Perspectives on Future Supersymmetry at Colliders

Sunghoon Jung
Korea Institute for Advanced Study

CERN Friday Seminar, Oct 24 2014

Based on collaborations with
S.Gori, L.T.Wang, J.D.Wells,
G.Barenboim, E.J.Chun, B.S.Kyae, W.I.Park
1312.1802, 1404.2691, 1407.1218, 1410.6287, 1411,xxxx

The “well”ness

- Can we discover XXX SUSY models at future collider?
  How “well” can we do?
  How well do we “need” to do?

The "well"ness

- Can we discover XXX SUSY models at future collider?
  How "well" can we do?
  How well do we "need" to do?

- I will interpret results specifically for
  "Future SUSY"
  with the spectrum:
  lighter gauginos and higgsinos ~O(100-1000)GeV and
  heavier scalars.

Future SUSY

- Many aspects of current SUSY analyses move over to future SUSY analyses.

- But Future SUSY has important generic differences too that need qualitatively different studies.

What my talk is about

- (What) can a 100TeV collider say definitive about Future SUSY?
  Or, what do we eventually need for that?

- Future SUSY @ 14-100TeV vs. old 100GeV-ish SUSY: qualitative differences, new relations and new approaches.

- Best discovery mode: gluinos, EWinos, stops?

Split spectrum

J.D.Wells
N.Arkani-Hamed, S.Dimopoul
G.Giudice, A.Romanino
A.Arvanitaki, et. al.
N.Arkani-Hamed, et. al.
Y.Kahn, et. al.
W.Altmannshofer, et. al.
D.McKeen, et. al.
…

- Data driven: EWinos light, gluinos and sfermions are heavy. (null LHC, flavor, CP, and mh)
- Half of universe is generically split SUSY-like.
- Pheno attractive. (unification, DM)
- Important mass scales: ~1 TeV Higgsino DM, ~3 TeV Wino DM.
  => Testing Future SUSY up to these mass scales is both an important mission and a useful goal.

Generic features

- Pure gauginos and higgsinos.
  => No cascade, Gaugino code is a primary observable.

- Decays between them governed by Goldstone Equivalence Theorem.
  => New simplifying relations.

- LHC Inverse Problem is infamous.
  => New relations are useful.

- Several disparate mass scales.
  => Large logarithms and its resummation needed.

Gaugino code

- Gaugino code (= gaugino mass ratio) is a fundamental measure of the split spectrum.
- Gauginos are least model-dependent fields encoding SUSY breaking mediation info.

K.Choi, H.P.Nilles

$$\text{mSUGRA pattern} \;:\; M_a \propto \frac{\alpha_a}{4\pi}\Lambda$$

$$\text{AMSB pattern} \;:\; M_a \propto \frac{b_a \alpha_a}{4\pi} m_{3/2}$$

$$\text{mirage pattern} \;:\; M_a \propto \frac{\alpha_a}{4\pi}\left(b_a + \frac{1}{0.1\alpha}\right) m_{3/2}$$

Overview

- 1. Gluino pair
  - Wino thermal DM, gaugino code, resummation.

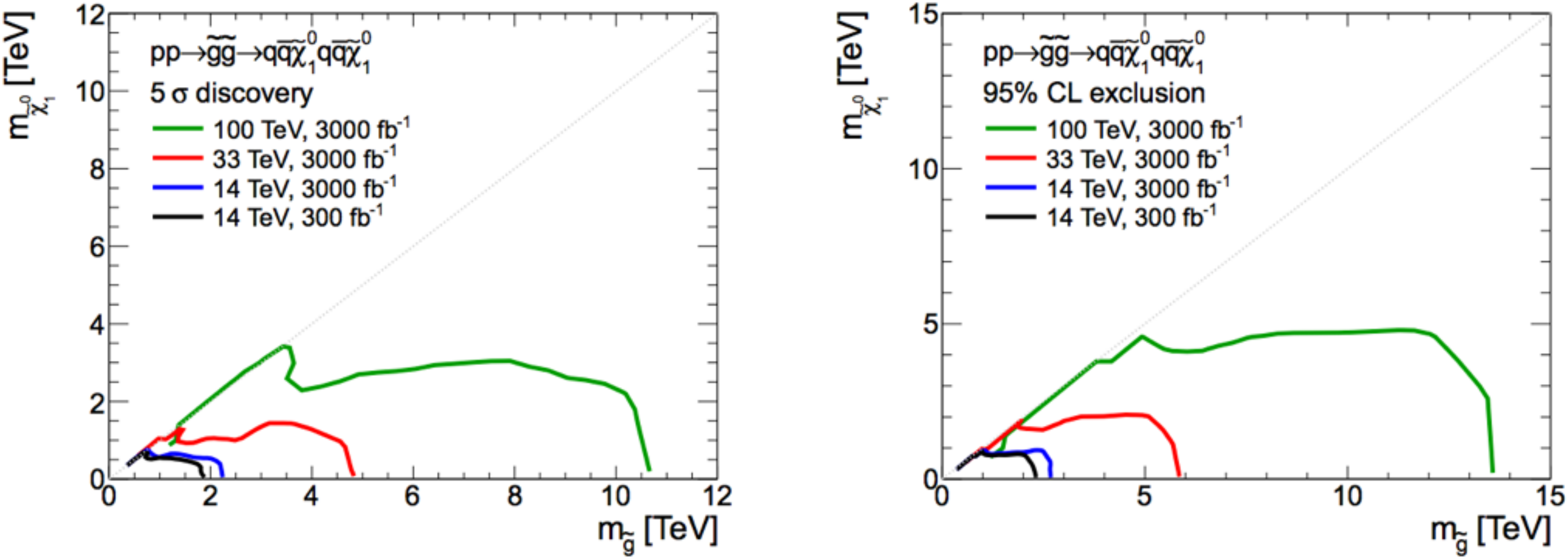
- 2. NLSP Electroweakino pair
  - Higgsino thermal DM, Higgsino relations from Goldstone Eq Thm, Inverse Problem, exceptions.

