Search for dark matter particles predicted by extended Higgs models

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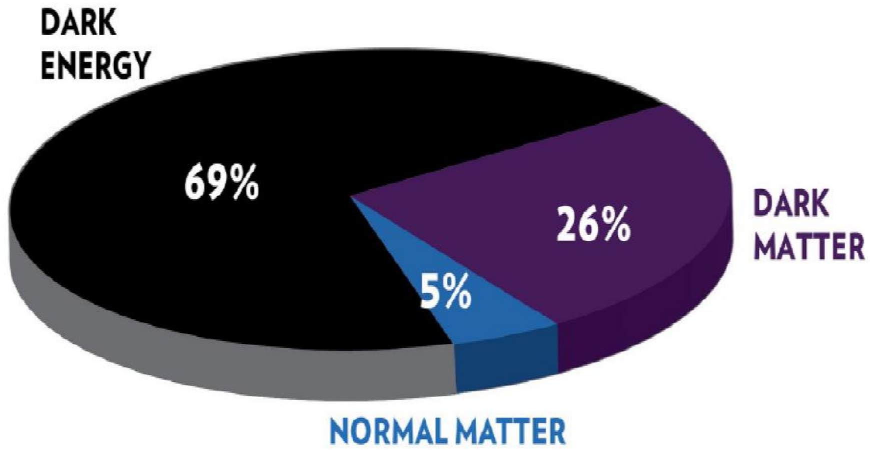
Introduction: Dark Matter



Dark matter (DM) is

- Not interacting (very weakly interacting) with ordinary matter
- Electrically neutral
- Stable in terms of cosmological time (14 bill. years)
- Initiated in the early stage of the Universe (till the change of the regimes, from radiation-dominant epoch to epoch of matter domination)

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

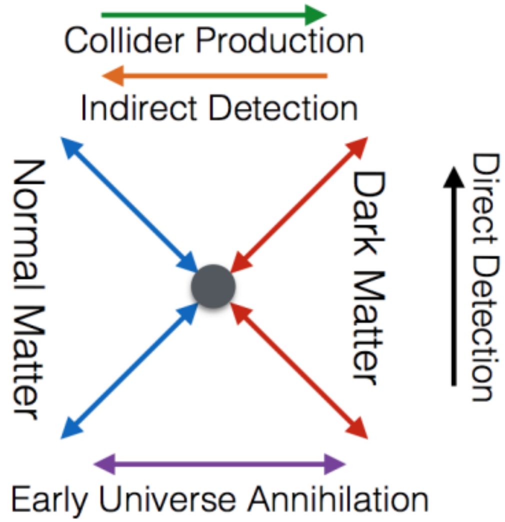
- Anisotropy of cosmic microwave background, flatness of the Universe, the prevalence of the elements and necessity of DM.
- Forming of the early Universe structure, the growth of the initial inhomogeneities

DM candidates

- Baryonic matter (massive astrophysical compact halo objects - MACHO)

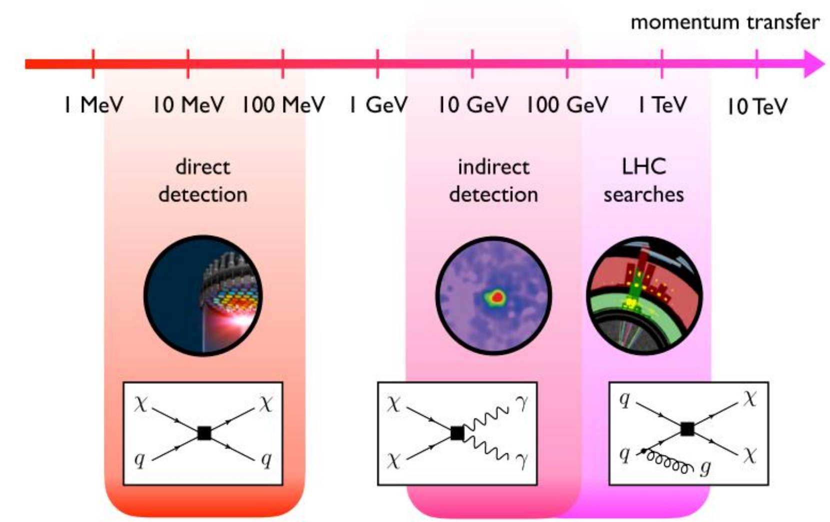
- Non-baryonic matter (sterile neutrinos, weakly interacting massive particles – WIMPs, axions, supersymmetric particles, etc.)

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



The LHC is able to probe energies higher than ever with huge luminosities:

- Largest dataset to date to analyze at 13 TeV
- Perfect tool to try and detect DM particles
- Able to study a large range of particle masses and cross-sections
- The two multipurpose detectors (CMS, ATLAS) are mostly able to search for DM particles

However, if producing dark matter particles is theoretically possible, detecting them directly is impossible, as they are not expected to interact with detector.

How to detect DM?

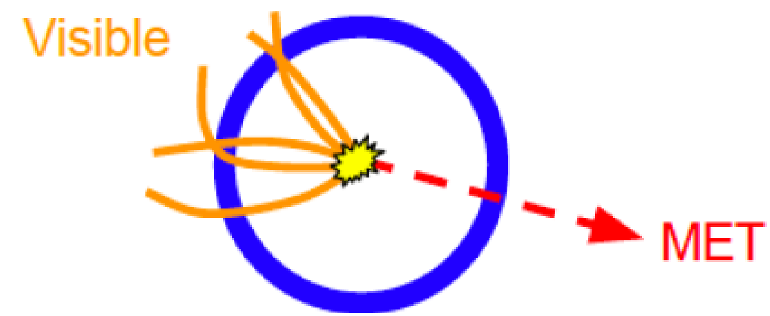
The CMS detector is not able to directly detect eventual dark matter particles

The key variable to detect DM is the missing transverse energy (MET):

- Defined as the imbalance in transverse momentum in the plane perpendicular to the beam direction p_T^{miss}

$$p_T^{\text{miss}} = -|\sum \overrightarrow{p_T}| = 0$$

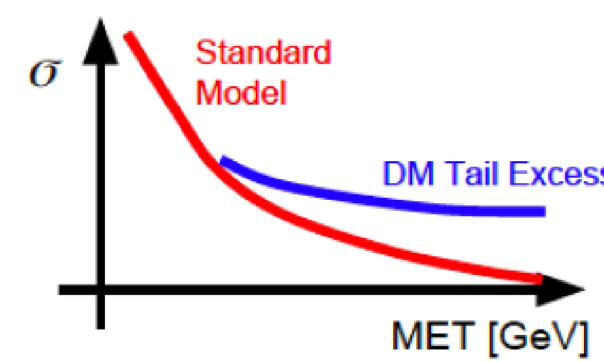
- This quantity is $p_T^{miss} \neq 0$ if something escapes the detector undetected



Most of the DM searches are therefore dependant on p_T^{miss}

However, $p_T^{miss} \neq 0$ does not mean that we discovered new physics, as common processes can have the same effect:

- Neutrino production
- Limited detector resolution



2HDM+a/S Models

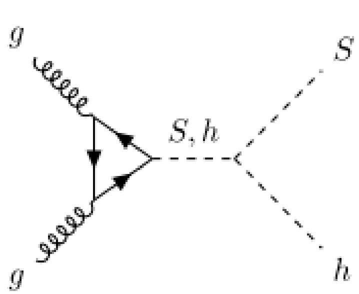
The two-Higgs-doublet model (2HDM) is a way to extend Higgs sector

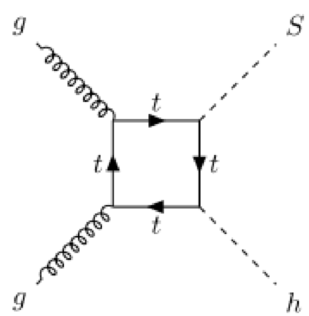
- neutral CP-even scalars *h, H*
- neutral CP-odd pseudoscalar *A*
- charged H^+, H^-

2HDM+s **arXiv:1612.03475**

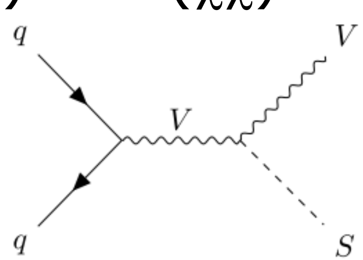
2HDM + S (neutral scalar singlet)

h (bbar) + S ($\chi\chi$) = bbar + MET





V (W/Z) + S ($\chi\chi$) = Z (ll) + MET

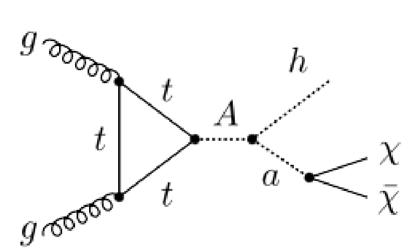


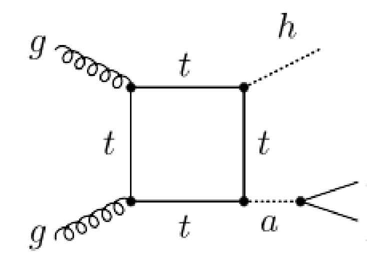
http://feynrules.irmp.ucl.ac.be/wiki/DMGISM0

2HDM+a **arXiv:1701.07427**

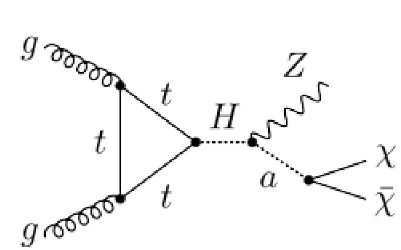
2HDM + a (neutral pseudoscalar singlet)

