

# Dark Matter Particle Production in Extended 2HDM Models

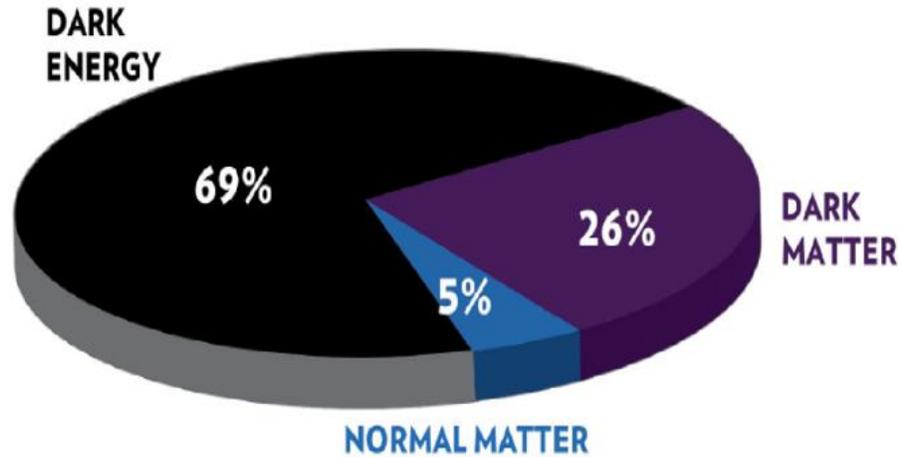
K. Slizhevskii behalf CMS Collaboration

**Conference on High Energy Physics  
Yerevan, Armenia, 29.09 – 03.10, 2025**

JINR DM Team in CMS:

Korsakov I.  
Kodolova O.  
Lanev A.  
Nikitenko A.  
Savina M.  
Shmatov S.  
Slizhevskii K.  
Zhizhin I.

# Introduction: Dark Matter



## DM candidates:

- Baryonic matter (massive astrophysical compact halo objects - MACHO)
- Non-baryonic matter (sterile neutrinos, weakly interacting massive particles – WIMPs, axions, supersymmetric particles, etc.)

## Dark matter (DM):

- Not interacting (very weakly interacting) with ordinary matter
- Electrically neutral

## Arguments for dark matter existence:

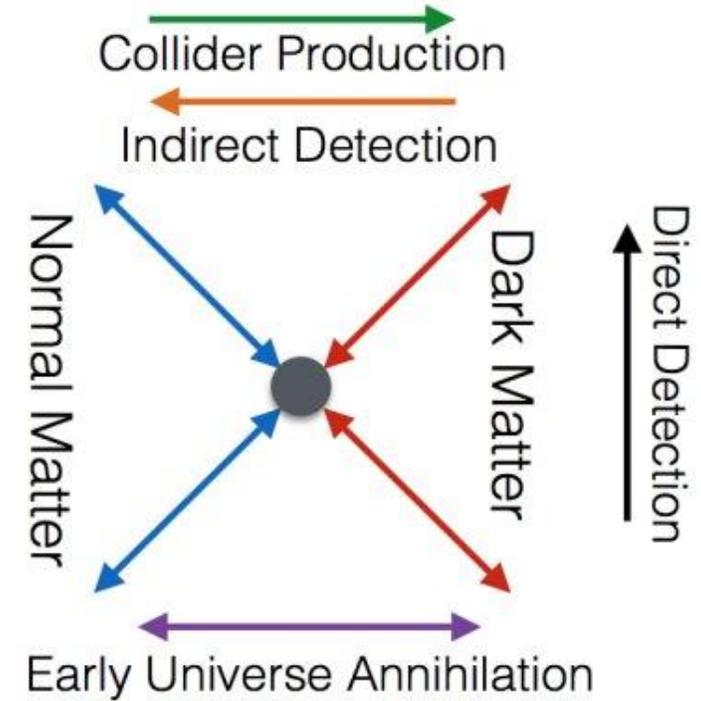
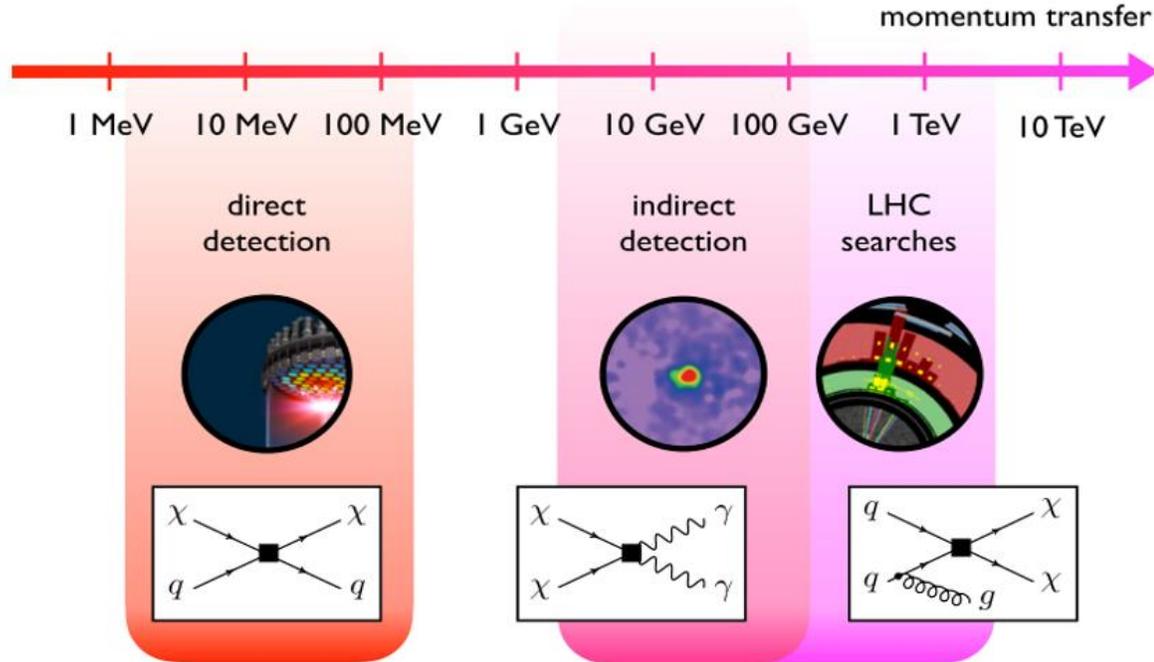
### Astrophysical:

- Curved rotation of galaxies, virial theorem “violation”, ultra diffuse galaxies and satellites of galaxies, spiral structures of galaxies
- Gravitational lensing, evaluation of potentials and masses of galaxies/clusters of galaxies (“Bullet” cluster etc.)

