Multicomponent dark matter:
disentangling different cases in future e^+e^- colliders

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in collaboration with **Bohdan Grządkowski**,
work in progress

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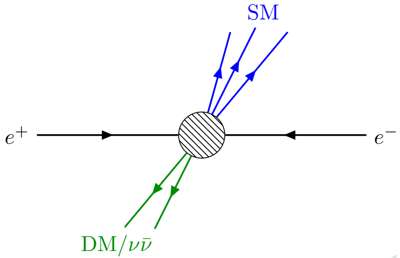
Introduction

Why more than 1 dark component?

- One-component WIMP – perfect in large scales, but severely constrainted (ID, DD)
- Galactic scale problems (cusp-core, too-big-to-fail) – two-component DM among possible solutions
- Why only one component? (vs. 17 particles of SM)

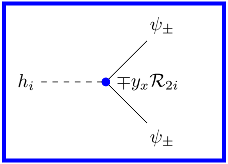
Collider search for dark matter

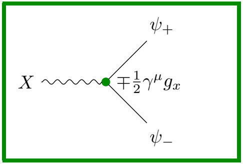
- Experimental approach: missing-energy analysis
- Signal more clear at e^+e^- than at hadron colliders
- Near-future plans: ILC, CLIC...

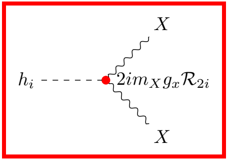


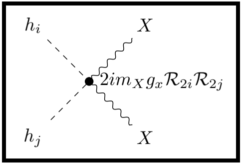
- Gauge group: $\mathcal{G} = \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{Standard Model gauge group}} \times U(1)_X$.
- Dark particles: vector X_μ ($U(1)_X$ gauge field) and fermion $\psi_\pm$ mediated by the Higgs portal

$$\mathcal{L}_{\text{int}}^{\text{DM}} = -\frac{y_x}{2}(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-)\phi - \frac{i}{4}g_x(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+)X_\mu$$
$$+ v_x g_x^2 X^\mu X_\mu \phi + \frac{g_x^2}{2} X^\mu X_\mu \phi^2$$



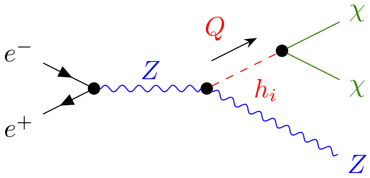






$\phi = \sin\theta \; h_1 + \cos\theta \; h_2$ $\quad h_i = h_1$ (SM Higgs) or h_2 $\quad \mathcal{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

Considered process



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

$\chi = X_\mu,\ \psi_\pm$

The differential cross-section:

$$\frac{d\sigma}{dE_Z}(E_Z) = \frac{g_v^2 + g_a^2}{12\cdot(2\pi)^3}\sqrt{E_Z^2 - m_Z^2}\left(2m_Z^2 + E_Z^2\right)\left(\frac{g^2}{\cos\theta_W^2}\frac{1}{s - m_Z^2}\right)^2 \times$$
$$\times\ \frac{(\sin 2\theta)^2\cdot(m_1^2 - m_2^2)^2\cdot Q^4}{\left[(Q^2 - m_1^2)^2 + (m_1\Gamma_1)^2\right]\left[(Q^2 - m_2^2)^2 + (m_2\Gamma_2)^2\right]}\times$$
$$\times\sqrt{1 - 4\frac{m_{DM}^2}{Q^2}}\times\begin{cases} 2\left(\frac{y_X}{m_{\rm DM}}\right)^2\left[\frac{m_{\rm DM}^2}{Q^2} - 4\left(\frac{m_{\rm DM}^2}{Q^2}\right)^2\right] & \text{(FDM)}\\ \left(\frac{g_X}{m_{\rm DM}}\right)^2\left[1 - 4\frac{m_{\rm DM}^2}{Q^2} + 12\left(\frac{m_{\rm DM}^2}{Q^2}\right)^2\right] & \text{(VDM)}\end{cases}$$

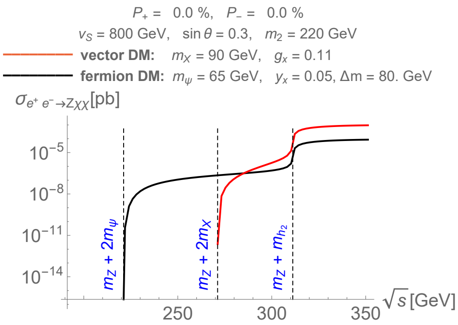
note: in principle $\Gamma_i^{(\rm VDM)} \neq \Gamma_i^{(\rm FDM)}$

In **theory** a substantial difference between vector and fermion DM!

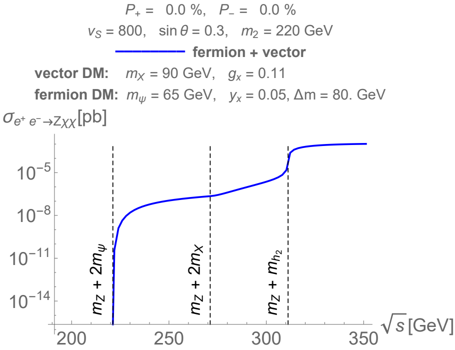
similar discussion in
- Ko, Yokoya, 1603.04737
- Kamon, Ko, Li, 1705.02149

Method 1: measuring the total cross-section $\sigma(\sqrt{s})$
– mass and couplings determination

- Masses of dark particles and h_2 determinable from the thresholds:
  - minimal energy for DM in the final state: $\sqrt{s} = m_Z + 2m_{\text{DM}}$
  - minimal energy for h_2 on-shell: $\sqrt{s} = m_Z + m_{h_2}$
- Couplings have to be fitted



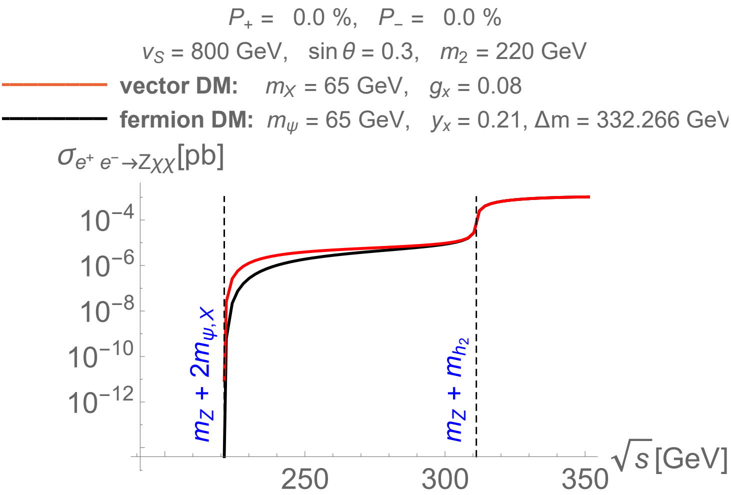
fermion and **vector** case separately



sum (observed shape)

Method 1: measuring the total cross-section $\sigma(\sqrt{s})$ – spin determination

- Spin determinable from the shape
- The same shape of σ dependence on $\sqrt{s}$ above the on-shell-Higgs threshold



Method 2: measuring the differential cross-section $\frac{d\sigma}{dE_Z}(E_Z)$ – methodology

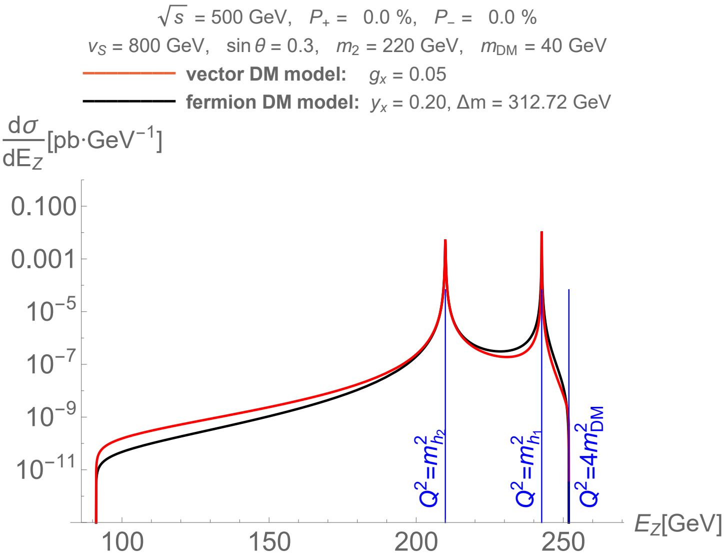
- One-component case
- Given $\sqrt{s}$
- $\sin\theta$, v_x assumed to be known
- $m_2 \Leftarrow$ position of the pole, $m_{DM} \Leftarrow$ right cut of the distribution:

$$E_Z < \frac{s - 4m_{\text{DM}}^2 + mz^2}{2\sqrt{s}}$$

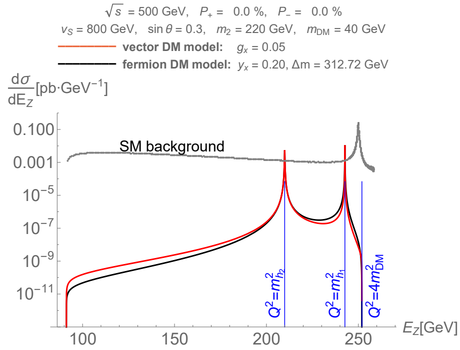
- y_x obtained from fitting $\frac{d\sigma_{\text{fer}}}{dE_Z}$ to $\frac{d\sigma_{\text{vec}}}{dE_Z}$
  (100 uniformly distributed points, weigth $\sim \sqrt{\frac{d\sigma_{\text{vec}}}{dE_Z}}$
  $\Rightarrow$ at maximum both values almost equal)
- Determining the spin

$$\frac{d\sigma}{dE_Z}(E_Z) = [\text{common part}] \times \begin{cases} 2\left(\frac{y_X}{m_{\text{DM}}}\right)^2 \left[\frac{m_{\text{DM}}^2}{Q^2} - 4\left(\frac{m_{\text{DM}}^2}{Q^2}\right)^2\right] & \text{(FDM)} \\ \left(\frac{g_X}{m_{\text{DM}}}\right)^2 \left[1 - 4\frac{m_{\text{DM}}^2}{Q^2} + 12\left(\frac{m_{\text{DM}}^2}{Q^2}\right)^2\right] & \text{(VDM)} \end{cases}$$

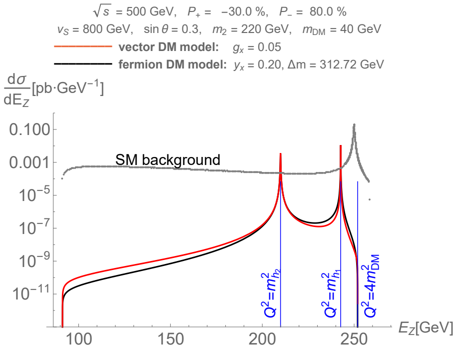
Method 2: measuring the differential cross-section $\frac{d\sigma}{dE_Z}(E_Z)$ – results



Method 2: measuring the differential cross-section $\frac{d\sigma}{dE_Z}(E_Z)$ – SM background and polarized beams



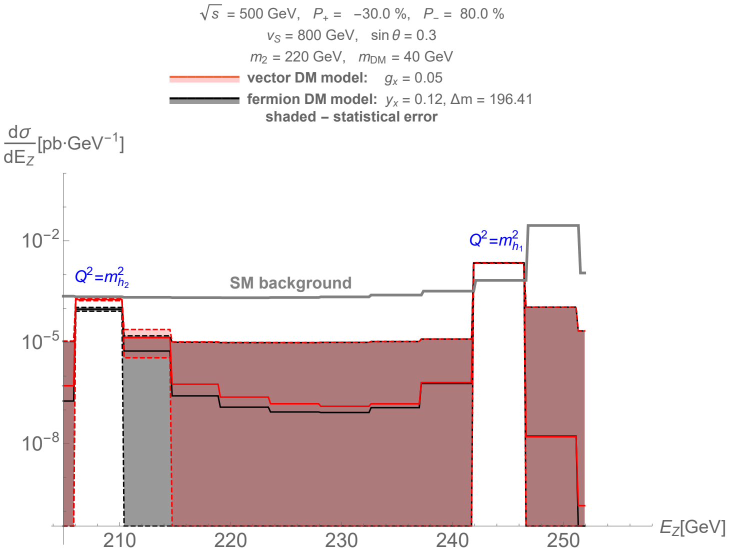
unpolarized beams



polarized beams

e^- : 80% (RH), e^+ : 30% (LH)

Method 2: measuring the differential cross-section $\frac{d\sigma}{dE_Z}(E_Z)$ – detector's resolution and statistical error



CLIC predictions (1208.1402): $\int \mathscr{L} dt \Big|_{\sqrt{s}=500\text{ GeV}} = 500\text{ fb}^{-1}$

Summary

- Complementary methods of detecting DM in colliders:
  - $\longrightarrow$ total cross-section σ as a function of $\sqrt{s}$
  - $\longrightarrow$ differential cross-section $\frac{d\sigma}{dE_Z}$ as a function of E_Z
- The main issues:
  - $\longrightarrow$ finite resolution of detectors
  - $\longrightarrow$ statistical uncertainity (solution: higher luminosity)
  - $\longrightarrow$ substantial SM background (partial solution: polarized beams)
- Masses – relatively easy to determine
- Spin determination – hard, but theoretically possible
- Couplings have to be fitted
- Conclusion: DM possible to detect but its properties hard to determine

Summary

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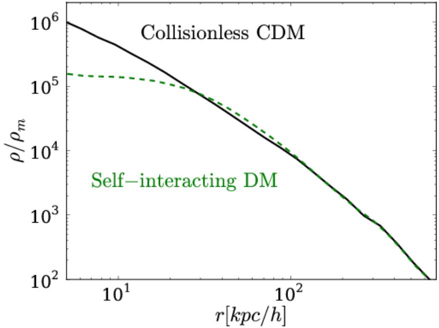
THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

Small scale problems

- core-cusp problem



  - ◇ simulations
    ⇒ **cuspy** decreasing of DM density with radius
  - ◇ observations
    ⇒ **flat** distribution in the core

- too-big-to-fail / missing satellites problem
  where are the predicted satellite galaxies of Milky Way?

Symmetries of the Lagrangian

$$\mathcal{L}_{\text{int}} = -\frac{y_X}{2}(\bar{\psi}_+\psi_+ + \bar{\psi}_-\psi_-)\phi - \frac{i}{4}g_X(\bar{\psi}_+\gamma^\mu\psi_- - \bar{\psi}_-\gamma^\mu\psi_+)X_\mu$$
$$+ v_x g_X^2 X^\mu X_\mu \phi + \frac{g_X^2}{2} X^\mu X_\mu \phi^2$$

Symmetry	X_μ	ψ_+	ψ_-	ϕ
$\mathbb{Z}_2$	$-$	$+$	$-$	$+$
$\mathbb{Z}_2'$	$-$	$-$	$+$	$+$
$\mathbb{Z}_2''$	$+$	$-$	$-$	$+$

- The lightest odd particle stable
- No DM$\rightarrow$SM decays

The statistical error

Let

$$\sigma_{\text{bin}} = \int_{\text{bin}} \frac{d\sigma}{dE_Z} dE_Z.$$

The number of counts in a given bin is

$$N_{\text{bin}} = \eta \sigma_{\text{bin}} \mathcal{L} t$$

$$\Delta N_{\text{bin}} = \sqrt{N_{\text{bin}}}$$

The value of bin in $\frac{d\sigma}{dE_Z}$ plot is

$$[\text{bin value}] = \frac{\eta \sigma_{\text{bin}}}{[\text{bin width}]}$$

$$\Delta[\text{bin value}] = \sqrt{\frac{[\text{bin value}]}{\mathcal{L} t \cdot [\text{bin width}]}}$$

$\mathcal{L}$ – luminosity
t – time of measuring (integrated luminosity assumed to be $\sim 500\ \text{fb}^{-1}$)
η – efficiency of detector (100% assumed)

Distinguishing the scenarios – comparing data with the model

χ^2 test can be used to control the fitting quality:

$$\chi^2 = \sum_{b \in \text{bins}} \left(\frac{[\text{bin value}]_b - [\text{predicted bin value}]_b}{\Delta[\text{bin value}]_b} \right)^2$$

- to estimate the goodness of fit – use the χ^2 distribution to find the statistical significance of the measurements
- to compare two models – calculate and compare the statistical significances

Comparison with Ko & Yokoya

1603.04737

In their paper: widths not calculated within the model!

$g_x = 0.1$, $y_x = 0.2$

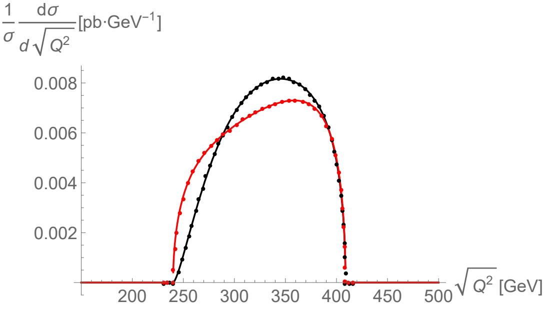
masses and widths in GeV:

$m_{\text{fer}} = m_{\text{vec}} = 120$, $m_{h_2} = 500$

$\Gamma_{h_1} = 0.99 \times \Gamma_{h\text{SM}}$, $\Gamma_{h_2} = 1.71815$

• Ko — exact result

fermion vector



$g_x = 1.5$, $y_x = 0.2$

masses and widths in GeV:

$m_{\text{fer}} = m_{\text{vec}} = 120$, $m_{h_2} = 500$

$\Gamma_{h_1} = 0.99 \times \Gamma_{h\text{SM}}$, $\Gamma_{h_2} = 137.579$

• Ko — exact result

fermion vector