Experimental introduction to extended Higgs models: a CMS perspective

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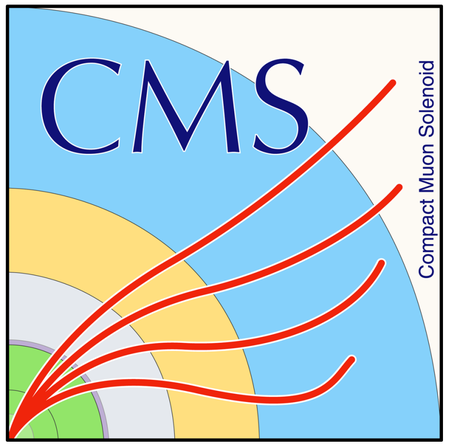
LHC Dark Matter Working Group Workshop:

Roadmap of Dark Matter models for Run 3

Geneva, 15.05.2024

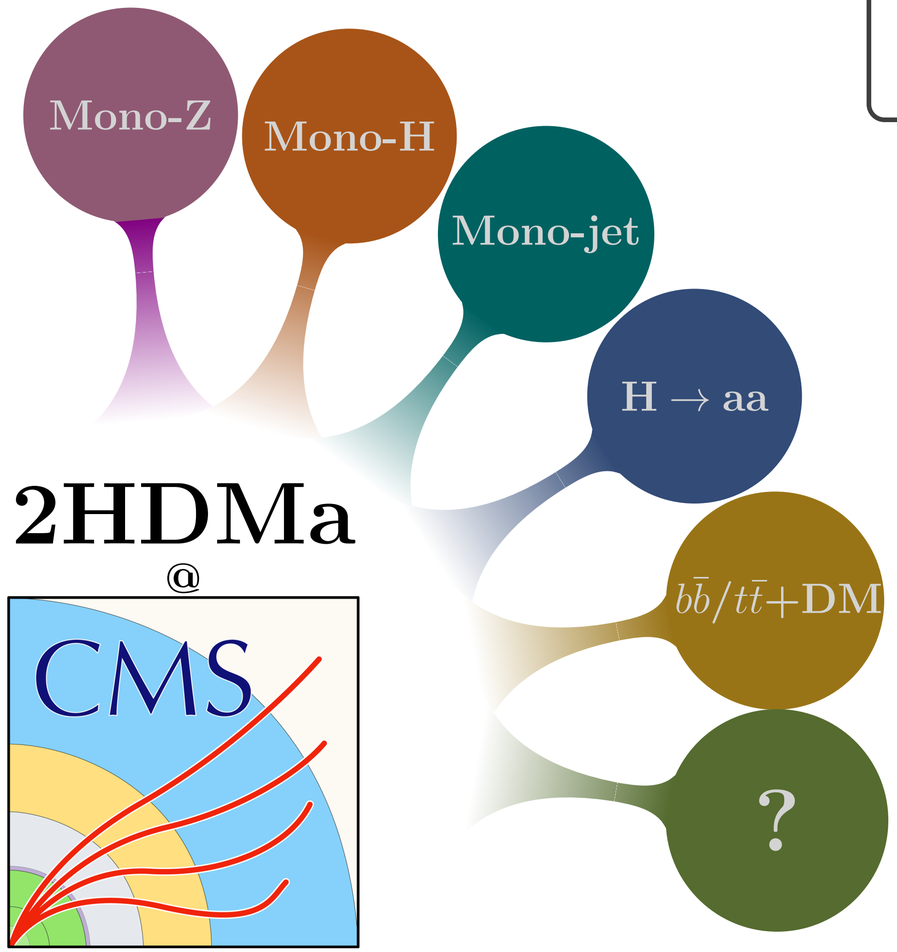
RWTH AACHEN UNIVERSITY



Introduction

JHEP 05 (2017) 138 | Phys.Dark Univ. 27 (2020) 100351

$$\mathcal{V}_{2HDM+a}(H_1, H_2, P, \chi) = \mathcal{V}_{2HDM}(H_1, H_2) + \frac{1}{2}m_P^2 P^2 + P(ib_P H_1^\dagger H_2 + \text{h.c.}) + P^2(\lambda_{P_1} H_1^\dagger H_1 + \lambda_{P_2} H_2^\dagger H_2) + iy_\chi P \bar{\chi}\gamma_5\chi$$



An ultraviolet completion for DM

- Simple gauge-invariant & renormalisable model with *pseudoscalar* mediator

A pseudoscalar mediator and an isosinglet fermion

- Avoids constraints from direct detection while at the same time correctly predicting the relic density through DM annihilation into SM fermions via s-channel

Resonant enhancement of typical Mono-X processes

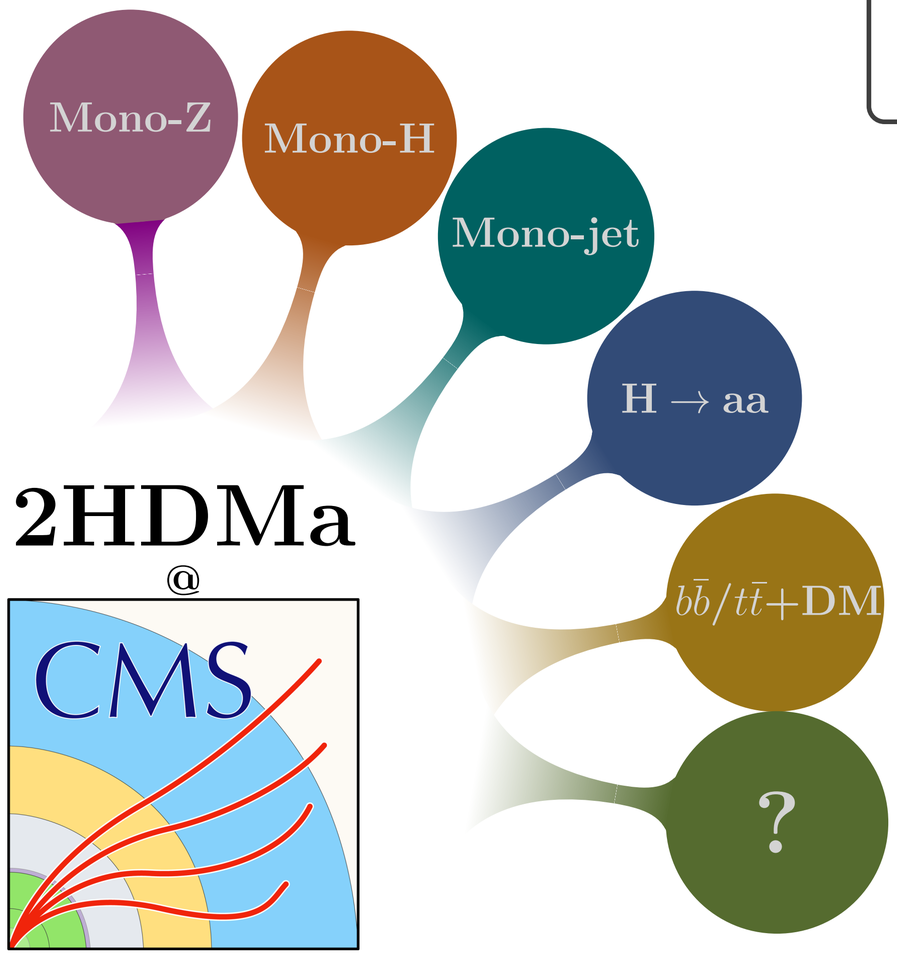
- $H \to Za$ & $A \to ha$ decays *boost* the cross-section of Mono-Z and Mono-Higgs

Rich dynamics that motivate novel search channels

- Different parameter configurations and the presence of $H^\pm$ can lead channels such as b-quark or tW associated production of DM to become quite relevant

Introduction

$$\mathcal{V}_{2HDM+a}(H_1, H_2, P, \chi) = \mathcal{V}_{2HDM}(H_1, H_2) + \frac{1}{2}m_P^2 P^2 + P(ib_P H_1^\dagger H_2 + \text{h.c.}) + P^2(\lambda_{P_1} H_1^\dagger H_1 + \lambda_{P_2} H_2^\dagger H_2) + iy_\chi P \bar{\chi}\gamma_5\chi$$



- Presenting ***five**** groups of searches performed at CMS connected to 2HDMa

- In the following, when not specified, the 2HDMa configurations below are implicit
  - ➡ Assuming a Type II Yukawa assignment
  - ➡ Benchmark parameter choices as indicated in arXiv:1810.09420

$$m_H = m_A = m_{H^\pm} \qquad m_\chi = 10\,GeV$$

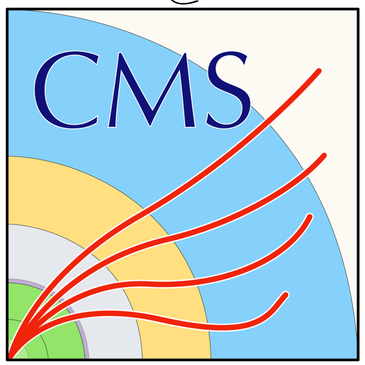
$$\cos(\beta - \alpha) = 0 \qquad y_\chi = 1$$

$$\lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3$$

*Plus a bonus study linked to CMS

Experimental searches

2HDMa
@



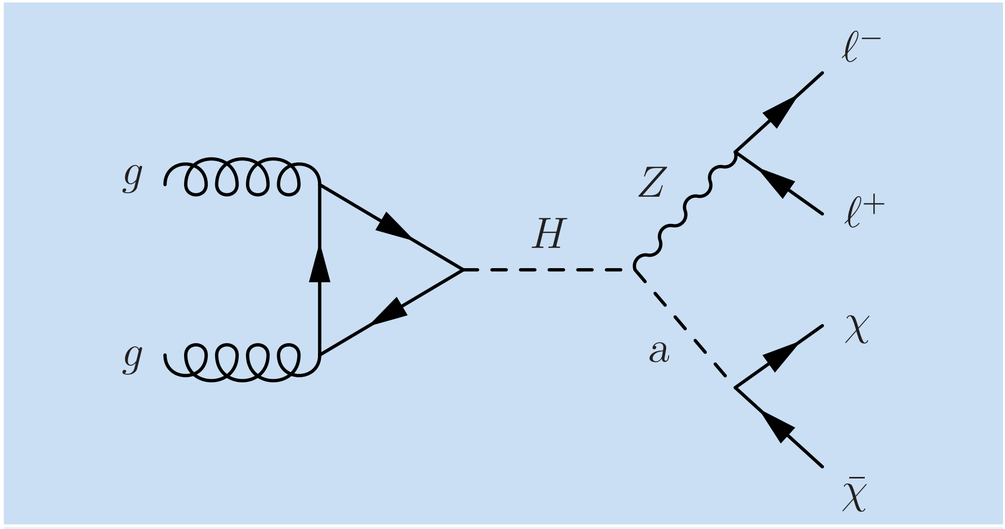
Mono-Z search

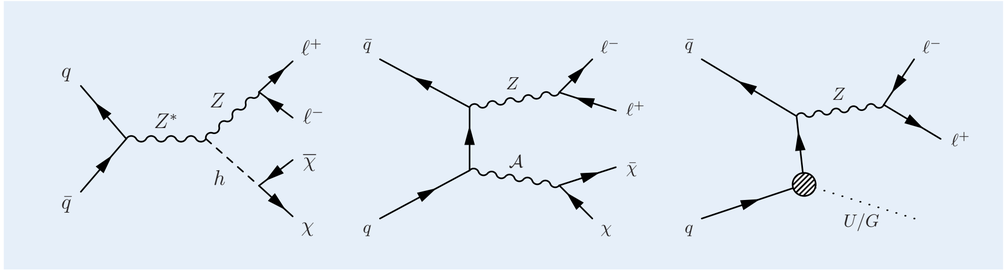
Eur. Phys. J. C 81 (2021) 13

Events with a $Z(\rightarrow l^+l^-)$ boson recoiling against DM or other BSM invisible particles

