Multiple Bosons and SUSY

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August 26, 2016

The organizers asked me to talk about new physics signals with multiple bosons from SUSY.

Before I talk about SUSY, let me digress with some general remarks on effective field theory and TGCs.

Triple Gauge Couplings

These are often parametrized following Hagiwara, Peccei, Zeppenfeld, and Hikasa (1987):

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V \left(W^+_{\mu\nu}W^{-\mu}V^\nu - h.c.\right) + i\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\nu\lambda}V^\mu_\lambda$$
$$+ i\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{m_W^2}W^+_{\mu\nu}W^{-\nu\lambda}\tilde{V}^\mu_\lambda + \cdots,$$

The CP-odd couplings feed into EDMs at one loop and so are highly constrained by experiment. Let's focus on the CP-even ones. In terms of gauge-invariant operators:

$$\begin{aligned}
\mathcal{O}_W &= \epsilon_{abc}W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda, \\
\mathcal{O}_{hW} &= H^\dagger H W^a_{\mu\nu}W^{a\mu\nu}, \\
\mathcal{O}_{hB} &= H^\dagger H B_{\mu\nu}B^{\mu\nu}, \\
\mathcal{O}_{WB} &= (H^\dagger \sigma^a H)W^a_{\mu\nu}B^{\mu\nu}
\end{aligned}$$

$$\delta\kappa_Z = \frac{v^2 s_W}{c_W}a_{WB}, \qquad \delta\kappa_\gamma = -\frac{v^2 c_W}{s_W}a_{WB},$$

$$\delta\lambda_Z = \delta\lambda_\gamma = \frac{6m_W^2 a_W}{g}$$

Triple Gauge Couplings

In other words, in one choice of basis for dimension-six operators we see that:

κ couplings come from the S-parameter operator

$$(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$

In particular,

$$S = \frac{4 s_W c_W v^2 a_{WB}}{\alpha} = \frac{4 c_W^2}{\alpha} \delta\kappa_Z = -\frac{4 s_W^2}{\alpha} \delta\kappa_\gamma.$$

λ couplings come from the W^3 operator

$$\epsilon_{abc} W^{a\nu}_{\mu} W^{b\lambda}_{\nu} W^{c\mu}_{\lambda}$$

TGC versus S

- Current TGC bounds on κ include

$$\mathrm{LEP}: \;\; \delta\kappa_\gamma \in [-0.099, +0.066] \quad \Rightarrow S \in [-12, +8]$$

$$\mathrm{CMS}: \;\; \delta\kappa_Z \in [-0.04, +0.04] \;\; \Rightarrow S \in [-16, +16]$$

- Current fit for *S*-parameter (*T* = 0, 2 sigma): $|S| \lesssim 0.07$

- So TGC searches for κ are subdominant compared to electroweak precision. (Or Higgs to gamma gamma!)

- TGC searches for λ are orthogonal to standard EWPT and so may have more hope for new physics.

Why Focus on *S*, *T* ?

Any SU(2)$_L$-charged particles, coupling to the Higgs or not, contribute at one loop to two dimension-6 operators:

$$c_{WWW}\, g \epsilon_{ijk} W^i_{\mu\nu} W^{j\nu}_{\rho} W^{k\rho\mu}$$

"TGC"

$\lambda_\gamma = \lambda_Z$

$$c_{WWW} = \frac{g^2}{2880\pi^2} \sum_{\text{rep } R,\ \text{mass } M} (-1)^F \frac{T(R)}{M^2},$$

$$c_{JJ} D^\mu W^i_{\mu\nu} D_\lambda W^{i\lambda\nu}$$

"*W* parameter"

$$c_{JJ} = -\frac{g^2}{960\pi^2} \sum_{\text{rep } R,\ \text{mass } M} a_F \frac{T(R)}{M^2},$$

where $a_F = 4$ for Weyl fermions and 1 for complex scalars.

Unfortunately, their perturbative coefficients are very small. (Could be lucky to have many new degrees of freedom?)

Very unlikely to see **if new physics is weakly coupled.**

Summary: EFT

- Perturbative theories of new physics (like SUSY) predict small corrections to λ-type TGCs. Good target for searches: a signal would be surprising, but strong hint of compositeness

- (Others like *ZZZ* even more unexpected: dim. 8!)

- SUSY predicts deviations in *S* and *T* parameters and Higgs couplings. Precision measurements of Higgs coupling ratios like $\Gamma(h \to \gamma\gamma)/\Gamma(h \to ZZ^*)$ are one way the LHC can surpass LEP in EWPT.

Multiple Bosons from SUSY

Now I'll review various ways that supersymmetric new physics can lead to signals with multiple electroweak bosons.

A relatively clear recent summary of electroweakino physics is 1309.5966 by T. Han, S. Padhi, and S. Su.

I'll also take the opportunity to try to explain a way to think clearly about branching ratios. The SUSY literature is full of mixing matrix elements, cosines and sines, and undifferentiated "neutralinos" and "charginos."

Thinking in terms of gauge eigenstates—binos, winos, higgsinos, Higgs doublets—and inserting VEVs is usually a more straightforward way to see the approximate result.