### Cosmological:

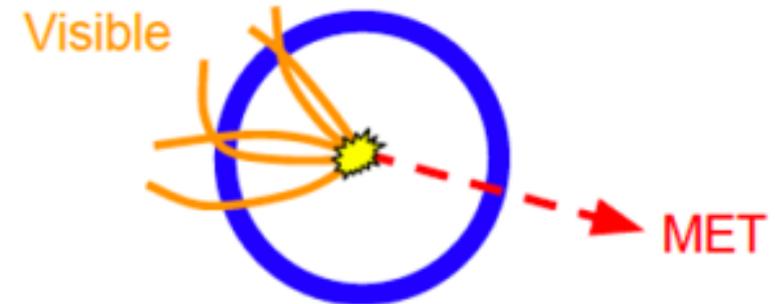
- Anisotropy of cosmic microwave background, flatness of the Universe, the prevalence of the elements and necessity of DM.
- Forming of the early Universe structure, the growth of the initial inhomogeneities

# DM in particle accelerators



Dark matter can be produced within particle accelerators if:

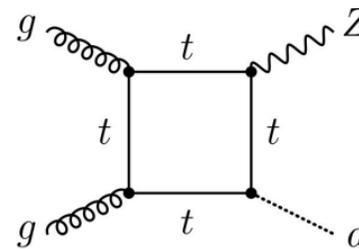
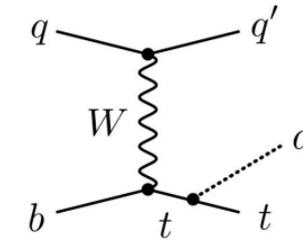
- The dark matter mass is low enough
- Its production cross section is large enough
- Dark and ordinary matter interact at least weakly with each other



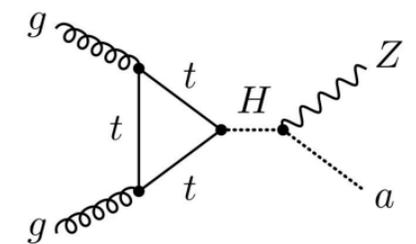
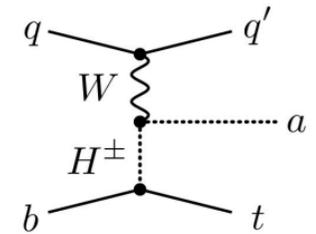
# Extended Higgs Models

- Standard Model (SM)
- SM + additional pseudoscalar
- Two-Higgs-Doublet Model (2HDM)
- 2HDM with pseudoscalar mediator (2HDM+a)

**a → Dark Matter**



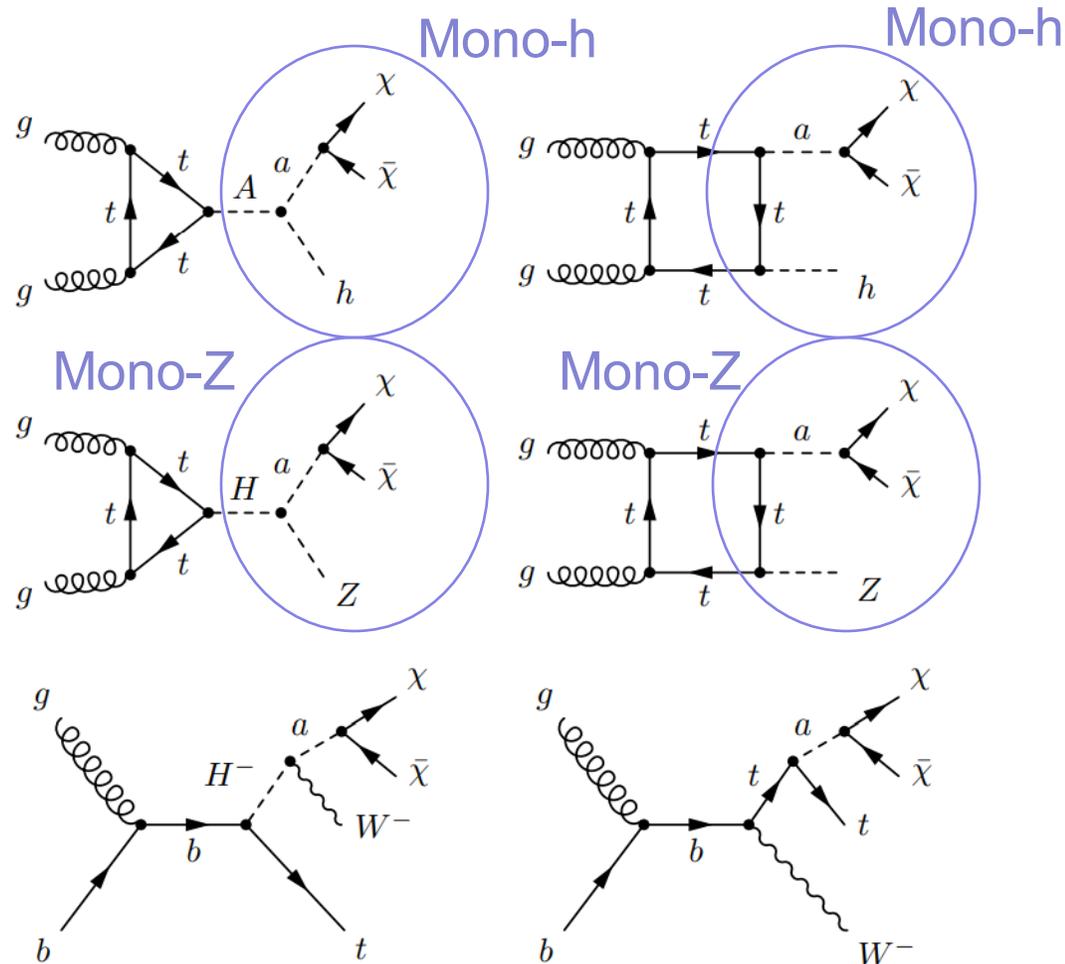
**Simplified model  
with pseudoscalar**



**2HDM+a**

Simplified dark matter models with two Higgs doublets: I.  
Pseudoscalar mediators [arXiv:1701.07427v3]

# 2HDM + Pseudoscalar



## 2HDM + a

- neutral CP-even scalars  $h, H$
- neutral CP-odd pseudoscalar  $A$
- charged  $H^+, H^-$
- pseudoscalar mediator  $a$
- dark matter particle  $\chi$

**Key discovery signatures: MET + X**

**Selected channel: MET + Z ( $\mu^+\mu^-$ )**

# Model Parameters

## Masses:

- SM-like Higgs boson:  $m_h = 125$  GeV
- Heavy CP-even scalar:  $m_H \in [200, 1800]$  GeV
- CP-odd scalar:  $m_A \in [200, 1800]$  GeV
- Charged Higgs bosons:  $m_{H^\pm} \in [200, 1800]$  GeV
- Additional pseudoscalar:  $m_a \in [100, 900]$  GeV
- Dark matter mass:  $m_\chi \in [1, 500]$  GeV

## Mixing angles and couplings:

- Ratio of vevs:  $\tan\beta \in [0.5, 50]$
- h, H mixing angle:  $\cos(\beta - \alpha) \in [-0.05, 0.05]$
- Pseudoscalar mixing angle:  $\sin\theta \in [0, 1]$
- Couplings:  $y_\chi \in [10^{-3}, 1]$ ,  $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- Mediator–Higgs couplings:  $g_{aZh}, g_{aH} \in [10^{-4}, 1]$

$$\left\{ \begin{array}{l} v, M_h, M_A, M_H, M_{H^\pm}, M_a, m_\chi \\ \cos(\beta - \alpha), \tan\beta, \sin\theta, \\ y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2} \end{array} \right\}$$

The lower boundary is taken from previous analyses of direct observation and theory. The upper boundary is an approximate kinematic limit of LHC.

