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"*Physics at the Terascale*"
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DESY

Searches for SUSY in Final States with Photons at CMS

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- GMSB and GGM
- Photon Searches at CMS
- Results and Limits

GMSB and GGM

- **Gauge-Mediated SUSY Breaking (GMSB)**
  [G. Giudice and R. Rattazzi, arXiv:hep-ph/9801271]
  = SUSY couples to normal matter through gauge interactions
  = Gravitino: LSP

- **General Gauge Mediation (GGM)**
  [P. Meade, N. Seiberg, D. Shih, arXiv:0801.3278]
  = neutralino NLSP a mixture of Bino, Wino and Higgsino
  = photon/Z+Gravitino or W+Gravitino final states
  -> one or two photons + MET
  = focus on strong production: many jets

GGM Phenomenology at the LHC

Neutralino NLSP mixture of Bino, Wino and Higgsino

- **Bino-like NLSP:**

$$\tilde{\chi}_1^0 \to \gamma + G \quad \text{or} \quad \tilde{\chi}_1^0 \to Z^0 + G$$

- **Wino-like (co-)NLSP:**

$$\tilde{\chi}_1^0 \to \gamma + G \quad \text{or} \quad \tilde{\chi}_1^0 \to Z^0 + G$$

$$\text{and/or} \quad \tilde{\chi}_1^{\pm} \to W^{\pm} + G$$

- **Bino-Higgsino-like NLSP:**

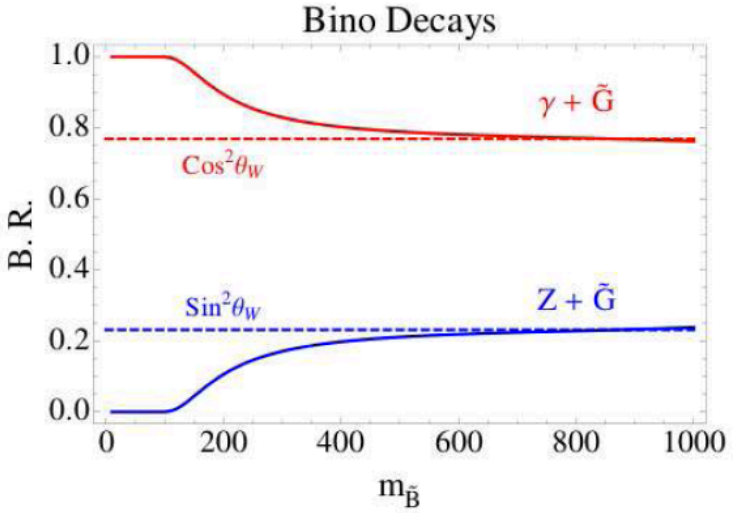
$$\tilde{\chi}_1^0 \to \gamma + G \quad \text{or} \quad \tilde{\chi}_1^0 \to Z^0 + G$$

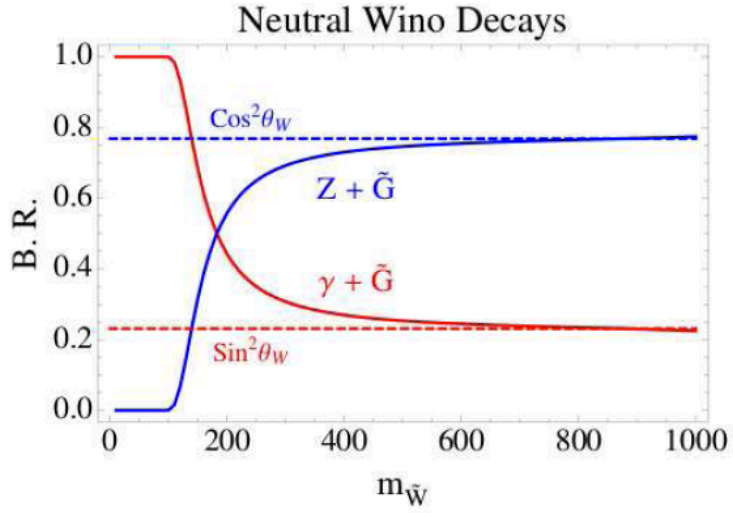
$$\text{and/or} \quad \tilde{\chi}_1^0 \to h + G$$

R-parity is conserved

-> 2 LSPs per event

★ MET is defining signature





[J. Ruderman, D. Shih, arXiv:1103.6083]

GGM with Photons at CMS

- **Search for new physics in events with photons, jets, and missing transverse energy in pp collisions at $\sqrt{s}$ = 7 TeV**

  [CMS-SUS-12-001, arXiv:hep-ex/1211.4784 - A. Askew, B. Cox, D. Elvira, Y. Gershtein, G. Hanson, M. Hildreth, D. Jang, A. Ledovskoy, Y.F. Liu, D. Mason, D. Morse, U. Nauenberg, M. Paulini, R. Stringer, R. Yohay, S.L. Zang, C. Autermann, U. Gebbert, M. Hoffmann, P. Schleper]

- **Search for Supersymmetry in Events with Photons and Missing Energy ($\sqrt{s}$ = 8 TeV)**

