Searches for New Physics in Photon+Missing Energy Signatures at ATLAS

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Outline

- Motivating Photon + Missing Energy search
- ATLAS searches with 1 fb\(^{-1}\) of 7 TeV data
- Interpretations in models of supersymmetry and universal extra dimensions
- Other searches with photons
- Future photon+missing energy searches
Motivation for Photon+Missing Energy

- High-energy photons provide a clean signature with limited Standard Model background
  - Clean photon signature allows for low-momentum trigger threshold at hadron colliders
  - Missing energy > 100 GeV comes from high-energy neutrinos in known weak decays or from gross detector mismeasurements
- Signature-based $\gamma + E_t^{\text{miss}}$ searches have few parts, yet yield insight into several interesting models of new physics beyond the Standard Model
  - Targeting more specific $\gamma + E_t^{\text{miss}}$ signatures improves sensitivity even more
- General enough to be open to unknown frontiers
Gauge-Mediated SUSY Breaking

- SUSY breaking occurs in a “hidden” or “secluded” sector
- Standard gauge interactions communicate the breaking to the usual MSSM fields via a messenger sector
  - Main feature/consequence is no flavor violation
- Key differences with respect to mSUGRA/cMSSM
  - SUSY breaking happens at a lower mass scale
  - Lightest SUSY particle is the gravitino $\tilde{G}$, with $m << \text{GeV}$
- Experimental signatures determined by nature of NLSP
  - Bino, Wino, or Higgsino – like gaugino
  - slepton, stau
- There are still several mass scale parameters to choose...
Minimal vs General Gauge Mediation

- Certain GGM considerations raised by Ruderman & Shih [arXiv:1103.6083] are important for LHC
- In MGM, messengers couple to both the SUSY-breaking sector and to the MSSM sparticles
  - Small number of parameters control couplings and relations: $\tan\beta$, $\mu$, $M_{\text{mess}}$, SUSY-breaking scale $\Lambda$, # copies of SU(5) messenger fields
  - Colored particles are much heavier than electroweak particles
- In GGM, mass relations are dropped
  - Colored particles can be much lighter than electroweak: light gluinos compare to heavy sleptons and squarks
  - Trade-off is much greater number of parameters and larger parameter space to explore
GGM Phenomenology

- We set all mass parameters (sparticle masses) to 1.5 TeV, except for the gluino and bino masses
  - This is a specific case that Tevatron cannot reach
  - Effectively shuts off weak production for this study
- SUSY pair production of color-charged sparticles through gluon interactions leads to cascade decay
  - We do not use the features of this cascade decay in our search
- If the lightest neutralino is “bino-like” [couplings similar to SM U(1) gauge boson], then \( \tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G} \)
  - We pick coupling parameters such that this decay is prompt

Final state signature: two high-\(E_T\) photons and missing energy
Universal Extra Dimensions

- All SM fields propagate through small-scale extra dimensions with typical $1/R = \text{TeV}$
- Each field appears as a tower of Kaluza-Klein states, with states for each field at
  $$m^2_{X(n)} = \frac{n^2}{R^2} + m^2_{X(0)}$$
- Radiative corrections break the tree-level degeneracy
  - Higher-$n$ states are separated by $\sim 100$ GeV
- One possibility: cascade decays down to LKP $- \gamma^*$
- If there are additional dimensions accessible only to gravity, then the LKP can decay to $\gamma + \text{G}$

Final state signature: two high-$E_T$ photons and missing energy
Dark Matter Connections

• Gauge mediation: gravitino is LSP, and NLSPs are short-lived, but is the dark matter purely gravitinos?
  – keV gravitinos overclose universe, but eV gravitinos are not enough to account for observed dark matter
  – Proposals of “entropy injection” after gravitino freeze-out, sufficiently diluting the keV gravitino abundance

• Universal extra dimensions
  – Possible candidates: KK photon, KK graviton with $1/R = \text{TeV}$