2HDM Heavy Higgs

A. Katz, MR, A. Sajjad 1406.1172

Can get dibosons from decays of the heavy Higgses.
Expected branching ratio: $\Gamma(H \to hh) \approx 9\ \Gamma(H \to ZZ)$

Easy to see: work with combinations that get VEV or don't

$$
\begin{aligned}
h = \sin\beta\, H_u + \cos\beta\, H_d^\dagger &= \begin{pmatrix} iG^+ \\ (v + h^0 + iG^0)/\sqrt{2} \end{pmatrix} \\
H = -\cos\beta\, H_u + \sin\beta\, H_d^\dagger &= \begin{pmatrix} iH^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}.
\end{aligned}
$$

Coupling comes from quartic term with three *h* and one *H*.

$$
V \supset \tilde{\lambda}_1 \left(H^\dagger h + h^\dagger H\right) h^\dagger h \supset \tilde{\lambda}_1 \left(v H^0 G^+ G^- + \frac{v}{2} H^0 G^0 G^0 + \frac{3v}{2} H^0 h^0 h^0 + H^0 h^0 G^+ G^- + \ldots \right)
$$

Combinatoric factor of 3 in the amplitude. *hh* wins by factor of 9 in rate, but is harder to see.

Goldstone Equivalence

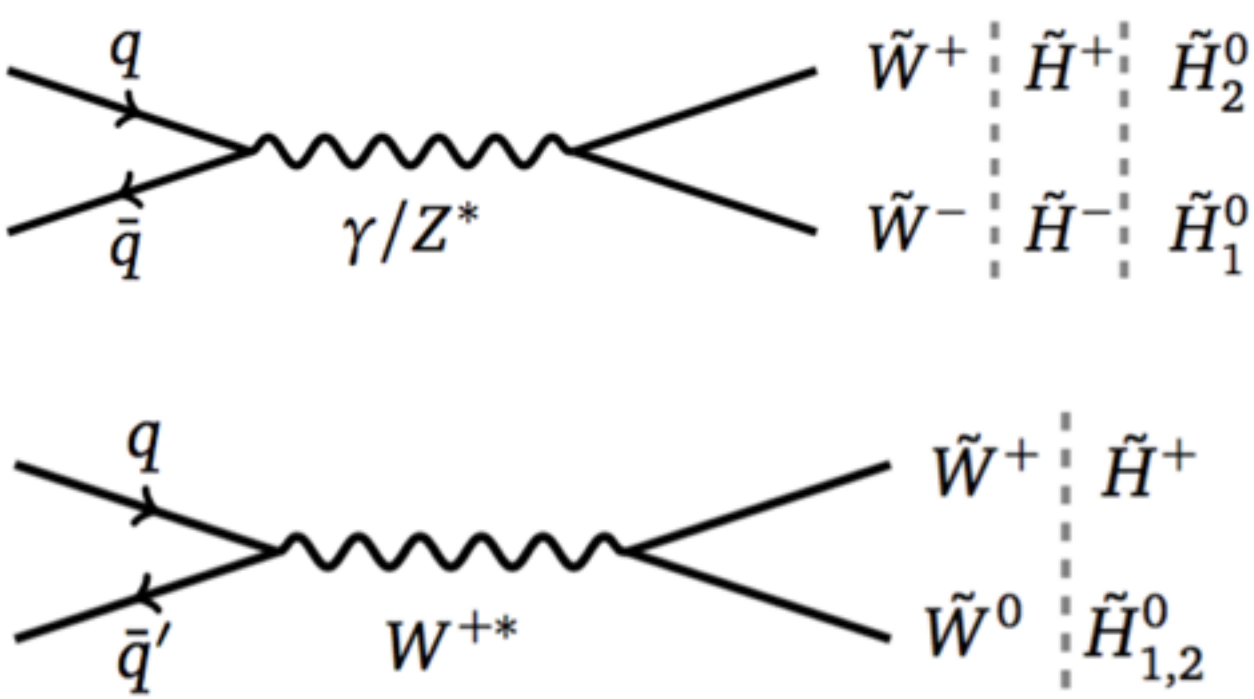
The 2HDM calculation exemplifies a more general lesson: the Goldstone boson equivalence theorem is often very useful for determining the expected relative branching ratios.

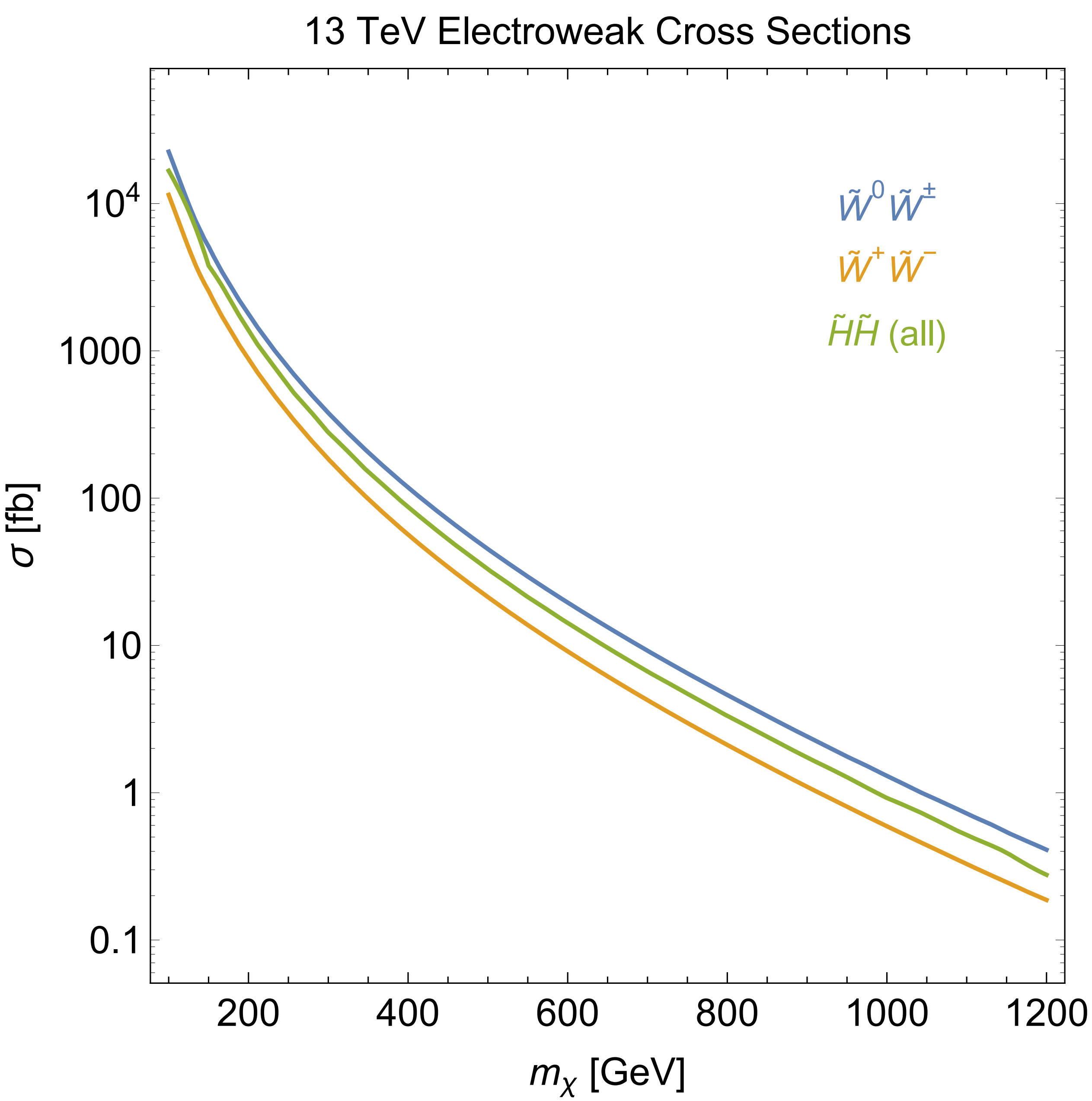
New singlet particles should give equal rates of Z and h, because they live in the same SU(2) doublet.

