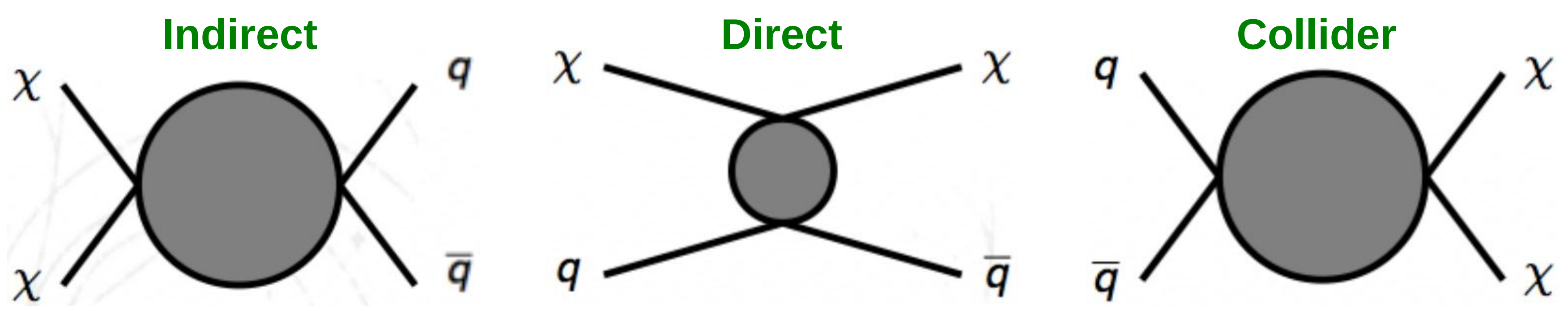
Recent results from a search for dark matter production in the CMS experiment

M. Weinberg on behalf of
the CMS Collaboration

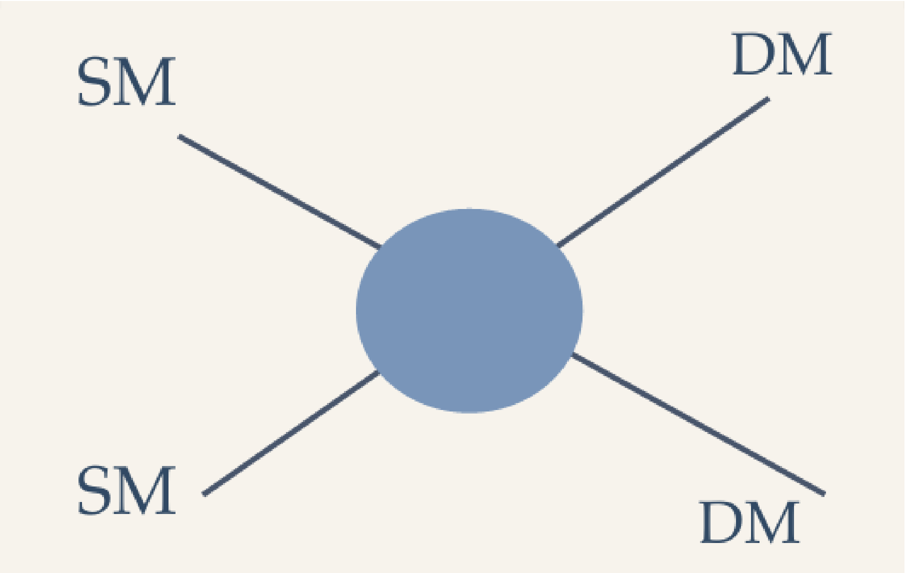
Dark matter

- **Strong astrophysical evidence for existence of dark matter**
  - **Rotation curves of galaxies, bullet cluster, gravitational lensing, etc**
- **Direct detection experiments**
  - **Look for recoil of dark matter from nucleus**
  - **Excesses observed in some experiments and not others**
- **Need independent verification from non-astrophysical experiments**
  - **Low mass region inaccessible to direct detection experiments**
    - **Limited by threshold effects, energy scale, backgrounds**
    - **Less sensitive to spin-dependent couplings**
- **Colliders provide alternative, complementary approach to dark matter searches**



Phenomenology

- **Assumptions:**
  - **DM particle only new state accessible to collider**
  - **Effective field theory: Interaction between DM and SM particles via contact**
  - **Massive mediator: Can be integrated out**



- **Lagrangian:**

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^{\mu}\partial_{\mu}X - M_X\bar{X}X + \sum_{q}\sum_{i,j}\frac{G_{qij}}{\sqrt{2}}[\bar{X}\Gamma_i X][\bar{q}\Gamma^j q]$$

