Dark matter searches via SM or BSM Higgs signatures with the CMS detector

Alicia Calderón (IFCA – Univ. Cantabria - CSIC)

On behalf of CMS Collaboration

Work supported by PID2020-113304RB-I00

UC CSIC Consejo Superior de Investigaciones Científicas

IFCA Instituto de Física de Cantabria

CATCH22+2 1-5 May 2024

MINISTERIO DE CIENCIA E INNOVACIÓN

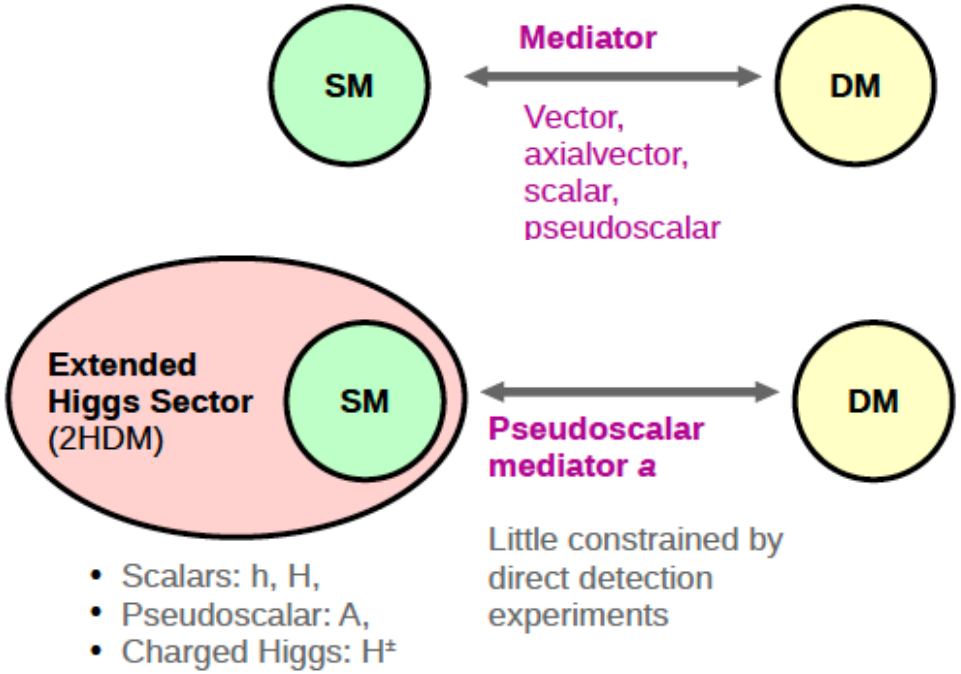
AGENCIA ESTATAL DE INVESTIGACIÓN

This talk

- Focusing on WIMP hypothesis of DM
- Only prompt signals considered.
- Interactions involving a SM Higgs or extended Higgs sector:
  - SM Higgs as a candle (*mono-Higgs*)
  - SM Higgs as a portal
  - Extra dark Higgs bosons

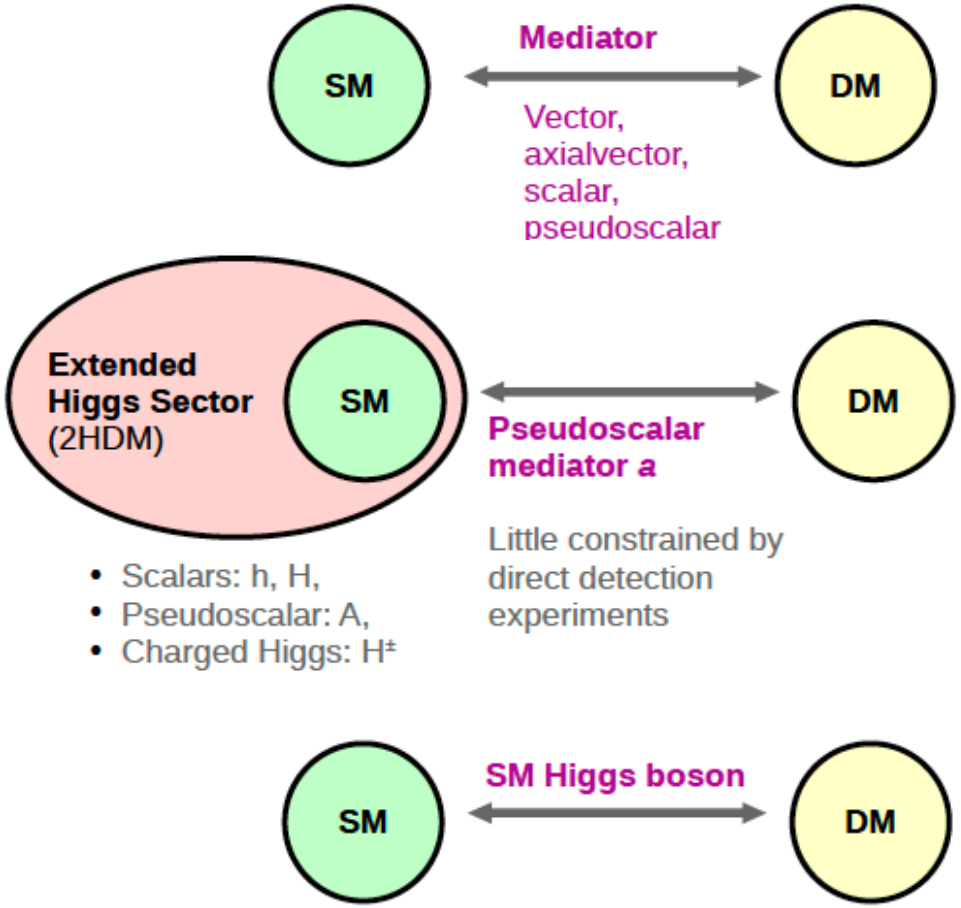
This talk

- Focusing on WIMP hypothesis of DM
- Only prompt signals considered.
- Interactions involving a SM Higgs or extended Higgs sector:
  - SM Higgs as a candle (*mono-Higgs*)
  - SM Higgs as a portal
  - Extra dark Higgs bosons



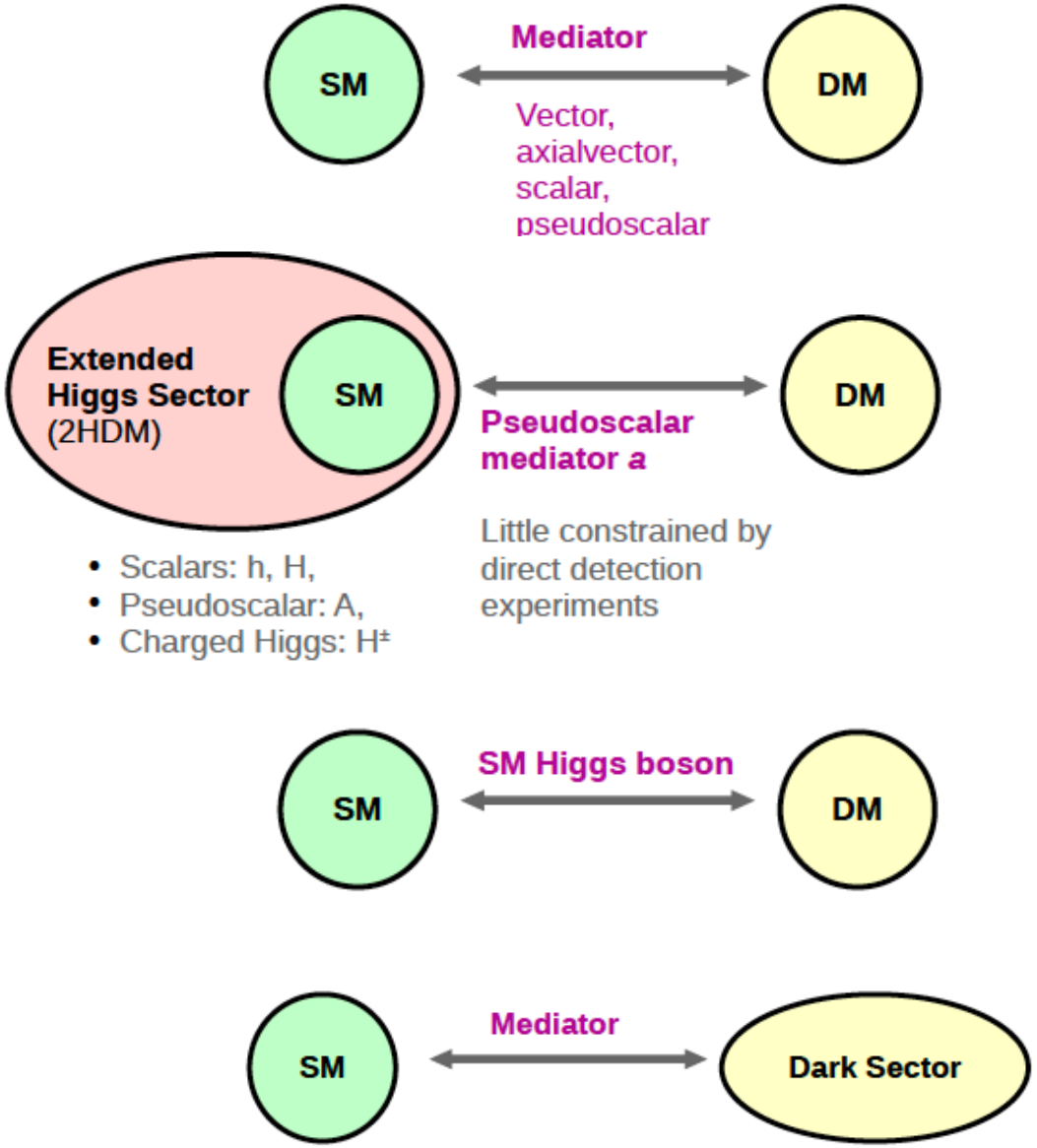
This talk

- Focusing on WIMP hypothesis of DM
- Only prompt signals considered.
- Interactions involving a SM Higgs or extended Higgs sector
  - SM Higgs as a candle (*mono-Higgs*)
  - SM Higgs as a portal
  - Extra dark Higgs bosons



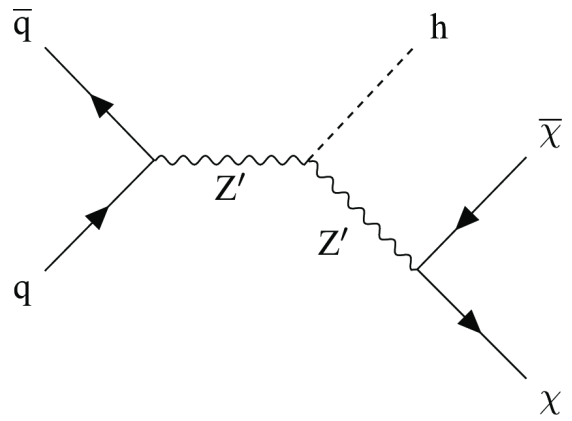
This talk

- Focusing on WIMP hypothesis of DM
- Only prompt signals considered.
- Interactions involving a SM Higgs or extended Higgs sector
  - SM Higgs as a candle (*mono-Higgs*)
  - SM Higgs as a portal
  - Extra dark Higgs bosons

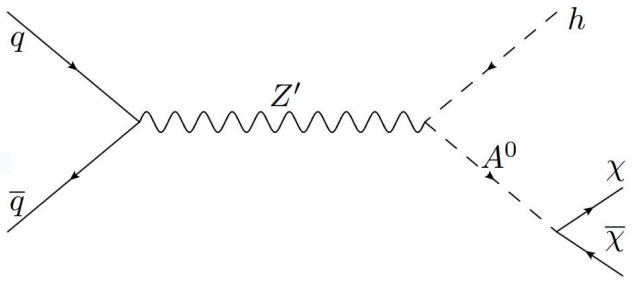


Mono-Higgs models

Phys. Rev. D 89, 075017 (2014)



1402.7074



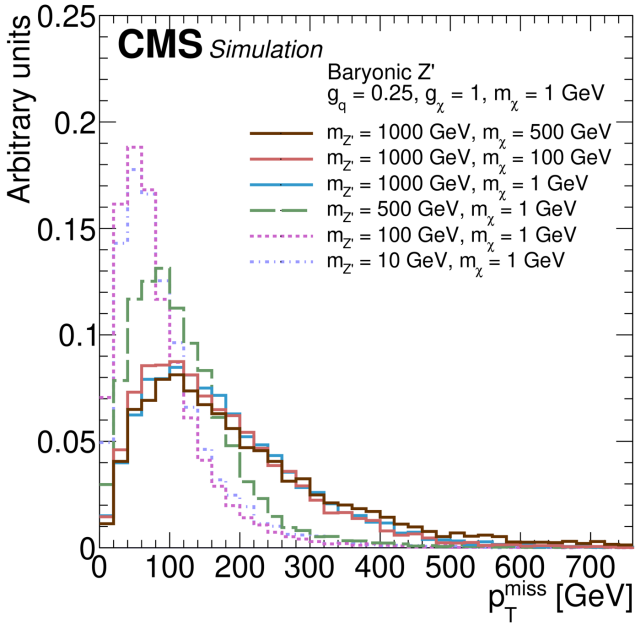
Interpretation: Z'-Baryonic

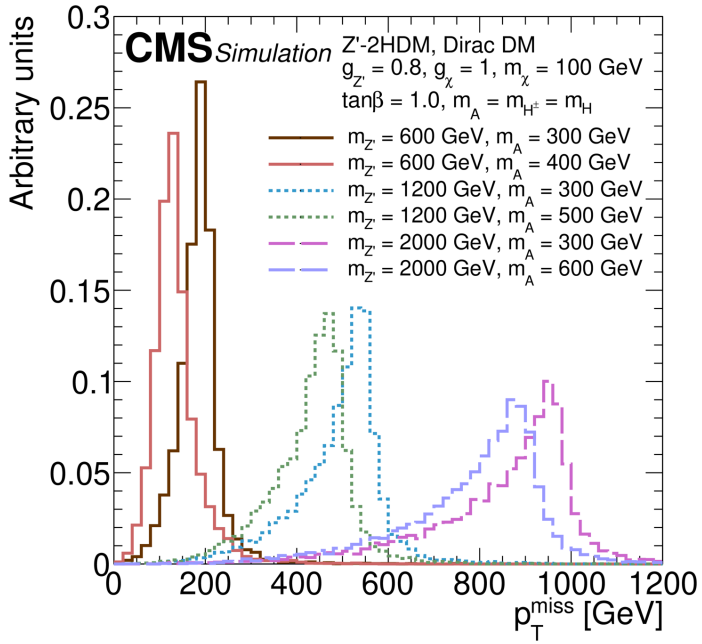
- New $U(1)_B$ symmetry → Z' boson
- Symmetry broken by a heavy Higgs field with boson H_B that mixes with SM Higgs boson

Interpretation: Z'-2HDM

- 2HDM model extended by a $U(1)_{Z'}$ group
- Vector Z' produced resonantly, decays into SM-like h and heavy pseudoscalar A^0 that couples to DM.