But particles with SU(2) charges can pick out directions in SU(2) space and have decay rates that distinguish Z from h.

Electroweakino Production

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

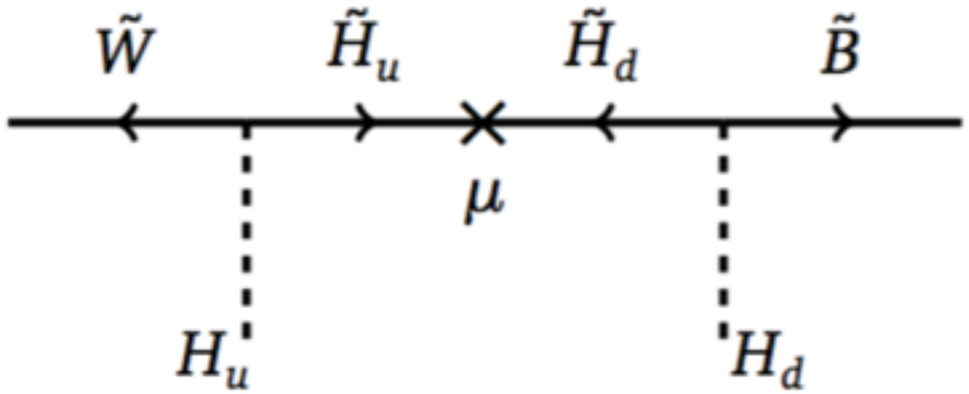




For on-shell bosons: produce one multiplet, decay to another.

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:

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

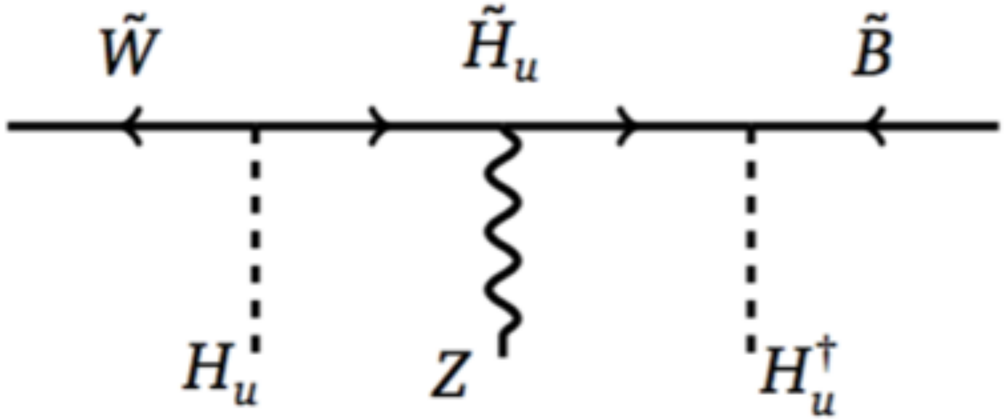
Plus phase-space suppressed 3-body decays:

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

(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*):



