



Determination of Heavy Slepton Masses at CLIC (3 TeV)

OUTLINE

- Physics benchmark parameters and goal
- Event Simulation and Reconstruction tools
- Low level physics observables performances
- Sleptons cross sections and mass determination
- Summary

Study done for the CLIC CDR assuming $\int L = 2 \text{ ab}^{-1}$.

Full simulation and reconstruction, with overlay of beam-beam induced background: $\gamma\gamma \rightarrow h$.

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Physics Benchmark Parameters

- mSUGRA parameters for SUSY benchmarks:

$m_0=966$ GeV, $m_{1/2}=800$ GeV, $\tan\beta=51$, $\mu>0$, $A_0=0$

- Sleptons and gauginos masses:

$m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = 1010.8$ GeV; $m_{\tilde{e}_L} = m_{\tilde{\mu}_L} = 1100.4$ GeV; $m_{\tilde{\nu}_e} = 1097$ GeV

$m_{\tilde{\chi}_1^0} = 340.3$ GeV, $m_{\tilde{\chi}_2^0} = 643.1$ GeV, $m_{\tilde{\chi}_{1\pm}} = 643.2$ GeV,

- Sleptons branching ratios

B.R: $\tilde{e}_R \rightarrow e + \tilde{\chi}_1^0 = 100\%$; $\tilde{\mu}_R \rightarrow \mu + \tilde{\chi}_1^0 = 100\%$

B.R: $\tilde{e}_L \rightarrow e + \tilde{\chi}_1^0 = 16\%$; $\tilde{e}_L \rightarrow e + \tilde{\chi}_2^0 = 29\%$; $\tilde{\nu}_e \rightarrow e + \tilde{\chi}_{\pm 1} = 56\%$

Process	σ (fb)	Decay Mode	$\sigma \times Br$ (fb)	$\sigma \times Br(ee4Q)$ (fb)
$e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$	0.7	$\mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	0.7	
$e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-$	6.1	$e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	6.1	
$e^+e^- \rightarrow \tilde{e}_L^+ \tilde{e}_L^-$	3.06	$e^+ e^- \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow e^+ e^- h^0 / Z^0 h^0 / Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$	0.25	0.16
$e^+e^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e$	13.7	$e^+ e^- \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow e^+ e^- W^+ W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	4.30	2.25

Cross sections



Background Cross sections and generation cuts

Process	Decay mode	$\sigma \times Br$ (fb) no cuts	$\sigma \times Br$ (fb) cuts
$e^+e^- \rightarrow \mu^+\mu^-$	$\mu^+\mu^-$	81.9	0.6
$e^+e^- \rightarrow \mu^+\nu_e\mu^-\nu_e$	$\mu^+\mu^-$	65.6	3.5
$e^+e^- \rightarrow \mu^+\nu_\mu\mu^-\nu_\mu$	$\mu^+\mu^-$	6.2	2.2
$e^+e^- \rightarrow W^+\nu W^-\nu$	$\mu^+\mu^-$	92.6	2.4
$e^+e^- \rightarrow Z^0\nu Z^0\nu$	$\mu^+\mu^-$	40.5	0.002
$e^+e^- \rightarrow \text{All SUSY} - (\tilde{\mu}_R^+\tilde{\mu}_R^-)$	$\mu^+\mu^-$	0.31	0.31
$e^+e^- \rightarrow e^+e^-$	e^+e^-	6226.1	77.1
$e^+e^- \rightarrow e^+\nu_e e^-\nu_e$	e^+e^-	179.3	91.1
$e^+e^- \rightarrow W^+\nu W^-\nu$	e^+e^-	92.6	2.4
$e^+e^- \rightarrow Z^0\nu Z^0\nu$	e^+e^-	40.5	0.002
$e^+e^- \rightarrow \text{All SUSY} - (\tilde{e}_R^+\tilde{e}_R^-)$	e^+e^-	1.04	1.04
$e^+e^- \rightarrow W^+W^-Z^0$	$e^+e^-W^+W^-$	1.35	0.61
$e^+e^- \rightarrow Z^0Z^0Z^0$	$e^+e^-Z^0Z^0$	0.045	0.023
$e^+e^- \rightarrow \text{SUSY} - (\tilde{e}_L^+\tilde{e}_L^- \text{ and } \tilde{\nu}_e\tilde{\nu}_e)$	$e^+e^- (WW \text{ or } h^0h^0 \text{ or } Z^0Z^0)$	0.77	0.12

$\sigma(B) \sim 10\text{-}10^4\text{fb} \gg \sigma(S) \sim 1\text{fb}$, to optimize statistics vs computing resources, pre-selection cuts applied at generator level on background events.

$10^\circ < \Theta(L) < 170^\circ$, $Pt(L) > 4\text{ GeV}$, $4^\circ < \Delta\Phi(L,L) < 176^\circ$, $Pt(L,L) > 10\text{ GeV}$ and $M(L,L) > 100\text{ GeV}$

Same cuts applied on signal after simulation and reconstruction



Slepton Benchmark Goal

Characterize the lepton energy resolution for 2L and 2L4J topologies,
Di-Jet mass resolution without/with $\gamma\gamma \rightarrow h$ background.

Set the requirements on the detector time stamping capability:

Pt and timing cuts used to reduce the impact of $\gamma\gamma \rightarrow h$ background

Assess the statistical accuracy reachable on:

slepton production cross sections:

- $e^+e^- \rightarrow \tilde{\mu}R^+ + \tilde{\mu}R^- \rightarrow \tilde{\chi}^0_1 \mu^+ + \tilde{\chi}^0_1 \mu^-$ (2L)
- $e^+e^- \rightarrow \tilde{e}R^+ + \tilde{e}R^- \rightarrow \tilde{\chi}^0_1 e^+ + \tilde{\chi}^0_1 e^-$ (2L)
- $e^+e^- \rightarrow \tilde{e}L^+ + \tilde{e}L^- \rightarrow \tilde{\chi}^0_2 e^+ + \tilde{\chi}^0_2 e^- \rightarrow \tilde{\chi}^0_1 h^0 e^+ + \tilde{\chi}^0_1 h^0 e^-$ (2L4J)
- $e^+e^- \rightarrow \tilde{\nu}e + \tilde{\nu}e \rightarrow \tilde{\chi}^\pm_1 e^+ + \tilde{\chi}^\mp_1 e^- \rightarrow \tilde{\chi}^0_1 W^\pm e^+ + \tilde{\chi}^0_1 W^\mp e^-$ (2L4J)

On $\tilde{\mu}R$, $\tilde{e}R$, $\tilde{\chi}^0_1$, $\tilde{\nu}e$ and $\tilde{\chi}^\pm_1$ masses determined using the end points of the leptons energy spectrum.



