

# MULTIJET SUSY STUDIES

Burak Bilki  
01/14/09

# Supersymmetry (SUSY)

New partner particles for all Standard Model (SM) particles:

SM Particle	SUSY Particle		
quarks	$q_L, q_R$	squarks	$\tilde{q}_L, \tilde{q}_R$
leptons	$l_L, l_R$	sleptons	$\tilde{l}_L, \tilde{l}_R$
gluon	$g$	gluino	$\tilde{g}$
W/Z boson	$W/Z$	wino/zino	$\tilde{W}/\tilde{Z}$
photon	$\gamma$	photino	$\tilde{\gamma}$
Higgs	$H_1, H_2$	higgsino	$\tilde{H}_1, \tilde{H}_2$

neutralinos  $\tilde{\chi}^0$   
charginos  $\tilde{\chi}^{\pm 1}$

SUSY as an exact symmetry predicts  $m(\text{SM})=m(\text{SUSY})$

... but, no SUSY particles observed so far

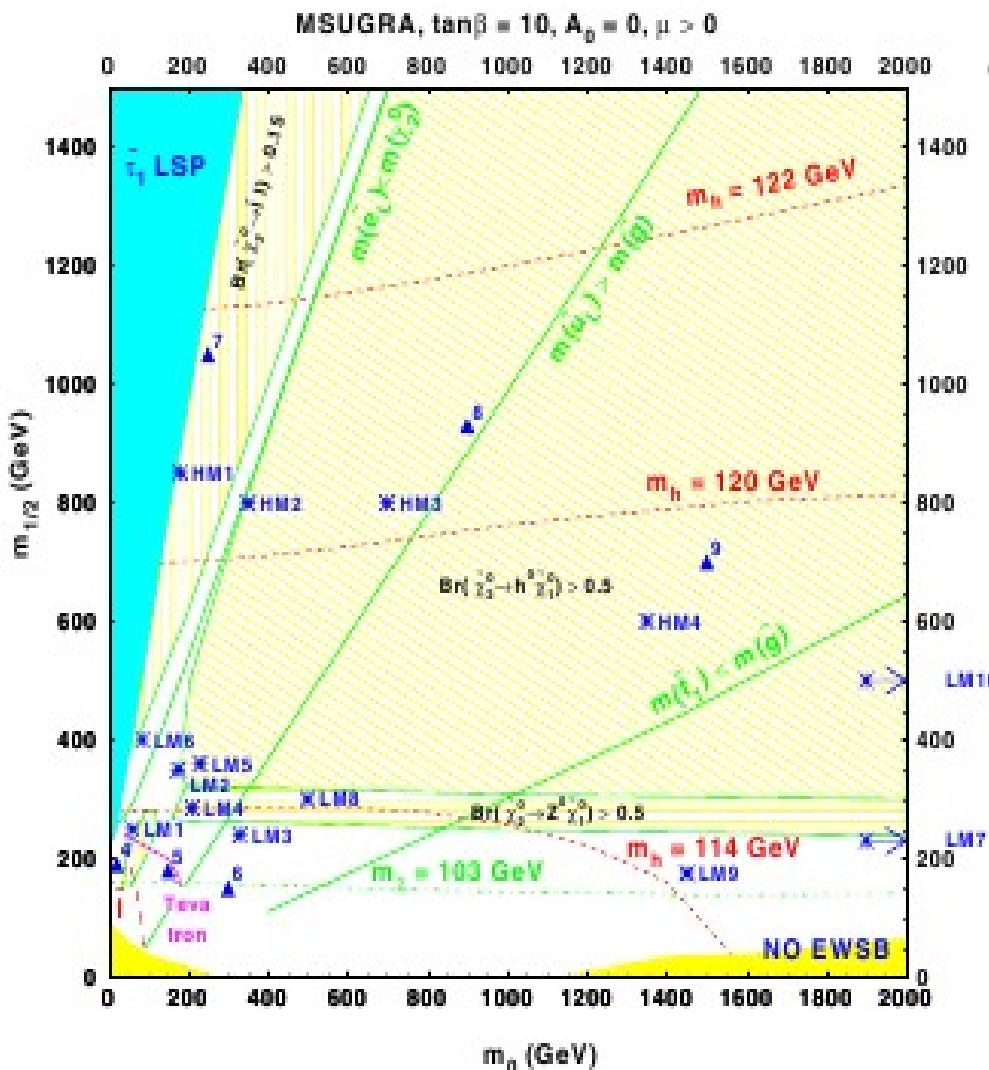
→ SUSY must be broken if realized in nature.

# Supersymmetry (SUSY)

SUSY breaking mechanism introduces 105 free parameters!

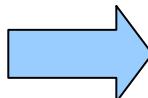
Constrained SUSY models assume specific SUSY breaking mechanisms.

**MinimalSUperGRAvity** (5 parameters  $m_0, m_{1/2}, A_0, \tan\beta, \text{sgn}(\mu)$ )<sup>1</sup>



- Point LM1:

- \* Same as post-WMAP benchmark point B' and near DAQ TDR point 4.
- \*  $m(\tilde{g}) \geq m(\tilde{q})$ , hence  $\tilde{g} \rightarrow \tilde{q}\bar{q}$  is dominant.
- \*  $B(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l) = 11.2\%$ ,  $B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) = 46\%$ ,  $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_l l) = 36\%$ .



Jets<sup>2</sup>  
+  
MET<sup>3</sup>

... However, not only SUSY events end up with jets and MET,

*QCD* (gumbo)

$t\bar{t} + \text{jets}, W + \text{jets}, Z + \text{jets}$  (chowder)

$Z \rightarrow \nu\nu$  (znunu)

<sup>1</sup> arXiv:hep-ph/0502014v2

<sup>2</sup> K. Kousouris, JTERM3, 01.13.2009

<sup>3</sup> G. Lungu, JTERM3, 01.13.2009

# Scope of the Analysis

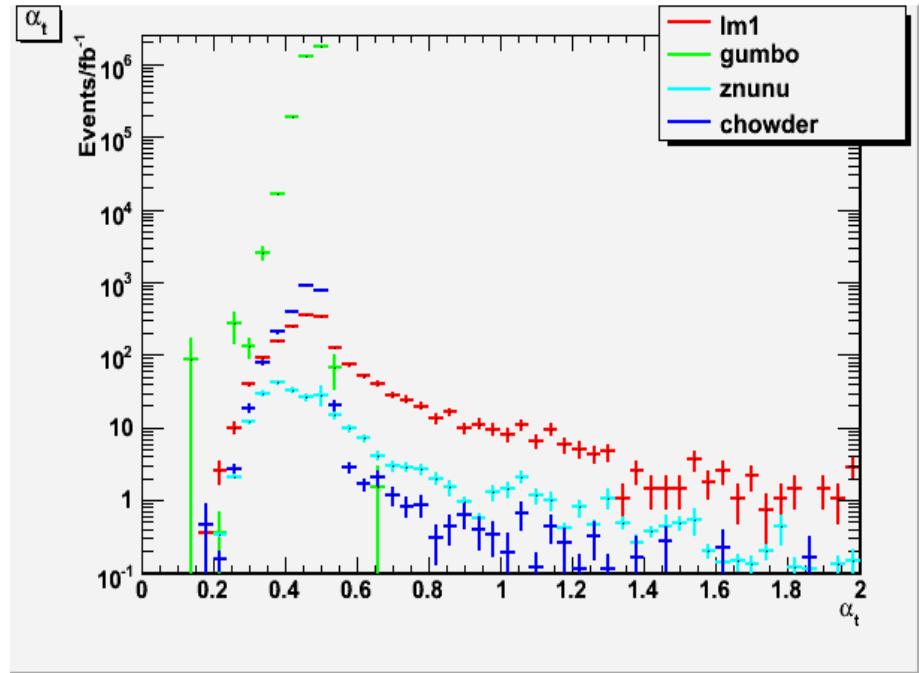
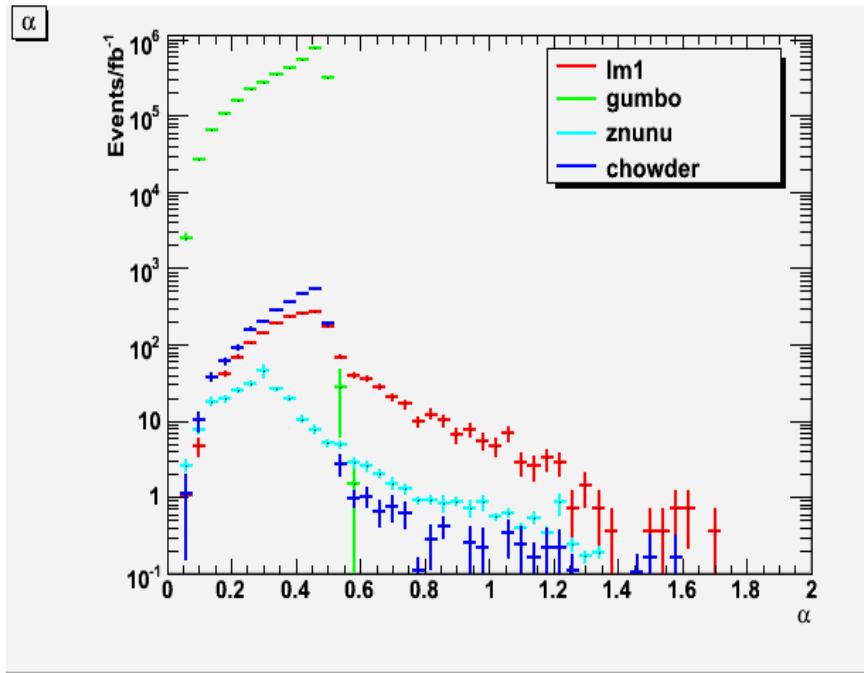
We need an enhanced toolkit for discriminating SUSY from SM.

One idea is to look at global kinematic variables whose distributions are predicted by QCD.



Validate SM QCD predictions for these kinematic variables with the intention of SUSY search.

