

Searches for dark matter in ATLAS and CMS

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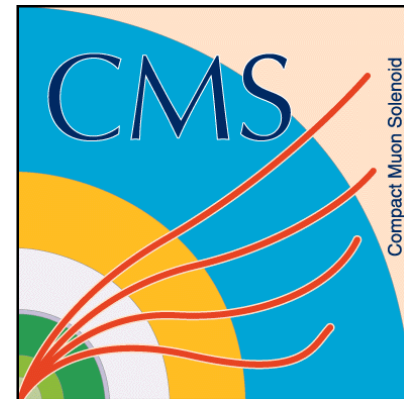
On behalf of the ATLAS and CMS Collaborations

July 24, 2015

EPS-HEP2015

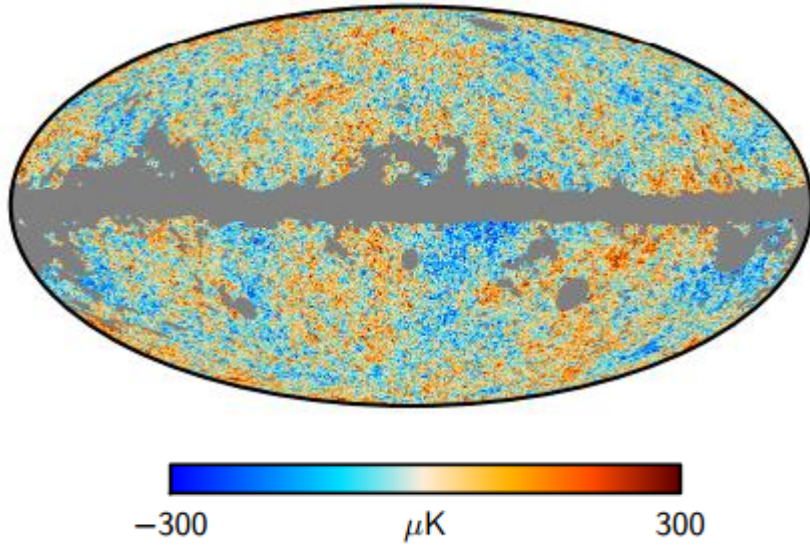
Vienna

- Introduction
- Searches and results
- Conclusions/Outlook



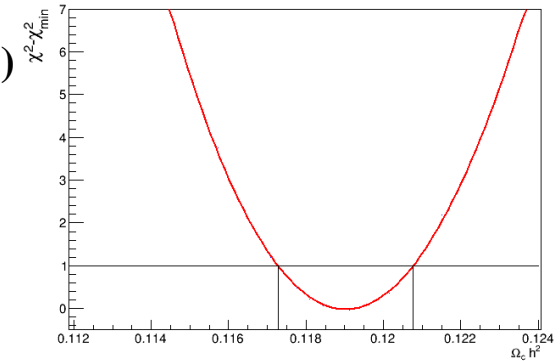
Introduction

Planck Collaboration, arxiv:1502.05956 and arXiv:1311.1657



CMB (Planck) + other probes + cosmological model

→ relic density ($\Omega_c h^2$)



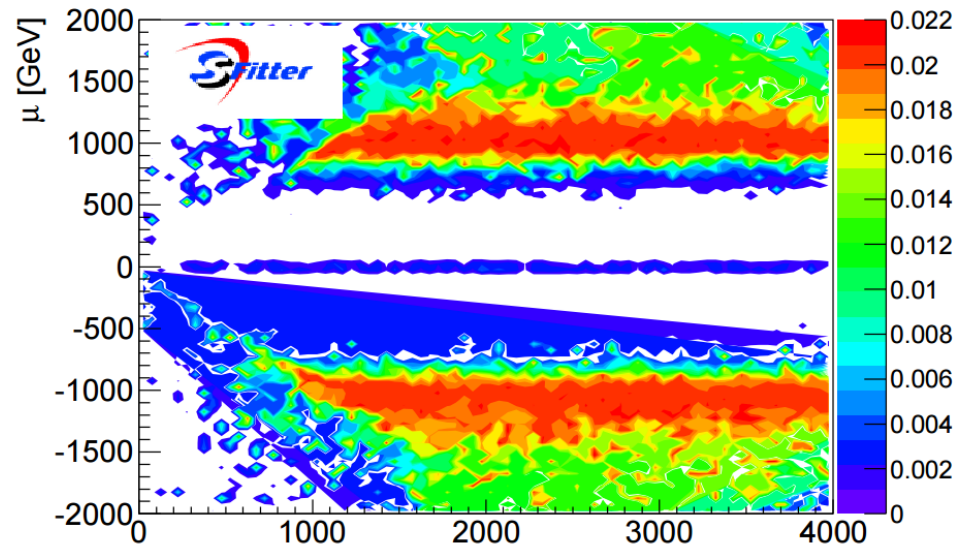
Particle Physics:

Relic density ($\Omega_c h^2$) (+other measurements)

+physics model of the dark matter candidate (spectrum, couplings) (e.g. SUSY)

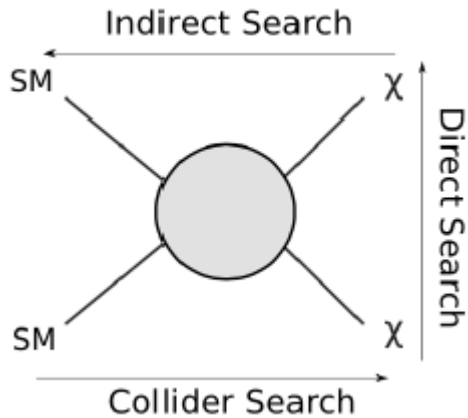
+annihilation cross sections (e.g. microMegas, darkSusy,...) and more

→ restriction on a model parameter space



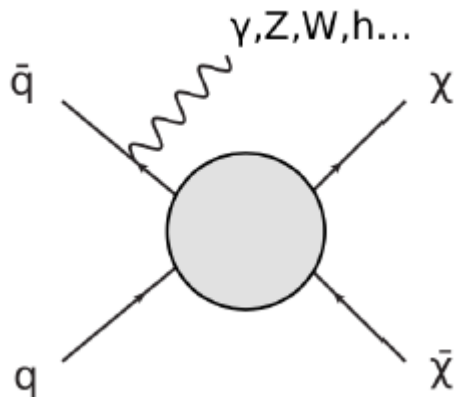
SFitter, Phys.Rev. D89 (2014) 5, 055017 M_1 [GeV]

See also talks by Fittino, MasterCode at this conference ²



Search for dark matter at the LHC:

