Split SUSY

Perspectives from Cosmology and Collider Physics

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March 25, 2017

Based in part on:

MR and Wei Xue, “SUSY’s Ladder: reframing sequestering at Large Volume,” arXiv:1512.04941

Prateek Agrawal, JiJi Fan, MR, and Wei Xue, “Deciphering the MSSM Higgs Mass at Future Hadron Colliders,” arXiv:1702.05484

1. Model-Building and Cosmology

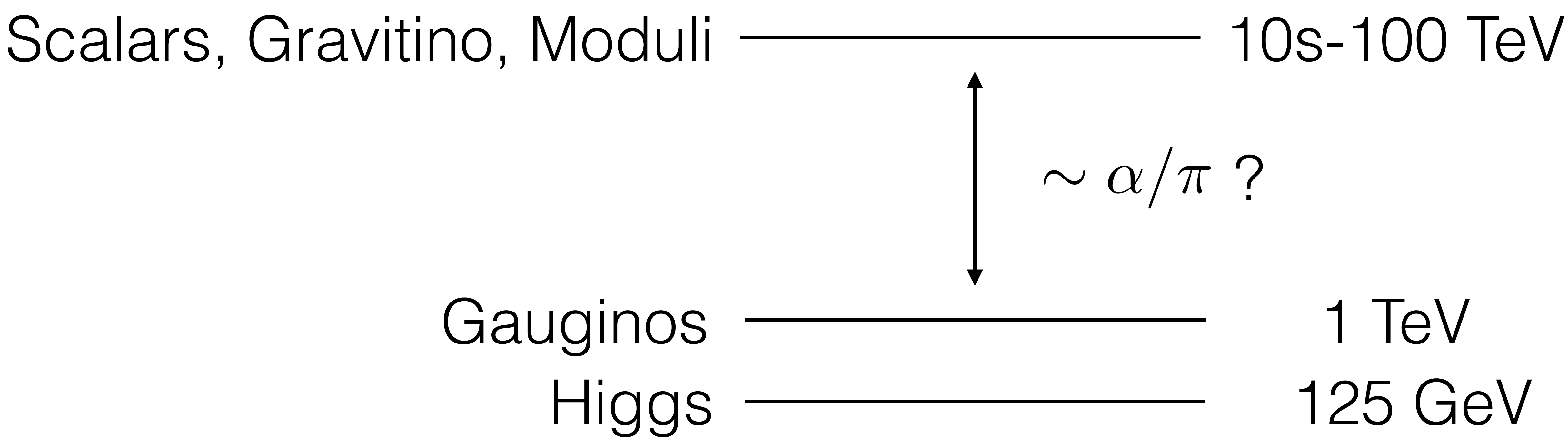
Reasons to like split SUSY

- Theory: simple models of SUSY breaking (gauge mediation, AMSB, …) tend to give

$$m_\lambda \ll m_{\widetilde{f}}$$

- Easy to achieve m_h = 125 GeV from loops
- Consistent with gauge coupling unification
- Simplicity: data is forcing us toward some amount of tuning anyway; why build elaborate models that require 1% tuning?
- Could be consistent with SUSY dark matter

Split SUSY, Take 1:



- Heavy scalars (10s of TeV) at large tan β: right Higgs mass
- Loop factor: arises in AMSB (Giudice, Luty, Murayama, Rattazzi ’98) and some moduli mediation
- Late-time gravitino and moduli decays populate nonthermal dark matter, e.g. winos (Moroi, Randall ’99; Kane et al.)

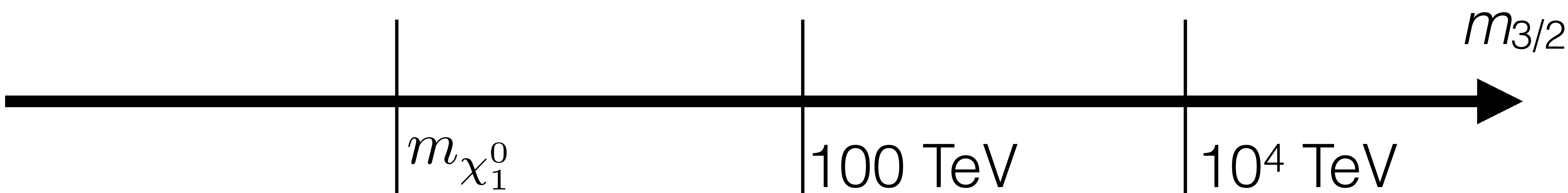
Many recent papers on “Mini-Split”: Arvanitaki et al., Arkani-Hamed et al., …

Gravitino Decays

Grav. strength $\Gamma_{3/2} = \frac{193}{384\pi}\frac{m_{3/2}^3}{M_{\rm Pl}^2}$. Decays when CMB temp. is

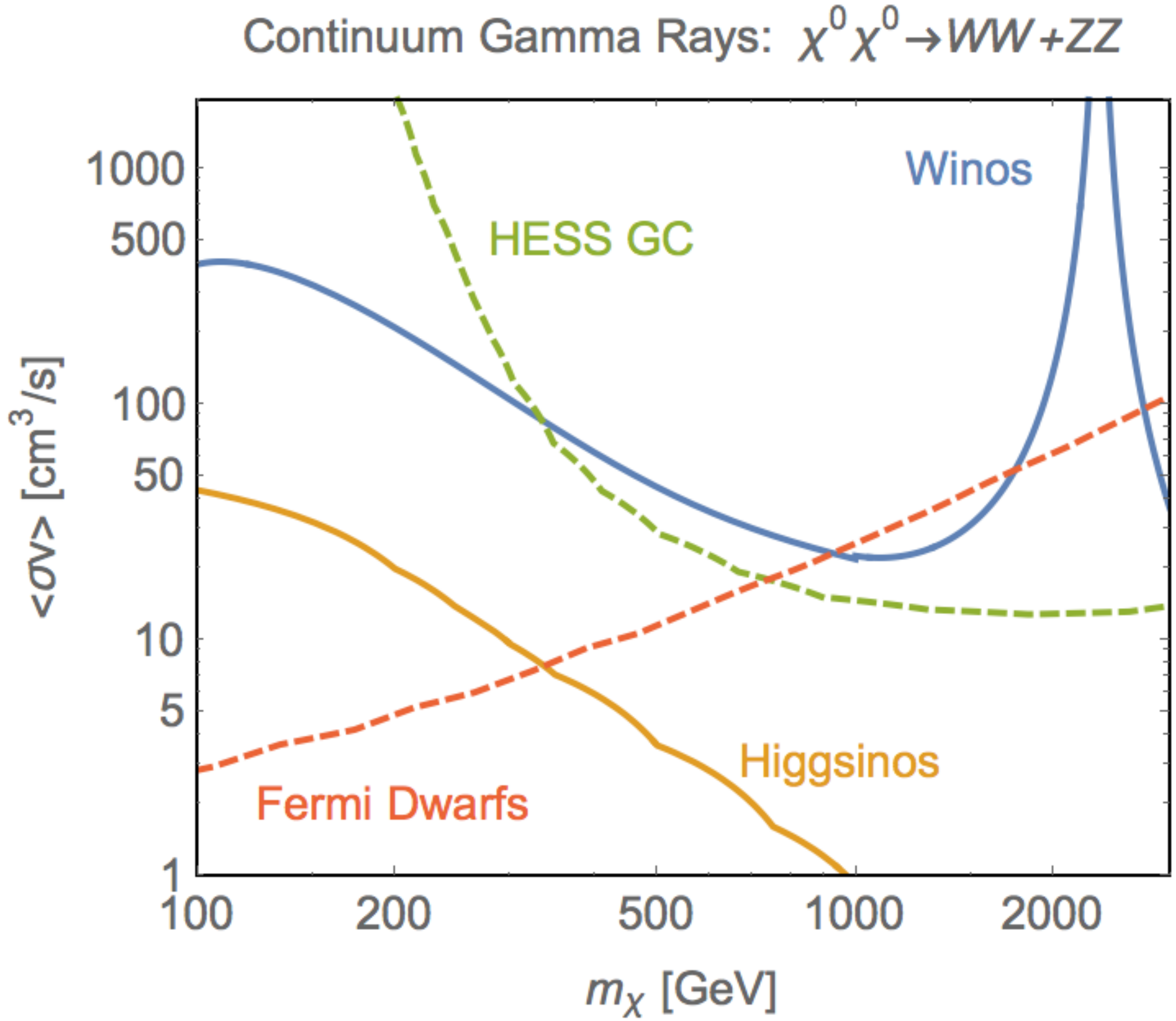
$$T_{dec} \approx 10\ \text{MeV}\left(\frac{m_{3/2}}{100\ \text{TeV}}\right)^{3/2}$$

