

Possibility of dark matter detection at future e^+e^- colliders

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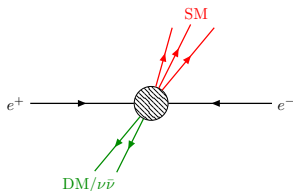
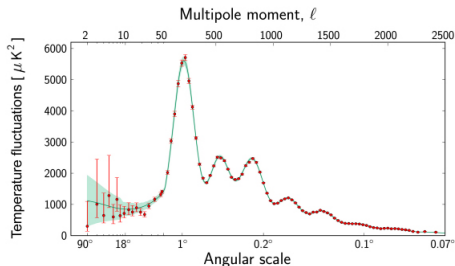


in collaboration with
B. Grządkowski, K. Mękała and A. F. Żarnecki
(work in progress)

Matter to the Deepest
Chorzów/Katowice, 1-6 September 2019

Dark matter

- rotation curves
- CMB fluctuations \Rightarrow ~~MOND~~
- gravitational lensing
- ...



Collider search for dark matter (DM)

- **Experimental approach:** missing-energy analysis
- **Signal** more clear at e^+e^- than at hadron colliders
- **Near-future plans:** ILC (Japan), CLIC (Europe), CEPC (China)...

1. Simple vector-DM and fermion-DM models
2. DM production at e^+e^- colliders
3. Determination of mass and spin
4. Current experimental limits and constraints
5. Maximizing the cross section, detectability

Vector DM model

- Gauge group: $\mathcal{G} = \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{Standard Model gauge group}} \times U(1)_X$.
- Vector X_μ ($U(1)_X$ g. f.) and complex scalar S introduced, $U(1) : S \rightarrow -S$
- Dark particle: X_μ
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} - V(H, S)$$

$$\mathcal{L}_{\text{DM}} = -\frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} + (\mathcal{D}^\mu S)^\dagger (\mathcal{D}_\mu S)$$

$$V(H, S) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \underbrace{\kappa |H|^2 |S|^2}_{\text{Higgs portal coupling}}$$

Higgs portal coupling

- SSB $H \rightarrow (\pi^+, v + i\pi^0 + h)^T / \sqrt{2}$ $S \rightarrow (v_s + \phi + i\sigma) / \sqrt{2}$
- We introduce h_1, h_2 :

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \quad \begin{aligned} m_1^2 &= \lambda_H v^2 (1 + \sec 2\alpha) + \lambda_S v_s^2 (1 - \sec 2\alpha) \\ m_2^2 &= \lambda_H v^2 (1 - \sec 2\alpha) + \lambda_S v_s^2 (1 + \sec 2\alpha) \end{aligned}$$

$$\mathcal{L}_{\text{DM}} \longrightarrow -\frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} + \frac{1}{2} \partial^\mu \phi \partial_\mu \phi + \frac{g_x^2 v_s^2}{2} X^\mu X_\mu + \frac{g_x^2}{2} X^\mu X_\mu \phi^2 + g_x^2 v_s X^\mu X_\mu \phi$$

$$V(H, S) \longrightarrow \frac{1}{2} m_1^2 h_1^2 + \frac{1}{2} m_2^2 h_2^2 + \text{const} + \mathcal{O}([\text{field}]^3)$$

Fermion DM model

- Gauge group: $\mathcal{G} = \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{Standard Model gauge group}} \times \mathbb{Z}_4$

Standard Model gauge group

- Left-handed fermion χ and real scalar S introduced, $\mathbb{Z}_4: \chi \rightarrow i\chi, S \rightarrow -S$
- Dark particle: Majorana fermion $\psi \equiv \chi + \chi^c$
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} - V(H, S)$$

$$\mathcal{L}_{\text{DM}} = i\bar{\chi}\not{\partial}\chi + \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{y_\chi}{2}(\bar{\chi}^c\chi + \bar{\chi}\chi^c)S$$

$$V(H, S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \frac{\mu_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 + \underbrace{\frac{\kappa}{2}|H|^2S^2}_{\text{Higgs portal coupling}}$$

Higgs portal coupling

- SSB $H \rightarrow (\pi^+, v + h + i\pi^0)^T/\sqrt{2} \quad S \rightarrow v_s + \phi$
- We introduce h_1, h_2

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$m_1^2 = \lambda_H v^2(1 + \sec 2\alpha) + \lambda_S v_s^2(1 - \sec 2\alpha)$$

$$m_2^2 = \lambda_H v^2(1 - \sec 2\alpha) + \lambda_S v_s^2(1 + \sec 2\alpha)$$

$$\mathcal{L}_{\text{DM}} \longrightarrow \frac{i}{2}\bar{\psi}\not{\partial}\psi + \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - \frac{y_\chi v_s}{2}\bar{\psi}\psi - \frac{y_\chi}{2}\bar{\psi}\psi\phi$$

$$V(H, S) \longrightarrow \frac{1}{2}m_1^2 h_1^2 + \frac{1}{2}m_2^2 h_2^2 + \text{const} + \mathcal{O}([\text{field}]^3)$$

Input parameters

$$V(H, S) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\kappa}{2} |H|^2 S^2$$

- Input parameters: $v, m_1, m_2, \sin \alpha, m_{DM}, v_s$

assumed to be SM-like

- Other parameters of the models in terms of the input parameters:

$$g_x = \frac{m_x}{v_s} \quad (\text{VDM}) \qquad y_x = \frac{m_x}{v_s} \quad (\text{FDM})$$

$$\lambda_H = \frac{m_1^2 \cos^2 \alpha + m_2^2 \sin^2 \alpha}{2v^2} \qquad \lambda_S = \frac{m_1^2 \sin^2 \alpha + m_2^2 \cos^2 \alpha}{2v_s^2}$$

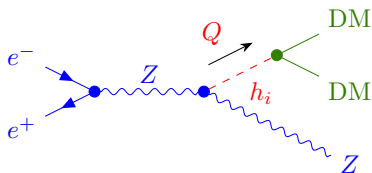
$$\mu_H^2 = \frac{1}{2} m_1^2 \cos^2 \alpha + \frac{1}{2} m_2^2 \sin^2 \alpha + \frac{1}{4} \frac{v_s}{v} (m_1^2 - m_2^2) \sin 2\alpha$$

$$\mu_S^2 = \frac{1}{2} m_1^2 \sin^2 \alpha + \frac{1}{2} m_2^2 \cos^2 \alpha + \frac{1}{4} \frac{v}{v_s} (m_1^2 - m_2^2) \sin 2\alpha$$

$$\kappa = \frac{(m_1^2 - m_2^2) \sin 2\alpha}{2vv_s}$$

- $m_2 = m_1 \Rightarrow \kappa = 0 \Rightarrow$ no Higgs portal \Rightarrow DM completely decoupled
- Tree-level stability condition always satisfied

$$\kappa > -2\sqrt{\lambda_H \lambda_S} \Leftrightarrow \frac{(m_1^2 - m_2^2) \sin 2\alpha}{2vv_s} > -\sqrt{\left[\frac{(m_1^2 - m_2^2) \sin 2\alpha}{2vv_s} \right]^2 + \frac{m_1^2 m_2^2}{v^2 v_s^2}}$$



$$Q^2 = s - 2E_Z \sqrt{s} + m_Z^2$$

$$\equiv m_{\text{rec}}^2$$

$$\text{DM} = X_\mu, \psi$$

note: in principle
 $\Gamma_i^{(\text{VDM})} \neq \Gamma_i^{(\text{FDM})}$

The differential cross-section:

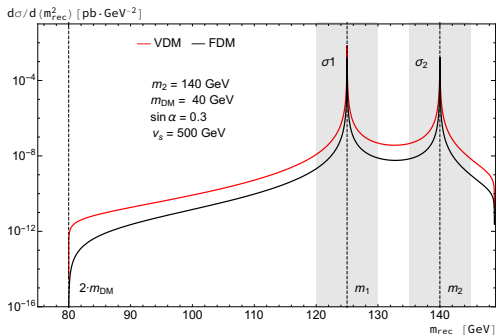
$$\frac{d\sigma}{dm_{\text{rec}}^2} = \frac{\sigma_{\text{SM}}(m_{\text{rec}})}{\pi} \sin^2 \alpha \cos^2 \alpha \frac{m_{\text{rec}} \cdot (m_1^2 - m_2^2)^2}{[(m_{\text{rec}}^2 - m_1^2)^2 + (m_1 \Gamma_1)^2][(m_{\text{rec}}^2 - m_2^2)^2 + (m_2 \Gamma_2)^2]} \cdot \frac{b(m_{\text{rec}}, m_{\text{DM}})}{v_s^2}$$

where

$$\sigma_{\text{SM}}(m_{\text{rec}}) \equiv \frac{g_V^2 + g_A^2}{24\pi} \left(\frac{g^2}{\cos^2 \theta_W} \frac{1}{s - m_Z^2} \right)^2 \frac{\lambda^{1/2}(s, m_{\text{rec}}^2, m_Z^2) [12 s m_Z^2 + \lambda(s, m_{\text{rec}}^2, m_Z^2)]}{8s^2}$$

$$b(m_{\text{rec}}, m_{\text{DM}}) \equiv \left[\frac{\mathcal{R}_{2i}}{v_s^2} \right]^{-1} \Gamma(h_i \rightarrow \text{DM}) = \frac{m_i^3}{32\pi} \sqrt{1 - \frac{4m_{\text{DM}}^2}{m_{\text{rec}}^2}} \cdot \begin{cases} 2 \left[\frac{m_{\text{DM}}^2}{m_{\text{rec}}^2} - 4 \left(\frac{m_{\text{DM}}^2}{m_{\text{rec}}^2} \right)^2 \right] & (\text{FDM}) \\ 1 - 4 \frac{m_{\text{DM}}^2}{m_{\text{rec}}^2} + 12 \left(\frac{m_{\text{DM}}^2}{m_{\text{rec}}^2} \right)^2 & (\text{VDM}) \end{cases}$$

Considered process



Spin and mass of DM possible to determine

- total σ as a function of \sqrt{s} (easy)
- shape fitting (not easy)

After integration

$$\sigma \approx \sigma_1 \cdot \mathbb{1}_{2m_{\text{DM}} < m_1 < \sqrt{s} - m_Z} + \sigma_2 \cdot \mathbb{1}_{2m_{\text{DM}} < m_2 < \sqrt{s} - m_Z}$$

$$\sigma_1 \equiv \sigma_{\text{SM}}(m_1) \cdot \cos^2 \alpha \cdot \text{BR}(h_1 \rightarrow \text{DM})$$

$$\sigma_2 \equiv \sigma_{\text{SM}}(m_2) \cdot \sin^2 \alpha \cdot \text{BR}(h_2 \rightarrow \text{DM})$$

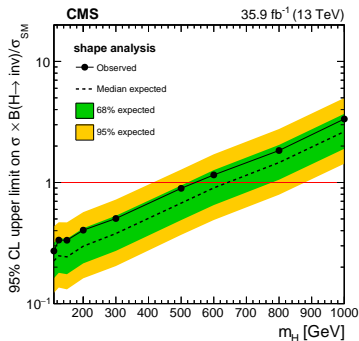
Current experimental limits and constraints

1. $|\sin \alpha| \lesssim 0.3$ 1601.07880

experiment	channel	observed signal rate	observed mass [GeV]
ATLAS	$h \rightarrow WW \rightarrow \ell\nu\ell\nu$	$1.08^{+0.22}_{-0.20}$	-
ATLAS	$h \rightarrow ZZ \rightarrow 4\ell$	$1.44^{+0.40}_{-0.33}$	124.51 ± 0.52
ATLAS	$h \rightarrow \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	125.98 ± 0.50
ATLAS	$h \rightarrow \tau\tau$	$1.42^{+0.43}_{-0.37}$	-
ATLAS	$Vh \rightarrow V(b\bar{b})$	$0.51^{+0.40}_{-0.37}$	-
CMS	$h \rightarrow WW \rightarrow \ell\nu\ell\nu$	$0.72^{+0.20}_{-0.18}$	-
CMS	$h \rightarrow ZZ \rightarrow 4\ell$	$0.93^{+0.29}_{-0.25}$	125.63 ± 0.45
CMS	$h \rightarrow \gamma\gamma$	$1.14^{+0.26}_{-0.23}$	124.70 ± 0.34
CMS	$h \rightarrow \tau\tau$	$0.78^{+0.27}_{-0.27}$	-
CMS	$Vh \rightarrow V(b\bar{b})$	$1.00^{+0.50}_{-0.50}$	-

source: 1501.02234

2. LHC $\Rightarrow BR(h_1 \rightarrow DM) < 19\%$ 1809.05937
3. DD experiments (XENON1T) and ν telescopes (IceCube)
 \Rightarrow limits on σ_{SI}^{DD} , σ_{SD}^{DD} 1805.12562 1601.00653
4. ID experiments (FERMI-LAT) \Rightarrow limit on $\langle\sigma v\rangle_{ID}$ 1611.03184
5. Planck $\Rightarrow h^2 \Omega_0^{DM} = 0.12 \pm 0.0012 \Rightarrow \langle\sigma v\rangle_{ann}$ 1807.06209



$$\sigma \approx \sigma_1 \cdot \mathbb{1}_{2m_{\text{DM}} < m_1 < \sqrt{s} - m_Z} + \sigma_2 \cdot \mathbb{1}_{2m_{\text{DM}} < m_2 < \sqrt{s} - m_Z}$$

$$\sigma_1 \equiv \sigma_{\text{SM}}(m_1) \cdot \cos^2 \alpha \cdot \text{BR}(h_1 \rightarrow \text{DM})$$

$$\sigma_2 \equiv \sigma_{\text{SM}}(m_2) \cdot \sin^2 \alpha \cdot \text{BR}(h_2 \rightarrow \text{DM})$$

$$(1) \quad \sigma_1 \stackrel{!}{<} 0.19 \sigma_{\text{SM}}(m_1)$$

$$(2) \quad \log \left[\frac{\sigma_2}{\sigma_{\text{SM}}(m_2)} \right] \stackrel{!}{<} 0.0011 \cdot \frac{m_2}{1 \text{ GeV}} - 0.63 \quad (\sqrt{s} = 13 \text{ TeV})$$

$$\left. \frac{\sigma_2}{\sigma_{\text{SM}}(m_2)} \right|_{\sqrt{s}=13 \text{ TeV}} = \sin^2 \alpha \cdot \text{BR}(h_2 \rightarrow \text{DM}) < 10^{-1} < 10^{\left[0.0011 \cdot \frac{m_2}{1 \text{ GeV}} - 0.63 \right]}$$

\Rightarrow for $\sin \alpha < 0.3$ condition (2) always satisfied

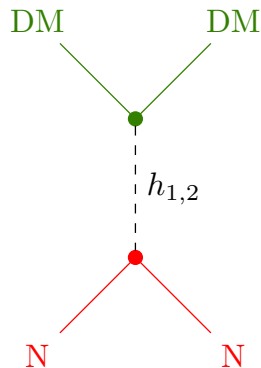
Direct detection: cross section

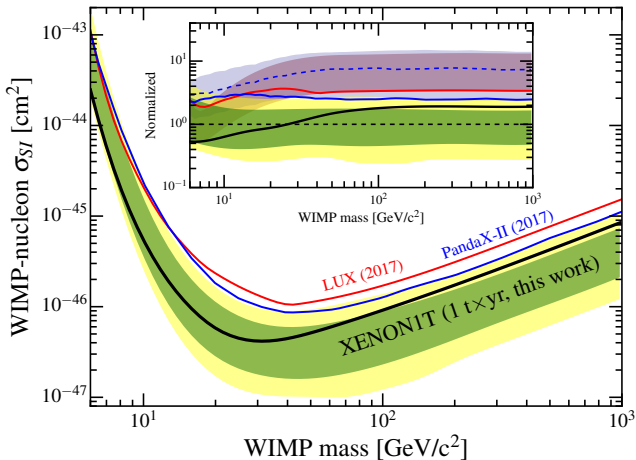
$$\sigma_{\text{SD}} = 0 \quad (\text{no axial couplings in our models})$$

$$\sigma_{\text{SI}} = \frac{\mu^2 m_{\text{DM}}^2}{\pi v_s^2} \cdot \frac{(m_1^2 - m_2^2)^2}{m_1^2 m_2^2} \cdot \sin^2 \alpha \cos^2 \alpha \cdot \frac{m_N^2}{v^2} f_N^2$$

where

$$\mu = \frac{m_N m_{\text{DM}}}{m_N + m_{\text{DM}}} \approx m_N \approx 0.94 \text{ GeV}, \quad f_N \approx 0.3$$

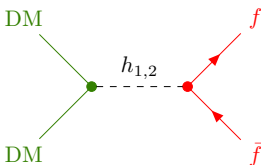




$$\frac{\sigma_{\text{SI}}^{\text{max}}}{1 \text{ cm}^2} \stackrel{!}{\approx} \frac{m_{\text{DM}}}{1 \text{ GeV}} \cdot 10^{-48.05}$$

$$\Rightarrow \frac{\sin^2 \alpha \cos^2 \alpha}{v_S^2} (m_1^2 - m_2^2)^2 \stackrel{!}{<} \frac{m_2^4}{m_{\text{DM}}} \cdot 1.5 \cdot 10^{-6} \text{ GeV}^{-1}$$

Indirect detection: cross section



$$\langle \sigma v \rangle_{f\bar{f}}^{\text{ID}} = \frac{1}{\pi} \frac{m_{\text{DM}} m_f^2}{v_s^2 v^2} \frac{(m_{\text{DM}}^2 - m_f^2)^{3/2} (m_1^2 - m_2^2)^2 \sin^2 \alpha \cos^2 \alpha}{[(m_1^2 - 4m_{\text{DM}}^2)^2 + m_1^2 \Gamma_1^2] [(m_2^2 - 4m_{\text{DM}}^2)^2 + m_2^2 \Gamma_2^2]} \times$$

$$\times \begin{cases} 1 & \text{VDM} \\ \frac{9}{8} \left(\frac{m_{\text{DM}}}{T}\right)^{-1} & \text{FDM} \end{cases} + [\text{higher orders in } (m_{\text{DM}}/T)^{-1}]$$

m_f^2 factor $\Rightarrow b\bar{b}$ contribution dominates.

- Let $\langle\sigma v\rangle_{bb}^{\text{ID}} = \sigma_0 \cdot (m_{\text{DM}}/T)^{-n} + \dots$ ($n = 0$ for VDM, $n = 1$ for FDM)
- In the standard freeze-out mechanism: $h^2\Omega_0^{\text{DM}} \sim (n+1)(m_{\text{DM}}/T_f)^{n+1}/\sigma_0$
- To ensure correct $h^2\Omega_0^{\text{DM}}$

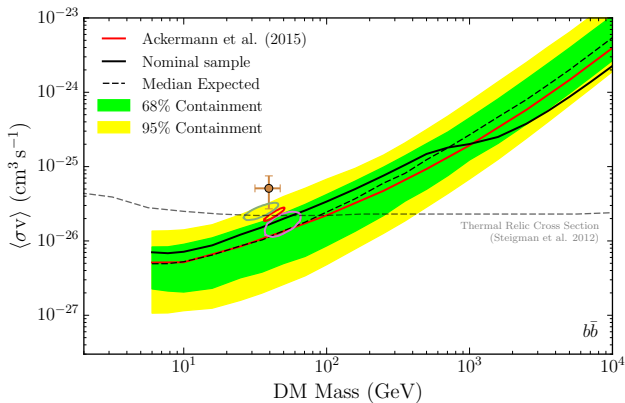
$$\langle\sigma v\rangle\Big|_{\text{now}} = (T_0/T_f)^n \cdot \langle\sigma v\rangle\Big|_{\text{freeze out}} \stackrel{!}{=} (T_0/T_f)^n \cdot (n+1) \cdot 1.9 \cdot 10^{-9} \text{ GeV}^{-2}$$

- $T_f \sim m_{\text{DM}}/25$, $T_0 = 2.73 \text{ K}$, hence

$$\begin{aligned} \frac{\sin^2 \alpha \cos^2 \alpha}{v_s^2} (m_1^2 - m_2^2)^2 &\stackrel{!}{=} \\ &= 2.1 \cdot 10^{-5} \text{ GeV}^{-2} \frac{[(m_1^2 - 4m_{\text{DM}}^2)^2 + m_1^2 \Gamma_1^2] [(m_2^2 - 4m_{\text{DM}}^2)^2 + m_2^2 \Gamma_2^2]}{m_{\text{DM}}(m_{\text{DM}}^2 - m_b^2)^{3/2}} \cdot k \end{aligned}$$

$$(k = 1 \text{ for VDM, } k = \frac{16m_\psi}{9T_f} \approx 44 \text{ for FDM})$$

FERMI-LAT limit:



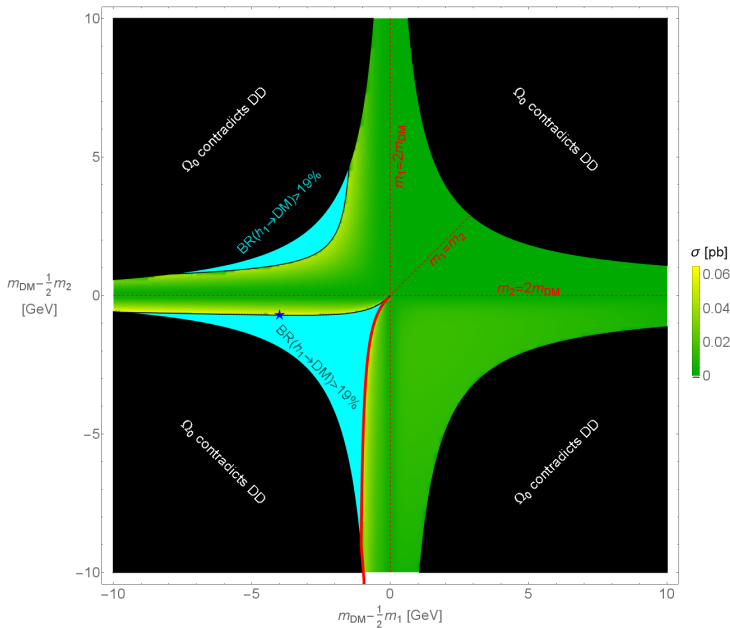
VDM: $m_X \gtrsim 30 \text{ GeV}$

FDM: thermal relic cross section 10^{-11} – 10^{-13} times lower than the ID limit

- Free parameters: m_2 , m_{DM} , $\sin \alpha$, v_s
- Constraints:
 - perturbativity: $\frac{m_{\text{DM}}}{v_s} < 4\pi$
 - $|\sin \alpha| \lesssim 0.3$
 - $\text{BR}(h_1 \rightarrow \text{DM}) < 19\%$
- Ω_0^{DM} :
$$\frac{\sin^2 \alpha \cos^2 \alpha}{v_s^2} (m_1^2 - m_2^2)^2 = \frac{[(m_1^2 - 4m_{\text{DM}}^2)^2 + m_1^2 \Gamma_1^2] [(m_2^2 - 4m_{\text{DM}}^2)^2 + m_2^2 \Gamma_2^2]}{m_{\text{DM}} (m_{\text{DM}}^2 - m_b^2)^{3/2}} \times$$

$$\times 2.1 \cdot 10^{-5} \text{ GeV}^{-2} \cdot \begin{cases} 1 & (\text{VDM}) \\ 44 & (\text{FDM}) \end{cases}$$
- DD:
$$\frac{\sin^2 \alpha \cos^2 \alpha}{v_s^2} (m_1^2 - m_2^2)^2 < \frac{m_2^4}{m_{\text{DM}}} \cdot 1.5 \cdot 10^{-6} \text{ GeV}^{-1}$$
- Value of v_s calculated from $\Omega_0^{\text{DM}} \Rightarrow$ 3 parameters left
- Cross section maximized with respect to $\sin \alpha \Rightarrow$ free parameters: m_2 , m_{DM}
- Low \sqrt{s} gives high cross section (CEPC: $\sqrt{s} = 240 \text{ GeV}$)

Results: maximal cross section for VDM



parameters of ★

$$m_2 = 118.4 \text{ GeV}$$

$$m_{\text{DM}} = 58.5 \text{ GeV}$$

$$\sin \alpha = 0.30$$

$$v_s = 561 \text{ GeV}$$

$$\Gamma_1 = 7.4 \cdot 10^{-3} \text{ GeV}$$

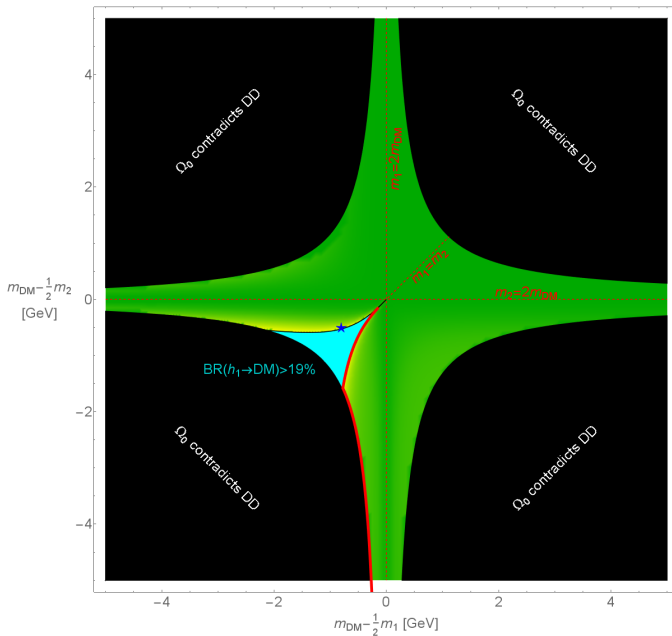
$$\Gamma_2 = 6.4 \cdot 10^{-3} \text{ GeV}$$

$$\text{BR}(h_1 \rightarrow \text{DM}) = 18\%$$

$$\text{BR}(h_2 \rightarrow \text{DM}) = 92\%$$

$$\sigma = 61 \text{ fb}$$

Results: maximal cross section for FDM



parameters of ★

$$m_2 = 124.4 \text{ GeV}$$

$$m_{\text{DM}} = 61.7 \text{ GeV}$$

$$\sin \alpha = 0.30$$

$$v_s = 57 \text{ GeV}$$

$$\Gamma_1 = 7.1 \cdot 10^{-3} \text{ GeV}$$

$$\Gamma_2 = 6.5 \cdot 10^{-3} \text{ GeV}$$

$$BR(h_1 \rightarrow \text{DM}) = 15\%$$

$$BR(h_2 \rightarrow \text{DM}) = 92\%$$

$$\sigma = 51 \text{ fb}$$

- Number of events:

$$\# = \sigma \times \mathcal{L}_{\text{tot}}$$

$$\mathcal{L}_{\text{tot}} \sim 5.6 \text{ ab}^{-1} \text{ (7-years period)}$$

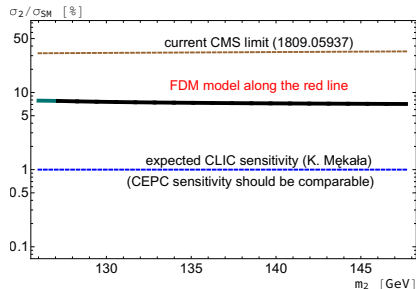
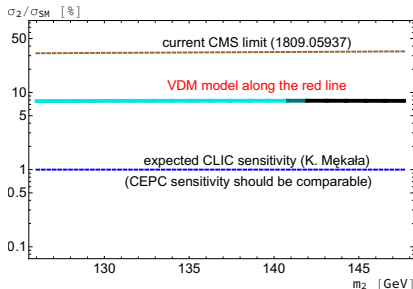
$$\star \Rightarrow \text{VDM: } 3.4 \cdot 10^5 \text{ events}$$

$$\text{FDM: } 2.9 \cdot 10^5 \text{ events}$$

$$\text{expected SM background (} e^+e^- \rightarrow Z\nu\bar{\nu} \text{): } 2.8 \cdot 10^6 \text{ events}$$

$$\Rightarrow [\text{signal}] \sim 10\% \times [\text{background}]$$

- σ_1 : $\text{BR}(h_1 \rightarrow \text{DM})$ detectable at the level of 0.3% (current CMS limit: 19%)
- σ_2 : $\sin^2 \alpha \cdot \text{BR}(h_2 \rightarrow \text{DM})$



Optimistic part

- Current experimental limits still allow DM to be detectable
- Signal-to-background ratio can be $\sim 10\%$
- Mass and spin in principle can be determined (but possibly not easily)

Pessimistic part

- If parameters far from optimal, DM hard (if possible) to be detected

Conclusion

- Let's build an e^+e^- collider and check!

BACKUP SLIDES

- DM annihilation rate in the Sun: Γ_A
- Capture rate: C_C
- Change of amount of DM in the Sun

$$\dot{N} = C_C - C_A N^2$$

where $C_A \equiv 2 \cdot \Gamma_A / N^2$

- Solution

$$N(t) = \sqrt{C_C / C_A} \cdot \tanh(t \sqrt{C_C C_A})$$

- For large t

$$N(t) \rightarrow \sqrt{C_C / C_A} \Rightarrow \Gamma_A = \frac{1}{2} C_C$$

- C_C expressible in terms of DM-nucleon cross section