

Searches for Dark Matter with CMS at 13 TeV

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Lake Louise Winter Institute



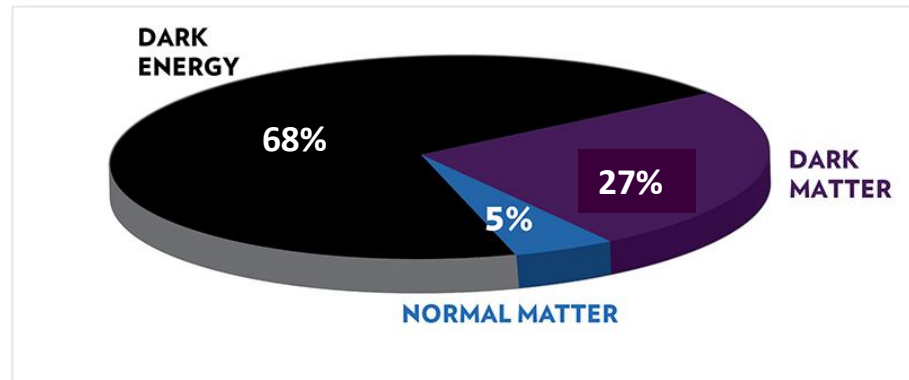
Dark Matter Searches

Dark Matter (DM) could be produced at the LHC, directly or through decays (LSP in SUSY cascades, Higgs portal).

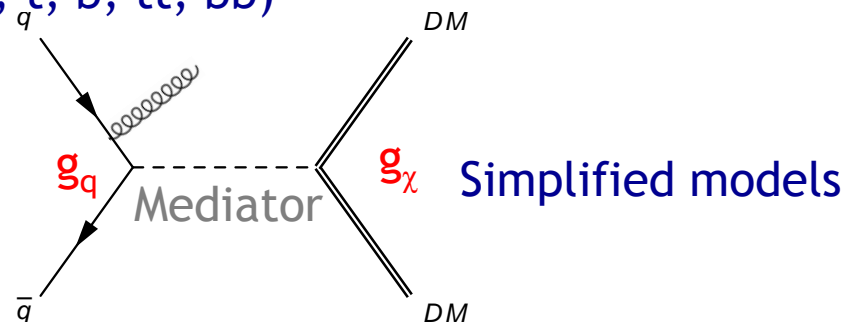
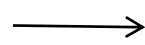
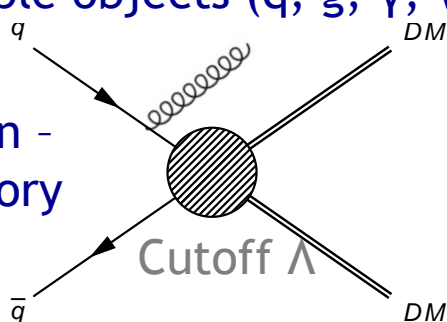
Collider searches:

- complementary to direct and indirect searches
- best for low DM masses and spin-dependent couplings

Direct production: only detectable as missing transverse momentum in association with additional, visible objects ($q, g, \gamma, W, Z, h, t, b, t\bar{t}, b\bar{b}$)



Contact interaction - effective field theory



Simplified models less model-dependent than UV-complete models (SUSY etc.)

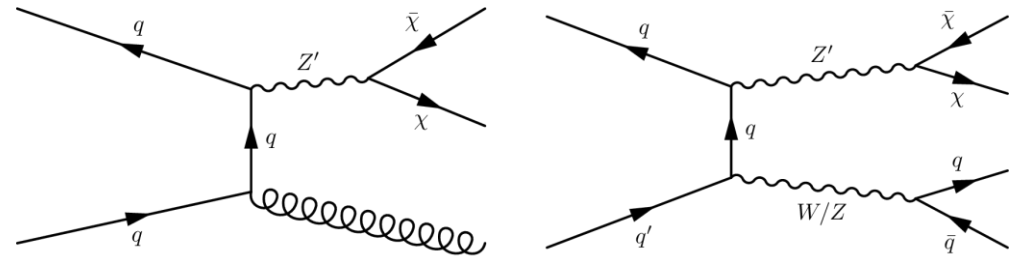
DM parameters: DM and mediator masses, couplings, type of mediator (scalar, pseudoscalar, vector, axial-vector, tensor).

e.g. ATLAS/CMS DM Forum, arXiv 1603.04156 (2016)



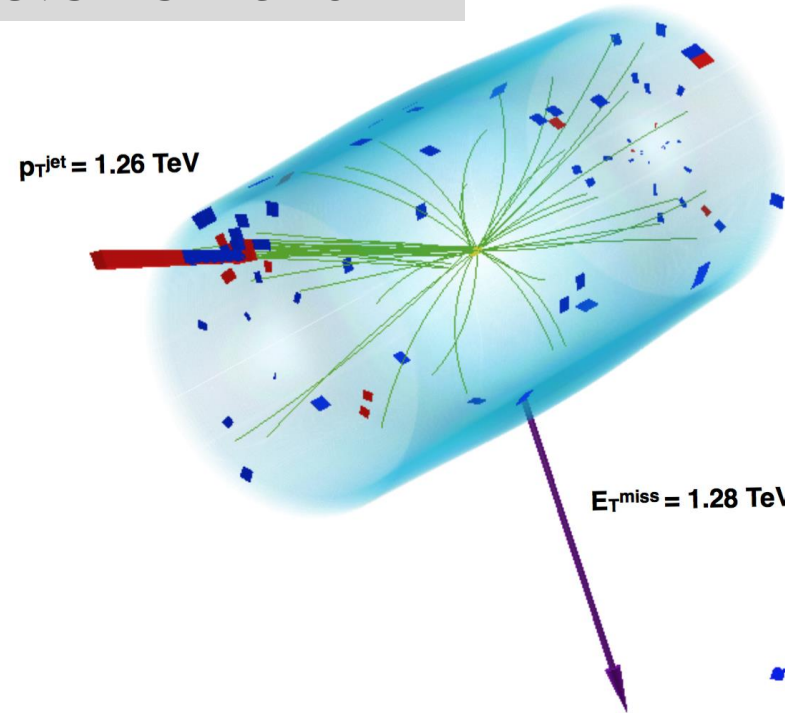
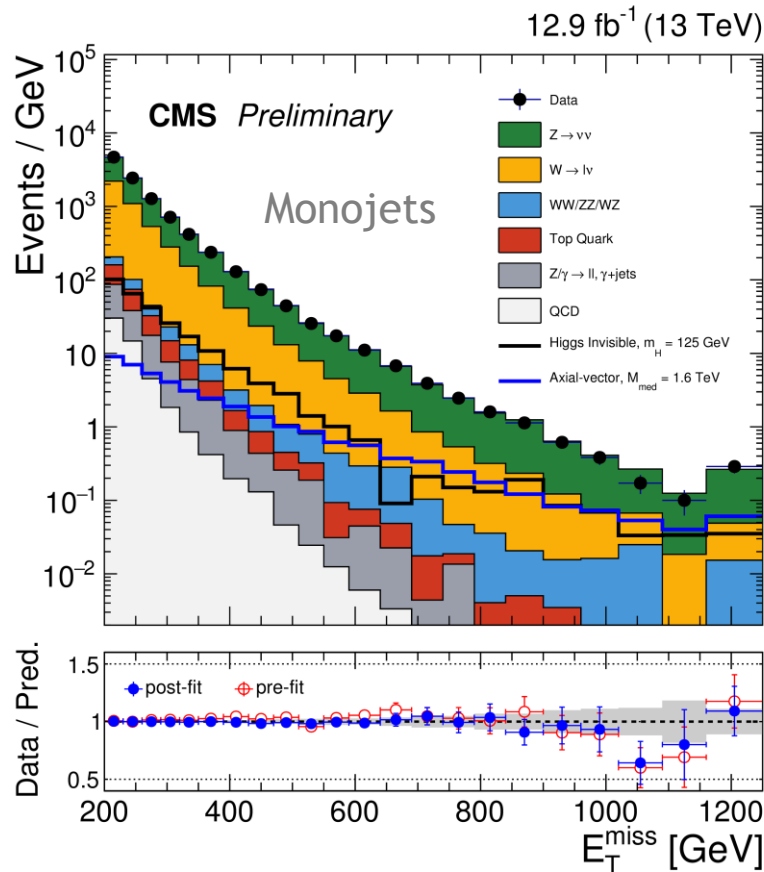
Monojets and hadronically decaying mono-V

Backgrounds:
 $Z(\nu\nu)+\text{jets}$ (irreducible) dominates
 $W(\ell\nu)+\text{jets}$: lepton veto
 $t\bar{t}$: b-jet veto
 QCD multijets: angular cuts



Examples: spin-1 mediator (V, AV)

