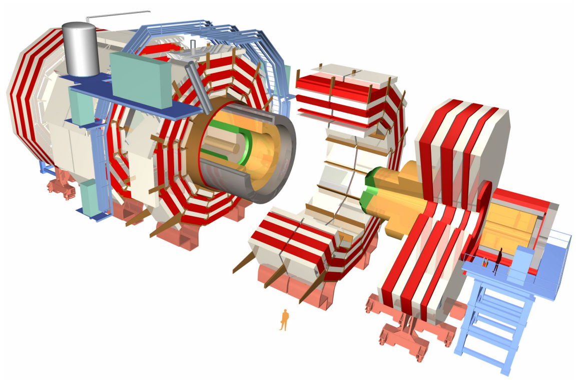
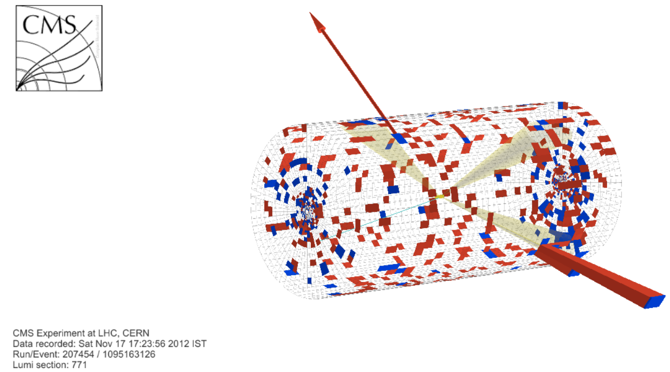
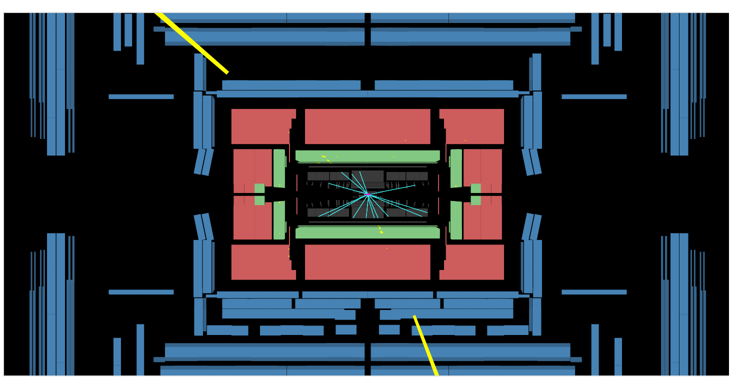


