LHCP2015, St.Petersburg/Russia on Aug 31 – Sep 5, 2015

Searches for direct production of Dark Matter at the LHC

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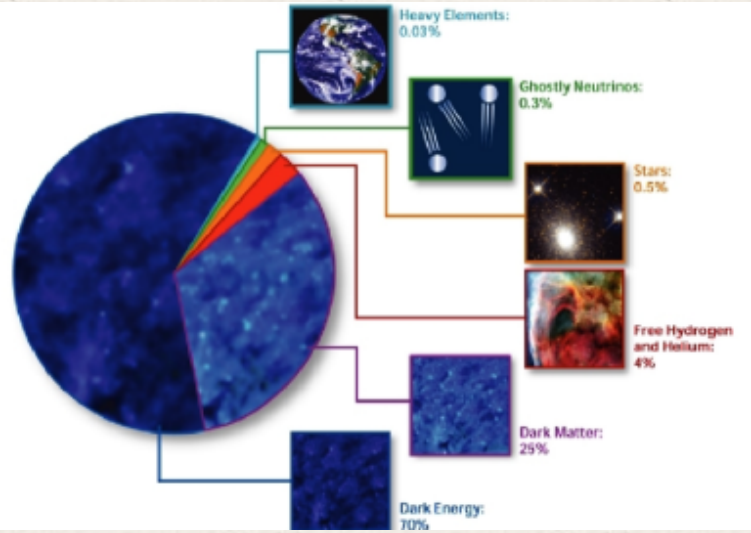
on behalf of the CMS and ATLAS collaborations

Motivation for dark matter

- **Non-baryonic Dark Matter is necessary component in the Universe (~25%).**
  - Supported by cosmology arguments and astrophysical observations.

- **DM candidate: weakly Interacting Massive Particles (WIMPs) .**
  - Consistency with observed relic density:

$$\Omega_{\rm DM} h^2 \simeq 0.1 \, \frac{3 \times 10^{-26} \ {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_A v \rangle}$$

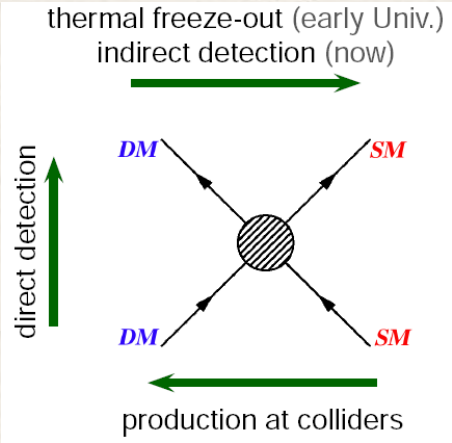


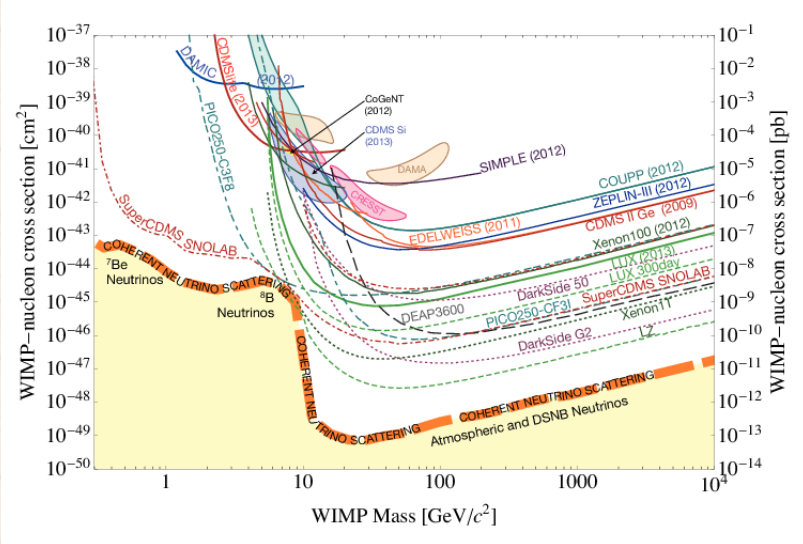
- Underlying nature of Dark Matter interactions with ordinary matter largely unknown.

- But weak scale interactions testable!

Detection of dark matter

- **Detection of WIMPs via three main search strategies:**





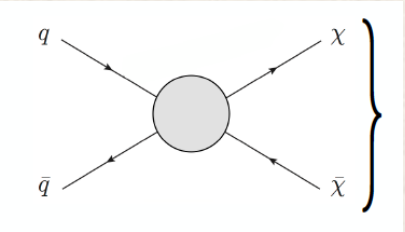
- **Direct detection**: probes DM-nucleon elastic scattering.
- **Indirect detection**: astrophysical observations of DM annihilation or decay.
- **Collider searches**: look for WIMPs pair-production in topologies with large MET recoiling against a visible system.

- **Underlying processes are related (eventually hope for common formalism).**

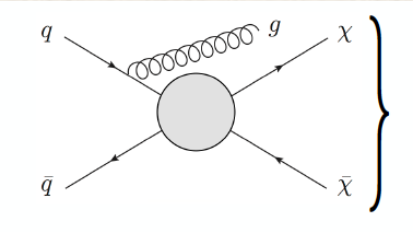
Collider searches:
the Mono-jet example

The mono-jet search

- **The Mono-jet search outline:**
  - **Formalism:** contact Interaction of DM with SM particles



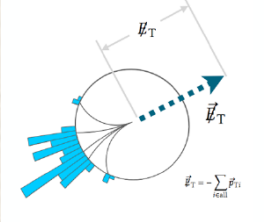
DM appears as missing energy



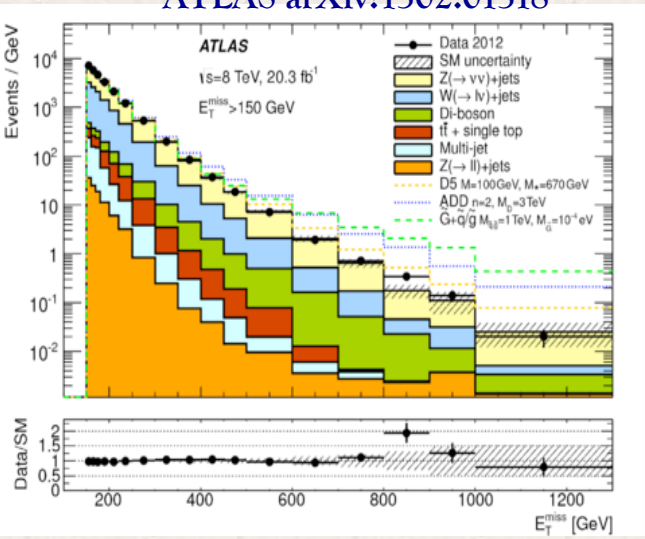
Monojet + DM (missing energy)

  - **Experimental signature:** hard Jet from ISR recoiling against MET:

$$\not{E}_T = -\sum_{obj} \vec{p}_T$$



ATLAS arXiv:1502.01518



- **Analysis strategy**: look for an excess of events in the tails of MET.
- ATLAS search split in nine signal regions defined by MET thresholds (150 to 700 GeV) / Δϕ(jet,MET)>1.
- SM backgrounds: Z(νν) constrained using Z/W(lep) control regions; W(lν) with lost lepton.

