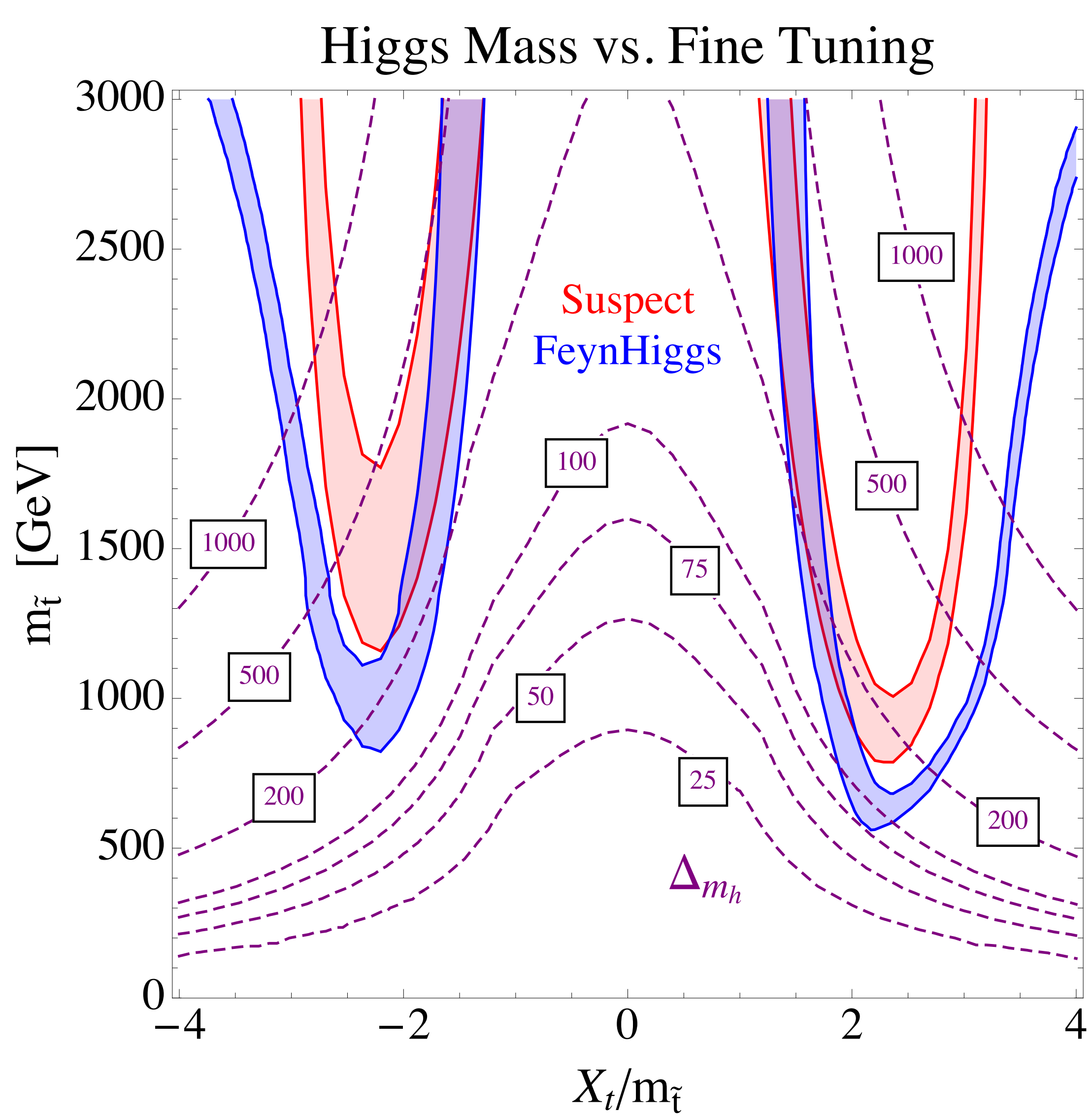
SUSY's Ladder and 100 TeV

Matt Reece
September 5, 2016

Based on:
MR and Wei Xue, 1512.04941 (JHEP 2016)
100 TeV BSM Report: 1606.00947, section 3.10
Prateek Agrawal, JiJi Fan, MR, and Wei Xue: work in progress

125 GeV: MSSM is Unnatural

In the MSSM, a 125 GeV Higgs mass requires heavy stops / large A-terms, but those **directly** undermine the naturalness argument for SUSY.

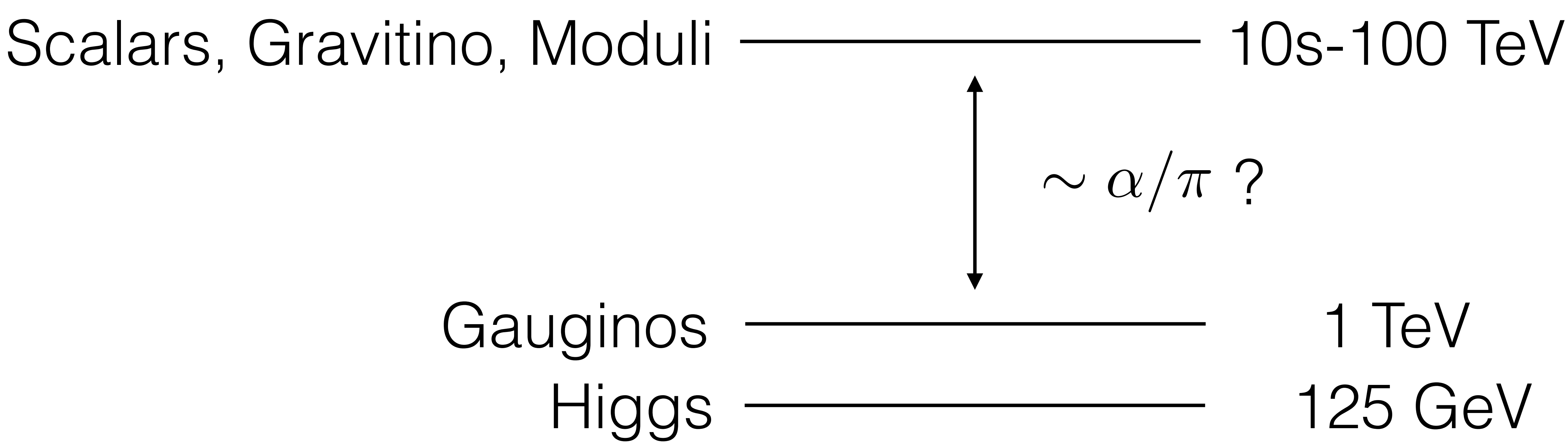


(Beyond MSSM is different story)

Tuning contours (Hall/Pinner/Ruderman 1112.2703) for **low-scale mediation**, $\Lambda = 10$ TeV.

Always **at least** a factor of 100 tuning.

Split SUSY, Take 1:

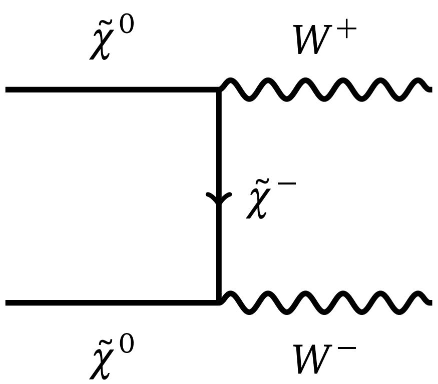


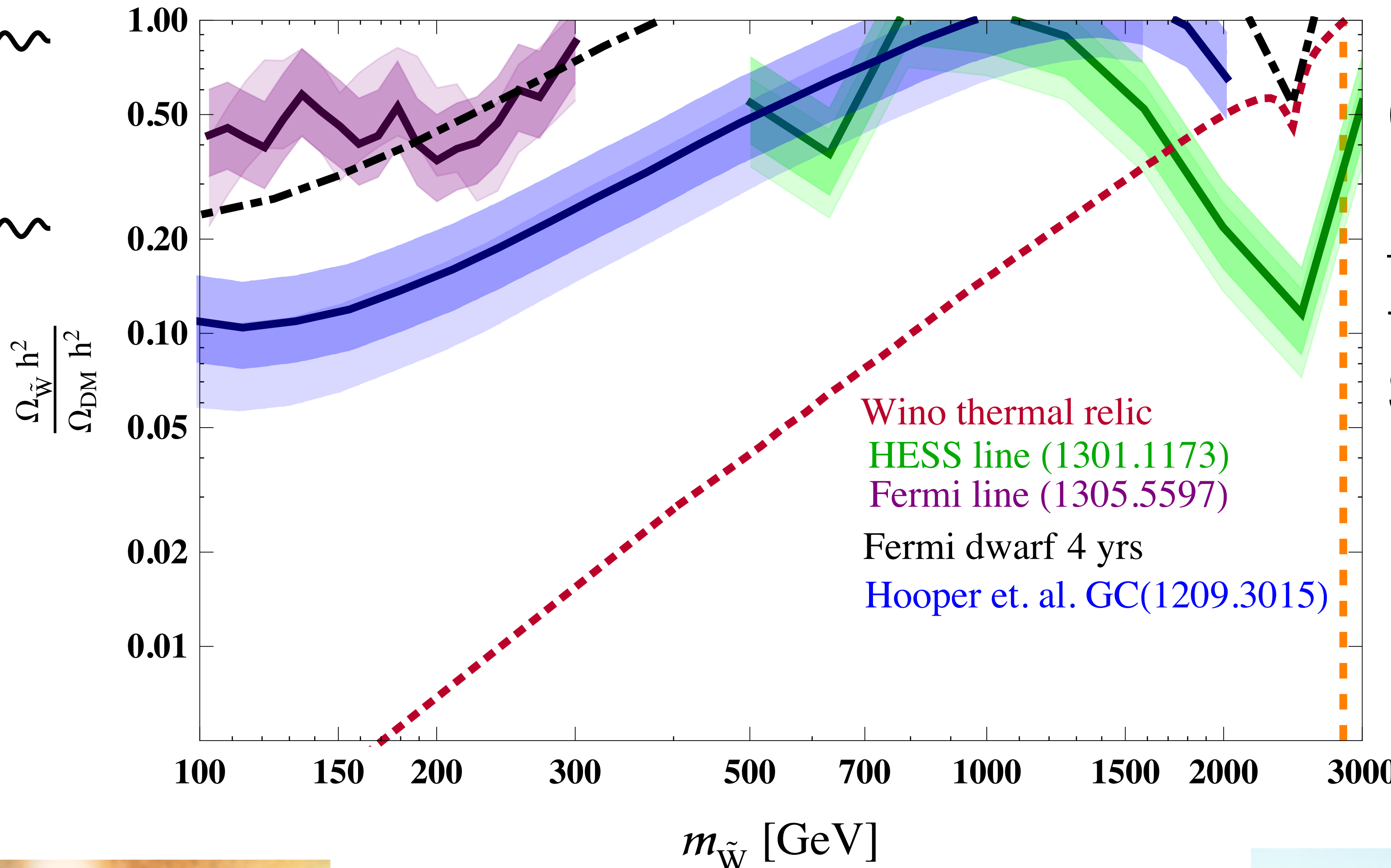
- Heavy scalars (10s of TeV) at large tan β: right Higgs mass
- Loop factor: arises in AMSB (Giudice, Luty, Murayama, Rattazzi ’98) and some moduli mediation
- Late-time gravitino and moduli decays populate nonthermal dark matter, e.g. winos (Moroi, Randall ’99; Kane et al.)

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

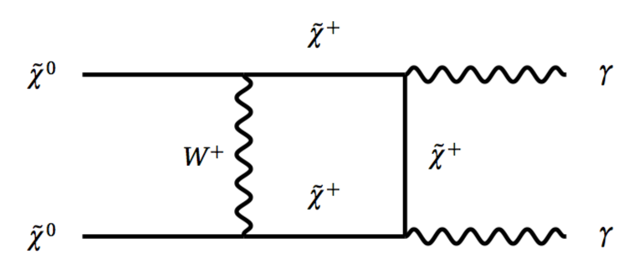
Wino DM?

