Searches for
Dark Matter in the Monophoton Channel

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Overview

- Introduction

- Effective Field Theory(EFT)

- DM pair production at LHC for Mono-X

- ATLAS monophoton results at 8 TeV with 20/fb of data (new this morning)
  - The search strategy
  - Backgrounds and systematics
  - Results

- CMS monophoton results at 8 TeV for 20/fb of data
  - The search strategy
  - Backgrounds and systematics
  - Results

- Summary

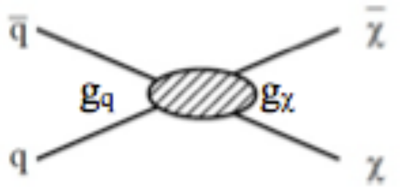
Introduction

Motivation

- Strong astrophysical evidence: rotation curves, gravitional lensing
- Contributes ~26% of total energy of universe
- Light WIMP states could be produced at large rates at colliders
- Complementarity with direct detection experiments

Effective Field Theory (EFT)

- Contact interaction with scale L, integrating out heavy mediator particle
- Simple model with only a few parameters: DM mass (m_χ), scale Λ, and couplings g_χ, g_q
- DM can be Dirac or Majorana fermion, complex or scalar
- Simple mapping of LHC results to χ-nucleon scattering cross section



DM production

pp → χ χ + x at the LHC

- χ - pair production is characterized with contract interaction operators

- Vector Operator/ Spin Independent (SI)

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

- Axial-Vector Operator/ Spin Dependent (SD)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

- χ-nucleon cross section depends on DM mass and the scale Λ

$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4} \qquad \sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4} \qquad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

- Scale Λ and g_χ, g_q couplings of mediator to the χ and SM particles respectively, are related as

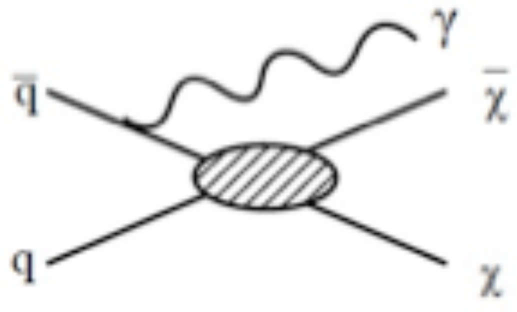
$$\Lambda = M/\sqrt{g_\chi g_q}$$

JHEP 1012:048 (2010),
Phys.Rev.D82:116010 (2010)
JHEP 1009:037 (2010)

ATLAS: Selection

ATLAS has searched for DM pair production with mono-photon final state at 7 TeV and 8 TeV

- Distinct and clean signature
- Studied in detail for other searches (LED, ADD)
- Sensitive to models where γ directly involved in EFT vertex
- **Focus on new 8 TeV, 20.3/fb result here: many updates**



Event Selection:

- MET trigger with threshold MET > 80 GeV
- MET > 150 GeV
- $p_T(\gamma) > 125$ GeV, $|\eta(\gamma)| < 1.37$, isolated
- Lepton/jet veto:
  - medium++ electron id
  - $p_T(\mu) > 7/6$ GeV, CB/ST muon
  - If > 1 jets with $p_T(j) > 30$ GeV, $|\eta(j)| < 4.5$
  - $\Delta\phi(\text{jet,MET}) > 0.4$

ATLAS-CONF-2014-051

ATLAS: Backgrounds

ATLAS-CONF-2014-051

Data Driven:

- γ+Z : Dominant and irreducible background (70%)
  - Estimate using dilepton control regions
- γ+W: Second largest background (15%)
  - Estimate using 1μ control region

  - Use isolated muons (electrons) with p_T > 6 (10) GeV and extend photon acceptance to $|\eta(\gamma)| < 2.37$ (excluding barrel-endcap gap) to increase statistics

- W/Z+jets, diboson, top, multijet (15%)
  - e/jet fake estimate from MET+e control sample / ABCD method

  - Jet-faking γ: control sample of loose photon id that fails nominal identification
  - e-fake γ: control sample of $Z\to ee$ events

Monte Carlo Simulation

- γ+jets: cross checked with data driven technique

ATLAS: Final Yields

Final results

ATLAS-CONF-2014-051

extrapolated from control region to signal regions

Process	Event yield
$Z(\rightarrow \nu\nu) + \gamma$	$389 \pm 36 \pm 10$
$W(\rightarrow \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$
$W/Z + \text{jet}, t\bar{t}, \text{diboson}$	$83 \pm 2 \pm 28$
$Z(\rightarrow \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$
$\gamma + \text{jet}$	$0.4^{+0.3}_{-0.4}$
Total background	$557 \pm 36 \pm 27$
Data	521

Systematic uncertainties

- CR statistics
- e/γ fakes
- Electron, muon efficiency
- e-γ energy scale
- PDF/scale
- JES/JER

Signal MC (7 TeV):

- simulated from MADGRAPH+PYTHIA events

- m_χ :1 GeV -1.3 TeV
- pT > 80 GeV
- scalar (D1), vector(D5), axial-vector (D8), tensor (D9) operators

A × ε for signal (7 TeV)

