Search for DM particles produced in association with a dark Higgs boson decaying to two W bosons

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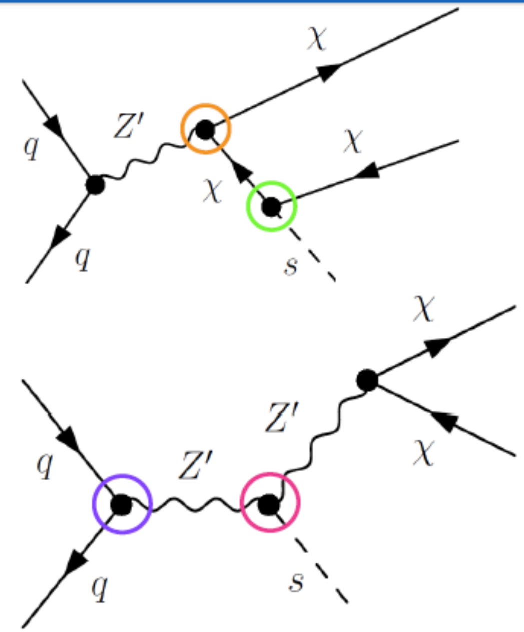
From Changqiao Li talk:
https://indico.cern.ch/event/1276564/#b-508133-dark-higgs

Dark Higgs model

JHEP 04 (2017) 143

- Simplified model for DM production at the LHC, extends spin-1 mediator models of LHC DM WG
  - Majorana DM (X) interacts with two different mediators:
    - massive vector boson Z' and a dark Higgs s



Interactions:

SM Quarks $\mathcal{L}_\chi = -g_q Z'^\mu \bar{q}\gamma_\mu q$

Dark Sector $\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^\mu \bar{\chi}\gamma^5\gamma_\mu\chi - g_\chi \frac{m_\chi}{m_{Z'}} s\bar{\chi}\chi + 2\, g_\chi\, Z'^\mu Z'_\mu \left(g_\chi\, s^2 + m_{Z'} s\right)$

Model parameters

- Model generation $\boldsymbol{s \rightarrow WW \rightarrow 2l2\nu\ /\ l\nu qq'}$ with Madgraph LO:
  - ZpHiggs_UFO
- Parameters and their recommended value from LHC DM WG: https://arxiv.org/abs/1507.00966
  - Small mixing between dark-Higgs (*s*) and SM Higgs: $\boldsymbol{\theta = 0.01}$
  - Dark-sector coupling $\boldsymbol{g_\chi = 1}$
  - Quark-*Z'* coupling $\boldsymbol{g_q = 0.25}$
- Analysis mass scan (GeV):
  - $\boldsymbol{m_\chi}$= [100, 150, 200, 300]
  - $\boldsymbol{m_s}$ = [160, 180, 200, 300, 400]
  - $\boldsymbol{m_{Z'}}$ = [200 - 2500]
- *Z'* and *s* bosons widths, relative to their masses, are below 1%.

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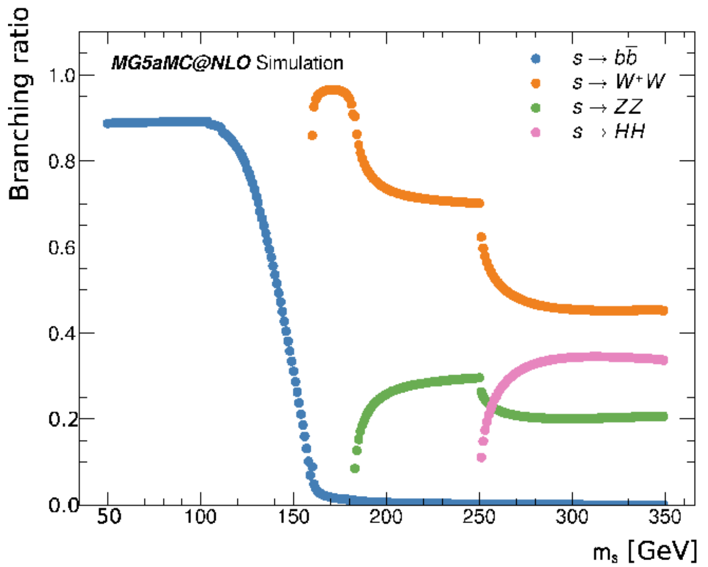
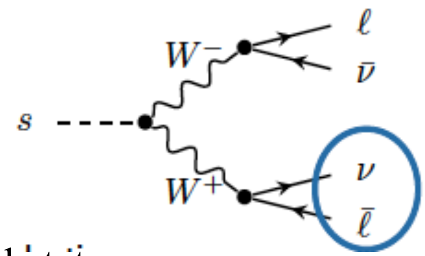


