# WIMP at Collider

Satoshi Shirai (Kavli IPMU)

Collaboration with

Hajime Fukuda, Natsumi Nagata, Hideyuki Oide and Hidetoshi Otono

ElectroWeak

# EWIMP at Collider

Wino, higgsino,…

Satoshi Shirai (Kavli IPMU)

Collaboration with
Hajime Fukuda, Natsumi Nagata, Hideyuki Oide and Hidetoshi Otono

# What's Dark Matter?

- Stable
- Weakly Interacting
- Cold
- Correct Production Mechanism

# Candidates

- Axion
- (Primordial) Black hole
- WIMP
- Others…

# WIMP Dark Matter

Weakly Interacting Massive Particle

# WIMP Dark Matter

Weakly Interacting Massive Particle

~Electroweak ~100 GeV – 10 TeV

# Minimal SUSY Standard Model（MSSM）

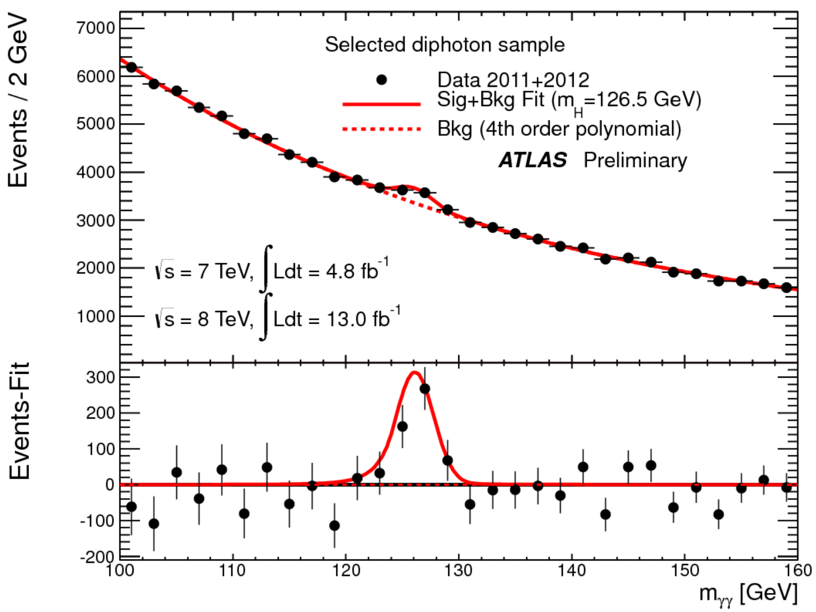
| Standard Model（SM） | SUSY Partner |
|---|---|
| Lepton | Scalar Lepton |
| Quark | Scalar Quark |
| Scalar Higgs | Higgsino |
| Gauge Boson | Gaugino |
| gluon | gluino |
| weak boson | wino |
| photon | bino |

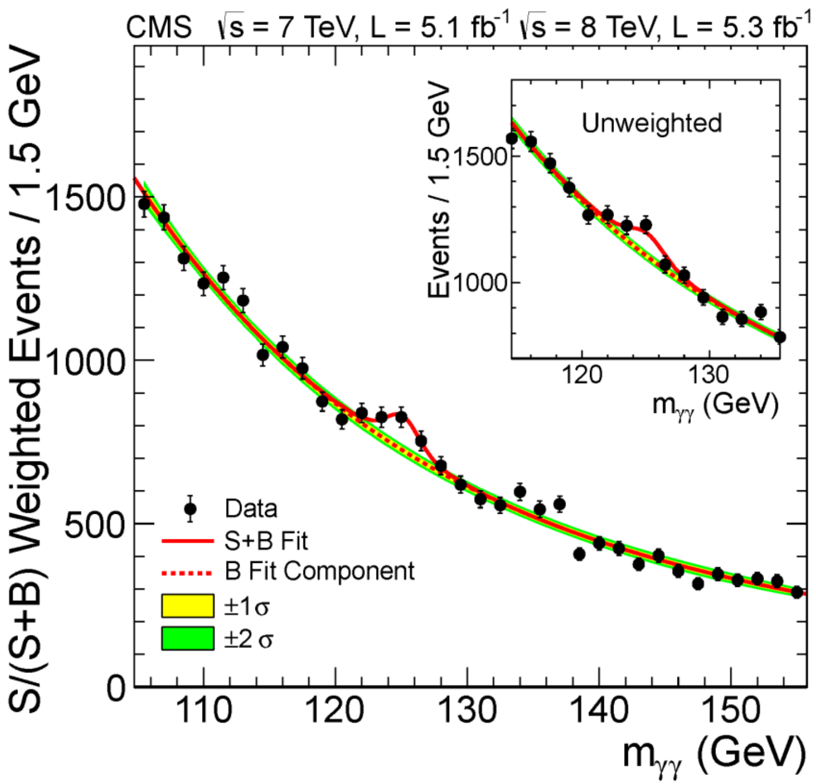
# What is Wino?

## Wino is

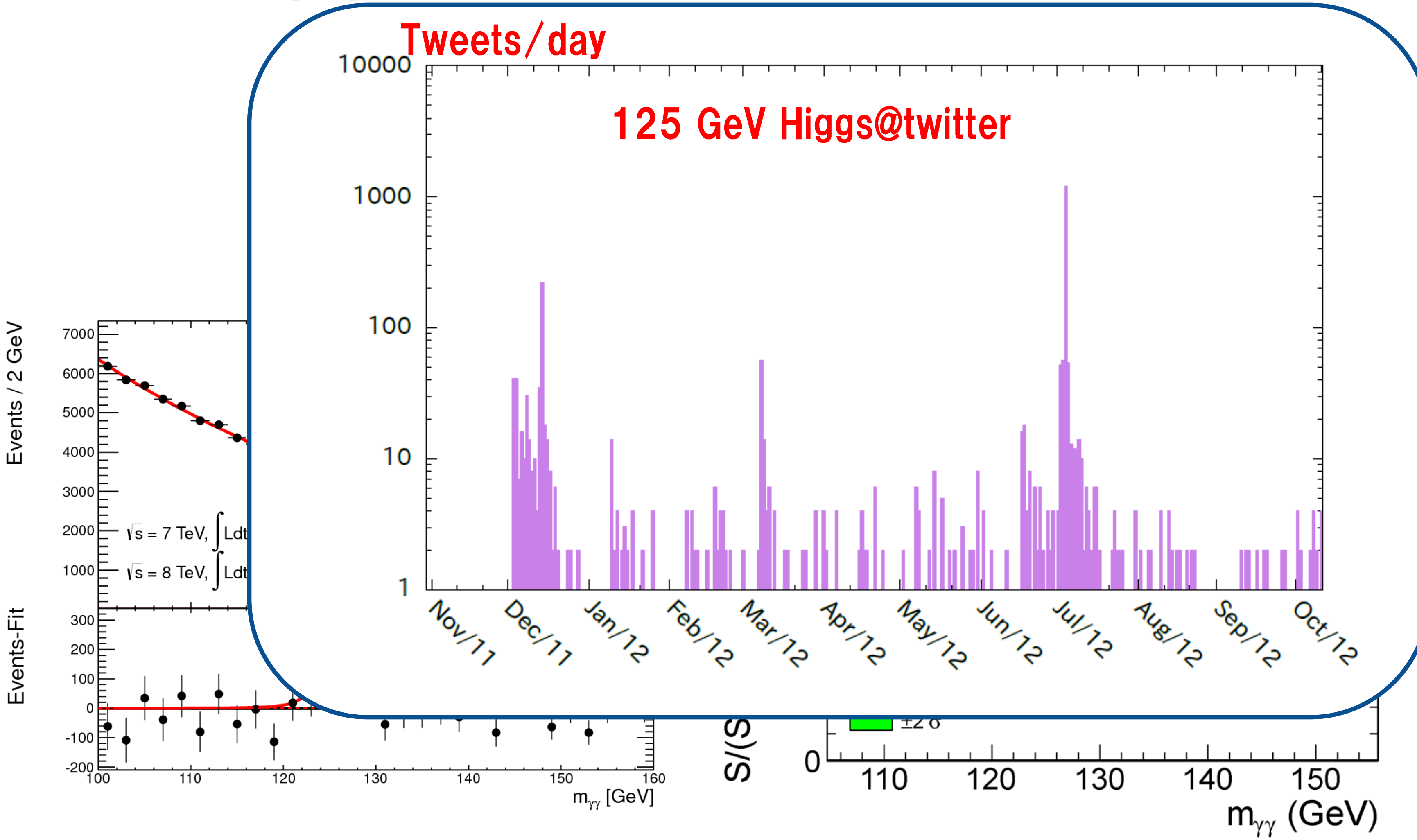
- Majorana fermion
- Hypercharge Y=0
- SU (2) triplet $\begin{pmatrix} \widetilde{W}^{+} \\ \widetilde{W}^{0} \\ \widetilde{W}^{-} \end{pmatrix}$

# A "Higgs" Discovered!

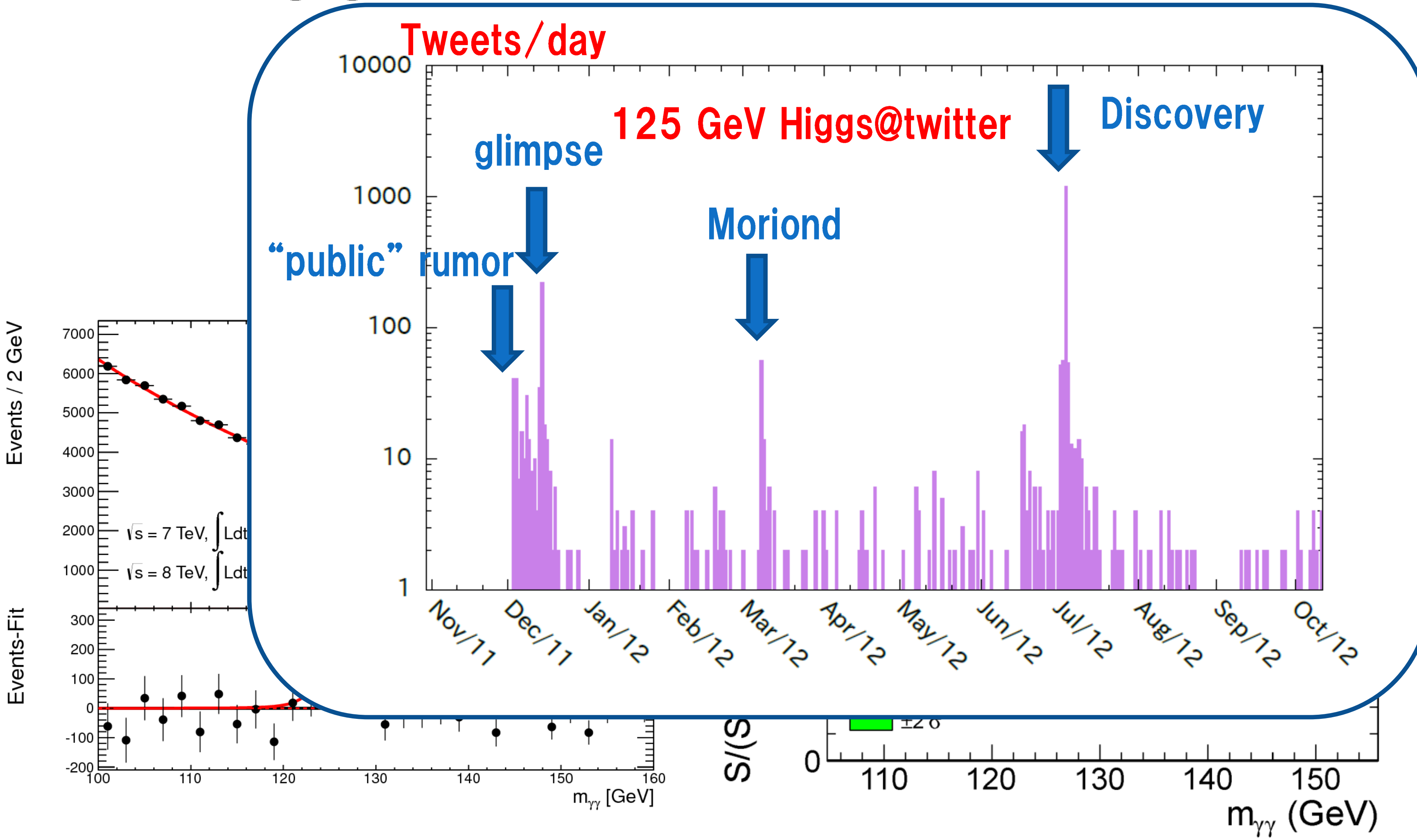


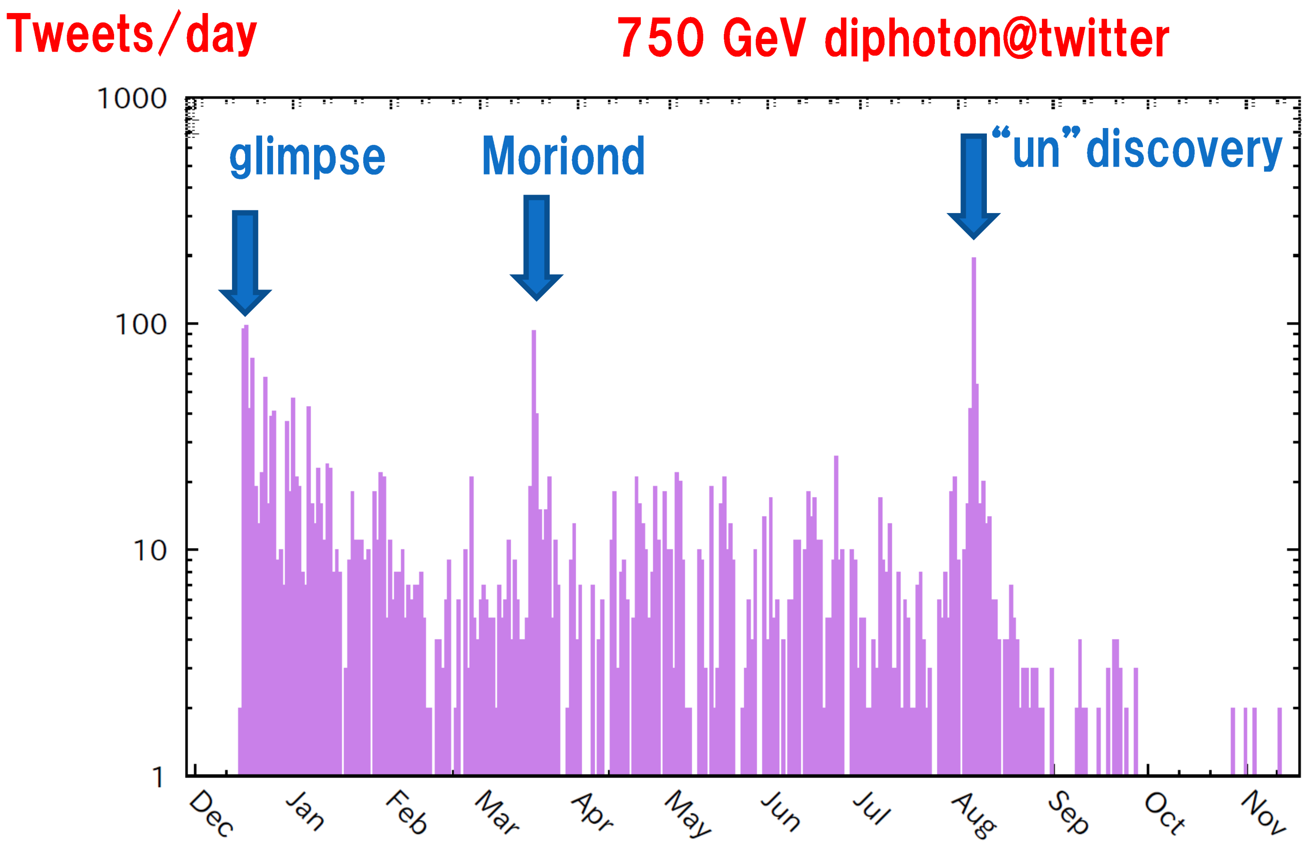
# A "Higgs" Discovered!



# A “Higgs” Discovered!



# 750 GeV case…



Tweets/day
750 GeV diphoton@twitter
1000
100
10
1
glimpse
Moriond
“un”discovery
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov

# SUSY Higgs

Higgs potential

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

In MSSM

$$\lambda = \frac{1}{4}(g_2^2 + \frac{3}{5}g_1^2)\cos^2(2\beta)$$

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

This is clearly less than observed 125 GeV Higgs!

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

# 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

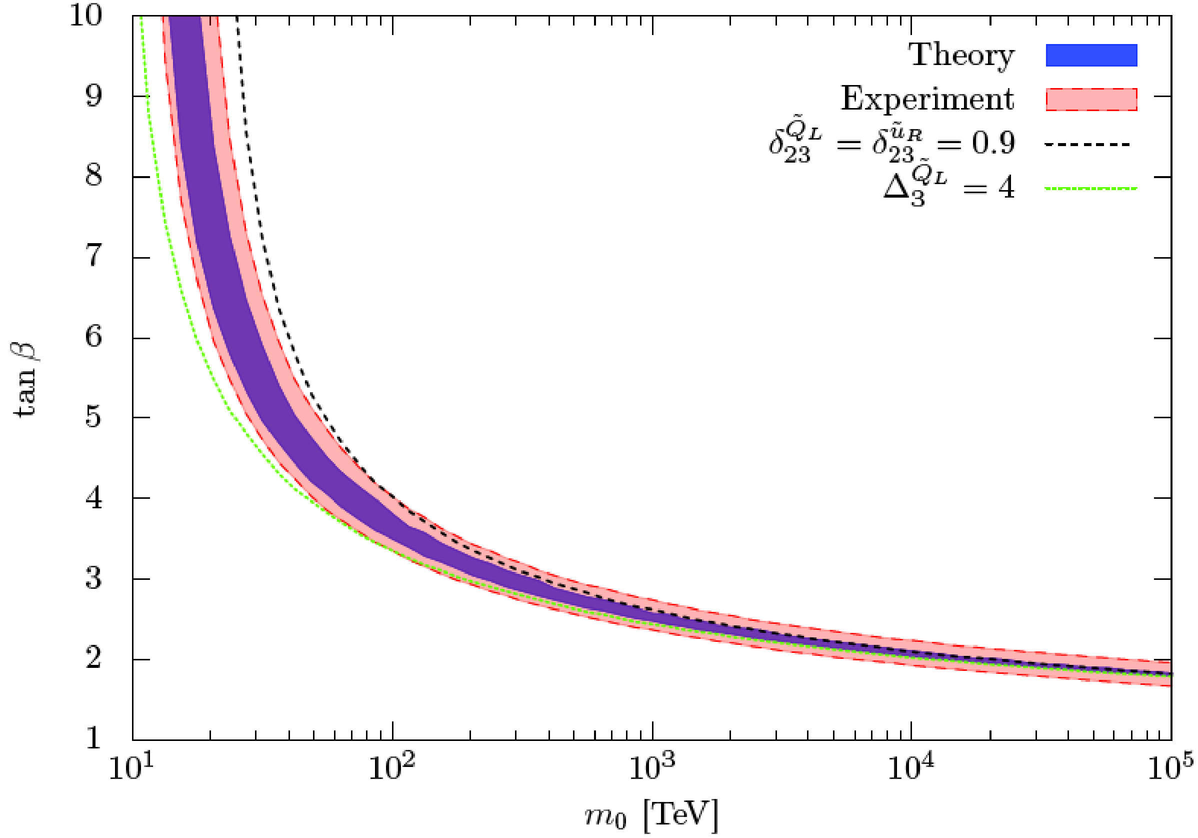
"4-th" family

NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

# Higgs Mass from Stop

**125 GeV Higgs OK regions**



# Mini-Split Mass Spectrum

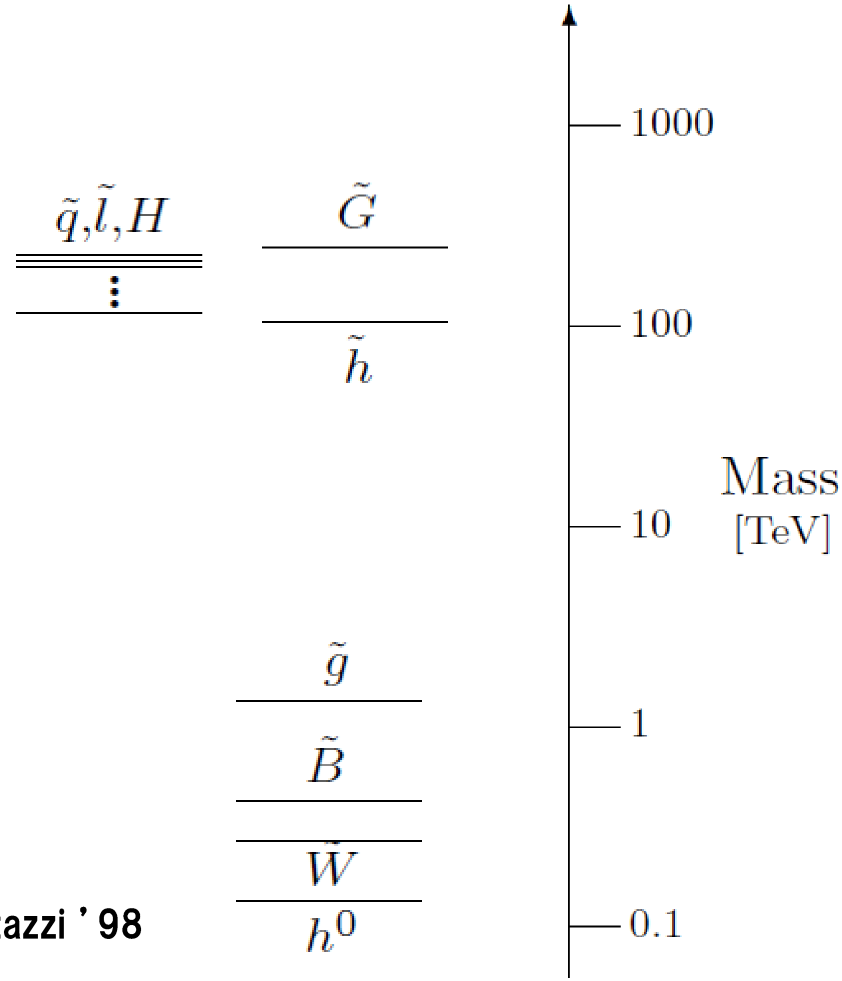
**Gravity Mediation**

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

**Anomaly Mediation**

$$M_i \sim \frac{\alpha_i}{4\pi} m_{3/2}$$

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



# Mini-Split Mass Spectrum

## Theory papers

Before Higgs Discovery

Wells, "PeV-Scale SUSY," 2004

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

After Higgs

Hall, Nomura, SS, "Spread SUSY"

Ibe, Matsumoto,Yanagida,.., " Pure Gravity Mediation"

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

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

and various literatures...

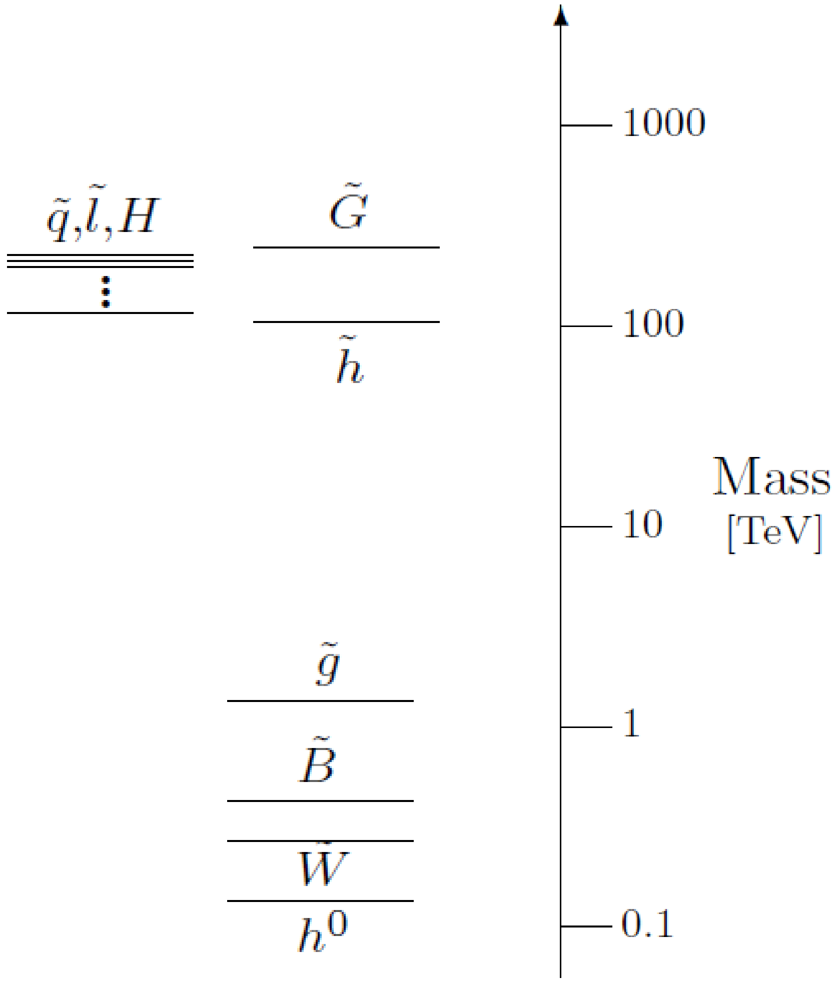
# Mini-Split Mass Spectrum

Gravity Mediation

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

Anomaly Mediation

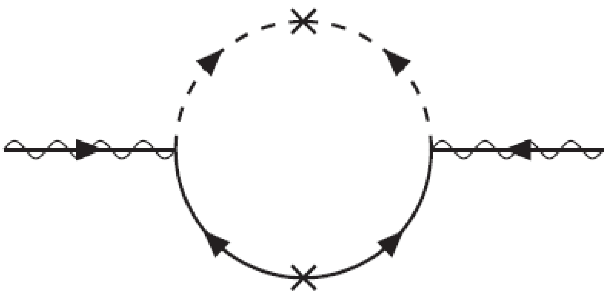
$$M_i \sim \frac{\alpha_i}{4\pi} m_{3/2}$$



# Gaugino Mass

$$
\begin{aligned}
M_1 &= \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L), \\
M_2 &= \frac{\alpha_2}{4\pi}(m_{3/2} + L), \\
M_3 &= \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).
\end{aligned}
$$

# Gaugino Mass



AMSB

$$M_1 = \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L),$$

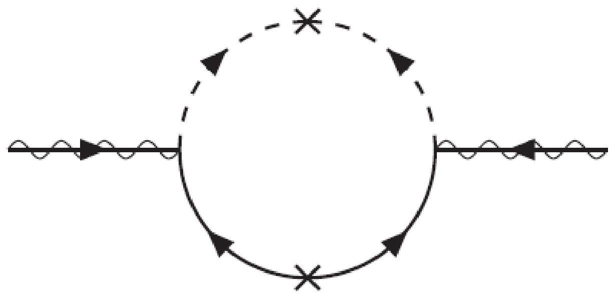
$$M_2 = \frac{\alpha_2}{4\pi}(m_{3/2} + L),$$

$$M_3 = \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).$$

Higgsino correction

Squark correction

# Gaugino Mass



AMSB

$$M_1 = \frac{3}{5}\frac{\alpha_1}{4\pi}(11m_{3/2} + L),$$

$$M_2 = \frac{\alpha_2}{4\pi}(m_{3/2} + L),$$

$$M_3 = \frac{\alpha_3}{4\pi}(-3m_{3/2})(1 + c_{\tilde{g}}).$$

Higgsino correction

Squark correction

gluino

bino

wino

Wino DM

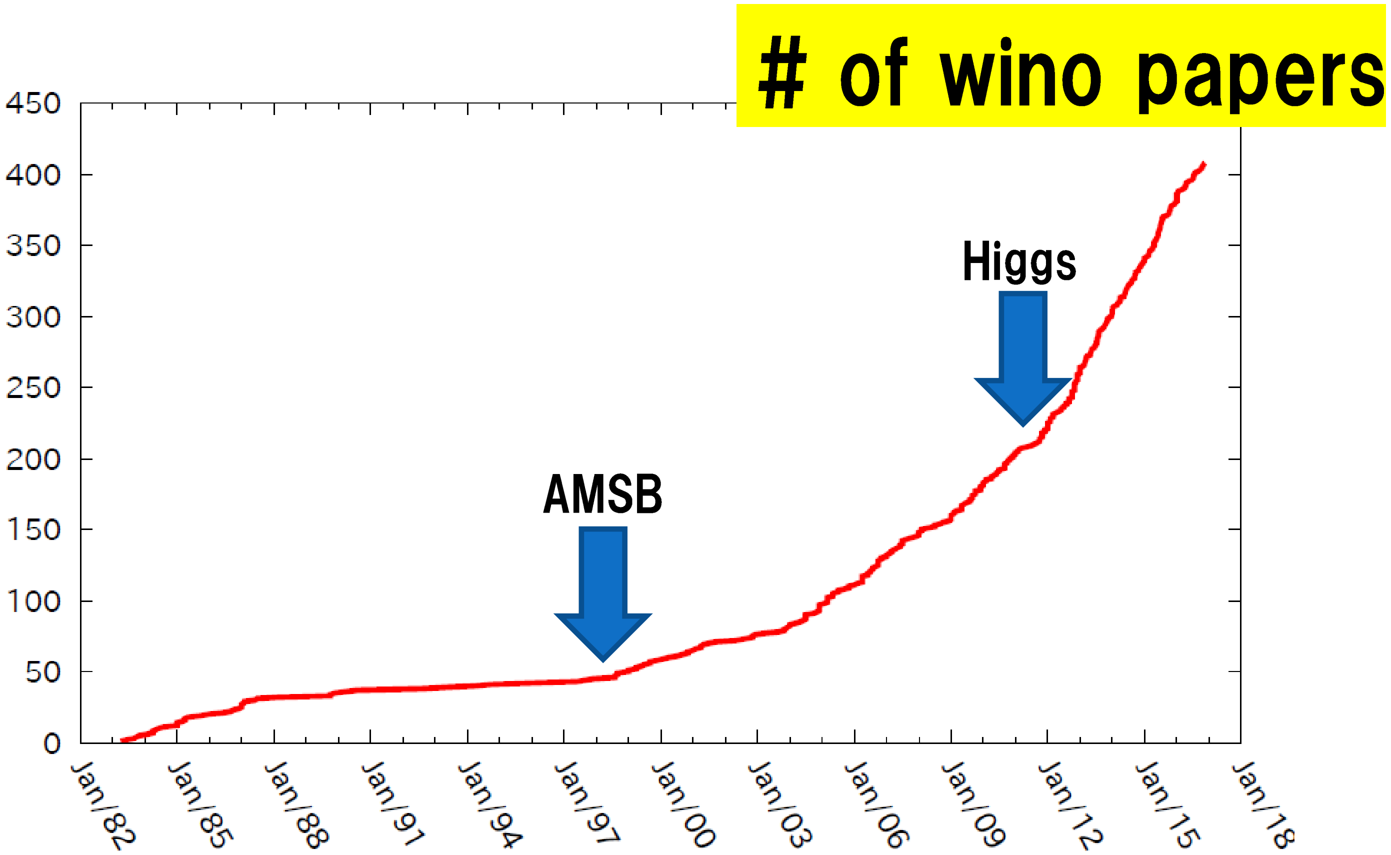
# Wino DM (bottom-up)

| Y \ n | 1 | 2 | 3 | 4 | … |
|---|---|---|---|---|---|
| 0 | | C | wino | C | |
| 1/2 | C | higgsino | C | | |
| 1 | C | C | | C | |
| 3/2 | C | C | C | | |
| 2 | C | C | C | C | |
| … | C | C | C | C | C |

Large hyper-charge is disfavored: (precision, DM detection) [Nagata, SS, 14]

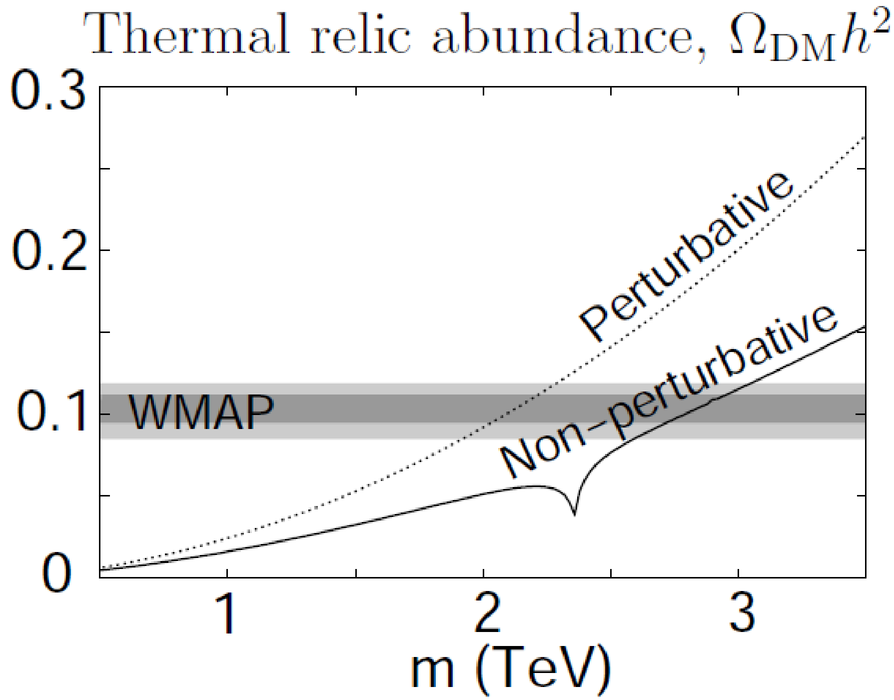
**Wino is minimum of "Minimum DM"**

# Wino is getting more popular



# Wino DM abundance

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

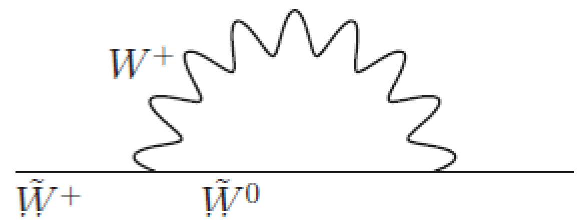



**Wino mass less than 3 TeV is target region**

# Wino at Collider

work in progress,
Nagata,Oide,Otono,SS

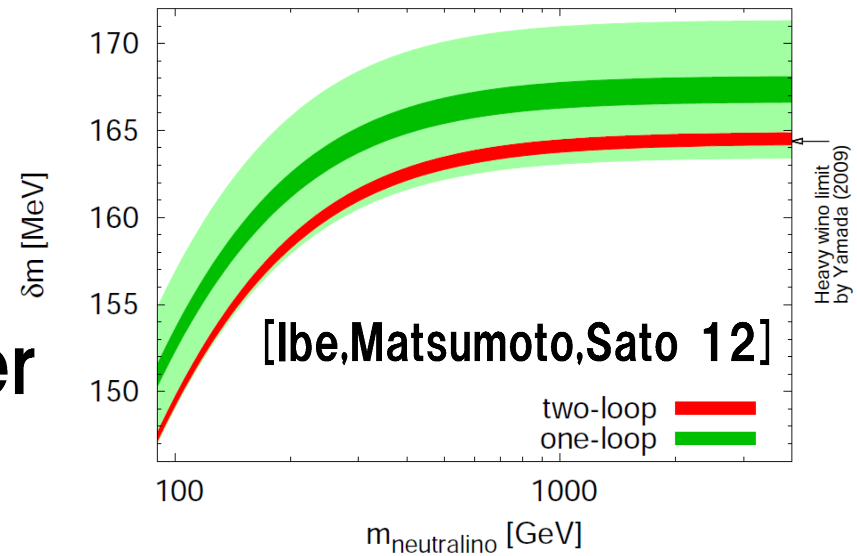
# Wino Spectrum




Radiative correction

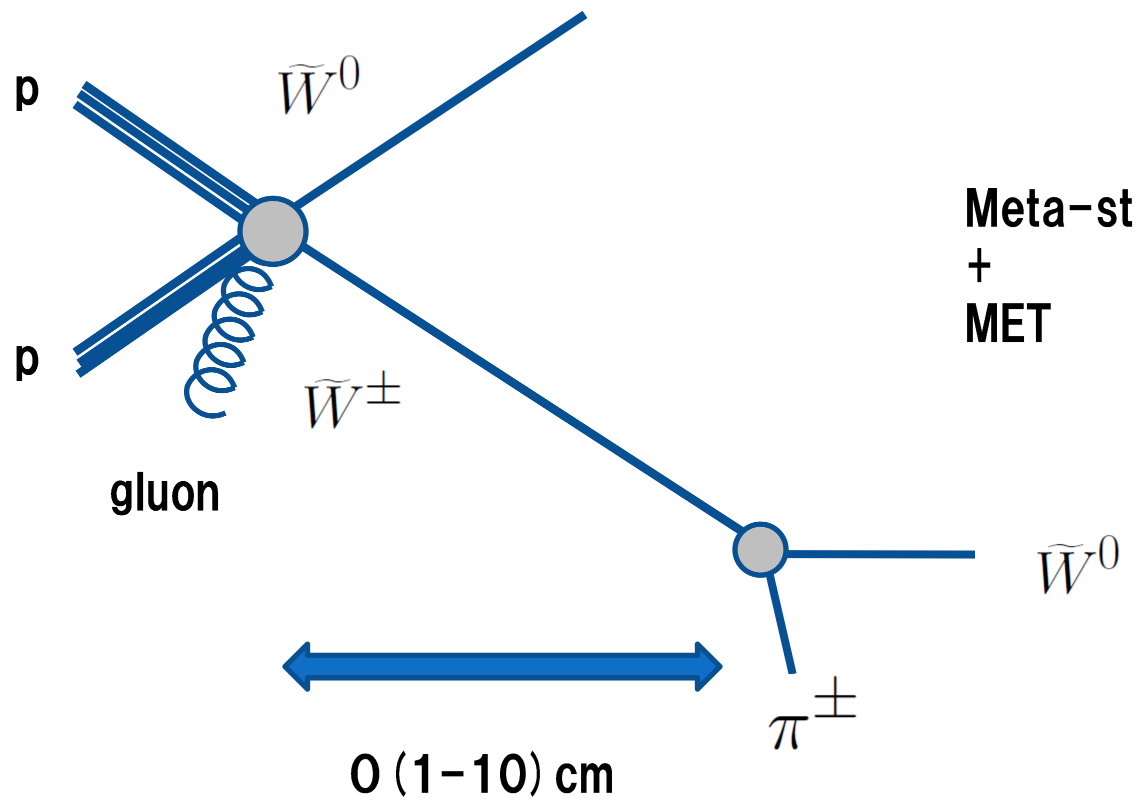
⬇

$\begin{pmatrix}\widetilde{W}^+\\ \widetilde{W}^0\\ \widetilde{W}^-\end{pmatrix}$ Charged slightly heavier



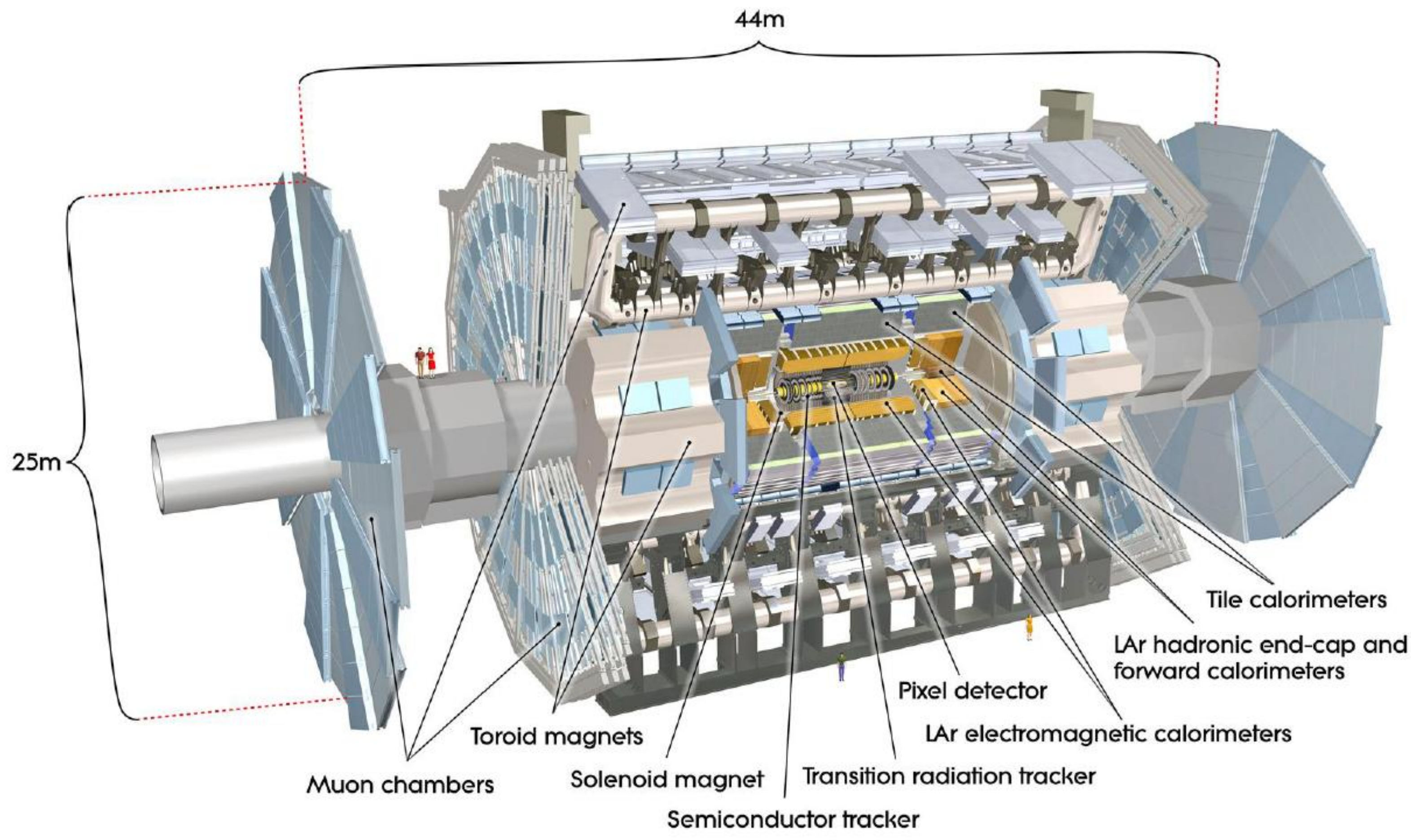

$$c\tau(\widetilde{W}^\pm \to \widetilde{W}^0\pi^\pm) \simeq 7\ \mathrm{cm}\left(\frac{\Delta m}{165\ \mathrm{MeV}}\right)^{-3}$$

# LHC Signals

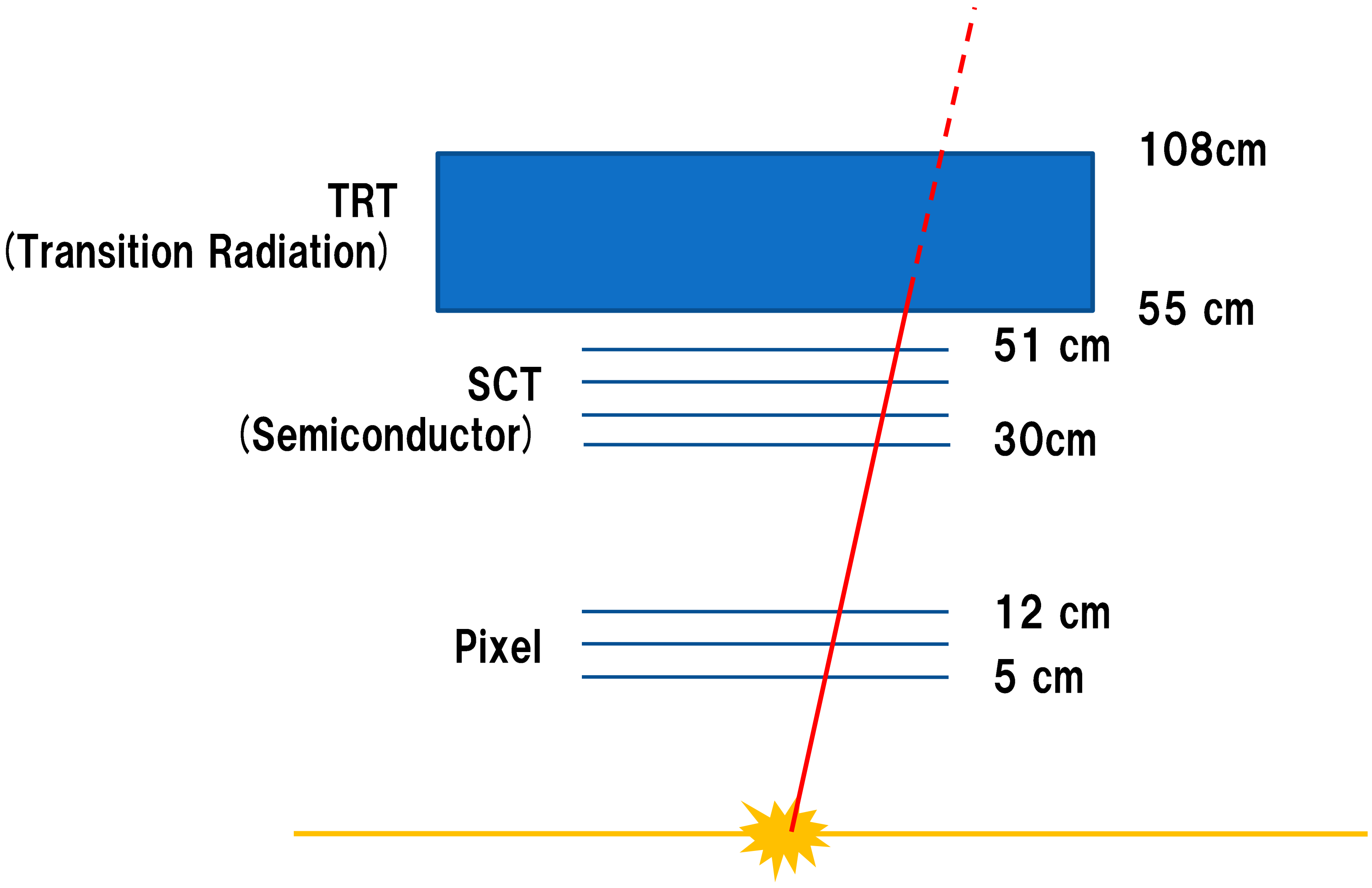



Meta-stable track
+
MET

# ATLAS Detector



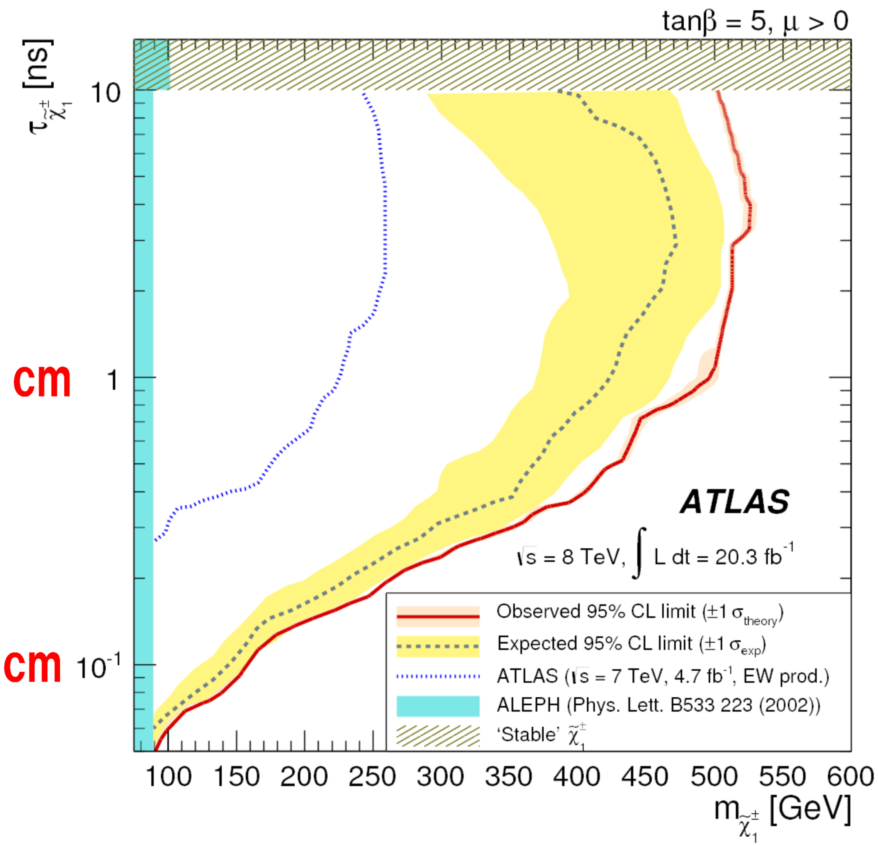
# Tracker

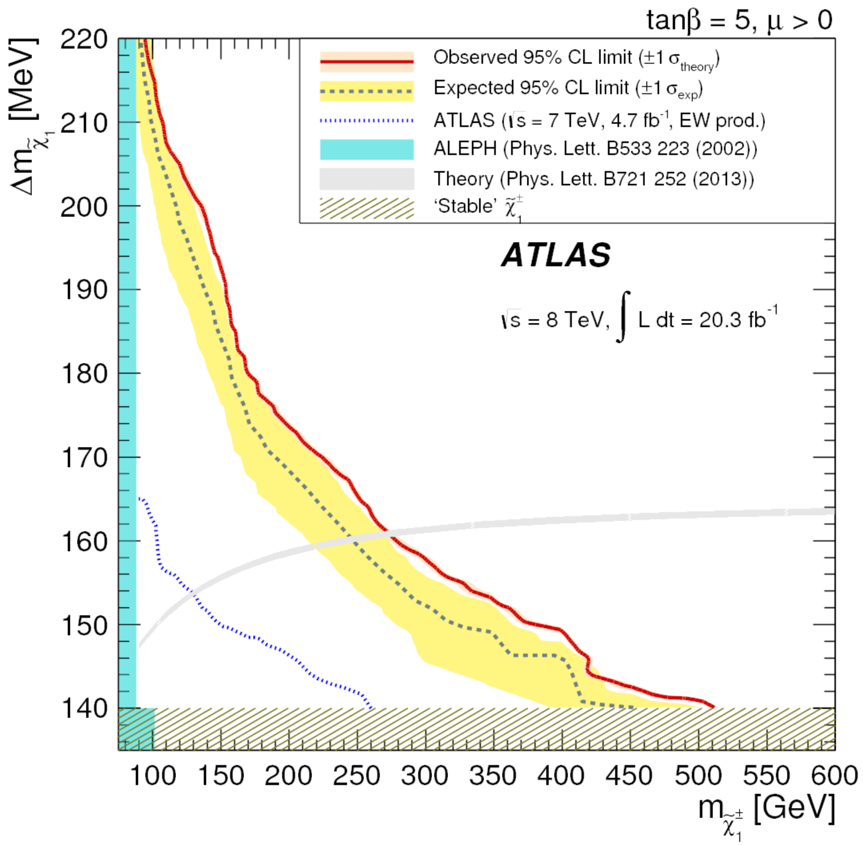

108cm
TRT
(Transition Radiation)
55 cm
51 cm
SCT
(Semiconductor)
30cm
12 cm
Pixel
5 cm

# Current Constraint

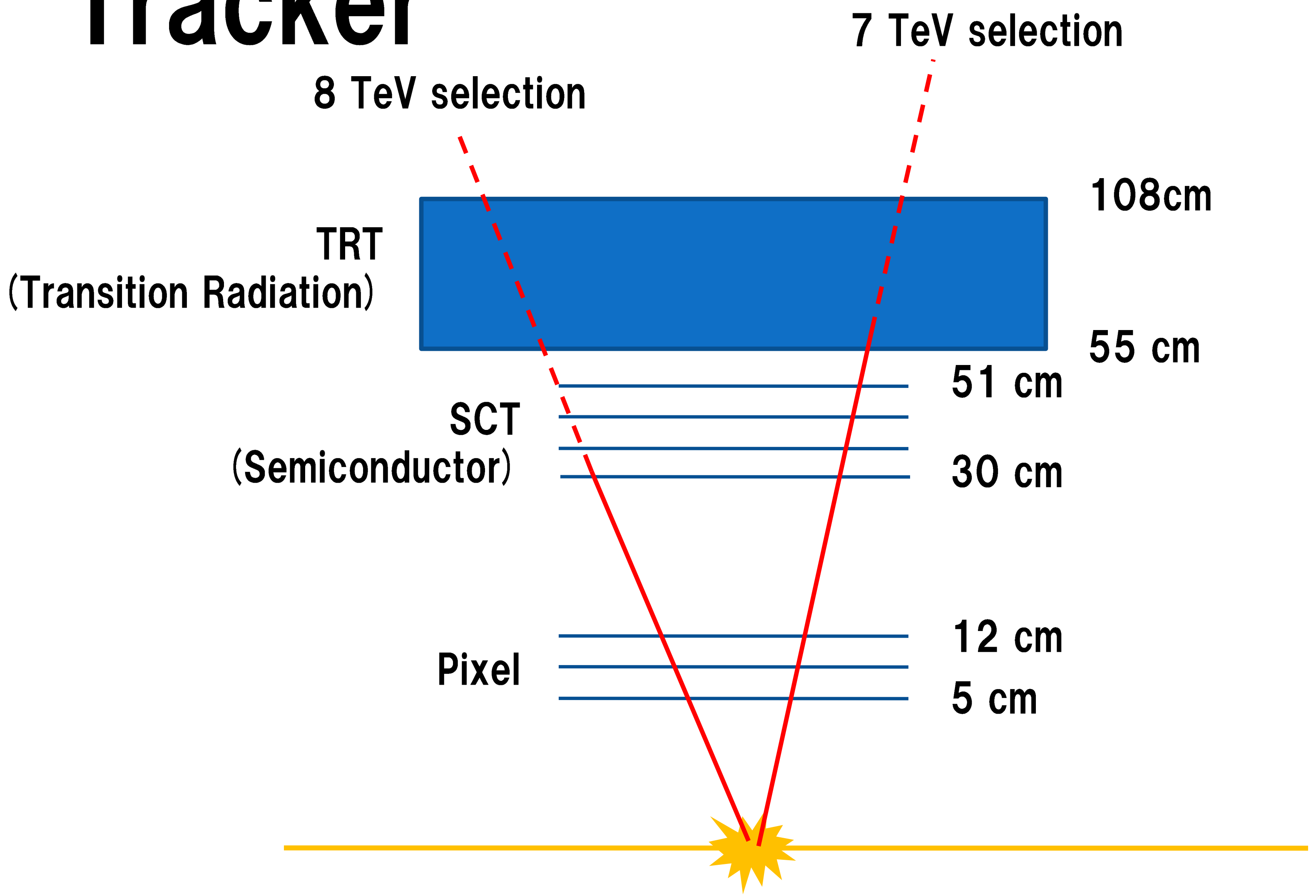
30 cm

3 cm



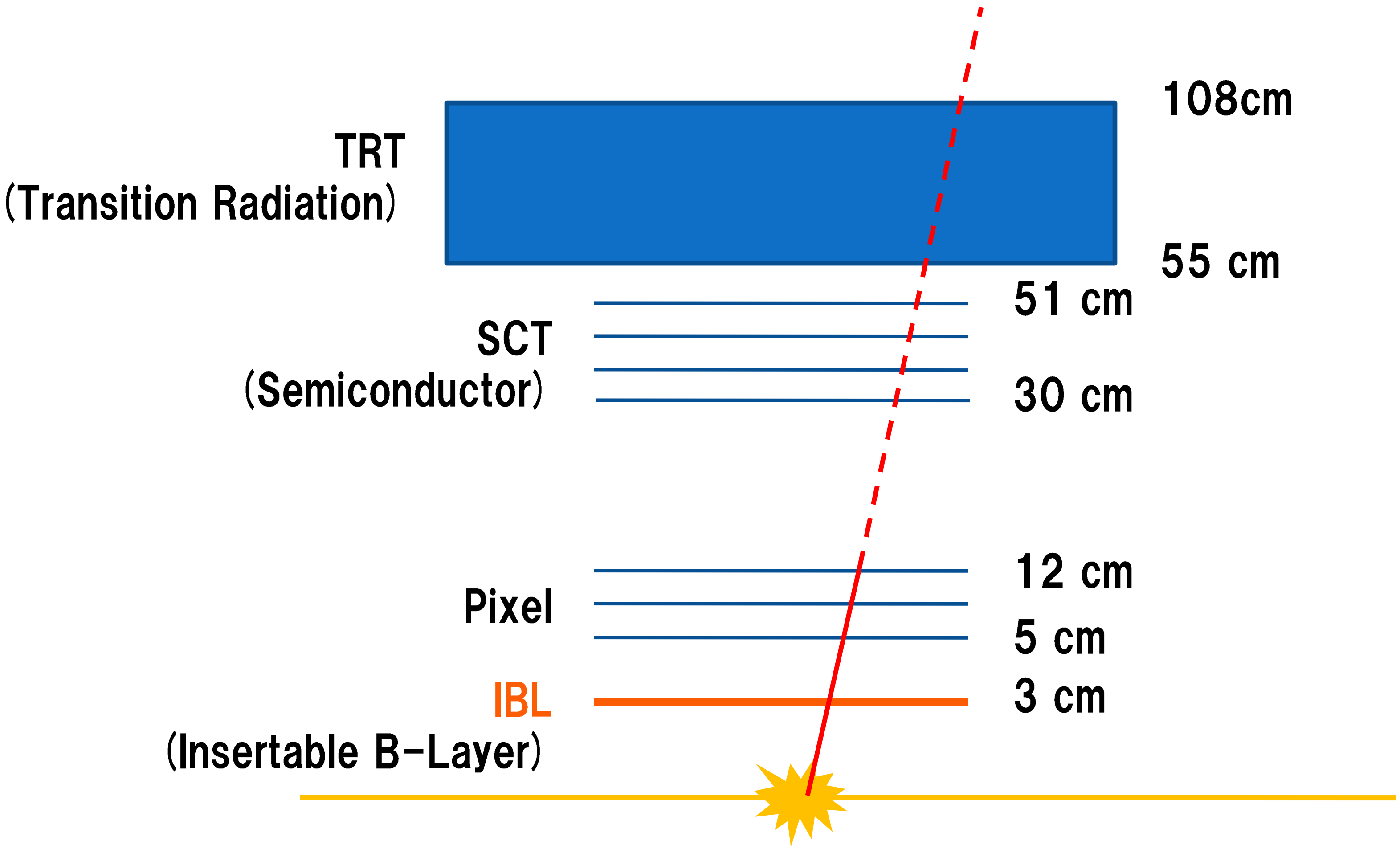



# Tracker



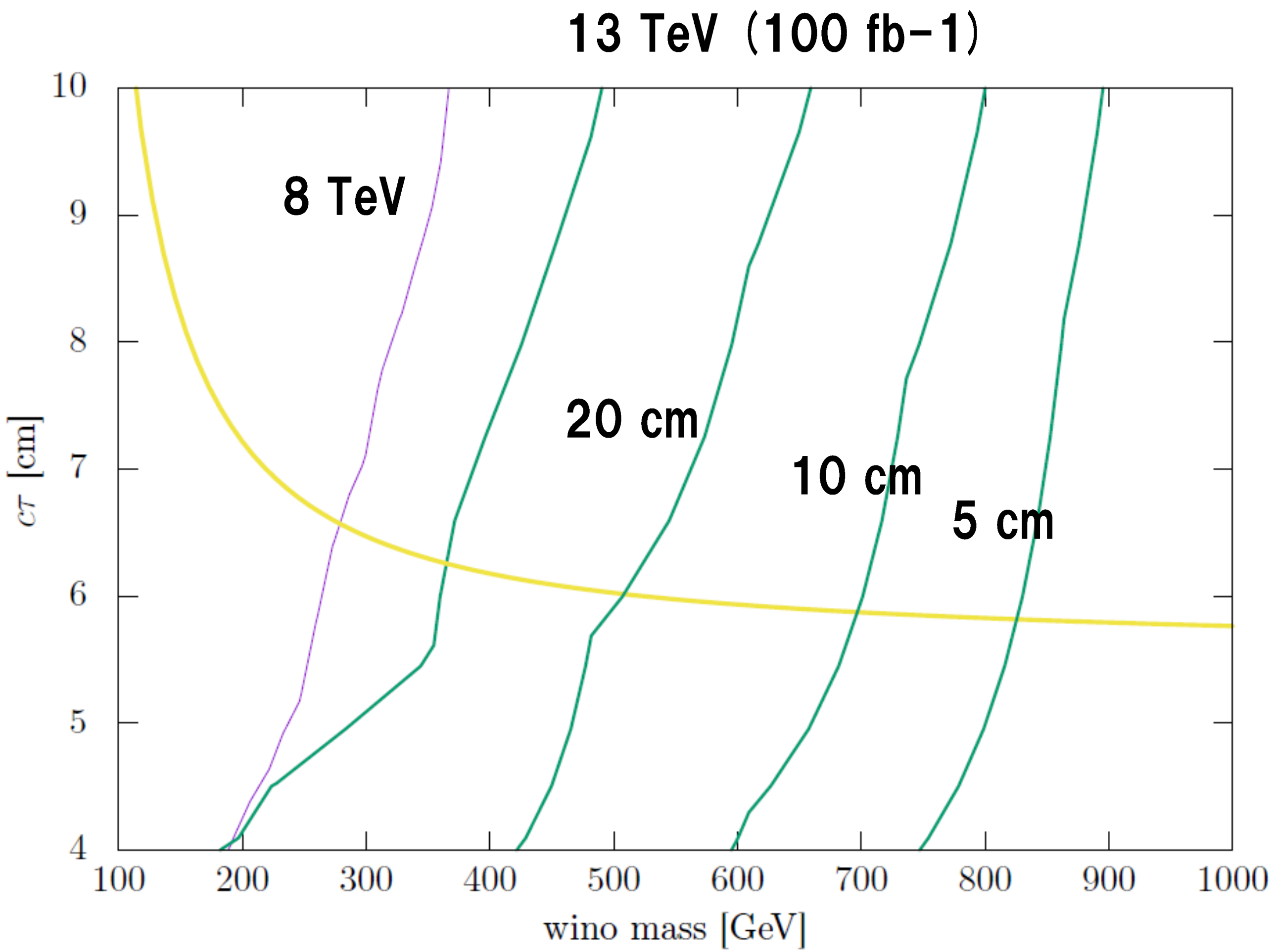
7 TeV selection
8 TeV selection
108cm
TRT
(Transition Radiation)
55 cm
51 cm
SCT
(Semiconductor)
30 cm
12 cm
Pixel
5 cm

# Tracker for Run2



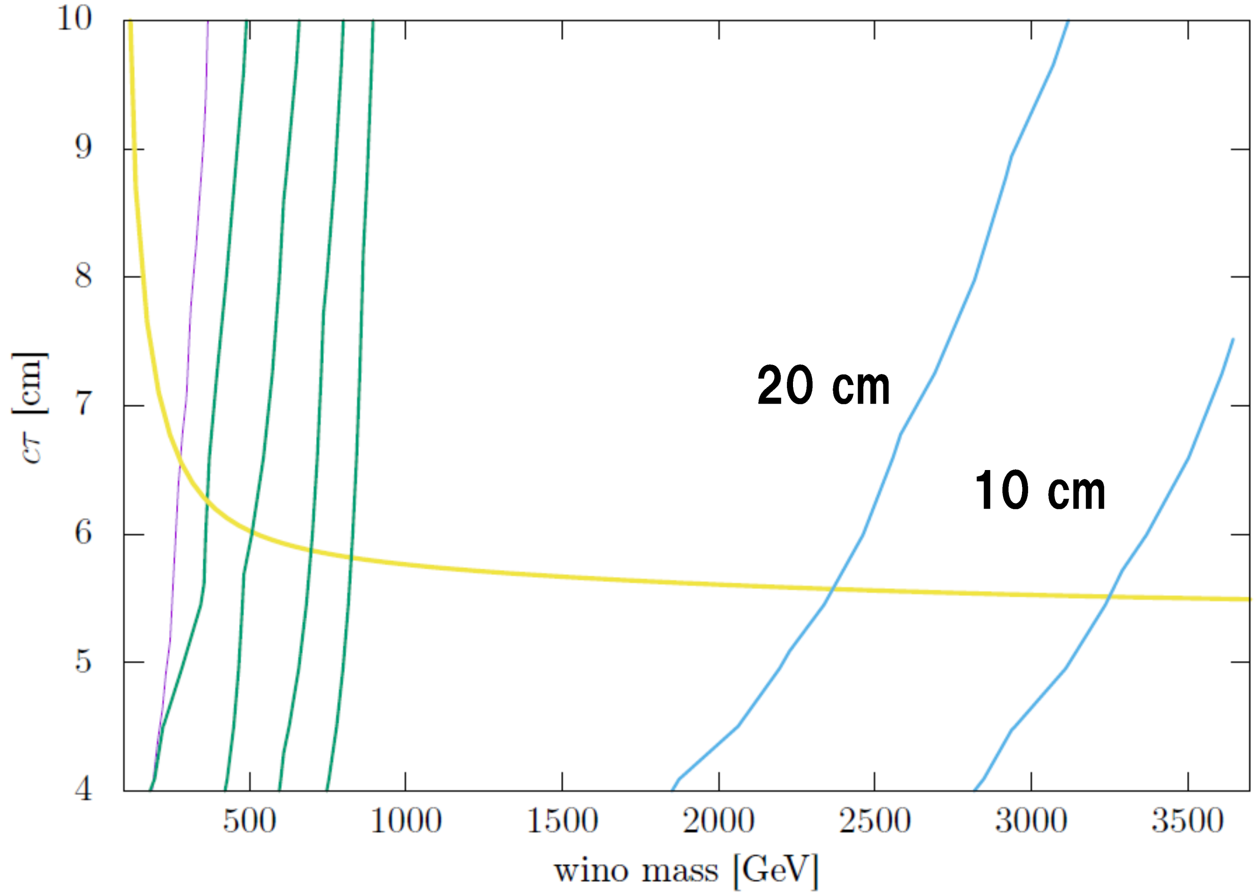
# Prospect

work in progress,
Nagata,Oide,Otono,SS



# Prospect for far future

100 TeV (1 ab-1)



# Wino Summary

- Wino is well-motivated DM
- Wino can be well probed with
  - Cosmic ray
  - Collider
  - Direct detection
  - Precision measurement
  - ….

# Higgsino Dark Matter

# Minimal SUSY Standard Model（MSSM）

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

# Higgsino DM (bottom-up)

| Y \ n | 1 | 2 | 3 | 4 | … |
|---|---|---|---|---|---|
| 0 | | C | wino | C | |
| 1/2 | C | higgsino | C | | |
| 1 | C | C | | C | |
| 3/2 | C | C | C | | |
| 2 | C | C | C | C | |
| … | C | C | C | C | C |

**Higgsino is also minimum of "Minimum DM"**

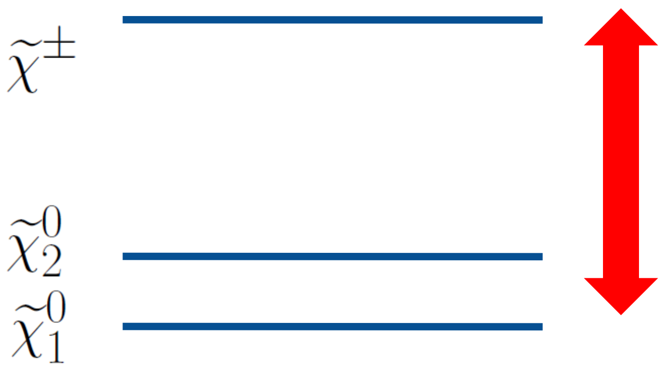
# What is Higgsino?

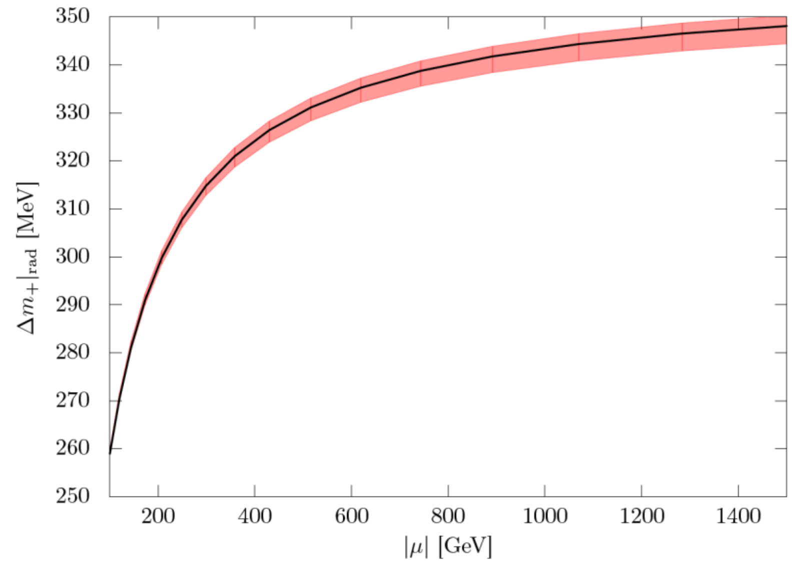
Higgsino is

- (pseudo) Dirac fermion
- Hypercharge |Y|=1/2
- SU(2) doublet $\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$
- <1 TeV $\Omega h^2 \simeq 0.1 \left( \frac{m_{\widetilde{H}}}{1.1\ \mathrm{TeV}} \right)^2$

# Higgsino Spectrum (with heavy gaugino)

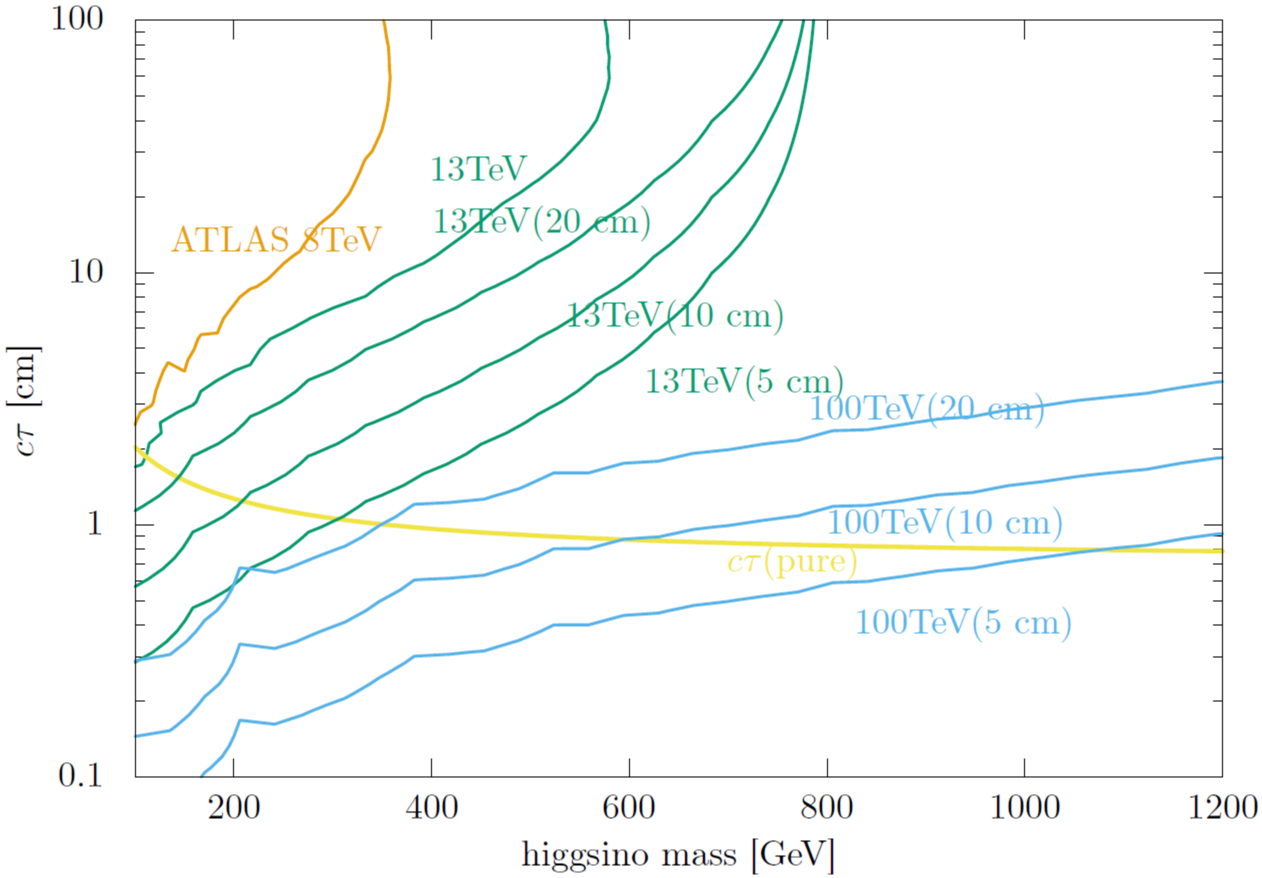
$$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix} \Rightarrow \quad \widetilde{\chi}_1^0 \quad \widetilde{\chi}_2^0 \quad \widetilde{\chi}^\pm$$



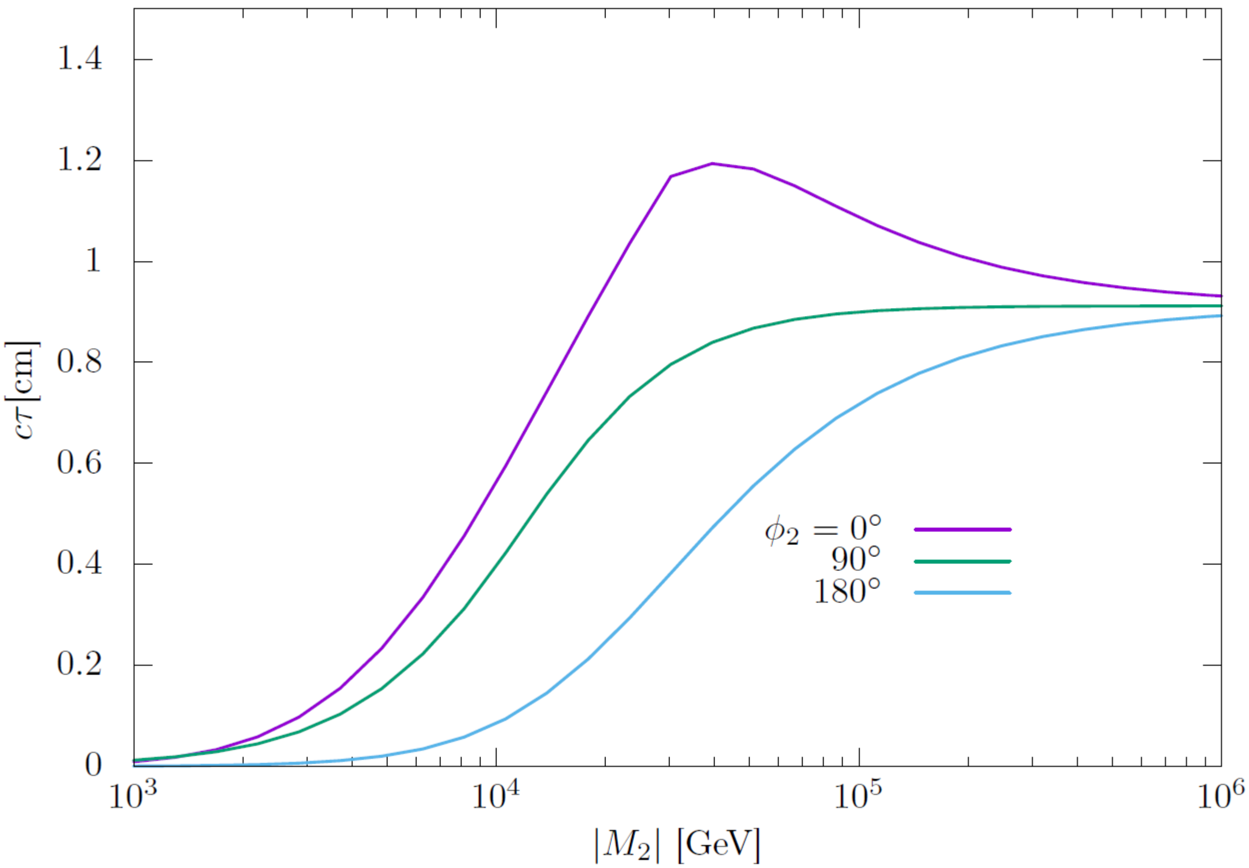




$$c\tau(\tilde{\chi}^\pm \to \tilde{\chi}^0\pi^\pm) = 1.1\ \mathrm{cm}\left(\frac{\Delta m_+}{300\ \mathrm{MeV}}\right)^{-3}\left[1 - \frac{m_{\pi^\pm}^2}{\Delta m_+^2}\right]^{-1/2}$$

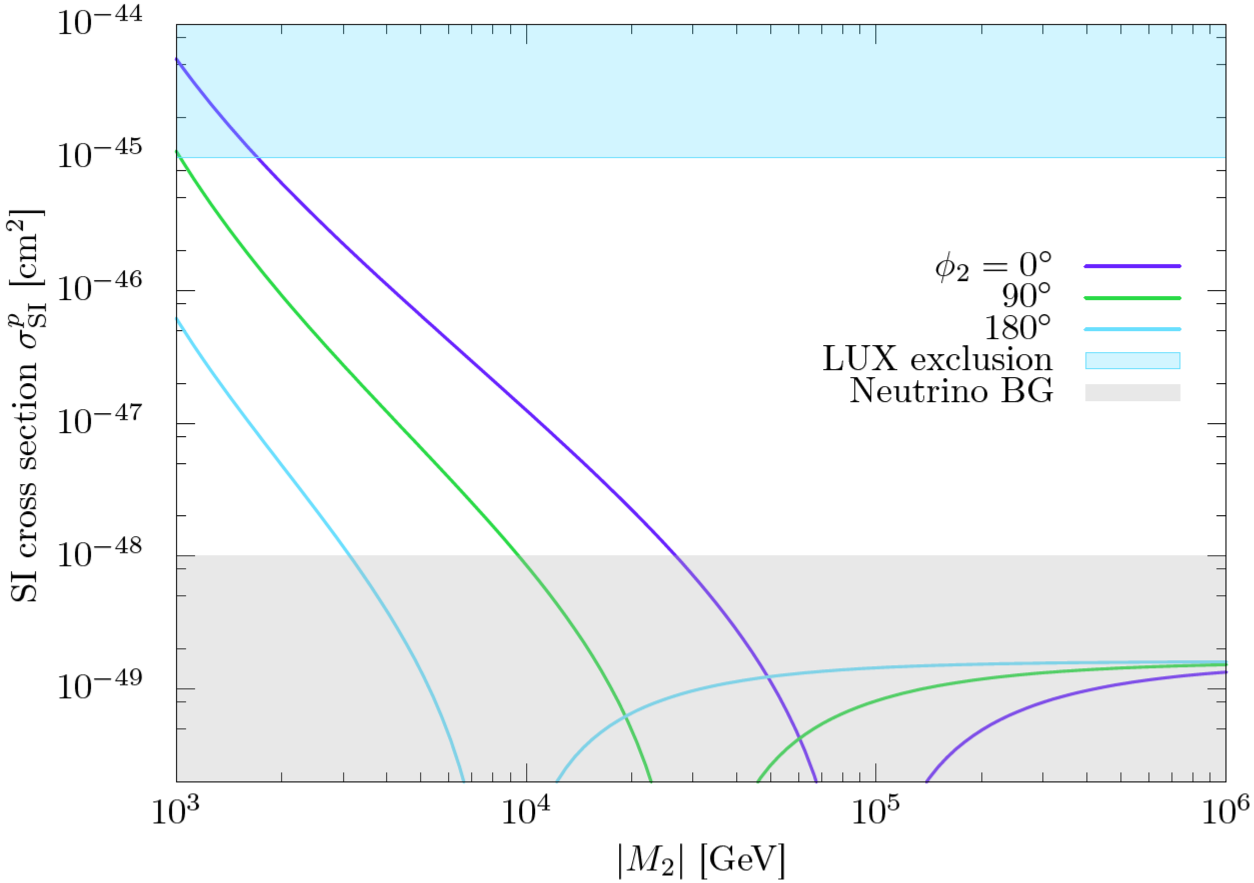
# Prospects for Higgsino



# Decay Length



# Interplay with DM direct detection



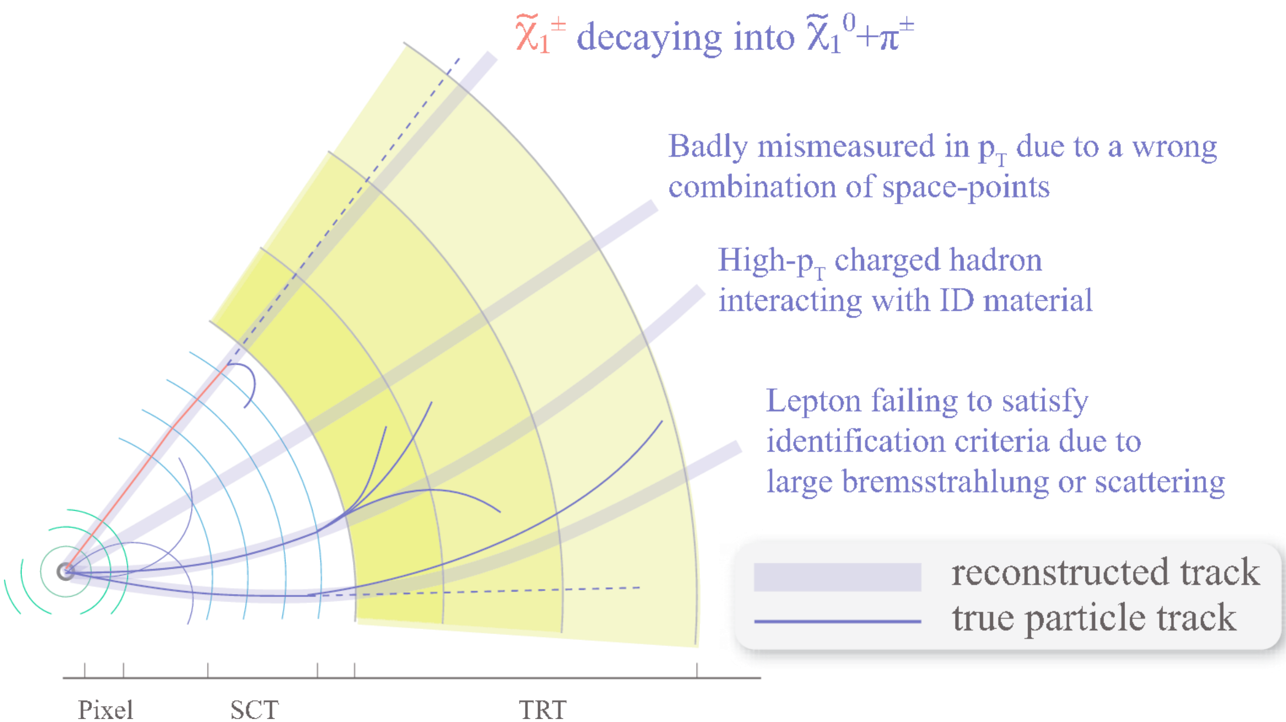
# Summary

- Disappearing track is useful for WIMP search
- Interplay with other DM searches

# Background

[ATLAS 13]

| | $p_T^{track} > 75$ GeV | $p_T^{track} > 100$ GeV | $p_T^{track} > 150$ GeV | $p_T^{track} > 200$ GeV |
|---|---|---|---|---|
| Observed events | 59 | 36 | 19 | 13 |
| Expected events | $48.5 \pm 12.3$ | $37.1 \pm 9.4$ | $24.6 \pm 6.3$ | $18.0 \pm 4.6$ |
| $p_0$ value | 0.17 | 0.41 | 0.46 | 0.44 |
| Observed $\sigma_{vis}^{95\%}$ [fb] | 1.76 | 1.02 | 0.62 | 0.44 |
| Expected $\sigma_{vis}^{95\%}$ [fb] | $1.42^{+0.50}_{-0.39}$ | $1.05^{+0.37}_{-0.28}$ | $0.67^{+0.27}_{-0.19}$ | $0.56^{+0.23}_{-0.16}$ |



# Challenge to Background

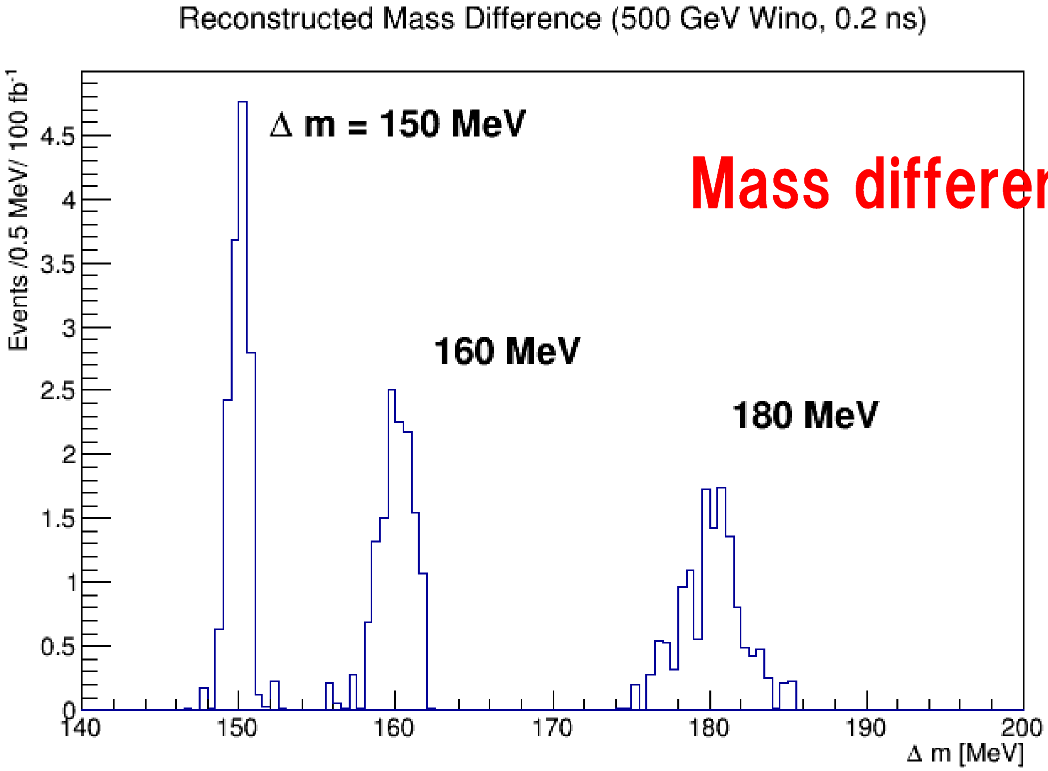
Shorter track, more background

- More optimized cut, MET, jet…
- Requiring 2 disappearing tracks
- Usage of soft pion (kink track)

$$\widetilde{W}^{\pm} \to \widetilde{W}^{0} \pi^{\pm}$$

# Measurement

Soft pion and disappearing track → Reconstruction of kinematics




**Mass difference measurement**