Event Simulation, Reconstruction and Selection

The Monte Carlo event samples were produced using:

WHIZARD : generation includes beam energy spread and initial state radiation

PYTHIA : hadronization, with final state radiation enabled.

MOKKA/GEANT4 : simulation with the CLIC_ILD detector geometry.

MARLIN : framework for digitization and track reconstruction

PANDORA: particle flow algorithm for calorimeter reconstruction and P ID

To study the impact of $\gamma\gamma \rightarrow$ hadron background, the digitized hits from simulated $\gamma\gamma \rightarrow$ hadrons events were added to the physics signal and background events, before event reconstruction.

FASTJET : algorithm used to cluster particles into jets (2L4J channels)

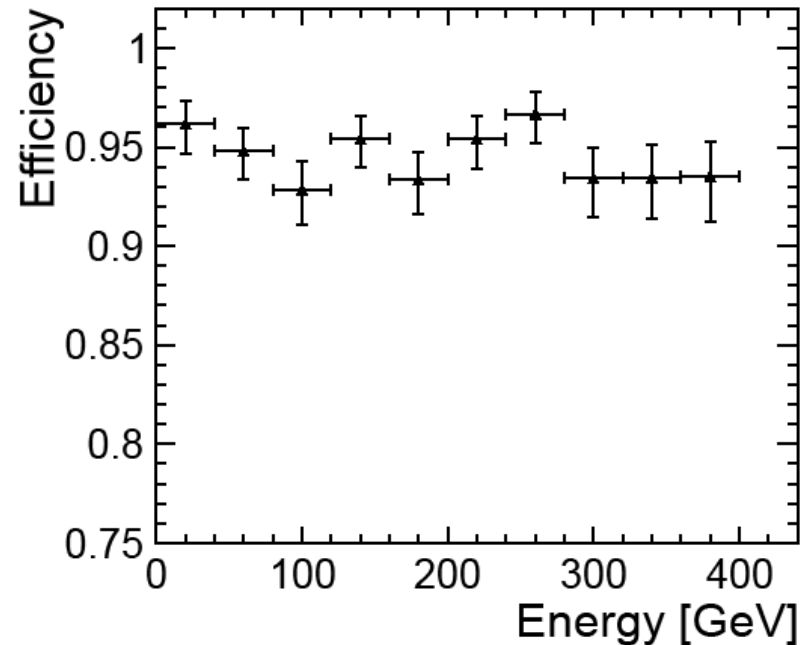
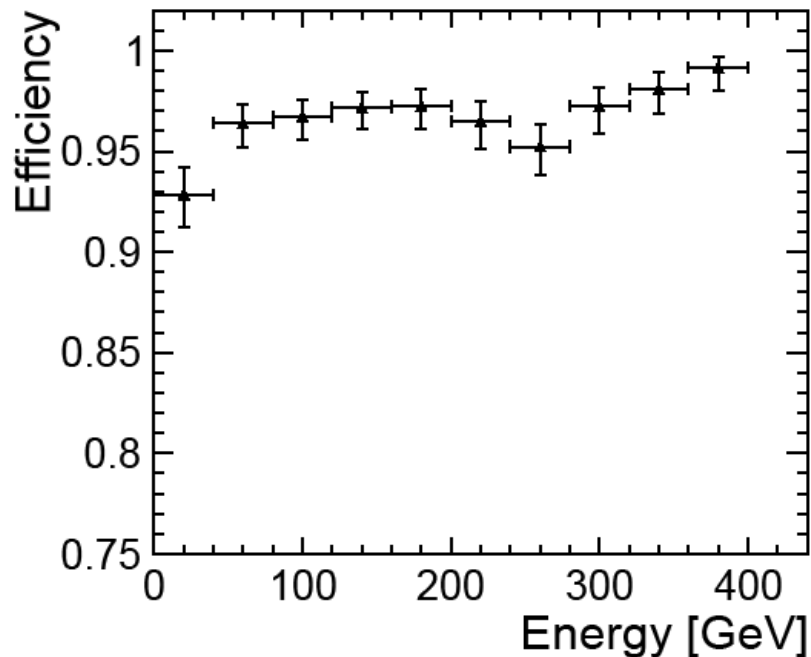
TMVA BDT : method, combines discriminating observables into a classifier

The event selection requires 2L or 2L+4J according to the channel considered and selects the events using the classifier value.



Particle Identification

Particle identification is performed by the PandoraPFA algorithm. Reconstructed charged particles are assumed to be pions unless they pass the lepton ID, requirements or are associated with a reconstructed displaced vertex (V^0)