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

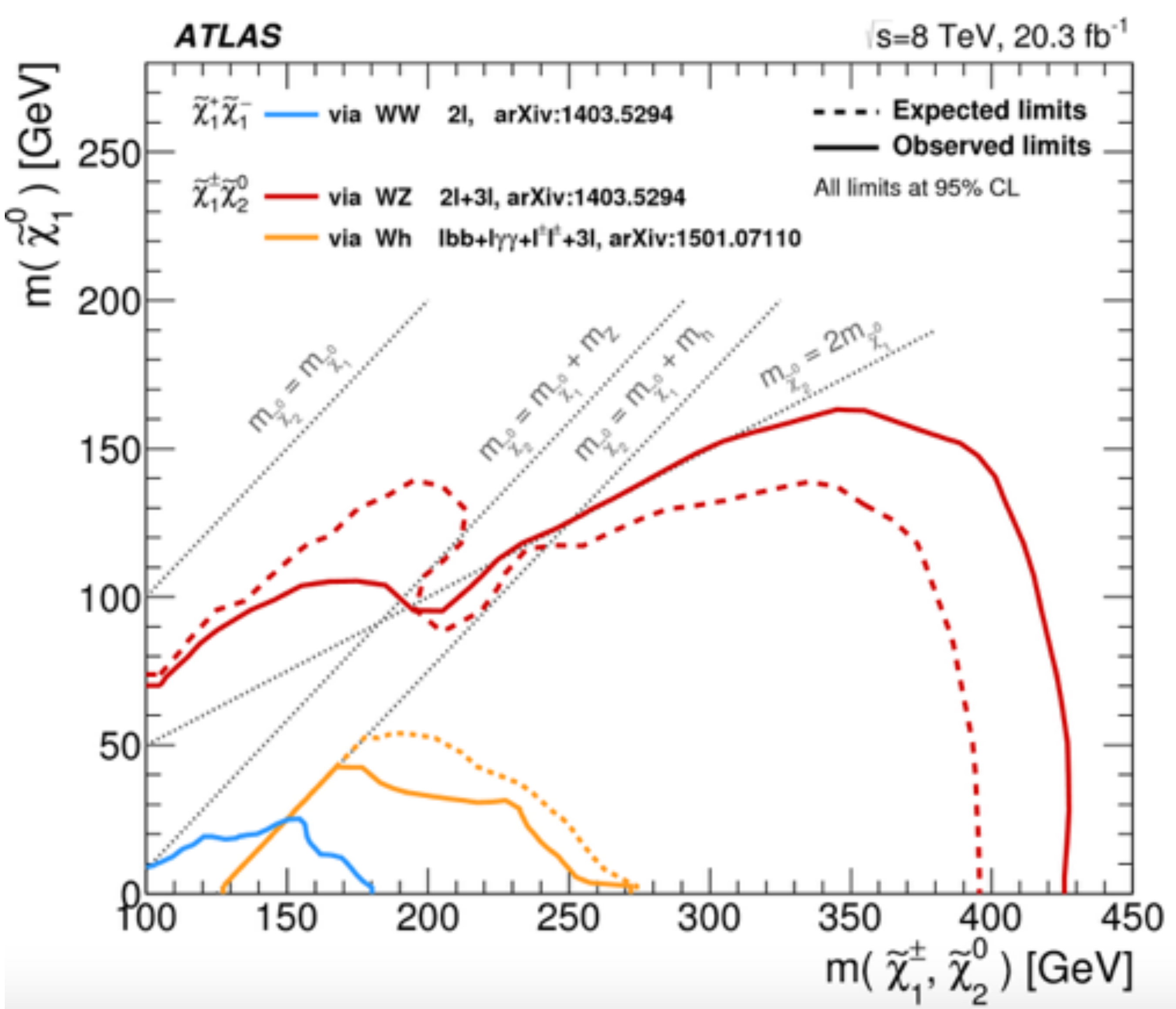
So, roughly expect the branching fraction of **Higgs relative to Z is enhanced:**

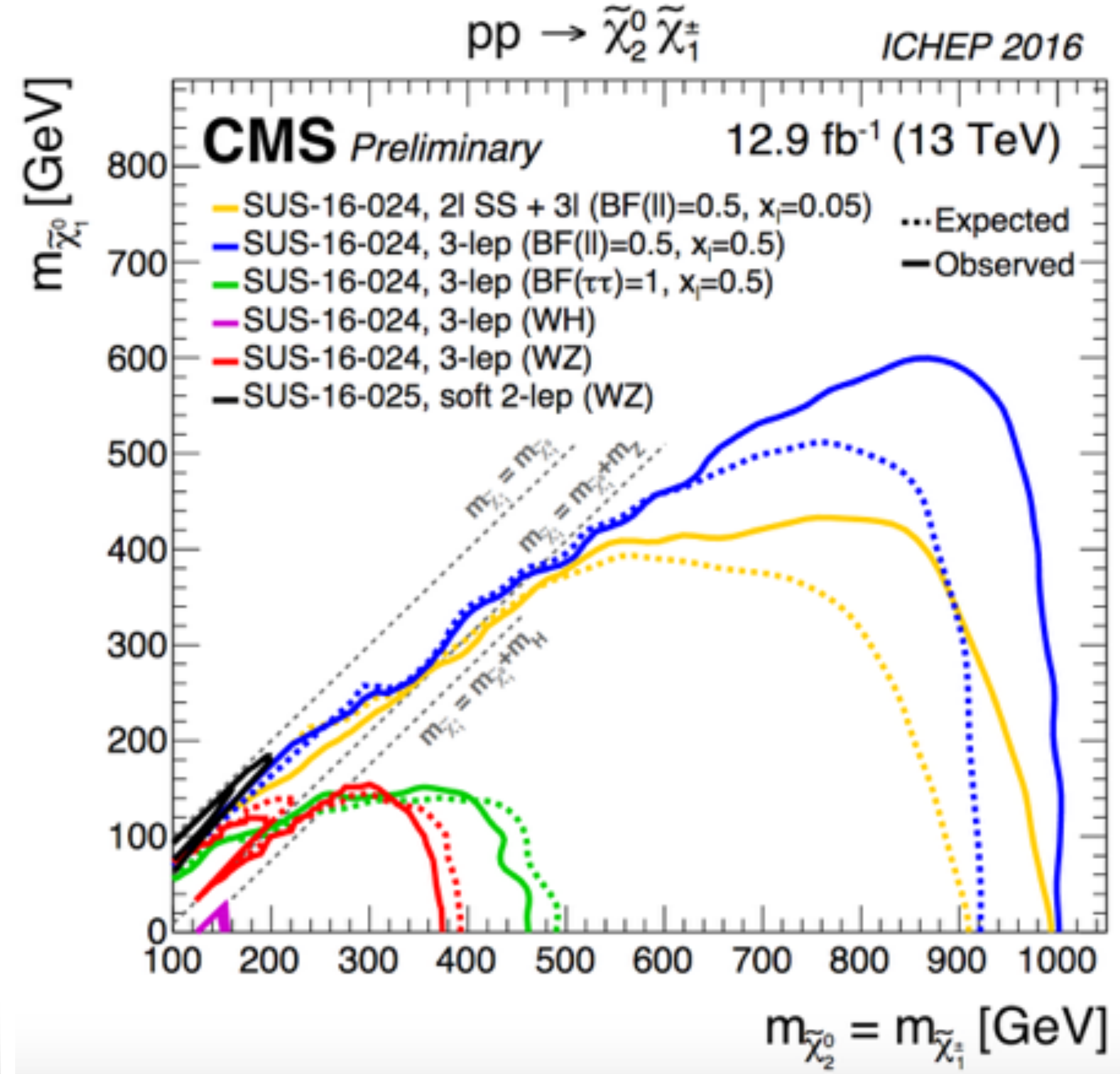
$$\frac{\Gamma(\tilde{W}^0 \to h\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to Z\tilde{B}^0)} \approx \frac{4\tan^2(2\beta)\mu^2}{M_2^2}\left(\frac{1+M_1/M_2}{1-M_1/M_2}\right)^2.$$

