WIMP search at future muon collider

Atsuya Niki (U. Tokyo)

based on JHEP 02 (2024) 214 (arXiv: 2310.07162)
collaboration with H. Fukuda, T. Moroi and S-F. Wei

2024/03/12 Berkeley week

Outline

- Minimal dark matter candidate as WIMP

- Muon collider as a future high energy collider
  - indirect search
  - direct search

- Result

- Summary

Weakly Interacting Massive Particle (WIMP)

- We consider new SU(2) multiplet (n-plet). Cirelli, Fornengo, Strumia (2005)
- Well-known **dark matter candidate** (WIMP miracle) and many models predict its existence, like MSSM. Jungman, Kamionkowski, Griest (1995)

Our target is where the WIMPs can explain the dark matter relic abundance through the freeze-out mechanism (**thermal mass target**).

We consider the femionic WIMP candidate:

- **Higgsino** $(n = 2, Y = 1/2)$: ~ 1 TeV
- **Wino** $(n = 3, Y = 0)$: ~ 2.7 TeV
- **Quintuplet minimal dark matter** $(n = 5, Y = 0)$: ~ 14 TeV

Y : hypercharge

Hisano, Matsumoto, Nagai, Saito, Senami (2007)
Cirelli, Strumia, Tamburini (2007)
Mitridate, Redi, Smirnov, Strumia (2017)

Collider search for WIMP

WIMP is one of the main target at **high energy collider experiment**.

- **LHC**

Charged state of **Wino** and **Quintuplet** is long-lived, $c\tau \sim \mathcal{O}(\mathrm{cm})$, and the decay product is soft due to small mass splitting. → Disappearing Track

Chen, Drees, Gunion (1996)
Ostdiek (2015)
ATLAS collaboration (2022)

Higgsino is not so long-lived due to large mass splitting. Even in this case, displaced soft pion can be used to discriminate the background.

Fukuda, Nagata, Oide, Otono, Shirai (2020)

- **ILC**

Lepton collider is a clean environment, where the kinematics can be fully reconstructed. This provides a great sensitivity, but the center of mass energy is not so large ($\sqrt{s} = 250$-1000 GeV).

ILC international development team (2021)

Muon collider

For WIMP search, **muon collider** has many **advantages**.

- high energy: $\sqrt{s} = \mathcal{O}$(1-10 TeV)
- large luminosity (circular collider): more than ab^{-1}
- low hadronic BG

But muon collider suffer from **Beam-Induced Background** (BIB).

It may become a main background of disappearing track signal…

Capdevilla, Meloni, Simoniello, Zurita (2021)

Then, WIMP search **without** using track information is important to show the capability of muon collider.

- ☐ mono-X search at $\mu^+\mu^-$ collider — Han+ (2021), Bottaro+ (2022)
- ☐ muon polarization, cut optimization, etc. — Fukuda, Moroi, AN, Wei, in progress

$\mu^+\mu^+$ collider

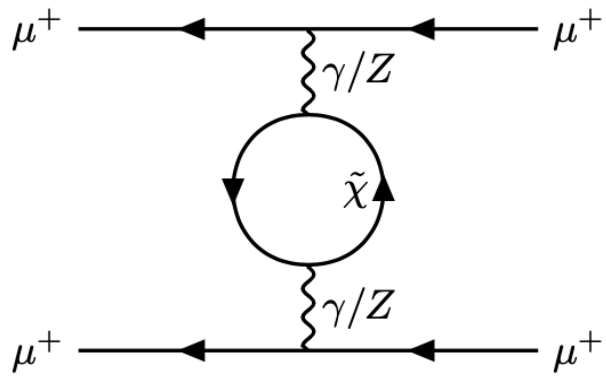
Recently, μ^+ cooling technique is developed, and **$\mu^+\mu^+$ collider seems a realistic option as a future collider experiment**.

Hamada, Kitano, Matsuda, Takaura, Yoshida (2022)

In this work, we consider WIMP search by **two different ways**.

1. **Indirect search**: angular distribution of $\mu^+\mu^+$ elastic scattering
2. **Direct search**: WIMP production and mono-μ channel

Indirect search



WIMP affects the $\mu^+\mu^+$ elastic scattering through the gauge boson propagator:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{C_{WW}}{4} W^a_{\mu\nu} \Pi(-D^2/m^2) W^{a\mu\nu} + \frac{C_{BB}}{4} B_{\mu\nu} \Pi(-\partial^2/m^2) B^{\mu\nu} + \cdots ,$$

where

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

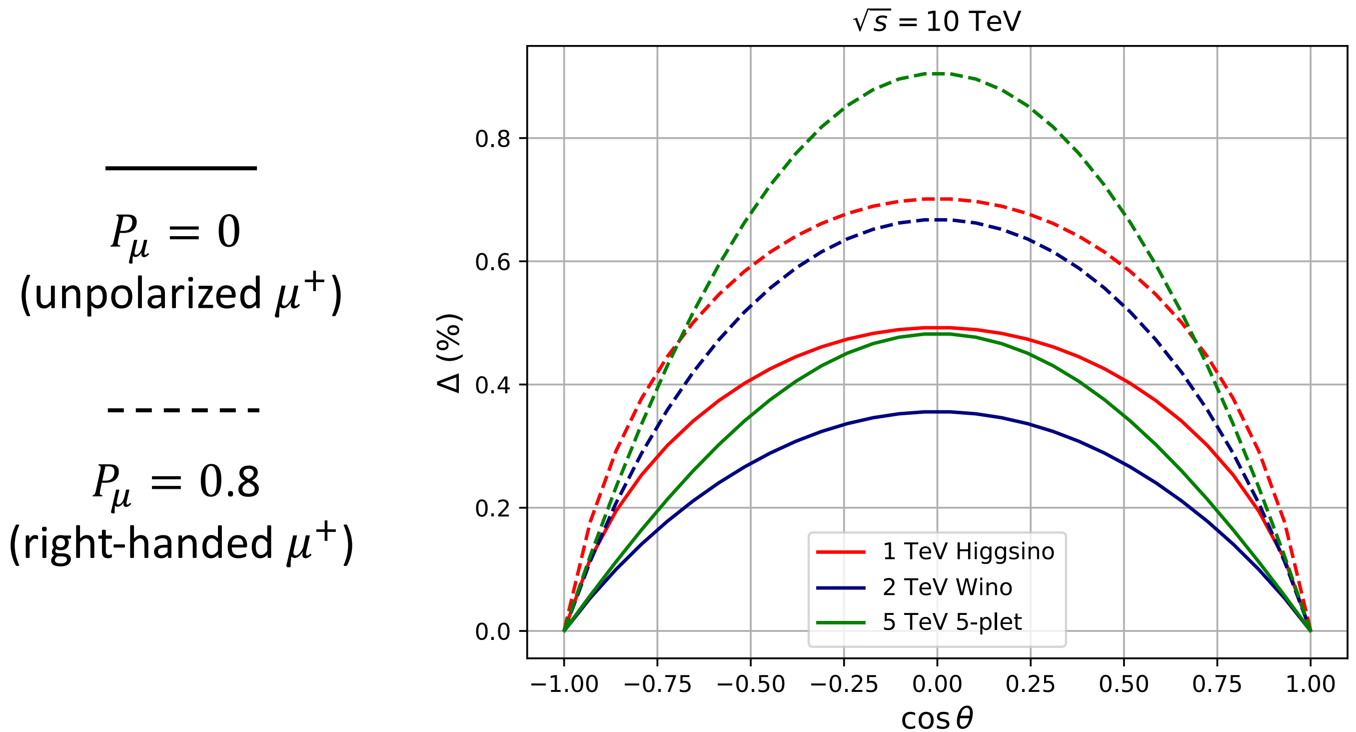
From the t,u-dependence of the self-energy Π,

<u>the angular distribution of μ is distorted.</u>

Indirect search

(WIMP contribution to cross section) / (SM contribution)

$$\Delta(\theta) \equiv \frac{\mathrm{d}(\sigma_{\mathrm{BSM}} - \sigma_{\mathrm{SM}}) \, / \, \mathrm{d}\cos\theta}{\mathrm{d}\sigma_{\mathrm{SM}} \, / \, \mathrm{d}\cos\theta}$$



Indirect search

Statistical method : **shape analysis**

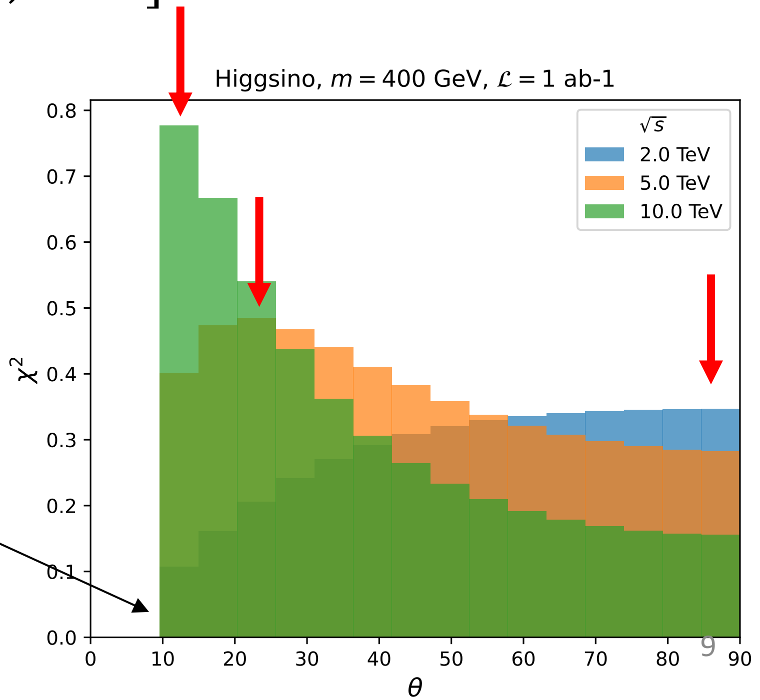
$$\chi^2 = \sum_{i \in \text{bin}} \frac{\left(N_i^{(SM+WIMP)} - N_i^{(SM)}\right)^2}{N_i^{(SM)} + (N_i^{sys})^2},$$

Bin: 15 intervals of the scattering angle, which satisfy $0 < \eta < 2.5$.

Systematic error: $N^{sys} = \epsilon N^{SM}$, $\epsilon \in [0\%, 0.3\%]$

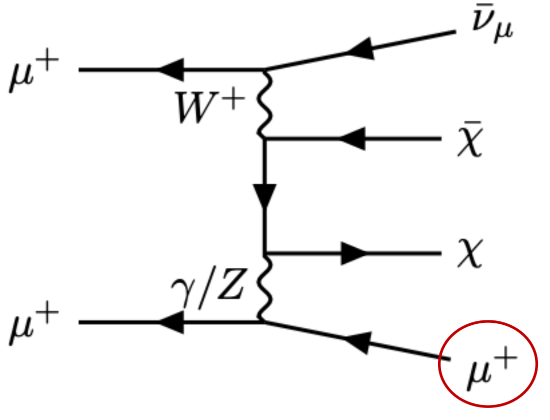
The most contributing bin is where $t \sim m^2$, and this makes **the peak structure** of each bin contribution to χ^2.

$\eta = 2.5$

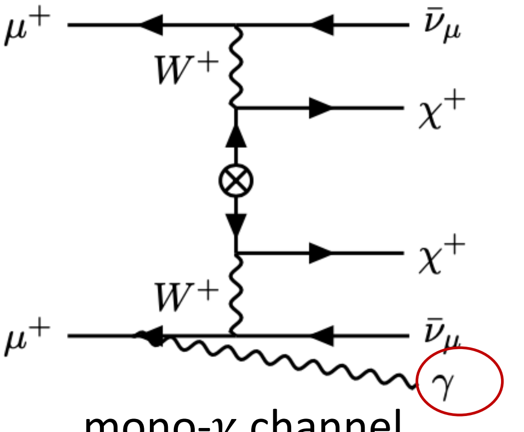


Direct search

At $\mu^+\mu^-$ collider, Drell-Yan production process is dominant, not at $\mu^+\mu^+$ collider.
Then **VBF process** is the dominant production process at $\mu^+\mu^+$ collider.



mono-μ channel



mono-γ channel

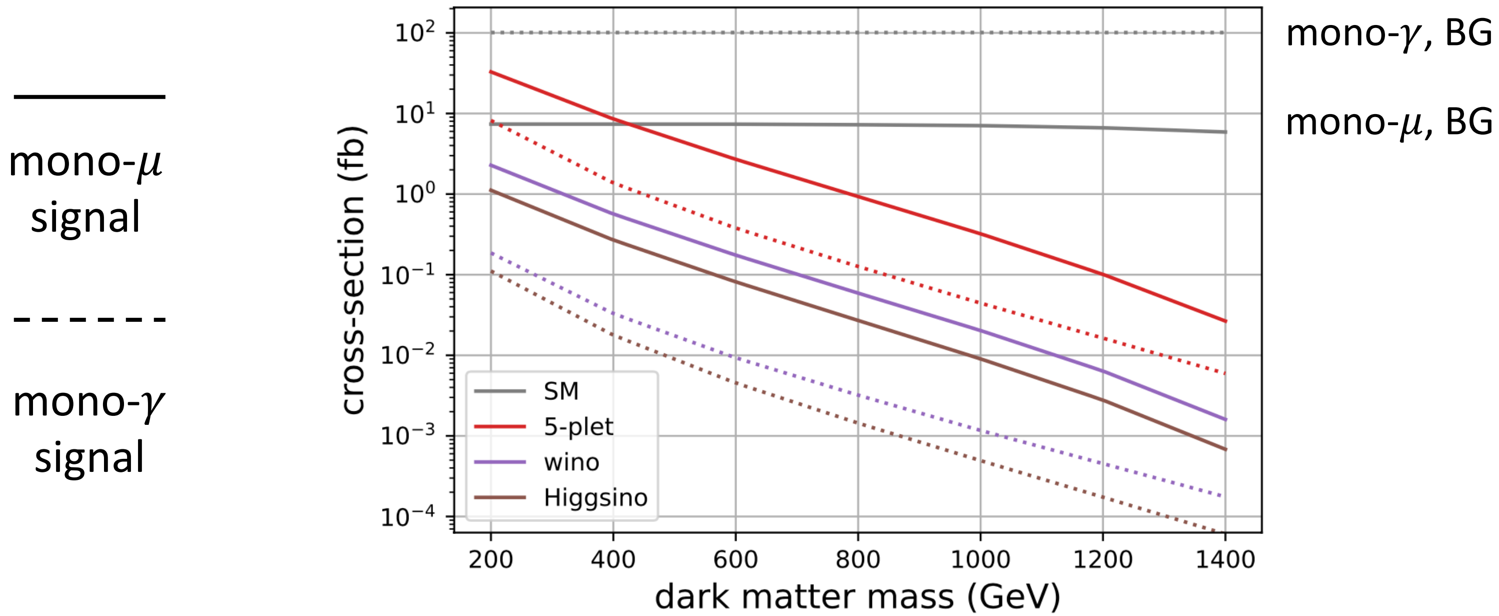
Signal channel is mono-X (X=μ, γ, W, ...).

Direct search

In the case of $\mu^+\mu^-$ collider, mono-μ channel is most sensitive because background can be discriminated **by the kinematical cut.**

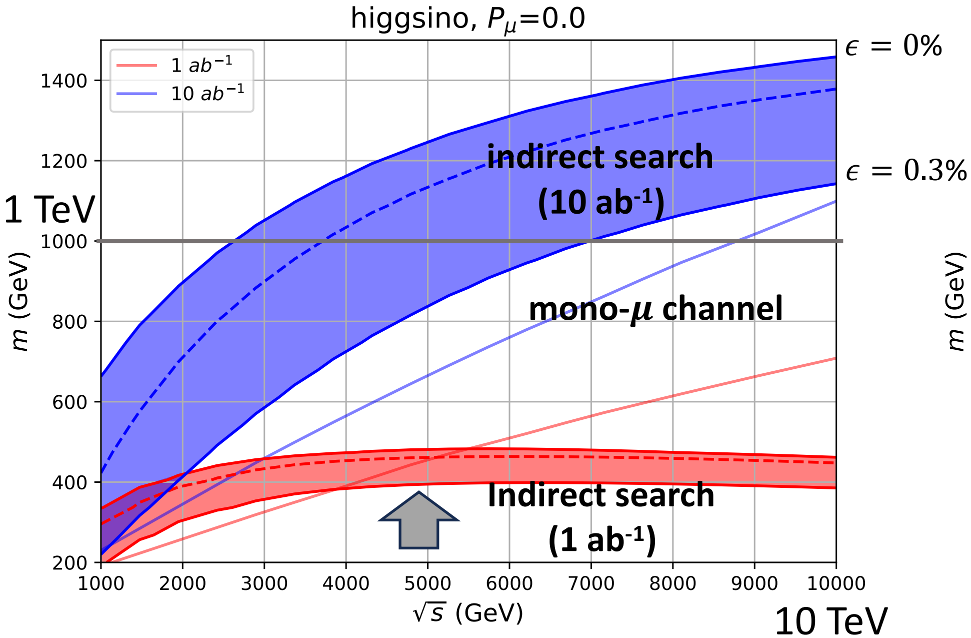
Han, Liu, Wang, Wang (2021)

This is also true at $\mu^+\mu^+$ collider.
We show **only mono-μ channel** in our result.

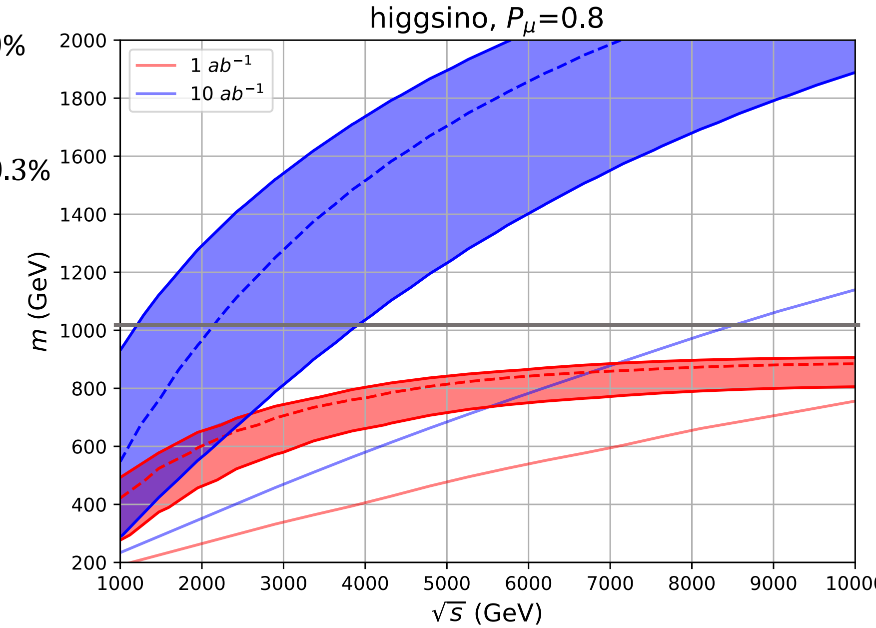


Result: Higgsino

unpolarized



(right-handed) polarized



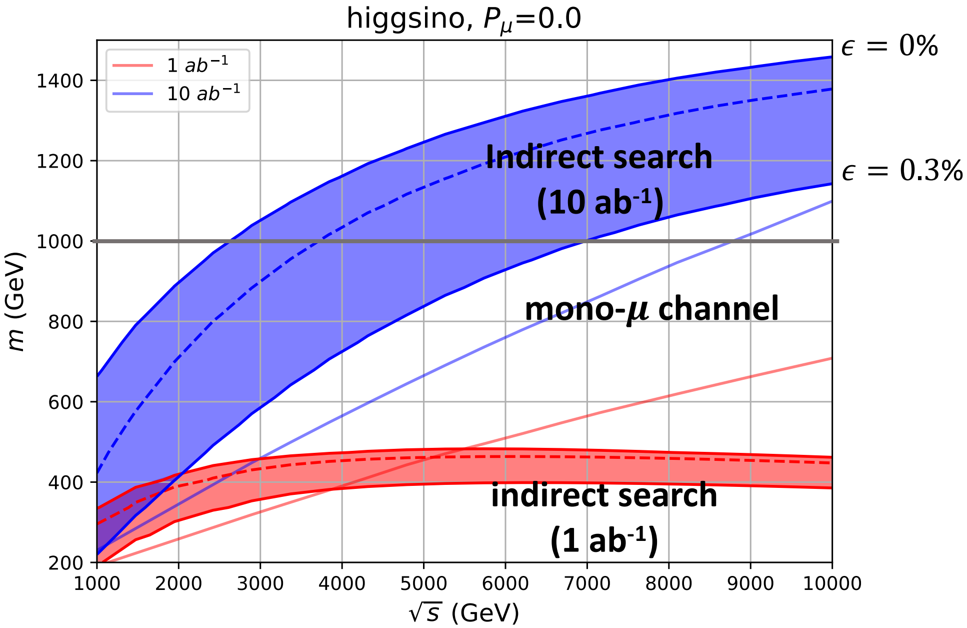
1 ab^{-1} : indirect search is more sensitive than direct search <u>with $\sqrt{s} \lesssim 5$ TeV</u>.

10 ab^{-1} : indirect search is more sensitive than direct search.

With 10 ab^{-1} luminosity, both searches can probe **the thermal target of higgsino.**

With **polarized muon**, <u>sensitivity of the indirect search is much enhanced</u>, due to the increase of the effective luminosity and SN ratio.

Result: Higgsino



$\mathcal{L}$: luminosity

Significance

Indirect search: $\chi^2 \propto \mathcal{L}/m^3$

Direct search: $\frac{N_{signal}}{\sqrt{N^{BG}}} \propto \sqrt{\mathcal{L}}/m^4$

fixed significance
e.g. 95% CL

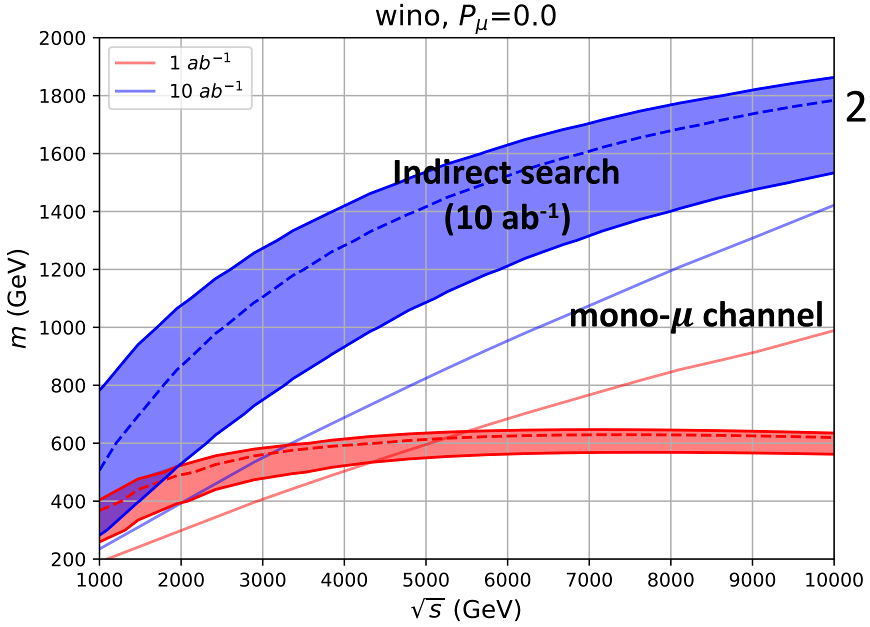
Indirect search: $m \propto \mathcal{L}^{1/3}$
Direct search: $m \propto \mathcal{L}^{1/8}$

Indirect search has larger sensitivity than direct search (mono-μ channel) with **large luminosity**.

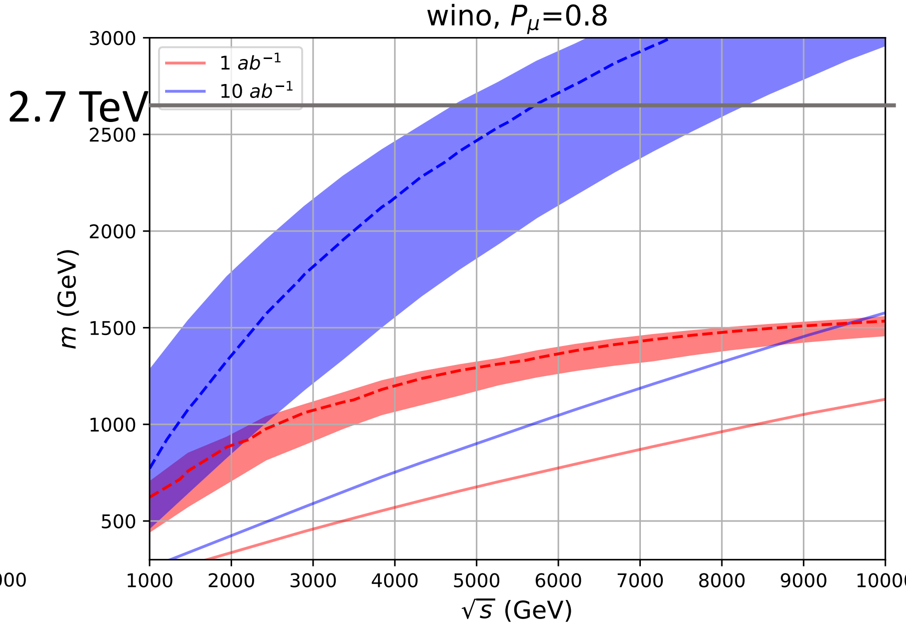
* When $\sqrt{s} \gg m^2$, χ^2 mass-dependence is different from what is discussed above due to the forward angular cutoff. See backup or our paper for more detail.

Result: Wino

unpolarized

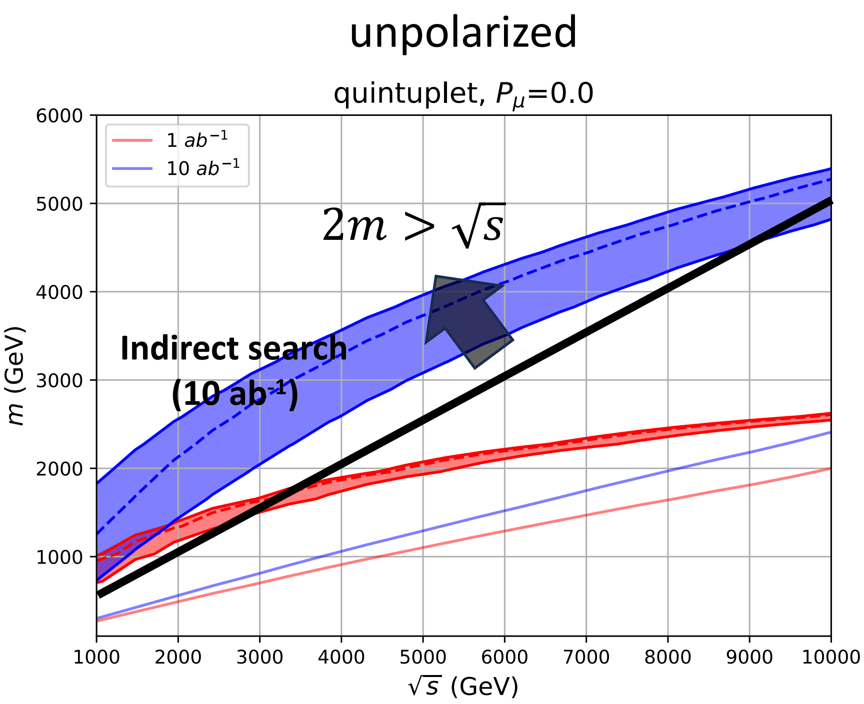


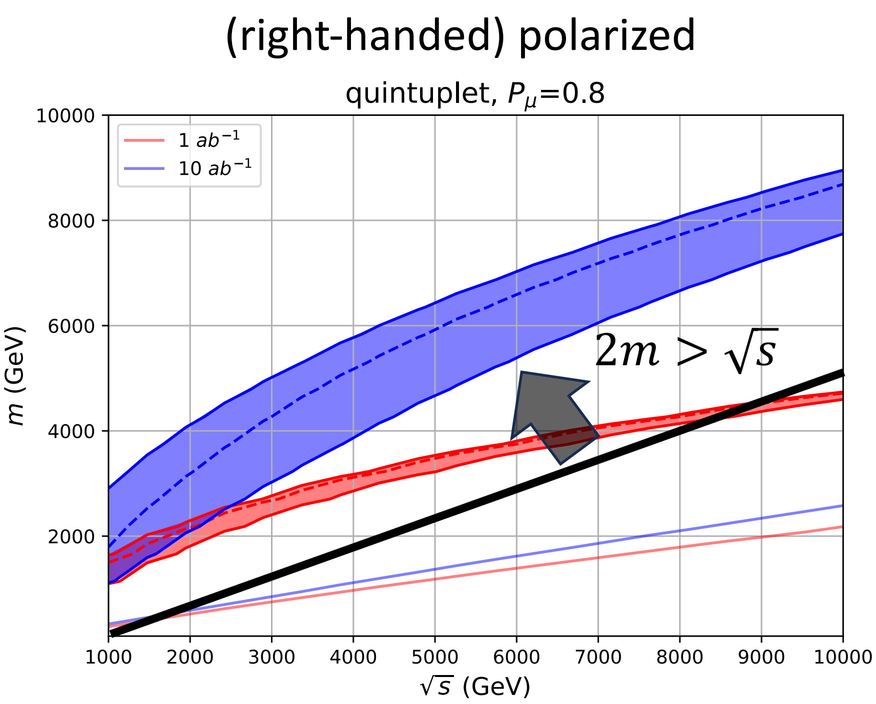
(right-handed) polarized



With **polarized muon beam**, the indirect search is sensitive to the thermal target ($m = 2.7$ TeV) with $\sqrt{s} \sim 5$ TeV, 10 ab^{-1} collider.

Result: Quintuplet





The indirect search is sensitive to the parameter regions, $\boldsymbol{2m > \sqrt{s}}$, where the direct search cannot search due to the kinematics.

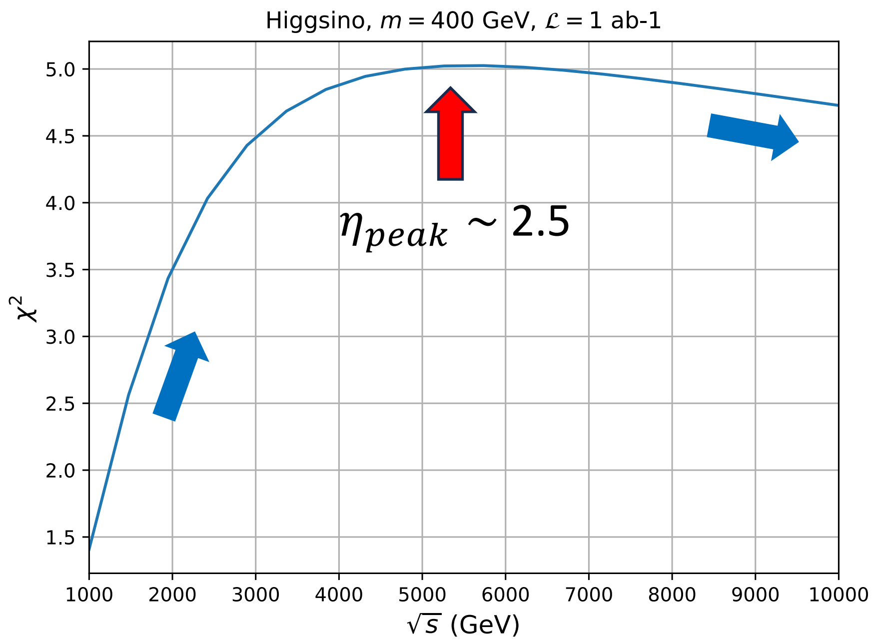
Summary

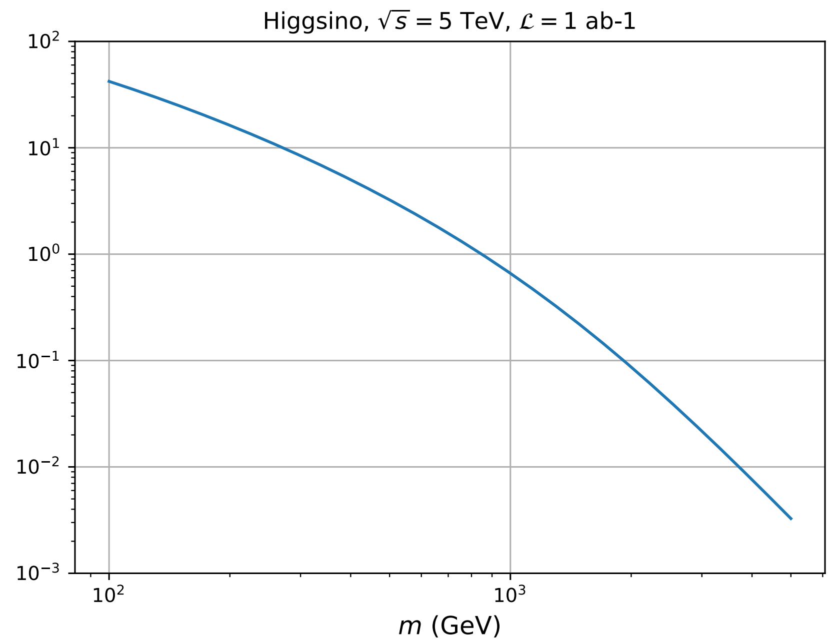
We estimate the sensitivity of the **indirect** and **direct** search for WIMP at $\mu^+\mu^+$ collider.

- Quantum correction from WIMP modifies the angular distribution of $\mu^+\mu^+$elastic scattering (indirect search).
- For the direct search, mono-μ channel has larger sensitivity than mono-γ channel.
- Indirect search has an advantage over the direct search with sufficient luminosity due to the difference of mass dependence.
- Initial state muon polarization enhances the sensitivity of the indirect search.
- With 10 ab^{-1} and polarized beam, the thermal target for Higgsino (Wino) can be probed when $\sqrt{s} \sim 2\ (6)$ TeV .

Backup

Indirect search





$d\chi^2/d\theta$ has a peak around $t \sim m^2$.

If this peak is inside the observed range, $\chi^2 \propto \sqrt{s}\,\frac{\mathcal{L}}{m^3}$.

If the peak is outside, χ^2 slightly decreases with large $\sqrt{s}$.

Direct production search

Kinematical cut

- $E_\mu > 0.23\sqrt{s}$
- $|\eta| < 2.5$
- $\left(p_{\mu,1}^{in} + p_{\mu,2}^{in} - p_{\mu}^{out}\right)^2 > 4m^2$

BG process for mono-μ channel