SM Lagrangian

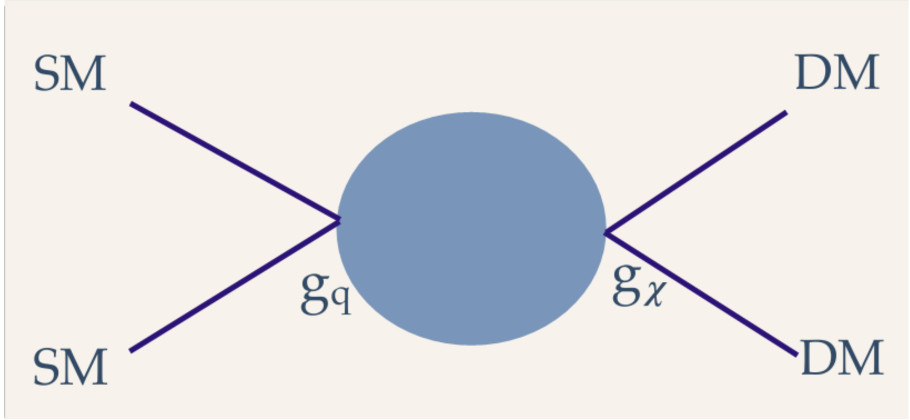
Kinetic terms for DM

4-fermion interactions between DM and SM quarks

- **Operators Γ describe scalar, pseudoscalar, vector, axial vector, tensor interactions**

Production of dark matter at colliders

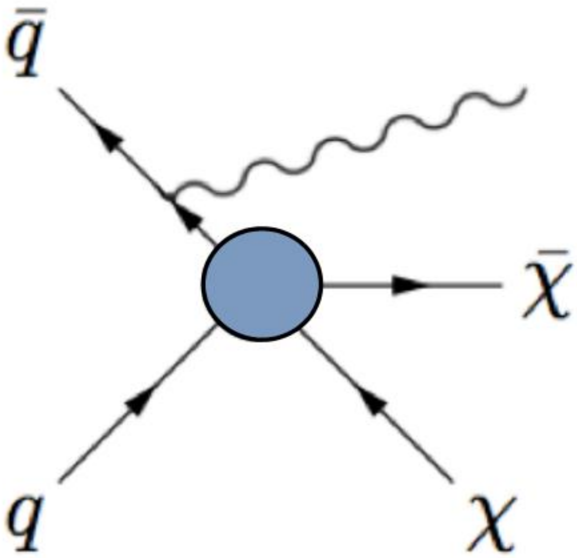
- **Assume DM is Dirac fermion, interaction characterized by contact interaction[1]**
  - **Set mediator mass M to very high value,** $\Lambda = M/\sqrt{g_\chi g_q}$
  - **Consider two possible mediators:**
    - **Vector operator:**
      $$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$
      (spin independent)
    - **Axial-vector operator:**
      $$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$
      (spin dependent)

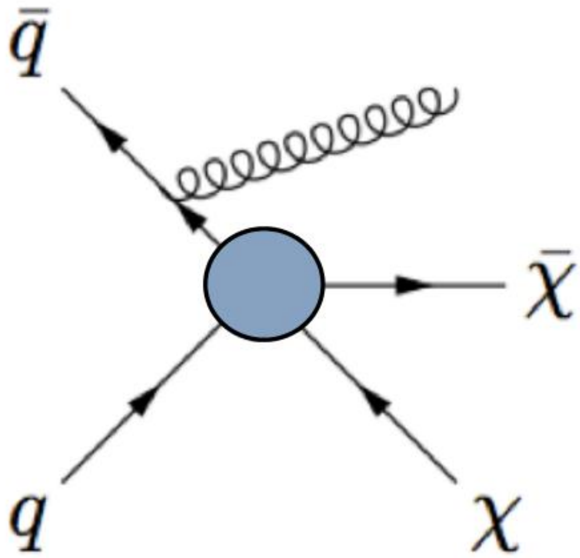


[1] Bai, Fox, and Harnik, JHEP 1012:048 (2010)

Production of dark matter at colliders

- **Dark matter pair production at LHC**
  - **DM particle production results in missing transverse energy (MET)**
  - **Photon or jet (from a gluon) radiated from initial state quarks**
    - **Final state: Single photon or jet plus MET**