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!)





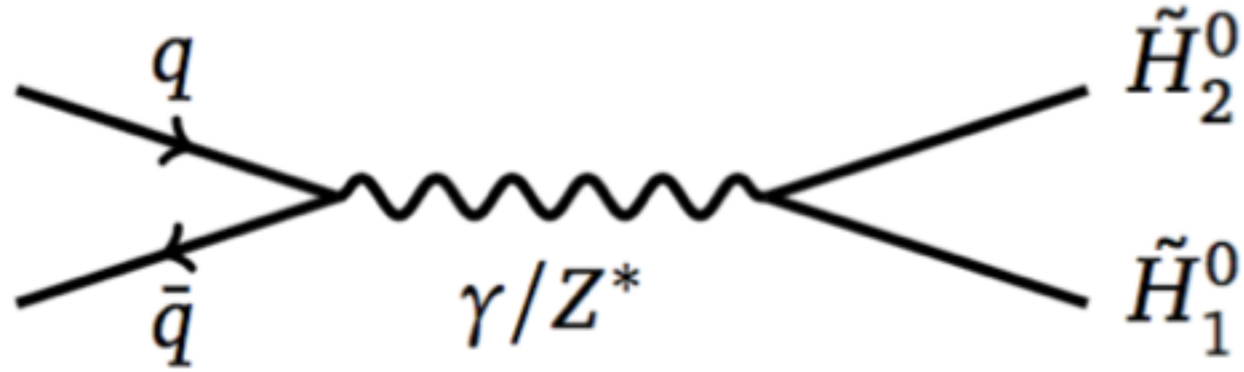
Presented results assume wino cross sections, but often **not** wino decay modes!

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.

Electroweakino Decays

In this way we could enumerate all of the diboson signals that can appear for transitions between a given set of electroweakinos.

Wino to bino: missing p_T plus W+W-, Wh (fewer WZ)

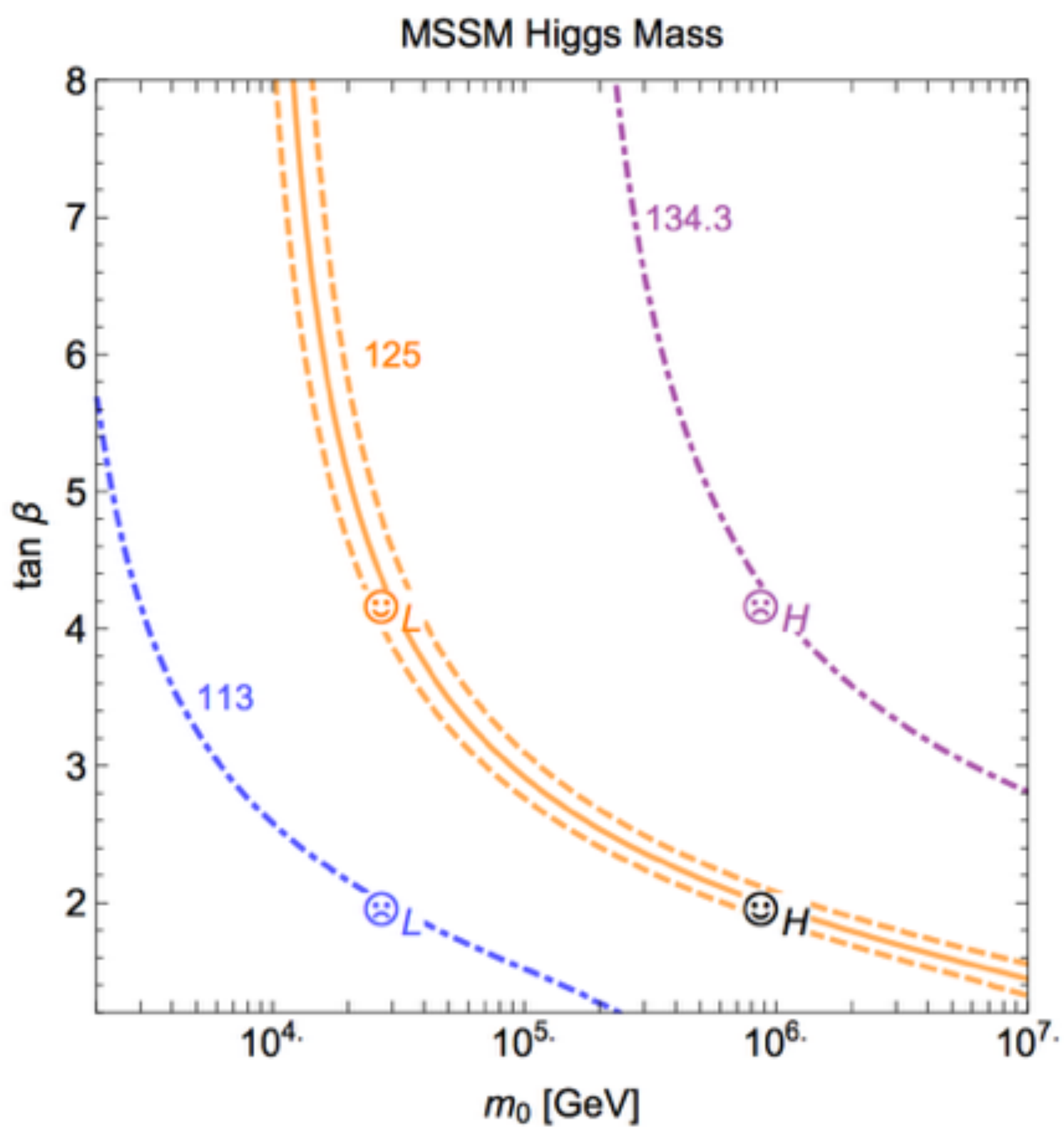
Higgsino to bino: missing pT plus W+W-, WZ, Wh, Zh, ZZ, hh (possibly fewer of the latter two)

