

Search for Dark Matter in Mono-X at CMS

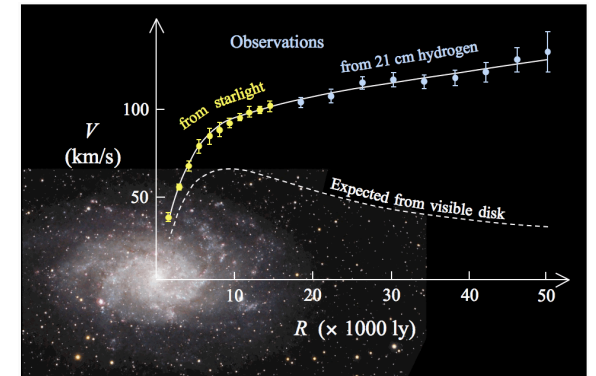
Shuichi Kunori

18-May-2017

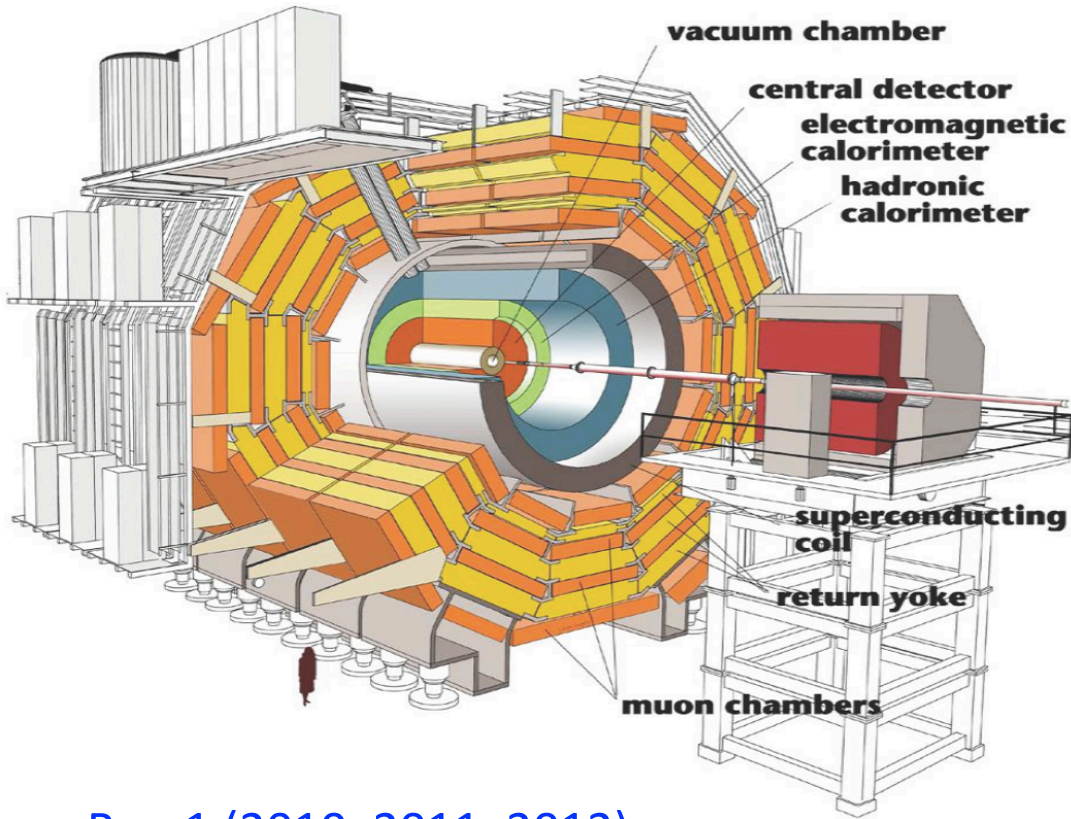
Mitchel Institute Workshop
On Collider and Dark Matter Physics

Dark Matter in Universe

- The well-established cosmological model says
 - 85% of the matter in the universe is dark matter (DM)
- There are strong astrophysical evidence of the existence of DM.
 - Those are only via gravitational interactions, e.g. galaxy rotation curve, gravitational lensing, bullet cluster
- There is no evidence of DM interaction with SM particles (yet).
 - Is the DM particle?
- Searches for DM particles (χ) in three types of experiments
 - Direct detection experiments χN scattering
 - Indirect detection experiments $\chi\chi$ annihilation
 - Collider (accelerator) experiments $\chi\chi$ production



CMS Detector



Run 1 (2010, 2011, 2012)

7 TeV 36 pb⁻¹, 5 fb⁻¹

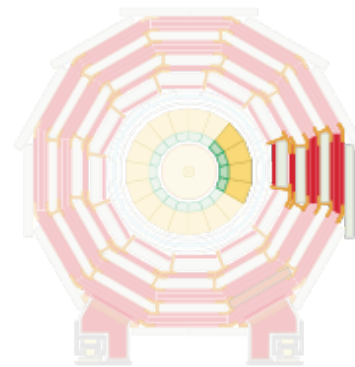
8 TeV 20 fb⁻¹,

Run 2 (2015, 2016)

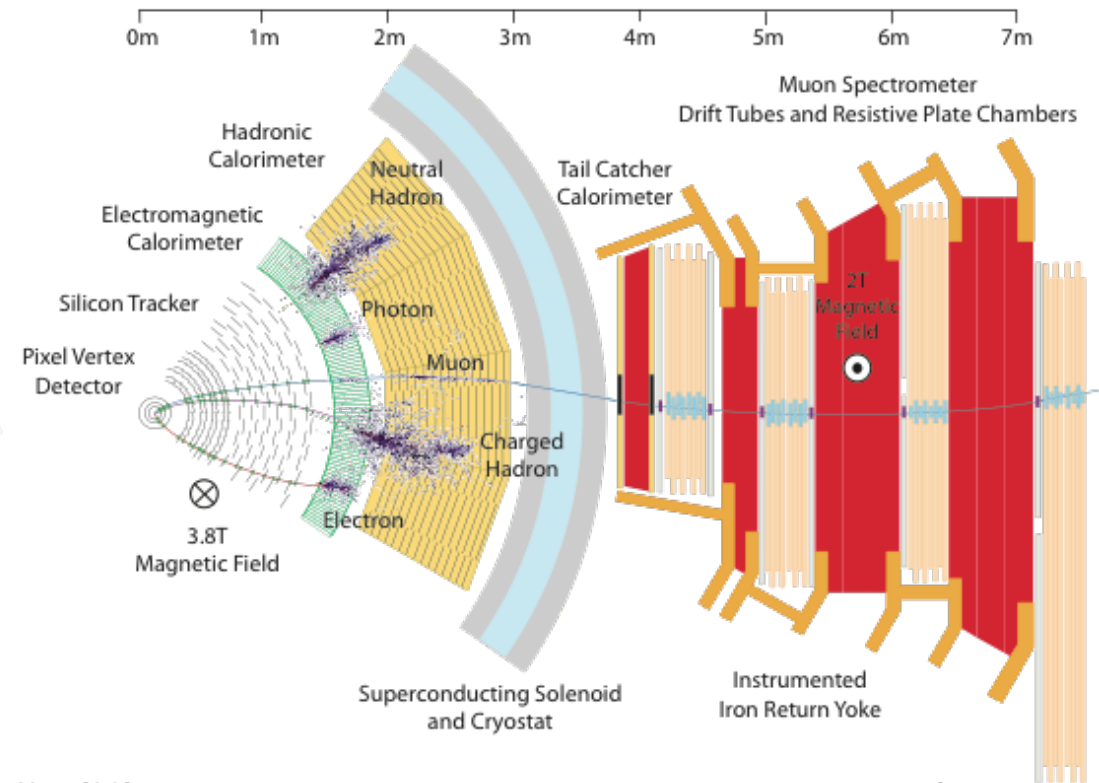
13 TeV 3 fb⁻¹, 36 fb⁻¹

2017 data taking starts in June.

Most of results shown today: 13 fb⁻¹



Transverse View of CMS Detector

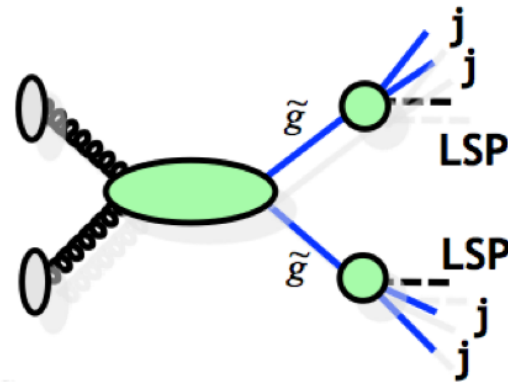


DM Searches in Run 1 (7/8 TeV) and Run2 (13TeV)

Property of Dark Matter: long life time (stable) and invisible (weak interaction) → escape from detector
 Signature: Missing Transverse Energy (MET) plus additional particles.

LSP (lightest SUSY particle) in decays of heavy particles

Missing E_T + jets +

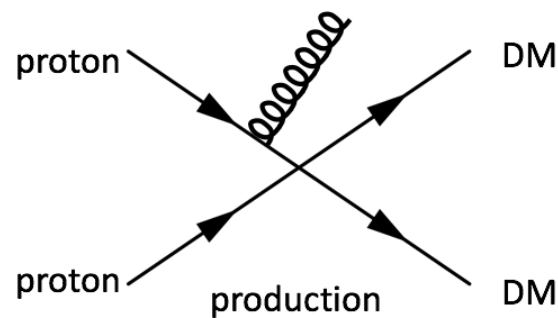


X (jet, γ , W, Z)

mono-X + Missing E_T

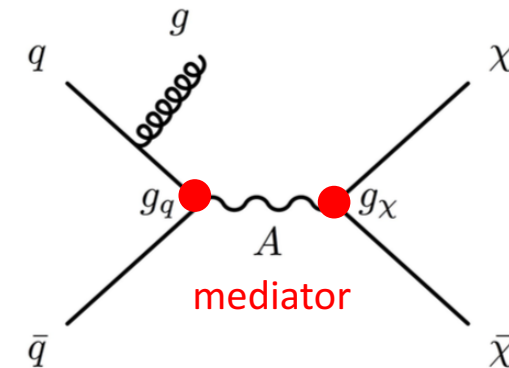
X: recoil against a pair of DM

gluon (jet), photon
 Z, W



EFT model (Run 1)

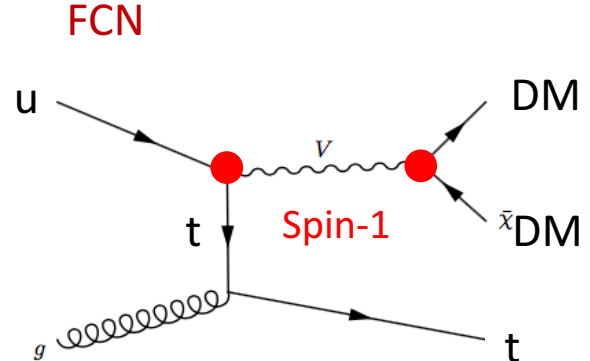
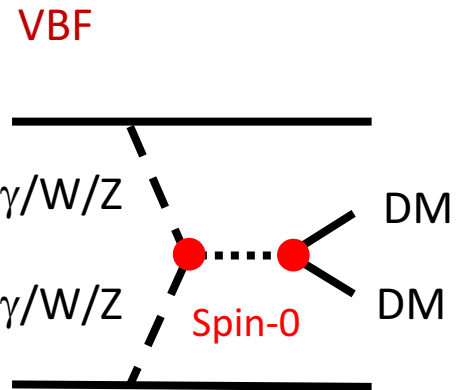
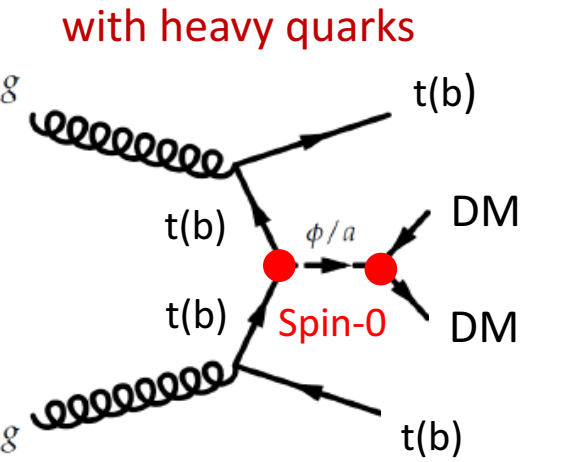
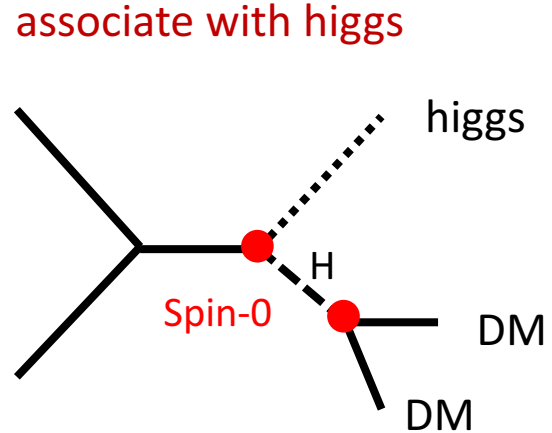
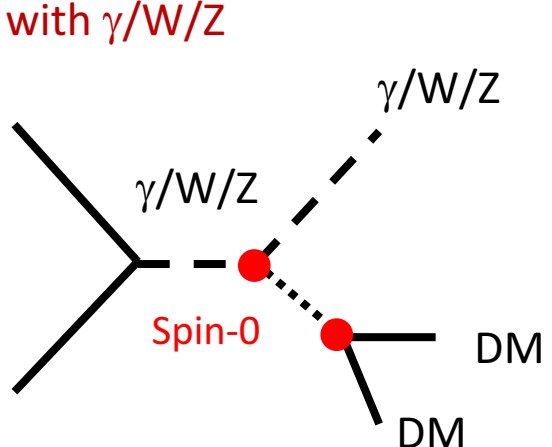
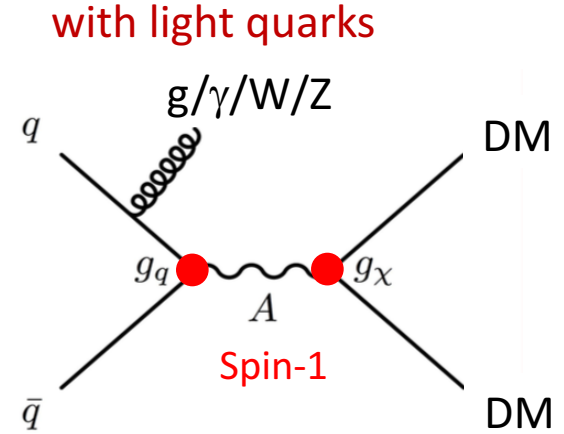
Parameters in Simplified Model:
 Mass(DM), Mass(med), $g(q)$, $g(\text{DM})$
 mediator width
 mediator (V, AV, S, PS)



Simplified model (Run 2)

DM Production at the LHC

Spin-1 and Spin-0 mediators coupling with DM and SM particles in simplified models.

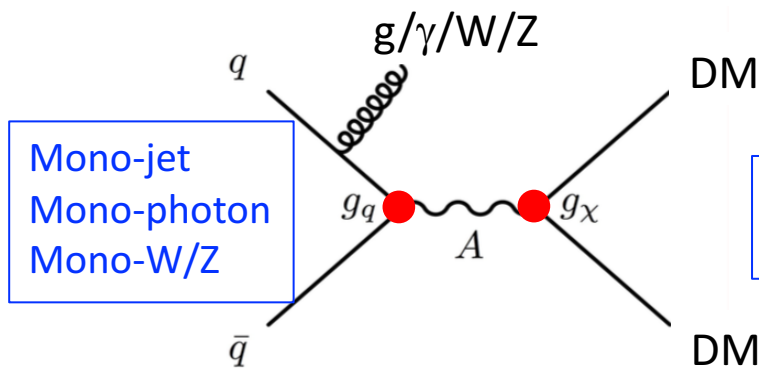


(not exhaustive list)

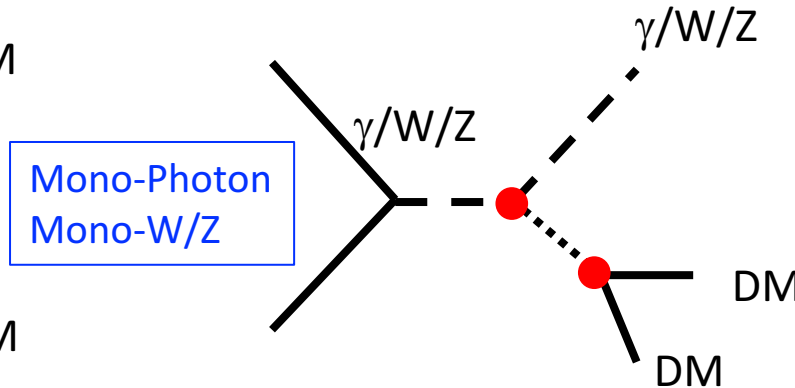
Signature – MET + X

Most of signal appear in **Mono-X**, where X is jet, photon, W, Z or higgs.

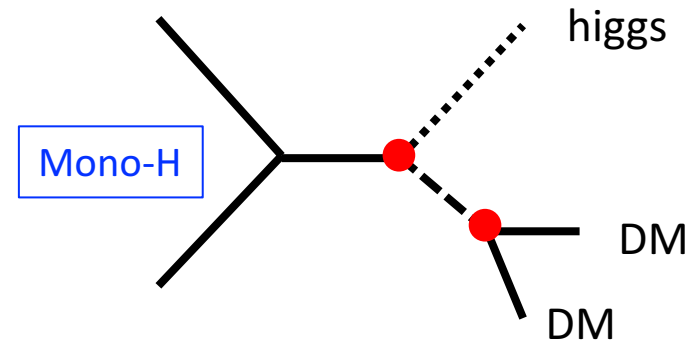
with light quarks



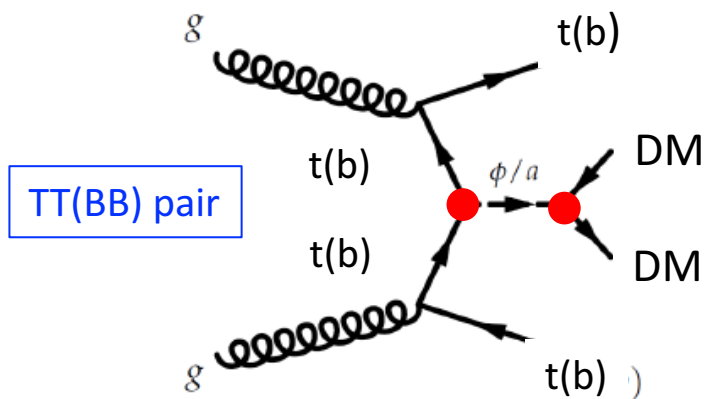
with $\gamma/W/Z$



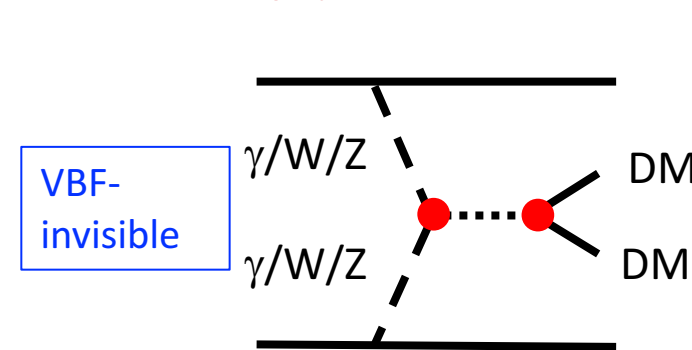
associate with higgs



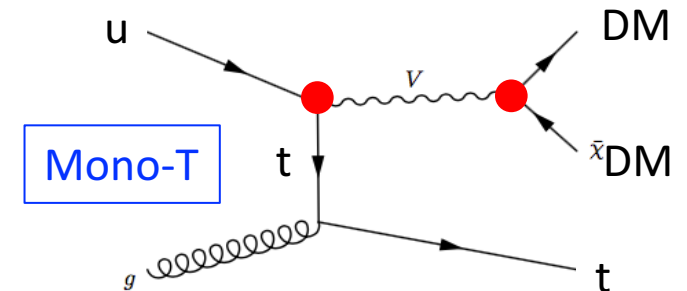
with heavy quarks



VBF

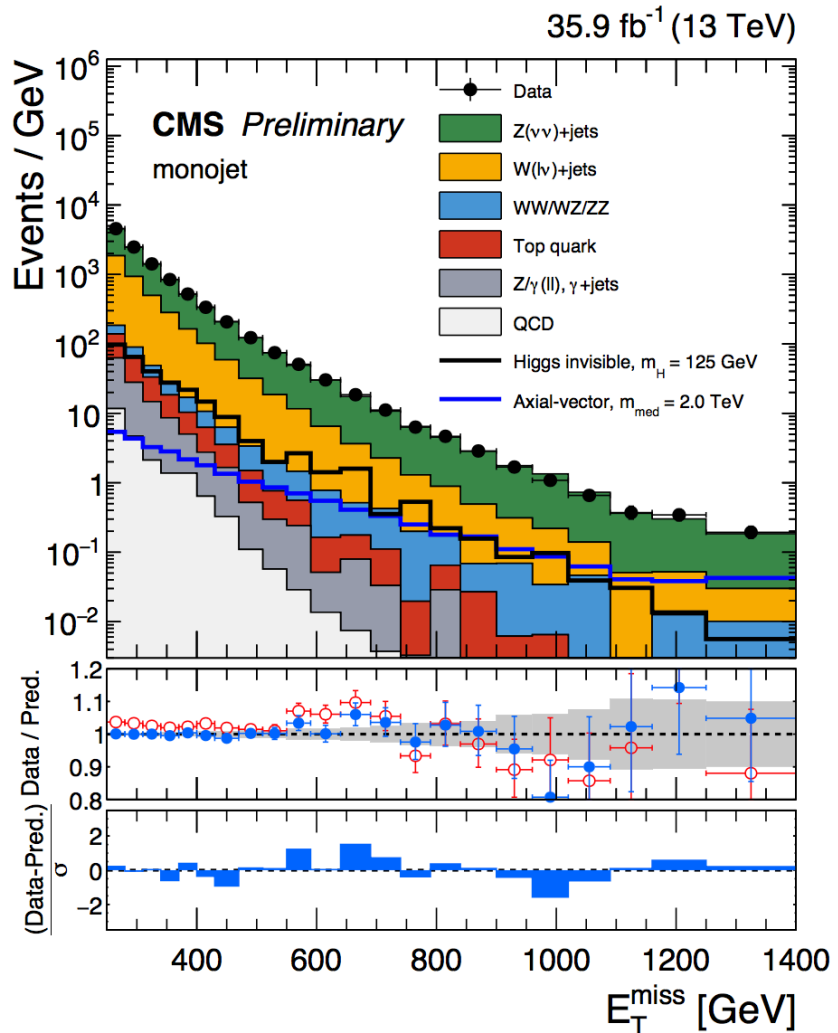
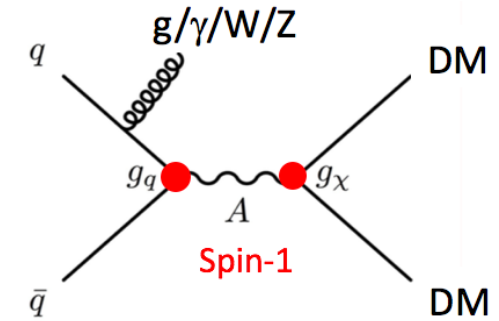


FCN



(not exhaustive list)

Monojet/Mono- γ /Mono-V



Mediator couple with light quarks.

Events are primarily selected with MET cuts in exponentially dumping MET spectra. Major remaining background are events with $Z(\nu\nu)$ or $W(l\nu)$ with lost lepton.

Mono-jet

Mono- γ

Mono-Z($ee, \mu\mu$)

Mono-V(had)

MET > 250 GeV

MET > 170 GeV

MET > 100 GeV

MET > 250 GeV

12.9 fb^{-1}

12.9 fb^{-1}

12.9 fb^{-1}

12.9 fb^{-1}

308613 events

400 events

265 events

7754 events

$Z(\nu\nu)+\text{jets}$ 60 %

$Z(\nu\nu)\gamma$ 55 %

$ZZ(\nu\nu)+WZ(\nu\nu)$

$Z(\nu\nu)+\text{jets}$ 55 %

$W(l\nu)+\text{jets}$ 35 %

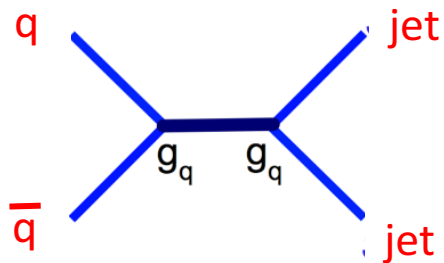
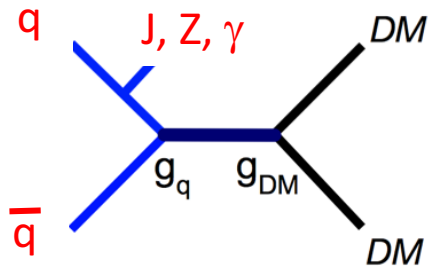
$W(l\nu)\gamma$ 15 %

75 %

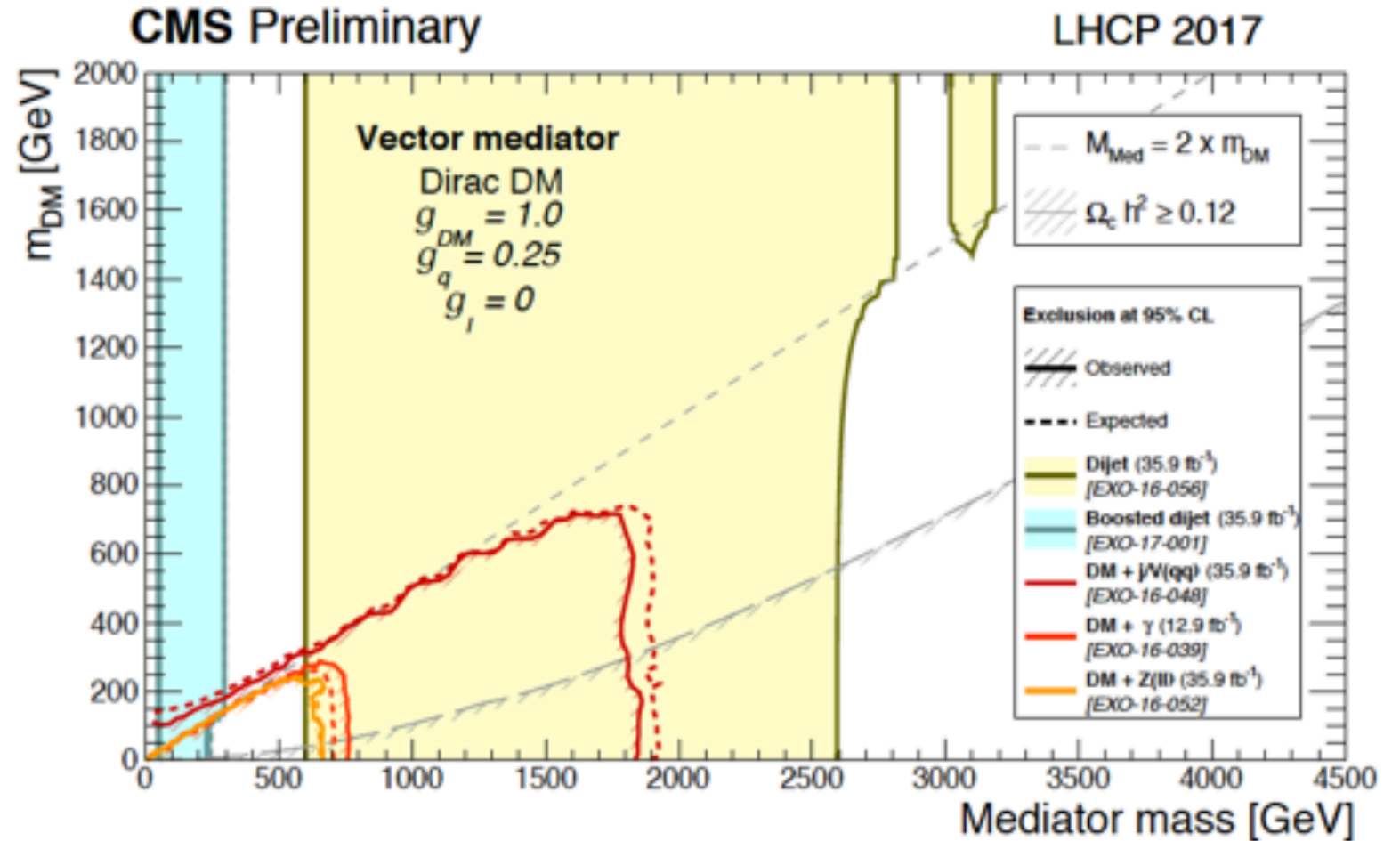
$W(l\nu)+\text{jets}$ 30 %

Search for Mediator in dijets

$$g_q = 0.25, g_{DM} = 1$$



Mono-J/Z(γ)	36 fb^{-1}
Mono-γ	13 fb^{-1}
Dijet	36 fb^{-1}



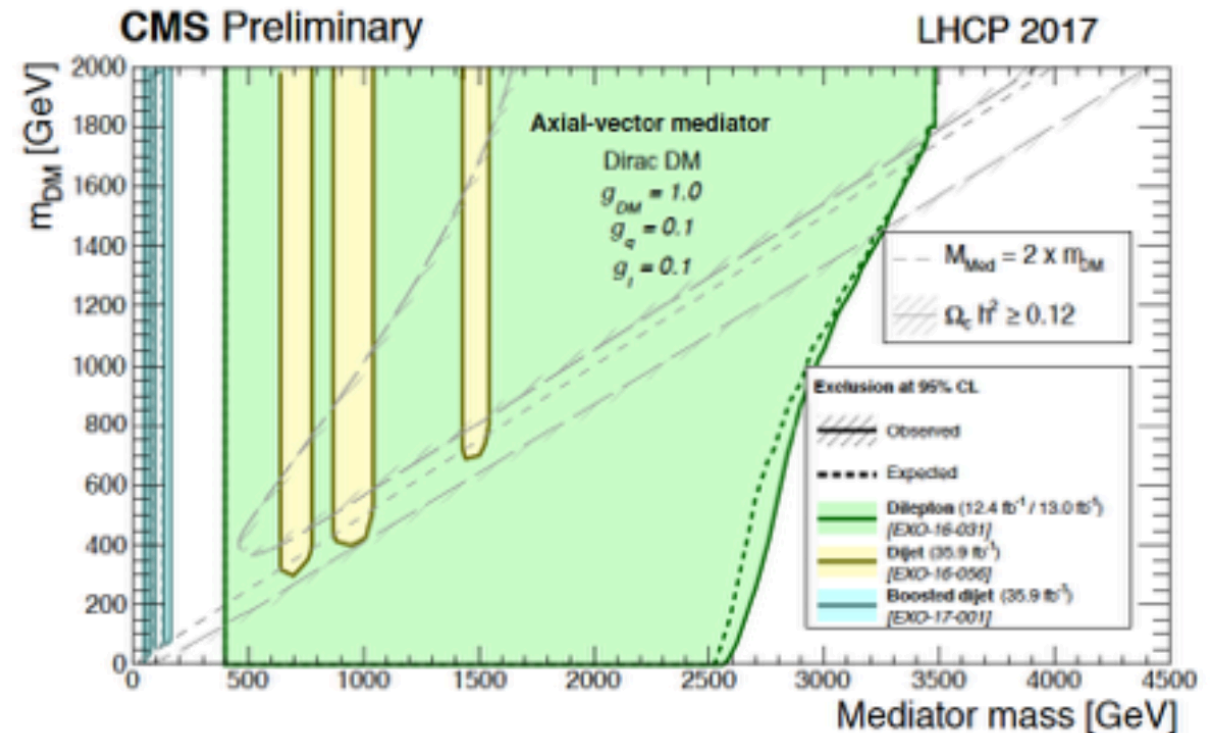
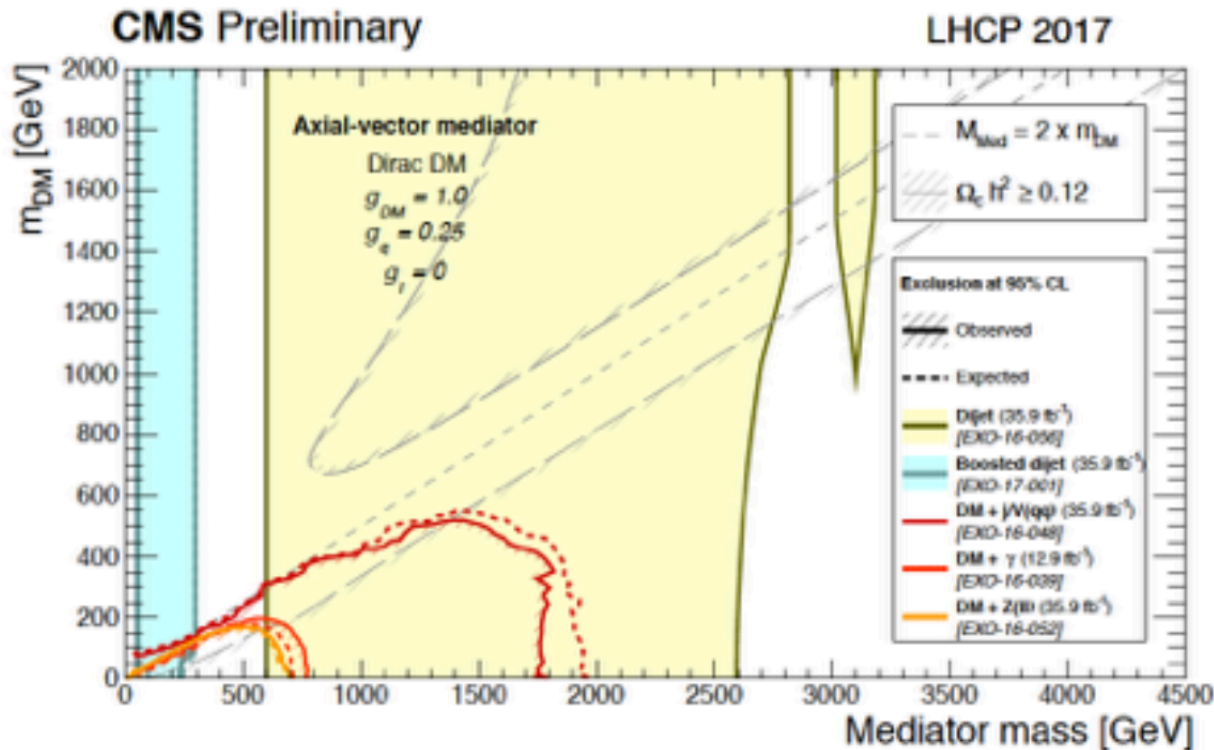
Searches for AV-Mediator: mono-X vs dijet

$g(q) = 0.25, g(\text{DM}) = 1.0$

$\text{BR}(Z' \rightarrow \text{jets}) \sim \text{BR}(Z' \rightarrow \text{DMDM})$

$g(q) = 0.1, g(l) = 0.1, g(\text{DM}) = 1.0$

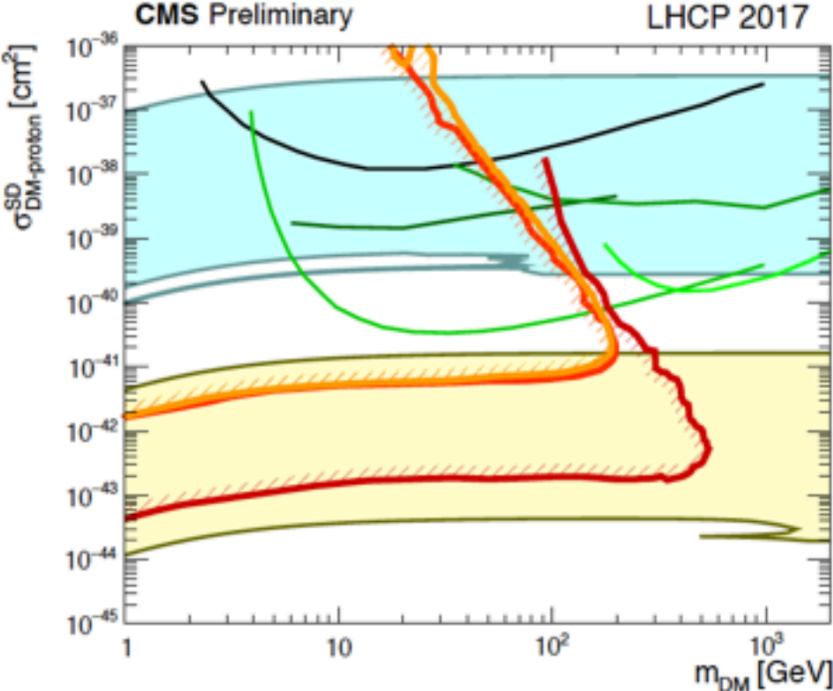
$\text{BR}(Z' \rightarrow \text{jets}) < \text{BR}(Z' \rightarrow \text{DMDM})$



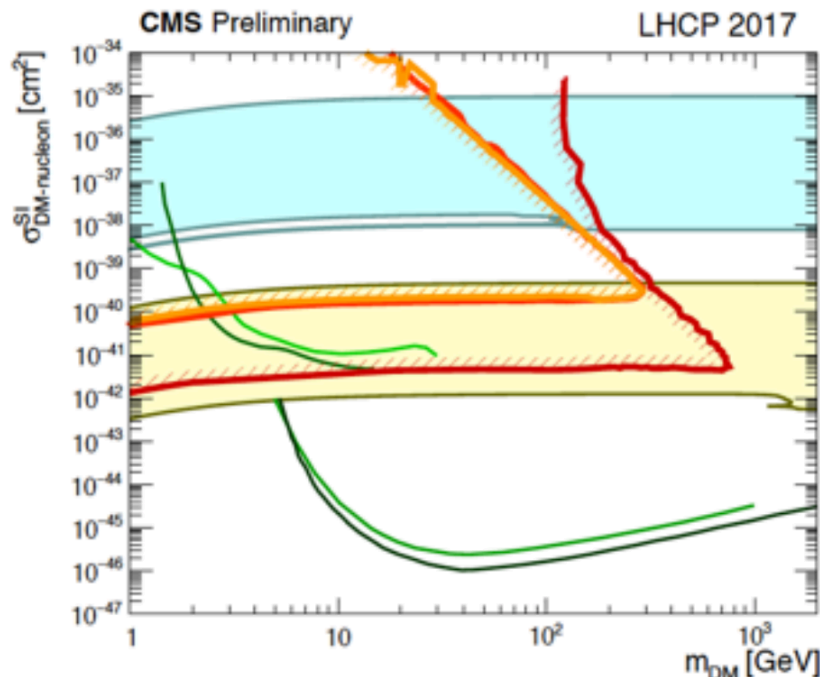
Exclusion area strongly depends on the coupling constants.

Exclusion Limits on $\sigma_{\text{DM-N}}$ scattering

$g_q = 0.25, g_{\text{DM}} = 1.0$



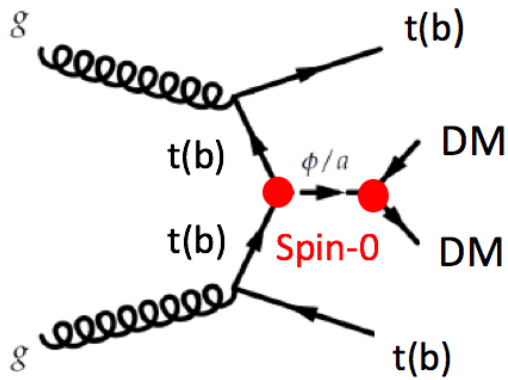
- CMS observed exclusion 90% CL**
Axial-vector med., Disc DM; $g = 0.25, g_{\text{DM}} = 1.0$
- Boosted dijet (35.9 fb⁻¹) [EXO-17-001]
 - Dijet (35.9 fb⁻¹) [EXO-16-056]
 - DM + jV_{eff} (35.9 fb⁻¹) [EXO-16-048]
 - DM + γ (12.9 fb⁻¹) [EXO-16-039]
 - DM + Z_0 (35.9 fb⁻¹) [EXO-16-052]
- DDID observed exclusion 90% CL**
- PICASSO [arXiv:1611.01499]
 - PICO-60 [arXiv:1702.07666]
 - Super-K ($b\bar{b}$) [arXiv:1503.04858]
 - IceCube ($b\bar{b}$) [arXiv:1612.05949]
 - IceCube (TI) [arXiv:1601.00653]



- CMS observed exclusion 90% CL**
Vector med., Disc DM; $g = 0.25, g_{\text{DM}} = 1.0$
- Boosted dijet (35.9 fb⁻¹) [EXO-17-001]
 - Dijet (35.9 fb⁻¹) [EXO-16-056]
 - DM + jV_{eff} (35.9 fb⁻¹) [EXO-16-048]
 - DM + γ (12.9 fb⁻¹) [EXO-16-039]
 - DM + Z_0 (35.9 fb⁻¹) [EXO-16-052]
- DD observed exclusion 90% CL**
- CRESST-II [arXiv:1509.01515]
 - CDMSlite [arXiv:1509.02448]
 - PandaX-II [arXiv:1607.07400]
 - LUX [arXiv:1608.07648]

DM Mediator couple with heavy quarks

Top quark pair (or b-pair)



Top pair event category

Semileptonic: MET > 160 GeV 53 events

pT(lepton) > 30 GeV

MT(Lepton, MET) > 160 GeV

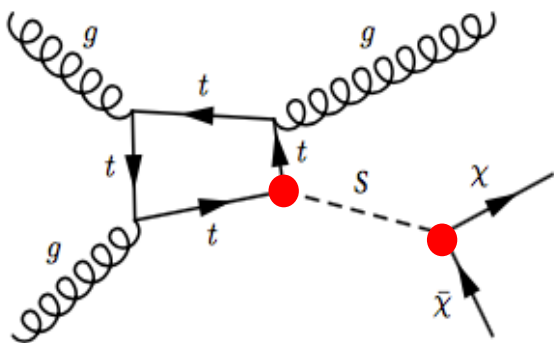
All hadronic: MET > 200 GeV

inclusive (2 b-tags) 333 events

two top tags (MVA) 181 events

less than two top tags (MVA) 305 events

Monojet



MVA inputs:

quark/gluon discriminants

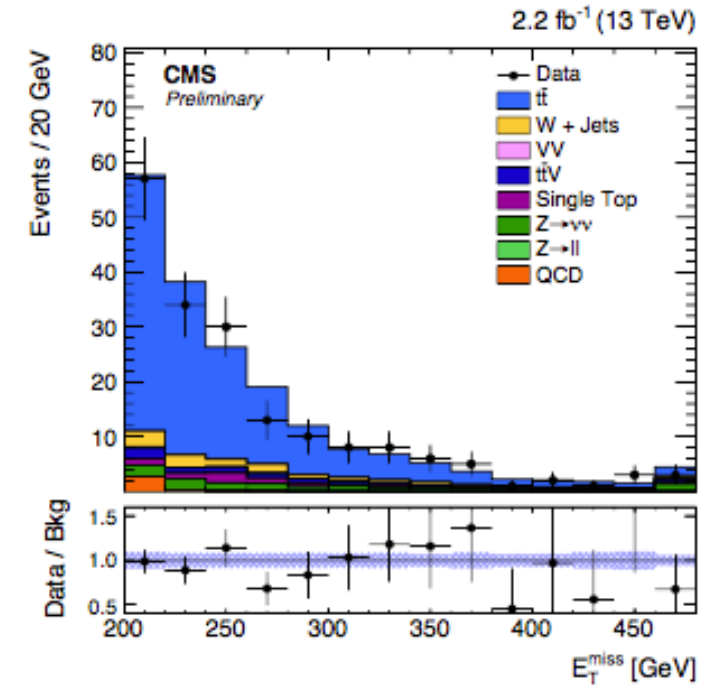
b-tag discriminants

angle between two jets from W

Monojet MET > 250 GeV

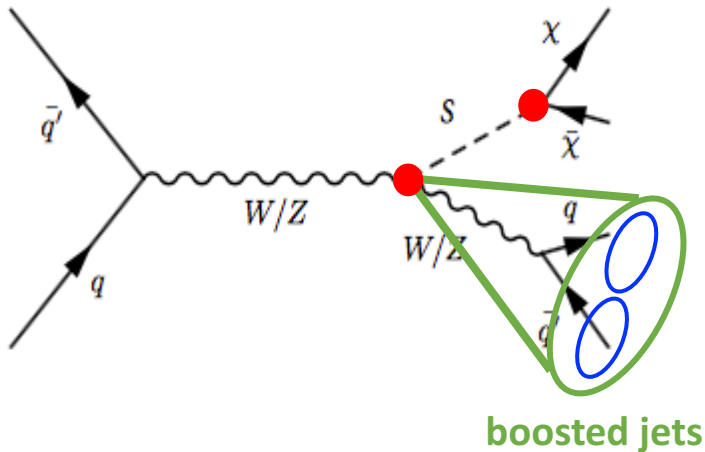
308613 events

MET for two top tagged events



DM Mediator couple with W/Z/ γ

Mono-V(hadronic)



Mono-V(had)

MET > 250 GeV

7754 events

no lepton

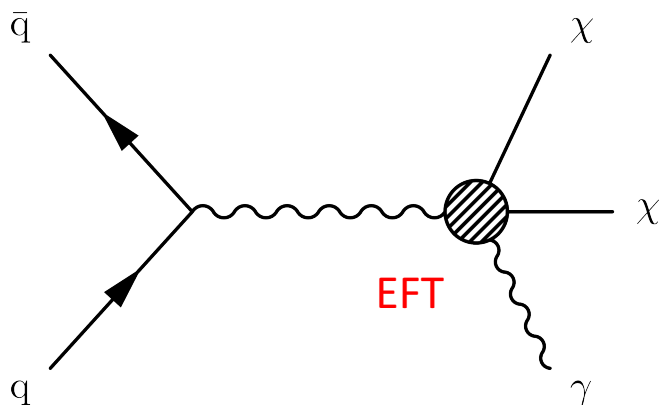
W/Z(had) selection

$p_T(\text{AK8 jet}) > 250 \text{ GeV}$

mass(AK8 jet) in W/Z region

jet subjetness (τ_2/τ_1)

Mono-photon



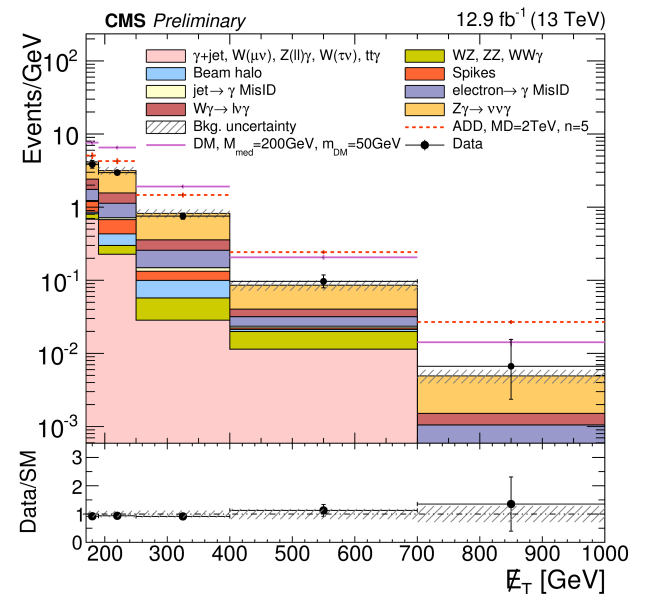
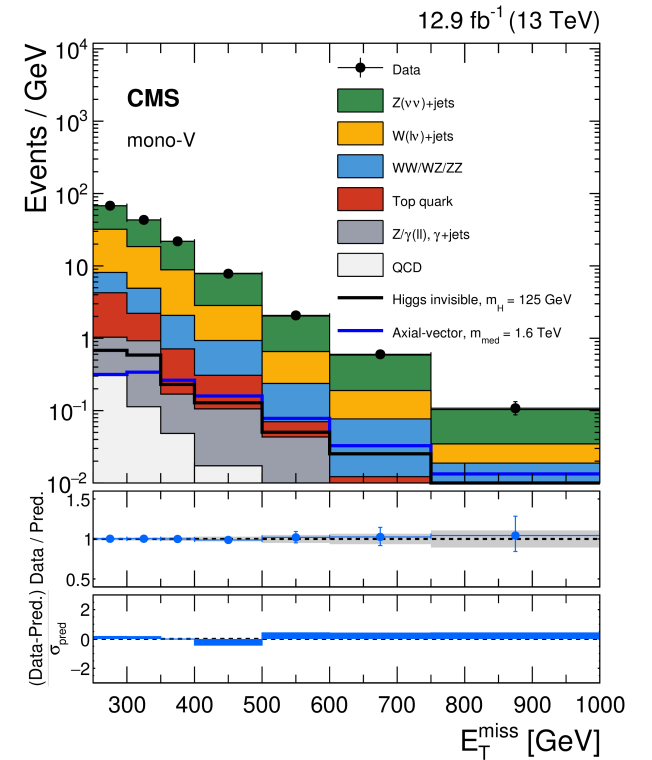
Mono-photon

MET > 170 GeV

400 events

γ : $P_t > 175 \text{ GeV}$

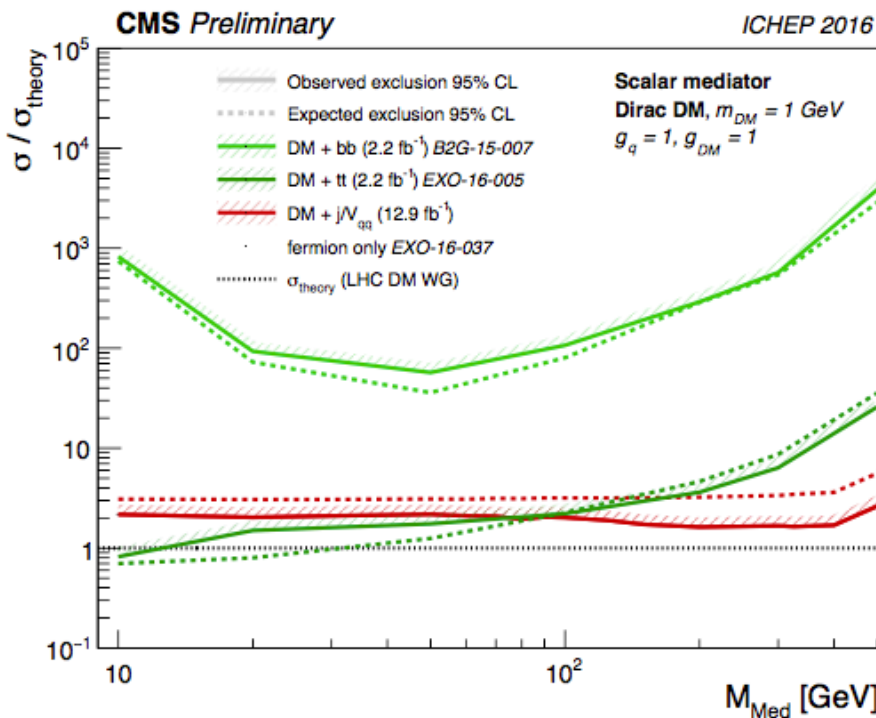
$|h| < 1.44$



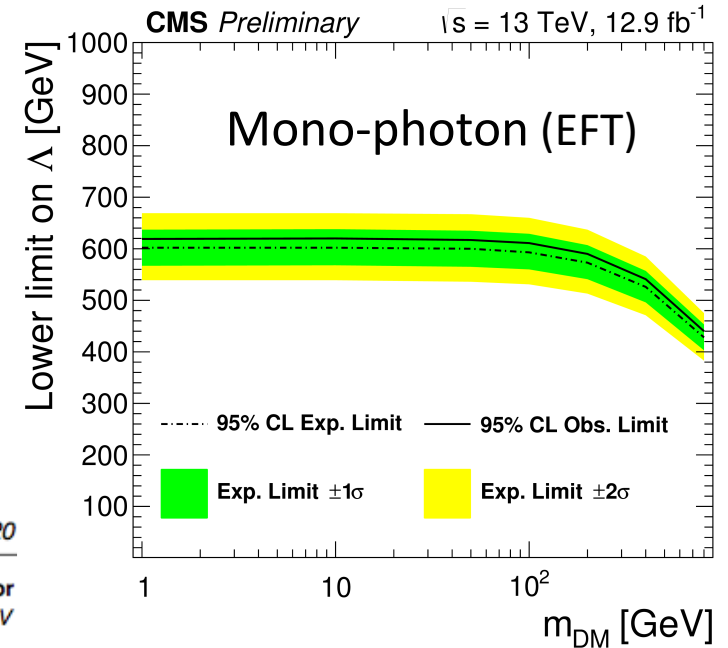
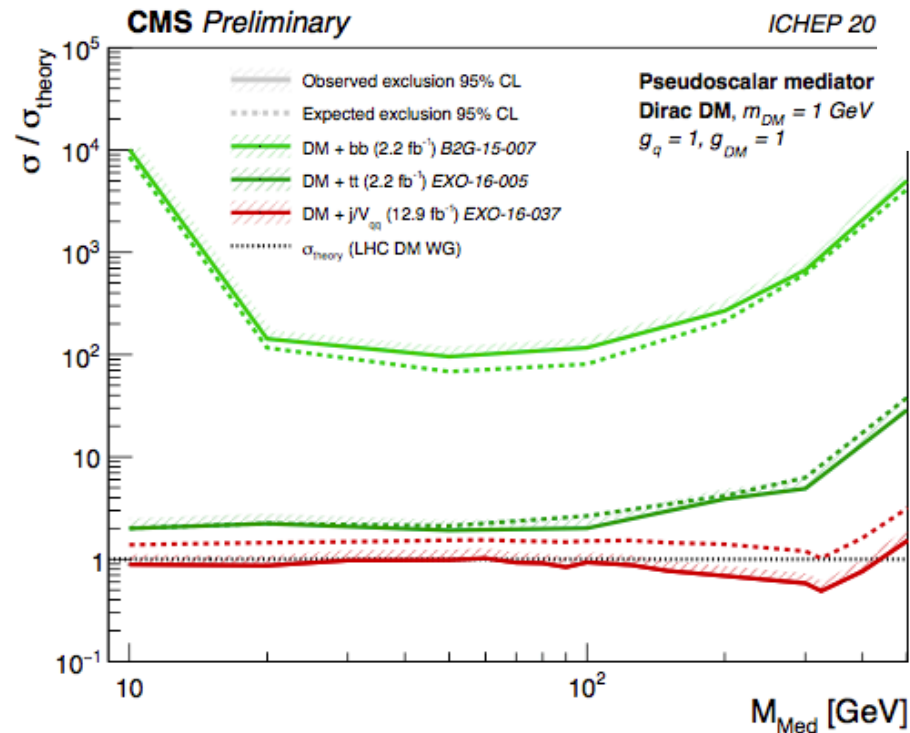
Exclusion Limits on spin-0 mediator

$$bb - \chi\chi, \quad tt - \chi\chi, \quad WW - \chi\chi$$

Scalar mediator



Pseudoscalar mediator



bb $\rightarrow \phi \rightarrow \text{DMDM}$

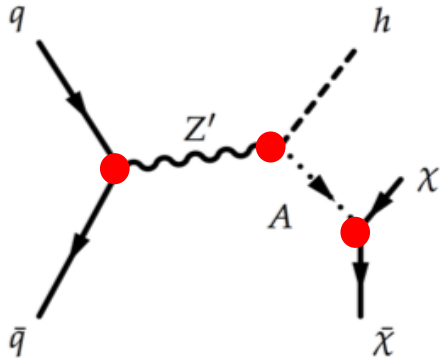
tt $\rightarrow \phi \rightarrow \text{DMDM}$

WW (ZZ) $\rightarrow s \rightarrow \text{DMDM}$

$Z' \rightarrow \text{higgs} + A, A \rightarrow \chi\chi$

Z'-2HDM

Mono-higgs



$h \rightarrow \gamma\gamma$

$\gamma: p_t > 20 \text{ GeV}, |h| < 2.5$

$\text{MET} > 105 \text{ GeV}$

$h \rightarrow bb$

resolved: 44 events

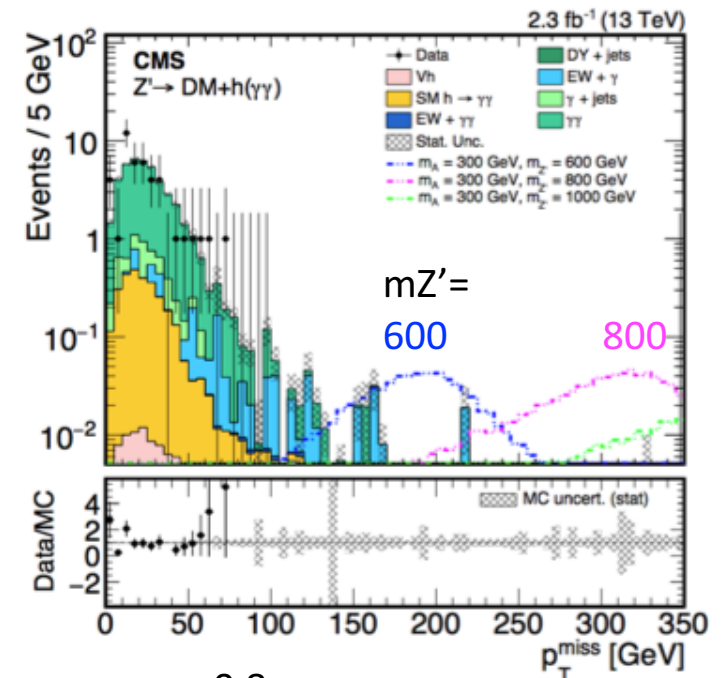
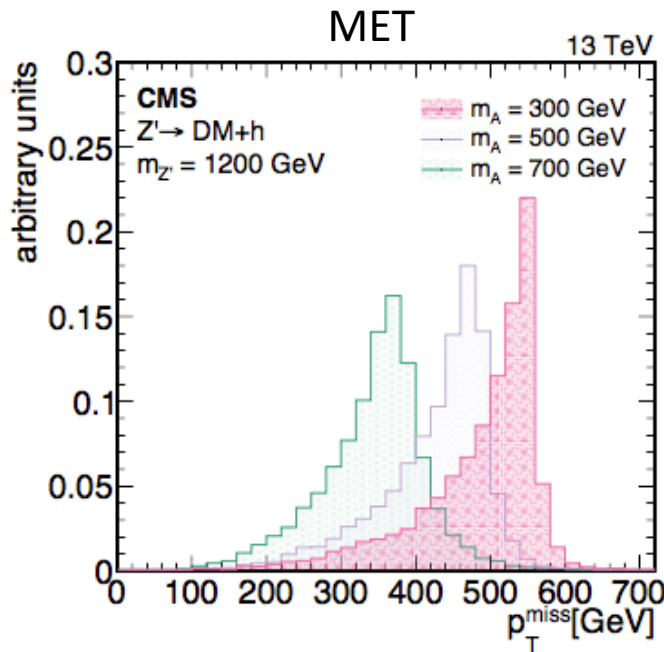
$\text{MET} > 170 \text{ GeV}$

$\text{jet(AK4)}: p_t > 30 \text{ GeV}, |h| < 2.4$

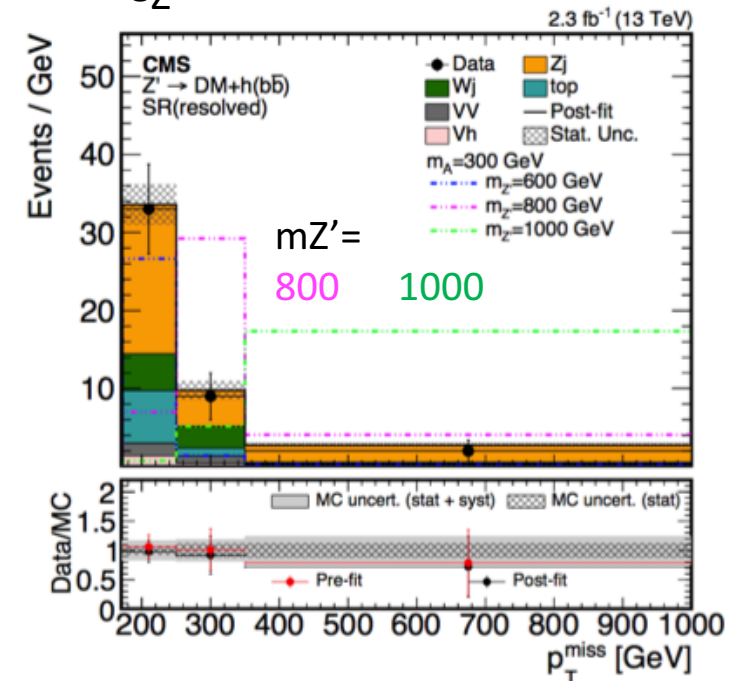
boosted: 38 events

$\text{MET} > 200 \text{ GeV}$

$\text{jet(AK8)}: p_t > 200 \text{ GeV}$

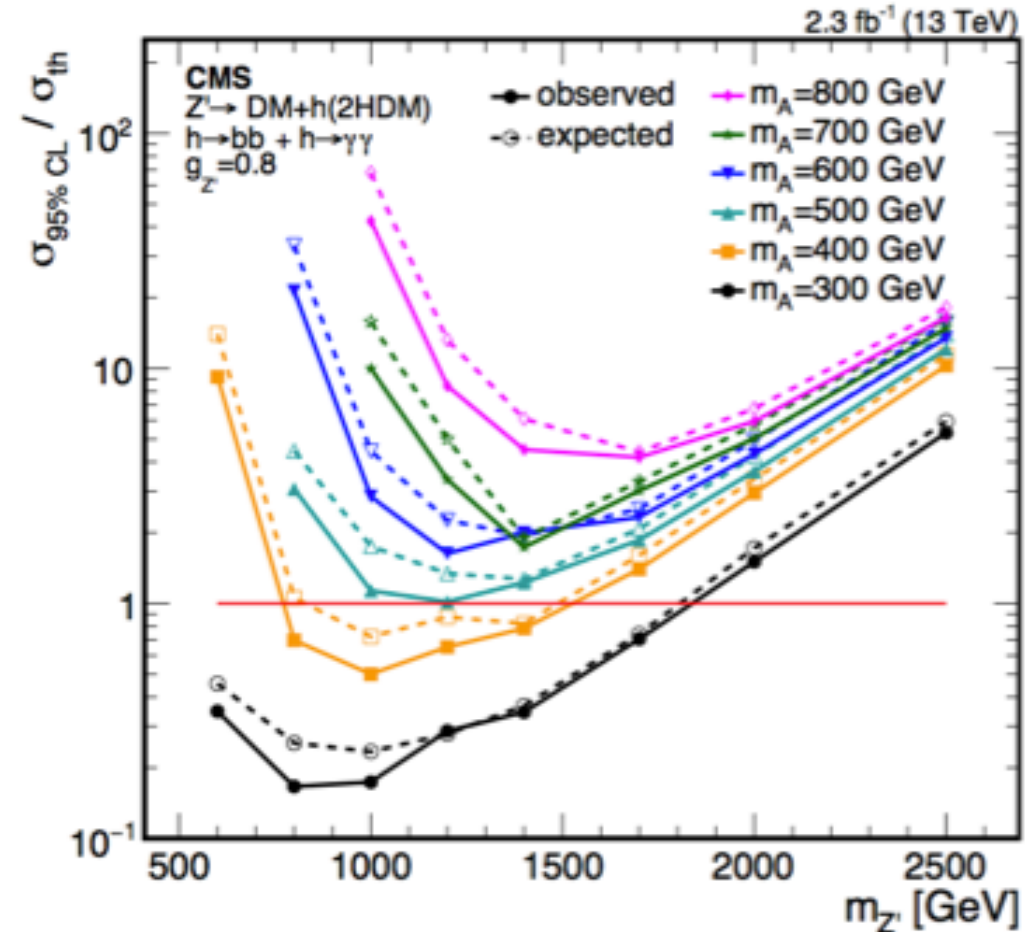
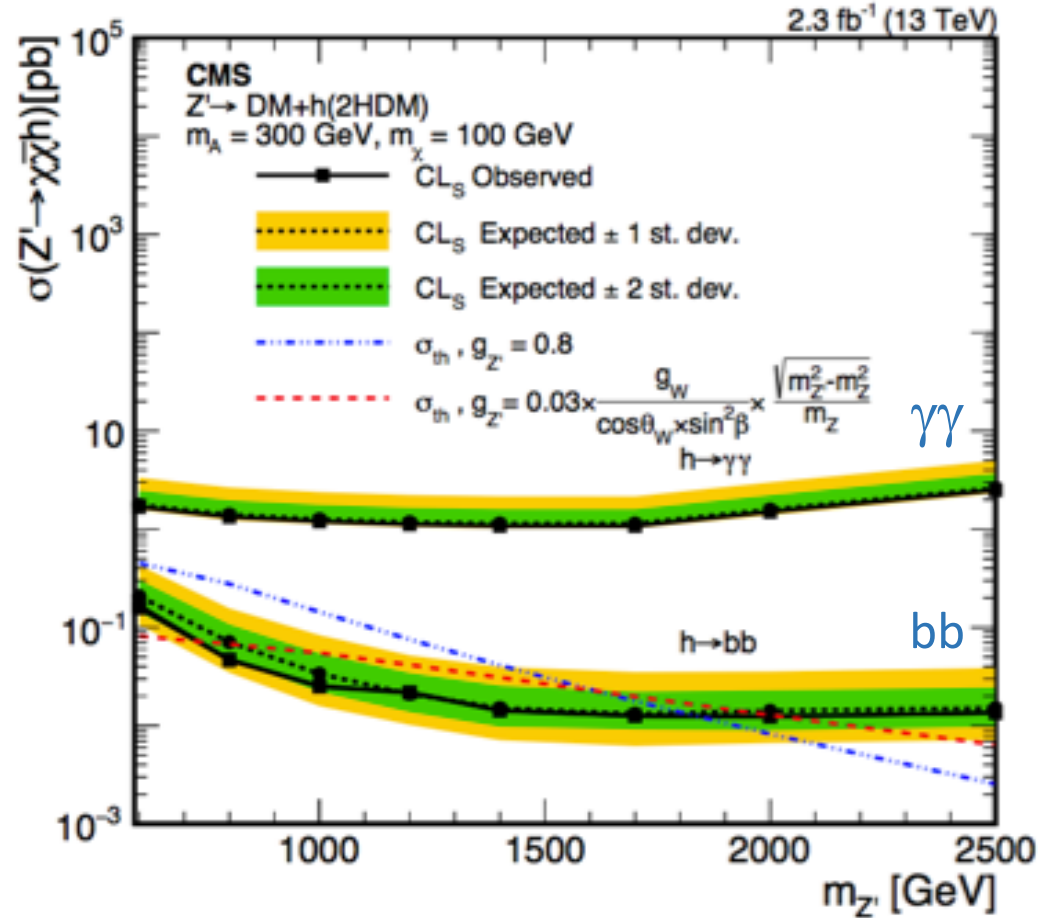
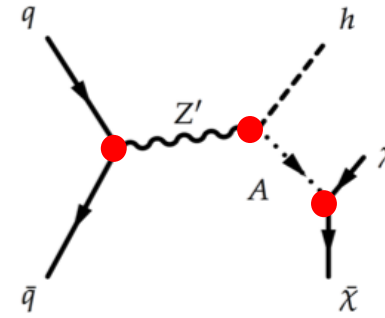


$g_{Z'} = 0.8$



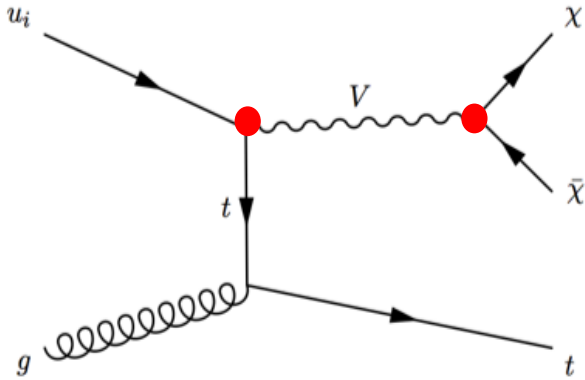
$Z' \rightarrow \text{higgs} + A, A \rightarrow \chi\chi$

Mono-higgs

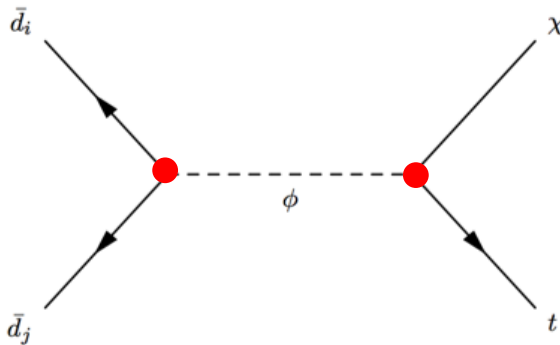


Mono-top (hadronic)

Flavor changing neutral current (FCNC)



Colored scalar mediator



Mono-top

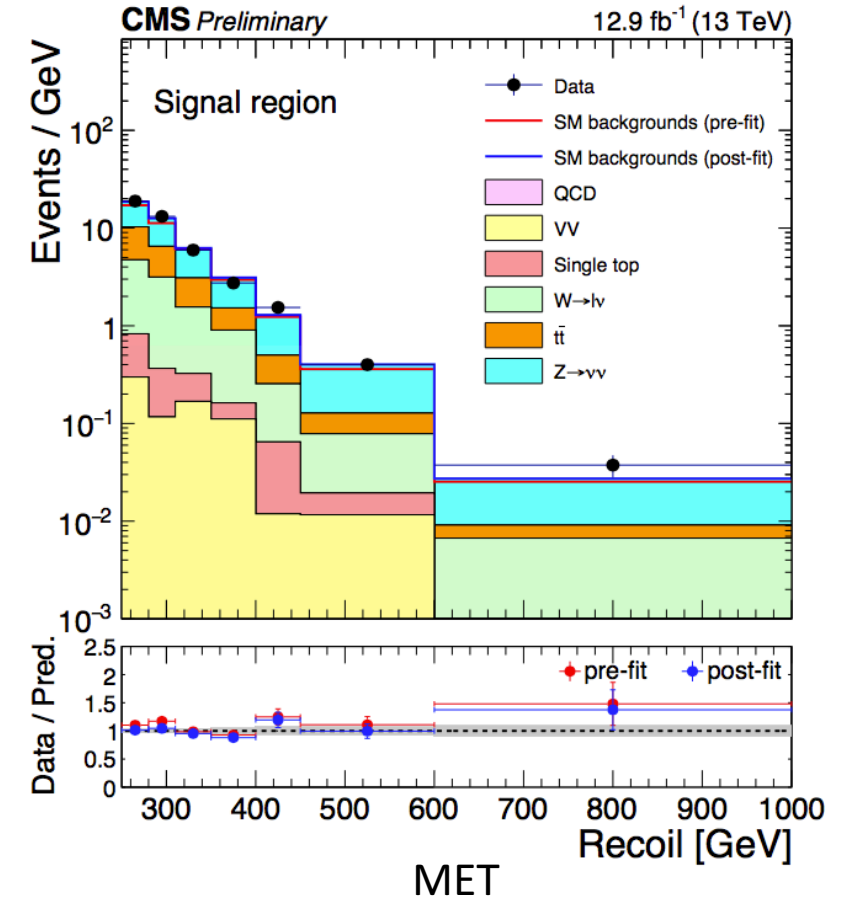
MET > 250 GeV
no lepton

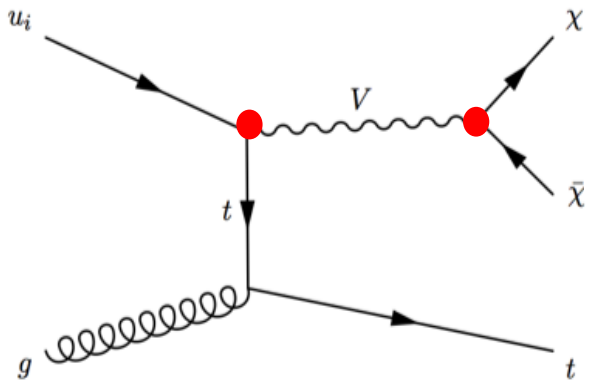
top-tag (boosted)

jet mass [110,210] GeV
subjettiness (τ_3/τ_2)

b-tag
→ eff 13 %

Baryon number: $-2/3 \rightarrow +1/3$
DM number: $0 \rightarrow 1$



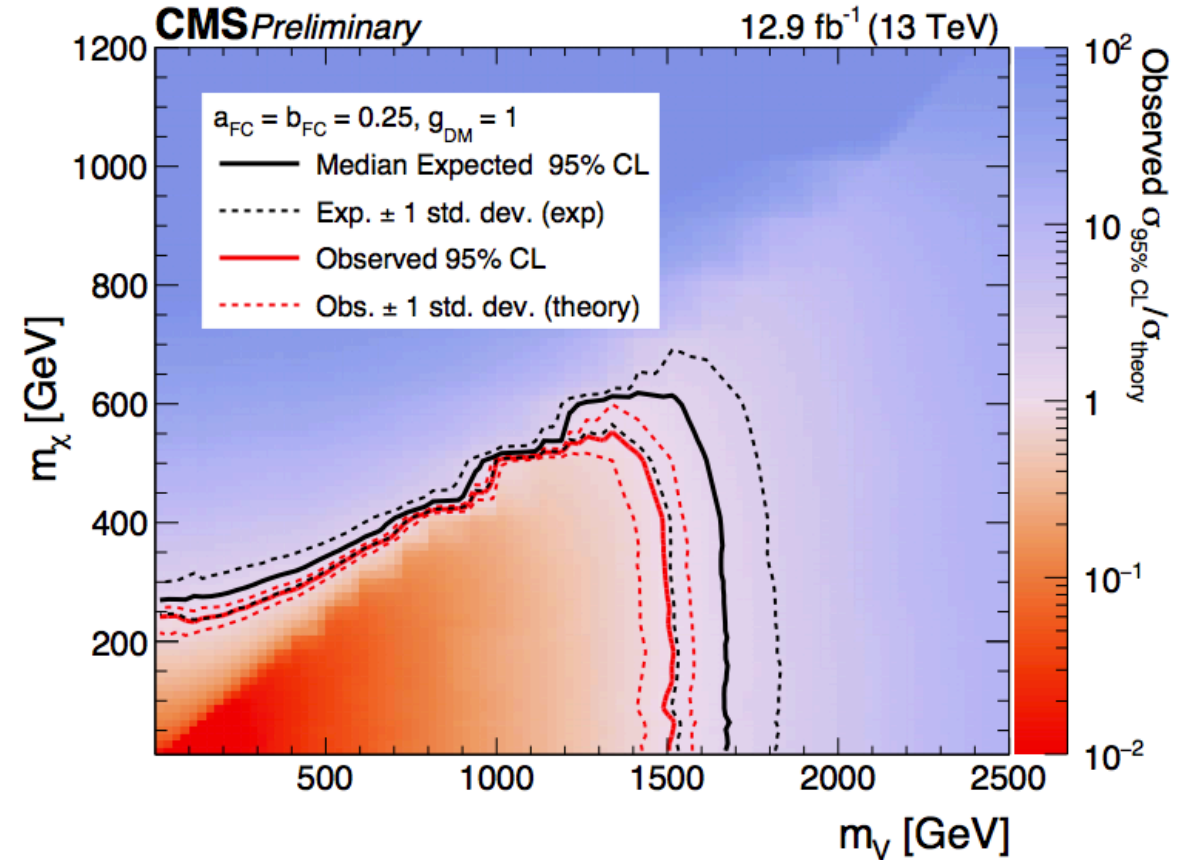
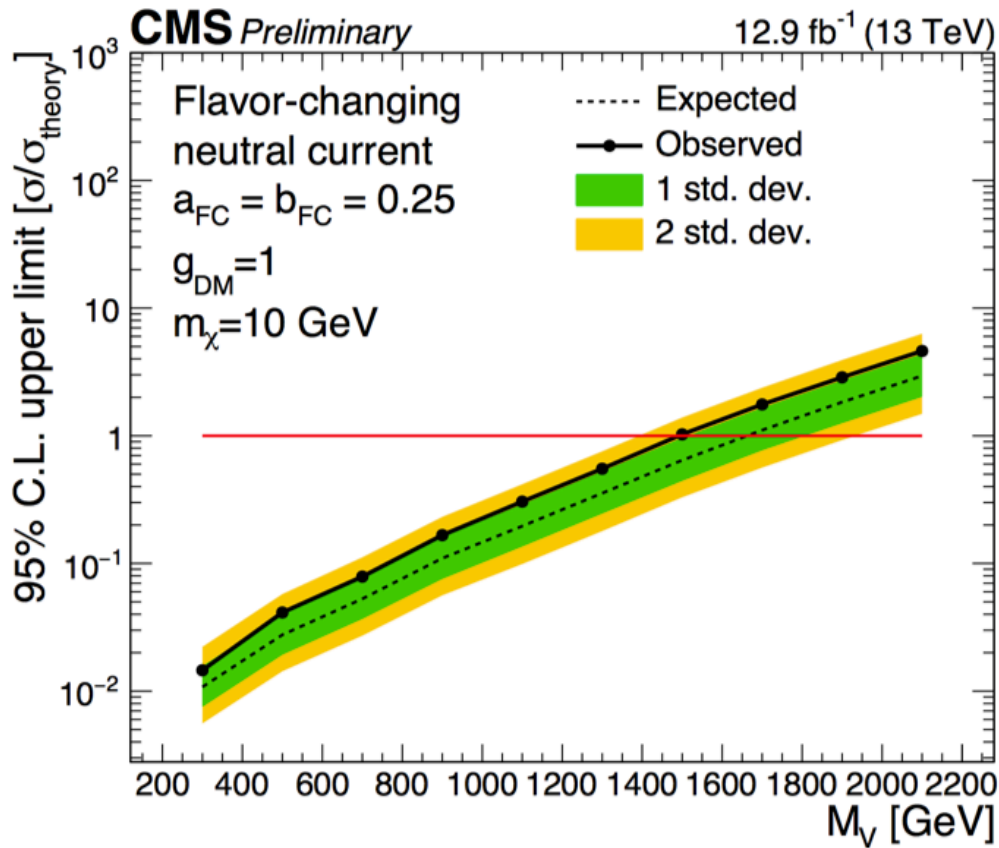


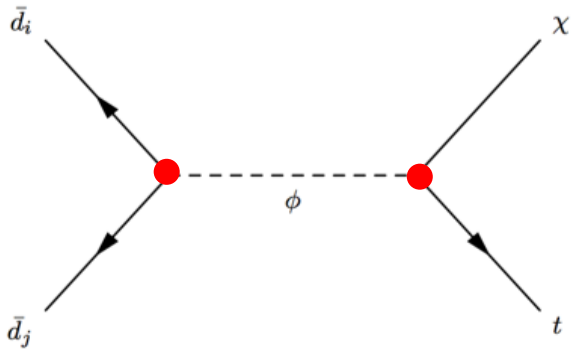
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + V_\mu (g_{R_\chi} \bar{\chi}_R \gamma^\mu \chi_R + g_{L_\chi} \bar{\chi}_L \gamma^\mu \chi_L) + V_\mu \bar{u}_i [(a_{FC})^{ij} \gamma^\mu + (b_{FC})^{ij} \gamma^\mu \gamma^5] u_j + \text{h.c.}$$

Mono-Top (FCNC)

$$a_{FC} = (a_R + a_L)/2$$

$$b_{FC} = (a_R - a_L)/2$$

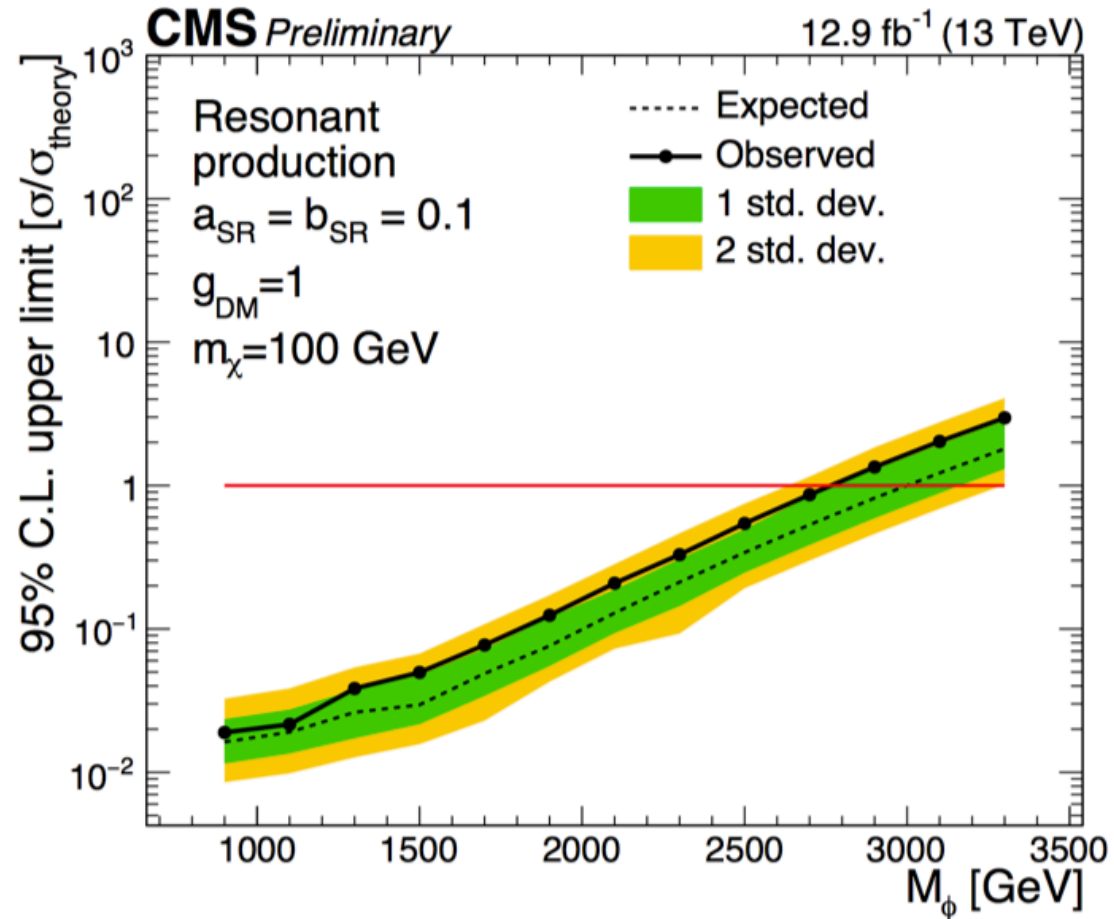




$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin}(\phi_s, \chi) + (\phi \bar{d}_i^C [(a_{SR}^q)^{ij} + (b_{SR}^q)^{ij} \gamma^5] d_j + \phi \bar{t} [a_{SR}^{1/2} + b_{SR}^{1/2} \gamma^5] \chi + \text{h.c.})$$

Mono-Top

Colored scalar mediator



Conclusion

- DM searches in Mono-X, tt+MET and VBF channels were presented for CMS.
 - No excess over SM is observed in early 2016 data.
 - Analysis of full 2016 data are in progress.
 - Results will be presented at Large Hadron Collider Physics (LHCP 2017, Shanghai) next week.
 - Dijet results give strong limits on spin-1 mediator.
- Results were translated to exclusion limits.
 - Most of them were interpreted with the Simplified Model.
- Exclusion limits were compared with those from Direct Detection and Indirect Detection experiments.

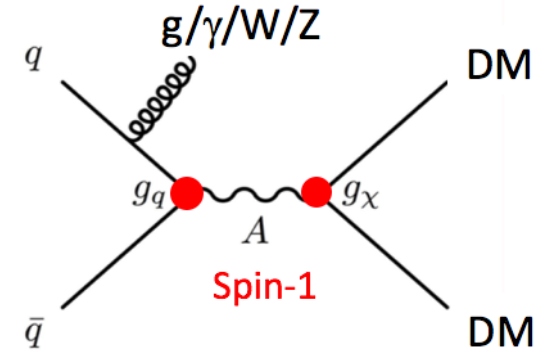
Additional Slides

Invisible Higgs

Summary of DM limits, ICHEP 2016,

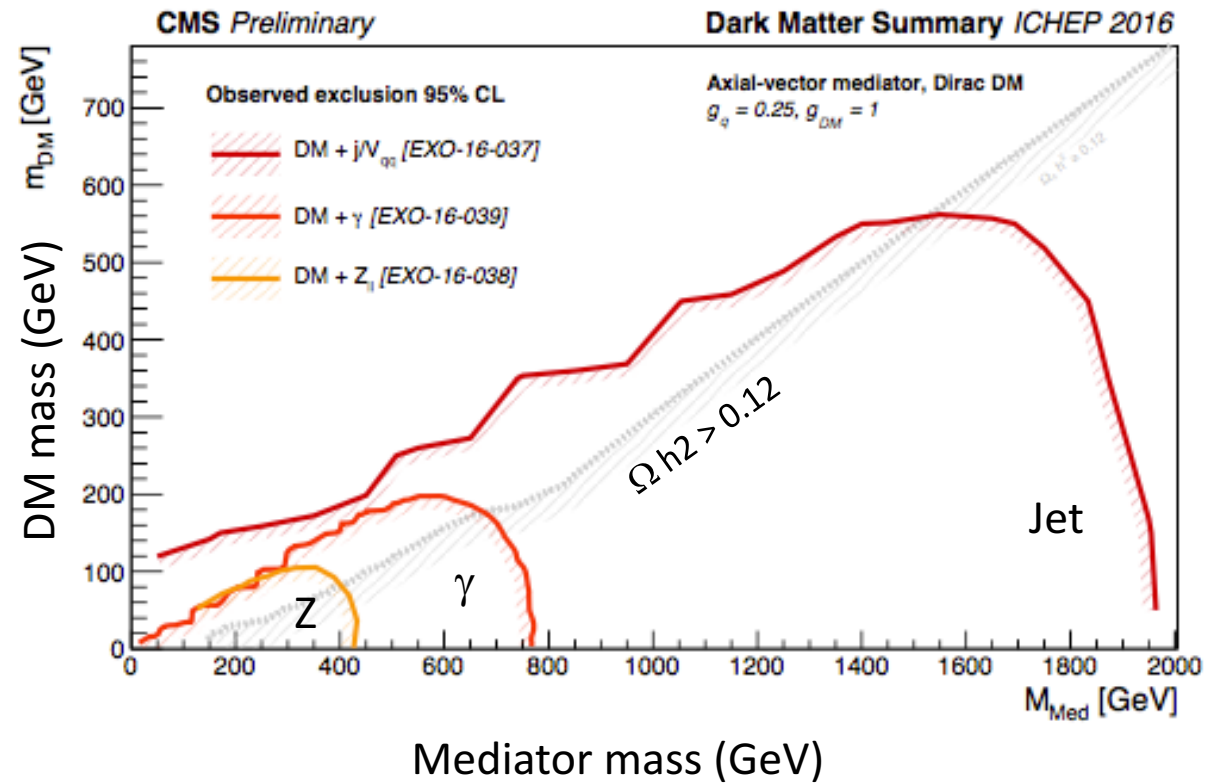
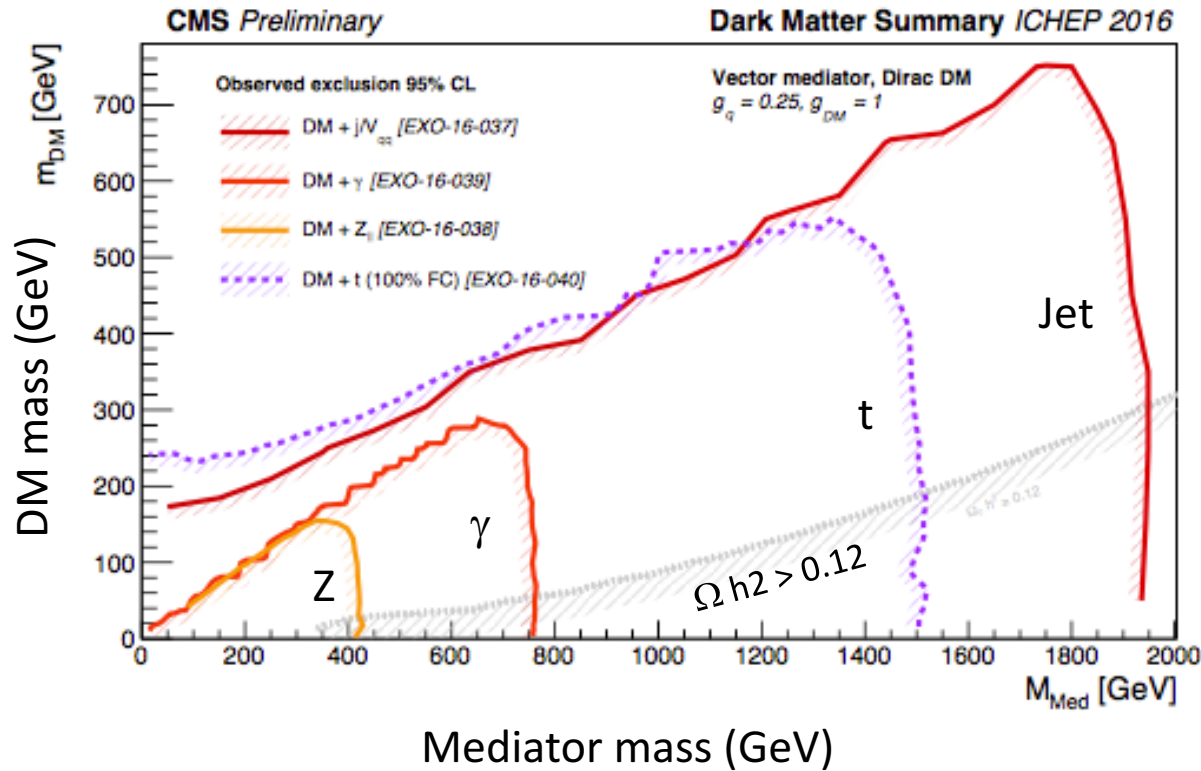
Exclusion Limits on spin-1 mediator

$$g_q = 0.25, g_{DM} = 1.0$$

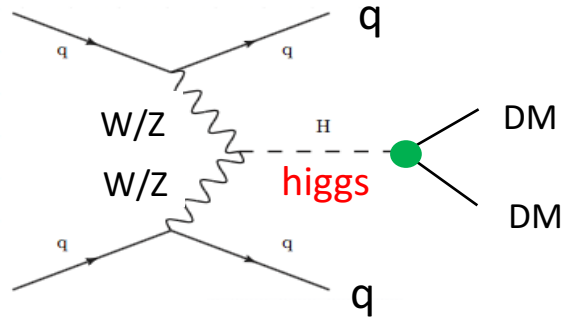


Vector Mediator

Axial-vector Mediator

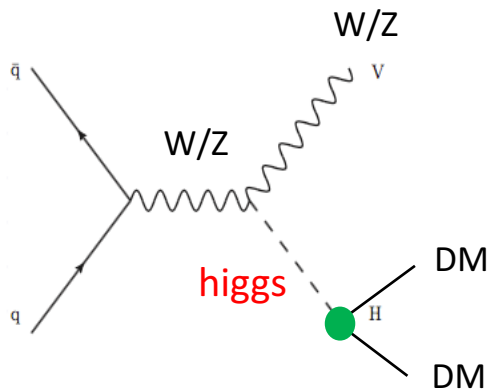


Invisible Higgs: $H \rightarrow \text{DM DM}$



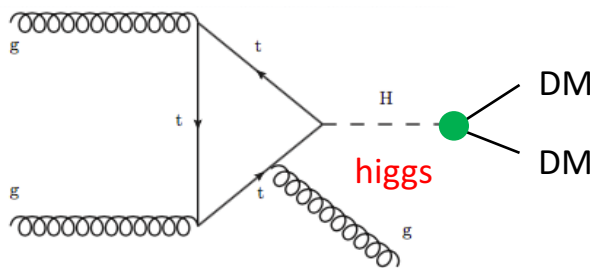
VBF

two jets- large $\Delta\eta(j1,j2)$, large $M(j1,j2)$
 MET > 90 - 200 GeV (run 1 run 2)
 BG: Z(nn)+jets, W(ln)+jets



ZH (leptonic)

pt(e,μ) > 20 GeV, in Z mass window
 MET > 120-100 GeV
 MT > 200 GeV
 BG: ZZ(νν), WZ(νν)



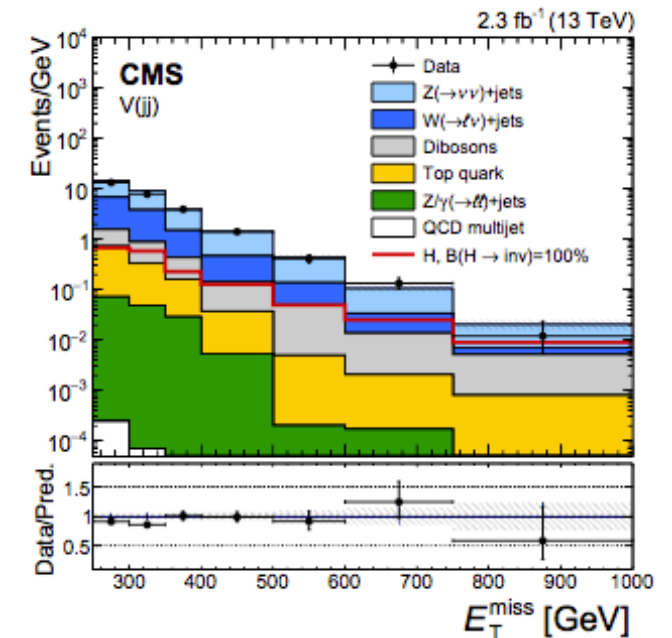
VH (W,Z hadronic)

MET > 250 GeV
 mass of wide jets
 subjettness (τ_2/τ_1)

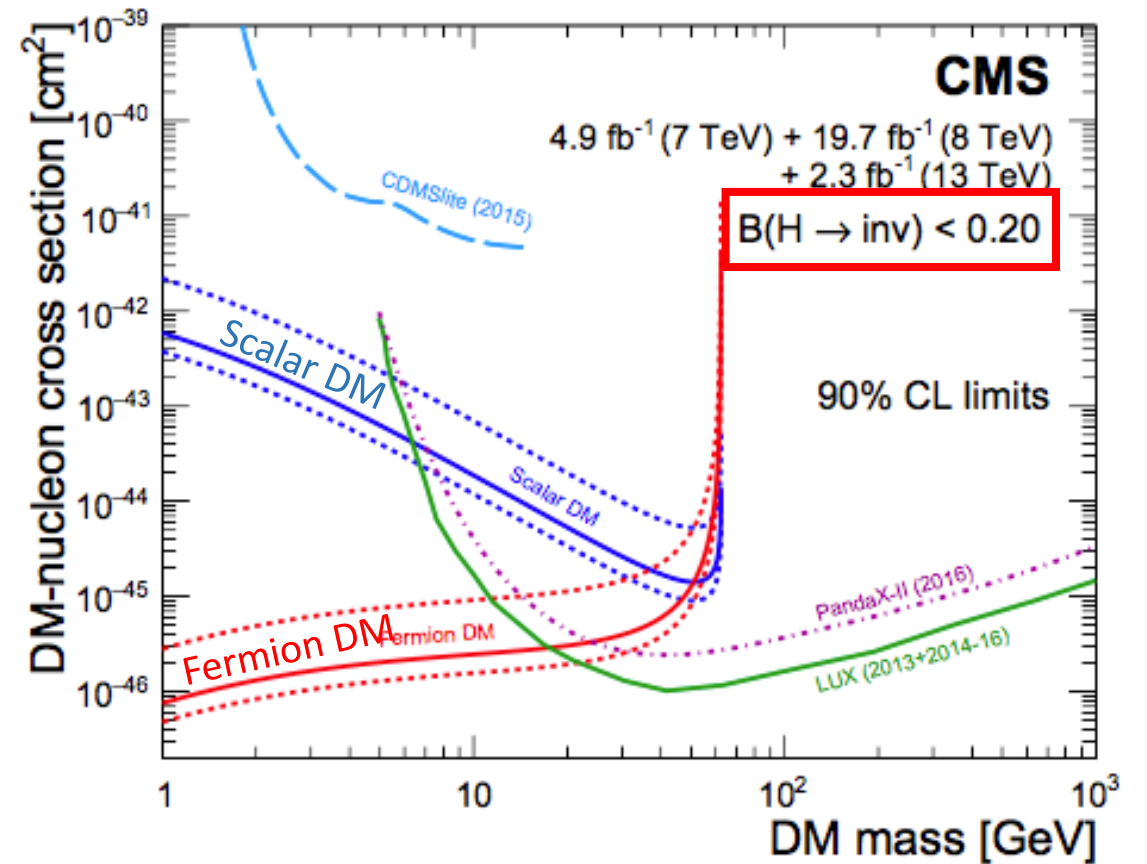
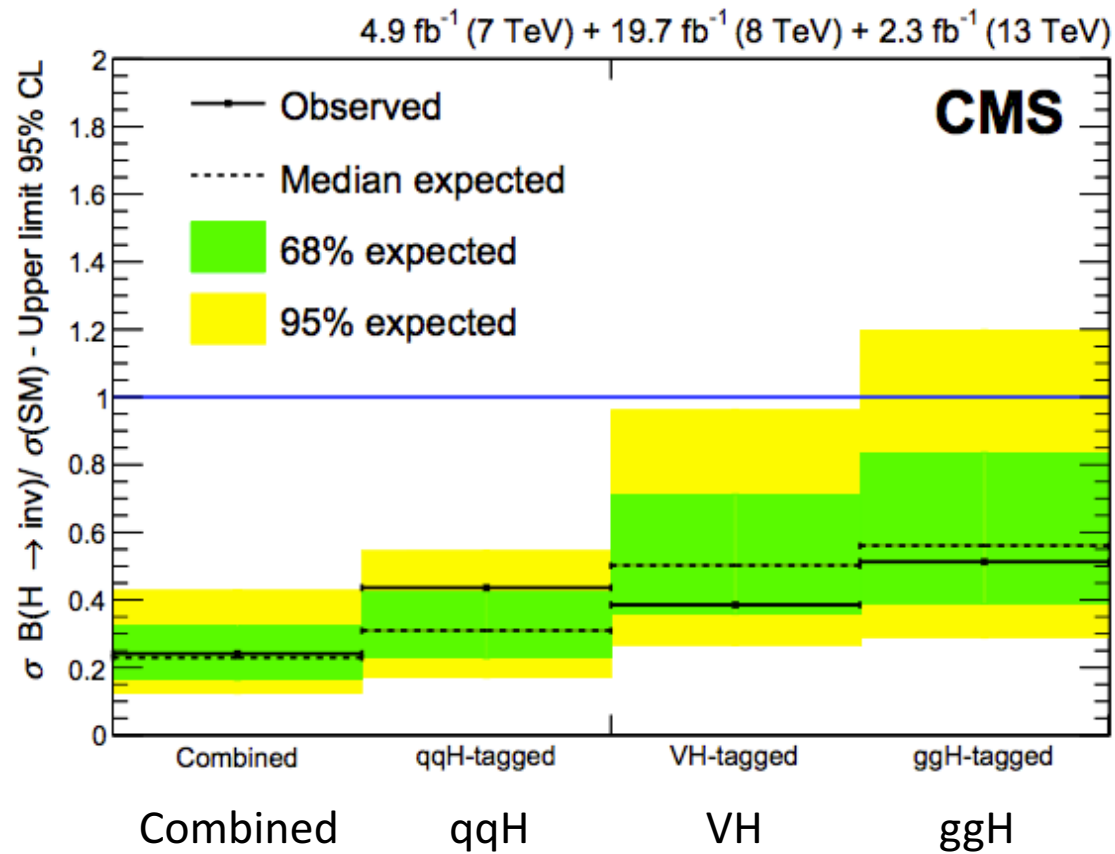
Monojet

MET > 200 GeV

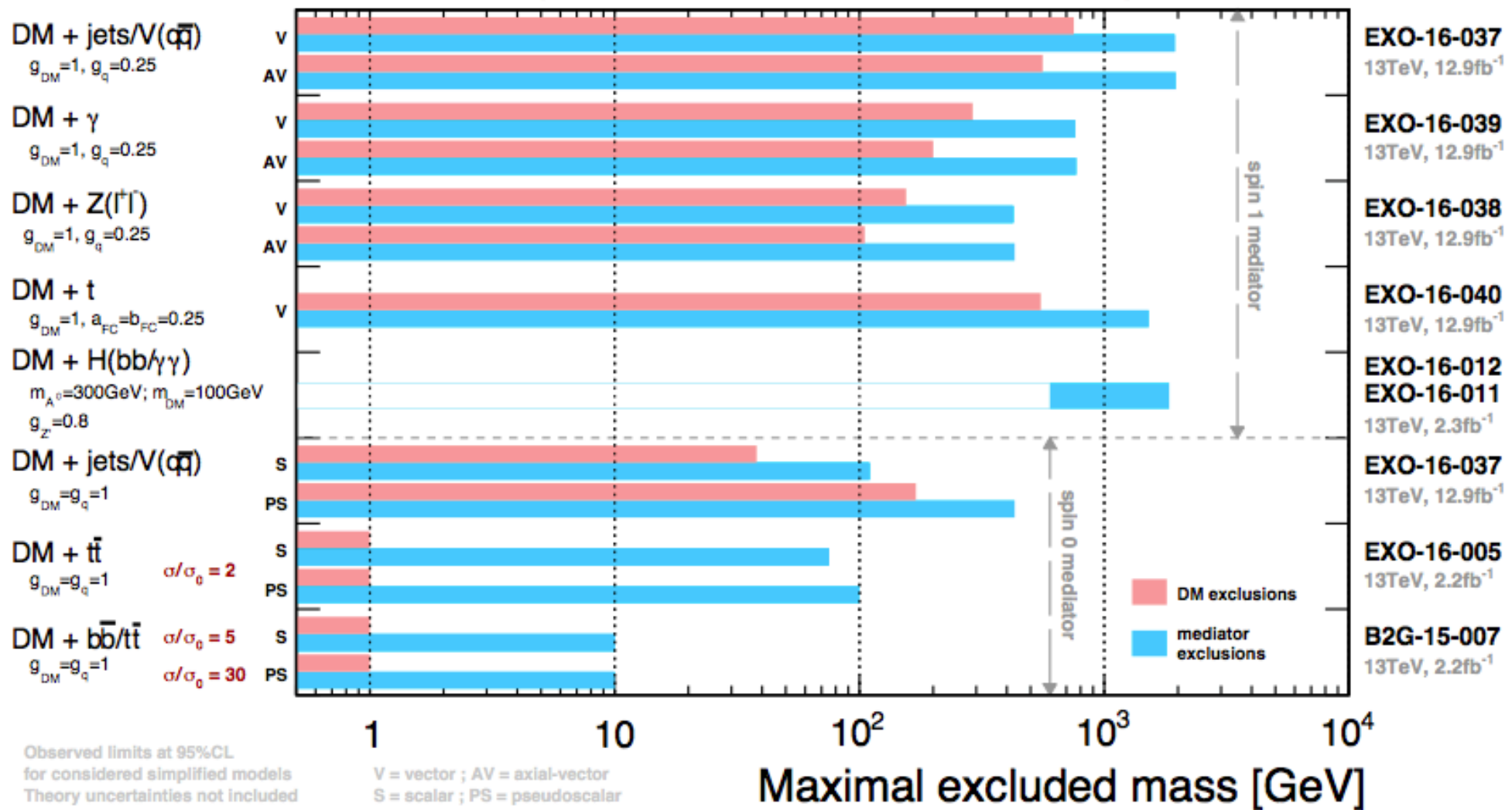
MET: VH hadronic



Limits on $H \rightarrow \chi\chi$



CMS Preliminary **Dark Matter Summary - ICHEP 2016**



Results from analyses of full 2016 data (36 fb⁻¹) are presented this week at LHCP 2017, Shanghai.