Regimes of gravitino mass:



Grav. LSP; tends to overclose. Light sparticles	Grav. decays spoil BBN	Grav. decays alter DM relic density	Grav. decays safe: $T_{dec} > T_{FO}$

Trouble: Indirect Detection



Continuum photons: Fermi-LAT dwarf galaxy bounds (1503.02641) and HESS galactic center with NFW profile (1607.08142)

Also line searches at high energies. Winos essentially ruled out as 100% DM! Higgsinos ruled out to ~340 GeV.
Cohen, Lisanti, Pierce, Slatyer 1307.4082; Fan, MR 1307.4400

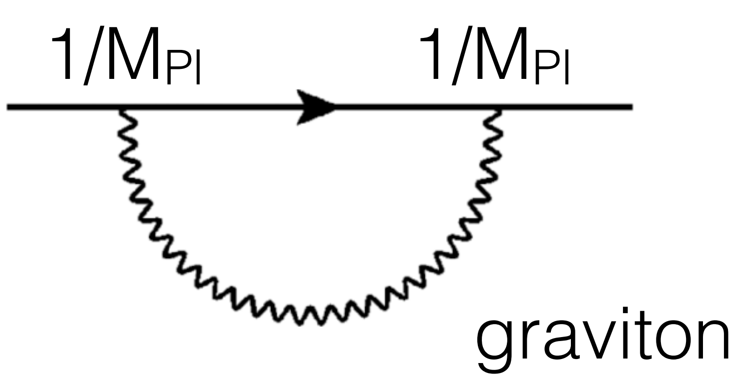
Ways Out?

- R-parity violation? Lose SUSY dark matter.
- Thermal inflation to dilute unwanted relics?
- MSSM decays to hidden sectors?
- Can we just **decouple** the gravitino while keeping DM at the weak scale?

Decoupling the Gravitino

Can we keep gauginos at a TeV (e.g. for dark matter, LHC signals) while putting the gravitino above 10^4 TeV?

Dimensional analysis / EFT: *yes*, but only in a theory with a low cutoff.



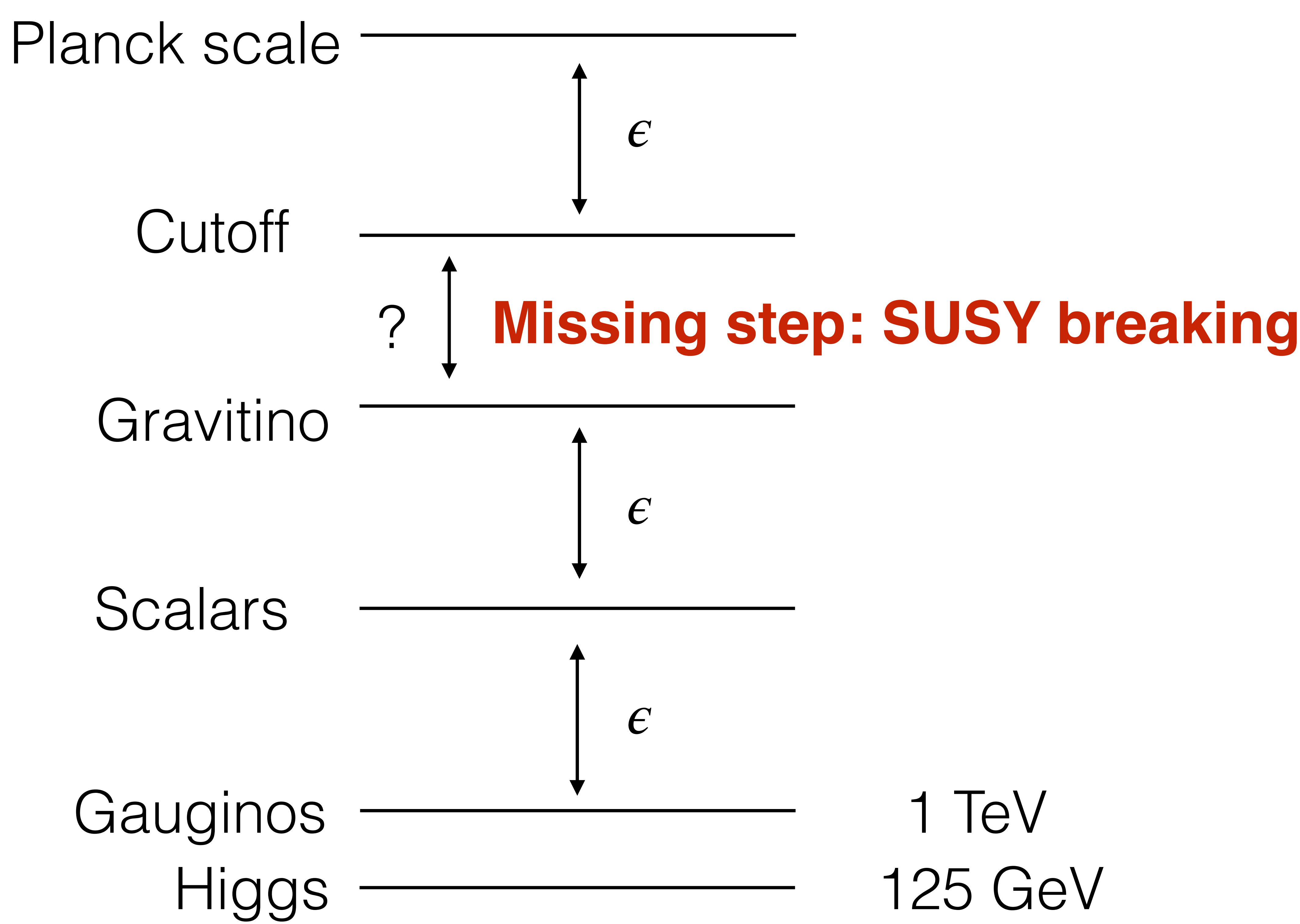
No SUSY: $\delta m^2 \sim \frac{\Lambda^4}{16\pi^2 M_{\rm Pl}^2}$

SUSY: $\delta m^2 \sim \frac{\Lambda^2 m_{3/2}^2}{16\pi^2 M_{\rm Pl}^2}$

Gauginos: gravitino mass breaks *R* and chiral symmetries

$$\delta m_\lambda \sim \frac{\Lambda^2}{16\pi^2 M_{\rm Pl}^2} m_{3/2}$$

Split SUSY, Take 2:



Where Did AMSB Go?

A naive expectation is that we ***always*** have

$$m_{\text{gaugino}} \gtrsim \frac{\alpha}{\pi} m_{3/2} \qquad \text{(naive)}$$

due to anomaly mediation. But AMSB can be suppressed! A useful approach is to work in superspace with the *conformal compensator* formalism, in which we have:

$$m_{\text{gaugino}} \gtrsim \frac{\alpha}{\pi} F_\phi \qquad \text{(correct)}$$

Key phenomenological question to decouple the gravitino (and, possibly, moduli) problems:

How to achieve $F_\phi \ll m_{3/2}$, i.e., **no-scale structure**?

Where Do We Find No-Scale Structure?

A simple, classic example is compactifying 5D supergravity on a circle. Gives rise to what I'll call **"single-field no-scale structure"**:

$$\int d^4\theta \, \phi^\dagger \phi \, (T + T^\dagger)$$

If this is the ***only*** term involving T in the Lagrangian,

$$\frac{\delta}{\delta F_T^\dagger} : \qquad F_\phi = 0$$

Ellis, Enqvist, Nanopolous '84
Luty, Sundrum '99
Arkani-Hamed, Dimopoulos '04

Scalar field with kinetic term *only* via mixing with gravity!

Single-Field No-Scale

MR and Xue, 1512.04941

When can an overall rescaling of *n* extra dimensions provide no-scale structure? KK reduce and Weyl transform to **remove** volume mode's kinetic term:

$$\mathcal{L} = -\frac{1}{16\pi G_d}\int d^d x \sqrt{-g}\mathcal{R}L^\alpha, \quad \text{where } \alpha = \sqrt{\frac{n(n+d-2)}{d-1}}$$

Want L^α to be **real part of chiral superfield** with shift symmetry. So when is α an **integer *p***? Then imaginary part of superfield can come from ***p*-form gauge field**.

