16th September, 2022

SUSY scenarios at FCC

Keisuke Harigaya (University of Chicago)

Outline

* Motivation of supersymmetry
* Higgs mass and scalar masses m_0 in the MSSM
* $m_0 \sim 10$ TeV
* $m_0 = 100 - 1000$ TeV
* $m_0 \gg 1000$ TeV

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1. Dark Matter

With R parity conservation, the lightest supersymmetric particle is stable

	boson	fermion
$Q, \bar{u}, \bar{d}, L, \bar{e}$	$-$	$+$
H_u, H_d	$+$	$-$
Gauge, gravity	$+$	$-$

Higgsino, bino, wino, gravitino, (sneutrino)

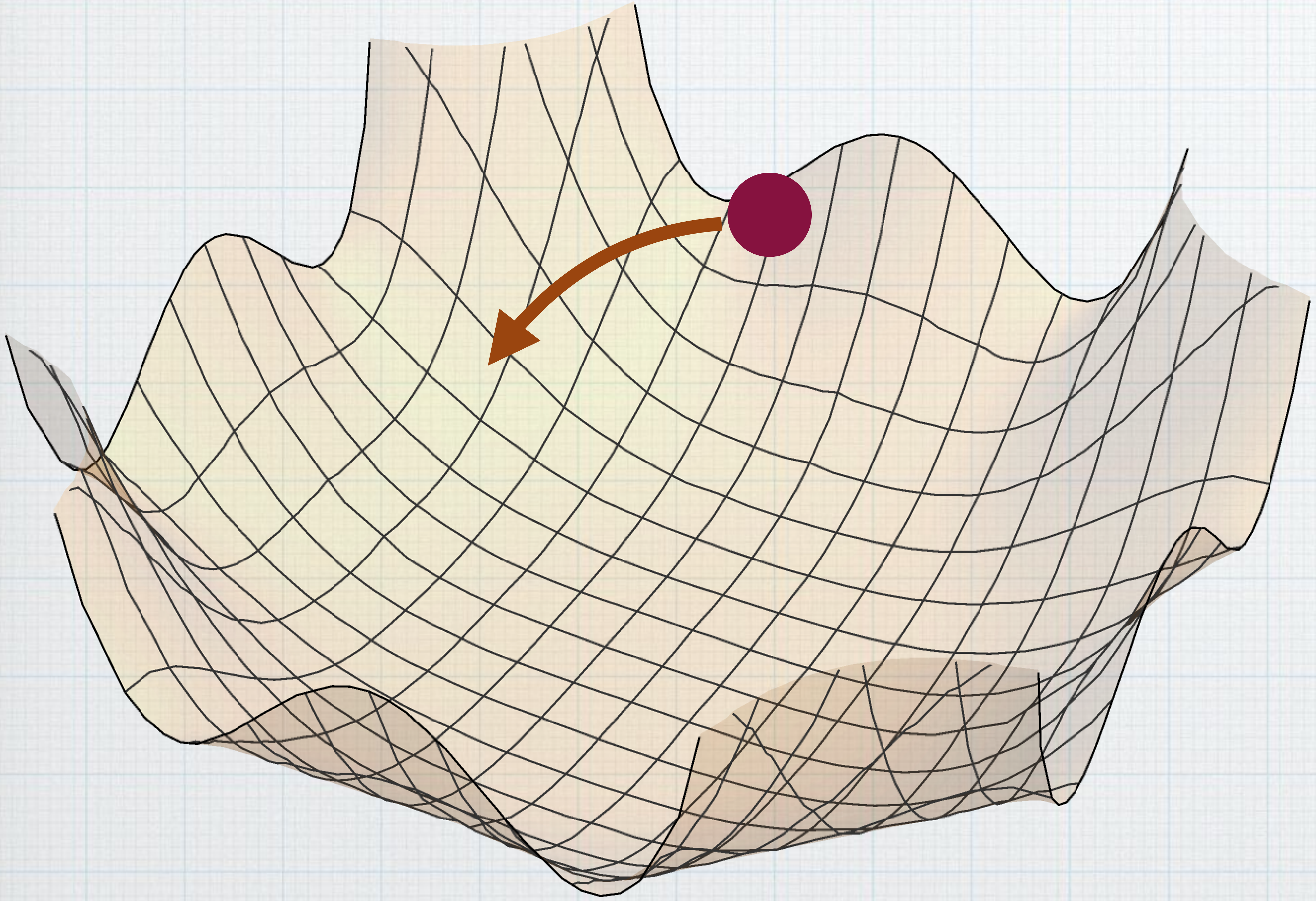
R parity can arise from $SO(10)$ or $B-L$ + 4D fermion number

"Fermion number" of $SO(10)$: $16 = (Q, \bar{u}, \bar{d}, L, \bar{e})$ is odd

Z_2 subgroup of $3(B-L)$: baryons and leptons are odd

2. Baryon asymmetry

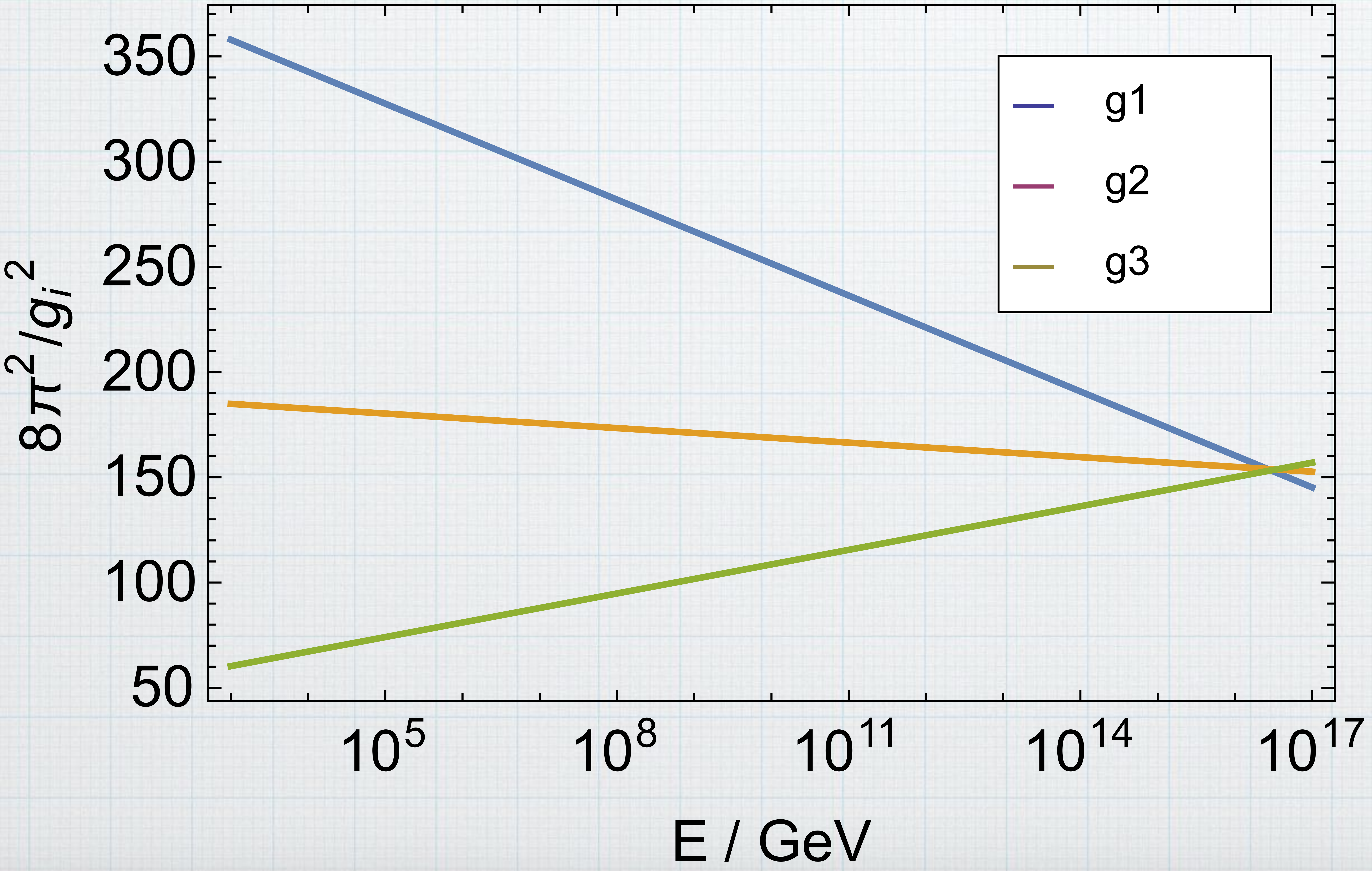
Affleck and Dine (1985)



Rotation of squarks or sleptons in the early universe can explain the baryon asymmetry of the universe

3. Precise gauge coupling unification

Dimopoulos, Baby, and Wilczek (1981)
Dimopoulos and Georgi (1981)
Sakai (1981), Ibanes and Ross (1981)



4. Electroweak scale

GUT-Planck

$10^{16} - 10^{18}$ GeV

$\approx$

SUSY

$1 - 1000$ TeV

EW

100 GeV

MSSM does not explain the EW scale fully naturally, but still the huge hierarchy problem is absent.

$$m_{\mathrm{SUSY}} \ll M_{\mathrm{PL}},\ M_{\mathrm{st}},\ M_{\mathrm{GUT}}$$

can be explained by dimensional transmutation

Witten (1981)

$$m_{\mathrm{SUSY}} \propto \exp\left(-\frac{8\pi^2}{bg^2}\right)$$

Dynamical SUSY breaking

5. Intermediate scales

Supersymmetry can stabilize intermediate scales in BSM models

* Peccei-Quinn symmetry breaking scale
* Parity symmetry breaking scale
* Right-handed neutrino mass scale
* Inflation scale
* ...

Today's strategy

Discuss canonical scenarios:

* Minimal supersymmetric Standard Model
* Sfermion masses are not hierarchical
* Unification
* Avoiding tuning except for the EW scale
* Thermal dark matter abundance not too large

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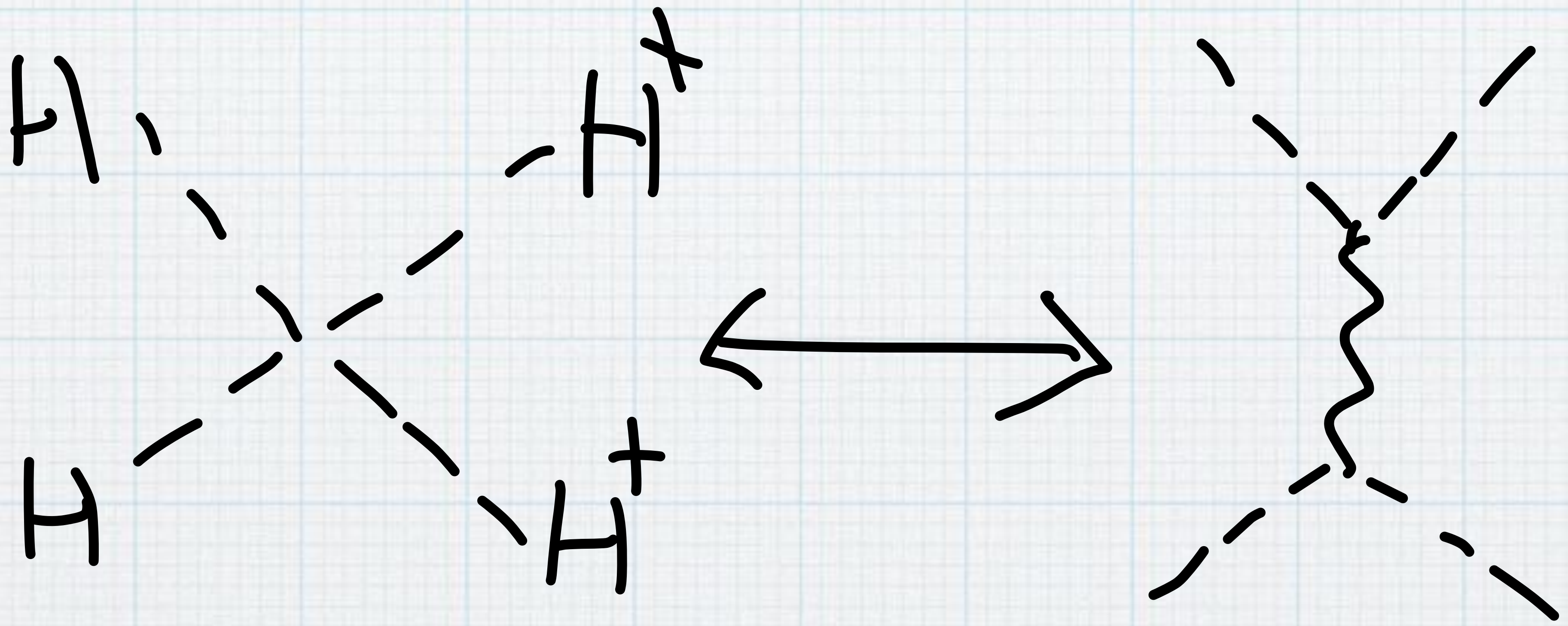
Higgs mass

$$V = \lambda |H|^4 - m^2 |H|^2 \qquad m_h = 2\sqrt{\lambda} \times 173\text{GeV}$$

In SUSY limit,



$$V_4 = \frac{g_2^2 + g_Y^2}{8}(|H_u|^2 - |H_d|^2)^2 \rightarrow \frac{g^2 + g_Y^2}{8}\cos(2\beta)|H|^4, \qquad \tan\beta = \frac{<H_u>}{<H_d>}$$

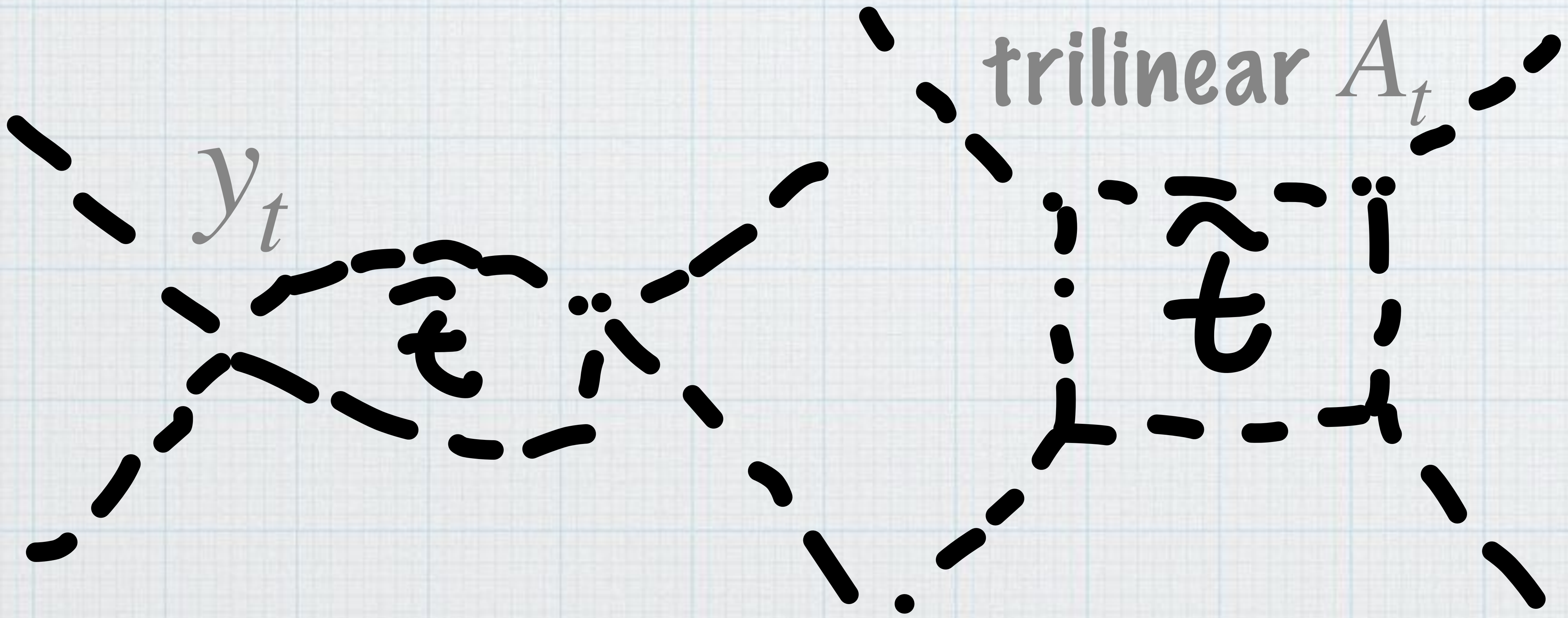
$$m_h = m_Z \times \cos(2\beta) < 90\ \text{GeV} < m_{h,\text{obs}}$$

