SUSY Multilepton Searches at ATLAS

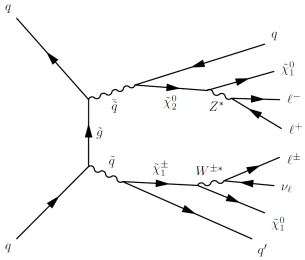
Jet Goodson

On behalf of the
ATLAS Collaboration
&
Stony Brook University

10 August, 2011

- Depending on model of SUSY, $\tilde{\chi}_i^0$ & $\tilde{\chi}_j^{\pm}$ potentially produced in abundance in pp-collisions at the LHC
- Leptonic decay possible through either gauge bosons or $\tilde{\ell}$, and potentially final states with multiple leptons ($\geq$3 for our purposes)
- See figure on slide for an example of multilepton SUSY production

- Multilepton state should make the SUSY signal stand out strongly from most Standard Model backgorunds, making the multilepton channel a strong candidate for interesting measurements



This analysis was made on the 2010 $\sqrt{s} = 7$ TeV pp-collision data collected by the ATLAS detector between 30 March 2010 and 29 October 2010, representing an integrated luminosity of 34 pb^{-1} ($\pm$11%)

ATLAS-CONF-2011-039

Event Selection in 2010 Data

Quality Cuts:

- Pass a good runs list based on quality criteria for ATLAS sub-detectors
- Primary Vertex must have $\geq$4 tracks associated with it
- (data only) Events are cut if they contain a 'bad jet' — energy mimicking jets due to EM calorimeter noise, hadronic calorimeter spikes, cosmic-rays, and beam background
- Cosmic Muons — Veto events with $|Z_0^{PV}| >$10 mm
- Veto on events with electrons reconstructed in $1.37 < |\eta| < 1.52$ due poor instrumentation in transition region of Liquid Argon detector

Triggers:

- Single electron or muon triggers without pre-scaling

Signal Cuts:

- At least 3 signal electrons & muons, with the leading two leptons $p_T > 20$ GeV
- Require at least 2 jets with $p_T > 50\ \mathrm{GeV}$
- Veto events with $|M_Z - M_{l^+,l^-}| <$5 GeV to control Z backgrounds
- $E_\mathrm{T}^\mathrm{miss} >$50 GeV

(please see our note, ATLAS-CONF-2011-039 for detailed discussion including object selection)

Systematics

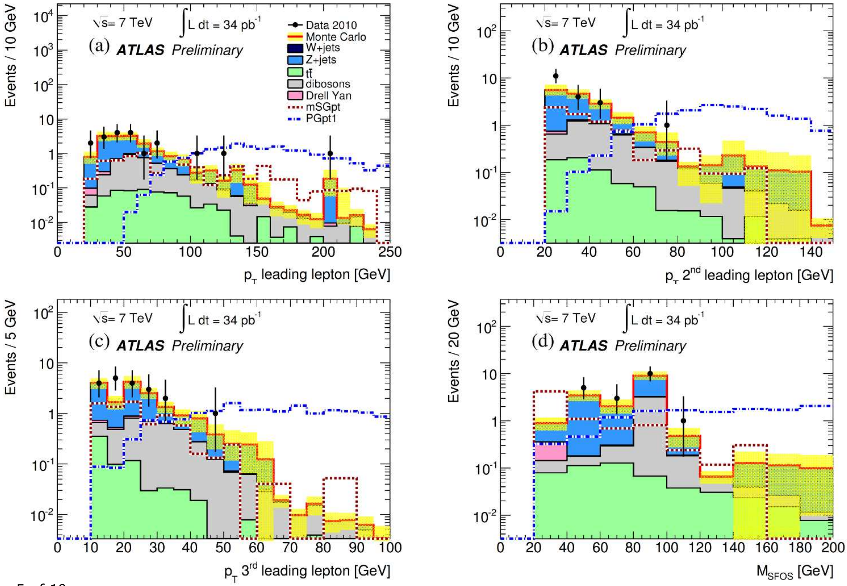
The following systematics have been considered in the analysis and found to be dominant (% change in event count)

- Jet energy scale ($\sim$12%)
- Electron energy scale ($\sim$20%)
- Electron energy resolution ($\sim$10%)
- Pile-up ($\sim$20%)
- MC cross-section uncertainty ($\sim$10%)

Other systematics examined but found not dominant were:

