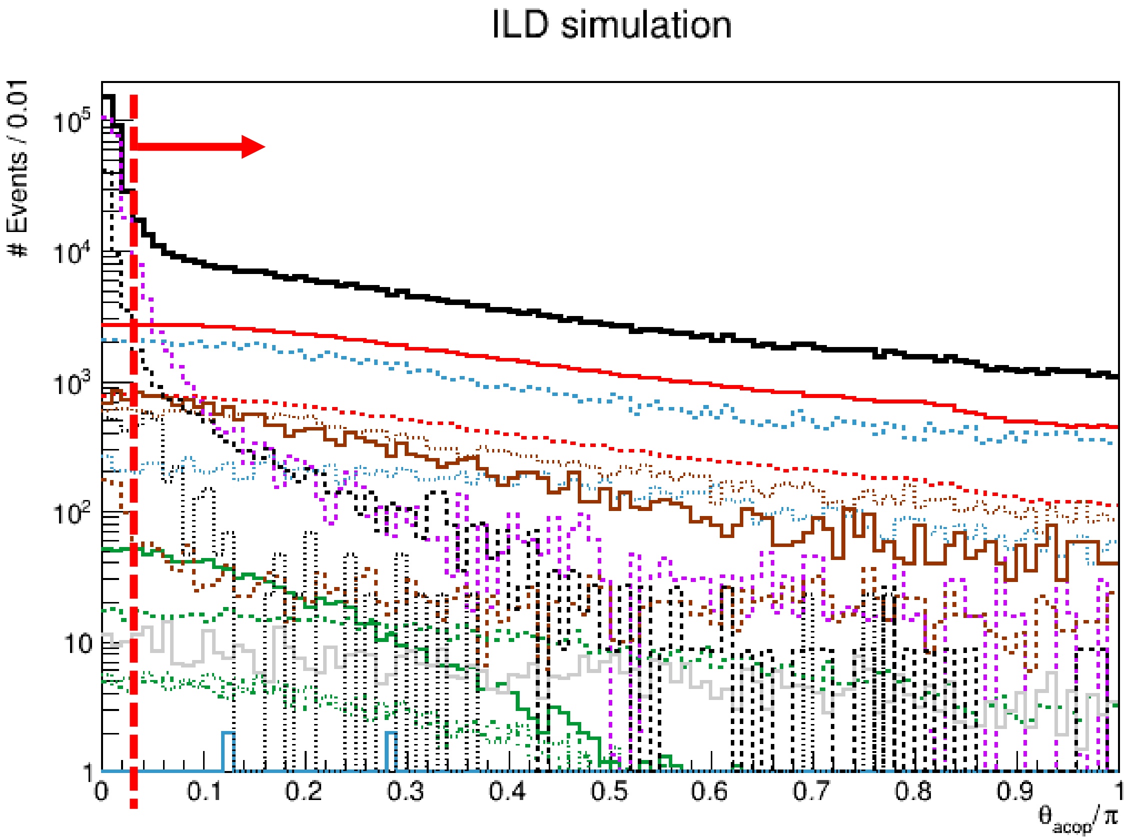
Cut on $M_{\mu\mu}$

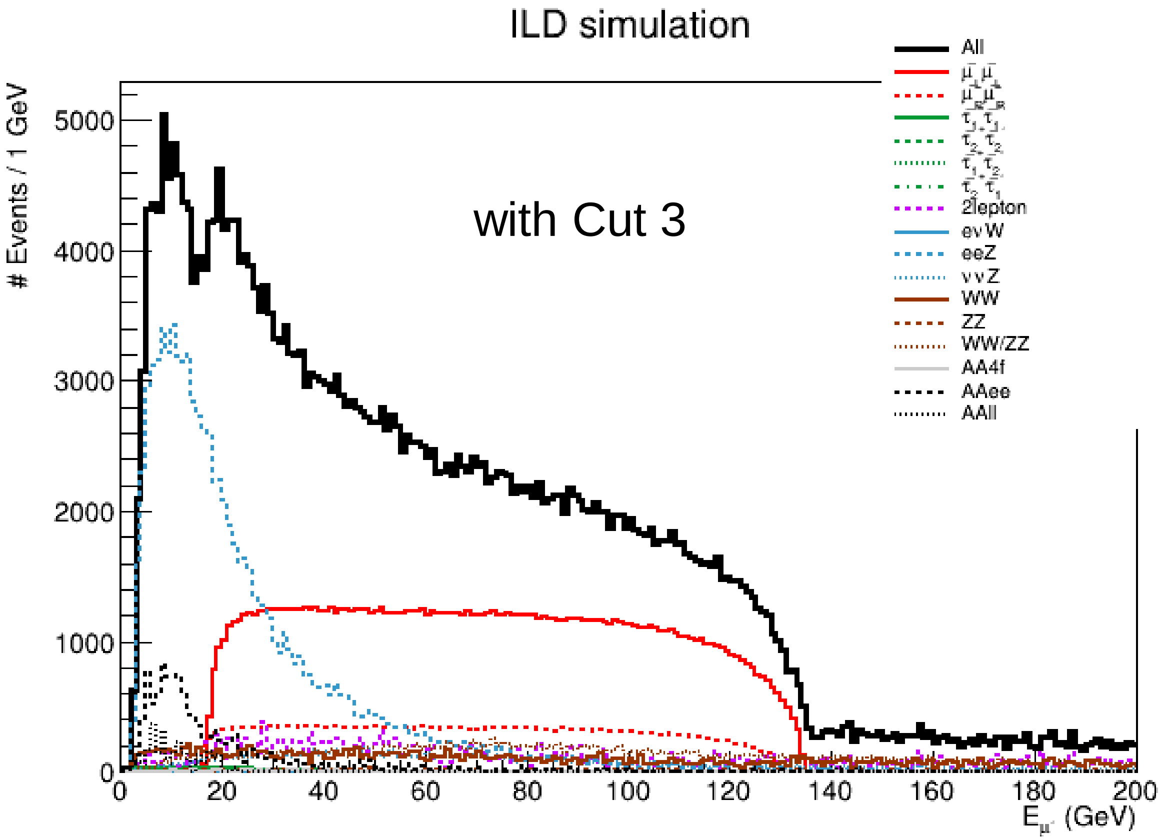




$M_{\mu\mu}$ ~ 0 GeV: two muons produced by photon
assume pair production: maximum of $M_{\mu\mu}$ is 250 GeV
Cut 2: 15 < $M_{\mu\mu}$ < 250 GeV

Cut on acoplanarity $\theta_{\mathrm{acop}} = \pi - (\phi_1 - \phi_2)$



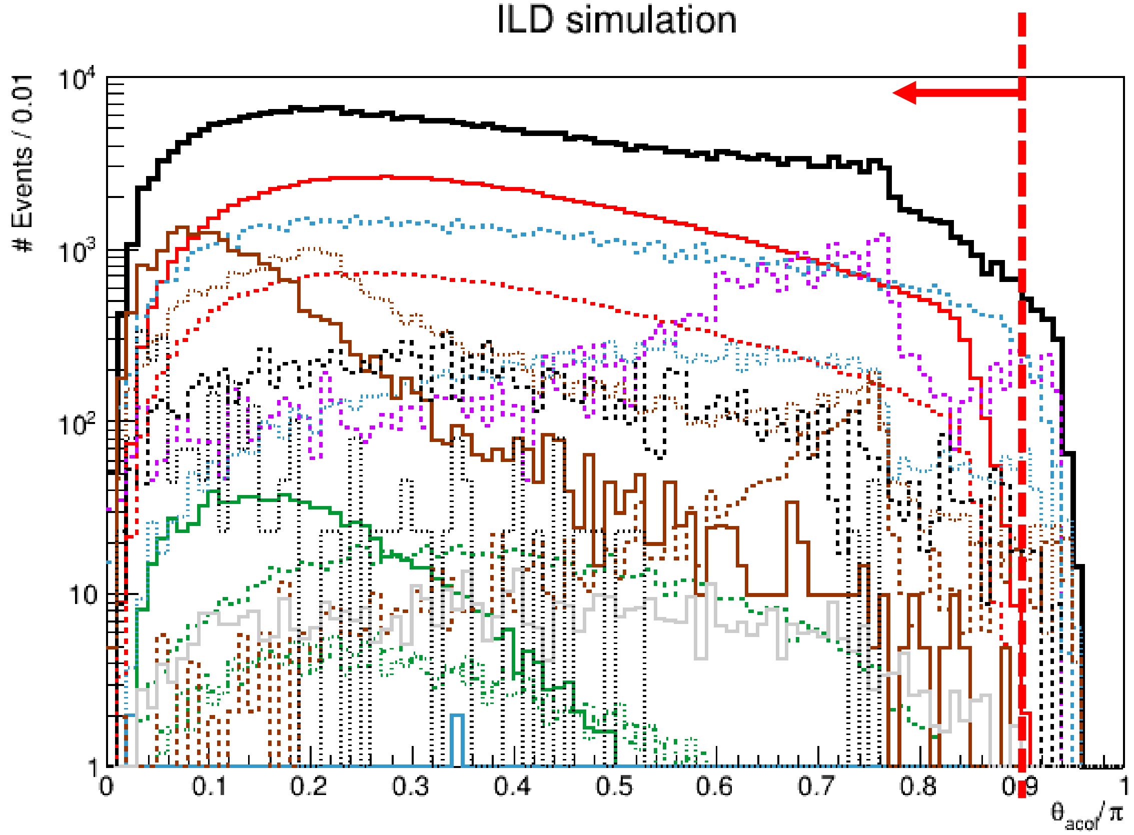


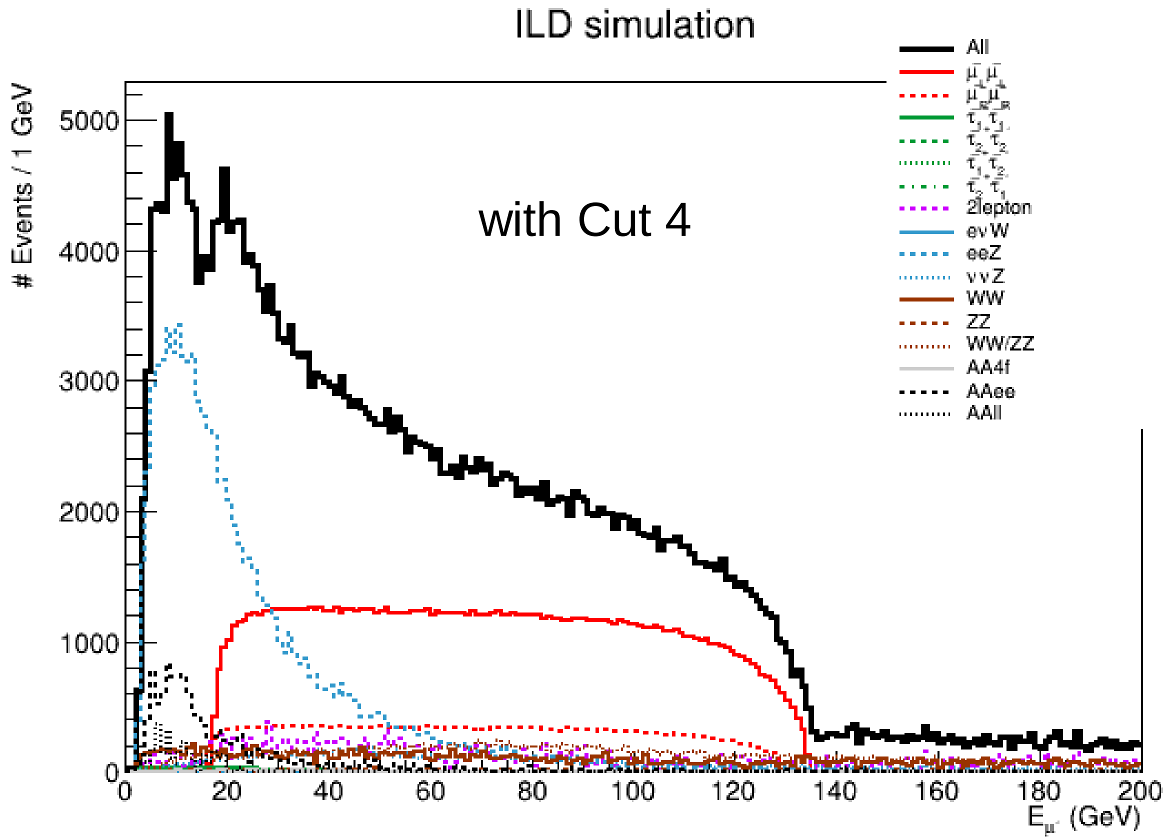
$\frac{\theta_{\mathrm{acop}}}{\pi} \sim 0$: two muons are back-to-back in xy-plane

mostly for SM background rejection, some signals rejected as well

Cut 3: $\frac{\theta_{\mathrm{acop}}}{\pi} > 0.03$

Cut on acolinearity $\theta_{\text{acol}} = \pi - (\theta_1 - \theta_2)$



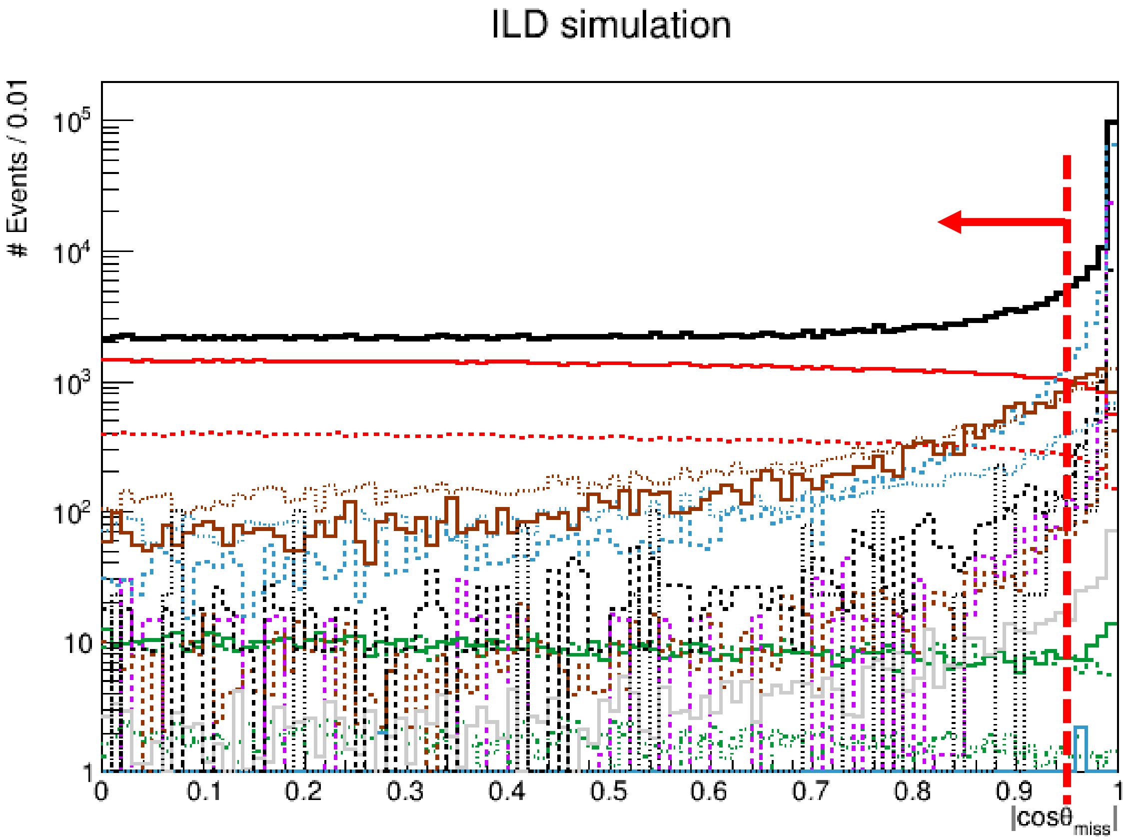


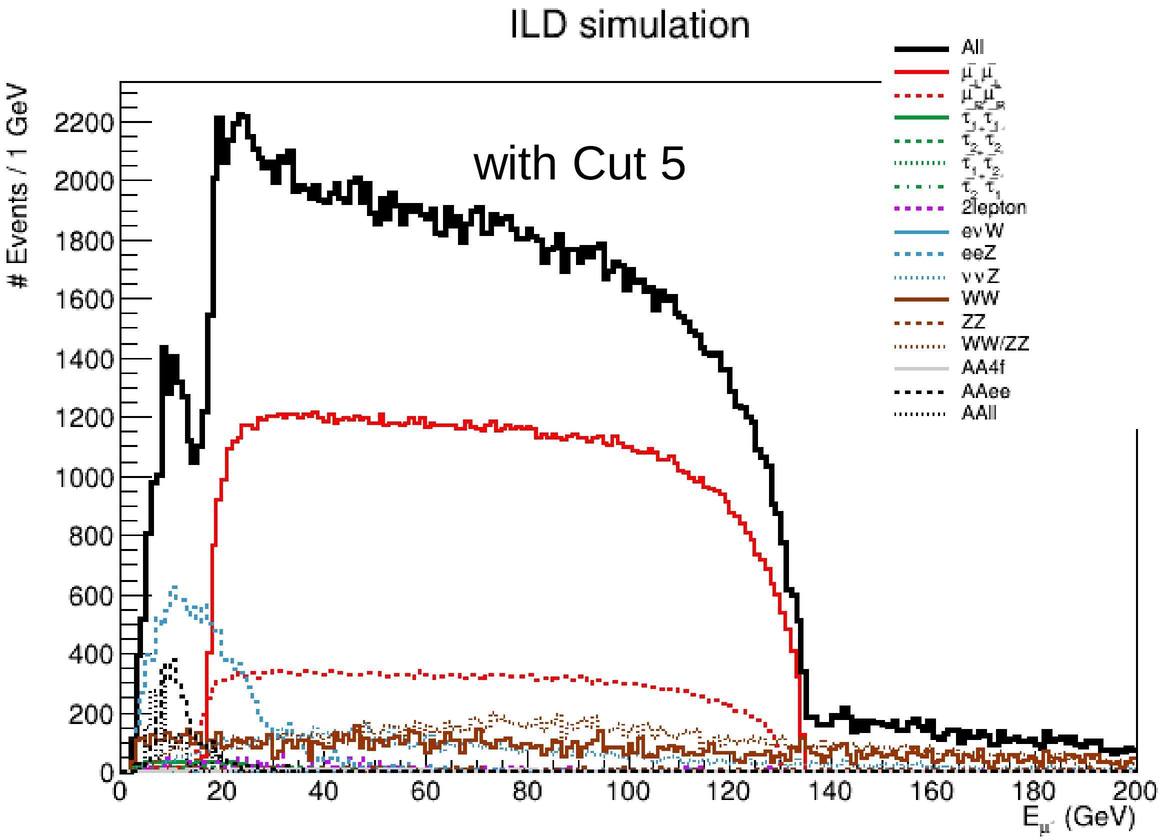
$\frac{\theta_{\text{acol}}}{\pi} \sim 1$: two muons flying the same direction

such probability is expected to be small in signal

Cut 4: $\frac{\theta_{\text{acol}}}{\pi} < 0.9$

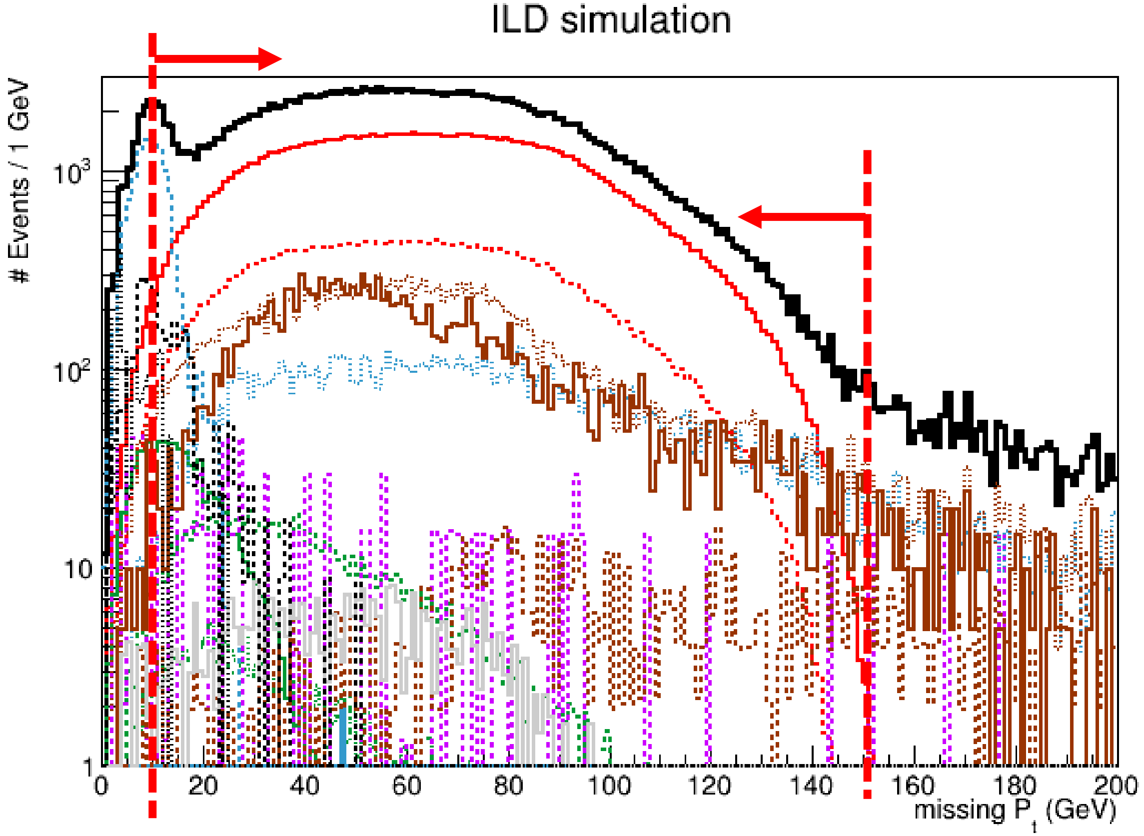
Cut on $\cos\theta_{\rm miss}$

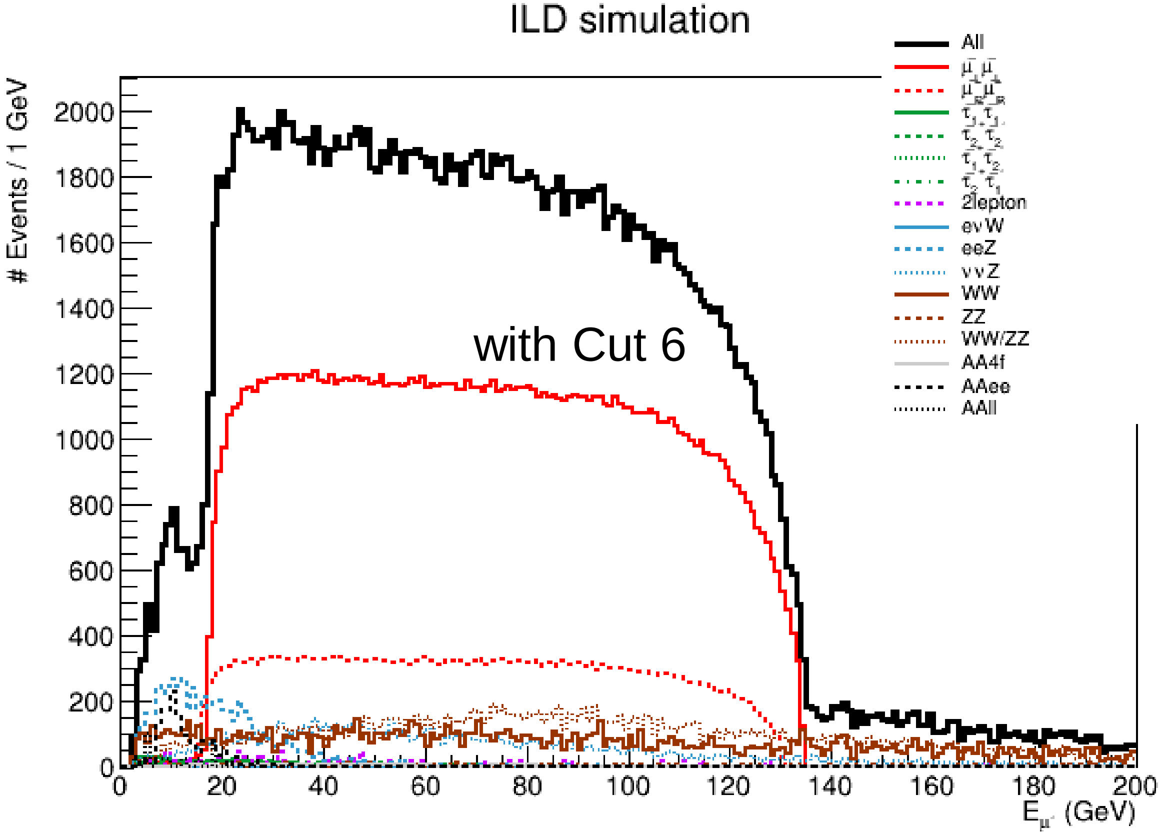




$|\cos\theta_{\rm miss}| \sim 1$: almost no missing component
signal have large missing component
Cut 5: $|\cos\theta_{\rm miss}| < 0.95$