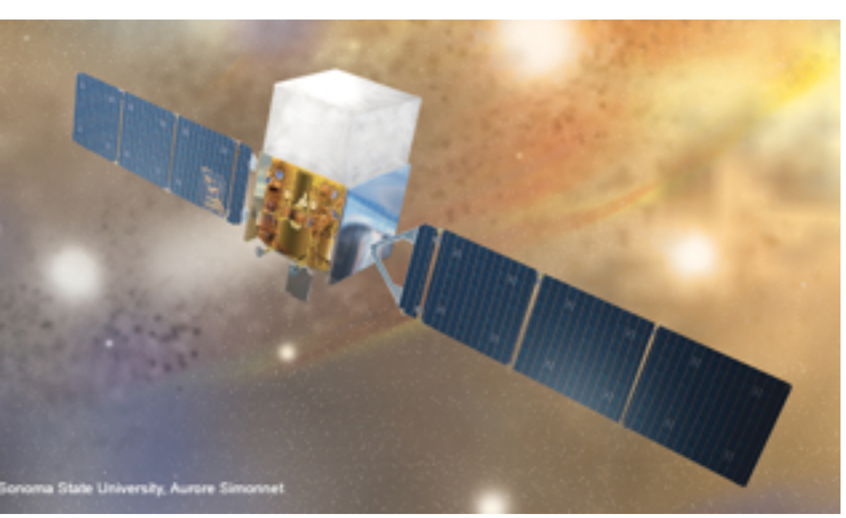
J. Fan, MR 1307.4400: data disfavors moduli→winos



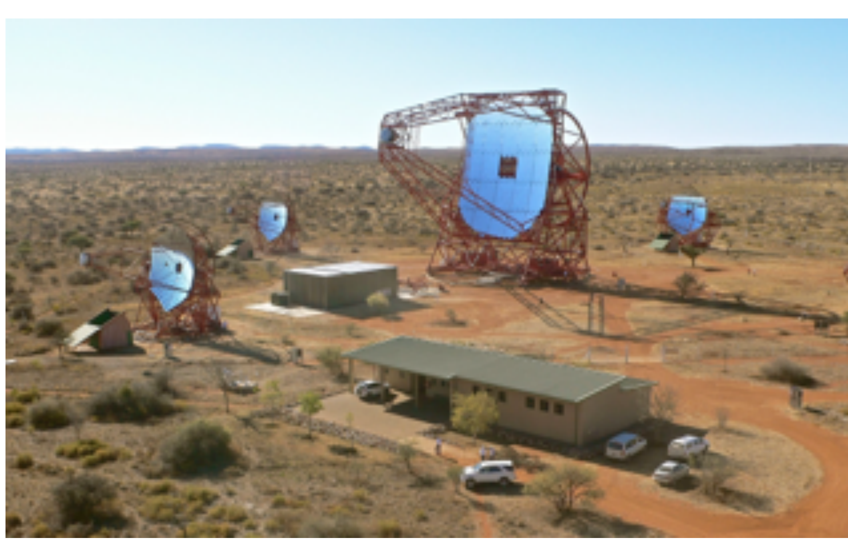


(see also Cohen, Pierce, Lisanti, Slatyer —more focus on thermal winos/ Sommerfeld)





Fermi-LAT telescope (in space) and HESS (in Namibia)



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

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

Regimes of gravitino mass:

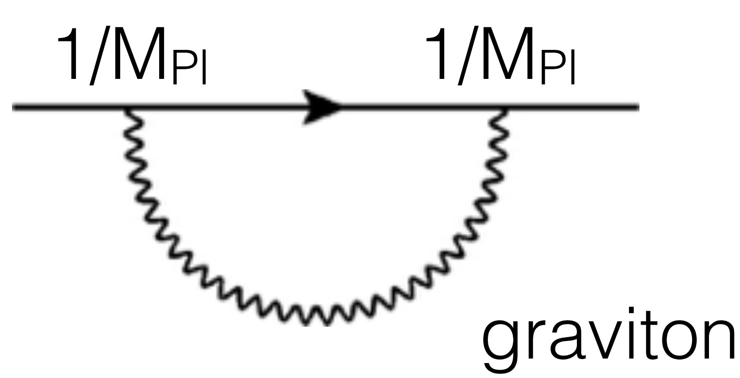
$m_{3/2}$

	$m_{\chi_1^0}$	100 TeV	10^4 TeV
Grav. LSP; tends to overclose. Light sparticles	Grav. decays spoil BBN	Grav. decays alter DM relic density	Grav. decays safe: $T_{dec} > T_{FO}$

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.



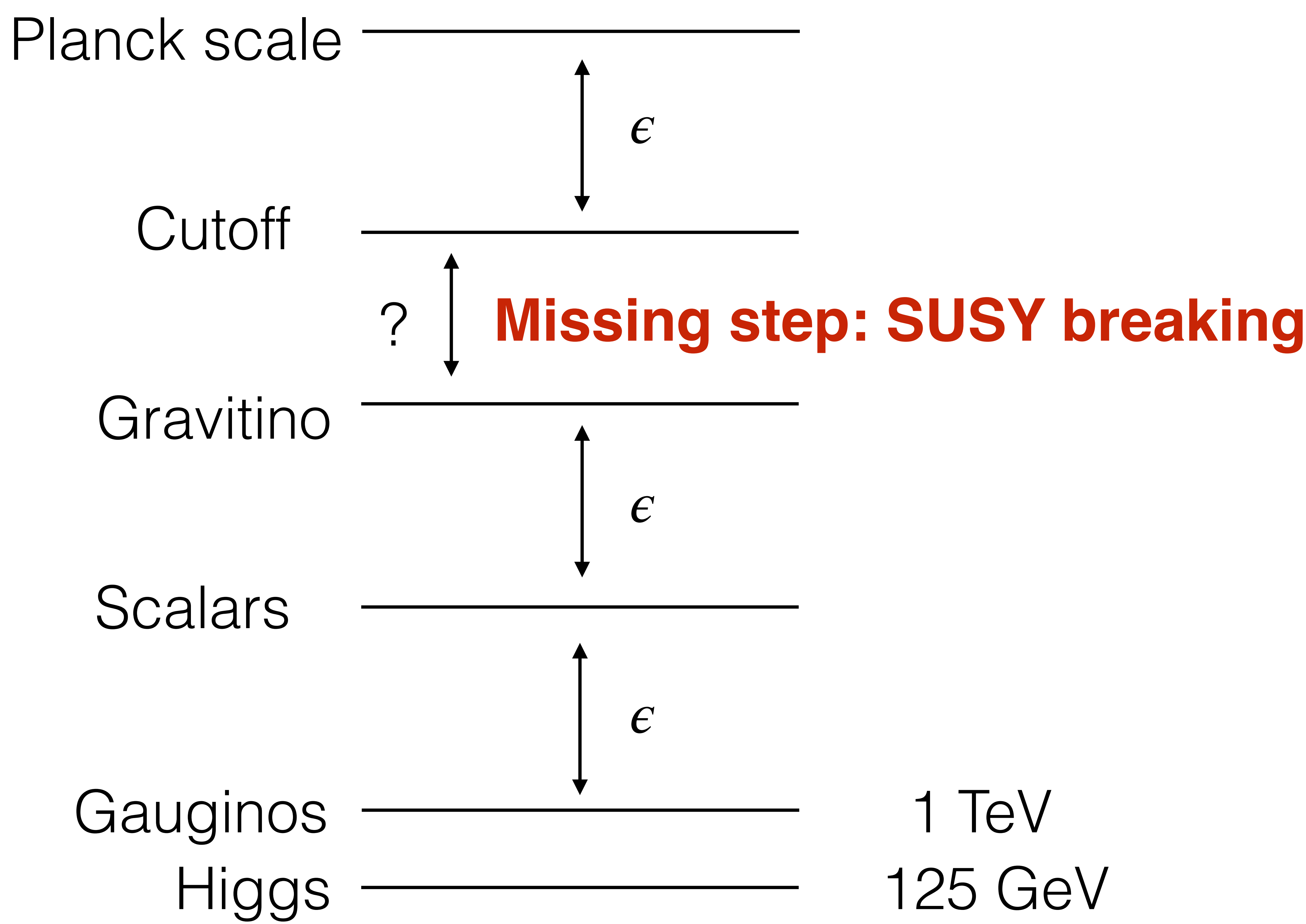
No SUSY: $\delta m^2 \sim \frac{\Lambda^4}{16\pi^2 M_{\rm Pl}^2}$

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"**:

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

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

More generally, when does the length scale of extra dimensions enforce this leading no-scale form? Compactify ***D* = *d* + *n*** down to *d*.

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + L^2 h_{lm}(y)dy^l dy^m, \quad h \text{ Ricci flat}$$

Kaluza-Klein: $\mathcal{L} = -\frac{V(h)}{16\pi G_D}\int d^d x\sqrt{-g}L^n\left(\mathcal{R} + \frac{(\partial L)^2}{L^2}\right)$

Weyl transform to **remove** *L* kinetic term:

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

Single-Field No-Scale Candidates

Compactify *n* dimensions of **overall length scale *L*:**

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

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 Candidates

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.

$d = 4$:

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

We've now motivated studying supergravity theories arising from 5D (heterotic M-theory on small Calabi-Yau?) or 10D Type IIB.

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

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

Gravitino Estimate

We need the moduli stabilization model to fill in the details, but can estimate:

$$m_{3/2} = \frac{1}{M_{\rm Pl}^2} \left\langle e^{K/(2M_{\rm Pl}^2)} W \right\rangle \sim \frac{M_{\rm Pl}}{\langle T + T^\dagger \rangle^{3/2}}$$

Leads to:

$$\text{10D Type IIB}: \quad m_{3/2} \sim \epsilon^2 M_{\rm Pl}$$

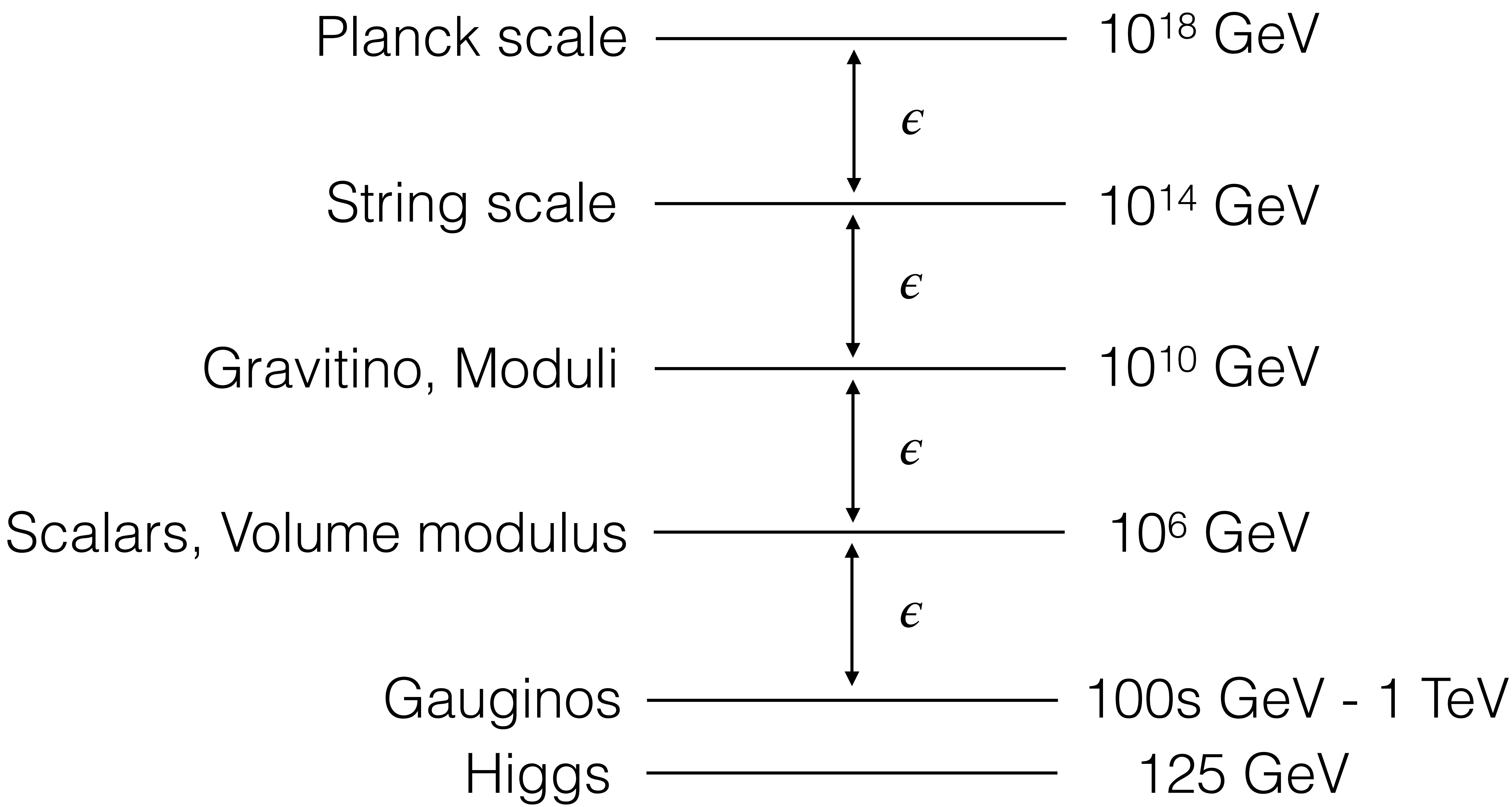
$$\text{5D}: \quad m_{3/2} \sim \epsilon^3 M_{\rm Pl}$$

Assumptions:

- W takes values near Planck scale
- Single-field dominance of <K> ~ -3 log<T>
- Cutoff at higher-dim Planck scale

SUSY’s Ladder

Possible realization of gravitino decoupling from 10D IIB



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.**

Next Steps

One reason phenomenologists have been wary of no-scale structure is largely that it’s not so easy to understand if corrections spoil all of the magic.