JHEP03(2020)025

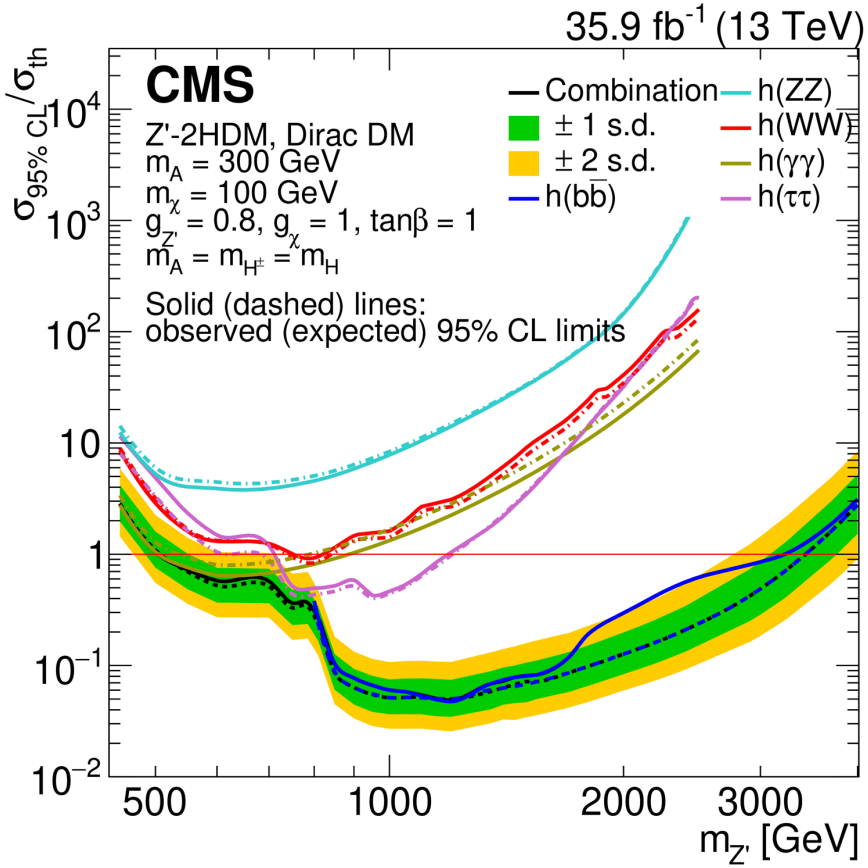




Mono Higgs ($\rightarrow b\bar{b}, \gamma\gamma, WW, ZZ$ and $\tau\tau$) + MET

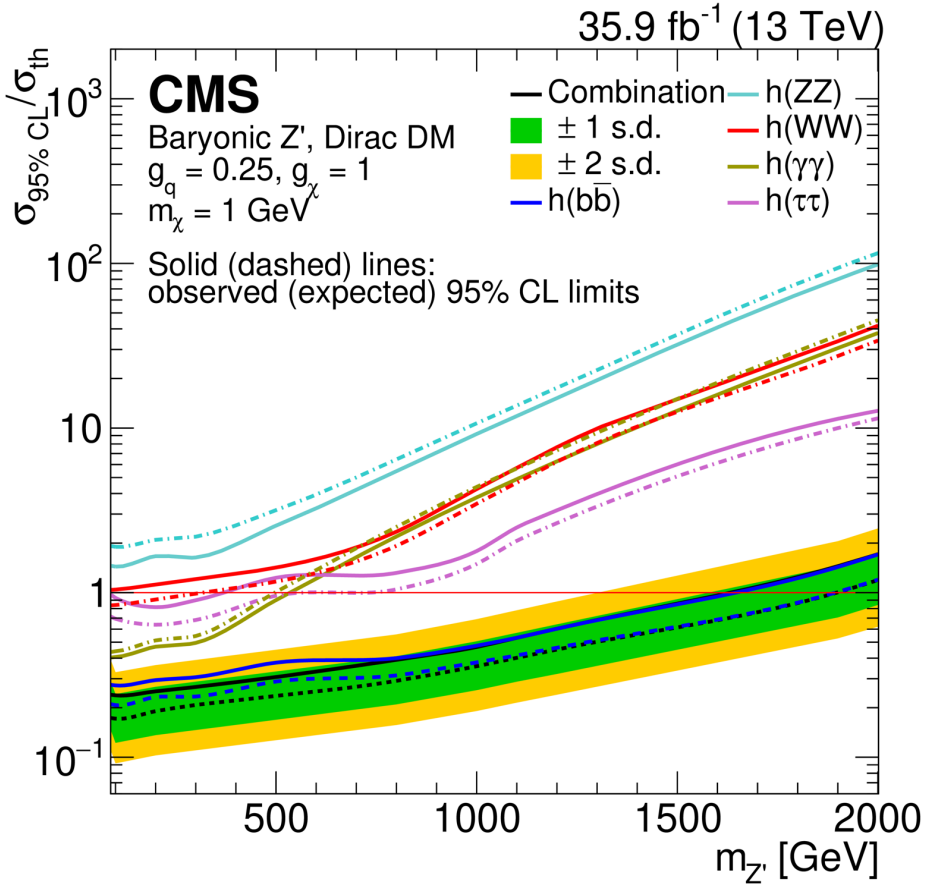
JHEP03(2020)025

Interpretation: Z'-2HDM



- Exclusion region: 1D scan of $m_{Z`}$ up to 500-3200 GeV.

Interpretation: Z'-Baryonic

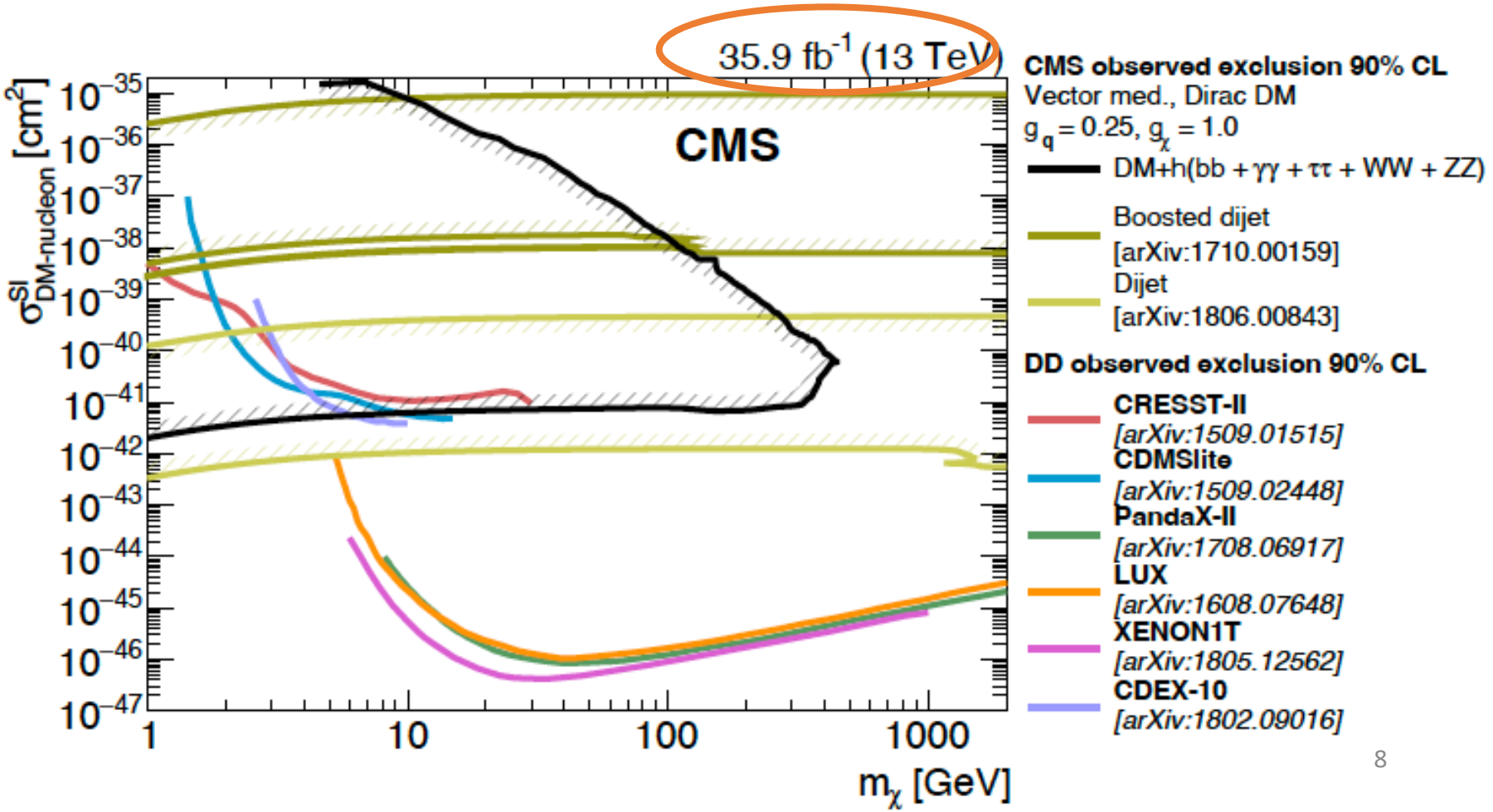


- Exclusion region: 1D scan of $m_{Z`}$ up to 100-1600 GeV.

Mono Higgs ($\rightarrow b\bar{b}, \gamma\gamma, WW, ZZ$ and $\tau\tau$) + MET

JHEP03(2020)025

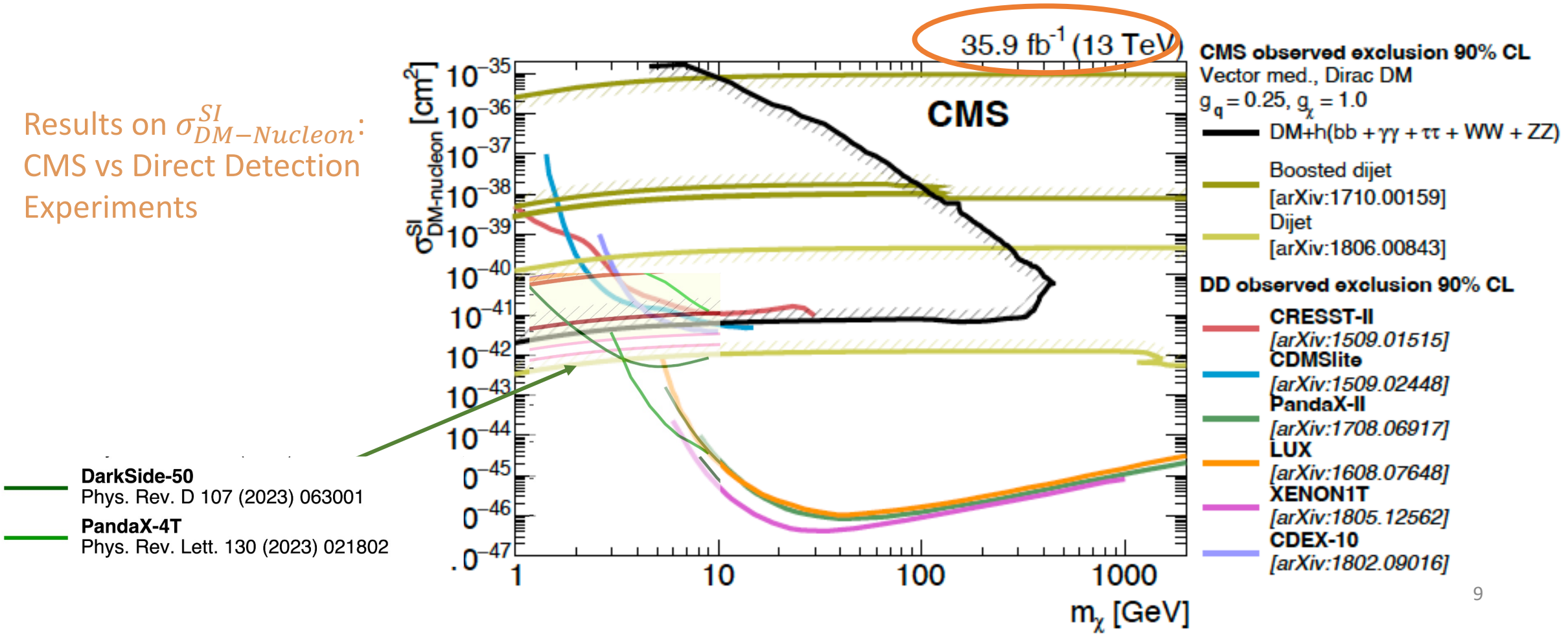
Results on $\sigma^{SI}_{DM-Nucleon}$: CMS vs Direct Detection Experiments



