Shedding light on dark matter with recent muon ($g-2$) and Higgs exotic decay measurements

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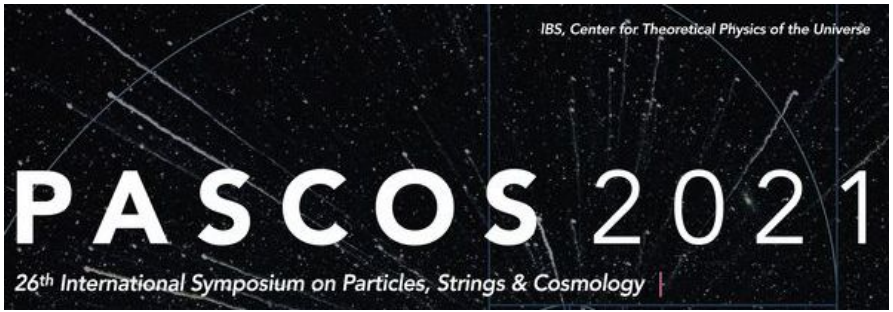
Collaborators :
Raymundo Ramos, Kingman Cheung
Ref : arXiv:2104.04503



Contents

Motivation – Dark Matter

Evidences for Dark Matter (DM)

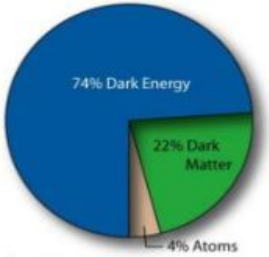
- WMAP measurement (Ω_m=0.25)
- rotation curves of galaxies
- the “bullet” cluster

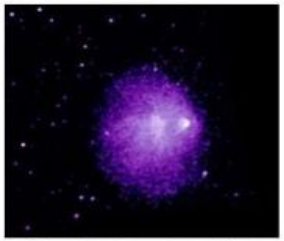
Open Problems

- DM nature
- DM interactions
- DM formation mechanism

Detection techniques

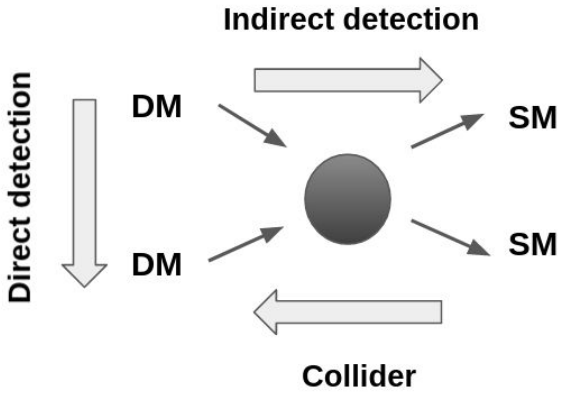
- signals from colliders
- direct detection
- indirect detection of annihilation products such as neutrinos, antiprotons or gamma-rays





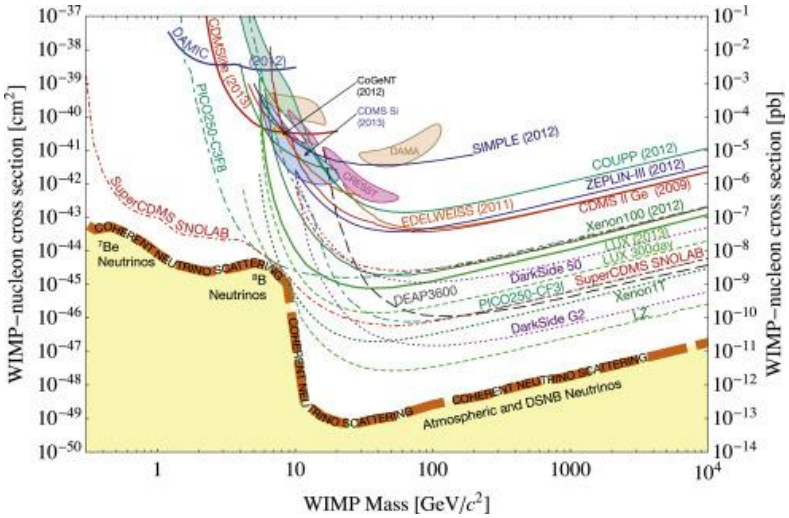
Chandra photo album: X-ray image of 1E0657-558