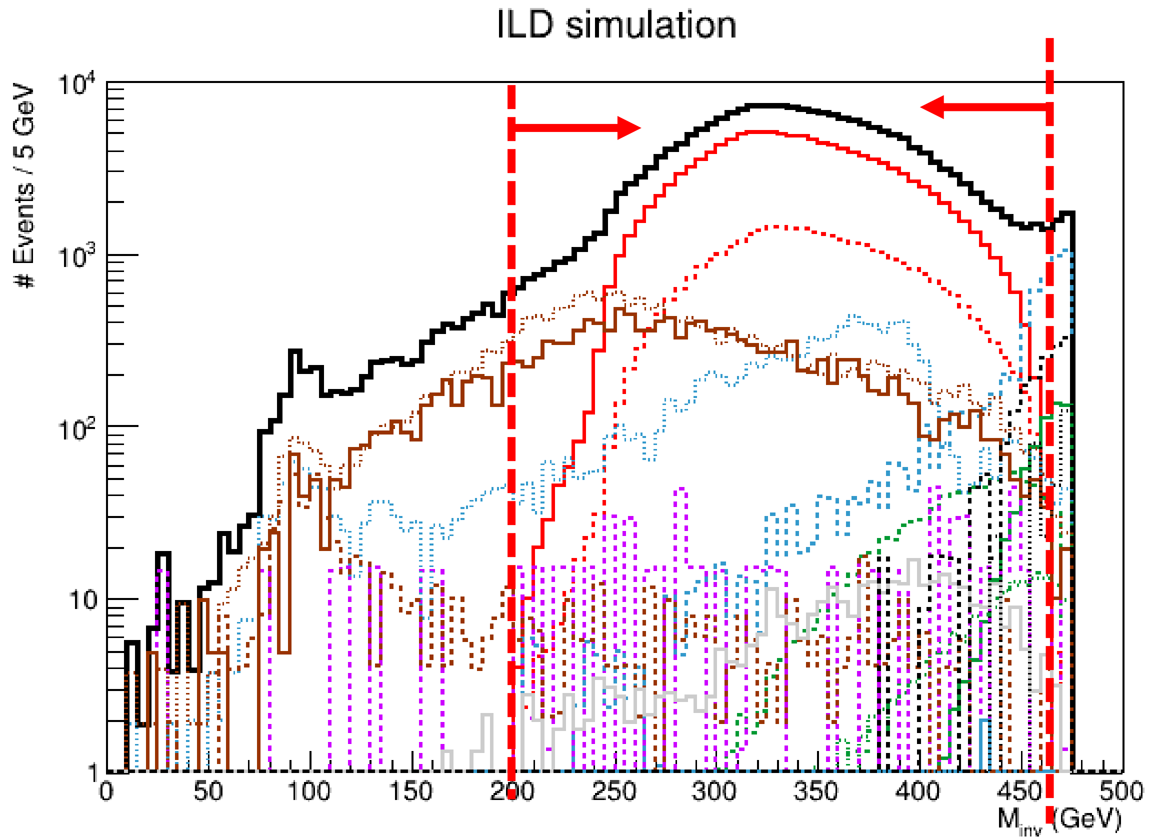
Cut on missing P_t

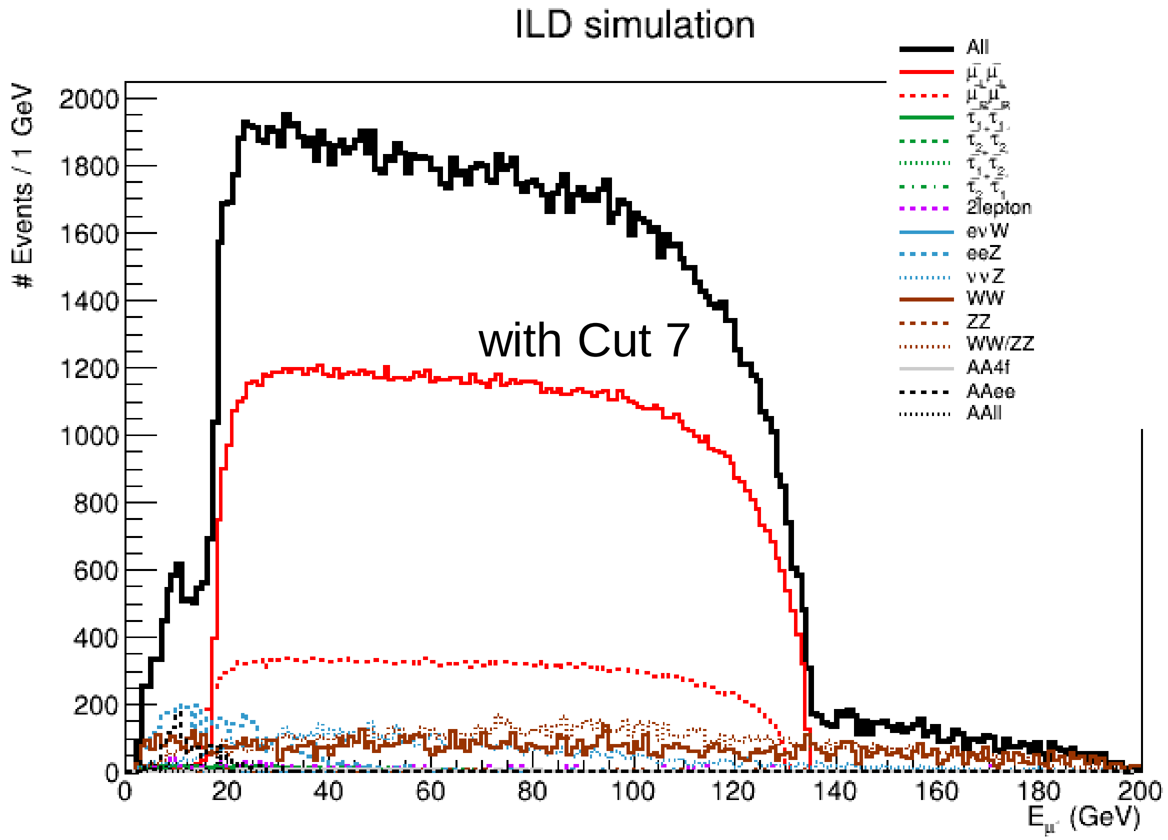




missing P_t ~ 0 GeV: almost no missing component
signal have large missing component
Cut 6: 10 < missing P_t < 150 GeV

Cut on M_{inv} (invariant mass of missing component)





M_{inv} ~ 500 GeV: almost all missing component
signal have large missing component
Cut 7: 200 < M_{inv} < 470 GeV

Cut table (Tight)

signal efficiency: ~79%

significance $= \frac{1.58\times10^5}{\sqrt{1.58\times10^5+4.68\times10^4}} = 349\sigma$

overall dominant backgrounds:
WW/ZZ, WW, nunuZ

affects E^- edge detection:
eeZ, (AAll, 170 event = 5 MC event)

	$\tilde{\mu}_L\tilde{\mu}_L$	$\tilde{\mu}_R\tilde{\mu}_R$	$\tilde{\tau}_1^+\tilde{\tau}_1^-$	$\tilde{\tau}_2^+\tilde{\tau}_2^-$	$\tilde{\tau}_1^+\tilde{\tau}_2^-$	$\tilde{\tau}_2^+\tilde{\tau}_1^-$
precuts	$1.38*10^5$	$3.77*10^4$	$2.71*10^3$	$1.11*10^3$	274	271
Cut 1	$1.38*10^5$	$3.77*10^4$	$1.20*10^3$	$1.01*10^3$	211	208
Cut 2	$1.37*10^5$	$3.75*10^4$	$1.03*10^3$	929	186	185
Cut 3	$1.29*10^5$	$3.51*10^4$	880	880	171	171
Cut 4	$1.29*10^5$	$3.51*10^4$	880	880	171	171
Cut 5	$1.25*10^5$	$3.40*10^4$	831	848	164	164
Cut 6	$1.24*10^5$	$3.38*10^4$	609	823	155	155
Cut 7	$1.24*10^5$	$3.38*10^4$	475	805	146	147

SM bkg	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	$6.44*10^5$	22.0	$3.72*10^5$	$2.97*10^4$	$3.20*10^4$	$3.74*10^3$	$9.78*10^4$	858	$4.42*10^5$	$1.69*10^6$
Cut 1	$2.28*10^5$	14.1	$2.15*10^5$	$2.54*10^4$	$2.55*10^4$	$3.42*10^3$	$3.51*10^4$	770	$1.26*10^5$	$1.69*10^5$
Cut 2	$2.23*10^5$	6.84	$9.39*10^4$	$1.42*10^4$	$2.33*10^4$	$2.53*10^3$	$2.76*10^4$	581	$6.59*10^4$	$4.19*10^3$
Cut 3	$2.58*10^4$	6.84	$8.77*10^4$	$1.36*10^4$	$2.11*10^4$	$2.10*10^3$	$2.76*10^4$	550	$1.20*10^4$	$2.76*10^3$
Cut 4	$2.51*10^4$	6.84	$8.72*10^4$	$1.33*10^4$	$2.11*10^4$	$2.03*10^3$	$2.57*10^4$	548	$1.20*10^4$	$2.76*10^3$
Cut 5	$1.02*10^3$	4.22	$1.25*10^4$	$1.08*10^4$	$1.60*10^4$	$1.19*10^3$	$2.06*10^4$	384	$2.87*10^3$	$1.37*10^3$
Cut 6	731	4.22	$5.66*10^3$	$9.84*10^3$	$1.54*10^4$	719	$1.93*10^4$	364	$1.62*10^3$	294
Cut 7	593	3.21	$4.62*10^3$	$8.89*10^3$	$1.29*10^4$	267	$1.61*10^4$	352	$1.30*10^3$	170

eRpL analysis

(repeating same cuts as I did in eLpR, only statistical number changed)

Statistics (eRpL)

	$\widetilde{e}_L\widetilde{e}_L$	$\widetilde{e}_R\widetilde{e}_R$	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^+\widetilde{\tau}_1^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_1^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_1^-$
No cuts	$3.57*10^4$	$8.75*10^4$	$4.15*10^4$	$1.48*10^5$	$1.39*10^5$	$4.21*10^4$	$1.04*10^4$	$1.04*10^4$

SM bkg	Bhabha	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	$e\nu W / eeZ / \nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
No cuts	$5.16*10^6$	$4.38*10^6$	$3.07*10^5$	$1.13*10^7$	$2.95*10^4$	$1.79*10^5$	$4.82*10^4$	$3.78*10^4$	$6.37*10^4$	$3.36*10^5$	$1.15*10^9$	$2.25*10^9$

precuts

$N_{\mu\text{-PFO}} == 2$

$N_{\text{chargedPFO}} == 2$

※These precuts might change when we switch to ILD full simulation because of different PFA performance and $\gamma\gamma \rightarrow$ low P_t hadron backgrounds.

※pfo->getType() does not work for SGV samples because it is always 0. Instead, getPDG() is used (this will pick up PDG value of detailed PID info) for SGV.

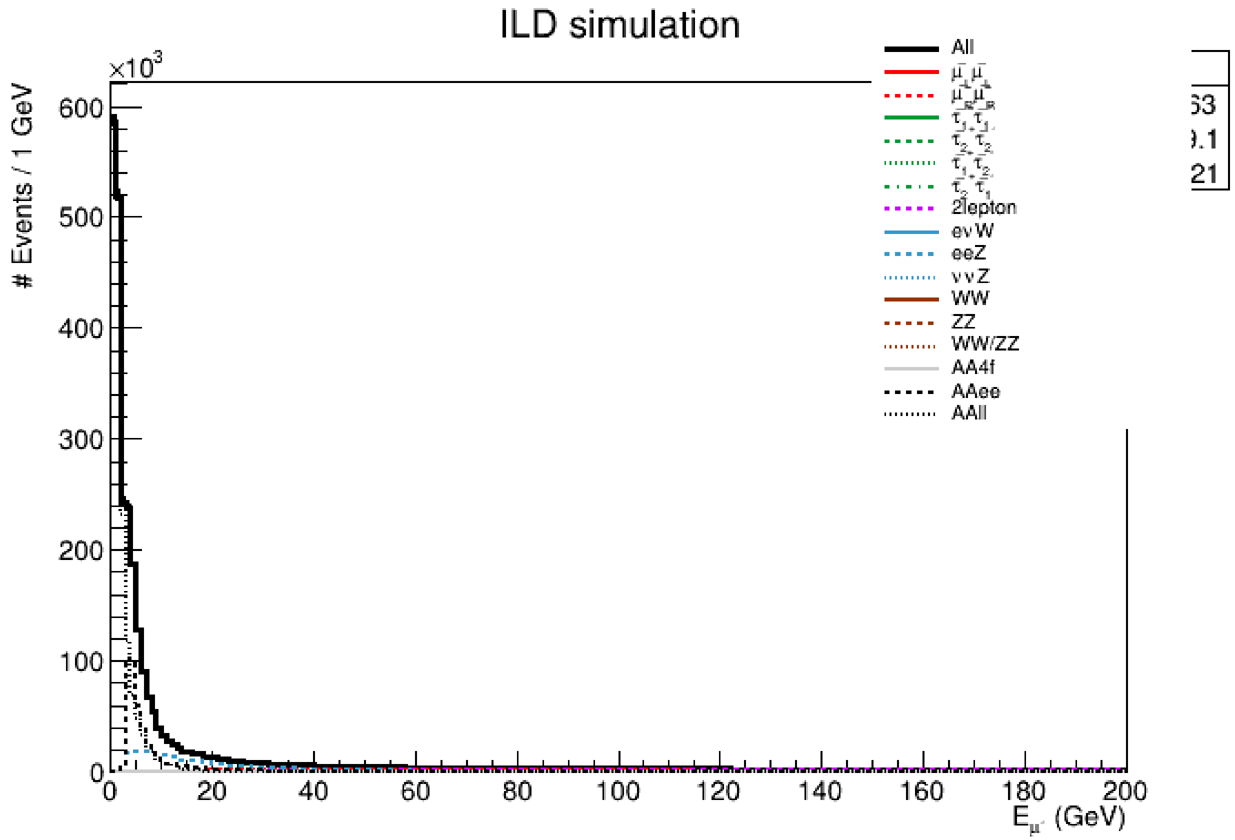
	$\widetilde{e}_L\widetilde{e}_L$	$\widetilde{e}_R\widetilde{e}_R$	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^+\widetilde{\tau}_1^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_1^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_1^-$
precuts	0	0	$3.62*10^4$	$1.29*10^5$	$2.54*10^3$	$1.01*10^3$	217	217

SM bkg	Bhabha	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	$e\nu W / eeZ / \nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	0	$5.00*10^5$	6.74	$3.72*10^5$	$3.35*10^3$	0	$2.11*10^3$	$2.29*10^3$	$7.96*10^3$	858	$4.42*10^5$	$1.69*10^6$

Distribution of E_{μ^-} at precuts

Solid Black histogram is the sum up all processes and this is the histogram we can obtain from the real experiment.

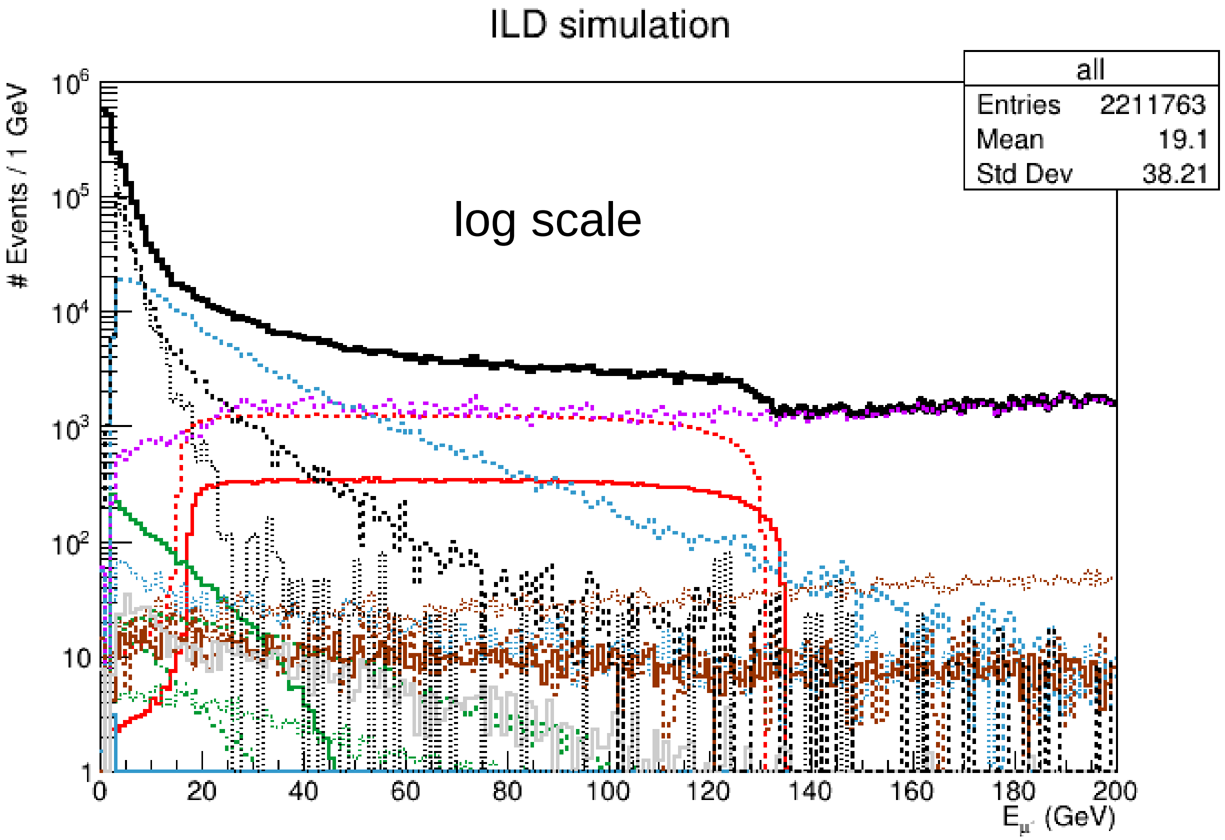
Clearly, more background rejection is necessary to measure edges.
Dominant backgrounds:
AAll, AAee, 2lepton, eeZ(singleZee)



Distribution of E_{μ^-} at precuts

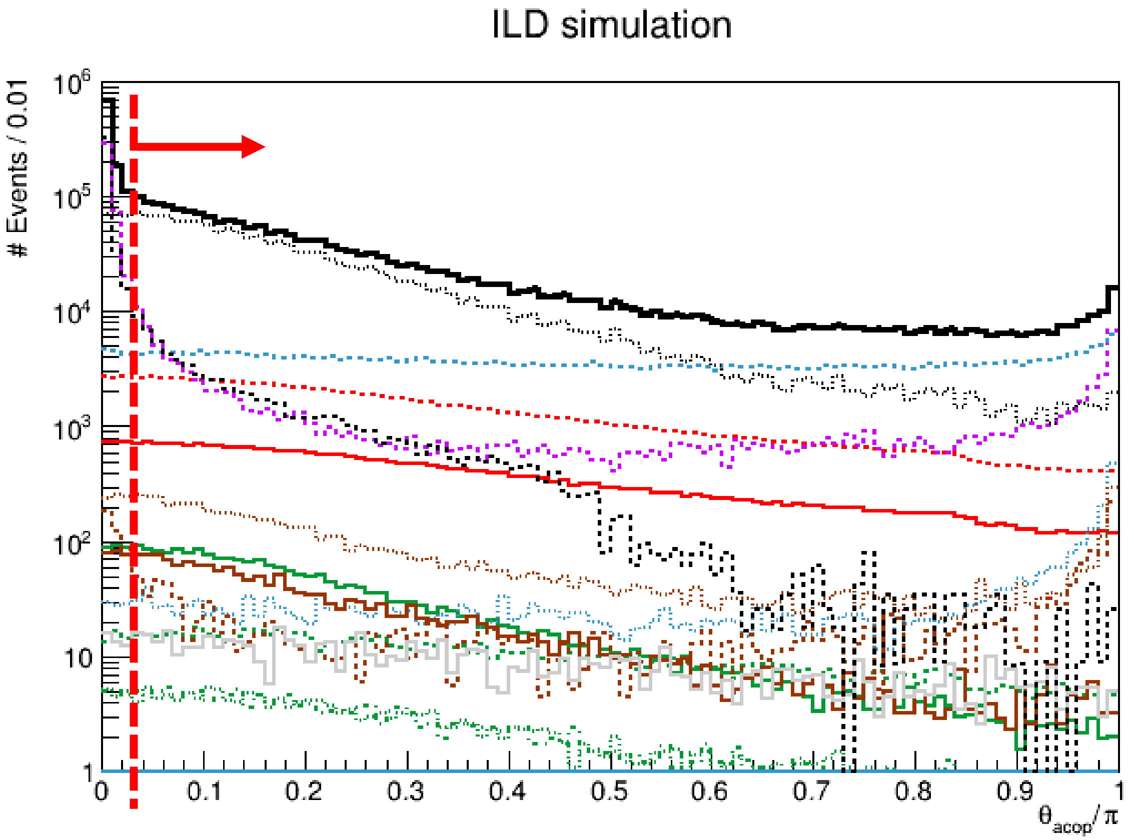
Solid Black histogram is the sum up all processes and this is the histogram we can obtain from the real experiment.