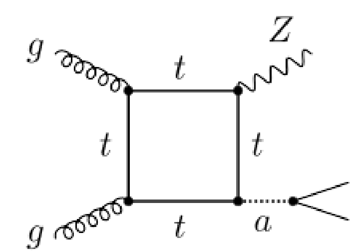
h (bbar) + a ($\chi\chi$) = bbar + MET





Z + a ($\chi\chi$) = Z (ll) + MET





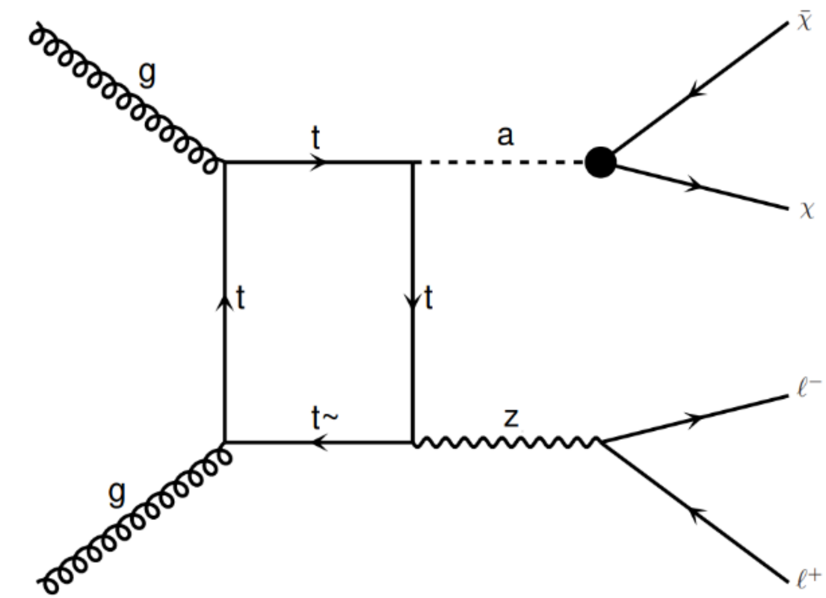
https://github.com/LHC-DMWG/model-repository/tree/master/models/Pseudoscalar_2HDM

Model Parameters and Signal Simulation

Generator: **MadGraph5MC@NLO.2.9.2**
(PS, frag./hadr. - **Pythia 8**)

Models: 2HDM+s or 2HDM+a + NNPDF 3.1 NNLO

Process: p p > Z χ χ (16 diagrams)



Free parameters for **2HDM + a**:

- masses of heavy higgses, $m_{H+/-} = m_H = m_A =$ [600:2000] GeV
- mass of dark matter particle, mχ = [1:2000] GeV
- mass of light pseudoscalar/scalar states, $m_a = m_S =$[300:1000] GeV
- the ratio of the vacuum expectation values of the two Higgs doublets, tan(β) = [0.5:50]
- the mixing angle of the two CP-odd weak spin-0 eigenstates (a/A), sin(Θ) = [0.15:0.7]
- the mixing angle between the two CP-even weak spin-0 eigenstates (h/H), sin(Θ) = 1

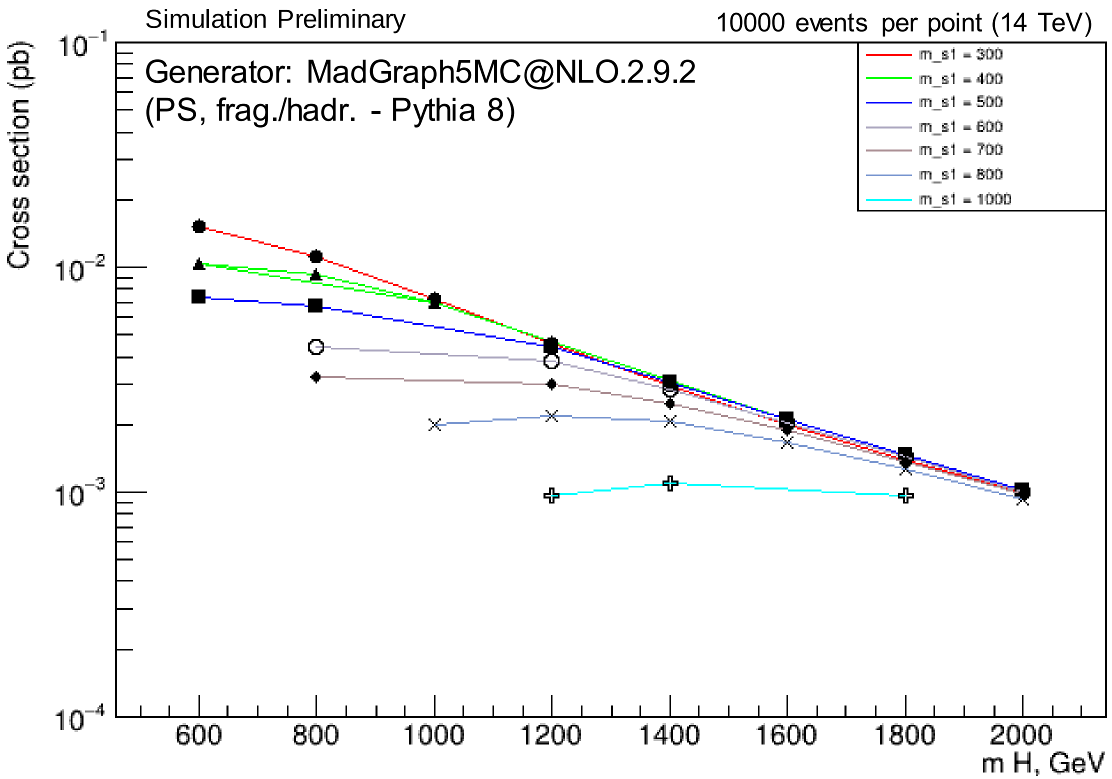
Free parameters for 2HDM + S:

$$H = \cos\theta S_1 - \sin\theta S_2,$$
$$S = v_S + \sin\theta S_1 + \cos\theta S_2.$$

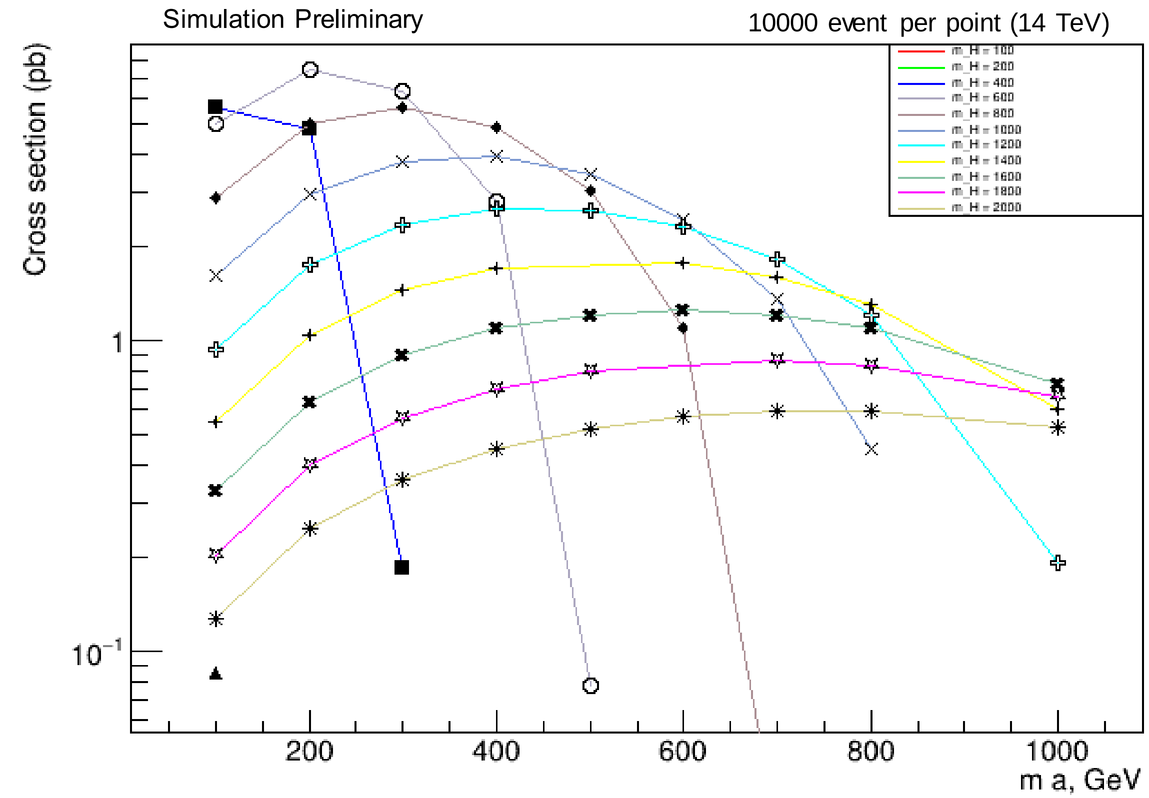
- Yukawa couplings
- Couplings of DM and mediators (a/S)
- Mass and widths of the w/ new states Interaction constants between two Higgs doublets (different for 2HDM+s and 2HDM+s)

RUN3 Expectations (cross sections)