Motivation – Dark Matter

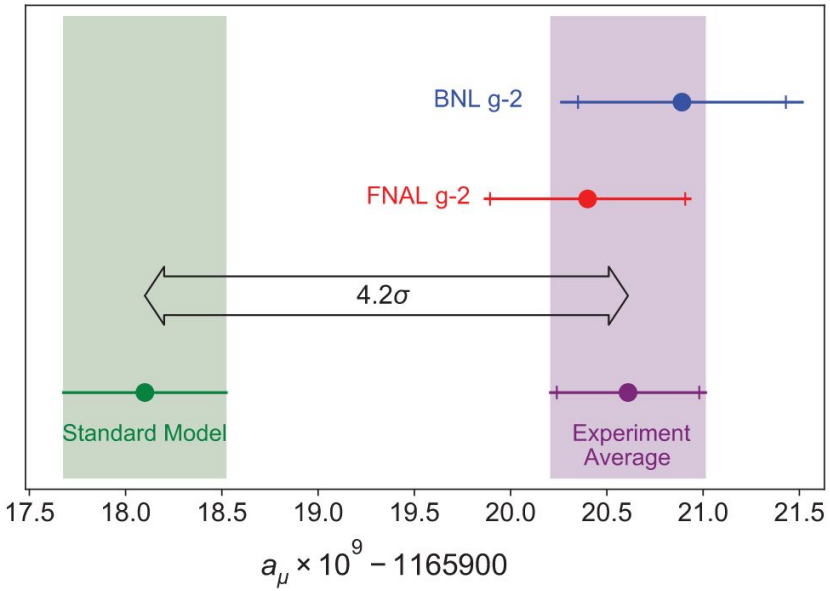


Is the Weakly Interacting Massive Particles (WIMP) dead ?

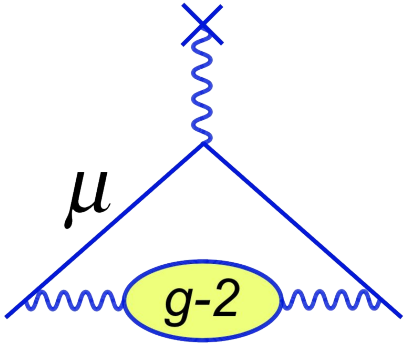
DM direct detection



Motivation – Muon (g-2)



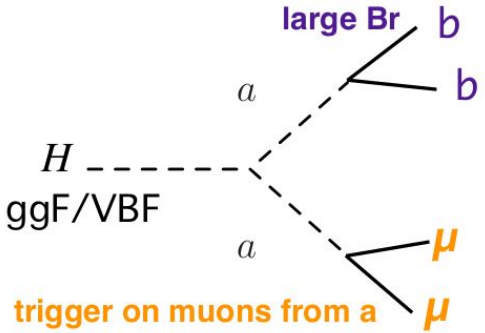
B. Abi *et al.* (Muon $g-2$ Collaboration)
Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

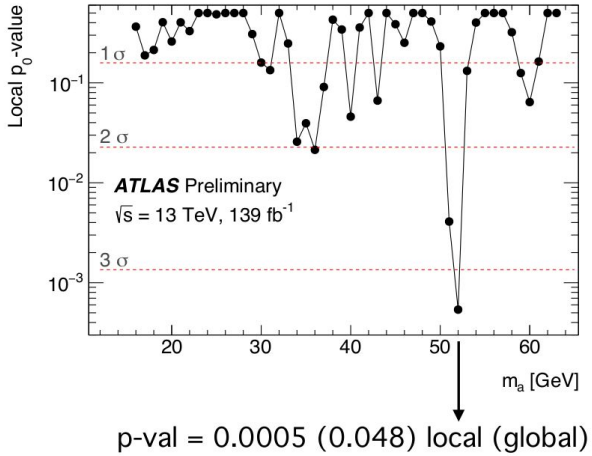


BSM inside the loop ?