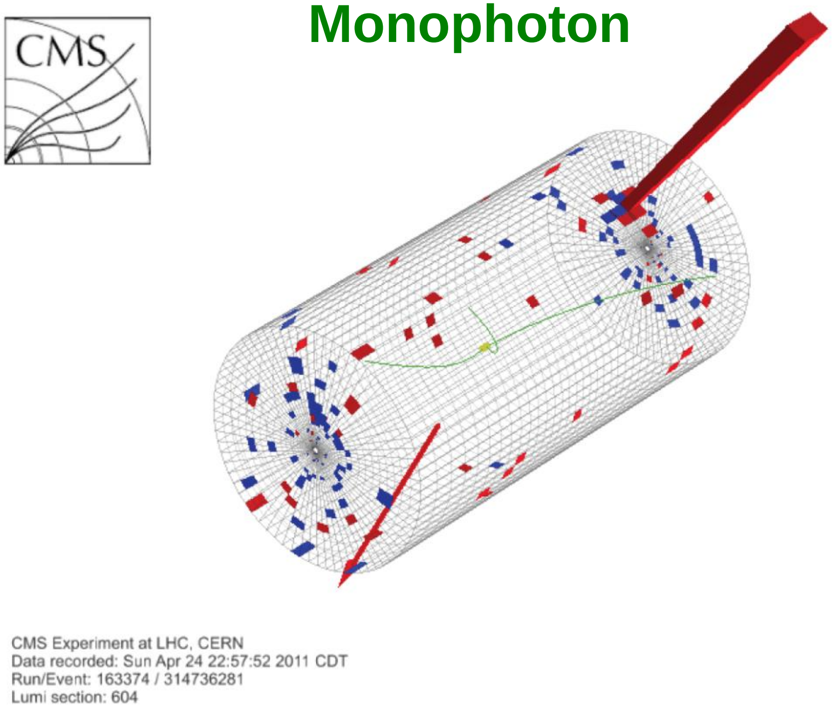




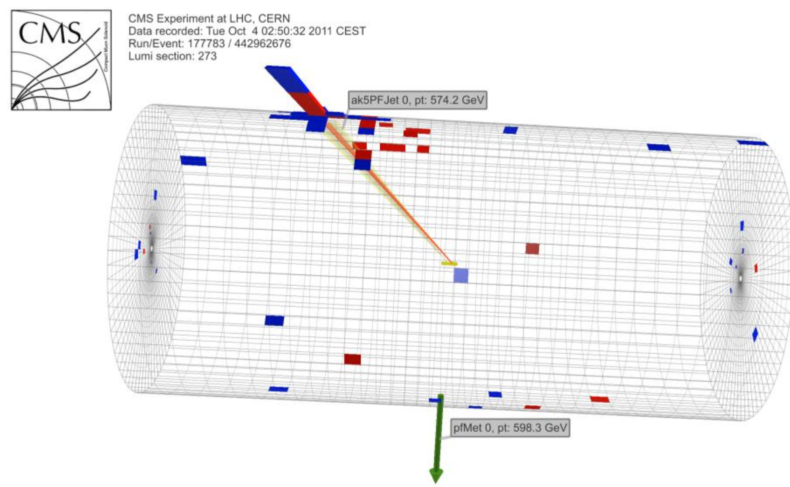
Monophoton/monojet events

- **Cylindrical view of example monophoton/monojet + MET events**
  - **Monophoton: photon pT = 384 GeV, MET = 407 GeV**
  - **Monojet: jet pT = 574 GeV, MET = 598 GeV**

Monophoton

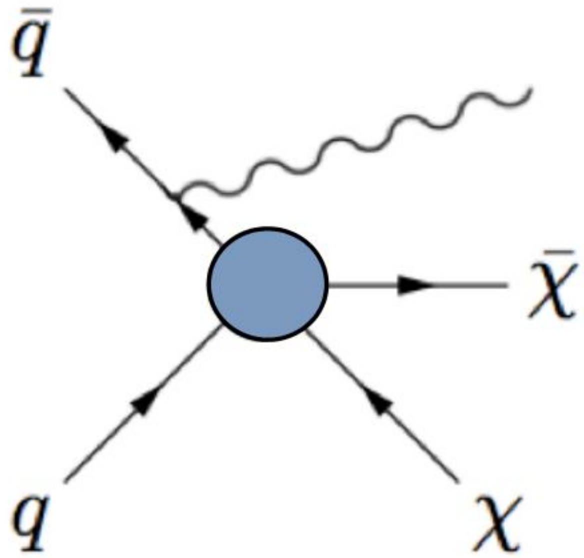


Monojet



Monophoton basic selection

- **Photon selection**
  - High energy photon: $p_T > 145$ GeV
  - Central region of detector, $|\eta| < 1.4442$
  - Shower shape in calorimeter consistent with photon
- **MET requirement**
  - MET > 130 GeV using "particle flow" method
- **Remove excessive hadronic activity**
  - No jet with $p_T > 40$ GeV and $|\eta| < 3.0$
  - No track with $p_T > 20$ GeV with $\Delta R < 0.04$ from photon



