Indirect Probe of Electroweak-Interacting Particles at μTRISTAN $\mu^+\mu^+$ Collider

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Outline

Introduction

EWIMP search by collider experiments

Why $\mu^+\mu^+$ collider?

Analysis & Results

Indirect effect of EWIMPs

Mass reach

Summary

EWIMP Dark Matter

Dark Matter (DM) is a serious problem in particle physics

Some DM models include **E**lectro**W**eak-**I**nteracting **M**assive **P**article (EWIMP)

Supersymmetry (SUSY)

Higgsino (doublet, Dirac fermion)

Wino (triplet, Majorana fermion)

Minimal Dark Matter (MDM)

Multiplet that contains
a lightest neutral particle

[Cirelli, Fornengo, Strumia (2005)]

EWIMP search by LHC

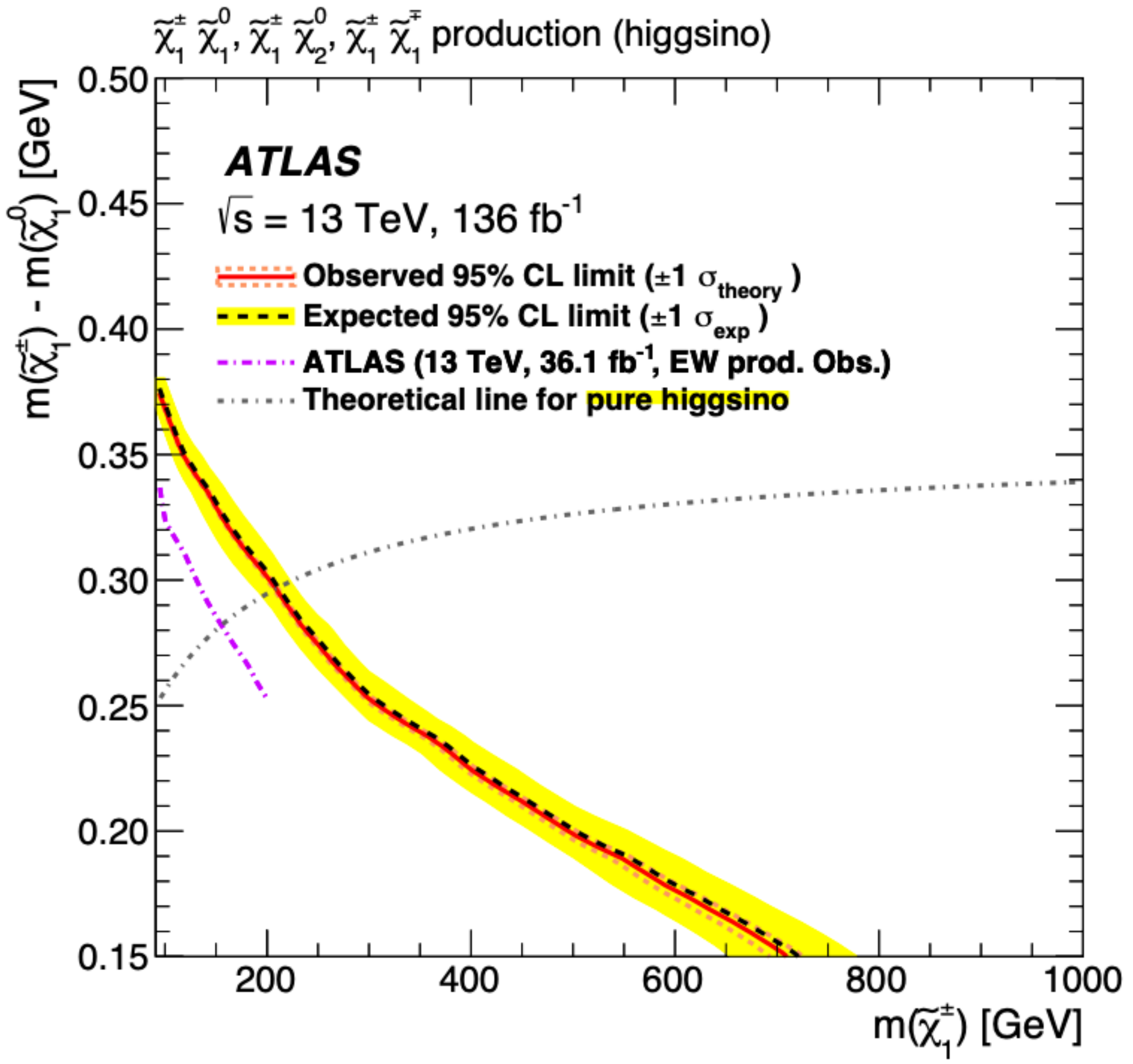
Disappearing Track analysis excluded…

pure Higgsino $\lesssim$ 200 GeV

pure Wino $\lesssim$ 650 GeV

- Still far from $O(1)$ TeV mass for thermal relic abundance of DM
- LHC search depends on mass splittings

Other collider search?



[ATLAS (2022)]

Colliders: pros & cons

	Pros	Cons
Proton	High energy	Noisy
Electron	Precise	Low energy
Muon	High energy Precise	Low Luminosity

Difficulty of muon collider

How to produce muons

$$p + \text{target} \rightarrow \pi^{\pm} + X$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \text{neutrino}$$

Velocities are widely distributed

▽

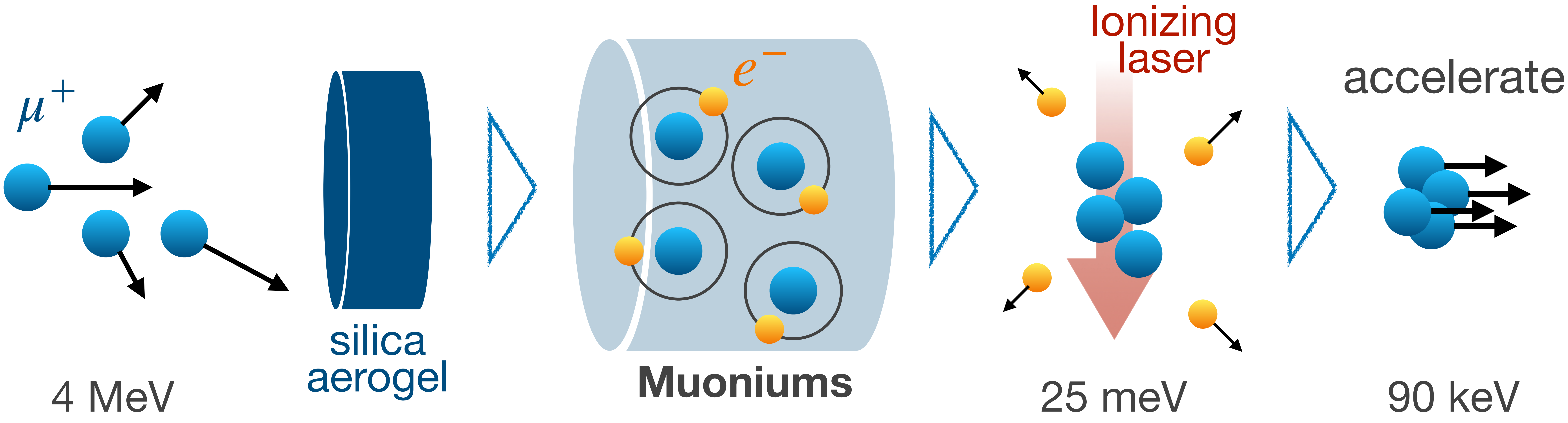
Low luminosity

Muon cooling technologies are necessary!

μ+ cooling

μ+ cooling technology has been developed for $(g-2)_\mu$ measurement

J-PARC succeeded in **cooling** & **accelerating** μ+



Last month's press release! [https://www.kek.jp/en/press/worlds-first-cooling-and-acceleration-of-muon]

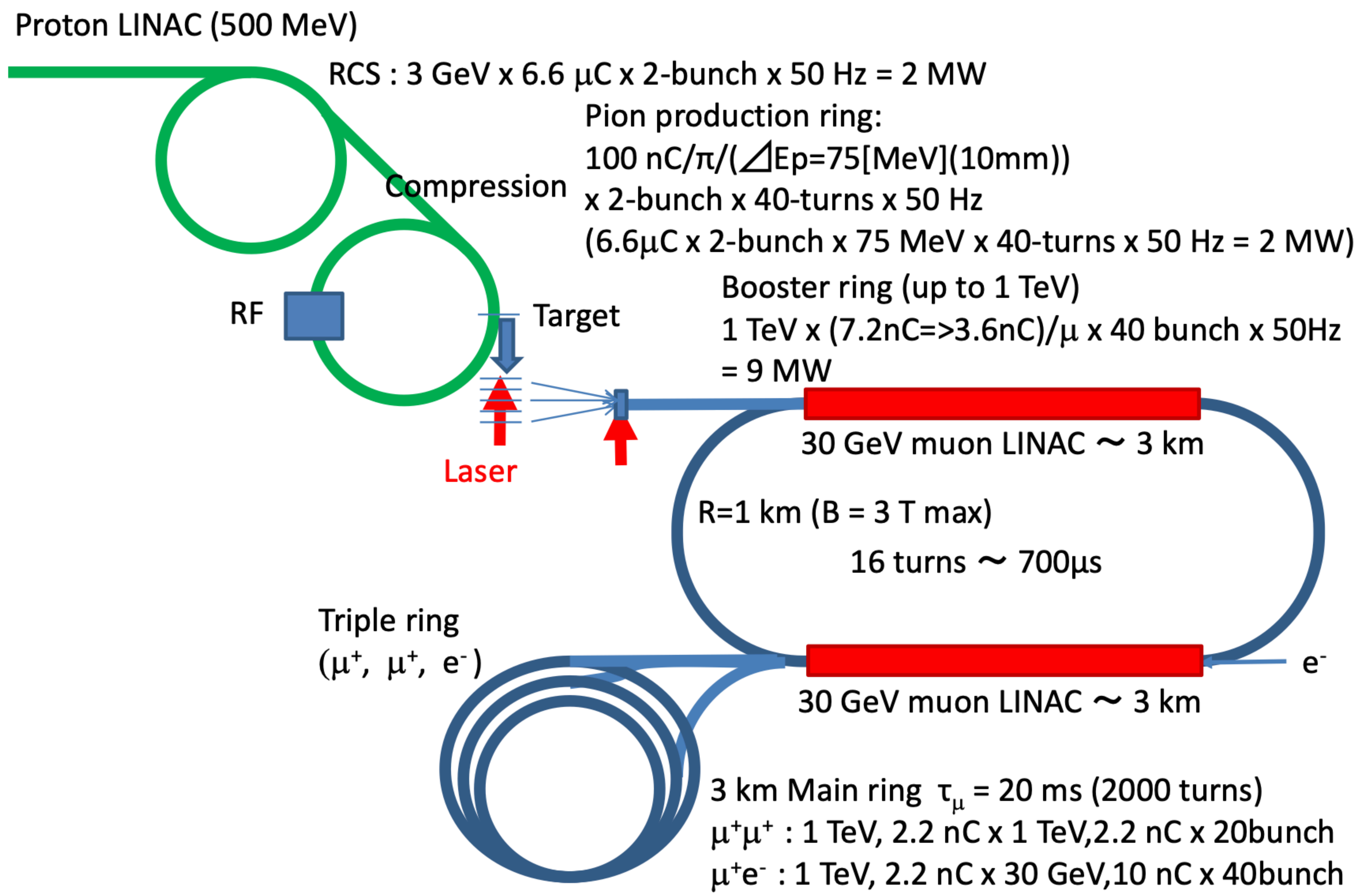
Concept of μTRISTAN

Let's use the low-emittance μ+ beam for TeV-scale colliders!

[Hamada, Kitano, Matsudo, Takakura, Yoshida (2022)]

Two types of ***μTRISTAN***

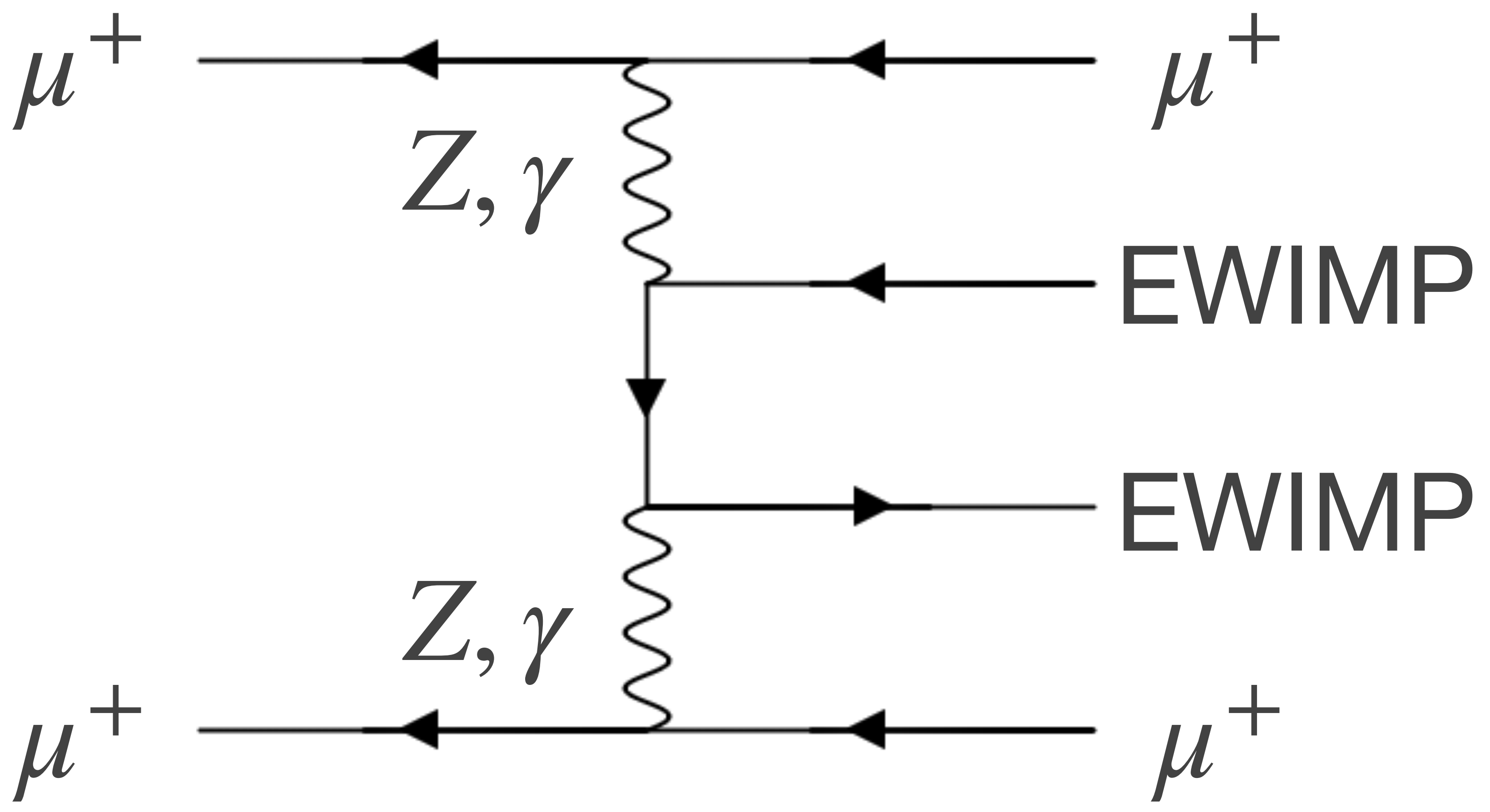
- μ+ e- collider
  - Use highly polarized e- beam
  - Higgs factory
- μ+ μ+ collider
  - New physics search



DM search by μ+μ+ collider

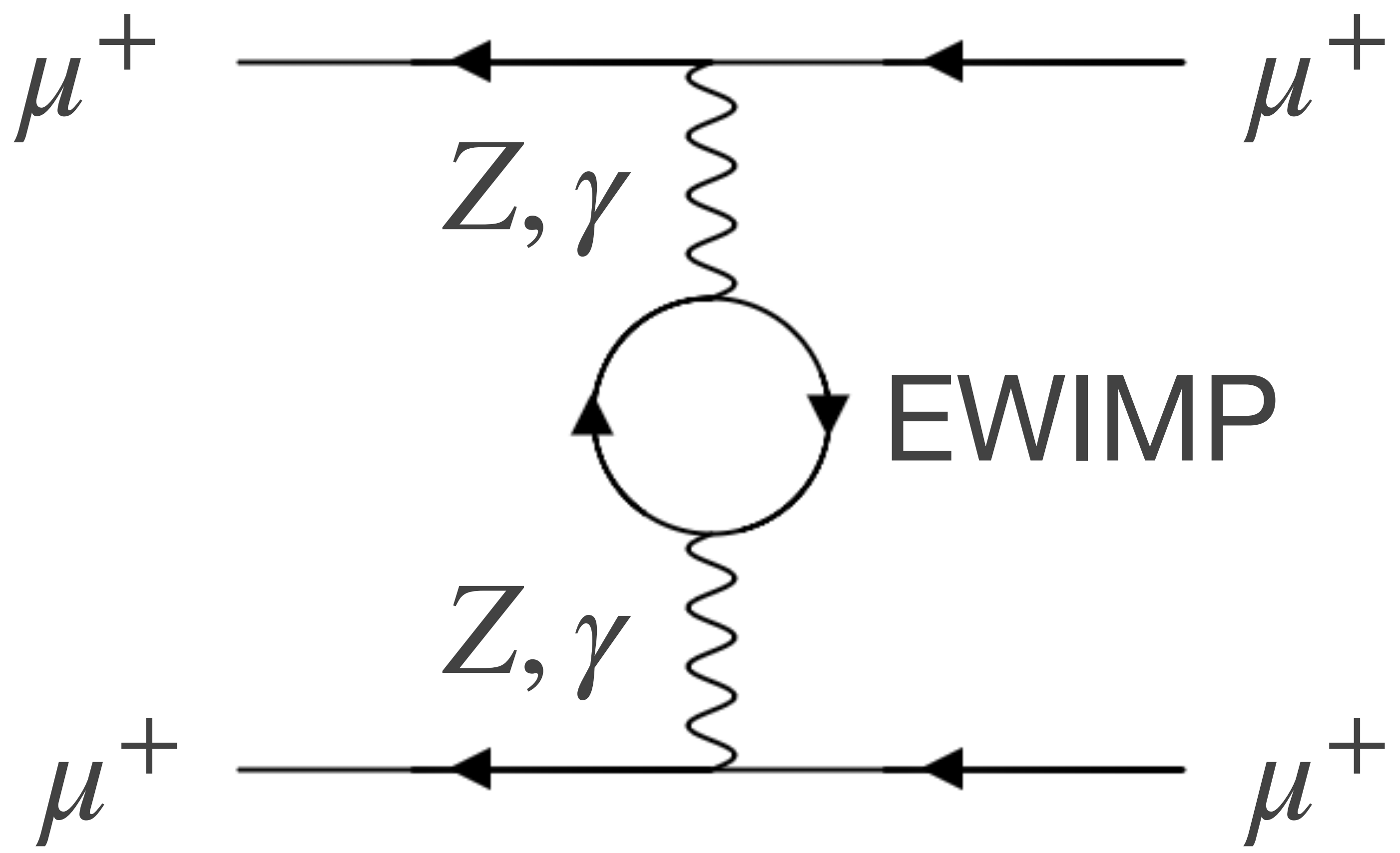
Direct production

- Small cross section
- Complicated analysis



Indirect search

- Accessible by precise measurements
- Not depend on mass splitting



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Benchmark DM models

SUSY

- Higgsino
- Wino

MDM [Cirelli, Strumia (2009)]

- 5-plet Majorana fermion
- 7-plet real scalar

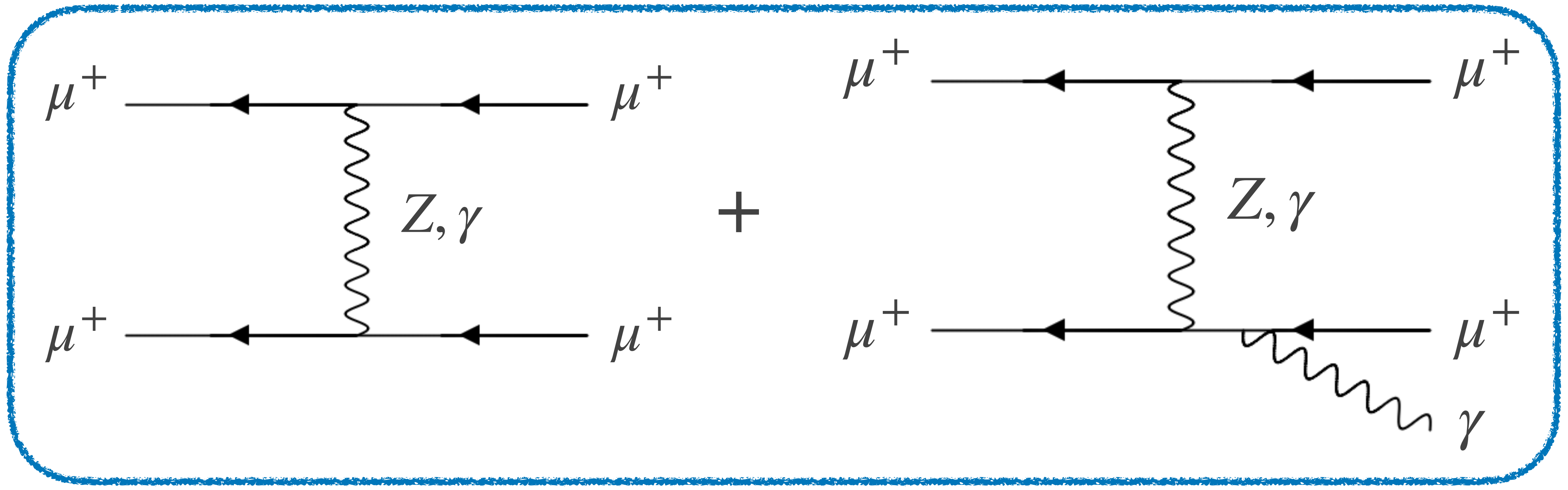
(Not excluded by direct detection, and stable)

$U(1)_Y$ \ $SU(2)_L$	2	3	4	5	6	7
0		**Wino**		**5-plet**		**7-plet**
1/2	**Higgsino**					

SM / BSM contributions to μ+μ+ scattering

$$i\mathscr{M}(\mu^+\mu^+ \to \mu^+\mu^+)$$

$\simeq$



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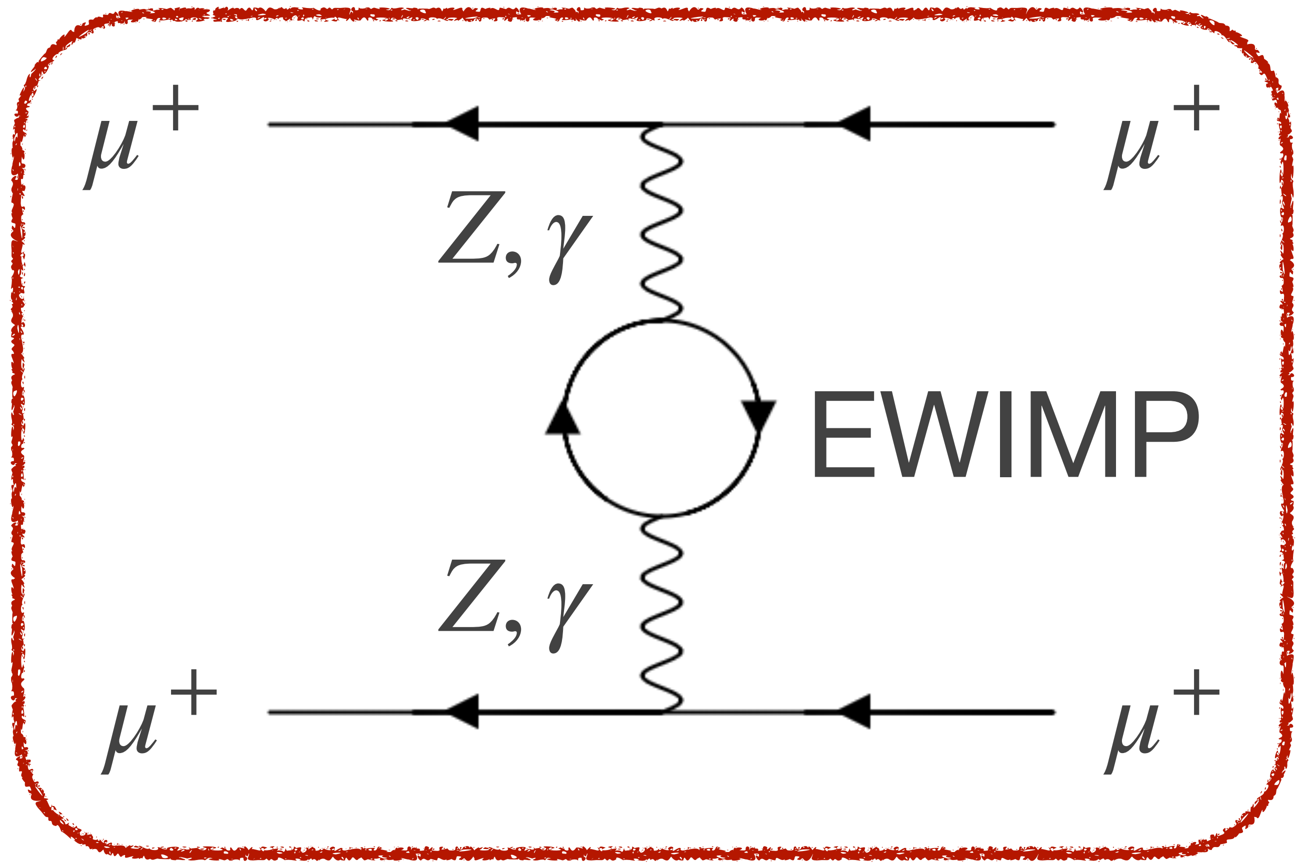


$i\mathscr{M}_{\mathrm{SM}}$ $\qquad$ $i\mathscr{M}_{\mathrm{BSM}}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}\cos\theta} + \frac{\mathrm{d}\sigma_{\mathrm{BSM}}}{\mathrm{d}\cos\theta}$$

▷

$$\frac{\mathrm{d}\sigma_{\mathrm{SM}}/\mathrm{d}\cos\theta}{\mathrm{d}\sigma_{\mathrm{BSM}}/\mathrm{d}\cos\theta} \simeq \frac{2\mathrm{Re}(\mathscr{M}_{\mathrm{SM}}\mathscr{M}^*_{\mathrm{BSM}})}{|\mathscr{M}_{\mathrm{SM}}|^2}$$

Angular dependency of BSM effect

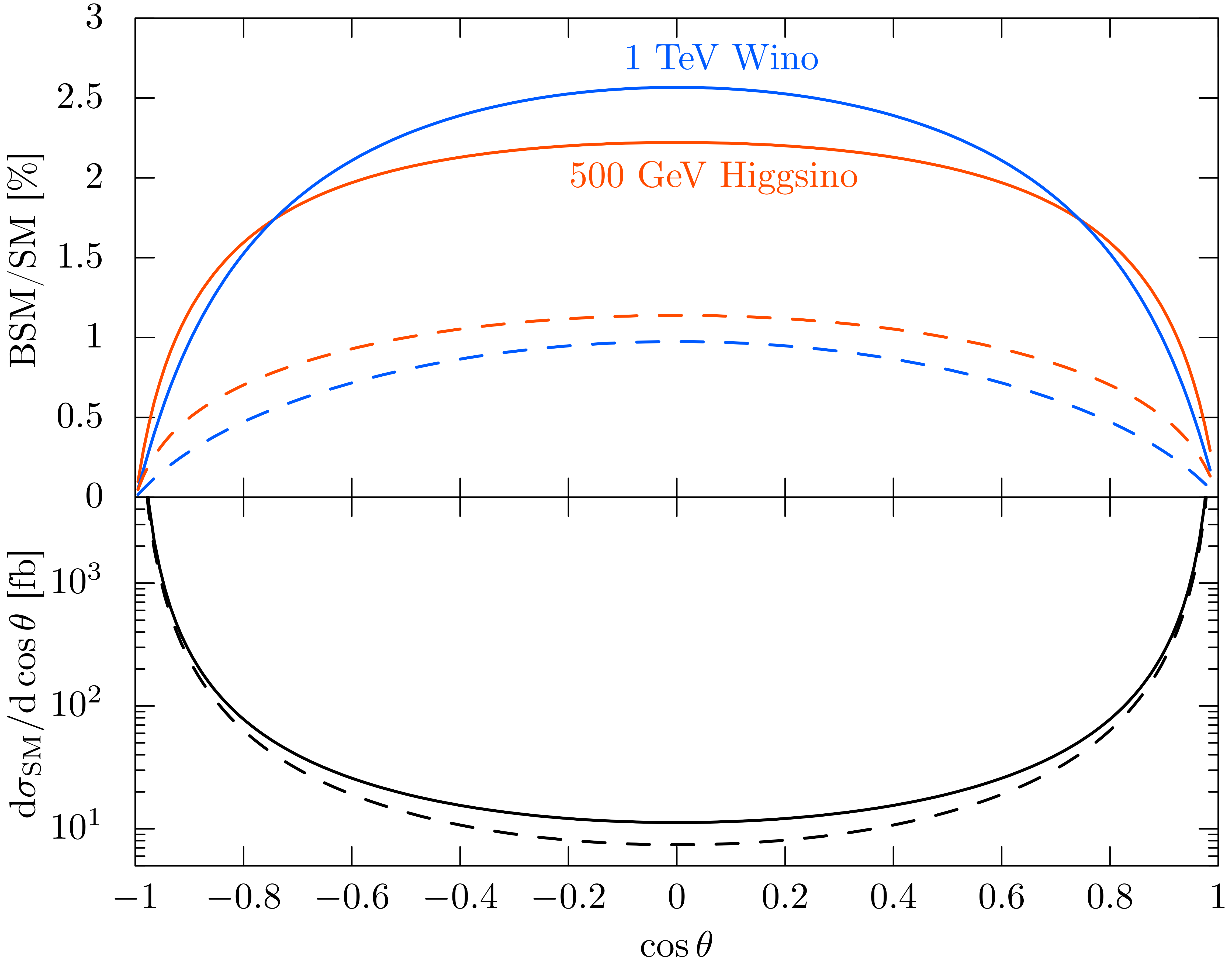
EWIMP effect can introduce

$$\mathcal{O}(1)\%\ \textbf{effect on}\ \frac{d\sigma_{\rm SM}/d\cos\theta}{d\sigma_{\rm BSM}/d\cos\theta}$$

------------ : unpolarized

——— : 100% right-handed polarized

$\sqrt{s}$ = 10 TeV



Chi-squared analysis

Binned χ^2 test

$\theta \in [16^\circ,\ 164^\circ]$ are divided into 10 bins

$$\chi^2 = \sum_{i=1}^{10} \chi_i^2 = \sum_{i=1}^{10} \frac{\left[N_i^{(\mathrm{BSM})}\right]^2}{N_i^{(\mathrm{SM})} + \left[\epsilon_i N_i^{(\mathrm{SM})}\right]^2}$$

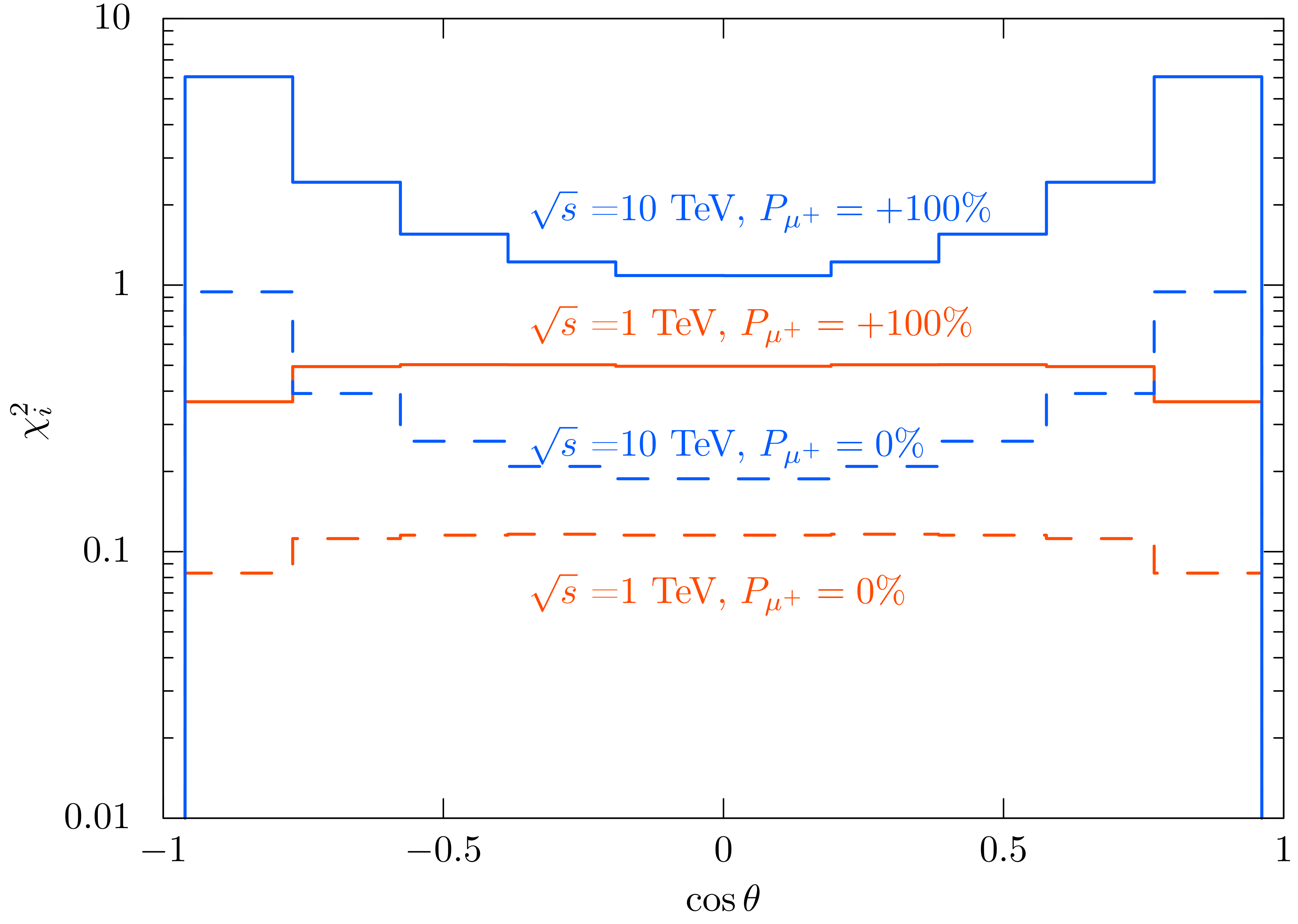
systematic error

$$N_i^{(\mathrm{SM/BSM})} = L \int_{i\text{–th bin}} \left(\frac{d\sigma_{\mathrm{SM/BSM}}}{d\cos\theta} \right)$$

C.L. 95% $\Leftrightarrow$ $\chi^2 = 3.8$

500 GeV Higgsino

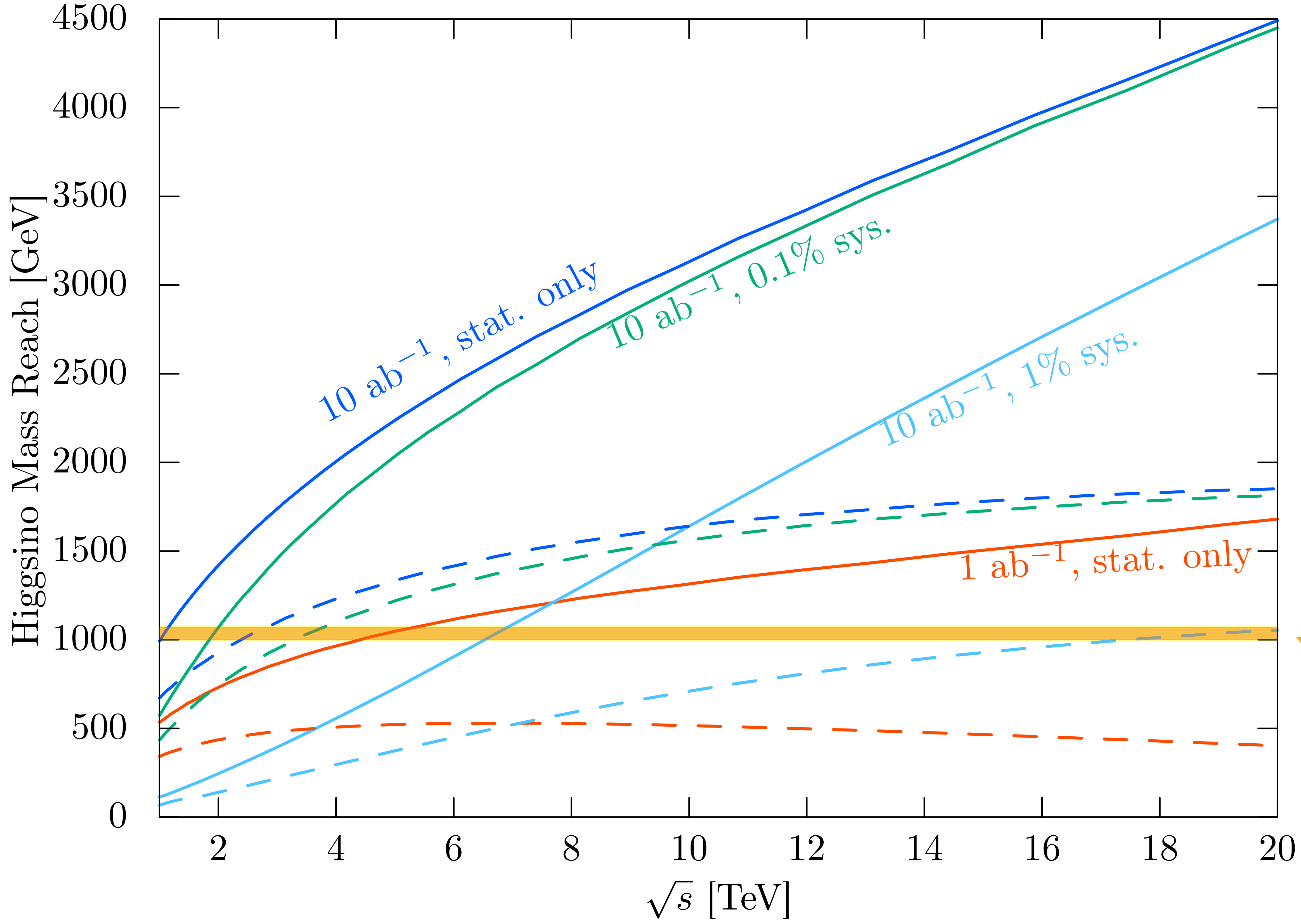
Integrated luminosity 1 ab^{-1}, $\epsilon_i = 0$



Results: Mass reach (SUSY)

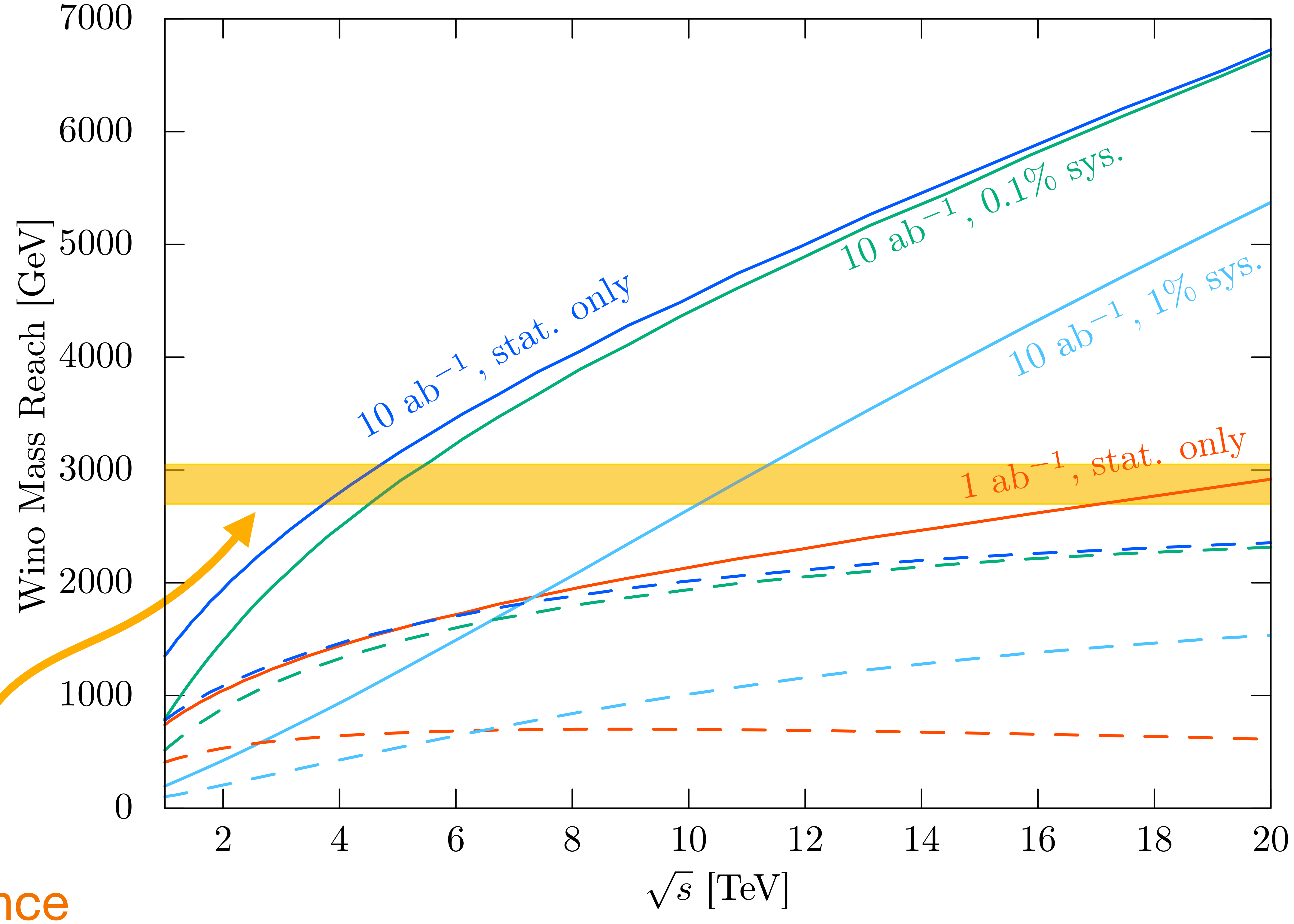
······· : unpolarized
—— : 100% polarized

Higgsino



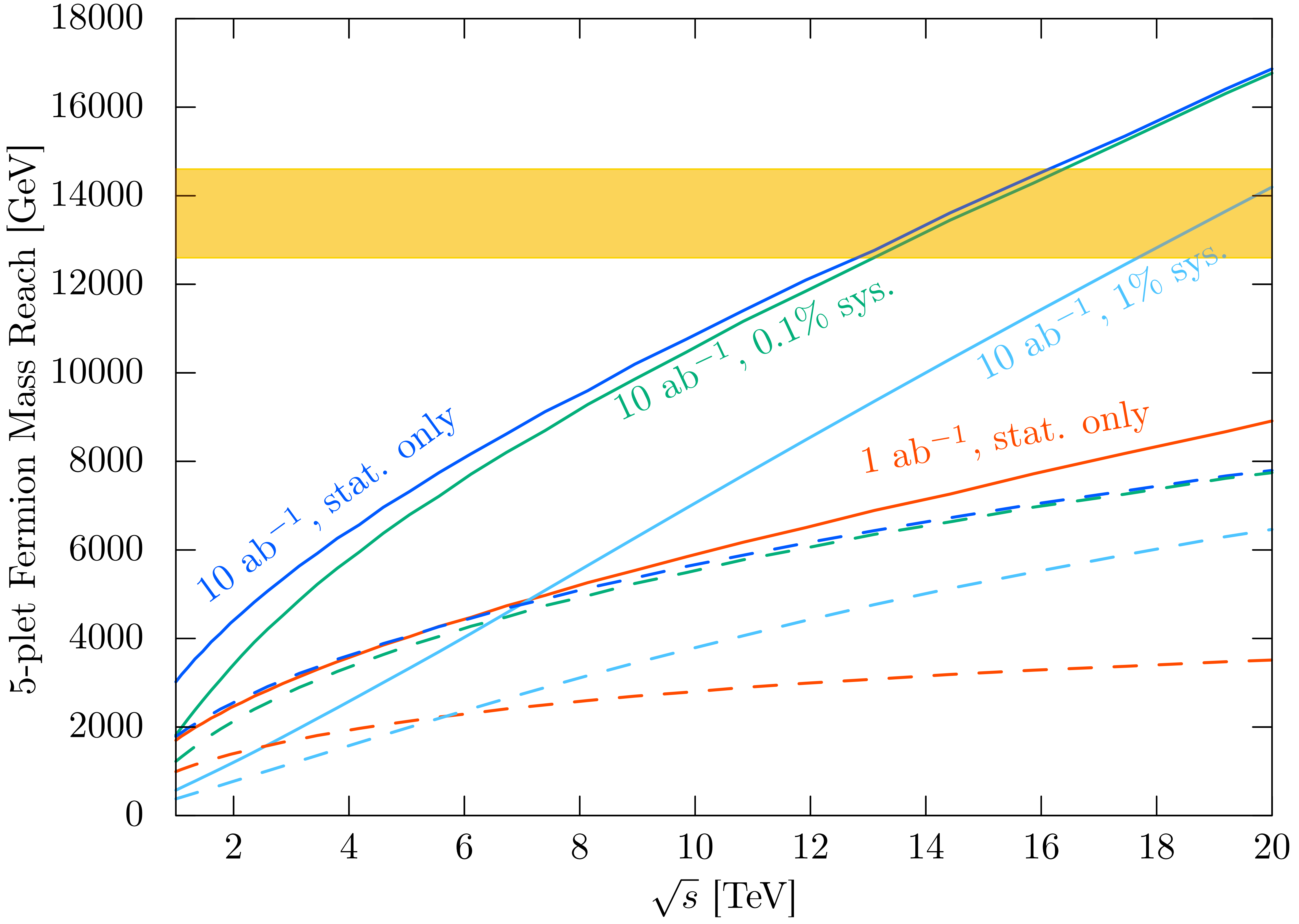
DM abundance

Wino



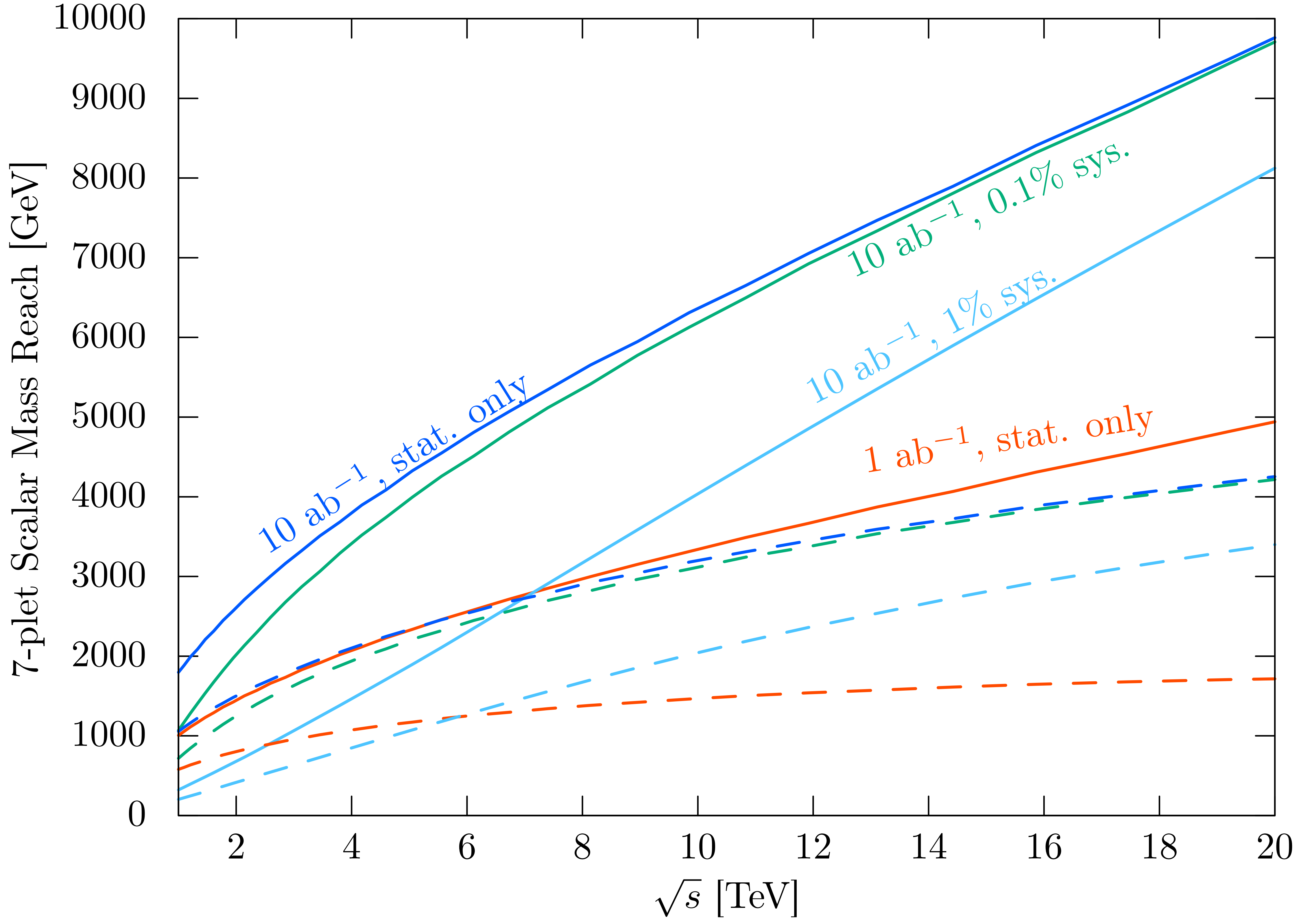
Results: Mass reach (MDM)

5-plet Majorana fermion



7-plet real scalar

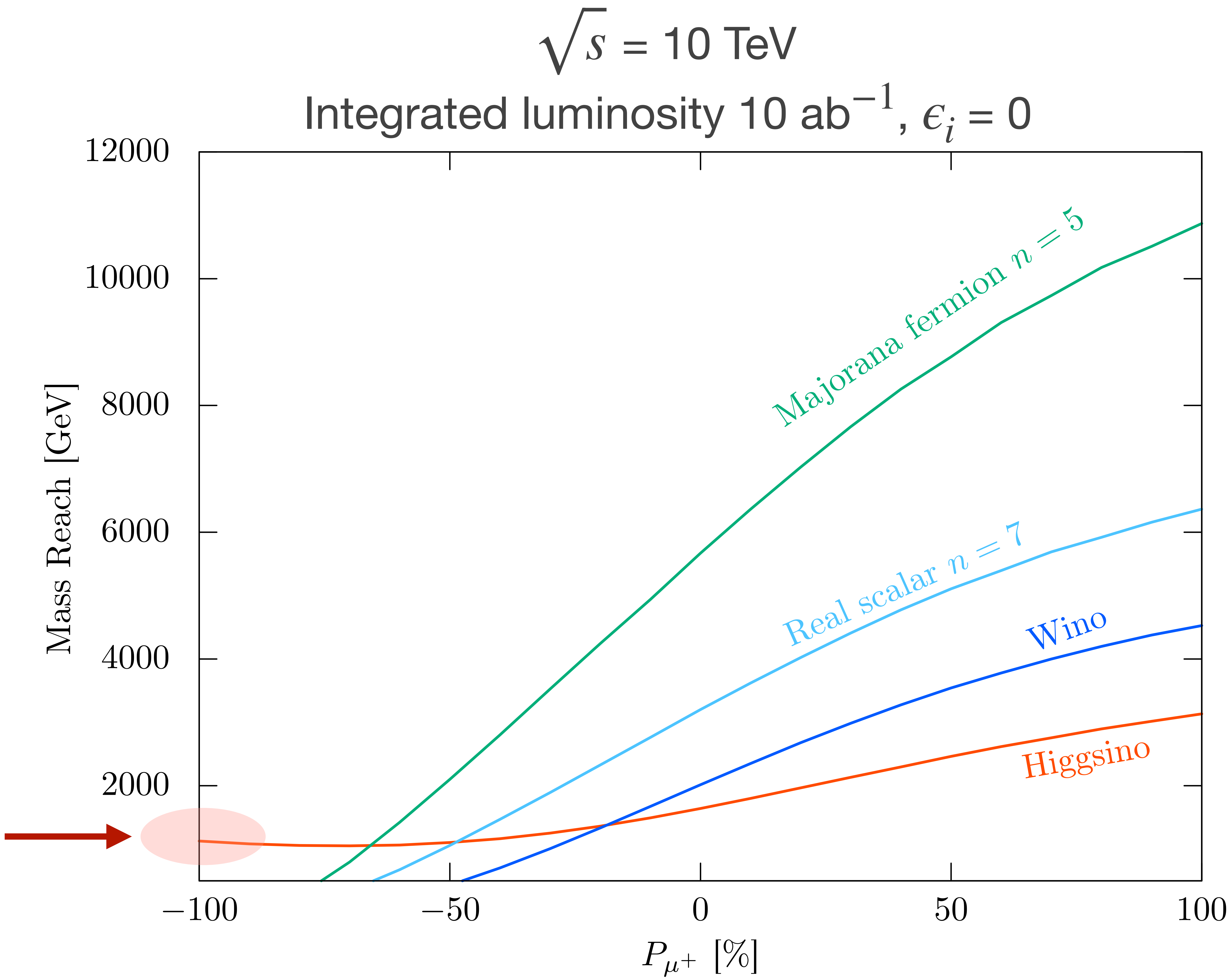
DM ~ 54 TeV



Polarization dependency

Beam polarization enhances sensitivity significantly

Purely from $U(1)_Y$



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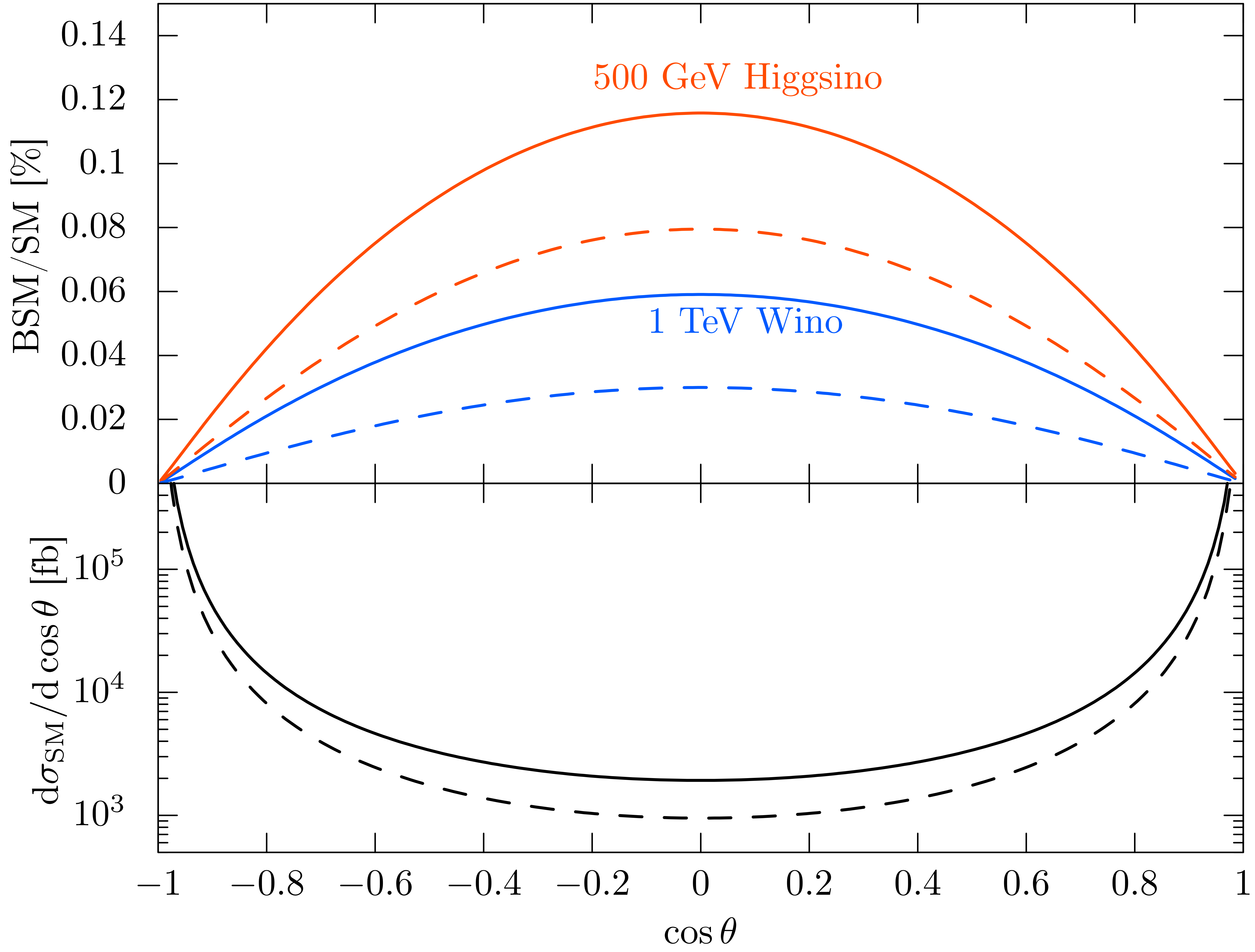
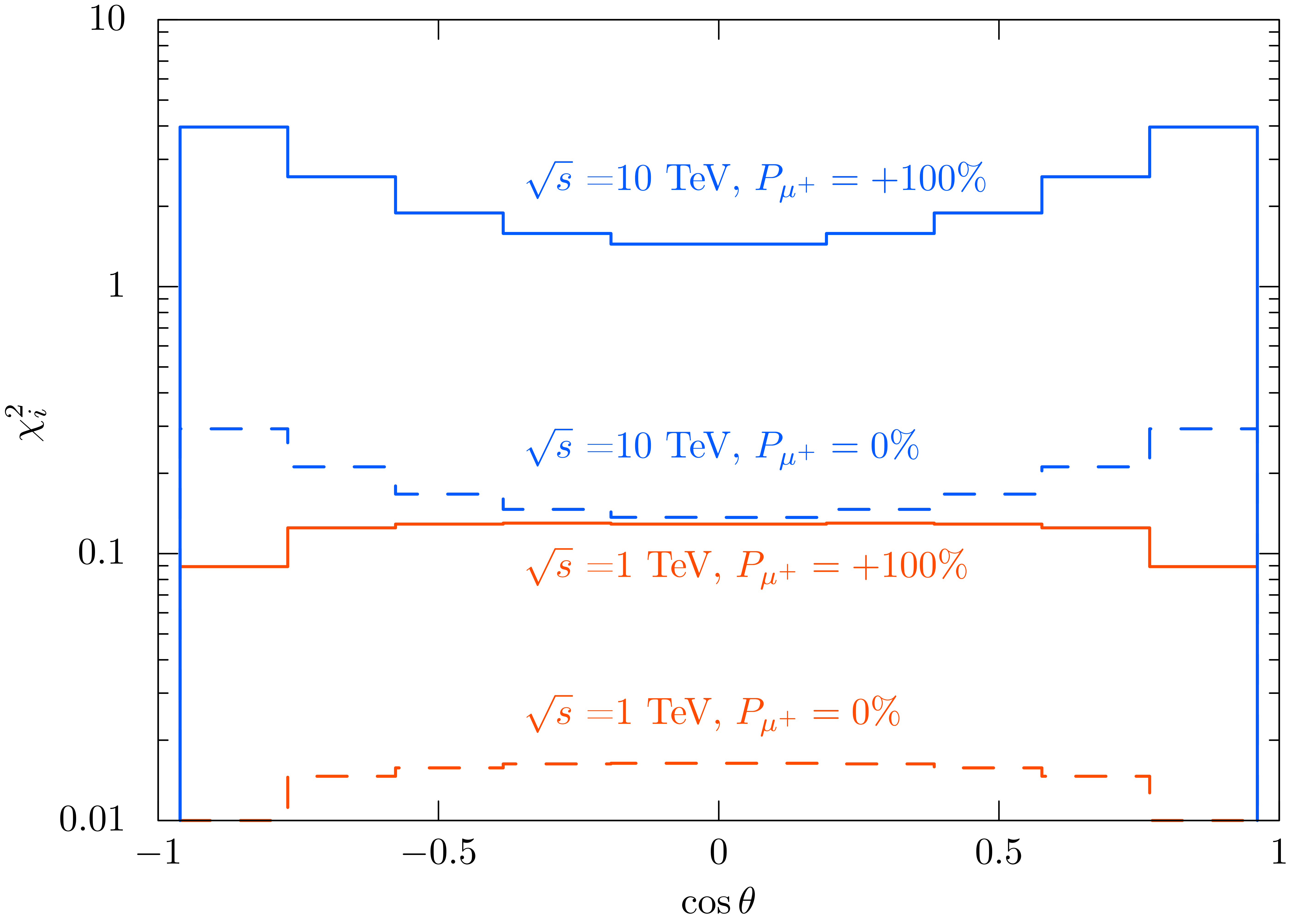
- **μ+ cooling** technique is in the process of evolving
    - "The year 2024 is the first year of muon acceleration"
- μTRISTAN **μ+μ+ collider** has the potential to search for EWIMPs
- EWIMP loop can introduce $O(1)$**% correction** to SM process
- **A few TeV beam energy** with $O(1)$ **ab**$^{-1}$ **integrated luminosity** can search for Higgsino & Wino that accounts for DM relic abundance
- This study will influence the design consideration of μTRISTAN

Backup

Anglar dependence for $\sqrt{s}$ = 1 TeV



Chi-squared value for 1 TeV Wino



Original design of μTRISTAN μ+μ+ collider

[Hamada, Kitano, Matsudo, Takakura, Yoshida (2022)]

- The original paper assumes 3 km storage ring = TRISTAN ring @ KEK
    - $\sqrt{s}$ = 2 TeV muon beam = 10 T magnetic field ≃ HL-LHC (11 T)
- "Ultra-cold" muon: ~ 4 mm mrad ≪ ionization cooling ~ 25 mm mrad
- 10 years of running -> integrated luminosity 120 fb^{-1}
- Beam polarization of P_{μ^+} = 0.8 is assumed
    - J-PARC aims beam polarization of $P_{\mu^+} > 0.9$