ATLAS GMSB Searches with $Z(\rightarrow \ell\ell)\gamma + \not{E}_T$ and $Z(\rightarrow \ell\ell)Z(\rightarrow \ell\ell) + \not{E}_T$ Final States

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GMSB Overview

- Popular class of SUSY breaking scenarios
  - SUSY broken at high scale, in the hidden sector
  - Usual $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interactions responsible for communicating this to the observable sector
- Parameters for mGMSB:

$$\Lambda,\ M,\ N,\ \tan\beta,\ \mu,\ C_{\mathrm{grav}}$$

- Phenomenology
  - Lightest SUSY particle (LSP) – gravitino
  - Next-to-lightest SUSY particle (NLSP) – neutralino, slepton, etc.

GMSB Overview (cont.)

- All SUSY particles decay (e.g., via cascades) to the NLSP, which then decays to the gravitino (LSP)

$$\tilde{A}_{\mathrm{NLSP}} \rightarrow A + \tilde{G}$$

The nature of the NLSP thus determines the signature in the detector!

- Assume lightest neutralino is the NLSP in our analyses
  - Neutralino is a mixture of gaugino and Higgsino eigenstates

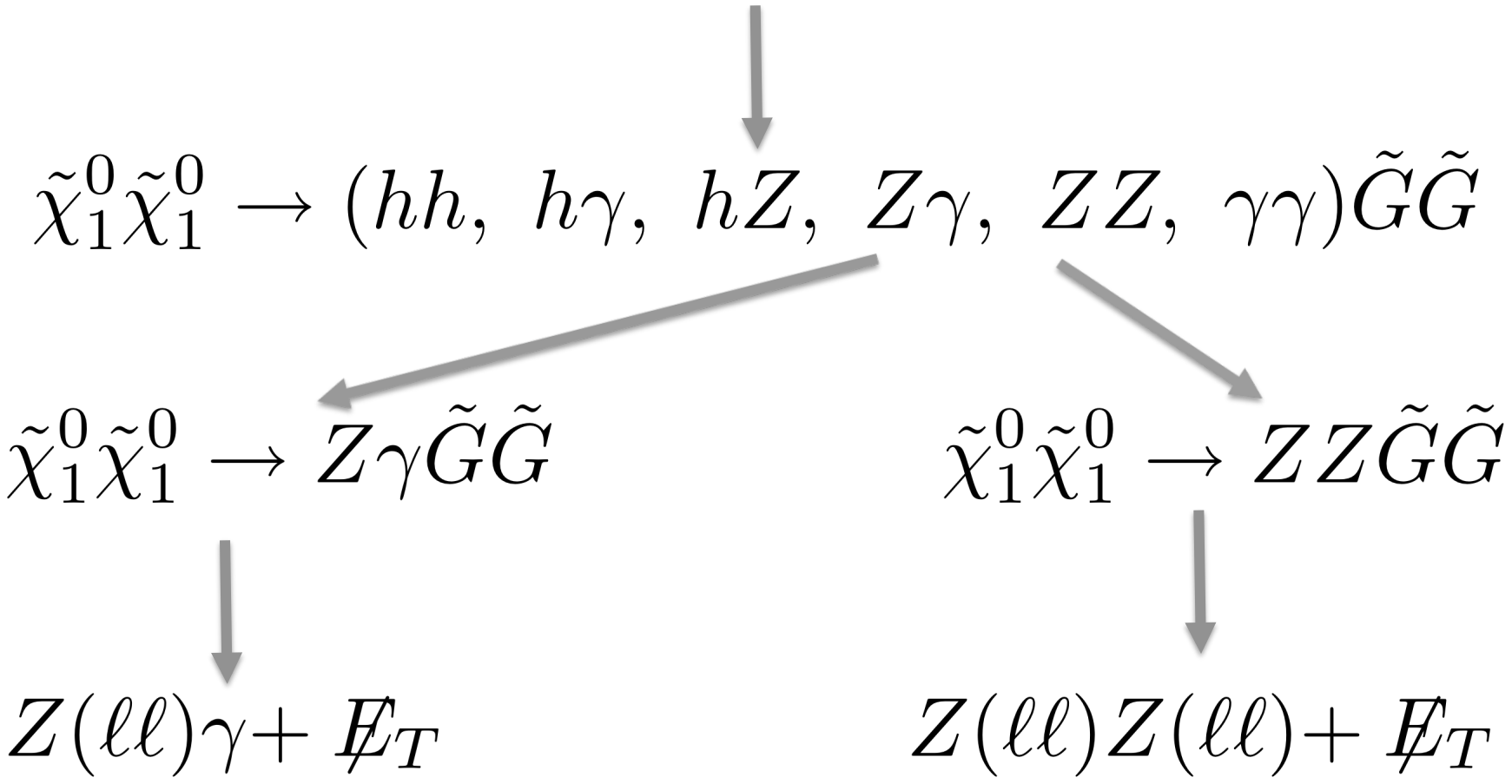
$$\tilde{\chi}_1^0 \rightarrow (h,\ \gamma,\ Z) + \tilde{G}$$

  - This leads to final states such as

$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow (hh,\ h\gamma,\ hZ,\ Z\gamma,\ ZZ,\ \gamma\gamma) + \tilde{G}\tilde{G}$$

Final States in our Analyses

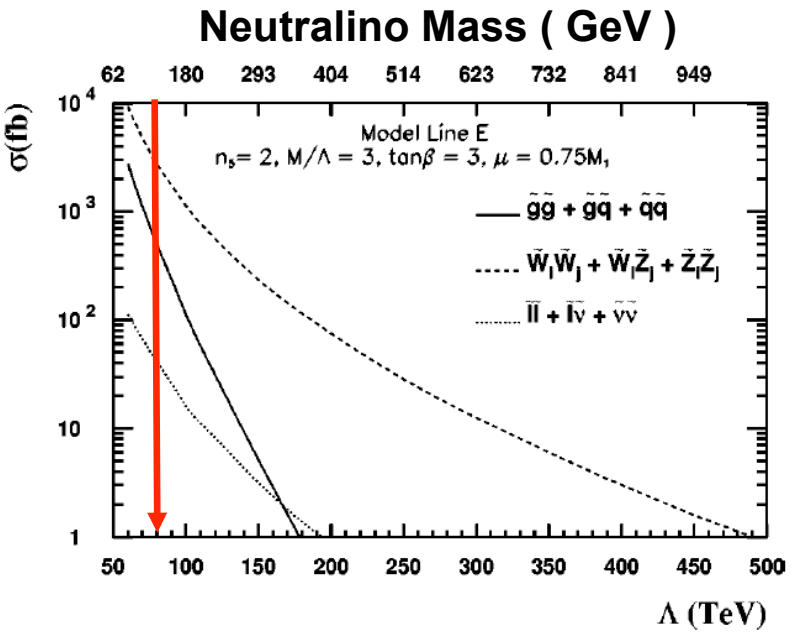
Lightest Neutralino ($\tilde{\chi}_1^0$)- NLSP

