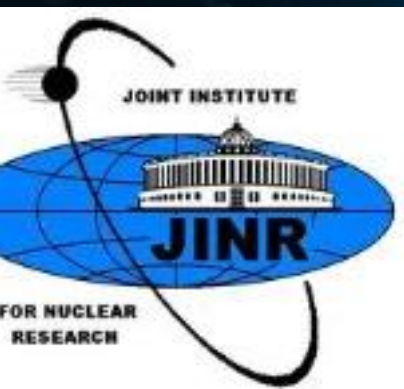


Prospects for Dark Matter in Pseudoscalar-Extended Two-Higgs- Doublet Model at Future e^+e^- Colliders



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STANDARD MODEL

□ The SM describes the fundamental constituents of matter and their interactions







$$\mathcal{L}_{\text{QCD}} = \sum_{\psi} \bar{\psi}_i \left(i\gamma^{\mu} (\partial_{\mu} \delta_{ij} - ig_s G_{\mu}^a T_{ij}^a) \right) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu},$$

$$\mathcal{L}_{\text{EW}} = \sum_{\psi} \bar{\psi} \gamma^{\mu} \left(i\partial_{\mu} - g' \frac{1}{2} Y_W B_{\mu} - g \frac{1}{2} \vec{\tau}_L \vec{W}_{\mu} \right) \psi - \frac{1}{4} W_a^{\mu\nu} W_{\mu\nu}^a - \frac{1}{4} B^{\mu\nu} B_{\mu\nu},$$

$$\mathcal{L}_{\text{H}} = \left| \left(\partial_{\mu} + \frac{i}{2} \left(g' Y_W B_{\mu} + g \vec{\tau} \vec{W}_{\mu} \right) \right) \varphi \right|^2 - \frac{\lambda^2}{4} (\varphi^{\dagger} \varphi - v^2)^2.$$


$$\mathcal{L}_{\text{Yukawa}} = \bar{U}_L G_u U_R \varphi^0 - \bar{D}_L G_u U_R \varphi^{-} + \bar{U}_L G_d D_R \varphi^{+} + \bar{D}_L G_d D_R \varphi^0 + \text{h. c.},$$

QUARKS


UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 	CHARM 1,275 GeV/c ² 2/3 1/2 	TOP 173,07 GeV/c ² 2/3 1/2 
DOWN 4,8 MeV/c ² -1/3 1/2 	STRANGE 95 MeV/c ² -1/3 1/2 	BOTTOM 4,18 GeV/c ² -1/3 1/2 


GLUON
 0
 0
 1


HIGGS BOSON
 126 GeV/c²
 0
 0








PHOTON
 0
 0
 1


GAUGE BOSONS

Z BOSON
 91,2 GeV/c²
 0
 1


W BOSON
 80,4 GeV/c²
 ±1
 1


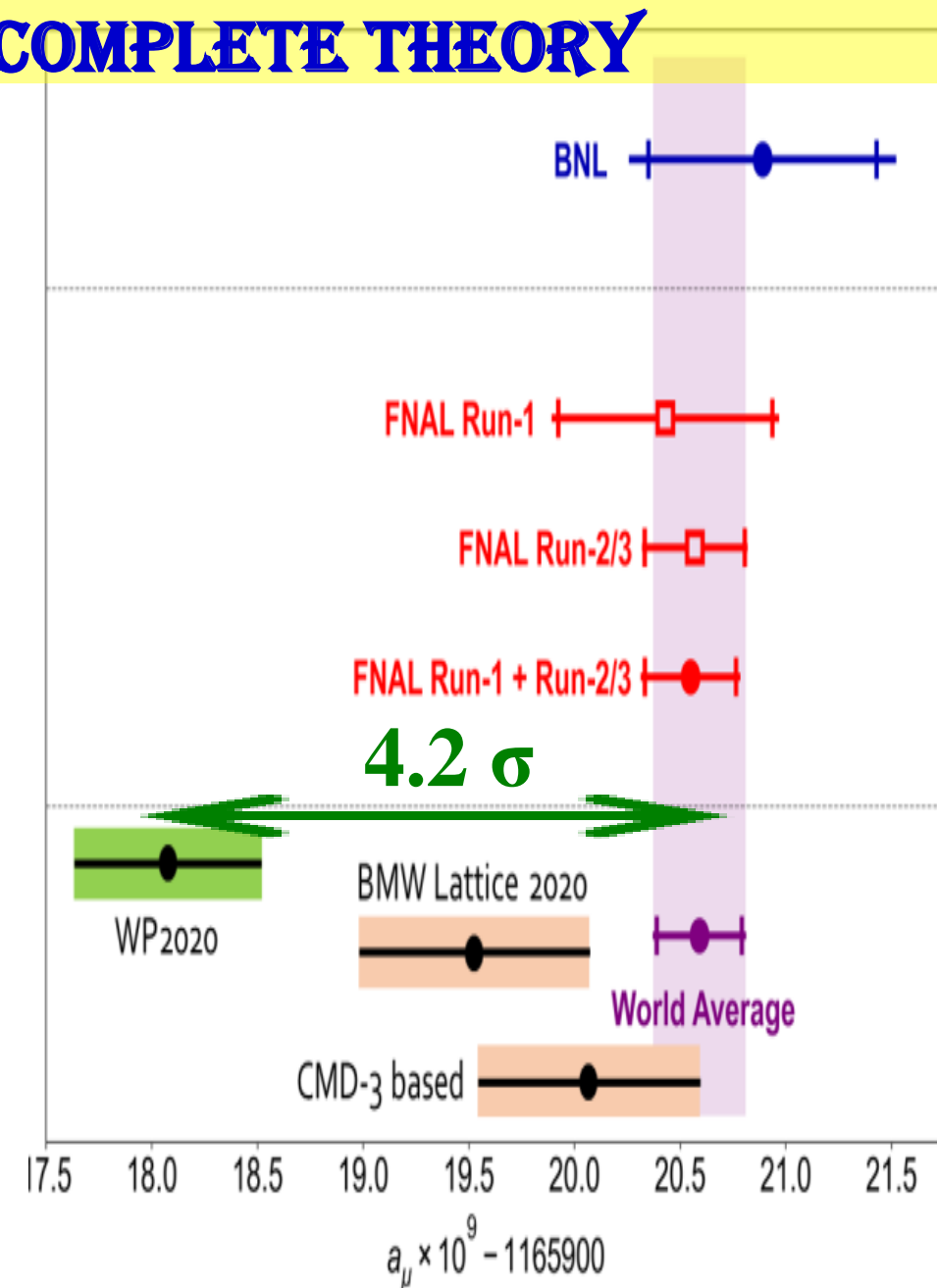
LEPTONS

ELECTRON 0,511 MeV/c ² -1 1/2 	MUON 105,7 MeV/c ² -1 1/2 	TAU 1,777 GeV/c ² -1 1/2 
ELECTRON NEUTRINO <2,2 eV/c ² 0 1/2 	MUON NEUTRINO <0,17 MeV/c ² 0 1/2 	TAU NEUTRINO <15,5 MeV/c ² 0 1/2 

