



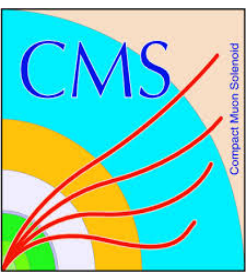
Search for Dark Matter with mono-X Signatures in CMS

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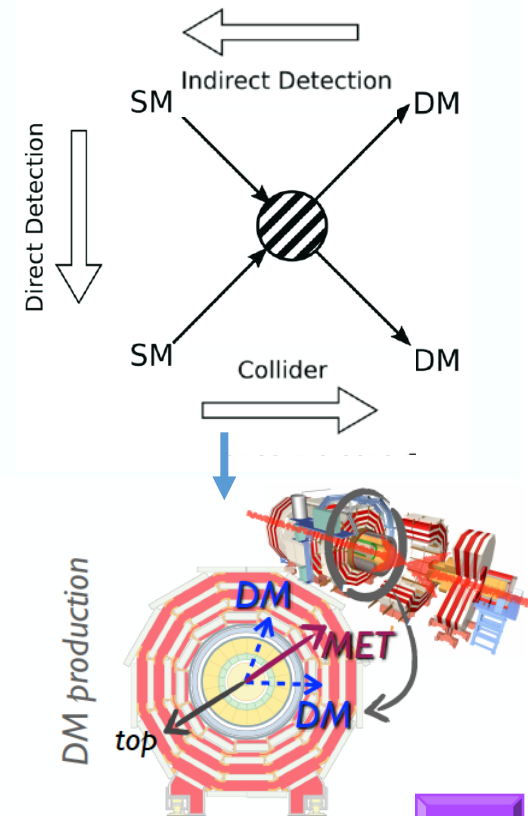
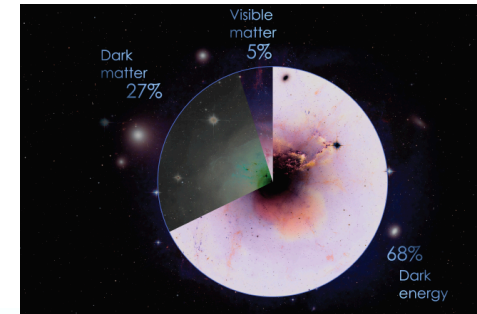
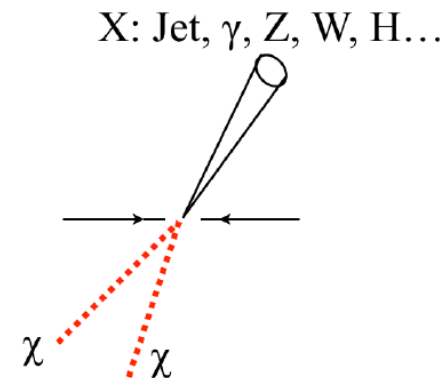
On behalf of CMS Collaboration



Dark Matter

What is the dark matter?

- Multiple evidence from astrophysical observations at different scales for Dark Matter (DM) existence.
 - DM interact gravitationally, long lived and neutral particles.
 - No information about its nature
- **Goal:** Understand the nature of dark matter
- **Dark Matter Searches:**
 - Indirect Detection: Products from DM annihilation
 - Direct Detection: Nuclear recoils from DM-nuclei scattering
 - Collider search: DM production in high energy collisions
- DM could be produced at colliders (rare process)
 - no direct trace in the detector, but could create a p_T imbalance ($\mathbf{p}_T^{\text{miss}}$)
 - need visible particle to which DM particle recoils against
 - “**mono-X searches**”: X includes jets, vector bosons, top, ...

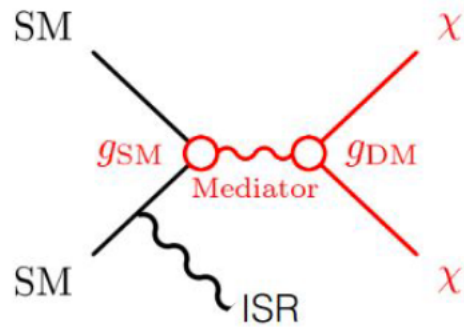


Overview of Dark Matter models

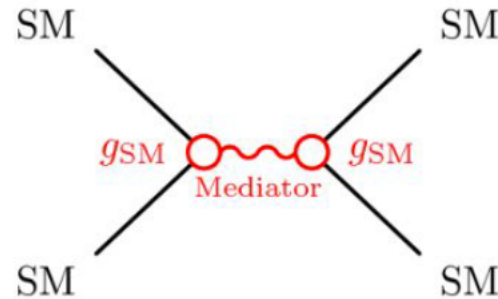
Simplified Models

- have a mediator and DM particle

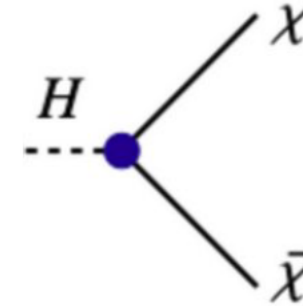
Mono-X searches



Mediator (resonance) searches



Higgs portal Model



- Mono-X signature is visible object recoil against missing energy
- X could be photon, W/Z boson, jets, Higgs boson
- ISR or associated production used to tag the event
- Look for deviation from SM background

- Visible final states from DM decay to SM particles
- Look for mass peak above background continuum
- Expect signal peak in invariant mass of two visible final state particle above the standard model background.

- Dark matter produced in the decay of the Higgs boson
- Look for enhance in Higgs to invisible decay.

DM search strategy

- **Selection:**

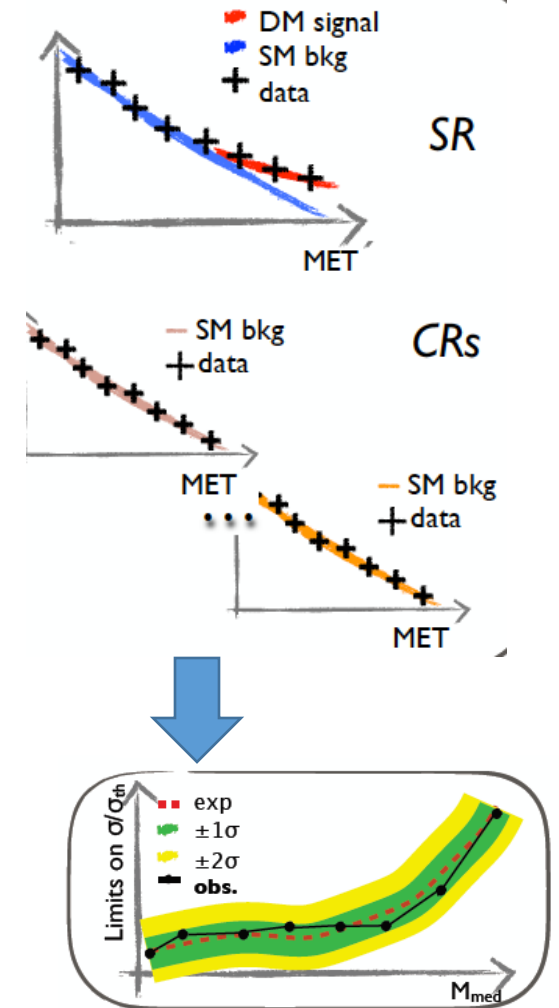
- Search for an excess of events in MET tail w.r.t SM in region enriched with signal (signal Region – SR)

- **Background:**

- Measuring the dominant background processes contributing in the SR
- Achieved using orthogonal Control Regions (CR)

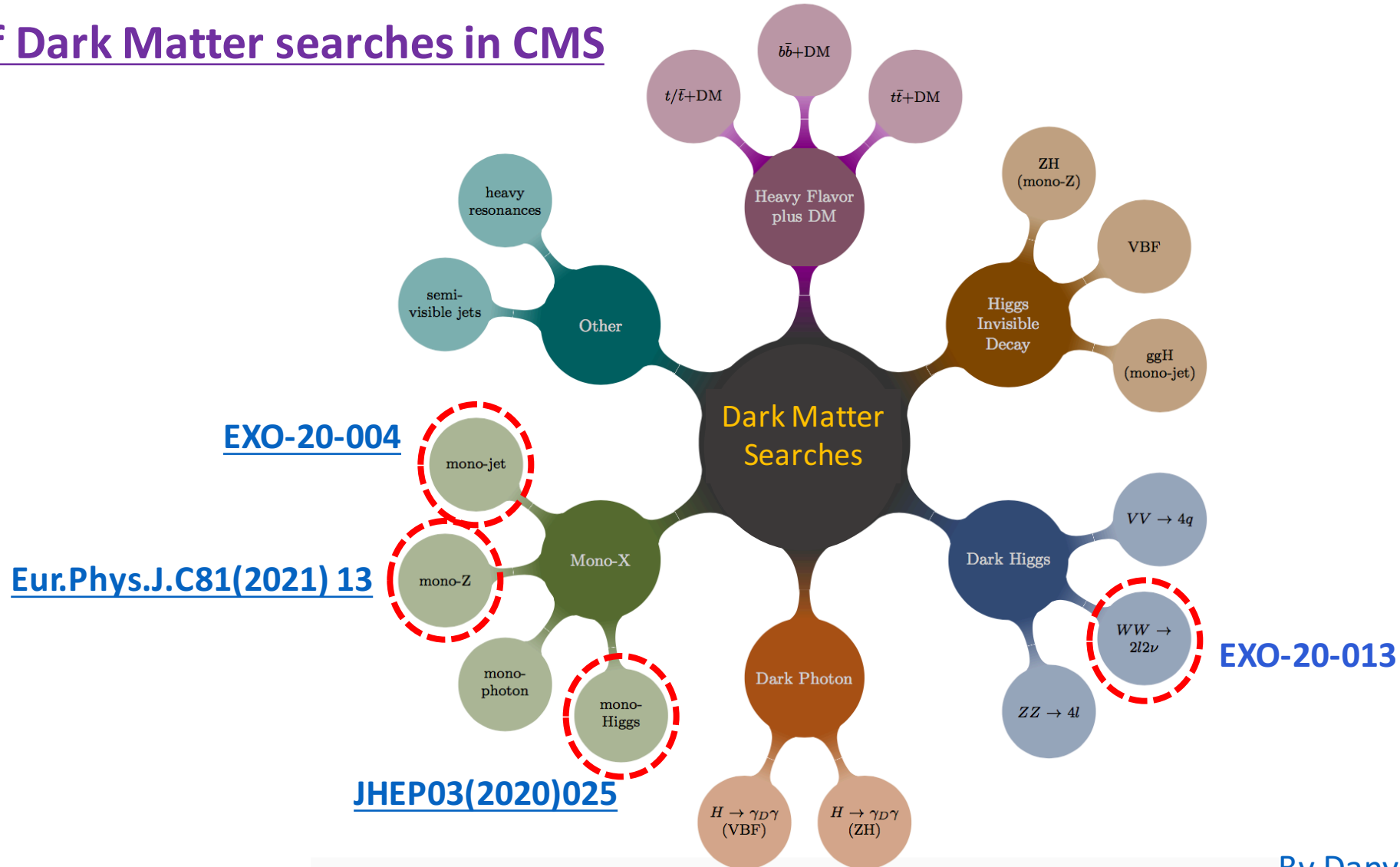
- **Results:**

- Compare data with SM prediction
- excess of events in data. Did we find DM?
- no excess, interpret result in terms of theory model parameters