- production of dark matter particles
- weakly interacting: no direct detection



Cross section depends on:

$$M_* = m_V / \sqrt{g_f g_\chi}$$

M_* : suppression mass

m_V : mediator mass

Search for particle X recoiling against dark matter

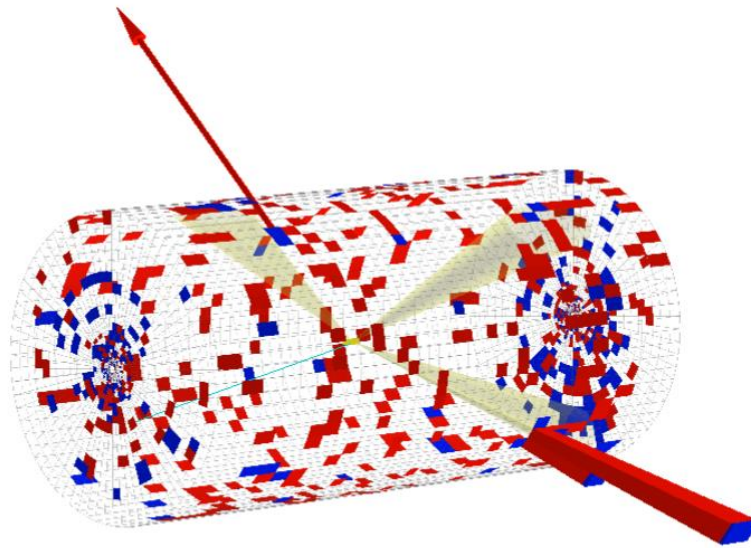
- X=photon, jet, W, Z, Higgs
- Relies heavily on ETmiss

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. Tait, H. Yu,
Phys.Rev.D82:116010,2010

Interpretation of results

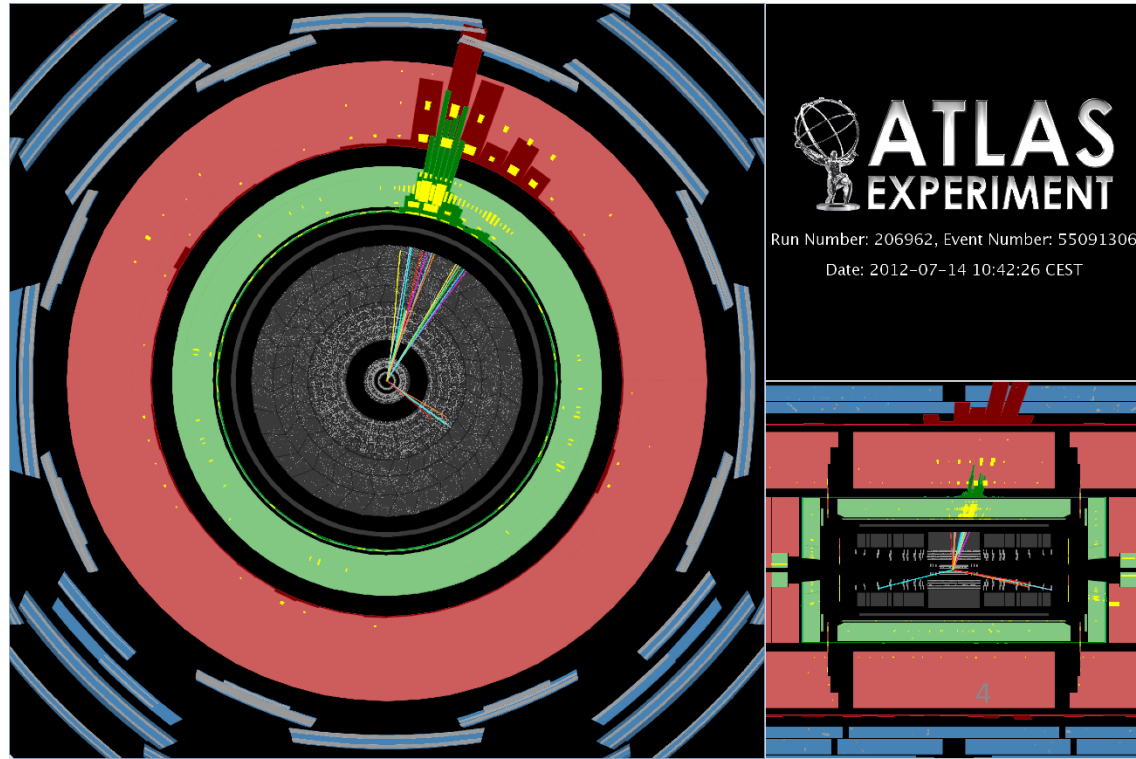
- Cross section limits
- Effective operators
- Simplified models



CMS mono-photon

CMS Experiment at LHC, CERN
Data recorded: Sat Nov 17 17:23:56 2012 IST
Run/Event: 207454 / 1095163126
Lumi section: 771

ATLAS mono-jet



Mono-photon search

ATLAS, Phys. Rev. D 91, 012008 (2015)

$E_{T}^{\text{miss}} > 150 \text{ GeV}$

$p_{T\gamma} > 125 \text{ GeV}$ (central)

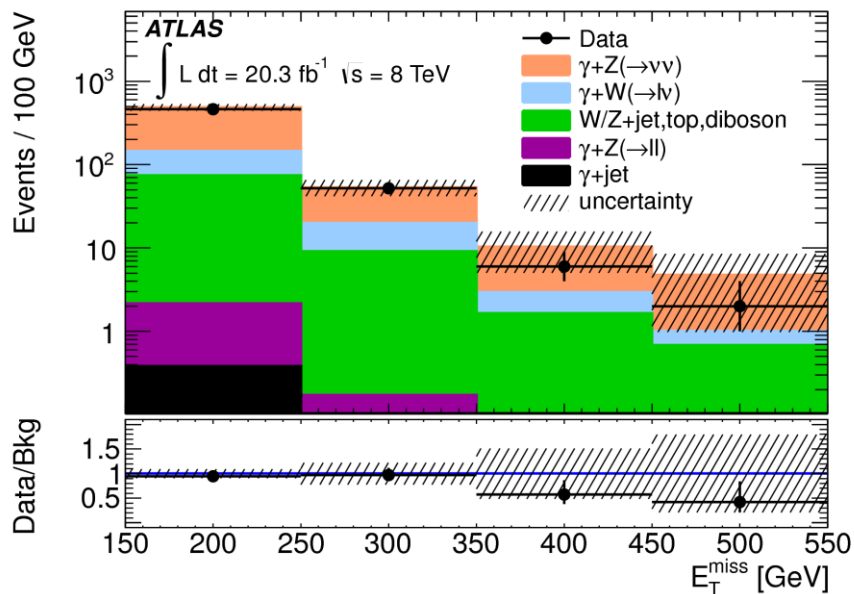
Accept 1jet

Lepton veto

Background estimation in CRs

(e.g. Z,W leptonic decays)

(Validation regions for Xcheck)