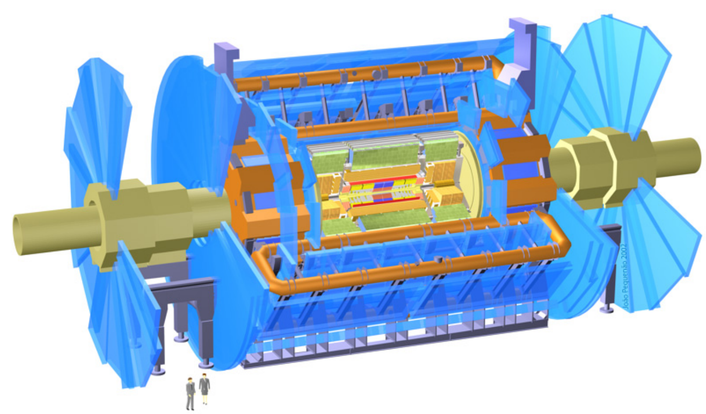


Mono- and Di-photon Searches at the LHC

Toyoko Orimoto, Northeastern University

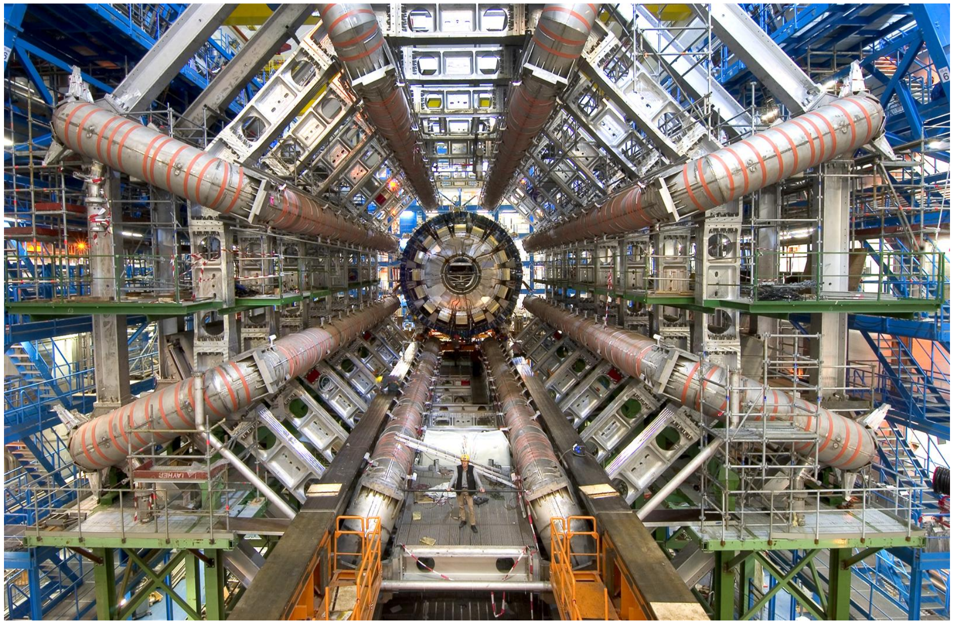
Astroparticle Physics 2014

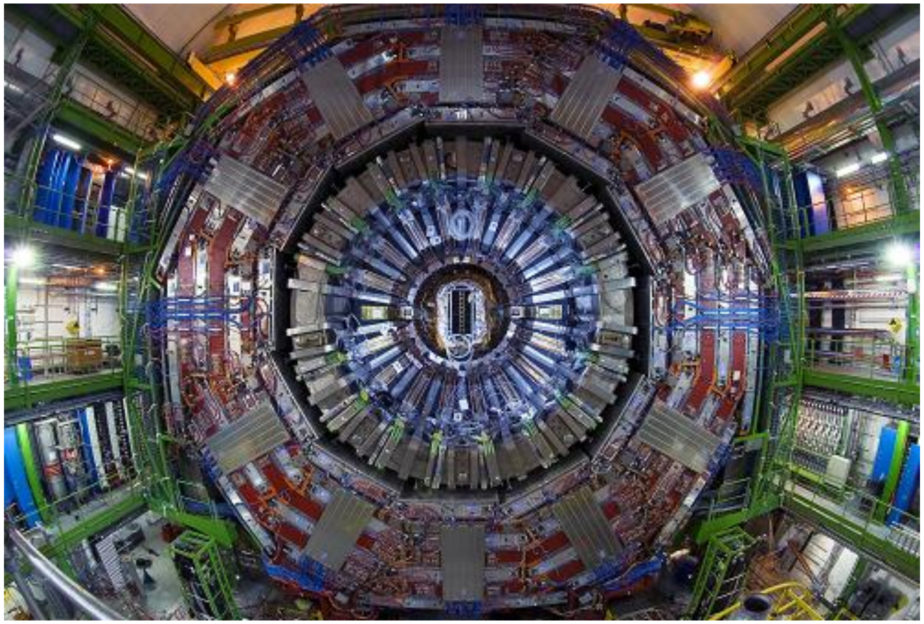




Introduction

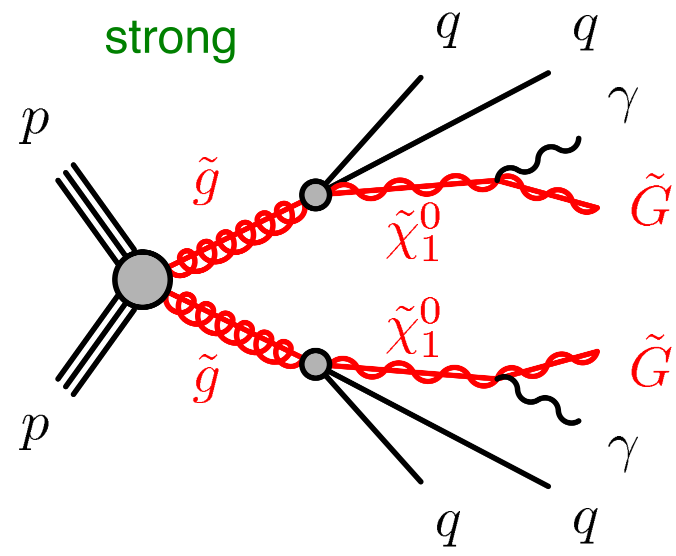
- ATLAS & CMS are two large, general purpose particle detectors
- One of our main goals is to discover a dark matter candidate particle (or other new physics) at the LHC
- Will highlight the most recent SUSY/BSM results from ATLAS & CMS studies with photon(s) in the final state
- High energy photons are among the cleanest and lowest background signatures at the LHC

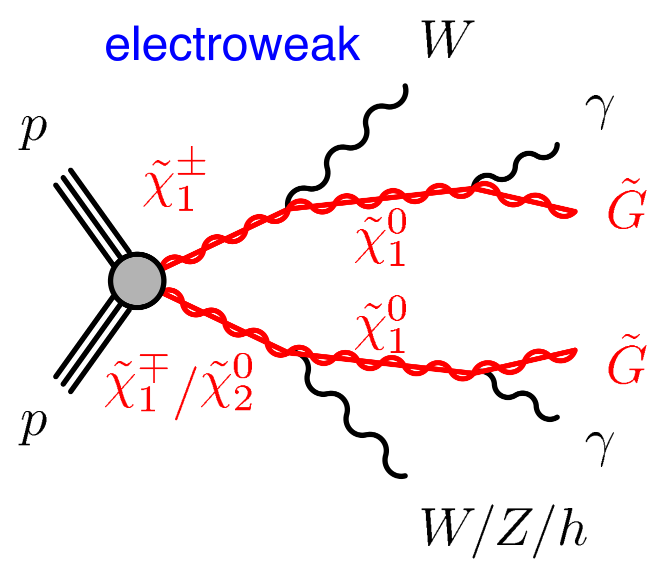




SUSY with Diphoton+MET

- General Gauge Mediation
- Gravitino is LSP
- NLSP is bino-like lightest neutralino ($\chi^0{}_1$), which decays predominately to gravitino (G) + photon
- Two production modes:
  - Strong production: NNLSP is gluino & SUSY events induced by gluino pair production
  - Electroweak production: NNLSP is wino ($\chi^0{}_2$ and $\chi^{\pm}{}_1$)
- We expect two energetic photons and significant missing transverse energy (MET)





SUSY with Diphoton+MET

<u>Backgrounds grouped into three primary components:</u>

1. "QCD": $\gamma\gamma$, γ + jet and multijet events with at least one jet mis-reconstructed as a photon
   - Estimated using data-control sample
2. "Electroweak": primarily W + X (where 'X' can be any number of jets + $\leq$ 1 photon) & tt events
   - Typically have at least one electron faking photon; Estimated using electron-photon data control sample
3. "Irreducible": W and Z bosons produced in association with 2 γ, with subsequent decays to one or more ν
   - W background is dominant and estimated using $\gamma\gamma l$ sample, while Z is estimated with MC

SUSY with Diphoton+MET

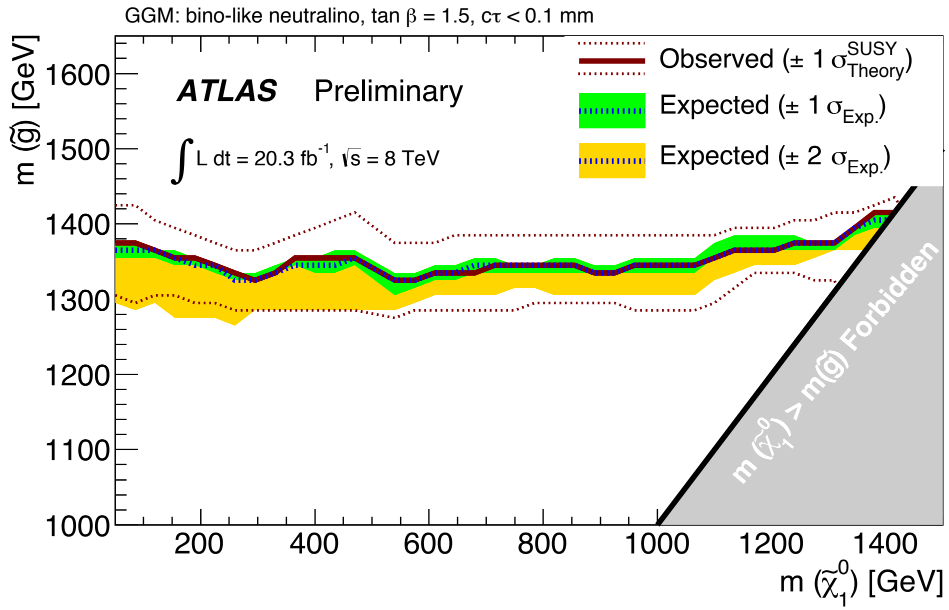
- Events must have ≥ 2 isolated photons E_T > 75 GeV & |η| < 2.4; jets required to have p_T > 30 GeV and |η| < 2.8
- To maximize sensitivity over wide range of model parameters (& kinematic properties), different signal regions (SR) optimized for:
  - SP1 & SP2: strongly-produced SUSY states at high mass
  - WP1 & WP2: weakly-produced SUSY states at interm. mass
  - Model-independent signal region (MIS) imposing no cut on mass scale variables, only minimum MET