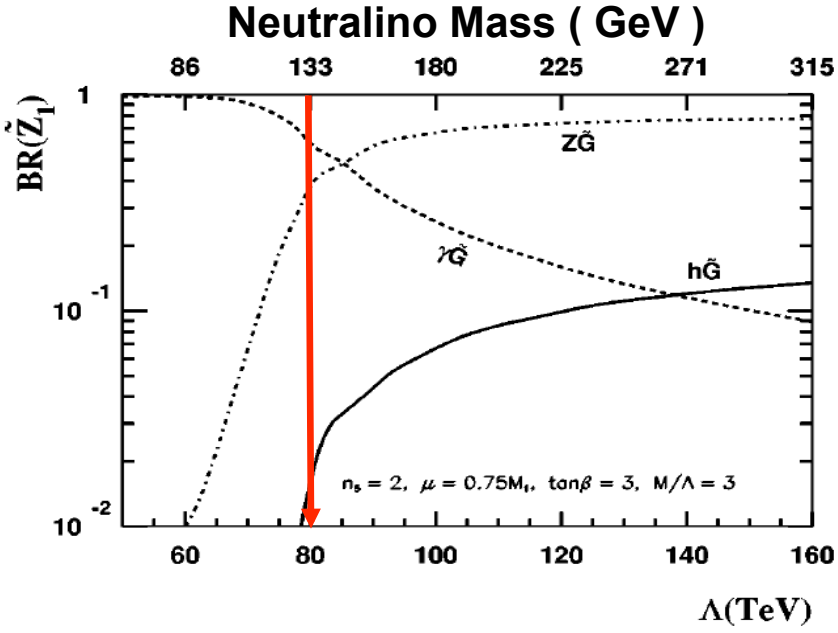


Neutralino Production & Decay

Higgsino-like neutralino model:

$M/\Lambda = 3, \quad N = 2, \quad \mu = 0.75 M_1, \quad \tan\beta = 3$ **(Phys. Rev. D62, 095007, 2000)**





$\Lambda = 80\,\text{TeV}, \quad \sqrt{s} = 10\,\text{TeV}$

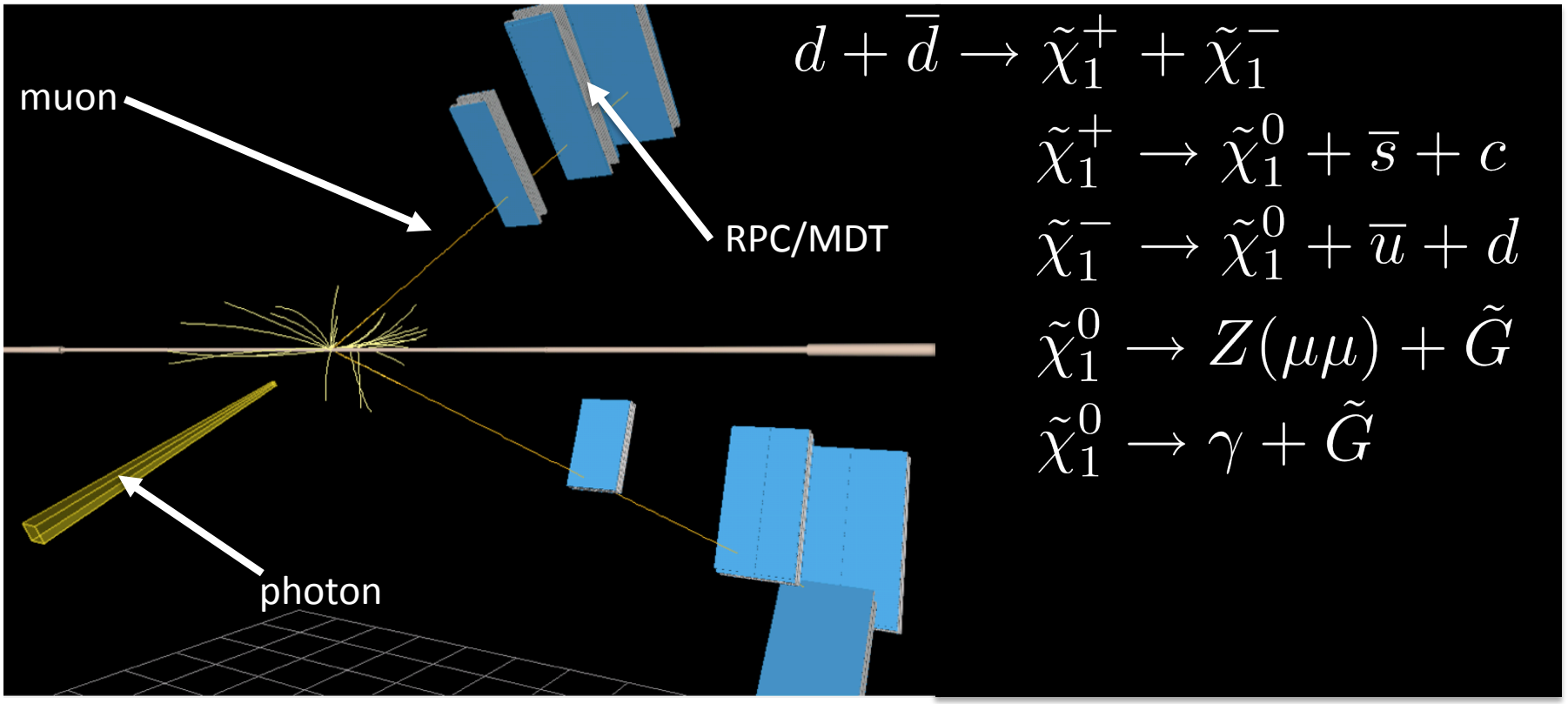
$\sigma(pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 1.88\,\text{pb}$

$$\sigma(pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to Z(\ell\ell)\gamma\tilde{G}\tilde{G}) = 56.2 \text{ fb}$$

$$\sigma(pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to Z(\ell\ell)Z(\ell\ell)\tilde{G}\tilde{G}) = 1.4 \text{ fb}$$

Note: $\ell = e, \mu$ above

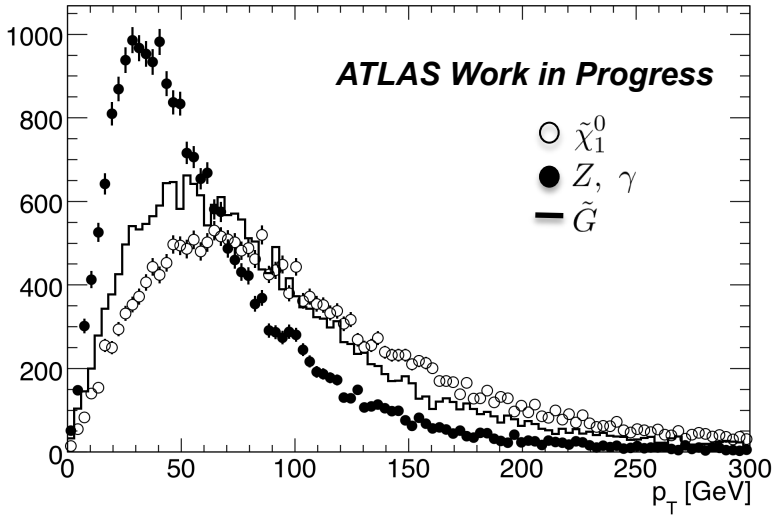
Visualization of Signal Events



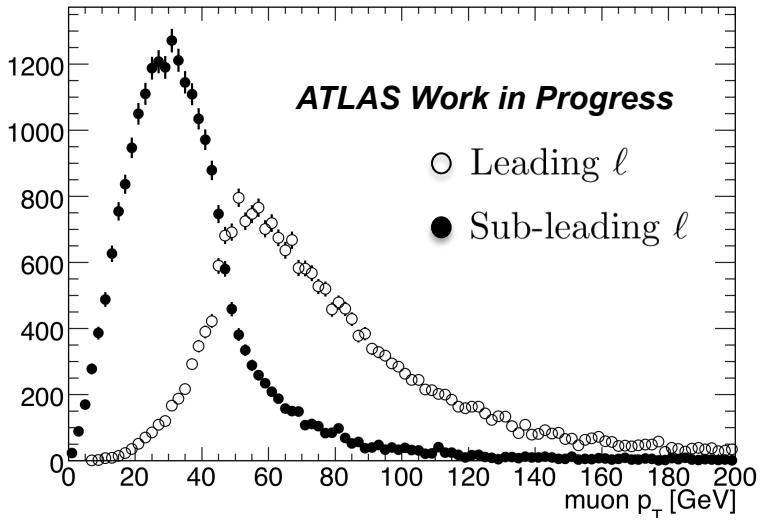
Virtual Point 1 (VP1) – an ATLAS event display program