Interaction	Gravitational	Weak	Electromagnetic	Strong	
		Electroweak		Fundamental	Residual
Property	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Acts on:	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Particles experiencing:	All particles	quarks, lepton _s	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (Not yet observed)	W ⁺ , W ⁻ and Z ⁰	γ (photon)	Gluons	Mesons
Strength at the scale of quarks:	10 ⁻⁴¹ (predicted)	10 ⁻⁴	1	60	Not applicable to quarks
Strength at the scale of protons/neutrons:	10 ⁻³⁶ (predicted)	10 ⁻⁷	1	Not applicable to hadrons	20

STANDARD MODEL PROBLEMS: AN INCOMPLETE THEORY

- ❑ Unknown nature of **Dark Matter**
- ❑ Very small cosmological constant and very weak gravity interaction
- ❑ Particle–antiparticle asymmetry in the Universe
- ❑ Problem of neutrino masses, mixing, oscillations
- ❑ Muon $(g-2)_\mu$ anomaly ($3.5\sigma \rightarrow 4.2\sigma$ BNL):
 $CMD-3 \sigma(e^+e^- \rightarrow \pi^+\pi^-) \rightarrow$ *new theoretical calculation!*
- ❑ B-anomalies (4.5σ): semi-leptonic B-decays
- ❑ CDF W-mass anomaly (7σ): *new ATLAS & CMS at 13 TeV result!*



Dark Matter Candidates

Axions (ALPs)

Mass: $\mu\text{eV} - \text{meV}$

Interaction:
very weak ($\propto 1/f_a$)

Search methods:

- Helioscopes (IAXO)
- Cavities (ADMX)

Sterile Neutrinos

Mass: $\text{keV} - \text{MeV}$

Interaction:
mixing with
active neutrinos

Search methods:

- X-ray telescopes
- Tritium (KATRIN)

WIMPs

Mass: $\text{GeV} - \text{TeV}$

Interaction:
electroweak

Search methods:

- Colliders (LHC, CEPC)
mono-X
- Direct searches
(LZ, XENONnT)

★ WIMP — Main candidate for CEPC research

2HDM (Two Higgs Doublet Model)

The Two Higgs Doublet Model (2HDM) is one of the simplest extension of the SM. Only one scalar multiplet with the same transformation under the SM gauge symmetries as the Higgs field is added to the field content of the SM. Consequently, the 2HDM Lagrangian can be written as:

$$L_{2HDM} = (D_\mu \phi_1)^\dagger D^\mu \phi_1 + (D_\mu \phi_2)^\dagger D^\mu \phi_2 - V_{2HDM} + L_{2HDM}^{Yuk} + L_{SM}^{noHiggs}$$

where



$$V_{2HDM} = \mu_1 \phi_1^\dagger \phi_1 + \mu_2 \phi_2^\dagger \phi_2 + (\mu_3 \phi_1^\dagger \phi_2 + h.c.) + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + (\lambda_5 (\phi_1^\dagger \phi_2)^2 + h.c.) + \phi_1^\dagger \phi_1 (\lambda_6 (\phi_1^\dagger \phi_2) + h.c.) + \phi_2^\dagger \phi_2 (\lambda_7 (\phi_1^\dagger \phi_2) + h.c.)$$

Ref. "Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle", Celine Degrande, Comput. Phys. Commun. 197 (2015) 239-262.

2HDM+a Model

Parameters:

$$v, M_h, M_A, M_H, M_{H^\pm}, M_a, m_\chi$$

$$\cos(\beta - \alpha), \tan \beta, \sin \theta,$$

$$y_\chi, \lambda_3, \lambda_{P1}, \lambda_{P2}$$

2HDM+a

arxiv.1701.07427

light neutral pseudoscalar
singlet

Parameter	Meaning
$\cos(\beta - \alpha)$	Determines how SM-like the light Higgs is.
$\tan \beta$	Ratio of the two Higgs doublet vacuum expectation values: $\tan\beta=v_2/v_1$. Controls the coupling of Higgs bosons to fermions.
$\sin \theta$	Mixing angle between the two CP-odd states: the doublet pseudoscalar A and the singlet pseudoscalar a. This parameter controls the coupling of the SM-like Higgs h to the mediator a.
y_χ	Yukawa coupling of the pseudoscalar mediator a to the Dark Matter χ .
λ_3	Quartic coupling between the two Higgs doublets in the scalar potential.
$\lambda_{P1}, \lambda_{P2}$	Quartic portal couplings between the singlet P and the two Higgs doublets.

The interaction of a pseudoscalar with dark matter is given by the Lagrangian:

$$\mathcal{L}_\chi = -iy_\chi P \bar{\chi} \gamma_5 \chi$$

$$V = V_H + V_{HP} + V_P$$

Doublet potential

$$V_H = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + (\mu_3 H_1^\dagger H_2 + \text{h.c.}) + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2$$

$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + [\lambda_5 (H_1^\dagger H_2)^2 + \text{h.c.}] ,$$

