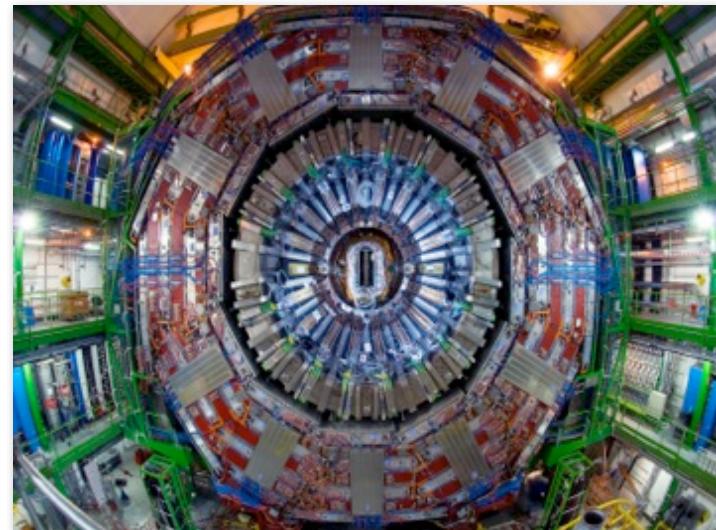


SEARCHES FOR *DARK MATTER* IN MONOJETS AND MONOPHOTON EVENTS AT CMS



Steve Worm

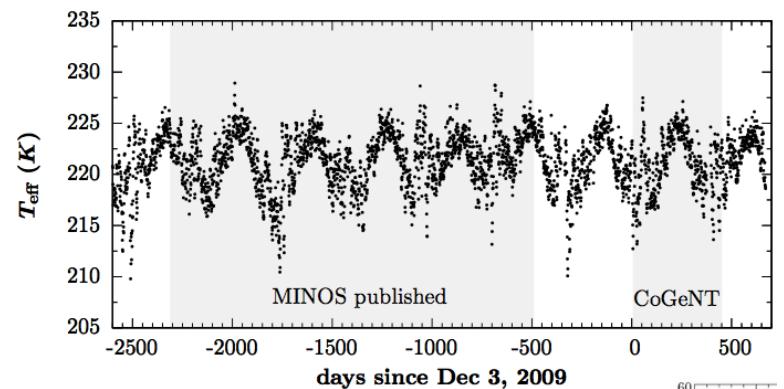
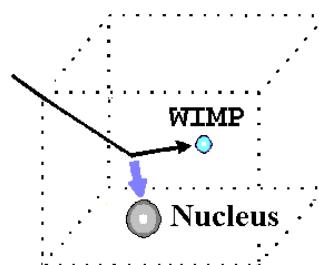
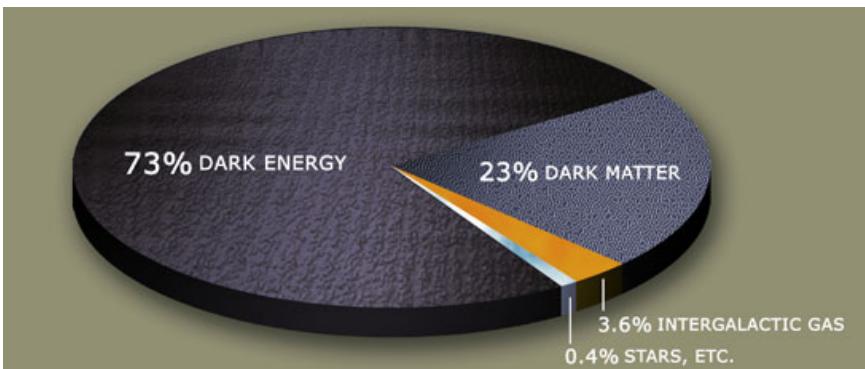
Moriond EWK “Hot Topic”

8 March 2012



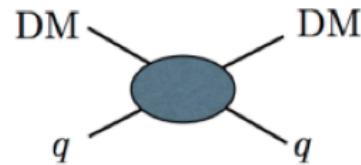
DARK MATTER... AT THE LHC?

- There is strong astrophysical evidence for the existence of dark matter
 - Evidence from bullet cluster, gravitational lensing, rotation curves
 - It is 6 times more abundant than baryons and contributes $\sim 1/4$ of the total energy budget!
 - Direct detection experiments
 - Aim to observe recoil of dark matter off nucleus
 - Excesses observed by several experiments, not confirmed by others
 - Consistent with a 10 GeV DM candidate?
 - Need for independent verification from non-astrophysical experiments
 - Low mass region not accessible to direct detection experiments
 - Limited by threshold effects, energy scale, backgrounds; less sensitive to spin-dependent couplings
- *Need for independent evidence from colliders*

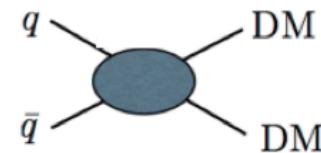


PRODUCTION OF DARK MATTER AT CMS

- Search for evidence of pair-production of Dark Matter particles (χ)

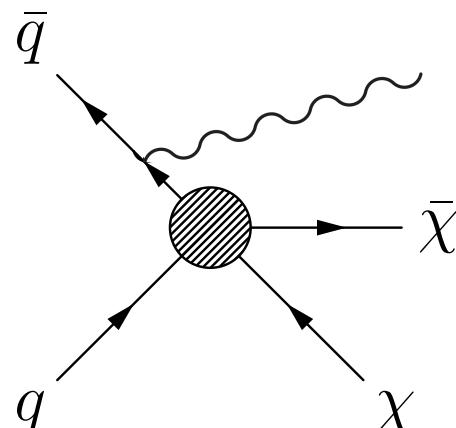


Direct Detection (t-channel)

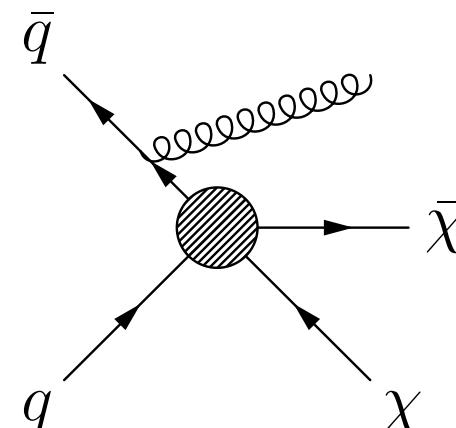


Collider Searches (s-channel)

- Dark Matter production gives missing transverse energy (MET)
- Photons (or jets from a gluon) can be radiated from quarks, giving monophoton (or monojet) plus MET



Monophoton + MET



Monojet + MET

PHENOMENOLOGY

- Pair-production of χ can be characterised by a contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \quad \text{vector --> spin independent (SI)}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} \quad \text{axial-vector --> spin-dependent (SD)}$$

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

$$\sigma_{SI} = 9 \frac{\mu^2}{\pi \Lambda^4}$$

$$\sigma_{SD} = 0.33 \frac{\mu^2}{\pi \Lambda^4}$$

*spin-independent
and spin-dependent
cross sections*

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

$$\mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

[Bai, Fox and Harnik,
JHEP 1012:048(2010)]

