BSM Searches with Photons at the LHC

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Dark Matter Introduction



• Key to collider searches: rotate Feynman diagrams assumed in directdetection experiments (use s-channel, instead of t-channel mode)



Dark Matter Signature





- Use QED/QCD initial state radiation (ISR) to "tag" DM events
 - results in a "monophoton" or "monojet" signature with missing transverse energy (MET) balancing the photon or jet



Dark Matter Phenomenology





• treat as an effective theory where we integrate out a massive mediator

$$\begin{split} \mathcal{O}_{\rm V} &= \frac{(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2} & \text{s-channel vector} \Leftrightarrow \text{spin independent (SI)} \\ \mathcal{O}_{\rm A} &= \frac{(\bar{\chi}\gamma_{\mu}\gamma_5\chi)(\bar{q}\gamma^{\mu}\gamma_5q)}{\Lambda^2} & \text{s-channel axial-vector} \Leftrightarrow \text{spin dependent (SD)} \\ \mathcal{O}_{\rm t} &= \frac{(\bar{\chi}P_{\rm R}q)(\bar{q}P_{\rm L}\chi)}{\Lambda^2} + ({\rm L}\leftrightarrow{\rm R}) & \text{t-channel} \Leftrightarrow (\text{mostly}) \text{ SI} \\ \\ \text{SI and SD} \\ \text{g-nucleon } \sigma \text{:} & \sigma_{\rm SI} = \frac{9}{\pi} \left(\frac{\mu}{\Lambda^2}\right)^2 & \sigma_{\rm SD} = \frac{0.33}{\pi} \left(\frac{\mu}{\Lambda^2}\right)^2 \\ & (\mu \text{ is the reduced mass of the } \chi \text{ and proton}) \end{split}$$

Bai, Fox, and Harnik, JHEP **12** (2010) 048

CMS Monophoton: Selection



• Require a single photon in an event with...

- High transverse momentum: p_T>145 GeV
- Central (best reconstruction purity): $|\eta| < 1.44$
- "particle flow" MET > 130 GeV
- photon must be isolated separately in the tracker, hadronic & electromagnetic calorimeters
- Suppress electroweak backgrounds with lepton (track) veto
 - Reject events with a track with $p_T>20$ GeV and $\Delta R>0.04$ from γ
- Suppress QCD background with jet veto
 - Reject events with a jet with $p_T>40$ GeV and $|\eta| < 3.0$ and $\Delta R>0.5$ from γ



73 events pass selection (and do not fail either veto)

CMS Monophoton: Photon Selection



- Isolation Criteria
 - Ecal Isolation: Sum E_T of the ECAL crystals within a hollow cone of $0.06 < \Delta R < 0.40$ about the supercluster, excluding a strip in η of 0.04, is $< 4.2 + 0.006 \times p_T$
 - Hcal Isolation: Sum E_T of the HCAL towers within a hollow cone of $0.15 < \Delta R < 0.40$ about the supercluster is $< 2.2 + 0.0025 \times p_T$
 - **Track Isolation**: Sum of p_T of tracks in a hollow cone of $0.04 < \Delta R < 0.40$ about the supercluster, excluding a strip in η of 0.015, is $< 2.0 + 0.001 \times p_T$
 - Had/EM: The hadronic energy within $\Delta R < 0.15$ about the photon super- cluster divided by the electromagnetic energy in the supercluster is < 0.05
- Shower shape criteria
 - $\sigma_{\eta\eta}$: The "width" of the shower in η -space is < 0.013 and >0.01 (to reject spikes)
 - $\sigma_{\varphi\varphi}$: The "width" of the shower in φ -space is >0.01 to reject spikes
- Timing
 - Largest inter-cluster time difference between crystals with E>1 GeV in cluster is < 5 ns
 - Timing of the crystal that seeds the clustering is ±3 ns of "ECAL 0"
- Electron rejection
 - No hits in the pixel tracker that seed a track that points to the ECAL cluster

CMS Monophoton: Monte Carlo Backgrounds

- $Z(vv)+\gamma$ (45.3 ± 6.8 events)
 - Irreducible background
 - Generated by Pythia; scaled to theoretical NLO cross section from Bauer
 - Detailed EWK study of this process at CMS in [PLB 701 (2011) 535]
- W+γ
 - lepton escapes isolated-track veto
 - Generated by Madgraph; scaled by NLO K factor from MCFM
- γ+jet
 - jet veto not flagged
 - due to jet/MET mis-measurement
- γγ
 - due to MET mis-measurement
- Contribution from W+ γ , γ +jet, and $\gamma\gamma$: 4.1 ± 1.0 events