Analysis selection: $s \to WW \to 2l2\nu$



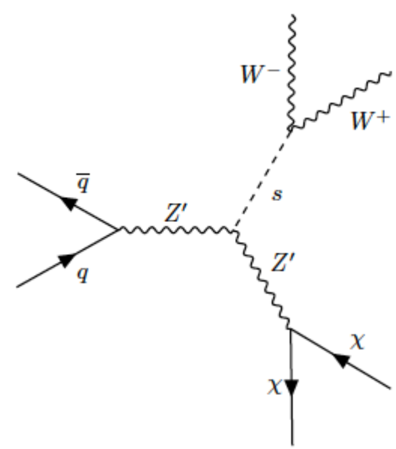
$2l2\nu$ Selections
nLeptons ≥ 2
Different flavour Opposite sign
p_T^{l1} / p_T^{l2} > 25 / 20 GeV
MET > 20 GeV min(proj.MET, proj.MET^{Tk}) > 20 GeV
Veto 3nd loose leptons if p_T^{l3} > 10 GeV
b-veto DeepCSV LooseWP
p_T^{ll} > 30 GeV
m^{ll} > 12 GeV
ΔR(l,l) < 2.5
m_T(ll + MET) > 50 GeV

2l + MET final state selection (nLeptons ≥ 2 through Veto 3nd loose leptons)

Reduce top-quark background (b-veto DeepCSV LooseWP)

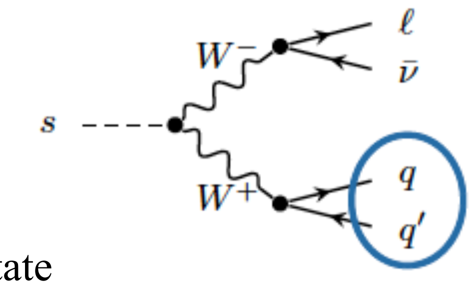
Reduce non-prompt background (p_T^{ll} > 30 GeV, m^{ll} > 12 GeV)

Target dark Higgs topology (ΔR(l,l) < 2.5, m_T(ll + MET) > 50 GeV)



Analysis selection: $s \to WW \to 2lqq'$

lνjj Selections
nLeptons ≥ 1
nJet Clean ≥ 2 (p_T > 30 GeV)
p_T^{l1} > trigger threshold
Veto 2nd loose leptons if p_T^{l2} > 10 GeV
65 < m^{jj} < 105 GeV
b-veto DeepCSV LooseWP (excluding W candidate jets)
Δϕ(ljj, MET) > 2
Δϕ(jj,l) < 1.8, ΔR(jj,l) < 3
m_T(l + MET) > 80 GeV
MET > 60 GeV
p_T^{ljj} > 60 GeV

