



Search for dark matter produced in association with a leptonically decaying Z boson with the CMS Experiment at the LHC

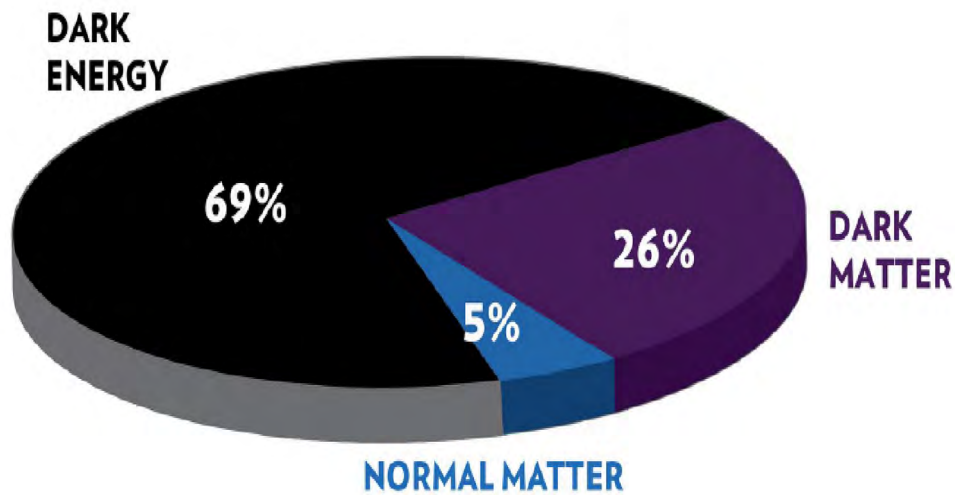
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Introduction: Dark Matter



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

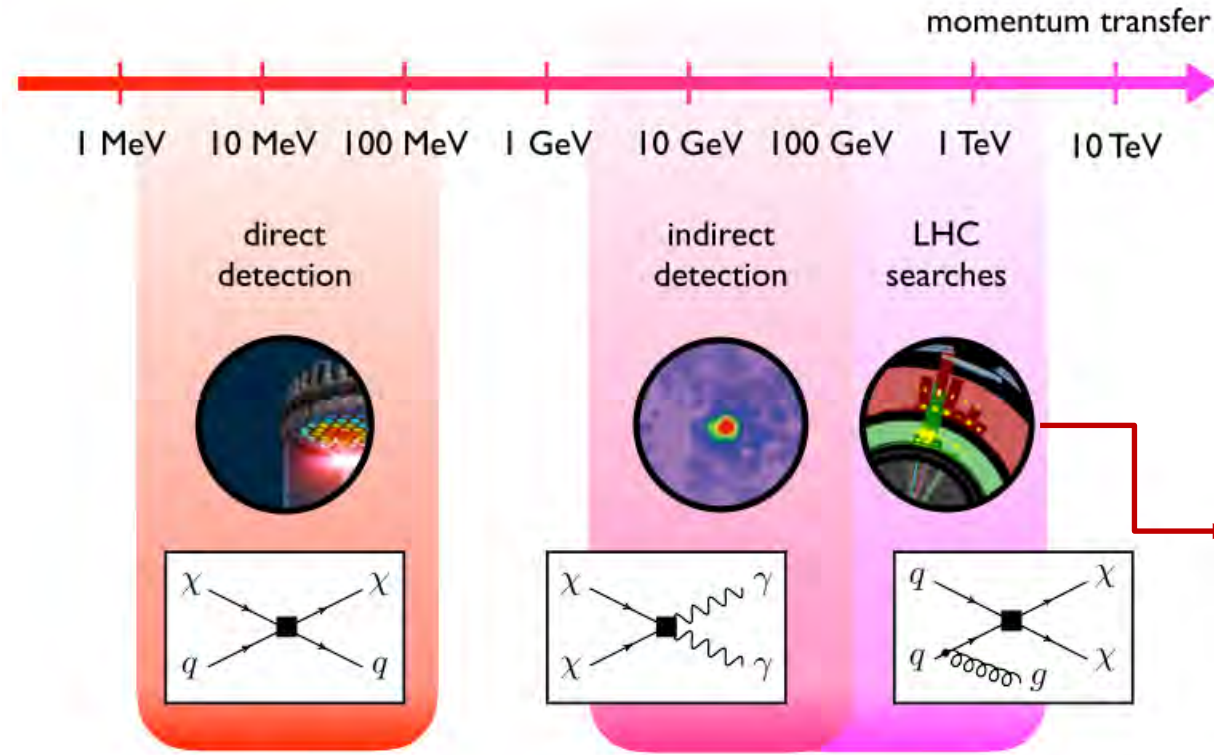
- Anisotropy of cosmic microwave background, flatness of the Universe, the prevalence of the elements and necessity of DM.
- Forming of the early Universe structure, the growth of the initial inhomogeneities

That's all we know.

DM candidates

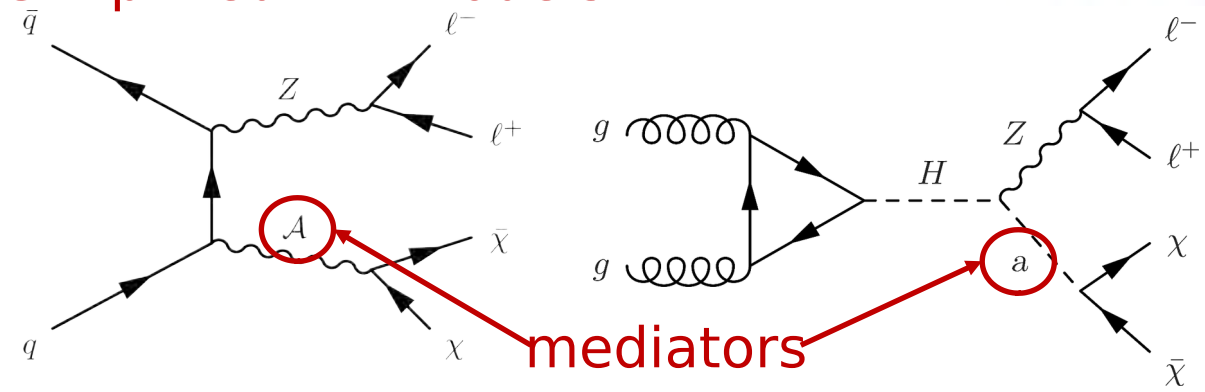
- Baryonic matter (massive astrophysical compact halo objects - MACHO)
- Non-baryonic matter (sterile neutrinos, weakly interacting massive particles - WIMPs, axions, supersymmetric particles, etc.)

How to search?