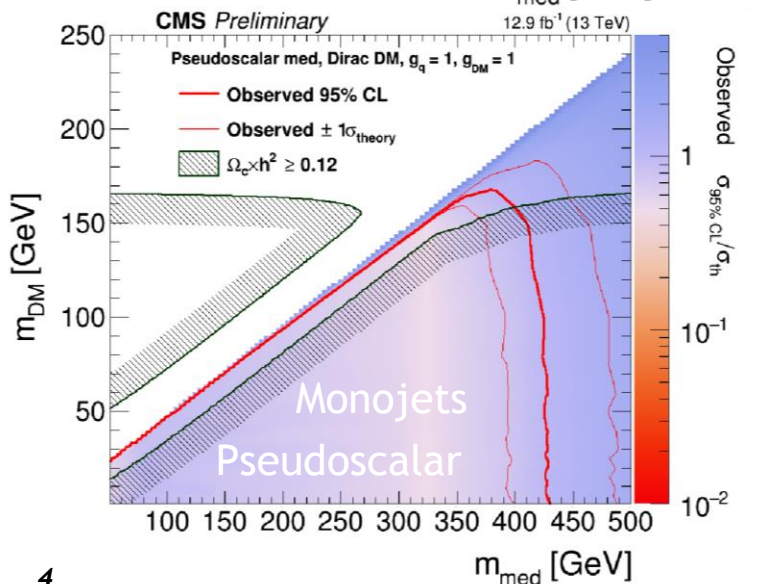
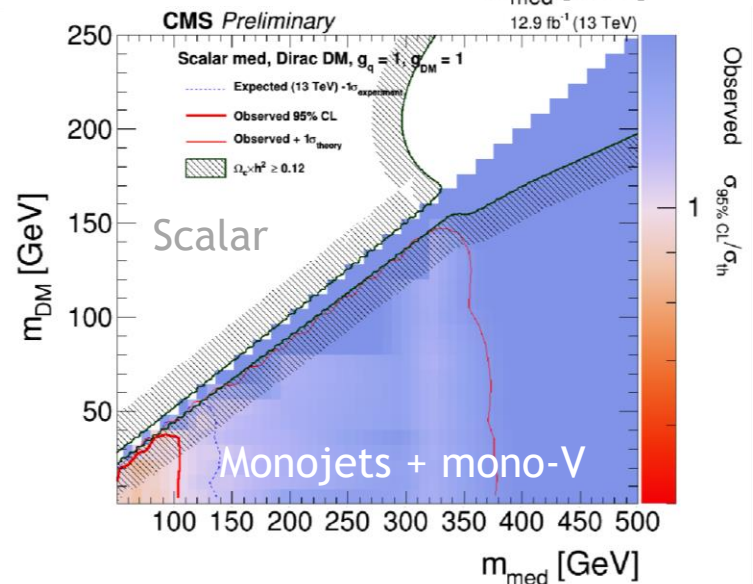
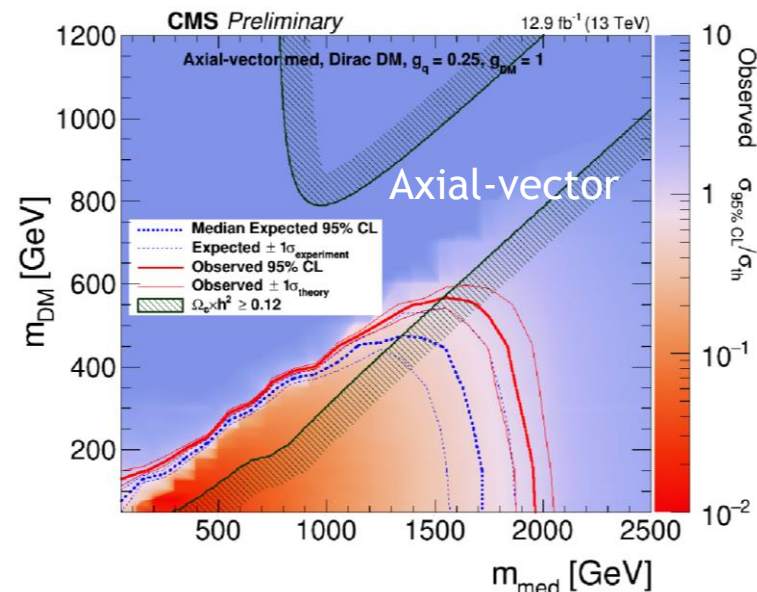
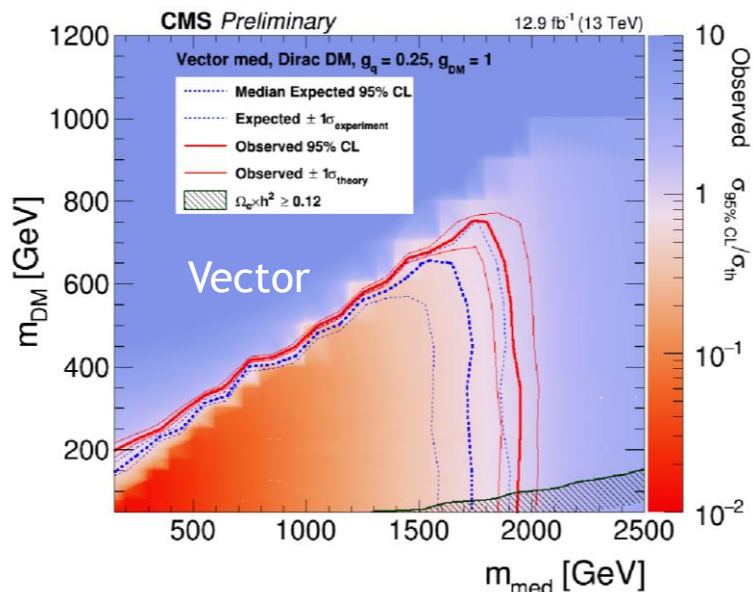
CMS-PAS-EXO-16-037





Monojets and hadronically decaying mono-V

Interpretation in terms of simplified model ($g_{DM} = 1$)



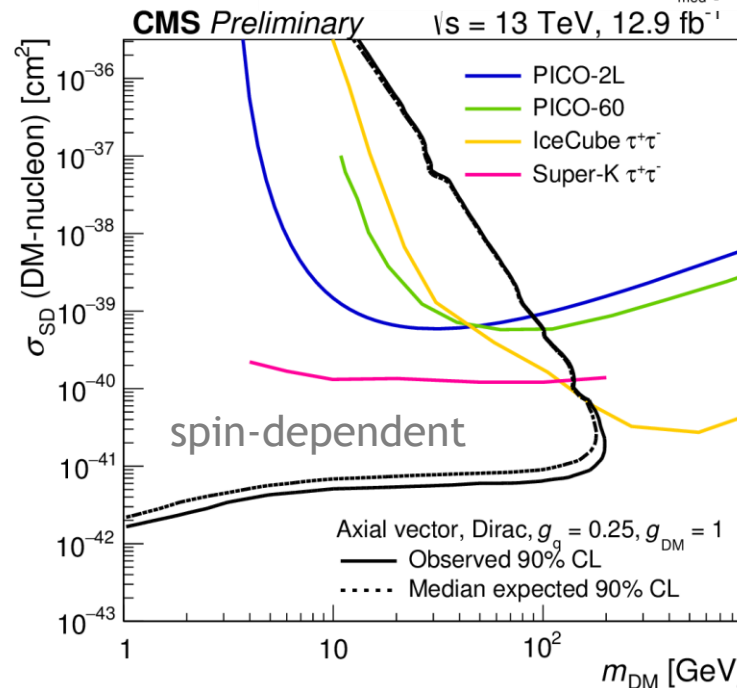
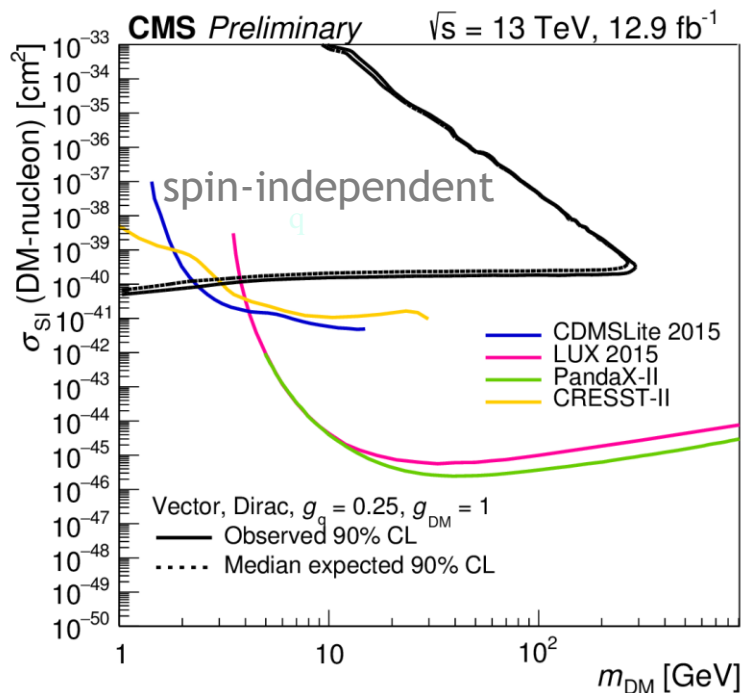
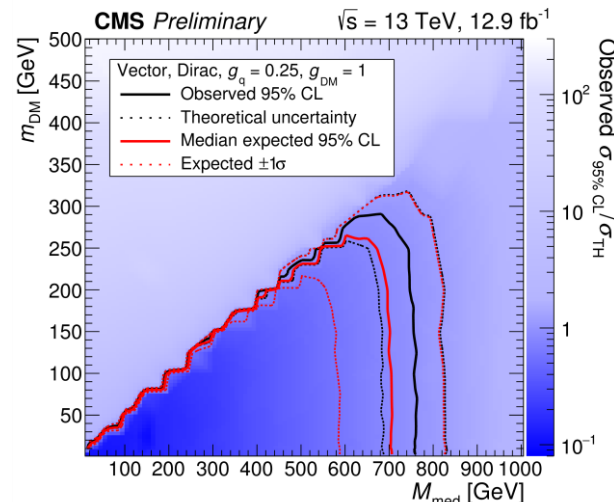
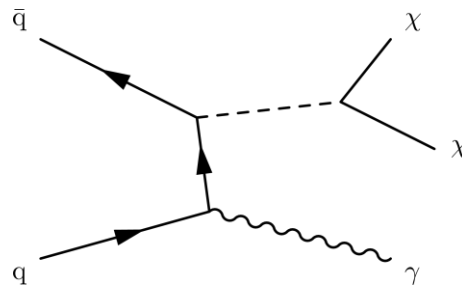


Monophotons

Cleaner than monojet channel, but less sensitive

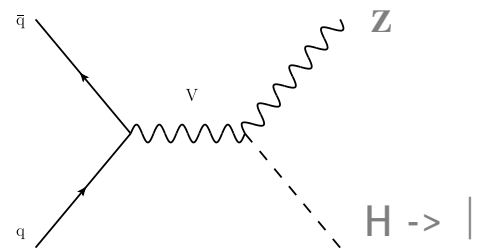
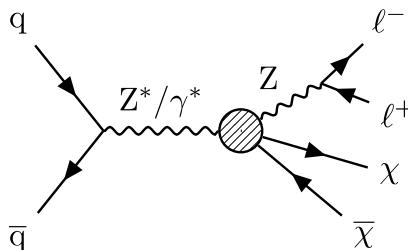
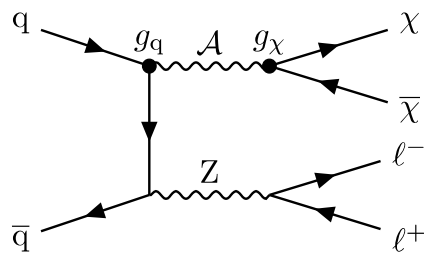
CMS-PAS-EXO-16-039

Event selection:
 single γ with $E_T > 175$ GeV and $|\eta| \leq 1.44$
 $E_{T,miss} > 170$ GeV