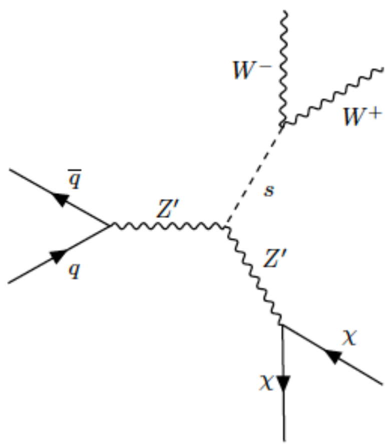


1 + 2 jets final state selection

Reduce W+jets background

Reduce top-quark background

Target dark Higgs topology



Background estimation overview

Process	Analysis	Estimation	CR/Validation
Top	$2l2\nu$ $l\nu jj$	MC + normalization freely floating, constrained by CR	Invert b-veto
W+jets	$l\nu jj$	MC + normalization freely floating, constrained by CR	$m_{jj} < 65$ || $m_{jj} > 105$ GeV
Non-prompt	$2l2\nu$	Fully data-driven estimation	Same lepton charge
	$l\nu jj$		$m_T(l + MET) < 30$ && $MET < 30$ GeV
WW	$2l2\nu$	MC + normalization freely floating, constrained by CR	$\Delta R(l,l) > 2.5$
Drell-Yan	$2l2\nu$	MC + normalization freely floating, constrained by CR	$m_T(ll + MET) < 50$ GeV

* Keeping other pre-selection requirements

Other small processes estimated directly from simulation:

$$HWW, V\gamma, V\gamma^*, VZ, VVV$$

Analysis strategy

Dilepton channel $s \to WW \to 2l2\nu$

- 3D fit in $\Delta R_{ll} - m_{ll} - m_T(l_2, MET)$
  - 3 SR in ΔR_{ll}(strong dependence with dark Higgs mass)

$\Delta R_{ll} < 1$
$1 < \Delta R_{ll} < 1.5$
$1.5 < \Delta R_{ll} < 2.5$

  - For m_{ll} and $m_T(l_2, MET)$ the binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.
- Allow the different signal mass points to populate the 3D parameter space while using the same background modelling procedure.

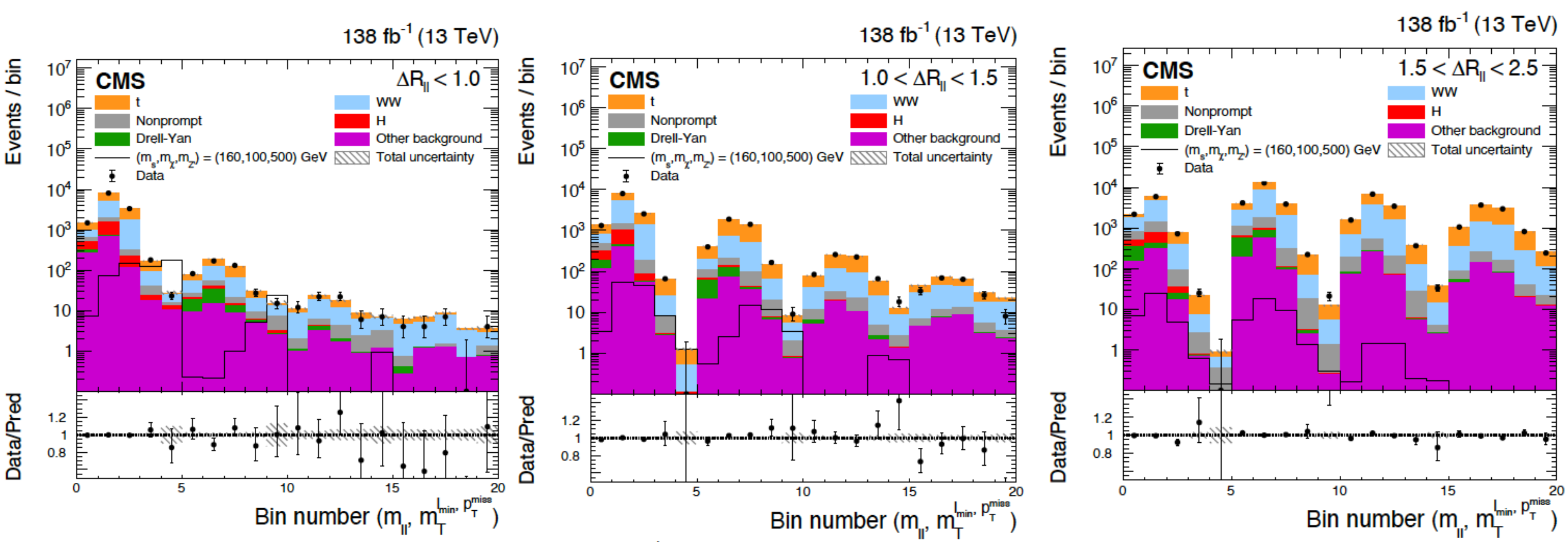
$$m_T^{\ell \min, p_T^{miss}} = \sqrt{2 p_T^{\ell \min} p_T^{miss} \left[1 - \cos \Delta\phi(\vec{p}_T^{\,\ell \min}, \vec{p}_T^{\,miss})\right]},$$

