Dark Matter Searches in the Monojet, Monophoton, and Monolepton Final States at CMS

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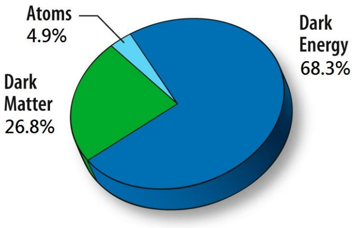
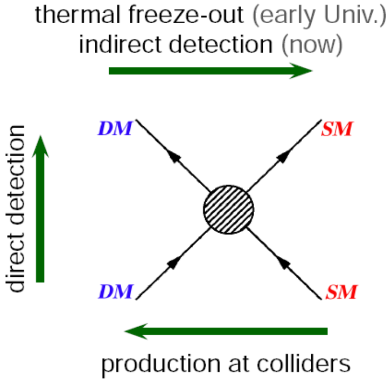
Lake Louise Winter Institute 2015

Introduction



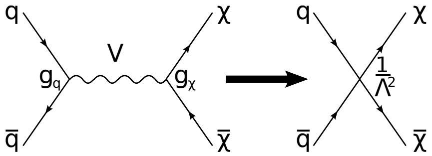


Overview

- Models and Signatures at CMS
- Monojet
- Monophoton
- Monolepton
- Dark Matter Interpretation
- Prospects for Run II

Models

- Effective Field Theories



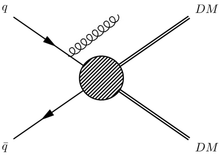
$\Lambda = \frac{M_V}{\sqrt{g_q g_\chi}}$

perturbative if $g_q g_\chi < 4\pi$

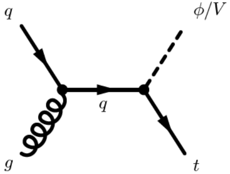
- Parameters: cut-off scale Λ, DM mass M_χ
- Operators: vector, axial-vector
  $\rightarrow$ spin-independent/spin-dependent interactions
- Validity: $M_V >$ invariant mass of DM pair
  $\rightarrow$ simplified models (monojet and monophoton)

Signatures at CMS

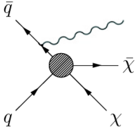
DM interacts weakly $\Rightarrow$ not detected $\Rightarrow$ use missing transverse energy (MET)