Simplified dark matter models with two Higgs doublets: I.  
Pseudoscalar mediators [arXiv:1701.07427v3]

Collider Searches for Dark Matter through  
the Higgs Lens [arXiv:2109.13597]

LHC Dark Matter Working Group: Next-generation spin-0  
dark matter models [doi.org/10.1016/j.dark.2019.100351]

# Model Parameters

## Masses:

- SM-like Higgs boson:  $m_h = 125$  GeV
- Heavy CP-even scalar:  $m_H \in [200, 1800]$  GeV
- CP-odd scalar:  $m_A \in [200, 1800]$  GeV
- Charged Higgs bosons:  $m_{H^\pm} \in [200, 1800]$  GeV
- Additional pseudoscalar:  $m_a \in [100, 900]$  GeV
- Dark matter mass:  $m_\chi \in [1, 500]$  GeV

## Mixing angles and couplings:

- Ratio of vevs:  $\tan\beta \in [0.5, 50]$
- h, H mixing angle:  $\cos(\beta - \alpha) \in [-0.05, 0.05]$
- Pseudoscalar mixing angle:  $\sin\theta \in [0, 1]$
- Couplings:  $y_\chi \in [10^{-3}, 1]$ ,  $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- Mediator–Higgs couplings:  $g_{aZh}, g_{aH} \in [10^{-4}, 1]$

## Benchmark parameter choices:

$m_H$ : [200, 1800] GeV

$m_a$ : [100, 900] GeV

$m_h = 125$  GeV,  $v = \sqrt{v_1 + v_2} = 246$  GeV

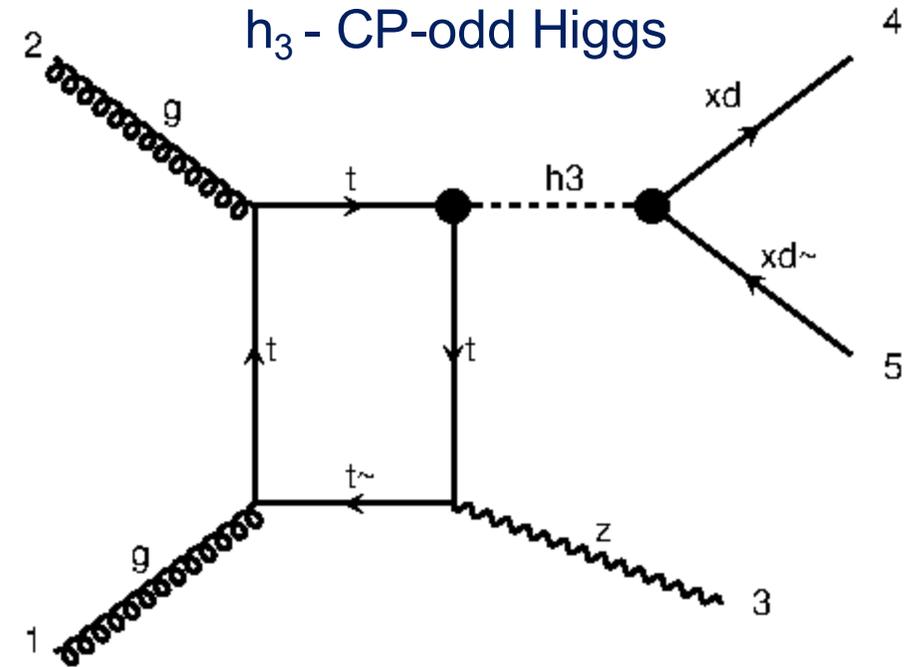
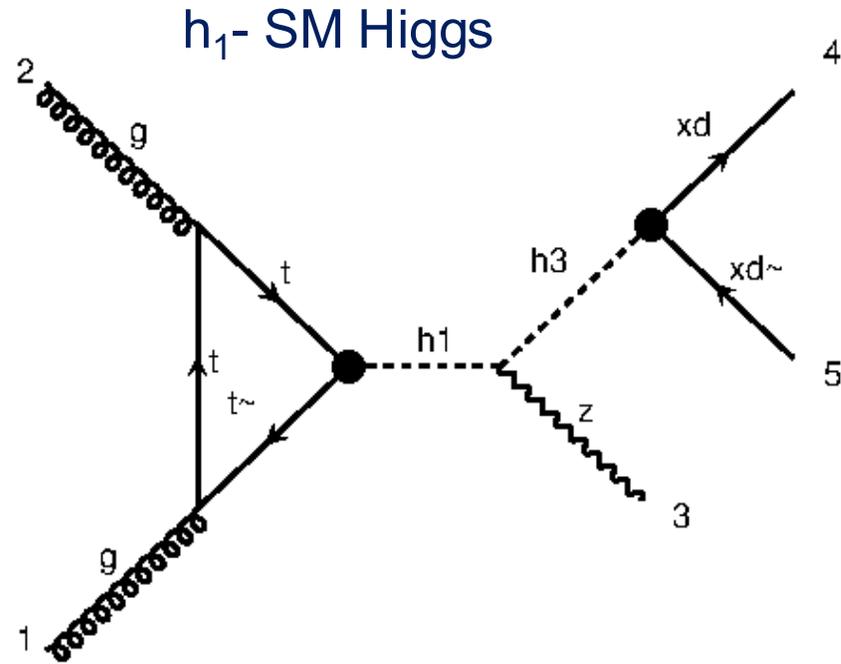
$M_H = M_A = M_{H^\pm}$ ,  $m_\chi = 10$  GeV,

$\cos(\beta - \alpha) = 0$ ,  $\tan\beta = 1$ ,  $\sin\theta = 0.35$

$y_\chi = 1$ ,  $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$ .

LHC Dark Matter Working Group: Next-generation spin-0  
dark matter models [doi.org/10.1016/j.dark.2019.100351]

# Signal generation



- Process:  $pp \rightarrow Z(\mu^+\mu^-) + \chi\bar{\chi}$
- Signal model: 2HDM+a
- MC generator: Madgraph5\_v2\_9\_2

**generate pp > z xd xd~ [noborn=QCD] или gg > l+ l- xd xd~ / h1 a**

UFO: [Pseudoscalar 2HDM](#)

Fullsim in CMSSW 13.0.2

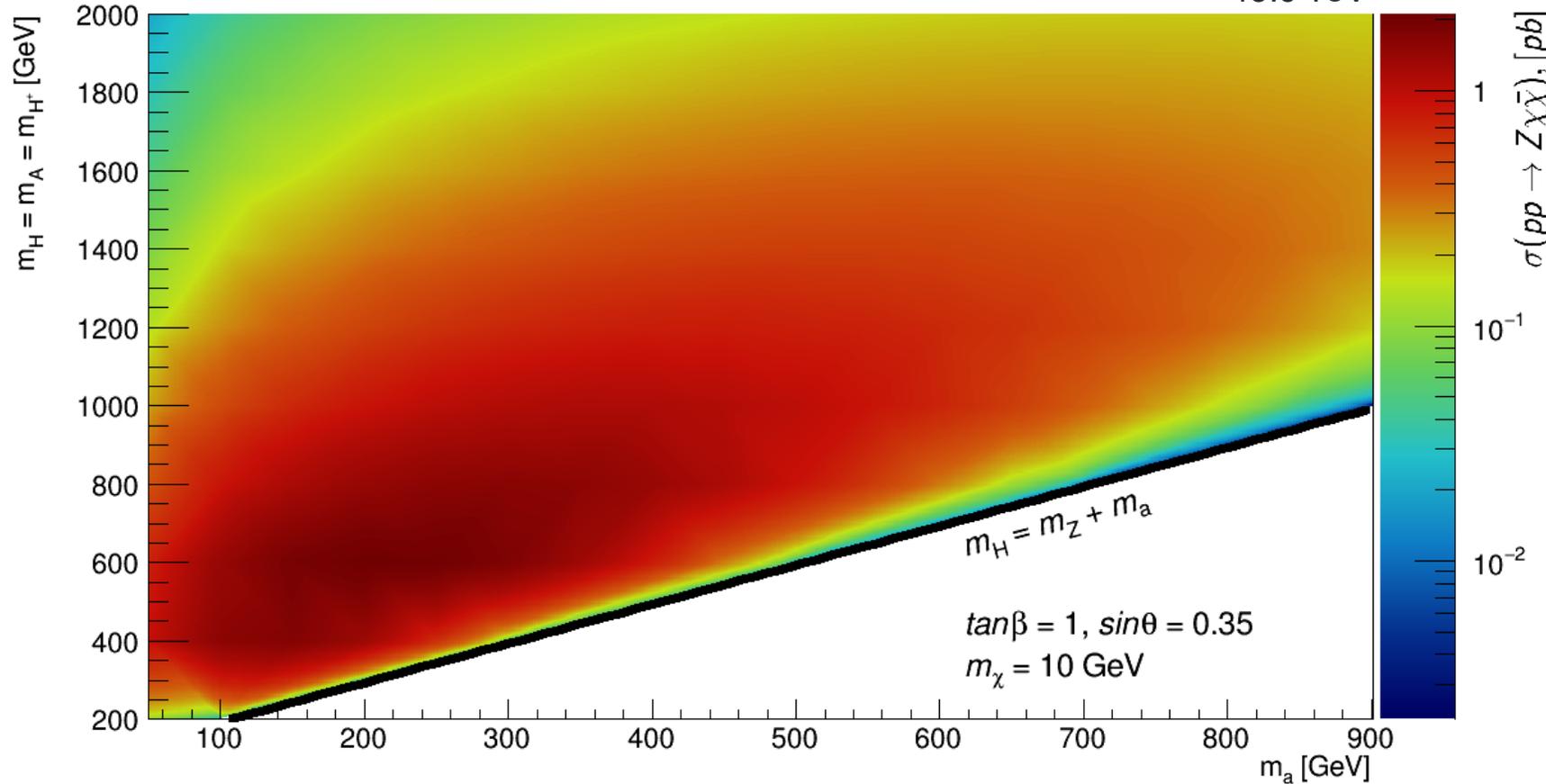
$$h_1 = h_{125} \leftrightarrow h_2 = H^0$$