Wino to higgsino: missing pT plus soft particles plus W+W-, **W+W+, W-W-**, WZ, Wh, Zh, ZZ, hh (again possibly fewer of last 2)

… and so on. Also longer cascades involving all 3 ewkinos, or gluinos, can give more bosons.

A Reason to Measure Tan Beta

In the “split” region of MSSM parameter space, the Higgs mass is a function of the stop mass scale and tan beta. (More generally, the left/right “A-term” mixing can matter.)



Can we test the MSSM by measuring tan beta and the scalar masses? Observables like ratio of *Z* and *h* in EWKino decays get tan beta; scalar masses from 1-loop gluino decays.

Agrawal, Fan, MR, Xue, work in progress. Partial results in 100 TeV FCC-hh study 1606.00947

Other Gauge Bosons

- In gauge mediated SUSY breaking, the lightest MSSM particle decays to its superpartner and a gravitino. So can get higgsino -> W, Z, h + gravitino.

- If hidden sectors exist, their U(1)s can mix with hypercharge ("dark photons"). Superpartners also mix, so can get a "dark bino" at bottom of spectrum —same decays as wino->bino or higgsino->bino, for instance. (Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell 0909.5440; Acharya, Ellis, Kane, Nelson, Perry 1604.05320)

- These can, in general, have displaced vertices.

Bilinear RPV

If we violate *R*-parity by violating lepton number, can add

$$W_{LNV} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \epsilon_i \mu L_i H_u$$

the bilinear term can be rotated away, but in general still have bilinear soft terms remaining:

$$\mathcal{L}_{LNV} \supset -\left(B_{L_i\mu}\mu \tilde{L}_i H_u + \tilde{m}^2_{H_d,L_i}\tilde{L}_i H_d^\dagger + \mathrm{h.c.}\right)$$

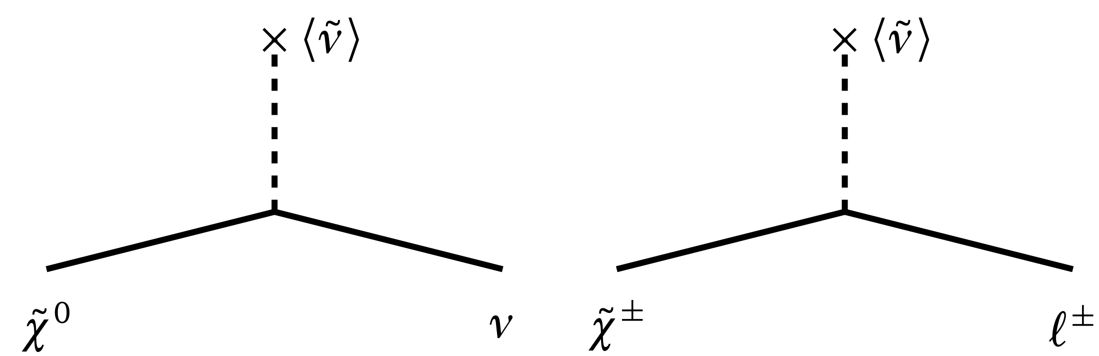
In the mini-split context would guess $B_{L_i\mu}\mu,\ \tilde{m}^2_{H_d,L_i} \sim \epsilon m^2_{3/2}$

Once the Higgs gets a VEV, these terms become sneutrino tadpoles, so the sneutrino gets a VEV:

$$\langle \tilde{\nu} \rangle \sim \epsilon v$$

Sneutrino VEVs

The sneutrino VEV has several interesting consequences.
Gauginos mix with leptons:



If winos are the LSPs, this will give them new decay modes:

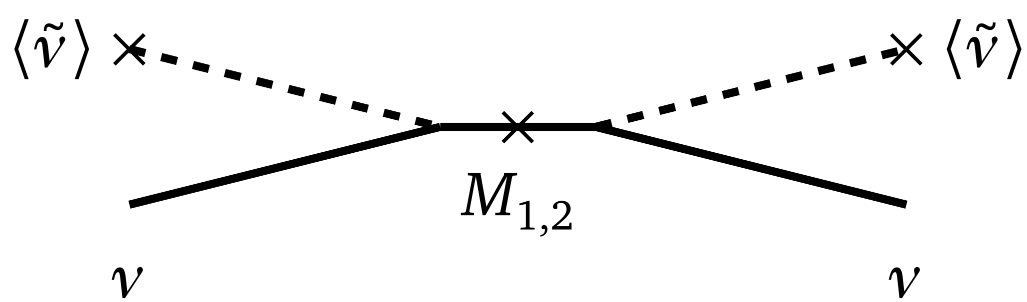
$$\tilde{W}^0 \to Z\nu, W^\pm \ell^\mp$$

$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm \nu$$

This would be a worthwhile search channel at the LHC.
(Probably the lepton is mostly tau? Need flavor model.)

Bilinear RPV

Also get a contribution to neutrino masses:



$$m_\nu \sim \epsilon^2 \frac{v^2}{M_{1,2}}$$

This implies an upper bound $\epsilon \sim 10^{-6}$.

This gives a *lower* bound on the lifetime of the two-body wino decays, ~ 100 microns.* So should look for

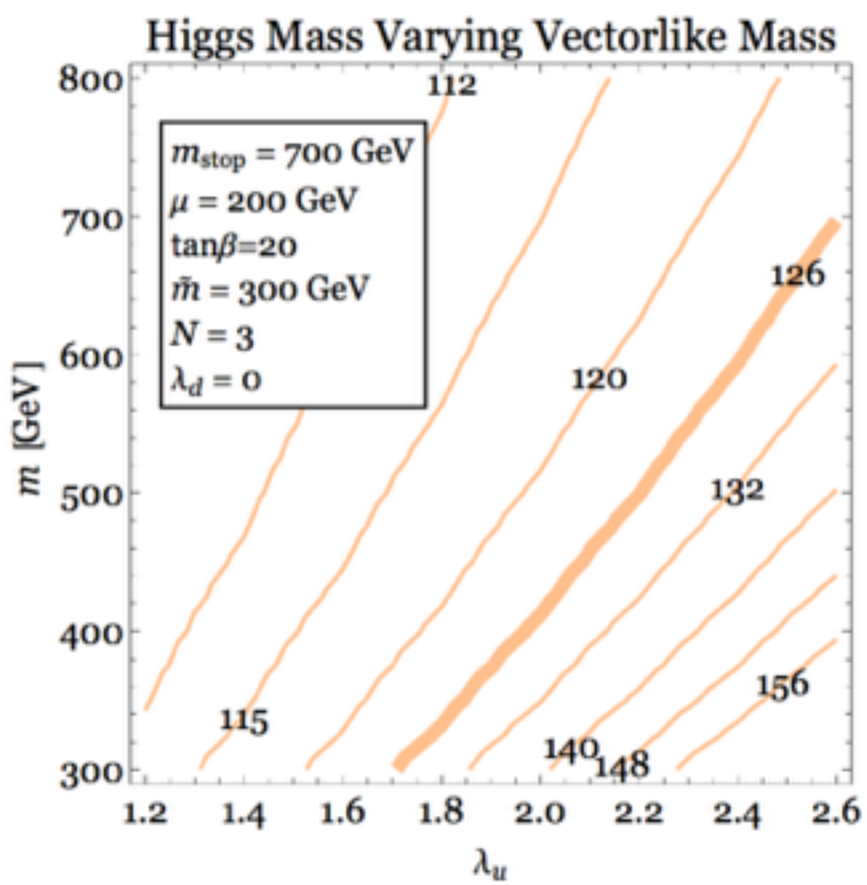
$$\tilde{W}^0 \to Z\nu, W^\pm \ell^\mp$$
$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm \nu$$

with displaced vertices! (Possibly macroscopically displaced; **standard lepton ID may fail**.)

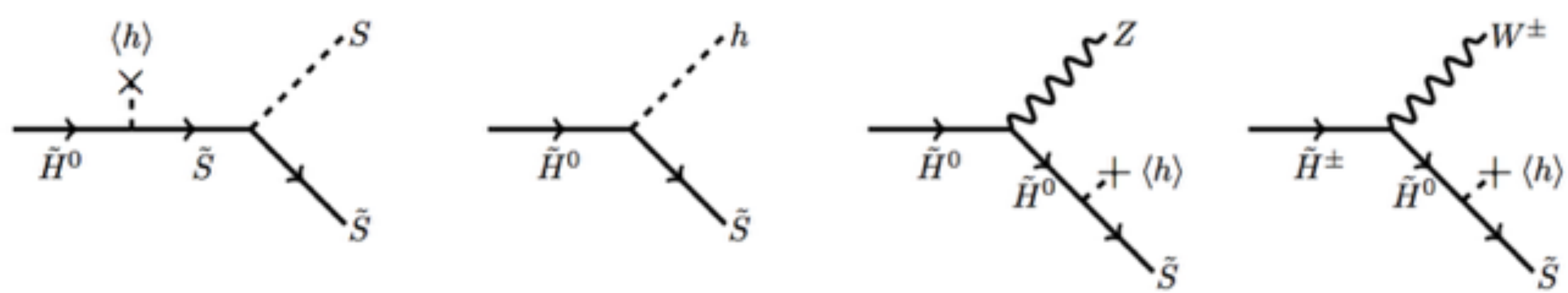
* Disclaimer: I haven't plugged in all order-one factors. See papers by Valle et al.