  [CMS PAS SUS-12-018 - A. Askew, M. Arenton, B. Cox, D. Elvira, B. Francis, G. Hanson, M. Hildreth, Y. Iiyama, D. Jang, Y-F. Liu, D. Mason, D. Morse, M. Paulini, R. Yohay, C. Autermann, U. Gebbert, M. Hoffmann, P. Schleper , VS]

- **SUSY Search in Photon(s)+jets+E_T^{miss} final state with the Jet-Gamma Balance method ($\sqrt{s}$ = 7 TeV)**

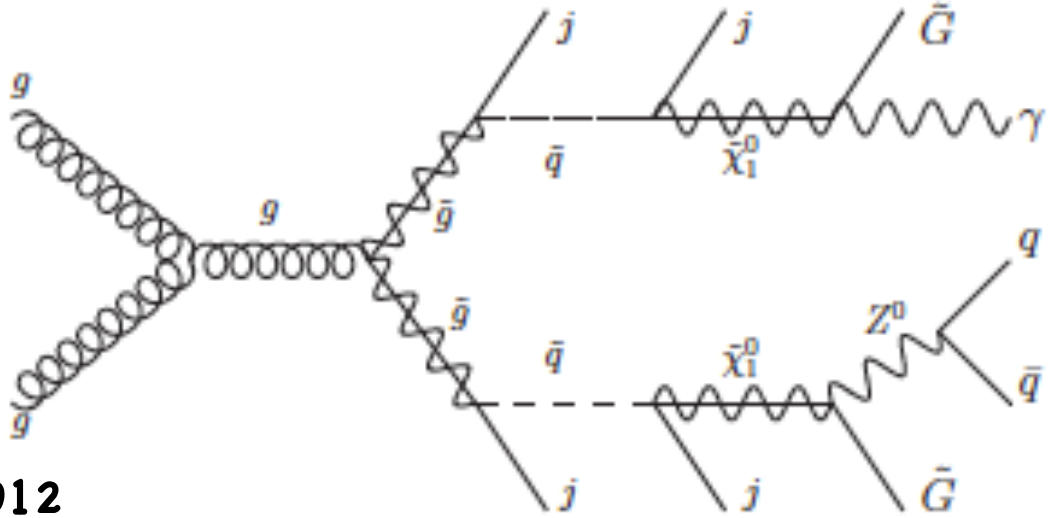
  [CMS PAS SUS-12-013 - E. Ntomari, T. Geralis, K. Theofilatos]

GGM with Photons at CMS

Final states with at least one photon

- γ + Jets + MET

It includes the case of Bino-Higgsino-like NSLP
γ + h + MET



Results presented in ICHEP 2012
$\int \mathcal{L} dt = 4.04\ fb^{-1}$ 2012 Data @ $\sqrt{s} = 8$ TeV

Photons	Jets	MET
≥ 1 E_T > 80 GeV $E_{iso}^{(\Delta R<0.3)}$ < 6 GeV $\|\eta\|$ < 1.442	≥ 2 p_T > 30 GeV $\|\eta\|$ < 2.6 H_T > 450 GeV	> 100 GeV

Jets = particle flow jets, anti-kT (R=0.5), photon rejected

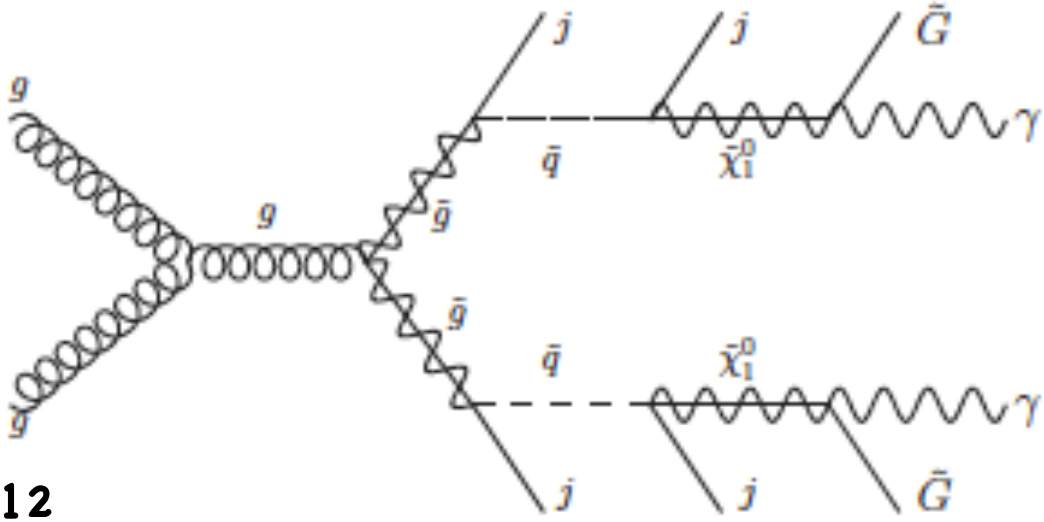
H_T = scalar sum of p_T of all jets with p_T>40 GeV and $|\eta|$<3, no photon rejection

[CMS Collaboration, PAS SUS-12-018]

GGM with Photons at CMS

Final states with at least two photons

- $\gamma\gamma$ + Jets + MET



Results presented in ICHEP 2012

$\int \mathcal{L} dt = 4.04$ fb^{-1} 2012 Data @ $\sqrt{s} = 8$ TeV

Photons	Jets	MET
≥ 2 E_T > 40, 25 GeV $E_{iso}^{(\Delta R<0.3)}$ < 6 GeV $\|\eta\|$ < 1.442	≥ 1 p_T > 30 GeV $\|\eta\|$ < 2.6	> 50 GeV