2HDM+S



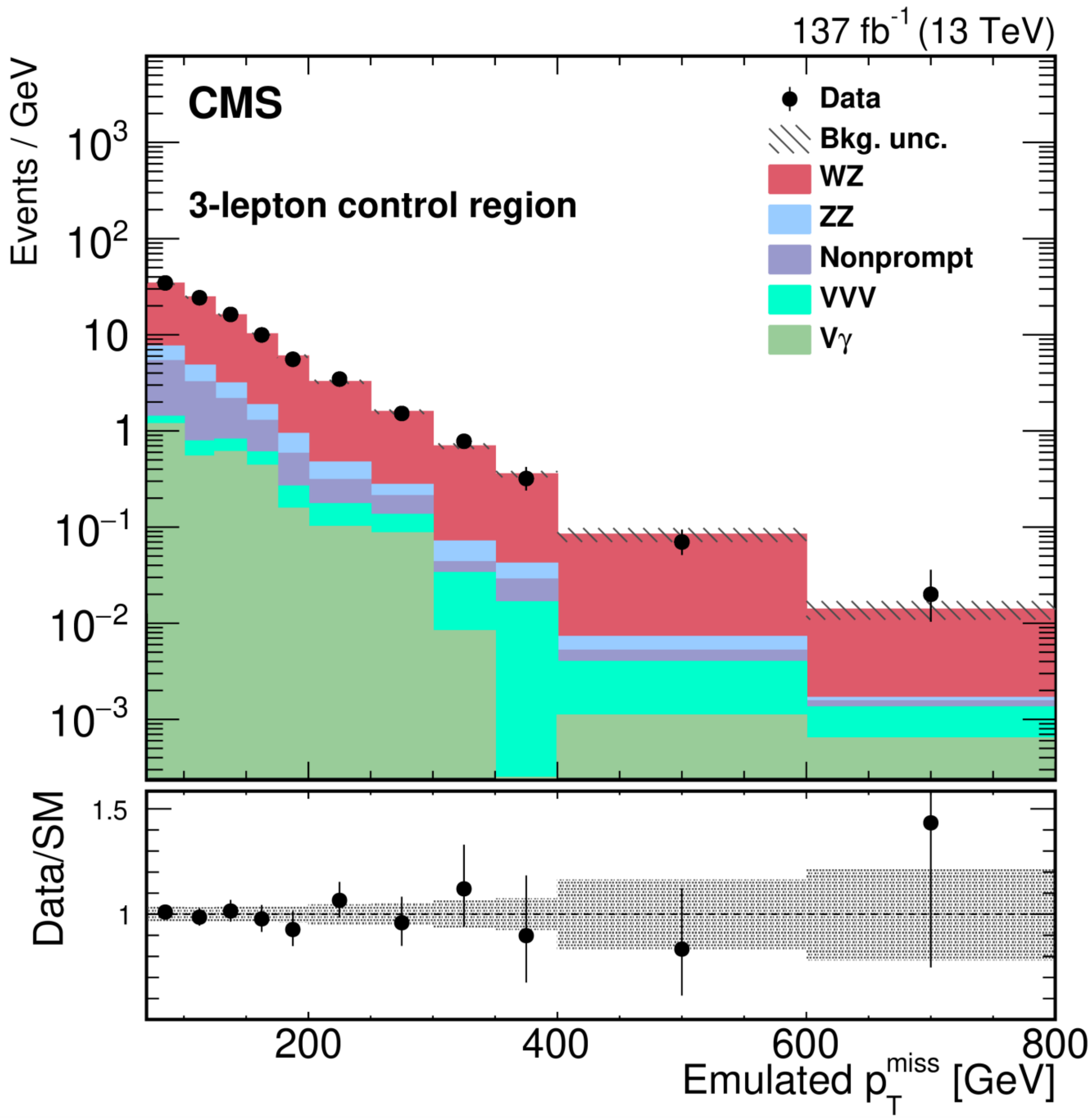
2HDM+a



$pp \rightarrow Z\chi\bar{\chi}$

In total about 1000 sets of model parameters

Background



Main background sources:
(pp → Z + MET → ll + MET)

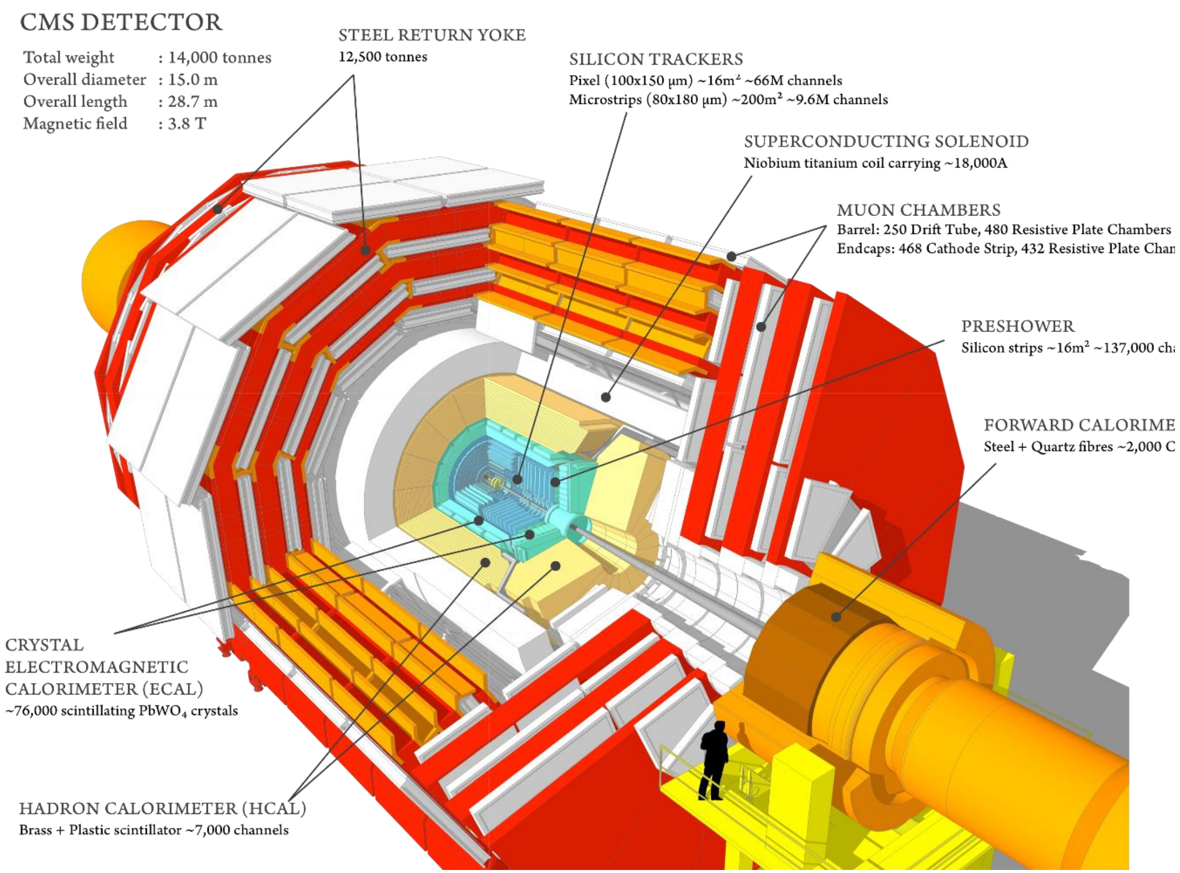
WZ → l ν l l

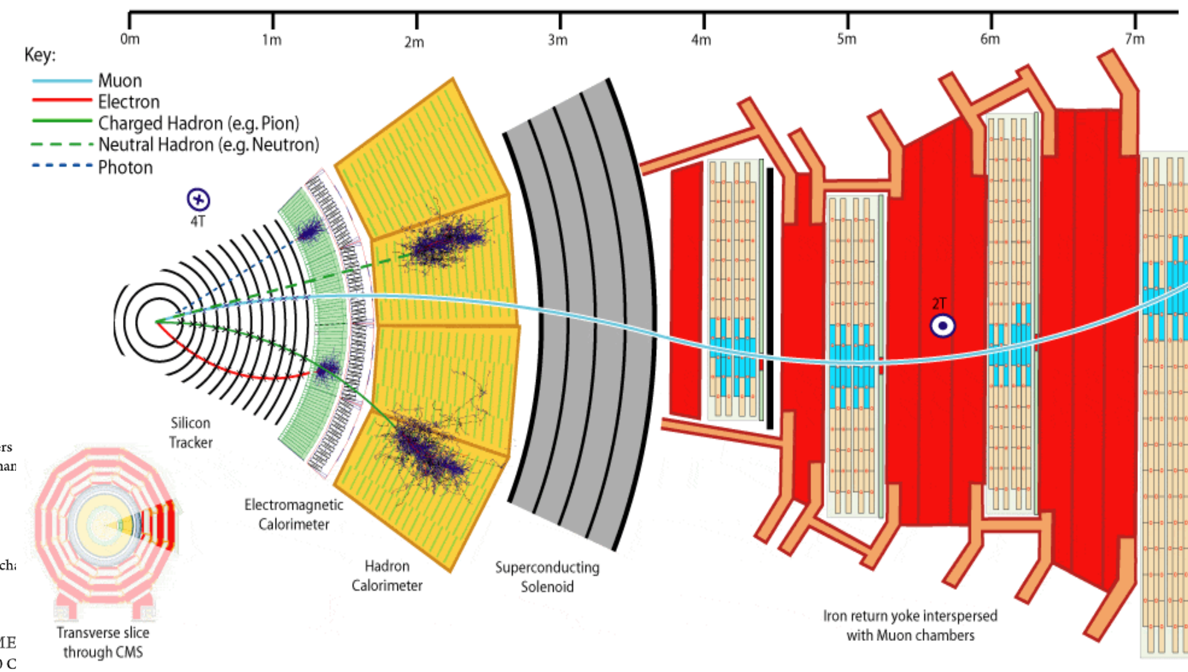
ZZ → 4l

Vɣ → ll + missreconstructed ɣ

VVV: (WWZ, WZZ, and ZZZ)
ttW → WWbbW, ttZ → WWbbZ,
and ttγ → WWbbγ

Experiment CMS at LHC





Analysis	Dataset	Document
mono-Z(ll)	137 fb^{-1}	EXO-19-003
mono-H combination	36 fb^{-1}	JHEP 03 (2020) 025 EPJC 79 (2019) 280 JHEP 11 (2018) 172
invisible Higgs boson	137 fb^{-1}	PLB 793 (2019) 520
dark photons in VBF Higgs boson	137 fb^{-1}	EXO-20-005