521 events for $557 \pm 36 \pm 27$ expected

CMS, arXiv:1410.8812

$E_{T}^{\text{miss}} > 140 \text{ GeV}$

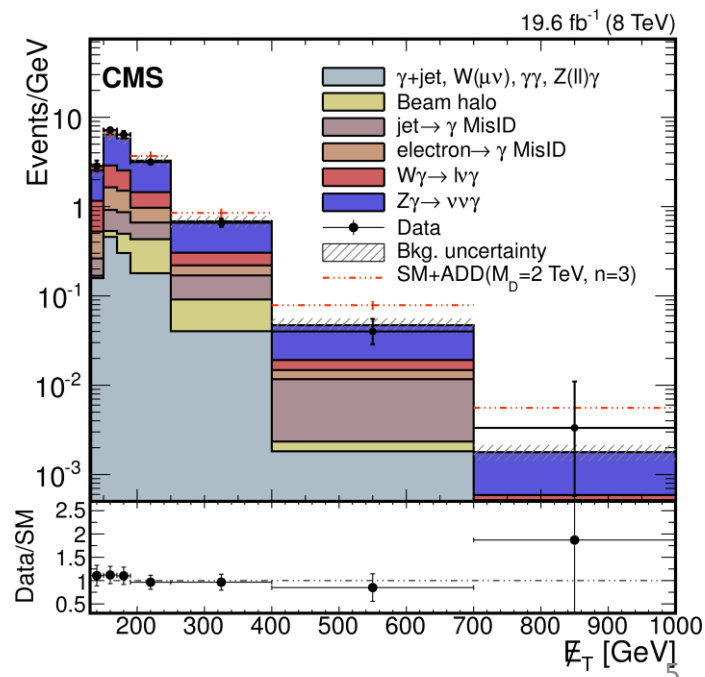
$p_{T\gamma} > 145 \text{ GeV}$ (central)

Accept 1jet

Background from simulation corrected

for data/MC differences

(CRs for Xcheck)

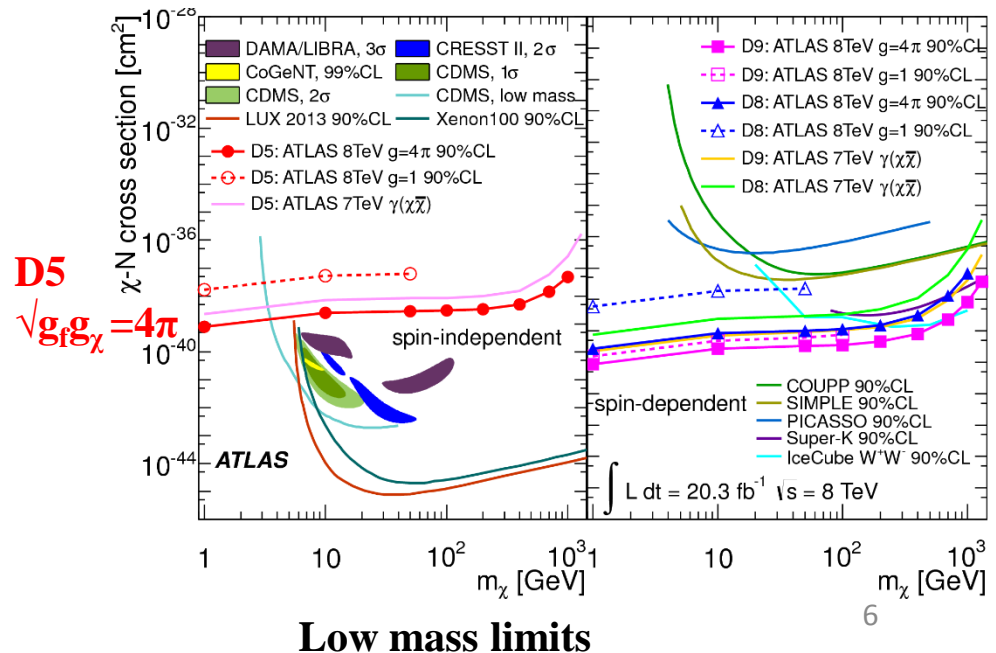
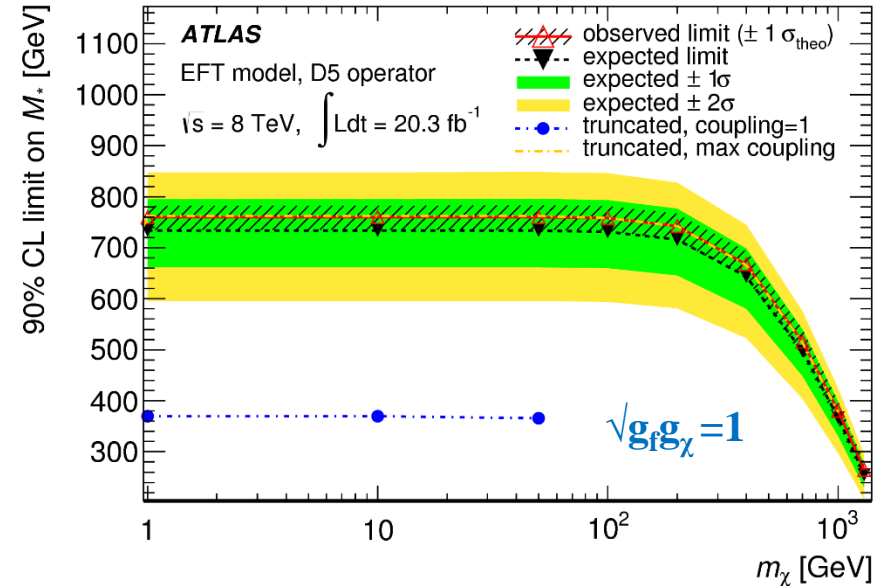
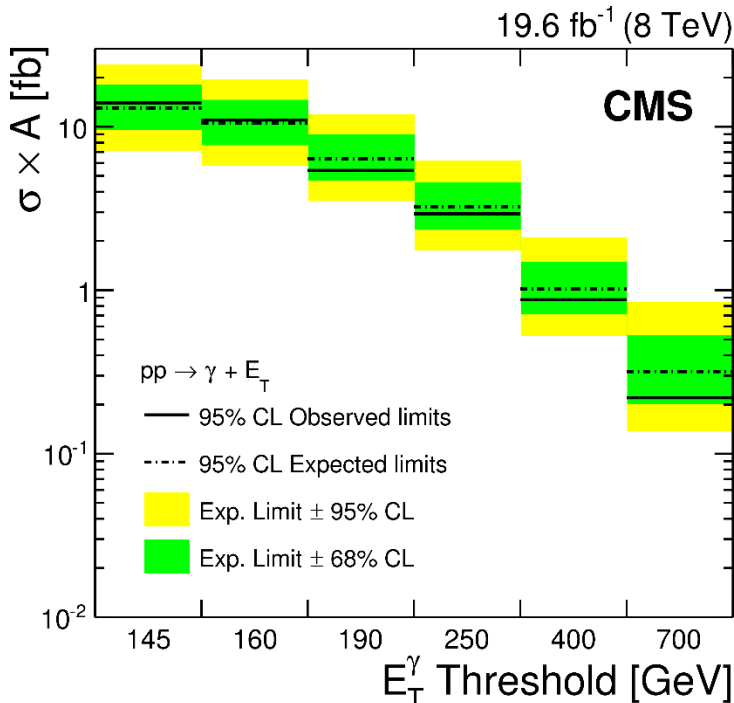


630 events for 614 ± 63 expected

Mono-photon search results

Absence of signal: limits

- **Limit on cross section (*acceptance) order of fb (and below)**
- **Limit M_* (suppression mass) as function of DM mass**
 - **EFT not a good approximation when $Q=m_V = M_* \sqrt{g_f g_\chi}$**
 - **Use only sim events with $Q < m_V$ for $\sqrt{g_f g_\chi} = 1, 4\pi$ (max)**
- **Limit on DM-nucleon scattering cross section**