List of DM searches

Full list of Dark Matter searches in CMS



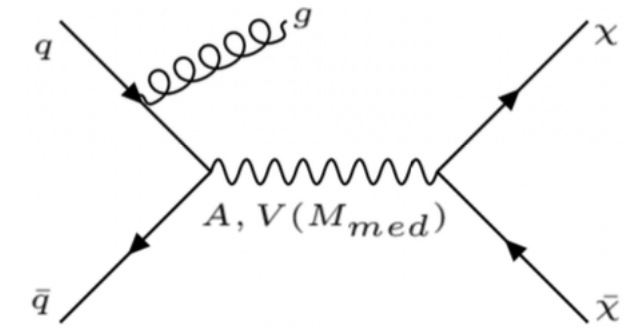
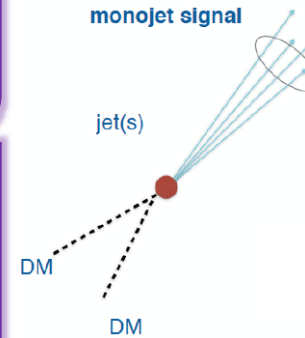
By Danyer Perez Adan

Mono-Jet/V analysis I

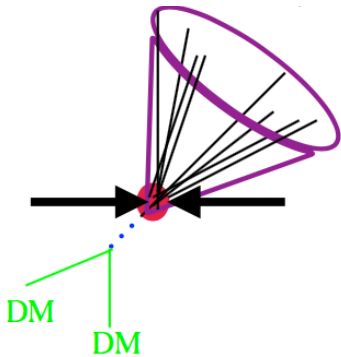
- The analysis aims to find an excess in the p_T^{miss} spectrum
- Detector Signature: High p_T Jet + p_T^{miss}
- The analysis is sensitive to a broad range of different models thanks to its general signature

Basic Selection:

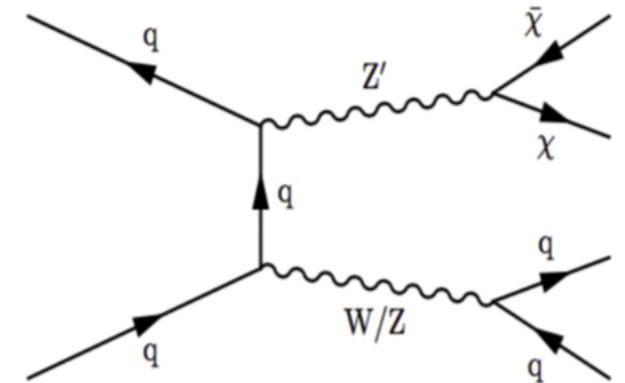
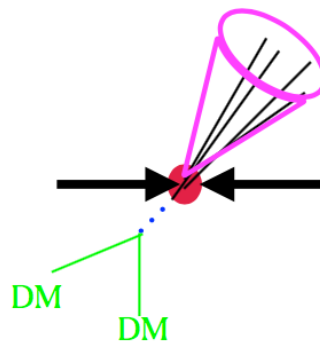
- Large MET (> 250 GeV)
- Lepton Veto
- *events categorized based on jet nature:*
 - One high p_T jet



Mono V



Mono Jet

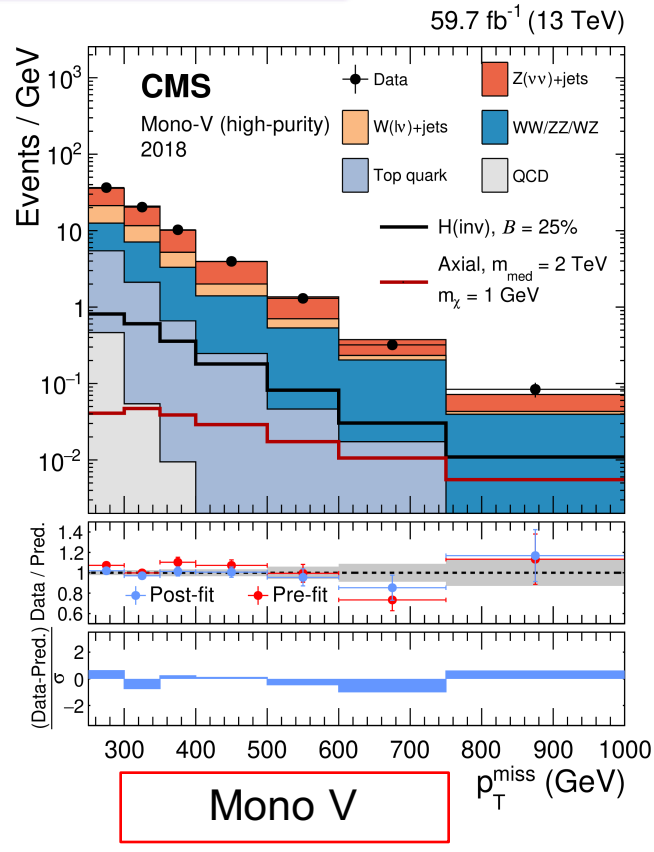
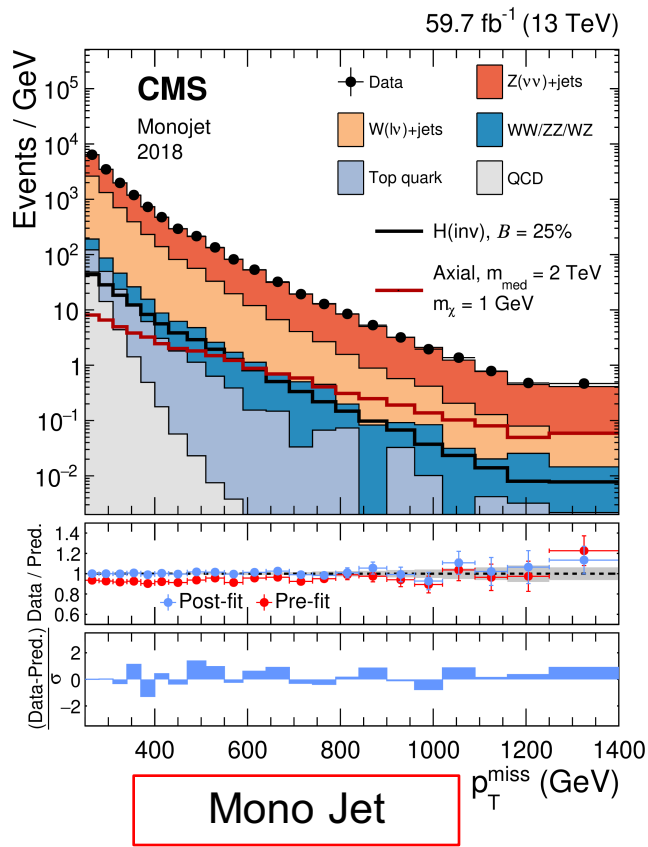
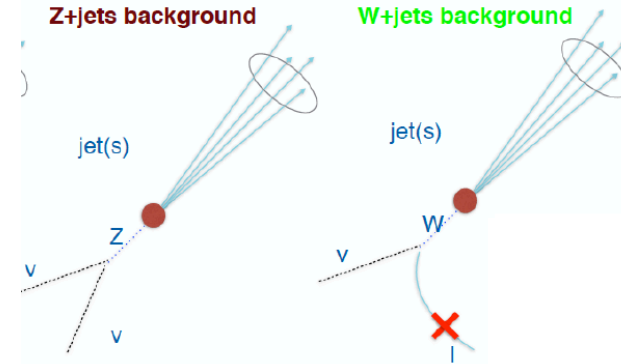


- AK8 Jet with $p_T > 250$ GeV
- Invariant jet mass consistent with V

- AK4 narrow jet with $p_T > 100$ GeV
- Not selected as mono-V

Mono-Jet/V analysis II

- Major Backgrounds:
 - $Z(\nu\nu)+\text{jets}$, $W(\ell\nu)+\text{jets}$
- Backgrounds are estimated from Control regions

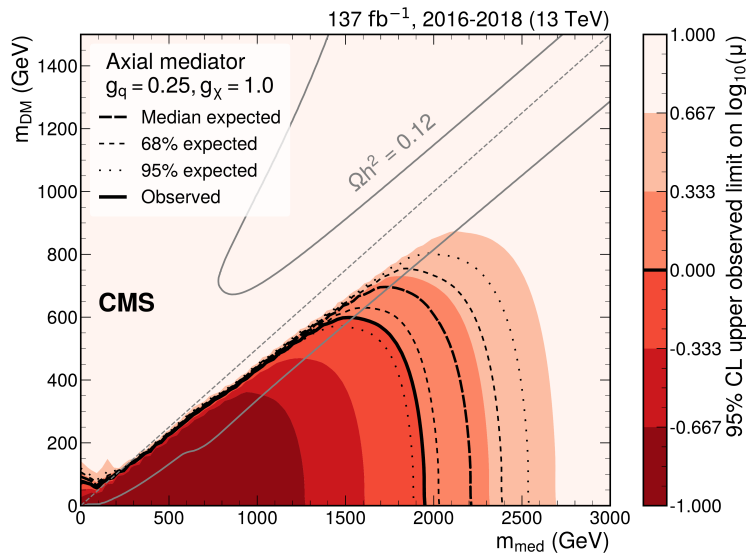


No deviations seen from the SM expectation. Place limits

Mono-Jet/V analysis III

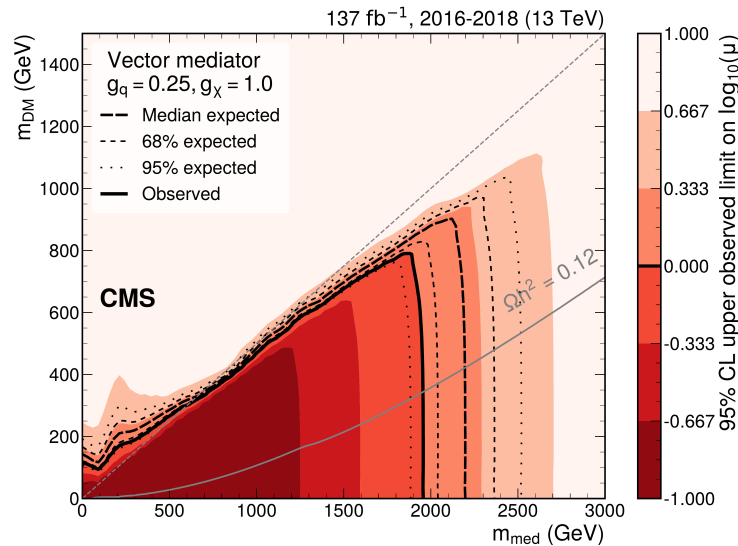
- The results are interpreted in term of DM models: Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{\text{th}}$ in the $m_{\text{med}} - m_{\text{DM}}$ plan.