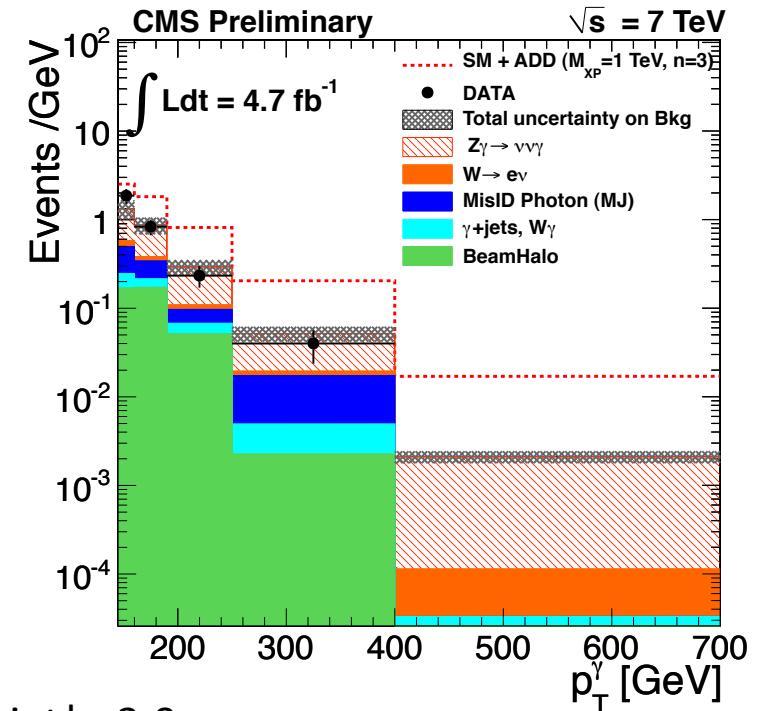
MONOPHOTON – SEARCH DETAILS

- Require a photon in an event with
 - High energy photon: $p_T(\gamma) > 145 \text{ GeV}/c$
 - In the central part of the detector: $|\eta| < 1.442$
 - Shower shape consistent with photon: $\sigma_{\eta\eta} > 0.013$
 - MET $> 130 \text{ GeV}$, using a particle flow method

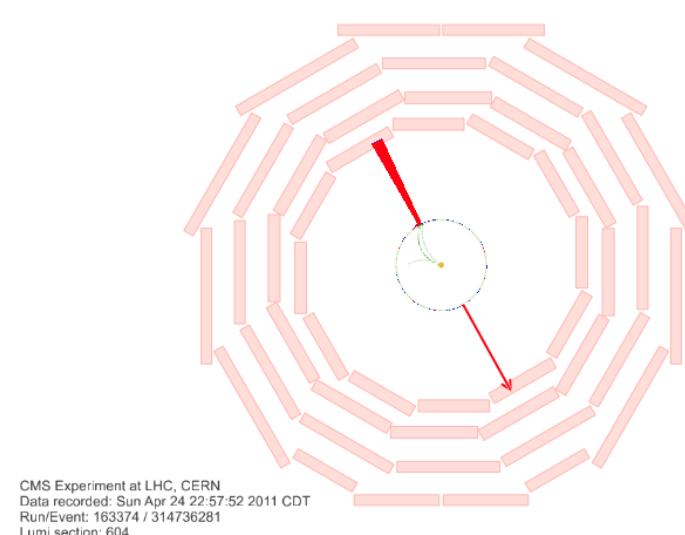
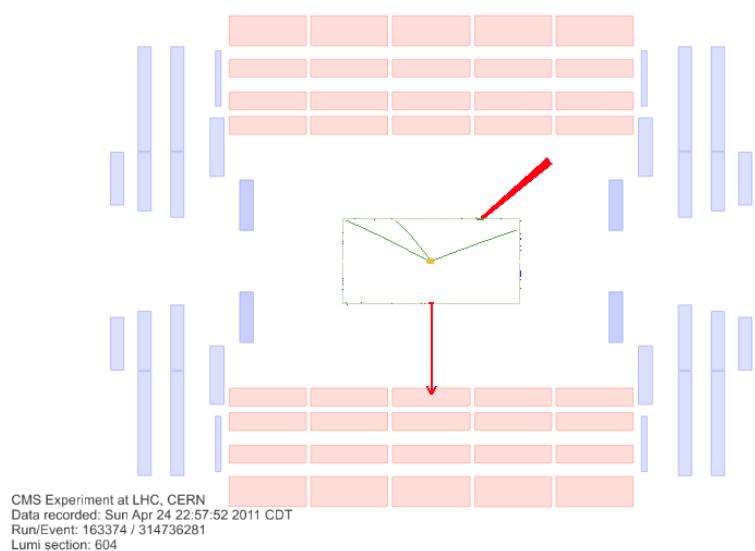
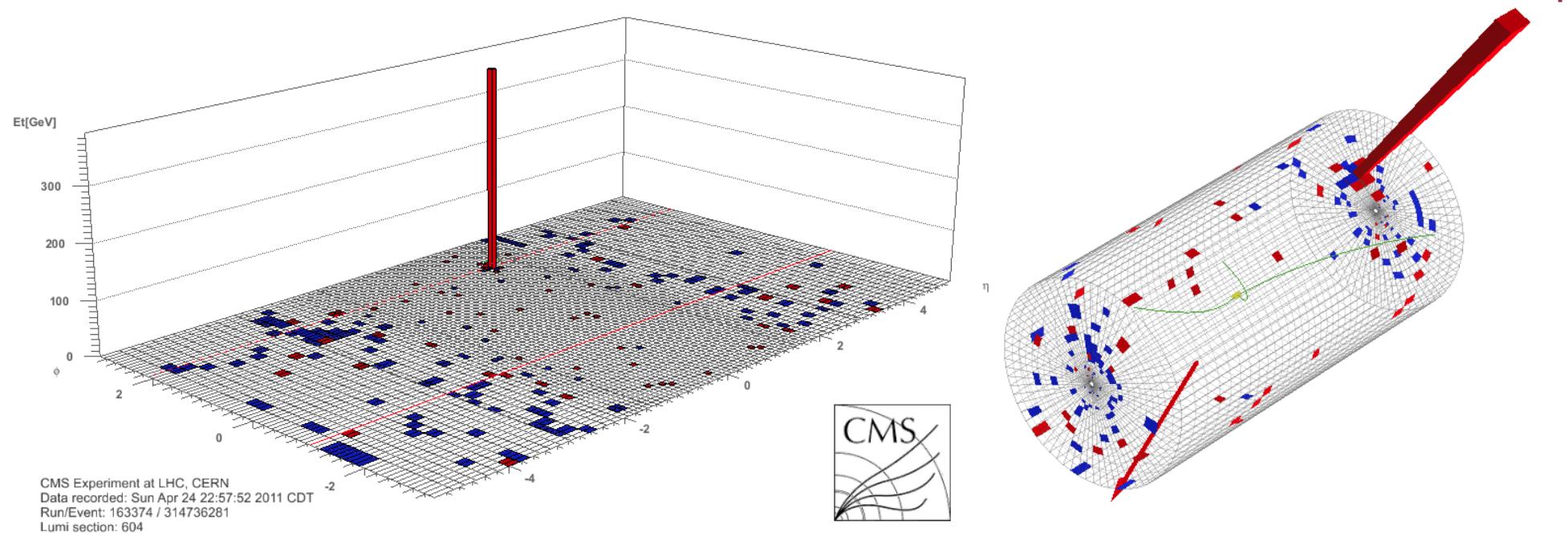
► *Single photon plus significant missing energy*

- Remove events with excessive nearby activity
 - No central jet: veto events with $p_T(\text{jet}) > 40 \text{ GeV}/c$ and $|\eta_{\text{jet}}| < 3.0$
 - Veto events with nearby tracks or pixel stubs
 - Veto events with significant electromagnetic calorimeter activity ($\Delta R < 0.4$)
 - Veto events with significant hadronic activity ($\Delta R < 0.4$, $E_{\text{HCAL}}/E_{\text{ECAL}} < 0.05$)
 - All reconstructed vertices are used for isolation calculations.