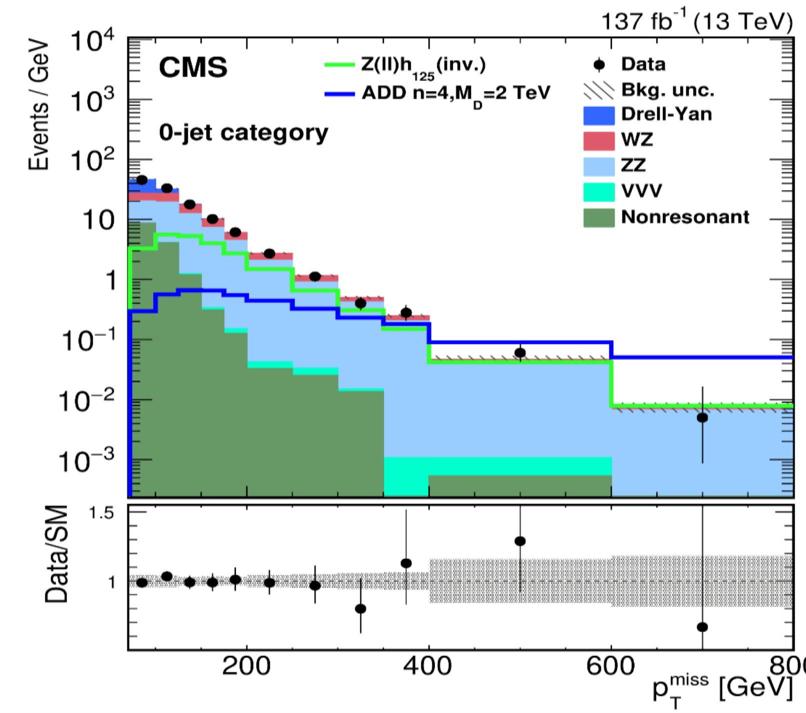
Summary of the kinematic selections for the signal region

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	$\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV	WW, top quark
Number of jets	$\leq$1 jet with $p_T^j > 30$ GeV	DY, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	DY
b tagging veto	0 b-tagged jet with $p_T > 30$ GeV	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18$ GeV	WZ
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,miss})$	>0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,miss})$	>2.6 radians	DY
$\lvert p_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.4	DY
$\Delta R_{\ell\ell}$	<1.8	WW, top quark
p_T^{miss} (all but 2HDM+a)	>100 GeV	DY, WW, top quark
p_T^{miss} (2HDM+a only)	>80 GeV	DY, WW, top quark
m_T (2HDM+a only)	>200 GeV	DY, WW, ZZ, top quark

CMS RUN2 Results

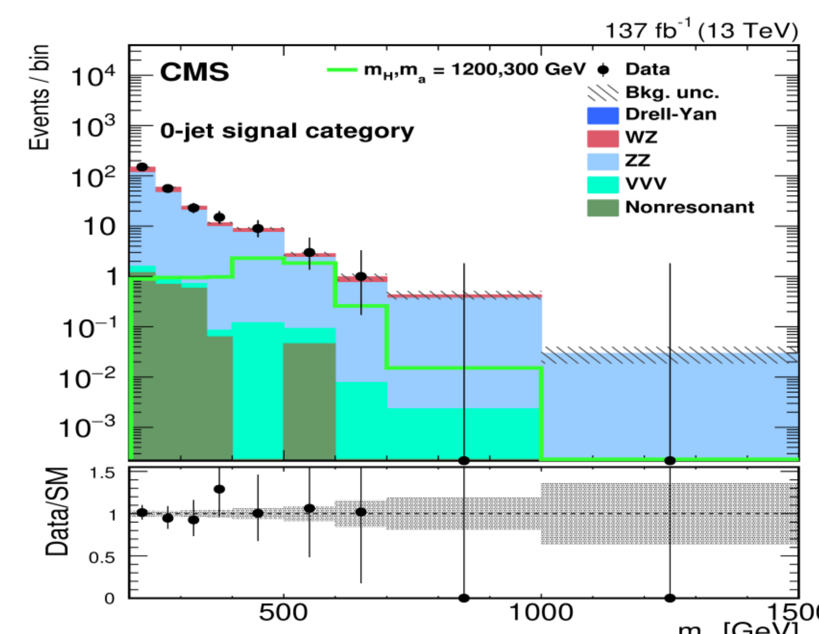
Observed number of events and post-fit background estimates

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



Expected yields and the product of acceptance and efficiency for several models probed in the analysis

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



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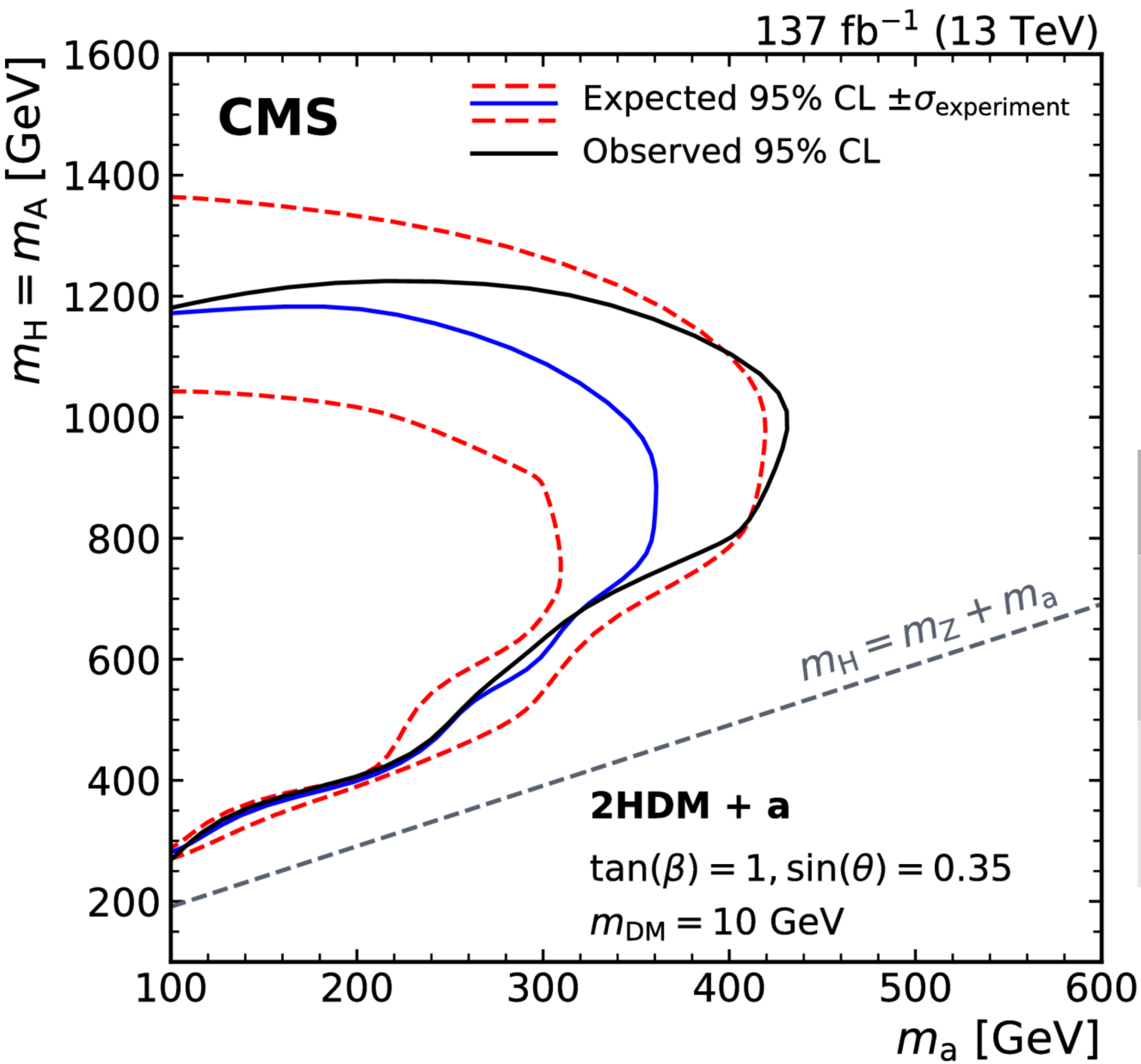
CMS RUN2 Exclusion Plot for 2HDM+a



The upper limits on the 2HDM+a model with the mixing angles set to tan β = 1 and sin θ = 0.35 and with a DM particle mass of mχ = 10 GeV.

Model	Parameter	Observed	Expected
2HDM+a m_H=1 TeV	m_a	330 GeV	440 GeV
2HDM+a m_a=100 Gev	m_H	1200 GeV	1200 GeV