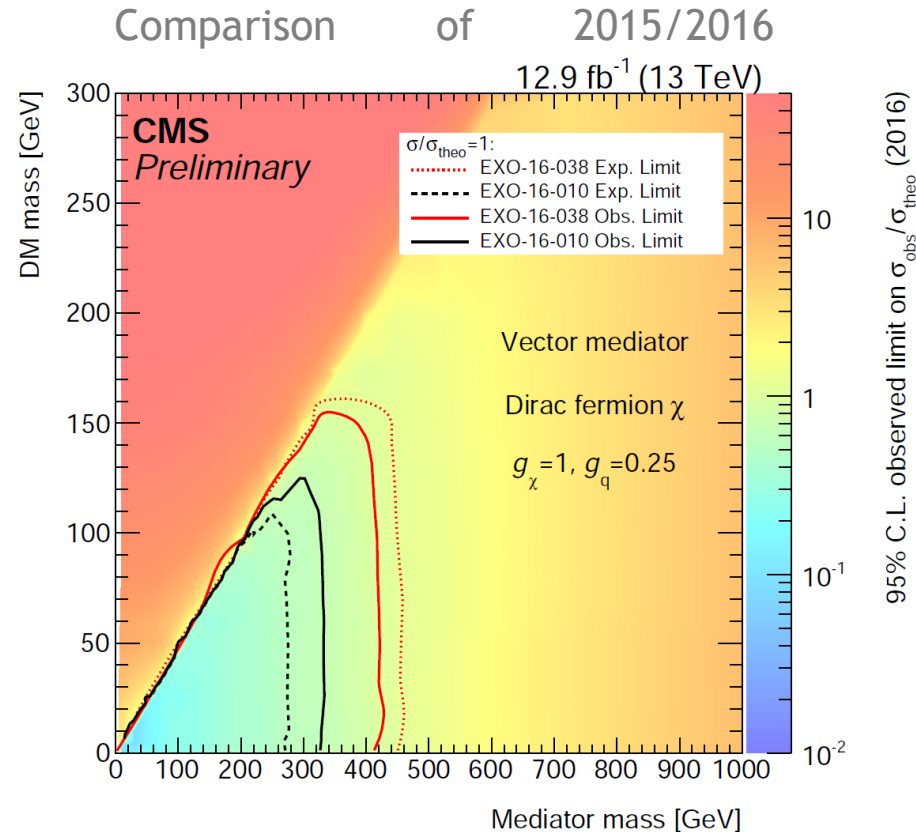
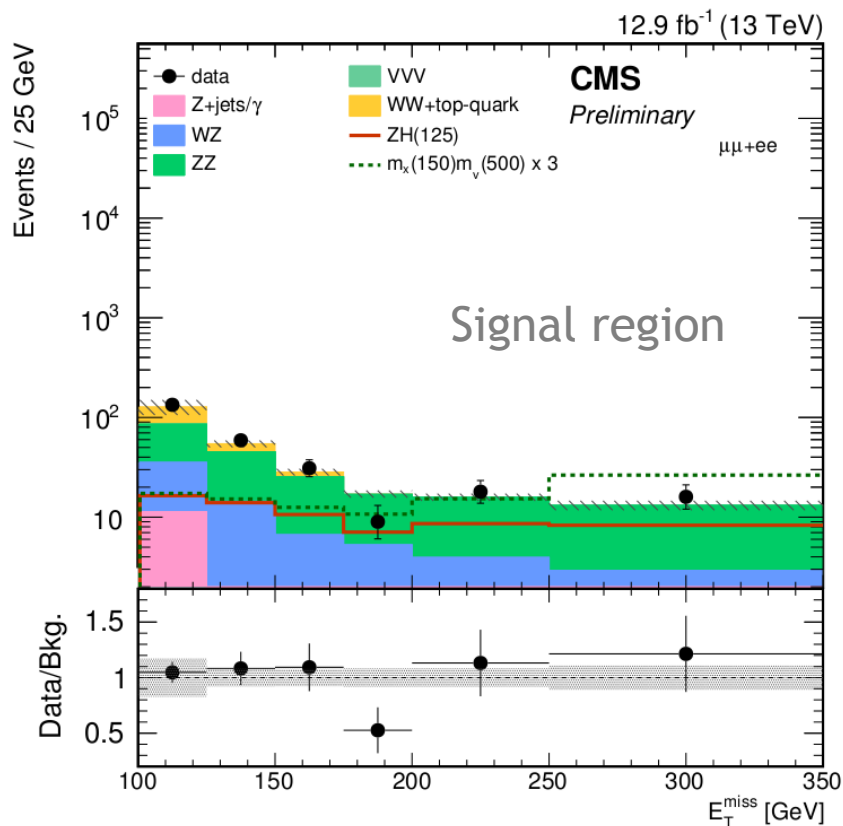


Mono-Z decaying to leptons (electrons, muons)



CMS-PAS-EXO-16-038, 16-010

Observed B(H->invisible): < 0.86

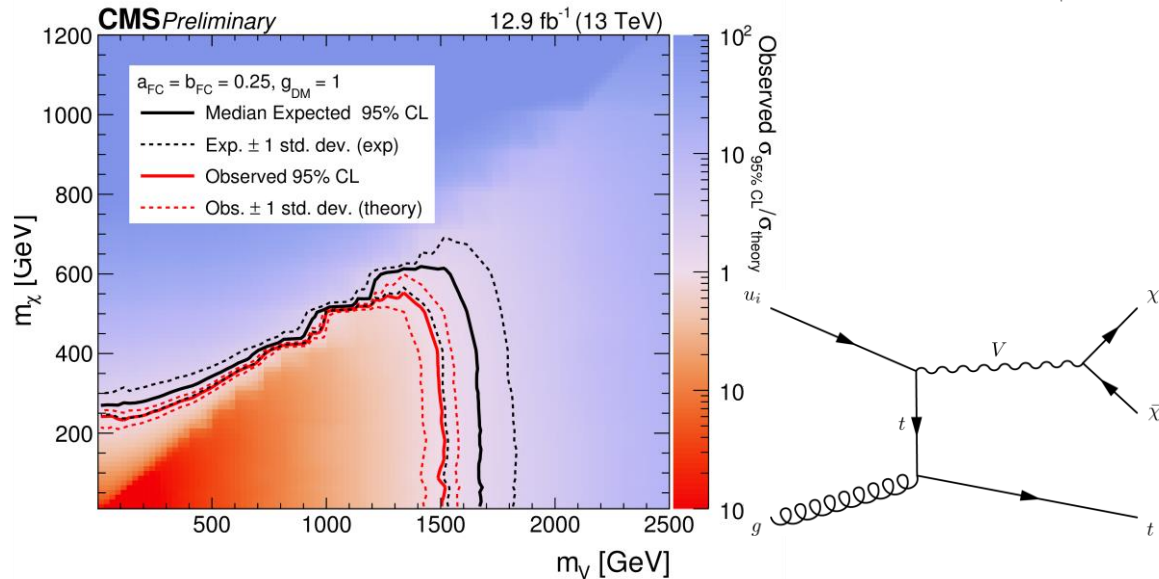
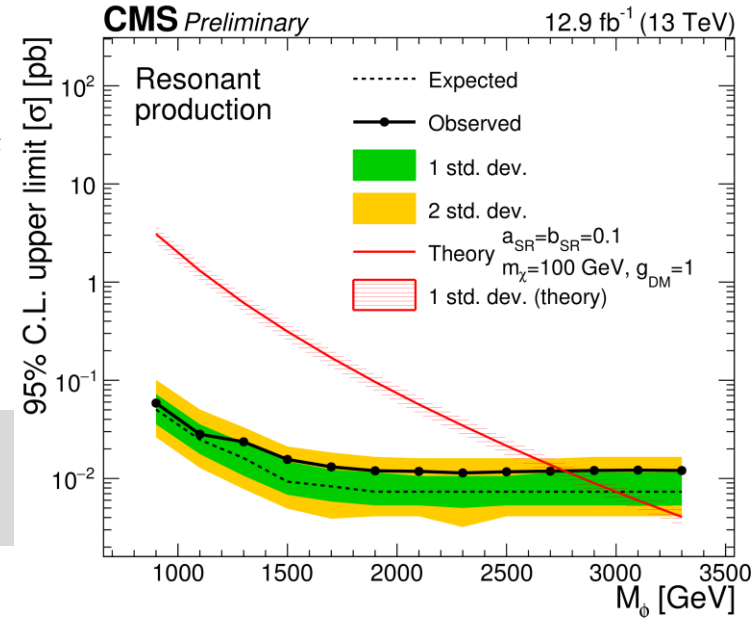
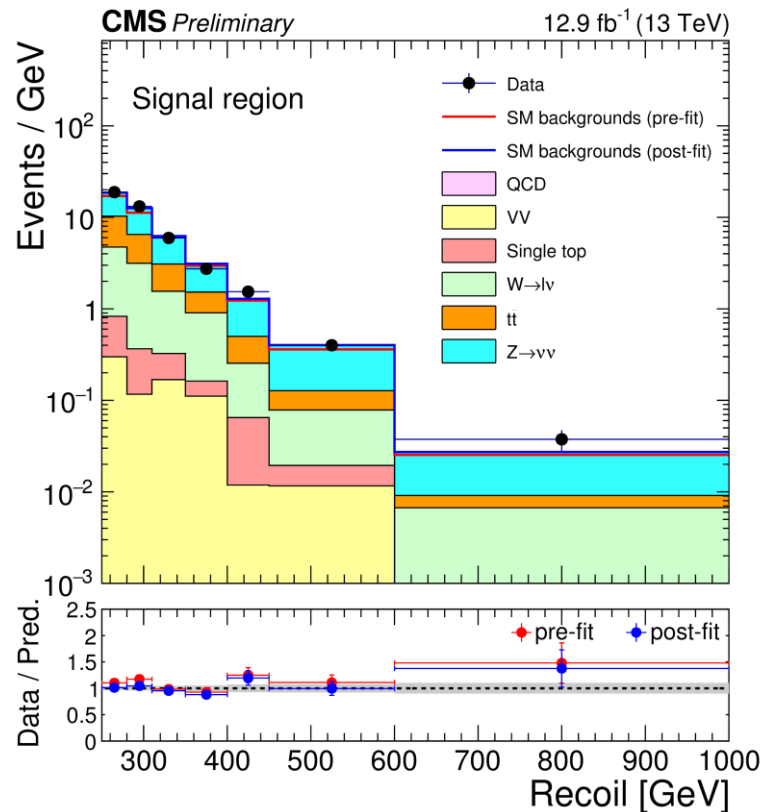
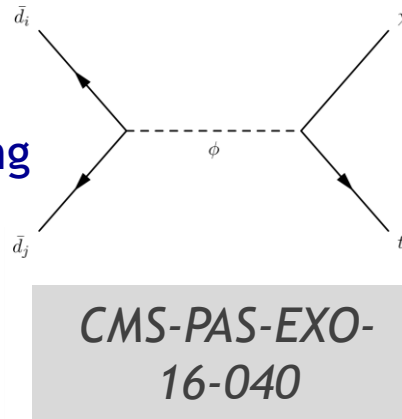




Boosted hadronically decaying monotops

Events with hadronically decaying W from t selected.
 $q-\chi$ couplings in scalar interactions could be enhanced for heavy flavors.

DM signal searched by fitting E_T^{miss} distribution in signal region, assuming background-only hypothesis