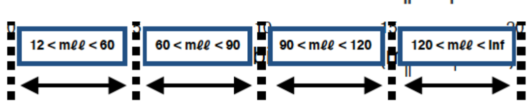
Semileptonic channel $s \to WW \to 2lqq'$

- Using BDT Discriminator
- 13 optimized kinematic inputs:
  - mostly sensitive to MET vs visible particles boost.
- 1 training for entire mass range with $m_{Z`} \geq 800\ GeV$ samples (boosted samples with small x-sec sensitivity)
- Binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.

Results: $s \rightarrow WW \rightarrow 2l2\nu$

- Profile likelihood fit for 3 SR, 1 top quark background CR, 1 DY background CR, and 1 WW background CR
  - Signal regions entering in the fit: 2D histograms of $m_{ll} - m_T(l_2, MET)$ for each SR.
  - Control regions information entering in the fit: 1-bin distributions. Top, WW, and DY normalization freely float within the global fit.

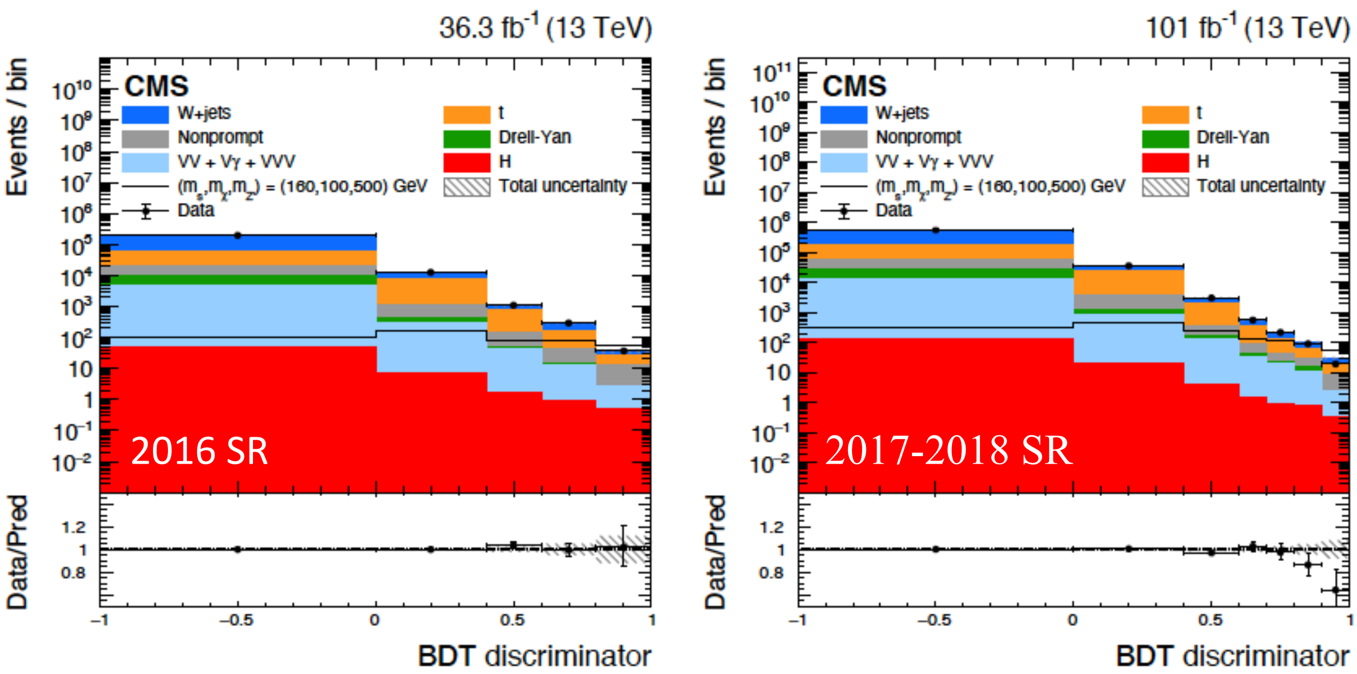




No significant excess over the SM prediction

Results: $s \rightarrow WW \rightarrow 2lqq'$

- Profile likelihood fit for1 SR, 1 Top quark background CR and 1 W+jets background CR:
  - Signal region information entering in the fit: 1D histograms of BDT output score.
  - Control regions information entering in the fit: 1-bin distributions. Top and W+Jets normalization freely float within the global fit

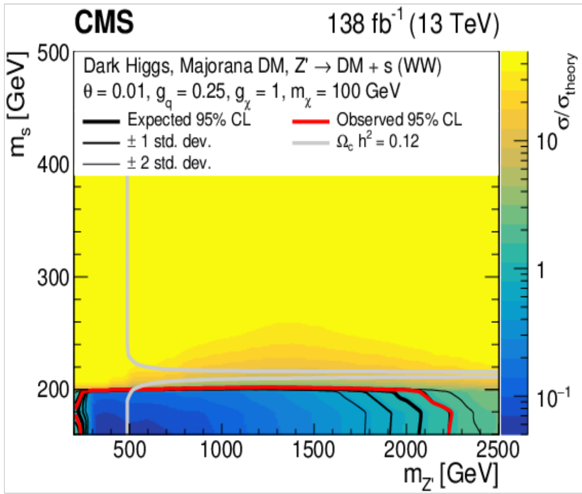


Finer binning in 2017-2018 to squeeze the sensitivity

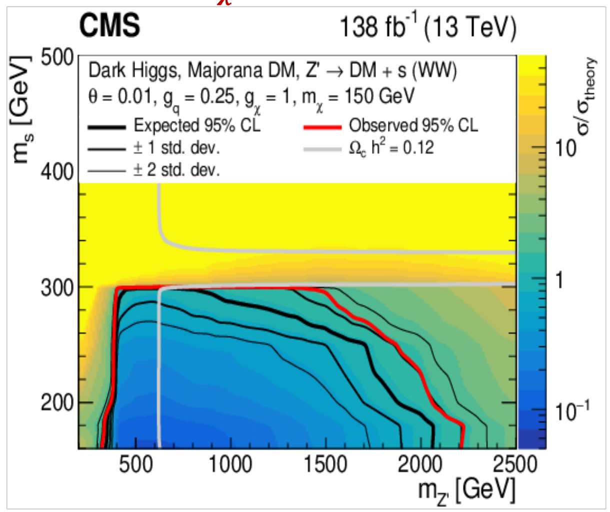
Results

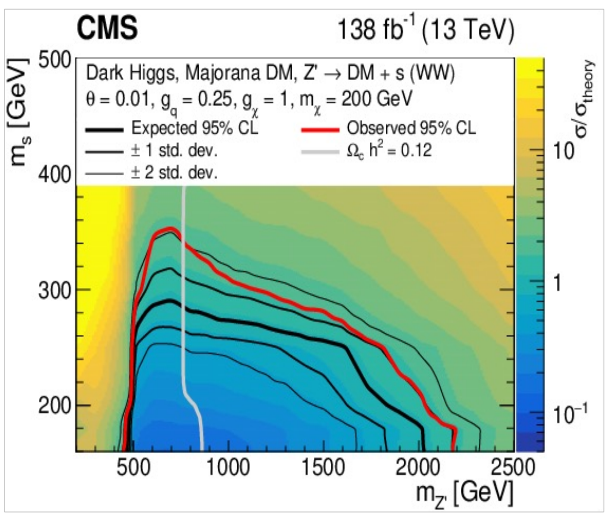
[2310.12229](https://arxiv.org/abs/2310.12229)

