Search for dark matter particles predicted by extended Higgs models
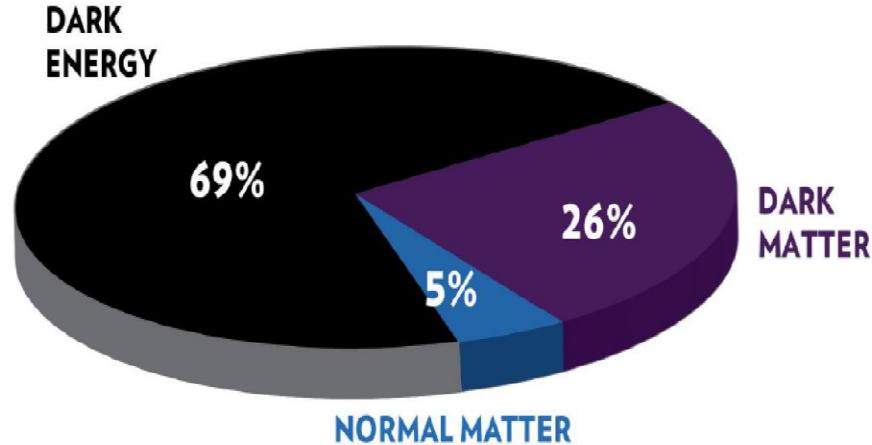
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MLIT, JINR

Dubna, 1 - 5 April, 2024

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
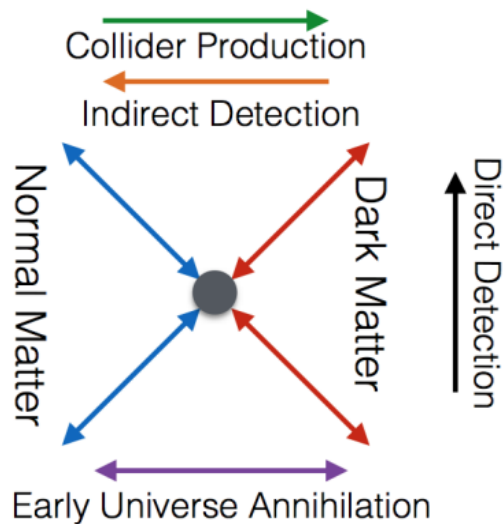
Astrophysical

- 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.
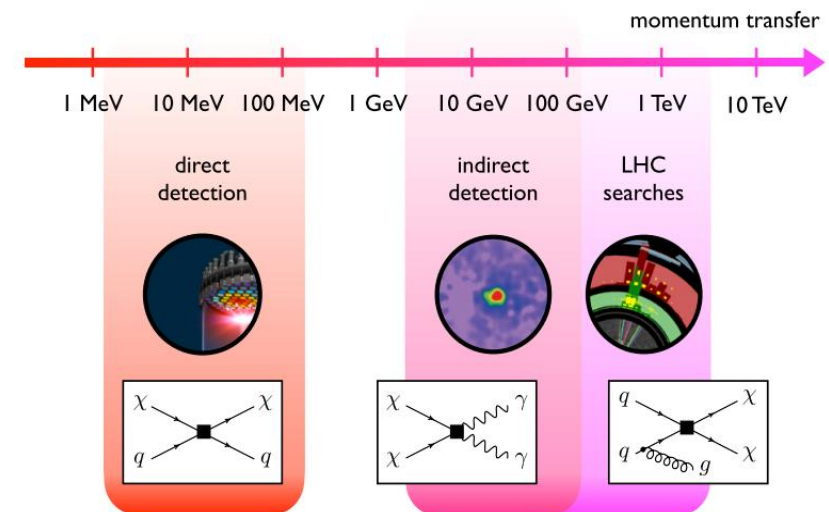- Forming of the early Universe structure, the growth of the initial inhomogeneities

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

Collider Production
Indirect Detection
Normal Matter
Dark Matter
Direct Detection
Early Universe Annihilation

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

momentum transfer

I MeV 10 MeV 100 MeV I GeV 10 GeV 100 GeV I TeV 10 TeV

direct detection   indirect detection   LHC searches

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}

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

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

Visible

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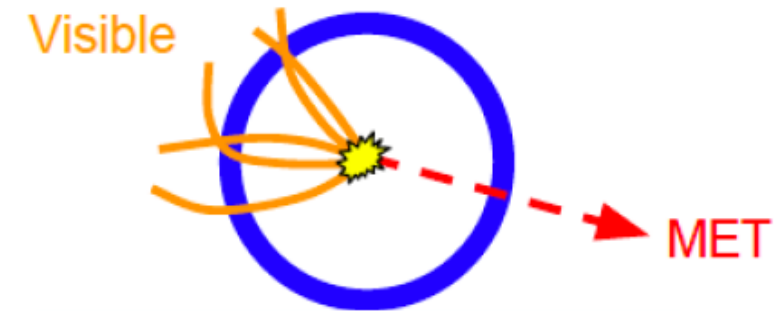
Most of the DM searches are therefore dependant on p_T^{miss}

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

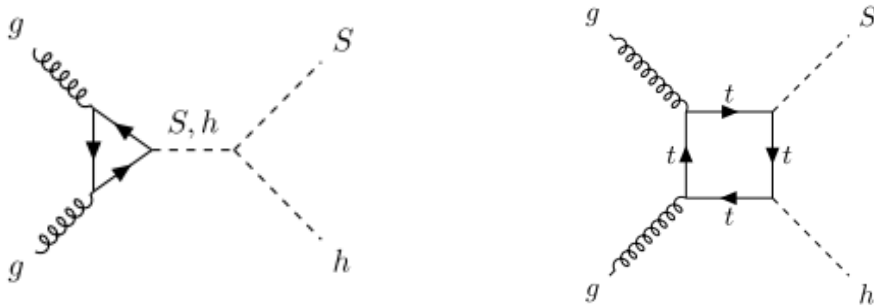- Neutrino production
- Limited detector resolution

σ

Standard Model

DM Tail Excess

MET [GeV]

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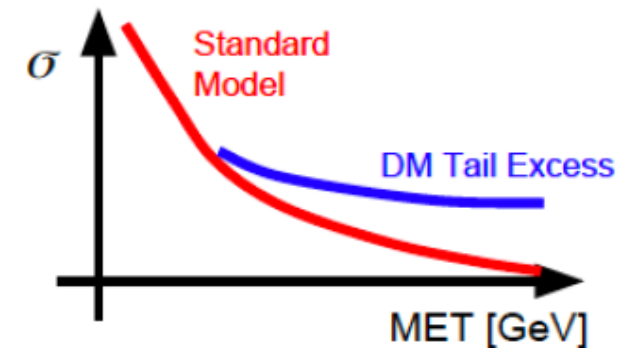
The two-Higgs-doublet model (2HDM) is a way to extend Higgs sector

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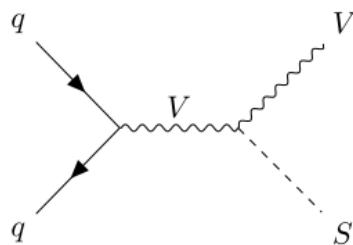- neutral CP-odd pseudoscalar A
- charged H^+, H^-

2HDM+s arXiv:1612.03475

2HDM + S (neutral scalar singlet)

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

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

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

2HDM+a arXiv:1701.07427

2HDM + a (neutral pseudoscalar singlet)

$$h\ (bbar) + a\ (\chi\chi) = bbar + MET$$
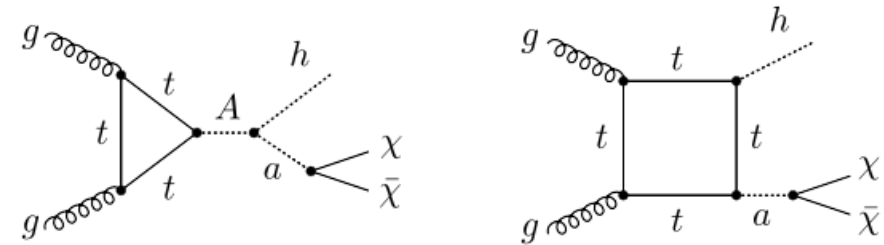
$$Z + a\ (\chi\chi) = Z\ (ll) + MET$$
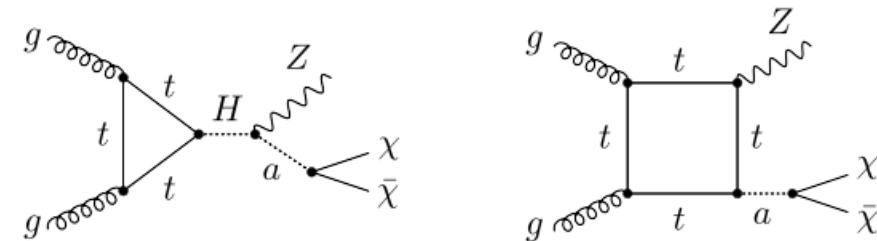
https://github.com/LHC-DMWG/model-repository/tree/master/models/Pseudoscalar_2HDM

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

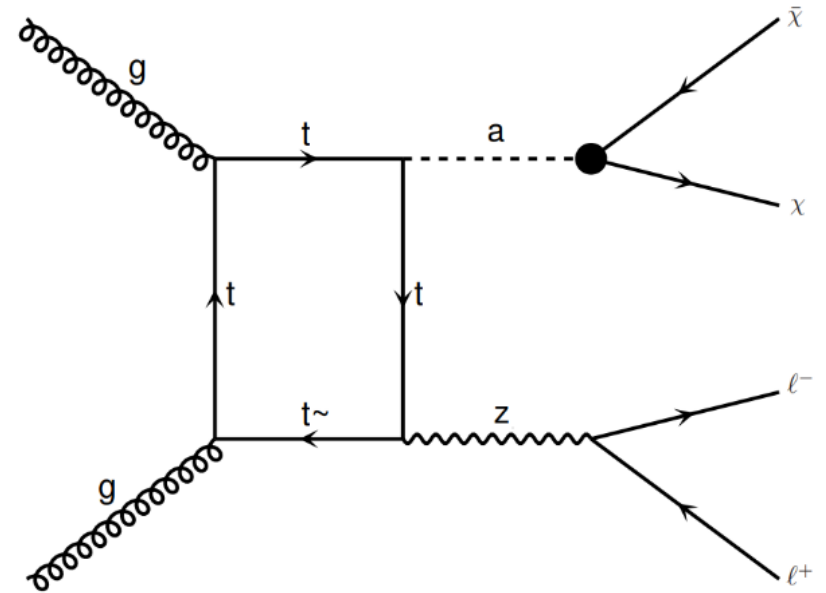Process: p p > Z χ χ (16 diagrams)