Mono-jet searches

ATLAS, Eur. Phys. J. C75 (2015) 299

$E_{T}^{\text{miss}} > 150 \text{ GeV} \dots 700 \text{ GeV}$

$p_{Tj} > 125 \text{ GeV}$ (central)

$p_{Tj}/E_{T}^{\text{miss}} > 0.5$

At least 1jet

Lepton and isolated track vetoes

Background estimation in CRs

Cross check in VRs

SR1 (150GeV)- SR9 (700GeV)

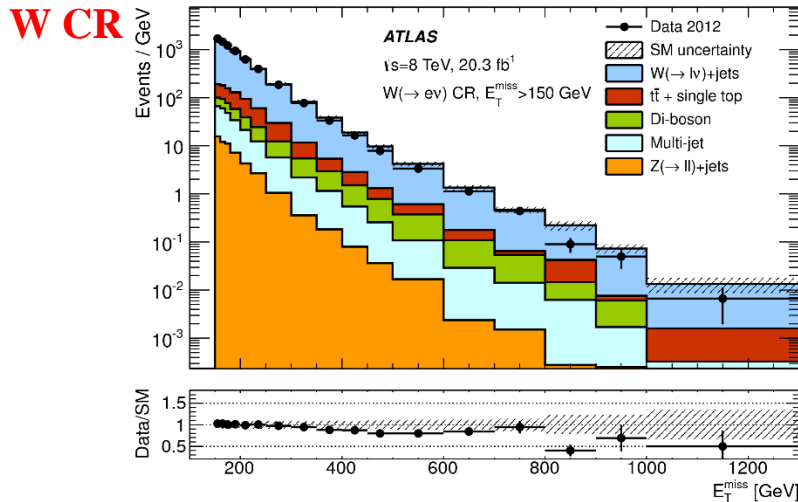
CMS, Eur. Phys. J. C75 (2015) 235

$E_{T}^{\text{miss}} > 120 \text{ GeV}$

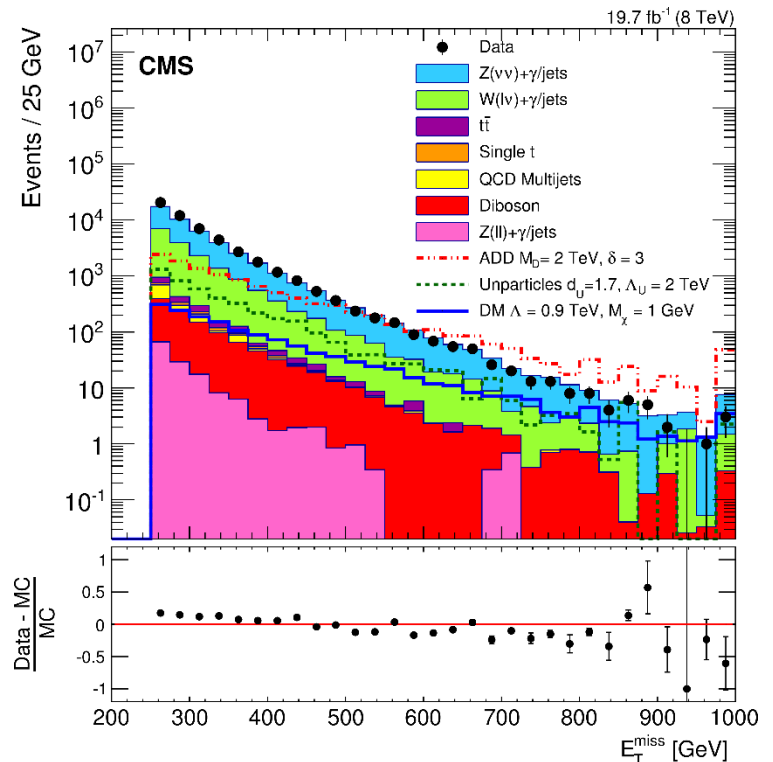
$p_{Tj} > 110 \text{ GeV}$ (central)

Accept second (separated) jet

Lepton vetoes



SR9: 126 obs for 97 ± 14 expected



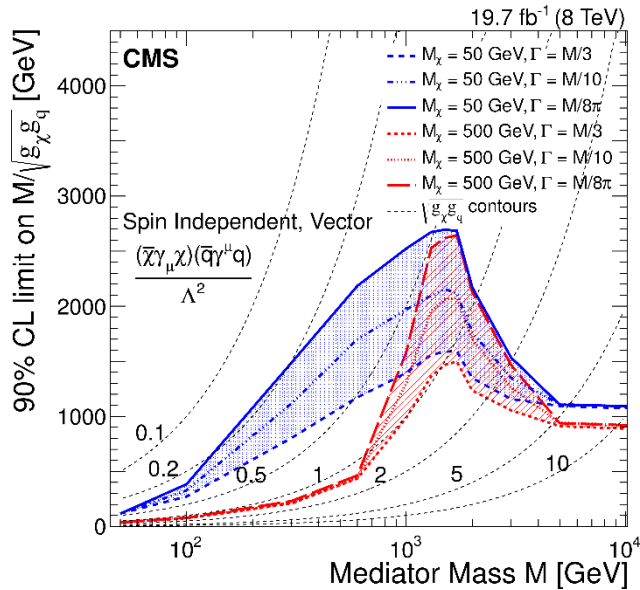
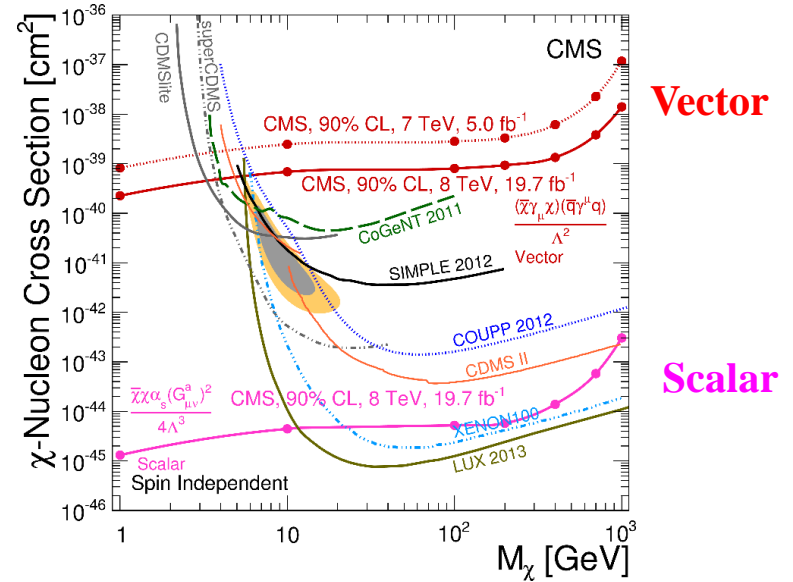
$E_{T}^{\text{miss}} > 550 \text{ GeV}$: 519 obs for 509 ± 66 expect