# Dijets



$$\alpha = \frac{E_T^{j2}}{M_{j1,j2}}$$

2



$$\alpha_T = \frac{E_T^{j2}}{M_{Tj1,j2}}$$

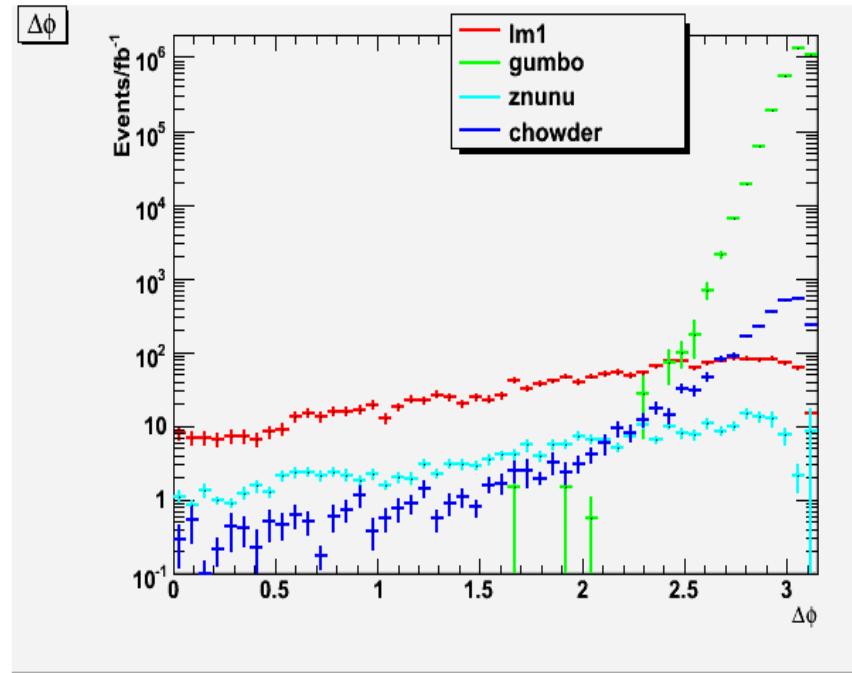
lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	<i>Z → νν</i>
chowder	<i>t t-bar + jets, W+jets, Z+jets</i>

Reproductions of CMS PAS SUS-08-005  
Please see the appendix for selection cuts.

<sup>1</sup> G. Tonelli, JTERM3, 01.12.2009

<sup>2</sup> arXiv:0806.1049v1

# Dijets

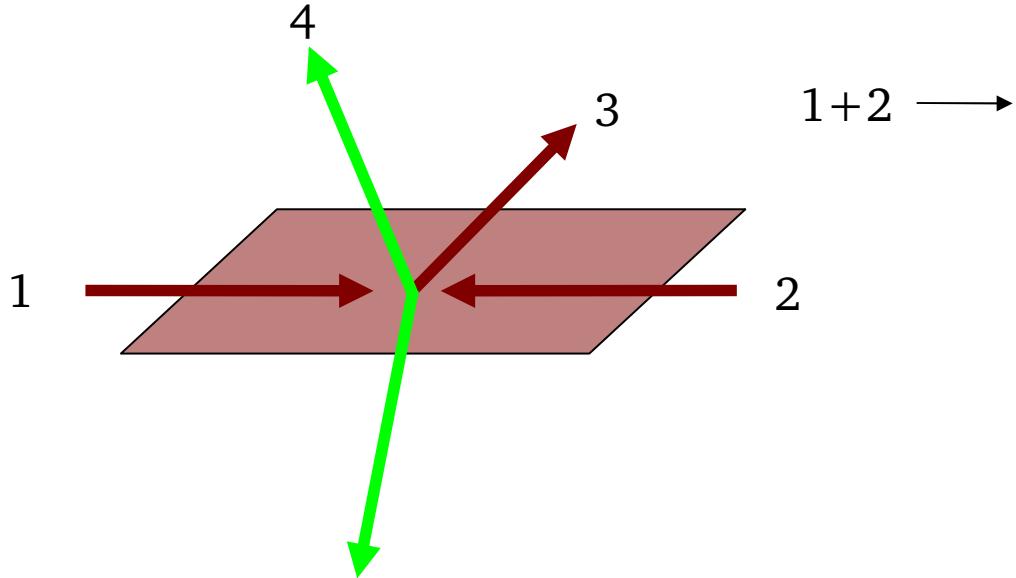


Angle between the jets.

Together with CMS PAS SUS-08-002 and CMS PAS EWK-07-002, a data driven background estimation is proposed and SUSY search is prepared.

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow vv$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

## 3-Jet Kinematic Variables



$1+2 \longrightarrow 3+4+5$

Tri-jet variables in the three-body rest frame:

$$M_{3J} \quad X_3 \quad X_4 \quad X_5 \quad \cos \theta_3 \quad \psi_3 \quad f_3 \quad f_4 \quad f_5$$

$$X_i = \frac{2E_i}{M_{3J}} \quad \rightarrow \quad \sum X_i = 2 \quad i=3,4,5 \quad (\text{for QCD and Chowder samples})$$

$$f_i = \frac{m_i}{M_{3J}}$$

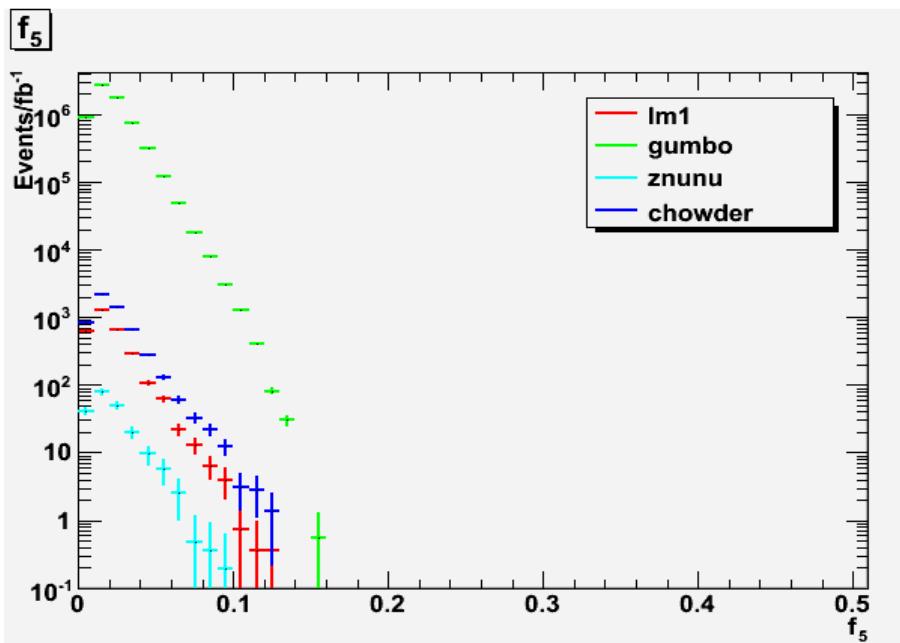
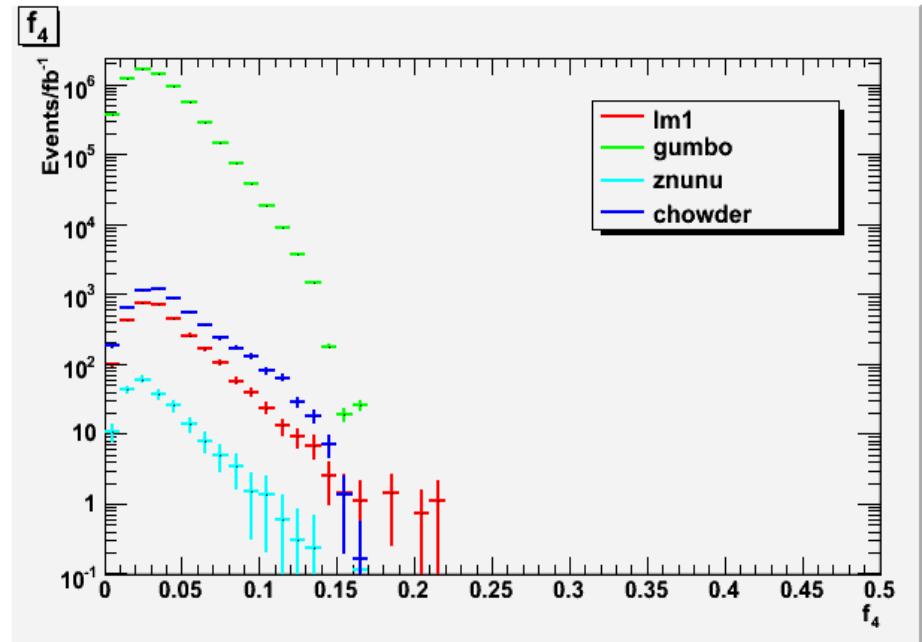
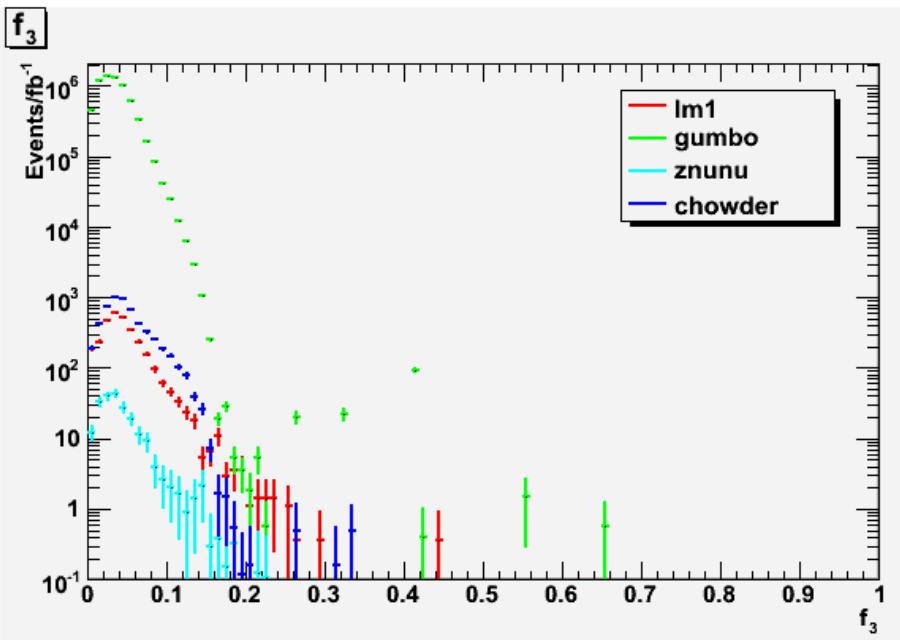
$$\cos \psi_3 = \frac{(\vec{p}_3 \times \vec{p}_{\text{av.}}) \cdot (\vec{p}_4 \times \vec{p}_5)}{(\vec{p}_3 \times \vec{p}_{\text{av.}})(\vec{p}_4 \times \vec{p}_5)}$$

Ellis-Karliner Angle:  $\lambda^1$

Angle between the two highest energy jets that result in boost in highest E jet direction.