► *Aggressive isolation-based clean-up to ensure purity*



MONOPHOTON – EVENT DISPLAY



MONOPHOTON – BACKGROUNDS

- Backgrounds from pp collisions

$pp \rightarrow Z \gamma \rightarrow vv \gamma$

irreducible background

$pp \rightarrow W \rightarrow ev$

electron mis-identified as photon

$pp \rightarrow \text{jets} \rightarrow \gamma + \text{MET}$

one jet mimics photon, MET from jet mis-measurement

$pp \rightarrow \gamma + \text{jet}$

MET from jet mis-measurement

$pp \rightarrow W \gamma \rightarrow l v \gamma$

charged lepton escapes detection

$pp \rightarrow \gamma \gamma$

one photon mis-measured to give MET

- Backgrounds unrelated to pp collisions

Showers induced by cosmics identified and removed

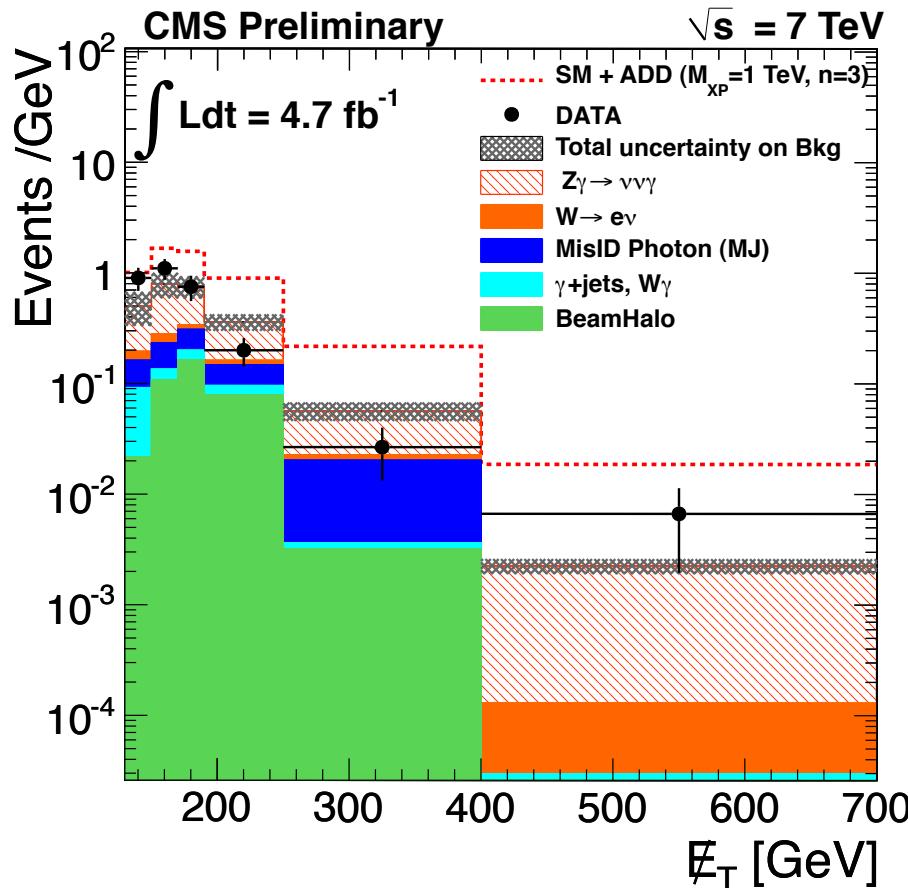
Neutron-induced signals identified and removed

Beam halo mostly removed; a residual contribution estimated

- Backgrounds estimated from MC and data-driven techniques

► *Look for excess of events above background (counting experiment)*

MONOPHOTON – SEARCH RESULTS



Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	2.8 ± 0.9
$\gamma + \text{jet}$	0.5 ± 0.2
$\gamma\gamma$	0.5 ± 0.3
$Z(\nu\bar{\nu})\gamma$	42.4 ± 6.3
Total Background	71.9 ± 9.1
Total Observed Candidates	73

- ▶ No excess observed – good agreement with Standard Model and background expectations

MONOPHOTON – DARK MATTER SIGNAL

- Signal Generation
 - Dark Matter model follows effective theory outlined in earlier slide
 - Madgraph4 + Pythia6 generation with 10 TeV mediator mass
 - Similar sensitivity to spin-dependent and spin-independent (no A^2 coherence factor)
- Acceptance times efficiency for Dark Matter signal
 - $A \times \epsilon \approx 0.3$, for both vector operator and axial-vector operator
 - Kinematics mainly from ISR photon; $A \times \epsilon$ is fairly constant in the range $m_\chi = 1\text{-}1000$ GeV
- Systematic uncertainties
 - Stats. uncertainty 1.7%
 - Photon PT uncertainty 2.3%
 - Jet Energy Scale 1.2%
 - MET modelling 0.5%
 - Pile-up modelling 2.4%

► *Good efficiency and modest systematics*

MONOPHOTON – LIMIT SETTING

- Limit-setting
 - CLs limits calculated for an integrated luminosity of 4.67 fb^{-1}
 - 71.9 ± 9.1 expected and 73 observed
 - 90% CL limits shown below, “expected” limits in parenthesis (95% also available)
- Extraction of χ -nucleon cross section
 - Upper limits on cross sections give lower limits on Λ , assuming a Λ^{-4} behaviour
 - The lower limits on Λ are then used to plot the χ -nucleon cross section limits versus DM mass

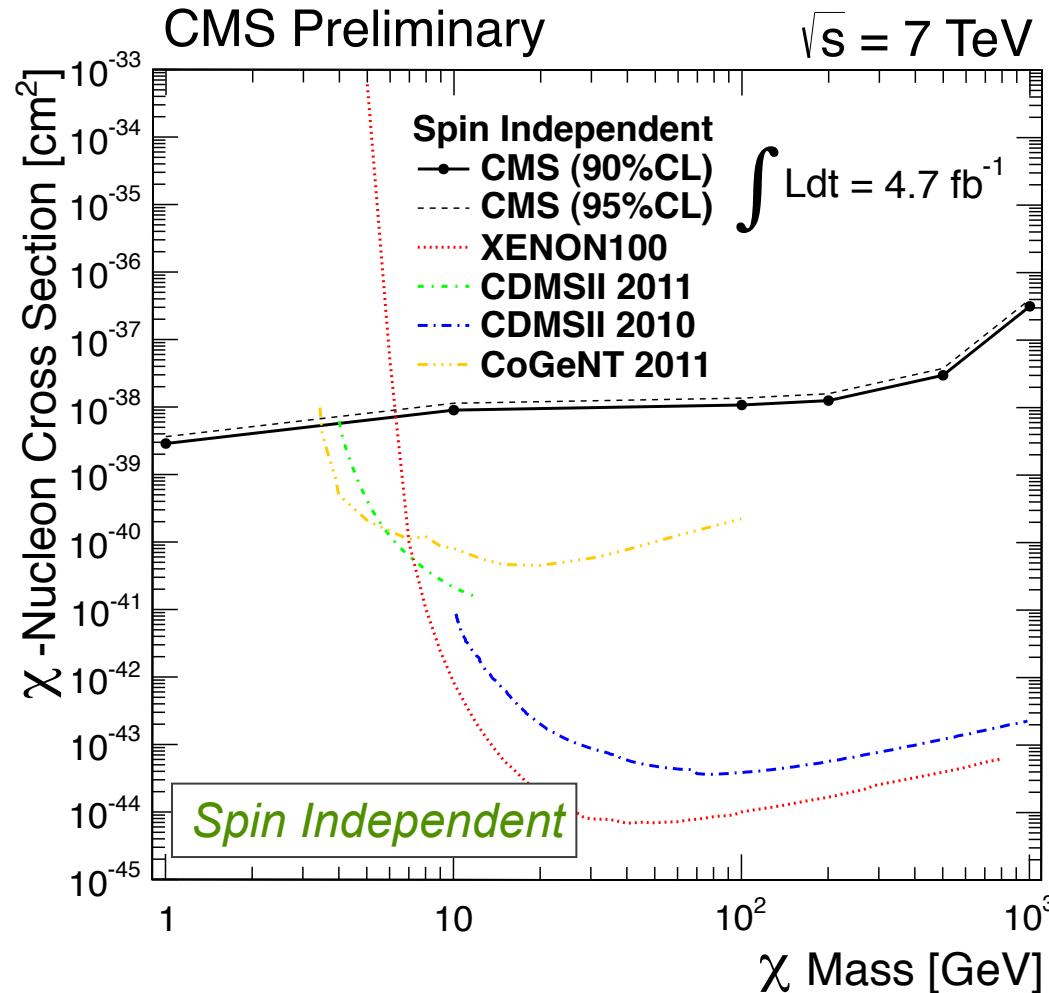
Spin Independent (Vector)