- **Experimental signature:** Z boson candidate reconstructed form di-leptonic (e^+e^- and $\mu^+\mu^-$) decays and large missing transverse momentum
- **Analyzed data:** pp collisions collected in 2016-2018 (full Run 2): 137 fb^{-1}
- **Selection:**

Quantity	Requirement	Target backgrounds
N_ℓ	=2 with additional lepton veto	WZ, VVV
p_{T}^{ℓ}	>25/20 GeV for leading/subleading	Multijet
Dilepton mass	$\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert < 15$ GeV	WW, top quark
Number of jets	≤1 jet with $p_{\mathrm{T}}^{\mathrm{j}} > 30$ GeV	DY, top quark, VVV
$p_{\mathrm{T}}^{\ell\ell}$	>60 GeV	DY
b tagging veto	0 b-tagged jet with $p_{\mathrm{T}} > 30$ GeV	Top quark, VVV
τ lepton veto	0 τ_{h} cand. with $p_{\mathrm{T}}^{\tau} > 18$ GeV	WZ
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{j}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	>0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	>2.6 radians	DY
$\lvert p_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell\ell}\rvert / p_{\mathrm{T}}^{\ell\ell}$	<0.4	DY
$\Delta R_{\ell\ell}$	<1.8	WW, top quark
$p_{\mathrm{T}}^{\mathrm{miss}}$ (all but 2HDM+a)	>100 GeV	DY, WW, top quark
$p_{\mathrm{T}}^{\mathrm{miss}}$ (2HDM+a only)	>80 GeV	DY, WW, top quark
m_{T} (2HDM+a only)	>200 GeV	DY, WW, ZZ, top quark





$$m_T = \sqrt{2p_{\mathrm{T}}^{ll}p_{\mathrm{T}}^{miss}[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{ll}, \vec{p}_{\mathrm{T}}^{miss})]}$$

Used for *S-**vs**-B* discrimination preferably over p_T^{miss} because of *resonant* origin of $Z(\rightarrow l^+l^-)$ and p_T^{miss} in the 2HDMa

Mono-Z search

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

✦ **Background estimation:** main background normalizations estimated from control regions (***2*** *more relevant below*, **4** in total)

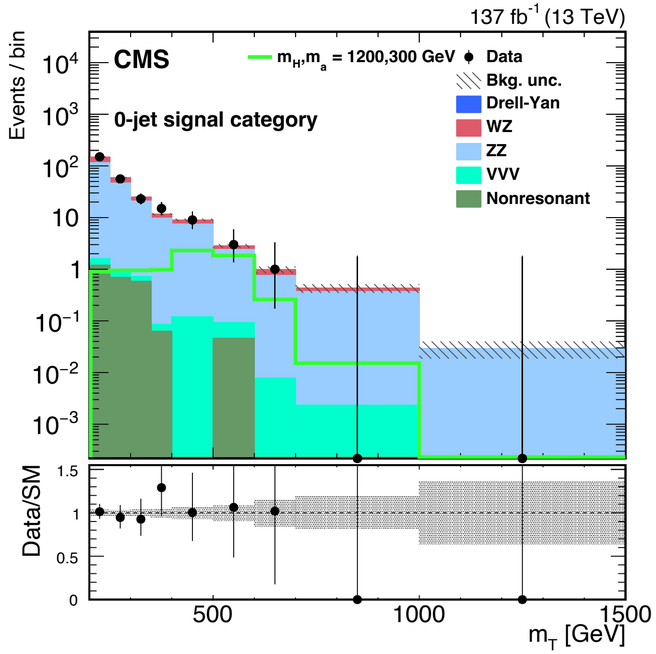
❖ $WZ \to l'\nu ll$

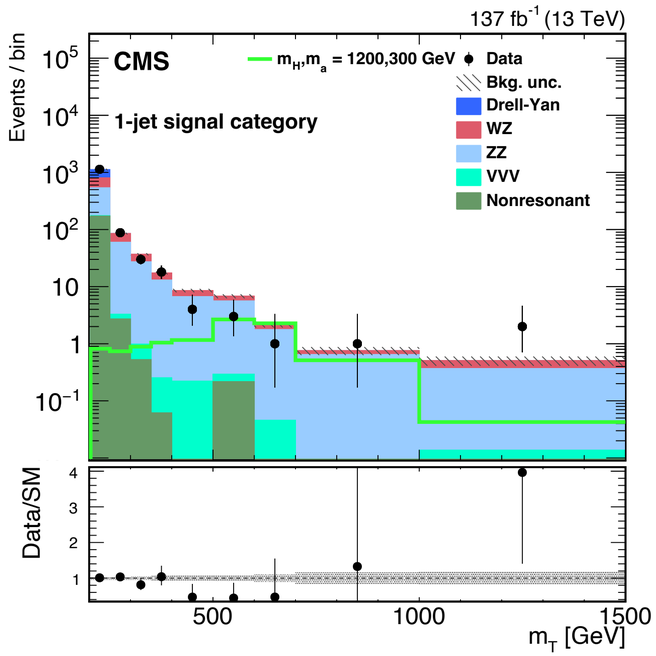
- l' escapes detection
- Controlled in a $3l$ sample

❖ $ZZ \to ll\nu\nu$

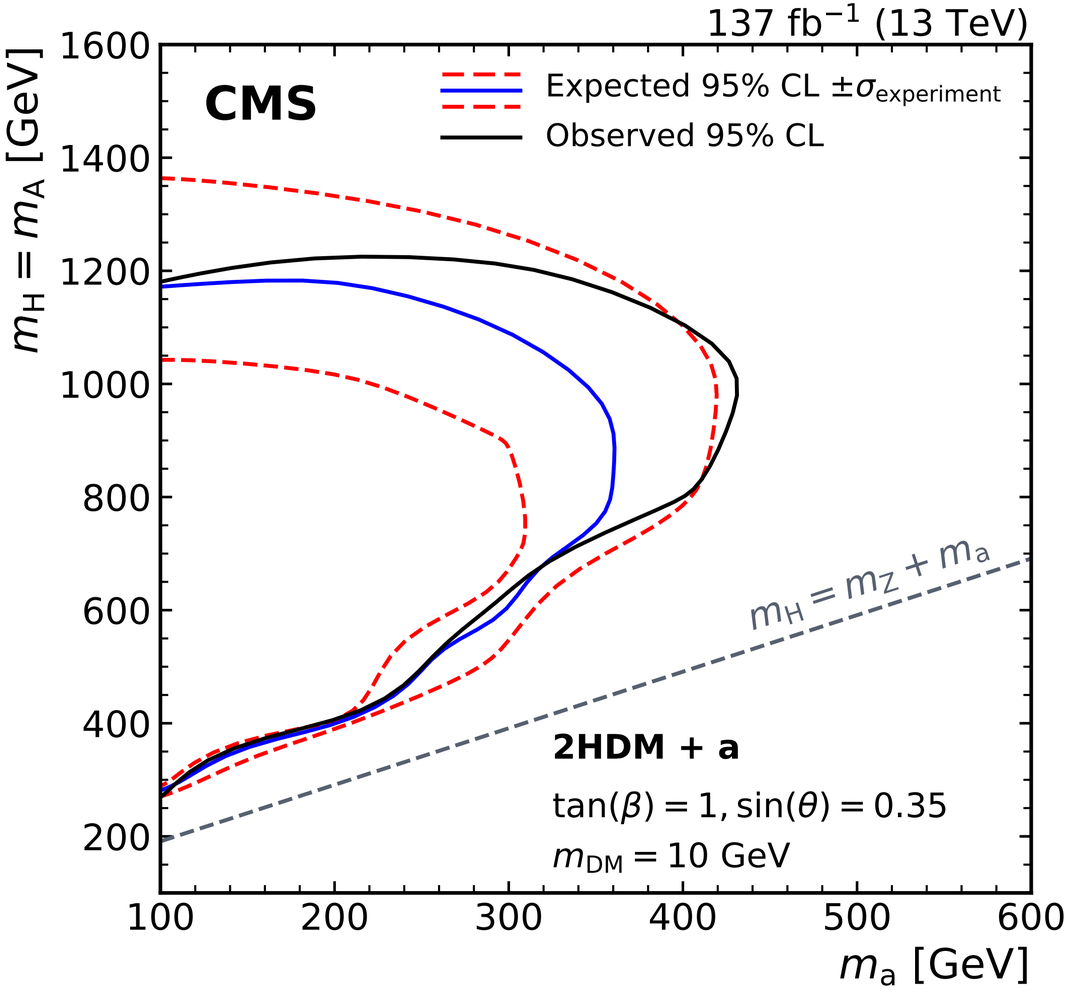
- Irreducible background
- Modelled via a $4l$ sample