-D1 : 11%
-D5,8: 18 %
-D9 : 23 %
-uncertainty: 1-2 %

ATLAS: P_T and MET

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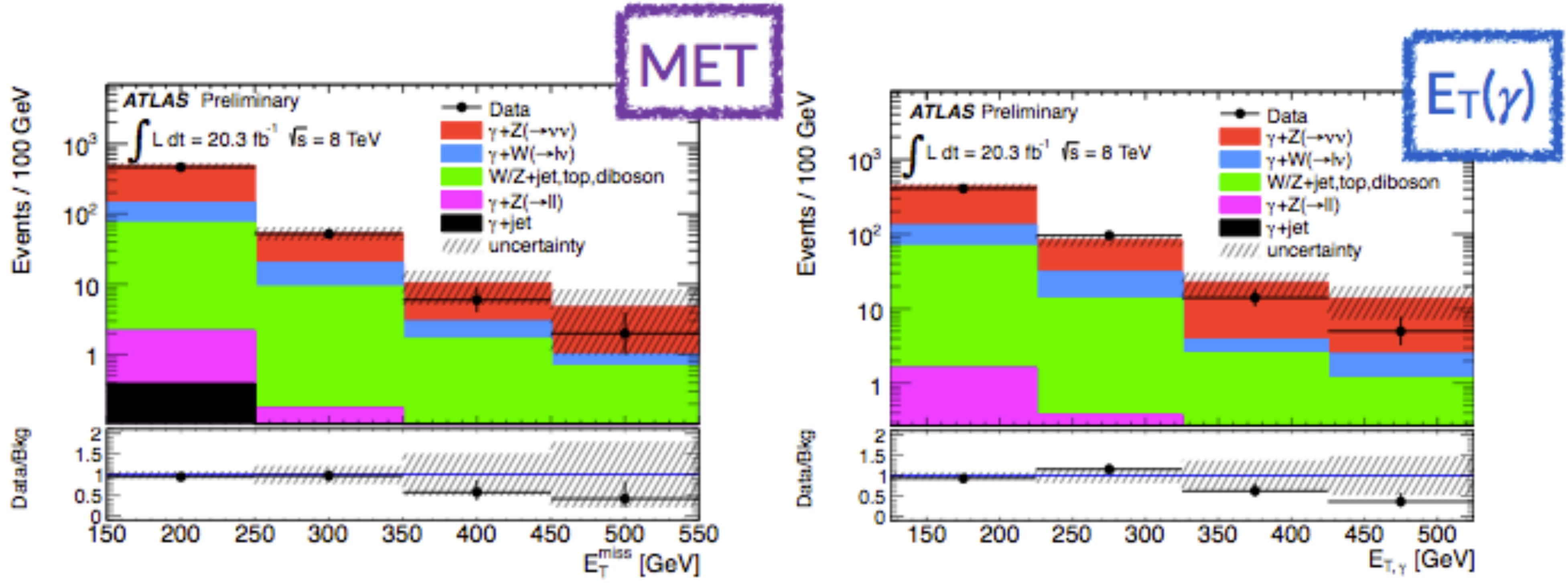


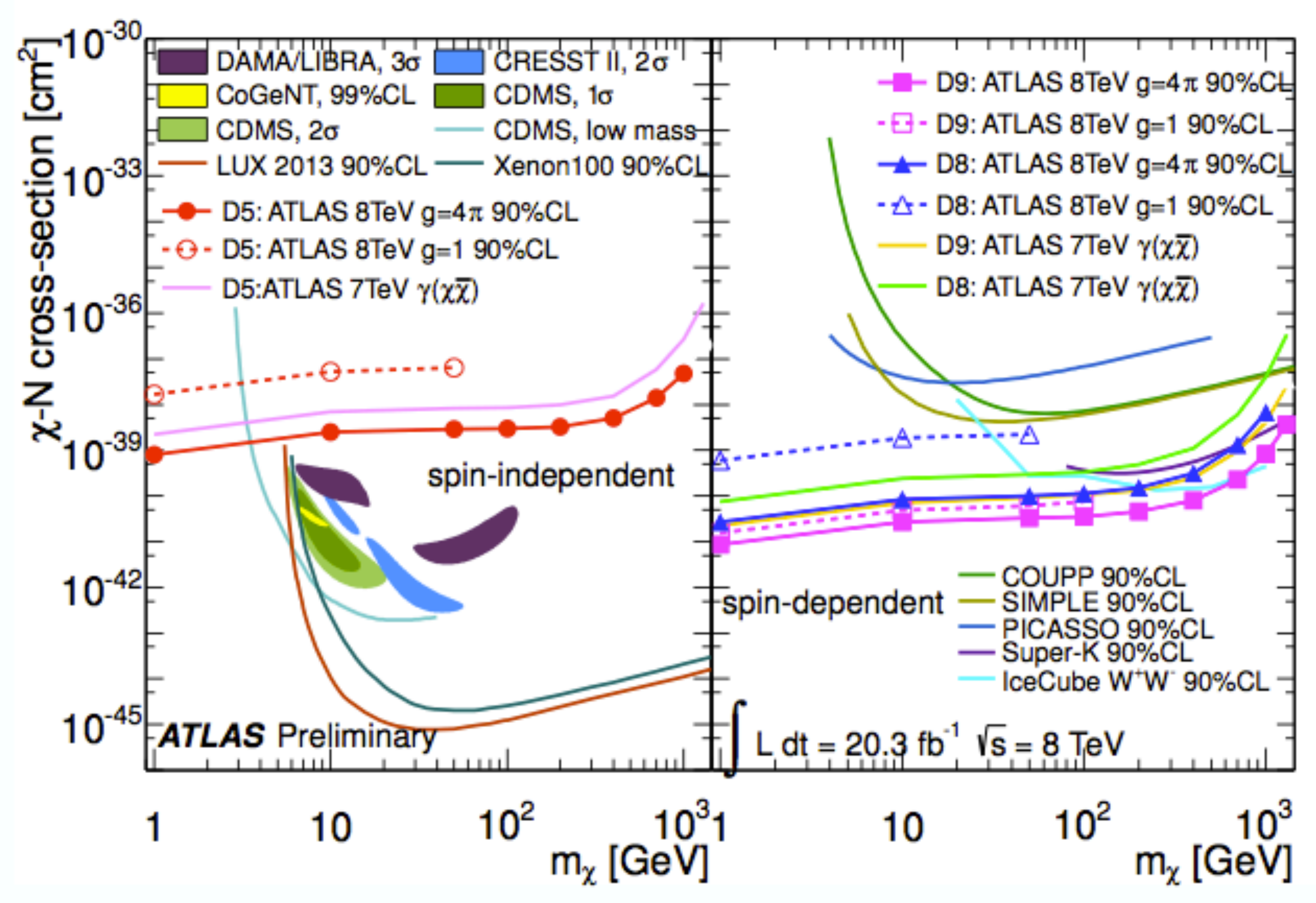
Cut-and-count analysis: observed number of events after selection is used to extract limits