Theoretical framework

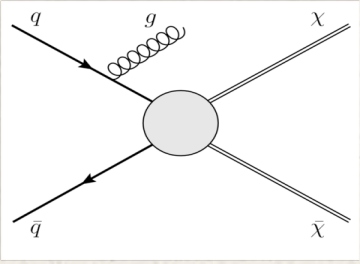
- **Effective Field Theory (contact interaction) vs a Simplified Model approach:**

Suppression scale:

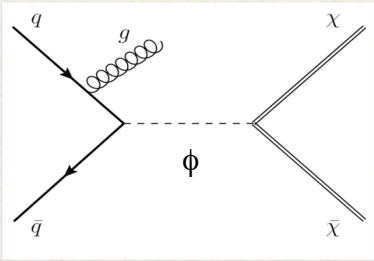
Λ,

$$\sigma = \frac{const}{\Lambda^4}$$

1 free parameter



Integrate out the mediator ϕ



$$\Lambda = \frac{M_{med}}{\sqrt{g_\chi g_{SM}}},$$

$$\sigma = c' \frac{g_{SM}^2 g_\chi^2}{M_{med}^4 \Gamma_{med}}$$

4 free parameters

- EFT provides framework to compare LHC results to direct detection results

Collider cross-section:

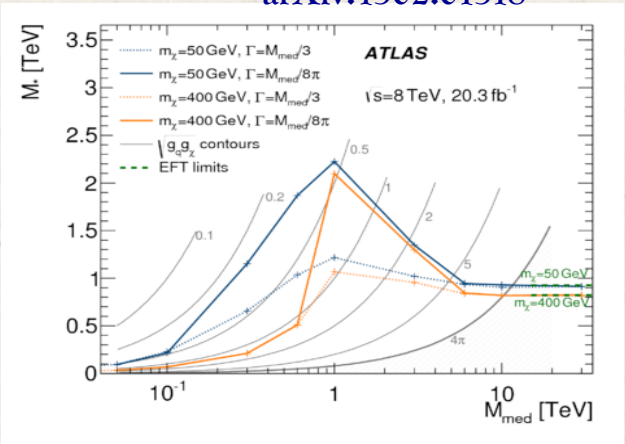
$$\sigma_{coll} \sim \frac{1}{(q^2 - M_{med}^2)^2 + \Gamma_{med}^2/4} \hat{s}$$

Direct detection cross-section:

$$\sigma_{scatter} \sim \frac{1}{M_{med}^4} \frac{m_N^2 m_\chi^2}{(m_N + m_\chi)^2}$$

- If DM interactions mediated by light particle: EFT breaks down/ violates unitarity -> have to include mediator explicitly.

arXiv:1502.01518



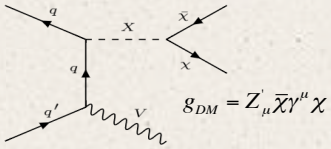
- For LHC: models with $M_{med} >\sim 5$TeV required
- Unless a narrow Mediator is produced on-shell decaying to DM particles .

More on Simplified Models: arXiv:1507.00966, Report of the ATLAS/CMS Dark Matter Forum

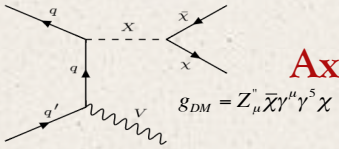
Interpretation of results within EFT

- DM couplings imply variety of topologies depending on the type of mediator :

Vector



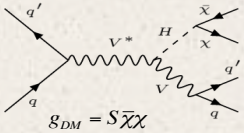
spin-independent



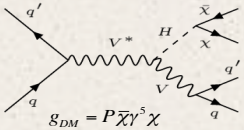
spin-dependent

Axial-Vector

Scalar



spin-independent

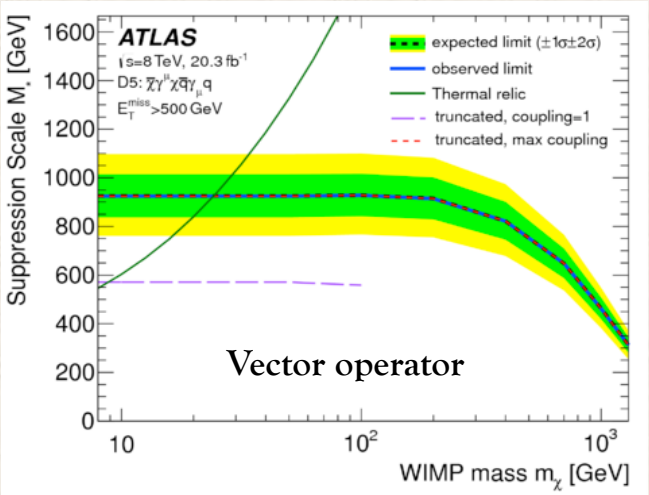


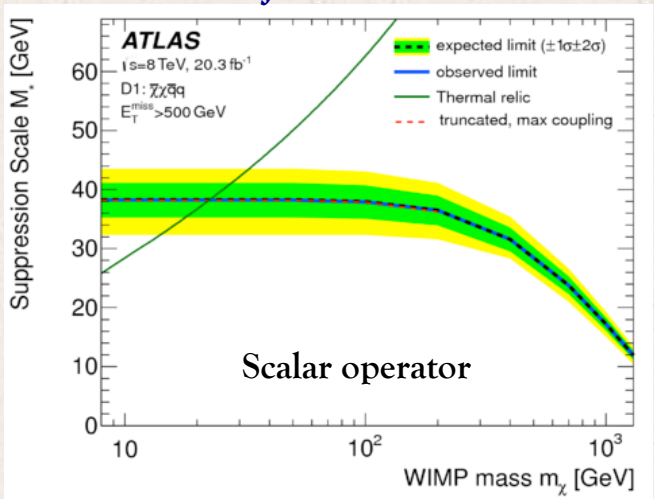
spin-dependent

Pseudo-scalar

- Analysis results set lower limits on suppression scale Λ (/M_*) as a function of the DM mass:

arXiv:1502.01518, Submitted to EPJC

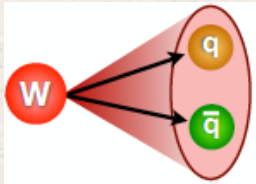


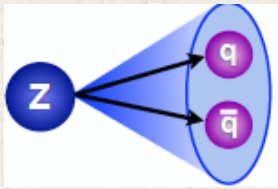


DM in Mono-object (V/jet) + MET topologies

Mono-V(had) generic search

- **Search for an excess of events with a jet or boosted Z/W, in association with large MET.**

Boosted 

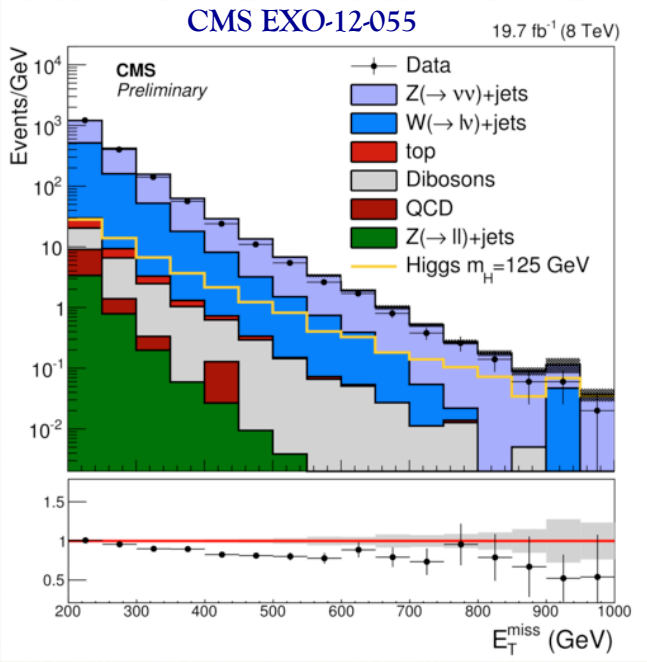
or 

or Jet + MET

- **Utilizes event categories via multivariate V-tagging techniques**
  - Based on boosted object (W/Z->had) topologies: split in resolved/unresolved boosted categories + monojet combination.

- SM backgrounds:
  Z(νν) ,W(lν) , ZZ, QCD
  => challenging to predict accurately the tails of MET

- Dominant systematic from EWK theoretical uncertainties.