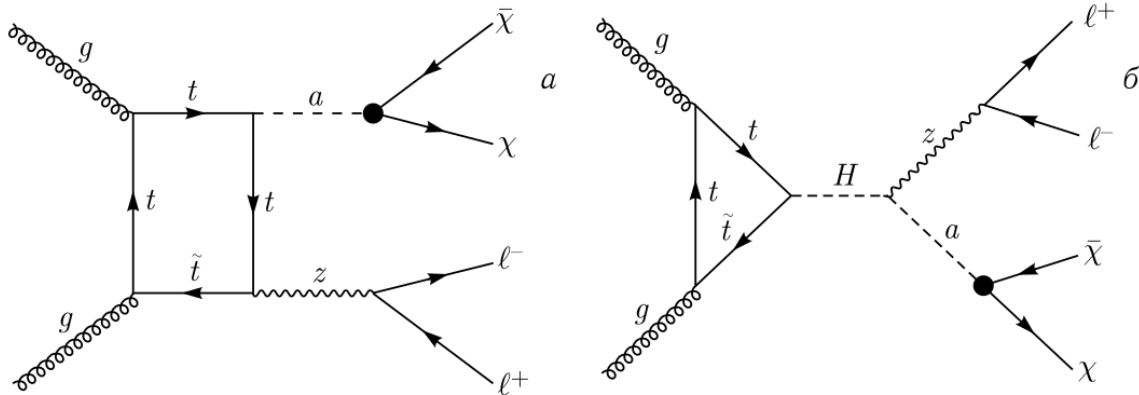
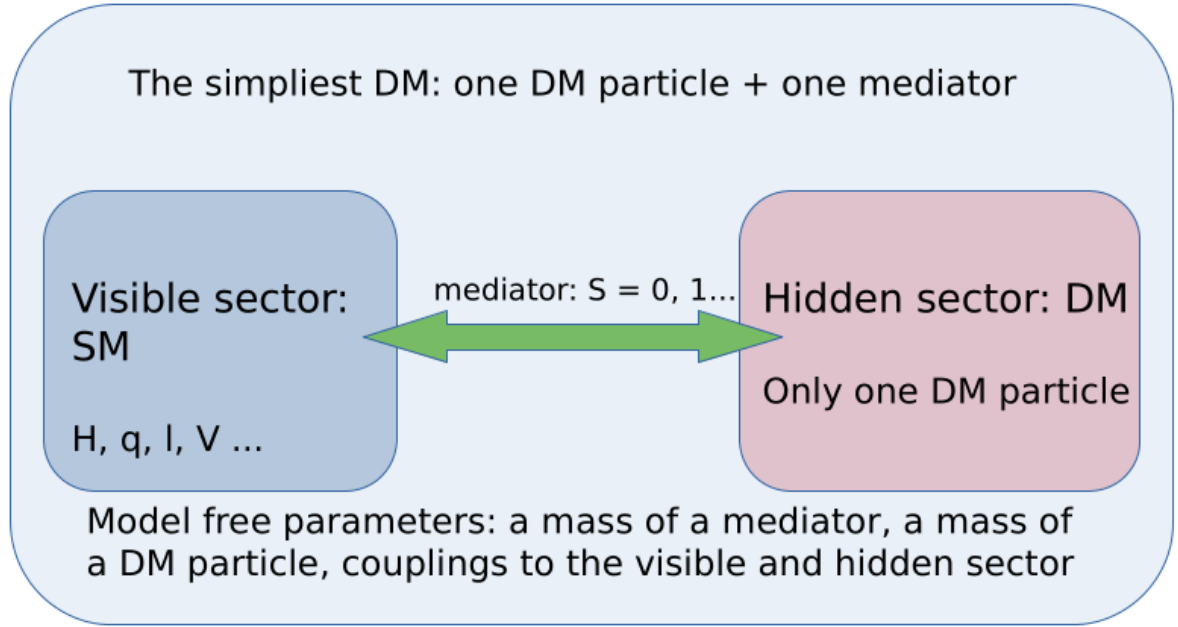
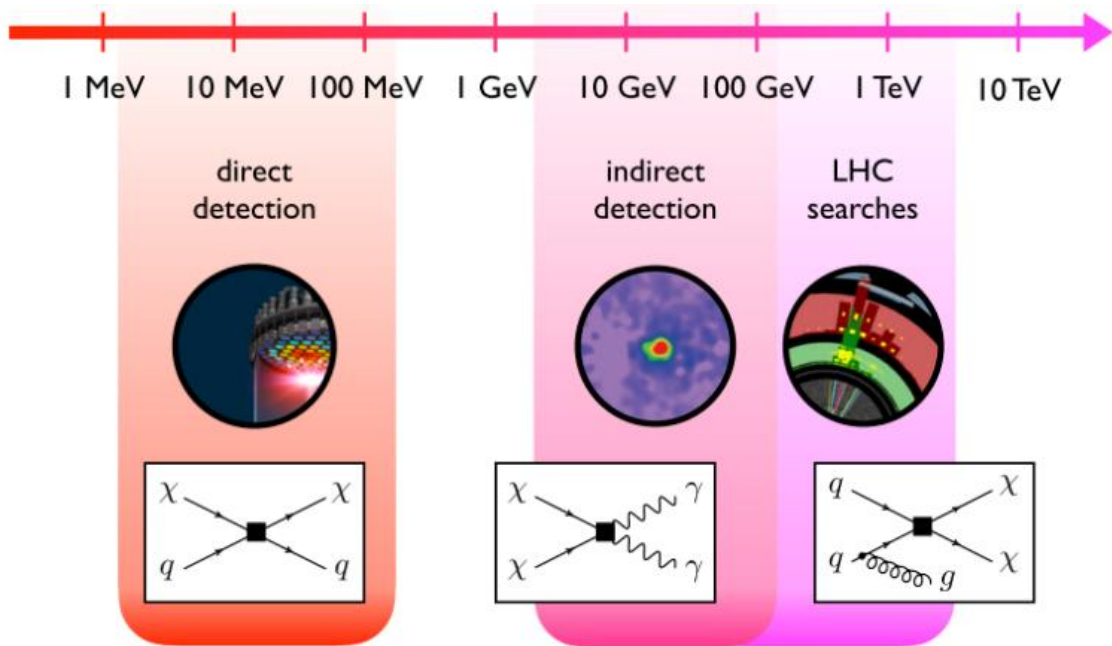
Singlet -doublet potential

$$V_{HP} = P (ib_P H_1^\dagger H_2 + \text{h.c.}) + P^2 (\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2) ,$$