Kinematics of $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\ell\ell)\gamma + \tilde{G}\tilde{G}$

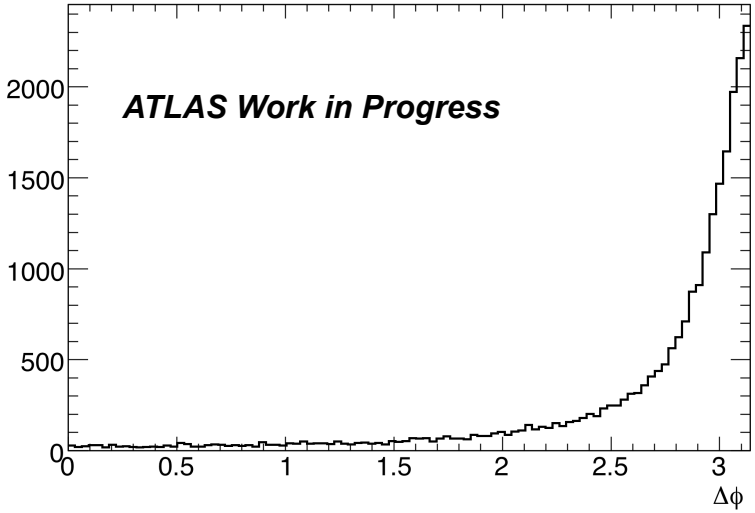
$\tilde{\chi}_1^0, Z/\gamma, \tilde{G}$ p_T



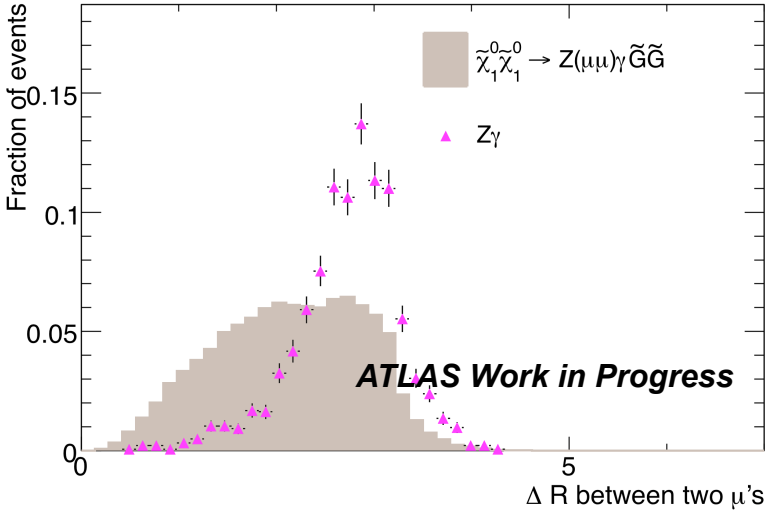
Lepton p_T



$\Delta\varphi$ between two neutralinos



$\Delta\varphi$ between muons



Background MC – $Z(\ell\ell)\gamma + \not{E}_T$

Sample	$\sigma_{\rm NLO}$[pb]	$\int \mathcal{L}\, dt$ [fb^{-1}]
$Z\gamma$	7.1	3
$t\bar{t}$	203	9
$Z \to ee + X$	1318	4
$Z \to \mu\mu + X$	1318	4
$W^-Z \to \ell\nu\ell\ell$	156	99
$W^-Z \to qq\ell\ell$	488	10
$W^-Z \to \tau\nu\ell\ell$	78	253
$W^+Z \to \ell\nu\ell\ell$	265	75
$W^+Z \to qq\ell\ell$	828	6
$W^+Z \to \tau\nu\ell\ell$	132	150

