Search for Dark Matter at CMS in Monophoton and Monojet Events

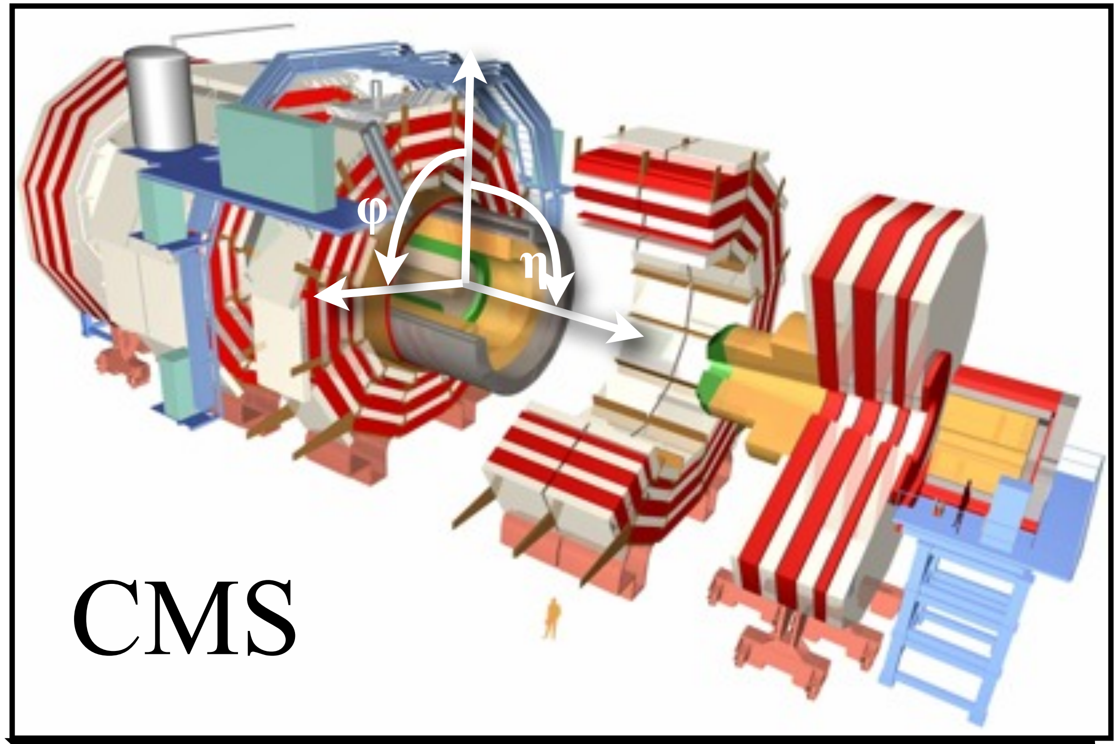
Tia Miceli
For the CMS Collaboration

More at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11096
http://arxiv.org/abs/1204.0821
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012
http://cdsweb.cern.ch/record/1376675/files/EXO-11-059-pas.pdf
http://indico.in2p3.fr/getFile.py/access?contribId=100&sessionId=6&resId=0&materialId=slides&confId=6001

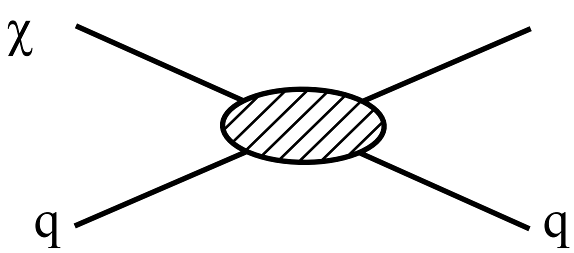
PASCOS 2012
June 3 - June 8

The Large Hadron Collider and the Compact Muon Solenoid

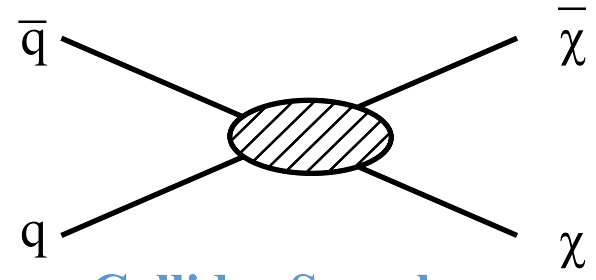
- We used 5.0 fb^{-1} (4.7 fb^{-1}) of integrated luminosity from p-p collisions at the LHC running at 7 TeV for a dark matter search in monophoton (monojet) events.
- The data was collected with CMS, a layered detector that identifies particles coming from these proton collisions.



Dark Matter (χ) Production at the LHC

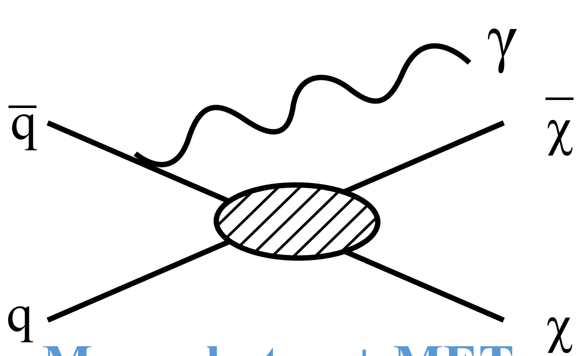


Direct Searches
Nuclear Recoil
(t-channel)

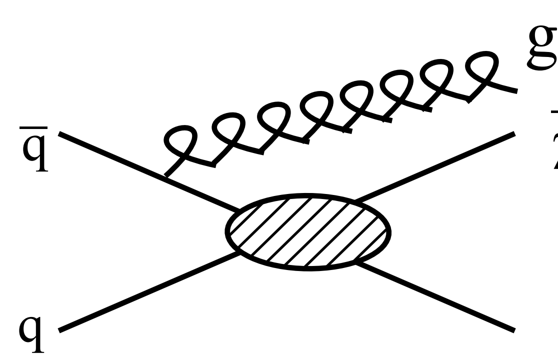


Collider Searches
Pair Production
(s-channel)

- Dark matter passes through CMS undetected, giving rise to "missing transverse energy", E_T^{miss}.
- To make this process visible, radiation of a photon or gluon is required. Searches in the final states of $\gamma + E_T^{miss}$ and jet + E_T^{miss} are presented.



Monophoton + MET



Monojet + MET

Phenomenology 1

- Bai, Fox, and Harnik [JHEP 1012:048(2010)] have cast this process as a contact interaction with the effective operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu \chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$ **Vector Operator ⇒ Spin Independent**

$$O_A = \frac{(\bar{\chi}\gamma_\mu \gamma^5 \chi)(\bar{q}\gamma^\mu \gamma_5 q)}{\Lambda^2}$$ **Axial-Vector Operator ⇒ Spin Dependent**

- The observed upper limit on the $\chi\bar{\chi}$ production cross section, $\sigma^{\chi\bar{\chi}}_{meas.}$, is transformed into a lower limit on the cut-off scale Λ (=$M_{moderator}/\sqrt{g_\chi g_q}$) taking advantage of the fact that $\sigma \propto \Lambda^{-4}$.
  - $\Lambda_{th.} \equiv$ 10 TeV (40 TeV) for monophoton (monojet)
  - $\sigma^{\chi\bar{\chi}}_{th.}$ is computed using Madgraph-4 and Pythia-6, for a given phase space

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma^{\chi\bar{\chi}}_{th.}}{\sigma^{\chi\bar{\chi}}_{meas.}} \right)^{1/4}$$

