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

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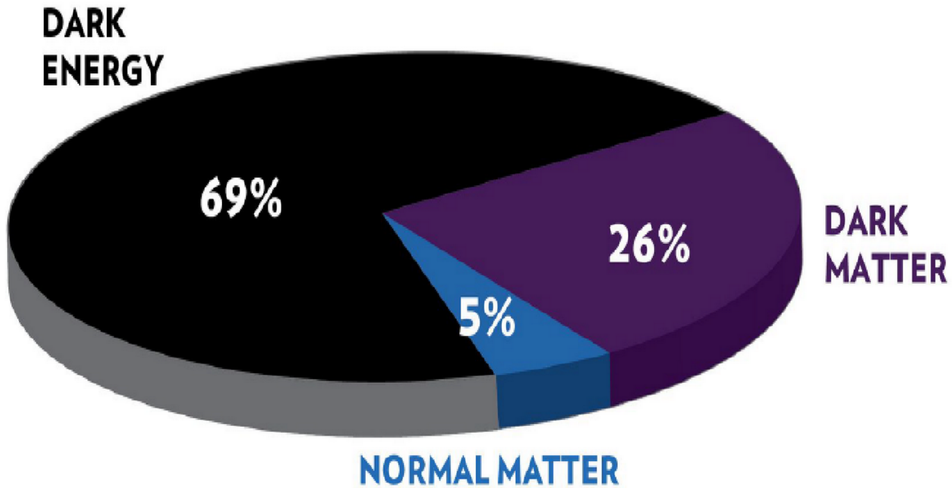
Introduction: Dark Matter



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

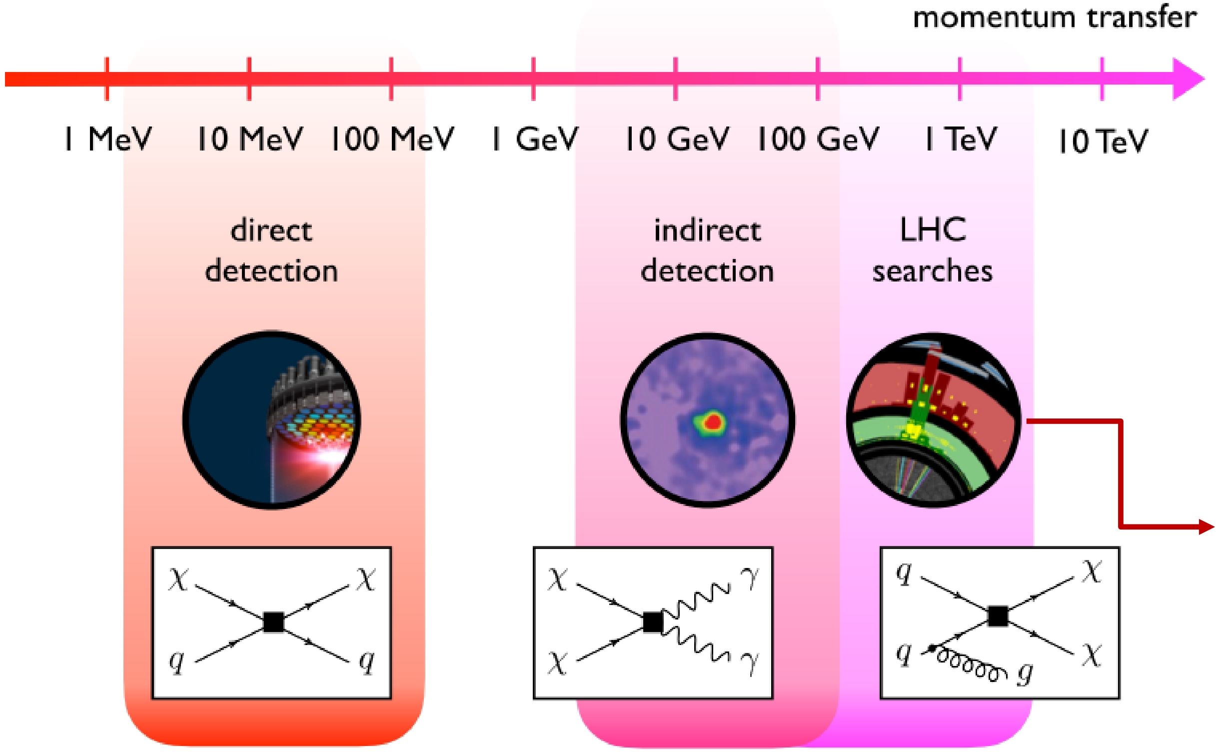
- ❑ Anisotropy of cosmic microwave background, flatness of the Universe, the prevalence of the elements and necessity of DM.
- ❑ Forming of the early Universe structure, the growth of the initial inhomogeneities

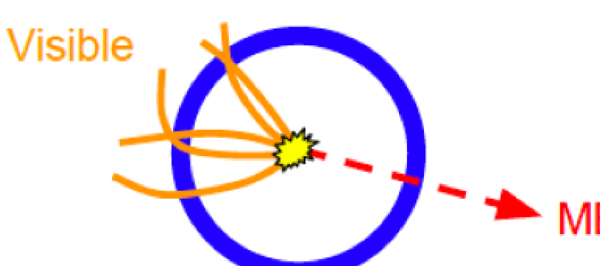
That’s all we know.

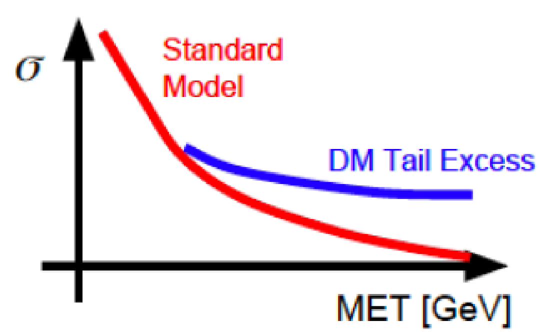
DM candidates

- ❑ 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?