NB: $\ell = e,\ \mu$

Preselection – $Z(\ell\ell)\gamma + \not{E}_T$

Leptons

$p_T(\ell) > 6$ GeV, $|\eta(\ell)| < 2.5$

$p_T(\text{leading } \ell) > 30$ GeV

electron ID – used BDT

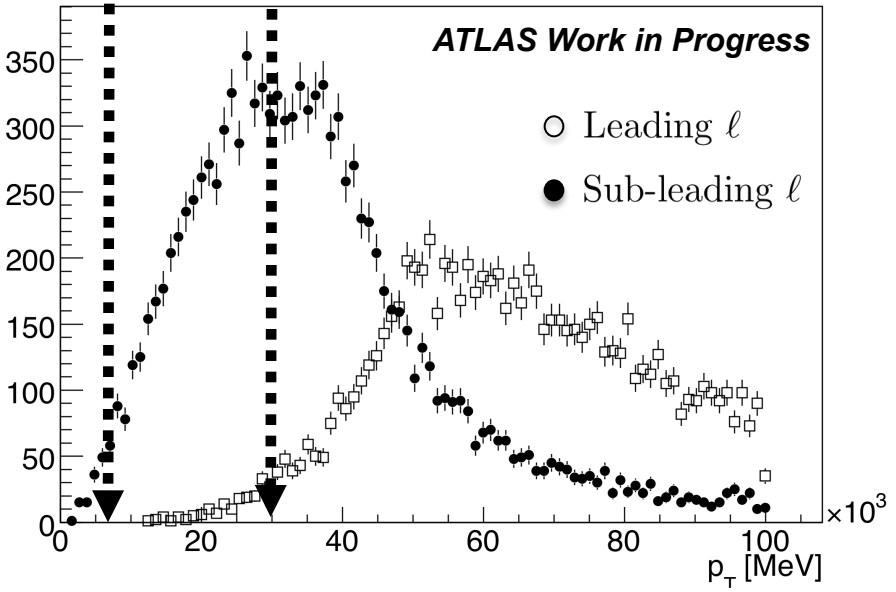
Photons

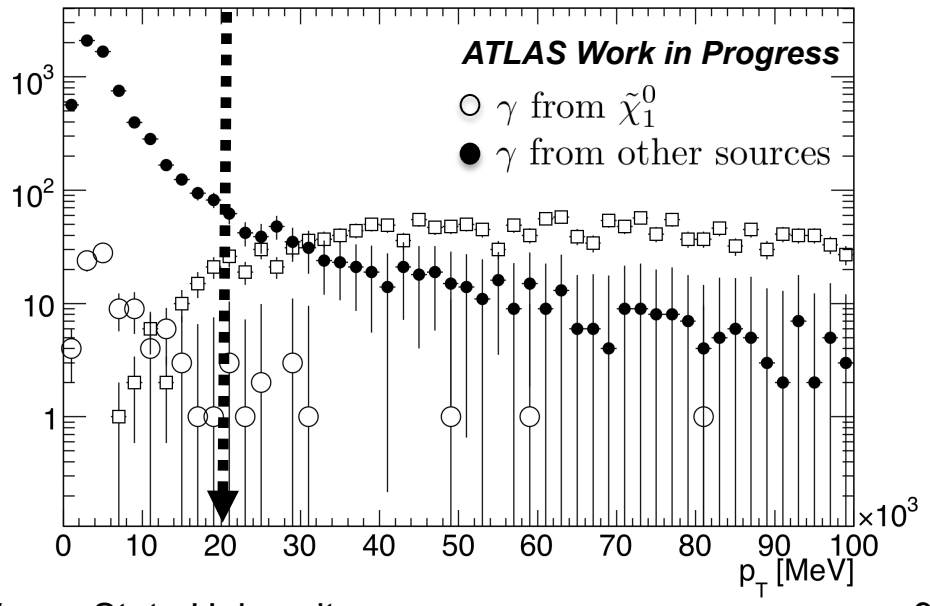
Isolation: $\Delta R > 0.1$

$p_T(\gamma) > 20$ GeV

Z Candidate

$M_{\ell\ell} \in [70, 110]$ GeV

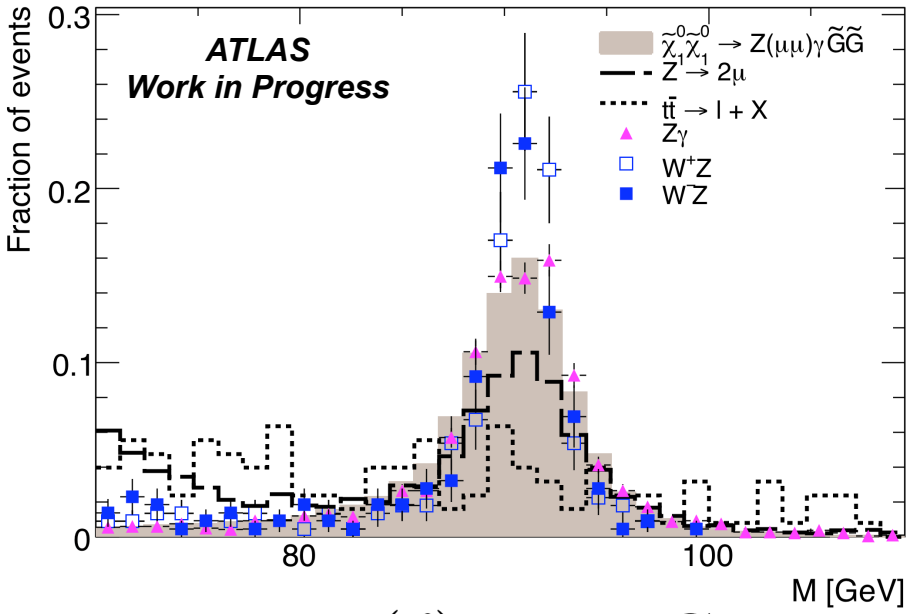


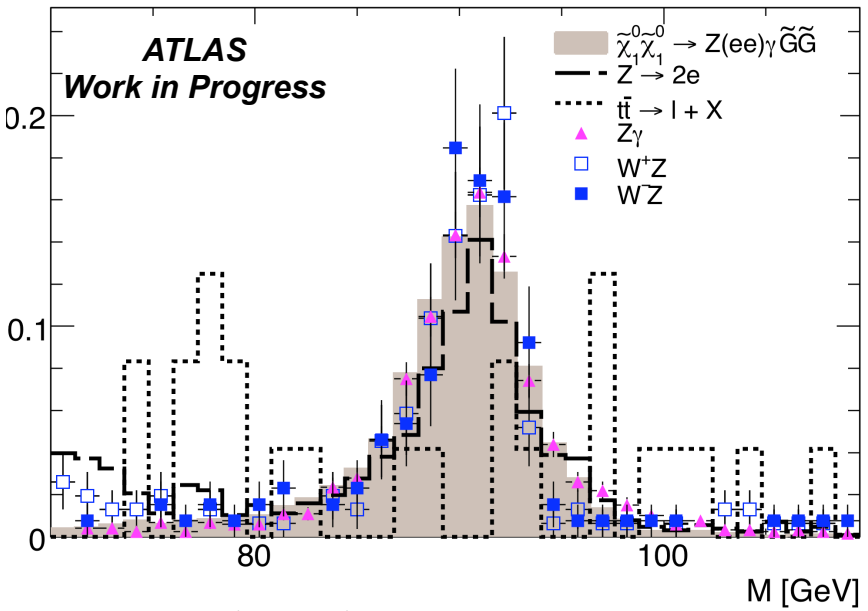


Signal & Background Contributions
(after preselection)

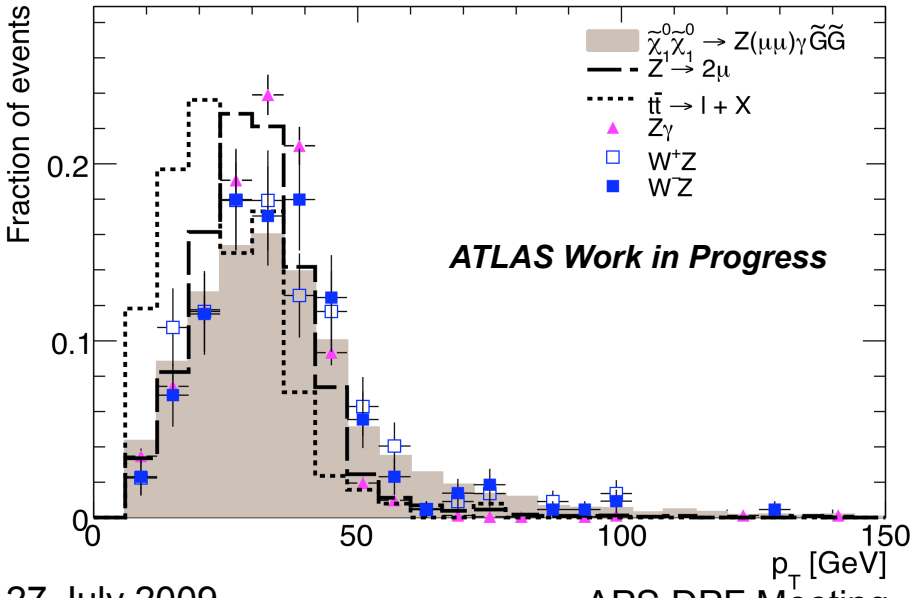
	Process	$\sigma_{\mathrm{PRESEL}}[\mathrm{fb}]$
Muon Sample	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\mu\mu)\gamma\tilde{G}\tilde{G}$	10
	$Z\gamma$	581
	$t\bar{t}$	14
	$Z(\mu\mu) + X$	644
Electron Sample	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(ee)\gamma\tilde{G}\tilde{G}$	6
	$Z\gamma$	374
	$t\bar{t}$	4
	$Z(ee) + X$	349