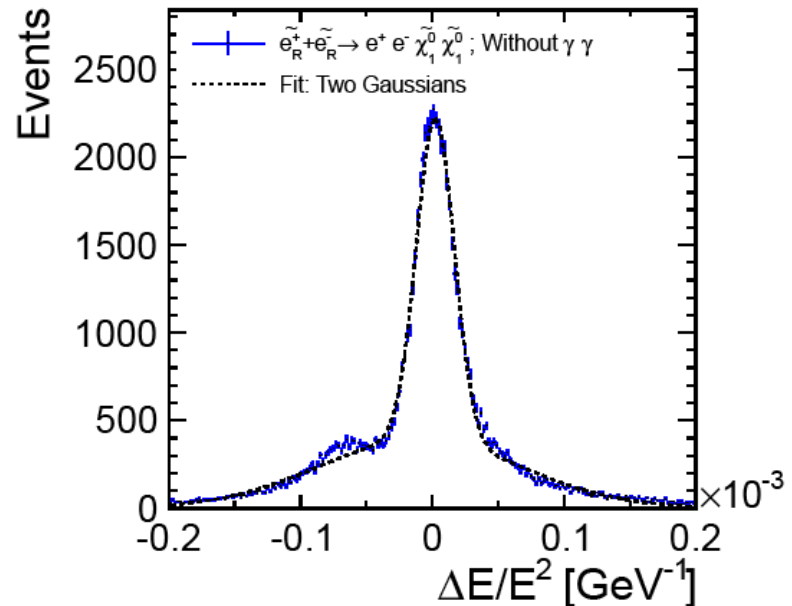
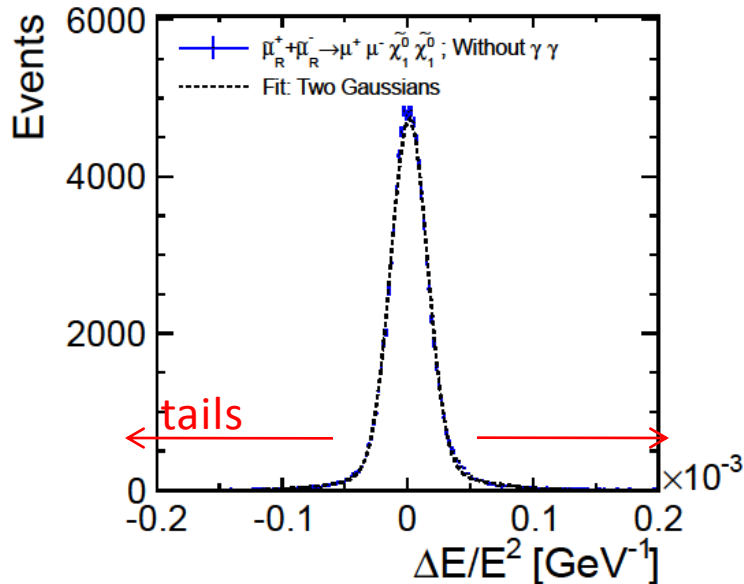
Electron ID efficiency vs energy(left) ; Photons (right)

Identification efficiency $\sim 96\%$ for electrons , $\sim 93\%$ for photons, it is 99% for muons.



Muon and electron energy resolution, 2L topology

The lepton momentum is measured with the tracking system. Energy correction is applied when Final State Radiation or bremsstrahlung photons, measured in ECAL, are found in a 20° cone around the lepton.



$\Delta E = E(\text{generated}) - E(\text{reconstructed})$; Two gaussians fit to take into account the tails

μ^\pm final state: $\Delta E/E^2 = G1(1.4 \times 10^{-5}) + G2(4.9 \times 10^{-5})$; tails = 4.1/%, $\epsilon_R = 97.5\%$

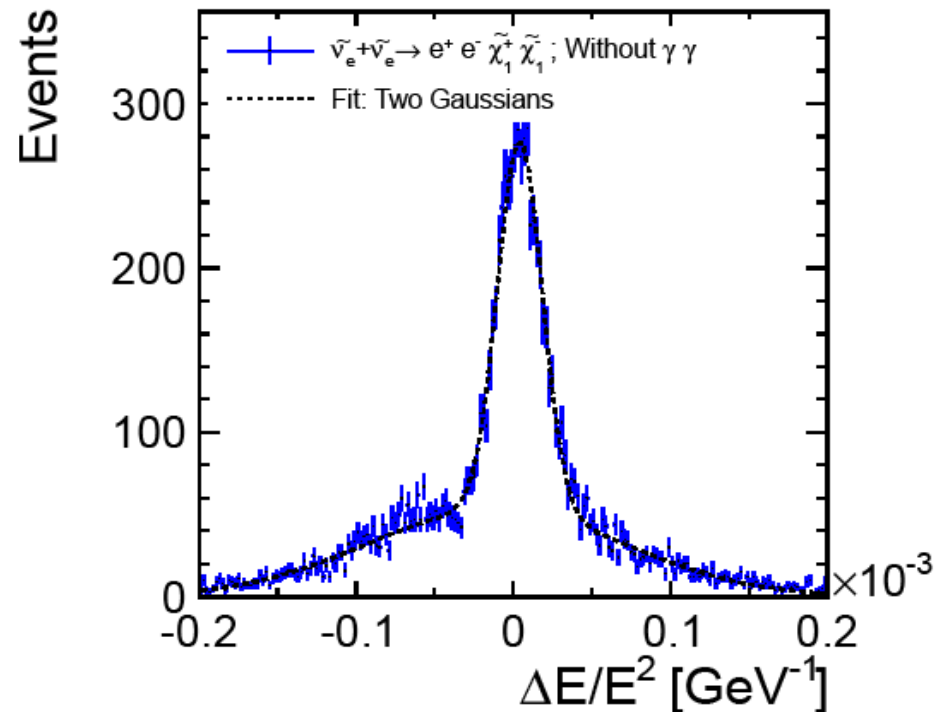
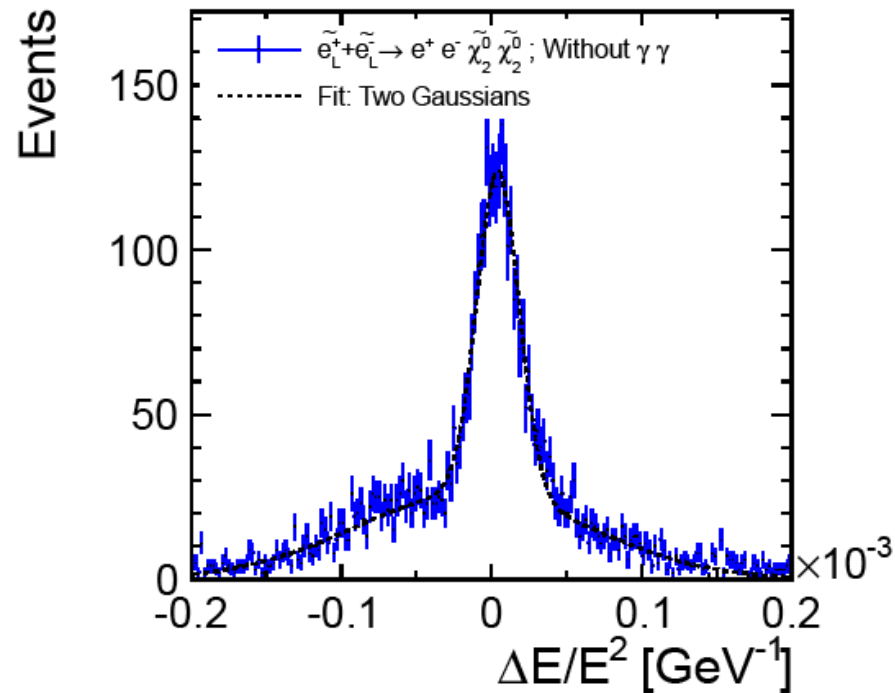
e^\pm final state: $\Delta E/E^2 = G1(1.4 \times 10^{-5}) + G2(7.7 \times 10^{-5})$; tails = 27.1 %, $\epsilon_R = 94.6\%$



Electron energy resolution

2L4J topology

For 2L4J events, particles are clustered into jets; 6 jet events with two of the jets identified as isolated leptons, without or with photons are selected.