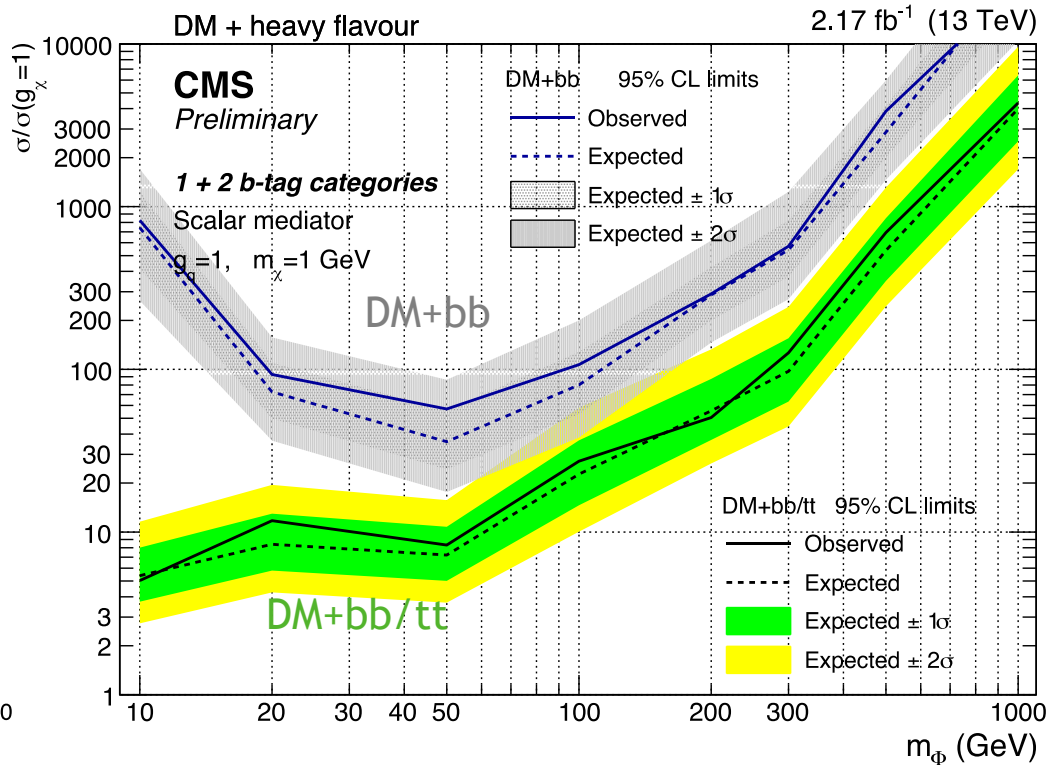
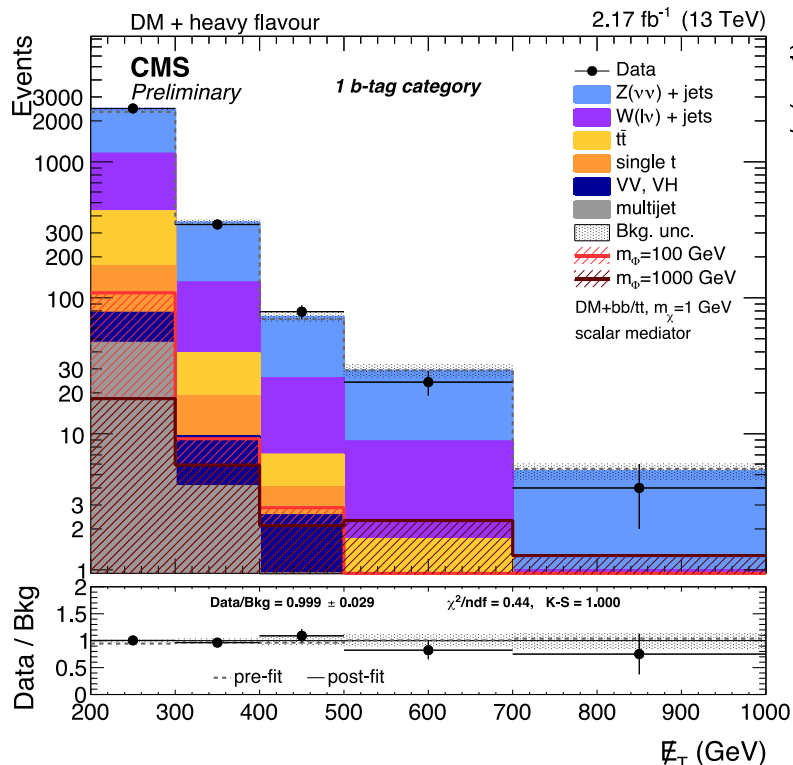
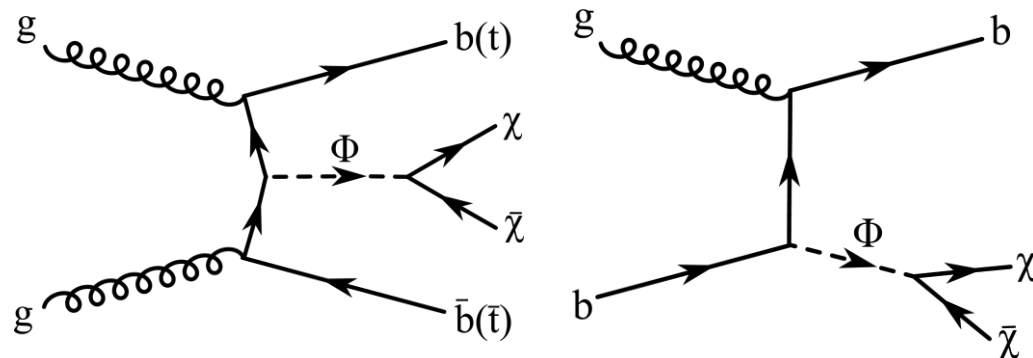




Dark Matter in association with b quarks

Signature: b (1 or 2) + E_T^{miss}
 This analysis is sensitive also to DM production processes in association with t quarks, which decay to b 's.

CMS-PAS-B2G-15-007



Mediator-DM couplings down to $5 \times \sigma/\sigma(g_{\text{DM}}=1)$ for a scalar mediator are excluded.



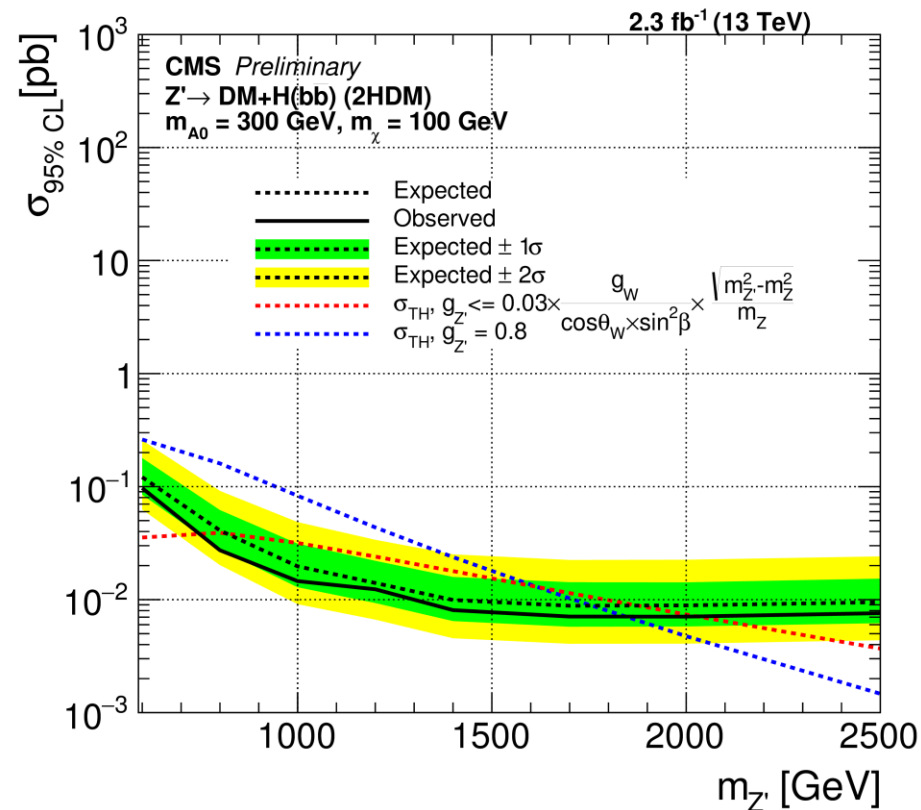
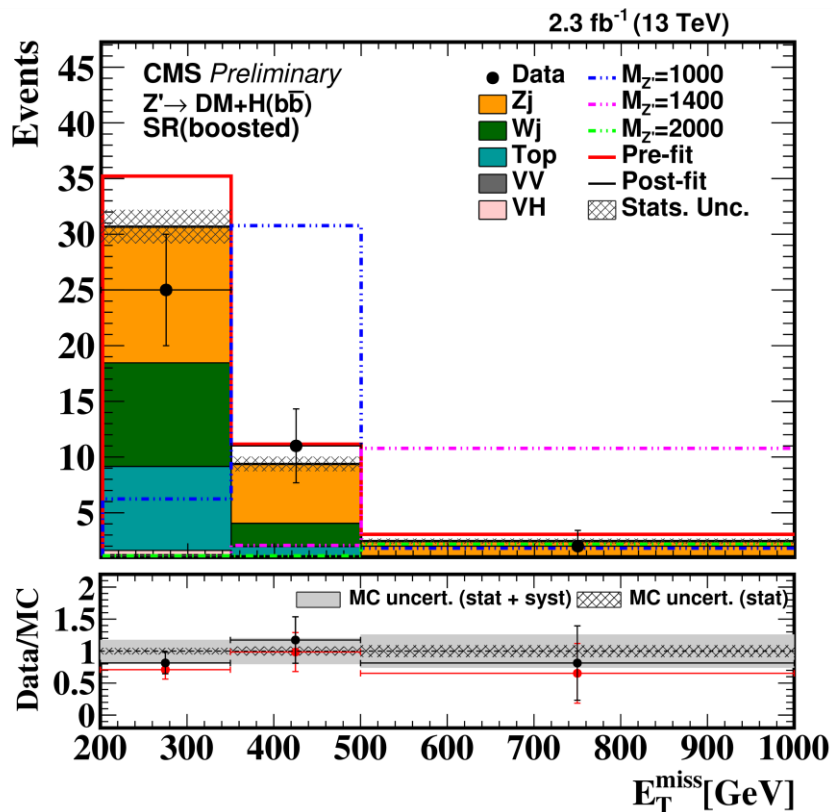
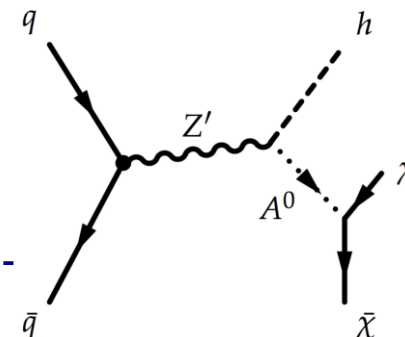
Dark Matter in association with $H \rightarrow b\bar{b}$

CMS-PAS-EXO-16-012

2H-doublet-model with invisibly decaying pseudoscalar A^0

doi:10.1007/JHEP06(2014)078

Event selection dependent on p_T : H reconstructed from 2 small- or 1 large-radius jet - resolved and boosted topologies.