Only two integer solutions:

$d = 4$:

$n = 1$, $p = 1$. 5D → 4D, 1-form gauge field

$n = 6$, $p = 4$. 10D → 6D, 4-form gauge field

Single-Field No-Scale

MR and Xue, 1512.04941

It isn't an accident that phenomenological models of no-scale structure have been discussed in the literature mostly in two cases:

5D SUGRA compactified on a circle
10D Type IIB SUGRA at large volume
(IIB, not IIA, because of the 4-form)

Any other case will involve multiple fields enforcing no-scale and is likely less robust.

Only two integer solutions:

$d = 4$:
$n = 1$, $p = 1$. 5D → 4D, 1-form gauge field
$n = 6$, $p = 4$. 10D → 6D, 4-form gauge field

Need to study moduli stabilization and SUSY breaking to complete the spectrum I drew earlier.

Decoupled gravitino problem, but not the moduli problem.

For the IIB case, we can draw on the well-studied string theory **Large Volume Scenario** for SUSY breaking:

Balasubramanian, Berglund, Conlon, Quevedo '04
Conlon, Quevedo, Suruliz '05
…
Aparicio, Cicoli, Krippendorf, Maharana, Muia, Quevedo '14

These papers are full of mysterious cancelations. We found that they are all easily understood by working in the right superspace formalism: Cheung-D'Eramo-Thaler gauge.

Cheung/D'Eramo/Thaler Gauge

Work in superspace with a conformal compensator:

$$\mathbf{\Phi} = e^{\mathbf{Z}/3}(1 + f_\Phi \theta^2)$$
$$\mathbf{Z} = \frac{1}{M_{\rm Pl}^2}\left[\left\langle K/2 - iM_{\rm Pl}^2 \arg W\right\rangle + \langle K_i \rangle \left(\mathbf{X^i} - \left\langle X^i \right\rangle\right)\right]$$

removing kinetic mixing of modulus and graviton.
No-scale limit: conformal compensator $\mathbf{\Phi}$ linear in modulus but lacks *F*-term: $\mathbf{\Phi} = \frac{1}{\langle T + T^\dagger \rangle^{1/2}} e^{-\mathbf{T}^c/(\sqrt{3}M_{\rm Pl})}\left(1 + \frac{\mathbf{T}^c|_{\theta^2}}{\sqrt{3}M_{\rm Pl}}\theta^2\right)$

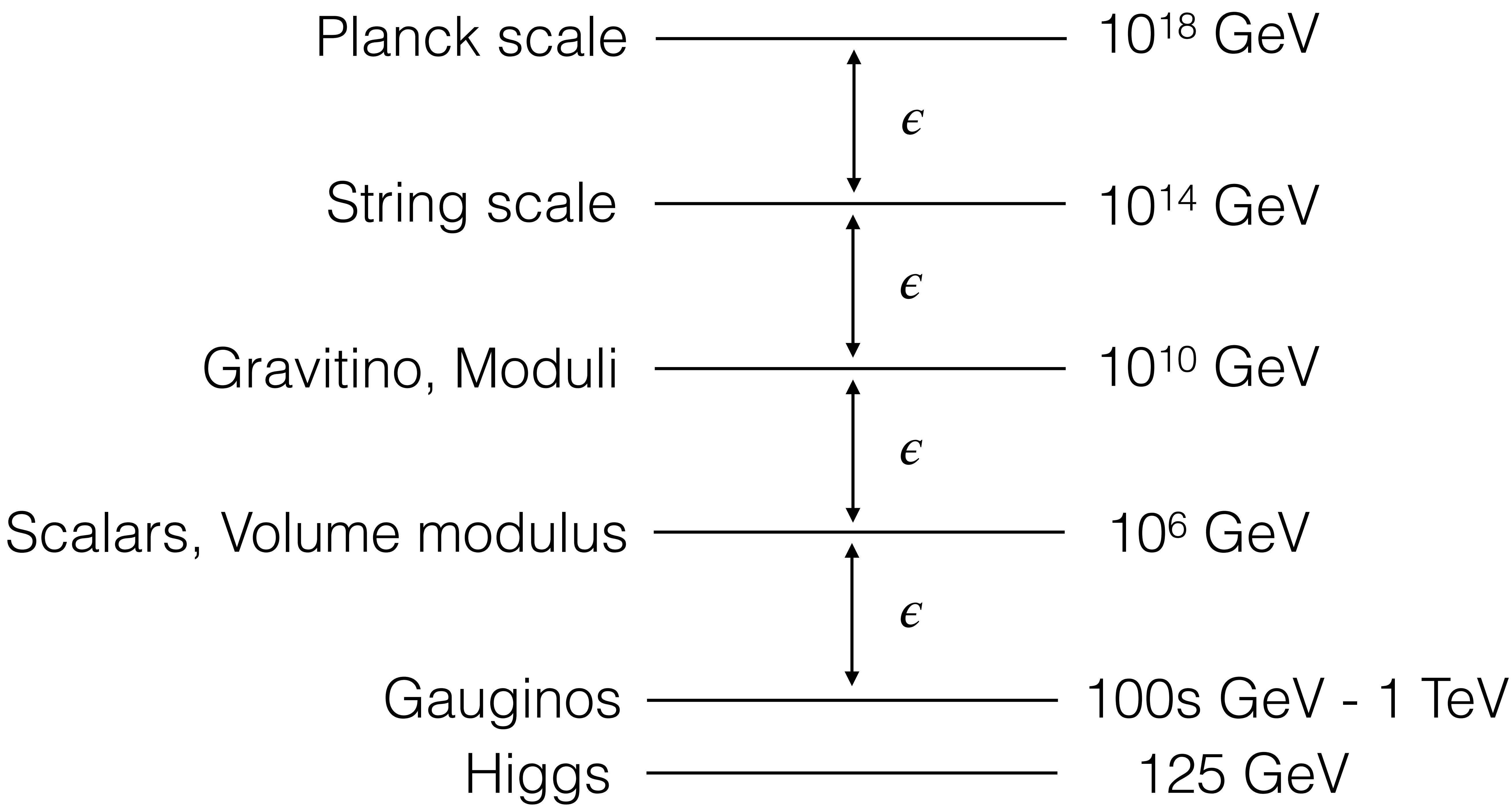
Result: sequestered Kähler potential

$$\int d^4\theta\, \mathbf{\Phi}^\dagger \mathbf{\Phi} \left[\mathbf{Q}^\dagger \mathbf{Q} + \bar{\mathbf{Q}}^\dagger \bar{\mathbf{Q}} + (z \bar{\mathbf{Q}} \mathbf{Q} + \text{h.c.})\right]$$

leads to moduli decays to scalars but not fermions in the Q multiplets! Unfortunately, doesn't seem to immediately solve our dark matter overabundance problem.

SUSY's Ladder

Simple estimate of moduli stabilization possibilities leads to possible realization of gravitino decoupling from 10D IIB



SUSY's Ladder

Simple estimate of moduli stabilization possibilities leads to possible realization of gravitino decoupling from 10D IIB

Planck scale — 10^{18} GeV

Scalar mass ~ 1000 TeV: good for m_h = 125 GeV starting from universal scalar masses at GUT scale. (RG running gives tan beta = 2)

see: Bagnaschi, Giudice, Slavich, Strumia 1407.4081

ϵ

Scalars, Volume modulus — 10^{6} GeV

ϵ

Gauginos — 100s GeV - 1 TeV

Higgs — 125 GeV

Loop Corrections: Coleman-Weinberg

Can ask: are the volume-suppressed Kähler terms we assume radiatively stable? Have quadratic divergences:

$$\delta K = \frac{\Lambda^2}{16\pi^2} \log\det K^{(2)}$$

(one of several terms in 1-loop C-W potential)

matrix of 2nd derivs of Kähler potential

Key point: cutoff scale is field-dependent; at most, it's the string scale ~ $M_{\rm Pl}/(T+T^\dagger)^{3/4}$

$$\mathbf{\Omega} = \mathbf{T} + \mathbf{T}^\dagger - \mathbf{Q}^\dagger\mathbf{Q} - \frac{\beta^2}{16\pi^2}\frac{\gamma + \log(\mathbf{T}+\mathbf{T}^\dagger)}{(\mathbf{T}+\mathbf{T}^\dagger)^{1/2}} + \frac{\beta^2}{16\pi^2}\frac{\gamma + 1 + \log(\mathbf{T}+\mathbf{T}^\dagger)}{(\mathbf{T}+\mathbf{T}^\dagger)^{3/2}}\mathbf{Q}^\dagger\mathbf{Q} + \ldots$$