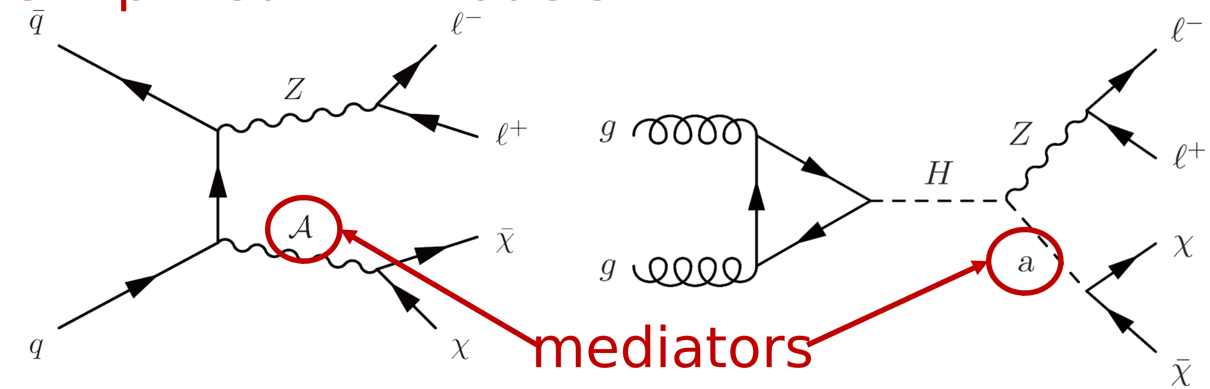


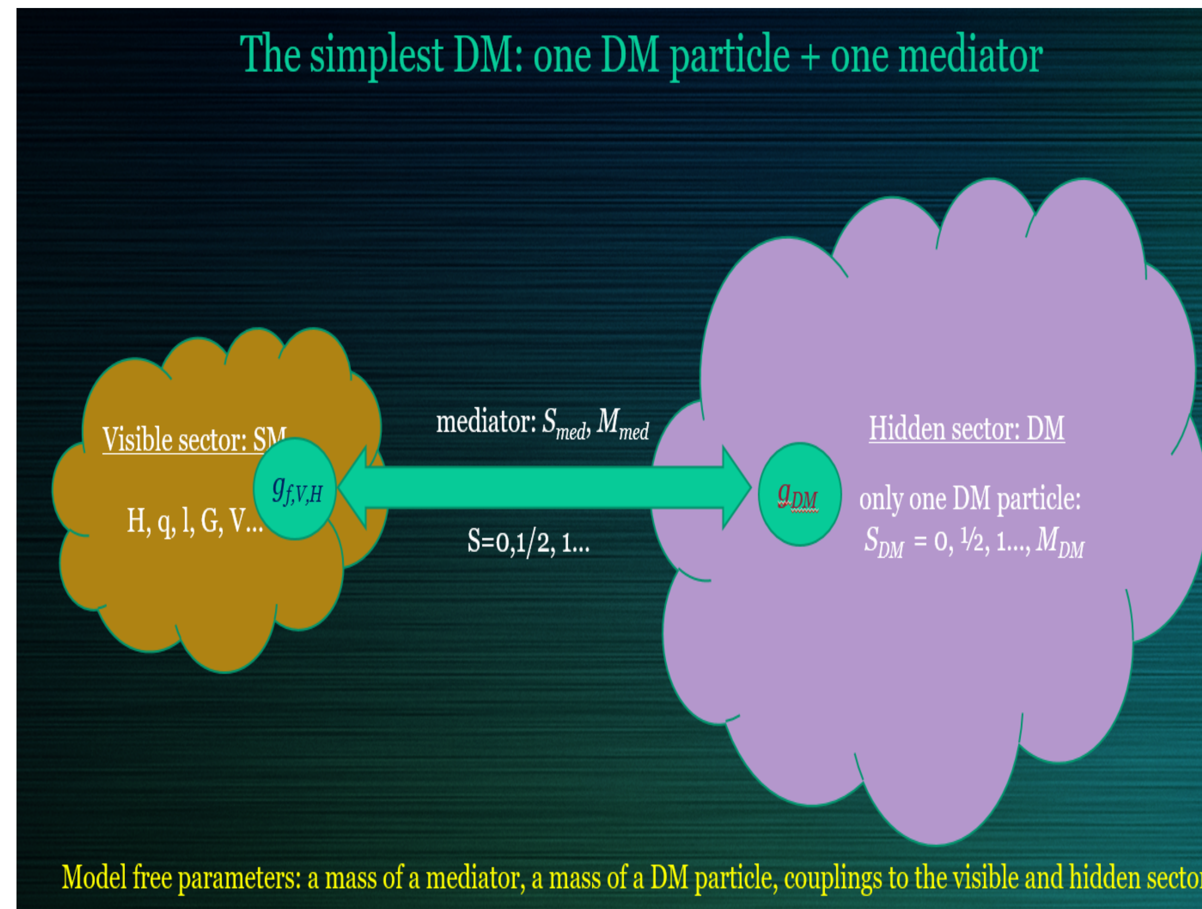




Simplified DM Models

2HDM+





2HDM+a/S Models

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

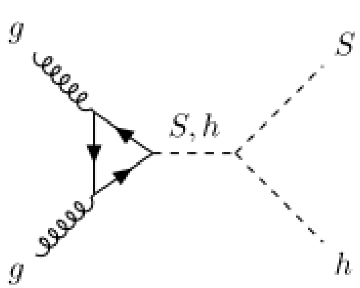
- neutral CP-even scalars *h, H*
- neutral CP-odd pseudoscalar *A*
- charged H^+, H^-

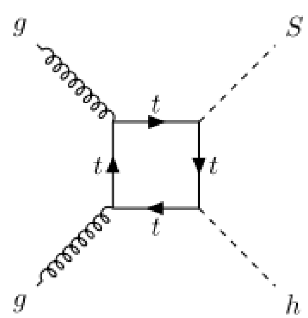
Dark Matter Sector can be probed by Extra Scalar/Pseudocalar Mediator

2HDM+s [arXiv:1612.03475]

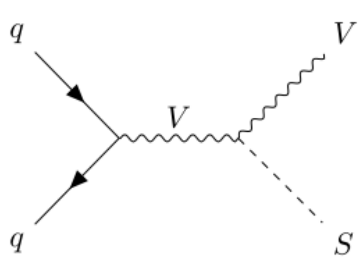
2HDM + S (neutral scalar singlet)

h (bbar) + S ( ) = bbar + MET





V (W/Z) + S ( ) = Z (ll) + MET

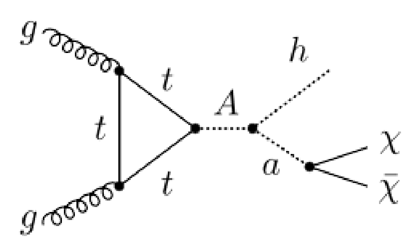


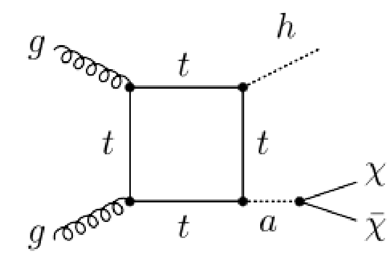
http://feynrules.irmp.ucl.ac.be/wiki/DMGISM0

2HDM+a arXiv:1701.07427

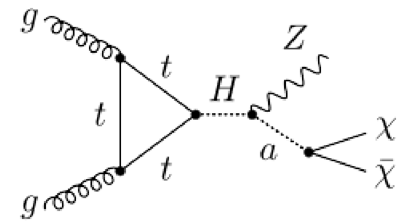
2HDM + a (light neutral pseudoscalar singlet)