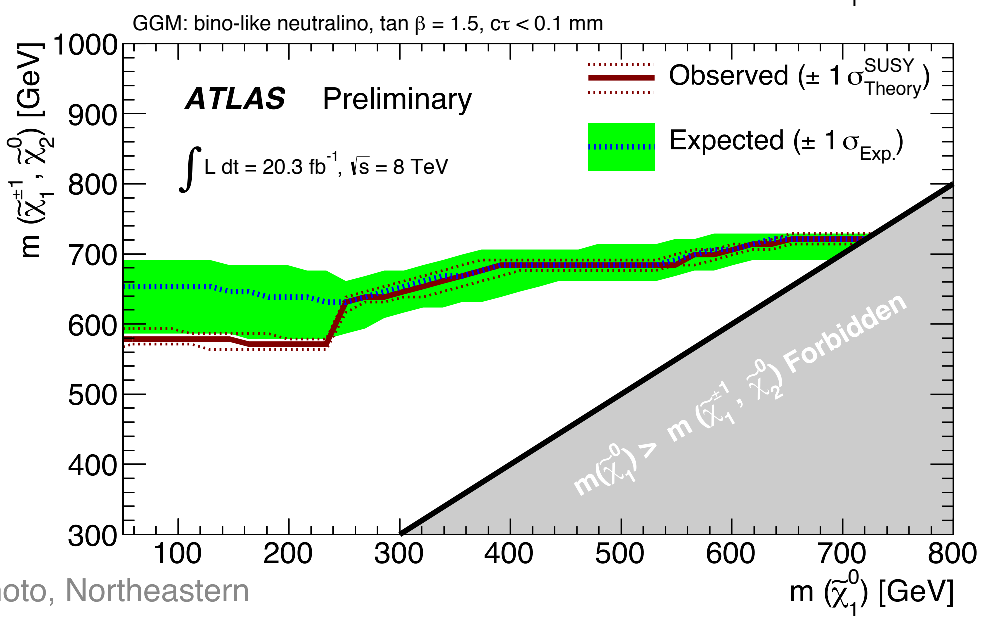
Background	SP1	SP2	WP1	WP2	MIS
QCD	$0.00^{+0.20}_{-0.00}$	$0.22^{+0.53}_{-0.22}$	0.29 ± 0.29	0.89 ± 0.60	0.73 ± 0.53
Electroweak	< 0.02	0.02 ± 0.02	0.15 ± 0.07	0.67 ± 0.22	0.24 ± 0.10
$W(\to \ell\nu) + \gamma\gamma$	0.03 ± 0.02	0.02 ± 0.01	0.44 ± 0.18	0.74 ± 0.27	0.47 ± 0.19
$Z(\to \nu\bar{\nu}) + \gamma\gamma$	< 0.01	< 0.01	0.13 ± 0.07	0.08 ± 0.04	0.15 ± 0.08
Total	$0.03^{+0.20}_{-0.02}$	$0.26^{+0.53}_{-0.22}$	1.01 ± 0.36	2.38 ± 0.69	1.59 ± 0.58
Observed events	0	0	1	5	2

ATLAS-CONF-2014-001

SUSY with Diphoton+MET

- **No evidence for new physics in 20.3 fb^{-1} of 8 TeV data**
- 95% CL on # events observed, translated to limits on the visible σ for new physics, then to limits on masses
- **Lower limits on masses of gluino (1280 GeV) & wino (570 GeV) for bino masses above 50 GeV**
- Largest systematic uncertainty from photon energy scale (11-17%) and jet energy scale (20-22%)

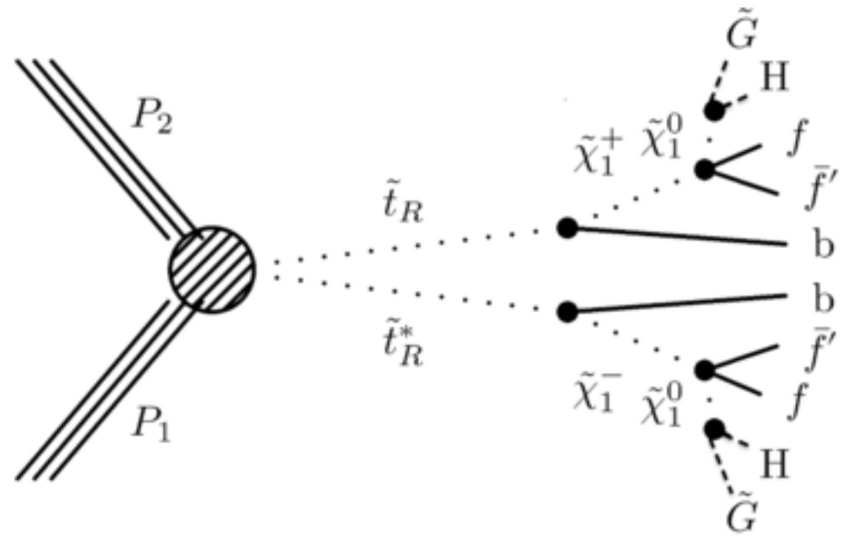




ATLAS-CONF-2014-001

SUSY Top Squark/Higgsino

- Search for "natural" SUSY with GMSB; assume only top squark & Higgsino are accessible
- The lightest chargino (χ_1^+) and neutralinos (χ_1^0, χ_2^0) are almost pure Higgsinos and therefore almost mass-degenerate
- For significant fraction of parameter space, lightest neutralino decays as $\chi_1^0 \rightarrow$HG
- Final state of two Higgs bosons, MET from gravitino, and in the case of strong production, two b-quark jets from top squark decay



- Require at least one Higgs decay to $\gamma\gamma$ and at least two b-jets are present from either Higgs or top squark decays