Mono-jet search results

ATLAS

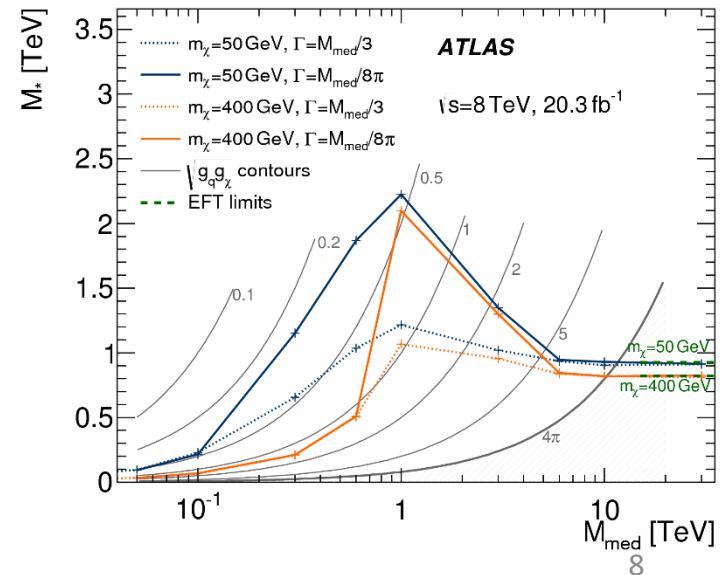
Limit on $\sigma \cdot A \cdot \epsilon$

Signal Region	95% CL Observed (Expected)
SR1	726 (935)
SR2	194 (271)
SR3	90 (106)
SR4	45 (51)
SR5	21 (29)
SR6	12 (17)
SR7	7.2 (7.2)
SR8	3.8 (3.6)
SR9	3.4 (1.8)



Simplified Models:

- $M_\chi = 50 \text{ GeV}$
- $M_\chi = 400/500 \text{ GeV}$
- Γ



Mono-W or -Z searches

$\xi=1$ ($uu\chi\chi=dd\chi\chi$) reduces cross section wrt $\xi=-1$

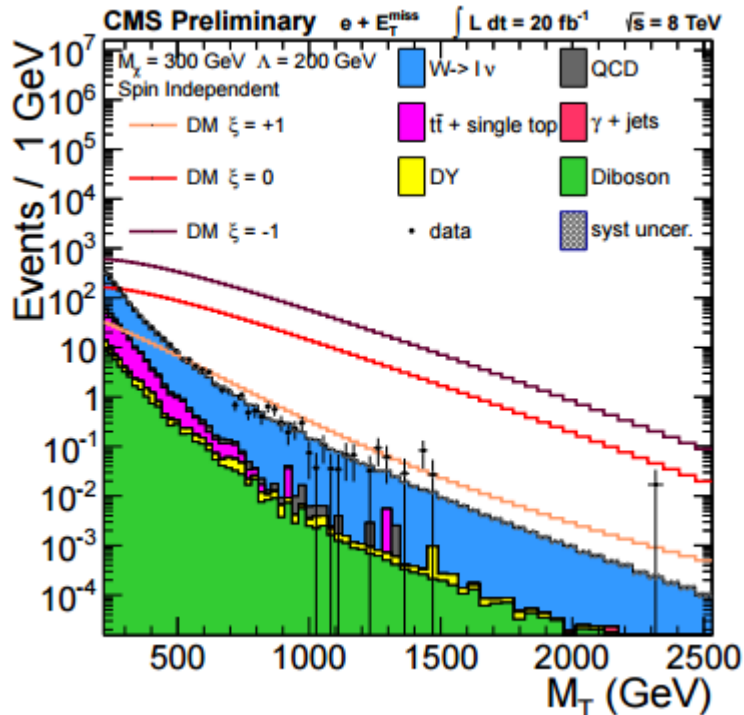
CMS, EXO-PAS-13-004

Leptonic W decay

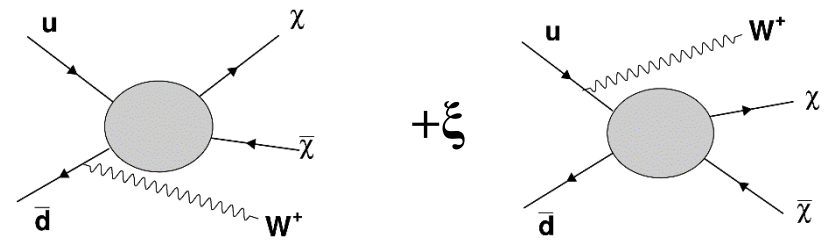
$p_{Tl} > 45/100 \text{ GeV}$ ($\mu/\text{electron}$)

$0.4 < p_{Tl}/E_{T\text{miss}} < 110 \text{ GeV}$

Accept second (separated) jet



$M_T > 1 \text{ TeV}$:
 e : 22 events for 26 ± 2.5 expected
 μ : 33 events for 26 ± 4 expected



ATLAS, Phys. Rev. Lett 112, 041802 (2014)

(hadronic W/Z decays)

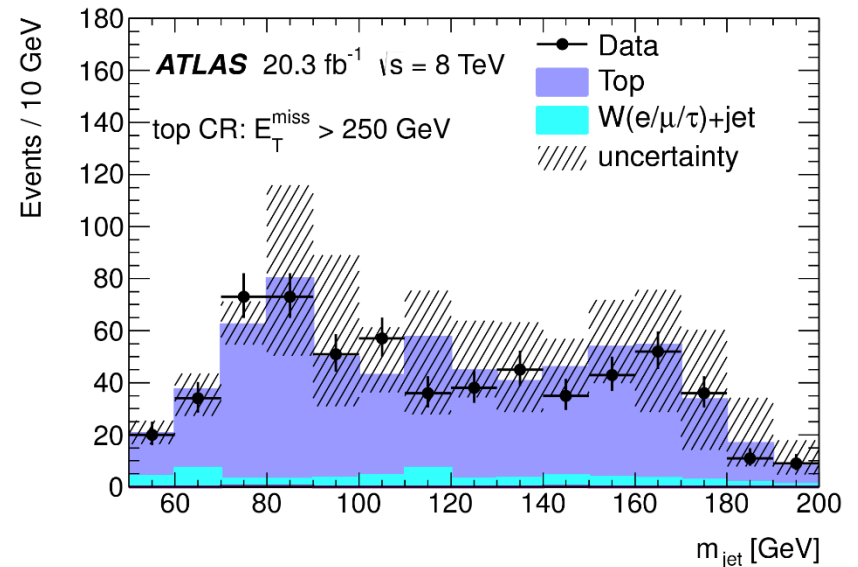
$E_{T\text{miss}} > 350 \text{ GeV}/500 \text{ GeV}$

Large radius (C/A $R=1.2$) central jet

$p_{Tj} > 250 \text{ GeV}$

$50 \text{ GeV} < m_{\text{jet}} < 120 \text{ GeV}$

Momentum balance: $\sqrt{y} = \min(p_{T1}, p_{T2}) \Delta R / m_{\text{Jet}} < 0.4$