Mono Higgs ($\rightarrow b\bar{b}, \gamma\gamma, WW, ZZ$ and $\tau\tau$) + MET

JHEP03(2020)025

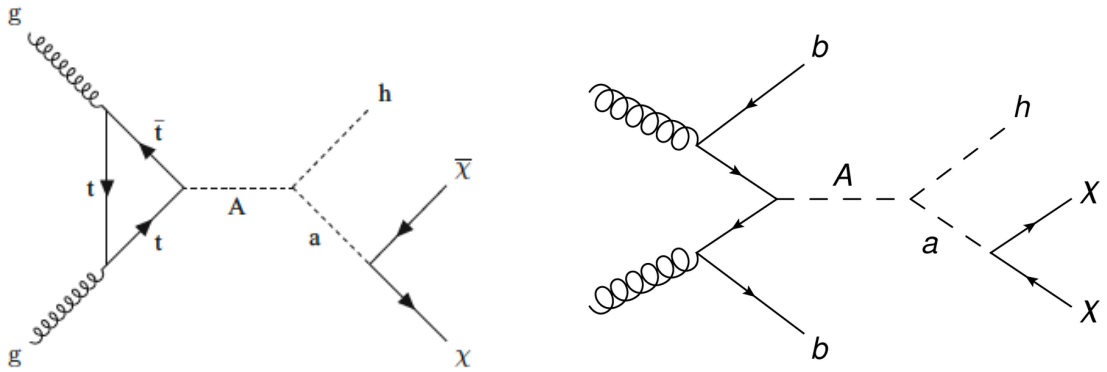
Results on $\sigma^{SI}_{DM-Nucleon}$: CMS vs Direct Detection Experiments



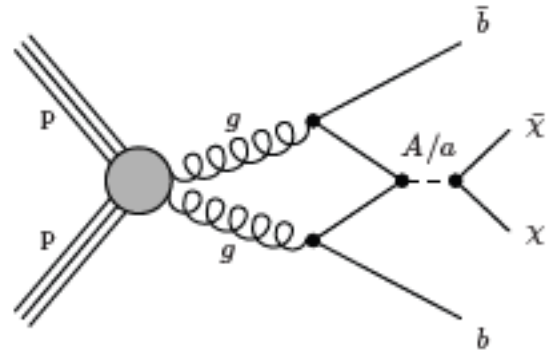
Extended Higgs sector: 2HDM+a

- Following the LHC DM WG benchmark white paper (1810.09420)
- Two-Higgs doublet model 2HDM extended by a new pseudoscalar a
  - Simplest renormalizable and gauge-invariant
  - Pseudoscalar portal (a) to dark matter, with moderate mixing with A through the θ angle.
  - Reduced constraints from DD.

$H(b\bar{b})$ + *MET* (resonant production)



$b\bar{b}/t\bar{t}$ + *MET* (non-resonant production)



Benchmark Parameters

$m_H = m_{H^\pm} = m_A$

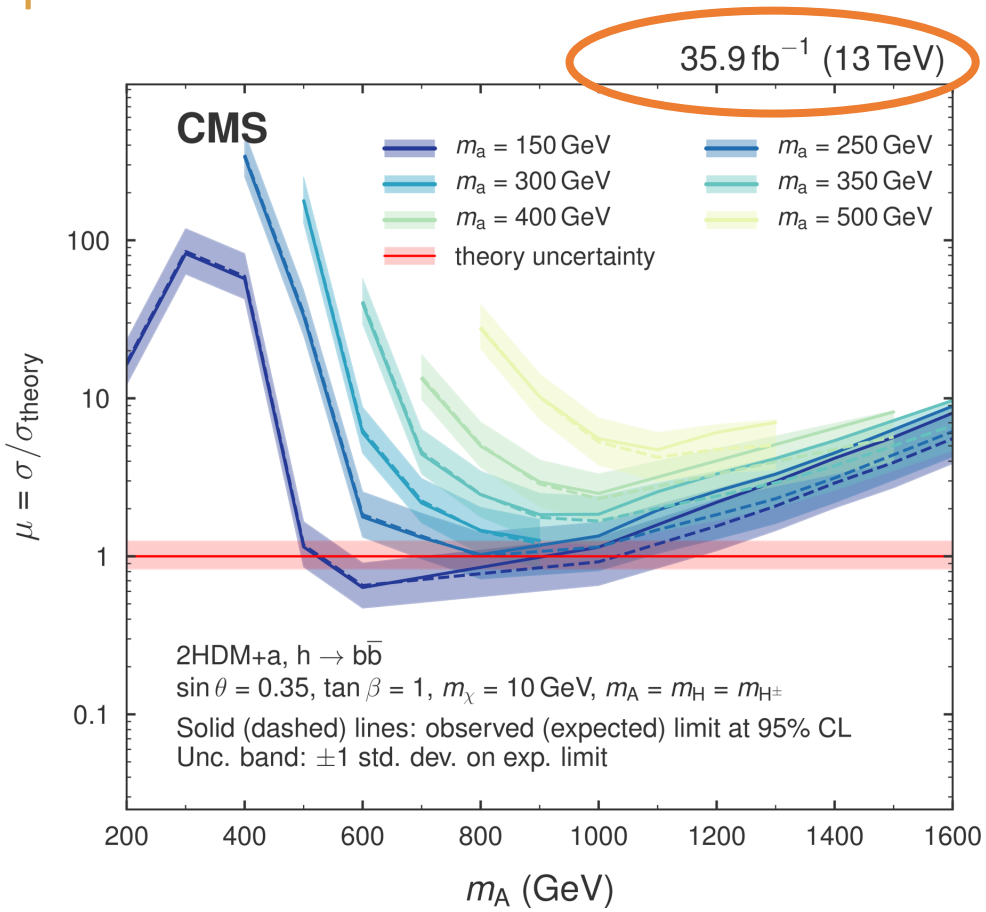
$\tan\beta < 50, \cos(\beta - \alpha) = 0$

$low\ m_\chi$

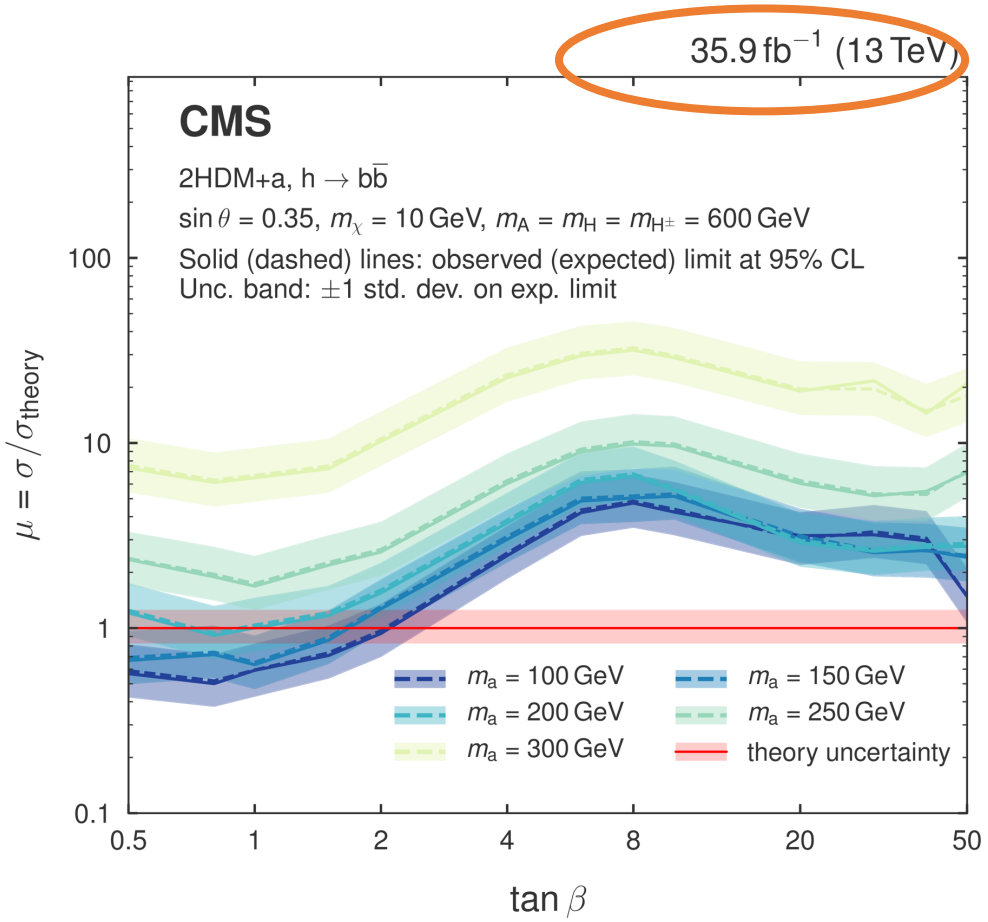
Mono Higgs ($\rightarrow b\bar{b}$) + MET (resonant)

Eur.Phys.J.C (2019) 79

Interpretation: 2HDM+a



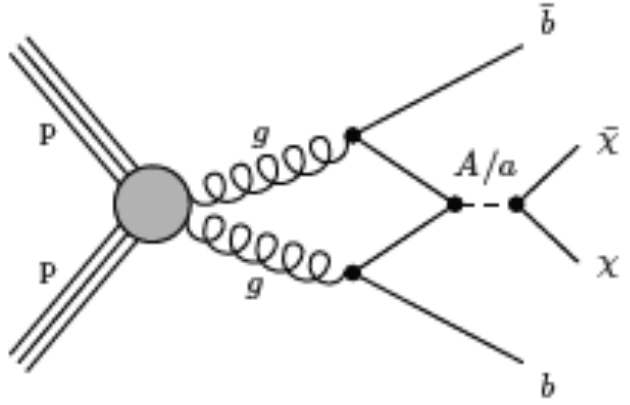
- Exclusion region: 1D scan of m_A in the range ~500-1000 GeV for $m_a = 150$ GeV



- Exclusion region: 1D scan of tan β up to ~ 2 for $m_a = 100$ GeV

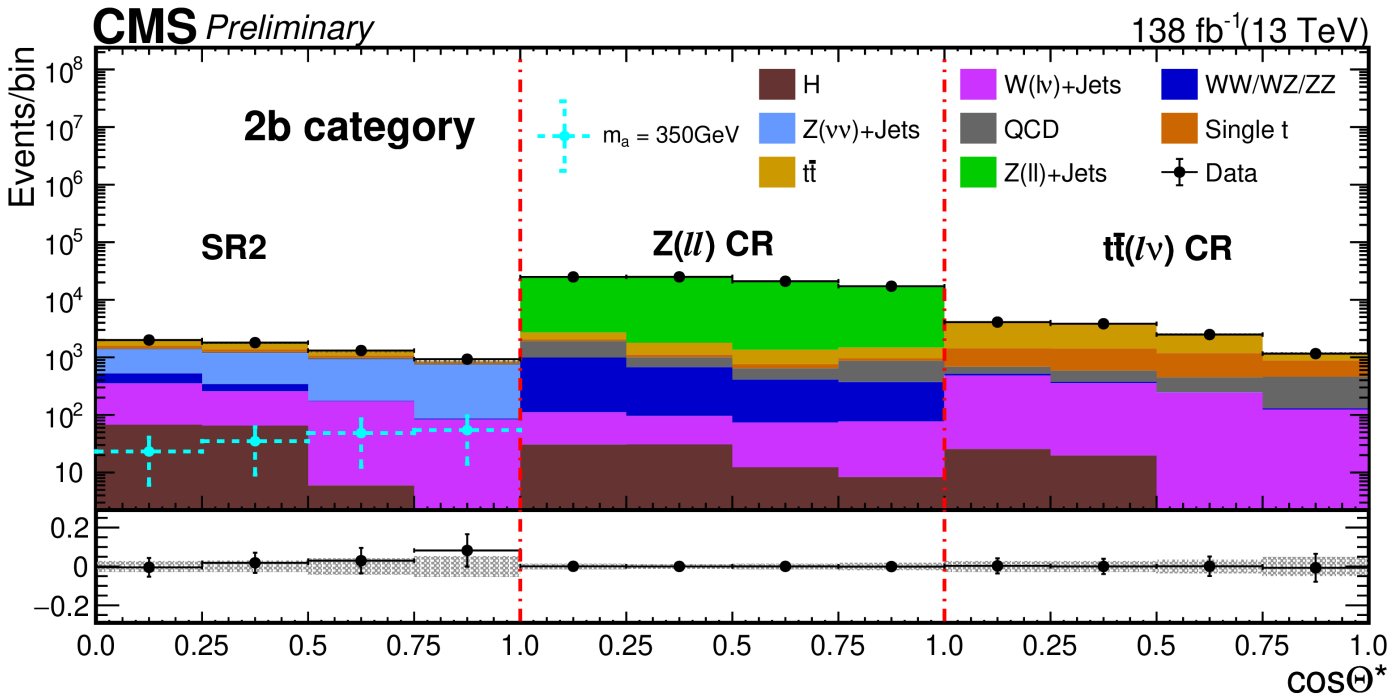
$b\bar{b}$ + MET (non-resonant)