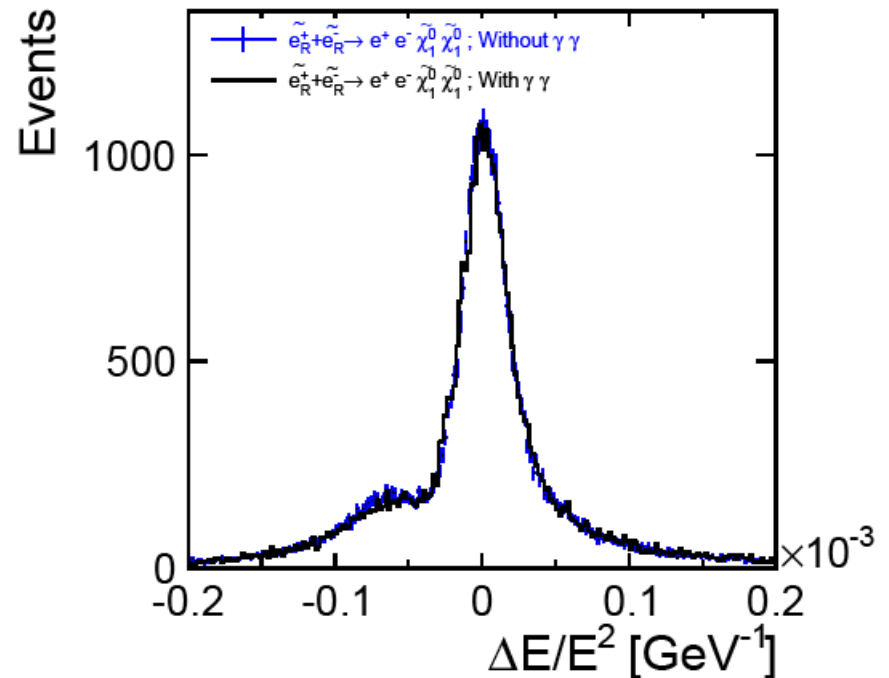
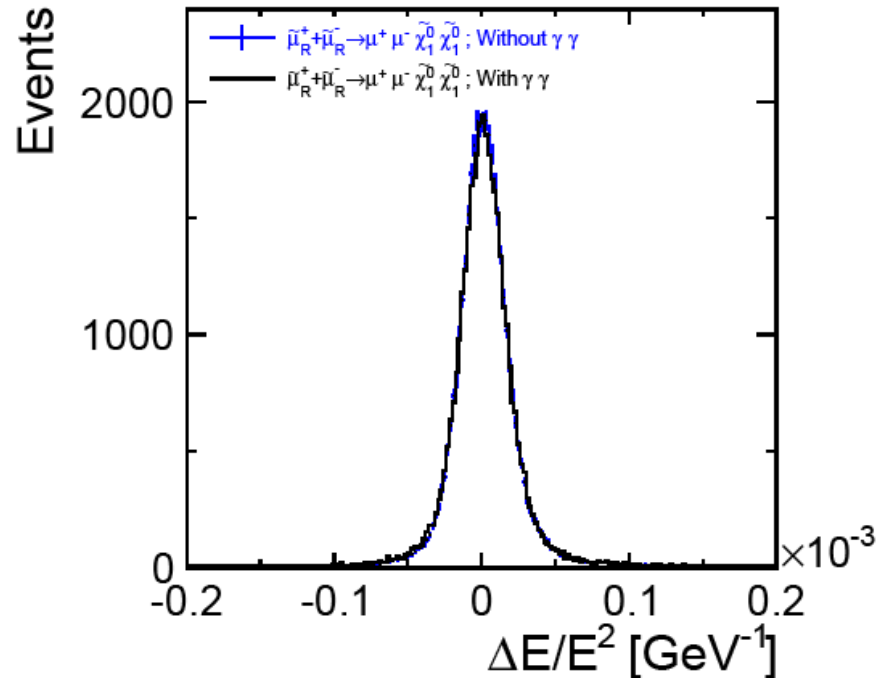


$$\Delta E/E^2 = G1(1.4 \times 10^{-5}) + G2(7.9 \times 10^{-5}); \text{tails} = 30\%$$

The energy resolution for 2L4J is similar to the 2L topology energy resolution.



Muon and electron energy resolution, 2L topology, without/with and $\gamma\gamma \rightarrow h$