<sup>1</sup> J. Ellis and I. Karliner, Nucl. Phys. B148 141, (1979)

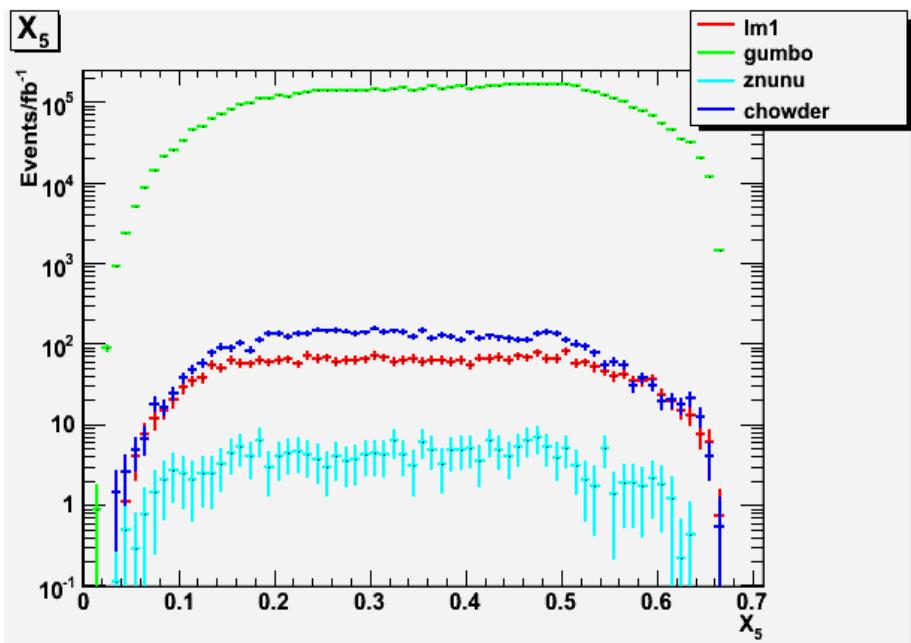
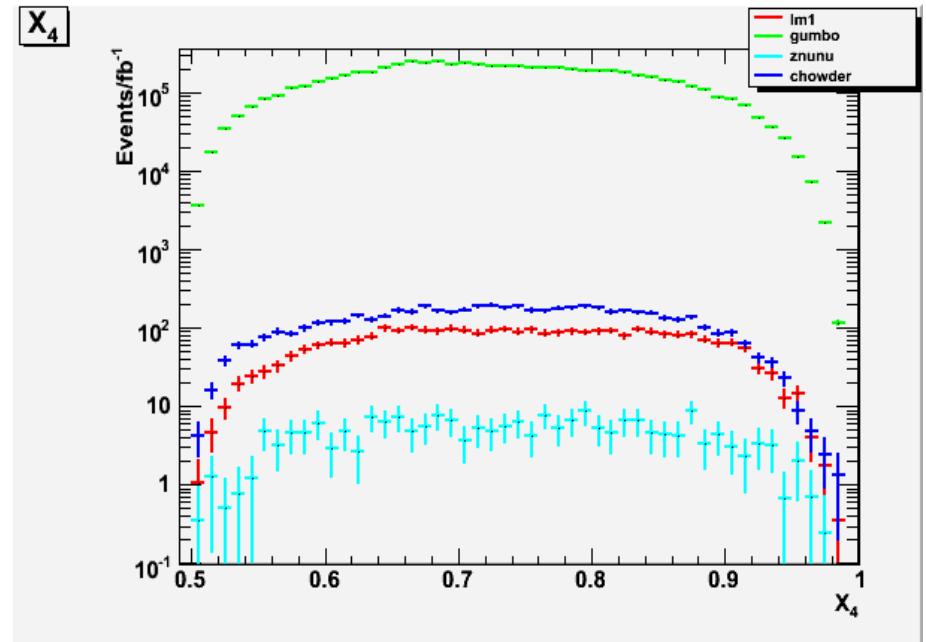
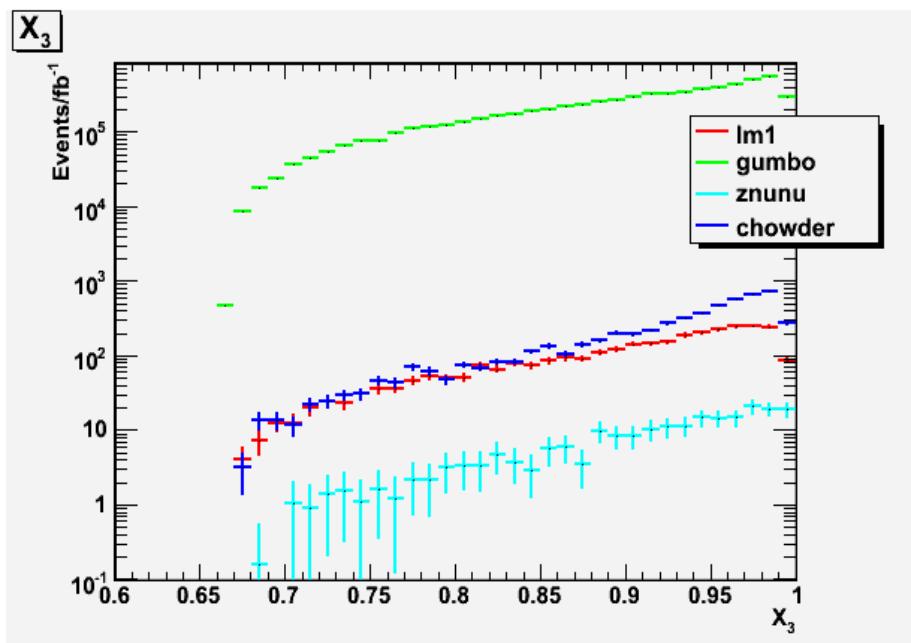
# 3-Jet Kinematic Variables



$$f_i = \frac{m_i}{M_{3J}}$$

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

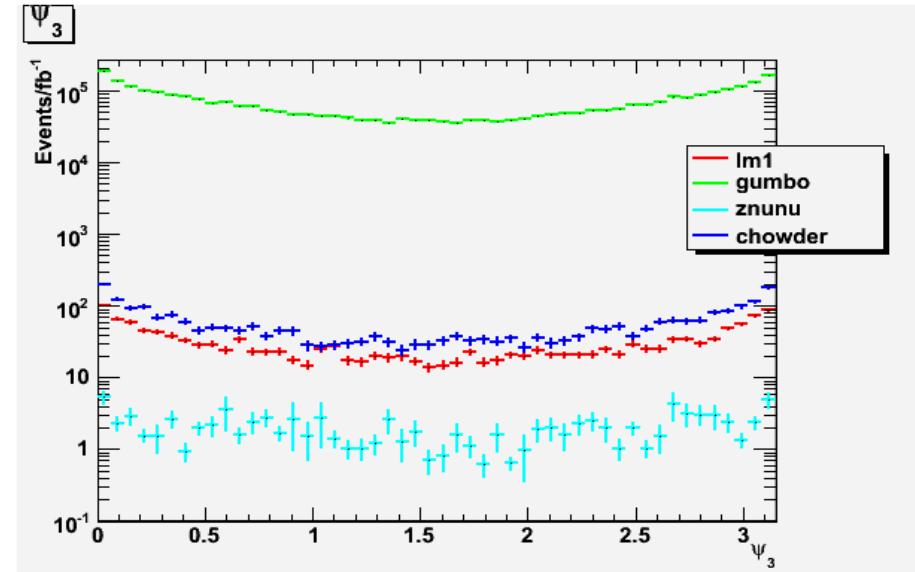
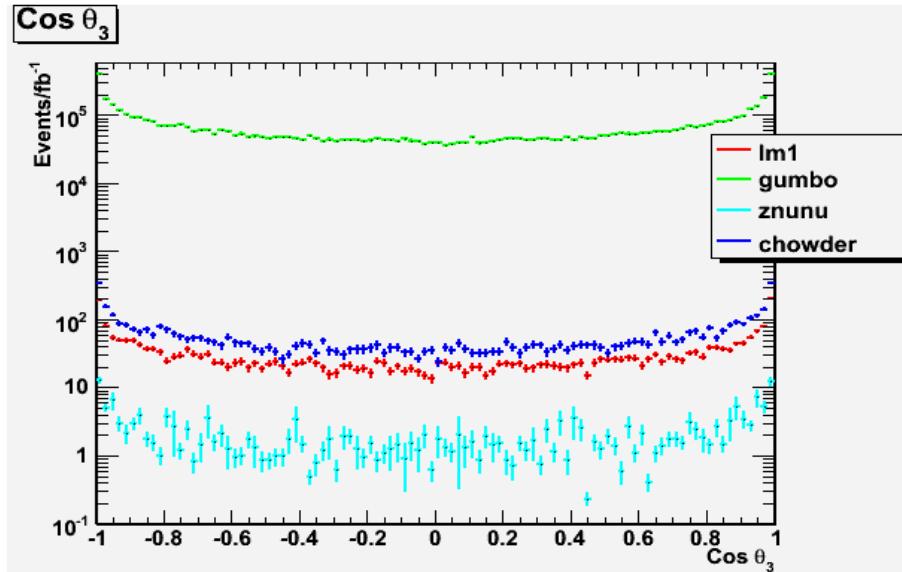
# 3-Jet Kinematic Variables