CMS-PAS-SUS-23-008



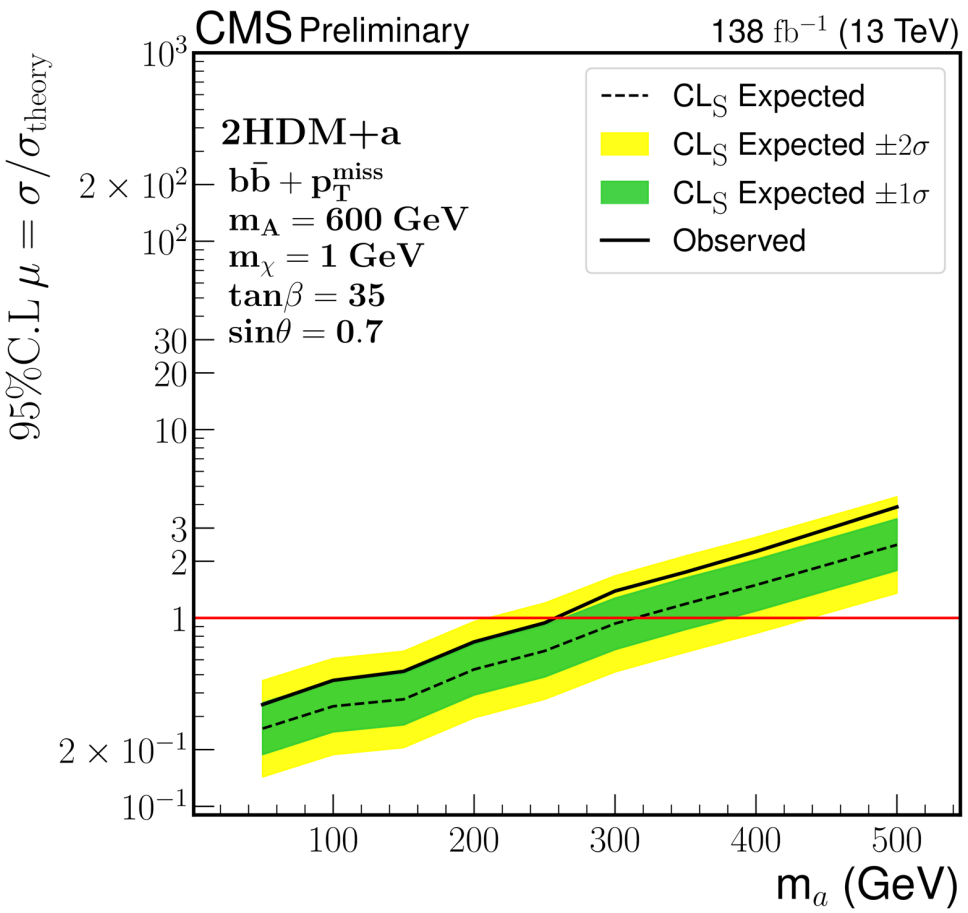
- High $tan\,\beta$ enhanced: g_{bba}, g_{bbA} couplings are proportional to tanβ.
- 1 and 2 b-jet categories + high MET
  - $p_T^{miss} > 250\ GeV$
- Main observable $\cos\theta^*$ between b-jets in the most sensitive region with 2 b-jets.

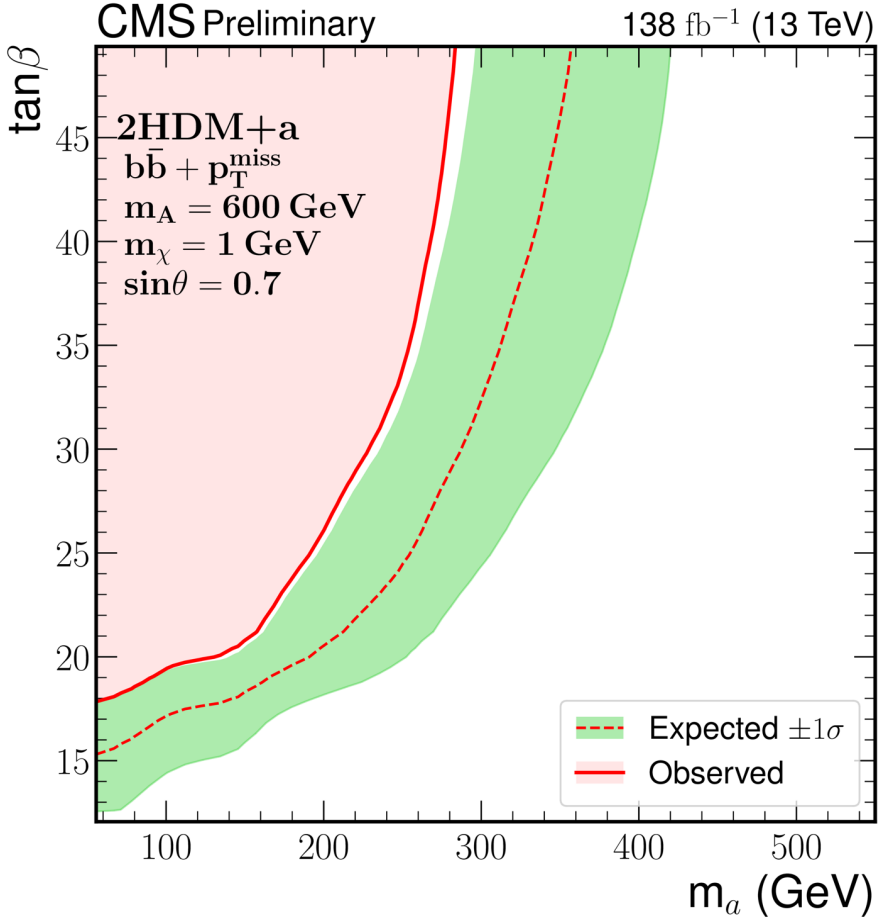
$$\cos\Theta^* = \left|\tanh\left(\frac{\eta_1 - \eta_2}{2}\right)\right|$$



$b\bar{b}$ + MET (non-resonant)

CMS-PAS-SUS-23-008





m_a excluded up to ~ 260 GeV for m_A=600 GeV.

Better sensitivity at high tanβ

Higgs boson portal

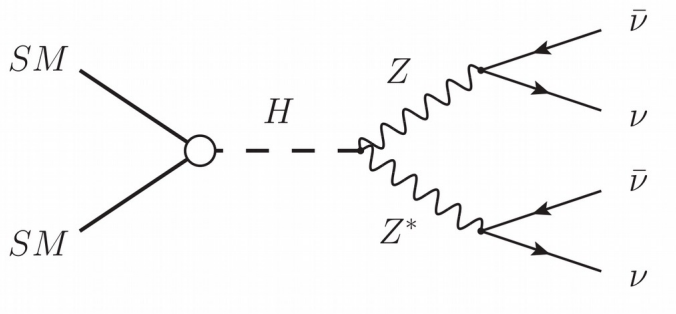
- The only SM way the Higgs boson can decay without leaving any traces in the LHC detectors is through the four-neutrino decay, H → ZZ → 4ν, with:

  SM $BR_{h\to inv} \sim 0.1\%$.

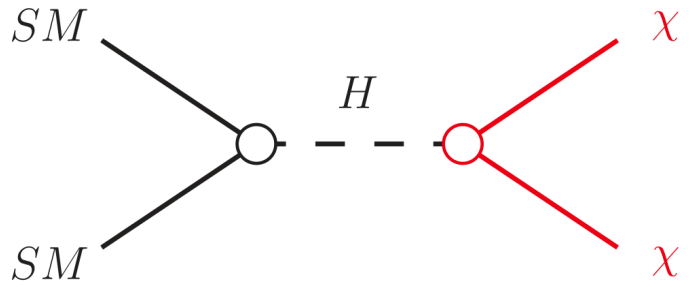
- **Simple extension**: additional scalar singlet which mixes with the SM Higgs.
- Most sensitive channel is the VBF production, but also measured in the ggH, ttH and VH production modes.

$$B(H \to inv) = \frac{\Gamma_{inv}}{\Gamma_{SM}+\Gamma_{inv}}$$

$$\Gamma_{SM} = 4.07\text{MeV}$$



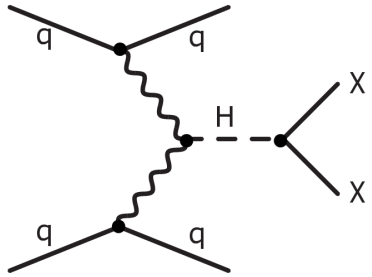
Standard Model $h \to inv$ process.



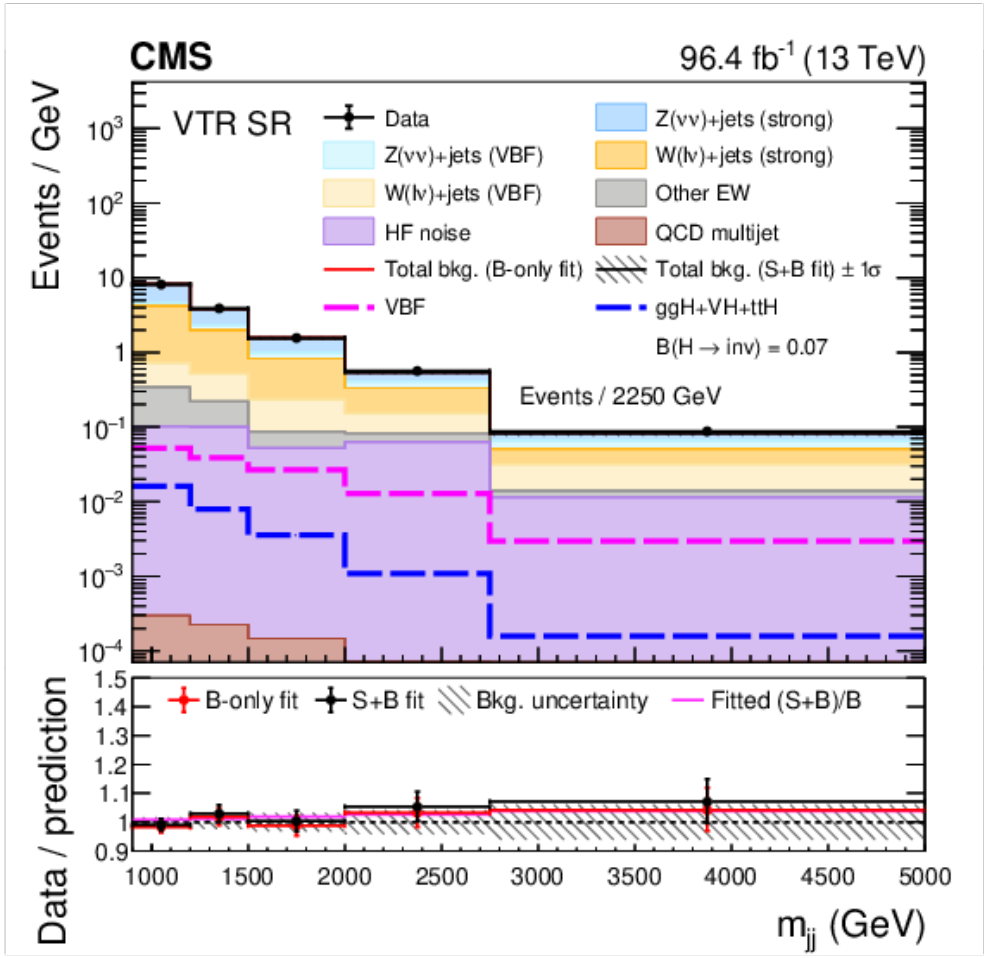
Signature: *Large branching fraction of Higgs to invisible.*

Higgs boson portal: VBF Higgs to invisible

PRD 105,092007(2022)



- Two main signal regions based on:
  - p_T^{miss}/H_T trigger (p_T^{miss} > 250 GeV)
  - VBF-jets+ p_T^{miss} trigger (160 < p_T^{miss} < 250 GeV)
- Jets with large separation in η and hence large m_{jj}, and low separation in $\Delta\phi$.



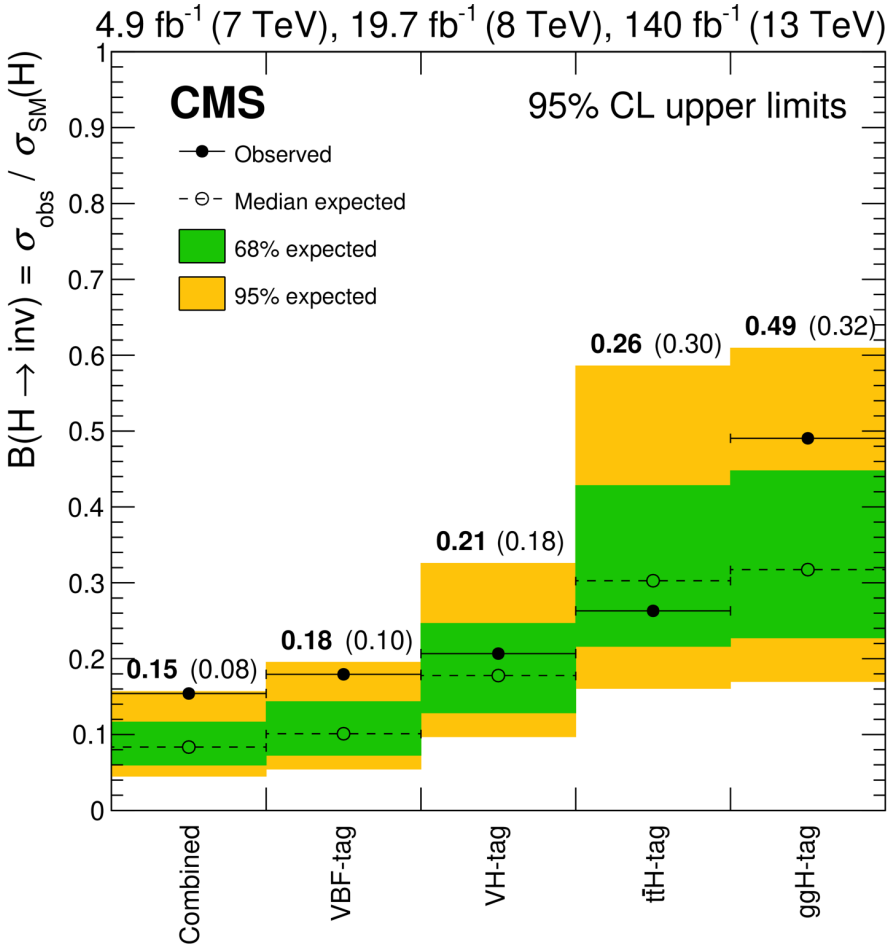
95% C.L. upper limit:
Observed (expected) $BR_{VBF\,h\to inv} = 0.18\,(0.10)$

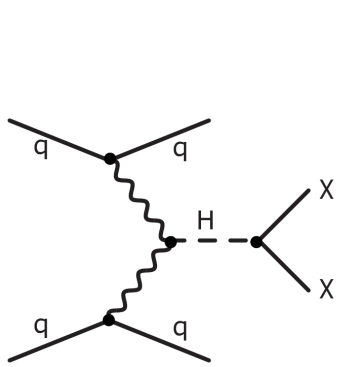
Higgs boson portal

EPJC 83(2023)933

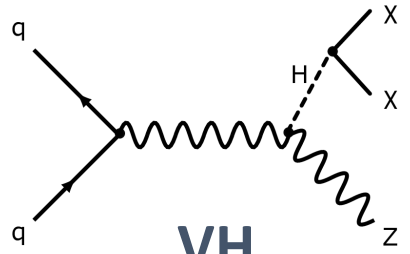
- A combined likelihood fit is performed across all Run 1 and Run 2.