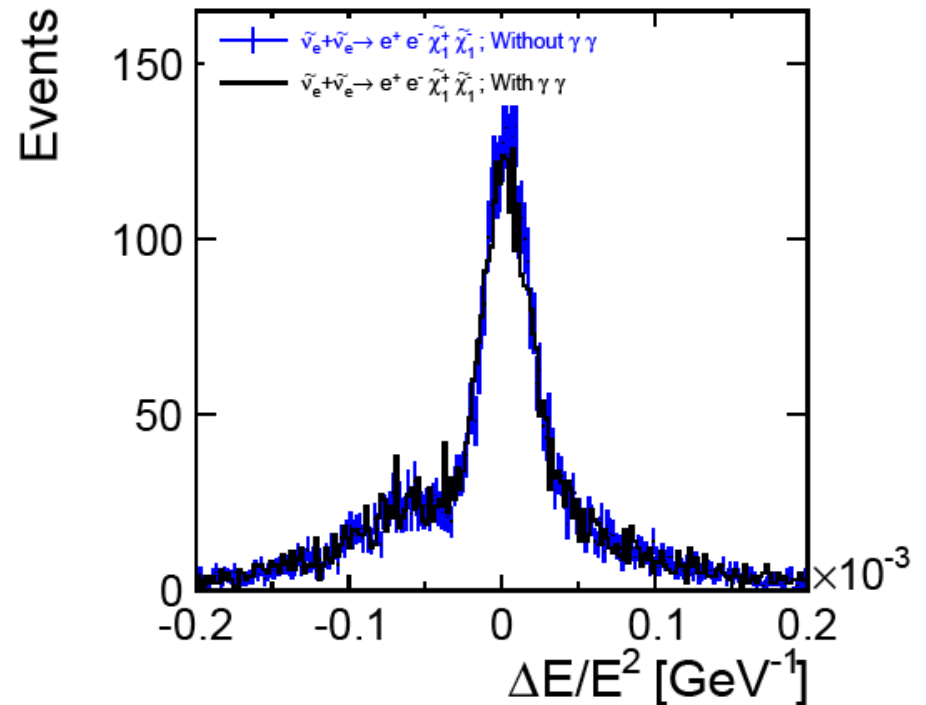
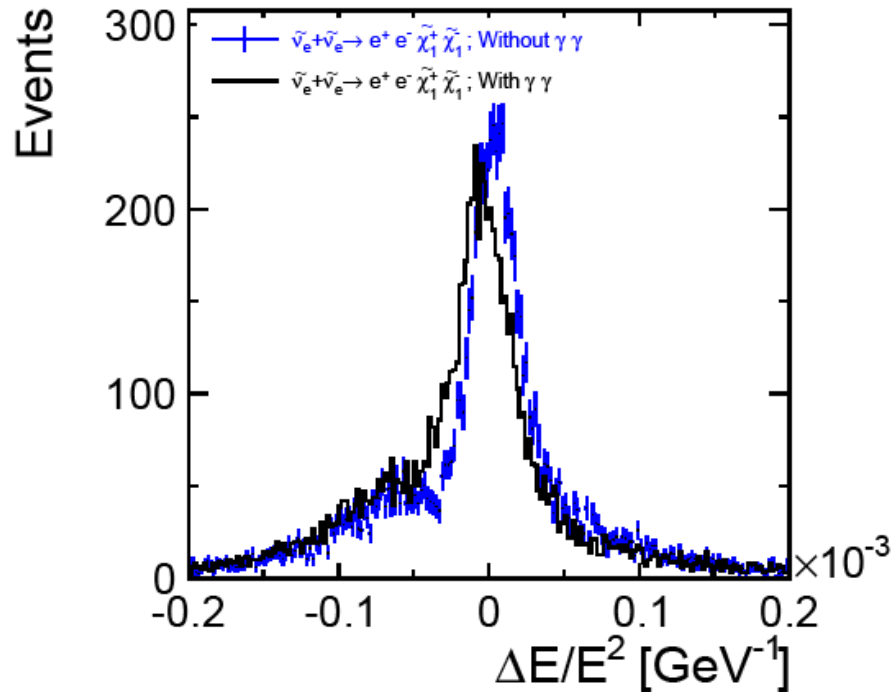
For 2L topology events, requiring $P_t > 4$ GeV to remove particles from $\gamma\gamma \rightarrow h$

Energy resolution is preserved

inefficiency = 1 % for μ^\pm events and 5% for e^\pm events.



Electron energy resolution topology 2L4J, without/with $\gamma\gamma \rightarrow h$



FSR and Bremsstrahlung correction in presence of $\gamma\gamma \rightarrow h$ introduce a bias due to additional particles associated to the electron (left plot).

For 2L+4J events a Pt cut of 4GeV would bias the jet energy resolution=>next slide

With tight time selection cuts: the bias is removed and the energy resolution is preserved (right plot); the inefficiency introduced is $\sim 6\%$.



Tight time cuts

Cuts based on the p_t of the particle and time information are used, their values depend on the particle ID and on the angular region. Three list of particles are produced; they correspond to three different sets of cuts: loose, standard, tight .