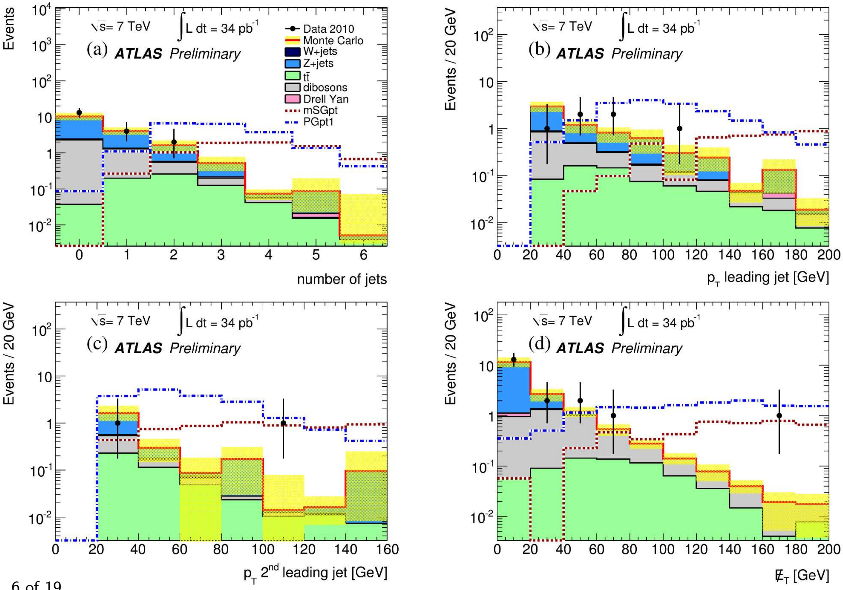
- Jet energy resolution
- muon energy resolution
- muon energy scale
- lepton reconstruction efficiencies
- lepton trigger efficiencies
- parton density function (PDF) uncertainty
- Effects due to inefficient regions of the electromagnetic calorimeter

Yellow error bars are statistical $\oplus$ systematic uncertainties



Jets & E_T^{miss} after $N_l \geq 3$ Cut

Yellow error bars are statistical $\oplus$ systematic uncertainties

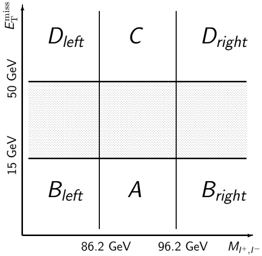


Z+jets Background Estimation

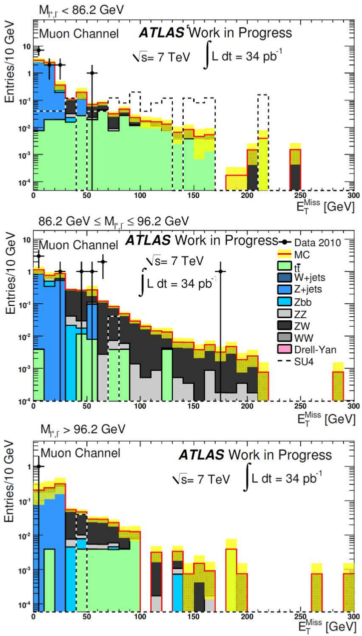
For 2010 data attempted to use a sideband method to estimate Z+jets contribution (which necessitated the $|M_Z - M_{l^+,l^-}| < 5$ GeV cut)

$$D^{Est}_{left} = B^{Data}_{left} \left(\frac{C^{Data}}{A^{Data}}\right)\left(\frac{D^{MC}_{left}}{B^{MC}_{left}}\right)\left(\frac{A^{MC}}{C^{MC}}\right) \quad (1)$$

$$D^{Est}_{right} = B^{Data}_{right} \left(\frac{C^{Data}}{A^{Data}}\right)\left(\frac{D^{MC}_{right}}{B^{MC}_{right}}\right)\left(\frac{A^{MC}}{C^{MC}}\right) \quad (2)$$



- Few events landed in region C (only muons, no electrons)
  Determined that the uncertainty of the method would only fall below 100% with over 120 pb^{-1} of data
- Below 50% after nearly 500 pb^{-1}.
- Opted to continue to use MC till a better method developed



Results for 2010

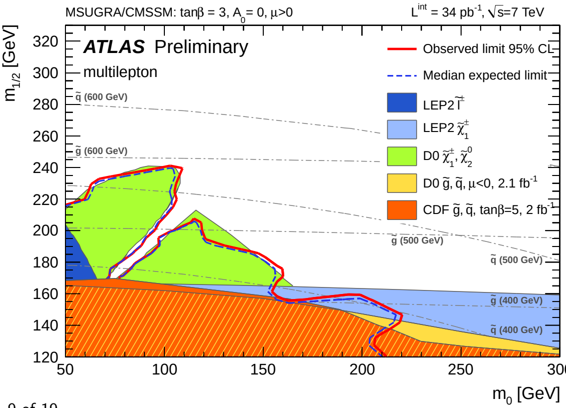
Results for data and Standard Monte Carlo after the $N_l \geq 3$ Cut (no jet cuts, $|M_Z - M_{l^+,l^-}| < 5$ GeV cut, or E_T^{miss} applied)