[CMS Collaboration, PAS SUS-12-018]

Jets = particle flow jets, anti-kT (R=0.5), photon rejected

E_{iso} = isolation variables corrected for pile-up effect in all photon selections

Standard Model Backgrounds

Analysis	Fake photons - QCD (jets)	Fake photons - EWK (electrons)	Irreducible (photons)
γ + Jets + MET	γ + Jet j $\rightarrow \gamma$		
$\gamma\gamma$ + Jets + MET	γ + Jet j $\rightarrow \gamma$		

Dominant Background

Sub-dominant Background

Negligible Background

Data - Driven

QCD Background

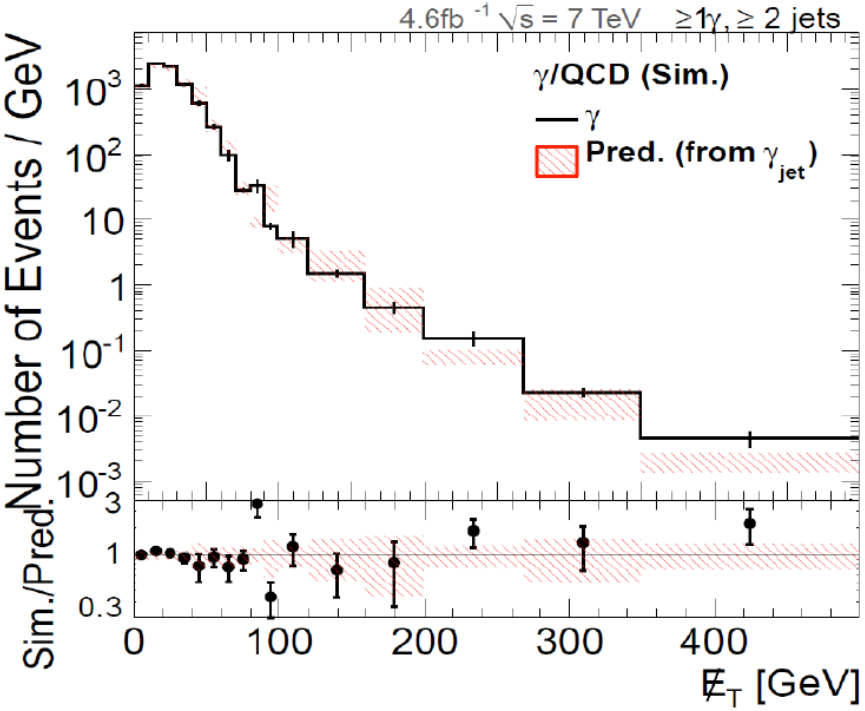
Mis-measurement of MET in QCD processes
-> direct di-photon, photon+jets, and multijet production
with jets mimicking photons

- γ + Jets + MET
  looser γ isolation requirements (γ_{jet}) orthogonal to signal selection
  p_T spectra reweighted in low MET region (MET<100 GeV)
  systematic uncertainty of 10% assigned

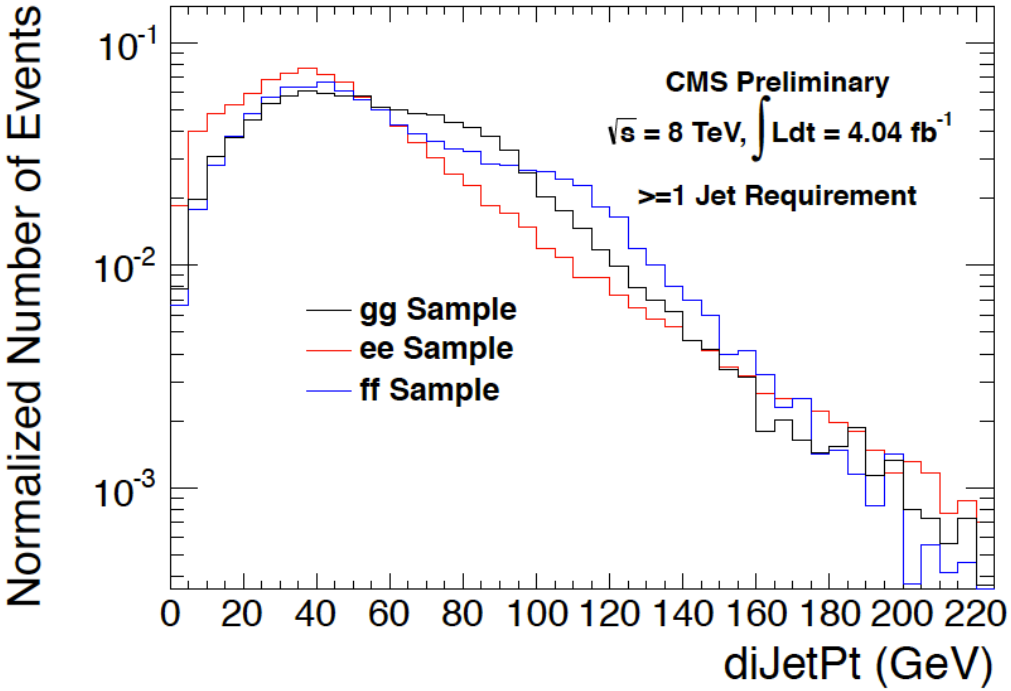
- $\gamma\gamma$ + Jets + MET
  two fake photons (ff) sample used to estimate the background
  p_T spectra is reweighted to reproduce the E_T distribution in data
  ee control sample used to derive the systematic uncertainty