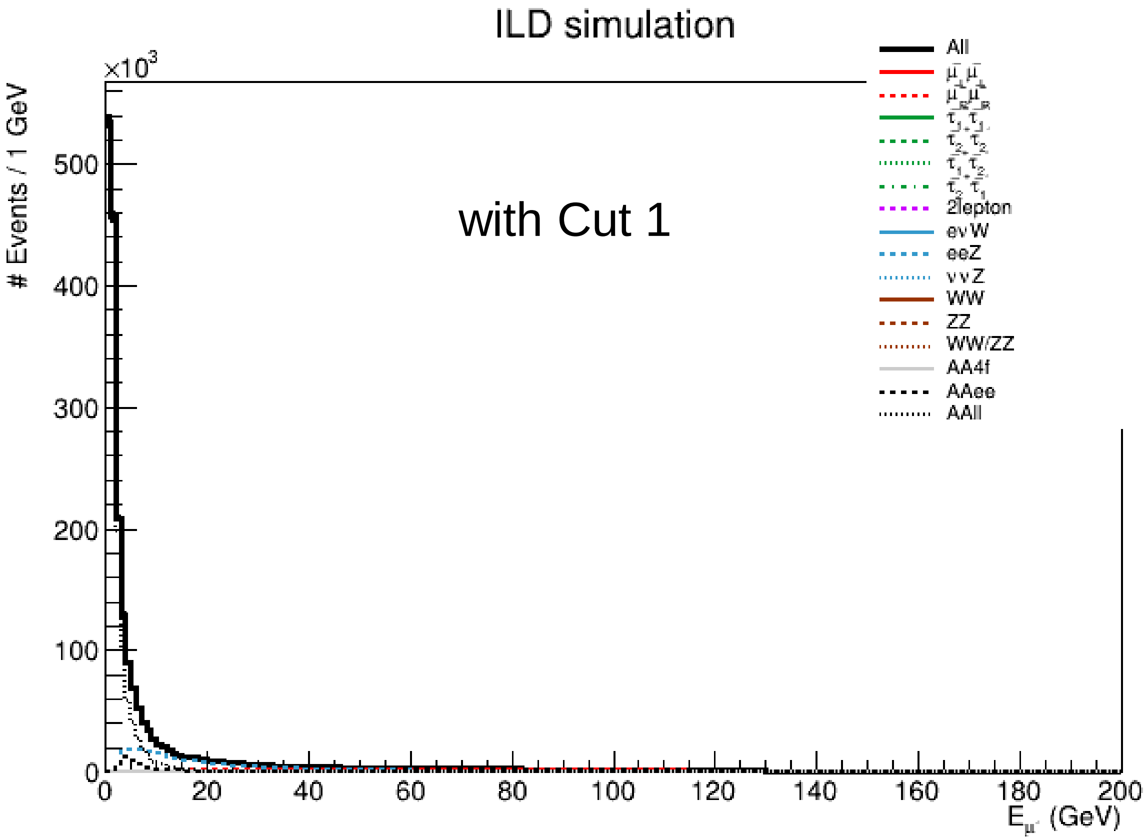
Clearly, more background rejection is necessary to measure edges.
Dominant backgrounds:
AAll, AAee, 2lepton, eeZ(singleZee)



Loose cuts (eRpL)

Cut on acoplanarity $\theta_{\mathrm{acop}} = \pi - (\phi_1 - \phi_2)$



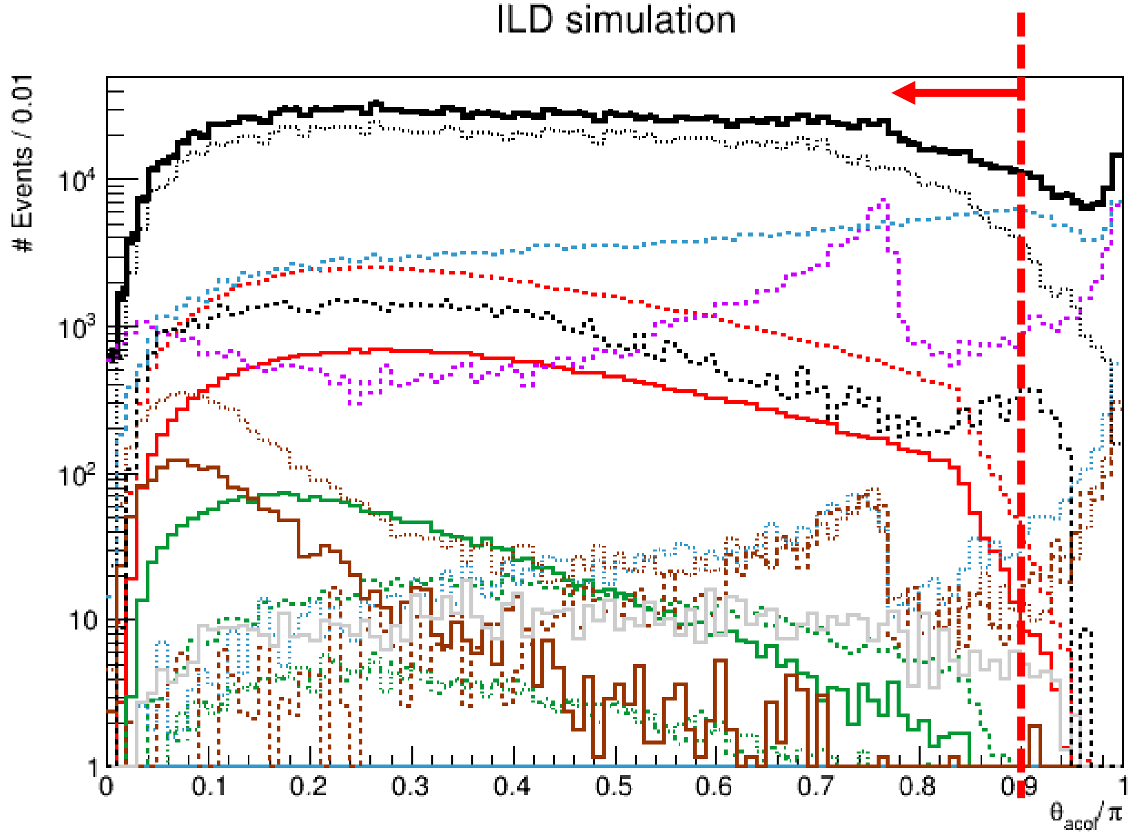


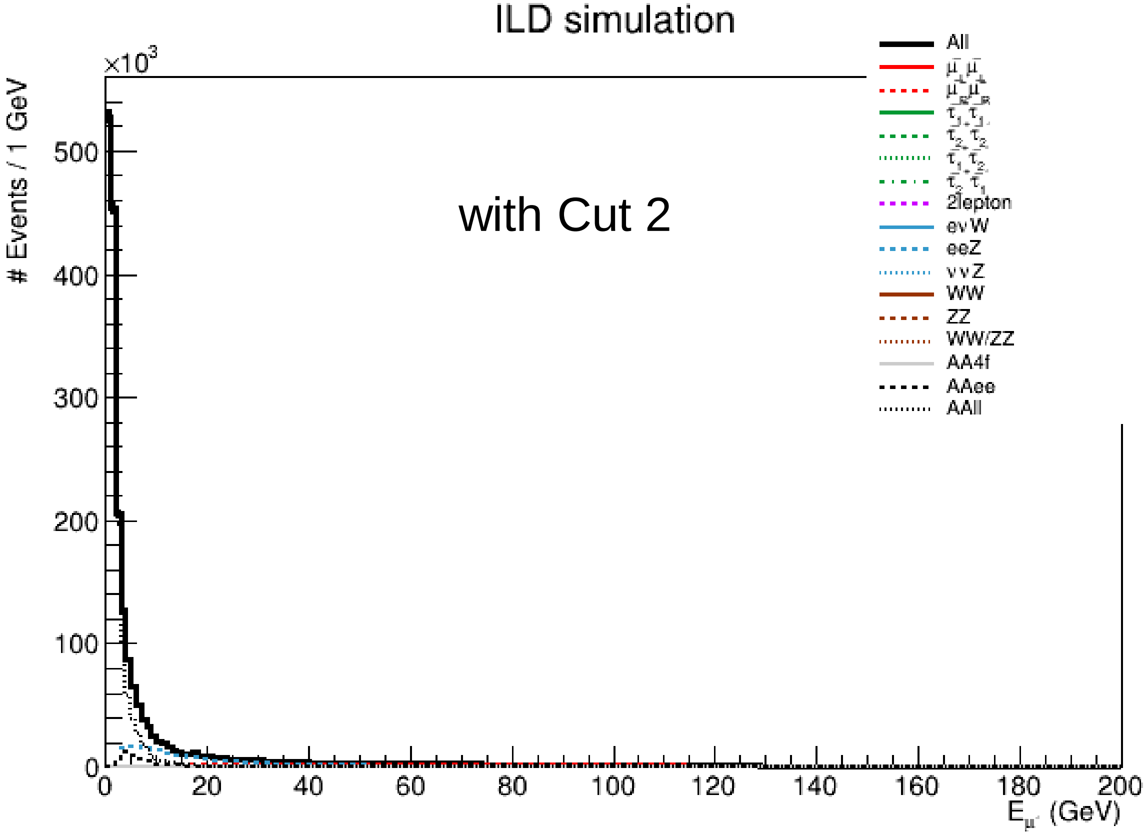
$\frac{\theta_{\mathrm{acop}}}{\pi} \sim 0$: two muons are back-to-back in xy-plane

mostly for SM background rejection, some signals rejected as well

Cut 1: $\frac{\theta_{\mathrm{acop}}}{\pi} > 0.03$

Cut on acolinearity $\theta_{\mathrm{acol}} = \pi - (\theta_1 - \theta_2)$



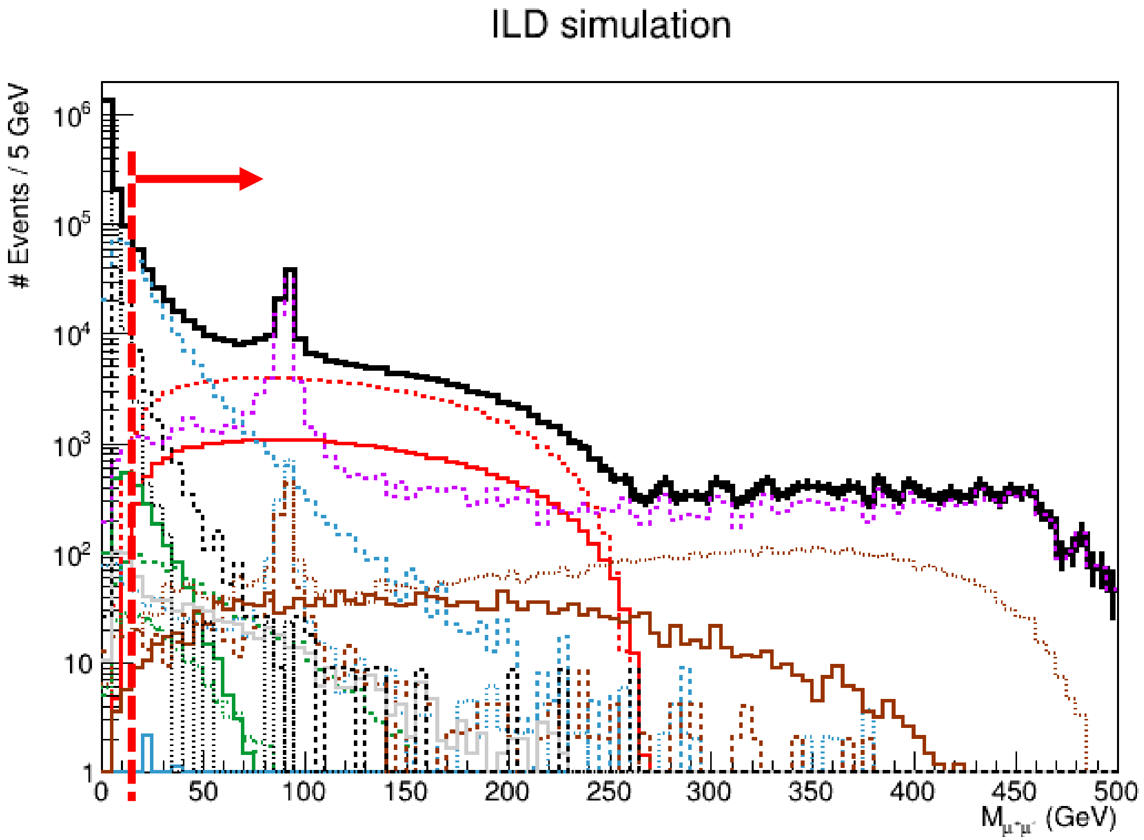


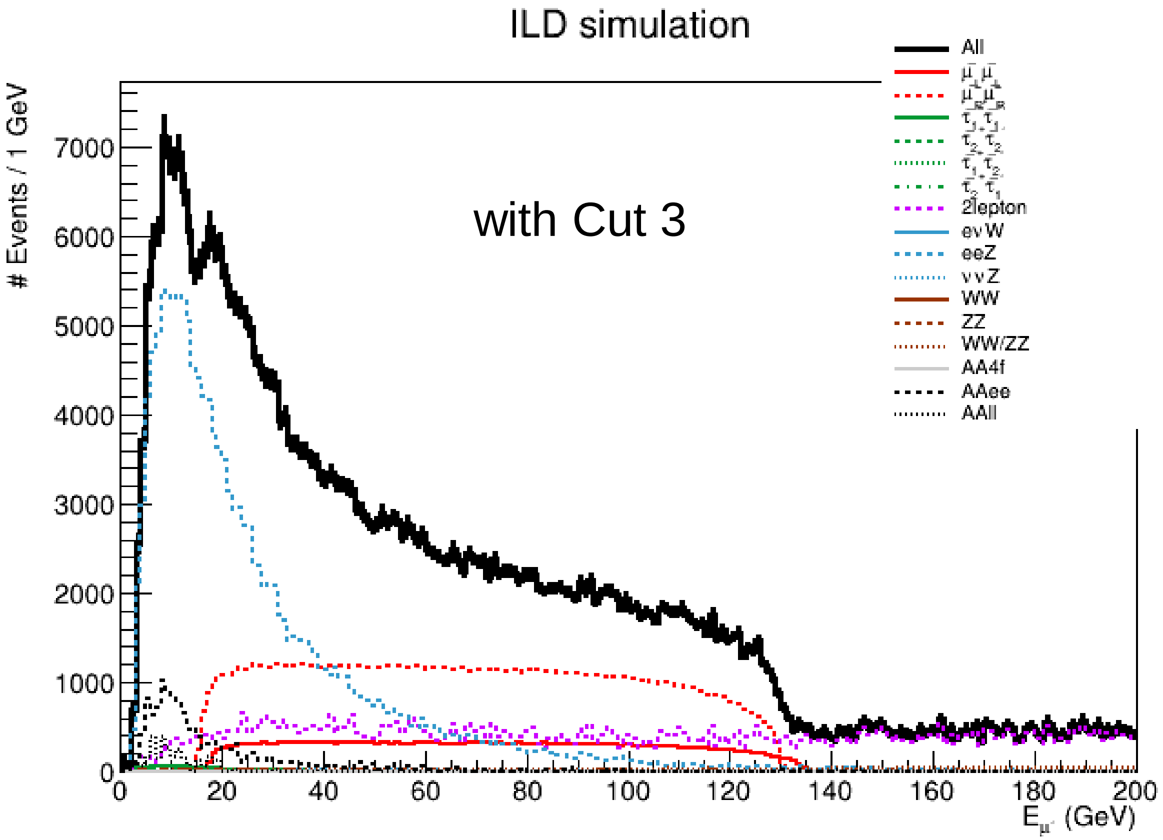
$\frac{\theta_{\mathrm{acol}}}{\pi} \sim 1$: two muons flying the same direction

such probability is expected to be small in signal

Cut 2: $\frac{\theta_{\mathrm{acol}}}{\pi} < 0.9$

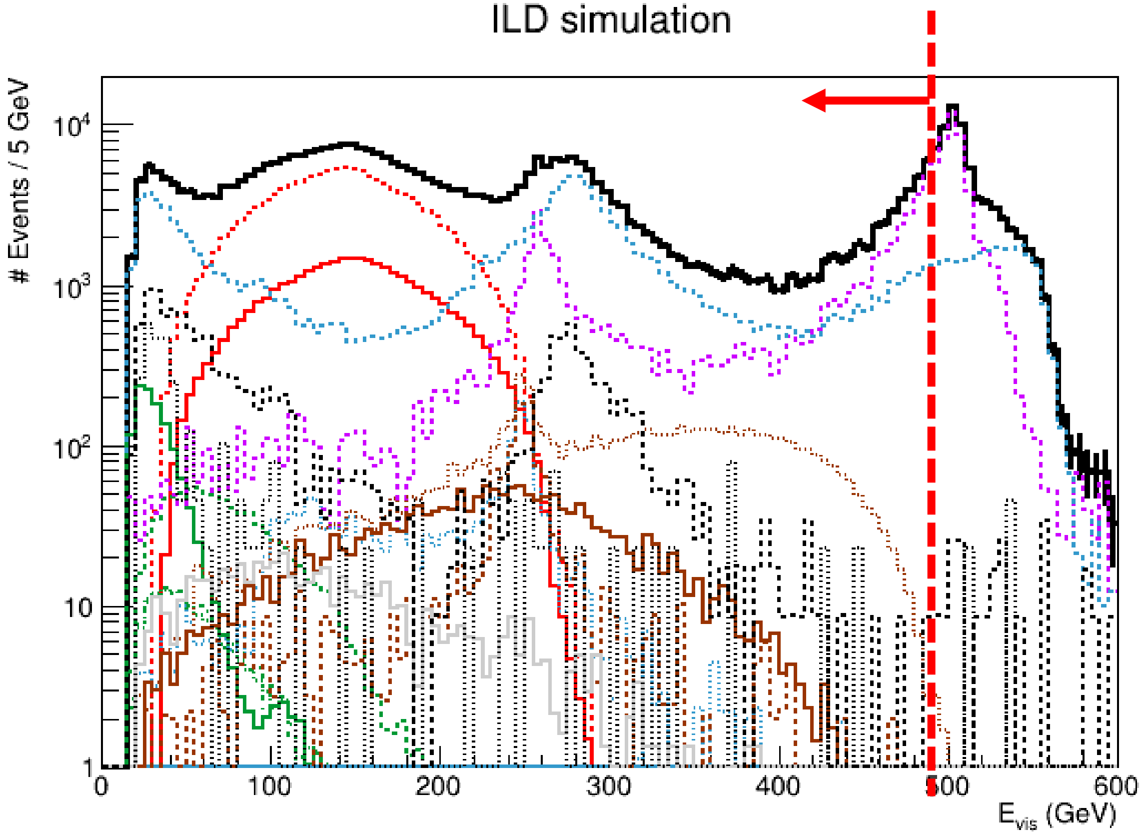
Cut on $M_{\mu\mu}$

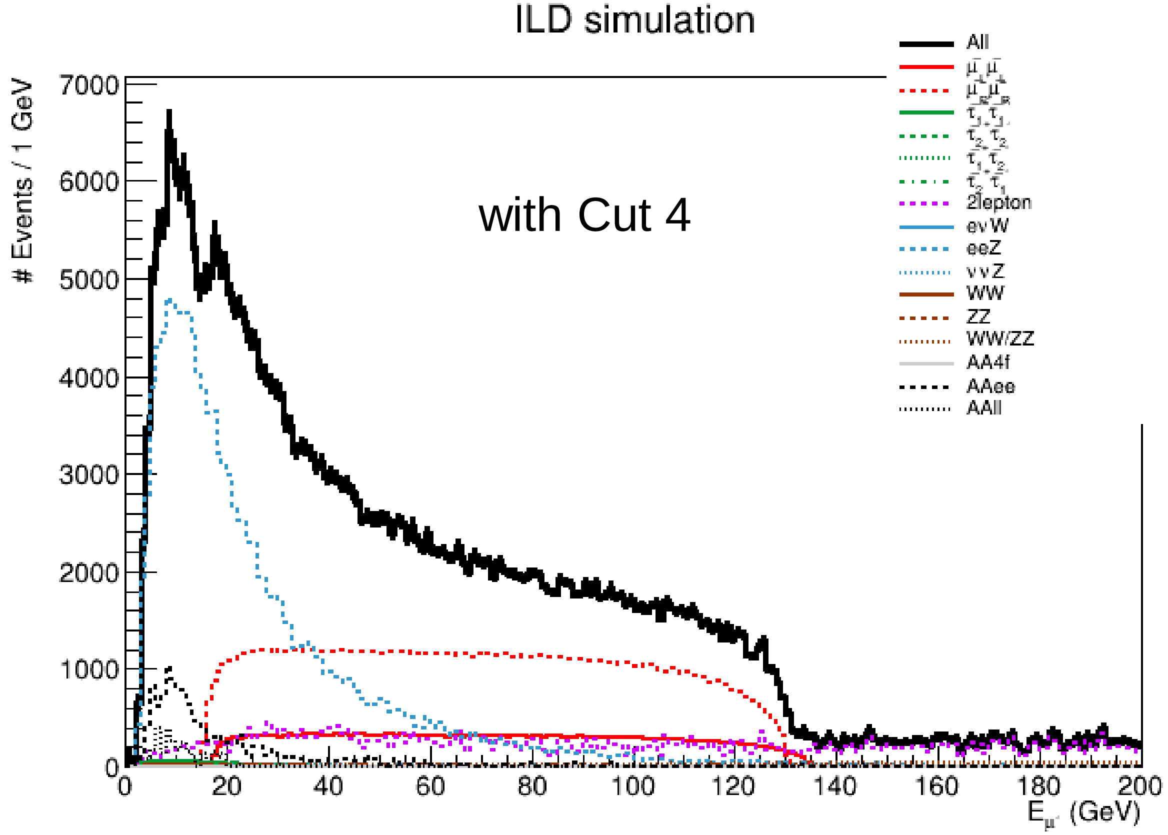




$M_{\mu\mu}\sim 0$ GeV: two muons produced by photon
expect no peaks around that region for signal
Cut 3: $M_{\mu\mu} > 15$ GeV

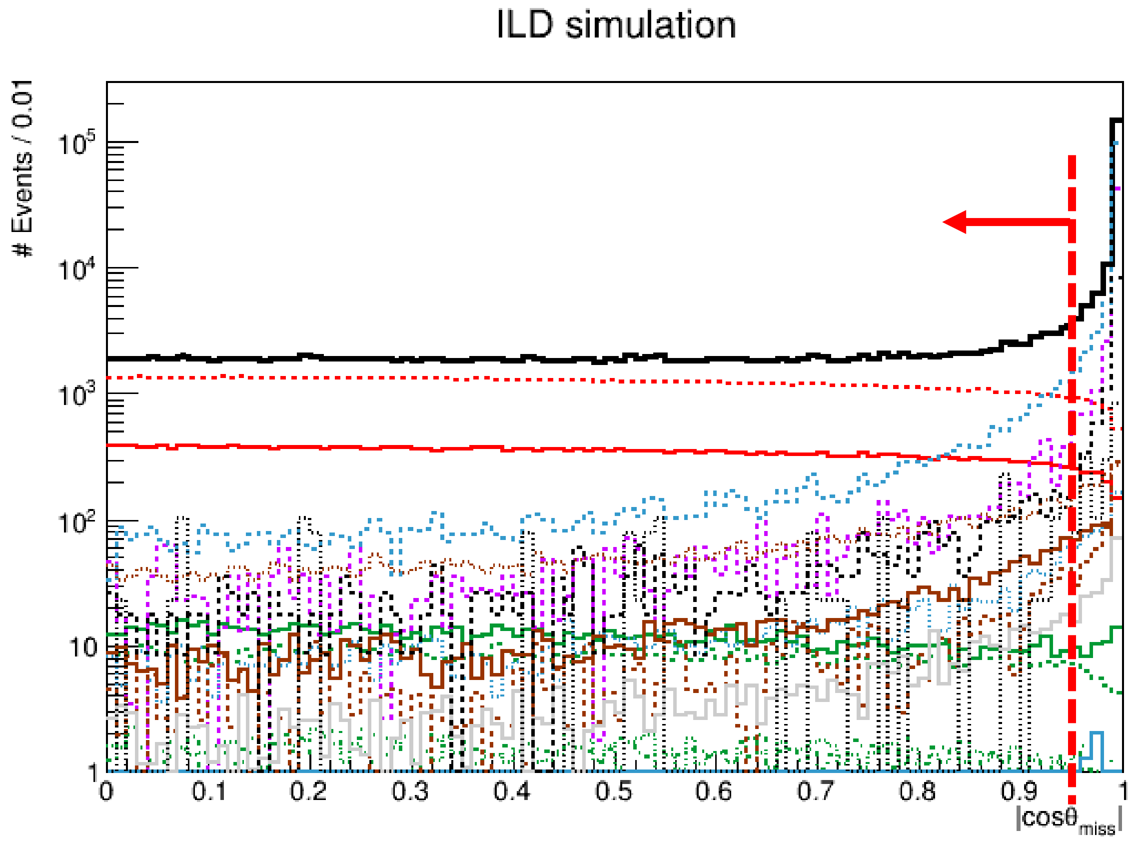
Cut on E_{vis}

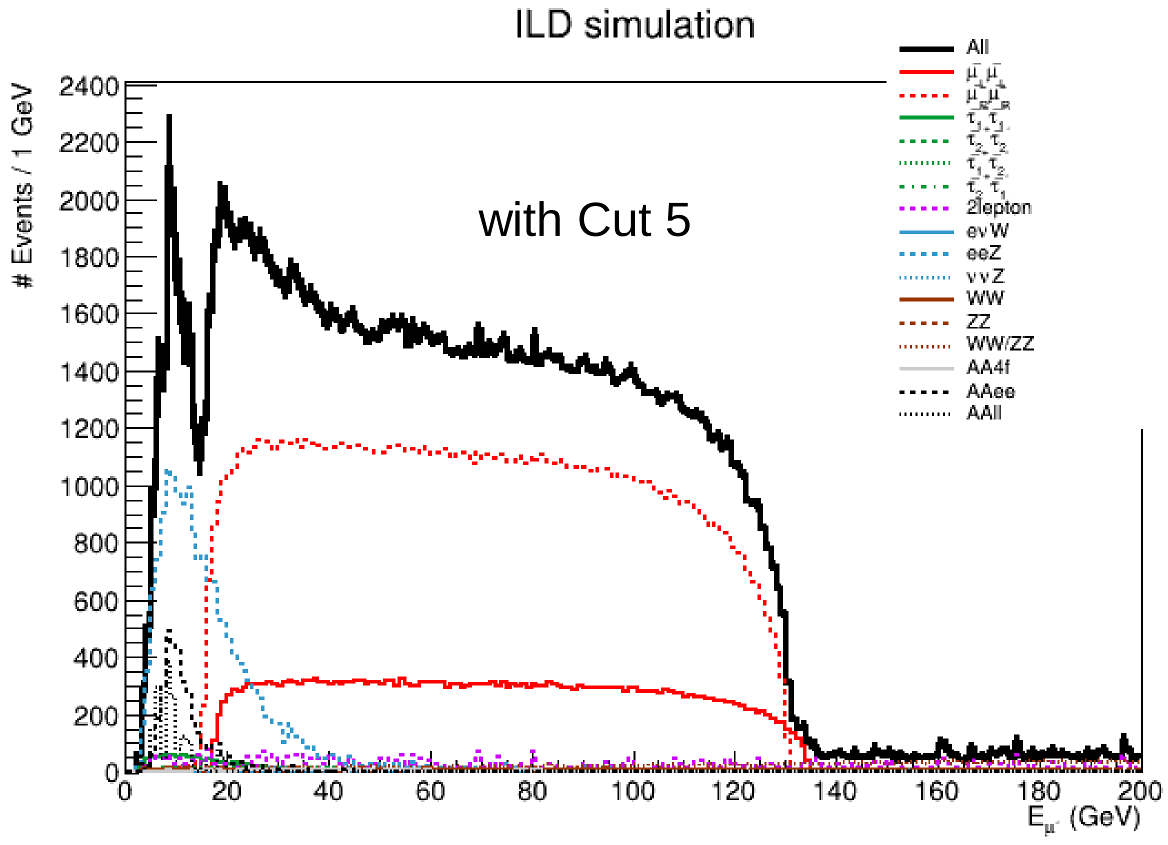




E_{vis} ~ 500 GeV: almost no missing component
signal have large missing component
Cut 4: E_{vis} < 490 GeV

