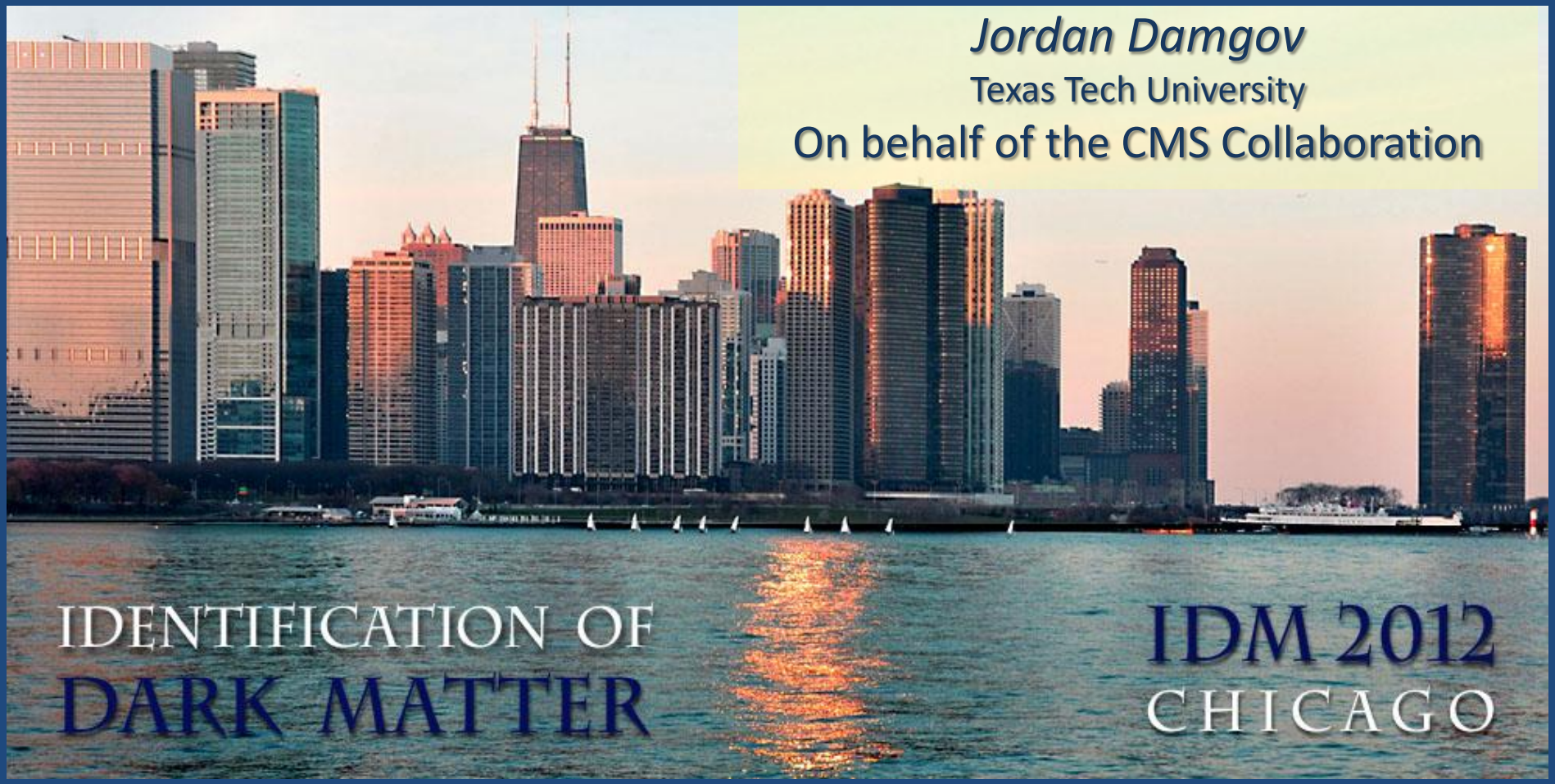
Recent results from a search for Dark Matter production in the CMS experiment

Jordan Damgov
Texas Tech University
On behalf of the CMS Collaboration



Dark Matter

❖**There is strong astrophysical evidence for the existence of dark matter**

- ➢Evidence from bullet cluster, gravitational lensing, rotation curves

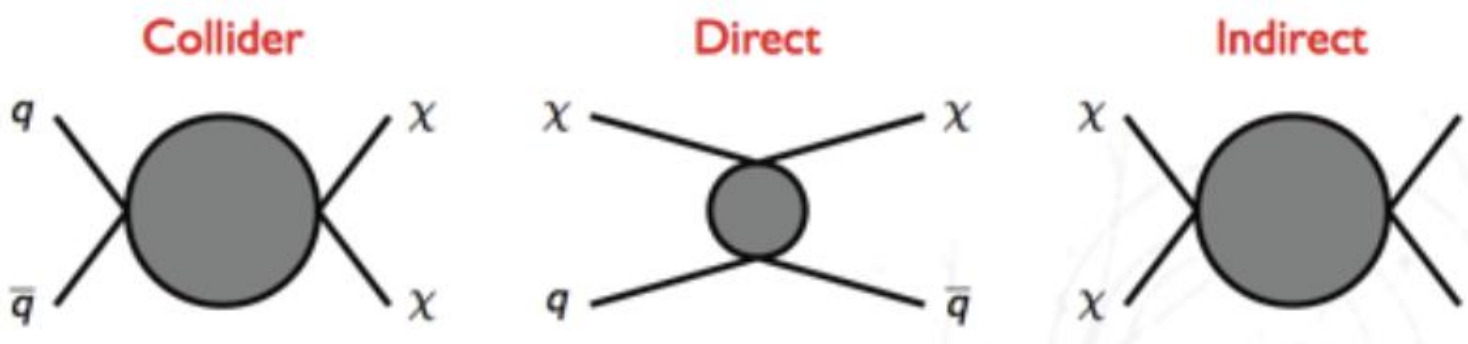
❖**Direct detection experiments**

- ➢ Aim to observe recoil of dark matter off nucleus
- ➢ Excesses observed by several experiments, not confirmed by others

➢ **Need for independent verification from non-astrophysical experiments**

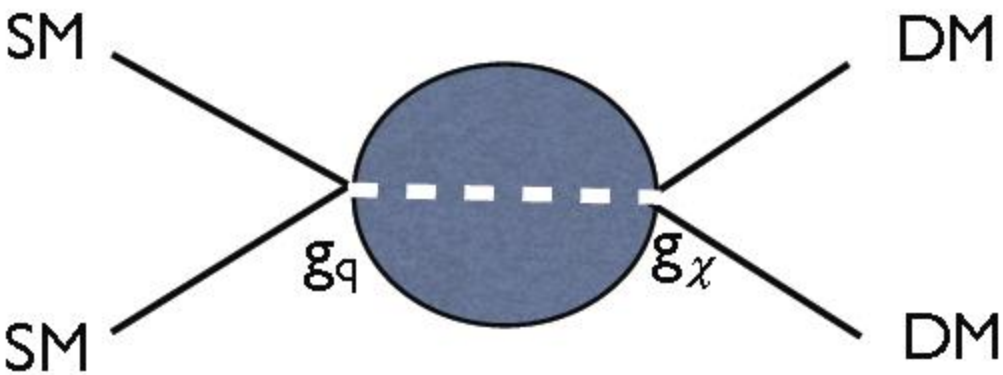
- ✓ Low mass region not accessible to direct detection experiments
- ✓ Limited by threshold effects, energy scale, backgrounds; less sensitive to spin-dependent couplings