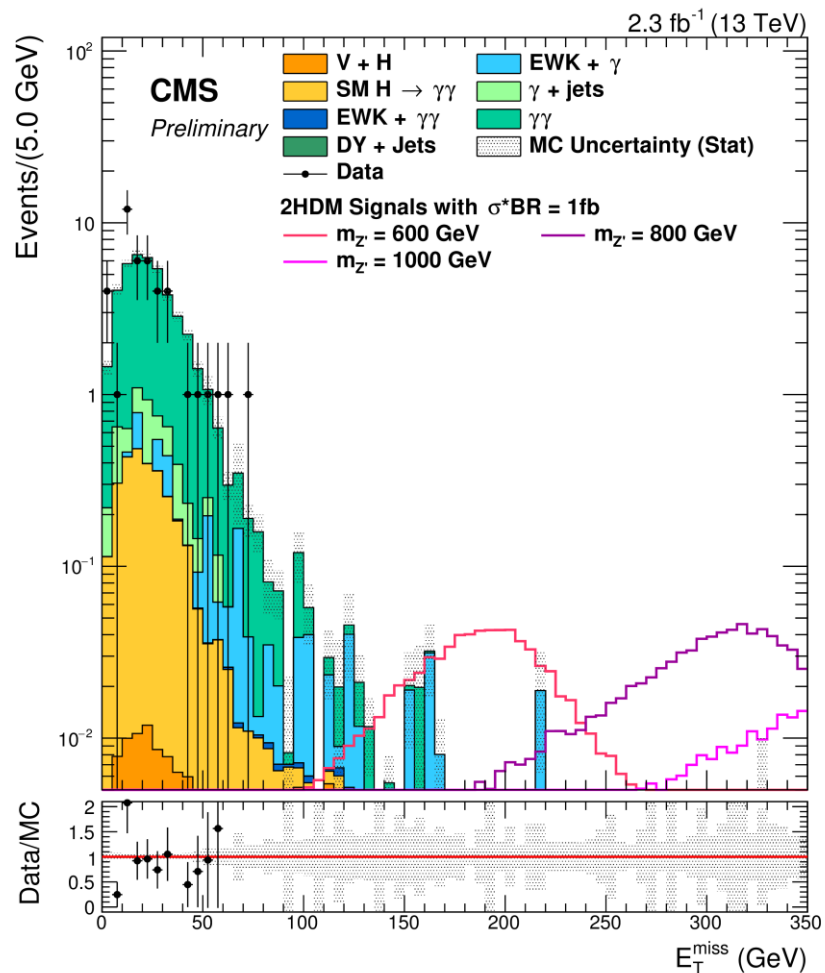


Dark Matter in association with $H \rightarrow \gamma\gamma$

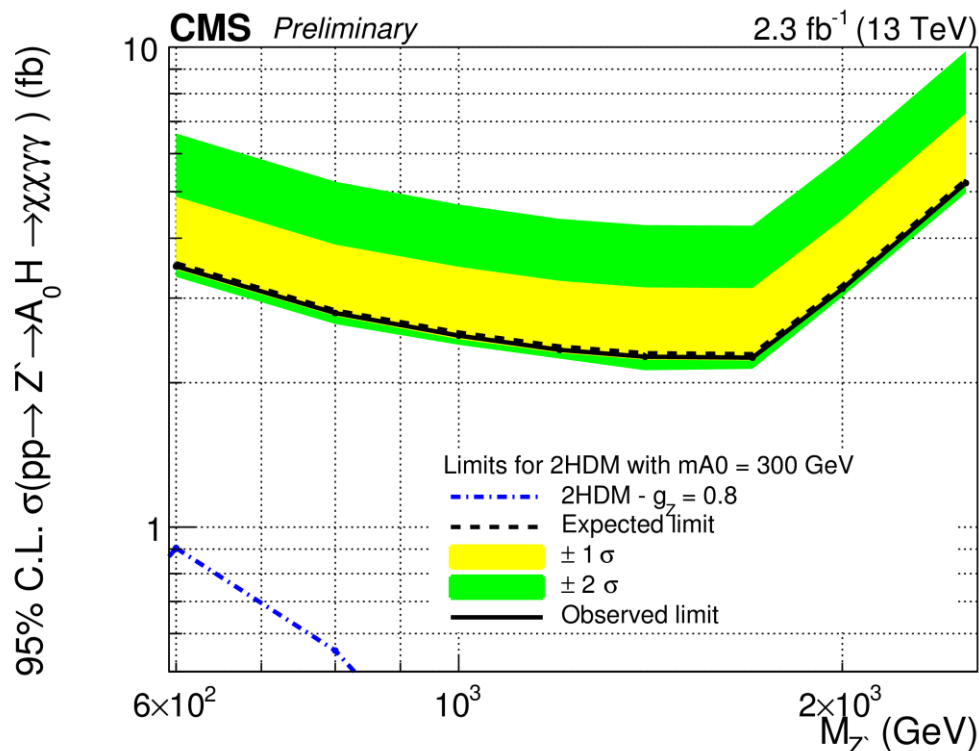
Same 2-HDM as for $H \rightarrow b\bar{b}$.

Event selection:

2 photon candidates with kinematic requirements on $p_T/m_{\gamma\gamma}$, $m_{\gamma\gamma}$, E_T^{miss}

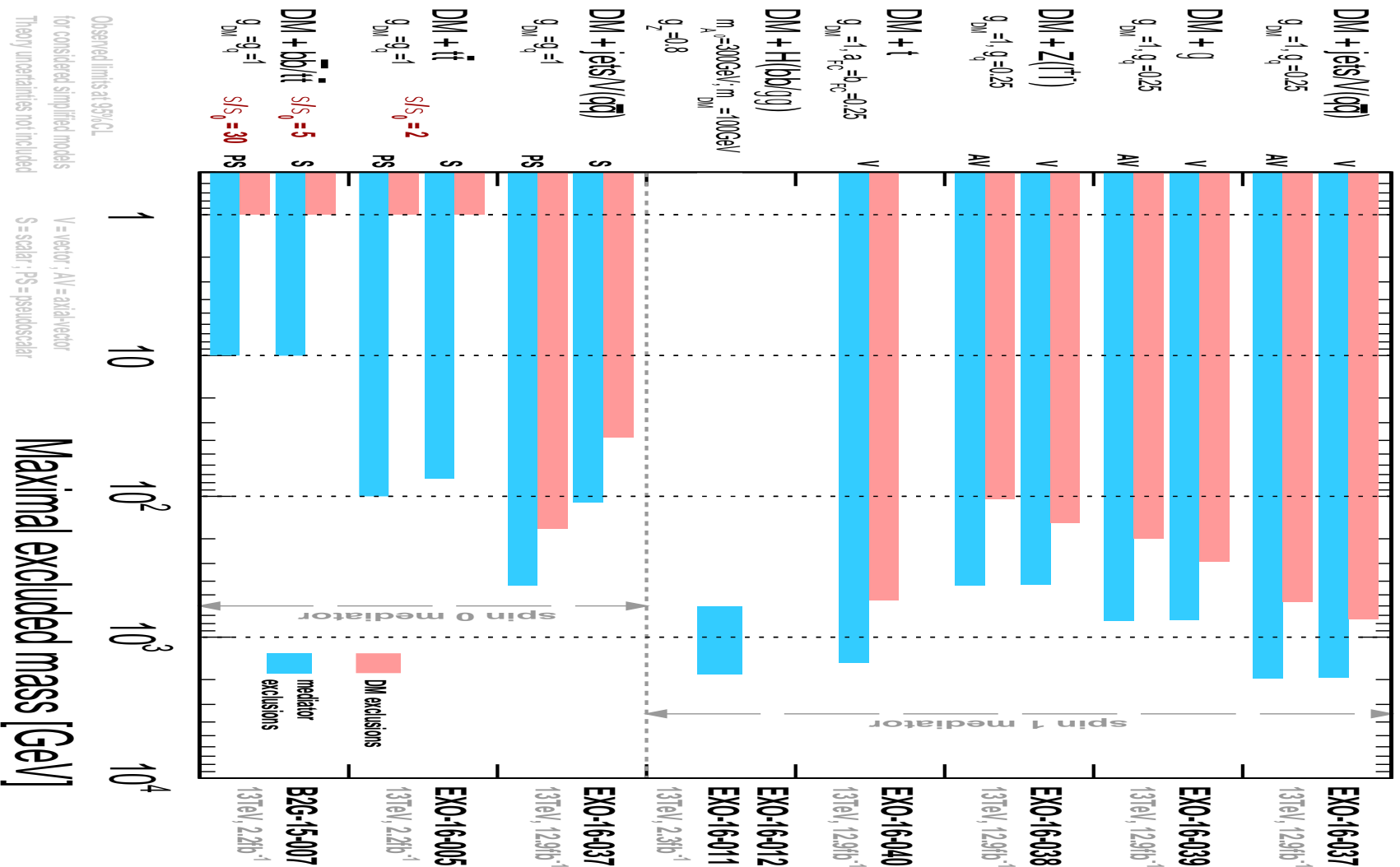


CMS-PAS-EXO-16-011





Dark Matter Mass Limits





Conclusions

- CMS has recently studied dark matter signatures with $\sqrt{s} = 13$ TeV data and has derived limits as no excesses have been found.
- Simplified models are replacing EFT approach for Run 2 searches.
- If WIMP dark matter is not confirmed soon other scenarios such as SIMP dark matter might also be studied.
- In any case, we have to be open to all kinds of dark matter searches (WIMP, SIMP, axions, ...) across different types of experiments - colliders, direct detection, indirect detection, and specialized experiments.
- Lots of data are still to come before the next LHC shutdown, so stay tuned!



BACKUP



Dark Matter Bibliography

- **Monojets:** EXO-16-037, EXO-15-003 ($\sqrt{s} = 13$ TeV), EXO-12-048 ($\sqrt{s} = 8$ TeV)
- **Dijets:** EXO-16-013?, EXO-16-032, EXO-14-004 (8 TeV, razor)
- **Monophotons:** EXO-16-039, EXO-12-047 (8 TeV)
- **Mono-Z:** EXO-16-010, EXO-16-038, EXO-12-054 (8 TeV)
- **Mono-W:** EXO-16-013, EXO-16-037, EXO-12-060 (8 TeV)
- **MET + top:** EXO-16-017, EXO-16-040, B2G-14-004, B2G-13-004, B2G-12-022 (8 TeV)
- **MET + tt:** EXO-16-005, EXO-16-028
- **MET + Higgs:** EXO-16-011, EXO-16-012
- **Associated b quarks:** B2G-15-007 (13 TeV)

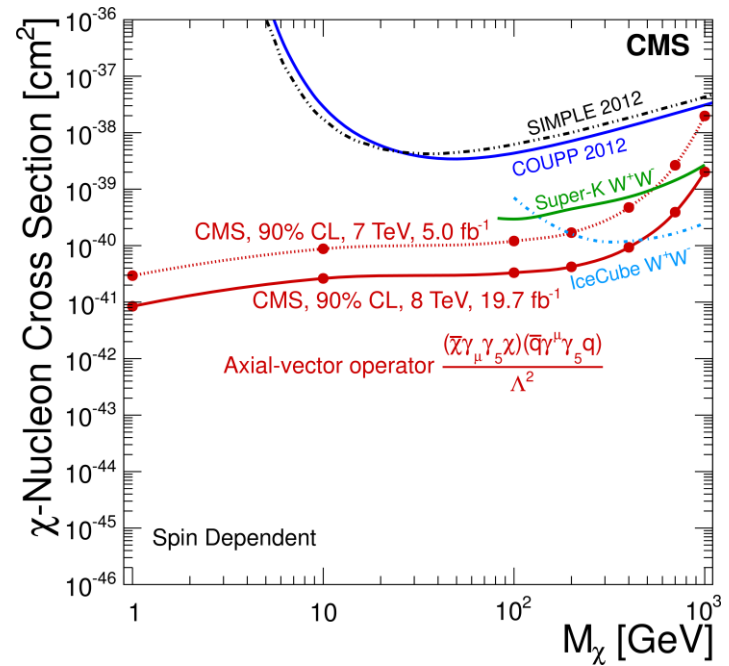
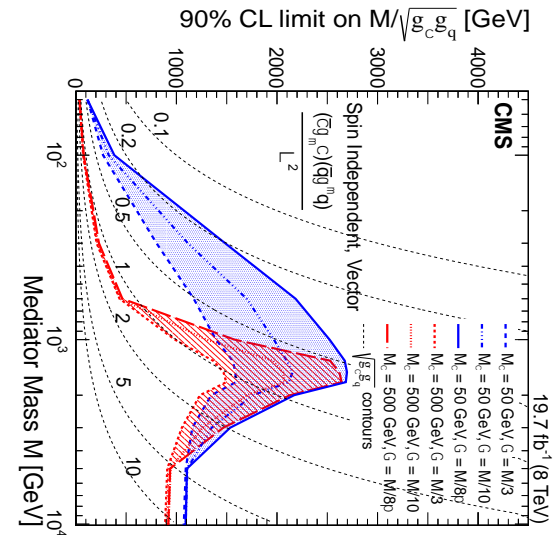
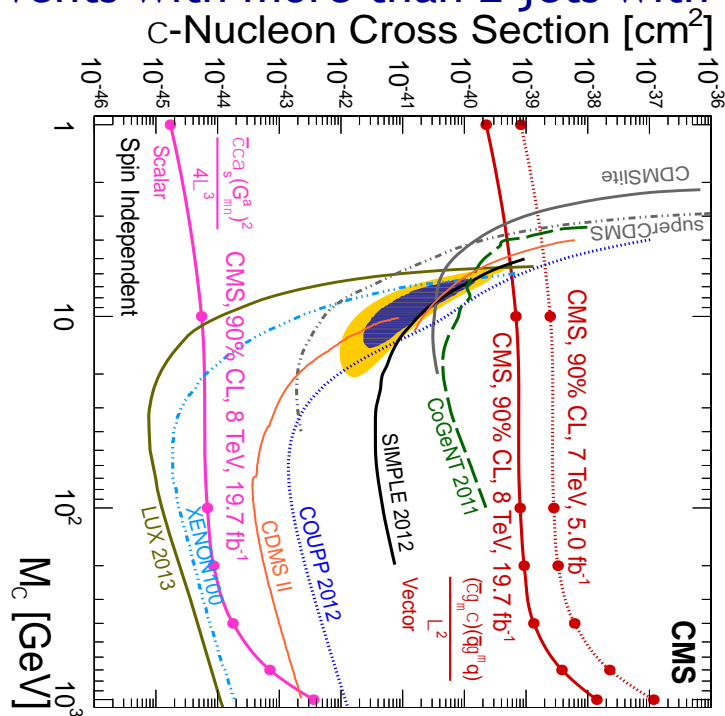
<http://cms-results.web.cern.ch/cms-results/public-results/publications>