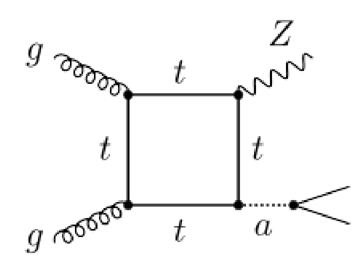
h (bbar) + a ( ) = bbar + MET





Z + a ( ) = Z (ll) + MET





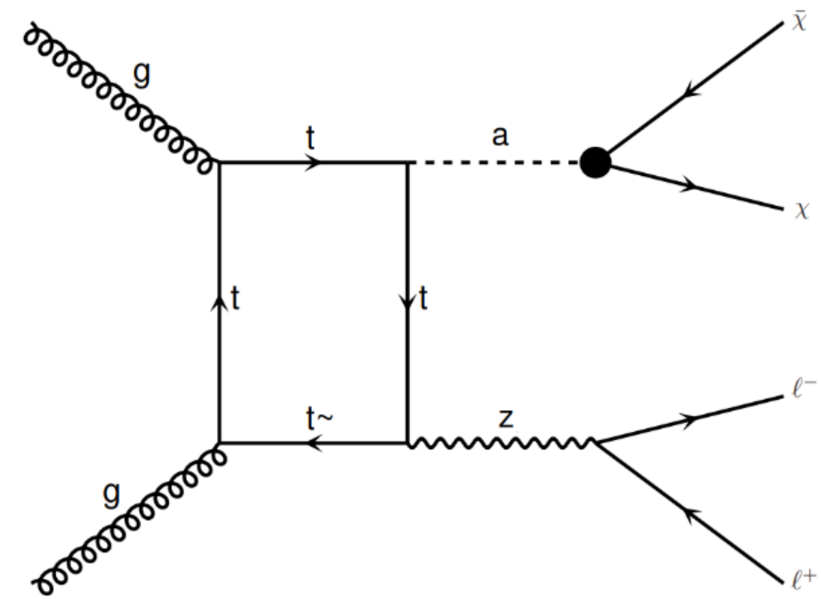
https://github.com/LHC-DMWG/model-repository/tree/master/models/Pseudoscalar_2HDM

Model Parameters and Signal Simulation

Generator: MadGraph5MC@NLO.2.9.2

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

Process: p p > Z χ χ (16 diagrams)



Free parameters for 2HDM + a:

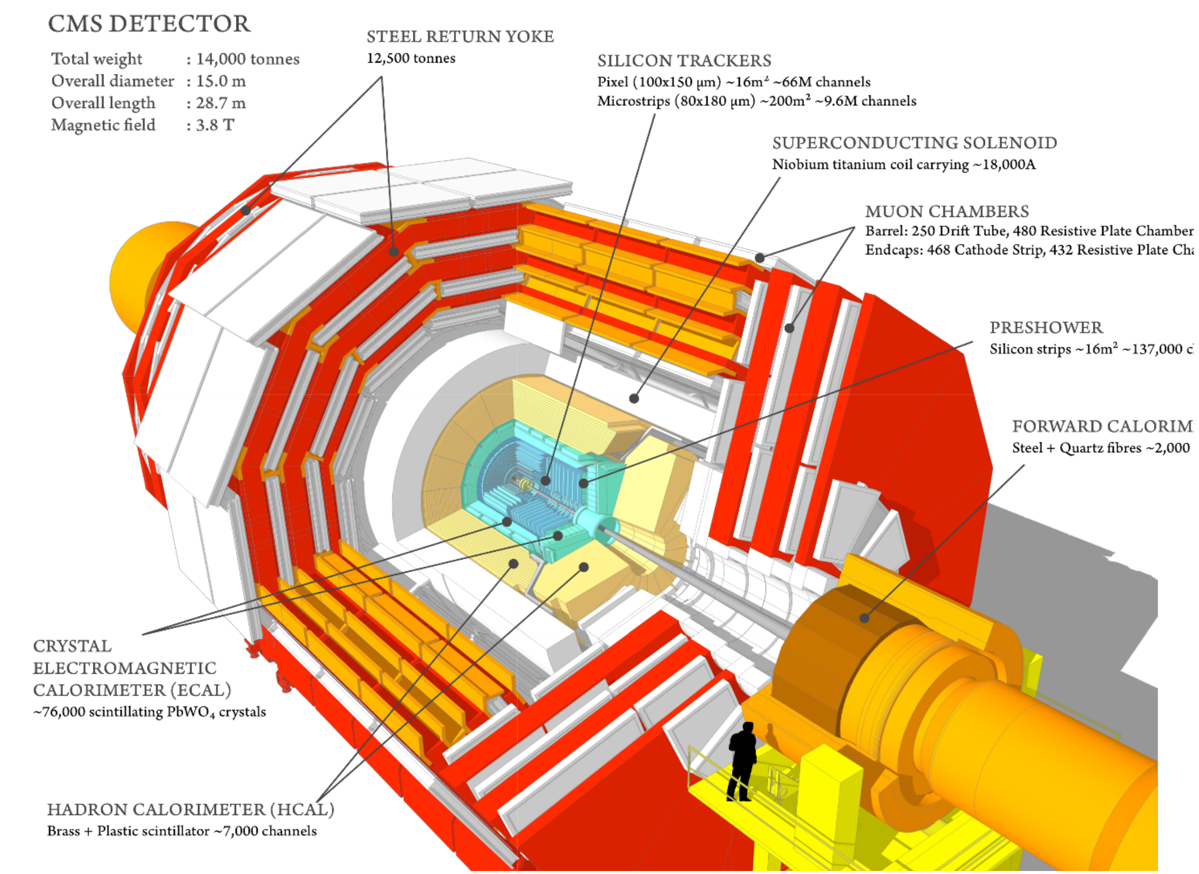
- masses of heavy higgses, $m_{H+/-}$= m_H= m_A= [600:2000] GeV
- mass of dark matter particle, mχ = [1:2000] GeV
- mass of light pseudoscalar/scalar states, m_a= m_S=[300:1000] GeV
- the ratio of the vacuum expectation values of the two Higgs doublets, tan(β) = [0.5:50]
- the mixing angle of the two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

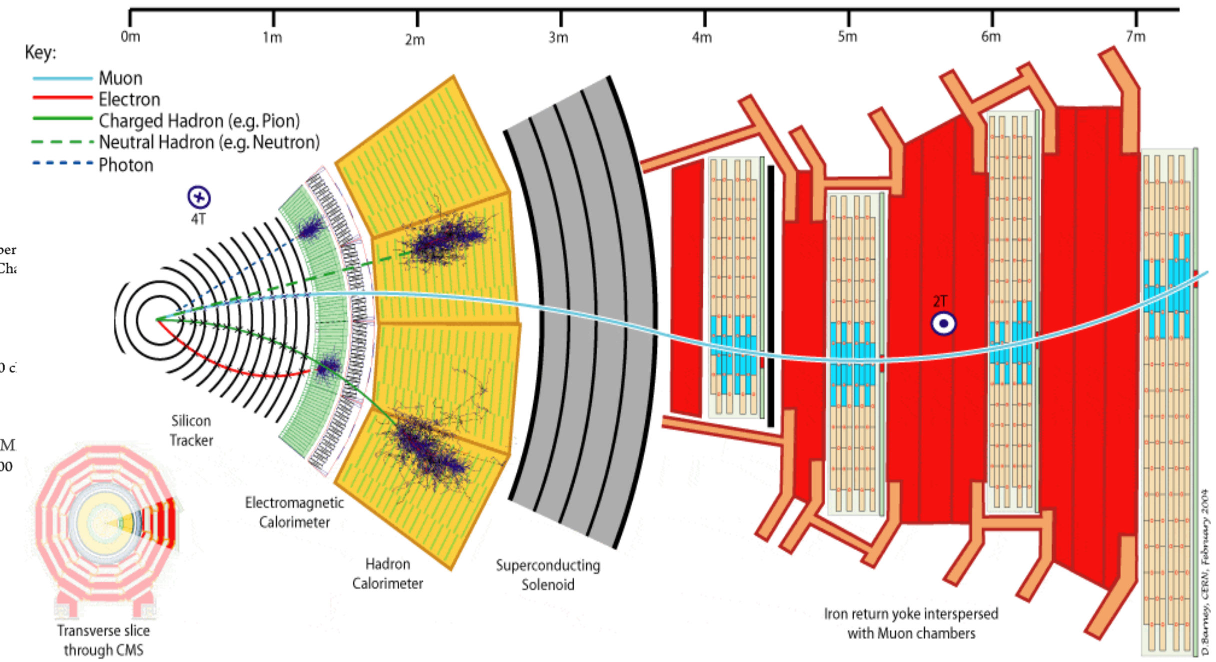
Free parameters for 2HDM + S:

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

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

Experiment CMS at LHC

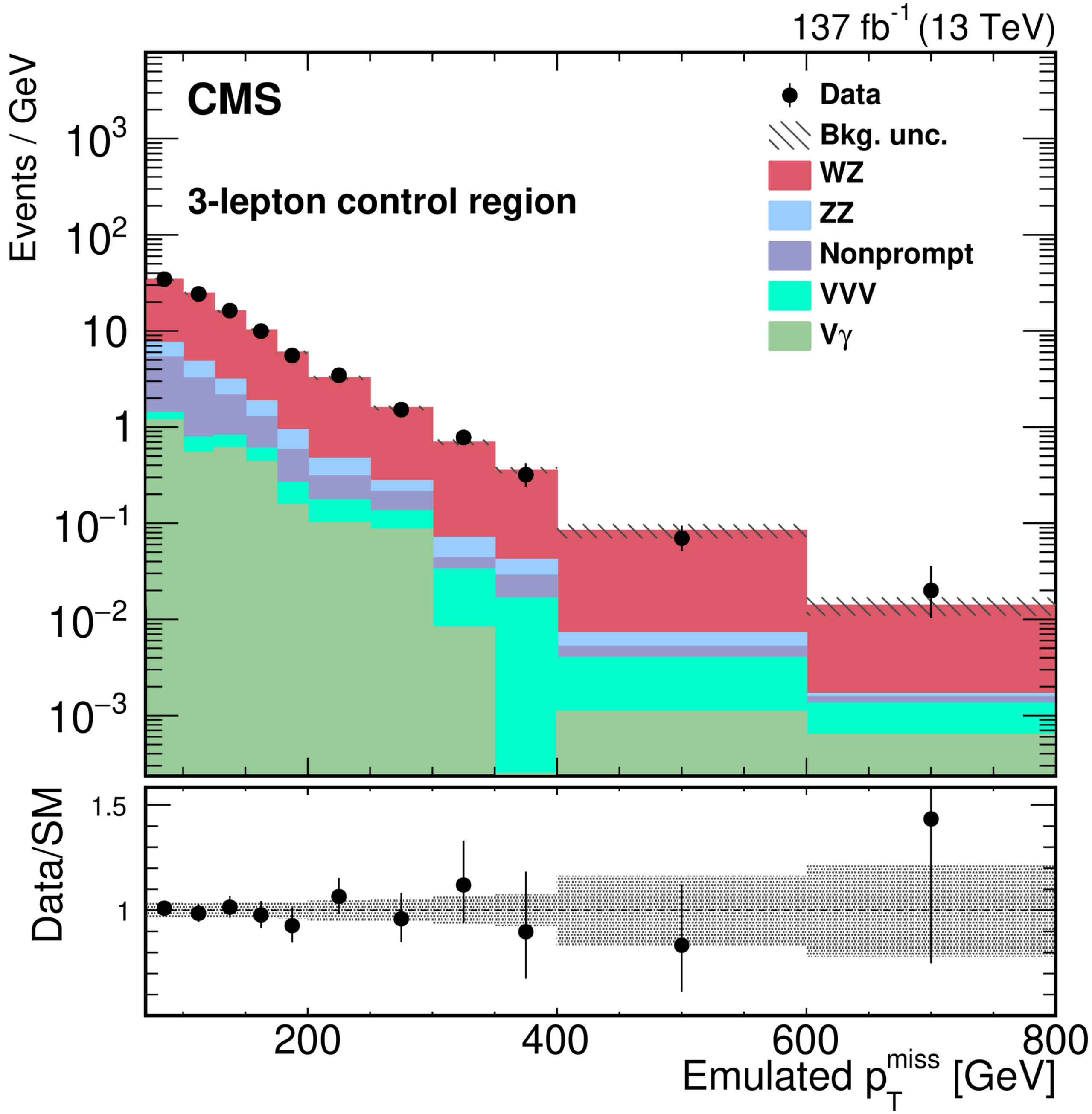




	RUN1	RUN2	RUN3
Energy(TeV)	7, 8	13	13.6
Integrated luminosity (fb^{-1})	4.5, 19.7	163.2	300
Year	2009-2014	2015-2018	2022-2027

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

Background



Main background sources:

WZ → l nu l l

ZZ → 4l

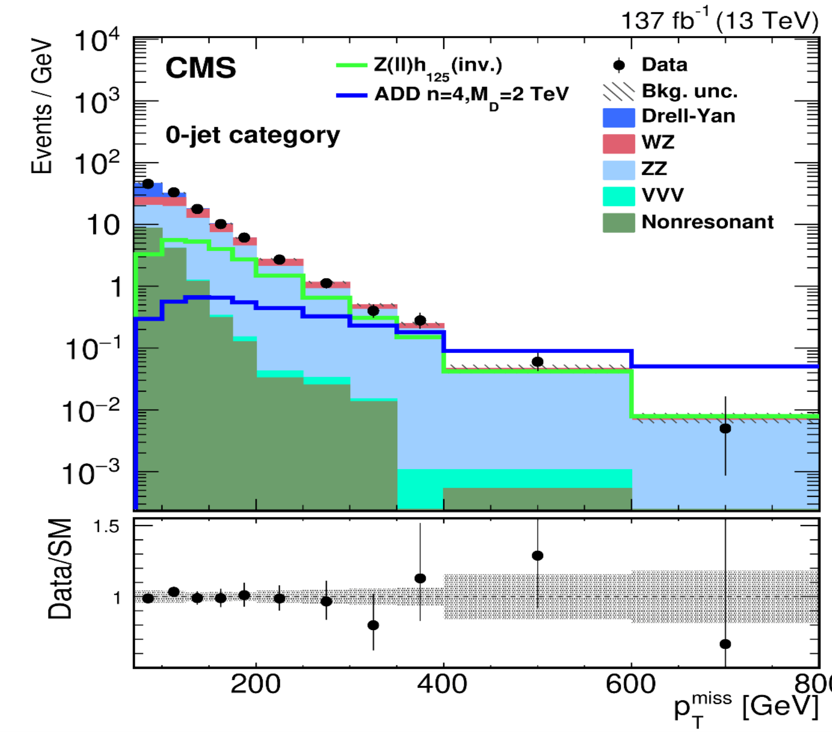
DY: This process does not produce undetectable particles.