Colliders provide alternative, complementary way to search for dark matter



Production of Dark Matter at colliders

- **In framework of effective theory, assume DM(χ) is a Dirac fermion and interaction is characterized by *contact interaction***
  - Set mass of mediator (M) to very high value



✓heavy mediator can be integrated out

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

❖ Consider two possibilities:

a) Vector mediator:
   - Spin dependent

b) Axial-Vector mediator:
   - Spin independent

Effective operators

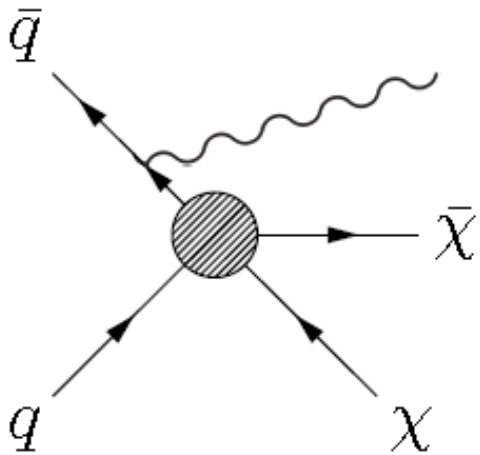
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

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

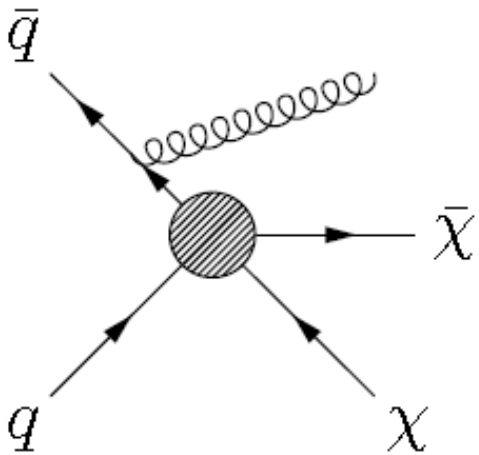
Production of Dark Matter at colliders

- Dark Matter production results in missing transverse energy (MET)

- Photons (or jets from a gluon) can be radiated from quarks
  - monophoton (or monojet) plus MET