Free parameters for **2HDM + a**:
- masses of heavy higgses, $m_{H+/-} = m_H = m_A = [200:2000]$ GeV
- mass of dark matter particle, $m\chi = [1:2000]$ GeV
- mass of light pseudoscalar/scalar states, $m_a = m_S = [100:1000]$ GeV
- the ratio of the vacuum expectation values of the two Higgs doublets, $\tan(\beta) = [0.5:50]$
- the mixing angle of the two CP-odd weak spin-0 eigenstates (a/A), $\sin(\Theta) = [0.15:0.7]$
- the mixing angle between the two CP-even weak spin-0 eigenstates (h/H), $\sin(\Theta) = 1$

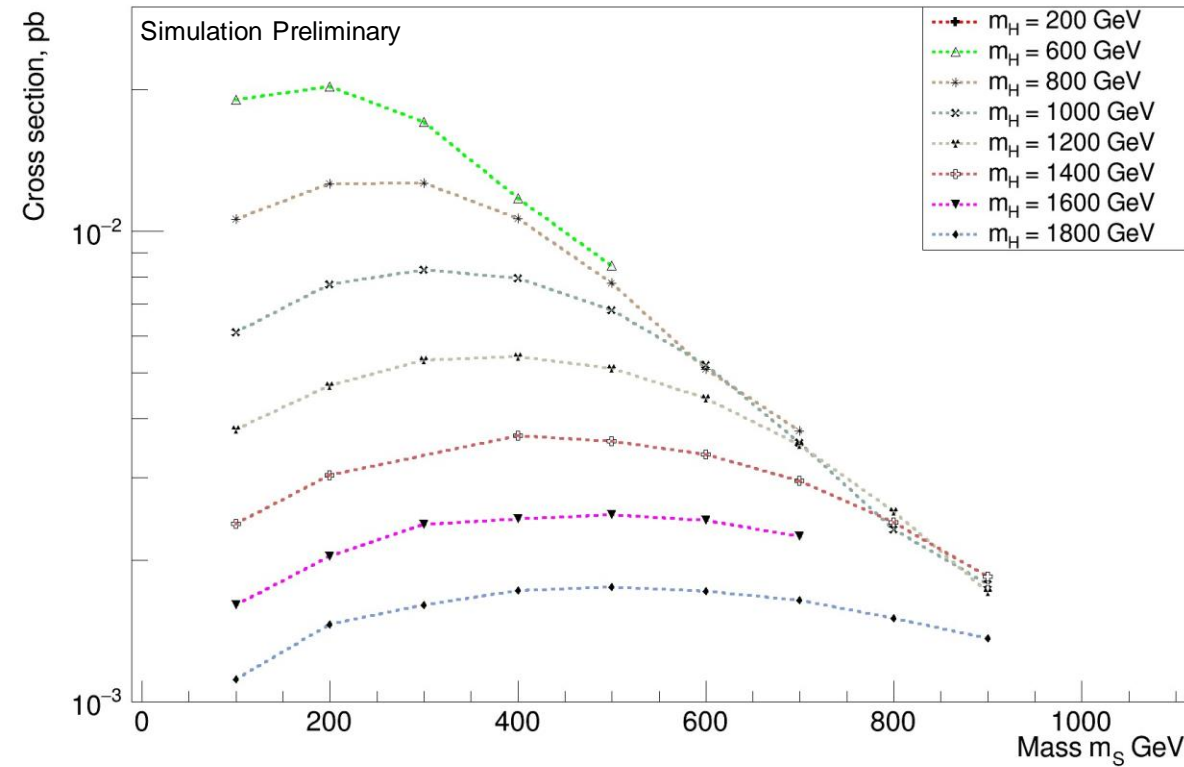Free parameters for 2HDM + S:

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

- 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)
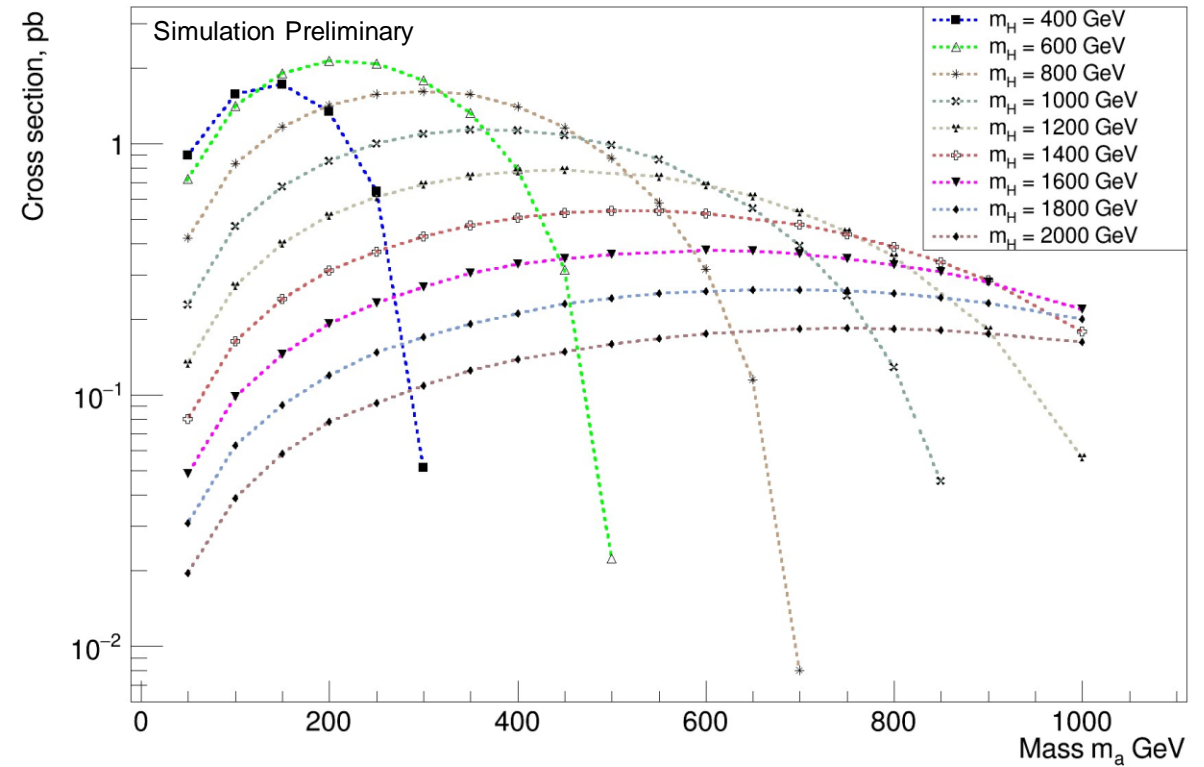
RUN3 Expectations (cross sections)

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

Simulation Preliminary

Legend:
- m_H = 200 GeV
- m_H = 600 GeV
- m_H = 800 GeV
- m_H = 1000 GeV
- m_H = 1200 GeV
- m_H = 1400 GeV
- m_H = 1600 GeV
- m_H = 1800 GeV

Cross section, pb — Mass m_S GeV

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

Simulation Preliminary

Legend:
- m_H = 400 GeV
- m_H = 600 GeV
- m_H = 800 GeV
- m_H = 1000 GeV
- m_H = 1200 GeV
- m_H = 1400 GeV
- m_H = 1600 GeV
- m_H = 1800 GeV
- m_H = 2000 GeV

Cross section, pb — Mass m_a GeV

10000 events per point (13.6 TeV)