Axial Vector mediator



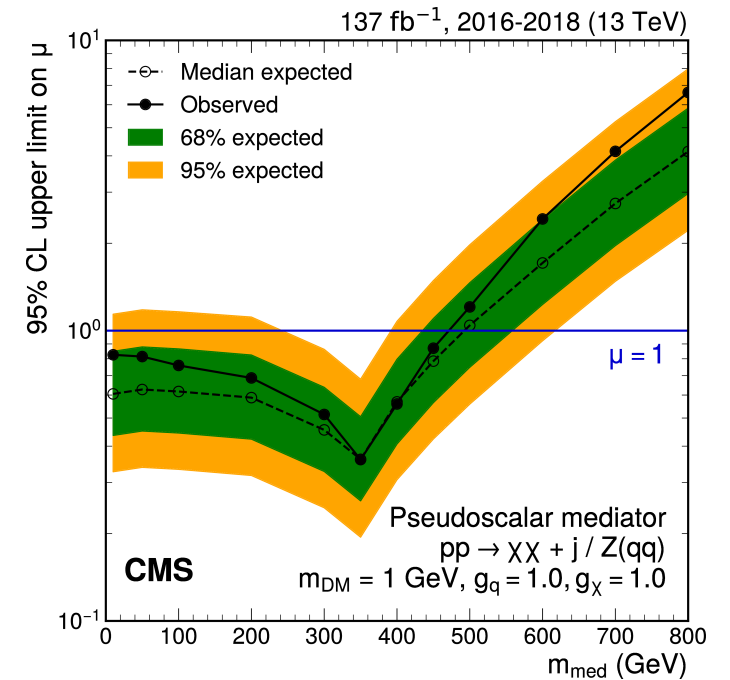
Exclude $m_{\text{med}} < 1.95 \text{ TeV}$

Vector mediator



Exclude $m_{\text{med}} < 1.95 \text{ TeV}$

Pseudo-scalar mediator

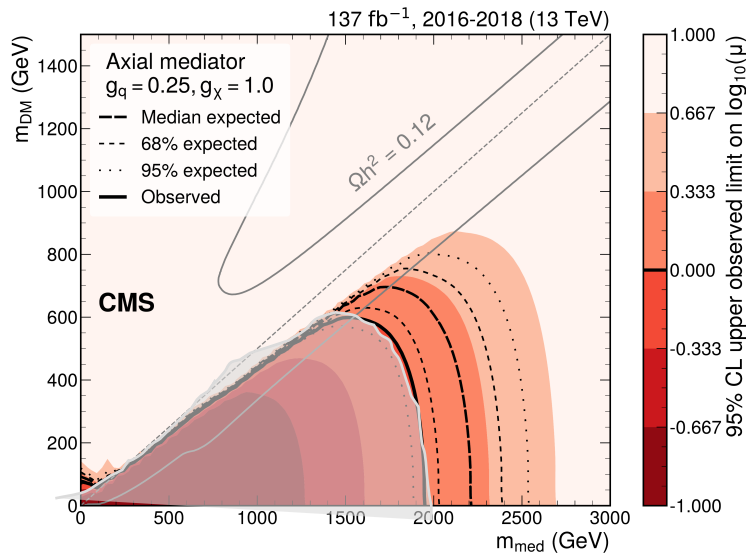


Exclude $m_{\text{med}} < 450 \text{ GeV}$ for constant $m_{\text{DM}} = 1 \text{ GeV}$

Mono-Jet/V analysis III

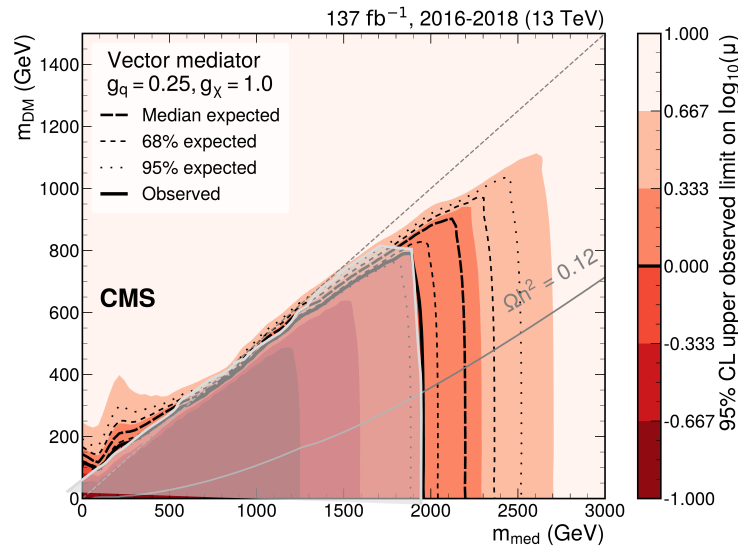
- The results are interpreted in term of DM models: Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{\text{th}}$ in the $m_{\text{med}} - m_{\text{DM}}$ plan.

Axial Vector mediator



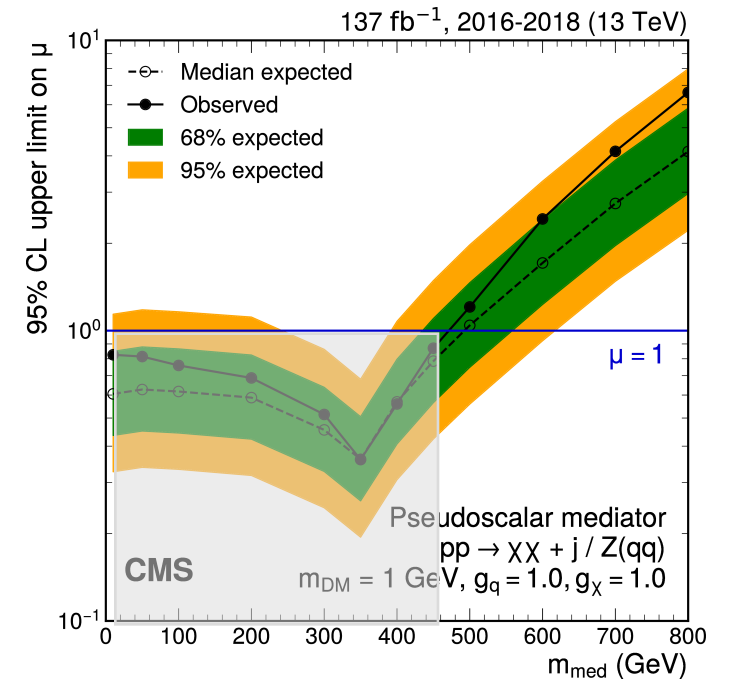
Exclude $m_{\text{med}} < 1.95 \text{ TeV}$

Vector mediator



Exclude $m_{\text{med}} < 1.95 \text{ TeV}$

Pseudo-scalar mediator

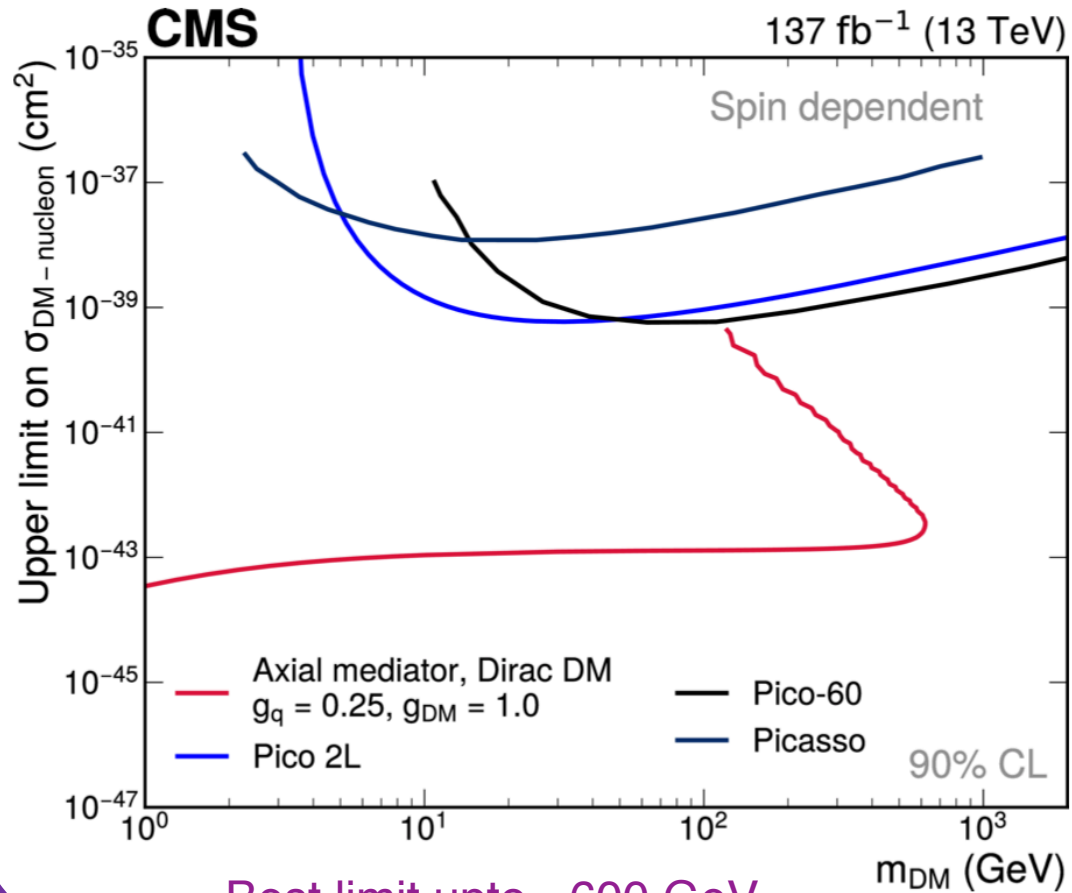


Exclude $m_{\text{med}} < 470 \text{ GeV}$ for constant $m_{\text{DM}} = 1 \text{ GeV}$