$$h_3 = A^0 \leftrightarrow h_4 = a$$

# Cross section calculation using MG5

Cross section  $pp \rightarrow Z \chi \bar{\chi}$  (2HDM+a)

13.6 TeV



Process:  $pp \rightarrow Z(\mu^+\mu^-) + \chi\bar{\chi}$   
Signal model: 2HDM+a  
MC generator: MG5\_v2\_9\_2  
1 Point - 10000 Event  
 $m_H$  - every 200 GeV  
 $m_a$  - every 50 GeV

# Signal generation

*Distribution of sum  $p_T$  of a pair of DM particles (pdgID 52 and pdgID -52) at gen level*

**THIS SUM IS INTERPRETED AS MET**

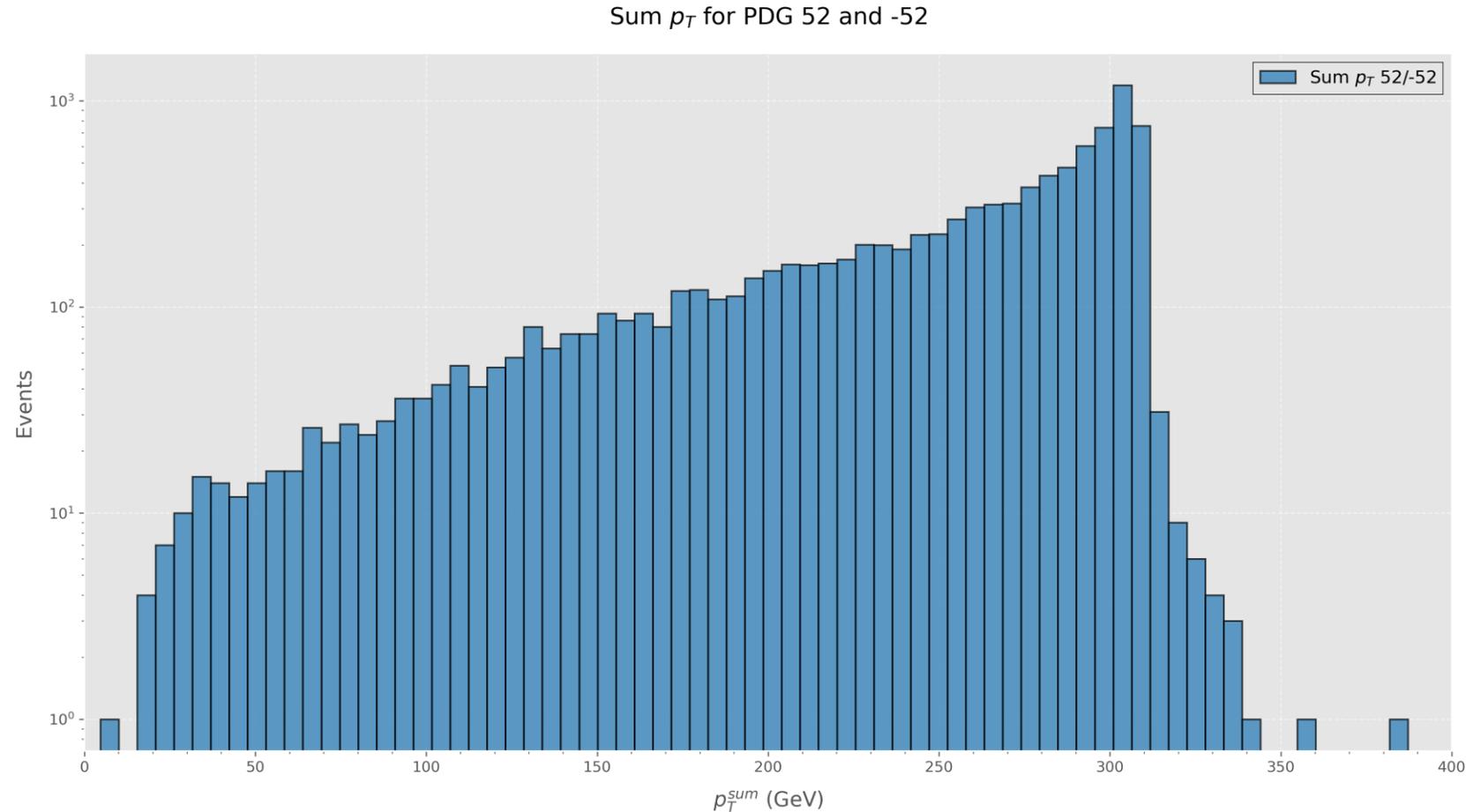
$$M_a = 300, M_H = 750$$

$$M_H = M_A = M_{H^\pm}, \quad m_\chi = 10 \text{ GeV},$$

$$\cos(\beta - \alpha) = 0, \quad \tan \beta = 1, \quad \sin \theta = 0.35,$$

$$y_\chi = 1, \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3.$$

$$m_\chi = 10 \text{ GeV and } y_\chi = 1$$



# Background

## Simulated background datasets for Run 3

Process	Dataset Name	Cross Section* [ $\text{pb}^{-1}$ ]
$Z/\gamma^* \rightarrow l^+l^-$	DYJetsToLL_M-50_TuneCP5_13p6TeV-madgraphMLM-pythia8	5558
$ZZ \rightarrow 2l2\nu$	ZZto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8	1.031
$ZZ \rightarrow 2l2Q$	ZZto2L2Q-1Jets_TuneCP5_13p6TeV_amcatnloFXFX-pythia8	3.860
$ZZ \rightarrow 4l$	ZZto4L-1Jets_TuneCP5_13p6TeV_amcatnloFXFX-pythia8	1.499
$WZ \rightarrow l\nu 2Q$	WZtoLNU2Q_TuneCP5_13p6TeV_powheg-pythia8	15.870
$WZ \rightarrow 2l2Q$	WZto2L2Q_TuneCP5_13p6TeV_powheg-pythia8	7.568
$WZ \rightarrow 3l\nu$	WZto3LNU_TuneCP5_13p6TeV_powheg-pythia8	4.924
$WW \rightarrow l\nu 2Q$	WWtoLNU2Q_TuneCP5_13p6TeV_powheg-pythia8	48.940
$WW \rightarrow 2l2\nu$	WWto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8	11.790
$tW^- \rightarrow 2l2\nu$	TWminusto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8	35.99
$\bar{t}W^+ \rightarrow 2l2\nu$	TWplusto2L2Nu_TuneCP5_13p6TeV_powheg-pythia8	36.05
$t\bar{t} \rightarrow 2l2\nu$	TTTo2L2Nu_CP5_13p6TeV_powheg-pythia8	762.1