1 pb ~ 30 000 events
10^{-3} pb ~ 300 events

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

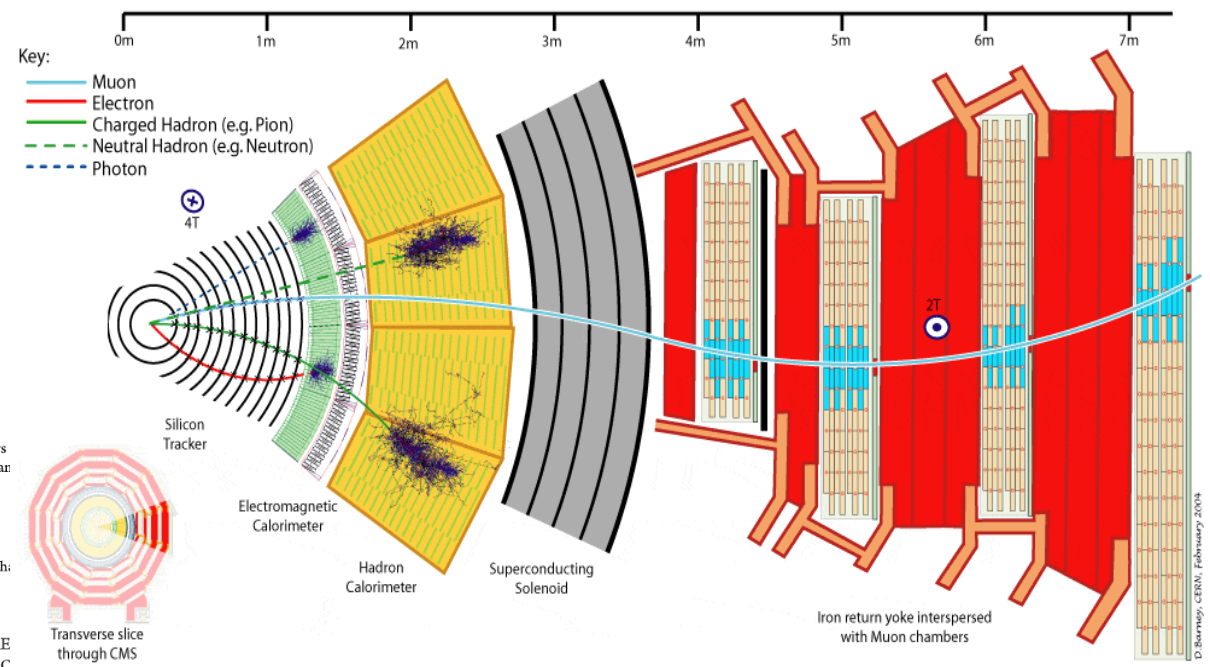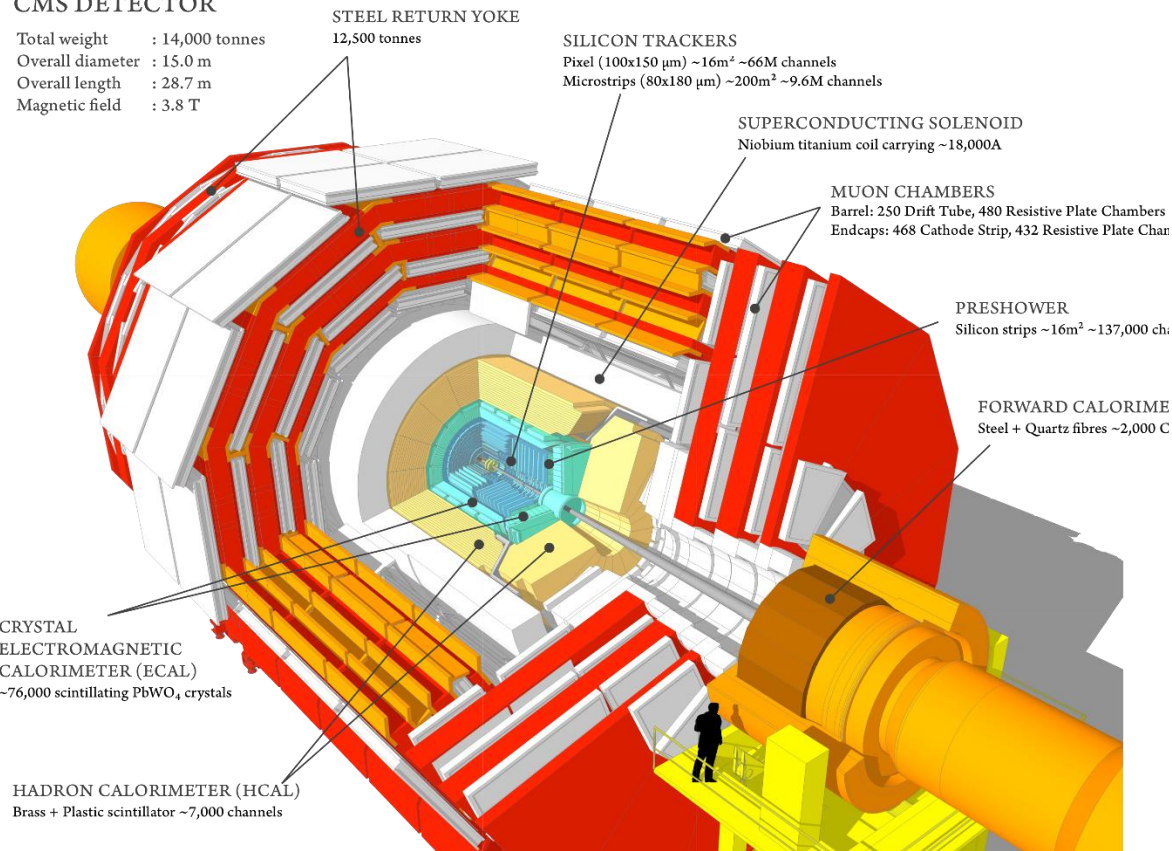In total about 1000 sets of model parameters

Experiment CMS at LHC

CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chan

PRESHOWER
Silicon strips ~16m² ~137,000 ch

FORWARD CALORIME
Steel + Quartz fibres ~2,000 C

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

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

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 $m_{\text{med}} = 1000\,\text{GeV}, m_\chi = 1\,\text{GeV}$	64.8 ± 6.1	17.6 ± 1.7