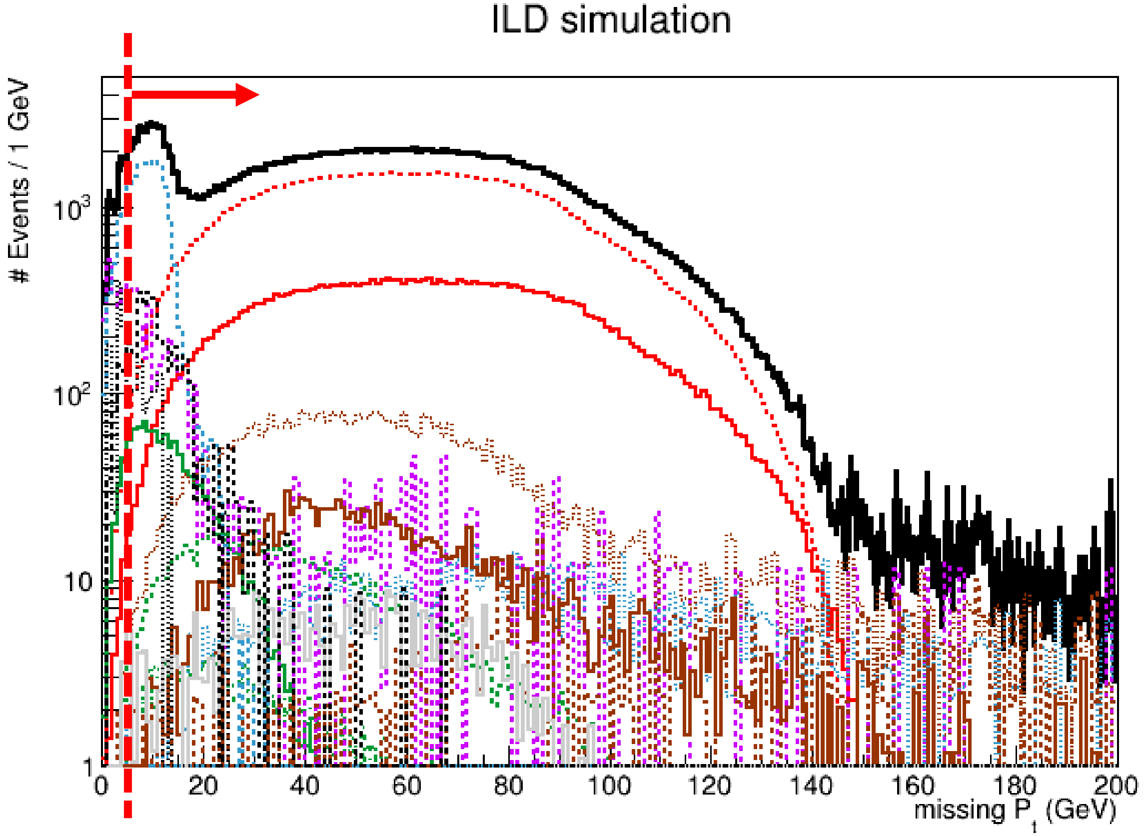
Cut on $\cos\theta_{\rm miss}$

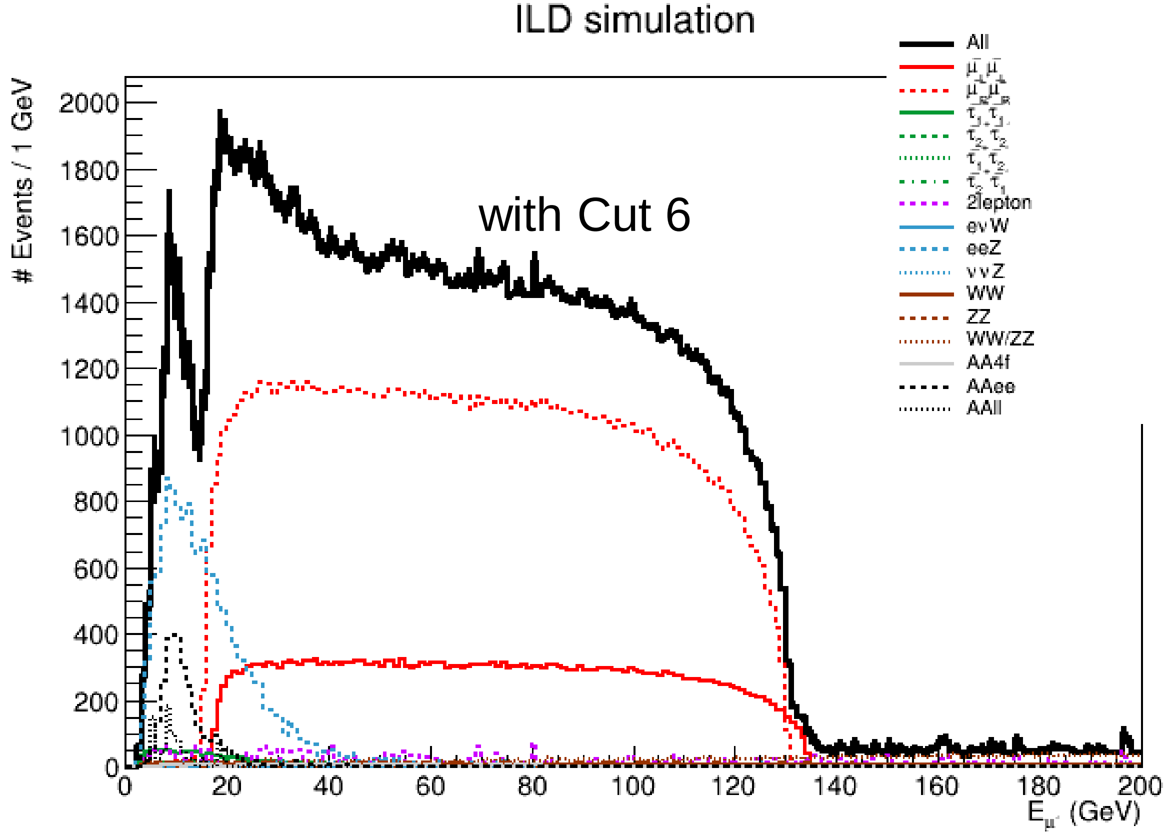




$|\cos\theta_{\rm miss}| \sim 1$: almost no missing component
signal have large missing component
Cut 5: $|\cos\theta_{\rm miss}| < 0.95$

Cut on missing P_t





missing P_t ~ 0 GeV: almost no missing component
signal have large missing component
Cut 6: missing P_t > 5 GeV

Cut table (Loose)

signal efficiency: ~79%

significance $= \frac{1.50\times10^5}{\sqrt{1.50\times10^5+3.37\times10^4}} = 350\sigma$

overall dominant backgrounds:
eeZ, WW/ZZ, 2lepton

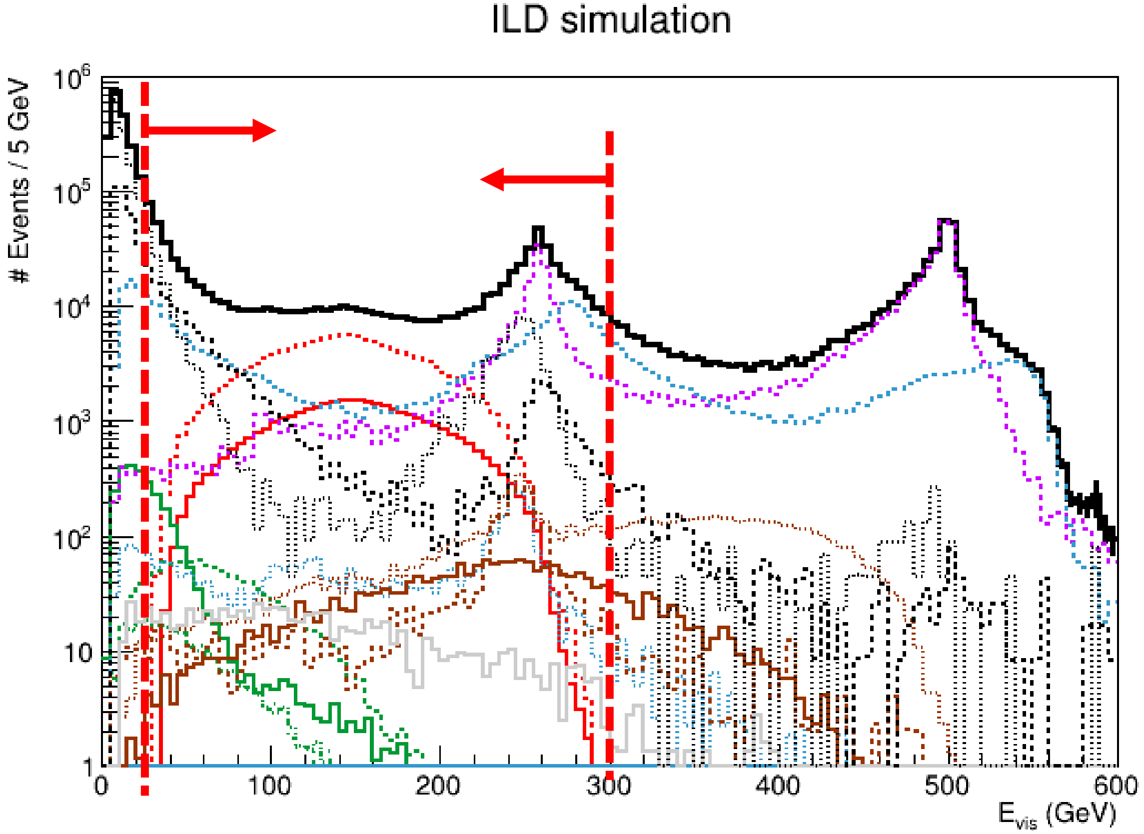
affects E^- edge detection:
eeZ, AAll

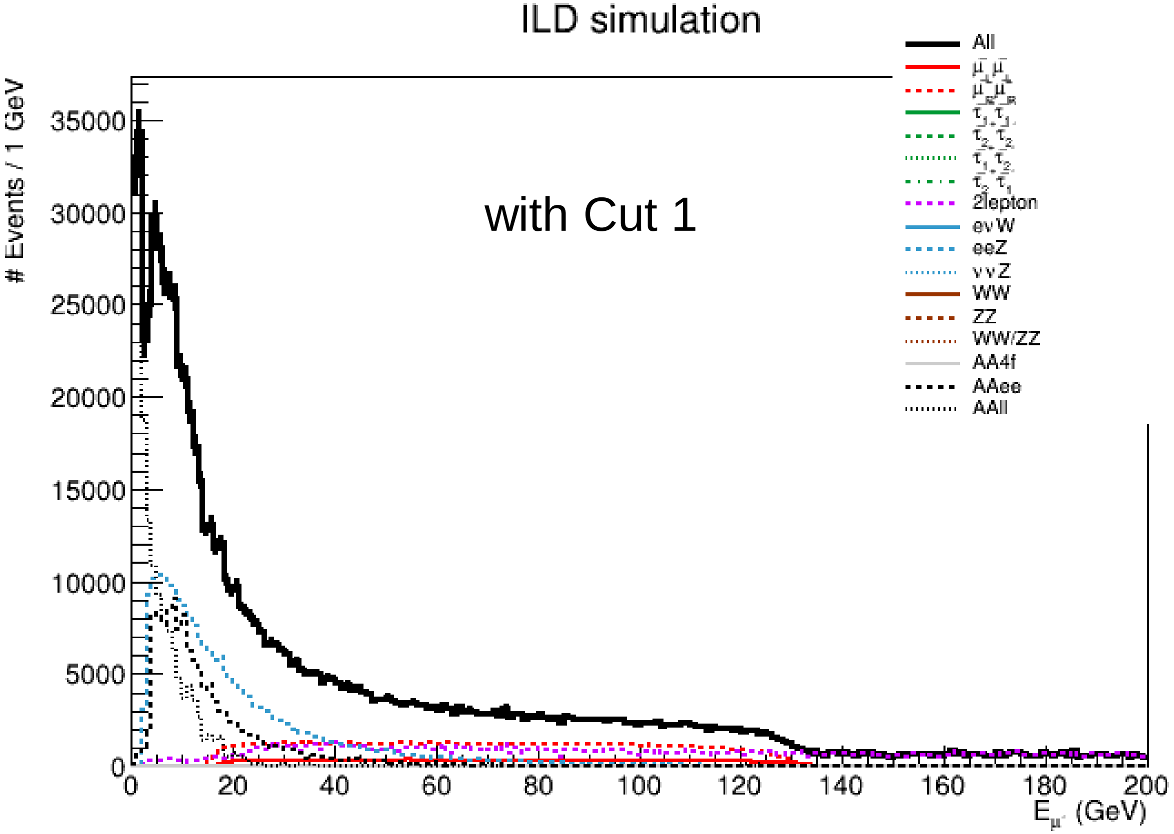
	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^+\widetilde{\tau}_1^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_1^+\widetilde{\tau}_2^-$	$\widetilde{\tau}_2^+\widetilde{\tau}_1^-$
precuts	$3.62*10^4$	$1.29*10^5$	$2.54*10^3$	$1.01*10^3$	217	217
Cut 1	$3.40*10^4$	$1.21*10^5$	$2.27*10^3$	967	202	202
Cut 2	$3.40*10^4$	$1.21*10^5$	$2.27*10^3$	966	202	202
Cut 3	$3.39*10^4$	$1.21*10^5$	$1.17*10^3$	821	144	148
Cut 4	$3.39*10^4$	$1.21*10^5$	$1.17*10^3$	821	144	148
Cut 5	$3.29*10^4$	$1.17*10^5$	$1.12*10^3$	793	139	142
Cut 6	$3.28*10^4$	$1.17*10^5$	$1.01*10^3$	788	136	139

SM bkg	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	$5.00*10^5$	6.74	$3.72*10^5$	$3.35*10^3$	$2.11*10^3$	$2.29*10^3$	$7.96*10^3$	858	$4.42*10^5$	$1.69*10^6$
Cut 1	$1.19*10^5$	6.74	$3.58*10^5$	$3.26*10^3$	$1.87*10^3$	$1.90*10^3$	$7.22*10^3$	817	$7.45*10^4$	$1.48*10^6$
Cut 2	$9.92*10^4$	5.05	$3.08*10^5$	$1.88*10^3$	$1.87*10^3$	$1.22*10^3$	$6.56*10^3$	782	$7.28*10^4$	$1.46*10^6$
Cut 3	$9.74*10^4$	4.81	$1.48*10^5$	$1.67*10^3$	$1.86*10^3$	$1.17*10^3$	$6.51*10^3$	572	$1.42*10^4$	$3.32*10^3$
Cut 4	$5.21*10^4$	4.81	$1.27*10^5$	$1.67*10^3$	$1.86*10^3$	$1.17*10^3$	$6.50*10^3$	571	$1.39*10^4$	$3.23*10^3$
Cut 5	$5.66*10^3$	1.54	$1.73*10^4$	$1.21*10^3$	$1.46*10^3$	667	$5.46*10^3$	402	$3.52*10^3$	$1.62*10^3$
Cut 6	$3.87*10^3$	1.54	$1.46*10^4$	$1.21*10^3$	$1.46*10^3$	665	$5.46*10^3$	396	$3.14*10^3$	814

Tight cuts (eRpL)

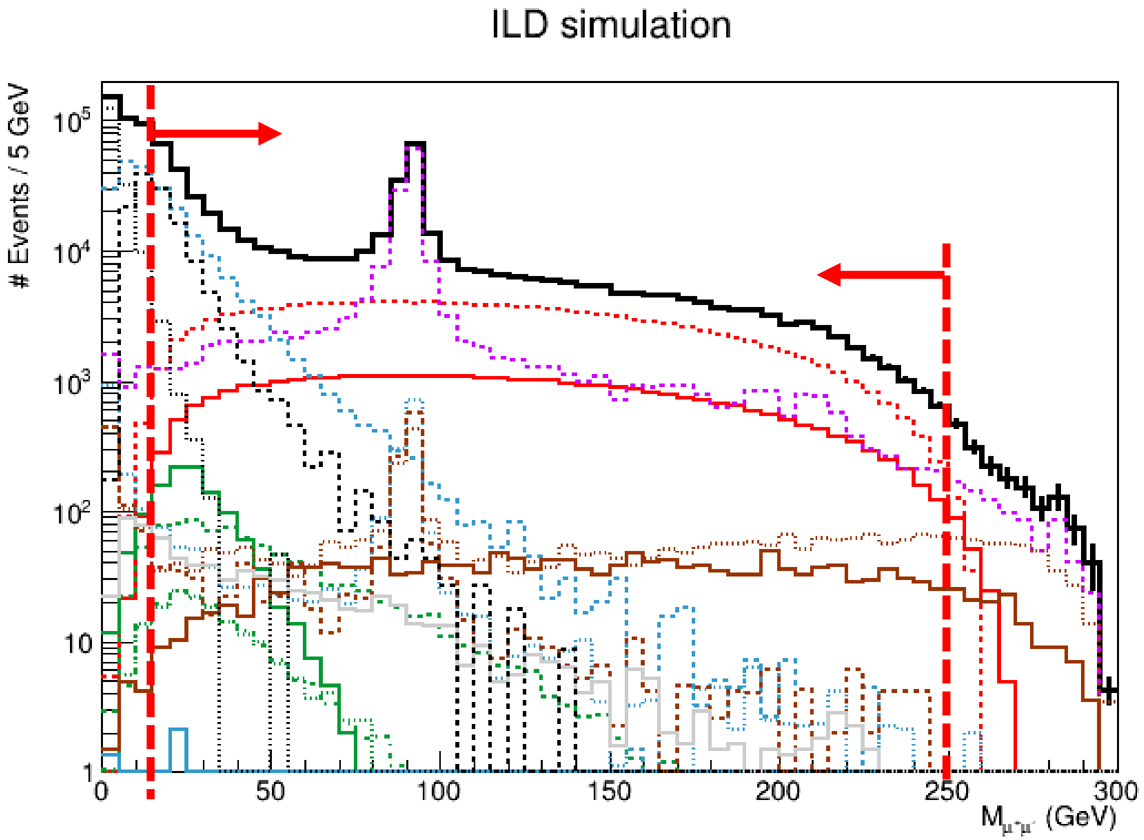
Cut on E_{vis}

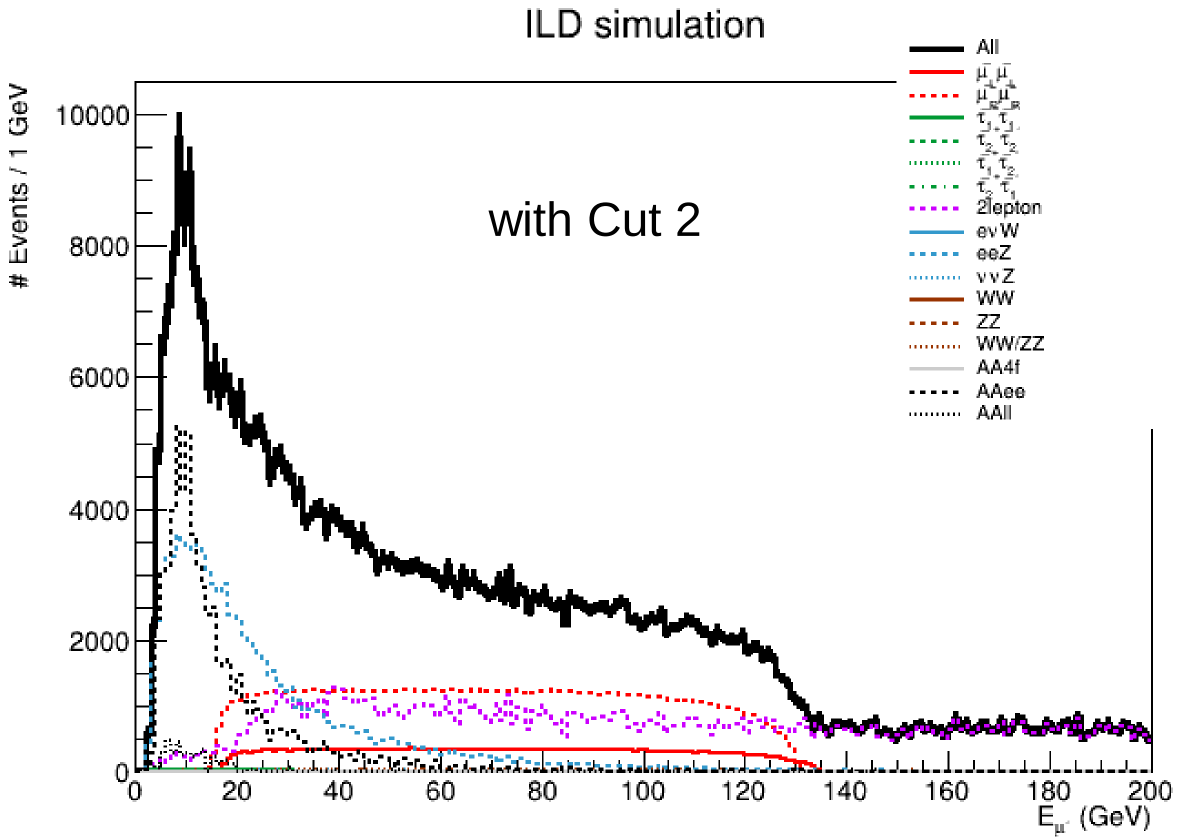




E_{vis} ~ 500 GeV: almost no missing component
E_{vis} ~ 0 GeV: almost all missing component
Cut 1: 25 < E_{vis} < 300 GeV

