# Probing EWIMPs with Drell–Yan process at 100 TeV colliders

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Based on **1810.07349** with S. Chigusa and T. Moroi (Tokyo U.)

# Introduction

# ElectroWeakly Interacting Massive Particle (EWIMP)

- EWIMP: massive particles charged under $\mathrm{SU}(2)_L$.
- Motivated by many Standard Model extensions.
- Good candidate for Dark Matter.

➡ Extensive searches being performed.

## MSSM

- Higgsino: SU(2) doublet

  $m \simeq 1\,\mathrm{TeV}$ for thermal relic.

  e.g. "natural SUSY" [Baer+ 12; ...]

- Wino: SU(2) triplet

  $m \simeq 3\,\mathrm{TeV}$ for thermal relic.

  e.g. "mini-split" [Arvanitaki+ 12; ...]

## Minimal DM

[Cirelli+ 05, 07]

- 5-plet fermion

  $m \simeq 10\,\mathrm{TeV}$ for thermal relic.

- 7-plet scalar

  $m \simeq 25\,\mathrm{TeV}$ for thermal relic.

* additional stabilization for 7-plet [Del Nobile+ 15]

# Conventional search

## DM detection

- direct detection

  wino, MDM: well within future prospect, higgsino: under neutrino floor

- indirect detection

  wino, MDM: strongly constrained

  subject to astrophysical uncertainties

## Collider search

- disappearing charged track

  wino: strong way to probe

  depends strongly on lifetime, or mass difference

- mono-X search

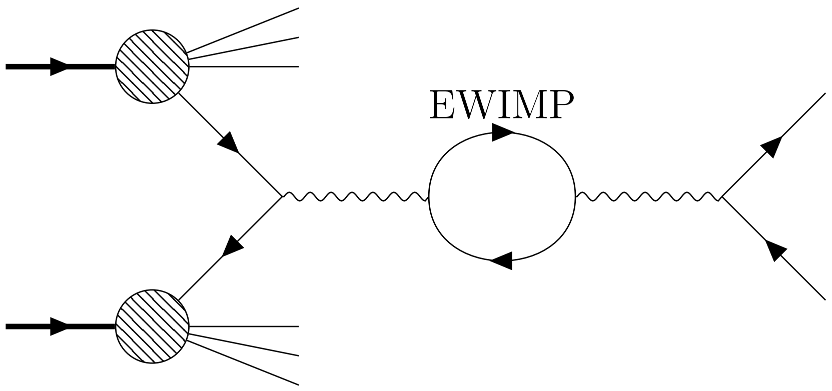
* Higgsino is basically more difficult to probe.

# Collider "indirect" search

- Today's topic: Drell-Yan process @ 100 TeV hadron collider.

  * Focus on $ee, \mu\mu$ channels in this talk.

  [See also Harigaya+ 15; Matsumoto+ 17, 18; Di Luzio+ 18]




- Not directly produce EWIMPs = "indirect" search.

  ✔ insensitive to lifetime and decay products.

  ✘ EWIMP effects only @ NLO

  ✘ Have to deal with backgrounds and systematics.

- Offers complementary information, to say the least.

# Outline

1. Introduction
2. EWIMP effect on Drell-Yan
3. Detection reach
4. Summary

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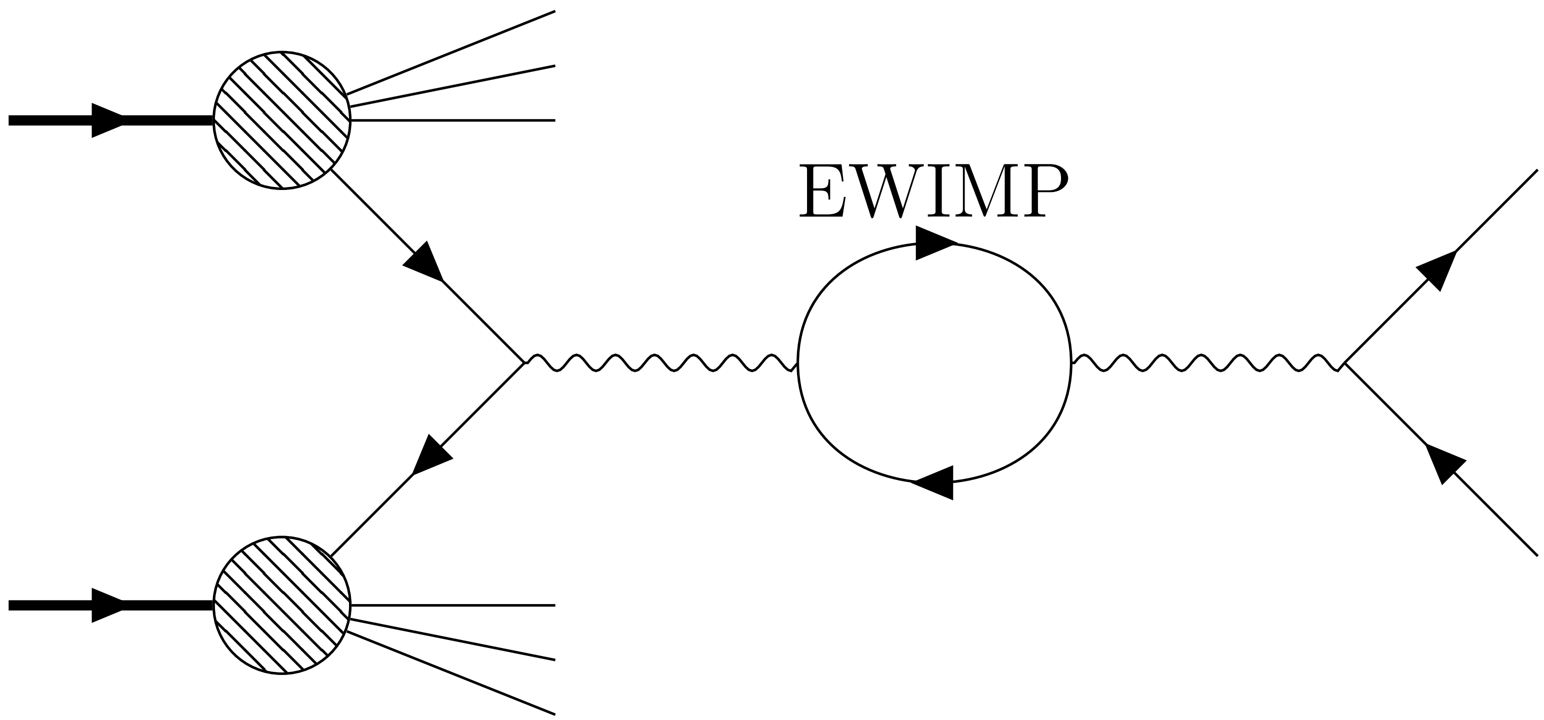
# Oblique correction

- EWIMP acts as an oblique correction:




- We take into account the full contribution.

  ← important to distinguish from systematics (discussed later).

[Peskin&Takeuchi 90,92; Barbieri+ 04; ...]

c.f. $S, T, U, (W, Y, \cdots)$ for $\sqrt{s} \ll m_{\rm NP}$,

and the gauge coupling running for $\sqrt{s} \gg m_{\rm NP}$.

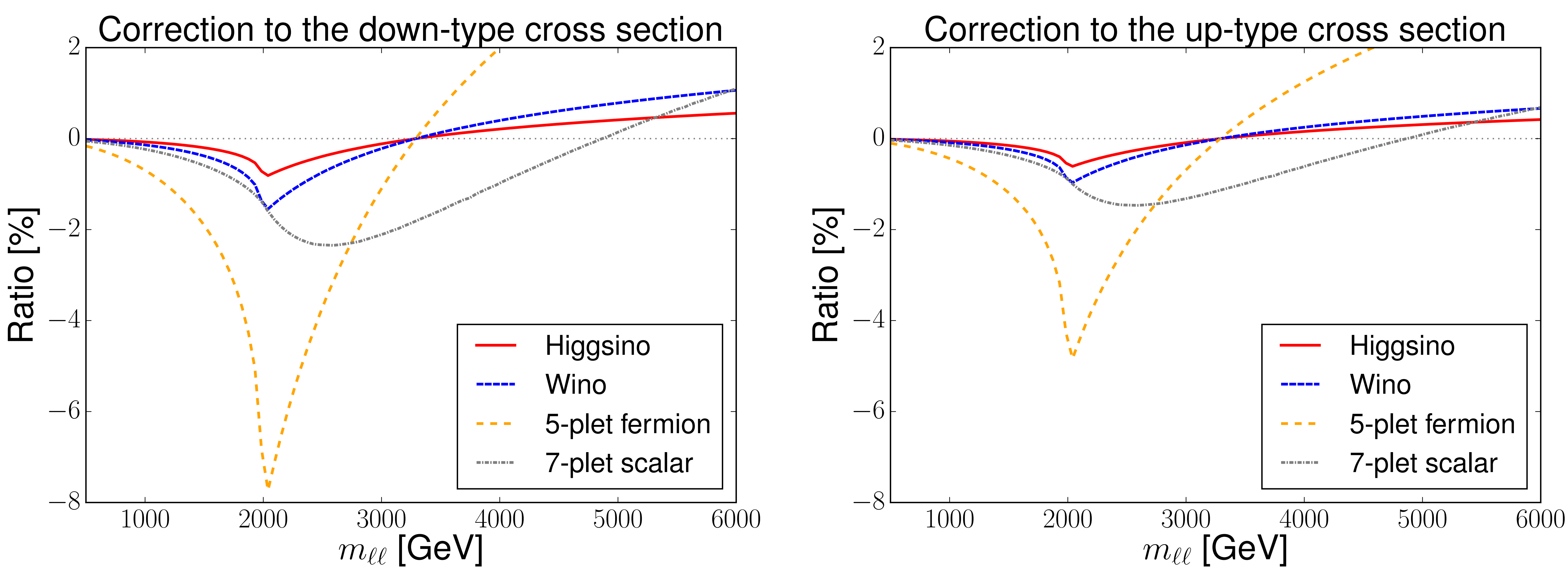
[Alves+ 14; Gross+ 16; ...]

# EWIMP effect

- Define the EWIMP correction

$$\delta_\sigma(m_{ll}) \equiv \frac{d\sigma_{\rm EWIMP}/dm_{ll}}{d\sigma_{\rm SM}/dm_{ll}}$$ for each parton.

- Plot of $\delta_\sigma(m_{ll})$ for $m_{\rm EWIMP} = 1\,{\rm TeV}$ :




- Correction peaked at $m_{ll}/2 = m_{\rm EWIMP}$ → suitable for 100 TeV collider!

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# Event generation and model

- Experiment not performed yet.

➡ Events generated by Monte-Carlo (MadGraph5 & Pythia8 & Delphes3)

$$\mathcal{L} = 30\,\mathrm{ab}^{-1}, \quad 500\,\mathrm{GeV} < m_{ll} < 15\,\mathrm{TeV}, \quad 145\,\mathrm{bin}$$

* NLO: event # → $\times 2$ , detector: $\times 0.8$ and smear momentum.

- Theoretical prediction also computed by MC.

Event #: $\tilde{x}_i(\mu) = \sum_{m_{ll}^{(i)} < m_{ll}^{\mathrm{obs}} < m_{ll}^{(i+1)}} \left[1 + \mu\, \delta_\sigma(m_{ll}^{\mathrm{true}})\right]$ for *i*-th bin,

where $m_{ll}^{\mathrm{obs}}$ : observed invariant mass (simulated by Delphes),

and $m_{ll}^{\mathrm{true}}$ : true invariant mass (read from MadGraph output).

* Pure SM limit: $\mu = 0$, full EWIMP effect: $\mu = 1$.

# Fitting based approach

- Many sources for systematic uncertainties:

  luminosity, beam energy, PDF choice, factorization/renormalization scale, ...

  ➡ Introduce nuisance parameters $\boldsymbol{\theta} = \{\theta_i\}$ to absorb them:

$$\tilde{x}_i(\mu, \boldsymbol{\theta}) = \tilde{x}_i(\mu) f_{\mathrm{sys},i}(\boldsymbol{\theta}), \quad f_{\mathrm{sys},i}(0) = 1.$$

- Variation of nuisance parameters = systematics uncertainties.

- For illustration, we take in the following

$$f_{\mathrm{sys},i} = e^{\theta_1}(1 + \theta_2\, p_i) p_i^{(\theta_3 + \theta_4 \ln p_i + \theta_5 \ln^2 p_i)}, \quad p_i = 2m_{ll,i}/\sqrt{s},$$

that is known to work for LHC. [CMS collaboration 08]

* This choice is just an example.

# Fitting based approach

- Define test statistics as [Cowan+ 10]

$$q_0 \equiv -2\ln\frac{L(\boldsymbol{x};\mu=0,\hat{\hat{\boldsymbol{\theta}}})}{L(\boldsymbol{x};\hat{\mu},\hat{\boldsymbol{\theta}})},$$

where

$$L(\boldsymbol{x};\mu,\boldsymbol{\theta}) \equiv \underbrace{\left(\prod_i \exp\left[-\frac{(x_i-\tilde{x}_i(\mu,\boldsymbol{\theta}))^2}{2\tilde{x}_i(\mu,\boldsymbol{\theta})}\right]\right)}_{\text{likelihood in signal region}} \underbrace{\left(\prod_\alpha \exp\left[-\frac{\theta_\alpha^2}{2\sigma_\alpha^2}\right]\right)}_{\text{our knowledge on systematics}},$$

likelihood in signal region — our knowledge on systematics

$\hat{\hat{\boldsymbol{\theta}}}$ : **maximize** $L(\boldsymbol{x};\mu=0,\boldsymbol{\theta})$, $(\hat{\mu},\hat{\boldsymbol{\theta}})$ : **maximize** $L(\boldsymbol{x};\mu,\boldsymbol{\theta})$.

$\sqrt{q_0}=n$ corresponds to $n\sigma$ discovery. [WIlk 38]

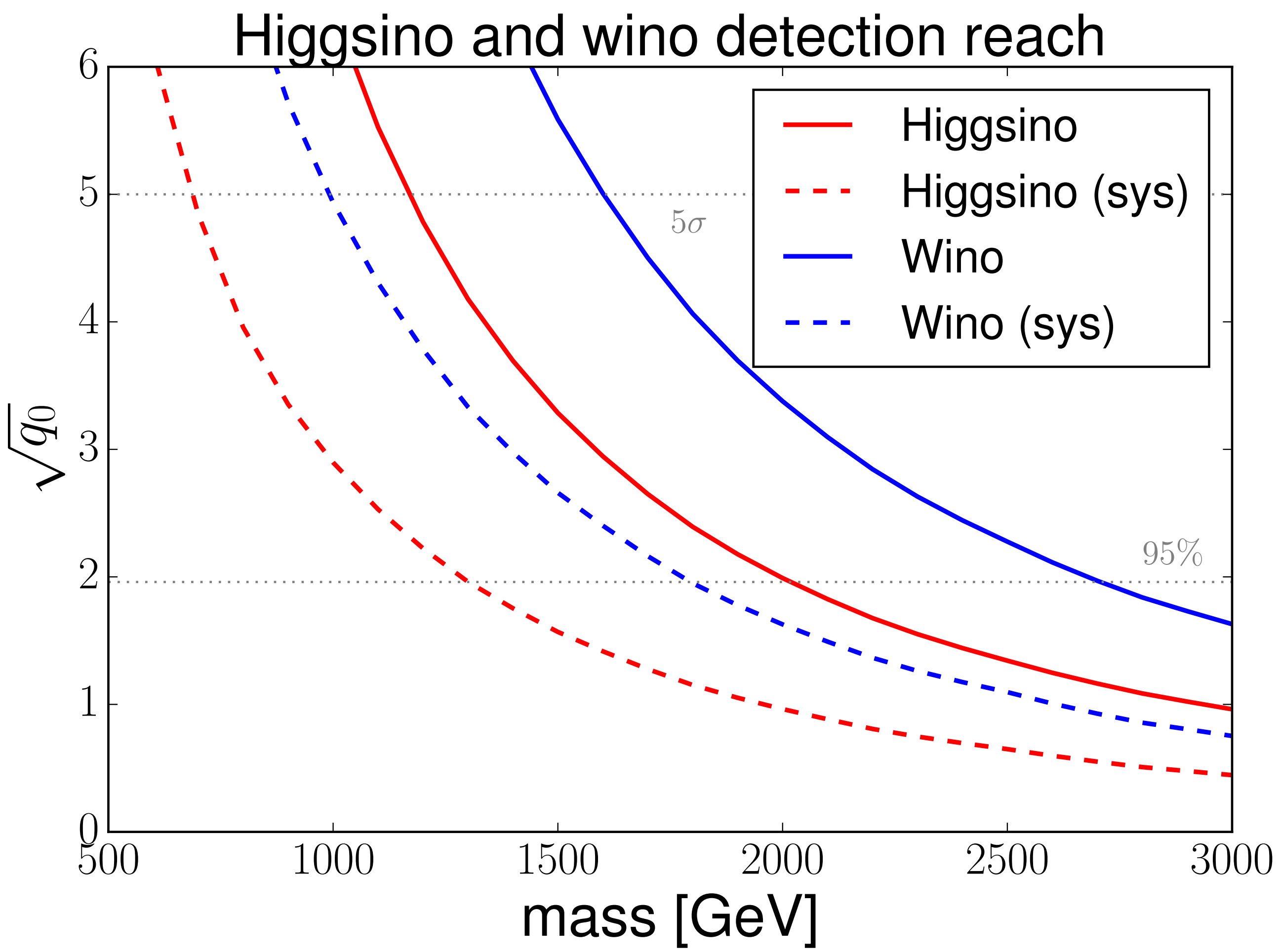
- Estimated the variance $\sigma$ by varying one of the followings:

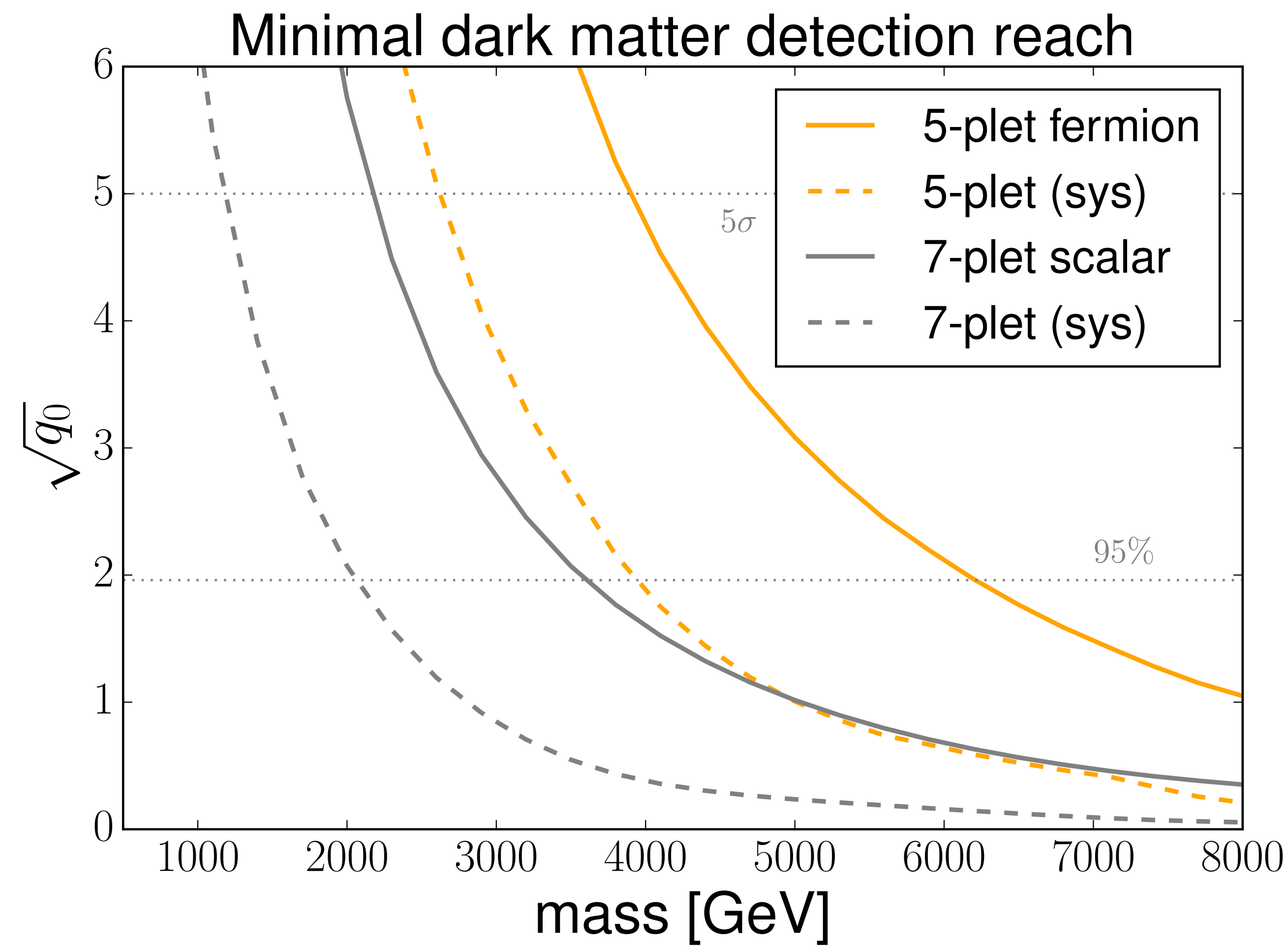
  - luminosity: $\pm 5\,\%$
  - beam energy: $\pm 1\,\%$
  - renormalization scale: $2Q, Q/2$
  - factorization scale: $2Q, Q/2$
  - PDF choice

* They are well fitted by our choice of $f_{\mathrm{sys},i}$ .

# Result

$$\mathcal{L} = 30\,\mathrm{ab}^{-1}$$




| | Higgsino | Wino | 5-plet | 7-plet |
|---|---|---|---|---|
| $5\sigma$ | 0.7 TeV | 1.0 TeV | 2.6 TeV | 1.2 TeV |
| 95% C.L. | 1.3 TeV | 1.8 TeV | 3.9 TeV | 2.1 TeV |

# Comparison

$\mathcal{L} = 30\,\text{ab}^{-1}$

- **Higgsino:**

| | mono-jet | disappearing track | indirect |
|---|---|---|---|
| $5\sigma$ | 0.2 - 0.5 TeV | 0.9 - 1.3 TeV | 0.7 (- 1.2) TeV |
| 95% C.L. | 0.9 - 1.4 TeV | 1.1 -1.5 TeV | 1.3 (- 2.0) TeV |

Indirect method can be strongest!

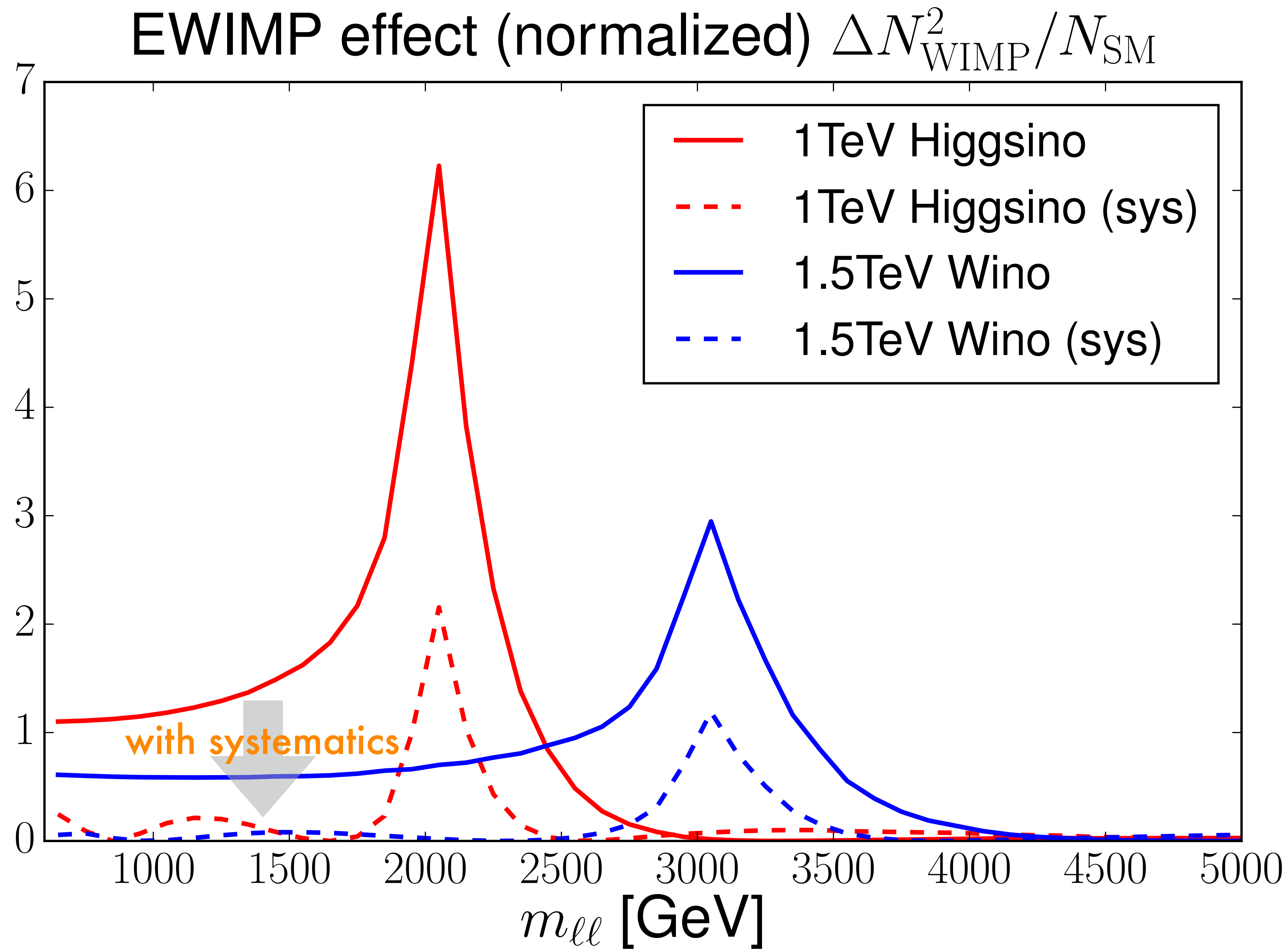
- **Wino:**

| | mono-jet | disappearing track | indirect |
|---|---|---|---|
| $5\sigma$ | 0.5 - 1.0 TeV | 3.6 - 5.4 TeV | 1.0 (- 1.6) TeV |
| 95% C.L. | 1.5 - 2.0 TeV | 4.5 -6.6 TeV | 1.8 (- 2.7) TeV |

Disappearing track seems best way,
indirect method still provides complementary information.

* Mono-jet and disappearing track taken from 1805.00015.

# Contribution from each bin




- Peak is the dominant contribution.
- Peak is not absorbed by systematics.

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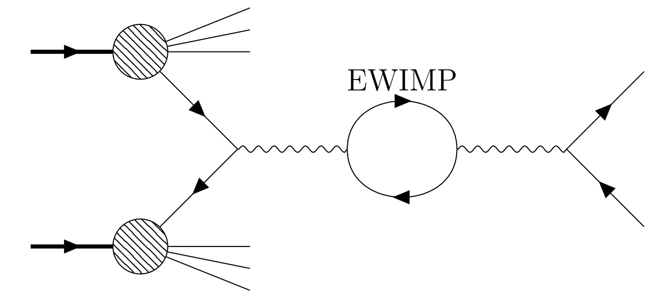
# Summary




- Introduced "indirect" method to probe EWIMPs.
- Study prospect at future 100 TeV hadron collider.
- Indirect method can be the strongest probe for Higgsino.
- Provides complementary information for other EWIMPs.
- Reducing systematic uncertainties has a significant effect.

| | Higgsino | Wino | 5-plet | 7-plet |
|---|---|---|---|---|
| $5\sigma$ | 0.7 TeV | 1.0 TeV | 2.6 TeV | 1.2 TeV |
| $5\sigma$ (opt.) | 1.2 TeV | 1.6 TeV | 3.9 TeV | 2.2 TeV |
| 95% C.L. | 1.3 TeV | 1.8 TeV | 3.9 TeV | 2.1 TeV |
| 95% C.L. (opt.) | 2.0 TeV | 2.7 TeV | 6.2 TeV | 3.6 TeV |

# Back up

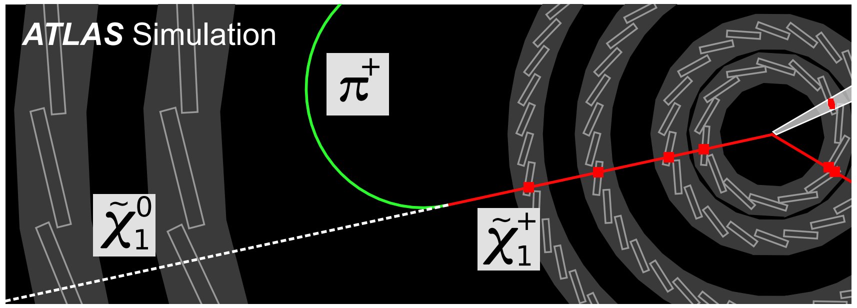
# Conventional DM search

- DM direct detection [Hil and Solon 13; Hisano+ 15; XENON collaboration 18; ...]
  - ✓ Wino, MDM: well within the future detection reach.
  - ✗ Higgsino: below the neutrino floor, difficult to detect.
    (assuming mass splitting (pseudo Dirac) to avoid Z-boson exchange)
- DM indirect detection [Fermi-LAT collaboration 15; HESS collaboration 16,18; ...]
  - ✓ Wino, MDM: severely constrained. (or even excluded for cuspy DM profile)
  - ✗ Higgsino: difficult to probe due to smaller coupling.
  - ✗ Uncertainties of astrophysical origin, e.g. DM profile.

* EWIMP must be the dominant component of DM for both methods.

# Conventional collider search

- Disappearing charged track:




✓ For pure wino/higgsino: $m_{\tilde{W}} < 460\,\mathrm{GeV},\ m_{\tilde{h}} < 152\,\mathrm{GeV}.$

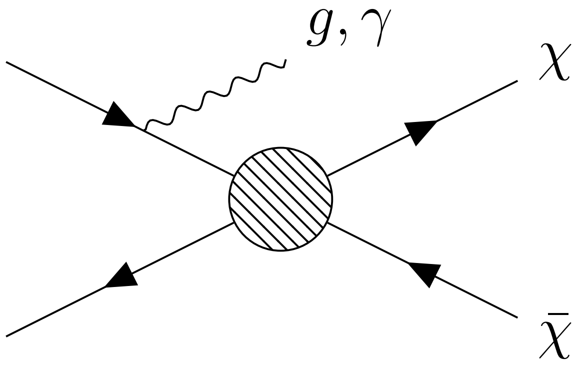
[ATLAS 17; CMS 18]

✓ Wino thermal relic can be well covered by future colliders.

✗ strongly depends on lifetime, or mass difference.

* higgsino: dim-5, and wino: dim-7 in terms of EFT.

- Mono-X search:

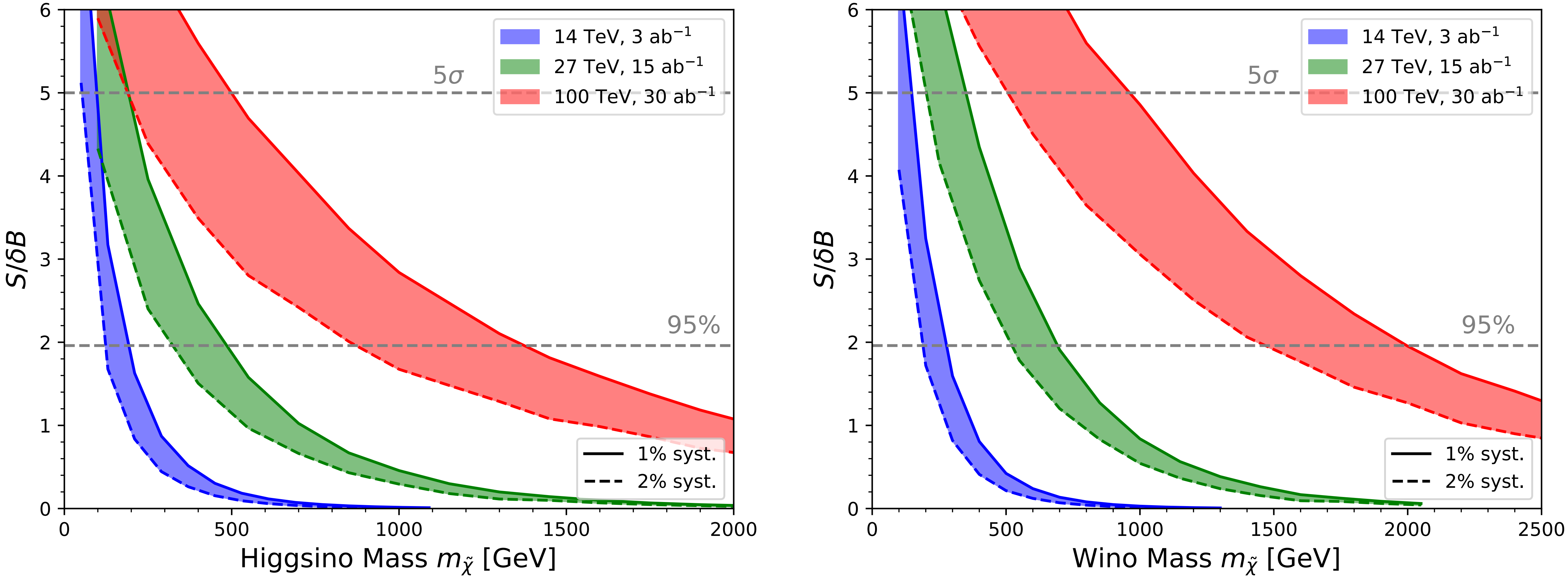



✗ Signal and background: similar distribution

e.g. no significant bound on higgsino at LHC14 [Baer+ 14; ...]

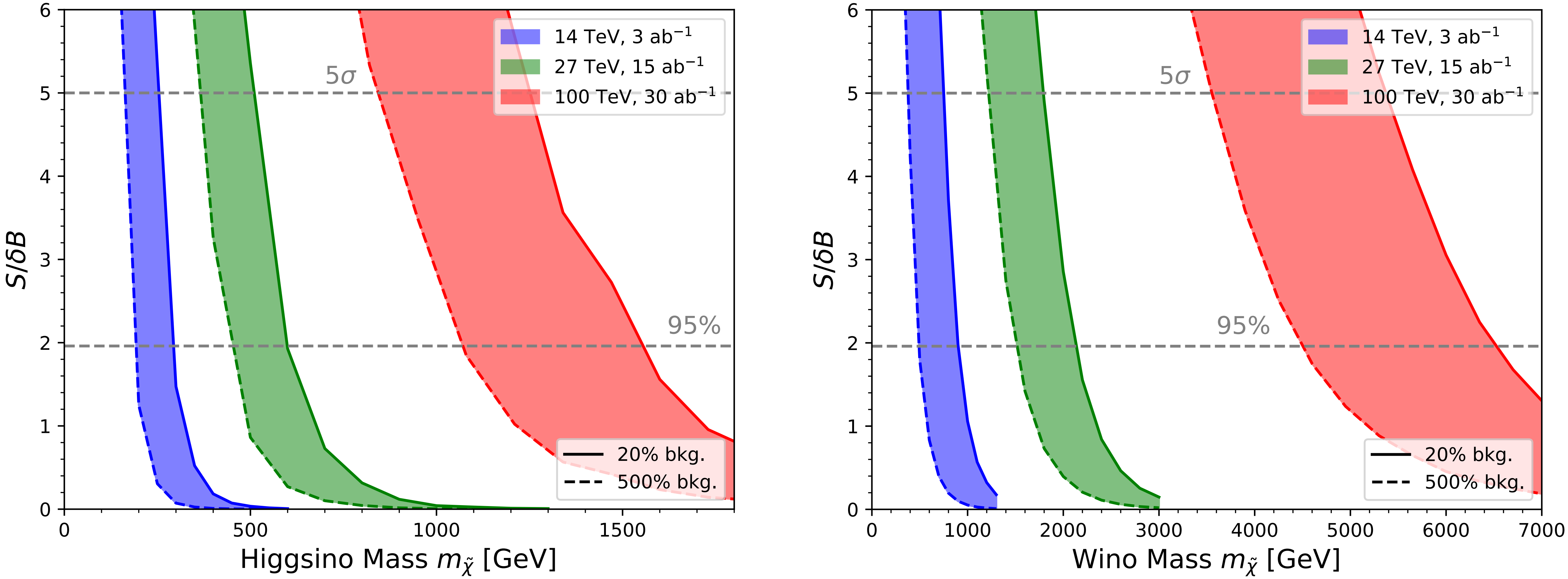
# Collider: mono-jet

[Han+ 18]



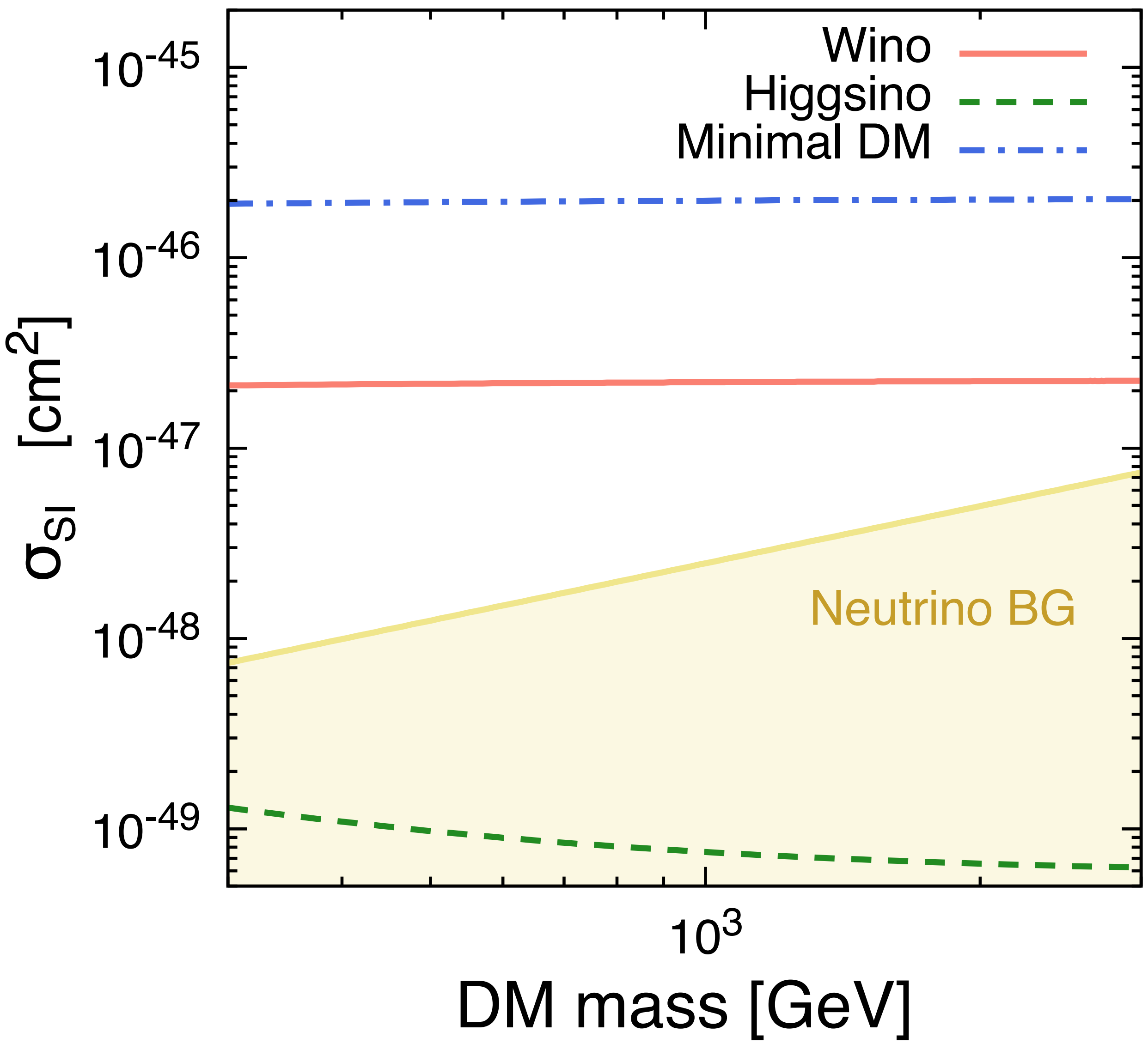
# Collider: disappearing track

[Han+ 18]

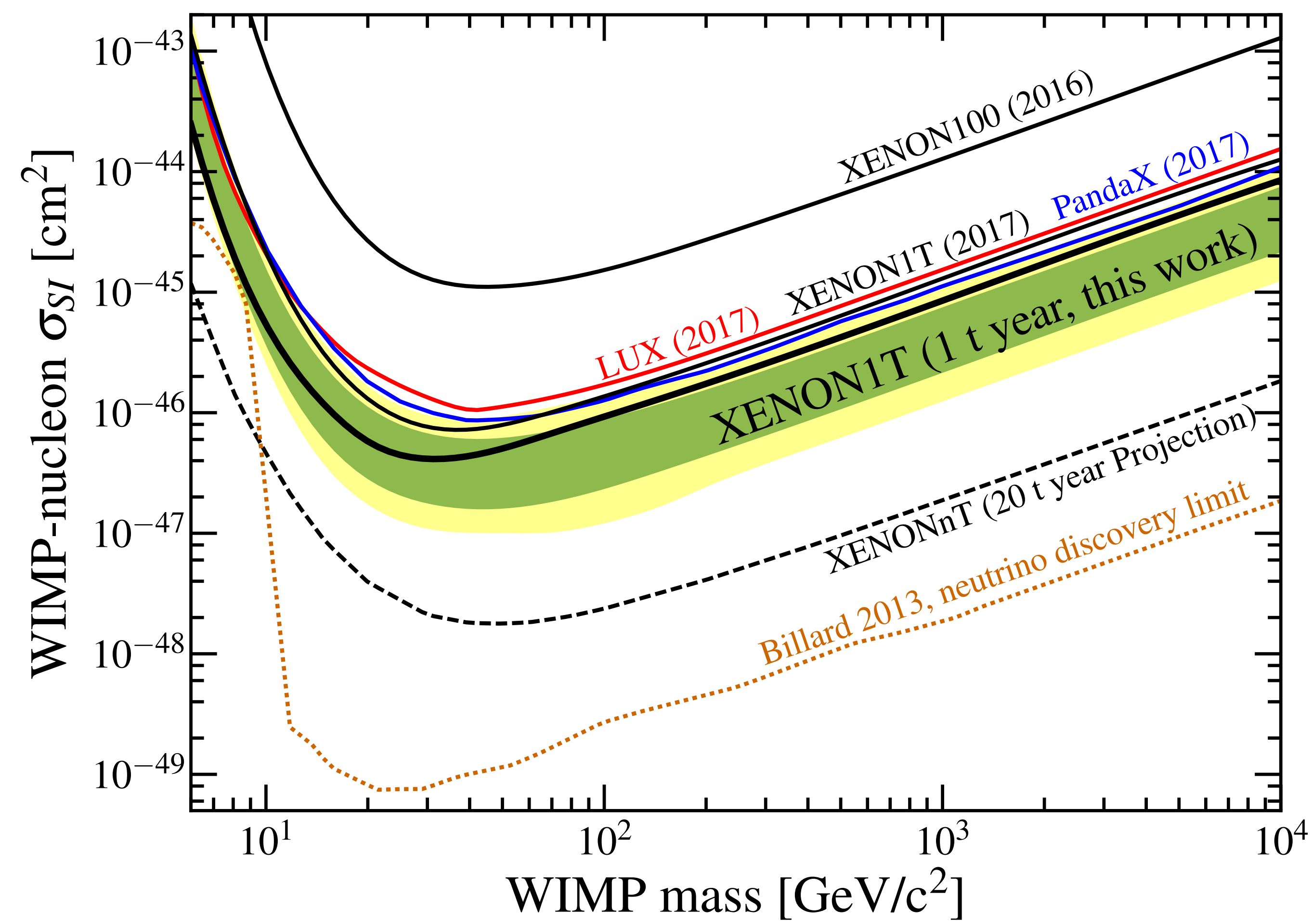


# DM direct detection

[Hisano+ 15]

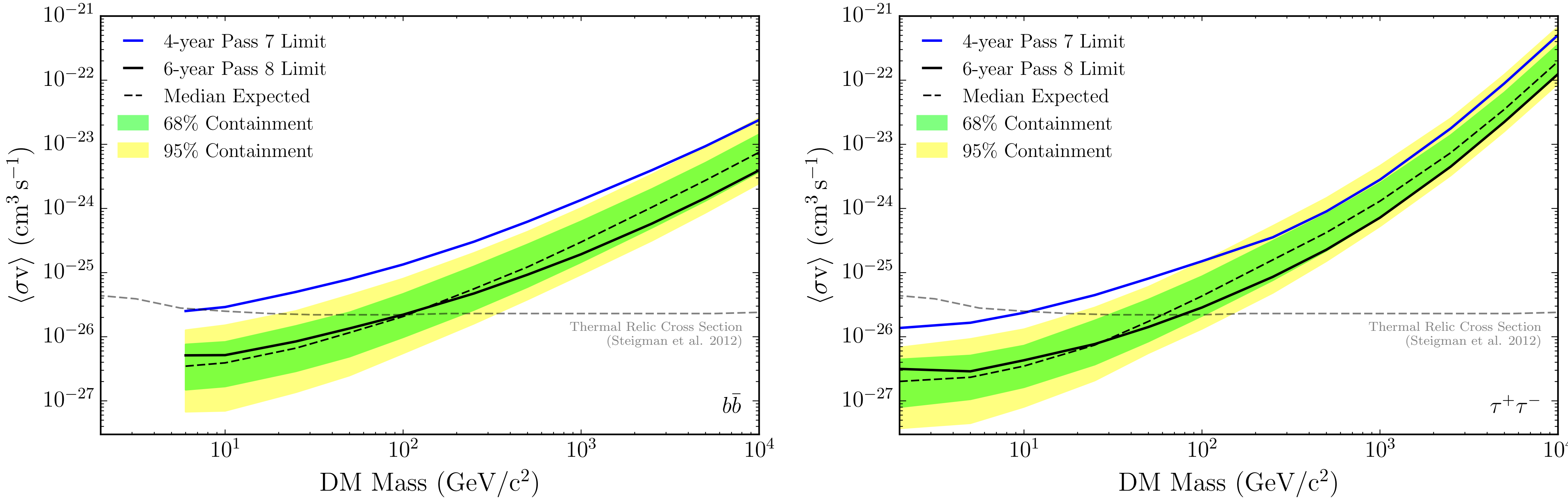



[XENON collaboration 18]

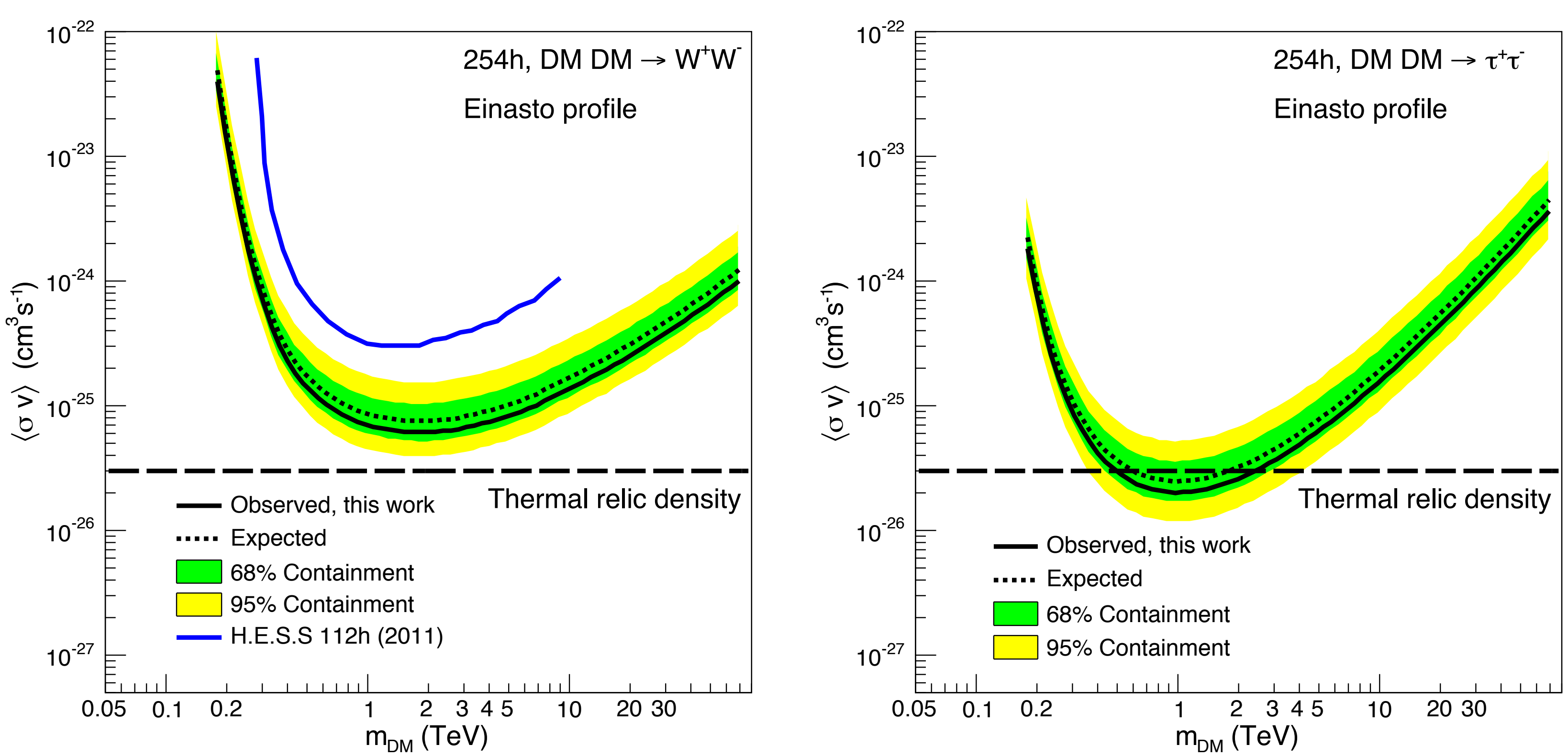


# DM indirect detection

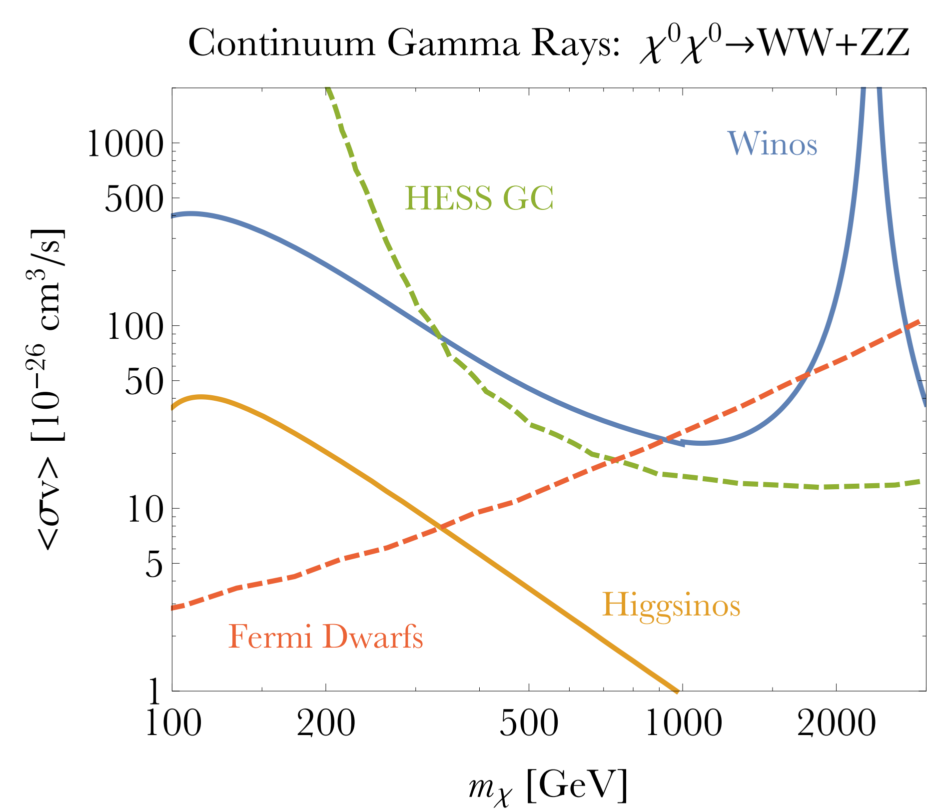
## dwarf spheroidal galaxy [Fermi-LAT collaboration 15]




## galactic center [HESS collaboration 16]




## [Krall and Reece 17]




* Einasto (cuspy) profile is assumed for HESS.

# Mass determination