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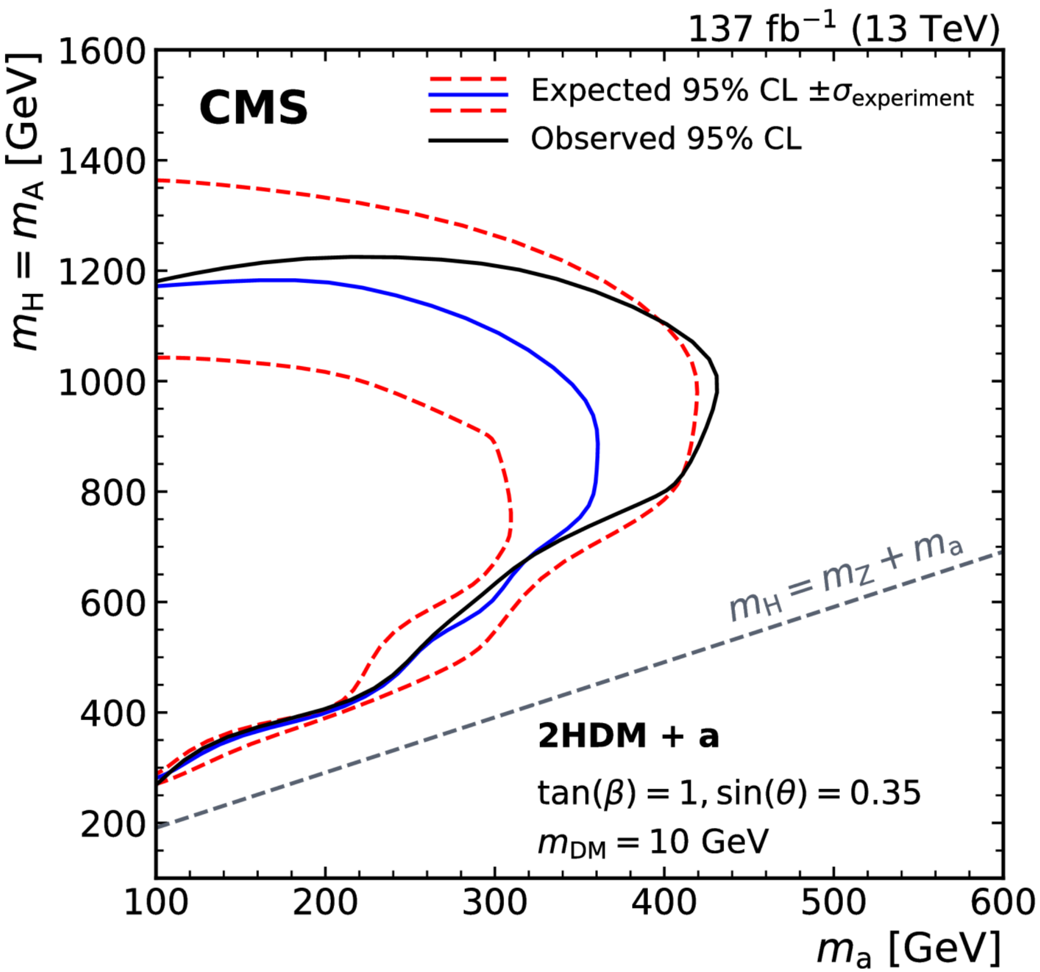
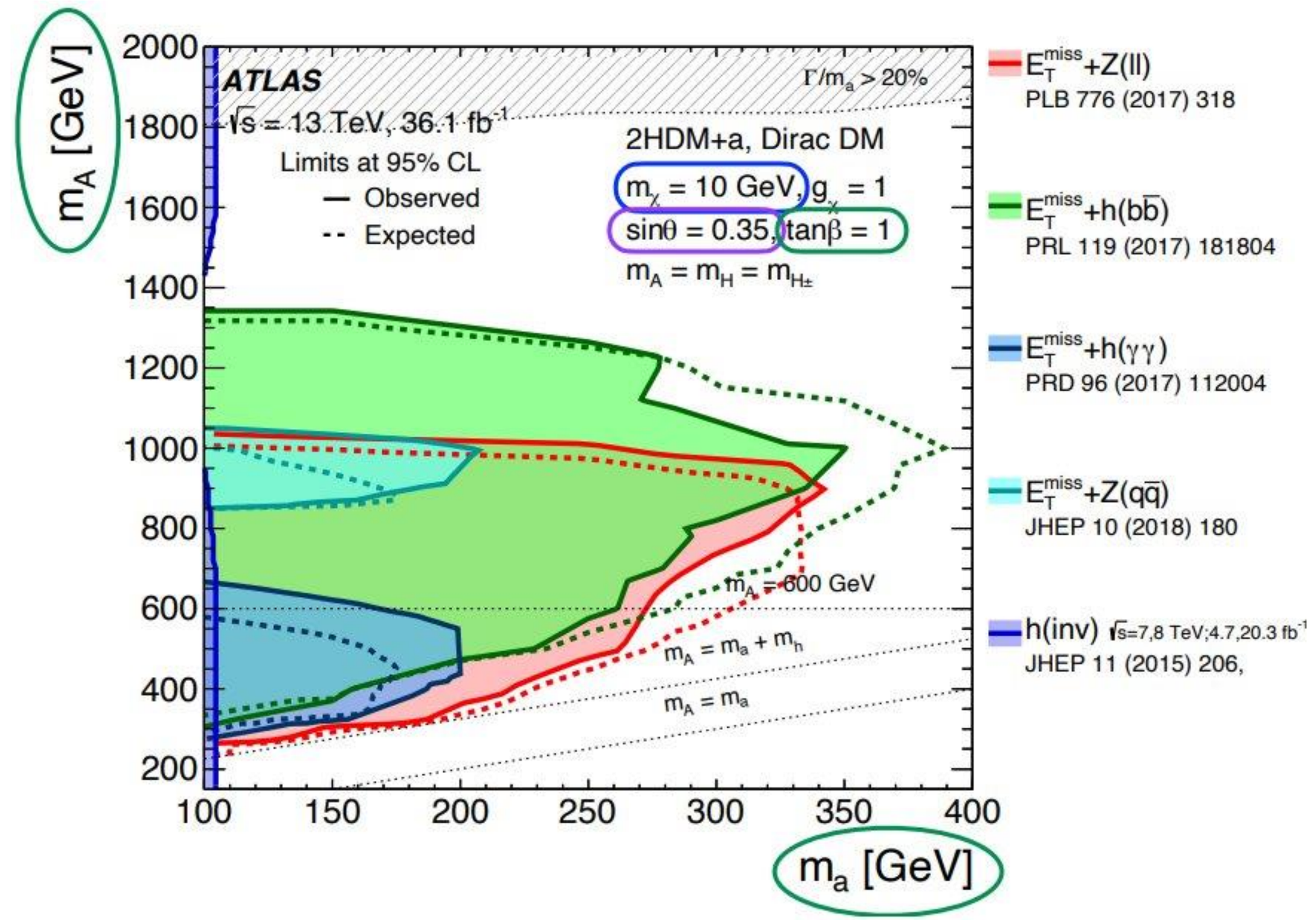
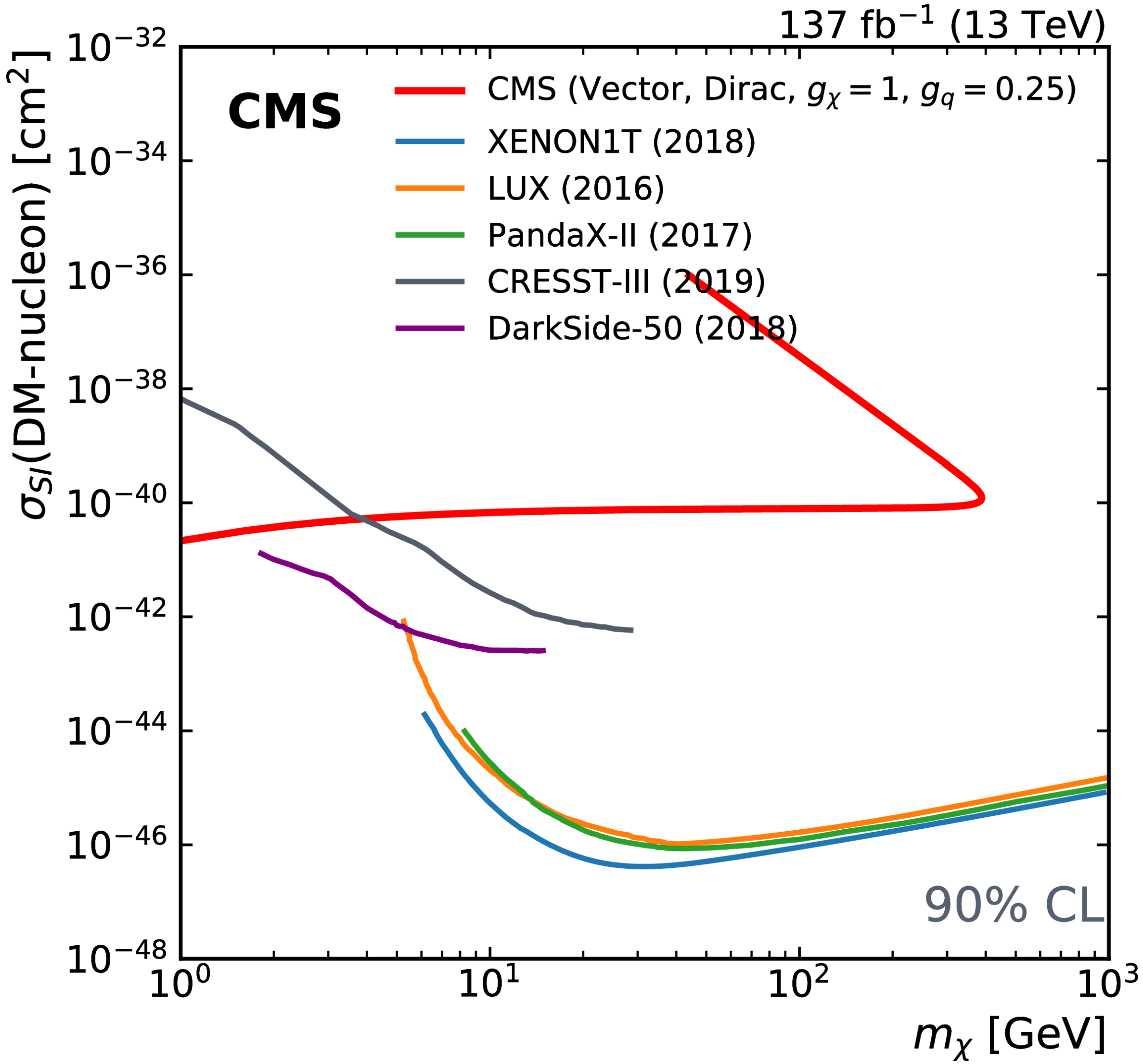
CMS RUN2 Exclusion Plot for 2HDM+a