Cut on $M_{\mu\mu}$



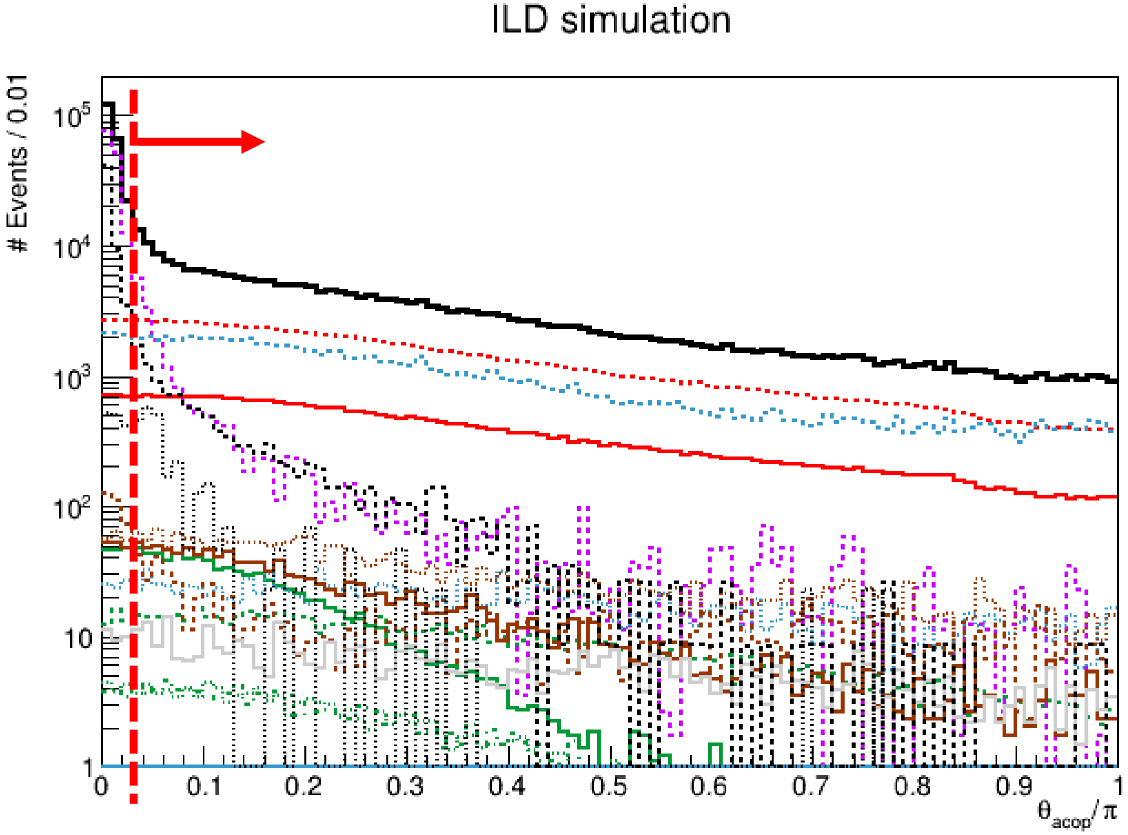


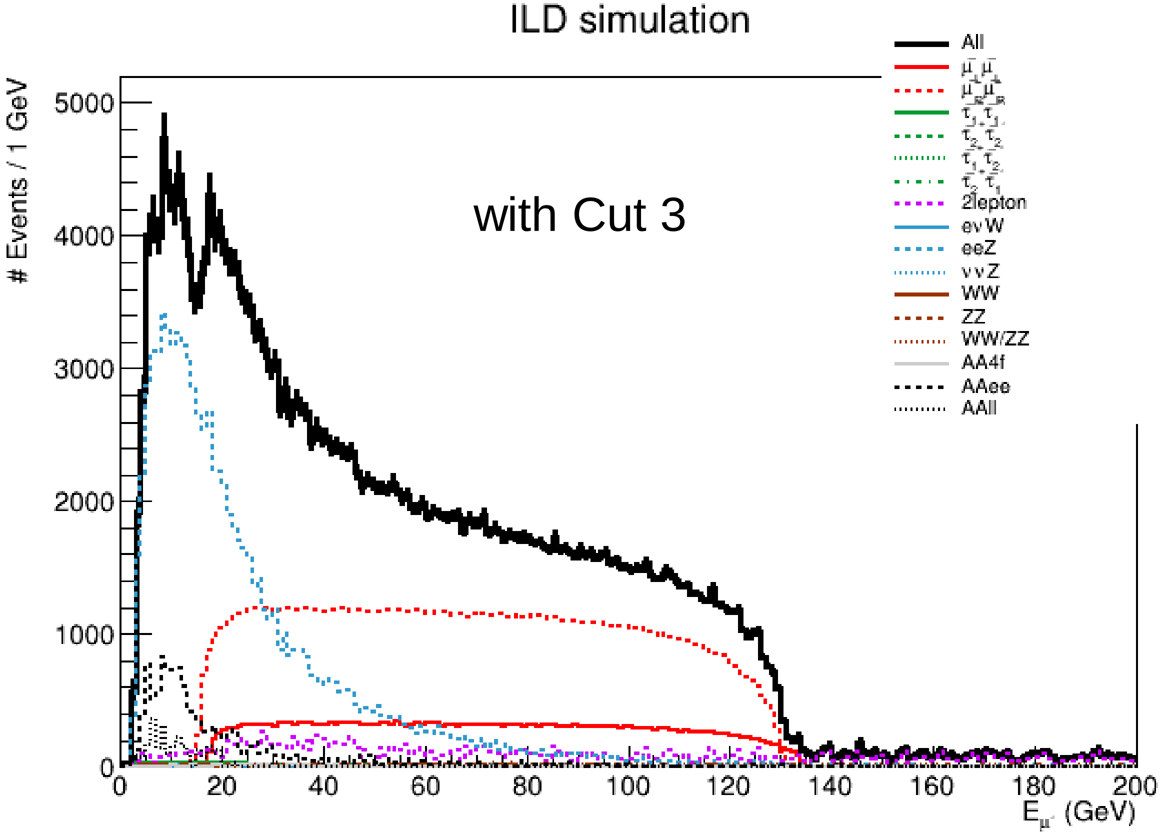
$M_{\mu\mu}$ ~ 0 GeV: two muons produced by photon

assume pair production: maximum of $M_{\mu\mu}$ is 250 GeV

Cut 2: 15 < $M_{\mu\mu}$ < 250 GeV

Cut on acoplanarity $\theta_{\mathrm{acop}} = \pi - (\phi_1 - \phi_2)$



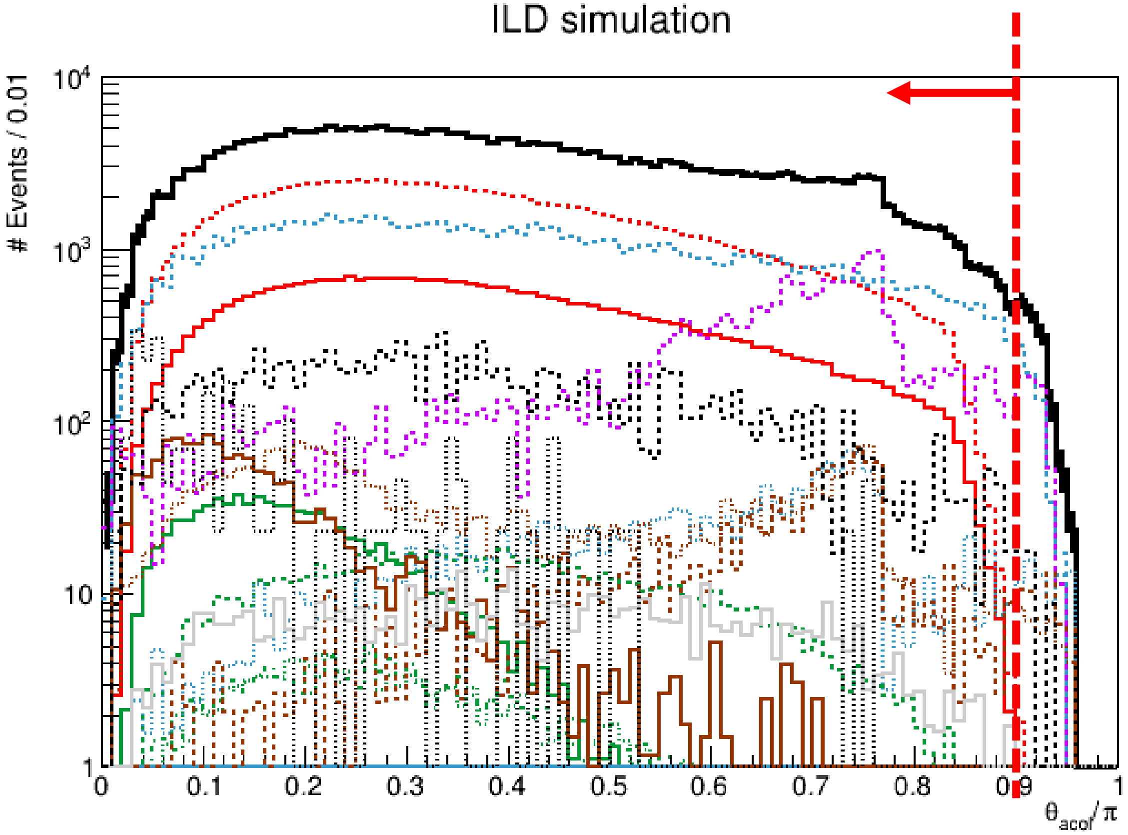


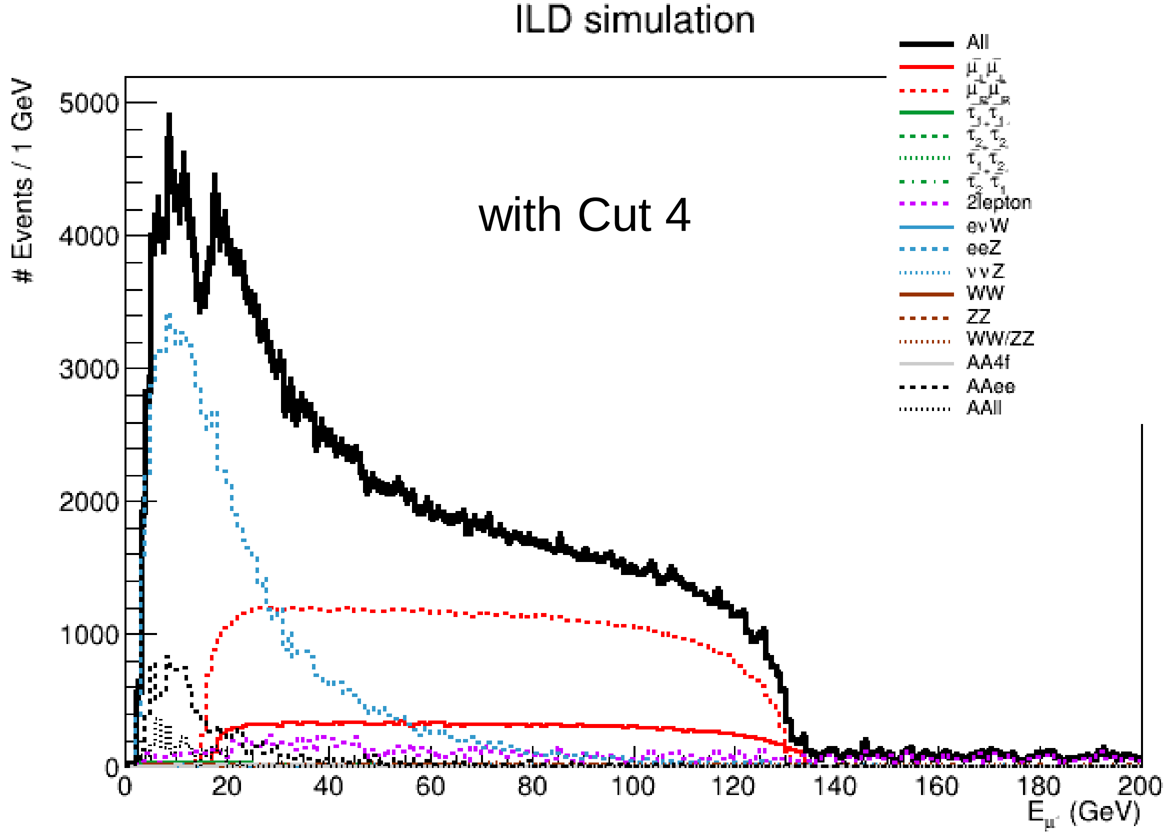
$\frac{\theta_{\mathrm{acop}}}{\pi} \sim 0$: two muons are back-to-back in xy-plane

mostly for SM background rejection, some signals rejected as well

Cut 3: $\frac{\theta_{\mathrm{acop}}}{\pi} > 0.03$

Cut on acolinearity $\theta_{\text{acol}} = \pi - (\theta_1 - \theta_2)$



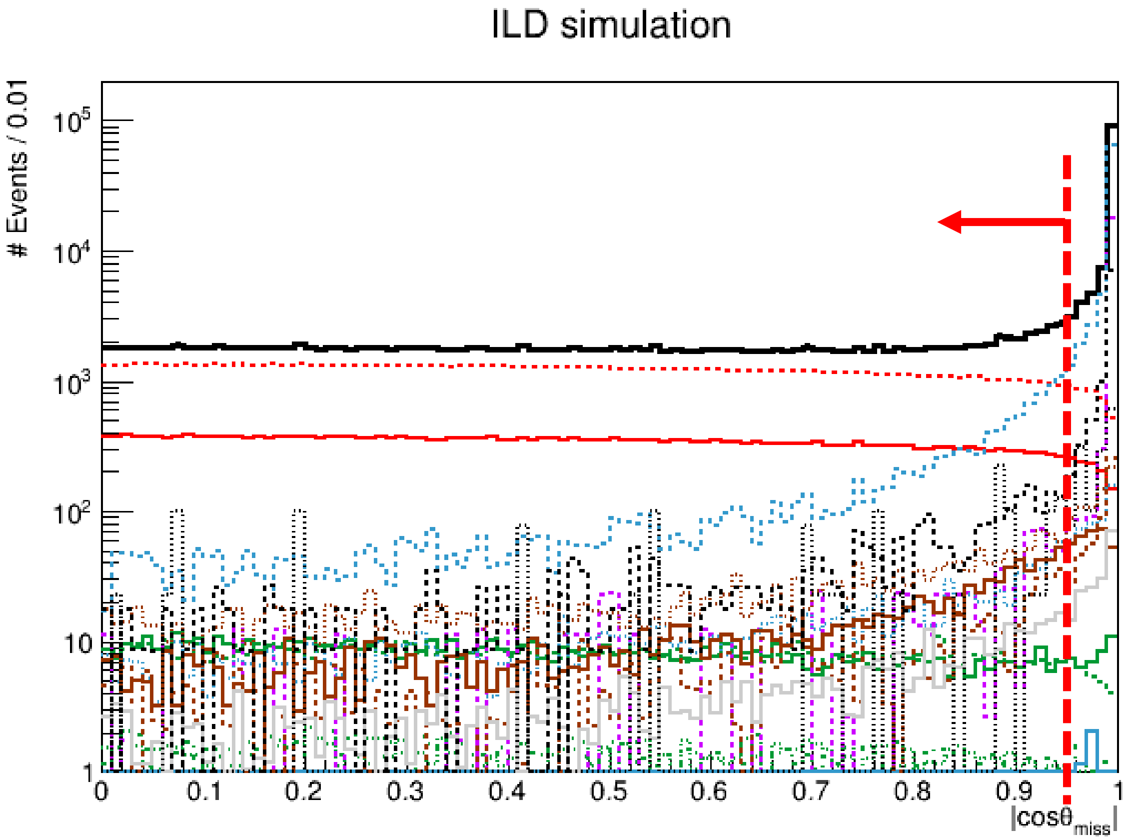


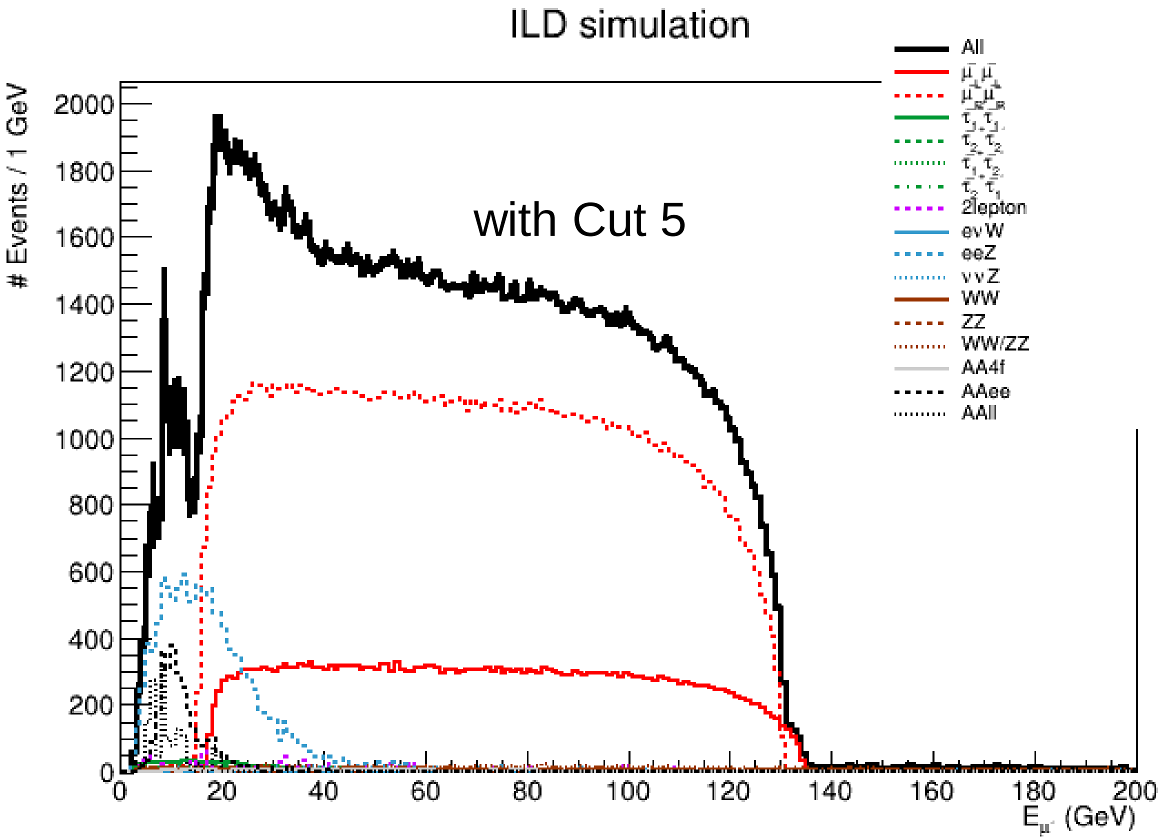
$\frac{\theta_{\text{acol}}}{\pi} \sim 1$: two muons flying the same direction

such probability is expected to be small in signal

Cut 4: $\frac{\theta_{\text{acol}}}{\pi} < 0.9$

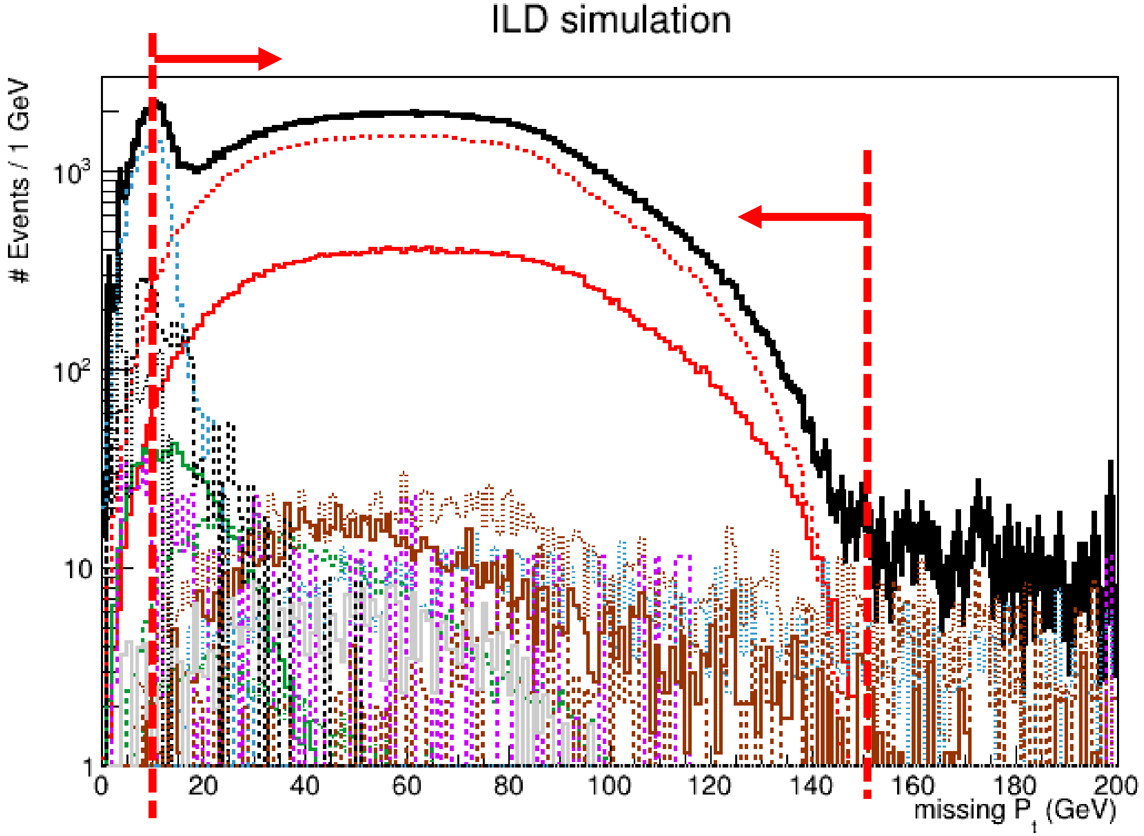
Cut on $\cos\theta_{\mathrm{miss}}$

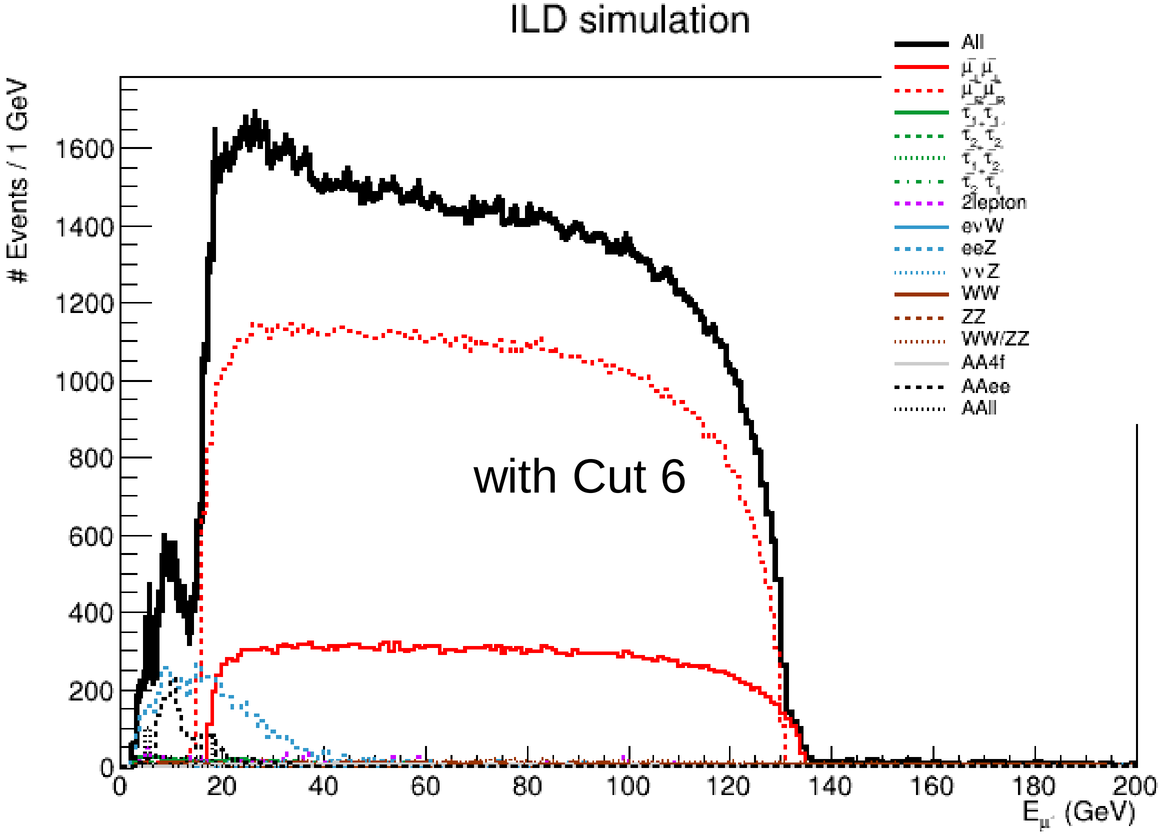




$|\cos\theta_{\mathrm{miss}}| \sim 1$: almost no missing component
signal have large missing component
Cut 5: $|\cos\theta_{\mathrm{miss}}| < 0.95$