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CMS RUN2 Exclusion Plot for 2HDM+a
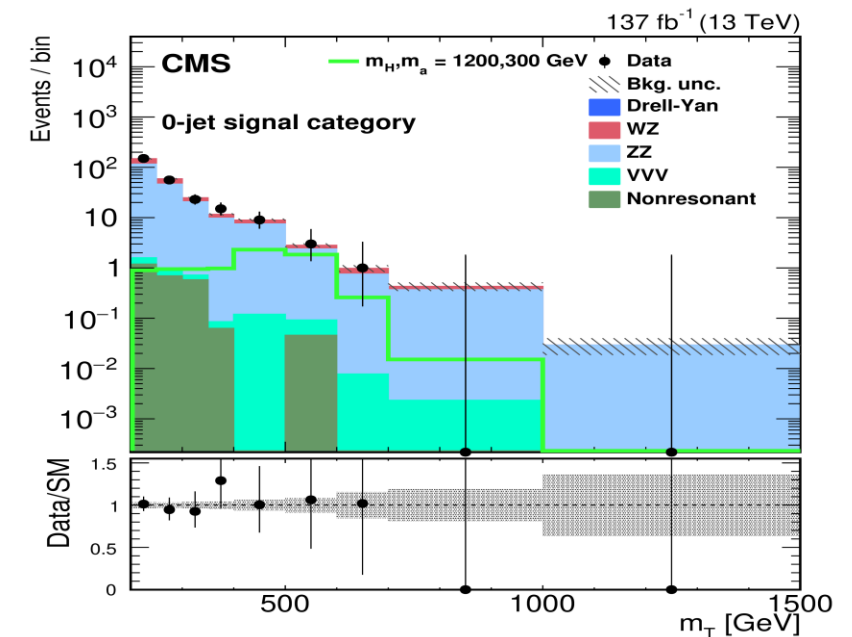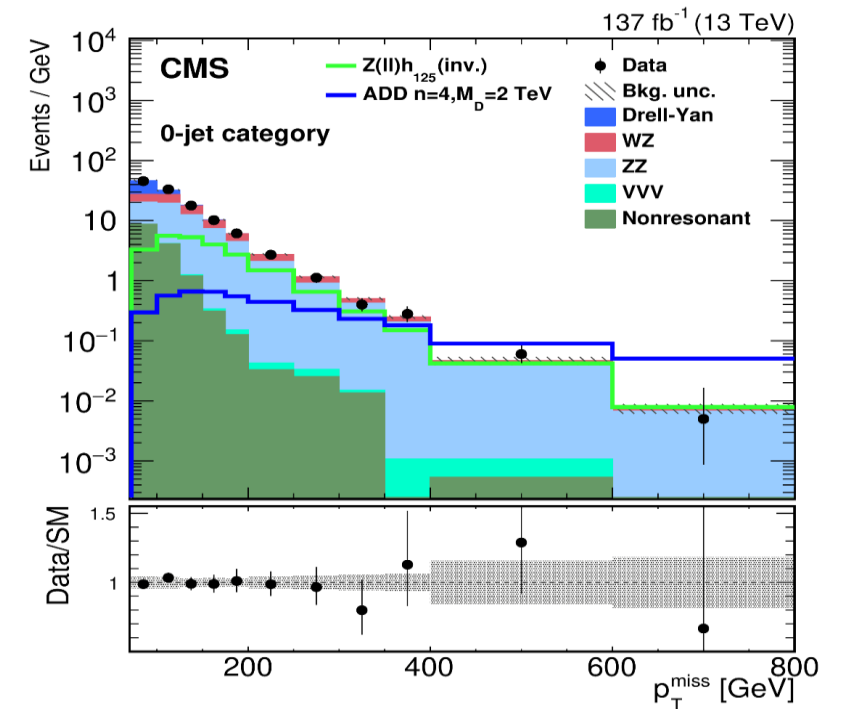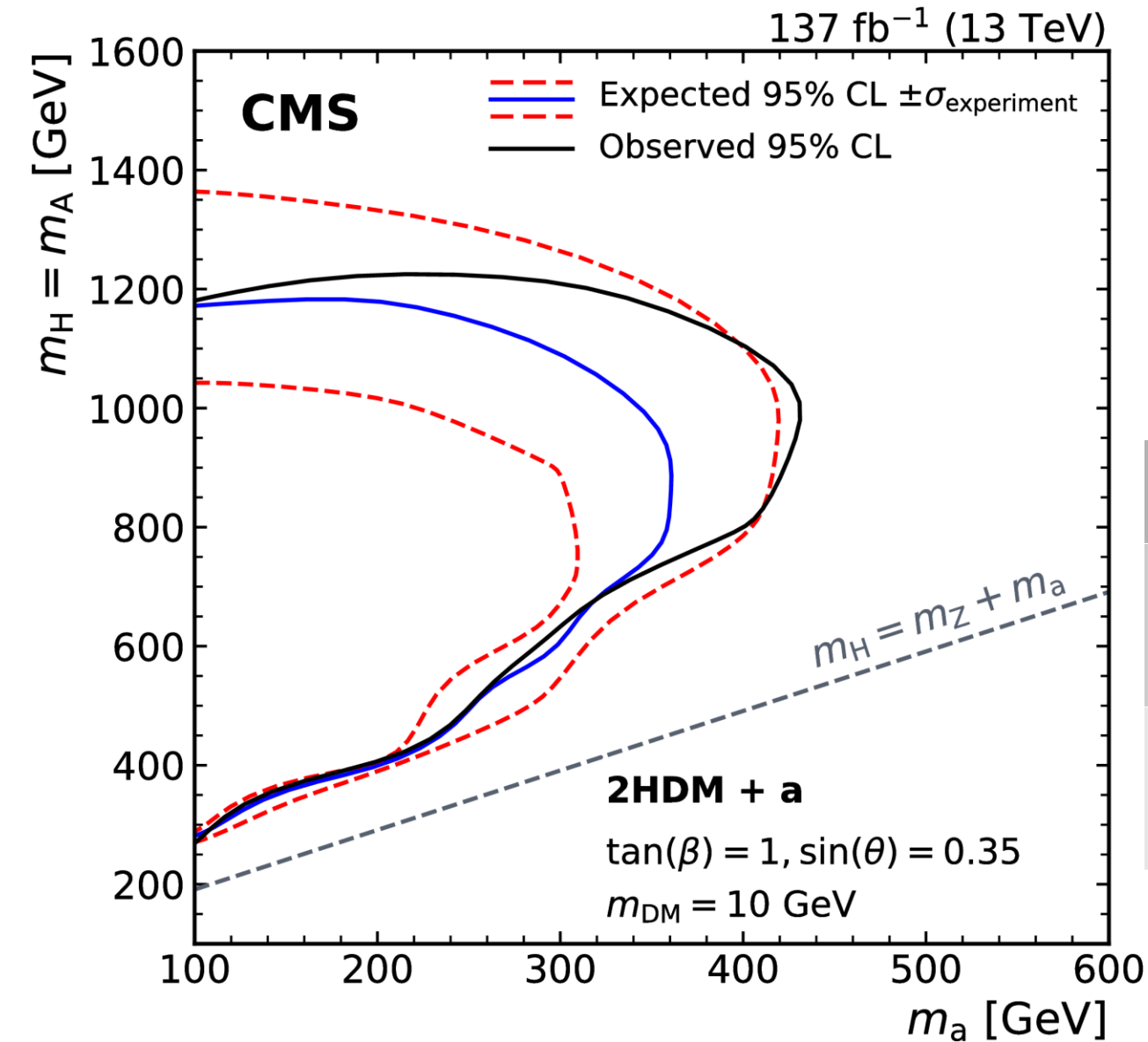
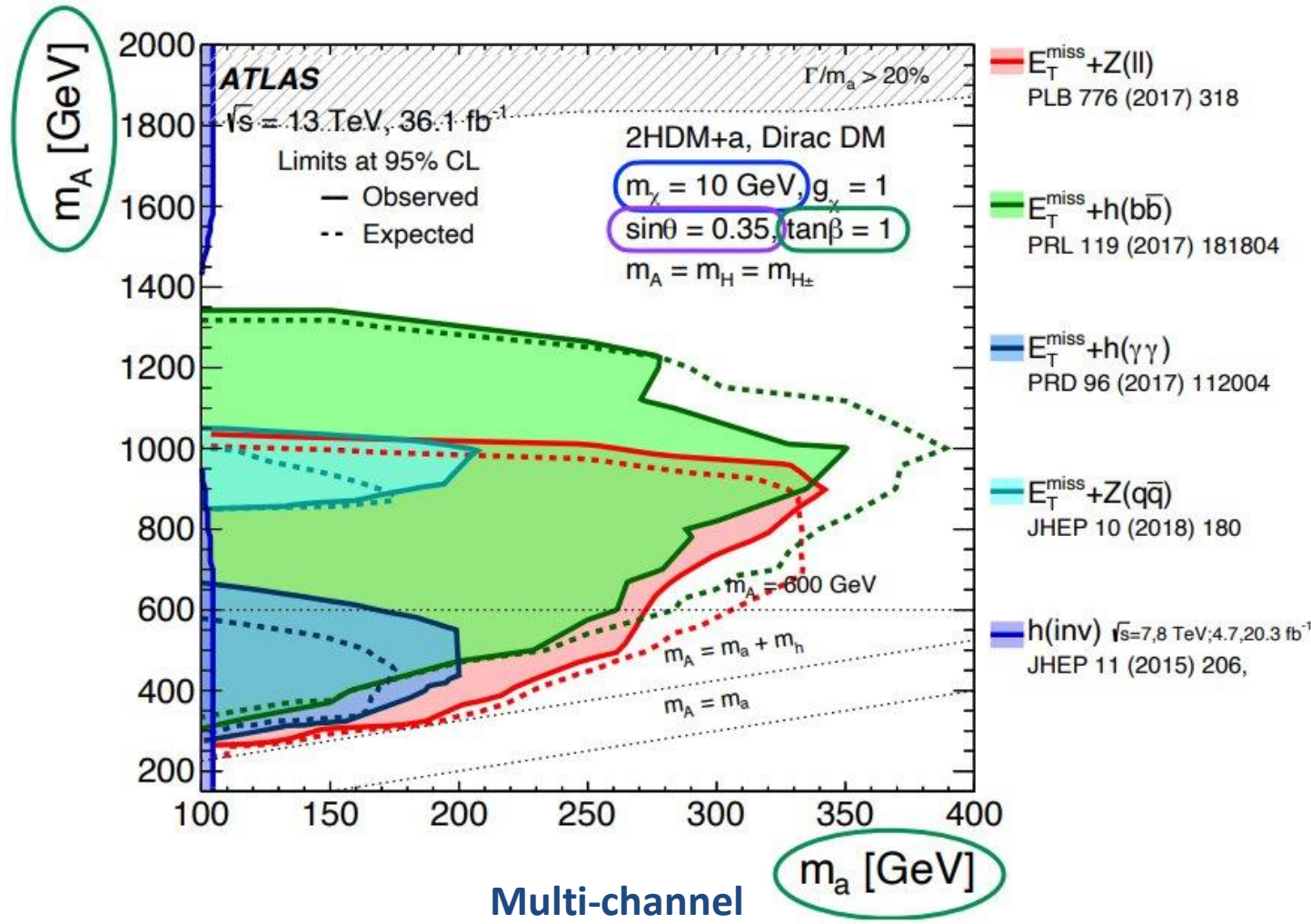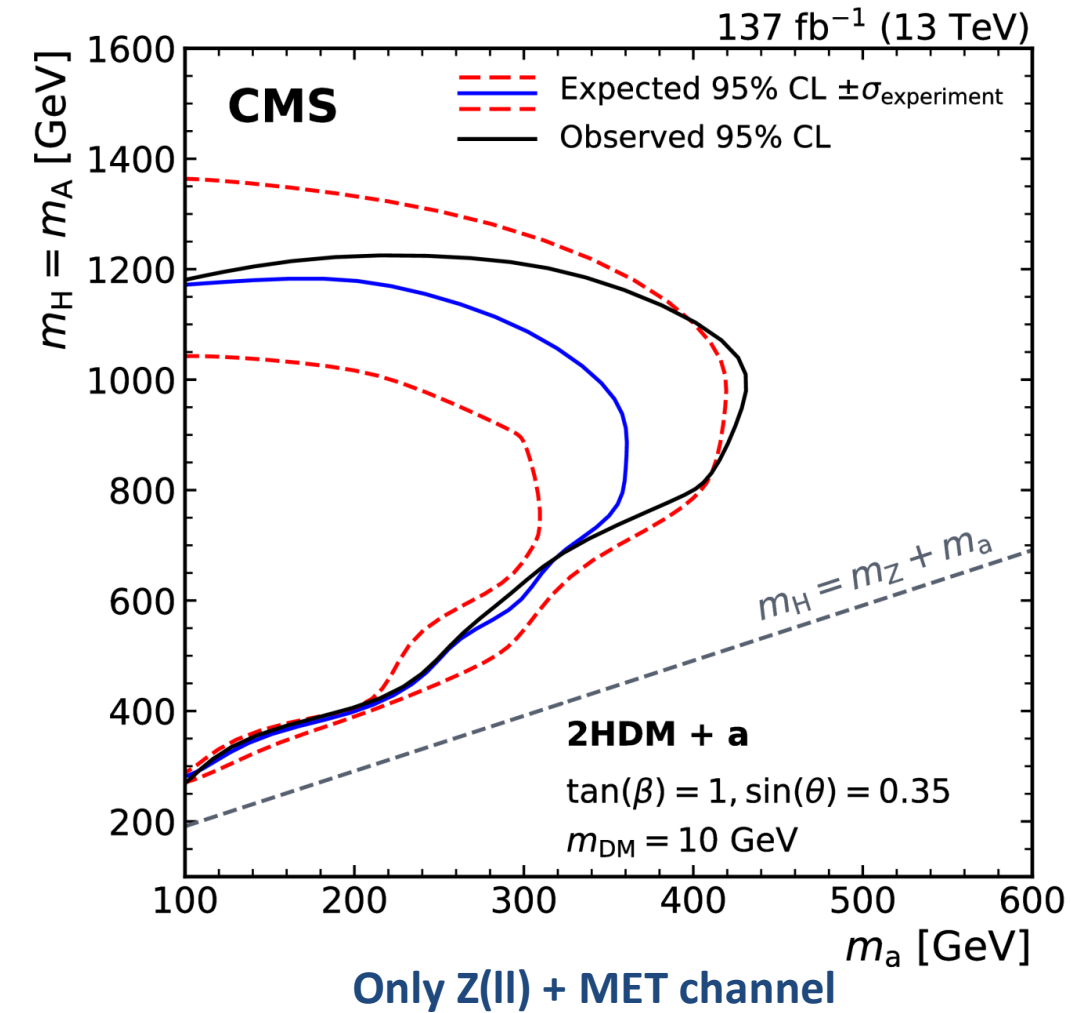The upper limits on the 2HDM+a model with the mixing angles set to tan β = 1 and sin θ = 0.35 and with a DM particle mass of m_χ = 10 GeV.