χ Mass [GeV]	90% CL Limits	
	$\sigma [\text{fb}]$	$\Lambda [\text{GeV}]$
1	16.8 (16.4)	549 (553)
10	16.8 (16.4)	549 (552)
100	16.8 (16.3)	546 (550)
200	16.8 (16.4)	527 (530)
500	16.1 (15.6)	425 (428)
1000	16.6 (16.1)	235 (237)

Spin Dependent (Axial-Vector)

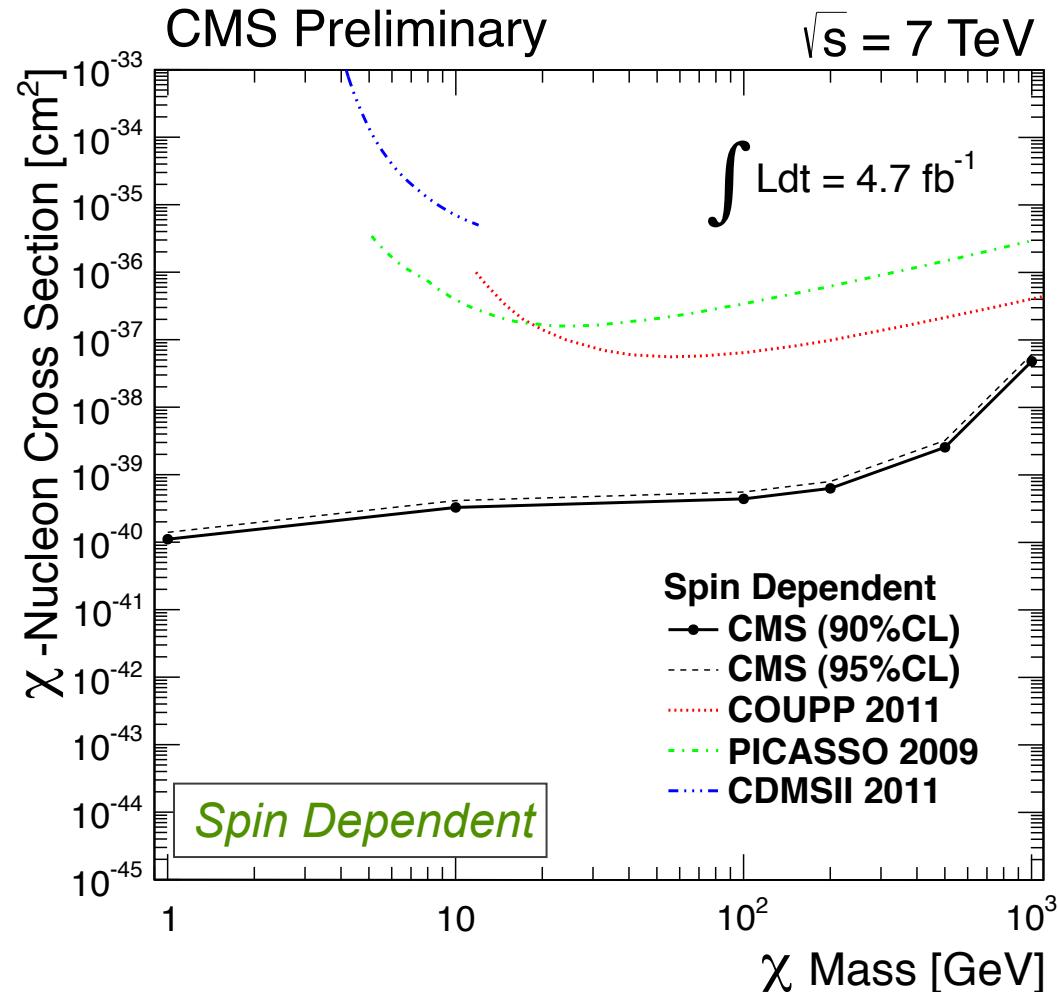
χ Mass [GeV]	90% CL Limits	
	$\sigma [\text{fb}]$	$\Lambda [\text{GeV}]$
1	17.6 (17.1)	543 (546)
10	16.6 (16.1)	550 (554)
100	16.4 (15.9)	532 (536)
200	16.5 (16.1)	488 (491)
500	16.1 (15.7)	344 (346)
1000	16.4 (15.9)	165 (166)

MONOPHOTON – SPIN-INDEPENDENT LIMITS



[CDMS II: Science 327 (2010) 1619]
[XENON100: Phys. Rev. Lett 17 (2011) 131302]
[CoGeNT: Phys. Rev. Lett. 106 (2011) 131301]

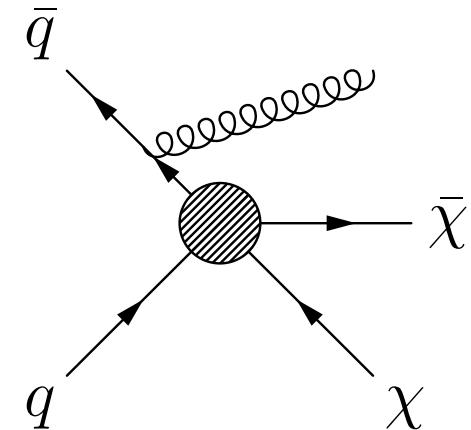
MONOPHOTON – SPIN-DEPENDENT LIMITS



[CDMS II: Science 327 (2010) 1619]
[PICASSO: Phys. Lett. B 682 (2009) 185–192]
[COUPP: Phys. Rev. Lett. 106 (2011) 021303]