Mono-Jet/V analysis III

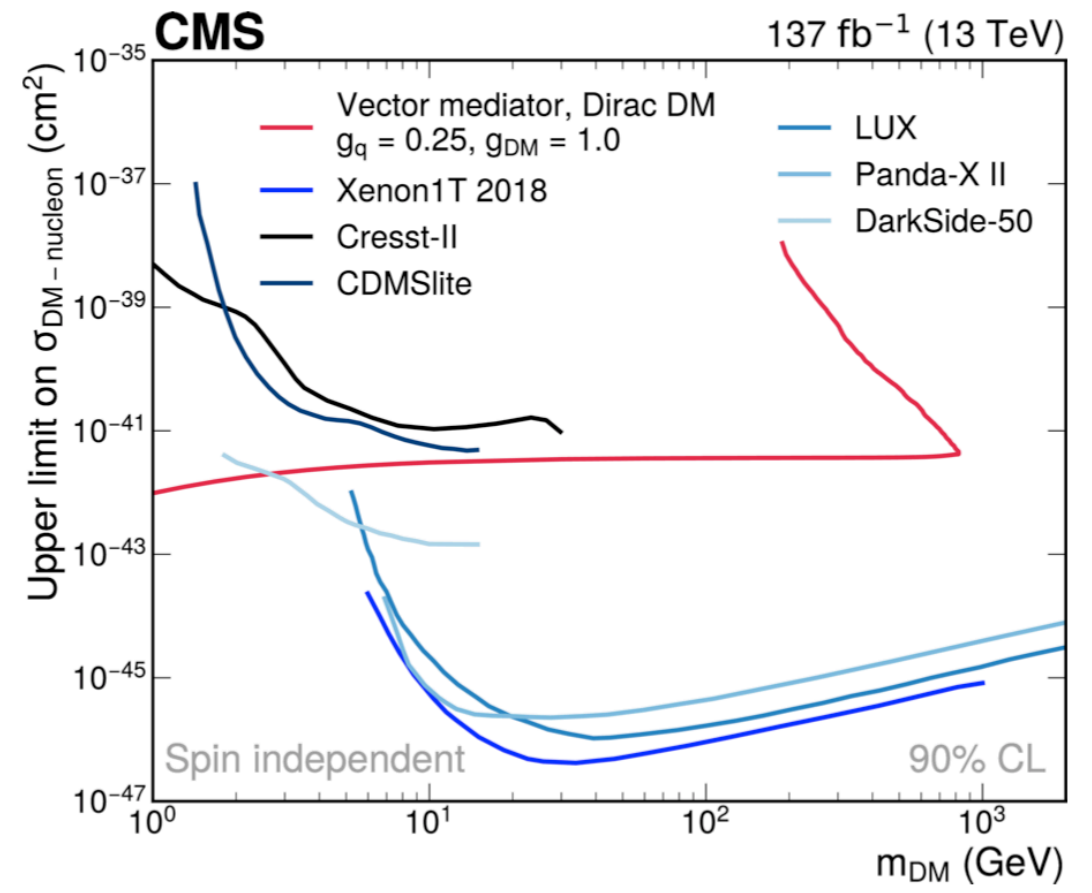
- Comparison from direct-detection (DD) experiments

Axial Vector mediator



Best limit upto ~600 GeV

Vector mediator



Compatible with direct detection at low mass

Mono Z($\ell\ell$) analysis I

- **Basic selection:**

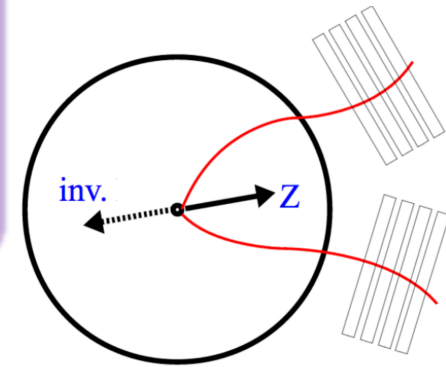
- MET > 100 GeV
- Lepton1 pT > 25 GeV , Lepton2 pT > 20 GeV
- $|m_{ll} - m_Z| < 15$ GeV

- Different models for interpretation in one analysis:

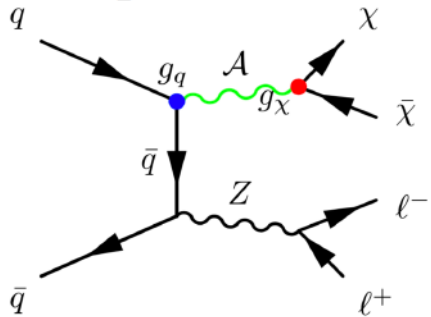
- DM simplified model , 2HDM+a
- Analysis divided in 0 and 1 jet category to increase the sensitivity

- **Main Background:**

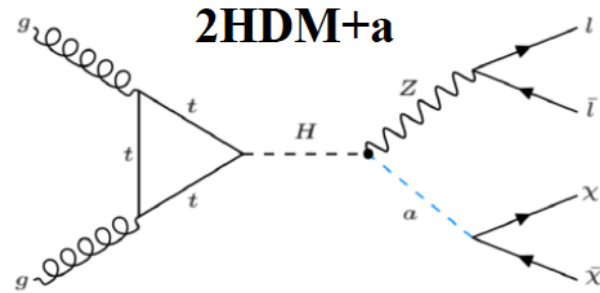
- $ZZ \rightarrow \ell\ell\nu\nu$, $WZ \rightarrow \ell\nu\ell\ell$, DY, ...
- Dedicated control regions for dominant background.



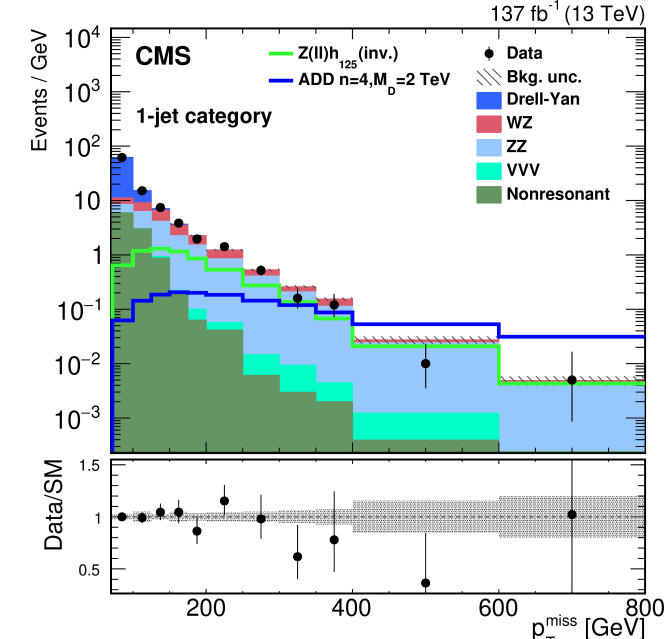
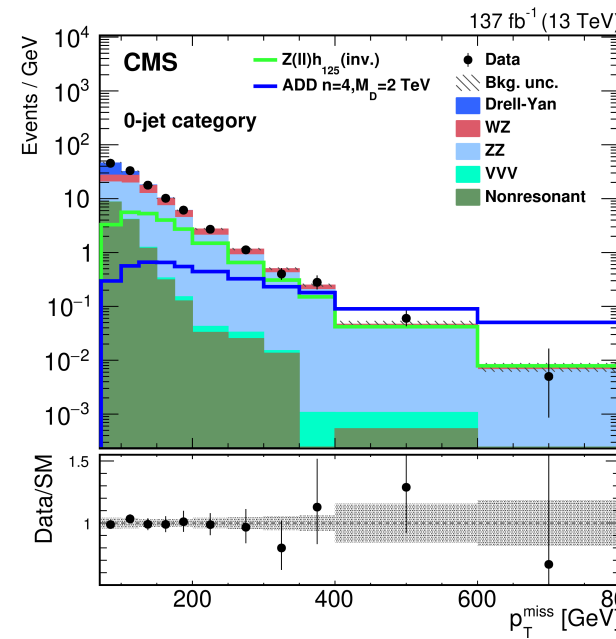
Simplified DM



2HDM+a



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



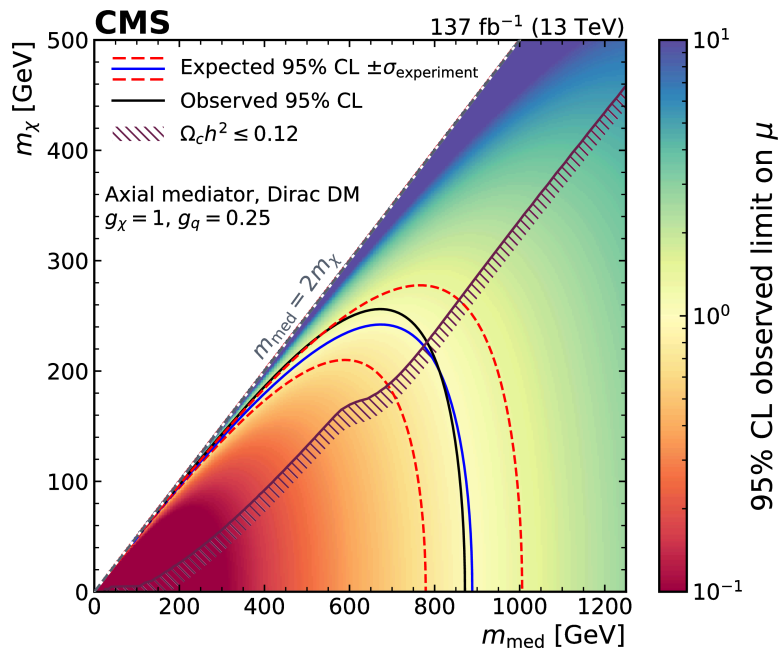
No deviations seen from the SM expectation. Place limits

Mono Z($\ell\ell$) analysis II

- Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{\text{th}}$ in the $m_{\text{med}} - m_{\text{DM}}$ plane.