ATLAS Preliminary

Multilep. events	All	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$t\bar{t}$	0.68±0.16	0.032±0.016	0.24±0.07	0.31±0.08	0.096±0.030
Z backgrounds	15.6±1.3	3.8±0.8	1.60±0.34	7.9±1.0	2.4±0.4
Other backgrounds	0.28±0.13	0.02±0.14	0.03±0.06	0.21±0.09	0.01±0.11
Total SM	16.6±1.3	3.8±0.8	1.9±0.4	8.4±1.0	2.5±0.4
Data	19	2	1	10	6

- No events with 4 leptons above p_T thresholds
- 10 events pass $|M_Z - M_{l^+,l^-}| < 5$ GeV cut, but fail jet cuts
- 3 events have $E_T^{miss} > 50$ GeV, but fail the jets or $|M_Z - M_{l^+,l^-}| < 5$ GeV cut
- No events pass all of our selection cuts; these cuts reduce the Standard Model background to $\sim$0.1 events
- 95% C.L. limit of 62 fb on cross-section$\times$branching ratio$\times$ acceptance of new physics with $3\ell+$ jets $+E_T^{miss}$

- Use common mSUGRA model constraints used to simplify to 5 parameters, m_0, $m_{1/2}$, A_0, $tan\beta$, sign(μ)
- We use $\tan\beta = 3$, $A_0 = 0$ $\mu > 0$
- $m_0 \in (40, 1160)$ GeV $\times$ $m_{1/2} \in (110, 340)$ GeV
- Interpreted in $m_0 - m_{1/2}$ plane
- Exclusions preformed using a profile-likelihood ratio method laid out at arXiv:1102.5290v1



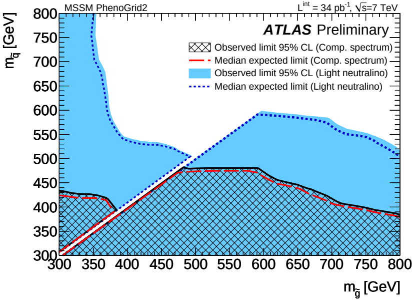
MSSM Phenomenological Grids

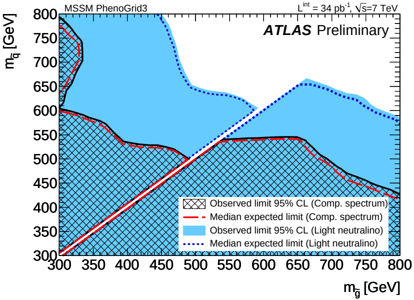
- 1st Phenomenological Grid
- Based on MSSM 24 parameters, without mass constraints of mSUGRA
- LSP bino-like, $\tilde{\chi}_2^0$ & $\tilde{\chi}_1^\pm$ wino-like
- 3rd generation scalers placed at high mass, excluding them from phenomonology
- $m_{\tilde{\ell}}$ placed in between LSP & $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$, increasing lepton signatures
- Two modes:
  - Compressed spectrum, with heavier LSP
  - Broad spectrum, with light LSP$\sim$100 GeV

- 2nd Phenomenological Grid
  - Similar to first, but $m_{\tilde{\ell}_\mathrm{R}}$ inceased to higher mass
  - Increases favorability of leptonic decays
  - Reduced cross section
- Both interpreted in $m_{\tilde{g}} - m_{\tilde{q}}$ plane

MSSM Phenomenological Grids — Results

- 1st Phenomenological Grid at top right
- 2nd Phenomenological Grid at bottom right
- Empty strip at $m_{\tilde{g}} = m_{\tilde{q}}$ due to change in leptonic branching ratios — $m_{\tilde{g}} > m_{\tilde{q}}$ hadronic $\tilde{g}$ decay dominates
- For $m_{\tilde{g}} = m_{\tilde{q}} + 10$ place limit on $m_{\tilde{q}}$ of 480 (600) GeV in compressed spectrum (light neutralino) for 1st grid
  For 2nd Grid place limit on $m_{\tilde{q}}$ of 540 (670) GeV in compressed spectrum (light neutralino)