Upper limits at 95% CL on B(H→inv).





VBF



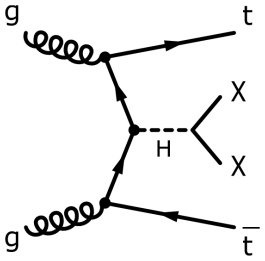
VH

$V(jj)$H

Z(ll)H

Z(bb)H

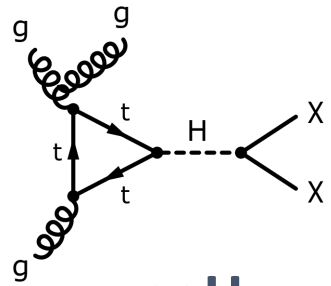
Boosted VH



ttH

Hadronic

Leptonic



ggH

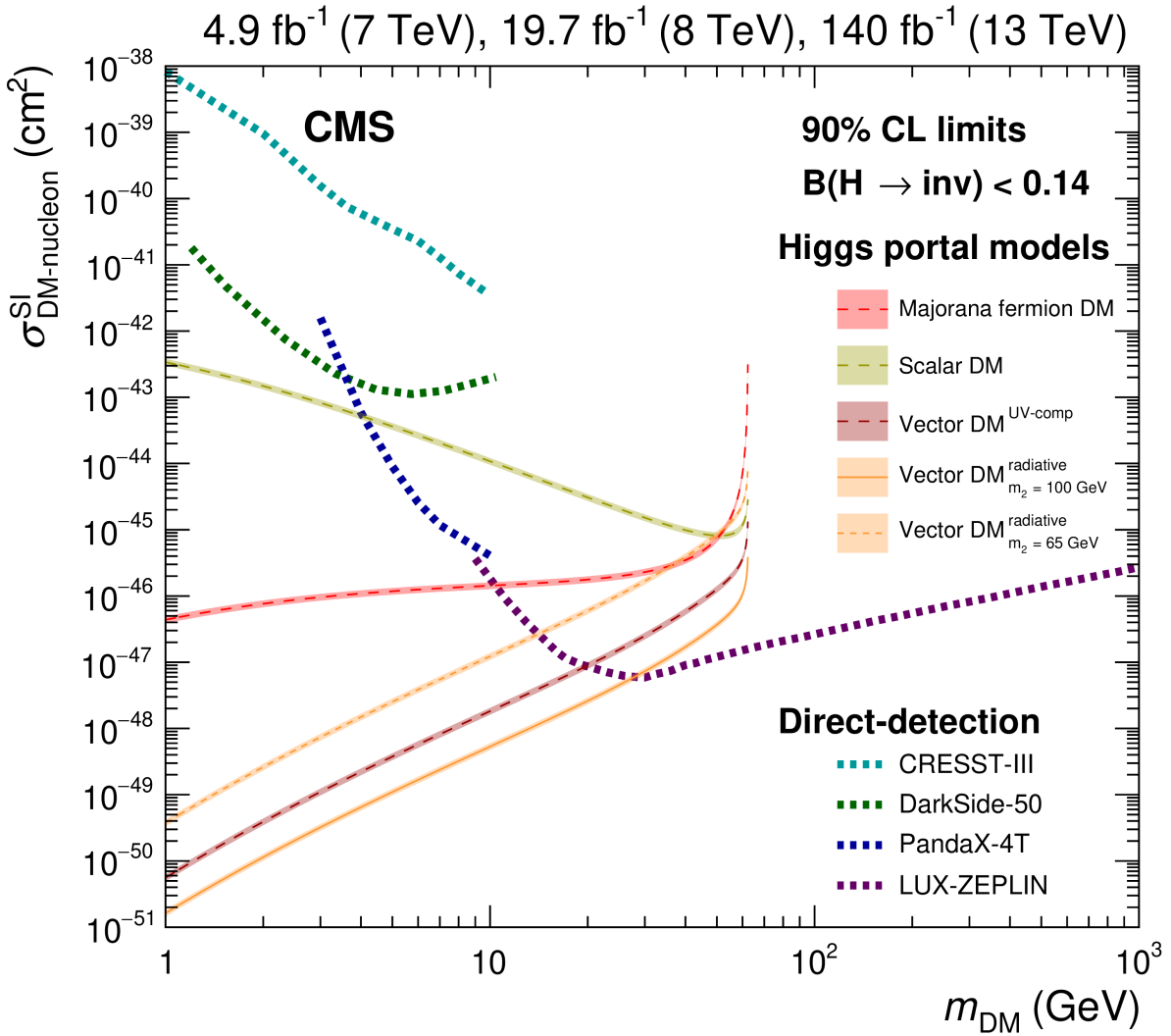
Observed (expected) $BR_{h\to inv} = 0.15\ (0.08)$

Other channels improve VBF-standalone by about 20%

Higgs boson portal vs DD results

EPJC 83 (2023) 933

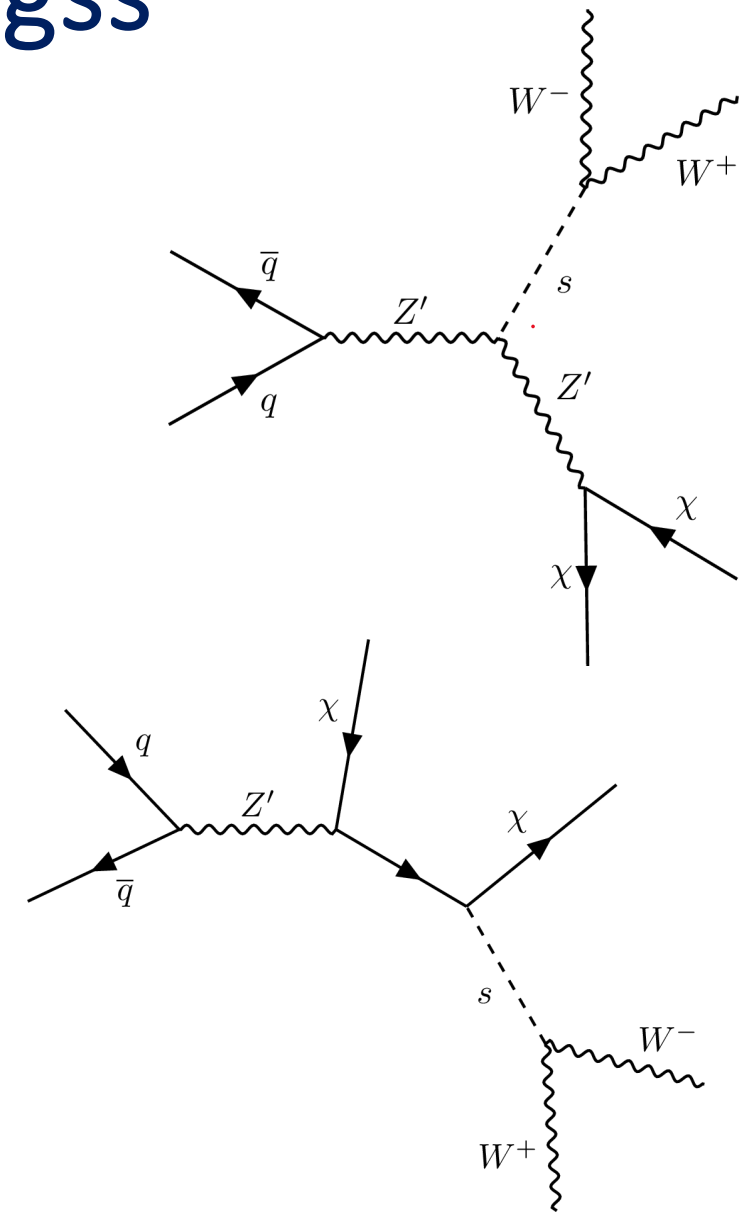
- Results can be interpreted as limit on a set of Higgs portal models of DM interactions:
  - A singlet scalar, fermion or vector DM has a substantial coupling to a SM Higgs boson.
- Upper bounds on SI DM-nucleon scattering are presented using an EFT model or a UV-completed models (LHEP 2022 (2022) 270) for dark-Higgs masses of 65 and 100 and mixing angle of $\theta = 0.2$.
- Have better sensitivities than those of direct searches over the 1–20 GeV range of DM masses.



Extended dark sector: dark Higgs

JHEP 1704(2017)143

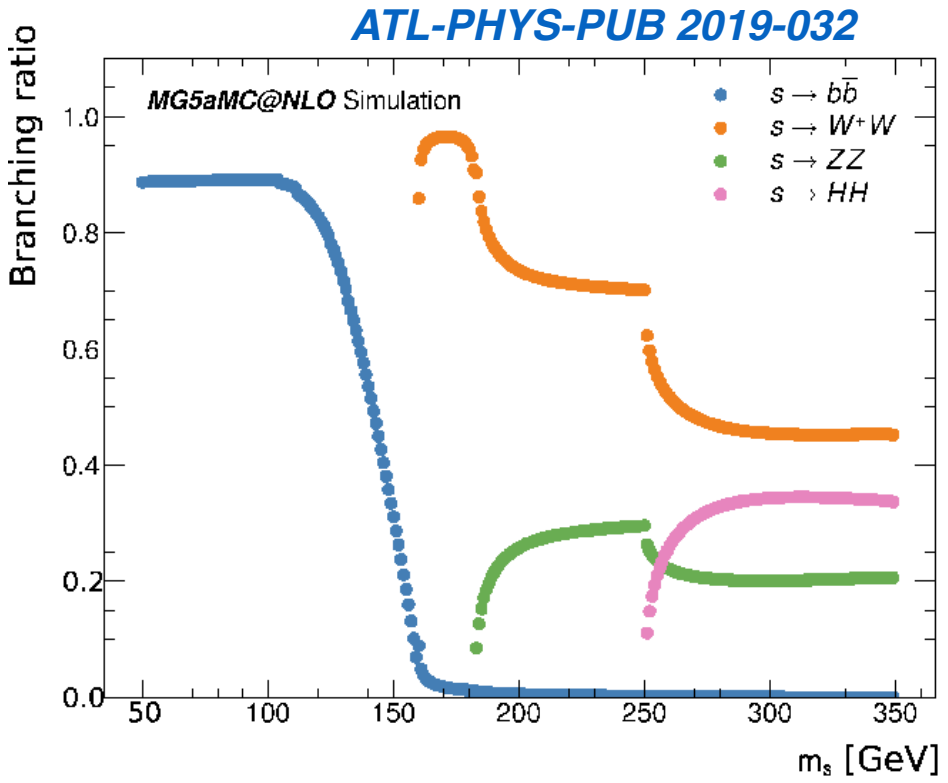
- Search directly for the dark Higgs production.
- Introduce new U(1)‘ symmetry and scalar (dark-Higgs *s*) which breaks the it:
  - Generates mass of the Majorana DM particle (χ), the vector boson Z'
- SM Higgs does not couple to DM.
- The Z‘ acts as a vector mediator between the SM and the dark sector.
- Dark-Higgs mixes minimally with the SM Higgs.