- 3. Stop vs. gluino / EWino vs. gluino

1. Gluino pair

Wino thermal DM,
Gaugino code,
Resummation

Searches of guino pairs

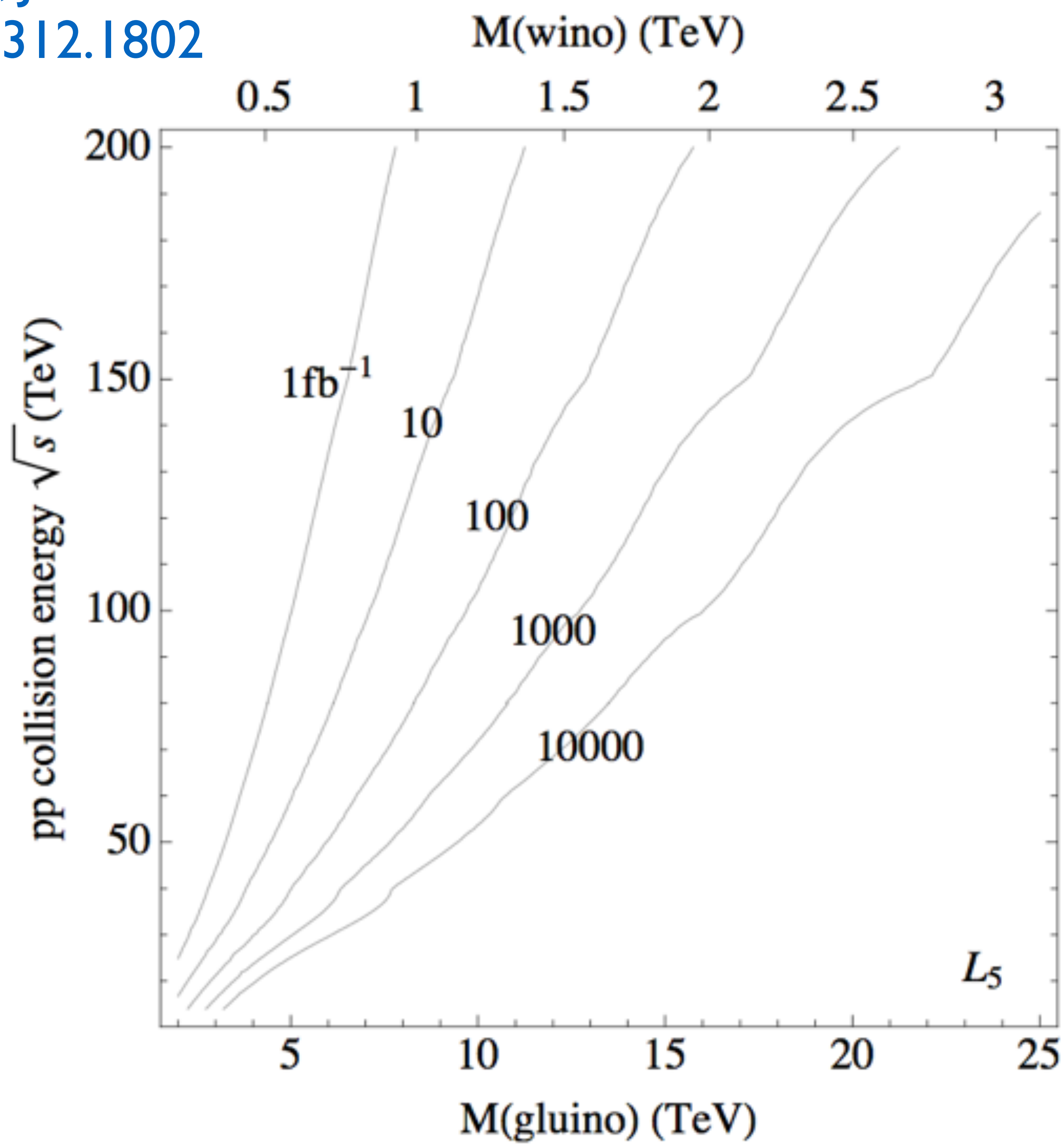


T.Cohen et. al.

- Traditional Meff is good enough.
- At 100 TeV collier, 11 TeV gluinos are discoverable, 14 TeV are excludable.

Wino DM (AMSB)

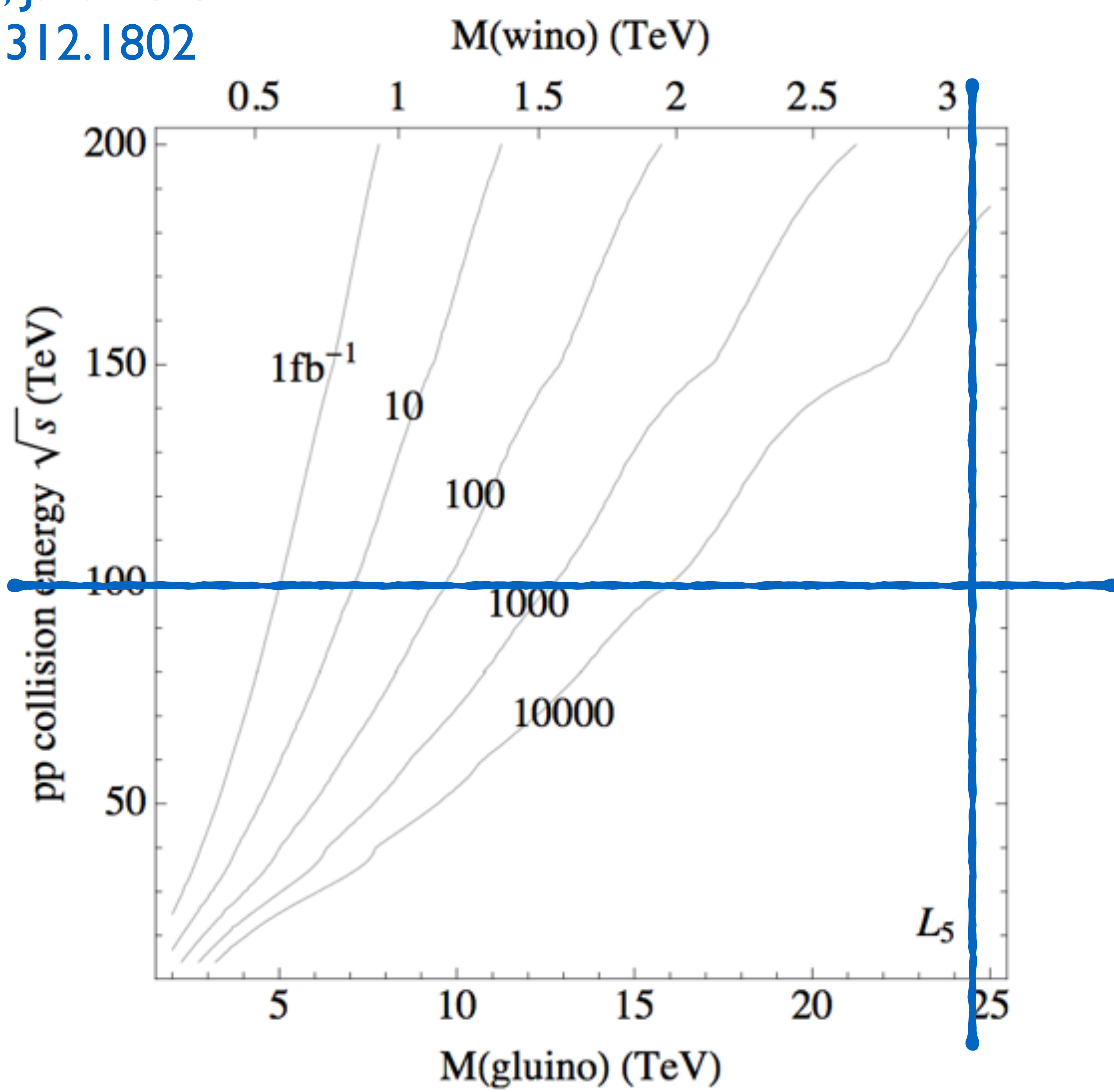
SJ, J.D.Wells
1312.1802



- m(gluino) / m(Wino) ~ 7 (largest hierarchy among Gaugino code)

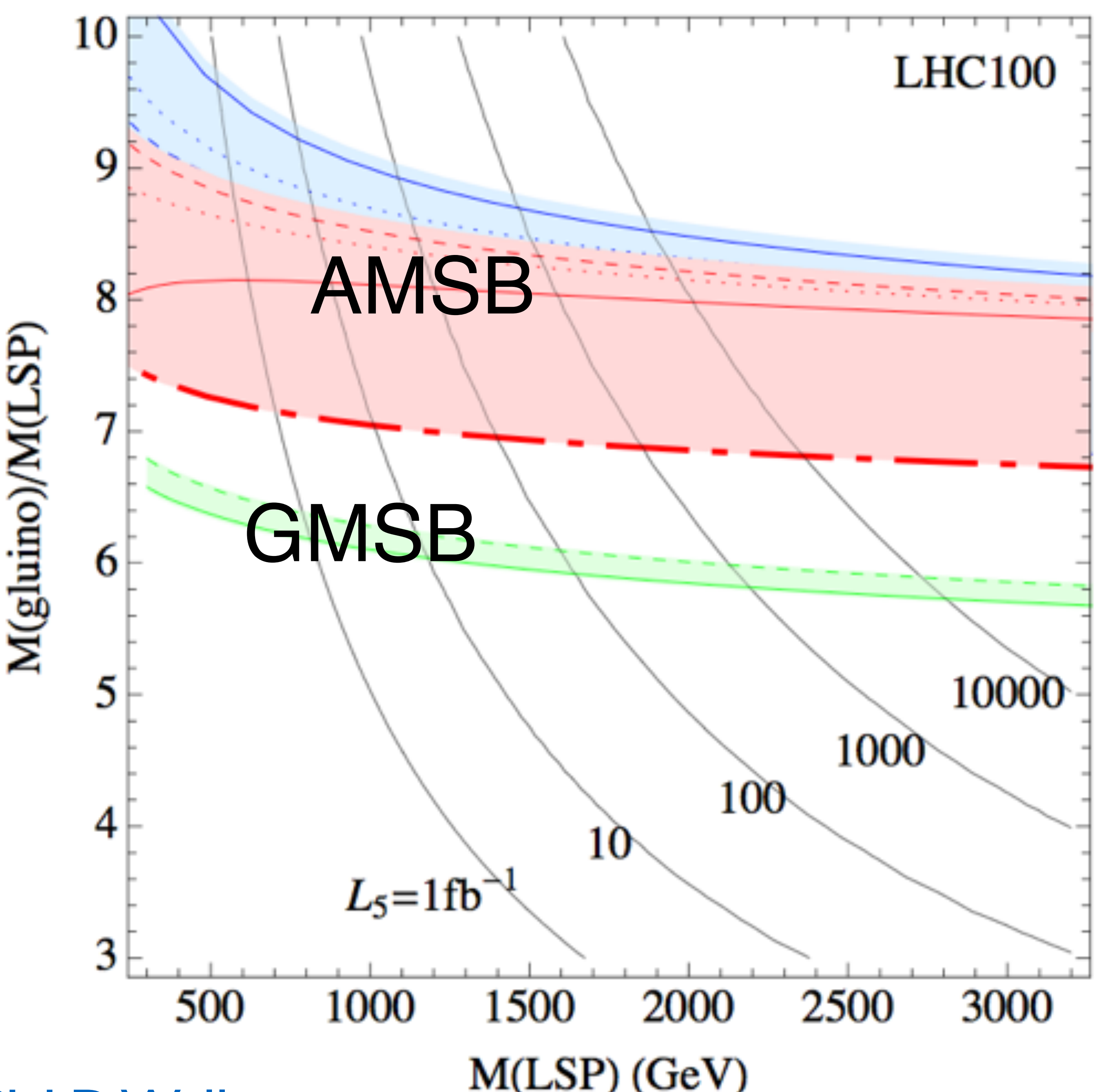
Wino DM (AMSB)