MONOJET – SEARCH DETAILS

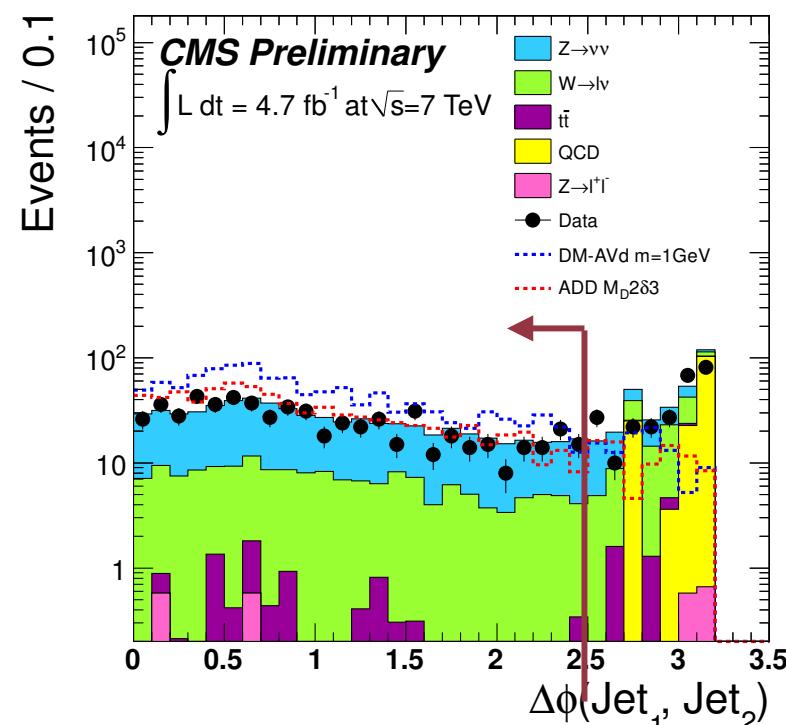
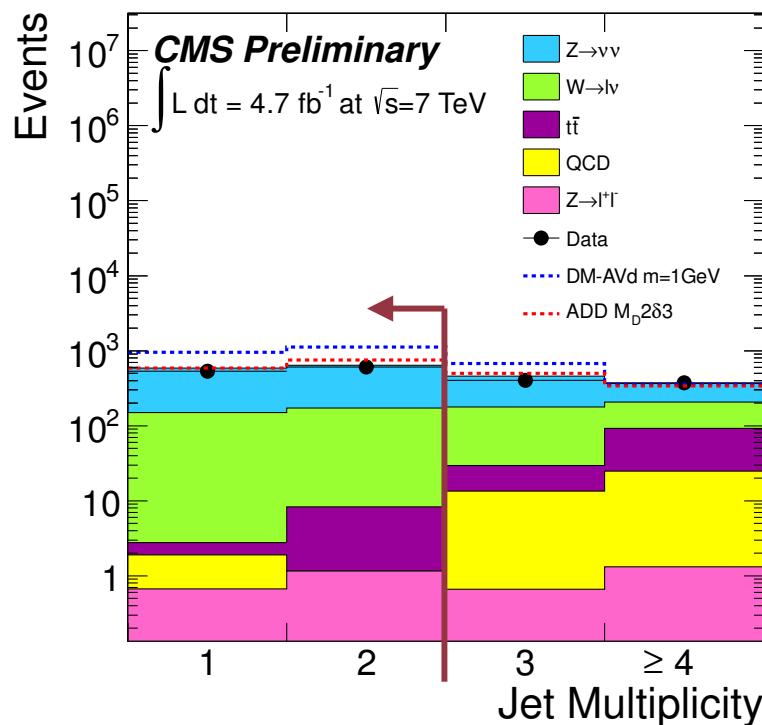
- Select sample of Monojet+MET events (keeping muons)
 - Basic cuts on jet constituents – charged and neutral HAD and EM fractions
 - Removes cosmics, instrumental backgrounds, mismeasured jets
- Basic topological selection
 - MET > 200 GeV, # of Jets = 1 or 2
 - Particle flow jets; anti- k_T with $R = 0.5$
 - Leading Jet: $pT > 110$ GeV, $|n| < 2.4$
 - Second Jet: $pT > 30$ GeV
 - $\Delta\varphi(\text{jet1}, \text{jet2}) < 2.5$
- Monojet Signal Sample (Lepton Rejection)
 - Reject events with e, μ isolated in a cone of $\Delta R = 0.3$
 - Reject events with tracks isolated in a cone of $\Delta R = 0.3$
 - MET > 350 GeV for DM search
- Data-driven Background Estimation (Lepton Identification)
 - Isolated muon > 20 GeV/c
 - Obtain Z+jet sample from $M(\mu\mu)$, W+jet sample from $p_T(\mu) + \text{MET}$



MONOJET – BASIC SELECTION

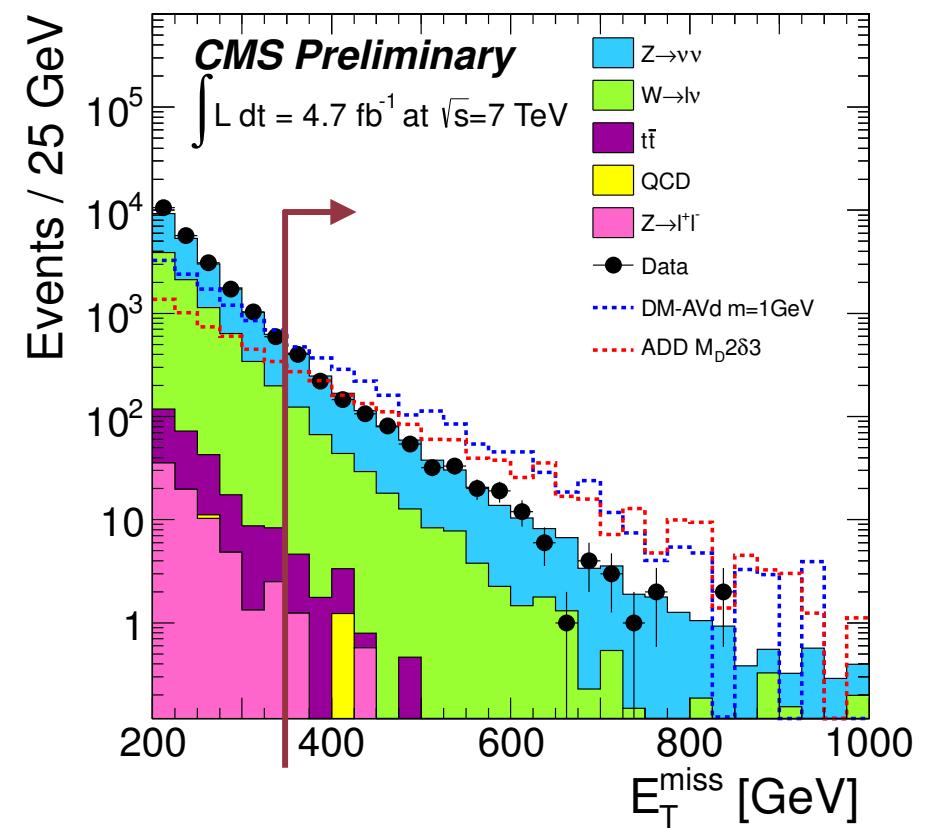
- Basic topological selection
 - MET > 200 GeV, # of Jets = 1 or 2
 - Leading Jet: pT > 110 GeV, $|\eta| < 2.4$
 - Second Jet: pT > 30 GeV
 - $\Delta\phi(\text{jet1}, \text{jet2}) < 2.5$

► *QCD rejection accomplished by topological cuts*



MONOJET – DATA SAMPLE

- Final monojet signal sample obtained by
 - Rejecting events with isolated e, μ
 - Rejecting events with isolated tracks
 - Good agreement for full MET range
 - Sensitivity to new physics (DM, ADD) in the tails
 - Optimise search for best expected sensitivity to new physics
 - $\text{MET} > 350 \text{ GeV}$ for DM search
- *Search high MET events for DM*