QCD Background

γ + Jets + MET



$\gamma\gamma$ + Jets + MET



Standard Model Backgrounds

Analysis	Fake photons - QCD (jets)	Fake photons - EWK (electrons)	Irreducible (photons)
γ + Jets + MET	γ + Jet j $\rightarrow \gamma$	W, top e $\rightarrow \gamma$	
$\gamma\gamma$ + Jets + MET	γ + Jet j $\rightarrow \gamma$	W+γ, W+jet e $\rightarrow \gamma$, j $\rightarrow \gamma$	

Dominant Background

Sub-dominant Background

Negligible Background

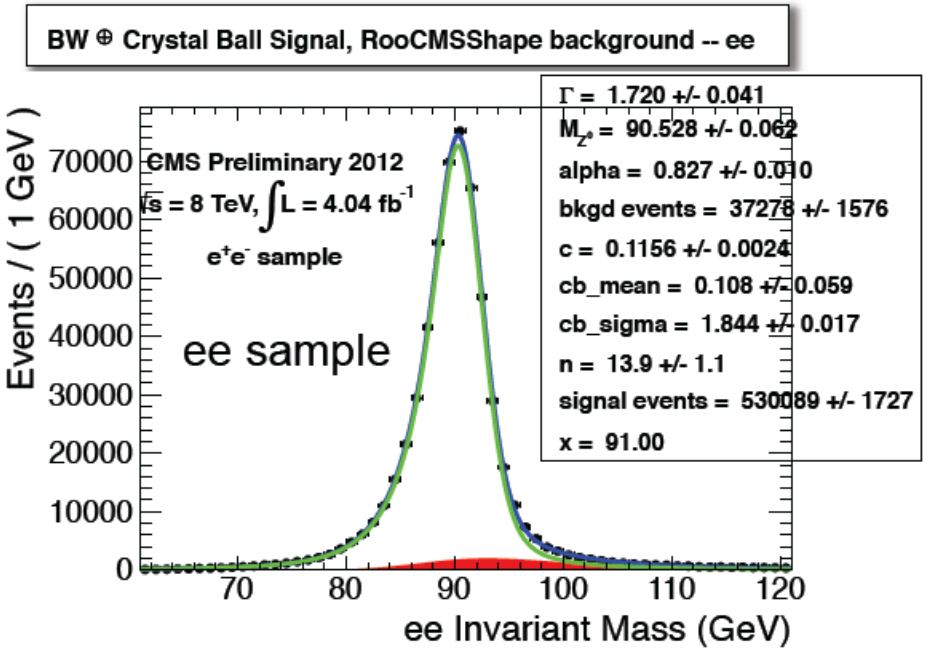
Data - Driven

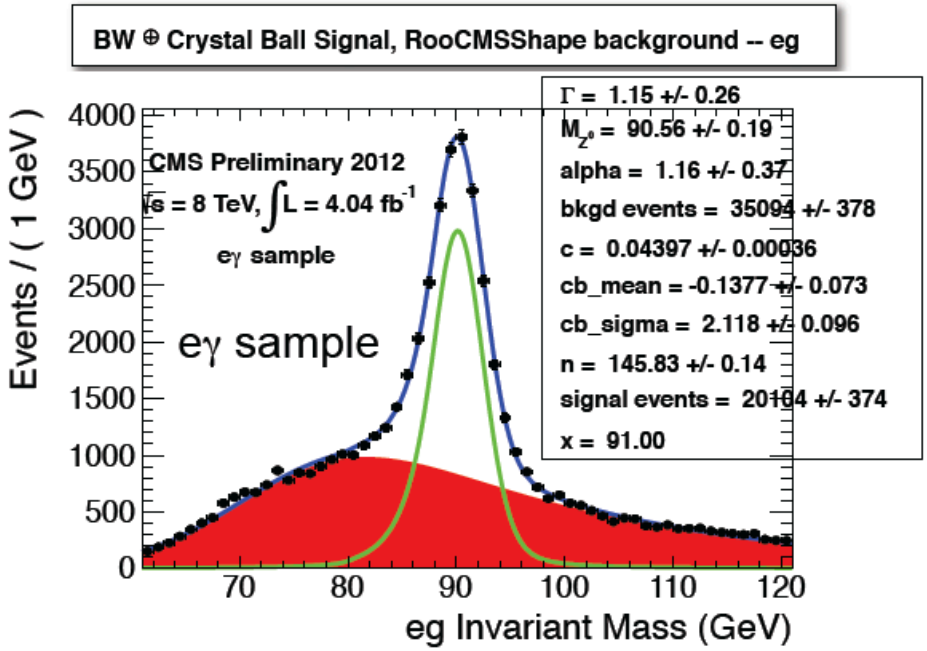
Data - Driven

EWK Background

Events with true MET and an electron misidentified as a photon

-> compare $Z \to ee$ events to $Z \to e\gamma$ to obtain $e \to \gamma$ fake rate





