Dark Matter Searches in CMS

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Dark Matter at LHC

- **To observe the Dark Matter (DM) at Large Hadron Collider (LHC) we find the signature produced in association with a Standard Model (SM) particle 'X', Where, 'X' = {Jet, W, Z, Photon, Higgs }.**

  ➔ mono-X searches at LHC

- **In proton-proton collisions, the 'X' can be emitted from a light quark as Initial State Radiation (ISR) or it may be emitted as part of the new effective vertex coupling of DM to the SM.**
- **One popular candidate for dark matter is a weakly interacting massive particle (WIMP), which arises naturally in several models of physics beyond the standard model such as supersymmetry.**
- **Like neutrinos, WIMPs, leave detector silently and remain undetected. The missing transverse energy (MET) is most effective tool for searching DM particle in collider searches.**

Benchmark Models

- **Simplified Models** : In this, one considers an explicit model, in which new massive particle mediates the SM-DM interaction. The new massive particle can be: vector mediator Z', pseudo-scalar A_0 mediator, and scalar Mediator.
  - DM particle is a Dirac Fermion, χ
  - Minimal Flavor Violation is applied
  - Mediator exchange in s-channel only
  - Parameters: $M_{Med}, m_\chi, g_q, g_\chi, \Gamma_{Med}$
  - Specific Model for X=higgs(h): Mediator radiates higgs and decays to $\chi\chi$.

- **Effective Field Operator** : Different non - renormalizable operators, valid only if the M_{Med} >> momentum transfer at LHC.

ATLAS/CMS Dark Matter Forum
arXiv:1603.04156, arXiv:1507.00966

Results at 8 TeV

Mono-Photon

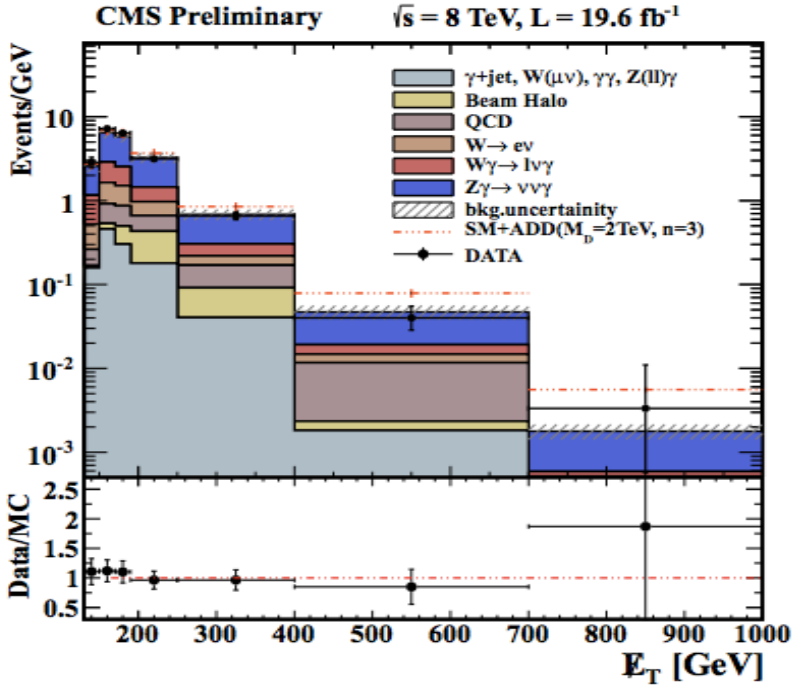
- DM particles (χ) can be produced in the process qq → γ χ χ , where the photon is radiated by one of the incoming quarks
- Events:

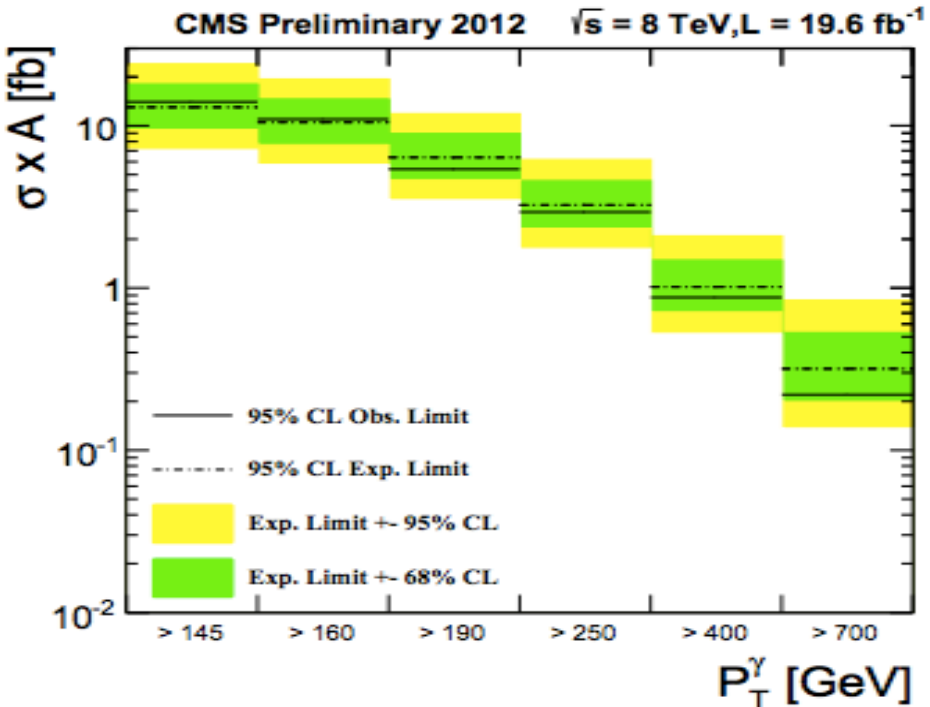
  $E_T^{\gamma} > 145$ GeV, $|\eta^{\gamma}| < 1.4442$

  H/E < 0.05
- Backgrounds:

  Dominant: W(lν)γ, Z(νν)γ,γ+jet,Z(ll)γ,di-Photon

  Sub-Dominant: QCD Multijets, W(lν)





The observed 95% CL upper limit on σ.A varies from 11.94 to 0.16 fb for 145 GeV <p_T^{γ}< 700GeV

Physics Letters B 755 (2016) 102–124

8 TeV & 19.6 fb^{-1}

Mono-Lepton

- **Dark matter in final state with one electron or muon and MET**

Events:

Single - muon (with offline p_T > 45 GeV)

Single - electron (with offline p_T > 100 GeV)