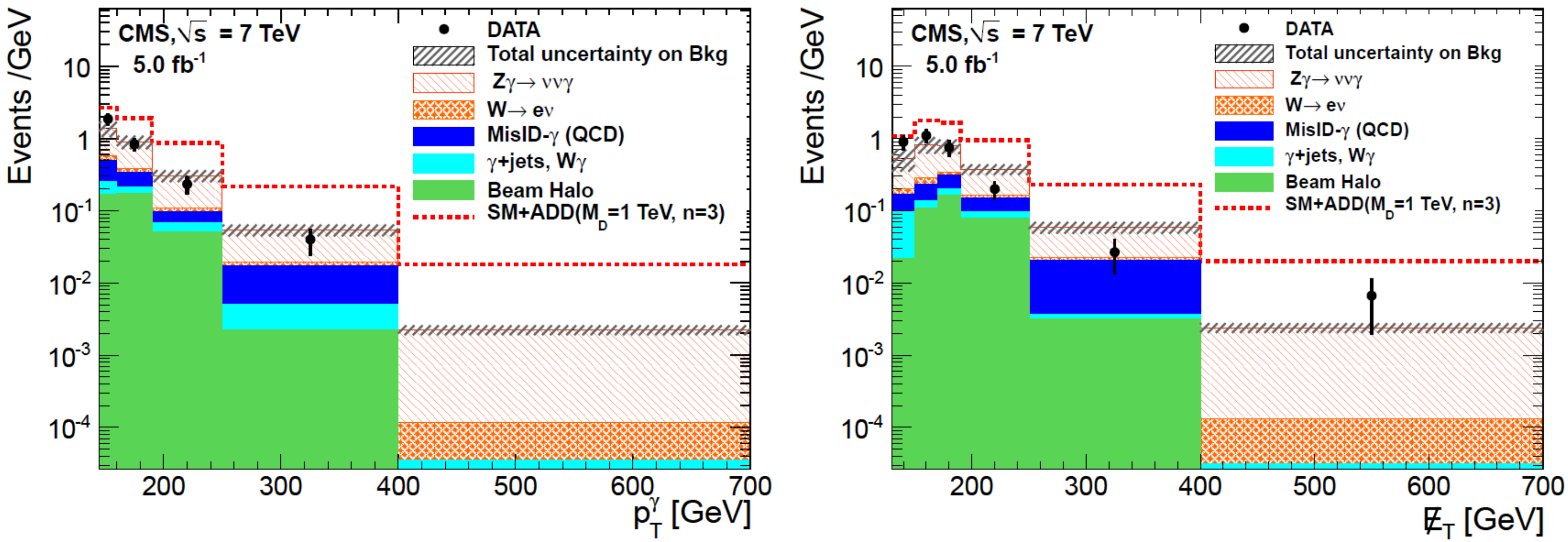
Monophoton backgrounds

- Backgrounds estimated from MC and data-driven techniques
- Backgrounds from pp collisions:
  - pp → Zγ → ννγ: Irreducible background (from MC)
  - pp → W → eν: Electron misidentified as photon (from data)
  - pp → jets → “γ” + MET: One jet mimics photon, MET from jet mismeasurement (from data)
  - pp → γ + jet: MET from jet mismeasurement (from MC)
  - pp → Wγ → lνγ: Charged lepton escapes detection (from MC)
  - pp → γγ: One photon mismeasured to give MET (from MC)
- Other backgrounds:
  - Showers induced by cosmic rays: Identified and removed
  - Neutron-induced signals: Identified and removed
  - Beam halo: Mostly removed; residual contribution estimated from data

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

Monophoton search results

- **Distributions for photon p_T and MET**
  - **Background processes describe data well**
- **No excess of events over expected SM backgrounds**
  - **Total background: 71.9 ± 9.1**
  - **Total observed candidates: 73**



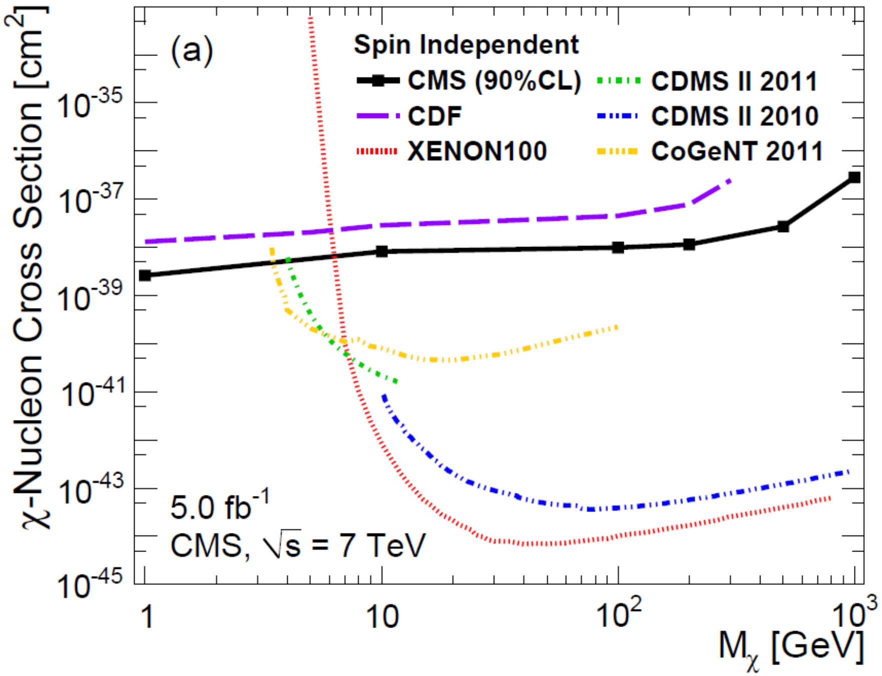
Monophoton limit setting

- Find cross sections using Monte Carlo simulation
- Events generated using MADGRAPH 4 and PYTHIA 6
- Observed (expected) 90% CL upper limits on DM production
  - Cross section σ and cutoff scale Λ as function of DM particle mass
  - Sensitivity to spin-dependent and spin-independent interactions quite similar