SUSY Top Squark/Higgsino

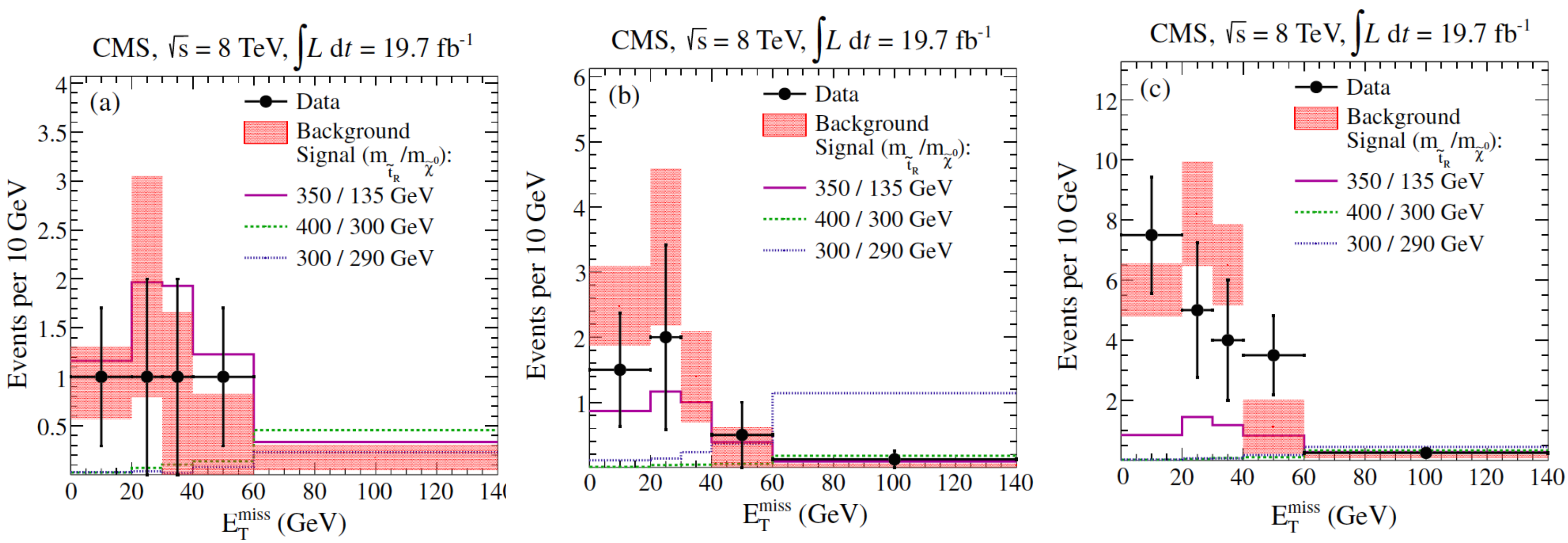
- Require additionally 2 central photons (p_T > 40, 25 GeV) and ≥ 2 jets (E_T > 30 GeV, |η| < 2.4 and loose b-tag)
- γγ in final state allows use of diphoton mass sidebands for a data-driven estimate of the background, without sensitivity to the exact composition of the background
- Background dominated by QCD production of γγbb & γbb + jet
- Separate events into three different background categories:
  1. At least one additional b-jet in addition to the two
  2. Invariant mass of the two b-jets is within Higgs mass window
  3. All other events
- For small top squark-Higgsino mass differences, most of signal populates category (2), while for large differences (1) and (3)

CMS: PRL 112, 161802 (2014)

SUSY Top Squark/Higgsino

- Power law fit to γγ mass sidebands to normalize background distributions
- MET is most sensitive variable wrt exp. limits

Category $m_{\sim tR}/m_{\chi 01}$ (GeV)	(i)	(ii)	(iii)
Signal 350/135	10.7	2.0	6.8
Signal 300/290	2.1	10.1	3.9
Signal 400/300	4.0	1.4	2.8
Expected background	6.7 ± 1.4	10.5 ± 1.8	29.7 ± 2.8
Observed	6	7	33

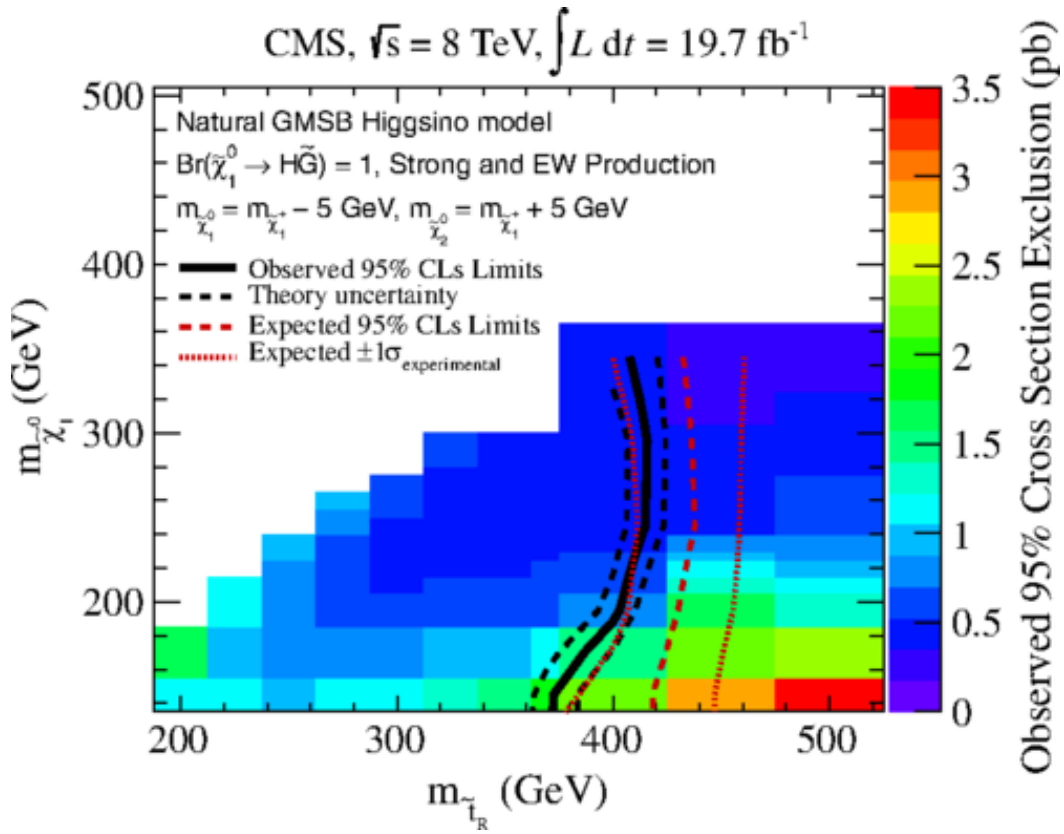


CMS: PRL 112, 161802 (2014)

SUSY Top Squark/Higgsino

- Data (19.7 fb^{-1} of 8 TeV) agrees with expected background and thus limits are calculated

- Top squark masses below 360 to 410 GeV are excluded at 95% CL
- Largest uncertainty is from statistical uncertainty in background determination
- Dominant systematic uncertainty from b-jet ID efficiency & jet energy scale (between 1-17%)