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

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Only Z(ll) + MET channel
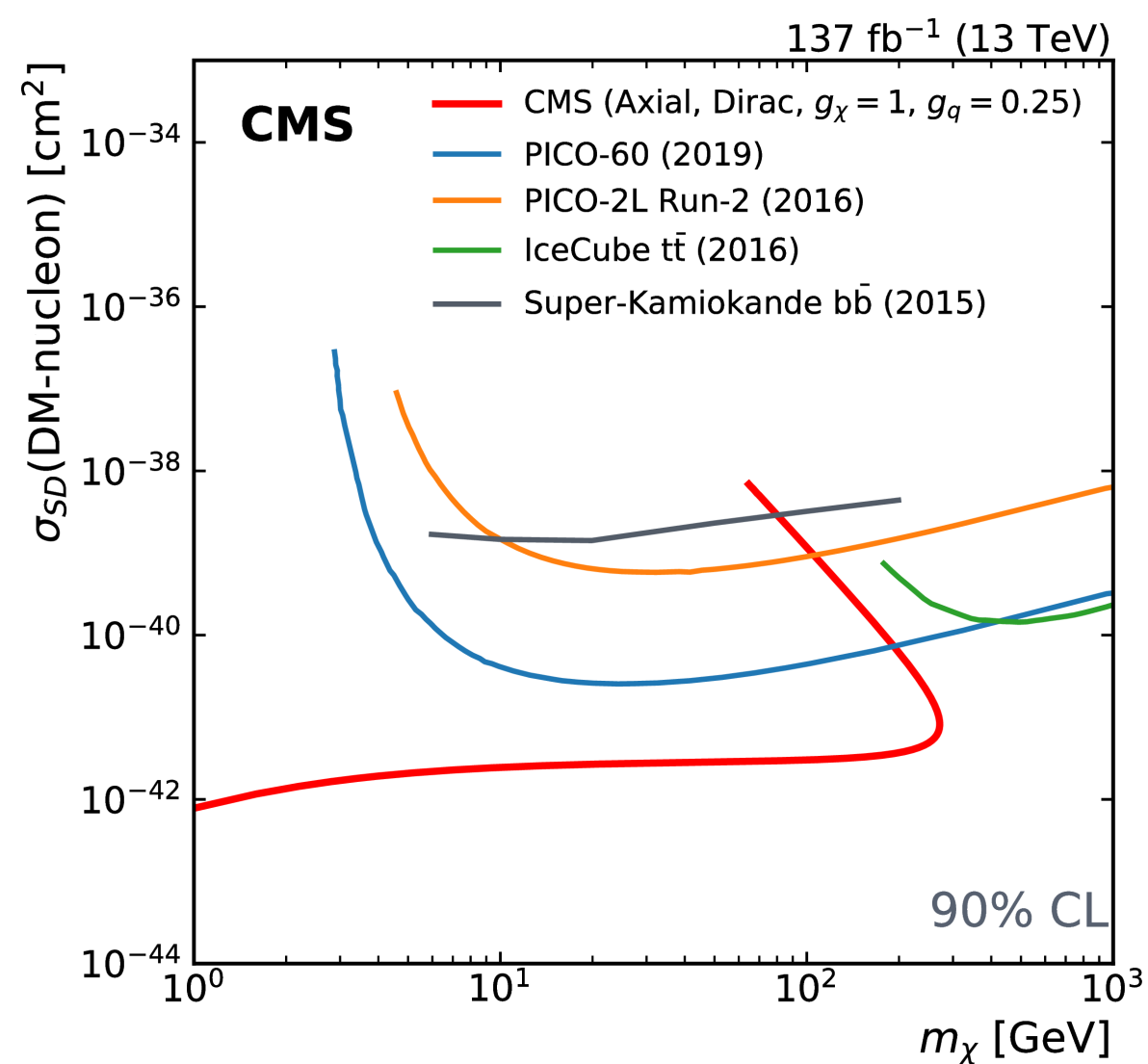
Multi-channel

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

The spin-independent case with vector couplings
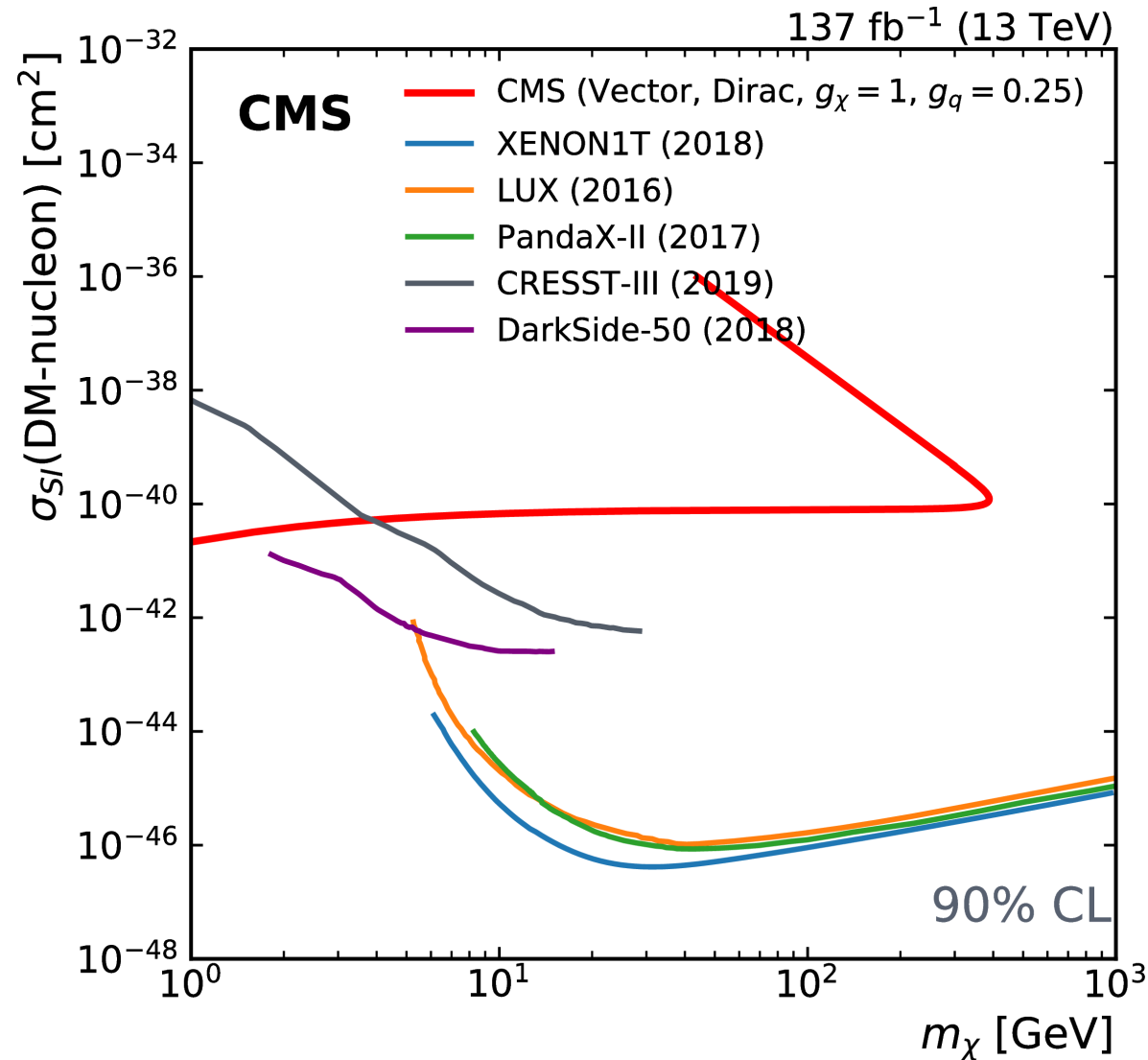
The spin-dependent case with axial-vector couplings

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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!

Background
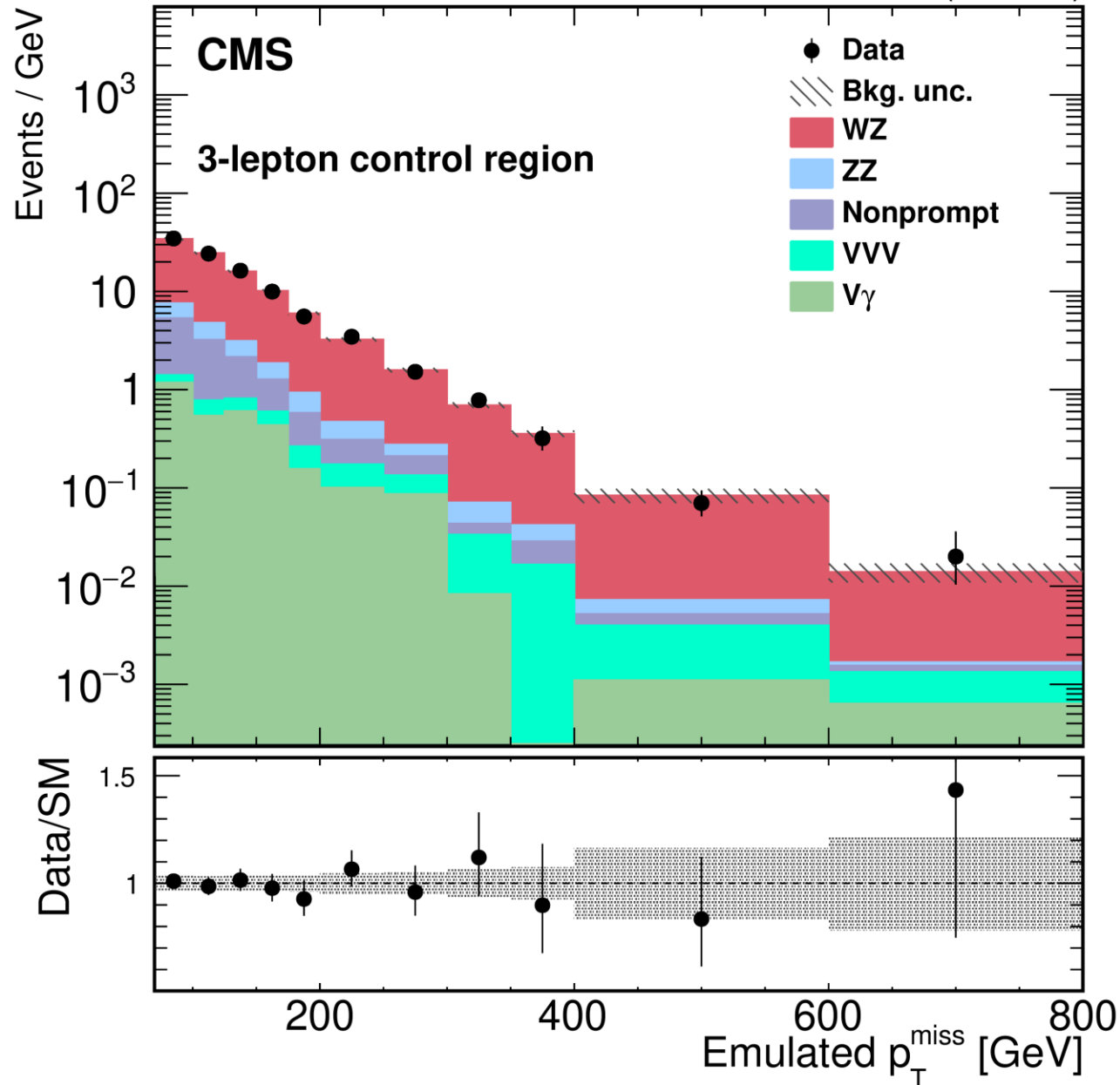
Main background sources:
$(pp \rightarrow Z + MET \rightarrow ll + MET)$