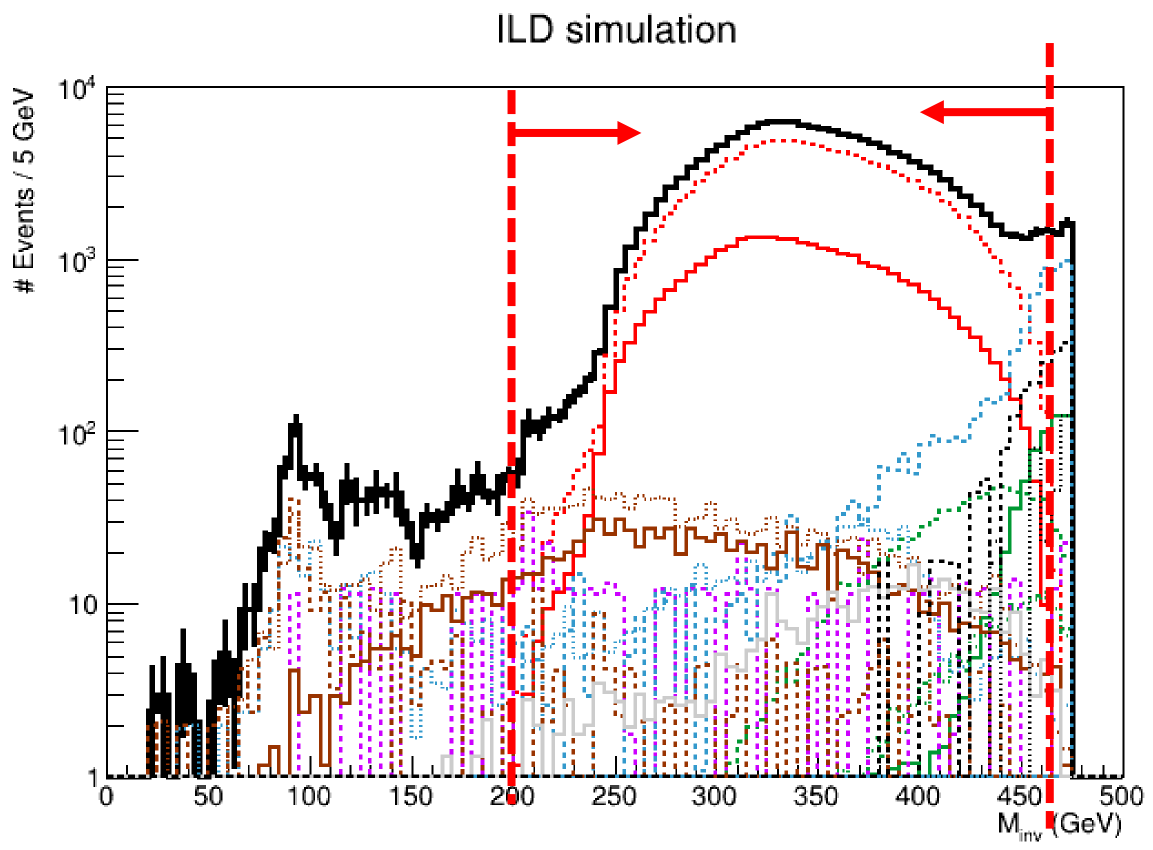
Cut on missing P_t

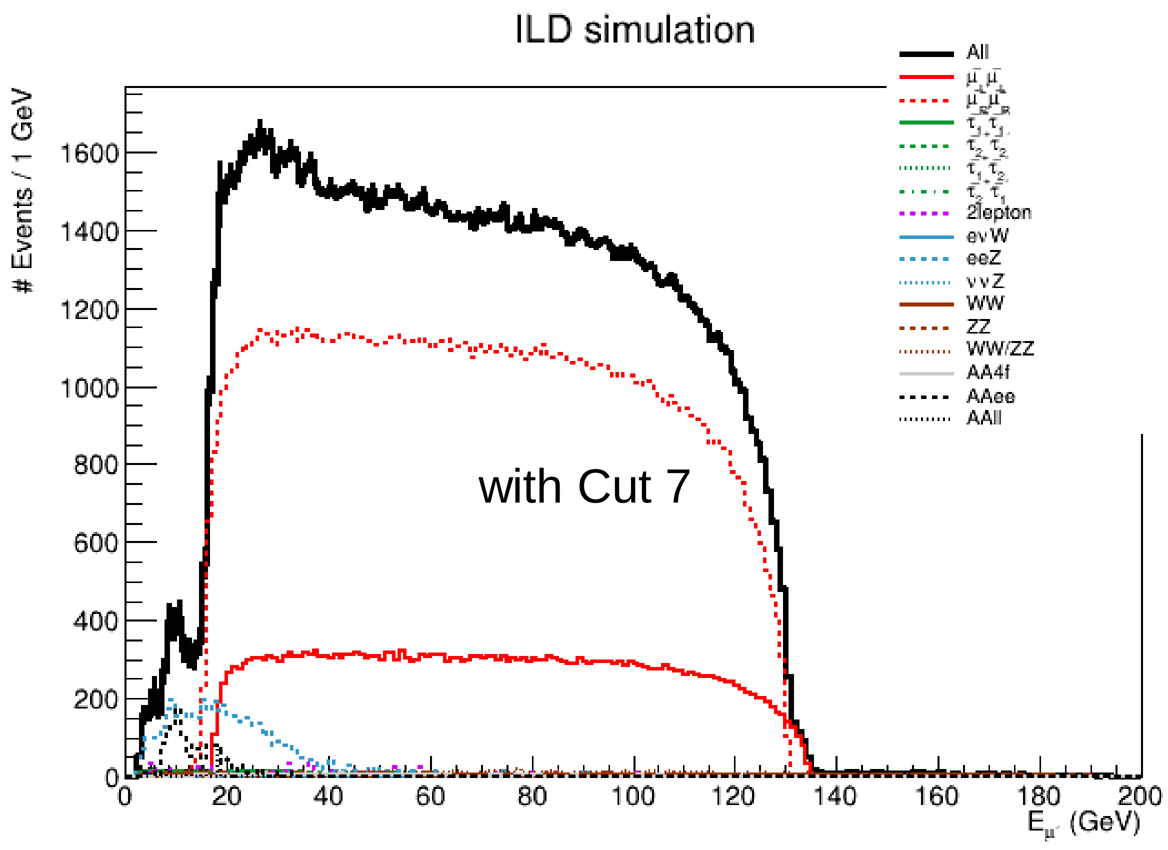




missing P_t ~ 0 GeV: almost no missing component
signal have large missing component
Cut 6: 10 < missing P_t < 150 GeV

Cut on M_{inv} (invariant mass of missing component)





M_{inv} ~ 500 GeV: almost all missing component
signal have large missing component
Cut 7: 200 < M_{inv} < 470 GeV

Cut table (Tight WIP)

signal efficiency: ~79%

significance $= \frac{1.49\times10^5}{\sqrt{1.49\times10^5+1.15\times10^4}} = 372\sigma$

overall dominant backgrounds:
eeZ, WW/ZZ, AAee

affects E^- edge detection:
eeZ, (AAll, 170 event = 5 MC event)

	$\widetilde{\mu}_L\widetilde{\mu}_L$	$\widetilde{\mu}_R\widetilde{\mu}_R$	$\widetilde{\tau}_1^{+}\widetilde{\tau}_1^{-}$	$\widetilde{\tau}_2^{+}\widetilde{\tau}_2^{-}$	$\widetilde{\tau}_1^{+}\widetilde{\tau}_2^{-}$	$\widetilde{\tau}_2^{+}\widetilde{\tau}_1^{-}$
precuts	$3.62*10^4$	$1.29*10^5$	$2.54*10^3$	$1.01*10^3$	217	217
Cut 1	$3.62*10^4$	$1.29*10^5$	$1.17*10^3$	920	167	167
Cut 2	$3.59*10^4$	$1.29*10^5$	964	843	149	149
Cut 3	$3.38*10^4$	$1.21*10^5$	823	801	137	137
Cut 4	$3.38*10^4$	$1.21*10^5$	823	801	137	137
Cut 5	$3.28*10^4$	$1.17*10^5$	783	774	132	132
Cut 6	$3.26*10^4$	$1.16*10^5$	576	752	124	124
Cut 7	$3.26*10^4$	$1.16*10^5$	452	733	118	118

SM bkg	2lepton	$e\nu W$	eeZ	$\nu\nu Z$	WW	ZZ	WW/ZZ	AA4f	AAee	AAll
precuts	$5.00*10^5$	6.74	$3.72*10^5$	$3.35*10^3$	$2.11*10^3$	$2.29*10^3$	$7.96*10^3$	858	$4.42*10^5$	$1.69*10^6$
Cut 1	$1.65*10^5$	6.26	$2.15*10^5$	$2.99*10^3$	$1.72*10^3$	$2.07*10^3$	$3.99*10^3$	770	$1.26*10^5$	$1.69*10^5$
Cut 2	$1.61*10^5$	4.69	$9.41*10^4$	$1.77*10^3$	$1.58*10^3$	$1.46*10^3$	$2.96*10^3$	581	$6.59*10^4$	$4.19*10^3$
Cut 3	$1.97*10^4$	4.69	$8.77*10^4$	$1.69*10^3$	$1.42*10^3$	$1.15*10^3$	$2.78*10^3$	550	$1.20*10^4$	$2.76*10^3$
Cut 4	$1.91*10^4$	4.69	$8.71*10^4$	$1.62*10^3$	$1.42*10^3$	$1.09*10^3$	$2.75*10^3$	548	$1.20*10^4$	$2.76*10^3$
Cut 5	772	1.54	$1.23*10^4$	$1.16*10^3$	$1.11*10^3$	619	$2.09*10^3$	384	$2.87*10^3$	$1.37*10^3$
Cut 6	574	1.54	$5.73*10^3$	909	$1.06*10^3$	351	$1.75*10^3$	364	$1.62*10^3$	294
Cut 7	453	1.34	$4.77*10^3$	651	903	136	$1.33*10^3$	352	$1.30*10^3$	170

Summary (1)

- Performed SUSY event sample generation and DELPHES simulation
- Observed clear edge structure in selectron/smuon events as expected, but stau events are complicated
- Analysis of background rejection and edge detection started with smuon events
- At least relevant SM backgrounds are included
- Worked on the 2 types of cut design (loose, tight)

Summary (2)

- Even Loose cuts, we can discover SUSY particle.
- eRpL gives higher significance: automatic suppress of some SM background (e.g.: WW)

Next step

- Mass extraction by edge detection
  - Assume some function and perform fit [DESY-THESIS-09-004]
  - Got a mass fit macro from Keisuke Fujii [Phys. Rev. D **51**, 3153 (1995)]
    - Need to understand the philosophy of code
  - FIR (finite impulse response) filter [NIMA 1010 (2021) 165555]

BACKUP

Problems / Questions / Next Step (1)

- When I include Pythia, it crushed.
  - Up to Xsec calculation works, but not for event generation.
- I set Tauola is on, but it keeps PDG +-15 (no decay of tau) in the event.

- **Solved:** These are solved when I put the sentence "$ps_PYTHIA_PYGIVE = "MDCY(C1000022,1)=0"" in sindarlin file explicitly (written in Whizard manual).

Problems / Questions / Next Step (2)

- When running TAUOLA, I got the following message.
  - Subroutine fill_pyjets_spin_data: tau helicity information is not set, though polarized tau decay was requested. Most likely, the SINDARIN file does not include polarized for particles and/or not ?polarized_events=true
  - Still no tau decay exist in tau events. Maybe due to this message?

- **Solved:** Put the sentence “?polarized_events=true” in global.

Problems / Questions / Next Step (3)

- Found ~4[7]% events have stable tau (no daughters of tau) in stau1+stau2-[stau1+stau1-] event.
- The biggest difference with Keita’s study is with or without SUSY contribution.

- **Solved**: need to apply patch for PYTHIA6 (many thanks to Mikael Berggren (DESY))
  - This needs: fresh download of Whizard2.8.5, apply patch to PYTHIA6, compile and install. The Whizard2.8.5 which is already installed in KEKCC is not enough to handle stau BSM world.

Problems / Questions / Next Step (4)

- How to do detector simulation?
  - DELPHES? SGV? ILD full simulation?
  - In any case, I need to learn how to run the jobs. Started to learn DELPHES first.
  - Sometimes DELPHES does not work ---> **Solved**: some version difference (many thanks to Daniel), input file was too large.

Workflow (1)

WHIZARD 2.8.5

- used “blr1.slha” and SINDARIN file
- download from scratch, apply patch for PYTHIA6, compile and install

working place:
/home/ilc/skawada/SUSYg-2/blr1_STDHEP
/home/ilc/skawada/SUSYg-2/blr1_LCIO
procedure:
(1) source /home/ilc/skawada/SUSYg-2/SK-setup-whizard-2.8.5.sh
(2) go to working place, type “. job.sh” and “. run.sh”
(3) wait ~1-2 hours and done
※MC samples are stored in multiple files: 50K events / 1 file.

STDHEP file

LCIO file

can use for future ILD full simulation
stored at:
/hsm/ilc/users/skawada/SUSYg-2/blr1_sample/LCIO

Workflow (2)

STDHEP file

necessary for DELPHES simulation
(LCIO is not supported as the input for DELPHES)
stored at:
/hsm/ilc/users/skawada/SUSYg-2/blr1_sample/STDHEP

↓

DELPHES + DELPHES2LCIO

- used ILC generic card for detector
- used DELPHES2LCIO for LCIO output

working place:
/home/ilc/skawada/SUSYg-2/blr1_DEL
procedure:
(1) source /home/ilc/skawada/DJ-delphes-setup.sh
(2) go to working place and type “. run.sh”
(3) type “. check.sh”, failed job must be recovered by hand
※I don’t know why several jobs at KEKCC batch server fail.
The failure rate is ~10% even jobs controlled by one script.
※The EventSummary collection will be created at the end of each file.

↓

DELPHES result (LCIO file)

Workflow (3)

DELPHES result (LCIO file)

contains DELPHES simulation result
event header information is lost
stored at:
/hsm/ilc/users/skawada/SUSYg-2/blr1_sample/DEL

MARLIN

- used to recover (or restore) event header information
- recovered cross-section, beam polarization, E_{CM} (500 GeV), process ID/name
- remove unnecessary EventSummary collection

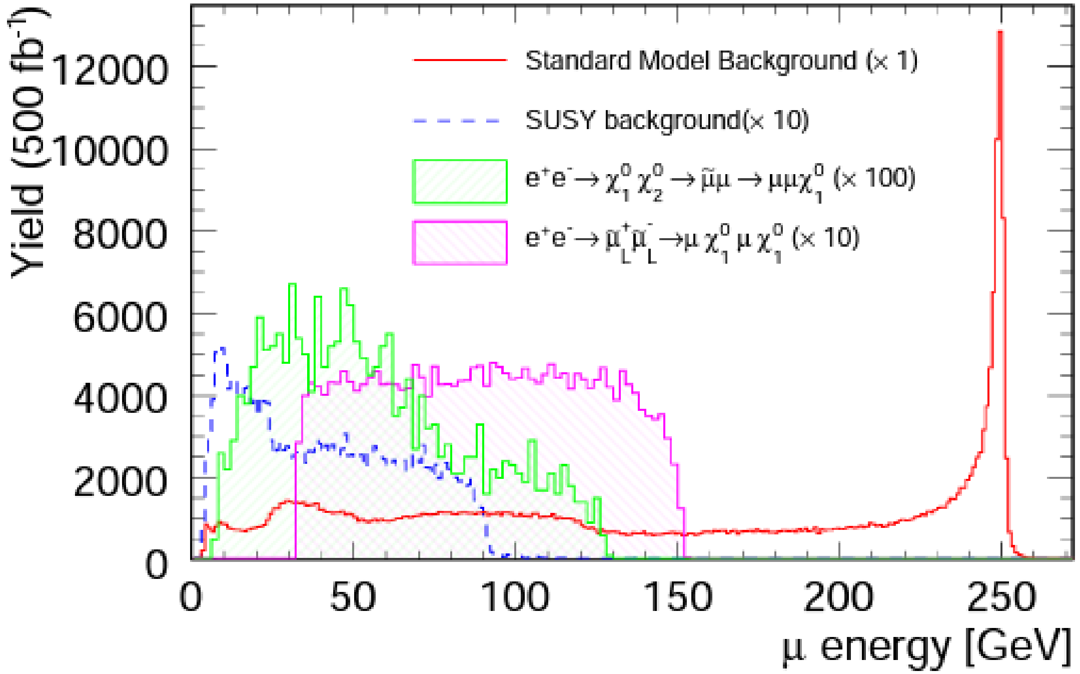
working place:
/home/ilc/skawada/SUSYg-2/analysis/modification
procedure:
(1) source /home/ilc/skawada/init_ilcsoft_v020202.sh
(2) source /home/ilc/skawada/SUSYg-2/analysis/use.sh
(3) go to working place and type “. run_modify.sh”
(4) wait ~10 minutes and done
※Need to assume each sample has exactly 50K + EventSummary

DELPHES result (LCIO file)
+ event header info

contains DELPHES simulation result and event header info
stored at:
/home/ilc/skawada/SUSYg-2/analysis/DEL_sample

Energy plot

- Since selectron/smuon decay is two-body decay, the energy distribution of visible decay products have “edges”.
- Stau is technically two-body decay as well, but difficult to measure edges.



“edges” at ~30 GeV and ~150 GeV
in smuon events (magenta)

Two-body decay kinematics (1)

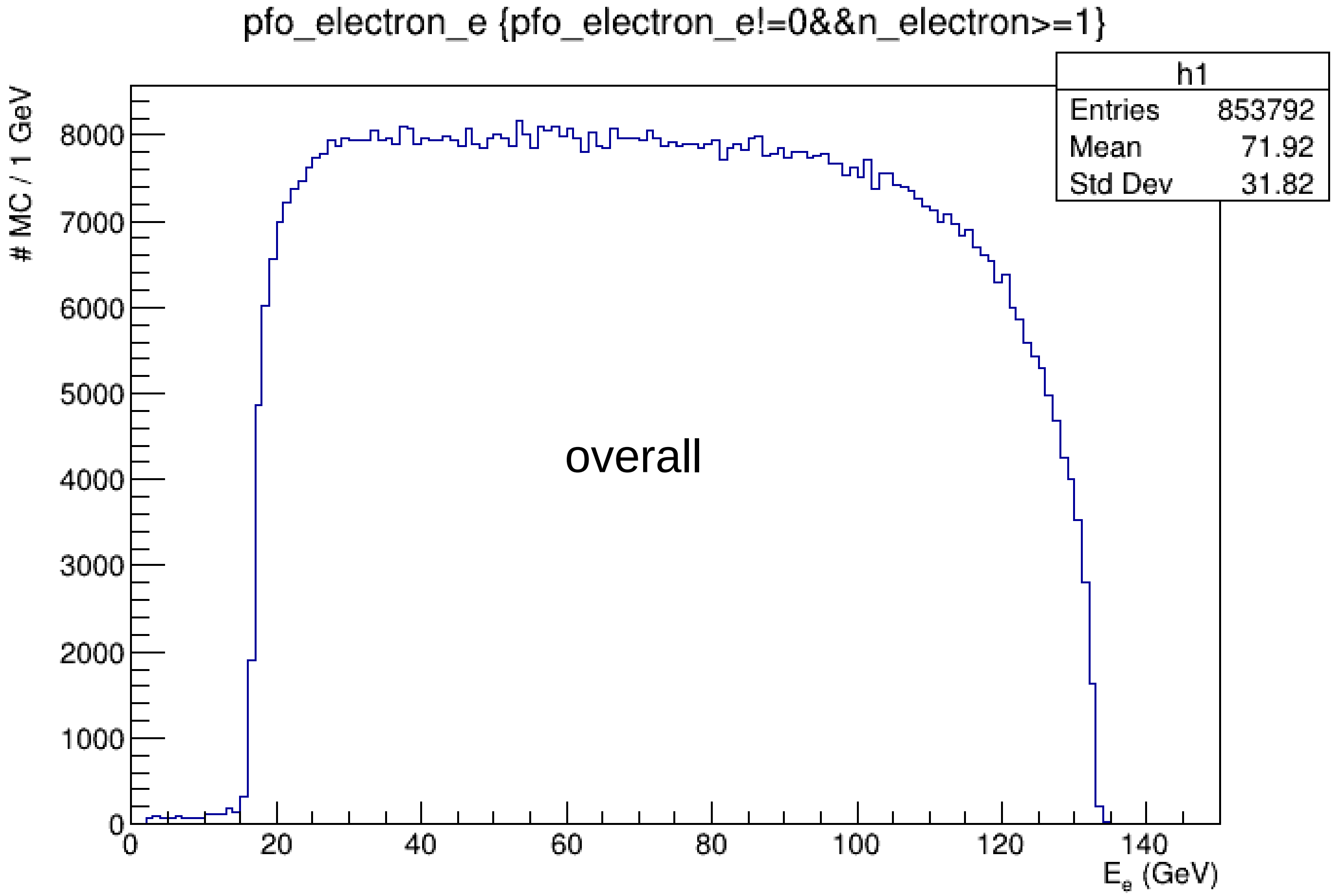
- In the end, we have
  - $E^{+} = \frac{\sqrt{s}}{4}\left[1-\left(\frac{m_{\chi}}{m_{\mathrm{SUSY}}}\right)^{2}\right]\left[1+\sqrt{1-4\left(\frac{m_{\mathrm{SUSY}}}{\sqrt{s}}\right)^{2}}\right]$
  - $E^{-} = \frac{\sqrt{s}}{4}\left[1-\left(\frac{m_{\chi}}{m_{\mathrm{SUSY}}}\right)^{2}\right]\left[1-\sqrt{1-4\left(\frac{m_{\mathrm{SUSY}}}{\sqrt{s}}\right)^{2}}\right]$
  - where E^{+}/E^{-} is the maximum/minimum energy of lepton (electron/positron/muon/tau), m_{SUSY} is the mass of SUSY particle (selectron/smuon/stau), $\sqrt{s}$ = 500 GeV in this analysis, and m_{χ} is the neutralino mass and equals to 99 GeV on BLR1 parametrization
  - Ignored lepton masses

Two-body decay kinematics (2)