Up to logs, recover assumed structure. **Stable against loops.**

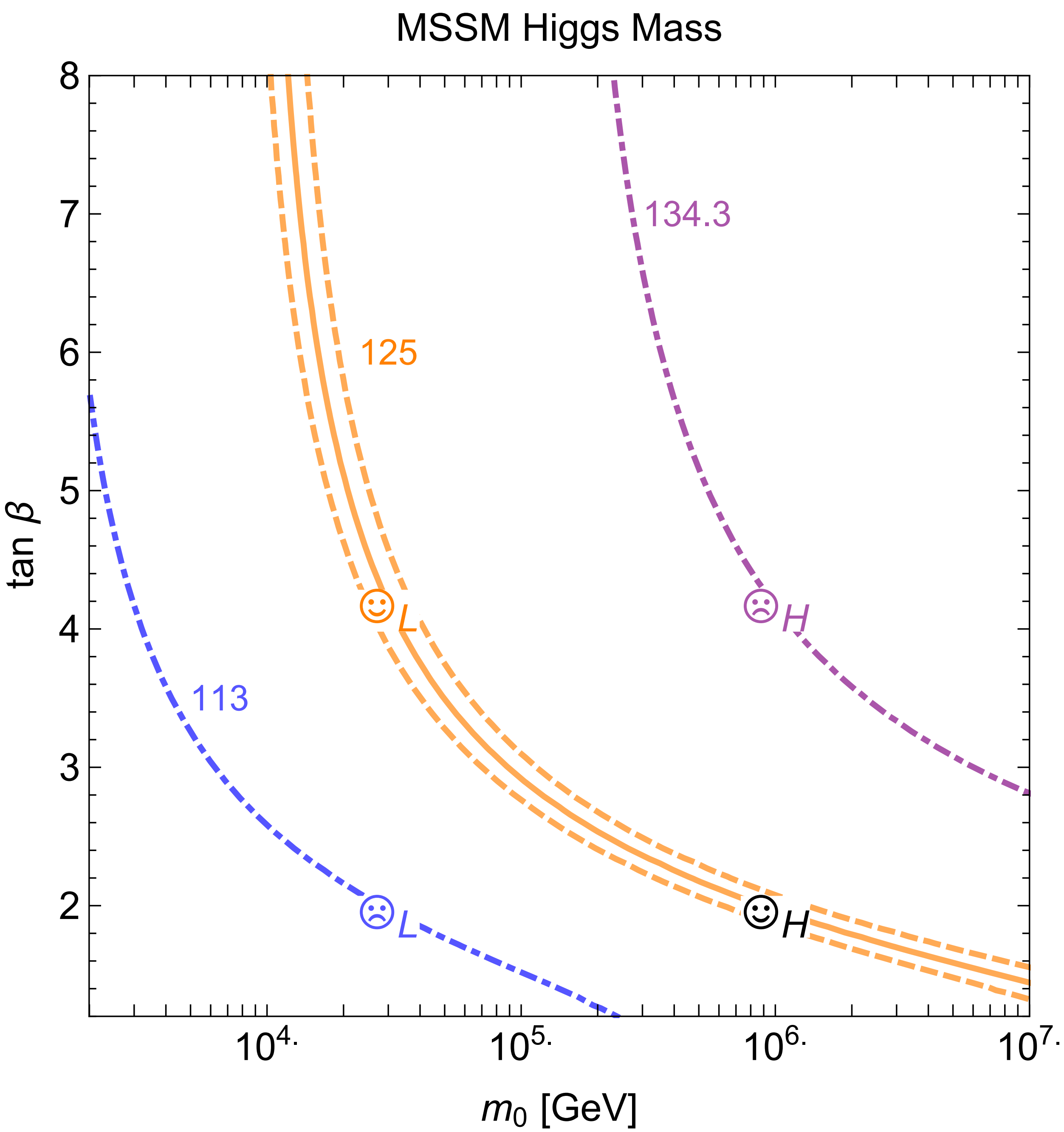
2. Signals at Future Colliders

(focusing on a 100 TeV pp collider)

Agrawal, Fan, MR, Xue, arXiv:1702.05484

A Future Collider Challenge: Why 125 GeV?

Agrawal, Fan, MR, Xue, arXiv:1702.05484

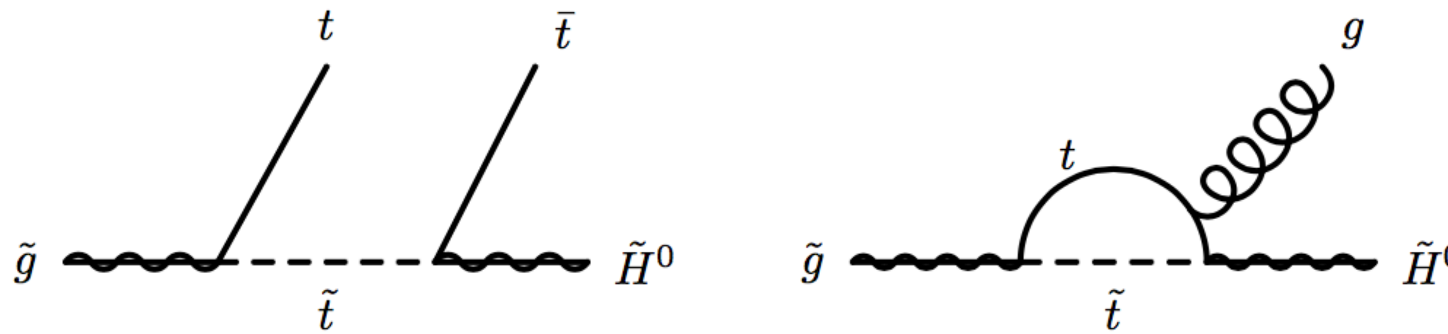


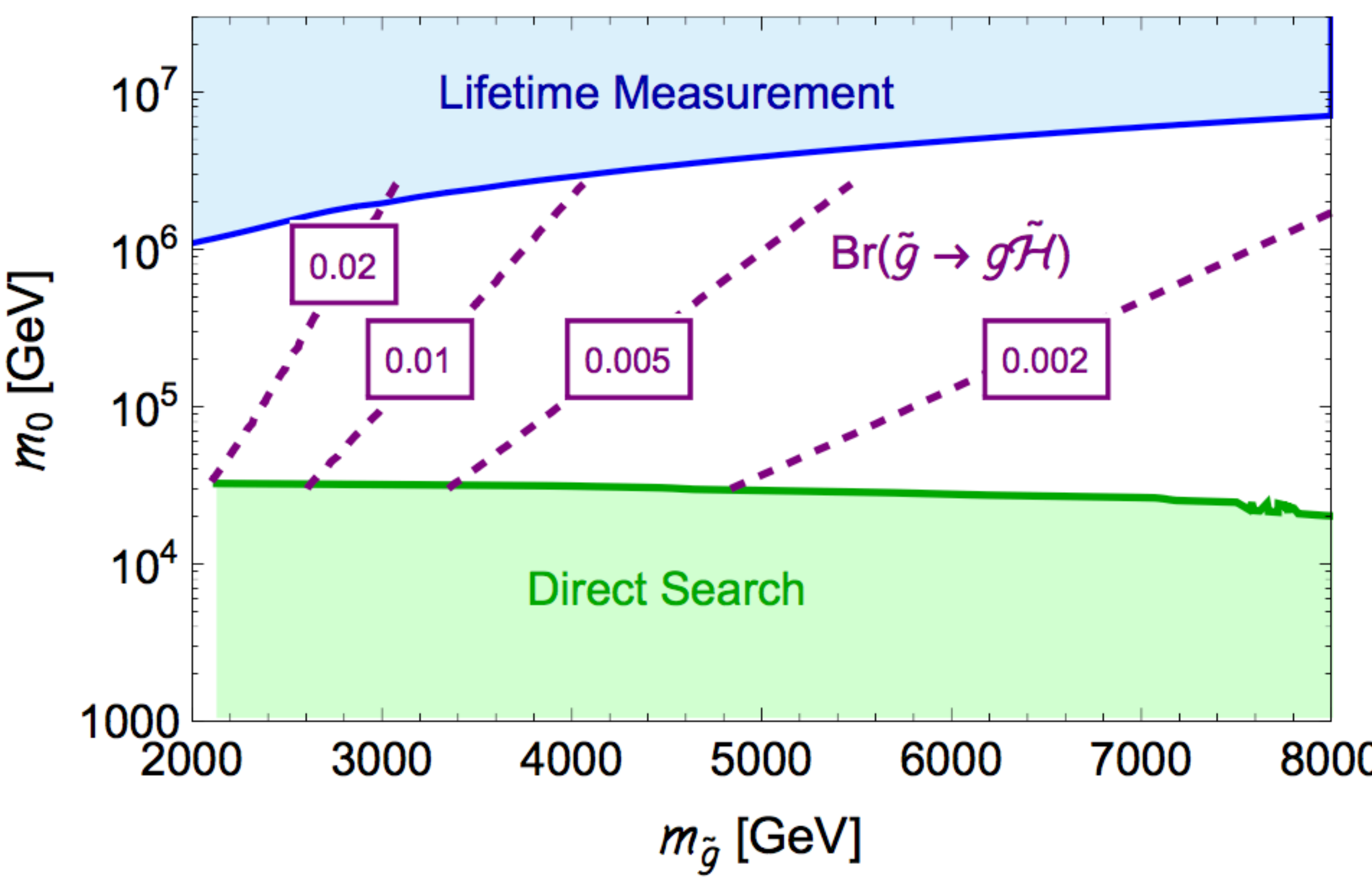
In the MSSM: basically a function of the stop mass and tan beta.