Improvements for 2011 Analysis

Currently being prepared for SUSY11 Changes to object defs:

- Electron selection of $p_T >$10 GeV due to better understanding of electron scale and resolution systematics
- Jets expanded to $|\eta| < 2.8$ due to better understanding of systematics in that region

Changes to event selection:

- Jet cuts no longer applied as default
- $|M_Z - M_{l^+,l^-}| <$5 GeV cut no longer applied as default

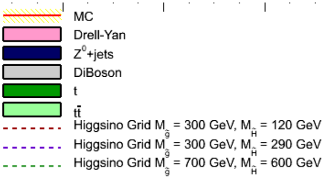
The changes to the event selection cuts are intended to give us greater flexibility for differing SUSY scenarios by instead determining control regions for looking for signals with or without strong jets, or that include (or exclude) Zs in SUSY decays, or with larger numbers of leptons than the default $\geq$3 lepton cut

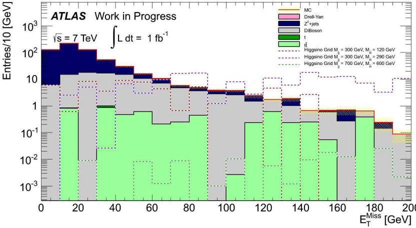
General Gauge Mediation Models

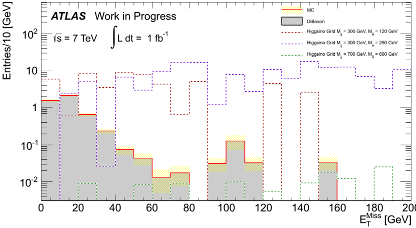
- Example of SUSY where the SM gauge interactions cause supersymmetry breaking
- Lack of hierarchy between colored & non-colored states giving way to large cross-sections
- Interested in two simple examples — both have gravitino for LSP
  - Higgsino Grid — NLSP is $\tilde{H}$-like and decays to $\gamma\tilde{G}$ or $Z\tilde{G}$ (available)
  - Wino Grid — Co-NLSPs are Wino-like (charged and neutral) and decays to $W\tilde{G}$ or $Z\tilde{G}$ (under production)
- Both scenarios give rise to decays through Z that can result in $Z \to \ell^+\ell^-$, making the multilepton channel a promising avenue to examining this theory

Higgsino Grid — Early Studies — E_T^{miss}

- Require $N_l \geq 3$, $p_{T,\ell} > 10$ GeV
- Other selections match updated to 2011 analysis
- Top plot requires one (and only one) Z determined by $|M_Z - M_{l^+,l^-}| < 10$ GeV
- Bottom plot requires two (and only two) Zs determined by $|M_Z - M_{l^+,l^-}| < 10$ GeV

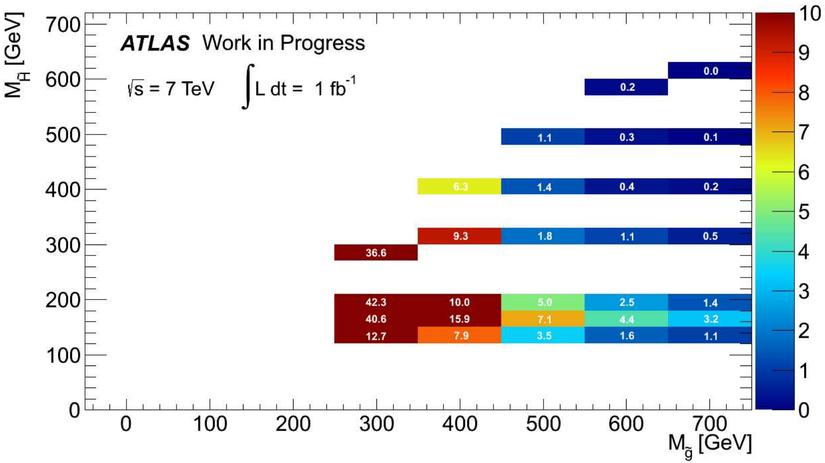






- Require $N_l \geq 3$, $p_{T,\ell} > 10\ \mathrm{GeV}$
- Other selections match updated to 2011 analysis
- Plot on next slide requires one (and only one) Z determined by $|M_Z - M_{l^+,l^-}|$ <10 GeV
- Plot on slide following next requires two (and only two) Zs determined by $|M_Z - M_{l^+,l^-}|$ <10 GeV
- Both plots require $E_{\mathrm{T}}^{\mathrm{miss}}$ >50 GeV
- Significance, $Z_{llr} = \sqrt{2((S+B)ln[1+\frac{S}{B}] - S)}$
- Preliminary results quite promising