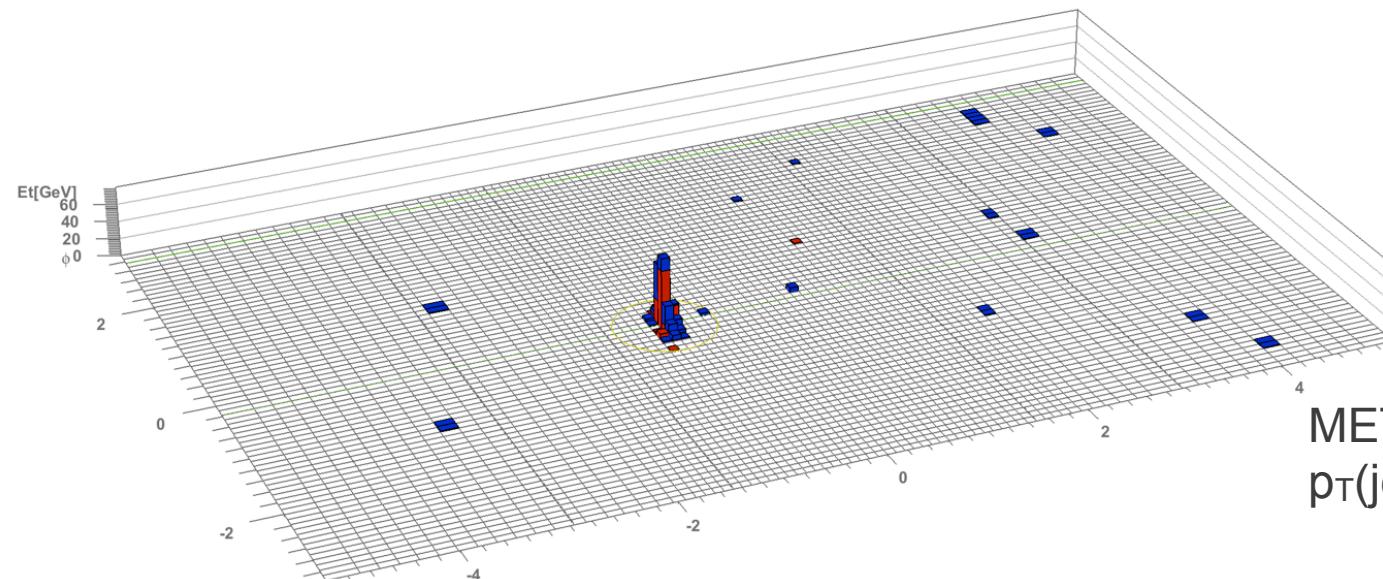


MONOJET – ANALYSIS CUT FLOW

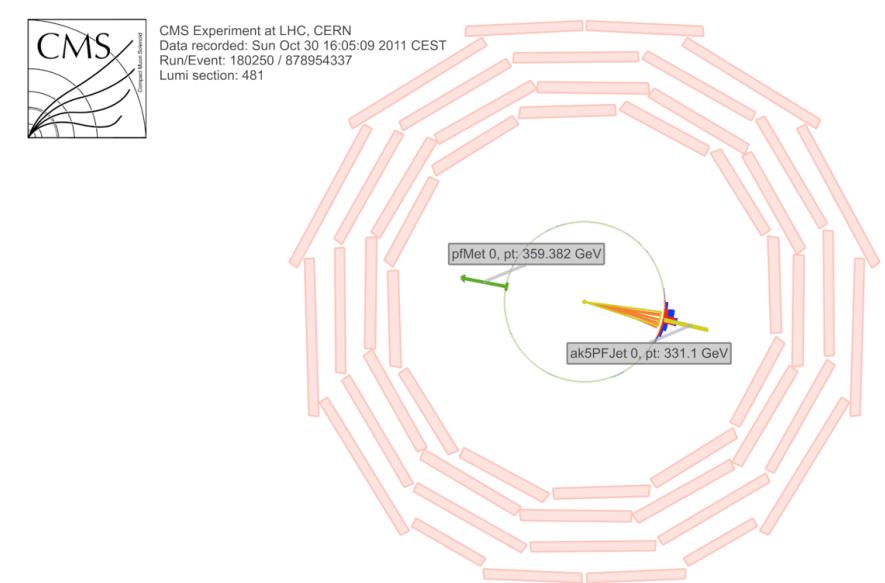
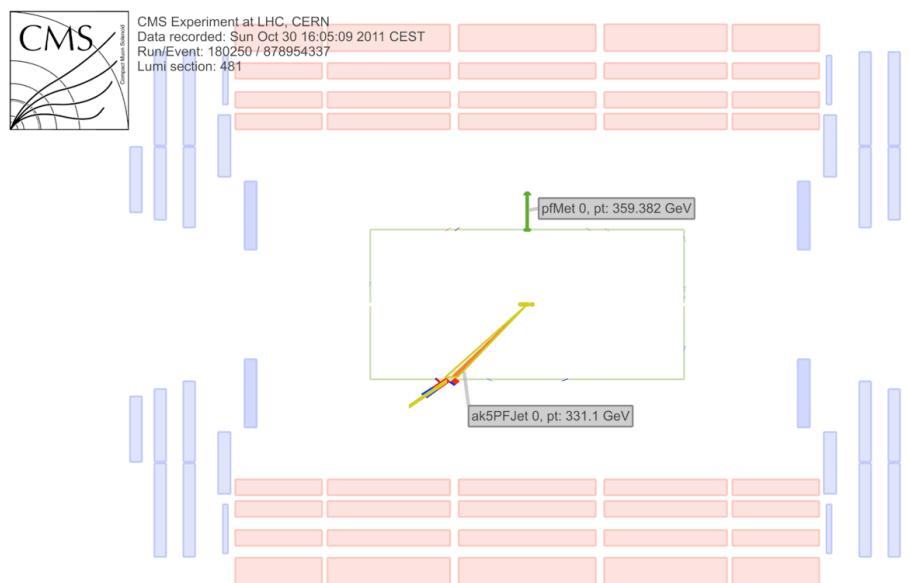
- Primary backgrounds normalised to data-driven estimation
- Remaining backgrounds after full event selection: Z(vv) ($\approx 70\%$), W+jets ($\approx 30\%$),
- Other backgrounds from QCD, top, Z+jets negligible ($\approx 1\%$) – estimated from MC
 - ▶ *Good agreement between data and SM backgrounds*

Requirement	W+jets	Z(vv) +jets	Z($\ell\ell$) +jets	$t\bar{t}$	Single t	QCD multijet	Total bgd	Data
$E_T^{\text{miss}} > 200 \text{ GeV}$	55269	30312	4914	12455	1090	14959	118999	104485
$p_T(j_1) > 110 \text{ GeV}/c,$ $ \eta(j_1) < 2.4$	52100	28267	4590	11107	968	14743	111775	100658
$N_{\text{jets}} \leq 2$	37112	21245	3229	1484	256	4952	68278	62395
$\Delta\phi(j_1, j_2) < 2$	33123	19748	2936	1256	222	58	57343	53846
Lepton Removal	9561	14663	76	200	33	2	24535	23832
$E_T^{\text{miss}} > 250 \text{ GeV}$	2632	5106	21	65	10	2	7836	7584
$E_T^{\text{miss}} > 300 \text{ GeV}$	816	1908	6	21	3	1	2755	2774
$E_T^{\text{miss}} > 350 \text{ GeV}$	312	900	2	8	1	1	1224	1142
$E_T^{\text{miss}} > 400 \text{ GeV}$	135	433	1	3	0	1	573	522