\* taken from Cross Section DB (XSDB) Tool [xsecdb]

# Kinematic selections

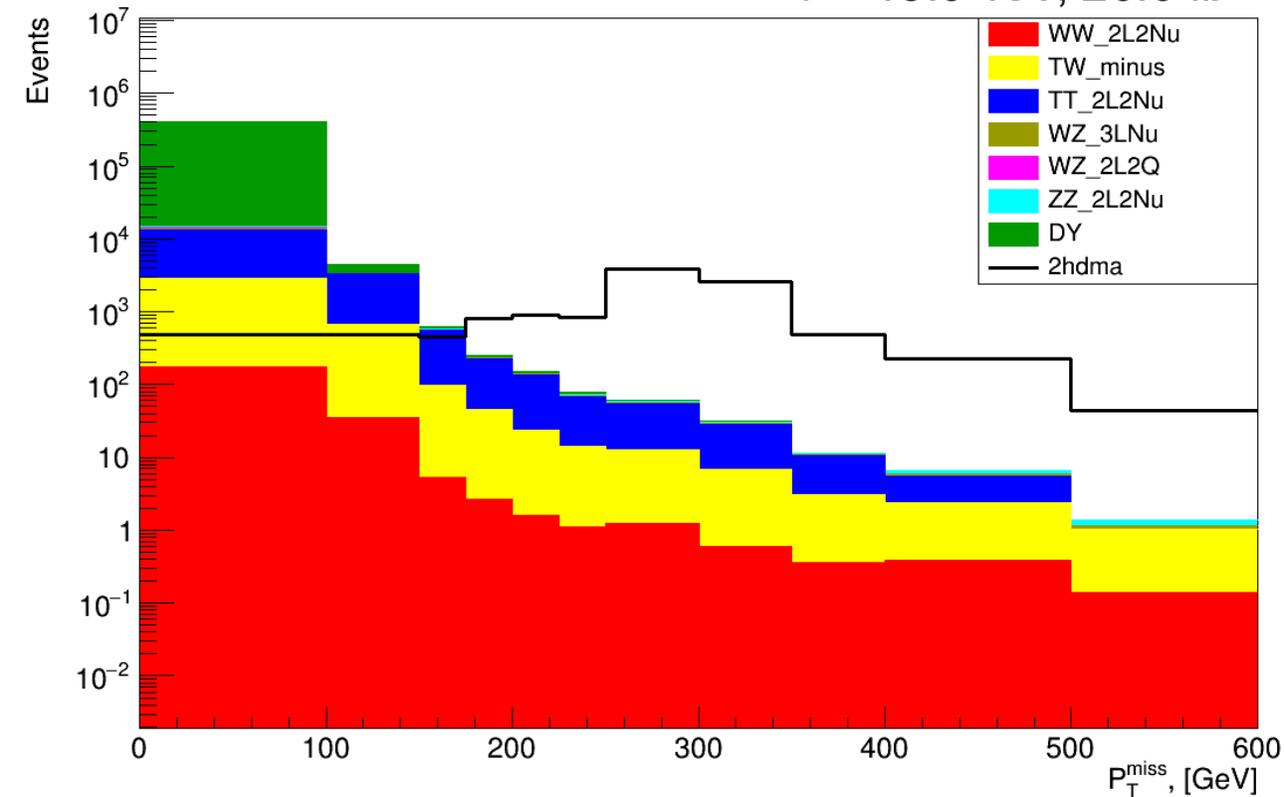
Summary of the kinematic selections for the signal region

$N_\ell$	$= 2$	WZ, VVV
$p_T^\ell$	$> 28/10 \text{ GeV}$ for leading / subleading	Multijet
Dilepton mass	$ m_{\ell\ell} - m_Z  < 15 \text{ GeV}$	WW, top
Number of jets	$\leq 1$ jet with $p_T^j > 30 \text{ GeV}$	DY, top, VVV
$p_T^{\ell\ell}$	$> 60 \text{ GeV}$	DY
b tagging veto	0 b-tagged jet with $p_T > 30 \text{ GeV}$	top, VVV
$\tau$ lepton veto	0 $\tau$ cand. with $p_T > 18 \text{ GeV}$	WZ
$\Delta\phi(p_T^\ell, p_T^{\text{miss}})$	$> 0.5$ radians	DY, WZ
$\Delta\phi(p_T^{\ell\ell}, p_T^{\text{miss}})$	$> 2.6$ radians	DY
$ p_T^{\text{miss}} - p_T^{\ell\ell}  / p_T^{\ell\ell}$	$< 0.4$	DY
$\Delta R_{\ell\ell}$	$< 1.8$	WW, top quark
$p_T^{\text{miss}}$	$> 100 \text{ GeV}$	DY, WW, top
$m_T$	$> 200 \text{ GeV}$	DY, WW, ZZ, top

Selections taken from arXiv:2008.04735

# Signal generation

Missing  $p_T$  13.6 TeV, 26.6 fb<sup>-1</sup>



The signal generated for  $m_a = 300$  GeV,  
 $m_H = 750$  GeV

These parameters are excluded based on  
results of previous analysis

Eur. Phys. J. C 81 (2021) 1

It's evident that there is a significant  
excess of signal over background, which  
was **not observed** in the experiment

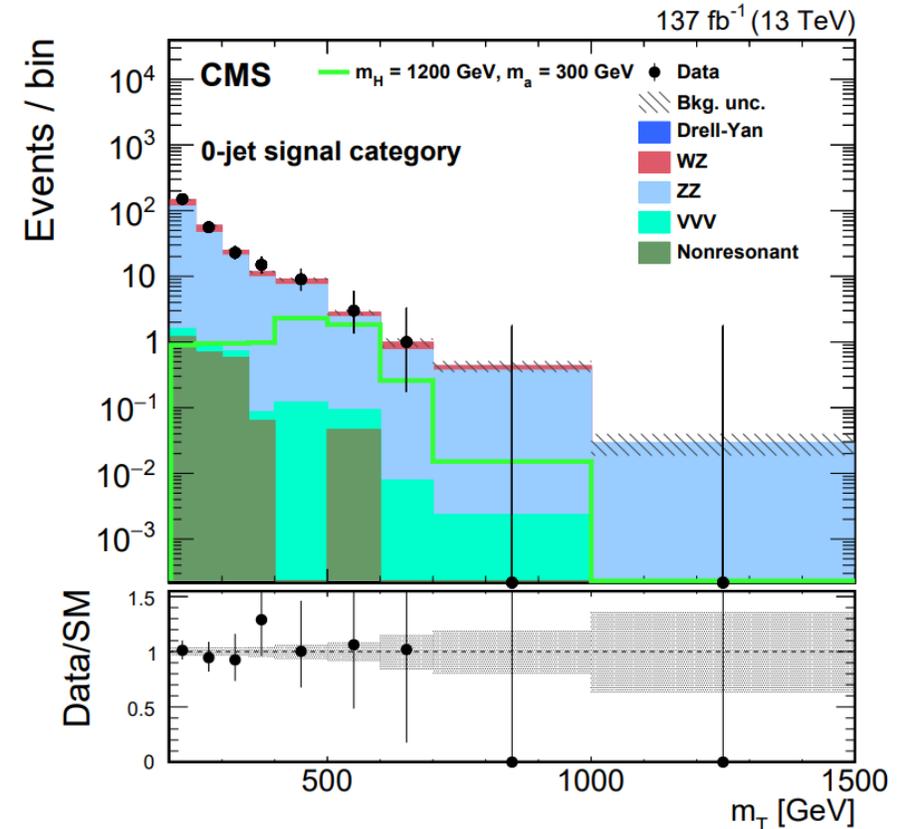
# CMS RUN2 Results

## Observed number of events and post-fit background estimates

Process	0-jet category	1-jet category
Drell-Yan	$502 \pm 94$	$1179 \pm 64$
WZ	$1479 \pm 53$	$389 \pm 16$
ZZ	$670 \pm 27$	$282 \pm 13$
Nonresonant background	$384 \pm 31$	$263 \pm 22$
Other background	$6.3 \pm 0.7$	$6.8 \pm 0.8$
Total background	$3040 \pm 110$	$2120 \pm 76$
Data	3053	2142