One-sided profile likelihood test statistics, with CLs modified frequentist technique

ATLAS: EFT Limits

χ-nucleon scattering cross section at 7 and 8 TeV:

7 TeV: PRL 110, 011802 (2013)
8 TeV: **ATLAS-CONF-2014-051**



ATLAS: Simplified Model Limits

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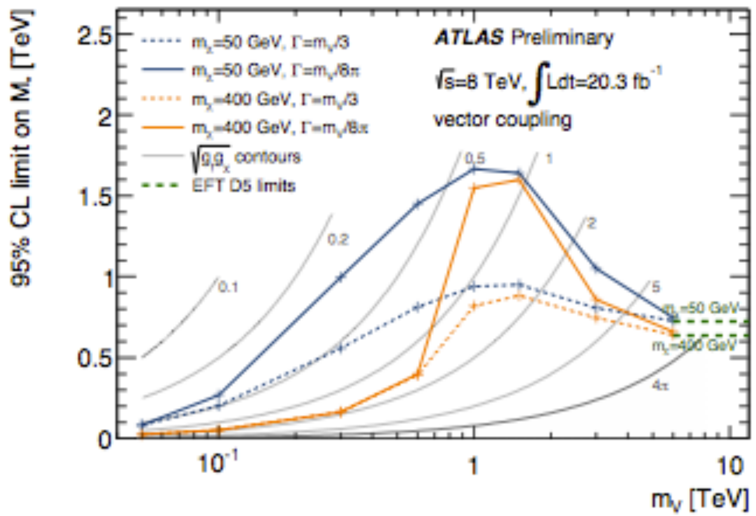
Go beyond EFT to a more UV complete theory:

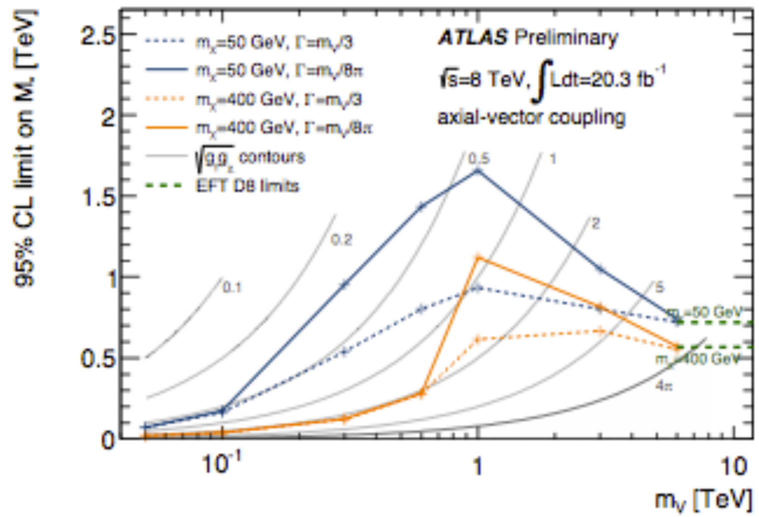
- Z like mediator with mass m_v and vector/ axial vector interaction
- Limit in terms of coupling $\sqrt{g_f g_\chi}$, as a function of m_χ, m_v and minimum coupling for relic density

arXiv: 1109.4398

$$\sigma(pp \to \bar{\chi}\chi + \gamma) \propto \frac{g_f^2 g_\chi^2}{(Q_{\rm tr}^2 - m_V^2)^2 + m_V^2\Gamma^2/4}\sqrt{\hat{s}}$$

Contact interaction approached for high m_v

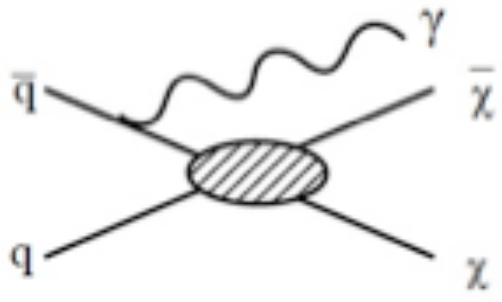




CMS: Selection

CMS experiment has also searched for DM pair production in monophoton final state

- Results for 7 TeV (5/fb) and 8 TeV (19.7/fb)
- Selection criteria for both analyses are quite similar
- focus on 8 TeV result here



