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

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On behalf of CMS Collaboration

Roadmap of Dark Matter models for Run 3
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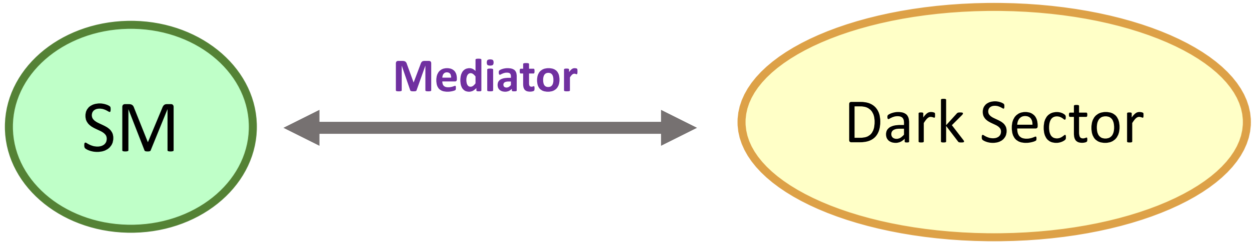
Dark Higgs Model

JHEP 1704(2017)143
arXiv:1606.07609v2

Dark Higgs models extend the dark sector



© Diagram from Katharina Behr

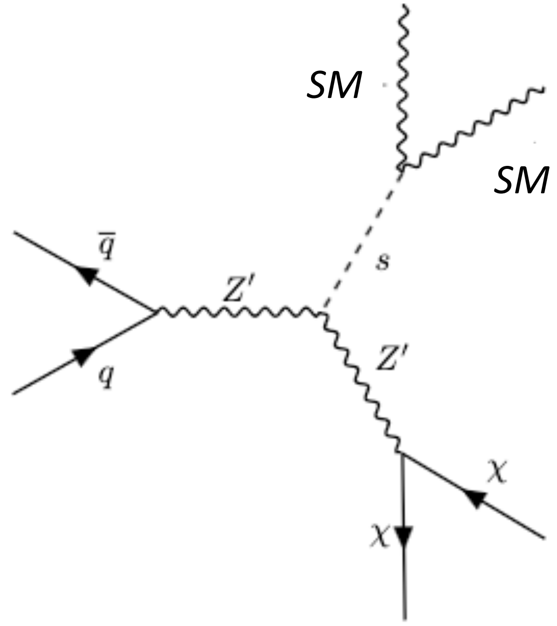
- **An approach to probe DM at the LHC is based on a two-mediator DM (2MDM) scenario:**
  - Two new bosons: Z' (spin 1) and dark-Higgs (s) (spin 0)
  - Dark-Higgs mixes minimally with the SM Higgs: constraint from measurements of the Higgs signal strengths.
  - Dark Higgs is the lightest state in the dark sector: $m_s \lesssim 2m_\chi$

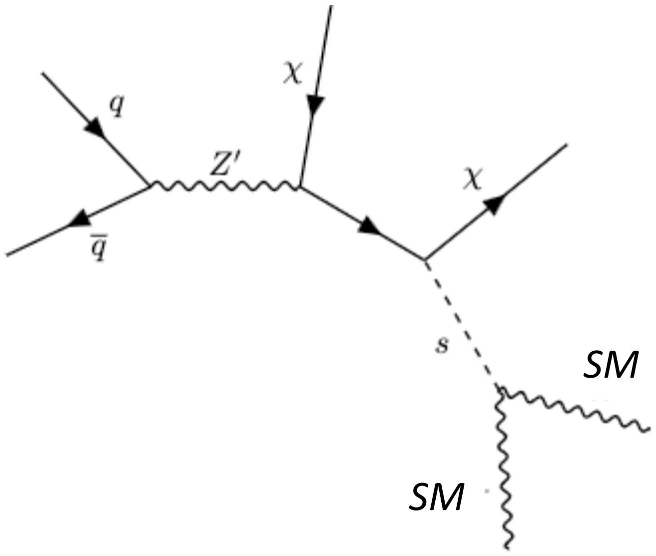
Dark Higgs Model

- The interactions between the dark-Higgs s and SM arise from mixing between the two Higgs bosons.
- Six independent parameters:

Particle masses		Coupling constants	
DM mass	m_χ	Dark-sector coupling	g_χ
Z' mass	$m_{Z'}$	Quark-Z' coupling	g_q
Dark-Higgs mass	m_s	Higgs mixing angle	θ

- Parameters and their recommended values from LHC DM WG: 1507.00966
  - Small mixing between dark-Higgs (s) and SM Higgs: $\theta = 0.01$
  - Dark-sector coupling $g_\chi = 1$
  - Quark-Z' coupling $g_q = 0.25$





Dark Higgs: $\boldsymbol{MET + s(WW)}$

JHEP 03(2024)134

- Search directly for the dark Higgs production.
- Dominant Dark Higgs decay modes:
  - $b\bar{b}$ for $m_s < 160\ GeV$
  - WW for $m_s > 160\ GeV$
- First attempt at CMS using WW final state targeting:
  - $MET + s(WW), WW \rightarrow 2l\ 2\nu$
  - $MET + s(WW), WW \rightarrow l\nu\ qq\grave{}$

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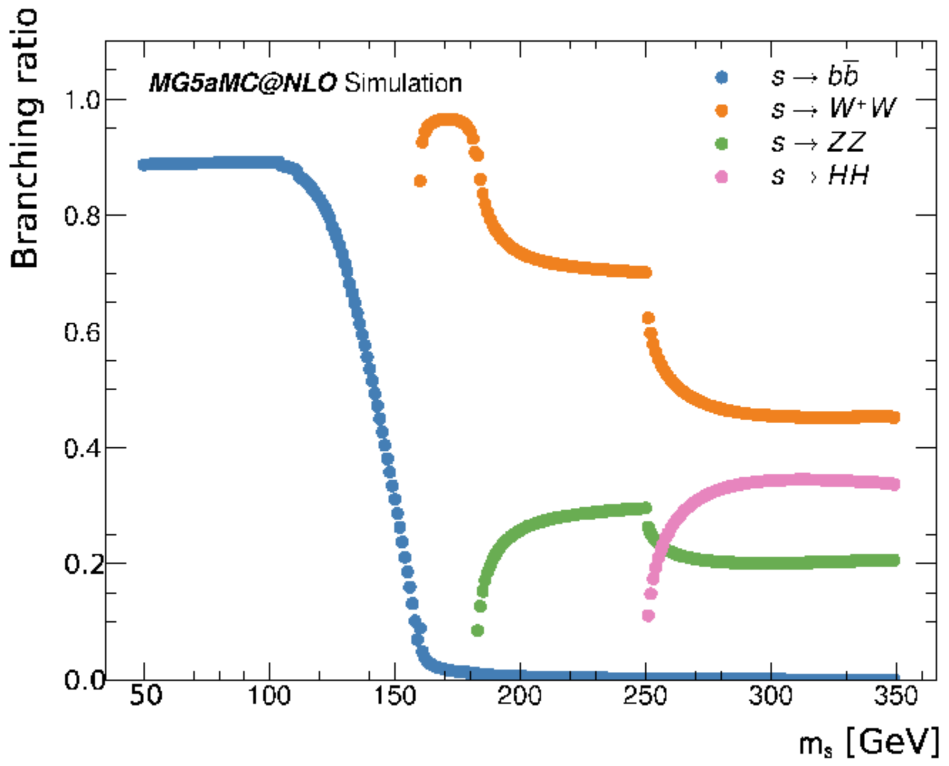
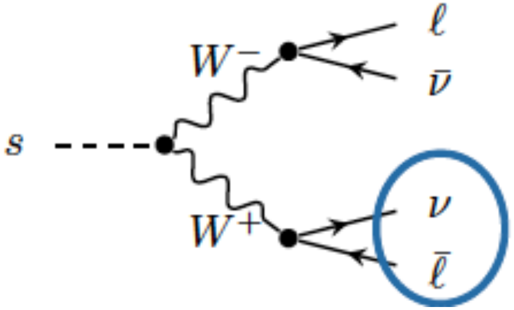


