Minimal vector-like leptonic dark matter and its signature at LHC

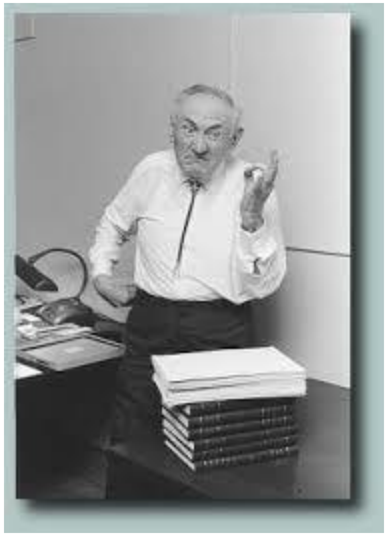
with S. Bhattacharya and Nirakar Sahoo [arXiv: 1510.02760, PRD93, 2016]
with S. Bhattacharya, S. Patra and Nirakar Sahoo [arXiv:1601.01569, JCAP 1606, 2016]

Narendra Sahu
Dept. of Physics, IIT Hyderabad, INDIA

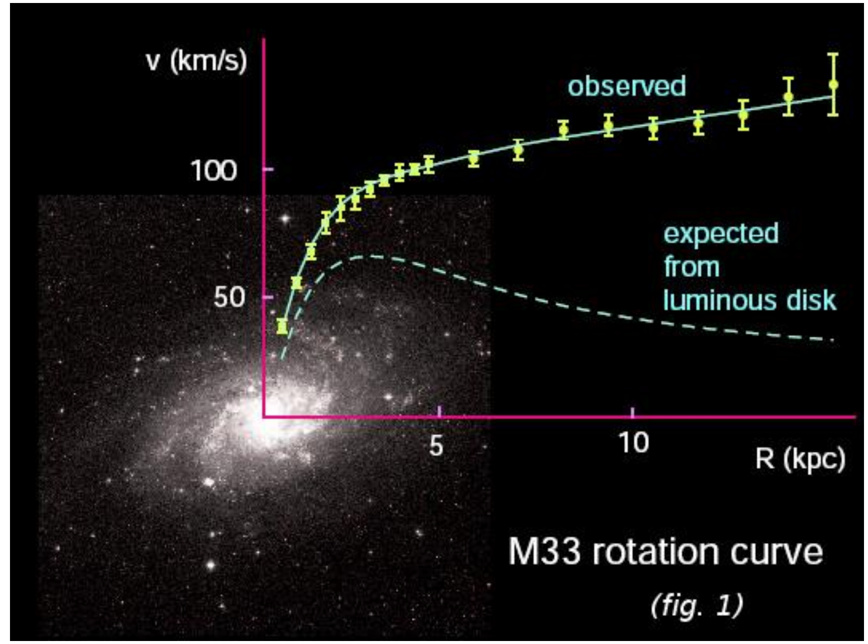
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

@TeVPA, 16-09- 2016, CERN, Geneva

Early evidence of DM in Coma cluster



Fritz Zwicky in 1930s



Used Virial Theorem

$$\langle K.E \rangle = -\frac{1}{2} P.E.$$

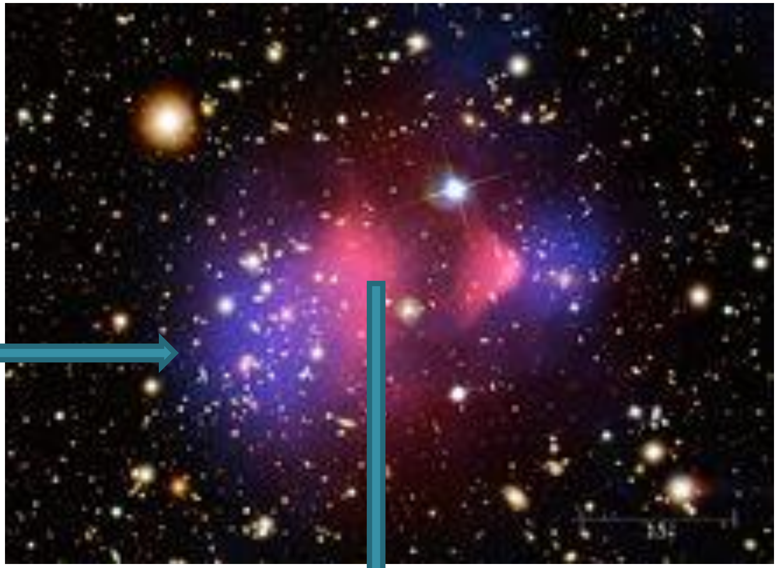
$$\langle v^2 \rangle = -\frac{GM}{R}$$

Mass inferred >> Baryonic Mass seen

Missing mass ~ Non-baryonic

Other Astrophysical Evidences of DM

(Collision of galaxies in Bullet cluster)

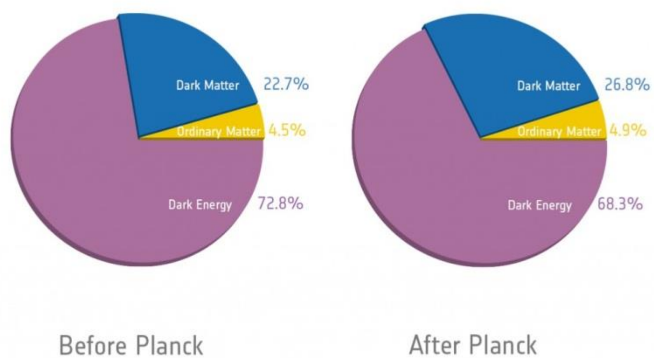


Dark matter seen through lensing.

Hot gas seen through X-ray at the central part

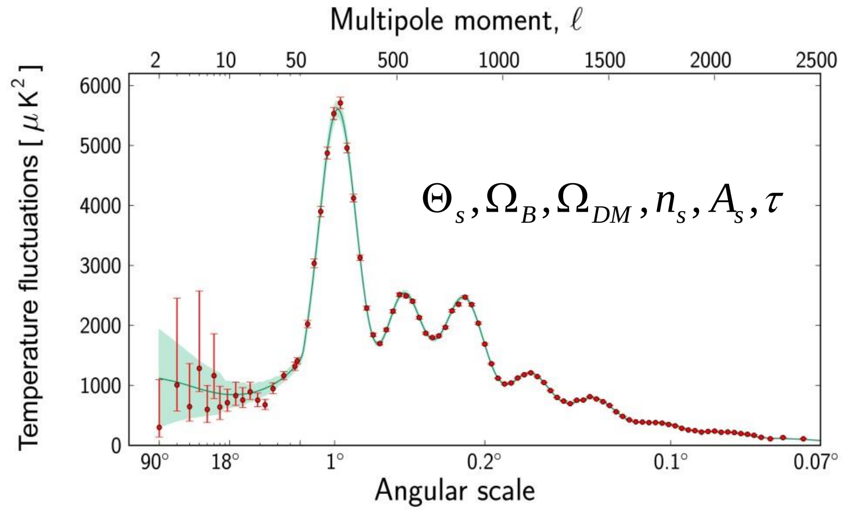
Gravitational lensing observed by Hubble in Abel 1689 cluster

Evidence of DM in Cosmological scale

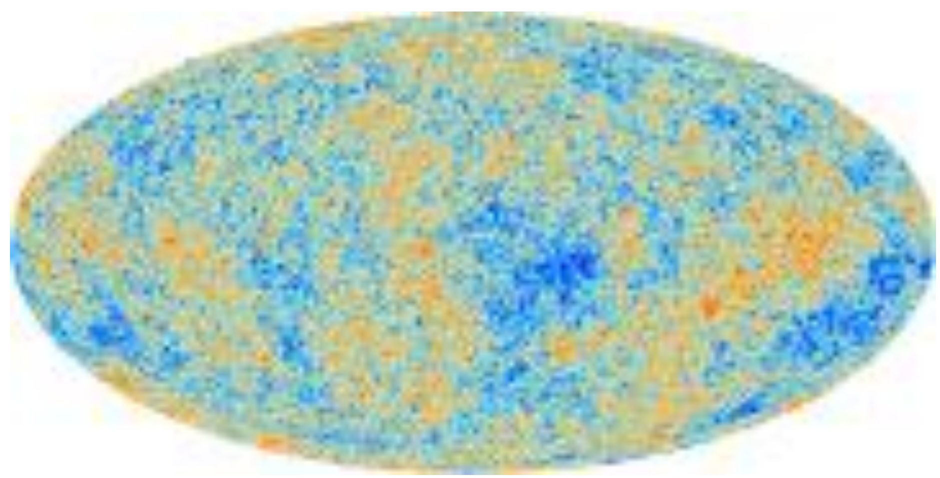


@WMAP(Wilkinson Microwave Anisotropy Probe)

@ PLANCK 2013



$$\Theta_s, \Omega_B, \Omega_{DM}, n_s, A_s, \tau$$



Nature of Dark Matter…

From the astrophysical evidences of dark matter we infer that…

- ✓ DM should be a massive particle and hence interact gravitationally.
- ✓ It is electrically neutral and colorless. Therefore it could hide itself easily.
- ✓ It is stable on the cosmological time scale and therefore the large scale structure exists.

However,
We don't know …

Mass of DM= ?
Spin of DM= ?, Charge of DM= ?
Interaction apart from gravity ?
Relic abundance (symmetric/asymmetric ?)

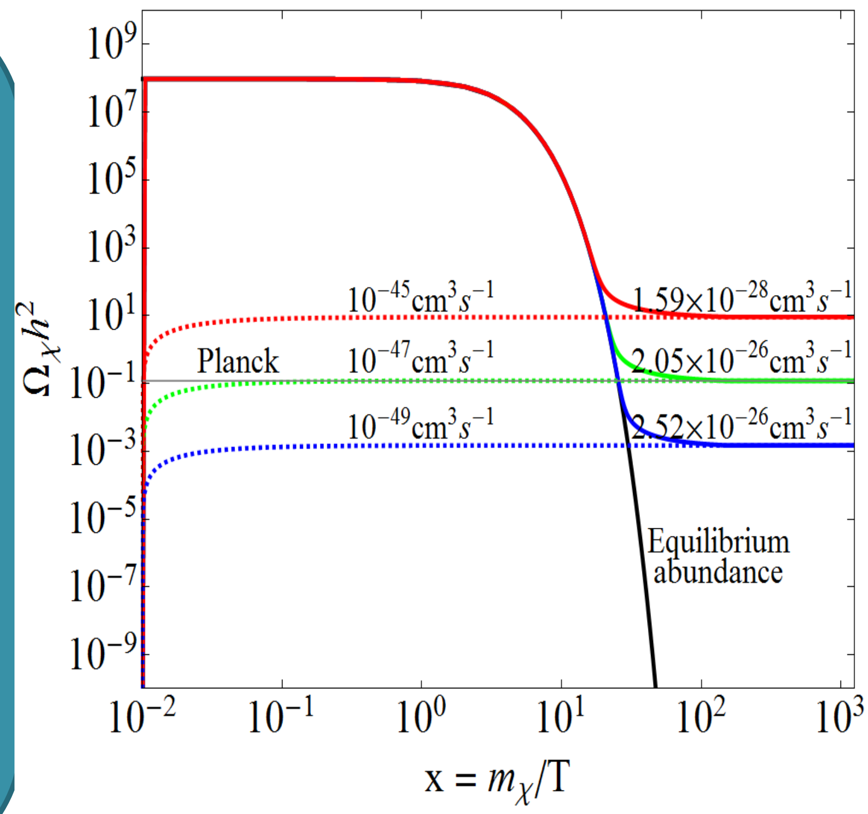
↓

Many unanswered questions!