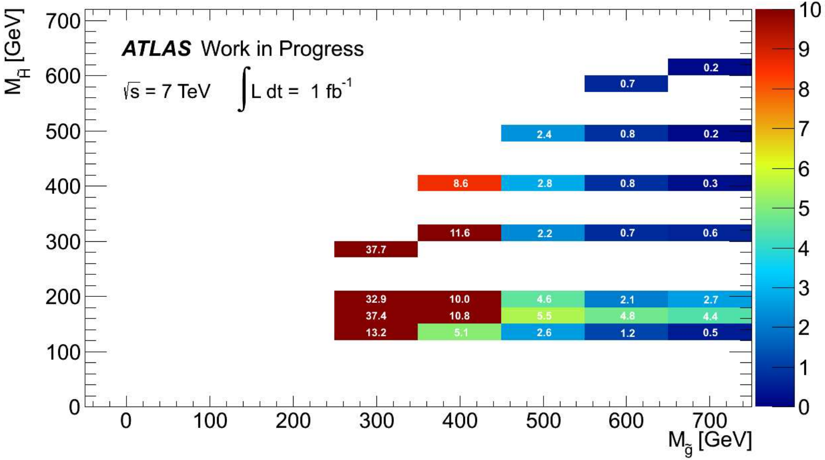
Higgsino Grid — Early Studies — Significance



Calculation limited to statistical significance at this juncture — no systematics

Requiring $N_Z == 1$

Higgsino Grid — Early Studies — Significance



Calculation limited to statistical significance at this juncture — no systematics

Requiring $N_Z == 2$

Z+jets Background Estimation

For 2011, developing matrix method:

- Tag dilepton events with Z-candle and use matrix method to estimate 3rd lepton from QCD component
- Use isolation as efficiency variable (loose leptons = no isolation, tight = isolated)
- $N_{loose} = N_{EW} + N_{QCD}$, $N_{iso} = \epsilon_{EW} N_{ew} + \epsilon_{QCD} N_{QCD}$
- Results in $N_{iso}^{QCD} = \frac{N_{non-iso} - (1/\epsilon_{EW} - 1) N_{iso}}{1/\epsilon_{EW} + 1/\epsilon_{QCD}}$
- For QCD, use control region based on jet trigger, $E_{\mathrm{T}}^{\mathrm{miss}} < 10$ GeV and cuts against Z & W
- For EW, use tag & probe method from $Z \to \ell^+\ell^-$ in $E_{\mathrm{T}}^{\mathrm{miss}} < 10$ GeV region
- Events with two tight leptons forming Z-candidates in $E_{\mathrm{T}}^{\mathrm{miss}}$ signal region are used for final estimate, applying matrix method to loose leptons in event
- Allows removal of Z-veto, which allows for SUSY scenarios where decays proceed through Z

Conclusion

- 2010 run produced no events passing our full selection
- Limits set for mSUGRA are in agreement with those observed at other experiments
- Additional limits set for less constrained MSSM models
- Analysis group making changes for 2011 summer analysis to improve flexibility and scope
- Investigating additional SUSY models for 2011
- Improving background estimation

Object Selection in 2010 Data

- Electrons
  - $p_T > 20$ GeV
  - $|\eta_{cl}| < 2.47$
  - Various quality cuts based on shower shape, inner detector hits, and inefficient regions of ATLAS
  - MC events re-scaled to match efficiency seen in data
- Muons
  - $p_T > 10$ GeV
  - $|\eta| < 2.4$
  - Quality cuts on ID hits and ID/MS agreement
  - Muons must be combined from inner detector and muon spectromer tracks or from an inner detector track paired with muon spectrometer hits or calorimeter energy
- Jets
  - Reconstructed with anti-k_T algorithm using $\Delta R = 0.4$ cone size
  - MC-optimized jet-energy scale applied
  - $p_T > 20$ GeV
  - $|\eta| < 2.5$

Object Selection in 2010 Data (continued...)