✦ **Signal regions:**

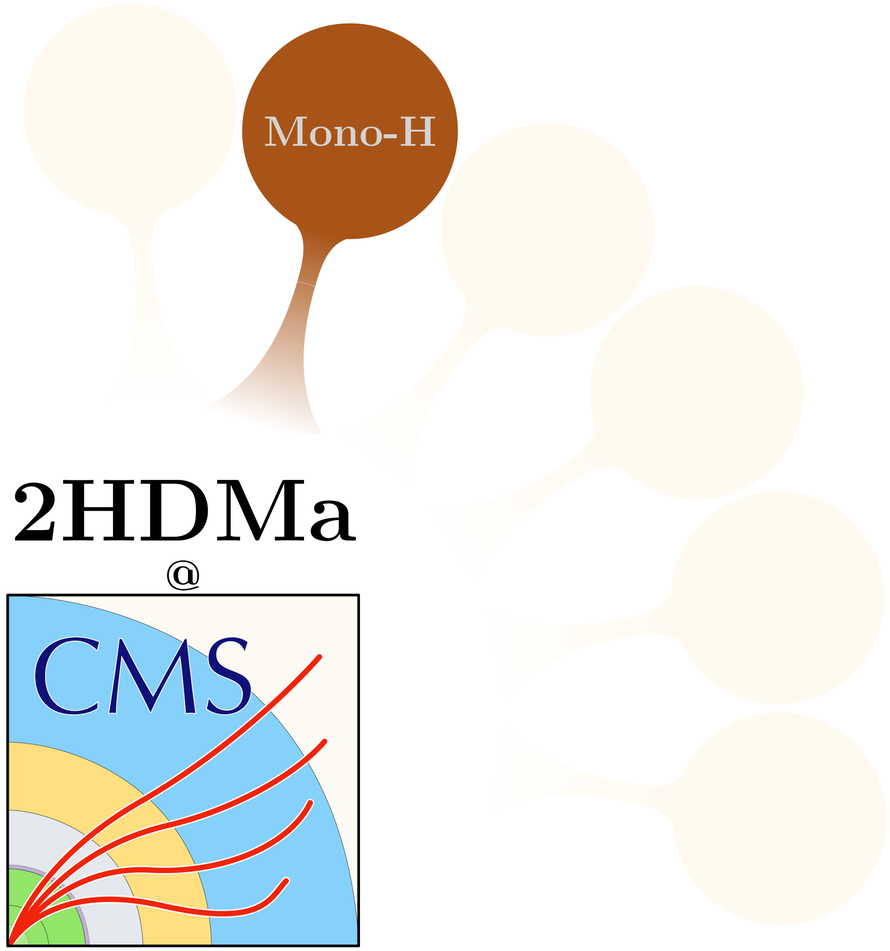




Exclusions: 2D m_a vs m_A plane



Experimental searches

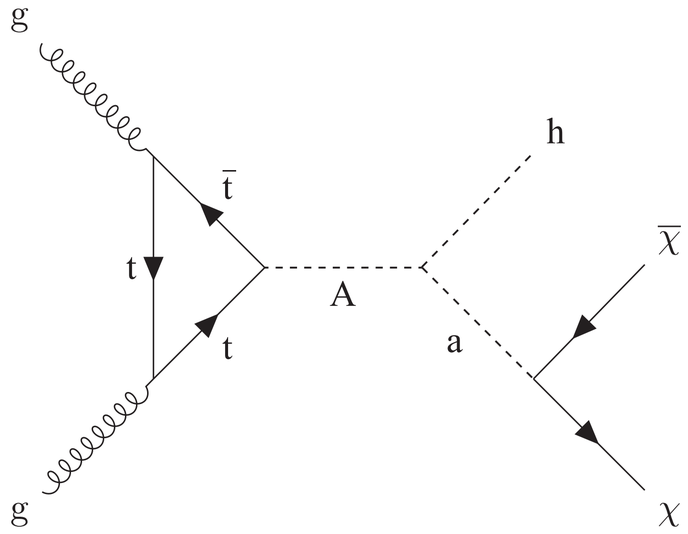


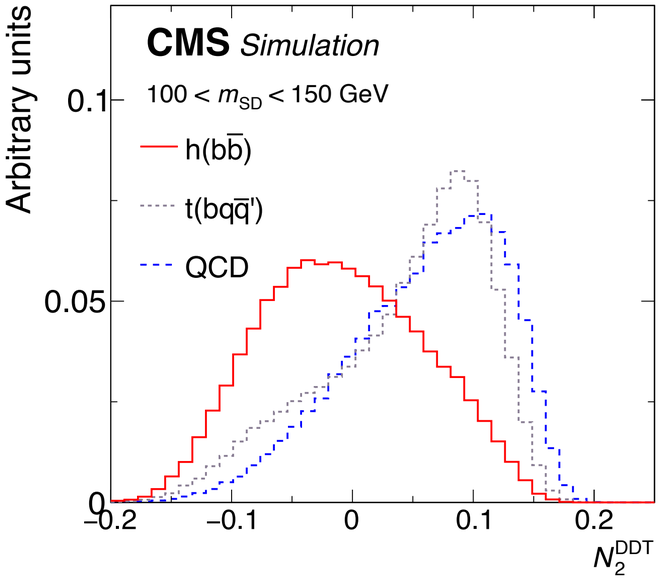
Mono-Higgs search

Eur. Phys. J. C 79 (2019) 280

Search for a single Higgs boson decaying into a $b\bar{b}$ pair produced in association with DM

- **Experimental signature:** Higgs boson candidate reconstructed from *fat-jet* with *double* b-tagging applied and presence of large missing transverse momentum
- **Analyzed data:** pp collisions collected in 2016: 35.9 fb^{-1}
- **Selection:**
  - Exactly one *fat-jet* (Cambridge-Aachen algorithm with $\Delta R = 1.5$)
    - $p_T > 200GeV$ & $|\eta| < 2.4$
    - $100GeV < m_{SD} < 150GeV$ (SD: ***soft-drop*** jet grooming algorithm)
    - $N_2^{\mathrm{DDT}} < 0$: ***2***-prong ***designing decorrelated tagger*** (DDT)
  - $p_T^{\mathrm{miss}} > 200GeV$ & $\min\{\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jets}})\} > 0.4$
  - No additional AK4 jets (anti-k_t, $\Delta R = 0.4$) outside the fat-jet
  - Multivariate identification of two b-quarks inside fat-jet: *double b-tagger*



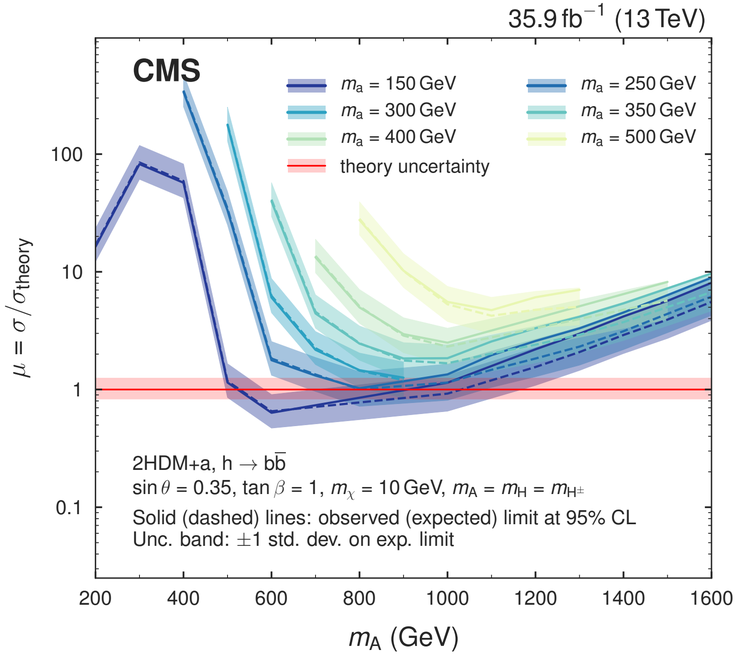


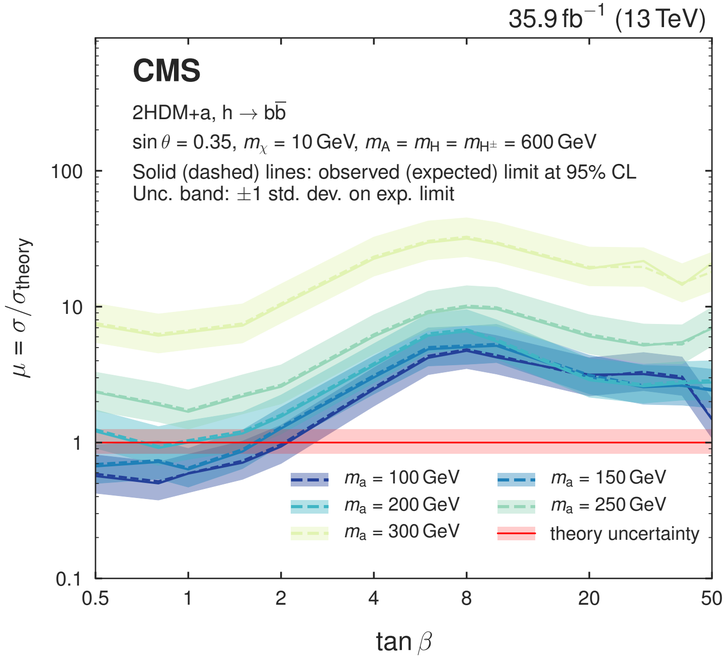
Mono-Higgs search

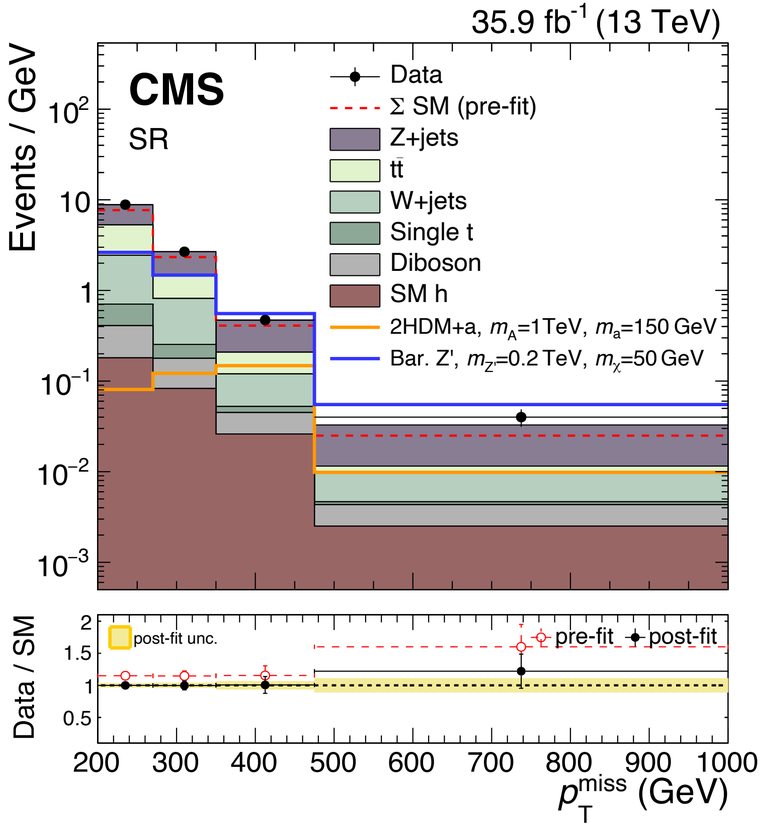
Eur. Phys. J. C 79 (2019) 280

- **Discriminant variable:** p_T^{miss}
- **Background estimation:** p_T^{miss} spectrum of dominant processes predicted by designing subsidiary measurements in control regions

Region	Main background process	Additional AK4 b tag	Leptons	Double-b tag
Signal	Z+jets, $t\bar{t}$, W+jets	0	0	pass
Single-lepton	W+jets, $t\bar{t}$	0	1	pass/fail
Single-lepton, b-tagged	$t\bar{t}$, W+jets	1	1	pass/fail
Dilepton	Z+jets	0	2	pass/fail