$$X_i = \frac{2E_i}{M_{3J}}$$

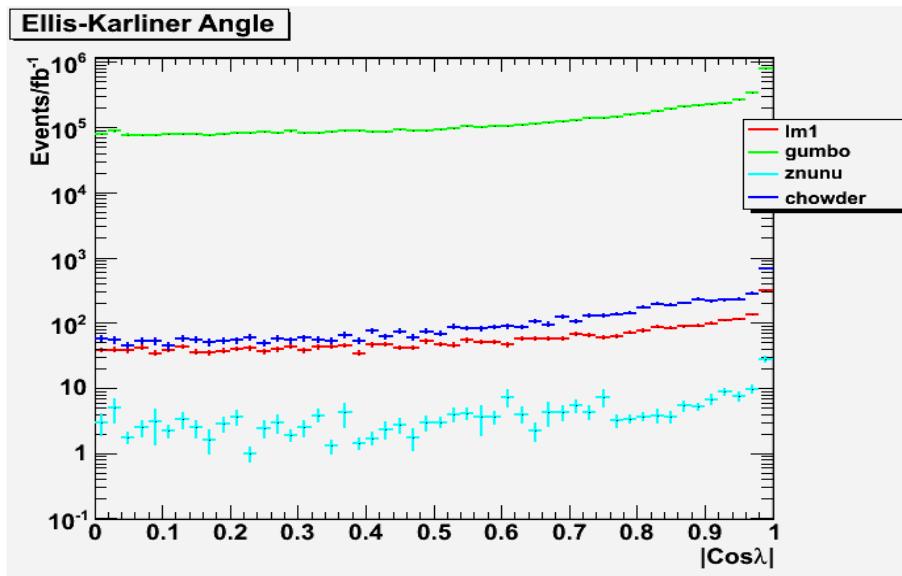
lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + \text{jets}, W + \text{jets}, Z + \text{jets}$

# 3-Jet Kinematic Variables



$\cos \theta_3$  Angle between the beam direction and  
The hardest jet

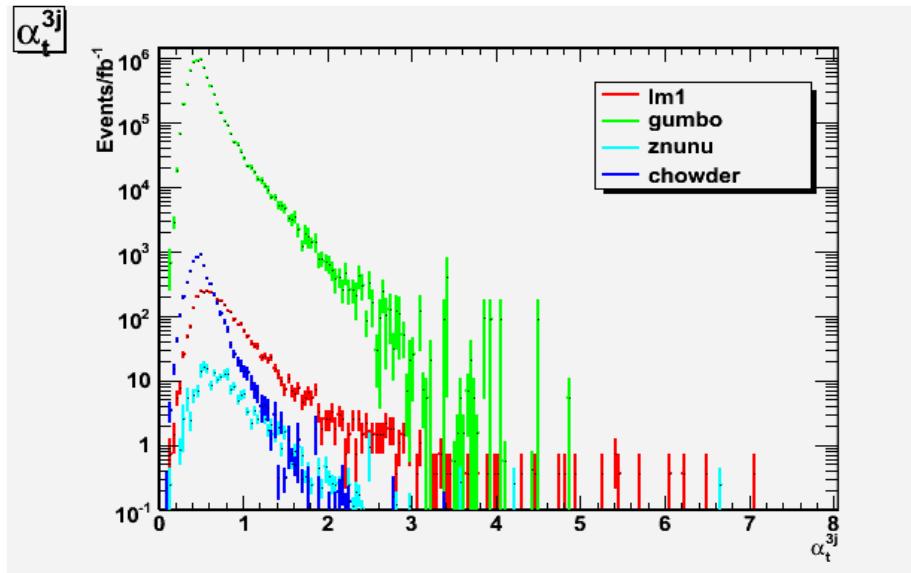
$$\cos \Psi_3 = \frac{(\vec{P}_3 \times \vec{P}_{\text{av.}}) \cdot (\vec{P}_4 \times \vec{P}_5)}{(\vec{P}_3 \times \vec{P}_{\text{av.}})(\vec{P}_4 \times \vec{P}_5)}$$



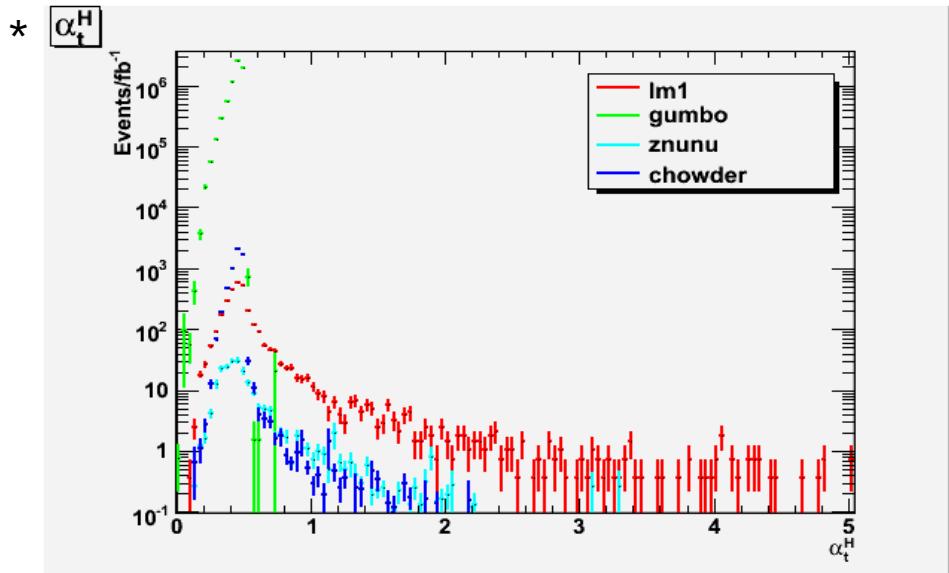
lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow vv$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

$\lambda$  Angle between the two highest energy jets that result in boost in highest E jet direction.

# 3-Jet $\alpha$ and $\alpha_t$



$$\alpha_t^{3j} = \frac{E_t^{jj_2}}{M_t^{j_1 j_2 j_3}}$$

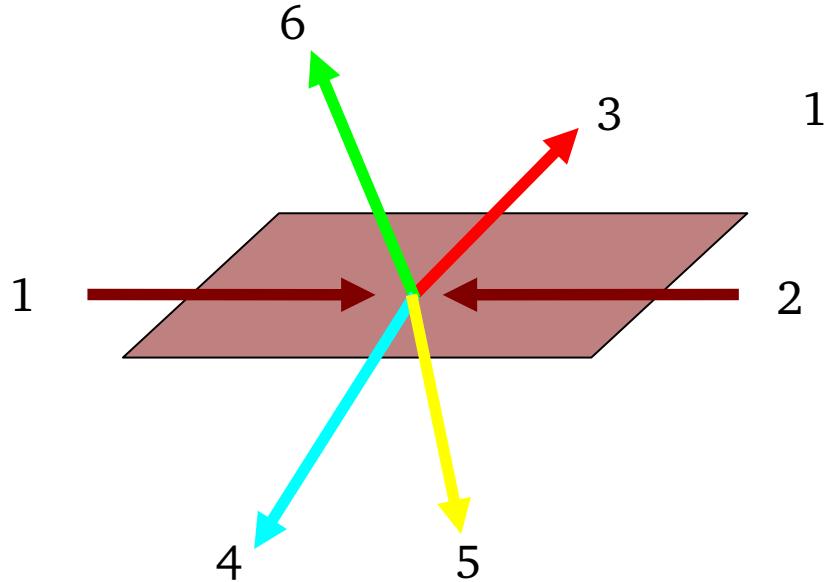


$$\alpha_t^H = \frac{E_t^{H_2}}{\sqrt{2 E_t^{H_1} E_t^{H_2} (1 - \cos \Delta\phi)}}$$

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow \nu\nu$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

\* See CMS Physics TDR Section 13.4 for the definition of Hemisphere algorithm. <sup>11</sup>

## 4-Jet Kinematic Variables



$$1+2 \longrightarrow 3+4+5+6$$

Four-jet variables in the four-body rest frame:

$$M_{4J} \quad X_3, \quad X_4, \quad X_5, \quad \cos \theta_3, \quad \psi_3, \quad f_3, \quad f_4, \quad f_5,$$

$$f_A \quad f_B \quad X_A \quad \psi_{AB}$$

$$X_A \equiv \frac{E_A}{E_A + E_B}$$

$$\cos \Psi_{AB} = \frac{(\vec{P}_A \times \vec{P}_B) \cdot (\vec{P}_{AB} \times \vec{P}_{av.})}{(\vec{P}_A \times \vec{P}_B)(\vec{P}_{AB} \times \vec{P}_{av.})}$$

## 4-Jet Kinematic Variables

**Bengtsson-Zerwas angle :**

Angle between the plane containing the two leading jets and the plane containing the two non-leading jets.