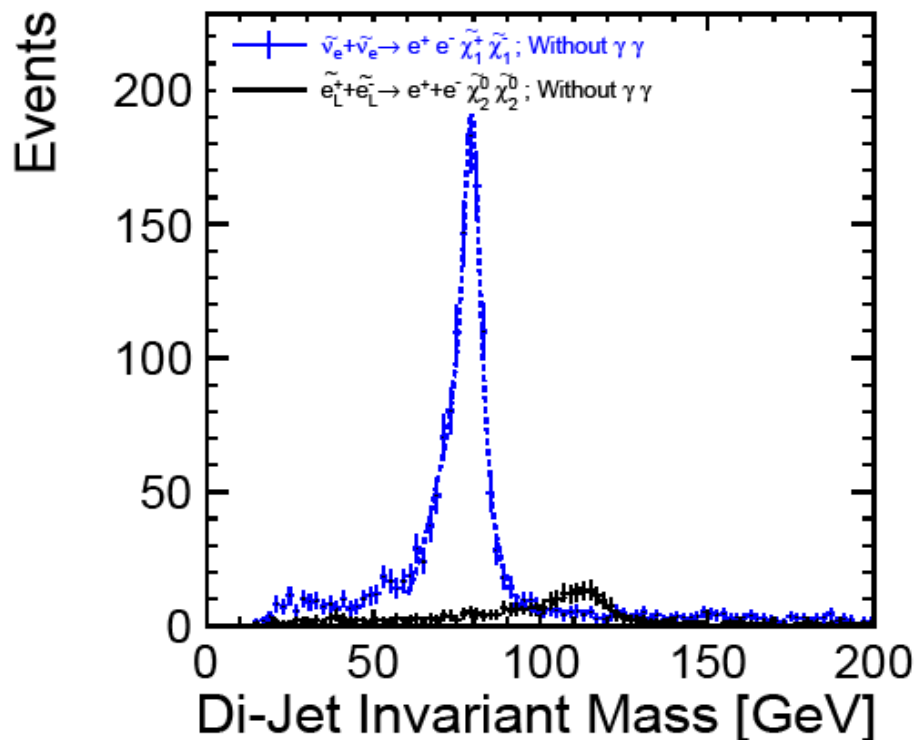
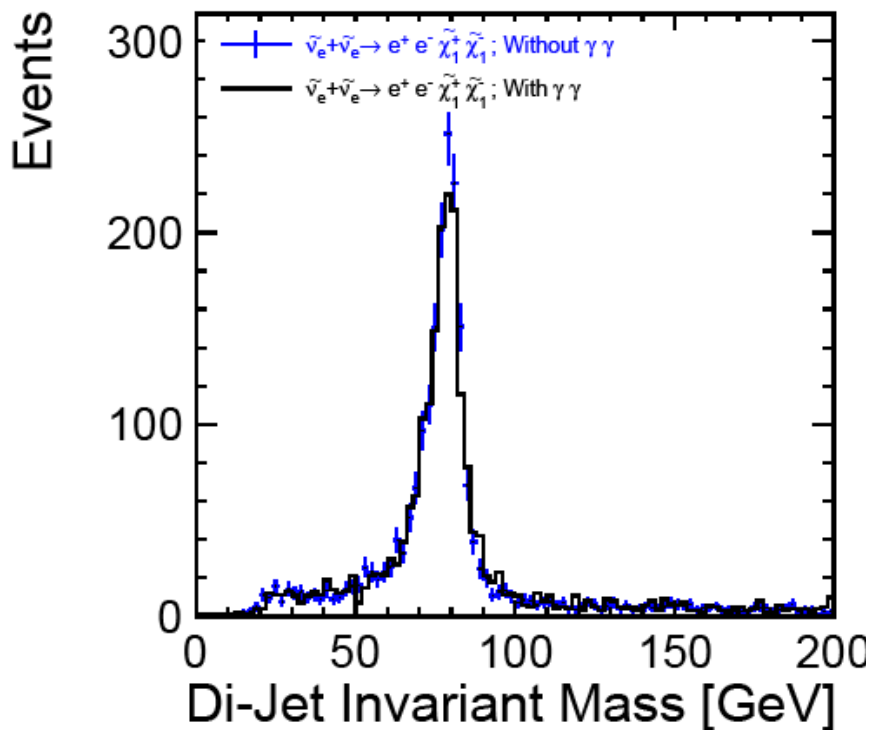
<i>Region</i>	<i>p_t range</i>	<i>Time cut</i>
Photons		
central ($\cos \theta \leq 0.95$)	$1.0 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$ $0.2 \text{ GeV} \leq p_t < 1.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$ $t < 1.0 \text{ nsec}$
forward ($\cos \theta > 0.95$)	$1.0 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$ $0.2 \text{ GeV} \leq p_t < 1.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$ $t < 1.0 \text{ nsec}$
Neutral hadrons		
central ($\cos \theta \leq 0.95$)	$1.0 \text{ GeV} \leq p_t < 8.0 \text{ GeV}$ $0.5 \text{ GeV} \leq p_t < 1.0 \text{ GeV}$	$t < 2.5 \text{ nsec}$ $t < 1.5 \text{ nsec}$
forward ($\cos \theta > 0.95$)	$1.0 \text{ GeV} \leq p_t < 8.0 \text{ GeV}$ $0.5 \text{ GeV} \leq p_t < 1.0 \text{ GeV}$	$t < 1.5 \text{ nsec}$ $t < 1.0 \text{ nsec}$
Charged PFOs		
all	$1.0 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$ $0. \text{ GeV} \leq p_t < 1.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$ $t < 1.0 \text{ nsec}$

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Di-Jet Mass Resolution

2L4J topology, without/with $\gamma\gamma \rightarrow h$



Without $\gamma\gamma \rightarrow h$ background, a fit of the W mass (B-W+Gauss) $\rightarrow \sigma E = 4.1$ GeV (left plot)

With $\gamma\gamma \rightarrow h$ and no cuts, the Di-Jet mass doesn't show a peak.

With tight time selection cuts the Di-Jet mass resolution is 4.7 GeV (left plot)

The mass resolution allows to tell apart WW and $h^0 h^0$ final states (right plot).



Sleptons and Gauginos Mass Determination

The slepton mass is $f(\sqrt{s}, E_H, E_L)$ (1)

the gauginos mass is $f(m_{\tilde{l}}, \sqrt{s}, E_H, E_L)$ (2)

Where E_L and E_H are the lower and upper edges of the lepton energy distribution.

The masses are determined using a 2 parameters fit to the reconstructed energy spectrum, dN/dE ; S+B-B(MC).

For a set of masses, a template spectrum of N events is modeled according to (3), $N=N_{data}$.

For each event \sqrt{s} is generated taking into account ISR + Beamstrahlung spectrum.

The energy is smeared using $\Delta E/E^2$, slide 7,8.

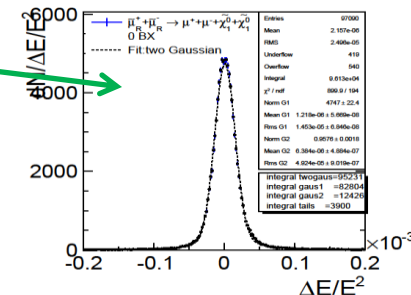
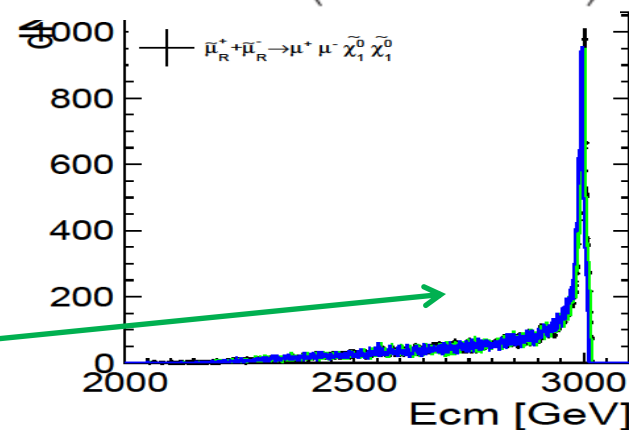
The $\chi^2 = \sum(\text{data-template})^2/\text{err}^2$ is computed.