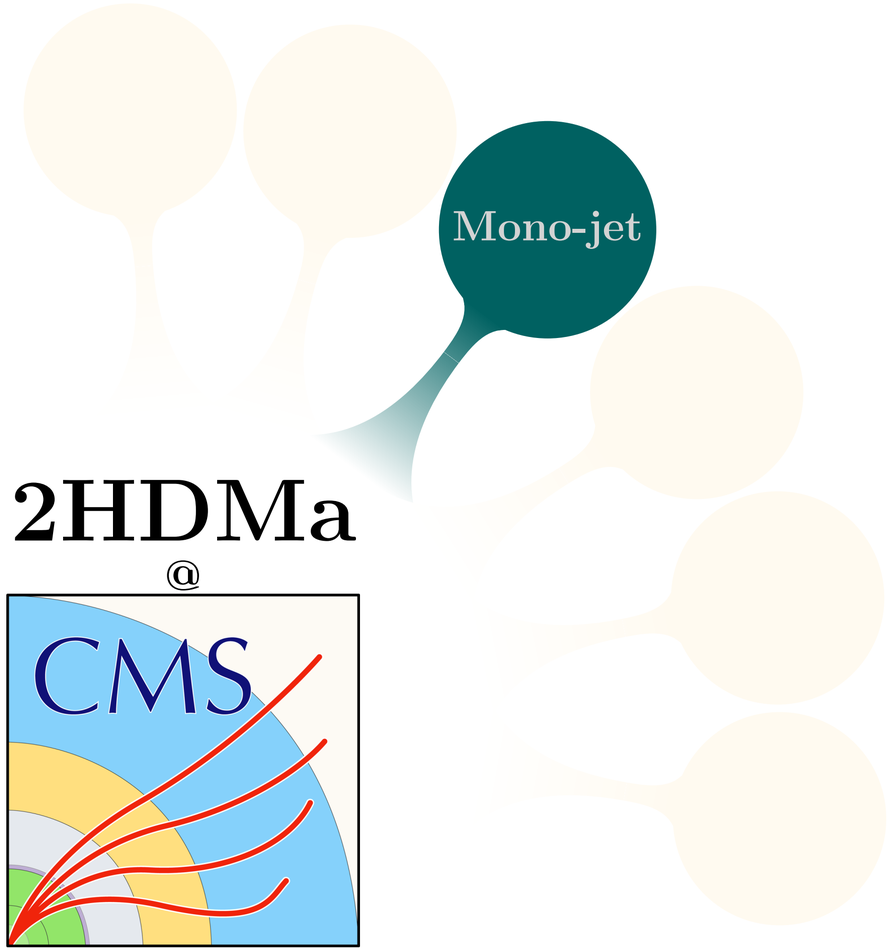




2HDMa exclusions

- 1D m_A profile
- 1D $\tan\beta$ profile

Experimental searches



Mono-jet search

JHEP 11 (2021) 153

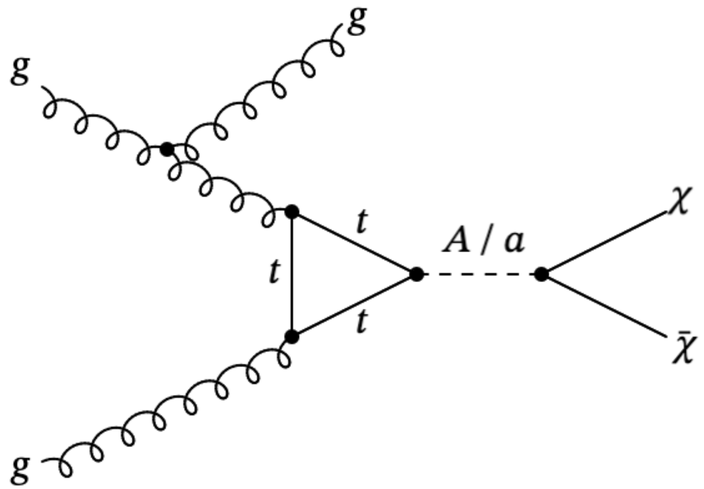
Events with a jet recoiling against invisible particles
*** analysis did not particularly targeted 2HDM, but signature fairly model independent to be sensitive**

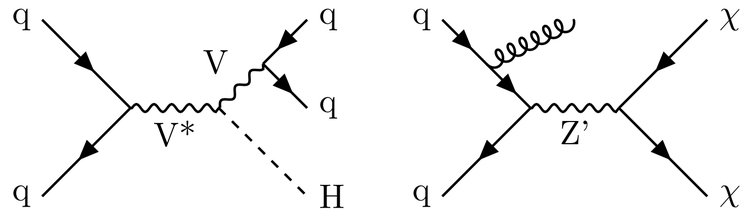
✦ **Experimental signature:** Comprises one or more energetic jets (including *fat-jets*) and large missing transverse momentum

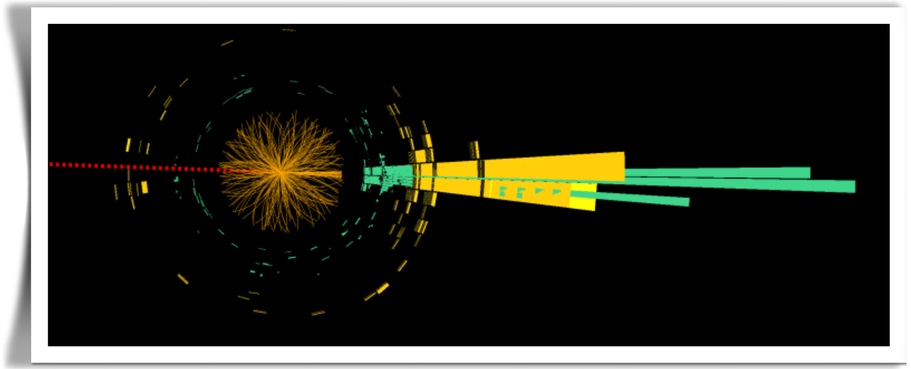
✦ **Analyzed data:** pp collisions collected in 2016-2018 (full Run 2): 137 fb^{-1}

✦ **Selection:**

- Two two types of jets employed: **AK4** and **AK8**
  - AK4: devised for signatures where the jet originates mostly from ISR (e.g. 2HDMa)
  - AK8: dedicated to 'mono-V' signatures where the two jets collimate and form a *fat-jet*
- $p_T^{\text{miss}} > 250GeV \;\&\; \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jets}}) > 0.5$
- Events with μ, e, τ, γ, or b-tagged AK4 jets are vetoed
- Categorization based on type of jet utilized in event selection
  - ➡ **Mono-V**: $p_T^{\text{AK8}} > 250GeV\ ,\ |\eta| < 2.4\ ,\ 65GeV < m_{\text{SD}} < 120GeV$
    - Sub-categorization (*low-* and *high-purity*) based on AK8 V-tagging
  - ➡ **Mono-jet**: $p_T^{\text{AK4}} > 100GeV \;\&\; |\eta| < 2.4$







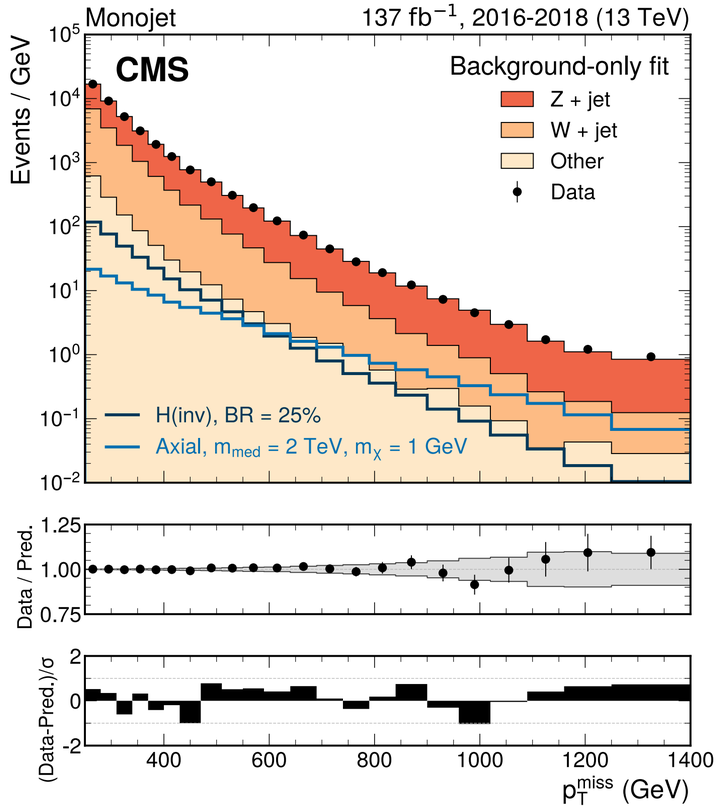
Mono-jet search

JHEP 11 (2021) 153 | **CMS DM Summary Plots**

- **Background estimation:** p_T^{miss} distribution (*recoil*: proxy of p_T^V) modeled in control regions constructed for dominant backgrounds

❖ $Z(\rightarrow \nu\nu)$ + jets
- Comparable to signal
- Estimated in a $2l$ (Z-window) region

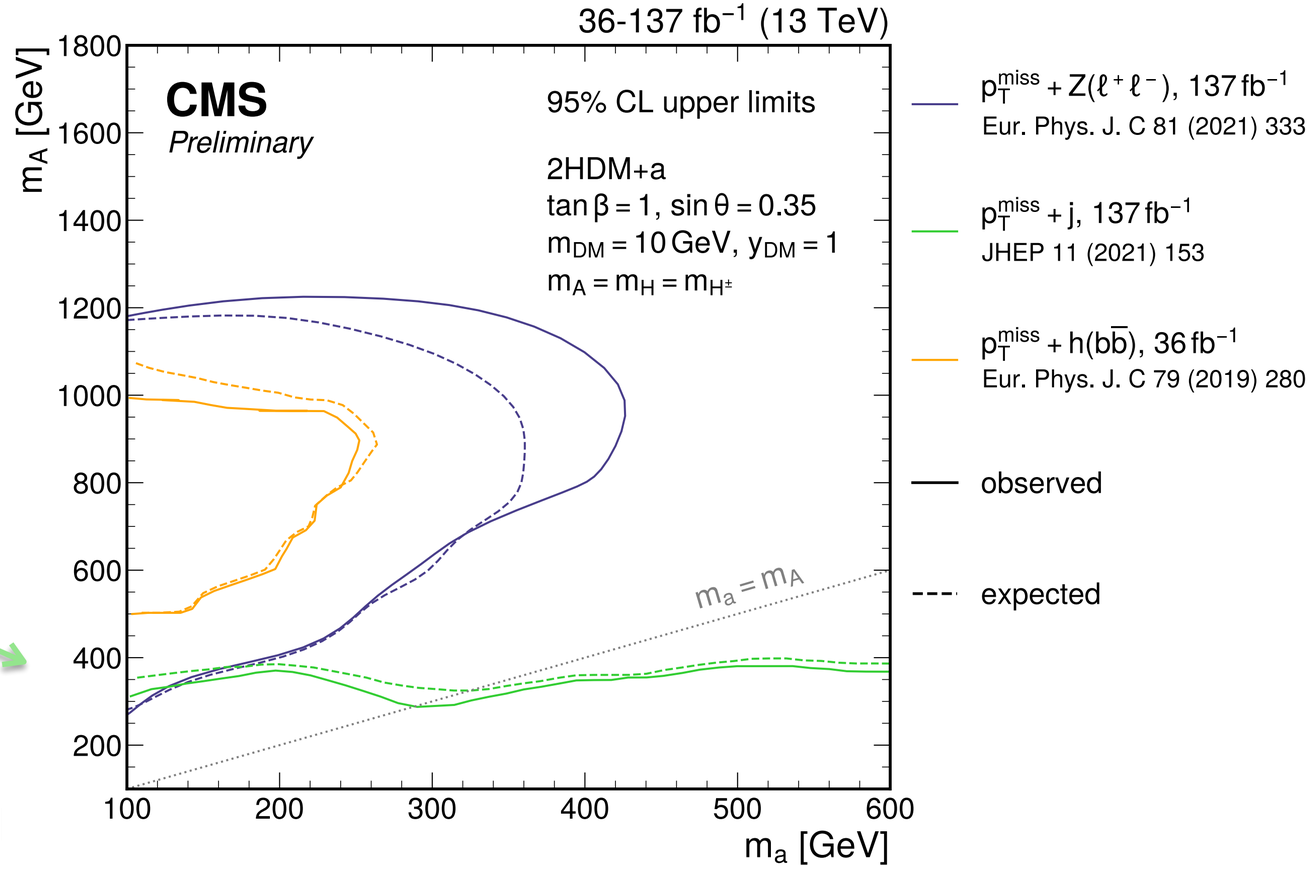
❖ $W(\rightarrow l\bar{\nu})$ + jets
- l escapes detection
- Assessed in a $1l$ sideband with $m_T^{l,p_T^{miss}} < 160GeV$