We’ve found that working in superspace in the conformal compensator formalism makes many cancelations obvious. Good starting point for asking EFT questions.

Need to develop this systematically. Power-counting in volume suggests a **spurion-based EFT approach** to no-scale breaking that can be convincing. Possibly can help to reorganize and clarify results in string pheno literature.

Phenomenology

Many aspects already discussed in LVS papers. Wei Xue and I have rederived many of these results in a superspace formalism. **Many cancelations become manifest.**

Important phenomenological consequences:

- The hierarchies $m_{\text{gaugino}} \sim \epsilon^2 m_{3/2}$ and $m_{\text{scalar}} \sim \epsilon m_{3/2}$ can be consistently achieved in effective field theory.

- The lightest modulus—arising from the field *T* that controls no-scale structure—has special SUSY-breaking couplings so it can decay rarely to *R*-parity odd particles (Cicoli, Conlon, Quevedo '12; Higaki, Takahashi, '12)

Modulus Decays

Relatively clear in Cheung-D'Eramo-Thaler gauge

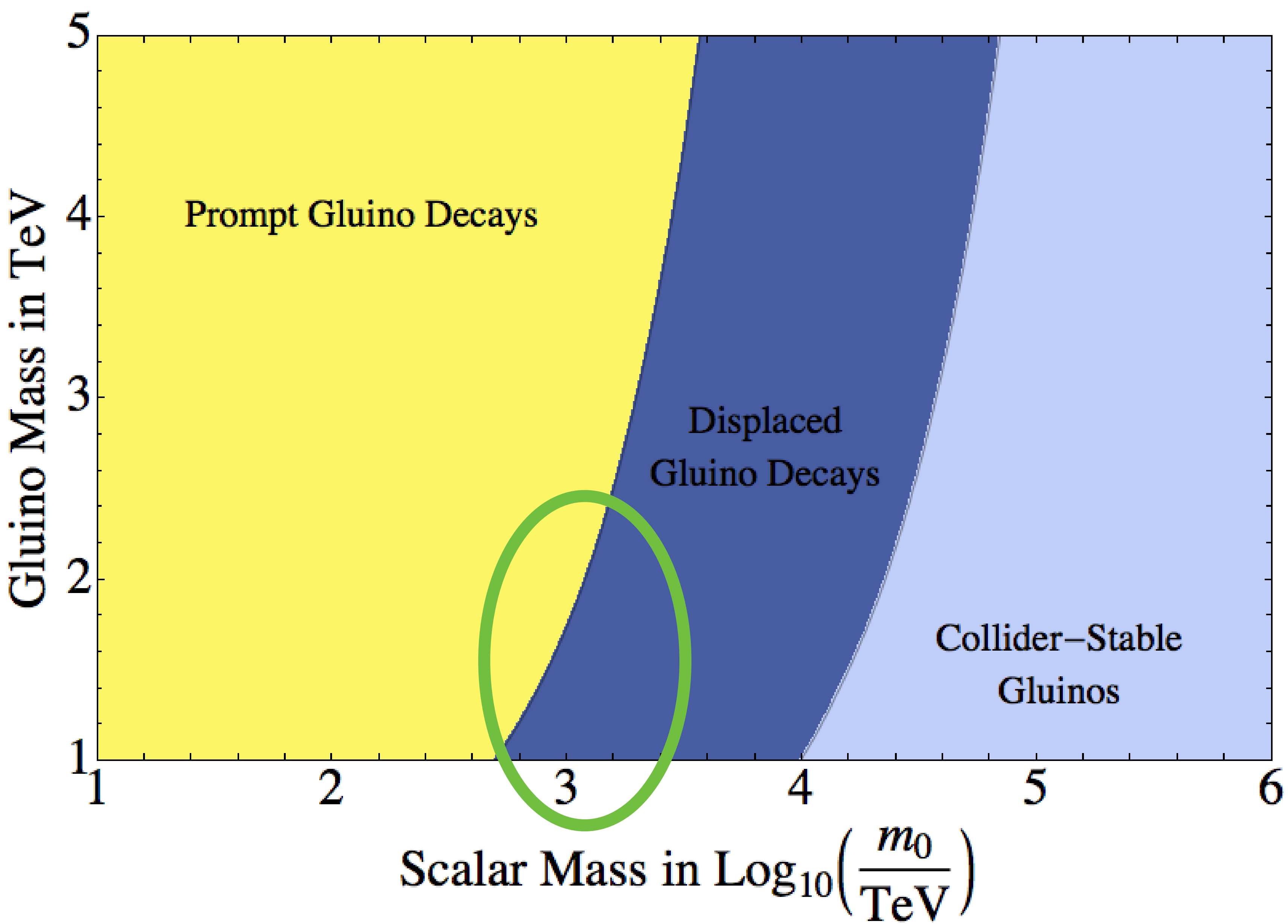
$$\mathbf{\Phi} = e^{\mathbf{Z}/3}(1 + f_\Phi \theta^2)$$
$$\mathbf{Z} = \frac{1}{M_{\rm Pl}^2}\left[\langle K/2 - iM_{\rm Pl}^2 \arg W\rangle + \langle K_i\rangle (\mathbf{X^i} - \langle X^i\rangle)\right]$$

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! Need to more thoroughly explore whether this can be used for dark matter abundance.

Gluino Lifetime

The obvious experimental handle on this theory is the gluino. Can we use it to learn the scalar mass scale?

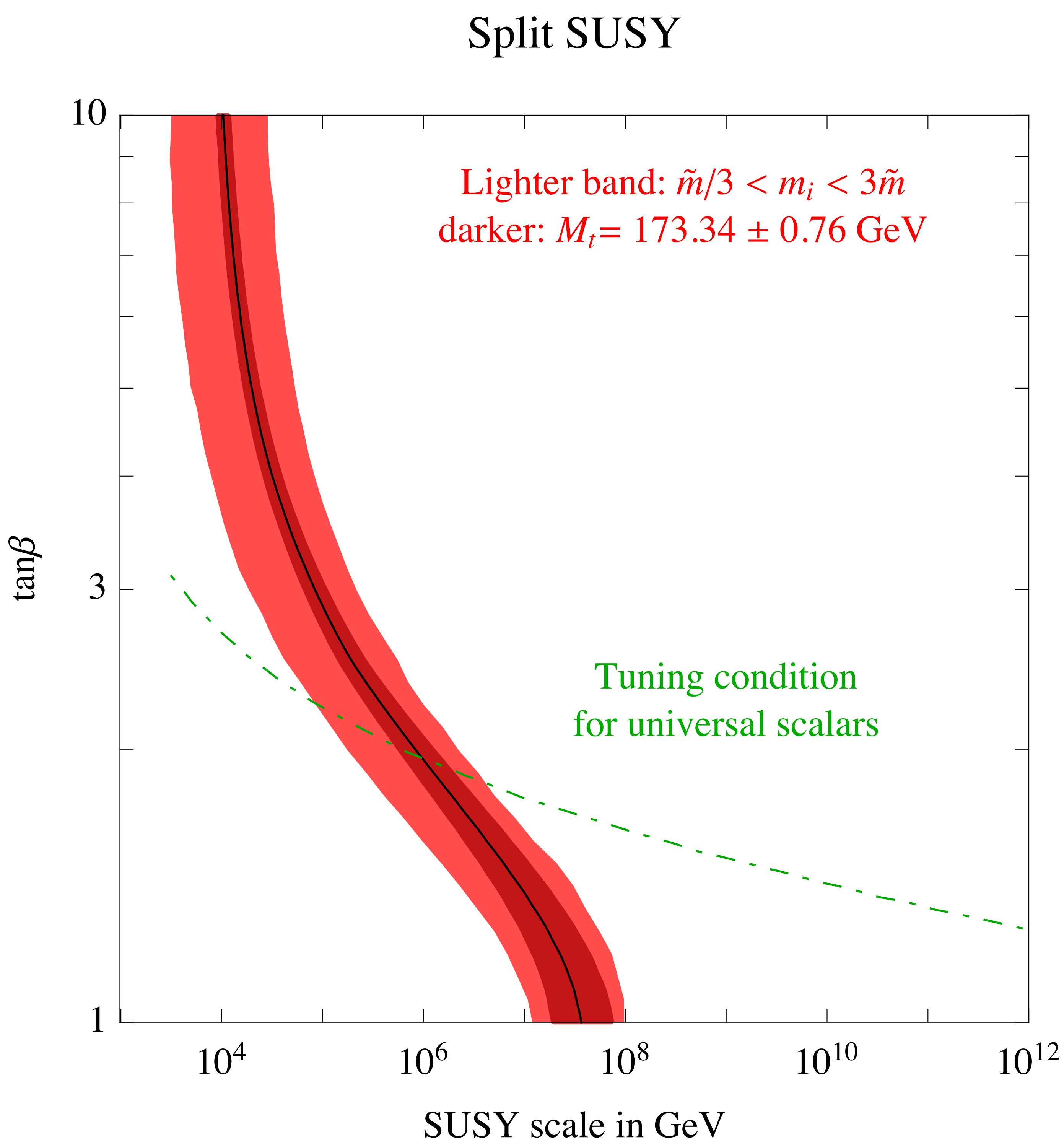


Arvanitaki, Craig, Dimopoulos, Villadoro ’12

We’re on the border, ~100 μm decay lengths. Experimentally challenging, but possible?

Higgs Mass in Split SUSY

Bagnaschi, Giudice, Slavich, Strumia 1407.4081



If we start with universal scalar masses:

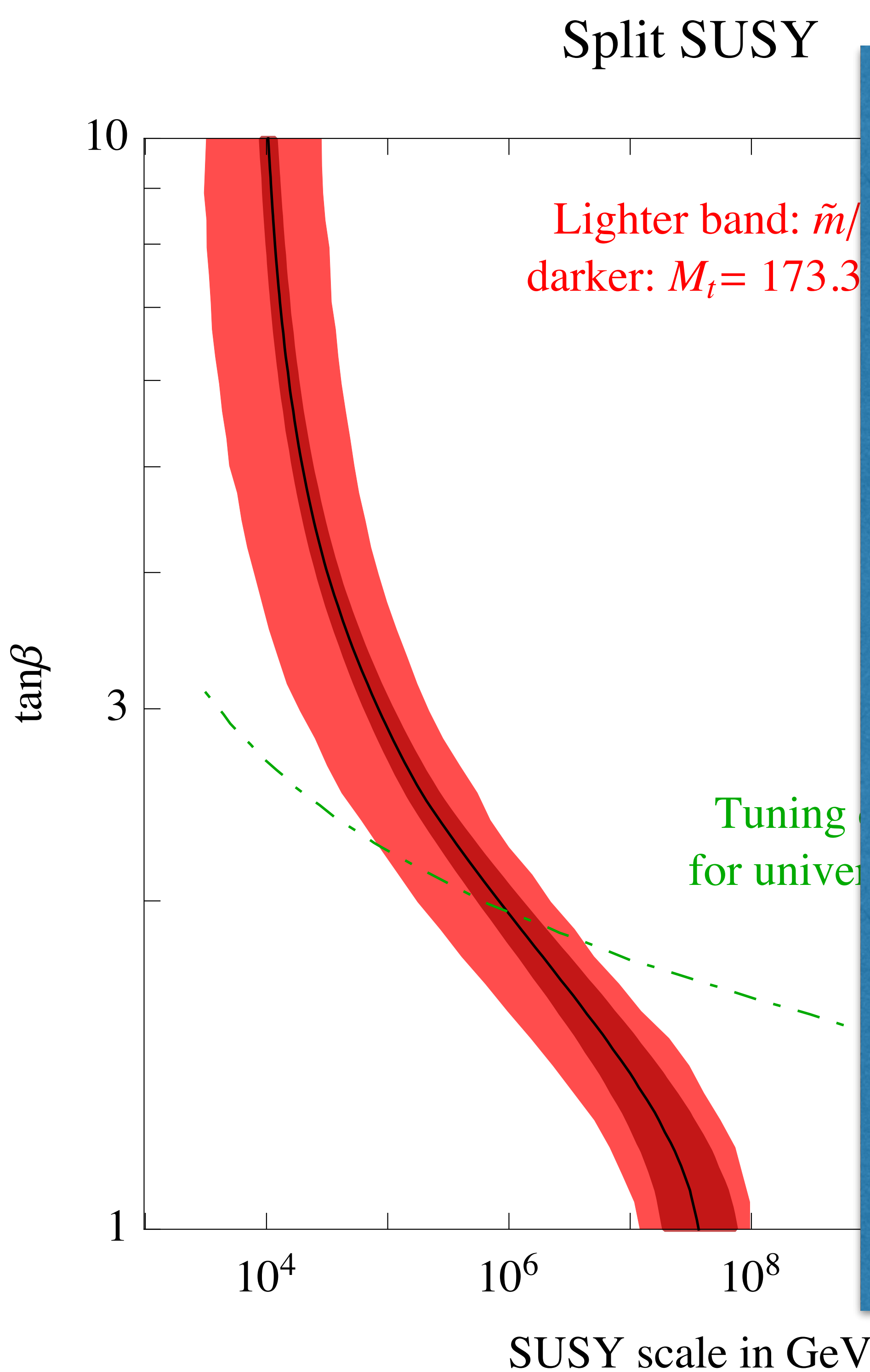
$$m_{H_u}^2 = m_{H_d}^2 = m_0^2$$

then a 125 GeV Higgs occurs when they are about 10^6 GeV. RG running lowers $m_{H_u}^2$ relative to $m_{H_d}^2$: end up with

$$\tan\beta \approx 2$$

Higgs Mass in Split SUSY

Bagnaschi, Giudice, Slavich, Strumia 1407.4081



The value of the universal scalar mass that predicts the Higgs mass correctly is ~ PeV, in the same range that we want for the "SUSY's Ladder" maximally spread spectrum!

Looks consistent with no-scale structure, Large Volume Scenario.

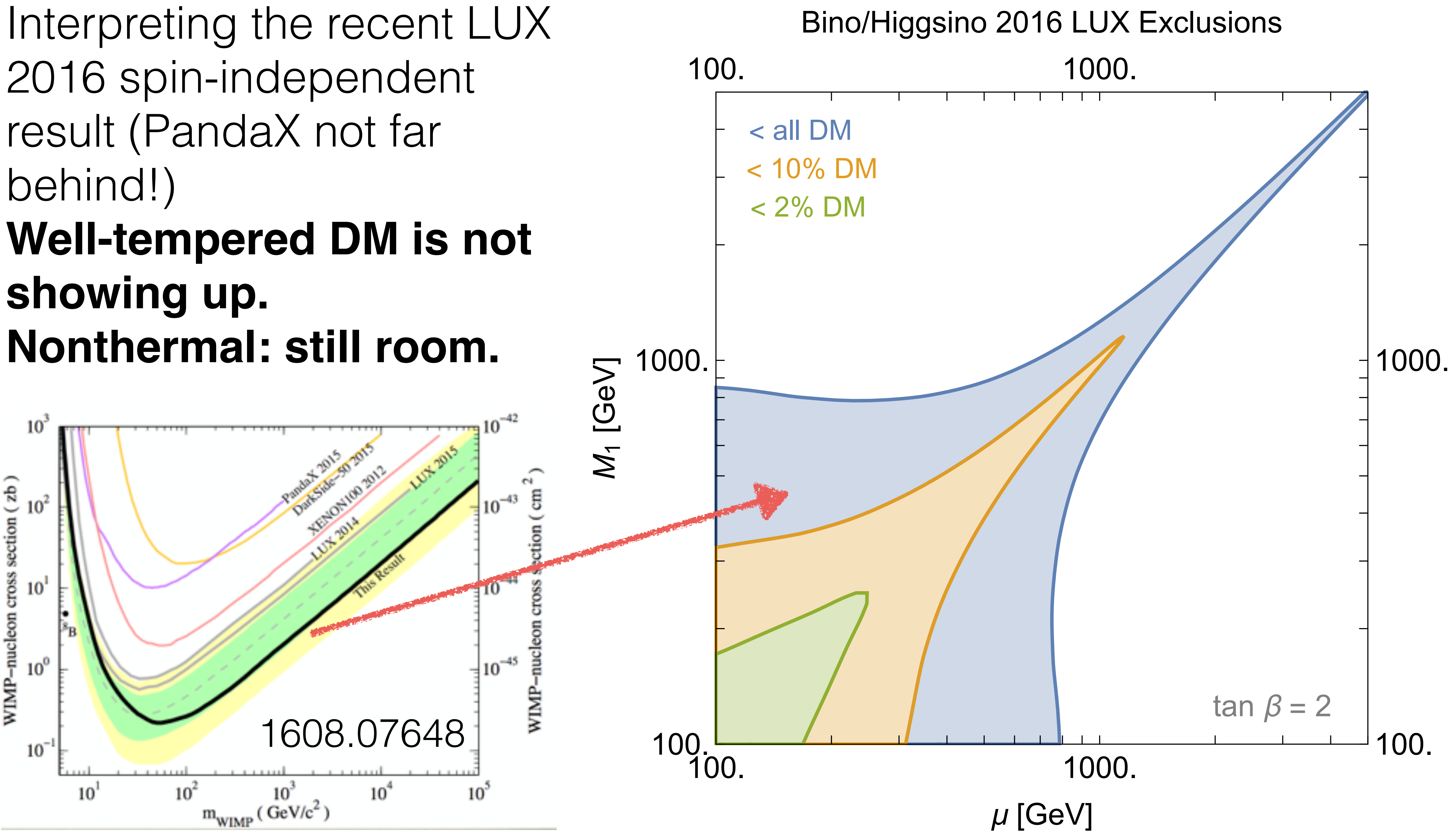
Higgsino/Bino DM Directly

(higgsino/wino is a similar story)

Interpreting the recent LUX 2016 spin-independent result (PandaX not far behind!)

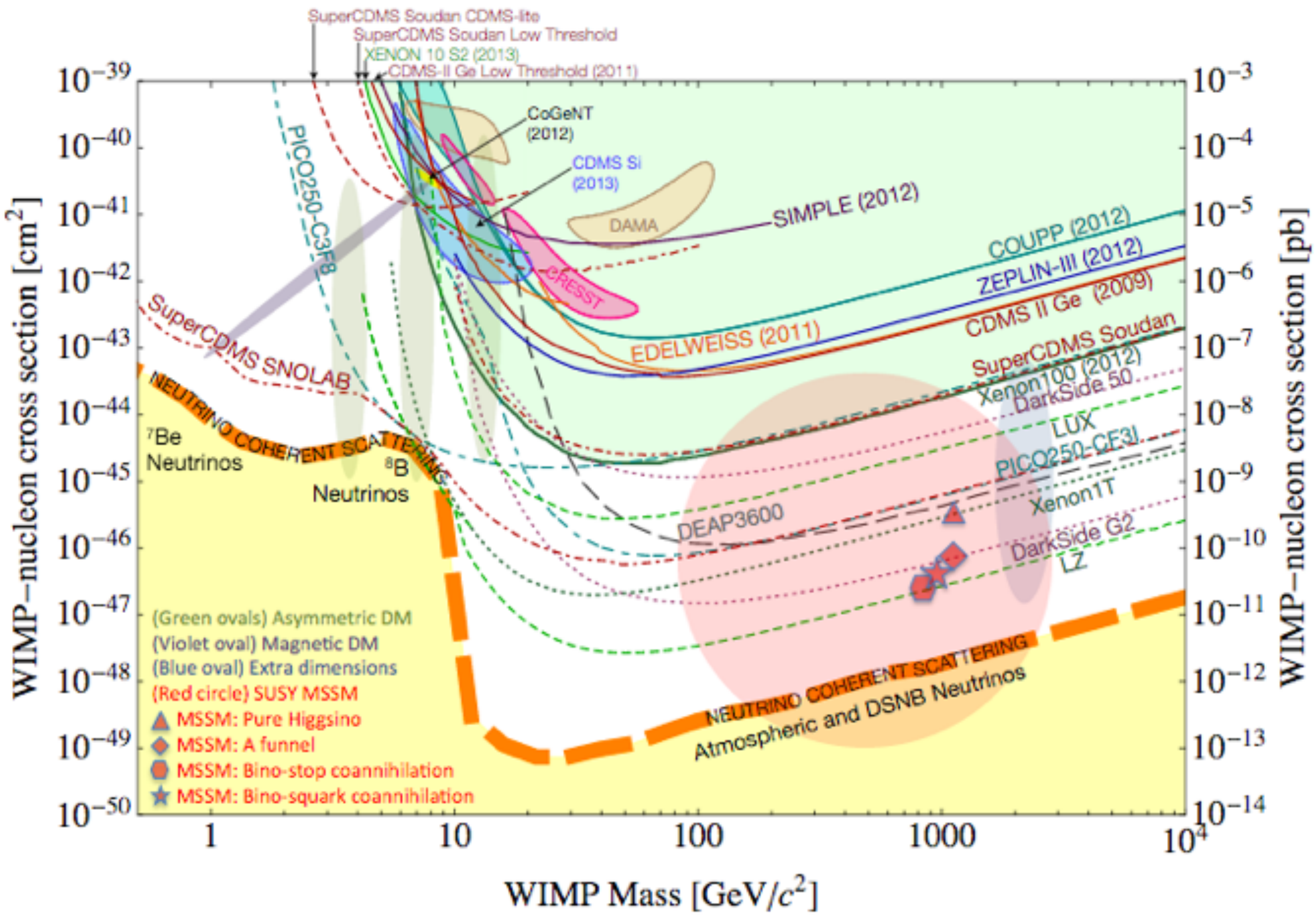
Well-tempered DM is not showing up.

Nonthermal: still room.