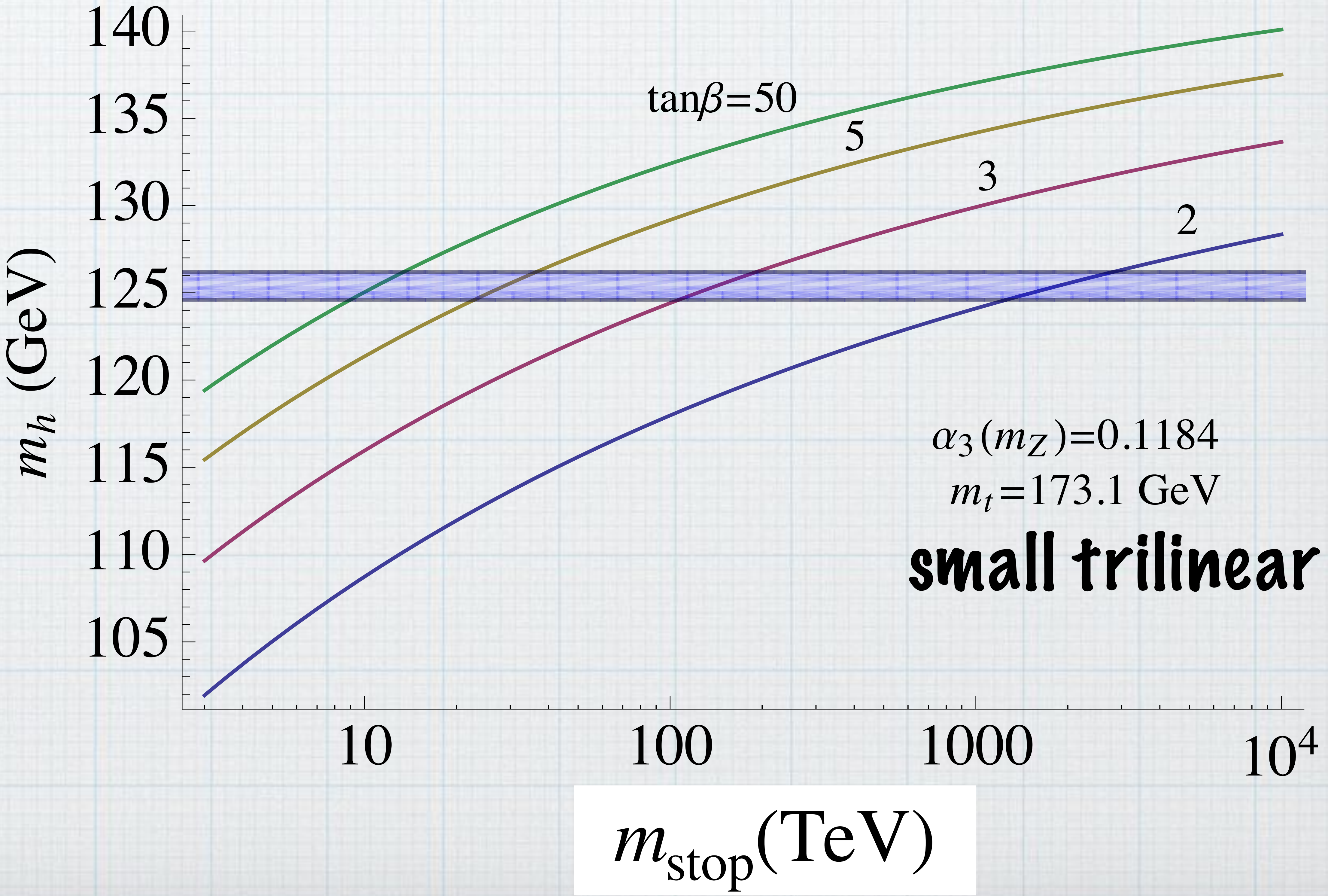
Higgs mass and SUSY breaking

Okada, Yamaguchi, Yanagida (1991
Ellis, Ridolfi, and Zwirner (1991)
Haber and Hempfling (1991)

$$V = \lambda |H|^4 - m^2 |H|^2 \qquad m_h = 2\sqrt{\lambda} \times 173\text{GeV}$$

$$\lambda = \lambda_{\text{SUSY}} + \delta\lambda$$

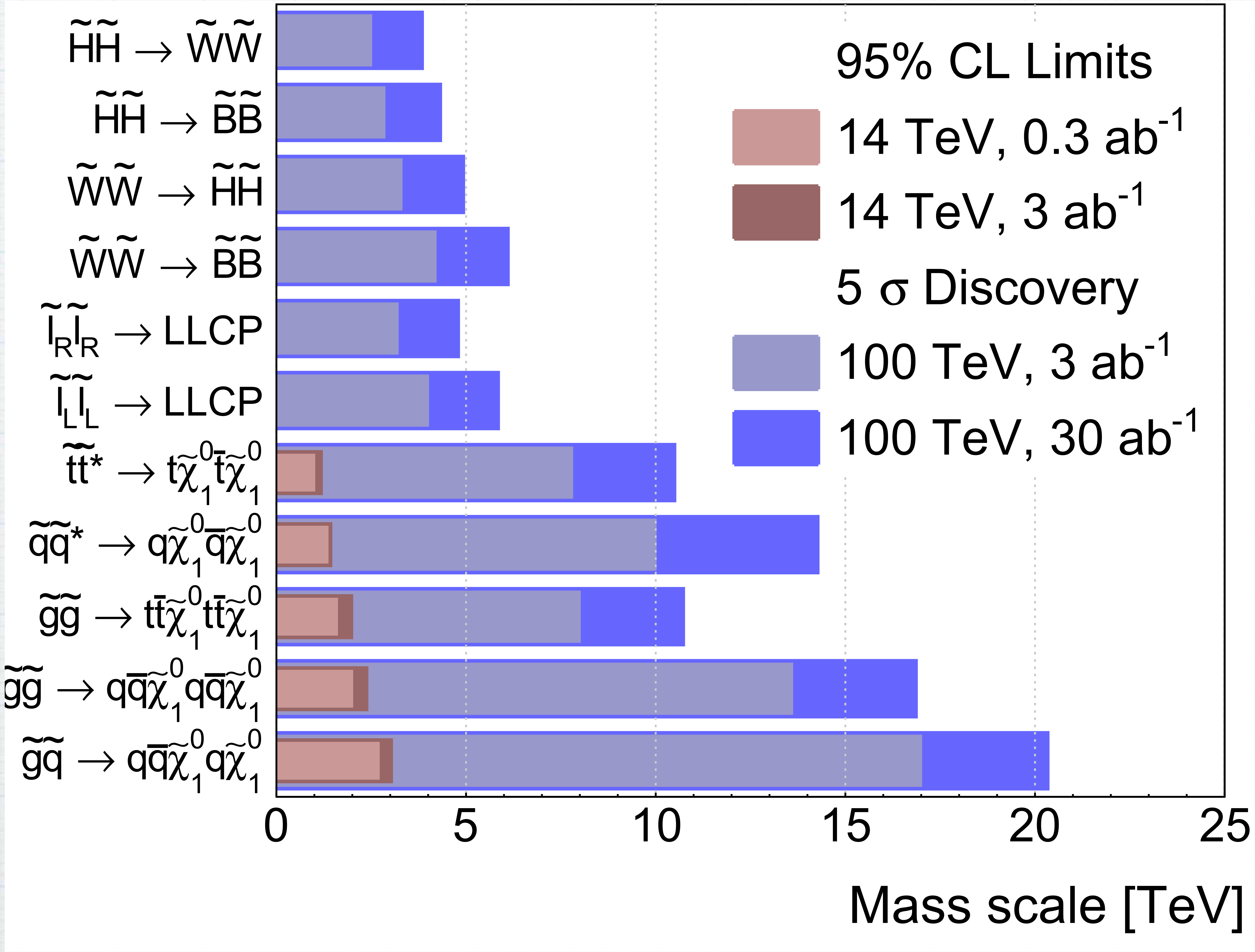




Fours scenarios in the MSSM

* $m_0 = \text{few TeV}$ **with** $\tan\beta \gg 1$ **and a large trilinear**
* $m_0 \sim 10\ \text{TeV}$ **with** $\tan\beta \gg 1$
* $m_0 \sim 100 - 1000\ \text{TeV}$ **with** $\tan\beta = O(1)$
* $m_0 \gg 1000\ \text{TeV}$ **with** $\tan\beta \simeq 1$

FCC-hh



FCC Physics Opportunities (2019)

Fours scenarios in the MSSM

* $m_0 =$ few TeV **with** $\tan\beta \gg 1$ **and a large trilinear**
* $m_0 \sim 10$ TeV **with** $\tan\beta \gg 1$
* $m_0 \sim 100 - 1000$ TeV **with** $\tan\beta = O(1)$
* $m_0 \gg 1000$ TeV **with** $\tan\beta \simeq 1$

more challenging? (last three scenarios)

Outline

* Motivation of supersymmetry
* Higgs mass and scalar masses m_0 in the MSSM
* $m_0 \sim 10$ TeV ←
    - Gravity mediation
    - Gauge mediation
* $m_0 = 100 - 1000$ TeV
* $m_0 \gg 1000$ TeV

Gravity mediation

SUSY breaking ⟷ **MSSM**

Planck-scale $M_{\rm PL}$ suppressed interactions

$$\mathscr{L} \sim \frac{FF^\dagger}{M_{\rm PL}^2}\tilde{q}^\dagger\tilde{q}$$

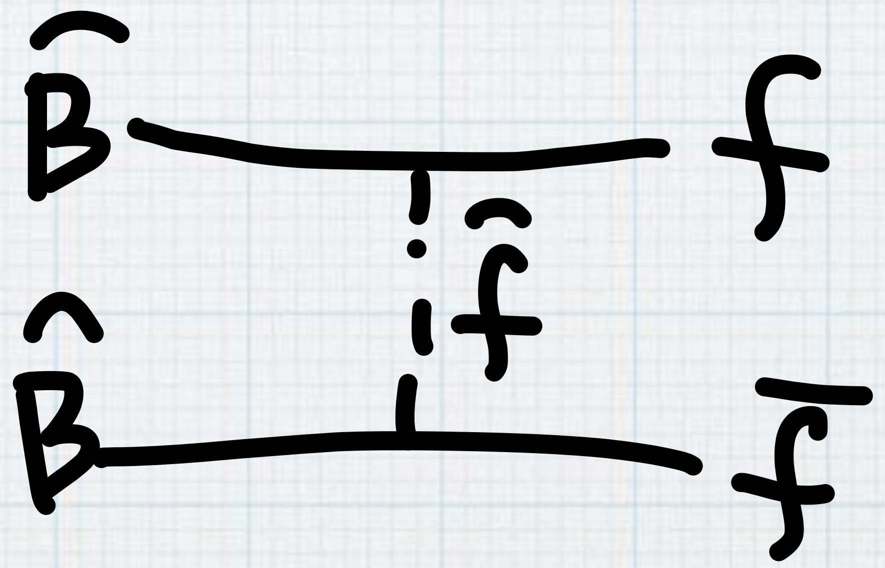
F : SUSY breaking parameter

Gravity mediation

A canonical scenario:

- All sfermion masses are around 10 TeV
- Unification : $m_{\rm bino} : m_{\rm wino} : m_{\rm gluino} \simeq 1 : 2 : 5$

Pure bino LSP annihilates ineffectively, and DM is overproduced



- small coupling
- heavy scalar
- chirality suppression

To avoid LSP overproduction, $m_{\rm higgsino} < 1$ TeV is required

1. Nearly pure Higgsino LSP : Natsumi Nagata's talk
2. Higgsino-bino mixed LSP (well-tempered) $m_{\rm bino} \lesssim 1$ TeV $\rightarrow m_{\rm gluino} \lesssim 5$ TeV

Large $< H_u > / < H_d >$ is natural

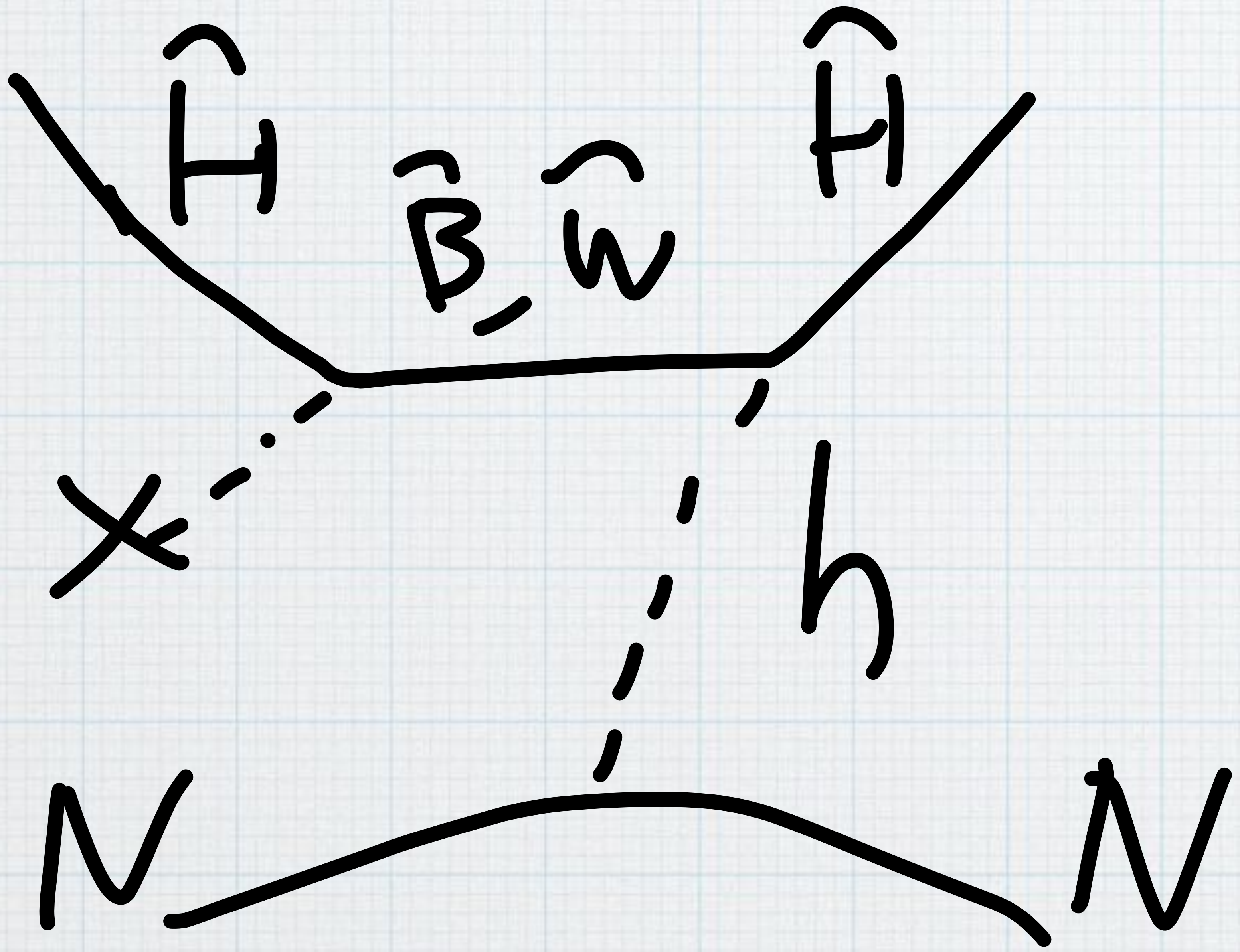
$$V = (\mu^2 + m_{H_u}^2)\,|H_u|^2 + (\mu^2 + m_{H_d}^2)\,|H_d|^2 + (B\mu H_u H_d + \mathrm{h.c.})$$