$|M_Z - M_{\ell\ell}| < 13$ GeV

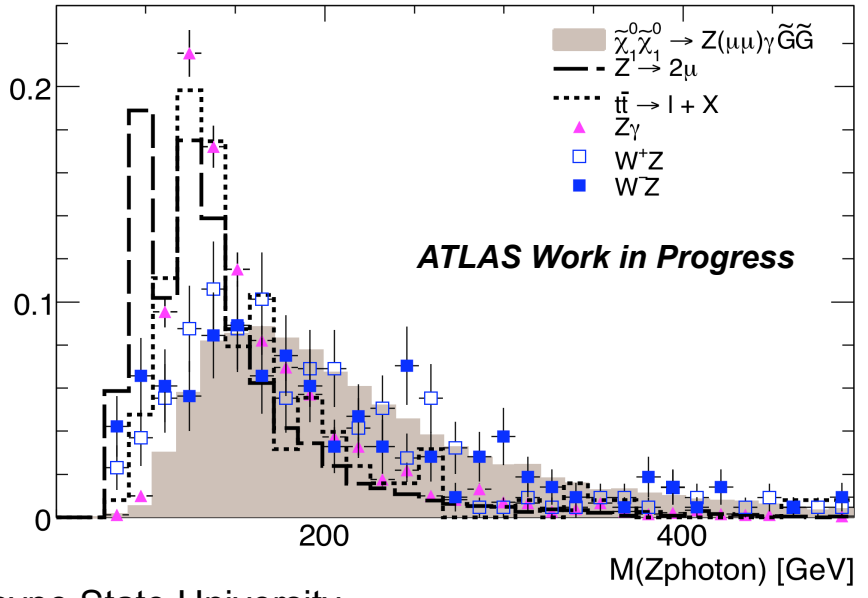




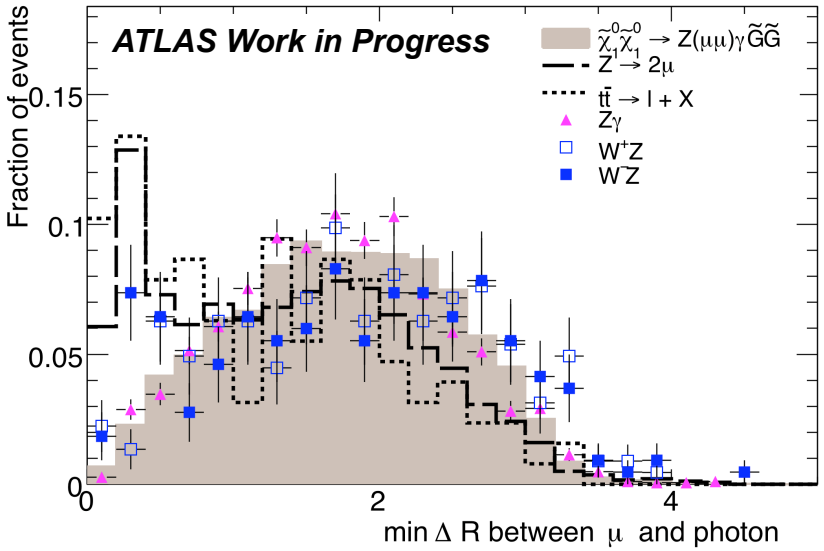
$p_{T,\min}(\ell) > 10$ GeV



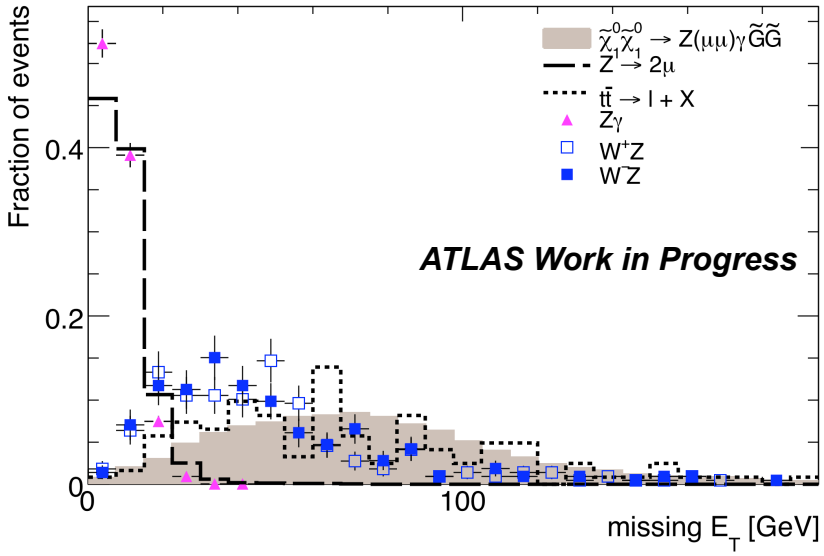
$M(Z\gamma) > 110$ GeV



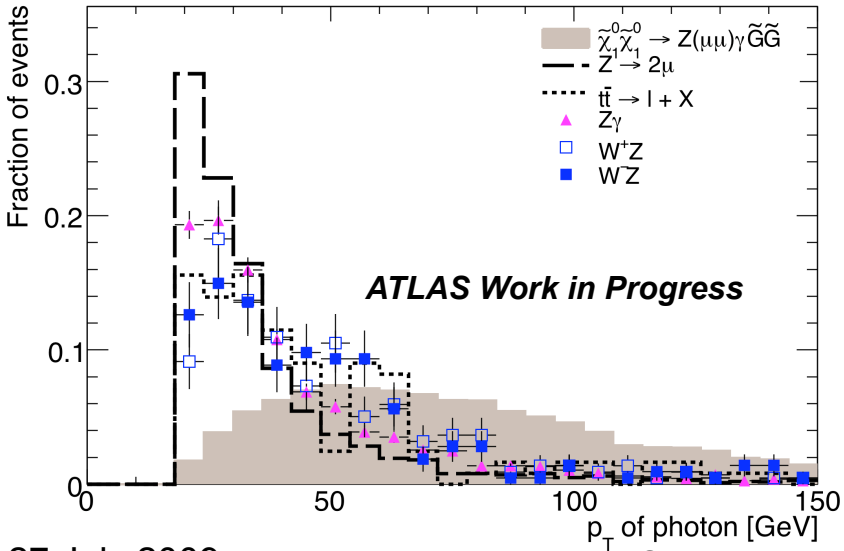
$\Delta R_{\min}(\gamma, \ell) > 0.4$



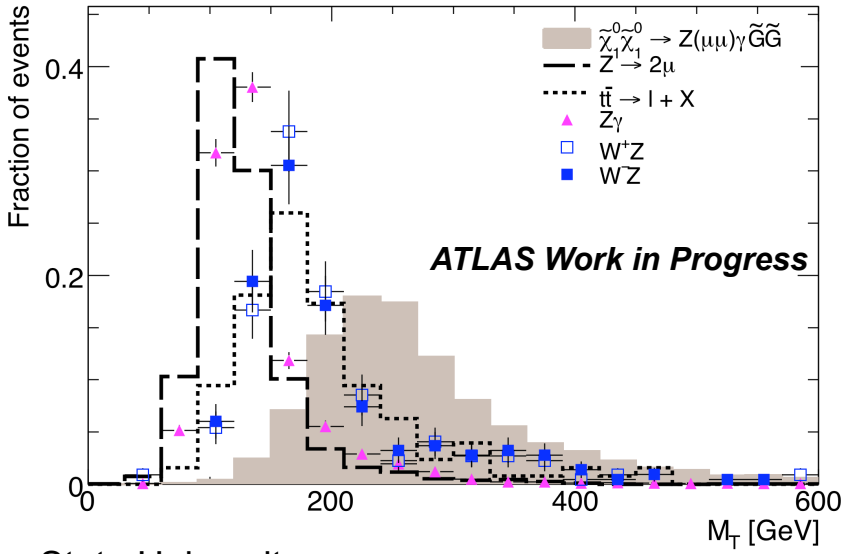
$\not{E}_T > 40$ GeV



$p_T(\gamma) > 30$ GeV



$M_T(\ell\ell, \gamma, \not{E}_T) > 210$ GeV



Results of $Z(\ell\ell)\gamma + \not{E}_T$ Selection (1fb^{-1})