Is DM a WIMP (Gravity+ weak) ?

Steigman and Turner, 1984

The DM is assumed to be in equilibrium in the early Universe via the weak interaction processes. As the temperature, due to expansion of the Universe, falls below the mass scale of DM, the latter gets freeze-out from the thermal bath and gives the correct relic abundance.



$$\frac{dY_\chi}{dx} = \frac{-x\langle\sigma |v|\rangle s}{H(m_\chi)}(Y_\chi{}^2 - Y_{eq}{}^2)$$

$$Y_\chi = \frac{n_\chi}{s}, x = \frac{m_\chi}{T}$$

$$\Omega_{DM} h^2 = \frac{1.1\times 10^9 GeV^{-1} x_F}{g_*^{1/2} M_{pl} \langle \sigma |v| \rangle_F} = 0.1198 \pm 0.0026$$

Analytical estimation of a WIMP relic density

The observed relic abundance of DM by WMAP and PLANCK

$$< \sigma |v| >|_F \approx 3\times 10^{-26} cm^3/\sec \approx 2.6\times 10^{-9} GeV^{-2}$$

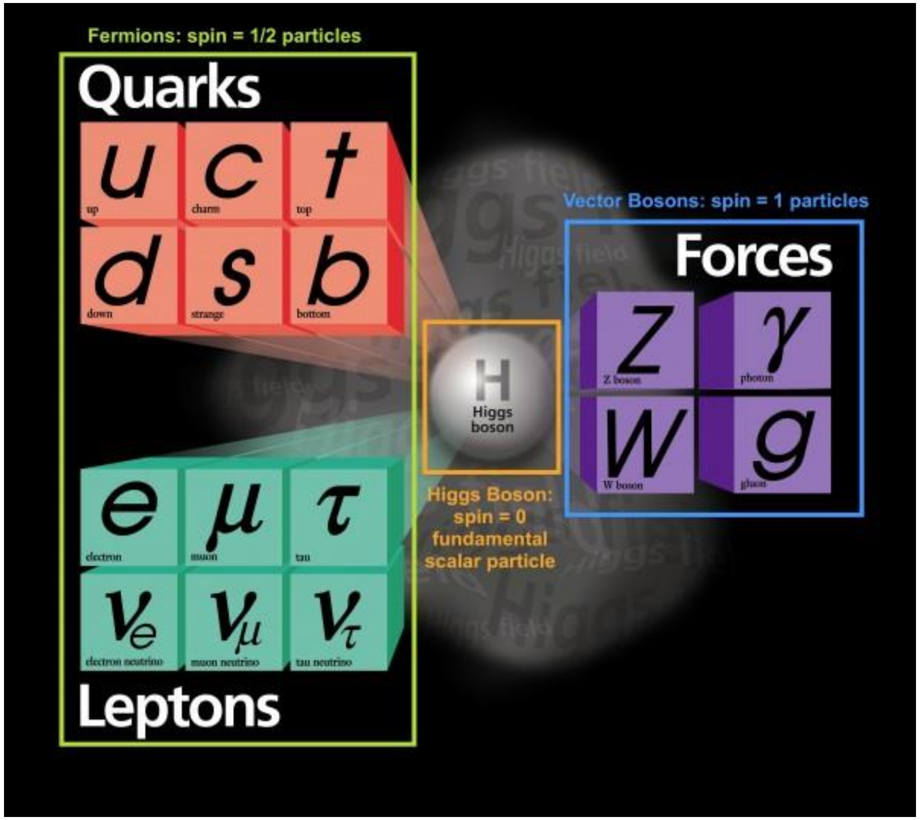
$$\approx O(10^{-36}) cm^2$$

Which is typically a weak interaction cross-section.

WIMP Miracle

Therefore one believes that DM could be a WIMP.

DM: The physics beyond the SM



The only particles in SM which seem to satisfy some properties of DM are neutrinos:

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5eV} \approx 0.0024$$

$$<< \Omega_{DM} h^2$$

Cowsik and McClelland, PRL 1972

So, we need to look for a candidate of DM in the beyond standard model of particle physics, which is heavy (> a few GeV).

Lee and Weinberg, PRL 1977

Some guiding principle for DM physics

Since we don't know many things about the dark matter, the main guiding principles would be:

- ✓ Look for a non-baryonic cold dark matter in a beyond SM framework which is stable on cosmological time scale.
- ✓ Motivated by theory
- ✓ May be simplicity

$$\mathcal{L}_{\text{new}}=\mathcal{L}_{SM}+\mathcal{L}_{DM}+\mathcal{L}_{DM}$$

Apply the relevant constraints

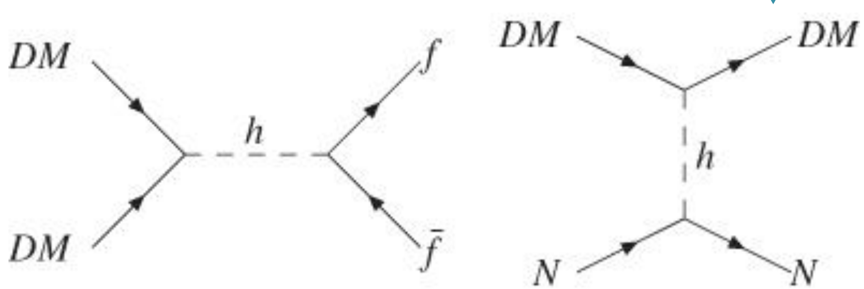
Look for the testable prediction !

We will discuss only about fermionic dark matter candidates

Singlet Fermion as cold Dark Matter

$$\mathcal{L}_{DM} = \bar{\chi} i \gamma^{\mu} \partial_{\mu} \chi + M \bar{\chi} \chi + \frac{\bar{\chi} \chi H^{+} H}{\Lambda}$$

Higgs portal coupling



Where Λ is the scale of new physics

χ is the candidate of dark matter due to a residual symmetry Z_2

H is the SM Higgs doublet.

$$\Omega_{DM} h^2 = F(M_{\chi}, \Lambda) \qquad \sigma_{SI}(DM - N) = f(M_{\chi}, \Lambda)$$

(1) Relic abundance is large for $\Lambda \simeq 1TeV$ apart from the Higgs funnel.
(2) We can not do any further prediction about our weak interaction assumption of dark matter.

Can a vector-like doublet fermion be DM ?

$$\mathcal{L}_{DM} = \overline{N} i\gamma^{\mu} D_{\mu} N + M \overline{N} N \qquad N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1)$$

N^0 can be made stable using a residual Z_2 symmetry.

However $\overline{N^0} N^0 \to W^+ W^-$ is so large that relic abundance is very small.

$\sigma(N^0 - n)$ via Z-boson is also much larger than the current LUX limit.

So N^0 alone can not be a dark matter candidate.

Note: It can be a viable asymmetric DM in presence of scalar triplet which can induce neutrino masses through type-II seesaw.

Ref. C. Arina and N. Sahu, 1108.3967, NPB854, 2012.

Vector-like Singlet-Doublet Fermion DM

$$\mathcal{L}_{\text{new}} = \mathcal{L}_{SM} + \mathcal{L}_{DM}$$

$$\mathcal{L}_{DM} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + h.c.] + \overline{N} i\gamma^\mu D_\mu N + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

where $N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1), H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1,2,1), \chi^0 \equiv (1,1,0)$

After EW phase transition the mass matrix for neutral vector-like fermions is given by

$$\begin{pmatrix} \overline{N^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} N^0 \\ \chi^0 \end{pmatrix}$$

Hep-th/0501082, hep-ph/0510064,
arXiv: 0705.4493, arXiv:0706.0918, arXiv:0804.4080,
arXiv:1109.2604, arXiv:1311.5896, arXiv:1504.07892, arXiv:1505.03867

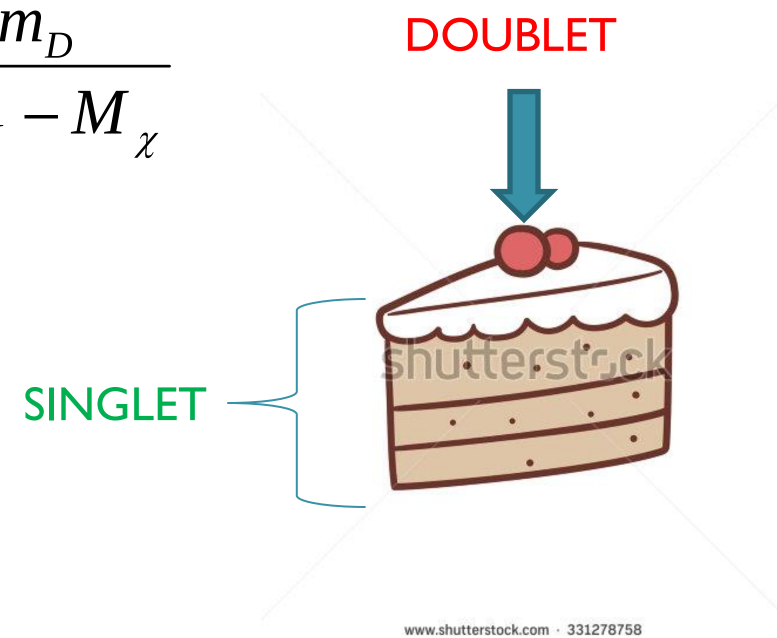
$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}; N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}; N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

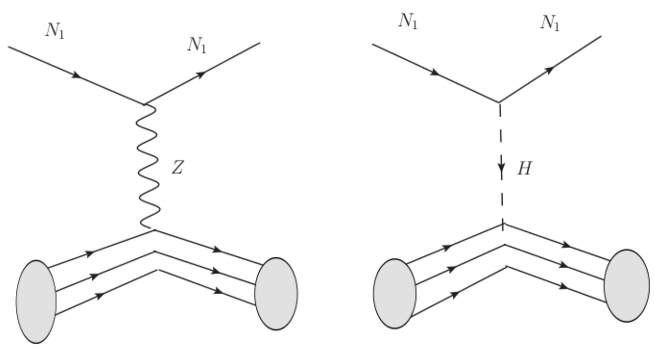
$$M^\pm = M_1 \sin^2\theta + M_2 \cos^2\theta = M_N; N^\pm$$