Motivation – ATLAS Higgs boson exotic decay excess

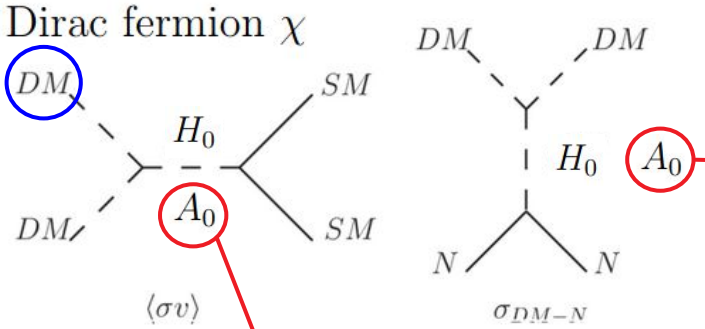
- $H \rightarrow aa \rightarrow 2b2\mu$, $16 < m_a[\text{GeV}] < 62$
  - **Excess of 3.3σ (1.7σ) local (global) observed at m_a=52 GeV**

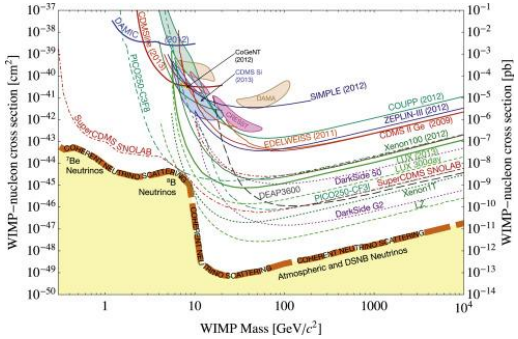




ATLAS-CONF-2021-009

Motivation – Combine them together ?





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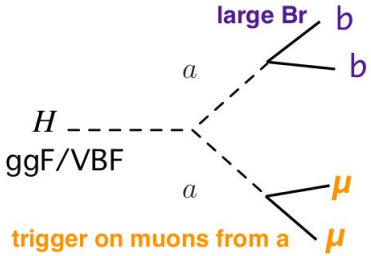
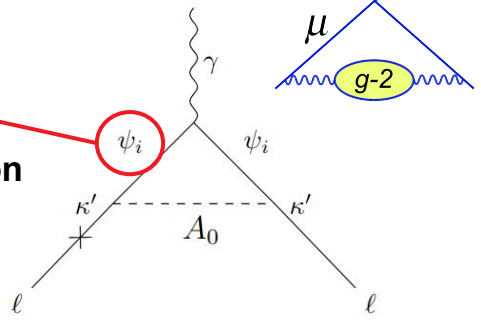


vector-like muon lepton (VLML)



Renormalizable simplified dark matter model

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{\chi}(i\partial\!\!\!/ - M_\chi - ig_\chi A\gamma_5)\chi + \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2}m_A^2 A^2$$
$$- (\mu_A A + \lambda_{HA} A^2)(H^\dagger H - \frac{v^2}{2}) - \frac{\mu'_A}{3!}A^3 - \frac{\lambda_A}{4!}A^4$$
$$+ \left[-\kappa \overline{L}_\mu H \psi_R + i\kappa' \overline{\mu}_R A \psi_L - iy\overline{\psi}_L A \psi_R + M_\psi \overline{\psi}_L \psi_R + \text{H.c.}\right].$$

$$\begin{pmatrix} H_0 \\ A_0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ A \end{pmatrix}$$

Note that the dimension-3 terms with μ_A and μ'_A break the parity

S. Baek, P. Ko and J. Li, Phys. Rev. D **95**, no.7, 075011 (2017)

G. Hiller, C. Hormigos-Feliu, D. F. Litim and T. Steudtner, Phys. Rev. D **102**, no.7, 071901 (2020)

Similarly, the VLML and muon will mix together after EWSB.