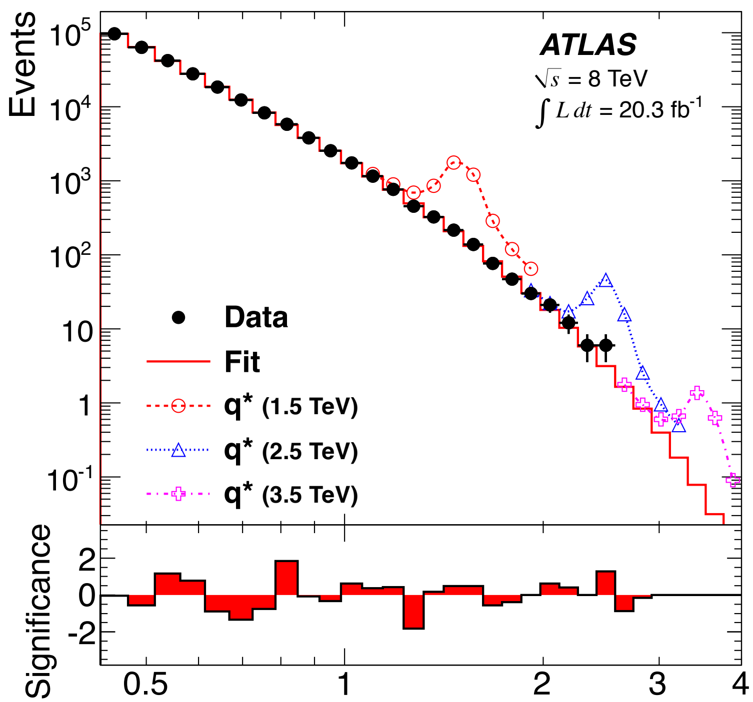
Exotic Photon+Jet

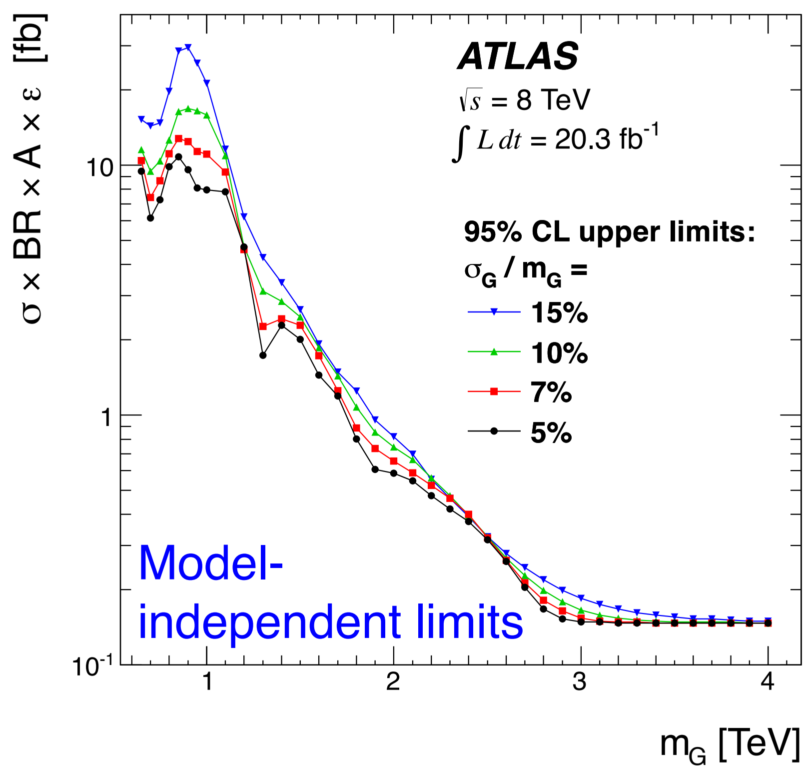
- Several exotic production mechanisms that can produce massive γ + jet final states:
  - Non-thermal quantum black holes (QBHs): can be produced with masses ~M_D at LHC as a consequence of large ED; would evaporate quickly and decay into few particles
  - Excited quarks: produced via fusion of quark and gluon; would provide evidence that quarks have substructure
  - Also explore generic Gaussian-shaped resonance with arbitrary σ
- SM backgrounds arise from:
  - γ + jet, primarily from qg scattering
  - Radiation off of final-state quarks
  - Dijet or multijet events
- Require ≥ 1 central γ candidate & ≥ 1 jet candidate, each with $p_T > 125$ GeV

ATLAS: Phys. Lett. B 728C (2014) 562-578

Exotic Photon+Jet

- Background is smoothly falling and thus can fit for data-driven background estimate
- Functional form validated on MC and data control samples
- No significant excess observed in 20.3 fb^{-1} of 8 TeV data



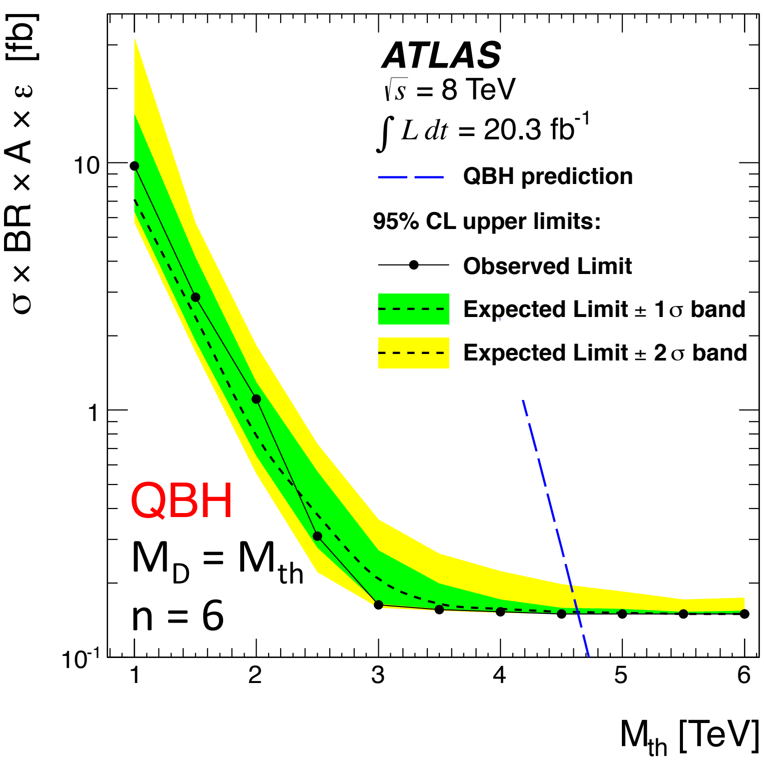


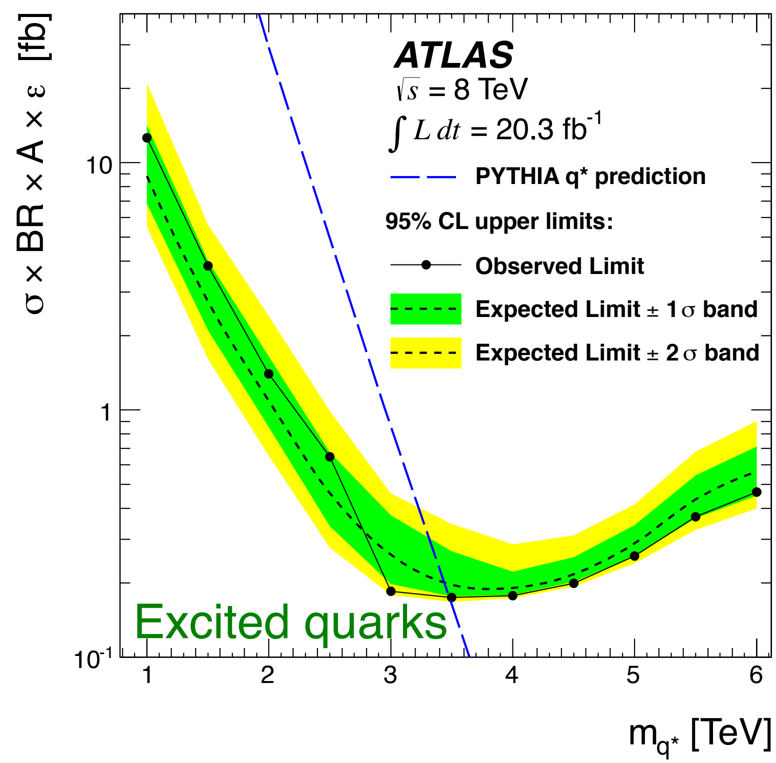
$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2} x^{-(p_3+p_4 \ln x)}$$