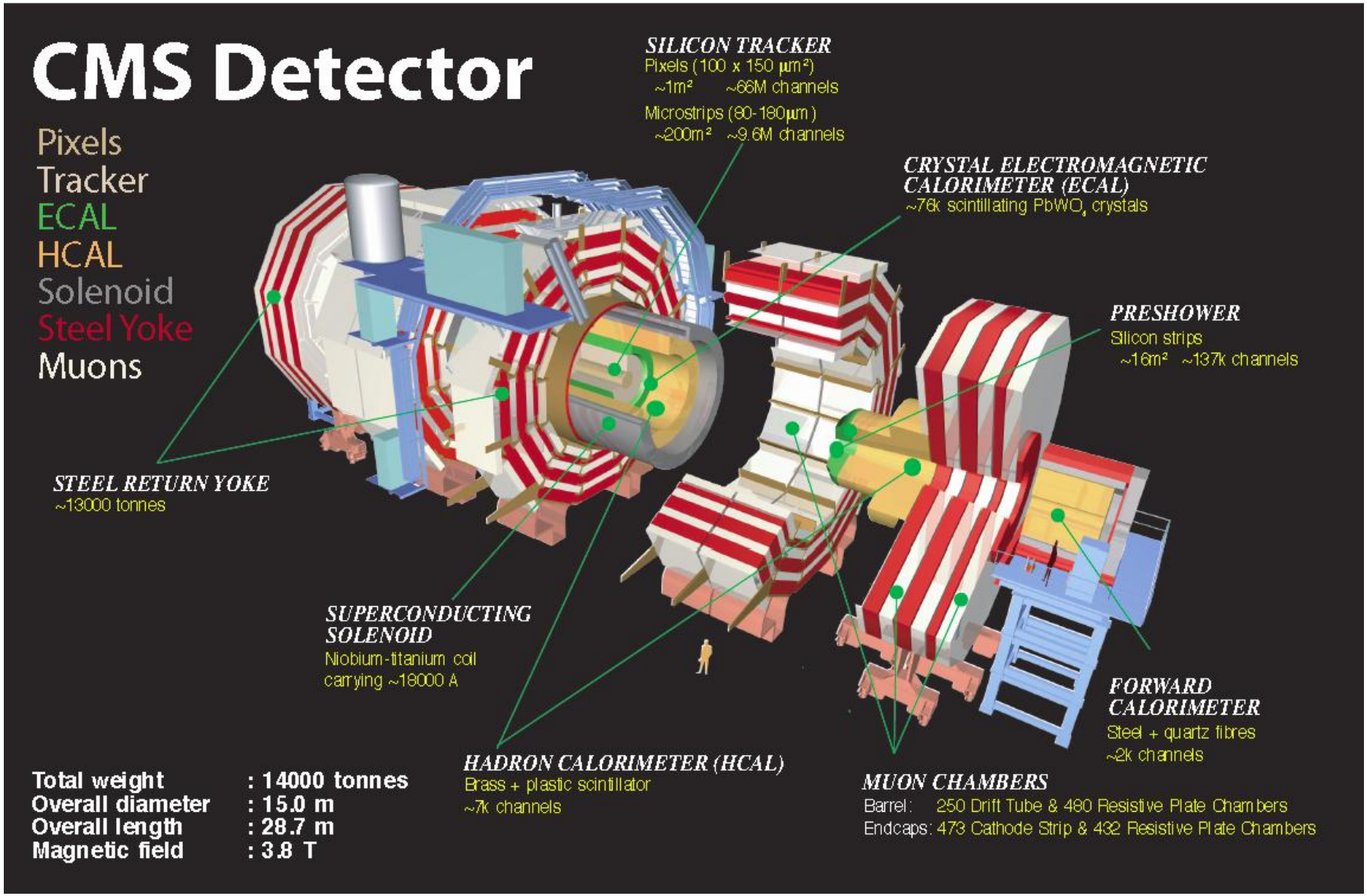


Monophoton + MET



Monojet + MET

CMS detector

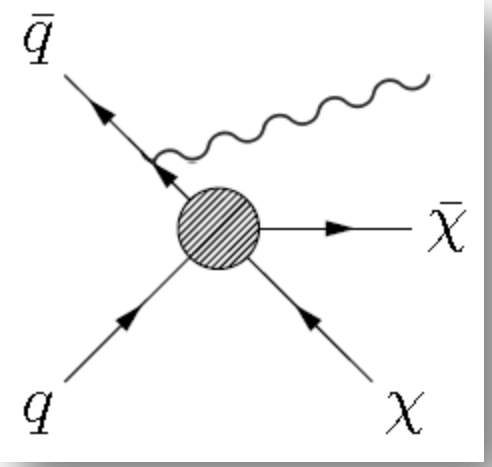


Monophoton- Search Details

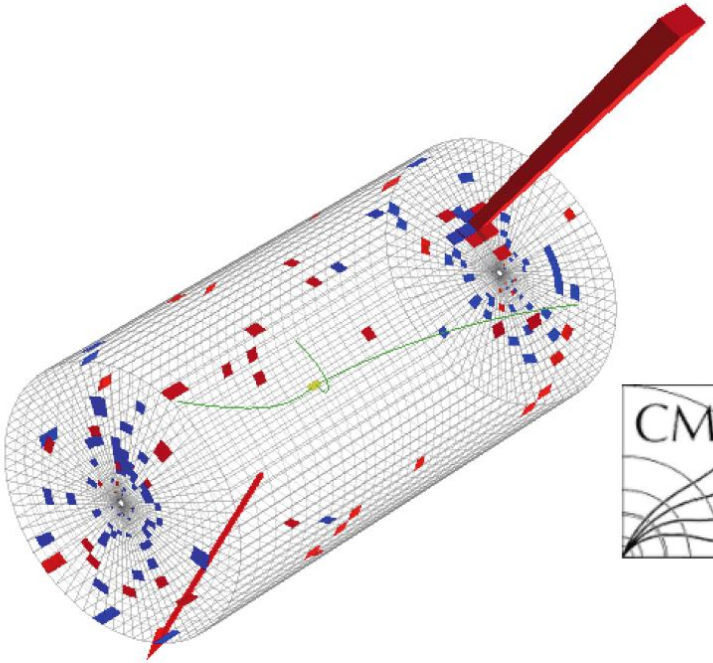
- Require a photon in an event :
  - ✓High energy photon: $p_T(\gamma) > 145$ GeV/c
  - ✓In the central part of the detector: $|\eta| < 1.442$
  - ✓Veto events with nearby tracks or pixel stubs
  - ✓Veto events with significant electromagnetic calorimeter activity ($\Delta R < 0.4$)
  - ✓Veto events with significant hadronic activity ($\Delta R < 0.4$, $E_{HCAL}/E_{ECAL} < 0.05$)
  - ✓Shower shape consistent with photon: $\sigma_{i\eta i\eta} < 0.013$
  - ✓ All reconstructed vertices are used for isolation calculations.

- MET > 130 GeV, using a particle flow method

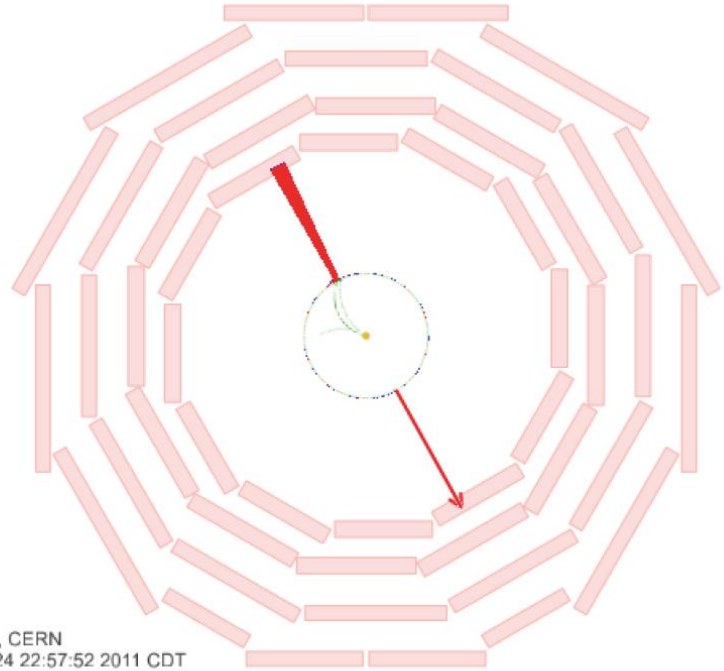
- Remove events with excessive activity
  - ✓ No central jet: veto events with $p_T(\text{jet}) > 40$ GeV/c and $|\eta\text{jet}| < 3.0$
  - ✓No tracks with $p_T > 20$ GeV/c



Monophoton- Event Display



CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604



CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

Monophoton - Backgrounds

- *Backgrounds estimated from MC and data-driven(DD) techniques*
- Backgrounds from pp collisions

$pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$	irreducible background *(MC)*
$pp \rightarrow W \rightarrow e\nu$	electron mis-identified as photon *(DD)*
$pp \rightarrow$ jets $\rightarrow$ "γ" + MET	one jet mimics photon, MET from jet mis-measurement *(DD)*
$pp \rightarrow \gamma$ + jet	MET from jet mis-measurement *(MC)*
$pp \rightarrow W\gamma \rightarrow l\nu\gamma$	charged lepton escapes detection(*MC*)
$pp \rightarrow \gamma\gamma$	one photon mis-measured to give MET(*MC*)

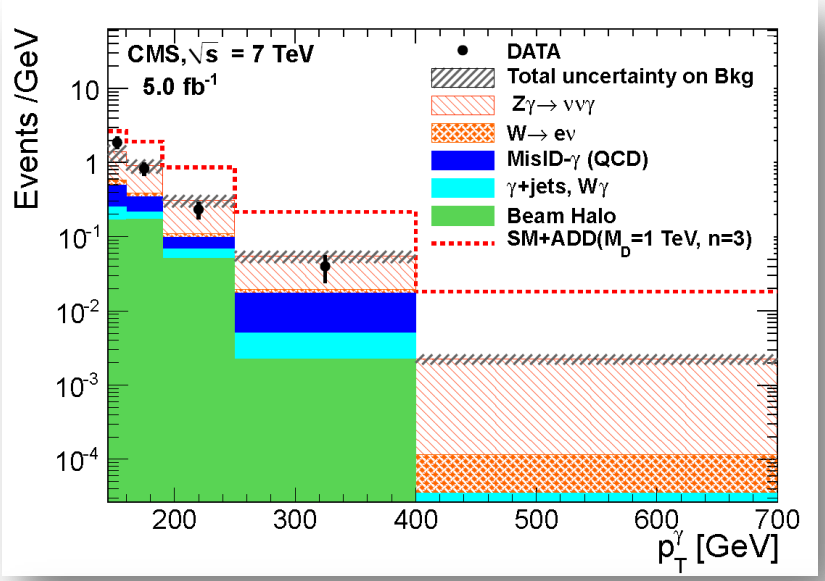
- Backgrounds unrelated to pp collisions

