



# Wino theory and future prospects

Satoshi Shirai (Kavli IPMU)

# Contents

## 1. Wino Dark Matter

- as Minimal Dark Matter
- as SUSY DM
- Simplest SUSY breaking scenario

## 2. Wino Signal

- Uncertainty of Wino abundance
- Collider, (In)Direct Detection

## 3. Summary

# What is Wino

- Majorana fermion  $\widetilde{W}$
- Hypercharge  $Y=0$
- $SU(2)_L$  triplet  $\begin{pmatrix} \widetilde{W}^+ \\ \widetilde{W}^0 \\ \widetilde{W}^- \end{pmatrix}$
- Mass  $< 3 \text{ TeV}$

[Hisano, Matsumoto, Nagai, Saito & Senami, 06]

# Why Wino.

- Most **minimal dark matter**.
  - Only one free parameter.
- Natural prediction of anomaly mediation in SUSY model.

Randall & Sundrum '98

Giudice, Luty, Murayama & Rattazzi '98

- SUSY models consistent with flavor/CP, Higgs mass and GUT.
- Rich signature at direct/indirect dark matter search.
  - Within a few decades, both searches can cover all the region.
- Rich signature at LHC.
  - LHC search technology is also applicable to broad BSM.

# Minimal **WIMP** Dark Matter

**W**eakly **I**nteracting **M**assive **P**article

Minimal setup of DM:

Adding a DM particle to Standard Model

$$\text{SM} + \widetilde{W}$$

Correct DM is realized via Electroweak interaction

Wino is Most **minimal WIMP DM**

# SUSY Standard Model

## Standard Model (SM)

Lepton

Quark

Scalar Higgs

Gauge Boson

gluon

weak boson

photon

## SUSY Partner

Scalar Lepton

Scalar Quark

Higgsino

Gaugino

gluino

**wino**

bino

Figure 1 consists of two panels. The top panel shows the diphoton invariant mass distribution for the selected diphoton sample. The y-axis is labeled "Events / 2 GeV" and ranges from 0 to 7000. The x-axis is labeled  $m_{\gamma\gamma}$  [GeV] and ranges from 100 to 160. The data points are black circles. A solid red line represents the "Sig+Bkg Fit ( $m_H=126.5$  GeV)", and a dotted red line represents the "Bkg (4th order polynomial)". The text "Selected diphoton sample" is at the top. The text "ATLAS Preliminary" is on the right. The bottom panel shows the "Events-Fit" on the y-axis, ranging from -200 to 300. The x-axis is the same as the top panel. The data points are black circles with error bars. A solid red line represents the fit. The text " $\sqrt{s} = 7$  TeV,  $\int \mathcal{L} dt = 4.8 \text{ fb}^{-1}$ " and " $\sqrt{s} = 8$  TeV,  $\int \mathcal{L} dt = 13.0 \text{ fb}^{-1}$ " is on the left.

# SUSY Constrained!

$$m_{\tilde{q}} \gtrsim 2 \text{ TeV}$$

ATLAS SUSY Searches* - 95% CL Lower Limits										ATLAS Preliminary	
December 2017										$\sqrt{s} = 7, 8, 13 \text{ TeV}$	
Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^{\text{min}}$	$ \mathcal{L}_{\text{eff}} (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$		Reference	Reference	
Inclusive Searches	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{q}^*$	0	2-6 jets	Yes	36.1	1	1.57 TeV	$m(\tilde{t}) > 200 \text{ GeV}, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1712.02332		
	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{q}^*$ (compressed)	mono-jet	1-3 jets	Yes	36.1	1	710 GeV	$m(\tilde{q}) > m(\tilde{q}^*) + 5 \text{ GeV}$	1711.02031		
	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{q}^*$	0	2-6 jets	Yes	36.1	1	2.92 TeV	$m(\tilde{q}) > 200 \text{ GeV}, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1712.02332		
	$\tilde{R}\tilde{R} \rightarrow \mu\tilde{R}\tilde{R}^*$	0	2-6 jets	Yes	36.1	1	2.01 TeV	$m(\tilde{R}) > 200 \text{ GeV}, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1712.02332		
	$\tilde{R}\tilde{R} \rightarrow \mu\tilde{R}\tilde{R}^*$	$\epsilon, \mu, \tau$	2 jets	Yes	14.7	1	1.71 TeV	$m(\tilde{R}) > 200 \text{ GeV}$	1611.05791		
	$\tilde{R}\tilde{R} \rightarrow \mu\tilde{R}\tilde{R}^*$	$\epsilon, \mu, \tau$	4 jets	Yes	36.1	1	1.87 TeV	$m(\tilde{R}) > 200 \text{ GeV}$	1706.03731		
	$\tilde{R}\tilde{R} \rightarrow \mu\tilde{R}\tilde{R}^*$	0	7-11 jets	Yes	36.1	1	1.8 TeV	$m(\tilde{R}) > 200 \text{ GeV}$	1706.02794		
	GMSB (f NLSIP)	$1-2 + 0-1$	0-2 jets	Yes	3.2	2	2.6 TeV	$m(\tilde{R}) > 200 \text{ GeV}, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1607.05979		
	GGM bino NLSIP	7	2 jets	Yes	36.1	1	2.65 TeV	$m(\tilde{1}^{\text{st}} \text{ gen.}) > 1700 \text{ GeV}, m(\tilde{2}^{\text{nd}} \text{ gen.}) > 1.5 \text{ TeV}$	ATLAS-COM-2017-040		
	GGM higgsino bino NLSIP	7	2 jets	Yes	36.1	1	2.65 TeV	$m(\tilde{1}^{\text{st}} \text{ gen.}) > 1700 \text{ GeV}, m(\tilde{2}^{\text{nd}} \text{ gen.}) > 1.5 \text{ TeV}$	ATLAS-COM-2017-040		
1 <sup>st</sup> gen. sources direct production	Gravitino LSP	0	mono-jet	Yes	20.3	2	$\mu\text{R}^{\text{th}}$ scale	$m(\tilde{0}) > 1.8 \times 10^{-1} \text{ eV}, m(\tilde{2}^{\text{nd}} \text{ gen.}) > 1.5 \text{ TeV}$	1502.01518		
	$\tilde{R}\tilde{R} \rightarrow h\tilde{R}\tilde{R}^*$	0	3-6	Yes	36.1	1	1.92 TeV	$m(\tilde{R}) > 600 \text{ GeV}$	1711.01901		
	$\tilde{R}\tilde{R} \rightarrow h\tilde{R}\tilde{R}^*$	$0-1 \epsilon, \mu$	3-6	Yes	36.1	1	1.97 TeV	$m(\tilde{R}) > 200 \text{ GeV}$	1711.01901		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	0	2-6	Yes	36.1	1	950 GeV	$m(\tilde{h}_1) > 420 \text{ GeV}$	1706.02986		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$2+0 \mu(\text{SS})$	1-6	Yes	36.1	1	275-700 GeV	$m(\tilde{h}_1) > 200 \text{ GeV}, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1706.03731		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$0-2 \epsilon, 1-6$	Yes	4.713.3	1	1117-1010 GeV	200-720 GeV	$m(\tilde{h}_1) > 2m(\tilde{h}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1209.01202, ATLAS-COM-2016-077		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$0-2 \epsilon, \mu$	$0-2 \text{ jets } 1-2 b$	Yes	20.3, 6.1	1	90-108 GeV	$m(\tilde{h}_1) > 1 \text{ GeV}$	1506.08616, 1708.04181, 1711.11520		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	0	mono-jet	Yes	25.1	1	90-420 GeV	$m(\tilde{h}_1) > 1 \text{ GeV}$	1711.03361		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$2+0 \mu(2)$	1-6	Yes	20.3	1	140-600 GeV	$m(\tilde{h}_1) > 1 \text{ GeV}$	1404.5252		
	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$3+0 \mu(2)$	1-6	Yes	36.1	1	290-170 GeV	$m(\tilde{h}_1) > 0 \text{ GeV}$	1706.03986		
EW direct	$\tilde{h}_1, \tilde{h}_2 \rightarrow h\tilde{h}_1^*$	$1-2 \epsilon, 4-6$	Yes	36.1	1	320-880 GeV	$m(\tilde{h}_1) > 0 \text{ GeV}$	1706.03986			
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$2 \epsilon, \mu$	0	Yes	36.1	1	90-500 GeV	$m(\tilde{t}_1) > 0$	ATLAS-COM-2017-039		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	36.1	1	790 GeV	$m(\tilde{t}_1) > 0, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	ATLAS-COM-2017-039		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	36.1	1	780 GeV	$m(\tilde{t}_1) > 0, m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1708.07875		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	36.1	1.13 TeV	$m(\tilde{t}_1) > m(\tilde{t}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	ATLAS-COM-2017-039		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	36.1	580 GeV	$m(\tilde{t}_1) > m(\tilde{t}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	ATLAS-COM-2017-039		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	36.1	276 GeV	$m(\tilde{t}_1) > m(\tilde{t}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1501.07110		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	Yes	20.3	635 GeV	$m(\tilde{t}_1) > m(\tilde{t}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1450.5086		
	GGM (bino NLSIP) weak prod. $\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$1 \epsilon, \mu$	0	Yes	20.3	1	115-370 GeV	$\epsilon < 1 \text{ mm}$	1607.04563		
	GGM bino NLSIP weak prod. $\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$2 \tau$	0	Yes	36.1	1	1.06 TeV	$\epsilon < 1 \text{ mm}$	ATLAS-COM-2017-040		
Long-lived particles	Direct $\tilde{t}_1, \tilde{t}_2$ prod., long-lived $\tilde{t}_1^*$	Disapp. trk	1 jet	Yes	36.1	1	460 GeV	$m(\tilde{t}_1) > 160 \text{ MeV}, c\tau(\tilde{t}_1) > 0.2 \text{ m}$	1712.02118		
	Direct $\tilde{t}_1, \tilde{t}_2$ prod., long-lived $\tilde{t}_1^*$	cdx trk trk	-	Yes	18.4	1	495 GeV	$m(\tilde{t}_1) > 160 \text{ MeV}, c\tau(\tilde{t}_1) > 0.2 \text{ m}$	1506.05332		
	Stable, stopped $\tilde{t}_1$ hadron	0	1-5 jets	Yes	27.9	1	850 GeV	$m(\tilde{t}_1) > 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{t}_1) < 100 \mu\text{s}$	1310.8554		
	Stable $\tilde{t}_1$ hadron	trk	-	3.2	1	1	1.59 TeV	$m(\tilde{t}_1) > 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{t}_1) < 100 \mu\text{s}$	1606.05109		
	Metastable $\tilde{t}_1$ hadron	cdx trk trk	-	3.2	1	1	1.57 TeV	$m(\tilde{t}_1) > 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{t}_1) < 100 \mu\text{s}$	1606.04520		
	Measurable $\tilde{t}_1$ hadron, $\tilde{t}_1 \rightarrow q\tilde{t}_1^*$	displ. vtx	-	Yes	32.8	1	537 GeV	$m(\tilde{t}_1) > 100 \text{ GeV}, 1.7 \text{ m} < c\tau(\tilde{t}_1) < 100 \text{ GeV}$	1710.04951		
	GMSB, stable $\tilde{t}_1 \rightarrow \tilde{t}_1 + \text{hadron}$	$1-2 \mu, \tau$	-	Yes	19.1	1	1.0 TeV	$1-10 \mu\text{s} < \tau(\tilde{t}_1) < 100 \text{ GeV}$	1411.0795		
	GMSB, $\tilde{t}_1 \rightarrow \tilde{t}_1 + \text{hadron}$	2 $\tau$	-	Yes	20.3	1	440 GeV	$1 \text{ cm} < c\tau(\tilde{t}_1) < 10 \text{ cm}, \text{SPS model}$	1408.5542		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow \text{neutrino} + \text{jet}$	displ. cdx jet/jet	-	20.3	1	1	1.0 TeV	$7 \text{ cm} < c\tau(\tilde{t}_1) < 740 \text{ mm}, m(\tilde{t}_1) > 1.3 \text{ TeV}$	1504.05162		
	LFV $\tilde{p}\tilde{p} \rightarrow h\tilde{t}_1 + X, \tilde{t}_1 \rightarrow q\tilde{t}_1^*$	$q\tilde{t}_1^*$ jet	-	3.2	1	1	1.9 TeV	$\tilde{A}_{\tilde{t}_1\tilde{t}_1^*} > 0.07$	1607.08079		
RPV	Binlinear RPV CMSSM	$2+0 \mu(\text{SS})$	$0-3 b$	Yes	20.3	1	1.45 TeV	$m(\tilde{g}) > m_{\tilde{t}_1} + 1 \text{ GeV}$	1404.2500		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$4 \epsilon, \mu$	-	Yes	13.9	1	1.14 TeV	$m(\tilde{t}_1) > 400 \text{ GeV}, \tilde{A}_{\tilde{t}_1\tilde{t}_1^*} > 0.1$	ATLAS-COM-2016-055		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$3 \epsilon, \mu + \tau$	-	Yes	20.3	1	450 GeV	$m(\tilde{t}_1) > 2m(\tilde{t}_2), m(\tilde{1}^{\text{st}} \text{ gen.}) < m(\tilde{2}^{\text{nd}} \text{ gen.})$	1408.50875		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	4-5 large $p_{\text{T}}$ jets	-	36.1	1	1.475 TeV	$m(\tilde{t}_1) > 1075 \text{ GeV}$	SUSY-16-022		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$1-2 \mu, \tau$	8-10 jets $0-4 b$	-	36.1	1	1.4 TeV	$m(\tilde{t}_1) > 1 \text{ TeV}, \tilde{A}_{\tilde{t}_1\tilde{t}_1^*} > 0$	1704.08493		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$1-2 \mu, \tau$	8-10 jets $0-4 b$	-	36.1	1	1.65 TeV	$m(\tilde{t}_1) > 1 \text{ TeV}, \tilde{A}_{\tilde{t}_1\tilde{t}_1^*} > 0$	1704.08493		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	0	2 jets $+ 2 b$	-	36.1	1	170-470 GeV	$m(\tilde{t}_1) > 170 \text{ GeV}$	1710.07711		
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t\tilde{t}_1^*$	$2+0 \mu, \tau$	2-6	-	36.1	1	6.4-14 TeV	$\text{BR}(\tilde{t}_1 \rightarrow h\tilde{t}_1) > 30\%$	1710.05544		
	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}^*$	0	2 $\tau$ jets	20.3	1	1	510 GeV	$m(\tilde{c}) > 200 \text{ GeV}$	1501.01325		

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on  $\mu = 0$ .

\*Only a selection of the available mass limits on new stable phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# SUSY Higgs

Higgs potential

$$V(H) = \frac{\lambda}{2} (HH^\dagger - v^2)^2$$

In minimal SUSY model

$$\lambda = \frac{1}{4} (g_1^2 + g_2^2) \cos(2\beta)$$

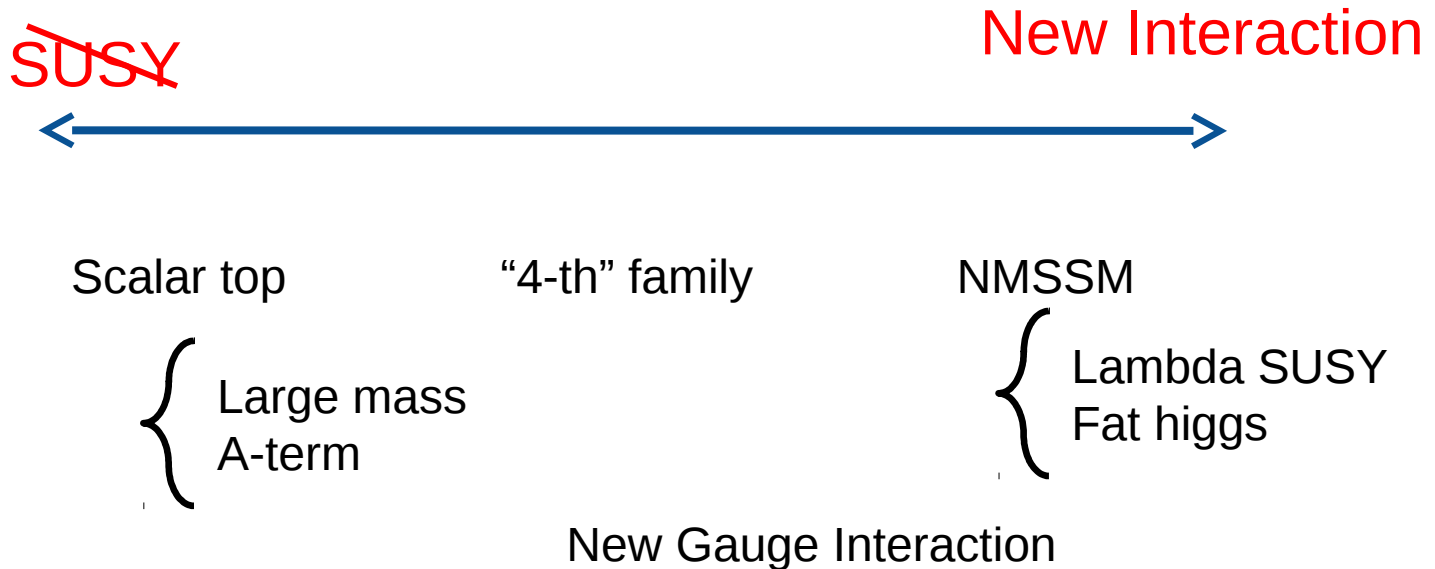
$$m_h = m_Z \cos(2\beta) \lesssim 91 \text{ GeV}$$

This is clearly less than observed 125 GeV Higgs!

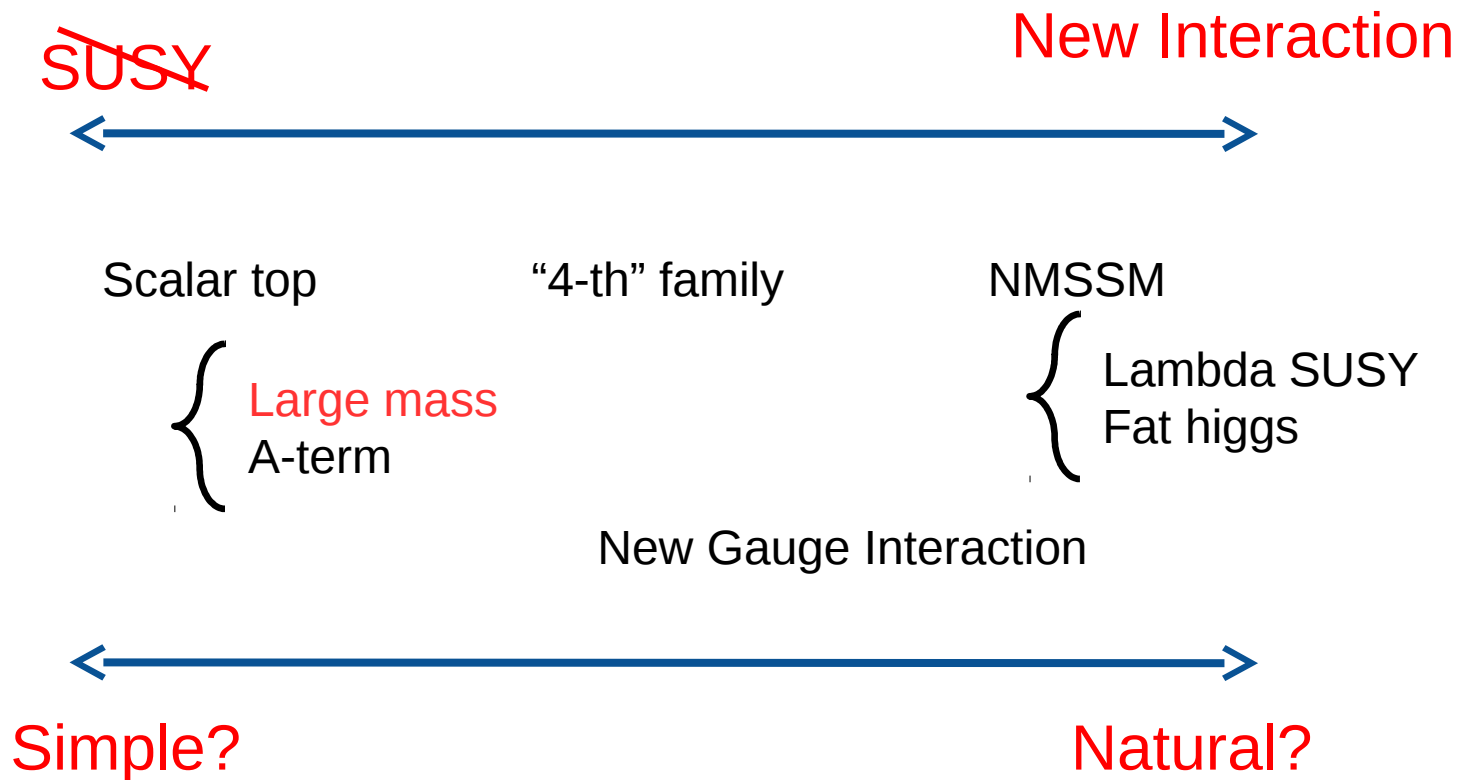
$$\lambda = \lambda_{\text{MSSM}} + \lambda_{\text{SUSY breaking}} + \lambda_{\text{new interaction}}$$



# SUSY after 125 GeV Higgs

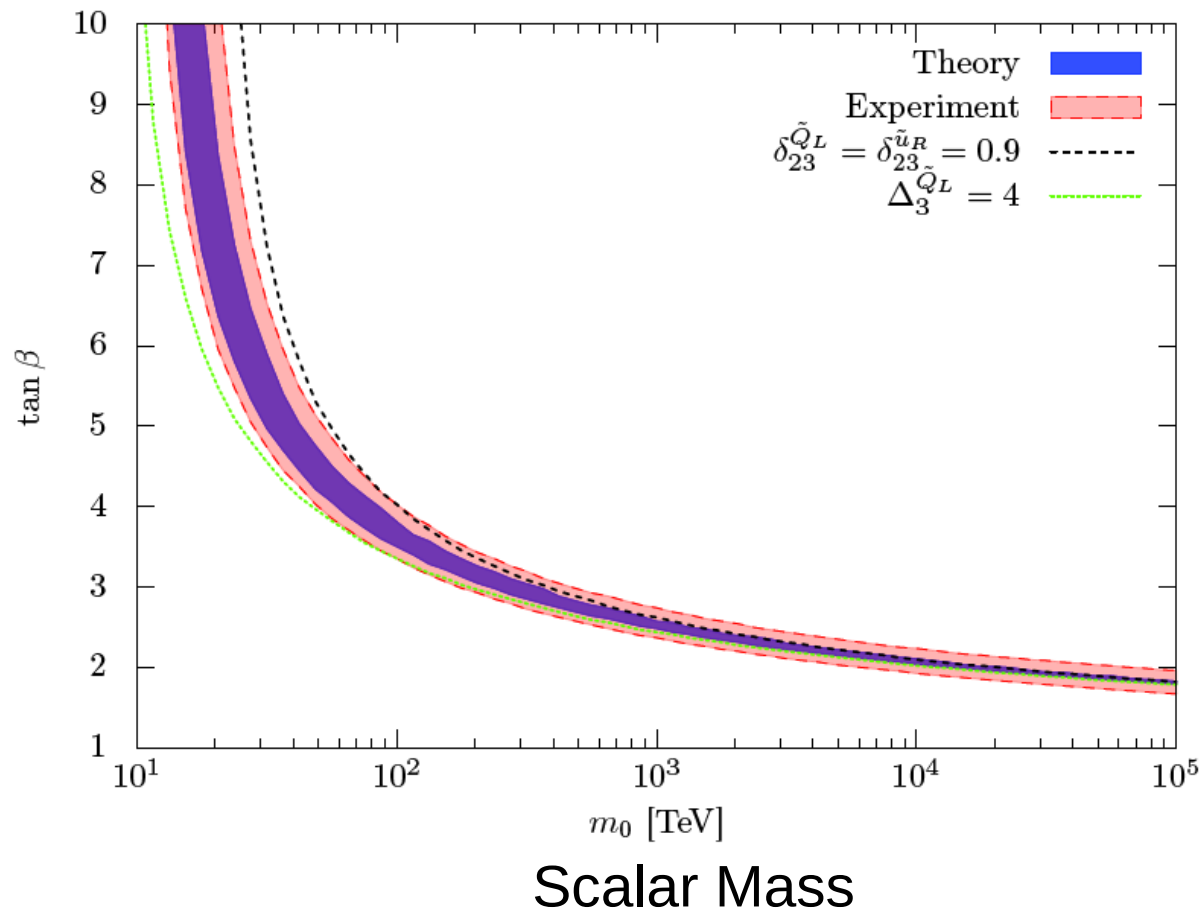


# SUSY after 125 GeV Higgs



# Higgs Mass from Stop

125 GeV Higgs OK regions



# Mini-Split Mass Spectrum

Tree level Gravity Mediation

$$m_0 \sim m_{3/2}$$

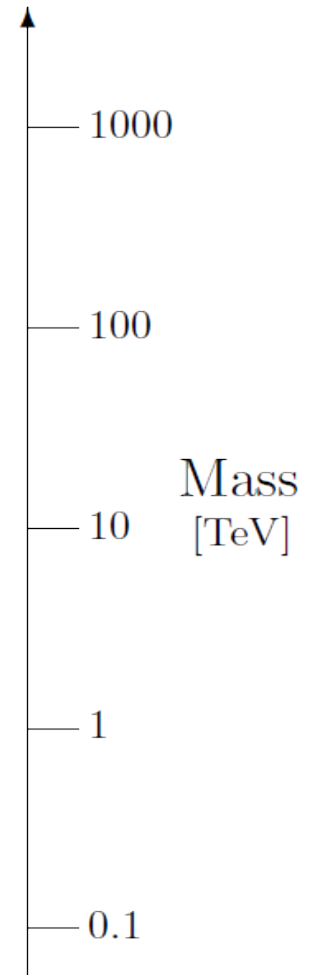
$$\frac{\tilde{q}, \tilde{l}, H}{\vdots} \quad \frac{\tilde{G}}{\tilde{h}}$$

Loop suppressed: Anomaly Mediation

$$M_a \sim \frac{\alpha_a}{4\pi} m_{3/2}$$

Randall, Sundrum '98  
Giudice, Luty, Murayama, Rattazzi '98

$$\frac{\tilde{g}}{\tilde{B}} \quad \frac{\tilde{W}}{h^0}$$



# Gaugino Mass

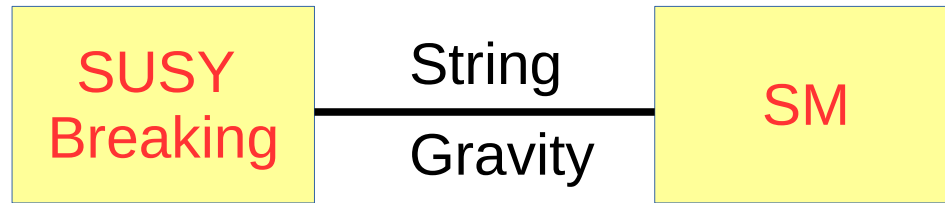
$$M_{\text{bino}} = 11 \times \frac{3}{5} \frac{\alpha_1}{4\pi} \times m_{3/2}$$

$$M_{\text{wino}} = \frac{\alpha_2}{4\pi} \times m_{3/2}$$

$$M_{\text{gluino}} = -3 \times \frac{\alpha_3}{4\pi} \times m_{3/2}$$

In anomaly mediation, the **Wino** is the lightest particle.

# Setup



- Spontaneous SUSY breaking
- No light particles coupling directly both ~~SUSY~~ and SM sector
  - Planck Scale Effects (Gravity or String) communicated
- **Global Symmetry** to suppress Gaugino Mass
  - Necessary condition of SUSY Breaking (Nelson-Seiberg theorem)

**This setup automatically realizes mini-split**

# Mini-Split Models

## Theory papers

### Before Higgs Discovery

Wells, "PeV-Scale SUSY," 2004

Arkani-Hamed, et.al., "(Minimal) Split SUSY," 2005

### After Higgs

Hall, Nomura, "Spread SUSY," 2011

Ibe, Yanagida, "Pure Gravity Mediation," 2011

Arvanitaki, et.al., "Mini-Split," 2012

Arkani-Hamed, et.al., "Simply Unnatural SUSY," 2012

Nomura, Shirai, "SUSY from Typicality," 2014

and various literatures...

# Benefit and demerit of SUSY

## Benefit

- Hierarchy Problem
- GUT unification
- DM

## Possible demerit

- Flavor/CP Problem
- Cosmological Gravitino Problem
- Model building



# Benefit and demerit of SUSY

## Benefit

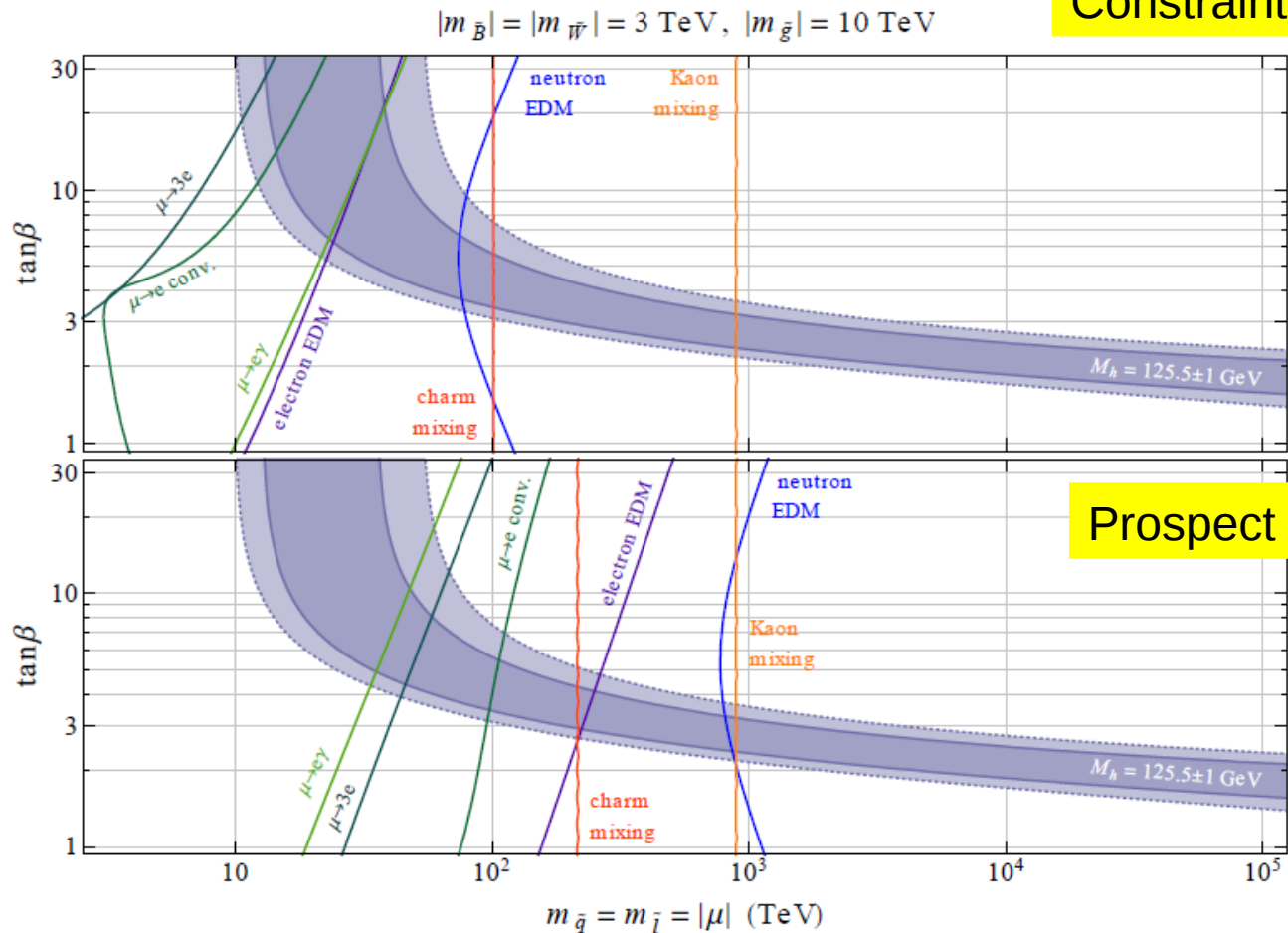
- Hierarchy Problem
- ✓ • GUT unification
- ✓ • DM

## Possible demerit

- ✓ • Flavor/CP Problem
- ✓ • Cosmological Gravitino Problem
- ✓ • Model building

# Flavor/CP Constraints

[Altmannshofer, Harnik, Zupan, 1308.3653]

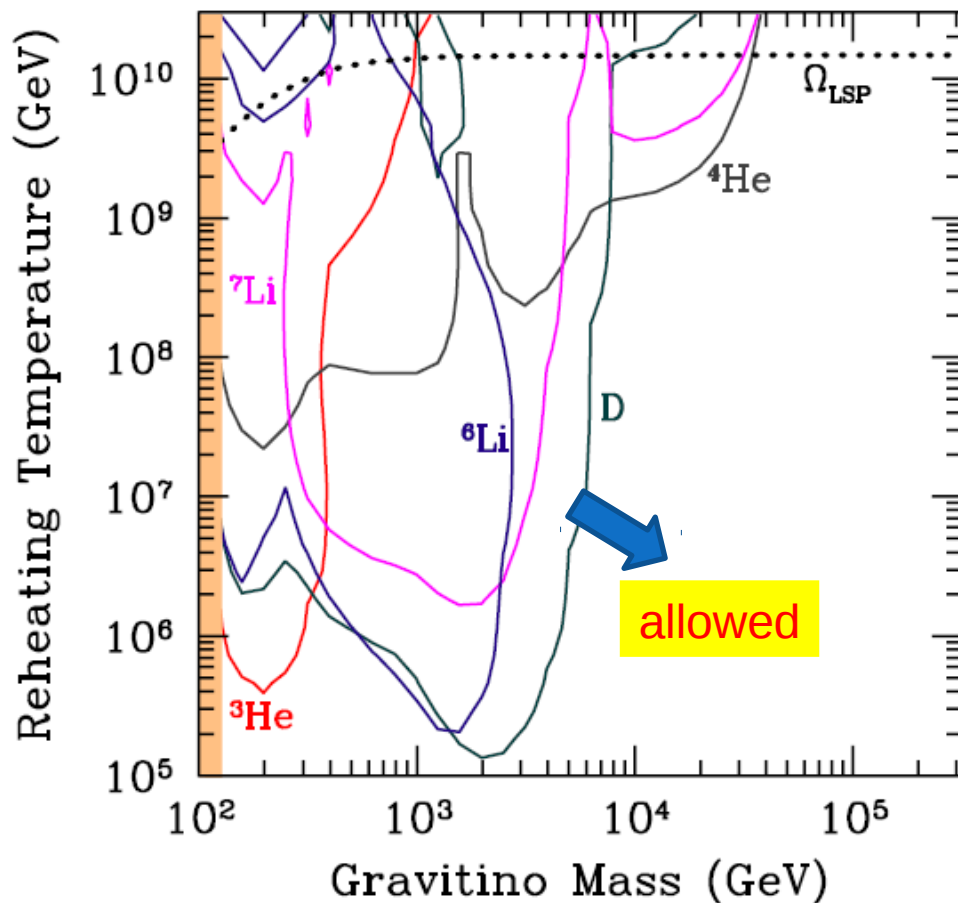


For O(100) TeV Sfermion, no Flavor/CP problems

# Constraint from Cosmology

[Kawasaki et.al, arXiv:0804.3745]

## Cosmological constraints



$$\tau_{\tilde{G}} \simeq 10 \left( \frac{m_{3/2}}{10 \text{ TeV}} \right)^{-3} \text{ sec}$$

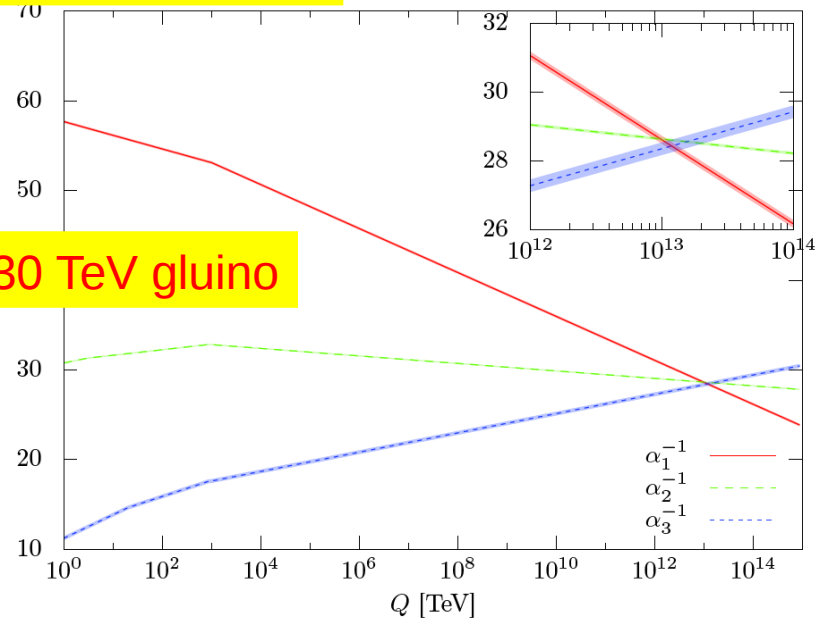
Decay before BBN era ( $\sim 1$  sec)

For  $O(100)$  TeV Gravitno, no BBN problems

# GUT

Sfermion 1000TeV

3 TeV Wino and 30 TeV gluino

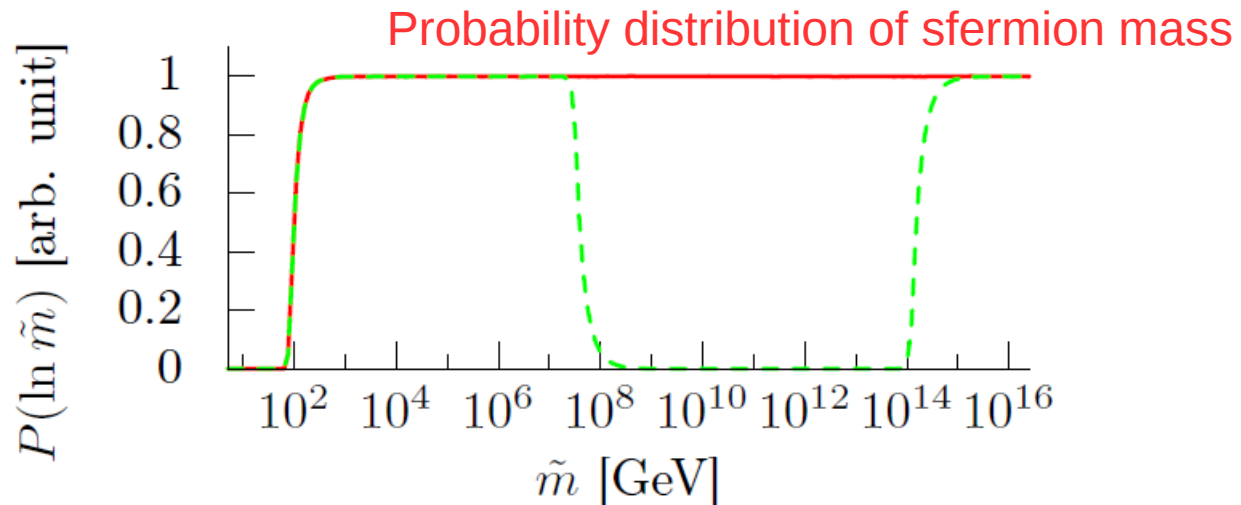


- Coupling Unification better than Weak Scale SUSY
- Minimal SU(5) GUT is Viable

# Typical SUSY

From view point of string landscape,  
mini-split is most “typical” spectrum, if

- Cosmological constant and EW scale are tuned,
- Dynamical SUSY breaking,
- Minimal SU(5) GUT.



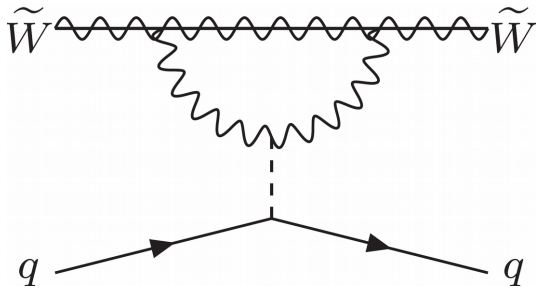
# Theoretical view of Wino

- Most Minimal DM
- Prediction of Simplest SUSY scenario.
  - Minimal assumption of SUSY breaking
  - Higgs mass is OK
  - Flavor/CP and cosmological problem OK
  - Favored by string landscape



# Wino Signal

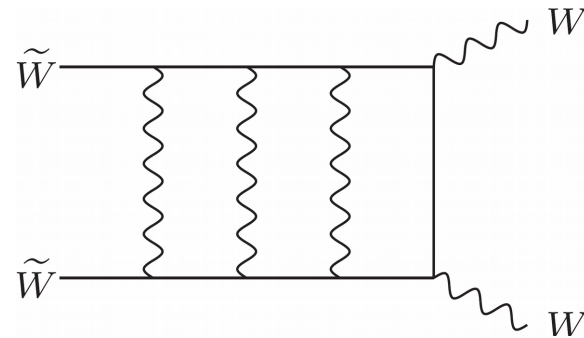
# Wino Signal



## Direct Detection

[Hisano, Ishiwata & Nagata, 12]

Wino-Nucleon XS  $\sim 10^{-47} \text{ cm}^2$



## Indirect Detection

[Hisano, Matsumoto, Nojiri & Saito, 04]

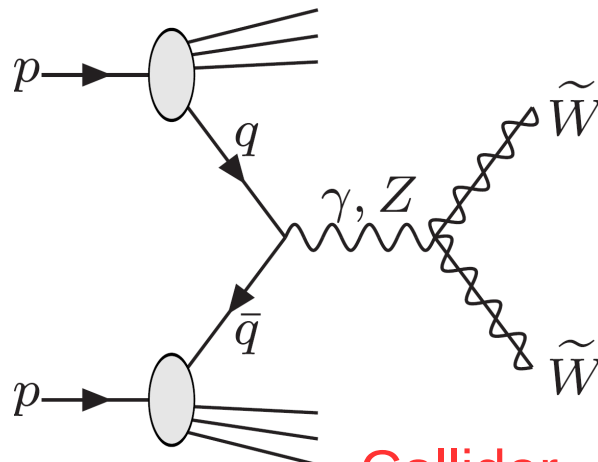
$$\widetilde{W}\widetilde{W} \rightarrow \gamma V$$

Line Photon

$$\widetilde{W}\widetilde{W} \rightarrow WW$$

Continuum Photon

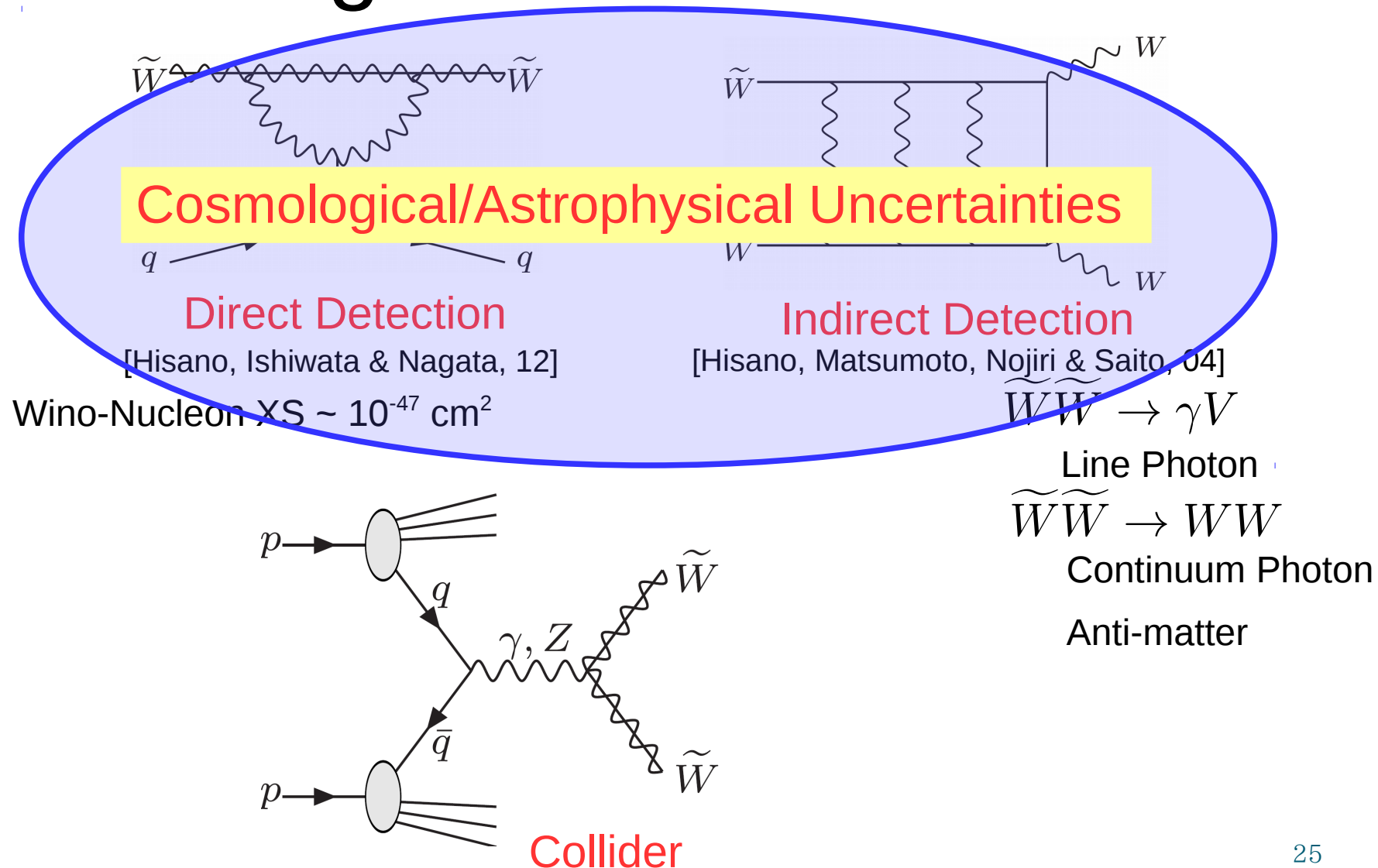
Anti-matter



Collider

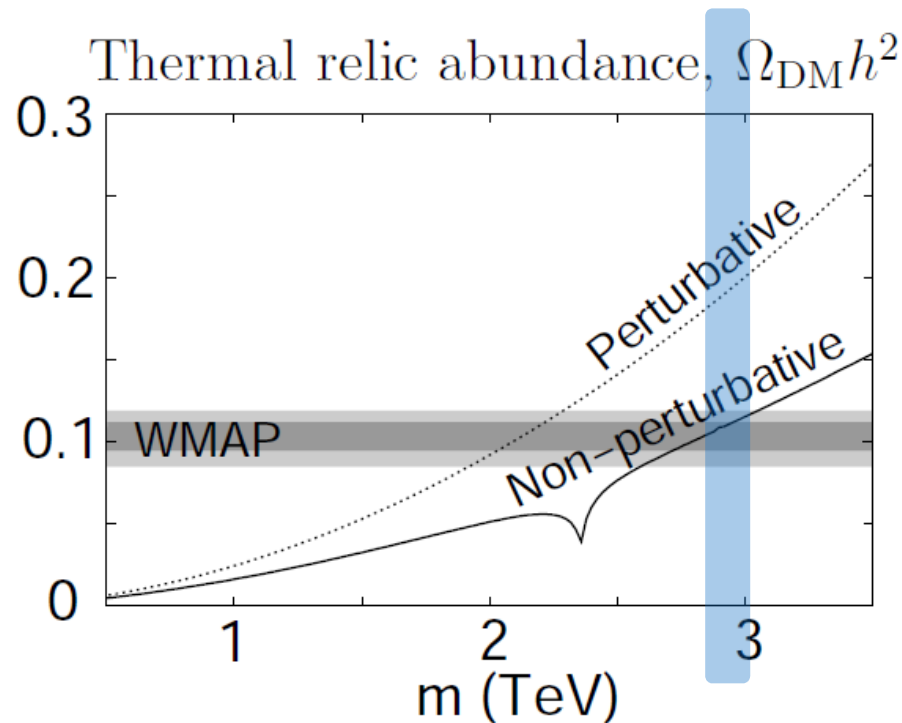


# Wino Signal

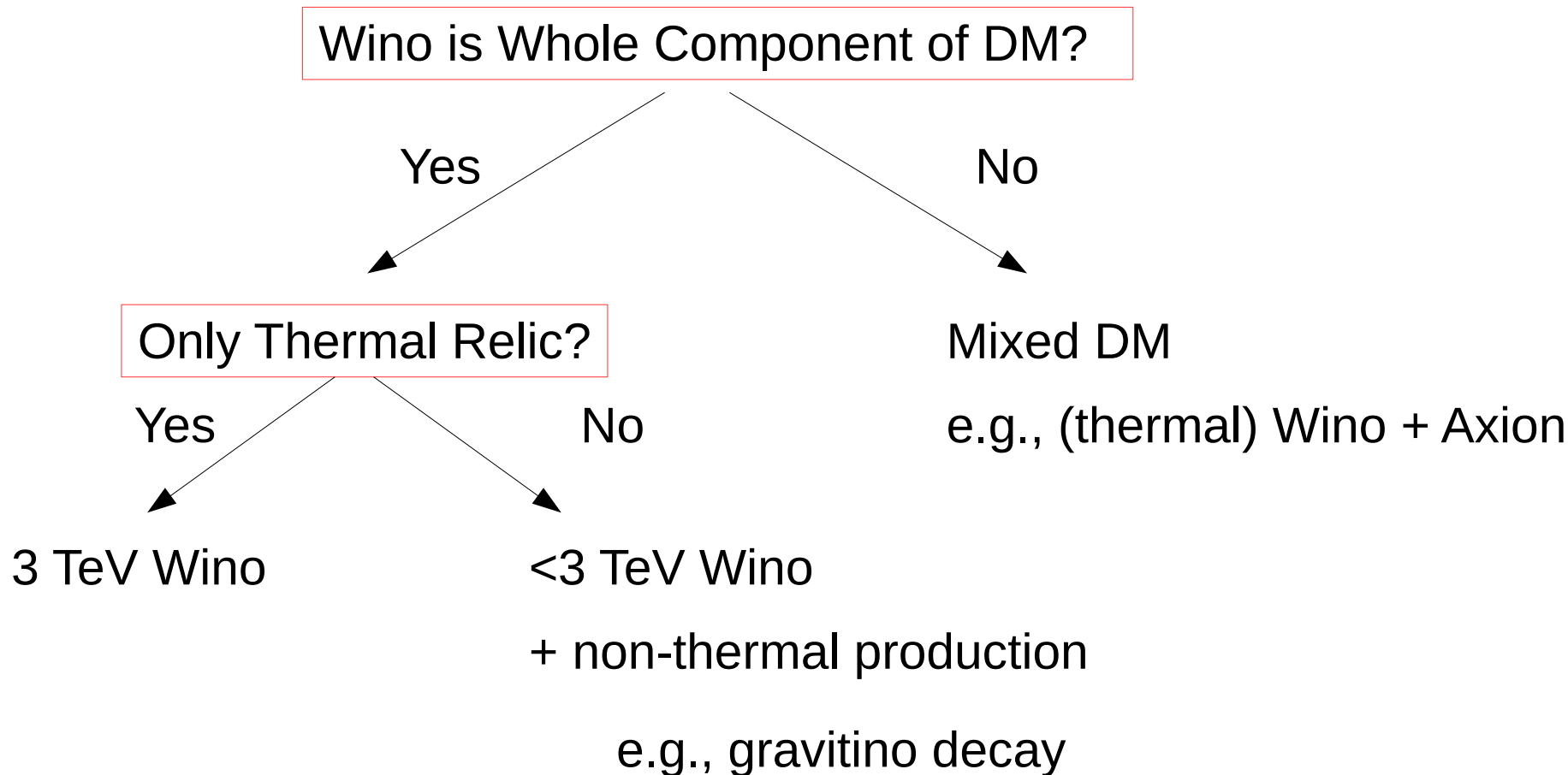


# Wino Thermal Abundance

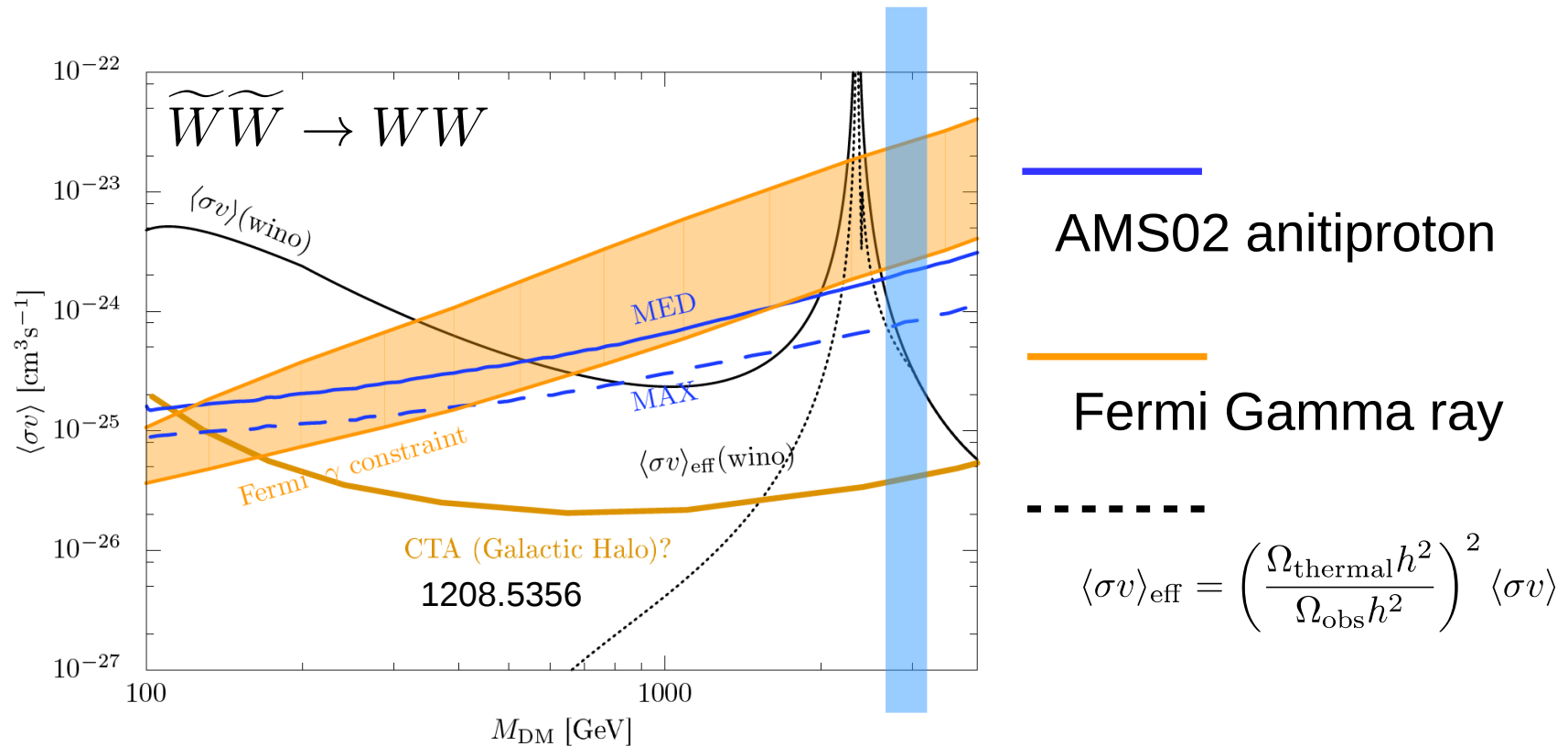
[Hisano, Matsumoto, Nagai, Seto, Senami, 06]



# Wino Abundance Uncertainty

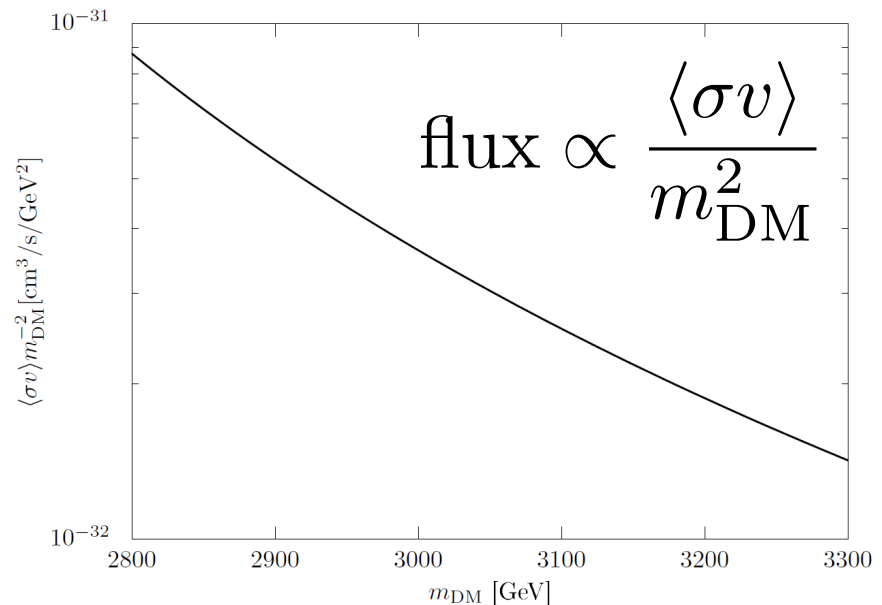
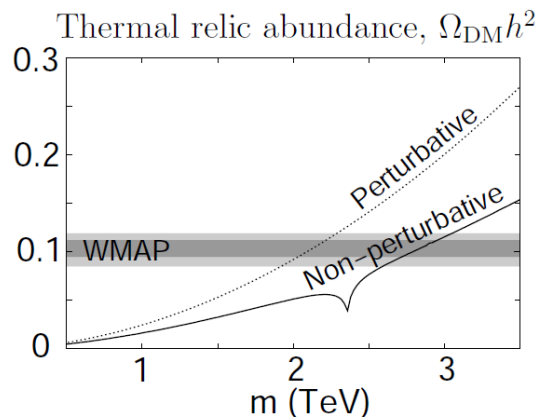


# Cosmic Ray Signals



Large Uncertainty of Astrophysical model and DM density

# How Robust 3 TeV Wino?

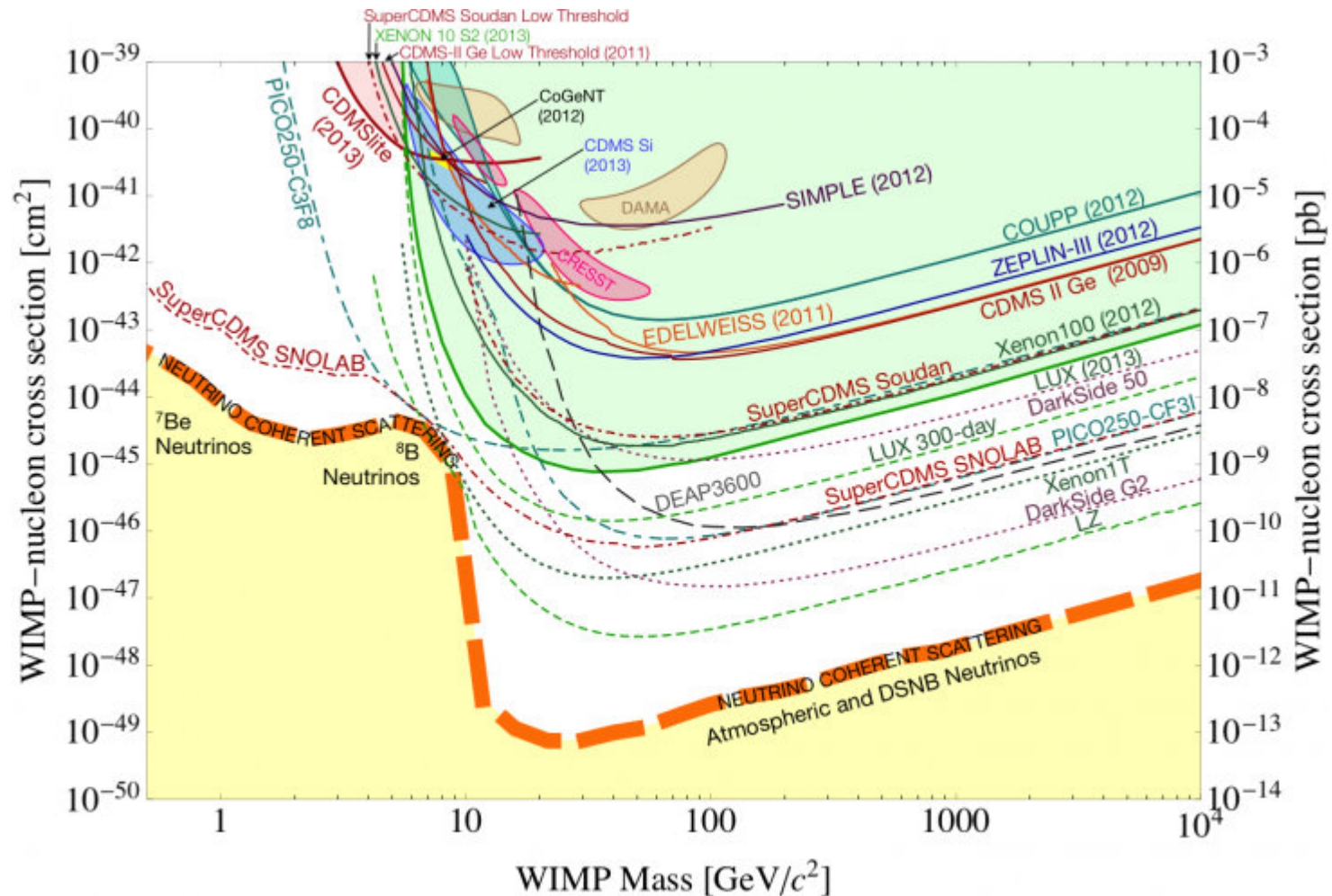


- Thermal effect,
  - Higher-order Correction,
  - Non-perturbative effect (bound state formation...)
- can change the thermal abundance.

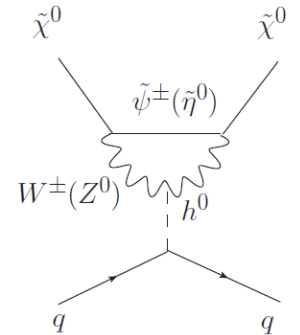
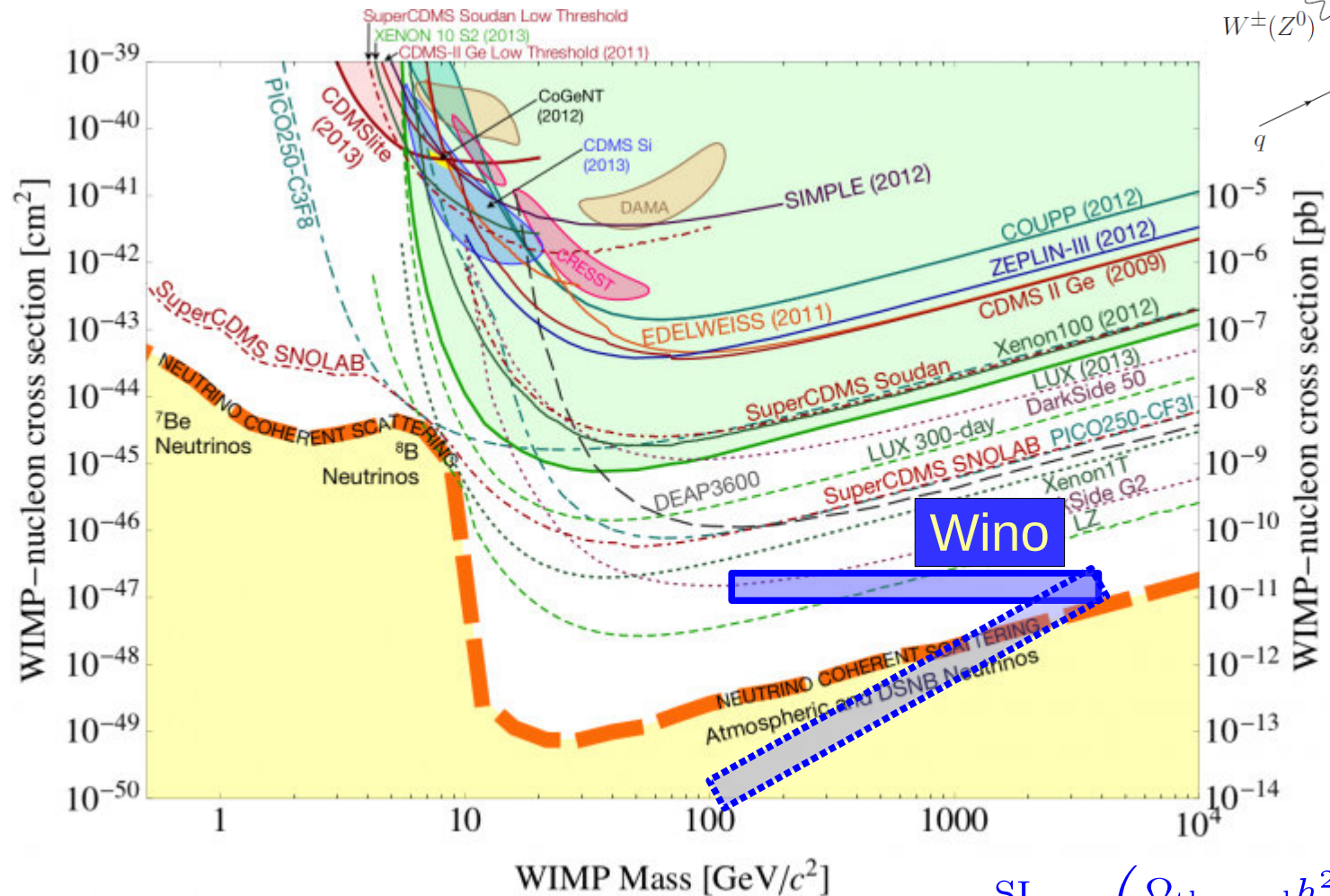


O(10)% effect on abundance  $\rightarrow$  O(100)% effect on flux

# Direct Detection



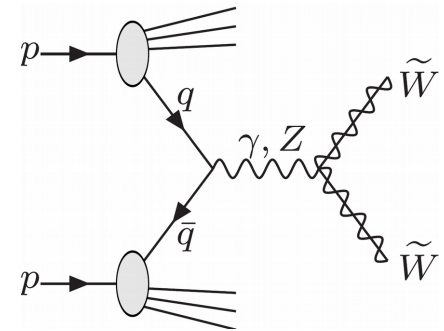
# Direct Detection



$$\sigma_{\text{eff}}^{\text{SI}} = \left( \frac{\Omega_{\text{thermal}} h^2}{\Omega_{\text{obs}} h^2} \right) \sigma^{\text{SI}}$$

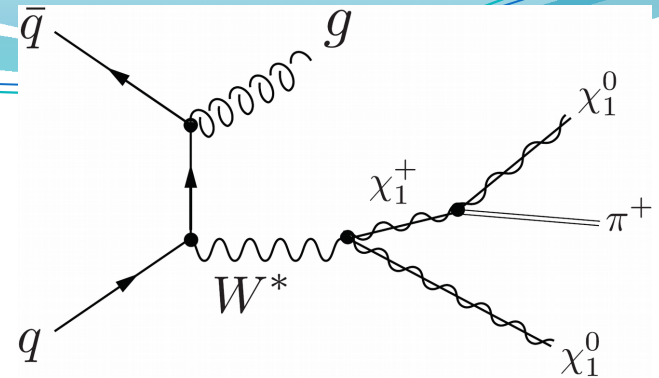
# LHC Signatures of Wino

- Mono-jet + missing energy
- (Disappearing) charged tracks
- (Displaced) soft tracks
- Quantum effects to the SM processes

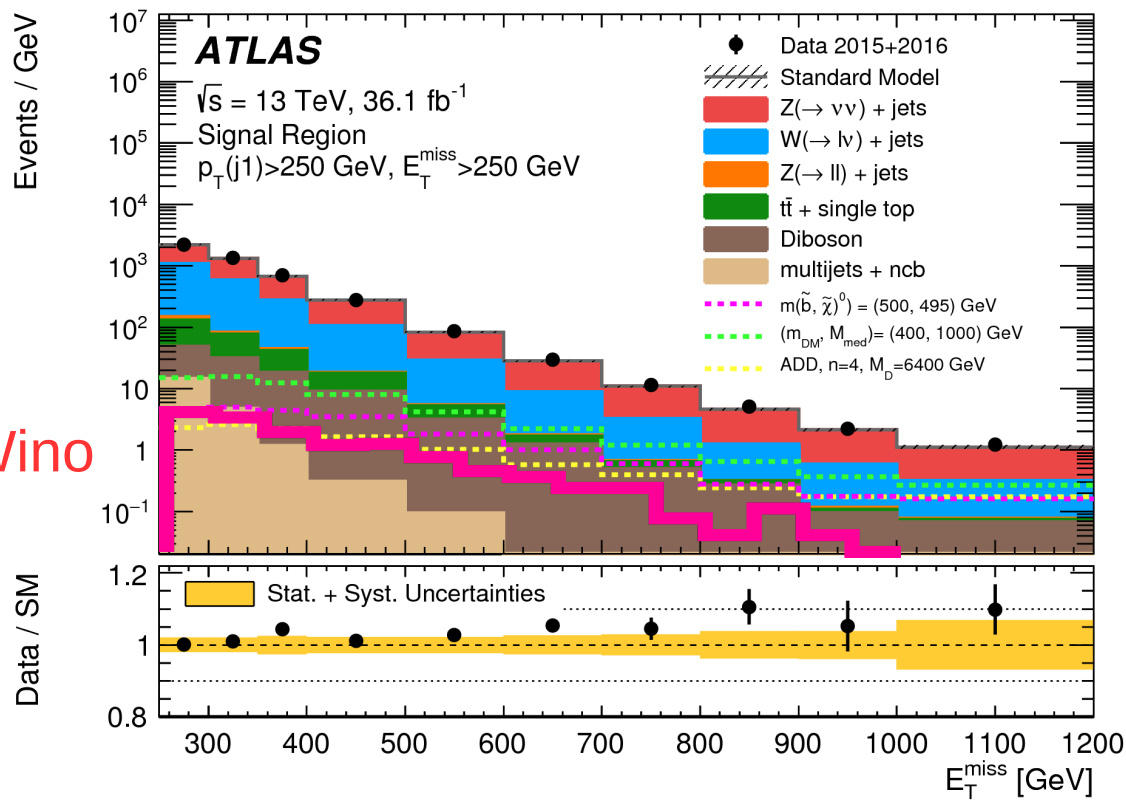




# Mono-jet Signatures



350 GeV Wino

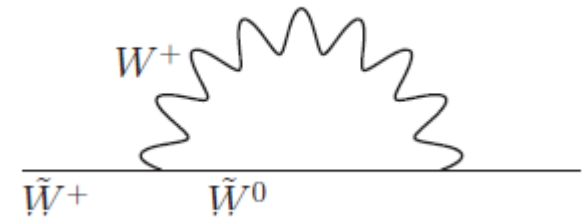


Not so useful for Wino search

# Beyond Mono-Jet?

- Combination of jet + photon + MET.
  - S/N can be improved by around 50%  
[Ismail, Izaguirre & Shuve, 1605.00658]
- Mono W or Z.
  - Most sensitive in some DM model.  
[Bai & Tait, 1208.4361]
- Decay of charged Wino

# Wino Spectrum



$\tilde{W}^\pm$  \_\_\_\_\_

$\tilde{W}^0$  \_\_\_\_\_



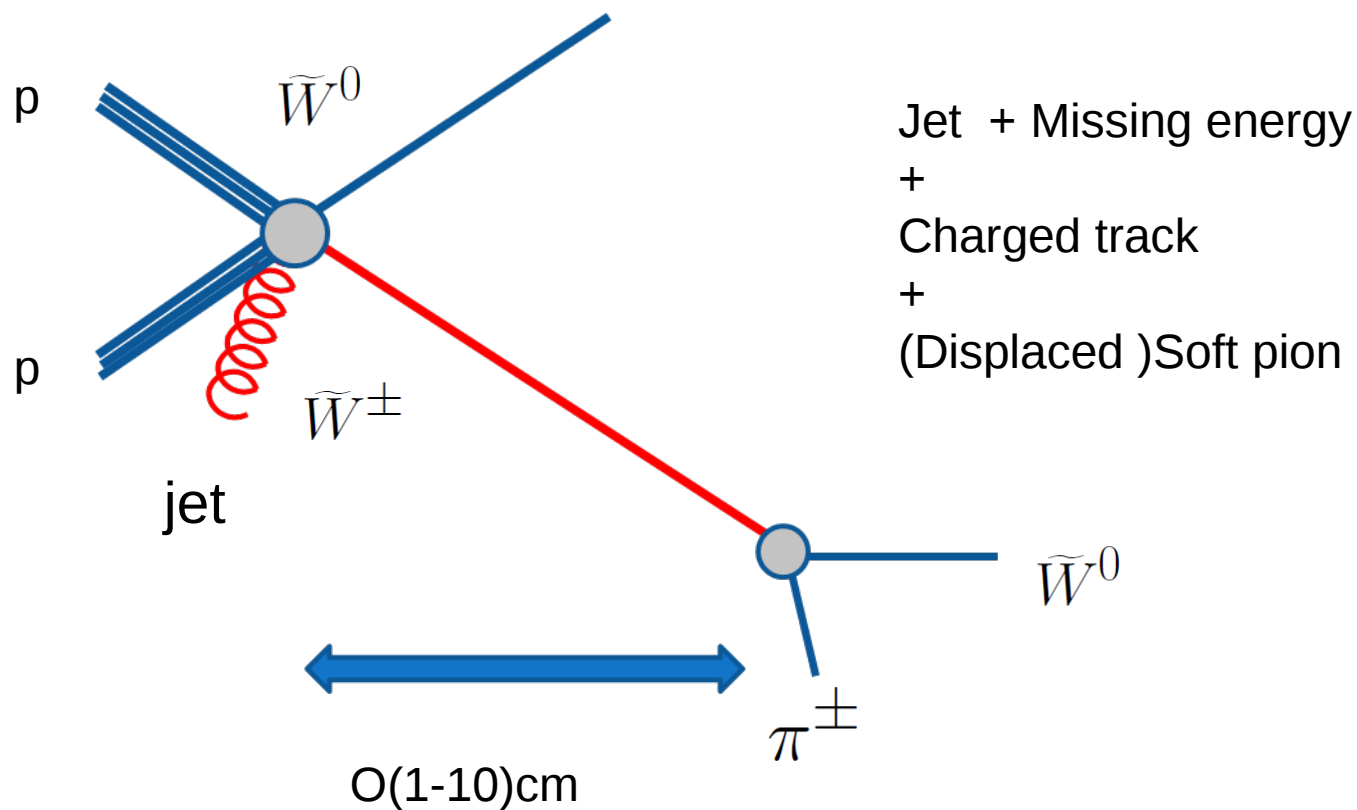
Radiative correction

$$\Delta m \simeq 165 \text{ MeV}$$

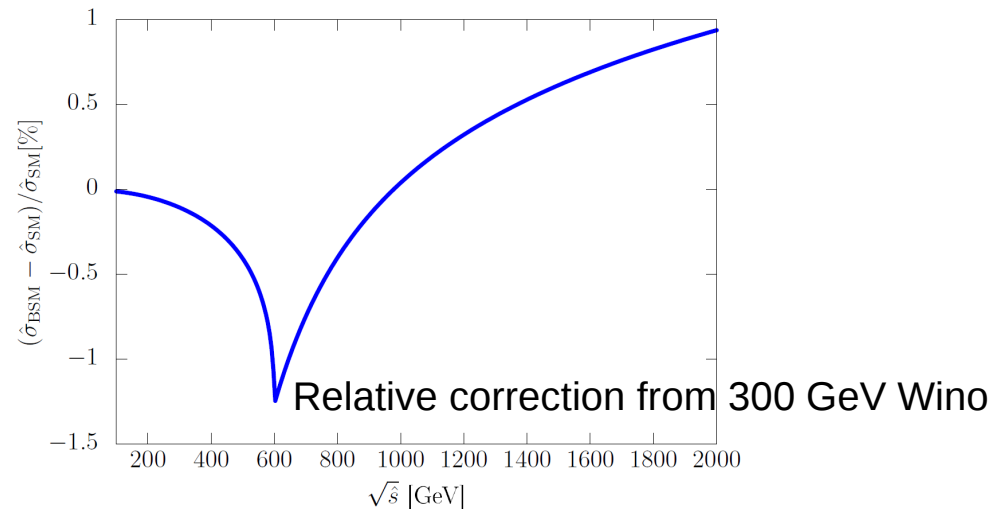
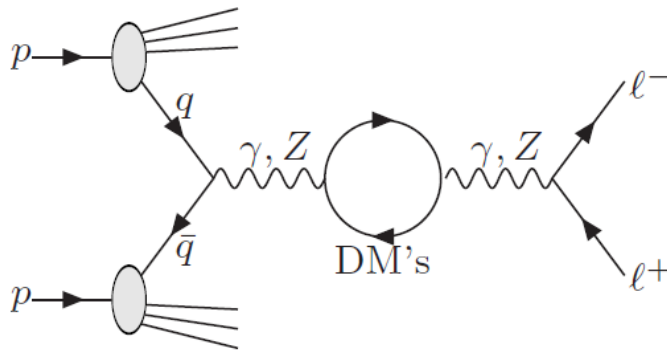
[Ibe, Matsumoto, Sato 12]

$$c\tau(\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm) \simeq 7 \text{ cm} \left( \frac{\Delta m}{165 \text{ MeV}} \right)^{-3}$$

# Direct LHC Signals



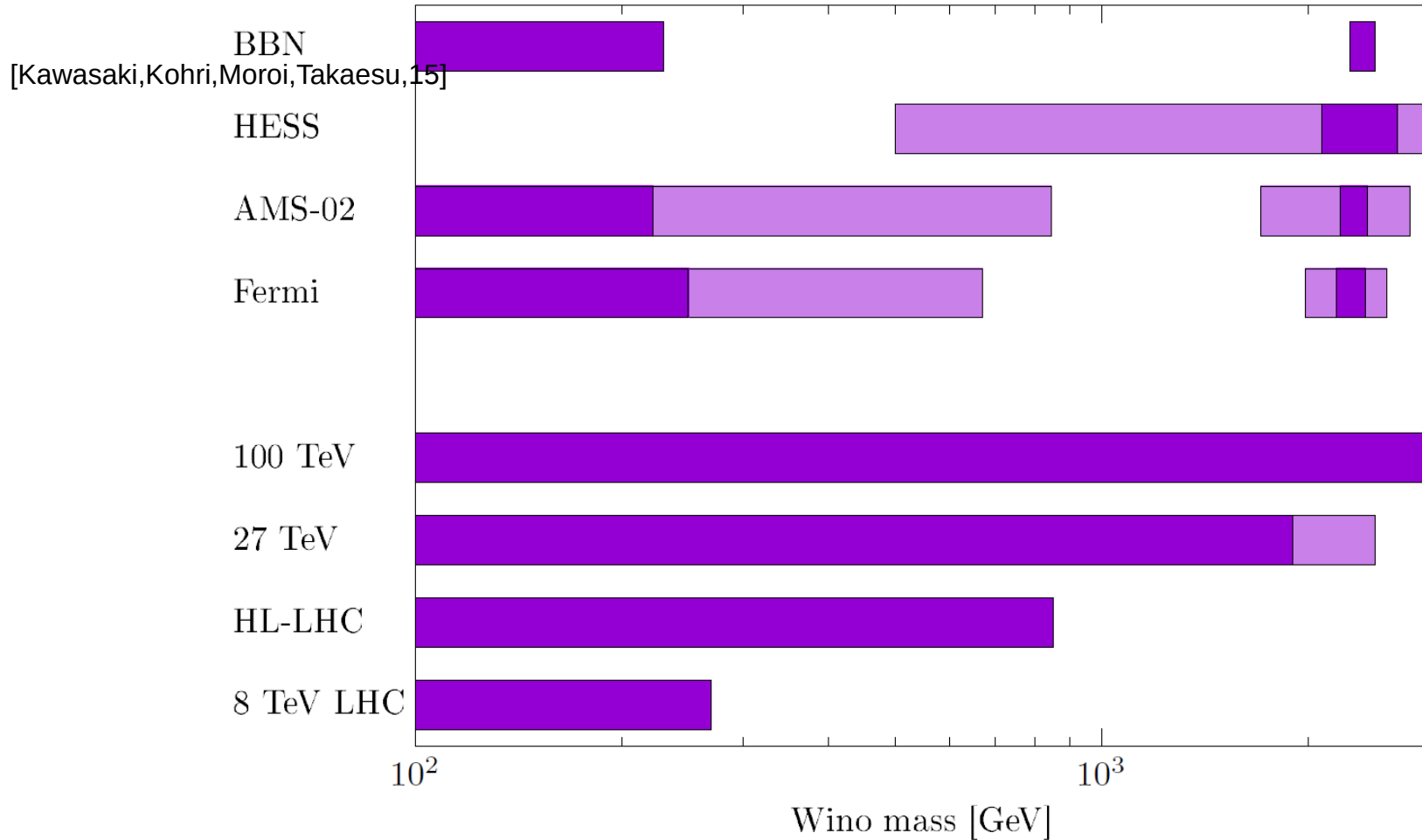
# Indirect Signatures



Indirect probe of quantum effect of DM

Precision measurement of SM processes

# DM Search and synergy



# DM Search and synergy

At collider, we can discover DM-like particles.

But we cannot conclude this is really DM particle.

The most important feature of DM is its lifetime

$$> 10^{27} \text{ sec}$$

Lifetime measurement is difficult at collider.

# DM Search and synergy

Biggest advantage of collider:

- Absence of astrophysical/cosmological uncertainty
- Measurement
  - Cross section
  - Mass spectrum
  - Lifetime of DM partner
  - ...

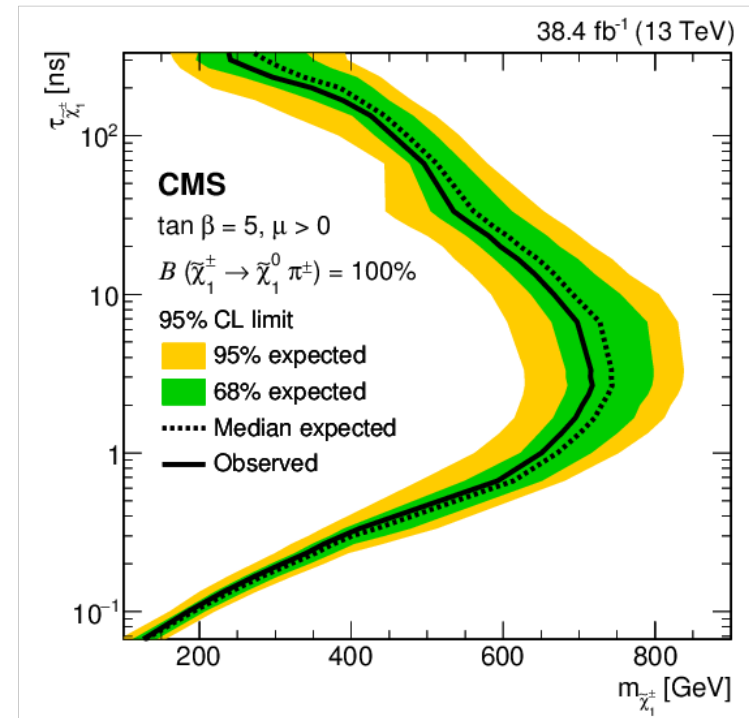
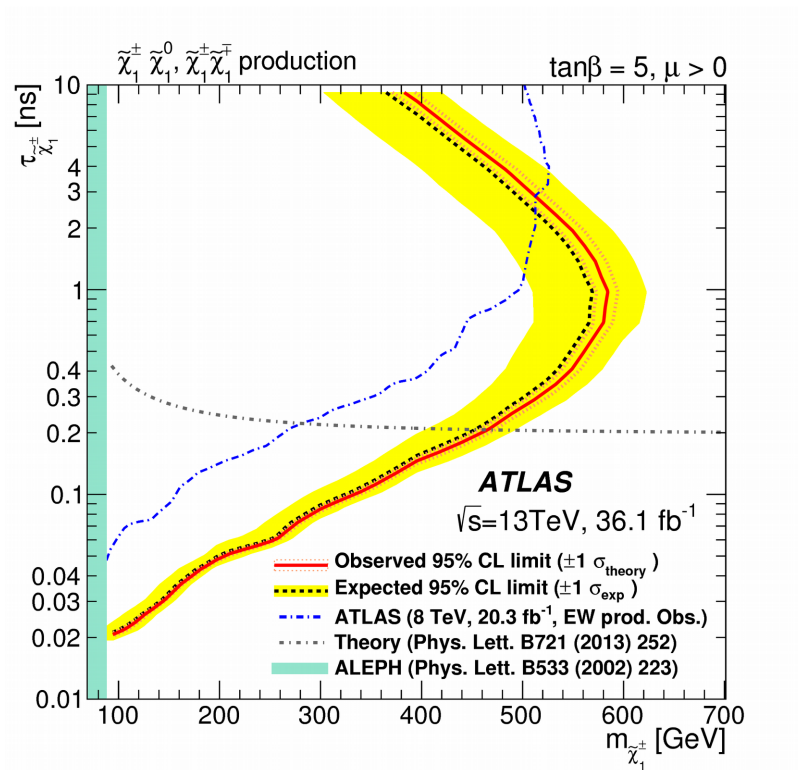
Cross check of direct/indirect DM signatures is essential.



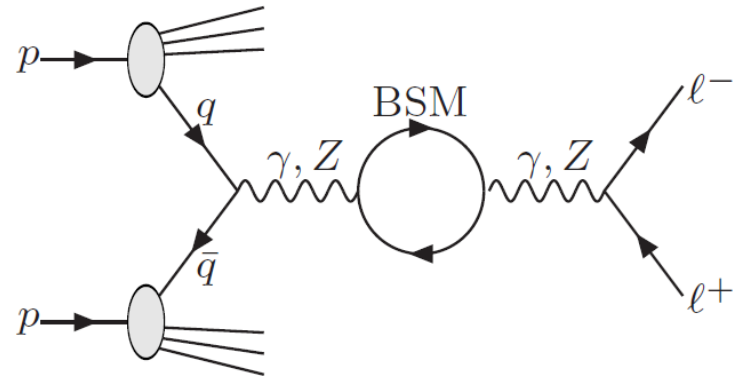
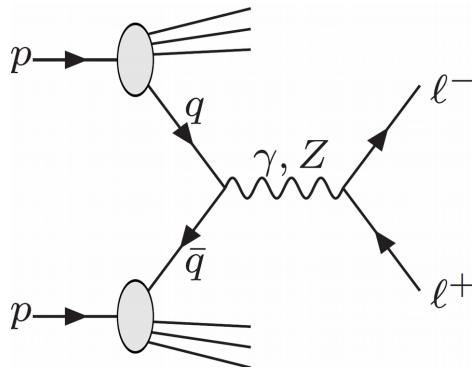
# Summary

- Wino is the most promising candidate for DM
  - Simplest SUSY model consistent with every measurement
- Various interesting features:
  - Abundance from non-perturbative effect
  - Cosmic ray signature
  - Direct detection
  - LHC signature of exotic tracks
- Synergy reveals Wino model and cosmological history

# Disappearing track search

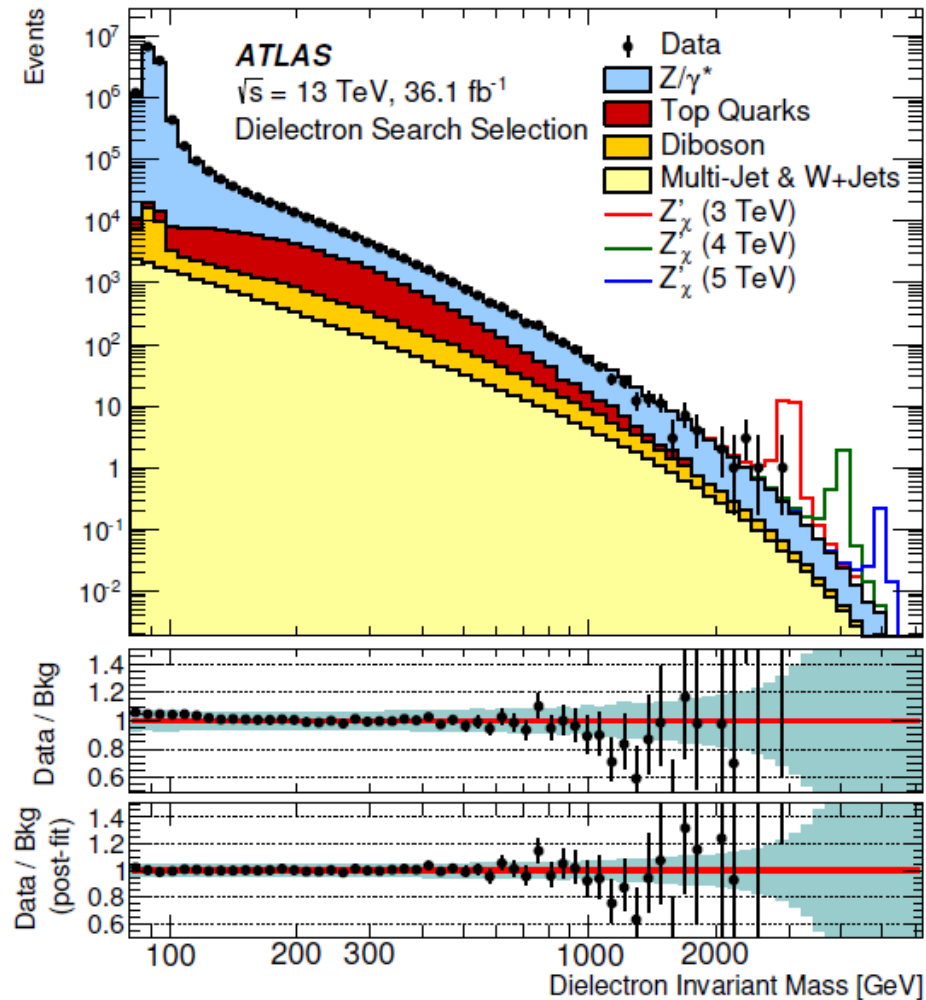


# Indirect Probe at LHC



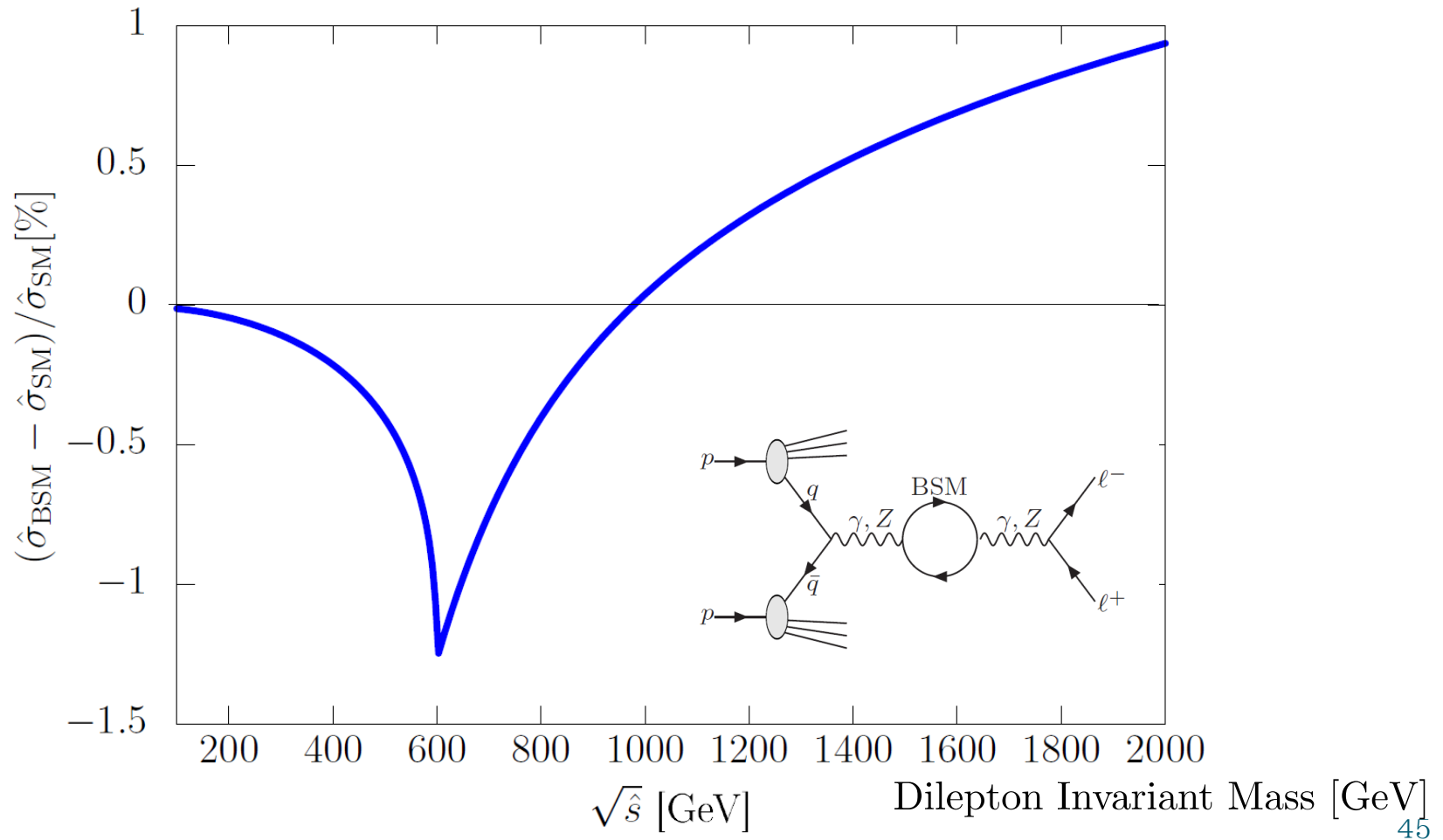
Interference between SM and BSM gives correction

# Observed Data

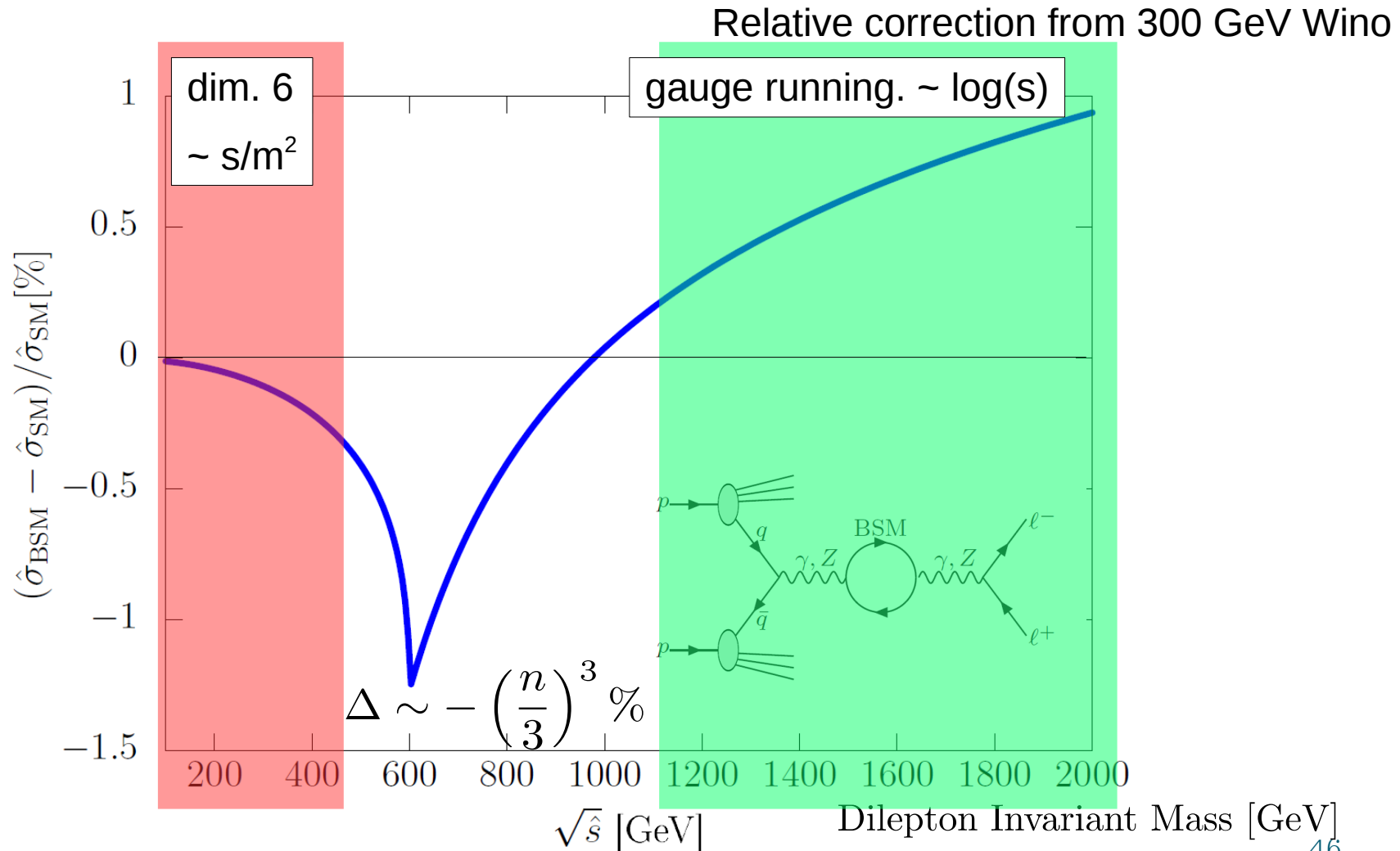


# Correction from DM

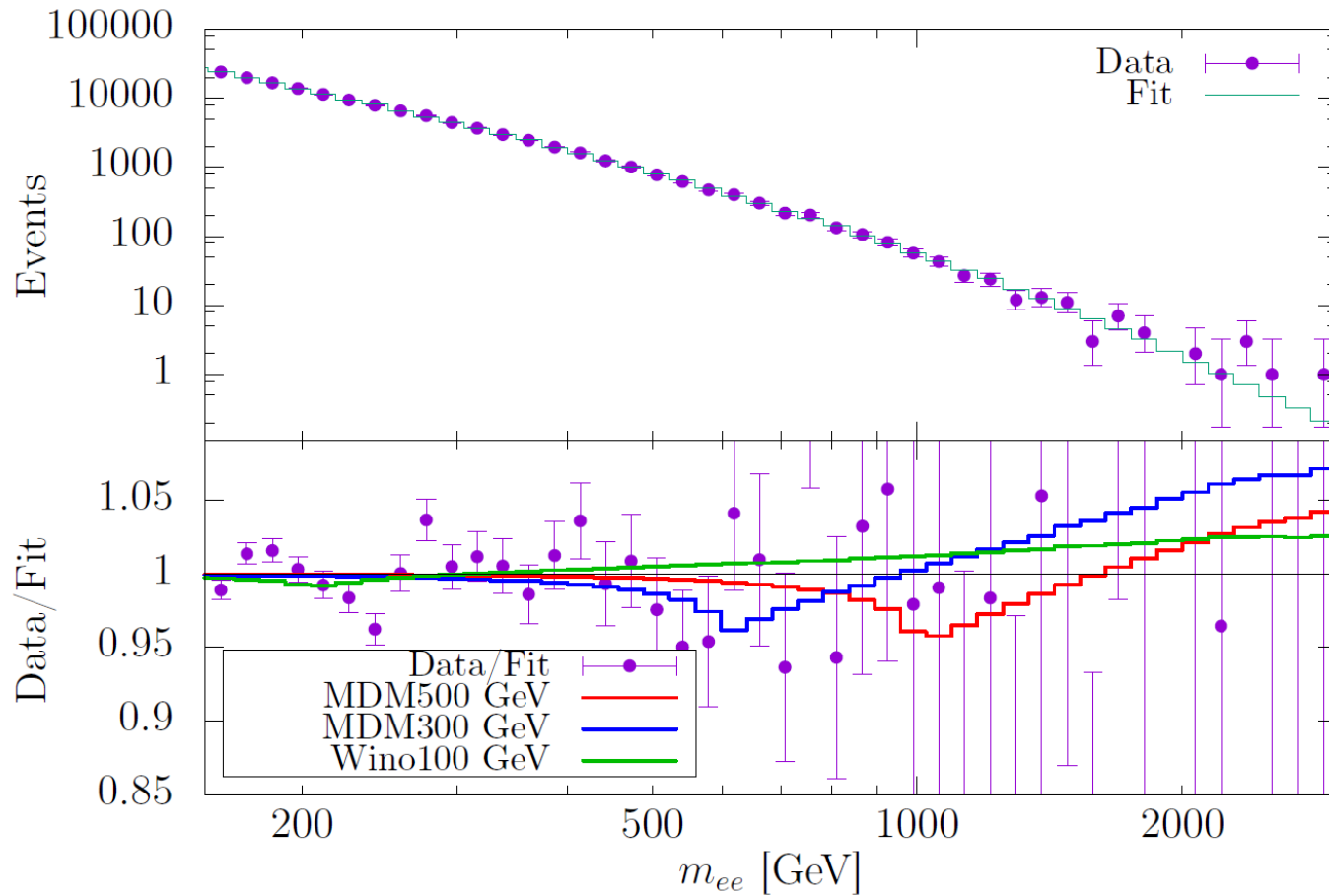
Relative correction from 300 GeV Wino



# Correction from DM

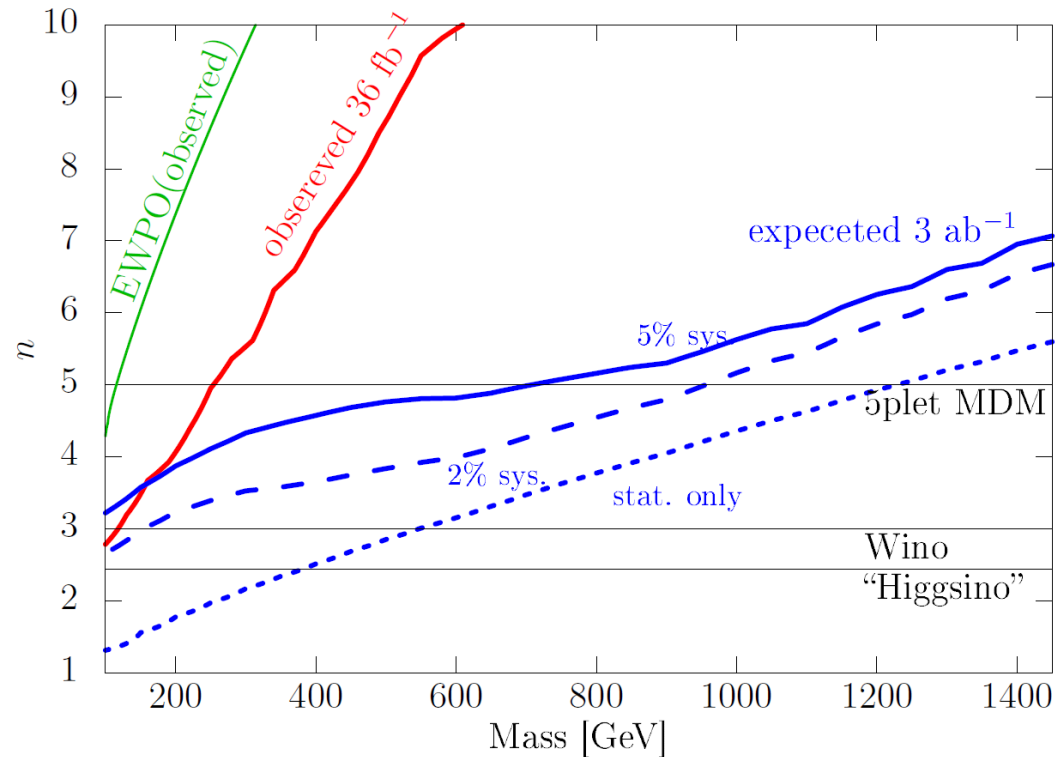


# Indirect Probe at LHC



# Indirect Probe at LHC

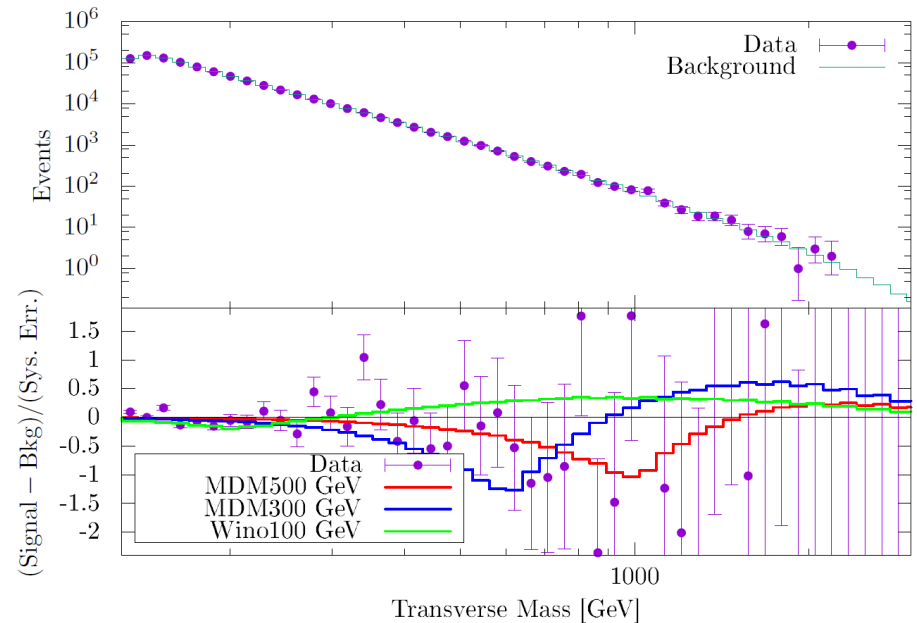
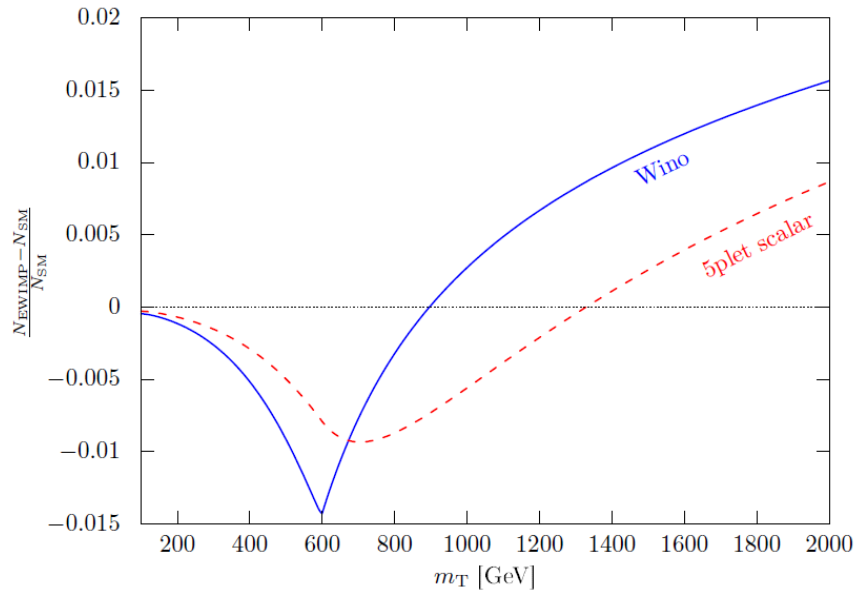
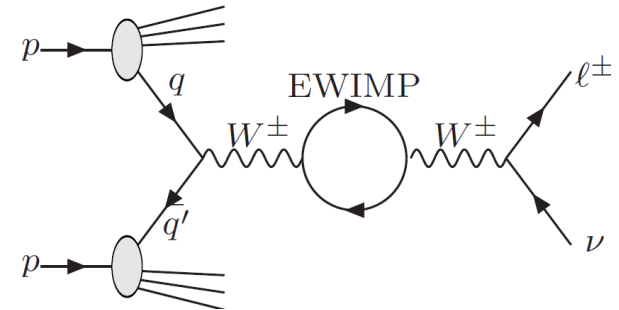
# of  $SU(2)_L$  representation





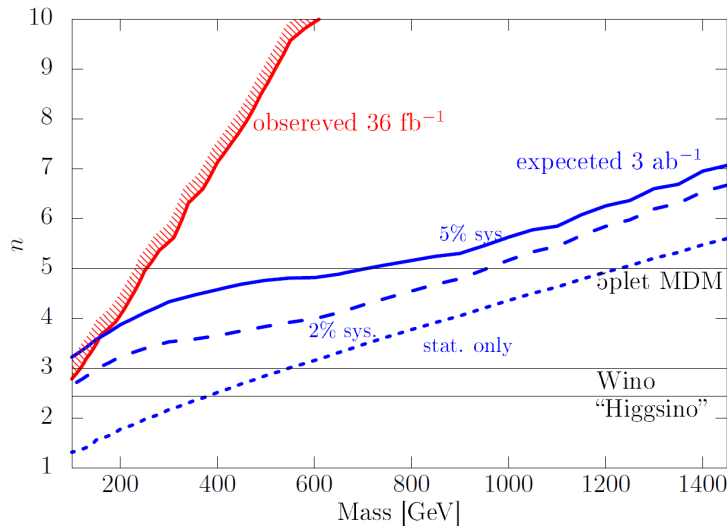
# Mono-lepton Case

Mono-lepton signal may be better.

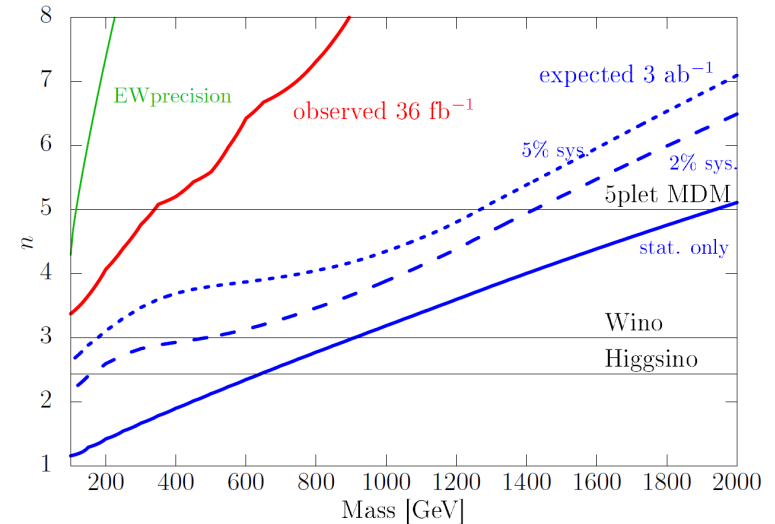
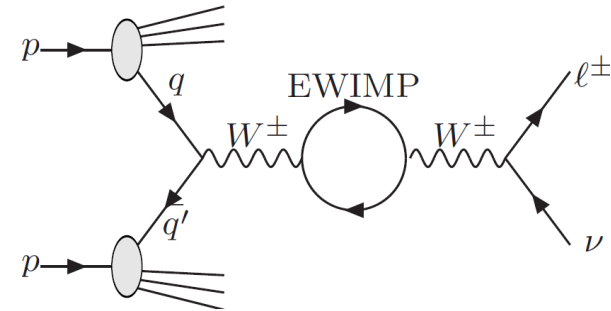


# Indirect Probe at LHC

# of SU(2) representation



dilepton



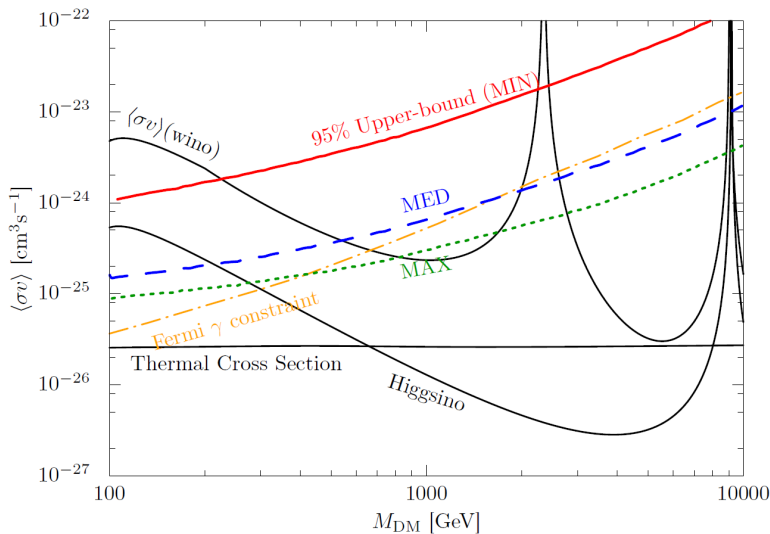
mono-lepton

# Indirect Search

- Precision measurements can probe DM, and be as powerful as mono-jet + MET search.
  - Future 100 TeV collider covers even Higgsino DM.  
[Chigusa, Ema & Moroi, 1810.07349, and Luzio, Grober & Panico, 1810.10993]
- Applicable to any kinds of BSM particle which has gauge charge.
- Independent on how particle decays.

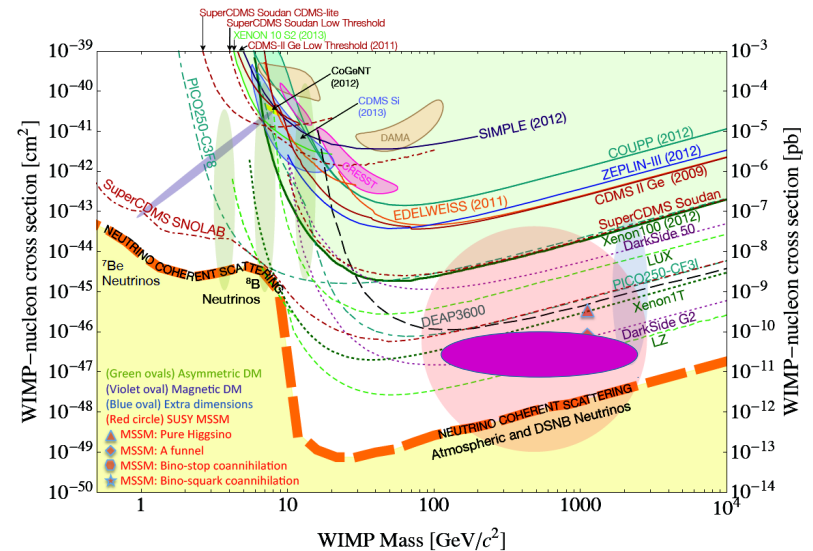
# DM Search and synergy

[1310.8327]



Large Wino annihilation rate

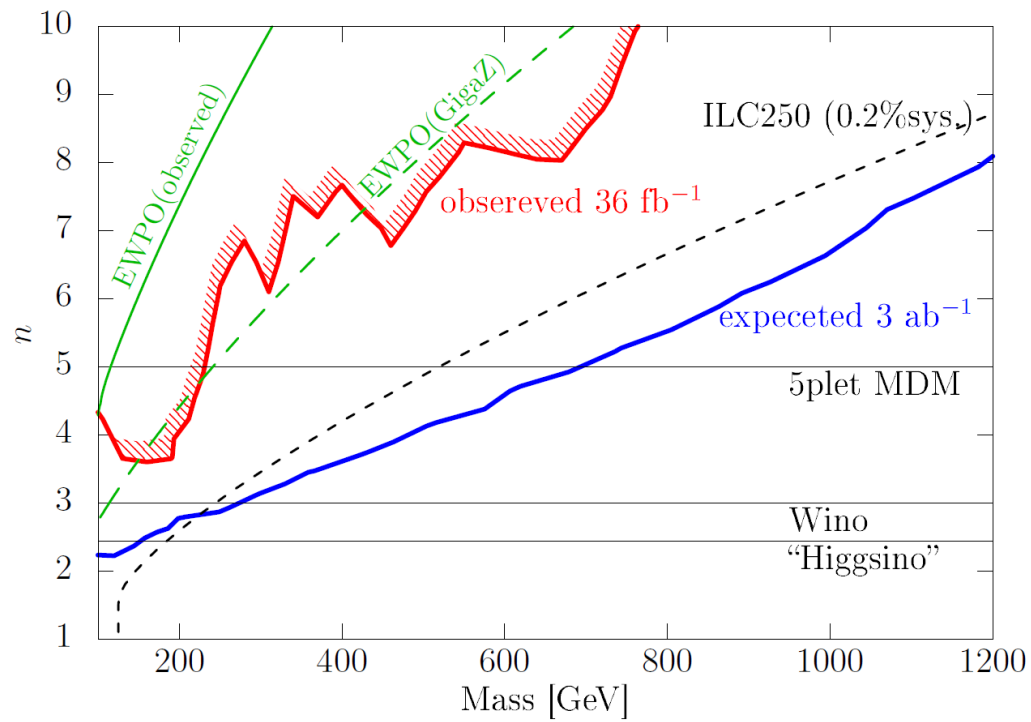
[Hisano, Matsumoto, Nojiri, Osamu & Saito, 04]



Wino-Nucleon XS  $\sim 10^{-47} \text{ cm}^2$

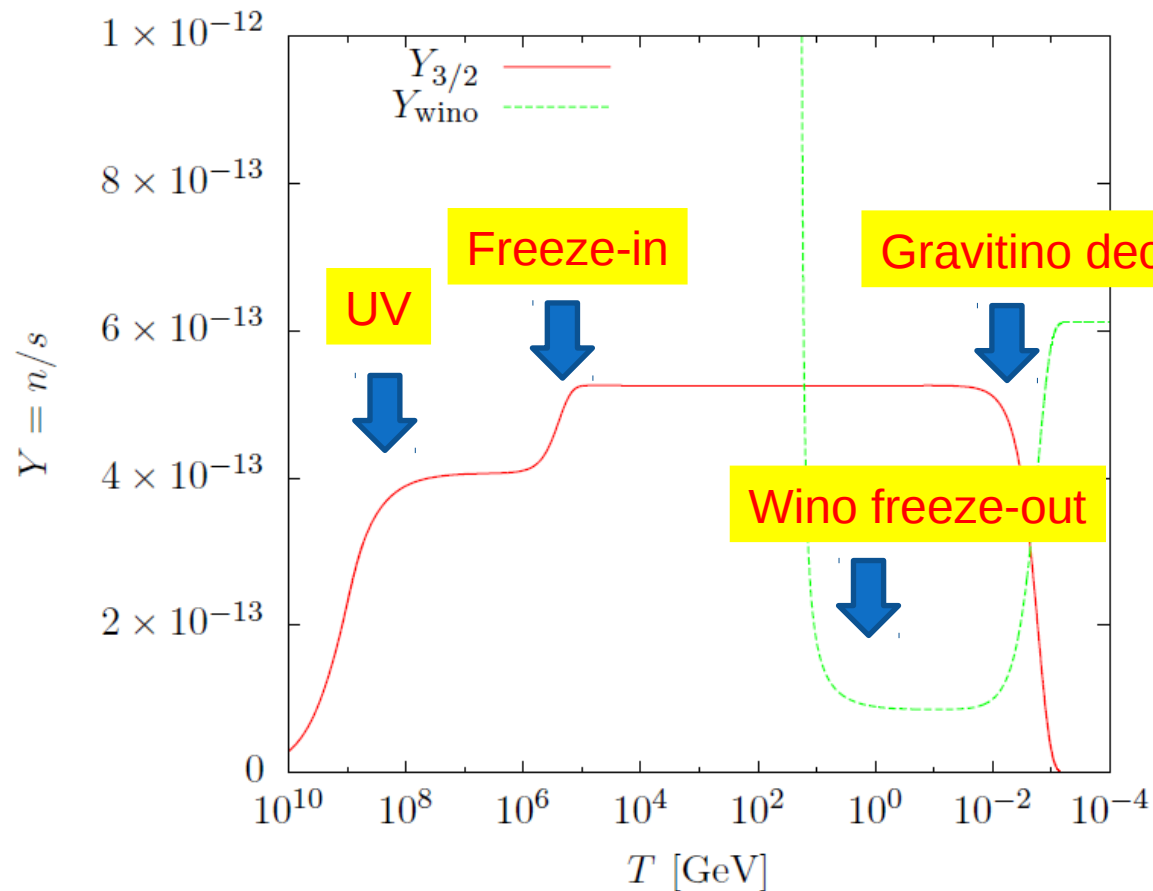
[Hisano, Ishiwata & Nagata, 12]

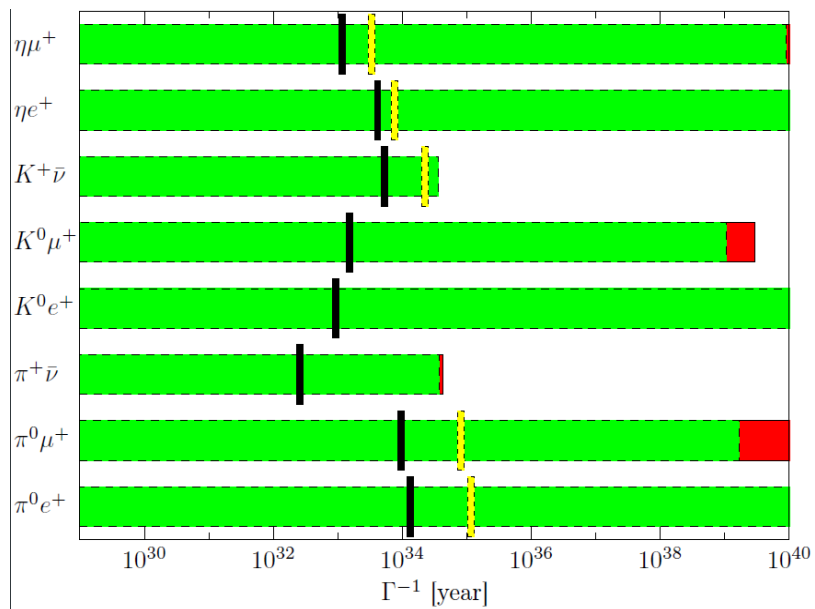
# Fit



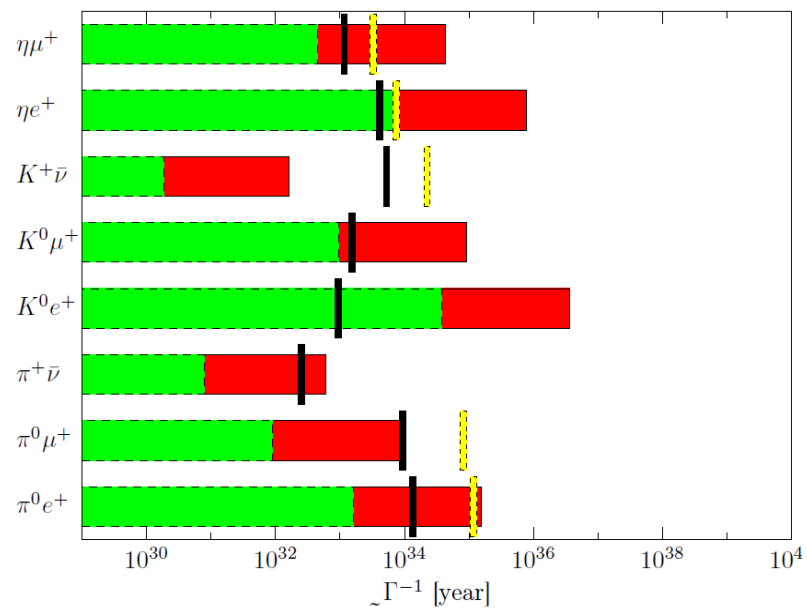
# Non-thermal Example

If reheating temperature is large, gravitino leads non-thermal Wino





(a) Minimal FV



(b)  $\delta_{13}^{\tilde{Q}_L} = 0.1$