Singlet potential

$$V_P = \frac{1}{2} m_P^2 P^2 .$$

Results of CMS observations

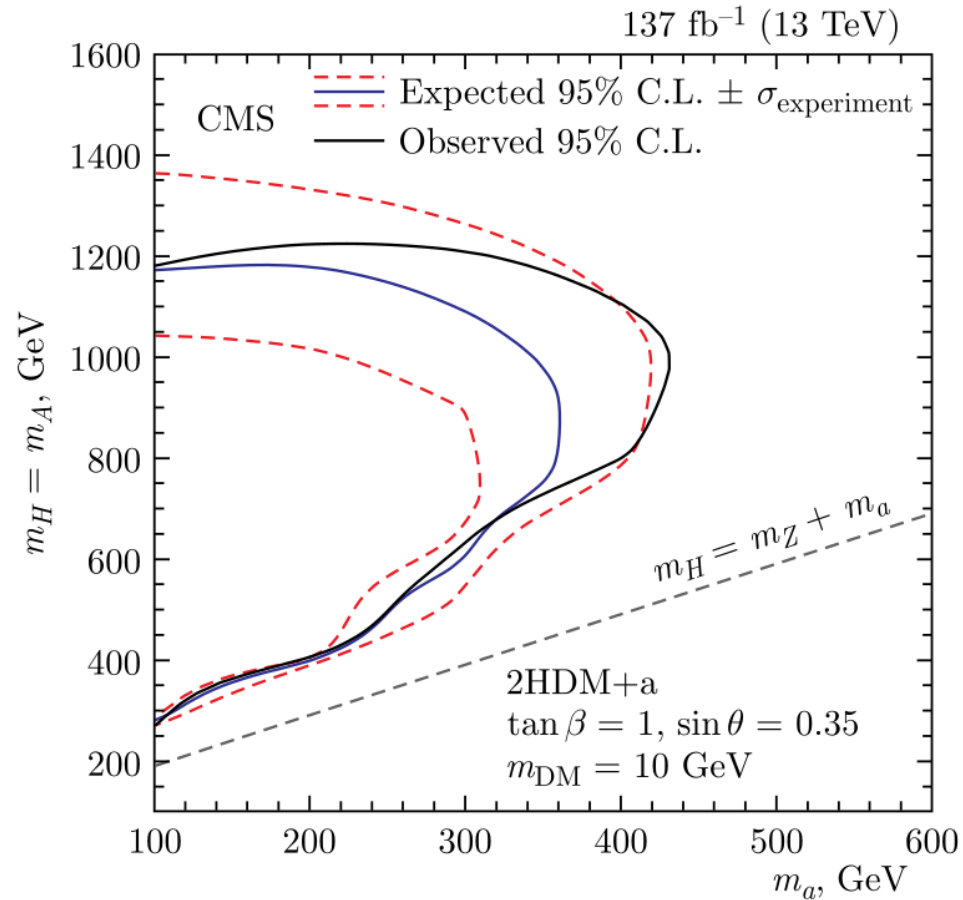


More variety in leading MET

signatures:

- mono-tt
- mono-jet
- mono-Higgs
- mono-Z
- mono-top

Results of CMS observations



Sirunyan A. M. et al. (CMS Collab.). Search for Dark Matter Produced in Association with a Leptonically Decaying Z Boson in Proton–Proton Collisions at $s = 13$ TeV // Eur. Phys. J. C. 2021. V. 81. P. 13; Erratum: Eur. Phys. J. C. 2021. V. 81. P. 333

The 95% CL upper limits on the 2HDM+a model with the mixing angles set to $\tan \beta = 1$ and $\sin \theta = 0.35$ and with a DM particle mass of $m_\chi = 10$ GeV. The limits are shown as a function of the heavy Higgs boson and the pseudoscalar masses.

Dark matter observations at CEPC

Simplified Dark matter models: - Scalar/Fermion/Vector portals

Ref. New Physics Search at the CEPC: a General Perspective, 67-88, arXiv:2505.24810v2

Portal	Effective operator	\sqrt{s} [GeV]	$\mathcal{L}[ab^{-1}]$	Sensitivity of CEPC (HL-LHC)	Figs.	Ref.
Scalar	$\lambda_{HP} H ^2 S^2 \rightarrow$ scalar mixing $\sin \theta$	250	5	invisible S, $\sin \theta \approx 0.03$ (0.20 global-fits)	24	[220]
Fermion	$y\ell\bar{\chi}_L S^\dagger \ell_R + \text{H.c.}$	250	5	covering $100 \text{ GeV} < m_S < 170 \text{ GeV}$	25	[45]
	$\kappa\Phi\bar{q}'_L \ell_R + \text{H.c.}$ (dark QCD)	250	5	$m_\Phi \sim 10 \text{ TeV}$ for $c\tau_{\text{darkpion}} \in [1, 10^3] \text{ cm}$ (Null)	27	[221]
	$y\Phi\bar{F}_L \ell_R + \text{H.c.}$	240	5.6	$y\theta_L \in [10^{-11}, 10^{-7}]$ ($\lesssim 10^{-8} - 10^{-9}$)	-	[222]
Vector	$A'_\mu (e\epsilon J_{\text{em}}^\mu + g_D \bar{\chi}\gamma^\mu \chi)$	250	5	$\epsilon \sim 10^{-3}$ for $g_D = e$ and $m_{A'} < 125 \text{ GeV}$ ($\epsilon \sim 0.02$)	28, 29	[220]
	$\epsilon A_\mu \bar{\chi}\gamma^\mu \chi$, (millicharge DM)	250	5	$\epsilon \sim 0.1$ for $m_\chi \sim 50 \text{ GeV}$	-	[223]
		91.2	2.6	$\epsilon \sim 0.02$ for $m_\chi \sim 5 \text{ GeV}$		
		160	16	$\epsilon \sim 0.5$ for $m_\chi \sim 10 \text{ GeV}$		
	$\frac{1}{2}\mu_\chi \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{1}{2}d_\chi \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$	91.2	100	$\mu_\chi, d_\chi \sim 4 \times 10^{-7}$ (4×10^{-6}) μ_B for $m_\chi < 25 \text{ GeV}$	30	[224]
240		20	$a_\chi, b_\chi \sim 10^{-6}$ (2×10^{-6}) GeV^{-2} for $m_\chi < 80 \text{ GeV}$			

TABLE : Recent results from the CEPC study on dark sector signals. The first column lists the signal signatures, the second column presents the corresponding relevant operators, the third and fourth columns provide the center-of-mass energy and the integrated luminosity. The fifth column presents the sensitivity to the coupling, suppression scale, or branching ratios at the CEPC. Where relevant HL-LHC sensitivities are available, they are shown in parentheses or with Null meaning HL-LHC constraints do not apply.

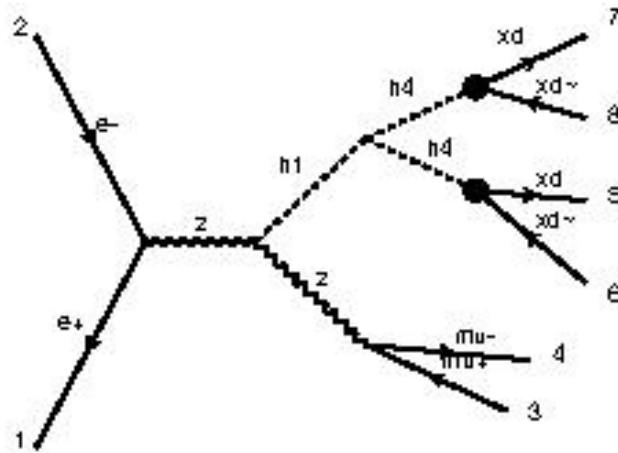
Model Parameters and Signal Simulation

Generator: MadGraph5MC@NLO.2.9.2

Model: 2HDM+a + NNPDF 3.1 NNLO

Process: $e^+ e^- \rightarrow z h1, (h1 \rightarrow h4 h4, h4 \rightarrow \chi \chi^-), z \rightarrow \mu^+ \mu^-$

2HDM+a



Free parameters:

$m_{h1} = [80:160]$ GeV

$m_a = [20:80]$ GeV

$\sin\theta = 0.03.$

$\sin\theta = 0.05.$

$\sin\theta = 0.1.$

General settings:

Energy 250 GeV

Mass of Dark matter particle $m_\chi = 5, 10$ GeV

Vacuum expectation values of the two Higgs doublets, $\tan(\beta) =$

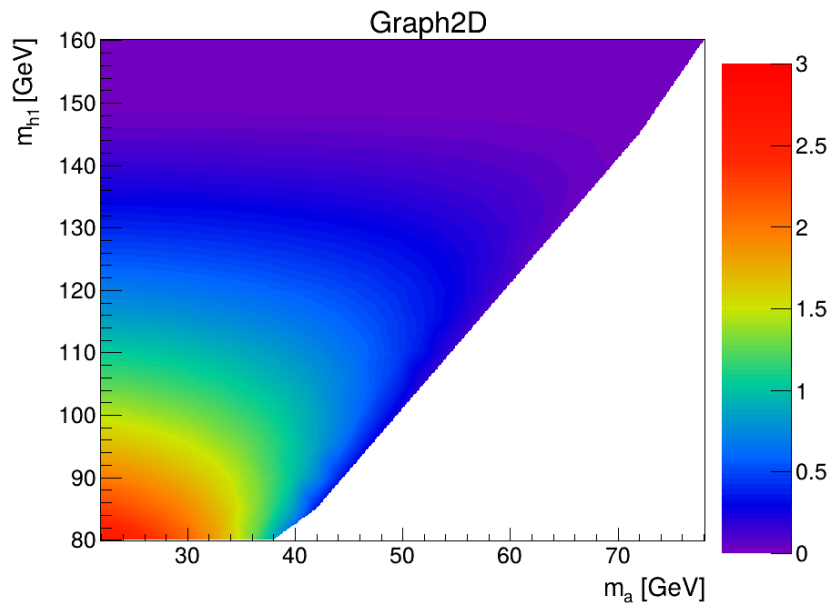
1

Coupling of mediator to DM $g_{PXd} = 1$

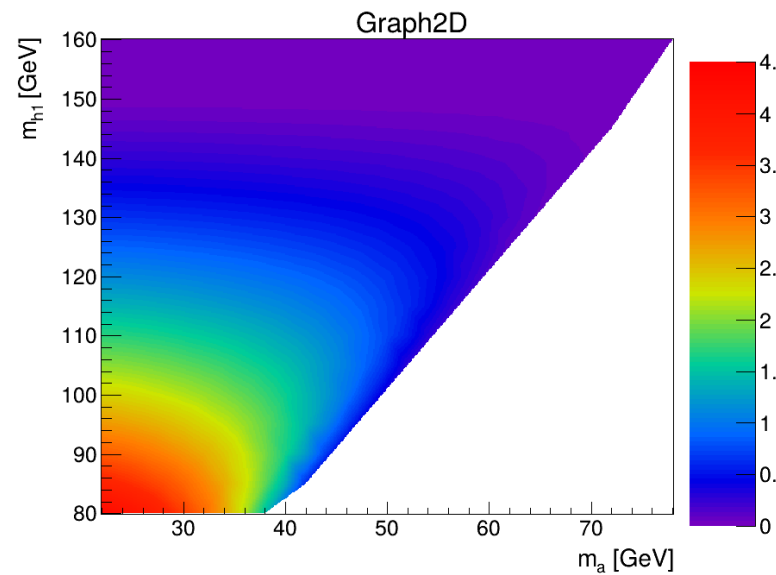
https://github.com/LHC-DMWG/model-repository/tree/master/models/Pseudoscalar_2HDM