SJ, J.D.Wells
1312.1802



- m(gluino) / m(Wino) ~ 7 (largest hierarchy among Gaugino code)
- Full coverage of 3.1 TeV Wino DM in AMSB is still limited at 100 TeV.
- Good to keep in mind 200 TeV.

Reach in gaugino code

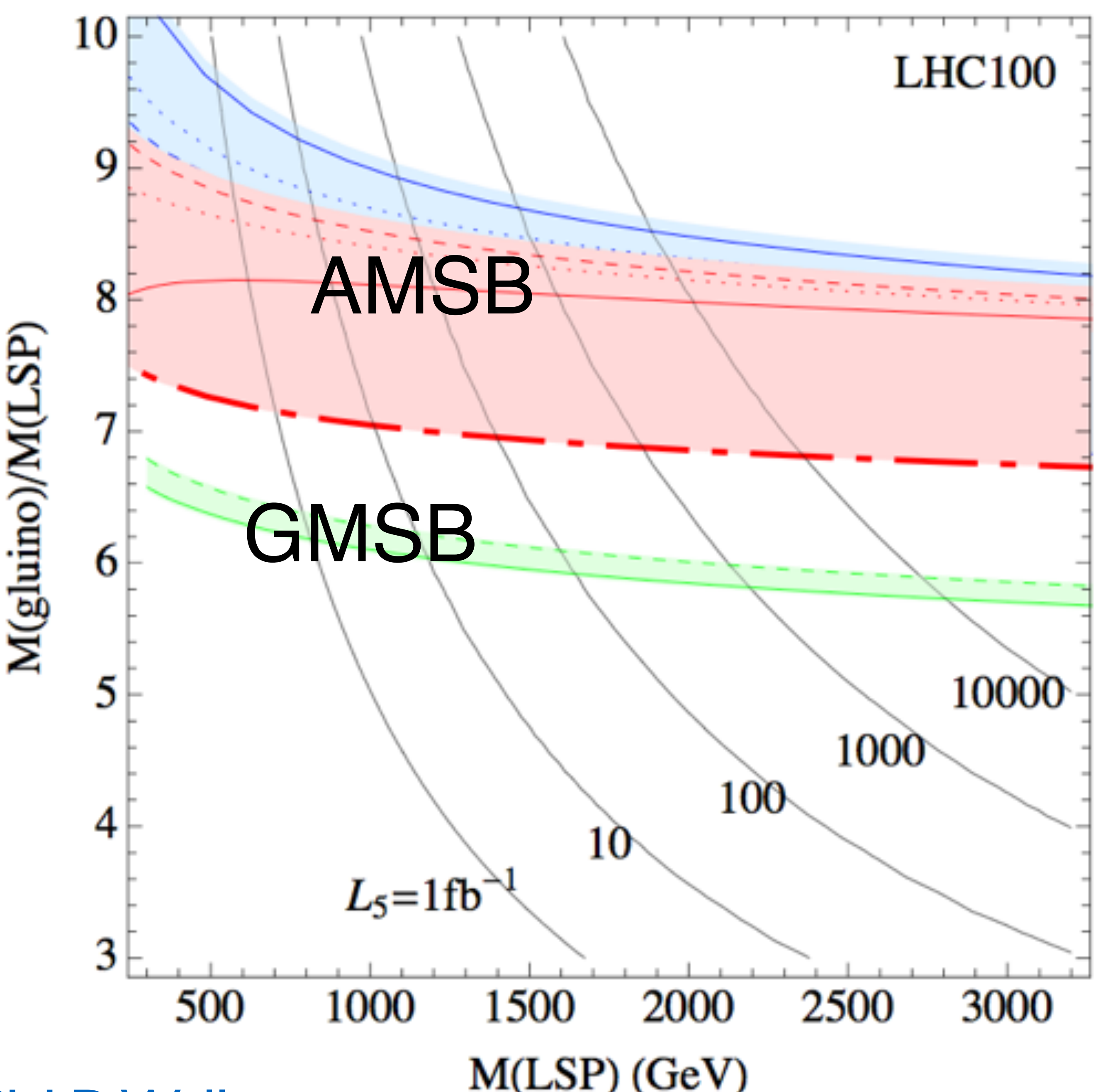


SJ, J.D.Wells
1312.1802

- Reach in the (gaug)ino mass ratio!
  (If gaugino code is such a fundamental observable and crucial for discovery)

- No definitive coverage of Higgsino DM here.