$WZ \rightarrow l\,\nu\,l\,l$

$ZZ \rightarrow 4l$

$V\gamma \rightarrow ll +$ missreconstructed γ

VVV: (WWZ, WZZ, and ZZZ)
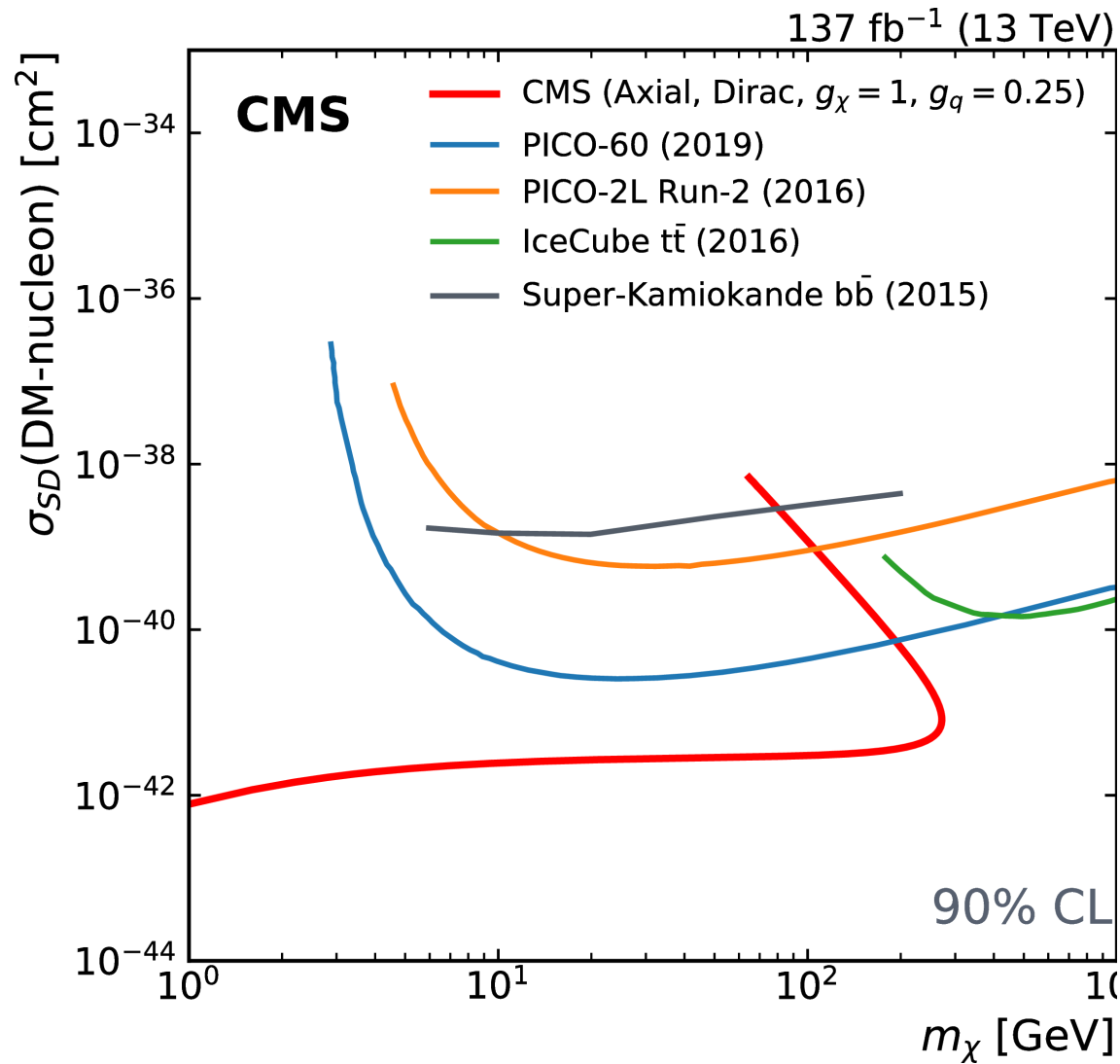$ttW \rightarrow WWbbW$, $ttZ \rightarrow WWbbZ$,
and $tt\gamma \rightarrow WWbb\gamma$

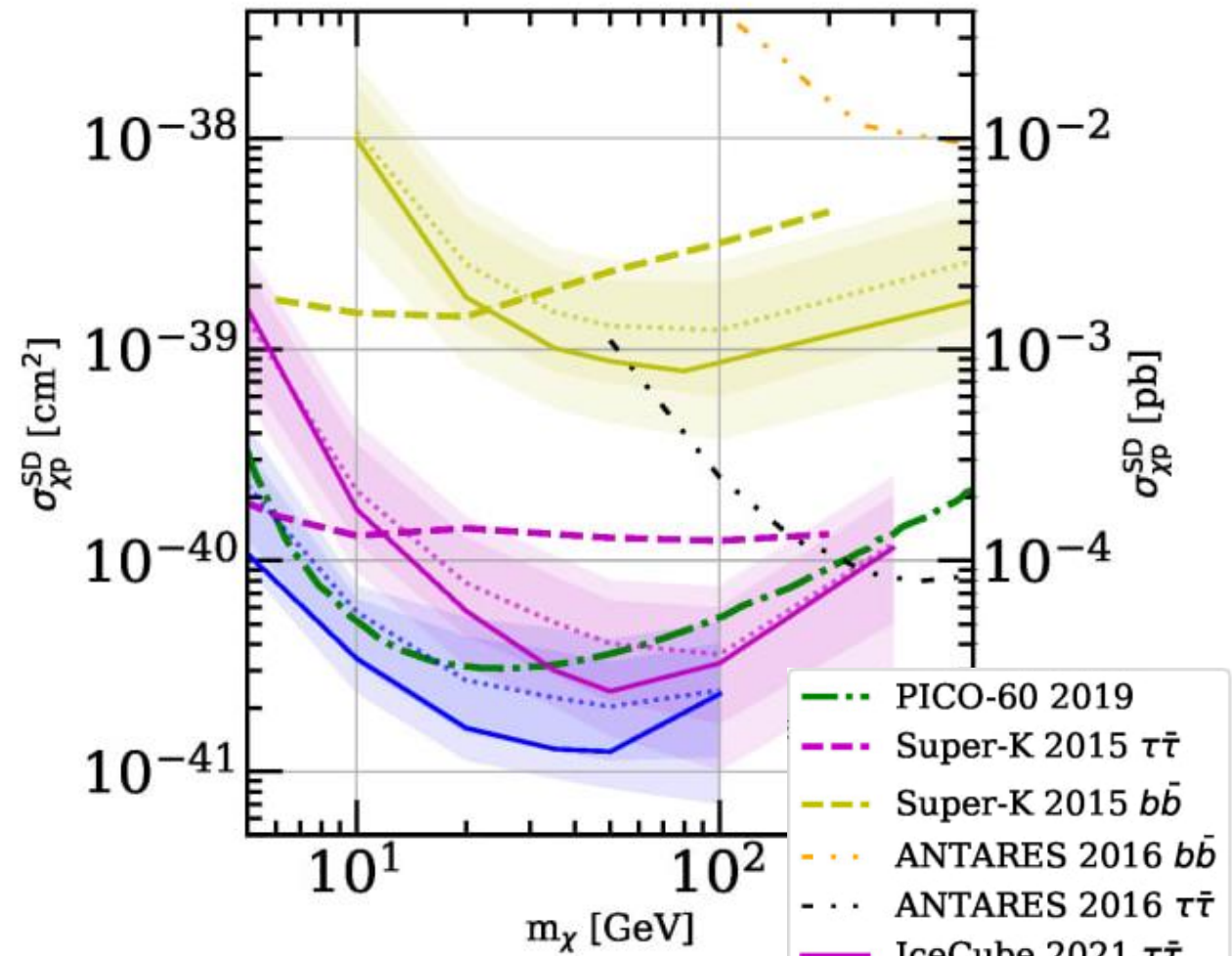# Summary of the kinematic selections for the signal region

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	$\left\| m_{\ell\ell} - m_Z \right\| < 15\,\mathrm{GeV}$	WW, top quark
Number of jets	≤ 1 jet with $p_T^j > 30\,\mathrm{GeV}$	DY, top quark, VVV
$p_T^{\ell\ell}$	>60 GeV	DY
b tagging veto	0 b-tagged jet with $p_T > 30\,\mathrm{GeV}$	Top quark, VVV
τ lepton veto	0 τ_h cand. with $p_T^\tau > 18\,\mathrm{GeV}$	WZ
$\Delta\phi(\vec{p}_T^{\,j}, \vec{p}_T^{\,\mathrm{miss}})$	>0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,\mathrm{miss}})$	>2.6 radians	DY
$\|p_T^{\mathrm{miss}} - p_T^{\ell\ell}\|/p_T^{\ell\ell}$	<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