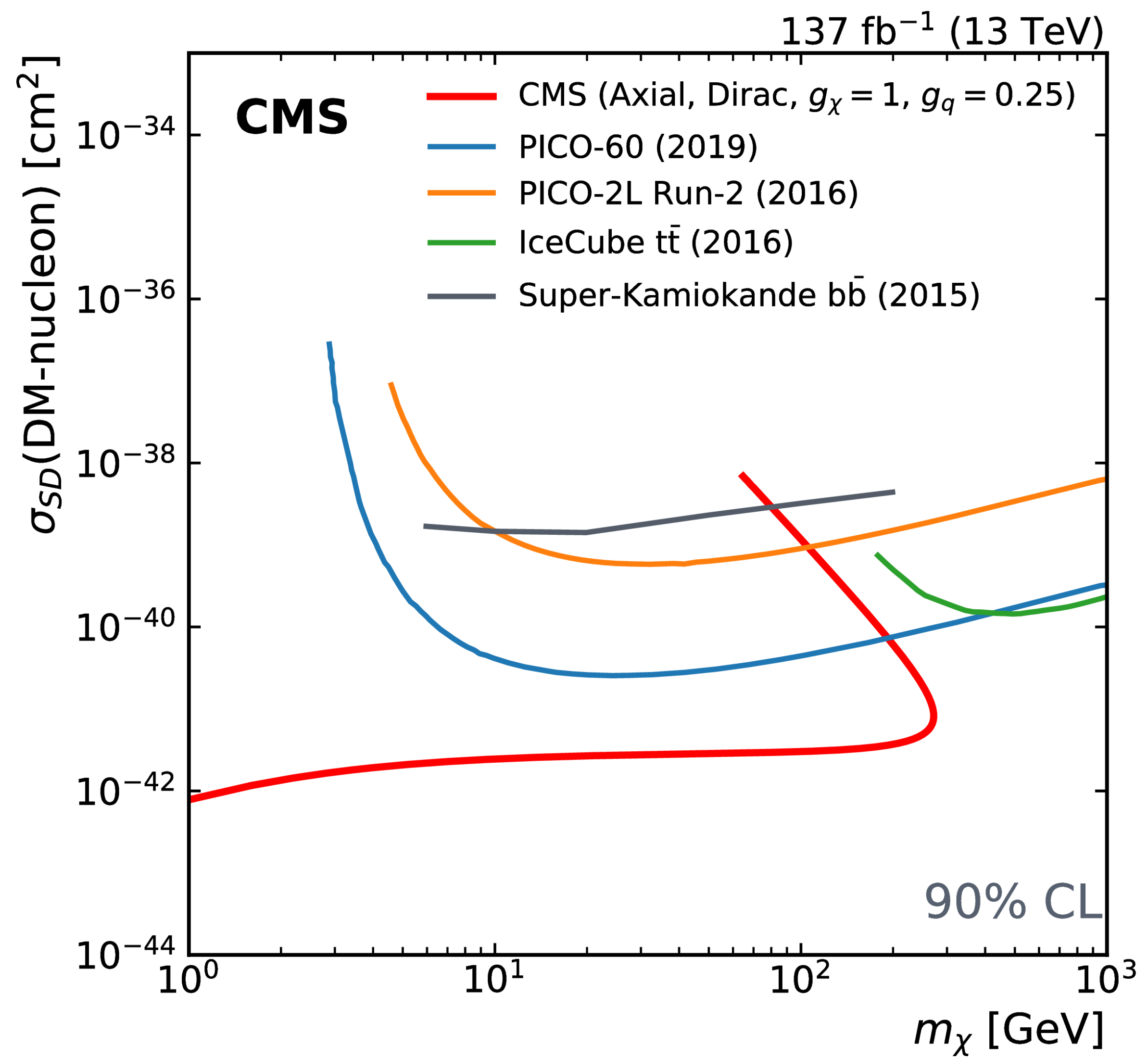


DM-nucleon upper limits on the cross section for simplified DM

The spin-independent case with vector couplings



The spin-dependent case with axial-vector couplings



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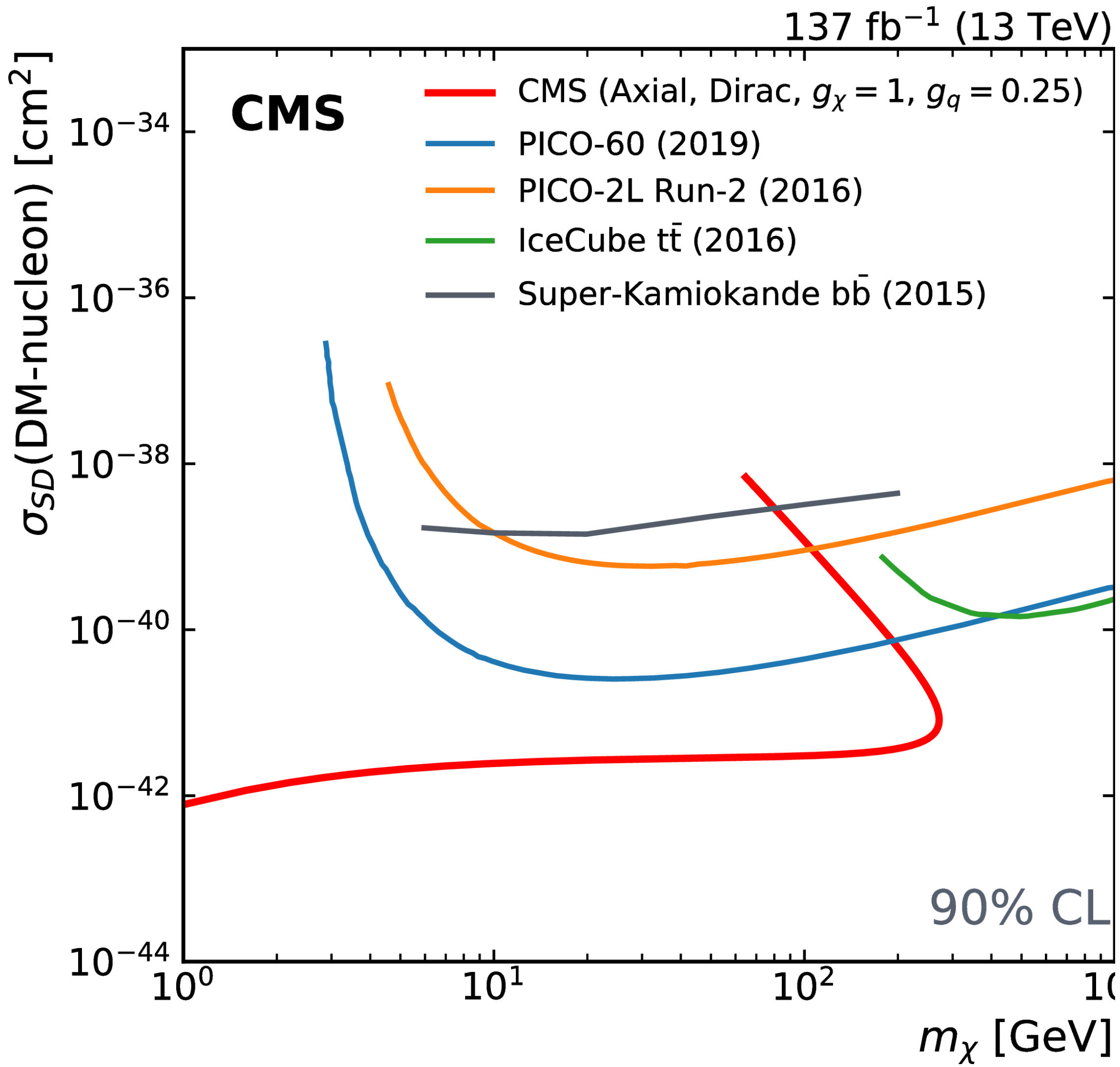
SUMMARY

- 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^{-1}
  – 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.

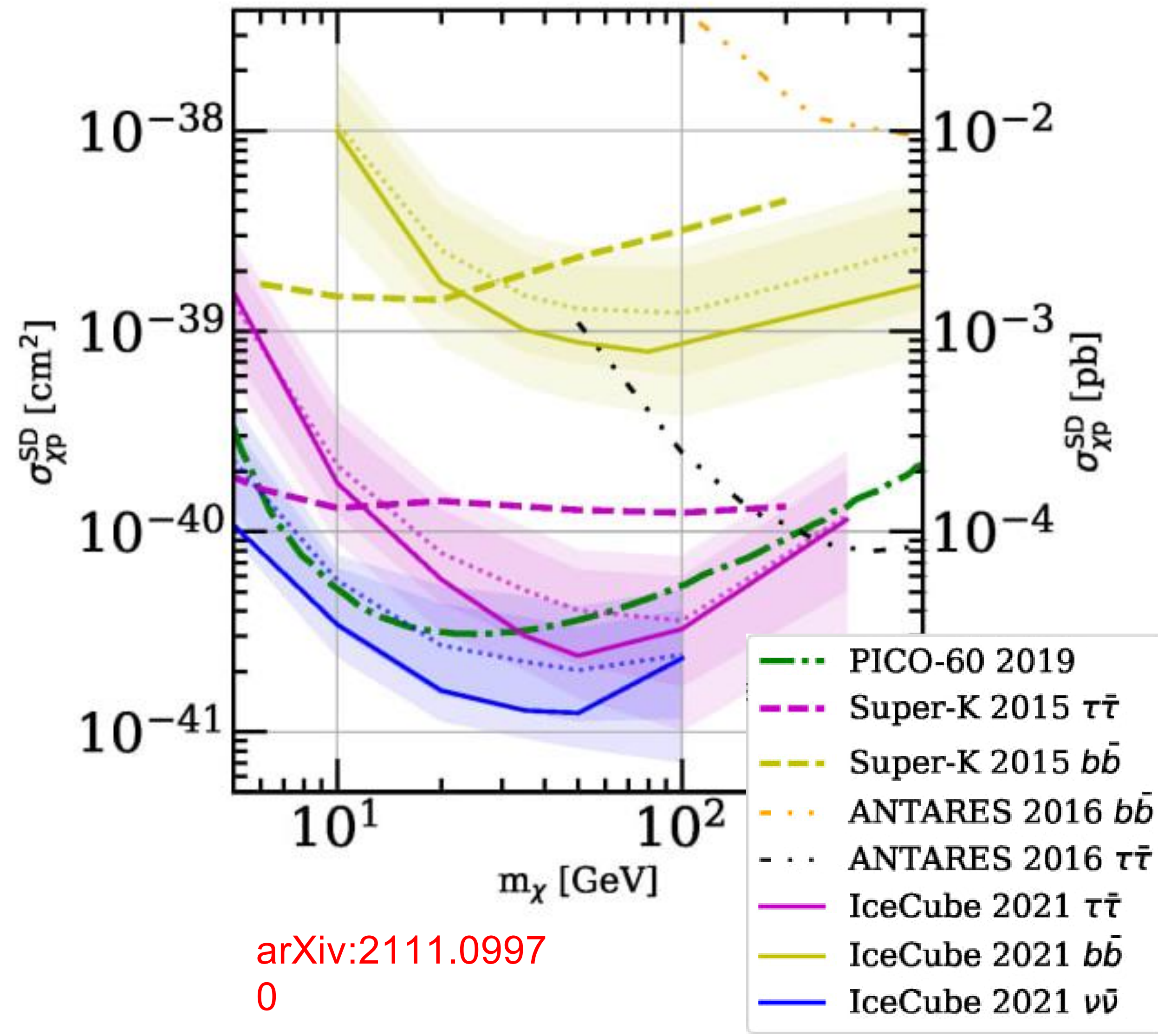
- For the preparation of LHC RUN3 data analysis, the cross sections of dark matter production in association with a leptonically decaying Z boson have been calculated for
  – 2HDM + a model (additional pseudoscalar mediator)
  – 2HDM + S model (additional scalar mediator)
- These processes were simulated for about 1000 sets of model parameters
- The next steps are full simulation (right now) and RUN3 data analysis (waiting for data of 2023)

THANK YOU FOR YOUR ATTENTION!