Out-of-the-box MET data/MC comparison

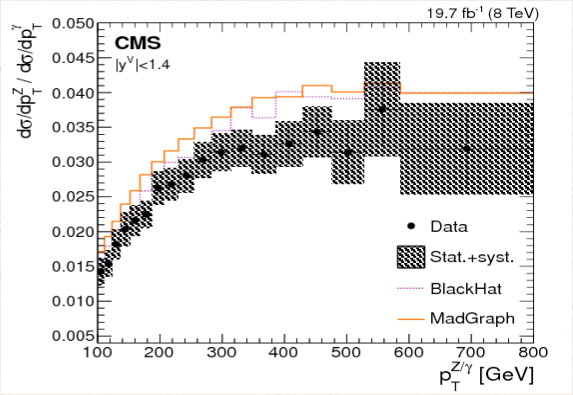
Background prediction in MET

- **Correct data/MC discrepancy: use control regions with no real MET**
  - Simultaneous fit to multiple control regions in Z(μμ) and γ+jets samples, MET shape.

$$\text{"fake"}\ \not{E}_T = -\sum_{all\ \ particles} \vec{p}_T$$

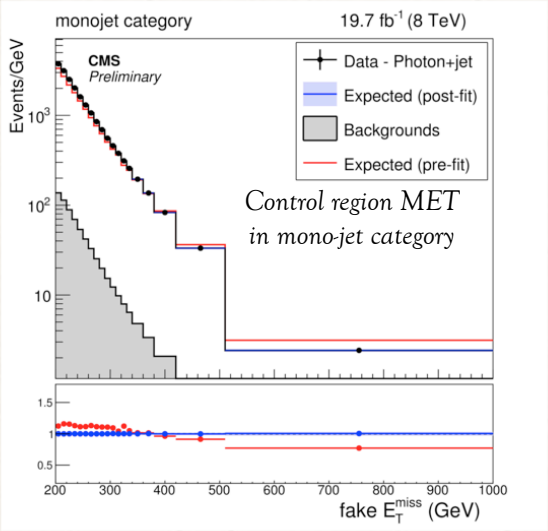
  - Rely on photon p_T spectrum to model the Z p_T →

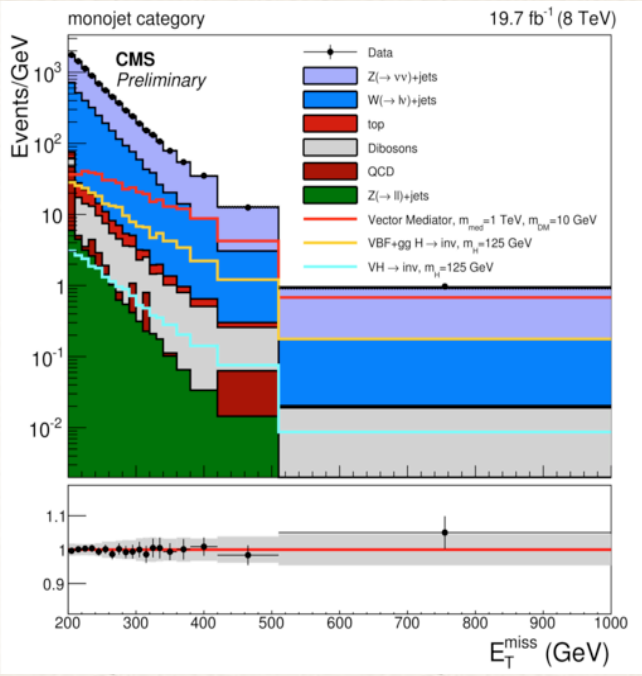
CMS SMP-14-055



- **Recovers very good data – MC agreement in post-fit MET :**

CMS EXO-12-055



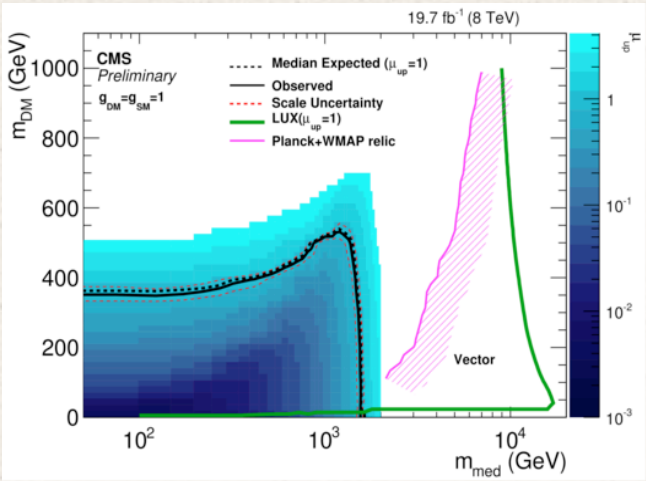


Simplified model interpretation

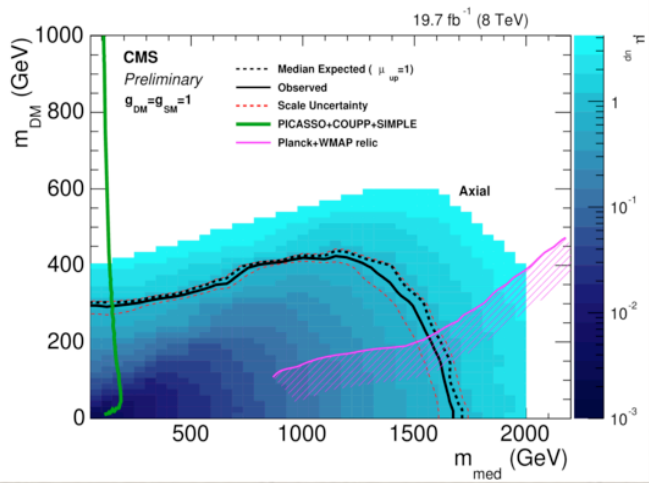
- Simplified model results: scanning over mediator m_{med} and dark matter m_χ for different mediator models.

CMS PAS EXO-12-055

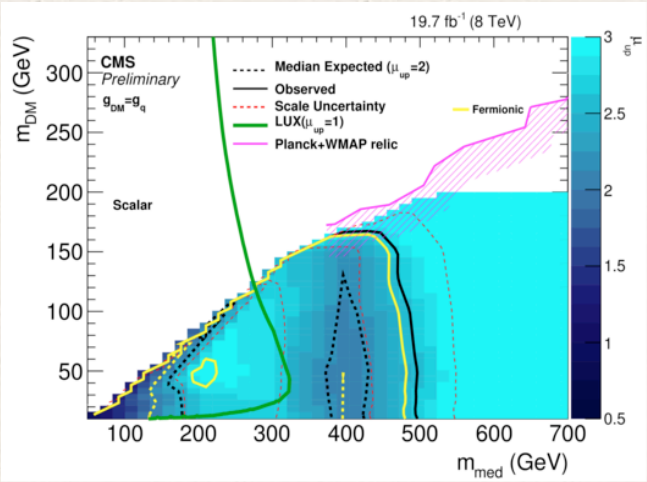
Vector



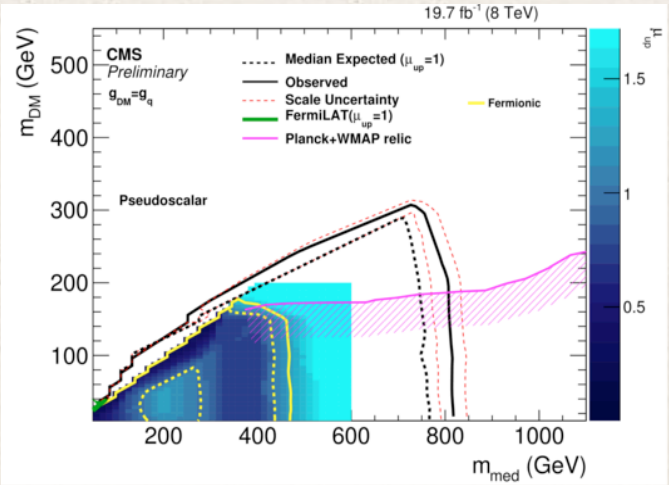
Axial-Vector



Scalar

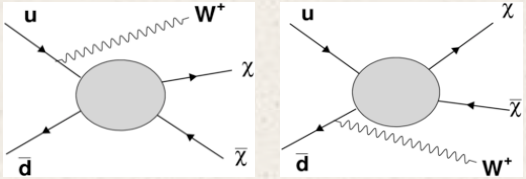


Pseudo-scalar

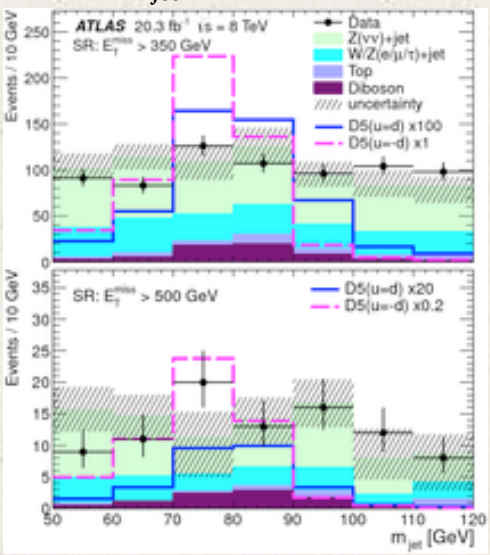


Atlas Mono-W/Z (had)