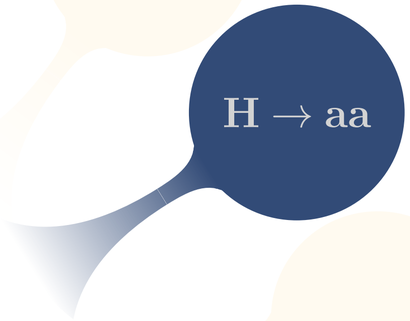
2HDMa Exclusions
2D m_a vs m_A plane

recasting

Overlayed with previously shown Mono-jet & Mono-H



Experimental searches



2HDMa
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CMS

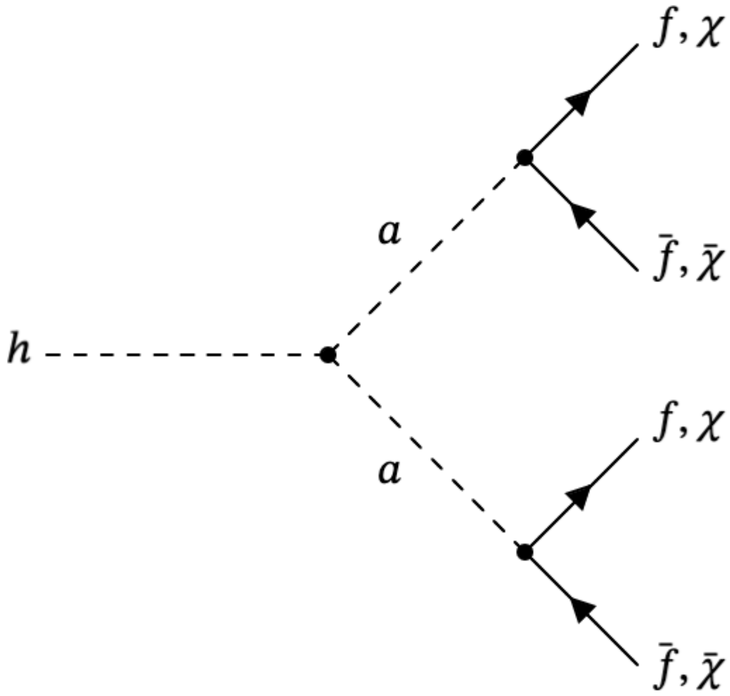
Higgs exotic decay searches

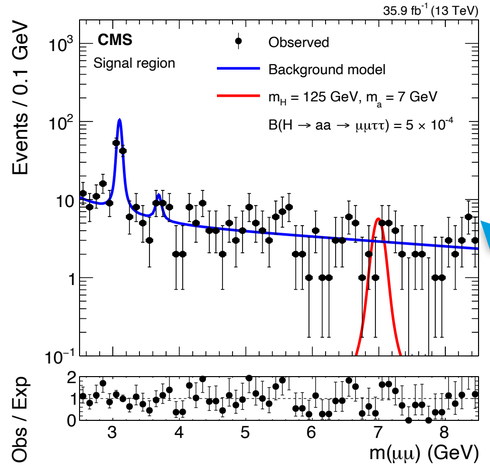
JHEP 08 (2020) 139 | Phys. Lett. B 800 (2019) 135087
Phys. Lett. B 795 (2019) 398 | Phys. Lett. B 785 (2018) 462

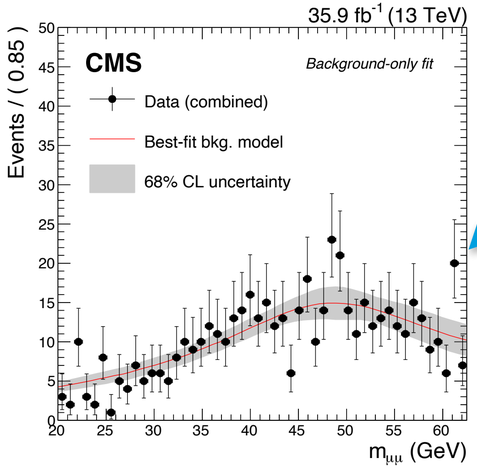
Decays of the SM-like Higgs boson into a pair of pseudo-scalars with subsequent decay of these into SM fermions or DM candidates

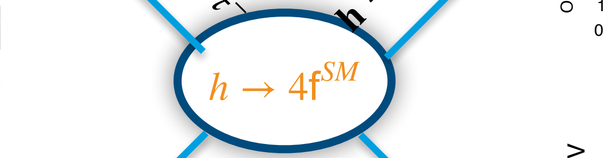
✦ **Experimental signature:**

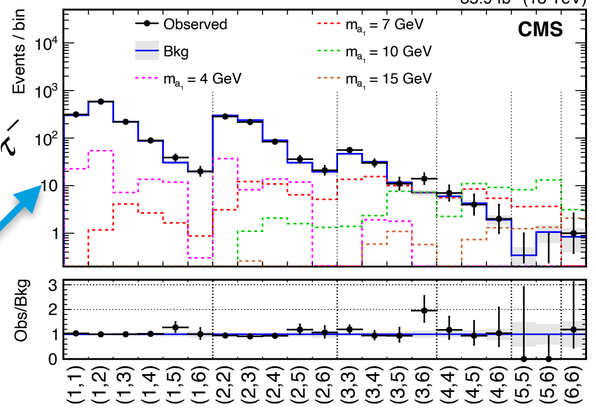
- $h \rightarrow 4f^{SM}$: Four-fermion final states with several possible combinations of physics objects depending on the studied decays (typically optimized for **ggF**)
- $h \rightarrow$ Inv: Sufficient amount of p_T^{miss} accompanied by jets and leptons depending on the targeted Higgs production modes (*e.g.* Mono-jet [**ggF,VH]**, Mono-Z [**ZH]**, $t\bar{t}$ + DM [**ttH]**)

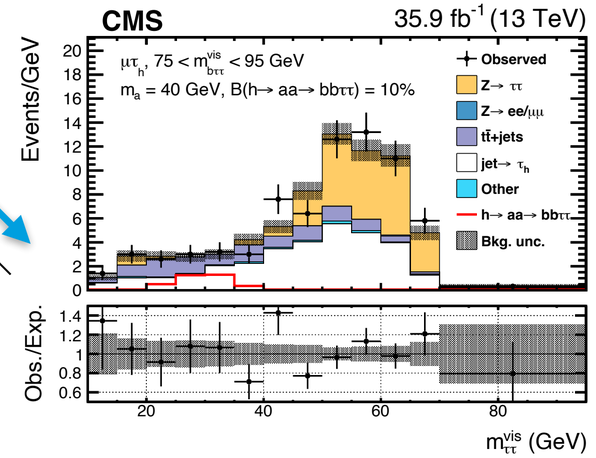












Higgs exotic decay searches

CMS DM Summary Plots

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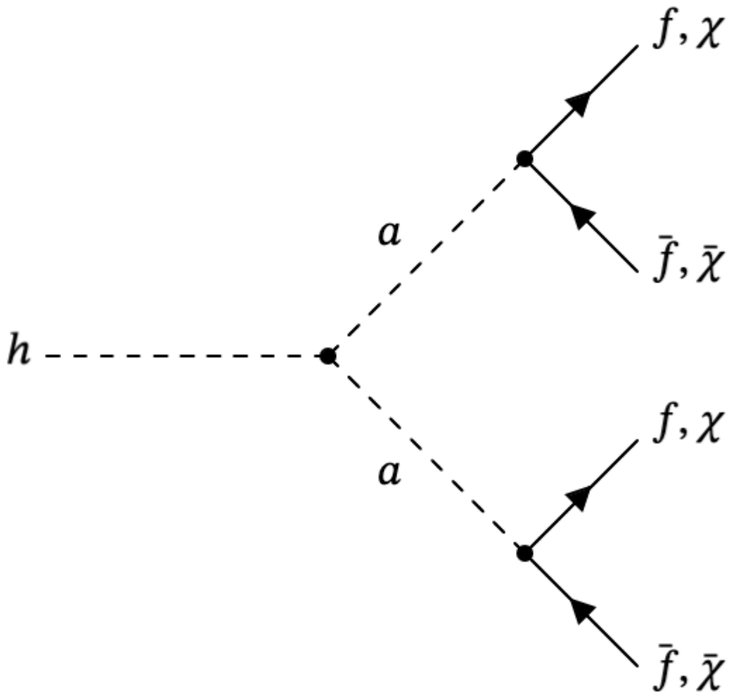
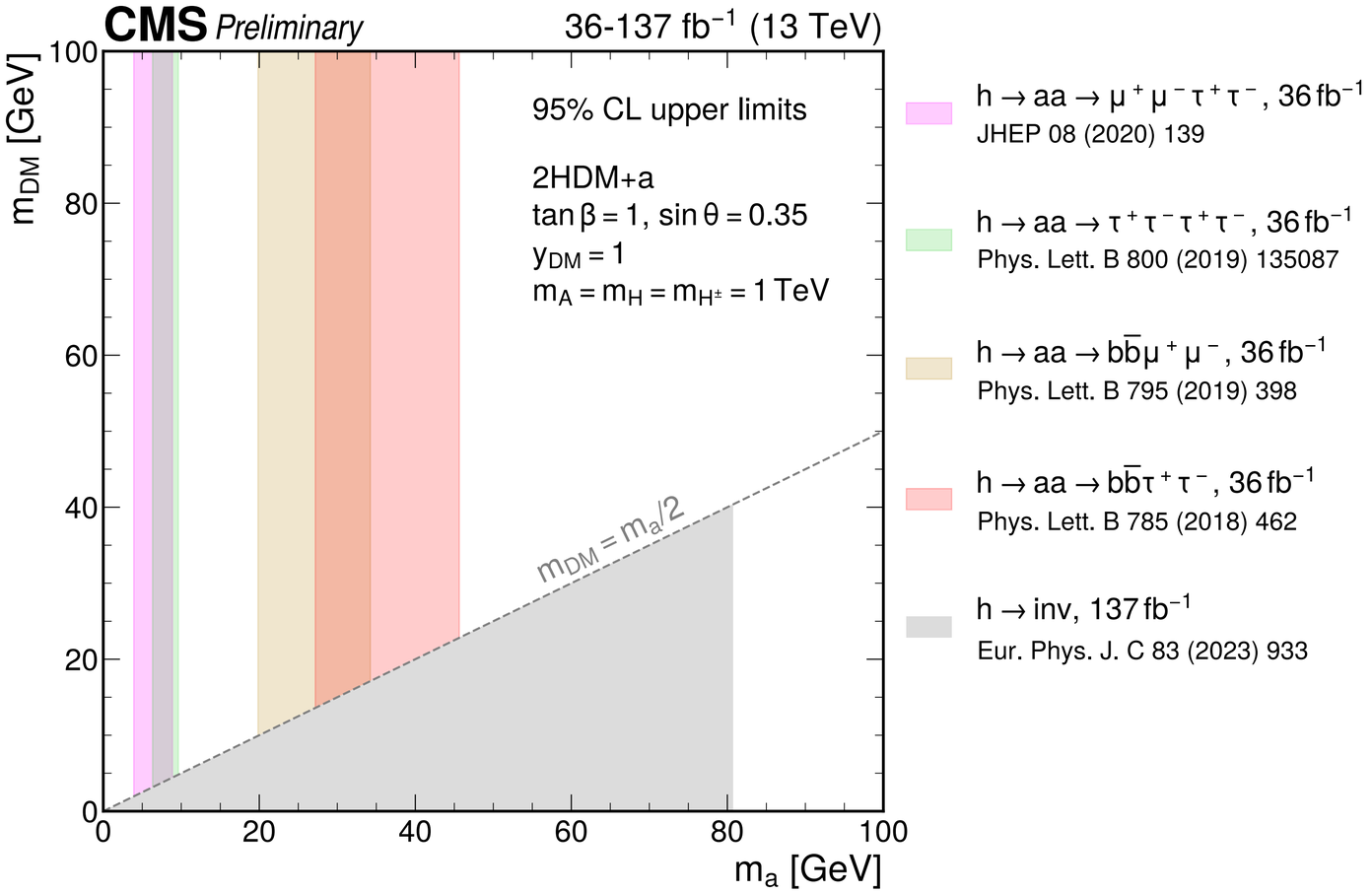
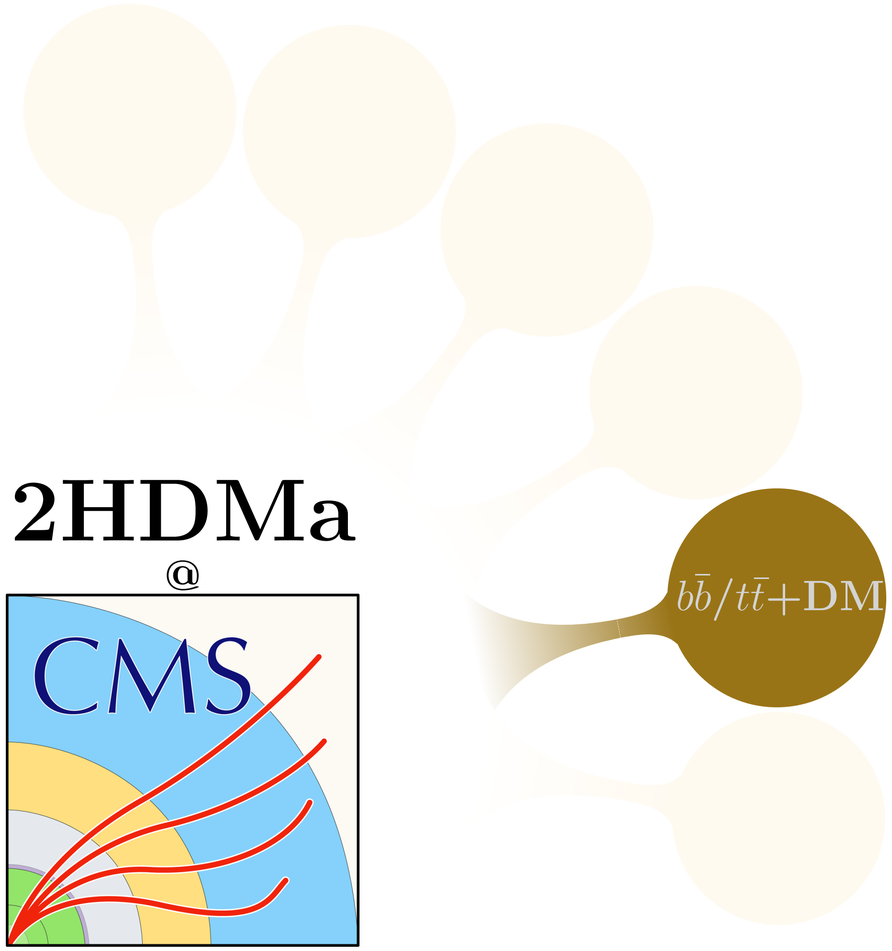