Phenomenology 2

- With this lower limit on Λ, the upper limits on χ-N cross-sections for the spin-independent and spin-dependent interactions can be computed for various dark matter masses, m_{DM}.

$$\sigma_{SI}^{\chi\text{-N}} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin-Independent

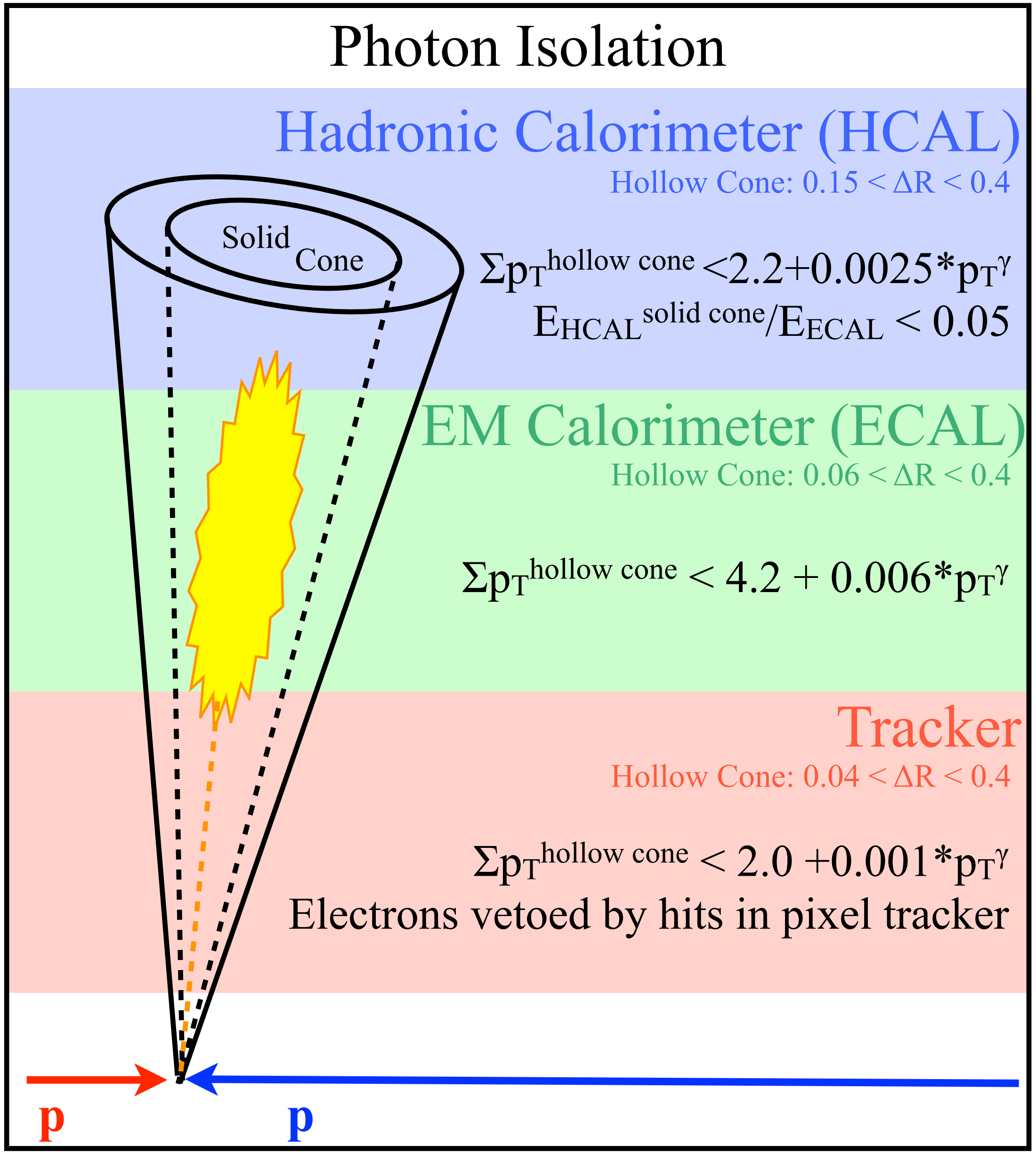
$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

Spin-Dependent

$$\mu = \left(\frac{m_{DM}\ m_p}{m_{DM} + m_p}\right)$$

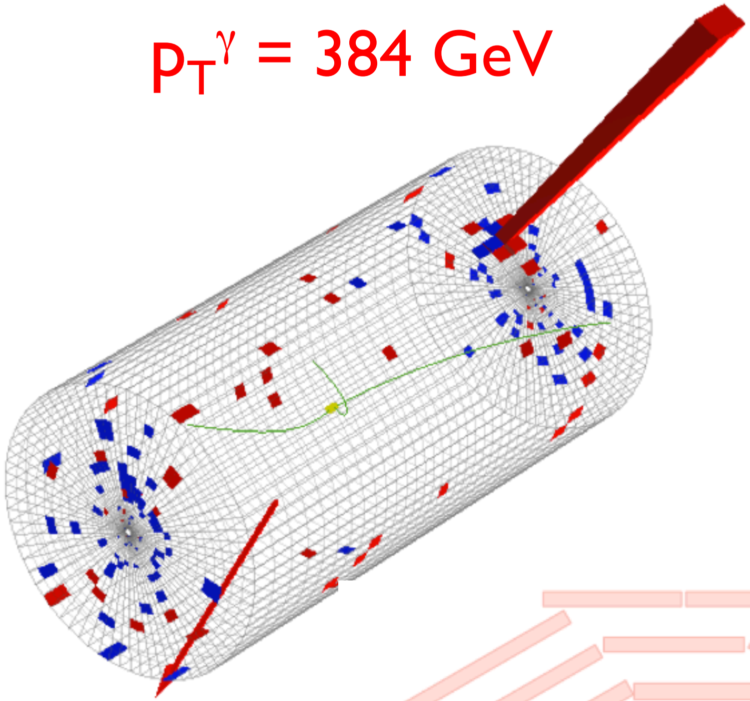
Monophoton - Candidate Selection

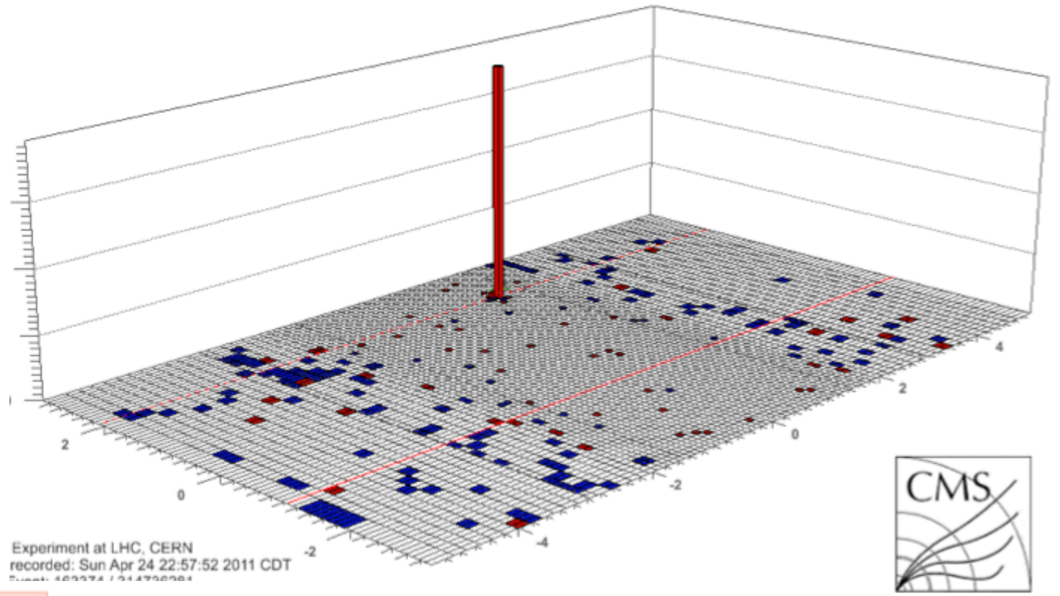
- Require an isolated photon with:
  - High energy: $p_T^{\gamma} > 145$ GeV
  - Centrally located: $|\eta^{\gamma}| < 1.4442$
  - Deposit shape is photon-like: $\sigma_{i\eta i\eta} < 0.013$ (a measure of the shower profile width along η)
- Require sufficient E_T^{miss} using particle flow method, pfMET > 130 GeV
- Remove events with excessive nearby activity:
  - No centrally located pfJets with $p_T > 40$ GeV and $|\eta^{jet}| < 3.0$
  - No tracks with $P_T > 20$ GeV within $\Delta R(track,\gamma) > 0.04$, where $\Delta R^2 = \Delta\varphi^2 + \Delta\eta^2$