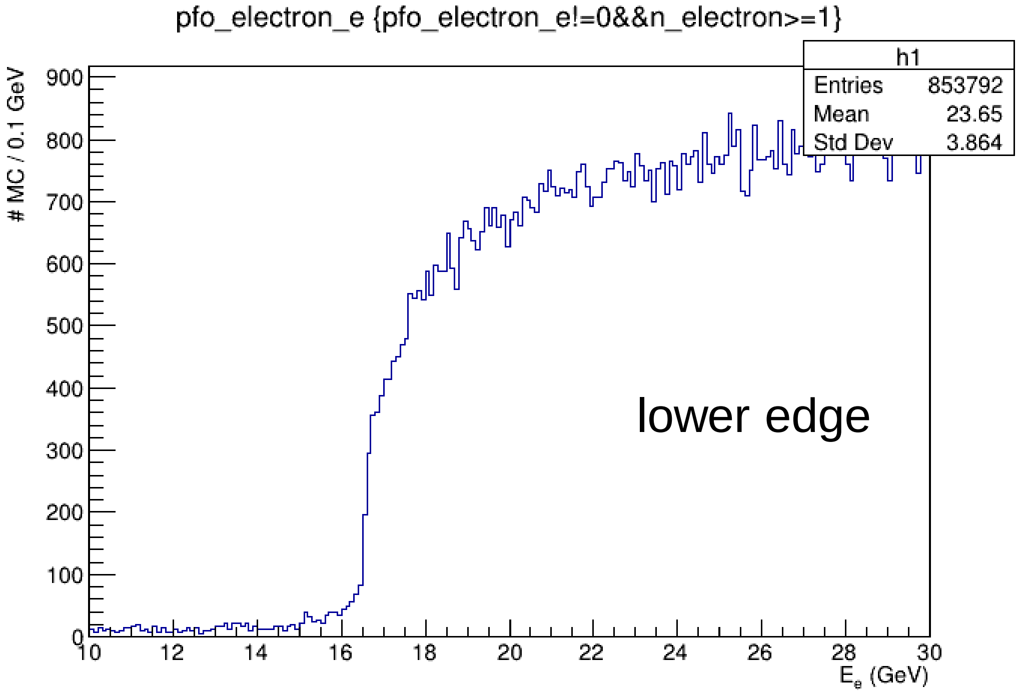
$\sqrt{s}$ = 500 GeV, $\widetilde{\chi_1^0}$ = 99 GeV, ignored lepton masses

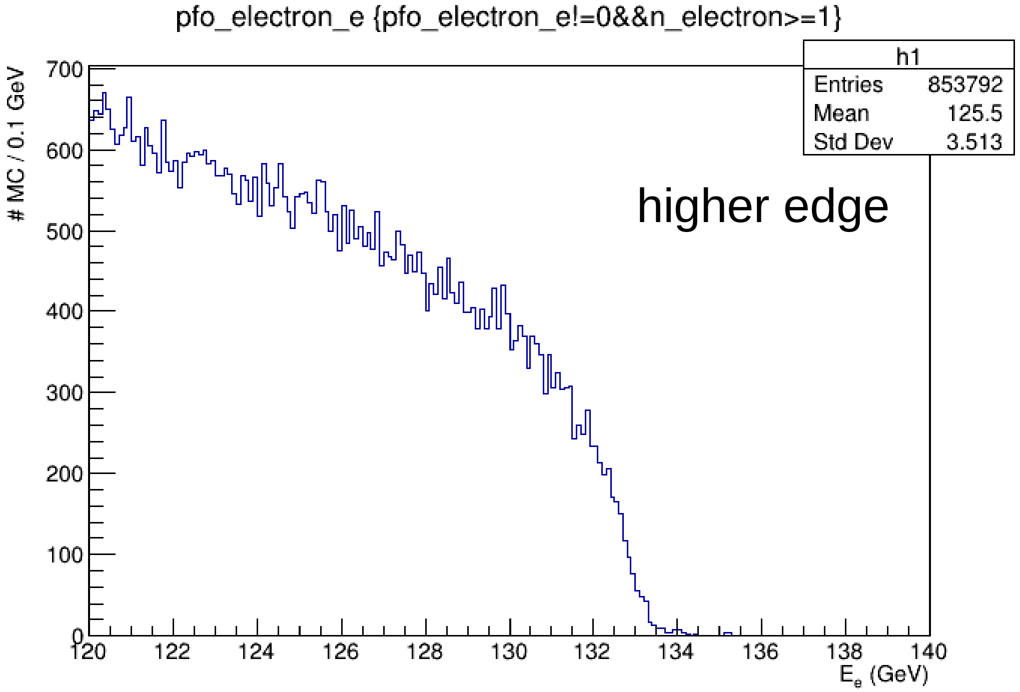
SUSY particle	mass (GeV)	E^+ (GeV)	E^- (GeV)
$\widetilde{e_L}$	157	133.9	16.7
$\widetilde{e_R}$	156	133.0	16.3
$\widetilde{\mu_L}$	158	134.8	17.1
$\widetilde{\mu_R}$	154	131.1	15.6
$\widetilde{\tau_1}$	113	55.0	3.1
$\widetilde{\tau_2}$	190	150.2	31.9

Selectron ($\tilde{e}_L$) events

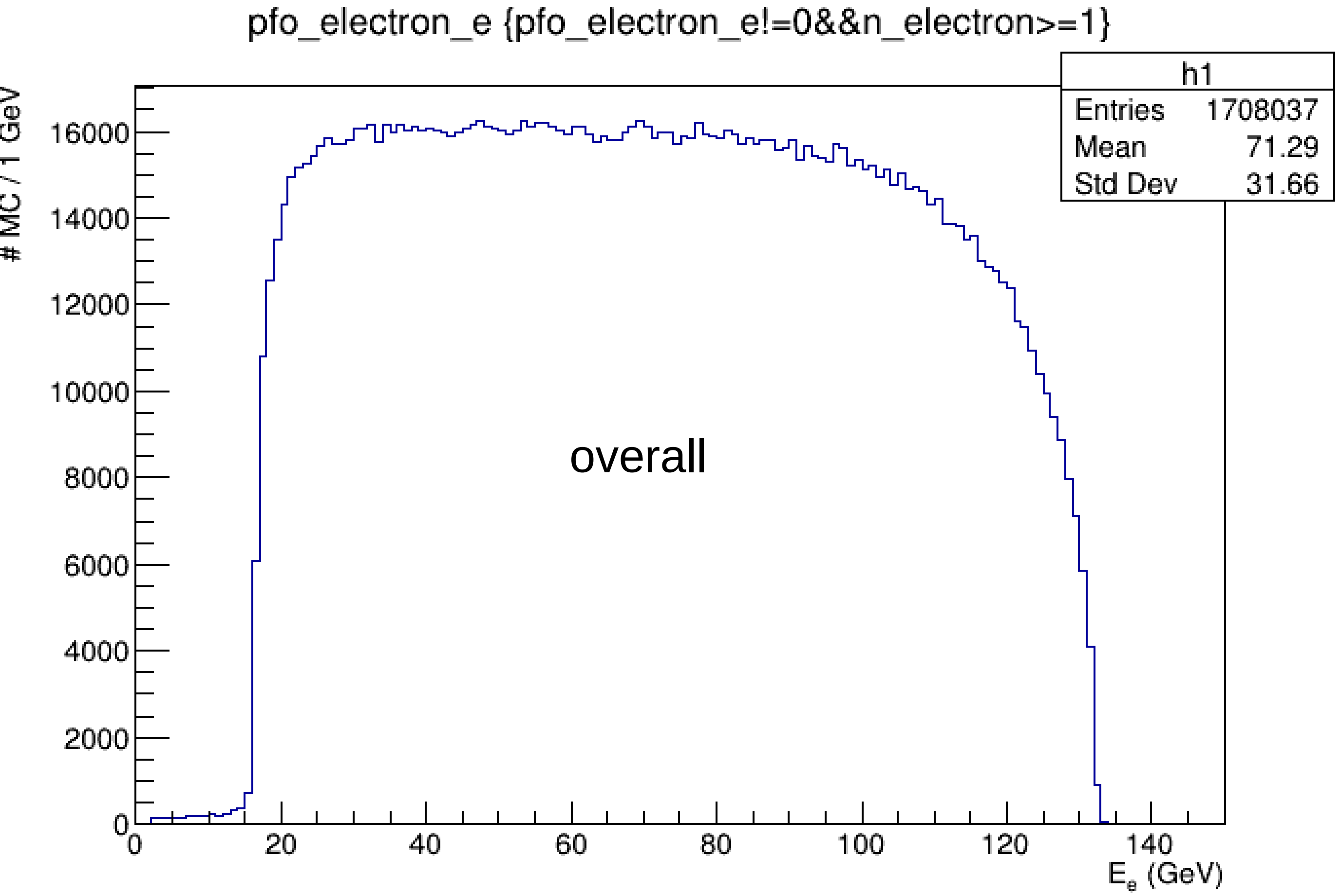


se11_eLpR (mass = 157 GeV)
e >= 1, plotted energy of electron PFOs
E^+ = 133.9 GeV and E^- = 16.7 GeV

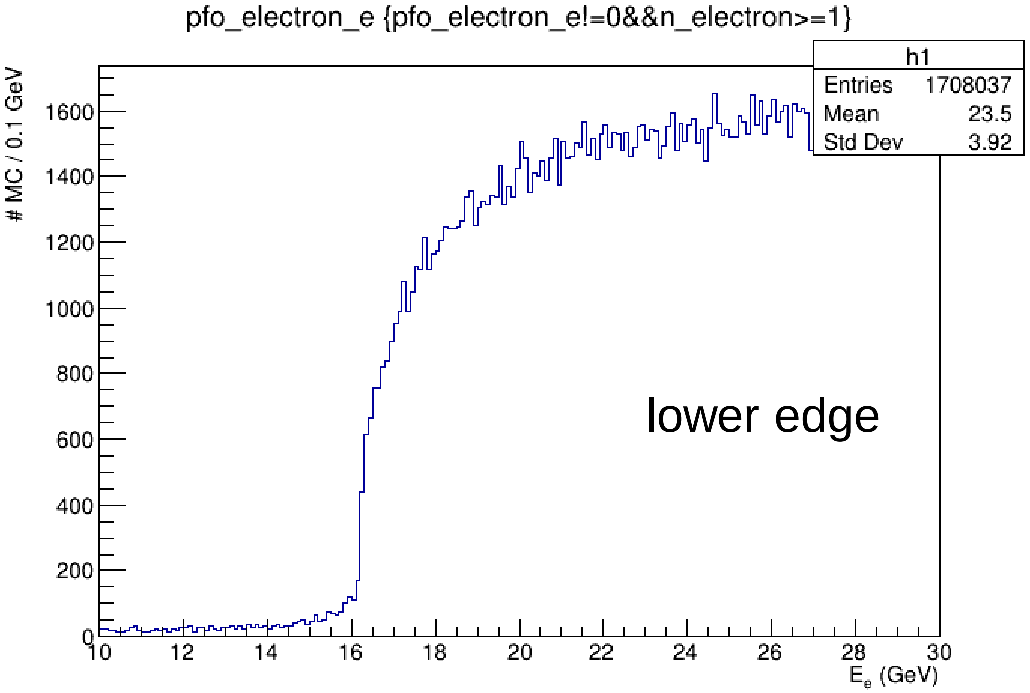


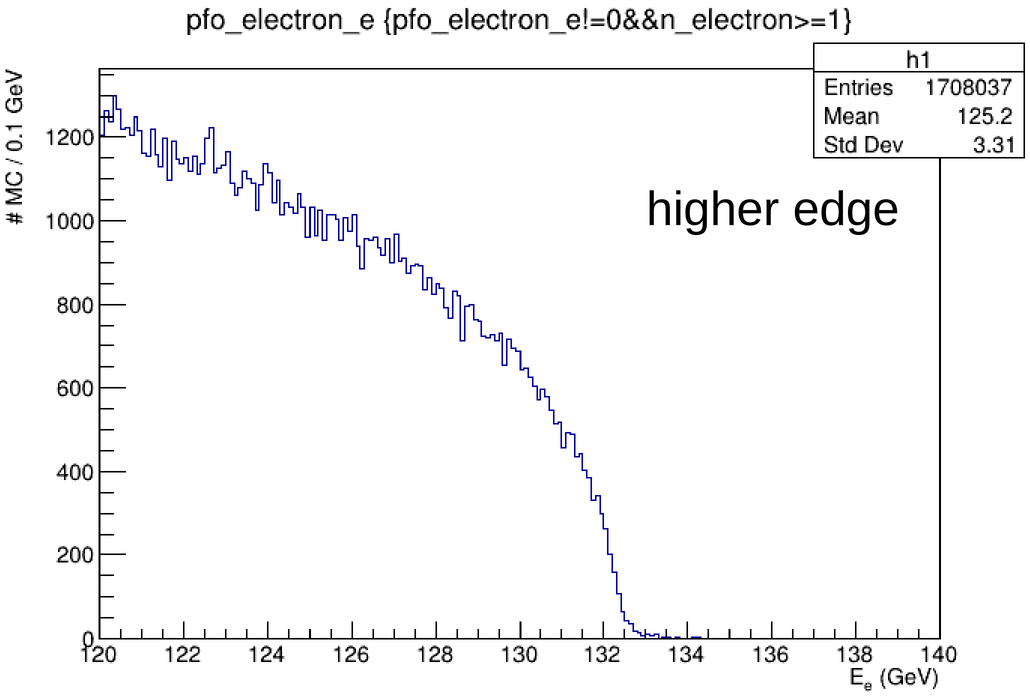


Selectron ($\widetilde{e_R}$) events

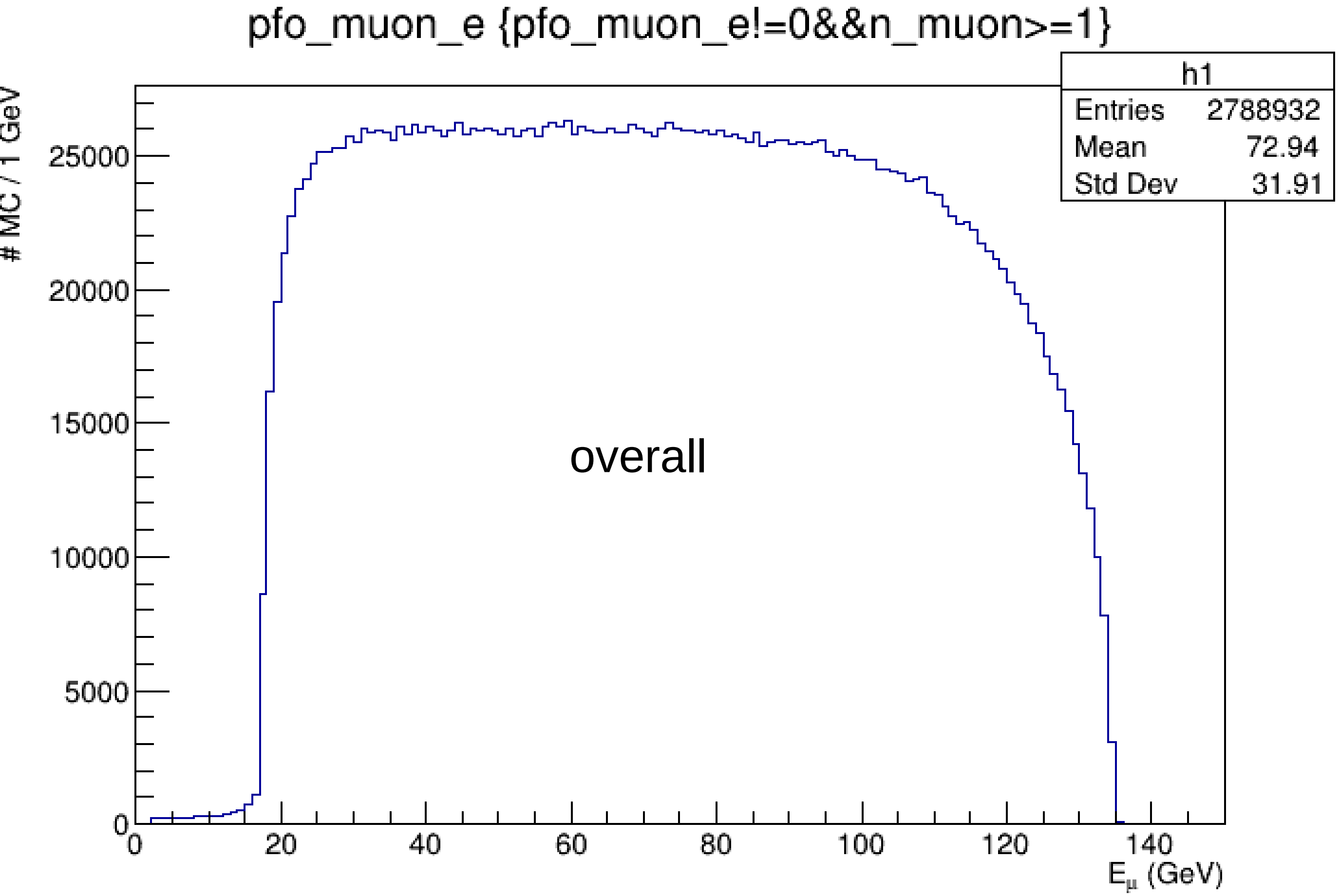


se22_eLpR (mass = 156 GeV)
e >= 1, plotted energy of electron PFOs
E^+ = 133.0 GeV and E^- = 16.3 GeV

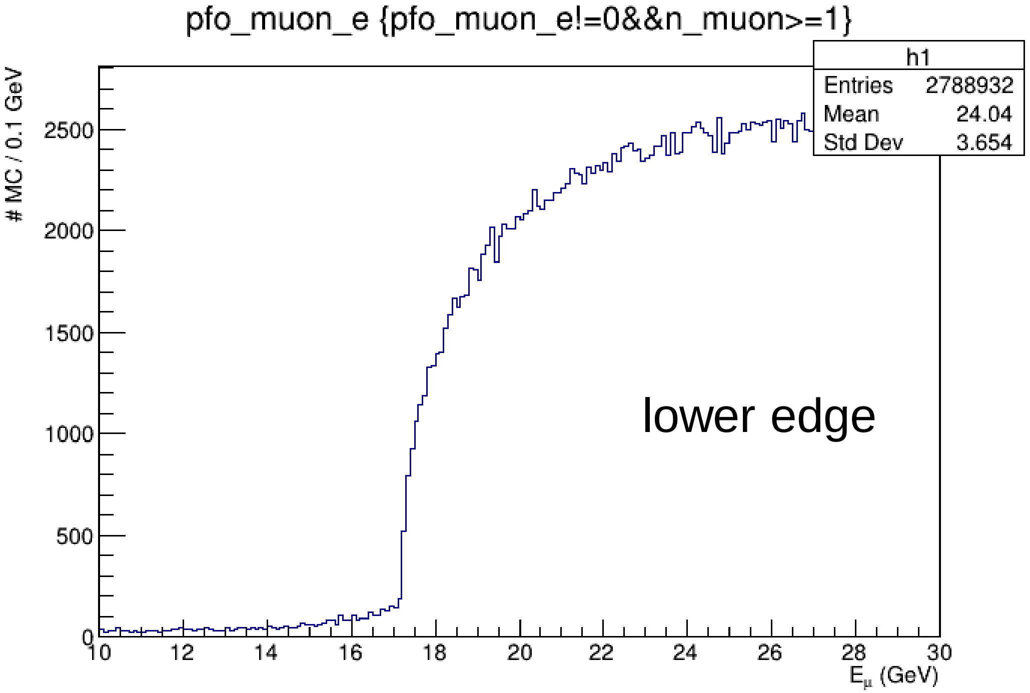


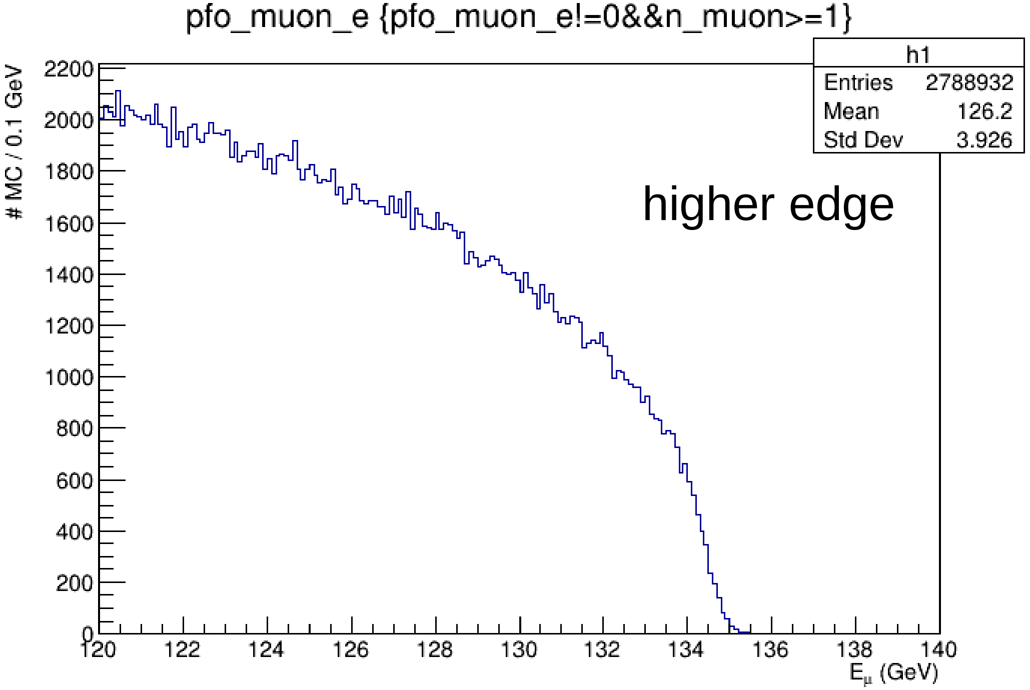


Smuon ($\widetilde{\mu_L}$) events

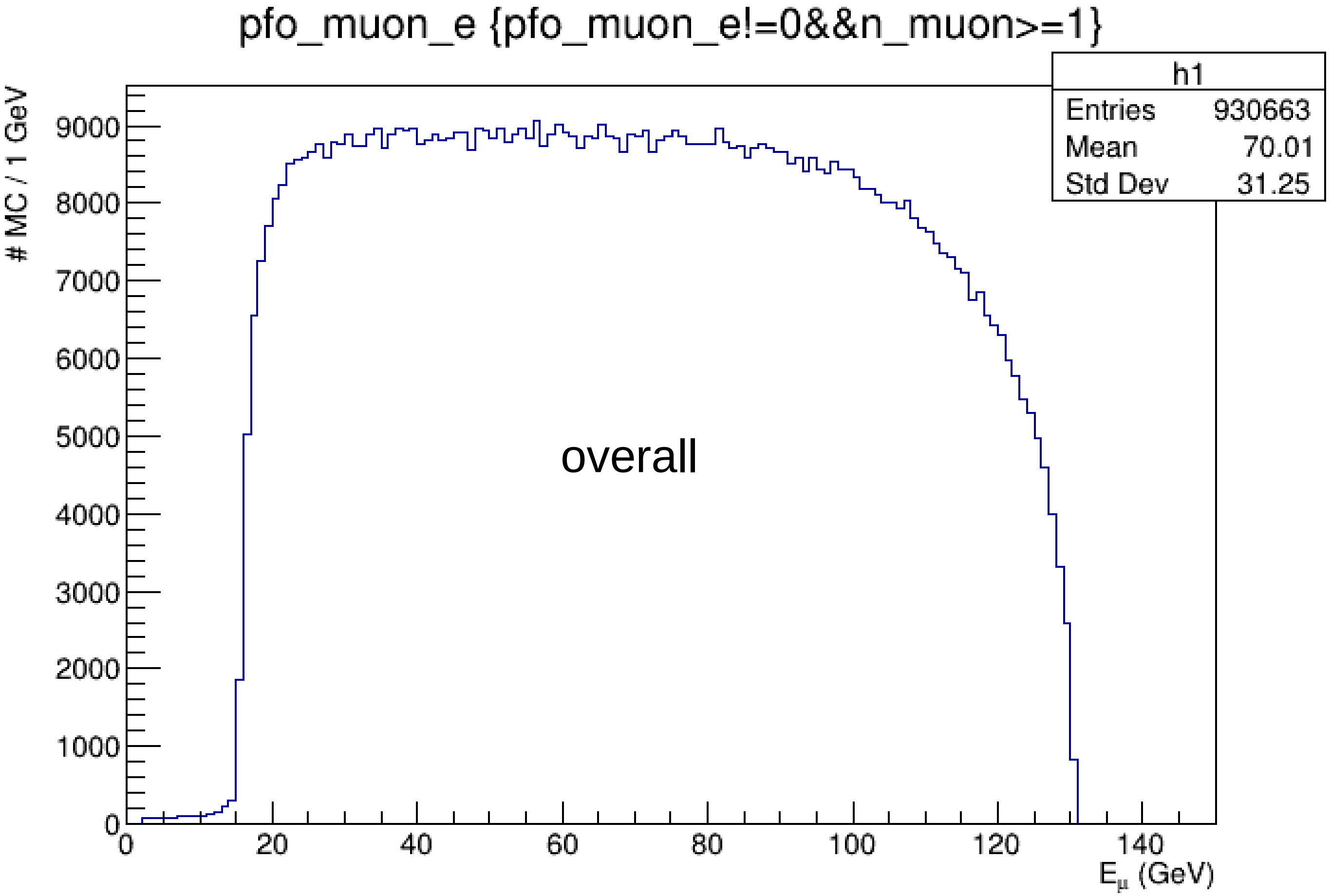


smu11_eLpR (mass = 158 GeV)
mu >= 1, plotted energy of muon PFOs
E^{+} = 134.8 GeV and E^{-} = 17.1 GeV