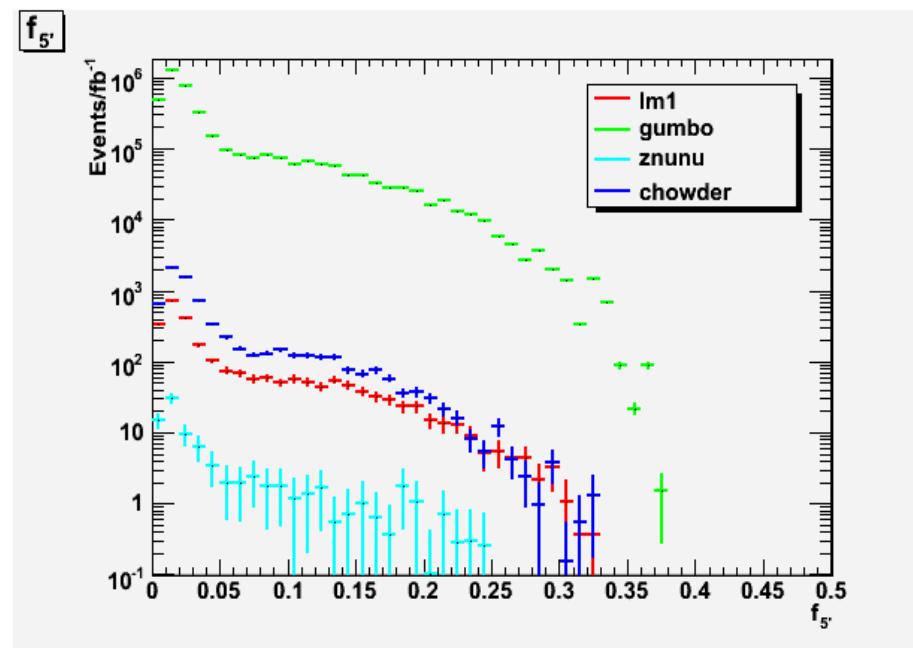
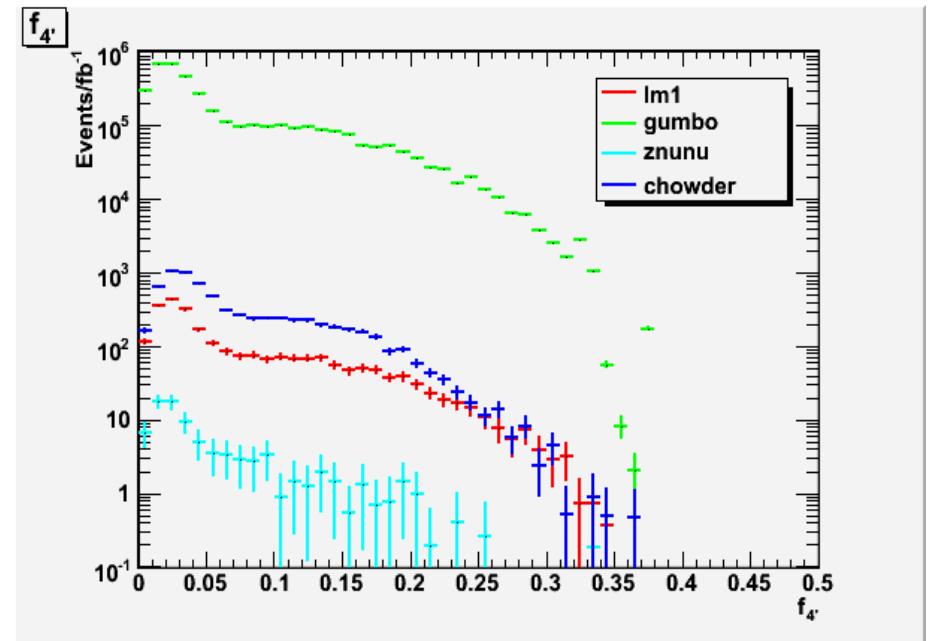
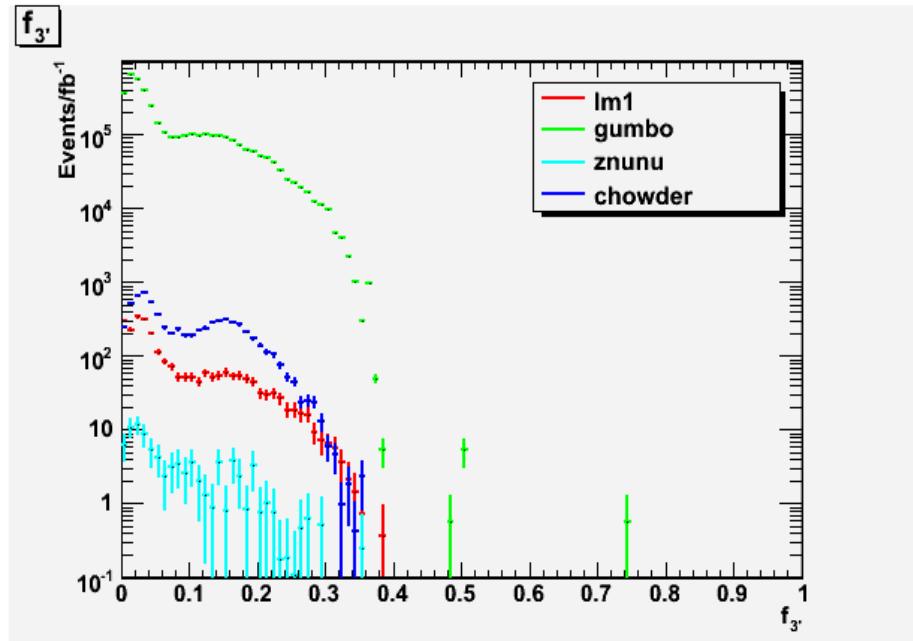
$$\cos \chi_{BZ} = \frac{(\vec{P}_3 \times \vec{P}_4) \cdot (\vec{P}_5 \times \vec{P}_6)}{(\vec{P}_3 \times \vec{P}_4)(\vec{P}_5 \times \vec{P}_6)}$$

**Nachtmann-Reiter angle:**

Angle between the momentum vector differences of the leading jets and the two non-leading jets:

$$\cos \theta_{NR} = \frac{(\vec{P}_3 - \vec{P}_4) \cdot (\vec{P}_5 - \vec{P}_6)}{(\vec{P}_3 - \vec{P}_4)(\vec{P}_5 - \vec{P}_6)}$$

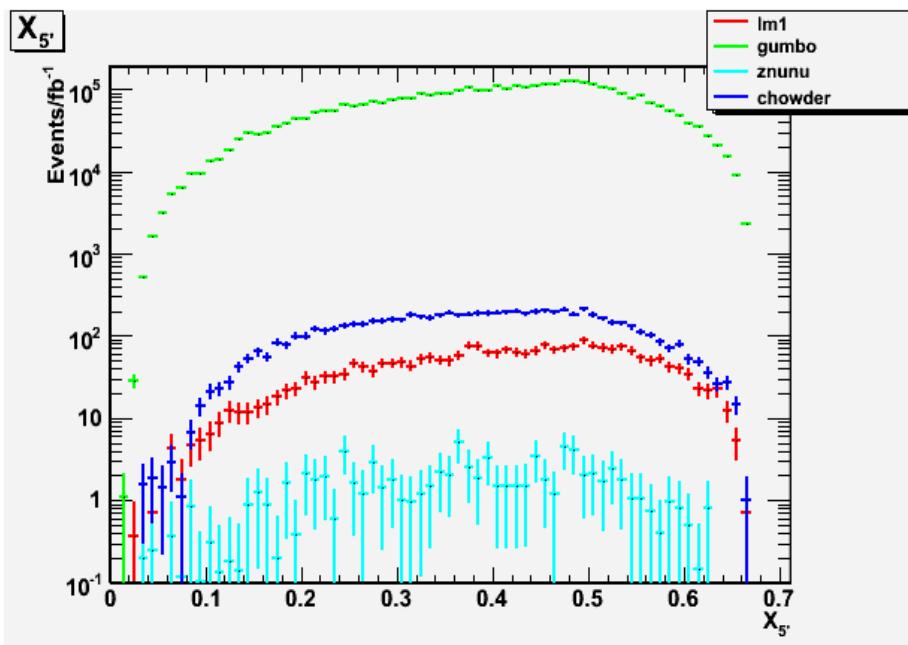
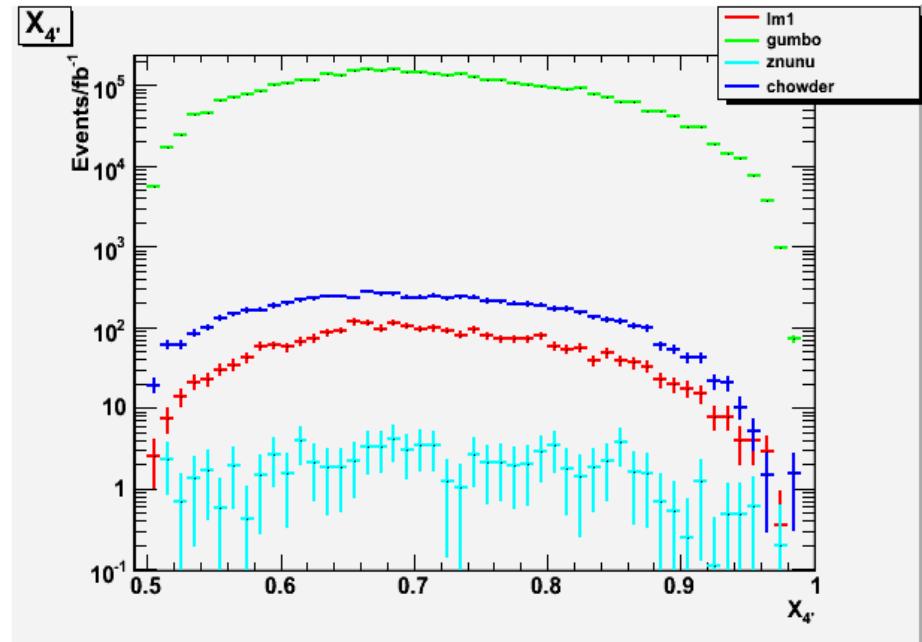
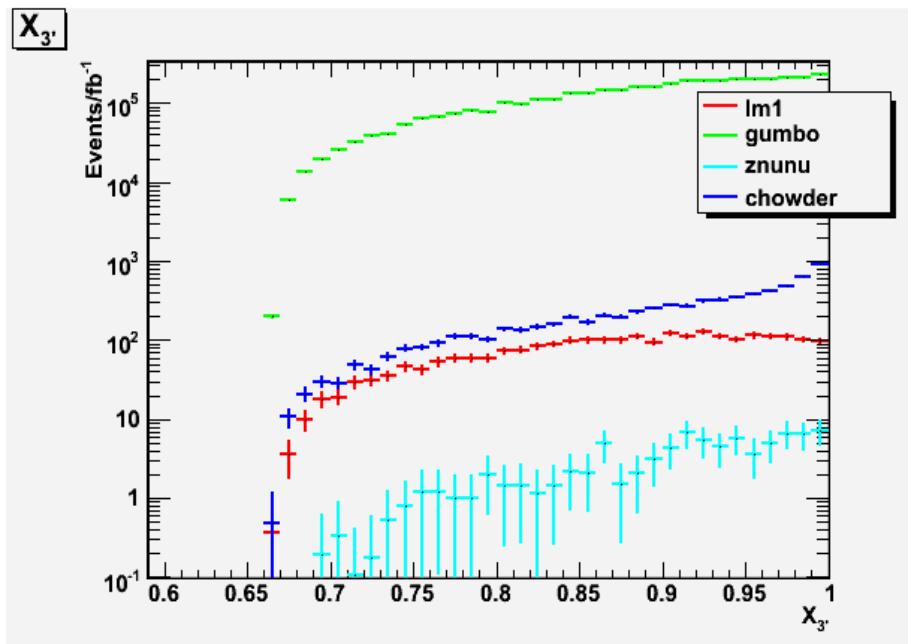
# 4-Jet Kinematic Variables



$$f_{i'} = \frac{m_{i'}}{M_{3J}}$$

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + \text{jets}, W + \text{jets}, Z + \text{jets}$