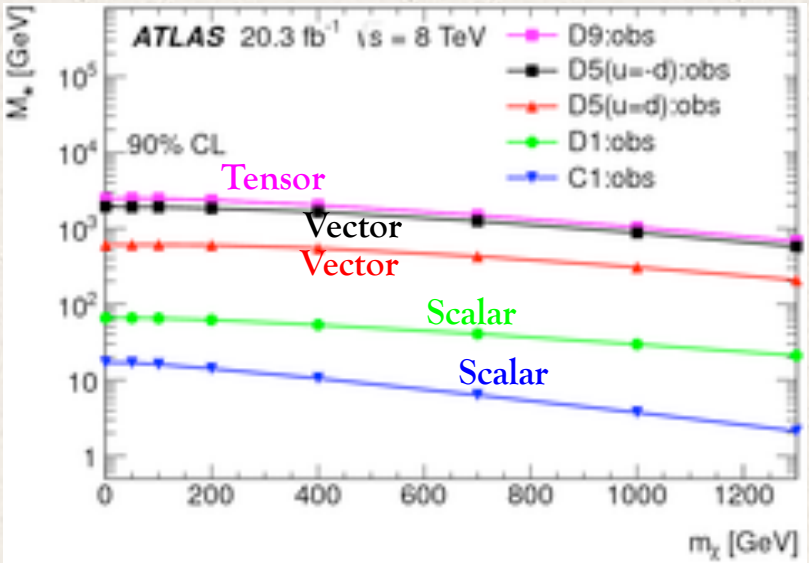
- **Search sensitive to WIMP pair production**
  - Identify "large-radius" jets with dedicated algorithms; capture hadronic decay products of W and Z bosons.



M_{jet} distribution



ATLAS arXiv:1309.4017

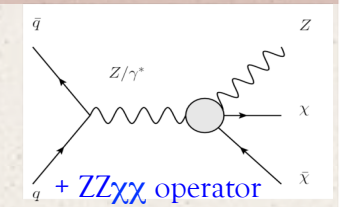


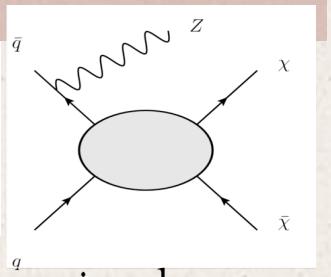
Lower limits on the suppression scale M_*

- Two S.R.s in MET>350, >500 GeV.
- Z(νν) and W(lν) estimated in contol regions obtained by inverting μ-veto.

Mono-Z(lep)

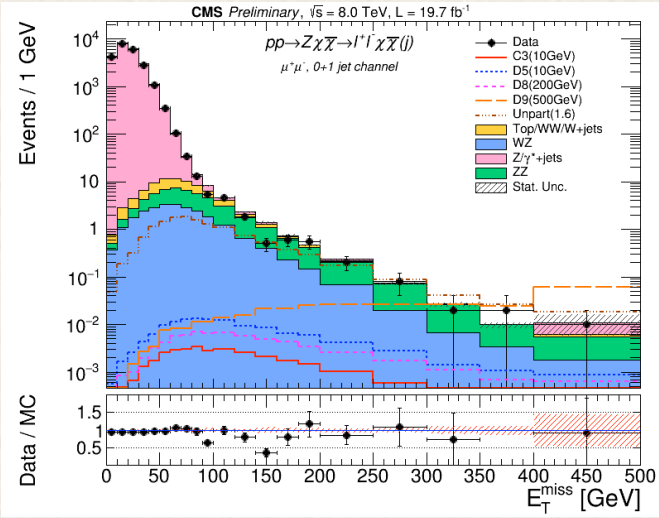
- **Mono-Z + DM: select two opposite-sign electrons or muons from the Z and look in MET.**



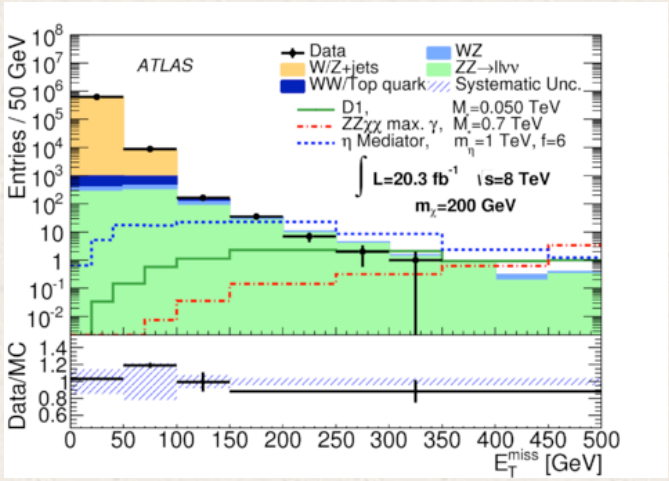


- ATLAS analysis considers both a Z from ISR as well as a scheme of associated production Zχχ.
- Main background syst. dominated by ZZ(llνν) theoretical uncertainties.

CMS EXO-12-054



ATLAS arXiv:1404.0051v3

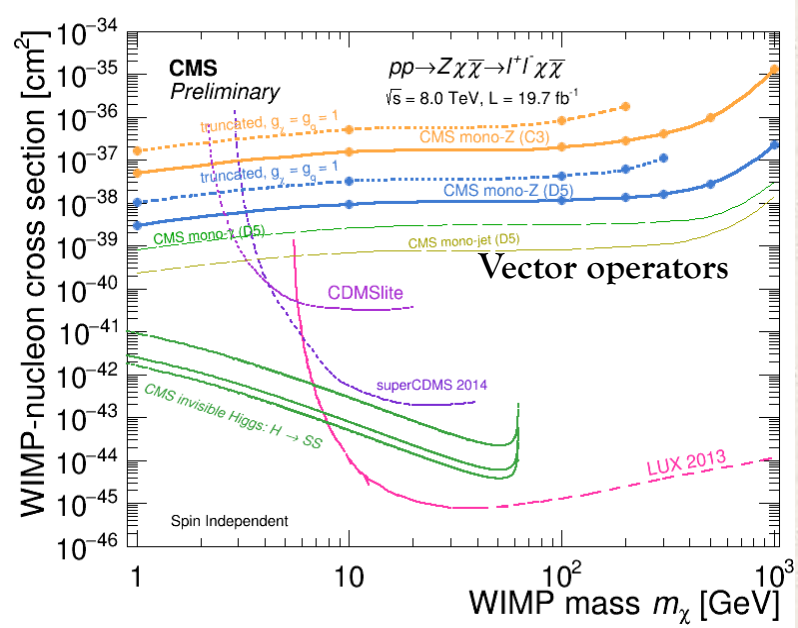


- Non-resonant backgrounds via data-driven methods; di-boson ZZ and WZ via MC simulation at NLO.