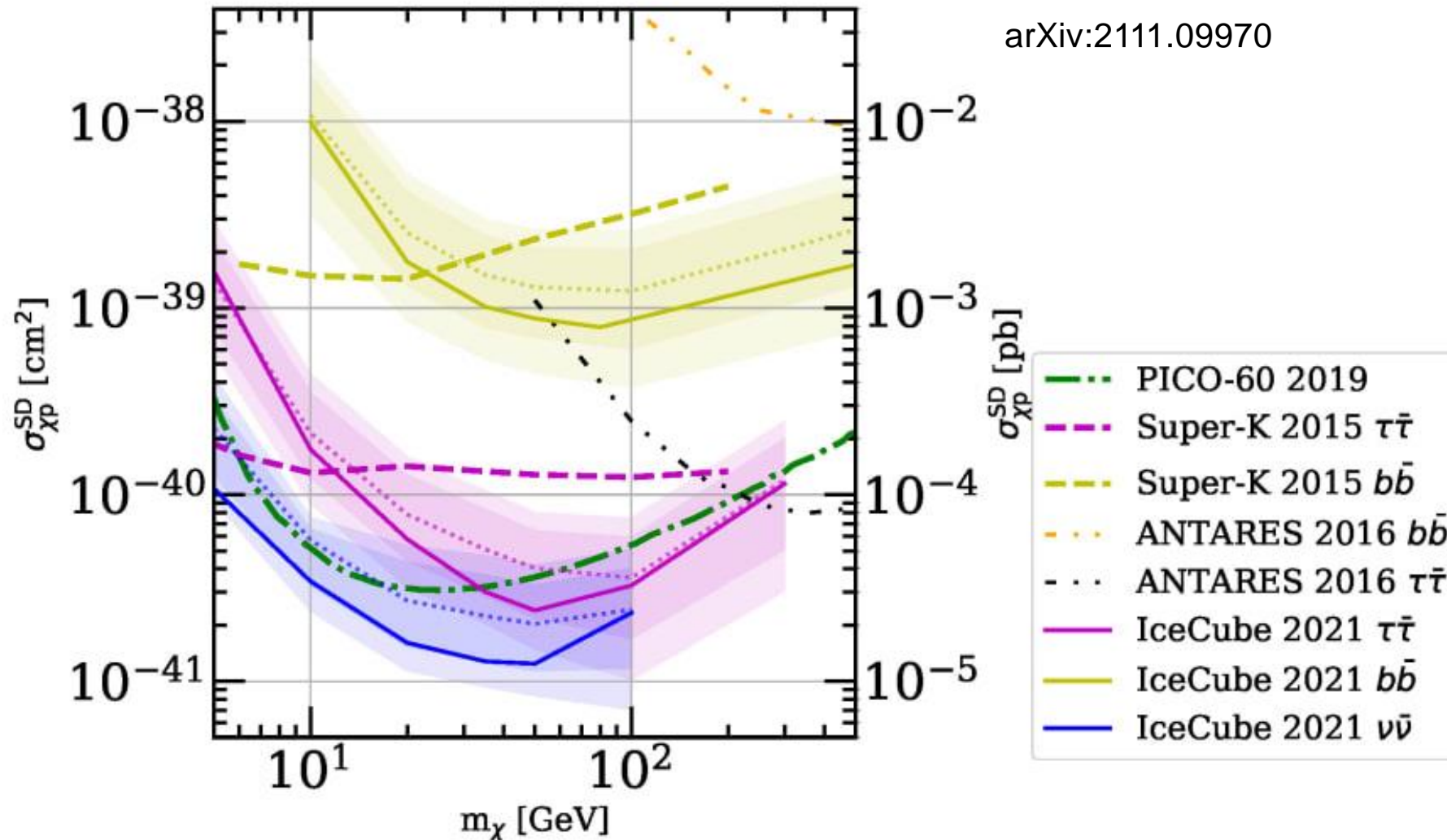# DM-nucleon upper limits on the cross section

CMS
137 fb⁻¹ (13 TeV)

- CMS (Axial, Dirac, $g_\chi = 1$, $g_q = 0.25$)
- PICO-60 (2019)
- PICO-2L Run-2 (2016)
- IceCube t̄t (2016)
- Super-Kamiokande b̄b (2015)

90% CL

arXiv:2008.04735

- PICO-60 2019
- Super-K 2015 $\tau\bar{\tau}$
- Super-K 2015 $b\bar{b}$
- ANTARES 2016 $b\bar{b}$
- ANTARES 2016 $\tau\bar{\tau}$
- IceCube 2021 $\tau\bar{\tau}$
- IceCube 2021 $b\bar{b}$
- IceCube 2021 $\nu\bar{\nu}$

arXiv:2111.09970

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
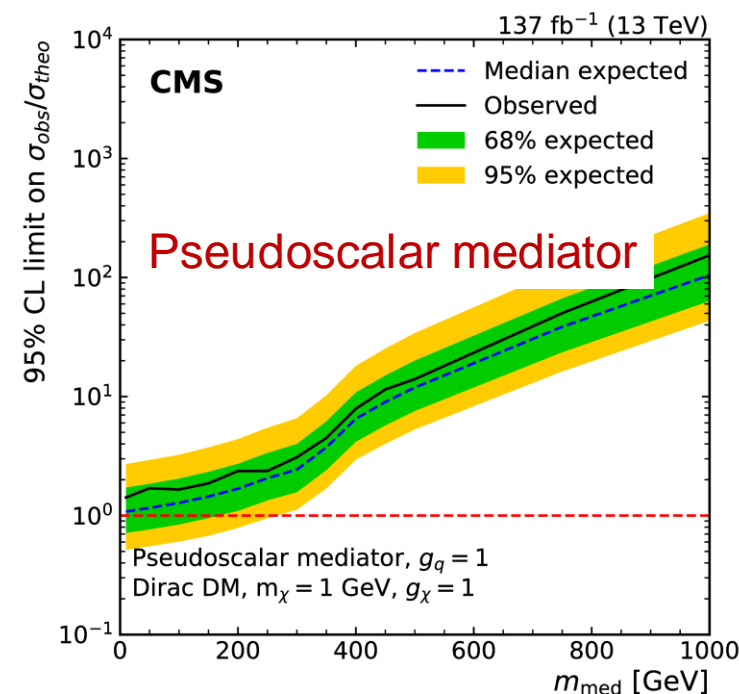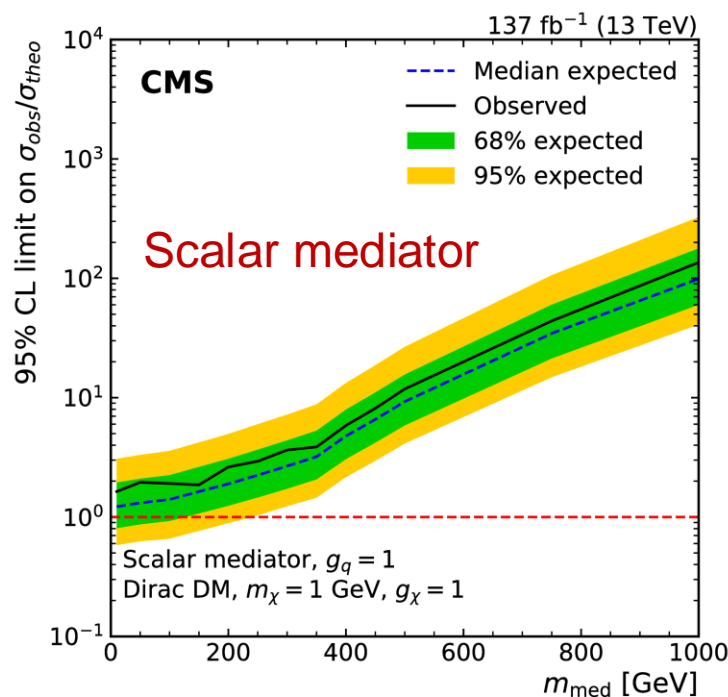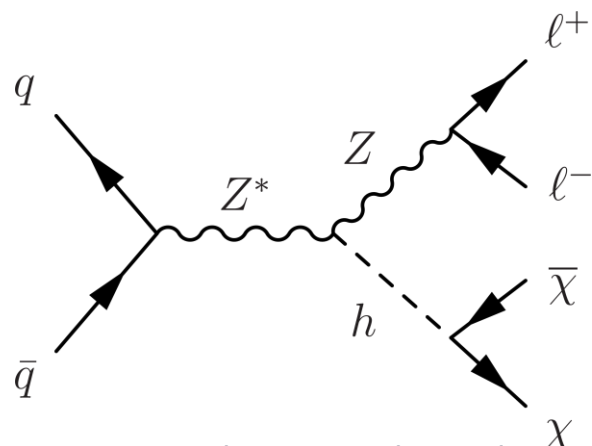
The simplified dark matter model for a spin-1 (vector or axial-vector) mediator
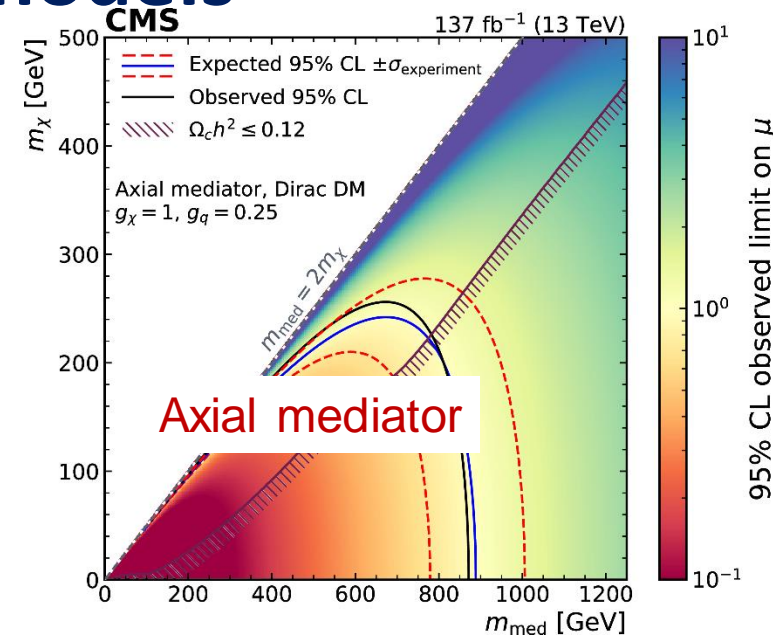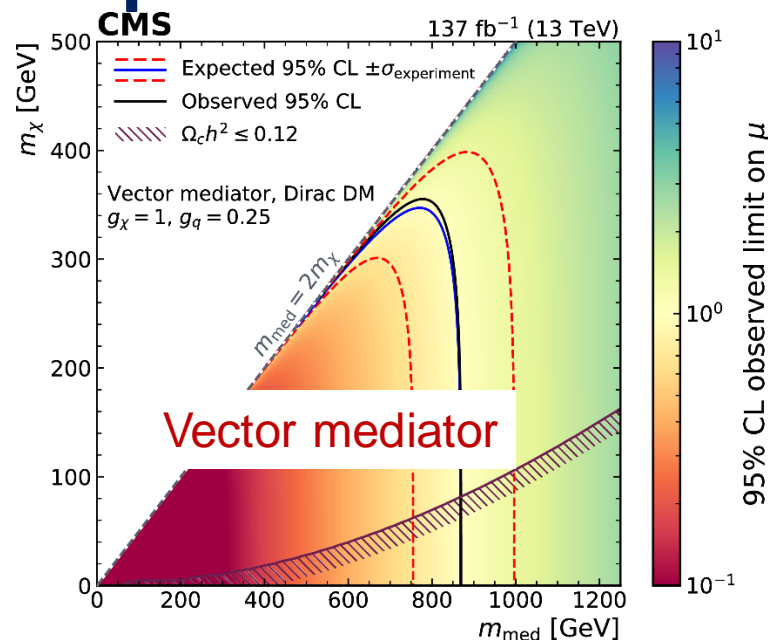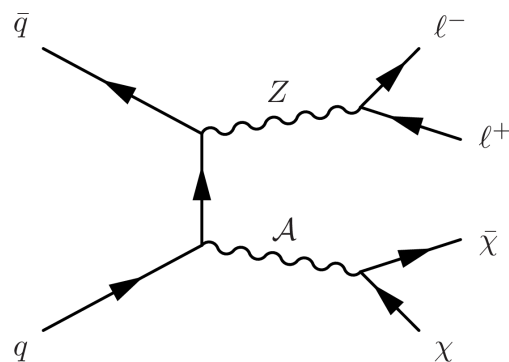
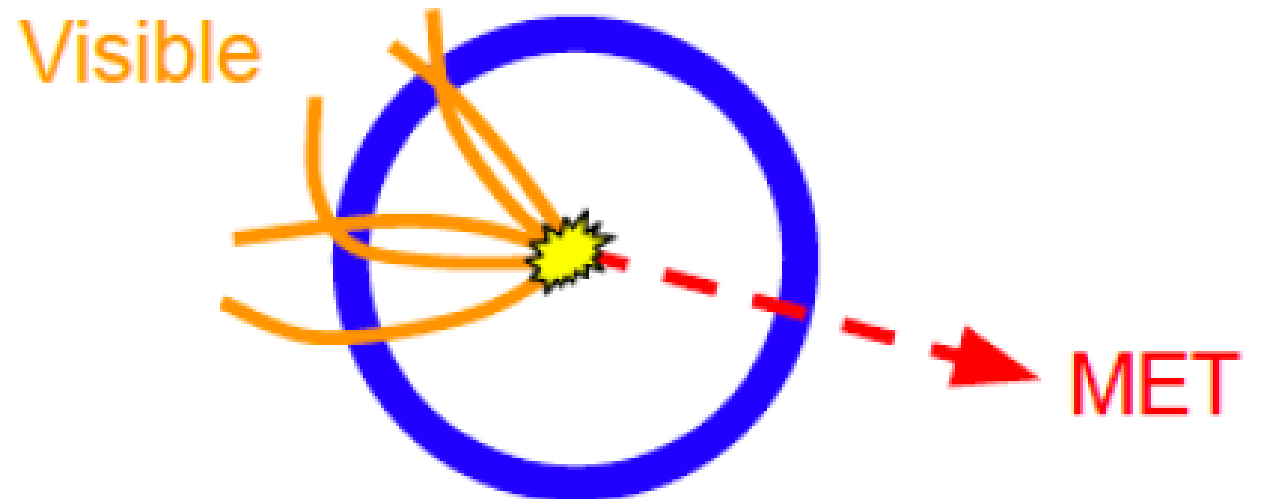The simplified dark matter model for a spin-0 (scalar or pseudoscalar) mediator