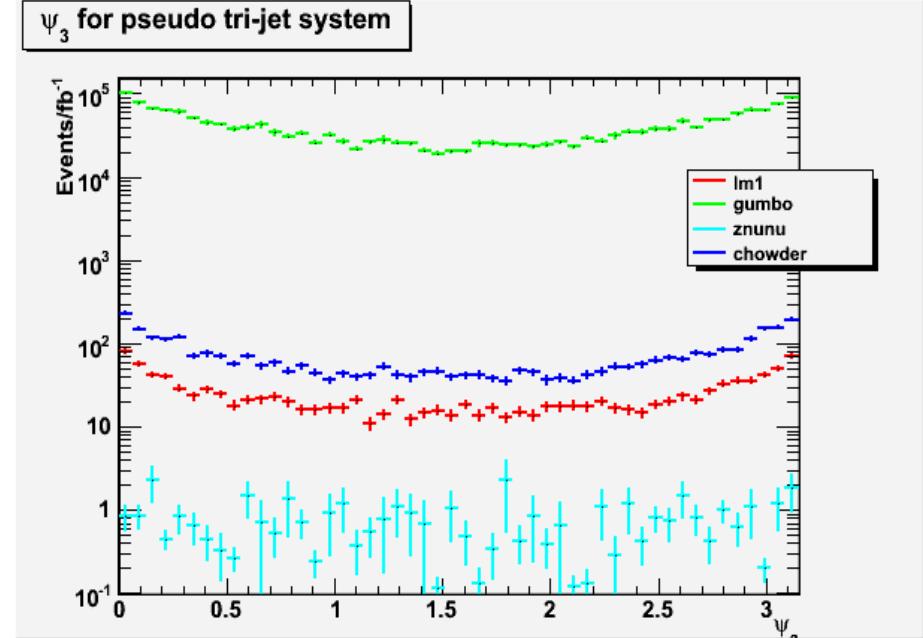
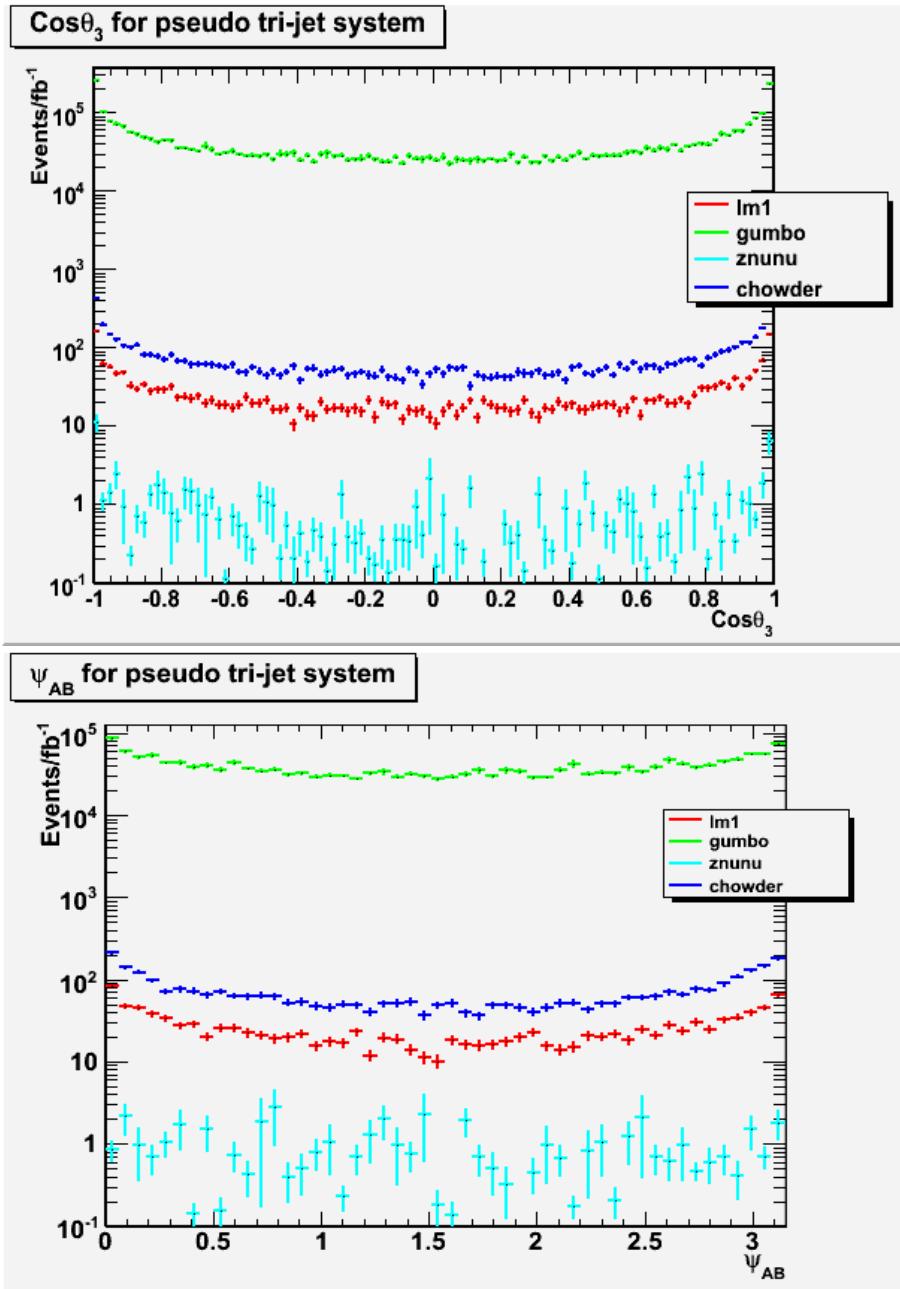
# 4-Jet Kinematic Variables



$$X_{i'} = \frac{2E_{i'}}{M_{3J}}$$

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow \nu\nu$
chowder	$t\bar{t} + \text{jets}, W + \text{jets}, Z + \text{jets}$

# 4-Jet Kinematic Variables



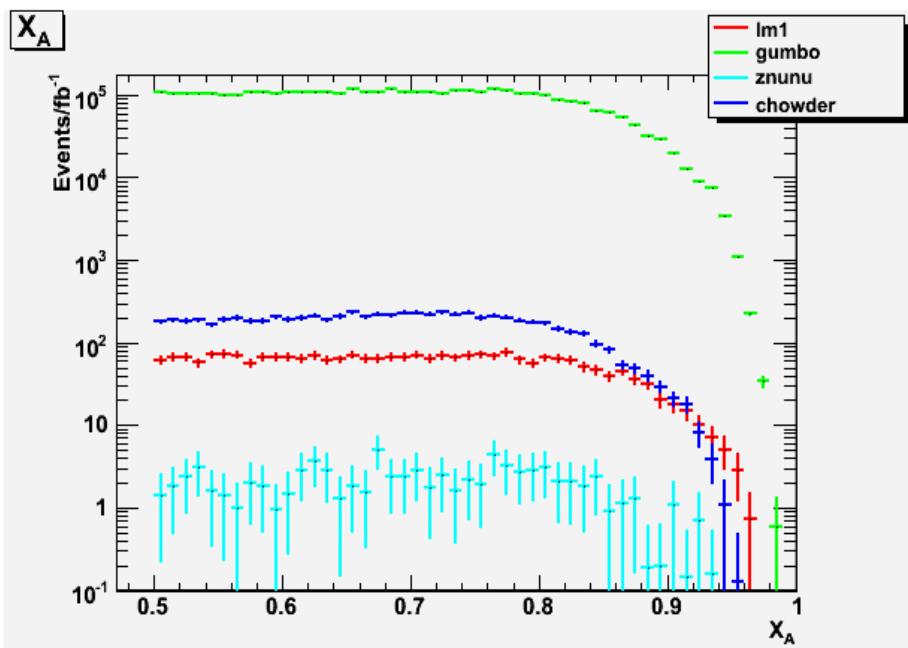
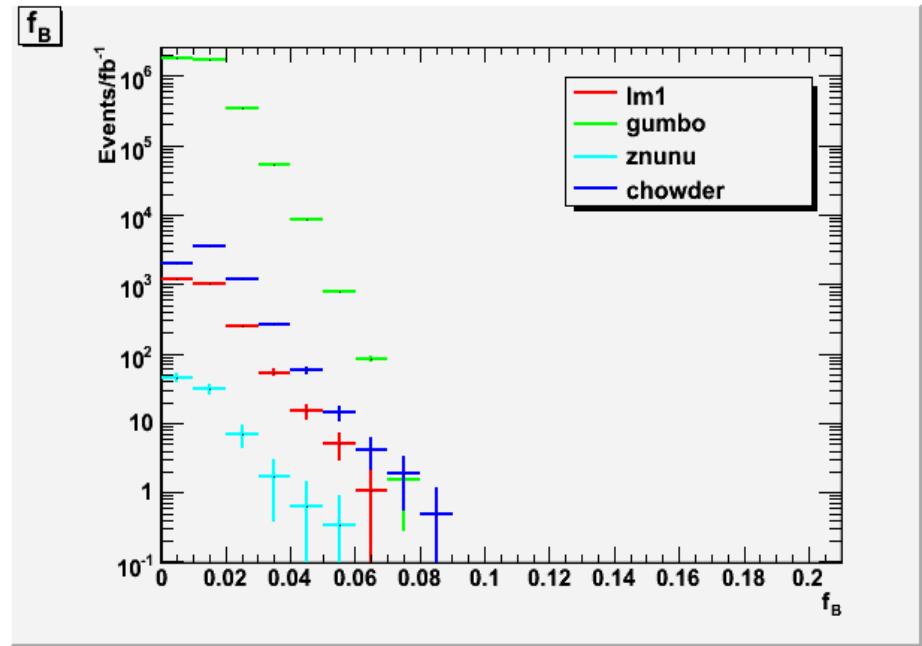
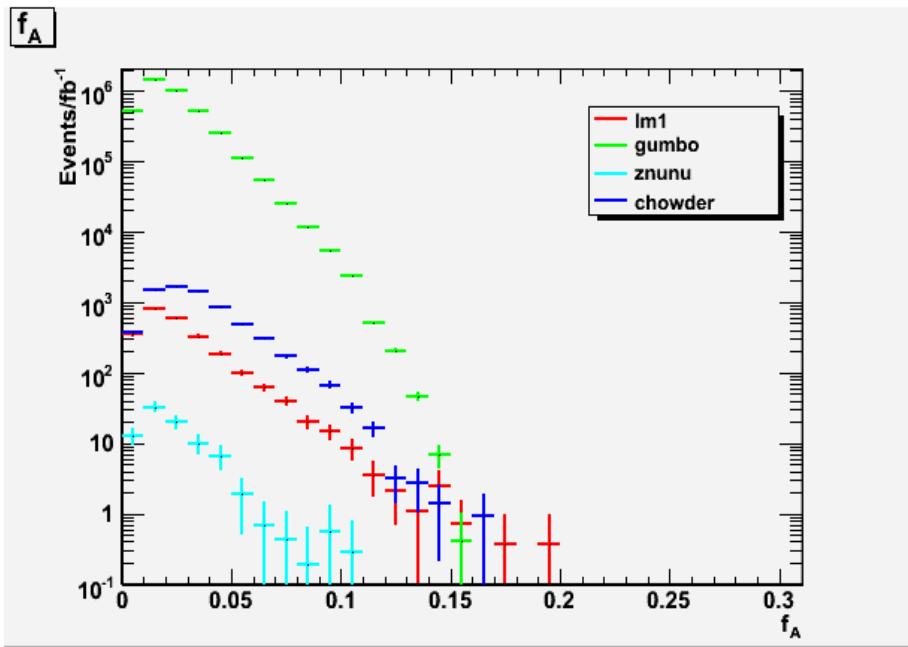
$\cos \theta_3$  Angle between the beam direction and  
The hardest jet