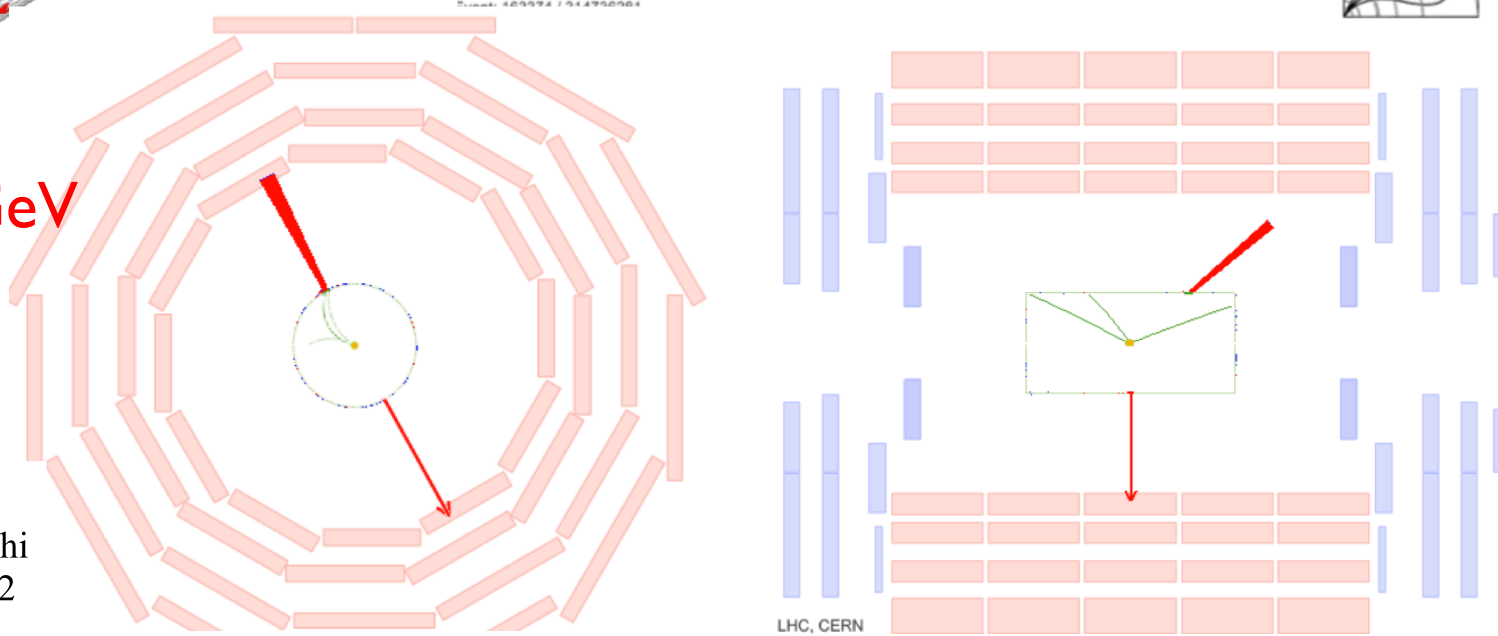
Monophoton - Highest p_T^γ Event

$p_T^\gamma = 384$ GeV





$E_t^{miss} = 407$ GeV



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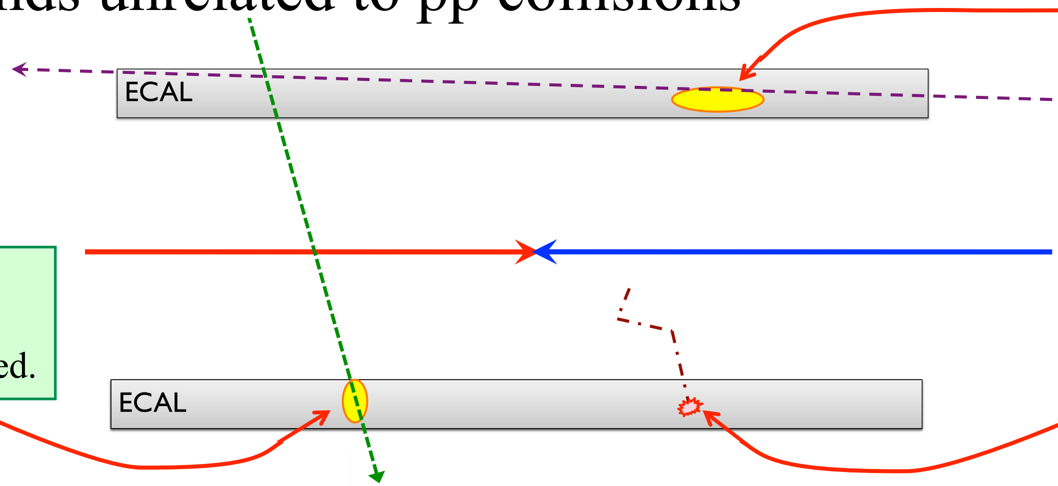
UCLA Dark Matter 2012

Monophoton - Backgrounds

- Backgrounds are estimated using data-driven (DD) and Monte Carlo (MC) techniques.
  - $pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$ — irreducible background, estimated to NLO **(MC)**
  - $pp \rightarrow W \rightarrow e\nu$ — electron misidentifies as γ **(DD)**
  - $pp \rightarrow \text{Njets} \rightarrow$ "γ"+ E_T^{miss} — one jet mimics γ, E_T^{miss} from jet energy mismeasurement. Appreciable due to the high rate of Njets. **(DD)**
  - $pp \rightarrow \gamma + \text{jet}$ — E_T^{miss} due to mismeasurement of jet **(MC)**
  - $pp \rightarrow W\gamma \rightarrow l\nu\gamma$ — charged lepton escapes detection **(MC)**
  - $pp \rightarrow \gamma\gamma$ — one photon mismeasured to create E_T^{miss} **(MC)**
- Backgrounds unrelated to pp collisions