Future Direct Detection

Snowmass: Cushman et al. 1310.8327



← Z exchange

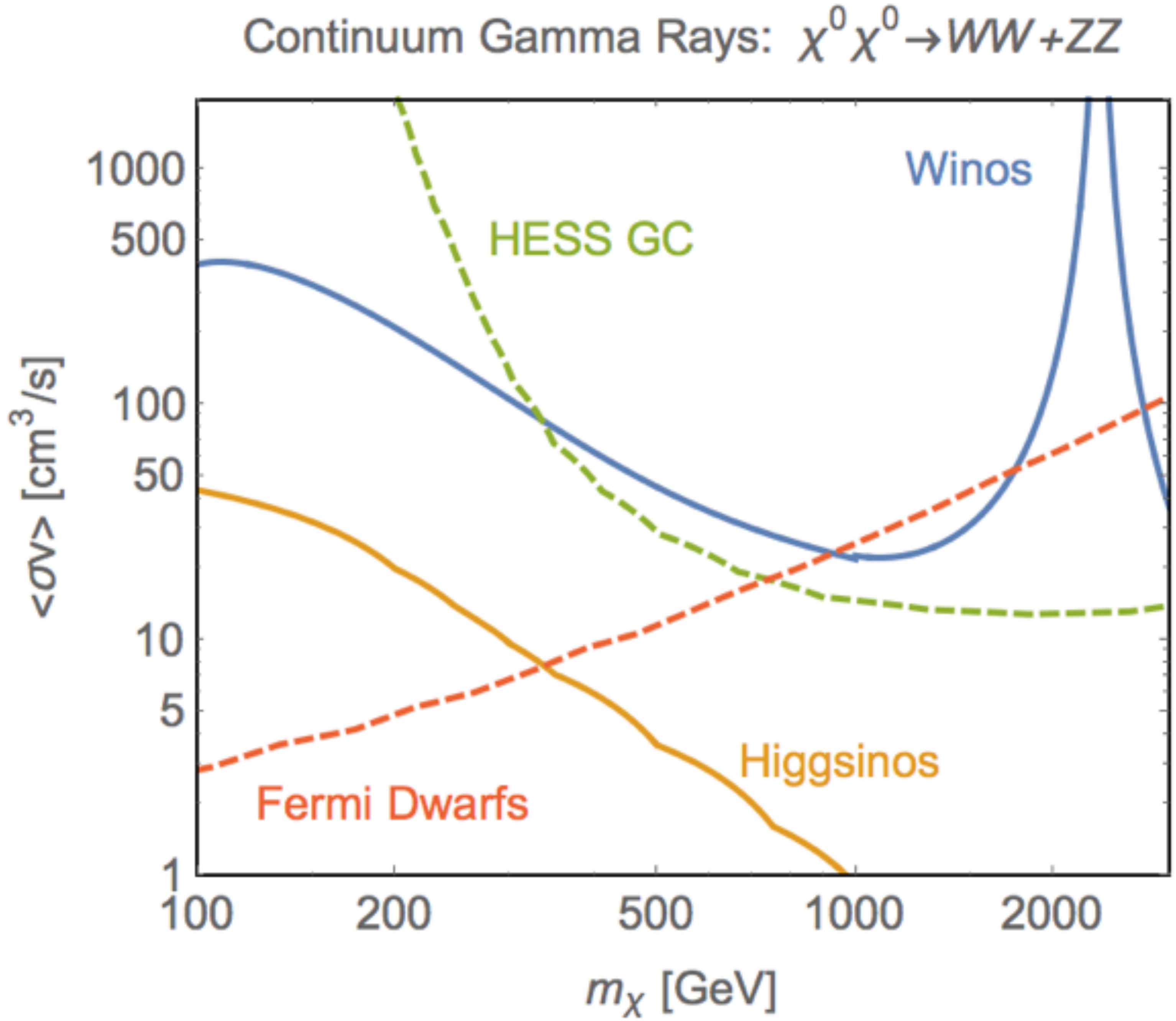
← *h* exchange

← *W* loop (wino)

← *W* loop (higgsino)

SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.

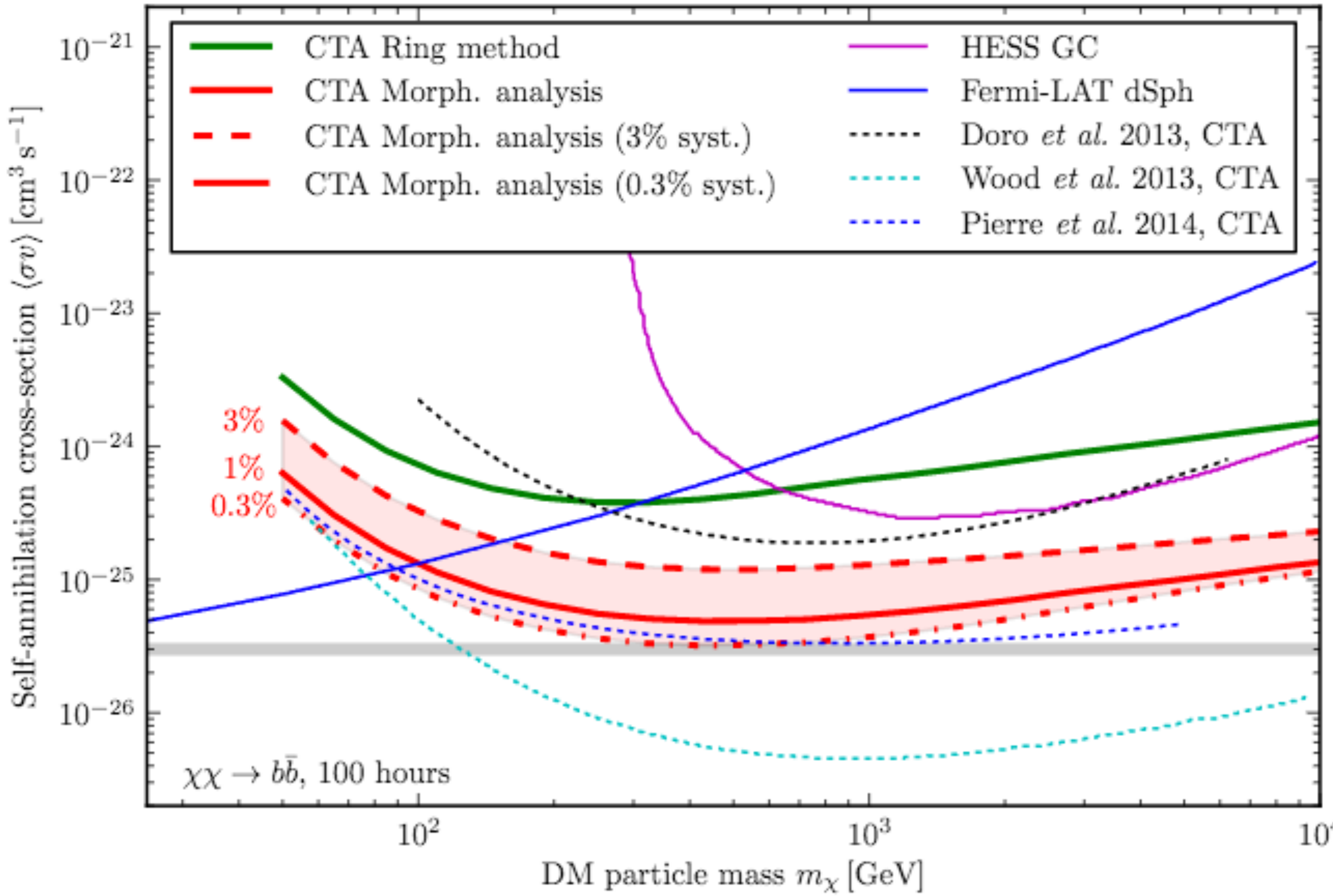
Indirect Detection



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

Future Indirect Detection



1408.4131
Silverwood, Weniger, Scott, Bertone

CTA (Cherenkov Telescope Array) will get *close* to ruling out thermal relic dark matter over most of the hundreds-of-GeV range, but will likely not quite reach TeV higgsinos.

(Assuming no significantly new techniques.)

100 TeV?

Future colliders are being discussed at different energies

FCC-hh: 100 km tunnel, 100 TeV proton-proton
SppC: 55 km tunnel, 70 TeV proton-proton

The energy reached depends on **magnet technology**.
12 Tesla seems completely feasible; 16 Tesla within reach; 20 Tesla boldly optimistic.

SppC could fall short of 70 TeV, without a bigger tunnel.

Do we have a clear physics case for 50 TeV, 70 TeV, 100 TeV, 120 TeV, …? Need well-defined questions to assess.

Precision BSM at 100 TeV

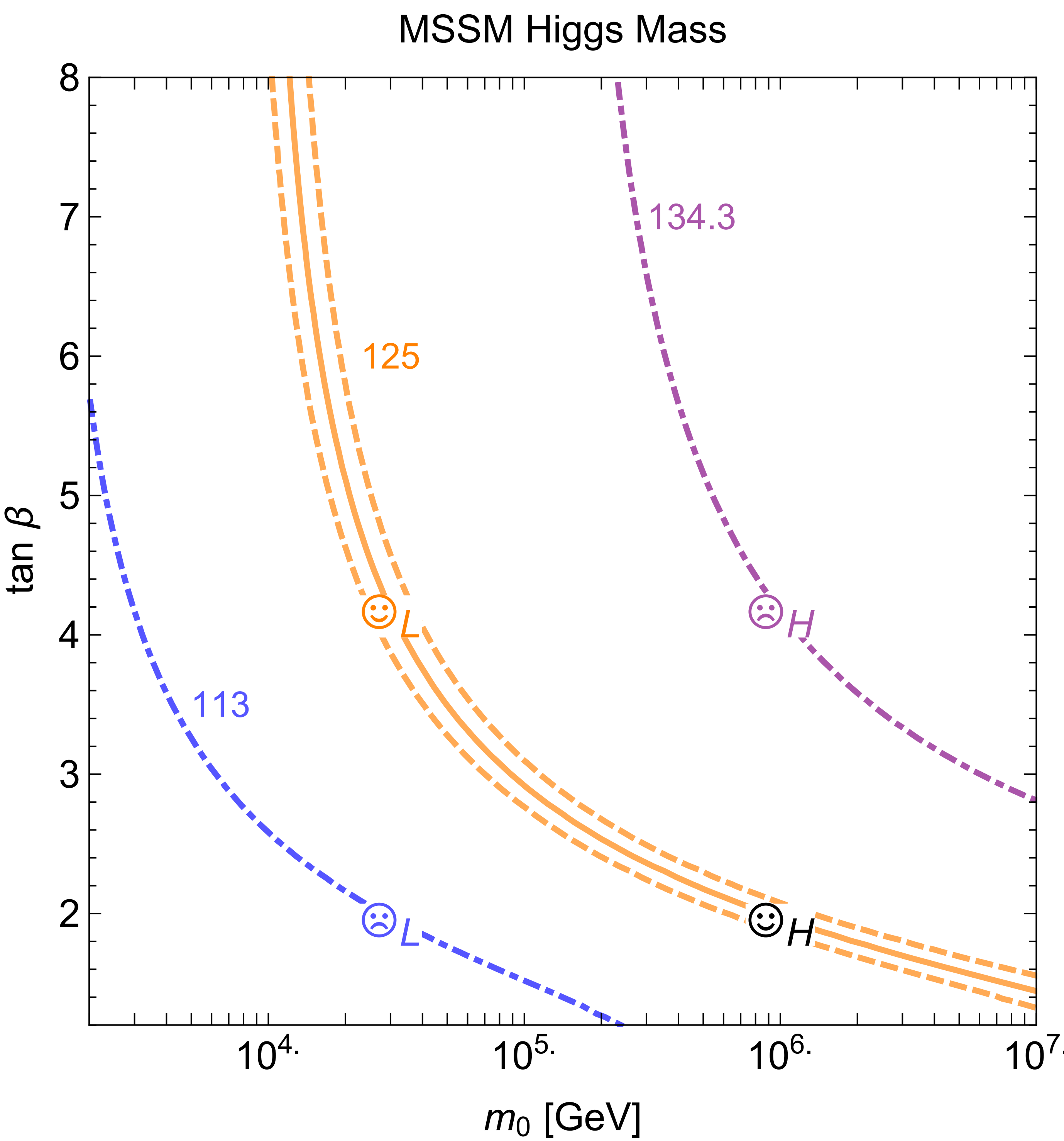
If the LHC discovers new physics, it will likely only provide the first glimpse of it.

A higher-energy, high-luminosity collider would help solidify the new Standard Model.

Most 100 TeV BSM studies to date are simple estimates of exclusion/discovery reach of very heavy particles.

We need more investigation of the real power of such a machine to reveal *couplings*, *mechanisms*, and *principles*, not just bumps.

One Such Collider Challenge: Why 125 GeV?