Muon Analysis

	N_{events}
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\to \mu\mu)\gamma\tilde{G}\tilde{G}$ (N_s)	5.4 ± 0.06
$Z\gamma \to \ell\ell\gamma$	0.3 ± 0.3
$t\bar{t} \to \ell + X$	0.3 ± 0.2
$Z(\to \mu\mu) + X$	1.1 ± 0.5
$W^+Z \to \ell\nu\ell\ell + X$	0.28 ± 0.06
$W^-Z \to \ell\nu\ell\ell + X$	0.26 ± 0.05
$W^+Z \to \tau\nu\ell\ell + X$	0.07 ± 0.02
$W^-Z \to \tau\nu\ell\ell + X$	0.04 ± 0.01
Total BG (N_b)	$\mathbf{2.4 \pm 0.65}$
N_s/N_b	**2.3**

Electron Analysis

	N_{events}
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\to ee)\gamma\tilde{G}\tilde{G}$ (N_s)	3.38 ± 0.05
$t\bar{t} \to \ell + X$	0.4 ± 0.2
$Z(\to ee) + X$	0.3 ± 0.3
$W^+Z \to \ell\nu\ell\ell + X$	0.17 ± 0.05
$W^-Z \to \ell\nu\ell\ell + X$	0.06 ± 0.02
$W^+Z \to \tau\nu\ell\ell + X$	0.06 ± 0.02
$W^-Z \to \tau\nu\ell\ell + X$	0.02 ± 0.01
Total BG (N_b)	$\mathbf{1.0 \pm 0.35}$
N_s/N_b	**3.3**

Results for 1 fb^{-1}
10 TeV vs. 14 TeV

		10 TeV	**14 TeV**
Signal	Muon:	5.4 ± 0.06	7.8 ± 0.2
	Electron:	3.4 ± 0.05	4.7 ± 0.15
	Combined:	8.8 ± 0.08	12.5 ± 0.2
Background	Muon:	2.4 ± 0.65	2.1 ± 0.6
	Electron:	1.0 ± 0.35	2.1 ± 1.0
	Combined:	3.4 ± 0.7	3.8 ± 1.2

Discovery Sensitivity for $Z(\ell\ell)\gamma + \not{E}_T$

10 TeV

- 1fb^{-1} – 3σ evidence

	$Z(\mu\mu)\gamma + \not{E}_T$	$Z(ee)\gamma + \not{E}_T$	**Combined**
N_s	5.4 ± 0.06	3.4 ± 0.05	8.80 ± 0.08
N_b	2.4 ± 0.65	1.0 ± 0.35	3.4 ± 0.7
p-value (20% sys)	0.009	0.036	0.0014
Significance (20% sys)	2.4σ	1.8σ	$\mathbf{3}\sigma$

- $<$ 3 fb^{-1} – 5σ discovery
  - 5.4σ can be reached with 3 fb^{-1}

14 TeV

- $<$2 fb^{-1} – 5σ discovery!
  - 5.9σ can be reached with 2 fb^{-1}

Background MC – $Z(\ell\ell)Z(\ell\ell)+\not\!\!E_T$ 14 TeV

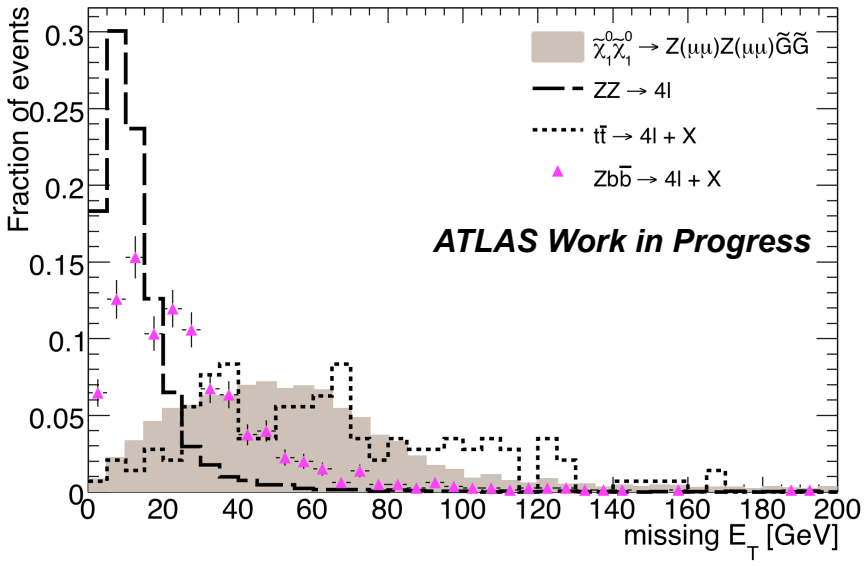
Sample	σ_{NLO}[fb]	$\int \mathcal{L}\, dt$ [fb^{-1}]
ZZ	66	742
$t\bar{t}$	6064	65
$Zb\bar{b}$	695	444

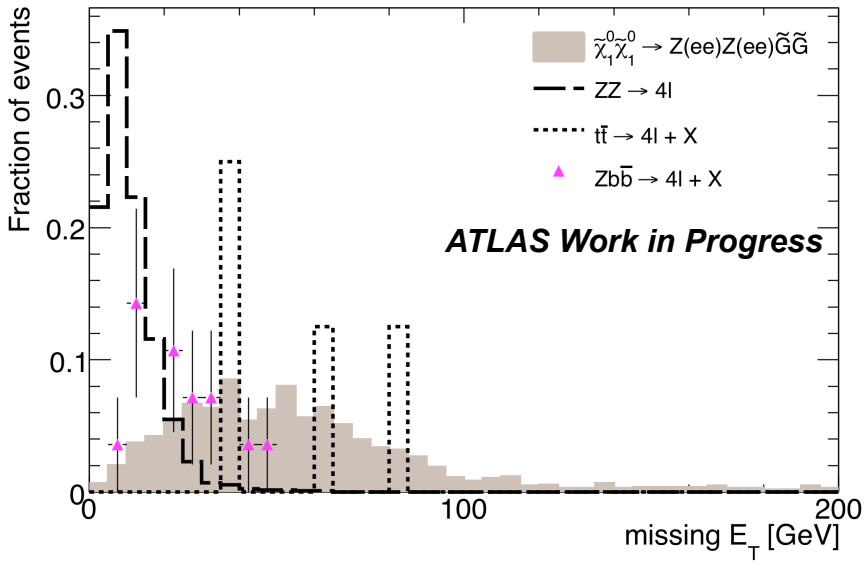
- Preselection – use same cuts as for $Z(\ell\ell)\gamma+\not\!\!E_T$ analysis