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)

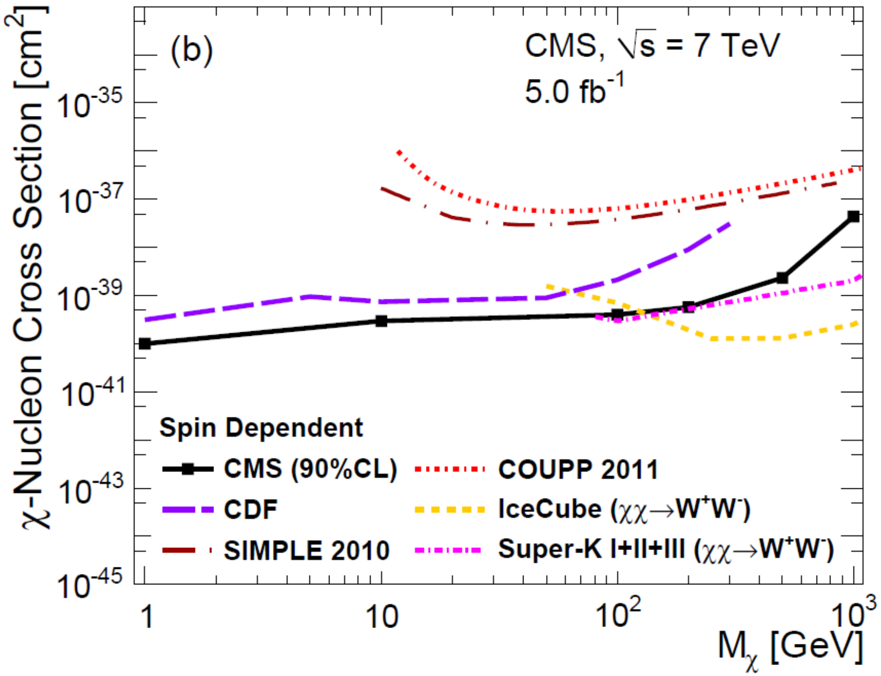
Monophoton spin-independent limits

- **90% CL upper limits on χ-nucleon cross section as function of M_χ for spin-independent scattering**
  - **Best constraints for low mass dark matter below 3.5 GeV, region unexplored by direct detection experiments**