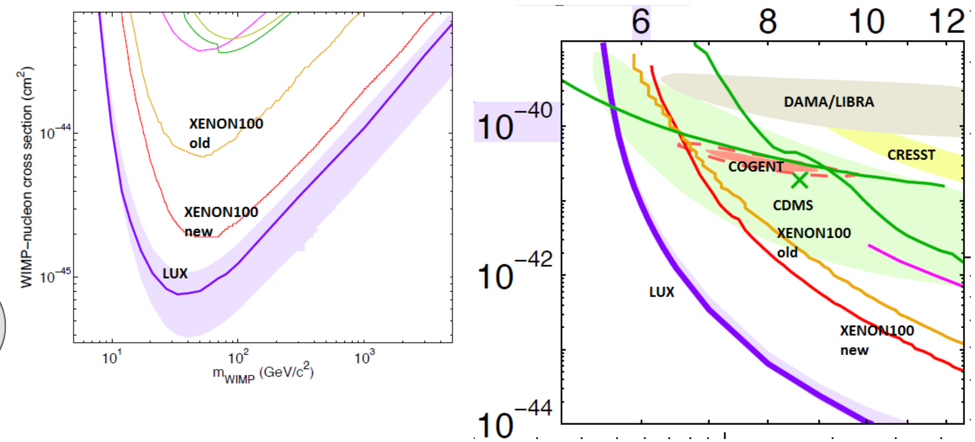
$$\tan 2\theta = \frac{m_D}{M_N - M_\chi}$$

The lightest particle N_1 is the candidate of dark matter with appropriate mixing angle θ

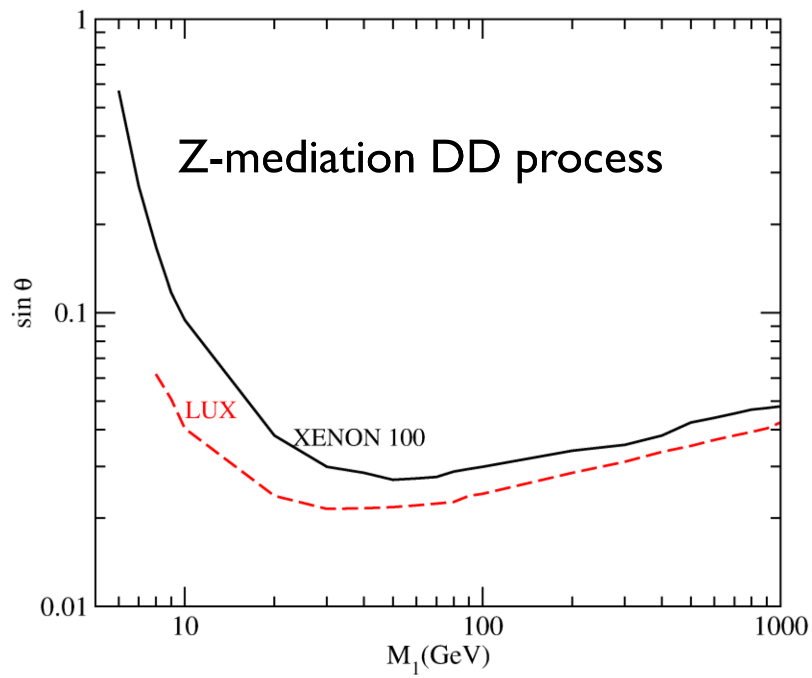


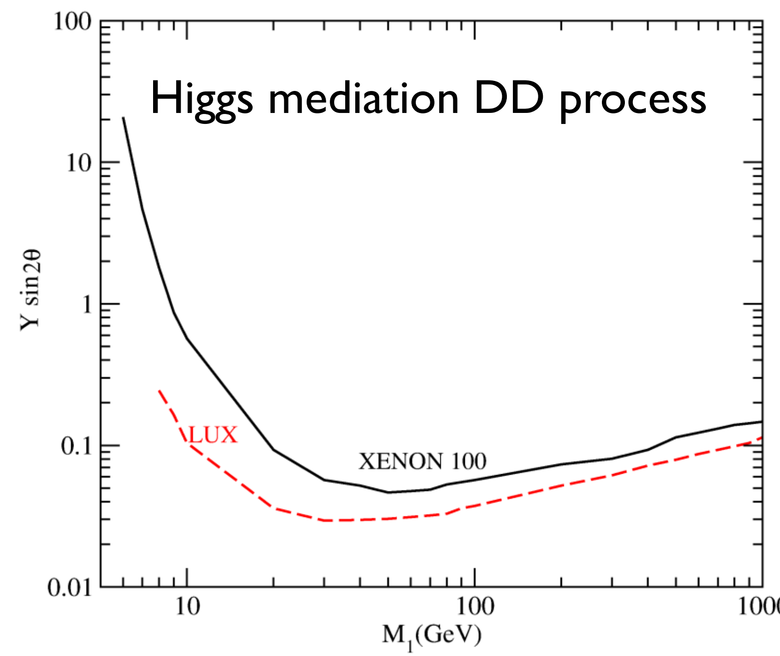
Constraints from direct search of DM

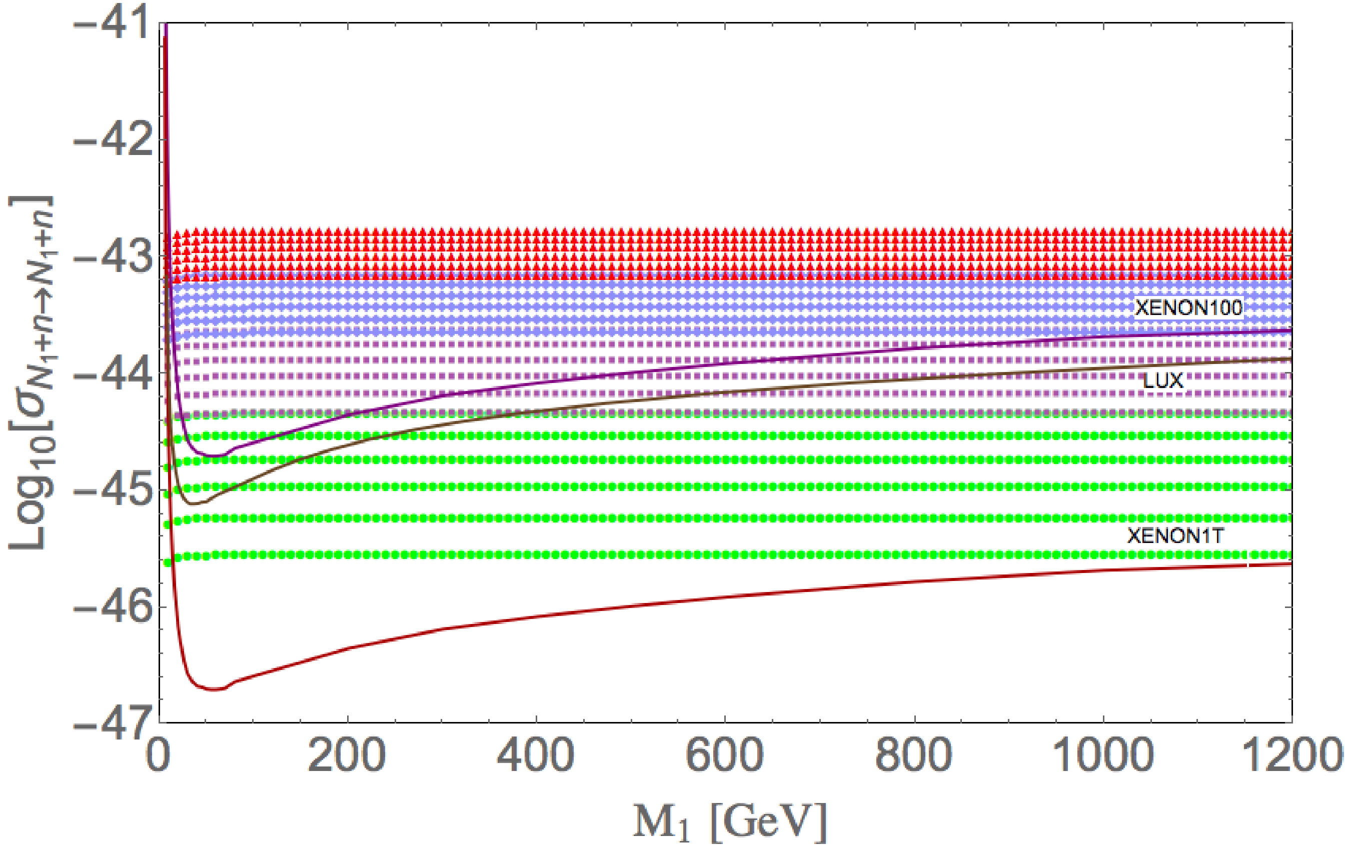




LUX collaboration, PRL,112,091303 (2014)







$\sin\theta = 0.05 - 0.1$ (Green)

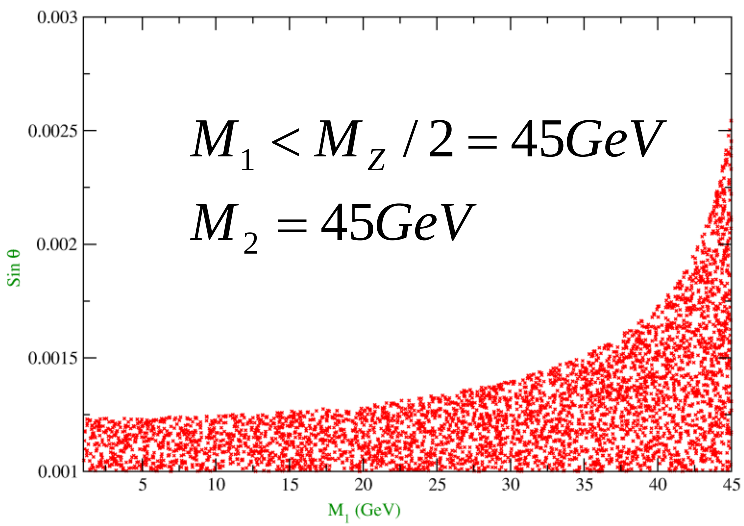
$\sin\theta = 0.1 - 0.15$ (Purple)

$\sin\theta = 0.15 - 0.2$ (Lilac)

$\sin\theta = 0.2 - 0.25$ (Red)

Other Constraints…

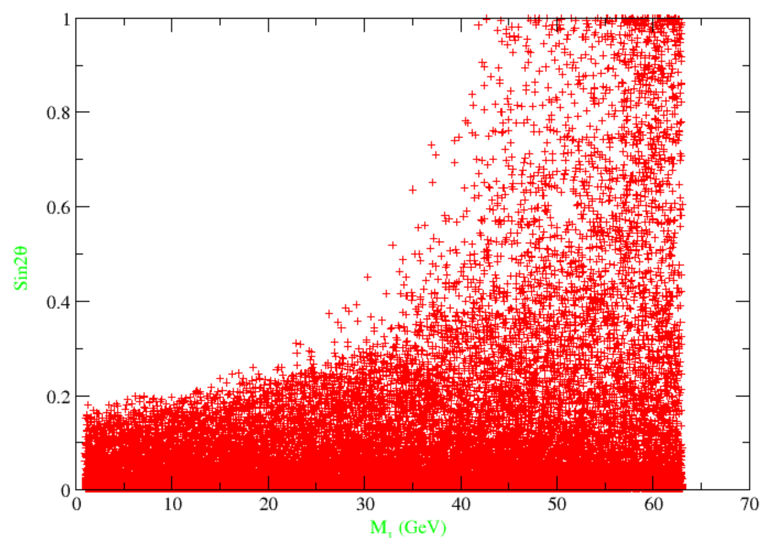
LEP Constraints from Z-decay



$$Br_{inv} = \frac{\Gamma_h^{inv}}{\Gamma_h^{SM} + \Gamma_h^{inv}} < 0.3$$

ATLAS collaboration
1508.07869 (hep-ex)

Constraints from invisible Higgs decay keeping all possible values of M_2 that allow Higgs decay.



