Deciphering the MSSM Higgs Mass at FCC-pp

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Prateek Agrawal, JiJi Fan, MR, and Wei Xue: 1702.05484
(also 100 TeV BSM report 1606.00947, section 3.10)

Precision BSM at 100 TeV

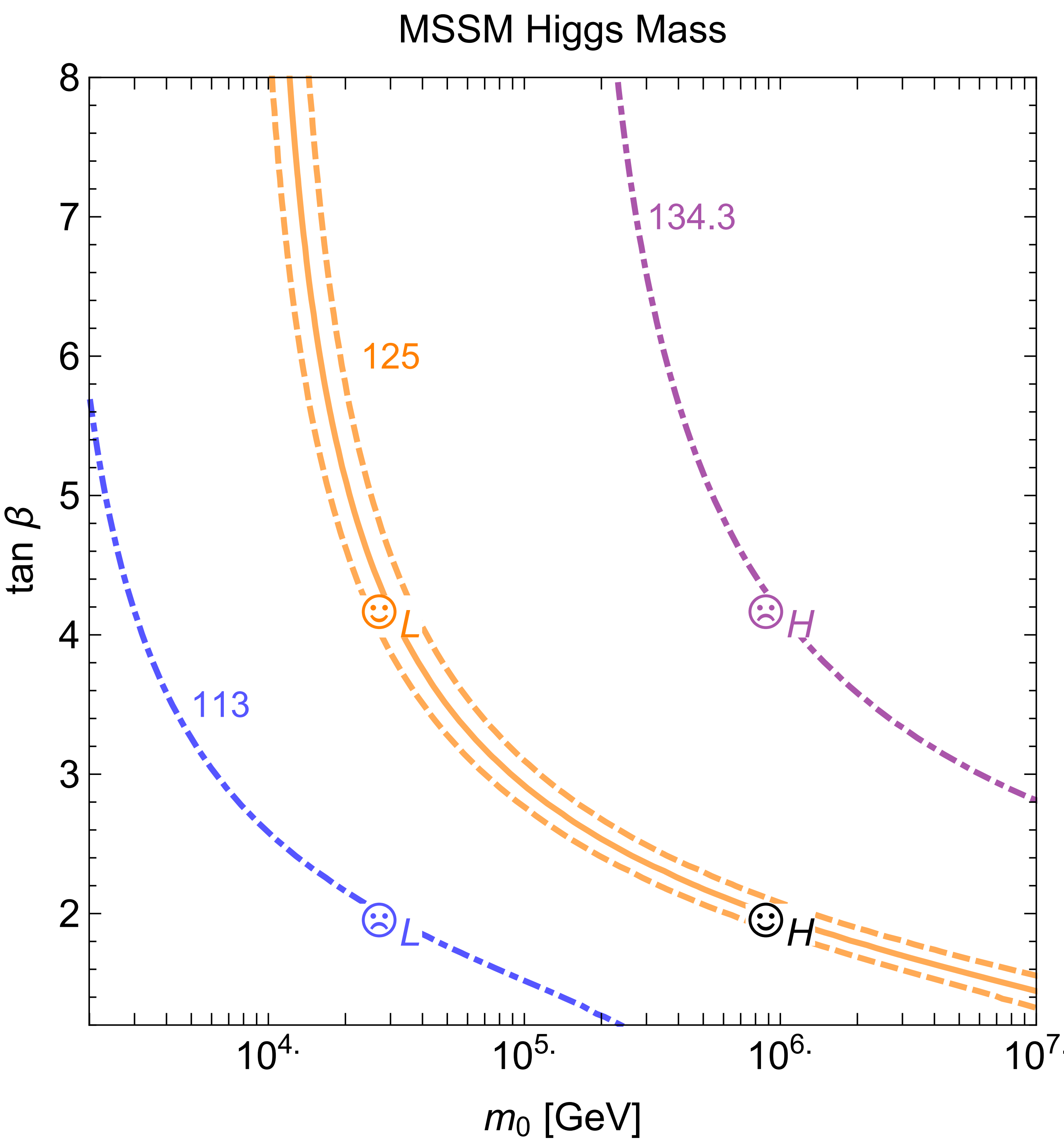
If the LHC discovers new physics, it will likely only provide the first glimpse of it.

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

Many (not all!) 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?



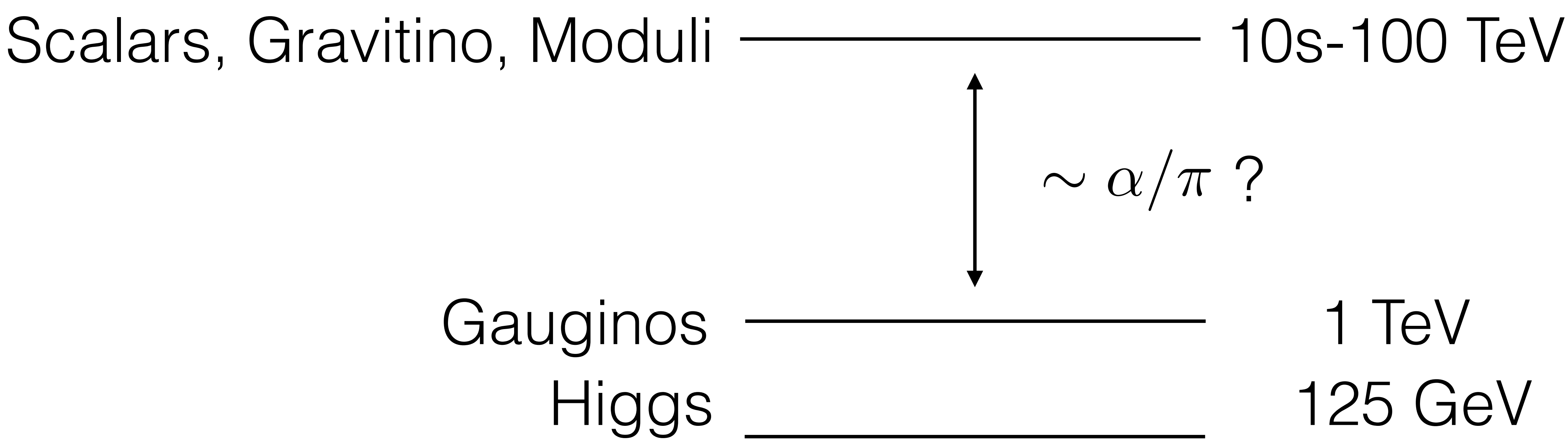
In the MSSM: basically a function of the stop mass and tan beta.

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

Focused on the (mini-)***split SUSY*** limit.