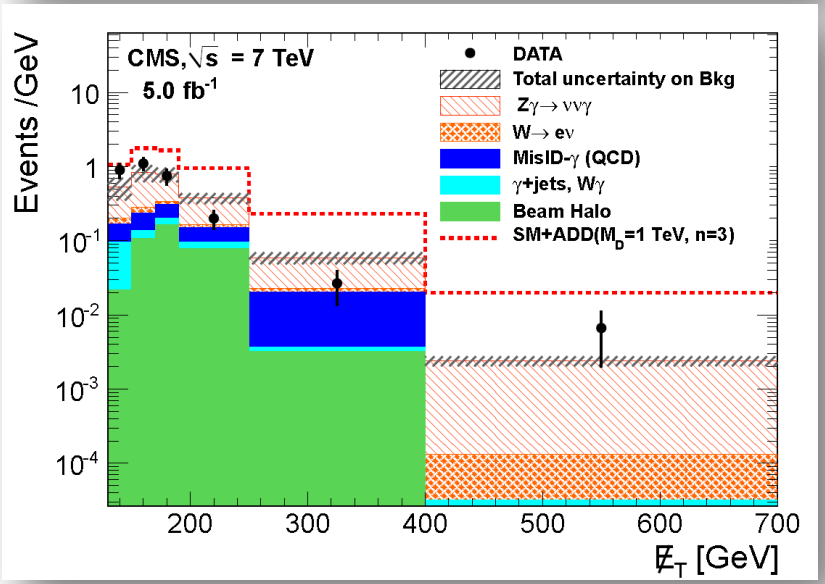
Showers induced by cosmics	identified and removed *(DD)*
Neutron-induced signals	identified and removed *(DD)*
Beam halo	mostly removed; a residual contribution estimated *(DD)*

The procedure consists of estimating expected number of events from SM processes (and other backgrounds) and look for excess of events.

- 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
$W\gamma$	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

Background processes describe the data well and no excess is observed.

Monophoton - Dark Matter Signal

- **Signal Generation**
  - Dark Matter model follows effective theory outlined in earlier slide
  - Madgraph4 + Pythia6 generation with 10 TeV mediator mass and assume cross section scales as Λ^{-4}.
  - Similar sensitivity to spin-dependent and spin-independent

- **Acceptance times efficiency for Dark Matter signal**
  - A × ε ≈ 0.3, for both vector operator and axial-vector operator
  - Kinematics mainly from ISR photon; A × ε is fairly constant in the range m_χ = 1-1000 GeV

  - **Systematic uncertainties**
    - Stats. Uncertainty 1.7%
    - Photon PT uncertainty 2.3%
    - Jet Energy Scale 1.2%
    - MET modeling 0.5%
    - Pile-up modeling 2.4%
    - Jet veto modeling 10 %

Monophoton - limit setting

❖ **Limit-setting**

- Use Modified Frequentist CLs approach of PDG [J. Phys. G37 (2010) 075021].
- For an integrated luminosity of 5.0 fb^{-1} : 75.1 ± 9.5 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 the scale Λ, assuming a Λ^{-4} behavior
- The lower limits on Λ are then used to calculate the χ-nucleon cross section limits versus DM mass

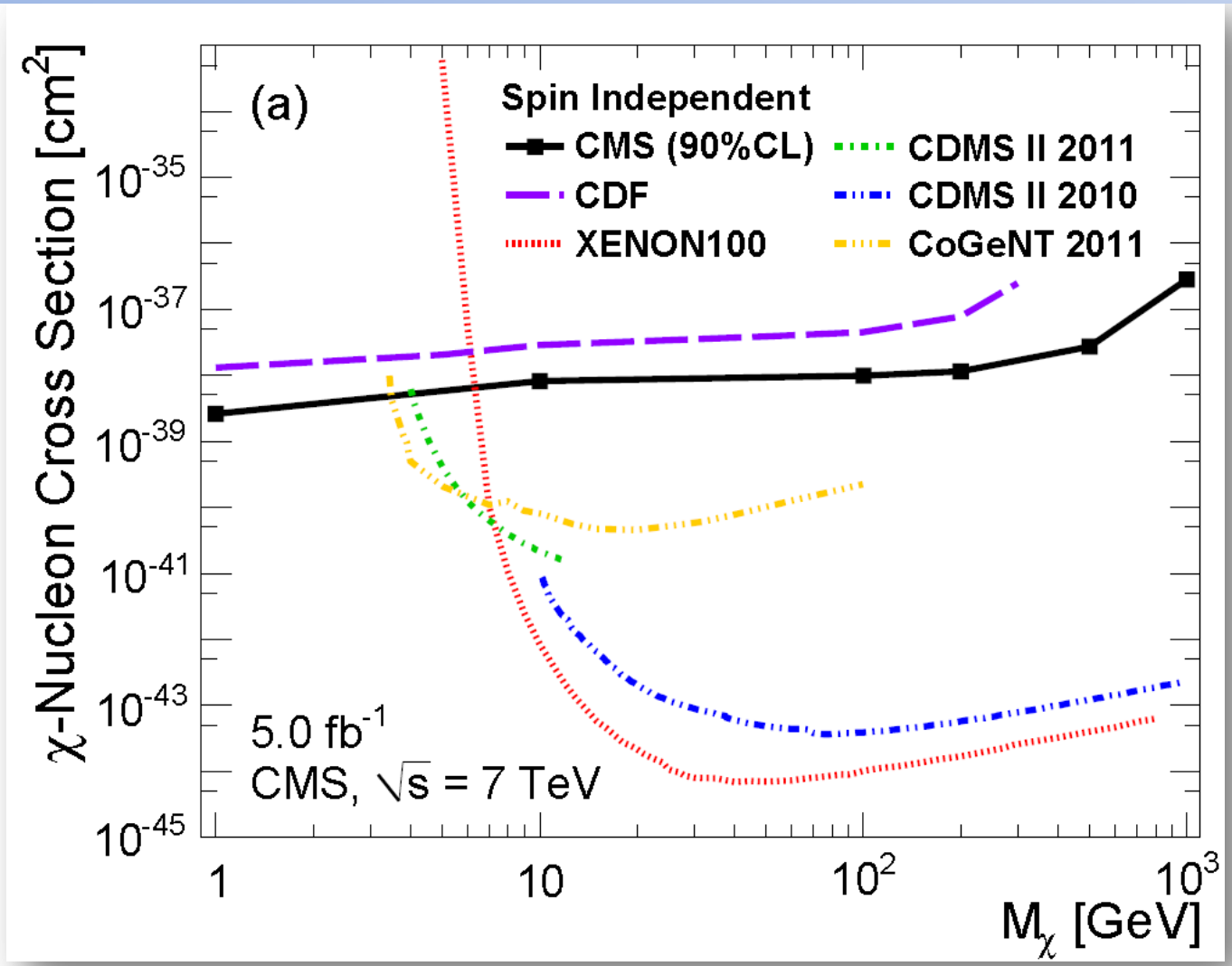
$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4} \quad \sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4} \quad \text{where } \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

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

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)