• Collider searches can play a role in constraining dark matter candidates, especially mass or dimensional scales
Earliest ATLAS Results

- Null search result interpreted in GGM framework
  - GGM benchmark points entered in HepData

![Graph showing ATLAS expected and observed limits for GGM: bino-like neutralino, $\tan\beta = 2$, $c\tau_{NLSP} < 0.1$ mm. The graph displays $m_{\tilde{g}}$ vs $m_\chi$ with limits at $\int Ldt = 36$ pb$^{-1}$, $\sqrt{s} = 7$ TeV. The ATLAS observed CL limit is shown in red, with ATLAS expected CL limit in blue. Additionally, CMS observed limit (35 pb$^{-1}$) is indicated in green with $+1\sigma$ uncertainty.]
Spectrum of the missing transverse energy in diphoton events as measured by ATLAS at the LHC, compared to the background expected from Standard Model processes (QCD, W decays) as well as to signals expected from a model of gauge-mediated supersymmetry breaking (GGM) and a model with one universal extra dimension (UED).

From the ATLAS Collaboration: Search for diphoton events with large missing transverse energy with 36 pb⁻¹ of 7 TeV proton–proton collision data with the ATLAS detector.
Overview of ATLAS Detectors
Integrated luminosity in ATLAS at 7 TeV during Mar-Nov 2011

(Stops in July and September to commission and study LHC)

Peak inst lumi: $3.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Fraction of “good quality” data collected

Luminosity-weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign.
Photon Reconstruction Improvements

How to reduce $e \rightarrow \gamma$ fakes and reduce large background contribution?

Define categories of

- **2-track conversions**: Transition Radiation consistent with electron; reconstructed vertex
- **1-track conversions**: Transition Radiation consistent with electron, missing hits in live pixel layers

Electrons not consistent with 1-track conversions are rejected.
ATLAS Search with 1 fb$^{-1}$ at 7 TeV

- Non-resonant diphoton search with large missing $E_T$
  - Assume diphotons are prompt (short-lived parent)
  - Appropriate for gauge mediation models with Bino NLSP and for 1 UED models

- Increased data (x30) gives hope for candidate events!

- Re-optimize event selection to maximize sensitivity
  - Expect largest background contrib from W+jets (incl. top quark)
  - Re-evaluate missing $E_T$ calculation and cut value
**Event Selection Criteria**

- **Diphoton trigger:** 2 loose $e/\gamma$ objects with $E_T > 20$ GeV
- **Two photons with tighter offline selection**
  - $E_T > 25$ GeV, $|\eta| < 1.81$ (excluding barrel/endcap crack region)
  - Calorimeter-based isolation to reject jets: not more than 5 GeV of additional energy within cone of $R = \sqrt{(\Delta \phi^2 + \Delta \eta^2)} = 0.2$
- **Missing transverse energy > 125 GeV**
  - Calculated from locally-calibrated calorimeter clusters
- **Primary vertex with at least 4 tracks**
  - This has little rejection power: initial state color must hadronize
- **Reject events with muon** $|z_0| > 1$ mm or $|d_0| > 2$ mm
Typical Photon Energies

- High-mass particles in decay chain lead to high-\(E_T\) \(\gamma\)
  - But note scale factors for signal! Need missing \(E_T\) cut

\[
\int L dt = 1.07 \text{ fb}^{-1}
\]

- Data 2011 (\(\sqrt{s} = 7 \text{ TeV}\))
- GGM \(m_\tilde{g} = 800 \text{ GeV}, m_\tilde{\chi} = 400 \text{ GeV} (\times 100)\)
- SPS8 \(\Lambda = 140 \text{ TeV} (\times 100)\)
- UED \(1/R = 1200 \text{ GeV} (\times 100)\)
Background Modeling

Simplify by modeling only the missing $E_T$ distribution [based on D0 technique in *PRL 105 (2010) 221802*]