- Overlap
  - Remove jets within $\Delta R < 0.2$ of electron
  - Then remove muons & electrons within $\Delta R < 0.4$ of jet
  - In case of $\Delta R_{\mu,e} < 0.1$ remove both electron & muon to eleminate muons undergoing bremsstrahlung
- After overlap — lepton isolation
  - Signal Electrons — Calorimeter isolation: ΣE_T in cone $\Delta R = \sqrt{(\Delta n)^2 + (\Delta\phi)^2} < 0.2$ divided by p_T of the electron required to be less than 0.15 (after overlap removal)
  - Signal Muons — The sum of track $p_T > 1$ GeV within $\Delta R = \sqrt{(\Delta n)^2 + (\Delta\phi)^2} < 0.2$ of the muon must be < 1.8 GeV
- Drell-Yan — Remove charged lepton pairs $M_{l^+,l^-} < 20$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} \rightarrow E_{\mathrm{x(y)}}^{\mathrm{miss}} = E_{\mathrm{x(y)}}^{\mathrm{miss,e}} + E_{\mathrm{x(y)}}^{\mathrm{miss,jets}} + E_{\mathrm{x(y)}}^{\mathrm{miss,cl}} + E_{\mathrm{x(y)}}^{\mathrm{miss},\mu}$
  - $E_{\mathrm{x(y)}}^{\mathrm{miss,e}}$ built from electrons passing reconstruction quality cuts and $p_T >$10 GeV
  - $E_{\mathrm{x(y)}}^{\mathrm{miss,jets}}$ built from jets with $p_T >$20 GeV and jet-energy scale applied
  - $E_{\mathrm{x(y)}}^{\mathrm{miss,cl}}$ built from all EM-scale topoclusters not associated with an electron or jet
  - $E_{\mathrm{x(y)}}^{\mathrm{miss},\mu}$ built from all muons without isolation requirements applied

Backup - Jet Cleaning

Quality cuts based on anti-$k_T(R = 0.4)$ algorithm jets. For jets with $p_T^{emscale} > 10GeV$, if:

- HEC Noise Bursts, event rejected if:
  $\frac{E^{jet,HEC}}{E^{jet}} > 0.8$ AND $N_{cells}(\sum_{N_{cells}} E_{cell} >= 0.9E^{jet}) < 6$
  OR $\frac{E^{jet,HEC}}{E^{jet}} > 0.5$ AND $|\frac{\sum_{problem\ cells} E_{cell}^{jet,LAr}}{E^{jet,LAr}}| >= 0.8$
- EM Noise Bursts, event rejected if:
  $|\frac{\sum_{problem\ cells} E_{cell}^{jet,LAr}}{E^{jet,LAr}}| >= 0.8$ AND $\frac{E^{jet,LAr}}{E^{jet}} >= 0.95$
- Cosmics-Beam background:
  $|t^{jet} - t_{avg}^{event}| > 25\ ns$
  OR $\frac{E^{jet,LAr}}{E^{jet}} < 0.05$
  OR $|\eta_{jet}| < 2$ AND $\frac{E_{maxsamplinglayer}^{jet}}{E^{jet}} > 0.99$

Backup - 2010 Monte Carlo

Below is the Monte Carlo used in the 2010 analysis including generator used, NLO cross-sections (including filter efficiencies and k-factors, LO for DiJet QCD), and the integrated luminosity each sample represents

Process	Generator	σ [pb]	$\int \mathcal{L}dt$ [fb^{-1}]
SU4	Herwig++	59.95	0.8
mSGpt	Herwig++	24.74	0.4
PGpt1	Herwig++	6.19	1.6
PGpt2	Herwig++	6.19	1.6
$t\bar{t}$	MC NLO	89.40	8.6
ZZ	Herwig	1.27	197.4
ZW	Herwig	5.55	45.0
WW	Herwig	17.44	14.3

QCD dijet samples generated by Pythia, with LO cross-section			
Process	p_T slice [GeV]	σ [pb]	$\int \mathcal{L}dt$ [fb^{-1}]
J0	8-17	9.75×10^{9}	1.44×10^{-7}
J1	17-35	6.73×10^{8}	2.1×10^{-6}
J2	35-70	4.12×10^{7}	3.4×10^{-5}
J3	70-140	2.19×10^{6}	6.4×10^{-4}
J4	140-280	8.78×10^{4}	1.6×10^{-2}
J5	280-560	2.23×10^{3}	0.6
J6	560-1120	33.85	39.8
BBbar	-	2.02×10^{3}	0.1
CCbar	-	1.60×10^{3}	0.2

For 2011, the Higgsino grid was produced using pythia
Also added MC NLO single top MC

Below is the Monte Carlo used in the 2010 analysis for $W/Z + \mathrm{jets}$, *Wbb*, *Zbb* & Drell-Yan channels