SUSY + Hidden Valley

Y. Nakai, MR, R. Sato 1511.00691



Mixing with hidden sector can lead to new Higgsino decays to higgs, W, Z + singlino

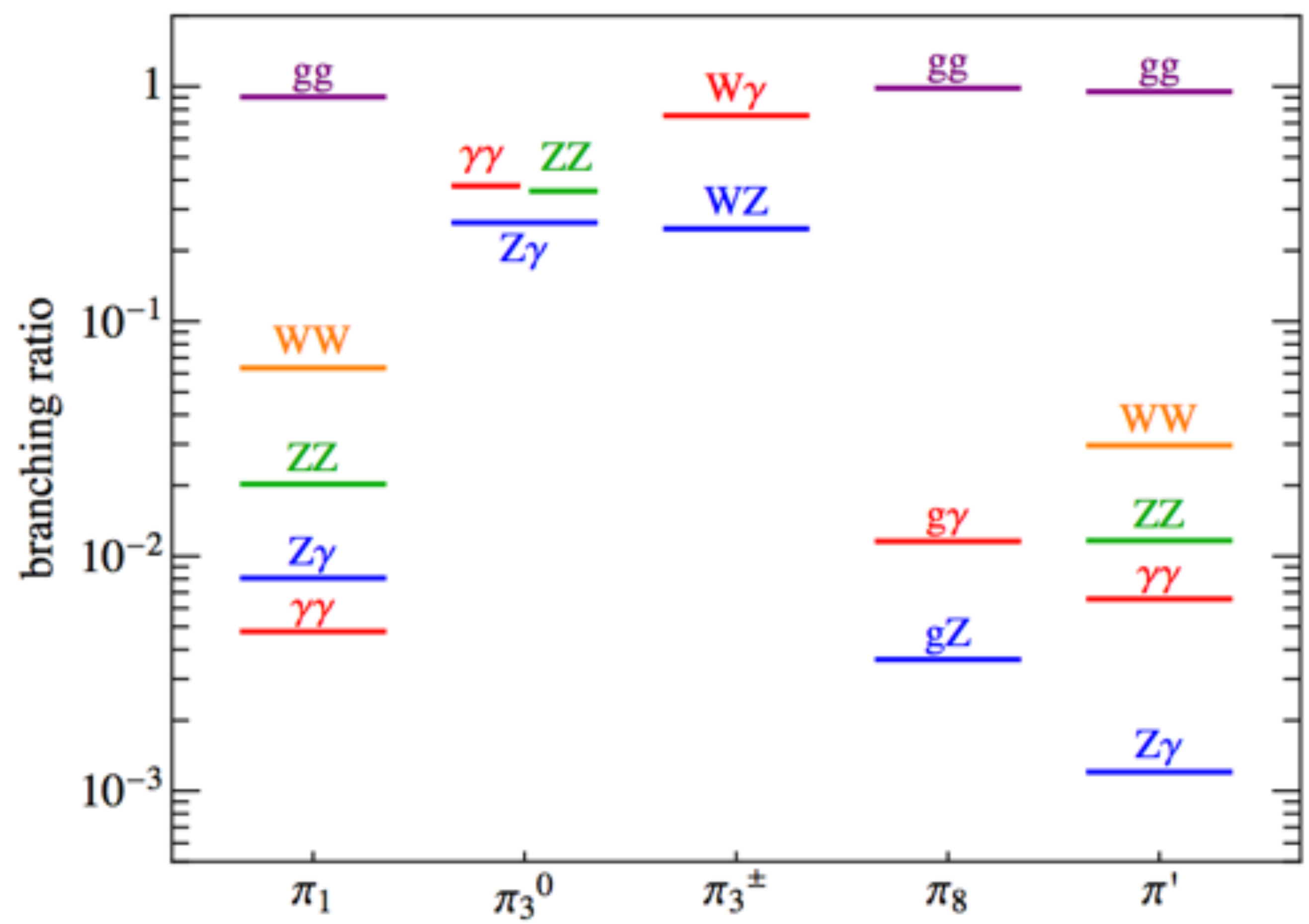


(earlier work along related lines: Babu, Gogoladze, Kolda hep-ph/0410085; Martin 1012.2072)

Composite Pions

Arkani-Hamed, D'Agnolo, Low, Pinner 1608.01675

meson	constituents	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
π_8	D^cD	$(\mathbf{8},\mathbf{1})_0$
π_3	LL^c	$(\mathbf{1},\mathbf{3})_0$
π_1	$2D^cD - 3LL^c$	$(\mathbf{1},\mathbf{1})_0$
$Q_X = (X_{-1/3}, X_{-4/3})$	LD	$(\mathbf{3},\mathbf{2})_{-5/6}$
$Q_X^* = (X_{4/3}, X_{1/3})$	D^cL^c	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$
π'	$D^cD + LL^c$	$\mathbf{1}$



Largest diboson rates are always 2 gluons; but gluon + photon, W + photon, WZ, ZZ, … also arise.

On Dark Matter

One motivation for searching for the electroweak superpartners is neutralino dark matter. You often hear about **thermal relic dark matter** (or the “WIMP miracle”). For instance, a pure higgsino is a good **thermal** DM particle if its mass is 1 TeV (unnatural!).

However, more complete theories involve particles like **gravitinos, moduli, modulinos, saxions, axinos, etc.** whose decays in the early universe can lead to **non-thermal** dark matter. Often produce **more** DM than thermal abundance.

Lesson for LHC: **don’t fixate on thermal relic assumption!**

Conclusions

- Many varieties of new physics can lead to signals with multiple gauge or Higgs bosons
- Non-resonant and resonant signals both arise in SUSY, in both minimal and non-minimal models
- Relative counts of different diboson final states as fingerprint: e.g. deviations from 50% Z/h signals new SU(2)-charged states
- Lots of incentives to keep looking!