Ratio of signal used to estimate fake rate $f_{e \to \gamma}$

average value: $f_{e \to \gamma} = 0.0181 \pm 0.0003(\text{stat}) \pm 0.0009(\text{syst})$

$p_T > 80$ GeV: $f_{e \to \gamma} = 0.011 \pm 0.002\ (\text{stat}) \pm 0.001\ (\text{syst})$

Inclusive electron spectrum scaled by $f_{e \to \gamma}$ to obtain EWK bkg

Standard Model Backgrounds

Analysis	Fake photons - QCD (jets)	Fake photons - EWK (electrons)	Irreducible (photons)
γ + Jets + MET	γ + Jet j $\rightarrow \gamma$	W, top e $\rightarrow \gamma$	ISR/FSR Z/W/top + γ
$\gamma\gamma$ + Jets + MET	γ + Jet j $\rightarrow \gamma$	W+γ, W+jet e $\rightarrow \gamma$, j $\rightarrow \gamma$	Z/W + $\gamma\gamma$

Dominant Background

Sub-dominant Background

Negligible Background

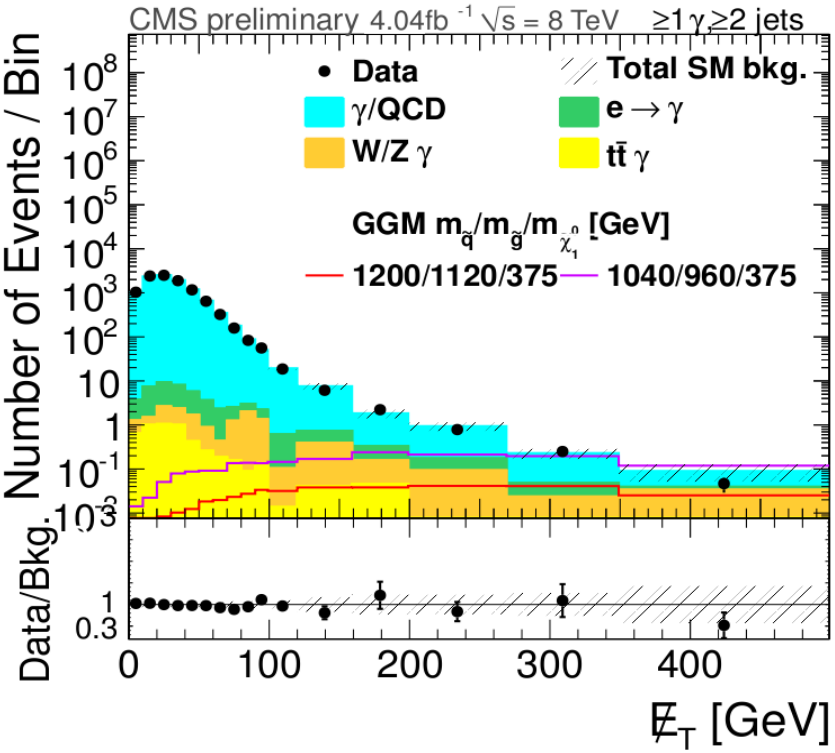
Data - Driven

Data - Driven

Simulation

MadGraph, 50% uncertainty on the Xsec

Single Photon MET Spectrum



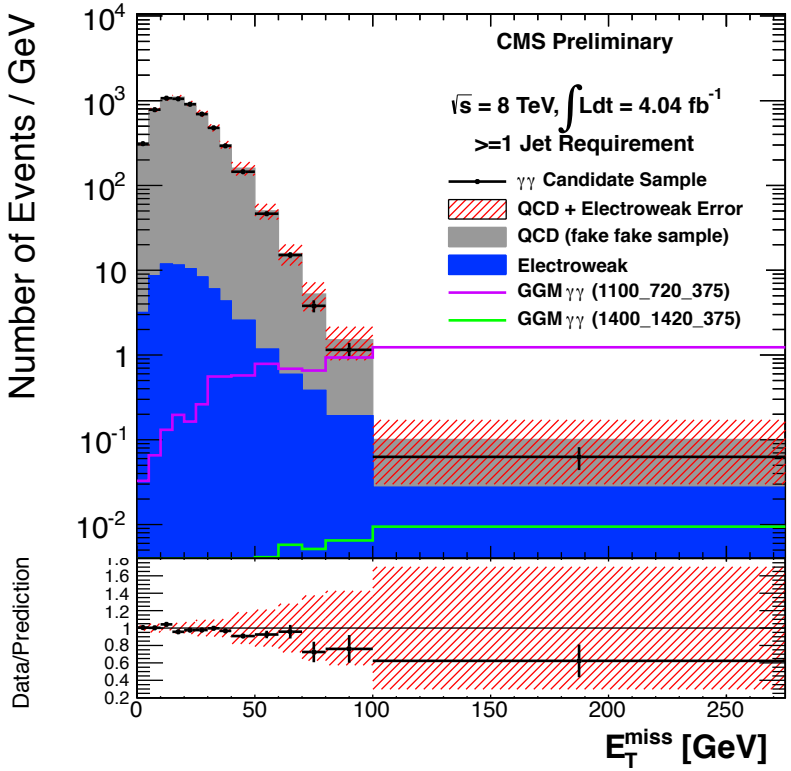
No excess observed over SM expectations

Six bins in MET > 100 GeV used to set limits

[100, 120, 160, 200, 270, 350, ∞)