705 events for 707^{+48}_{-38} expected
 89 events for 89^{+9}_{-12} expected

Mono-W or -Z searches: New analyses

CMS, EXO-12-054

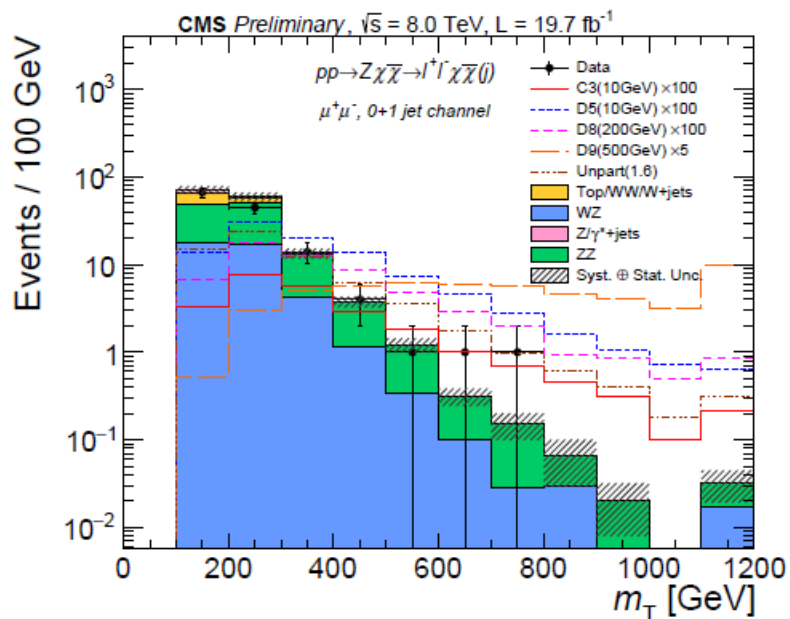
2leptons compatible with Z boson

$E_{T\text{miss}} > 80\text{GeV}$

Top veto, 3rd lepton veto

$p_{T\text{ll}} > 50\text{GeV}$

$|\frac{E_{T\text{miss}} - p_{T\text{ll}}}{p_{T\text{ll}}}| < 0.2$



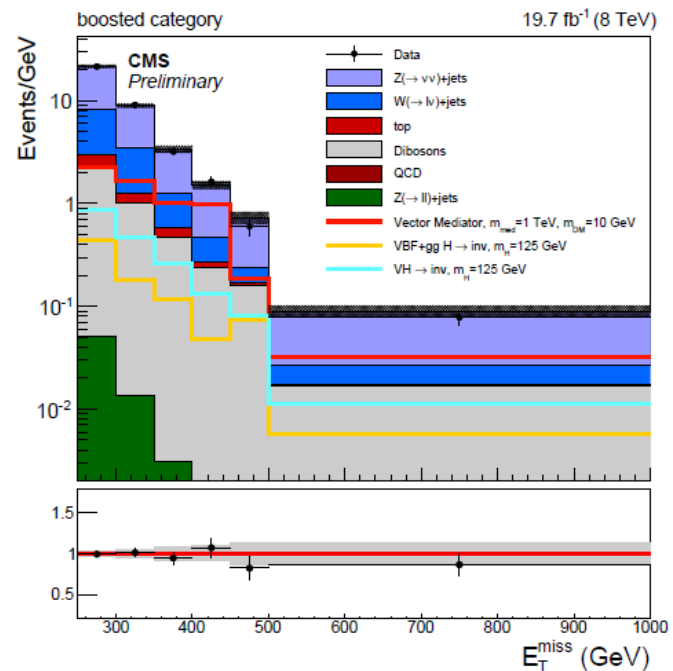
e: 111 events for $113 \pm 4.0 \pm 12.5$ expected
 μ : 133 events for $150.9 \pm 3.9 \pm 17.8$ expected

CMS, EXO-12-055

$E_{T\text{miss}} > 200\text{GeV}$

C/A R=0.8 or anti-kT=0.5

- Boosted (pruning, subjettiness)
- Resolved (q/g, mass drop)
- Mono-jet



510(500)GeV < $E_{T\text{miss}} < 1\text{TeV}$:

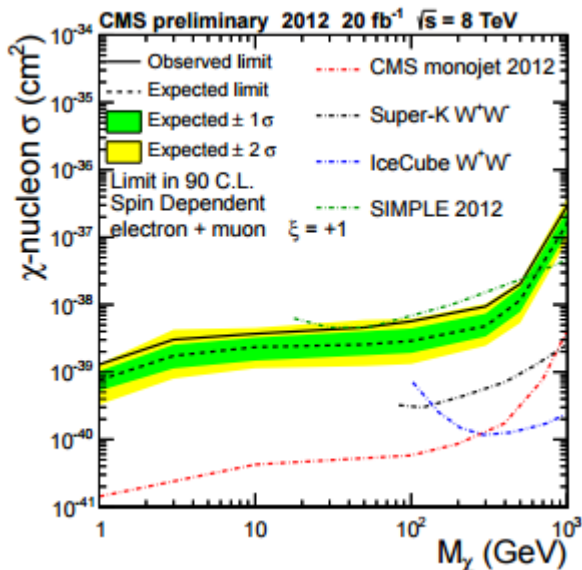
Boosted: 39 events for 54 ± 8.5 expected

Resolved: 617 events for 587.1 ± 48.3 expected

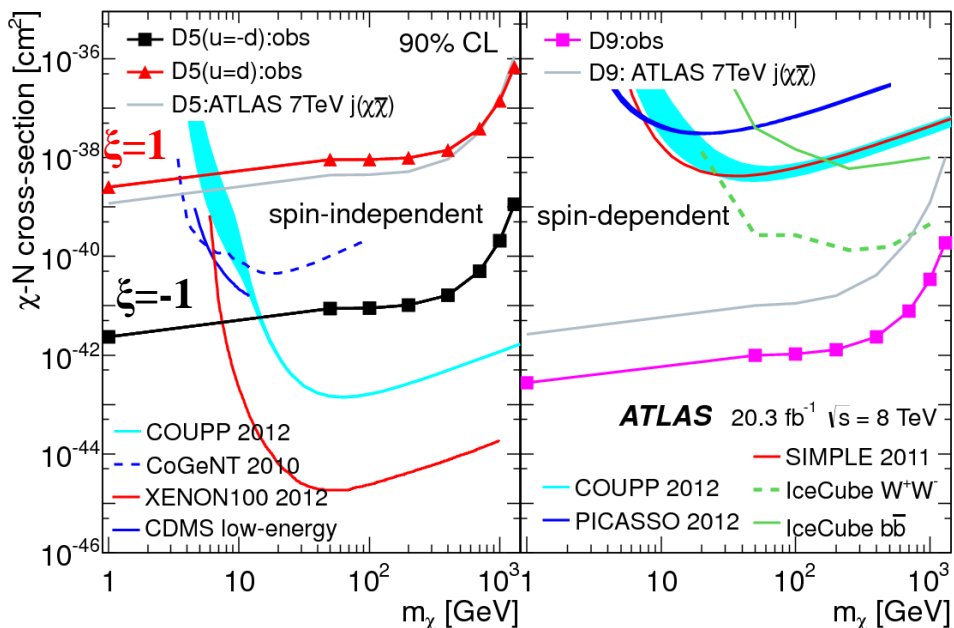
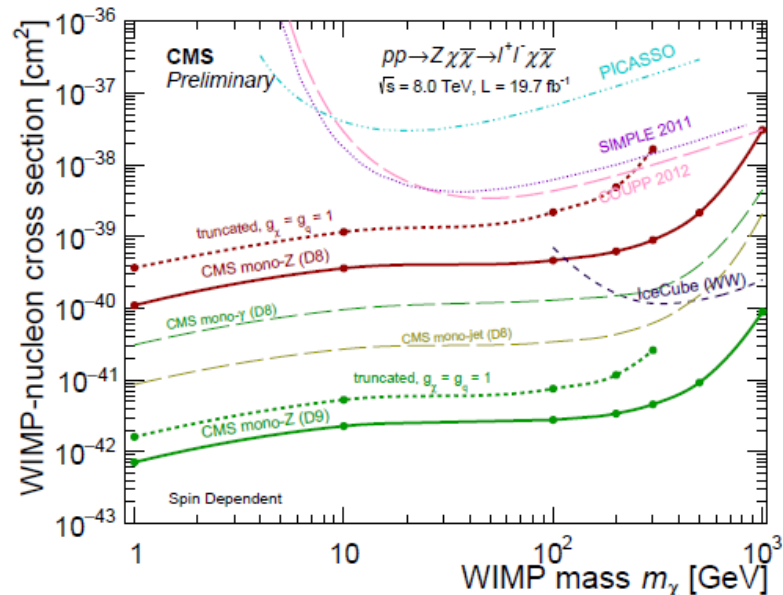
Mono-jet: 476 events for 413 ± 71 expected