Can a future hadron collider measure them well enough to test if this is the right theory?

Precision physics: millions of gluino pairs.

Finding the Scalar Mass





displaced decays

logs from loops

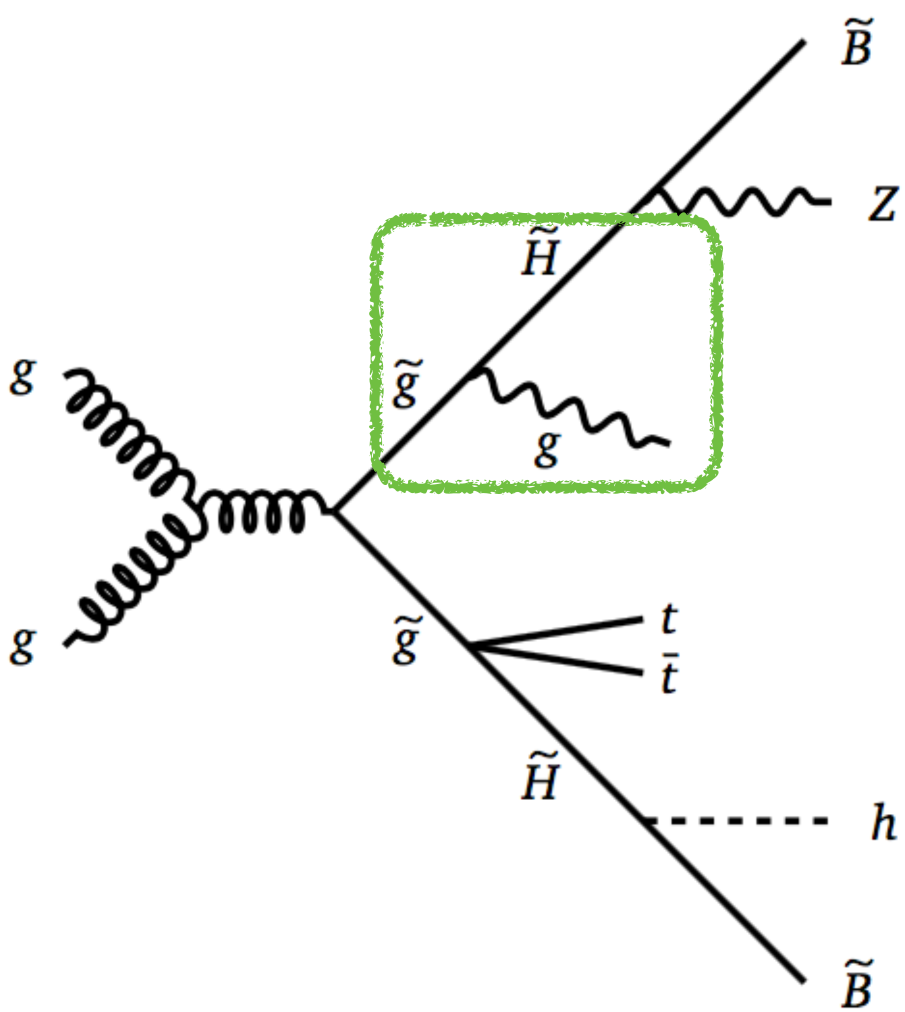
(also see Sato, Shirai, Tobioka 1207.3608)

gluino/valence squark

Scalar mass: collider benchmark

$$\boldsymbol{M_2 > |\mu| > M_1}$$

$$M_3 = 2\ \text{TeV}, \quad M_2 = 800\ \text{GeV}, \quad M_1 = 200\ \text{GeV}, \quad \text{and} \quad \mu = 400\ \text{GeV}.$$



Diagnostic of scalar mass: rate of 1-loop

$$\widetilde{g} \to \widetilde{H} + g$$

so find a hard jet and Z on one side of event

$$H_T > 2\ \text{TeV}, \qquad p_T^{\text{missing}} > 1\ \text{TeV}, \qquad p_T(j_1) > 1\ \text{TeV},$$
$$N_{\text{jet}} < 5,\ \text{one leptonic } Z\ (80\ \text{GeV} < m_{\ell\ell} < 100\ \text{GeV}),$$
$$m_{j_1 Z} > m_{\text{all other jets}},\ M_{T2}^{\ell\ell} > 80\ \text{GeV}.$$