$$\cos \Psi_3 = \frac{(\vec{P}_3 \times \vec{P}_{\text{av.}}) \cdot (\vec{P}_4 \times \vec{P}_5)}{(\vec{P}_3 \times \vec{P}_{\text{av.}})(\vec{P}_4 \times \vec{P}_5)}$$

lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow vv$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

$$\cos \Psi_{AB} = \frac{(\vec{P}_A \times \vec{P}_B) \cdot (\vec{P}_{AB} \times \vec{P}_{\text{av.}})}{(\vec{P}_A \times \vec{P}_B)(\vec{P}_{AB} \times \vec{P}_{\text{av.}})}$$

# 4-Jet Kinematic Variables

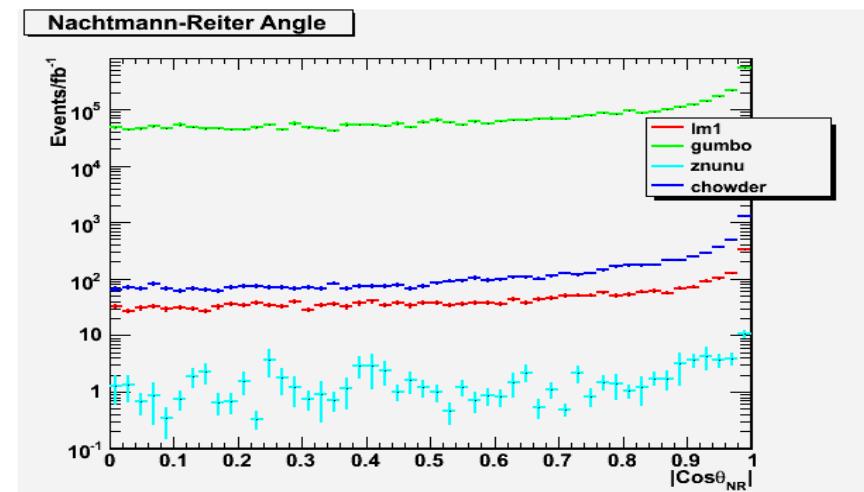
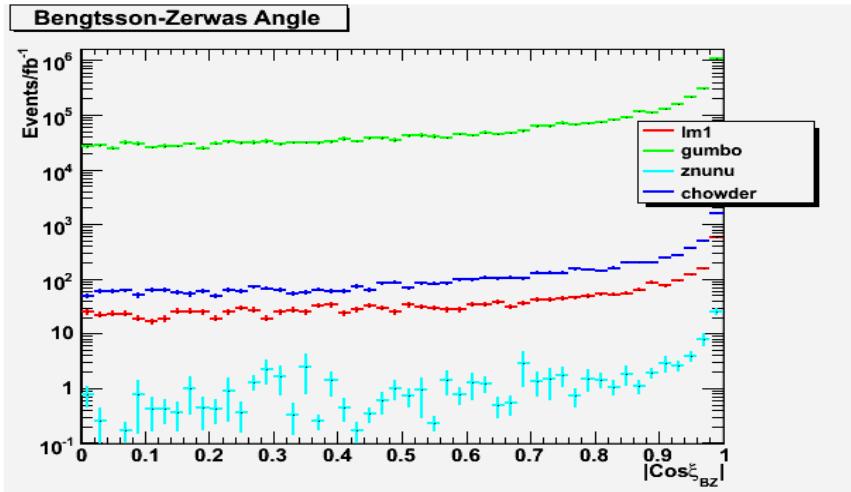


$$f_i = \frac{m_i}{M_{3J}}$$

$$X_A \equiv \frac{E_A}{E_A + E_B}$$

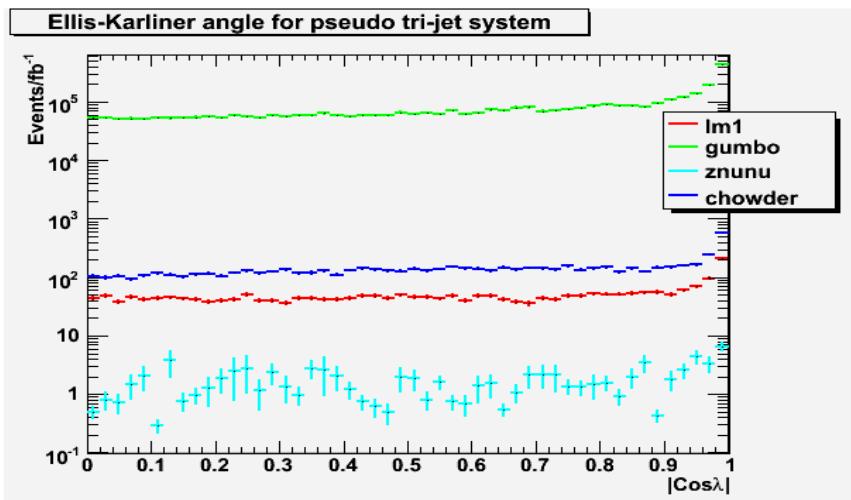
lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

# 4-Jet Kinematic Variables



$$\cos \chi_{BZ} = \frac{(\vec{p}_3 \times \vec{p}_4) \cdot (\vec{p}_5 \times \vec{p}_6)}{(\vec{p}_3 \times \vec{p}_4)(\vec{p}_5 \times \vec{p}_6)}$$

$$\cos \theta_{NR} = \frac{(\vec{p}_3 - \vec{p}_4) \cdot (\vec{p}_5 - \vec{p}_6)}{(\vec{p}_3 - \vec{p}_4)(\vec{p}_5 - \vec{p}_6)}$$



lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow \nu\nu$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

$\lambda$  Angle between the two highest energy jets that result in boost in highest E jet direction.

## Higher Jet Multiplicities

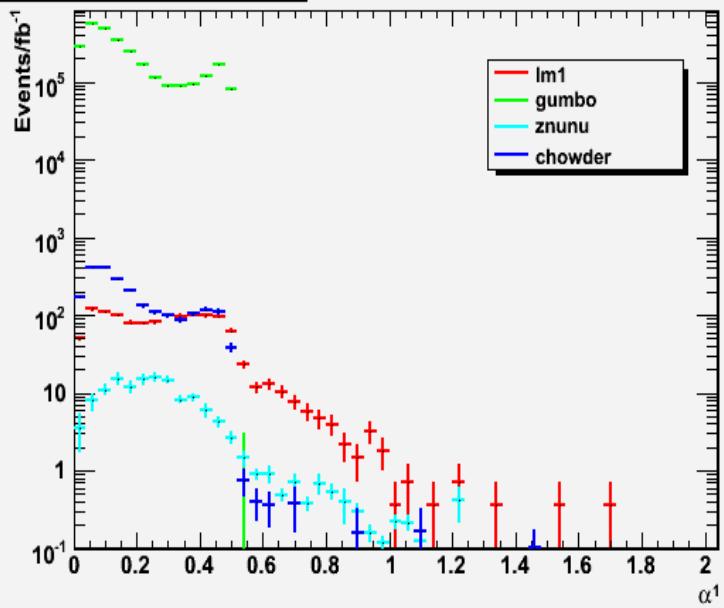
Higher jet multiplicities are reduced to a pseudo-tri-jet system by combining smallest mass dijets into a single jet successively.( e.g. see Phys. Rev. D 53, 4793 - 4805 (1996))

But no significant sample type discrimination from multijet kinematic variables (so far). In order to reduce this more complicated scenario into a form that can be studied more easily I will use the following jet reductions and calculate  $\alpha$  and  $\alpha_t$  for the resulting pseudo-dijet system.