Mono-W or -Z search results

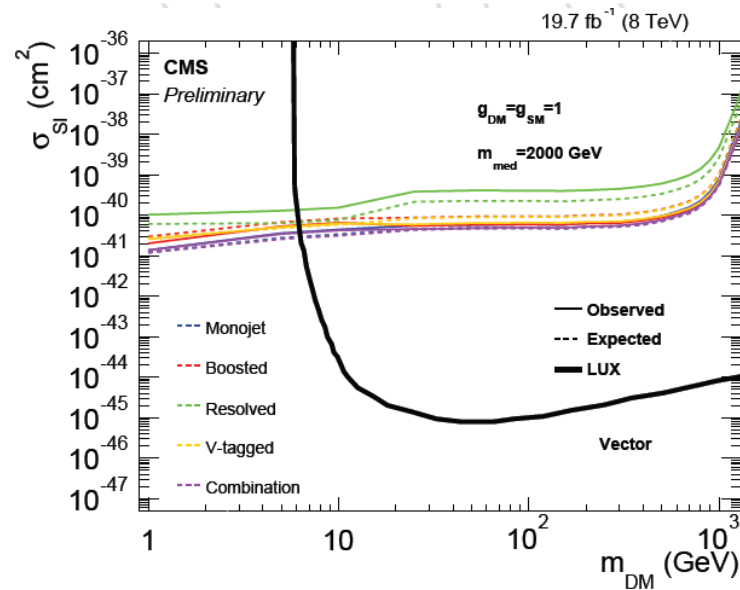
Leptonic W
decay SD



Leptonic Z
decay SD



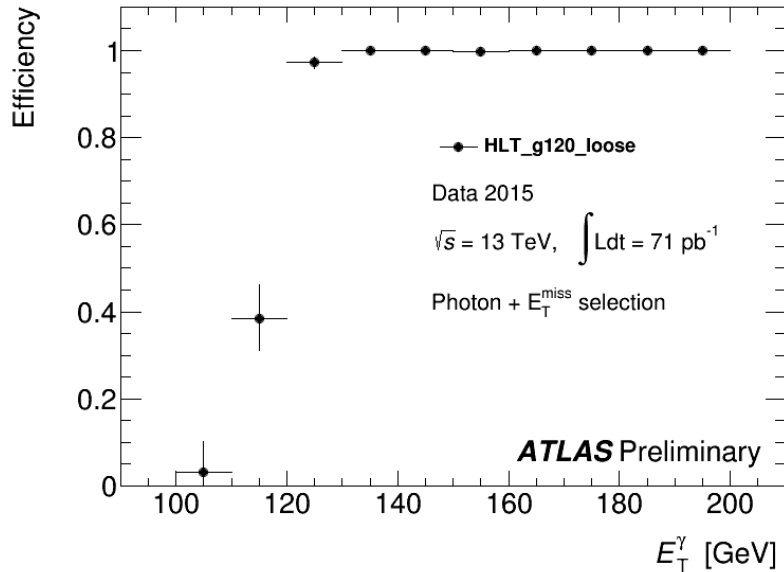
Hadronic decay of Z,W



Hadronic decays

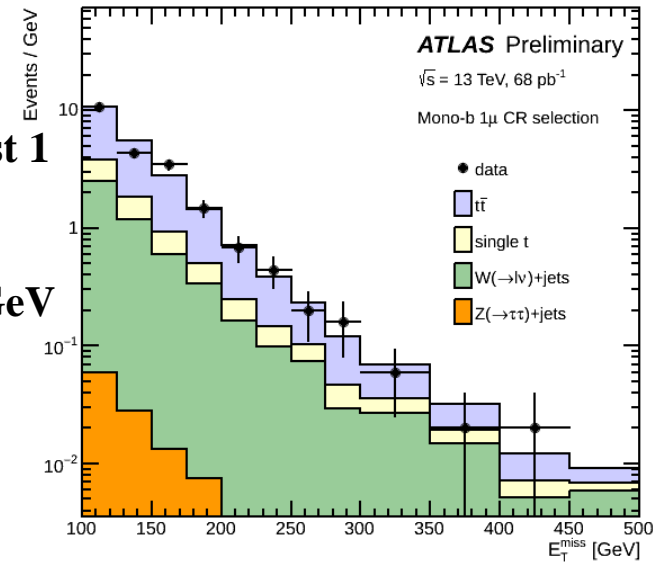
And 13TeV?

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/EXOT-2015-005>



Mono-b:
CR with at least 1
b-jet

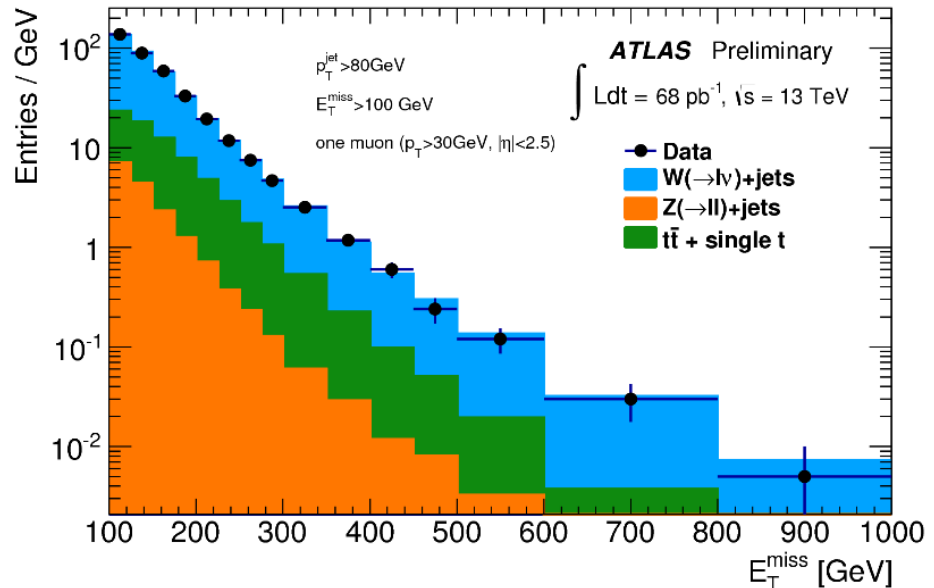
$E_{T}^{\text{miss}} > 100 \text{ GeV}$
 $p_{Tj} > 80 \text{ GeV}$
1 muon
Up to 4 jets