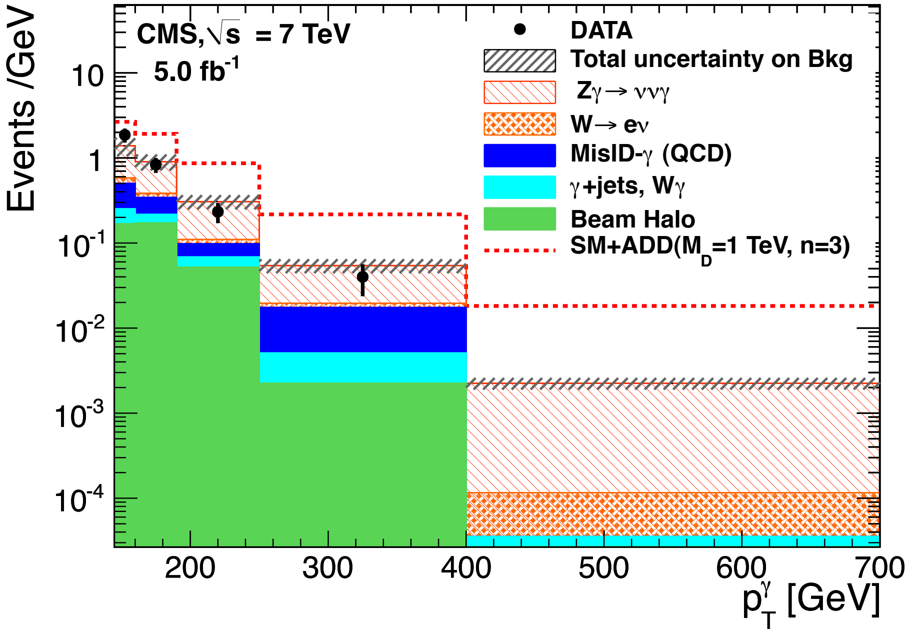


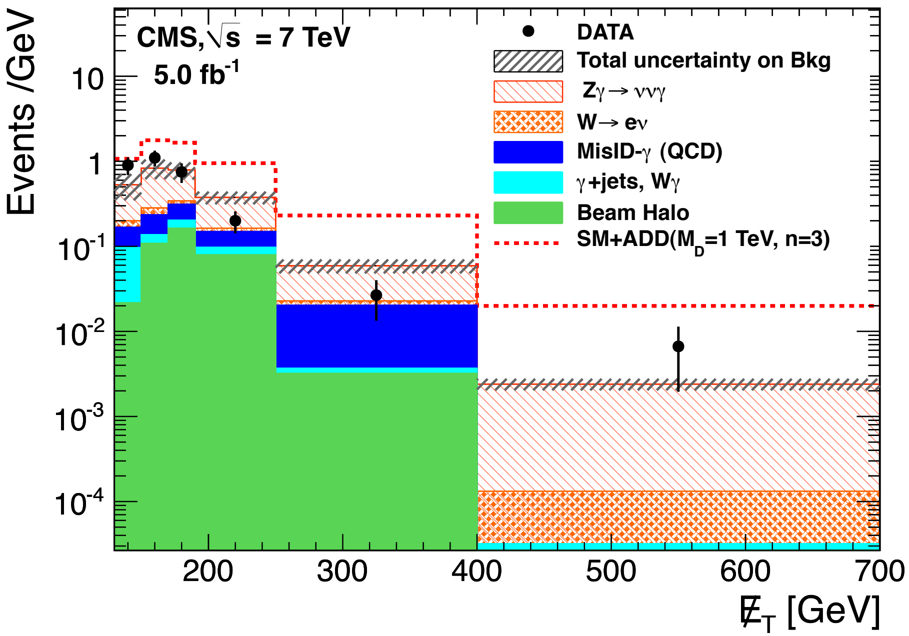
1. Beam Halo Muon Showers
Mostly removed. Residual estimated.

2. Cosmic Muon Induced Showers
Identified and removed.

3. Neutron Induced Spurious Signals
Identified and removed.

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
$W\gamma$	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

No excess observed.
Background describes data well.

Monophoton - Acceptance, Efficiency, and Uncertainties

- A x ε_{MC} is stable over the range m_χ=1-1000 GeV because the signal is an ISR γ
  - Vector χ (spin independent): 30.5%-31.0%
  - Axial-Vector χ (spin dependent): 29.2%-31.4%
- Uncertainties in A x ε_{MC} total to +4.8% -4.9% from:
  - photon energy scale
  - missing transverse energy scale and resolution
  - jet energy scale and resolution
  - photon vertex assignment
  - overlapping events (pile up)
  - parton distribution function
- The scale factor between this MC A x ε and data is estimated

Source	Estimate for SF
Trigger	1.00 ± 0.02
Consistent Cluster Timing	0.98 ± 0.01
Photon ID Efficiency	0.96 ± 0.02
Jet and Track Veto	1.00 ± 0.10
Cosmic Muon Veto	0.95 ± 0.01
Total	**0.90 ± 0.11**

Monophoton - Limit Setting

- Use the Modified Frequentist CLs approach [J. Phys. G37(2010) 075021]
- For integrated luminosity 5fb^{-1}, null hypothesis expected 75.1 ± 9.5 events and observed 73 events.
- 90% CL limits are shown compared to the expected limit in parentheses.

M_χ [GeV]	Vector		Axial-Vector	
	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)

$\sigma^{\chi\bar{\chi}}_{meas.}$

The measured cross section upper limit is translated into a lower limit on Λ.

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma^{\chi\bar{\chi}}_{th.}}{\sigma^{\chi\bar{\chi}}_{meas.}} \right)^{1/4}$$

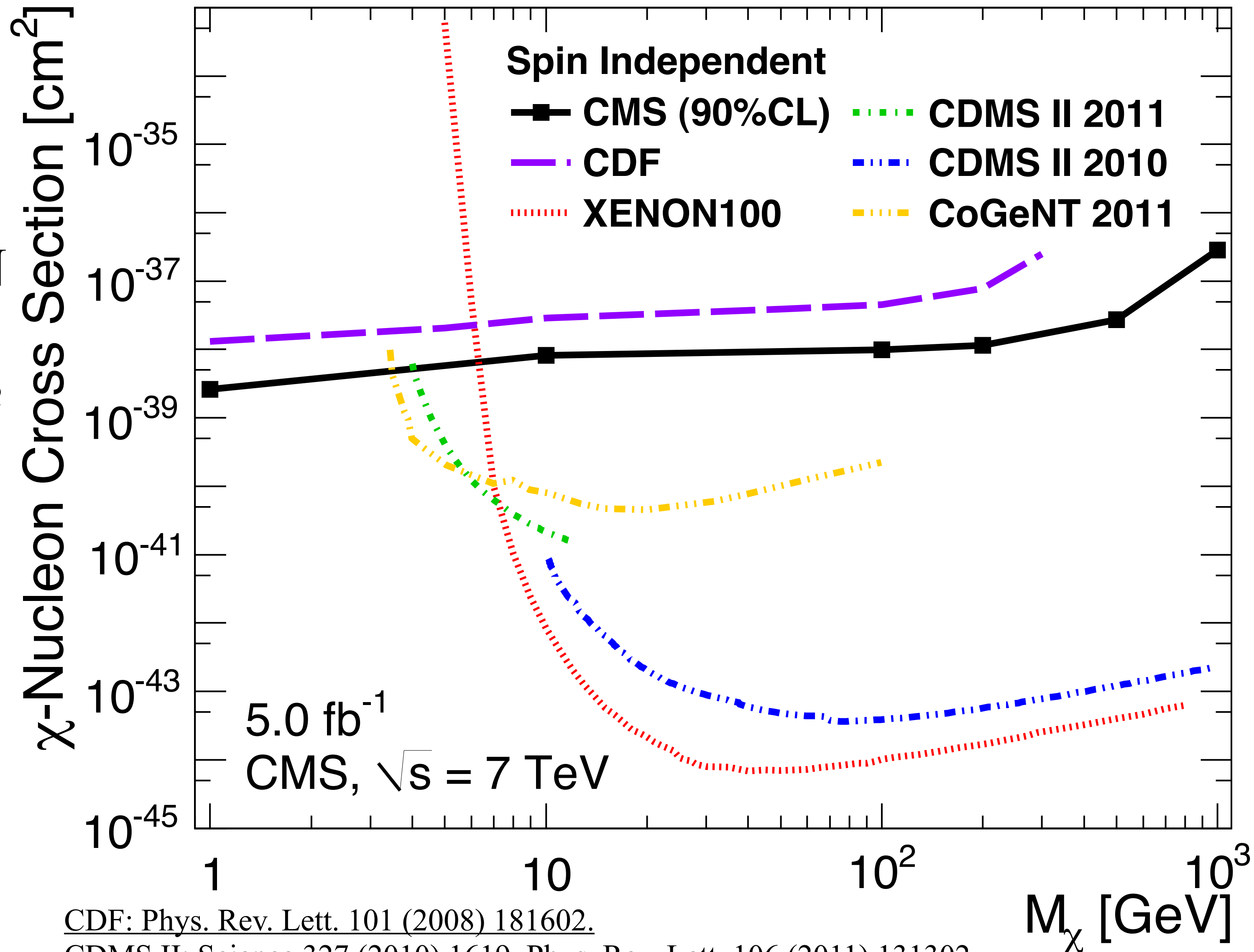
$\Lambda_{th.} \equiv 10$ TeV
$\sigma^{\chi\bar{\chi}}_{th.}$ from MC