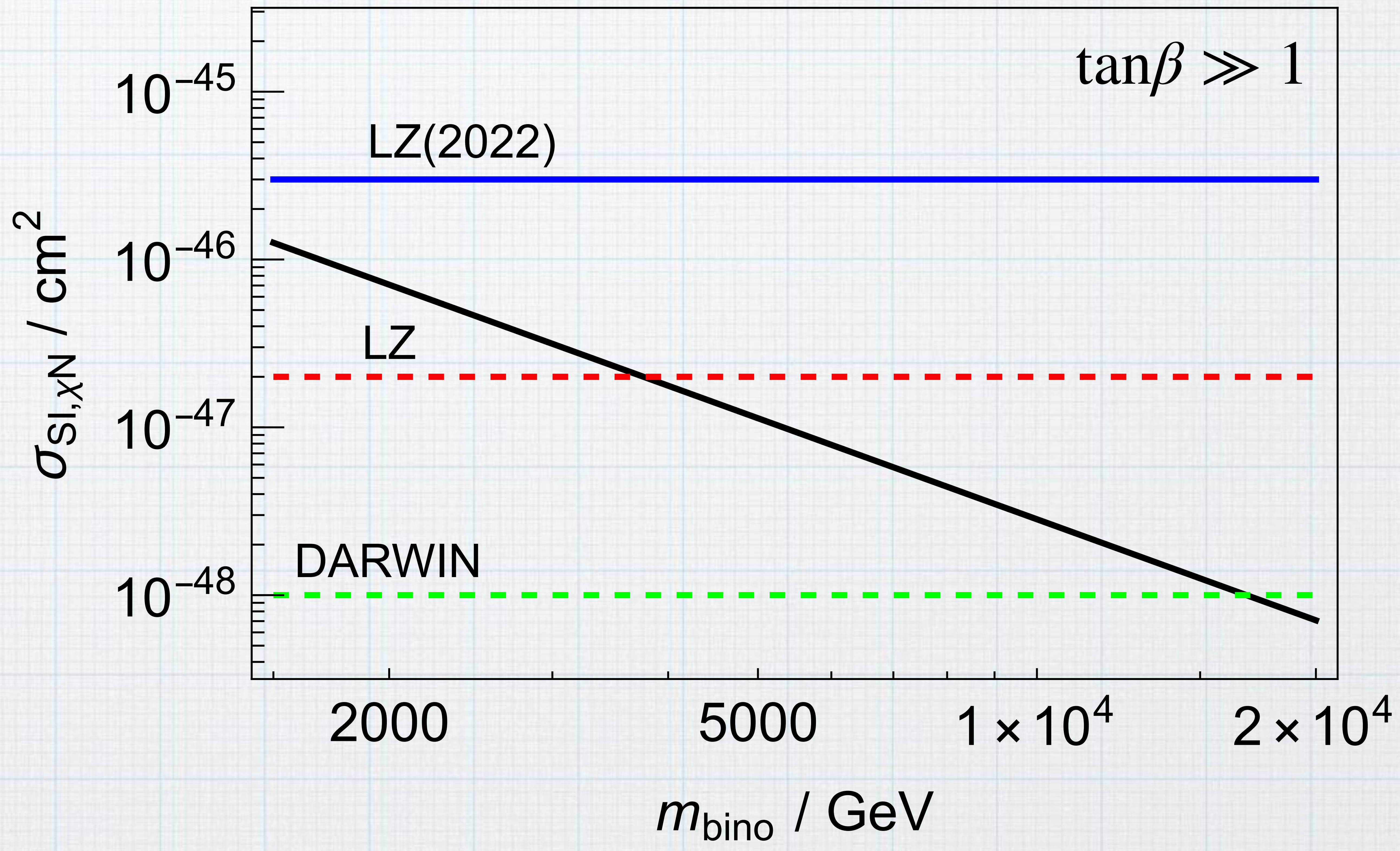
SUSY breaking terms

supergravity gives $B \sim m_{3/2} \sim m_0$

$$\tan\beta \simeq 2\frac{m_{H_u}^2 + m_{H_d}^2 + 2\mu^2}{B\mu} \gg 1$$

Direct detection?





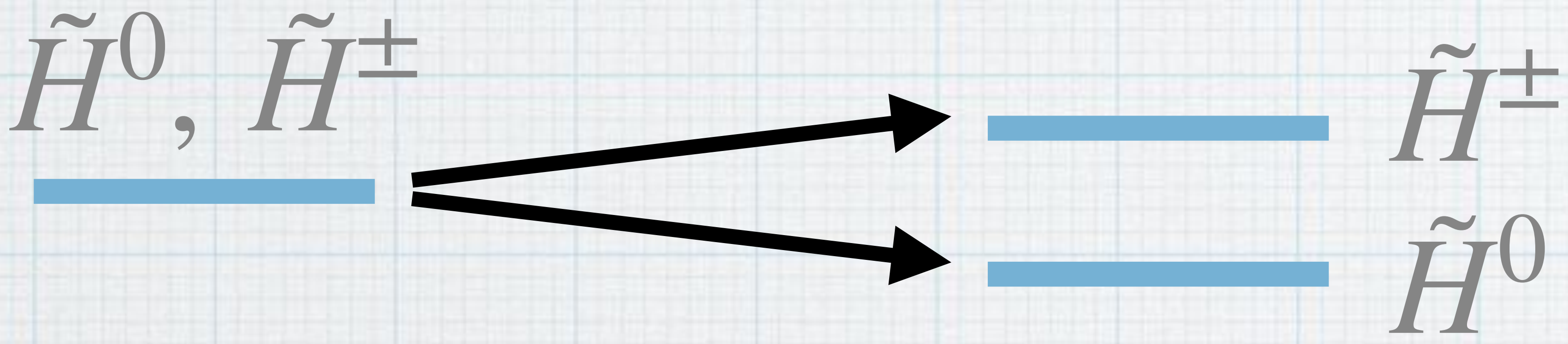
→ Direct detection determines the bino mass

* $m_{\rm bino} \lesssim$ TeV gives a different prediction

prompt gluino
at FCC
LZ
DARWIN
m_{stop}
$m_{gluino} > 100$ TeV
quantum
correction
10 TeV
too large stop mass,
too large Higgs mass
prompt stop
at FCC
3 TeV
4 TeV
20 TeV
m_{bino}

Stop and gluino search

* Decay products include a long-lived charged higgsino



tree-level and quantum correction

$$c\tau_{\tilde{H}^\pm} = \text{few} - 10\ \text{mm}$$

Natsumi Nagata's talk

Slight improvement of sensitivity by displaced vertices or disappearing tracks??

Note the significant boost : $\dfrac{p}{m_{\text{higgsino}}} = O(10)$

Gauge mediation

SUSY breaking ⟷ **MSSM**

Gauge interaction

$$\mathscr{L} = \frac{FF^\dagger}{M_m^2}\tilde{q}^\dagger \tilde{q}$$

F : SUSY breaking parameter

$$M_m \ll M_{\rm Pl}$$

Predictable, so less assumptions

* Minimal supersymmetric Standard Model
* ~~Sfermion masses are not hierarchical~~ automatic
* Unification
* ~~Avoiding tuning except for the EW scale~~ no tunable parameter (after EW tuning)
* ~~Thermal dark matter abundance not too large~~

mass scale solely determined by the higgs mass

Gauge mediation

$$V = (\mu^2 + m_{H_u}^2)|H_u|^2 + (\mu^2 + m_{H_d}^2)|H_d|^2 + (\underline{B\mu} H_u H_d + \mathrm{h.c.})$$

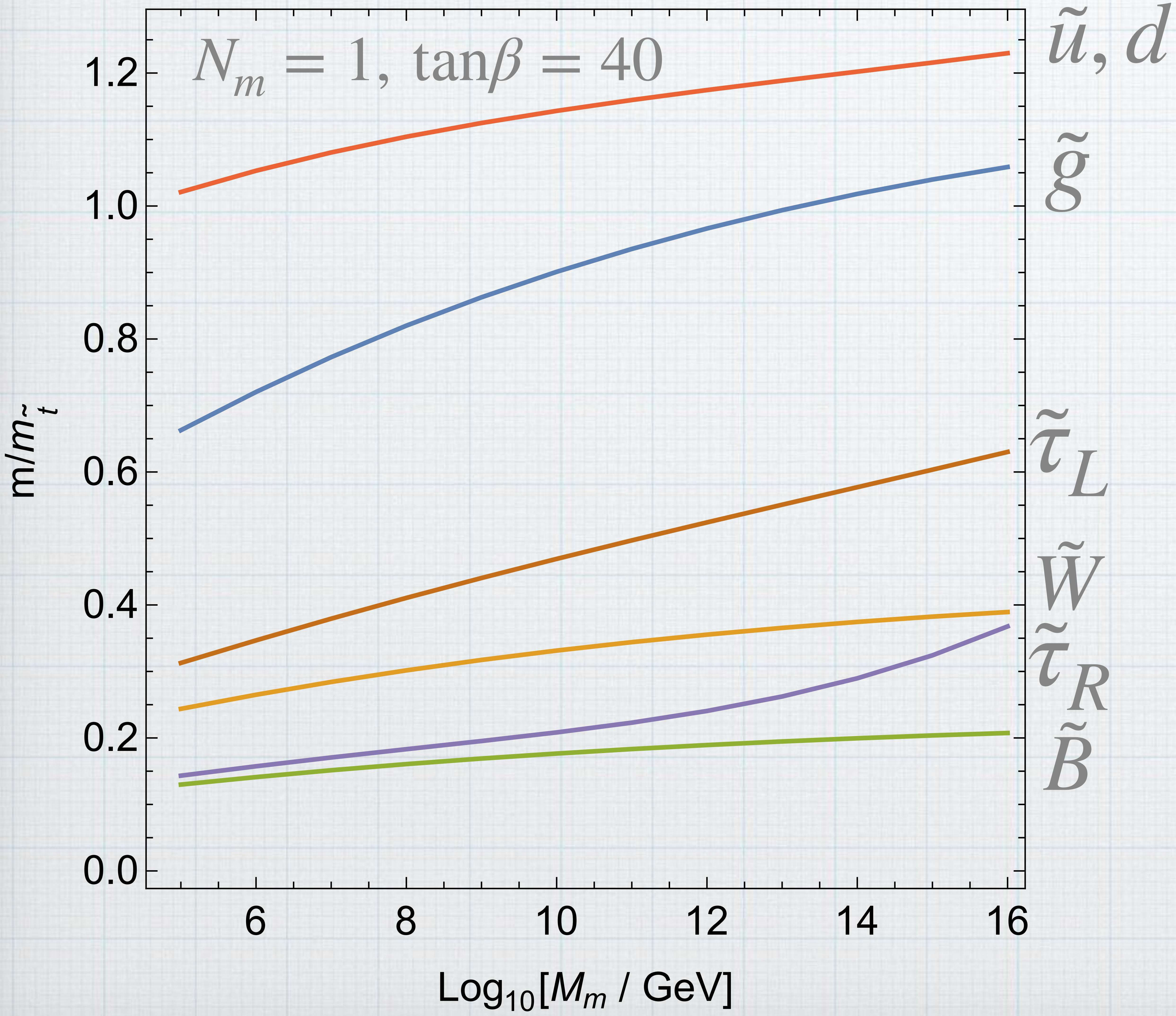
arises at higher order corrections
in the minimal setup

$$\tan\beta \simeq 2\frac{m_{H_u}^2 + m_{H_d}^2 + 2\mu^2}{B\mu} \gg 1$$

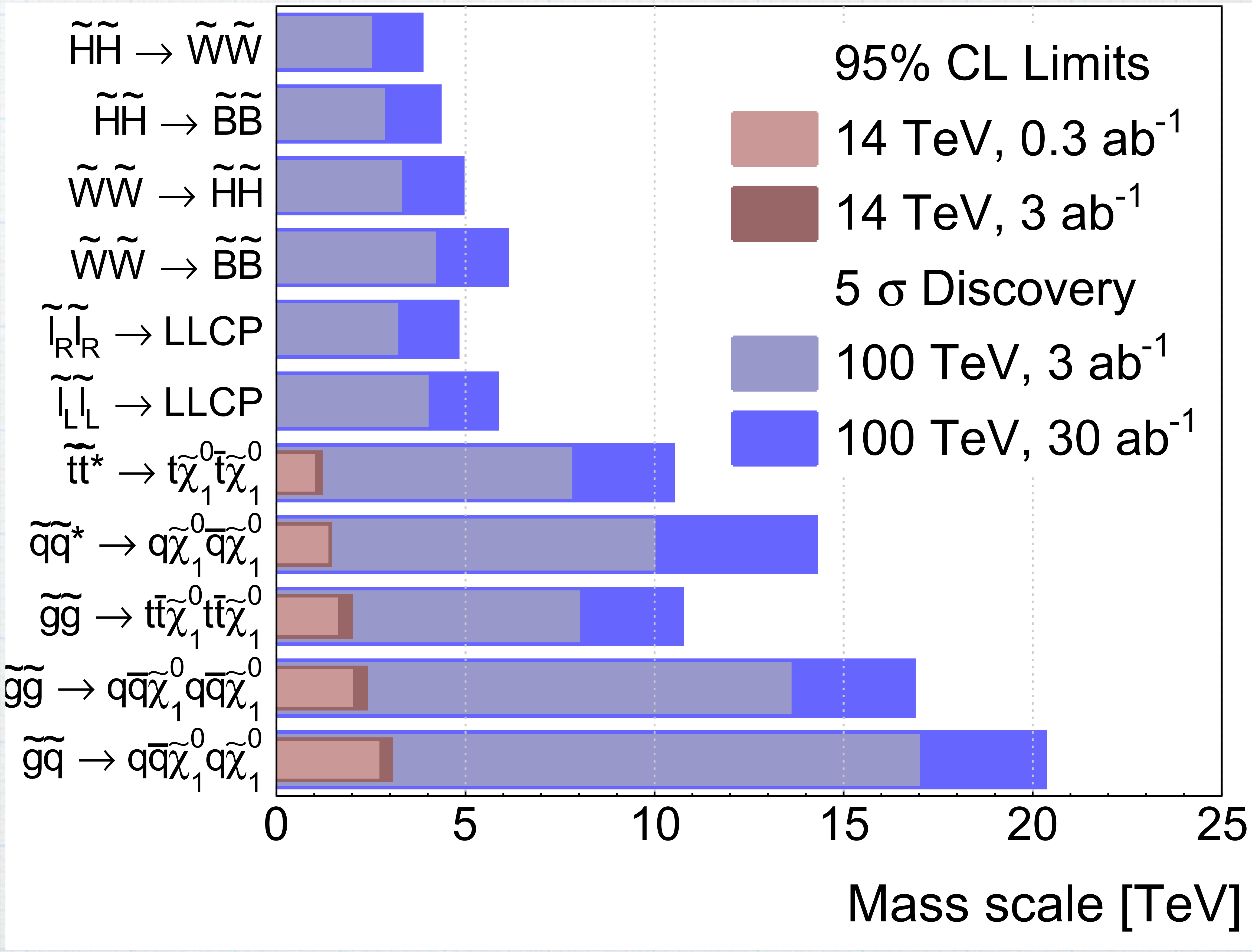
$$m_{\tilde{t}} \leq 10 - 15\ \mathrm{TeV}$$

(For $m_t = 173\ \mathrm{GeV}$. For $m_t \simeq 172\ \mathrm{GeV}$, **20% larger stop mass**)