Reach in gaugino code



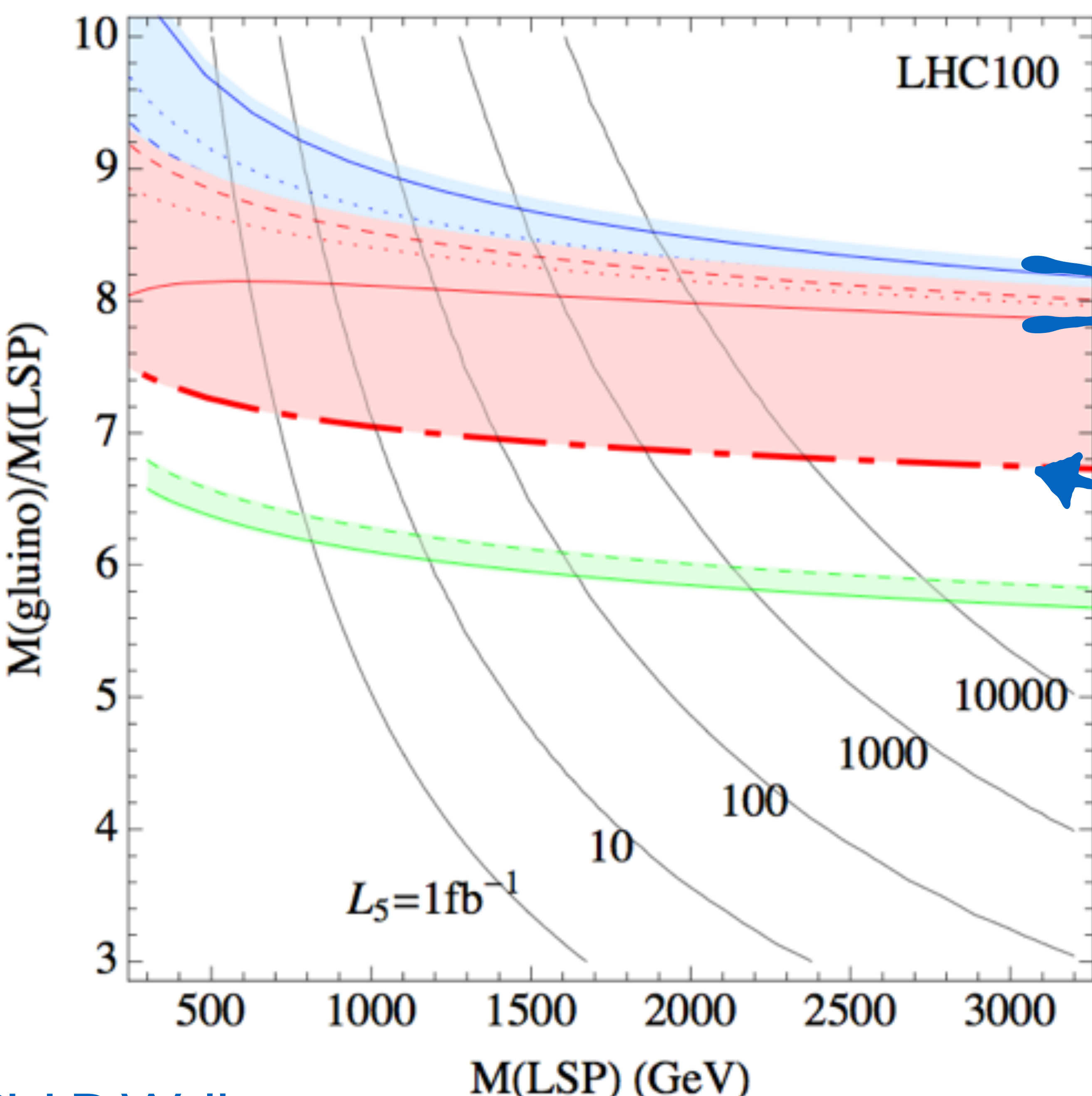
SJ, J.D.Wells
1312.1802

- Reach in the (gaug)ino mass ratio!
  (If gaugino code is such a fundamental observable and crucial for discovery)

- No definitive coverage of Higgsino DM here.

This is a useful way to present future SUSY search results.

Resumming the split hierarchy



- Large logs inevitable.

One-loop split
(w/ tan beta dep.)

No split
(no large log)

SJ, J.D.Wells
1312.1802

4 TeV Higgsino

Aside: NLO+NLL gaugino code

- 1) NLO matching correction — O(alpha^2). For GMSB, gaugino screening theorem works. For AMSB, no further quantum corrections as anomaly is one-loop exact.

$$M_i^G(M_m) = \frac{\alpha_i(M_m)}{4\pi}\left(1 + T_{G_i}\frac{\alpha_i(M_m)}{2\pi}\right)\frac{F}{M_m}$$

Arkani-Hamed, Giudice, Luty, Rattazzi

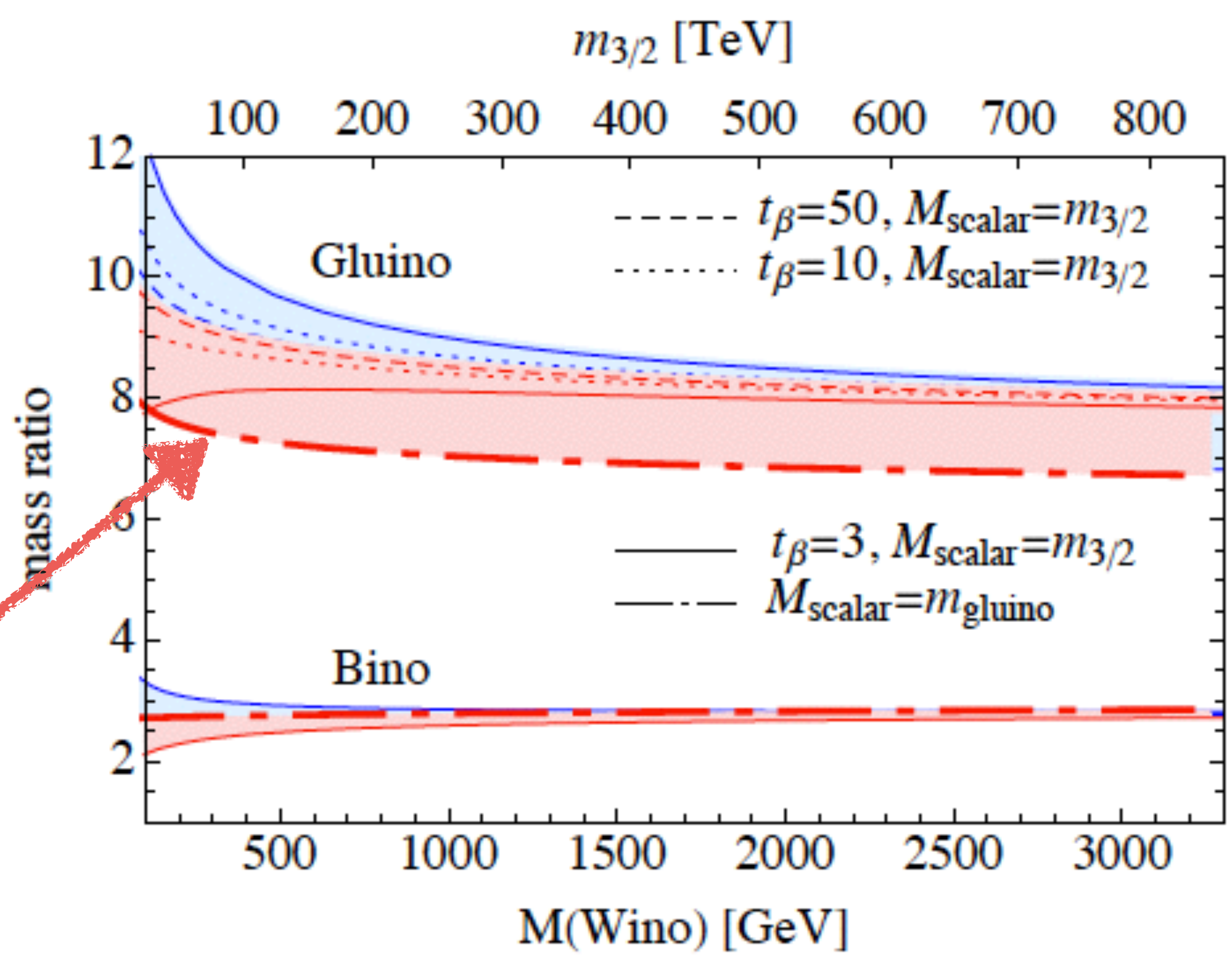
- 2) Two-loop RGE — resuming next-to-leading log formally the same order as one-loop finite correction. It is dominant corrections to AMSB bino and wino.

$$M_{1,2}^A = \frac{b_{1,2}^{2-loop}\alpha_{1,2}}{4\pi}m_{2/3} = \frac{b_{1,2}^{1-loop}\alpha_{1,2}}{4\pi}m_{2/3}\left(1 + \mathcal{O}(\alpha_s, \alpha_t)\right)$$

- 3) One-loop threshold corrections — from heavy particles. Gaugino pole masses in terms of running masses. Origin can be understood from a low-energy effective theory.