Analysis selection: $s \to WW \to 2l2\nu$

$2l2\nu$ 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

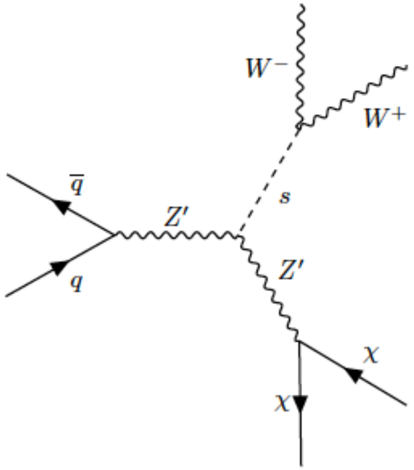
2lep + MET final state selection



Reduce top-quark background

Reduce non-prompt background

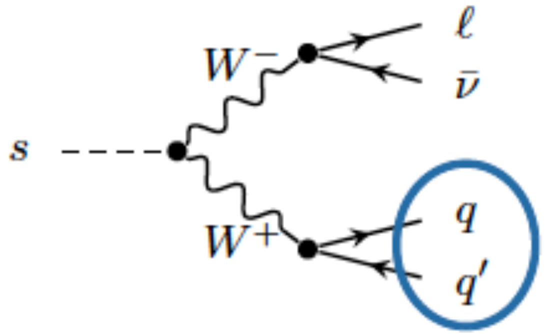
Target dark-Higgs topology



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

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

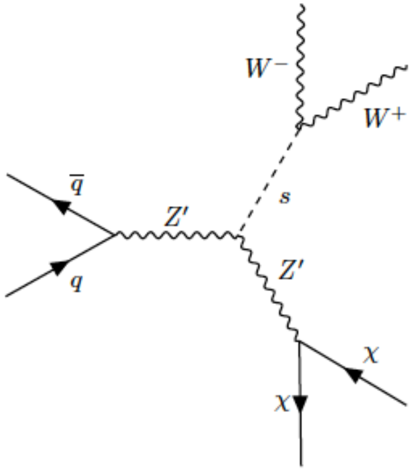
1lep + 2 jets final state selection.



Reduce W+jets background

Reduce top-quark background

Target dark-Higgs topology



Background estimation overview

Process	Analysis	Estimation	CR/Validation
Top	2l2ν lνjj	MC + normalization freely floating, constrained by CR	Invert b-veto
W+jets	lνjj	MC + normalization freely floating, constrained by CR	$m_{jj} < 65$ || $m_{jj} > 105$ GeV
Non-prompt	2l2ν	Fully data-driven estimation	Same lepton charge
	lνjj		m_T(l + MET) < 30 && MET < 30 GeV
WW	2l2ν	MC + normalization freely floating, constrained by CR	$\Delta R(l,l) > 2.5$
Drell-Yan	2l2ν	MC + normalization freely floating, constrained by CR	m_T(ll + MET) < 50 GeV

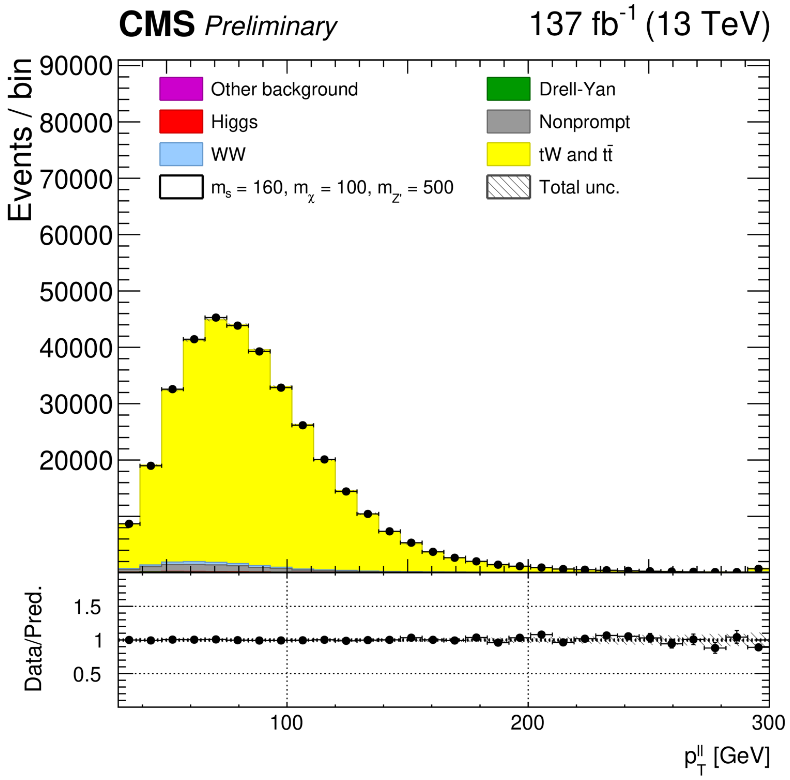
Other small processes estimated directly from simulation:
$HWW, V\gamma, V\gamma^{*}, VZ, VVV$