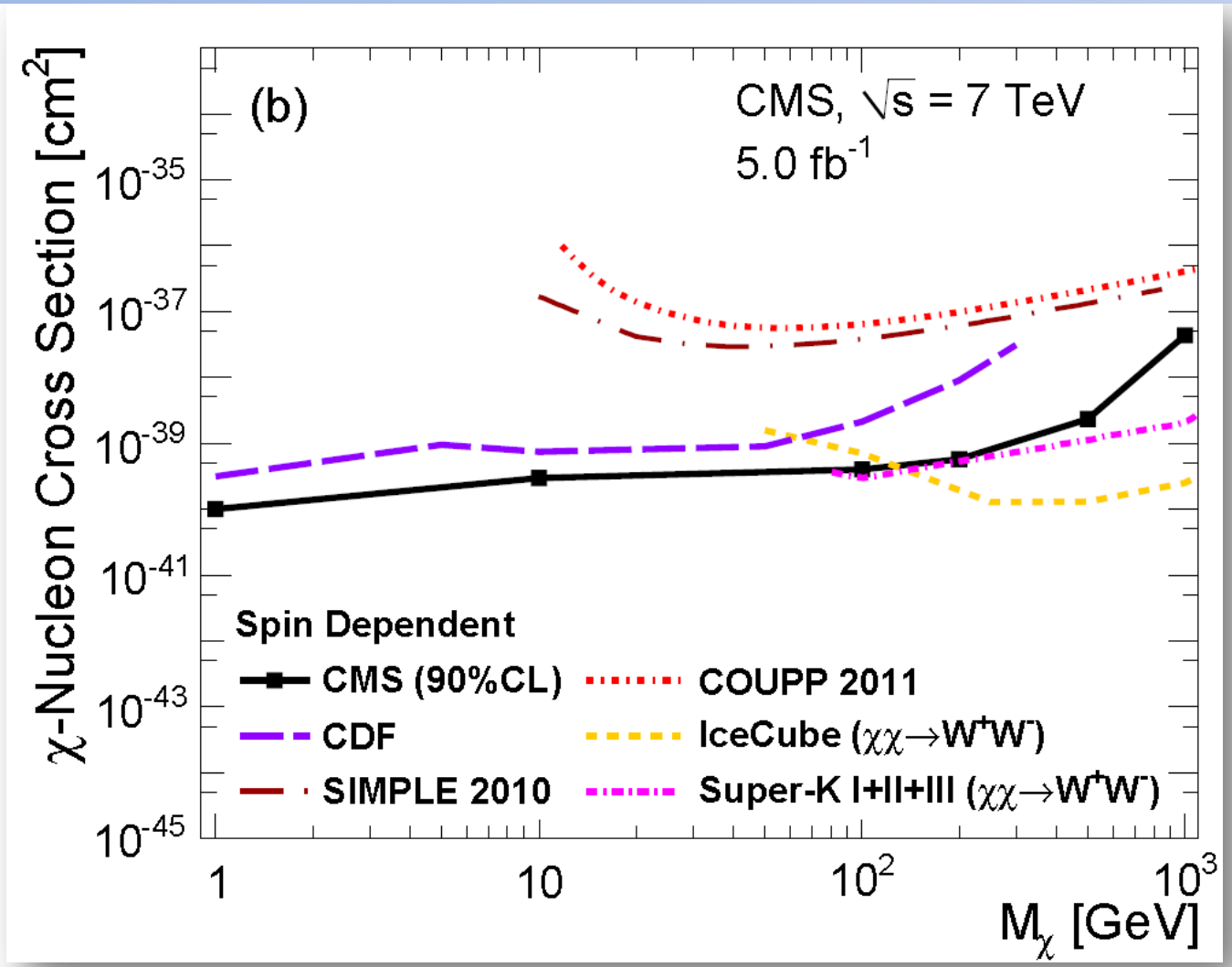
Observed(expected) 90% CL upper limits on the DM production cross section σ, and 90% CL lower limits on the cutoff scale Λ for vector and axial-vector operators as a function of the dark matter mass M_χ

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]

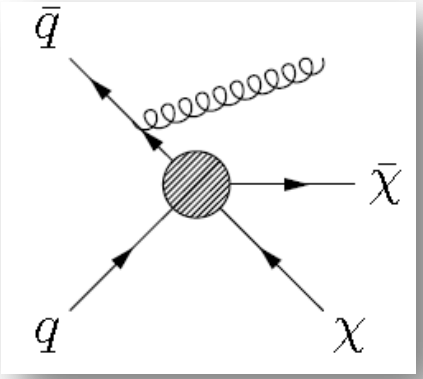
Monojet - search details

❖ **Select sample of Monojet+MET events (keeping muons)**

- Basic cuts on jet constituents- charged and neutral HAD and EM fractions
- Removes cosmics, instrumental backgrounds, mis-measured jets

❖ **Basic topological selection**

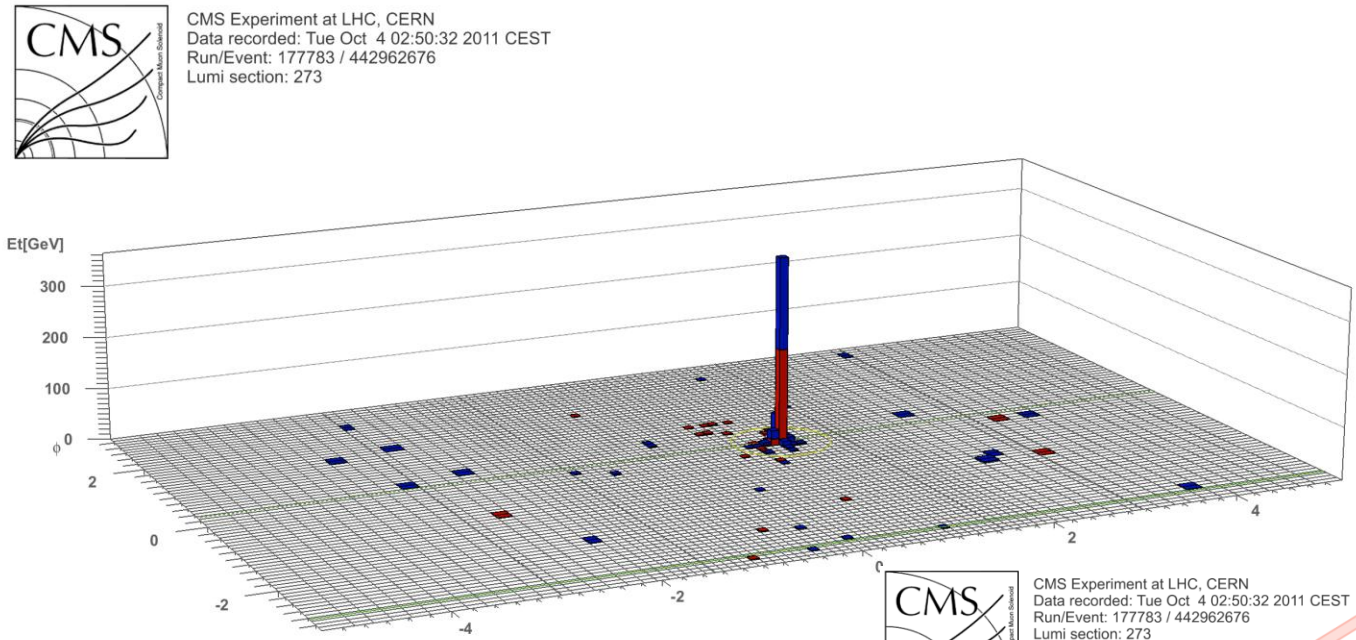
- MET > 200 GeV, number of Jets = 1 or 2
- Particle flow jets; anti-k_T with R = 0.5
- Leading Jet: p_T > 110 GeV, $|\eta|<2.4$
- Second Jet: p_T > 30 GeV
- $\Delta\varphi$(jet1,jet2) < 2.5