CMS Monophoton: Jets Backgrounds



- Jets mimicking photons (11.2 ± 2.8 events)
 - dominated by jets fluctuation to a hard $\pi^0 \, \text{or} \, \eta$
 - Probability for a jet to fake a photon is determined by a range of factors
 - kinematics (p_T), geometry (detector effects), jet structure (narrow versus wide), quark versus gluon, light versus heavy, etc.
 - Varies more than order of magnitude <0.1% to ~1%
- Use a "fake rate" technique
 - Rather than parameterize in terms of jets, find a "common denominator" i.e. a loose photon
 - by which I mean a photon with looser isolation/shape criteria and not tight
 - Basic concept: measure the ratio of tight to loose photons in control sample and apply it to the loose signal sample
 - Control sample has the same (loose) photon selection as the signal, but with MET<20 GeV and no track/jet vetos
 - Use $\sigma_{\eta\eta}$ templates to statistically subtract out prompt photon contribution to the control sample
- Dominant uncertainty comes from the statistical uncertainty on the loose signal sample

CMS Monophoton: Out-of-Time Backgrounds



- Out-of-time backgrounds (11.1 ± 5.6 events)
 - dominated by beam-halo events
 - there is also a tiny contribution from noise/spikes
- Background Estimation technique
 - Release both timing and shower-shape criteria and form timing templates for each type of out-of-time background
 - beam-halo timing template: find energy in the HCAL endcap "upstream" of the ECAL barrel photon
 - noise/spike timing template: reverse shape cuts to select for noise
 - prompt template: invert tracking isolation critera
 - Fit full timing distribution (±25 ns) for prompt, noise, and beam-halo templates
 - Reapply timing and shower shape cuts to estimate residual contribution

CMS Monophoton: Electron Backgrounds



- Electrons mimicking photons (3.5 ± 1.5 events)
 - Principally from W→ev
 - Electrons and photons are distinguished by hits in the pixel tracker. The inefficiency is small (<0.5%) and well-predicted in simulation
 - Select signal events but with an inverted pixel-seed veto (i.e. electron enhanced)
 - Extrapolate from the inverted sample based on known inefficiency

CMS Monophoton: Background Summary





Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ +jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu \bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73

Data show generally good agreement with standard model predictions (both rate and shape)

CMS Monophoton: Event Display





CMS Monophoton: Limit Setting



- Model signal with Madgraph4 (matrix element) + Pythia6 (showering)
 - Λ=M=10 TeV (mediator couplings set to unity)
 - small systematic uncertainties from photon energy scale (2.3%), pile-up modeling (2.4%), jet-energy scale (1.2%), etc.
- Use modified frequentist CL_S prescription to set 90% CL limits on production cross section for additional signal contribution

MICAU	Vector		Axial-Vector	
M_{χ} [Gev]	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	14.3 (14.7)	572 (568)	14.9 (15.4)	565 (561)
10	14.3 (14.7)	571 (567)	14.1 (14.5)	573 (569)
100	15.4 (15.3)	558 (558)	13.9 (14.3)	554 (550)
200	14.3 (14.7)	549 (545)	14.0 (14.5)	508 (504)
500	13.6 (14.0)	442 (439)	13.7 (14.1)	358 (356)
1000	14.1 (14.5)	246 (244)	13.9 (14.3)	172 (171)

90% CL limits for V and AV couplings (expected limits shown in parentheses)

CMS Monophoton: Cross Section Limits





 XENON100: PRL 107 (2011) 131302
 SIMPLE: PRL 105 (2010) 211301

 CDMS 2010: Science 327 (2010) 1619
 COUPP: PRL 106 (2011) 021303

 CDMS 2011: PRL 106 (2011) 131302
 IceCube: PRD 85 (2012) 042002

 CoGeNT: PRL 106 (2011) 131301
 Super-K: ApJ 742 (2011) 78

 CDF: arXiv:1203.0742 (submitted to PRL)

CMS Monojet: Cross Section Limits





Presents best limits for low mass (<6 GeV) in the SI mode and up to ~200 GeV in the SD mode

Extra Dimensions



- Arkani-Hamed, Dimopoulos, Dvali (ADD) proposal: suppose that the fundamental scale of gravity, is ~10³ GeV, not 10¹⁹ GeV [Phys. Lett. B429 (1998) 263]
 - The gravitation strength is diluted below the TeV scale due to the presence of extra spacial dimensions
 - SM lives on the surface (brane-world scenario), while gravity propagates through the "bulk"



Phenomenology



- Compactified dimensions result in "particle-in-a-box" phenomenology
 - Results in towers of excitations: Kaluza-Klein (KK) gravitons
 - KK gravitons are massive in 3+1 spacetime with energy spacings on order the inverse size of the extra dimension
 - Enhanced production cross section since there are many excitable modes and KK graviton couples to SM with gravitational strength
- Effects grow at high energy → low energy phenomenology remain insensitive to extra dimension effects