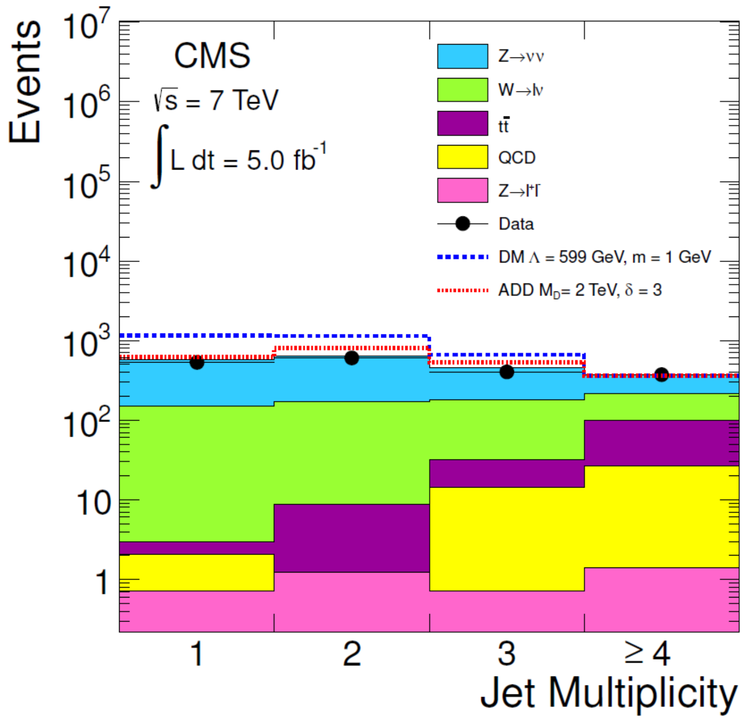
Monophoton spin-dependent limits

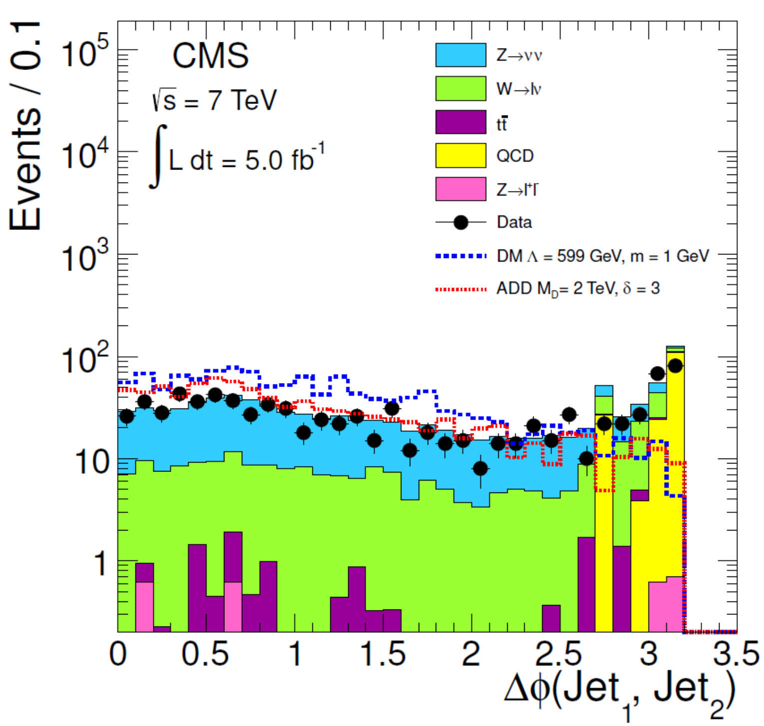
- **90% CL upper limits on χ-nucleon cross section as function of M_χ for spin-dependent scattering**
  - **Stringent constraints by colliders over large DM mass range**



Monojet basic selection

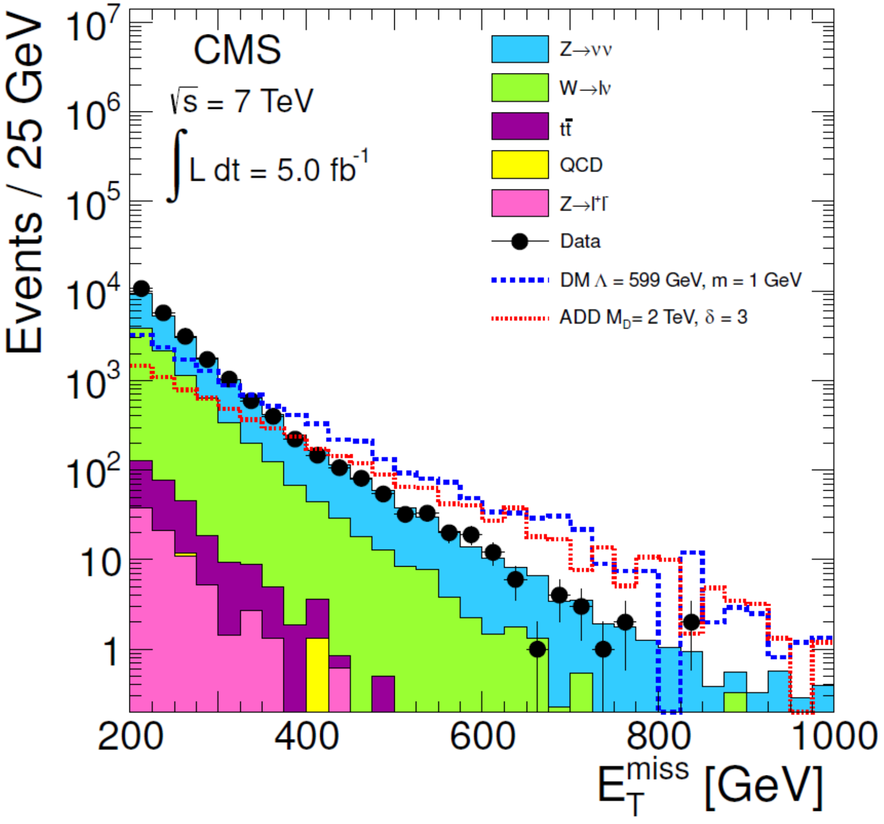
- **Basic topological selection**
  - **MET > 200 GeV, number of jets = 1 or 2**
  - **Leading jet p_T > 110 GeV, |η| < 2.4**
  - **Second jet p_T > 30 GeV**
  - **Δφ(jet1, jet2) < 2.5 (QCD rejection)**





Monojet data sample

- **Final monojet sample:**
  - Reject events with isolated e, μ
  - Reject events with isolated tracks
- **Good agreement for full MET range**
  - Sensitive to new physics (DM, ADD) in tails
- **Optimize selection for best expected sensitivity to new physics**
  - MET > 350 GeV for DM search