Dark Higgs: $MET + s(WW)$

JHEP 03(2024)134

- Analysis driven by the branching ratio of the dark-Higgs.
- 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:
  - $MET + s(WW), WW \rightarrow 2l\ 2\nu$
  - $MET + s(WW), WW \rightarrow l\nu\ qq`$

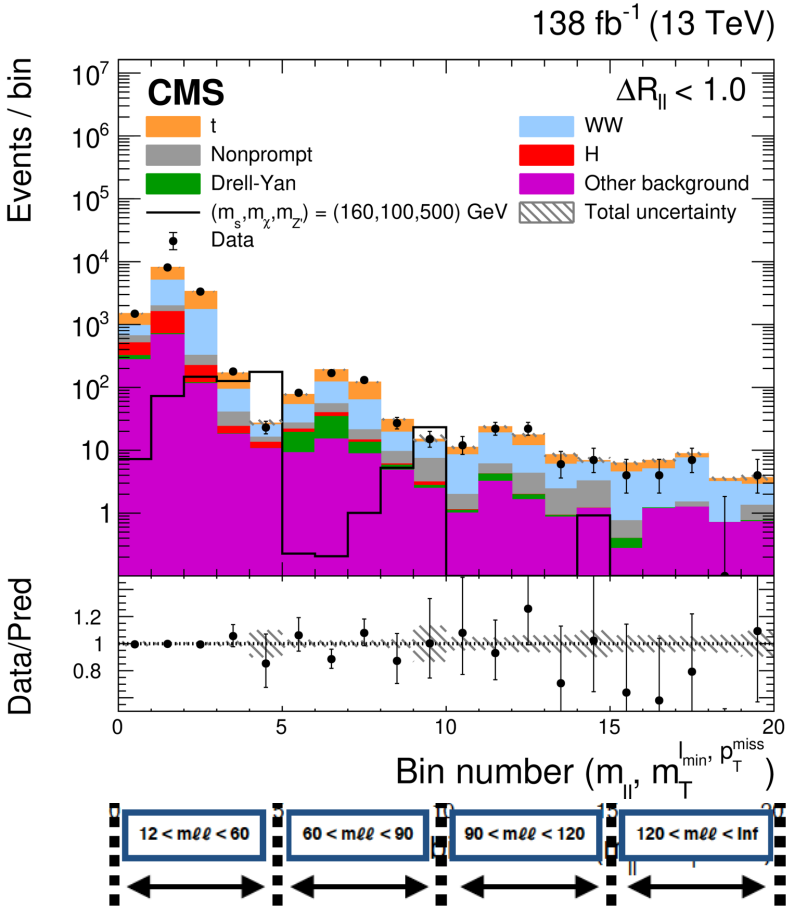


Dark Higgs: $MET + s(WW)$

JHEP 03(2024)134

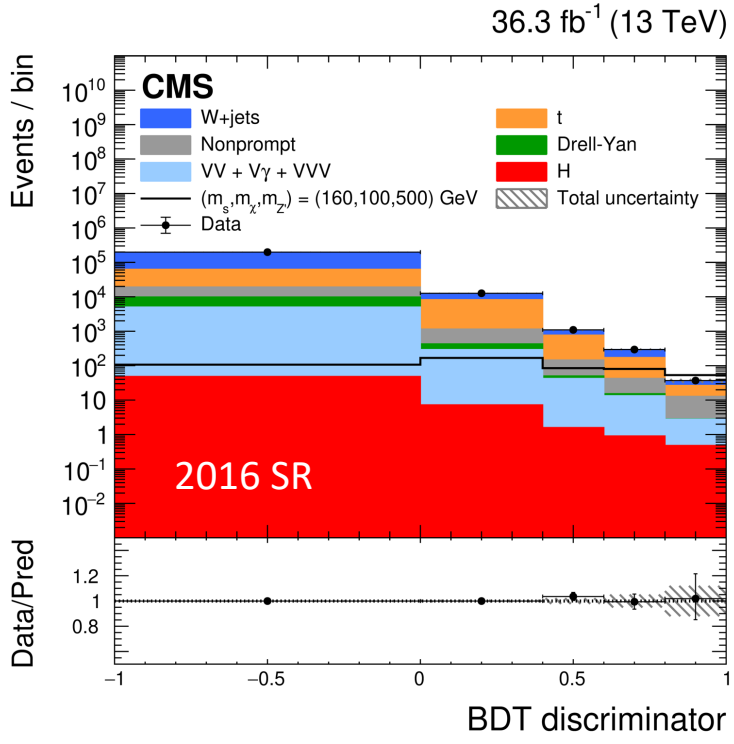
$s \to WW \to 2l2\nu$

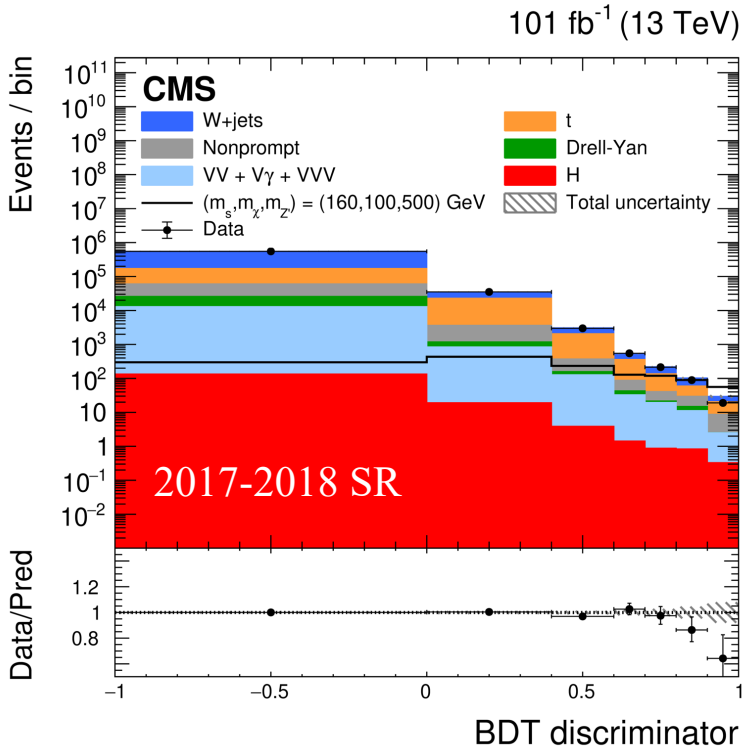
- **3D fit in $\Delta R_{ll} - m_{ll} - m_T(l_2, MET)$**



$s \to WW \to 2lqq'$

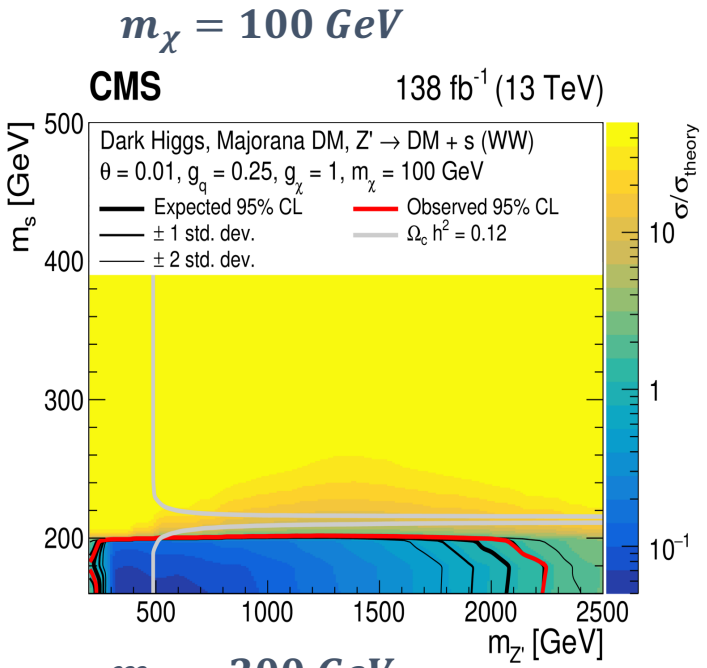
- Using a **BDT Discriminator**

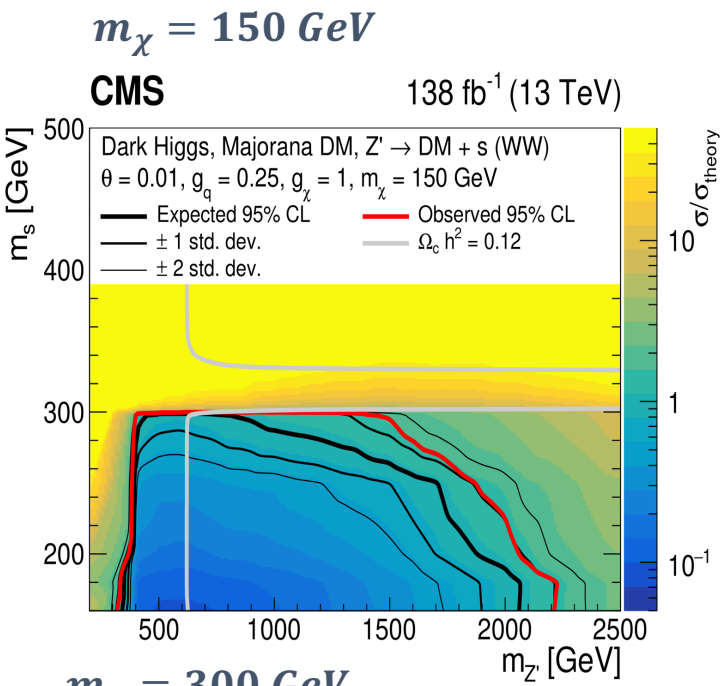


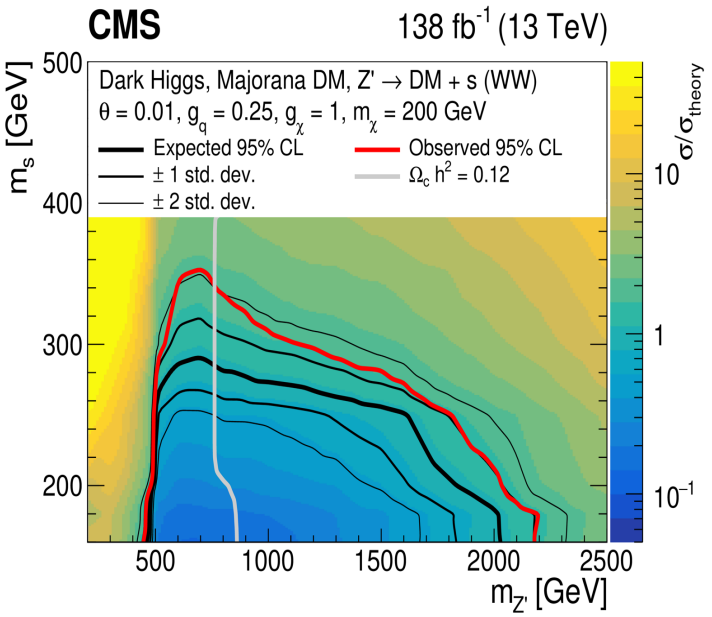


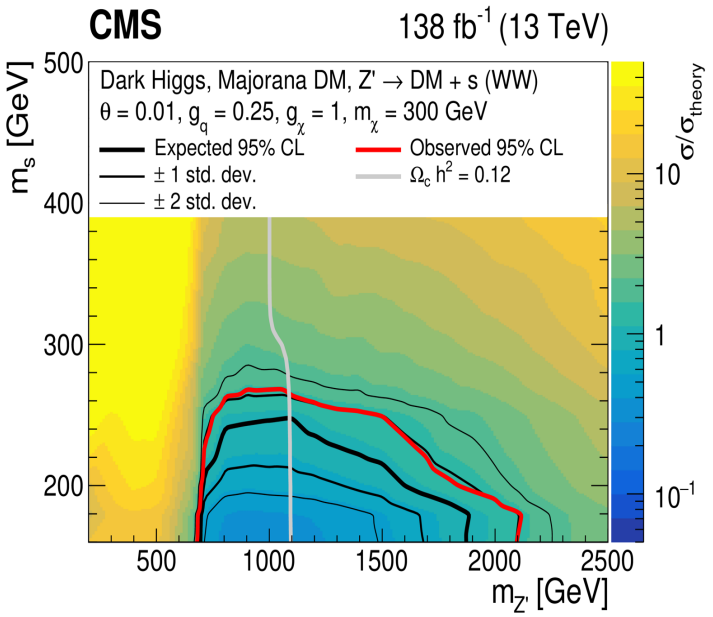
Finer binning in 2017-2018 to squeeze the sensitivity

Dark Higgs: $MET + s(WW)$





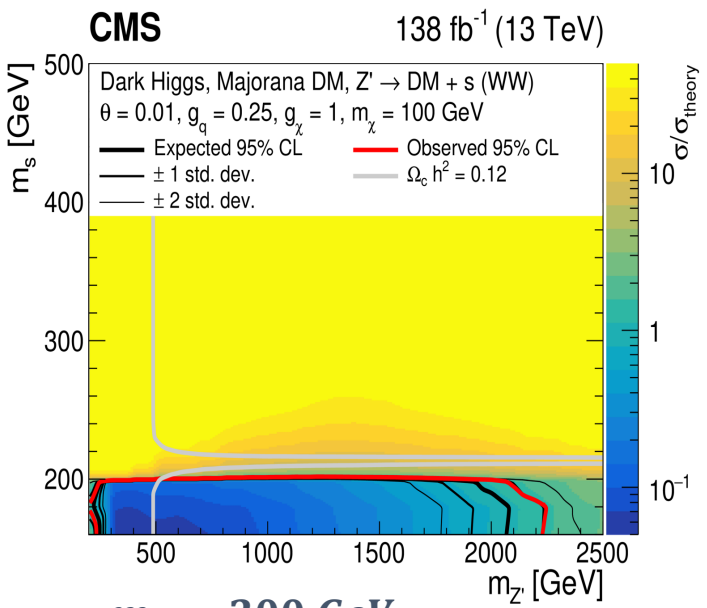




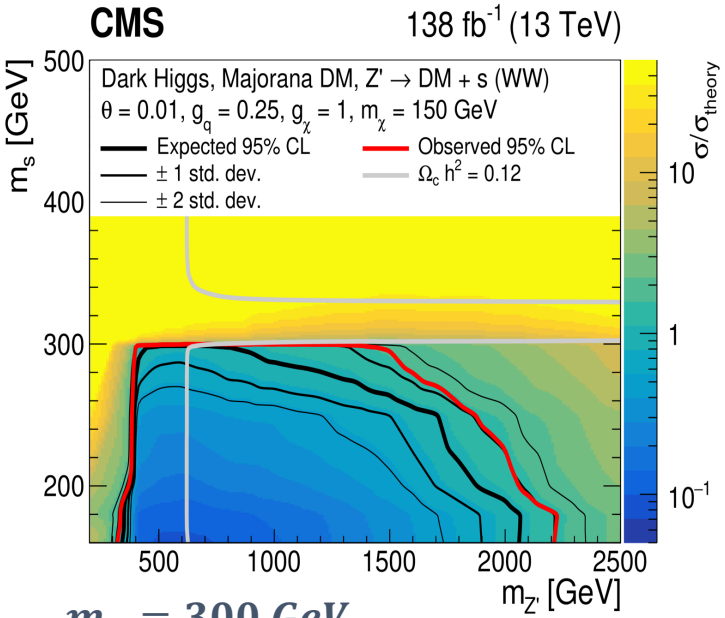
- Observed > Expected (but still below 2 sigma) due to slight data deficit in some of the sensitive bins.
- **$s \to \chi\chi$ bound reached** for $m_s \geq 2m_\chi$
- Gray lines indicate where the model parameters produce exactly the current observed relic density, using MadDM (*Eur.Phys. J. C 83 (2023)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