CMS-EXO-12-047

Event Selection

- Single γ and γ+MET trigger
- pf MET > 140 GeV (130 GeV at 7 TeV)
- $p_T(\gamma) > 145$ GeV, $|\eta(\gamma)| < 1.44$
- Medium PF-based isolation and identification
- Consistency with shower shape and prompt timing of seed crystal of EM shower
- Select using MET-significance to reduce fake-MET events
- Lepton/jet veto:
  - $p_T(e) > 10$ GeV, $|\eta(e)| < 2.4$, loose ID
  - $p_T(\mu) > 10$ GeV, $|\eta(\mu)| < 2.4$, loose ID; $\Delta R(\gamma,e/\mu) > 0.5$
  - If > 1 jets with $p_T(j) > 30$ GeV, $|\eta(j)| < 3.0$, loose and pileup jet ID & $\Delta R(\gamma,\text{jet}) > 0.5$
- $\Delta\phi(\gamma, \text{pf MET}) > 2.0$

CMS: Backgrounds

From MC Simulation:

- Z(νν)γ : Main and irreducible background
  - estimated from full simulation of events from MADGRAPH+PYTHIA
  - corrected for pT(γ) dependent k-factor from MCFM prediction: 1.42 ± 0.13(sys.)
  - cross checked with data-driven estimation

- Wγ: Second largest background
  - estimated from full simulation of MADGRAPH+PYTHIA
  - corrected with k-factor : 1.57 ± 0.23(sys.) from MCFM

- γγ, γ+jet: Estimated from simulated events of PYTHIA

- Z(ll)γ: From MADGRAPH+PYTHIA

Data-driven:

- jet-faking γ: Using data control sample of EM-enriched QCD events
  - fake ratio of isolated to non-isolated γ is estimated in control sample
  - contribution of direct γ in control sample is corrected using shower shape templates
  - ratio is applied to a data sample similar to non-isolated photons in signal region

- e-faking γ: arise from W(eν)γ and estimated with Z(→ee) events from data
  - estimated inefficiency of pixel seed match to EM shower about 1.57% for $p_T(\gamma) > 100$ GeV
  - applied to a data sample with nominal selection but selecting electron

CMS: Final Yields

Non collisions backgrounds:

- Beam Halo: Estimated using timing distribution in seed crystal and EM shower width
  - timing templates were extracted for beam-halo using ECAL based mip-tagger
  - fraction of halo are extracted within prompt timing window of 3ns

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

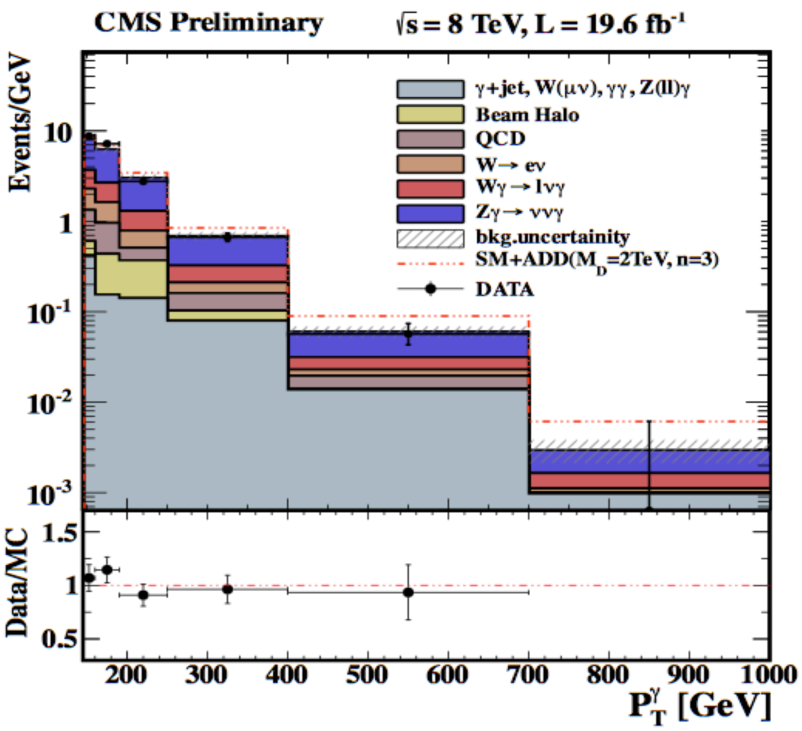
Main systematics:

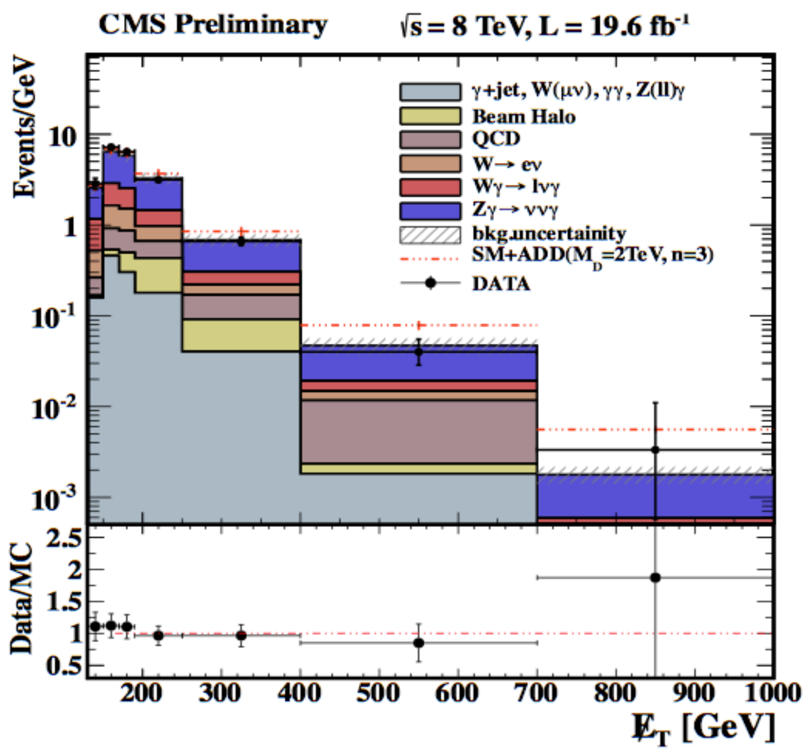
- k-factor for Wγ (Zγ):
  -15% (10%) from scale, PDFs, α_s variations
- jet-faking γ:
  - 30% from side-band choice for correcting fake ratio for direct photons
- e-faking γ:
  - 5% from PDF and 10% MC closure
- Luminosity: 2.6 %