Scalar mass: collider benchmark

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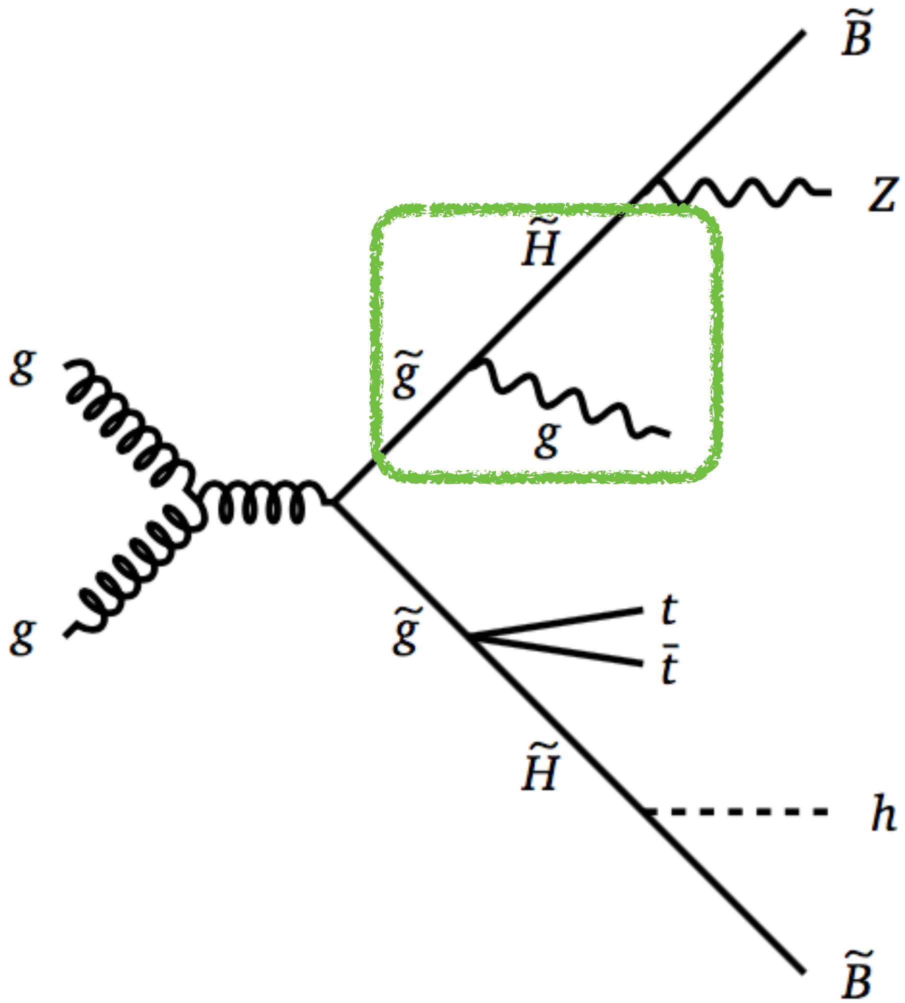
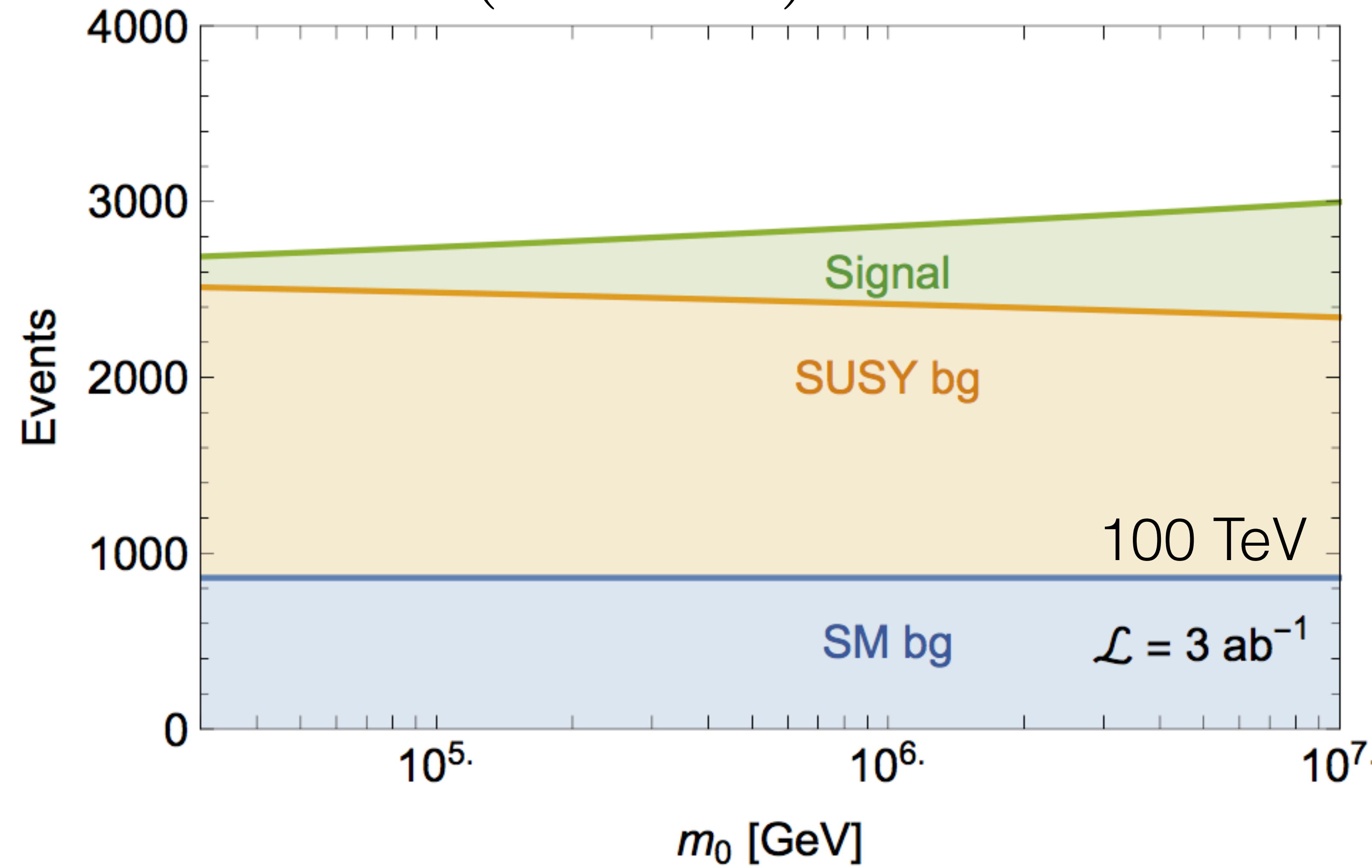


SM backgrounds:

$$Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu}) + \text{jets}$$
$$t\bar{t} + Z(\to \ell^+\ell^-)$$



Tan Beta = 1 Physics

Certain couplings turn off. ("**Blind spot**")

Neutral higgsinos mix; Majorana mass eigenstates

$$\widetilde{H}^0_\pm = \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_u \pm \widetilde{H}^0_d\right)$$. exact at $\tan\beta = 1$

Off-diagonal Z coupling:

$$\frac{g}{2\cos\theta_W} Z_\mu \left(\widetilde{H}^{0\dagger}_+ \overline{\sigma}^\mu \widetilde{H}^0_- + \widetilde{H}^{0\dagger}_- \overline{\sigma}^\mu \widetilde{H}^0_+\right).$$

Higgs coupling (limit of 1 light higgs):

$$\frac{\cos\beta}{2\sqrt{2}}(v+h)\left(g\widetilde{W}^0 - g'\widetilde{B}^0\right)\left[(1-\tan\beta)\widetilde{H}^0_+ - (1+\tan\beta)\widetilde{H}^0_-\right] + \text{h.c.}$$

One mass eigenstate **decouples from higgs** at $\tan\beta = 1$

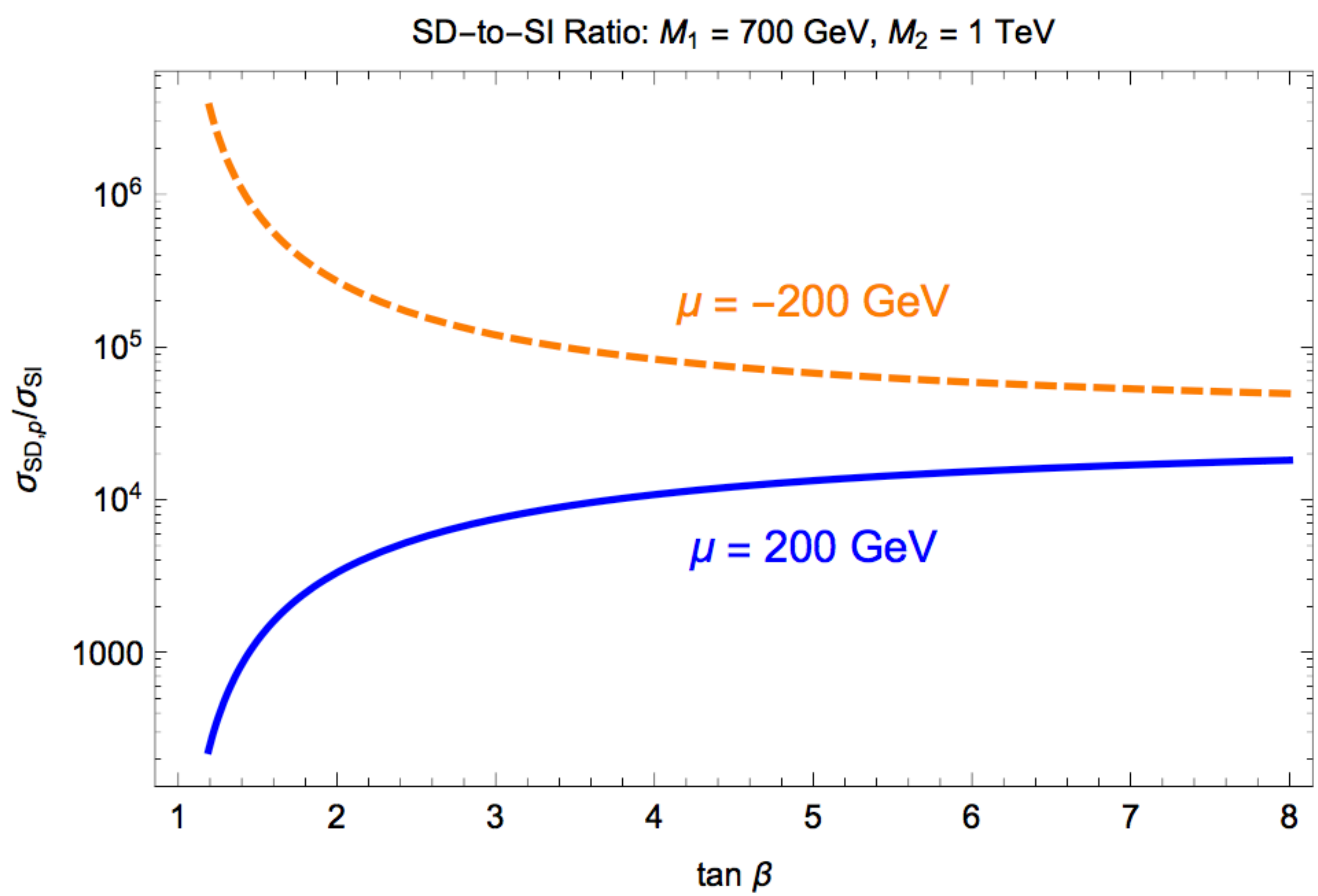
Direct Detection & Tan Beta

Mostly-higgsino dark matter: measuring both spin-dependent and spin-independent scattering.