Process		σ [pb]	$\int \mathcal{L}dt$ [fb^{-1}]	Process		σ [pb]	$\int \mathcal{L}dt$ [fb^{-1}]
6*Z+jets	($\ell\ell$+Np0)	830.13	0.4	6*W+jets	($\ell\nu$+Np0)	8288.15	0.2
	($\ell\ell$+Np1)	166.24	0.4		($\ell\nu$+Np1)	1550.14	0.2
	($\ell\ell$+Np2)	50.28	0.4		($\ell\nu$+Np2)	452.09	0.4
	($\ell\ell$+Np3)	13.92	0.4		($\ell\nu$+Np3)	120.97	0.4
	($\ell\ell$+Np4)	3.62	0.4		($\ell\nu$+Np4)	30.33	0.4
	($\ell\ell$+Np5)	0.94	0.5		($\ell\nu$+Np5)	8.27	0.4
4**Zbb*	(*ee*+Np0)	6.52	23.0	4**Zbb*	($\mu\mu$+Np0)	6.53	23.0
	(*ee*+Np1)	2.25	44.5		($\mu\mu$+Np1)	2.47	40.5
	(*ee*+Np2)	0.88	45.4		($\mu\mu$+Np2)	0.88	45.3
	(*ee*+Np3)	0.39	25.7		($\mu\mu$+Np3)	0.39	25.9
4**Zbb*	($\tau\tau$+Np0)	6.53	23.0	4**Wbb*	(W+Np0)	3.90	1.7
	($\tau\tau$+Np1)	2.48	40.3		(W+Np1)	3.17	1.7
	($\tau\tau$+Np2)	0.88	45.3		(W+Np2)	1.71	1.8
	($\tau\tau$+Np3)	0.39	25.6		(W+Np3)	0.73	2.0
6*Drell-Yan	(*ee*+Np0)	3054.70	0.3	6*Drell-Yan	($\mu\mu$+Np0)	3054.90	0.3
	(*ee*+Np1)	84.91	3.5		($\mu\mu$+Np1)	84.78	3.5
	(*ee*+Np2)	41.19	12.1		($\mu\mu$+Np2)	41.13	12.1
	(*ee*+Np3)	8.35	17.9		($\mu\mu$+Np3)	8.34	17.9
	(*ee*+Np4)	1.85	21.6		($\mu\mu$+Np4)	1.87	21.4
	(*ee*+Np5)	0.46	21.7		($\mu\mu$+Np5)	0.46	21.7
6*Drell-Yan	($\tau\tau$+Np0)	3054.80	0.3				
	($\tau\tau$+Np1)	84.88	3.5				
	($\tau\tau$+Np2)	41.28	12.1				
	($\tau\tau$+Np3)	8.35	17.9				
	($\tau\tau$+Np4)	1.83	21.9				
	($\tau\tau$+Np5)	0.46	21.7				

The Interesting Event

- Run: 165591, Event: 15545300
- 3 leptons, $P_T^{\mu^-} = 209.8$ GeV, $P_T^{e^+} = 49.6$ GeV, $P_T^{\mu^+} = 16.5$ GeV
- $\phi = (-2.07, 1.48, 2.46)$, $\eta = (-0.73, -2.01, -0.24)$
  item1 jet, $p_T^{jet} = 75.1$ GeV
- Lead muon pt isolation ($\delta R = .2$) = 0 GeV
- Lead muon energy isolation ($\delta R = .2$) = 2.8 GeV
- Lead muon $\chi^2_{match}/DOF = 3.03/5$
- Lead muon p_{T} resolution = 3.8%
- Lead Muon Pixel hits = 3
- Lead Muon SCT hits = 10
- Lead muon TRT hits = 24
- Lead Muon MDT hits = 14
- $p_{exPV}^{ID} = 299.7$ GeV, $p_{exPV}^{MS} = 219.6$ GeV
- Track p = 268.6 GeV
- $Z_0^{exPV} = 0.087$ mm
- d_0 = -0.35 mm
- $E_{\mathrm{T}}^{\mathrm{miss}} = 170.7$ GeV, $Simp\ Sig_{E_{\mathrm{T}}^{\mathrm{miss}}} = 25.8$, $Sig_{E_{\mathrm{T}}^{\mathrm{miss}}} = 63.9$, $\phi_{E_{\mathrm{T}}^{\mathrm{miss}}} = 1.28$
- Using $Simp\ Sig_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}}/\Sigma E_{\mathrm{T}}$ and $Sig_{E_{\mathrm{T}}^{\mathrm{miss}}} = E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{\sum_{i=1}^{N} \sigma_i^2 \cos^2(\Delta\phi_i)}$
- Channels with negligible $E_{\mathrm{T}}^{\mathrm{miss}}$ (e.g., Z+jets) typically display $E_{\mathrm{T}}^{\mathrm{miss}}$-signiciance <10 for either measure
- $\Delta\phi_{E_{\mathrm{T}}^{\mathrm{miss}}, l_0} = 3.35$