Interesting ties between scalar mass scale and UV completions

Split SUSY, Take 1:

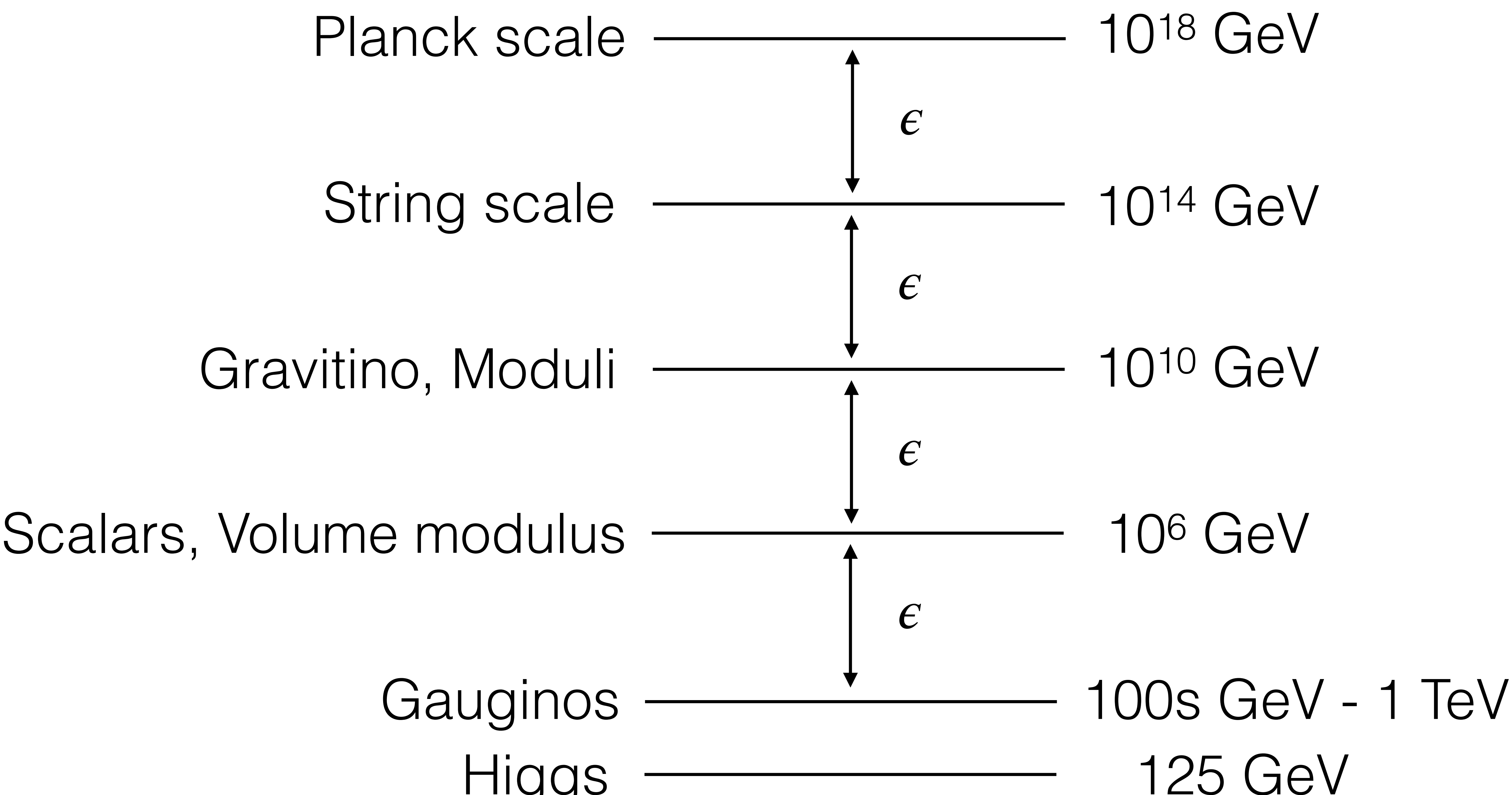


- Heavy scalars (10s of TeV) at large tan β: right Higgs mass
- Loop factor: arises in AMSB (Giudice, Luty, Murayama, Rattazzi '98) and some moduli mediation
- Late-time gravitino and moduli decays populate nonthermal dark matter, e.g. winos (Moroi, Randall '99; Kane et al.)

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

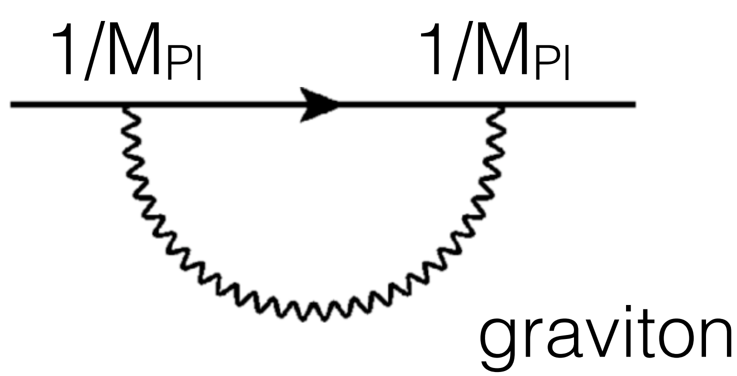
Split SUSY, Take 2: “SUSY’s Ladder”

MR, W. Xue 1512.04941; cf. Large Volume Scenario: Conlon, Quevedo, Suruliz ’05; Aparicio, Cicoli, Krippendorf, Maharana, Muia, Quevedo ’14



Heavy Scalars and Sequestering

These theories have an interesting power counting in terms of the small ratio of cutoff to Planck scale:



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

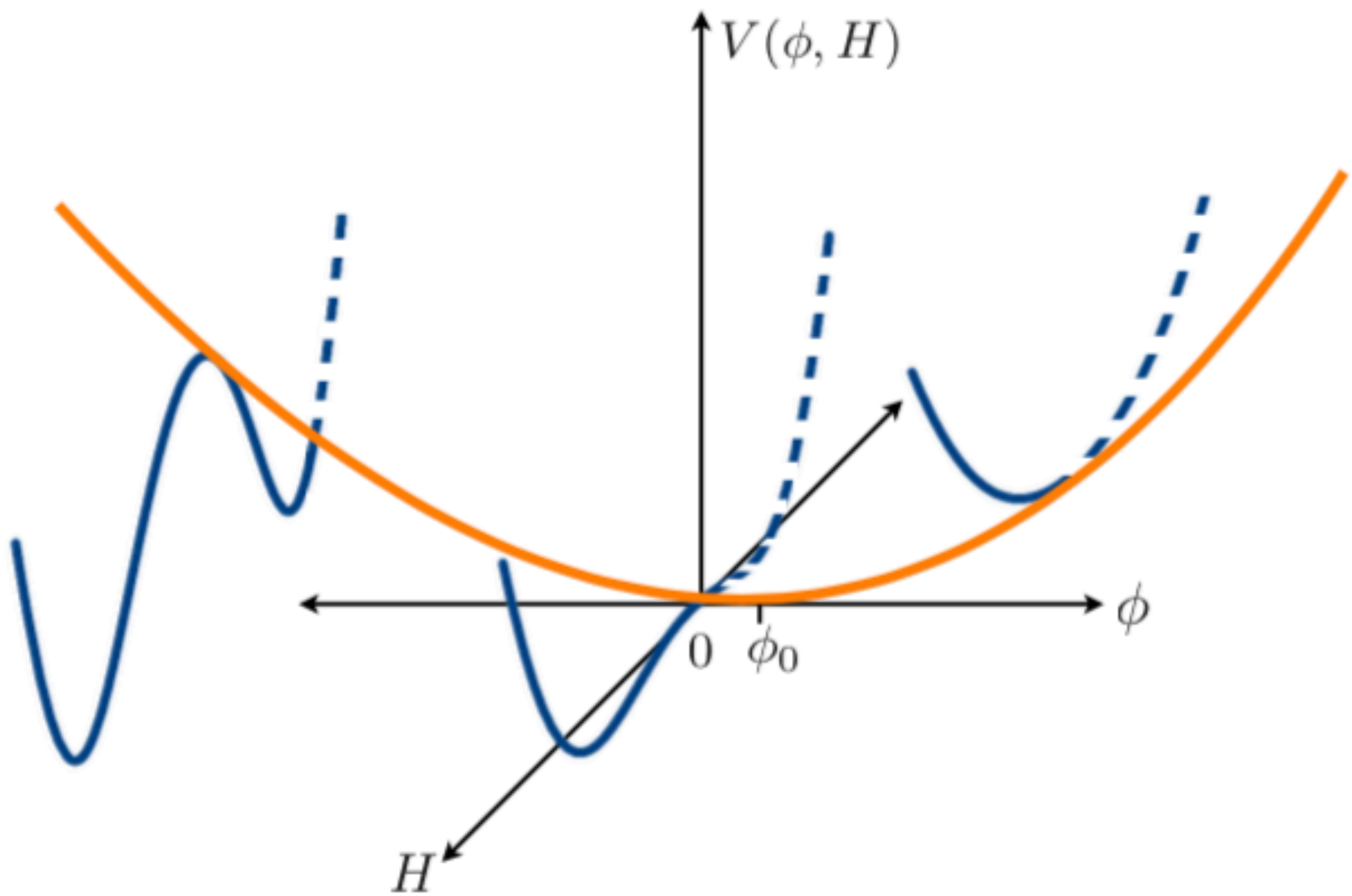
SUSY: $\delta m^2 \sim \frac{\Lambda^2 m_{3/2}^2}{16\pi^2 M_{\rm Pl}^2}$