- Signal MC: used from MADGRAPH+PYTHIA
  - m_χ :1GeV to 1 TeV
  - vector and axial-vector operators only

- $A \times \varepsilon$ for signal ranges from 41% - 45% for vector and axial-vector

CMS: P_T and MET

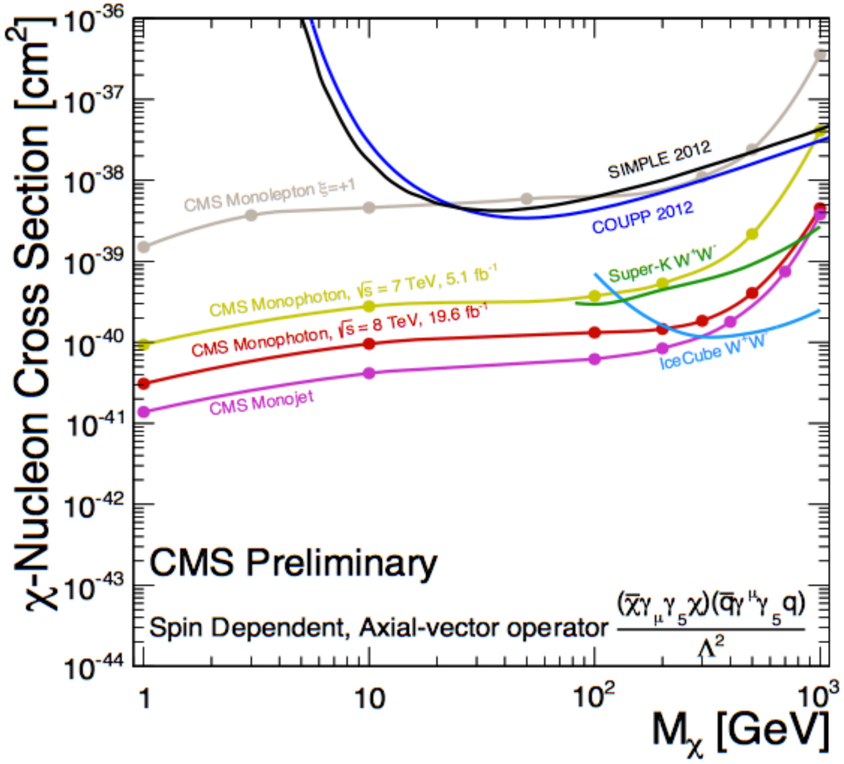


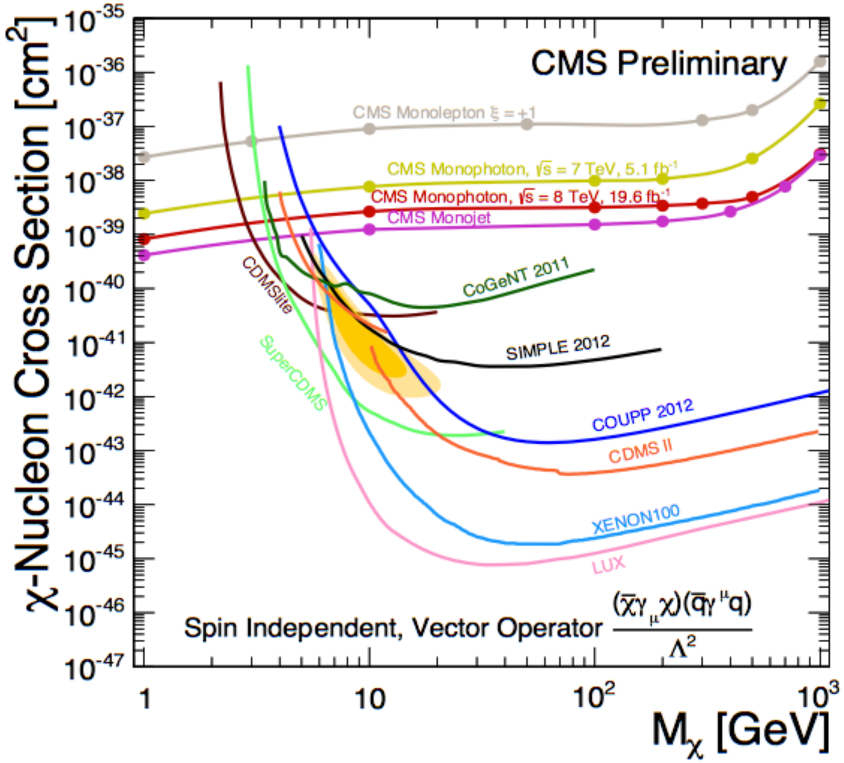


- The observed data and SM expectations are consistent within uncertainties
- The pT(γ) distribution is used to set the limits on cross section and subsequently on χ-nucleon cross section
- CLs based method is used to set limits on Lambda and x-nucleon cross section

CMS: Results at 7 and 8 TeV

7 TeV: PRL 108, 261803 (2012)
8 TeV: CMS-EXO-12-047





- 7 TeV results were the first bound from LHC on any Mono-X DM search
  - cut & count based limits