A MONOJET EVENT

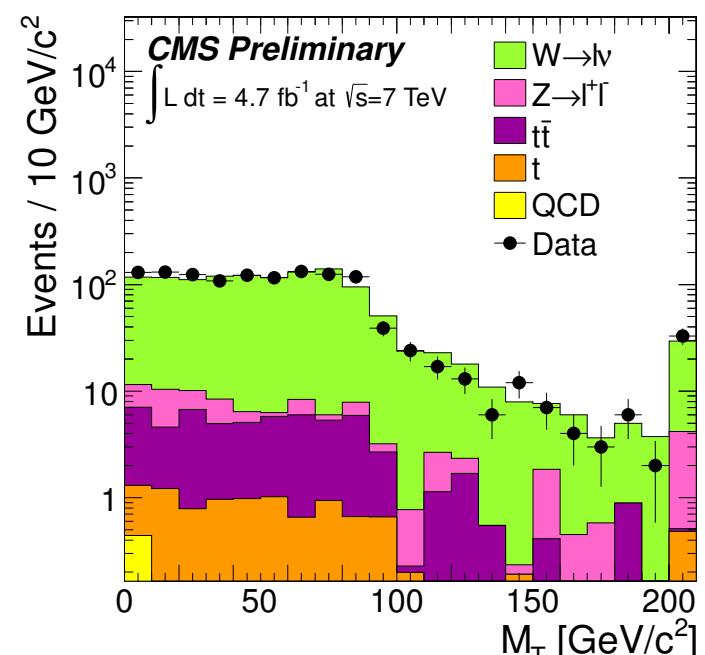
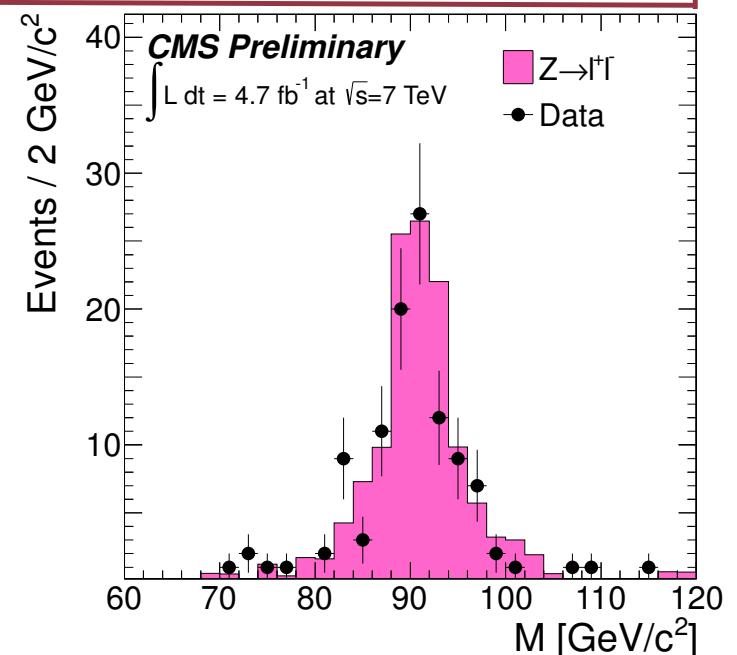


MET = 359 GeV
 $p_T(\text{jet1}) = 331 \text{ GeV}$



MONOJET – BACKGROUND NORMALISATION

- Data-driven estimation of $Z + \text{jets} \rightarrow \nu\nu + \text{jets}$
 - $Z + \text{jets} \rightarrow \mu\mu + \text{jets}$ control sample derived directly from our monojet data sample
 - Require two muons passing selection
 - Invariant mass 60-120 GeV, opposite sign
 - Uncertainty in method is 10.4% mainly from stats (9.5%)
 - Similar for $W + \text{jets} \rightarrow \nu l + \text{jets}$, where lepton is “lost”
 - lepton lost if outside detector acceptance or not reconstructed/isolated
 - Require single lepton and M_T between 50-100 GeV
 - Primary uncertainties from error on acceptance (7.7 %) and selection efficiency (6.8 %)
 - Uncertainty in method is 11.3%
- *Data-driven measure of main backgrounds*

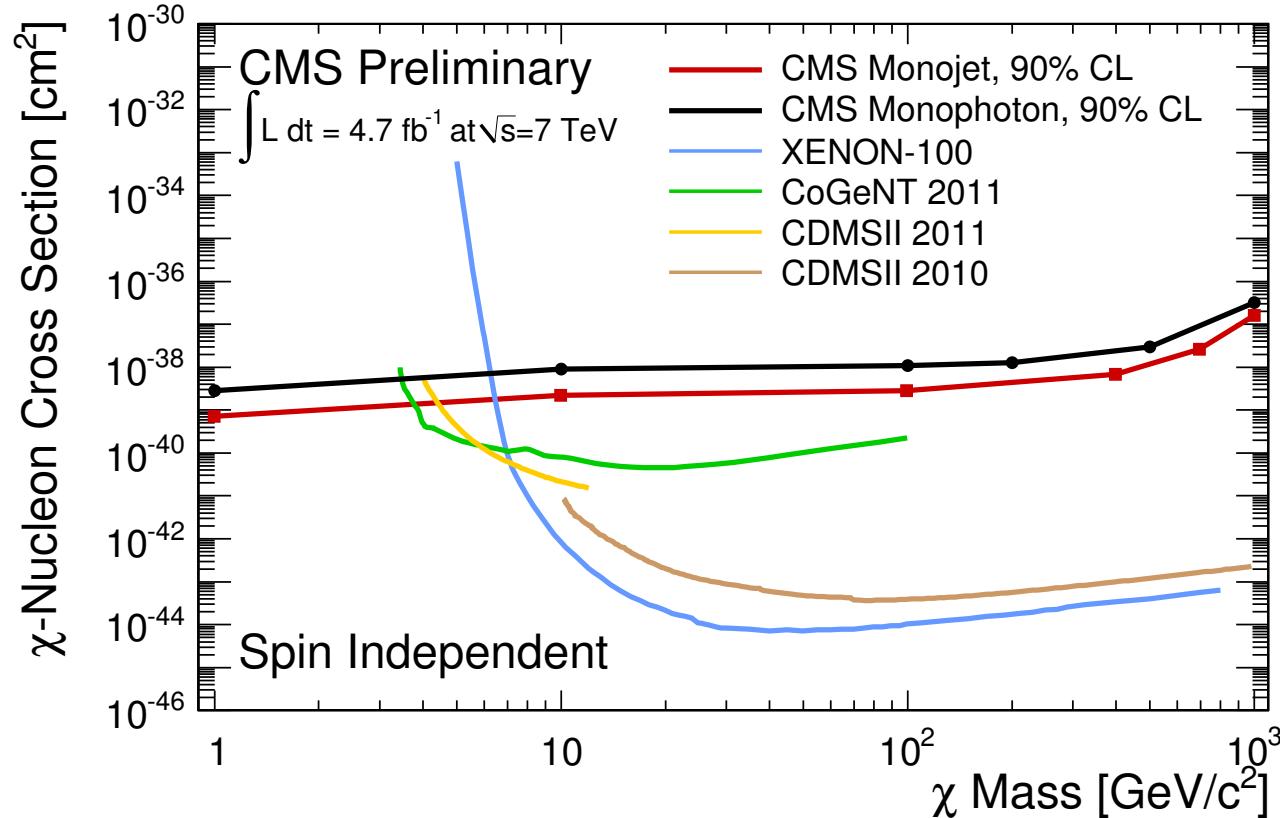


MONOJET – DARK MATTER SIGNAL

- Monojet Signal Generation
 - Madgraph5 + Pythia6 generation with 40 TeV mediator mass
- Systematic uncertainties $\leq 15\%$, main contributions from
 - Jet Energy Scale $\sim 10\%$
 - PDF (PDF4LHC) $2\text{-}4\%$
 - Jet Energy Resolution 2%
 - Luminosity 4.5%
- Final numbers for $\text{MET} > 350 \text{ GeV}$: 1224 ± 101 background, 1142 data
 - ▶ *Good efficiency and modest systematics \rightarrow limit-setting as before*