Monophoton - Spin Independent Limits

- Lower limit on Λ used to compute χ-N cross-section.

$$\sigma_{SI}^{\chi\text{-}N} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

- Extends the cross-section lower limits for $M_\chi < 3.5$ GeV.



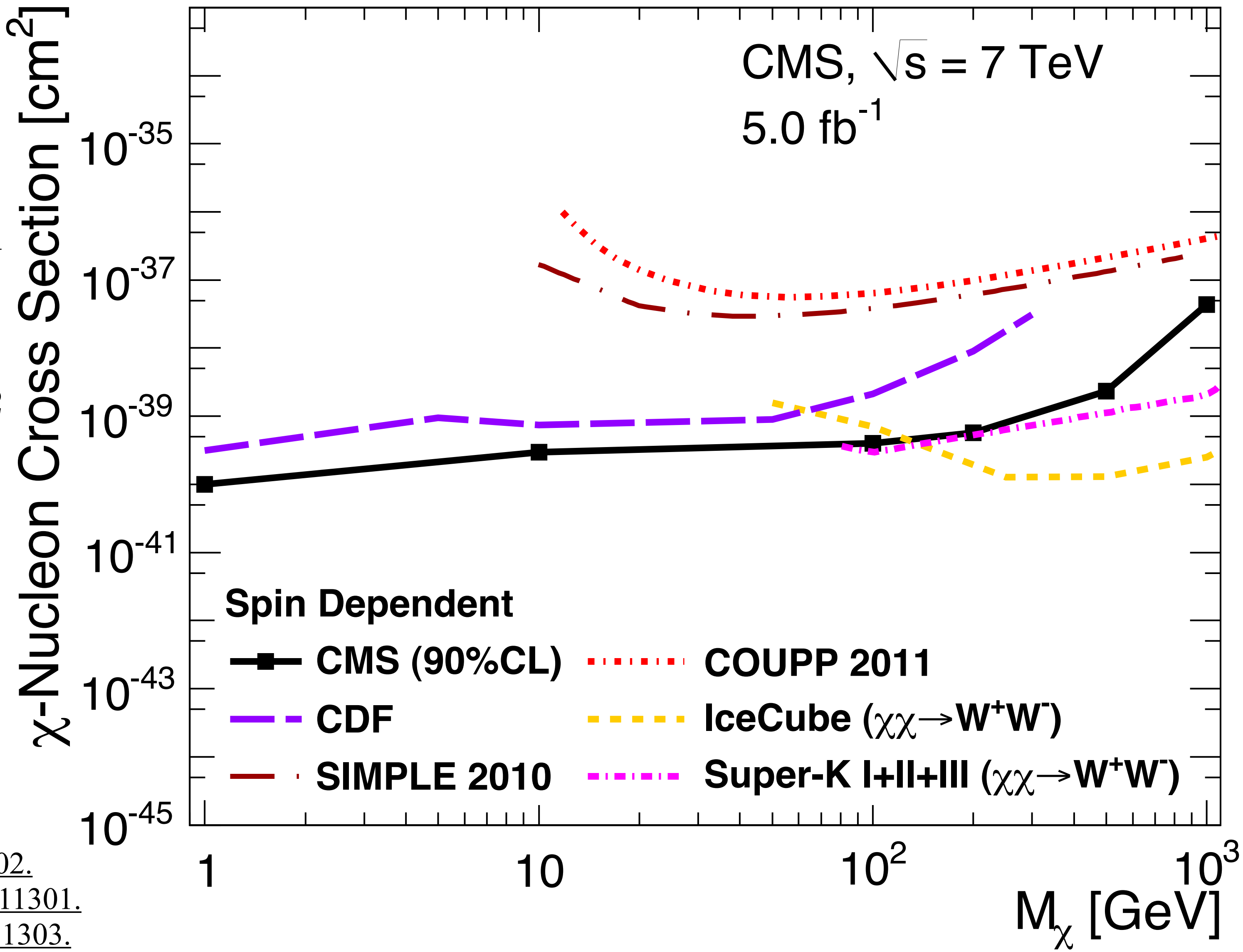
CDF: Phys. Rev. Lett. 101 (2008) 181602.
CDMS II: Science 327 (2010) 1619. Phys. Rev. Lett. 106 (2011) 131302.
XENON100: Phys. Rev. Lett 107 (2011) 131302
CoGeNT: Phys. Rev. Lett 106 (2011) 131301

Monophoton - Spin Dependent Limits

- Lower limit on Λ used to compute χ-N cross-section.

$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

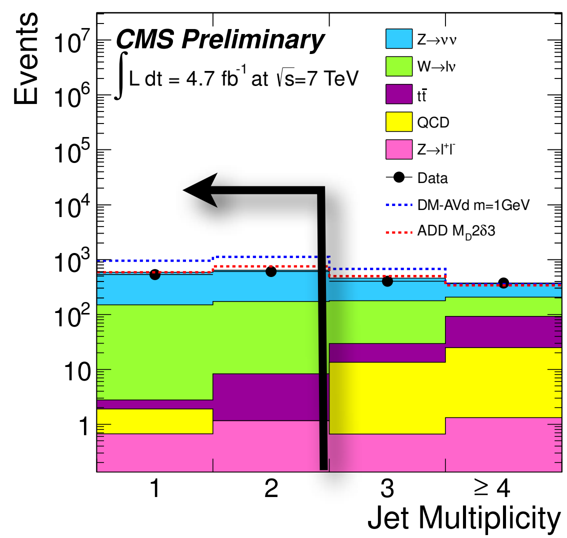
- Extends the cross-section lower limits for $M_\chi < 100$ GeV.