Experimental searches



bb+DM search

CMS-PAS-SUS-23-008

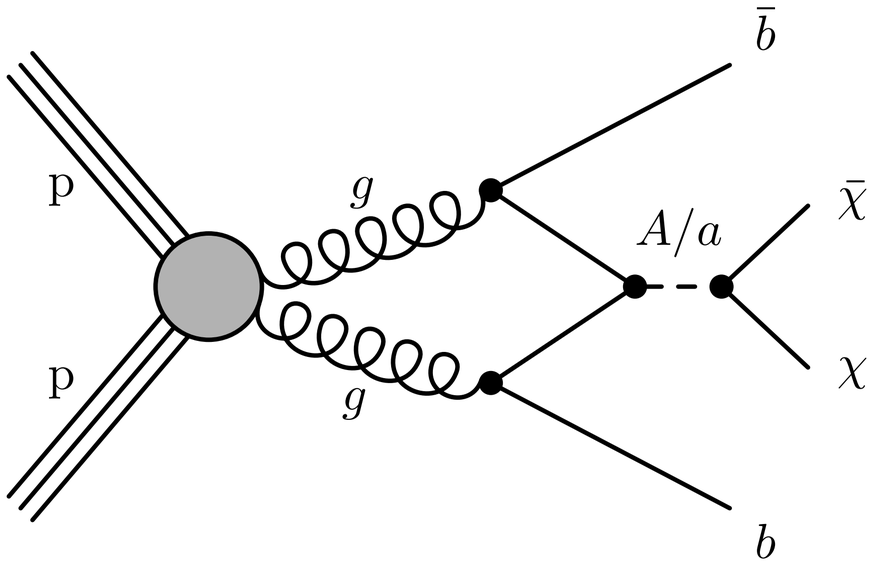
Events with DM particles produced in association with bottom quarks

✦ **Experimental signature:** Comprises one or two b-tagged jets accompanied by large missing transverse momentum

✦ **Analyzed data:** pp collisions collected in 2016-2018 (full Run 2): 138 fb^{-1}

✦ **Selection:**

- At least one jet with $p_T > 100GeV$ & $|\eta| < 2.5$, rest $p_T > 30GeV$
- $p_T^{\text{miss}} > 250GeV$ & $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jets}}) > 0.5$
- Events with μ, e, τ, or γ are vetoed
- Categorization based on (b-)**jet** multiplicity
  - ➡ **1b SR**: $N_{\text{jet}} \leq 2$ & $N_{\text{bjet}} = 1$
    - Signal extraction: p_T^{miss}
  - ➡ **2b SR**: $N_{\text{jet}} \leq 3$ & $N_{\text{bjet}} = 2$
    - Signal extraction: $\cos\Theta^* = \|\tanh(\frac{\eta_1 - \eta_2}{2})\|$



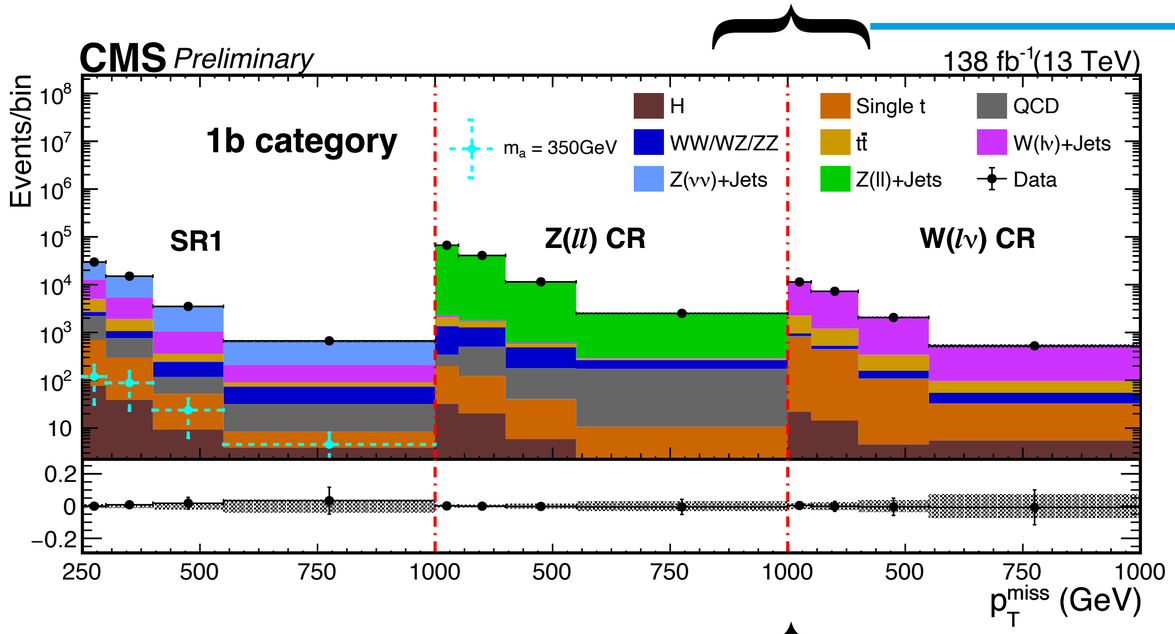
❖ $\mathbf{b\bar{b}}$ + DM channel cannot compete with $t\bar{t}$ + DM in the context of simplified models

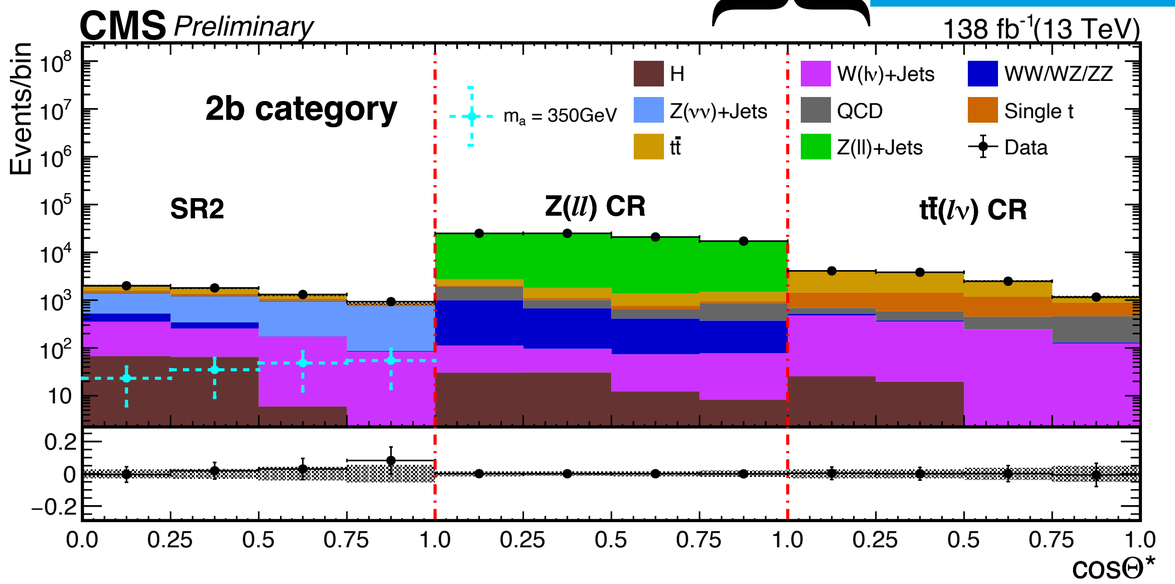
- Absence of differential quark couplings that could enhance $b\bar{b}$ associated production
- Challenging experimentally: significantly *more forward/backward b-jets* with *softer* p_T spectrum