- Biggest variations at NLO are from model parameters:

$$m_0,\ \mu,\ \tan\beta,\ M(LSP)$$

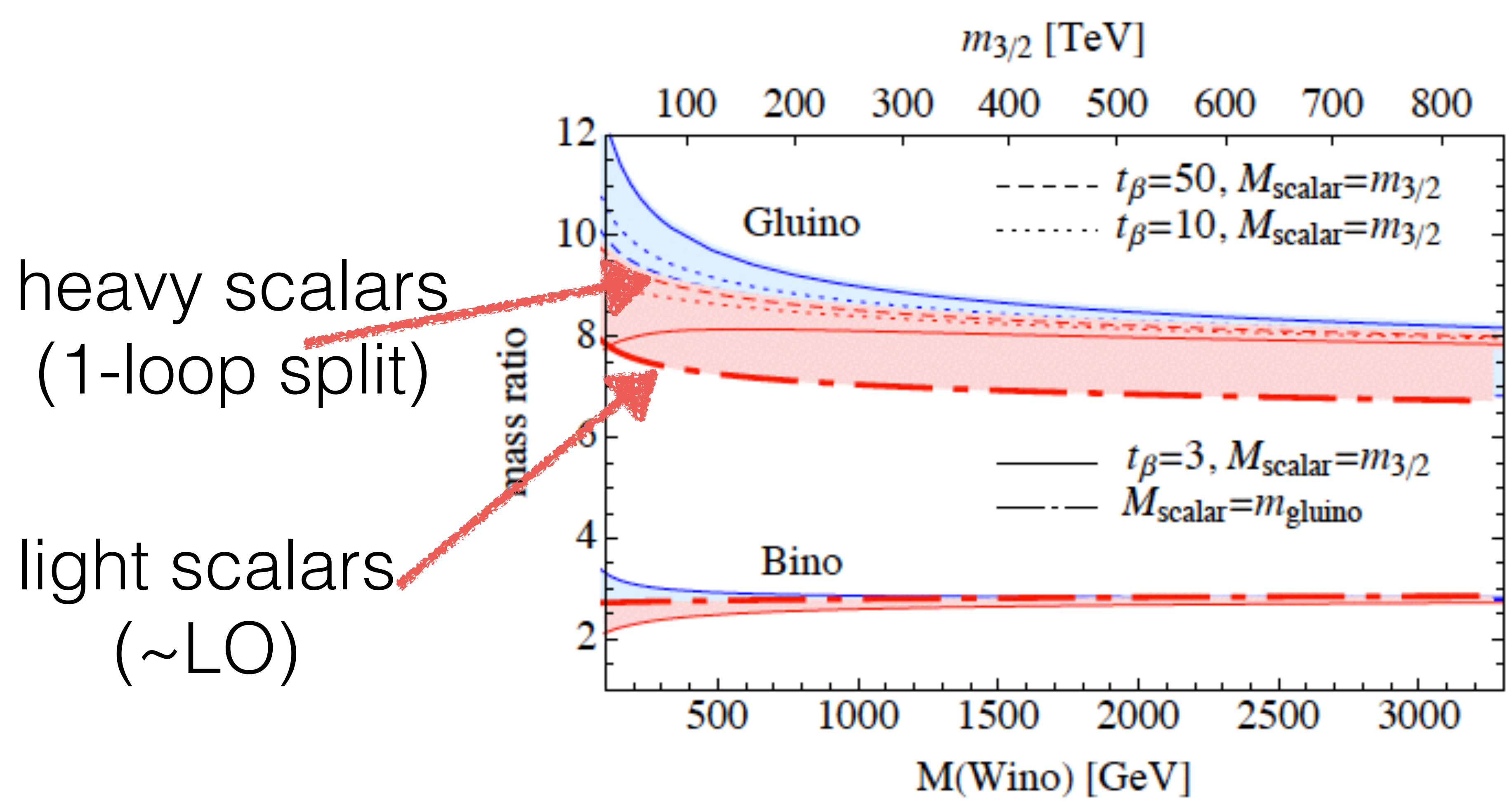


light scalars (~LO)

AMSB

SJ, J.D.Wells
1312.1802

- Heavy m0 implies large logs of m0/Ma. Heavy squarks raise the gluino mass.



SJ, J.D.Wells
1312.1802

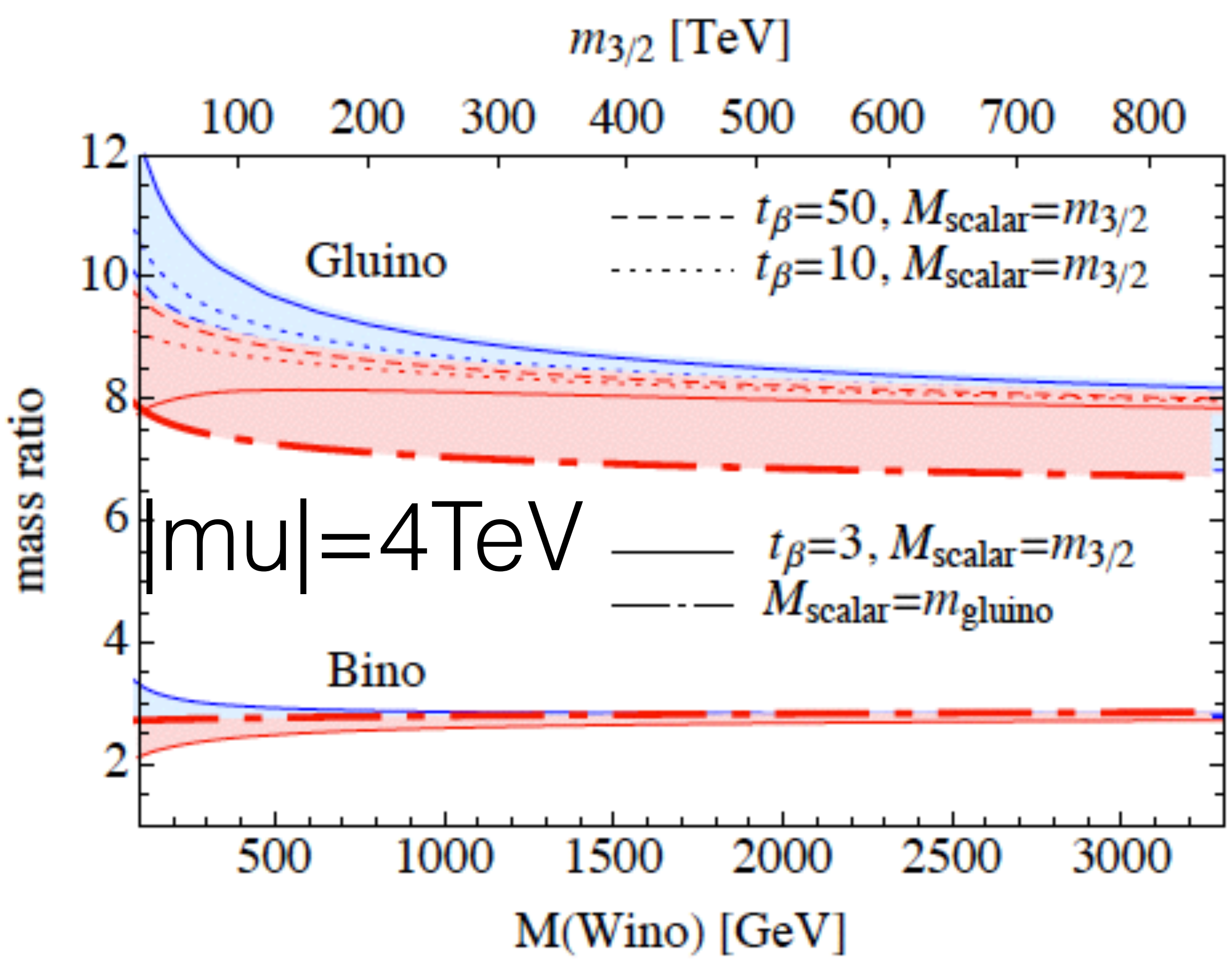
- Heavy higgsino effects are large for small tan beta.