Dark Matter Searches - Monojets

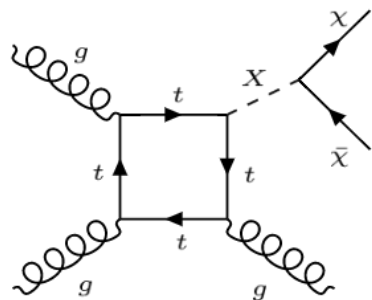
CMS-EXO-12-048, EPJC 75 (2015) 235

Data sample:
 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, 5.0 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$
 Background:
 $Z(\nu\nu)$ estimated from $Z(\mu\mu)$ control sample,
 $t\bar{t}$ and QCD multijets removed by excluding
 events with more than 2 jets with $p_T > 30 \text{ GeV}$

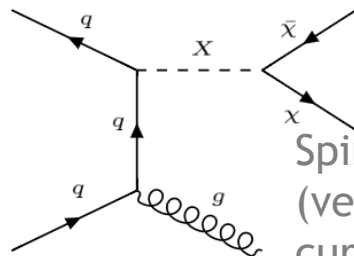




Dark Matter Searches - Monojets



Spin-0 mediator X (scalar or pseudoscalar current)

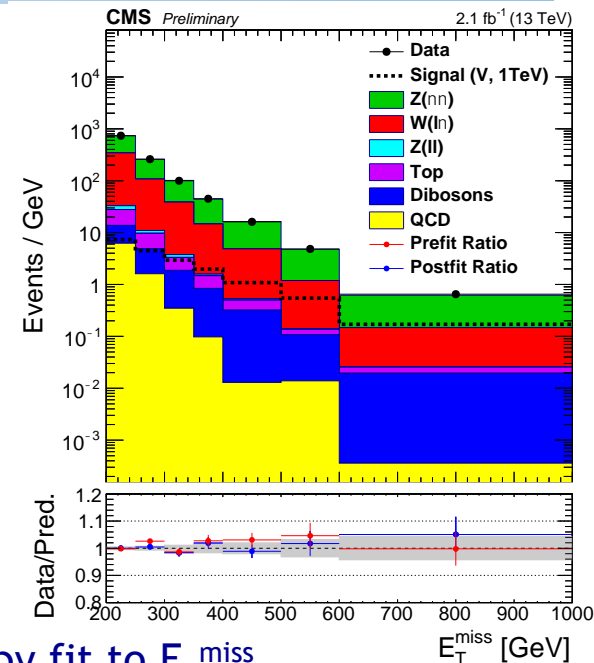


Spin-1 mediator X
(vector or axial-vector current)

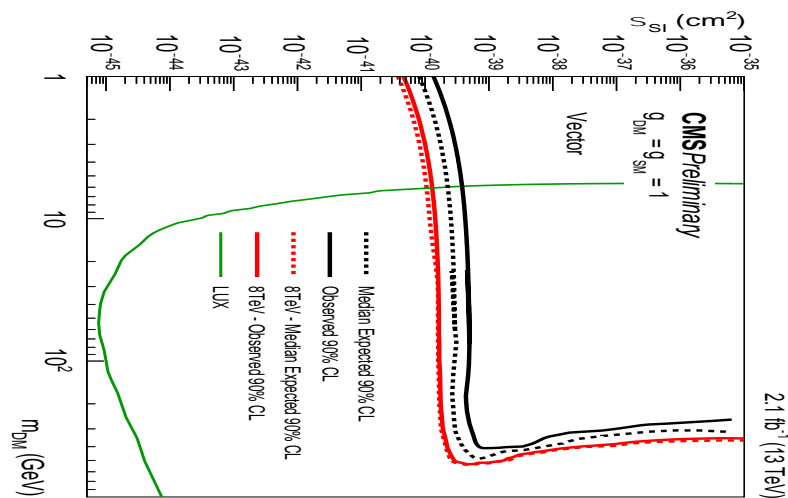
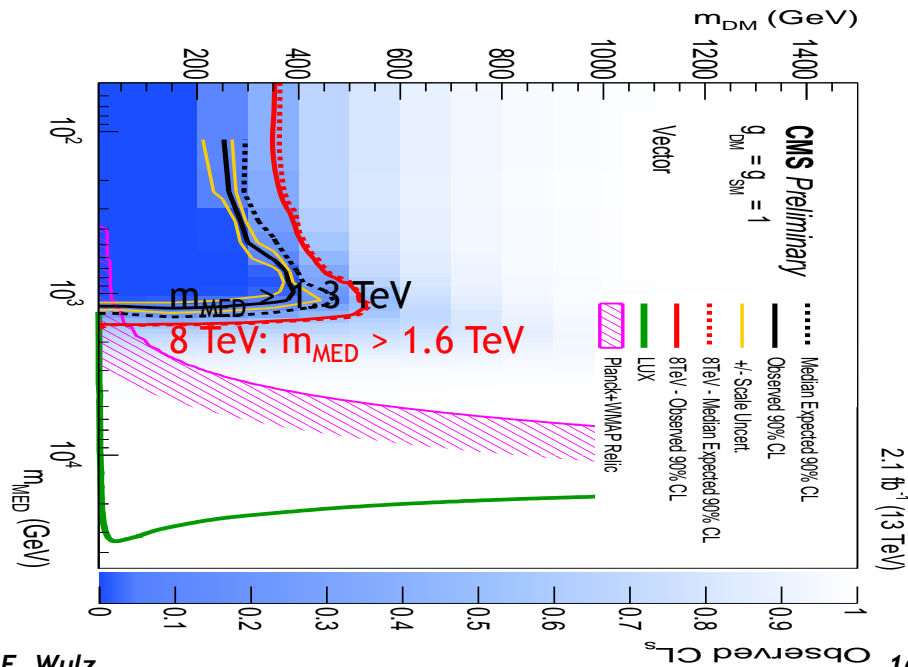
CMS-EXO-15-003

Event selection: ≥ 1 jets with $E_T > 100$ GeV, $E_T^{\text{miss}} > 200$ GeV

Data sample: 2.1 fb^{-1} at $\sqrt{s} = 13$ TeV



DM signal extracted by fit to E_T^{miss}



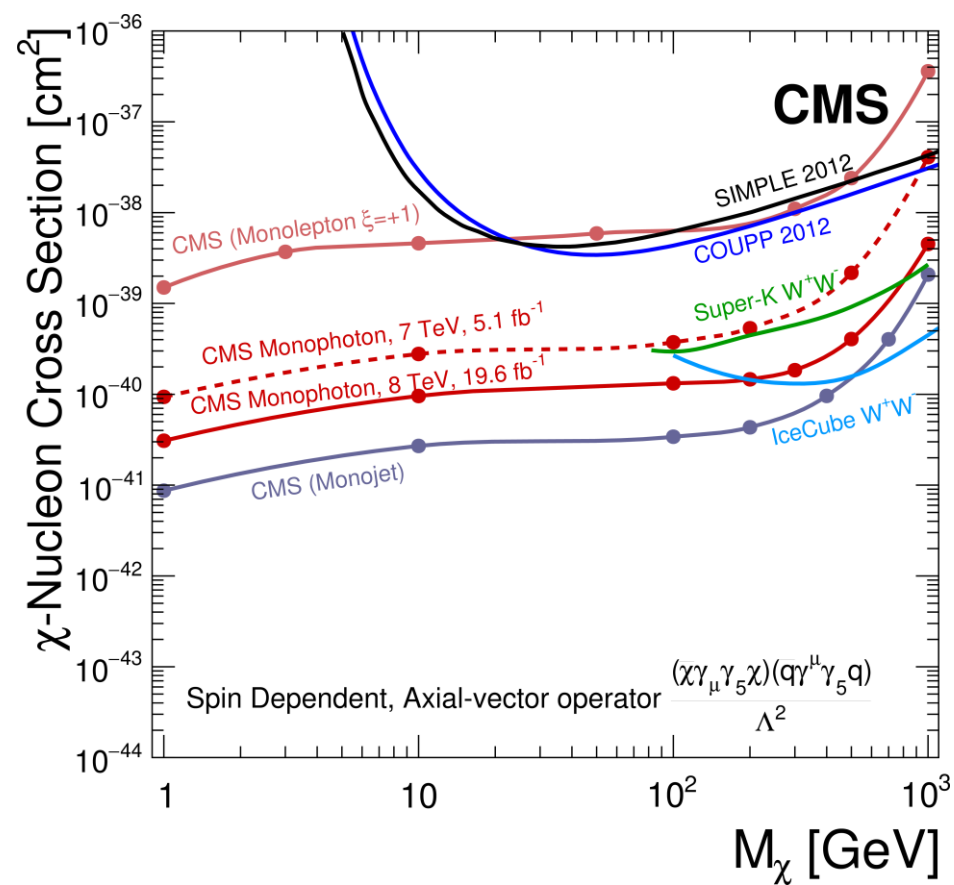
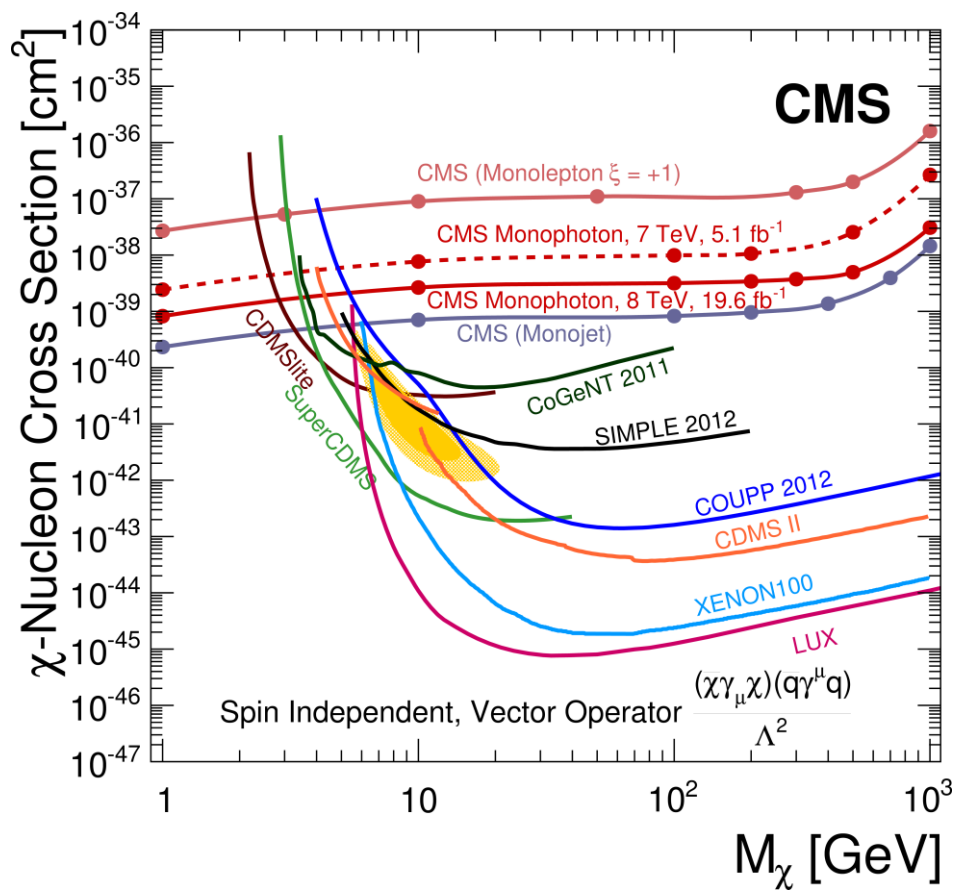