* Keeping other pre-selection requirements

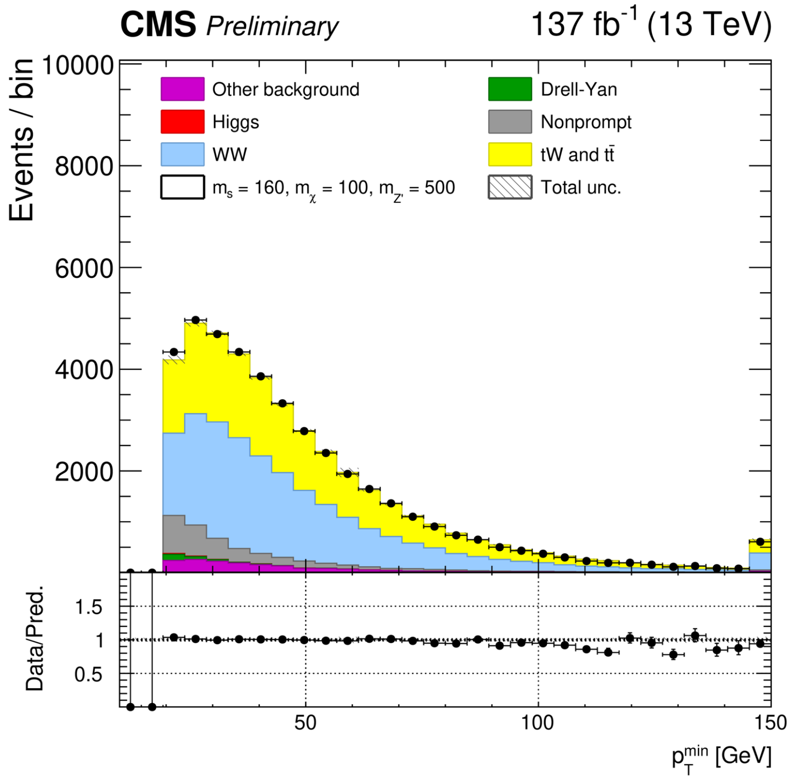
Background estimation overview

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

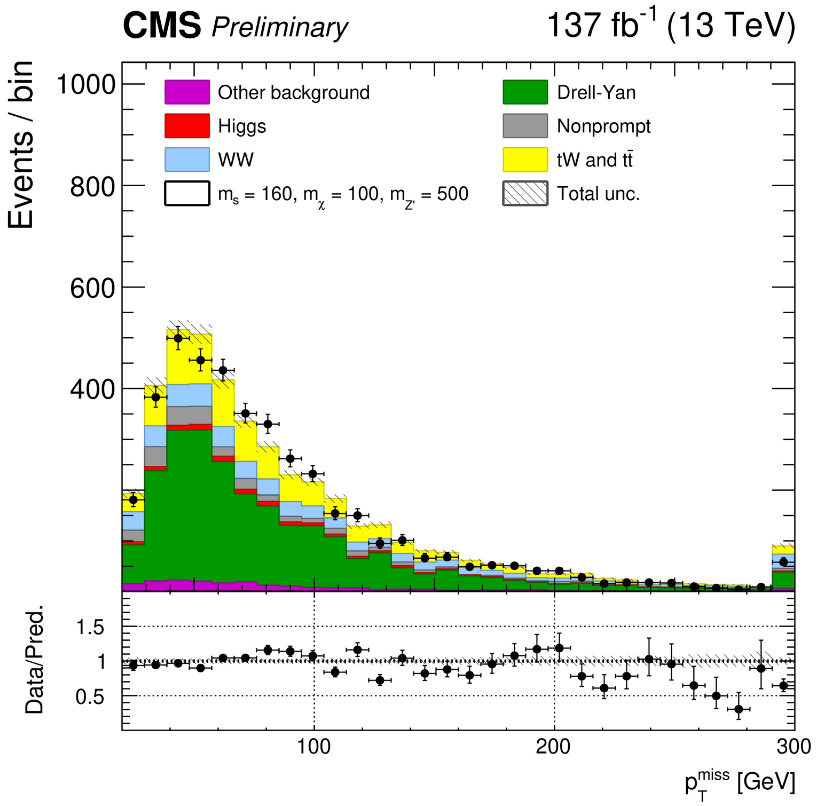
Top CR



WW CR



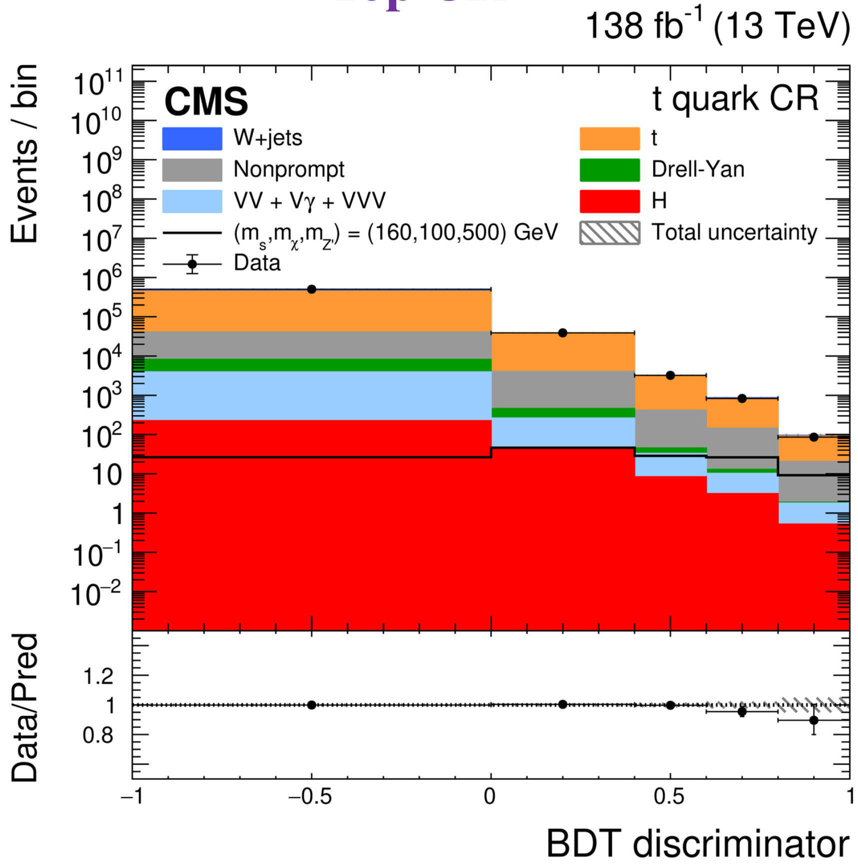
Drell-Yan CR



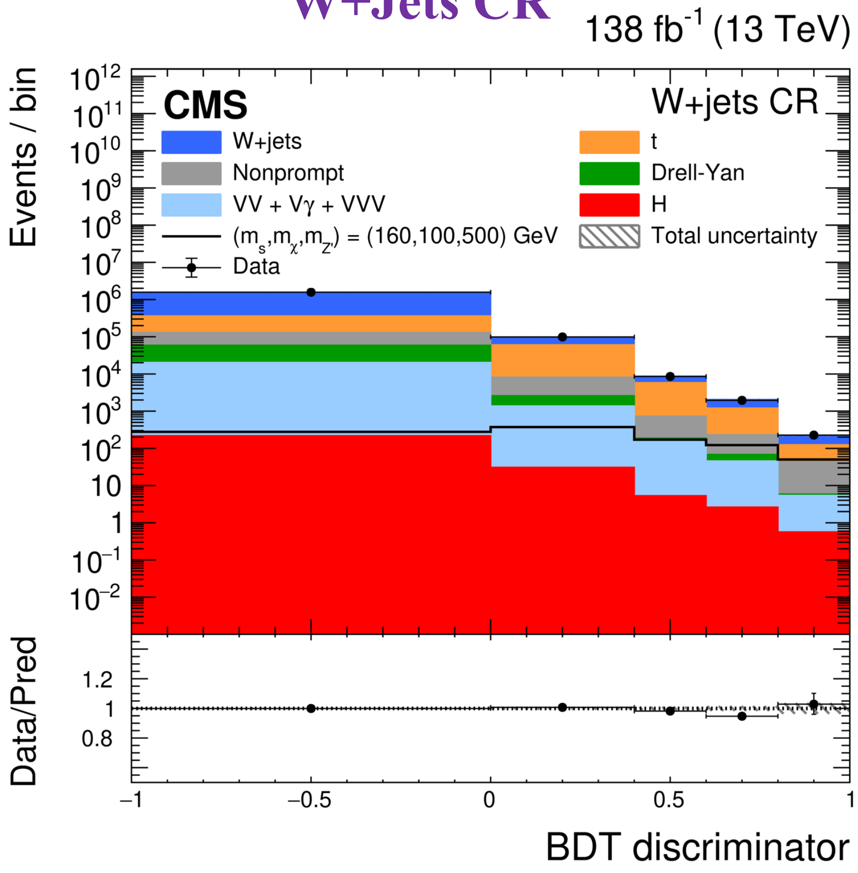
Background estimation overview

$s \rightarrow WW \rightarrow 2lqq'$

Top CR



W+Jets CR



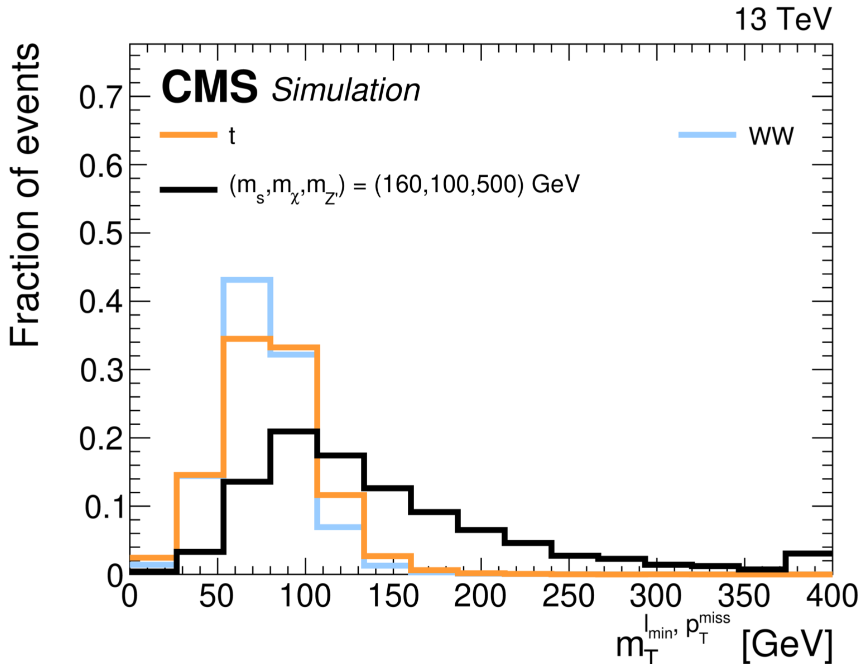