Vector mediator
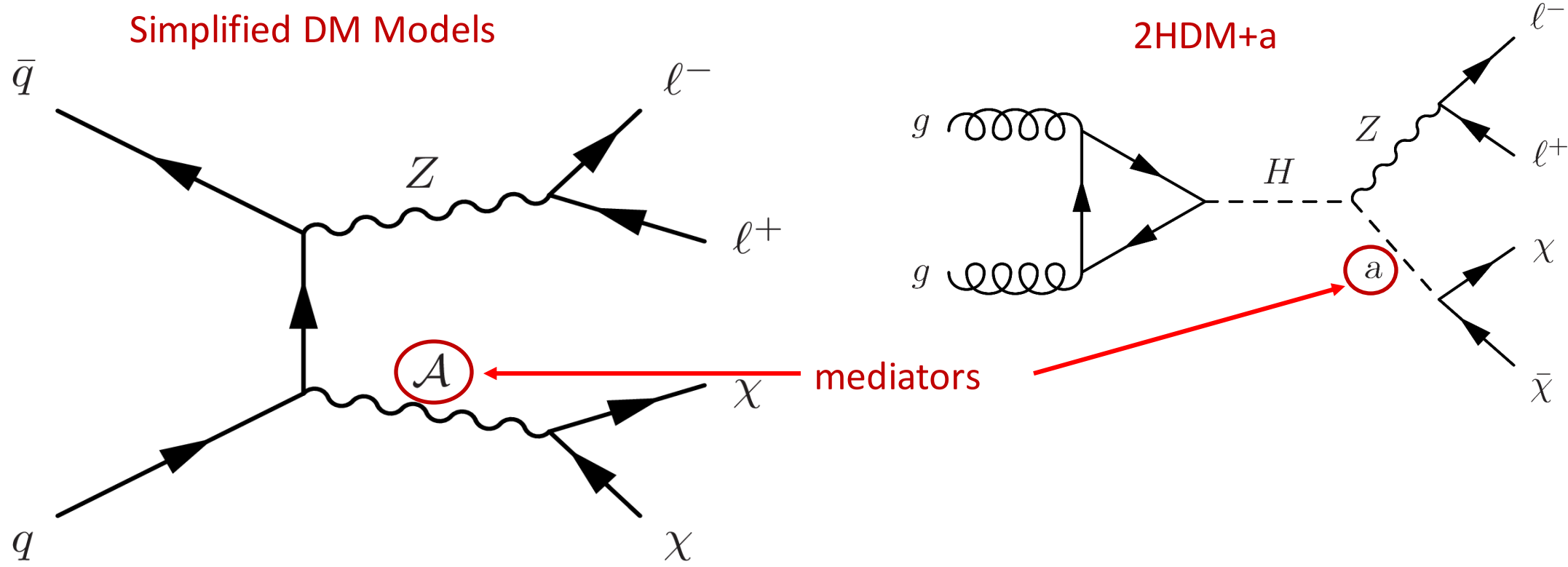
Axial mediator

Scalar mediator

Pseudoscalar mediator

Search DM in collider experiment
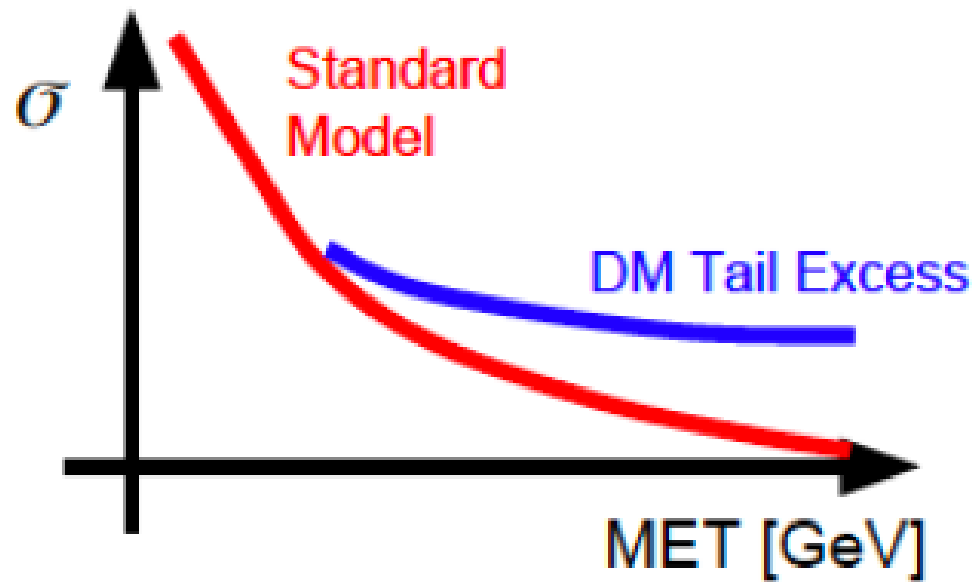
Expected deviation from predictions SM

Dark matter cannot be observed directly in accelerators.

Models BSM

Simplified DM Models

2HDM+a

mediators

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

Наш интерес