Results of the calculation of the total cross section for the processes

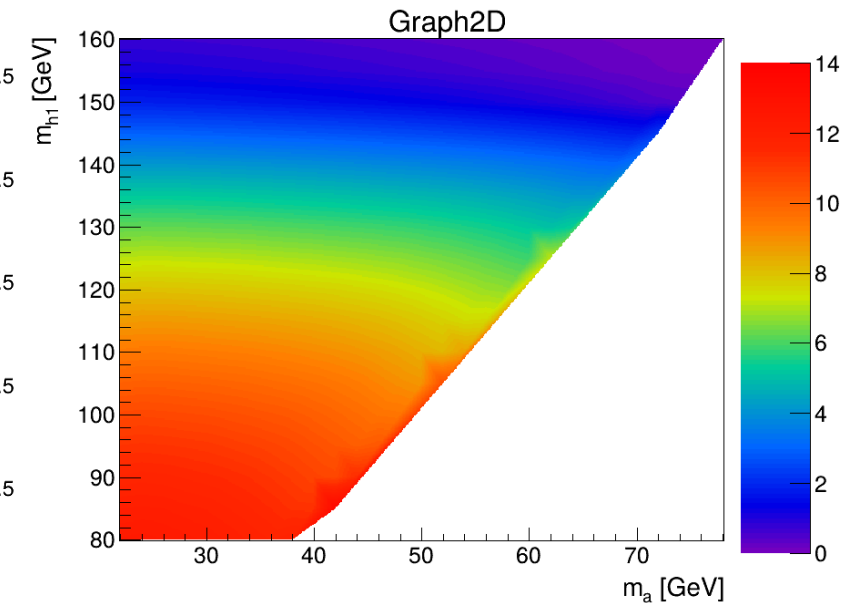
$\sin\theta = 0.03$



$\sin\theta = 0.05$



$\sin\theta = 0.1$



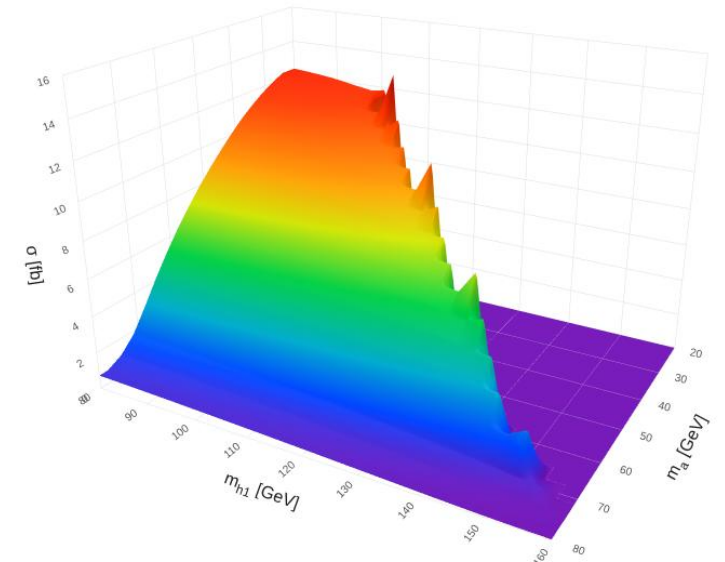
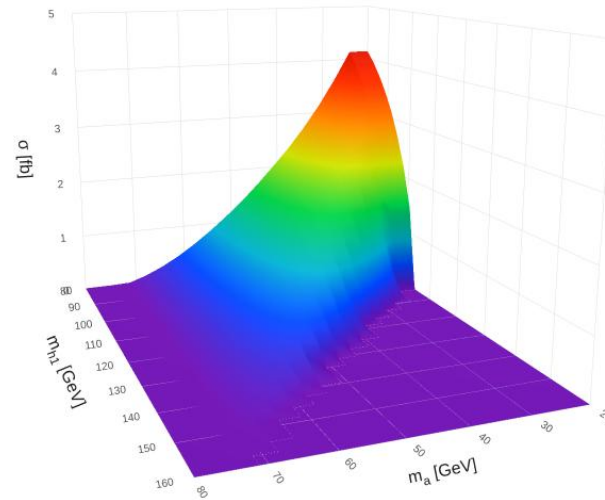
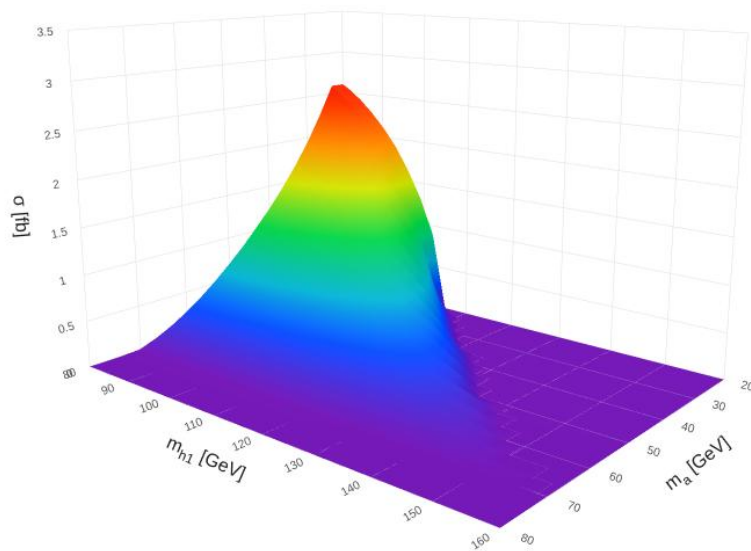
Cross section for $m_\chi = 10$ GeV: $\sin\theta = 0.03 \rightarrow$ very small; $\sin\theta = 0.05 \rightarrow$ moderate; $\sin\theta = 0.1 \rightarrow$ larger.

Results of the calculation of the total cross section for the processes

$\sin\theta = 0.03$

$\sin\theta = 0.05$

$\sin\theta = 0.1$



Cross section for $m_\chi = 10$ GeV: $\sin\theta = 0.03 \rightarrow$ very small; $\sin\theta = 0.05 \rightarrow$ moderate; $\sin\theta = 0.1 \rightarrow$ larger.

Summary

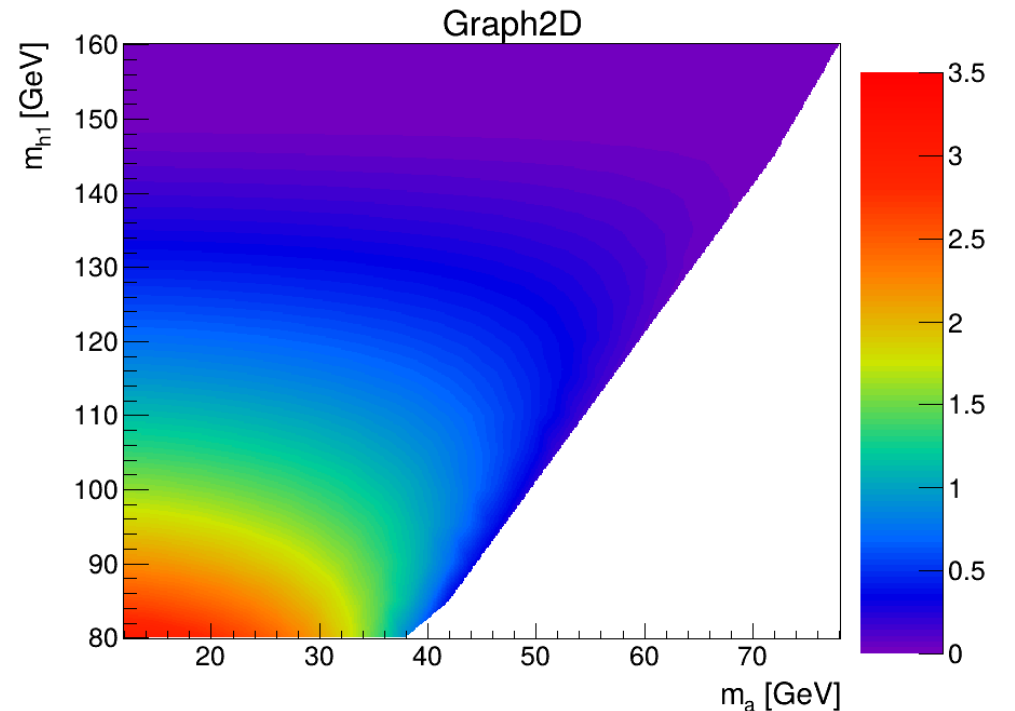
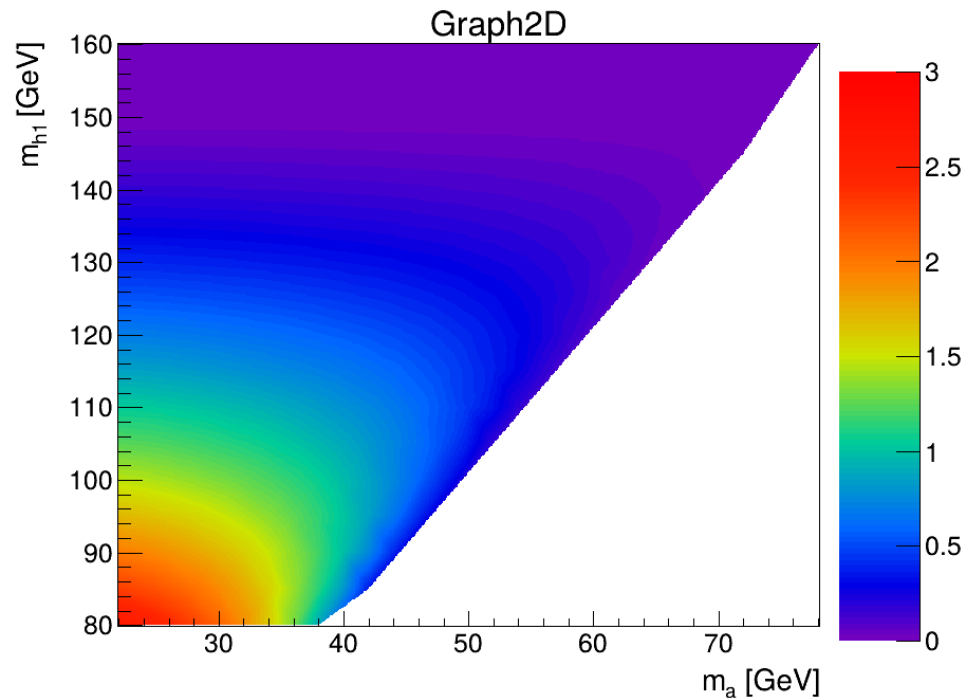
Parameter	0.03	0.05	0.1
m_a range	22 - 78	22 - 78	22 - 78
m_h1 range	80 - 160	80 - 160	80 - 160
Max σ [fb]	2.6423	4.2856	13.5240
zmax on plots	3.0	4.5	14.0