Analysis strategy $s \rightarrow WW \rightarrow 2l2\nu$

- **3D fit in $\Delta R_{ll} - m_{ll} - m_T(l_2, MET)$**

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

  - 3 SR in ΔR_{ll}(strong dependence with dark Higgs mass)

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

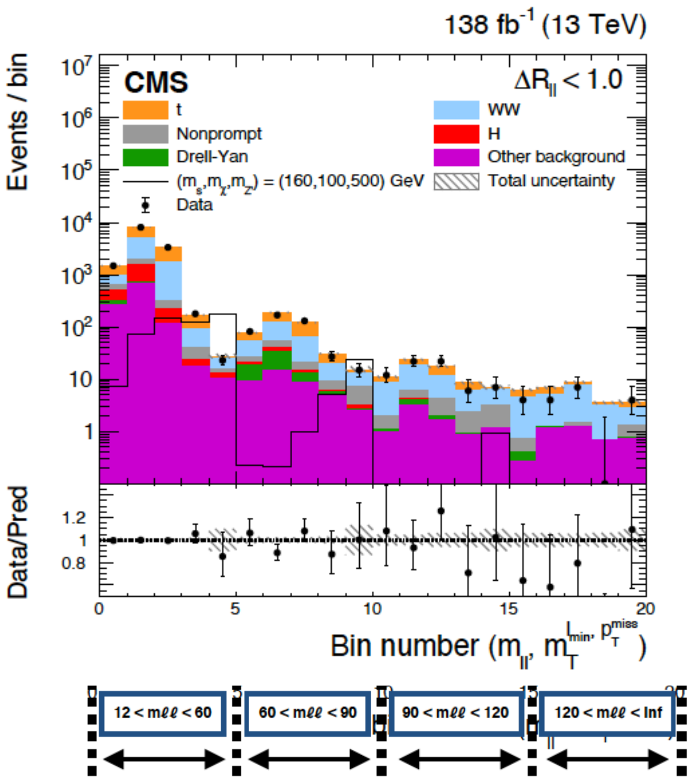


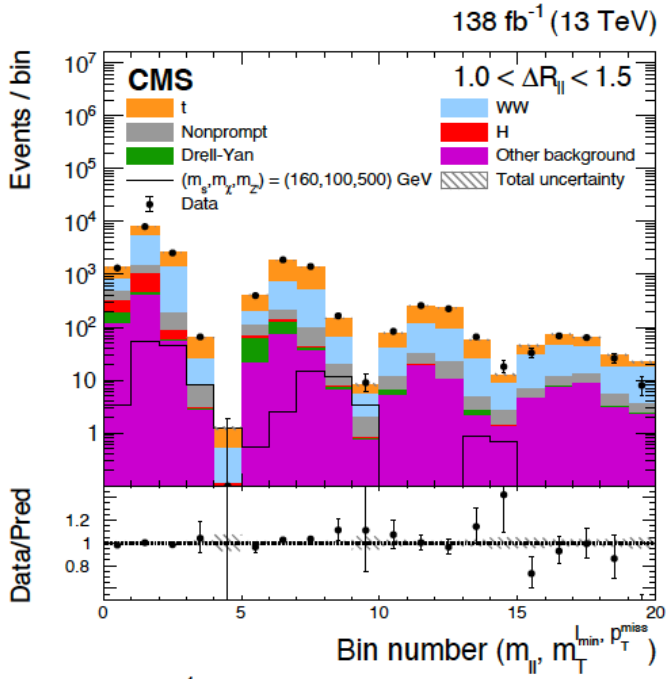
  - For m_{ll} and $m_T(l_2, MET)$ the binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.