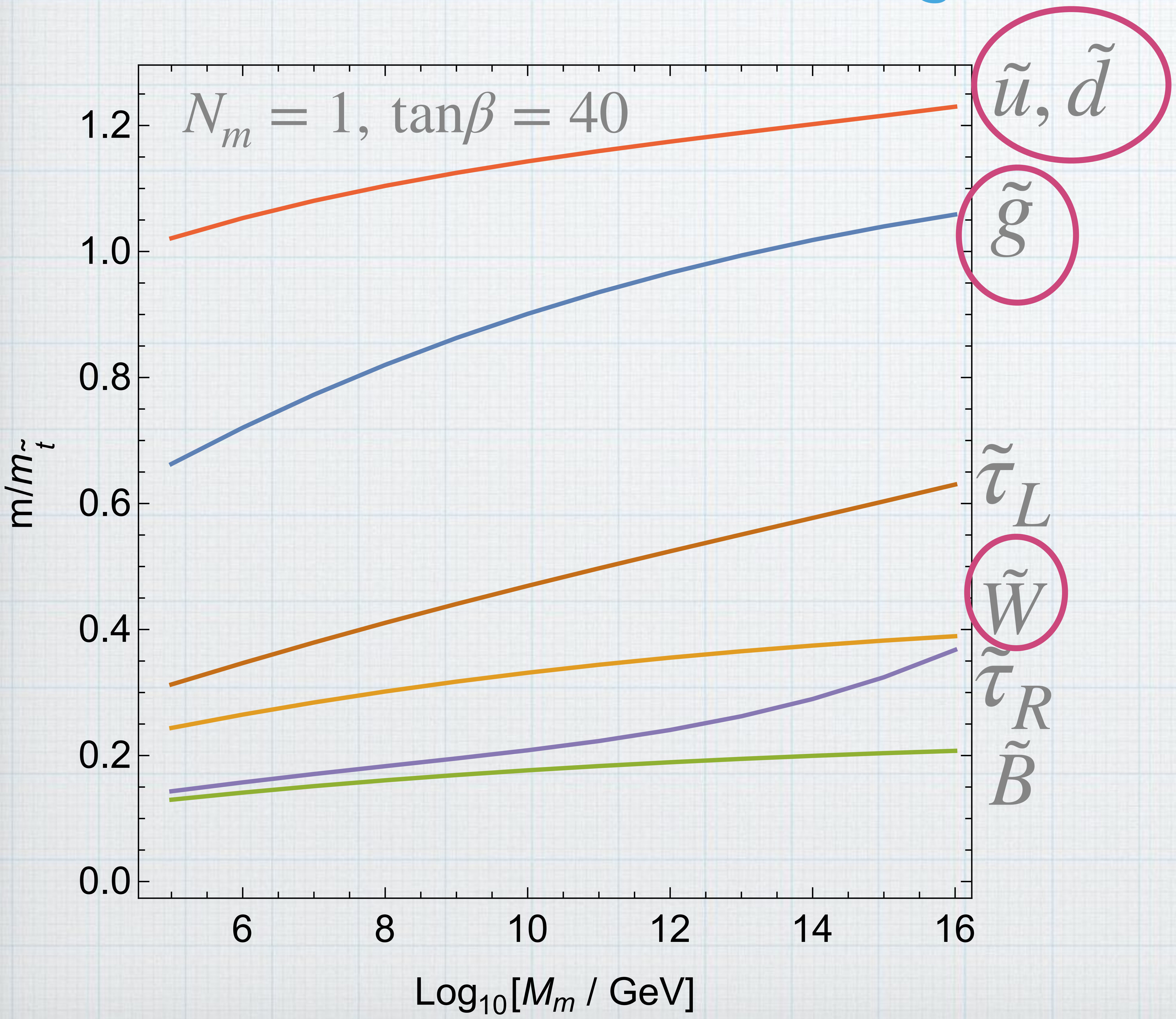
Gauge mediation



$m_{\tilde{t}} \leq 10 - 15$ TeV



Gauge mediation



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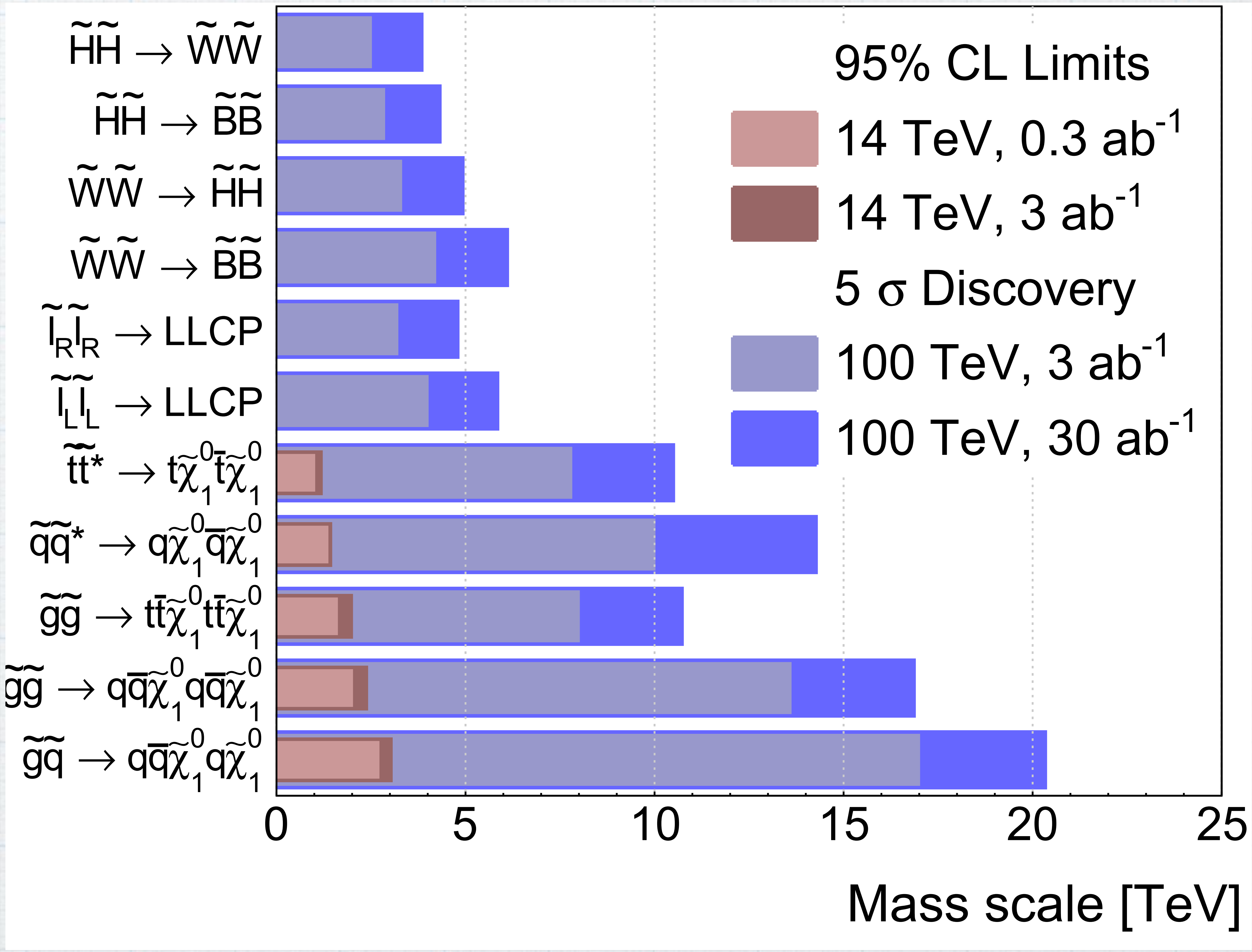

Gauge mediation

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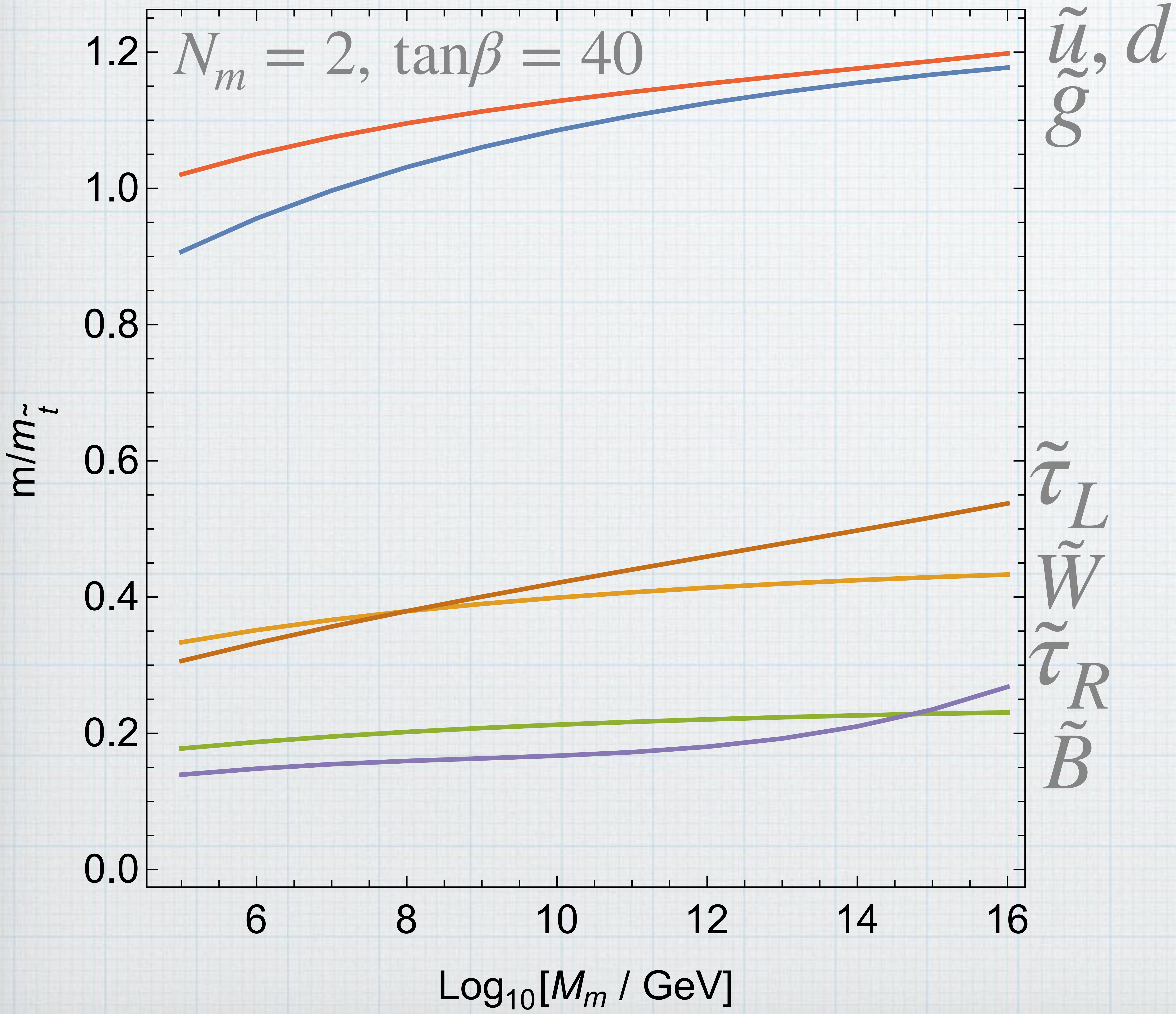
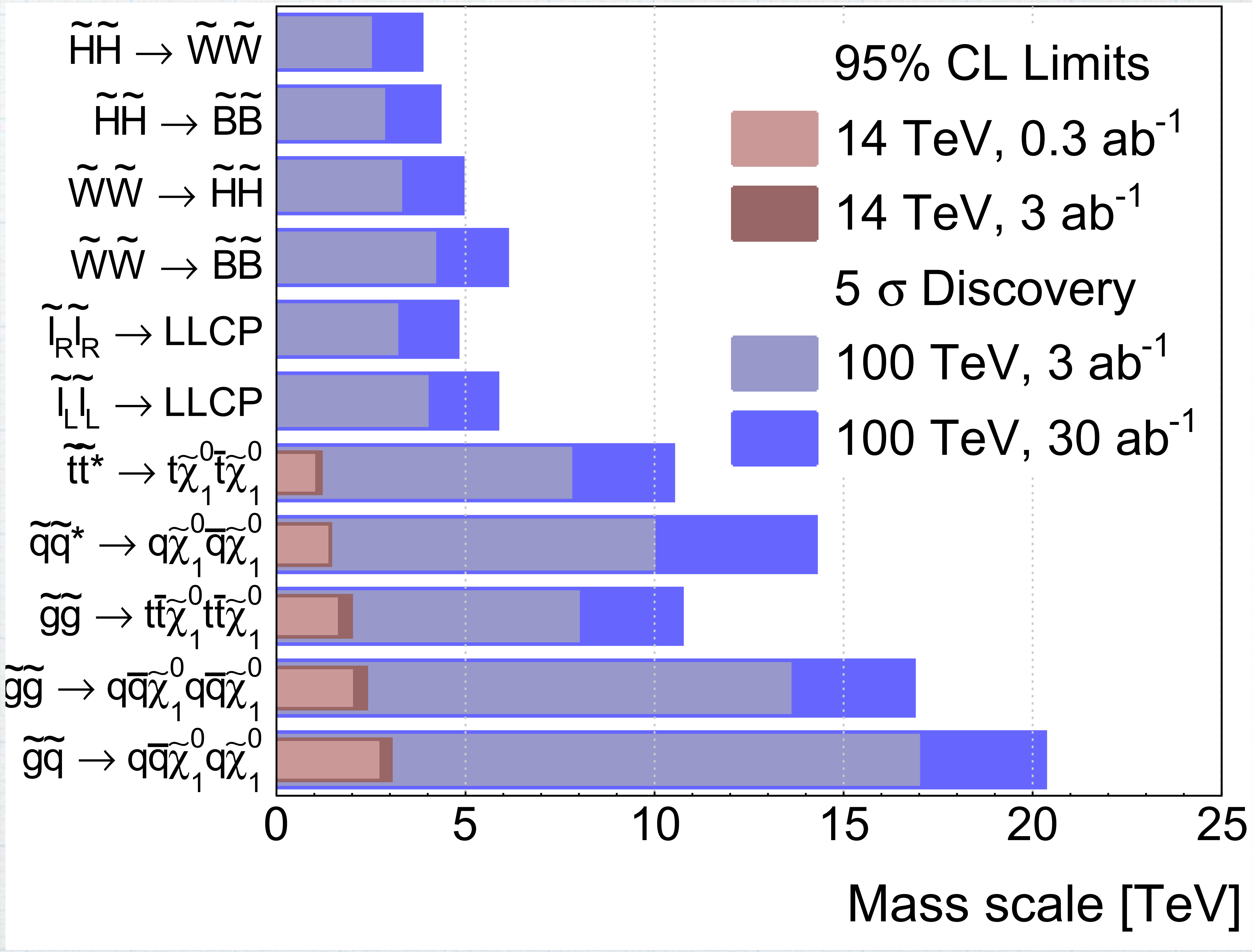
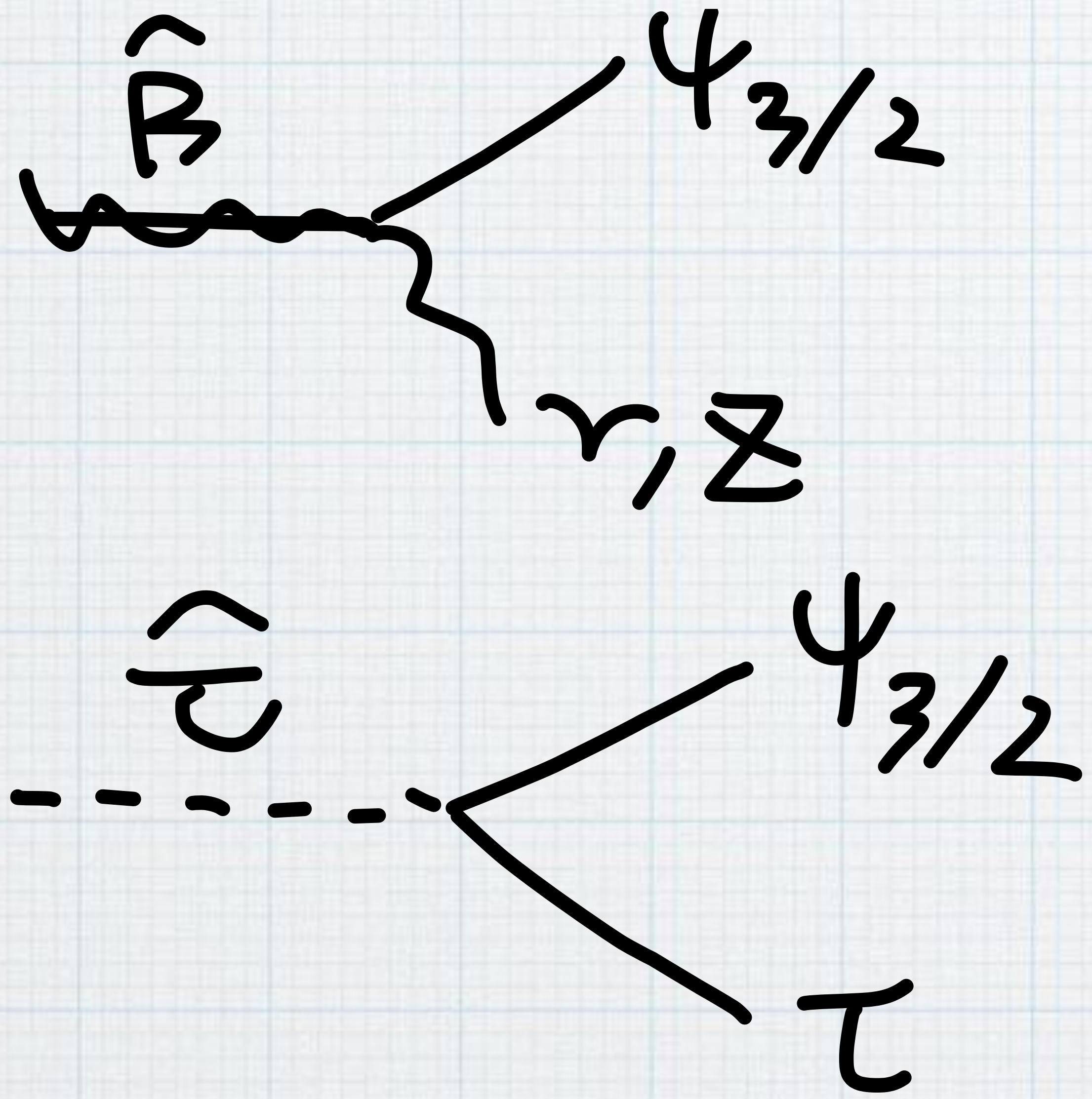




Decay into gravitino



$$c\tau \simeq 10^6 \text{ m} \left(\frac{m_{3/2}}{\text{GeV}}\right)^2 \left(\frac{3 \text{ TeV}}{m_{\text{NLSP}}}\right)^4$$

→ NLSP can be long-lived

ex. charged track from stau NLSP
displaced vertex from bino NLSP

Less assumption because of the

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Mini-split?