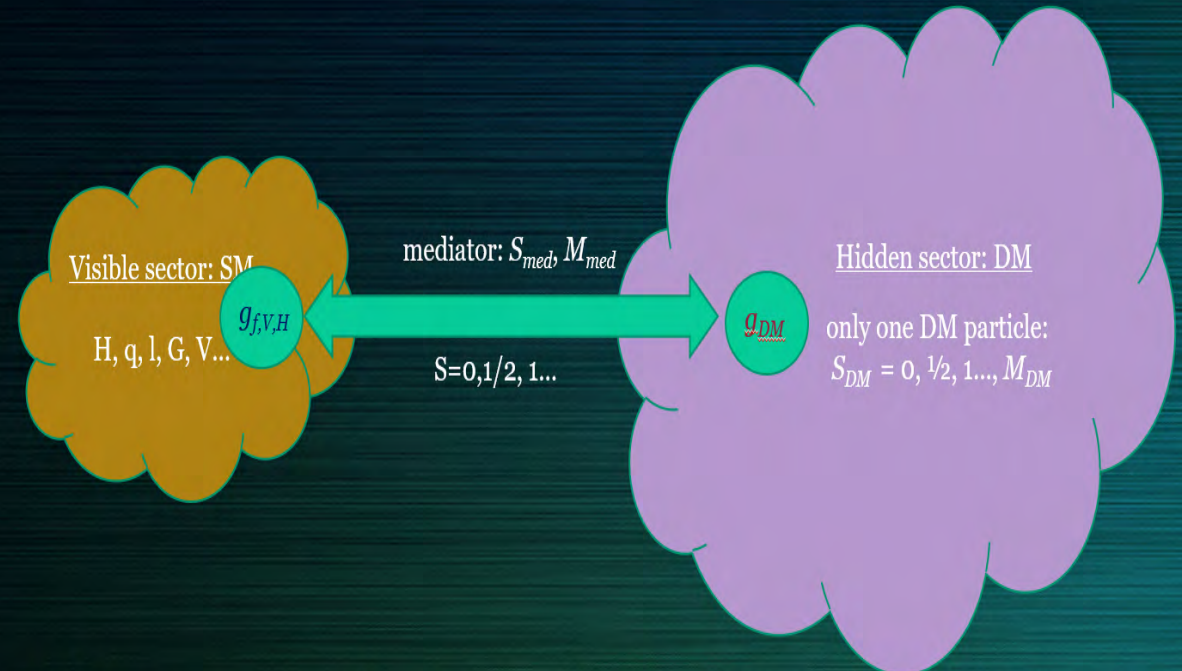


Simplified DM Models

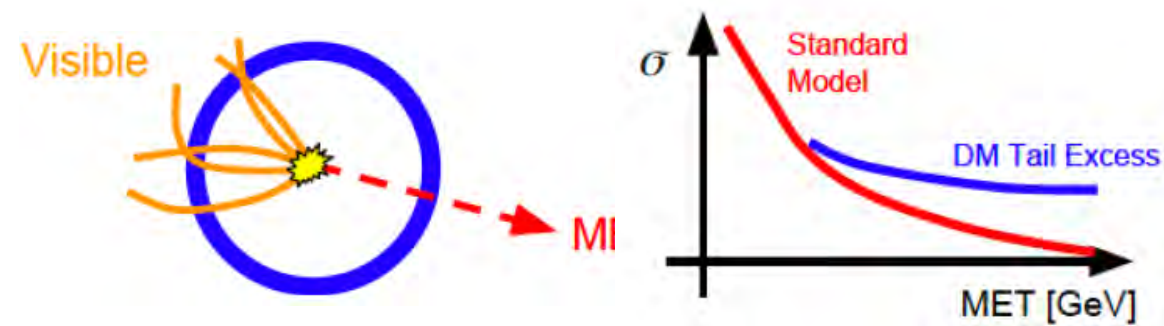
2HDM+



The simplest DM: one DM particle + one mediator



Model free parameters: a mass of a mediator, a mass of a DM particle, couplings to the visible and hidden sector



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^-

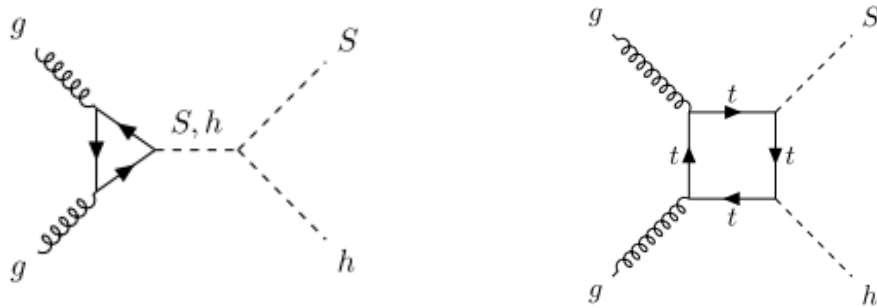
Dark Matter Sector can be probed by Extra Scalar/Pseudoscalar Mediator

2HDM+s [arXiv:1612.03475](https://arxiv.org/abs/1612.03475)

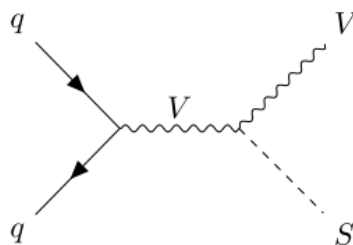
2HDM+a [arXiv:1701.07427](https://arxiv.org/abs/1701.07427)

2HDM + S (neutral scalar singlet)

$h (b\bar{b}) + S () = b\bar{b} + MET$



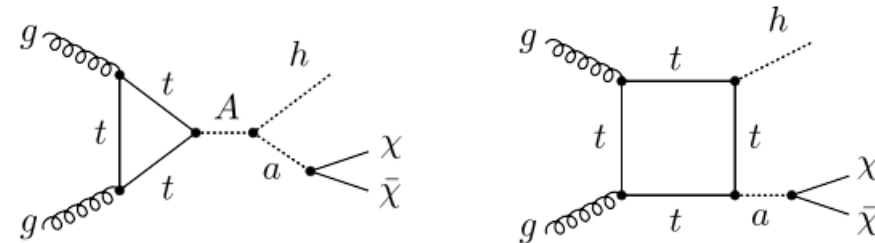
$V (W/Z) + S () = Z (II) + MET$



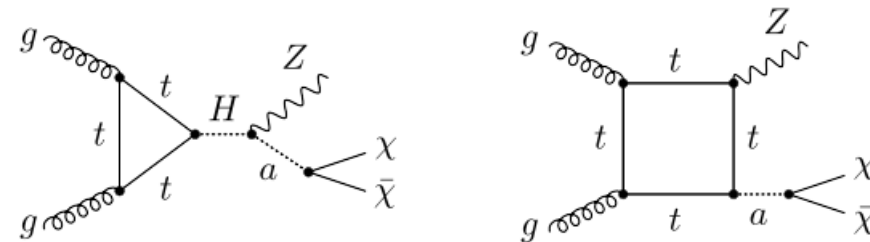
<http://feynrules.irmp.ucl.ac.be/wiki/DMGISM0>