Dark Higgs: $MET + s(WW)$

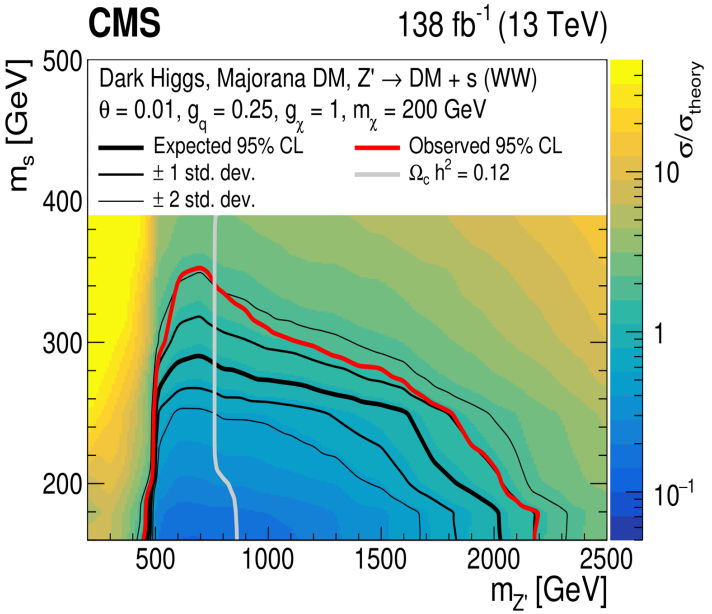
$m_\chi = 100\ GeV$



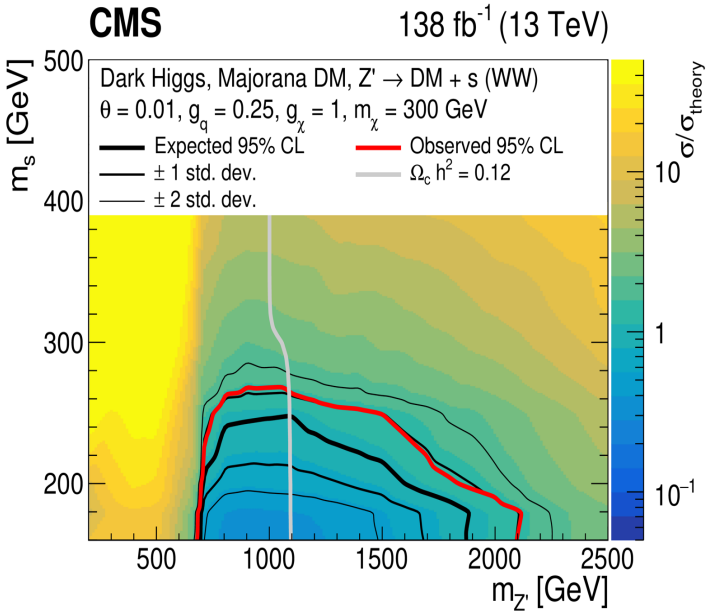
$m_\chi = 150\ GeV$



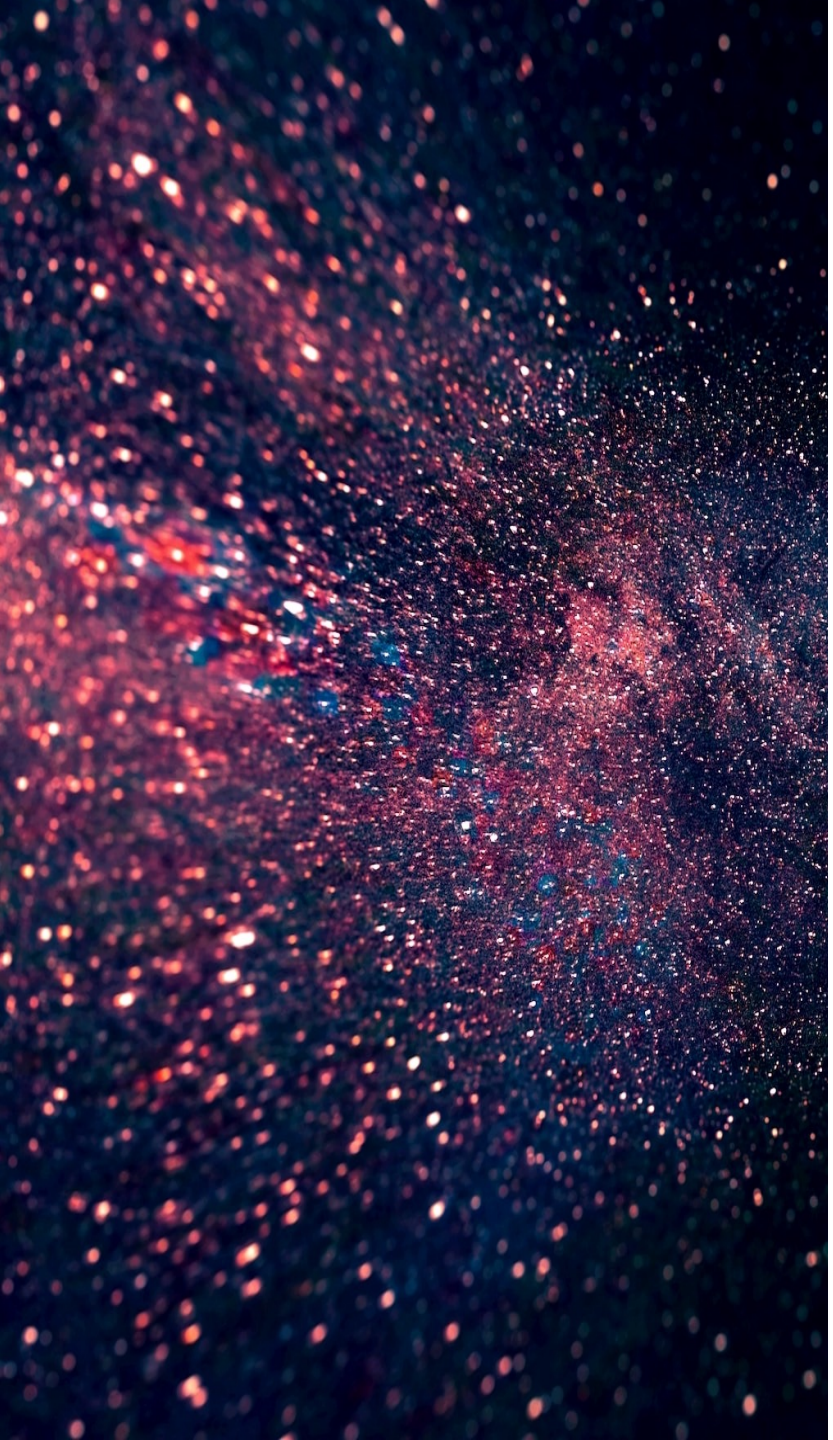
$m_\chi = 200\ GeV$



$m_\chi = 300\ GeV$



- 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

- Some analysis still need to include the full Run2 data, while looking to the Run3 data.
- In most cases we are relying on several assumptions to look for DM at the LHC
- But... at the end we are looking for deviations with respect to the SM Higgs.
  - Connection to SM precision measurements.
- Not covered here but there are also LHC signatures with a Higgs boson decaying to to long-lived particles or Higgs decaying to exotic particles

BacKup

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

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

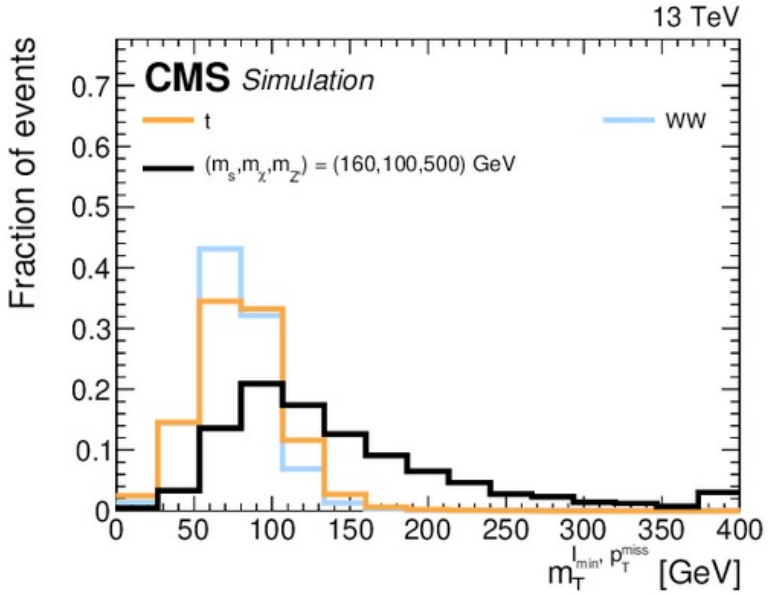
  - 3 SR in ΔR_{ll}(strong dependence with dark Higgs mass)

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

$$m_{\mathrm{T}}^{\ell\,\mathrm{min}, p_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 p_{\mathrm{T}}^{\ell\,\mathrm{min}} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\,\mathrm{min}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]},$$

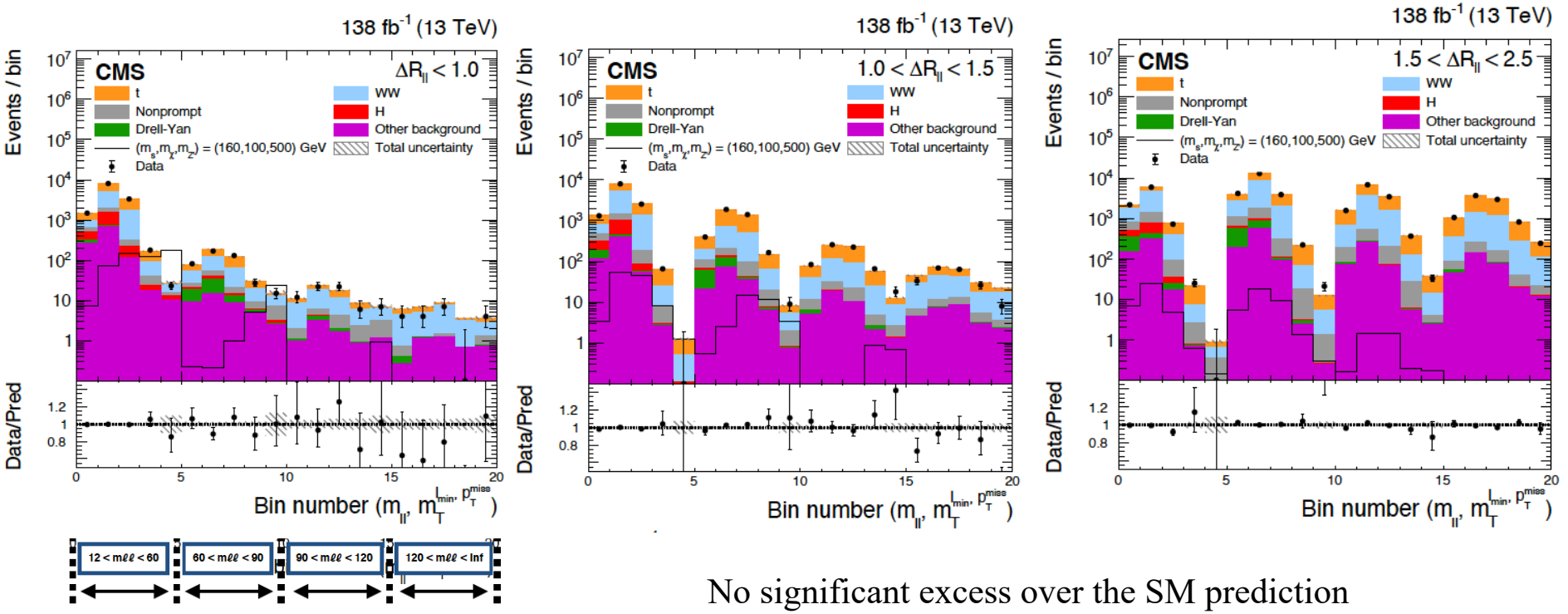
  - For m_{ll} and $m_T(l_2, MET)$ the binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.