• Energy spacings smaller than detector resolution with high energy final states

Virtual Graviton Production



- Pair production of particles is enhanced through virtual graviton process
 - Many finely-spaced off-shell modes contribute to production
 - Exhibits non-resonant, continuum excess of dilepton/ diboson events at high mass



- diphoton production dominates, because spin-2 graviton can decay in the s-wave
- Sum of KK states is divergent, so a UV cutoff to the sum must be applied
 - Assign cutoff at scale M_S : relationship to M_D is determined by the (unknown) UV completion of the theory
 - Several equivalent conventions exist for how to define M_S:

$$\eta_{G} = \frac{\mathcal{F}}{M_{S}^{4}} \qquad \begin{array}{l} \mathcal{F} = 1 \quad (\text{GRW: Nucl. Phys. B544 (1999) 3}) \\ \mathcal{F} = \begin{cases} \log(M_{S}^{2}/\hat{s}) & \text{if } n_{\text{ED}} = 2 \\ 2/(n_{\text{ED}} - 2) & \text{if } n_{\text{ED}} > 2 \end{array} \quad (\text{HLZ: Phys. Rev. D59 (1999) 105006}) \\ \mathcal{F} = \pm \frac{2}{\pi} \quad (\text{Hewett: Phys. Rev. Lett. 82 (1999) 4765}) \end{array}$$

Direct Production of Gravitons in ADD



- Direct Graviton production is also possible in this model
 - Graviton propagates in the bulk: appears as missing ET in the our 3+1 dimensional detector



• Challenging final state: monophoton, monojet, Z+MET

Randall-Sundrum Graviton Production



- Another model of extra dimensions [PRL 83 (1999) 3370; PRL 83 (1999) 4690]
 - single, bounded extra dimension with AdS metric
 - Fundamental Planck scale determined by the warped geometry



- Phenomenology
 - No low mass KK excitations, and couplings are determined by the weak scale
 - Particle-in-a-box phenomenology: many resonances, but first few appear at the TeV scale, and may be resolved distinctly (narrow)
 - Can re-parameterize k and r into the width and mass of the first KK excitation

CMS Monophoton: ADD Interpretation



- Can interpret analysis in the ADD model of extra dimensions
 - Set limits on the fundamental Planck scale M_D as a function of the number of extra dimensions



Diphoton Searches for Extra Dimensions at CMS and ATLAS



- Look for excess of diphoton production above SM expectation: extra dimensions signature is central and has large invariant mass, $m_{\gamma\gamma}$
 - Use sherpa to simulate signal+SM together (to include interference effects)
- Also look for Randall-Sundrum graviton resonances



- Primary background is SM diphoton production
 - Recale Pythia generation to NLO prediction from diphox ($m_{\gamma\gamma}$ dependent K factor)
- Secondary backgrounds due to jets mimicking isolated photons
 - Use similar technique to monophoton search

Diphoton Spectra





Search for RS Gravitons





CMS GMSB Searches for Photons+Jets +MET



- Canonical gauge-mediated SUSY breaking searches look for Photon(s)+MET
 - diphoton: $p_T(\gamma 1)>40$ GeV, $p_T(\gamma 2)>25$ GeV, 1 jet, and large MET
 - photon+jet: pT(γ)>80 GeV, 2 jets, and large MET

NLSP type	$\gamma + 2 \text{ jets} + E_{\text{T}}^{\text{miss}}$	$\gamma\gamma$ + jet + $E_{\rm T}^{\rm miss}$
Bino	$jets + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow jets + \gamma + Z + \tilde{G}\tilde{G}$	$ \text{ jets} + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \text{ jets} + \gamma \gamma + \tilde{G}\tilde{G} $
Wino	$ \begin{array}{c} jets + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to jets + \gamma + Z + \tilde{G}\tilde{G} \\ jets + \tilde{\chi}_1^0 \tilde{\chi}_1^{\pm} \to jets + \gamma + W^{\pm} + \tilde{G}\tilde{G} \end{array} $	$ ext{jets} + ilde{\chi}_1^0 ilde{\chi}_1^0 o ext{jets} + \gamma \gamma + ilde{G} ilde{G}$



CMS GMSB Limits





Conclusions



- Limits demonstrate that hadron-collider experiments can offer an important piece to the dark-matter puzzle
 - Of course, any observation of a monophoton/monojet excess must be interpreted in the context of other searches for DM
 - too many other theories produce the same signatures; it's unlikely that they could be conclusively disentangled
- But, collider searches do have distinct advantages
 - Sensitivity to very low mass DM
 - Does not pay a large penalty for spin-dependent interactions
 - DM is produced directly; not sensitive to systematic uncertainties related to galactic density, velocity dispersion, etc.
- Diphoton searches are excluding large space of parameters for ADD and RS models of extra dimensions
 - Increase in \sqrt{s} much more important than increase in lumi for these searches
 - We are waiting to see what lies in store at 8 TeV