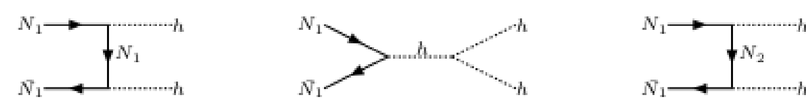
Relic density of singlet-doublet Fermion DM

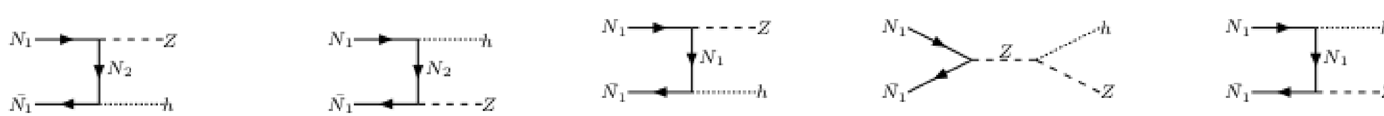
$$\Omega_{N_1} h^2 = \frac{1.09 \times 10^9}{g_*^{1/2} (M_{pl}/GeV)} \frac{1}{J(x_f)}$$

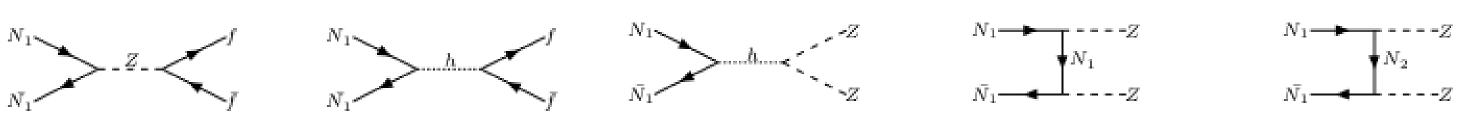
$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma |v| \rangle_{eff}}{x^2} dx$$

Griest and Seckel: PRD 1991

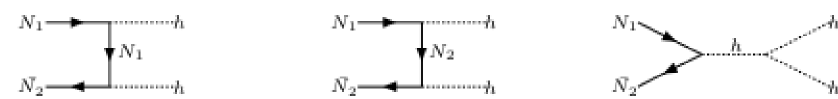
Annihilation processes

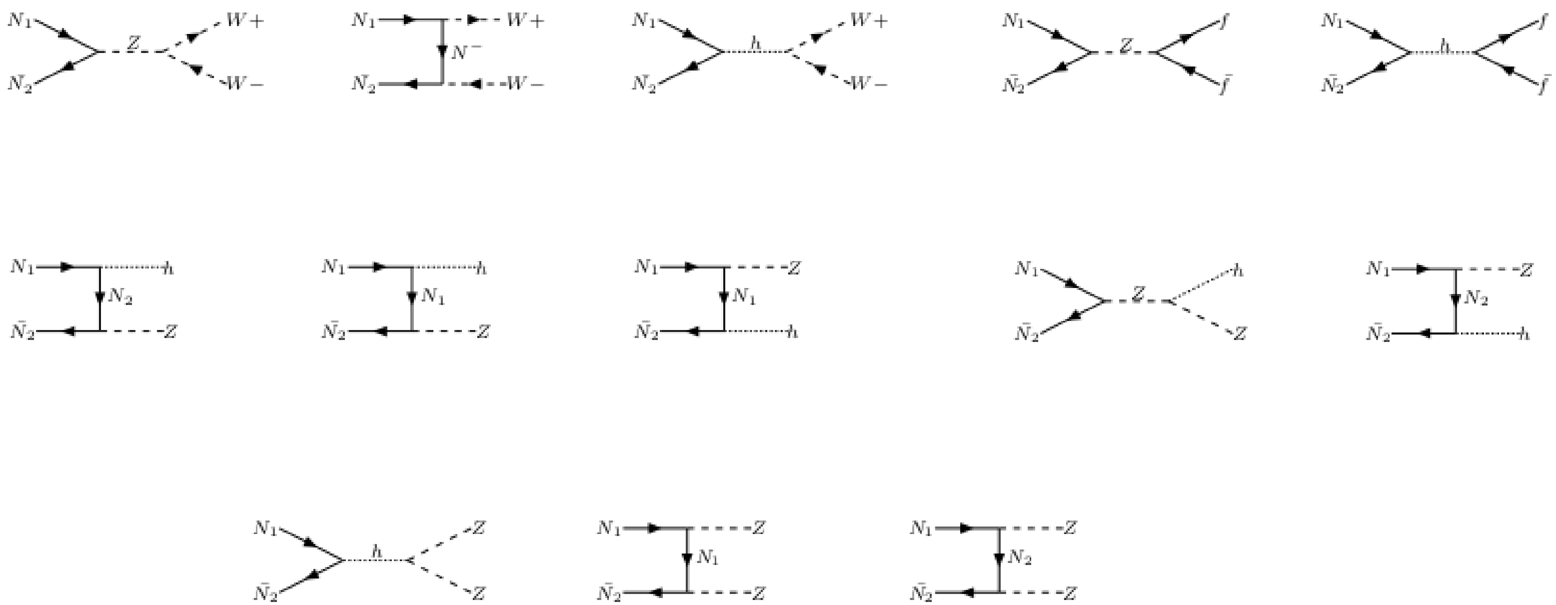






Co-annihilation process

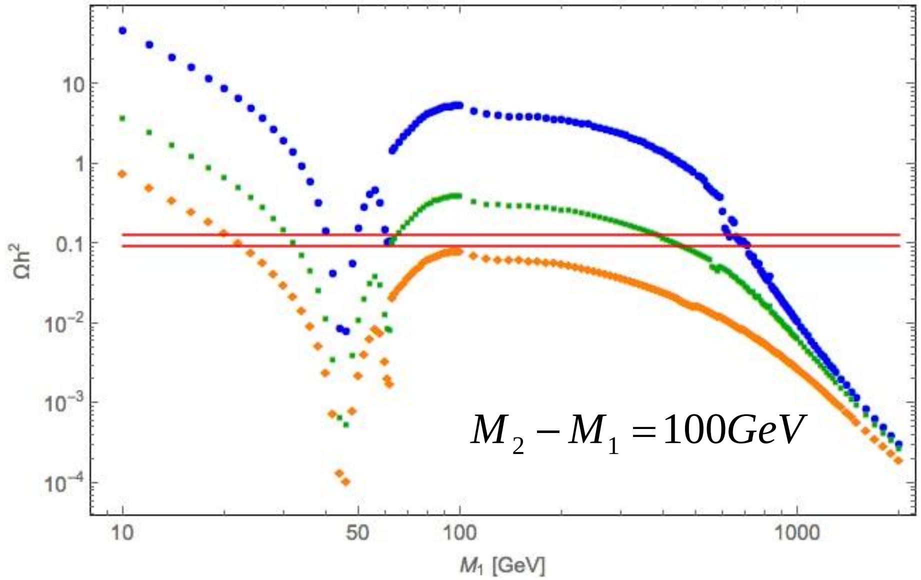




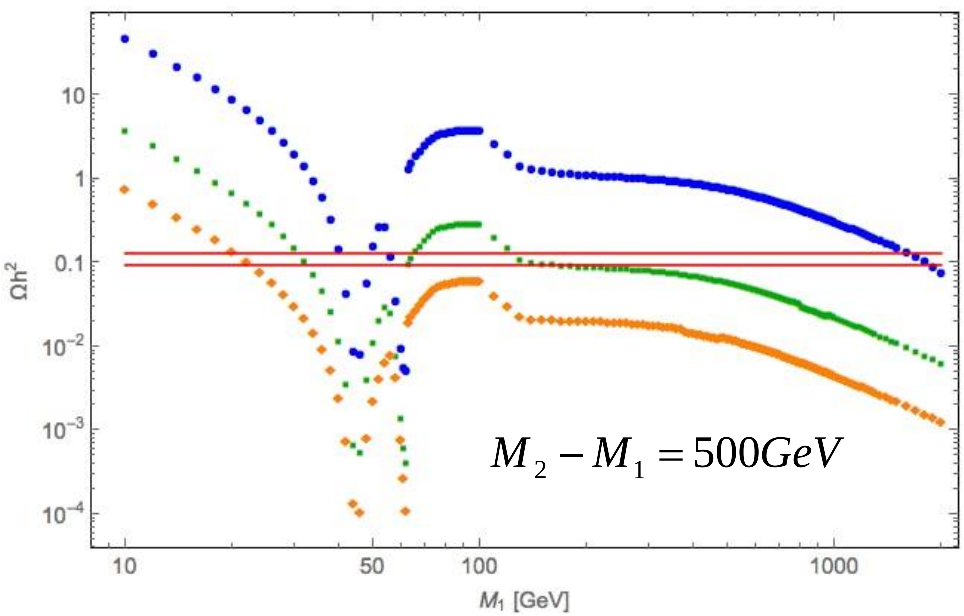
We look for the observed relic abundance in the parameter space spanned by

$$M_1, M_2 \approx M^{\pm}, \sin\theta \qquad Y = \frac{\Delta M \sin 2\theta}{2v}$$

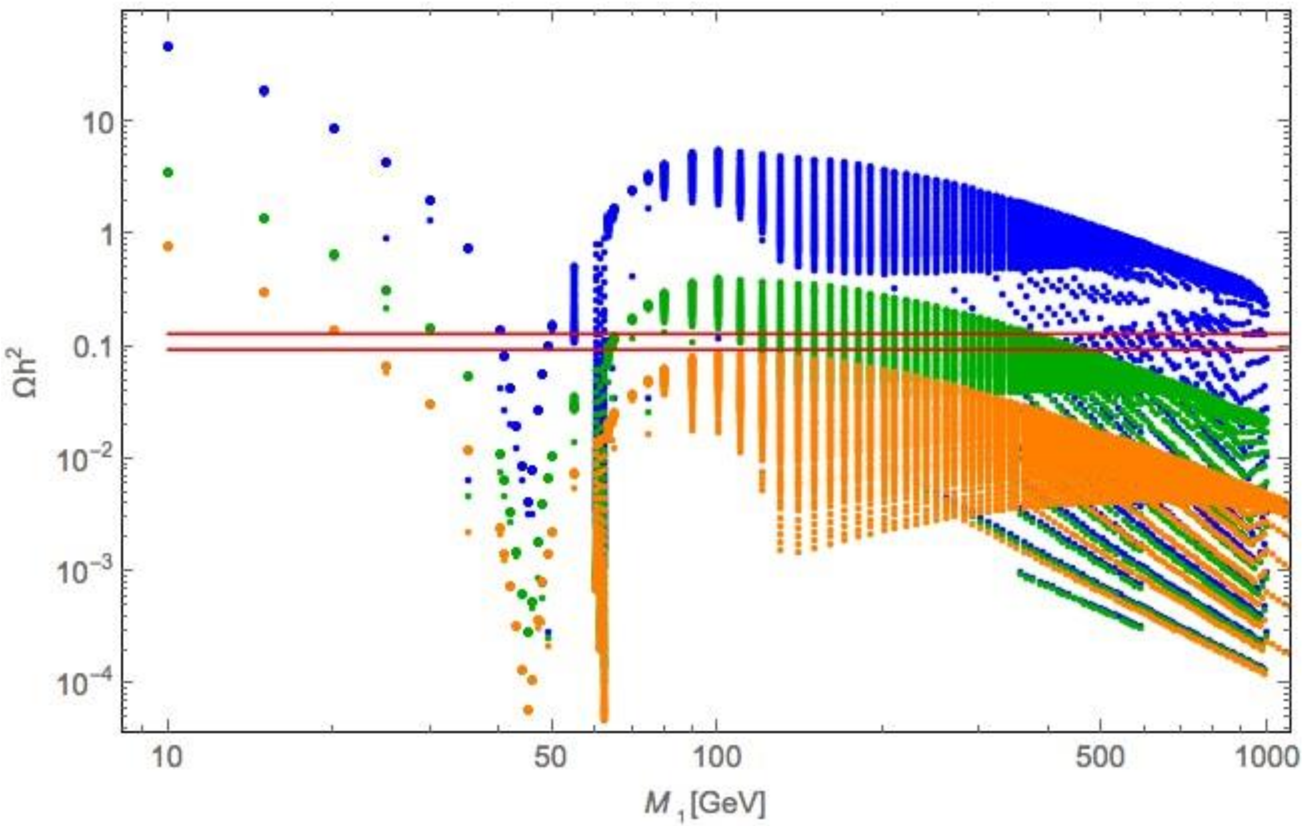
$$\sin\theta = 0.1(Blue), 0.2(Green), 0.3(orange)$$