Results of $Z(\ell\ell)Z(\ell\ell)+\not{E}_T$ Preselection

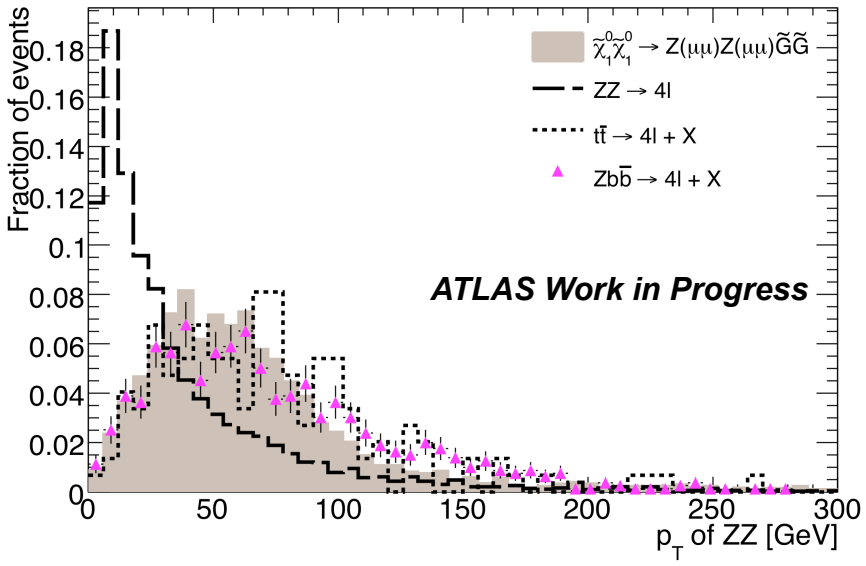
	Process	$\sigma_{\rm PRESEL}$ (fb)
4μ	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\mu\mu)Z(\mu\mu)\tilde{G}\tilde{G}$	0.25
	$ZZ \to 4\ell$	5.7
	$t\bar{t} \to 4\ell + X$	2.3
	$Zb\bar{b} \to 4\ell + X$	1.8
$4e$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(ee)Z(ee)\tilde{G}\tilde{G}$	0.09
	$ZZ \to 4\ell$	1.8
	$t\bar{t} \to 4\ell + X$	0.06
	$Zb\bar{b} \to 4\ell + X$	0.03
$2\mu 2e$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\mu\mu)Z(ee)\tilde{G}\tilde{G}$	0.3
	$ZZ \to 4\ell$	6.5
	$t\bar{t} \to 4\ell + X$	0.9
	$Zb\bar{b} \to 4\ell + X$	0.55

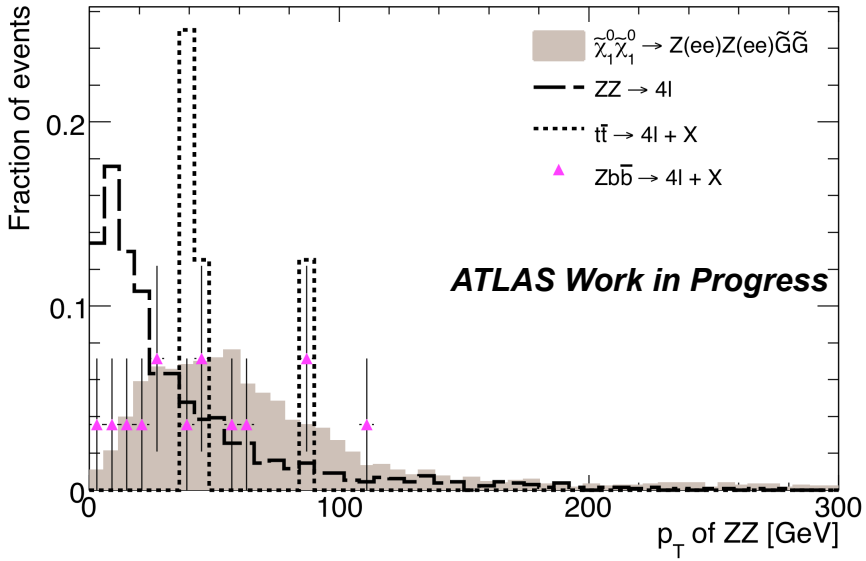
$\not{E}_T > 40$ GeV





$p_T(ZZ) > 30$ GeV





Results of $ZZ + \not{E}_T$ Selection for 30 fb^{-1}

	Process	N_{events}
4μ	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\mu\mu)Z(\mu\mu)\tilde{G}\tilde{G}$	3.29 ± 0.06
	$ZZ \to 4\ell$	2.7 ± 0.3
	$t\bar{t} \to 4\ell + X$	< 1
	$Zb\bar{b} \to 4\ell + X$	< 0.15
$4e$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(ee)Z(ee)\tilde{G}\tilde{G}$	1.17 ± 0.04
	$ZZ \to 4\ell$	0.24 ± 0.09
	$t\bar{t} \to 4\ell + X$	< 1
	$Zb\bar{b} \to 4\ell + X$	< 0.15
$2\mu 2e$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\mu\mu)Z(ee)\tilde{G}\tilde{G}$	4.01 ± 0.07
	$ZZ \to 4\ell$	1.4 ± 0.2
	$t\bar{t} \to 4\ell + X$	< 1
	$Zb\bar{b} \to 4\ell + X$	< 0.15
Combined	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z(\ell\ell)Z(\ell\ell)\tilde{G}\tilde{G}$ (N_s)	8.5 ± 0.1
	Total BG (N_b)	4.3 ± 0.4
	N_s/N_b	2

Discovery Sensitivity for 30 fb^{-1}

$Z(\ell\ell)Z(\ell\ell)+\not{E}_T$

	4μ	$4e$	$2\mu 2e$	**Combined**
N_s	3.29 ± 0.06	1.17 ± 0.04	4.01 ± 0.06	8.5 ± 0.1
N_b	2.7 ± 0.3	0.24 ± 0.09	1.4 ± 0.2	4.3 ± 0.4
p-value (10% sys)	0.077	0.23	0.019	0.0015
Significance (10% sys)	1.4σ	0.7σ	2.1σ	3σ

Can also use BDTs – significance is improved!

	4μ	$4e$	$2\mu 2e$	**Combined**
N_s	3.75 ± 0.08	1.36 ± 0.05	4.44 ± 0.08	9.56 ± 0.12
N_b	1.43 ± 0.24	0.12 ± 0.07	0.69 ± 0.17	2.24 ± 0.30
p-value (10% sys)	0.022	0.124	1.12E-3	1.09E-5
Significance (10% sys)	2σ	1.15σ	3.05σ	4.24σ