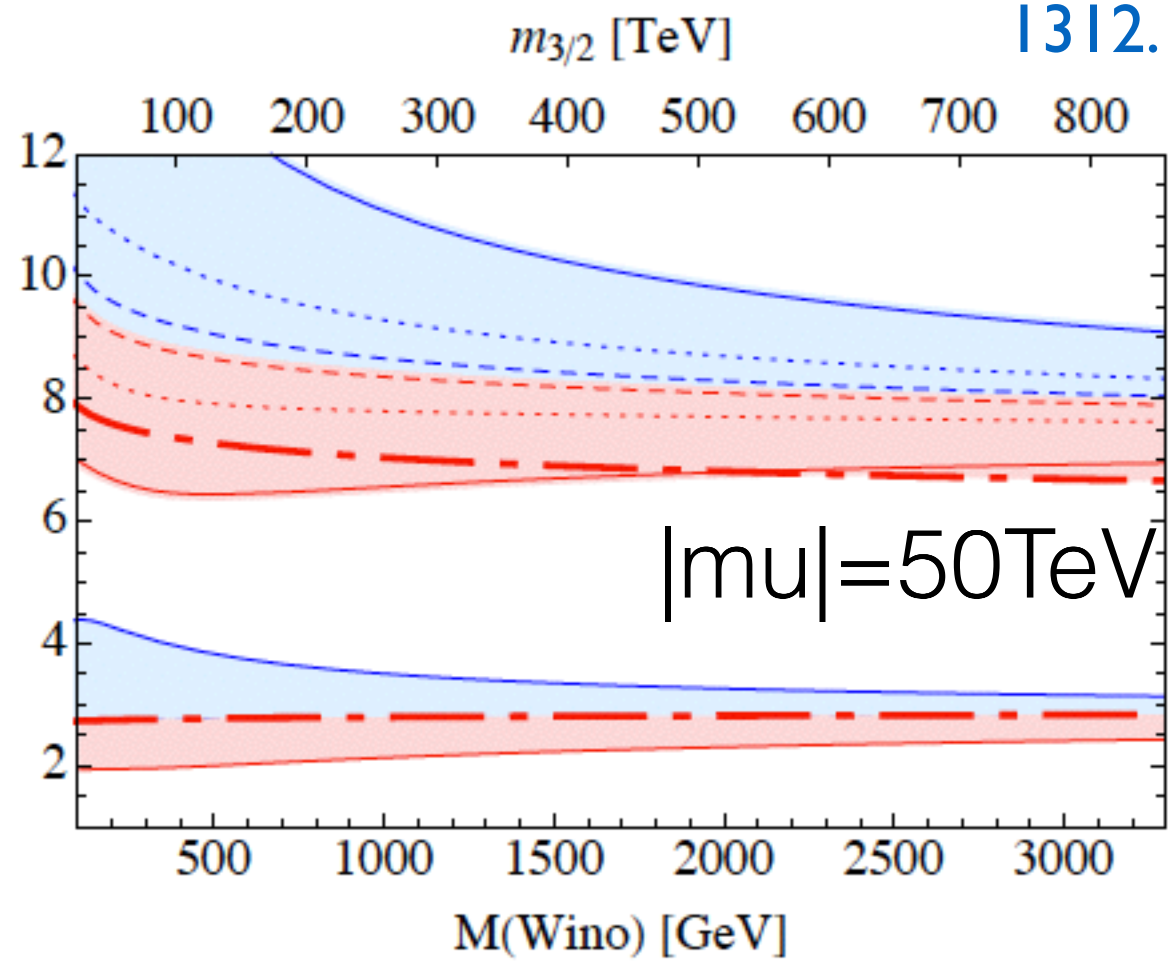
$$\delta M_2(pole) \sim -\frac{\alpha_2}{8\pi}\, 2\mu\, \sin 2\beta\, \log\frac{\mu^2}{m_0^2}$$

Pierce,Bagger, Matchev,Zhang
Gherghetta, Giudice,Wells

- In the low-energy effective theory (SUSY broken), mu and EWino masses mix by RGE.

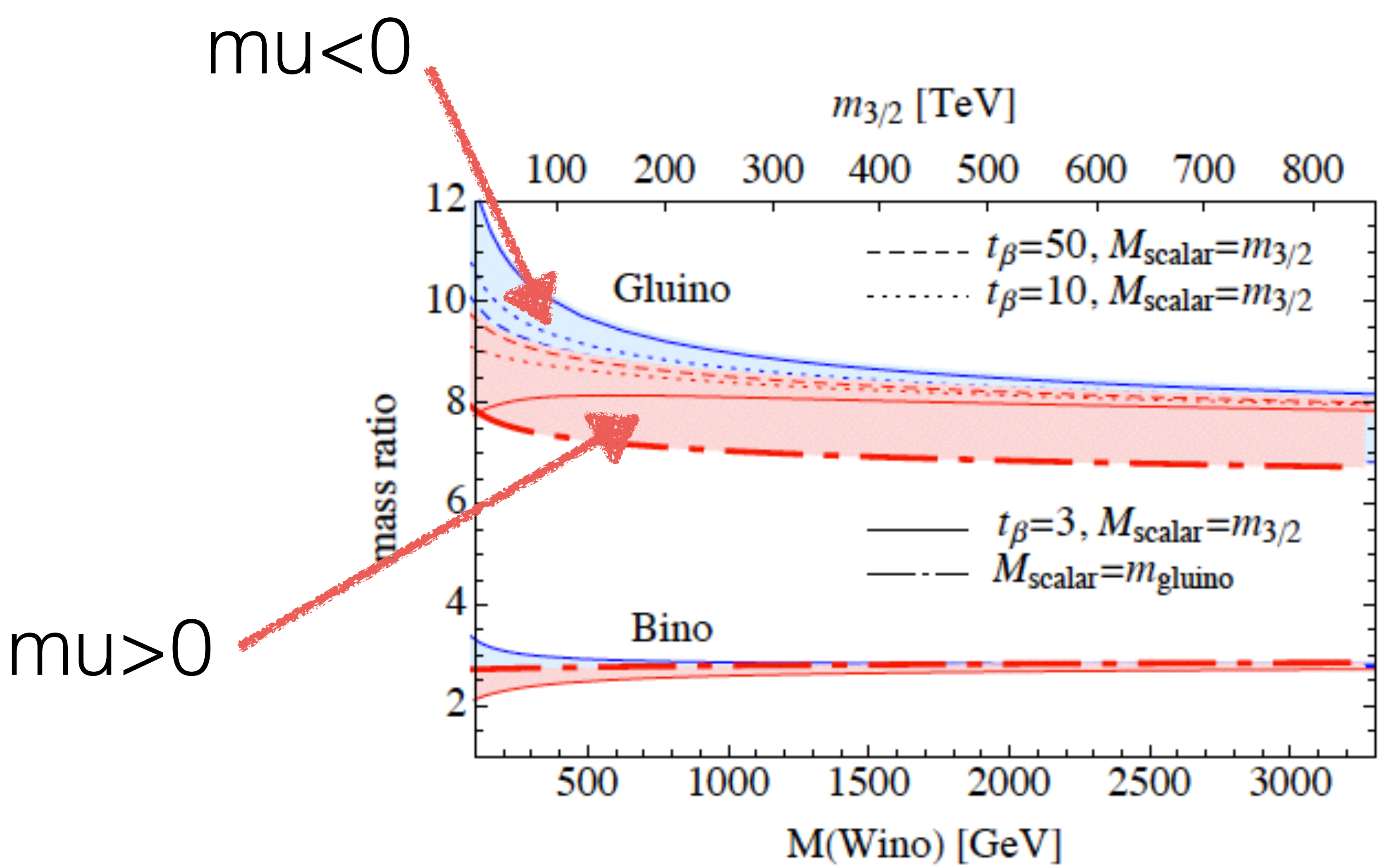
SJ, J.D.Wells
1312.1802





- Also, the sign of mu is important. Wino becomes lighter with negative mu.

$$\delta M_2(pole) \sim -\frac{\alpha_2}{8\pi}\, 2\mu\, \sin 2\beta\, \log\frac{\mu^2}{m_0^2}$$