Wei Xue and I showed how to use a convenient supergravity gauge developed by Cheung, D'Eramo, and Thaler, removing kinetic mixing of modulus and graviton. No-scale limit: conformal compensator $\mathbf{\Phi}$ linear in modulus but lacks *F*-term:

$$\mathbf{\Phi} = \frac{1}{\langle T + T^\dagger \rangle^{1/2}} e^{-\mathbf{T}^c/(\sqrt{3}M_{\rm Pl})} \left(1 + \frac{\mathbf{T}^c|_{\theta^2}}{\sqrt{3}M_{\rm Pl}}\theta^2\right)$$

Fun field theory here, but that's a different talk!

Fine-Tuning and Cosmological Dynamics



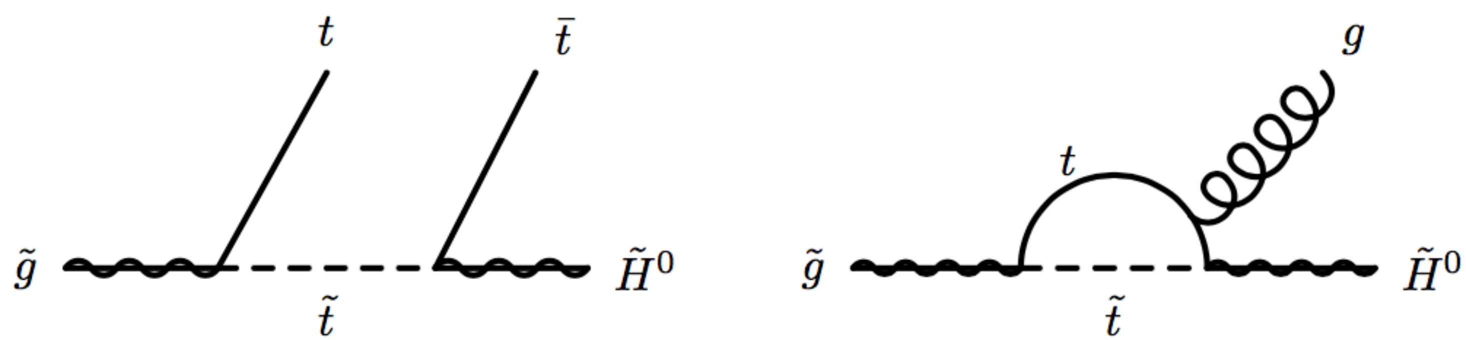
(Mini-)Split SUSY with moduli could carry interesting consequences for cosmological dynamics.

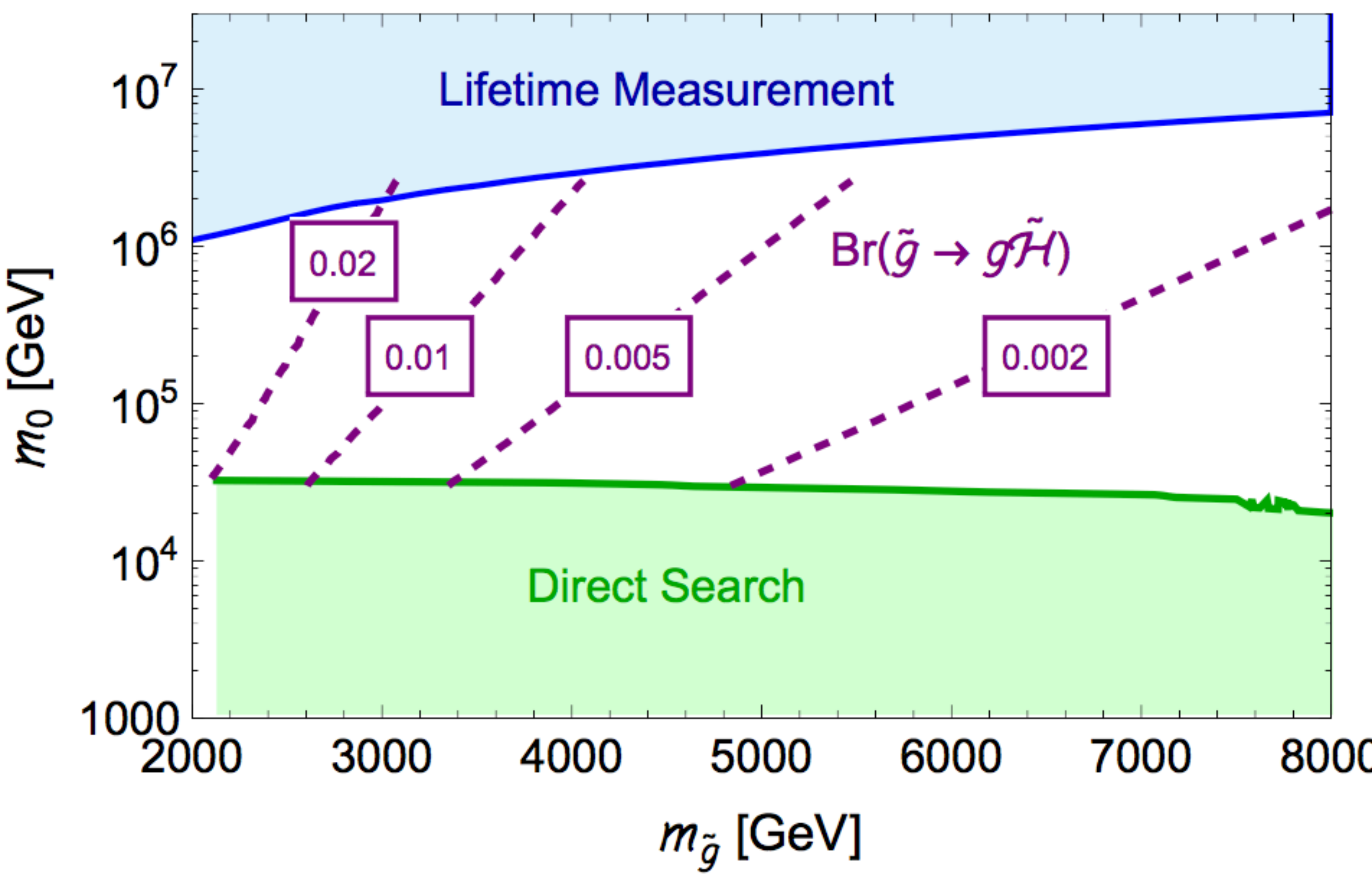
Modulus oscillates, tachyonic Higgs production $\Longrightarrow$ modulus fragments, gravitational waves, rich dynamics.