Dark Matter Searches - Monophotons

CMS-EXO-12-047, PLB 755 (2016)102

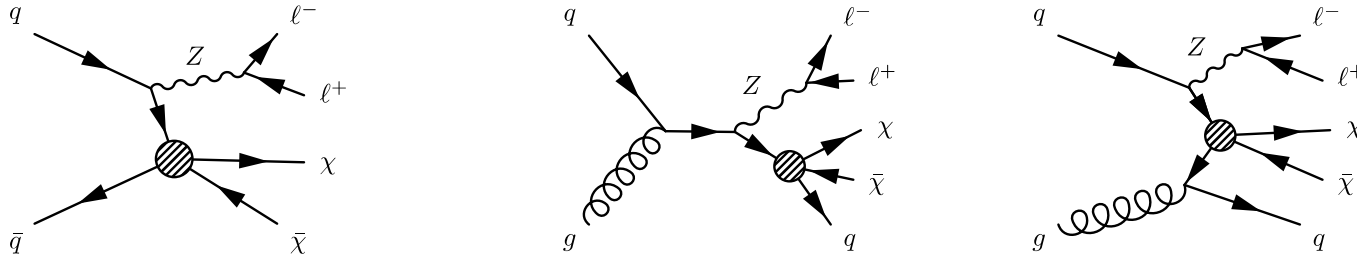
Data sample: 19.6 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, 5.1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$

Event selection: single photon with $E_T > 145 \text{ GeV}$ and $|\eta| \leq 1.44$, $E_T^{\text{miss}} > 140 \text{ GeV}$



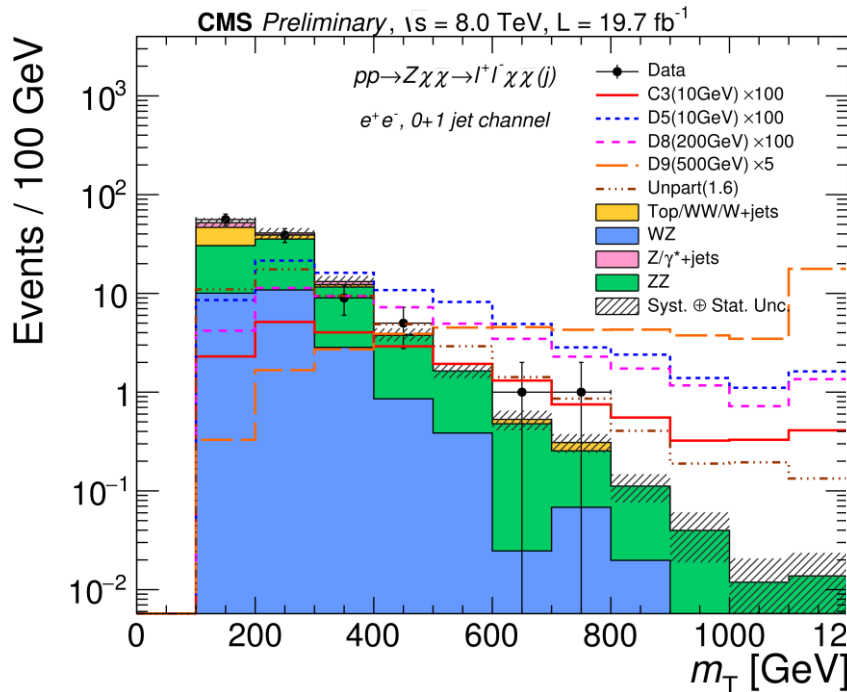


Dark Matter Searches - Mono-Z



Event selection: 2 isolated, opposite-charge e/μ each with $p_T > 20$ GeV and invariant mass compatible with Z, no additional e/μ with $p_T > 20$ GeV, dilepton $p_T > 50$ GeV, no b-tagged jet

CMS-EXO-12-054



Operators for Dirac fermion (D) or complex scalar (C) DM coupling to SM quarks, Λ being the coupling scale of interactions between DM and quarks:

Vector coupling, spin-independent (D5): $\frac{\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q}{\Lambda^2}$

Axial-Vector coupling, spin-dependent (D8): $\frac{\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q}{\Lambda^2}$

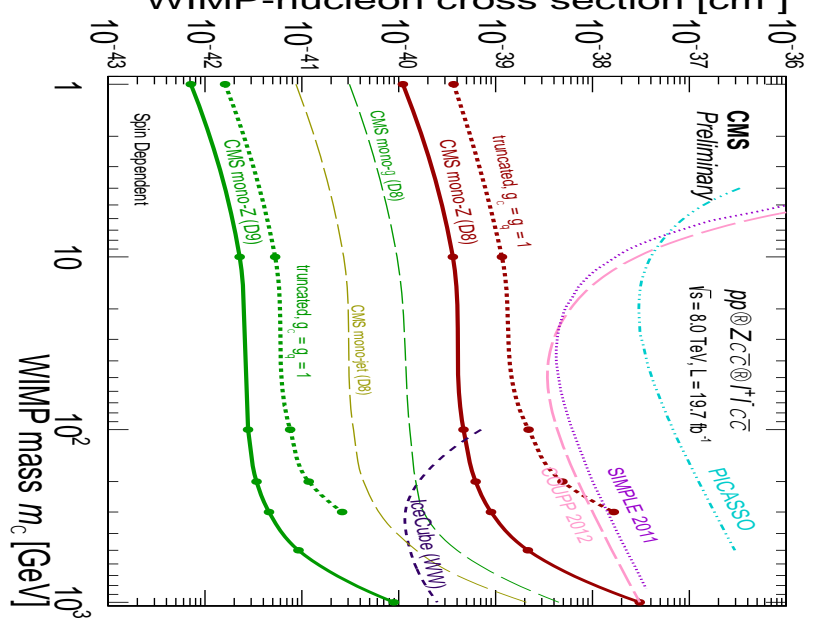
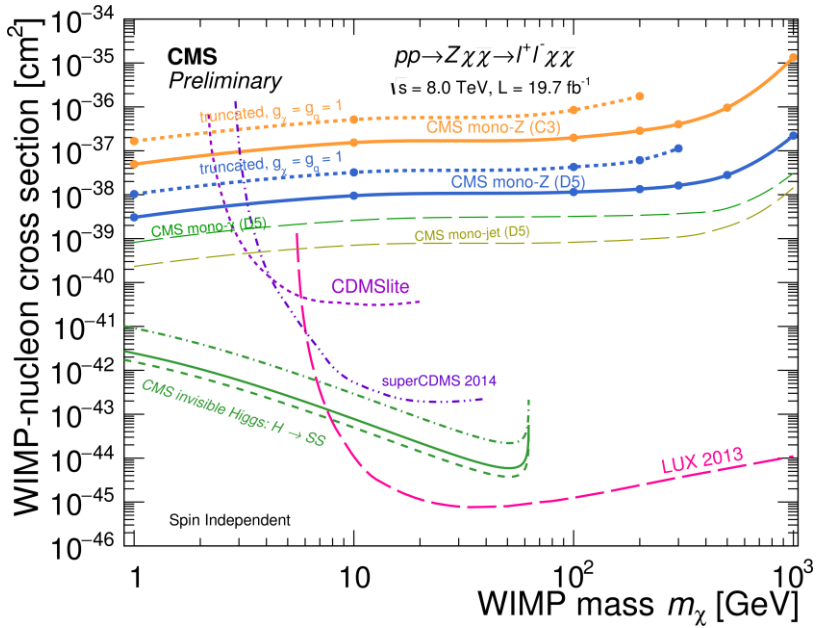
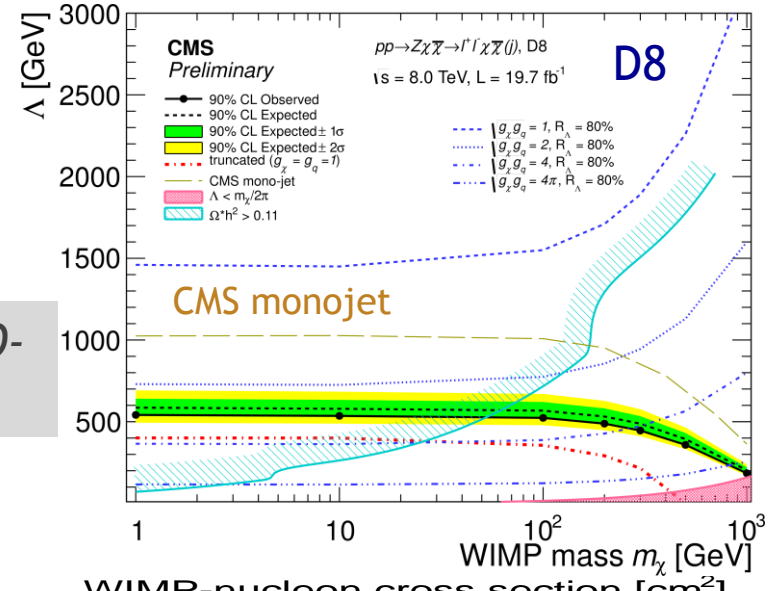
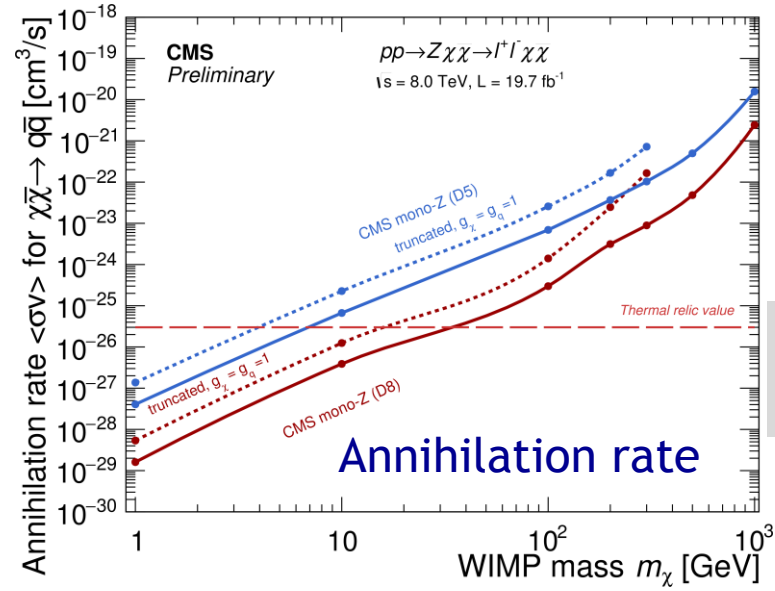
Tensor coupling, spin-dependent (D9): $\frac{\bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q}{\Lambda^2}$