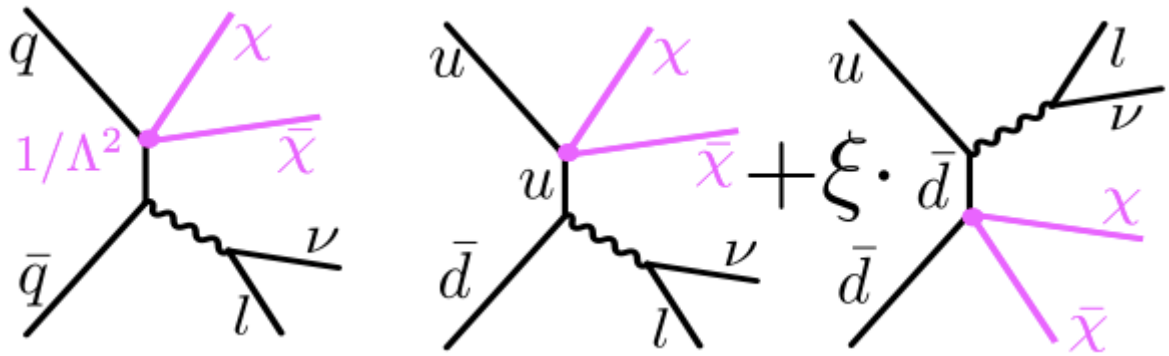
$0.4 < p_T / E_T^{miss} < 1.5$

- **Backgrounds:**

Dominant:W(lv), tt +single top,DY

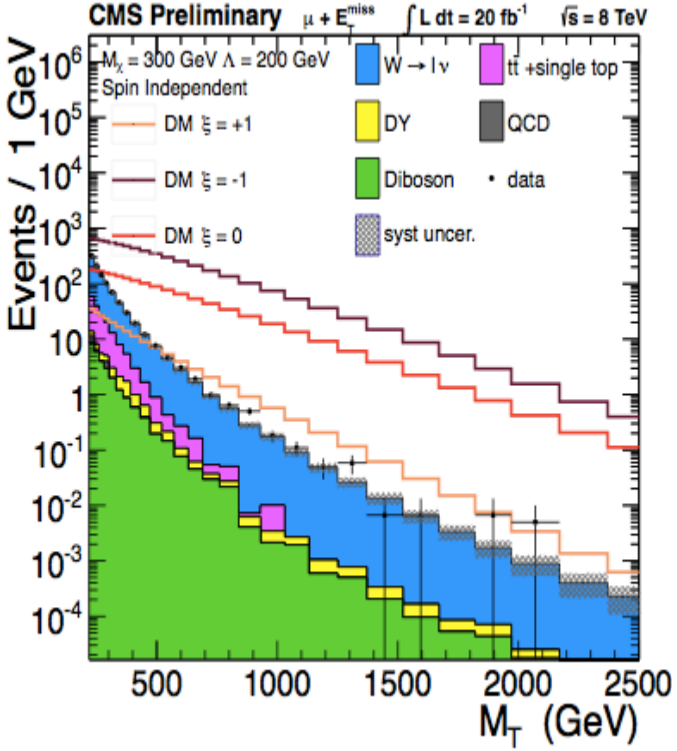
SubDominant: QCD Multijets, Diboson

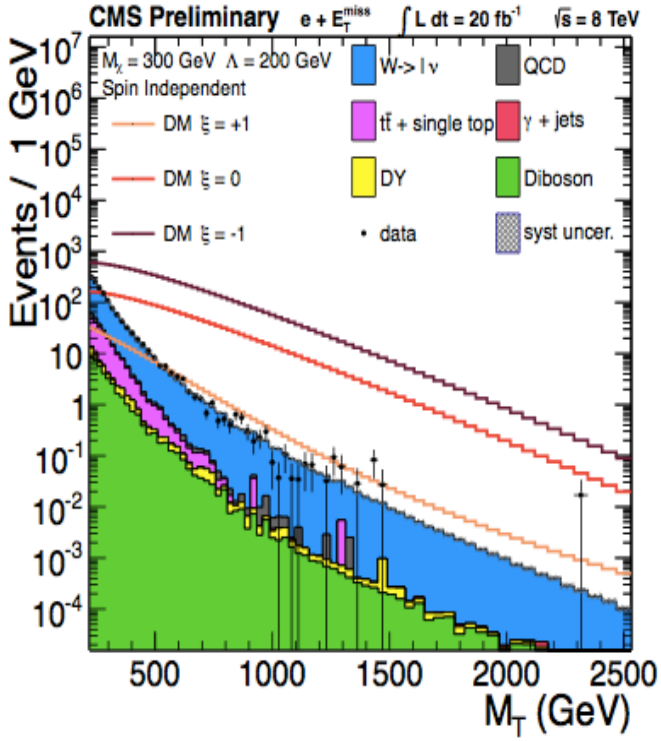
Limits are determined using full M_T spectrum for M_T>220 GeV



Highest M_T=2.3 TeV

Highest M_T=2.1 TeV





Top Quark Pair + MET

- **DM particles in association with ttbar in di-lepton events,**
  (considered scalar type of coupling between dark matter particles and top quarks)

Events:

m_{ll}>20 GeV, E_T^{miss} > 320 GeV

$|m_{ll} - 91\ GeV| > 15\ GeV$

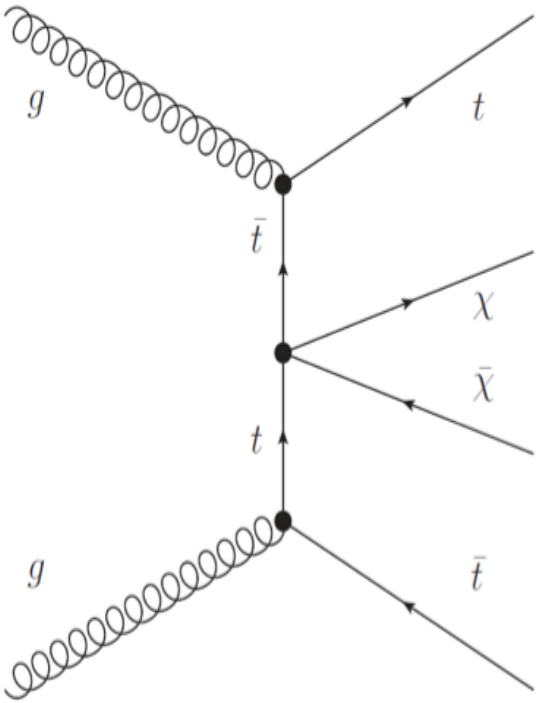
(to suppress DY)

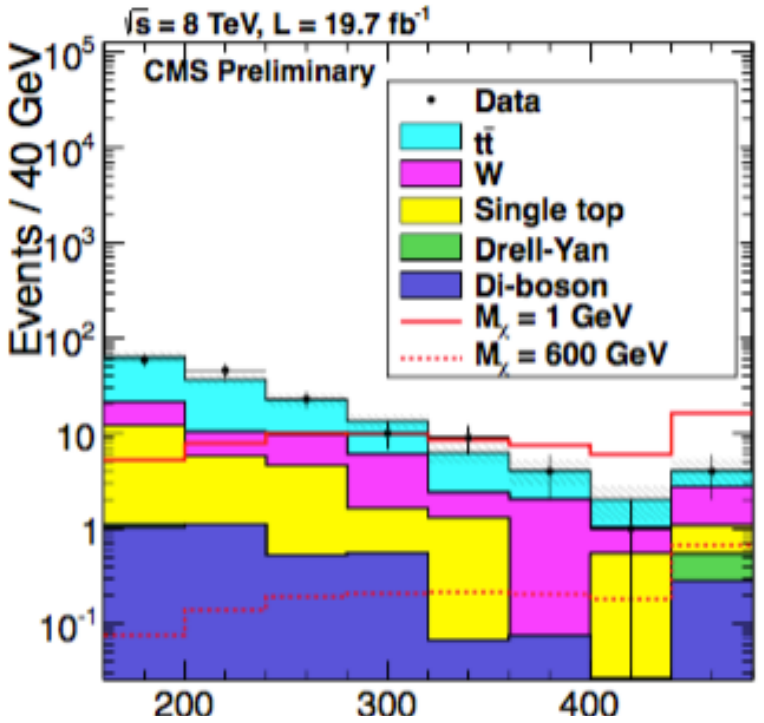
P_T < 400 GeV for two jets

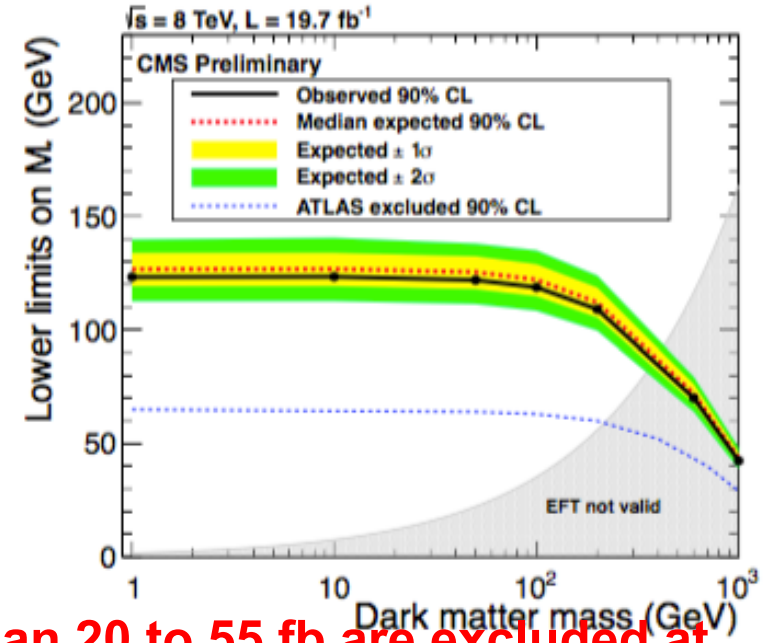
M_T < 160 GeV

- **Backgrounds:**

tt+single top,DY, Diboson







Cross sections higher than 20 to 55 fb are excluded at the 90% CL for dark matter particles with masses ranging from 1 GeV to 1 TeV.

Results at 13 TeV

Mono-Top

- **DM candidate particle is produced in association with a top quark.**
- **Events:**

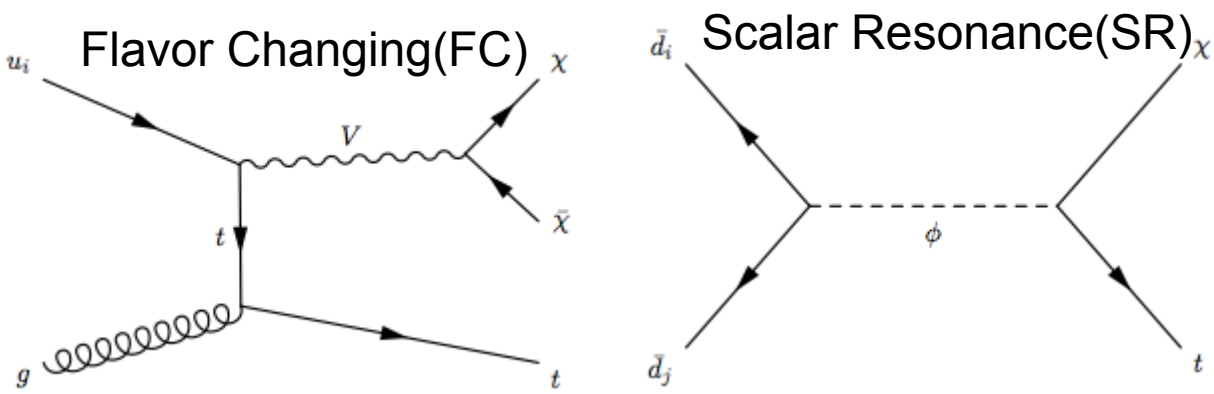
  E_T^{miss} > 90 GeV

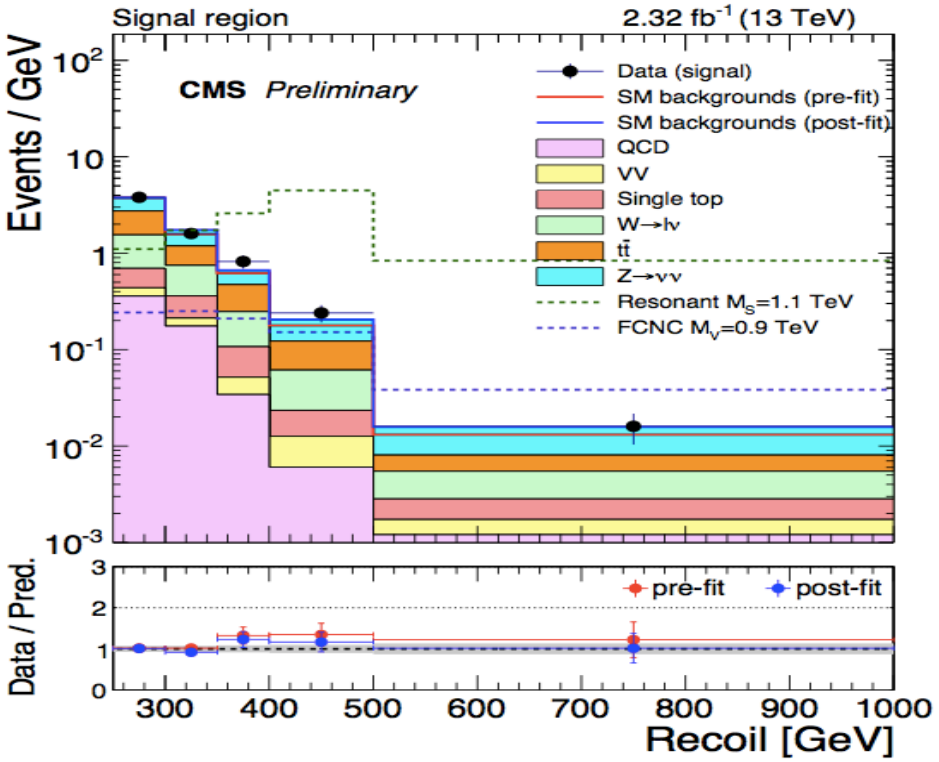
  H_T^{miss} > 90 GeV

  Leading Jet:

  p_T > 250 GeV, $|\eta|$ < 2.5
- **Backgrounds:**

  Dominant: ttbar,Z +jets,W+jets,QCD Multijets





Choosing Different Couplings($a_{SR/FC}$=$b_{SR/FC}$=0.1): 900< M_s < 2100 GeV at M_X=100 GeV For SR, 300< Ms< 1100 GeV at M_X=100 GeV For FC

Heavy Flavor

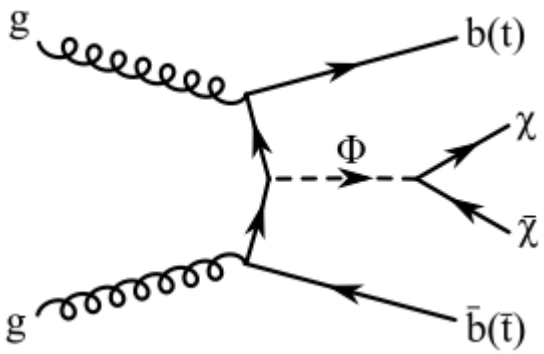
- **DM in association with one or more jets originating from the hadronization of bottom quarks.**
- **Events:**

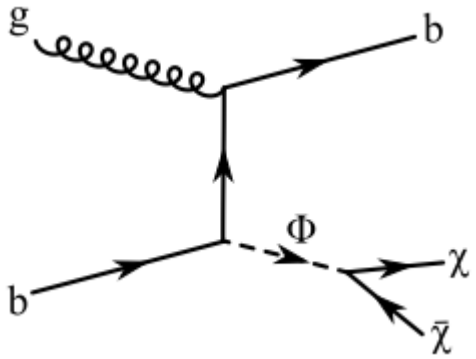
  $E_{T}^{miss} > 90$ GeV

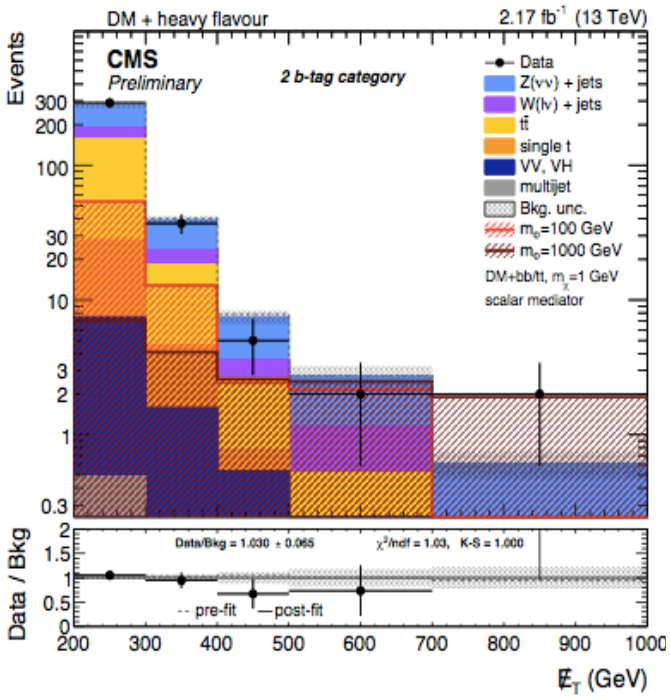
  $H_{T}^{miss} > 90$ GeV
- **Backgrounds:**

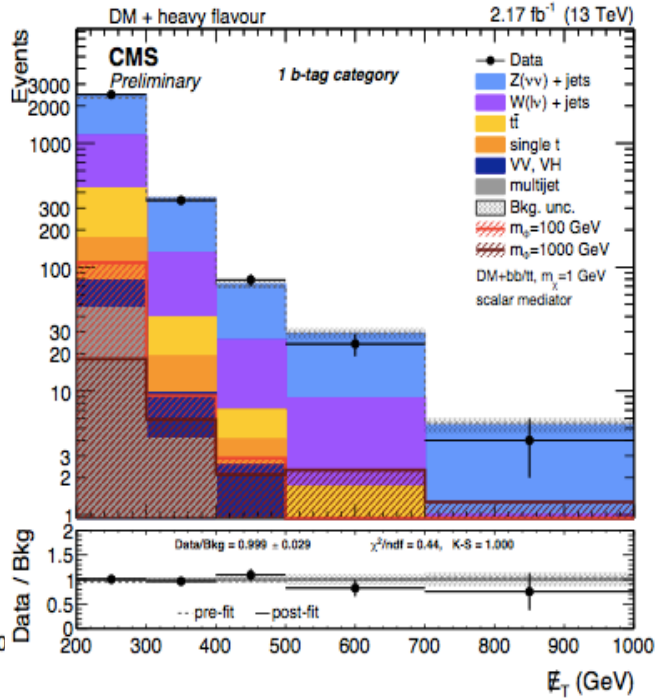
  Dominant: Z(vv) + jets, W(lv) + jets (~90%)

  SubDominant: ttbar, Single top, Di-Boson, VH,MultiJets





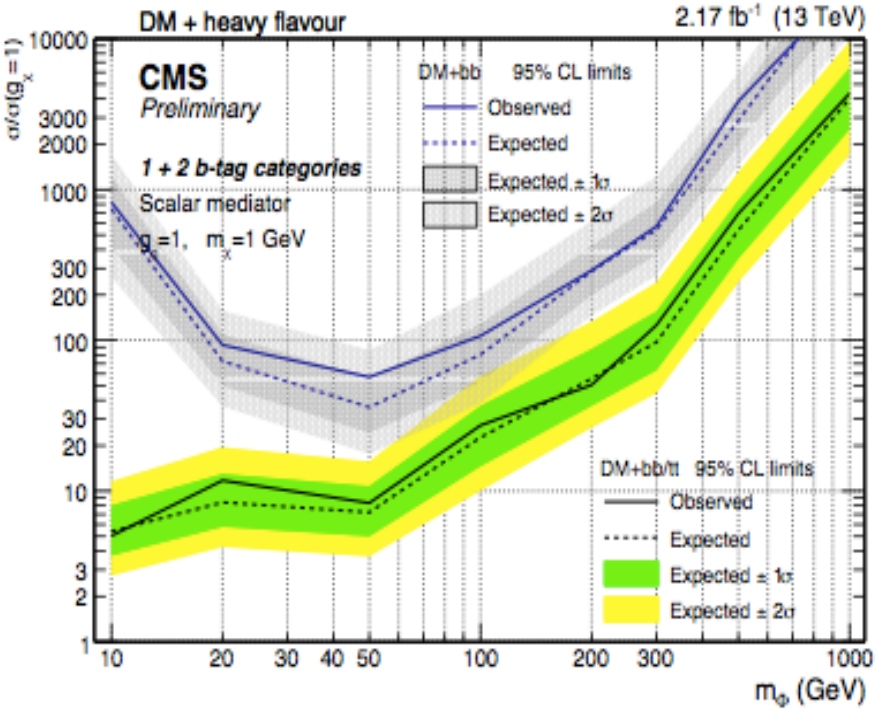


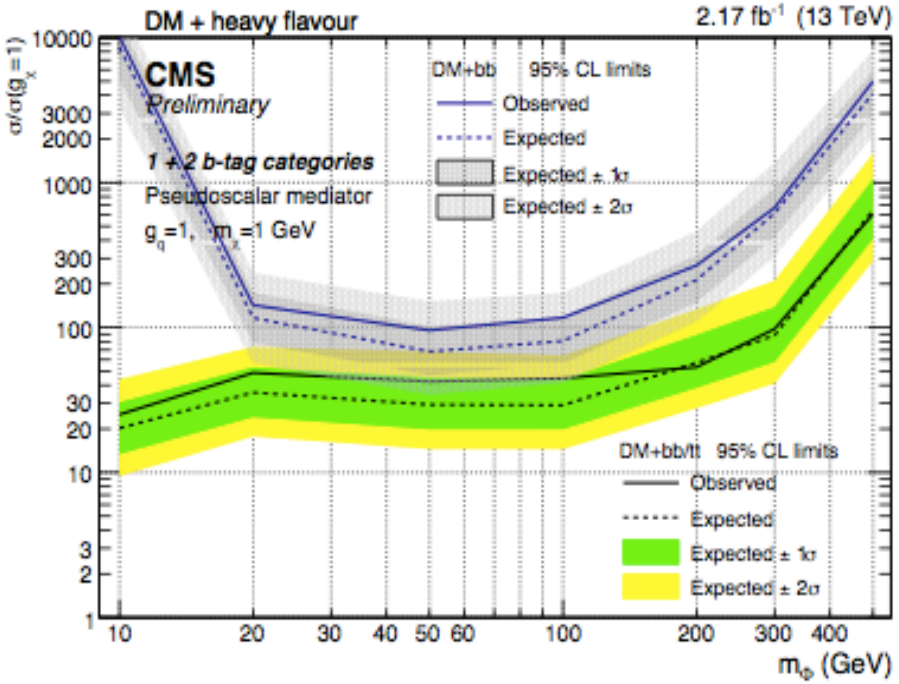


Heavy Flavor

With Scalar Mediator and Psuedo-Scalar Mediator

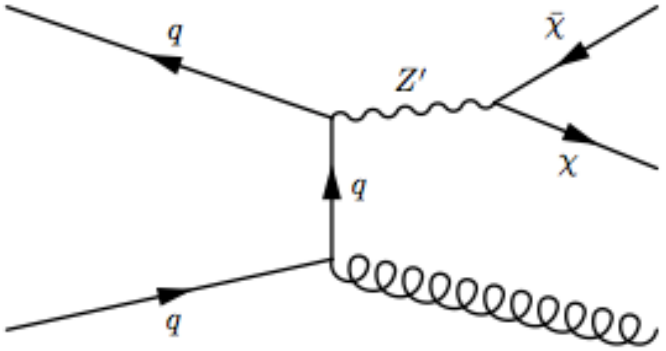
- Observed Exclusion limit and expected limit shown in 1σ, 2σ uncertainty Bands
- Combination of two categories(1 b-tag and 2 b-tag)
- DM is assumed to have mass of 1 GeV





Mono-jet

- **DM particles can be produced in pairs and recoil with large transverse momentum (p_T) against additional jets radiated from the initial state. This results in a 'Mono-jet' final state.**



- **Events:**

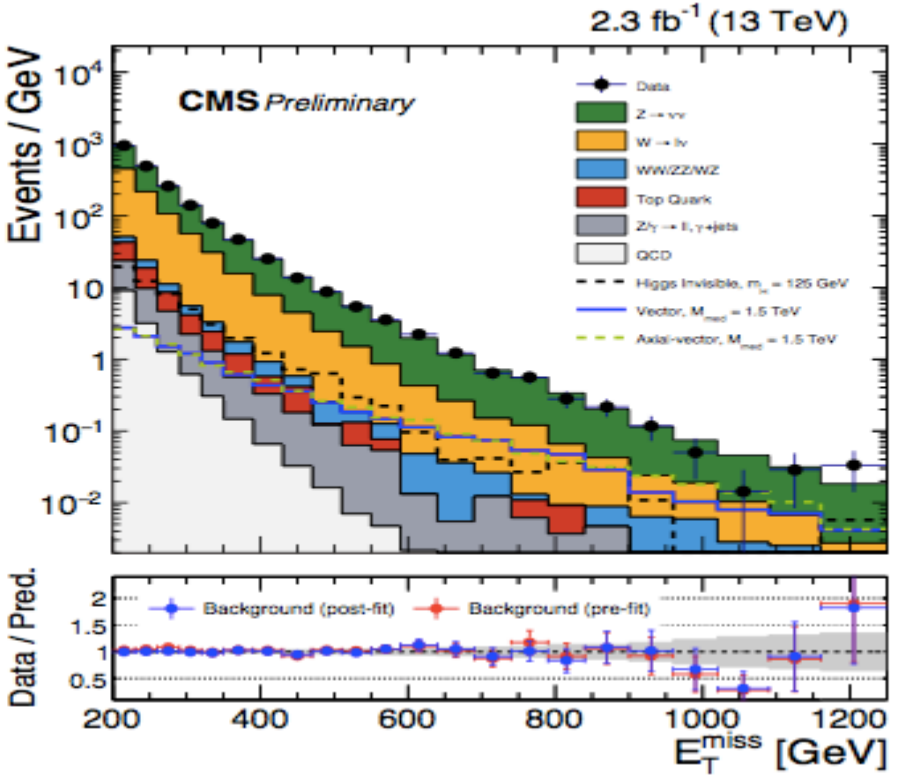
  E_T^{miss} > 90 GeV, H_T^{miss} > 90 GeV

  Leading jet: p_T > 100 GeV, |η| < 2.5

- **Backgrounds:**

  Dominant: Z(vv) + jets, W(lv) + jets (~90%)

  SubDominant: Single top, Di-boson, QCD Multijets



The Last Bin includes all events with E_T^{miss} > 1160 GeV

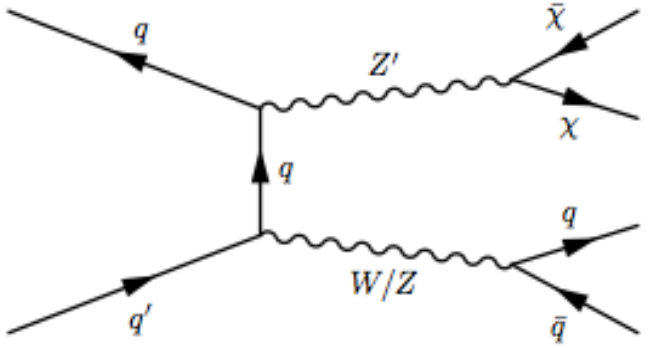
Mono-V

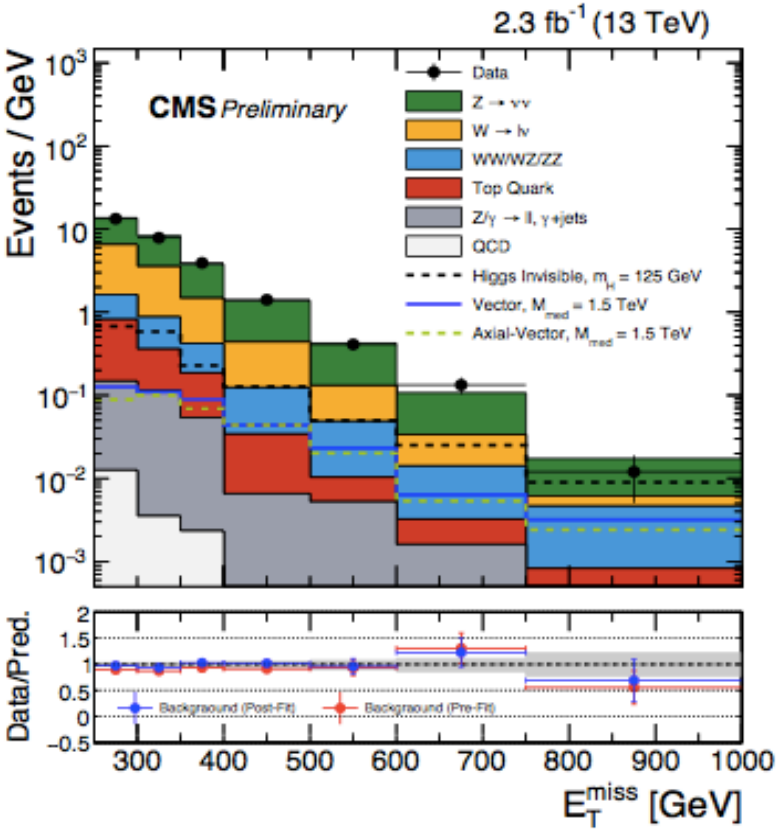
- **DM particle pair can be produced in association with a vector boson.**
- **Events:**
  - **E_T^{miss} > 250 GeV**
  - **Leading jet(AK8): p_T > 250 GeV, |η| < 2.4**
- **Backgrounds:**

Dominant: Z(νν) + jets and

W(lν) + jets (~90%)

SubDominant: ttbar , diBoson, QCD Multijets Events





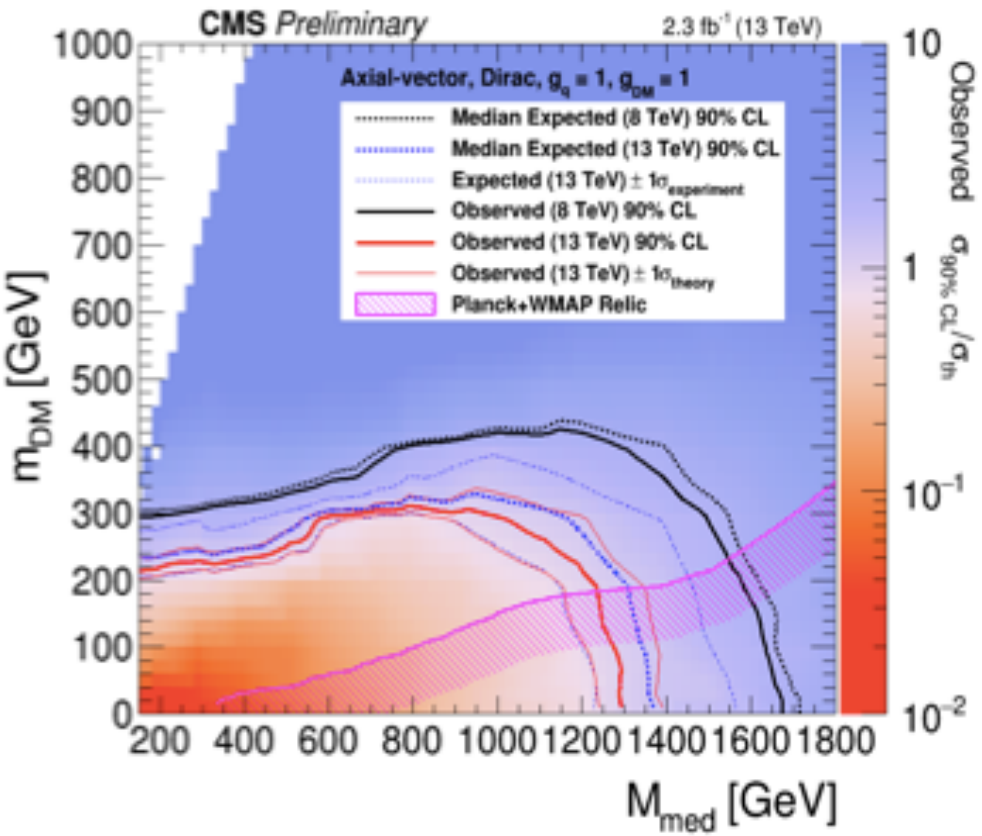
The Last Bin includes all events with E_T^{miss} > 750 GeV

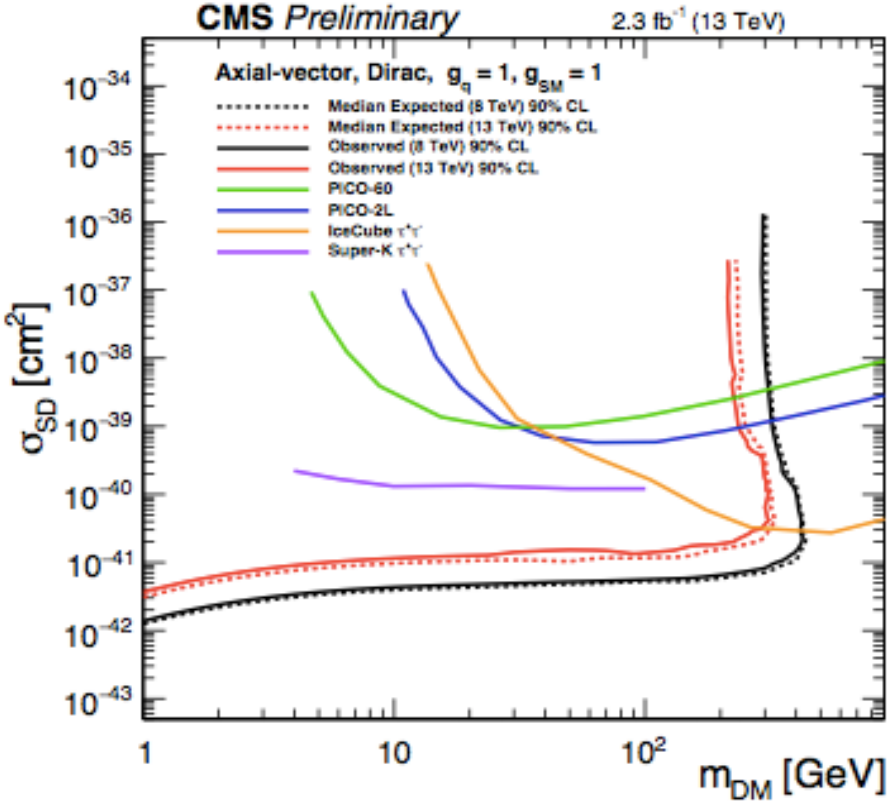
arXiv:1511.09375

Combined Mono-jet/V

With Axial-Vector Mediator

- Exclusion limit at 90% CL on (M_{Med}, m_{DM}) plane
- Results compared to PICO-2L, PICO-60, IceCube, Super Kamiokande in plane(m_{DM}- $\sigma_{SI/SD}$)



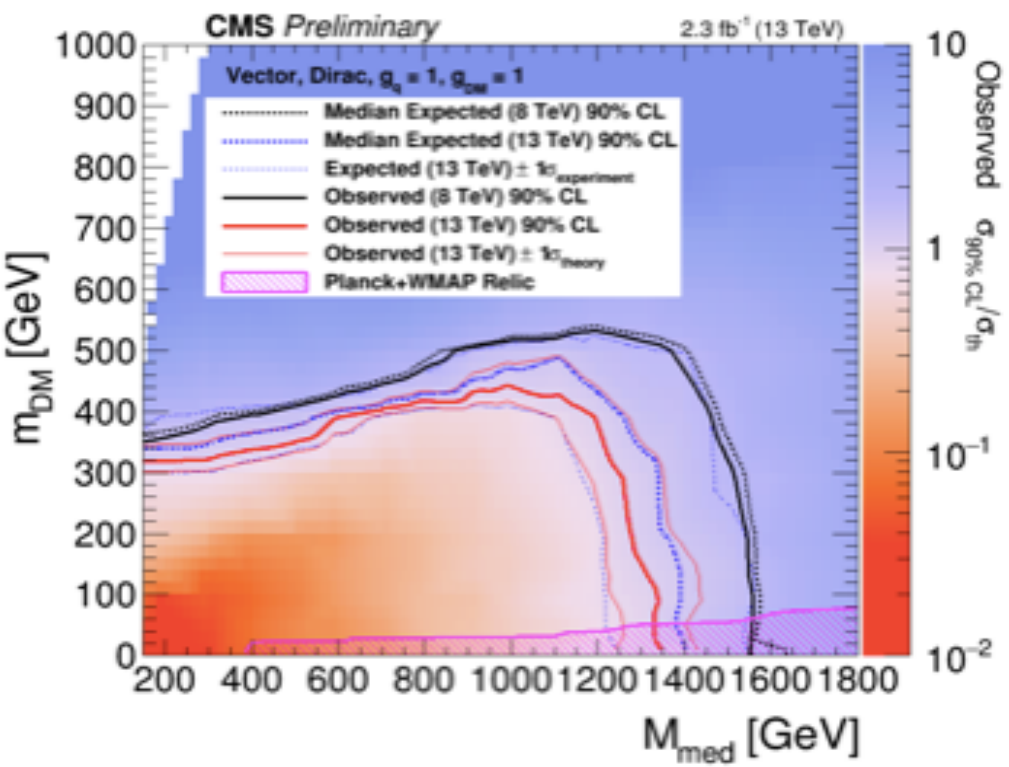


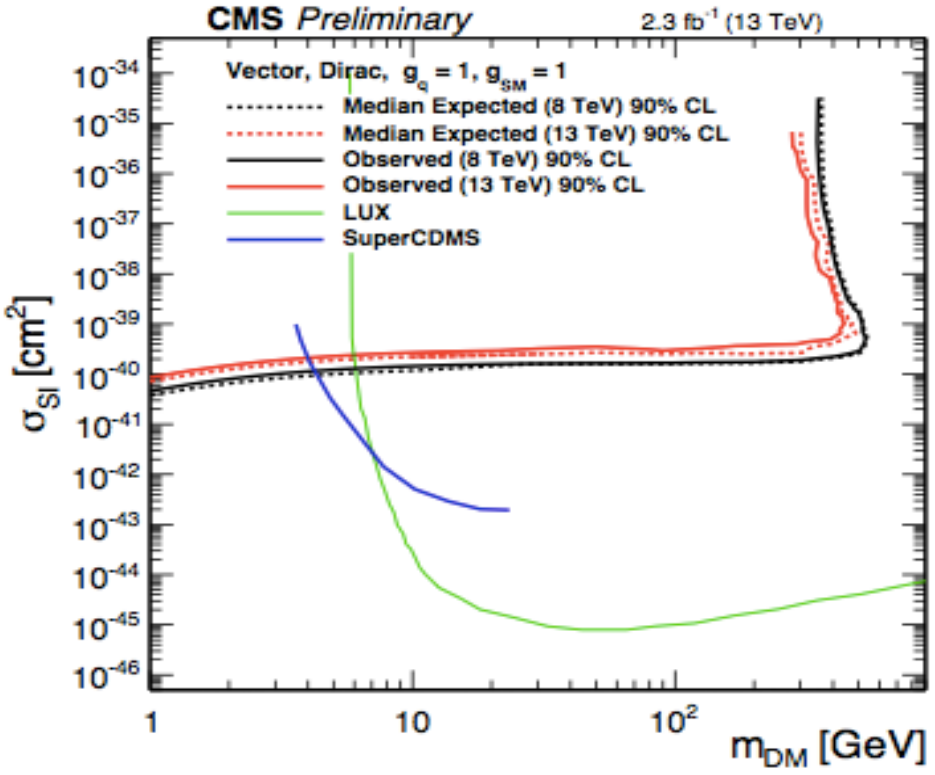
Combined Mono-jet/V

With Vector Mediator

Exclusion limit at 90% CL on (M_{Med}, m_{DM}) plane

Results compared to LUX and Super CDMS in plane(m_{DM}- $\sigma_{SI/SD}$)