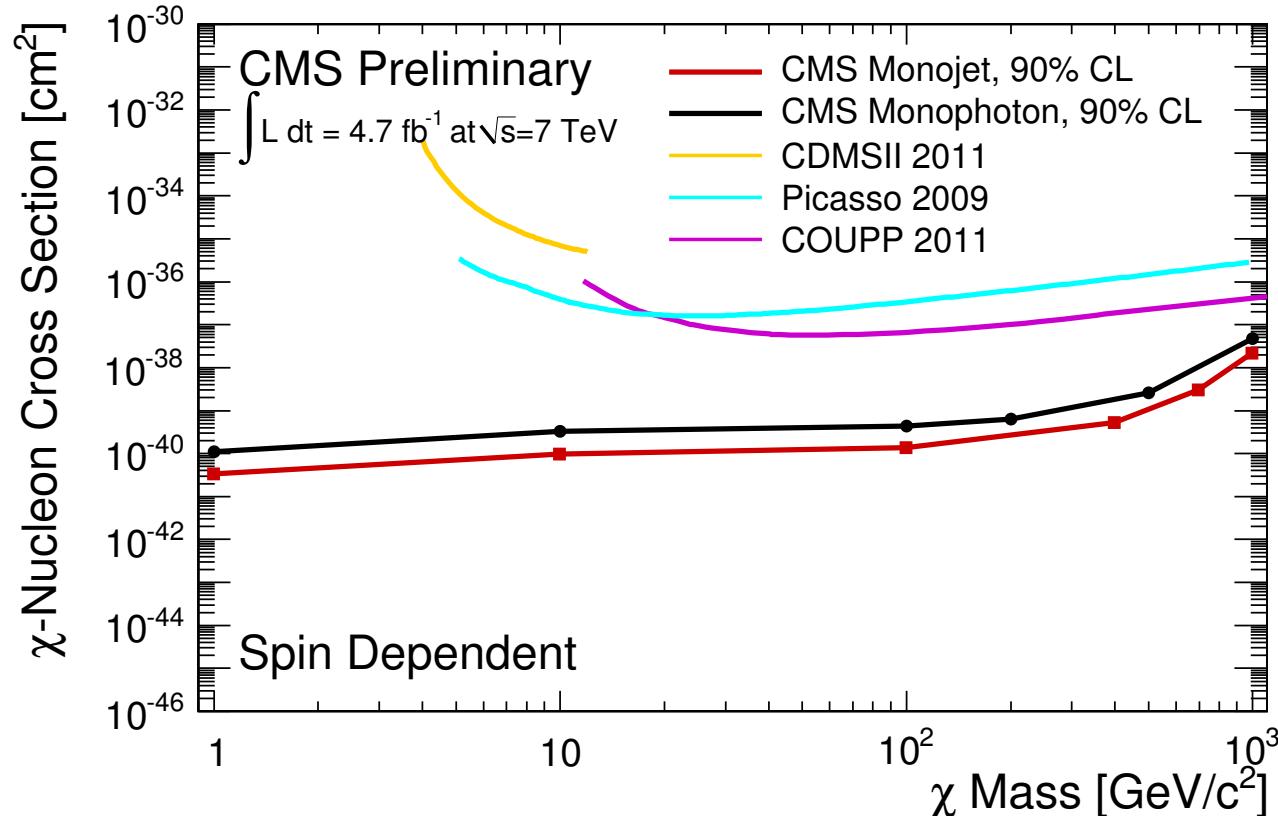
M_χ (GeV/c ²)	Spin-dependent		Spin-independent	
	$\sigma(\text{cm}^2)$	Λ (GeV)	$\sigma(\text{cm}^2)$	Λ (GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}	281

DARK MATTER SPIN-INDEPENDENT LIMITS



- ▶ Best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by direct detection experiments

DARK MATTER SPIN-DEPENDENT LIMITS



- ▶ *Limits represent the most stringent constraints by several orders of magnitude over entire 1-1000 GeV mass range*

CONCLUSIONS

Presented CMS searches for new physics in monojet and monophoton channels using 4.7 fb^{-1} of data.

Predictions for SM background consistent with observed data, *no excess* found. Limits set on Dark Matter production, resulting in a significant extension of previously excluded parameter space:

- ▶ *For spin-independent models, best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by the direct-detection experiments.*
- ▶ *For spin-dependent models, limits represent the most stringent constraints by several orders of magnitude over entire 1-1000 GeV mass range studied.*

Further reading: EXO-11-059 (monojet) and EXO-11-096 (monophoton) at
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

DARK MATTER LIMITS FROM CDF

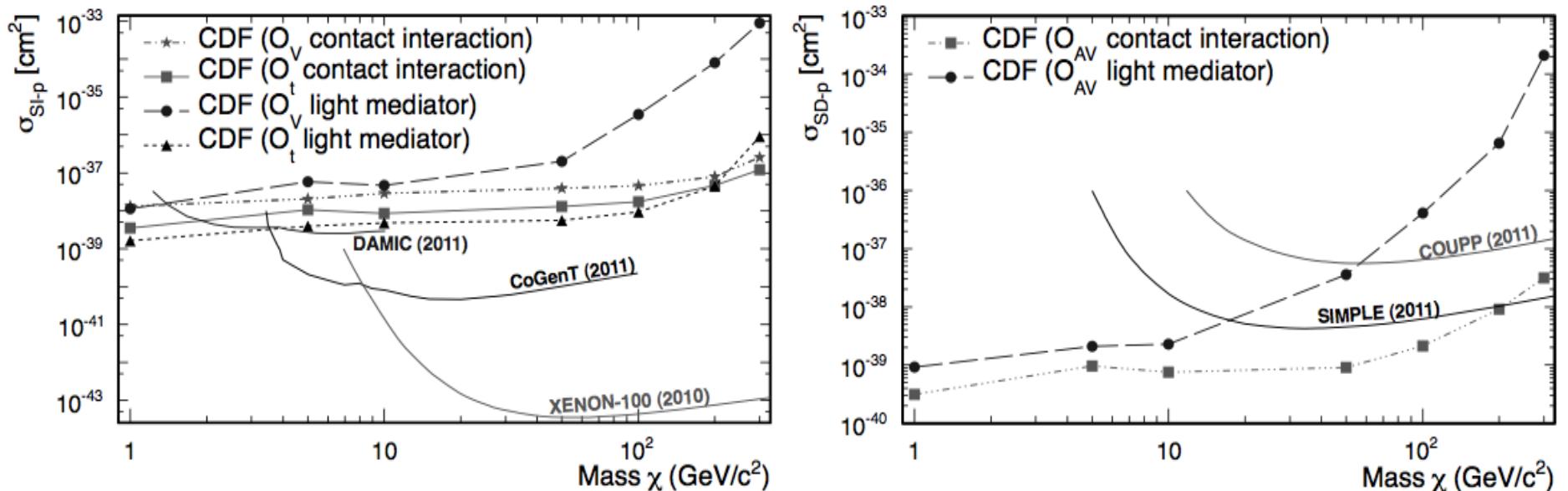


FIG. 2: Comparison of CDF results to recent results from DAMIC [34], CoGeNT [4], XENON-100 [35], SIMPLE [36], and COUPP [37]. Spin-independent (left) and spin-dependent (right) bounds are shown for the operators (defined in text) \mathcal{O}_{AV} , \mathcal{O}_V , and \mathcal{O}_t , assuming contact interactions. For comparison we also display CDF bounds assuming light mediators.

► *Limits from CDF posted a few days ago...*

[<http://arxiv.org/abs/1203.0742>]

MONOPHOTON – ISOLATION

For selection of isolated photons in a cone $\Delta R^2 = \Delta\varphi^2 + \Delta\eta^2$...

- Hadron Calorimeter (HCAL) isolation
 - Hollow Cone: $0.15 < \Delta R < 0.4$, $\sum p_T$ in hollow cone $< 2.2 + 0.0025 * p_T(\gamma)$
 - $(E_{HCAL} \text{ in cone})/E_{ECAL} < 0.05$
- EM Calorimeter (ECAL) isolation
 - Hollow Cone: $0.06 < \Delta R < 0.4$, $\sum p_T$ in hollow cone $< 4.2 + 0.006 * p_T(\gamma)$
- Tracker isolation
 - Hollow Cone: $0.04 < \Delta R < 0.4$, $\sum p_T$ in hollow cone $< 2.0 + 0.001 * p_T(\gamma)$
 - Electrons vetoed by hits in pixel tracker
- All reconstructed vertices are used for isolation calculations.