$$\sin\theta = 0.1(Blue), 0.2(Green), 0.3(orange)$$

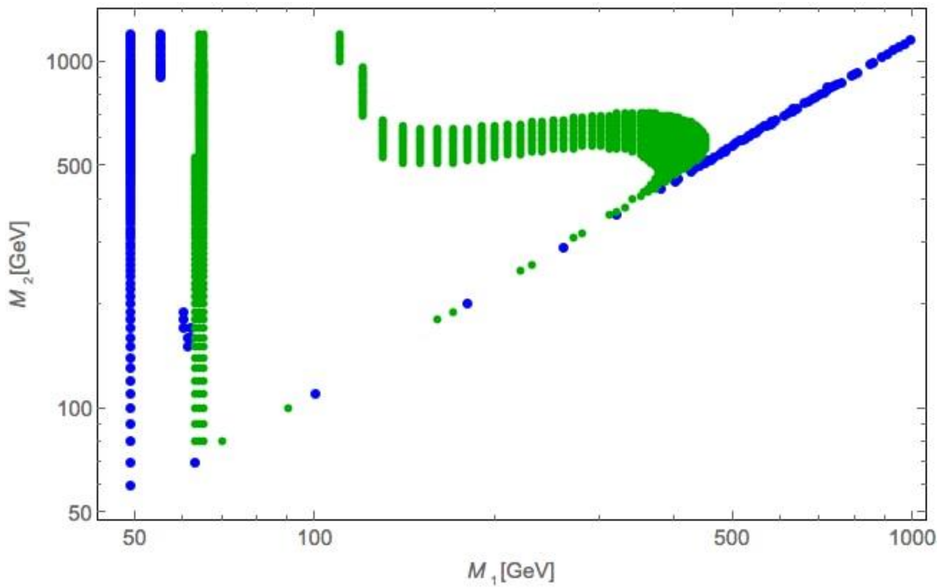


$$\sin\theta = 0.1(Blue), 0.2(Green), 0.3(orange)$$

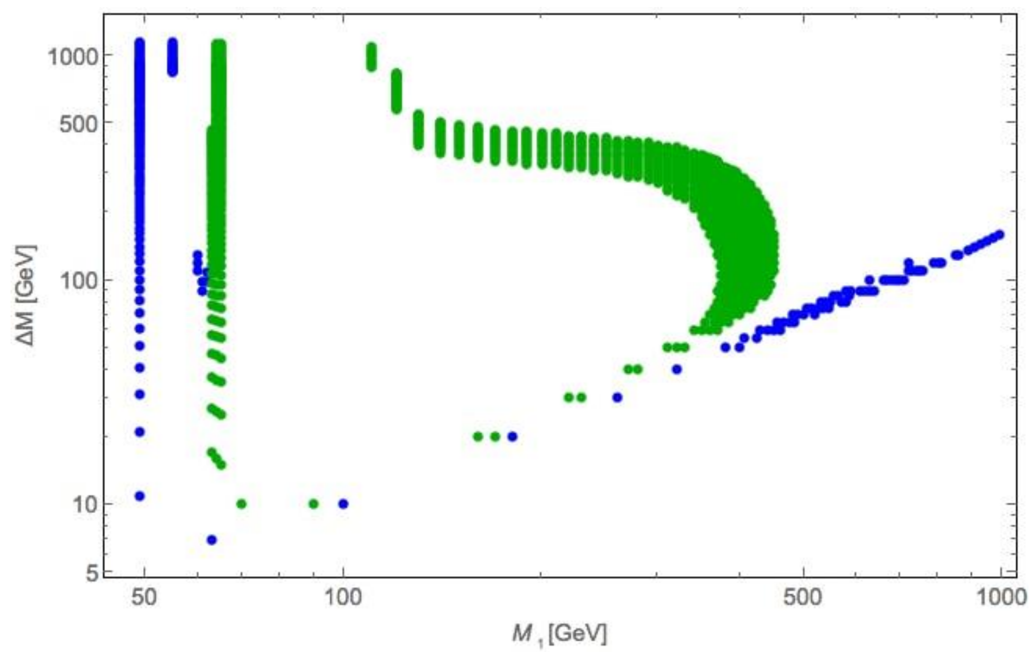


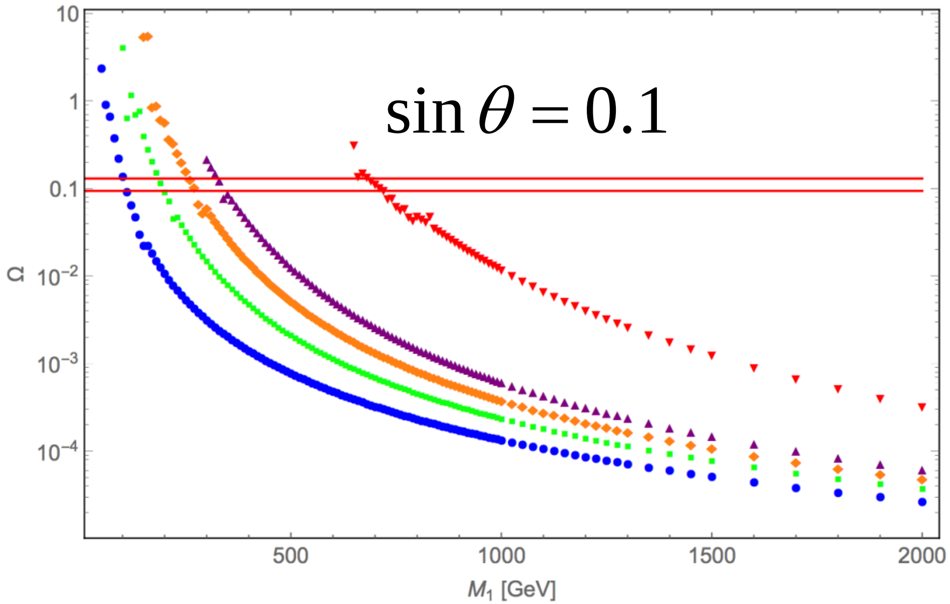
$$M_2 - M_1 = (10 - 1000) GeV$$

Contours of correct relic density



$$\sin\theta = 0.1(Blue), 0.2(Green)$$





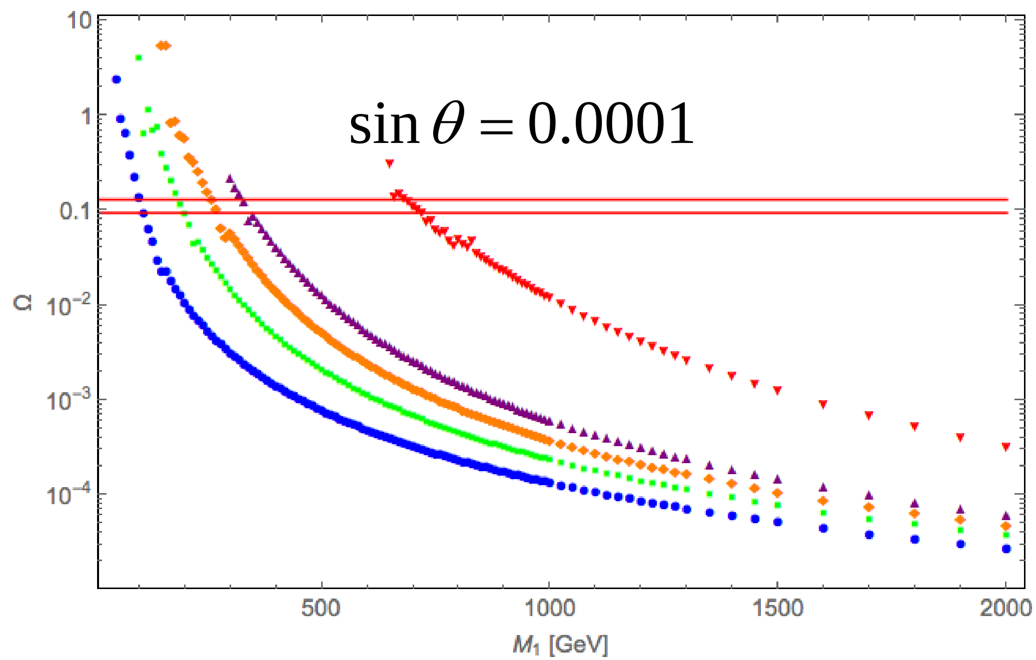
$\Delta M = 10GeV(Blue)$

$\Delta M = 20GeV(Green)$

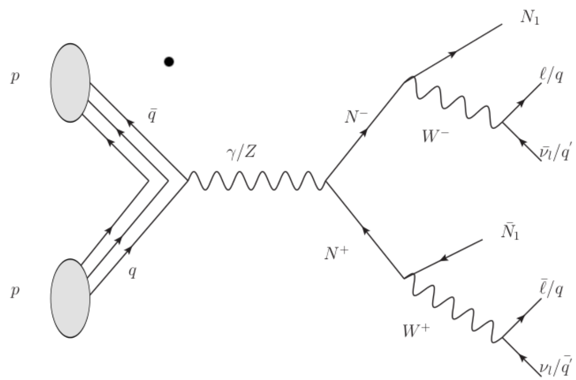
$\Delta M = 30GeV(Orange)$

$\Delta M = 40GeV(Purple)$

$\Delta M = 100GeV(\mathrm{Re}\,d)$



Collider search of DM

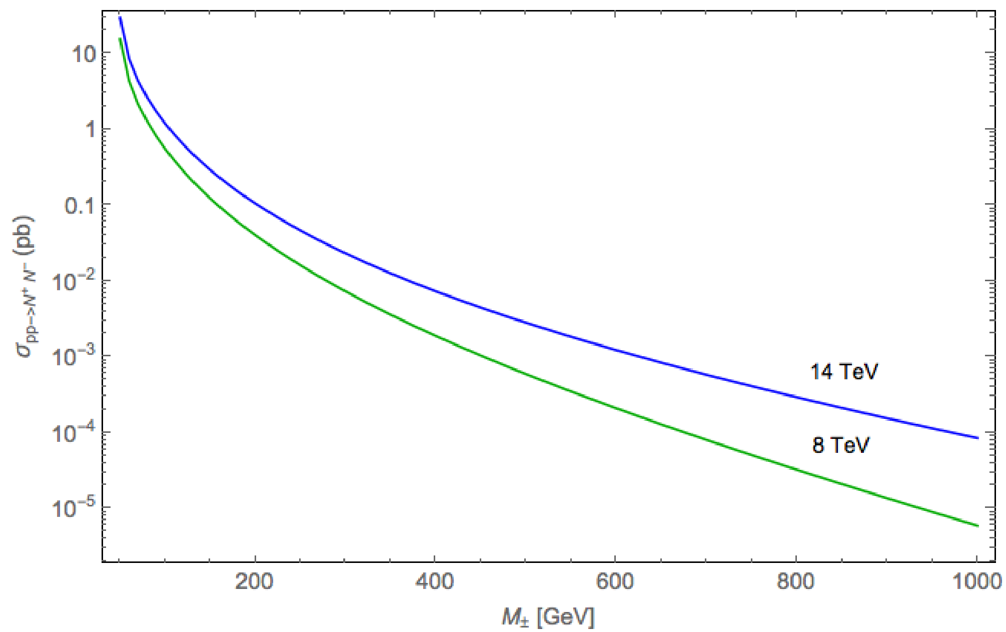