Minuit is used to iterate till the χ^2 is minimized

$$m_{\tilde{\ell}^\pm} = \frac{\sqrt{s}}{2} \left(1 - \frac{(E_H - E_L)^2}{(E_H + E_L)^2} \right)^{1/2} \quad (1)$$

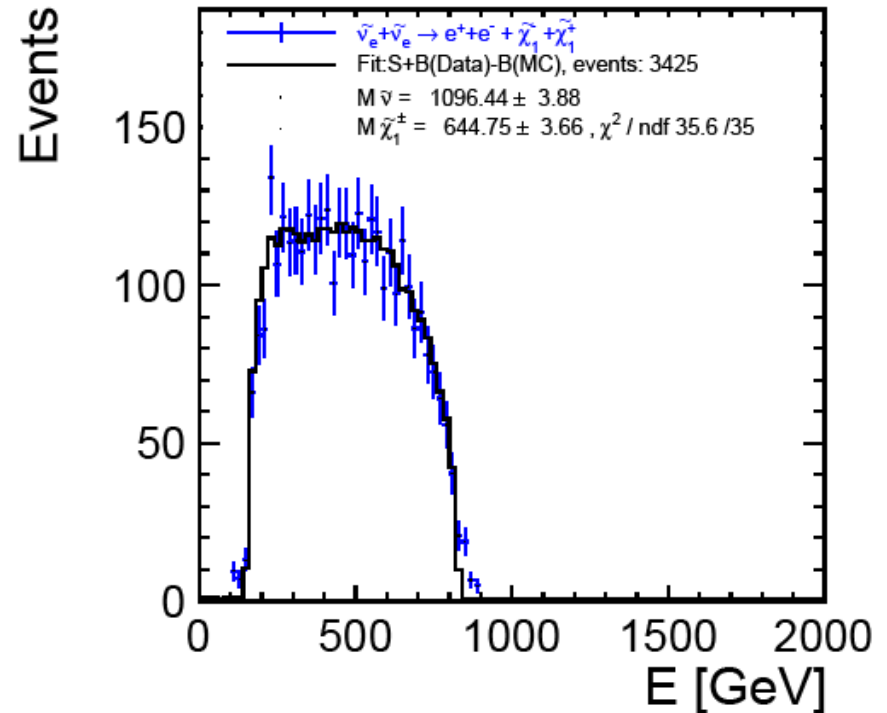
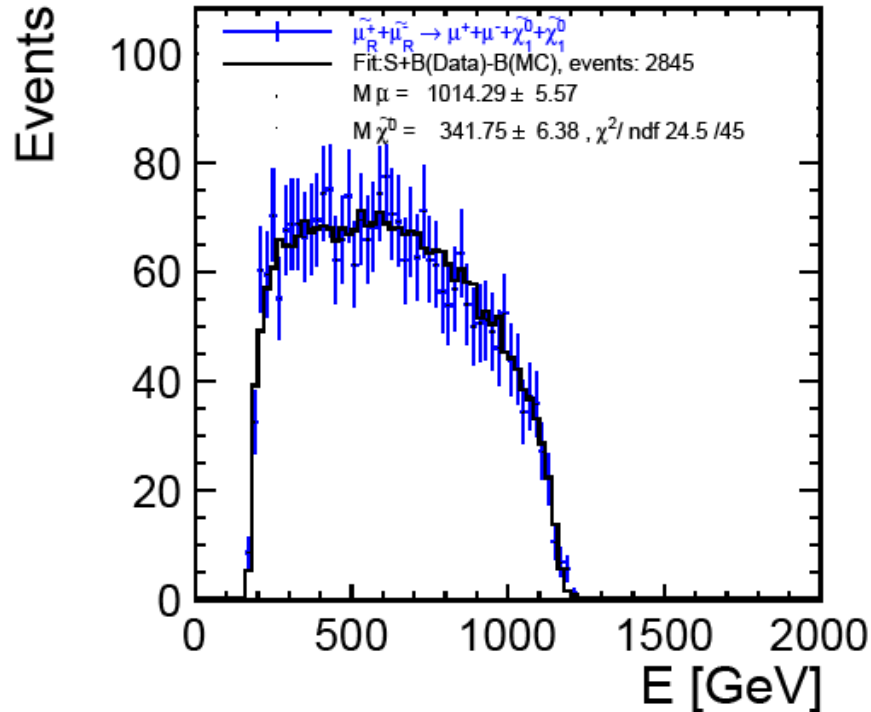
$$m_{\tilde{\chi}_1^0} \text{ or } m_{\tilde{\chi}_1^\pm} = m_{\tilde{\ell}^\pm} \left(1 - \frac{2(E_H + E_L)}{\sqrt{s}} \right)^{1/2} \quad (2)$$

$$E_{L,H} = \frac{\sqrt{s}}{4} \left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}^\pm}^2} \right) \left(1 \pm \sqrt{1 - 4 \frac{m_{\tilde{\ell}^\pm}^2}{s}} \right) \quad (3)$$





Results: $\int L = 2 \text{ab}^{-1}$



$\sigma m/m (\tilde{\mu}_R) \sim 0.6 \% ; \sigma m/m (\tilde{\chi}_1^0) \sim 2\% : \delta\sigma/\sigma = 2.6\%$

$\sigma m/m (\tilde{e}_R) \sim 0.5 \% ; \sigma m/m (\tilde{\chi}_1^0) \sim 1\% : \delta\sigma/\sigma = 0.7\%$

$\sigma m/m (\tilde{\nu}_e) \sim 0.4 \% ; \sigma m/m (\tilde{\chi}_{1\pm}) \sim 0.6\% : \delta\sigma/\sigma = 2.4\%$



Summary and Outlook

- For μ^\pm and e^\pm final states, $P_t > 4$ GeV cut remove $\gamma\gamma \rightarrow h$ background preserving the energy resolution.
- For $e^\pm 4J$ final states, detector timing information must be included to remove $\gamma\gamma \rightarrow h$ background, preserve the lepton energy resolution and the di-jet mass resolution. It requires detector time stamping capability of ~ 1 nsec and readout window ~ 10 nsec.
- With 2 ab^{-1} the $\tilde{\mu}_R, \tilde{e}_R, \tilde{e}_L$ and $\tilde{\nu}_e$ cross section are determined with a relative statistical uncertainty of $\sim 2.6\%$, 0.7% , 8% and 2.4% .
- The $\tilde{\mu}_R, \tilde{e}_R, \tilde{\nu}_e, \tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1$ masses are measured with a relative statistical accuracy of $\sim 0.6\%$, 0.5% , 0.4% , 1% and 0.6%
- Knowledge of the luminosity spectrum is essential for the mass fit.
- To establish the \tilde{e} and $\tilde{\mu}$ helicity requires beam polarization