Vector coupling, spin-independent (C3): $\frac{\chi^\dagger \overleftrightarrow{\partial}_\mu \chi \bar{q} \gamma^\mu q}{\Lambda^2}$



Dark Matter Searches - Mono-Z

CMS-EXO-12-054





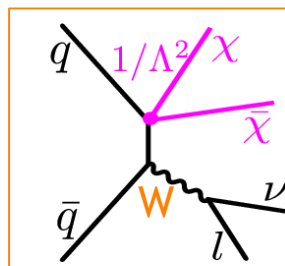
Dark Matter Searches - Mono-W

Dark matter interpretation of W' analysis

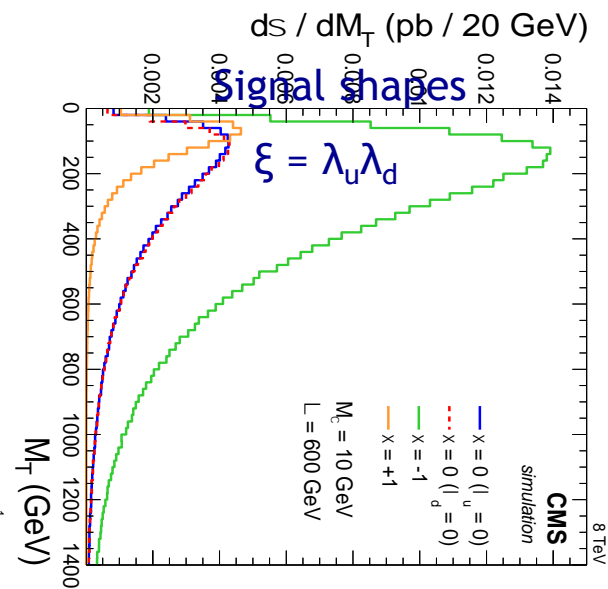
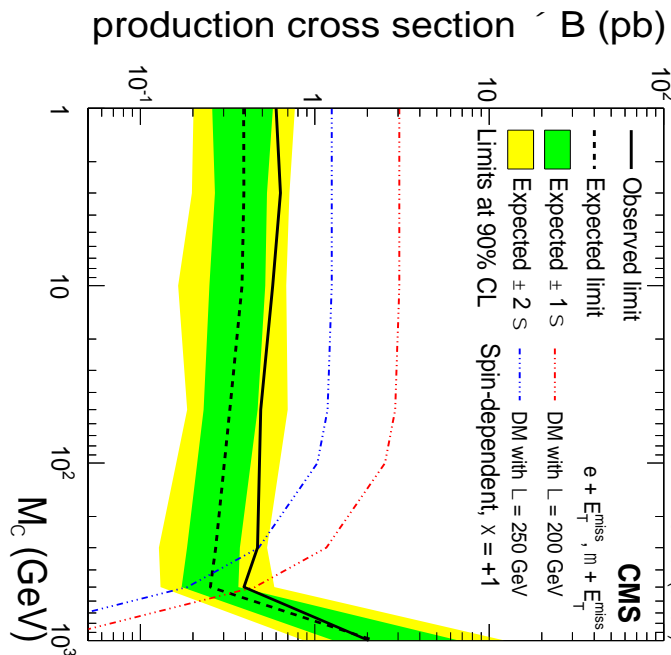
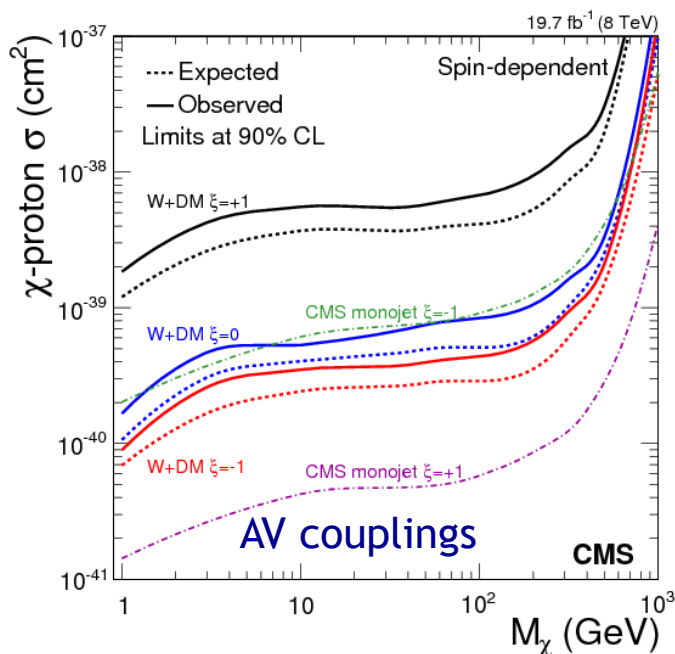
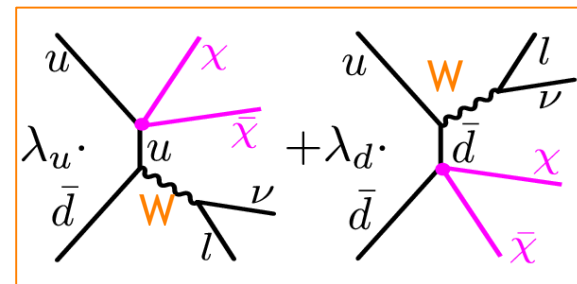
Data sample: 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$

Event selection: prompt or non-prompt (from τ) single e or μ and E_T^{miss}

Advantages over monojet and mono- γ channels: lower SM background and trigger lepton



DM interference

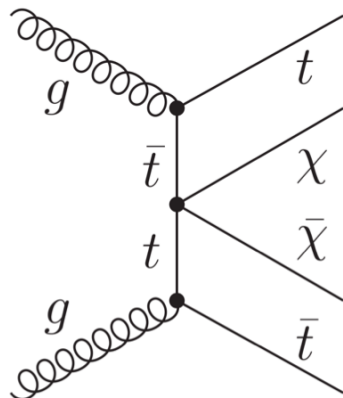


CMS-EXO-12-060, PRD 91 (2015) 092005



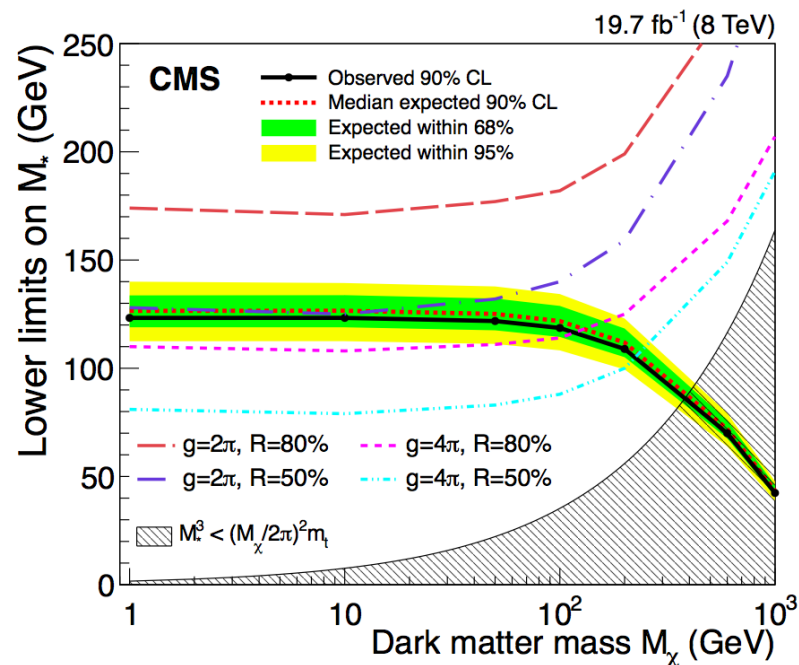
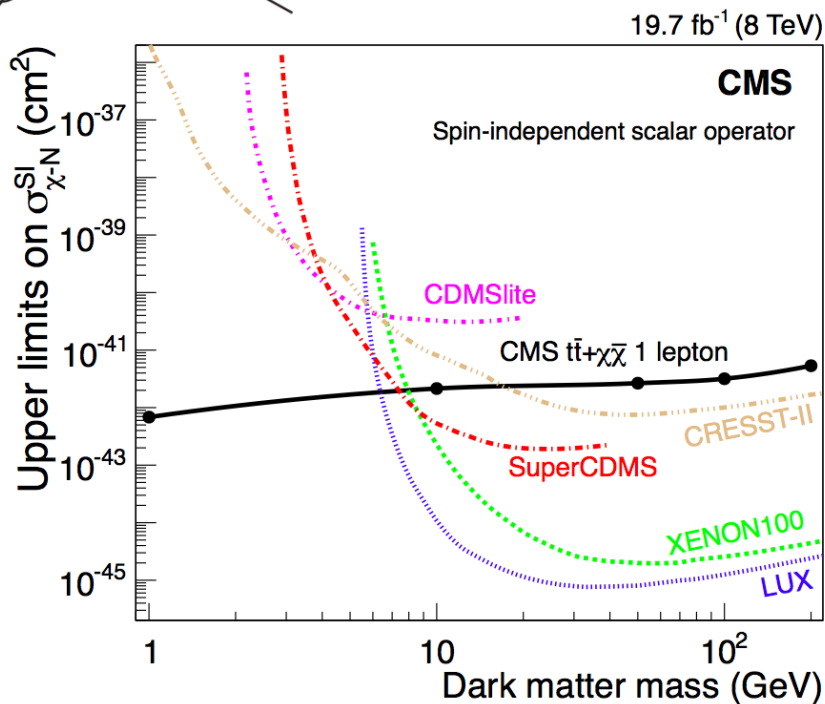
Dark Matter Searches - Top Pairs

q -| couplings for heavy flavors enhanced in scalar interactions



$tt + E_t^{\text{miss}}$ signature:
single lepton with jets, at least 1 b-tagged

JHEP 06 (2015) 121
CMS-B2G-14-004



M_* : scale of the interaction