1. All three datasets share the same (m_{h1} , m_a) grid (80–160, step 5; 22–78, step 2; 329 points). Only cross-section values differ, reflecting different $\sin\theta$ in 2HDM+a.
2. $\sin\theta = 0.05$ dataset has cross-sections ~50–80% larger than $\sin\theta = 0.03$ dataset across the whole space, with a uniform scaling factor.
3. $\sin\theta = 0.1$ dataset shows dramatic enhancement — up to higher values at specific resonances (e.g., (85,42): 0.353 \rightarrow 11.377 fb). These narrow spikes suggest resonant enhancement near a threshold or a second Higgs resonance.
4. Away from resonant peaks, $\sin\theta = 0.1$ follows a similar shape but scaled up by ~50–80% relative to $\sin\theta = 0.03$, similar to $\sin\theta = 0.05$.

Results of the calculation of the total cross section for the processes

$m_{xd} = 10 \text{ GeV}$

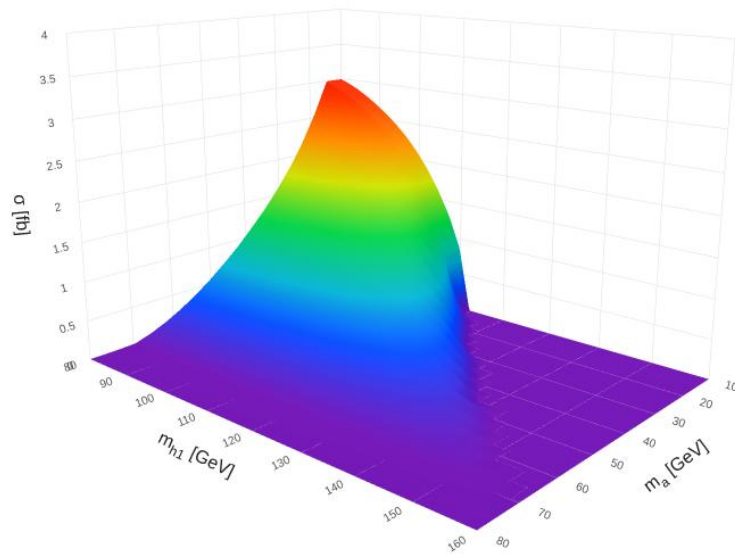
$m_{xd} = 5 \text{ GeV}$



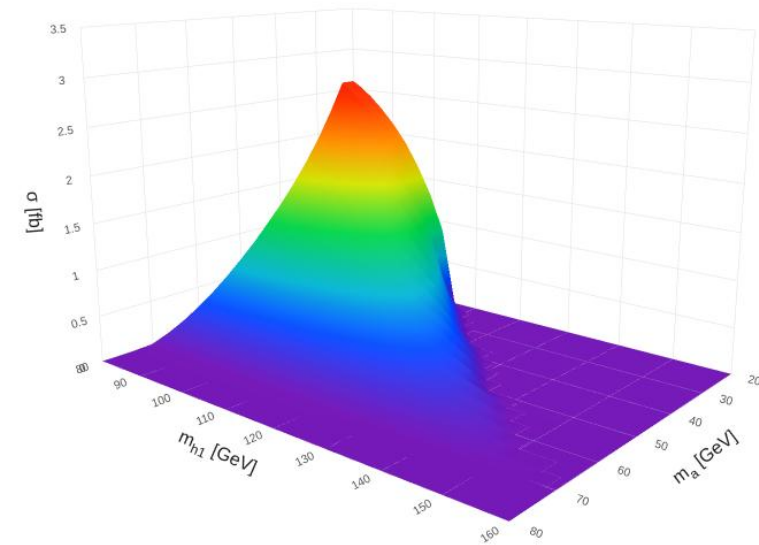
Cross section for $m_\chi = 10 \text{ GeV}$ and $m_\chi = 5 \text{ GeV}$ with $\sin\theta = 0.03$

Results of the calculation of the total cross section for the processes

$m_{\chi d} = 10 \text{ GeV}$



$m_{\chi d} = 5 \text{ GeV}$



Cross section for $m_{\chi} = 10 \text{ GeV}$ and $m_{\chi} = 5 \text{ GeV}$ with $\sin\theta = 0.03$

Summary

Parameter	10 GeV	5 GeV
m_a range	22 - 78	12 - 78
m_h1 range	80 - 160	80 - 160
Max σ [fb]	2.6423	3.0504
zmax on plots	3.0	3.5

1. Scans have m_a step 2 GeV and extends down to $m_a = 12$ GeV (vs 22 GeV).

Common points ($m_a \geq 22$): 329 points	
Metric	Value
Mean relative difference	-0.17%
Min difference	-2.32%
Max difference	+0.78%

2. Low m_a points (12–20 GeV) in $m_\chi = 5$ GeV give higher cross-sections, up to 3.05 fb at (80,12), vs 2.64 fb in $m_\chi = 10$ GeV at (80,22).

3. At $m_a \geq 22$ GeV, both datasets agree within $\sim 2\%$. $m_\chi = 10$ GeV is 1–2% lower at low masses and nearly identical at high masses.

Summary

- Motivation: why we search for Dark Matter at CEPC

The Standard Model does not explain the nature of Dark Matter. CEPC, with its clean e^+e^- environment, provides a unique sensitivity to invisible Higgs decays — $\text{BR}(H \rightarrow \text{inv}) < 0.26\%$, an order of magnitude better than LHC. This opens a window for discovering Higgs-portal Dark Matter.

- What has already been done at LHC (CMS Run 2)

CMS data (13 TeV, 137 fb^{-1}) showed no signal in the $pp \rightarrow Z + \text{MET}$ process. The low-mass region is excluded, but the high-mass region remains open. My analysis complements these searches in a clean e^+e^- environment with model-independent measurements.

Summary

- This Work: 2D Scan in 2HDM+a

A detailed 2D scan of the $e^+e^- \rightarrow Z h_1 \rightarrow \mu^+ \mu^- + 4\chi$ process was performed ($\sqrt{s} = 250$ GeV, $m_{h_1} = 80\text{--}160$ GeV, $m_a = 20\text{--}80$ GeV). The cross-section depends strongly on the coupling $\sin\theta$ and the DM mass m_χ .