DM-nucleon cross-section limits: summary

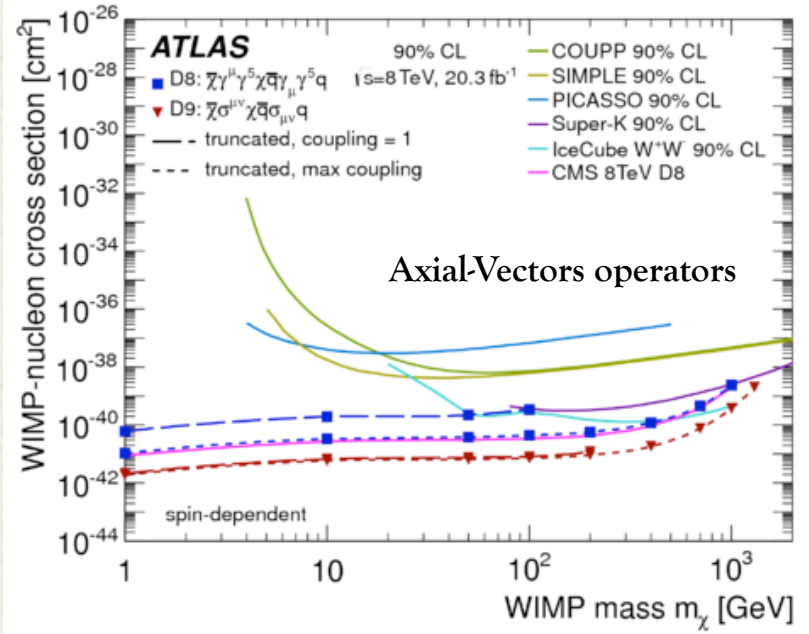
- **Connect with direct detection limits within EFT framework.**
  - Compare signal + background prediction with data.
  - Convert limits on the suppression scale Λ into limits on DM-nucleon scattering cross-section (direct detection limits)

CMS EXO-12-054



spin-independent

arXiv:1502.01518, Submitted to EPJC

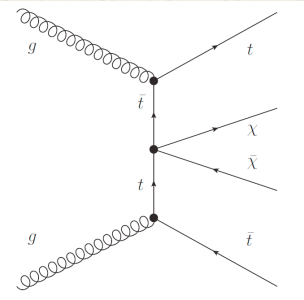


spin-dependent

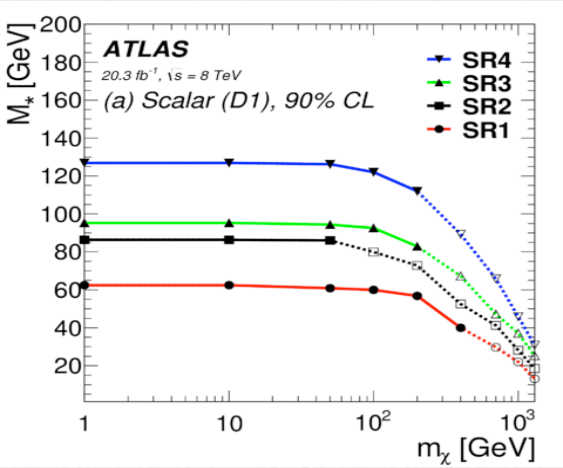
DM in
heavy-flavor topologies

DM with heavy quarks: tt(1lep)

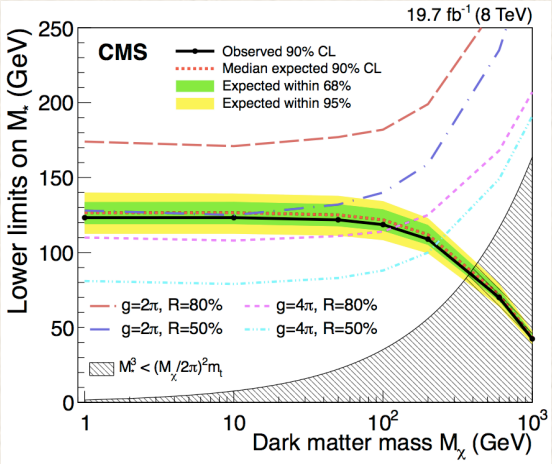
- **EFT with scalar interaction: proportional to quark mass**
  - Provides most stringent limits for this type of interaction.
- **CMS selection:** 1lep, >=3 jets, MET>320, M_T > 160
  - M_{T2}^W > 200 GeV
- **ATLAS selection:** defines S.R.s in MET (>300,300,200,270) and Njet (1-2,3-4,≥5, ≥4)



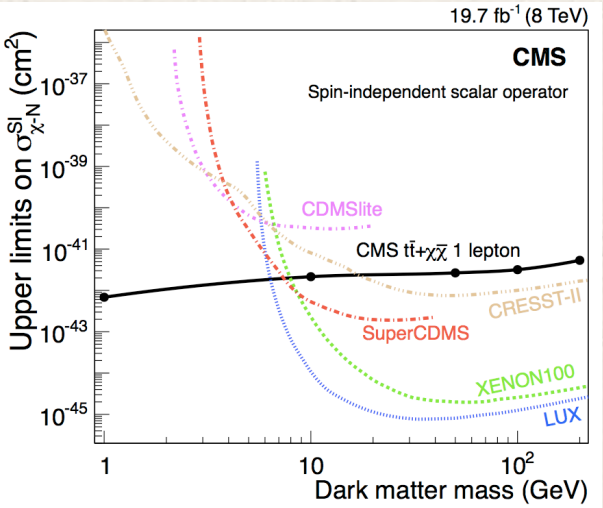
ATLAS arXiv:1410.4031



CMS arXiv:1504.03198, JHEP 06(2015)121



For m_χ=100 , CMS excludes:
Λ<~ 118 GeV

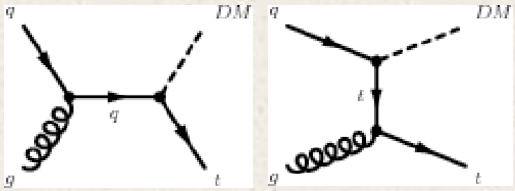


For m_χ < 6 GeV, CMS excludes:
$\sigma_{N\chi}$ >~ 1-2 x 10^{-42} cm^2

Mono-top

- **Search for dark matter particles produced in association with a single top quark**

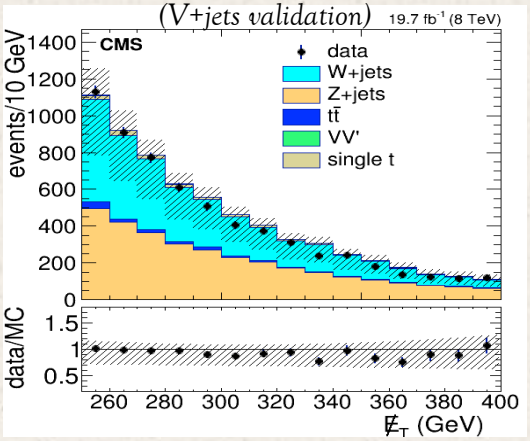
  $t \rightarrow bW \rightarrow bqq'$

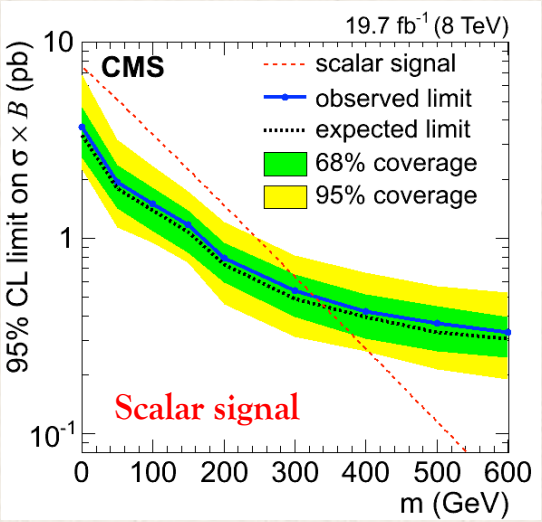


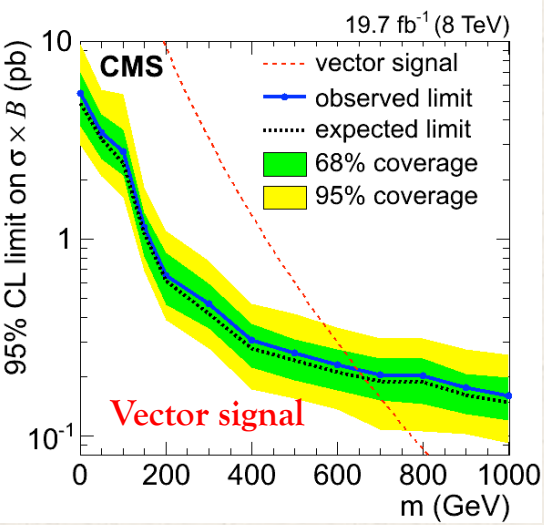
- SM backgrounds: tt and W+jets , QCD jets; non-instrumental Z(νν)+3jets.
- Signal selection: large Met, 3jets with >=1jet b-tagged.