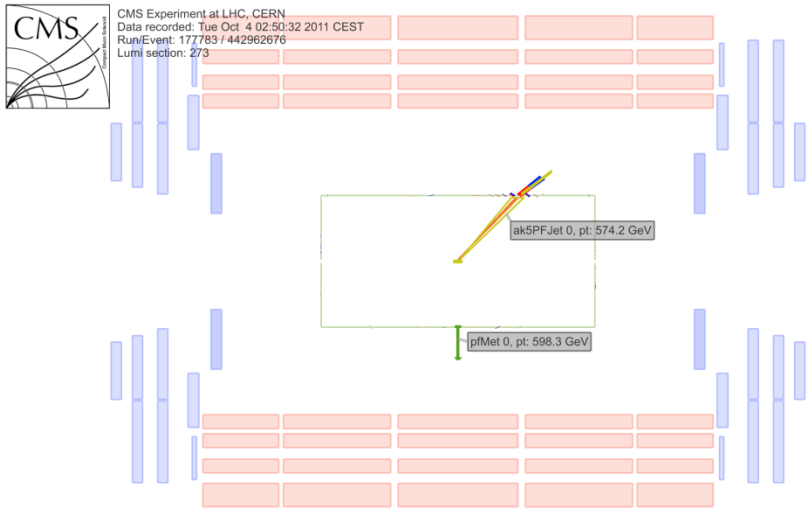


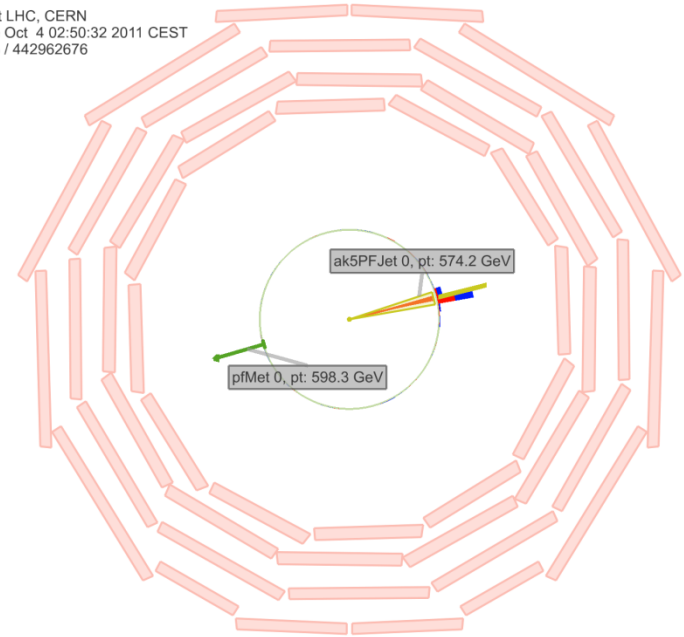
- **Monojet Signal Sample (Lepton Rejection)**
  - Reject events with e, μ isolated in a cone of ΔR = 0.3
  - Reject events with tracks isolated in a cone of ΔR = 0.3
  - MET > 350 GeV for DM search

- **Data-driven Background Estimation (Lepton Identification)**
  - Isolated muon > 20 GeV/c
  - Obtain Z+jet sample from M(μμ), W+jet sample from p_T(μ)+MET

Monojet – event display



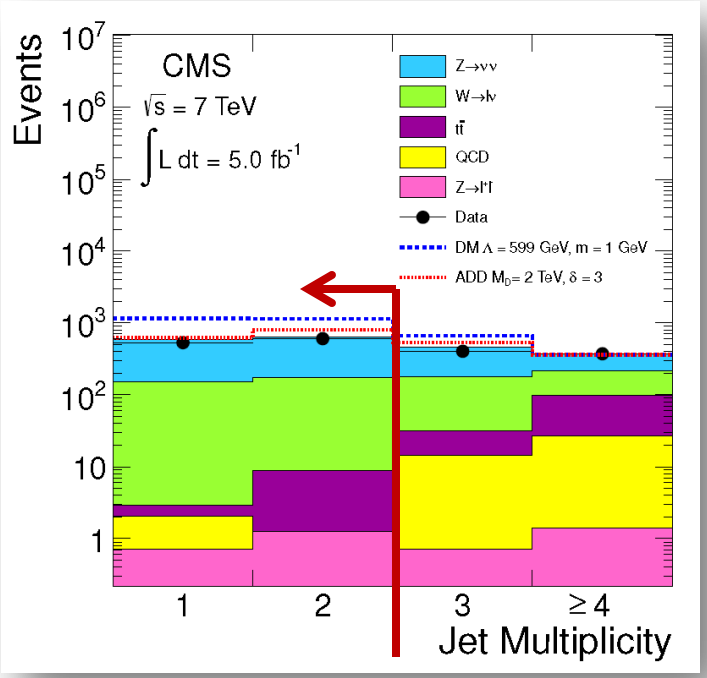


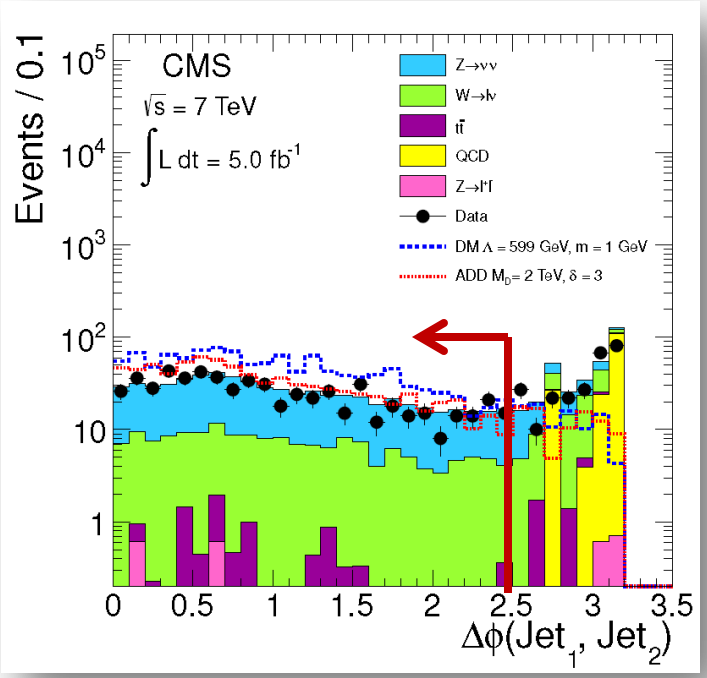


Monojet - basic selection

- **Basic topological selection**
  - MET > 200 GeV, number of Jets = 1 or 2
  - Leading Jet: pT > 110 GeV, |η|<2.4
  - Second Jet: pT > 30 GeV
  - Δφ(jet1,jet2) < 2.5

