Search for WIMPs at $\mu^+\mu^+$ colliders

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Outline

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Weakly Interacting Massive Particle (WIMP)

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We consider the following ferminoic WIMP with

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2. mass that explains the thermal relic abundance (thermal mass target)
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Our targets:

- Higgsino: Dirac, $n = 2$, $Y = 1/2$, $m \sim 1\,TeV$
- Wino: Majorana, $n = 3$, $Y = 0$, $m \sim 2.7\,TeV$
- Minimal quintuplet: Majorana, $n = 5$, $Y = 0$, $m \sim 14\,TeV$

Future muon collider

We focus on the possibility of the future $\mu^+\mu^+$ collider.

Benefit

- Lepton collision $\Rightarrow$ few hadronic background
- $m_\mu \gg m_e \Rightarrow$ high energy
- Easier to prepare μ^+ beams of $\mathcal{O}$(TeV) and low emittance
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- Huge beam-induced background $\Rightarrow$ disappearing track search is challenging N. Bartosik et al. (2022)
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We thus focus on the following strategies

- **Indirect**: WIMP Loop effect on the $\mu^+\mu^+ \to \mu^+\mu^+$ scattering
- **Direct**: Direct production of WIMP in the mono-μ channel

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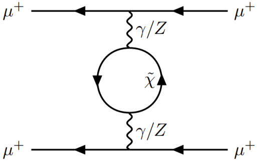
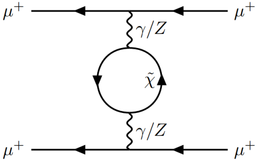
Indirect search



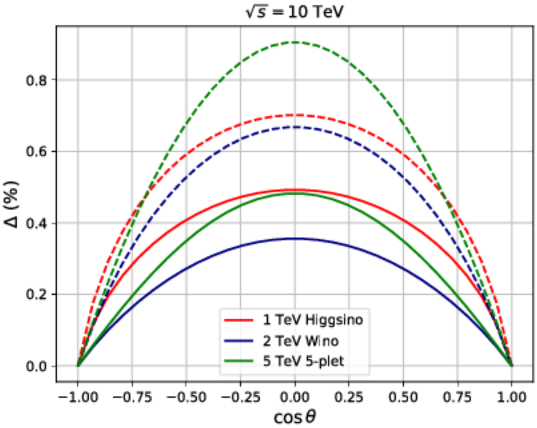
Indirect search



$$\Delta(\theta) = \frac{d\sigma_{\text{WIMP}}/d\cos\theta}{d\sigma_{\text{tree}}/d\cos\theta}$$

solid: unpolarized, $P_{\mu^+} = 0$

dashed: polarized, $P_{\mu^+} = 0.8$



Direct production

$$\text{Signal} \begin{cases} \mu^+\mu^+ & \to \mu^+\bar{\nu}_\mu \chi\bar{\chi} \\ \gamma\mu^+ & \to \mu^+\chi\bar{\chi} \end{cases} \qquad \text{Background} \begin{cases} \gamma\mu^+ & \to \mu^+ Z,\ Z \to \nu\bar{\nu} \\ \gamma\mu^+ & \to \bar{\nu}_\mu W^+,\ W^+ \to \nu_\mu \mu^+ \end{cases}$$

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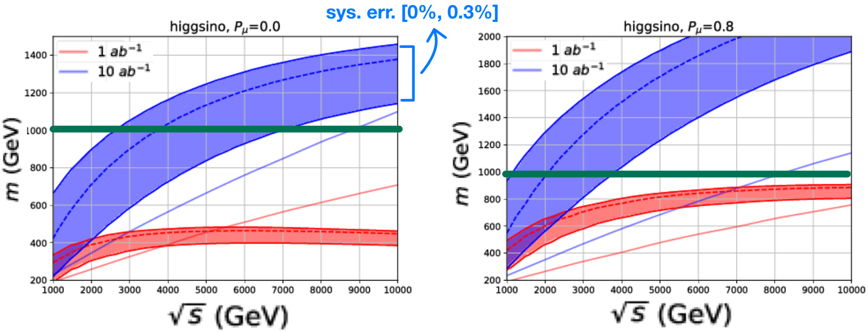
Simulation packages: FeynRules 2.0 and MadGraph5
Kinematic cuts as event-selection

- $E_\mu > 0.23\sqrt{s}$
- $|\eta_\mu| < 2.5$
- $\left(p^{\text{in}}_{\mu^+,1} + p^{\text{in}}_{\mu^+,2} - p^{\text{out}}_{\mu^+}\right)^2 > 4m_\chi^2$

Results: Higgsino

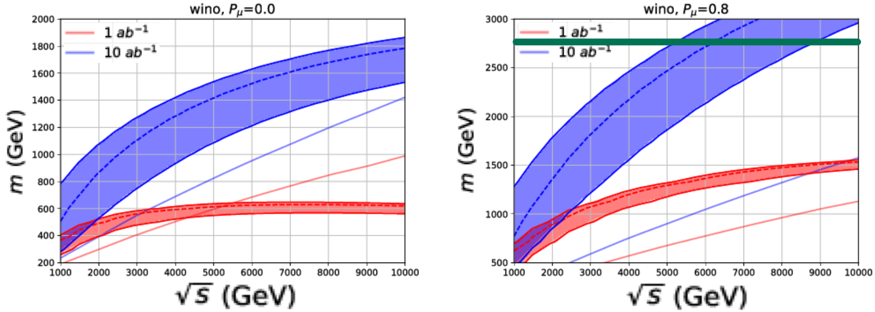
The 95% C.L. deiscovery reach (band: indirect, solid: direct):



- With $\mathcal{L} = 10\,\mathrm{ab}^{-1}$, the thermal target of Higgsino can be probed in both the indirect and direct approach.

Results: Wino

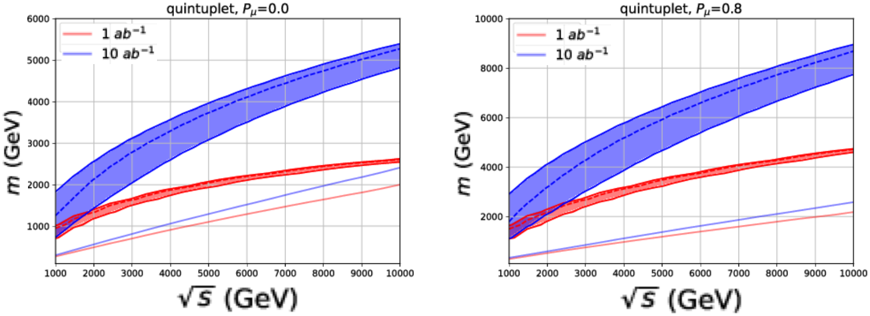
The 95% C.L. deiscovery reach (band: indirect, solid: direct):



- With $\mathcal{L} = 10\,\mathrm{ab}^{-1}$ and polarized beam, the thermal target of Wino can be probed in the indirect approach.

Results: quintuplet

The 95% C.L. deiscovery reach (band: indirect, solid: direct):



- The thermal target of quintuplet is still hard to be probed.

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Summary

- Searching WIMP in colliders is an active topic.
- The indirect (loop effect) and direct (DM production) approaches are studied in the future $\mu^+\mu^+$ collider.
- With $\mathcal{L} = 10\,\mathrm{ab}^{-1}$ and polarized beams, the thermal mass of Higgsino and Wino can be probed at $\sqrt{s} \simeq 2$ and 6 TeV, respectively.

Backup – Indirect cross section

The propagator is adjusted to

$$\sum_{V,V'=\gamma,Z} \frac{C_{VV'}\, t\Pi\left(t/m^2\right)}{\left(t-m_V^2\right)\left(t-m_V'^2\right)} - (u\text{-channel})\,, \text{ where } \begin{cases} C_{\gamma\gamma} = s_W^2 C_{WW} + c_W^2 C_{BB} \\ C_{ZZ} = c_W^2 C_{WW} + s_W^2 C_{BB} \\ C_{\gamma Z} = C_{Z\gamma} = s_W c_W^2 \left(C_{WW} - C_{BB}\right) \end{cases}$$

$$C_{WW} = \kappa \cdot \frac{2}{3} g^2 \left(n^3 - n\right),\ C_{BB} = \kappa \cdot 8 \left(g \tan\theta_W\right)^2 n Y^2, \text{ where } \begin{cases} \kappa = 1 & \text{for Dirac} \\ \kappa = 1/2 & \text{for Majorana} \end{cases}$$

$$\Pi(x) = \frac{1}{16\pi^2} \int_0^1 \mathrm{d}y\, y\,(1-y) \log\left(\frac{m^2 - xy(1-y)\, m^2}{\mu^2}\right)$$

Backup – Direct cross section

solid: mono-μ

dashed: mono-γ