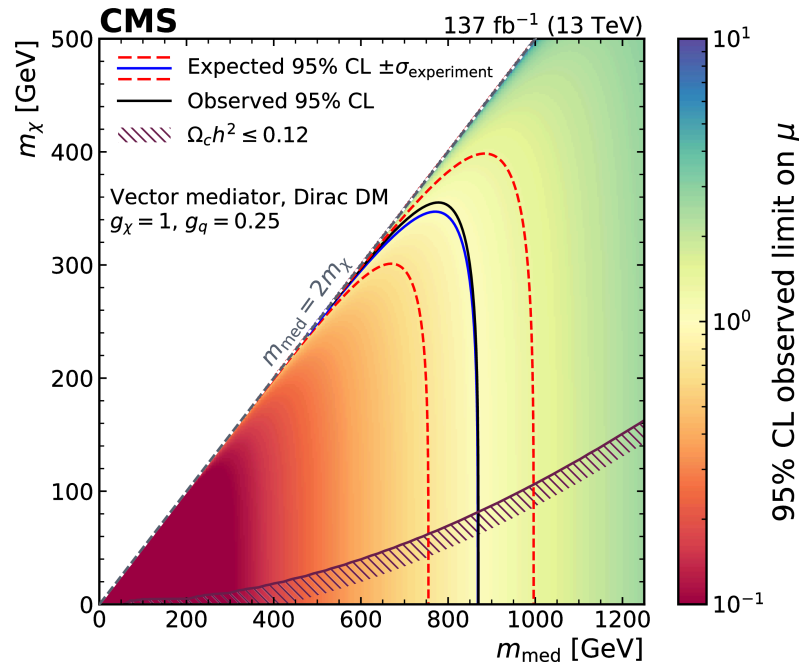
95% CL upper limit on m_a vs m_A plane

Axial Vector mediator



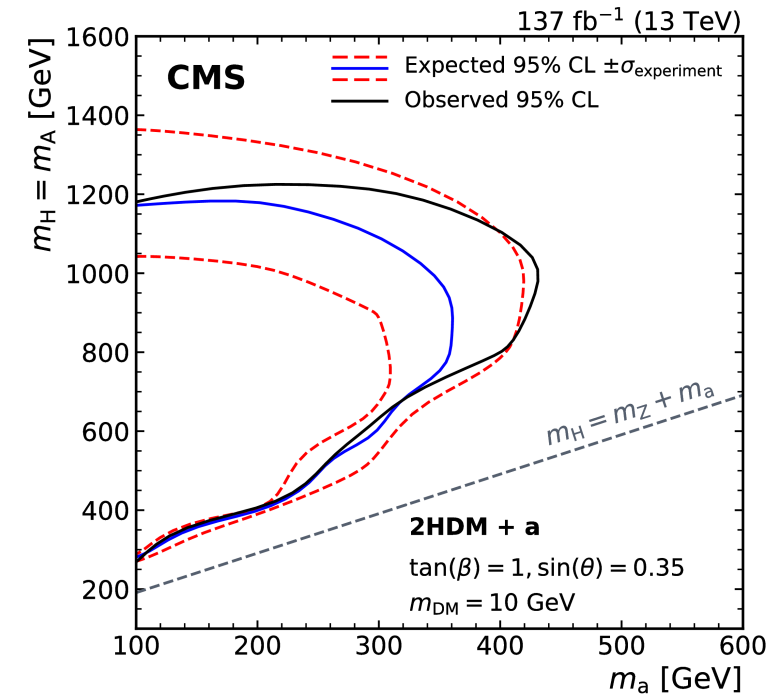
$M_{\text{med}} > 800$ GeV is allowed region

Vector mediator



$M_{\text{med}} > 870$ GeV is allowed region

2HDM+a Model

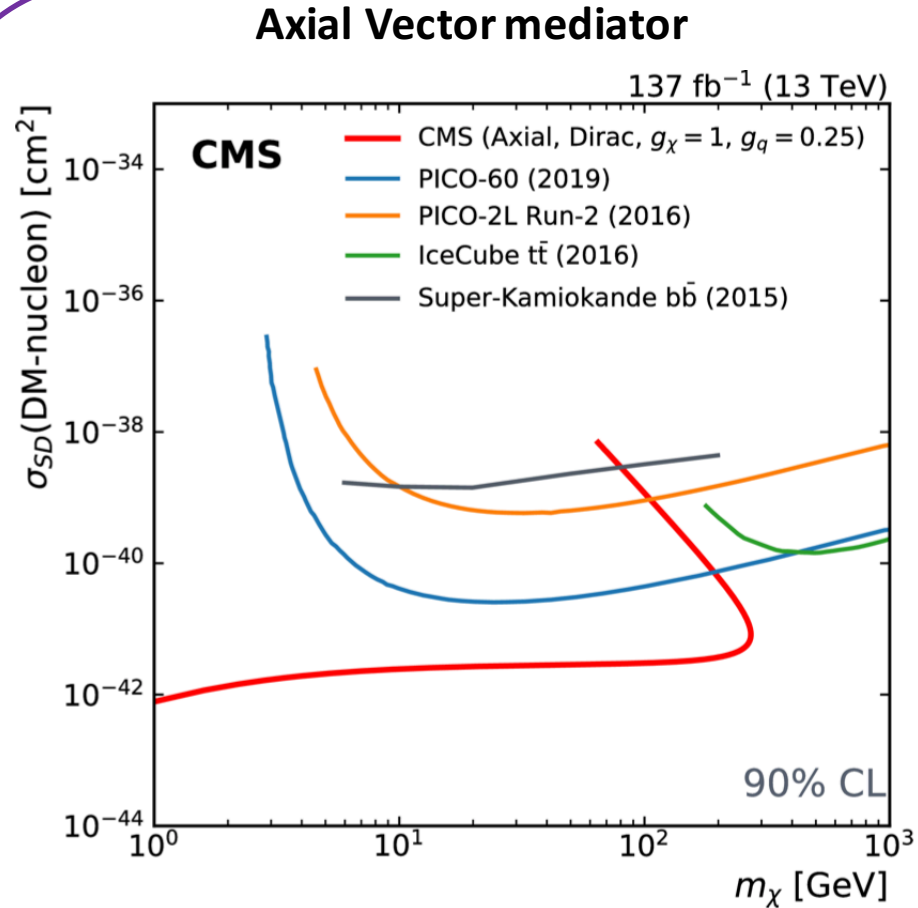


Observed limit on m_a is 440 GeV

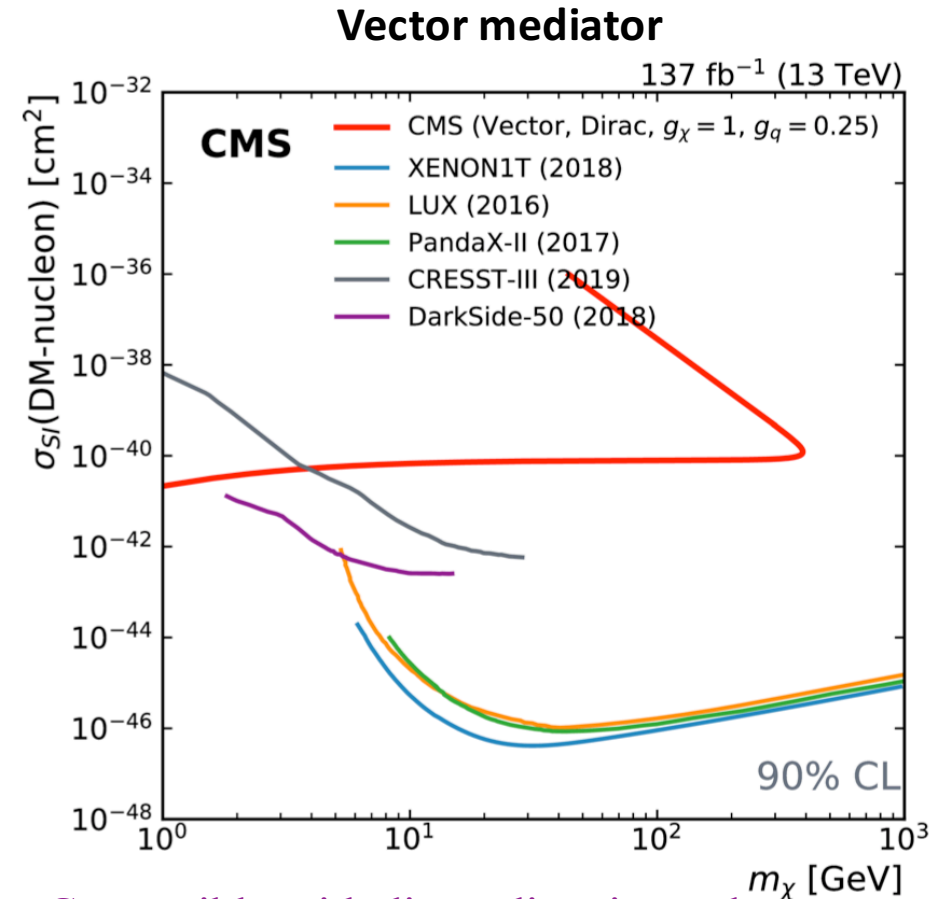
More interpretations are published \Rightarrow [Eur.Phys.J.C81\(2021\) 13](#)

Mono $Z(\ell\ell)$ analysis III

- Comparison from direct-detection (DD) experiments.