QCD rejection accomplished by topological cuts

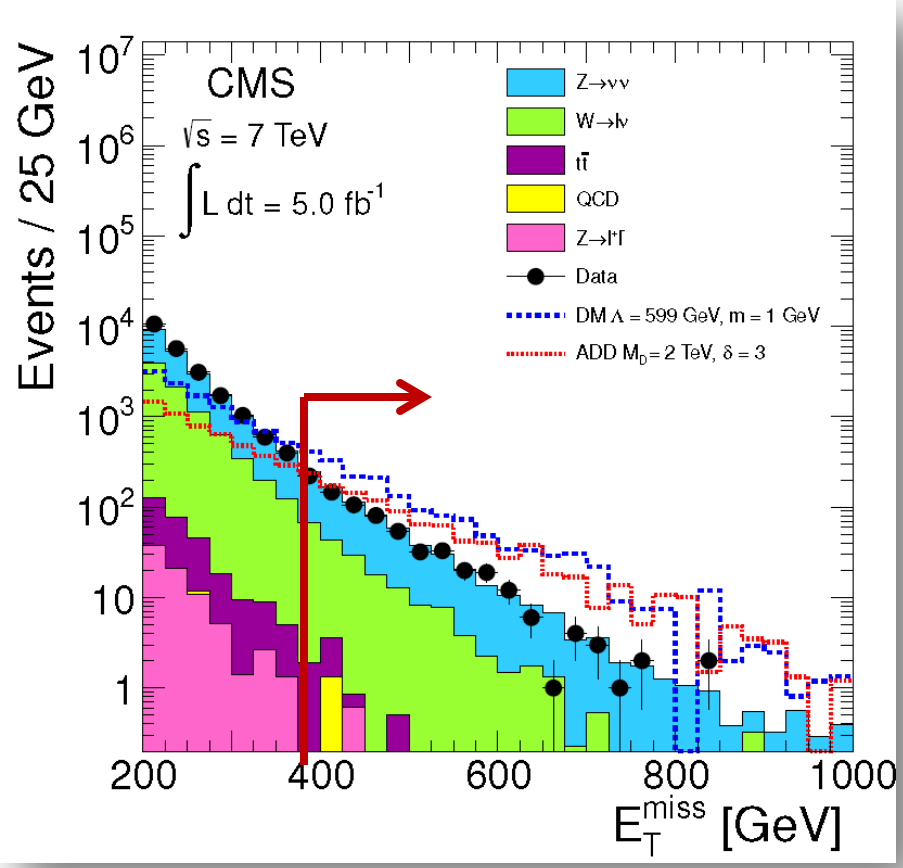




Monojet - data sample

- **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
- **Optimize search for best expected sensitivity to new physics :**
  - ✓ MET > 350 GeV for DM search

Search high MET events for DM



Monojet - analysis cut flow

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

E_T^{miss} (GeV/c) →	≥ 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

Monojet - background normalization

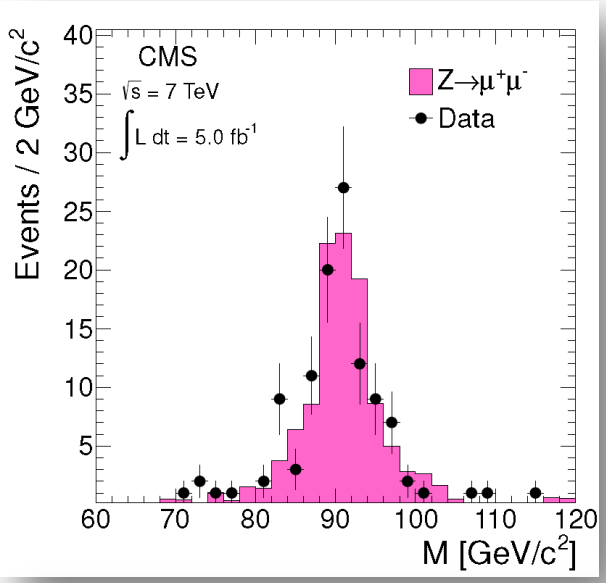
❖Data-driven estimation of Z+jets ➡ νν+jets

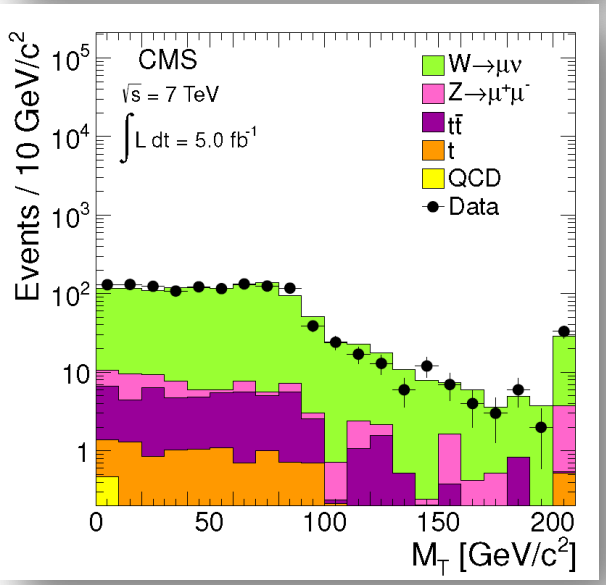
- Z+jets ➡ μμ+jets control sample derived directly from monojet data sample
- Require two muons passing selection
- Invariant mass 60-120 GeV, opposite sign
- Uncertainty in method is 10.4% mainly from stats (9.5%)

❖Similar for W+jets ➡ νl+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 uncertainties on acceptance (7.7 %) and selection efficiency (6.8 %)
- Total uncertainty in method is 11.3%

