Wino theory and future prospects

Satoshi Shirai (Kavli IPMU)

Contents

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 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

Weakly Interacting Massive Particle

Minimal setup of DM:

Adding a DM particle to Standard Model

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

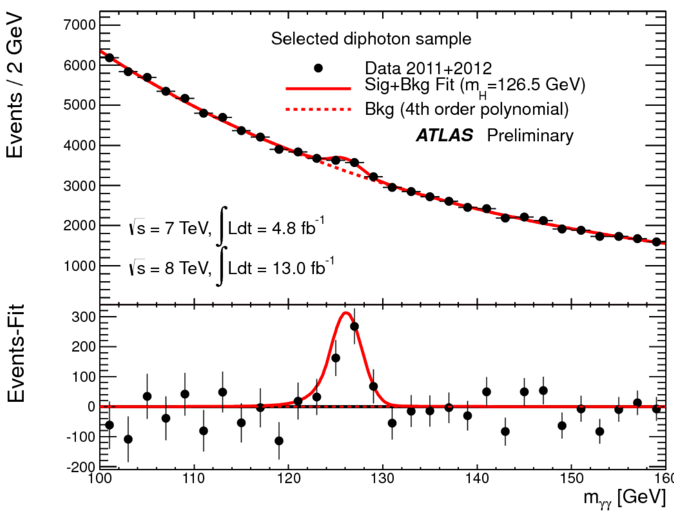
Correct DM is realized via Electroweak interaction

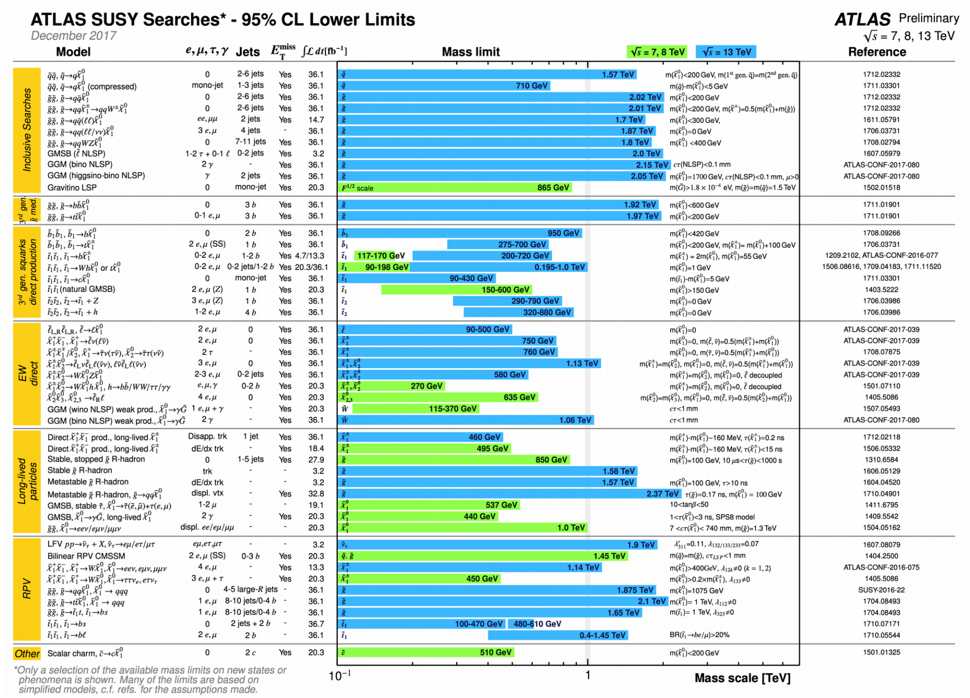
Wino is Most minimal WIMP DM

SUSY Standard Model

Standard Model (SM)	SUSY Partner
Lepton	Scalar Lepton
Quark	Scalar Quark
Scalar Higgs	Higgsino
Gauge Boson	Gaugino
gluon	gluino
weak boson	wino
photon	bino

Higgs and SUSY at LHC





Higgs Discovered!

SUSY Constrained!

$$m_h = 125.18 \pm 0.16 \text{ GeV}$$

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

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~~ ⟷ New Interaction

Scalar top
- Large mass
- A-term

"4-th" family

NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

SUSY after 125 GeV Higgs

~~SUSY~~ — New Interaction

Scalar top
- Large mass
- A-term

"4-th" family

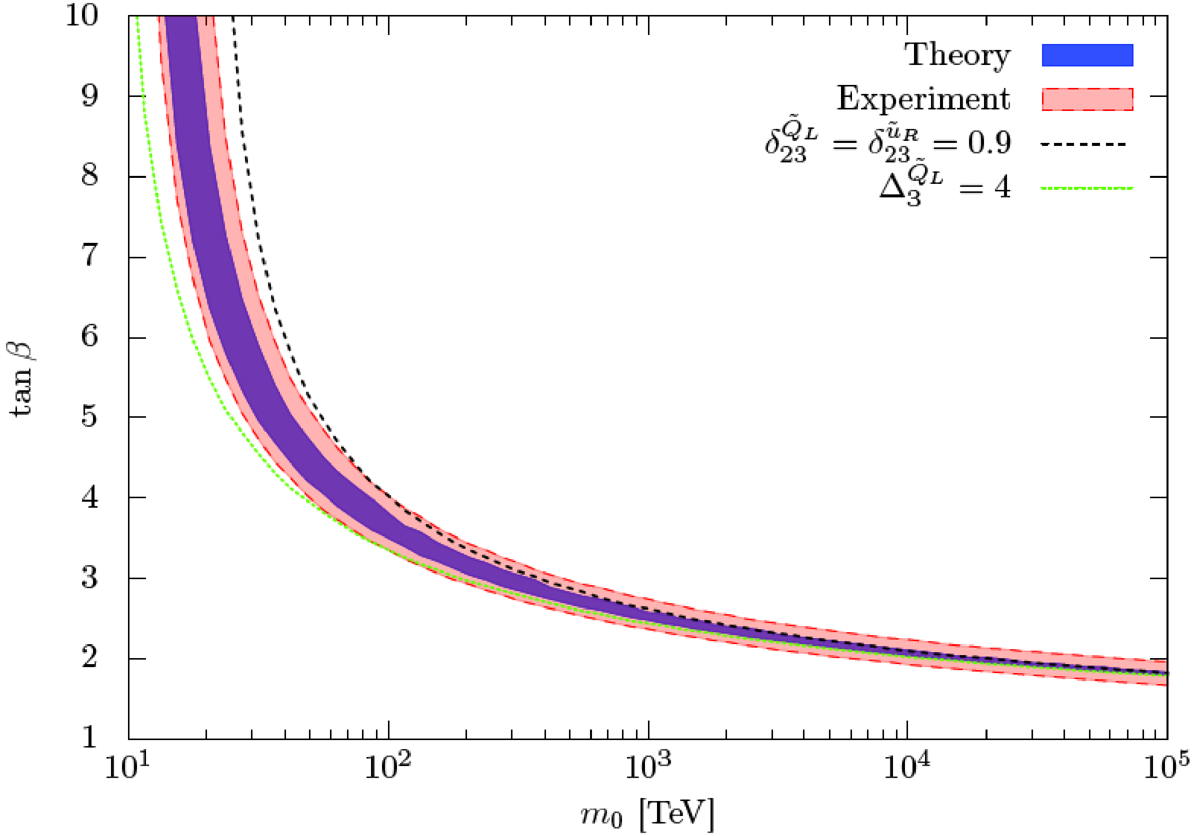
NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

Simple? — Natural?

Higgs Mass from Stop

125 GeV Higgs OK regions



Scalar Mass

Mini-Split Mass Spectrum

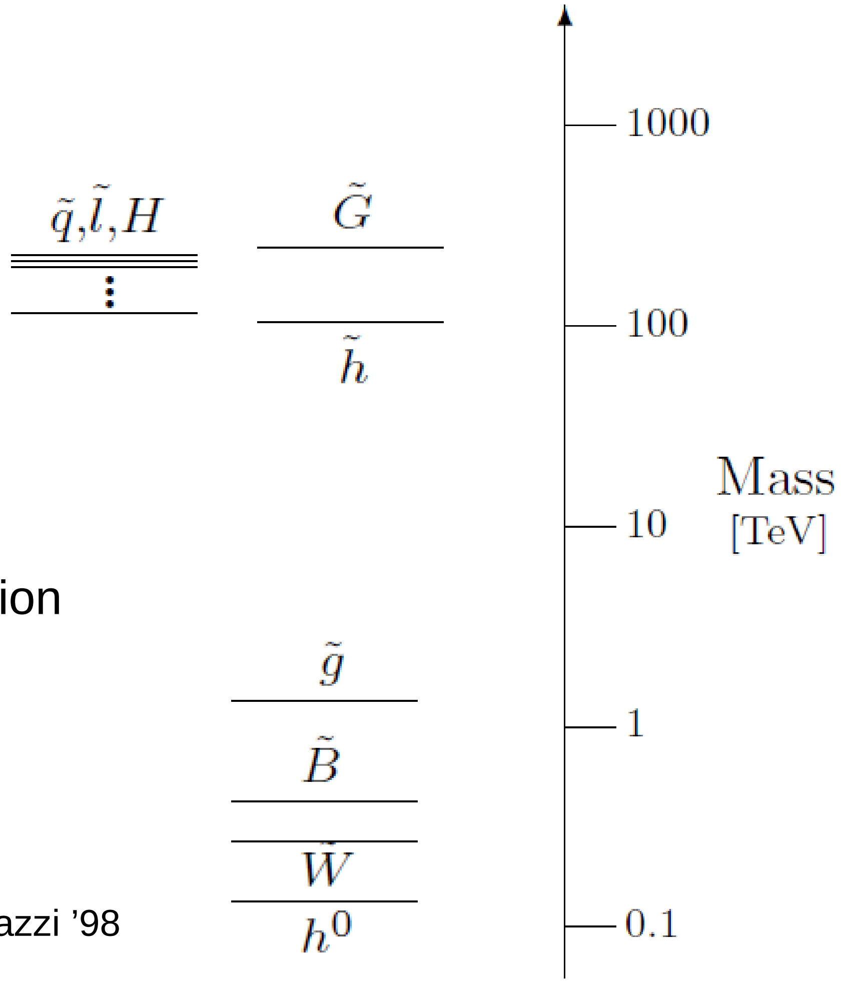
Tree level Gravity Mediation

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

Loop suppressed: Anomaly Mediation

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

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



Gaugino Mass

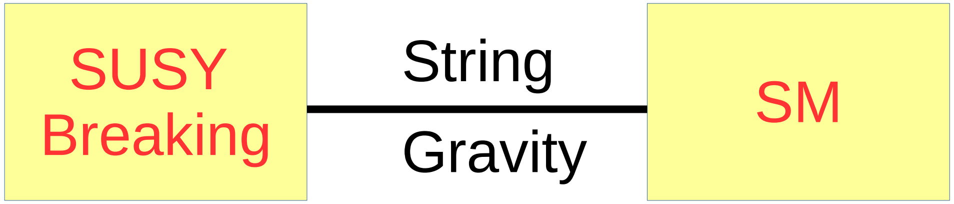
$$M_{\rm bino} = 11 \times \frac{3}{5}\frac{\alpha_1}{4\pi} \times m_{3/2}$$

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

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

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

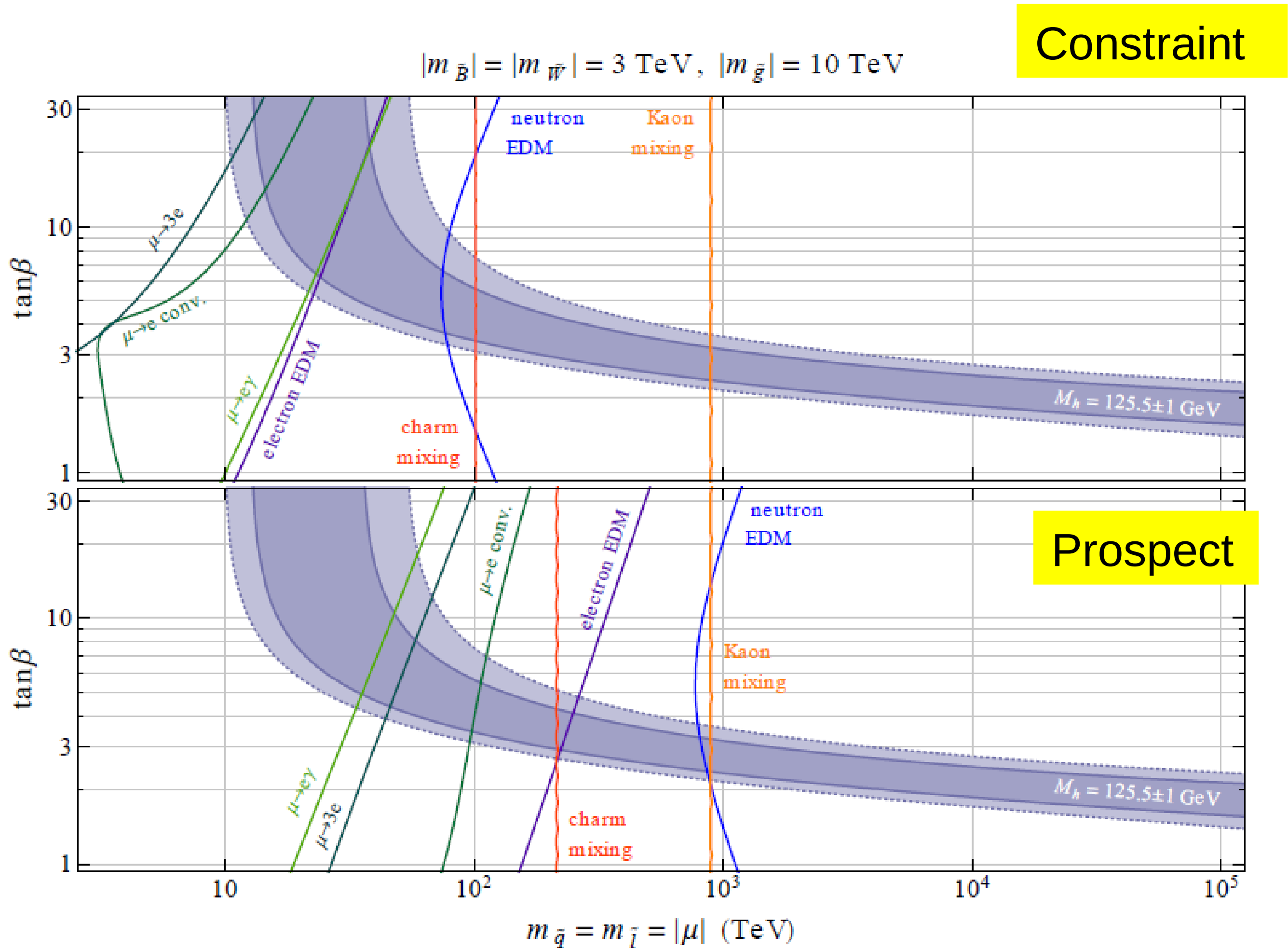
? • Hierarchy Problem
✓ • GUT unification
✓ • DM

Possible demerit

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

Flavor/CP Constraints

[Altmannshofer,Harnik,Zupan,1308.3653]

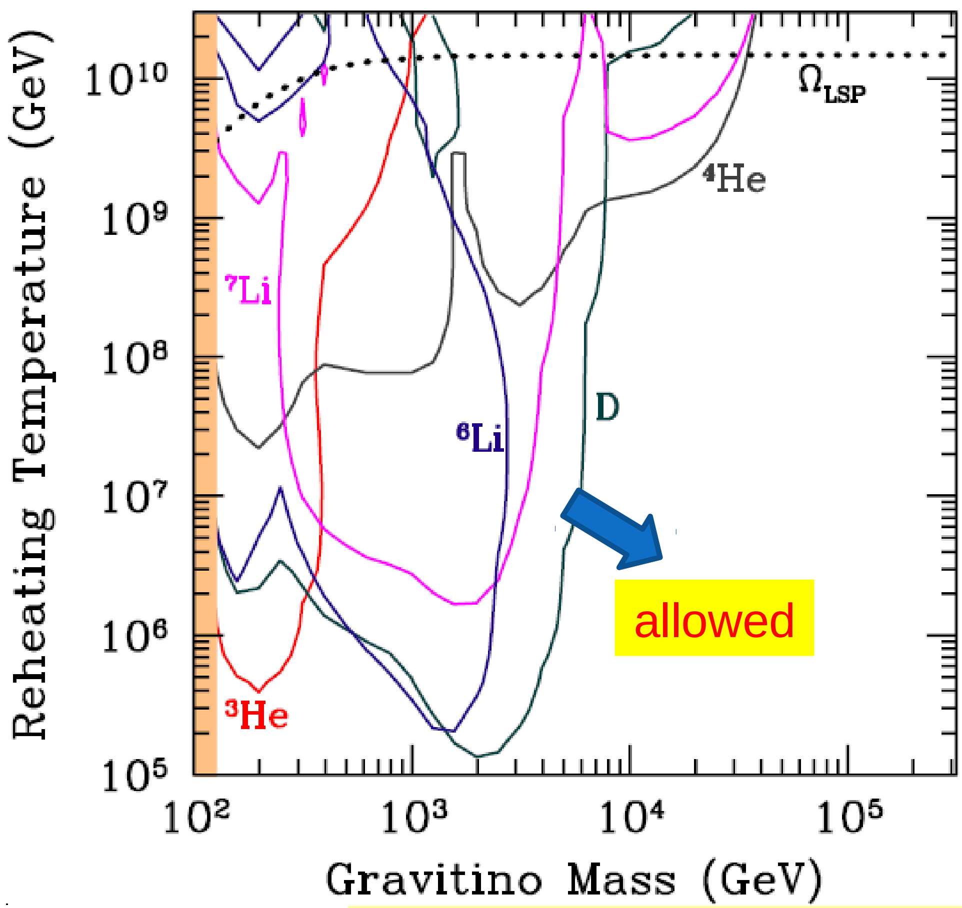


For O(100) TeV Sfermion, no Flavor/CP problems

Constraint from Cosmology

[Kawasaki et.al, arXiv:0804.3745]

Cosmological constraints

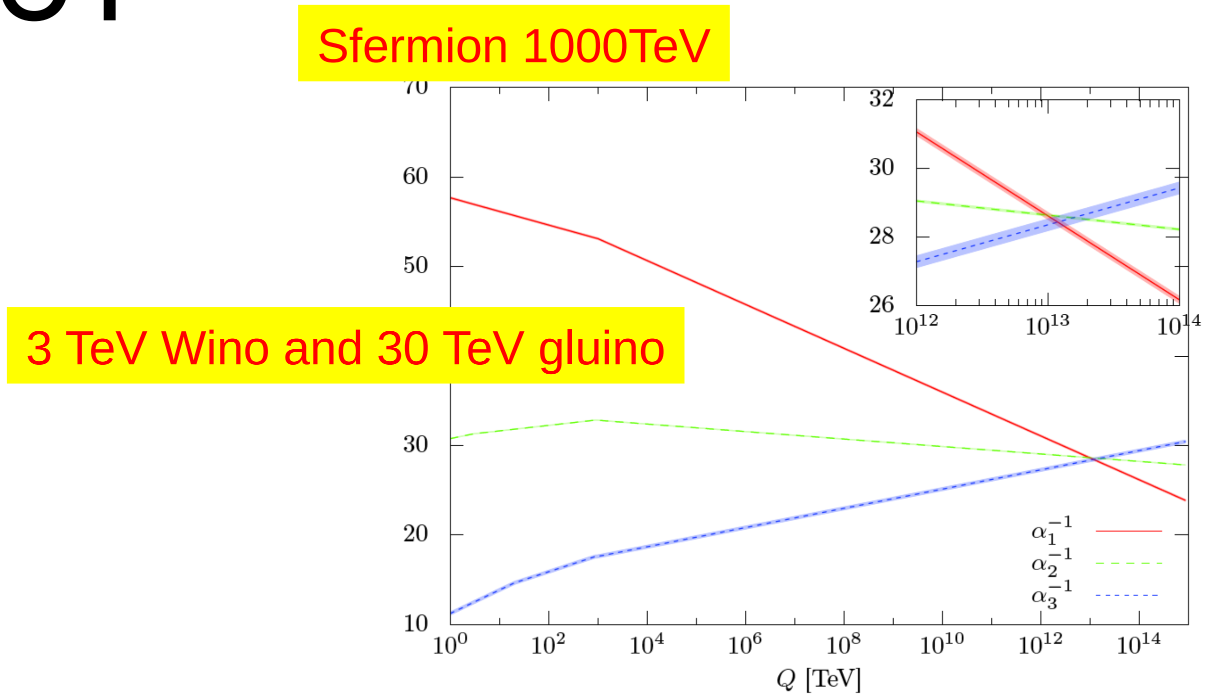


$$\tau_{\tilde{G}} \simeq 10 \left(\frac{m_{3/2}}{10 \text{ TeV}} \right)^{-3} \text{ sec}$$

Decay before BBN era (~1 sec)

For O(100) TeV Gravitno, no BBN problems

GUT



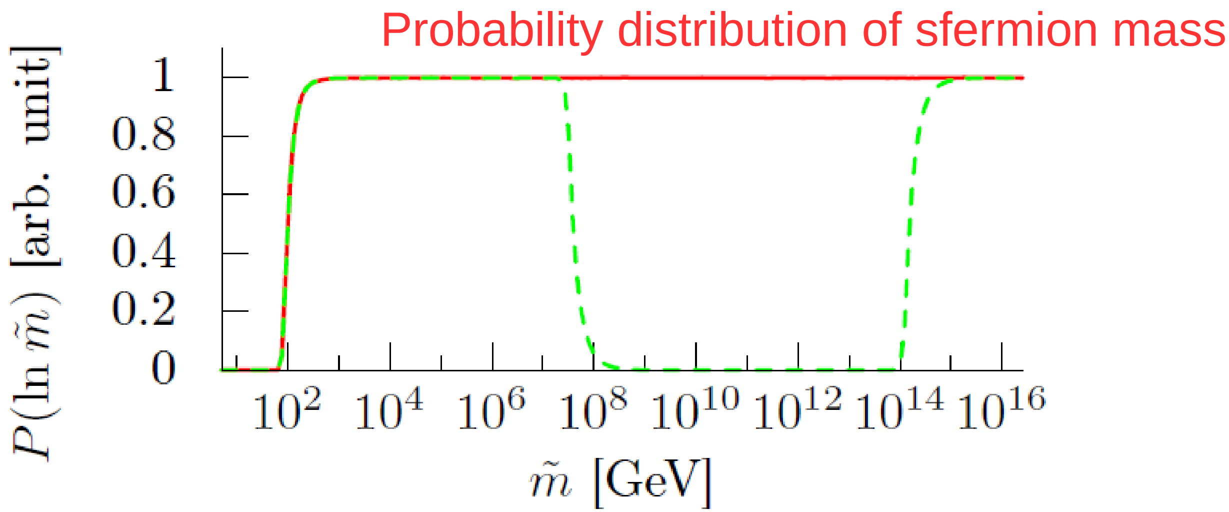
- Coupling Unification better than Weak Scale SUSY
- Minimal SU(5) GUT is Viable

Typical SUSY

Nomura&SS, PRL 113 (2014) 11, 111801

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.

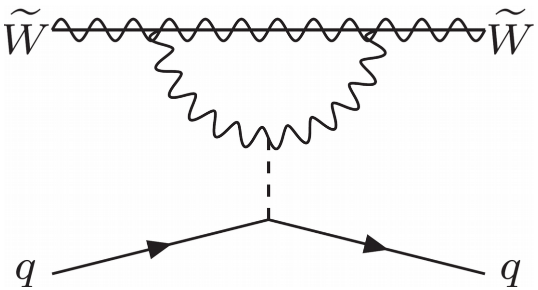


Theoretical view of Wino

- 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

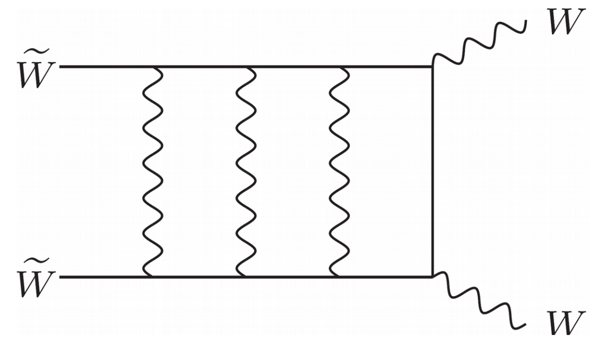
Wino Signal



Direct Detection

[Hisano, Ishiwata & Nagata, 12]

Wino-Nucleon XS ~ 10^{-47} cm^2



Indirect Detection

[Hisano, Matsumoto, Nojiri & Saito, 04]

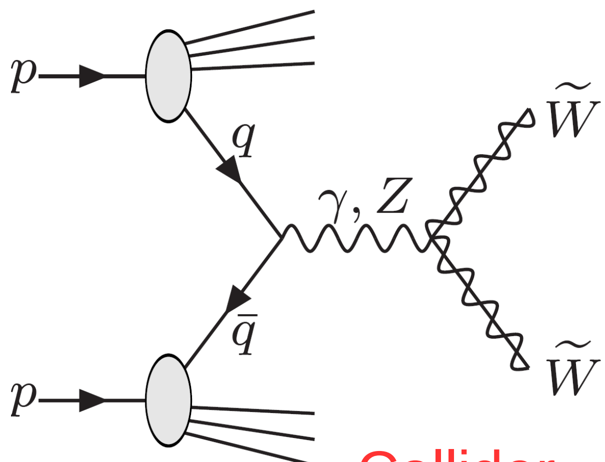
$$\widetilde{W}\widetilde{W} \to \gamma V$$

Line Photon

$$\widetilde{W}\widetilde{W} \to WW$$

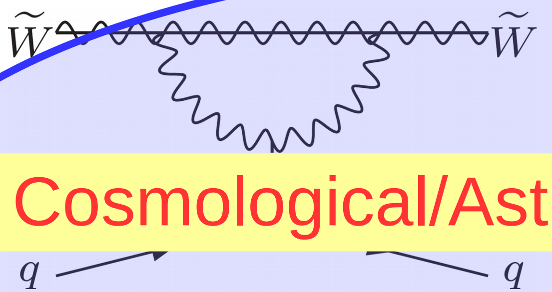
Continuum Photon

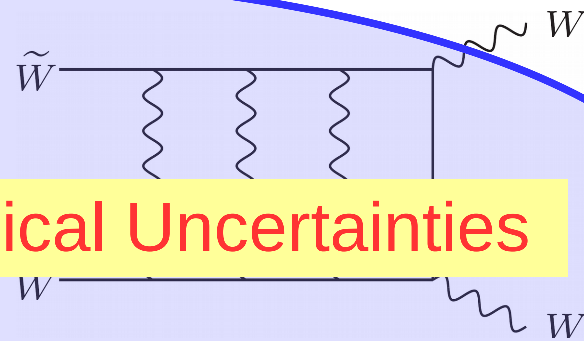
Anti-matter



Collider

Wino Signal





Cosmological/Astrophysical Uncertainties

Direct Detection

[Hisano, Ishiwata & Nagata, 12]

Wino-Nucleon XS ~ 10^{-47} cm^2

Indirect Detection

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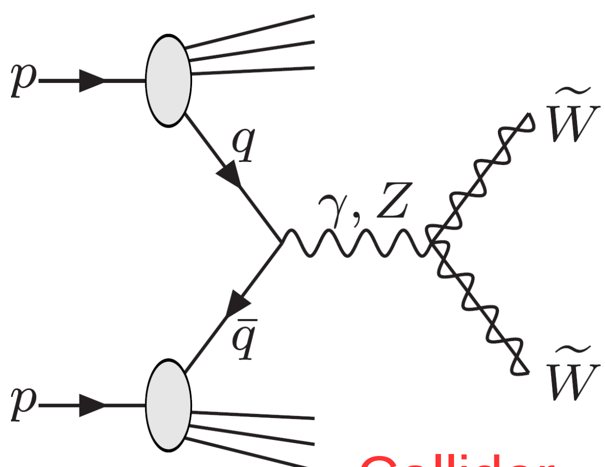
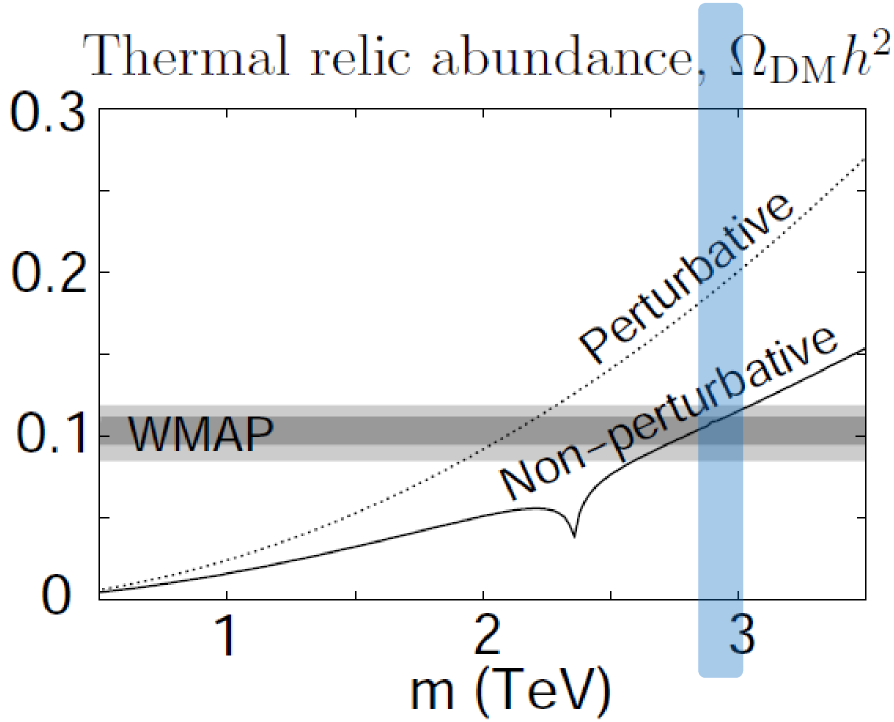


Collider

Wino Thermal Abundance

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



Wino Abundance Uncertainty

Wino is Whole Component of DM?

Yes

No

Only Thermal Relic?

Mixed DM

Yes

No

e.g., (thermal) Wino + Axion

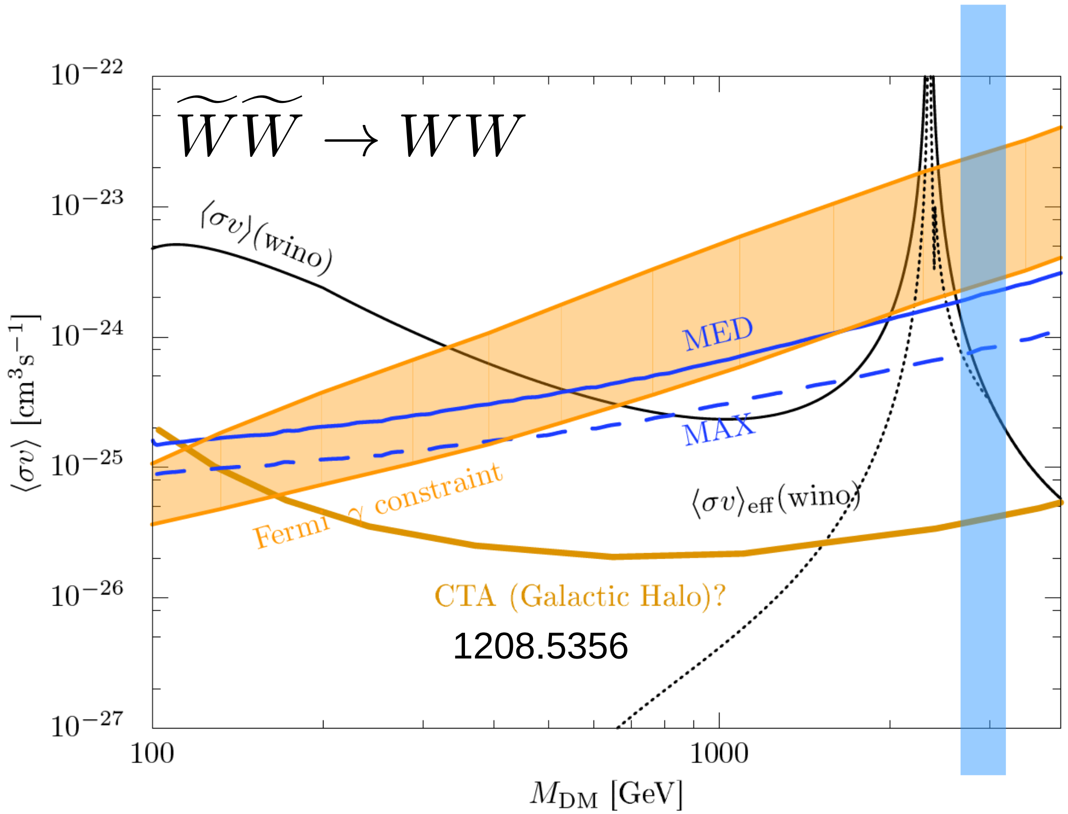
3 TeV Wino

<3 TeV Wino

+ non-thermal production

e.g., gravitino decay

Cosmic Ray Signals



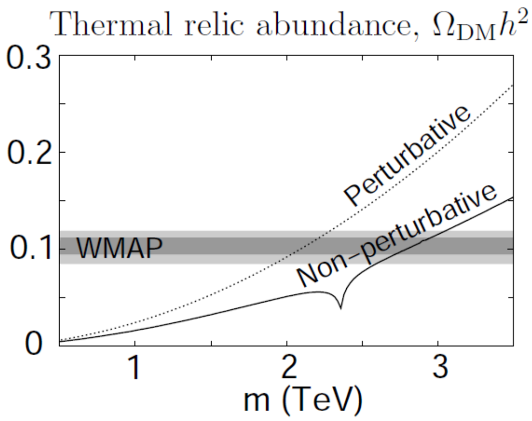
AMS02 anitiproton

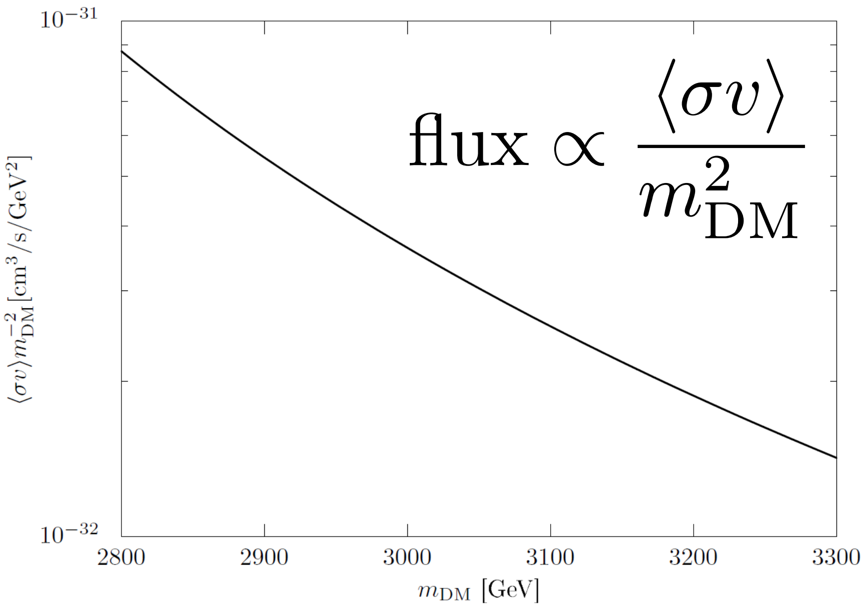
Fermi Gamma ray

$$\langle\sigma v\rangle_{\rm eff} = \left(\frac{\Omega_{\rm thermal} h^2}{\Omega_{\rm obs} h^2}\right)^2 \langle\sigma v\rangle$$

Large Uncertainty of Astrophysical model and DM density

How Robust 3 TeV Wino?



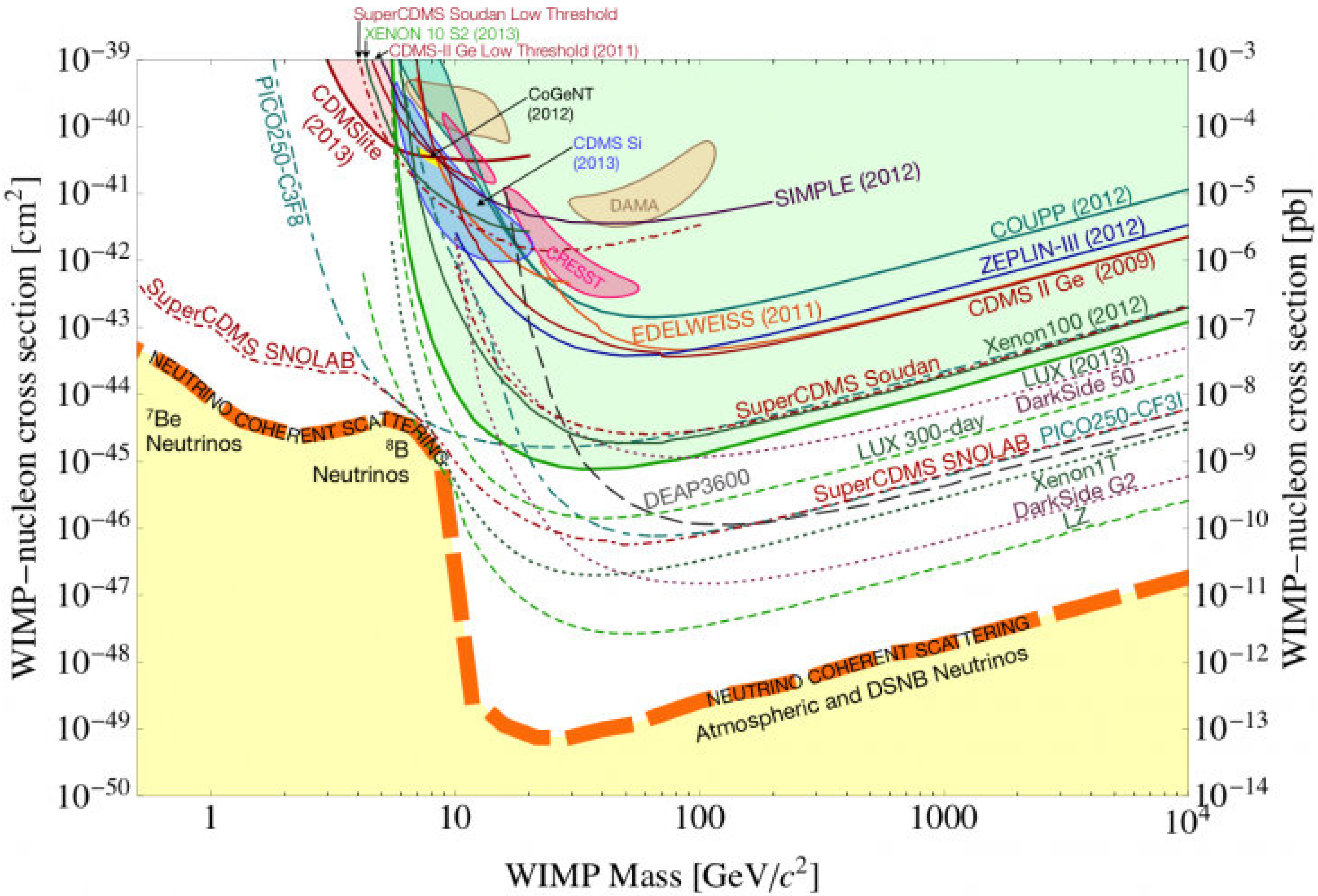


- Thermal effect,
- Higher-order Correction,
- Non-perturbative effect (bound state formation…)

can change the thermal abundance.

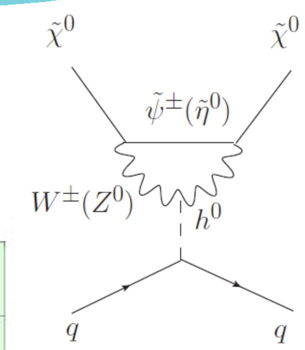
⇒ O(10)% effect on abundance → O(100)% effect on flux

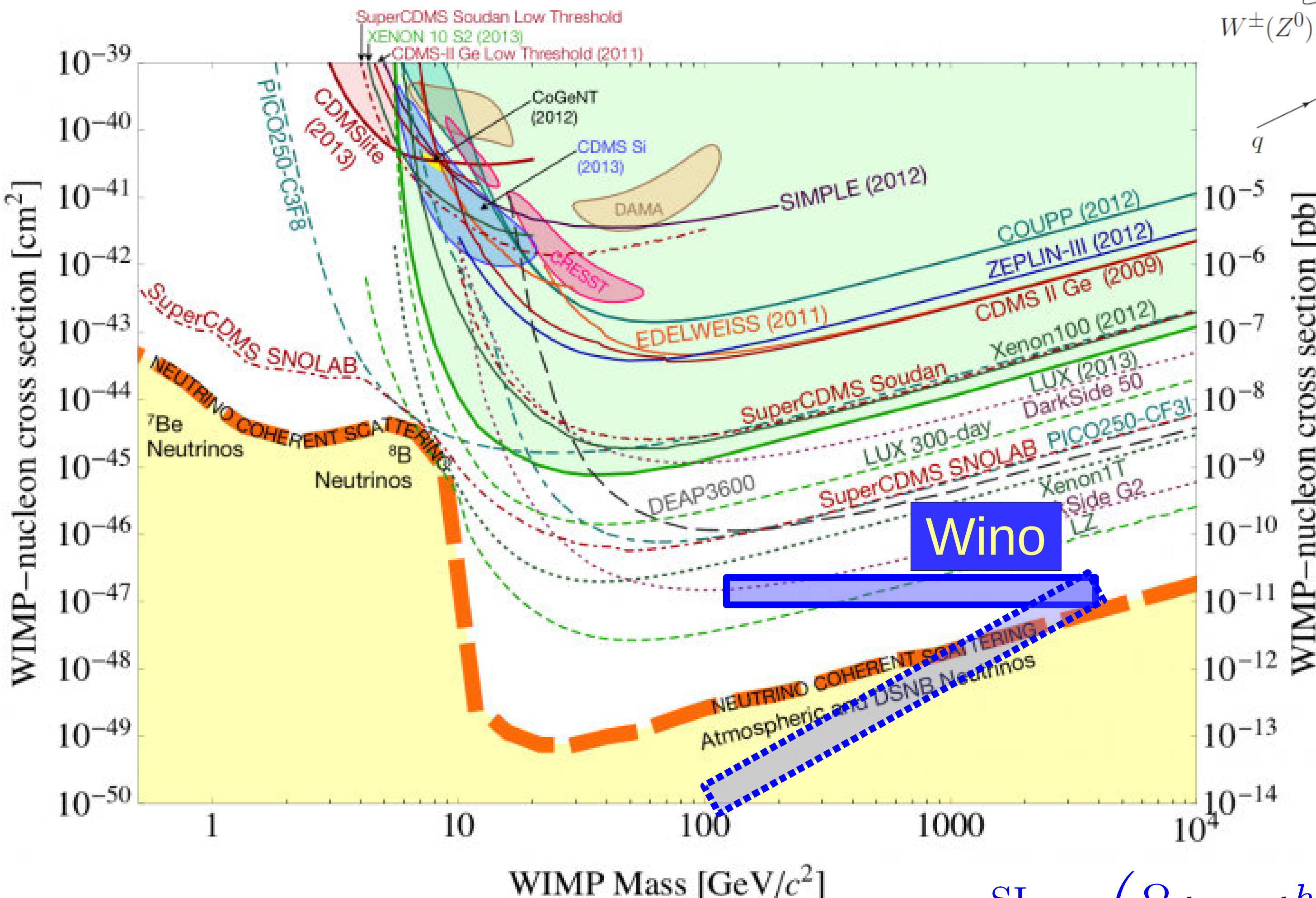
Direct Detection



Hisano, Ishiwata, Nagata & Takesako, 11

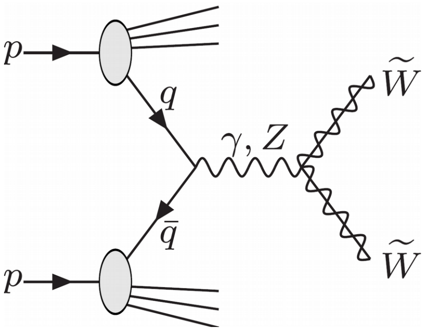
Direct Detection





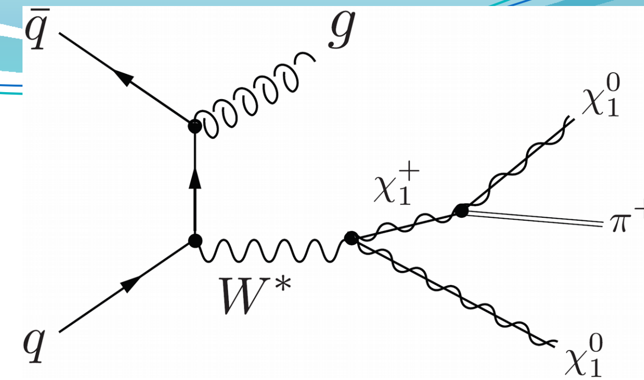
$$\sigma_{\rm eff}^{\rm SI} = \left(\frac{\Omega_{\rm thermal}h^2}{\Omega_{\rm obs}h^2}\right)\sigma^{\rm SI}$$

LHC Signatures of Wino

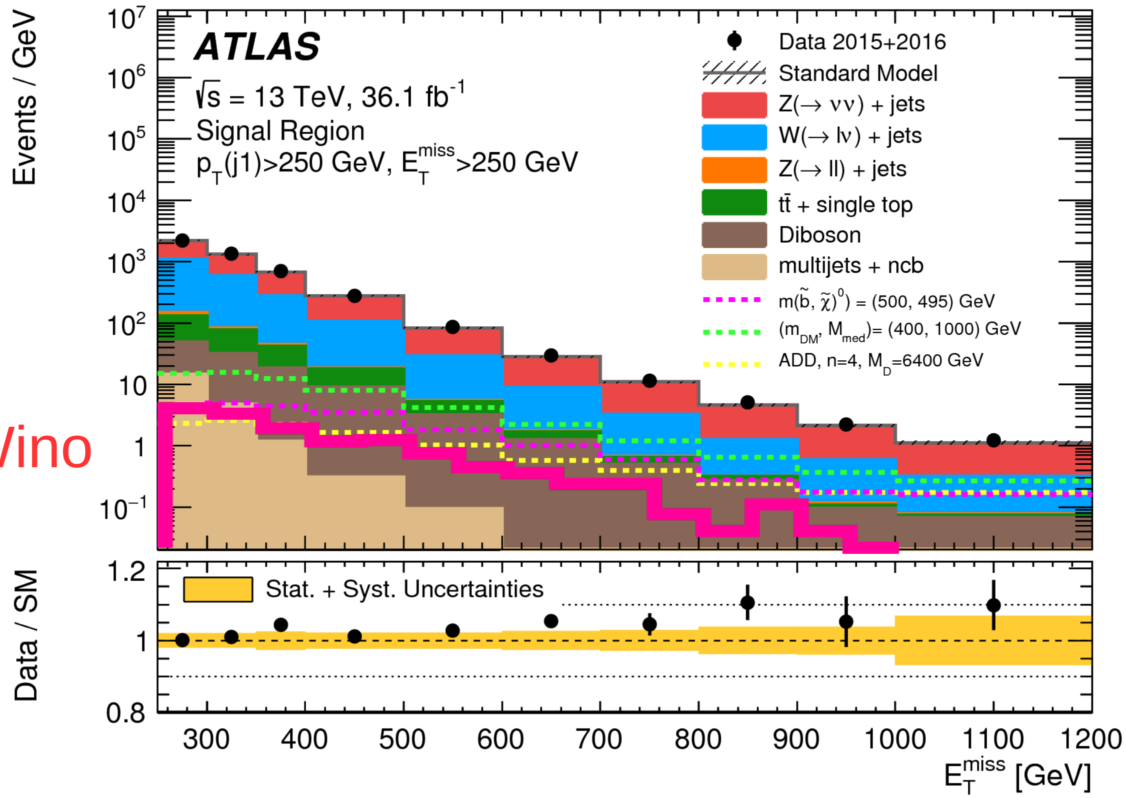


- Mono-jet + missing energy
- (Disappearing) charged tracks
- (Displaced) soft tracks
- Quantum effects to the SM processes

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%

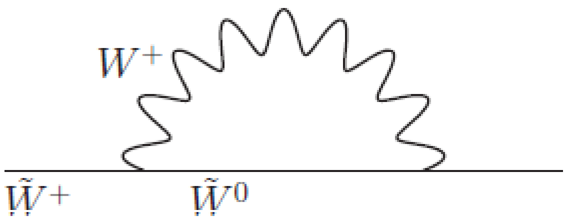
[Ismail, Izaguirre & Shuve,1605.00658]

- Mono W or Z.
  - Most sensitive in some DM model.

[Bai & Tait, 1208.4361]

- Decay of charged Wino

Wino Spectrum



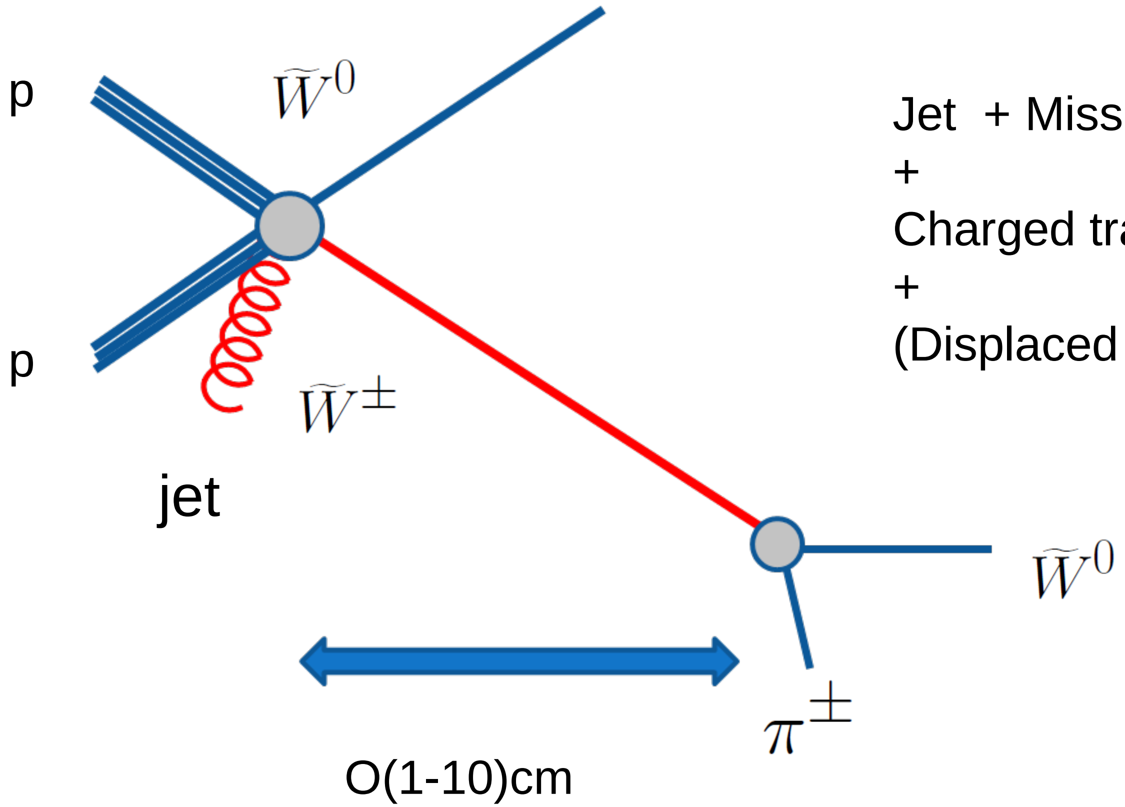
Radiative correction

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

[Ibe,Matsumoto,Sato 12]

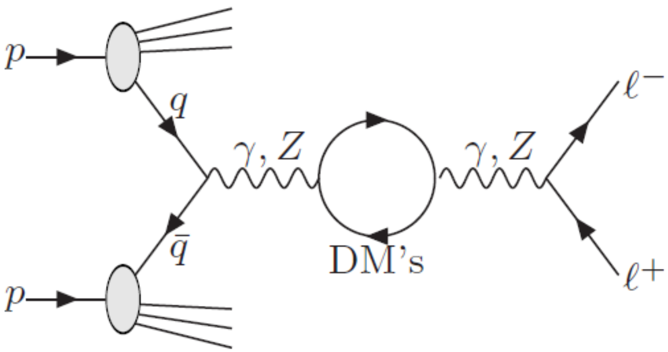
$$c\tau(\widetilde{W}^{\pm} \to \widetilde{W}^{0}\pi^{\pm}) \simeq 7 \text{ cm} \left(\frac{\Delta m}{165 \text{ MeV}}\right)^{-3}$$

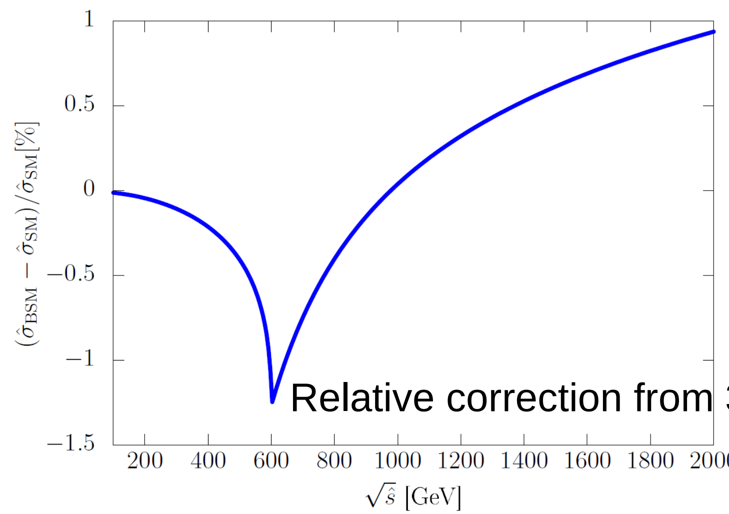
Direct LHC Signals



Jet + Missing energy
+
Charged track
+
(Displaced)Soft pion

Indirect Signatures





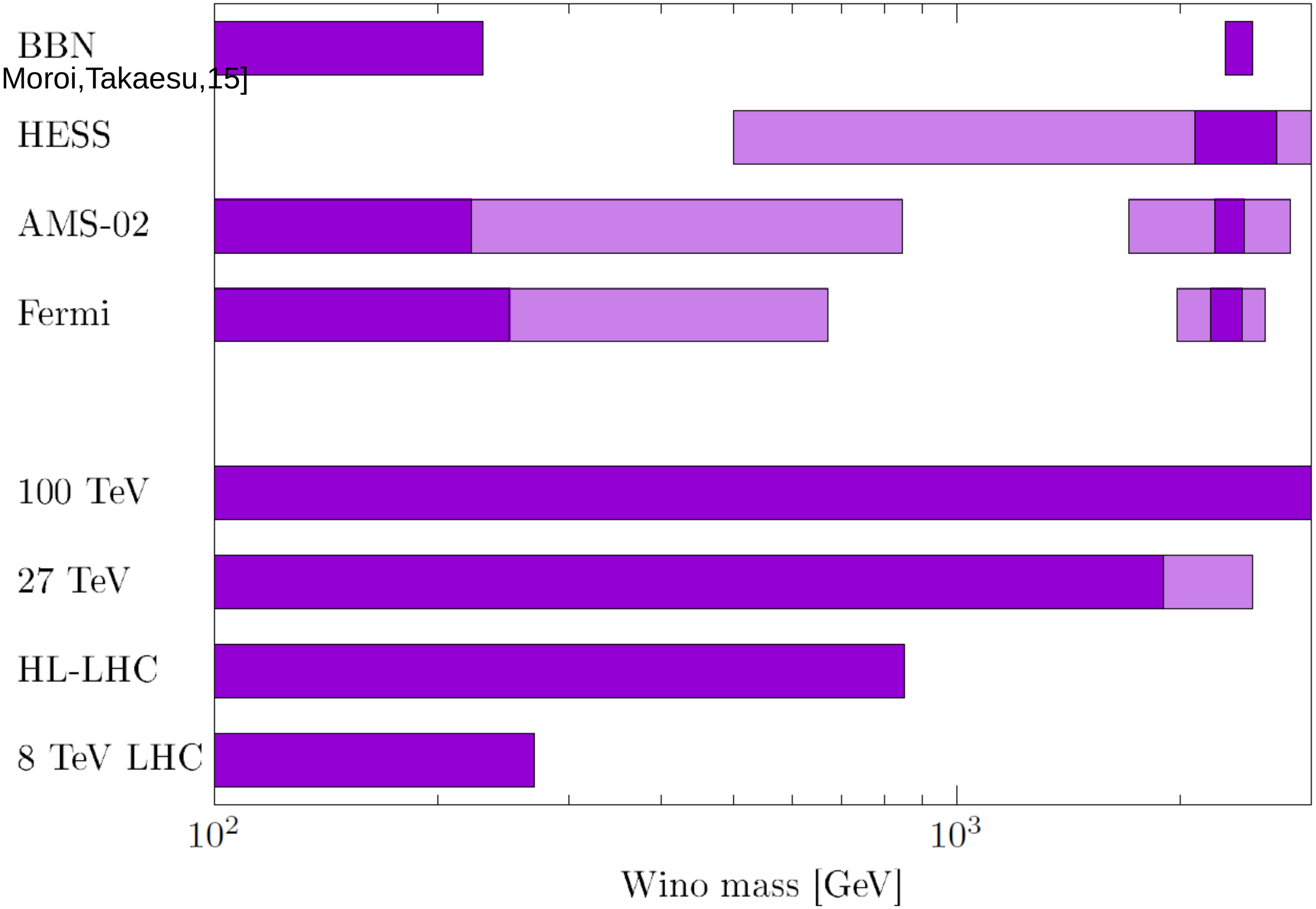
Relative correction from 300 GeV Wino

Indirect probe of quantum effect of DM

Precision measurement of SM processes

DM Search and synergy

[Kawasaki,Kohri,Moroi,Takaesu,15]



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

$> 10^{27}$ sec

Lifetime measurement is difficult at collider.

DM Search and synergy

Biggest advantage of collider:

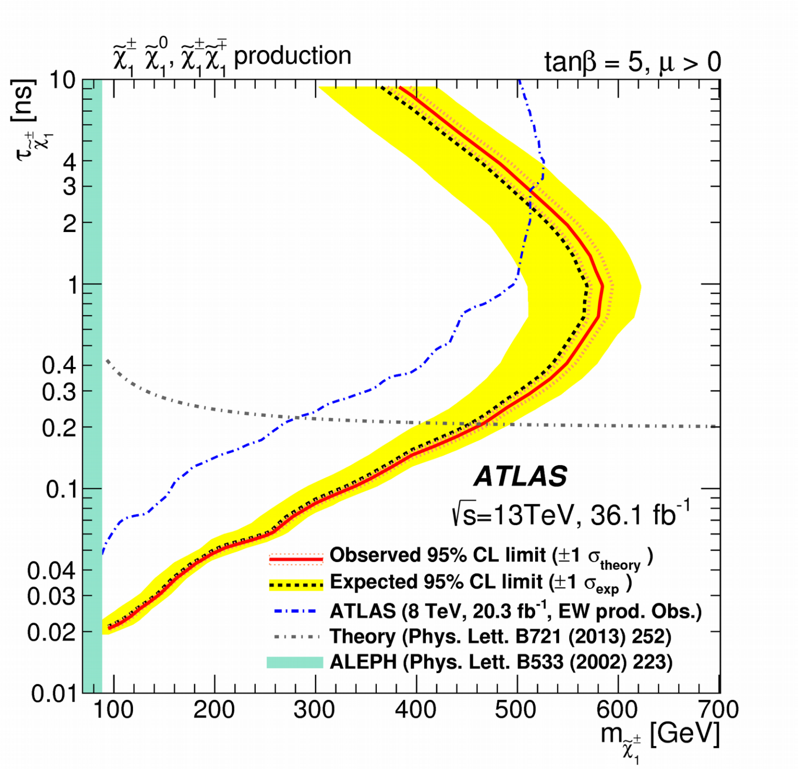
- Absence of astrophysical/cosmological uncertainty
- Measurement
  - Cross section
  - Mass spectrum
  - Lifetime of DM partner
  - …

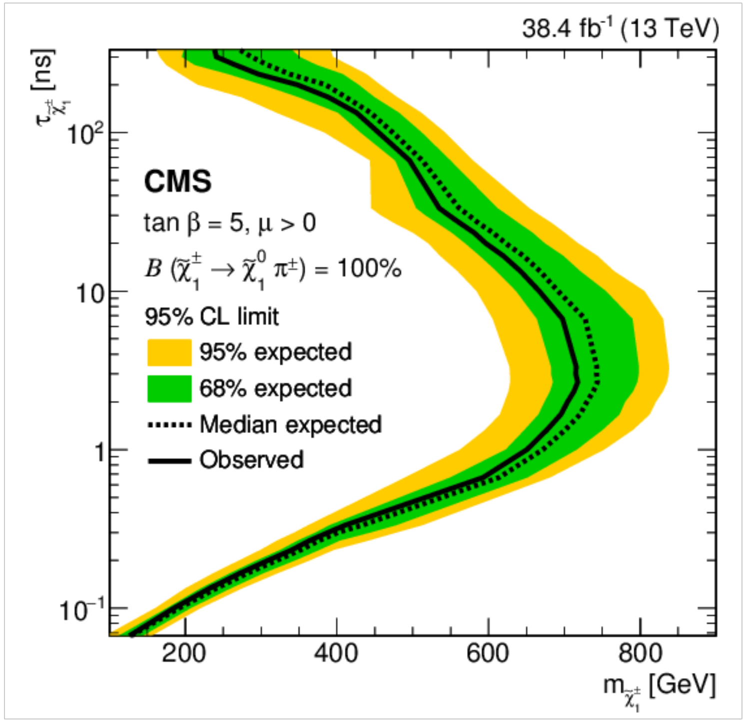
Cross check of direct/indirect DM signatures is essential.

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

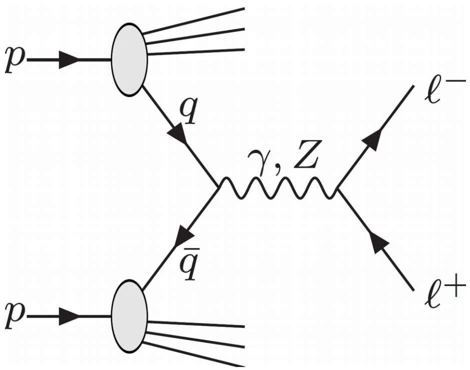
Disappearing track search

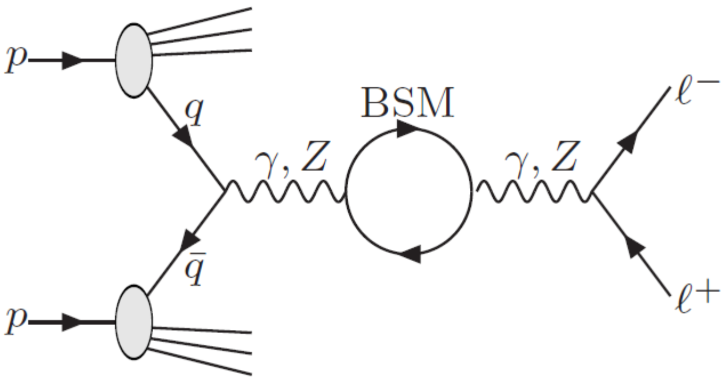




[Matsumoto, SS, Takeuchi, 1711.05449, 1810.12234]

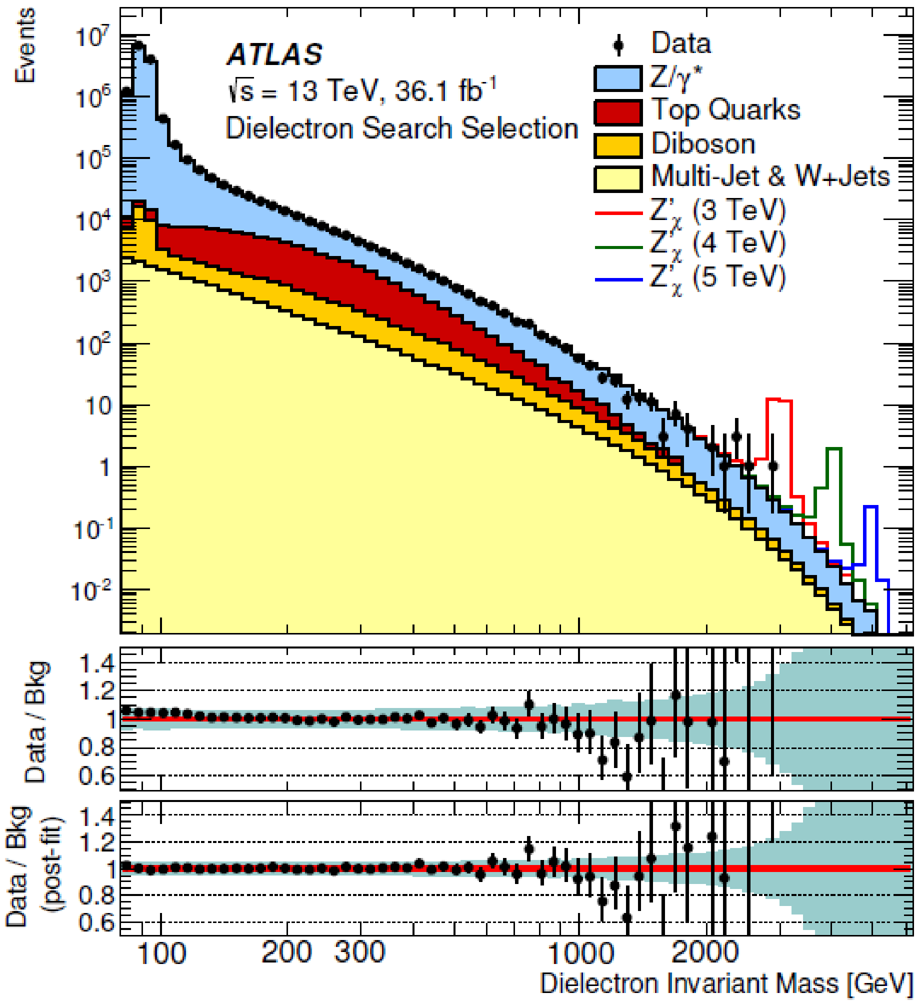
Indirect Probe at LHC





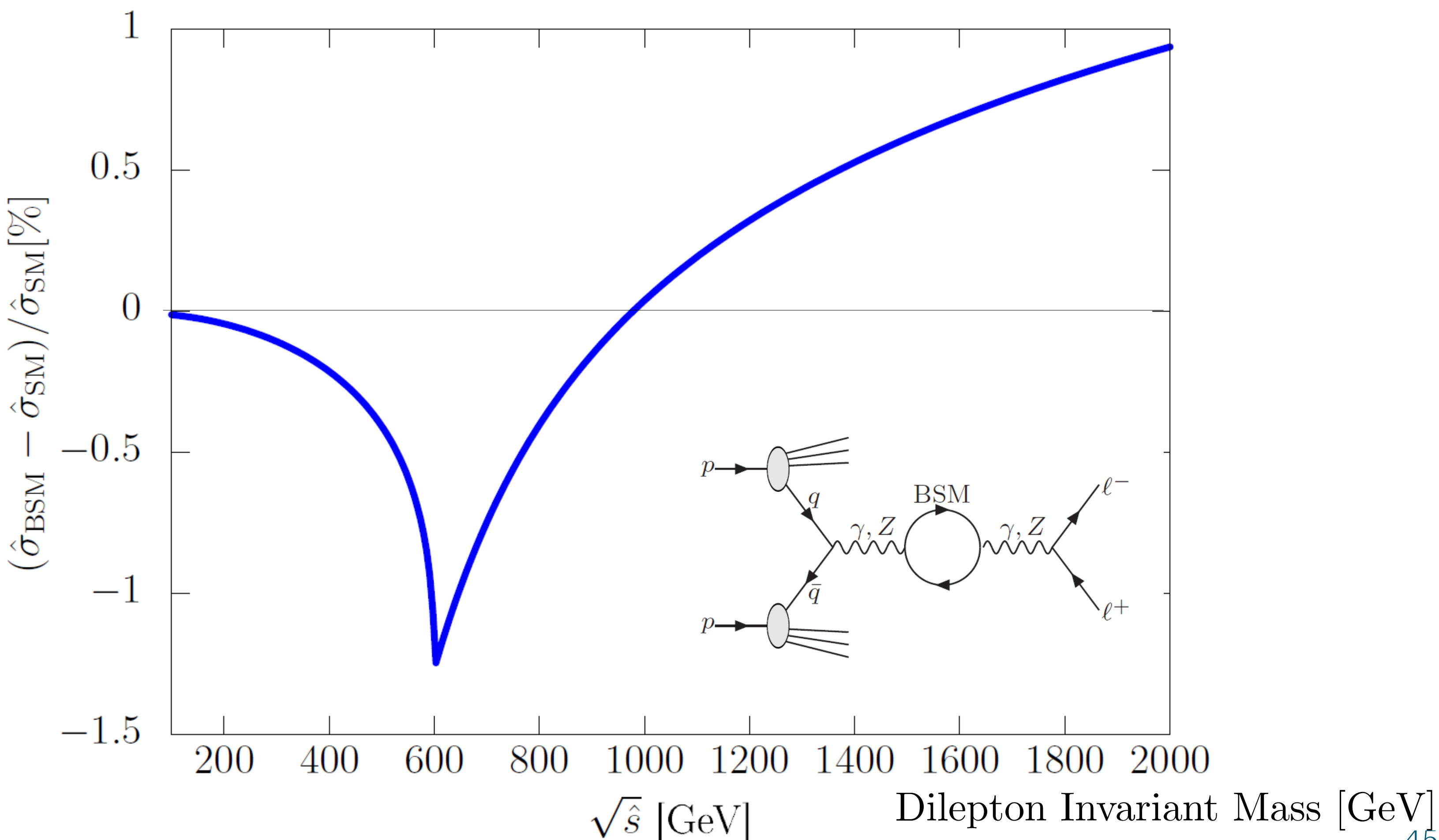
Interference between SM and BSM gives correction

Observed Data



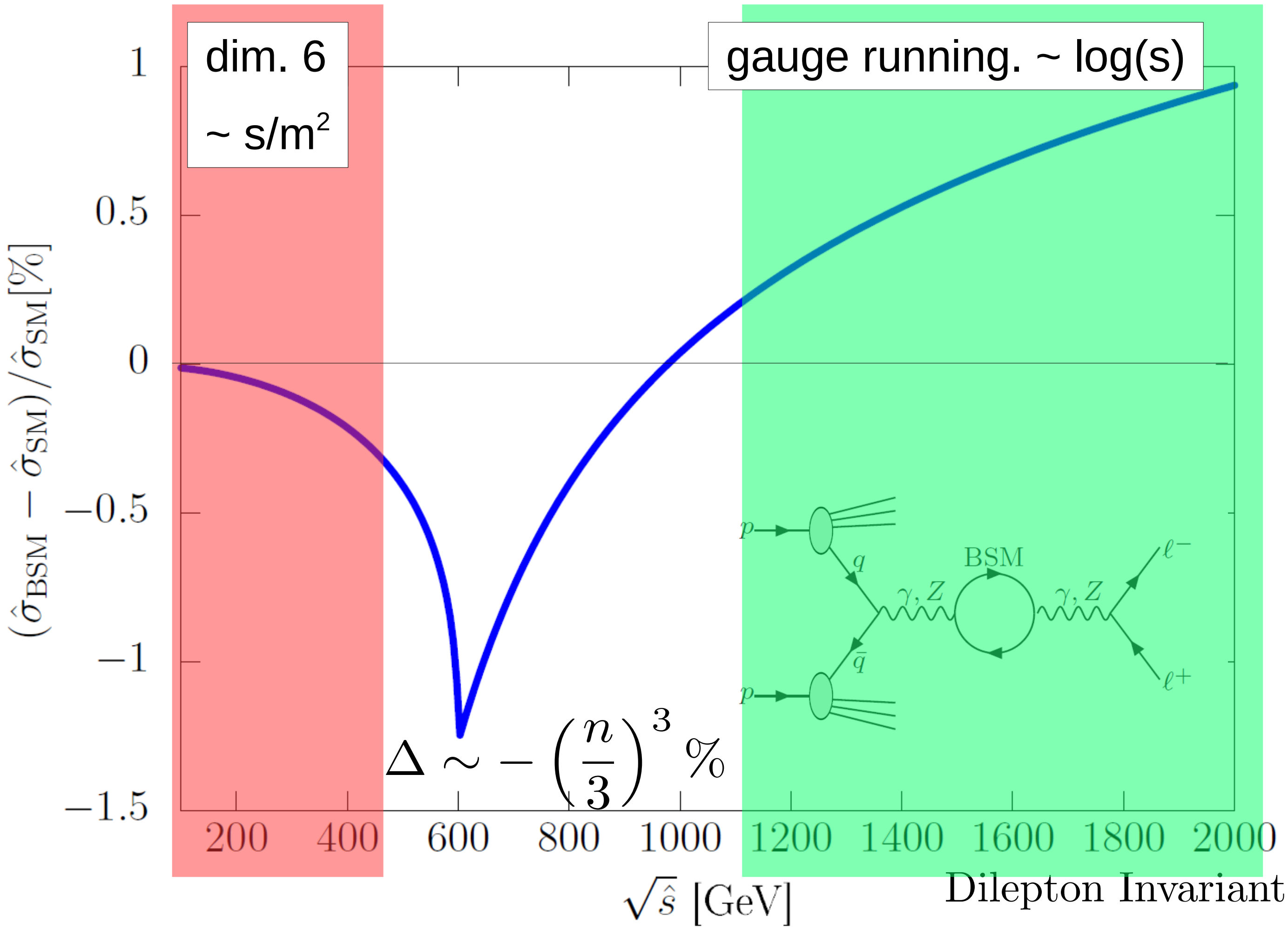
Correction from DM

Relative correction from 300 GeV Wino



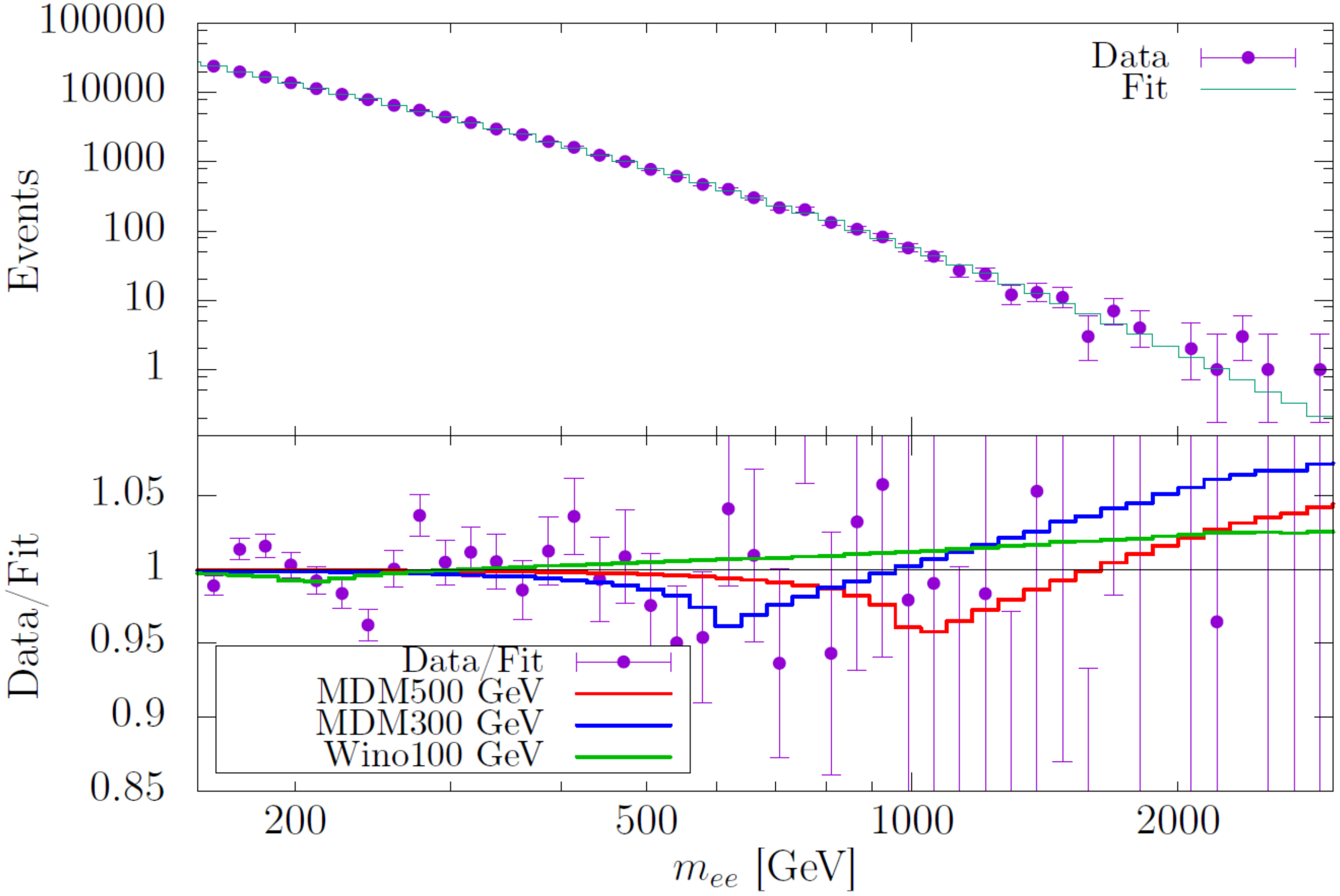
Correction from DM

Relative correction from 300 GeV Wino



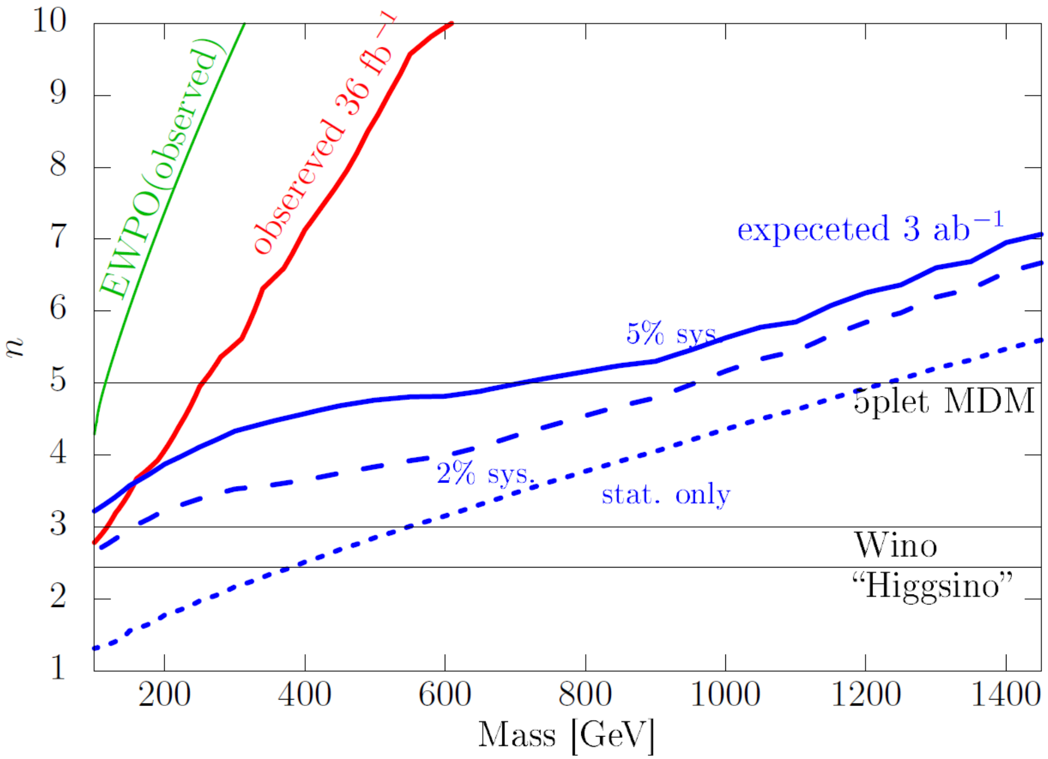
Dilepton Invariant Mass [GeV]

Indirect Probe at LHC



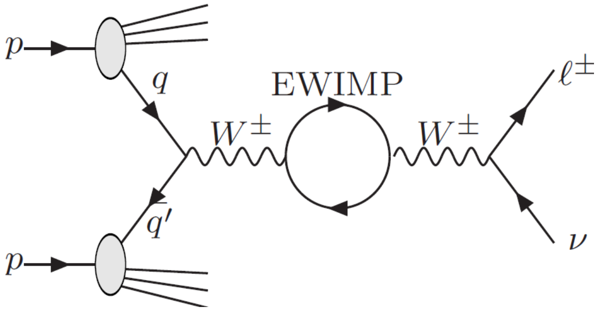
Indirect Probe at LHC

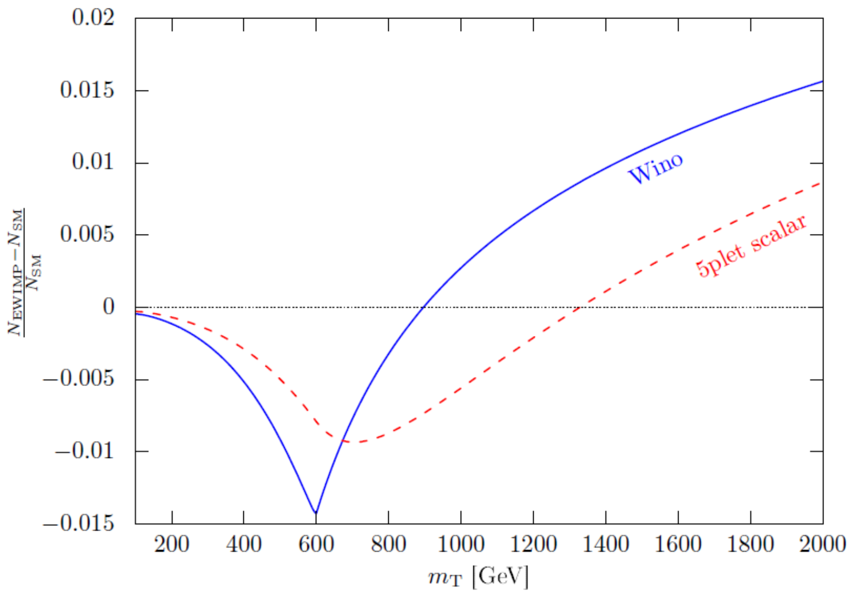
of SU(2)$_L$ representation

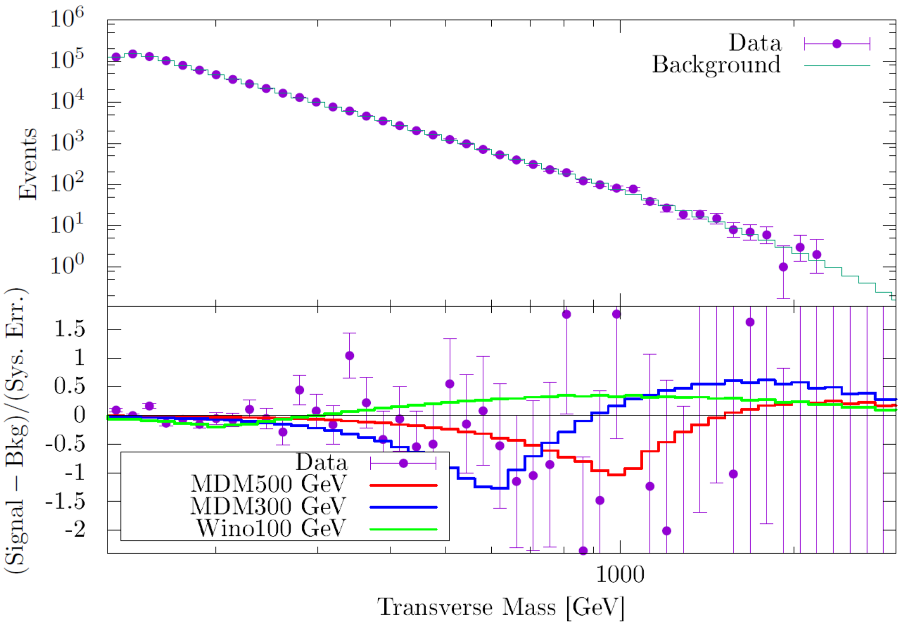


Mono-lepton Case

Mono-lepton signal may be better.

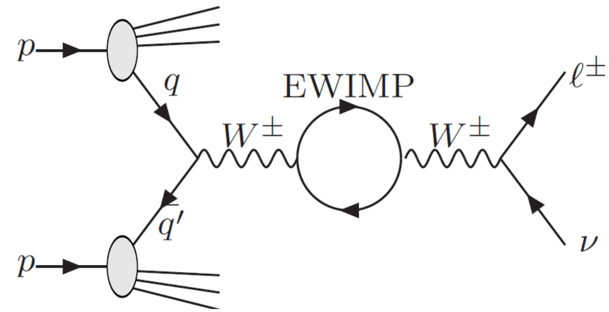


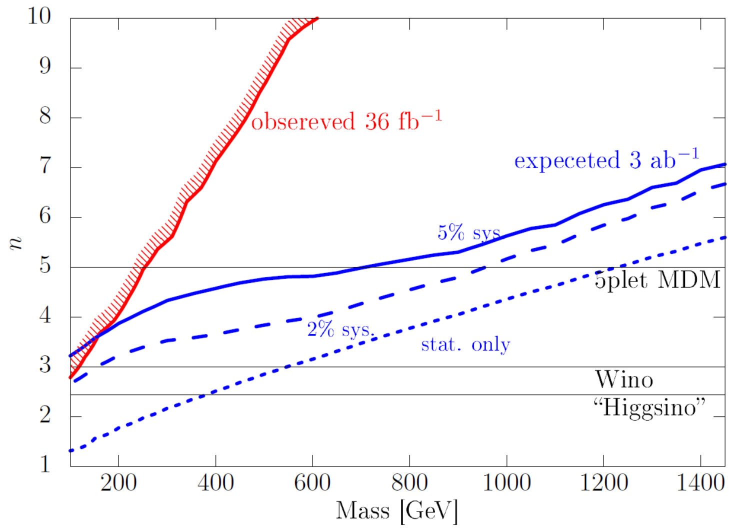




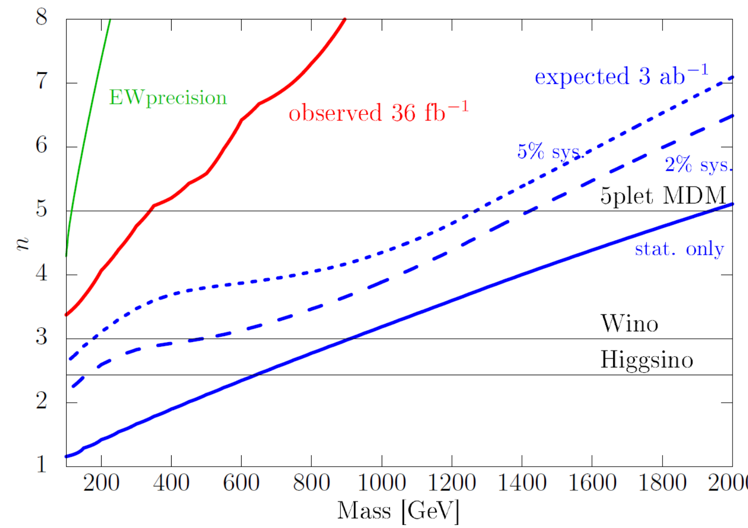
Indirect Probe at LHC

of SU(2) representation





dilepton



mono-lepton

Indirect Search

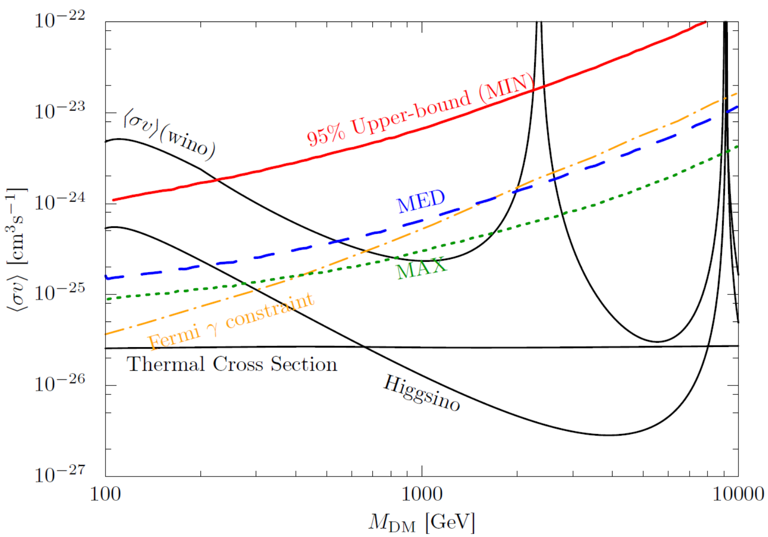
- Precision measurements can probe DM, and be as powerful as mono-jet + MET search.
  - Future 100 TeV collider covers even Higgsino DM.
    [Chigusa, Ema & Moroi, 1810.07349, and Luzio, Grober & Panico, 1810.10993]

- Applicable to any kinds of BSM particle which has gauge charge.

- Independent on how particle decays.

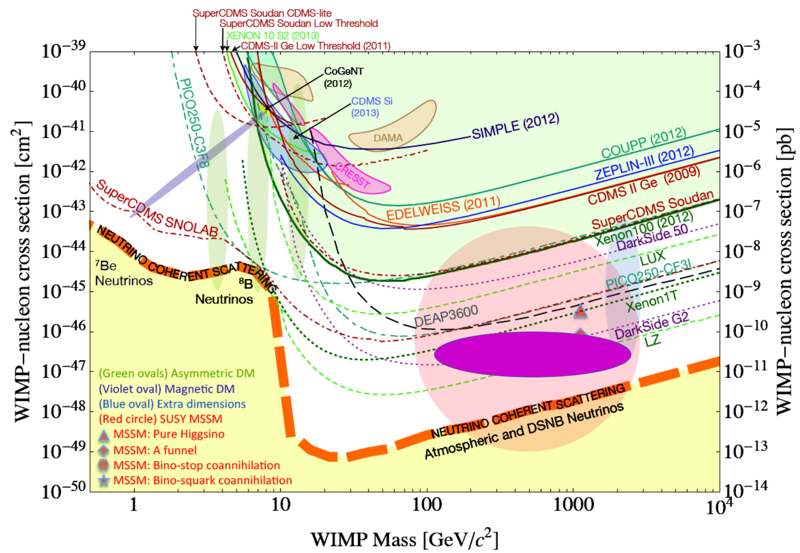
DM Search and synergy

[1310.8327]



Large Wino annihilation rate

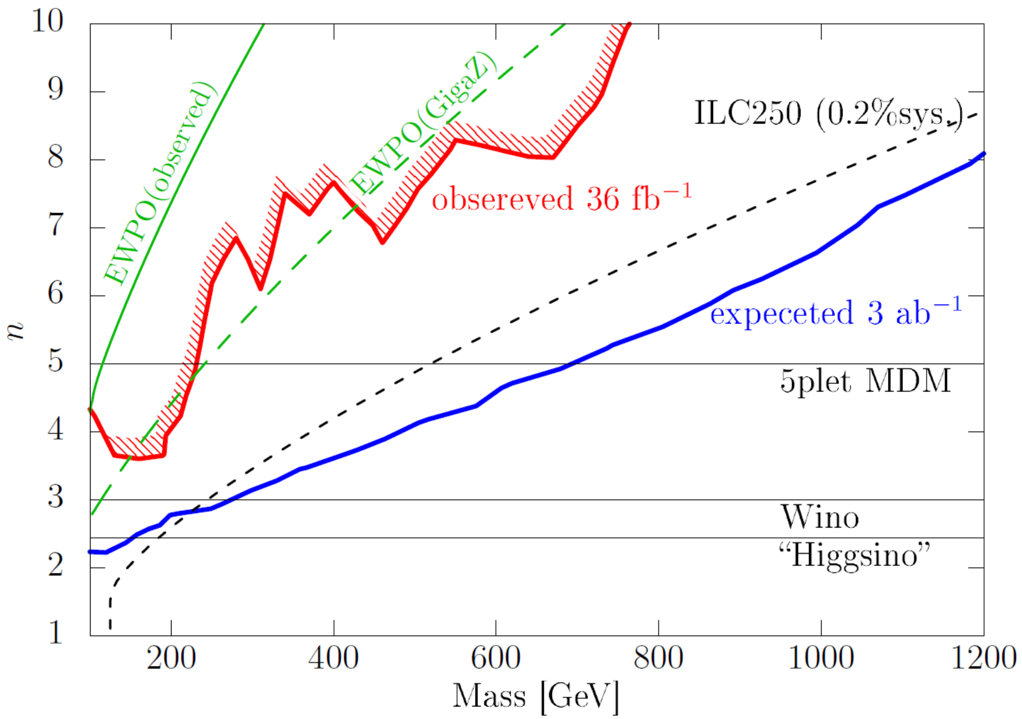
[Hisano, Matsumoto, Nojiri, Osamu & Saito, 04]



Wino-Nucleon XS ~ 10^{-47} cm^2

[Hisano, Ishiwata & Nagata, 12]

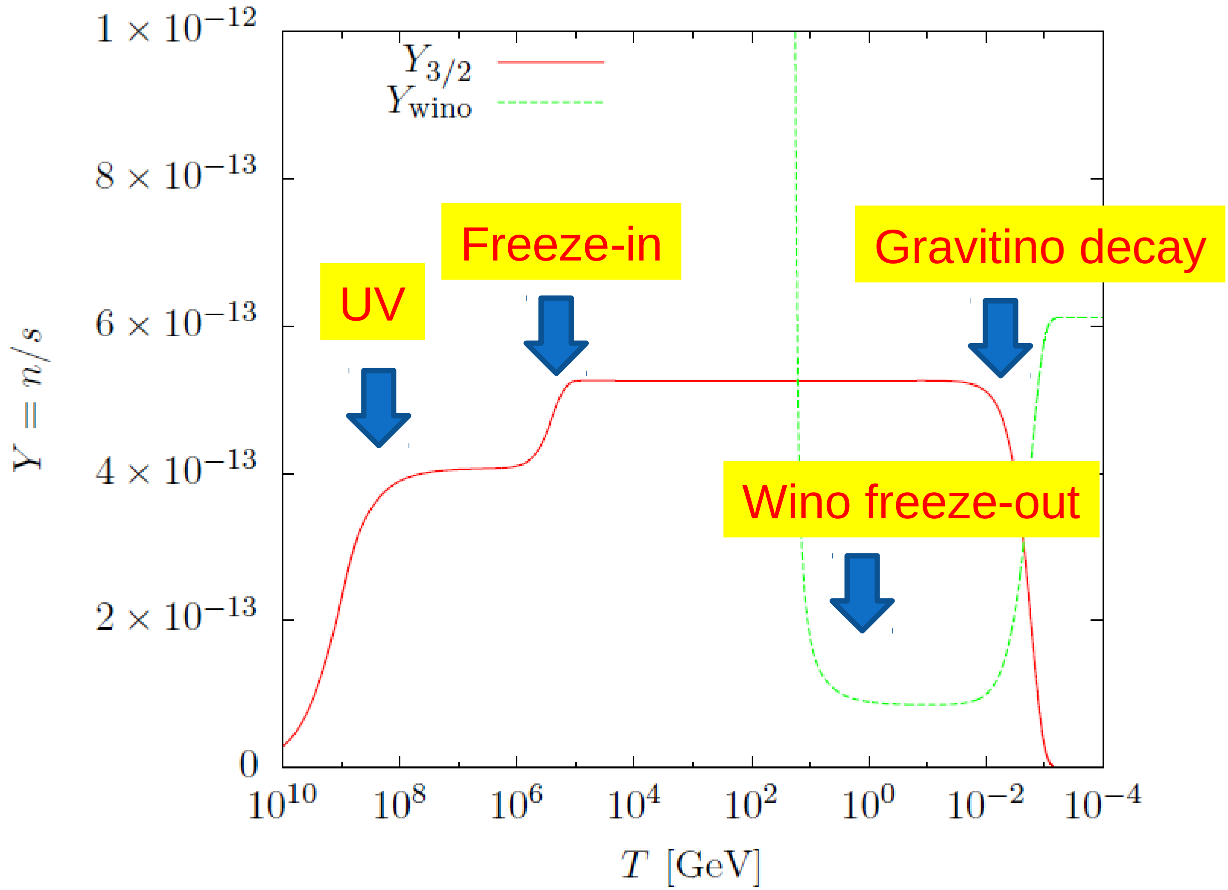
Fit

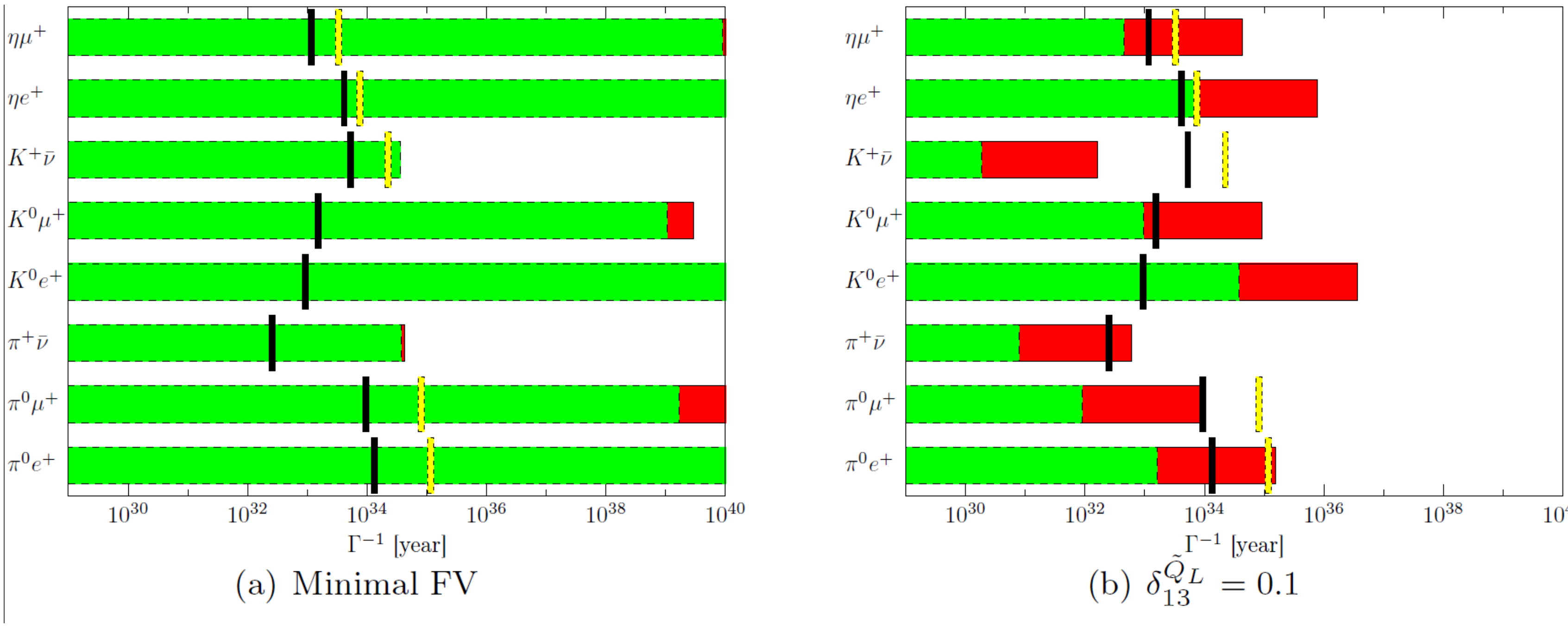


10
9
8
7
6
5
4
3
2
1
n
200
400
600
800
1000
1200
Mass [GeV]
EWPO(observed)
EWPO(GigaZ)
ILC250 (0.2%sys.)
obsereved 36 fb^{-1}
expeceted 3 ab^{-1}
5plet MDM
Wino
"Higgsino"

Non-thermal Example

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





(a) Minimal FV

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