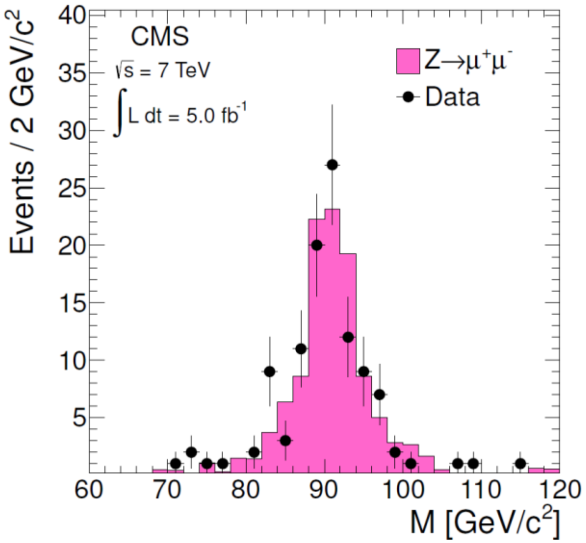
Monojet backgrounds

- **Primary backgrounds normalized via data-driven estimates**
  - **Remaining backgrounds after full event selection: Z(vv) (≈ 70%), W + jets (≈ 30%)**
- **Other backgrounds estimated from MC**
  - **QCD, top, Z + jets negligible (≈ 1%)**

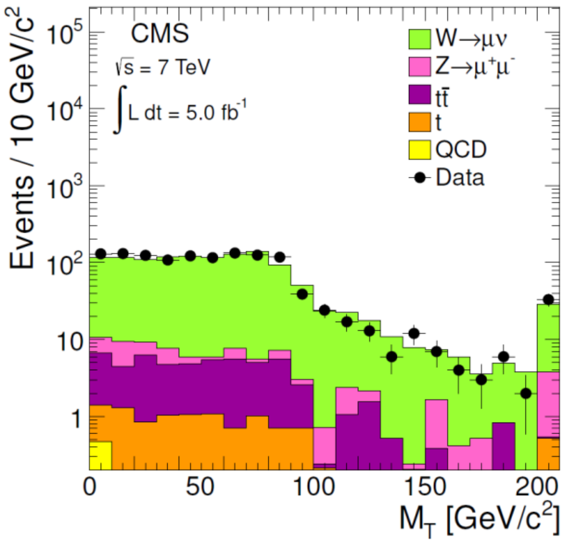
E_T^{miss} (GeV/c) $\rightarrow$	≥ 250	≥ 300	≥ 350	≥ 400
Process	Events			
$Z(\nu\bar{\nu})$+jets	5106 ± 271	1908 ± 143	900 ± 94	433 ± 62
W+jets	2632 ± 237	816 ± 83	312 ± 35	135 ± 17
$t\bar{t}$	69.8 ± 69.8	22.6 ± 22.6	8.5 ± 8.5	3.0 ± 3.0
$Z(\ell\ell)$+jets	22.3 ± 22.3	6.1 ± 6.1	2.0 ± 2.0	0.6 ± 0.6
Single t	10.2 ± 10.2	2.7 ± 2.7	1.1 ± 1.1	0.4 ± 0.4
QCD Multijets	2.2 ± 2.2	1.3 ± 1.3	1.3 ± 1.3	1.3 ± 1.3
Total SM	7842 ± 367	2757 ± 167	1225 ± 101	573 ± 65
Data	7584	2774	1142	522
Expected upper limit non-SM	779	325	200	118
Observed upper limit non-SM	600	368	158	95

Monojet background normalization

- **Estimate of Z + jets → νν + jets from data**
  - **Require 2 muons passing selection**
    - **Opposite sign, invariant mass 60 – 120 GeV**
    - **Uncertainty in method 10.4% (mainly statistical, 9.5%)**



- **Estimate of W + jets → νl + jets (where lepton "lost") from data**
  - **Require single lepton at M_T 50 – 100 GeV**
    - **Primary uncertainty from acceptance (7.7%) and selection efficiency (6.8%)**
    - **Total uncertainty in method 11.3%**