ATLAS: Phys. Lett. B 728C (2014) 562-578

Exotic Photon+Jet

- Observed (expected) lower limits (at 95% CL) are
  - QBH mass threshold: 4.6 (4.6) TeV
  - Excited-quark mass: 3.5 (3.4) TeV
- Largest uncertainty from background fit 1% (20%) at 1 TeV (3 TeV)

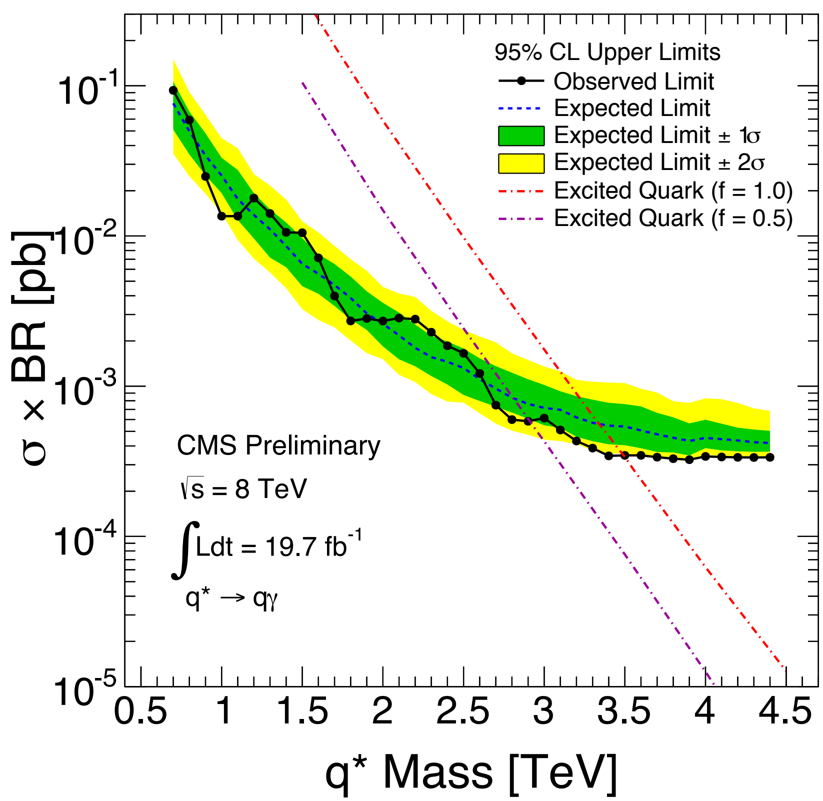


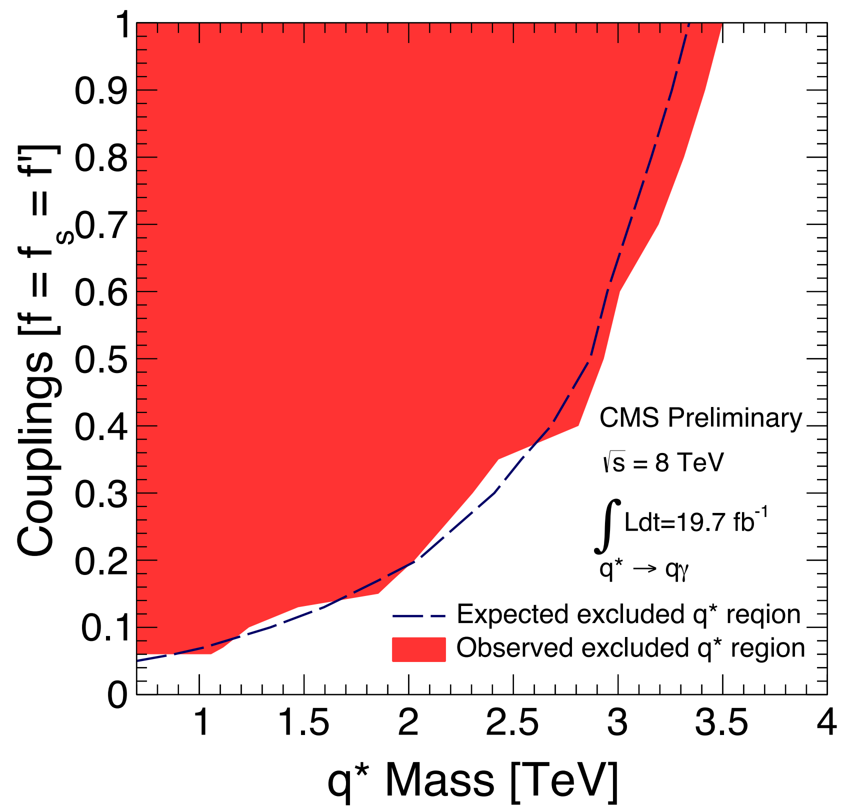


ATLAS: Phys. Lett. B 728C (2014) 562-578

CMS Exotic Photon+Jet

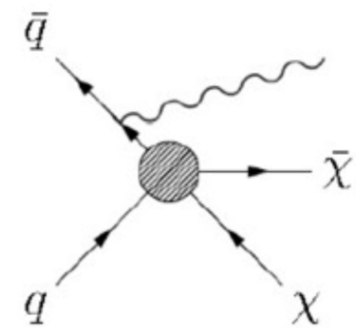
- Using 19.7 fb^{-1} of 8 TeV data, CMS excludes an excited quark state with mass $0.7 < M_{q*} < 3.5$ TeV and SM couplings at 95% CL
- Also, exclude mass as a function of coupling: exclude excited quark with mass $0.7 < M_{q*} < 2.9$ TeV for f = 0.5



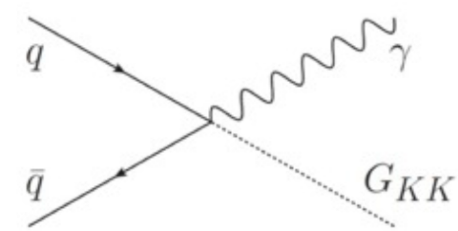


Exotic Photon+MET

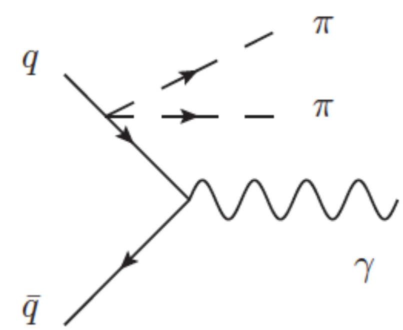
- Monophoton can be used to constrain variety of BSM scenarios
- **Dark Matter:**
  - At LHC, DM (χ) can be produced via qq → γ $\chi\chi$
  - Massive mediator couples SM to DM particles
  - Various processes contracted into an eff theory with contact interaction scale Λ