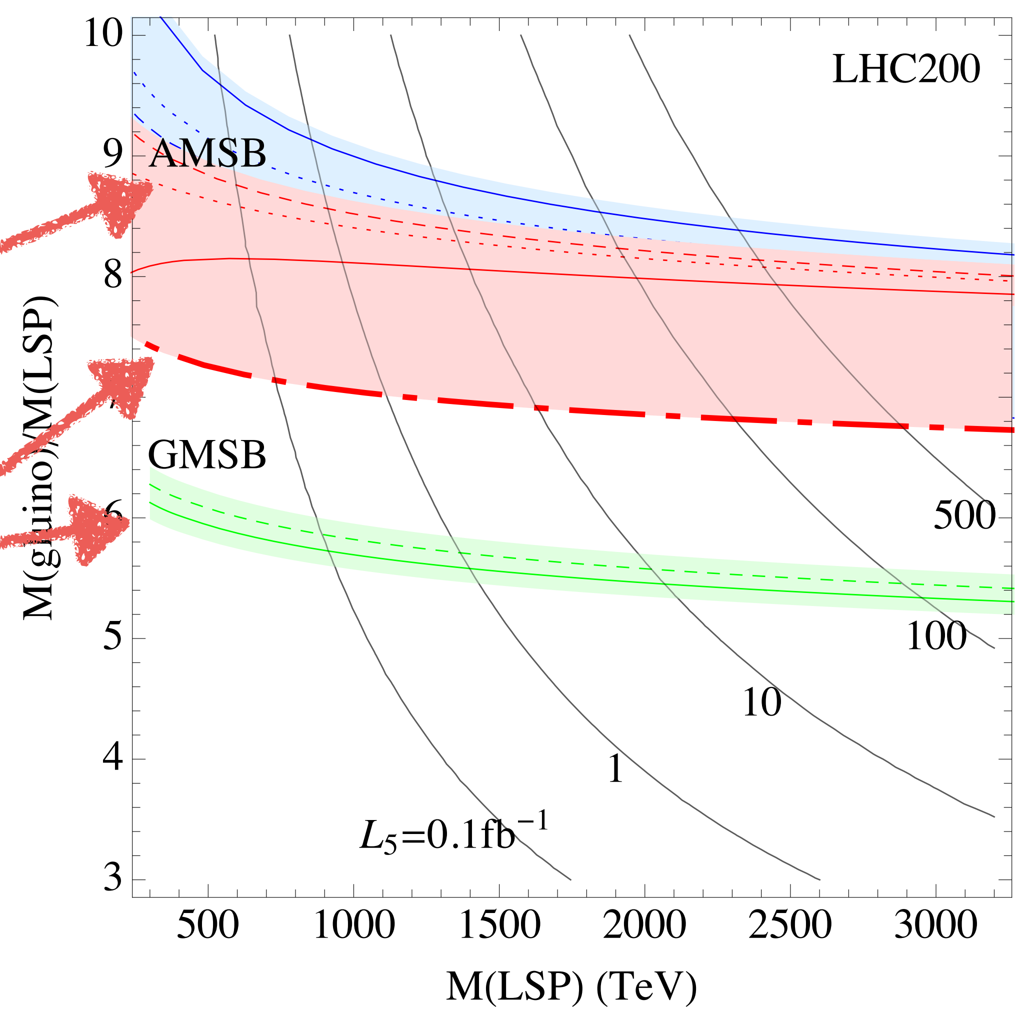
SJ, J.D.Wells
1312.1802

- Gaugino code not very robust against quantum corr.

- NLO uncertainty is ~20-30% (for one-loop split, requiring good unification). This could bother clear mapping of the mass ratio into SUSY breaking models.

One-loop split

No split

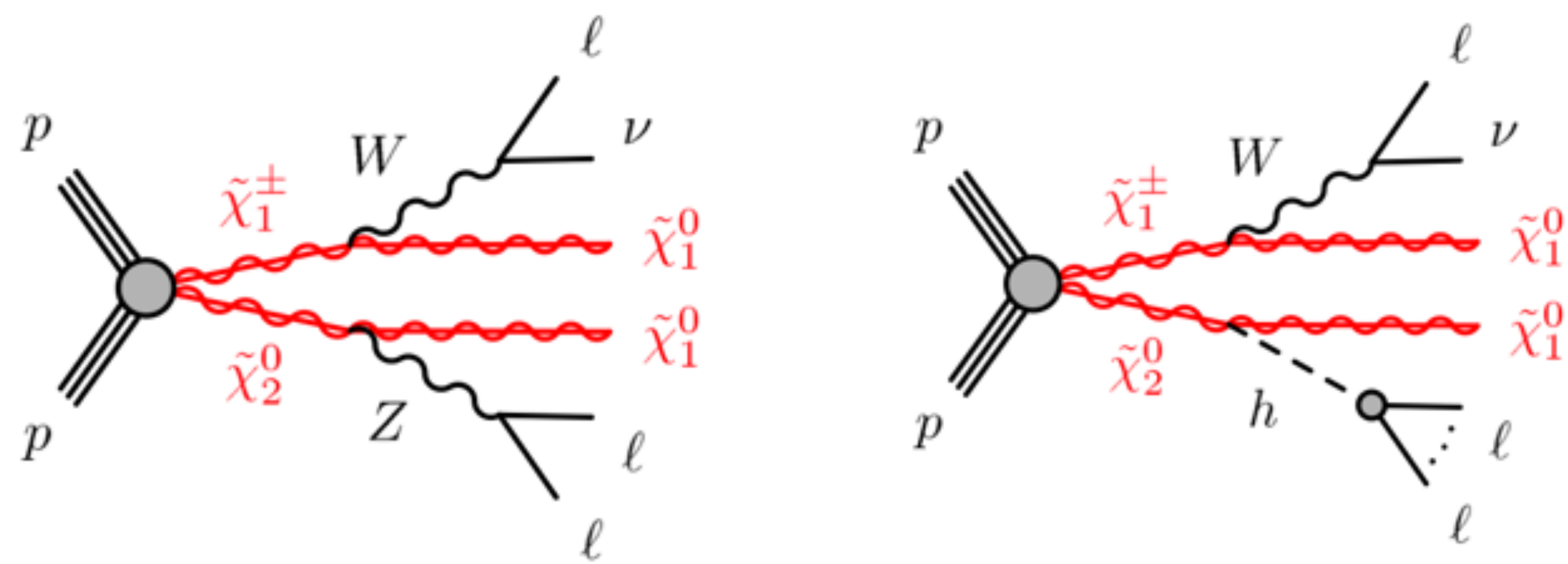


SJ, J.D.Wells
1312.1802

2. EWino pair

Higgsino thermal DM,
Higgsino relations from GET,
Inverse Problem

EWino NLSP searches



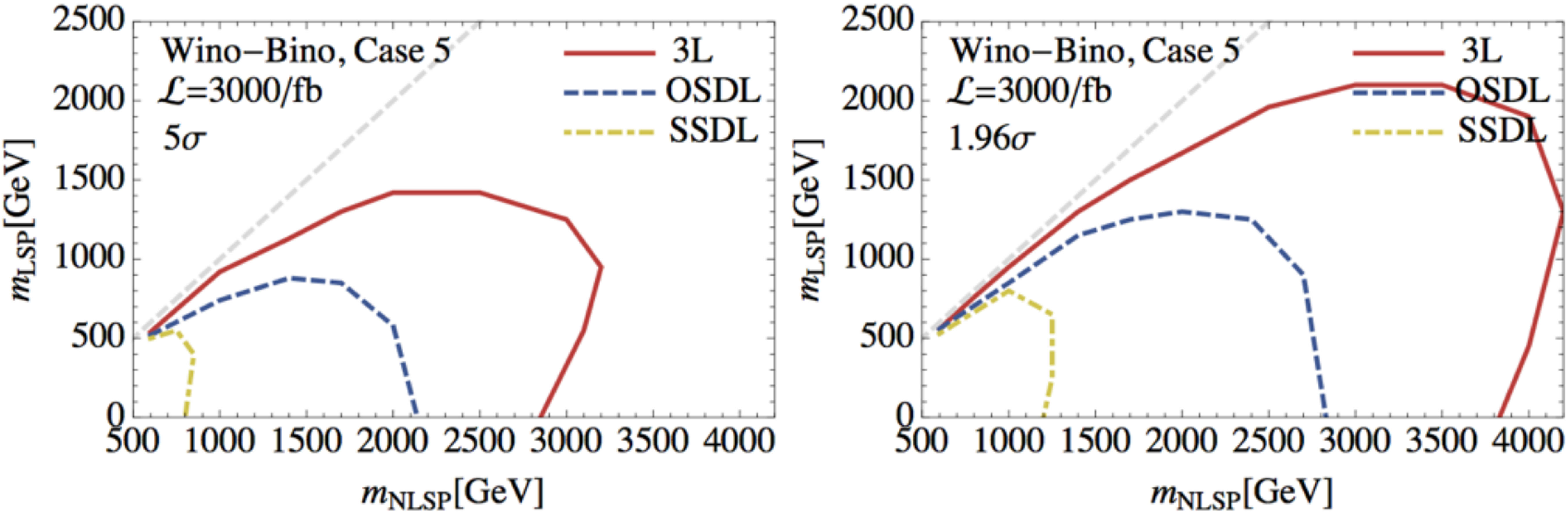
- In the split, EWinos decay always via gauge/Higgs bosons.