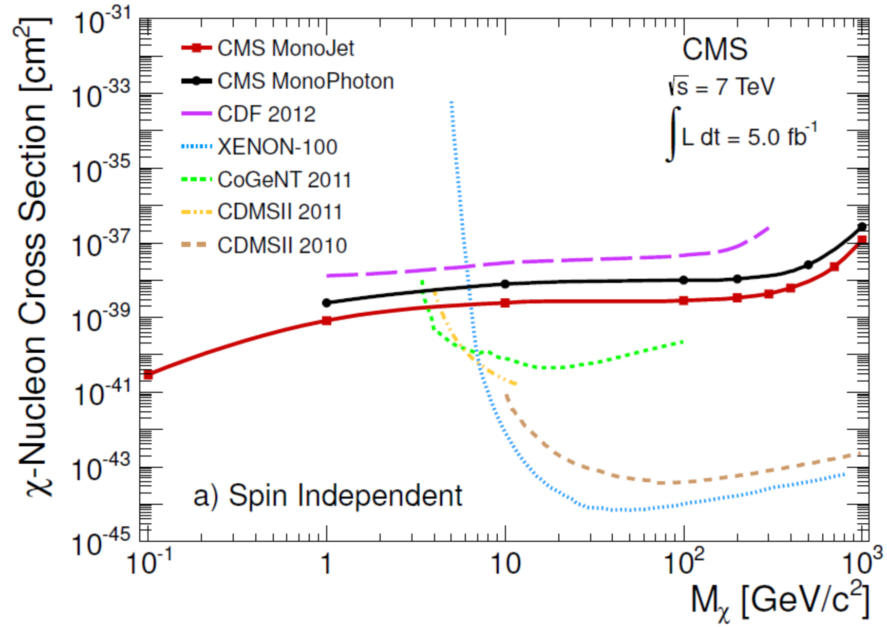
Monojet dark matter signal

- **Monojet signal generation**
  - MADGRAPH 5 + PYTHIA 6 with 40 TeV mediator mass
- **Systematic uncertainties ≤ 15%**
  - Main contributions from jet energy scale, PDFs, jet energy resolution, luminosity
- **No excess of events over expected SM backgrounds**
  - Total background: 1225 ± 101
  - Total observed candidates: 1142

	Spin-dependent		Spin-independent	
M_χ (GeV/c^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)
0.1	754	1.03×10^{-42}	749	2.90×10^{-41}
1	755	2.94×10^{-41}	751	8.21×10^{-40}
10	765	8.79×10^{-41}	760	2.47×10^{-39}
100	736	1.21×10^{-40}	764	2.83×10^{-39}
200	677	1.70×10^{-40}	736	3.31×10^{-39}
300	602	2.73×10^{-40}	690	4.30×10^{-39}
400	524	4.74×10^{-40}	631	6.15×10^{-39}
700	341	2.65×10^{-39}	455	2.28×10^{-38}
1000	206	1.98×10^{-38}	302	1.18×10^{-37}

Monojet spin-independent limits

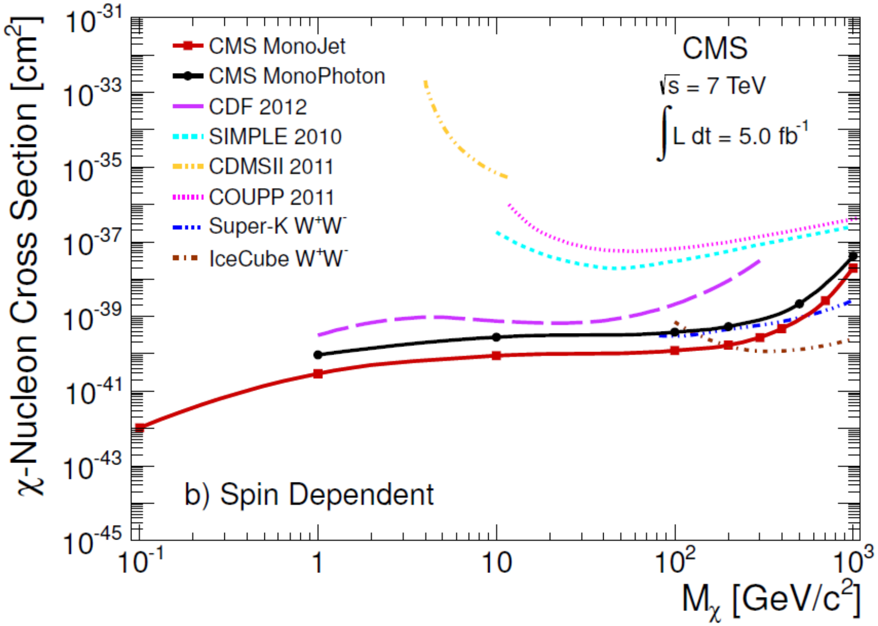
- **Comparison of 90% CL upper limits on χ-nucleon cross section as function of M_χ for spin-independent scattering**



  - ♦ **Best constraints for low mass dark matter below 3.5 GeV, region unexplored by direct detection experiments**

Monojet spin-dependent limits

- **Comparison of 90% CL upper limits on χ-nucleon cross section as function of M_χ for spin-dependent scattering**
  - **Stringent constraints by colliders over large DM mass range**



Summary

- **Results of searches for dark matter at CMS using monophotons / monojets + MET**
  - **Set limits on DM-nucleon scattering cross-section**
  - **Competitive constraints on spin-dependent cross section over large DM mass range**
  - **Extend spin-independent bounds into low DM mass**
    - **m_{DM} < 3.5 GeV, previously unexplored region**
- **Colliders provide competitive DM constraints**
- **Collider searches complementary to direct detection**