The production of $N^{\pm}$-pair is independent of the small mixing angle. However, its production cross-section decreases rapidly with its mass.

$$N^+N^- \to \ell 2j + \not{E}_T$$

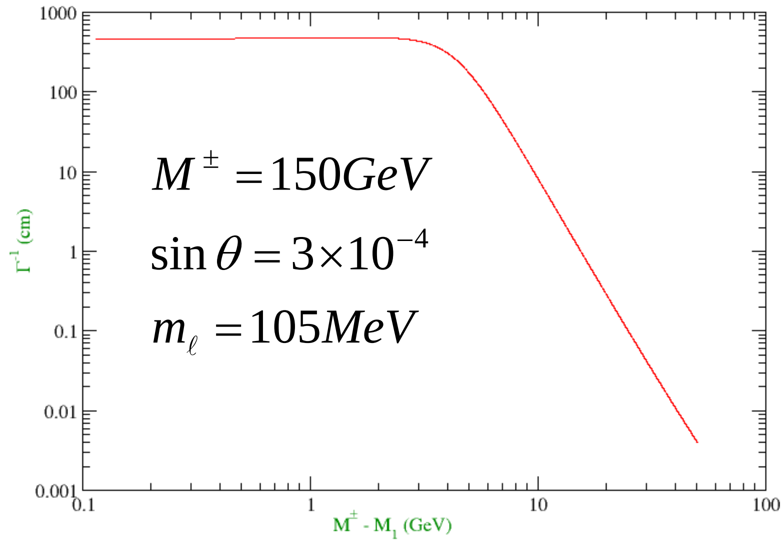
$$N^+N^- \to 2\ell + \not{E}_T$$

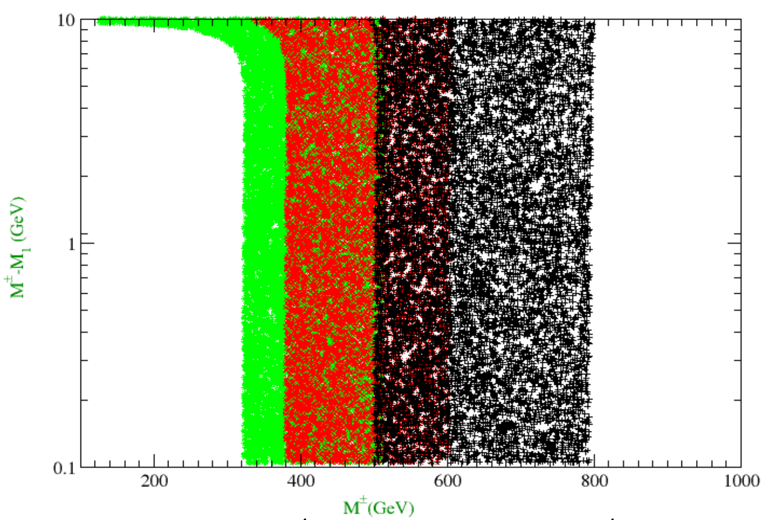
$$N^+N^- \to 4j + \not{E}_T$$



Displaced vertex signature of $N^{\pm}$ for small mixing angle:

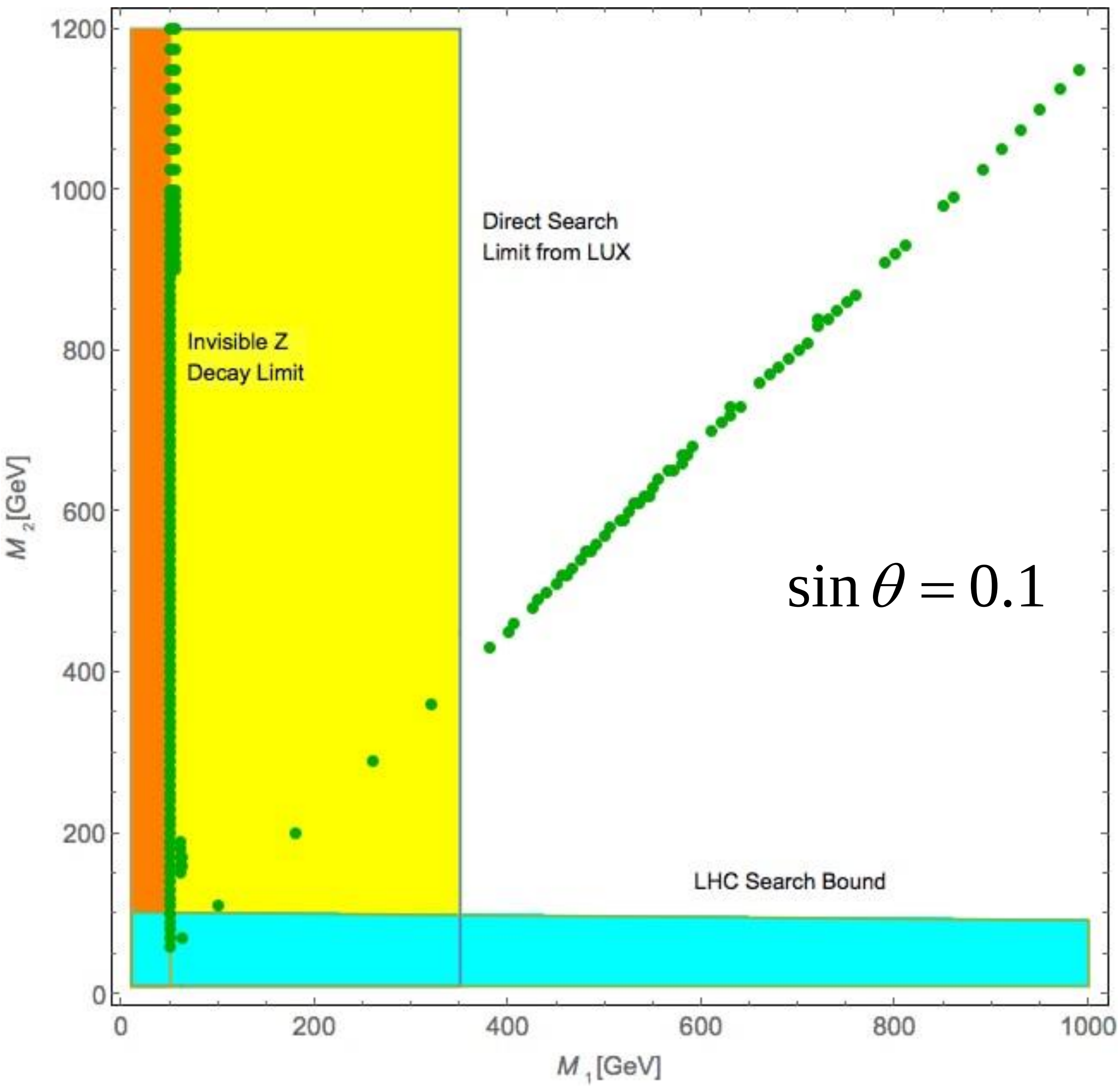
$$N^{\pm} \rightarrow N_1 + \ell^{\pm} + \nu_{\ell}$$





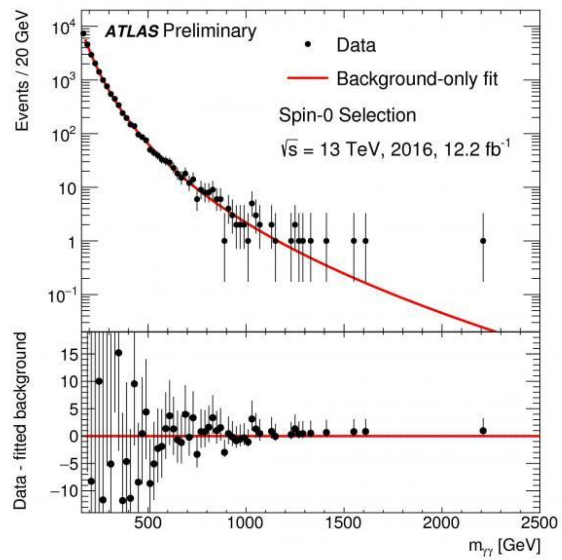
$$\sin\theta = 3\times10^{-4}(Green), 2\times10^{-4}(Red), 10^{-4}(Black)$$

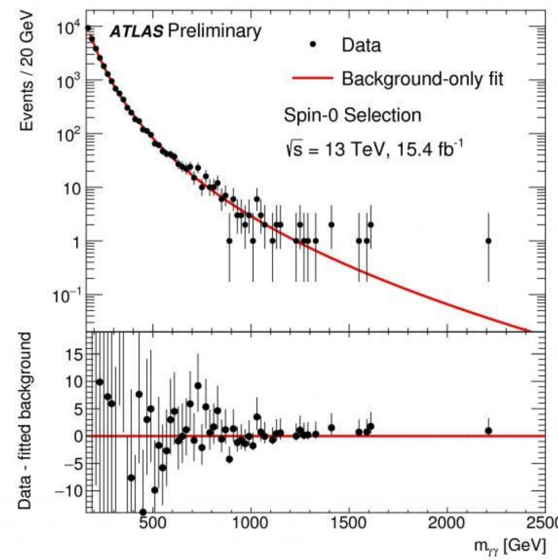
Thus for a small mass difference we expect a large displaced vertex signature of charged partner of the dark matter.