2HDM + a (light neutral pseudoscalar singlet)

$h (b\bar{b}) + a () = b\bar{b} + MET$



$Z + a () = Z (II) + MET$



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

Model Parameters and Signal Simulation

Generator: MadGraph5MC@NLO.2.9.2

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

Process: $p p > Z \chi \chi$ (16 diagrams)

Free parameters for 2HDM + a:

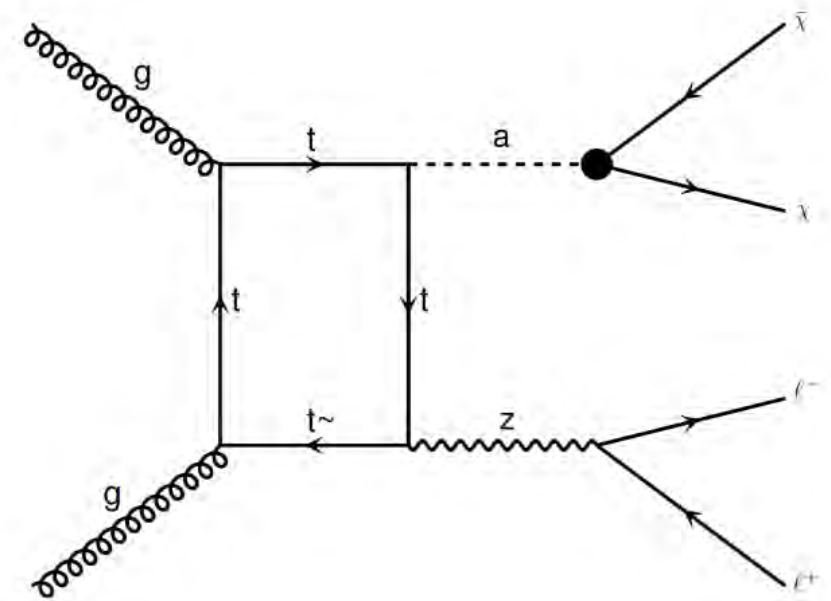
- masses of heavy higgses, $m_{H^{+/-}} = m_H = m_A = [600:2000]$ GeV
- mass of dark matter particle, $m_\chi = [1:2000]$ GeV
- mass of light pseudoscalar/scalar states, $m_a = m_s = [300:1000]$ GeV
- the ratio of the vacuum expectation values of the two Higgs doublets, $\tan(\beta) = [0.5:50]$
- the 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)





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) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
 Microstrips (80x180 μm) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000\text{A}$

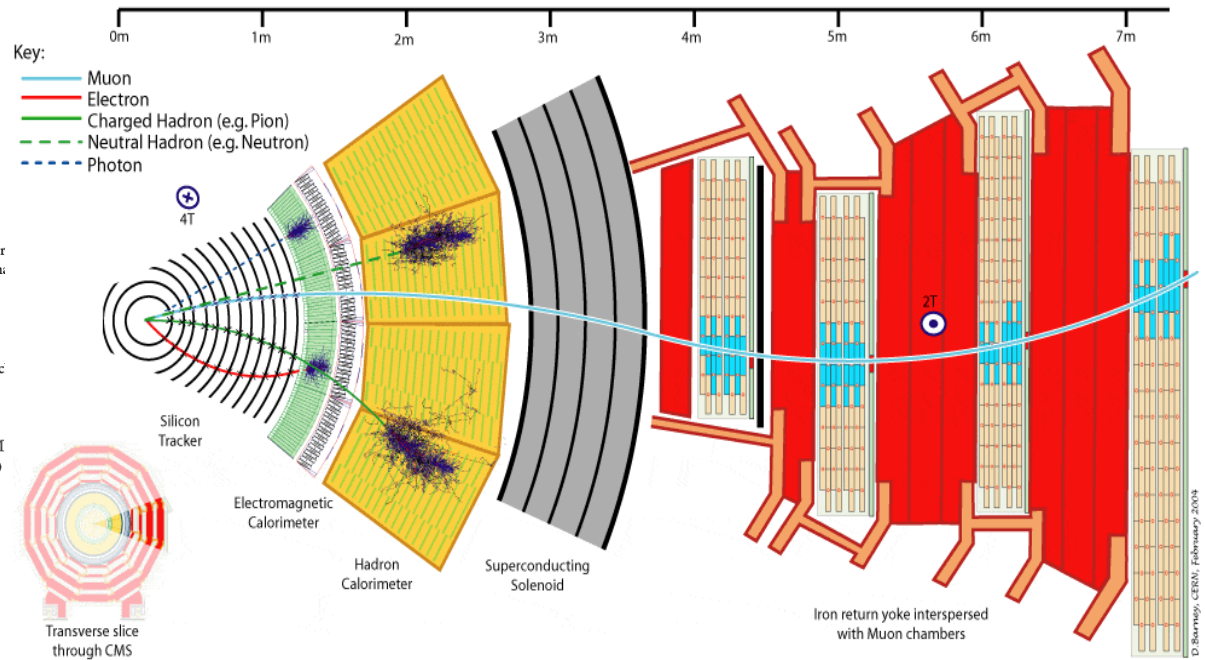
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chamber
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Ch.