  - 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

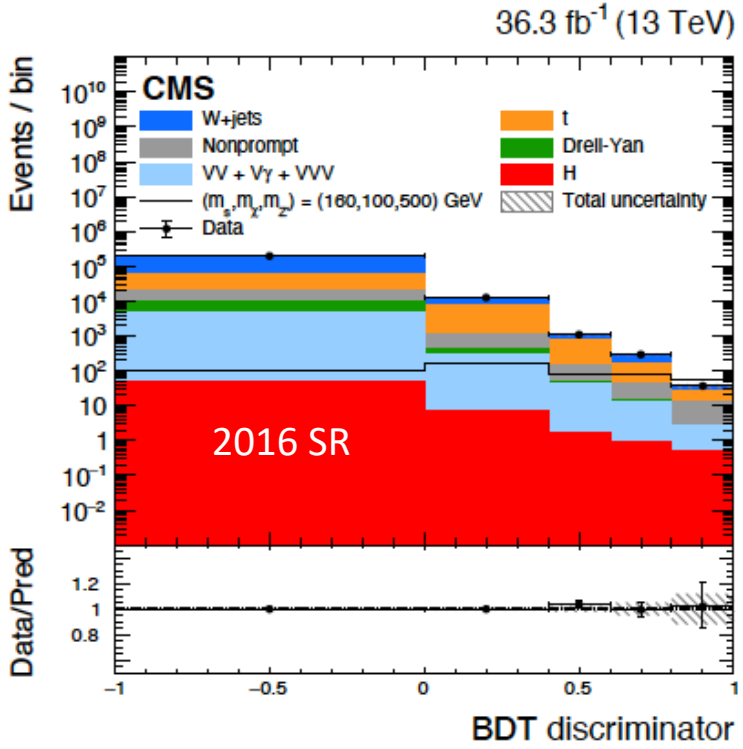
Analysis strategy $s \to WW \to 2lqq'$

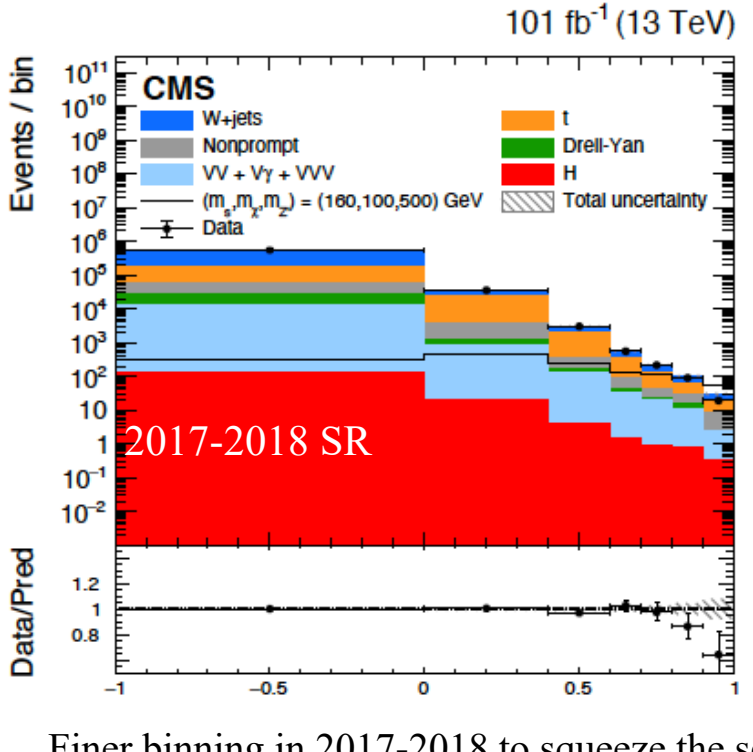
- Using a **BDT Discriminator**
- 11 optimized kinematic inputs:
  - mostly sensitive to MET vs visible particles boost.
- 1 training for entire mass range with $m_{Z'} \geq 800\ GeV$ samples (boosted samples with small x-sec sensitivity)
- Binning is optimized for $\frac{S}{\sqrt{S+B}}$ shape.

Variable	Definition
$p_{\mathrm{T}}^{\mathrm{jj}}$	p_{T} of the vectorial sum of the W candidate jets
$p_{\mathrm{T}}^{\ell\mathrm{jj}}$	p_{T} of the vectorial sum of the visible particles
$p_{\mathrm{T}}^{\mathrm{miss}}$	Magnitude of the missing transverse momentum vector
$\Delta\eta_{\ell,\mathrm{jj}}$ and $\Delta\phi_{\ell,\mathrm{jj}}$	$\Delta\eta$ and $\Delta\phi$ between the lepton and the dijet system
$\Delta\eta_{\mathrm{j,j}}$ and $\Delta\phi_{\mathrm{j,j}}$	$\Delta\eta$ and $\Delta\phi$ between the W candidate jets
$\lvert\eta_{\ell}\rvert$	The absolute value of the lepton pseudorapidity
$\Delta\phi_{\ell,\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$	$\Delta\phi$ between the lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
$\Delta\phi_{\ell\mathrm{jj},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$	$\Delta\phi$ between the vectorial sum of the visible particles and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$
$\min(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_2})/p_{\mathrm{T}}^{\mathrm{miss}}$	Minimum of the lepton p_{T} and the next-to-leading W candidate jet p_{T}, divided by $p_{\mathrm{T}}^{\mathrm{miss}}$
$\max(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_1})/p_{\mathrm{T}}^{\mathrm{miss}}$	Maximum of the lepton p_{T} and the leading W candidate jet p_{T}, divided by $p_{\mathrm{T}}^{\mathrm{miss}}$
$\max(p_{\mathrm{T}}^{\ell}, p_{\mathrm{T}}^{\mathrm{j}_1})/m_{\ell\mathrm{jj}p_{\mathrm{T}}^{\mathrm{miss}}}$	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 $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, which is taken to be massless

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

- 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



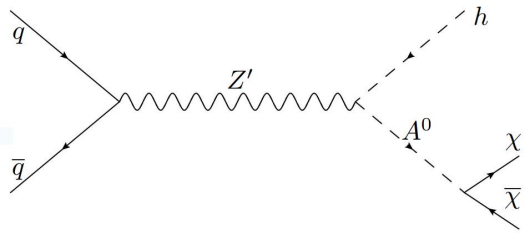


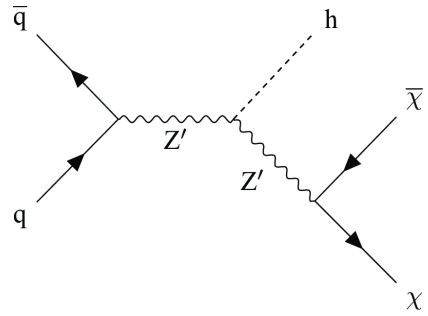
Finer binning in 2017-2018 to squeeze the sensitivity

Mono Higgs ($\rightarrow bb, \gamma\gamma, \tau\tau$, ZZ,WW) + MET

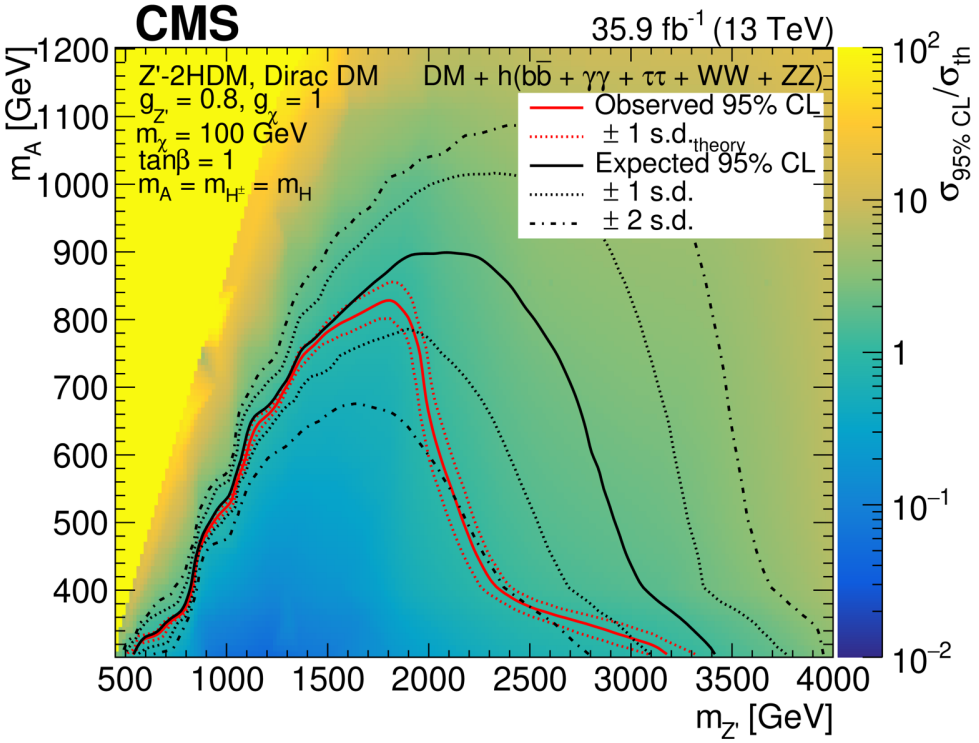
JHEP03(2020)025

Combined Results

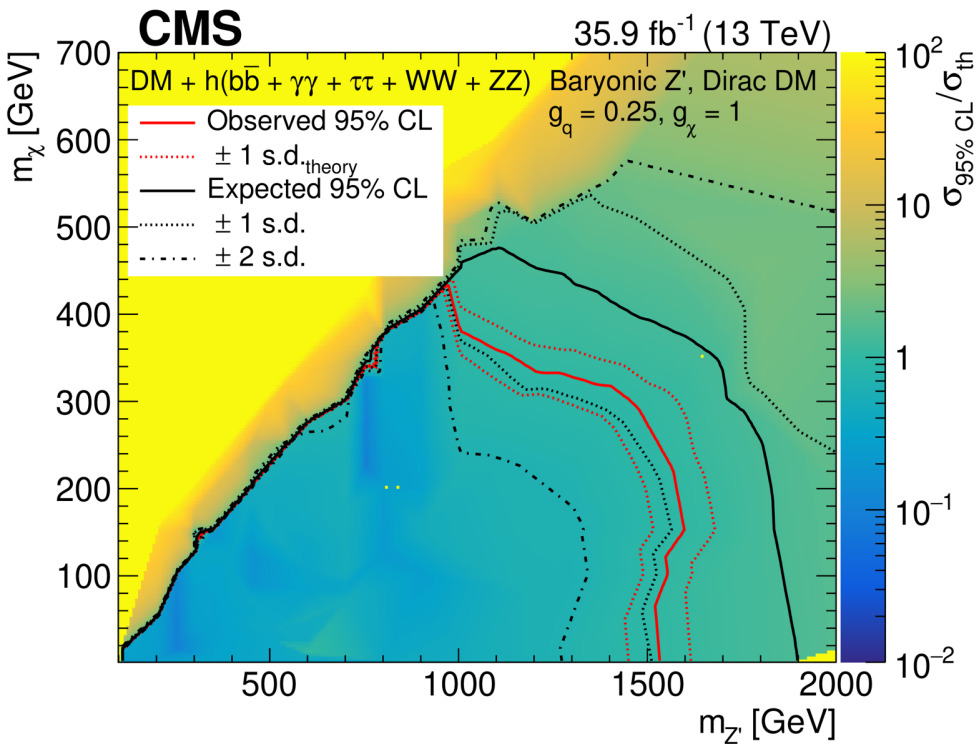




Interpretation: Z'-2HDM



Interpretation: Z'-Baryonic

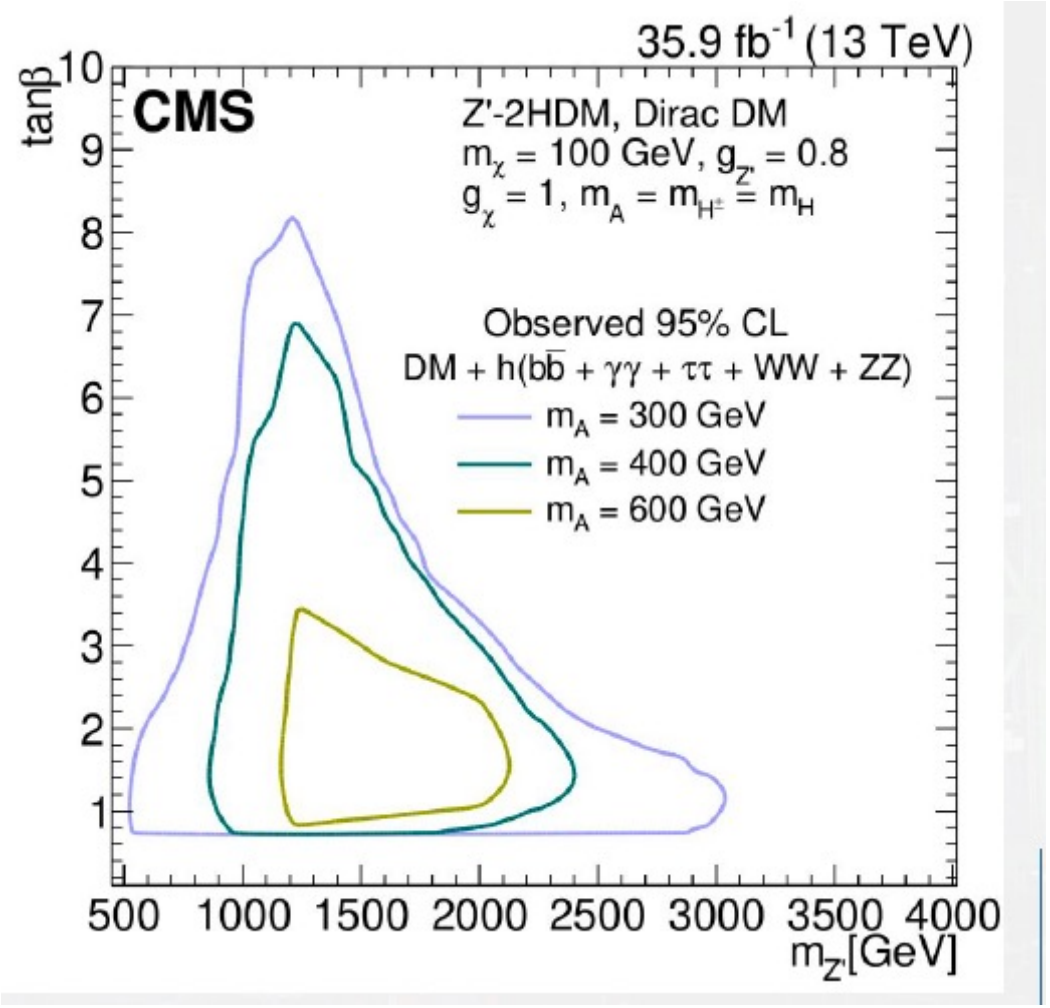


Mono Higgs ($\rightarrow b\bar{b}, \gamma\gamma, WW, ZZ$ and $\tau\tau$) + MET

JHEP03 (2020) 025

Interpretation: Z'-2HDM

- Exclusion region: $\tan\beta$ in the range 0.5 - 10 $m_{Z`}$ up to 500-3200 GeV.



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.

Higgs boson portal

- **Direct searches + indirect constraints**: most recent result from CMS has a best fit $\mathcal{B}(H \to inv.) \sim 7\% \pm 5\%$ (compatible with 0)