Mustafa Amin, JiJi Fan, Kaloian Lozanov, MR, to appear soon.

Again, this a different talk! On to colliders.

Finding the Scalar Mass





displaced decays

logs from loops

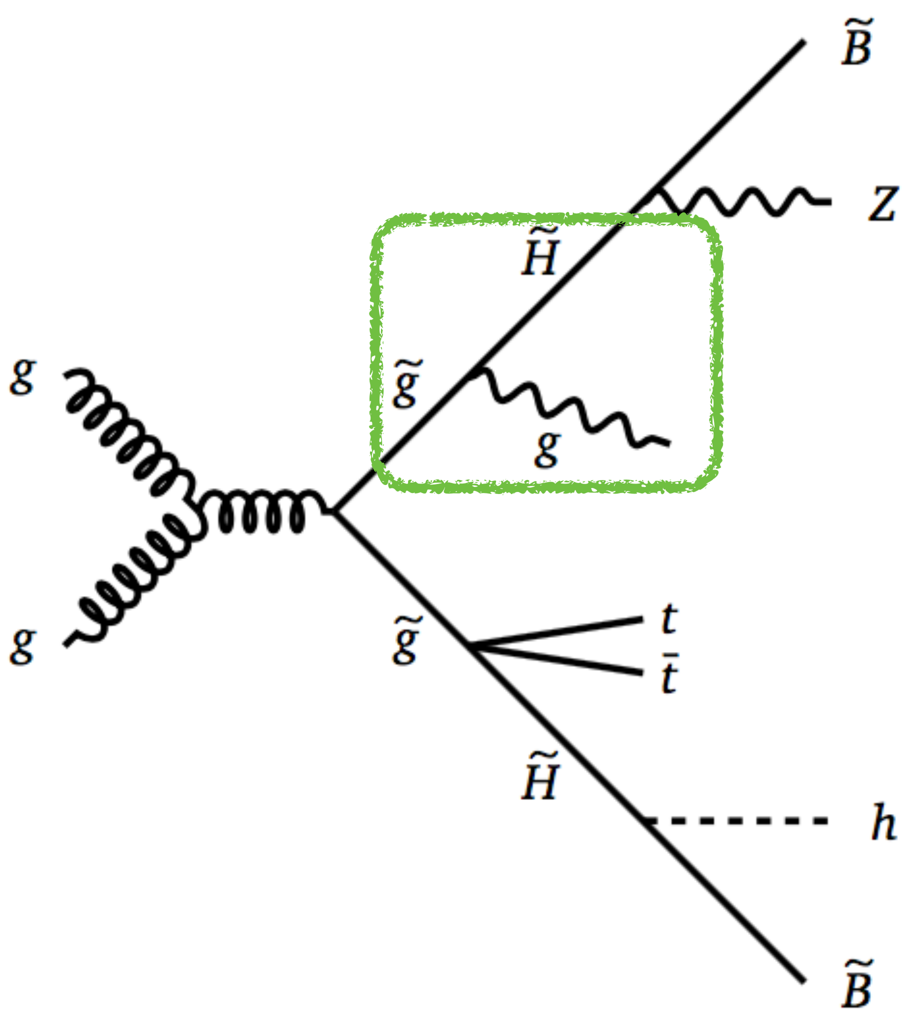
(also see Sato, Shirai, Tobioka 1207.3608)

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

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

Scalar mass: collider benchmark

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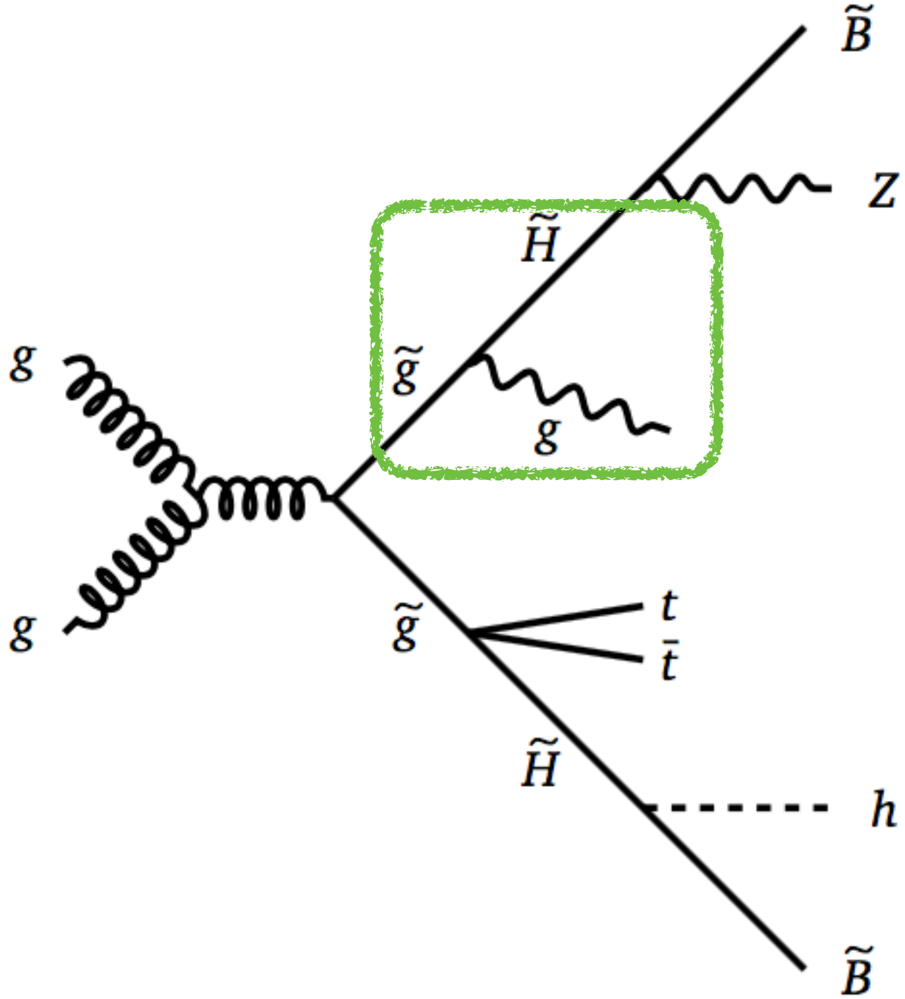
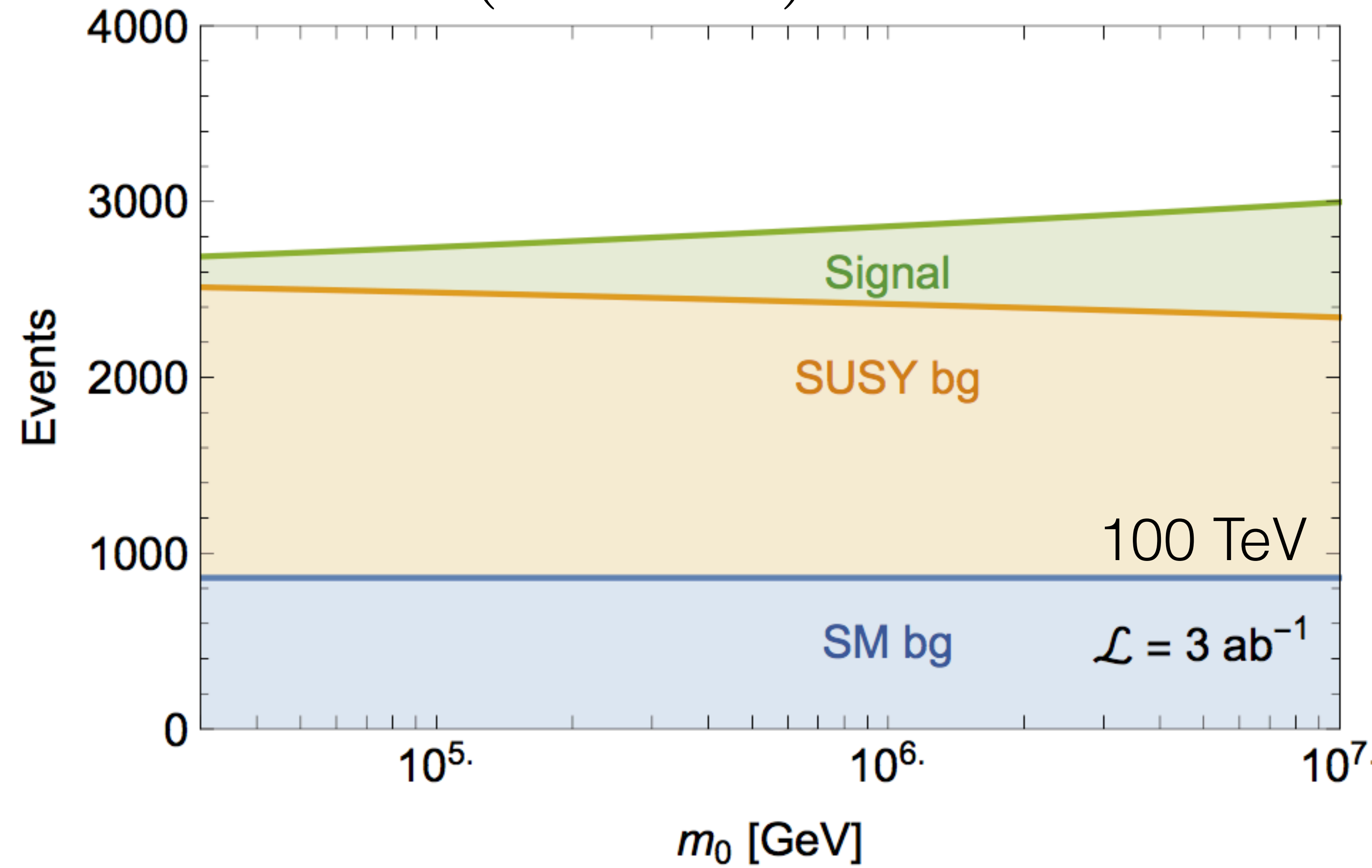