PRESHOWER
 Silicon strips $\sim 16\text{m}^2 \sim 137,000$ c

FORWARD CALORIM
 Steel + Quartz fibres $\sim 2,000$

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

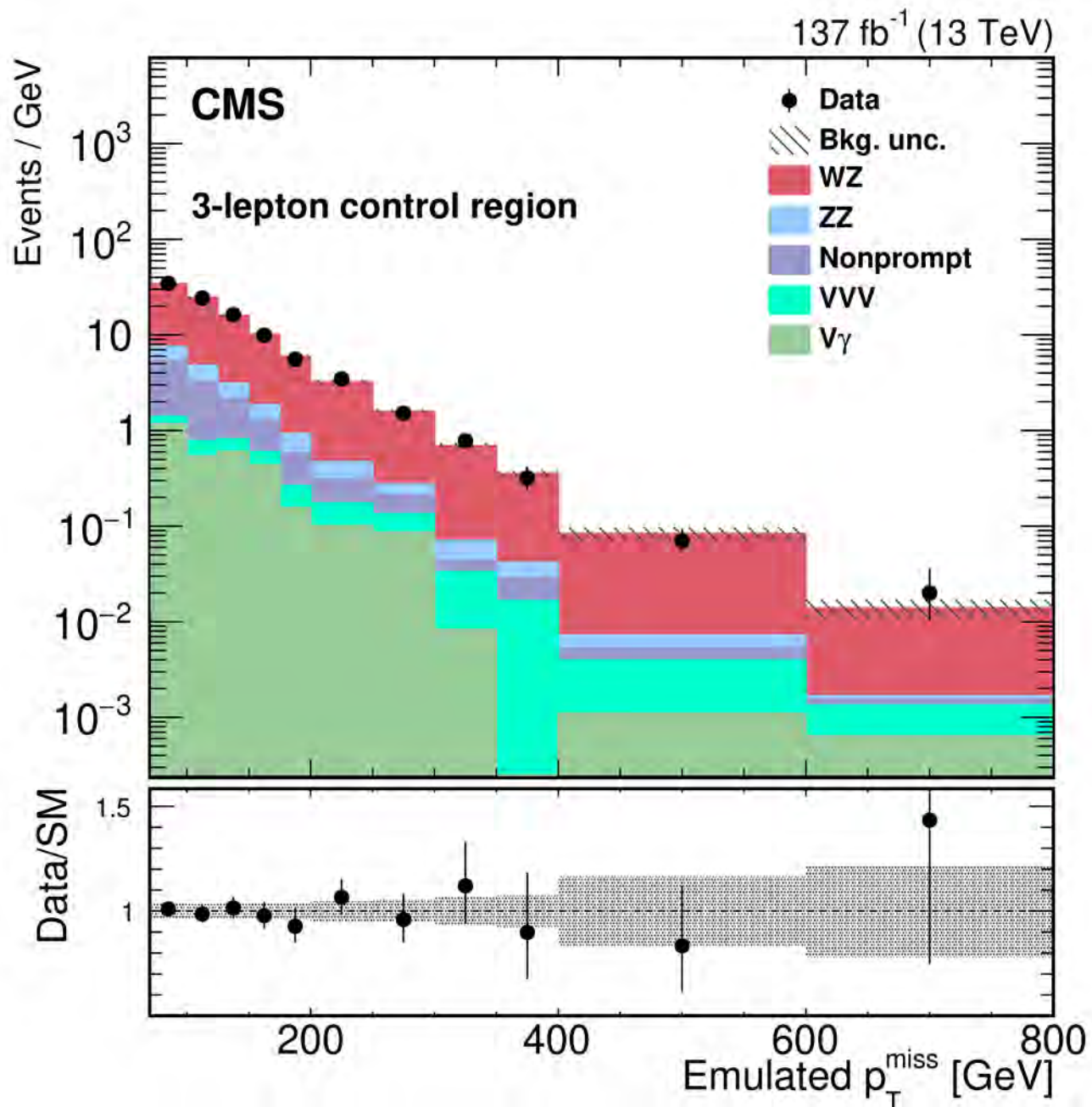
HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels



- Length - 22 m
- Diameter - 15 метров
- Magnetic field - 3.8 T
- Weight - 14 000 t!

	RUN1	RUN2	RUN3
Energy(TeV)	7, 8	13	13.6
Integrated luminosity (fb^{-1})	4.5, 19.7	163.2	300
Year	2009-2014	2015-2018	2022-2027

Background



Main background sources:

WZ \rightarrow l ν l l

ZZ \rightarrow 4l

DY: This process does not produce undetectable particles.

VVV: (WWZ, WZZ, and ZZZ)
 ttW \rightarrow WWbbW, ttZ \rightarrow WWbbZ,
 and tty \rightarrow WWbb γ

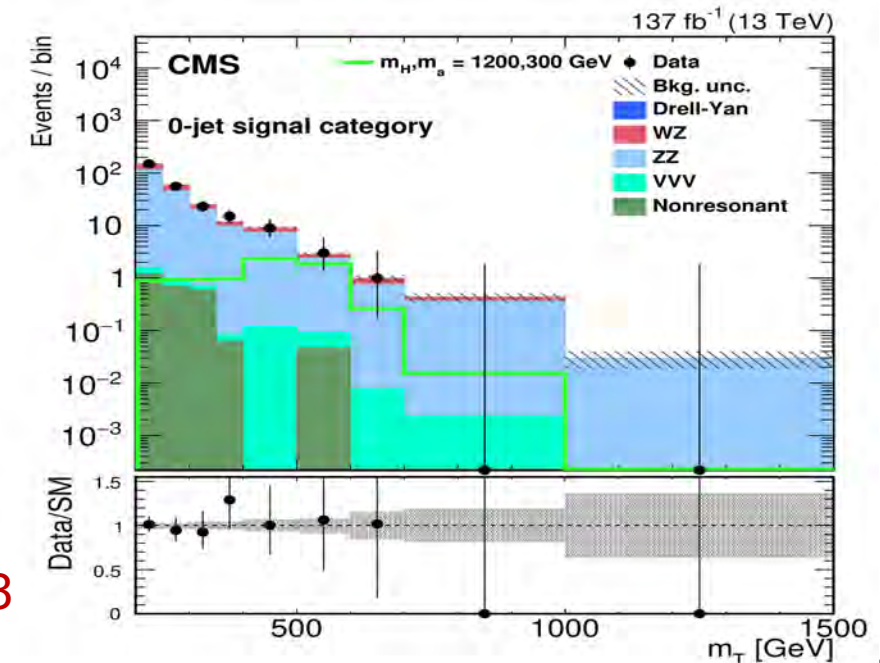
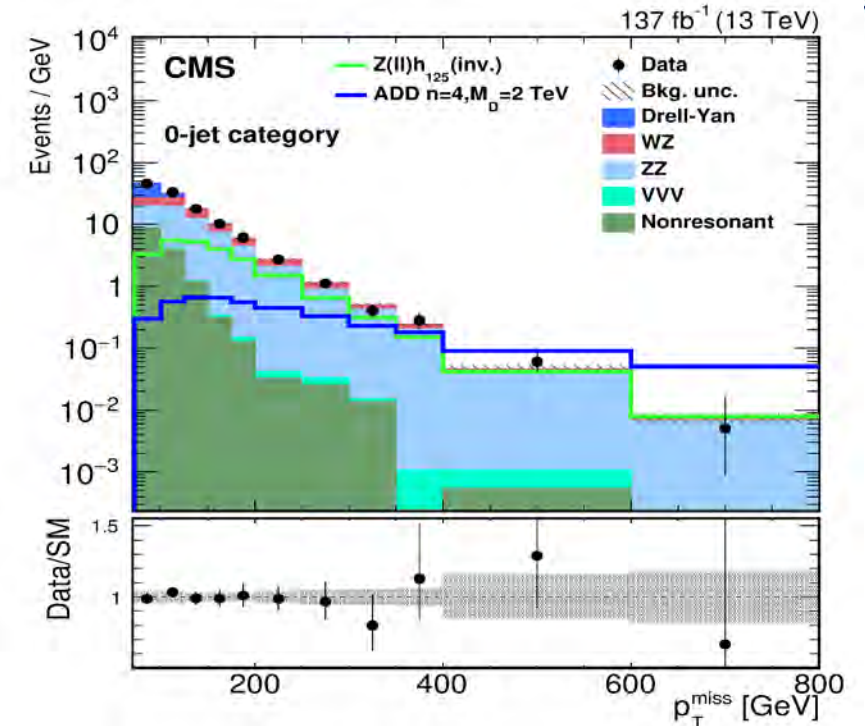
Observed number of events and post-fit background estimates