- **ADD Large Extra Dimensions:**
  - Solve hierarchy problem by lowering Planck scale to M_D, given by $M_{Pl}^2 \approx M_D^{n+2} R^n$
  - KK graviton (MET) produced with γ



- **Branon:**
  - If brane tension low, brane can fluctuate in ED
  - Scalar particles associated with such fluctuations are called branons



Exotic Photon+MET

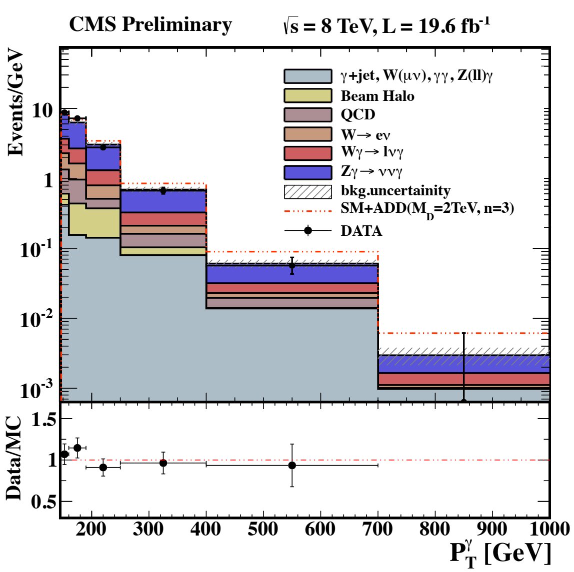
- Require events with at least one central photon with $E_T > 145$ GeV, MET > 140 GeV & $\Delta\phi(\text{MET},\gamma) > 2$
- Large number of backgrounds, which are estimated using a combination of MC and data-driven methods
  - Irreducible ($Z\gamma\rightarrow\nu\nu\gamma$): MC
  - Partially reducible ($W(\rightarrow l\nu)\gamma$): MC
  - Fake photons ($W\rightarrow l\nu$, QCD multijet): data driven fake rates
  - Fake MET (γ+jet, $Z\gamma\rightarrow ll\gamma$, diphoton): MC
  - Non-collision background from cosmic ray muons & beam halo muons: shower shape and timing
- Data control regions used to validate background estimates

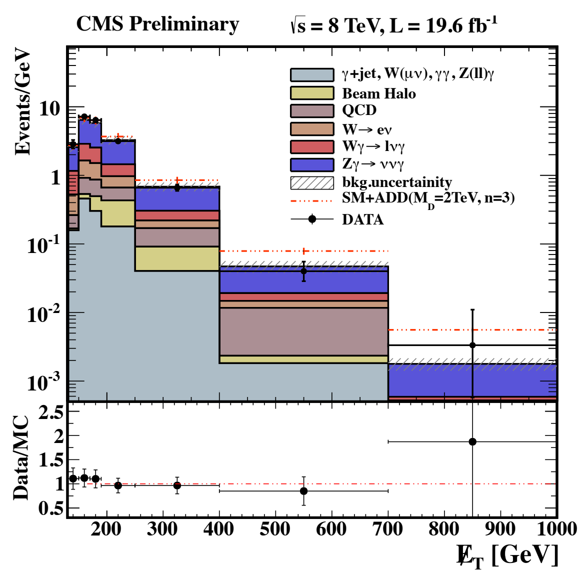
CMS-PAS-EXO-12-047

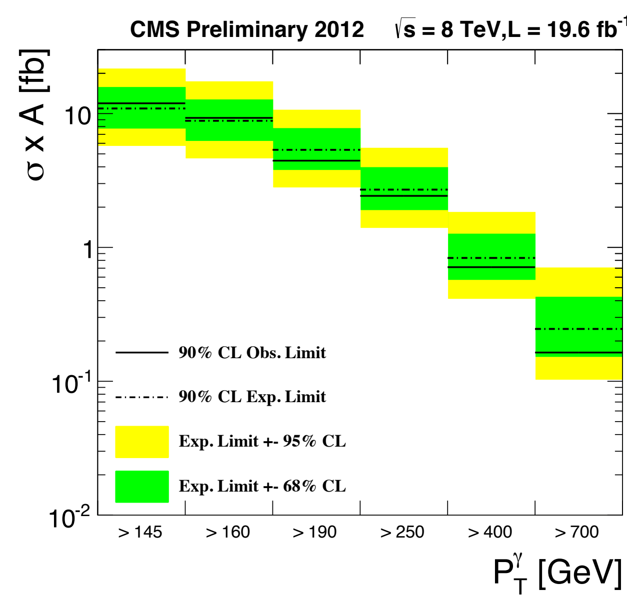
Exotic Photon+MET

- After selection, data (19.6 fb^{-1} at 8 TeV) compatible with expectations and 90% & 95% CL limits set as a function of γ p_T
- Largest systematic uncertainties arise from scale factors (~6%) and MC K-factors (10% $Z(\nu\nu)\gamma$: 15% $W\gamma$)

Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	344.8 ± 42.5
$W(\to \ell\nu) + \gamma$	102.5 ± 20.6
$W \to e\nu$	59.5 ± 5.5
jet $\to \gamma$ fakes	45.4 ± 13.9
Beam halo	24.7 ± 6.2
Others	35.7 ± 3.1
Total background	612.6 ± 63.0
Data	630.0