SI $\longrightarrow$ $$\left[\frac{1}{2}c_{h\chi\chi}h\chi\chi + \text{h.c.}\right] + c_{Z\chi\chi}\chi^\dagger\overline{\sigma}^\mu\chi Z_\mu$$ $\longleftarrow$ SD

$\tan\beta = 1$:
SD vanishes;
SI vanishes faster if $\mu<0$

Detecting an SI signal would **strongly motivate** intense exp. effort to find the SD signal.

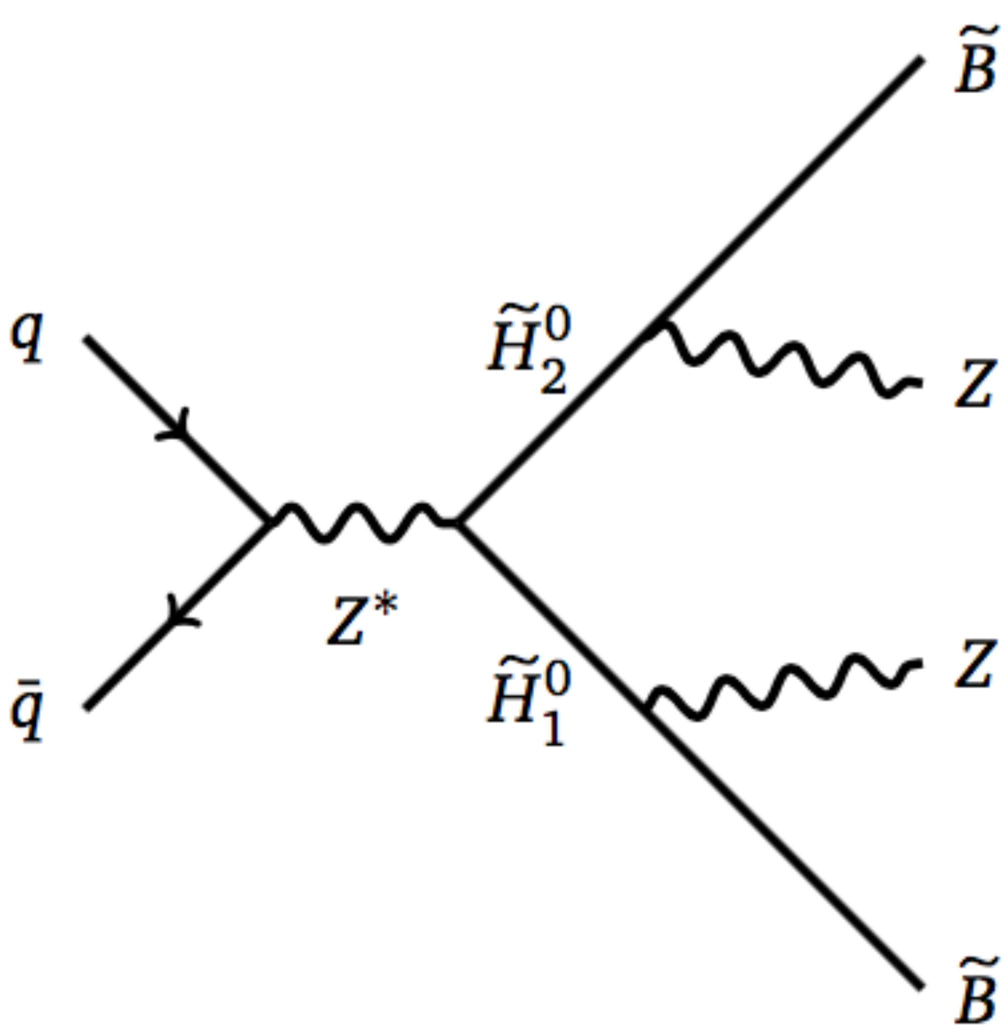


Tan beta: collider benchmark

$$\boldsymbol{M_2 > |\mu| > M_1}$$

$$M_3 = 2\ \text{TeV}, \quad M_2 = 800\ \text{GeV}, \quad M_1 = 200\ \text{GeV}, \quad \text{and} \quad \mu = 400\ \text{GeV}.$$

Off-diagonal Z boson coupling!



At tan β = 1, get h+Z+MET but no Z+Z+MET, so measure the Z+Z+MET rate in 4 leptons.

$$2\ \text{pairs},\ |m_{\ell\ell} - m_Z| < 10\ \text{GeV}$$

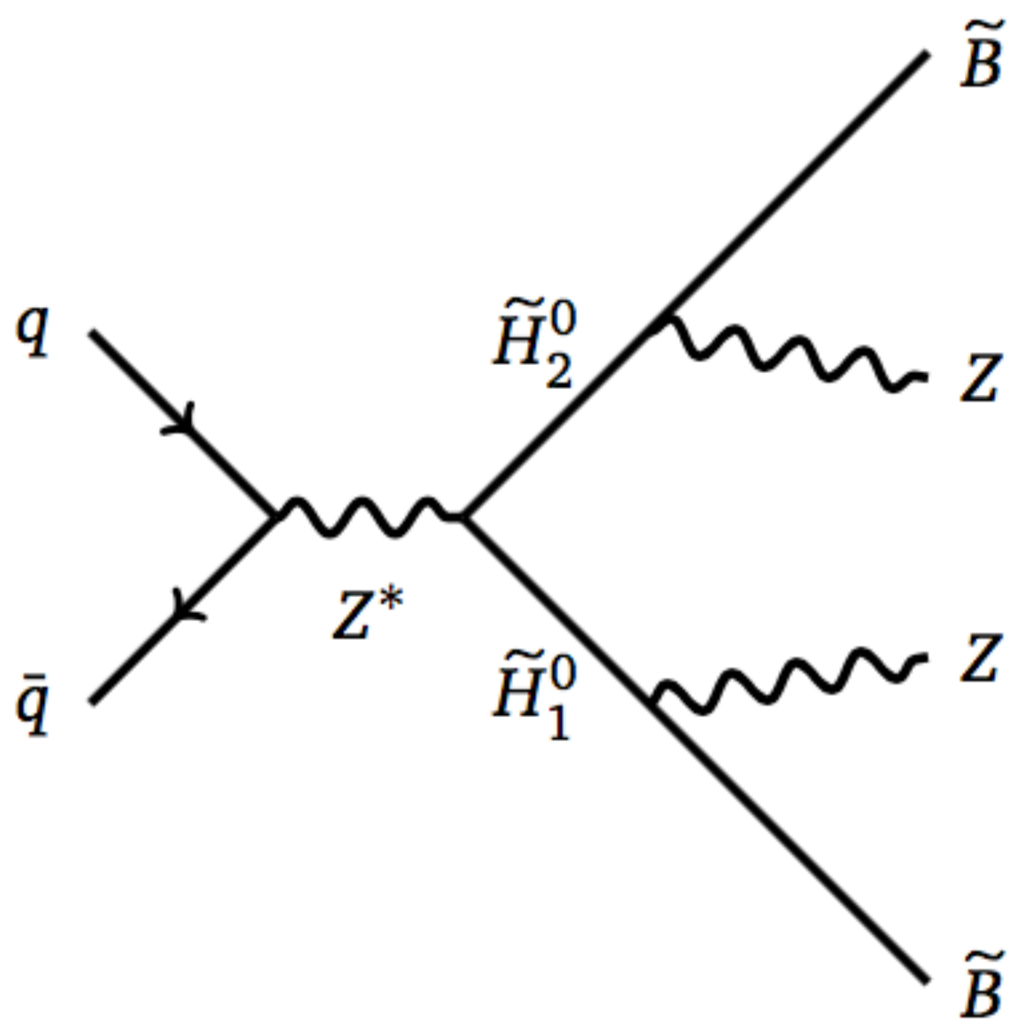
$$p_T^{\text{missing}} > 150\ \text{GeV}$$

$$\sum_{\text{visible}} |p_T| < 600\ \text{GeV}$$

Tan beta: collider benchmark

$$M_2 > |\mu| > M_1$$

$M_3 = 2$ TeV, $M_2 = 800$ GeV, $M_1 = 200$ GeV, and $\mu = 400$ GeV.