E_T^{miss} bins [GeV]	Bin 0 [100,120)	Bin 1 [120,160)	Bin 2 [160,200)	Bin 3 [200,270)	Bin 4 [270,350)	Bin 5 [350,∞)
QCD	394±41	267±51	60±17	53.7±14.6	14.5±4.7	8.9±4.3
EWK	10.6±2.9	13.4±3.7	6.9±1.9	5.6±1.6	1.9±0.5	1.0±0.3
ISR/FSR	2.0±1.2	13.8±8.5	5.6±3.5	5.9±3.7	1.7±1.3	4.7±4.7
Background	406±42	294±52	73±17	65.2±15.1	18.2±4.9	14.6±6.4
Data	392	239	89	55	20	8
Signal	113±8	281±15	277±15	538±25	529±25	640±29

Di-Photon MET Spectrum



No excess observed over SM expectations

Five bins in MET > 50 GeV used to set limits

[50, 60, 70, 80, 100, ∞)

E_T^{miss} bins	50-60 GeV	60-70 GeV	70-80 GeV	80-100 GeV	> 100 GeV
Observed Events	464	151	38	23	11
EW Background	$10.8 \pm 0.5 \pm 0.5$	$5.4 \pm 0.3 \pm 0.3$	$3.5 \pm 0.3 \pm 0.2$	$3.5 \pm 0.3 \pm 0.2$	$4.6 \pm 0.3 \pm 0.2$
QCD Background	$489.9 \pm 22.7 \pm 104.2$	$151.8 \pm 12.7 \pm 42.3$	$48.6 \pm 7.3 \pm 18.2$	$26.4 \pm 5.5 \pm 11.7$	$12.9 \pm 3.7 \pm 11.9$
Signal Yield	3.54 ± 0.65	2.58 ± 0.56	2.92 ± 0.59	8.9 ± 1.0	275.4 ± 5.8
Expected Limit	11.234 pb	6.756 pb	2.066 pb	0.496 pb	0.011 pb
Observed Limit	9.908 pb	6.489 pb	1.716 pb	0.404 pb	0.0074 pb

Limit Calculation

- Systematic errors

Systematics	Uncertainty [%]
Integrated luminosity	5
Pile-up study	0.6
Photon Data/MC scale & ID	0.1
Jet energy scale	2
Renormalization scale	11 - 22
PDF error on cross section	3 - 44
PDF error on acceptance	0.1 - 6.8

  = Theory errors: scale and PDF errors combined at each point and cross section varied by 1σ
  = Single Photon analysis include an extra 3% trigger unc

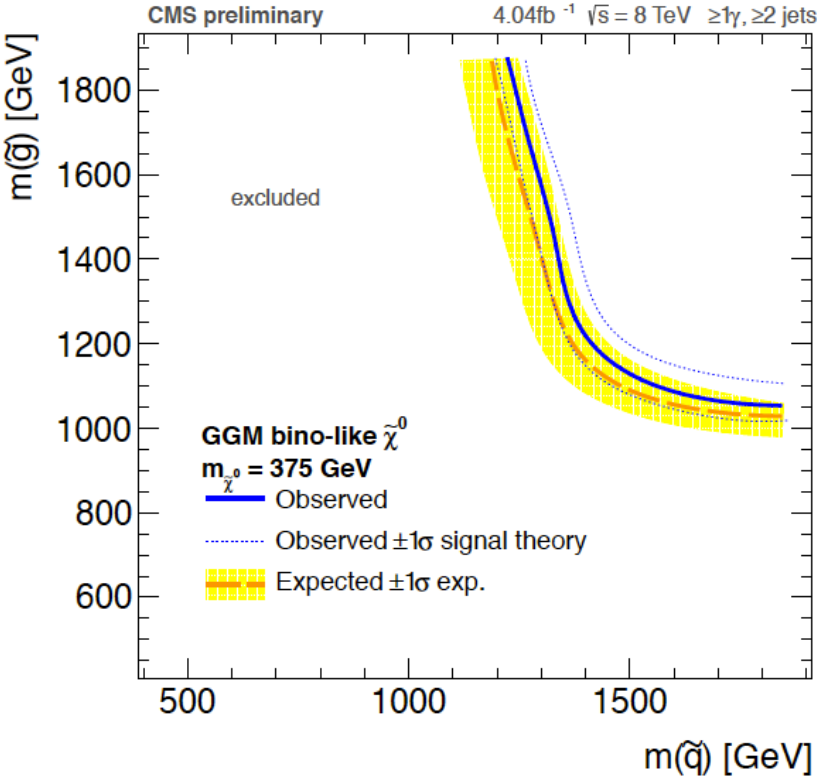
- Limit calculation
  = CL_s method with likelihood-ratio test statistics at 95%
  = full propagation of errors
  = GGM Signal Monte Carlo (grid scan)
  Prospino used for NLO cross section

