



# SUSY and Cosmology/Naturalness

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# 1. SUSY after LHC

Higgs Mass

Mini-split SUSY

Dark Matter

# 2. Dark Matter Signatures in Mini-split

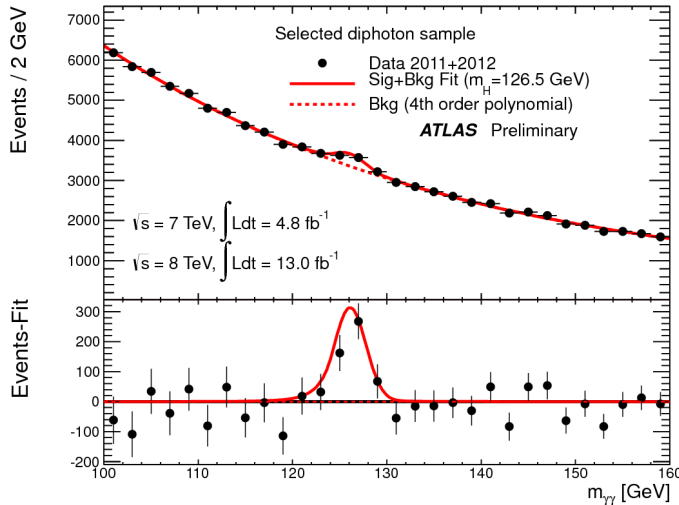
Wino

Gaugino coannihilation

Long lived particle signatures

# 3. Summary

# Higgs and SUSY at LHC



Higgs Discovered!

ATLAS SUSY Searches\* - 95% CL Lower Limits  
December 2017

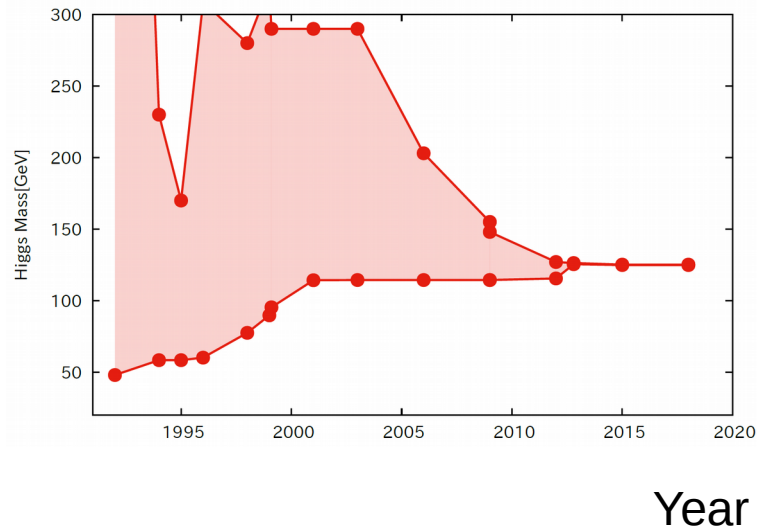
Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int L dt (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
<b>Inclusive Searches</b>	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-2 jets	Yes	36.1	1.57 TeV	$m(\tilde{g}) > 200 \text{ GeV}, m(\tilde{t}^{\text{gen.}}) > m(2^{\text{nd}} \text{ gen. } \tilde{t})$	1712.0232	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	710 GeV	$m(\tilde{g}) > 200 \text{ GeV}$	1711.0301
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-2 jets	Yes	36.1	2.02 TeV	$m(\tilde{g}) > 200 \text{ GeV}$	1712.0232	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-2 jets	Yes	36.1	2.01 TeV	$m(\tilde{g}) > 200 \text{ GeV}, m(\tilde{t}^{\text{gen.}}) > 0.5 m(\tilde{t}^{\text{gen.}}) + m(\tilde{g})$	1712.0232	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-2 jets	Yes	14.7	1.7 TeV	$m(\tilde{g}) > 300 \text{ GeV}$	1611.05791	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	3-6 jets	Yes	36.1	1.87 TeV	$m(\tilde{g}) > 0 \text{ GeV}$	1706.03731	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-7 jets	Yes	36.1	1.8 TeV	$m(\tilde{g}) > 400 \text{ GeV}$	1706.02794	
	GMSB ( $\beta$ NLSP)	1-2 $\tau$ + 0-1 $l$	0-2 jets	Yes	3.2	2.0 TeV	$m(\tilde{g}) > 170 \text{ GeV}, m(\text{NLSP}) > 0.1 \text{ mm}, m(\tilde{g}) > 1.5 \text{ TeV}$	1607.05979
	GGM (bino NLSP)	$2 \gamma$	Yes	36.1	2.15 TeV	$m(\tilde{g}) > 170 \text{ GeV}, m(\text{NLSP}) > 0.1 \text{ mm}, m(\tilde{g}) > 1.5 \text{ TeV}$	ATLAS-CONF-2017-080	
	GGM (Higgsino NLSP)	$2 \gamma$	Yes	36.1	2.05 TeV	$m(\tilde{g}) > 1.8 \times 10^4 \text{ eV}, m(\tilde{g}) > m(\tilde{g}) = 1.5 \text{ TeV}$	ATLAS-CONF-2017-080	
	Gravitino LSP	mono-jet	Yes	20.3	$F^{R, L} \text{ scale}$	865 GeV	1502.01518	
<b>1<sup>st</sup> gen. <math>\tilde{t}\tilde{t}</math></b>	$\tilde{t}\tilde{t} \rightarrow \text{hadrons}$	0-3 $b$	Yes	36.1	1.82 TeV	$m(\tilde{t}) > 600 \text{ GeV}$	1711.01901	
	$\tilde{t}\tilde{t} \rightarrow \text{hadrons}$	0-1 $e, \mu$	3 $b$	Yes	36.1	1.87 TeV	$m(\tilde{t}) > 200 \text{ GeV}$	1711.01901
<b>3<sup>rd</sup> gen. squarks <math>\tilde{t}\tilde{t}</math> direct production</b>	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	0-2 $b$	Yes	36.1	950 GeV	$m(\tilde{t}_1) > 400 \text{ GeV}$	1706.02926	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	$2 e, \mu$ (SS)	1 $b$	Yes	36.1	275-700 GeV	1706.03731	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	$0.2 e, \mu$	1-2 $b$	Yes	4.713.3	200-720 GeV	1209.2102, ATLAS-CONF-2016-077	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2 \rightarrow \text{hadrons}$	0-2 $e, \mu$	0-2 jets	1-2 $b$	Yes	20.3/36.1	1506.0816, 1709.0483, 1711.11520	
<b>3<sup>rd</sup> gen. squarks <math>\tilde{t}\tilde{t}</math> indirect production</b>	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2 \rightarrow \text{hadrons}$	0	mono-jet	Yes	36.1	90-430 GeV	1711.0301	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	0	mono-jet	Yes	36.1	150-600 GeV	1403.5222	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + Z$	$3 e, \mu$ (Z)	1 $b$	Yes	36.1	290-790 GeV	1706.03986	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + h$	$1-2 e, \mu$	3 $b$	Yes	36.1	320-880 GeV	1706.03986	
<b>EW direct</b>	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$2 e, \mu$	0	Yes	36.1	90-500 GeV	ATLAS-CONF-2017-039	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$2 e, \mu$ (SS)	1 $b$	Yes	36.1	750 GeV	ATLAS-CONF-2017-039	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$2 \tau$	-	Yes	36.1	750 GeV	1706.07875	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$3 e, \mu$	0	Yes	36.1	1.13 TeV	ATLAS-CONF-2017-039	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$2.3 e, \mu$	0-2 jets	Yes	36.1	580 GeV	ATLAS-CONF-2017-039	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$e, \mu, \tau$	0-2 $b$	Yes	20.3	270 GeV	1501.07110	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$4 e, \mu$	0	Yes	20.3	635 GeV	1405.5066	
	GGM (wino NLSP) weak prod., $\tilde{t}_1\tilde{t}_1 \rightarrow \gamma\gamma$	$1 e, \mu + \gamma$	-	Yes	20.3	115-370 GeV	1507.05493	
	GGM (bino NLSP) weak prod., $\tilde{t}_1\tilde{t}_1 \rightarrow \gamma\gamma$	$2 \gamma$	-	Yes	36.1	1.06 TeV	ATLAS-CONF-2017-080	
<b>Long-lived particles</b>	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1^0$	Disapp. $\text{trk}$	1 jet	Yes	36.1	450 GeV	1712.02118	
	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1^0$	disapp. $\text{trk}$	-	Yes	18.4	455 GeV	1606.03392	
	Stable, stopped $\tilde{t}_1$ R-hadron	$\text{trk}$	0-1.5 jets	Yes	27.9	850 GeV	1310.6584	
	Stable $\tilde{t}_1$ R-hadron	$\text{trk}$	-	3.2	-	1.58 TeV	1606.05129	
	Metastable $\tilde{t}_1$ R-hadron	disapp. $\text{trk}$	-	3.2	-	1.57 TeV	1604.04580	
	Metastable $\tilde{t}_1$ R-hadron, $\tilde{t}_1 \rightarrow \gamma\gamma^0$	disapp. $\text{trk}$	-	32.8	-	2.37 TeV	1710.04901	
	GMSB, stable $\tilde{t}_1, \tilde{t}_1^0 \rightarrow \text{hadrons} + \tau + e, \mu$	1-2 $\mu$	-	19.1	-	537 GeV	1411.6795	
	GMSB, $\tilde{t}_1^0 \rightarrow \gamma\gamma^0$ , long-lived $\tilde{t}_1^0$	$2 \gamma$	-	Yes	20.3	440 GeV	1409.3542	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + \mu\mu$	disapp. $e, \mu, \mu\mu$	-	20.3	-	1.0 TeV	1504.05162	
<b>RPV</b>	LFV $\tilde{g}\tilde{g} \rightarrow \tau\tau, \tau X, \tilde{g} \rightarrow \mu\mu, \tau\tau/\mu\mu$	$e, \mu, \tau, \mu\mu$	-	3.2	-	1.5 TeV	1607.08079	
	Linear RPV CMSSM	$2 e, \mu$ (SS)	0-3 $b$	Yes	20.3	1.45 TeV	1404.2500	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$4 e, \mu$	-	Yes	13.3	1.14 TeV	ATLAS-CONF-2016-075	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	$3 e, \mu + \tau$	-	Yes	20.3	450 GeV	1405.5066	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2, \tilde{t}_2\tilde{t}_2 \rightarrow \text{hadrons}$	0	4-5 large-R jets	Yes	36.1	1.875 TeV	SUSY2016.22	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}, \tilde{t}_1 \rightarrow \gamma\gamma^0$	$1 e, \mu$	0-10 jets	0-4 $b$	Yes	2.1 TeV	1704.08493	
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}, \tilde{t}_1 \rightarrow \gamma\gamma^0$	$1 e, \mu$	0-10 jets	0-4 $b$	Yes	1.65 TeV	1704.08493	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2 \rightarrow \text{hadrons}$	0	2 jets + 2 $b$	Yes	36.7	100-470 GeV, 1400-10 GeV	1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_2 \rightarrow \text{hadrons}$	$2 e, \mu$	2 $b$	Yes	36.1	0.41-4.5 TeV	1710.05544	
<b>Other</b>	Scalar charm, $\tilde{c}\tilde{c}^0$	0	2 $c$	Yes	20.3	510 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 simplified models, c.f. refs. for the assumptions made.

SUSY Constrained!

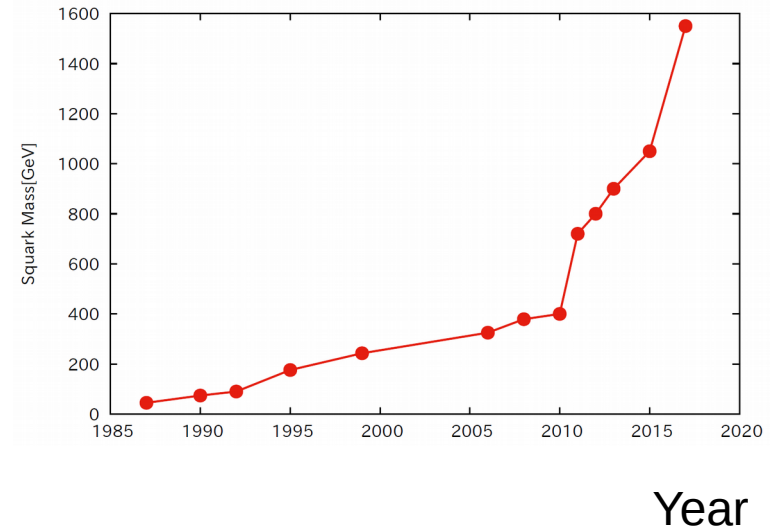
# Cornering Higgs and SUSY

## Higgs Mass Range



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

## Squark Mass Limit



$$m_{\tilde{q}} > 1550 \text{ GeV}$$

# SUSY Higgs

Higgs potential

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

In MSSM

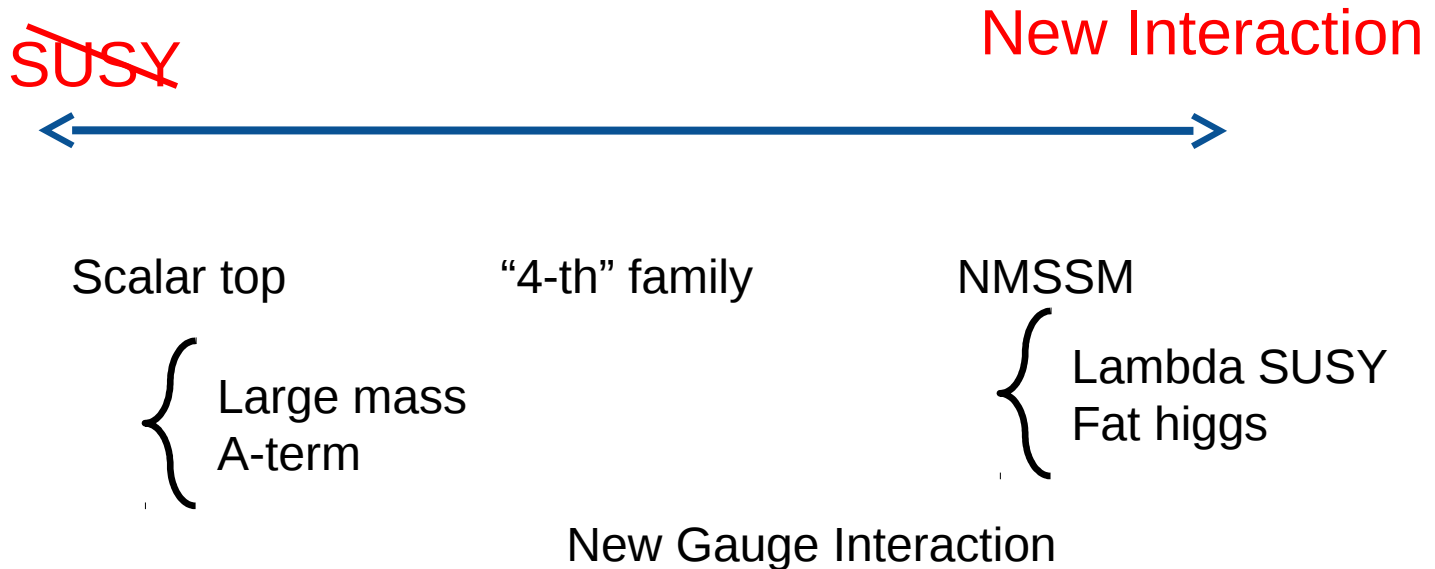
$$\lambda = \frac{1}{4} (g_1^2 + g_2^2) \cos(2\beta)$$

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

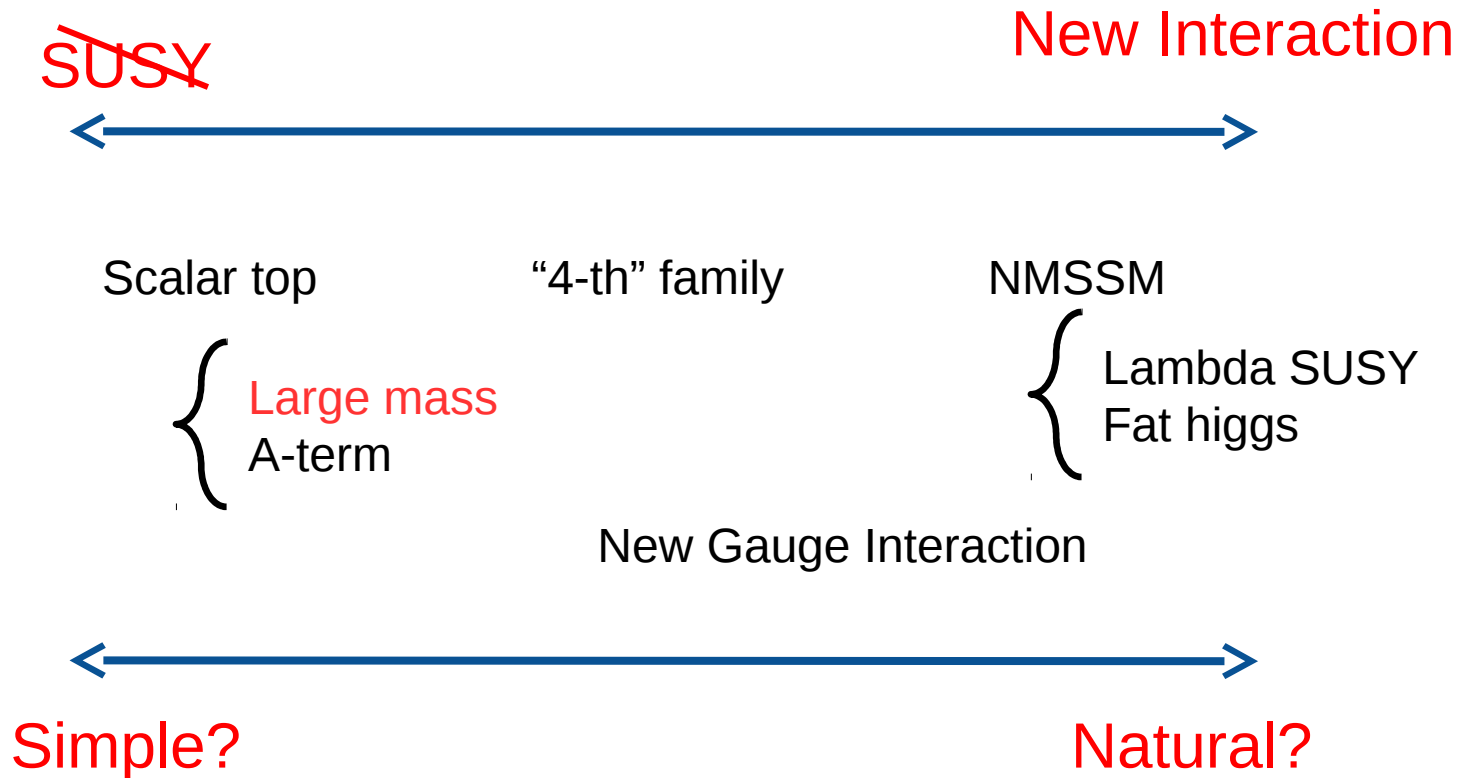
This is clearly less than observed 125 GeV Higgs!

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

# SUSY after 125 GeV Higgs

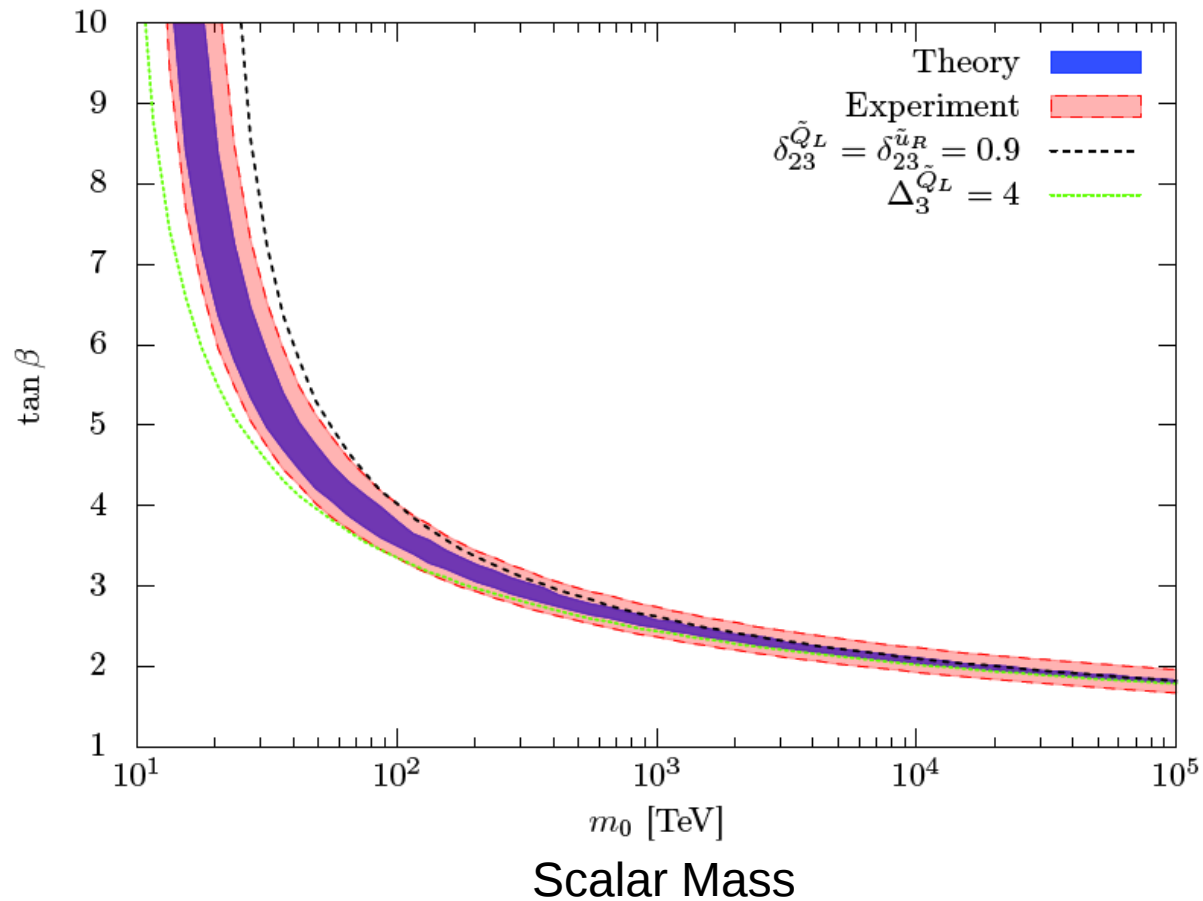


# SUSY after 125 GeV Higgs



# Higgs Mass from Stop

125 GeV Higgs OK regions





# Benefit and demerit of SUSY

## Benefit

- Hierarchy Problem
- GUT unification
- DM

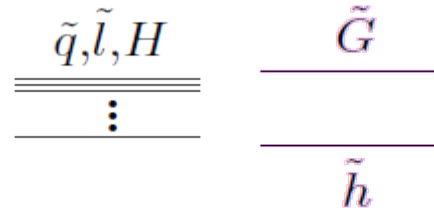
## Possible demerit

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

# Mini-Split Mass Spectrum

Tree level Gravity Mediation

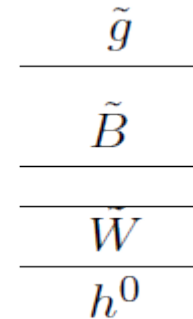
$$|m_0| \sim |\mu| \sim m_{3/2}$$



Loop suppressed: Anomaly Mediation

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

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



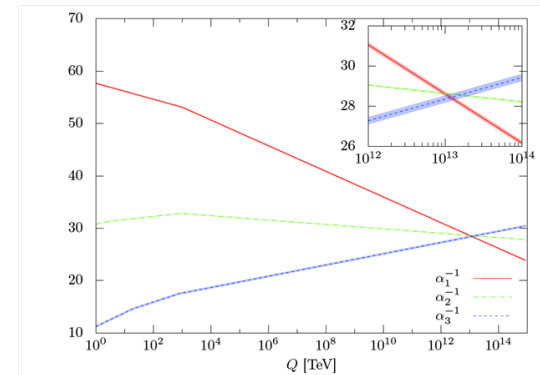
# Benefit and demerit of SUSY

## Benefit

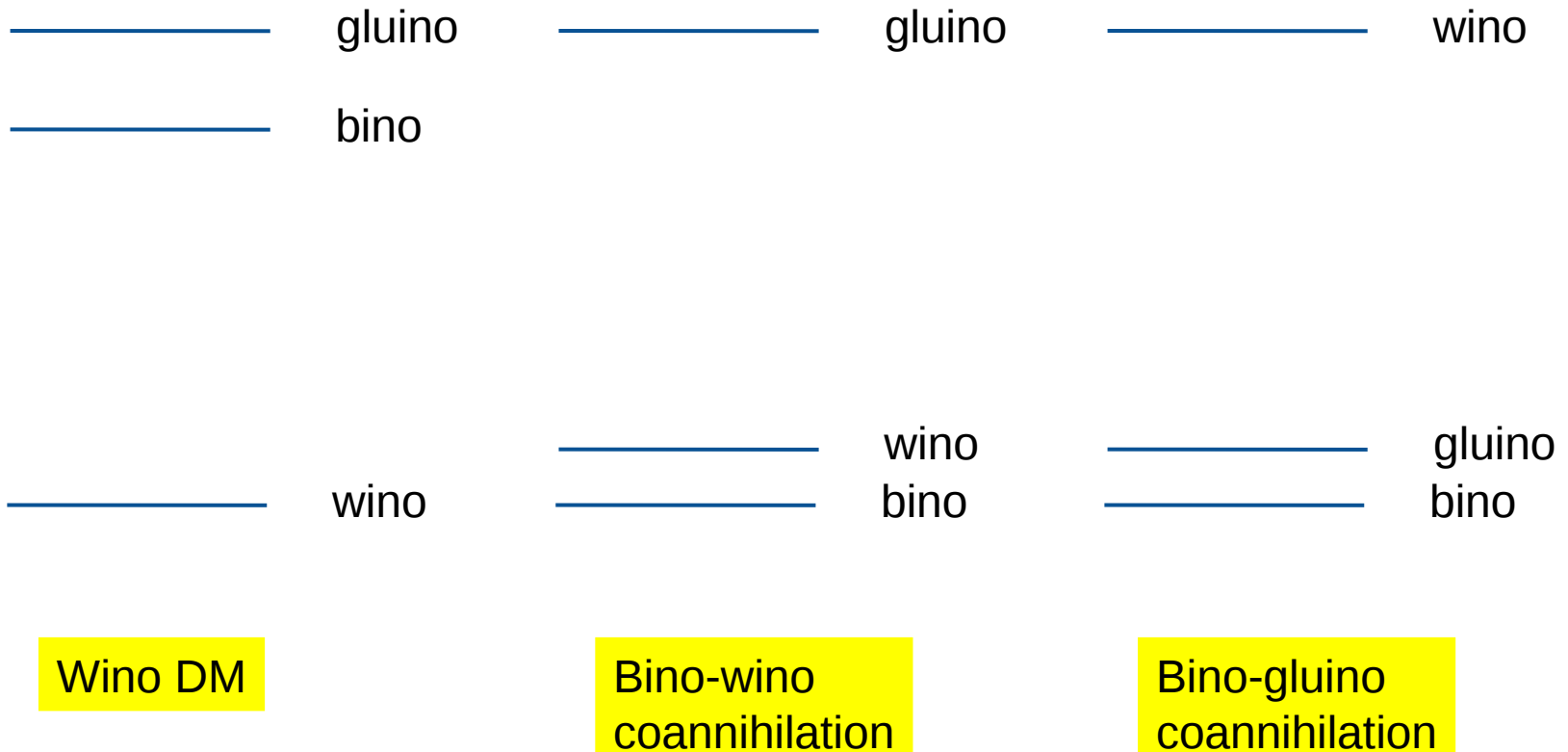
- ? • Hierarchy Problem
- ✓ • GUT unification
- ✓ • DM

## Possible demerit

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



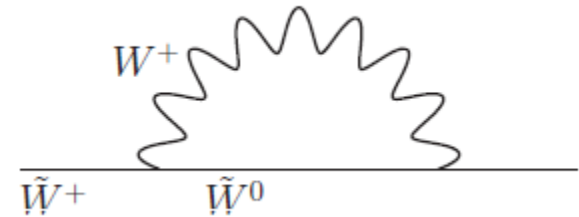
# Three Possibilities for DM



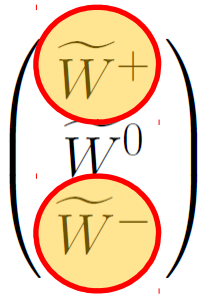


# Wino DM case

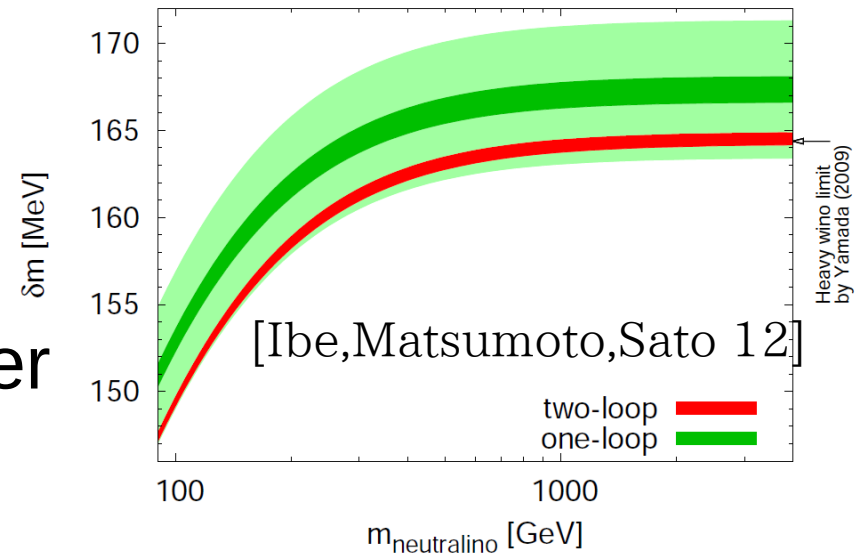
# Wino Spectrum



Radiative correction

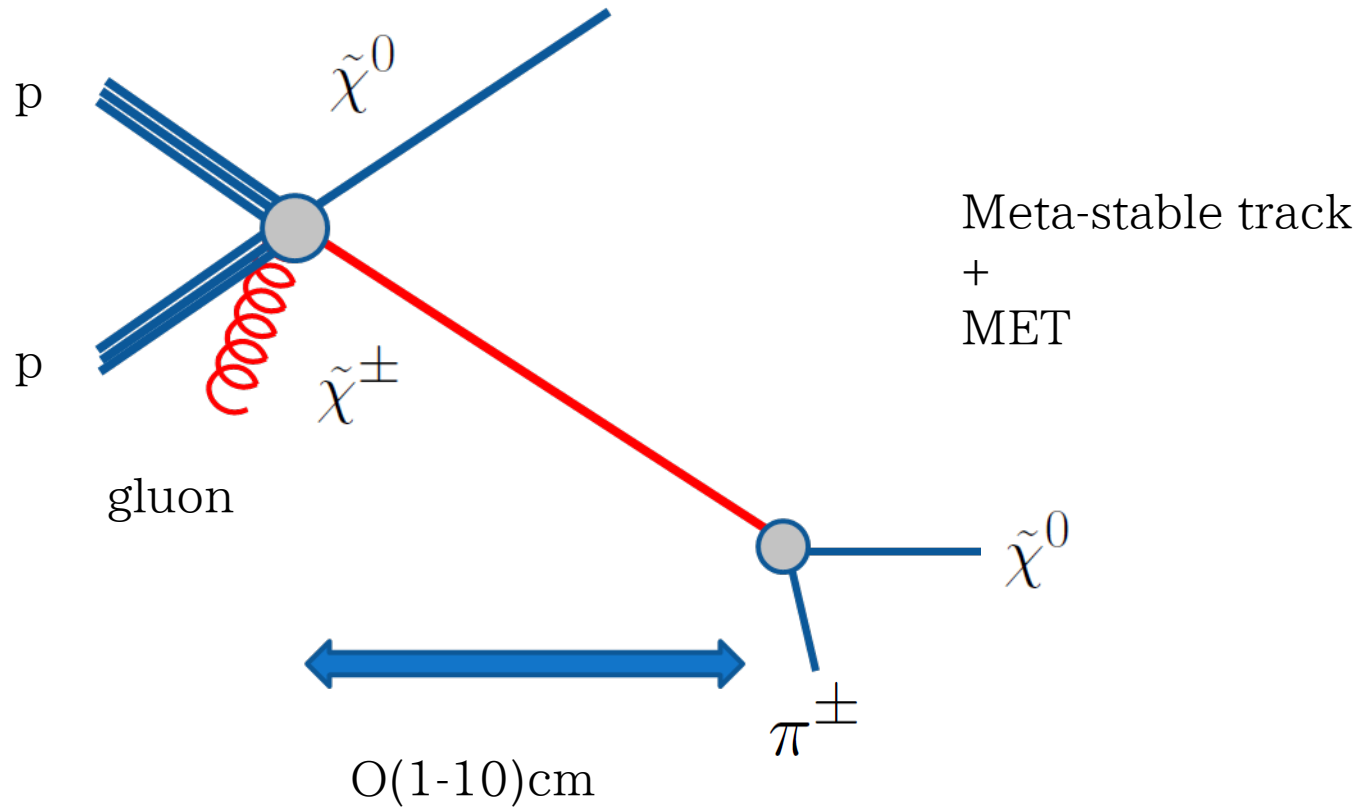


Charged slightly heavier

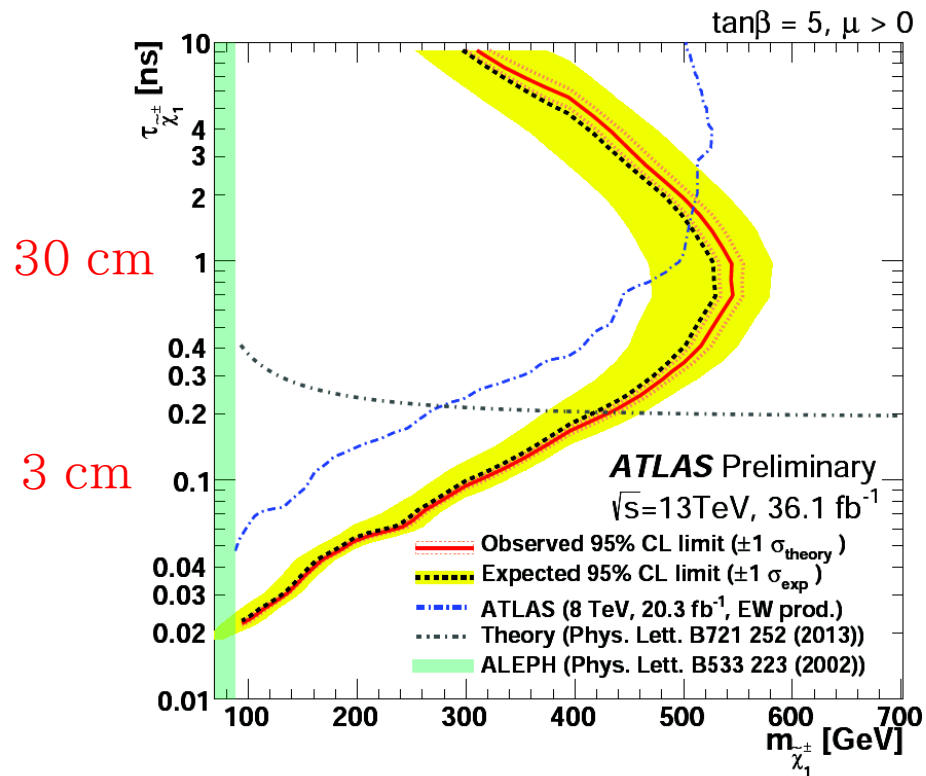


$$c\tau(\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm) \simeq 7 \text{ cm} \left( \frac{\Delta m}{165 \text{ MeV}} \right)^{-3}$$

# LHC Signals



# Current Constraint(wino)

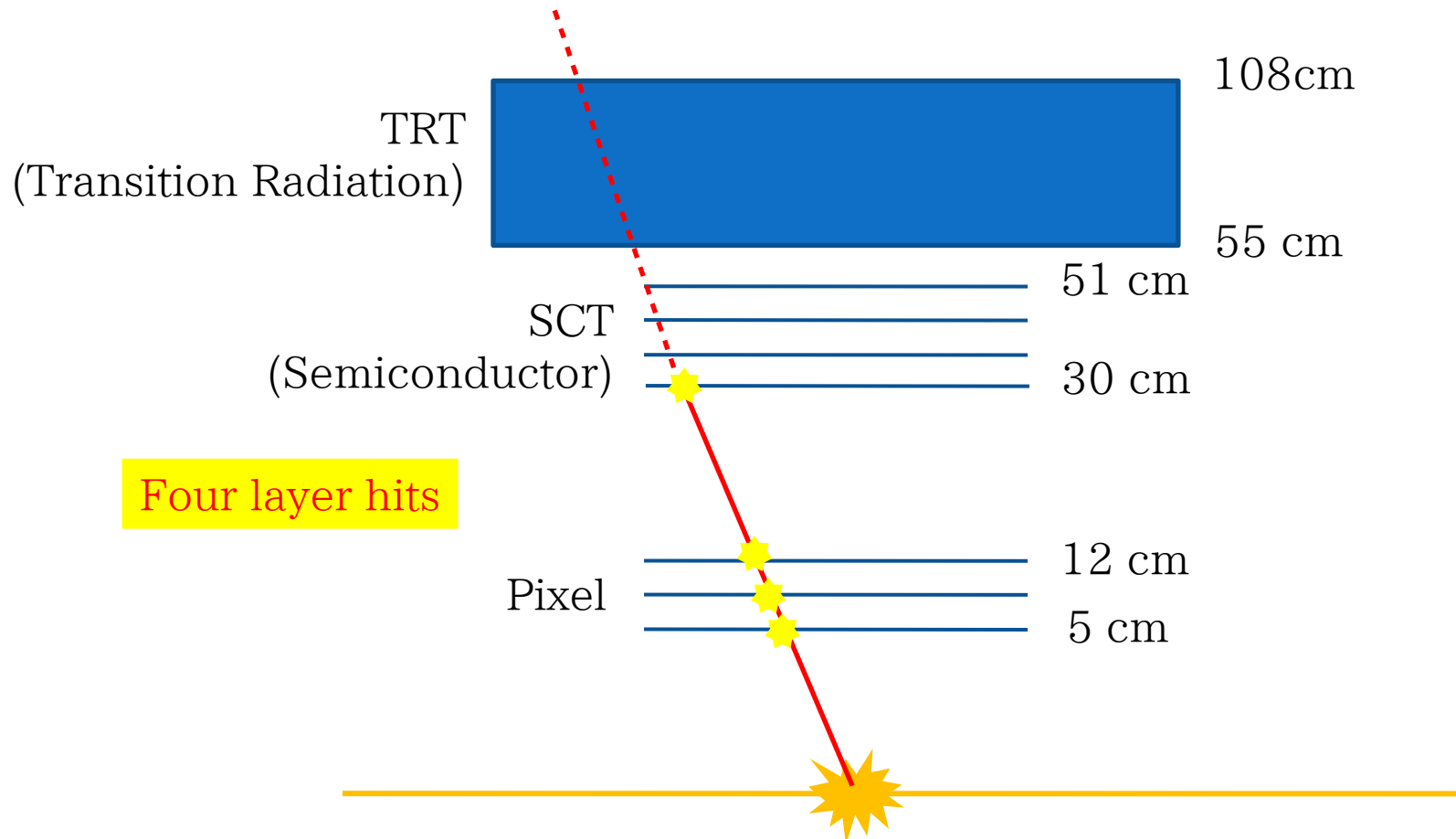


MET + disappearing track

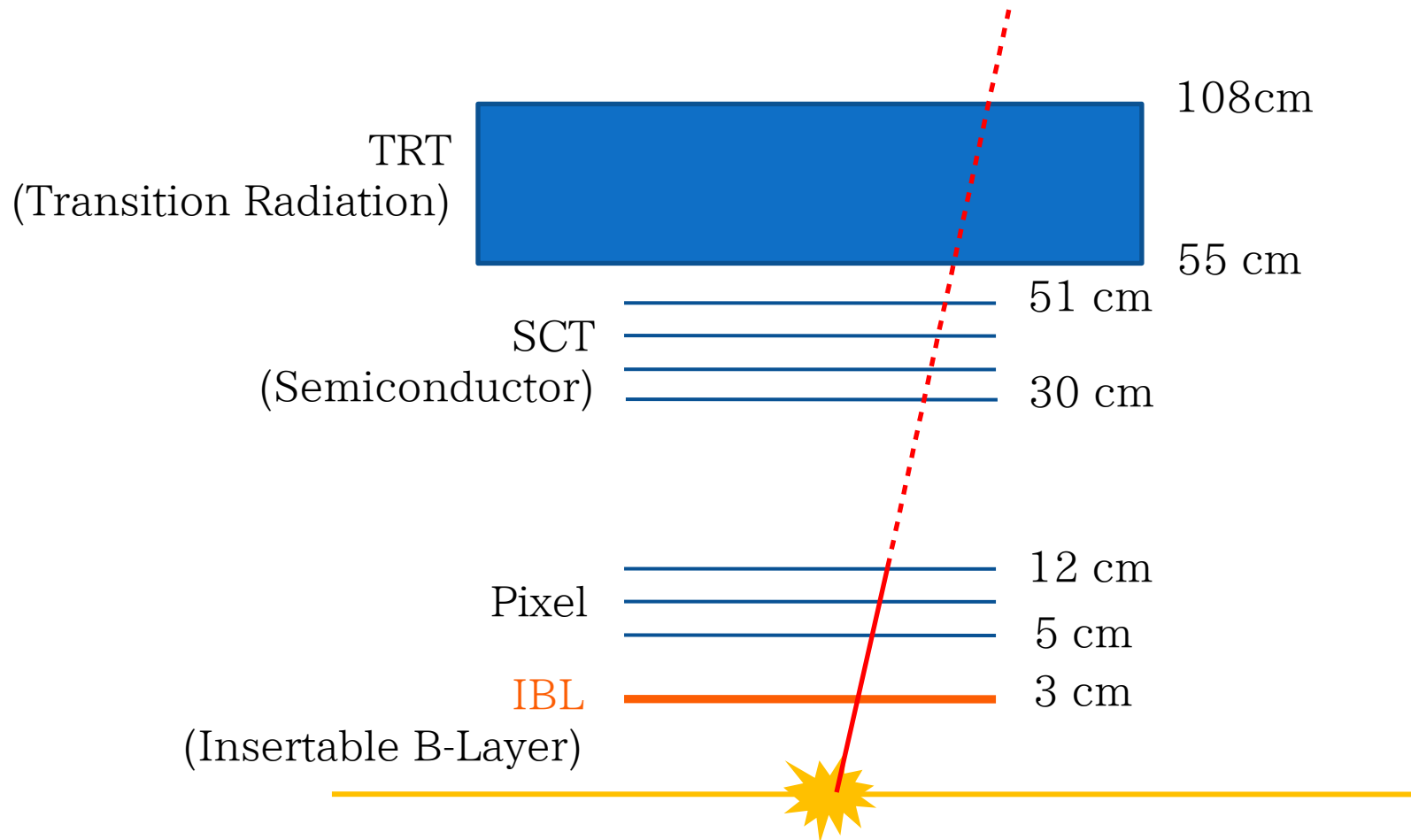


# Tracker for Run1

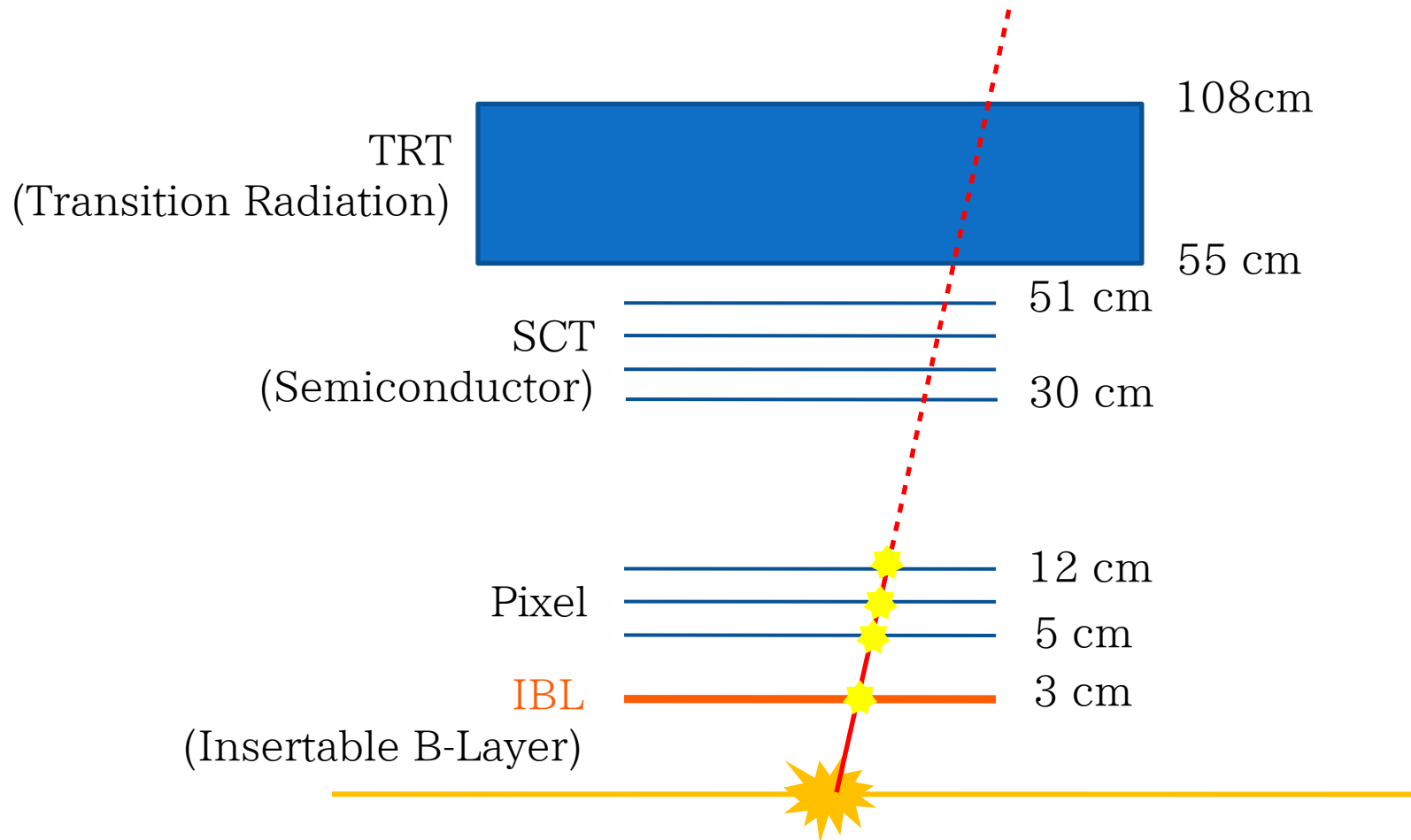
8 TeV selection



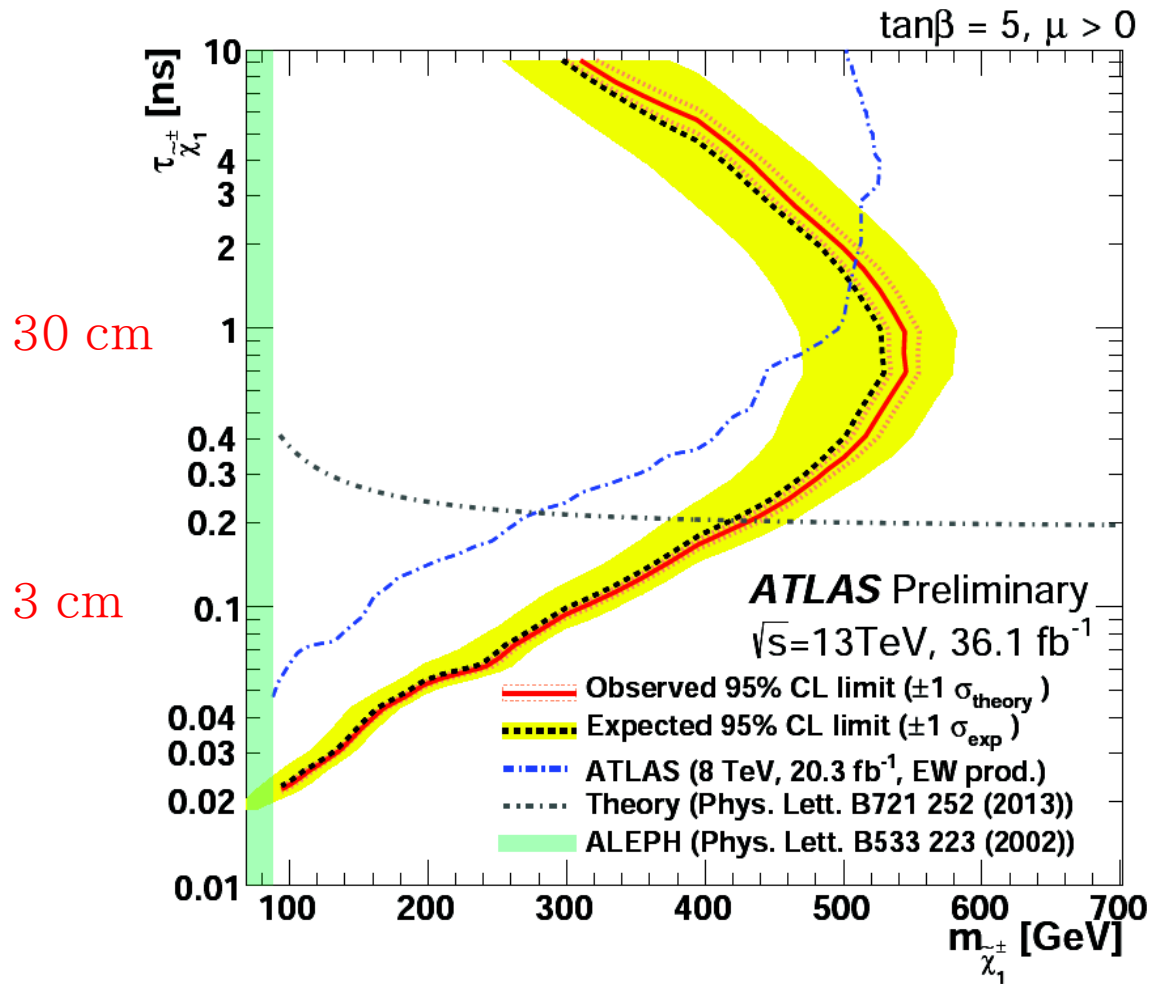
# Tracker for Run2



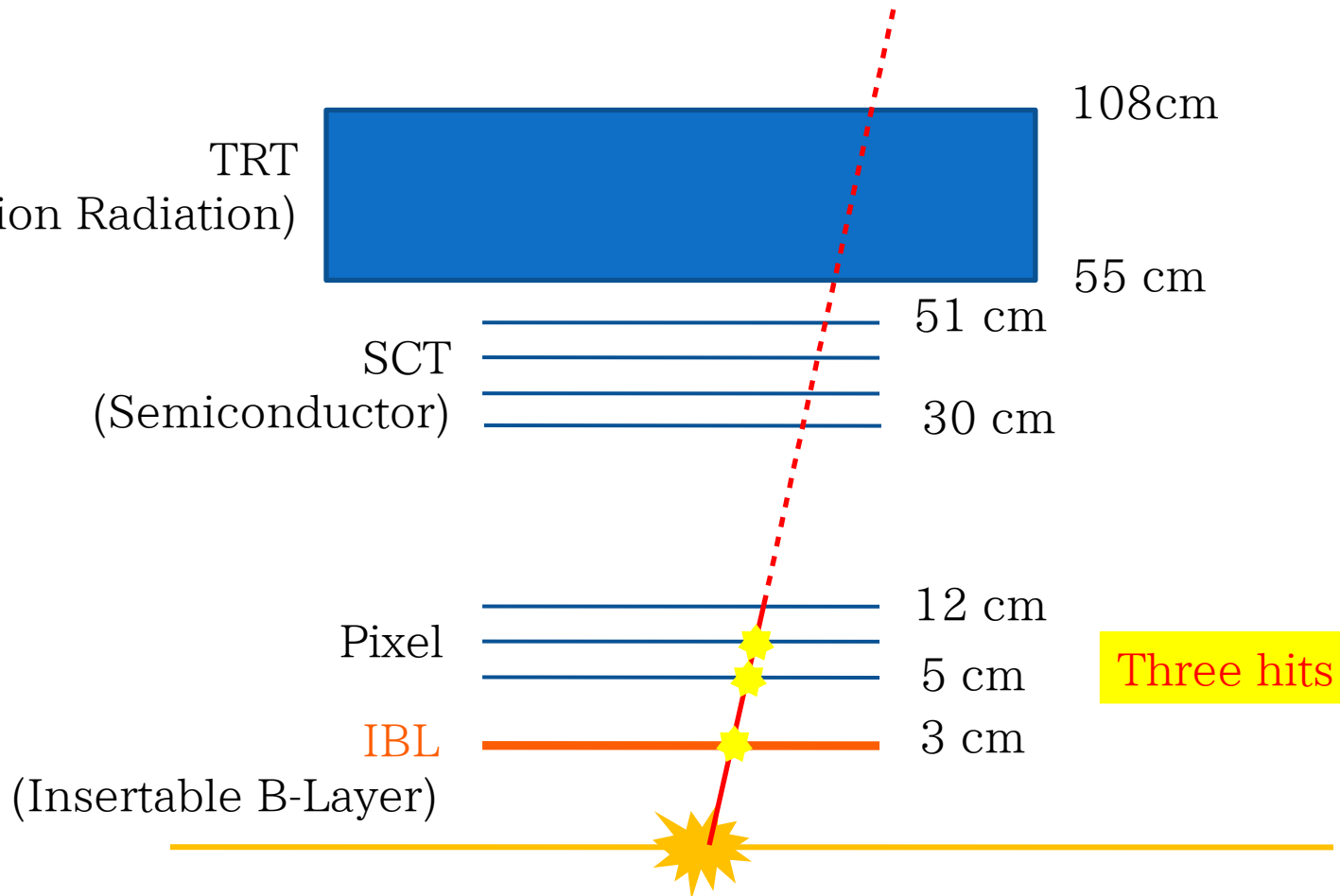
# Tracker for Run2



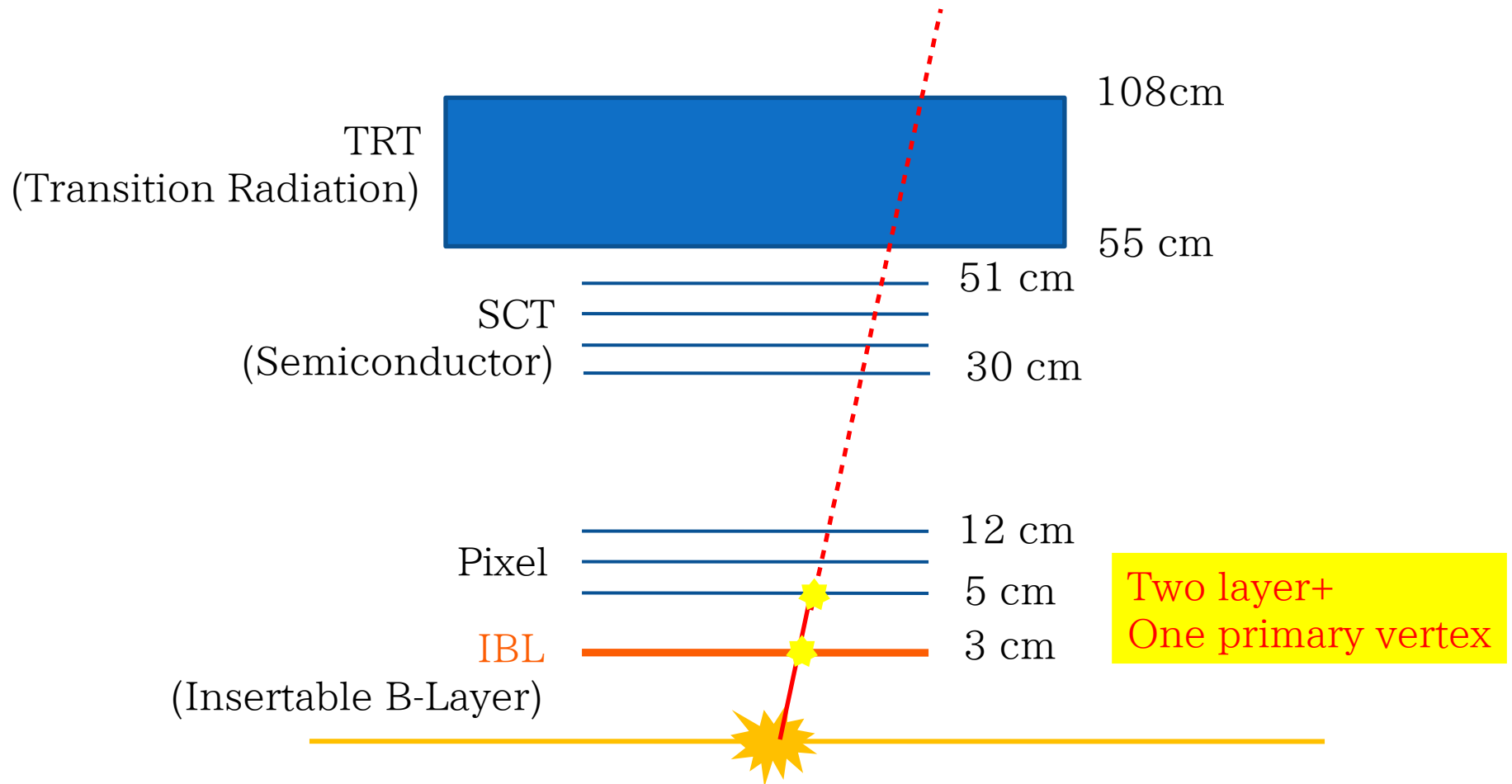
# Current Constraint(wino)



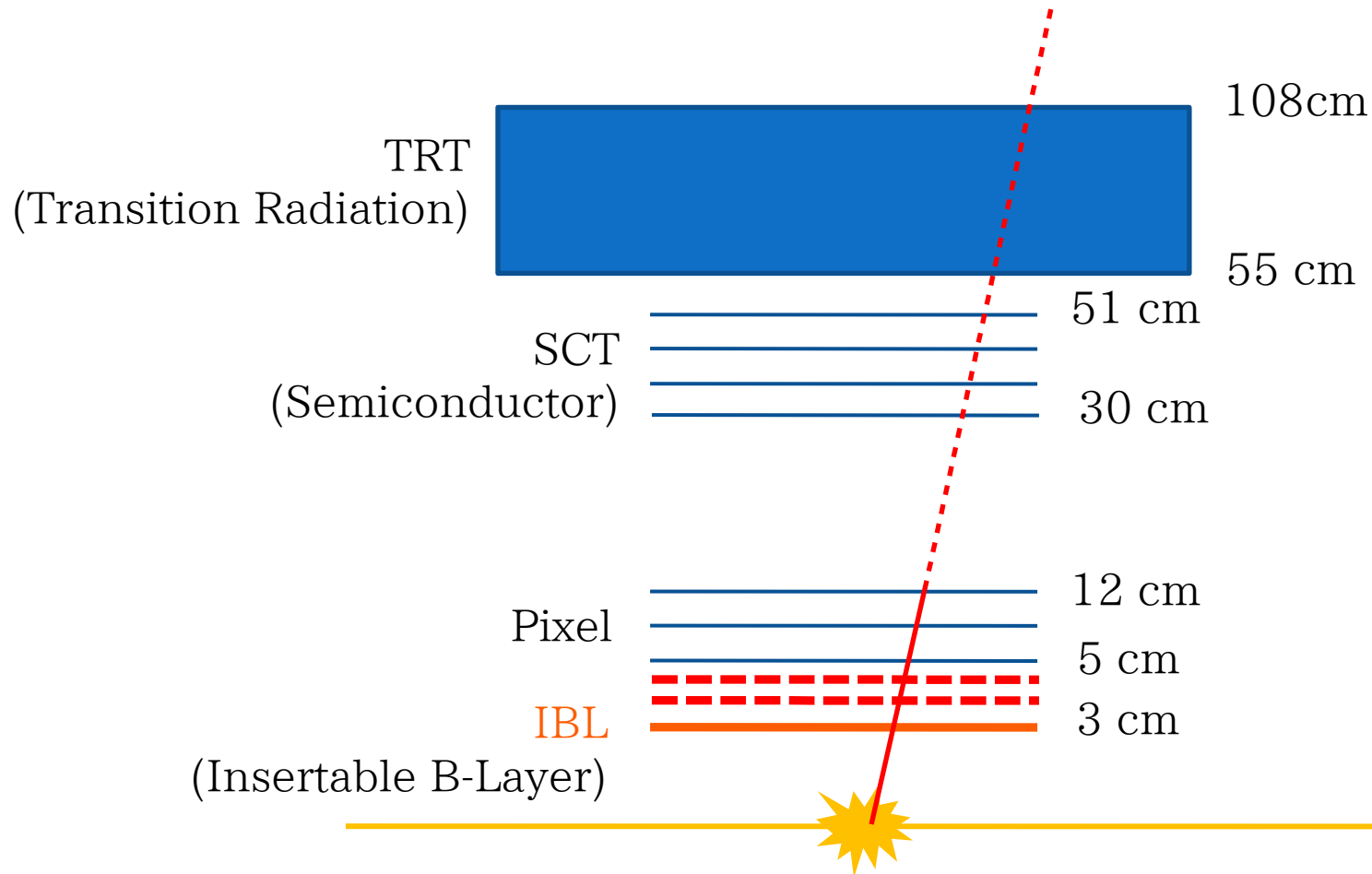
# Tracking shorter



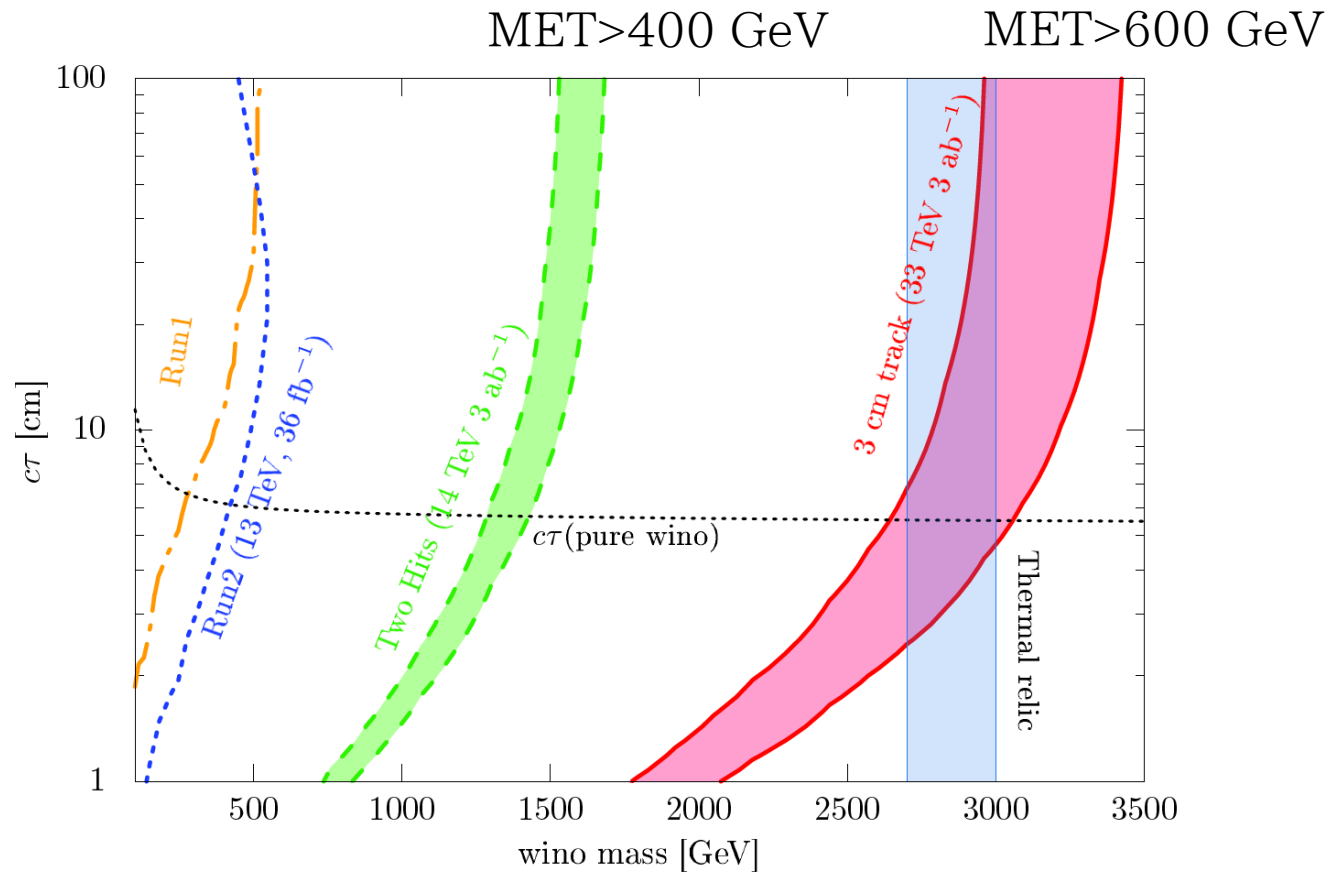
# Tracking shorter



# Tracker for Run???



# Prospects for Wino

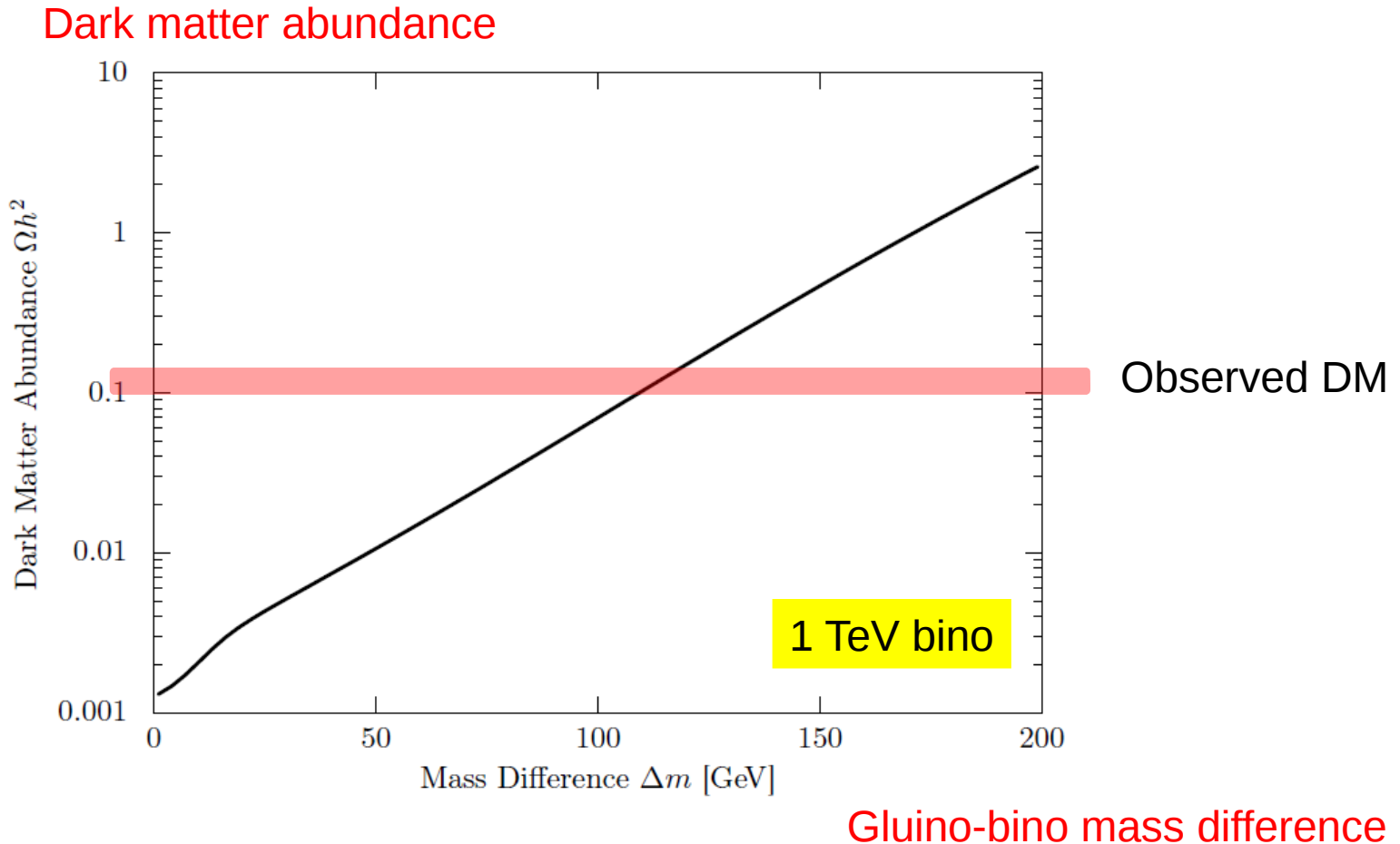




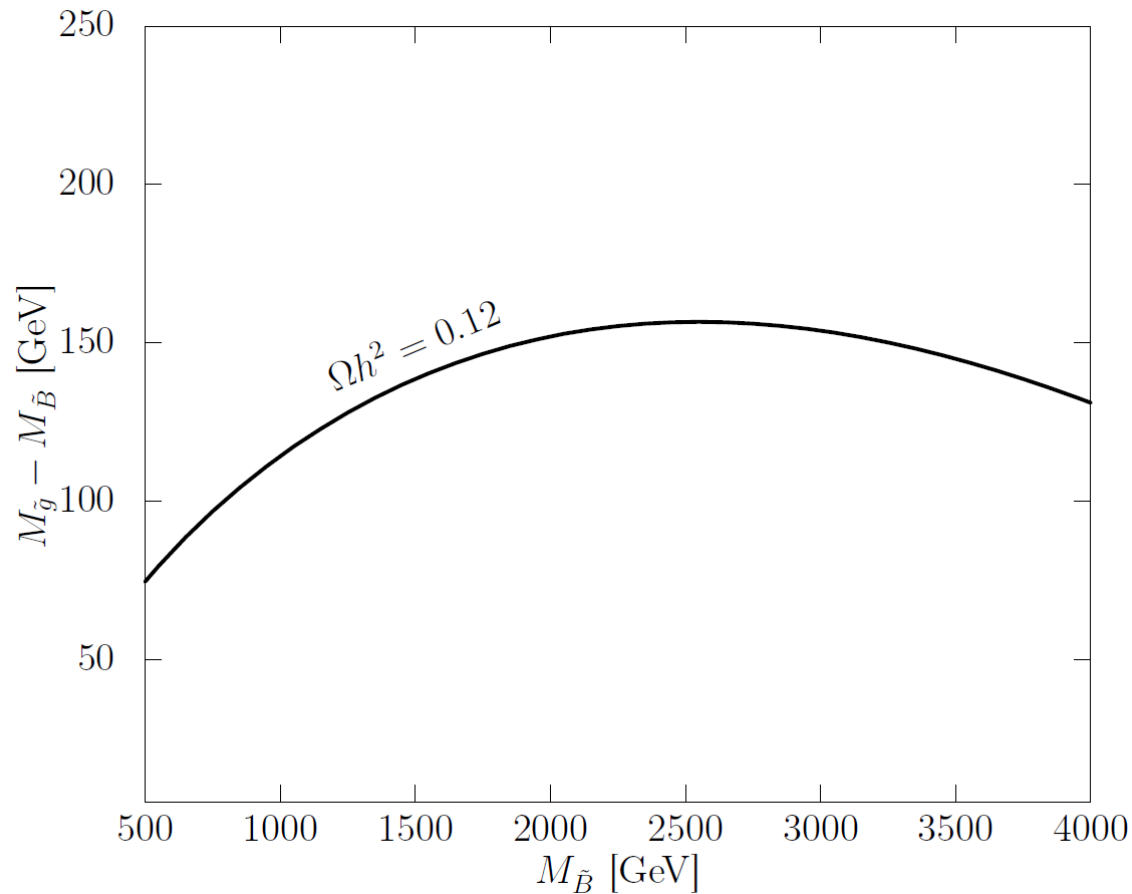


# Bino-Gluino Coannihilation

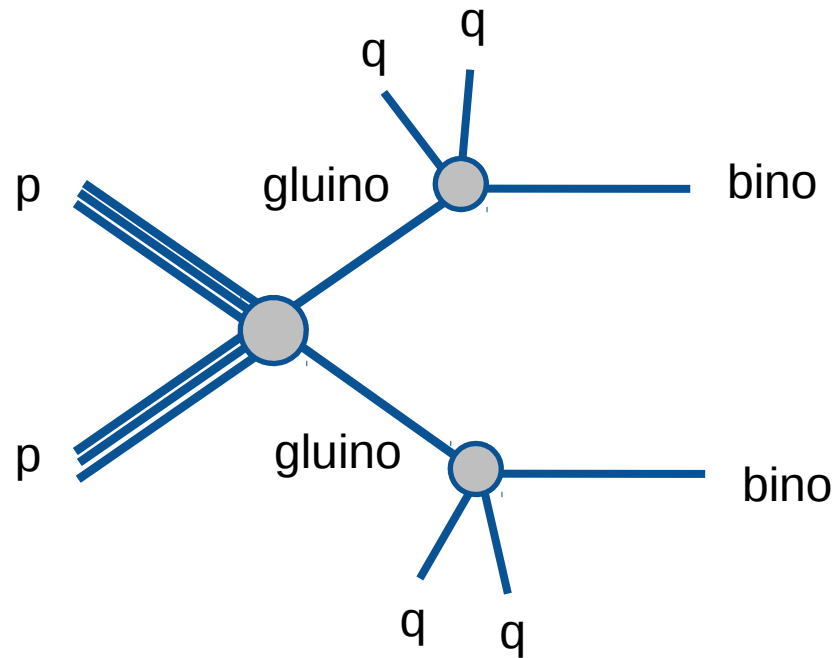
# Bino-Gluino Coannihilation 1



# Gluino Coannihilation

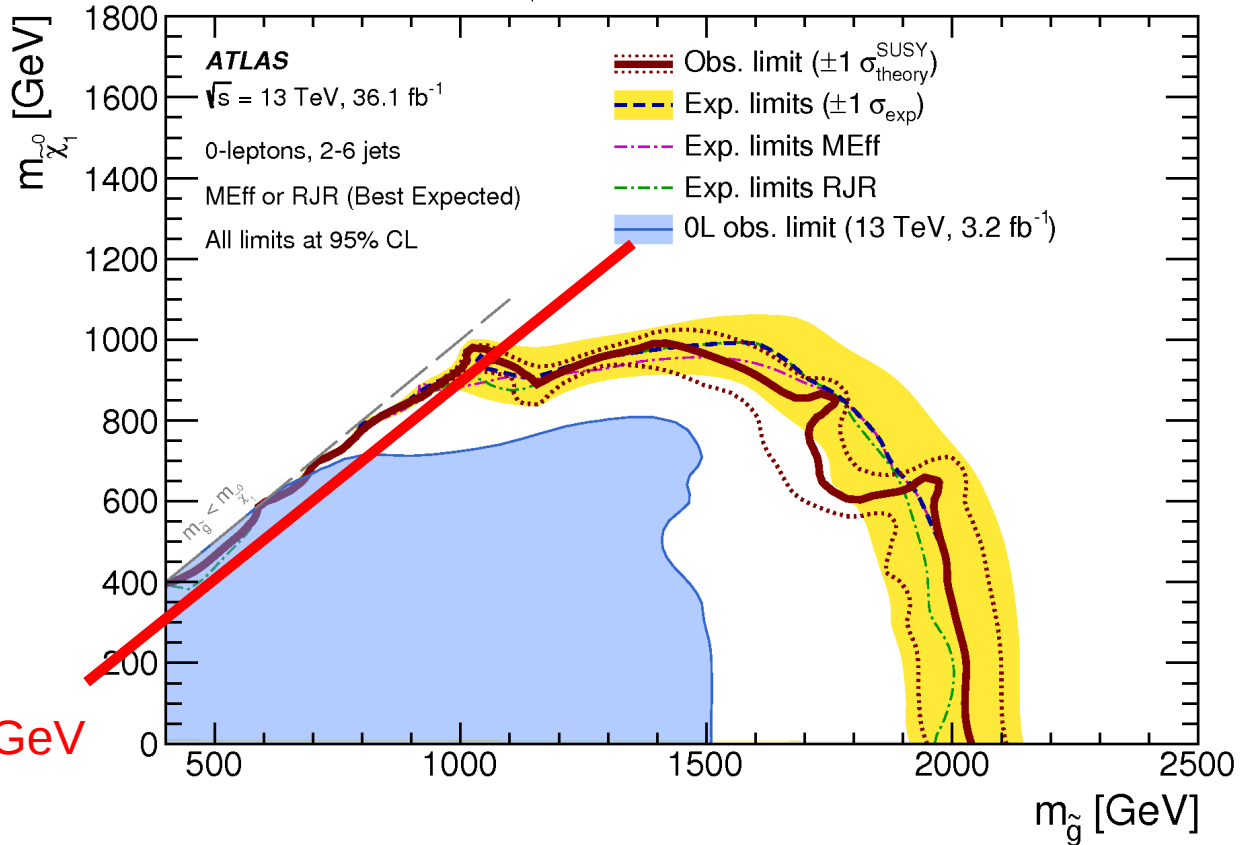


# LHC Signals



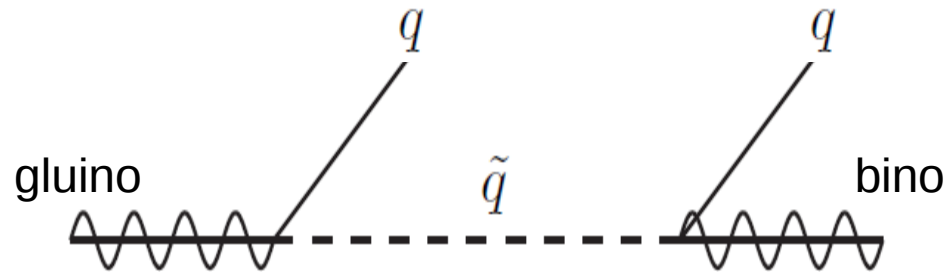
# Prompt Decay Case

$\tilde{g}\tilde{g}$  production,  $B(\tilde{g} \rightarrow qq\tilde{\chi}_1^0)=100\%$



Mass diff. = 100 GeV

# Bino-Gluino Interaction



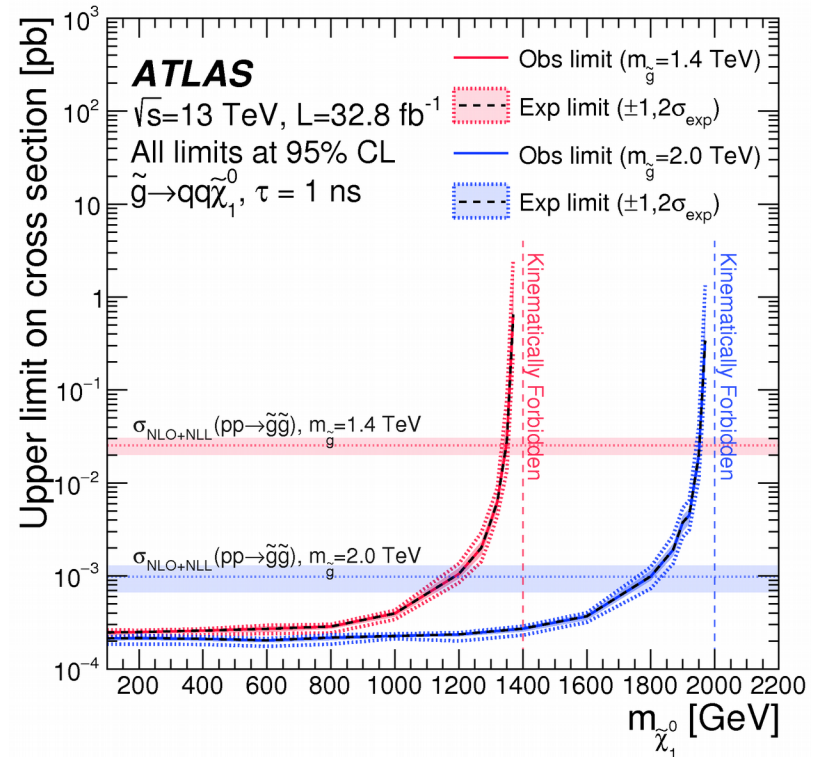
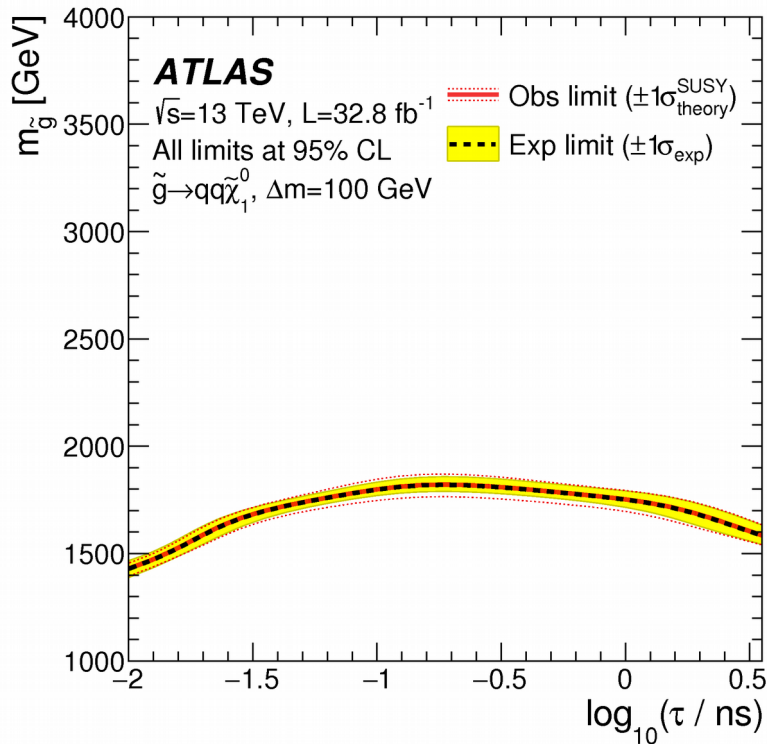
Bino-gluino interaction is suppressed by sfermion mass



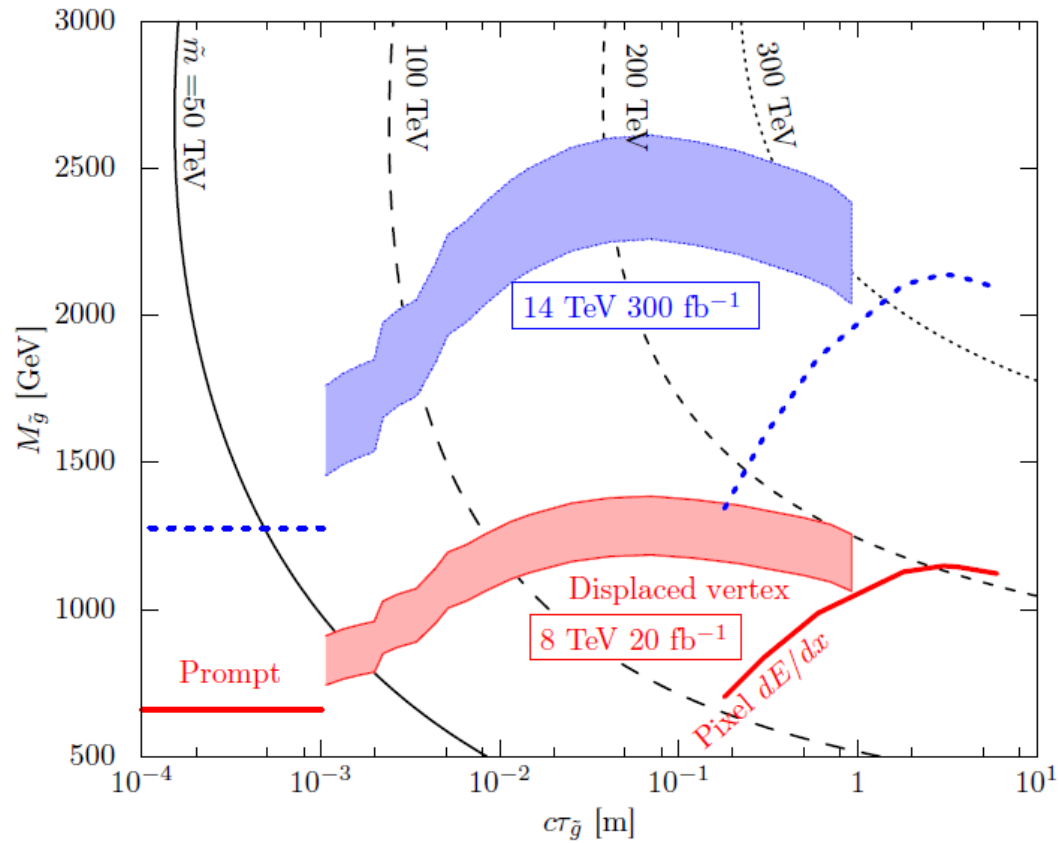
Long-lived gluino

$$c\tau_{\tilde{g}} = O(1) \left( \frac{\Delta m}{100 \text{ GeV}} \right)^{-5} \left( \frac{M_s}{100 \text{ TeV}} \right)^4 \text{ cm}$$

# Bino-Gluino Interaction



# Prospects

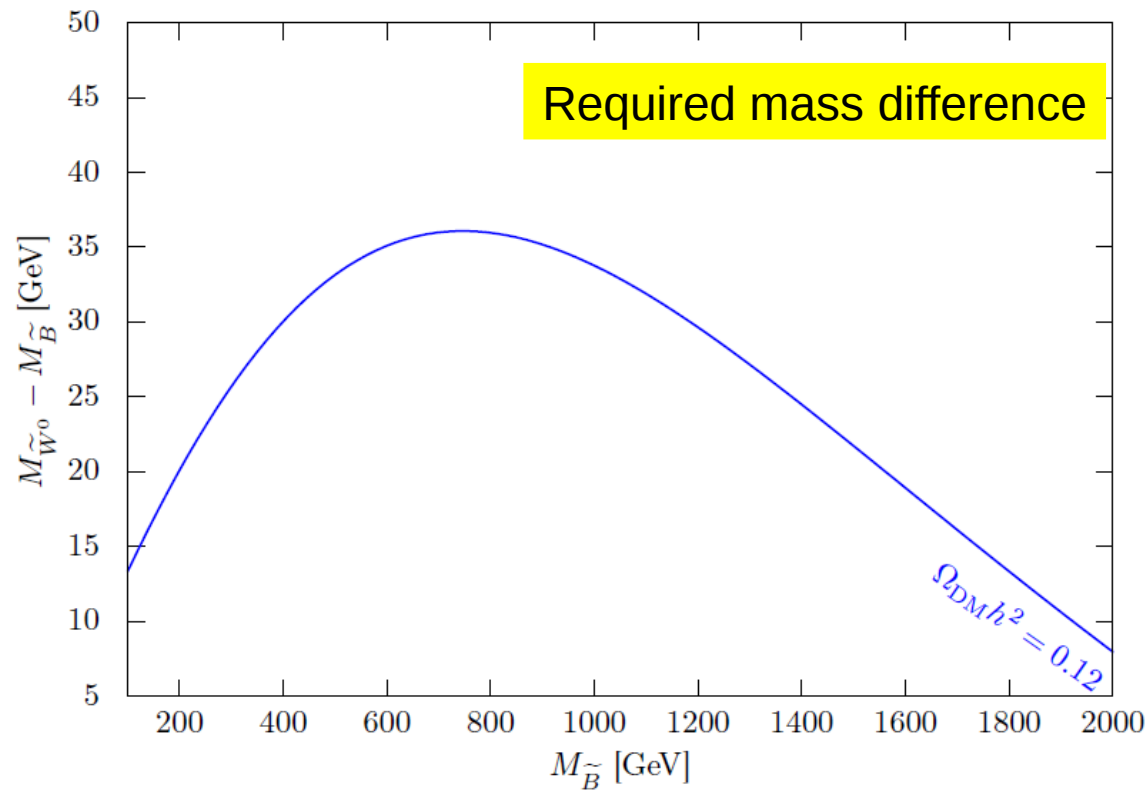




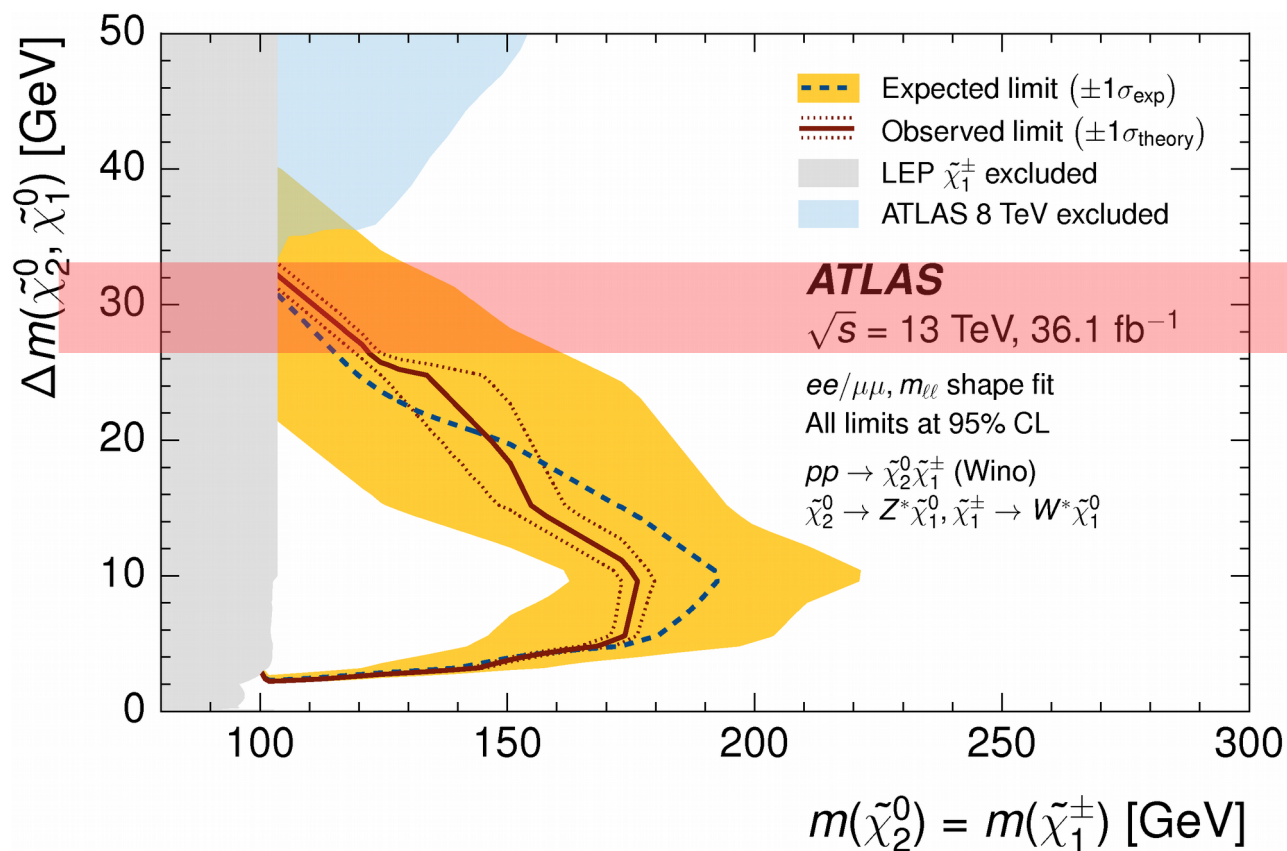


# Bino-Wino Coannihilation

# Bino-Wino Coannihilation

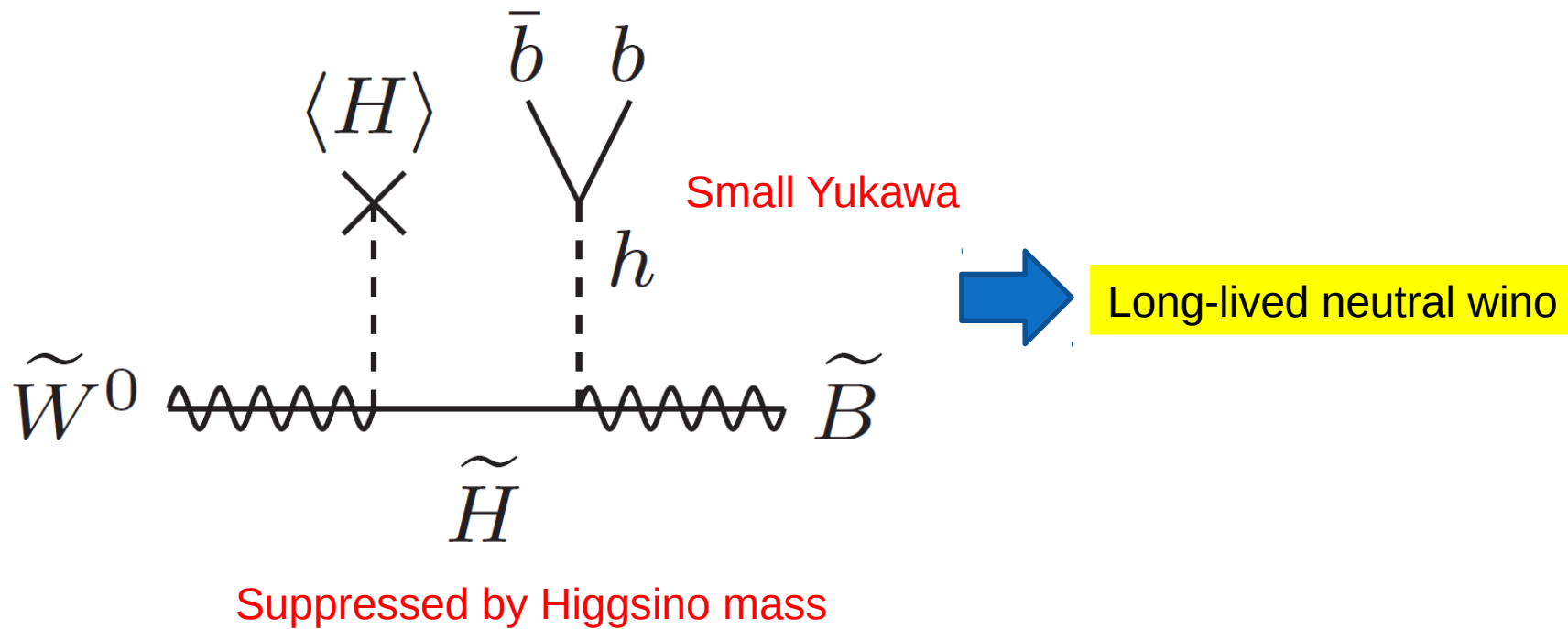


# LHC Signals



Mass diff. 30 GeV

# Wino Decay (tree)



# Wino Decay

$$\tilde{W}^\pm \rightarrow W^\pm + \tilde{B} \quad \propto \mu^{-1}$$

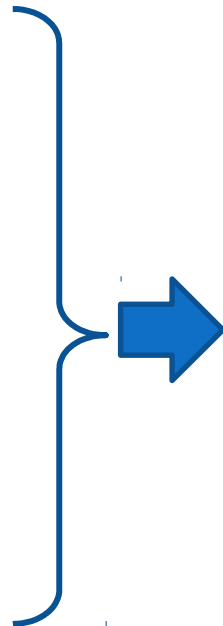


Prompt charged Wino decay

$$\tilde{W}^0 \rightarrow h + \tilde{B} \quad \propto \mu^{-1}$$

$$\tilde{W}^0 \rightarrow Z + \tilde{B} \quad \propto \mu^{-2}$$

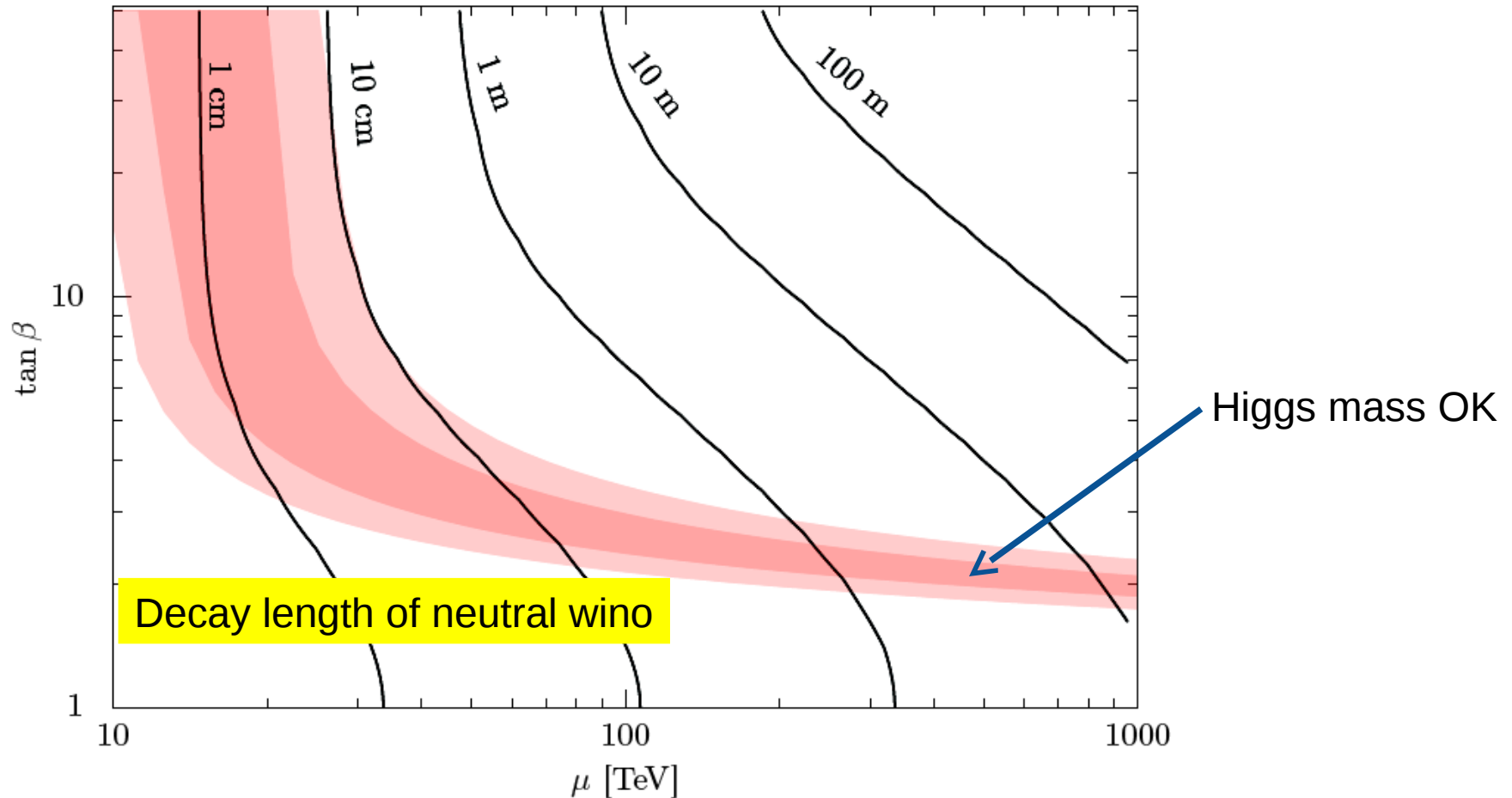
$$\tilde{W}^0 \rightarrow \gamma + \tilde{B} \quad \propto \frac{\alpha}{4\pi} \mu^{-2}, \left(\frac{\alpha}{4\pi}\right)^2 \mu^{-1}$$



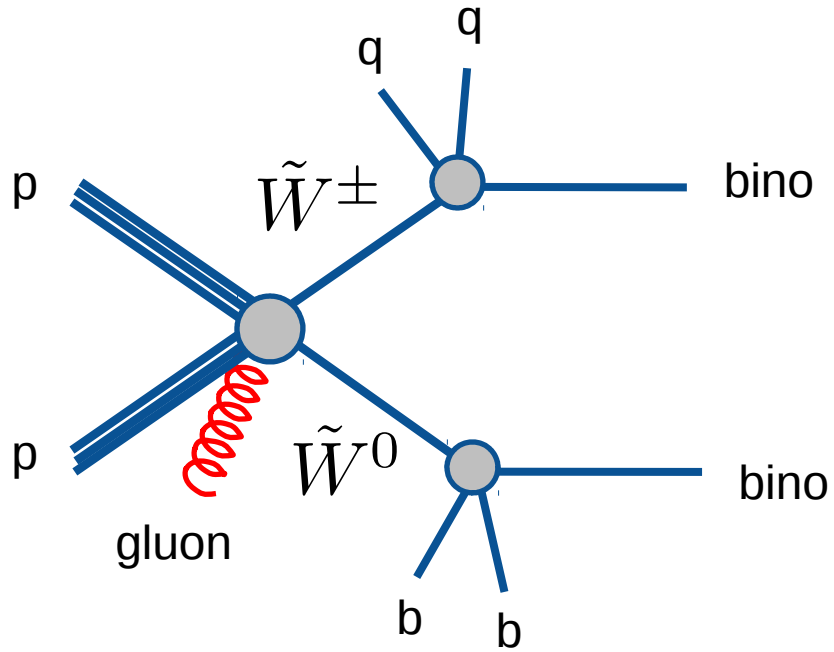
Displaced neutral Wino decay

# Wino Decay

Bino = 400 GeV  
Wino = 430 GeV

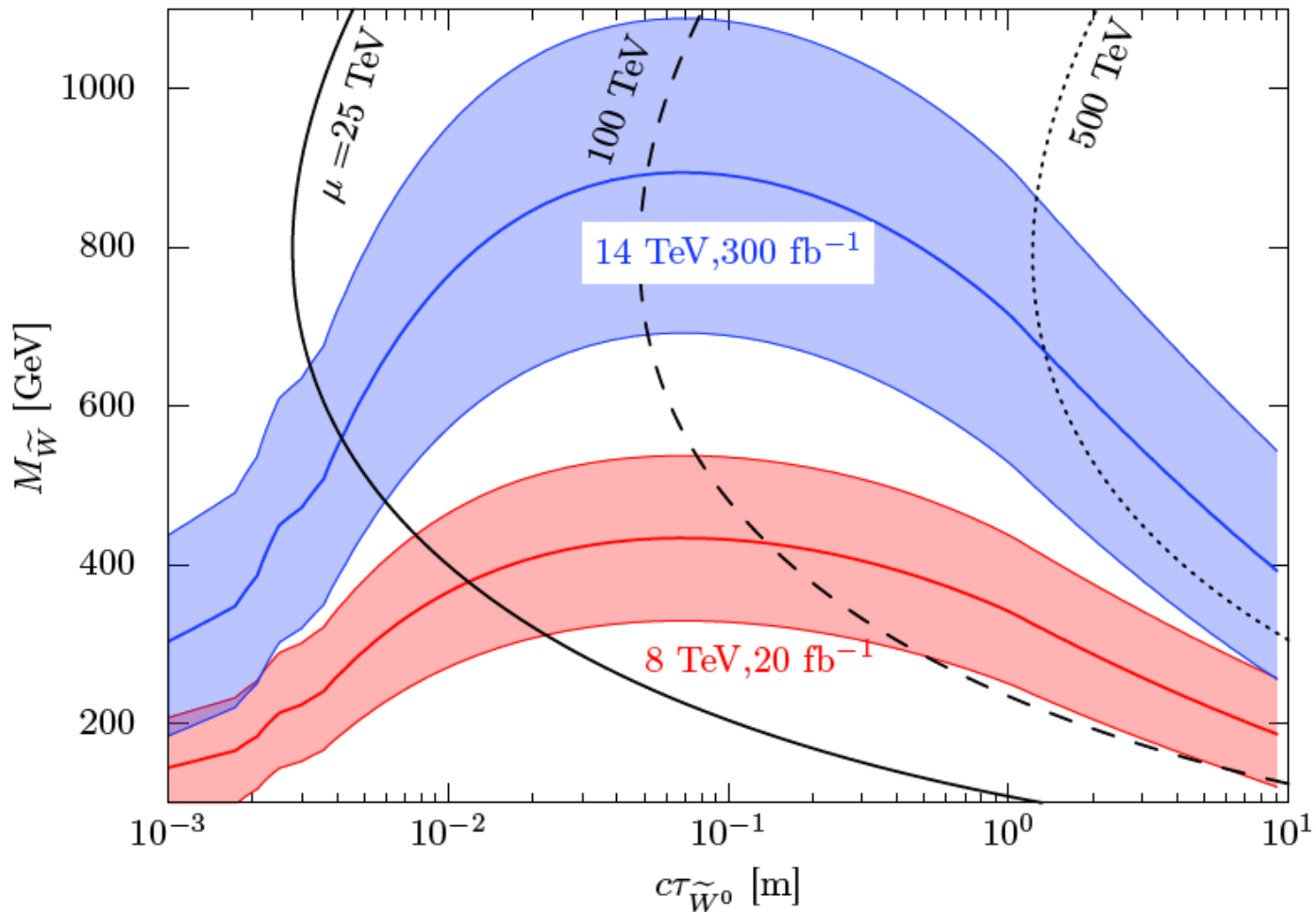


# LHC Signals



Low mass  $\sim 10$  GeV DV  
+  
MET

# LHC Signals





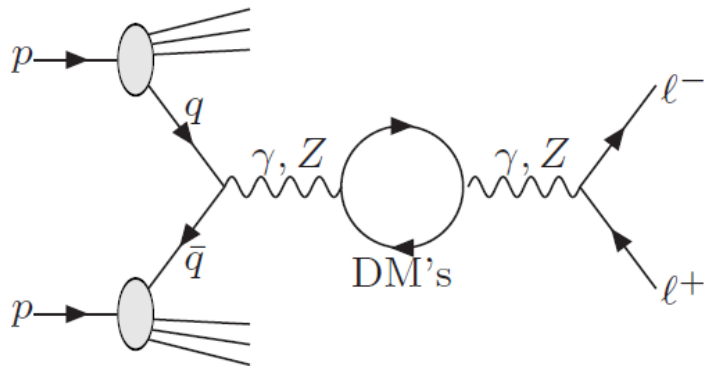
# Summary

- Mini-split is simplest SUSY model with 125 GeV Higgs
- DM in mini-split likely provide **meta-stable** particles
  - **Wino DM**: disappearing track
  - **Gluino-bino DM**: long-lived R-hadron
  - **Wino-bino DM**: long-lived neutral wino
- Improvement of LLP detection

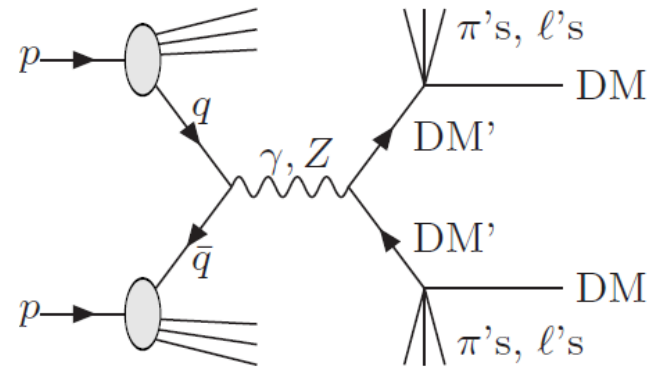


# Indirect Search @LHC

# DM Search



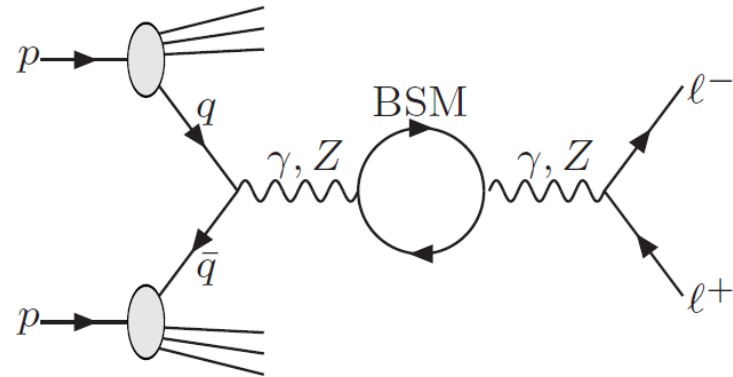
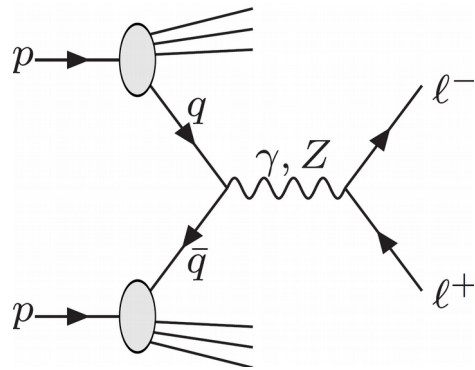
Indirect Search from SM precision



Exotic tracks:

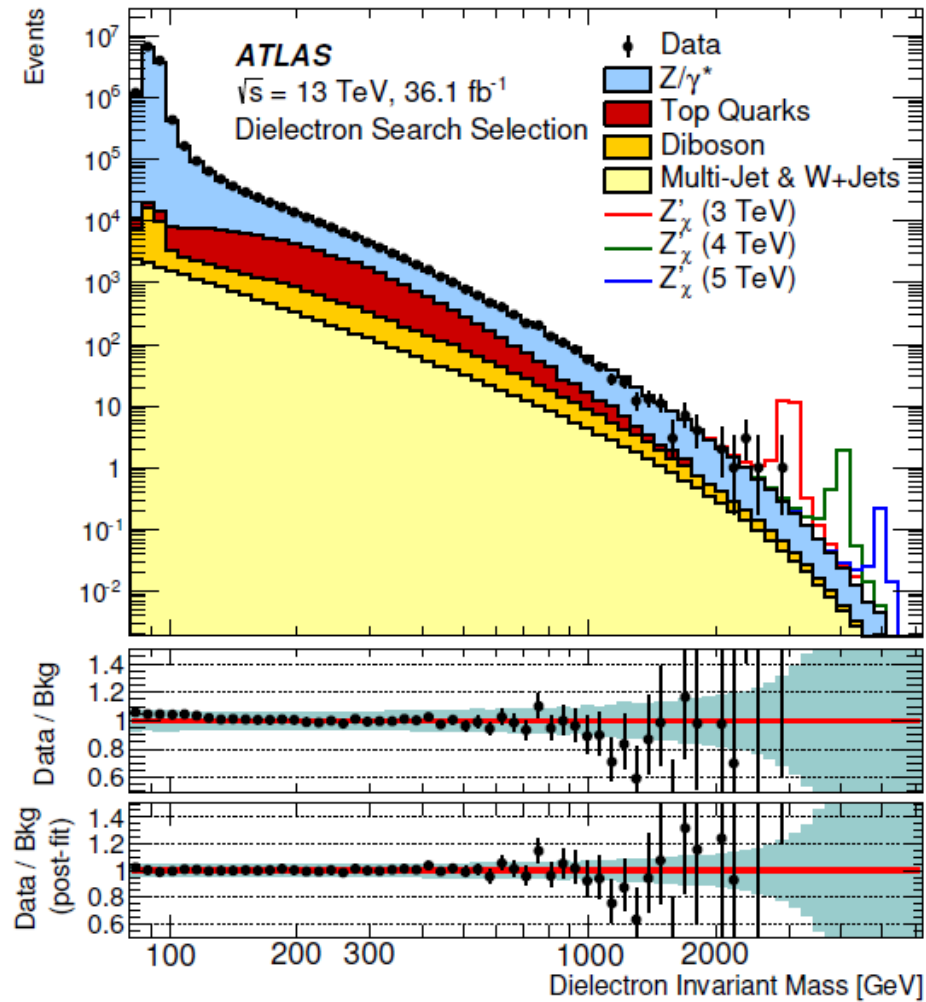
Disappearing track  
Displaced soft track

# Indirect Probe at LHC



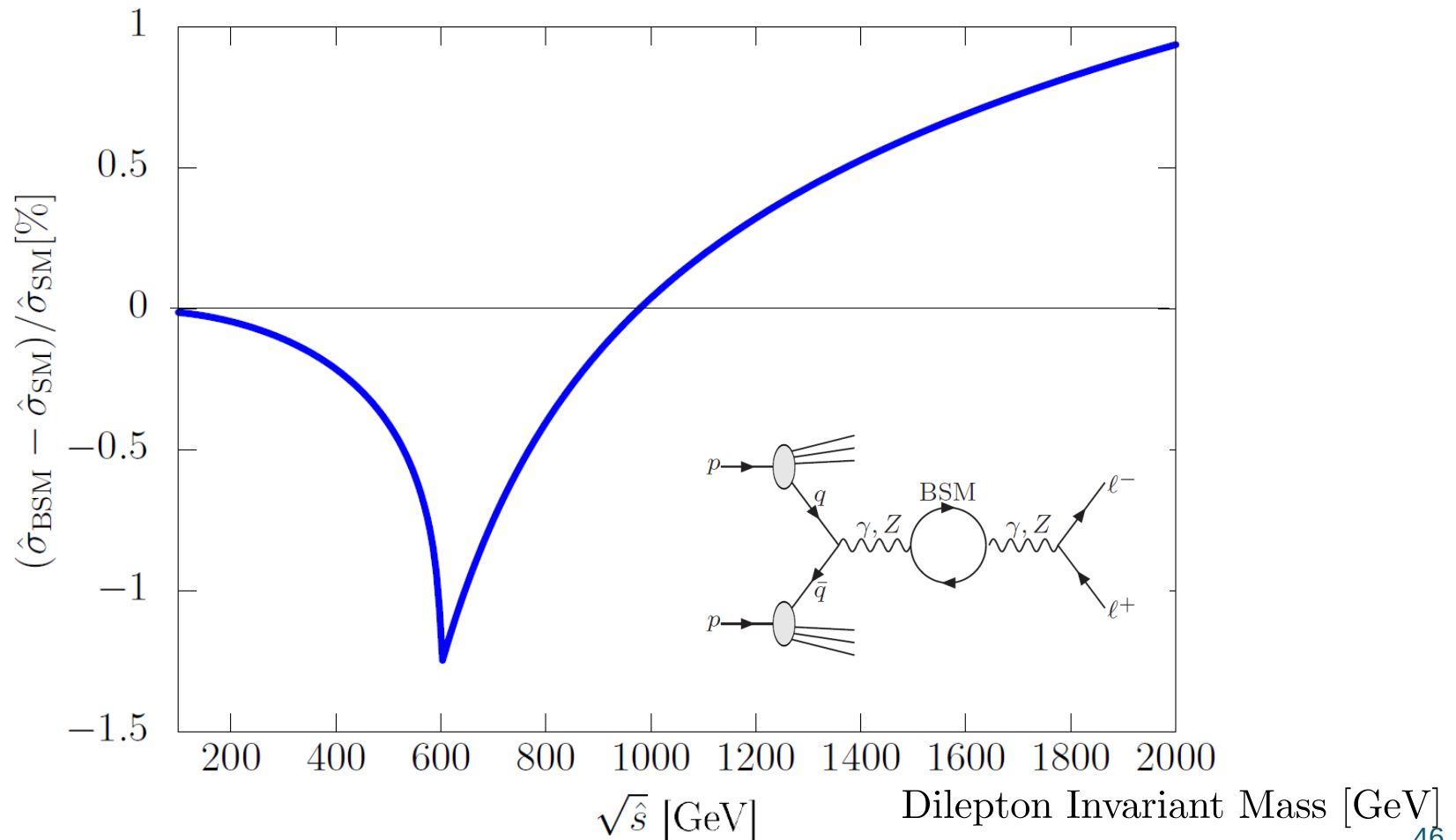
Interference between SM and BSM gives correction

# Observed Data

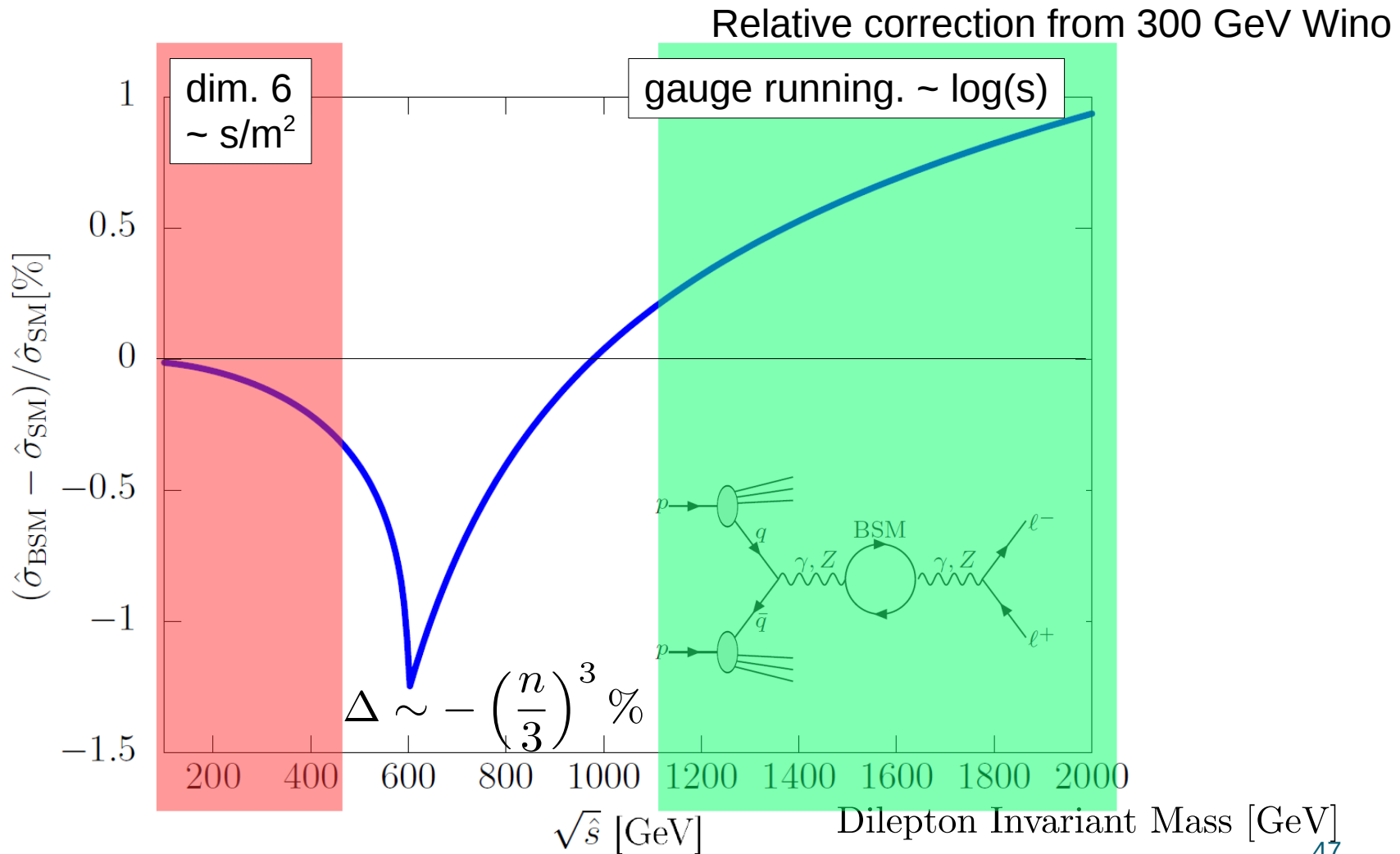


# Correction from DM

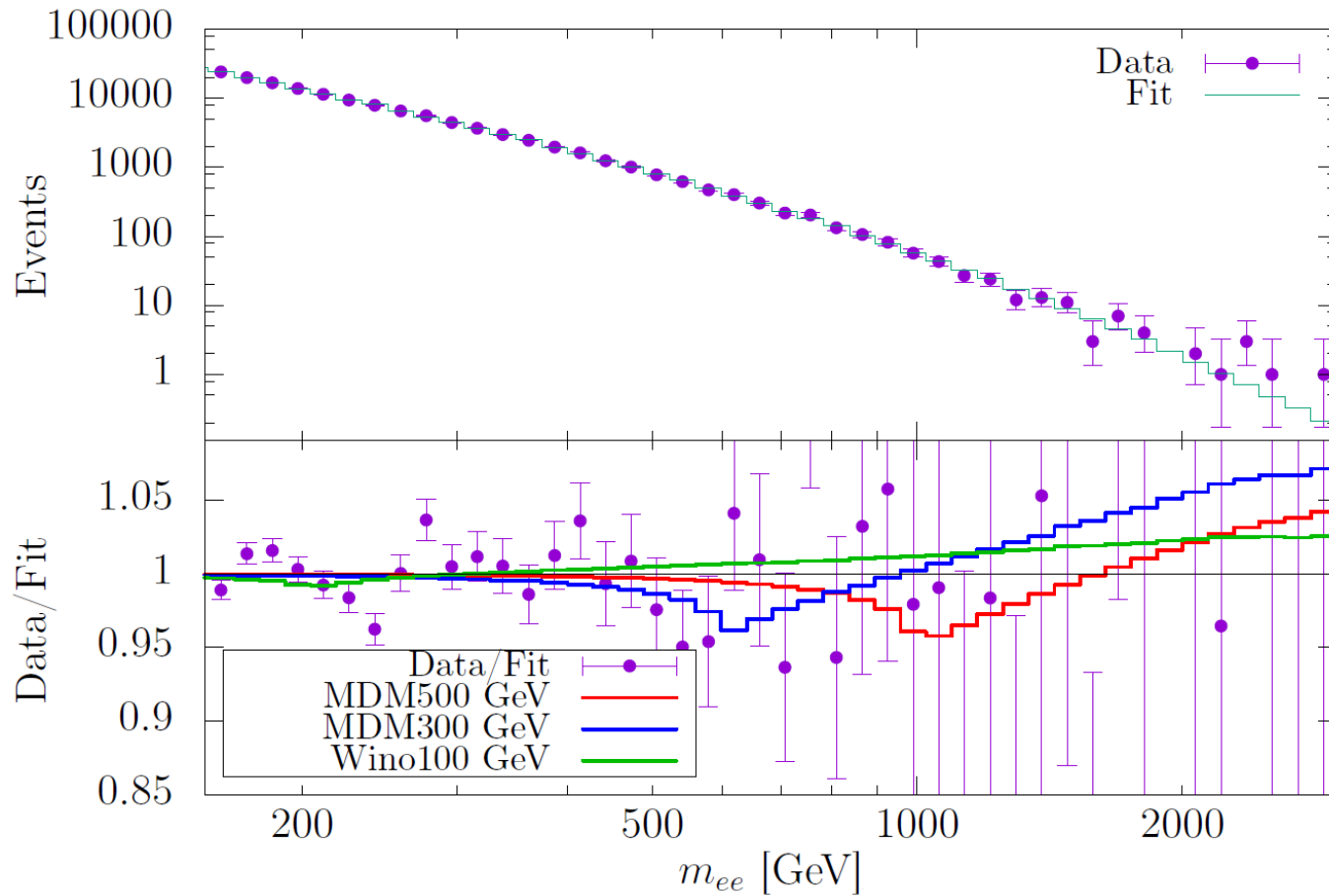
Relative correction from 300 GeV Wino



# Correction from DM



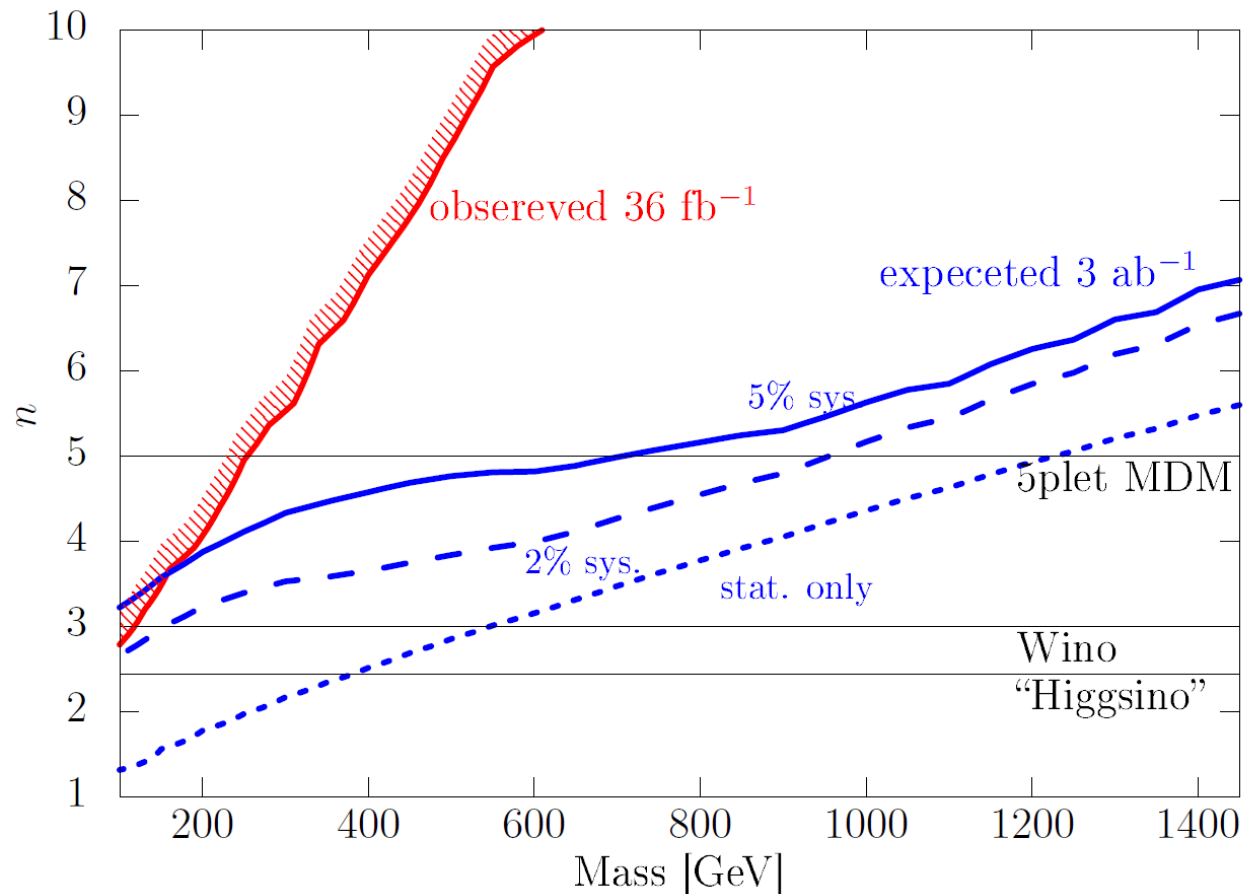
# Indirect Probe at LHC





# Indirect Probe at LHC

# of SU(2) representation



# LHC DM Search Summary

- LLP signals are great help for DM search
- Prevision measurements can also probe DM:  
as powerful as mono-jet + MET search



# Indirect Search @ILC

# Effective Operator

Case of beam energy  $< 2 \times$  mass.

Integrating out of MDM leads effective operators

$$-\frac{1}{\Lambda_{2W}^2} (D_\mu W_{\mu\nu}^a)^2 - \frac{1}{\Lambda_{2B}^2} (\partial_\mu B_{\mu\nu})^2 + \frac{g}{\Lambda_{3W}} W^3 \dots$$

$$\frac{1}{\Lambda_{2W}^2} = \frac{g^2}{16\pi^2} \frac{1}{15m^2} \frac{n(n-1)(n+1)}{6}$$

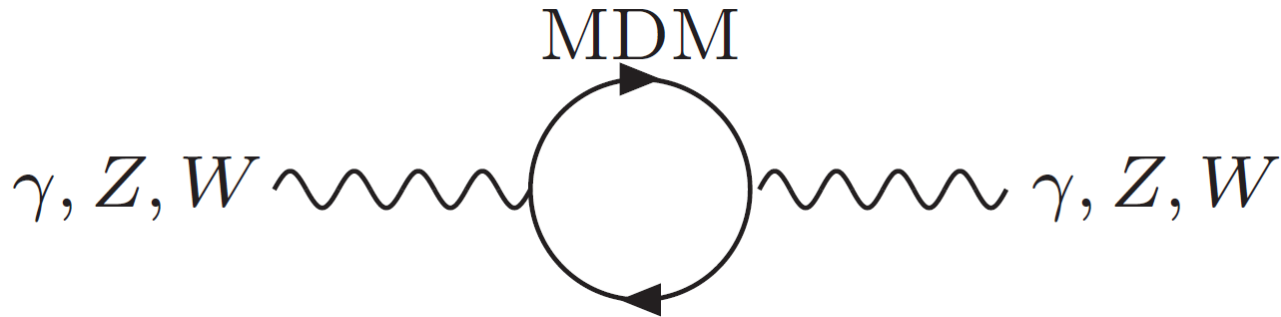
$$\frac{1}{\Lambda_{2B}^2} = \frac{g'^2}{16\pi^2} \frac{2nY^2}{15m^2}$$

$$\frac{1}{\Lambda_{3W}^2} = \frac{-1}{12\Lambda_{2W}^2} \quad (\text{Dirac Fermion})$$

Correction to gauge boson propagator and self-coupling

# On-Z Observables

Heavy DM cannot be produced at collider, but affects SM processes

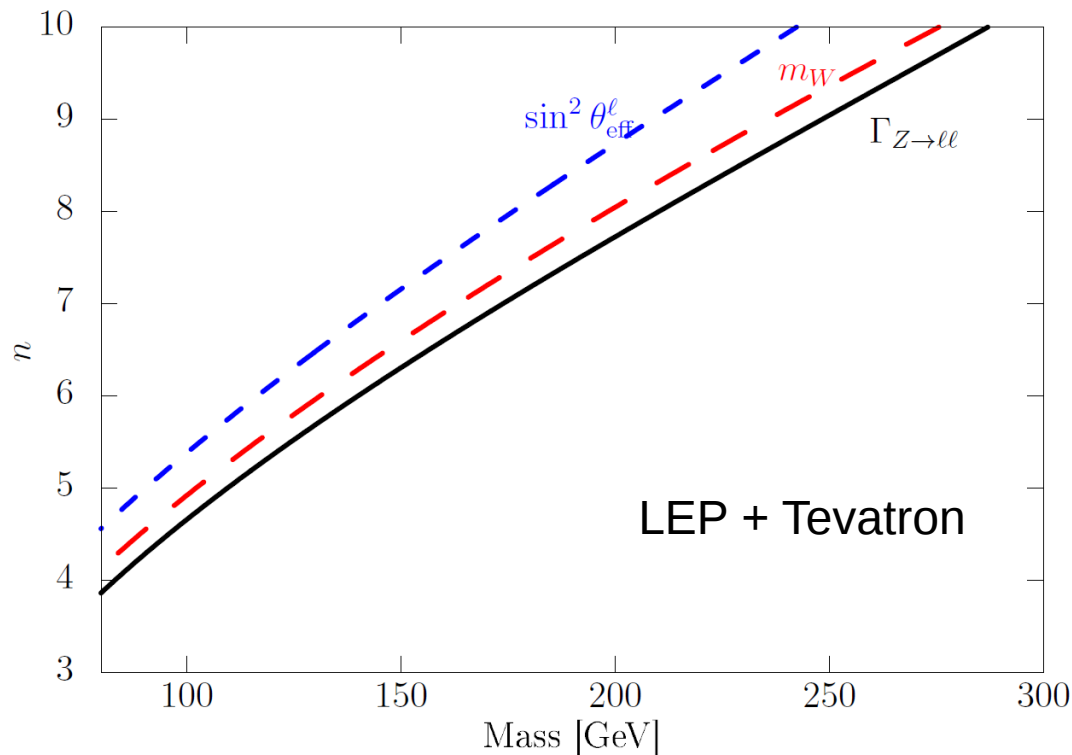


**Case 1:** Oblique correction to electroweak precision observables (EWPO)  
weak boson mass and so on

# Current Constraints from EWPO

# of SU(2) representation

Majorana Fermion

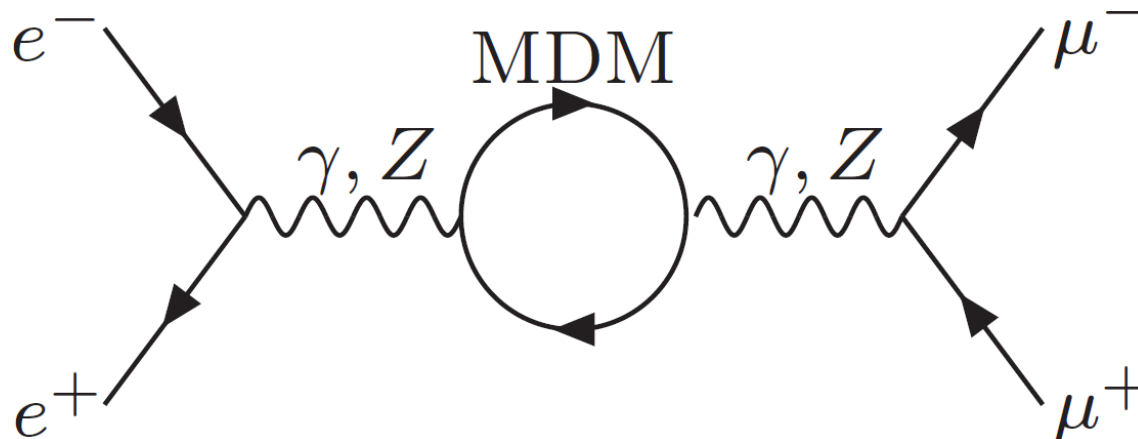


Corrections are roughly proportional to  $n^3 / m^2$

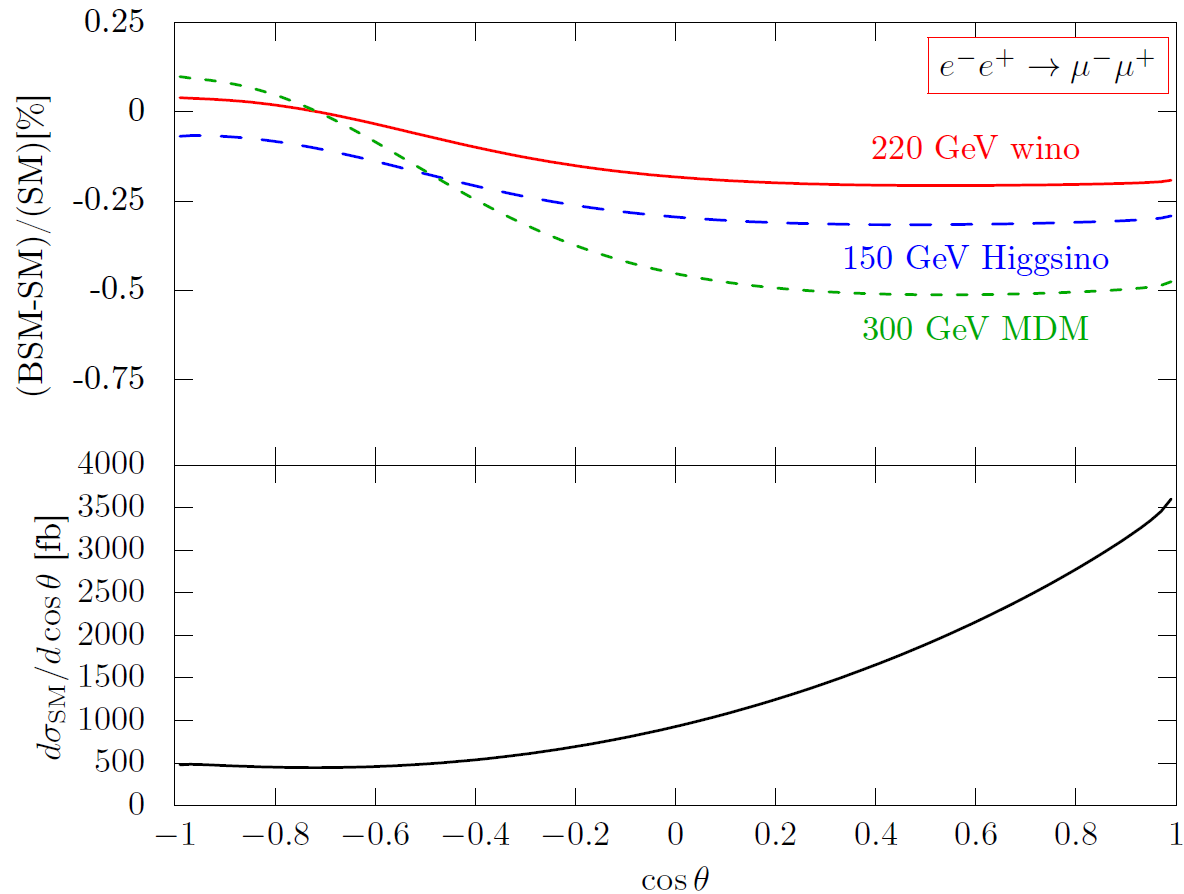
# ILC250 for MDM

See Suehara's talk

**Case 2:** Correction to di-fermion process at ILC.

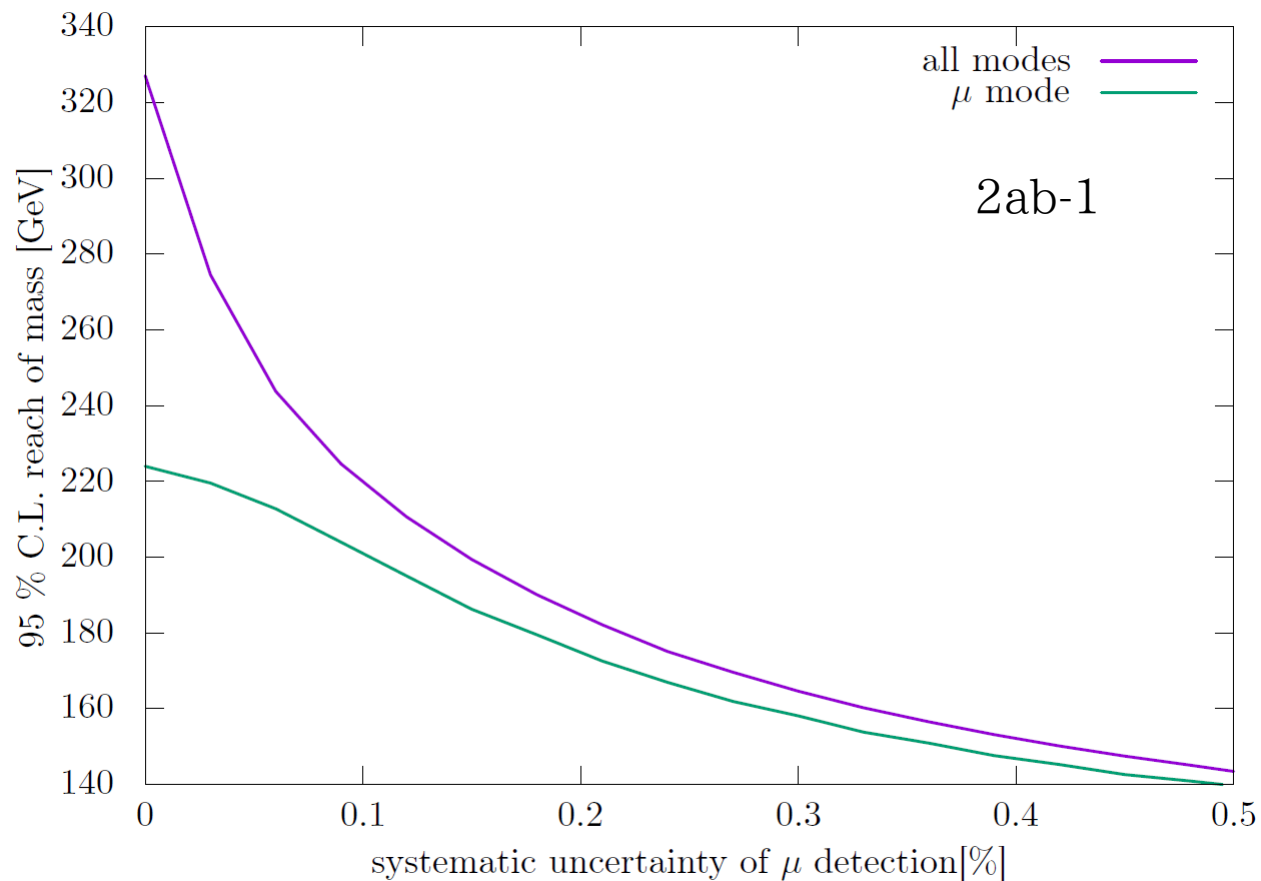


# ILC250 for Heavy MDM



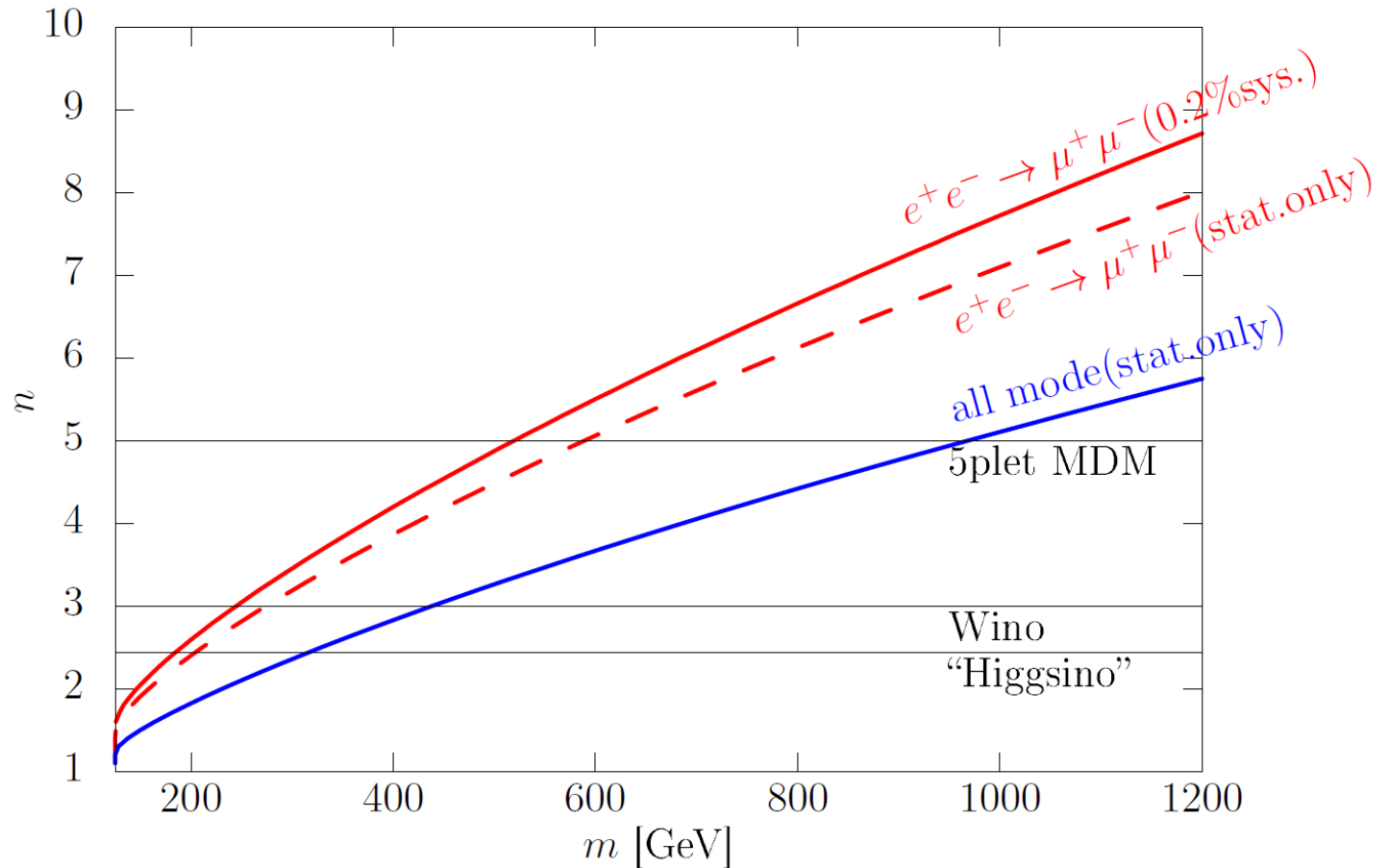


# Reach of ILC250 for Higgsino



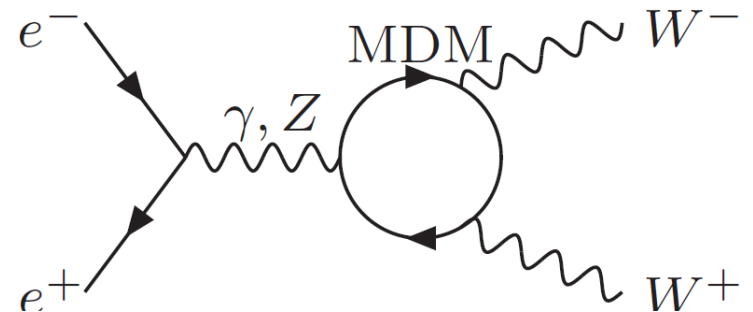
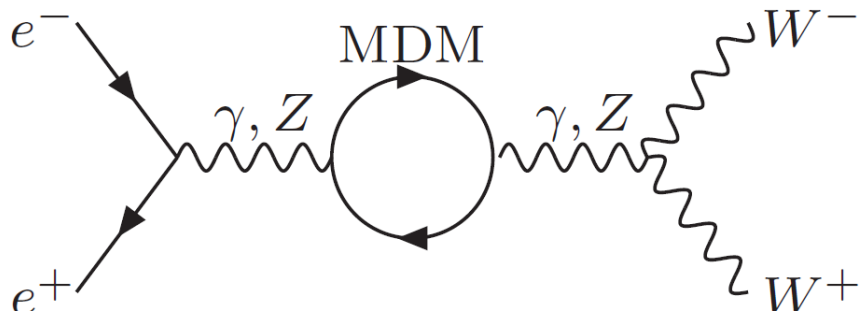
mu, e, b, c sys. Ratios: 2 : 1.5 : 5 : 10 assumed

# Reach of ILC250

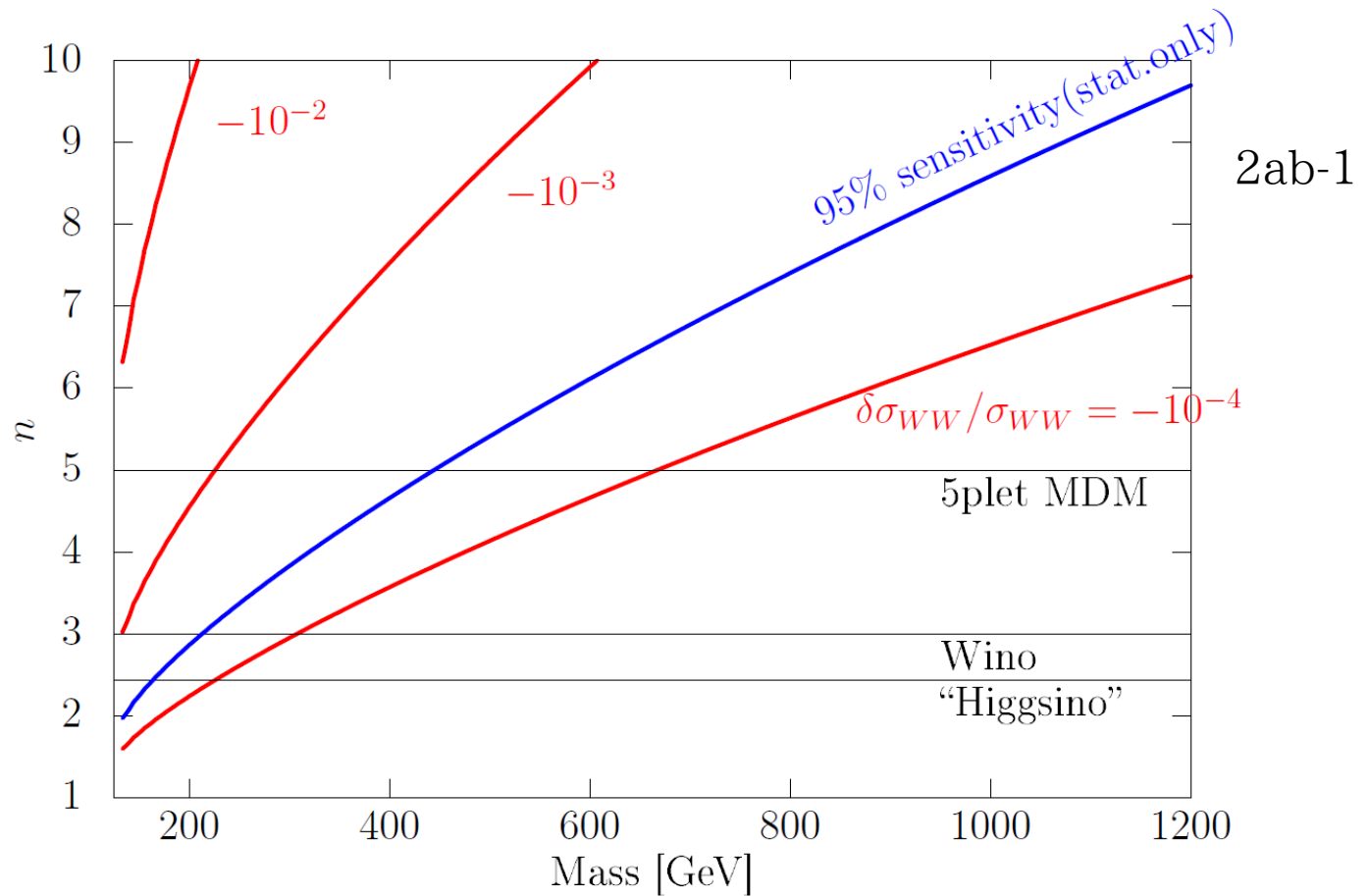


# ILC250 for MDM

Case 3: Correction to diboson process at ILC.

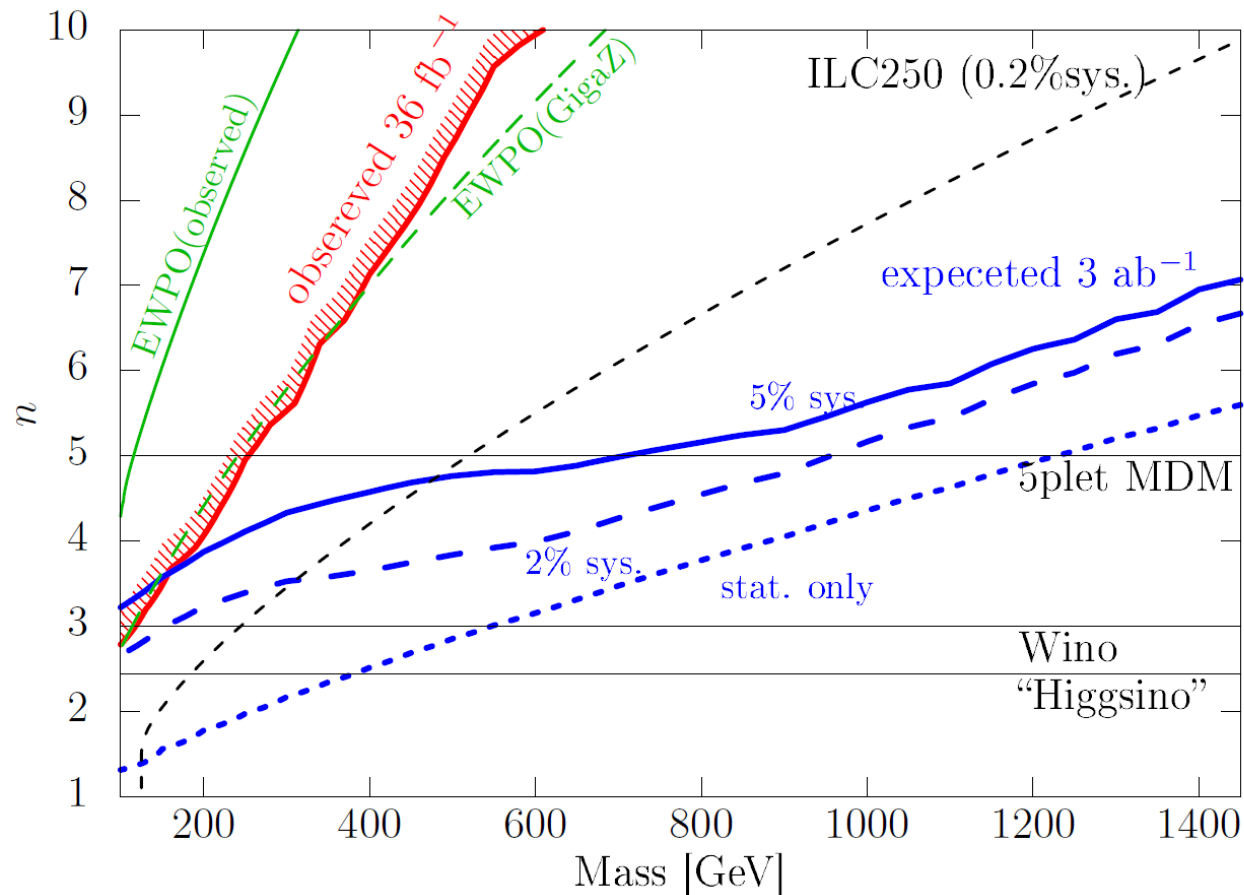


# ILC250 for MDM



# Indirect Probe Summary

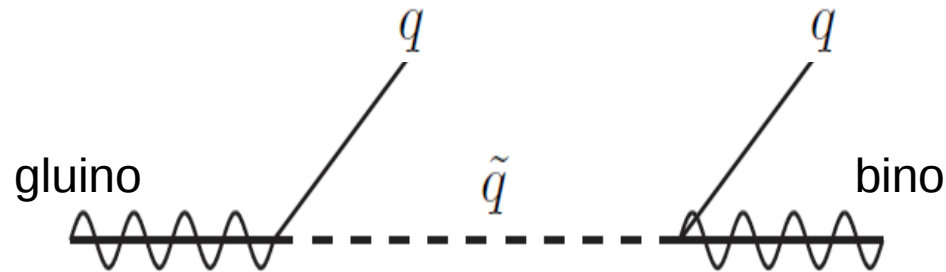
# of SU(2) representation



# Indirect Search Summary

- MDM can be indirectly tested at LHC and ILC
- As powerful as mono-jet + MET search
- This method uses only EW gauge interaction
  - Any EW interacting particle

# Bino-Gluino Interaction



Bino-gluino interaction is suppressed by sfermion mass



Long-lived gluino

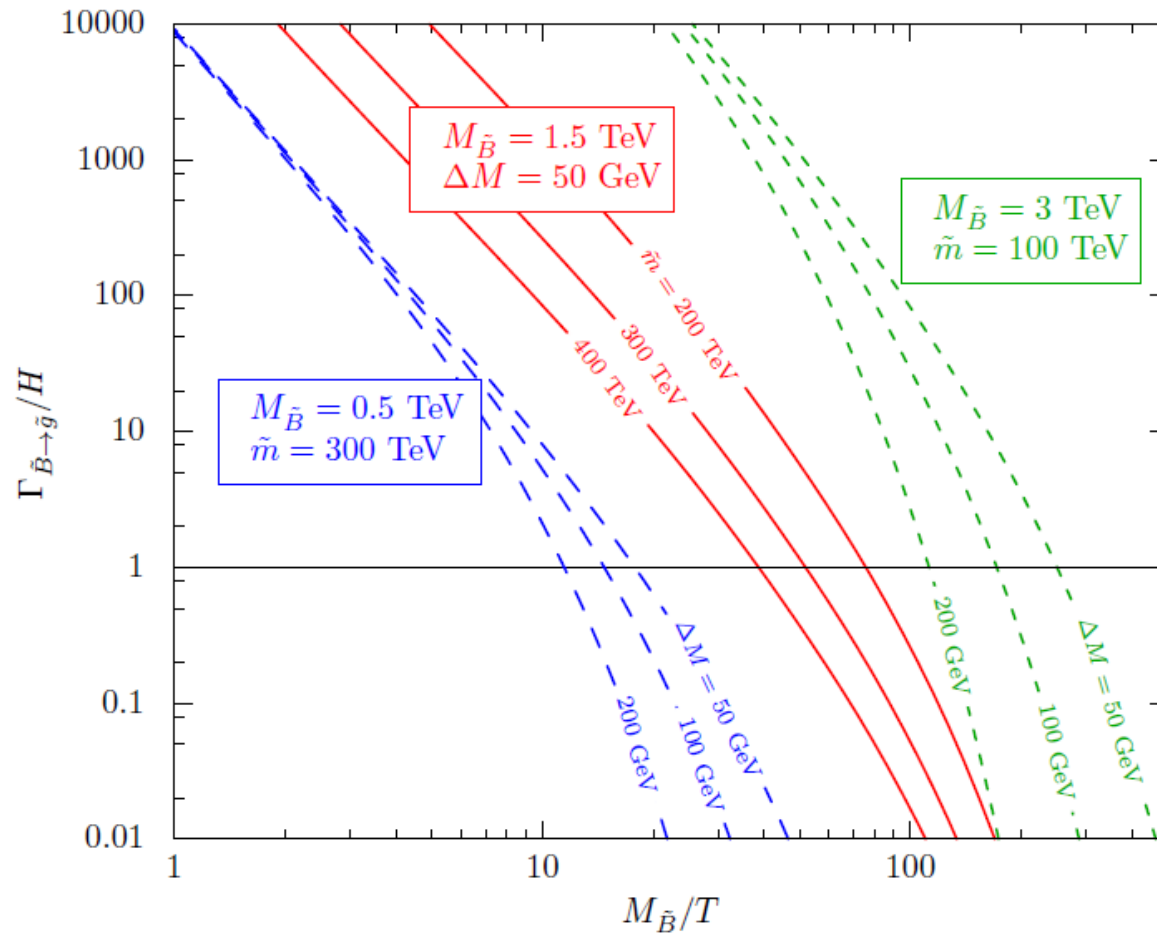
$$c\tau_{\tilde{g}} = O(1) \left( \frac{\Delta m}{100 \text{ GeV}} \right)^{-5} \left( \frac{M_s}{100 \text{ TeV}} \right)^4 \text{ cm}$$



Too heavy sfermion prevents coannihilation

$$M_s \lesssim 250 \left( \frac{M_{\text{bino}}}{1 \text{ TeV}} \right)^{3/4} \text{ TeV}$$

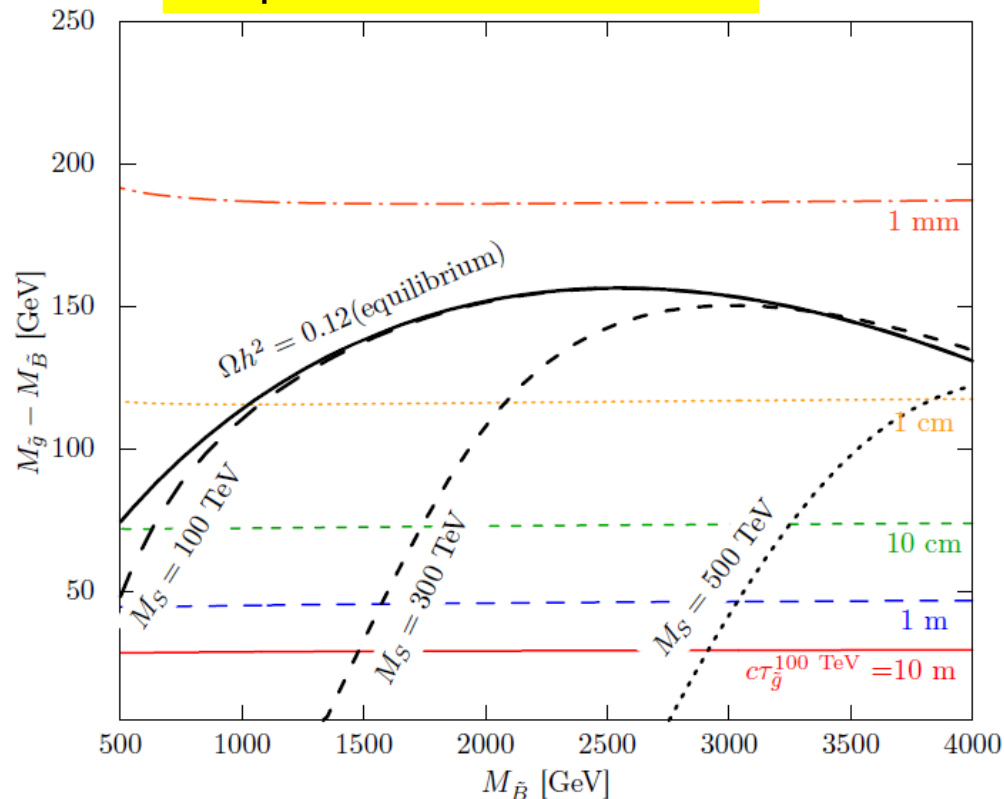
## Transition rate / Hubble rate





# Bino-Gluino Coannihilation 2

Required mass difference



E.g.,  
For 100 TeV  
sfermion,

Mass diff.  $\sim 100$   
GeV

Decay length  $\sim$  cm

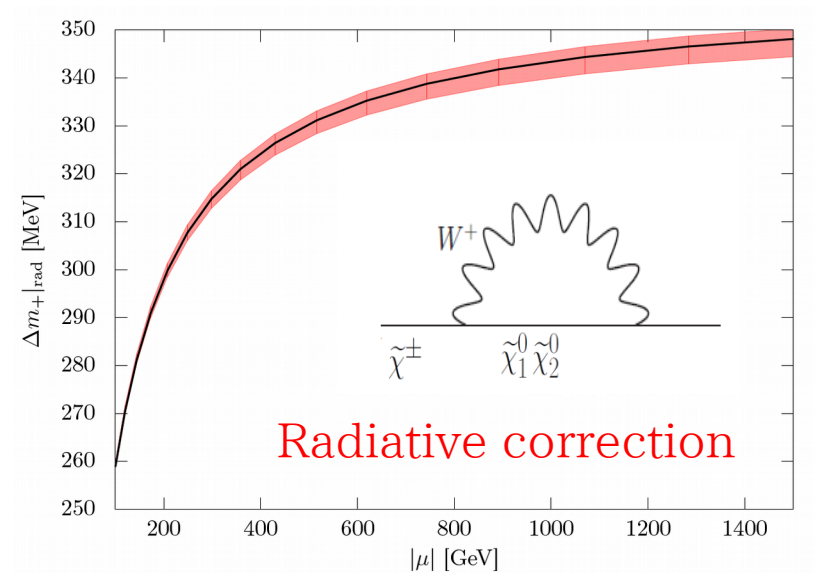
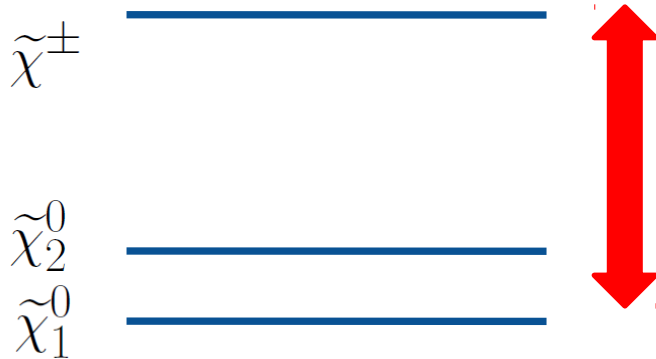
# EW interacting DM

SU(2)

U(1)	Y	SU(2)				
		n	1	2	3	4
	0		C	~5 cm	C	~ 2 cm
	1/2	C	~1 cm	C	~1 mm	C
	1	C	C	~1 mm	C	...
	3/2	C	C	C	~0.1 mm	...
	2	C	C	C	C	...
	...	C	C	C	C	...

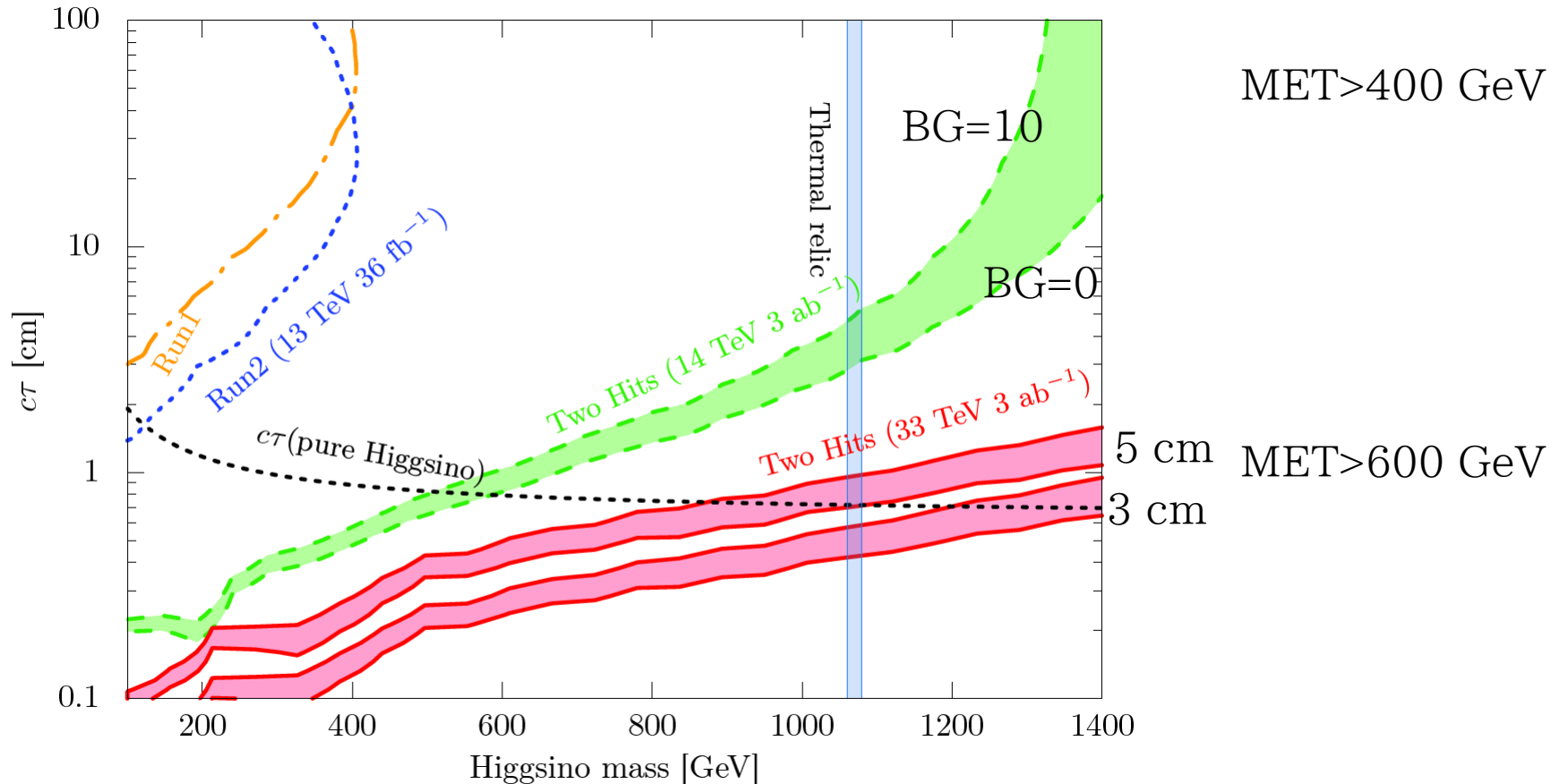
# Higgsino Spectrum

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



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

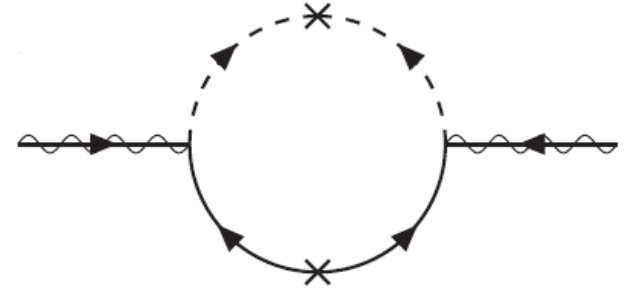
# Prospects for Higgsino



# Gaugino Mass

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

# Gaugino Mass



AMSB

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

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

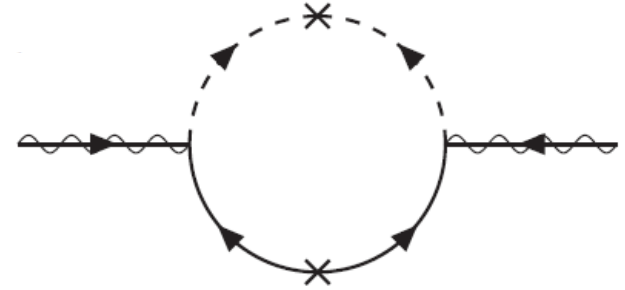
$$M_3 = \frac{\alpha_3}{4\pi} (-3m_{3/2})(1 + c_{\tilde{g}}).$$

Higgsino correction

Squark correction

+ High energy sector, such as Axion, also affects

# Gaugino Mass



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

AMSB

Higgsino correction

Squark correction

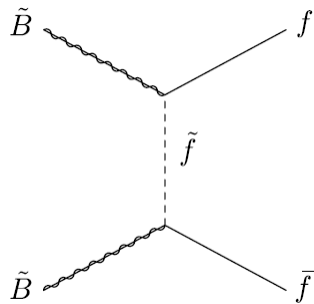
+ High energy sector, such as Axion, also affects



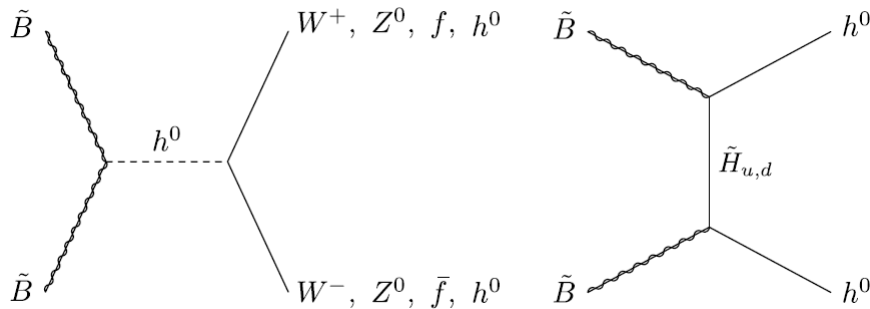
Free gaugino mass relation

# Bino DM 1

Bino interactions are **tiny**;  
 suppression by heavy higgsinos and sfermions



$$\Omega_{\tilde{B}}^{\text{sfermion}} h^2 \sim \mathcal{O}(10) \times \left( \frac{100 \text{ GeV}}{M_{\tilde{B}}} \right)^2 \left( \frac{M_s}{1 \text{ TeV}} \right)^4$$

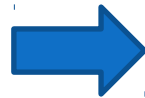


$$\Omega_{\tilde{B}}^{\text{Higgsino}} h^2 \sim \mathcal{O}(100) \times \left( \frac{\tan \beta}{10} \right)^2 \left( \frac{\mu}{1 \text{ TeV}} \right)^2$$



# Bino DM 2

Bino interactions are **tiny**;  
suppression by heavy higgsinos and sfermions



Too much abundance without **coannihilation**

Tiny constraints from CRs and direct detection.



Astrophysical probe is hard

**LHC search is most important!**