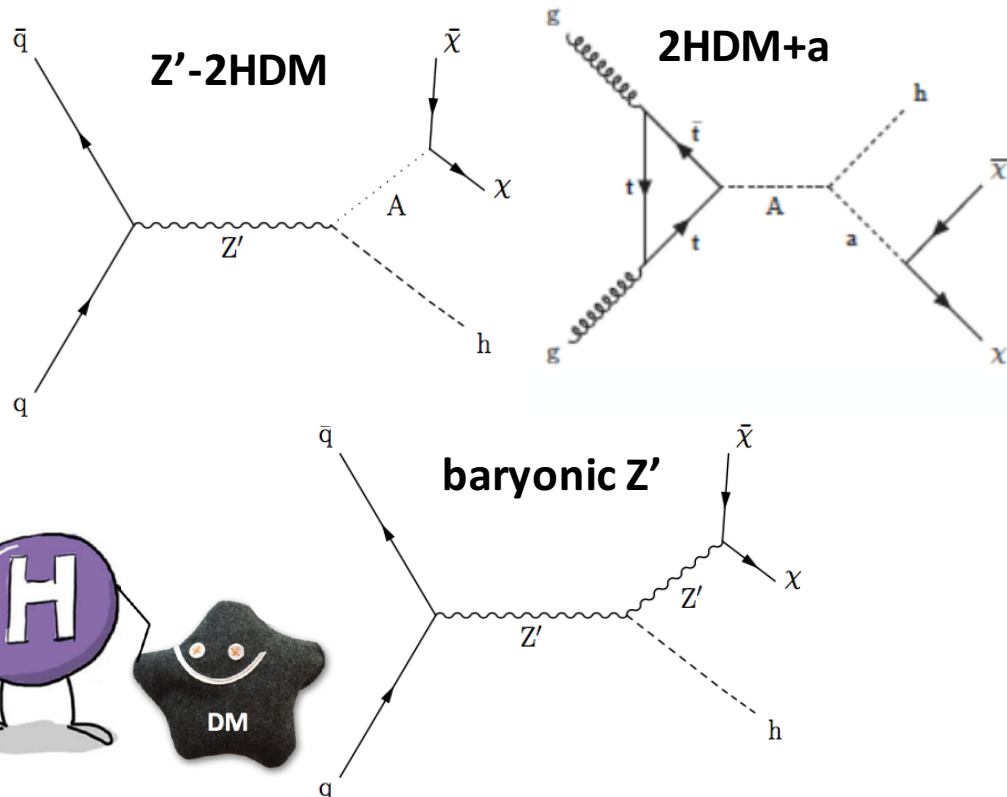
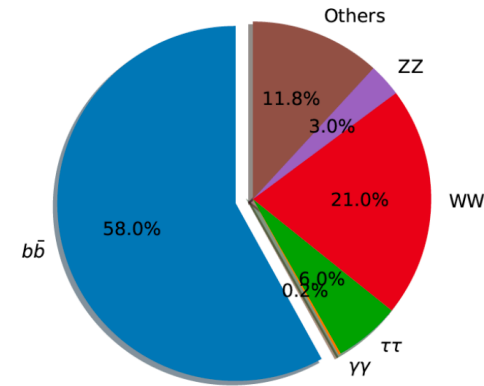
Best limits up to ~ 300 GeV (Spin dependent)



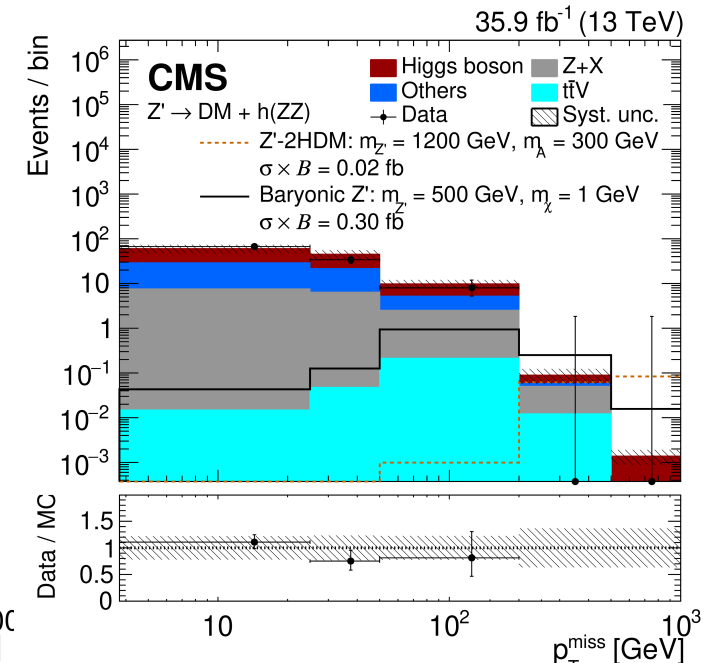
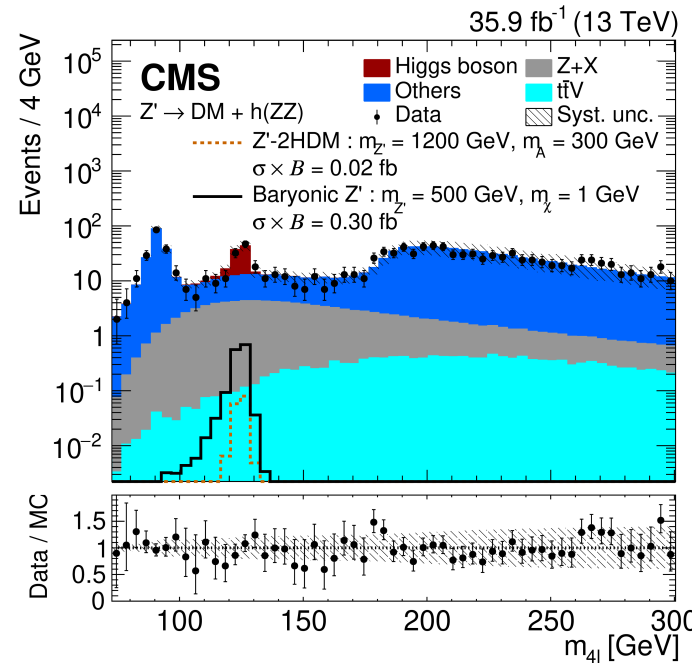
Compatible with direct detection at low mass
(Spin independent)

Mono-Higgs analysis I

- **Aim:** search for dark matter produced in association with Higgs boson (Higgs boson used as a tag)
- **Signature:**
- Large p_T^{miss} + Higgs boson
- Considering combination of 5 Higgs decay channels (**bb - $\gamma\gamma$ - $\tau\tau$ - WW - ZZ**)
- The analysis sensitivity is driven by bb channel
- **Models for interpretation:**



Mono-H(ZZ)4l analysis

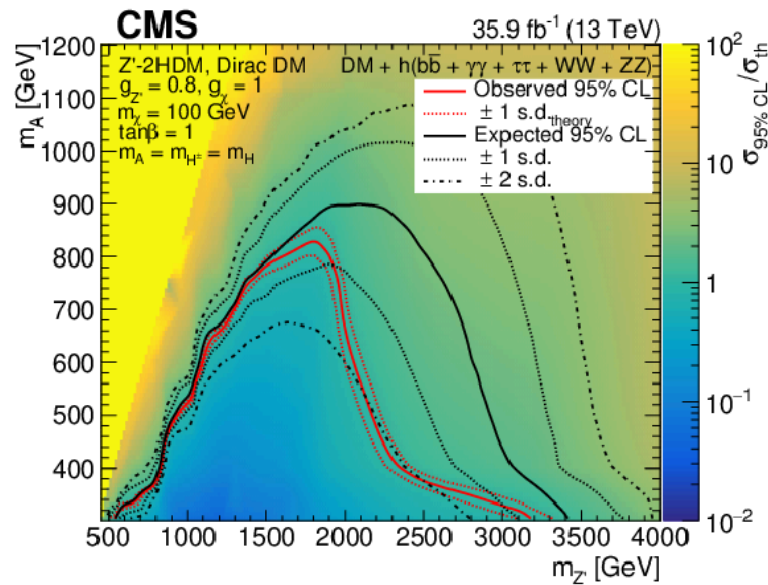


Mono-Higgs analysis II

- Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{th}$ in the 2D plan.

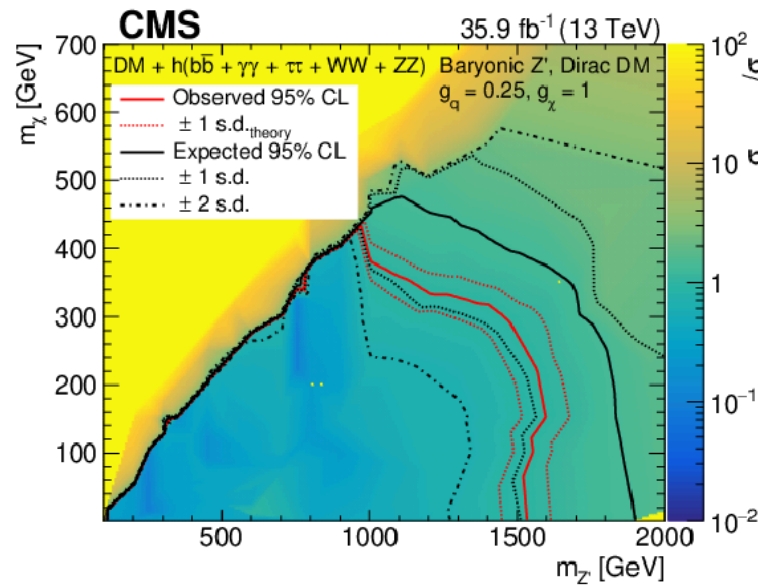
95% CL upper limit on $\mu = \sigma / \sigma_{th}$

Z' - 2HDM



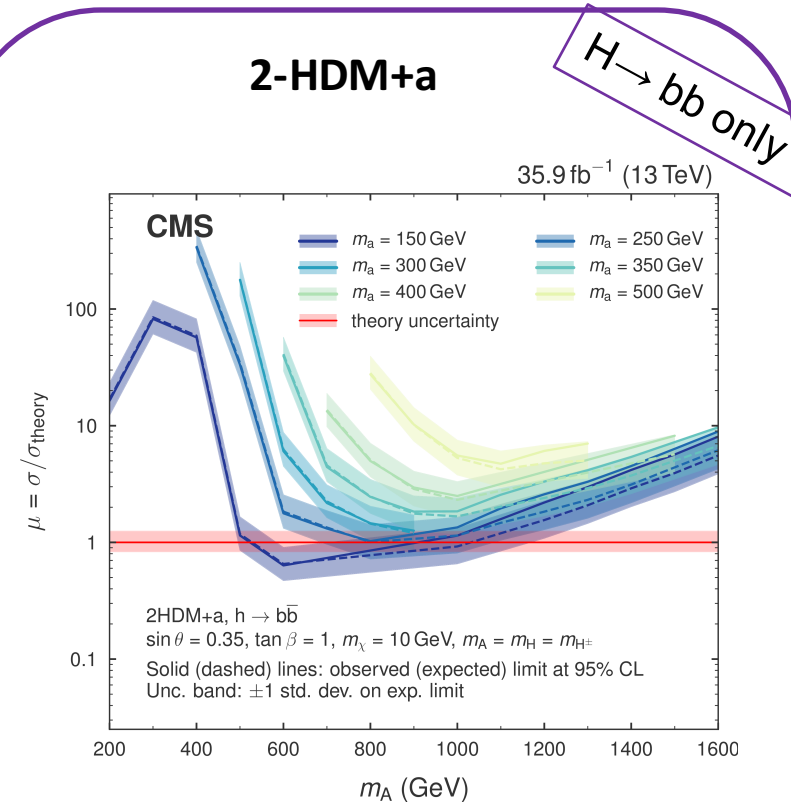
500 GeV < $M_{Z'}$ < 3200 GeV and
 300 GeV < m_A < 800 GeV excluded