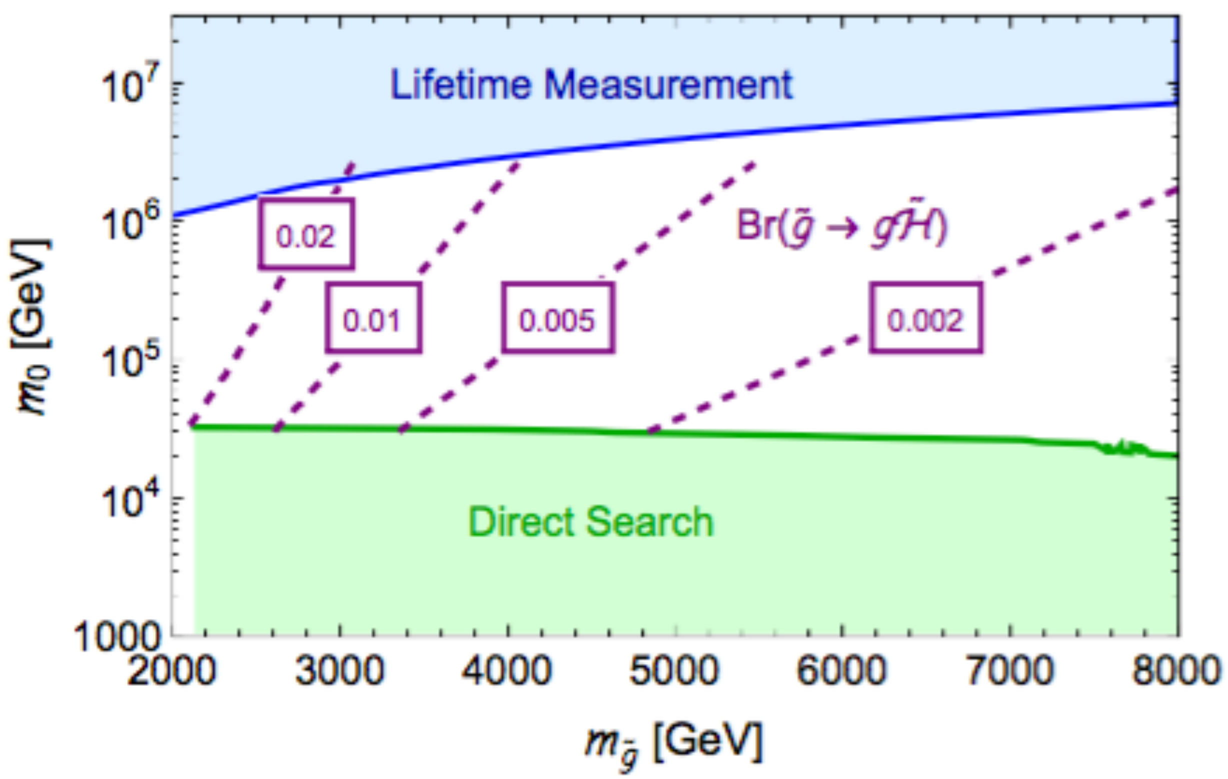
In the MSSM: basically a function of the stop mass and tan beta.

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

Precision physics: millions of gluino pairs.

(work in progress with P. Agrawal, J. Fan, W. Xue)

Testing MSSM 125 GeV



Agrawal, Fan, MR, Xue in progress

Scalar mass scale:
gluino lifetime;
log in one-loop branching ratio;
squark/gluino production
(also see Sato, Shirai, Tobioka 1207.3608)

Measuring tan beta is trickier. Several observables; which is best depends on ordering of bino, wino, and higgsino masses. For instance:

$$\frac{\Gamma(\tilde{W}^0 \to h\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to Z\tilde{B}^0)} \approx \frac{4\tan^2(2\beta)\mu^2}{M_2^2}\left(\frac{1+M_1/M_2}{1-M_1/M_2}\right)^2.$$

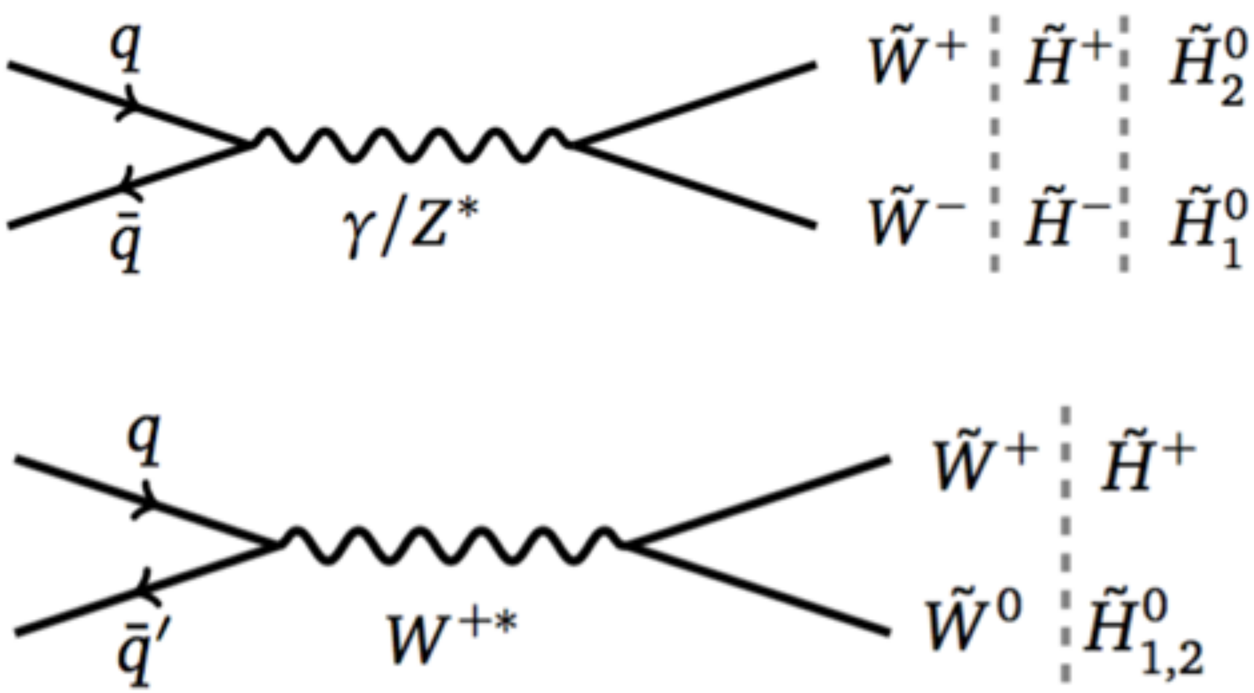
$$\frac{\Gamma(\tilde{g} \to b\bar{b}\tilde{H}^0)}{\Gamma(\tilde{g} \to t\bar{t}\tilde{H}^0)} \propto \tan^2\beta.$$

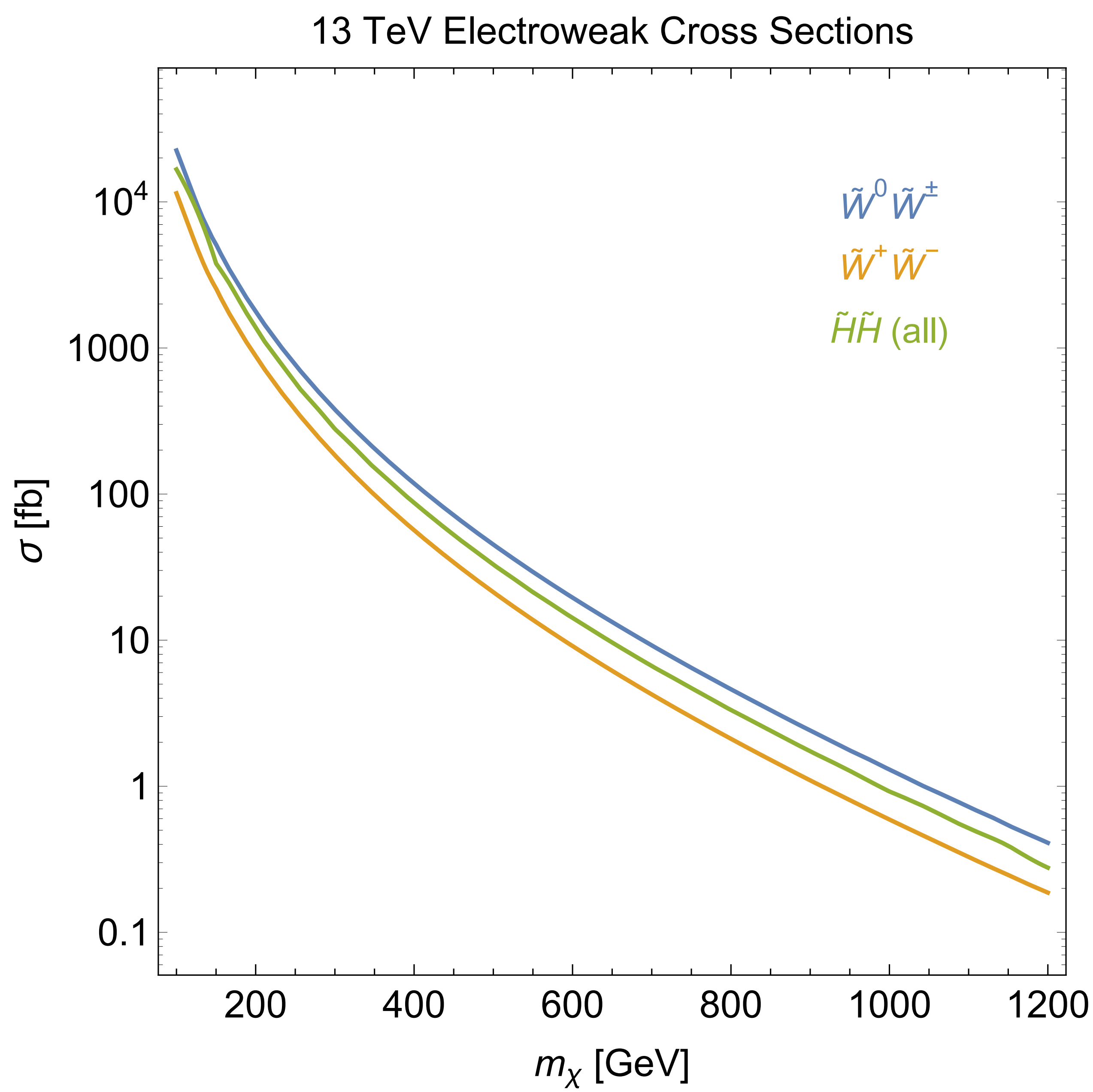
$$\frac{\Gamma(\tilde{W}^0 \to Zh\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to ZZ\tilde{B}^0)+\Gamma(\tilde{W}^0 \to hh\tilde{B}^0)} \propto \left(\frac{\sin\beta-\cos\beta}{\sin\beta+\cos\beta}\right)^2$$

Preliminary results in the CERN Report; paper this summer

Electroweakino Production

Winos and higgsinos can be pair-produced through their electroweak interactions.

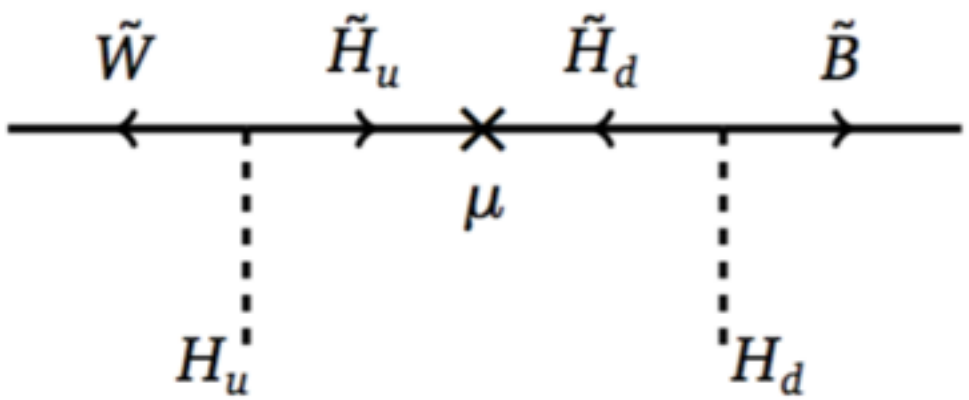




For on-shell bosons: produce one multiplet, decay to another.

Wino to Bino

There is no renormalizable coupling between winos and binos; the decay goes through their mutual interaction with higgsinos.