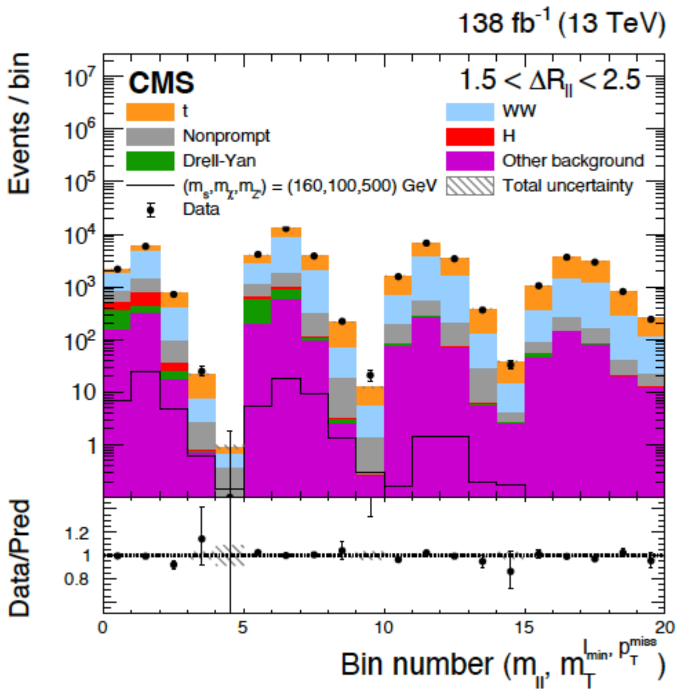
  - Allow the different signal mass points to populate the 3D parameter space while using the same background modelling procedure.

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

- 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

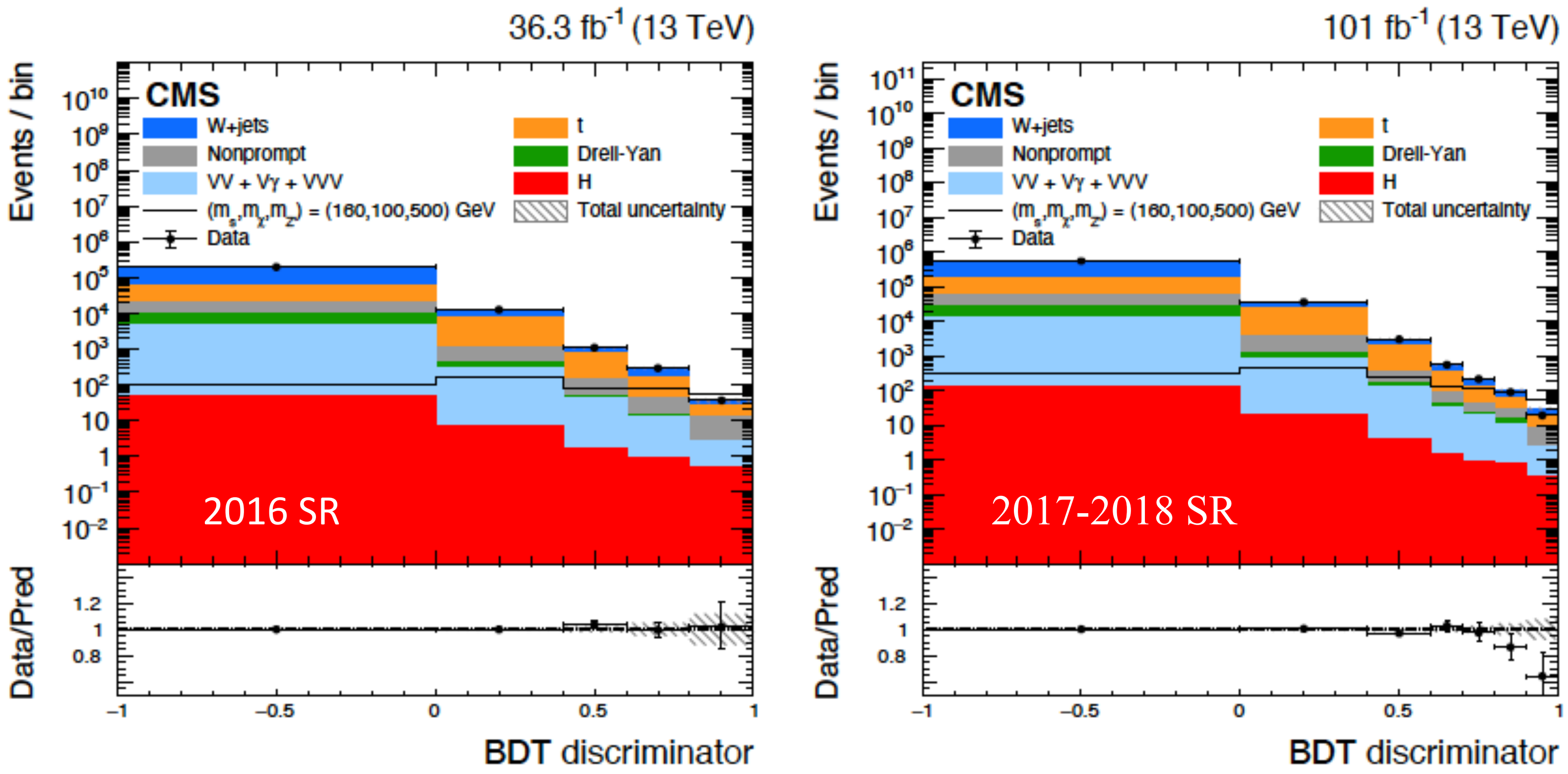
Analysis strategy $s \rightarrow WW \rightarrow 2lqq'$

- Using a **BDT Discriminator**
- 11 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.