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

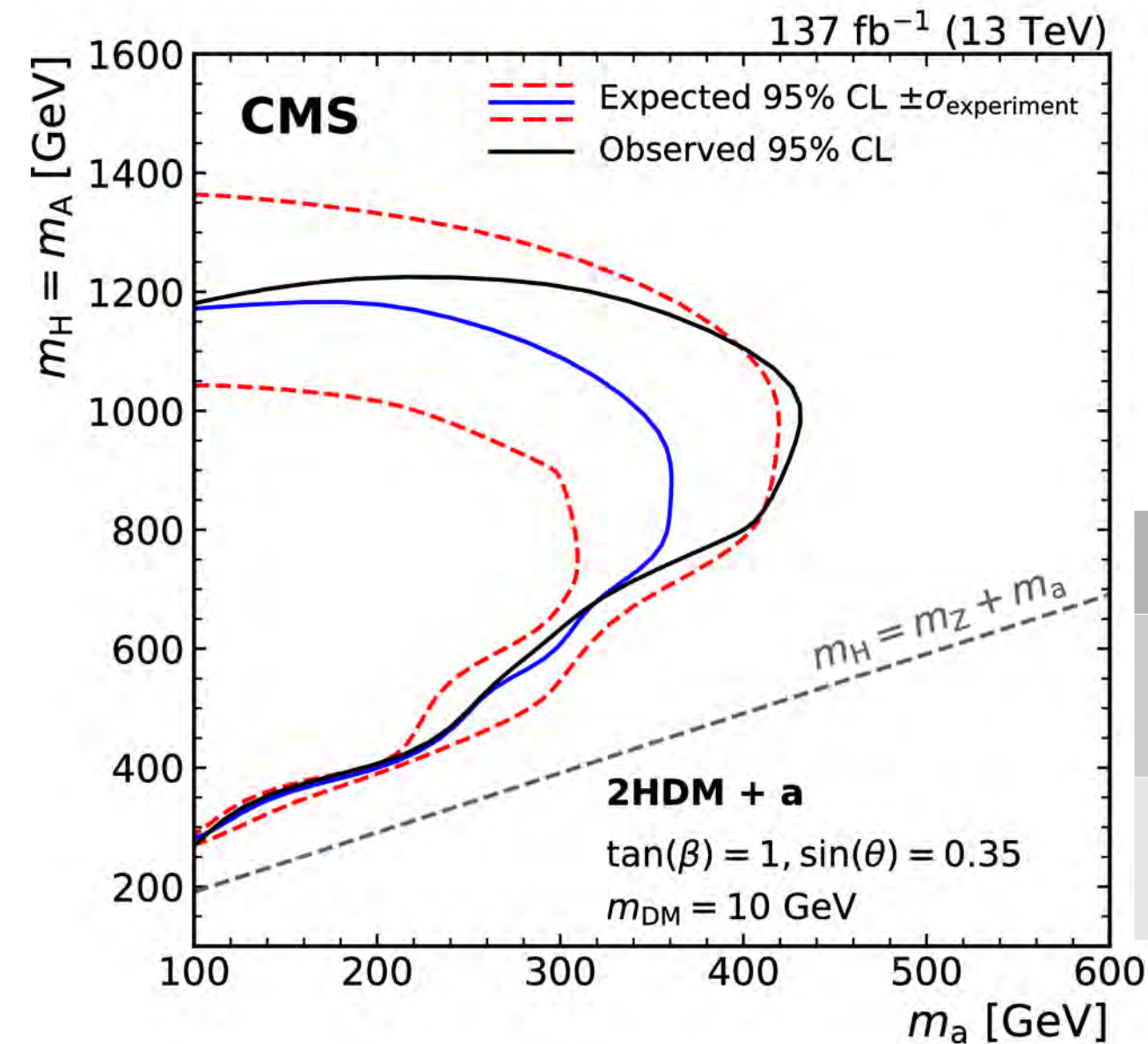
Expected yields and the product of acceptance and efficiency for several models probed in the analysis

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 mediator mass with the most sensitivity is $m_H = 1000 \text{ GeV}$, where the observed (expected) limit on m_a is 440 (340) GeV.

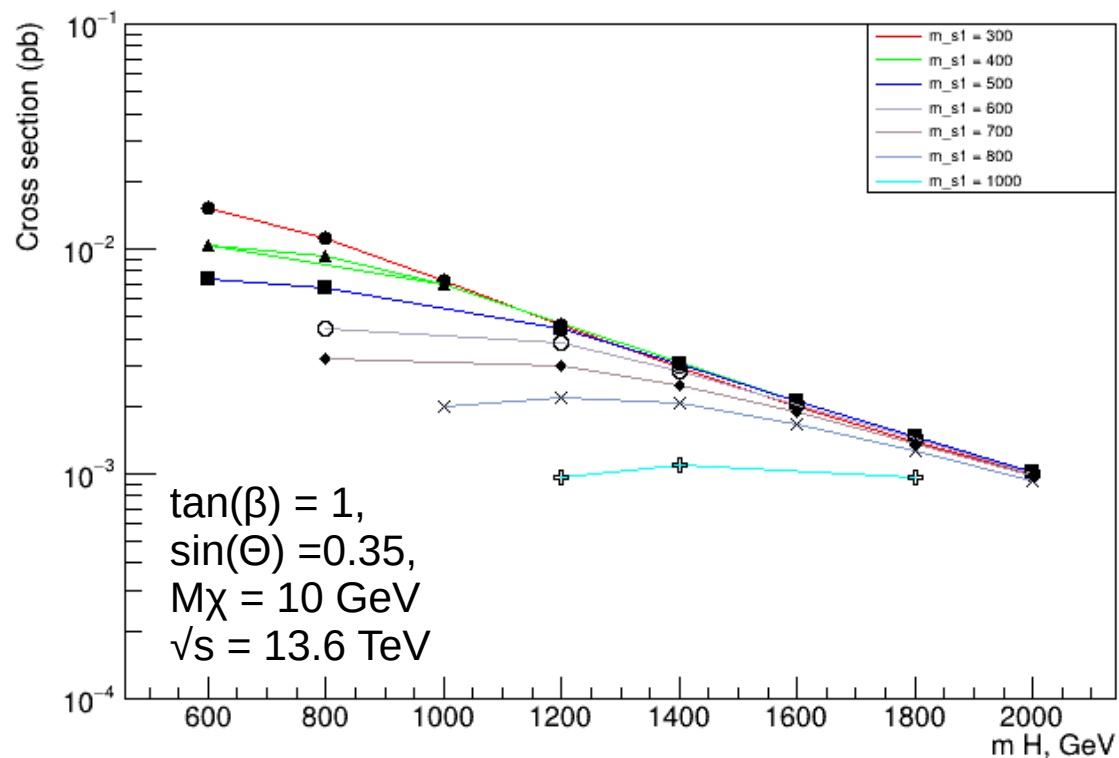
For small values of m_a the limit on m_H is about 1200 GeV.