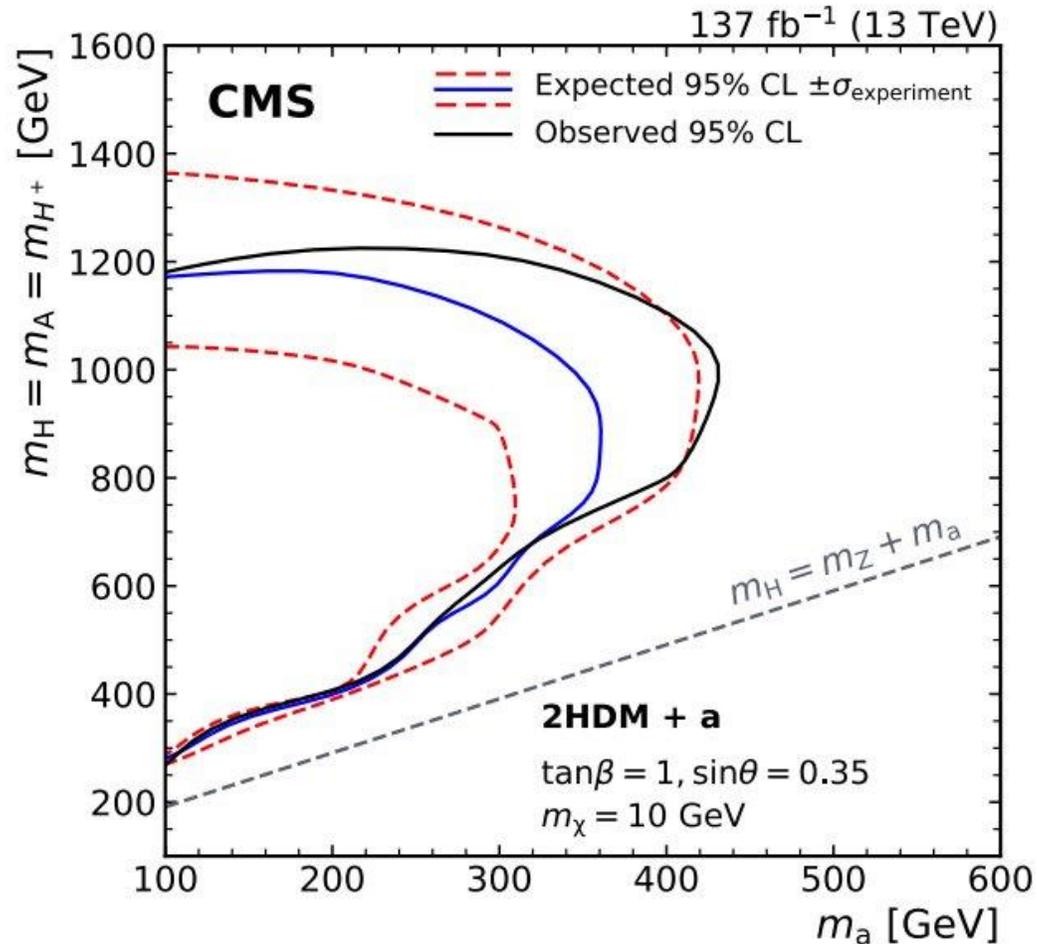
## Expected yields and the product of acceptance and efficiency

Model	Yields	Product of acceptance and efficiency (%)
Zh(125)	$864 \pm 64$	$10.6 \pm 0.8$
ADD $M_D = 3 \text{ TeV}, n = 4$	$35.1 \pm 2.4$	$18.6 \pm 1.3$
Unparticle $S_U = 0, d_U = 1.50$	$221 \pm 16$	$8.2 \pm 0.6$
2HDM+a $m_H = 1000 \text{ GeV}, m_a = 400 \text{ GeV}$	$14.1 \pm 4.0$	$12.7 \pm 2.7$
DM Vector $m_{\text{med}} = 1000 \text{ GeV}, m_\chi = 1 \text{ GeV}$	$64.8 \pm 6.1$	$17.6 \pm 1.7$

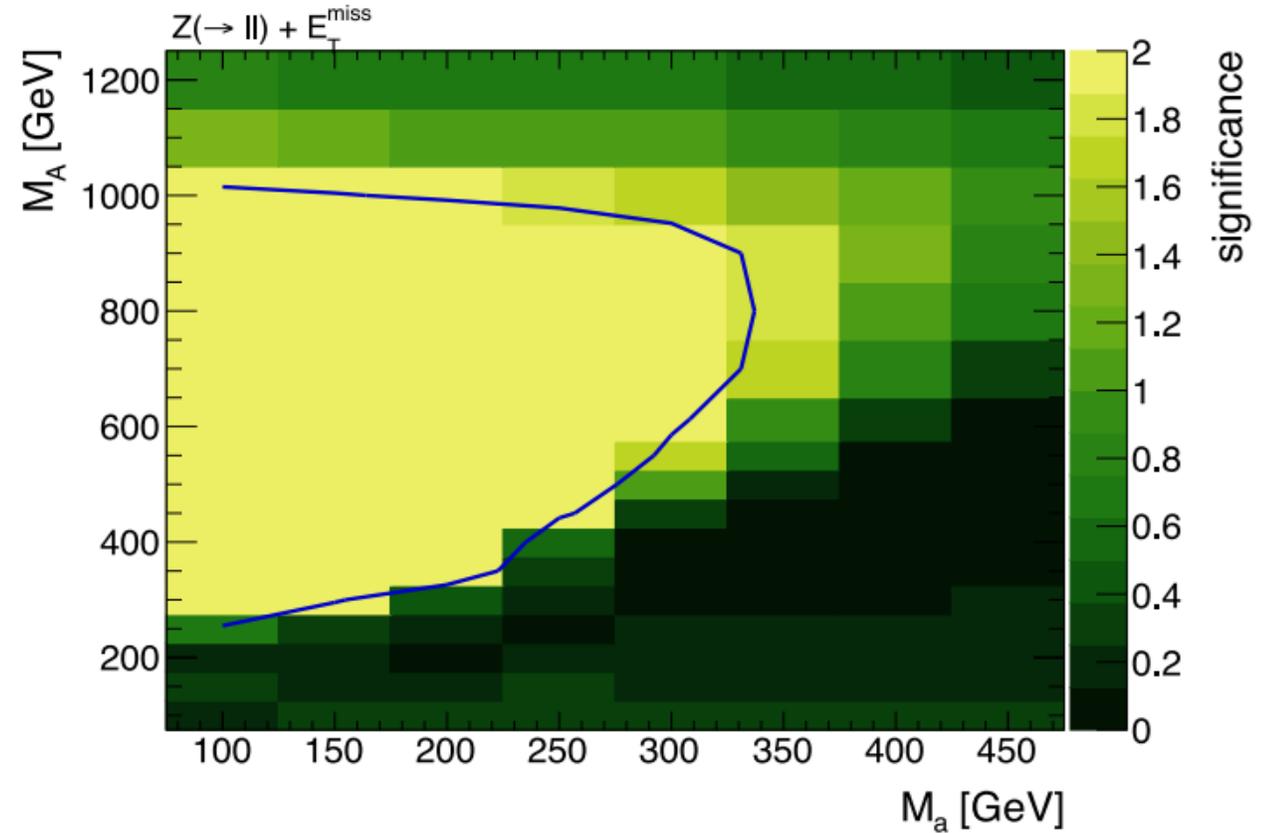


Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  [Eur. Phys. J. C 81 (2021) 13]