$Z \to l^+ l^-$ precision measurements ⟹ $\frac{\kappa v}{\sqrt{2}M_\psi} < \mathcal{O}(10^{-2})$.

where $M_\psi \sim v$ implies $\kappa \lesssim \mathcal{O}(10^{-2})$.

Renormalizable simplified dark matter model

we can read off ten undetermined parameters in this model:

$$g_\chi, \quad s_\alpha, \quad M_\chi, \quad \lambda_{HA}, \quad \mu'_A, \quad \lambda_A, \quad \kappa, \quad \kappa', \quad y, \quad M_\psi.$$

We can further fix $\mu'_A = 5.0\,\text{GeV}$, $\lambda_A = 1.0$ and $y = 0.01$ for this analysis

Scan parameters :

$$\begin{aligned}
10^{-3} &\leq g_\chi^{(*)} \leq 2.0\,, \\
5\times10^{-3} &\leq \sin\alpha^{(*)} \leq 0.3\,, \\
150.0 &\leq M_\psi/\text{GeV} \leq 450.0\,, \\
26.0 &\leq M_\chi/\text{GeV} \leq 0.9\times M_\psi/\text{GeV}\,, \\
5\times10^{-4} &\leq \lambda_{HA}^{(*)} \leq 10^{-2}\,, \\
3\times10^{-6} &\leq \kappa^{(*)} \leq 8\times10^{-2}\,, \\
1.0 &\leq \kappa' \leq \sqrt{4\pi}\,,
\end{aligned}$$

where the star $(*)$ indicates that the parameter is scanned logarithmically in base 10.

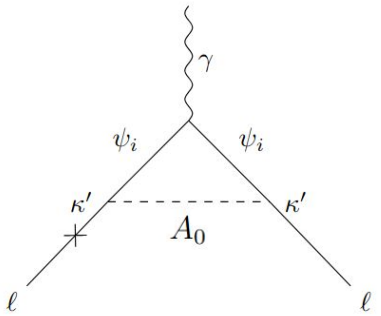
Experimental constraints

1. Muon g-2

$$\Delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$$

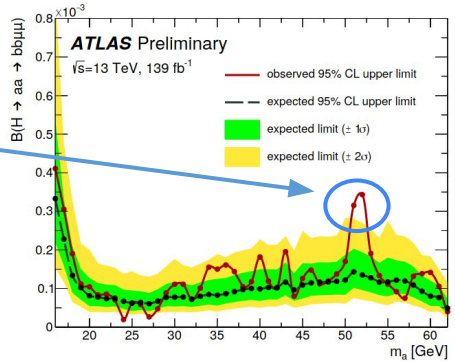
$$\Delta a_\mu = \frac{\kappa'^2}{96\pi^2}\frac{m_\mu^2}{M_\psi^2}\left[c_\alpha^2 f\left(\frac{M_{A_0}^2}{M_\psi^2}\right) + s_\alpha^2 f\left(\frac{M_{H_0}^2}{M_\psi^2}\right)\right]$$

where $f(t) = (2t^3 + 3t^2 - 6t^2 \ln t - 6t + 1)/(t-1)^4$.



2. ATLAS Higgs boson exotic decay excess

$\mathrm{BR}(H_0 \to A_0 A_0 \to b\bar{b}\mu^+\mu^-)$ is around 3.5×10^{-4}



A0 cannot simply be a SM singlet scalar or one of scalar/pseudoscalar in 2HDMs.

Experimental constraints

A. The LHC Higgs boson measurements

- **Higgs boson exotic and invisible decays**

  $\mathrm{BR}(H_0 \to \text{undetected}) < 19\%$ and $\mathrm{BR}(H_0 \to \text{invisible}) < 9\%$ at 95% C.L.