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

CMS RUN2 Results

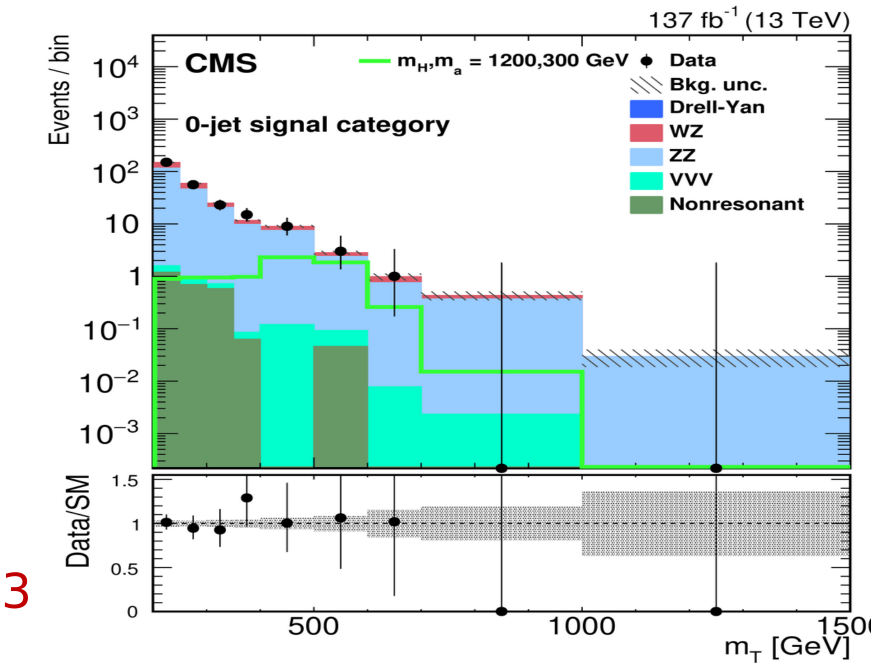
Observed number of events and post-fit background estimates

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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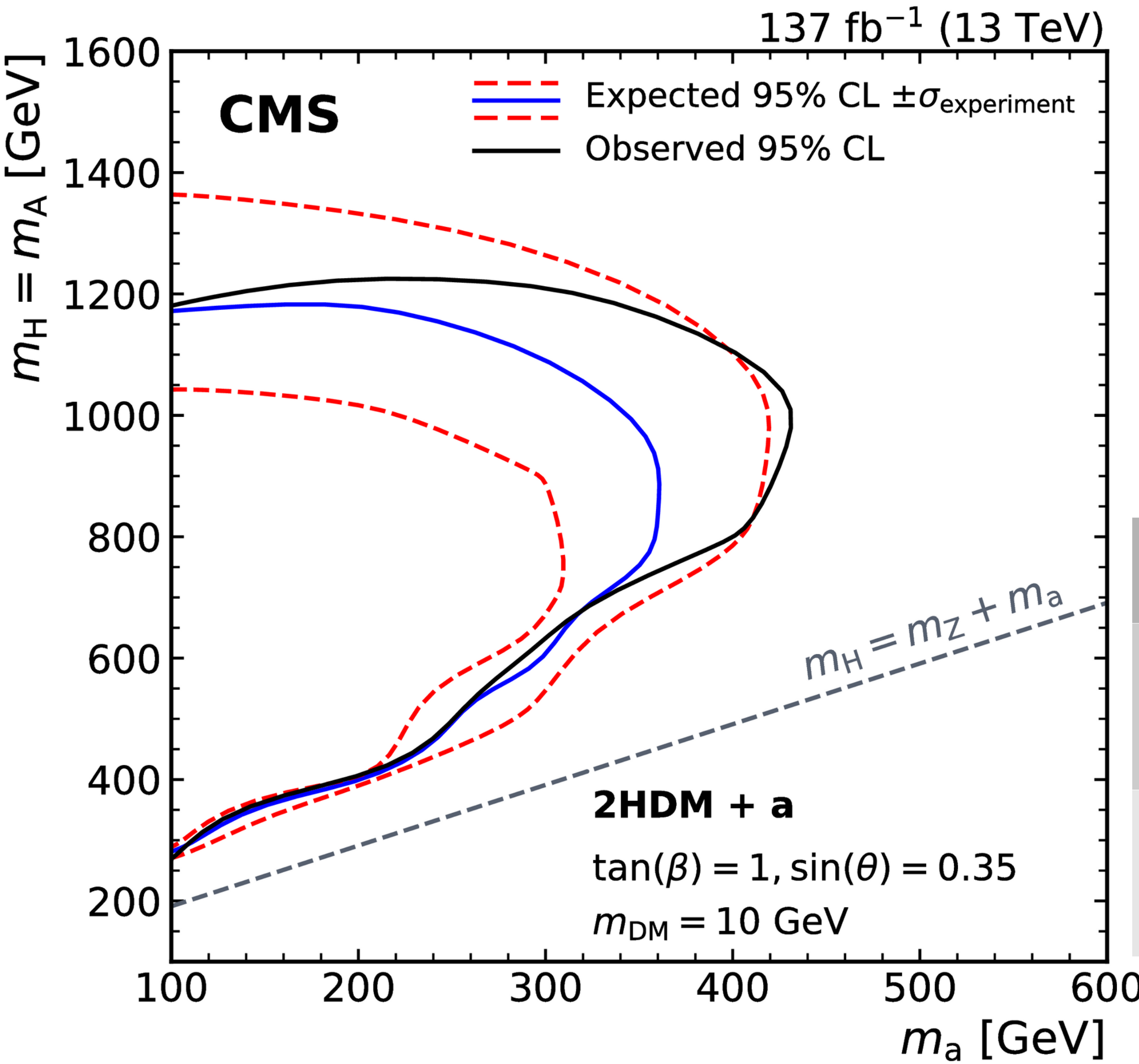
CMS RUN2 Exclusion Plot for 2HDM+a



The mediator mass with the most sensitivity is m_H = 1000 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 TeV	m_a	330 GeV	440 GeV
2HDM+a m_a=100 Gev	m_H	1200 GeV	1200 GeV