Conclusions

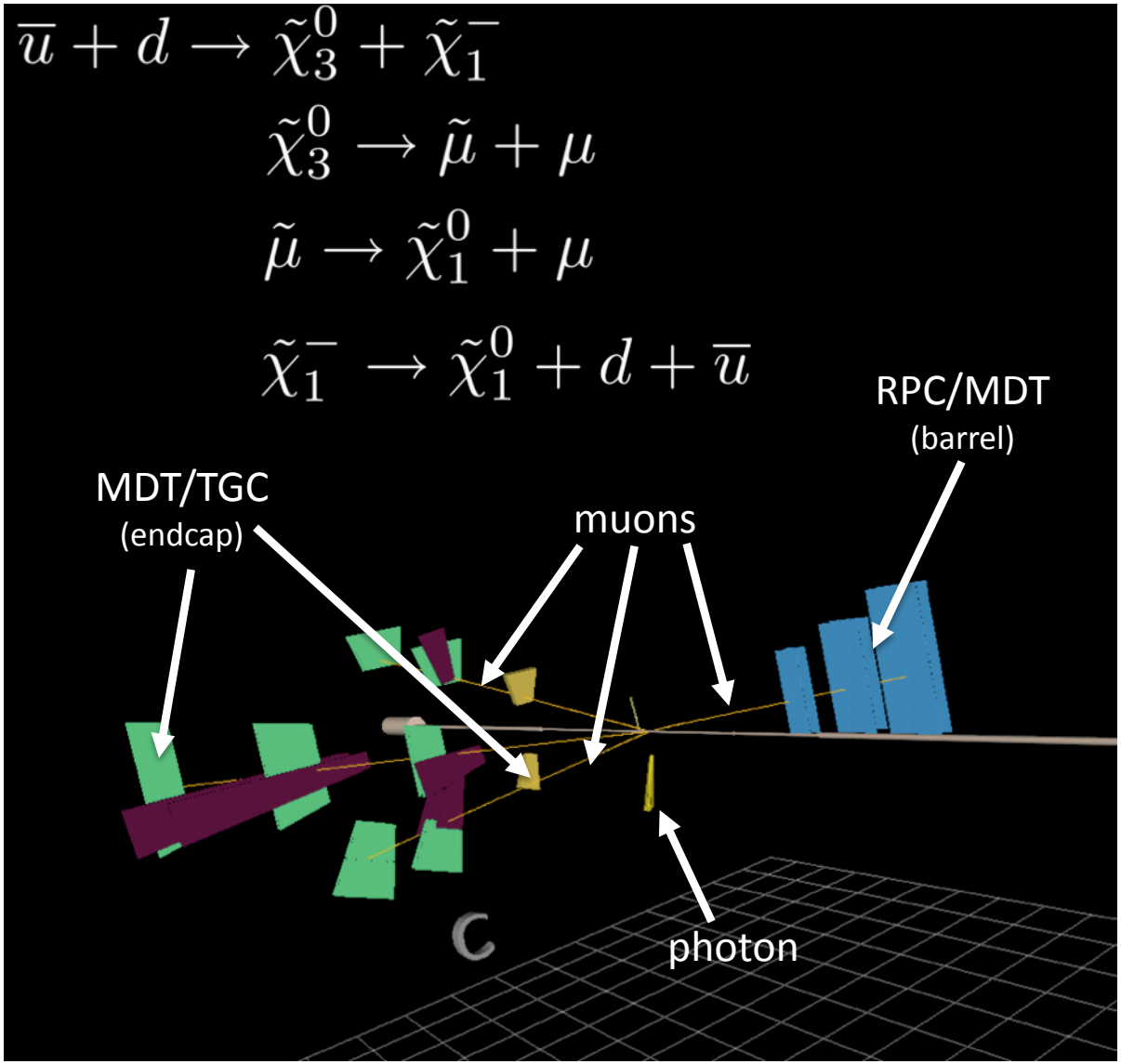
- GMSB models provide phenomenologically interesting topologies for SUSY searches
- ATLAS Sensitivity – for model line E

$$\Lambda = 80\ \mathrm{TeV},\ M/\Lambda = 3,\ N = 2,\ \mu = 0.75 M_1,\ \tan\beta = 3$$

  - 5σ discovery for $Z\gamma + \not{E}_T$ for < 3 fb^{-1} (10 TeV)
  - 5σ discovery for $Z\gamma + \not{E}_T$ for < 2 fb^{-1} (14 TeV)
    - 20% systematic uncertainty
  - 3σ for $ZZ + \not{E}_T$ for 30 fb^{-1}
  - 4σ for $ZZ + \not{E}_T$ for 30 fb^{-1} with BDT Analysis
    - 10% systematic uncertainty

Backup

VP1 Visualization of Signal Events

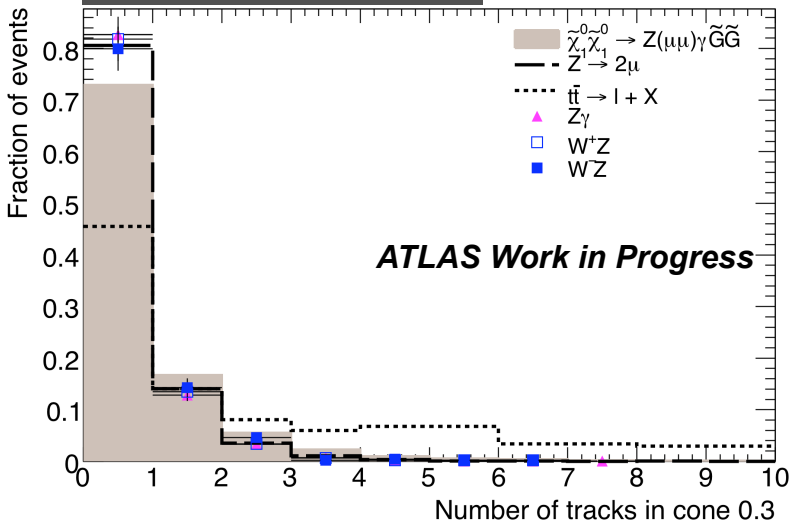


$Z(\ell\ell)\gamma + \not{E}_T$ – Selection Cuts

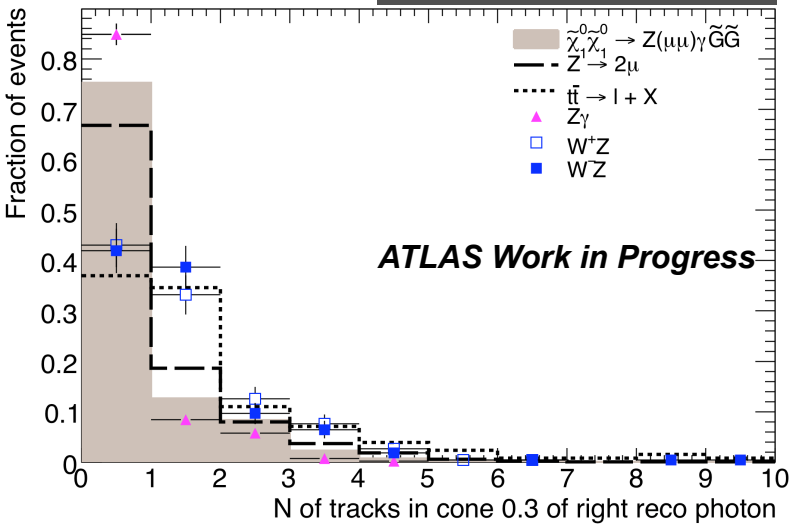
- $|M_Z - M_{ll}| < 13$ GeV
- min $(\Delta R) < 0.4$
- $p_T(\gamma) > 30$ GeV
- min p_T (l) > 10 GeV
- MET > 40 GeV
- $|\Delta d0| < 0.1\text{mm}/0.15\text{mm}$ && $|\Delta z0| < 1\text{mm}$
- M_T (ll γ MET) > 210 GeV
- N tracks in cone 0.3 around lepton/photon < 4

$N(\text{tracks in cone of } 0.3) < 4$

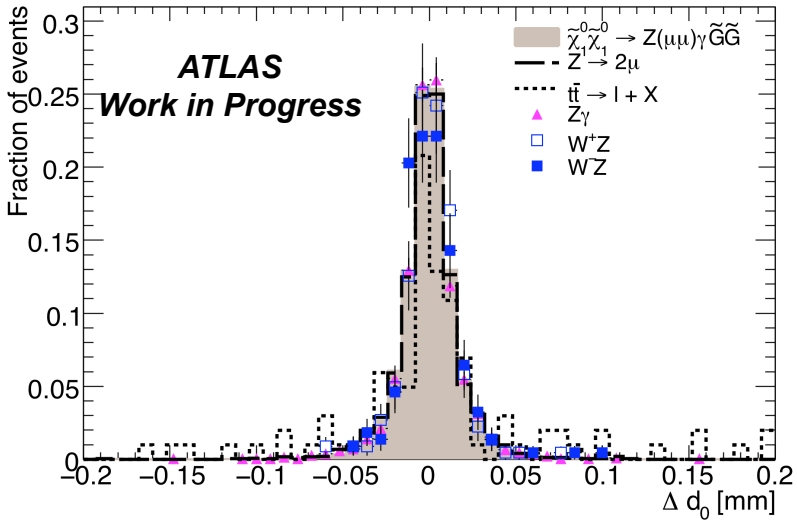
around muons



around photons



$\Delta d_0(\mu) < 0.1$ mm



$\Delta z_0(\mu) < 1$ mm