Giudice, Luty, Murayama, and Rattazzi (1998)
Wells (2003), Arkani-Hamed and Dimopoulos (2004), ...

Assume that the SUSY-breaking field is charged

scalars obtain masses by Planck-scale suppressed interaction with the SUSY breaking sector

$$\mathscr{L} = \frac{FF^\dagger}{M_{\rm PL}^2}\tilde{q}^\dagger \tilde{q}$$

Mini-split?

Giudice, Luty, Murayama, and Rattazzi (1998)
Wells (2003), Arkani-Hamed and Dimopoulos (2004), ...

Assume that the SUSY-breaking field is charged

coupling with gauginos is suppressed

$$\cancel{F\tilde{g}\tilde{g}}$$

$$\Rightarrow \quad m_{\text{gaugino,tree}} = 0$$

Gaugino masses are given by a quantum effect
(anomaly mediation)

Randall and Sundrum (1998)
Giudice, Lucy, Murayama, and Rattazzi (1998)

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gravitino
sfermions — 100 – 1000 TeV

collider targets

gauginos — 1 – 10 TeV

SM Higgs — 100 GeV

Mini-split

* Compatible with simple dynamical SUSY-breaking mechanisms

$m_{\rm SUSY} \propto \exp\left(-8\pi^2/bg^2\right)$ SUSY-breaking field is often charged

* Gravitino decay does not disturb BBN

$$\tau \simeq 0.1\ \text{sec} \left(\frac{100\ \text{TeV}}{m_{3/2}}\right)^3$$

* No moduli in the SUSY breaking sector

Gaugino masses

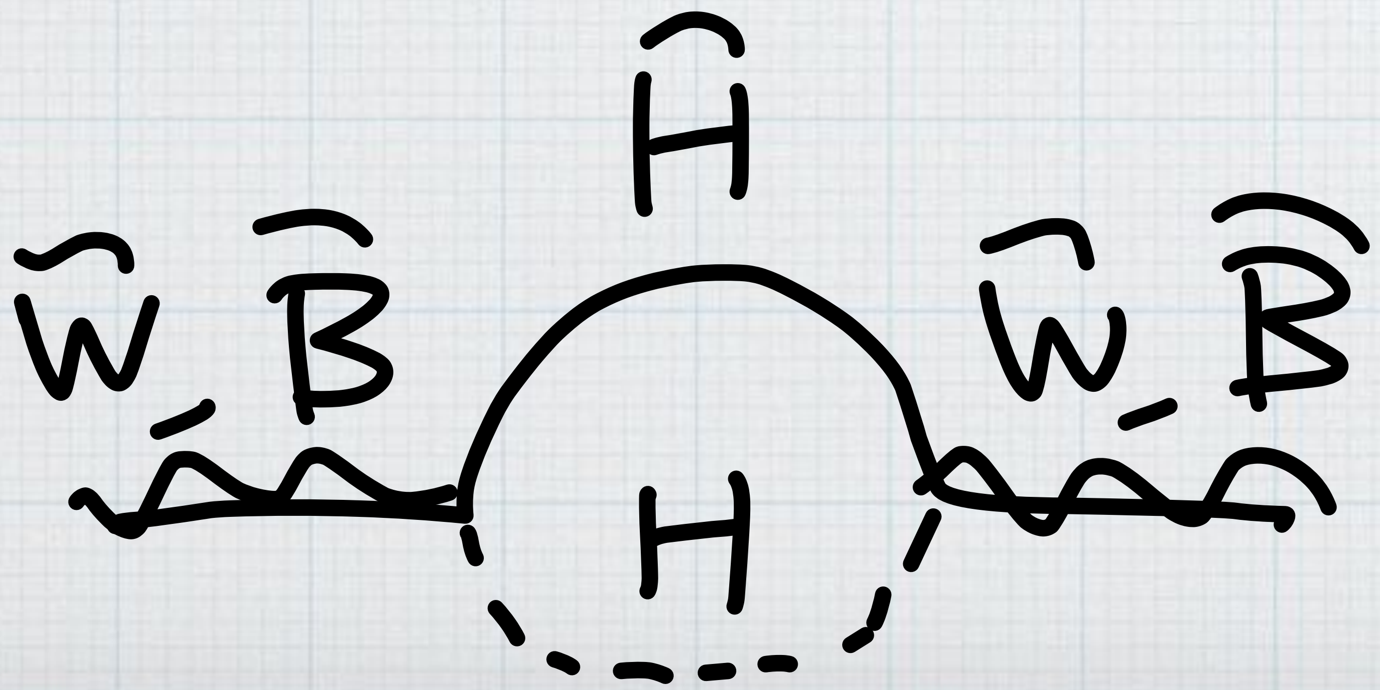
Anomaly mediation

$$m_{\rm bino} : m_{\rm wino} : m_{\rm gluino} \simeq 3 : 1 : 10$$

$$\propto m_{3/2}$$

$+$

Correction from Higgsino



$\propto \mu$

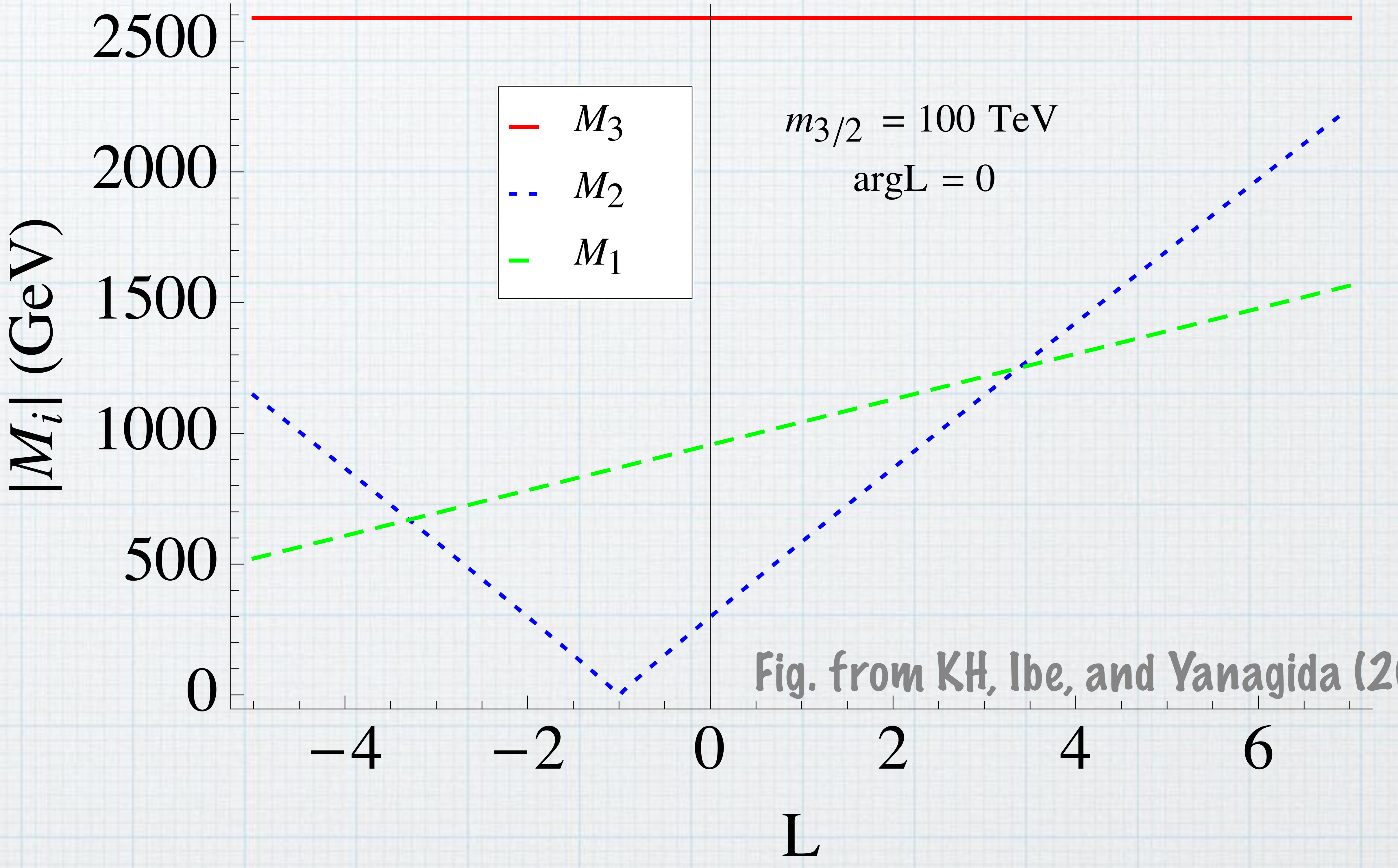
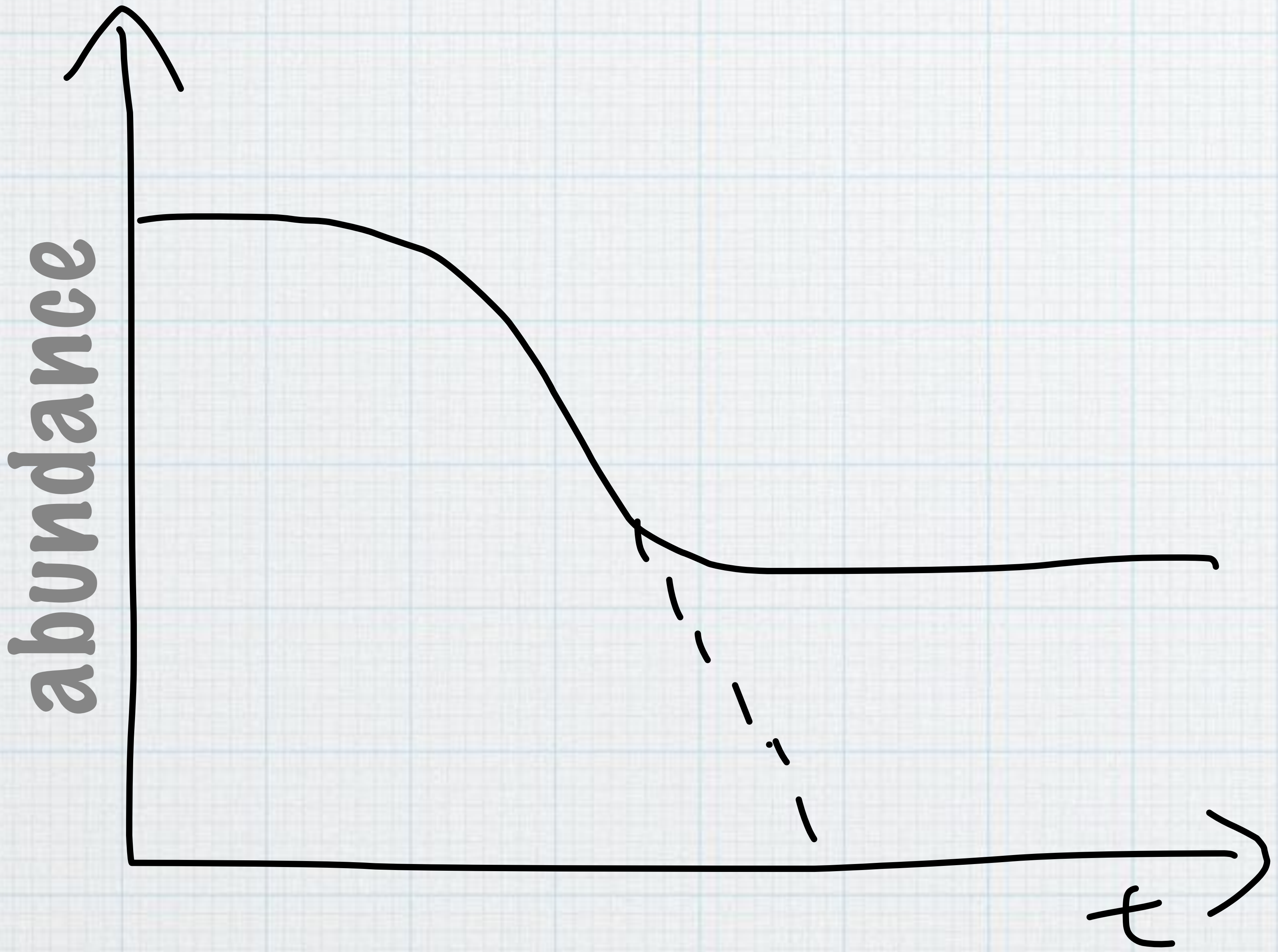


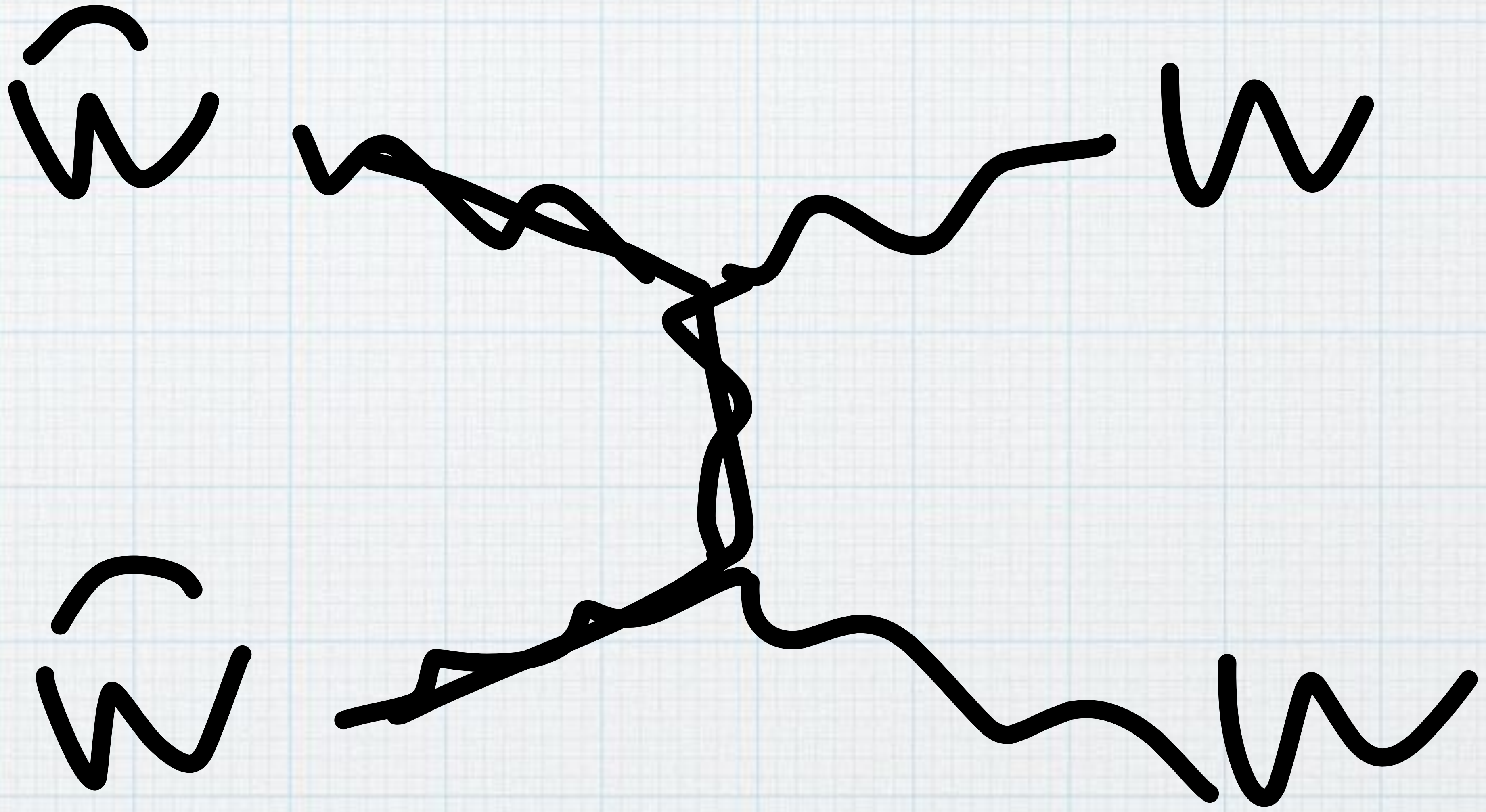
Fig. from KH, Ibe, and Yanagida (2013)

wino or bino LSP

$m_{\rm gluino} > 2 m_{\rm wino}$ for wino LSP

Thermal wino DM





$$m_{\rm wino} \simeq 3\ \text{TeV}, \quad m_{\rm gluino} \gtrsim 6\ \text{TeV}$$