Variable	Definition
p_T^{jj}	p_T of the vectorial sum of the W candidate jets
$p_T^{\ell jj}$	p_T of the vectorial sum of the visible particles
p_T^{miss}	Magnitude of the missing transverse momentum vector
$\Delta\eta_{\ell,jj}$ and $\Delta\phi_{\ell,jj}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and the dijet system
$\Delta\eta_{j,j}$ and $\Delta\phi_{j,j}$	$\Delta\eta$ and $\Delta\phi$ between the W candidate jets
$\|\eta_\ell\|$	The absolute value of the lepton pseudorapidity
$\Delta\phi_{\ell,\vec{p}_T^{miss}}$	$\Delta\phi$ between the lepton and $\vec{p}_T^{miss}$
$\Delta\phi_{\ell jj,\vec{p}_T^{miss}}$	$\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_T^{miss}$
$\min(p_T^\ell, p_T^{j_2})/p_T^{miss}$	Minimum of the lepton p_T and the next-to-leading W candidate jet p_T, divided by p_T^{miss}
$\max(p_T^\ell, p_T^{j_1})/p_T^{miss}$	Maximum of the lepton p_T and the leading W candidate jet p_T, divided by p_T^{miss}
$\max(p_T^\ell, p_T^{j_1})/m_{\ell jj p_T^{miss}}$	Maximum of the lepton p_T and the leading W candidate jet p_T, divided by the invariant mass of the system of all visible particles and $\vec{p}_T^{miss}$, which is taken to be massless

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

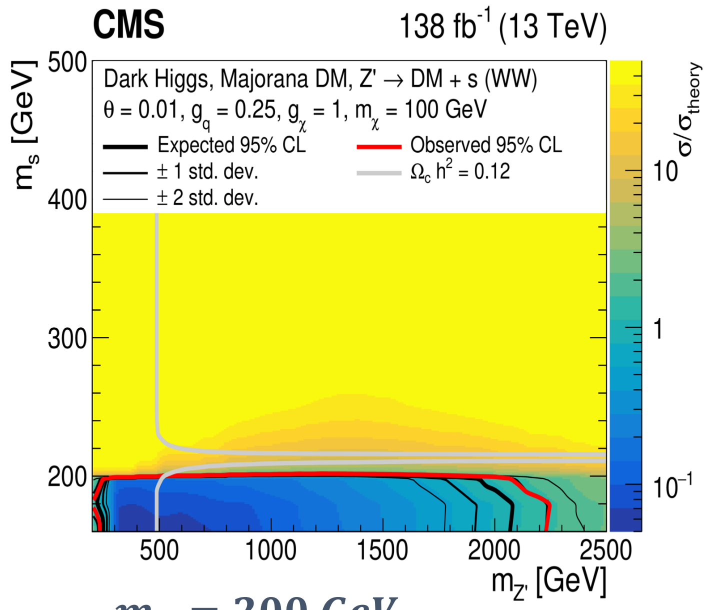
- Profile likelihood fit for1 SR, 1 Top quark background CR and 1 W+jets background CR:
  - Signal region information entering in the fit: 1D histograms of BDT output score.
  - Control regions information entering in the fit: 1-bin distributions. Top and W+Jets normalization freely float within the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



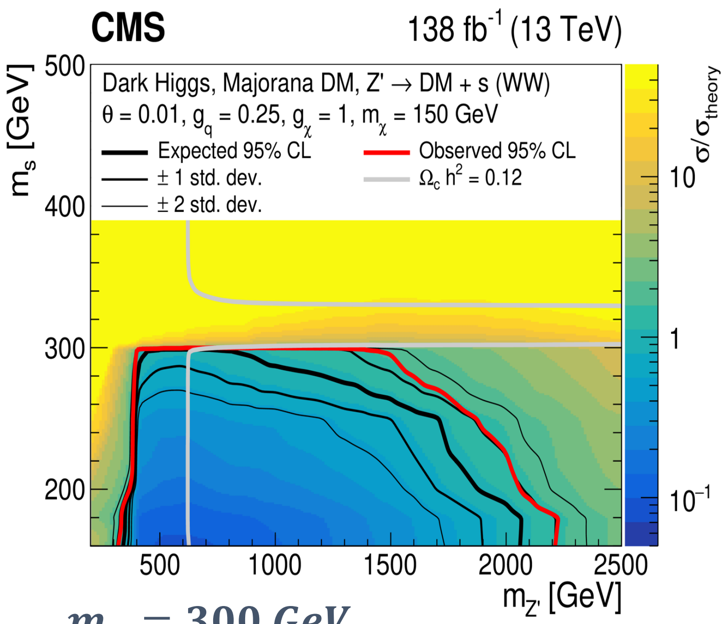
Finer binning in 2017-2018 to squeeze the sensitivity