To contribute to EU strategy document, ECM ~ 1.5 TeV, new benchmark



Backup Slides



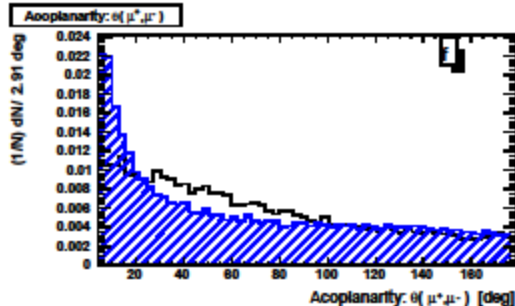
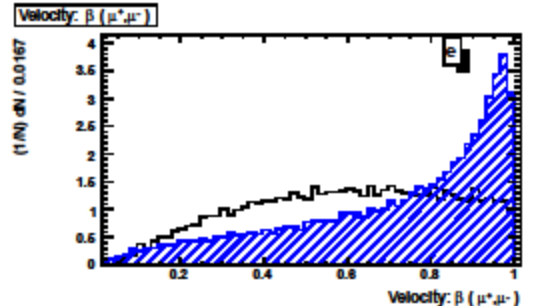
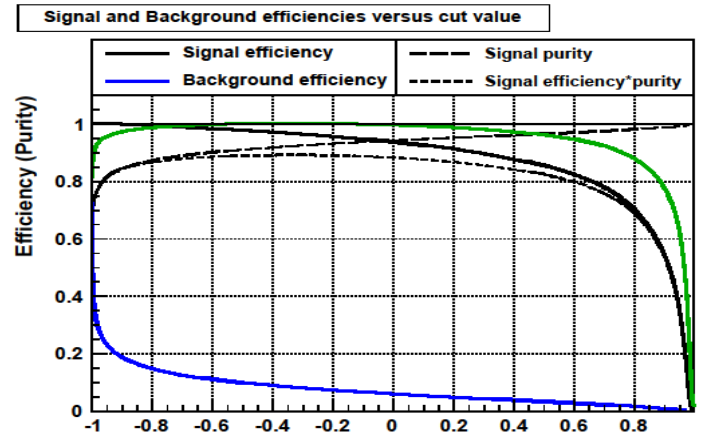
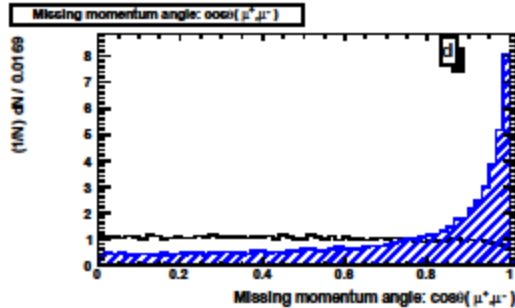
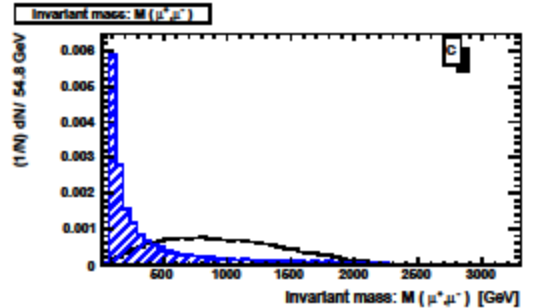
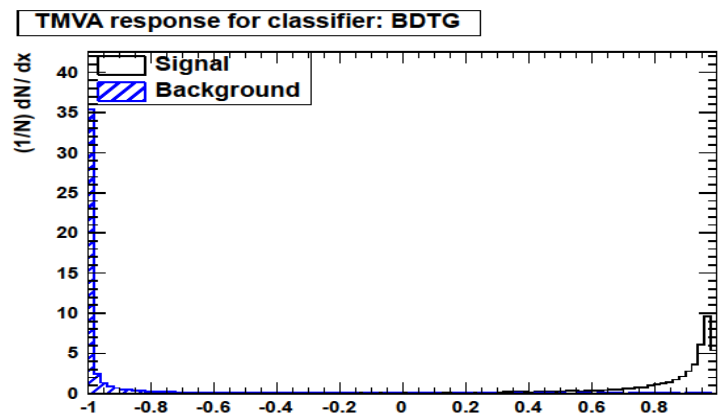
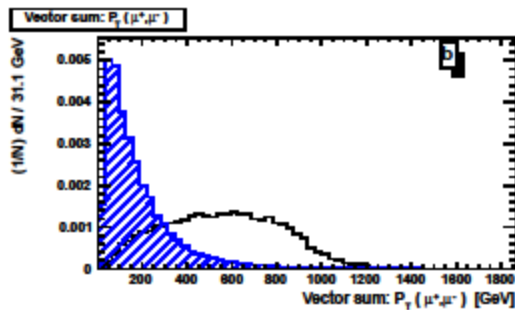
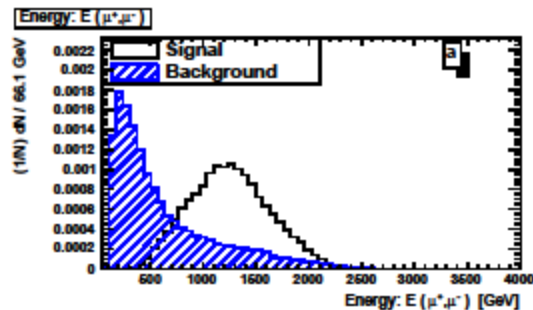
Discriminating variables

$E(L1)+E(L2)$	Visible energy, without neutral energy
$Pt(L1) + Pt(L2)$	Pt Vector Sum
$Pt(L1) + Pt(L2)$	Pt Algebraic Sum
$M(L1,L2)$	Invariant mass of the lepton pair
$Beta(L1,L2)$	β of the lepton pair
$Theta(L1,L2)$	Polar angle of Missing momentum vector
Acollinearity	of the lepton pair
Acoplanarity	of the lepton pair
$\Delta = E(L1) - E(L2) / E(L1) + E(L2)$; energy imbalance

L1 and L2 are the two leptons



Event Selection



TMVA is used to build PDF (S, B) out of input histograms (Evis, PT12,...) and combine them into a total probability classifier. Half of data sample is used to compute the PDF ; the second half is the data sample. The classifier ranks events to be S/B like; it is used to select the events.



dN/dE (S+B)