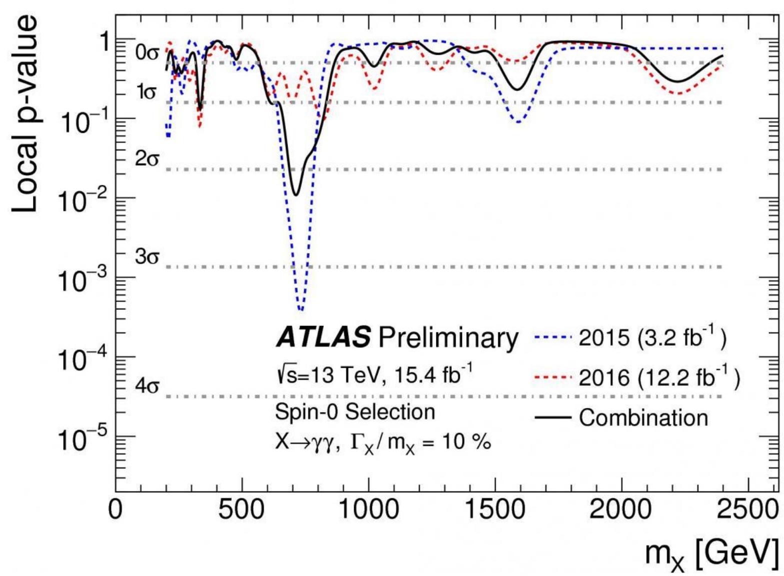


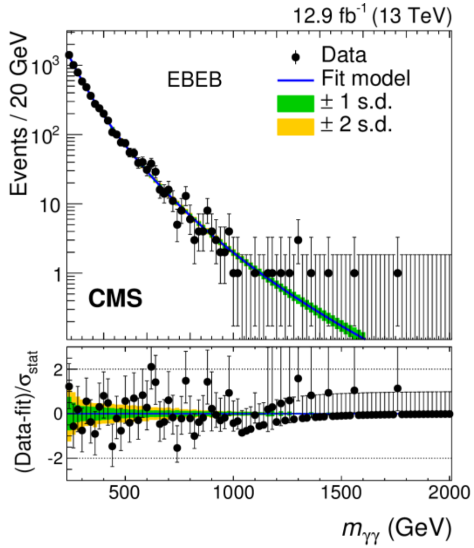
Direct Search
Limit from LUX
Invisible Z
Decay Limit
LHC Search Bound
$\sin\theta = 0.1$
M_2 [GeV]
M_1 [GeV]

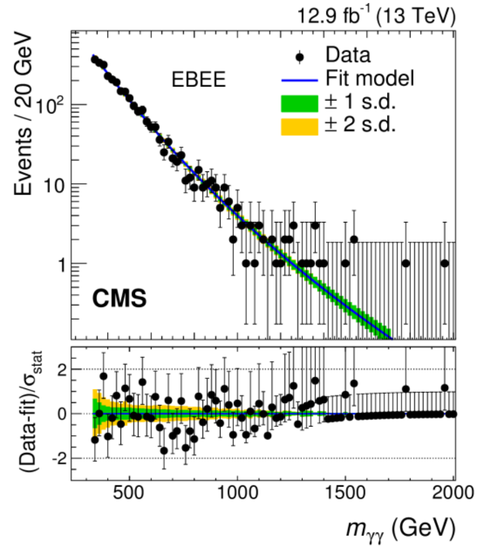
Di-photon excess at CERN LHC








12.9 fb^{-1} (13 TeV)
CMS
EBEB
Data
Fit model
± 1 s.d.
± 2 s.d.
Events / 20 GeV
(Data-fit)/σ_{stat}
$m_{\gamma\gamma}$ (GeV)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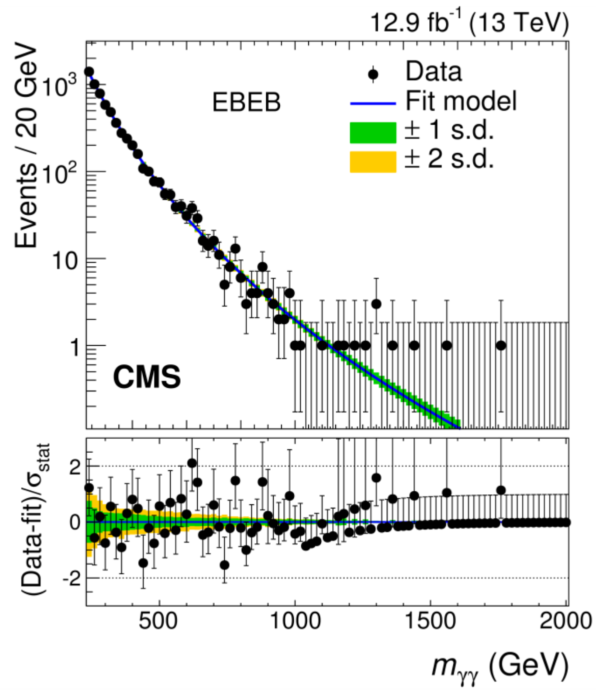

12.9 fb^{-1} (13 TeV)
CMS
EBEB
Data
Fit model
± 1 s.d.
± 2 s.d.
Events / 20 GeV
(Data-fit)/σ_{stat}
$m_{\gamma\gamma}$ (GeV)

Dark sector assisted diphoton excess

$$\mathcal{L}_{DM} = M_\psi \overline{\psi}\psi + f_\psi S\overline{\psi}\psi + f_\chi S\overline{\chi^0}\chi^0 + M_\chi \overline{\chi^0}\chi^0$$
$$+[Y\overline{\psi}\tilde{H}\chi^0 + h.c.] + \overline{\psi} i\gamma^\mu D_\mu \psi + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

$$\psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix} \equiv (1,2,-1), H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1,2,1), \chi^0 \equiv (1,1,0)$$

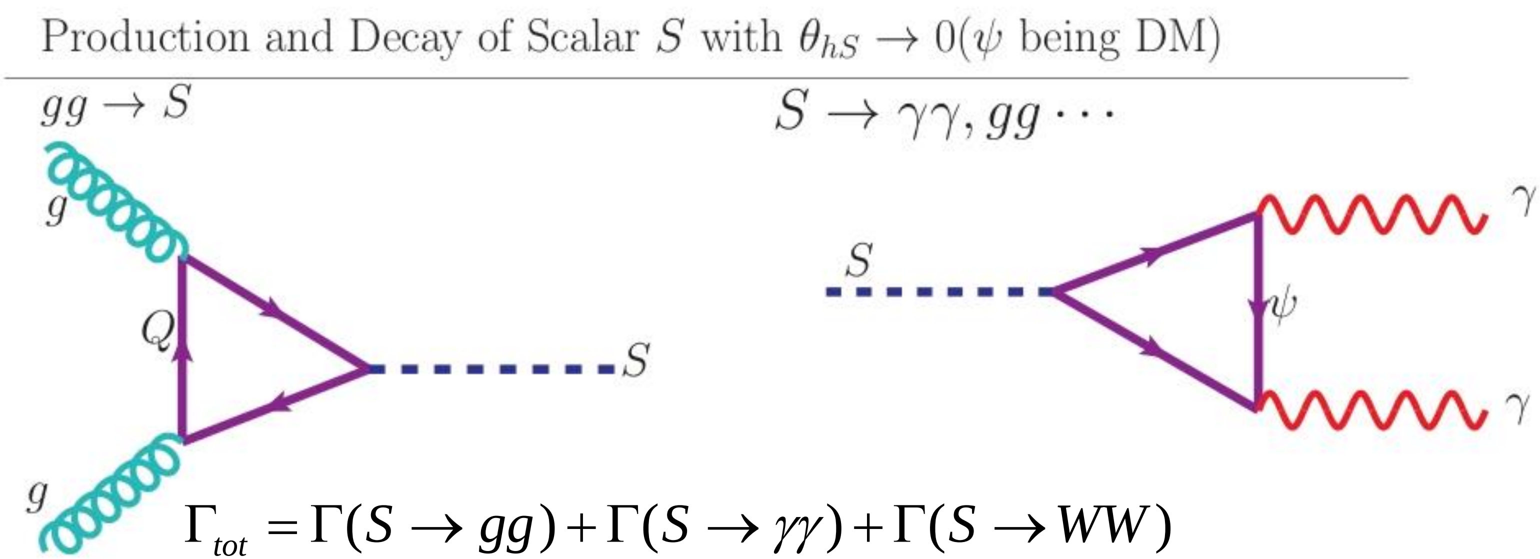
After electroweak phase transition, the mass matrix for vector-like fermion is given by

$$\begin{pmatrix} \overline{\psi^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_\psi & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} \psi^0 \\ \chi^0 \end{pmatrix}$$

Note: S does not acquire any vacuum expectation value. We assume that the bare mass of S is 750 GeV. We also assume that the tree-level decay of S to ψ and χ^0 is forbidden kinematically. This implies ψ and χ^0 masses are heavier than 385 GeV. So S can decay at loop level to $\gamma\gamma, WW, ZZ, Z\gamma$

Production and decay of S

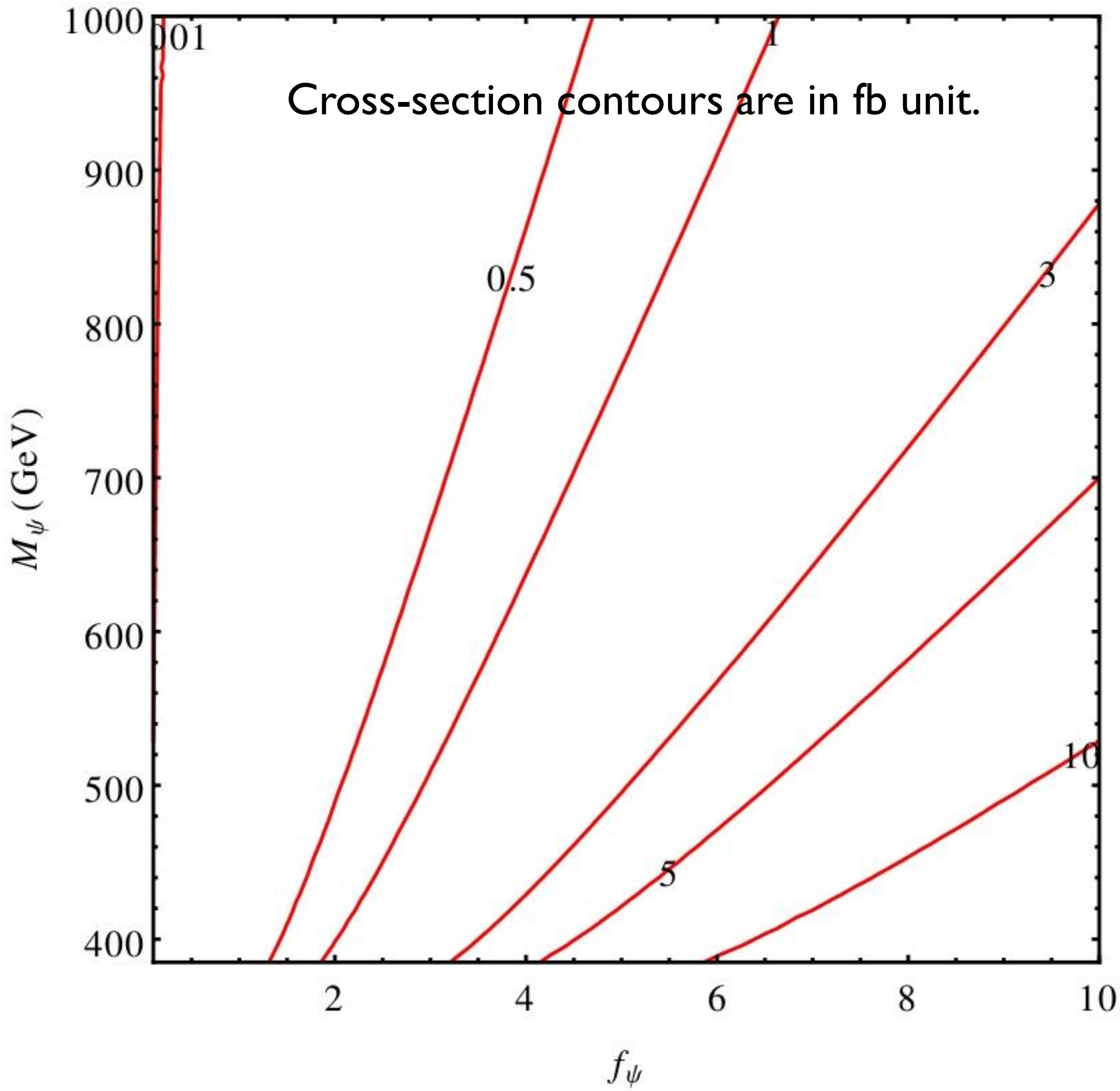
The production of S via the mixing with SM Higgs is very suppressed. However, we need a large cross-section. Therefore, we can introduce an iso-singlet vector-like quark so that S can copiously produced via gluon-gluon fusion process, similar to the Higgs production in the SM.