Wino be probed by FCC-hh (Natsumi Nagata's talk)

Non-thermal wino DM

$\longrightarrow t$

reheating

T_R

$gg \to \tilde{g}\psi_{3/2}$

wino freeze-out

$T = 10 - 100\ \mathrm{GeV}$

gravitino decay

$T = 10\ \mathrm{MeV}$

$\psi_{3/2} \to \tilde{W} + W$

$$\frac{\Omega_{\tilde{W}}}{\Omega_{\mathrm{DM}}} = \frac{m_{\mathrm{wino}}}{1\ \mathrm{TeV}} \frac{T_R}{2 \times 10^9\ \mathrm{GeV}}$$

Ex . $m_{\mathrm{wino}} \simeq 1\ \mathrm{TeV}, \quad m_{\mathrm{gluino}} \gtrsim 2\ \mathrm{TeV}$

Gluino search

$$\tilde{g}\tilde{g} \to qq\bar{q}\bar{q}\tilde{\chi}^0\tilde{\chi}^0$$

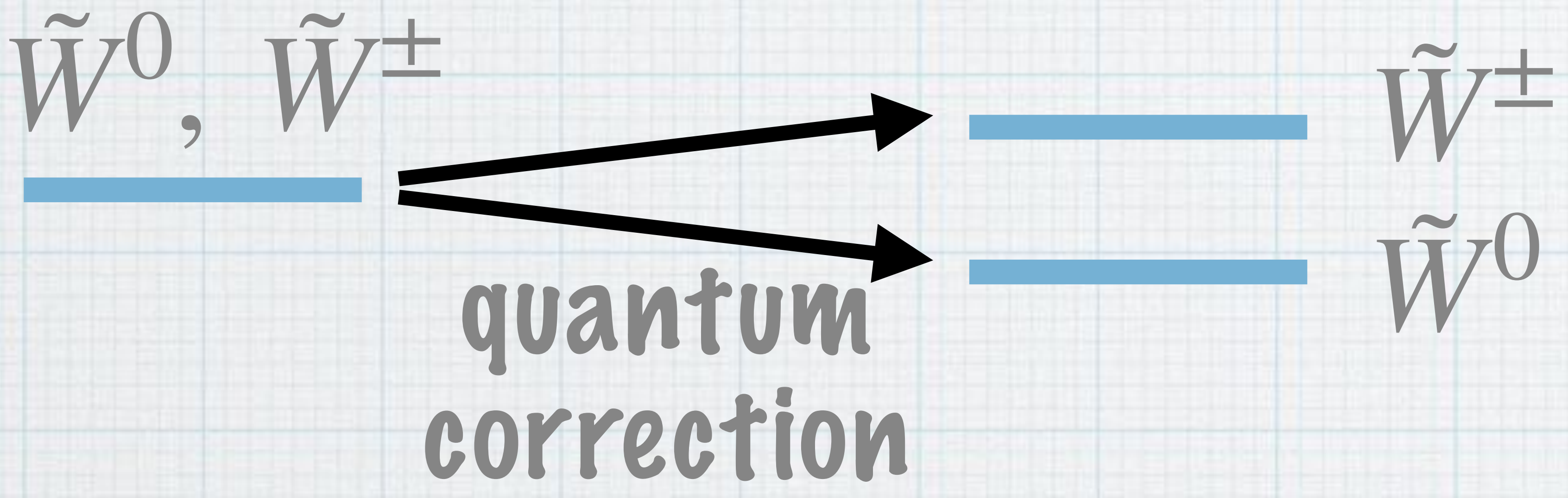
LHC (14 TeV, 3 ab^{-1}) : $m_{\text{gluino}} < 3$ TeV
FCC-hh (100 TeV, 3 – 30ab^{-1}) : $m_{\text{gluino}} < 13 - 17$ TeV

→ **FCC-hh will cover part of the parameter space**

Gluino search

* Decay products include a long-lived charged wino

e.g., Ibe, Matsumoto and Sato (2012)



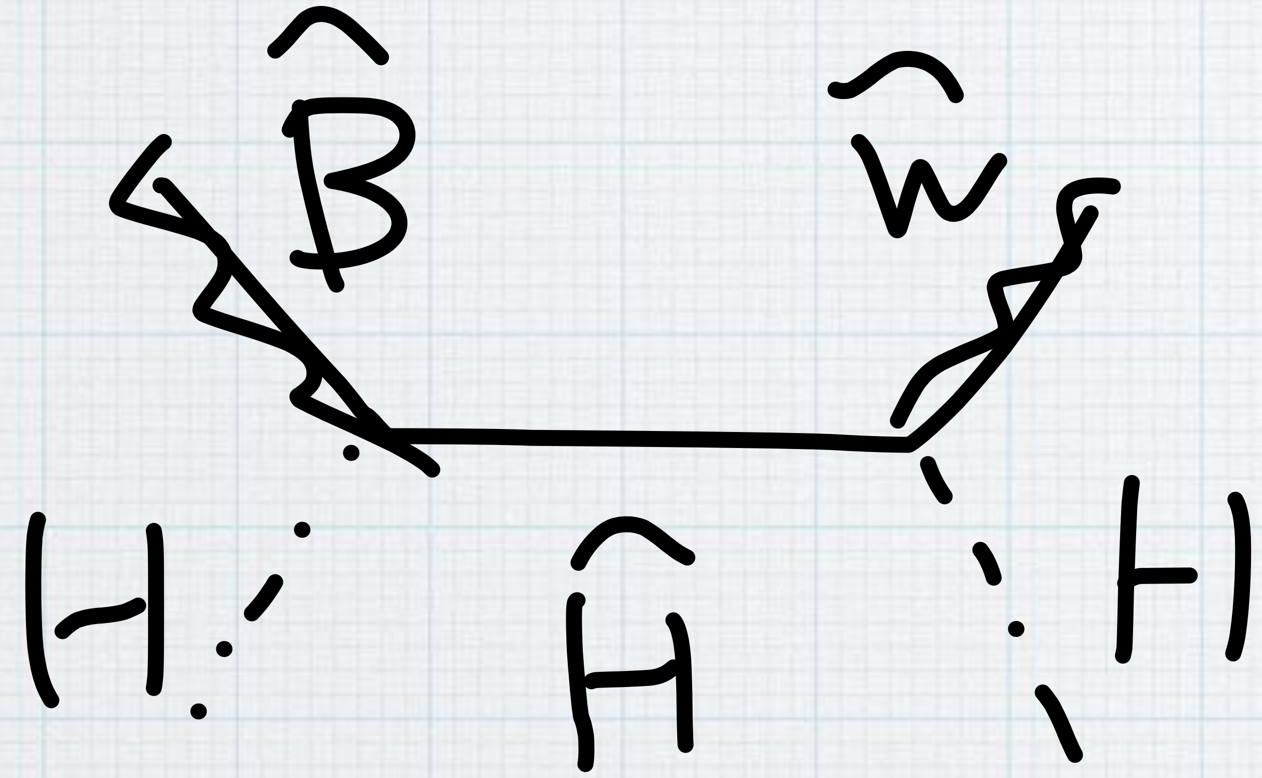
$$c\tau_{\tilde{W}^\pm} \simeq 7\ \mathrm{cm}$$

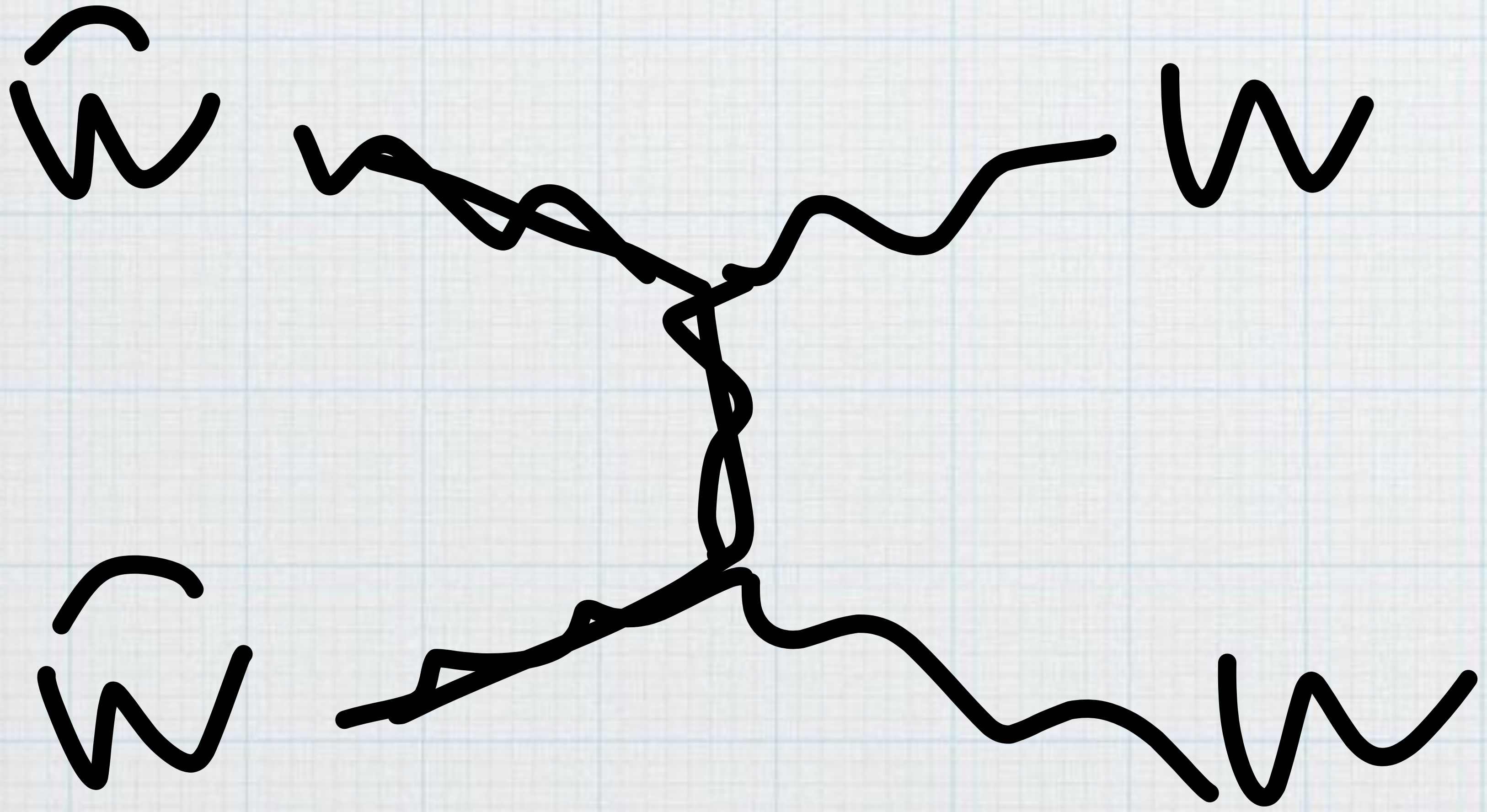
* The lifetime of the gluino itself may be long

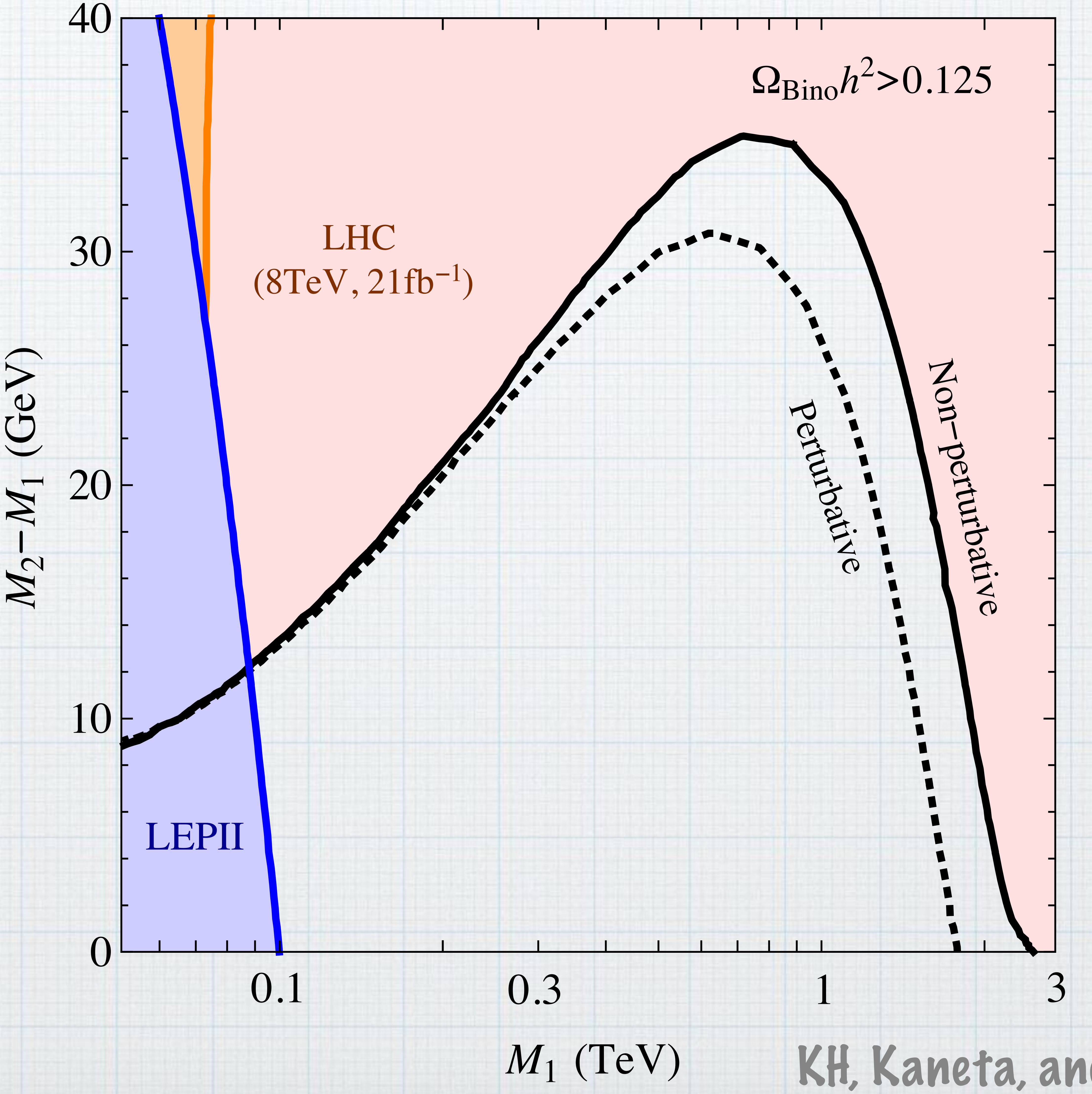
$$c\tau_{\tilde{g}} = O(1)\ \mathrm{mm} \left(\frac{4\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{m_0}{1000\ \mathrm{TeV}}\right)^4$$

Slight improvement of sensitivity by displaced vertices or disappearing tracks??