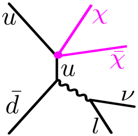
monojet



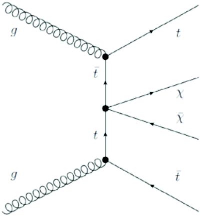
single top + MET



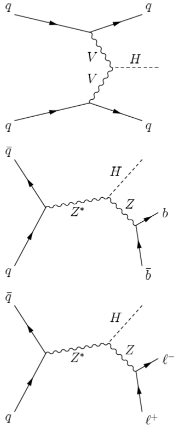
monophoton



monolepton

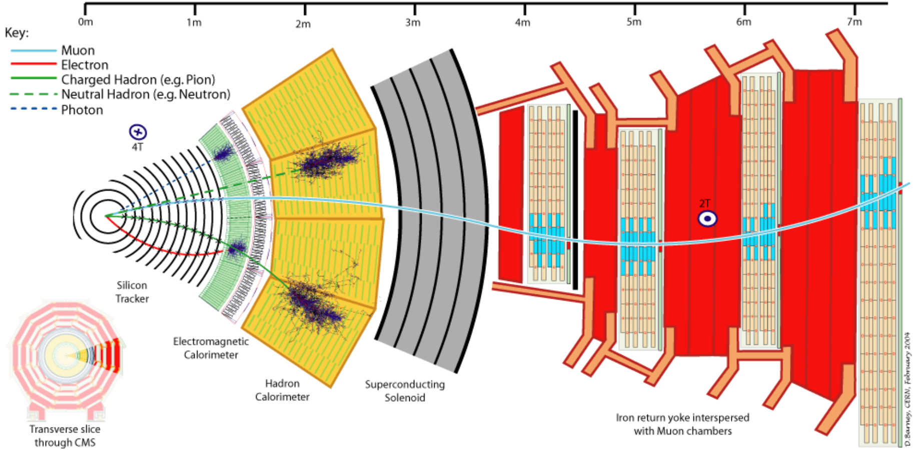


di-top + MET



Higgs portal
dark matter

The CMS Detector



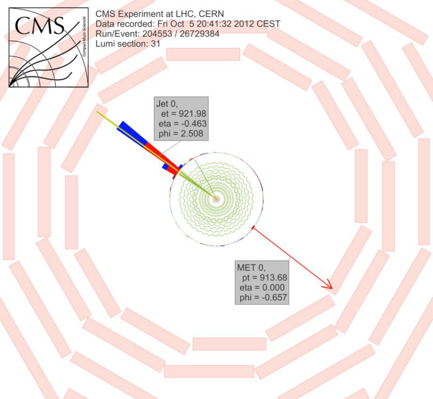
Monojet: Event selection

Jet:

Ref.: CMS-EXO-12-048 arXiv:1408.3583

- $p_T > 110$ GeV, $|\eta| < 2.4$
- jet content: $p_{T,neutral} < 70\%$, $p_{T,charged} > 20\%$
- allow 2nd jet ($p_T > 30$ GeV, $\Delta\phi_{j_1 j_2} < 2.5$)
- veto 3rd jet ($p_T > 30$ GeV)

$\Rightarrow$ **Reject QCD, $t\bar{t}$, instrumental backgrounds**



Missing Energy:

- main analysis variable
- high values

Leptons:

- veto isolated e, μ
- veto well-identified τ

$\Rightarrow$ **Reject W, Z, dibosons, single t**

Monojet: Background estimation and signal extraction

$Z(\nu\nu)$+jets

$Z(\mu\mu)$ control sample $\Rightarrow$ remove μ
correct for BR, A, ϵ, contamination
μ not taken into account in MET

$W(l\nu)$+jets

$W(\mu\nu)$ data $\Rightarrow$ correct $\frac{W(e/\tau\nu)}{W(\mu\nu)}$ ratio
correct for A, ϵ, contamination

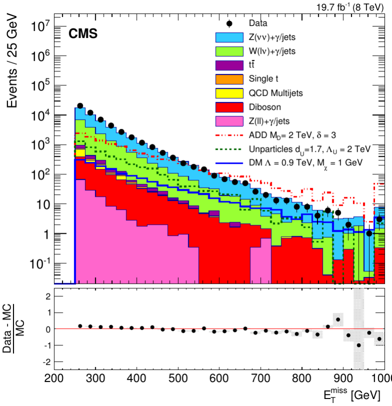
QCD

MC x scale factor

From simulation

$t\bar{t}$, $Z(ll)$+jets, single t, dibosons

Optimal MET cut: $E_T^{miss} > 500$ GeV
Single bin counting



E_T^{miss} (GeV) $\rightarrow$	>250	>300	>350	>400	>450	>500	>550
Total SM	51800 ± 2000	19600 ± 830	8190 ± 400	3930 ± 230	2050 ± 150	1040 ± 100	509 ± 66
Data	52200	19800	8320	3830	1830	934	519

Monophoton: Event selection

Ref.: CMS-EXO-12-047 arXiv:1410.8812

Photon:

- $E_T > 145$ GeV, $|\eta| < 1.44$
- photon ID: H/E < 0.05, shower shape
- isolated, timing requirement

Missing Energy:

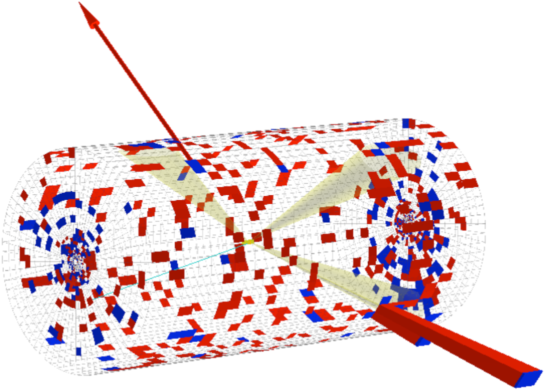
- $E_T^{miss} > 140$ GeV
- $\Delta\phi(E_T^{miss}, \gamma) > 2.0$

