Minimal Dark Matter Search at $\mu^+\mu^+$ Collider

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Outline

1. Minimal Dark Matter (MDM) Model

2. MDM search at collider experiment

3. MDM search at $\mu^+\mu^+$ collider
   - indirect search
   - direct search

4. Summary

Dark Matter

Cosmological & astrophysical observations suggests the existence of "**dark matter**"

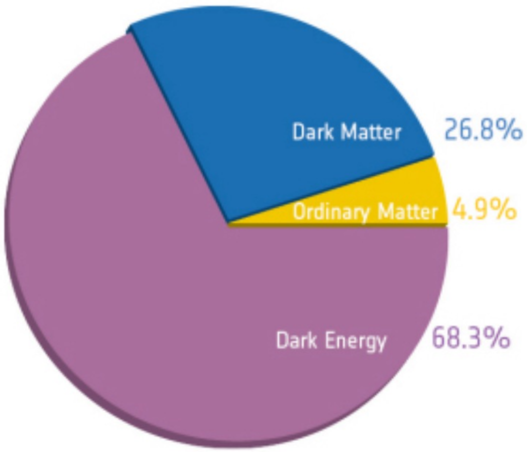


Figure from ESA

The property of dark matter:

- "weakly" interacting with SM particles
- non-relativistic
- stable
- collisionless

Among a plenty number of models,
Minimal Dark Matter (MDM) is a promising candidate as a **Weakly Interacting Massive Particles (WIMPs)** dark matter.

Minimal Dark Matter (MDM)

Cirelli, Fornengo, Strumia (2005)

We introduce **new SU(2) multiplet (n-plet) with hypercharge Y**.

MDM is well-known dark matter candidate and many models predict its existence: e.g. MSSM.

Jungman, Kamionkowski, Griest (1995)

MDM can explain the dark matter relic abundance through the freeze-out mechanism with $m_{DM} \sim \mathcal{O}(1\ \mathrm{TeV})$: **thermal mass target**

Femionic MDM candidate:

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

particle	n	Y	Tharmal target
Higgsino	2	1/2	1.1 TeV
Wino	3	0	2.7 TeV
Quintuplet	5	0	14 TeV

Collider Search for MDM

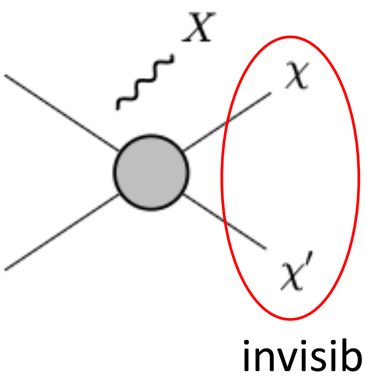
MDM is one of the main target at **high energy collider experiment** due to its interaction strength and the kinematical reach.

<u>Signal</u>

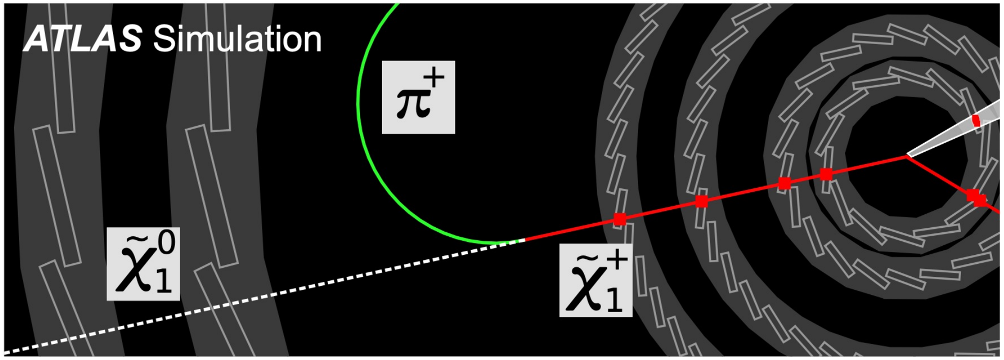
MDM cannot be detected in the detector, so MDM leaves **missing** signal.

In addition, some MDM candidate predicts **the long-lived charged particles** in their multiplet. These charged particle can hit the inner tracker.

Mono-X (X=SM final state)



Disappearing Track



ATLAS collaboration (2017)

Lepton Collider

In recent years, **lepton colliders** are discussed as future collider experiment:

- electron-positron collider — *e.g.* ILC, CLIC, FCC-ee
- muon collider — *e.g.* MAP, muTristan

Advantages of lepton collider:

- Beam particle is elementary particle (**not** composite particle like proton)
  → **kinematics** can be fully reconstructed
- Low hadronic background (maybe trigger is not needed)
- Use of beam polarization (Fukuda, AN 2406.XXXXX)

$\sqrt{s} \sim \mathcal{O}(1\ \mathrm{TeV})$ and large luminosity are needed to search for MDM.
→ **muon collider is suitable !**

$\mu^+\mu^+$ collider

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

In recent years, $\boldsymbol{\mu^+}$ **cooling technique** is developed, and the realization of **well-collimated** $\boldsymbol{\mu^+}$ **beam** is discussed.

$\boldsymbol{\mu^+\mu^+}$ **collider** seems a realistic option as a future collider experiment
e.g. muTristan (proposal): Energy: $\sqrt{s} \sim 2$ TeV, Luminosity: $\mathcal{L} \sim 1$ ab^{-1}

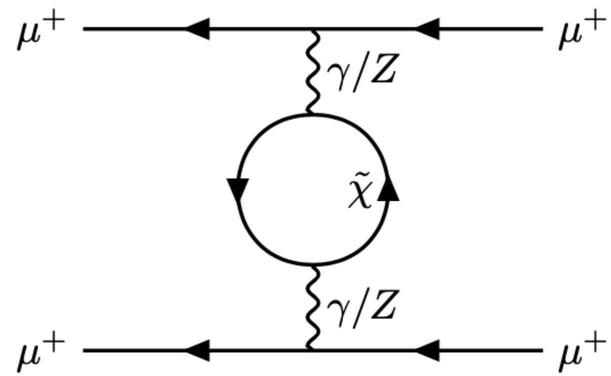
However, muon collider is actually **not** clean around the beam pipe due to **the Beam Induced Background (BIB)**.

Capdevilla+ (2021)
Collamati+ (2021)

<u>In our work</u>, we consider the MDM search at $\boldsymbol{\mu^+\mu^+}$ **collider**:

1. **Indirect search**:
   BSM effect to the angular distribution of $\mu^+\mu^+$ elastic scattering
2. **Direct search**:
   WIMP production, mono-X channel

Indirect search



MDM 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

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

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

the angular distribution of μ is distorted.

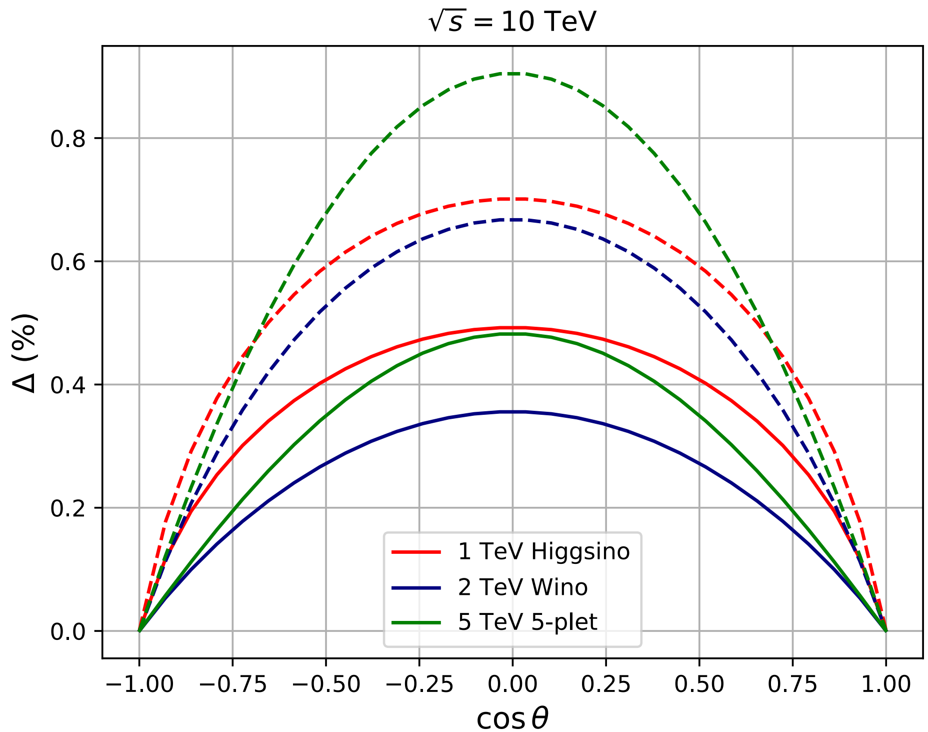
Indirect search

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

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

——— $P_\mu = 0$ (unpolarized μ^+)

- - - - - - $P_\mu = 0.8$ (right-handed μ^+)



Indirect search

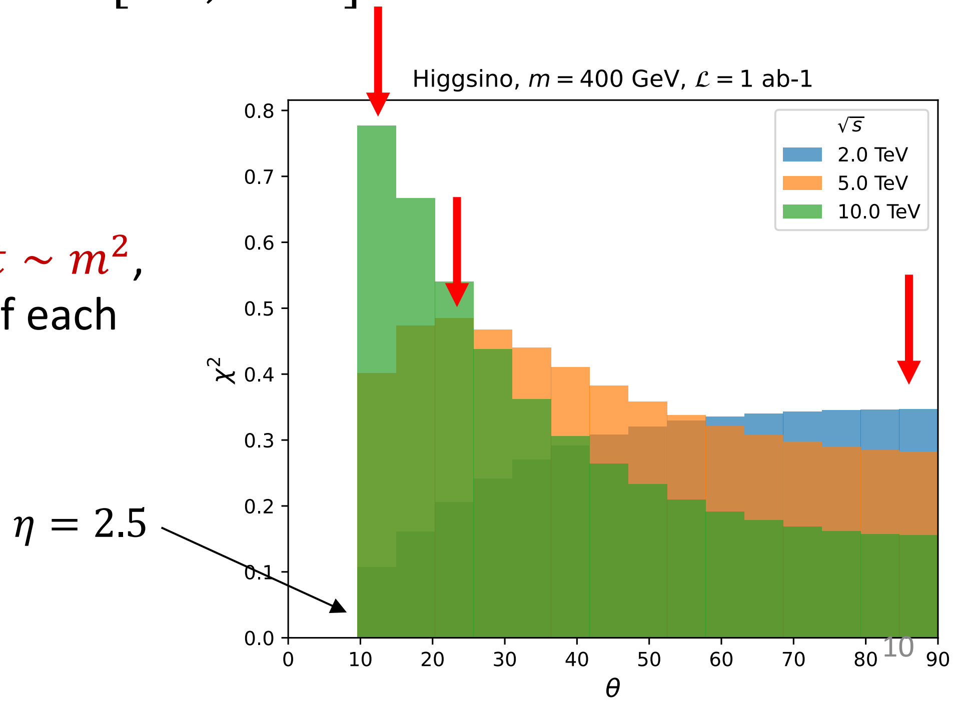
Statistical method : **shape analysis**

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

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

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

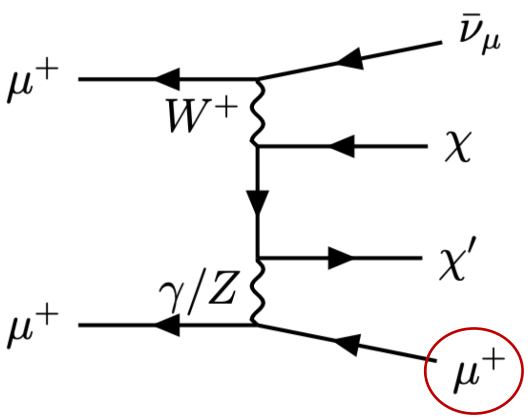
The most contributing bin is where $t \sim m^2$, and this makes **the peak structure** of each bin contribution to χ^2.



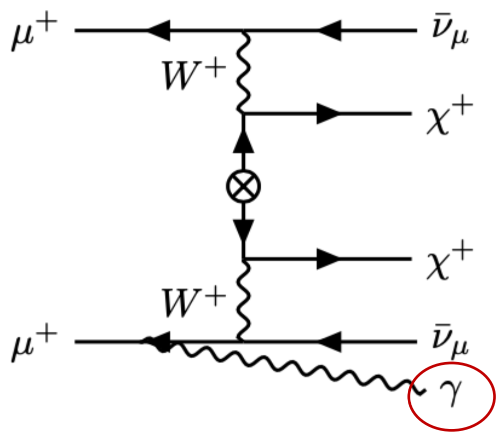
Direct search

Mono-X ($X = \mu^+, \gamma$) searches are considered.

At $\mu^+\mu^-$ collider, dominant production process of $\chi\chi$ is **Drell-Yan** production.
At $\mu^+\mu^+$ collider, **Vector Boson Fusion (VBF) process** is the dominant production process.



mono-μ channel



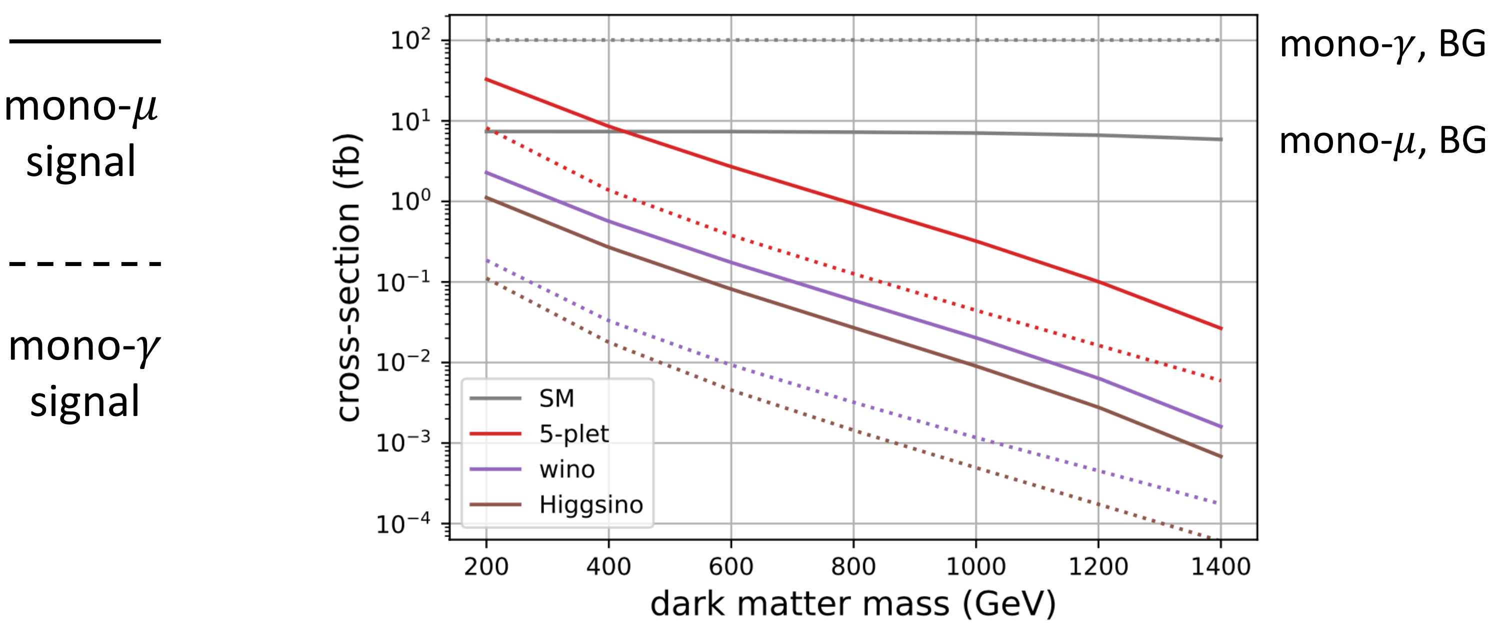
mono-γ channel

Direct search

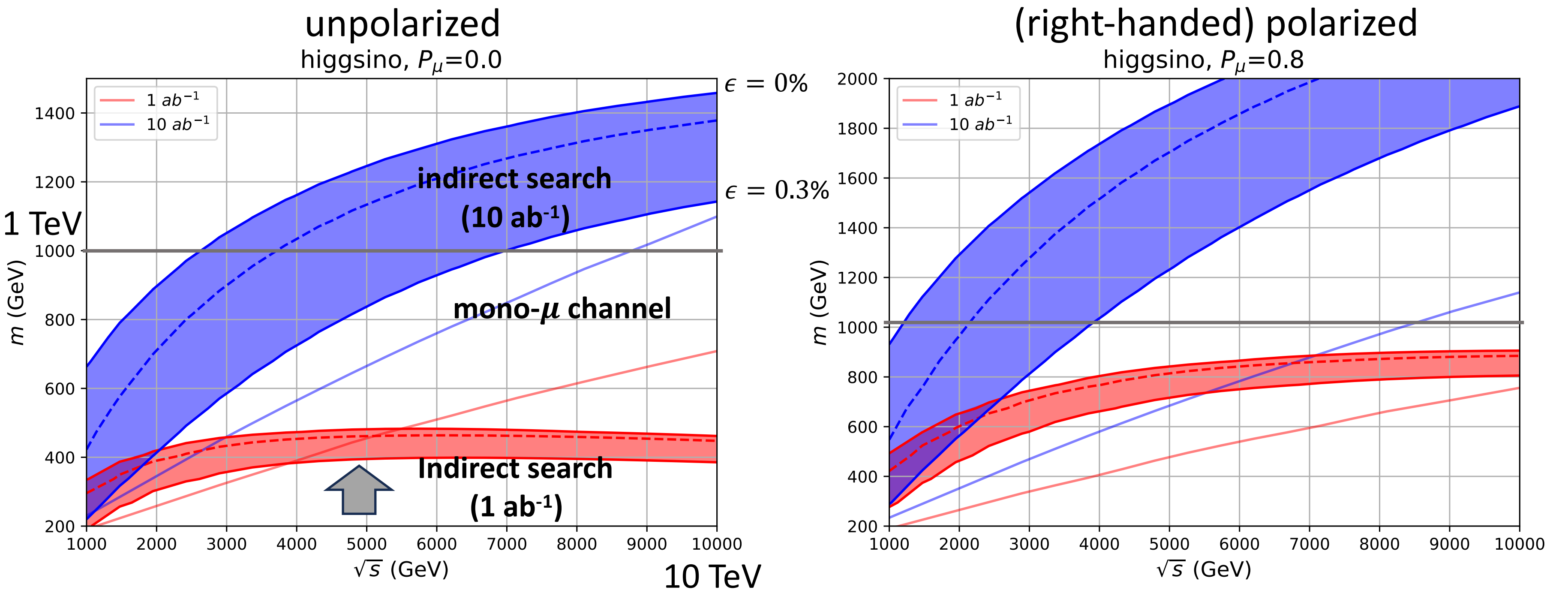
Even in the case of $\mu^+\mu^-$ collider, the **mono-μ channel** is more sensitive than the mono-γ channel, because backgrounds can be discriminated **by the kinematical cut.**

Han, Liu, Wang, Wang (2021)
Bottaro+ (2022)

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



Result: Higgsino



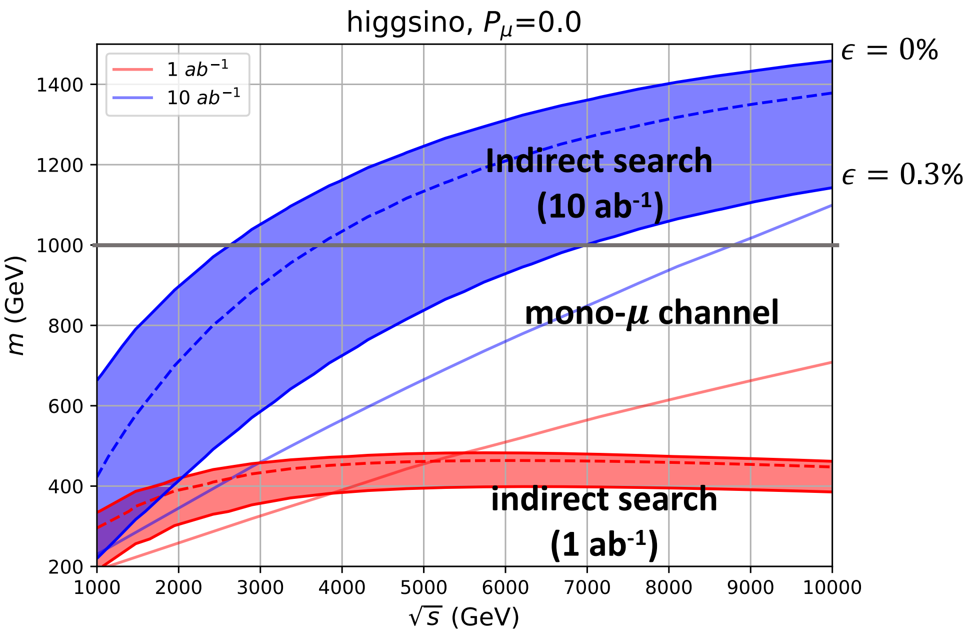
1 ab^{-1} : indirect search is more sensitive than direct search with $\sqrt{s} \lesssim 5$ TeV.

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

With 10 ab^{-1} luminosity, both searches can probe **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

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.

Summary

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

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

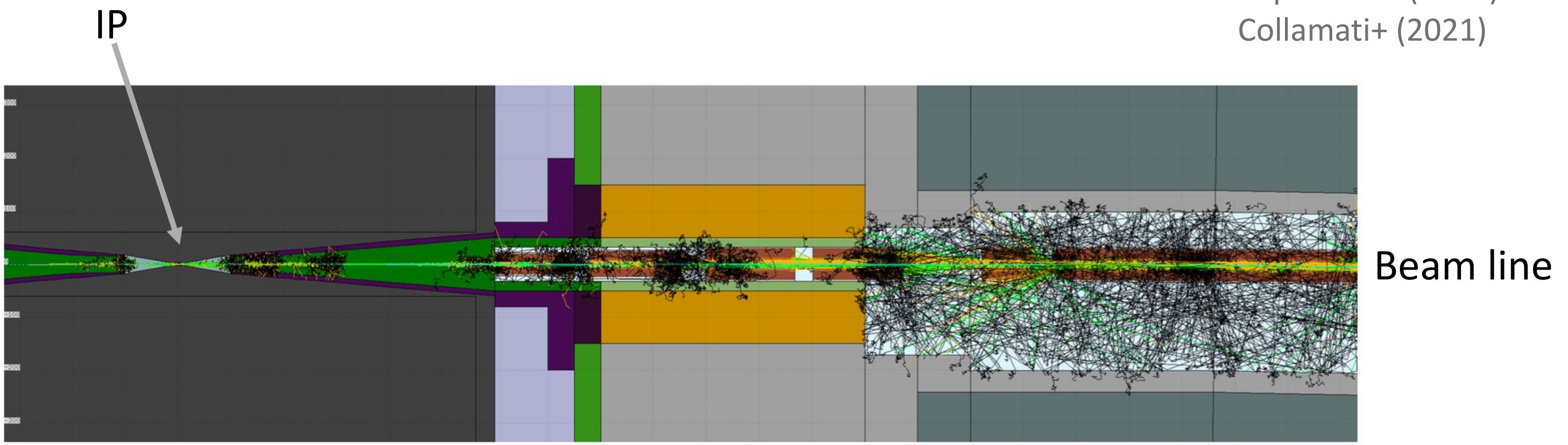
Backup

Muon Collider

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

It may be a main background of disappearing track signal…

Capdevilla+ (2021)
Collamati+ (2021)



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

- ☐ mono-X search at $\mu^+\mu^-$ collider
- ☐ muon beam polarization

Han+ (2021), Bottaro+ (2022)
Fukuda, Moroi, AN, Wei, in progress

Fukuda, AN, 2405.XXXXX

Collider Search for MDM

Wino, Quintuplet ($\mathbf{n = 3, 5\ \ Y = 0}$)

Charged state χ^+ is **long-lived**, $c\tau \sim \mathcal{O}(\text{cm})$.
The decay product is **soft** due to **small mass splitting** ($\delta m_+ \simeq 160$ MeV).

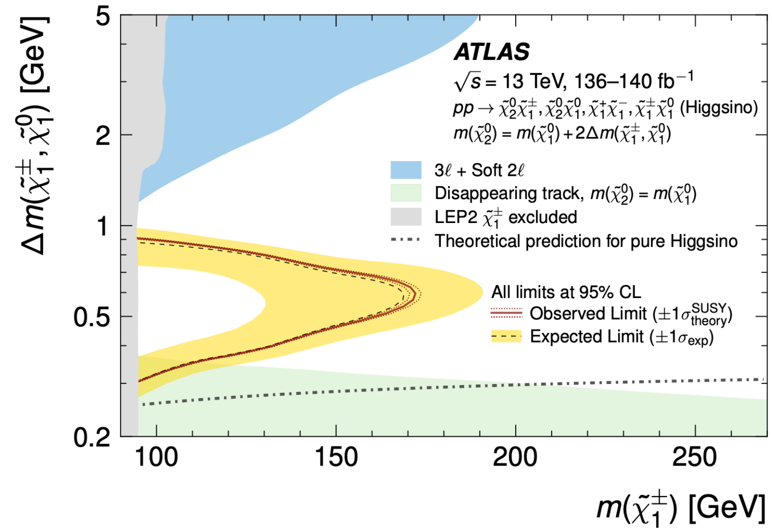
Constraint from disappearing track search at LHC Run2:
~ 660 GeV for pure Wino

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

Higgsino ($\boldsymbol{n = 2\ \ Y = 1/2}$)

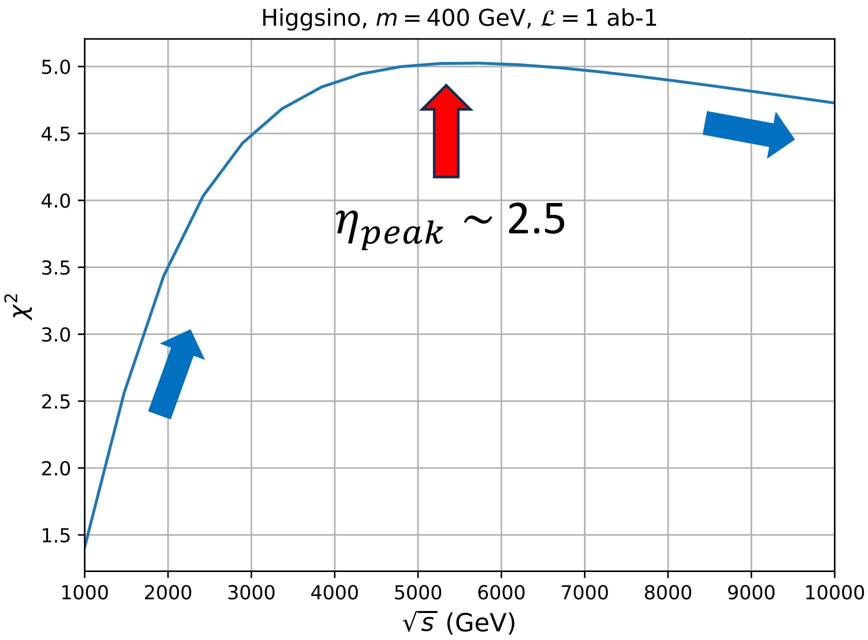
Large mass splitting ($\delta m_+ \simeq 340$ MeV)
and
not so long lifetime for disappearing track

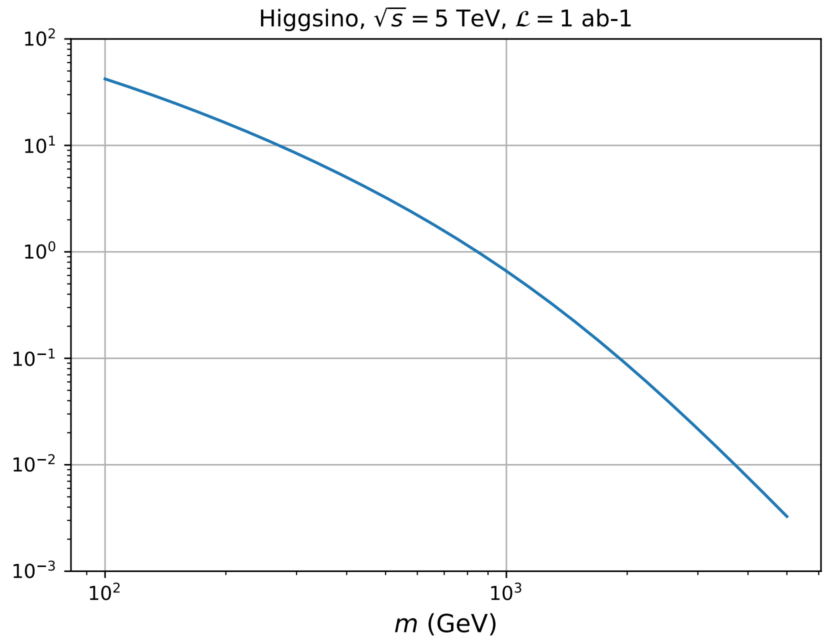
Even in that case, displaced soft pion
can be used to discriminate the background.



Fukuda, Nagata, Oide, Otono, Shirai (2020)
ATLAS collaboration (2024)

Indirect search





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

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

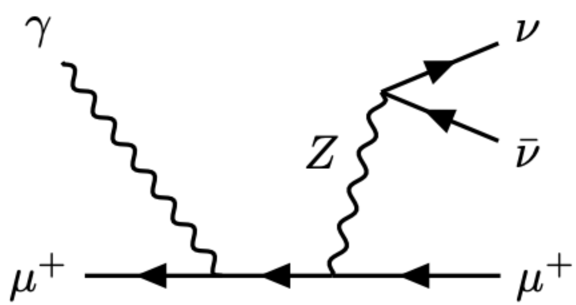
If the peak is outside, χ^2 slightly decreases with large $\sqrt{s}$.

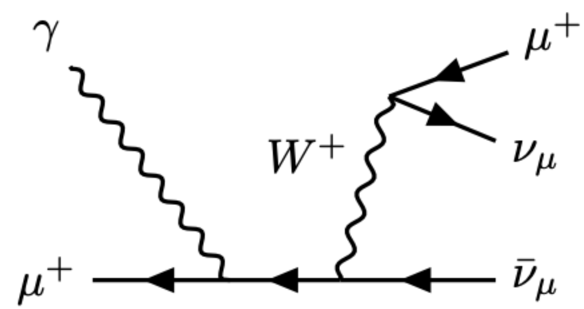
Direct production search

Kinematical cut

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

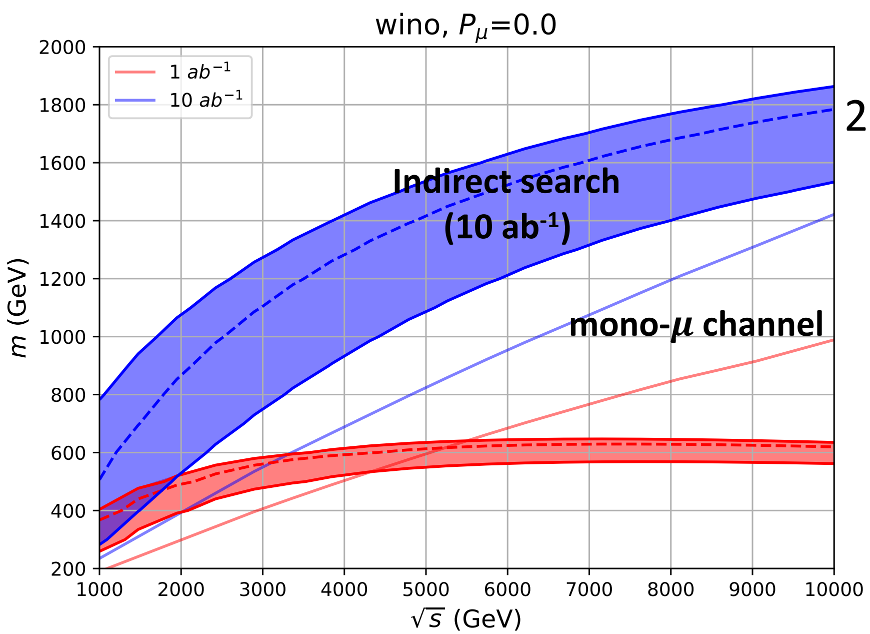
BG process for mono-μ channel



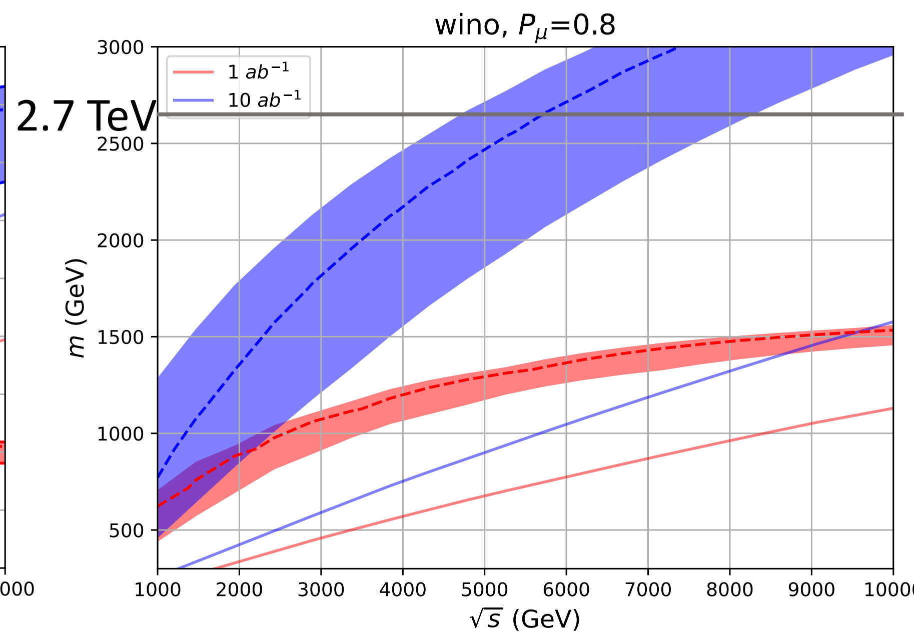


Result: Wino

unpolarized



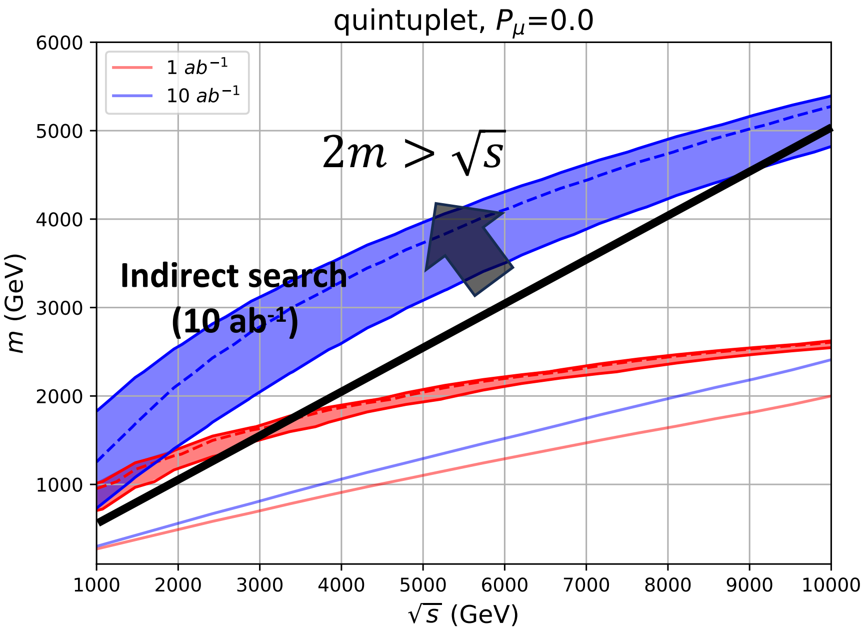
(right-handed) polarized



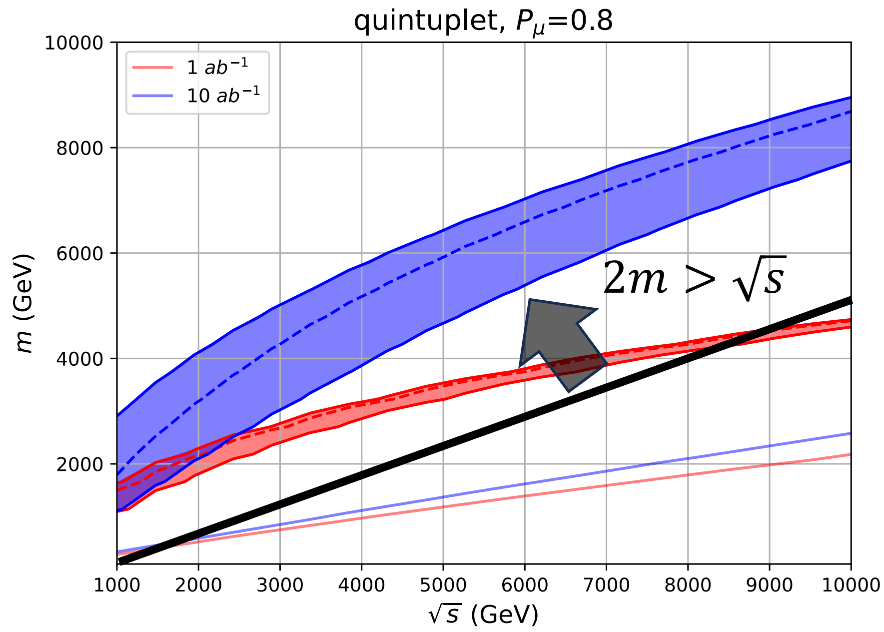
With **polarized muon beam**, the indirect search is sensitive to the thermal target ($m = 2.7$ TeV) with $\sqrt{s} \sim 5$ TeV, 10 ab^{-1} collider.

Result: Quintuplet

unpolarized



(right-handed) polarized



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