Tree level dimension 5:

$$\sim \frac{gg'}{\mu \tan\beta} \left(h^\dagger \sigma^i h\right) \tilde{W}^i \tilde{B}$$

Only two body decays are:

$$\tilde{W}^0 \to h\tilde{B}, \tilde{W}^\pm \to W^\pm \tilde{B}$$

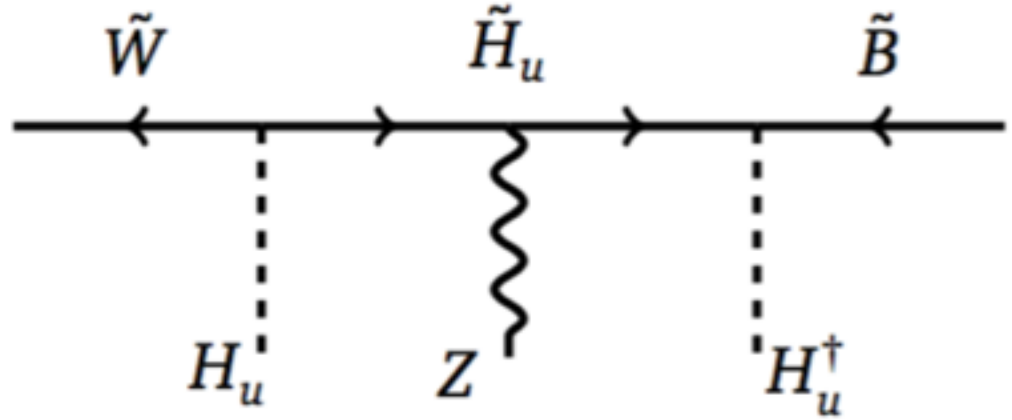
Plus phase-space suppressed 3-body decays:

$$\tilde{W}^0 \to hh\tilde{B}, ZZ\tilde{B}, W^+W^-\tilde{B}$$
$$\tilde{W}^\pm \to W^\pm h\tilde{B}, W^\pm Z\tilde{B}$$

(are these ever useful? I'm not aware of studies)

Wino to Bino

The 2-body decay to a Z boson happens only at dimension 6 (or at dim. 5 *at one loop*):



$$\frac{gg'}{\mu^2}\left(h^\dagger \sigma^i D_\mu h\right)\tilde{B}^\dagger \bar{\sigma}^\mu \tilde{W}^i$$

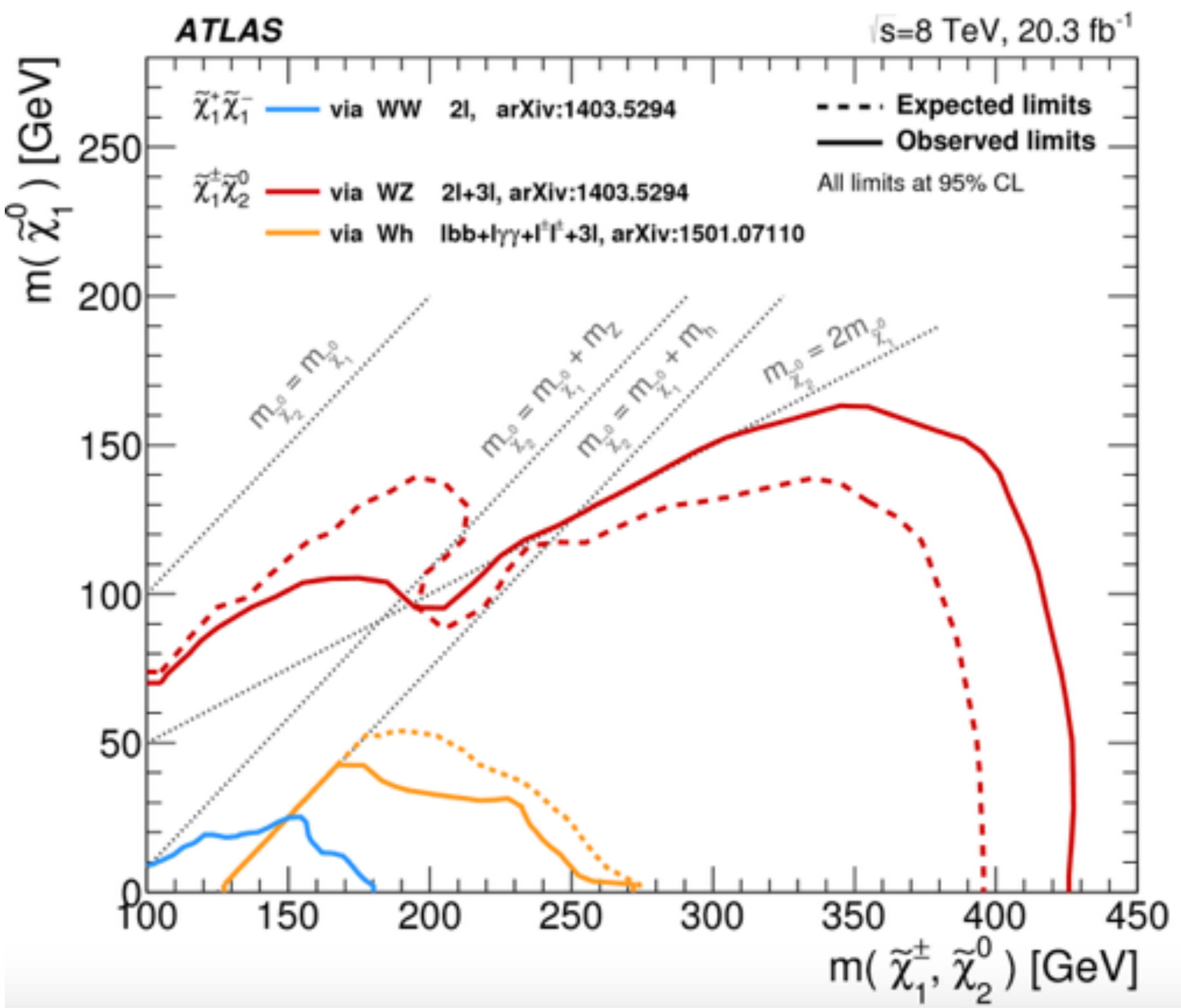
So, roughly expect the branching fraction of **Higgs relative to Z is enhanced:**

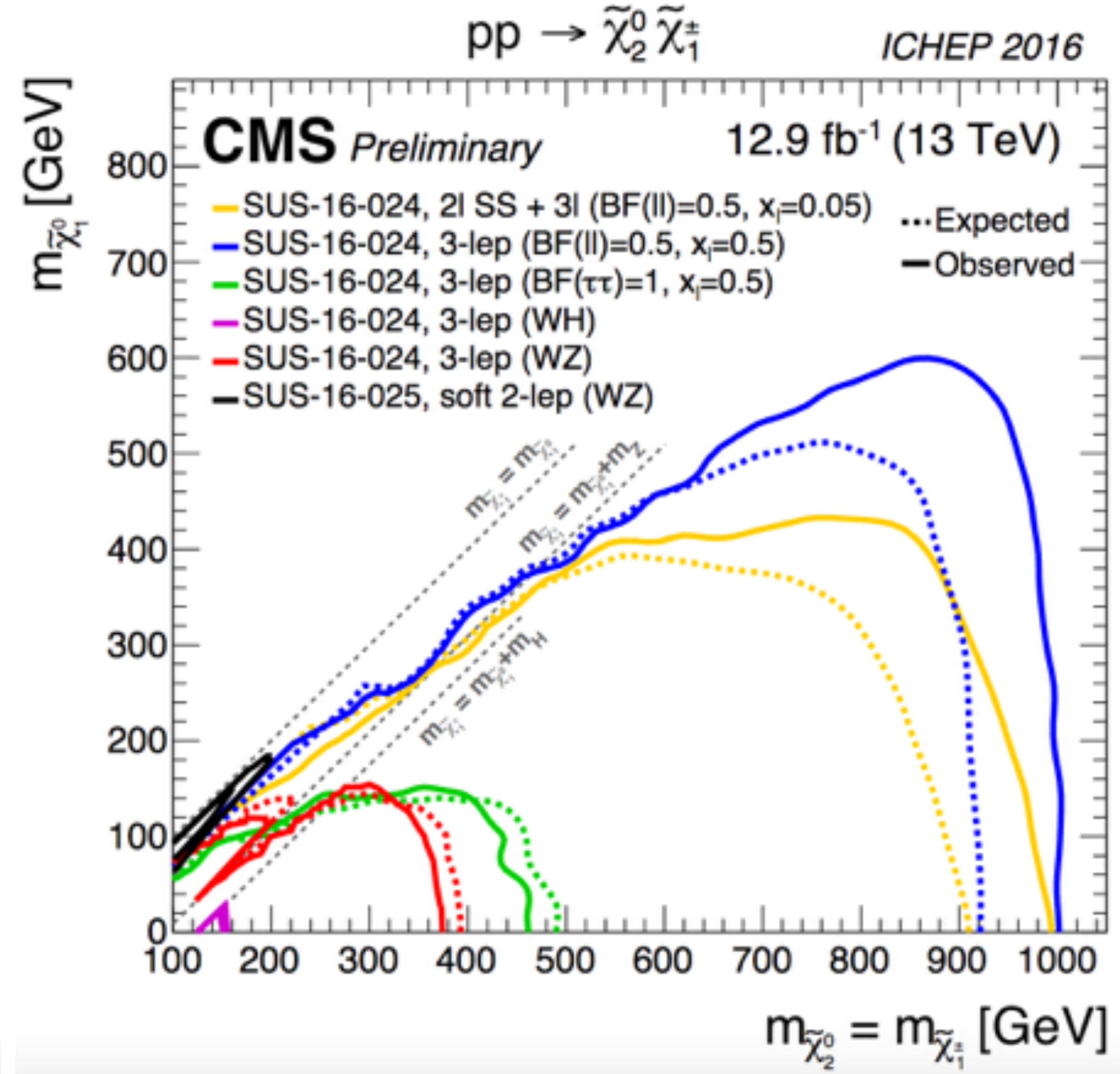
$$\frac{\Gamma(\tilde{W}^0 \to h\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to Z\tilde{B}^0)} \approx \frac{4\tan^2(2\beta)\mu^2}{M_2^2}\left(\frac{1+M_1/M_2}{1-M_1/M_2}\right)^2.$$

Upshot: **largest SUSY diboson rate in wino/bino is W + higgs + MET**, except at large tan β where Z appears.

(Howe, Saraswat 1208.1542; Baer, Barger, Lessa, Sreethawong, Tata 1201.2949)

Wh: Weak Bounds at LHC (So Far!)





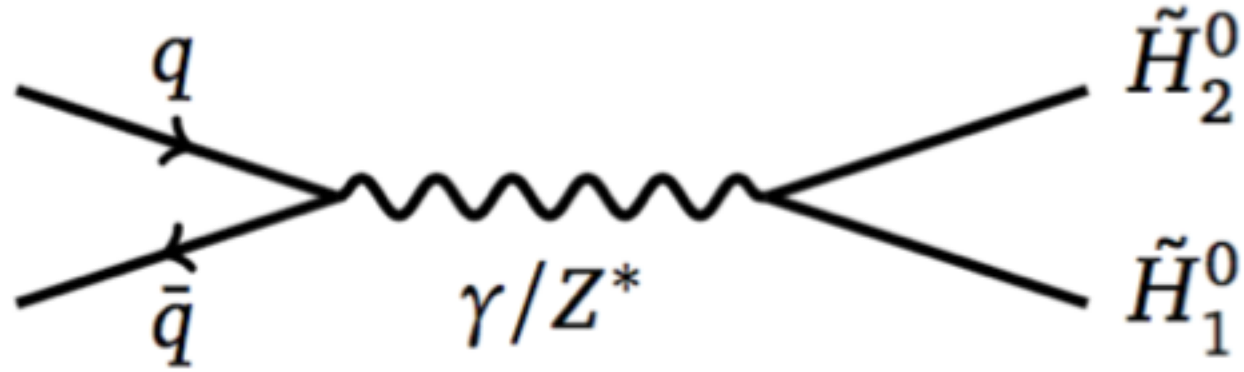
Presented results assume wino cross sections, but often **not** wino decay modes!

Higgsino Production

Higgsinos have a Dirac mass $\mu \tilde{H}_u \cdot \tilde{H}_d$ but mixing with binos and winos splits the neutral Dirac higgsino into two neutral Majorana particles. The combination is approximately

$$\tilde{H}_\pm \equiv \frac{1}{\sqrt{2}}\left(\tilde{H}_u^0 \pm \tilde{H}_d^0\right)$$

The Z-boson couples **off-diagonally:** make one of each neutral mass eigenstate.



Higgsino to Bino

If the bino is lighter, decays go via the couplings

$$\frac{g'}{2}\left(\tilde{H}_u^0 H_u^0 - \tilde{H}_d^0 H_d^0\right)\tilde{B}$$

(Goldstone, i.e. *Z*)

$$\propto \tilde{B}\left[h\left(\sin\beta\tilde{H}_u^0 - \cos\beta\tilde{H}_d^0\right) + iG^0\left(\sin\beta\tilde{H}_u^0 + \cos\beta\tilde{H}_d^0\right)\right]$$

(fine print: alignment limit assumed, $\beta \approx \alpha + \pi/2$)

If $\tan\beta \approx 1$, one Higgsino couples to each of the Higgs VEV eigenstates. **Make a higgsino pair, get one *Z* and one *h*.** At large tan β get an **equal mix** of *Z, h* on each side.