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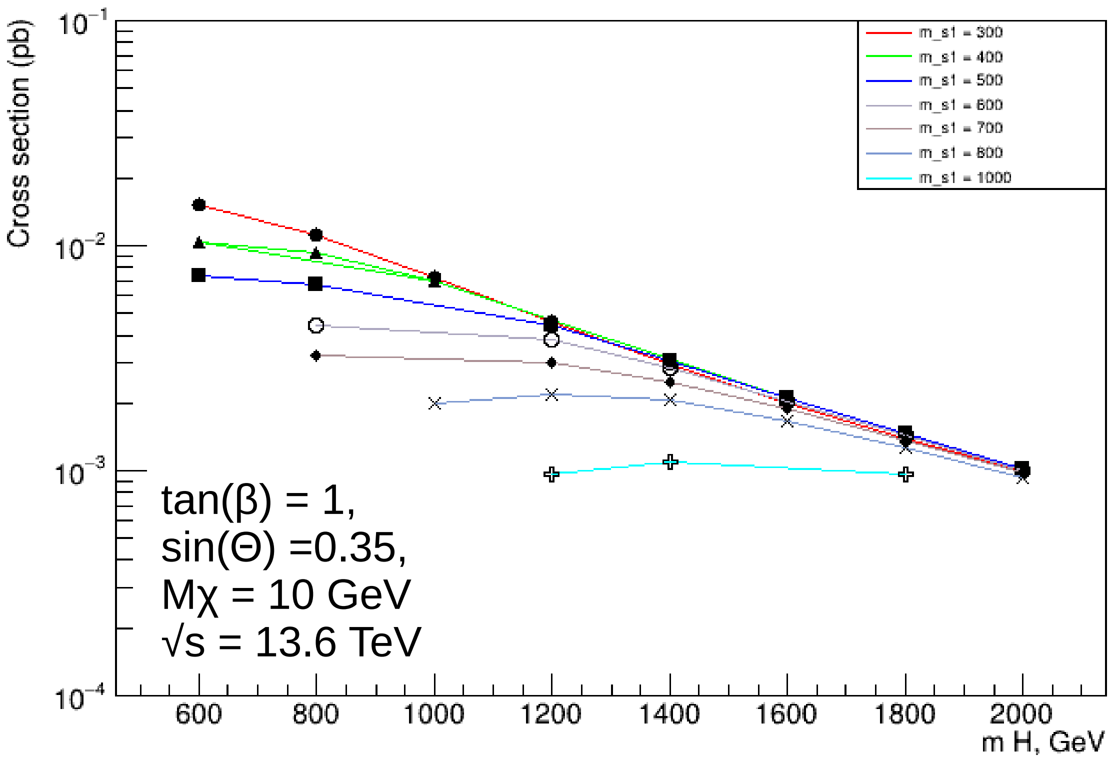
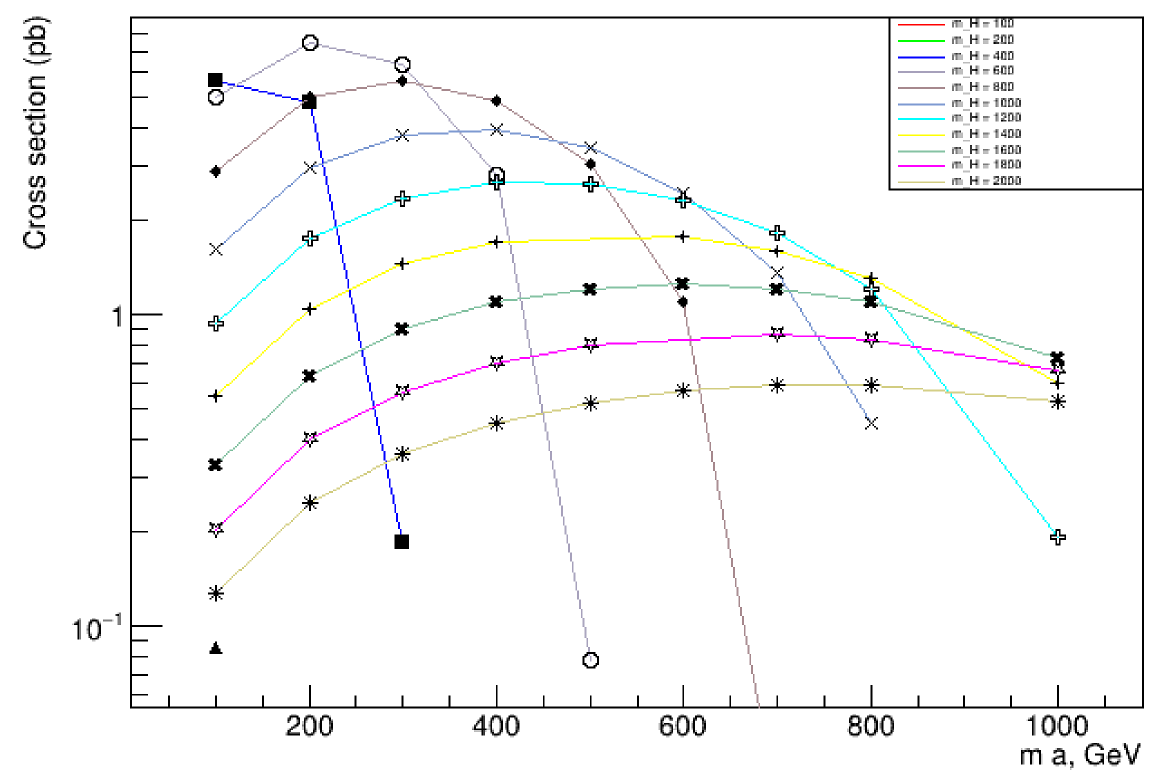
RUN3 Expectations (cross sections)

2HDM+S



2HDM+a



The total cross section of the process pp → 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!

CMS RUN2 Exclusion Plots: The simplified dark matter models

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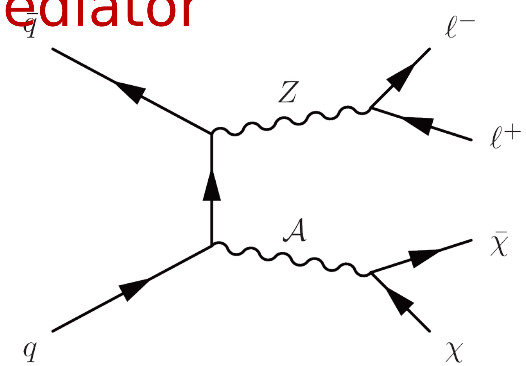
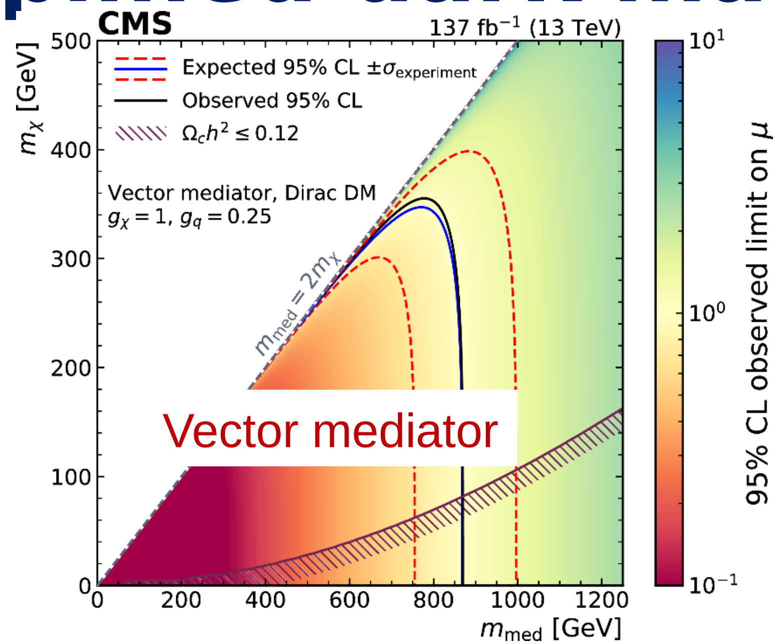
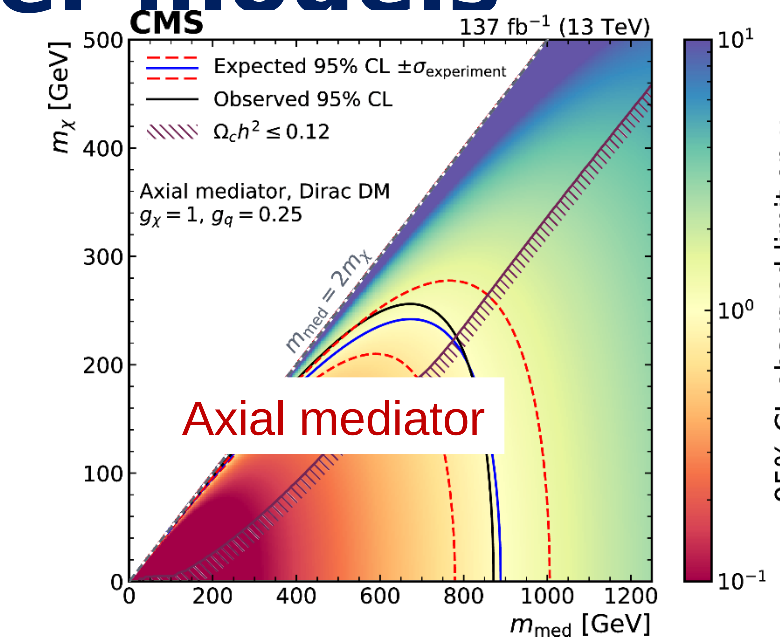
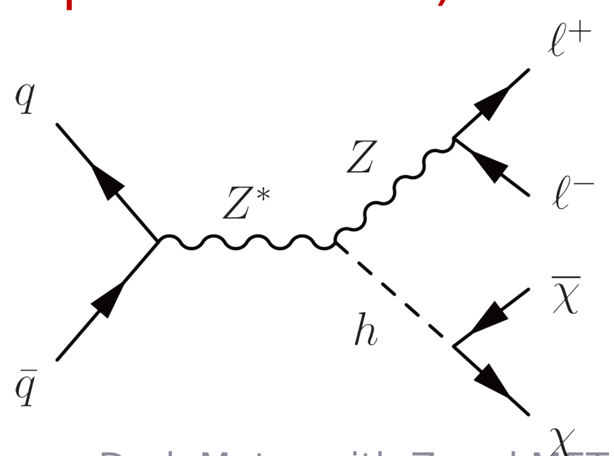
The simplified dark matter model for a spin-1 (vector or axial-vector) mediator