- Dependence on $\sin\theta$ (for $m_\chi = 10$ GeV)

$\sin\theta = 0.03$ (weak coupling) \rightarrow very small cross-section.

$\sin\theta = 0.05 \rightarrow$ cross-section is $\sim 50\text{--}80\%$ larger than for $\sin\theta = 0.03$.

$\sin\theta = 0.1 \rightarrow$ dramatic enhancement (at specific resonances, e.g., at $(m_{h_1}=85, m_a=42)$: from 0.353 fb to 11.377 fb).

- Dependence on m_χ (for $\sin\theta = 0.03$)

Lower DM mass ($m_\chi = 5$ GeV) gives a larger kinematic phase space.

Cross-section is higher for $m_\chi = 5$ GeV (e.g., up to 3.05 fb at $(80,12)$) compared to $m_\chi = 10$ GeV (2.64 fb at $(80,22)$).

Summary

- Conclusion & Novelty

This work provides a direct comparative analysis of the 2HDM+a model at CEPC. For the first time, the cross-section behaviour is mapped as a 2D function of m_{h1} and m_a , clearly showing its dependence on $\sin\theta$ and m_χ . The results help define optimal search strategies for the IDEA detector.

- Future Plans

- Extend the study to a direct comparison with the 2HDM+s (scalar portal) model.
- Perform scans for other benchmark values of $\sin\theta$ (e.g., 0.3) and higher collider energies ($\sqrt{s} = 360$ GeV).
- Include Standard Model backgrounds to estimate the realistic signal significance at CEPC with 5.6 ab^{-1} .

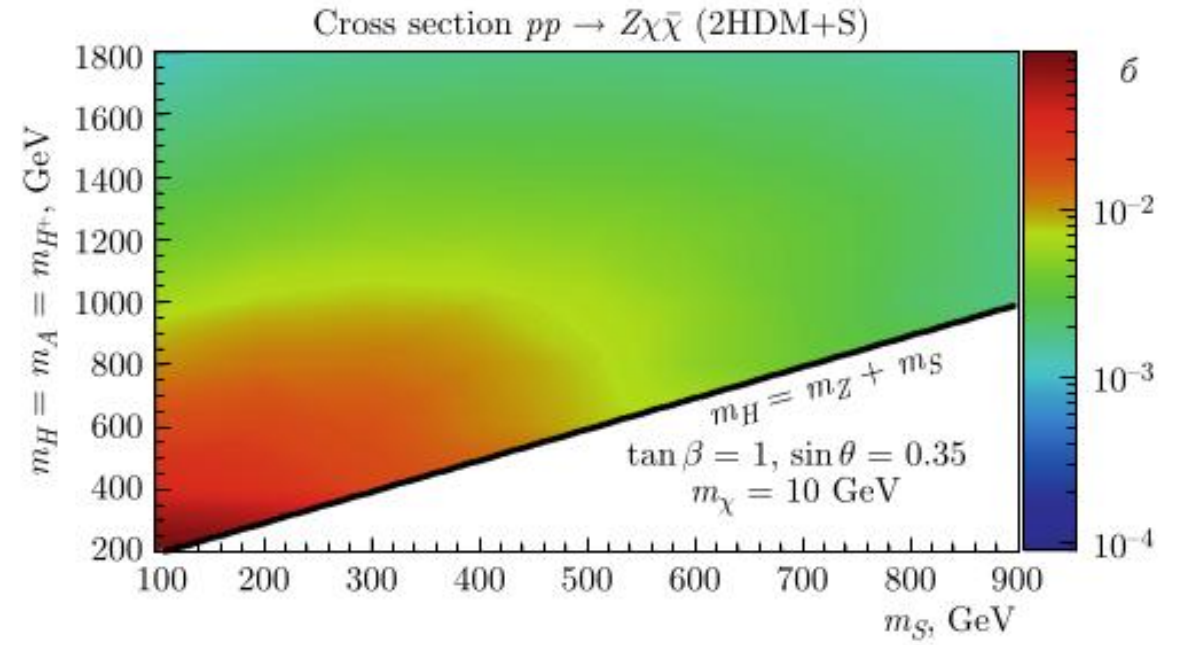
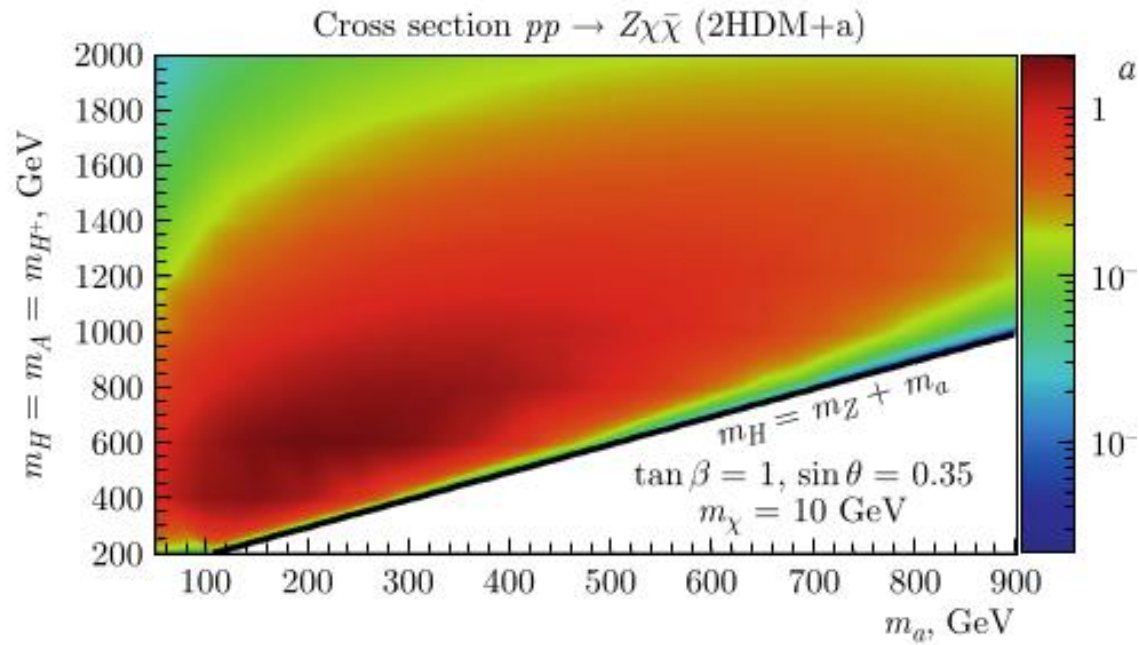
Akcnowledgements

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BACKUP SLIDES



Results of the calculation of the total cross section for the process $pp \rightarrow Z\chi\bar{\chi}$ for the 2HDM+a (left) and 2HDM+S (right) models depending on the masses of the heavy Higgses (M_H) and the mediator particle (m_a or m_s)