- 8 TeV limits almost an order of magnitude better compare to 7 TeV
  - shape based limits

CMS: Limits on Λ

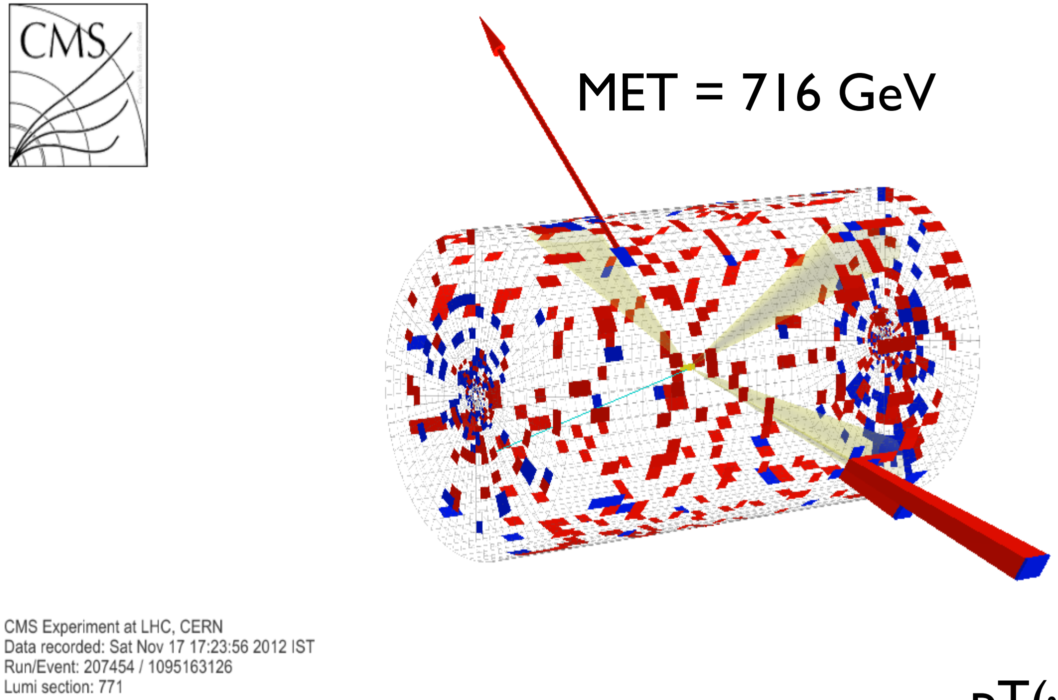
- 90% CL lower bound on Λ for axial-vector operator

Mass [GeV]	σ_{theor} [pb]	σ [fb]	Λ [GeV]	$\sigma_{\chi-nucleon}$ [cm^2]
1	2.4561e-7	7.9(10.5)	746(694	3.1e-41(4.1e-41)
10	2.4685e-7	7.9(11.0)	748(688)	9.6e-41(1.3e-40)
100	2.1842e-7	8.2(10.7)	718(671)	1.3e-40(1.7e-40)
200	1.6313e-7	6.7(9.5)	702(643)	1.5e-40(2.0e-40)
300	1.1254e-7	5.8(8.5)	663(604)	1.8e-40(2.6e-40)
500	4.8798e-8	5.5(8.1)	544(495)	4.0e-40(5.9e-40)
1000	4.2131e-9	5.3(7.7)	298(272)	4.5e-39(6.5e-39)

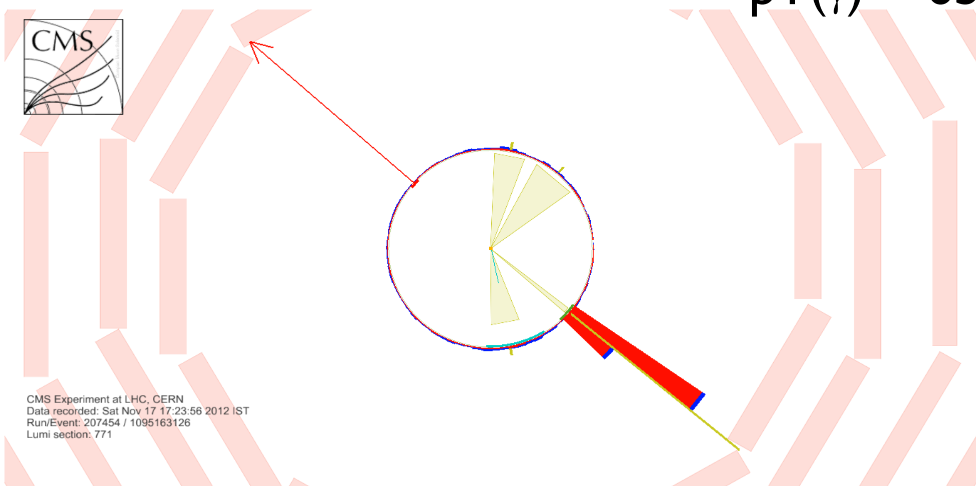
- 90% CL lower bound on Λ for vector operator

Mass [GeV]	σ_{theor} [pb]	σ [fb]	Λ [GeV]	$\sigma_{\chi-nucleon}$ [cm^2]
1	2.4666e-7	7.8(10.6)	750(694)	8.2e-40(1.1e-39)
10	2.4614e-7	8.0(10.5)	745(696)	2.6e-39(3.5-39)
100	2.4437e-7	8.0(11.2)	742(684)	3.2e-39(4.4e-39)
200	2.1687e-7	7.6(9.9)	729(684)	3.4e-39(4.4e-39)
300	1.786e-7	6.9(9.4)	714(660)	3.7e-39(5.1e-39)
500	1.0291e-7	5.2(7.8)	666(602)	4.9e-39(7.4e-39)
1000	1.539e-8	4.9(7.2)	422(382)	3.1e-38(4.6e-38)