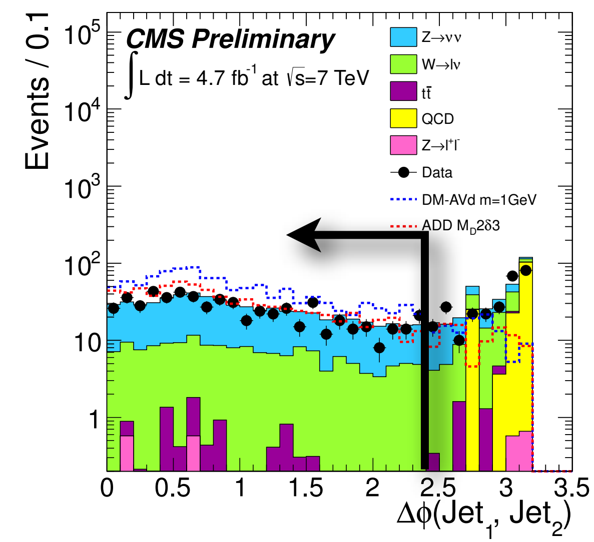


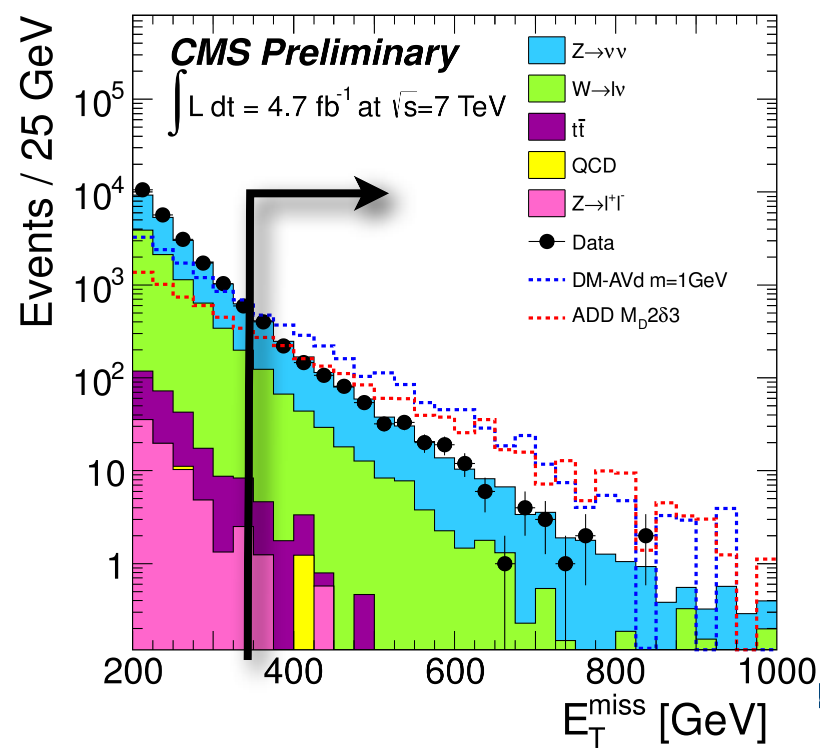
CDF: Phys. Rev. Lett. 101 (2008) 181602.
SIMPLE: Phys. Rev. Lett. 105 (2010) 211301.
COUPP: Phys. Rev. Lett. 106 (2011) 021303.
IceCube: Phys. Rev. D 85 (2012) 042002.
Super-K: ApJ 742 (2011) 78.

Monojet - Candidate Selection

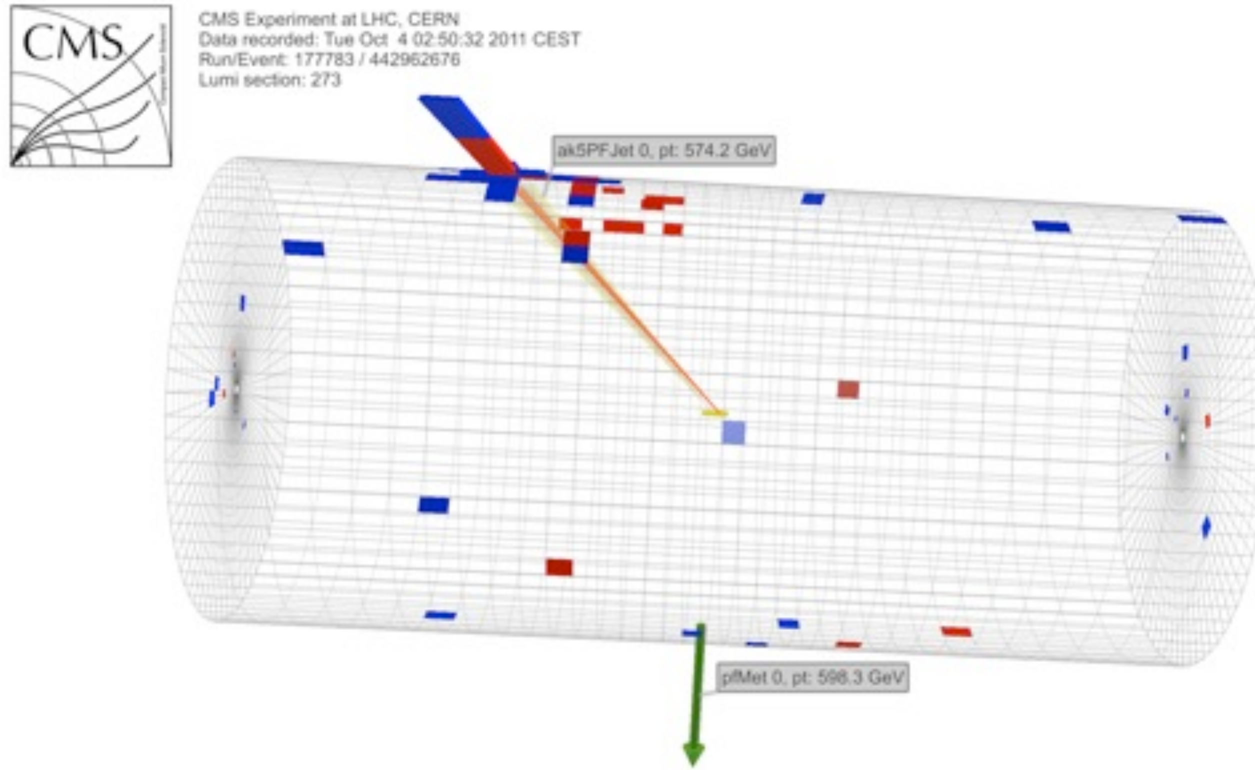
- Basic Topological Selection → reject prolific multijet events
  - n_{jets} = 1 or 2, E_T^{miss} > 200 GeV later tightened to 350
  - particle flow jets clustered using anti-k_T with R = 0.5
  - $p_T^{lead\ jet}$ > 110 GeV, $|\eta|<2.4$
  - $p_T^{second\ jet}$ > 30 GeV
  - $\Delta\varphi$(jet1, jet2) < 2.5
- Lepton removal
  - Reject events with isolated e or μ ($\Delta R_{isolation}$=0.3).
  - Reject events with isolated tracks ($\Delta R_{isolation}$=0.3).
- Optimize E_T^{miss} cut for DM search: E_T^{miss} > 350 GeV.