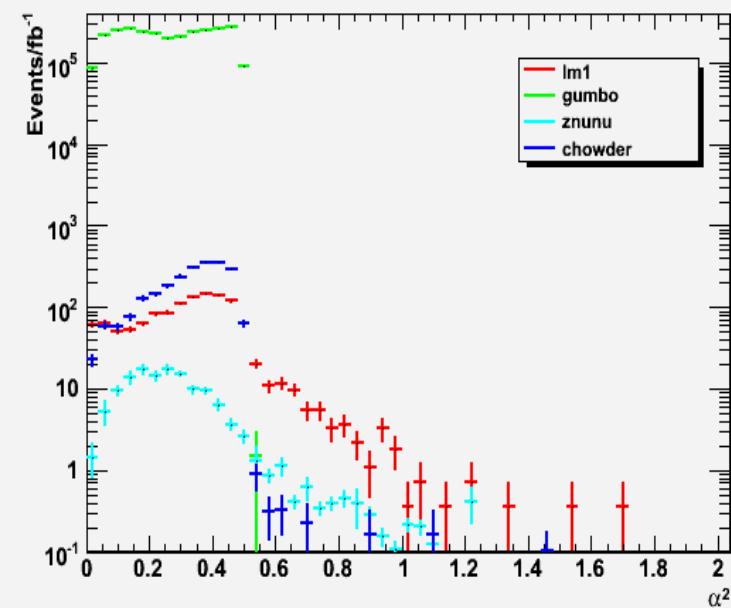
1. Combine lowest  $E_t$  dijets.
2. Combine smallest mass dijets.
3. Combine lowest  $E$  dijets.

# Higher Jet Multiplicities

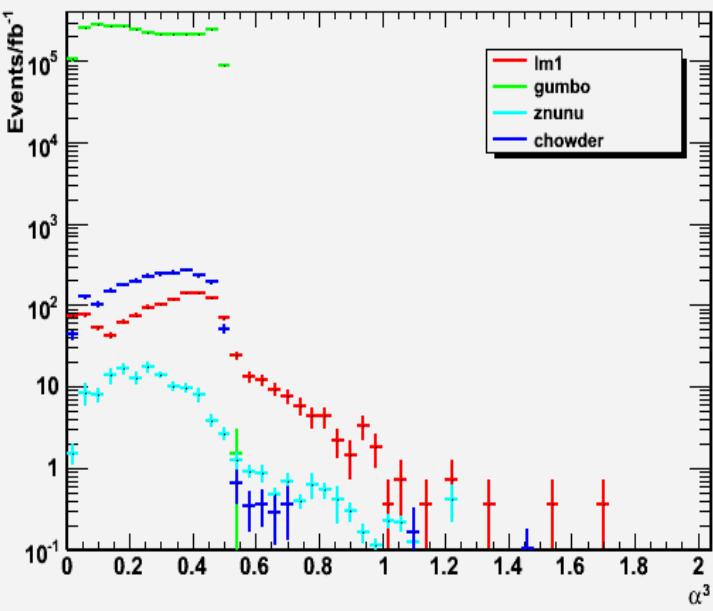
$\alpha^1$  (lowest  $E_t$  combined)



$\alpha^2$  (smallest mass combined)

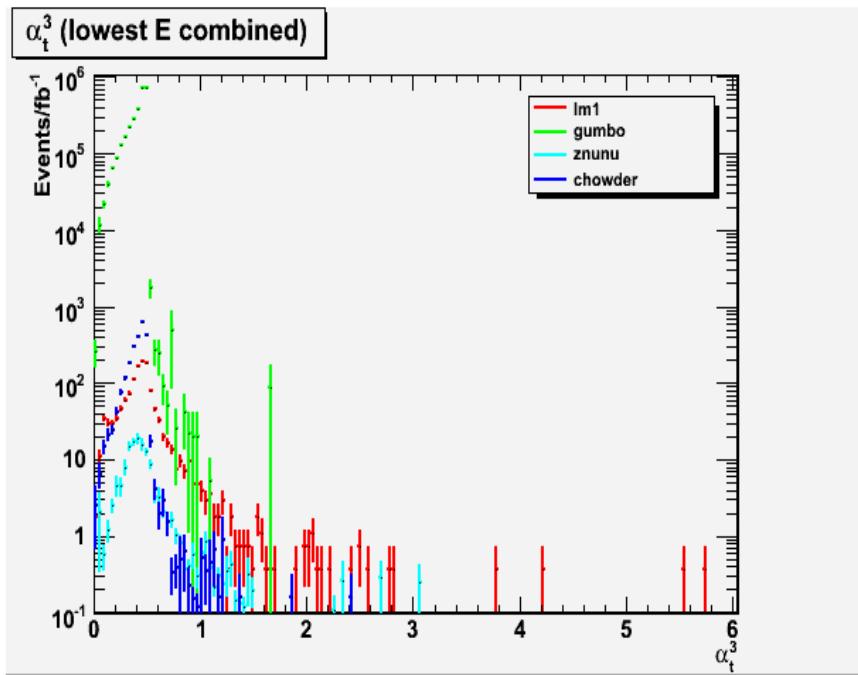
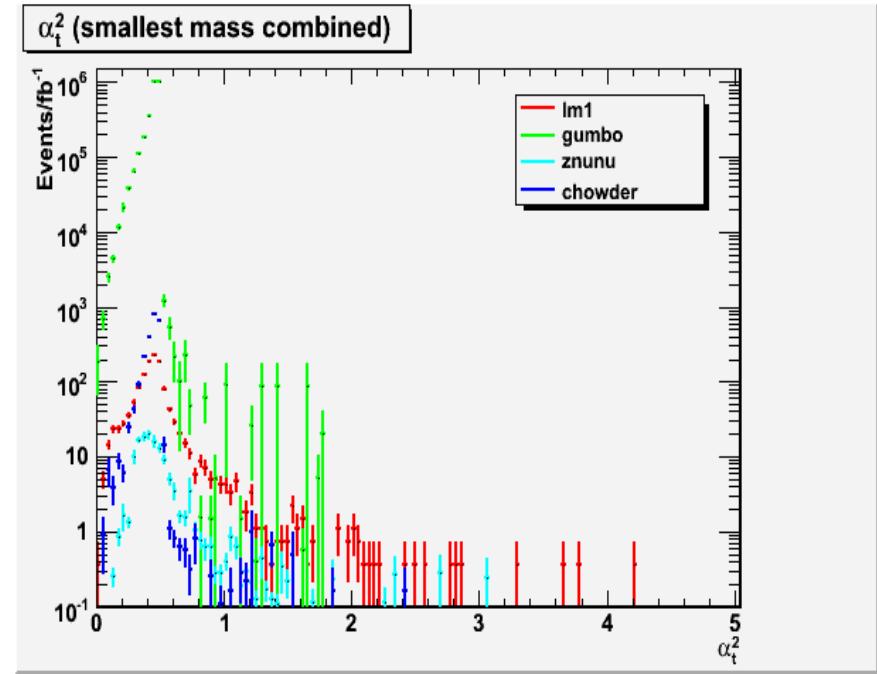
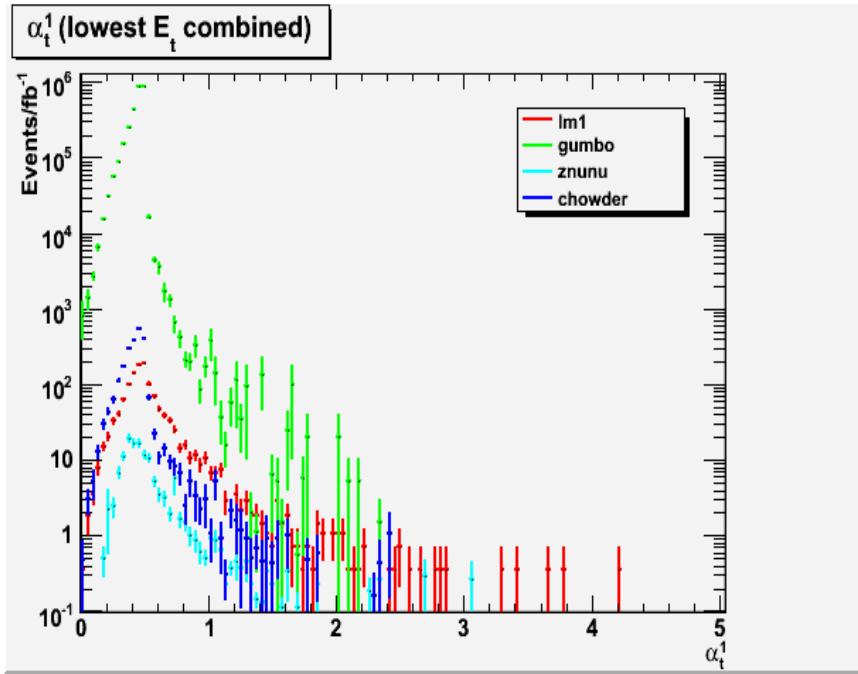


$\alpha^3$  (lowest  $E_t$  combined)



lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

# Higher Jet Multiplicities



lm1	<i>SUSY LM1</i>
gumbo	<i>QCD</i>
znunu	$Z \rightarrow VV$
chowder	$t\bar{t} + jets, W+jets, Z+jets$

# Conclusions

I will

- ★ continue exploring kinematic variables associated with multijets and validate SM QCD predictions,
- ★ try to extract useful information to be used in new Physics Searches.

# Appendix

## Event Selection Cuts

- Require HLT2Jet trigger
- Require jet  $p_t > 50 \text{ GeV}$  and EM fraction  $< 0.9$
- Leading jet: Require  $|\eta| < 2.5$
- Jets: Reject event if angular distance to missing  $E_t > 0.3 \text{ rad}$  and  $E_t > 30 \text{ GeV}$
- Leptons: Require  $p_t < 10 \text{ GeV}$
- Total hadronic  $p_t > 500 \text{ GeV}$