SM backgrounds:

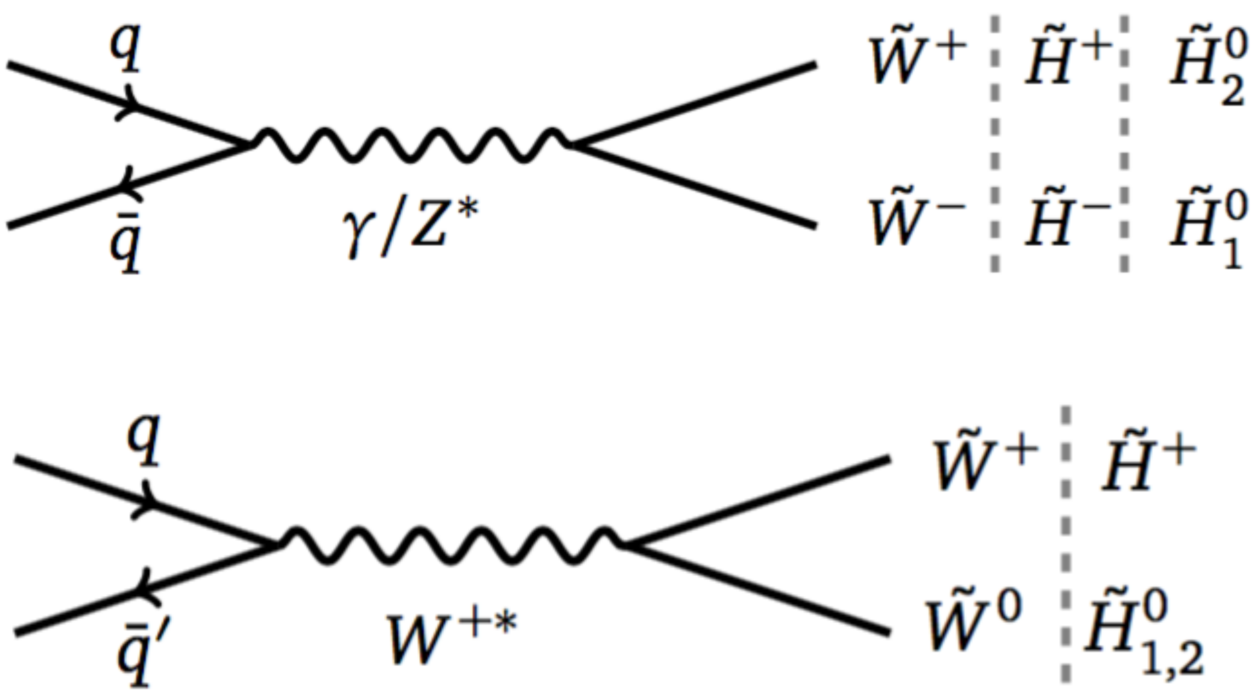
$$Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu}) + \text{jets}$$
$$t\bar{t} + Z(\to \ell^+\ell^-)$$