DM-nucleon upper limits on the cross section



arXiv:2008.04735



arXiv:2111.0997
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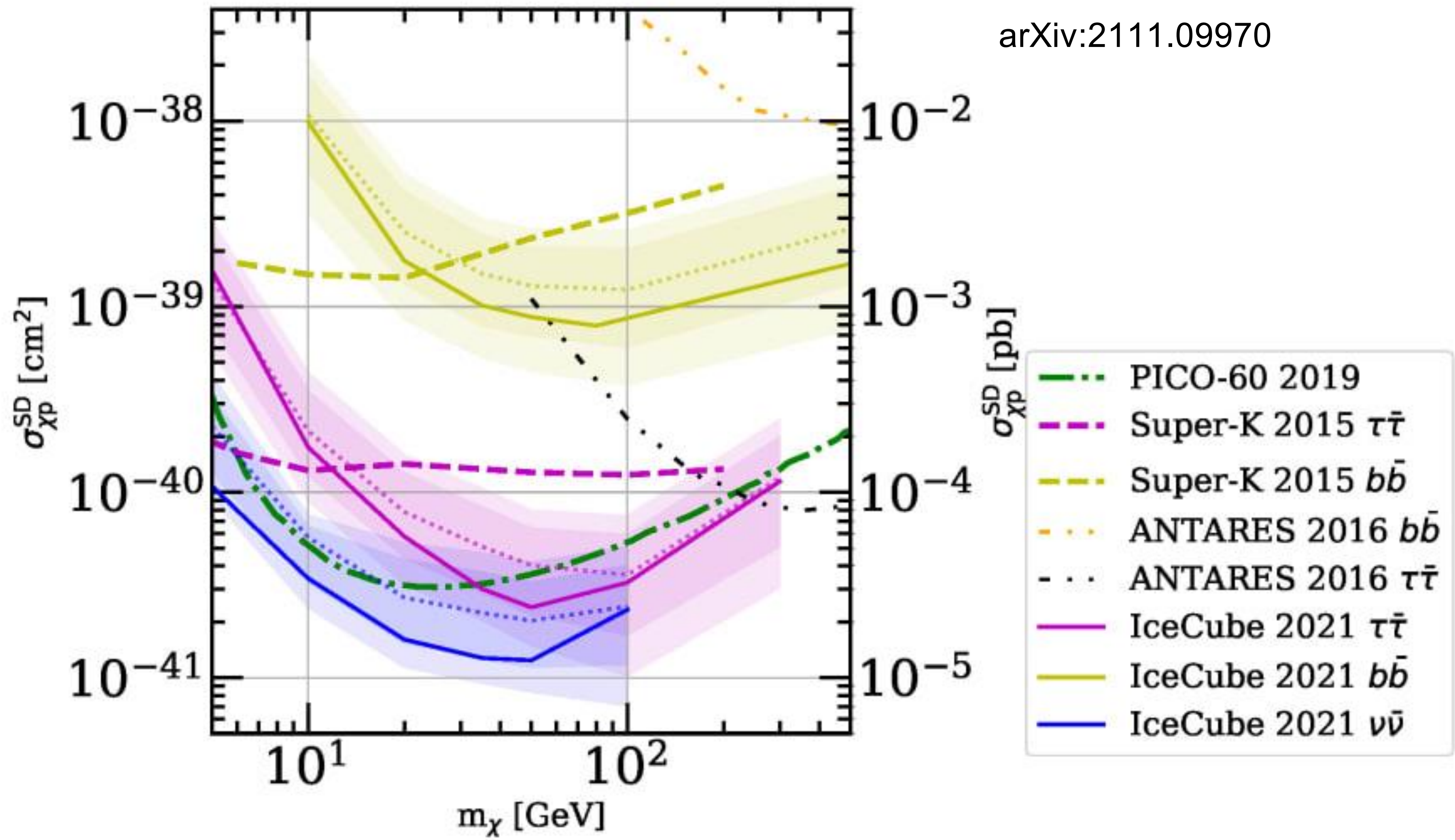
The upper limits on the cross section as a function of WIMP mass

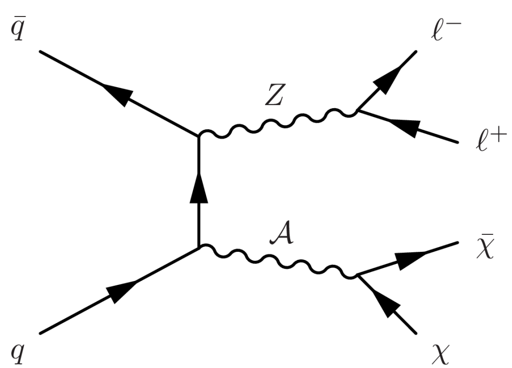
arXiv:2111.09970

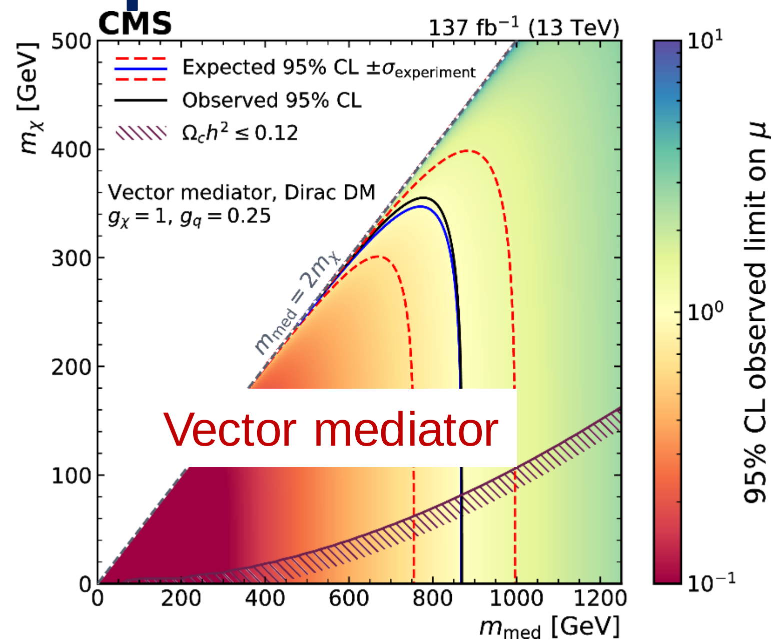


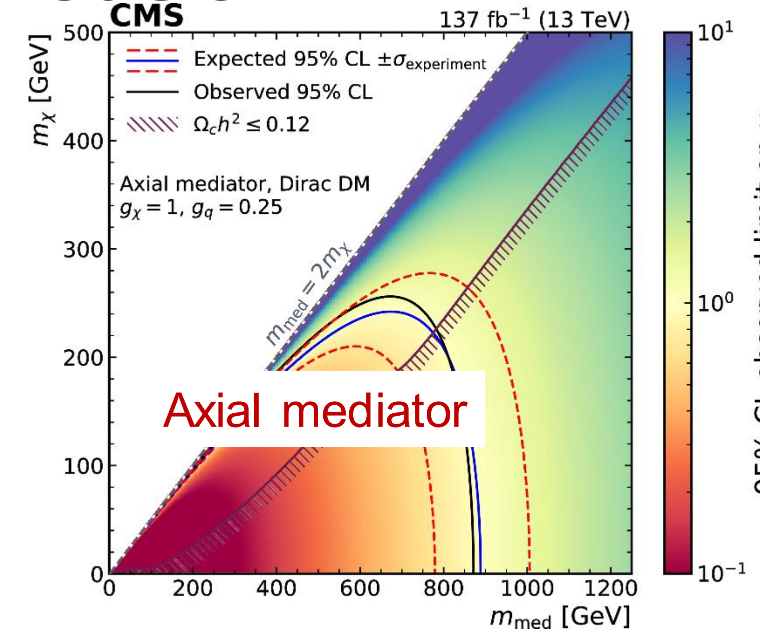
The 90% upper limits (solid lines) and expected sensitivity (dotted) on the spin-dependent cross section as a function of WIMP mass obtained by seven years of IceCube DeepCore data in this work. The shaded bands show the central 90% expected limits. Also shown are limits from the Super-K, PICO-60, and ANTARES experiments. Credit: IceCube Collaboration

CMS RUN2 Exclusion Plots:
The simplified dark matter models

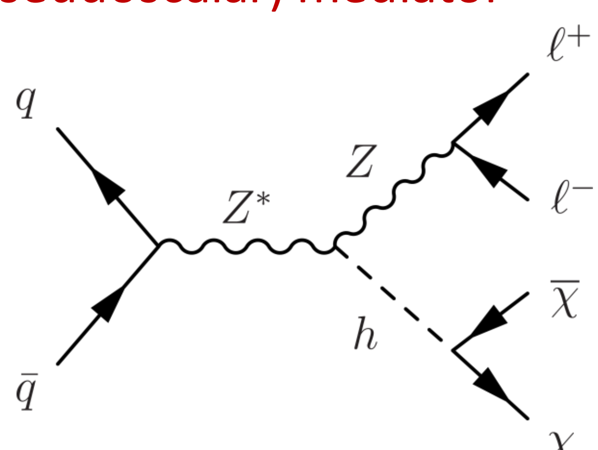
The simplified dark matter model for a spin-1 (vector or axial-vector) mediator