Model	Parameter	Observed	Expected
2HDM+a $m_H = 1 \text{ TeV}$	m_a	330 GeV	440 GeV
2HDM+a $m_a = 100 \text{ GeV}$	m_H	1200 GeV	1200 GeV

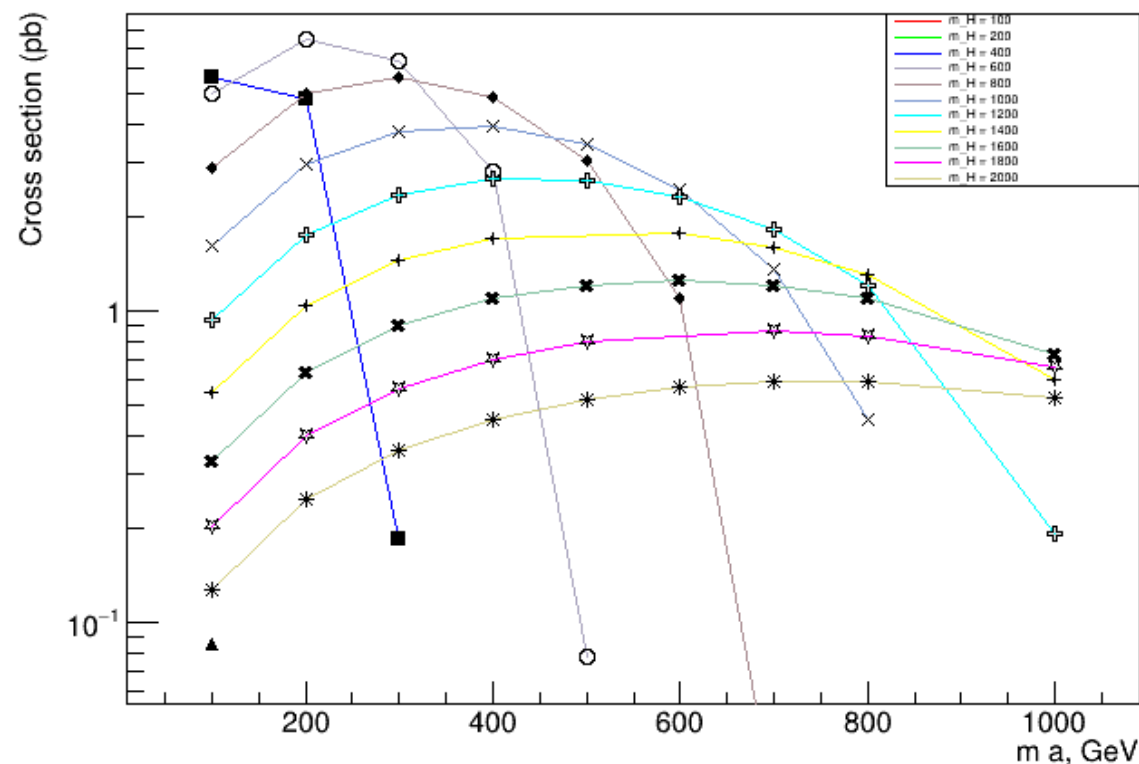
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RUN3 Expectations (cross sections)

2HDM+S



2HDM+a



The total cross section of the process $pp \rightarrow Z \chi \bar{\chi}$ in 2HDM+a model(right) and 2HDM+s (left). The observed limits on the production cross sections are used to constrain parameters of these models.

In total about **1000** sets of model parameters



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.
 - in addition, limits are provided for spin-dependent and spin-independent scattering cross sections and are compared to those from direct-detection experiment
- 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)

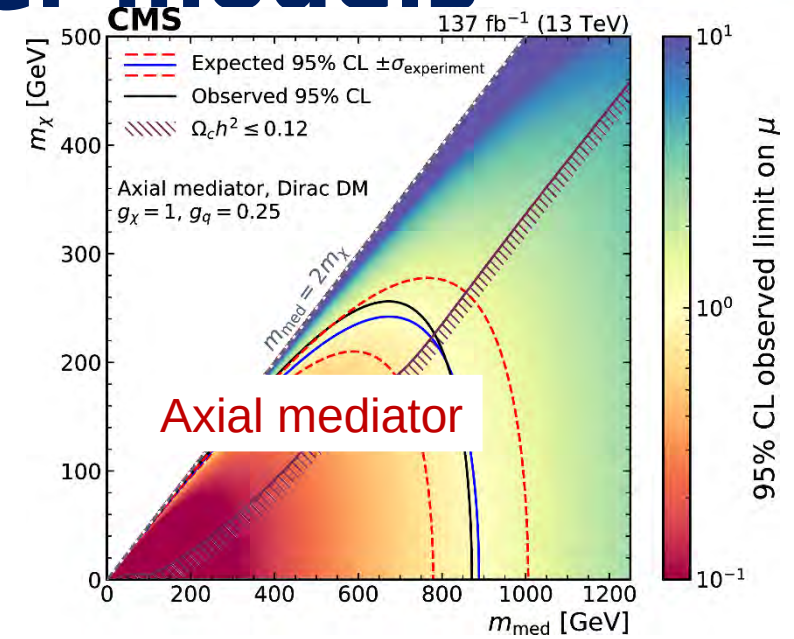
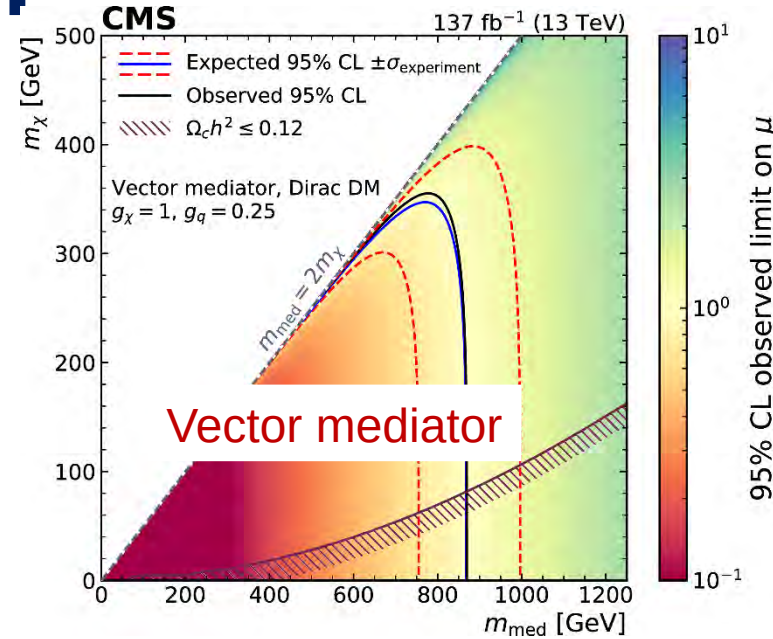
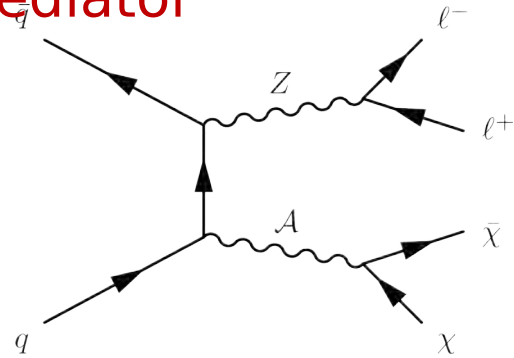