$\Rightarrow$ **Reject γ+jets**

Leptons:

- veto isolated e, μ

$\Rightarrow$ **Reject W(lν)γ**



Jets:

- veto 2nd jet ($p_T > 30$ GeV, $\Delta R > 0.5$)

$\Rightarrow$ **Reject QCD**

Monophoton: Background estimation and signal extraction

From simulation

$Z(\nu\nu)\gamma$, $W(l\nu)\gamma$, γ+jet, $Z(ll)\gamma$, $\gamma\gamma$

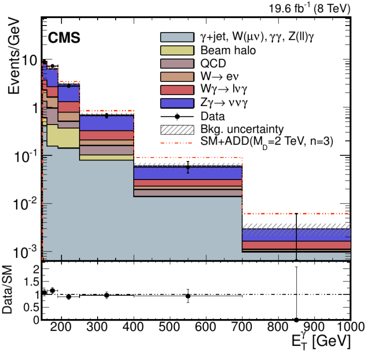
$W^* \rightarrow e\nu$

data-driven
e misidentified as γ
track matching inefficiency

QCD

data-driven
jet misidentified as γ
correct for QCD direct γ production

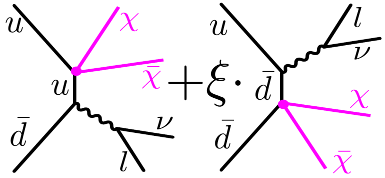
Single bin counting



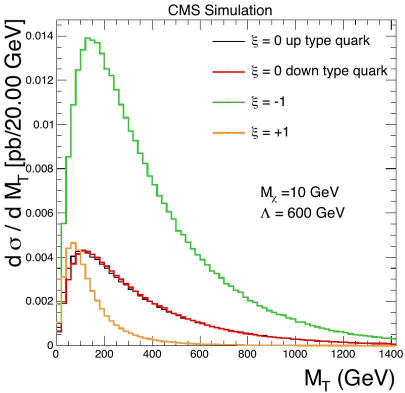
Process	Estimate
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\rightarrow \ell\nu) + \gamma$	103 ± 21
$W \rightarrow e\nu$	60 ± 6
jet $\rightarrow \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

Monolepton

- Clean leptonic signature
  ⇒ less background
  ⇒ easier to trigger
- Sensitive to different couplings to *u* and *d* quarks



Transverse mass M_T:
shape depends on ξ



Monolepton: Event selection

Ref.: CMS-EXO-12-060 arXiv:1408.2745

Electrons:

- $E_T > 100$ GeV
- isolated
- veto 2nd e ($E_T > 35$ GeV)
- impact param. w.r.t. primary vertex

$\Rightarrow$ **Reject Drell-Yan, cosmic rays**

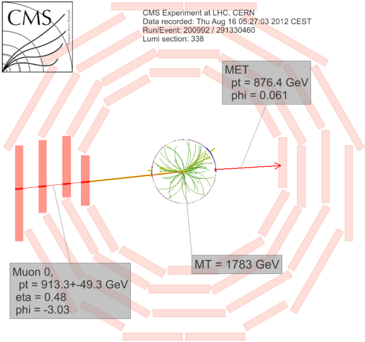
Muons:

- $p_T > 45$ GeV, $\frac{\sigma_{p_T}}{p_T} < 30\%$
- isolated
- veto 2nd μ ($p_T > 25$ GeV)
- impact param. w.r.t. primary vertex

Missing Energy:

- $0.4 < \frac{p_T^l}{E_T^{miss}} < 1.5$
- $\Delta\phi(l, E_T^{miss}) > 2.5$

$\Rightarrow$ **Reject QCD**



Monolepton: Background estimation and signal extraction

W($l\nu$)

MC x scale factor
scale factor: NLO QCD and EW corrections as a function of M_T

QCD

data-driven
jets misidentified as electrons
correct for contamination

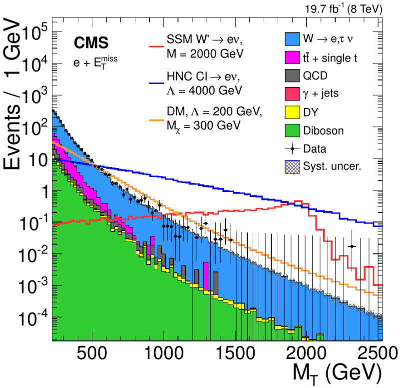
From simulation

$t\bar{t}$, single t, Drell-Yan, dibosons, γ+jets

background parametrization (tail):