Mono-photon: trigger working well

Mono-jet:
W-CR 13TeV
 68 pb^{-1}
 $E_{T}^{\text{miss}} > 100 \text{ GeV}$
 $p_{Tj} > 80 \text{ GeV}$
1 muon $> 30 \text{ GeV}$
Up to 4 jets

Promising



Conclusions/Outlook

Search for dark matter at the LHC via recoil against:

- Photons
- Jets
- Electroweak bosons
- Higgs($\rightarrow\gamma\gamma$) (ATLAS, not shown)
- heavy SM quarks (ATLAS, CMS, not shown)

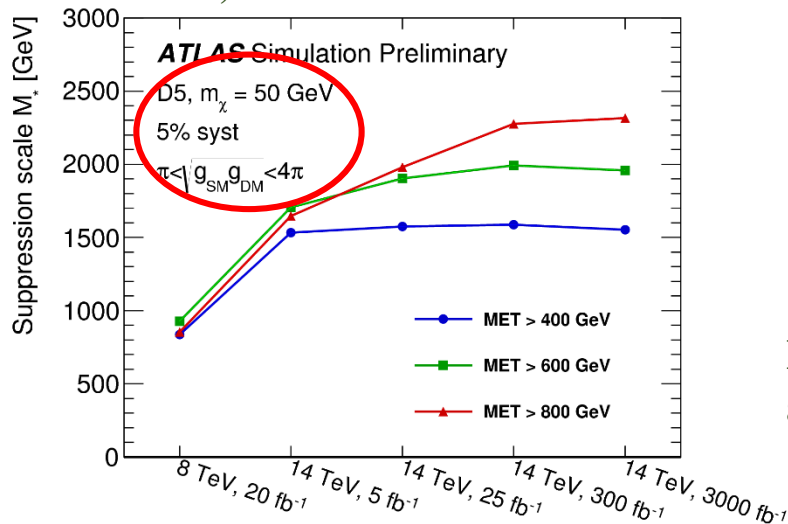
But also in the decay of other particles:

- Higgs (see talk by Philip Calfayan at this conference)
- RPC Supersymmetry (several talks at this conference)

No evidence for dark matter candidate so far

LHC Run2 will extend the cross section range and mass range:

ATLAS, ATL-PHYS-PUB-2014-007



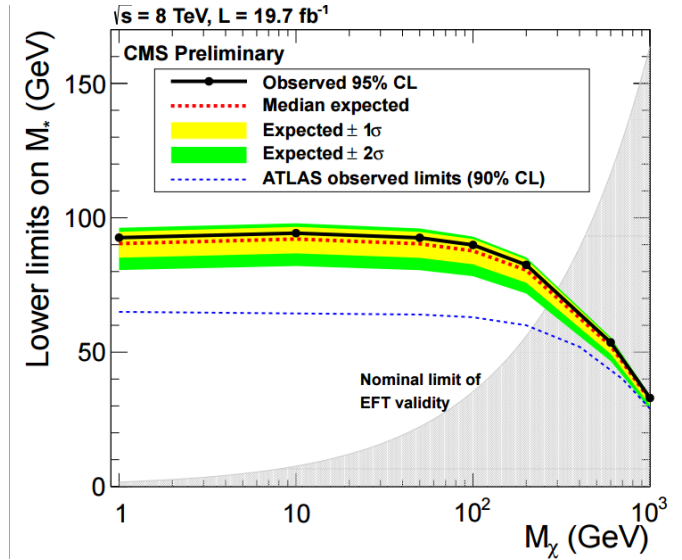
Or find a signal?

Big effort by ATLAS-CMS dark matter forum for RUN2:
arxiv:1507.00966

Heavy quark search results

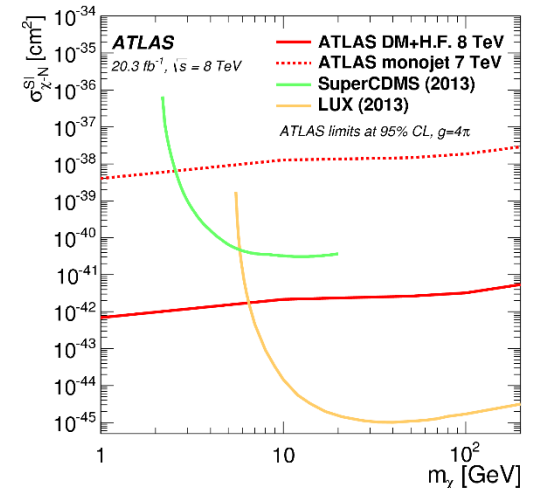
CMS-PAS-B2G-13-004 (Di-top)

Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$



ATLAS, Eur. Phys. J. C (2015) 75:92

Background source	SR1	SR2	SR3	SR4
$Z(\nu\bar{\nu})$ +jets	190 ± 26	90 ± 25	1_{-1}^{+6}	-
$W(\ell\nu)$ +jets	133 ± 23	75 ± 13		1.3 ± 0.3
$t\bar{t}$			87 ± 11	3 ± 1
Single top	39 ± 5	71 ± 9	8 ± 3	0.7 ± 0.3
$t\bar{t} + Z/W$	-	-	-	1.4 ± 0.4
Diboson	22 ± 4	8 ± 1	-	0.8 ± 0.4
Total expected background	385 ± 35	245 ± 30	96 ± 13	7 ± 1
Data	440	264	107	10
Expected signal - D1	10 ± 2	49 ± 8	28 ± 2	35 ± 5 antomx
Expected signal - C1	17 ± 2	61 ± 9	45 ± 4	51 ± 12
Expected signal - D9	147 ± 25	69 ± 12	2 ± 1	2 ± 1
Expected signal - b-FDM	192 ± 24	61 ± 8	1.0 ± 0.2	-
p-Value	0.09	0.29	0.24	0.18
Allowed non SM events - Obs.	124	79	41	10
Allowed non SM events - Exp.	81	67	33	7



Mono-Higgs searches

ATLAS, arXiv:1506.01081

$pT_\gamma > 0.35(0.25)m_{\gamma\gamma}$
 $105\text{GeV} < m_{\gamma\gamma} < 160\text{GeV}$
 $E_{T\text{miss}} > 90\text{GeV}$
 $pT_{\gamma\gamma} > 90\text{GeV}$