# CMS RUN2 Results for 2HDM+a



CMS Run 2 Exclusion Plot: Eur. Phys. J. C 81 (2021) 13



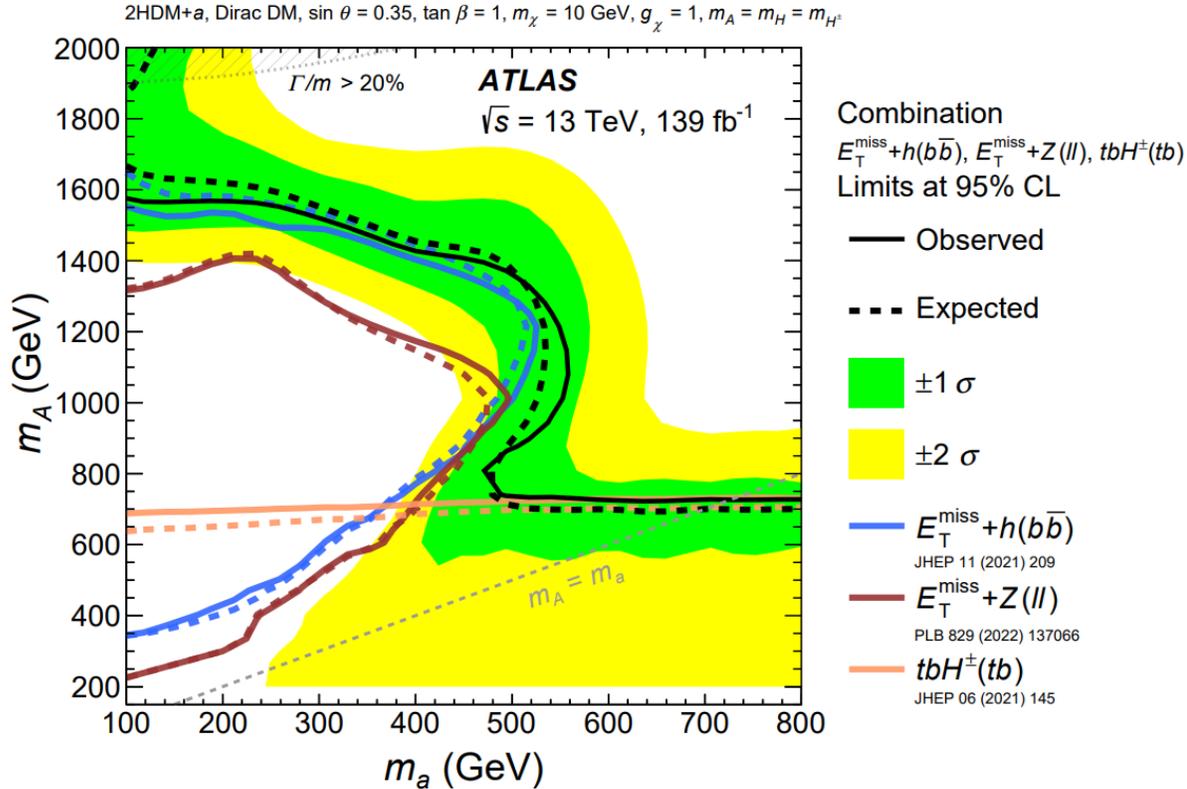
Estimated significance taken from:  
 LHC Dark Matter Working Group:  
 Next-generation spin-0 dark matter models  
[\[doi.org/10.1016/j.dark.2019.100351\]](https://doi.org/10.1016/j.dark.2019.100351)

# Conclusions

- *A search for dark matter particles can be performed using events with a Z boson and large missing transverse momentum*
- *Recent search has been performed with proton-proton collision data at a center-of-mass energy of 13 TeV, collected by the CMS experiment at the LHC in 2016-2018, corresponding to an integrated luminosity of 137 fb<sup>-1</sup>*
  - ***no evidence of physics beyond the standard model is observed***
  - *limits are set on dark matter particle production in the context of a two-Higgs-doublet model with an additional pseudoscalar mediator.*
- *Our group is working on the analysis, aiming to search for dark matter in events with a Z boson and large missing transverse momentum at a center-of-mass energy of 13.6 TeV, using the latest data from the CMS experiment taken during 2022-2024.*

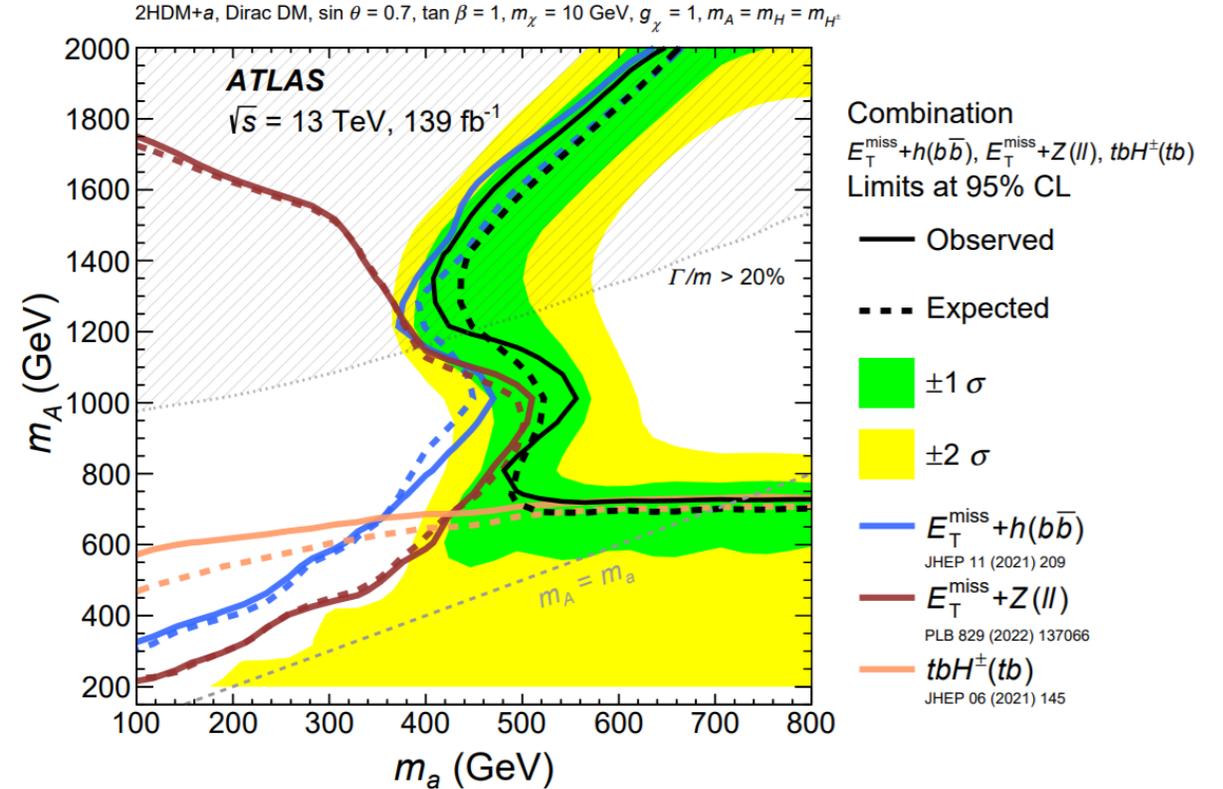
**Thank you for your attention!**

# ATLAS Plots. $m_a - m_A$ planes



(a)