Interpretation: Bino-like NLSP

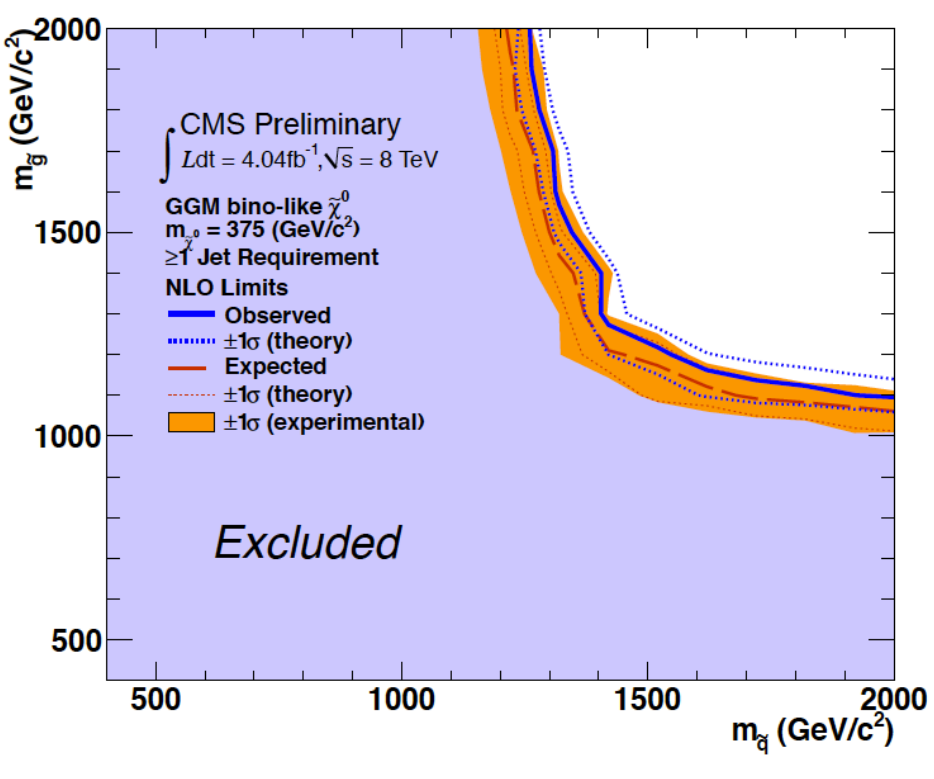
Bino-like GGM scan

$m_{\chi 0}$ = 375 GeV, $m_{squark,gluino}$ = 400-2000 GeV (step 80 GeV)
sleptons and all gauginos except NLSP @ 3.5 TeV