- **Instrumental $E_T^{\text{miss}}$** from mismeasurement: $\gamma\gamma$, $\gamma$-jet, dijet
  - Modeled with “pseudo-photon” data template normalized to $\gamma\gamma$ data sample in background-dominated region

- **Real $E_T^{\text{miss}}$** from neutrinos in final state with fake photon
  - Electron faking photon: $W+\gamma$, $W+$jets (incl. top pairs)
  - Modeled using $e+\gamma$ control sample scaled by $e\rightarrow\gamma$ fake rate

- **Irreducible**, but tiny: $Z+\gamma\gamma$, $W+\gamma\gamma$
  - Calculated with electroweak Monte Carlo programs
Instrumental Missing ET Backgrounds

*Encompasses* $\gamma\gamma$, $\gamma$-jet, dijet with no true missing energy

- Define *pseudo-photon*: passes loose requirements but fails at least one tight criterion
- Control sample template constructed with
  - Two e/g trigger objects with ET>20 GeV (quite loose)
  - At least one *pseudo-photon* (veto evts with 2 tight photons)
- Absolute normalization given by fit to $E_T^{\text{miss}} < 20$ GeV
  - Some uncertainty from template composition; cross-check using a 0-jet $Z(e^+e^-)$ sample

Prediction for this background category: $0.8\pm0.3\pm0.6$ events
Real Missing ET Backgrounds

Encompasses $W+\gamma$, $W+jet$, $ttbar$ -- with or without true $\gamma$

- Scale $e\gamma$ data by $e\rightarrow\gamma$ fake rate (measured in Z peak)
- First, subtract contributions from instrumental bkgds
- Second, apply fake rate scaling to obtain prediction for the contribution to $\gamma\gamma$

Prediction for this background category: $3.1\pm0.5\pm1.4$ events
Backgrounds Prediction in Sidebands

- Sum all backgrounds, including irreducible contribution
- Compare in various sideband regions of the relevant kinematic distribution, here $E_T^{\text{miss}}$

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ range [GeV]</th>
<th>Data events</th>
<th>Predicted background events (Stat. uncerts only)</th>
<th>Irreducible</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>20881</td>
<td>Total: 5968 ± 29 QCD: 5951 ± 28 W/$t\bar{t}$($\rightarrow ev$) + X: 13.3 ± 8.1</td>
<td>3.55 ± 0.35</td>
</tr>
<tr>
<td>20–50</td>
<td>6304</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50–75</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75–100</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100–125</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Recall that the dominant backgrounds are predicted from orthogonal control samples
  - Expect signal contamination in those regions to be small
Results from Photon+MET Data

- Expect 4.1±0.6 events at high $E_T^{\text{miss}}$; observe 5
  - Model-indep. limit on new physics: <7.1 events @ 95% CL
Limit on Production Cross Sections

- Provide direct exclusion on gluino pair cross section
  - Assumes specific kinematics due to masses

\[ \text{Cross section [fb] 95\% CL} \]

\[ \int \text{Ldt} = 1.07 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

GGM: bino-like neutralino, tan\(\beta = 2\), \(c_{\tau_{\text{NLSP}}} < 0.1 \text{ mm}\)

\[ m_{\tilde{g}} \text{ [GeV]} \]
\[ m_{\tilde{\chi}} \text{ [GeV]} \]

\[ \tilde{g} \text{ NLSP} \]

\[ \text{ATLAS} \]
Signal Uncertainties

• SUSY signals are calculated at NLO with Prospino, and UED signals are calculated with new Pythia process

• Major signal uncertainties include:
  – PDF errors (esp. GGM at low x, high $Q^2$)
  – Renormalization/factorization scale variation (/2, *2)
  – Photon and missing energy reconstruction

• Total uncertainties for GGM case ($m_{\tilde{g}} = 800$ GeV)
  – Experimental uncertainties 6.6%
  – PDF and scale uncertainties: 31% (~10% for min. GMSB, UED)
  – These uncertainties vary over the benchmark planes

• Much discussion on quoting experimental and theoretical uncertainties separately, but they’re combined here
Interpretation in General Gauge Mediation