❖ In **2HDMa**, however, there is preferential coupling of A/a to b-quarks for large $\tan\beta$ (Type II)

bb+DM search

CMS-PAS-SUS-23-008

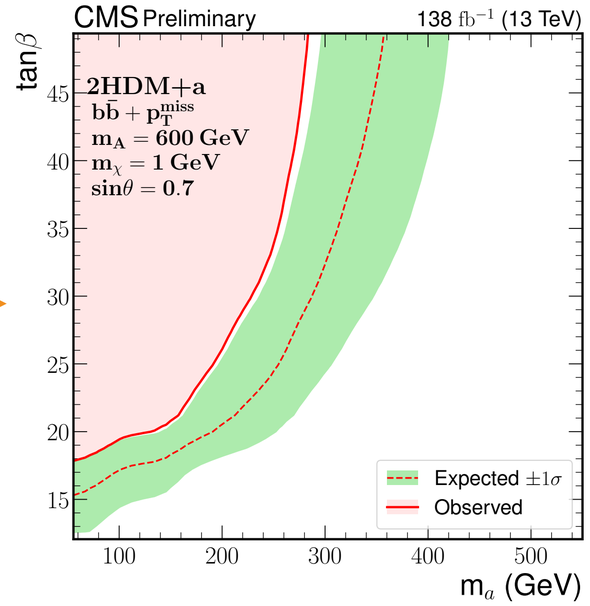


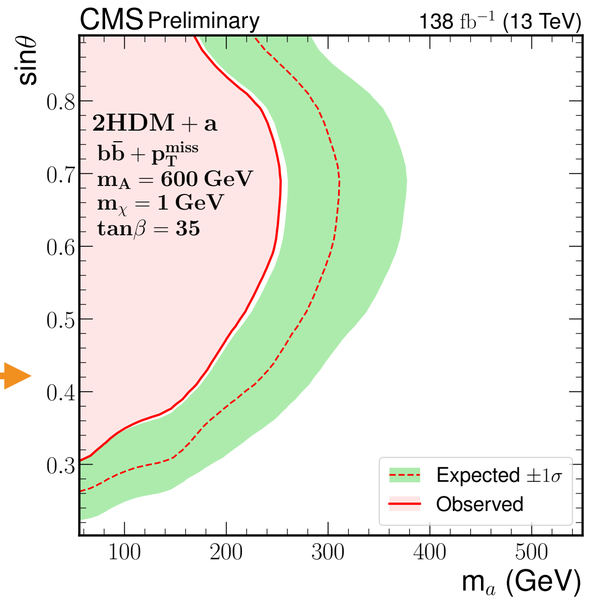


✦ **Background estimation:** two most predominant processes in each category modeled via per-bin *unconstrained linking parameters* in respective control regions

2HDMa Exclusions

- 2D m_a vs $\tan\beta$ plane
- 2D m_a vs $\sin\theta$ plane

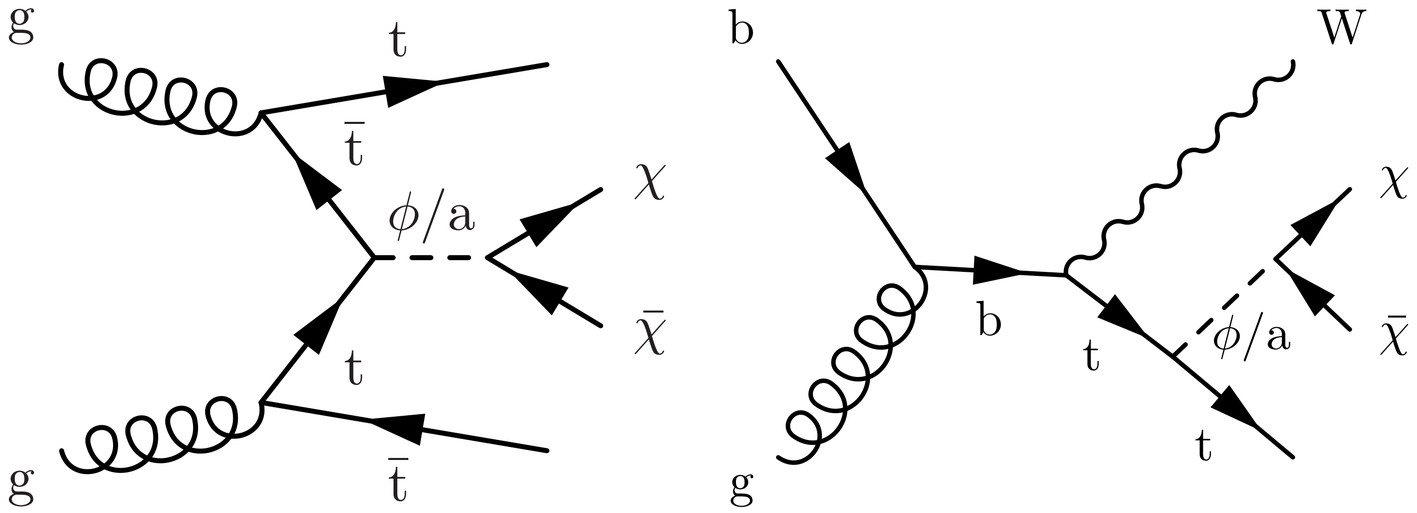




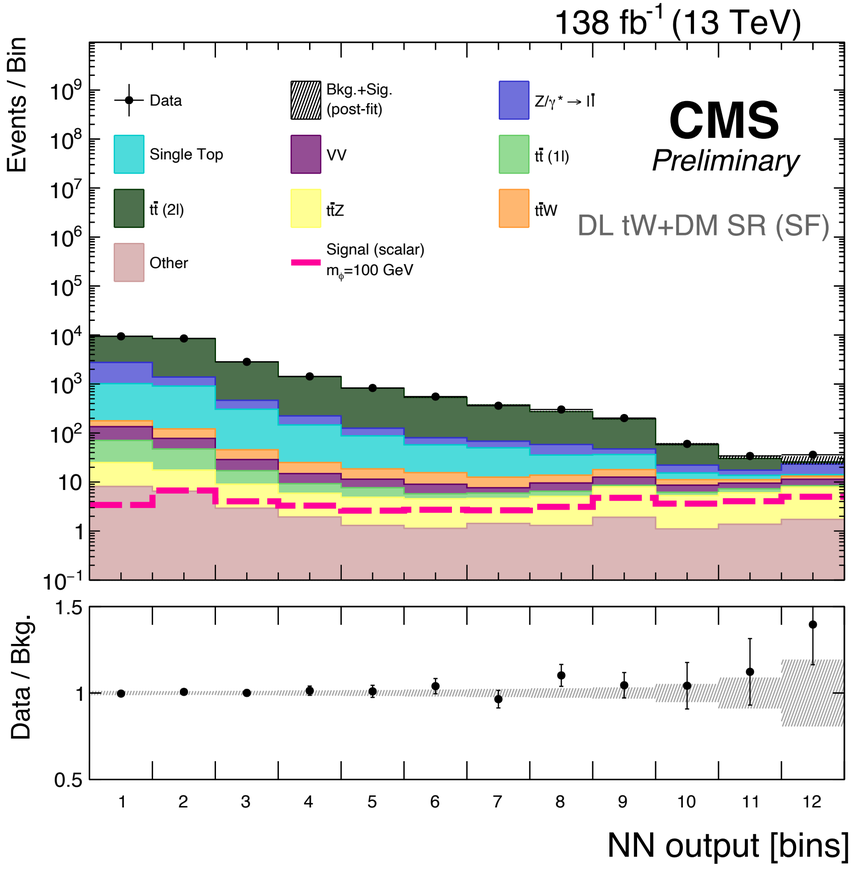
Some perspectives on tW+DM searches

CMS-PAS-EXO-22-014

- ***Currently,*** no dedicated search for single-top $\mathbf{tW}$ + **DM*** production in 2HDMa at CMS
  - Advantages of distinctive identification of boosted W not fully exploited in $0l$ and $1l$ channels
- ***However,*** recent *NEW* search released optimized for both $t\bar{t}$ and single-top associated DM production in the context of *simplified DM model*
  - $2l$ channel requires less meticulous techniques to identify lepton from W (even if boosted)
  - NN trained differentially in CMS analysis to discriminate $t\bar{t}$ + DM and tW + DM processes
  - $2l$ should dominate in sensitivity for low values of $m_{H^{\pm}}$

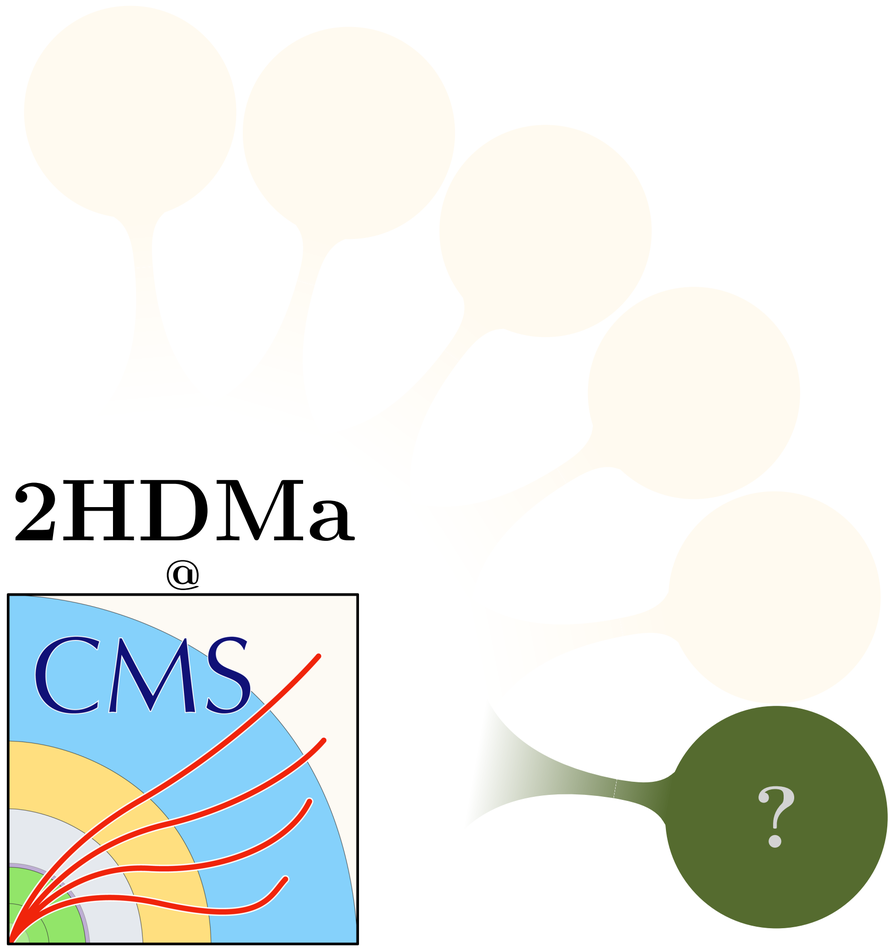


Mild excess seen by both **ATLAS** ($\approx 2\sigma$) and **CMS** ($\approx 1.5\sigma$) in $2l$ channel when targeting the tW + DM process