So produce signals of missing momentum plus:
Zh, *ZZ, hh* in a mixture related to tan beta;
or W^+W^- from chargino pairs*;*
or *WZ, Wh* in equal amounts from chargino+neutralino

Higgsino to/from Wino

- We could produce higgsinos that decay to lighter winos, or winos that decay to lighter higgsinos.

- The story is very similar to higgsino -> bino: for tan beta closer to 1 the decays approach 100% Z or 100% Higgs; for large tan beta, get a mix.

- If higgsinos are at the bottom of the spectrum, they are nearly degenerate and all essentially invisible. Wino->higgsino production populates all Z/h final states randomly.

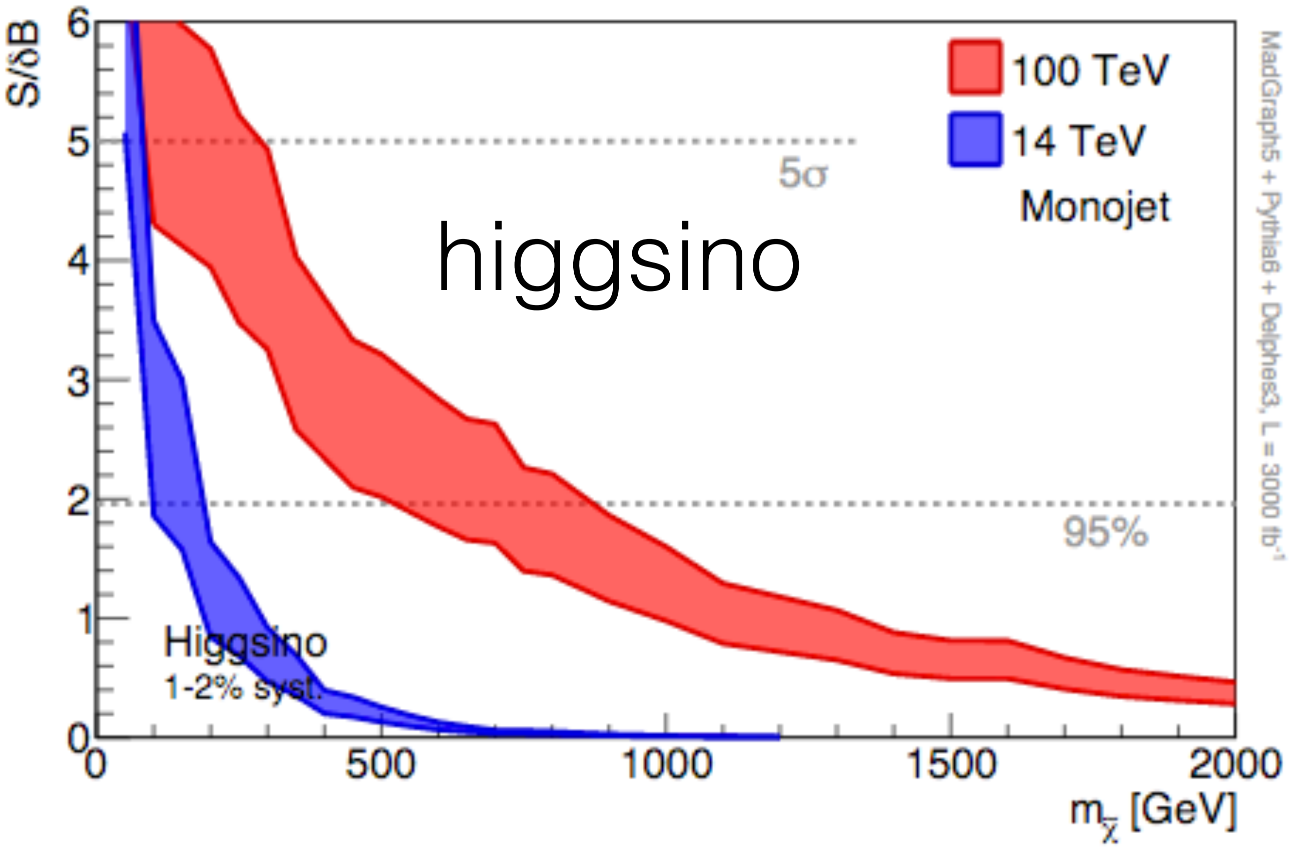
- Neutral -> charged decays can produce either sign of W boson.

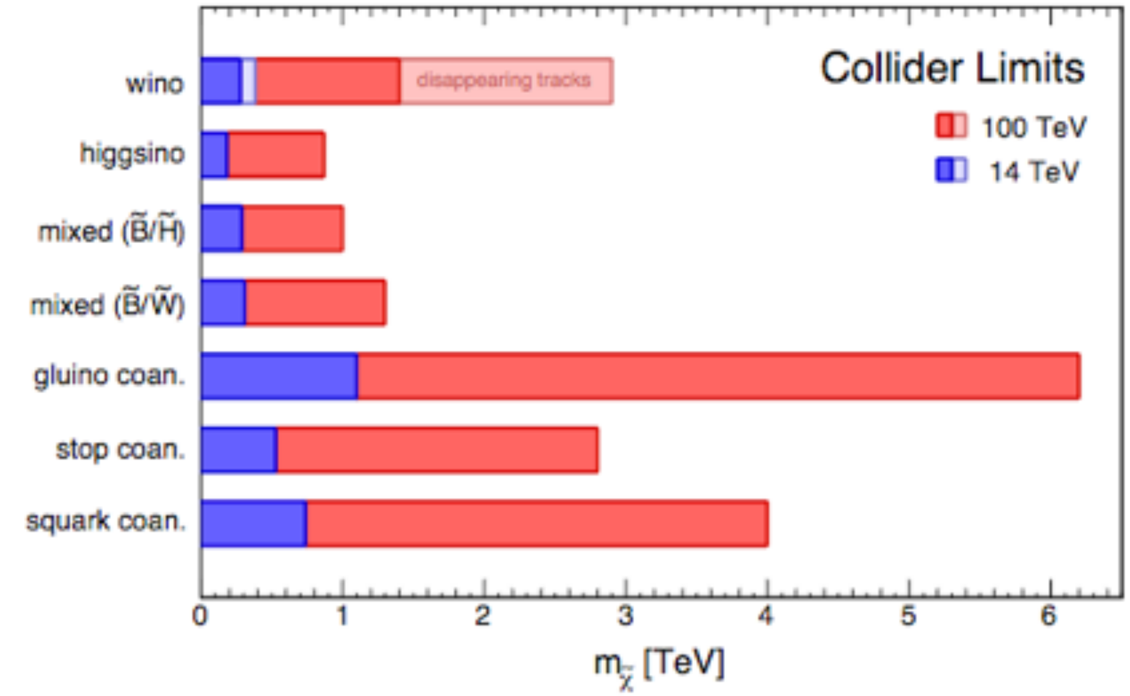
- Correlations between the two sides—equal Z and h on average but large deviations of hh:Zh:ZZ from 1:2:1—are a strong clue for higgsino production.

One lesson: precision electroweakino spectroscopy & branching measurements can tell us tan beta!

SU(2) Dark Matter at 100 TeV

M Low and L-T Wang: 1404.0682





Monojet searches cover much of the higgsino range. Not quite thermal?

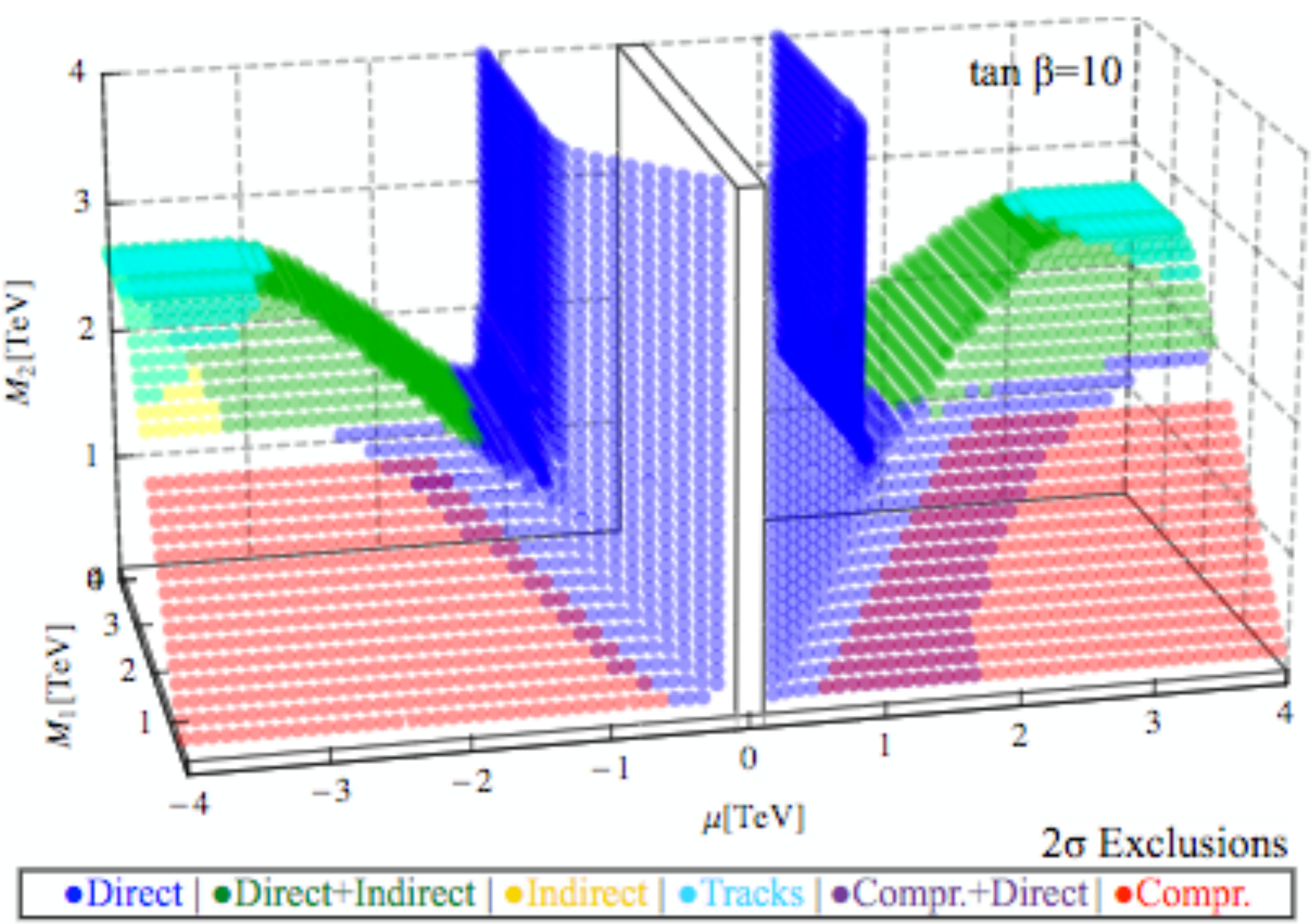
Notice **wide bands**: varying background systematics 1-2%. Big exp. challenge is well-characterized background!

some other 100 TeV SUSY DM studies: Cirelli, Sala, Taoso 1407.7058 (disappearing tracks for winos); Acharya, Bozek, Pongkitivanichkul, Sakurai 1410.1532 (wino->higgsino); Gori, Jung, Wang Wells 1410.6287 (multilepton, dilepton)

Fully Test Neutralino DM?

Bramante, Fox, Martin, Ostdiek, Plehn, Schell, Takeuchi 1412.4789
Bramante, Desai, Fox, Martin, Ostdiek, Plehn 1510.03460

Claim a 100 TeV collider can cover the full parameter space of thermal relic neutralinos. Difficult corner: mixed bino-winos from compressed searches at 100 TeV.



Red region:
compressed search

$$pp \to (\tilde{\chi}_2^0 \to \gamma \tilde{\chi}_1^0)(\tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \tilde{\chi}_1^0) j \to \ell^\pm \gamma j \not{p}_T$$

Higgsinos covered by direct detection ***if*** $M_{1,2}$<4 TeV. Smaller splittings still a challenge.

Conclusions

- Some version of “mini-split SUSY” is a compelling explanation of why the Higgs mass is 125 GeV.
- But what tethers split SUSY to the weak scale? Could be dark matter—but gamma ray constraints.
- Can explore if these can be evaded by no-scale structure; interesting EFT puzzles to solve.
- Mini-split SUSY, if true, requires a precision physics program that a high-energy collider (100 TeV?) might be well-suited for.