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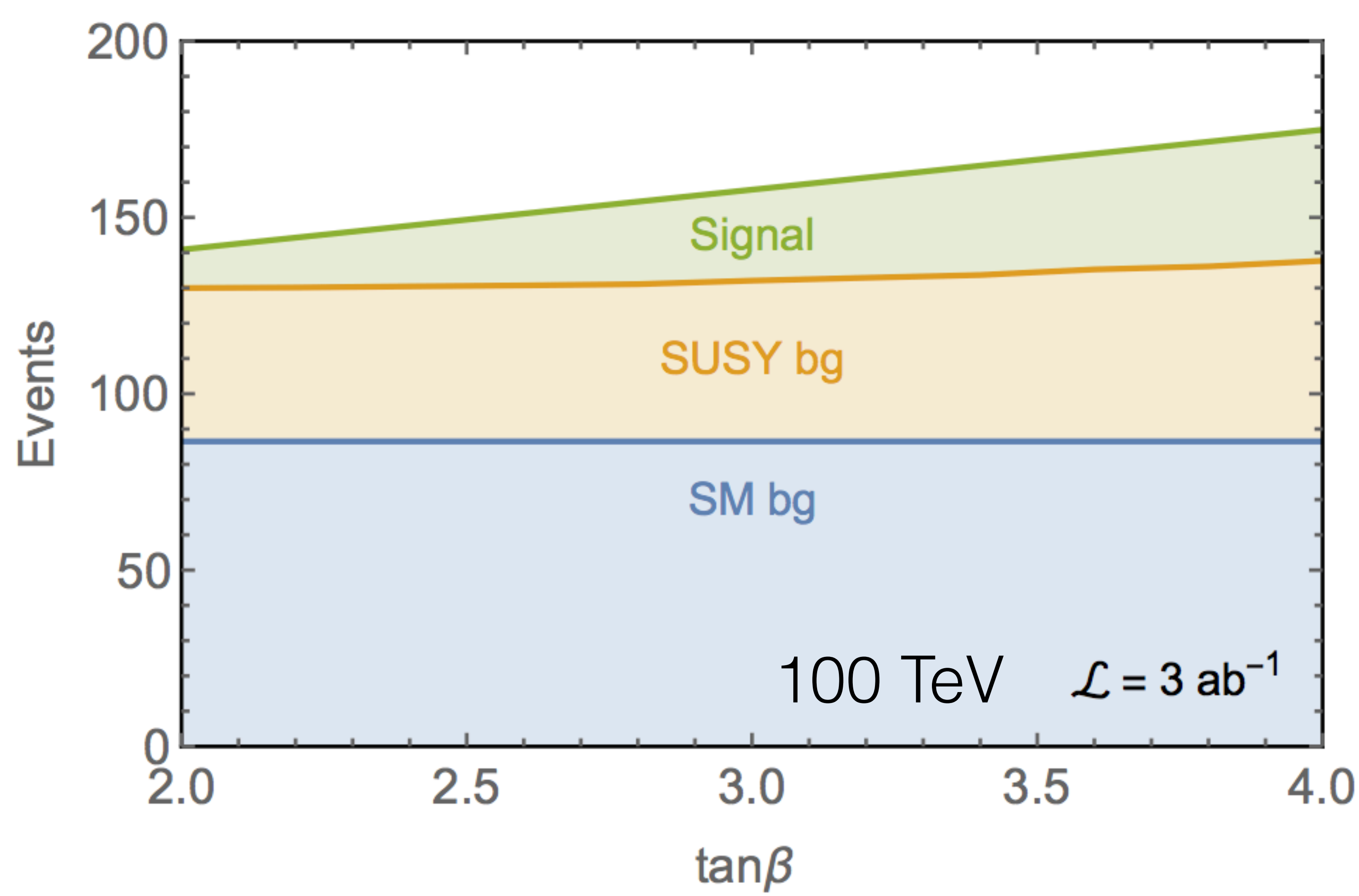
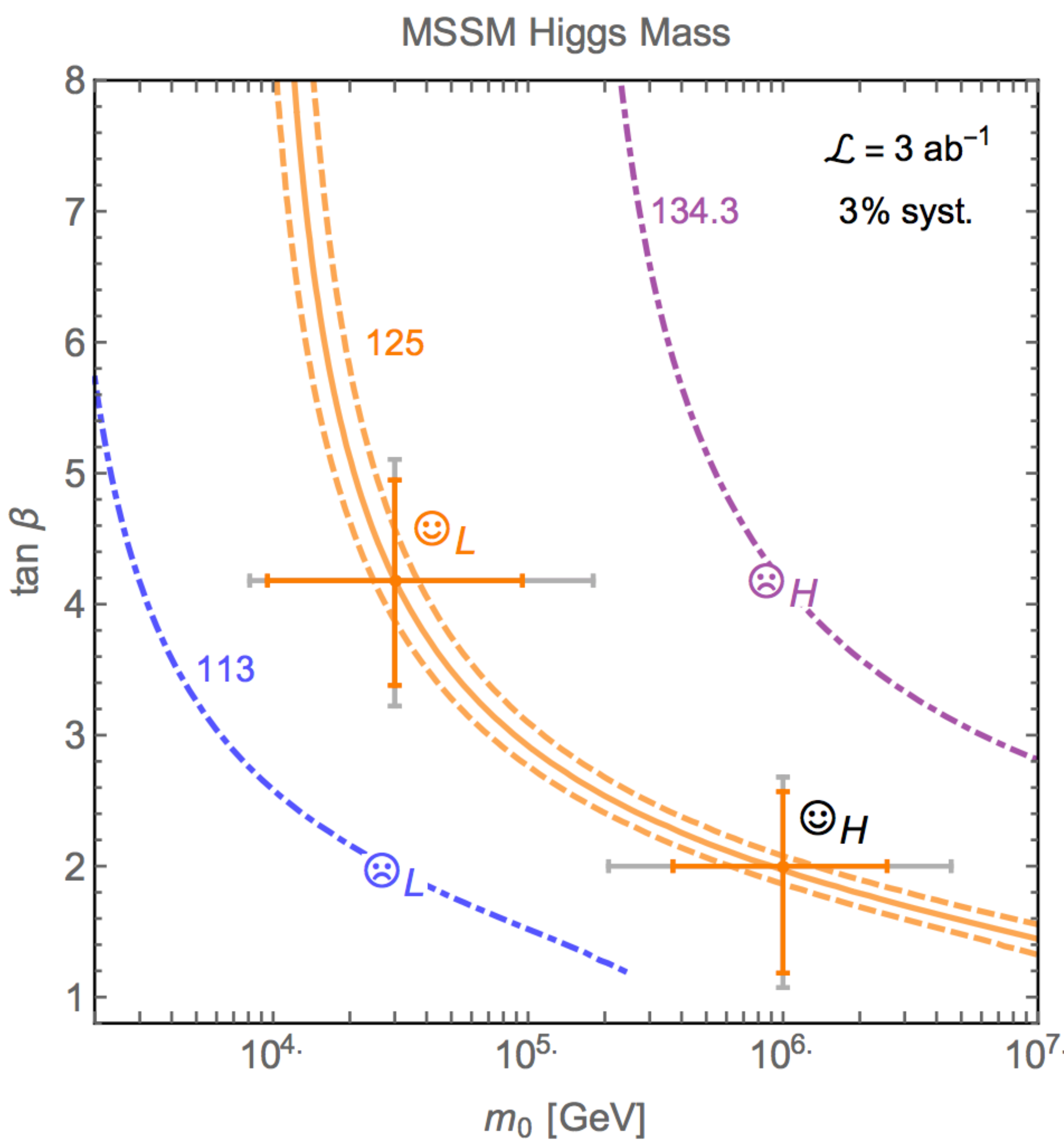
$$Z(\to \ell^+\ell^-) + Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu})$$



Testing the MSSM: benchmark result



A 100 TeV collider could test the MSSM.

Very simple preliminary studies: should be possible to do much better.

Next step: compare prospects of different collider scenarios.

Thank you