Dark matter searches @CMS, LHC CERN

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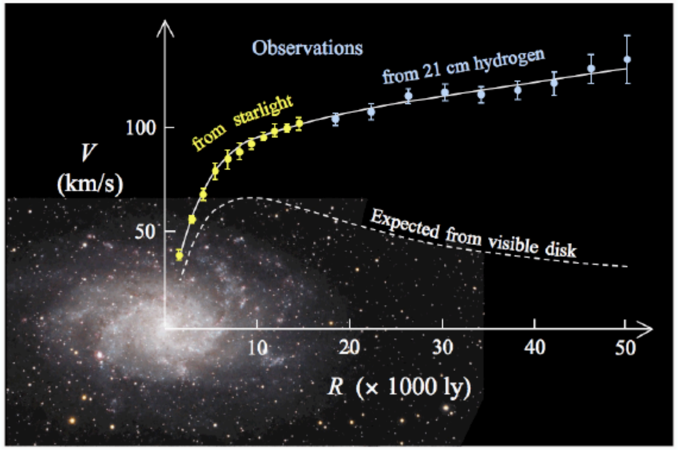
(ON BEHALF OF THE CMS COLLABORATION)

NuDM@2022
25th - 28th Sept 2022

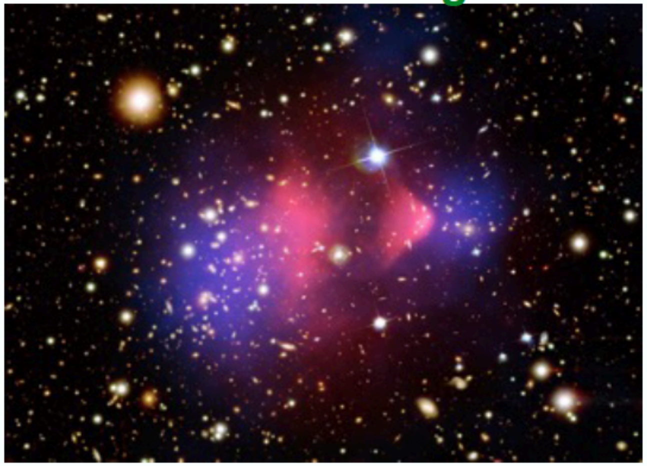
Introduction

Existence of dark matter known through its gravitational interactions

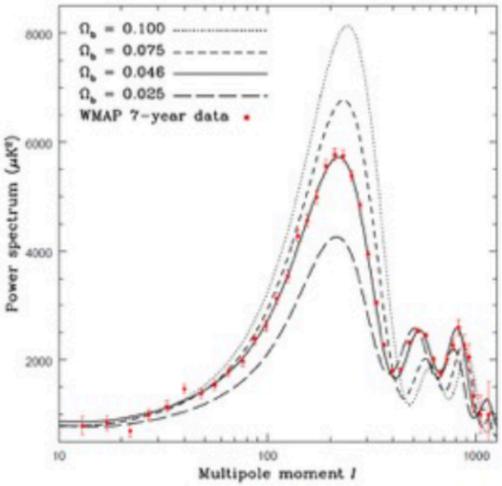
Galactic rotation



Weak lensing



CMB



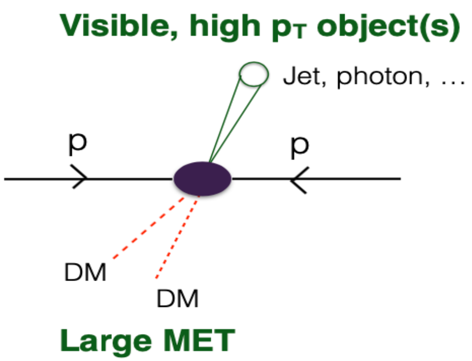
Underlying nature of dark matter (DM) remains unknown

There is a well established case for weakly interacting DM particles (WIMPs)

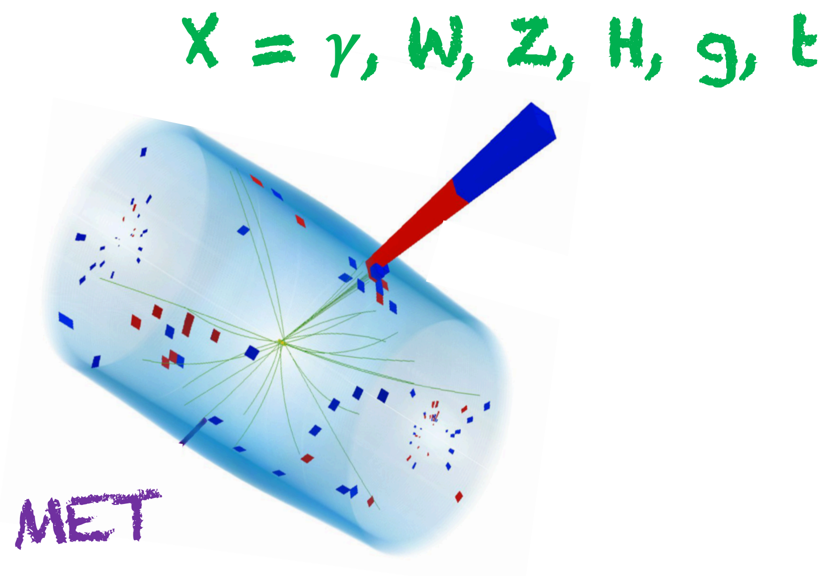
Such particles may be ***produced in high energy p-p collisions*** *at LHC!!*

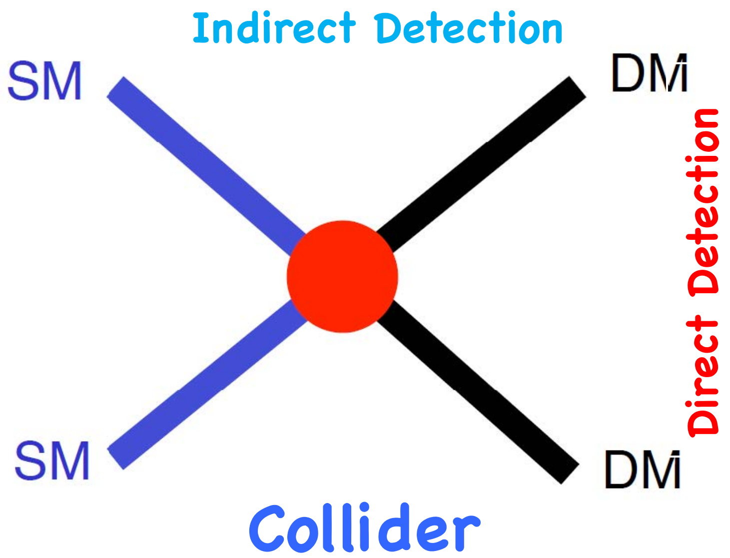
Dark Matter

- Favorite collider candidate: WIMP
- Weakly interacting, massive, stable



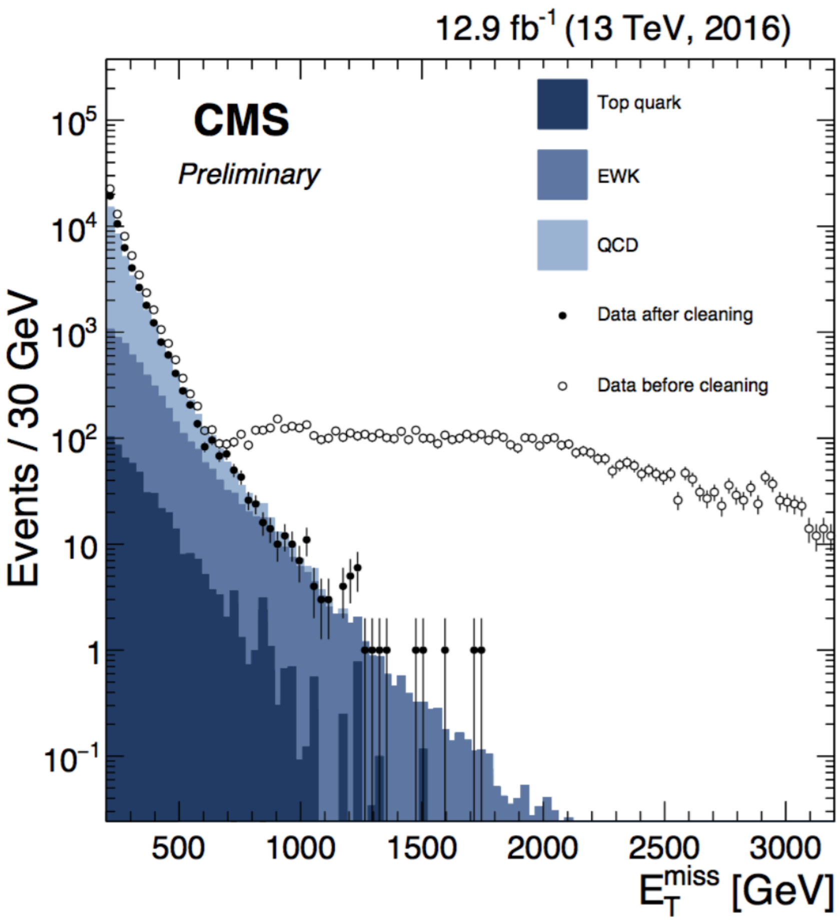
General collider strategy





Non-interacting particles cause momentum imbalance in the transverse plane of the beam

Challenges with Missing Transverse Momentum



Spurious detector signals can cause fake MET signatures that must be identified and suppressed.

Anomalous high MET can be due to:

- Particles striking sensors in the ECAL photodetectors
- Beam halo particles
- ECAL dead cells (real energy to have been missed)
- Noise in photodiode & readout box electronics in HCAL

Simplified Dark Matter Models

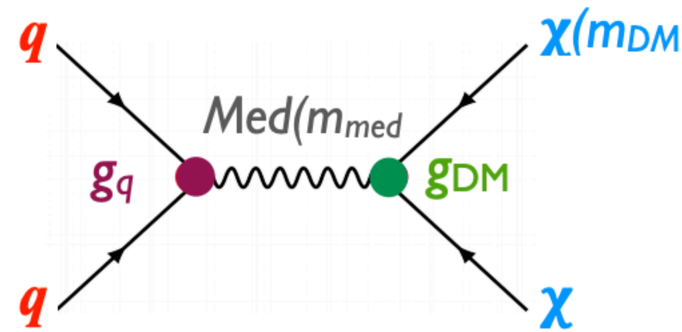
- Dark matter production in pp collisions described using ***"simplified models"***
- Capture the essential features of a variety of DM signals through a minimal set of parameters

✓ s – channel mediators

	vector	axial-vector
spin – 1	$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu \gamma^5 q$
	scalar	**pseudoscalar**
spin – 0	$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

✓ t – channel mediators

LHC DM Forum
arXiv:1507.00966



Parameters:
- Spin/Parity of mediator
- Mediator mass ***(M_{med})***
- DM Mass ***(M_{DM})***
- Mediator coupling to DM ***(g_{DM})***
- Mediator coupling to quarks ***(g_q)***

MonoJet

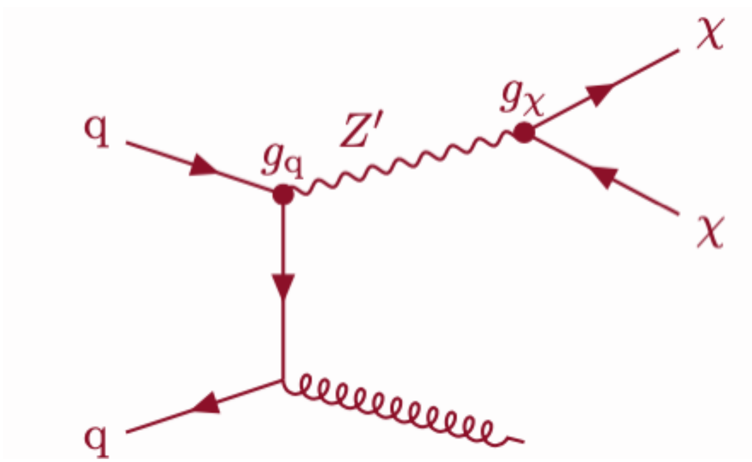
[CMS Result](#)

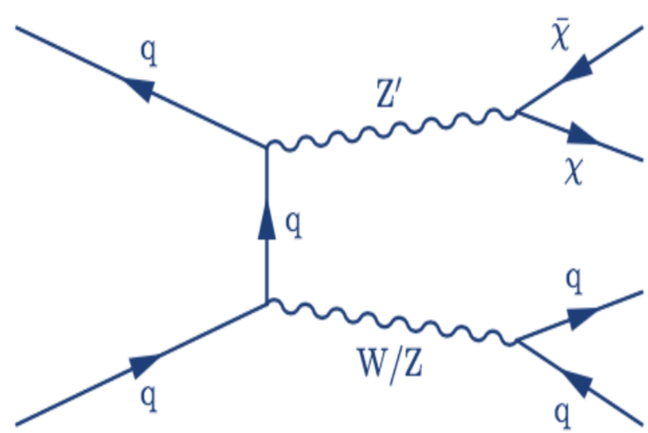
✓ Search for physics with particles that decay **invisibly** in association with a **jet**

✓ Search is performed in **MonoJet** and **MonoV** categories and combined

MonoJet: Jets come from the fragmentation of a single quark/gluon

MonoV: Jets come from a hadronically decaying V (W/Z) boson





Several new physics models predict such an experimental signature at the detector

MonoJet

[JHEP11(2021)153](#)

Signal Region: **Jets + MET**

Background: Z/W+jet, top, dibosons, multijet

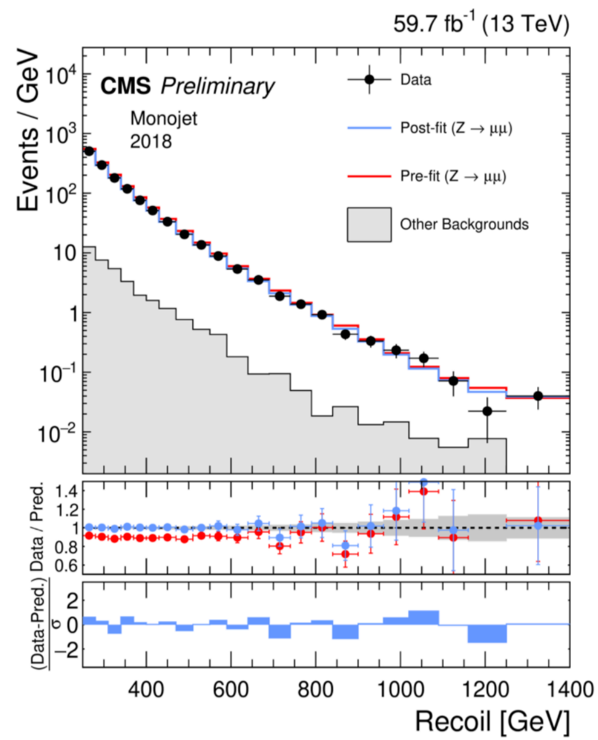
We employ semi-data driven technique, supported by statistically independent control regions (**1e/μ, 2e/μ, t, γ**), to constrain the normalization of SM backgrounds

- At least one high pT central jet
- Veto events with leptons (e, μ,τ) and photons γ
- MET (Hadronic Recoil) > 250 GeV

- Events are broadly categorized in mono-jet and mono-V based on leading jet pT

○ **Mono-V:** Jet pT (AK8) > 250 GeV

○ **Mono-jet:** Jet pT (AK4) > 100 (150) GeV

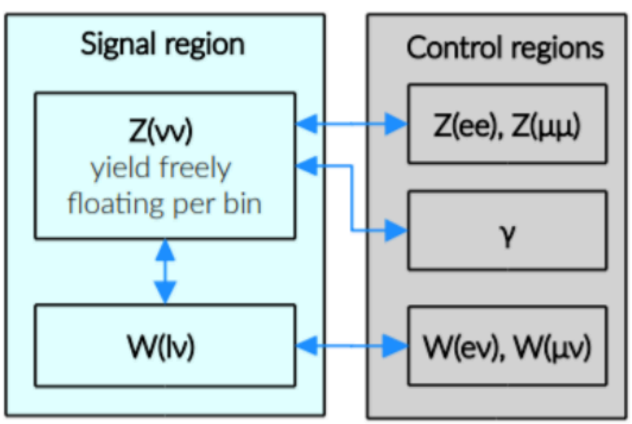


Data/background predictions in Control Regions

MonoJet Signal Extraction

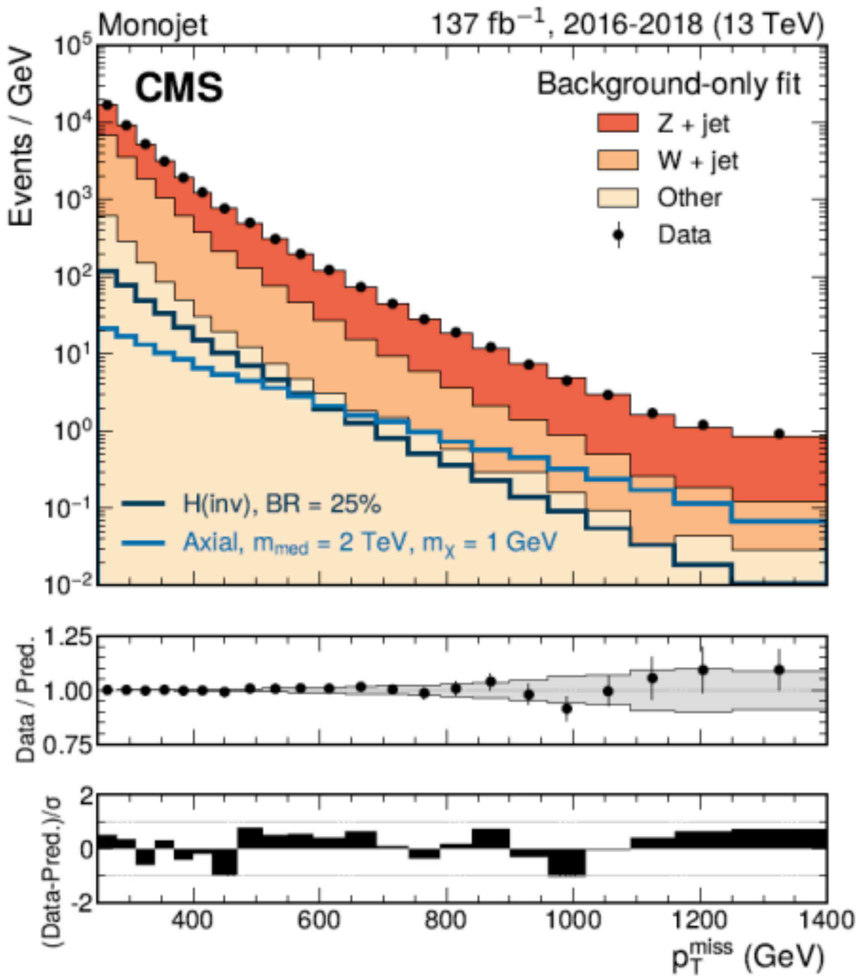
- Signal extraction is based on **MET** distribution, an unconstrained parameter per recoil bin per category and year.
  - Monojet: 22 bins   Mono-V: 7 bins
- **SR** and **CRs** are linked together with **binned transfer factors (TF).**
- The **TFs are constrained by simulations**, within theory and experimental uncertainties.
  - experimental uncertainties on TFs.
  - mixed QCD-EWK corrections and NNLO QCD on TFs

Maximum-likelihood fit



- Theory uncertainties for the V ratios and V+jets corrections are from the Lindert et al paper.
- This fit model is replicated in each category/year, then likelihoods across the categories/years are combined.

Monojet in SR



Selection

p_T^{miss} > 250 GeV, monojet+ monoV

Madgraph generator for major bkgs

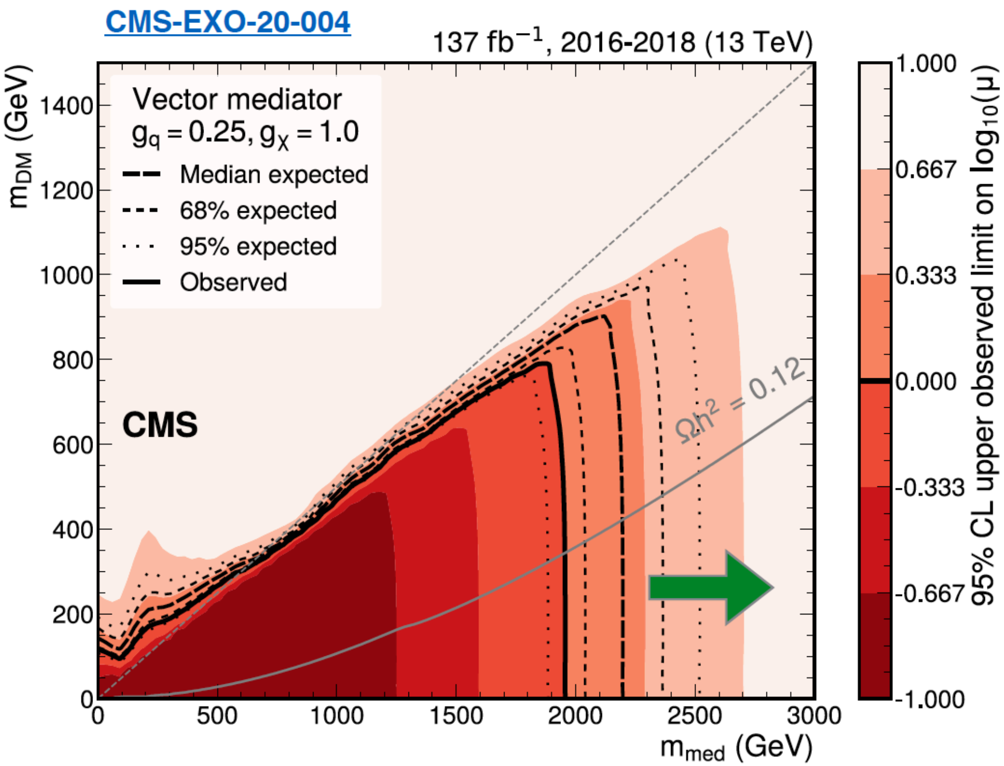
22 bins

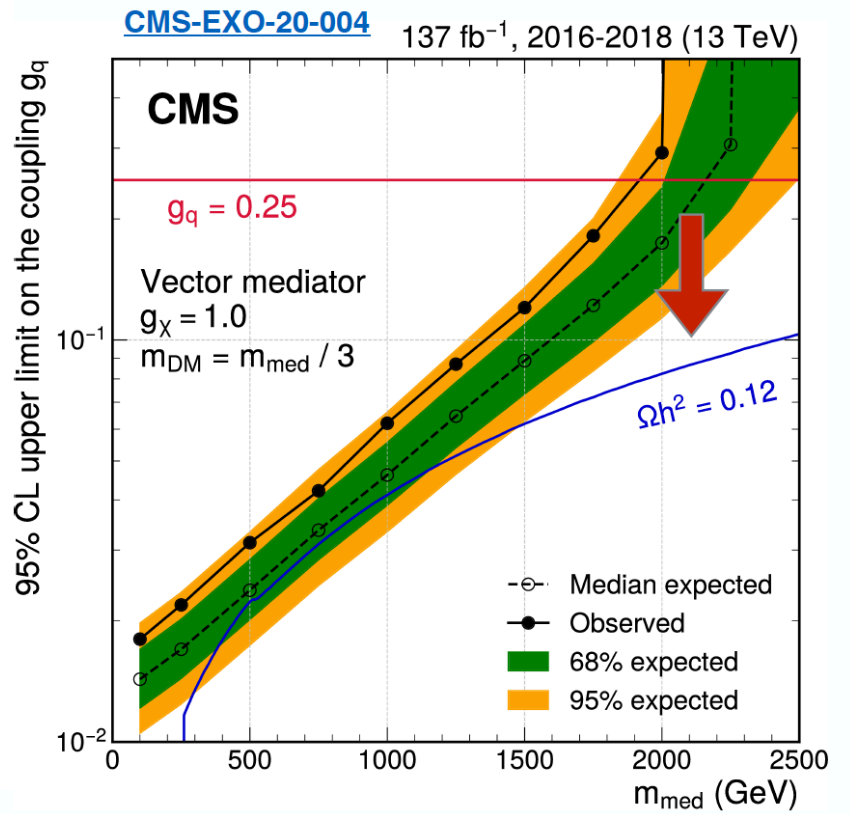
5 CR (2 W, 2 Z, 1 photon)

regions split by year

3x22 free floating parameters for monoJet + 3x7 for monoV

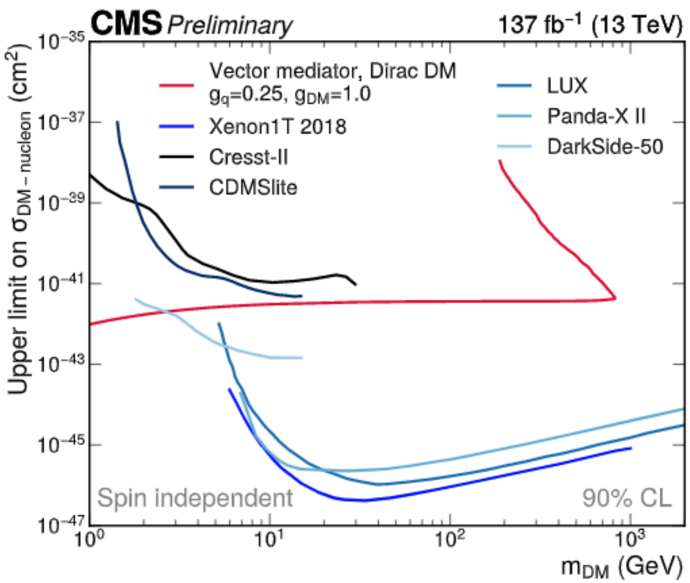
MonoJet Results



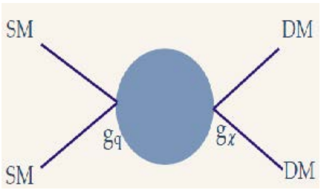


Goal is to probe **higher masses** and **lower couplings**

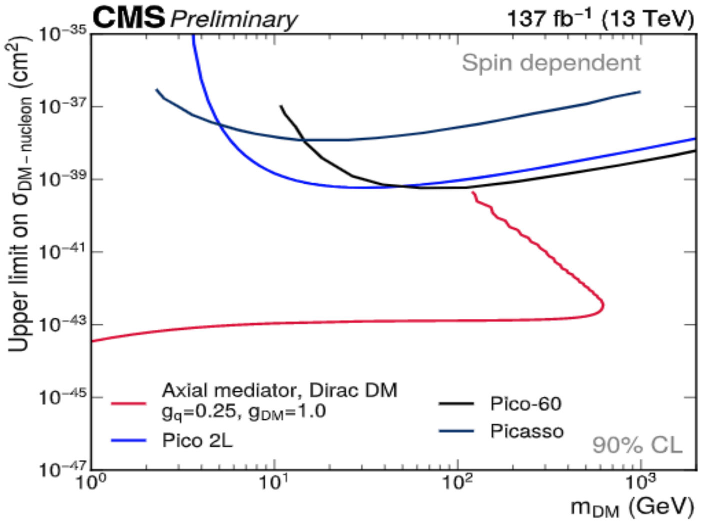
Comparing to the rest of the world

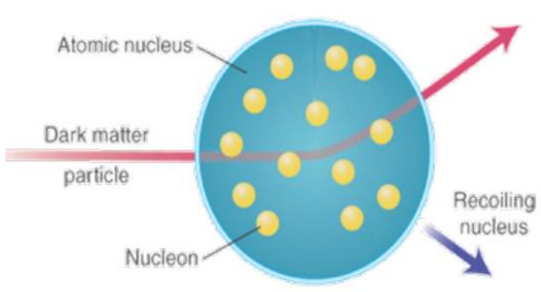


Comparison to direct detection experiments



Axial-vector mediator results are translated into 90% CL exclusion limits on the spin-dependent WIMP–nucleon scattering cross section σSD as a function of the WIMP mass





ATLAS provides WIMP annihilation rate as a function of WIMP mass [backup]

Mono-Z Search

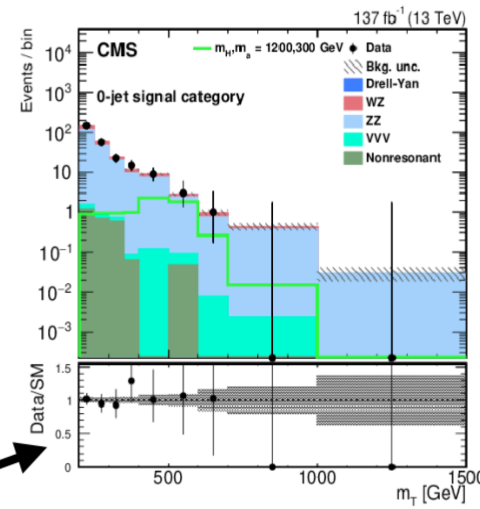
EPJC 81 (2021) 13

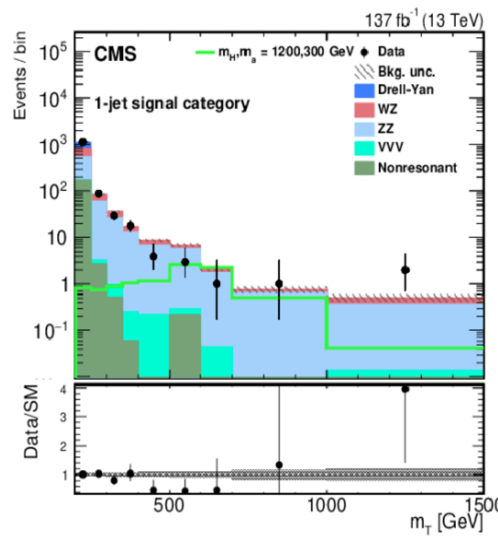
Signature: Z(ll)+MET

Model for interpretations:
- Simplified model
- 2HDM+a

p_T^{miss} for simplified, m_T for 2HDM+a model

$$m_T = \sqrt{2 p_T^Z p_T^{miss} (1 - \cos(\Delta\phi_{\ell\ell-\vec{p}_T^{miss}}))},$$

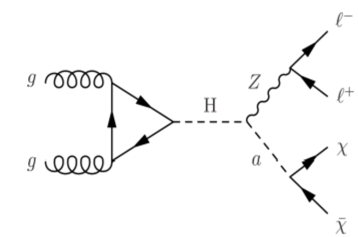


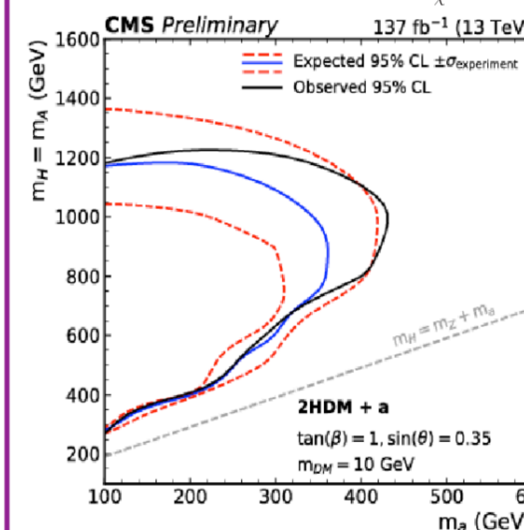


Basic selection:
- $p_{T(l1)} > 25$ GeV, $p_{T(l2)} > 20$ GeV
- $|m_{ll} - m_Z| < 15$ GeV
- $p_T^{miss} > 100$ GeV

Backgrounds:
- Drell-Yan, WZ, ZZ, VVV
- Dedicated Control regions to model the background

2HDM+a model interpretation





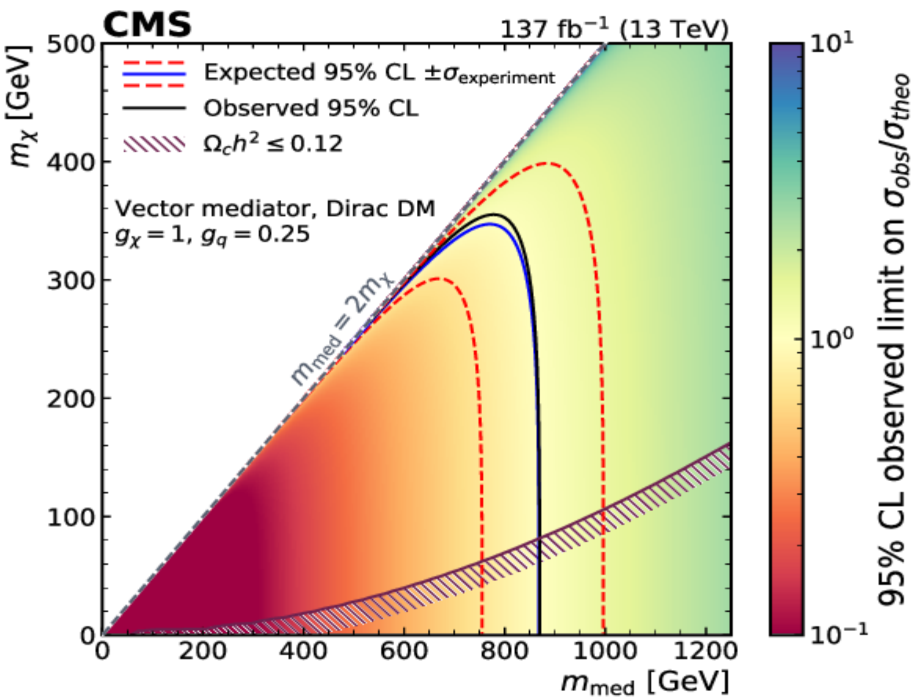
The 95% CL expected exclusion limits

Mono-Z Comparison

EPJC 81 (2021) 13

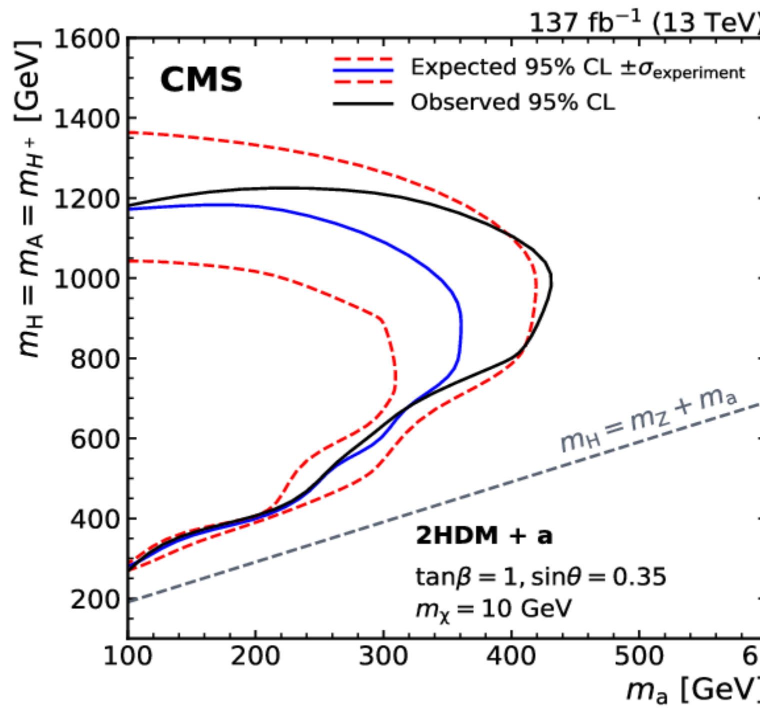
❖ **For Simplified DM model (Vector)**

Mediator mass excluded upto 800 GeV



For 2HDM+a model

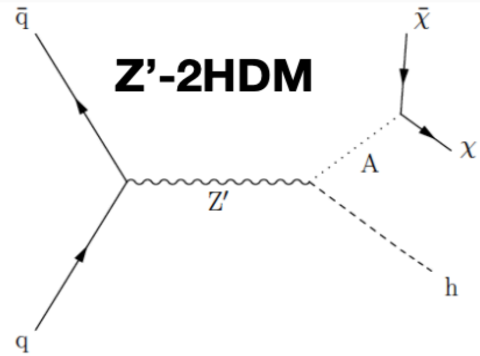
Maximal exclusion m_a = 350 GeV and M_H = 1.2 TeV



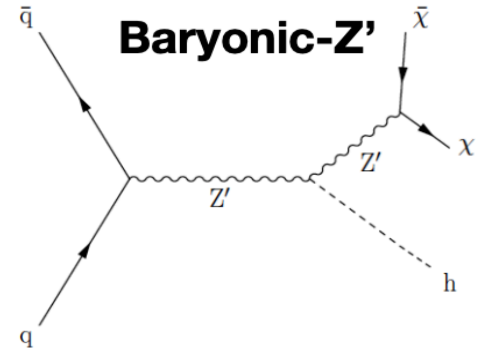
Mono-Higgs

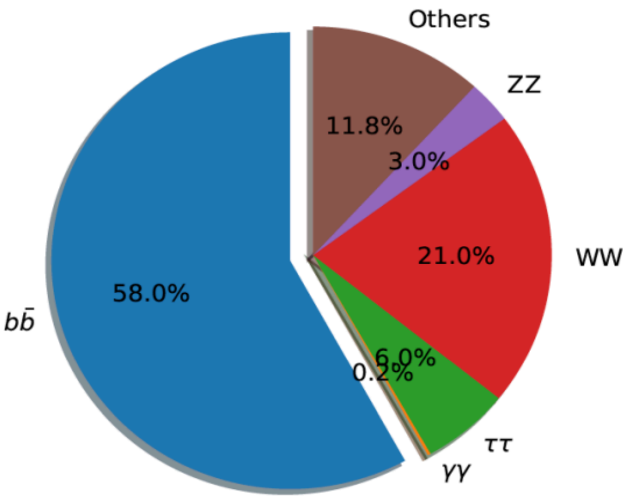
- After the discovery of the **Higgs boson (125 GeV)** it is possible to probe the DM using this new handle.
- **New massive particle** mediates the **Higgs**-**DM** interaction.
- Search performed in 5 decay channels and statistically combined.
  - $b\bar{b}, \gamma\gamma, WW, ZZ \text{ and } \tau\tau$
- Results interpreted using three simplified models.
  - Z'-2HDM
  - Baryonic-Z'
  - 2HDM+a

Z'-2HDM



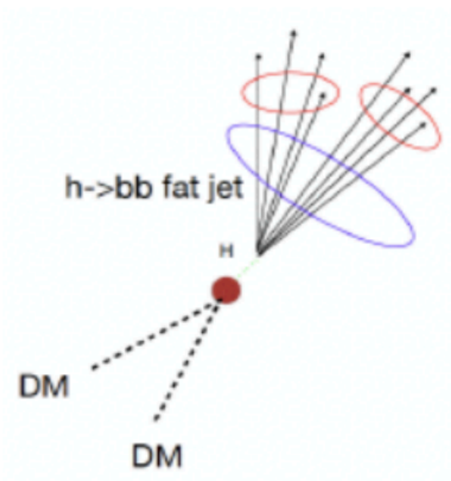
Baryonic-Z'





Mono-Higgs

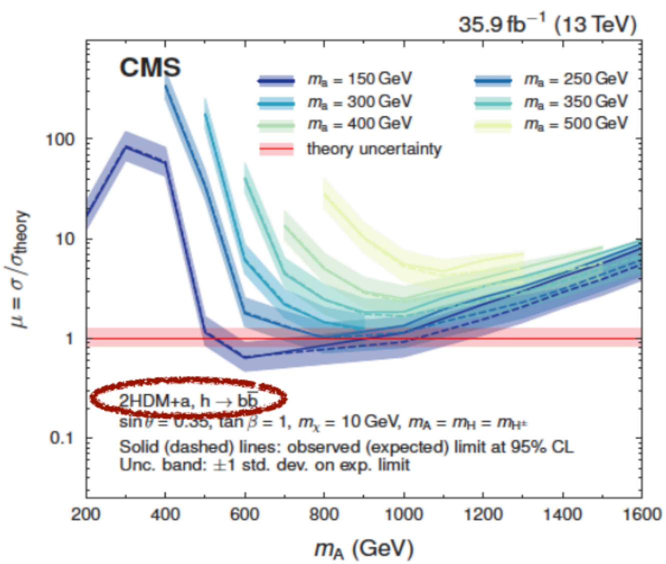
JHEP03(2020)025

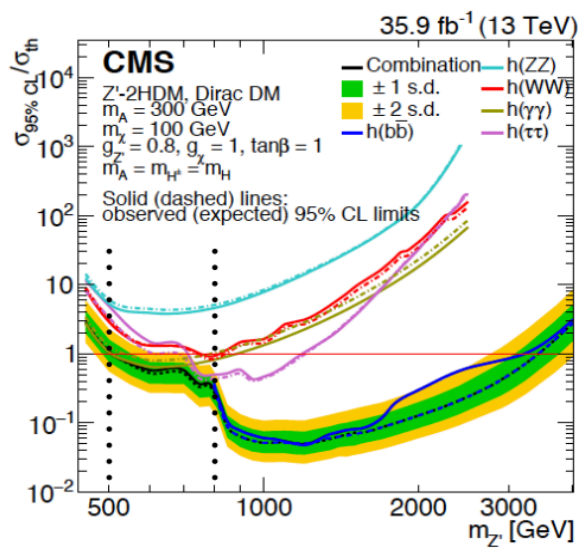


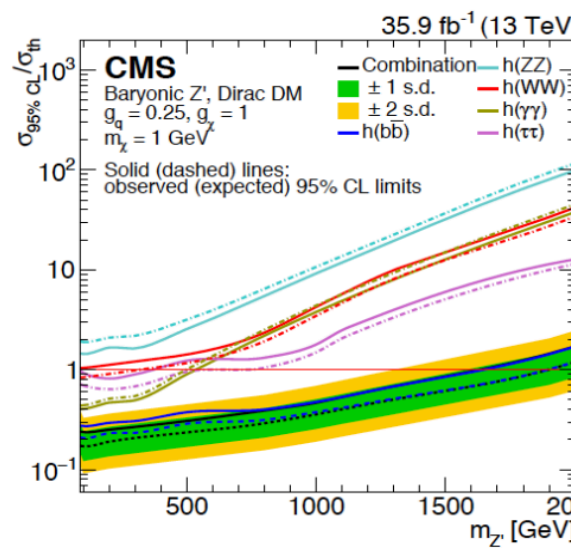
H→bb	most sensitive
2HDM+a	CA15 jets
Baryonic-Z’	CA15 jets
Z’-2HDM	AK8 jets

Decay channel	Final state or category
$h \to bb$	AK8 jet (Z'-2HDM) CA15 jet (Baryonic Z')
$h \to \gamma\gamma$	$p_T^{miss} \in 50$–$130\,GeV$ $p_T^{miss} > 130\,GeV$
$h \to \tau\tau$	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
$h \to WW$	$e\nu\mu\nu$
$h \to ZZ$	$4e$ 4μ $2e2\mu$

Final states orthogonal to each other





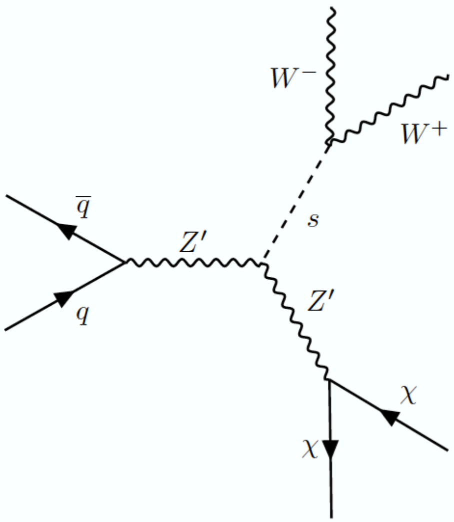


Dark Higgs (WW)

[CMS-EXO-20-013](#)

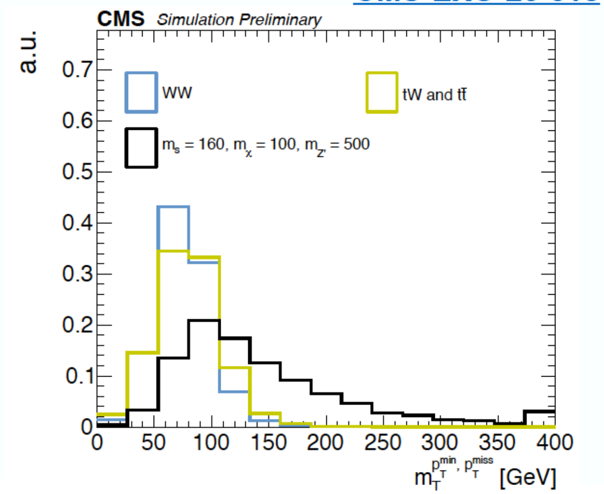
[CMS-EXO-20-013](#)

Dark Higgs (WW)



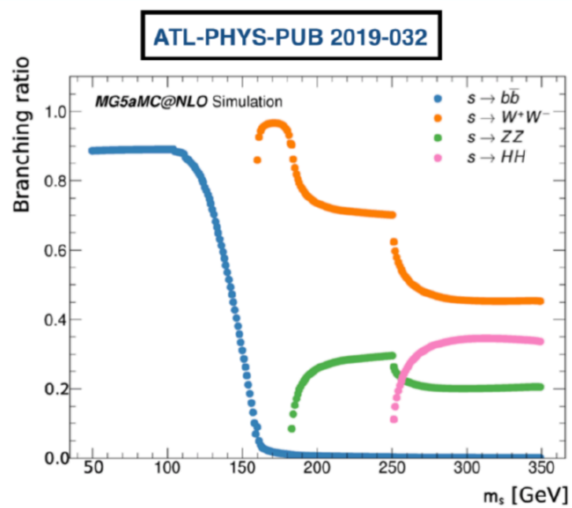
DM particles acquire their mass through their interactions with a Dark Higgs boson.

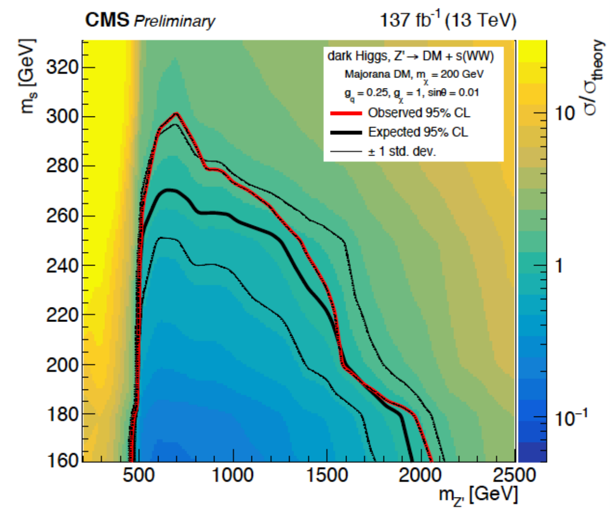
Signal extraction: 3D ML fit to ΔR(ll), mll, mT(lmin + pT)



Model parameters are:

- DM mass: mχ,
- Z′ mass: mZ′,
- dark Higgs mass: ms,
- Z′ couplings to quarks (gq)
- Z′ couplings to DM (gχ),
- the mixing angle between SM and the dark Higgs bosons (sin θ).





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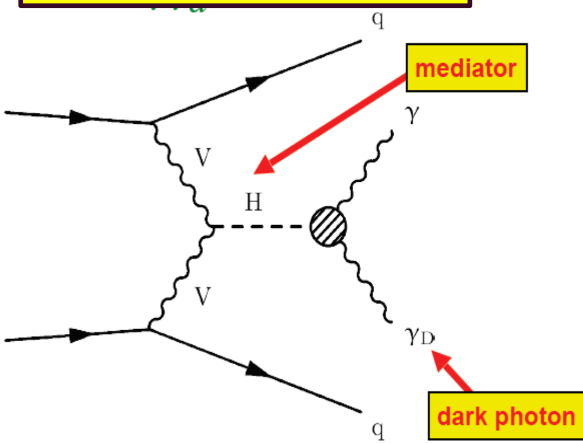
Dark photon : VBF H + photon + p_T^{miss}

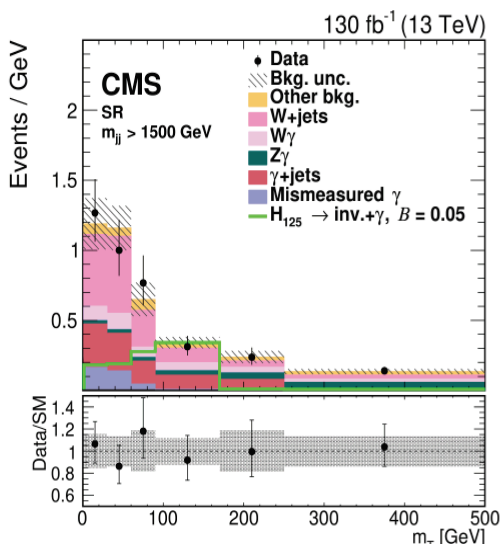
JHEP03(2021)011

- Another way to search for DM: **look for decays of a Higgs boson as the mediator to massless dark photon + SM particles**
- Signature: H produced via VBF whose decay produces an **isolated photon, p_T^{miss}, and two forward jets**
- **First search for decays to undetected particle and isolated photon in the VBF channel**

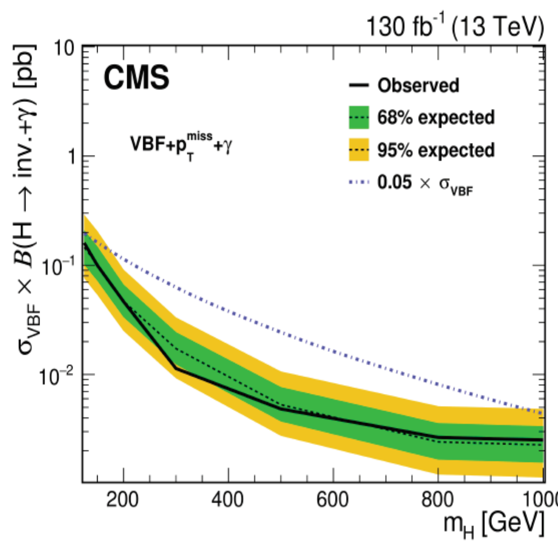
H-> $\gamma\,\gamma_d$ benchmark



Transverse mass (m_T):



Results with 130 fb-1:



Combination with analysis where H produced in association with a Z boson

For SM-like 125 GeV H boson:

	VBF	ZH	VBF+ZH
Observed 95% CL limits on $B(H\to\gamma\gamma_d)$	0.034	0.046	0.029

arXiv:1908.02699

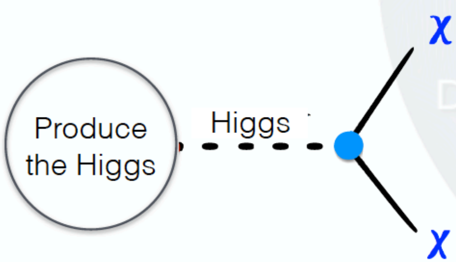
March 22, 2021

Higgs Invisible

Strong experimental evidence for DM from astrophysical observations. Most studied class of theories predict DM to be a weakly interacting massive particle.

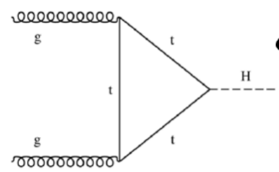
Higgs Portal

Known Higgs decay branching fractions allow decays to invisible particles ~20%



All Higgs production modes can be studied to tag the event

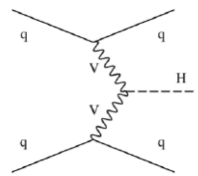
Gluon Fusion



$\sigma(gg \to H)$ = 48.52 pb
±3.9% (th.)
±3.2% (pdf)

(N³LO QCD + NLO EW)

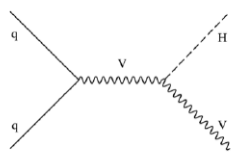
Vector Boson fusion



$\sigma(VBF)$ = 3.779 pb
±0.4% (th.)
±2.1% (pdf)

(NNLO QCD + NLO EW)

Associated Production with vector boson

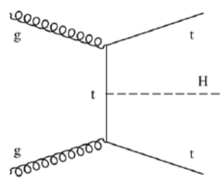


$\sigma(pp \to WH)$ = 1.369 pb
±0.7% (th.) ±1.9% (pdf)

$\sigma(pp \to ZH)$ = 0.8824 pb
±3.8% (th.) ±1.9% (pdf)

(NNLO QCD + NLO EW)

Associated Production with top quarks

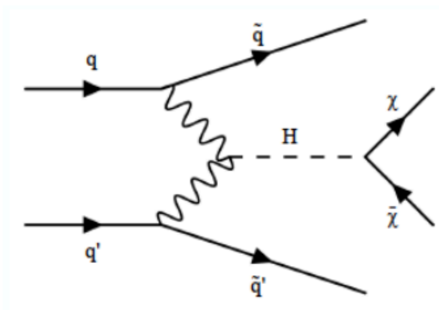


$\sigma(ttH)$ =0.5065 pb
$\pm^{5.8}_{9.2}\%$ (th.)
±3.6% (pdf)

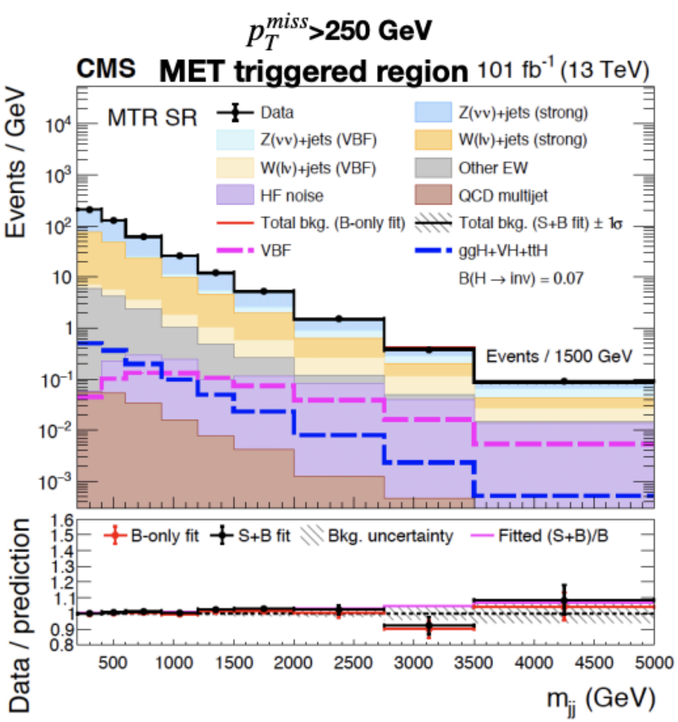
(NLO QCD + NLO EW)

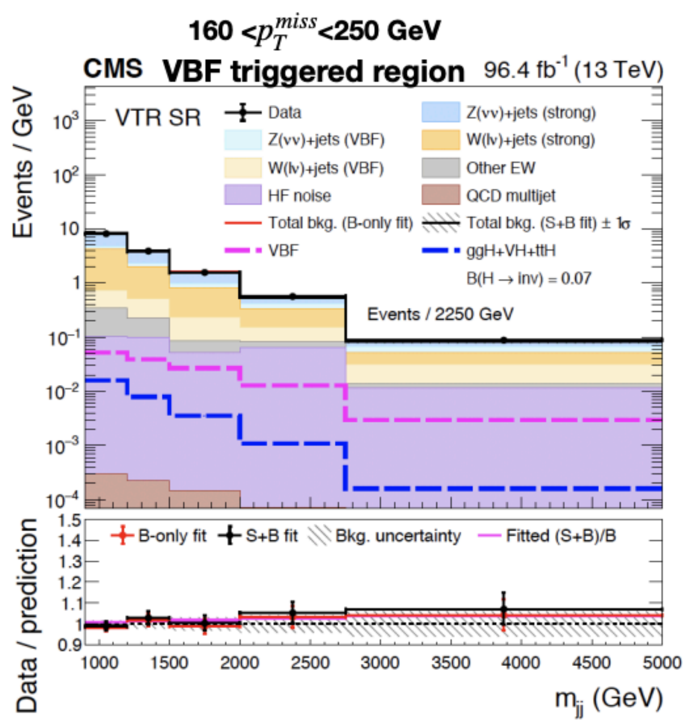
VBF Higgs Invisible

PRD.105.092007



- ☑ New trigger strategy: using jet properties from VBF production in addition to p_T^{miss} trigger.
- ☑ Using V+jets and $\gamma + jets$ CRs to constrain major backgrounds (Z(vv)+jet and W(lv)+jets).

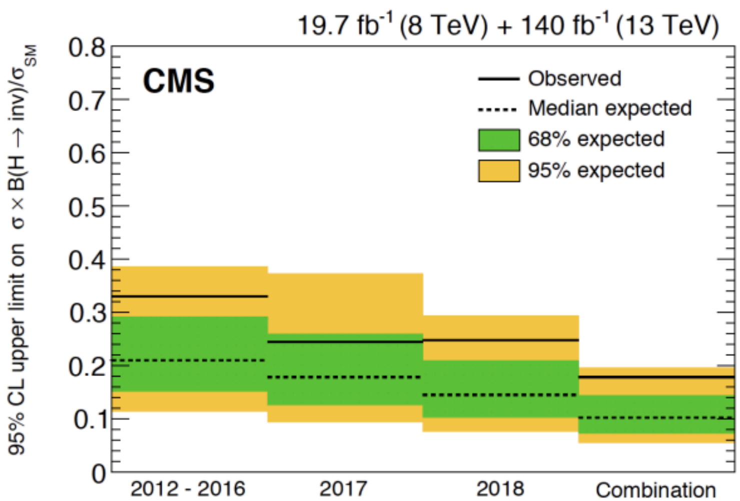


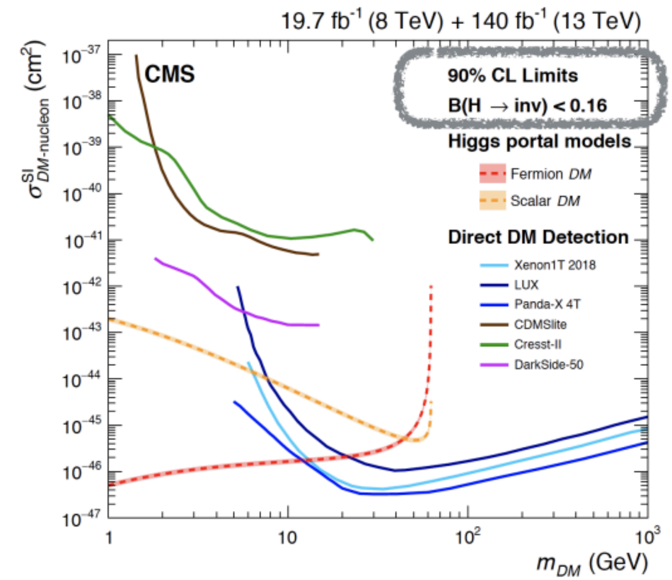


VBF Higgs Invisible

PRD.105.092007

- Combination of Run 1 and Run2
  - **95% CL** upper limit on the in **BR (H→invisible) < 0.18 (0.10)**





Constraints are compatible with SM H → invisible branching ratio.

Constraints on spin independent DM-neucleon cross-section

Summary

- **Performing a variety of searches for new phenomena at the LHC, including searches for dark matter, which provide access to the phase space**

- **Presented a few new results for CMS, all of which use the full Run2 results**

- **No signal observed yet, but more to do!** ***Need to look everywhere***

- ***More exciting Run2 results will be coming out in the comign months***
  - ***Stay tuned for this and the upcoming Run3!***

Thank You

Backup

MonoZ : Fitting Strategy

Fitting Strategy

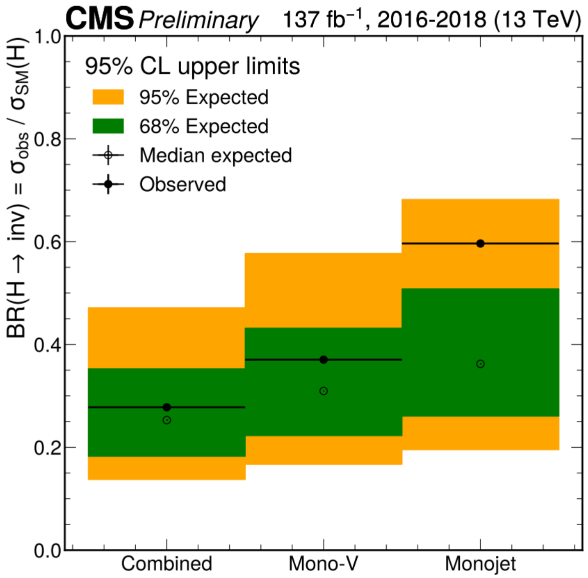
- ATLAS:
  - nonresonant and WZ production normalized from data
  - ZZ production not normalized from data, replying on simulation post-facto
- CMS:
  - nonresonant production normalized from data
  - $Z + \text{jets}$ events in 0 jet and 1 jet categories normalized from data
  - WZ and ZZ production estimated from data using a single normalization factor
  - large EWK correction uncertainties considered
  - VV shape: 3 additional nuisances ($\pm 10/20/30\%$) at low ($80 < p_T^{miss} < 200\text{GeV}$), medium ($200 < p_T^{miss} < 400\text{GeV}$), and high p_T^{miss} ($p_T^{miss} > 400\text{GeV}$) to allow for independent leverage in the fit
- Arguable, the last two set of uncertainties are a matter of choice, having both of them is a rather conservative approach

OTHER INTREPRETATIONS : CMS MONOJET

CMS PAS EXO-20-004

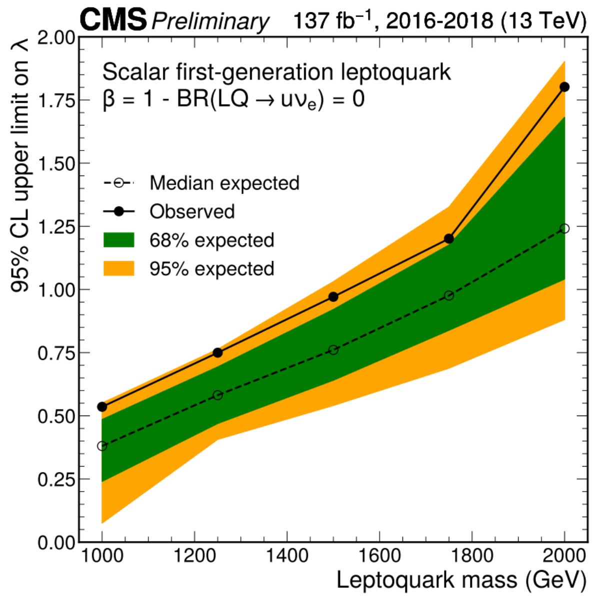
ATLAS: arXiv:2102.10874

NEW



Higgs Portal

B(H→inv) < 27.8 (25.3)

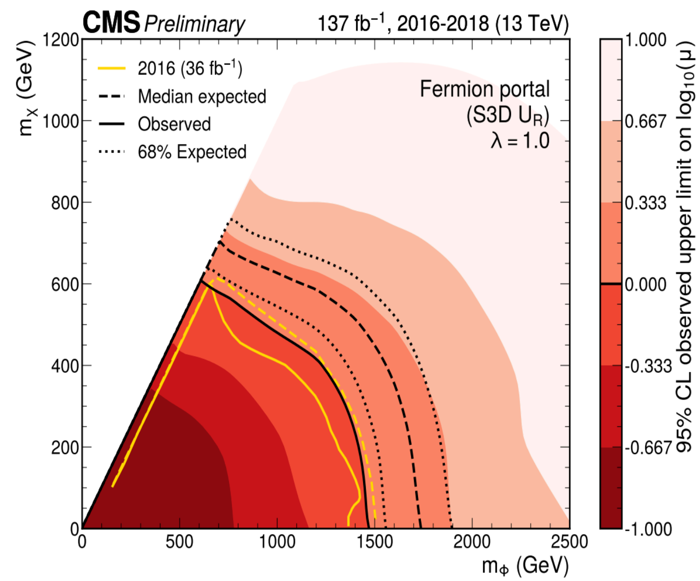


Lepto-quark

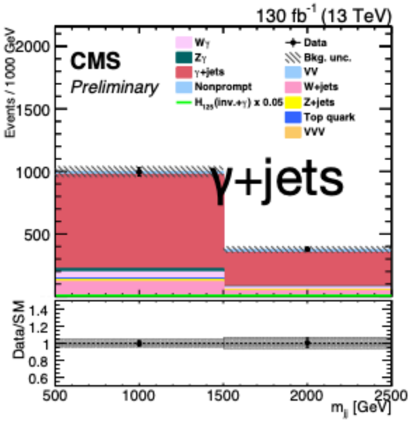
Pair production: dominates below λ < 1 TeV while single above 1 TeV

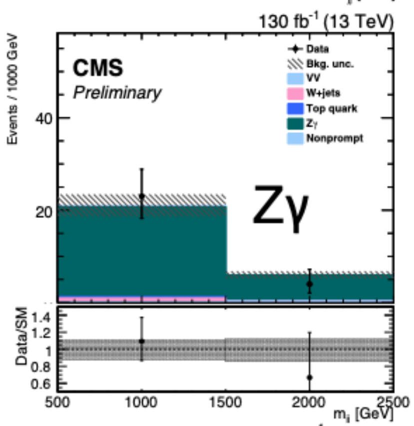
Fermion Portal: DM t-channel

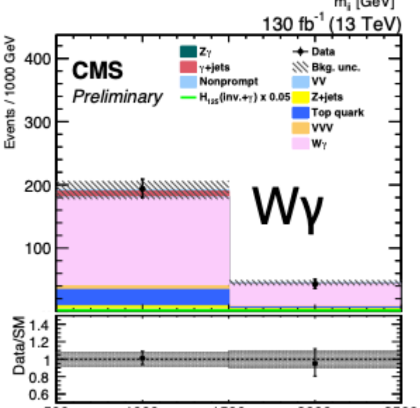
Mediater mass below ~1.5 TeV excluded for m_{DM} = 1 TeV



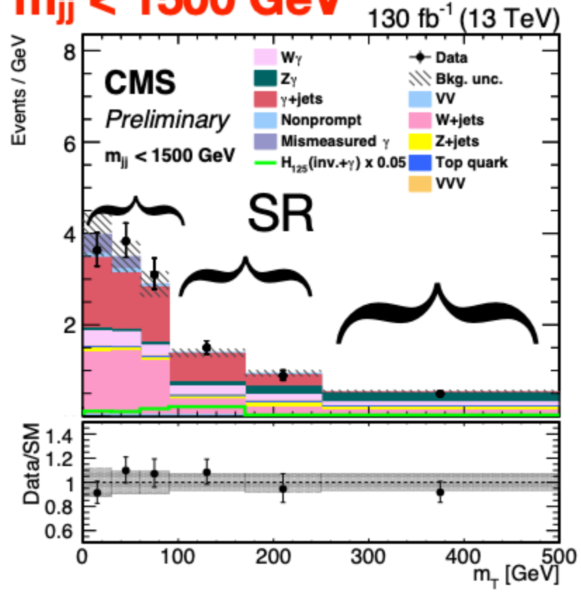
Dark photon in VBF Higgs



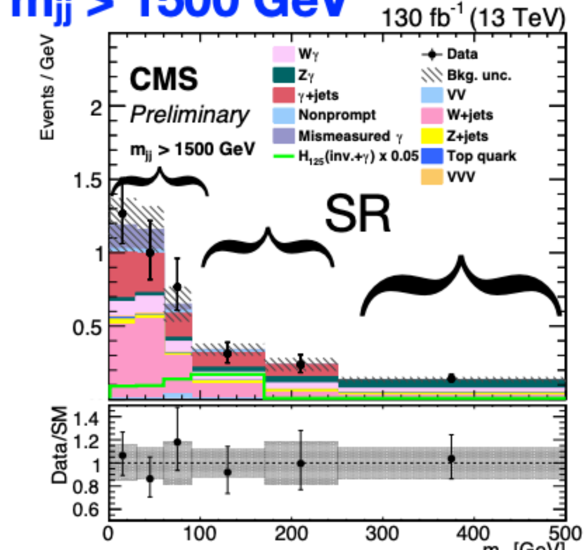


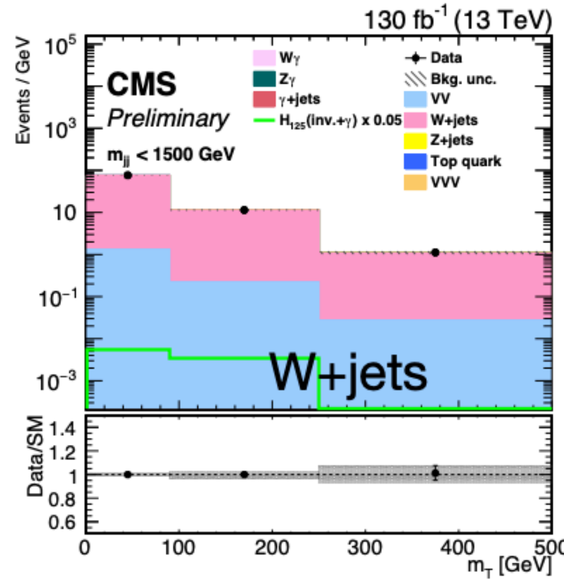


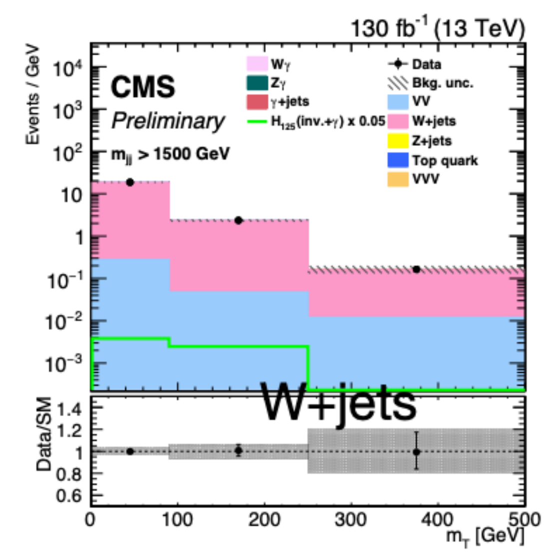
m_{jj} < 1500 GeV



m_{jj} > 1500 GeV



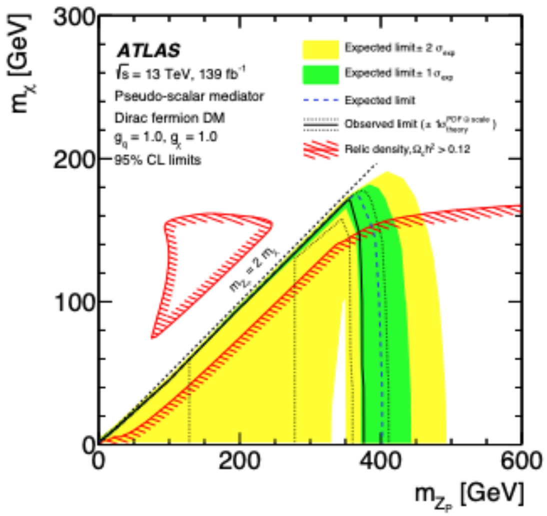




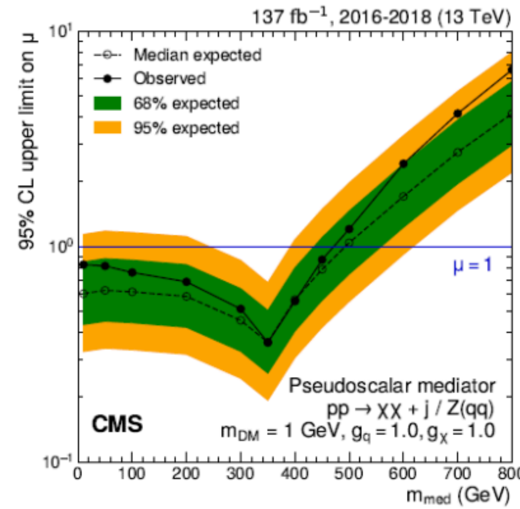
Monojet comparison with ATLAS

ATLAS-EXOT-2018-06
CMS-EXO-20-004

Pseudo-scalar mediator



Exclude m_{med}< 376 GeV

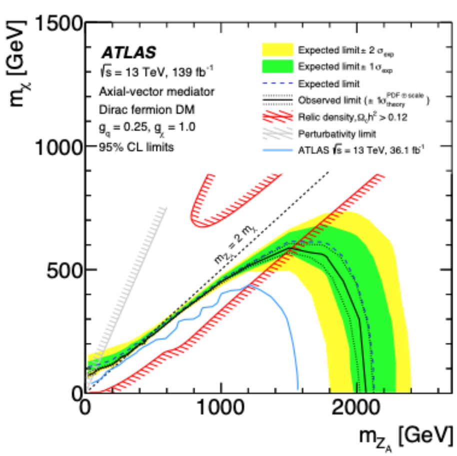


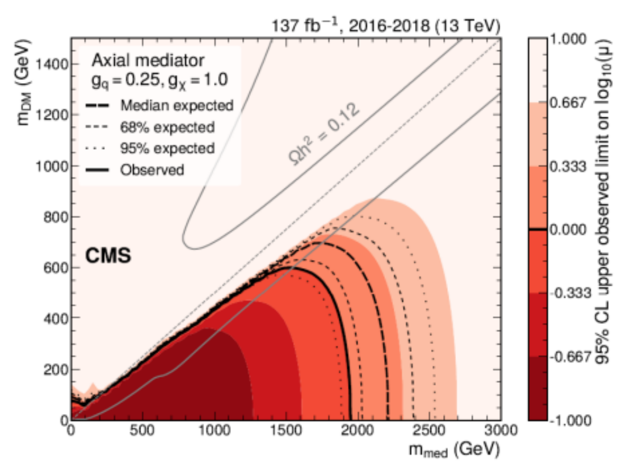
Exclude m_{med} < 470 GeV (490 GeV expected).

CMS has significantly better limits in pseudo-scalar mass exclusion

1

Axial-vector mediator





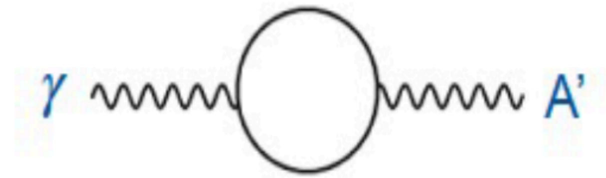
CMS and ATLAS pretty much similar limits for spin-1, exclude mediator mass upto 1.95 (2.1) TeV, for CMS(ATLAS), respectively

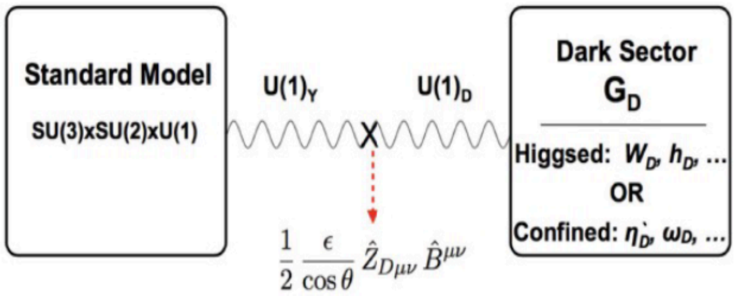
- CMS produces exclusion in coupling which ATLAS doesn't

Dark Photon

Add $U(1)_d$ from hidden sector

- **Connection between dark sector and SM**
- **Couple with SM via kinetic mixing, ε is kinetic mixing coefficient**
- **Massive gauge boson ($A/Z_d/\gamma_d$)**
- **ε and mass of ($A/Z_d/\gamma_d$) are key parameters**

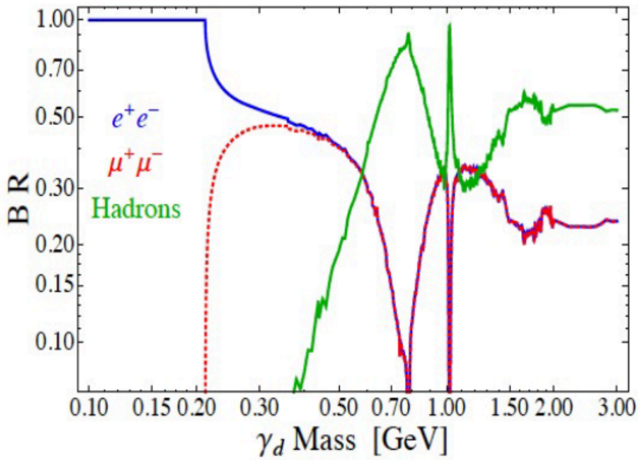




Search Strategy based on life:

- **Small : Prompt, resolved/collimated decay e.g. LJ**
- **Medium : Resolved/collimated decay e.g. delay LJ, displaced muons**
- **Long : stable particles, MET signature at colliders**

From arXiv:1002.2952

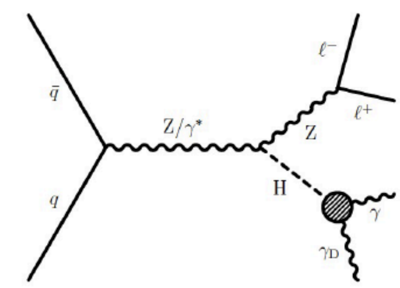


Dark Photon: ZH Channel

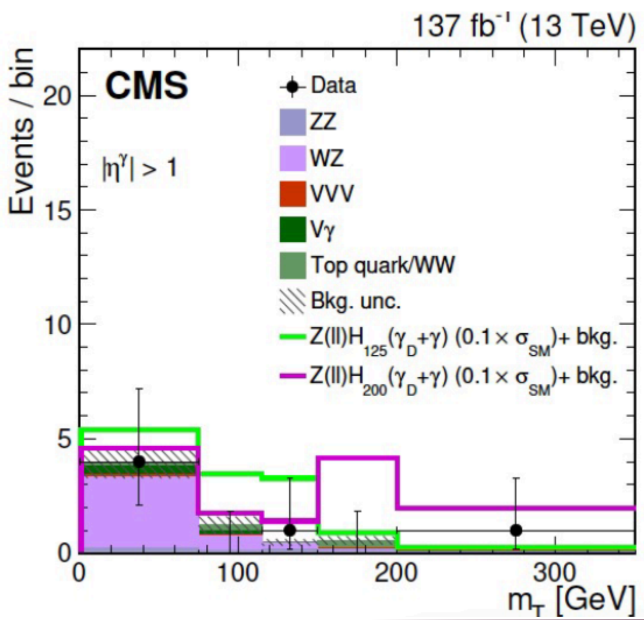
JHEP 10 (2019) 139 EXO-19-007

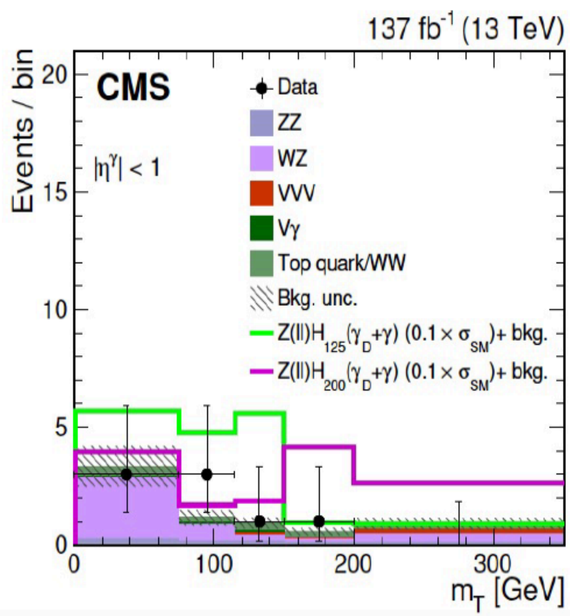
- **Probing a Higgs portal model with dark sector**
  - **$H \rightarrow \gamma\gamma_d$ where γ_d is massless dark photon**
  - **γ_d couples to Higgs through hidden charge sector**
  - **M_T of photon-MET system is used as discriminating variable**
  - **Dominate background normalized in control region**

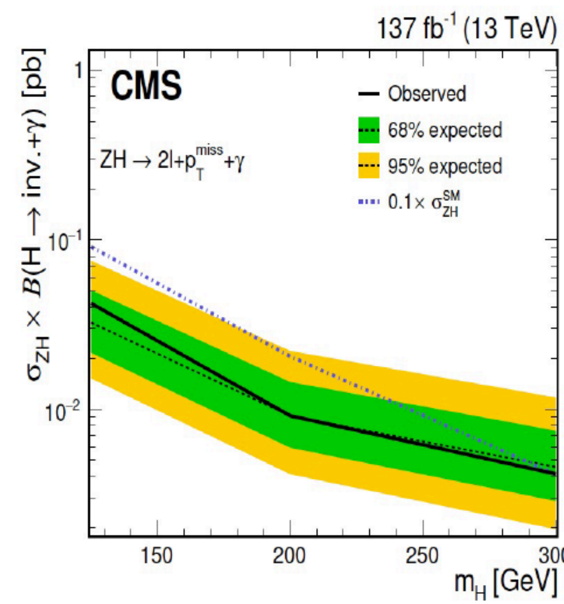
$$m_T = \sqrt{2p_T^{miss}E_T^{\gamma}[1-\cos(\Delta\phi_{\vec{p}_T^{miss},\vec{E}_T^{\gamma}})]}$$



Relatively clean final state **Limit on BR < 4.6% at 95% CL for SM H(γ+ Inv.)**







MonoHiggs bb

	0 lepton	1 muon	2 leptons
Aim	Signal regions	$t\bar{t}$ and W+HF control region	Z+HF control region
Fitted observable	m_h distribution	Muon charge (2 b-tag) Yields ($\geq$3 b-tag)	Yields
b-tag multiplicities	resolved (small-R jets): 2, $\geq$3 merged (variable-R track jets): 2 (inside Higgs candidate), $\geq$3 (2 inside Higgs candidate)		
$E_{\mathrm{T}}^{\mathrm{miss}}$ proxy	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T,\,lep.\,invis.}}^{\mathrm{miss}}$	$E_{\mathrm{T,\,lep.\,invis.}}^{\mathrm{miss}}$
Bins in $E_{\mathrm{T}}^{\mathrm{miss}}$ proxy	resolved: [150, 200], [200, 350] and [350, 500] GeV 2 b-tag merged signal regions (0 lepton): [500, 750] and [750, ∞) GeV Other merged regions: [500, ∞) GeV		

VBF+photon + MET

-taking years.

Data-taking year	2016	2017/2018	
Variable	VBF+γ	Single photon	$p_{\mathrm{T}}^{\mathrm{miss}}$
Number of photons		$\geq$1 photon	
p_{T}^{γ}	>80 GeV	>230 GeV	>80 GeV
Number of leptons		0	
$p_{\mathrm{T}}^{\mathrm{miss}}$	>100 GeV	>140 GeV	>140 GeV
Jet counting		2-5	
m_{jj}		>500 GeV	
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$		>3.0	
$\eta_{\mathrm{j}_1} \times \eta_{\mathrm{j}_2}$		<0	
$\Delta\phi$		>1.0	

Table 2: Summary of the binning choice in the SRs and CRs.

Region	Bins	Range (GeV)
SR, $m_{\mathrm{jj}} < 1500$ GeV	6	[0,30,60,90,170,250,inf]
SR, $m_{\mathrm{jj}} \geq 1500$ GeV	6	[0,30,60,90,170,250,inf]
W + jets CR, $m_{\mathrm{jj}} < 1500$ GeV	3	[0,90,250,inf]
W + jets CR, $m_{\mathrm{jj}} \geq 1500$ GeV	3	[0,90,250,inf]
$\mathrm{Z}(\ell\bar{\ell}) + \gamma$ CR, $m_{\mathrm{jj}} < 1500$ GeV	1	[0,inf]
$\mathrm{Z}(\ell\bar{\ell}) + \gamma$ CR, $m_{\mathrm{jj}} \geq 1500$ GeV	1	[0,inf]
$\mathrm{W}(\rightarrow \ell\nu) + \gamma$ CR, $m_{\mathrm{jj}} < 1500$ GeV	1	[0,inf]
$\mathrm{W}(\rightarrow \ell\nu) + \gamma$ CR, $m_{\mathrm{jj}} \geq 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{\mathrm{jj}} < 1500$ GeV	1	[0,inf]
γ + jets CR, $m_{\mathrm{jj}} \geq 1500$ GeV	1	[0,inf]

2HDM+Amodel parameters

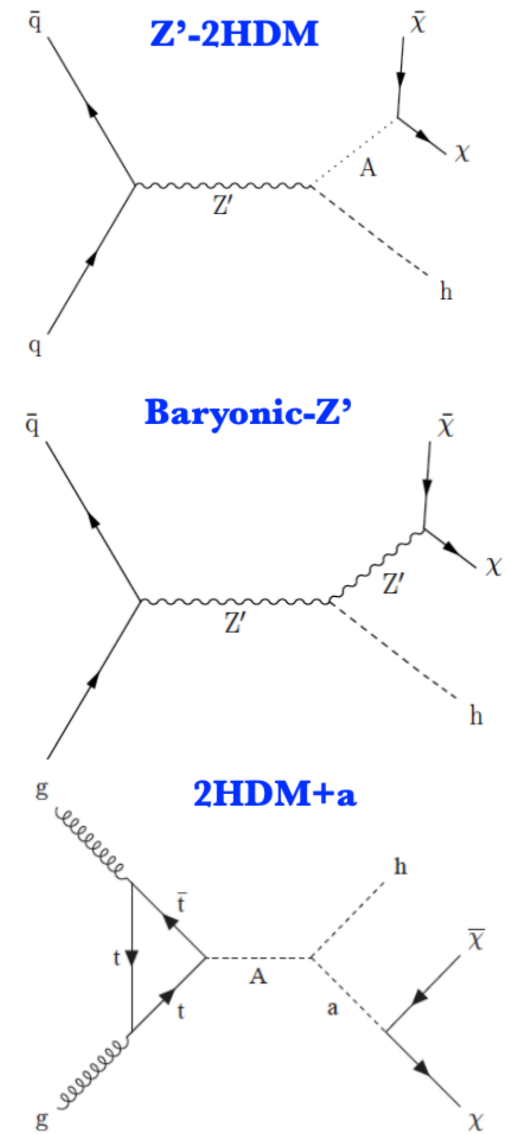
The phenomenology of the model is fully determined by 14 independent parameters: the masses of the Higgs bosons h, H, A, and $H^{\pm}$; the mass of the mediator a; the mass of the DM particle χ; the Yukawa coupling strength between the mediator and the DM particle, g_{χ}; the electroweak VEV, v; the ratio of the VEVs of the two Higgs doublets, $\tan\beta$; the mixing angles of the CP-even and CP-odd weak eigenstates, α and θ, respectively; and the three quartic couplings between the scalar doublets and the mediator ($\lambda_{P1}, \lambda_{P2}, \lambda_3$).