Wino-bino coannihilation

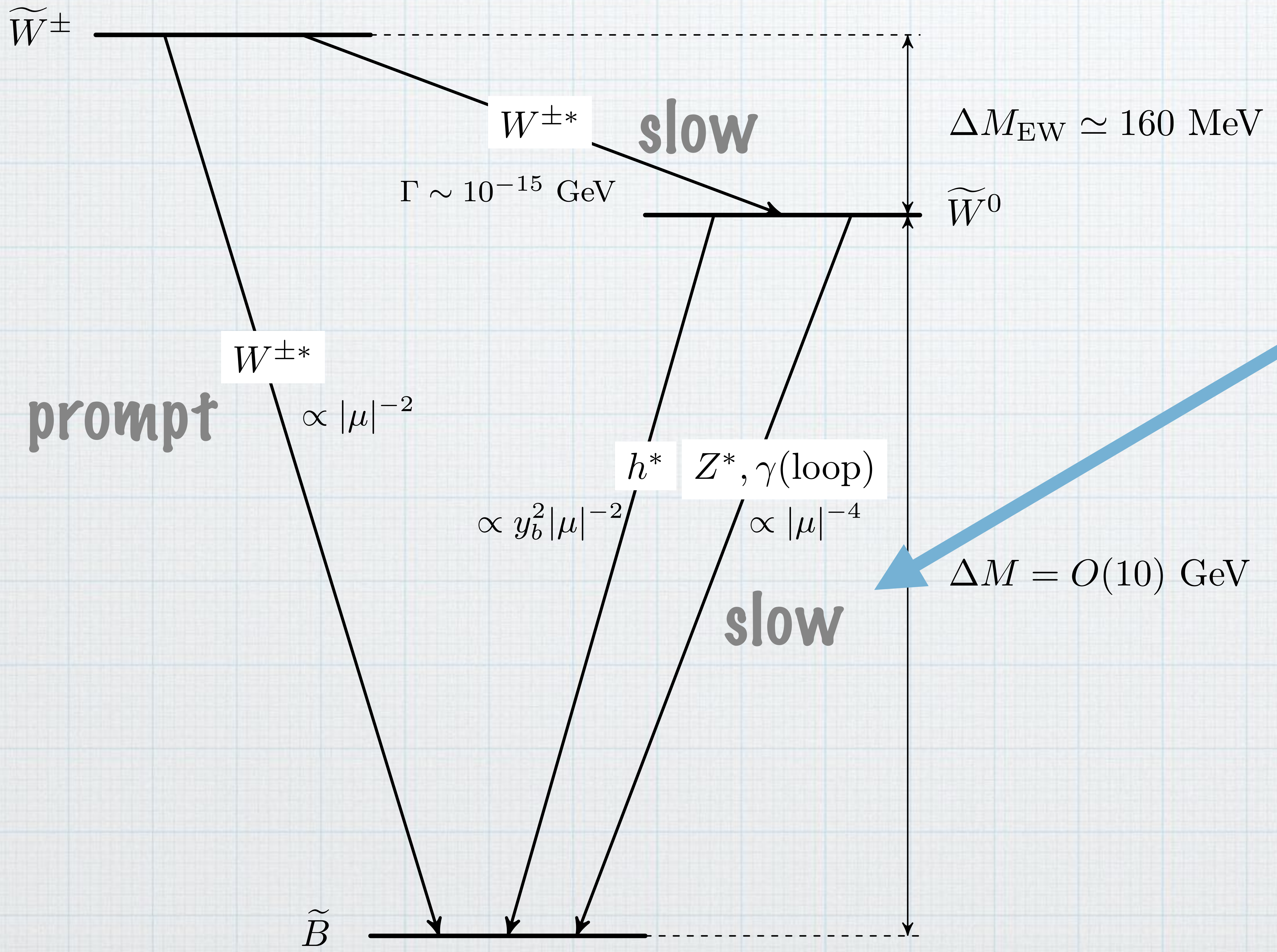






KH, Kaneta, and Matsumoto (2014)

Wino-bino at colliders



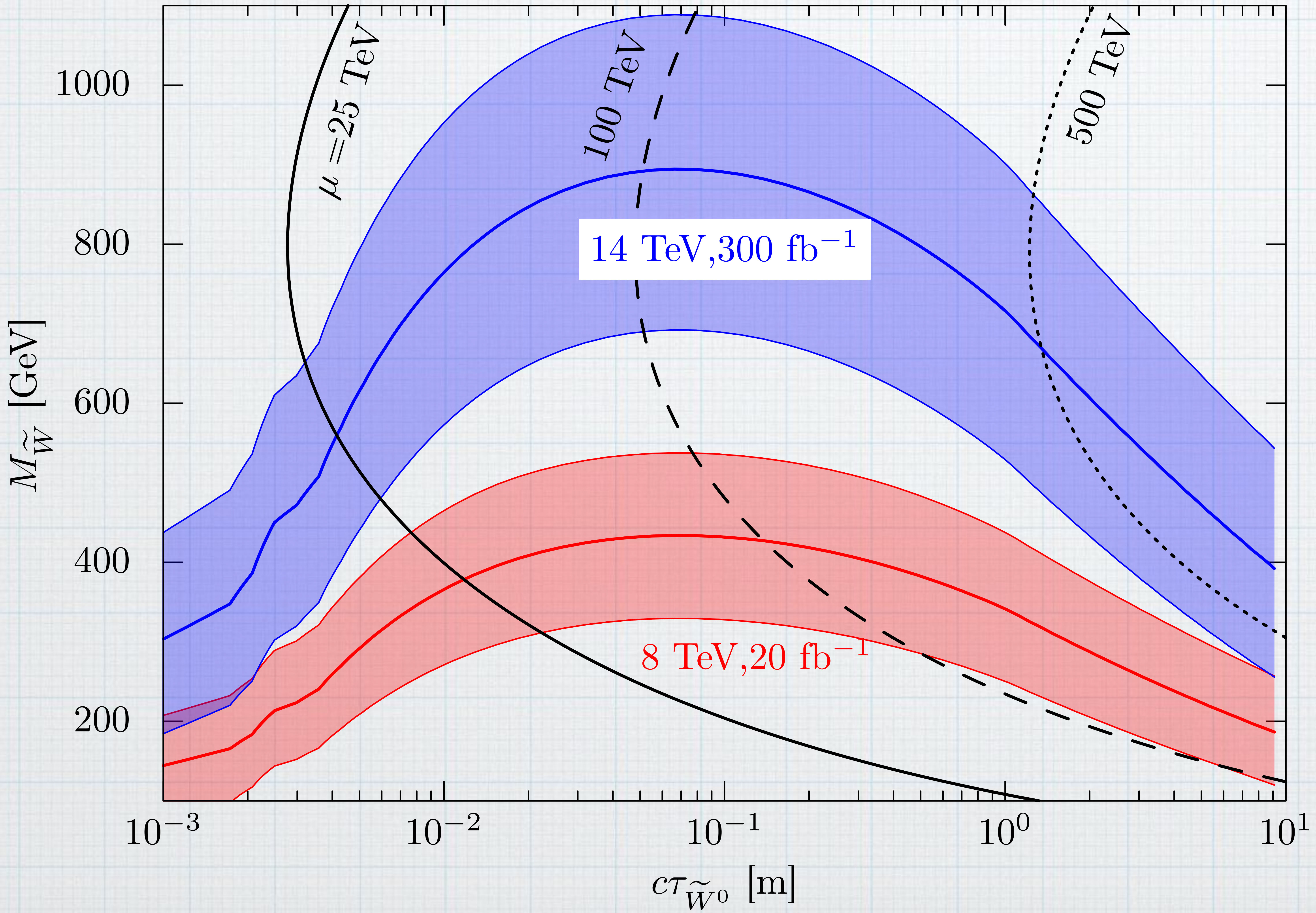
Nagata, Otono and Shirai (2014)

$$c\tau \gtrsim \text{cm}$$

Displaced vertex search

Wino-bino at colliders

Nagata, Otono and Shirai (2014)



FCC-hh?

Higgsino around TeV?

$$V = (\mu^2 + m_{H_u}^2)|H_u|^2 + (\mu^2 + m_{H_d}^2)|H_d|^2 + (B\mu H_u H_d + \mathrm{h.c.})$$

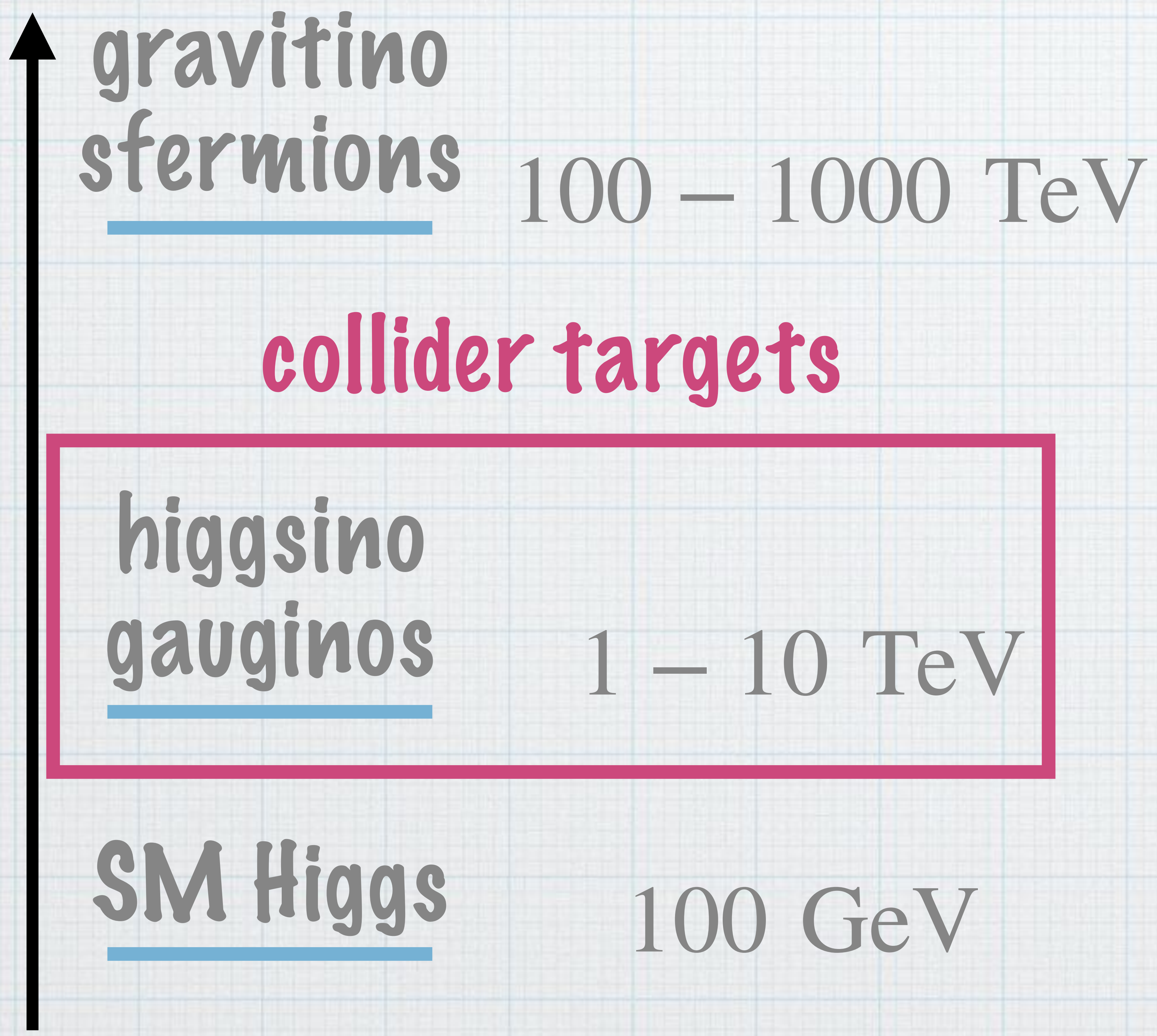
To avoid too large Higgs mass, $\tan\beta \simeq 2\frac{m_{H_u}^2 + m_{H_d}^2 + 2\mu^2}{B\mu} = O(1)$

supergravity gives $B \sim m_{3/2} \sim m_0$

We need $m_{H_d}^2 \ll m_{\rm stop}^2$, which is possible if $m_{H_d}^2$ at a high energy scale is small

$$m_{H_d}^2(10\ \mathrm{TeV}) \simeq 0.02 m_0^2 + \cdots$$

Higgsino around TeV



Very rich phenomenology

- Collider
- Dark matter detection

Natsumi Nagata's talk

- Electric dipole moment

Giudice and Romanio (2005)

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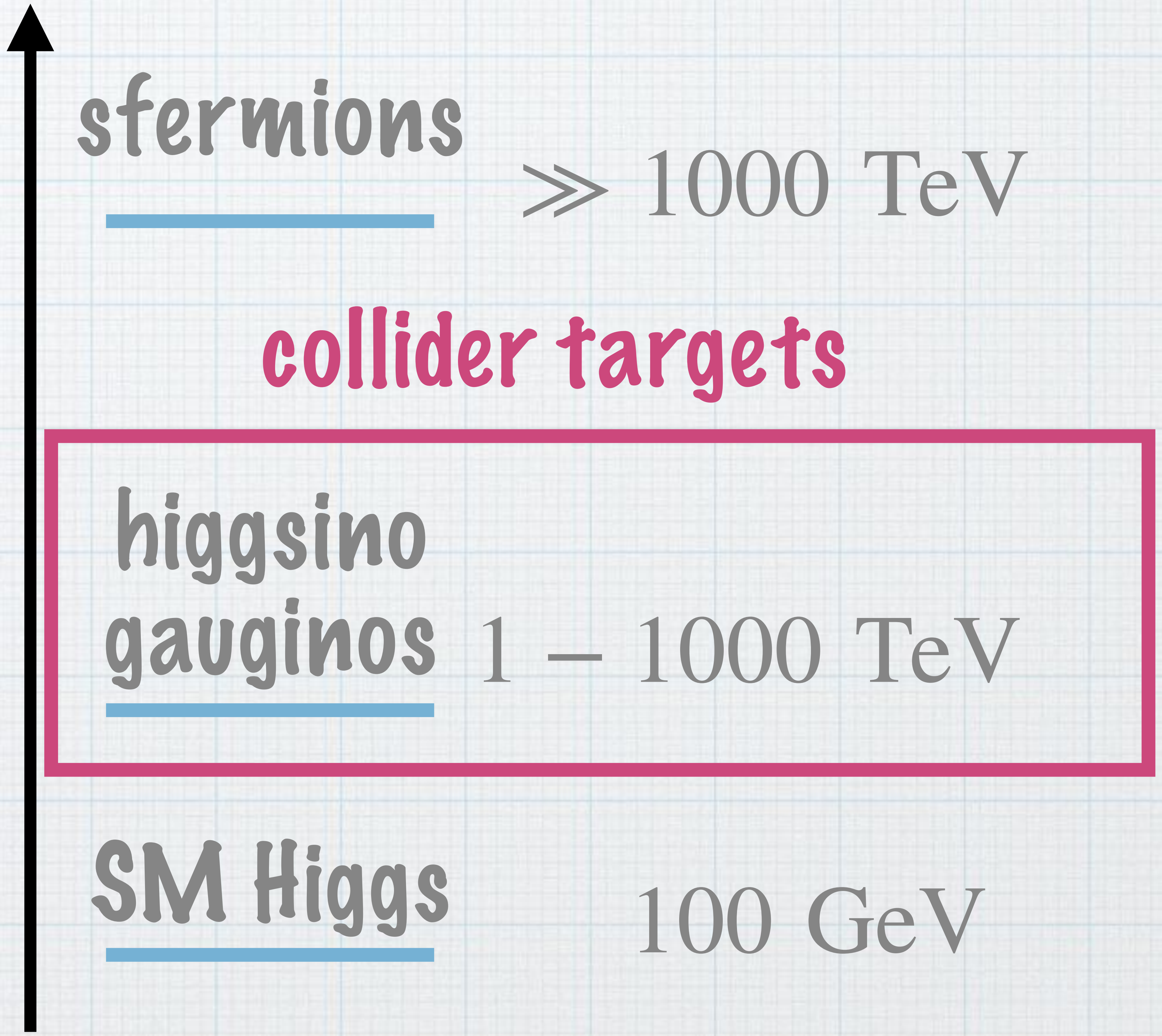
Unification?

Sfermions are in GUT complete multiplets
The effect of heavy higgs is minor

Light Higgsino and gauginos are enough
to maintain precise gauge coupling unification

Arkani-Hamed and Dimopoulos (2004)



Dark Matter?