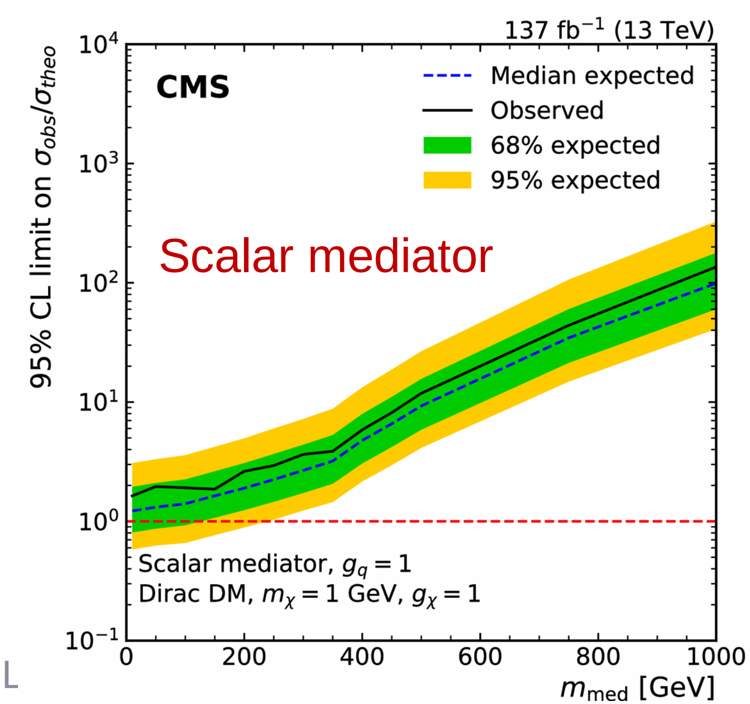


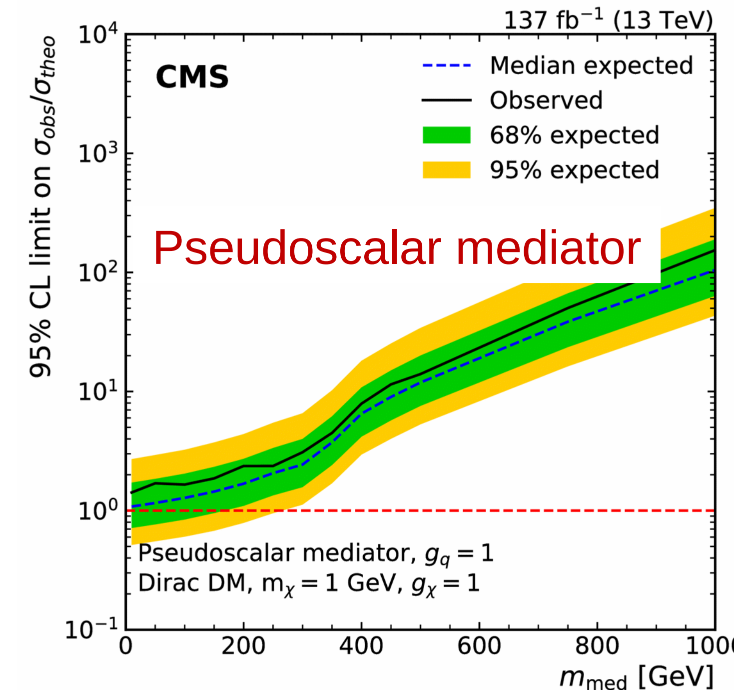




The simplified dark matter model for a spin-0 (scalar or pseudoscalar) mediator

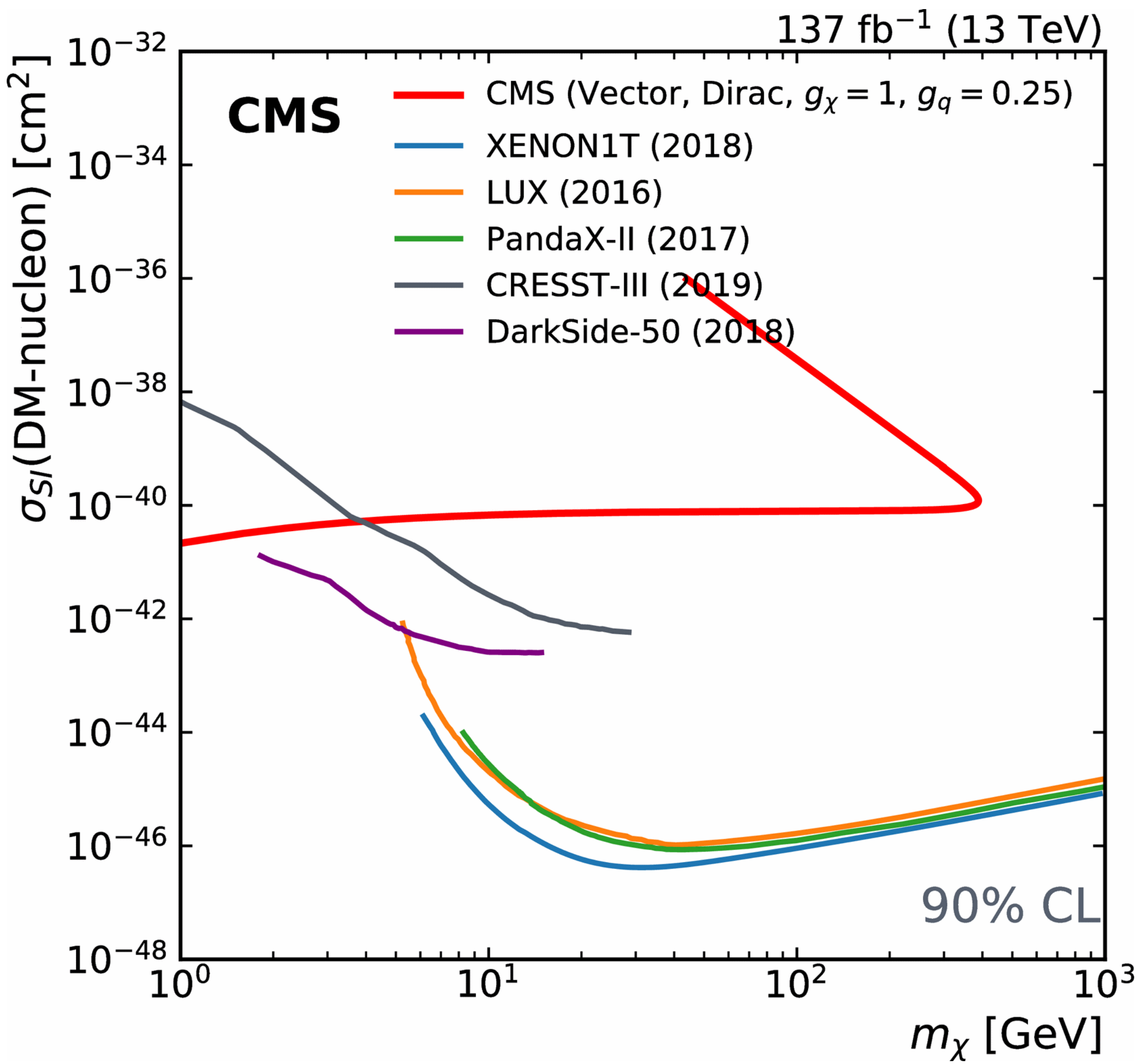




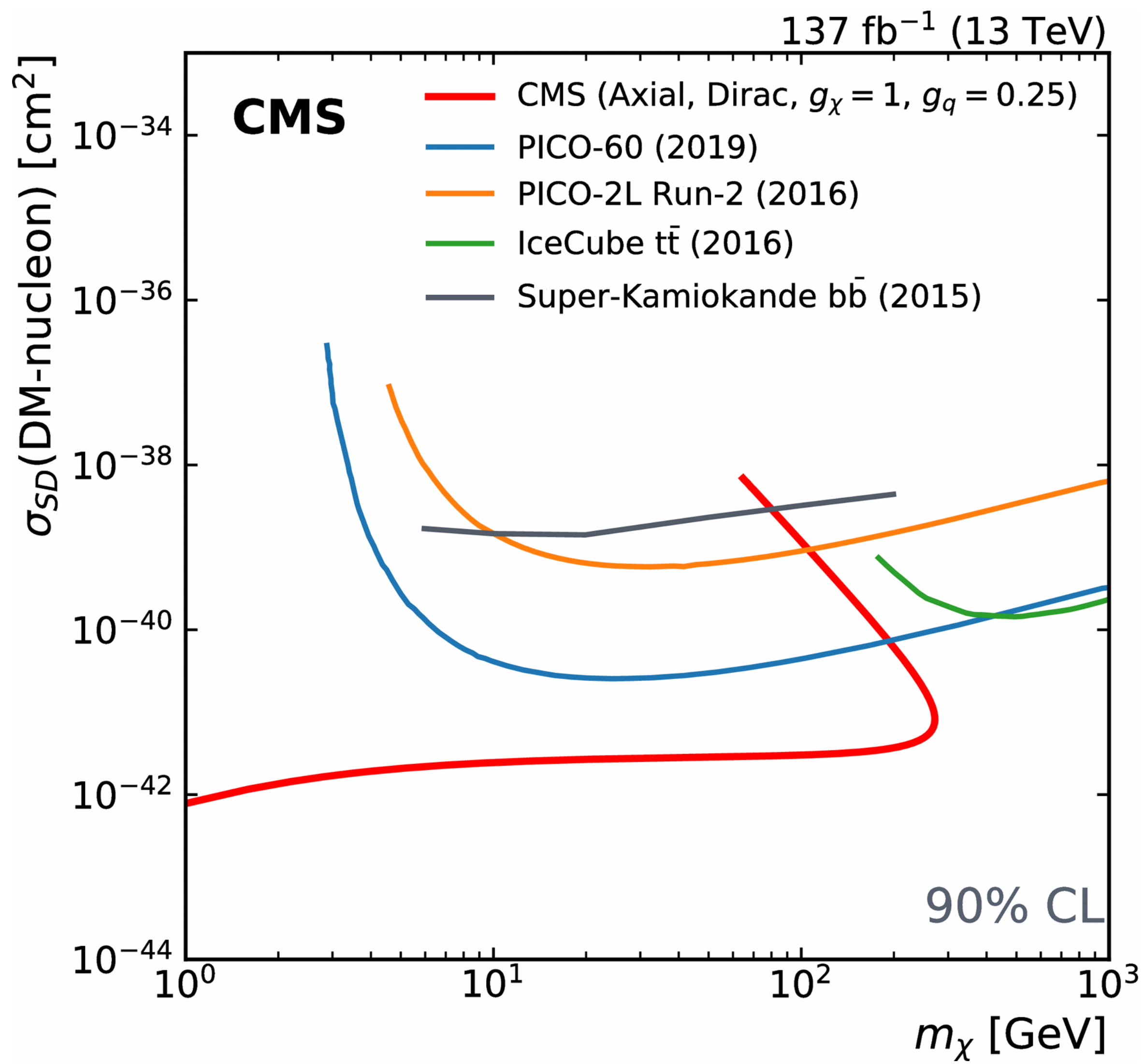


DM-nucleon upper limits on the cross section for simplified DM

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	$\left\| m_{\ell\ell} - m_{\mathrm{Z}} \right\| < 15\,\mathrm{GeV}$	WW, top quark
Number of jets	$\leq$1 jet with $p_{\mathrm{T}}^{\mathrm{j}} > 30\,\mathrm{GeV}$	DY, top quark, VVV
$p_{\mathrm{T}}^{\ell\ell}$	>60 GeV	DY
b tagging veto	0 b-tagged jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$	Top quark, VVV
τ lepton veto	0 τ_{h} cand. with $p_{\mathrm{T}}^{\tau} > 18\,\mathrm{GeV}$	WZ
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{j}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	>0.5 radians	DY, WZ
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	>2.6 radians	DY
$\|p_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell\ell}\| / p_{\mathrm{T}}^{\ell\ell}$	<0.4	DY
$\Delta R_{\ell\ell}$	<1.8	WW, top quark
$p_{\mathrm{T}}^{\mathrm{miss}}$ (all but 2HDM+a)	>100 GeV	DY, WW, top quark
$p_{\mathrm{T}}^{\mathrm{miss}}$ (2HDM+a only)	>80 GeV	DY, WW, top quark
m_{T} (2HDM+a only)	>200 GeV	DY, WW, ZZ, top quark