Z' - baryonic



100 GeV < $M_{Z'}$ < 1500 GeV and
 1 GeV < M_χ < 420 GeV excluded

2-HDM+a



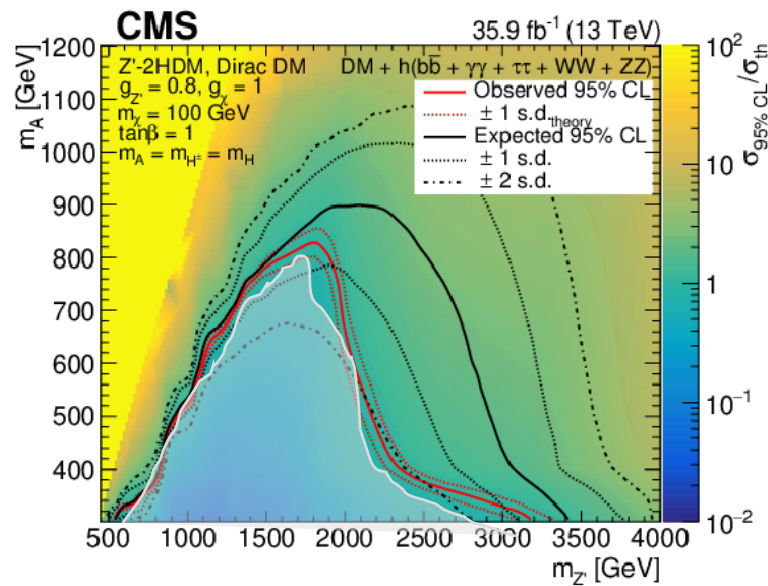
exclude m_A between 500 and 900 GeV
 for $m_a = 150$ GeV

Mono-Higgs analysis II

- Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{th}$ in the 2D plan.

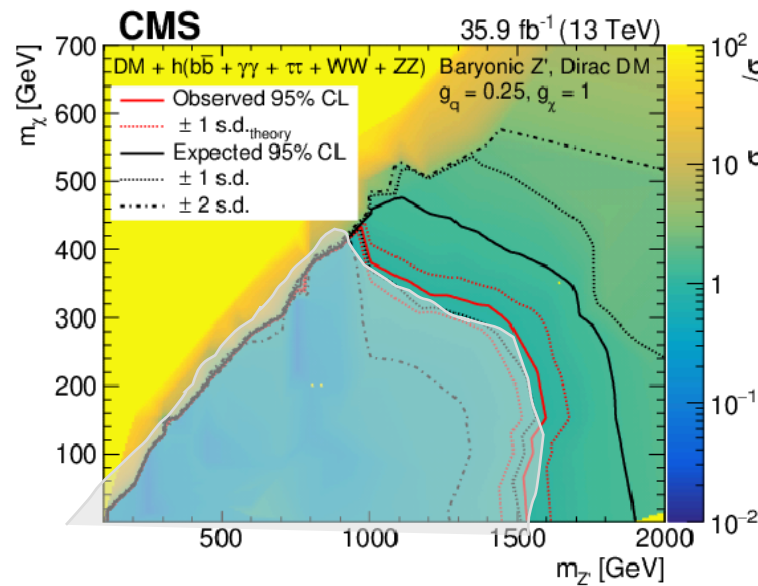
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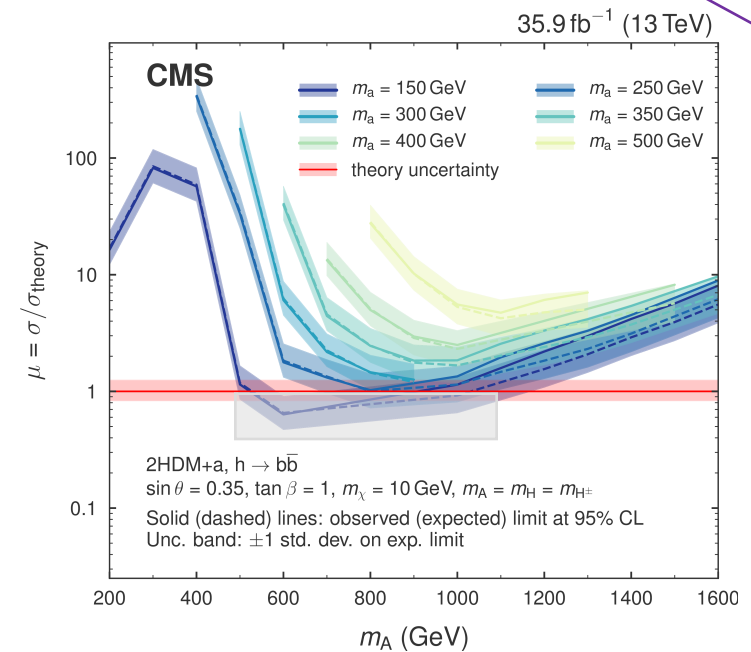
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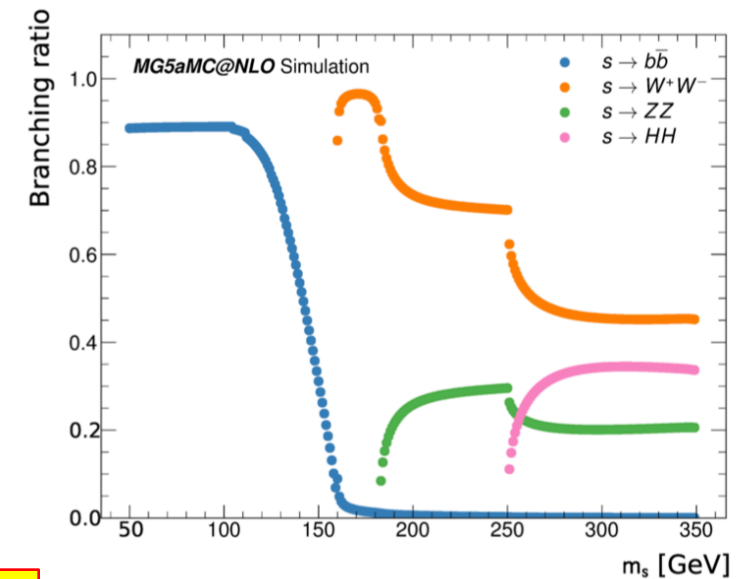
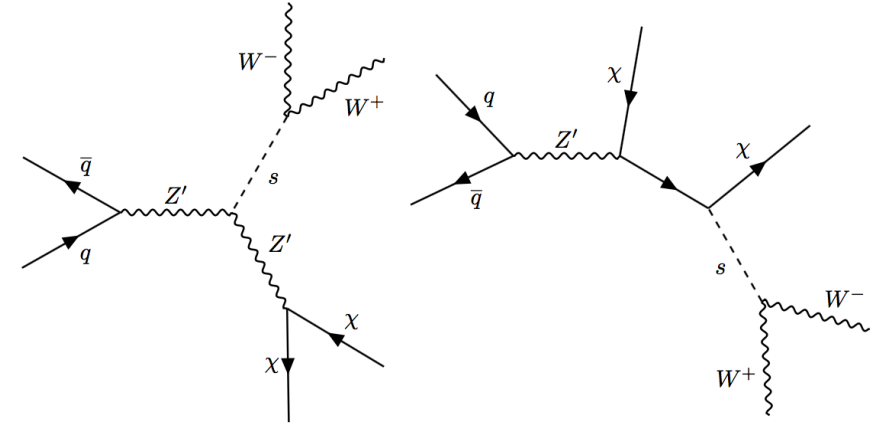
exclude m_A between 500 and 900 GeV
 for $m_a = 150 \text{ GeV}$

Dark Higgs boson (WW) search I

- This is the first time the CMS experiment explores the dark Higgs model
- Dark Higgs boson model: Dark Matter particle acquire mass through their interaction with a dark Higgs boson ([arXiv: 1701.08780](https://arxiv.org/abs/1701.08780))
- Dark Higgs mass $>$ WW mass threshold (160 GeV) \rightarrow to maximize the production cross section
- WW decay mode dominate the picture for $m_s > 160$ GeV (resonance)
- **Signature:** 2 opposite charged leptons + large MET

• Main background:

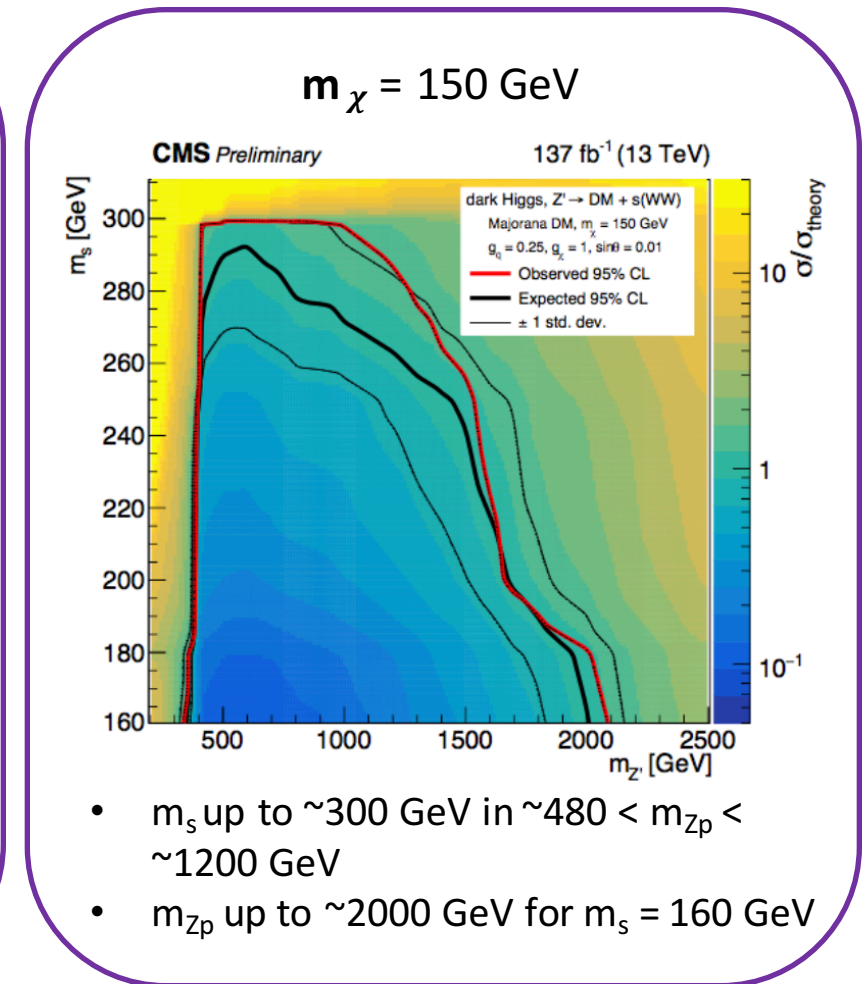
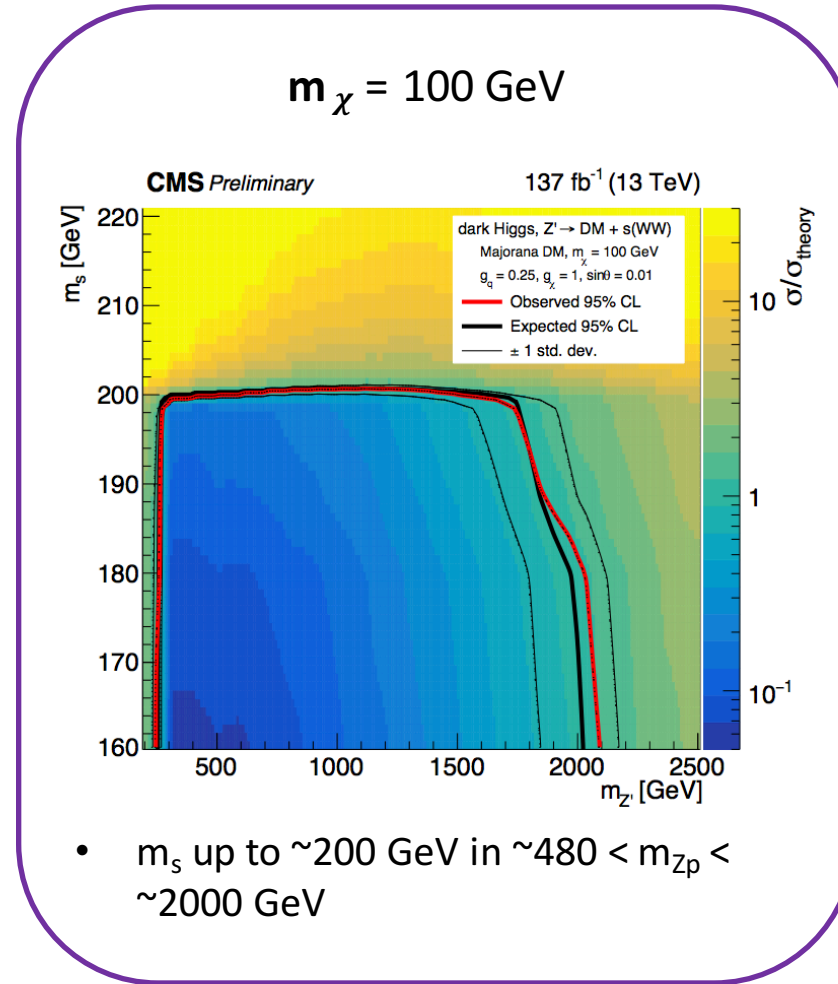
- WW, W+jets, Top background, Non prompt leptons
- Main backgrounds estimated from dedicated control regions



More Details will be shown tomorrow in the talks by **Binbin, Lesya**

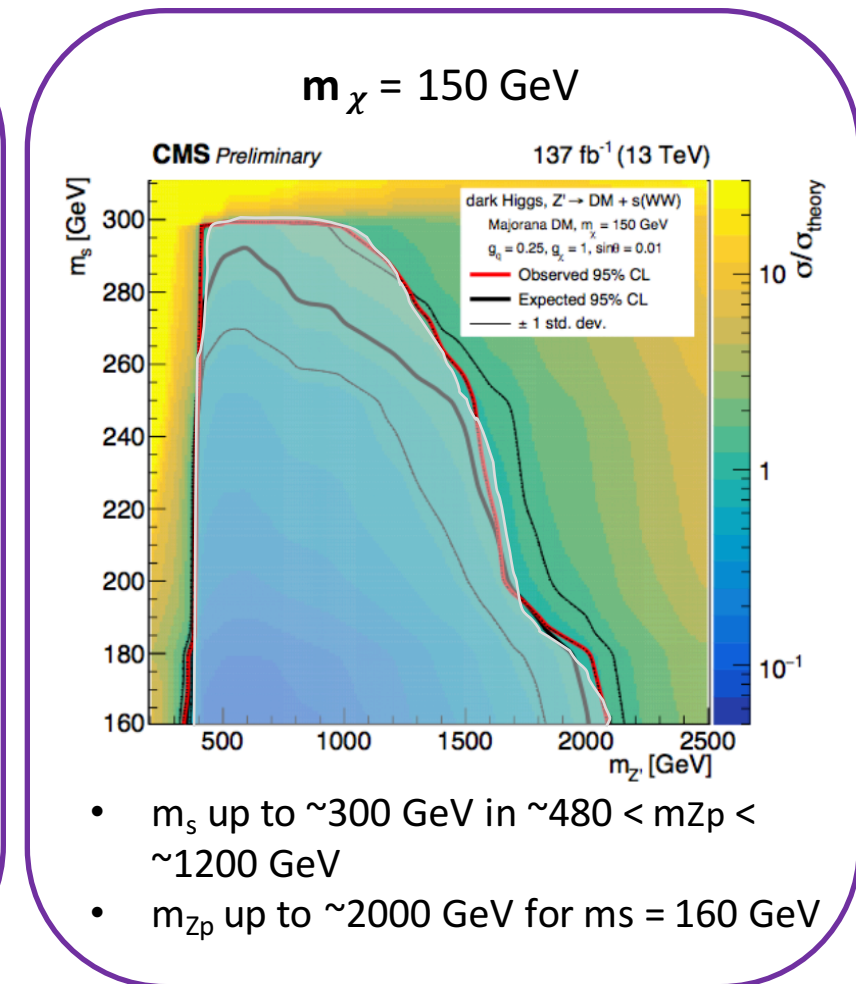
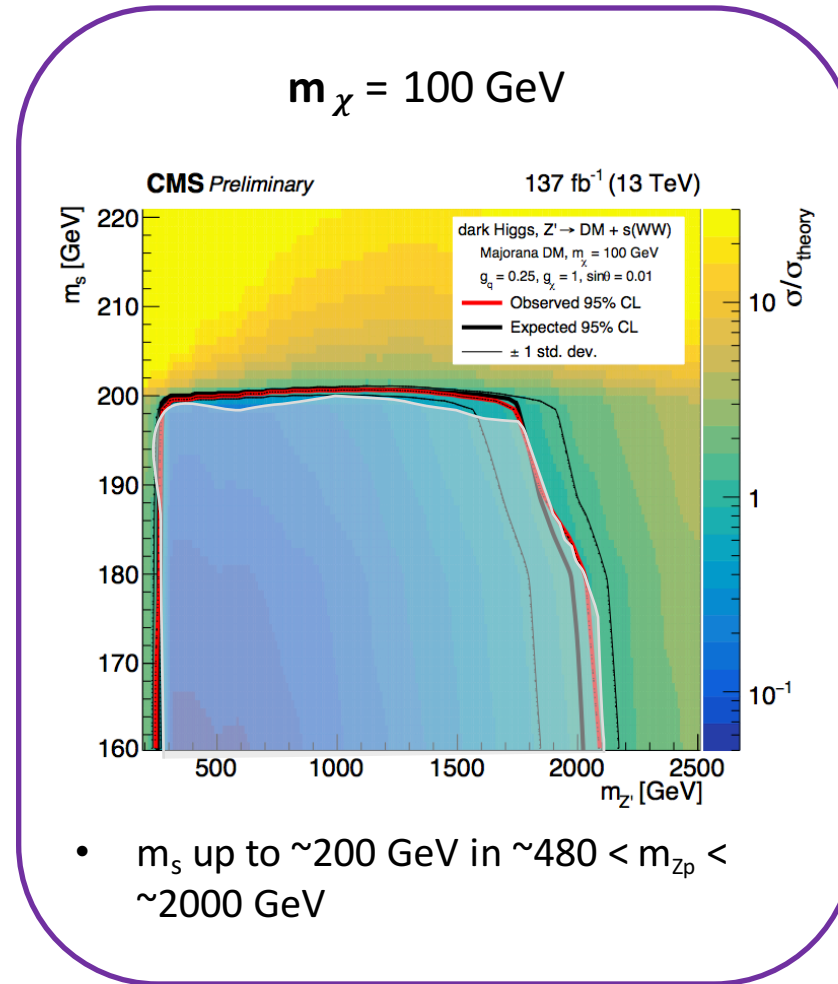
Dark Higgs boson (WW) search II

- No excess of events have been observed-> place limits
- Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{th}$ in the $m_{Z'} - m_s$ plan for different scenarios of m_χ (100 – 150 – 200 – 300 GeV)
- most stringent limit for $m_\chi=150$ GeV



Dark Higgs boson (WW) search II

- No excess of events have been observed → place limits
- Exclusion limits at 95% CL on $\mu = \sigma / \sigma_{\text{th}}$ in the $m_{Z'} - m_s$ plan for different scenarios of m_χ (100 – 150 – 200 – 300 GeV)
- most stringent limit for $m_\chi = 150$ GeV



Summary

- A brief summary of Dark Matter searches in CMS has been presented
- No excess of events over SM background has been observed so far in any analysis
- Exclusion limits have been set in terms of DM models for different analysis
- Many full Run II analysis are still in progress and about to come out soon.
- Stay tuned for new results.

Thank You