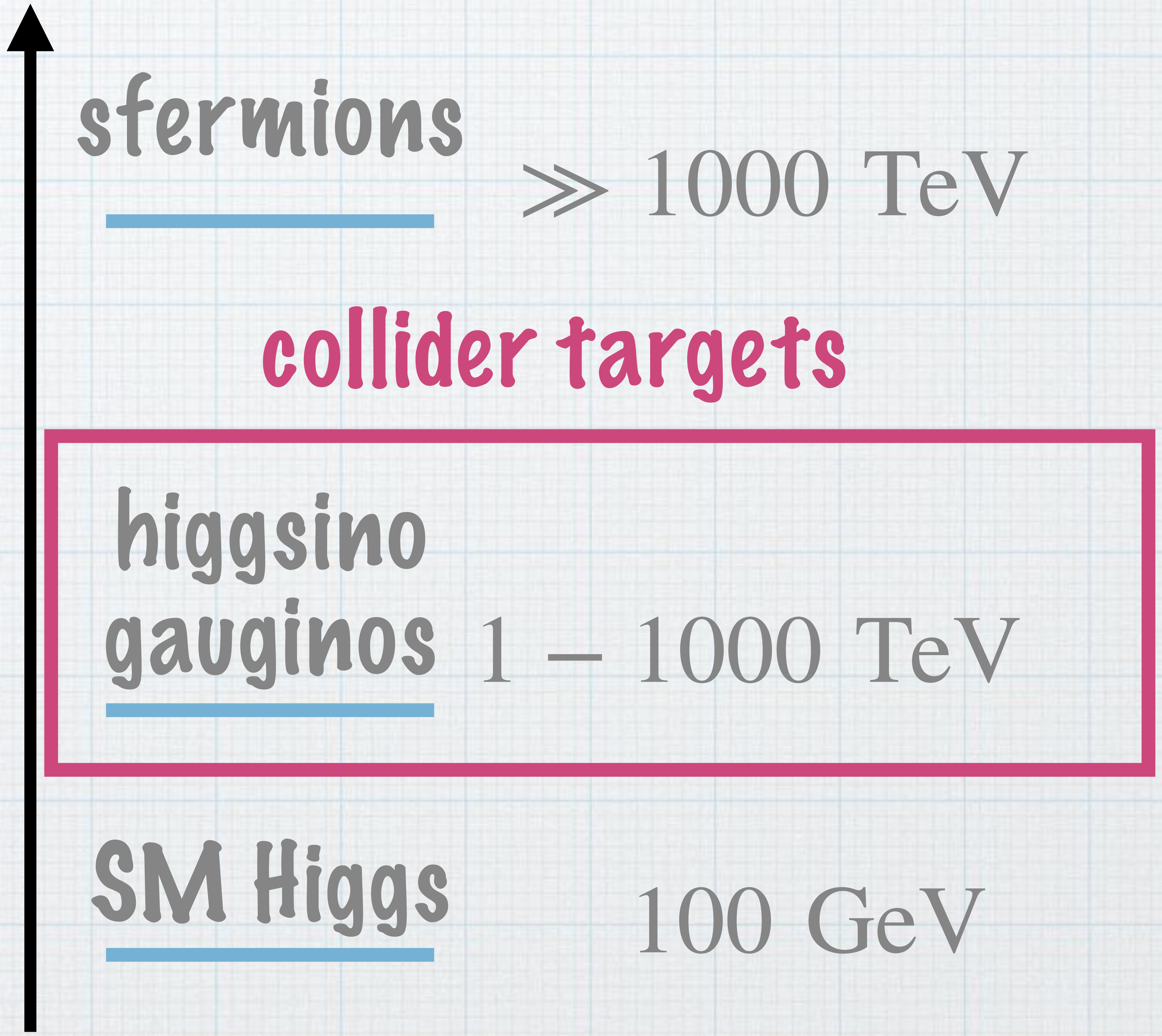
$$m_{\text{higgsino}} < 1\ \text{TeV}$$

or

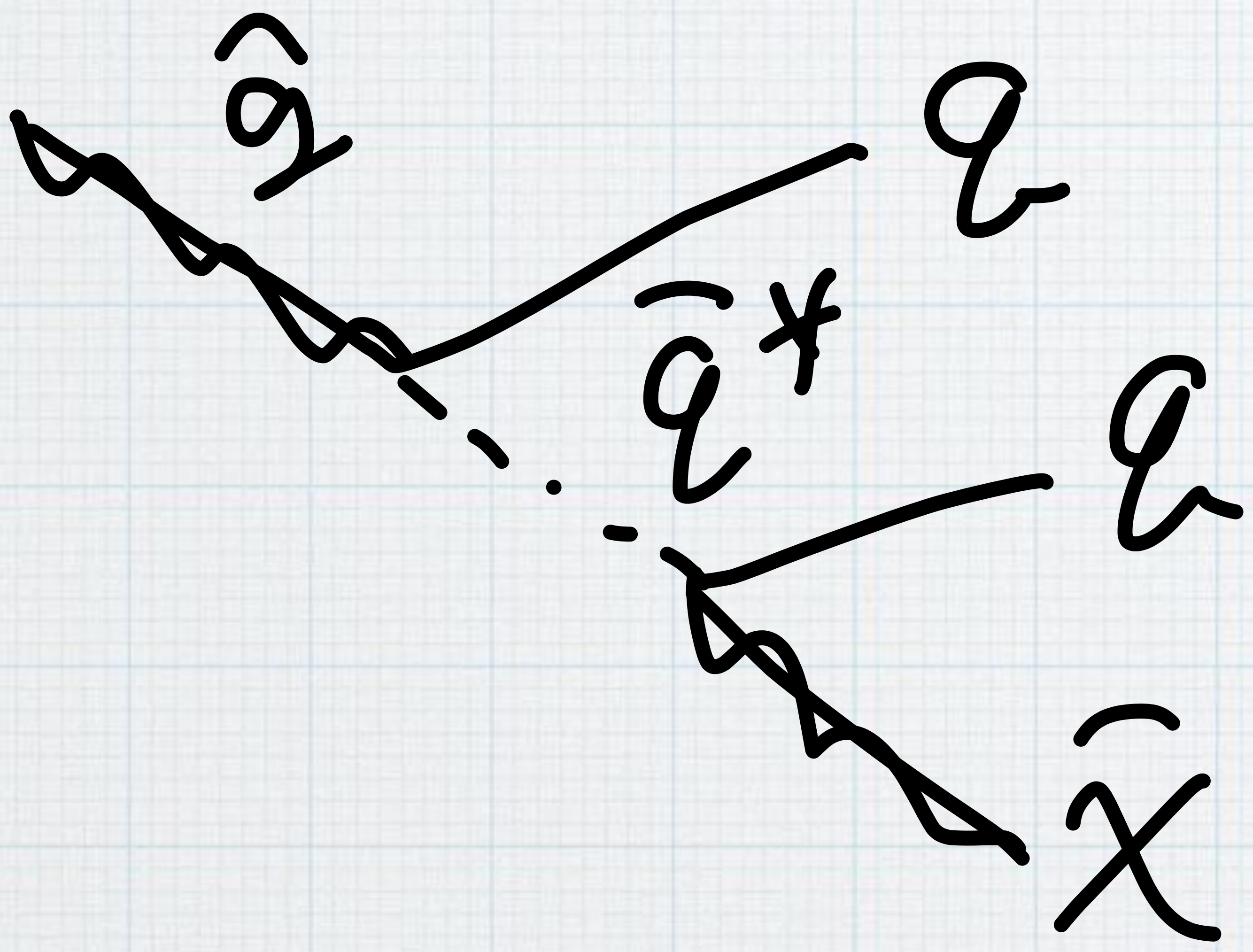
$$m_{\text{wino}} < 3\ \text{TeV}$$

similar EW-kino phenomenology as mini-split SUSY

Natsumi Nagata's talk



Gluino search



Arkani-Hamed and Dimopoulos (2004)

$$c\tau \sim 10^8\ \mathrm{m} \left(\frac{m_0}{10^{10}\ \mathrm{GeV}} \right)^4 \left(\frac{10\ \mathrm{TeV}}{m_{\mathrm{gluino}}} \right)^5$$

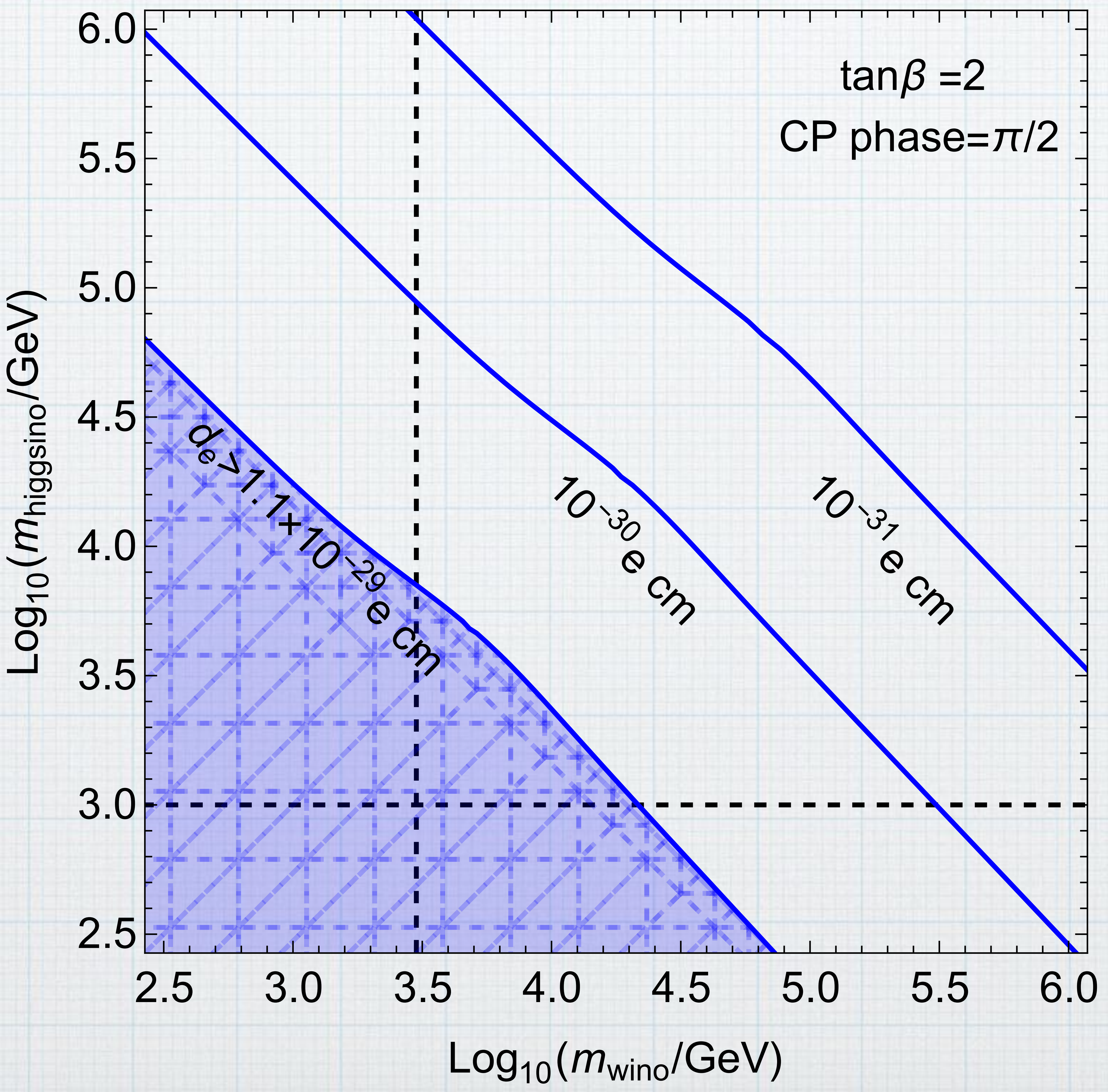
Stable at collider time scale : R-hadron

Summary

* Supersymmetry remains a well-motivated extension of the Standard Model
* Canonical scenarios can be probed by production of sparticles at the FCC-hh

Back up

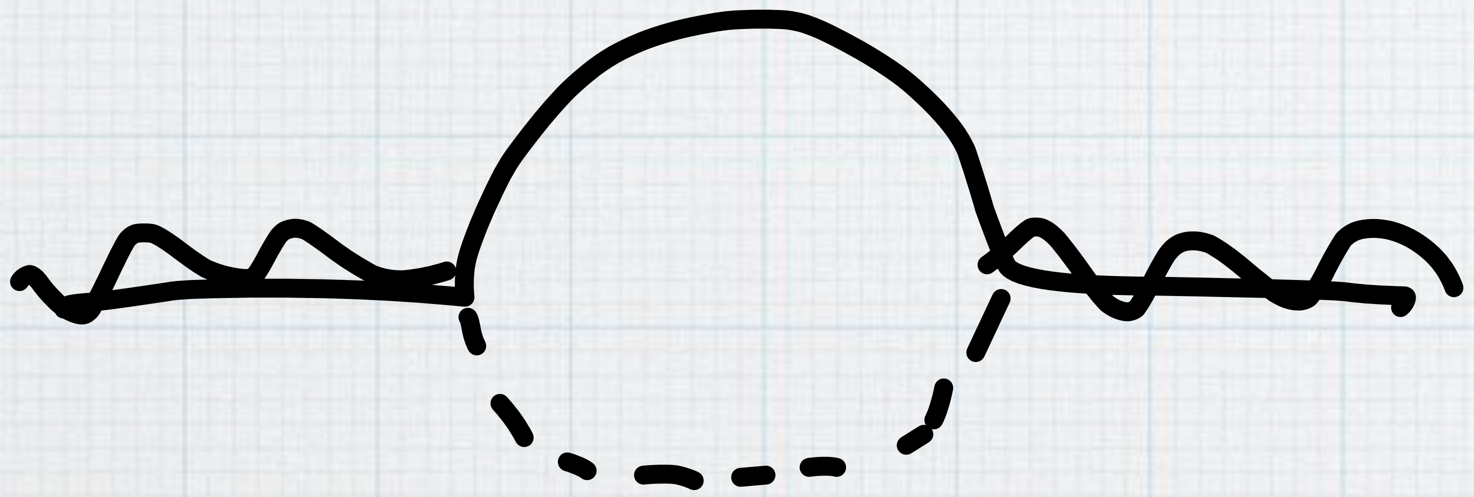
Electron EDM



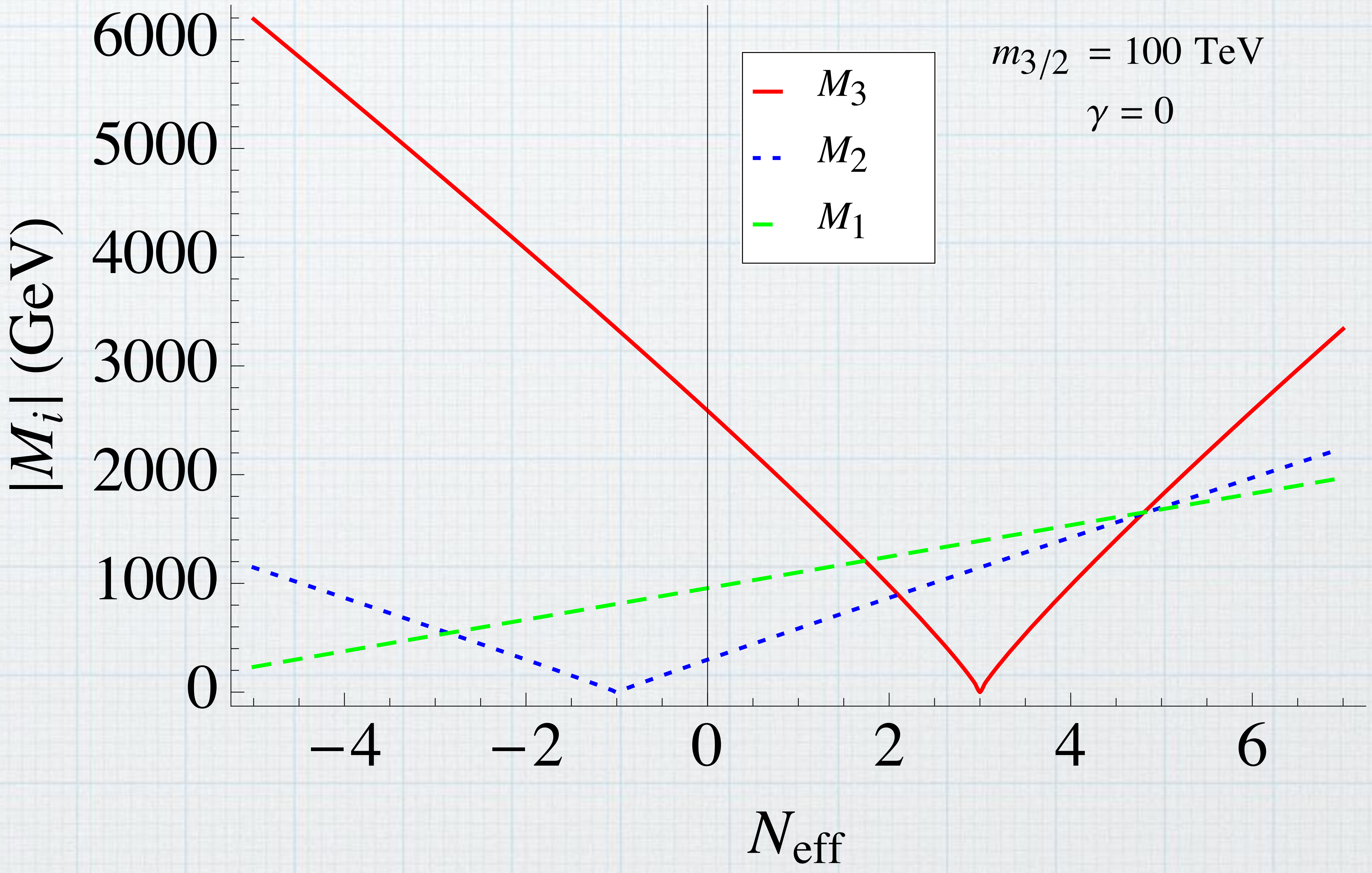
More on gaugino masses

Gaugino masses can receive further corrections

Ex. KSVZ QCD axion model



KSVZ fermions



- gluino mass can be even lighter

Fig. from KH, Ibe, and Yanagida (2013)

Gravitino DM in gauge mediation

$$T_R < 5 \times 10^5 \text{ GeV} \frac{m_{3/2}}{10 \text{ GeV}} \left(\frac{10 \text{ TeV}}{m_{\text{gluino}}} \right)^2$$