CMS: Event Display



pT(γ) = 653 GeV



Summary

- CMS limits at 7 TeV: first LHC bounds on DM pair production
- ATLAS studied additional operators e.g., tensor, scalars and have now looked beyond EFT
- Complementary to other final states like mono-jet, mono-leptons
- Competitive and complementarity with direct detection searches
- More work needed for presenting EFT limits when comparing to direct detection searches
  - some recent work: arXiv:1308.6799, arXiv:1409.2893
- No evidence of DM in monophoton channel......stay tuned for new data !!!
- & Thanks to Sushil S. Chauhan for providing slides

Thank you!!

Back-up Slides

DM Operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

$$\begin{aligned}
\sigma_0^{D1} &= 1.60\times 10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{20\mathrm{GeV}}{M_*}\right)^6, \\
\sigma_0^{D5,C3} &= 1.38\times 10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{300\mathrm{GeV}}{M_*}\right)^4, \\
\sigma_0^{D8,D9} &= 9.18\times 10^{-40}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{300\mathrm{GeV}}{M_*}\right)^4, \\
\sigma_0^{D11} &= 3.83\times 10^{-41}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{100\mathrm{GeV}}{M_*}\right)^6, \\
\sigma_0^{C1,R1} &= 2.56\times 10^{-36}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{10\mathrm{GeV}}{M_*}\right)^4, \\
\sigma_0^{C5,R3} &= 7.40\times 10^{-39}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{60\mathrm{GeV}}{M_*}\right)^4.
\end{aligned}$$

arXiv:1008.1783

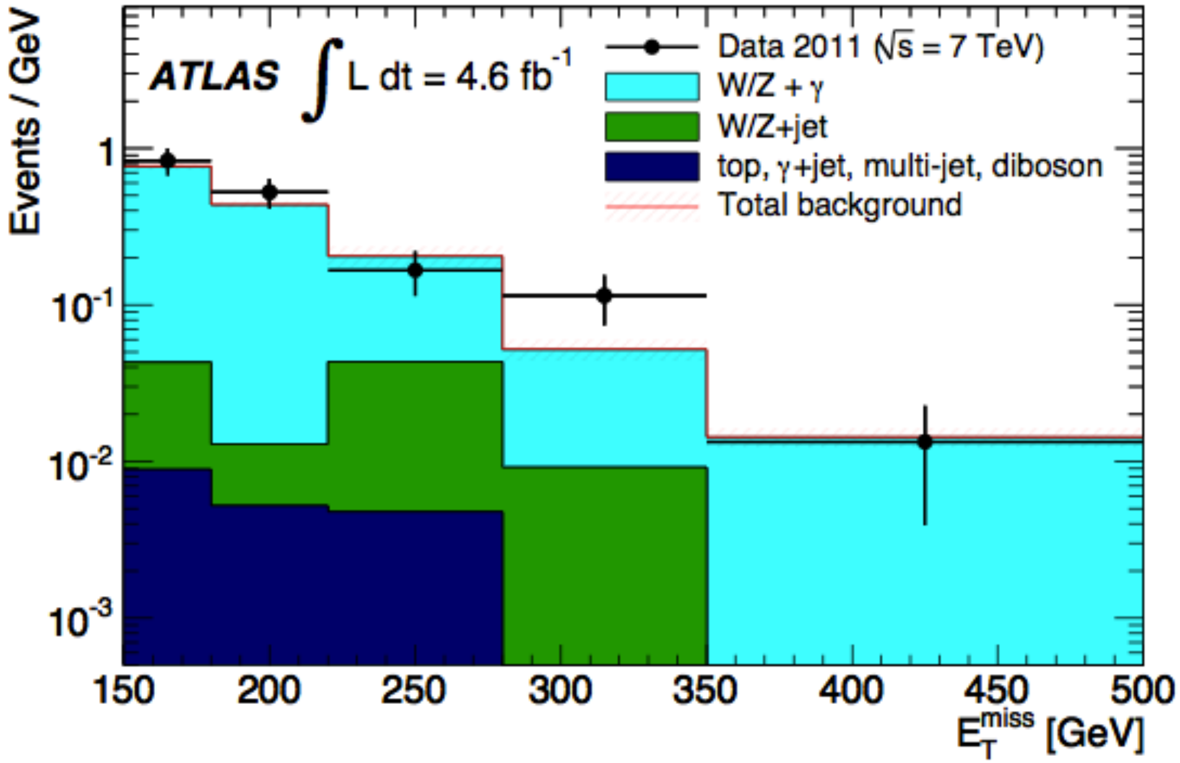
ATLAS: Systematics Details

Systematics	Impact on Background:
Photon energy scale (0.3-1.5%)	0.9%
Photon resolution, identification	1.1%
Jet energy resolution and jet energy scale	~ 1.0 %
PDF, scale	~ 1.0 %
Simulation SHERPA vs ALPGEN	~ 7 %
Total uncertainty on background prediction	~15%

Systematics	Impact on Signal
PDF	1-8%
ISR, FSR (theoretical)	3.5-10%
Factorization/Renormalization scale	1-2%