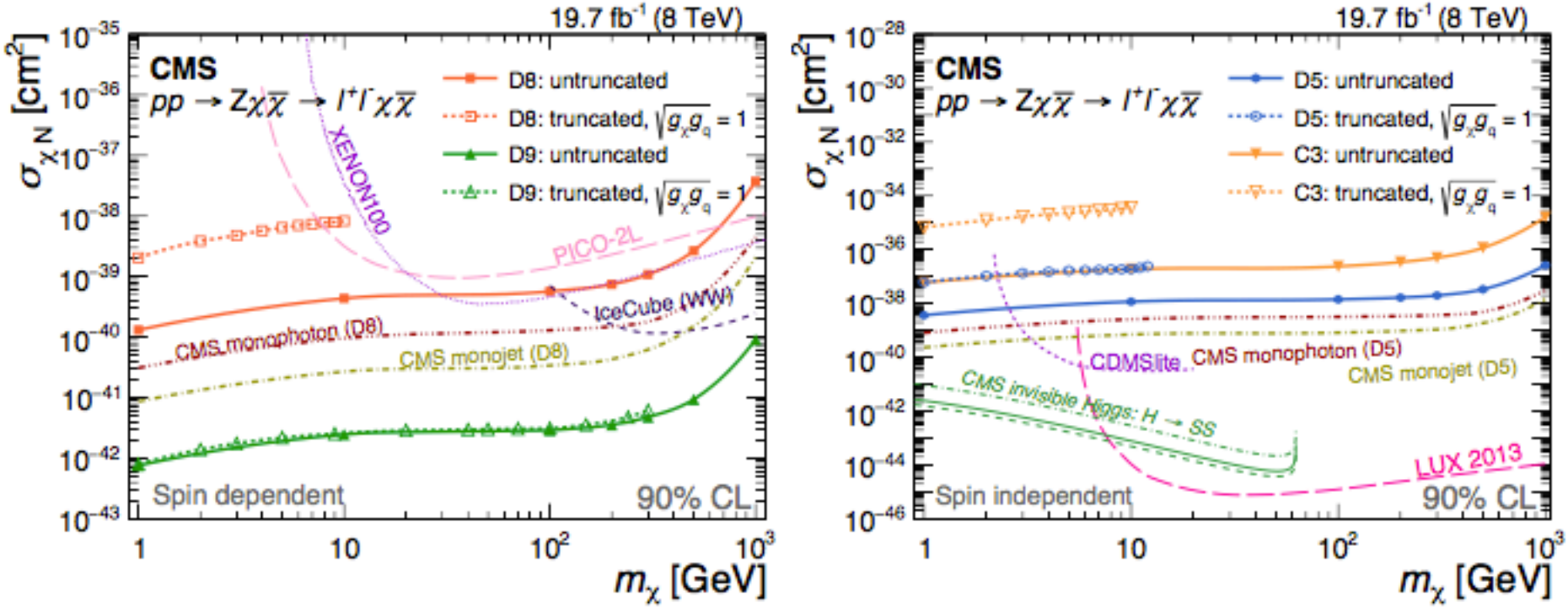


Figure 7: The 90% CL upper limits on the DM-nucleon cross section as a function of the DM particle mass. Left: spin-dependent limits for axial-vector (D8) and tensor (D9) coupling of Dirac fermion DM candidates, together with direct search experimental results from the PICO [101], XENON100 [102], and IceCube [7] collaborations. Right: spin-independent limits for vector coupling of complex scalar (C3) and Dirac fermion (D5) DM candidates, together with CDMSlite [8], LUX [11], as well as Higgs-portal scalar DM results from CMS [96] with central (solid), minimum (dashed) and maximum (dot dashed) values of Higgs-nucleon couplings. Collider results from CMS monojet [14] and monophoton [16] searches, interpreted in both spin-dependent and spin-independent scenarios, are shown for comparison. The truncated limits for D5, D8, D9, and C3 with $\sqrt{g_q g_\chi} = 1$ are presented with dashed lines in same shade as the untruncated ones.

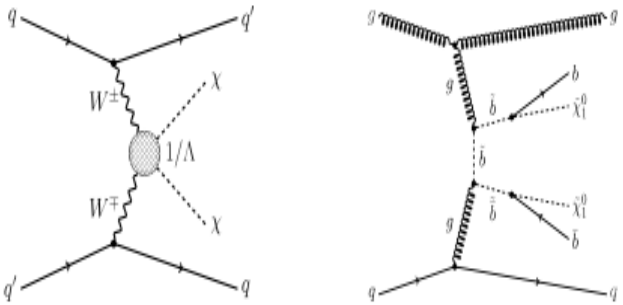


Figure 1: Feynman diagrams for dark matter pair production in a vector boson fusion process (left) and for bottom squark pair production (right). Given a nearly degenerate bottom squark and LSP, the final state b-quarks are too soft to be observed.

arXiv:1605.09305, Today

First ever search for direct pair production of DM through pure elec- troweak vector boson fusion (VBF) processes at a hadron collider.

The production of DM via VBF with masses below 420 GeV is excluded at a 95% confidence level for a chosen contact interaction scale Λ = 600 GeV.

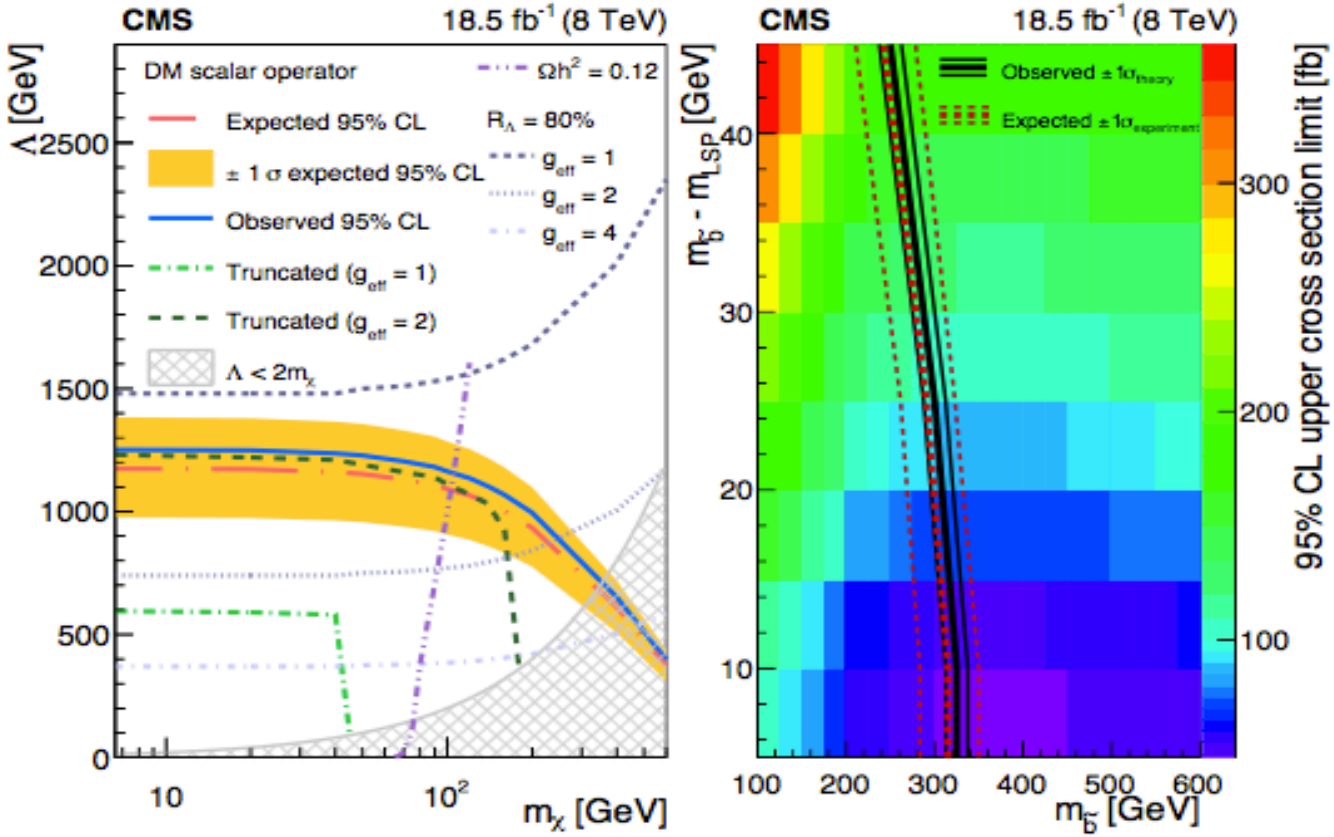


Figure 3: (left) Contact interaction scale limit at 95% CL as a function of the DM mass. The validity of the effective field theory is quantified by (i) $R_\Lambda = 80\%$ contours and (ii) truncated limits for different values of the effective coupling. The DM relic abundance $\Omega h^2 = 0.12$ is calculated as described in the text. (right) Bottom squark pair production 95% CL upper cross section limit as a function of the bottom squark mass and the mass difference between the bottom squark and the LSP. The observed (expected) cross section limit includes one standard deviation bands for the theoretical (experimental) uncertainty.

Conclusions

- Dark matter candidate is searched in mostly Mono-X searches at CMS using 8/13 TeV data.
- ATLAS-CMS DM forum gives a common platform for possible benchmark models and interpretation therof.
- No sign of DM so far but we could increase discovery and exclusion power of DM searches.
- LHC has restarted and we are hopeful to uncover more dark matter specific topologies.

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Stay Tuned