- Simplified model focused on gluino pair production
- All soft parameters are set to 1.5 TeV (decoupled)
Interpretation in Minimal Gauge Mediation

  – mGMSB parameters: \( N_{mess} = 1; \tan\beta = 15, \mu > 0, \frac{M_{mess}}{\Lambda} = 2 \)
  – This is actually a slope, with \( \Lambda \) as independent scale variable
  – Point 8 (SPS8) is defined with \( \Lambda = 100 \text{ TeV} \), giving \( m_{\tilde{g}} = 820 \text{ GeV} \)
• Tevatron has good sensitivity to direct neutralino production in this scenario, but LHC has caught up
  – This was one original motivation for considering GGM at LHC
• Snowmass benchmarks are not sacred, but they provide illustration of sensitivity to strong and weak production
  – Our own GGM points are preserved in HEPDATA database
Results for Snowmass SPS8 Benchmark

- First SPS8 sensitivity at pp collider
- $\sigma < (27-91) \text{ fb}$ or $\Lambda > 145$ TeV at 95% CL
- Sensitivity to neutralino mass comes from the parameter constraints of GMSB
Universal Extra Dimensions

- Model of 1 UED + N extra dimensions accessed by gravity
  - Typical compactification radius: $1/R = 1200$ GeV
  - Radiative mass correction cut-off scale: $\Lambda = 20/R$
- For $1/R \sim 1$ TeV, the branching ratio to $\gamma\gamma$ is close to 100%
  - By $1/R \sim 1.5$ TeV, the branching ratio is only 50%
- Typical first-level KK masses (vary by few % with $\Lambda R$):
  - $m_\gamma^1 = 1200$ GeV
  - $m_{\text{Quark}}^1 = 1387$ GeV
  - $m_{\text{gluon}}^1 = 1468$ GeV
Results for Universal Extra Dimensions

- $\sigma < (15-27) \text{ fb}$, depending on compactification scale $1/R$
- Model-specific limit: $1/R > 1.23 \text{ TeV}$ at 95% CL
- KK quark and gluon resonance masses shown for reference
• Published diphoton+missing energy signature search with interpretations in Phys. Lett. B 710 (2012) 519
• Total background: 4.1 ± 0.6 (stat) ± 1.6 (sys)
• 5 candidate events observed with $E_{t}^{\text{miss}} > 125$ GeV

• Model-independent limit: 7.1 events at 95% CL
• Model-dependent interpretations:
  – GGM: $m_{\text{gluino}} > 805$ GeV as long as $m_{\text{bino}} > 50$ GeV
  – SPS8: $\Lambda > 145$ TeV
  – UED: $1/R > 1.23$ TeV
High-Mass Diphoton Search

• Signatures are striking enough without missing energy
• One possible source of diphotons: Kaluza-Klein towers of graviton excitations due to extra dimensions
  – ADD (Arkani-Hamed—Dimopoulos—Dvali) model: flat, compactified dims. of compactification radius $R$ give rise to resonance mass splitting of $1/R$ (typically small) $\rightarrow$ continuous spectrum
  – RS (Randall--Sundrum) model: warped geometry dim. give large resonance mass splitting $\rightarrow$ resonances $O(1 \text{ TeV})$ apart
• In one case, the signal is non-resonant enhancement; in the other, a new high-mass resonance
• Decay to photon pairs is 2x the decay to lepton pairs, due to spin-2 graviton
Results of ATLAS Search

- Dominant SM $\gamma\gamma$ shape is PYTHIA reweighted to DIPHOX
- Backgrounds normalized in sideband $140 < m_{\gamma\gamma} < 400$ GeV
- p-value (prob. to find greater discrepancy) is 0.28
Randall-Sundrum Interpretation

- Limits on cross section, given kinematics of certain $m_G$
- Re-interpreted as limits on coupling to SM fields as a function of $m_G$