- $H_0 \to \mu^+\mu^-$

  $1.19^{+0.44}_{-0.42}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$

- $H_0 \to \gamma\gamma$

  $1.12^{+0.07}_{-0.06}(\text{stat})^{+0.06}_{-0.07}(\text{syst})$

B. The DM phenomenology

- **DM relic density**

  $\Omega_\chi h^2 = 0.12 \pm 0.001$

- **DM direct detection**

DM interacts with quarks via H0/A0 exchange resulting in a suppressed tree-level amplitude for DM-nucleon elastic scattering due to small momentum transfer.

Experimental constraints

C. The ATLAS multi-lepton search

Search for supersymmetry in events with four or more charged leptons in $139\,\text{fb}^{-1}$ of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (Mar 22, 2021)

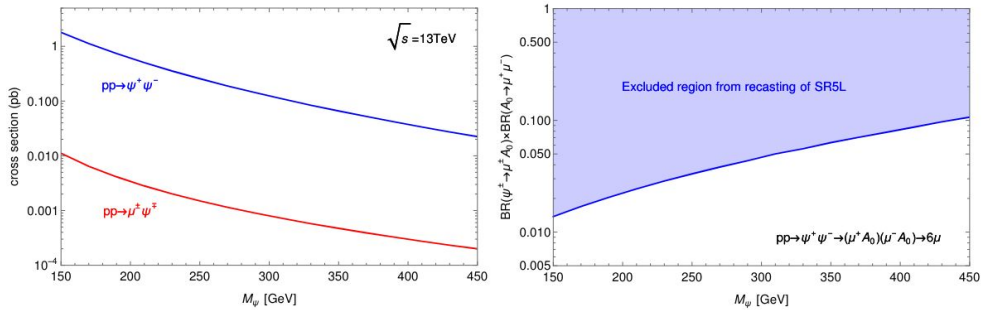


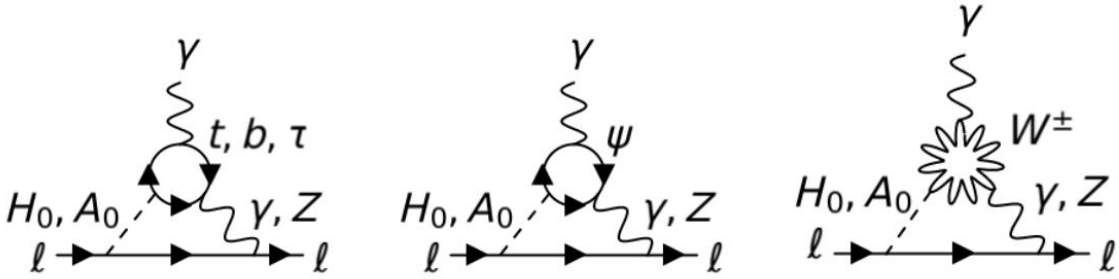
FIG. 1. Left panel: The production cross sections for the VLML $\psi^{\pm}$ at $\sqrt{s} = 13$ TeV. We fix $\sin\alpha = 0.1$, $\kappa = 5{\times}10^{-2}$ and $\kappa' = 2.0$ but vary M_ψ from 150−450 GeV. Right panel: Exclusion limit from recasting of the signal region **SR5L** in [69] on $(M_\psi, BR(\psi^{\pm} \to \mu^{\pm} A_0) \times BR(A_0 \to \mu^+\mu^-))$ plane.

Experimental constraints

D. The EDM of electron and muon

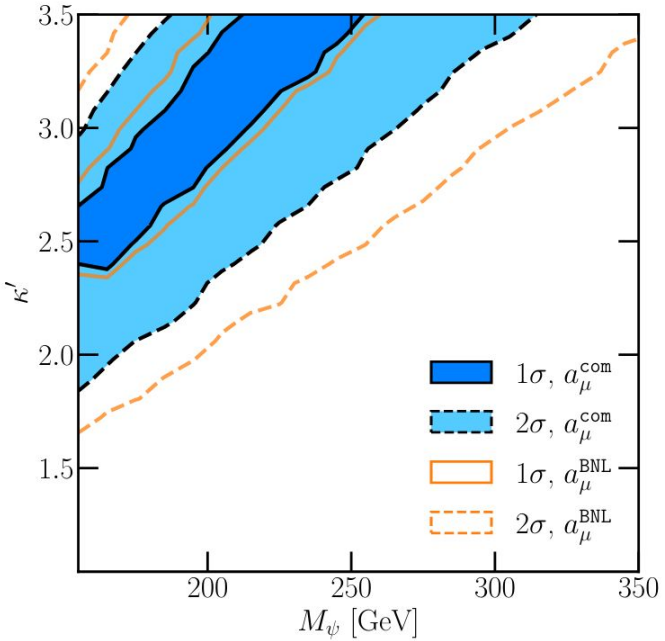
$|d_e^E| < 1.1 \times 10^{-29}\ e\text{cm}$ at 90% C.L.

$|d_\mu^E| < 1.9 \times 10^{-19}\ e\text{cm}$ at 95% C.L.



Results

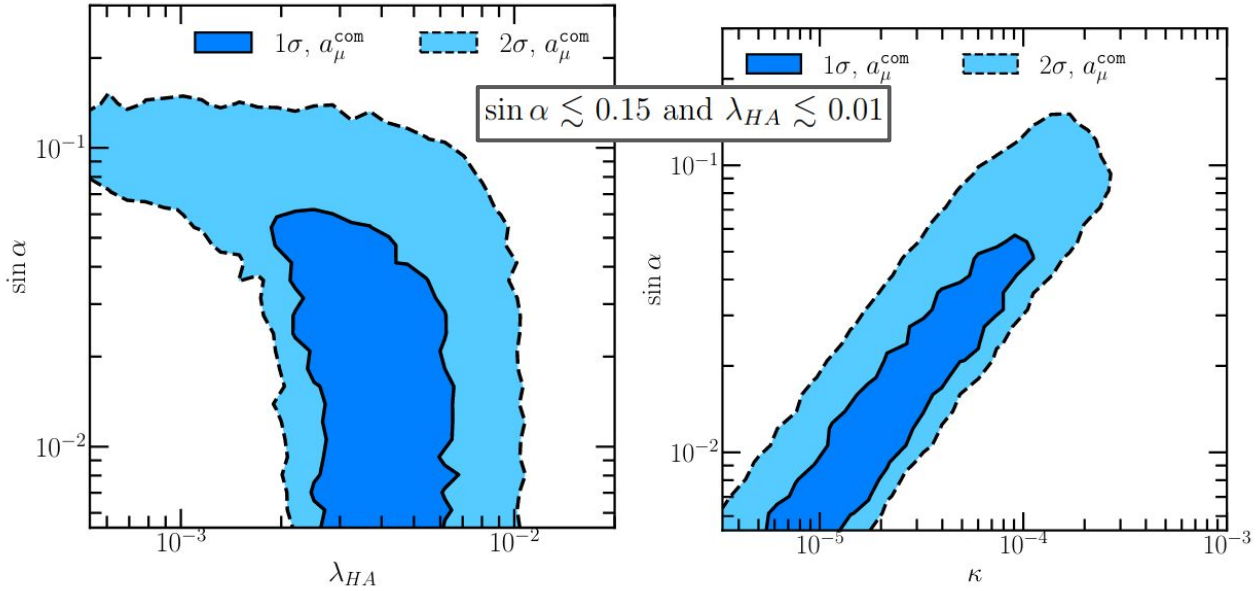
A. The impact from $(g-2)_\mu$ results on κ' and M_ψ



$\kappa' > 1.8$ and $M_\psi < 315\,\text{GeV}$

Results

B. The impact from Higgs measurements on $\sin\alpha$, λ_{HA}, and κ



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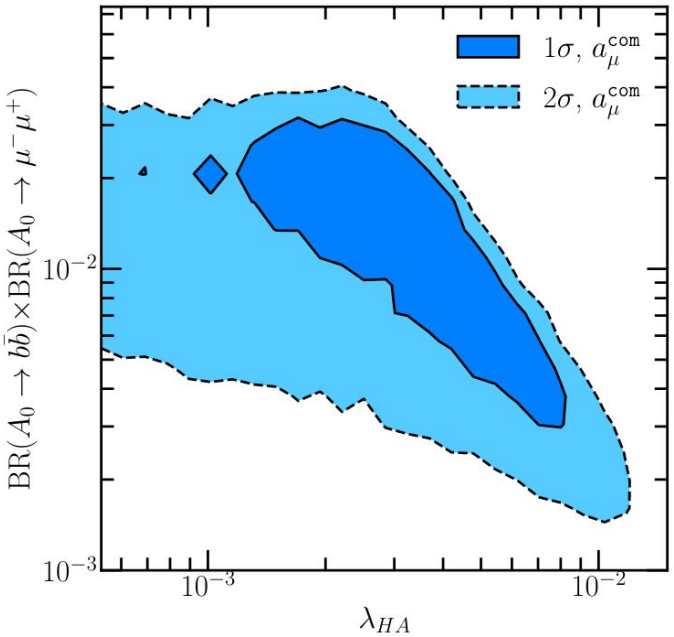
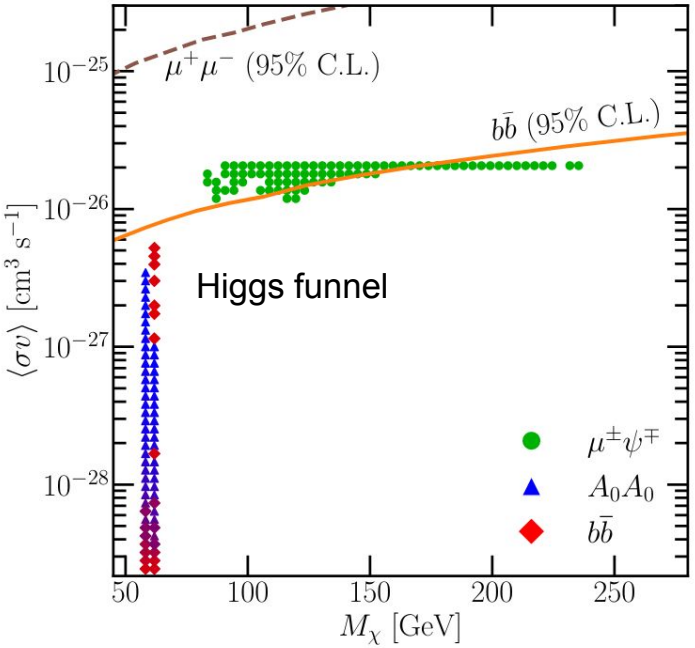


$$0.85 < \mathrm{BR}(A_0 \to b\bar{b}) < 0.89$$

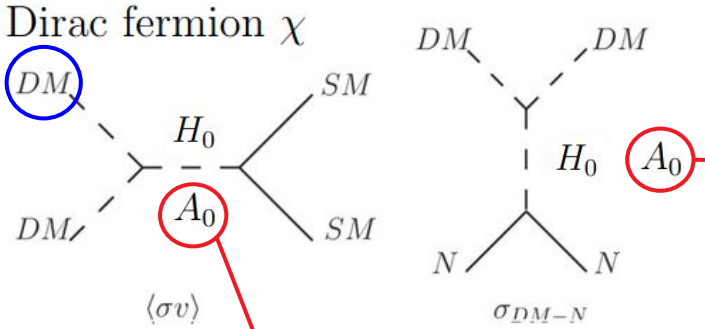
The 2σ allowed samples projected to $(M_\chi, \langle\sigma v\rangle)$ plane.

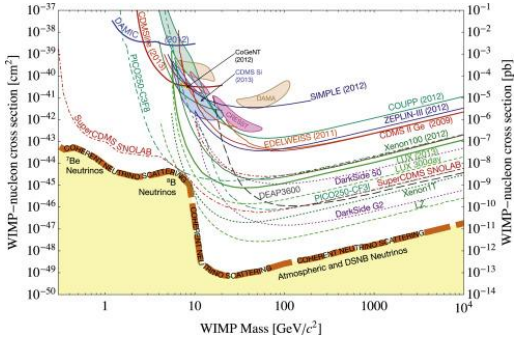


dSphs gamma ray data

$$\chi\bar{\chi} \to \mu^\pm\psi^\mp, \quad \psi^\mp \to b\bar{b}\mu^\pm$$

Conclusion





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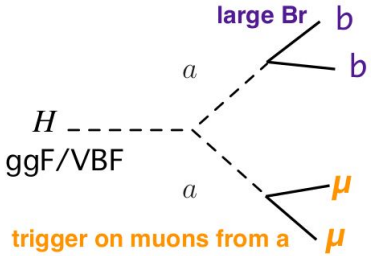

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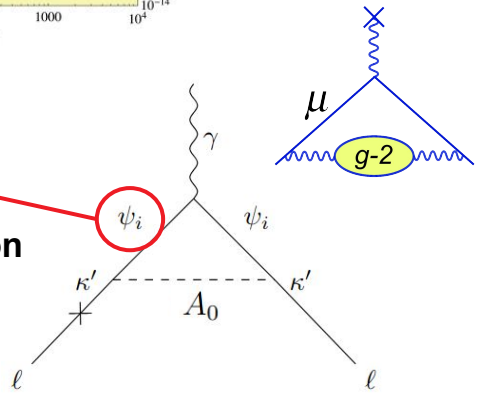

Thank you
for your attention

Backup-1

The Lagrangian to describe the interactions between the SM sector and DM sector via H_0 and A_0 portal can be written as

$$\mathcal{L}_{int}^{(H_0,A_0)} = -ig_\chi \left(H_0 s_\alpha + A_0 c_\alpha\right) \overline{\chi}\gamma_5\chi - \left(H_0 c_\alpha - A_0 s_\alpha\right) \left[\sum_{f\neq\mu} \frac{m_f}{v}\overline{f}f - \sum_{V=Z,W^\pm} \frac{\delta_V m_V^2}{v} V_\mu V^\mu\right]$$
$$- \left(\frac{m_\mu}{v} c_\alpha + ig_A\gamma_5 s_\alpha\right) H_0\overline{\mu}\mu + \left(\frac{m_\mu}{v} s_\alpha - ig_A\gamma_5 c_\alpha\right) A_0\overline{\mu}\mu \tag{5}$$

where $s_\alpha = \sin\alpha$, $c_\alpha = \cos\alpha$ and in the first-order approximation of κ,

$$g_A = \frac{\kappa'\kappa}{\sqrt{2}} \frac{v}{M_\psi} \tag{6}$$

and $\delta_V = 1(2)$ for $V = Z(W^\pm)$.

Backup-2

$$\begin{aligned}\mathcal{L}^{\psi}_{int} =& -e\overline{\psi}\gamma^{\mu}\psi A_{\mu} + \frac{g}{c_W}\overline{\psi}\gamma^{\mu}\psi Z_{\mu} - iy\overline{\psi}(H_0 s_{\alpha} + A_0 c_{\alpha})\gamma^5\psi \\ &+ \Bigg[-\frac{\kappa}{\sqrt{2}}(H_0 c_{\alpha} - A_0 s_{\alpha})\overline{\mu}_L\psi_R + i\kappa'(H_0 s_{\alpha} + A_0 c_{\alpha})\overline{\mu}_R\psi_L \\ &+ g'_z\overline{\mu}_L\gamma^{\mu}\psi_L Z_{\mu} + g'_w\overline{\nu}\gamma^{\mu}\psi_L W^{+}_{\mu} + \text{H.c.}\Bigg]\end{aligned}$$

where

$$g'_z = -\frac{g'_w}{\sqrt{2}c_W}, \quad g'_w = \frac{\kappa g}{2}\frac{v}{M_{\psi}}.$$