Phys. Rev. Lett. 114 (2015) 101801

Signal region with b-tag veto
(V+jets validation)





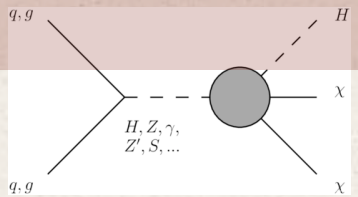


Excludes DM masses below 327 GeV (scalar) and 655 GeV (vector)

- ATLAS mono-top in single-lepton channel: arXiv:1410.5404

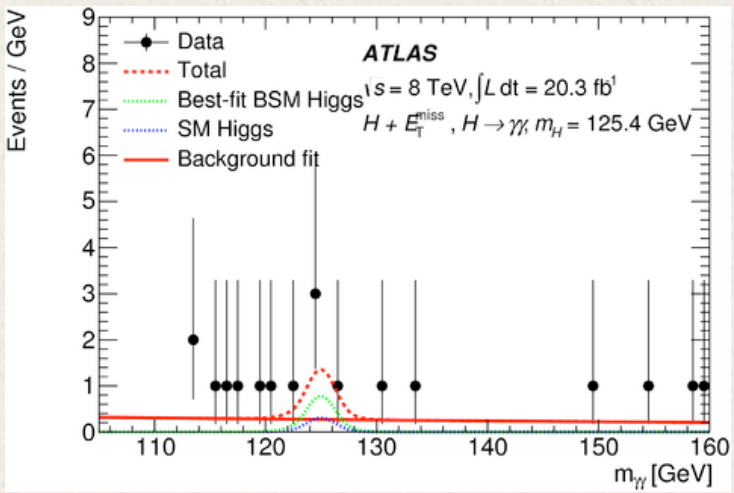
DM interacting through Higgs

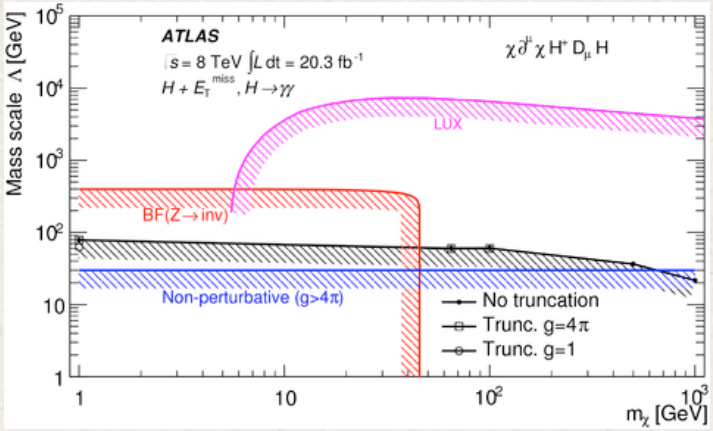
Mono-Higgs

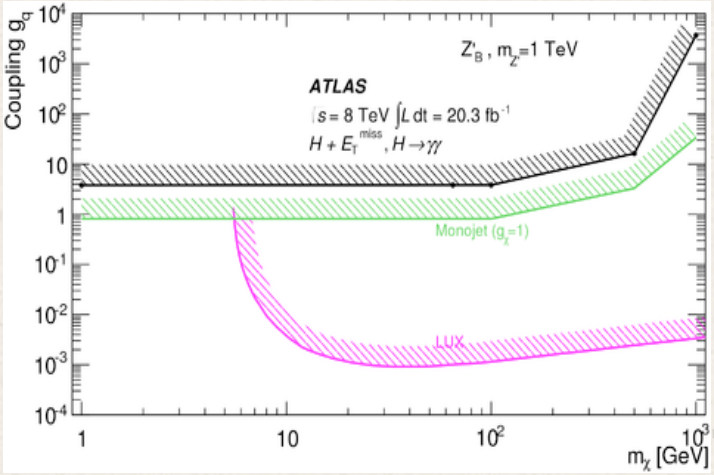


- **Recent results with mono-Higgs final state (H->γγ) - explores additional DM models for different kinematics.**
  - Complement constraints from WH, ZH and qqH on Hinv branching ratios.
  - Search for a localized excess of events in the $m_{\gamma\gamma}$ spectrum near m_H=125 GeV.

ATLAS arXiv:1506.01081





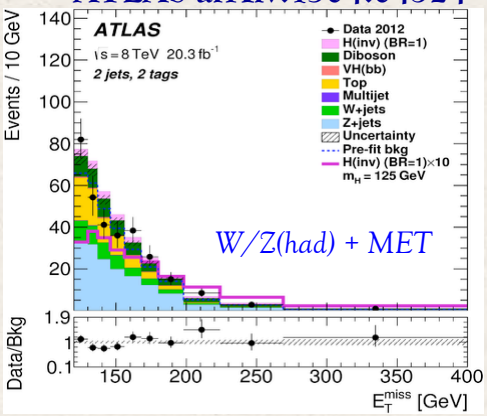


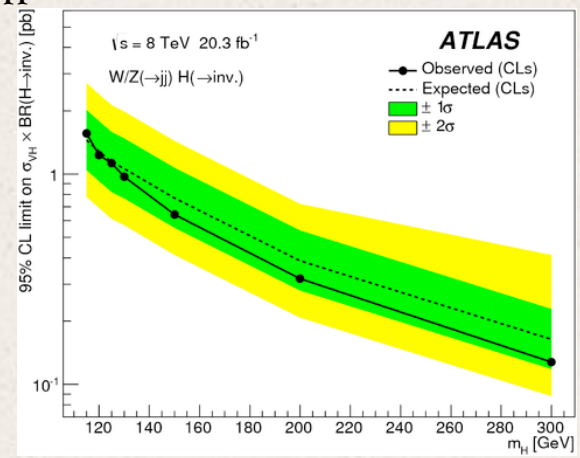
- Limits on scale Λ as a function of m_χ .
- Limits on couplings for simplified models (mediator mass at 1 TeV).

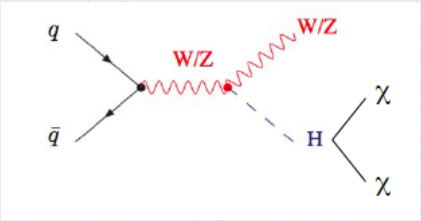
DM interpretations in H(inv)

- V + H(inv): associated production of Higgs with Z; Higgs decay to DM particles if kinematically allowed ($m_\chi < m_H/2$).

ATLAS arXiv:1504.04324



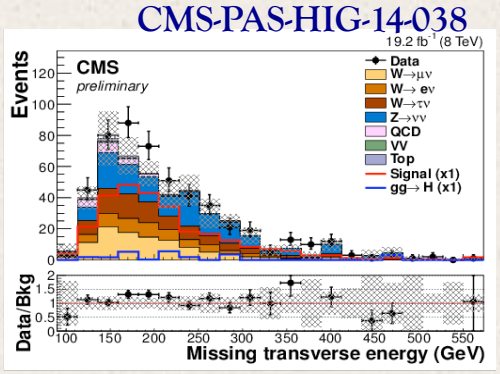


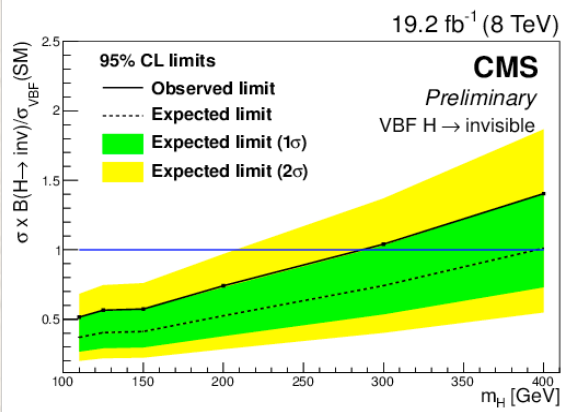


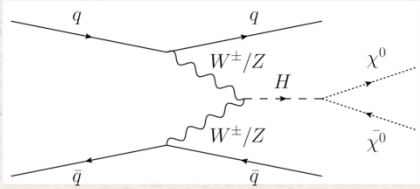
BR(Higgs ➔ invisible) < 78%

- VBF H(inv): vector boson fusion production of Higgs, decaying invisibly to DM particles:

CMS-PAS-HIG-14-038





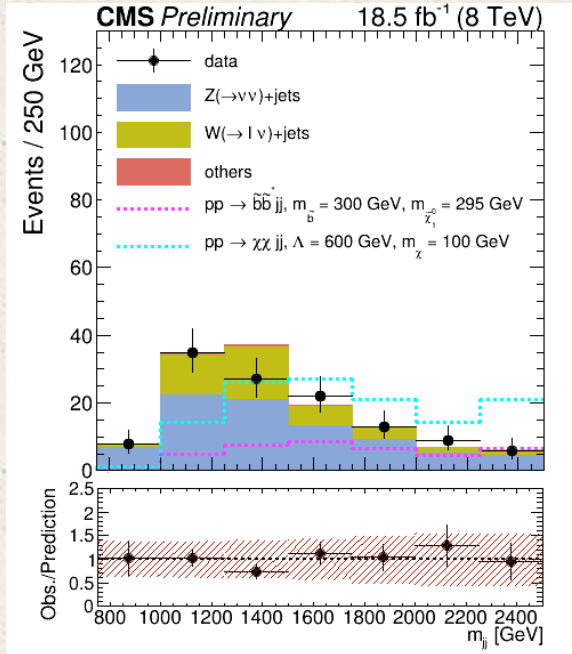


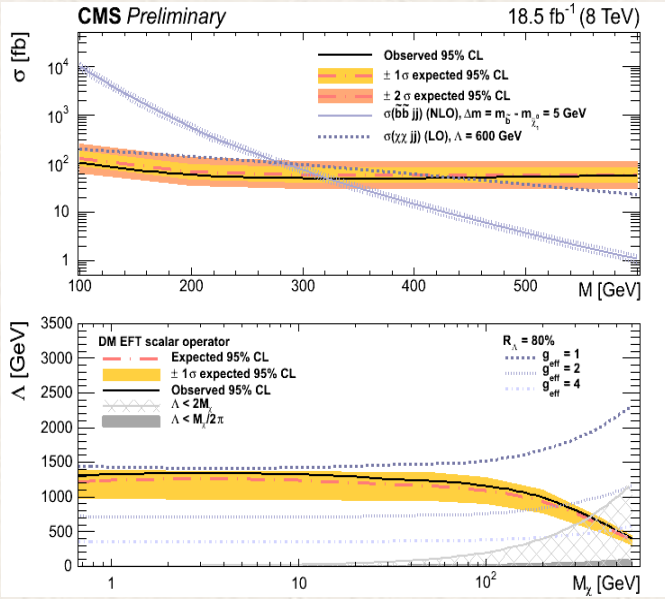
BR(Higgs ➔ invisible) < 47% (35%)
after combination with ZH(inv)

DM in VBF topology

- **Recent CMS result on DM search exploiting the VBF topology within super-symmetric models of compressed mass spectrum.**
  - 2 VBF jets + large MET from boosted LSPs (DM candidate).

- **Search used to constaint the signal production of :** $\chi\chi jj$





CMS SUS-14-019

- **Limits set on the cross-section and interaction scale Λ, for a scalar EFT.**
  - Excludes DM masses up to ~420 GeV in EFT with Λ=600 GeV.

Summary & outlook

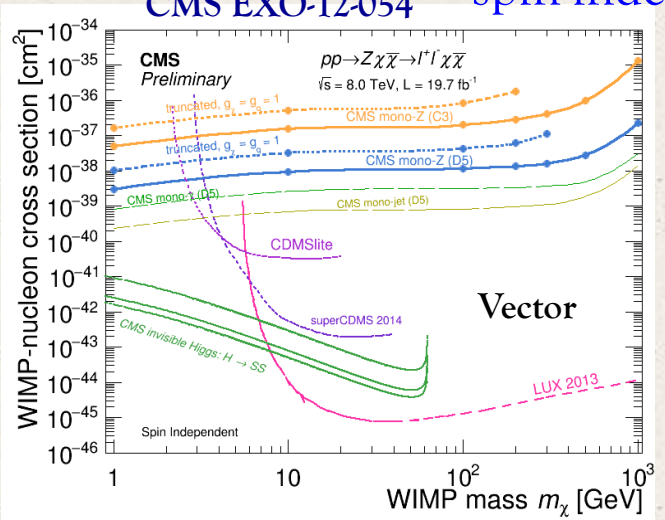
- Exciting time for Dark Matter searches!
- **Mono-jet searches at the LHC provide strong constraints on dark matter properties within effective field theory.**
  - EFT provides common framework to compare with direct searches but only valid for certain assumptions on parameter space.
  - Need to go beyond EFT -> Simplified models framework.
- **Collider results complement direct searches constraints:**
  - Exclude DM-nucleon cross-sections higher than ~ 10^{-40} – 10^{-39} cm^2 for m_χ ~ 6 GeV, assuming spin-independent vector type interactions
    - Extend sensitivity down to DM masses ~ O(5) GeV .
  - Add sensitivity for spin-dependent interactions over wide region in DM m_χ.
- **Special case: Dark Matter interacting through Higgs.**
  - Invisible Higgs searches will be very sensitive.

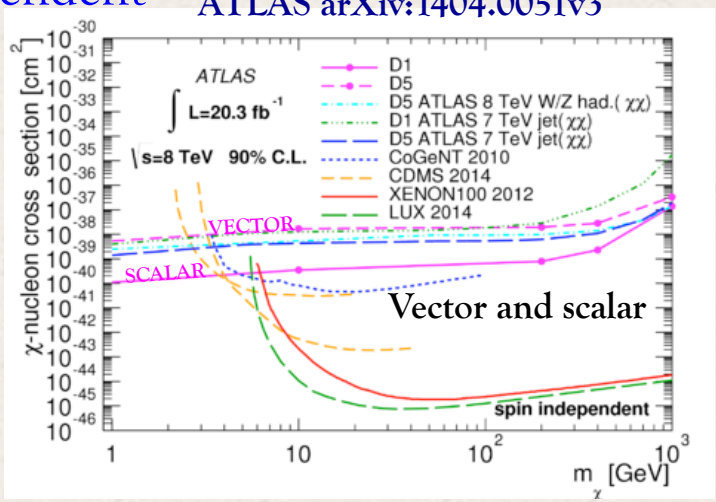
Back-ups

DM-nucleon x-section limits with mono-V

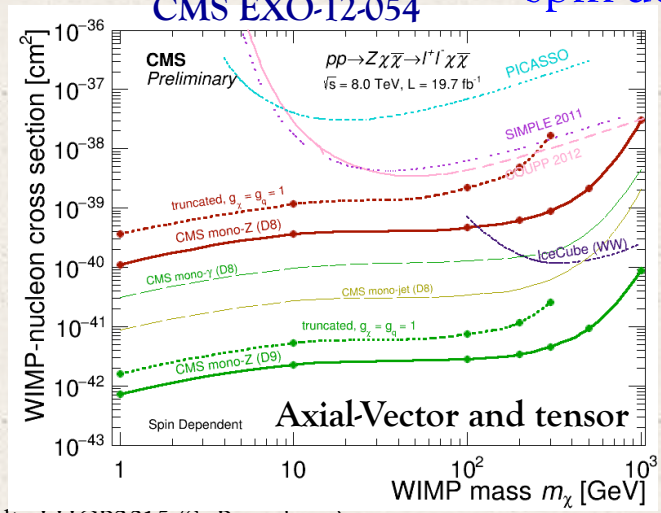
- Connect with direct detection limits within EFT framework:

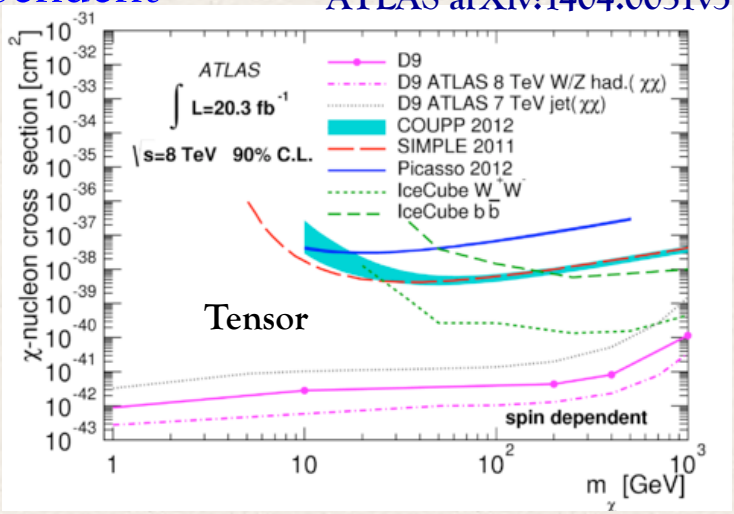
CMS EXO-12-054 spin-independent ATLAS arXiv:1404.0051v3





CMS EXO-12-054 spin-dependent ATLAS arXiv:1404.0051v3





DM using the razor variables

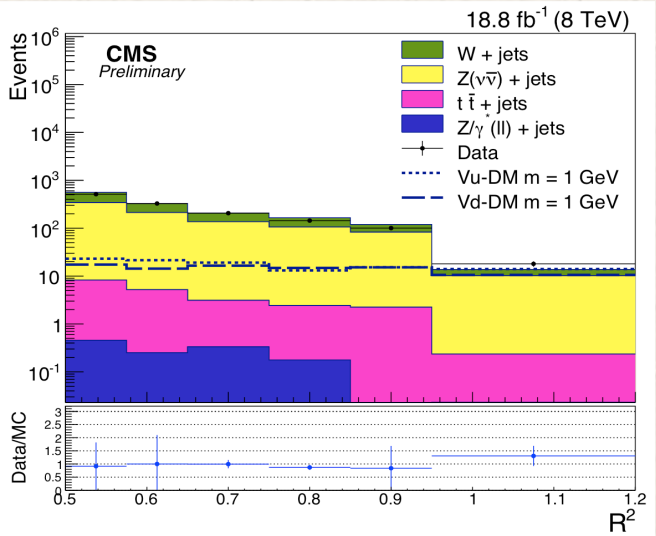
- Uses di-jet event topology of two "mega-jets" with $\Delta\phi(j1,j2) < 2.5$
- Compute the razor variables:

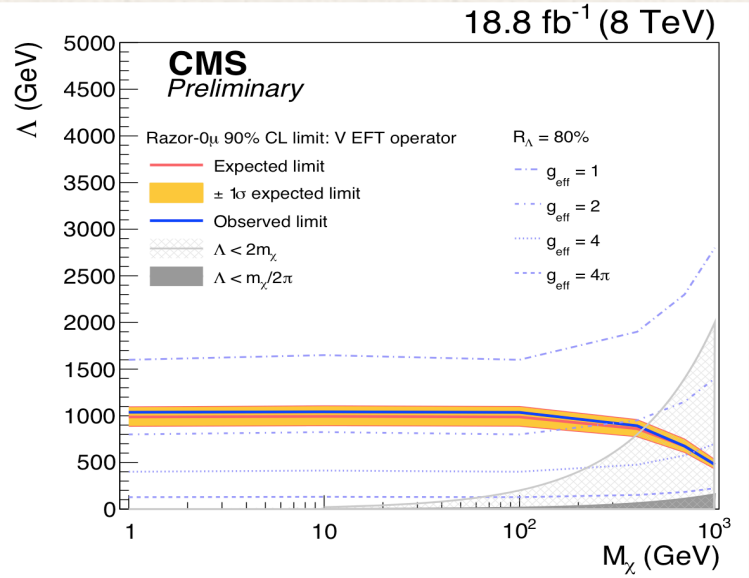
$$M_R \equiv \sqrt{\left(\left|\vec{p}_{j1}\right| + \left|\vec{p}_{j2}\right|\right)^2 - \left(p_z^{j1} + p_z^{j2}\right)^2}, \quad R \equiv \frac{M_T^R}{M_R}$$

$$\text{with} \quad M_T^R \equiv \sqrt{\frac{E_T^{miss}\left(p_T^{j1} + p_T^{j2}\right) - \vec{E}_T^{miss}\left(\vec{p}_T^{j1} + \vec{p}_T^{j2}\right)}{2}}$$

- M_R>200 GeV and R^2>0.5 (background peaked at low R^2; signal evenly distributed in R^2)
- Backgrounds estimated from muon control regions.

CMS EXO-14-004

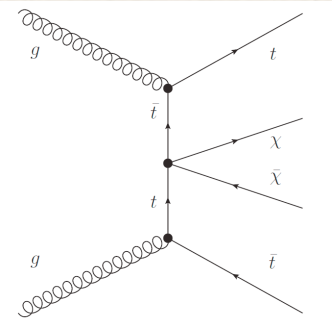




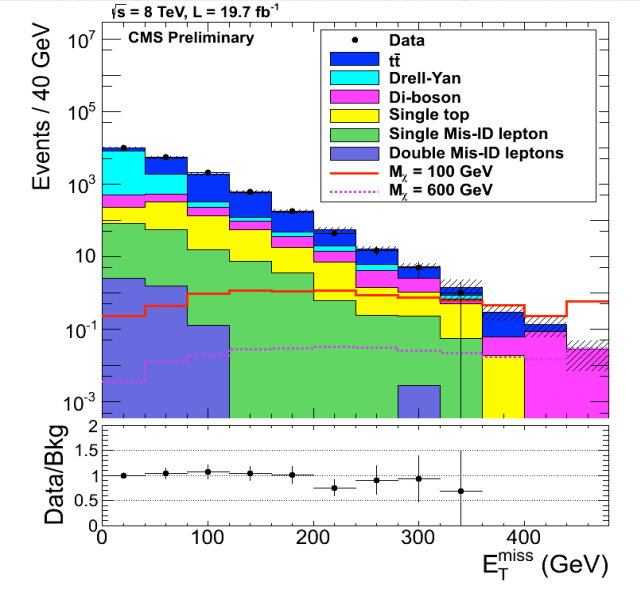
Limits comparable to the mono-jet search; albeit analyses mostly independent.

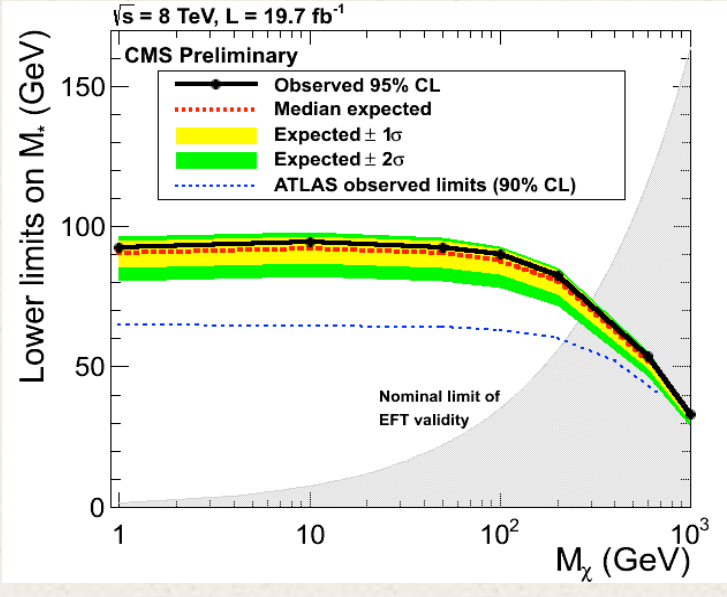
DM with heavy quarks: tt(2lep)

- **EFT with scalar interaction: proportional to quark mass**
  - Provides most stringent limits for this type of interaction.
- **Requires both top-quarks to decay leptonically.**
  - Exactly 2 leptons, >=2 jets
  - MET>320 GeV, pT(jj) < 400 GeV (suppresses tt bkg)
  - p_T(ll)>120 GeV and $\Delta\phi$(ll) < 2.



CMS B2G-13-004





CMS excludes int. scale up to ~90 GeV in scalar type interaction, for DM particle mass of 100 GeV