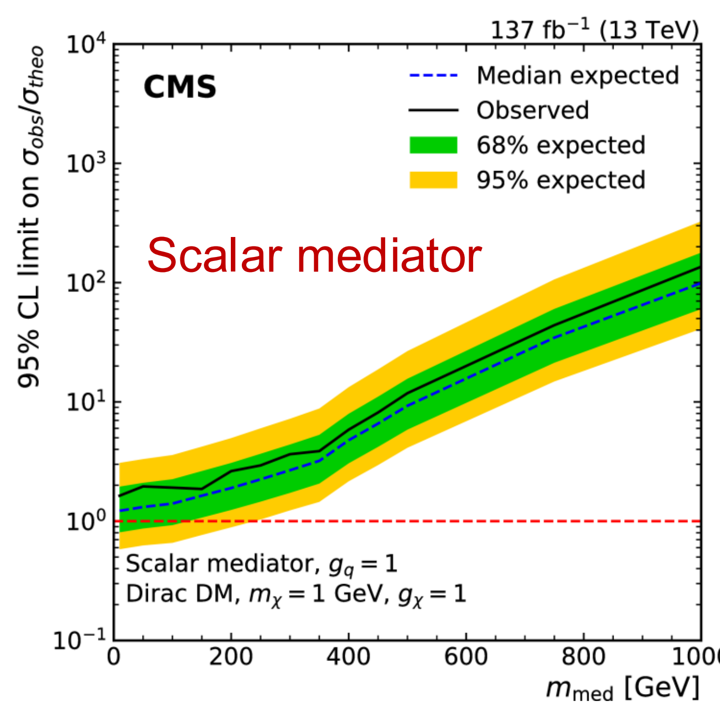


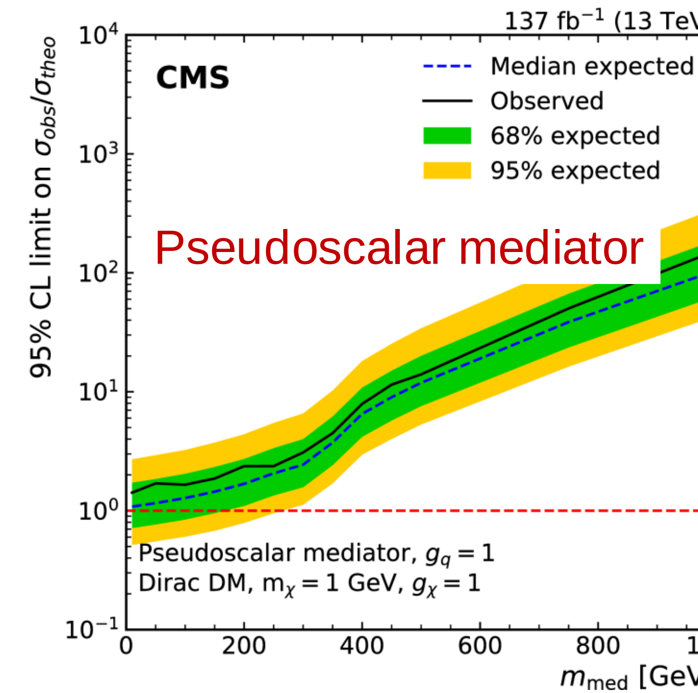




The simplified dark matter model for a spin-0 (scalar or pseudoscalar) mediator







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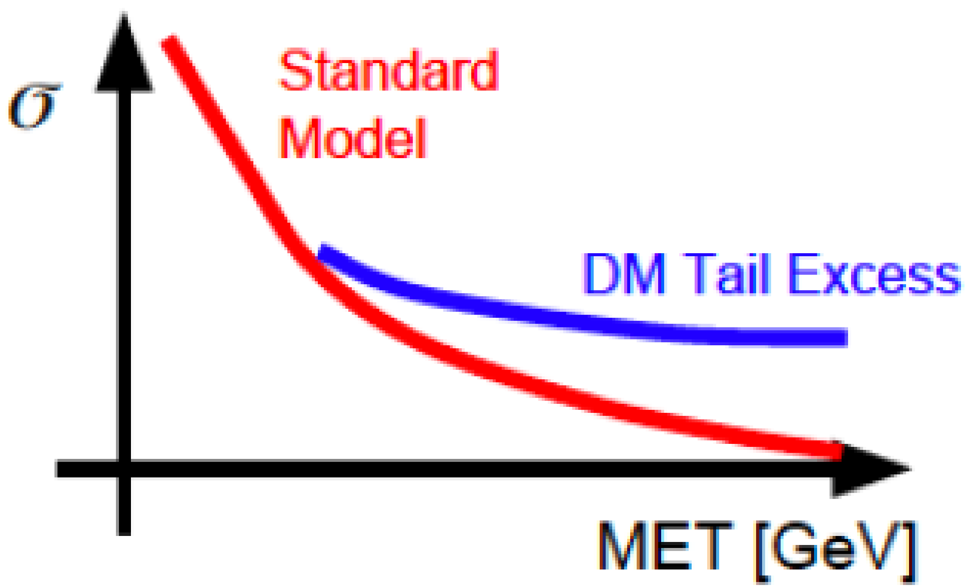
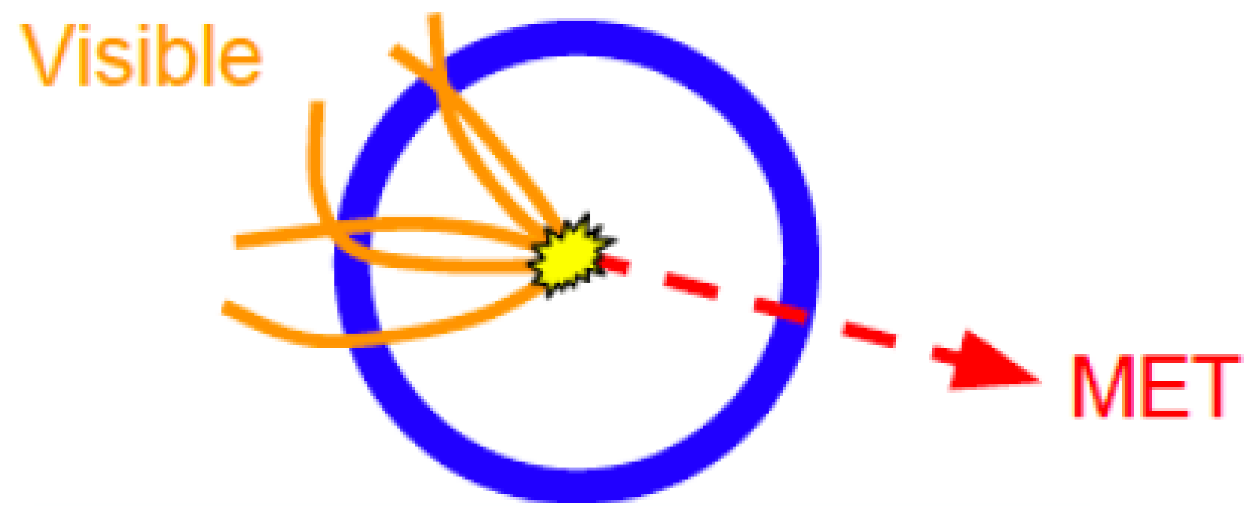
Search DM in collider experiment

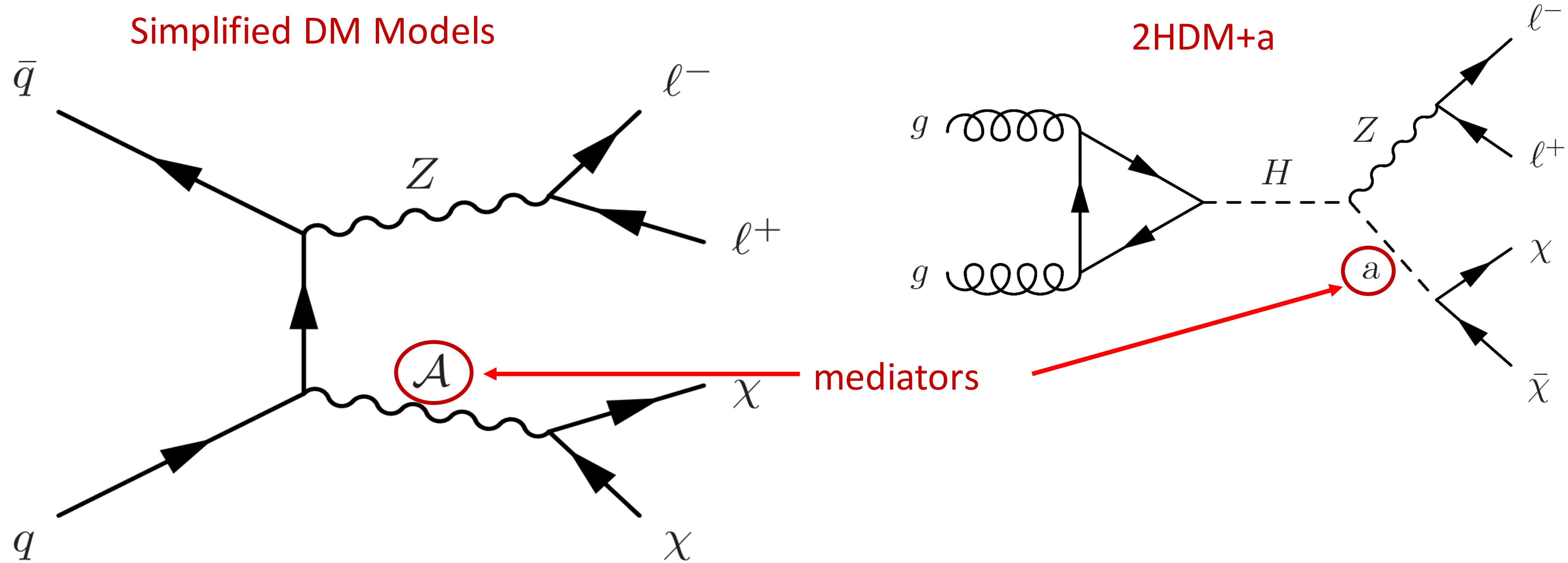


Expected deviation from predictions SM



Dark matter cannot be observed directly in accelerators.

Models BSM



Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

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