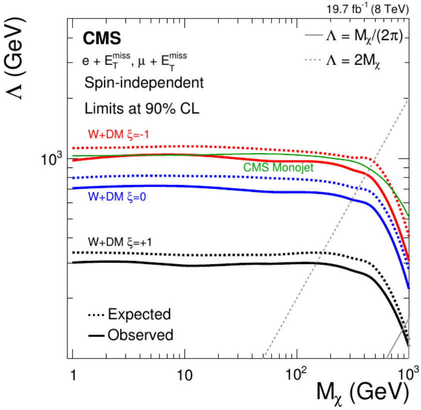
$$f(M_{\mathrm{T}}) = e^{a+bM_{\mathrm{T}}+cM_{\mathrm{T}}^2} M_{\mathrm{T}}^d$$

M_T shape analysis: multi-bin counting

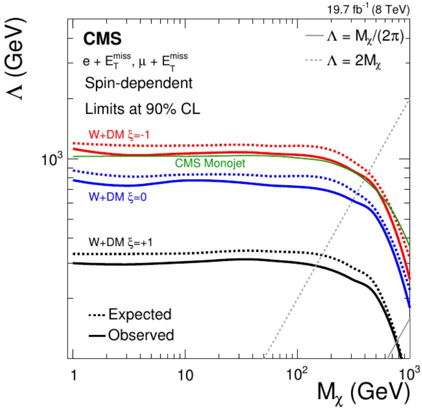


Monolepton: Limits on contact interaction scale

Vector
Spin-independent

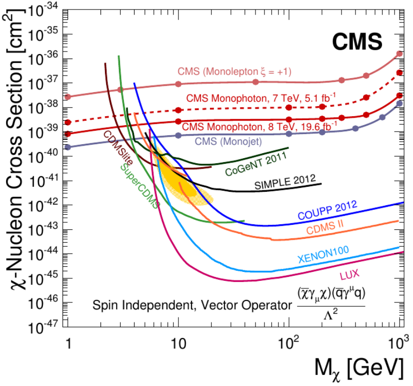


Axial-Vector
Spin-dependent

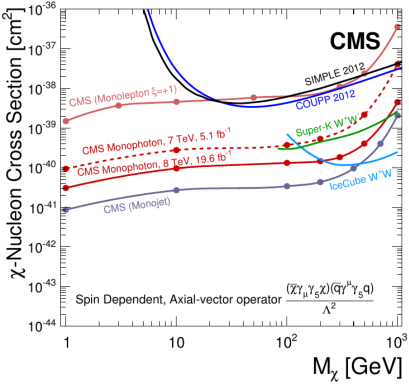


DM Interpretation: Limits on interaction x-section

Vector
Spin-independent

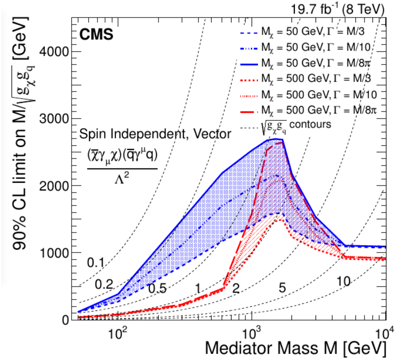


Axial-Vector
Spin-dependent

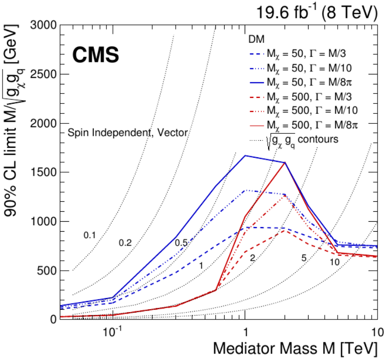


Simplified model where mediator mass is varied:

Monojet



Monophoton



- Vector interactions
- Light mediator, accessible at LHC
  $\Rightarrow$ resonant behaviour

- High M: $\sim$ EFT limits
- Medium M: stronger limits
- Low M: weaker limits

Prospects for Run II

LHC

- higher energy
- higher luminosity

Analysis improvements

- shape analysis
- refine background estimate

Interpretation

- make more comprehensive
- simplified models

Backup

Generators: Monojet

DM samples

MadGraph (LO)
Pythia 6.4.26 tune Z2*
CTEQ 6L1

Z+jets, W+jets, $t\bar{t}$, Wγ, Zγ

MadGraph (LO)
Pythia 6.4.26 tune Z2*
CTEQ 6L1

QCD, ZZ, ZW, WW

Pythia 6.4.26 tune Z2*
CTEQ 6L1

Single t

Powheg
Pythia 6.4.26 tune Z2*
CTEQ 6.6M

Generators: Monophoton

DM samples

MadGraph

$Z\gamma \rightarrow \nu\bar{\nu}\gamma$, $W\gamma \rightarrow l\nu\gamma$

MadGraph
corrected to NLO
(E_T^γ dependent, with MCFM)

$Z\gamma \rightarrow ll\gamma$, $\gamma\gamma$

Pythia 6.4.26 (LO)
CTEQ 6L1

γ+jet

Pythia 6.4.26 (LO)
CTEQ 6L1
corrected for NLO

Generators: Monolepton

$W \to l\nu$, Drell-Yan($\tau\bar{\tau}$), WW, WZ, ZZ

Pythia
corrected to NLO

Drell-Yan (ee, $\mu\mu$)

Powheg

QCD, γ+jet

Pythia

$t\bar{t}$

MC@NLO
Herwig
corrected to NNLO

Single t

Powheg
Pythia

Monojet: Background estimation

Z($\nu\nu$)+jets

control sample:

- selection
- no μ veto
- 2 μ, M_{inv} around Z-mass

remove μ
correct for BR, A, ϵ, contamination
μ not taken into account in MET

W($l\nu$)+jets

control sample:

- selection
- no μ veto
- μ, M_T around W-mass

W($\mu\nu$) correct $\frac{W(e/\tau\nu)}{W(\mu\nu)}$ ratio
correct for A, ϵ, contamination ($t\bar{t}$)

QCD

MC(signal region) x scale factor
scale factor = data/MC
from QCD enriched region in data:

- selection
- relax Njets, $\Delta\phi_{j_1,j_2}$
- $\Delta(E_T^{miss}, j_2) < 0.3$

Monophoton: Background estimation

W* $\rightarrow e\nu$

e misidentified as γ
track matching inefficiency ϵ:

- from $Z \rightarrow ee$ sample
- tag-and-probe

control sample:

- selection
- shower matched to track

control sample x $\frac{1-\epsilon}{\epsilon}$

QCD

jet misidentified as γ
correct for QCD direct γ production
sample x scale factor(control sample)
sample:

- selection
- fail γ isolation

scale factor $= \frac{\text{pass } \gamma \text{ iso } - \text{ true } \gamma}{\text{fail } \gamma \text{ iso}}$
control sample: $E_T^{miss} < 30$ GeV

Monolepton: Background estimation

W($l\nu$)

MC x scale factor
scale factor: NLO QCD and EW corrections as a function of M_T

QCD

jets misidentified as electrons
correct for contamination
sample x scale factor(control sample)
sample:

- selection
- fail e isolation

scale factor $= \frac{r}{1-r}$, $r = \frac{\text{isolated } e}{\text{all events}}$
control sample: $1.5 < E_T / E_T^{miss} < 10$

Dominant systematics

Monojet:

- renormalization/factorization scale
- ISR modeling
- JES, PDFs, pile-up, lumi

Monophoton:

- PDFs + renormalization/factorization scale
- Data/MC scale factor
- pile-up, energy calibration γ, jets, MET

Monolepton:

- μ momentum scale
- PDFs
- W K-factor (2 ways of combining EW and QCD corrections)
- *e* energy scale, Data/MC scale factor, MET, μ momentum resolution, *e* energy resolution, pile-up