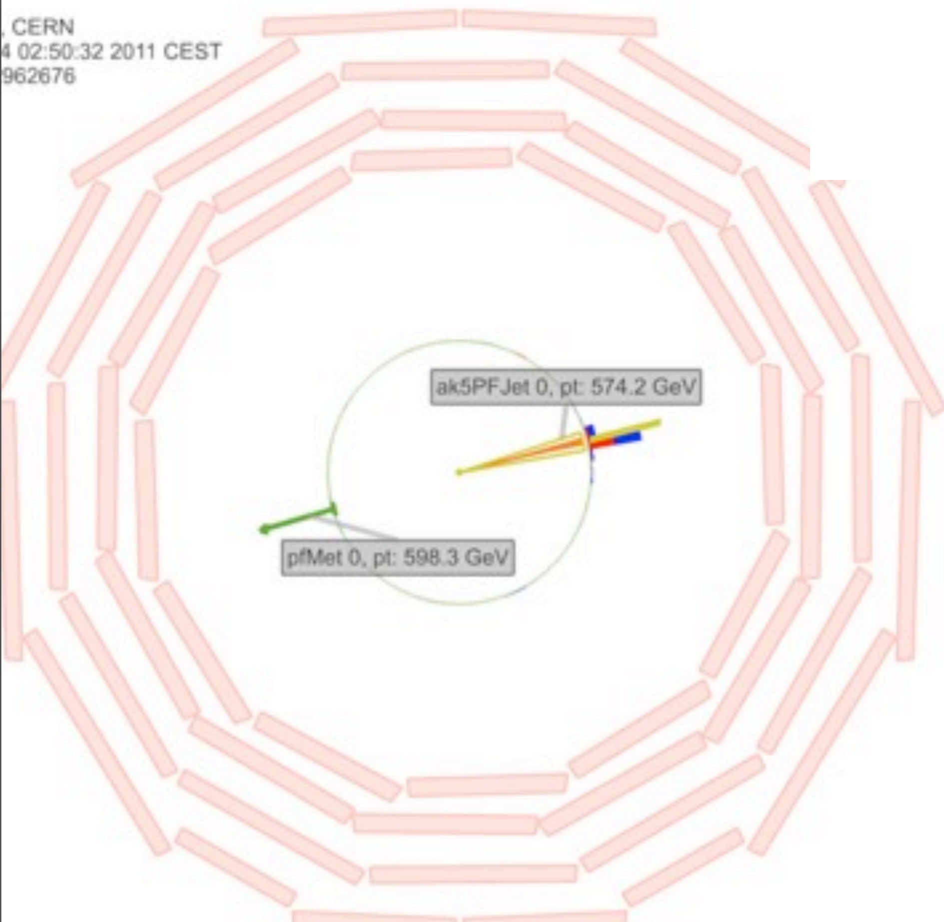


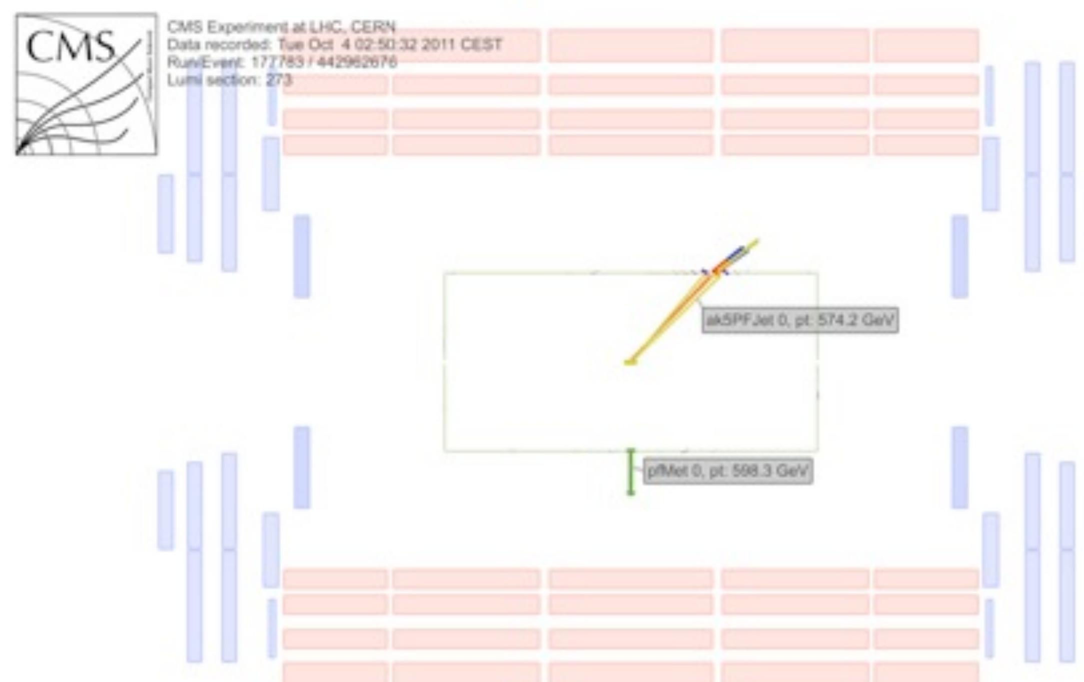


Monojet Event



$p_T^{jet} = 574.2$ GeV
$E_T^{miss} = 598.3$ GeV





Monojet - Backgrounds & Search Results

- Some backgrounds estimated with data-driven techniques, while others use Monte Carlo simulations

Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

No excess observed.
Background describes data well.

- Estimated Zνν from a Z(→μμ)+jet control sample
- Estimated W(→lν)+jet using Wμν control sample and detector acceptance and reconstruction efficiencies
- Remainder are from simulation

Monojet - Uncertainties and Limit Setting

- Limit setting as before, but with a $\Lambda_{th.}$ set to 40 GeV instead.

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma_{th.}^{\chi\bar{\chi}}}{\sigma_{meas.}^{\chi\bar{\chi}}} \right)^{1/4}$$

$\Lambda_{th.} \equiv 40$ TeV
$\sigma_{th.}^{\chi\bar{\chi}}$ from MC

M_χ (GeV/c^2)	Spin-dependent σ(cm^2)	Spin-dependent Λ(GeV)	Spin-independent σ(cm^2)	Spin-independent 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

