SUSY and Cosmology/Naturalness

Satoshi Shirai (Kavli IPMU)

1. SUSY after LHC

Higgs Mass

Mini-split SUSY

Dark Matter

2. Dark Matter Signatures in Mini-split

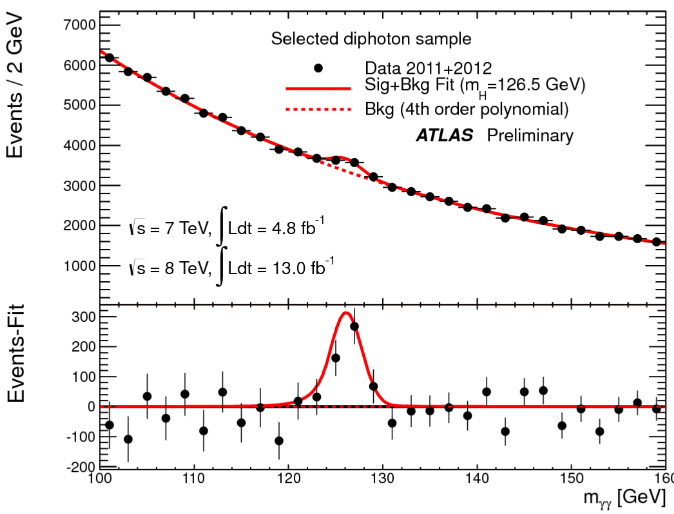
Wino

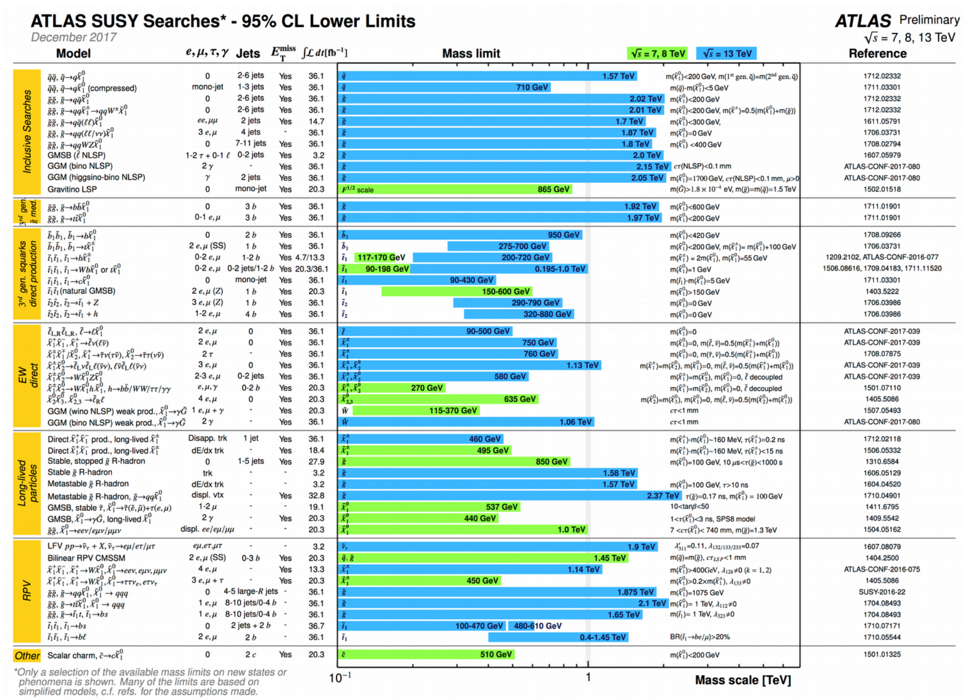
Gaugino coannihilation

Long lived particle signatures

3. Summary

Higgs and SUSY at LHC



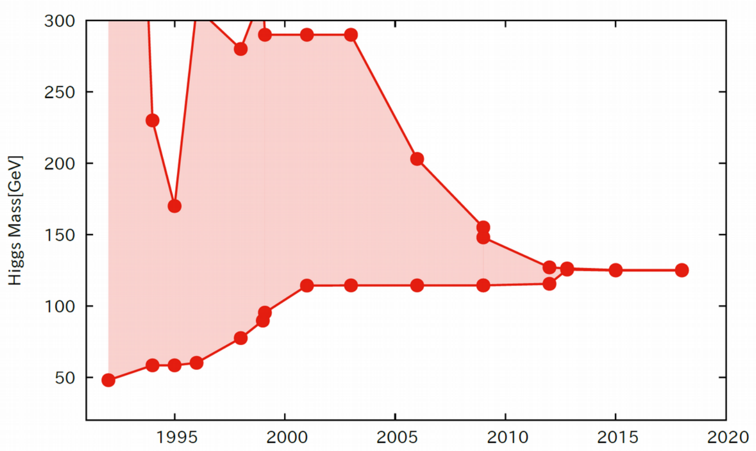


Higgs Discovered!

SUSY Constrained!

Cornering Higgs and SUSY

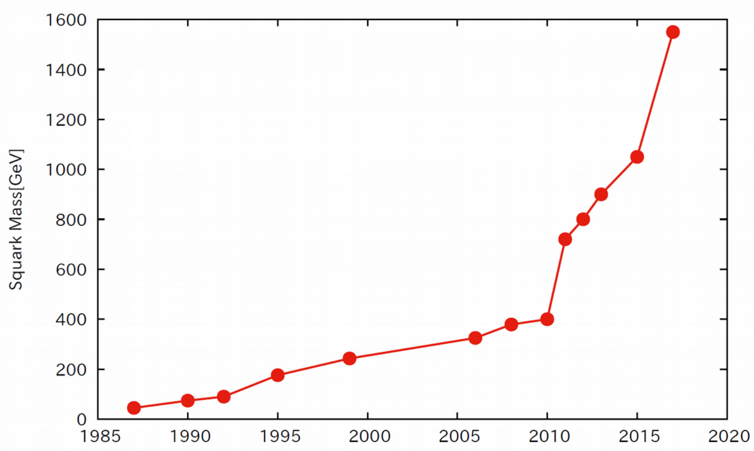
Higgs Mass Range



Year

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

Squark Mass Limit



Year

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

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~~ ⟷ 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

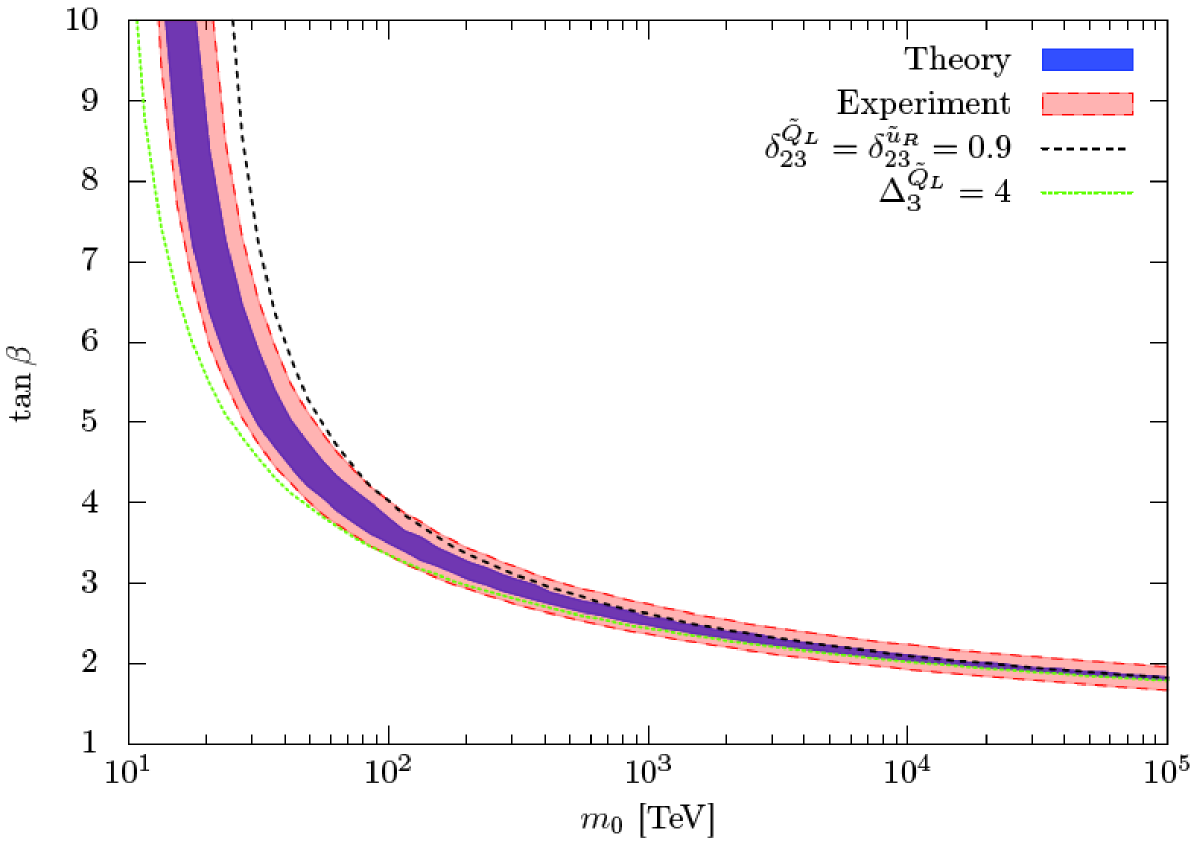
NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

Simple? ⟷ Natural?

Higgs Mass from Stop

125 GeV Higgs OK regions



Scalar Mass

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

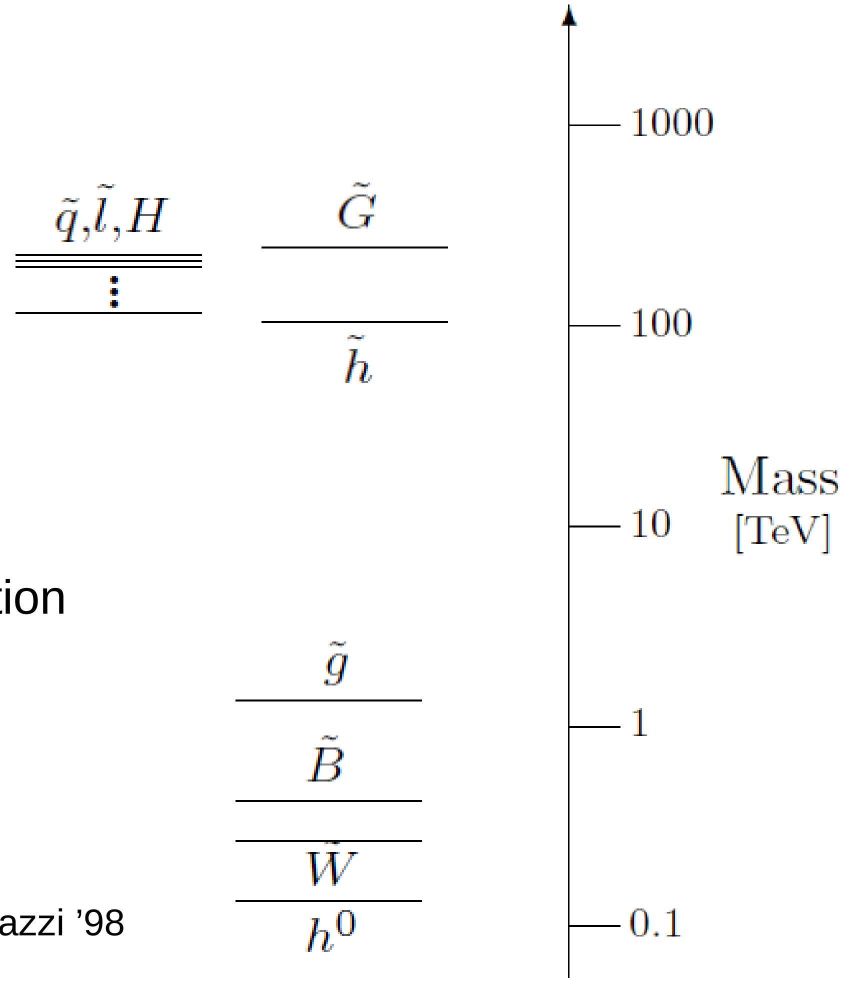
Tree level Gravity Mediation

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

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

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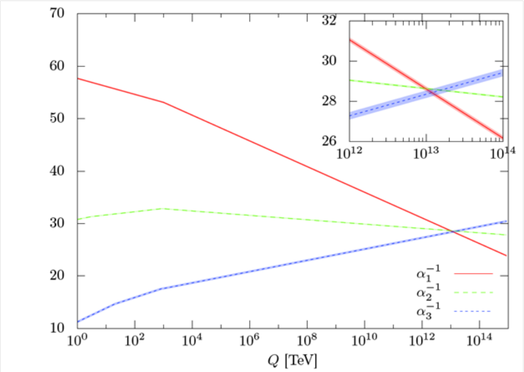
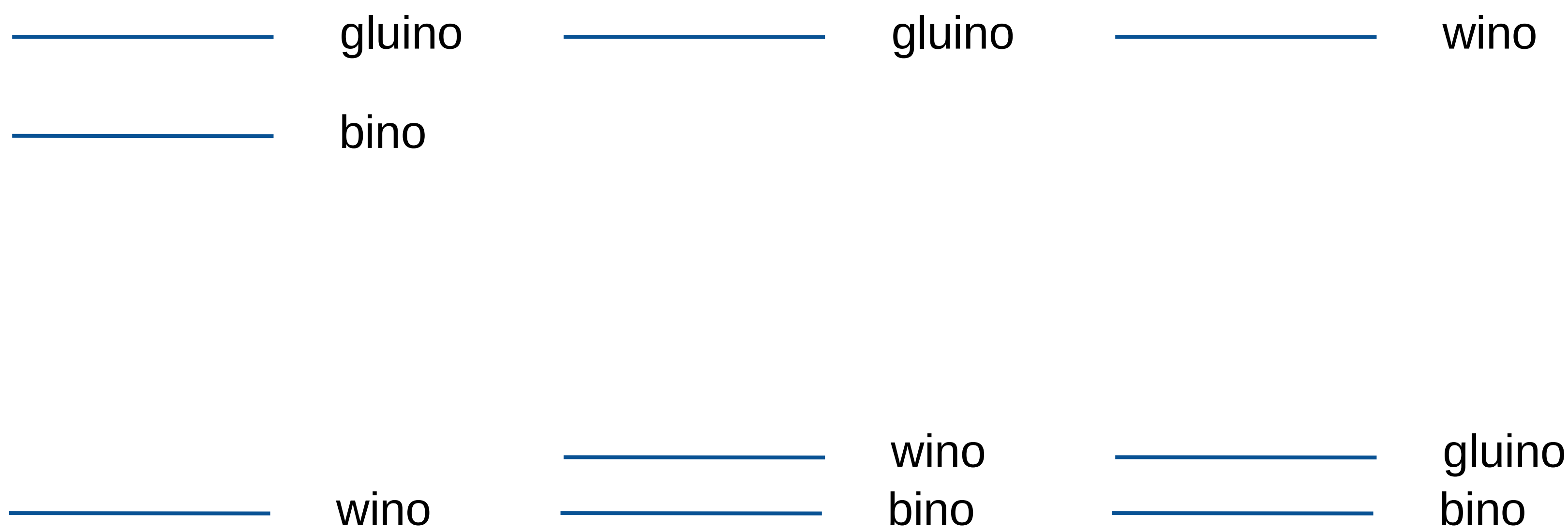


Possible demerit

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

Three Possibilities for DM



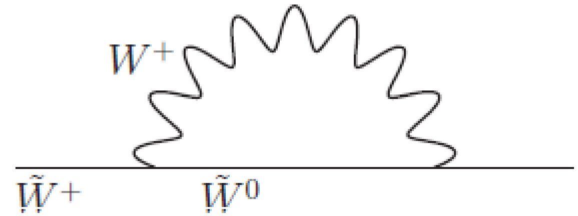
Wino DM

Bino-wino coannihilation

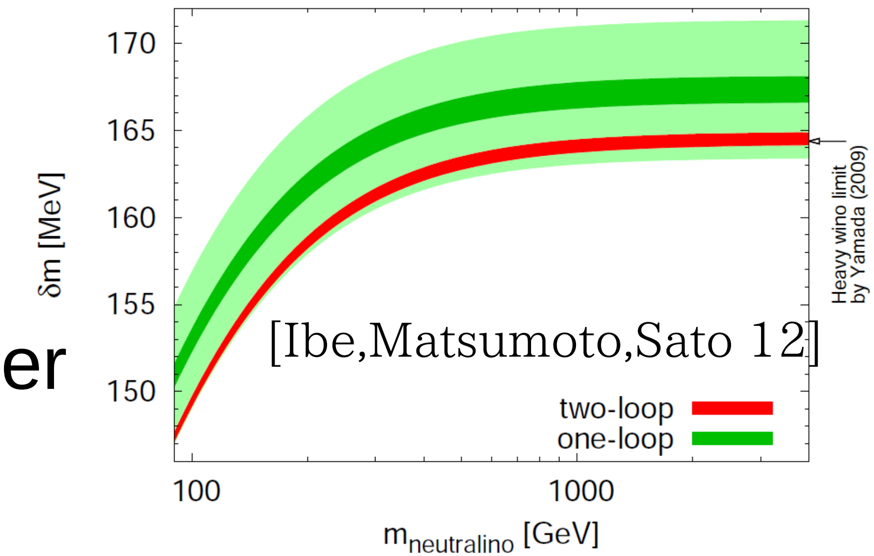
Bino-gluino coannihilation

Wino DM case

Wino Spectrum



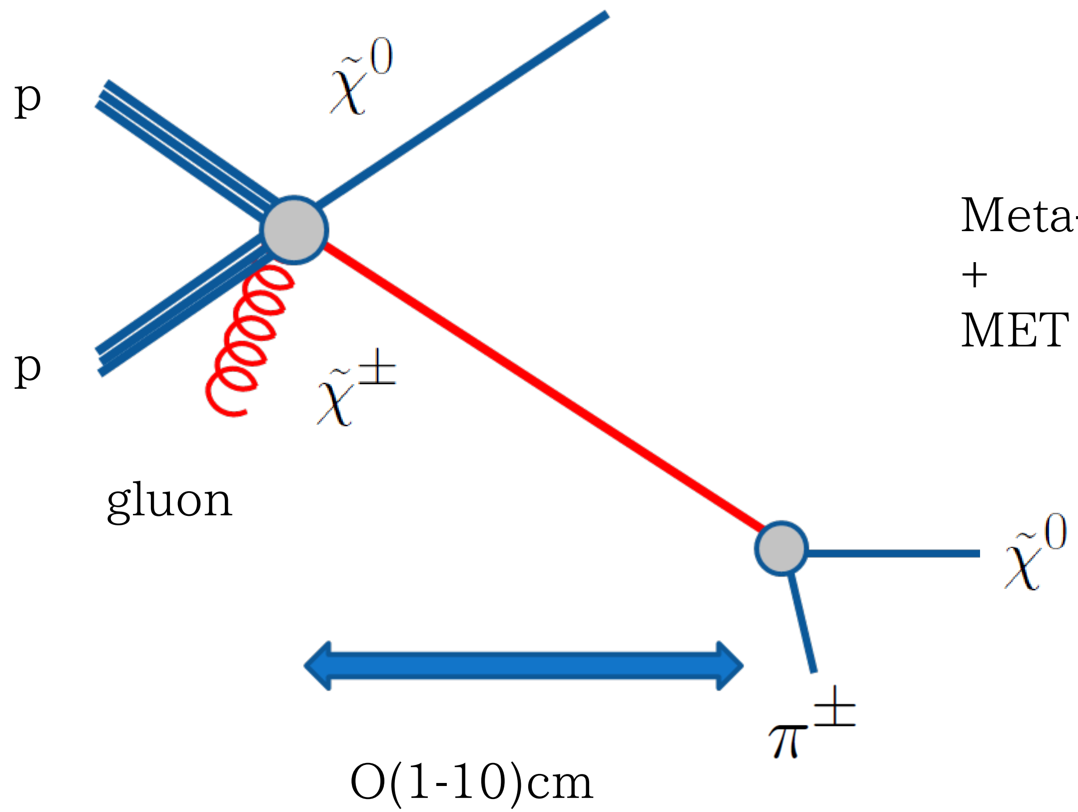
Radiative correction



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

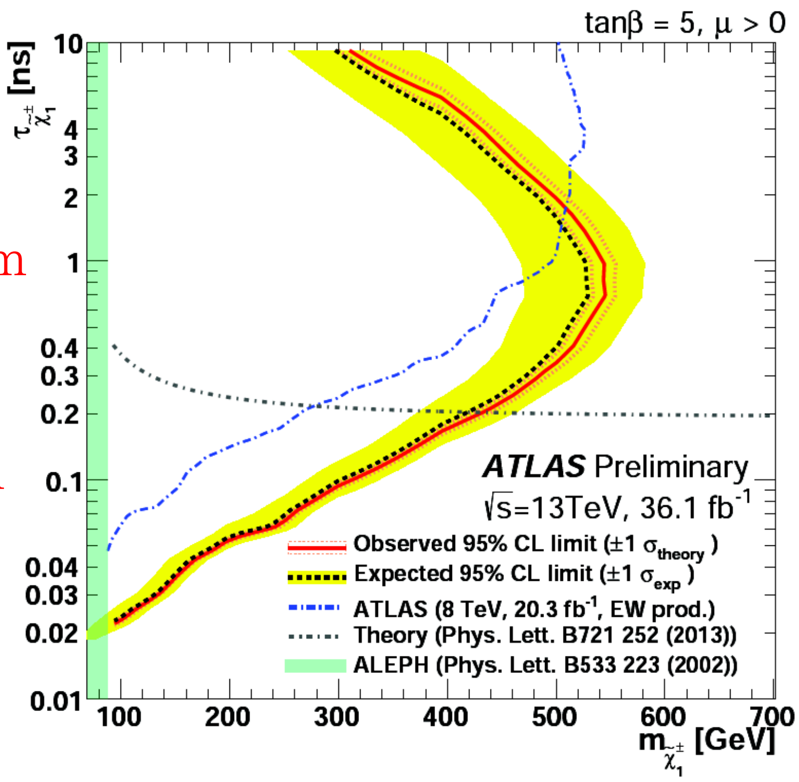


Meta-stable track
+
MET

Current Constraint(wino)