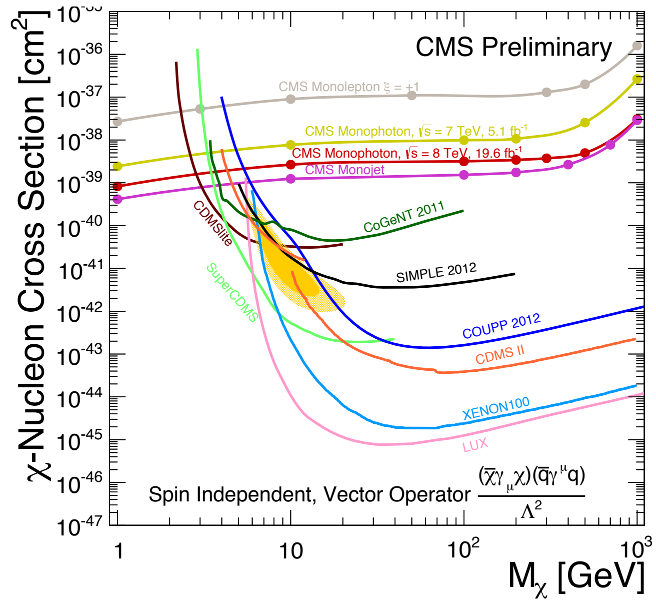


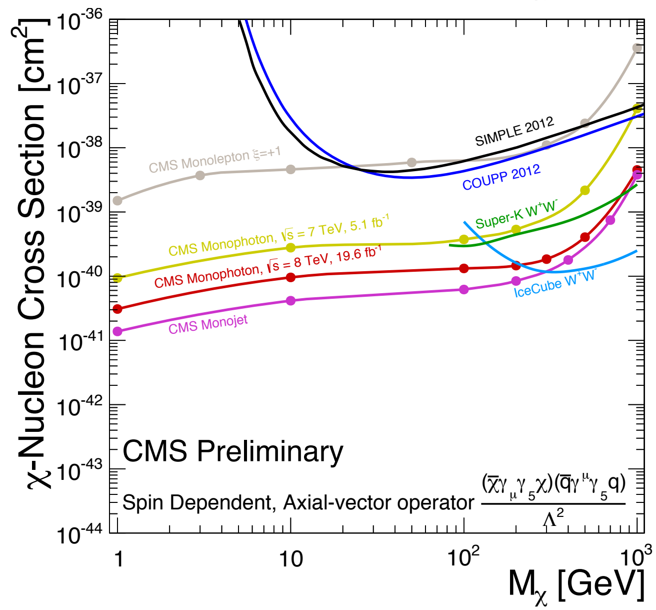


CMS-PAS-EXO-12-047

Photon+MET: DM Limits

- 90% CL upper limits placed on the DM production σ, as function of M_{χ}, for vector & axial-vector operators
- Then converted into corresponding lower limits on cutoff scale Λ, which are then then translated into upper limits on χ-nucleon cross-section
- Vector: Previously inaccessible masses below 3.5 GeV are excluded for a χ-nucleon cross section greater than 0.03 fb at 90% CL
- Axial-vector: the upper limits surpass all previous constraints for the mass range of 1–100 GeV

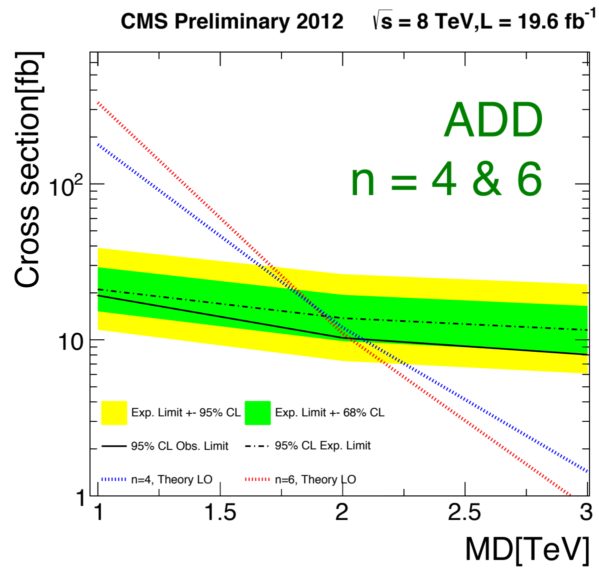


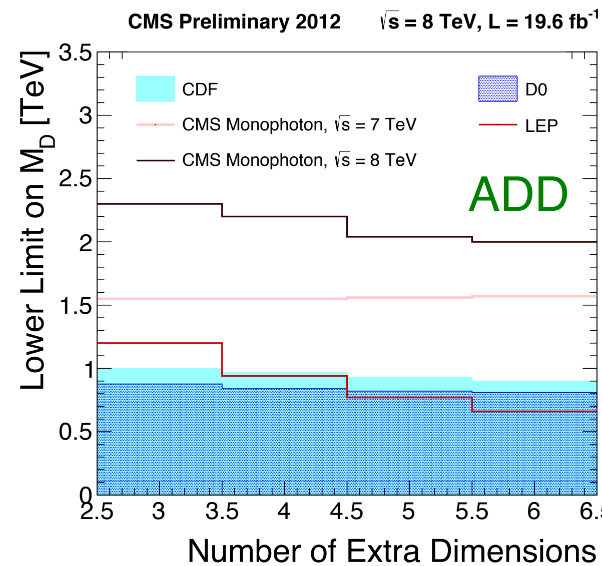


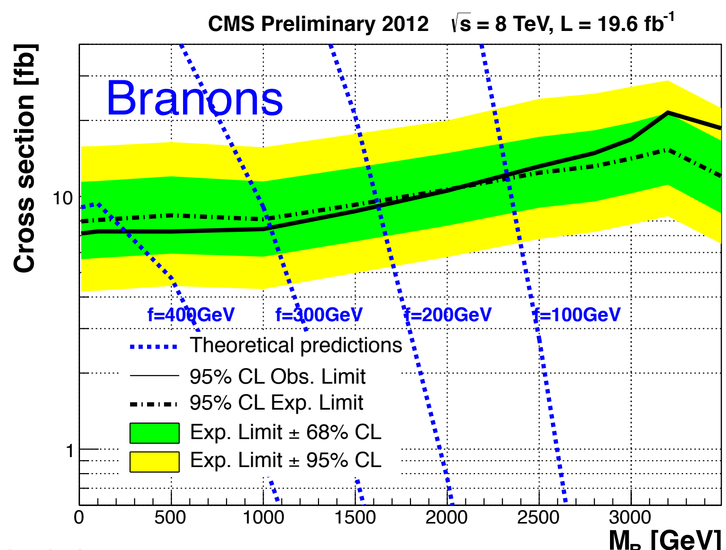
CMS-PAS-EXO-12-047

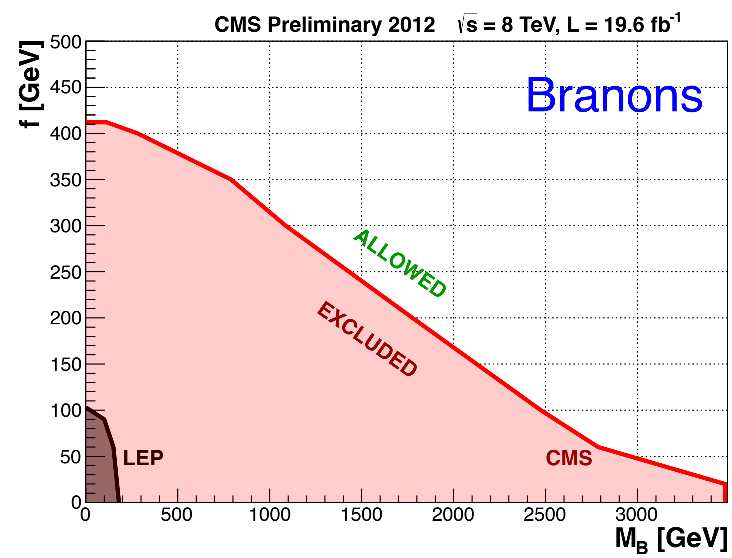
Photon+MET: ED Limits

- 95% CL upper limits placed on ADD & branon models
- ADD: $M_D > 2.0$ - 2.30 TeV for n=3-6
- Massless branons, tension f > 412 GeV
- For low brane tension (20 GeV), the branon mass > 3.5 TeV









CMS-PAS-EXO-12-047

Conclusions

- Monophoton and diphoton signatures at the LHC are phenomenogically rich, potentially providing a path to discover dark matter or other BSM physics
- Looking forward to exploring photon signatures at higher energy
- ATLAS:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- CMS:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults