Search for Dark Matter with Mono-X Signatures in CMS

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(ON BEHALF OF THE CMS COLLABORATION)

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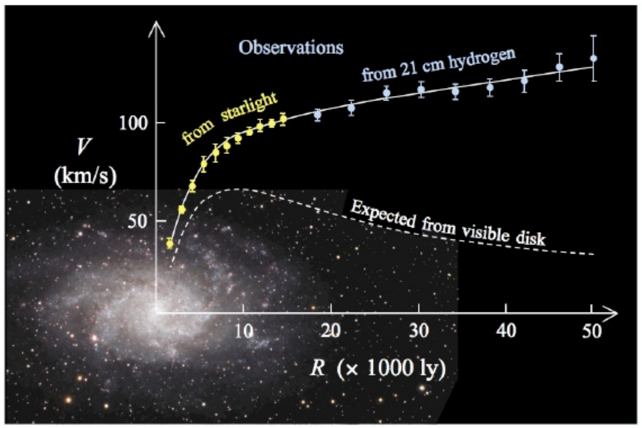
Introduction

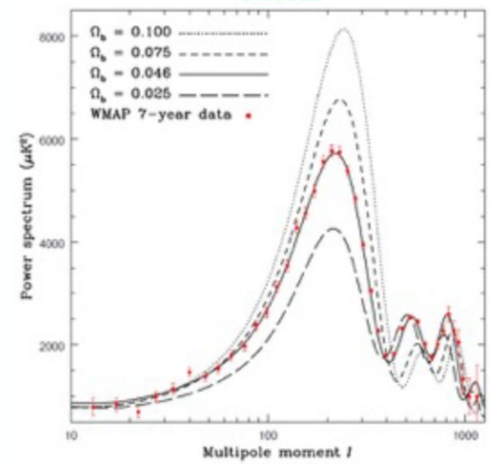
Existence of dark matter known through its gravitational interactions

Galactic rotation



Weak lensing

CMB

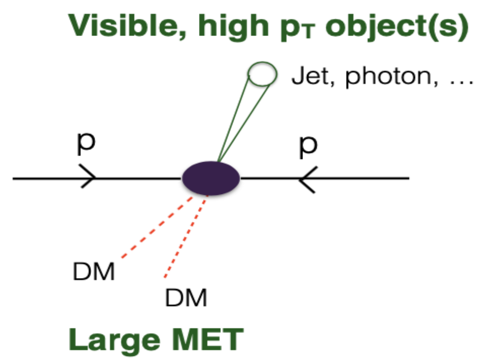


Underlying nature of dark matter (DM) remains unknown

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!!*

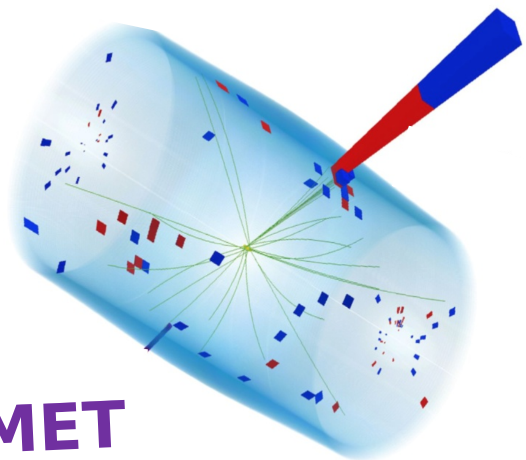
Dark Matter



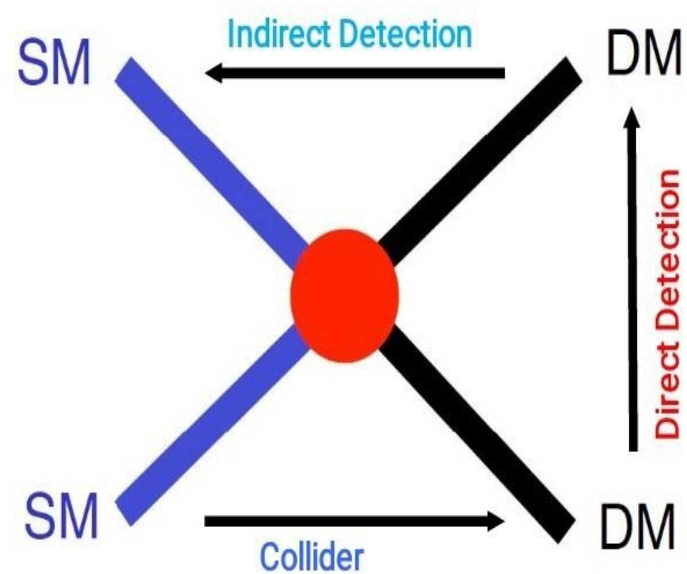
- Favorite collider candidate: WIMP
- Weakly interacting, massive, stable

General collider strategy

X = γ, W, Z, H, g, t

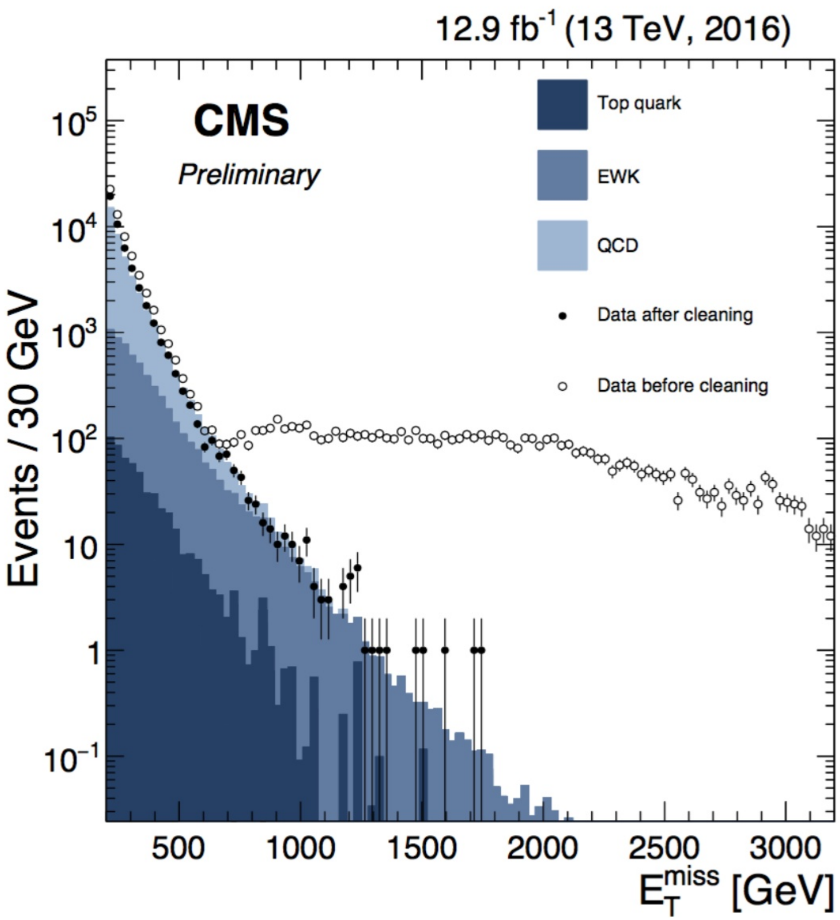


MET



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

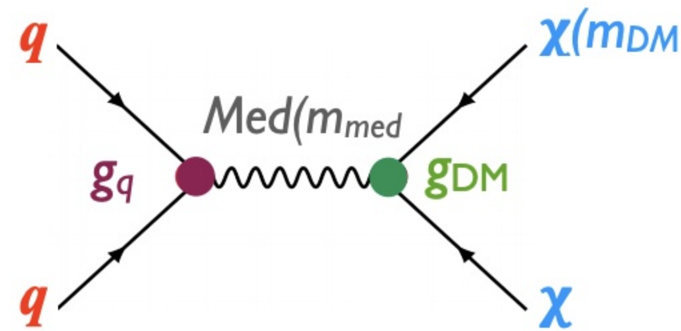
- Dark matter production in pp collisions described using ***"simplified models"***
- Capture the essential features of a variety of DM signals through a minimal set of parameters

✓ 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)***

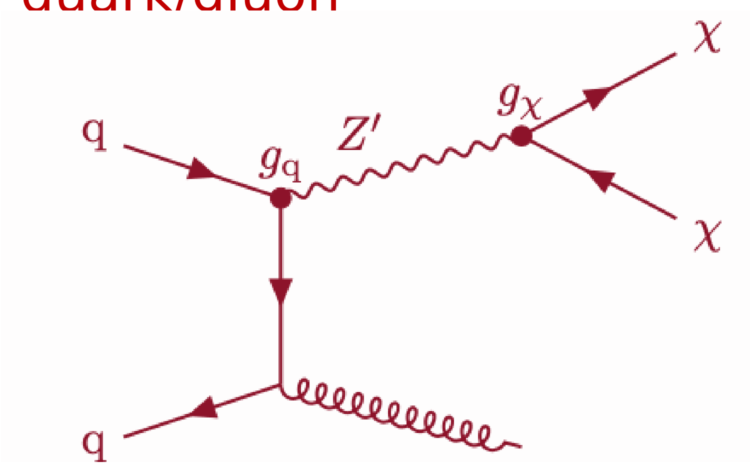
[CMS Result](#)

MonoJet

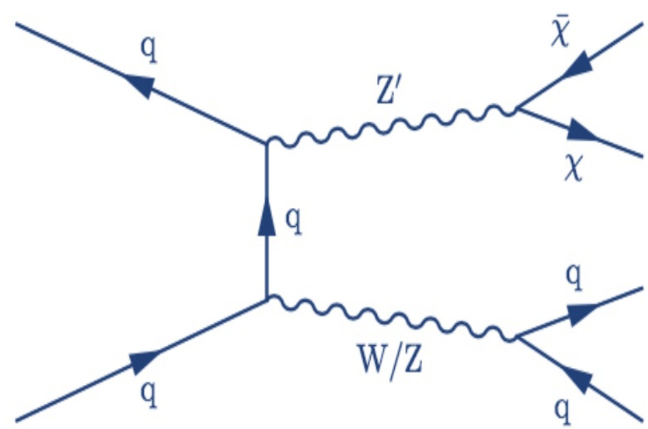
- ✓ Search for physics with particles that decay **invisibly** in association with a **jet**

- ✓ 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

CMS Result

Signal Region: **Jets + MET**

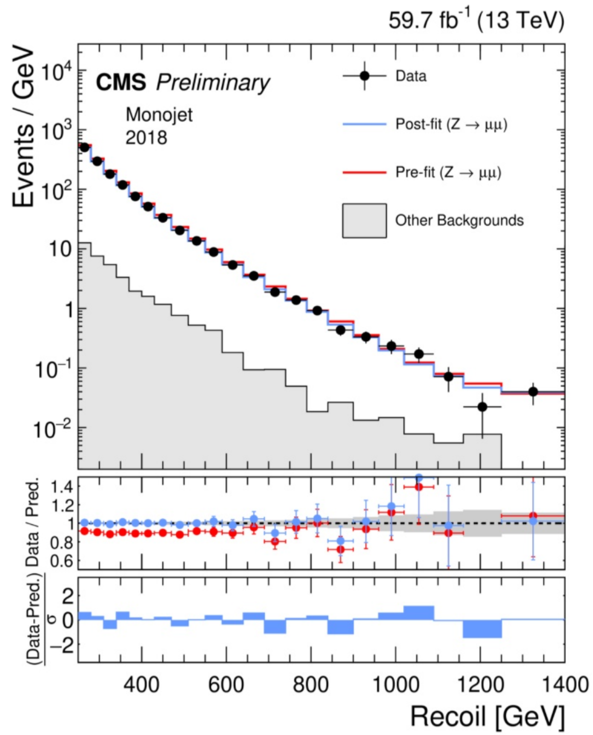
Background: Z/W+jet, top, dibosons, multijet

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

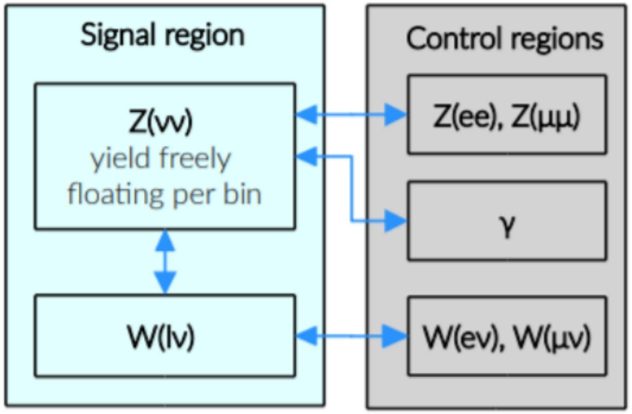


Data/background predictions in Control Regions

MonoJet Signal Extraction

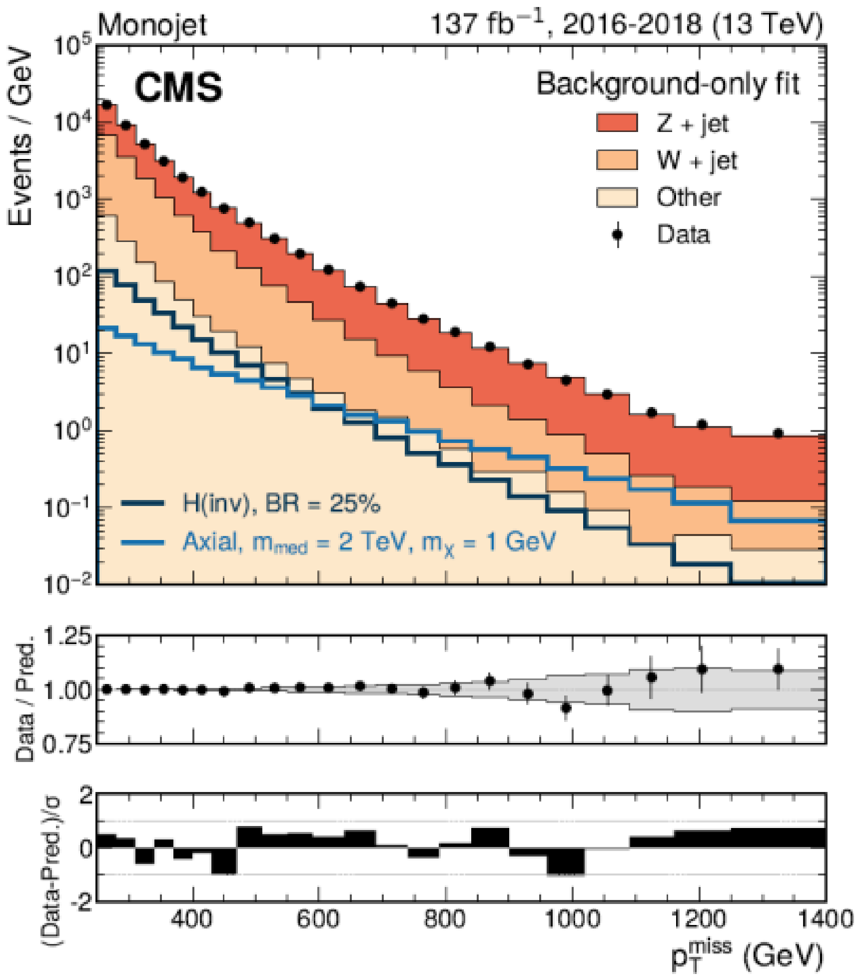
- Signal extraction is based on **MET** distribution, an unconstrained parameter per recoil bin per category and year.
  - Monojet: 22 bins   Mono-V: 7 bins
- **SR** and **CRs** are linked together with **binned transfer factors (TF).**
- The **TFs are constrained by simulations**, within theory and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

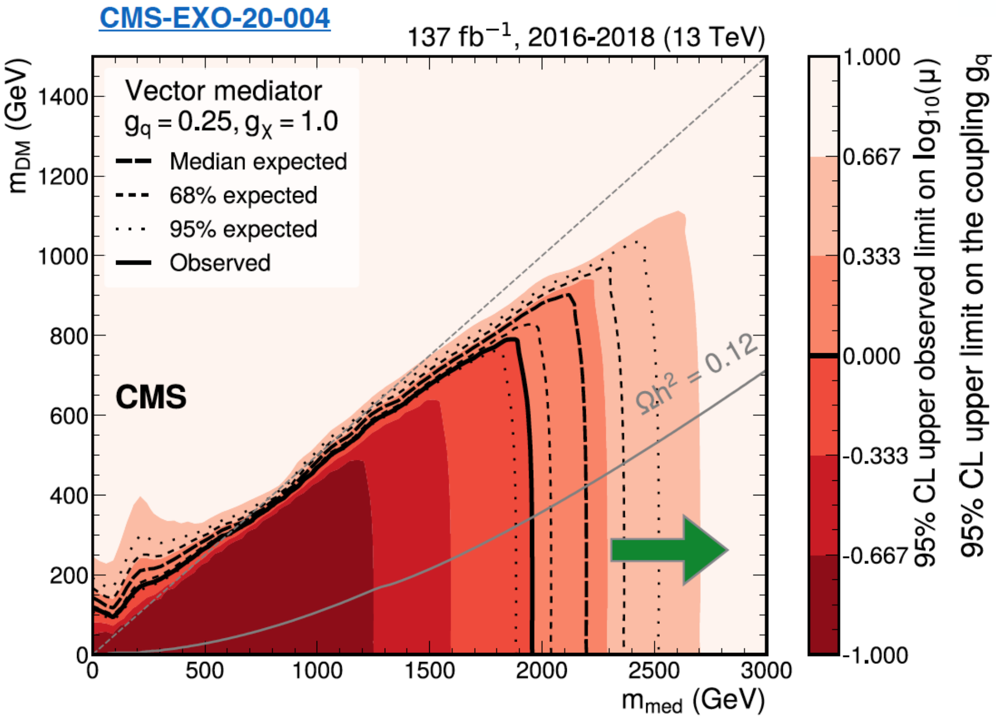
22 bins

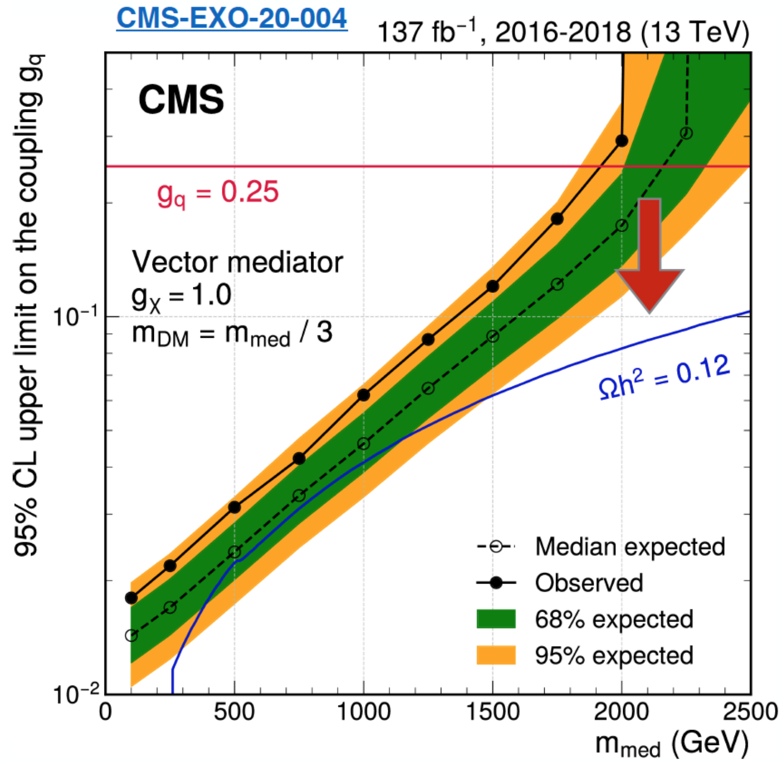
5 CR (2 W, 2 Z, 1 photon)

regions split by year

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

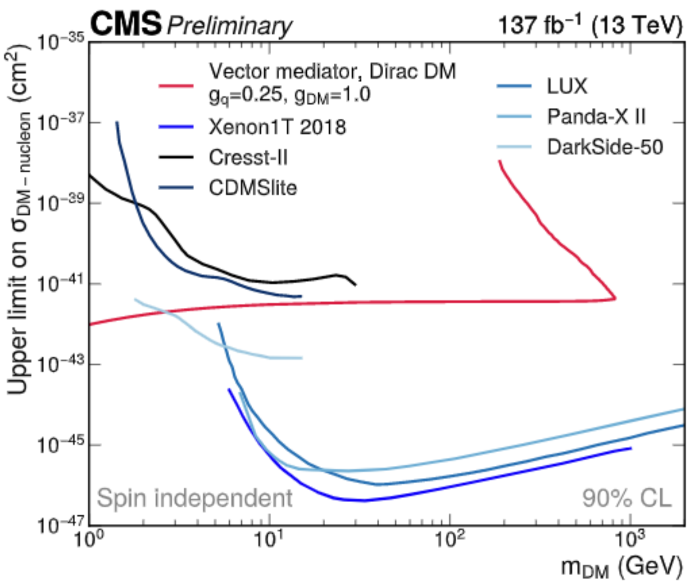
MonoJet Results

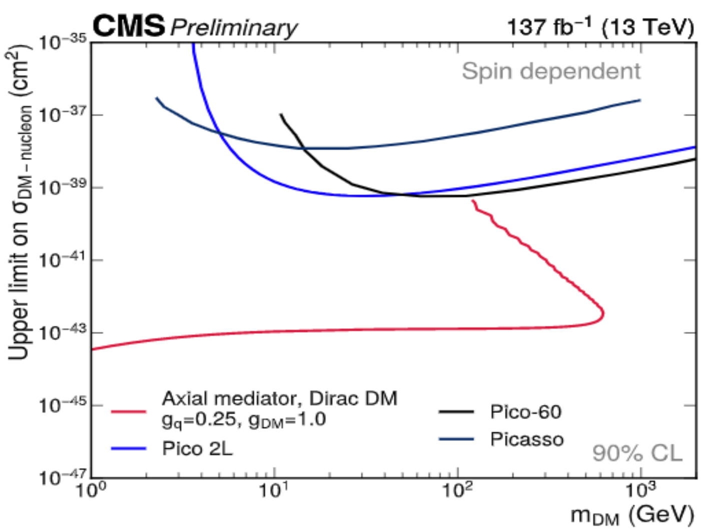




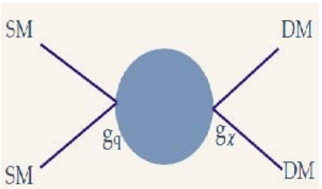
Goal is to probe **higher masses** and **lower couplings**

Comparing to the rest of the world

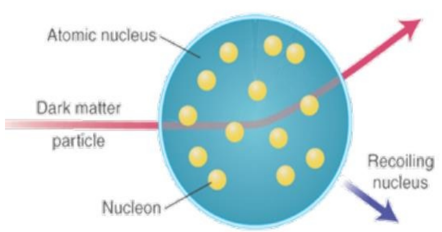




Comparison to direct detection experiments



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]

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Mono-Z Search

Signature: Z(ll)+MET

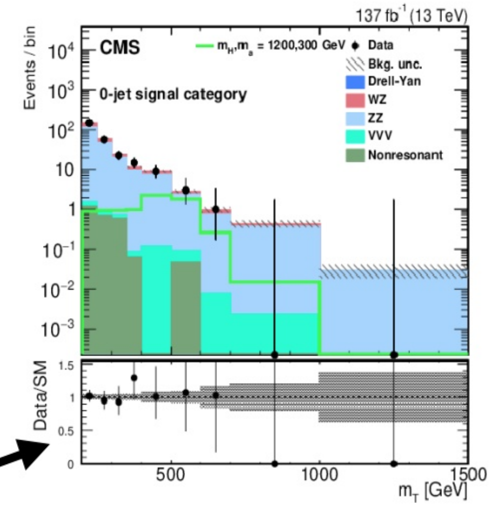
Model for interpretations:
- Simplified model
- 2HDM+a

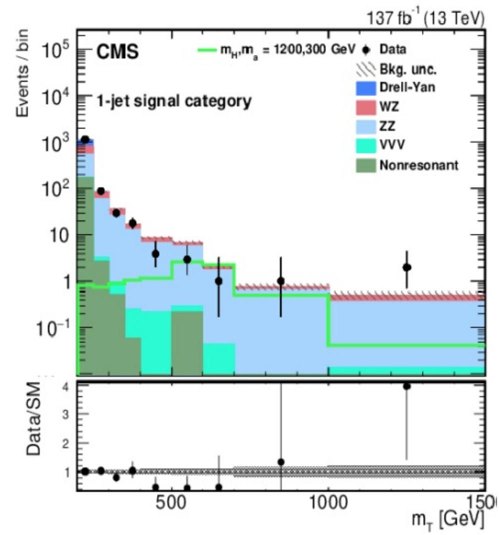
p_T^{miss} for simplified, m_T for 2HDM+a model

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

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



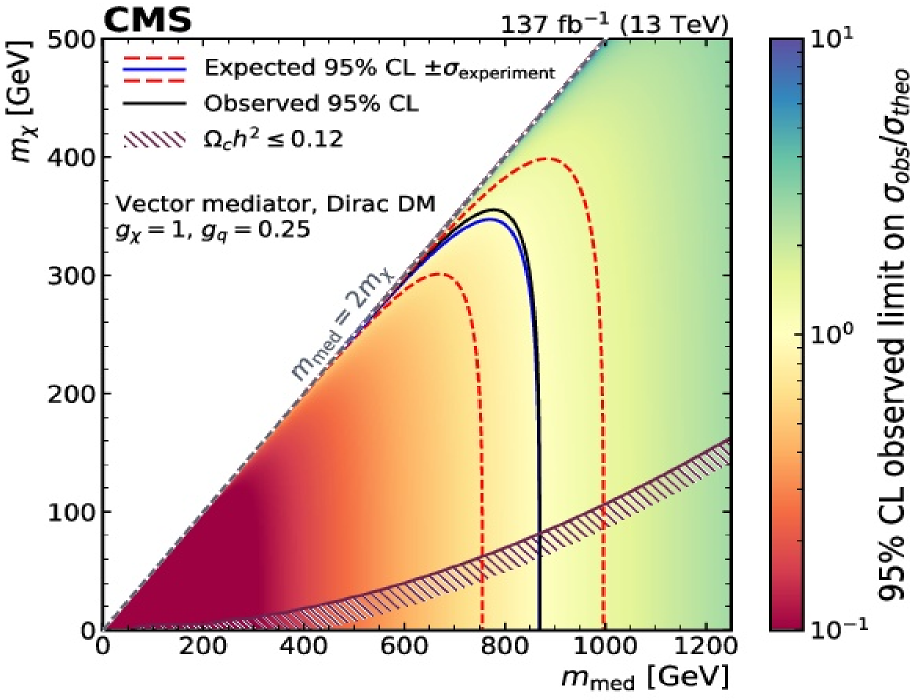


Mono-Z Comparison

Eur.Phy.J.C.81(2021) 13

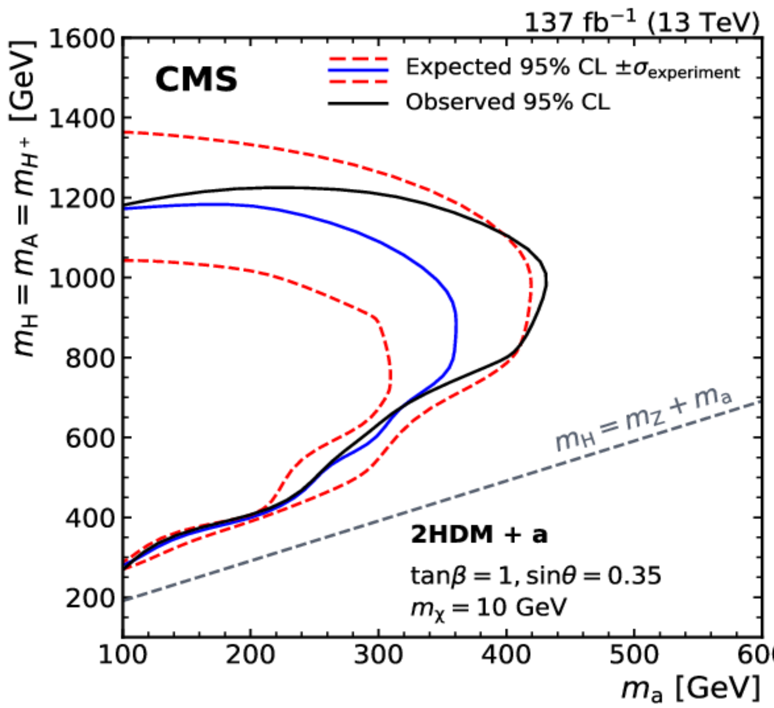
❖ **For Simplified DM model (Vector)**

Mediator mass excluded upto 800 GeV



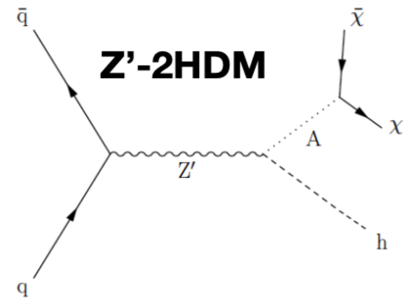
For 2HDM+a model

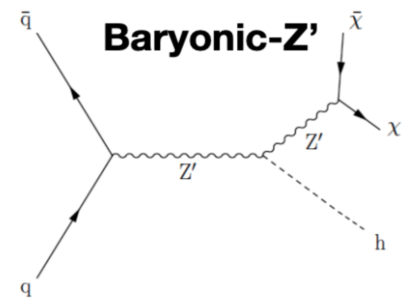
Maximal exclusion m_a = 350 GeV and M_H = 1.2 TeV

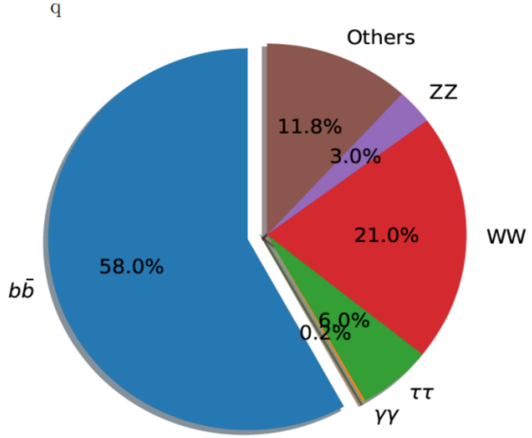


Mono-Higgs

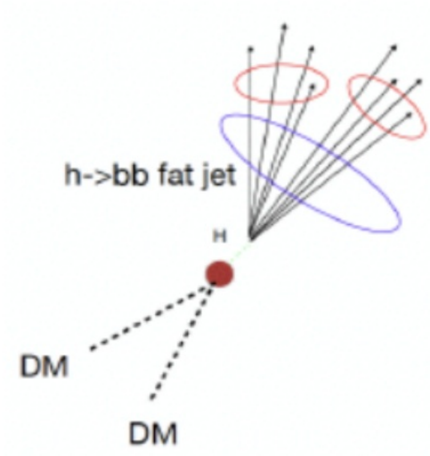
- After the discovery of the **Higgs boson (125 GeV)** it is possible to probe the DM using this new handle.
- **New massive particle** mediates the **Higgs-DM** interaction.
- Search performed in 5 decay channels and statistically combined.
  - $b\bar{b}, \gamma\gamma, WW, ZZ\ and\ \tau\tau$
- Results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







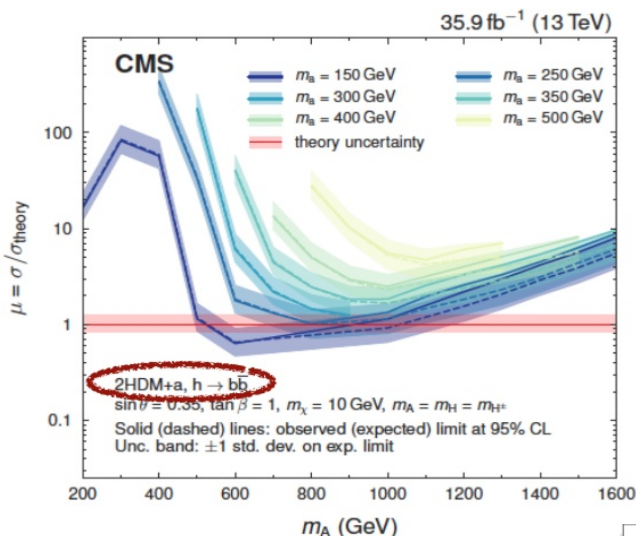
Mono-Higgs

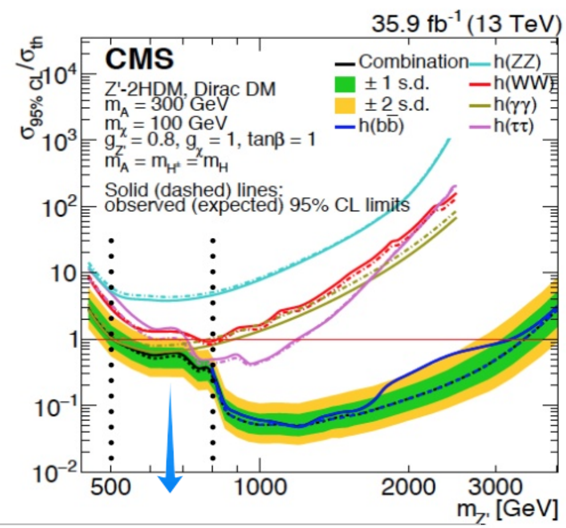


H→bb	most sensitive
2HDM+a	CA15 jets
Baryonic-Z’	CA15 jets
Z’-2HDM	AK8 jets

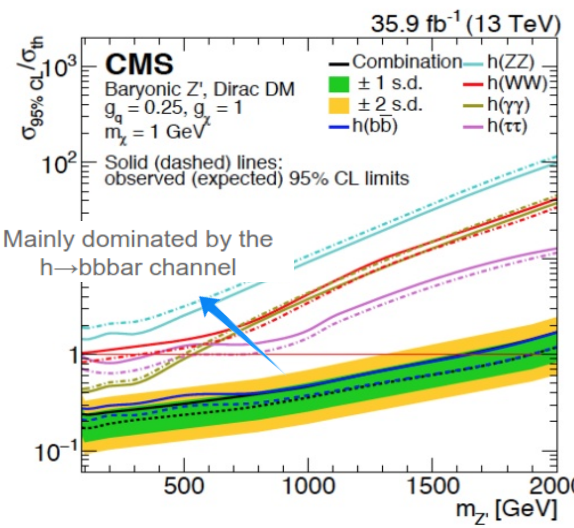
Decay channel	Final state or category
h → bb	AK8 jet (Z′-2HDM) CA15 jet (Baryonic Z′)
h → γγ	$p_T^{miss} \in$ 50–130 GeV $p_T^{miss} >$ 130 GeV
h → ττ	$\tau_h\tau_h$ $\mu\tau_h$ $e\tau_h$
h → WW	$e\nu\mu\nu$
h → ZZ	4e 4μ $2e2\mu$

Final states orthogonal to each other





h(bbbar) channel has no sensitivity for $m_{Z'}$<800GeV; h(γγ) and h(τ⁺τ⁻) contribute the most here



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 coming months***
  - ***Stay tuned for this and the upcoming Run3!***

Thank You

Backup

MonoZ : Fitting Strategy

Fitting Strategy

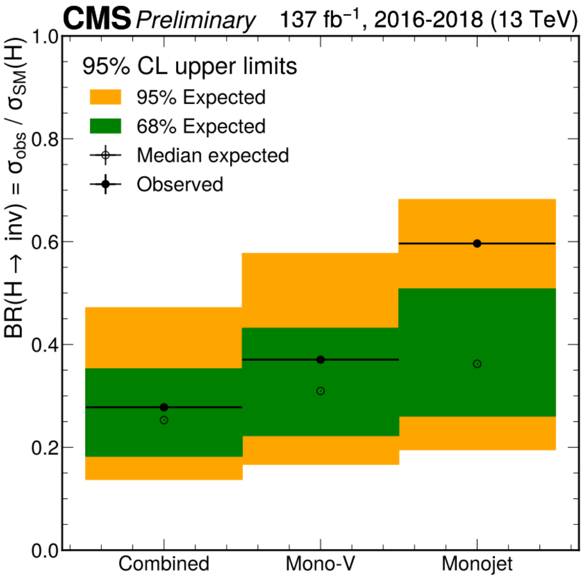
- ATLAS:
  - nonresonant and WZ production normalized from data
  - ZZ production not normalized from data, replying on simulation post-facto
- CMS:
  - nonresonant production normalized from data
  - $\mathrm{Z}+\mathrm{jets}$ events in 0 jet and 1 jet categories normalized from data
  - WZ and ZZ production estimated from data using a single normalization factor
  - large EWK correction uncertainties considered
  - VV shape: 3 additional nuisances ($\pm 10/20/30\%$) at low ($80 < p_{\mathrm{T}}^{\mathrm{miss}} < 200\mathrm{GeV}$), medium ($200 < p_{\mathrm{T}}^{\mathrm{miss}} < 400\mathrm{GeV}$), and high $p_{\mathrm{T}}^{\mathrm{miss}}$ ($p_{\mathrm{T}}^{\mathrm{miss}} > 400\mathrm{GeV}$) 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

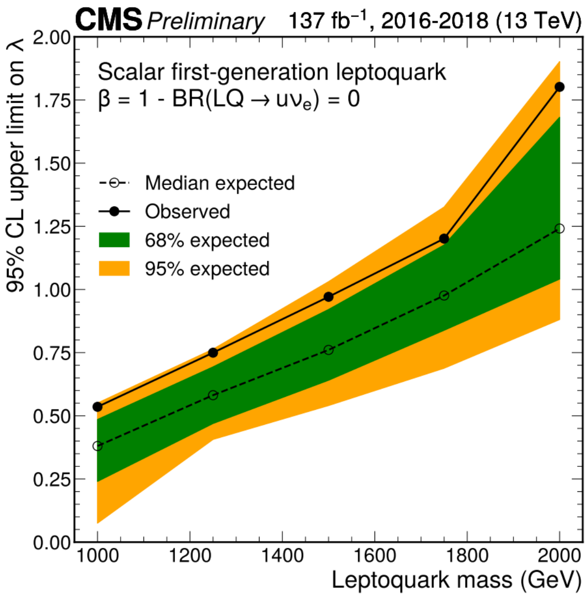
OTHER INTREPRETATIONS : CMS MONOJET

CMS PAS EXO-20-004

ATLAS : arXiv:2102.10874

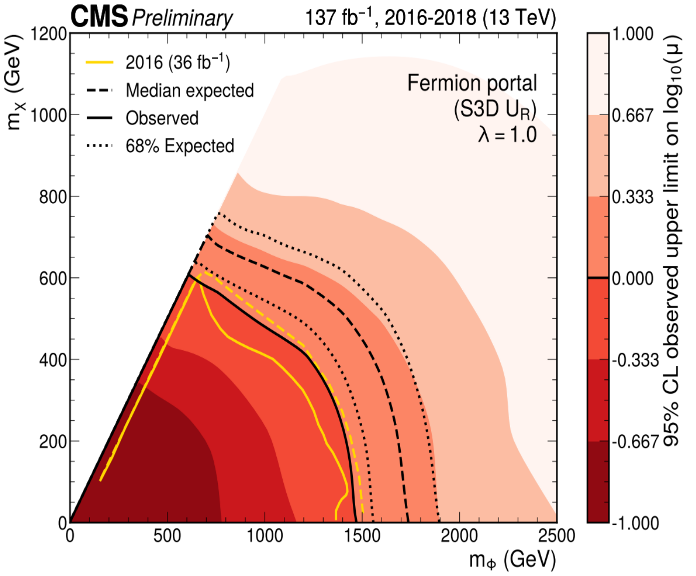
NEW





Fermion Portal: DM t-channel

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



Higgs Portal

B(Hinv) < 27.8 (25.3)

Lepto-quark

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

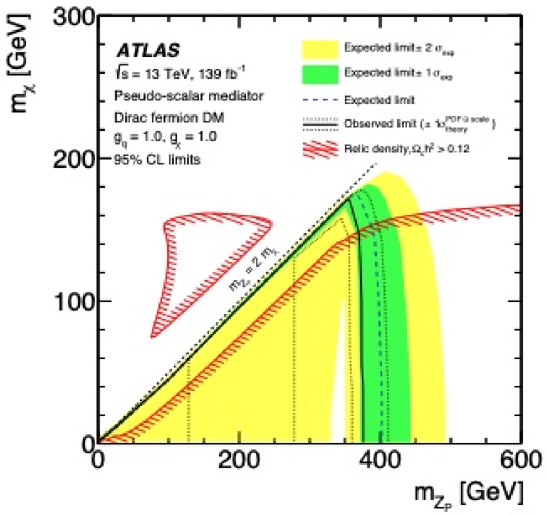
Higgs Portal

B(H→inv) < 27.8 (25.3)

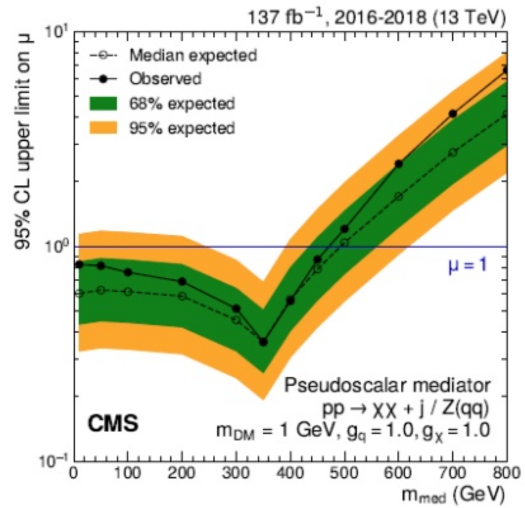
Monojet comparison with ATLAS

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

Pseudo-scalar mediator



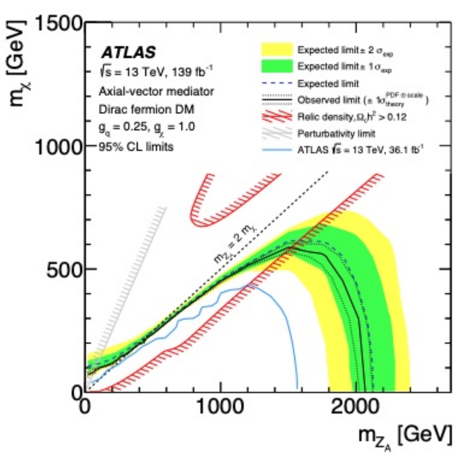
Exclude m_{med}< 376 GeV

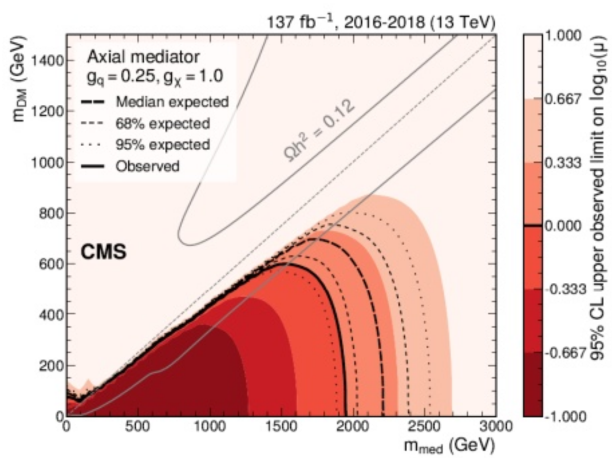


Exclude m_{med} < 470 GeV (490 GeV expected).

CMS has significantly better limits in pseudo-scalar mass exclusion

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

Monophoton ATLAS

Table 5: Observed and expected yields from SM backgrounds obtained from the 'simplified shape fit' described in Section 5. The normalisation factors obtained from the fit are also shown. The uncertainty includes both the statistical and systematic uncertainties. The individual uncertainties can be correlated and do not necessarily add in quadrature to equal the total background uncertainty.

	SRE1	SRE2	SRE3	SRI4
Observed events	3023	1164	679	427
Expected SM events	3070 ± 130	1182 ± 75	680 ± 53	448 ± 42
$Z(\to \nu\nu)\gamma$	1910 ± 110	758 ± 65	468 ± 49	306 ± 40
$W(\to \ell\nu)\gamma$	394 ± 22	159 ± 15	71.0 ± 8.2	56.7 ± 7.1
$Z(\to \ell\ell)\gamma$	33.2 ± 2.4	9.32 ± 0.89	4.26 ± 0.48	2.69 ± 0.37
γ + jets	87 ± 35	11.9 ± 4.8	2.7 ± 1.1	3.0 ± 1.2
Fake photons from e	511 ± 48	188 ± 18	100.9 ± 9.5	59.7 ± 5.6
Fake photons from jets	136 ± 28	56 ± 29	33 ± 16	20 ± 11
$k_{Z\gamma}$	0.99 ± 0.08	0.89 ± 0.09	0.90 ± 0.11	0.86 ± 0.12
$k_{W\gamma}$	0.81 ± 0.09	0.84 ± 0.11	0.74 ± 0.11	0.85 ± 0.13
$k_{\gamma+\text{jets}}$	0.82 ± 0.21			

Table 6: Summary of the uncertainties (%) in the background estimate for inclusive SRs after the background-only fit and for exclusive SRs after the 'simplified shape fit'. The individual uncertainties can be correlated and do not necessarily add in quadrature to equal the total background uncertainty.

	SRI1 [%]	SRI2 [%]	SRI3 [%]	SRI4 [%]	SRE1 [%]	SRE2 [%]	SRE3 [%]
Total (statistical+systematic) uncertainty	3.5	4.8	6.2	9.5	4.3	6.3	7.8
Statistical uncertainty	2.4	3.6	5.3	8.5	3.3	5.0	6.7
Fake photons from jets (Section 5)	1.4	2.5	2.8	4.1	1.4	3.6	3.7
Jet energy scale/resol [52]	1.6	2.2	2.5	2.7	2.2	2.2	2.3
Fake photons from electrons (Section 5)	2.1	2.0	2.0	2.0	2.3	2.3	2.1
Electrons reco/id/isolation eff. [47]	1.0	1.2	1.3	1.4	1.0	1.0	1.2
Electron/photon energy scale/resol [47]	0.8	0.6	0.7	0.9	0.9	0.9	0.6
Muon reco/id/isolation eff. [48]	0.7	0.8	0.9	1.0	0.6	0.7	0.9
E_T^{miss} soft term scale/resolution [55]	0.1	0.4	0.7	0.9	0.5	0.2	0.5
Theoretical $W/Z+\gamma$, γ + jets	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$\langle\mu\rangle$ reweighting in MC simulation	0.3	0.2	0.2	0.2	0.3	0.2	0.2

Monophoton ATLAS

Table 5: Observed and expected yields from SM backgrounds obtained from the 'simplified shape fit' described in Section 5. The normalisation factors obtained from the fit are also shown. The uncertainty includes both the statistical and systematic uncertainties. The individual uncertainties can be correlated and do not necessarily add in quadrature to equal the total background uncertainty.

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Fake photons from *e*	511 ± 48	188 ± 18	100.9 ± 9.5	59.7 ± 5.6
Fake photons from jets	136 ± 28	56 ± 29	33 ± 16	20 ± 11
$k_{Z\gamma}$	0.99 ± 0.08	0.89 ± 0.09	0.90 ± 0.11	0.86 ± 0.12
$k_{W\gamma}$	0.81 ± 0.09	0.84 ± 0.11	0.74 ± 0.11	0.85 ± 0.13
$k_{\gamma+\text{jets}}$	0.82 ± 0.21			

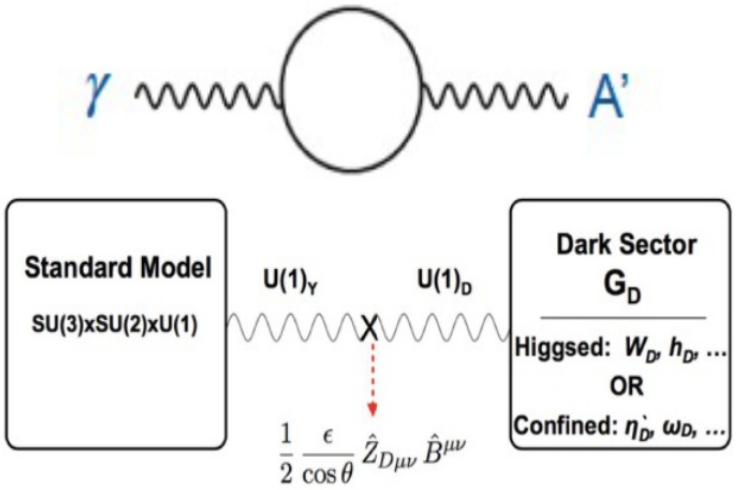
Towards Run3

- **MonoZ**
  - No major hurdles, uses standard objects/triggers
  - Improve ZZ control region (had low statistics in Run2)
  - Use aggressive approach for theory uncertainty for ZZ
  - Expand 2HDM+a results, include sin(theta) scan, as done by ATLAS
- **Monojet**
  - In Run2, electron/photon uncertainties are the leading limitations
    - Need to do in-house developments for the scale factors
  - Use of most recent MadGraph which includes NLO QCD & EW corrections, should help with simulation of V+jets background and reduce uncertainties
  - Better MET trigger turn-on could improve low-mass constraints
  - For MonoV category, develop trigger which includes boosted tagging
  - Reinterpretation : Publish full likelihood instead of simplified as ATLAS did for Run2 paper
- **Monophoton**
  - Include more intrepretation, ALP could be one
  - Use new madgraph samples which can include NLO QCD & EW corrections
- **Hinv**
  - VBF
    - Recovery of the HF jets -- currently detector issues cost ~30% of acceptance
    - Better trigger based on VBF + MET @ L1 / HLT, including angular cuts to reject QCD online
    - Theoretical constraints for V+jets background
      - Not available currently, work with theorists needed
  - ttH
    - Re-optimized AK8 taggers for Run-3
    - Use ML to separate ttH (H->inv) from ttbar

Dark Photon

Add $U(1)_d$ from hidden sector

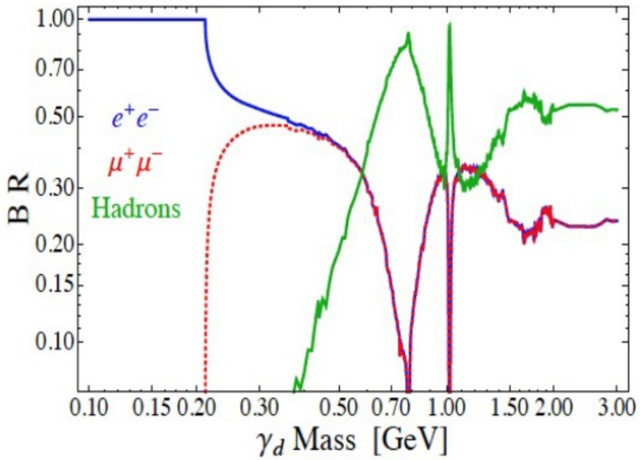
- Connection between dark sector and SM
- Couple with SM via kinetic mixing, ε is kinetic mixing coefficient
- Massive gauge boson ($A/Z_d/\gamma_d$)
- ε and mass of ($A/Z_d/\gamma_d$) are key parameters



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

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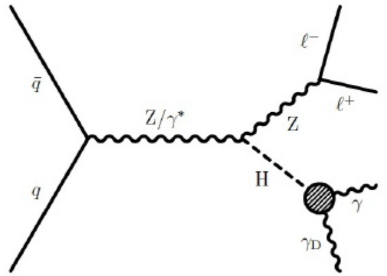
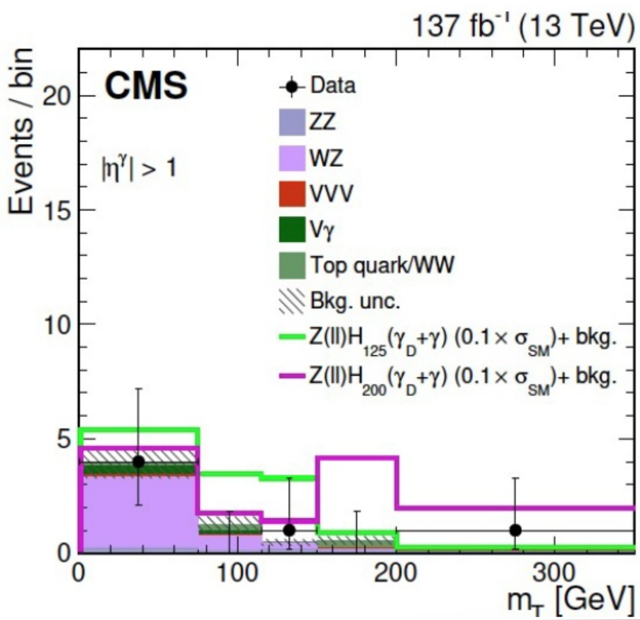
- **Probing a Higgs portal model with dark sector**
  - **H → $\gamma\gamma_d$ where γ_d is massless dark photon**
  - **γ_d couples to Higgs through hidden charge sector**
  - **M_T of photon-MET system is used as discriminating variable**
  - **Dominate background normalized in control region**

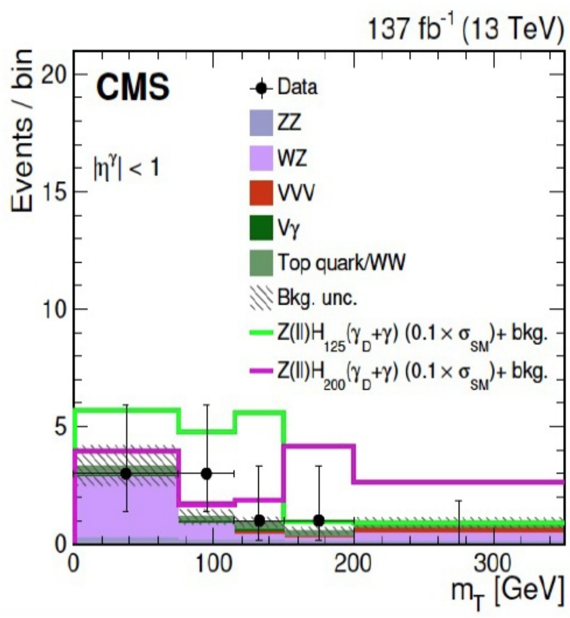
$$m_T = \sqrt{2p_T^{miss}E_T^{\gamma}[1-\cos(\Delta\phi_{\vec{p}_T^{miss},\vec{E}_T^{\gamma}})]}$$

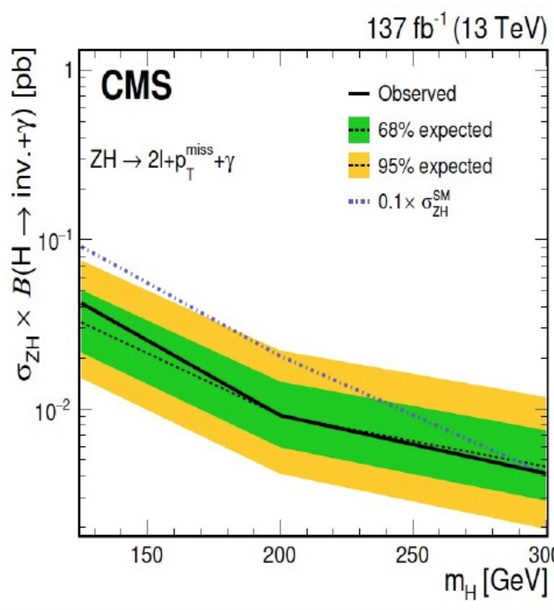


Relatively clean final state

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 (≥3 b-tag)	Yields
b-tag multiplicities	resolved (small-R jets): 2, ≥3 merged (variable-R track jets): 2 (inside Higgs candidate), ≥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_T^{miss}
Number of photons		$\geq$1 photon	
p_T^{γ}	>80 GeV	>230 GeV	>80 GeV
Number of leptons		0	
p_T^{miss}	>100 GeV	>140 GeV	>140 GeV
Jet counting		2-5	
m_{jj}		>500 GeV	
$\|\Delta\eta_{jj}\|$		>3.0	
$\eta_{j_1} \times \eta_{j_2}$		<0	
$\Delta\phi_{jet,\vec{p}_T^{miss}}$		>1.0	
z_{γ}^{*}		<0.6	
p_T^{tot}		<150 GeV	

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

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