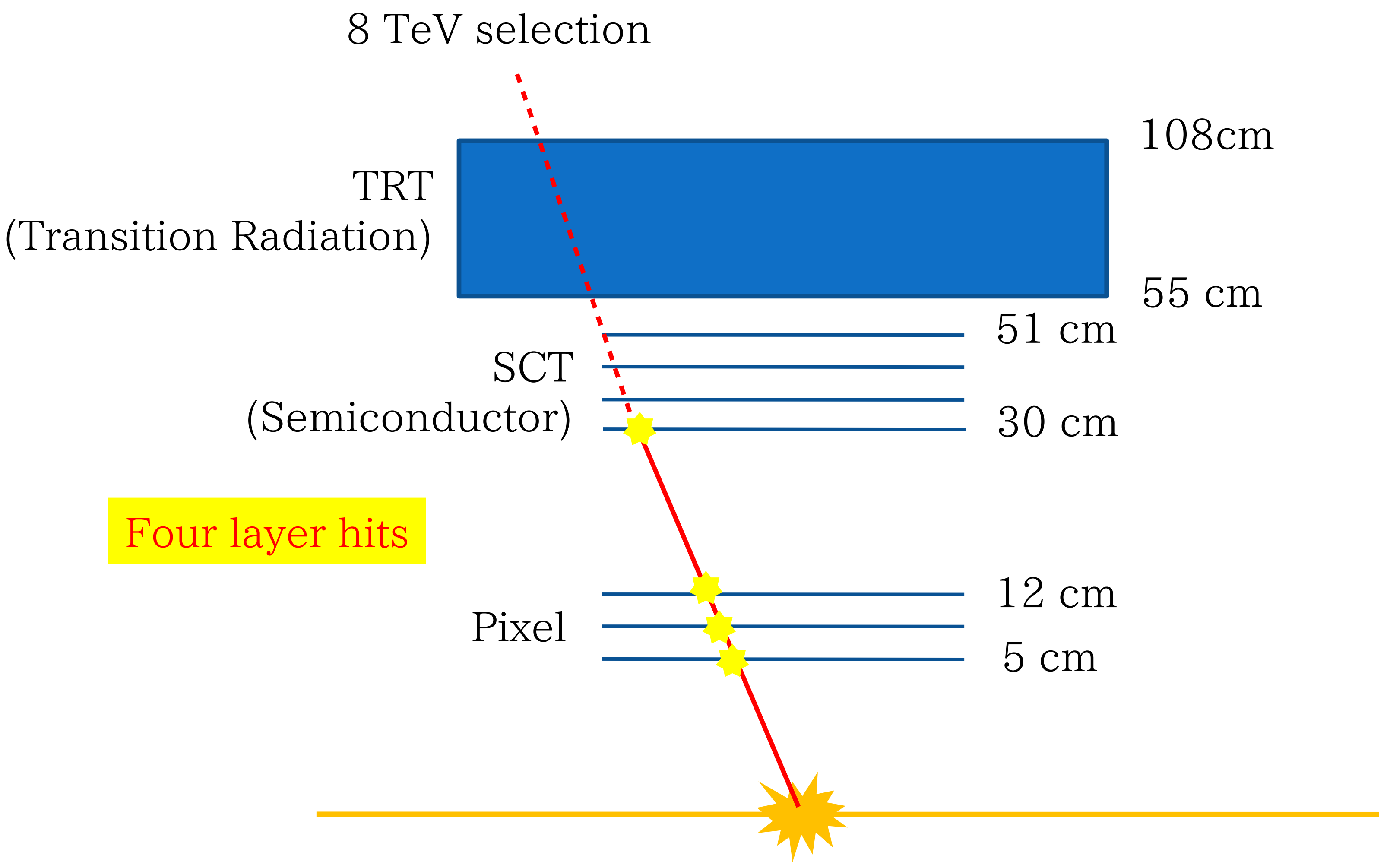
30 cm

3 cm

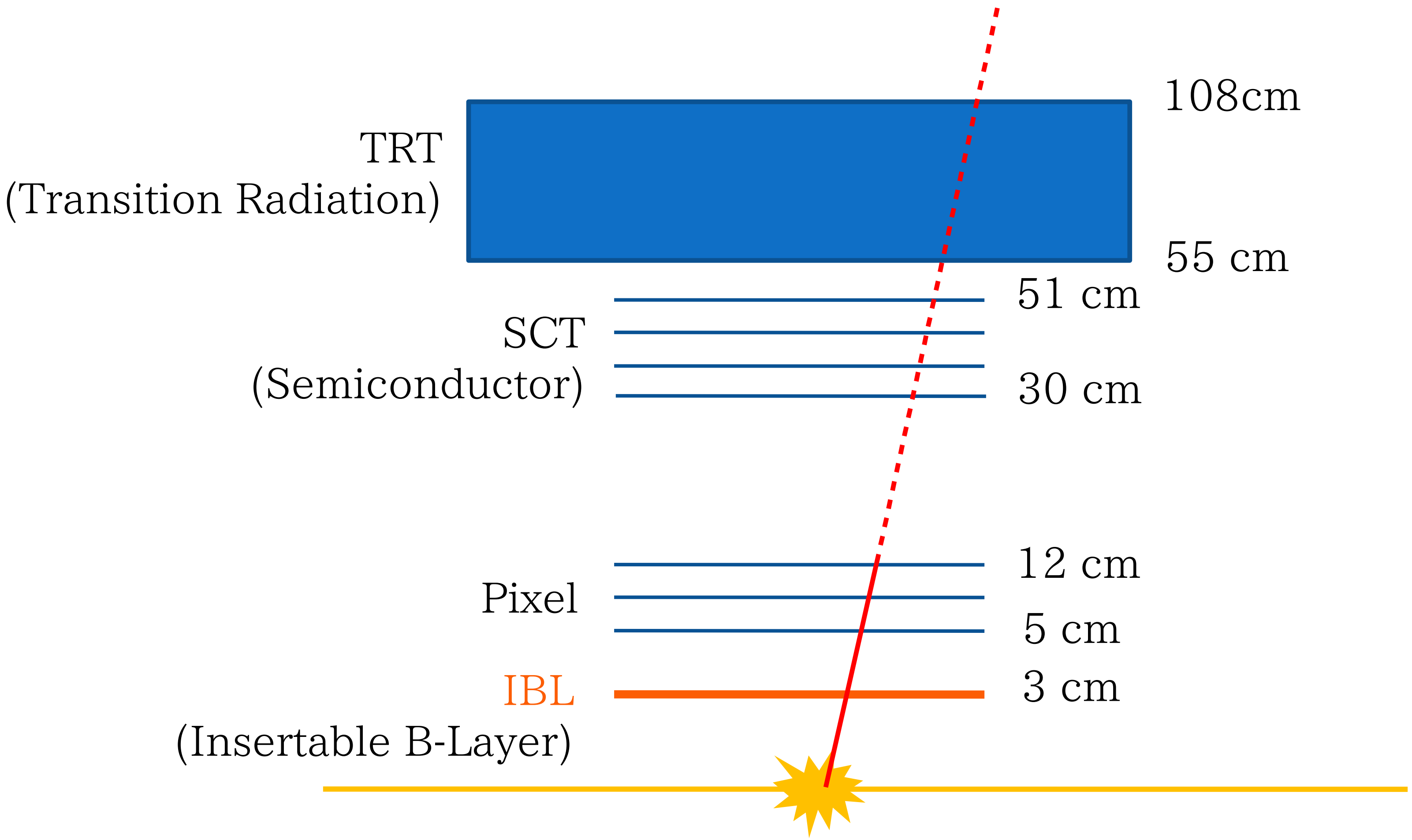


MET + disappearing track

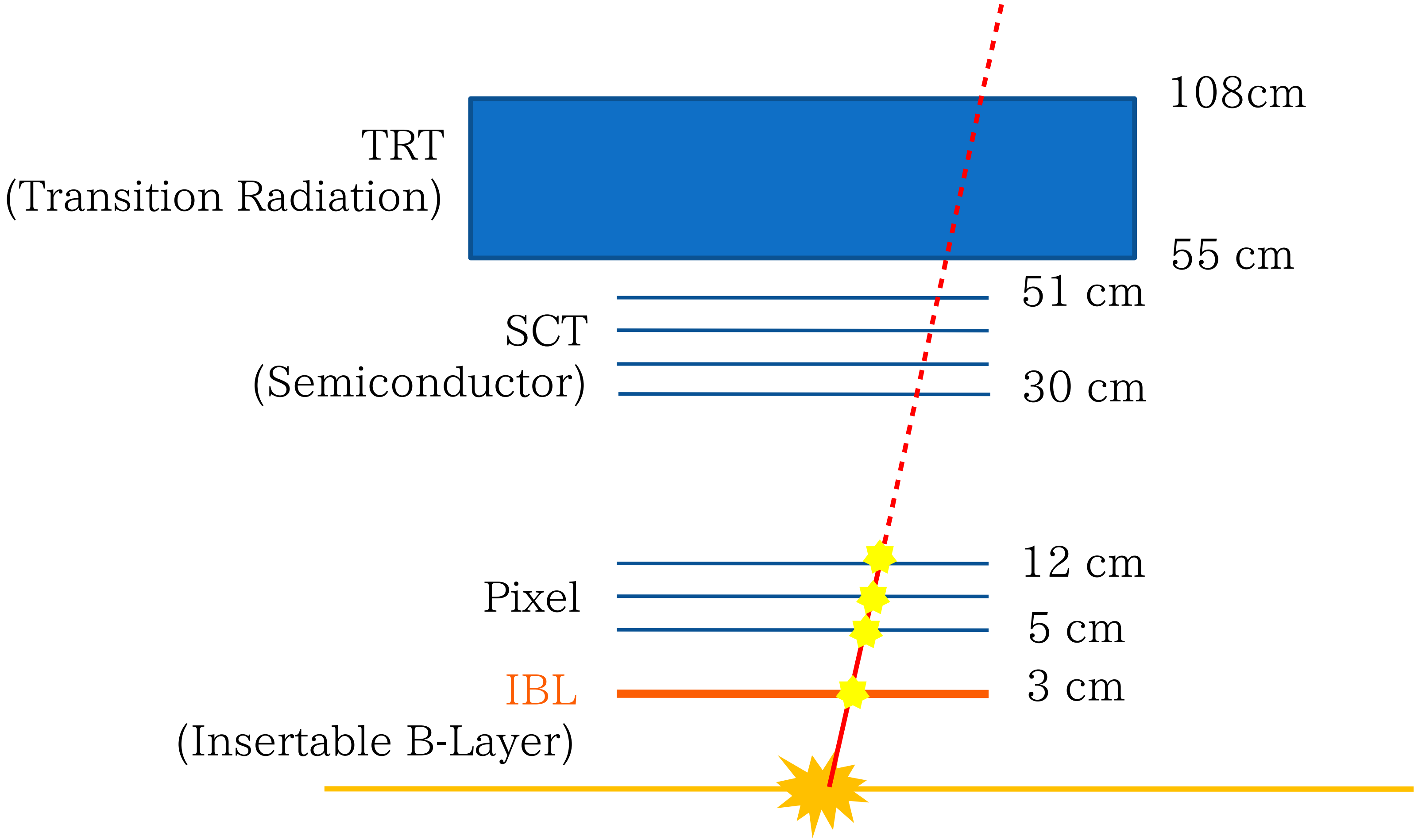
Tracker for Run1



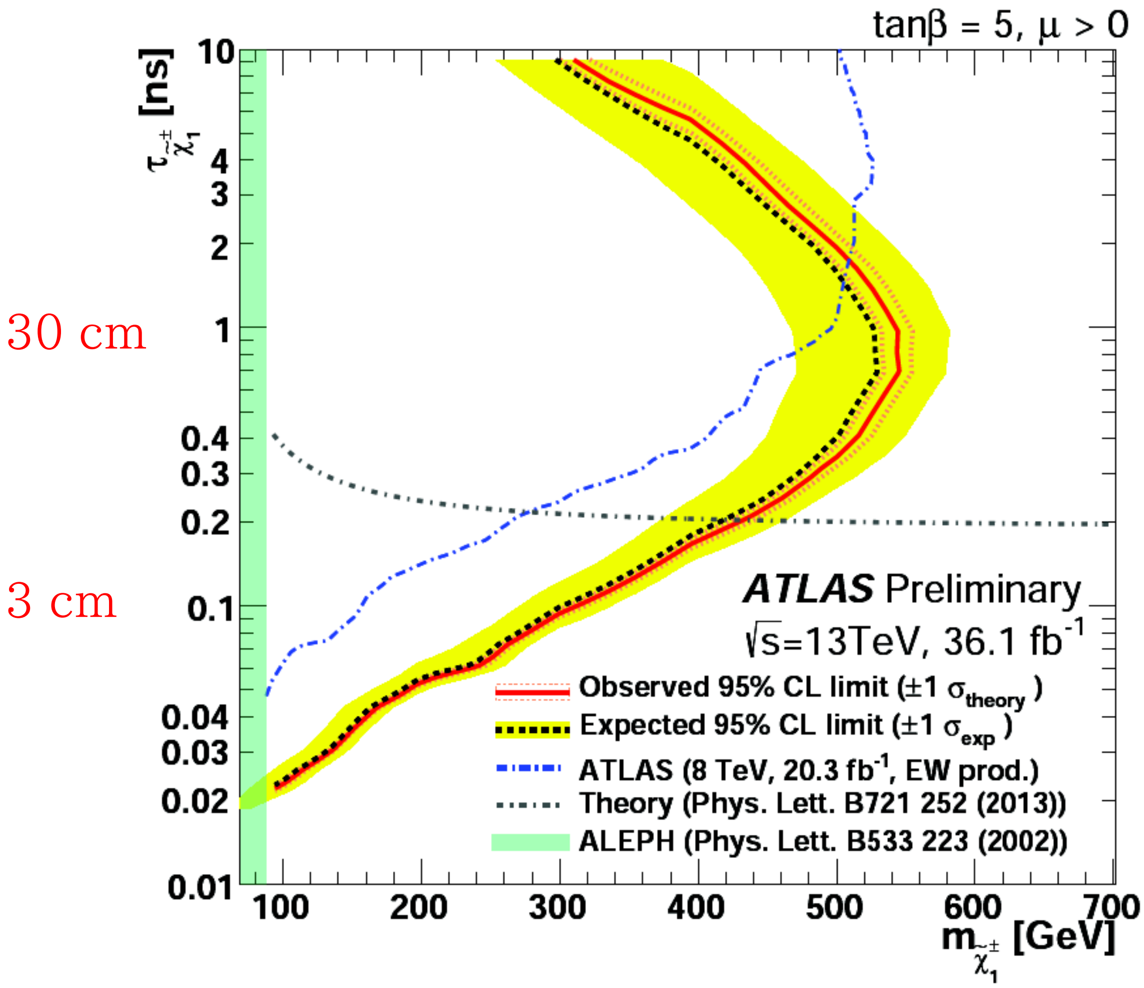
Tracker for Run2



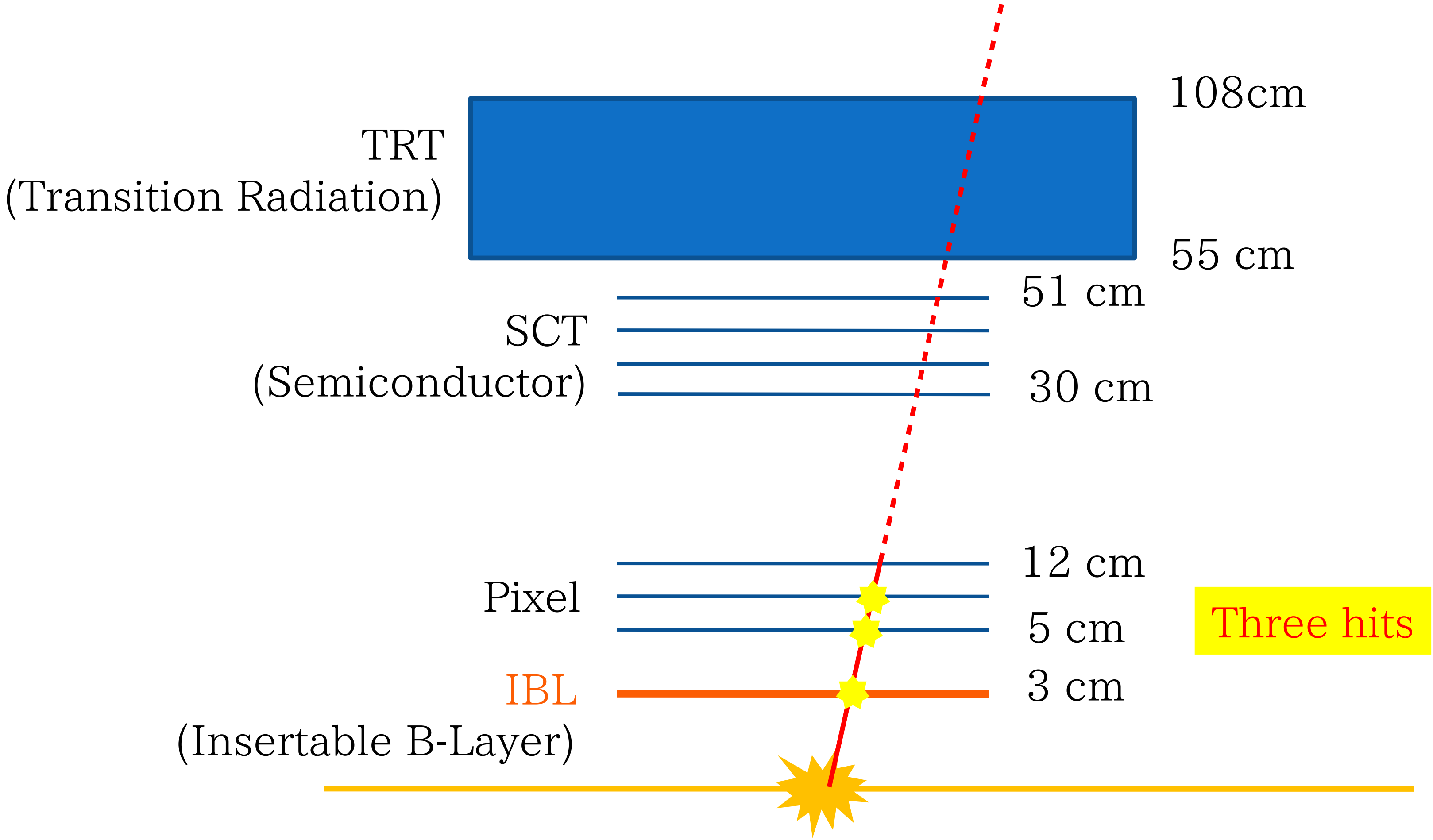
Tracker for Run2



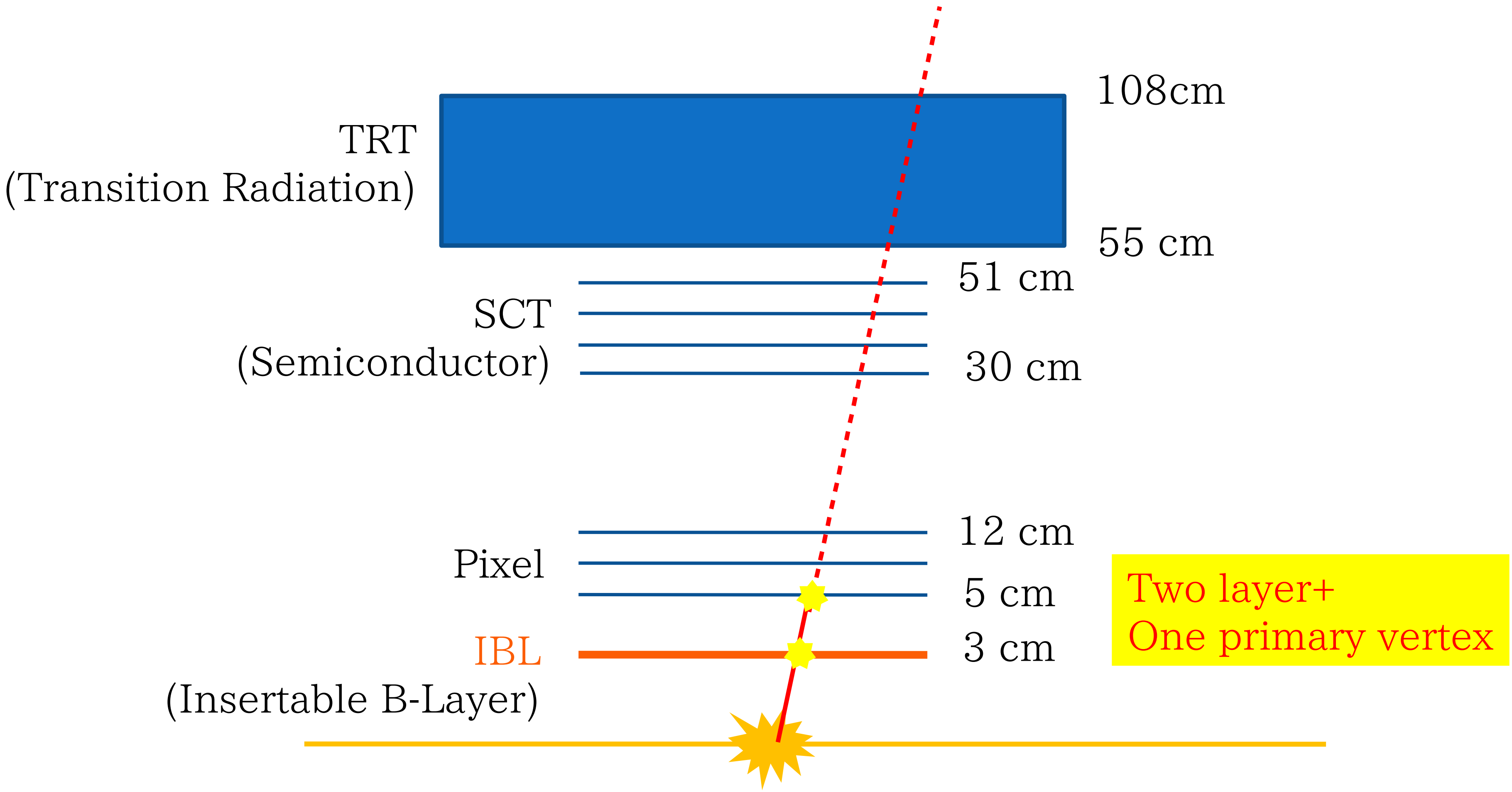
Current Constraint(wino)



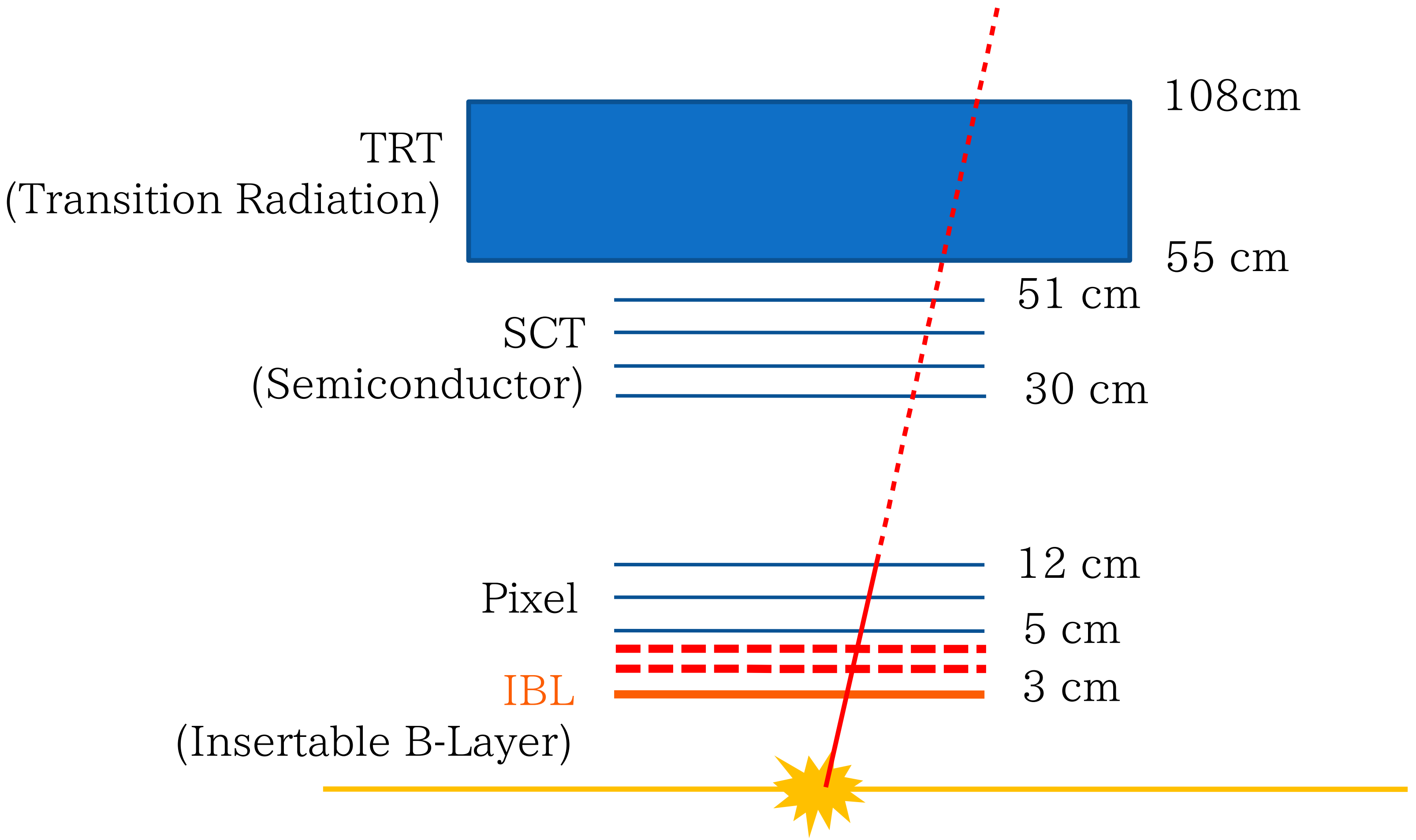
Tracking shorter



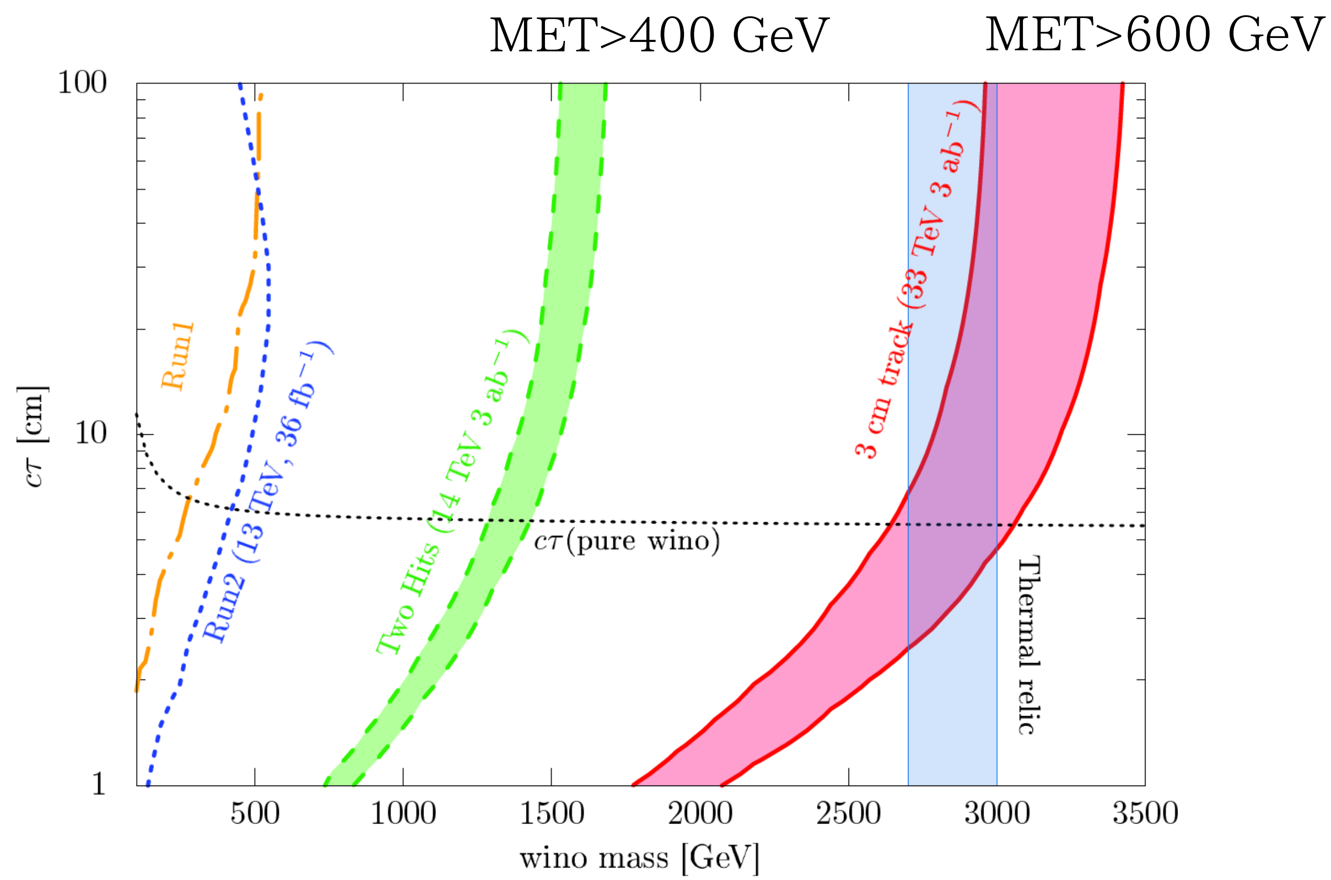
Tracking shorter



Tracker for Run???

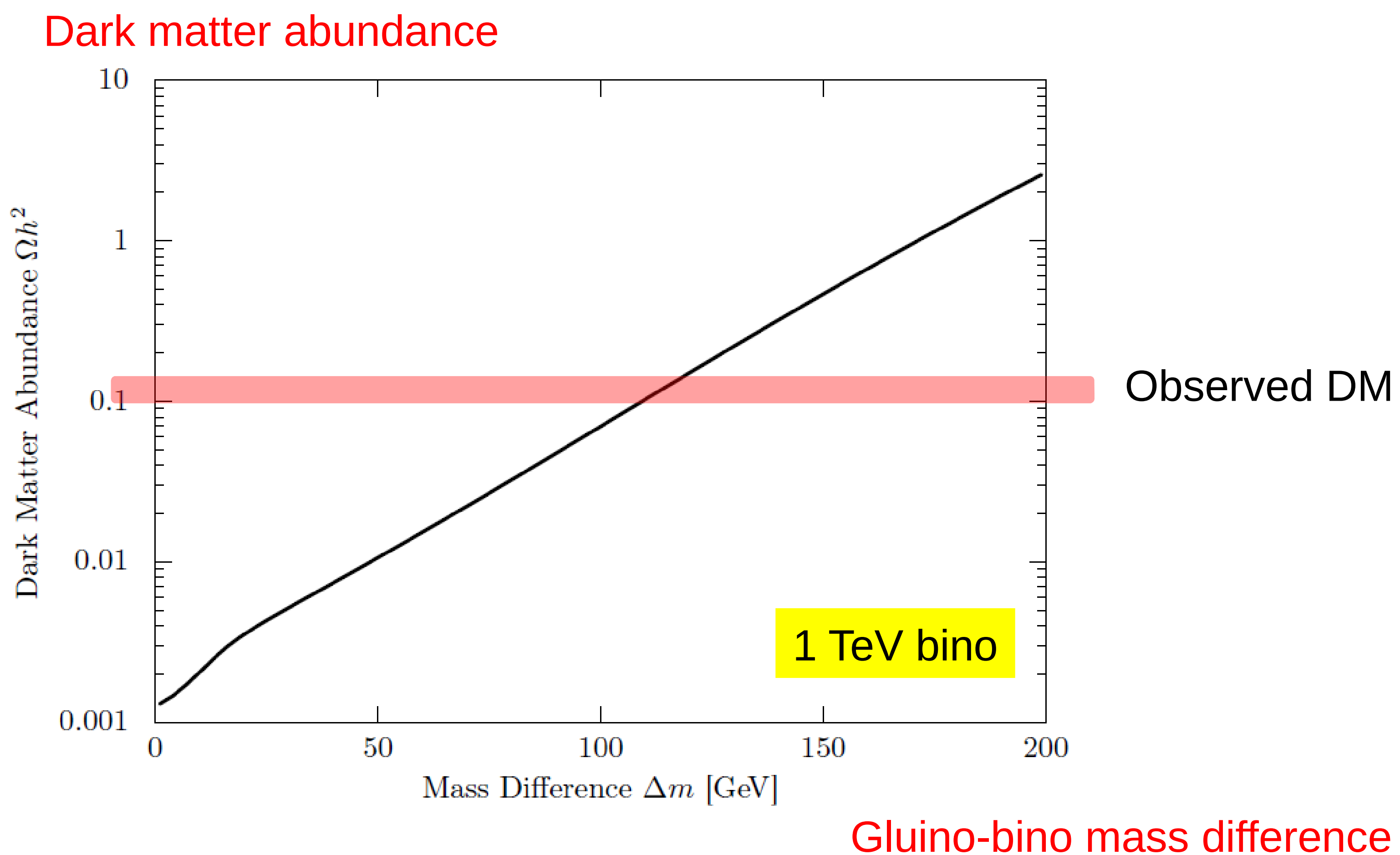


Prospects for Wino

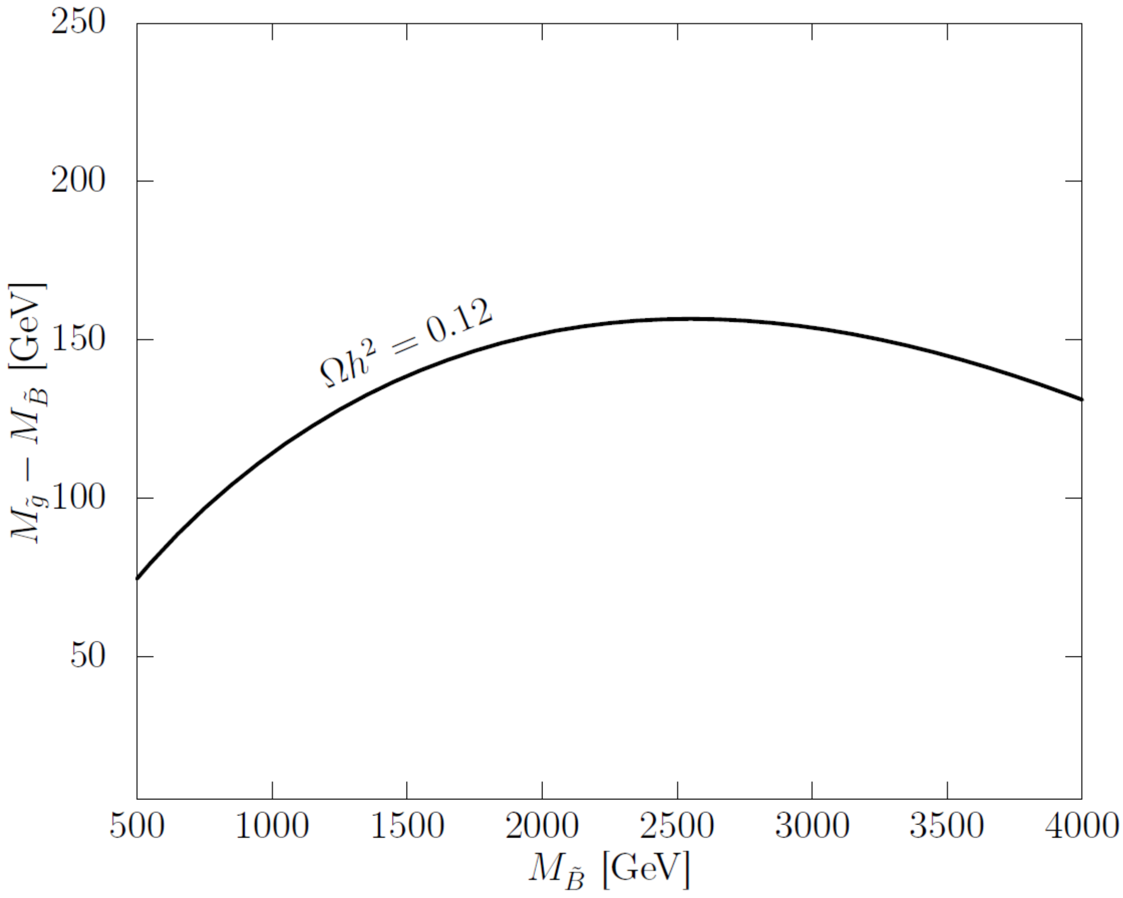


Bino-Gluino Coannihilation

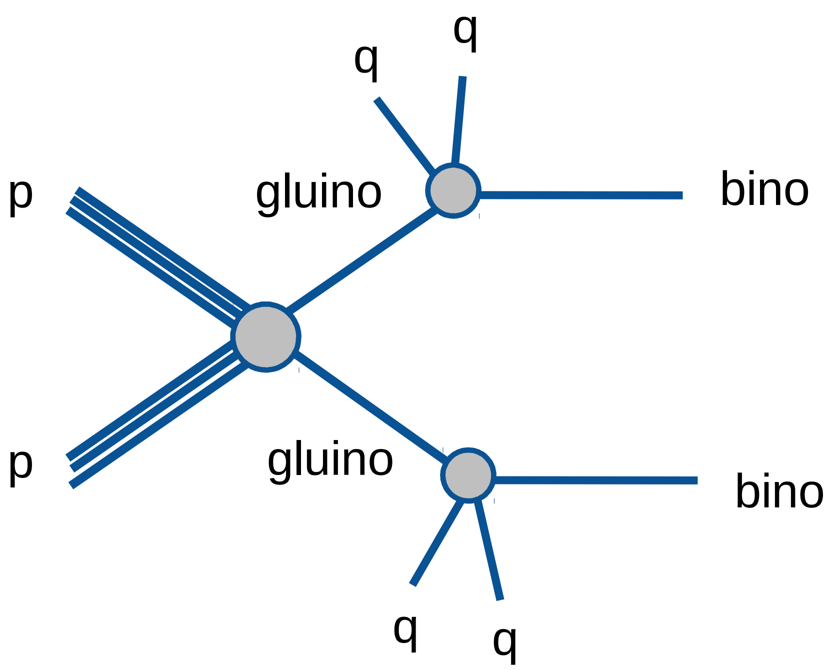
Bino-Gluino Coannihilation 1



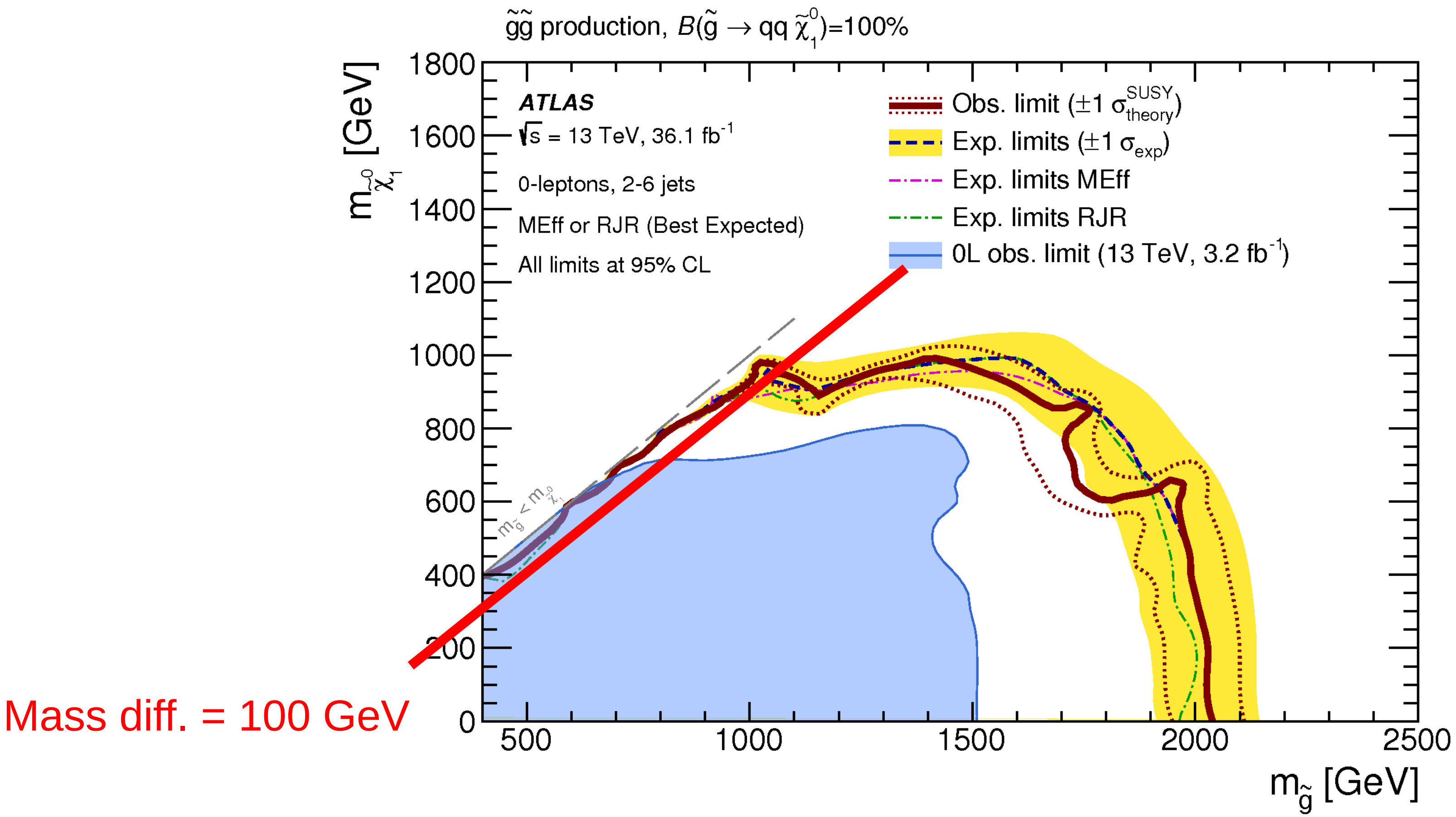
Gluino Coannihilation



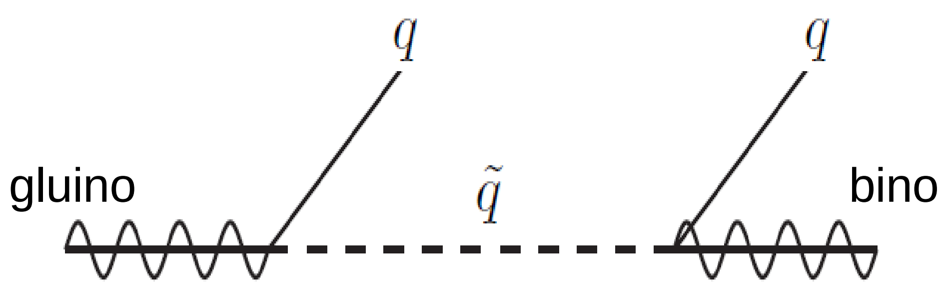
LHC Signals



Prompt Decay Case



Bino-Gluino Interaction

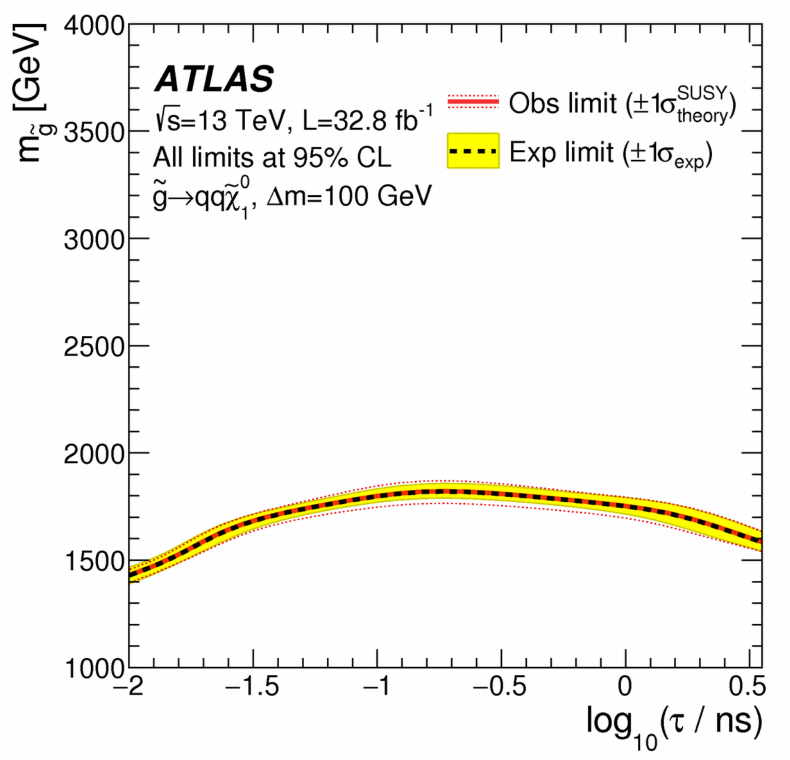


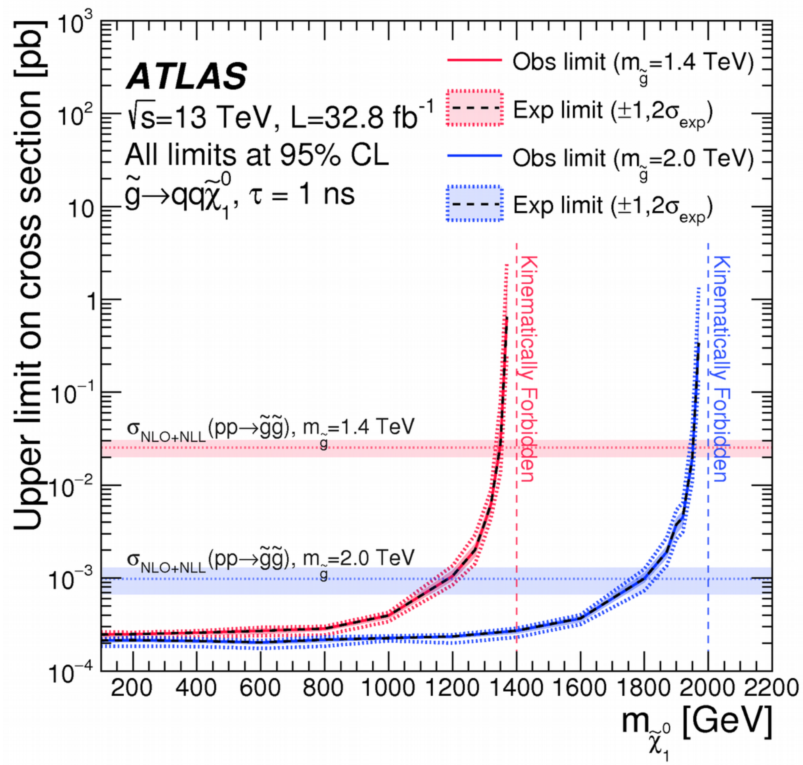
Bino-gluino interaction is suppressed by sfermion mass

⇒ Long-lived gluino

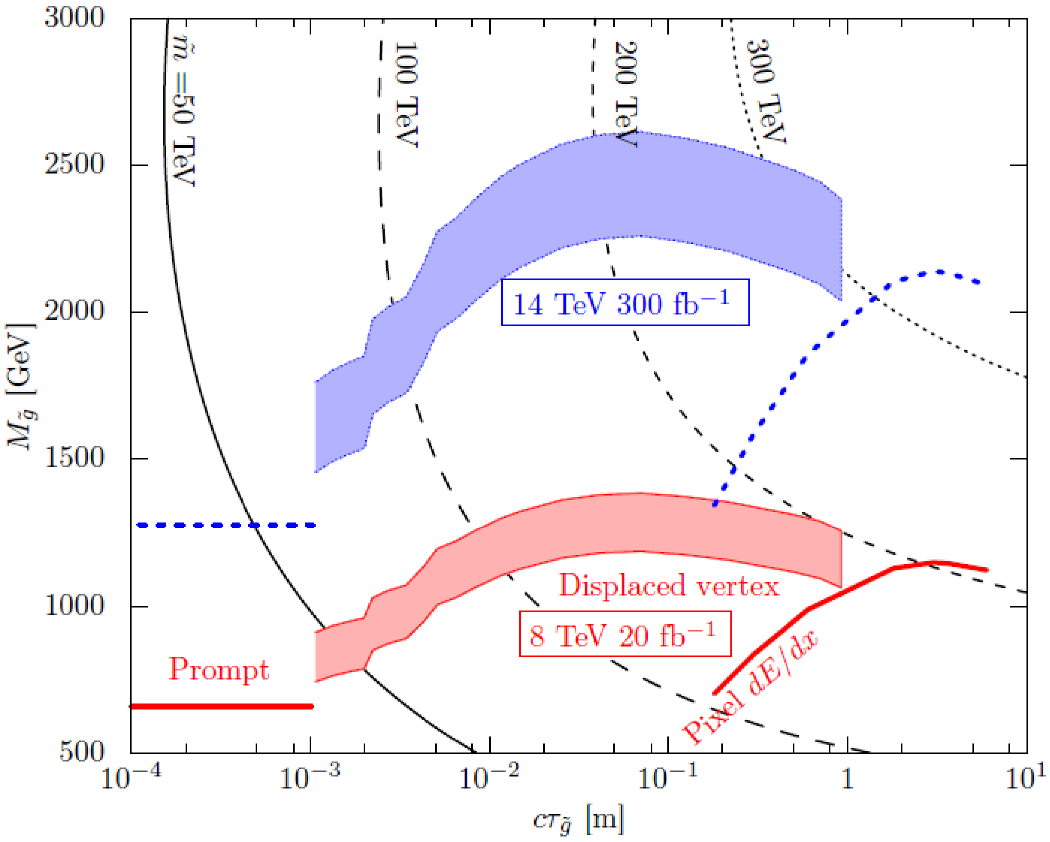
$$c\tau_{\tilde{g}} = O(1) \left(\frac{\Delta m}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{M_s}{100\ \mathrm{TeV}}\right)^{4}\ \mathrm{cm}$$

Bino-Gluino Interaction





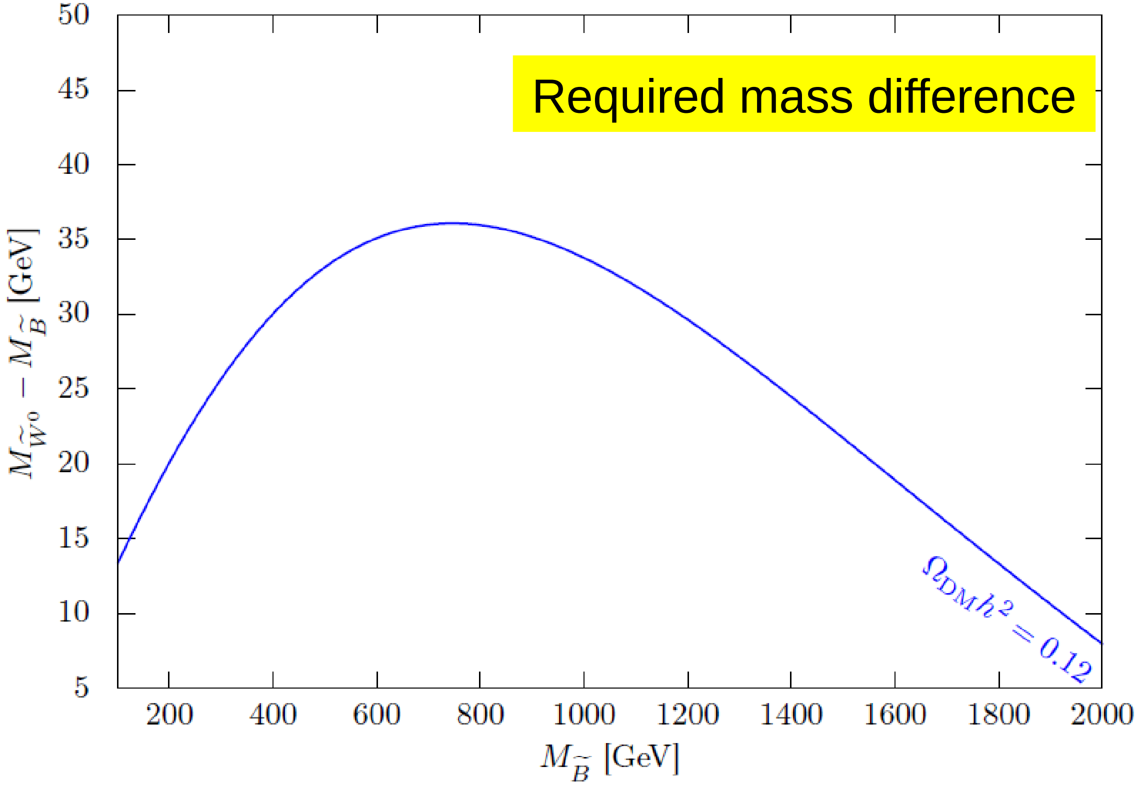
Prospects



3000
2500
2000
1500
1000
500
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10^{1}
$M_{\tilde{g}}$ [GeV]
$c\tau_{\tilde{g}}$ [m]
$\tilde{m}$ =50 TeV
100 TeV
200 TeV
300 TeV
14 TeV 300 fb^{-1}
Displaced vertex
8 TeV 20 fb^{-1}
Prompt
Pixel dE/dx

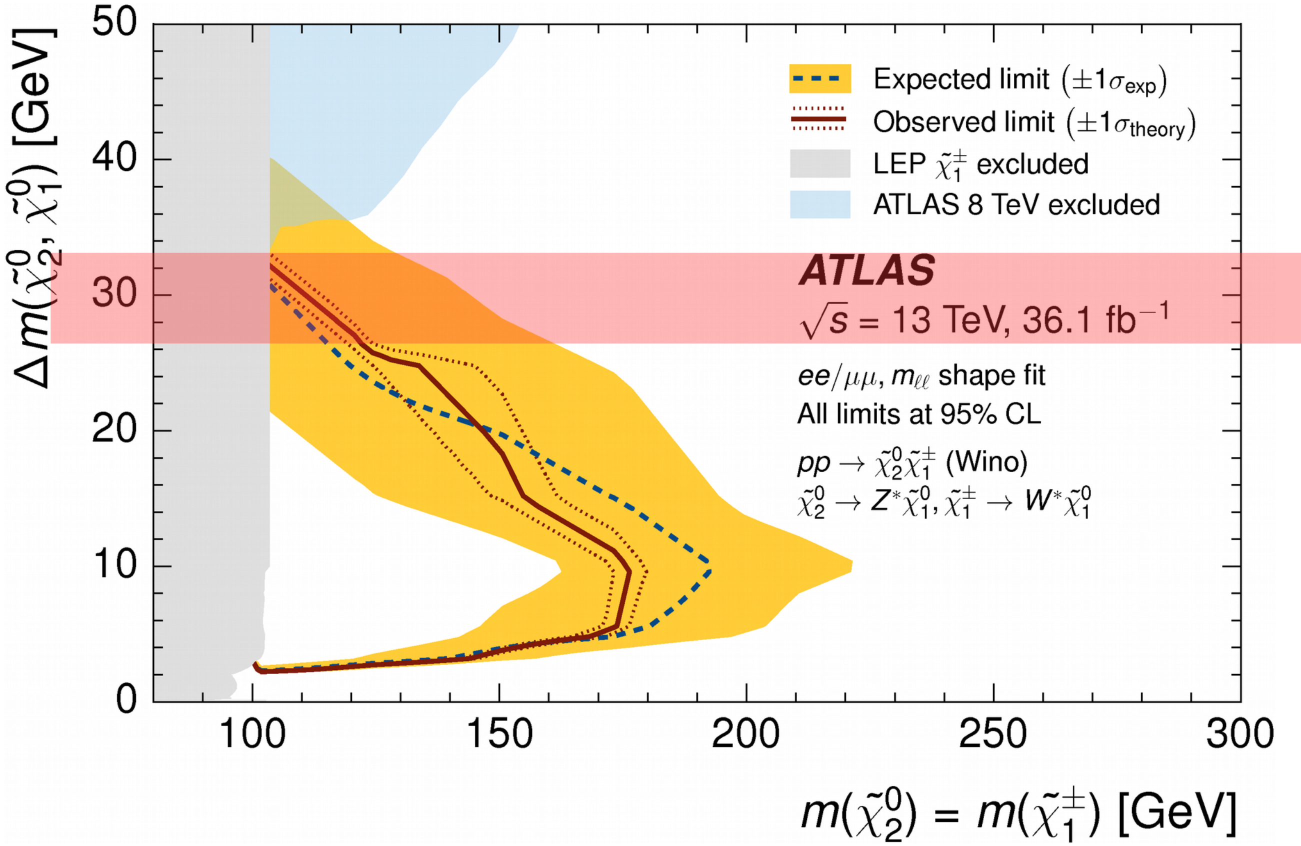
Bino-Wino Coannihilation

Bino-Wino Coannihilation



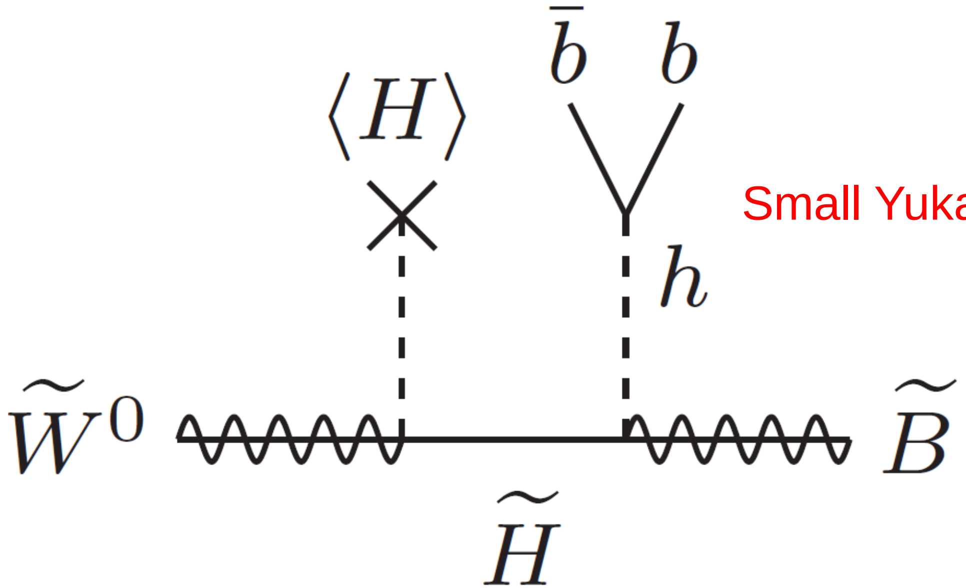
A few tens of GeV mass diff.

LHC Signals



Mass diff. 30 GeV

Wino Decay (tree)

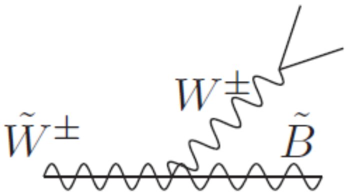


Small Yukawa

Suppressed by Higgsino mass

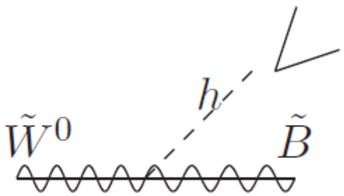
Long-lived neutral wino

Wino Decay

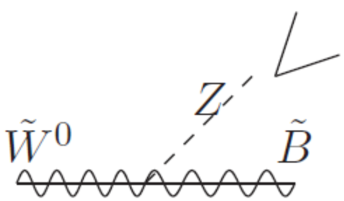


$\propto \mu^{-1}$

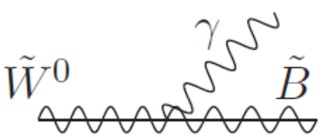
Prompt charged Wino decay



$\propto \mu^{-1}$



$\propto \mu^{-2}$

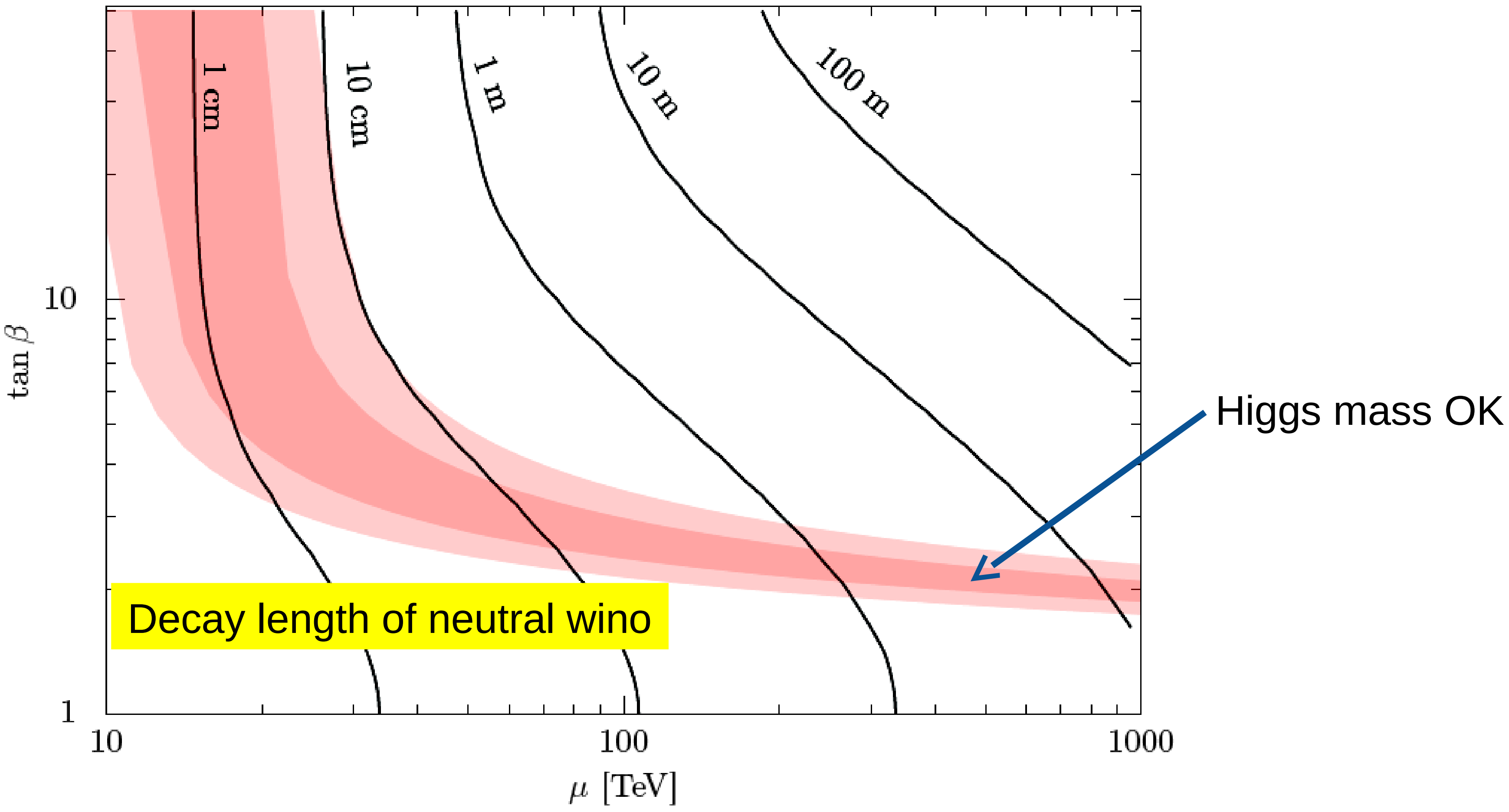


$\propto \frac{\alpha}{4\pi}\mu^{-2}, \left(\frac{\alpha}{4\pi}\right)^2 \mu^{-1}$

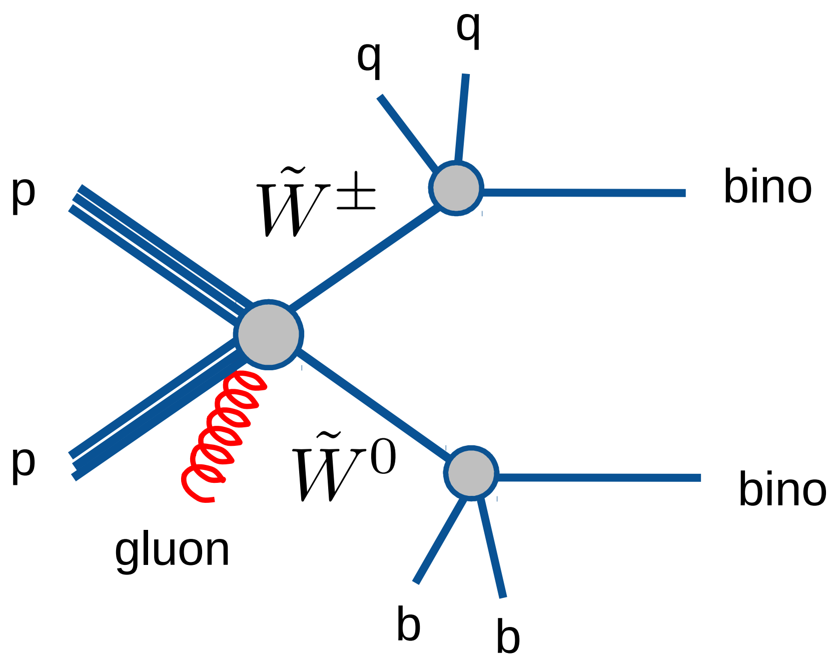
Displaced neutral Wino decay

Wino Decay

Bino = 400 GeV
Wino = 430 GeV

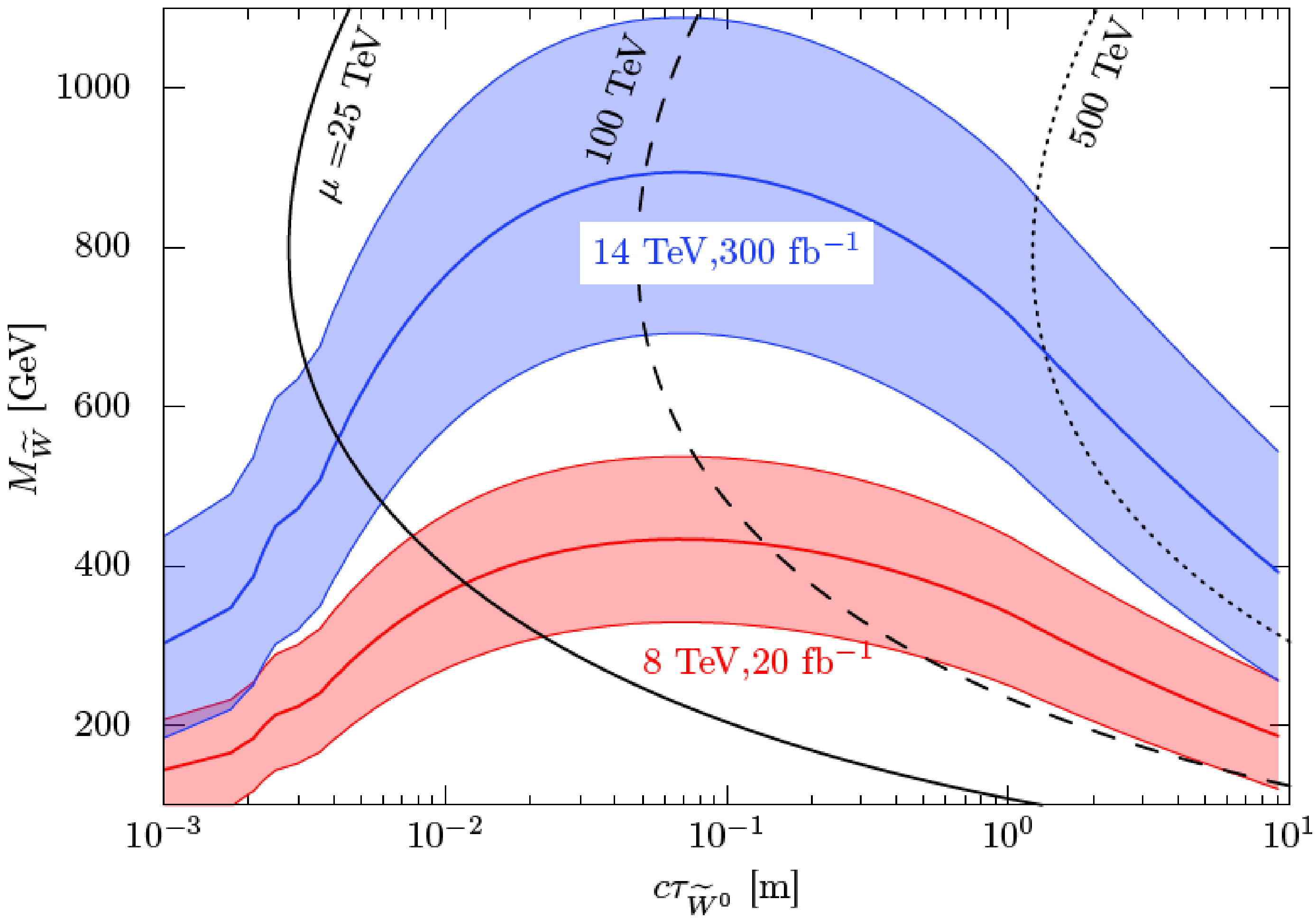


LHC Signals



Low mass ~ 10 GeV DV
+
MET

LHC Signals



μ =25 TeV
100 TeV
500 TeV
14 TeV,300 fb^{-1}
8 TeV,20 fb^{-1}
1000
800
600
400
200
$M_{\widetilde{W}}$ [GeV]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$c\tau_{\widetilde{W}^0}$ [m]

Summary

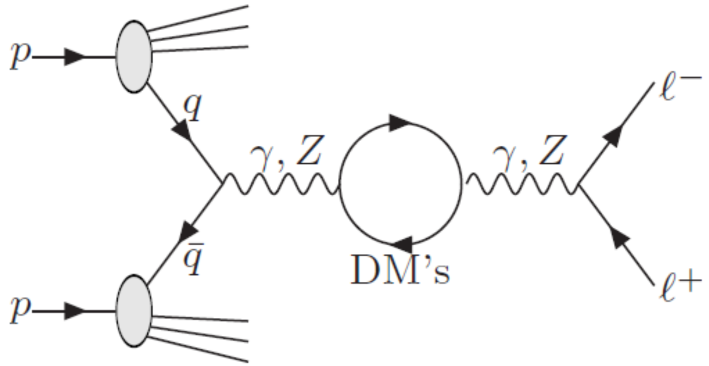
- Mini-split is simplest SUSY model with 125 GeV Higgs

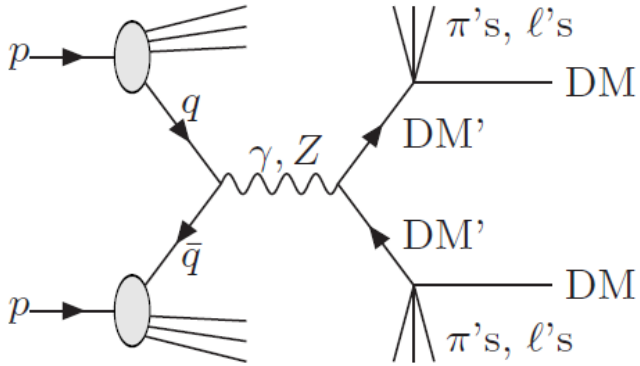
- DM in mini-split likely provide meta-stable particles
  - Wino DM: disappering track
  - Gluino-bino DM: long-lived R-hadron
  - Wino-bino DM: long-lived neutral wino

- Improvement of LLP detection

Indirect Search @LHC

DM Search





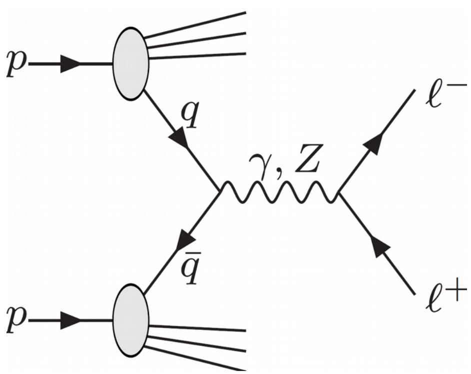
Indirect Search from SM precision

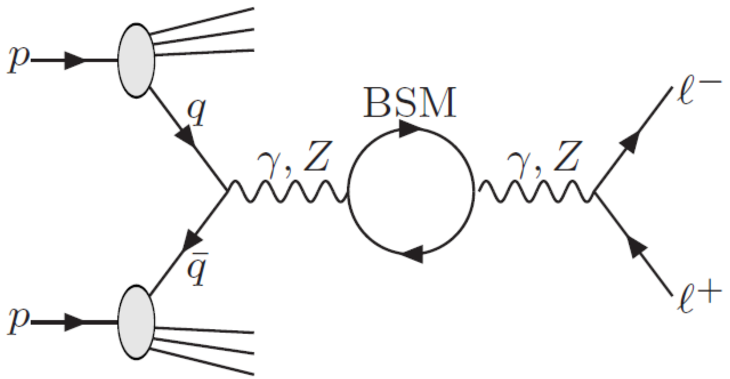
Exotic tracks:

- Disappearing track
- Displaced soft track

[Matsumoto, SS, Takeuchi, 1711.05449]

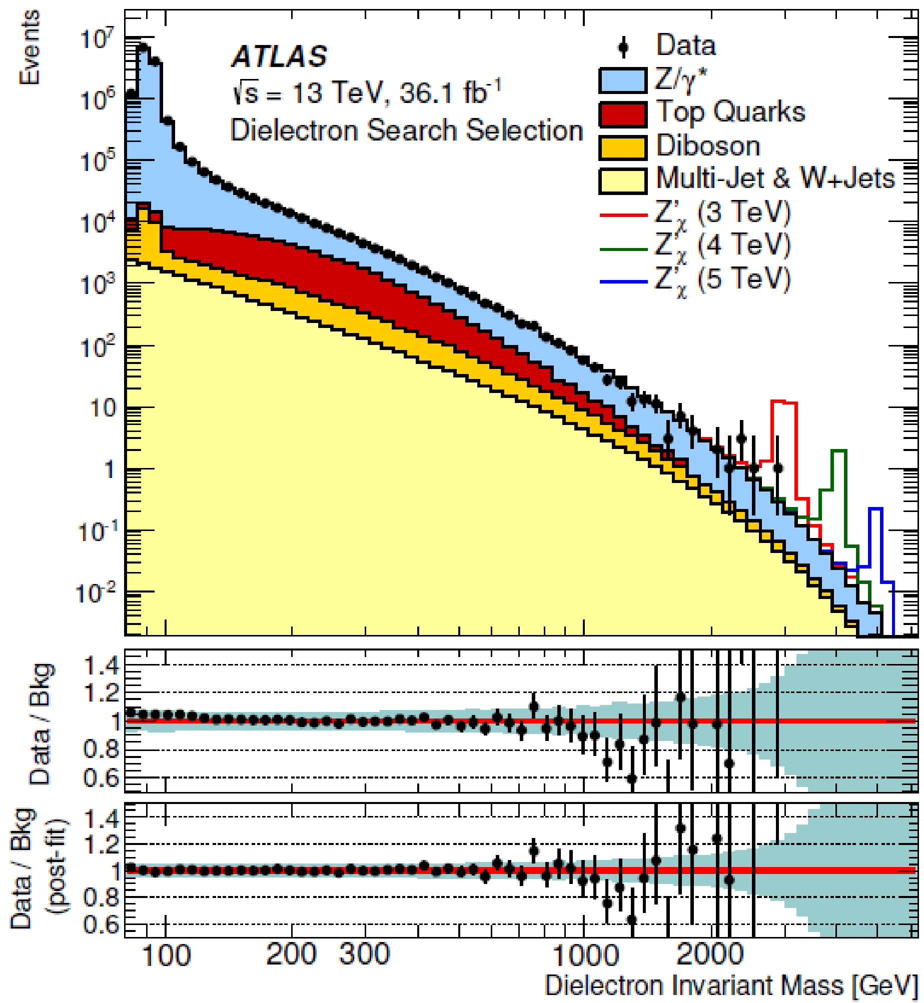
Indirect Probe at LHC





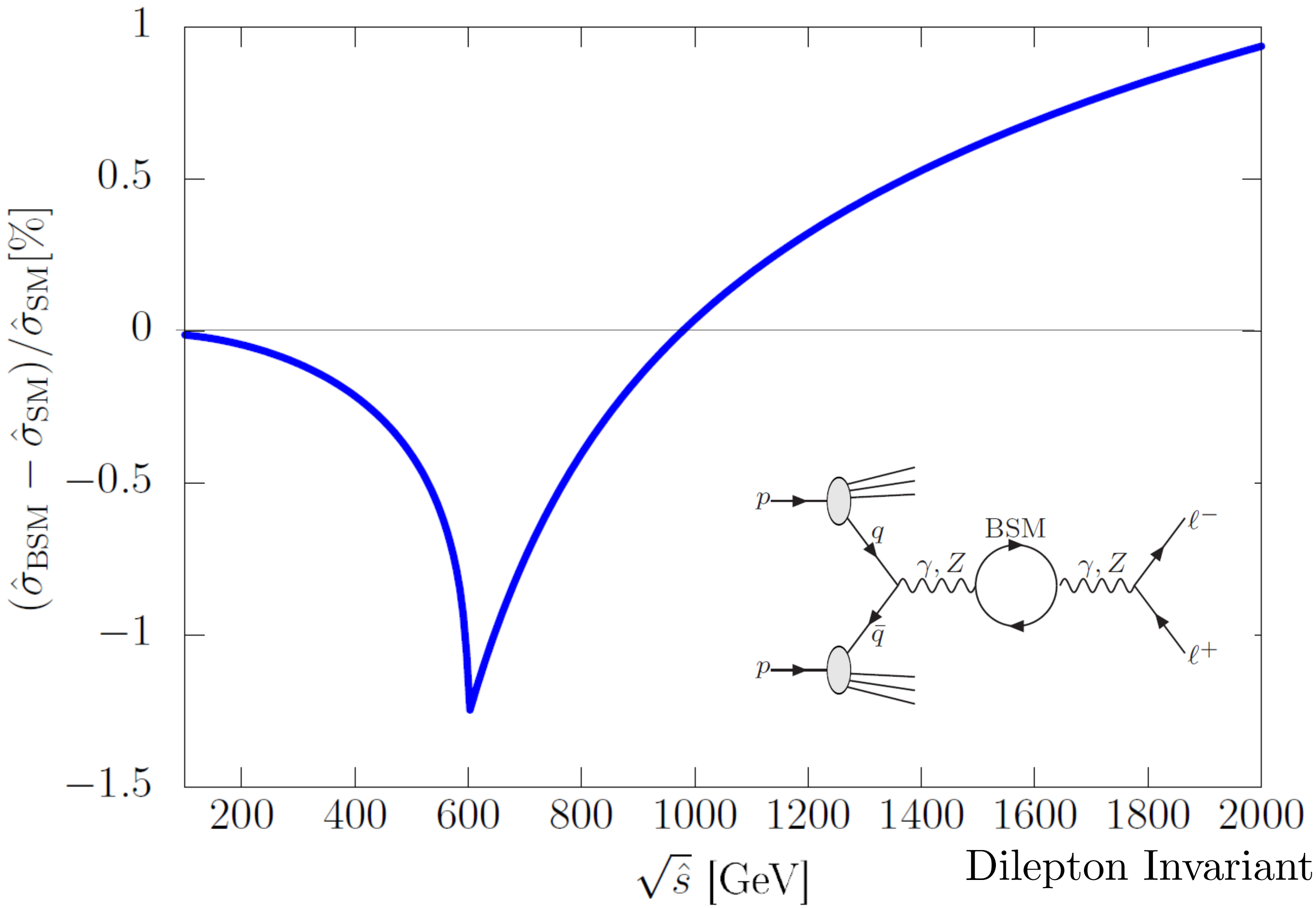
Interference between SM and BSM gives correction

Observed Data



Correction from DM

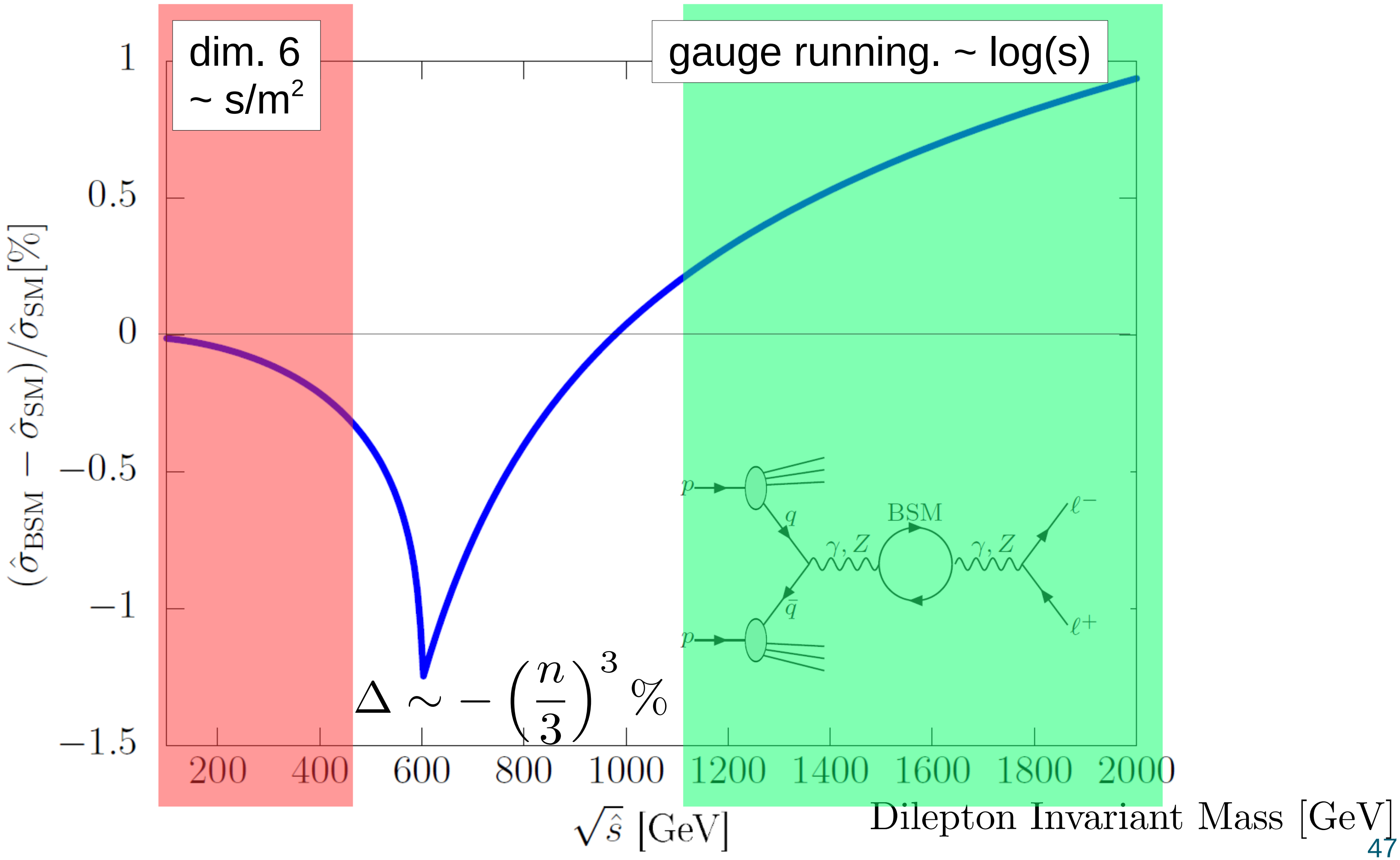
Relative correction from 300 GeV Wino



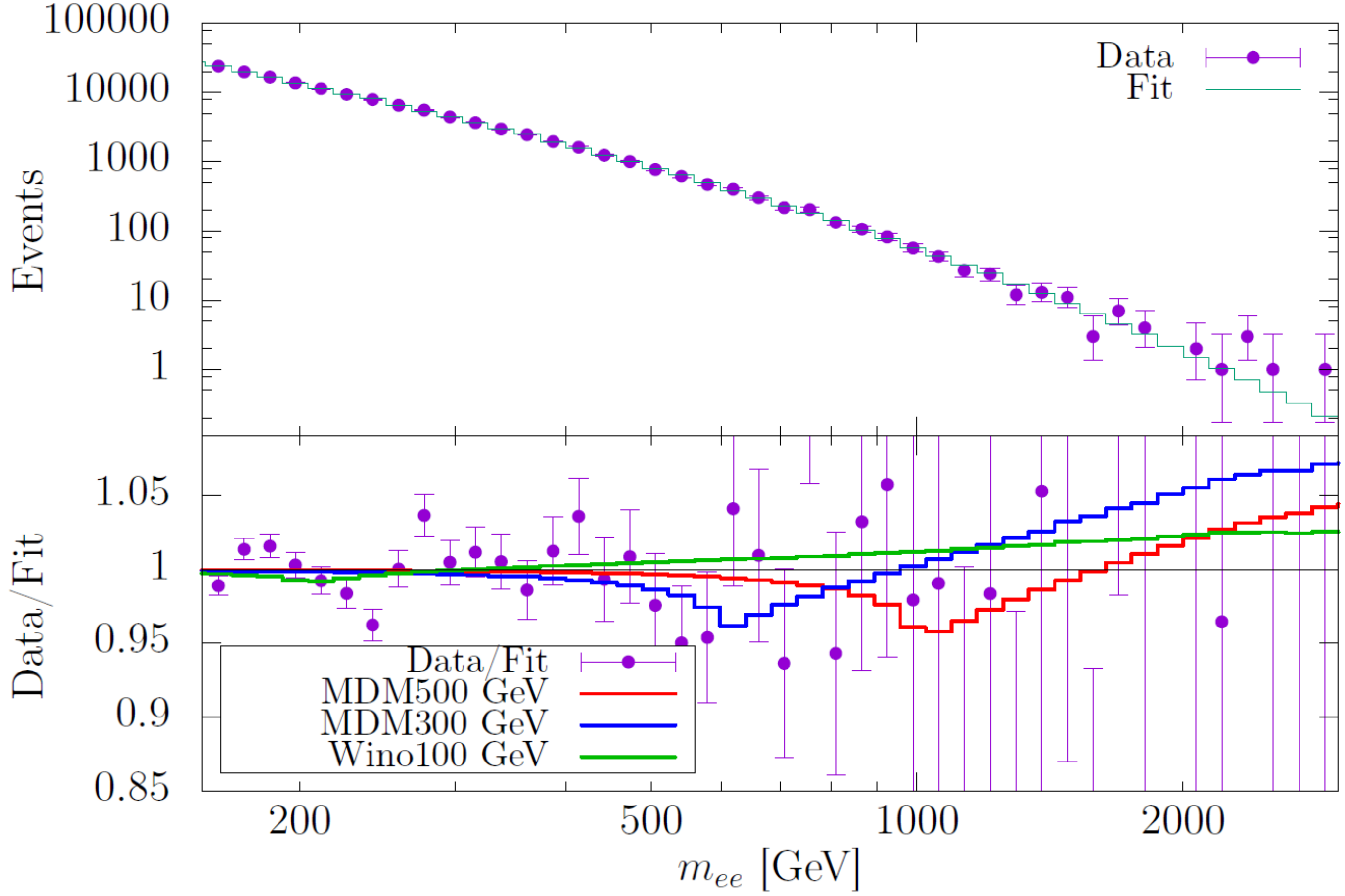
Dilepton Invariant Mass [GeV]

Correction from DM

Relative correction from 300 GeV Wino

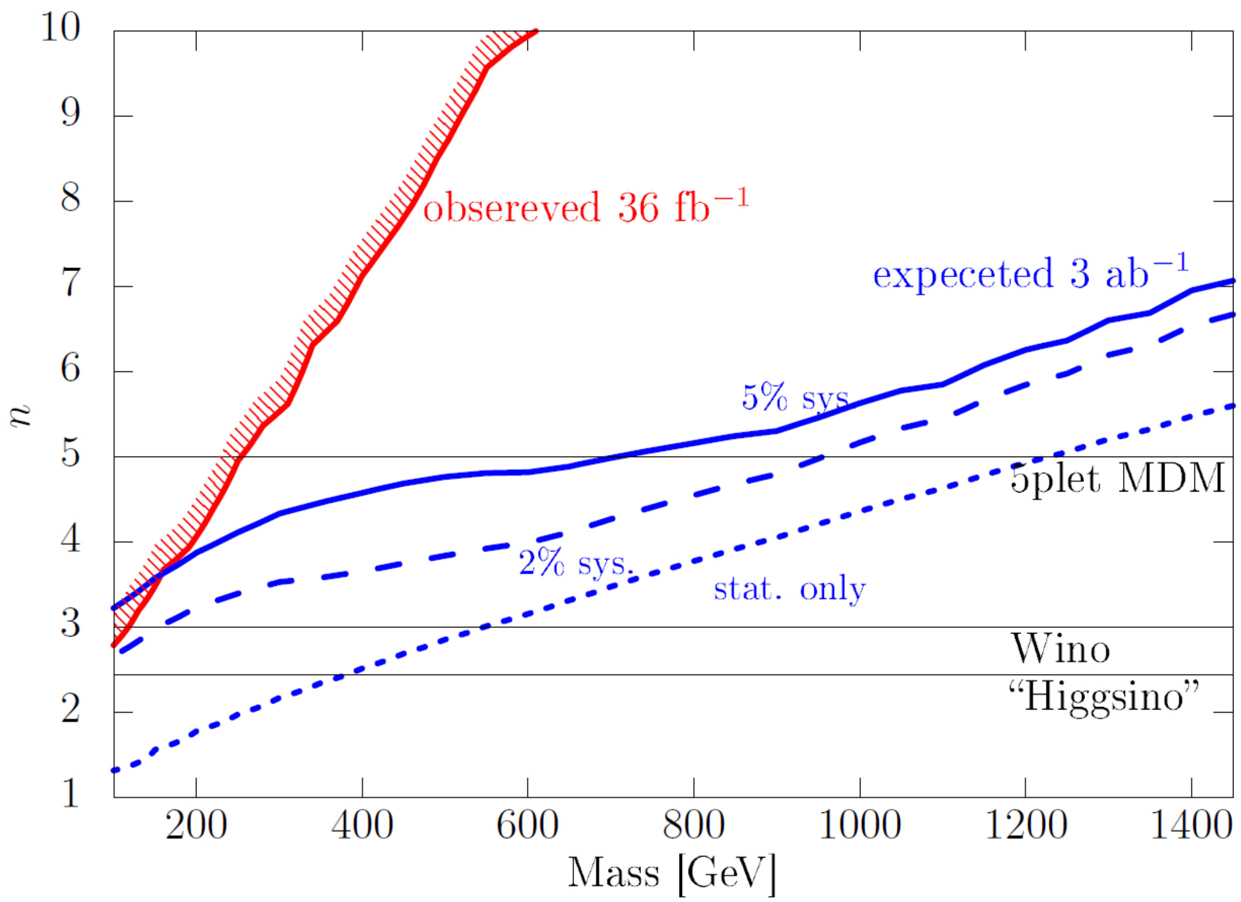


Indirect Probe at LHC



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 x mass.
Integrating out of MDM leads effective operators

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

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

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

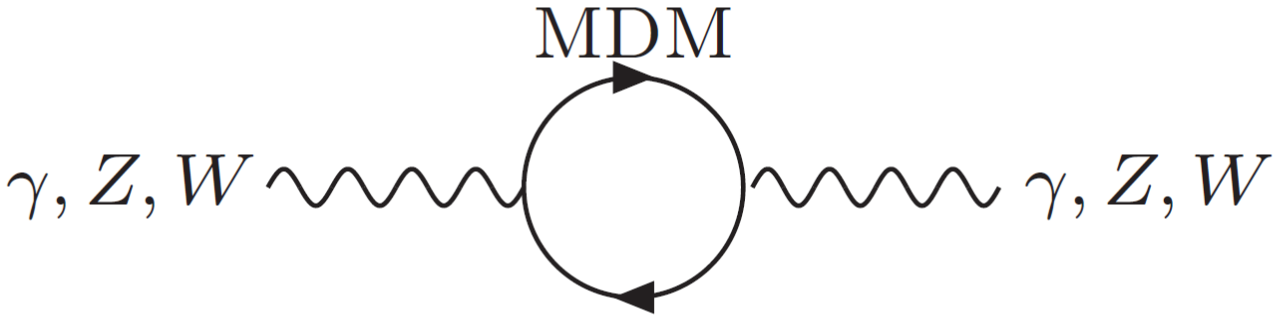
$$\frac{1}{\Lambda_{3W}^2} = \frac{-1}{12\Lambda_{2W}^2}$$

(Dirac Fermion)

Correction to gauge boson propagator and self-coupling

On-Z Observables

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

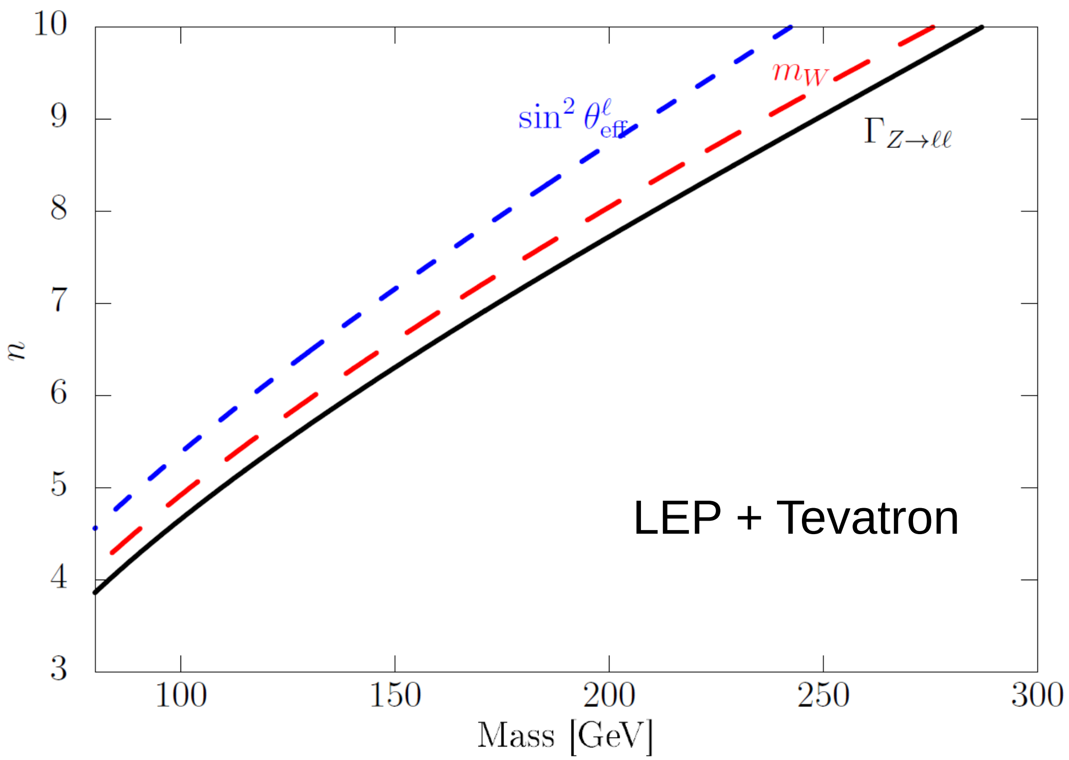


Case 1: Oblique correction to electoweak precision observables(EWPO)
weak boson mass and so on

Current Constraints from EWPO

of SU(2) representation

Majorana Fermion



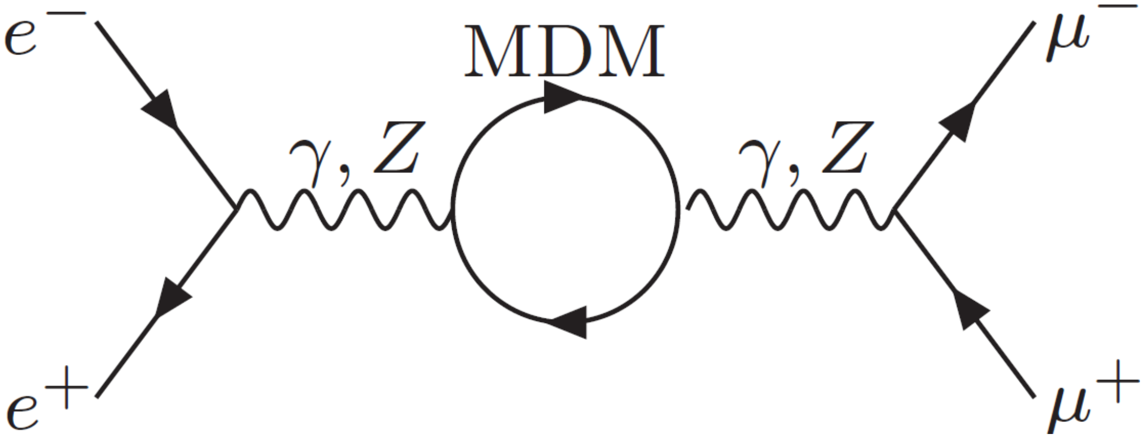
Corrections are roughly proportional to n^3 / m^2

[Harigaya+, 1504.03402]

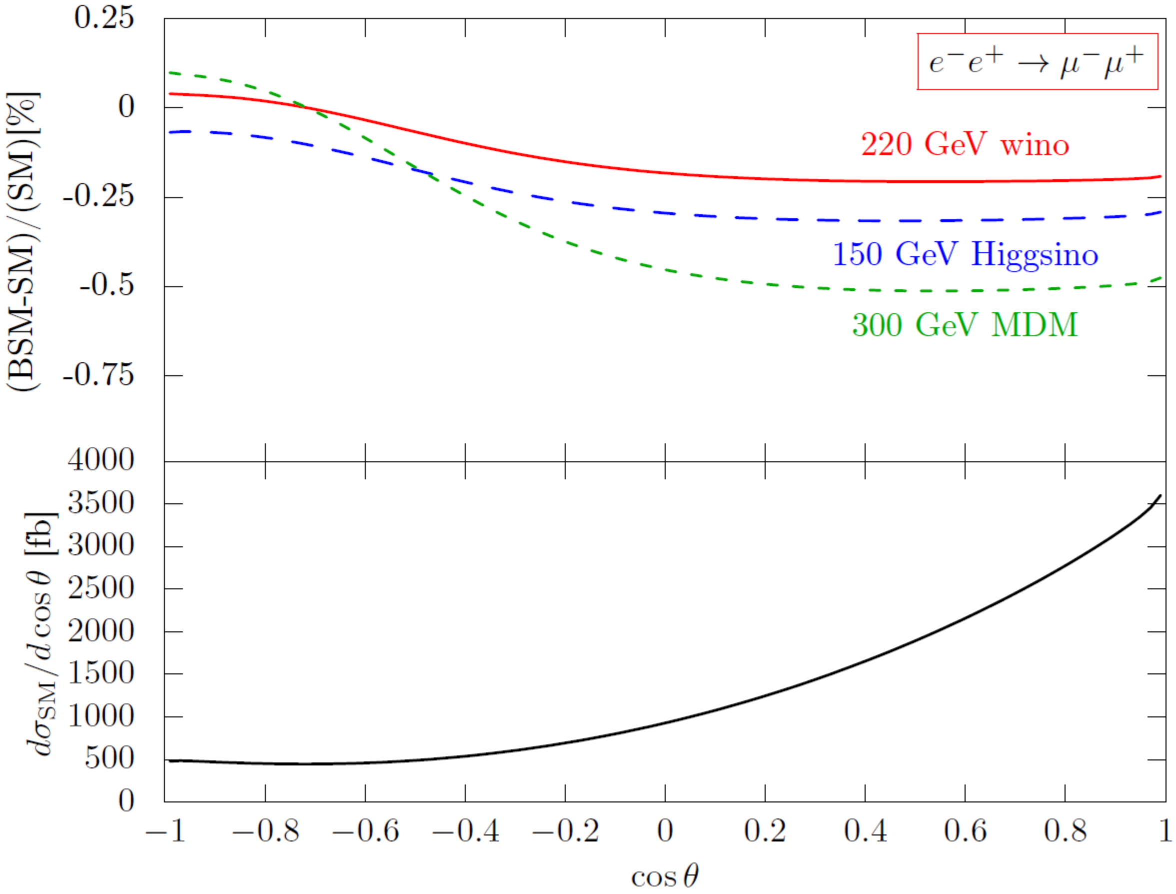
ILC250 for MDM

See Suehara's talk

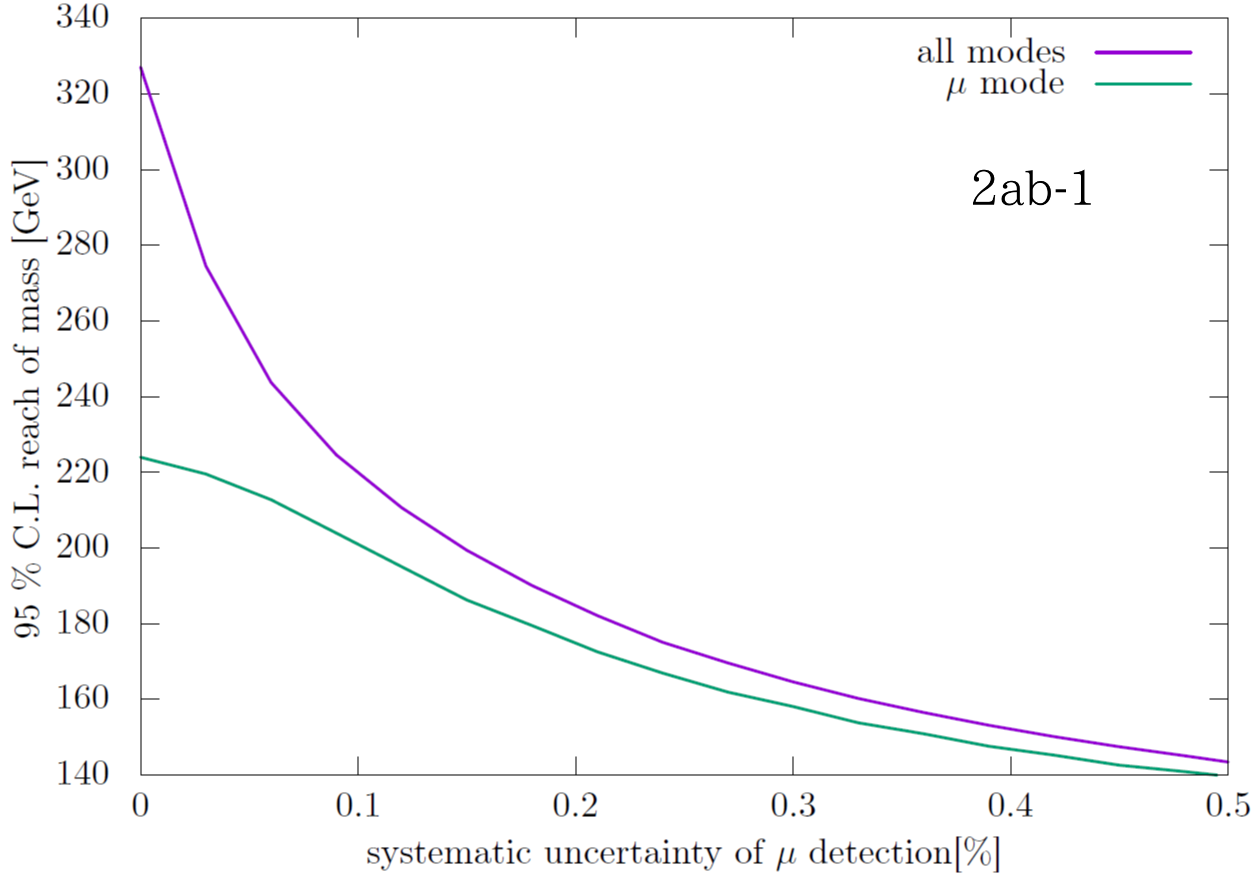
Case 2: Correction to di-fermion process at ILC.



ILC250 for Heavy MDM

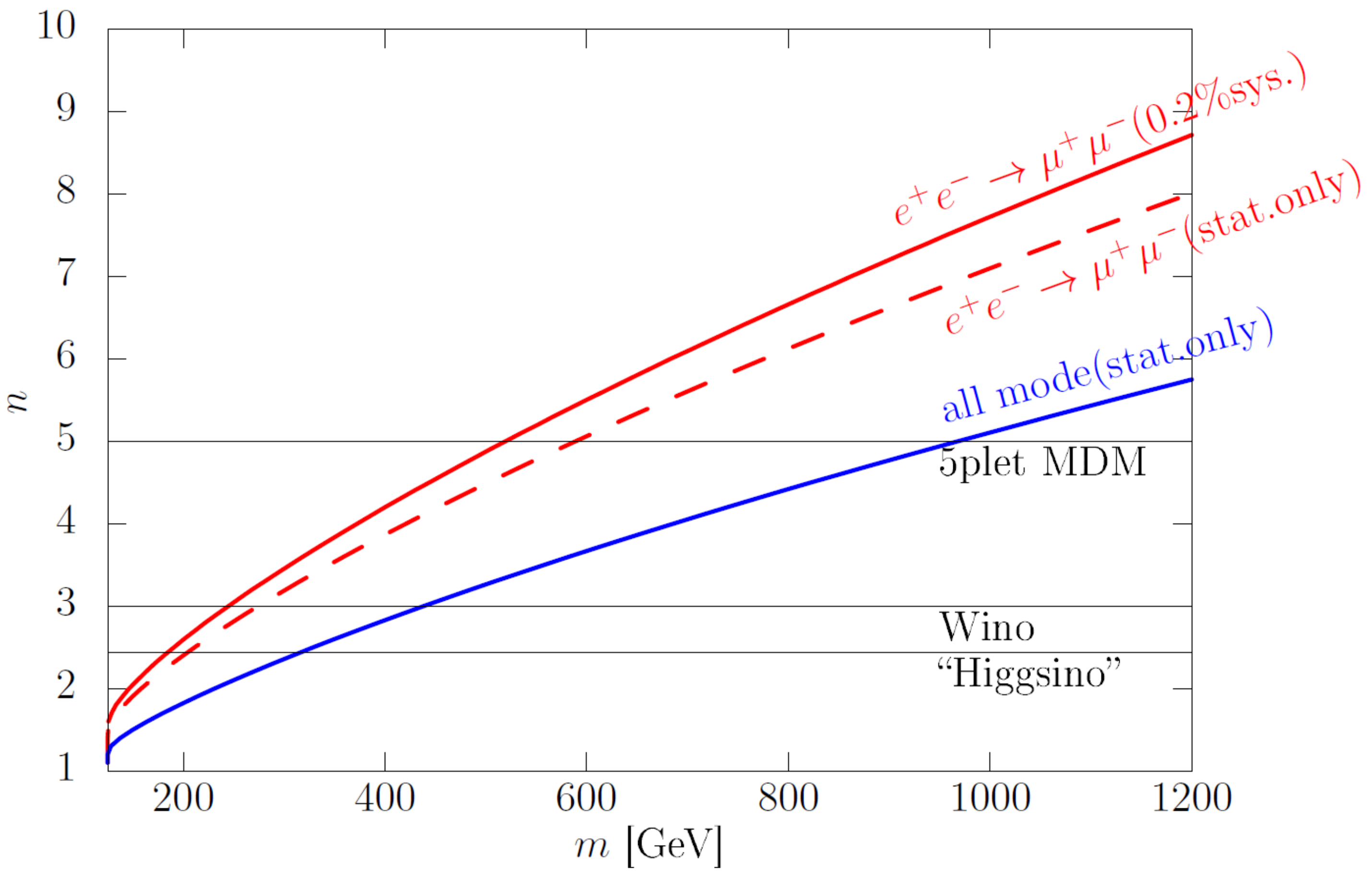


Reach of ILC250 for Higgsino



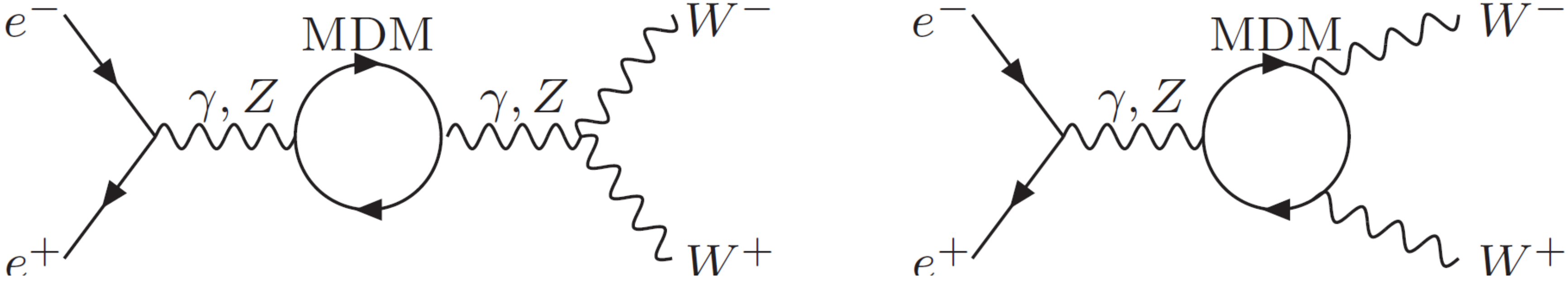
mu, e, b, c sys. Ratios: 2 : 1.5 : 5 : 10 assumed

Reach of ILC250

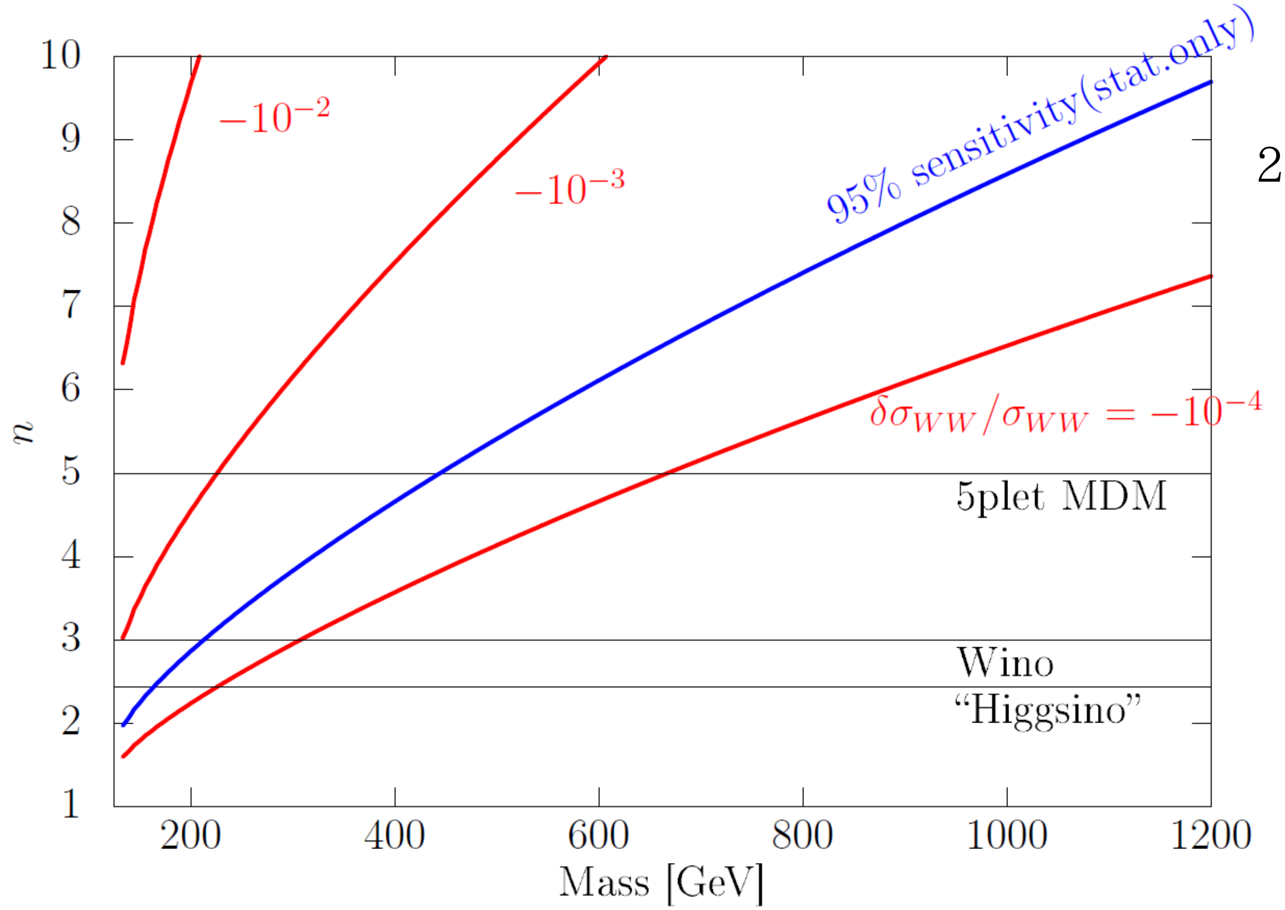


ILC250 for MDM

Case 3: Correction to diboson process at ILC.



ILC250 for MDM



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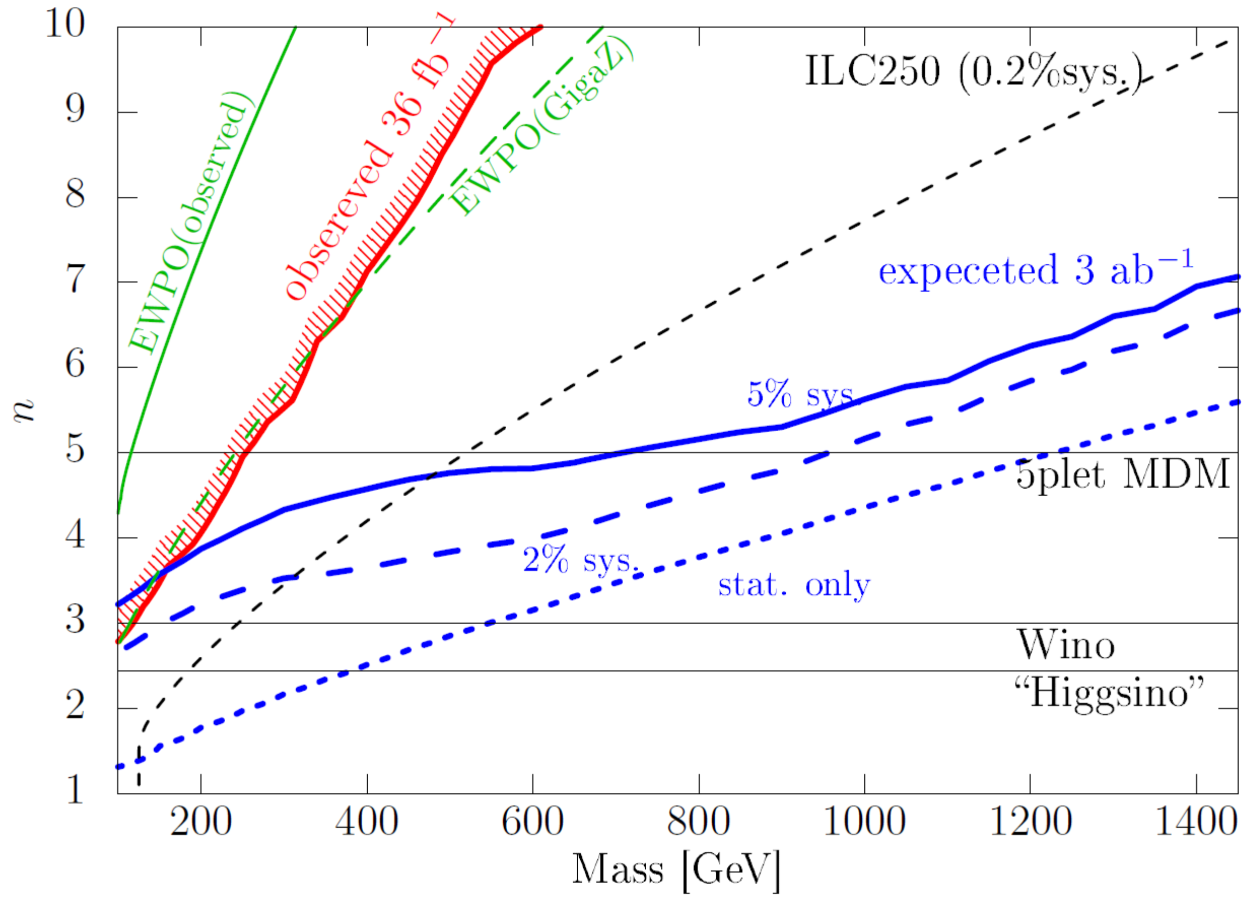
Indirect Probe Summary

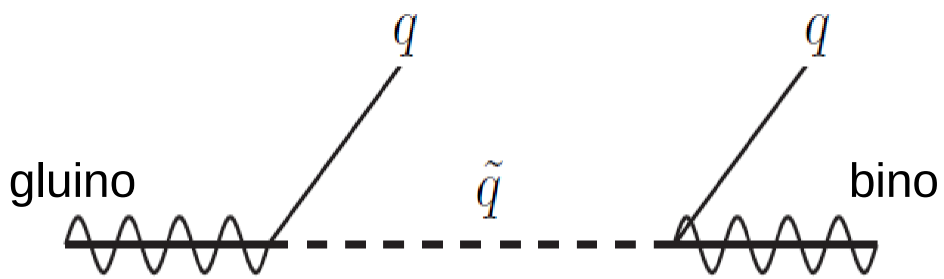
of SU(2) representation



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

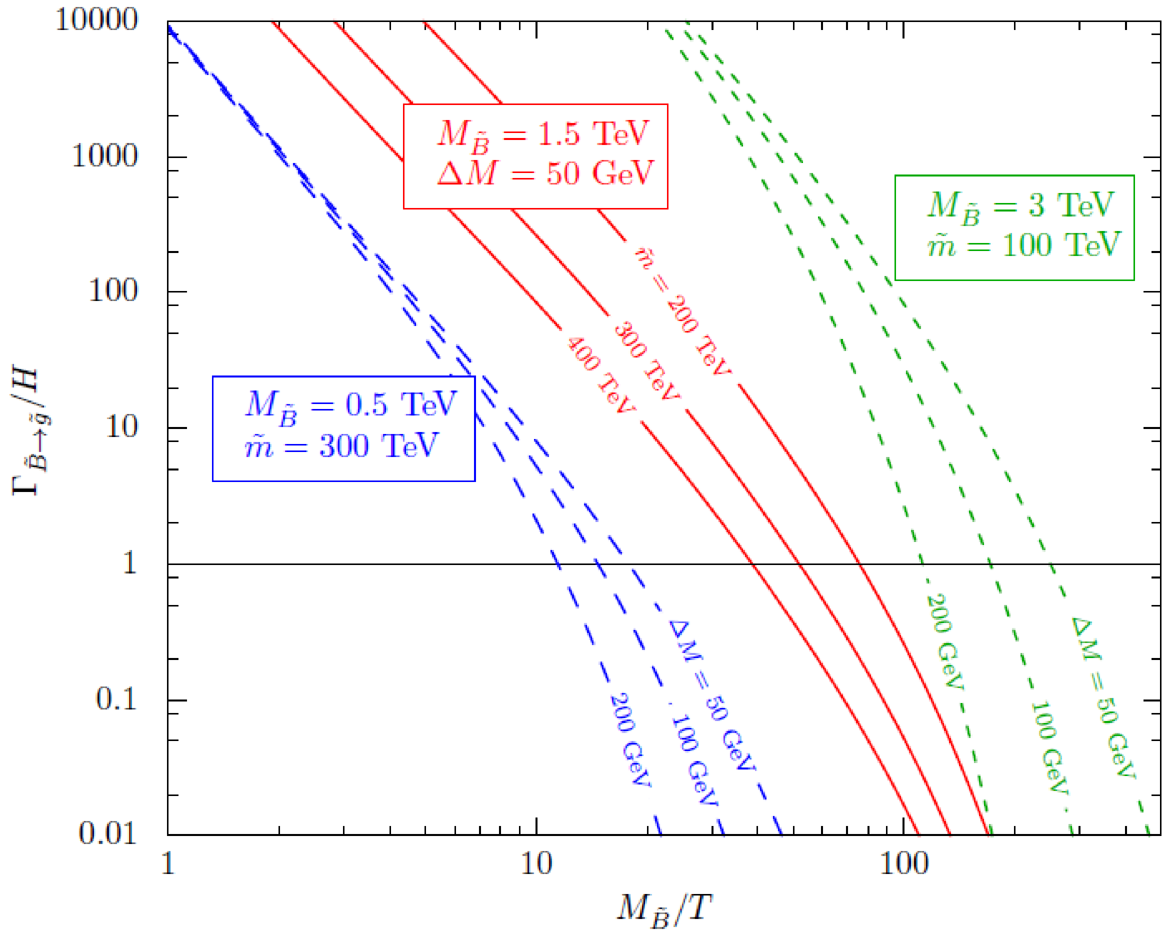
→ Long-lived gluino

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

→ Too heavy sfermion prevents coannihilation

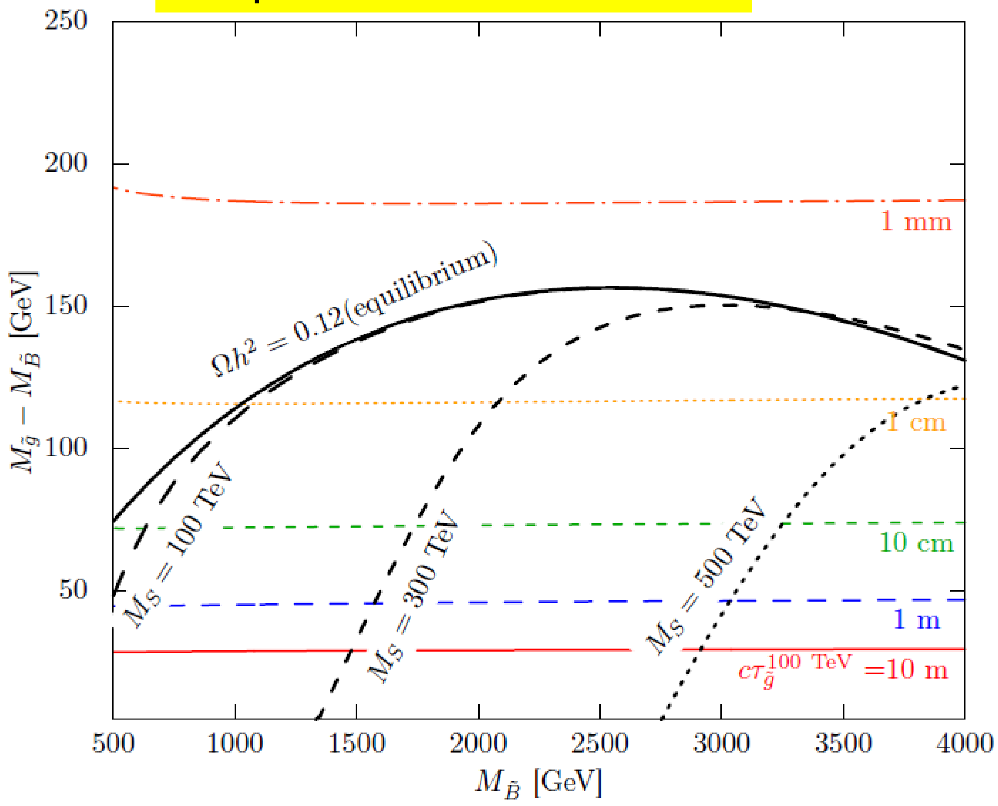
$$M_s \lesssim 250\left(\frac{M_{\mathrm{bino}}}{1\ \mathrm{TeV}}\right)^{3/4}\ \mathrm{TeV}$$

Transition rate / Hubble rate



Bino-Gluino Coannihilation 2

Required mass difference



E.g.,
For 100 TeV sfermion,

Mass diff. ~ 100 GeV
Decay length ~ cm

EW interacting DM

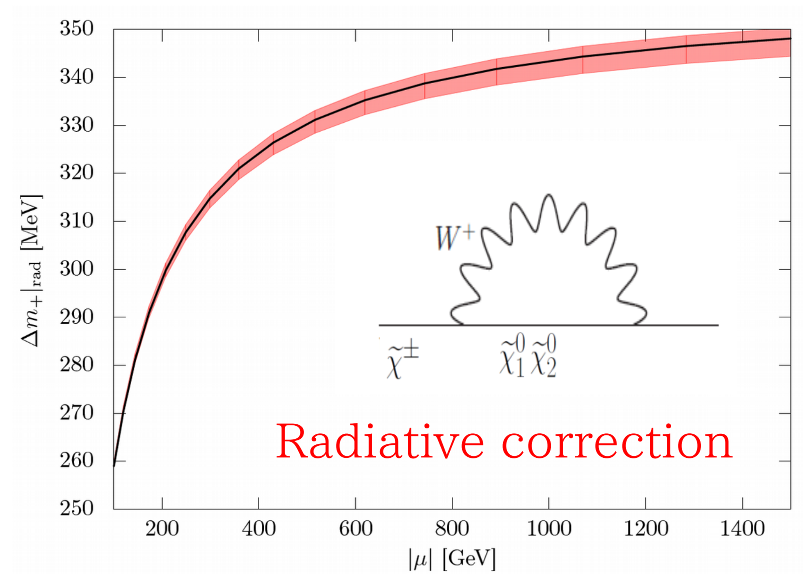
SU(2)

U(1)

n / Y	1	2	3	4	5
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	⋯

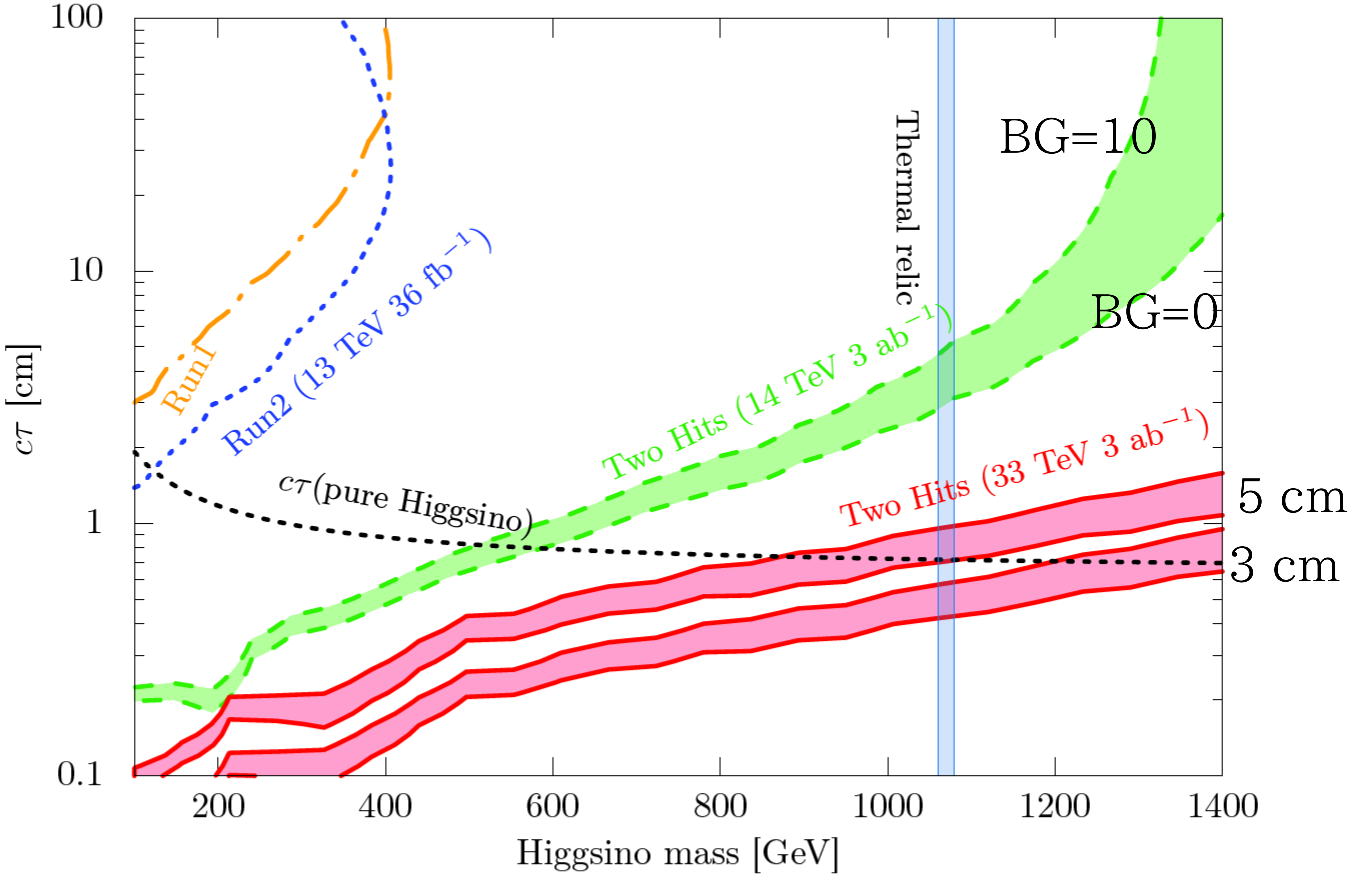
Higgsino Spectrum

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



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

Prospects for Higgsino



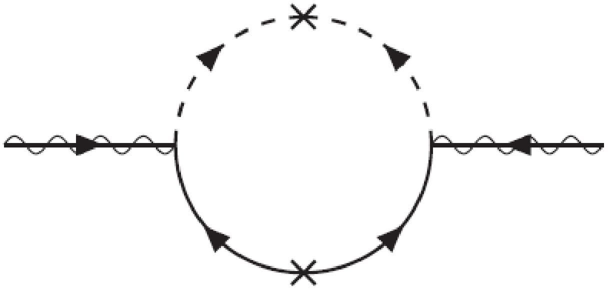
MET>400 GeV

MET>600 GeV

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

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

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

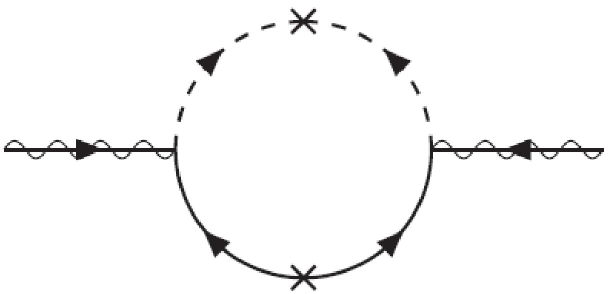
$$M_3 = \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).$$

Higgsino correction

Squark correction

+ High energy sector, such as Axion, also affects

Gaugino Mass



AMSB

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

Higgsino correction

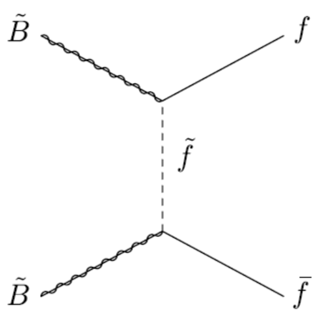
Squark correction

+ High energy sector, such as Axion, also affects

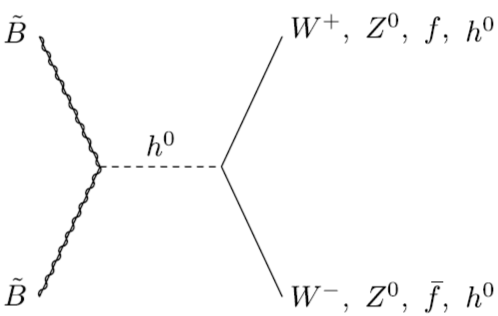
→ **Free gaugino mass relation**

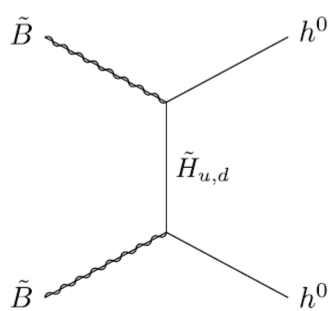
Bino DM 1

Bino interactions are tiny;
suppression by heavy higgsinos and sfermions



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





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

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!