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

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based on 2310.07162

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2023/11/08 KEK-PH 2023

Weakly Interacting Massive Particle (WIMP)

- We consider new SU(2) multiplet (n-plet). M. Cirelli, N. Fornengo, A. Strumia (2005)
- Well-known **dark matter candidate** (WIMP miracle) and many models predict its existence, like MSSM. G. Jungman, M. Kamionkowski, K. 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** $(n = 2, Y = 1/2) : \sim 1$ TeV
- **Wino** $(n = 3, Y = 0) : \sim 2.7$ TeV
- **Quintuplet minimal dark matter** $(n = 5, Y = 0) : \sim 14$ TeV

Y : hypercharge

J. Hisano, S. Matsumoto, M. Nagai,O. Saito, M. Senami (2007)
M. Cirelli, A. Strumia, M. Tamburini (2007)
A. Mitridate, M. Redi, J. Smirnov, A. 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, $c\tau \sim \mathcal{O}(\text{cm})$, and the decay product is soft due to small mass spllitting. → Disappearing Track

C-H. Chen, M. Drees, J.F. Gunion (1996)
B. 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.

H. Fukuda, N. Nagata, H. Oide, H. Otono, S. 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)

$\mu^+\mu^+$ collider

Recently, μ^+ cooling technique is developed, and **<u>$\boldsymbol{\mu^\pm\mu^\pm}$ collider seems a realistic option as a future collider experiment</u>**.

Y. Hamada, R. Kitano, R. Matsuda, H. Takaura, M. Yoshida (2022)

To observe $\mathcal{O}$(1 TeV) WIMP, muon collider has many **advantages**.

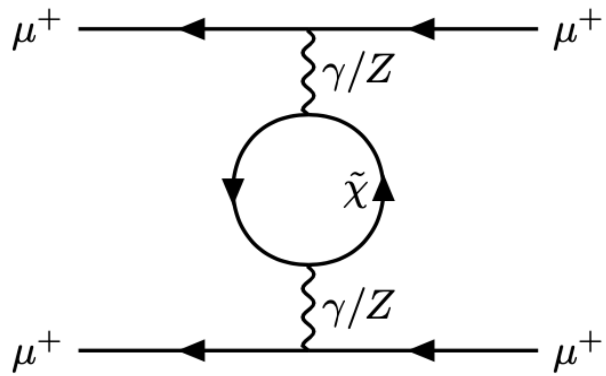
- high energy / large luminosity (circular collider)
- Lepton collider, low hadronic BG

But muon collider suffer from **Beam-Induced Background** (BIB), and it is the main background of disappearing track. R. Capdevilla, F. Meloni, R. Simoniello, . Zurita (2021)

<u>In this work</u>, we consider alternative ways to search for WIMP.

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

Indirect search



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

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

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)

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

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$P_\mu = 0$
(unpolarized μ^+)

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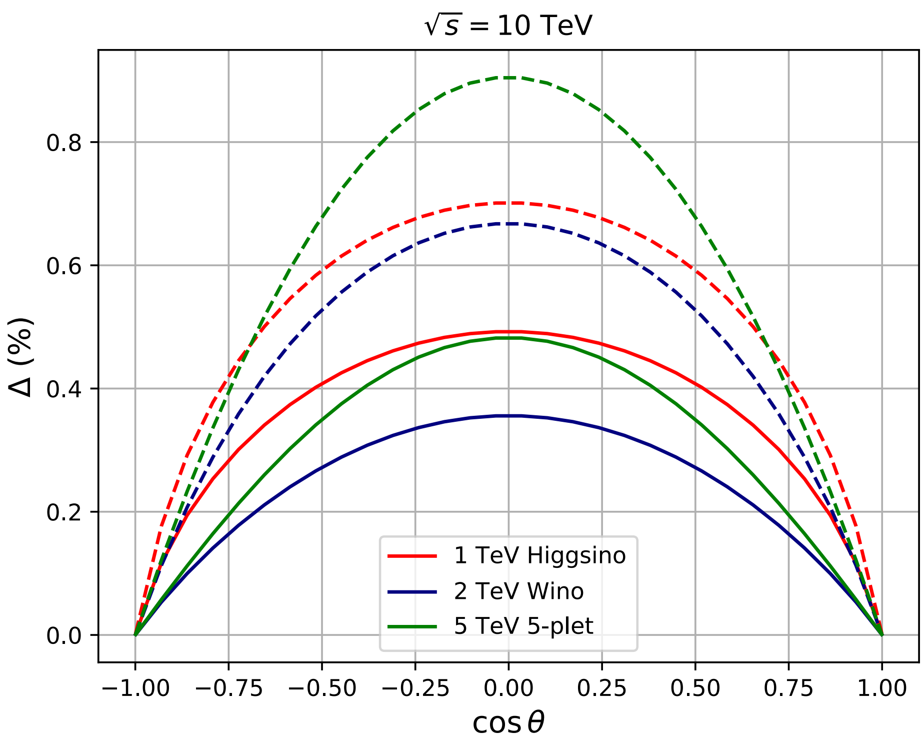
$P_\mu = 0.8$
(right-handed μ^+)



Indirect search

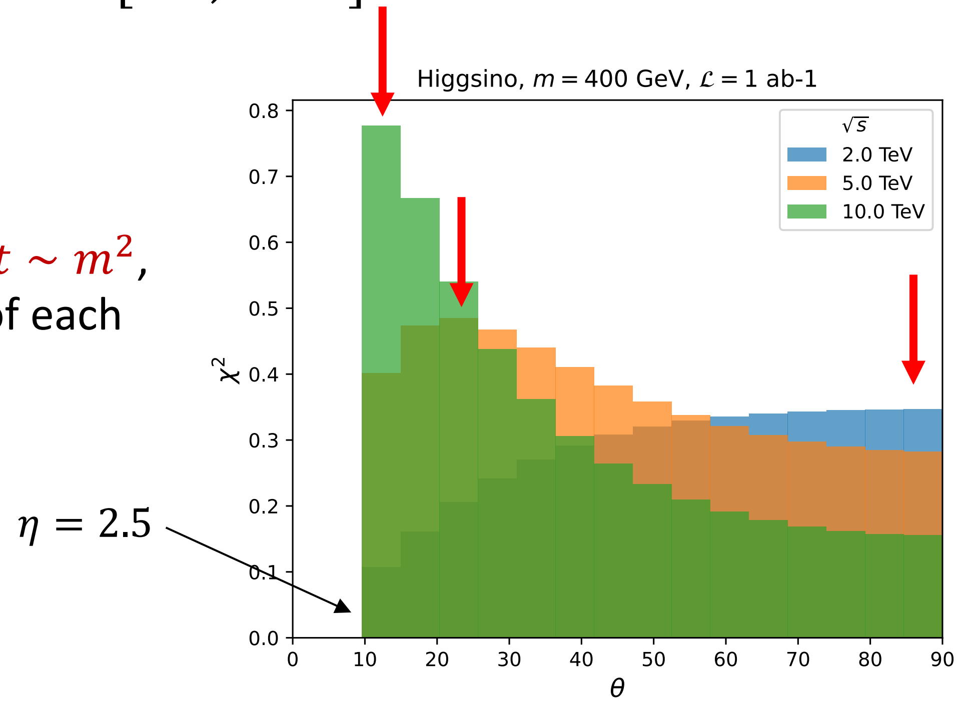
Statistical method : **shape analysis**

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

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

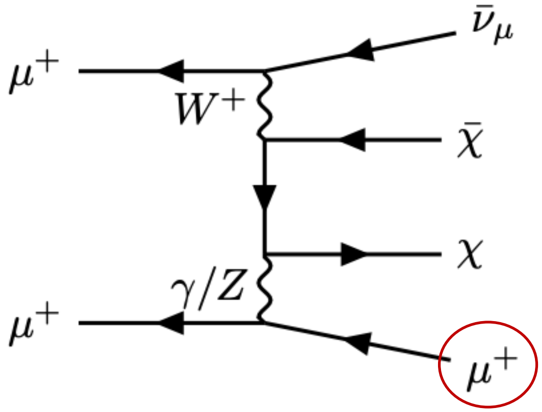
<u>Systematic error</u>: $N^{sys} = \epsilon N^{SM}, \ \epsilon \in [0\%, 0.3\%]$

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

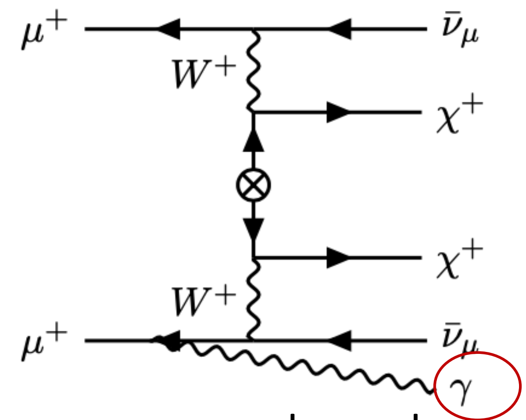


Direct search

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

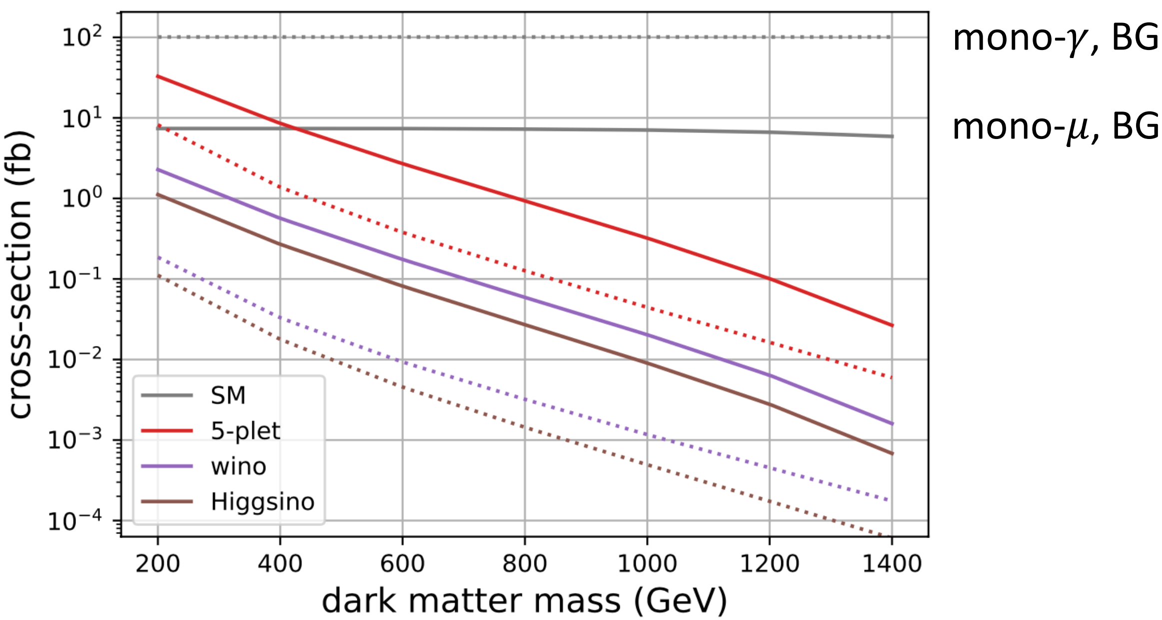
In the case of $\mu^+\mu^-$ collider, mono-μ channel is most sensitive because background can be discriminated **by the kinematical cut.**

T. Han, Z. Liu, L-T. Wang, X. Wang (2020)

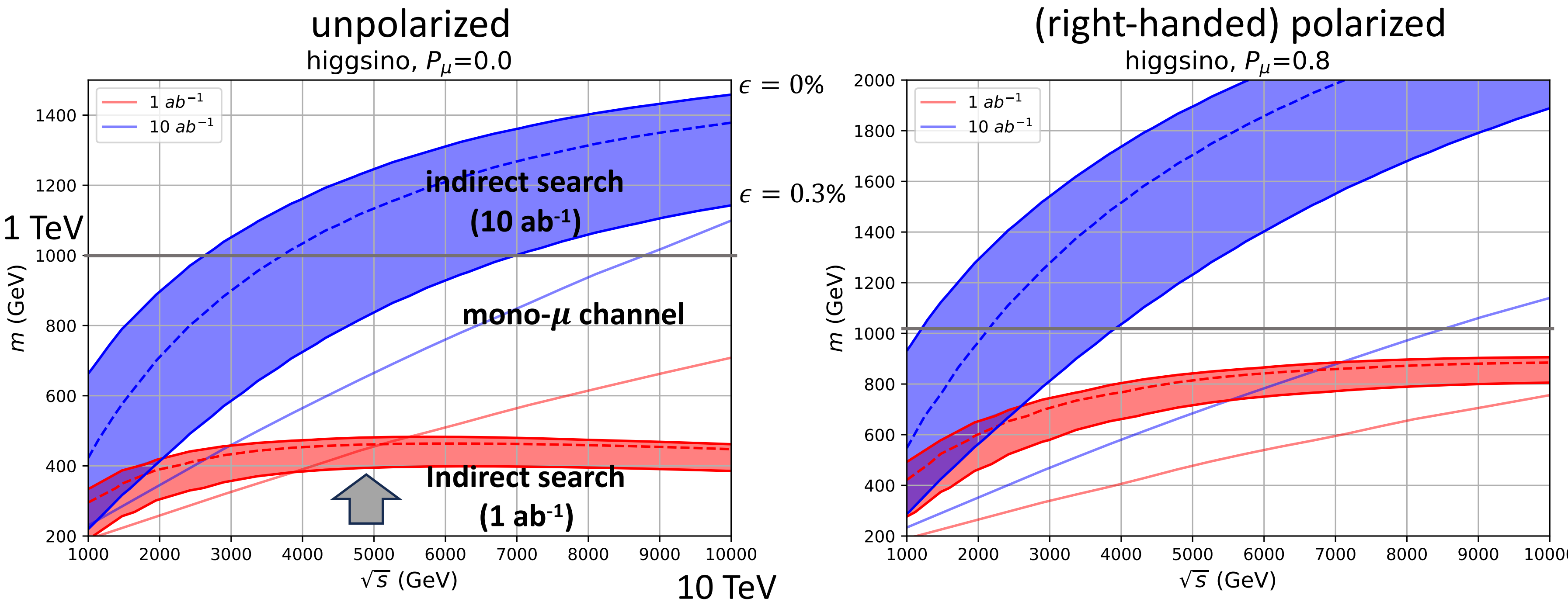
This is also true at $\mu^+\mu^+$ collider. In our result, we show **only mono-μ channel**.

———— mono-μ signal

- - - - - - mono-γ signal



Result: Higgsino



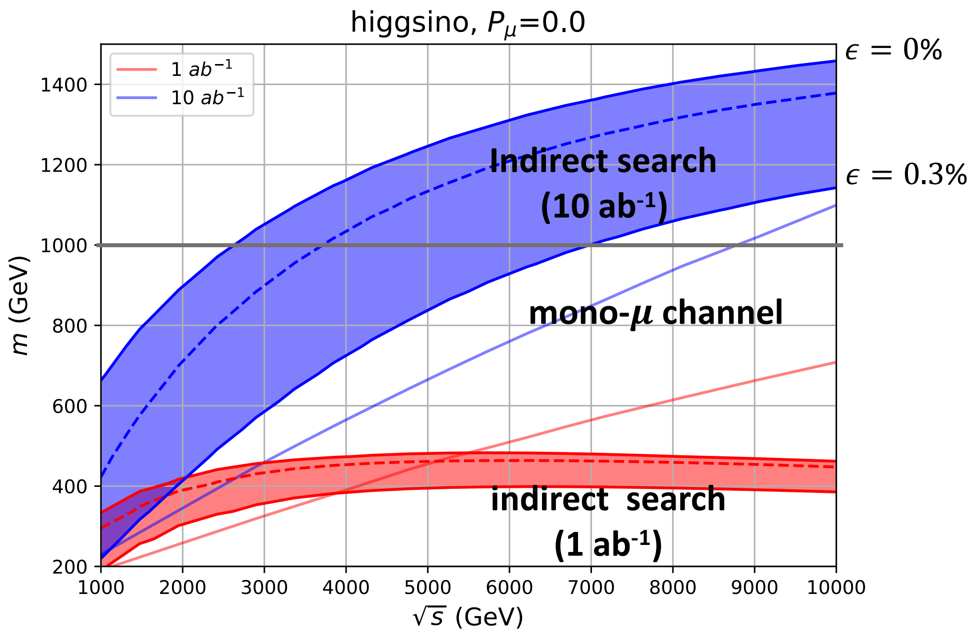
1 ab^{-1} : indirect search is more sensitive than direct search with $\sqrt{s} \lesssim 5$ TeV.

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

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

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

Result: Higgsino



$\mathcal{L}$: luminosity

<u>Significance</u>

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

$\boxed{\begin{array}{ll} \text{Indirect search:} & m \propto \mathcal{L}^{1/3} \\ \text{Direct search:} & m \propto \mathcal{L}^{1/8} \end{array}}$

<u>Indirect</u> search has larger sensitivity than <u>direct</u> 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 <u>angular cutoff</u>. See backup or our paper for more detail.

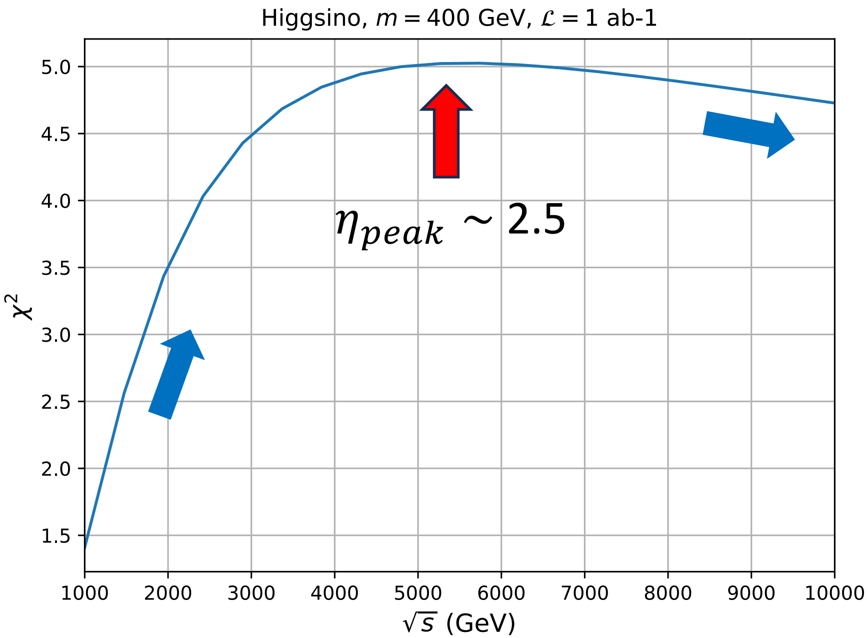
Summary

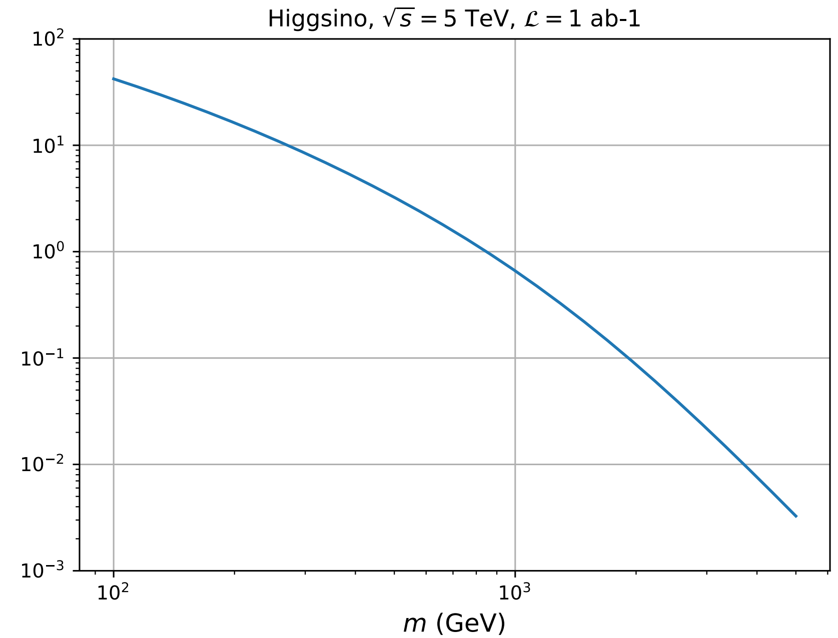
We estimate the sensitivity of the **indirect** and **direct** search for WIMP at $\mu^+\mu^+$ collider.

- 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 $t \sim m^2$.

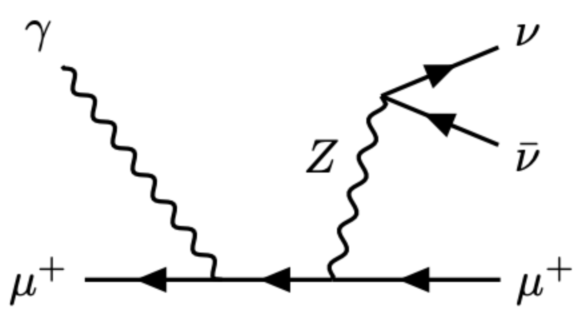
$\chi^2 \propto \sqrt{s}\frac{\mathcal{L}}{m^3}$, if this peak is inside the observed range. If the peak is outside, χ^2 slightly decreases with large $\sqrt{s}$.

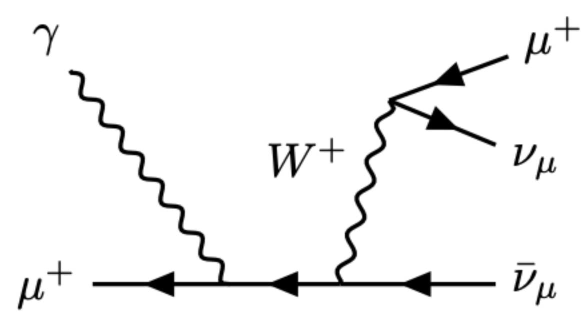
Direct search

Kinematical cut

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

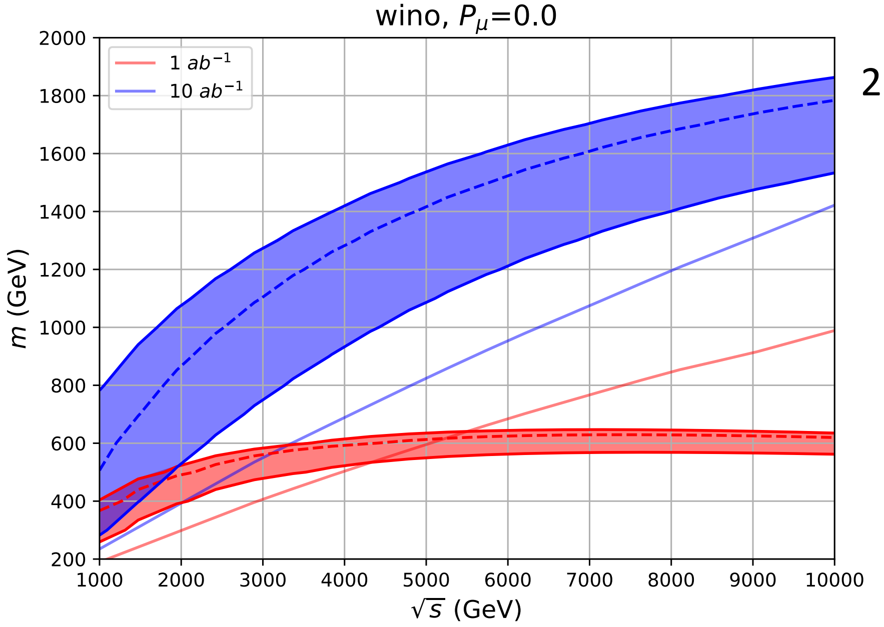
BG process for mono-μ channel



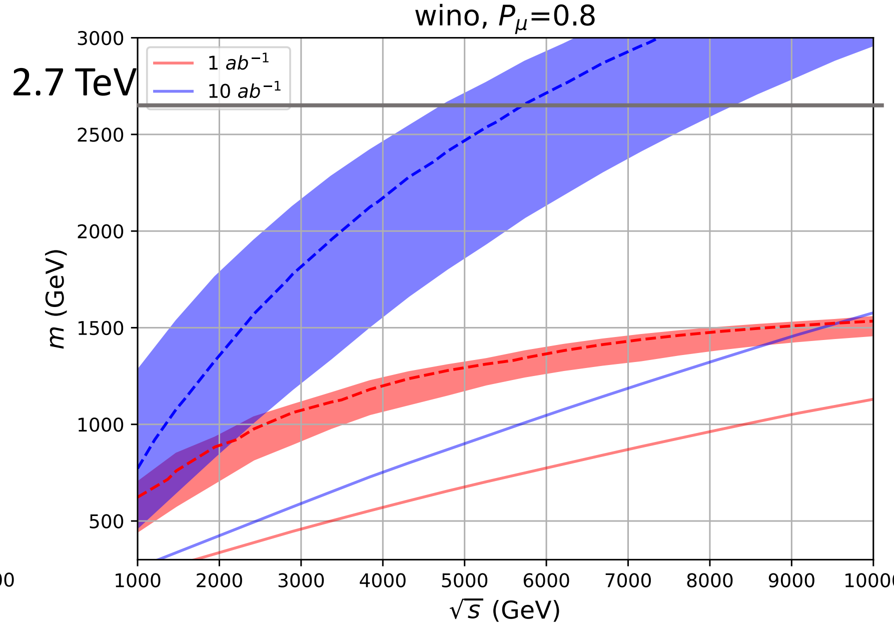


Result: Wino

unpolarized

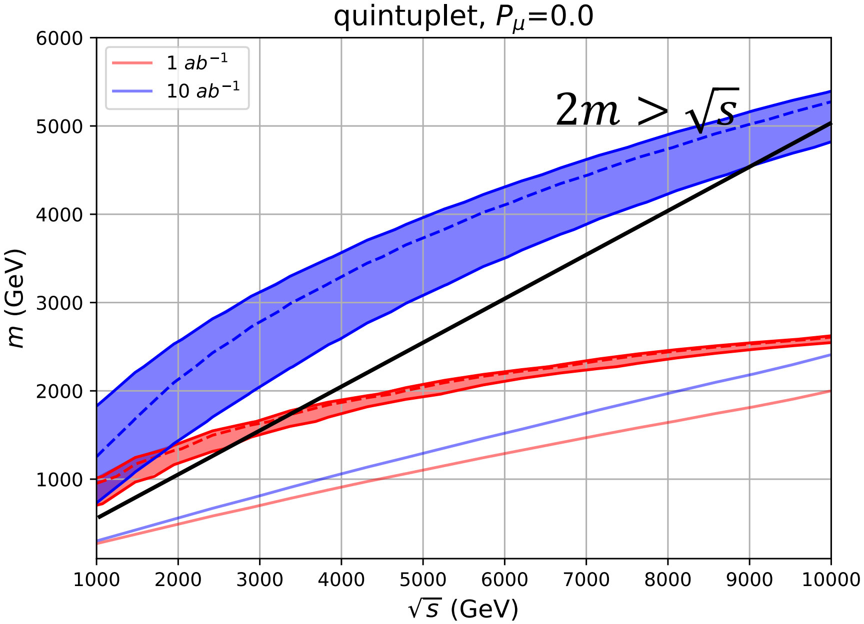


(right-handed) polarized



Result: Quintuplet

unpolarized



(right-handed) polarized