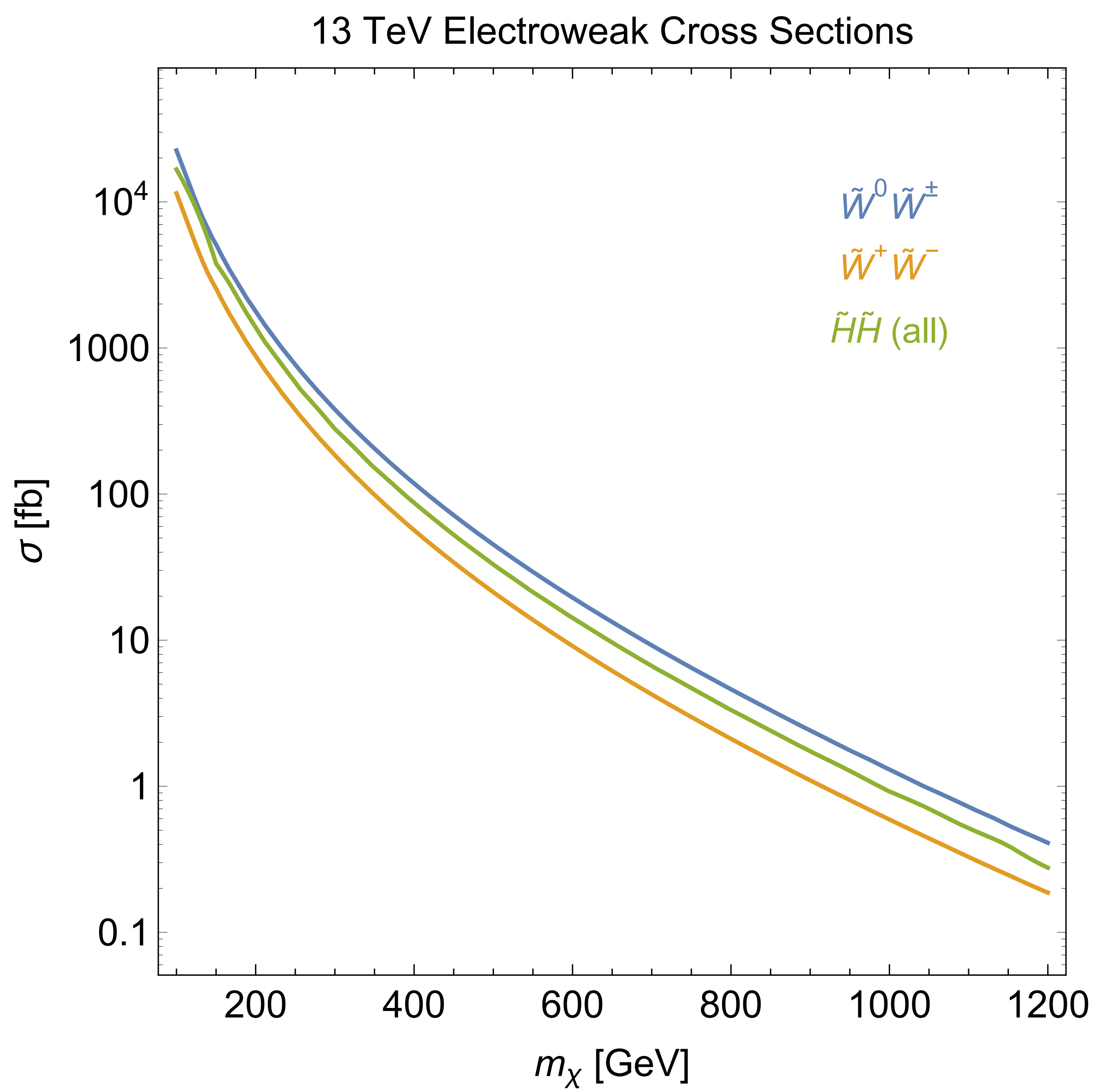


Measuring Tan Beta?

Different strategies for different electroweakino spectra.

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

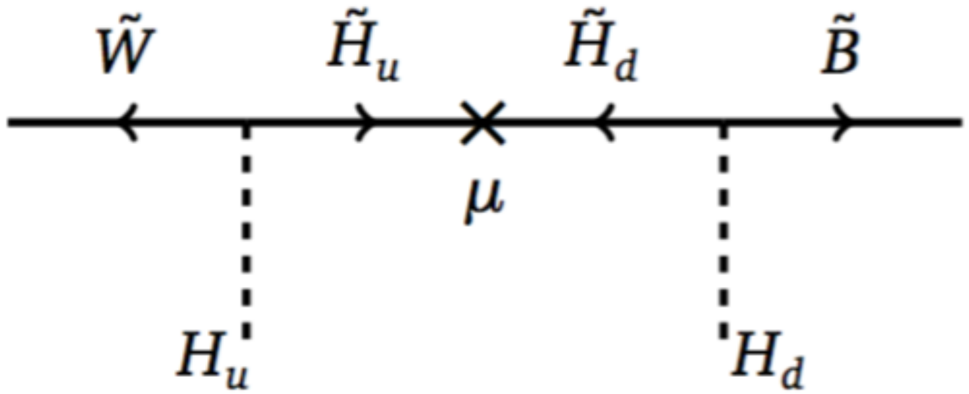




For on-shell bosons: produce one multiplet, decay to another.

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:

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

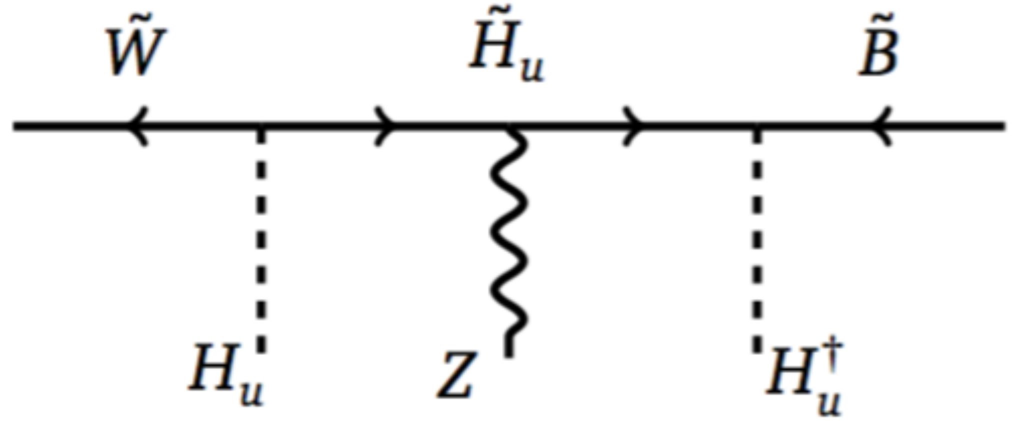
Plus phase-space suppressed 3-body decays:

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

(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.

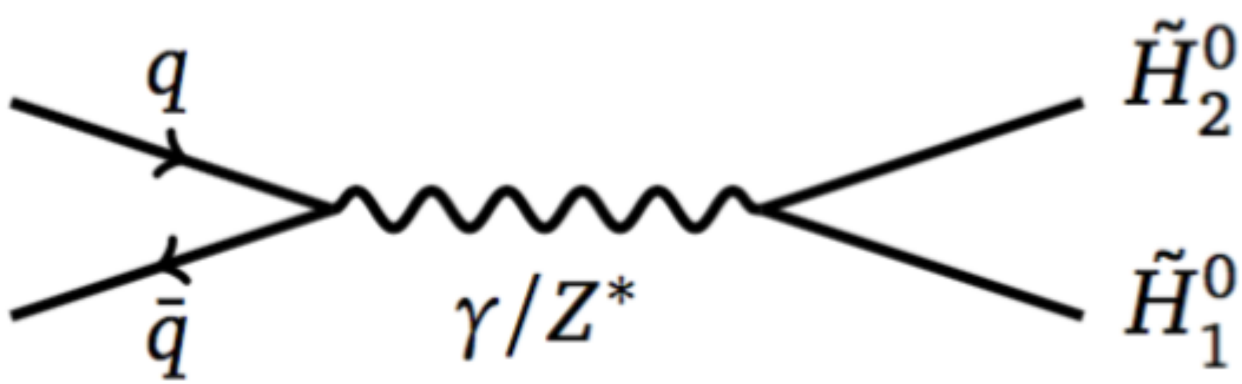
(Howe, Saraswat 1208.1542; Baer, Barger, Lessa, Sreethawong, Tata 1201.2949)

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.



Exactly true when

$$\tan\beta = 1$$

“blind spot”

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.