γ + ≥2 jets + MET



$\gamma\gamma$ + ≥1 jets + MET

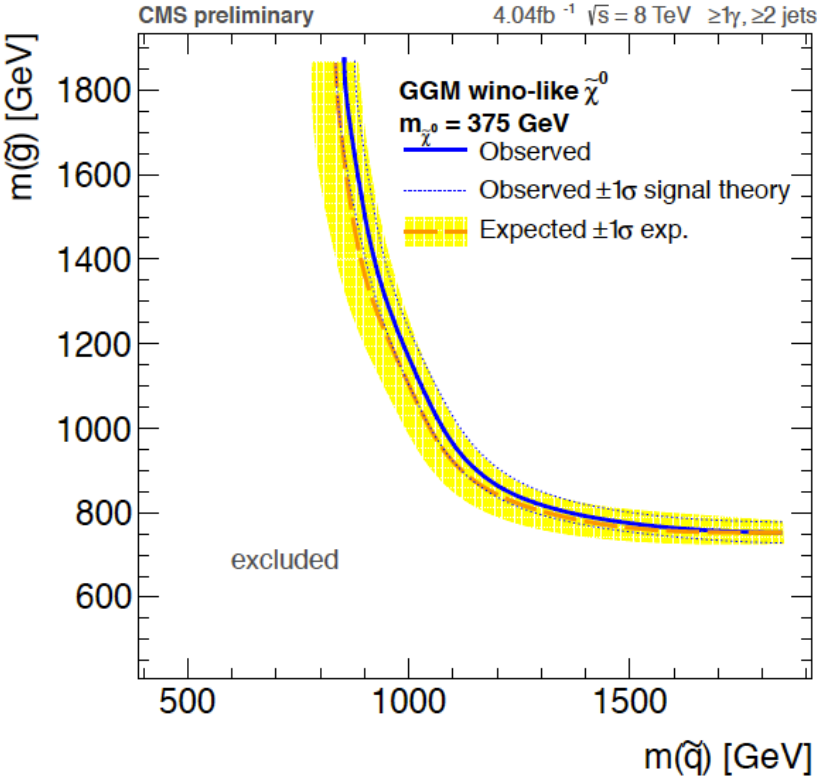


Interpretation: Wino-like NLSP

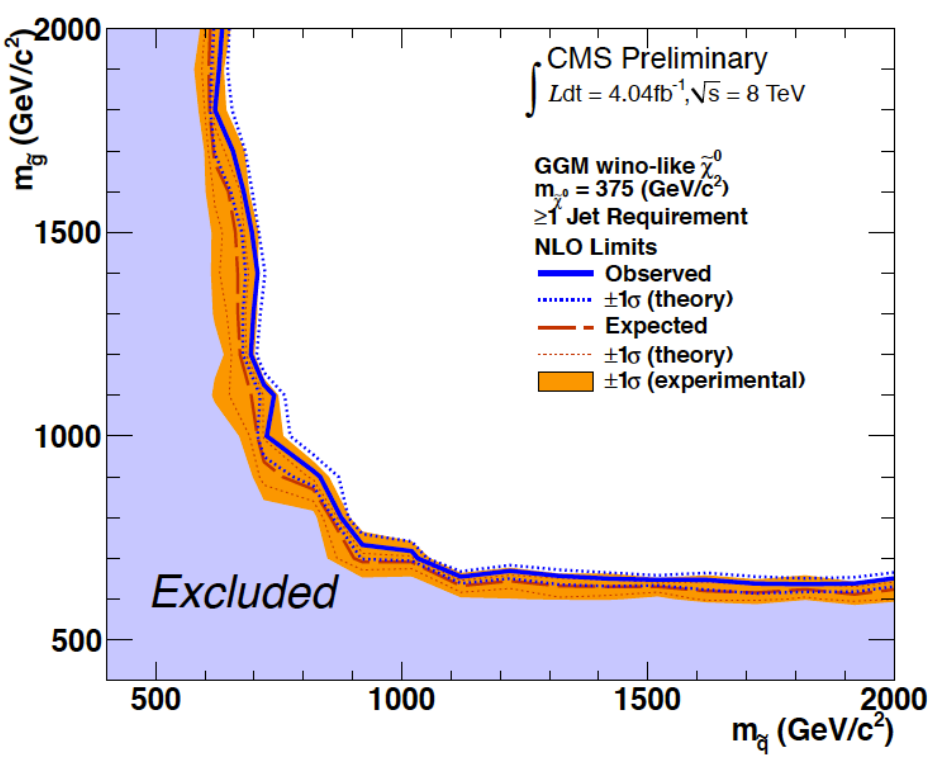
Wino-like GGM scan

$m_{\chi 0}$ = 375 GeV, $m_{squark,gluino}$ = 400-2000 GeV (step 80 GeV)
sleptons and all gauginos except NLSP @ 3.5 TeV

γ + ≥2 jets + MET



$\gamma\gamma$ + ≥1 jets + MET



Summary

- CMS analyses designed to cover a broad range of final state SUSY GMSB scenarios
  - = results updated with 4.04 fb^{-1} of 8 TeV data from 2012 running
  - = data-driven background extimate for QCD/EWK sources
  - = no excesses seen over SM predictions

- Exclusion limits set in bino- and wino-like neutralino NLSP
  - = bino like: m_{squark} < 1.2 TeV, m_{gluino} < 1.1 TeV excluded
  - = wino like: m_{squark} < 900 GeV, m_{gluino} < 800 GeV excluded

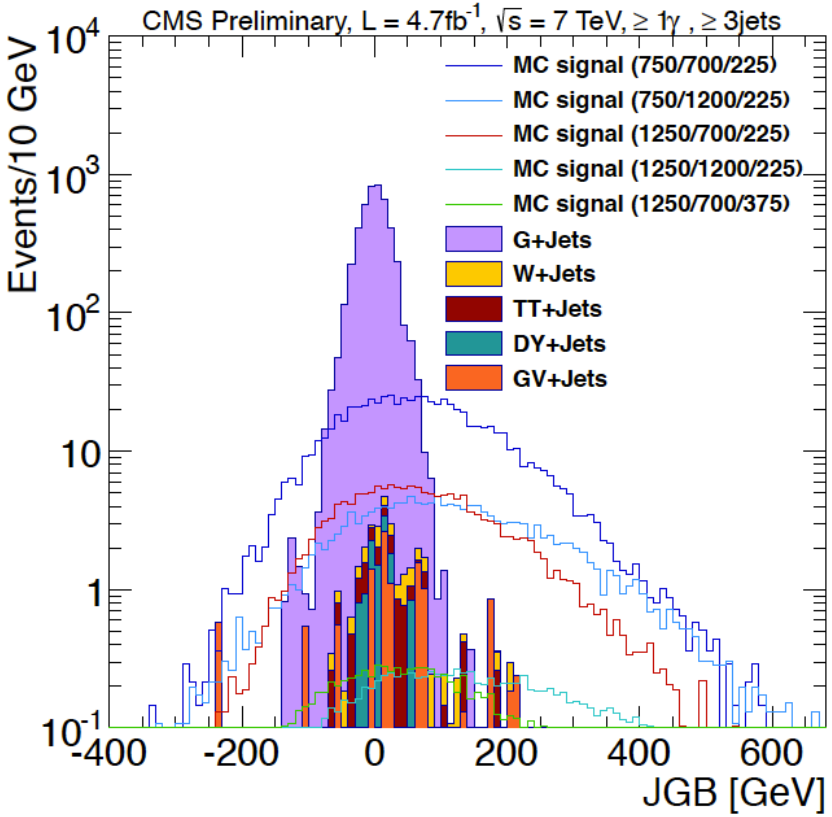
Backup

A Glimpse @ $\sqrt{s}$ = 7 TeV

Complementary signal selection method

$$JGB = |\sum \overrightarrow{p_T, jets}| - |\overrightarrow{p_T, \gamma}| = |\overrightarrow{E_T^{miss}} + \overrightarrow{p_T, \gamma}| - |\overrightarrow{p_T, \gamma}|$$

γ + ≥3 jets + JGB



[CMS Collaboration, PAS SUS-12-013]