![Graph showing limits on cross section as a function of $m_G$.](image)

\[ \int L \, dt = 2.12 \, fb^{-1} \]

\[ \int L \, dt = 1.08 \, fb^{-1} \]

\[ \int L \, dt = 1.21 \, fb^{-1} \]

\[ \sqrt{s} = 7 \, TeV \]

- Combined with similar dilepton resonance results
New Ideas for 5 fb$^{-1}$ Analysis

• More data, but only a factor of 5; can we do better?
  – Still dominated at very high $E_T^{\text{miss}}$ by fake photons

• Some possibilities for tightening criteria:
  – Photons should not pass “medium” electron criteria
  – Photon conversion location should not be reconstructed in pixel system (likely to be electron)

• Tuned event selections for different regions of GGM $m_{\tilde{g}}$ vs $m_{\tilde{\chi}}$ plane
Gauge Mediation Beyond Diphotons

• We have been educated by Ruderman and Shih!
  – “General Neutralino NLSPs” [arXiv:1103.6083], thorough treatment of GGM neutralino signatures

• Bino, Wino, and Higgsino NLSPs (or mixtures thereof) give a rich spectrum of search signatures
  – Each final state targeted by a signature-based search

• Photon channels enjoy triggering advantage over more general jets+$E_T^{\text{miss}}$ searches
  – Low statistics makes data-driven bkgd estimates challenging

• Leave no stone unturned...
• Signature of Wino NLSP
  – Charged and neutral winos are co-NLSPs

• Search at LHC benefits from strong production cross section, followed by cascade decays to winos
**bb+Photon+Missing Energy**

- Signature of NLSP bino-higgsino admixture
- Targeted search seems to out-perform general jets + missing energy searches

- For $|\mu|<0$ and small $\tan \beta$, sizable decay to Higgs and photon
- $\gamma+b+E_T^{\text{miss}}$ is also interesting as model-independent search
- Since top quark pairs are main bkgd, use $bb$ signature
GMSB Searches without Photons

- Search for 2 OS leptons + $E_T^{\text{miss}}$ matches some NLSPs
- Interpreted in minimal GMSB as parameter exclusion

\[ \text{Plan to extend this to all relevant search signatures; some work to be done on defining common parameters} \]
Possible LHC pp Run Schedule

- 2010-2011: 7 TeV, collected 5 fb\(^{-1}\) total
- 2012: 8 TeV, plan to collect 15 fb\(^{-1}\) more
- 2013-2014: 18-month shutdown for “Phase 0” upgrade
- 2014-2017: 14 TeV, 50 fb\(^{-1}\) (1 \(\times\) 10\(^{34}\) cm\(^{-2}\)s\(^{-1}\))
- 2018: 12-month shutdown for “Phase 1” upgrade
- 2019-2021: 14 TeV at full design luminosity, 300 fb\(^{-1}\)
- 2022: 12-month shutdown for “Phase 2” upgrade
- 2023-2030?: 14 TeV, potentially 3000 fb\(^{-1}\)
Summary

- The Large Hadron Collider is operating smoothly at 8 TeV, and the performance of the ATLAS experiment matches design expectations

- Searches for new physics in photon plus missing energy signatures put strong constraints on new physics models, AND...

- Motivate exploration in new signatures that give extended sensitivity for ATLAS

- Stay tuned for more news from the 8 TeV run this year!
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Backup Slides
CMS Result in Photons+Missing Energy

- Photon $E_T > 40, 25$ GeV; missing $E_T > 100$ GeV
- Jet $p_T > 30$ GeV

J. Nielsen

CMS Preliminary

$\int L dt = 4.7$ fb$^{-1}, \sqrt{s} = 7$ TeV

$m_{\tilde{g}} = 2500$ (GeV/c$^2$)

At least 1 jet requirement

NLO Limits

- Observed
- ±1σ (theory)
- Expected
- ±1σ (theory)
- ±1σ (experimental)

Excluded

$\tilde{g}$ NLSP

CMS PAS SUS-12-001