*Resonantly enhanced in the 2HDMa via $H^{\pm} \rightarrow W^{\pm}a$

Further probes



bbZ+DM: via heavy Higgs bosons in simplified models

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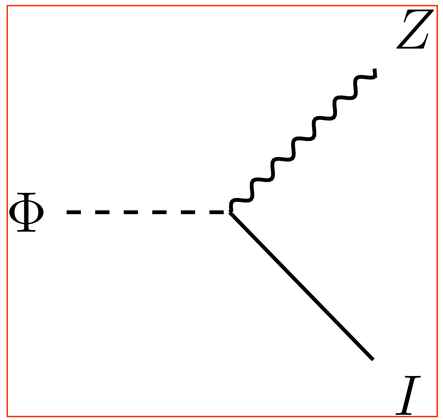
Phenomenological study performed using a Delphes simulation (solely - no real data) for the CMS detector

- **Characterization** of a *wider** class of topologies using a simplified model framework (three new particles: Φ , M , I)
- **Feasibility** and collider study of $bbZ + DM$ search in *comprehensive* set of decay topologies
- **Selection**

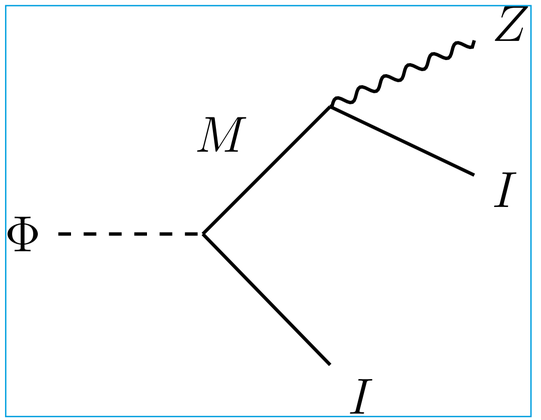
Quantity	Standard-SR	ForwardJets-SR
N_l (opposite-charge, same-flavour)	$= 2$ (with additional lepton veto)	
$p_T(l)$	50/20 GeV leading/trailing	
$m(l^+l^-)$	$86\,\text{GeV} < m(l^+l^-) < 106\,\text{GeV}$	
$p_T(l^+l^-)$	> 50 GeV	
$\Delta R(l^+, l^-)$	< 3	
$\Delta\phi(\vec{p}_T^{\,\text{miss}}, l^+l^-)$	> 0.5	
$m_T(\vec{p}_T^{\,\text{miss}}, l^+l^-)$	> 140 GeV	
$N_{\text{b-tag}}$	≥ 1	$= 0$
$\lvert\eta(j_1) - \eta(j_2)\rvert_{\max}$	–	> 2.5

*Typical DM searches at the LHC are conceived for an '*unbalanced*' topology

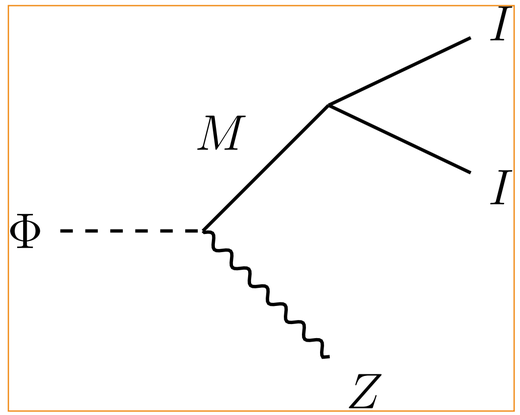
1-vs-1 unbalanced



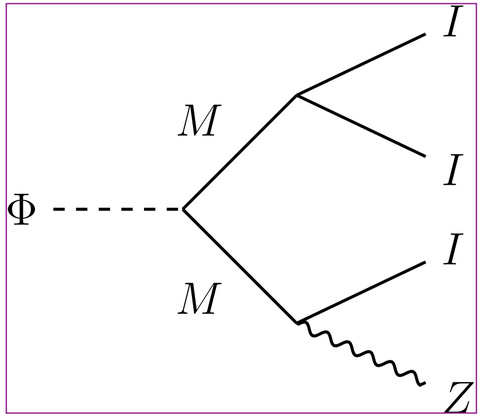
2-vs-1 balanced



2-vs-1 unbalanced



2-vs-2 balanced



2HDMa topology

bbZ+DM: via heavy Higgs bosons in simplified models

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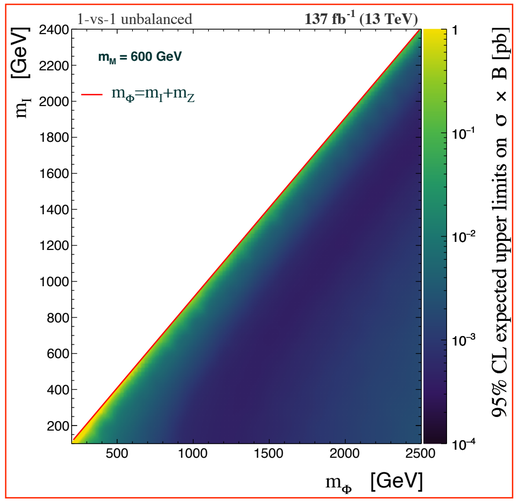
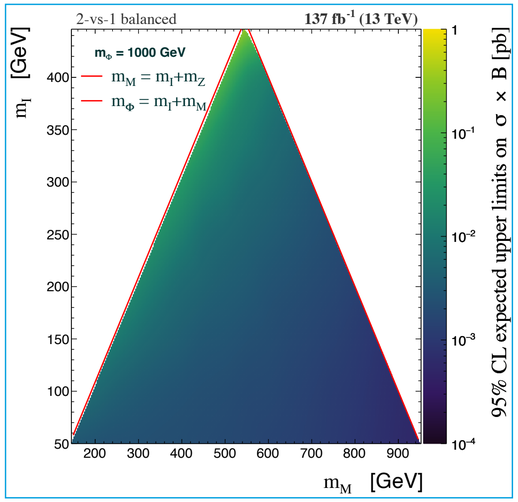
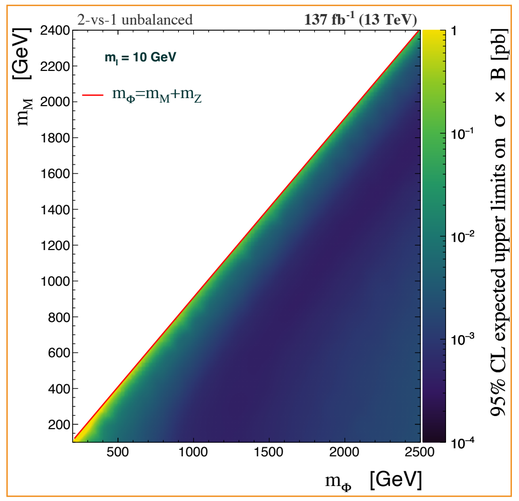
1-vs-1 unbalanced



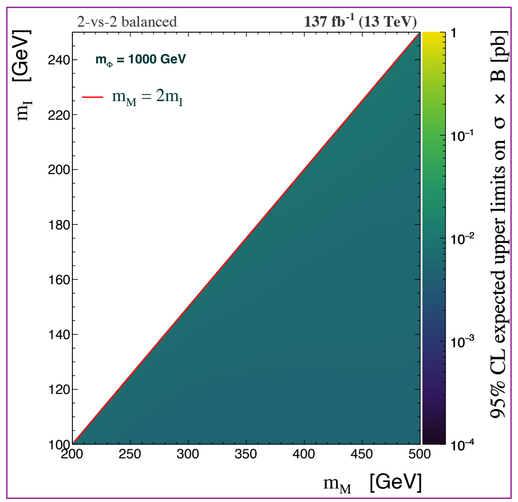
2-vs-1 balanced



2-vs-1 unbalanced

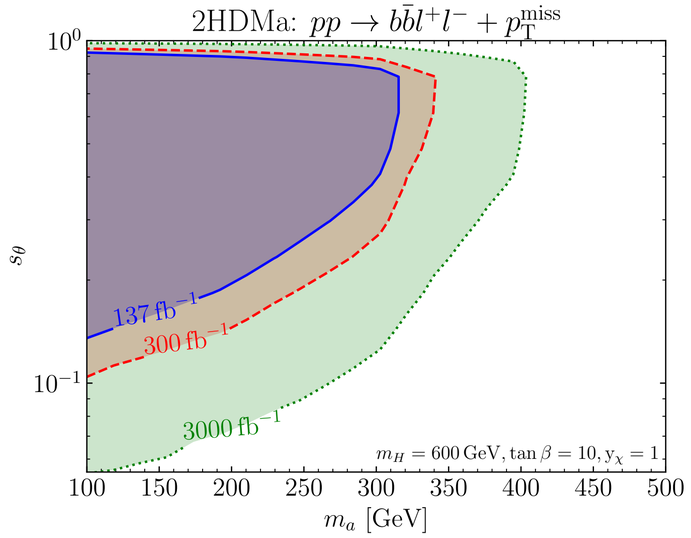


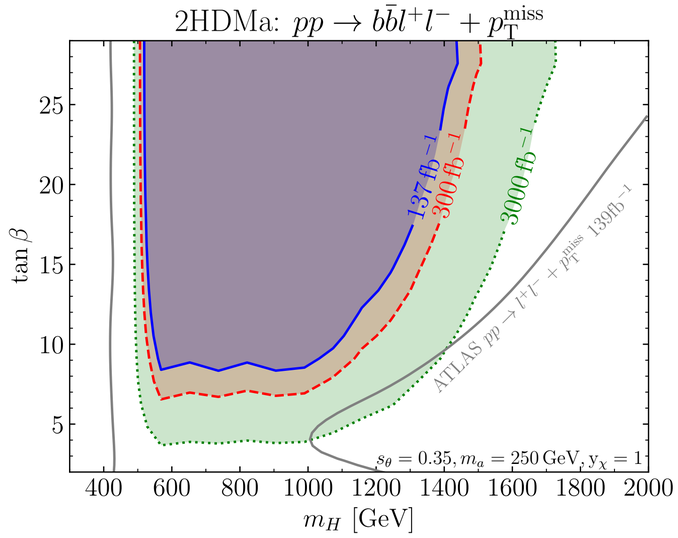
2-vs-2 balanced



Results

- *Sensitivity* of both signal regions is *comparable*: forward jets are relevant
- *Clear distinction* between **unbalanced** vs **balanced** scenarios
- *Indistinguishability for* unbalanced topologies
- *Decrease* in sensitivity for *compressed* scenarios: might require dedicated search for **balanced** cases
- Experimentally a *complementary* analysis to “Mono-Z”, but might* have *comparable* sensitivity in 2HDMa at large $\tan\beta$





*Only including bbH production in this 2HDMa interpretation

Summary

- Large variety of relevant 2HDMa signatures being covered by CMS searches
  - Many other interesting existing results not directly interpreted in 2HDMa but sensitive to it: Mono-$H(\rightarrow \tau^+\tau^-, \gamma\gamma)$, charged Higgs searches, $t\bar{t}t\bar{t}$, etc.
- Experimental techniques evolving to more sophisticated approaches
  - Use of multivariate analysis is consolidating and bringing substantial improvements
- Still more analyses and novel explorations to be ready in the near future with full Run 2 data
- No significant excess observed yet in these searches, but many new ideas emerging, and promising developments expected for Run 3

Thanks for your attention!

Thank you!

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