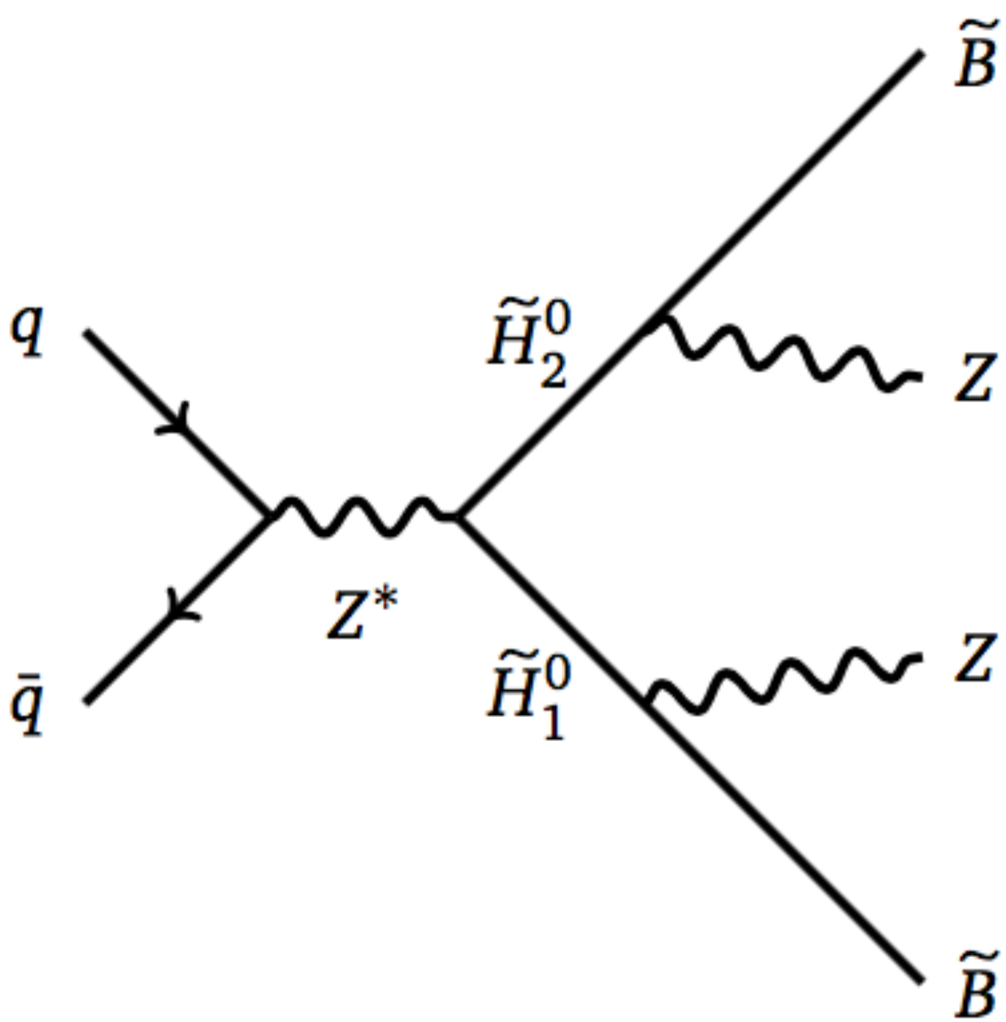
So produce signals of missing momentum plus:
Zh, *ZZ*, *hh* in a mixture related to tan beta;
or W^+W^- from chargino pairs;
or *WZ*, *Wh* in equal amounts from chargino+neutralino

Tan beta: 100 TeV benchmark

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

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

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.

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

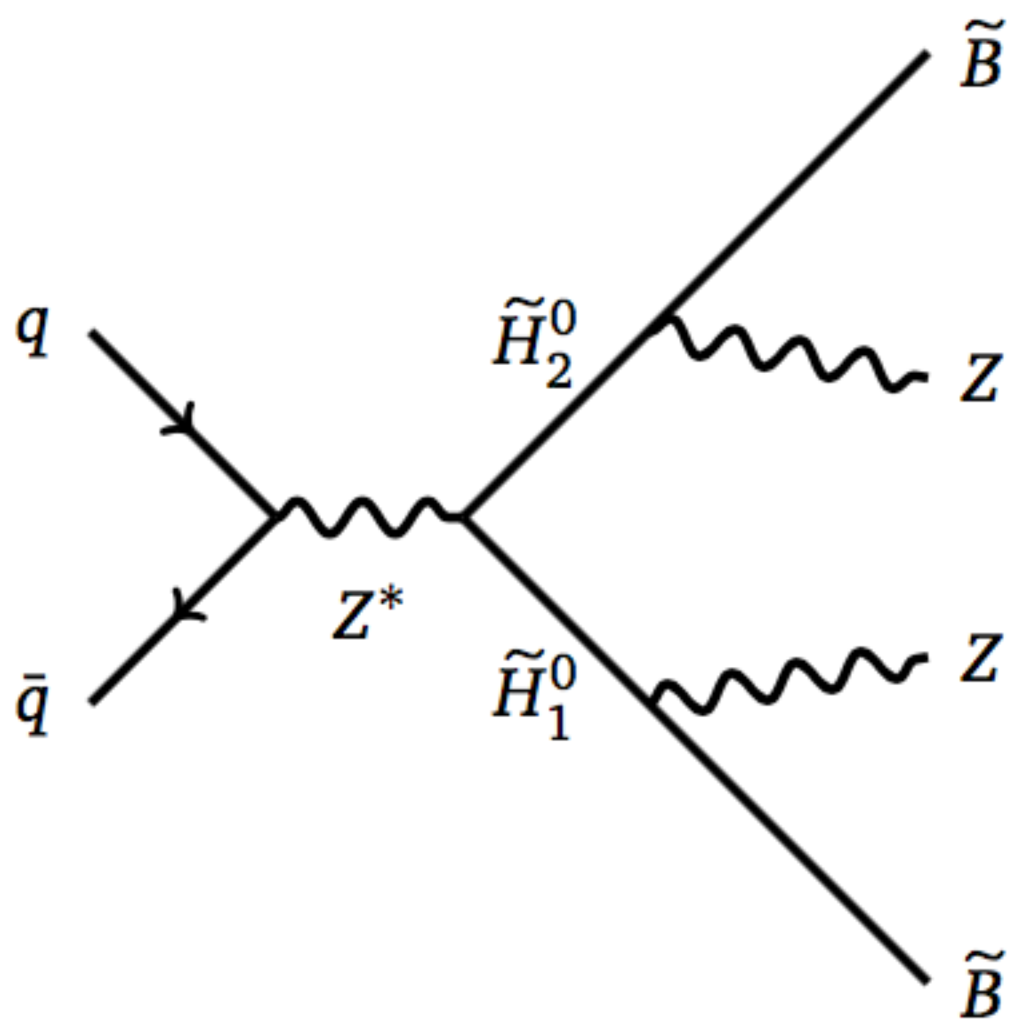
$$p_T^{\text{missing}} > 150 \text{ GeV}$$