Data-driven measure of main backgrounds



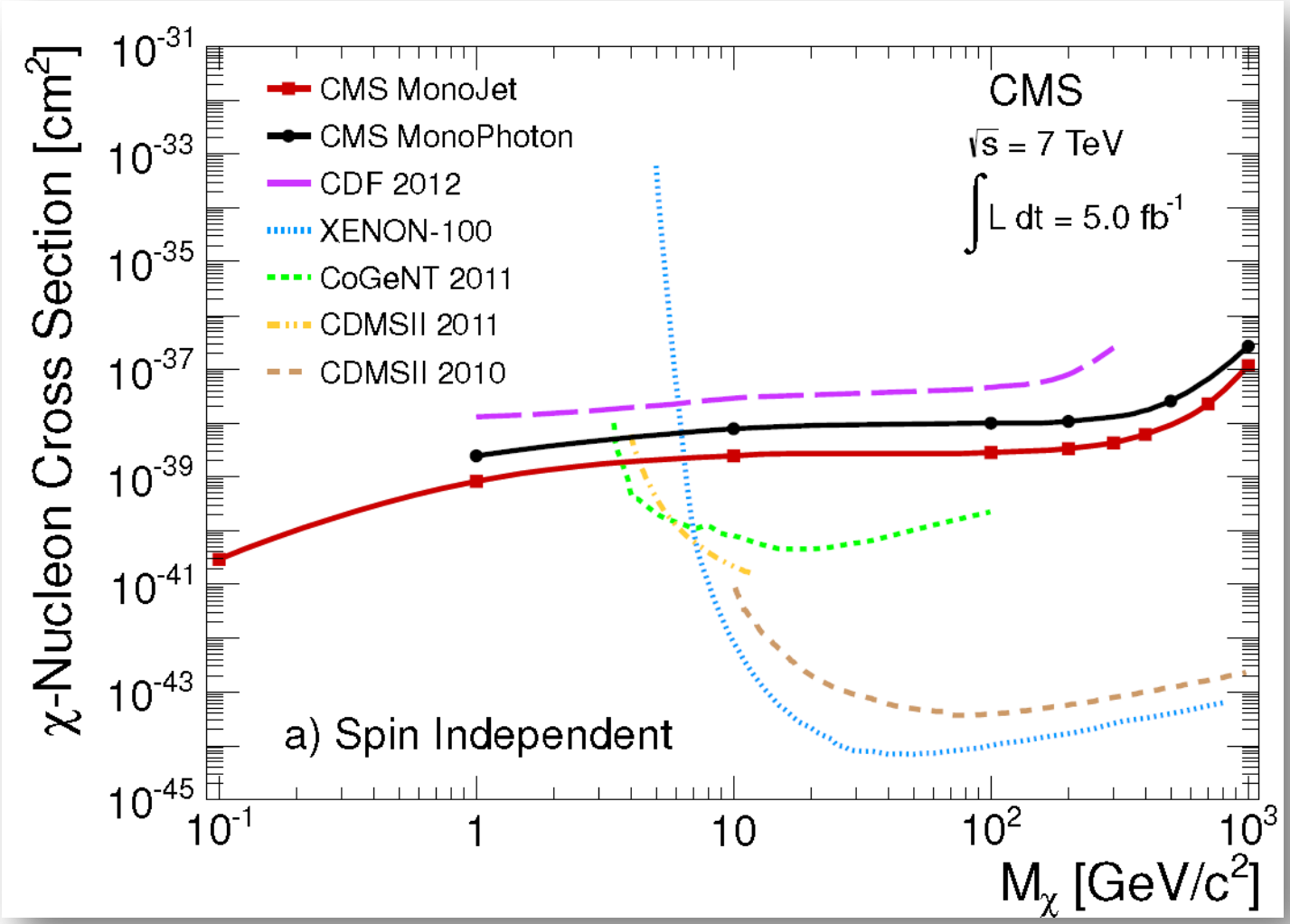


Monojet - Dark Matter Signal

- Monojet Signal Generation
  - Madgraph5 + Pythia6 generation with 40 TeV mediator mass
- Systematic uncertainties ≤15%, main contributions from
  - Jet Energy Scale
  - PDF (PDF4LHC)
  - Jet Energy Resolution
  - Luminosity
- Final numbers for MET > 350 GeV: 1225 ± 101 background, 1142 data

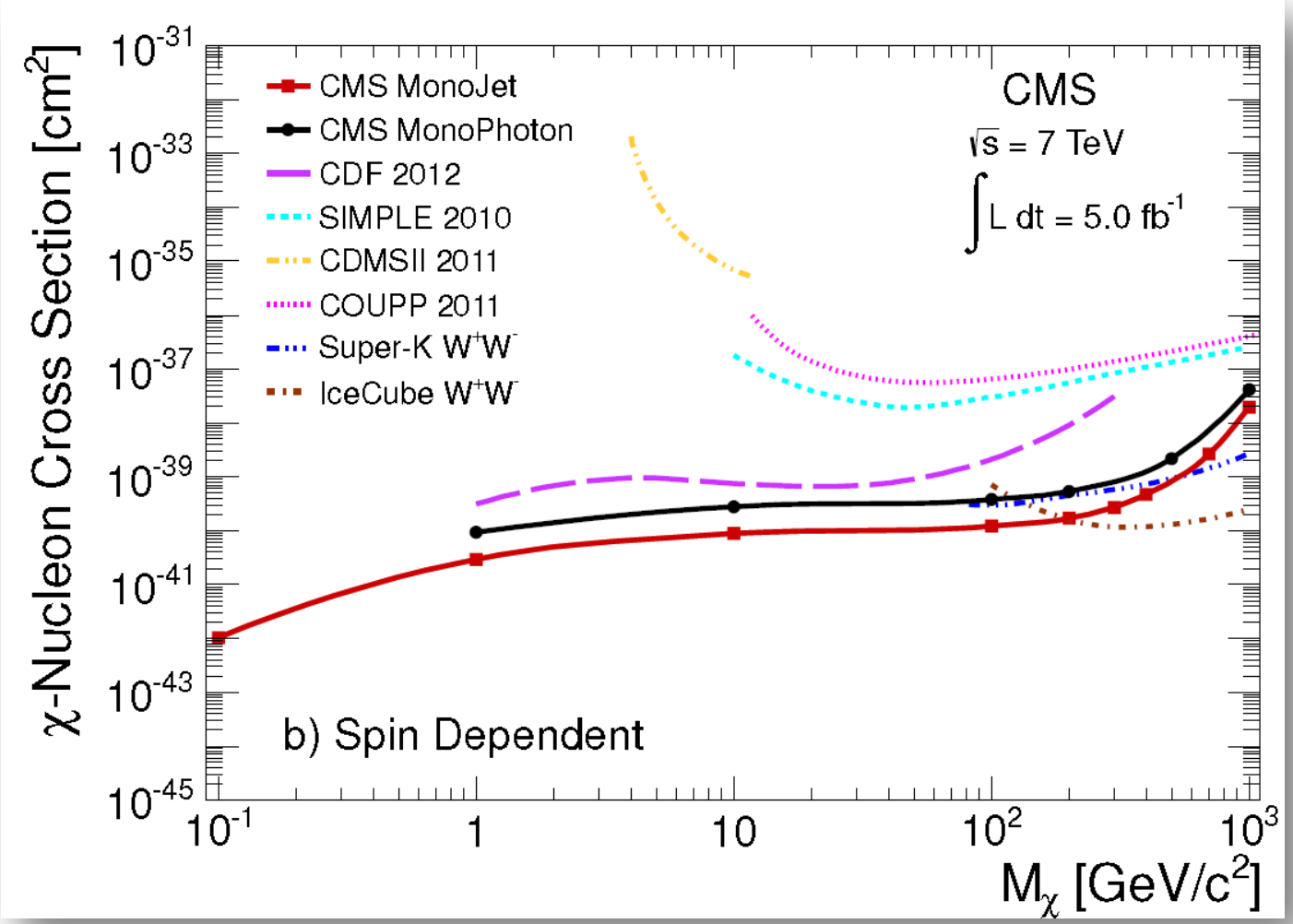
	Spin-dependent		Spin-independent	
M_χ (GeV/c^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)
0.1	754	1.03×10^{-42}	749	2.90×10^{-41}
1	755	2.94×10^{-41}	751	8.21×10^{-40}
10	765	8.79×10^{-41}	760	2.47×10^{-39}
100	736	1.21×10^{-40}	764	2.83×10^{-39}
200	677	1.70×10^{-40}	736	3.31×10^{-39}
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}

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 0.1-200 GeV mass range

Summary

- Presented searches for new physics in monojet and monophoton channels using 5.0 fb^{-1} of data.

- Predictions for SM background consistent with observed data, ***no excess*** found. Limits are 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 0.1-200 GeV mass range studied.***

References: *EXO-11-059 (monojet) and EXO-11-096 (monophoton) at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO*

Thank you !