$m_\chi = 100\ GeV$

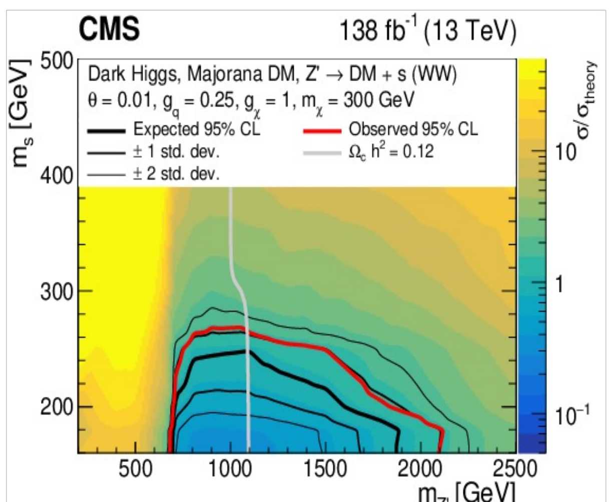


$m_\chi = 150\ GeV$





$m_\chi = 200\ GeV$

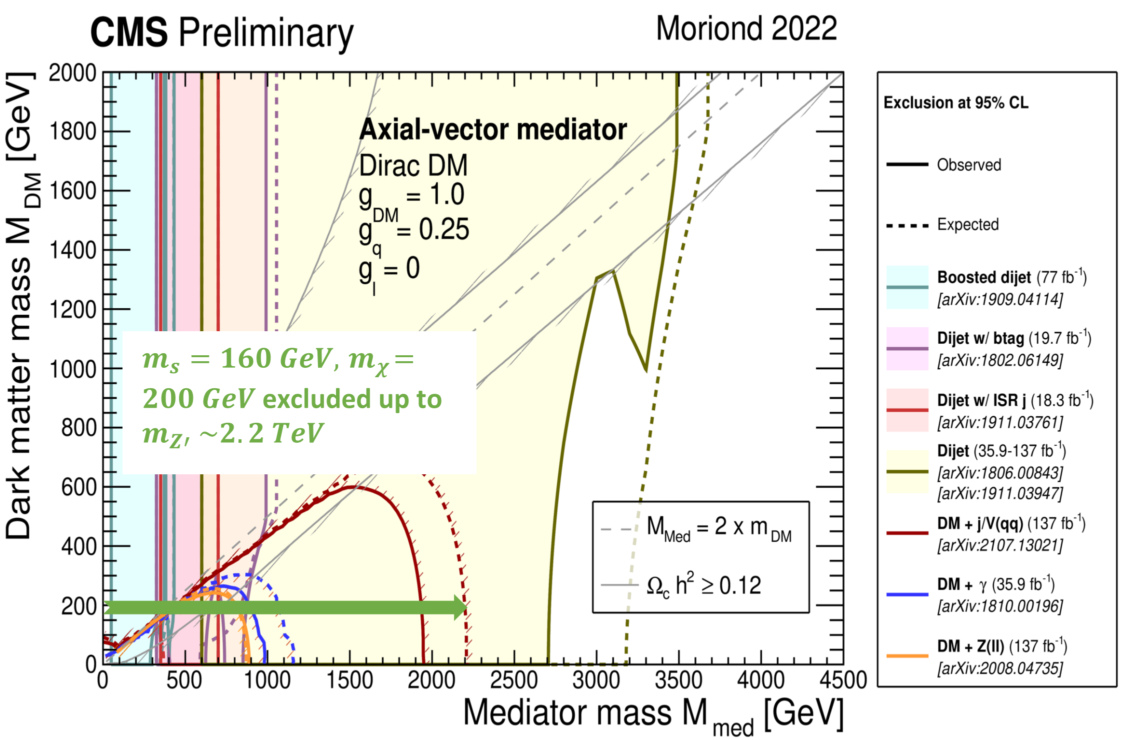


$m_\chi = 300\ GeV$

- Observed > Expected (but still below 2 sigma) due to slight data deficit in some of the sensitive bins.
- Most stringent limits for $m_\chi = 150\ GeV$:
  - $m_{Z'} \sim 2\ TeV$ for $m_s = 160 - 200\ GeV$
  - $m_s \sim 300\ GeV$ for $m_{Z'} = 250 - 1600\ GeV$
- $s \to \chi\chi$ bound reached for $m_s \geq 2m_\chi$
- Gray lines indicate where the model parameters produce exactly the current observed relic density.