Dark Higgs: $MET + s(WW)$

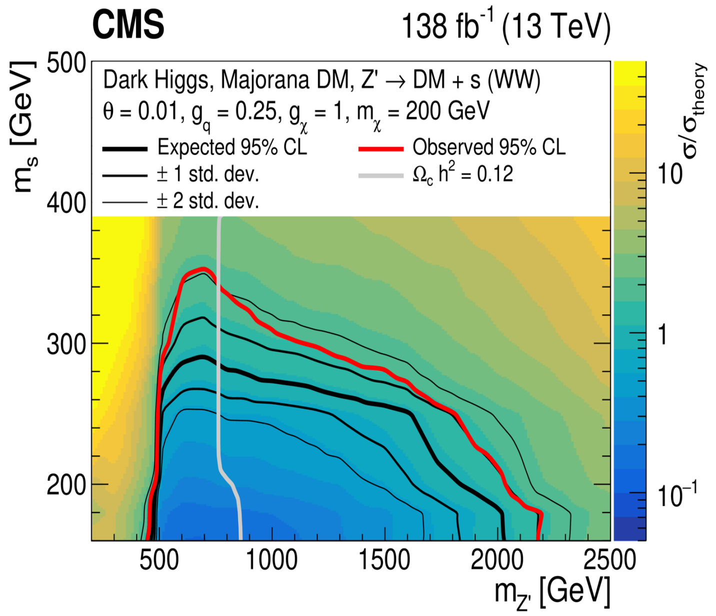
$m_\chi = 100\ GeV$



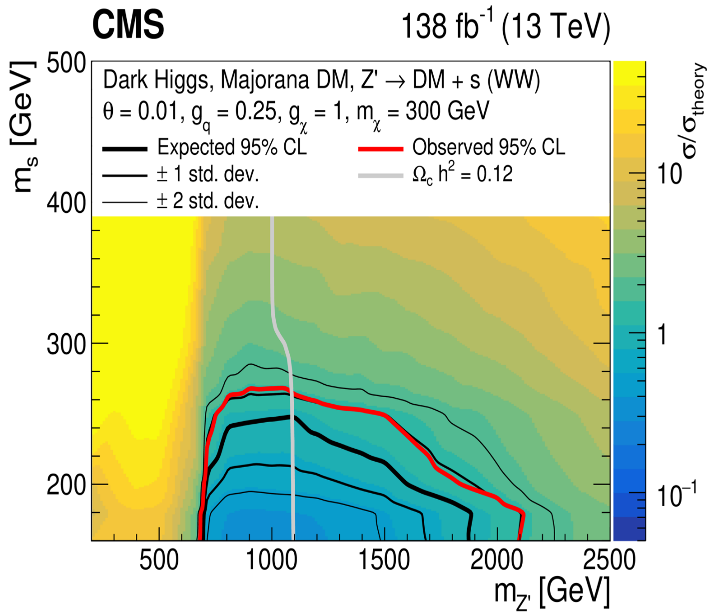
$m_\chi = 150\ GeV$



$m_\chi = 200\ GeV$



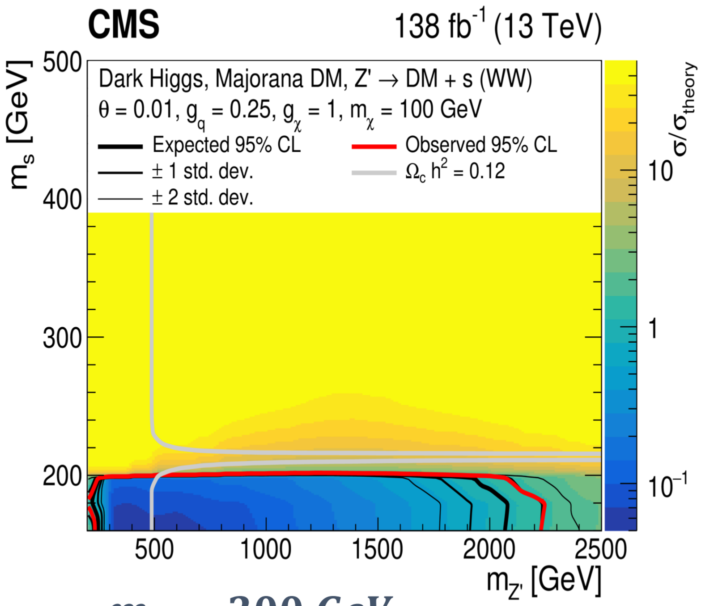
$m_\chi = 300\ GeV$



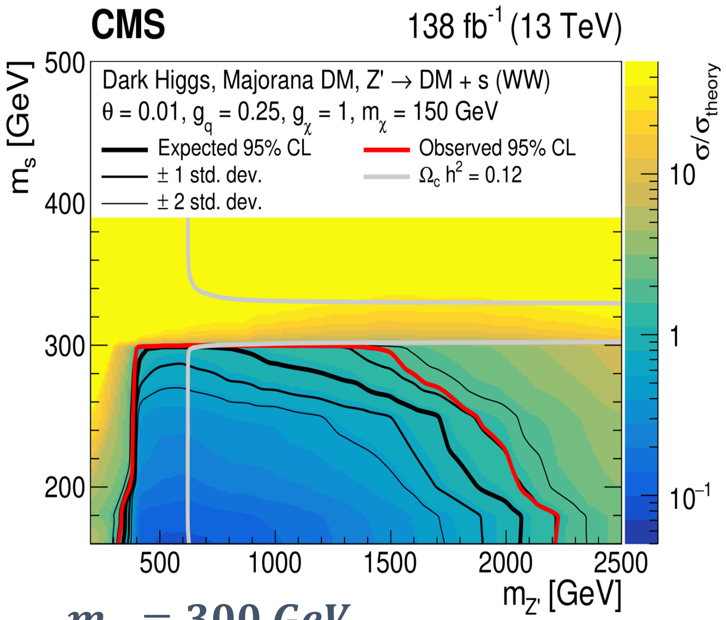
- Observed > Expected (but still below 2 sigma) due to slight data deficit in some of the sensitive bins.
- **$s \rightarrow \chi\chi$ bound reached** for $m_s \geq 2m_\chi$
- Gray lines indicate where the model parameters produce exactly the current observed relic density, using MadDM (*Eur.Phys. J. C 83 (2023) 241*).

Dark Higgs: $MET + s(WW)$

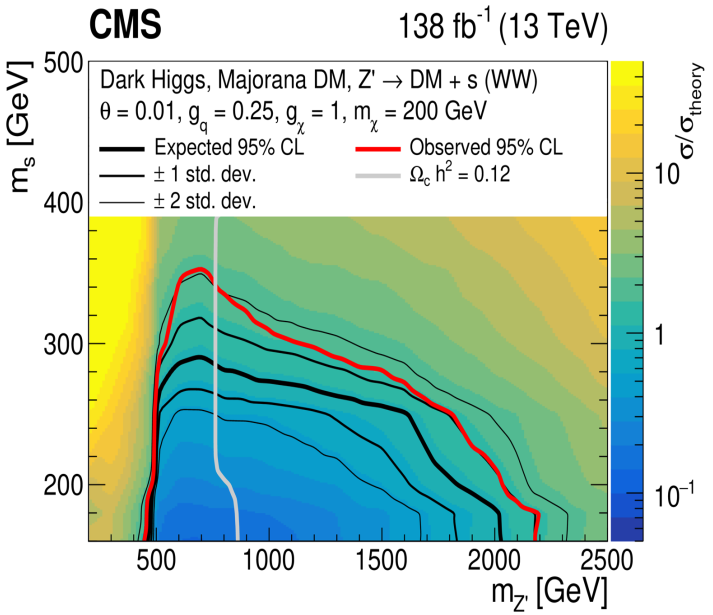
$m_\chi = 100\ GeV$



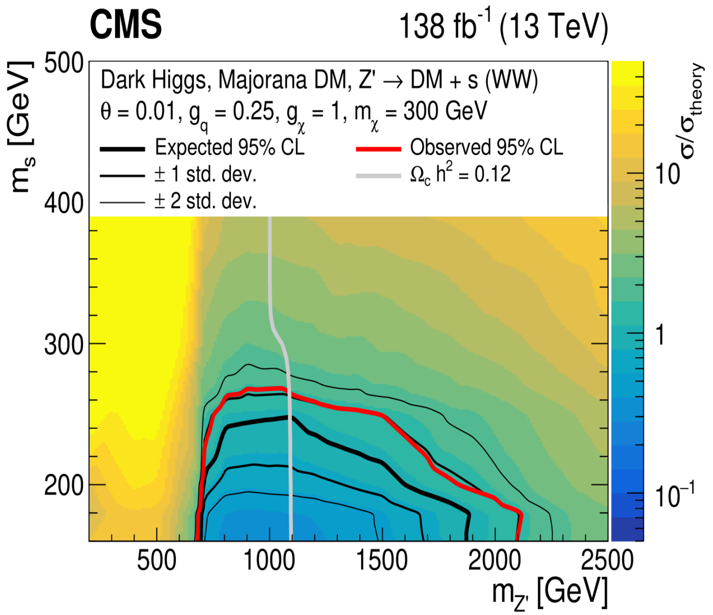
$m_\chi = 150\ GeV$



$m_\chi = 200\ GeV$



$m_\chi = 300\ GeV$



- Most stringent limits for $m_\chi = 150\ GeV$:
- For $m_s = 160 - 200\ GeV$ $< m_{Z'} \sim 2.2\ TeV$
- For $m_{Z'} = 250 - 1600\ GeV$ $160 < m_s < \sim 300\ GeV$

Final remarks

- The coupling g_q 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 explore the lower coupling parameter region where we 'could' be complementary to di-jet results.