arXiv:2008.04735



(b)

doi.org/10.1016/j.dark.2019.100351

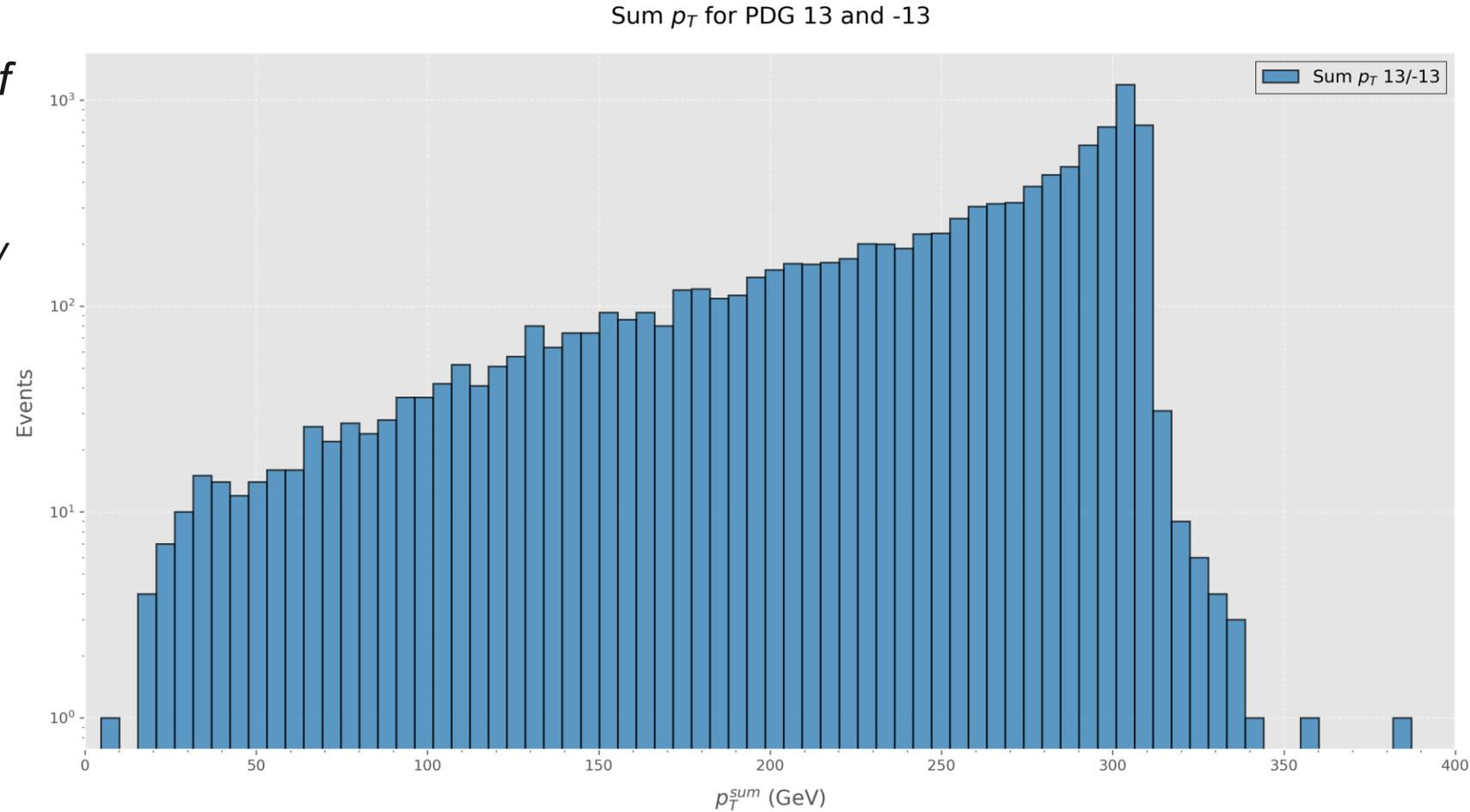
# Signal Simulation

*Distribution of sum  $p_T$  of a pair of muons at gen level*

*For  $M_a = 300$ ,  $M_H = 750$  peak at 307 GeV*

$$\lambda(m_A, m_B, m_C) = (m_A^2 - m_B^2 - m_C^2)^2 - 4m_B^2 m_C^2$$

$$p_{T,Z}^{\max} \simeq \frac{\lambda^{1/2}(M_H, M_Z, M_a)}{2M_H}$$

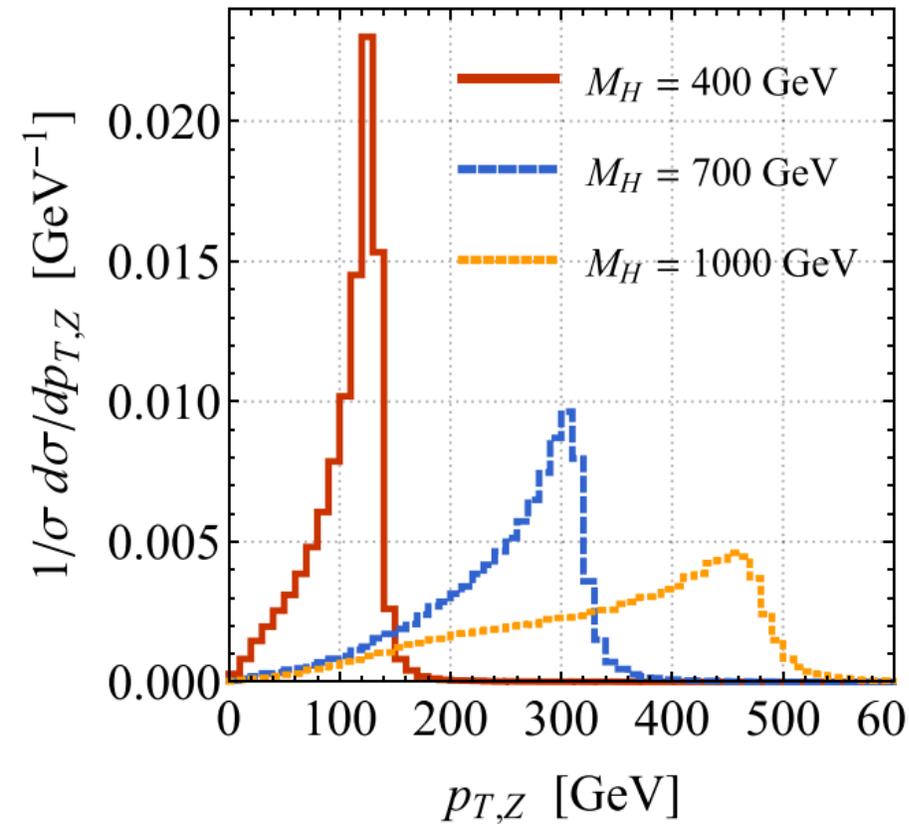


# Yakobian peak $p_T$

$$\lambda(m_A, m_B, m_C) = (m_A^2 - m_B^2 - m_C^2)^2 - 4m_B^2 m_C^2$$

$$p_{T,Z}^{\max} \simeq \frac{\lambda^{1/2}(M_H, M_Z, M_a)}{2M_H}$$

mono-Z,  $M_a = 200$  GeV



Yakobian peak  $p_{T,Z}^{\max}$ , GeV