THANK YOU FOR YOUR ATTENTION!

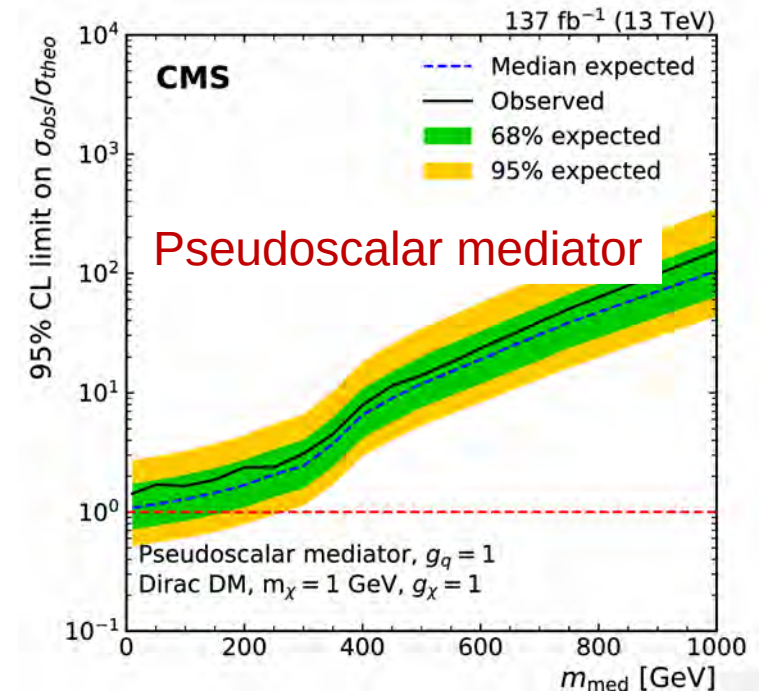
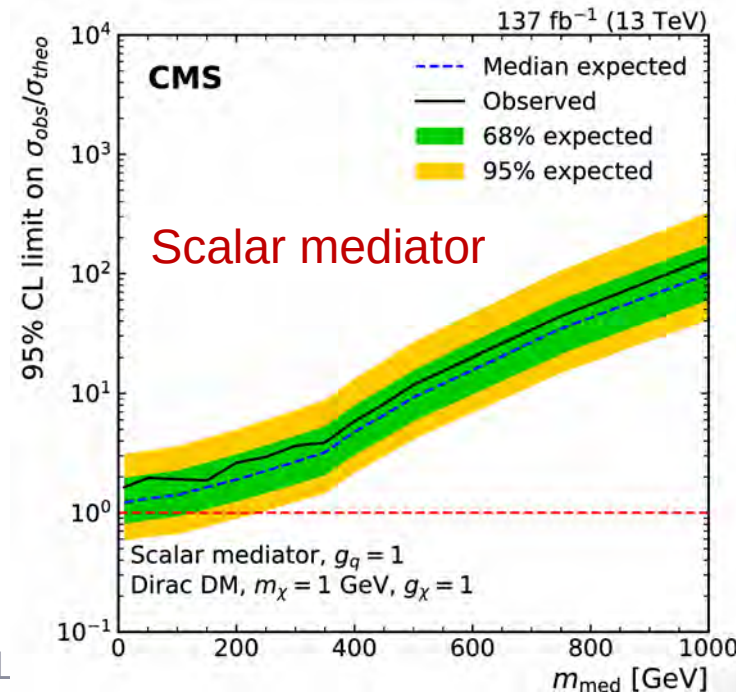
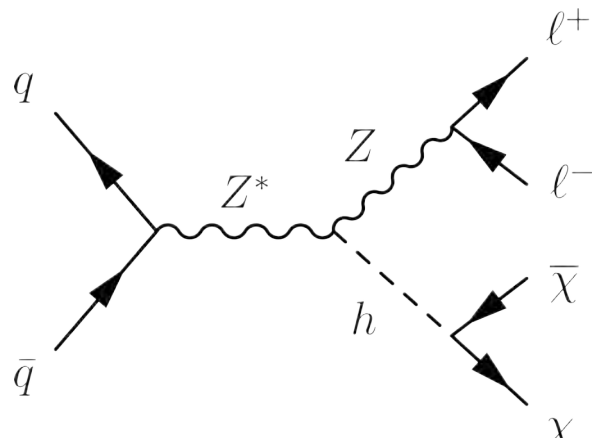