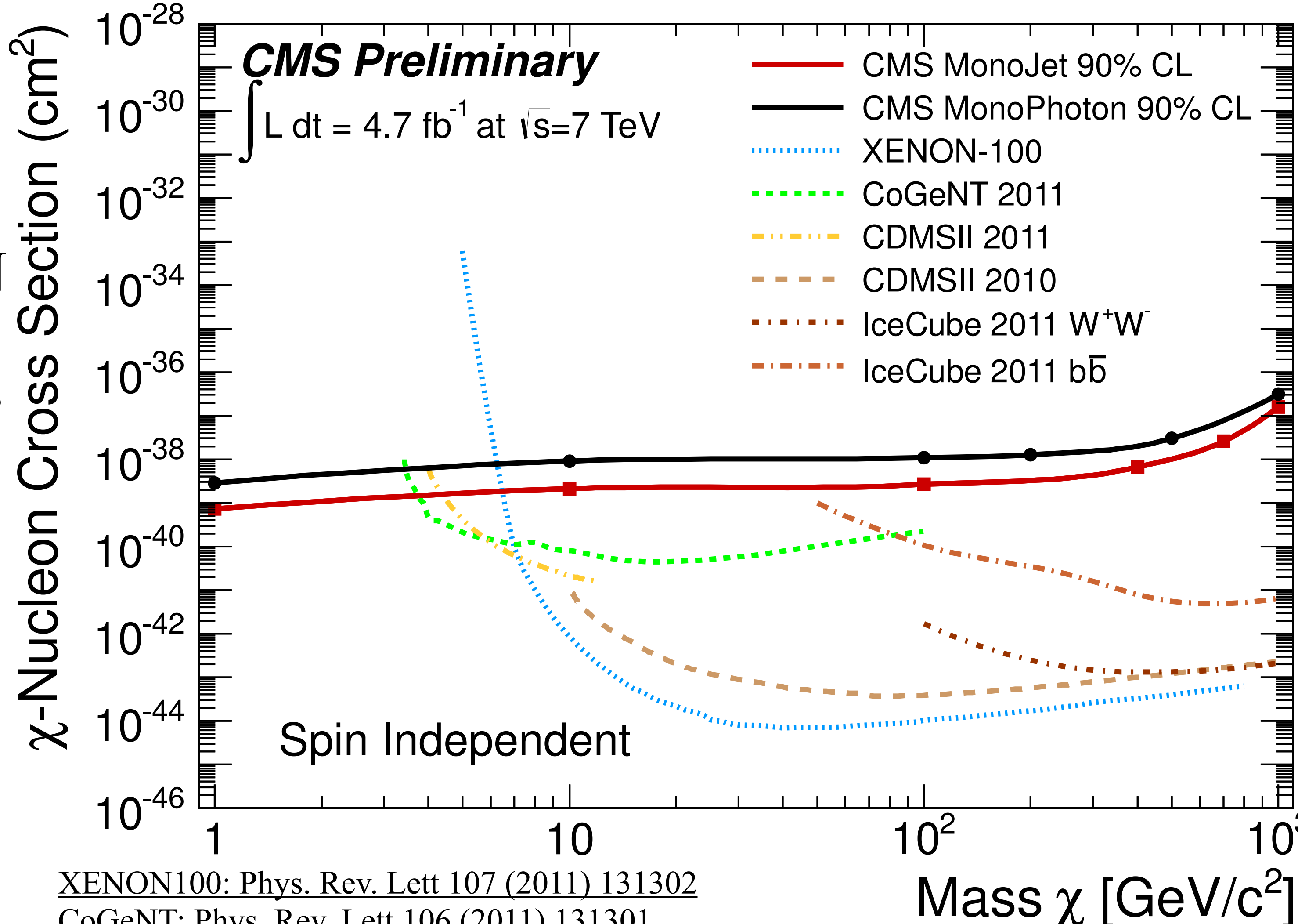
Borrowed from S. Worm
Moriond 2012

Monojet - Spin Independent Limits

- Lower limit on Λ used to compute χ-N cross-section.

$$\sigma_{SI}^{\chi\text{-}N} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

- Extends the cross-section lower limits for $M_\chi < 3.5$ GeV.



XENON100: Phys. Rev. Lett 107 (2011) 131302
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IceCube:

Monojet - Spin Dependent Limits

- Lower limit on Λ used to compute χ-N cross-section.

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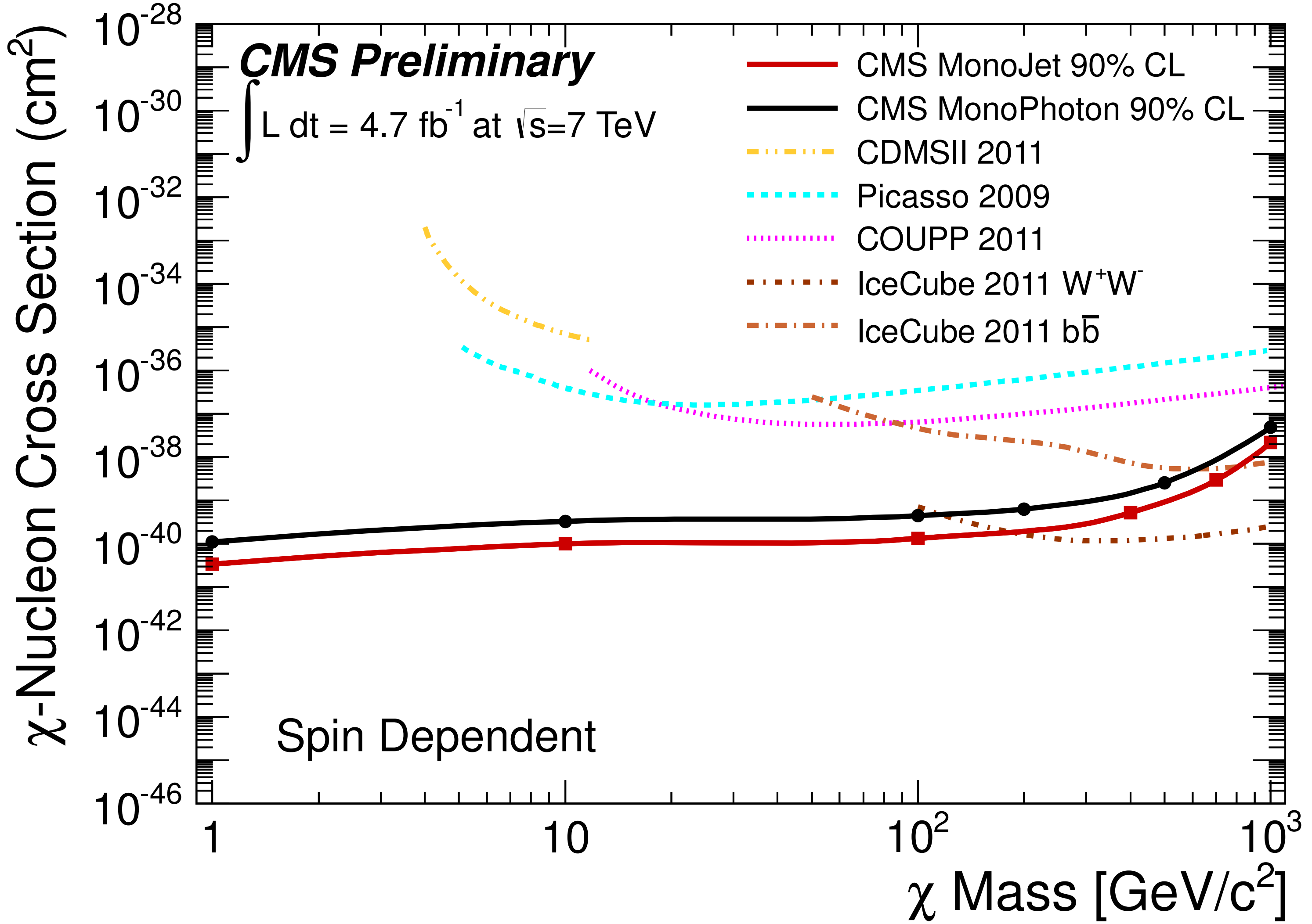

CDMSII: Phys. Rev. Lett. 106 (2011) 131302.
Picasso: Phys. Lett. B 682 (2009) 185.
COUPP: Phys. Rev. Lett. 106 (2011) 021303.
IceCube: Phys. Rev. D 85 (2012) 042002.

Conclusions

- A search was performed for dark matter production in the monophoton and monojet final states using 5.0 fb^{-1} and 4.7fb^{-1} of integrated luminosity produced by the LHC at 7 TeV and collected by the CMS experiment.

- Results are consistent with the Standard Model.

- The N-χ cross section limits on the spin-independent and spin-dependent moderator masses were extended.
  - $\sigma^{N\text{-}\chi}{}_{SI}$ extended for $m_\chi < 3.5$ GeV
  - $\sigma^{N\text{-}\chi}{}_{SD}$ extended for m_χ 1-100 GeV

- Now exploring 8 TeV!

Thank You!