Results

- The couplings combination adopted so far are excluded by di-jet resonances for a wide range of Z' masses, but similar sensitivity as the mono-jet results.
- Would be good to produce limits on $m_\chi - m_{Z'}$ mass plane and explore the lower coupling parameter region where we 'could' be complementary to di-jet results.



Results

- Comparison with ATLAS results.
- CMS $s \rightarrow b\bar{b}$ on going for $m_s < 160\ GeV$

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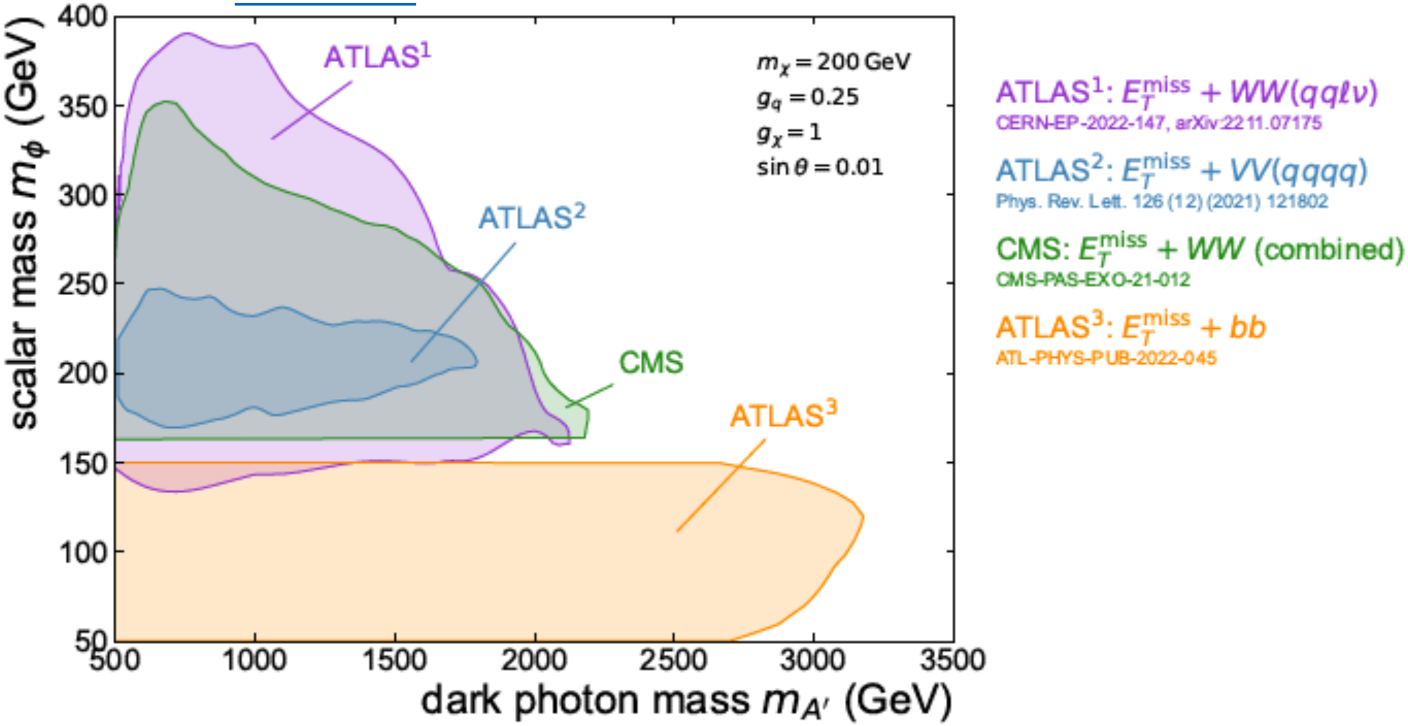

Backup

Relic density

- Relic density calculations are performed with the current dark Higgs model assumptions using MadDM
  - *C. Arina et al. Eur.Phys. J. C 83 (2023) 241, arXiv:2107.04598.*

- Gray lines in the limit figures indicate where the model parameters produce exactly the current measurement of the observed relic density.