The simplified dark matter models

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



Dark Matter with Z and MET at the L

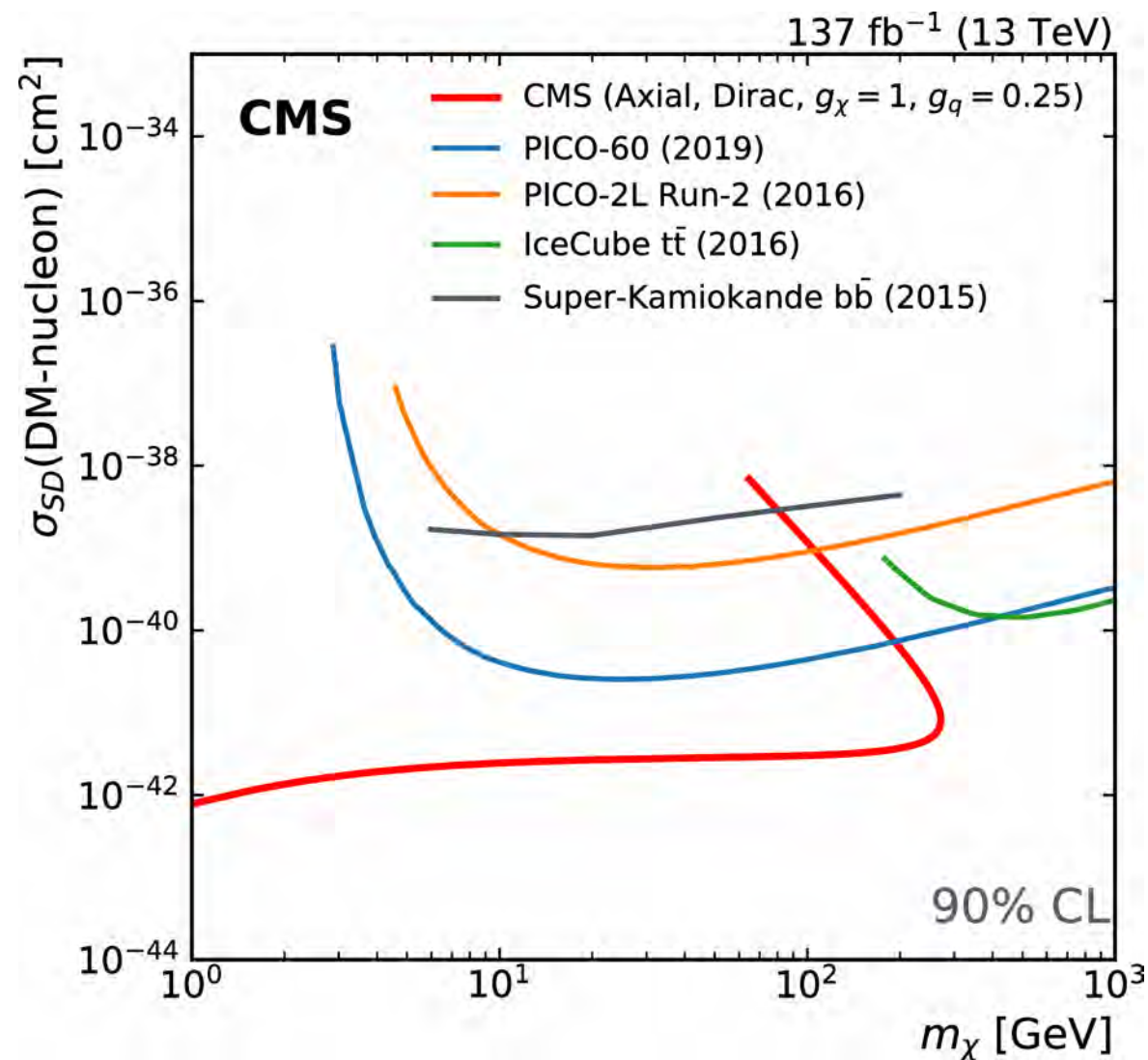
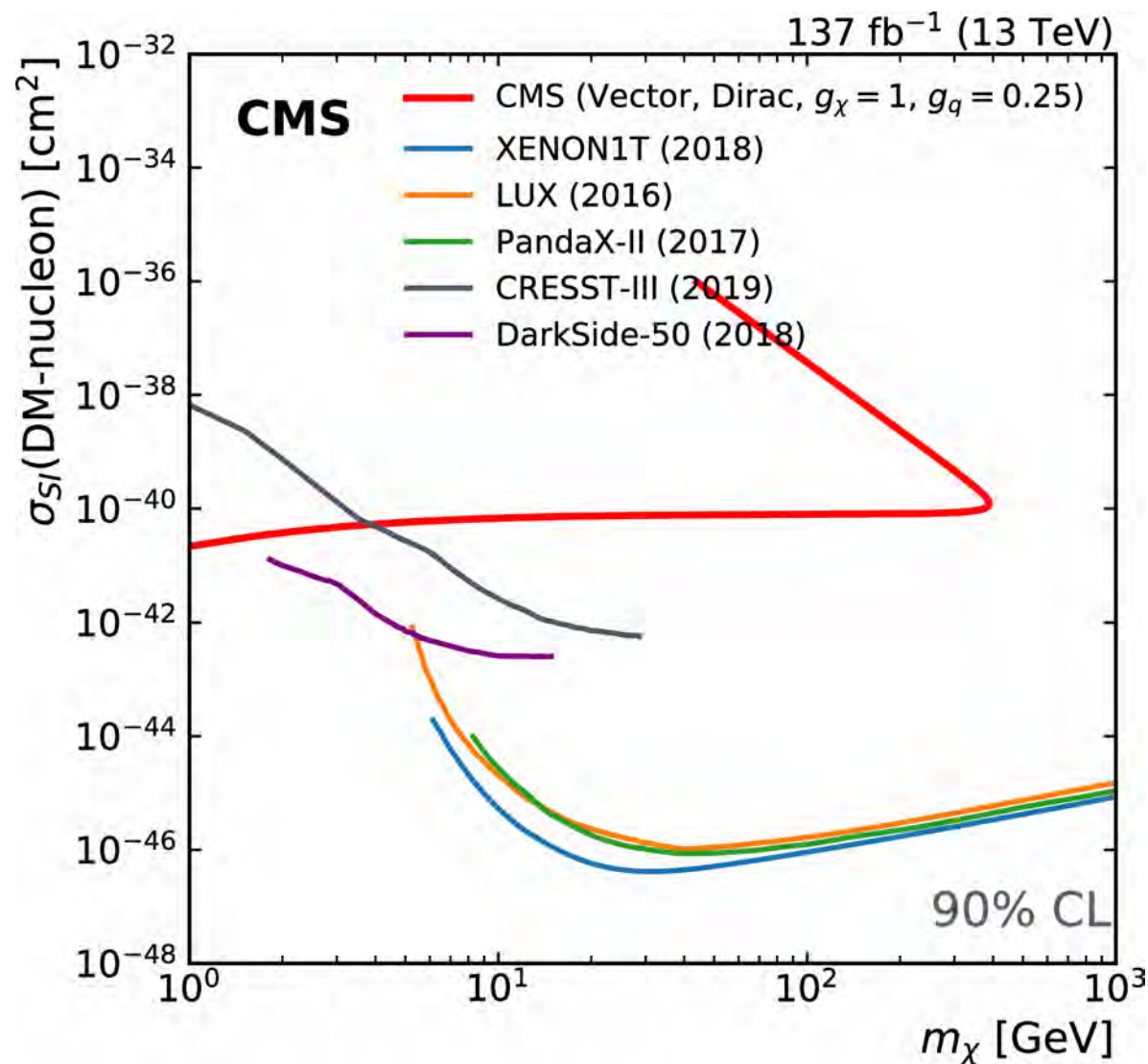


DM-nucleon upper limits on the cross section for simplified DM



The spin-independent case with vector couplings

The spin-dependent case with axial-vector couplings



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