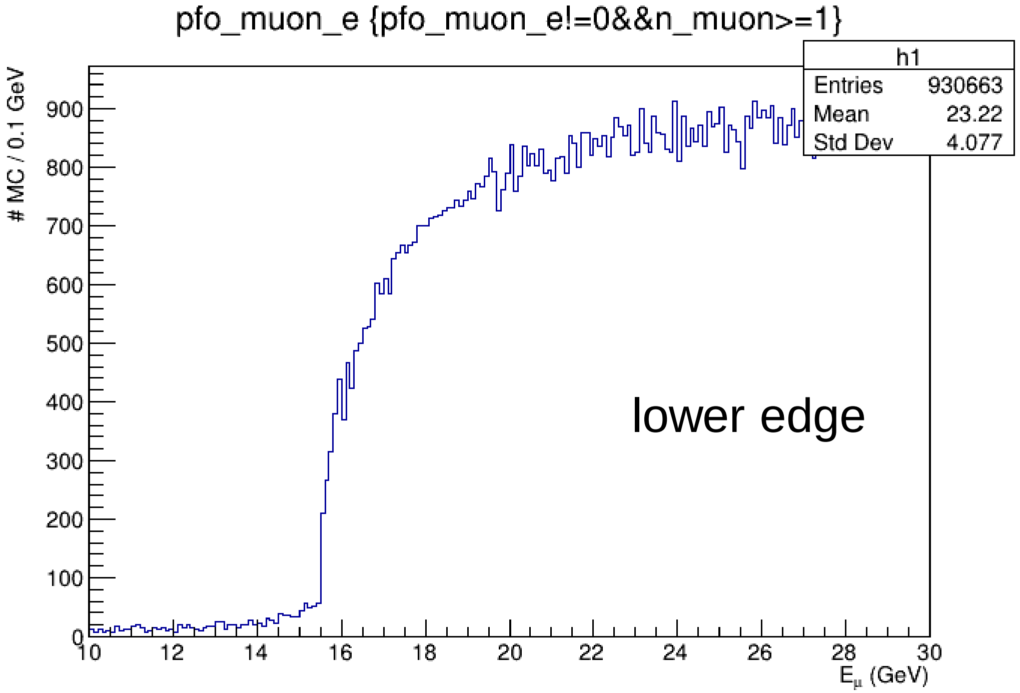


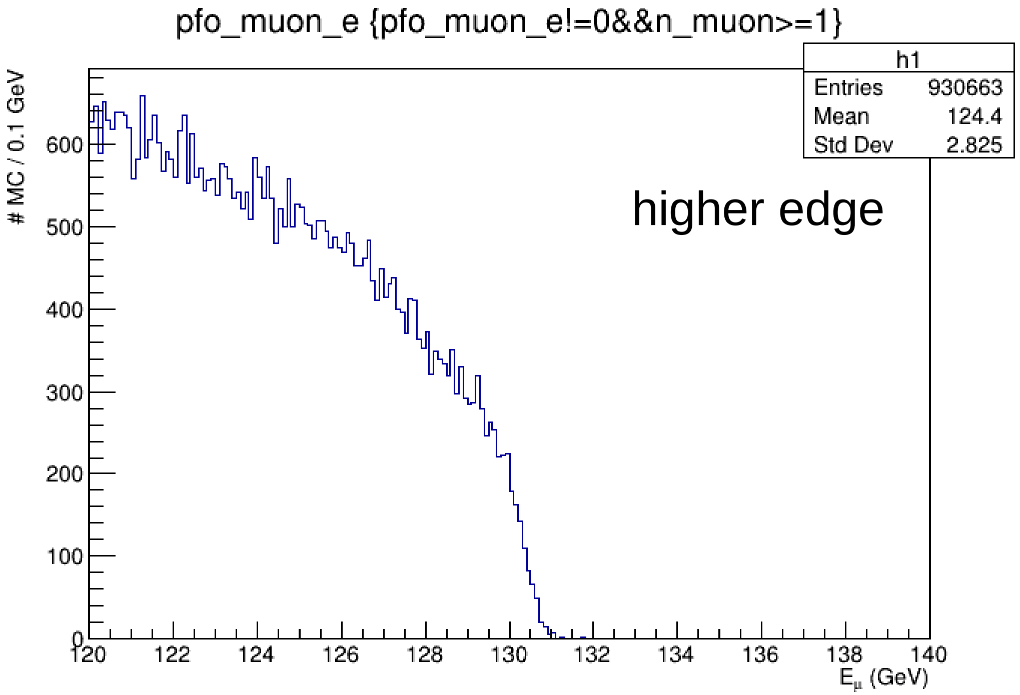


Smuon ($\widetilde{\mu_R}$) events



smu22_eLpR (mass = 154 GeV)
mu >= 1, plotted energy of muon PFOs
E^+ = 131.1 GeV and E^- = 15.6 GeV

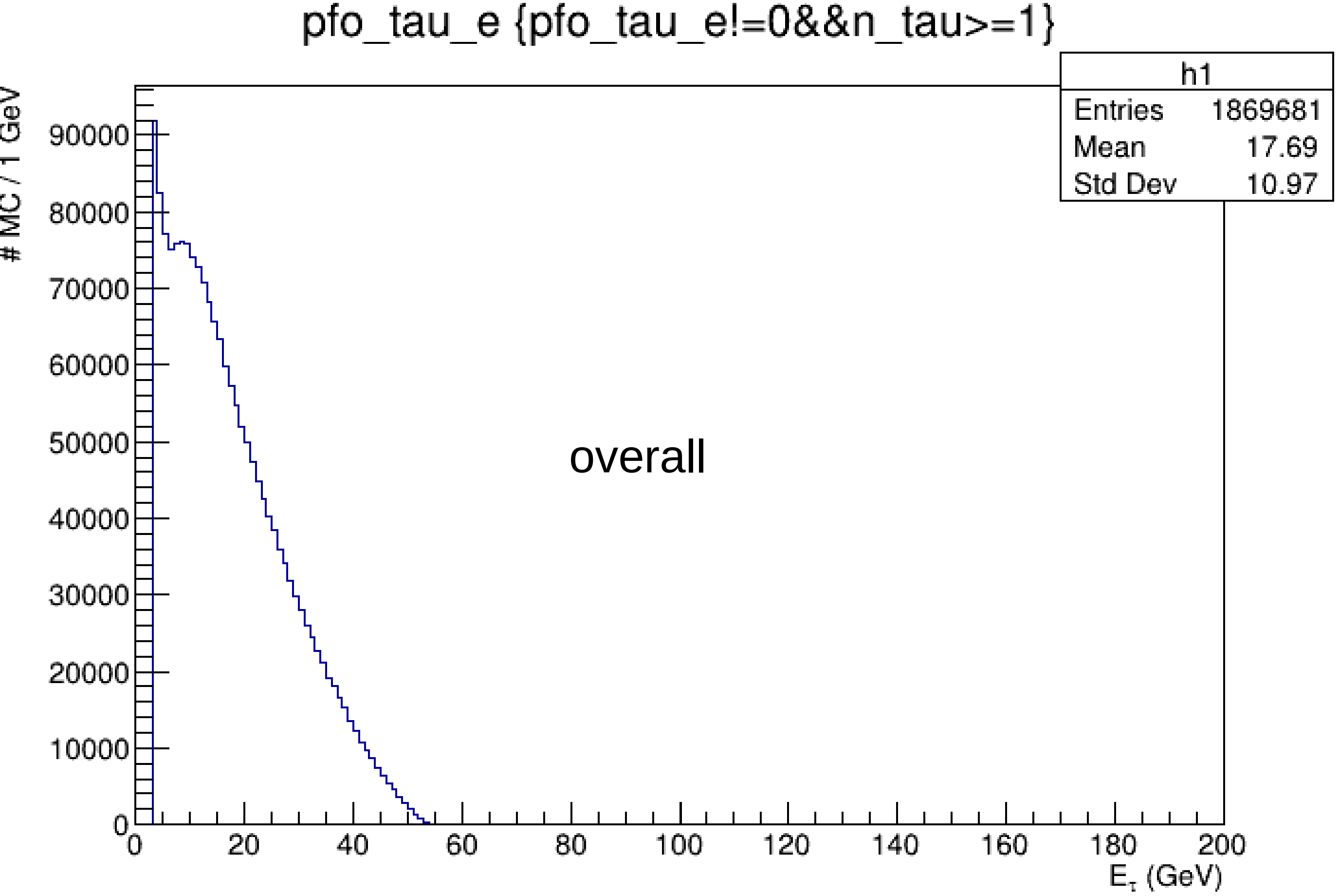




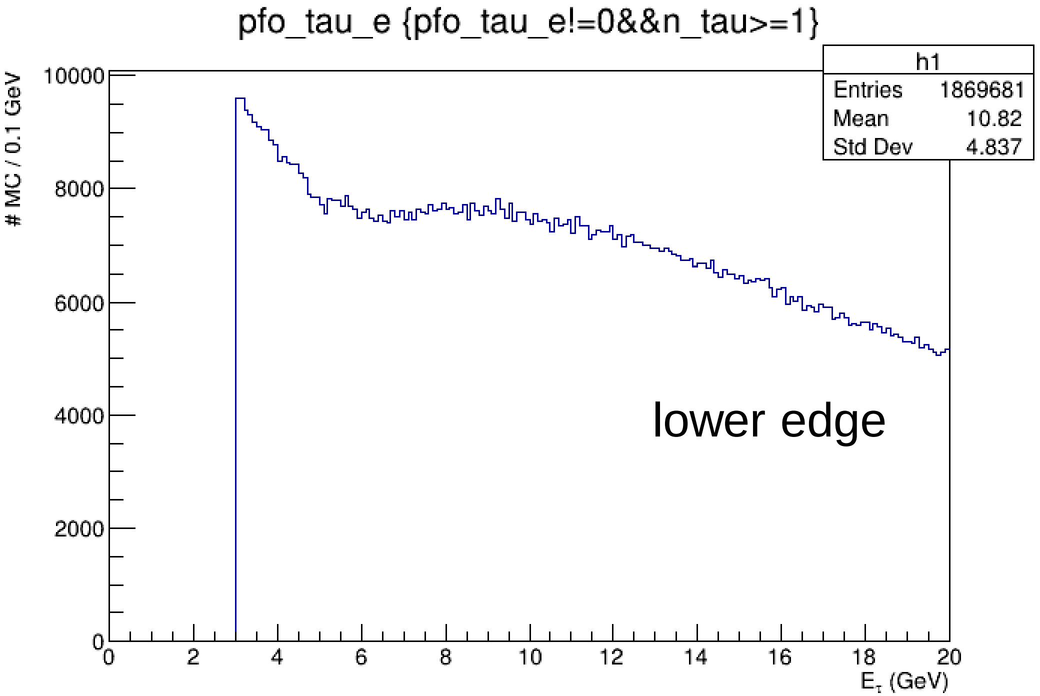
Energy distribution

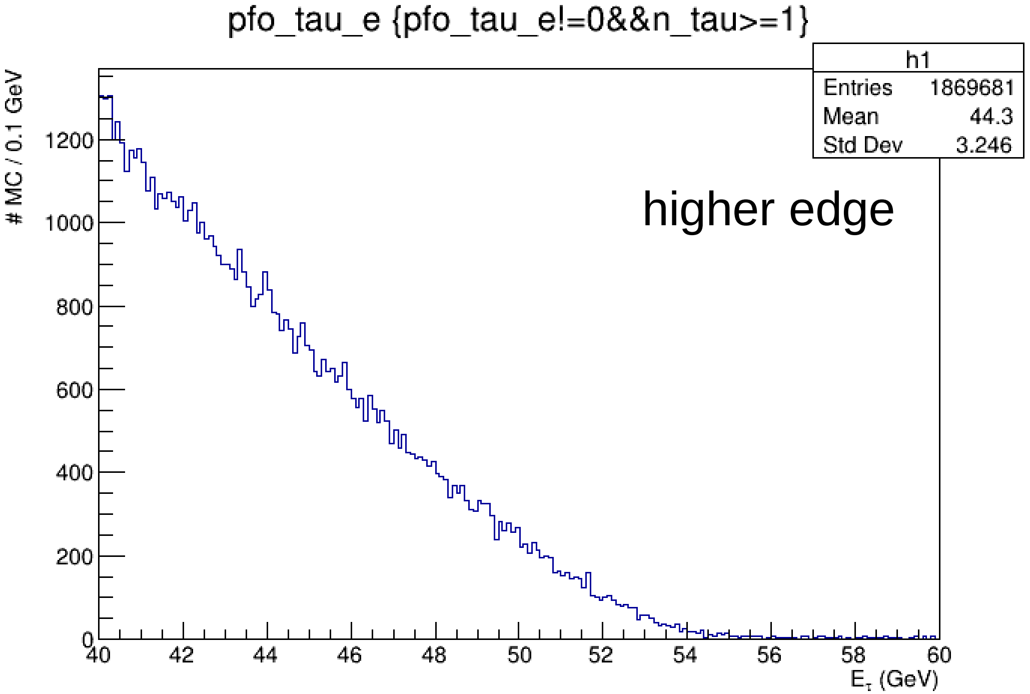
- Selectron/Smuon events have edges in both side as expected. This distribution can be used to extract the mass of neutralino/selectron/smuon.
- However, stau event is not easy: tau decays to something and make everything complicated.
  - Used TaJetClustering with default values for tau reconstruction
    - Choose energetic charged PFO as a seed and combine neutral PFO near to the seed to reconstruct a tau candidate
    - Apply some selection cuts

Stau ($\tilde{\tau}_1$) events

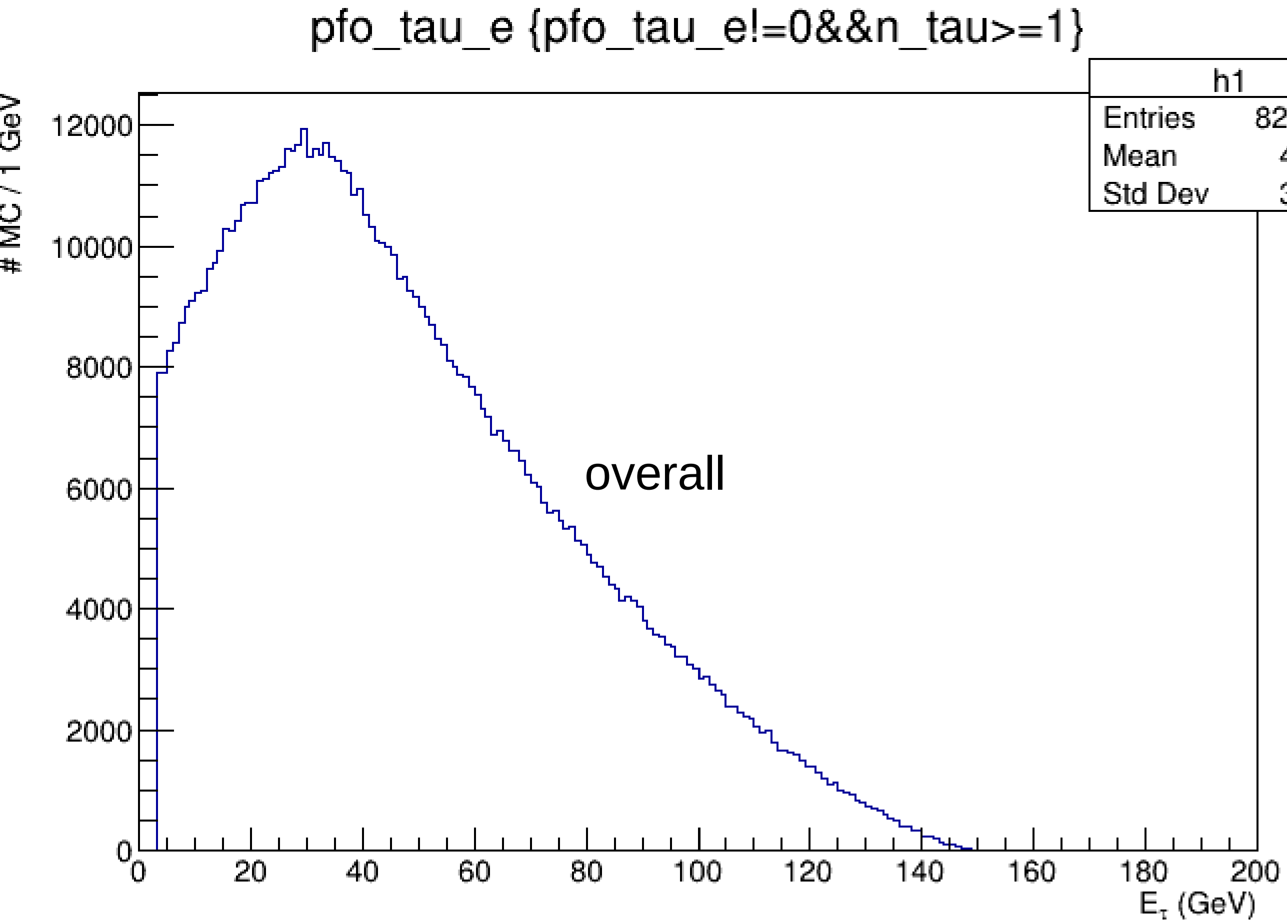


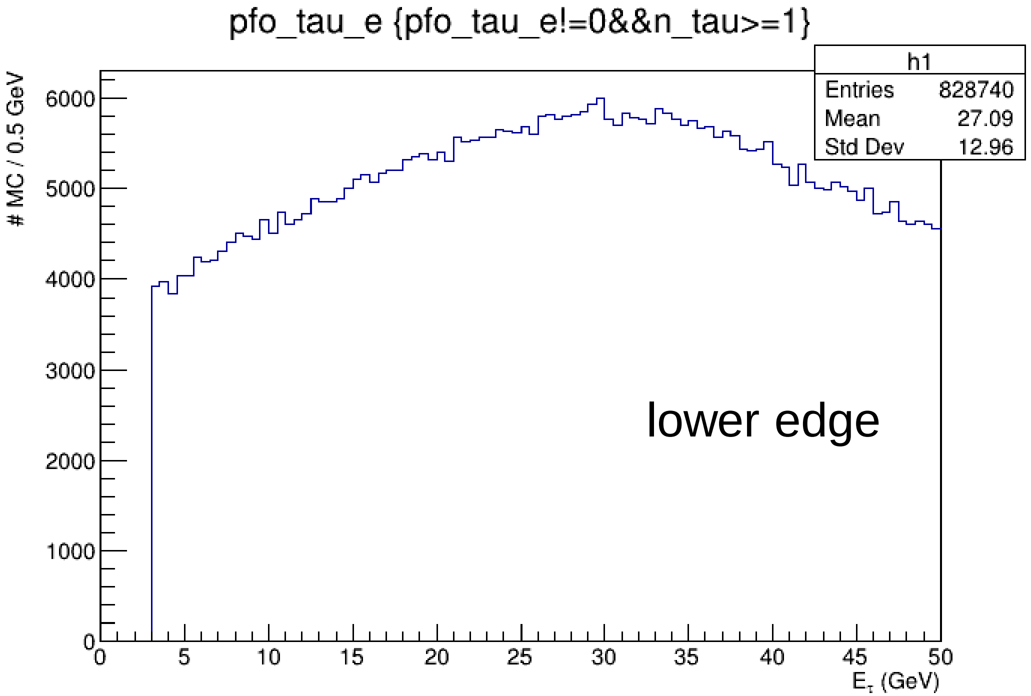
stau11_eLpR (mass = 113 GeV)
tau >= 1, plotted energy of reconstructed taus
E^+ = 55.0 GeV and E^- = 3.1 GeV

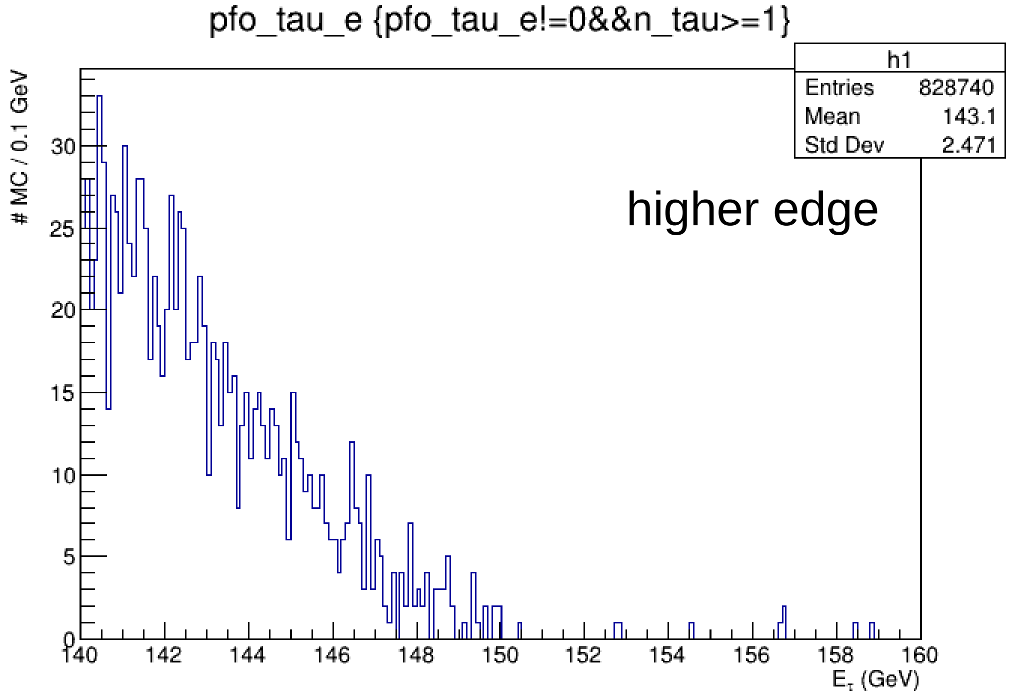




Stau ($\tilde{\tau}_2$) events







stau22_eLpR (mass = 190 GeV)
tau >= 1, plotted energy of reconstructed taus
E^+ = 150.2 GeV and E^- = 31.9 GeV

Mass extraction (future work with bkg)

- It is possible to extract the masses of selectron/smuon/neutralino once we measure E^+ and E^- from the experiment
- In the end, we have
  - $m_{\mathrm{SUSY}}^2 = (\sqrt{s})^2 \frac{E^+E^-}{(E^+ + E^-)^2}$
  - $m_\chi^2 = m_{\mathrm{SUSY}}^2 \left[1 - \frac{2(E^+ + E^-)}{\sqrt{s}}\right]$