$$\Gamma_{tot} = \Gamma(S \to gg) + \Gamma(S \to \gamma\gamma) + \Gamma(S \to WW) + \Gamma(S \to ZZ) + \Gamma(S \to Z\gamma) + \Gamma(S \to hh)$$

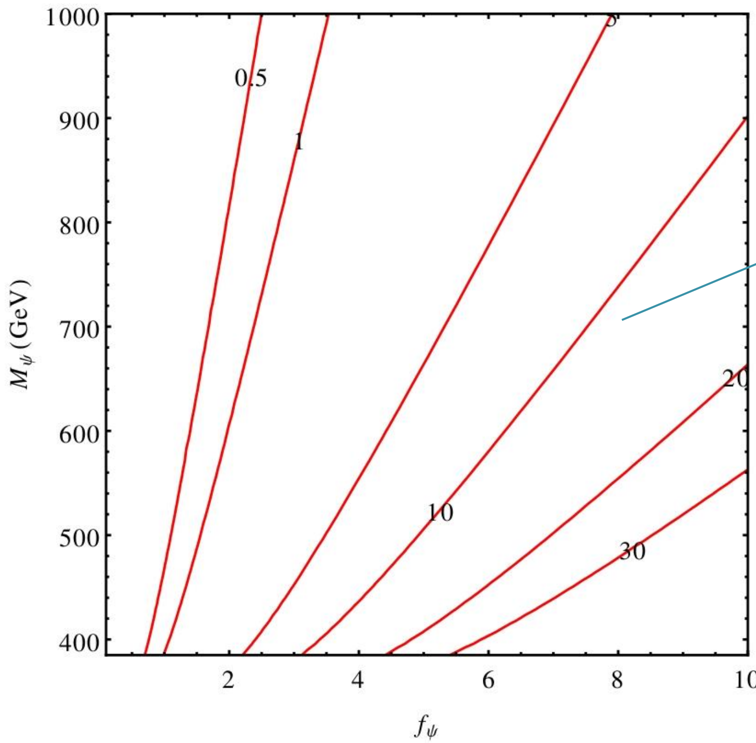
$$Br(S \to \gamma\gamma) = \frac{\Gamma(S \to \gamma\gamma)}{\Gamma_{tot}}$$

$$\sigma(pp \to S \to \gamma\gamma) = \frac{1}{M_S \hat{s}} C_{gg} \Gamma(S \to gg) Br(S \to \gamma\gamma)$$



$$f_\psi = f_Q$$

$$M_\psi = M_Q$$



Contours of total decay width in GeV unit.

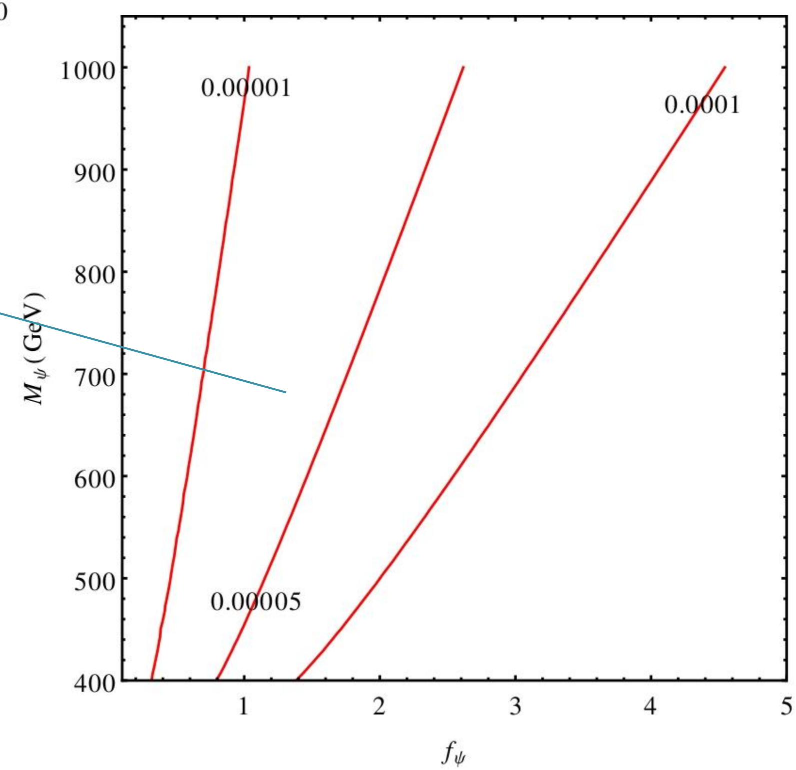
$$f_\psi = f_Q$$

$$M_\psi = M_Q$$

Contours of branching fraction with

$$f_Q = 2$$

$$M_Q = 400GeV$$



Conclusions

(1)The observed relic abundance of DM implies that its freeze-out cross-section (~0.1pb) is typically a weak interaction cross-section. So it is largely believed that the DM is a WIMP.

(2)We studied the case of a vector-like leptonic DM which satisfies the relic abundance in most of the parameter space.

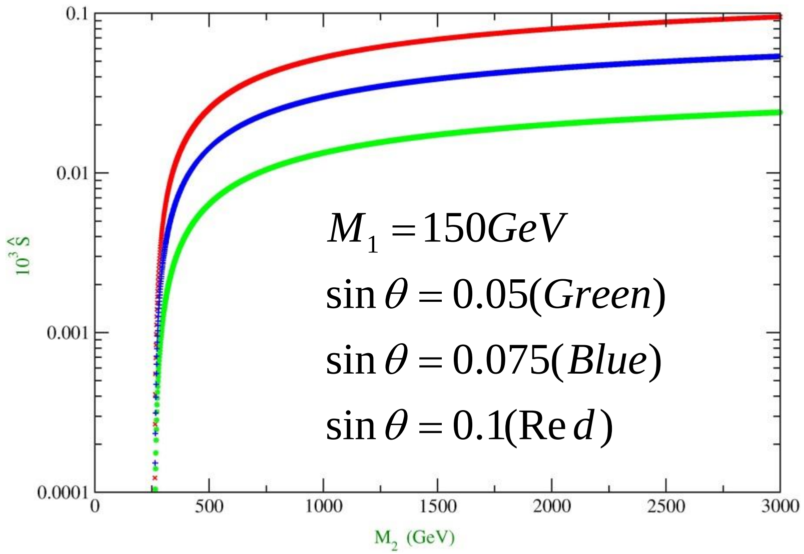
(3)The spin independent direct detection cross-section is within the reach of Xenon-1T.

(4)The displaced vertex signature of the charged partner looks interesting.

(5) The recent di-photon excess can be explained if the coupling of dark matter with the scalar resonance is large.

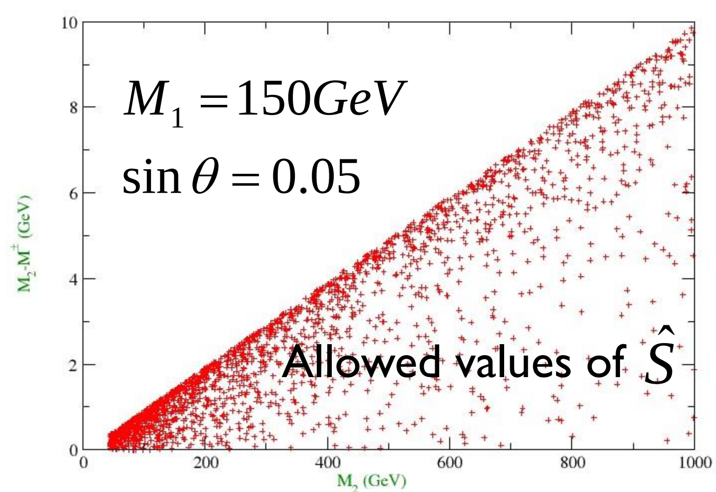
Thank you

Constraint from S parameters

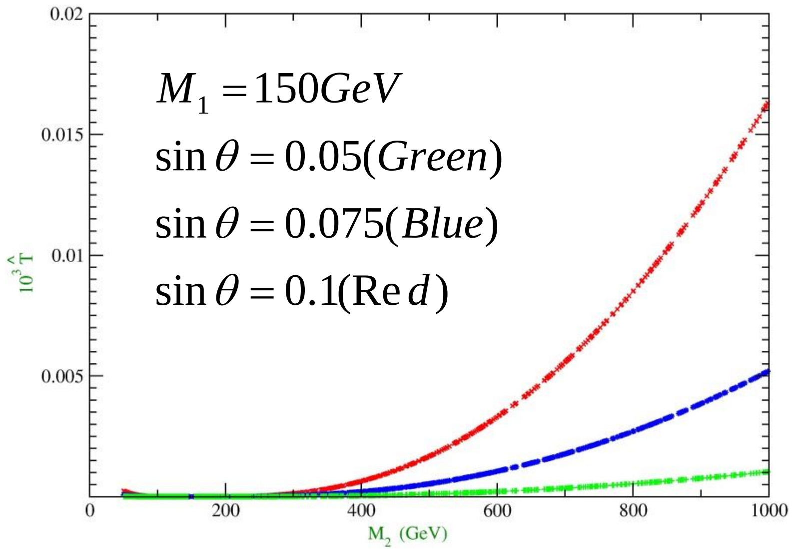


$$\hat{S} = \frac{\alpha S}{4\sin^2\theta_w}$$

$$1000\hat{S} = 0.0 \pm 1.3$$



Constraints from T parameter



$$\hat{T} = \alpha T$$

$$1000\hat{T} = 0.1 \pm 0.9$$