The values of some of these parameters are heavily constrained by both electroweak and flavour measurements as well as phenomenological considerations, such as the requirement that the Higgs potential is stable. Further parameter choices are driven by the desire to simplify the phenomenology of the model and reduce the space of independent parameters to be scanned by experimental searches. A summary of the parameter choices and the benchmark scans shown in this note is given in the following. A detailed description of the 2HDM+a benchmark scans recommended by the LHC Dark Matter Working Group is given in Ref. [22].

The following parameter settings are common to all benchmark scans shown in Section 6. The coupling g_{χ} is set to unity with a negligible effect on the shapes of the kinematic distributions of interest. As mentioned above, the alignment limit ($\cos(\beta - \alpha) = 0$) is assumed, and hence $m_h = 125$ GeV and $v = 246$ GeV. The quartic coupling $\lambda_3 = 3$ is chosen to ensure the stability of the Higgs potential for our choice of the masses of the heavy Higgs bosons which are themselves fixed to the same value ($m_A = m_H = m_{H^{\pm}}$) to simplify the phenomenology and evade the constraints from electroweak precision measurements [21]. The other quartic couplings are also set to 3 in order to maximise the trilinear couplings between the CP-odd and the CP-even neutral states.

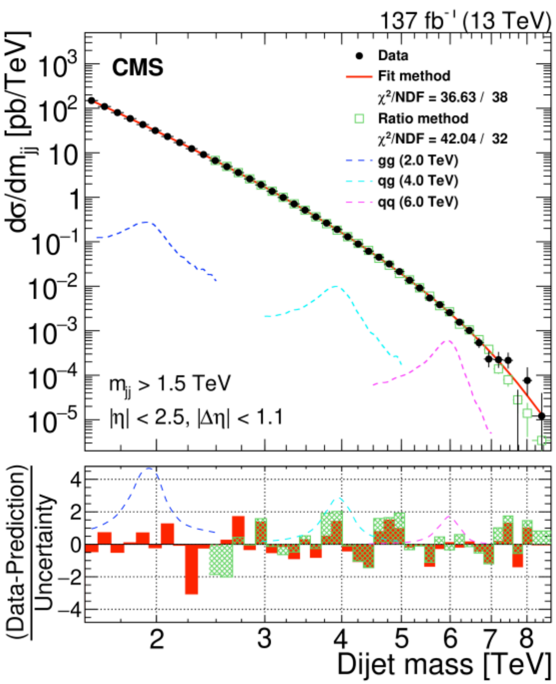
mono-Higgs: Interpretations

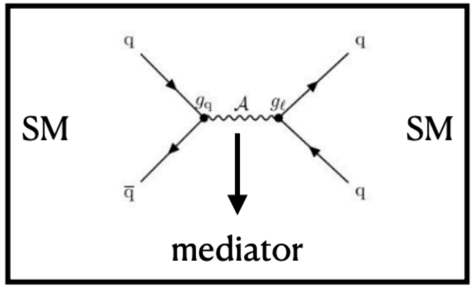
- **There are three simplified models available which predicts the mono-H signal.**
  - **Z'-2HDM:**
    - ➡ Heavy vector mediator is produced resonantly and decays into a SM-like Higgs boson and an intermediate pseudoscalar particle A.
  - **Baryonic-Z':**
    - ➡ A "baryonic-Higgs" boson mixes with the SM Higgs boson. A vector mediator Z' is produced in s-channel and decays into a pair of DM particles after radiating a Higgs boson.
  - **2HDM+a:**
    - ➡ Two-Higgs-doublet model extended by an additional pseudoscaler ***a*** which mixes with the scalar and pseudoscalar partner of the new Higgs boson and decays into a pair of DM particles.



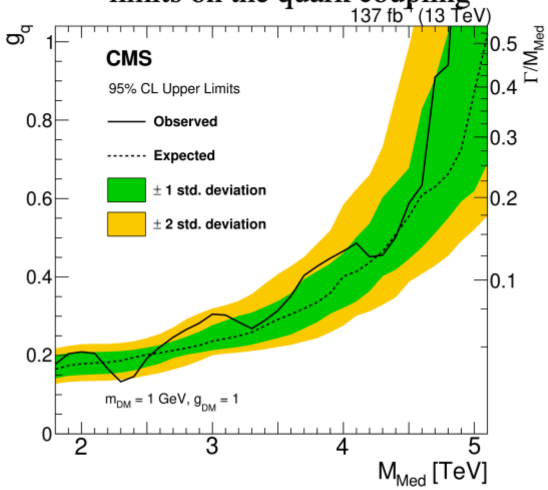
Dijet resonance search

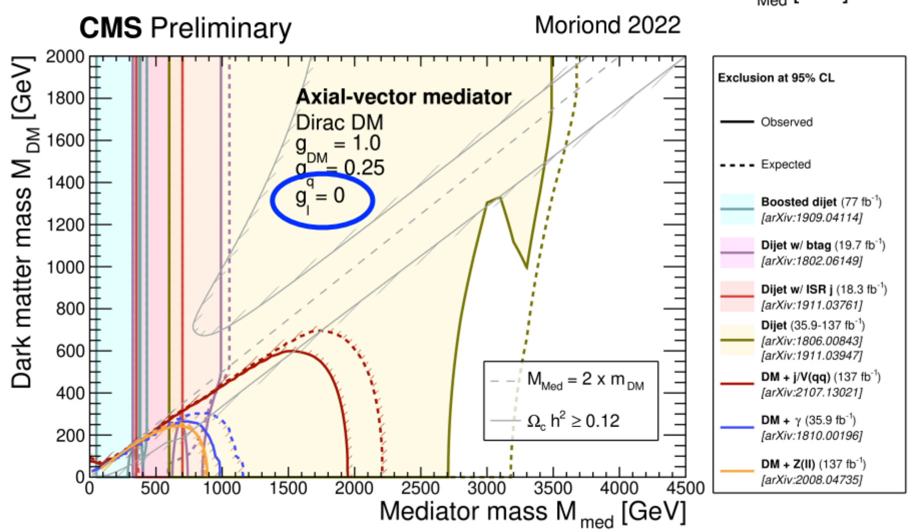
Bump hunt perfomed to find mediator





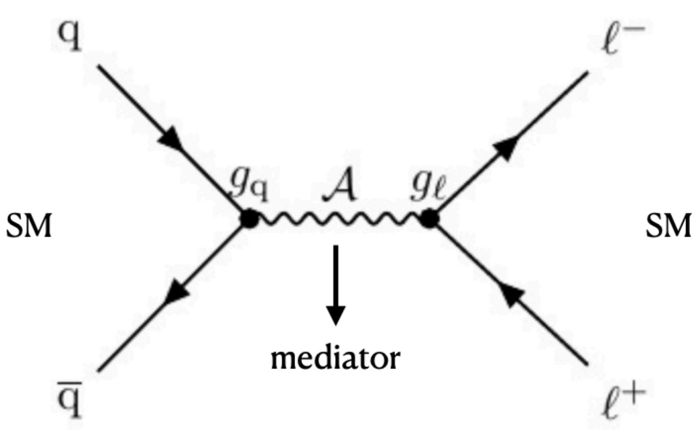
limits on the quark coupling





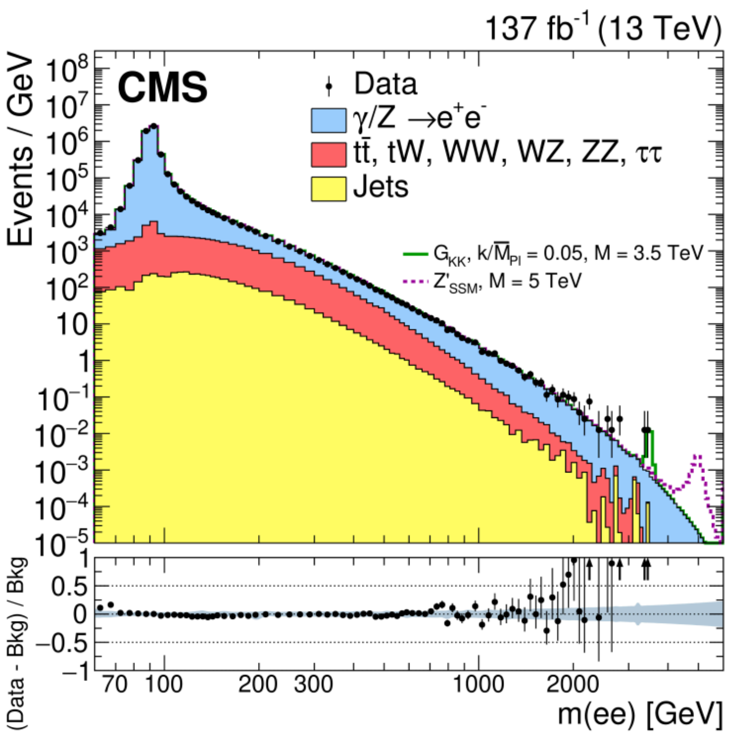
No peak is observed with respect to the SM background expectations.

Dilepton resonance search



Coupling to lepton introduced

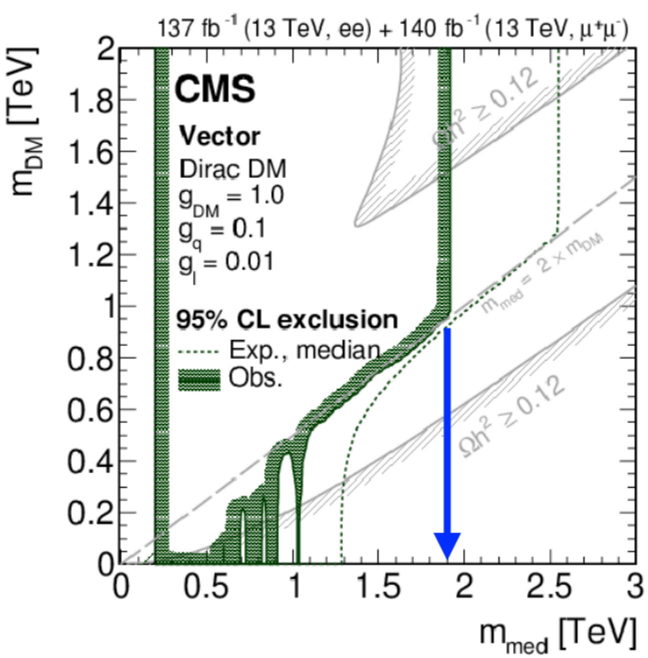
Bump hunt perfomed to find mediator



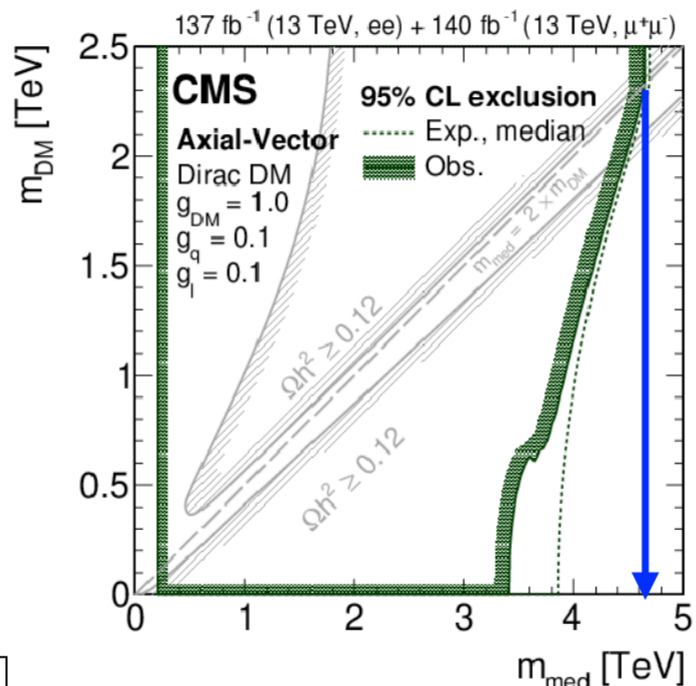
No peak is observed with respect to the SM background expectations

Interpretations

Coupling to lepton $g_l = 0.01$



Coupling to lepton $g_l = 0.1$



- m_{med} < 1.92 TeV excluded, for m_{DM} = 0, 1.04 TeV excluded
- Due to fluctuations in the observed limit, not all masses below that value are excluded

m_{med} < 4.64 TeV excluded, for m_{DM} = 0, 3.41 TeV excluded