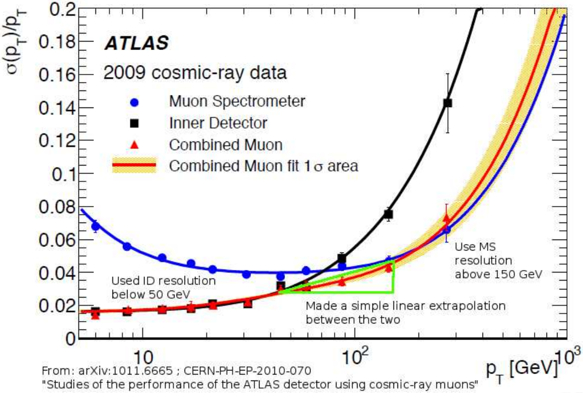
Object Resolutions & Comments for E_T^{miss} Sig

Now where do I get the resolutions?

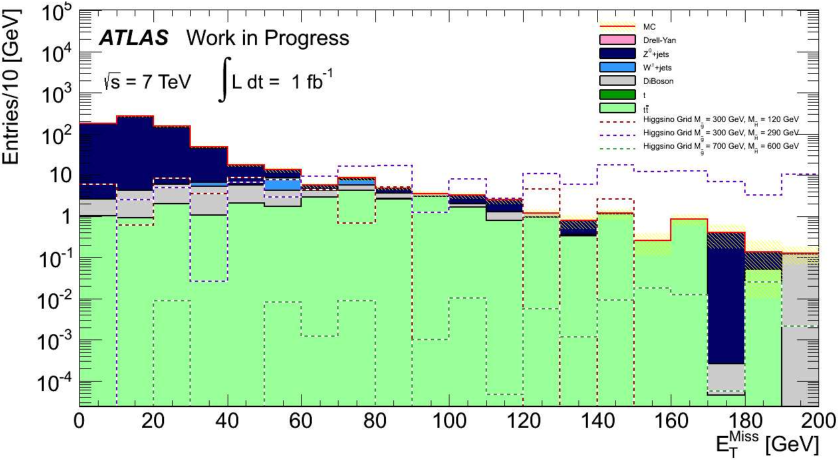
- Electron/Cluster Resolution — $\sigma_E/E = s/\sqrt{E} \oplus c$

  (similar to systematic);
  - sampling term 20%
  - constant term 100% for $0 < |\eta| < 1.4$
  - constant term 400% for $1.4 < |\eta| < 2.5$
- Jet Resolution — Using JERPRovider tool from JetEtMissWG
- Muon Resolution — cannibalizing muon smearing tool provided by MuonWG guided by ATLAS-COM-CONF-2011-003 & CERN-PH-EP-2010-070

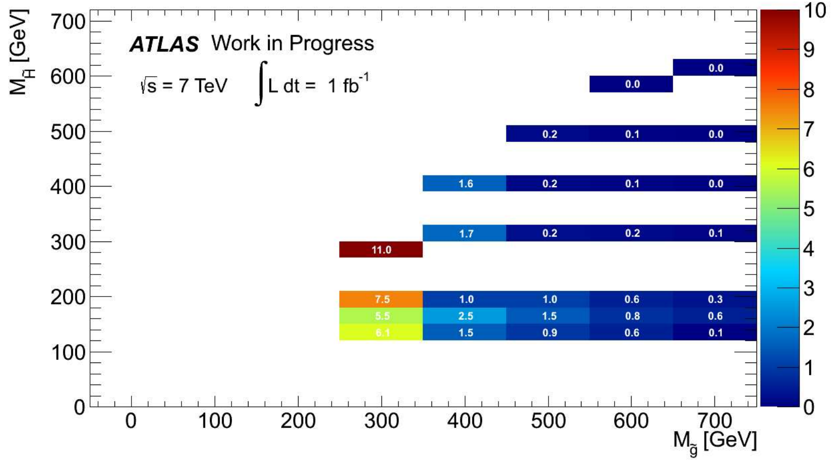
Show cosmics rusult for example only; used latest numbers for ID & MS res



No Z $E_{\mathrm{T}}^{\mathrm{miss}}$-Spectrum



No Z Significance



Calculation limited to statistical significance at this juncture — no systematics

Requiring $N_Z == 2$