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

Tan beta: 100 TeV 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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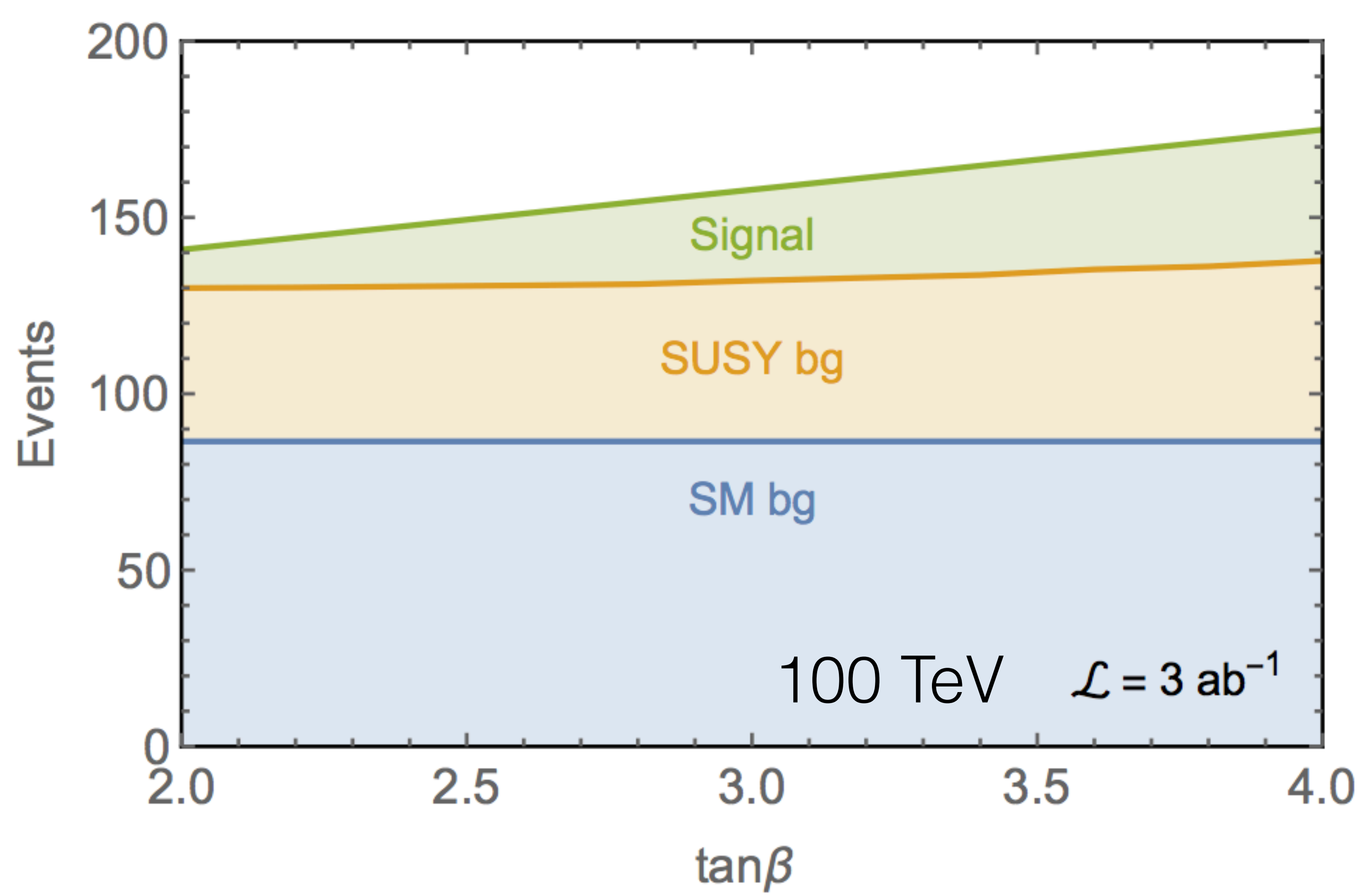
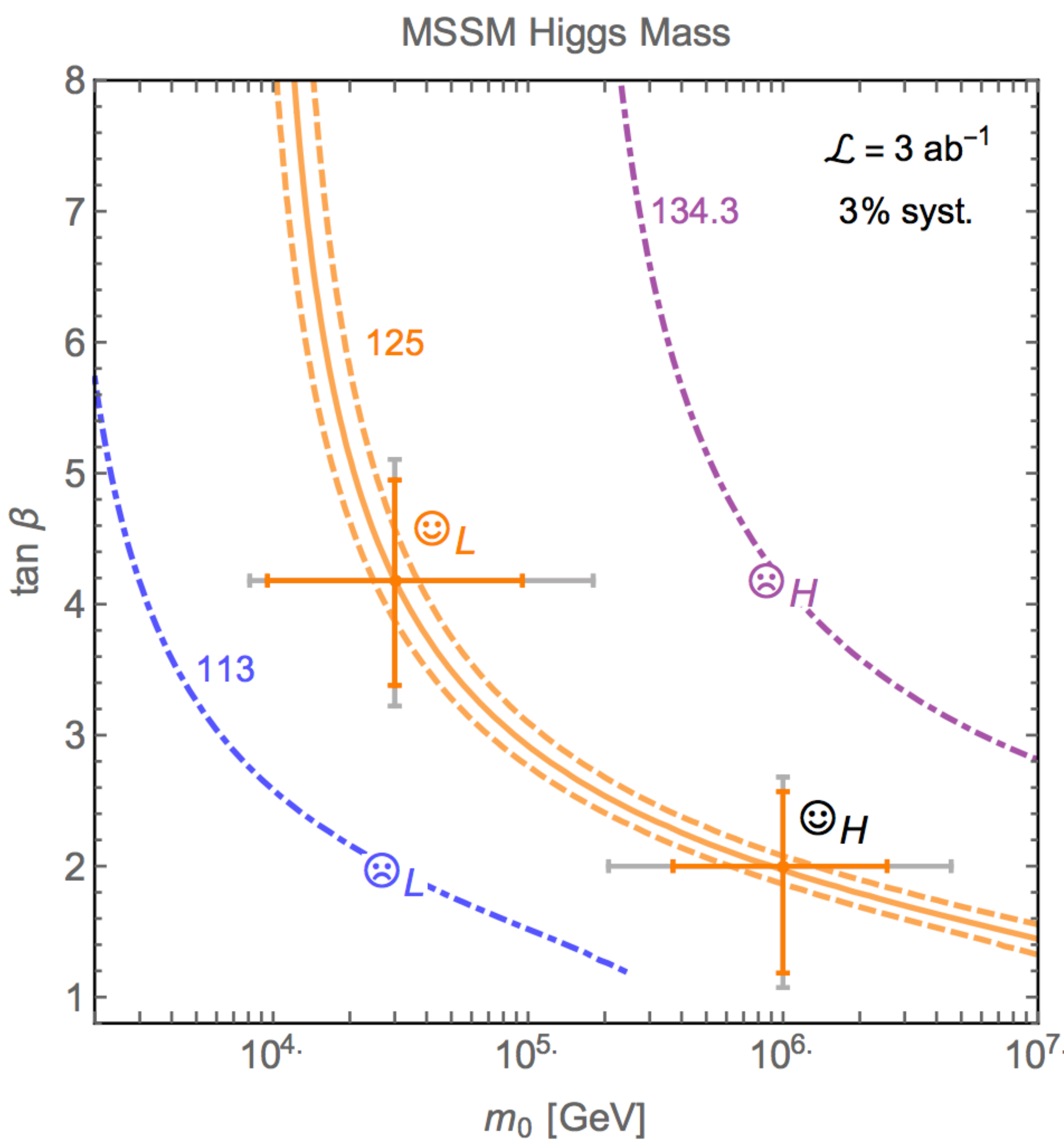
$Z(\to \ell^+\ell^-) + Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu})$



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.

Conclusions

- Some version of “mini-split SUSY” is a compelling explanation of why the Higgs mass is 125 GeV.
- Well-motivated theories of SUSY breaking tie this picture to scales of moduli, gravitinos…
- Important to measure the scalar mass scale, even if only indirectly
- Mini-split SUSY, if true, requires a precision physics program that a 100 TeV collider might be well-suited for.

Backups

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!

Direct Detection & Tan Beta

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

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

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.