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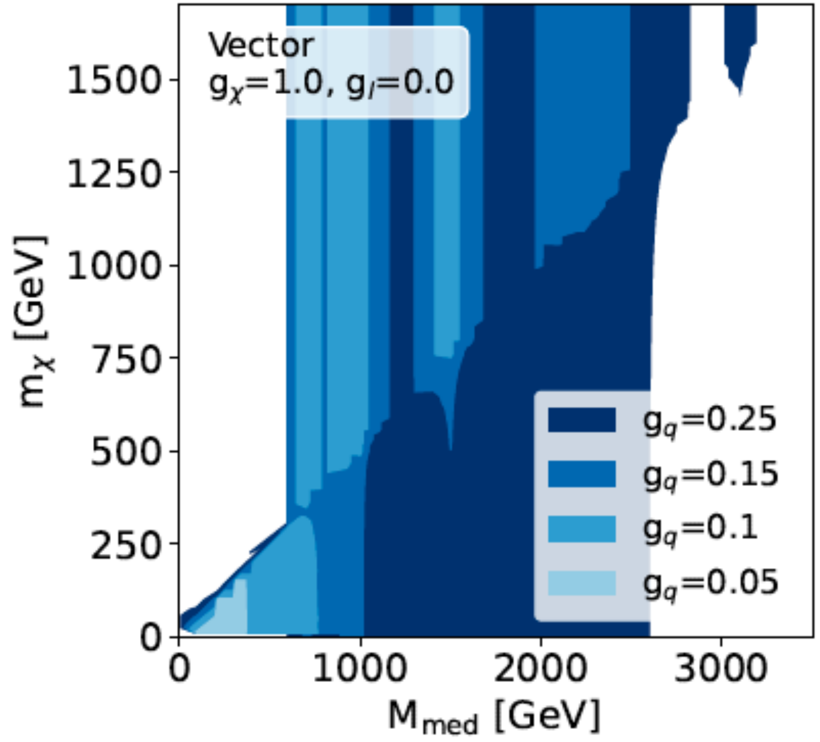
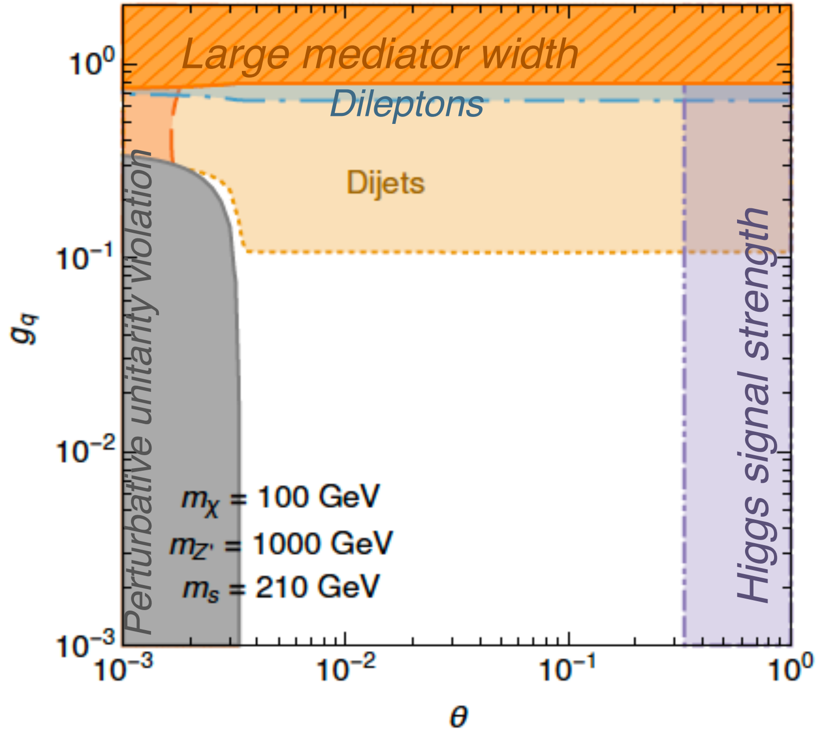


Exclusion limits of the dijet and monophoton CMS+ATLAS combined, corresponding to 36 fb−1 of LHC 13 TeV data.

1606.07609v2



Exclusion limits of the dijet and dileptons CMS+ATLAS combined, corresponding 8TeV and initial 13TeV of LHC data.

Backup

Model parameters

- Search directly for the dark Higgs production.
- Dominant Dark Higgs decay modes:
  - $b\bar{b}$ for $m_s < 160\ GeV$
  - WW for $m_s > 160\ GeV$
- First attempt at CMS using WW final state targeting: JHEP03(2024)134
  - $MET + s(WW), WW \rightarrow 2l\ 2\nu$
  - $MET + s(WW), WW \rightarrow l\nu\ qq`$

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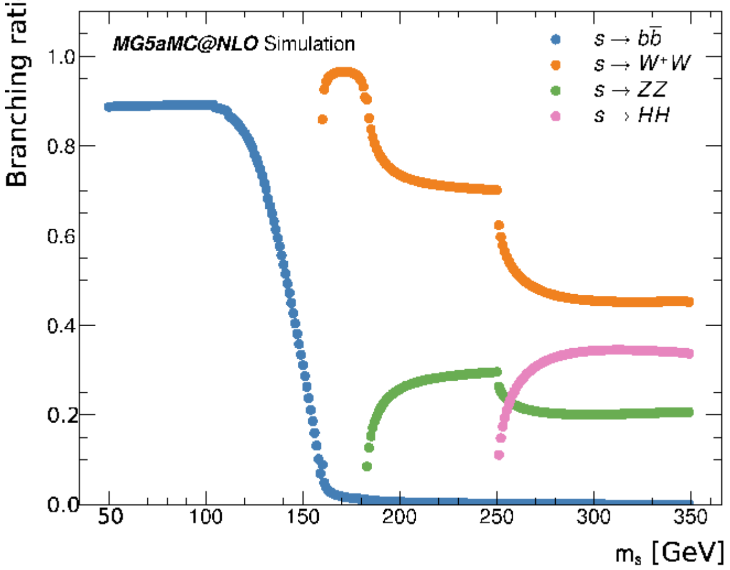

- Model generation with Madgraph @LO: ZpHiggs_UFO
- Analysis mass scan (GeV):
  - m_χ= [100, 150, 200, 300]
  - m_s = [160, 180, 200, 300, 400]
  - $m_{Z'}$ = [200 - 2500]
- Z' and s bosons widths, relative to their masses, are below 1%.

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.