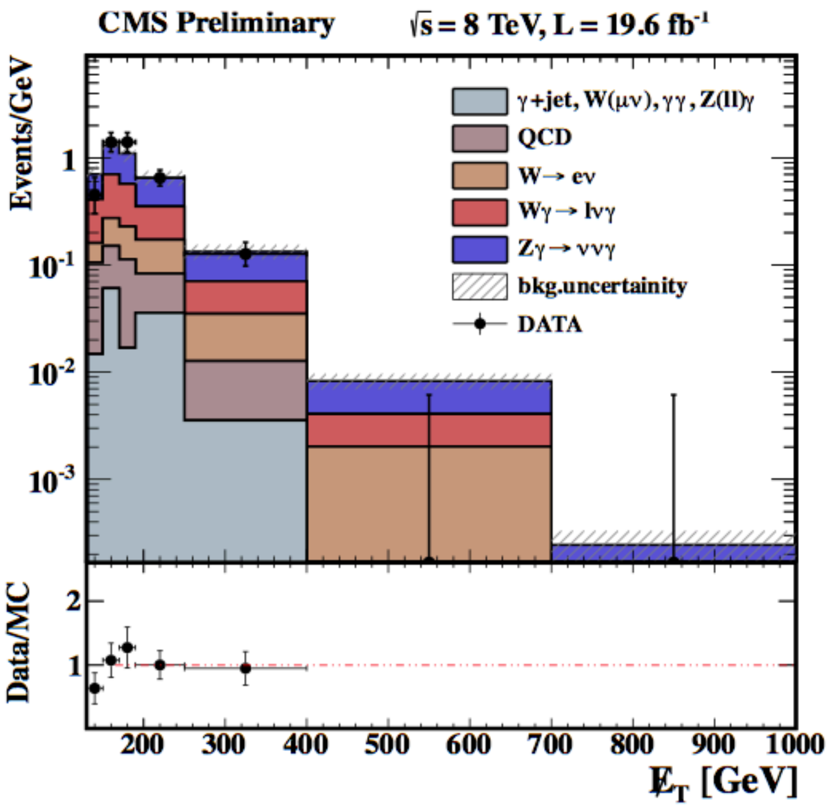
ATLAS: Controlled Region of Z/W+γ

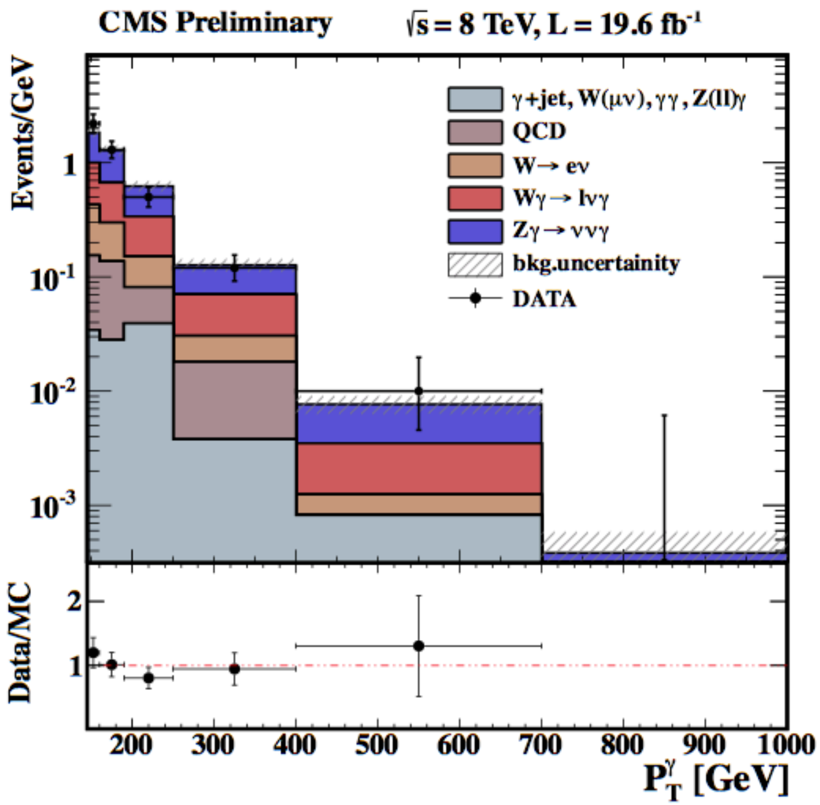
- γ+μ+MET controlled region with nominal selection but inverting muon veto



CMS: Control region for Zγ

- Nominal selection but $\Delta\phi(\gamma, \text{pfMET}) < 2.9$





Limit: MLQ >350 @ 95%CL

CMS: Main Systematics

Systematics	Uncertainty signal $A \times \varepsilon$
Photon energy scale	2.1%
Pile-up	0.3%
MET	~1.0%

Systematics	Impact on background
k-factor ($Z\gamma$ and $W\gamma$)	~15-20%
Data/MC scale factor	~ 6%

Total uncertainty on background prediction ~11%

CMS: MHT for fake MET

- A way to identify and reduce the fake met contribution
  - minimize the unclustered energy in the event
  - by trying to re-distribute the energy back into the visible objects

$$\chi^2 = \sum_{i=objects} \left(\frac{(p_T^{reco})_i - (\hat{p_T})_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\hat{\not{E}_T}}{\sigma_{\hat{\not{E}_T}}} \right)^2$$

$$\hat{\not{E}_{x,y}} = \not{E}_{x,y}^{reco} + \sum_{i=objects} (p_{x,y}^{reco})_i - (\hat{p_{x,y}})_i$$

$$\not{E}_T{}^2 = \not{E}_x^2 + \not{E}_y^2$$

- If the MET is intrinsic → result in a low-χ^2
- fake MET → result in a high-χ^2

- Variable to discriminate fake MET
- recalculated minimized MET > 120 GeV
- Prob(χ^2)