- Multileptons from disbosons are representative signatures.

- In the split, Goldstone eq thm generically applies and those decay modes are inherently related!

Wino NLSP – Bino LSP

S.Gori, SJ, L.T.Wang, J.D.Wells
1410.6287



tan beta = 50, mu = +5 TeV > lM2l > M1> 0, M2<0

UCSD

Are our Searches too much influenced by Simplified Models?

We have searched for WW, WZ, Wh, Zh, ZZ, and hh plus MET. When we do so, we search for one final state at a time.

Are we prepare for something like this:

```
DECAY   1000037     5.33993931E+00   # chargino2+ decays
#          BR        NDA      ID1        ID2
     2.58630618E-01   2     1000024       23   # BR(~chi_2+ -> ~chi_1+  Z )
     2.49797977E-01   2     1000022       24   # BR(~chi_2+ -> ~chi_10  W+)
     2.59870362E-01   2     1000023       24   # BR(~chi_2+ -> ~chi_20  W+)
     2.31701044E-01   2     1000024       25   # BR(~chi_2+ -> ~chi_1+  h )
```

26% X+ to Z X+

50% X+ to W X0

23% X+ to h X+

```
DECAY   1000025     5.33171141E+00   # neutralino3 decays
#          BR        NDA      ID1        ID2
     3.88604156E-02   2     1000022       23   # BR(~chi_30 -> ~chi_10  Z )
     2.11792763E-01   2     1000023       23   # BR(~chi_30 -> ~chi_20  Z )
     2.68240565E-01   2     1000024      -24   # BR(~chi_30 -> ~chi_1+  W-)
     2.68240565E-01   2    -1000024       24   # BR(~chi_30 -> ~chi_1-  W+)
     1.80468356E-01   2     1000022       25   # BR(~chi_30 -> ~chi_10  h )
     3.23973361E-02   2     1000023       25   # BR(~chi_30 -> ~chi_20  h )
```

25% X0 to Z X0

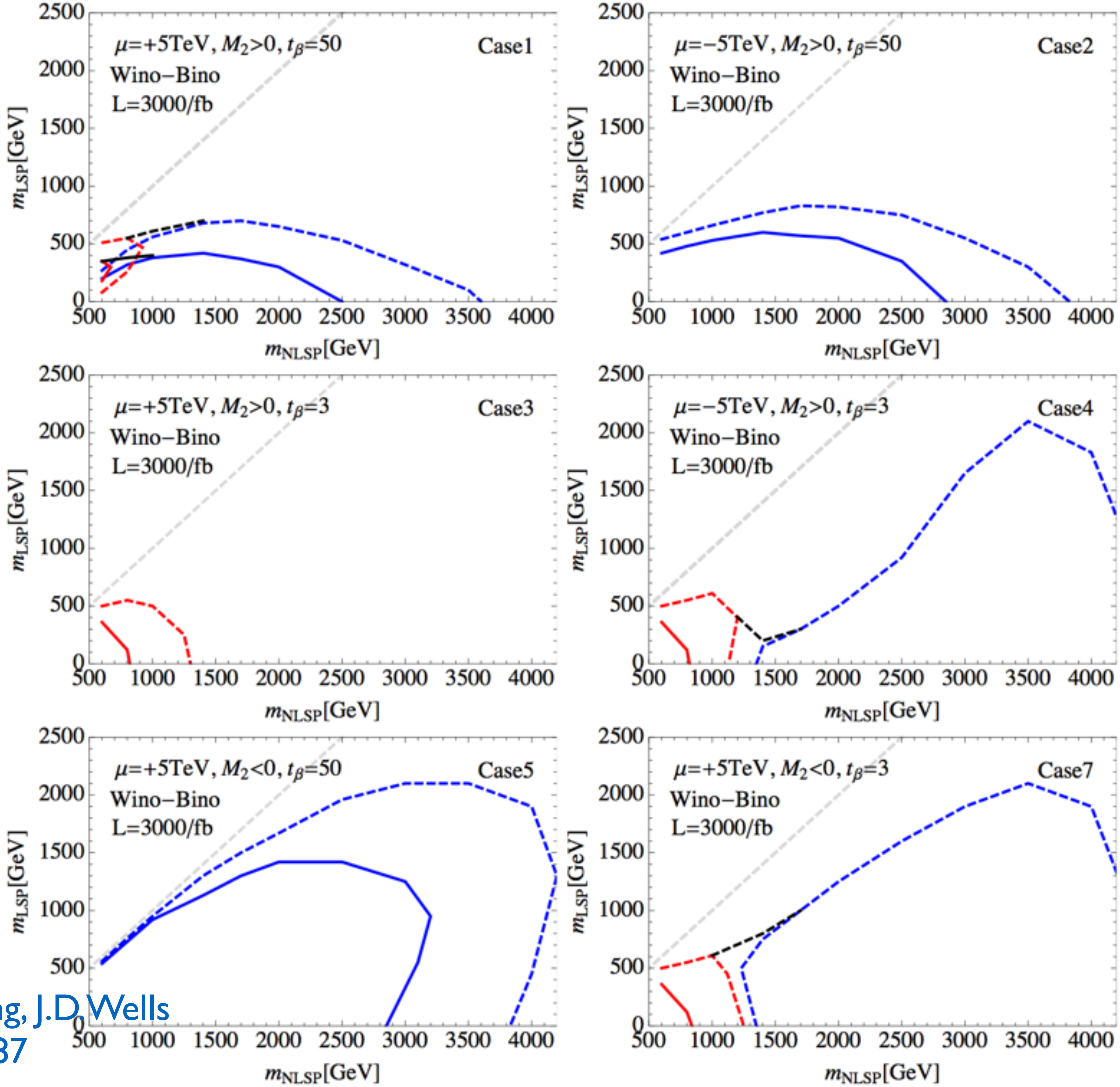
53% X0 to W X+

21% X0 to h X0

Di-boson + MET present at large rate, but none dominates.

The slide from ATLAS speaker Frank Wurthwein's talk

Blue:
WZ -> 3lep
Red:
Wh -> 3lep



S.Gori, SJ, L.T.Wang, J.D.Wells
1410.6287

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WZ -> 3lep
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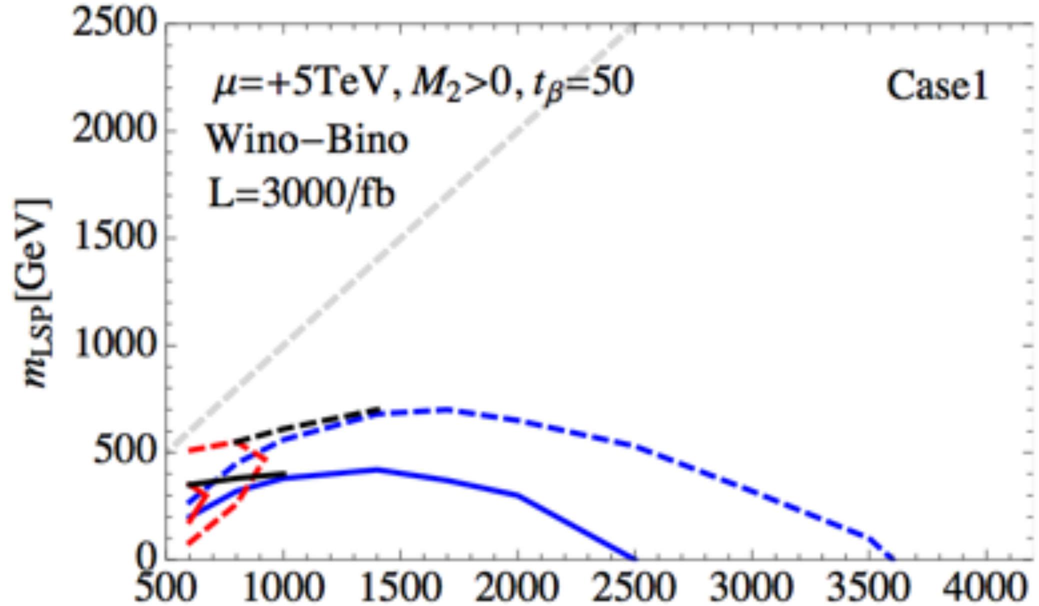
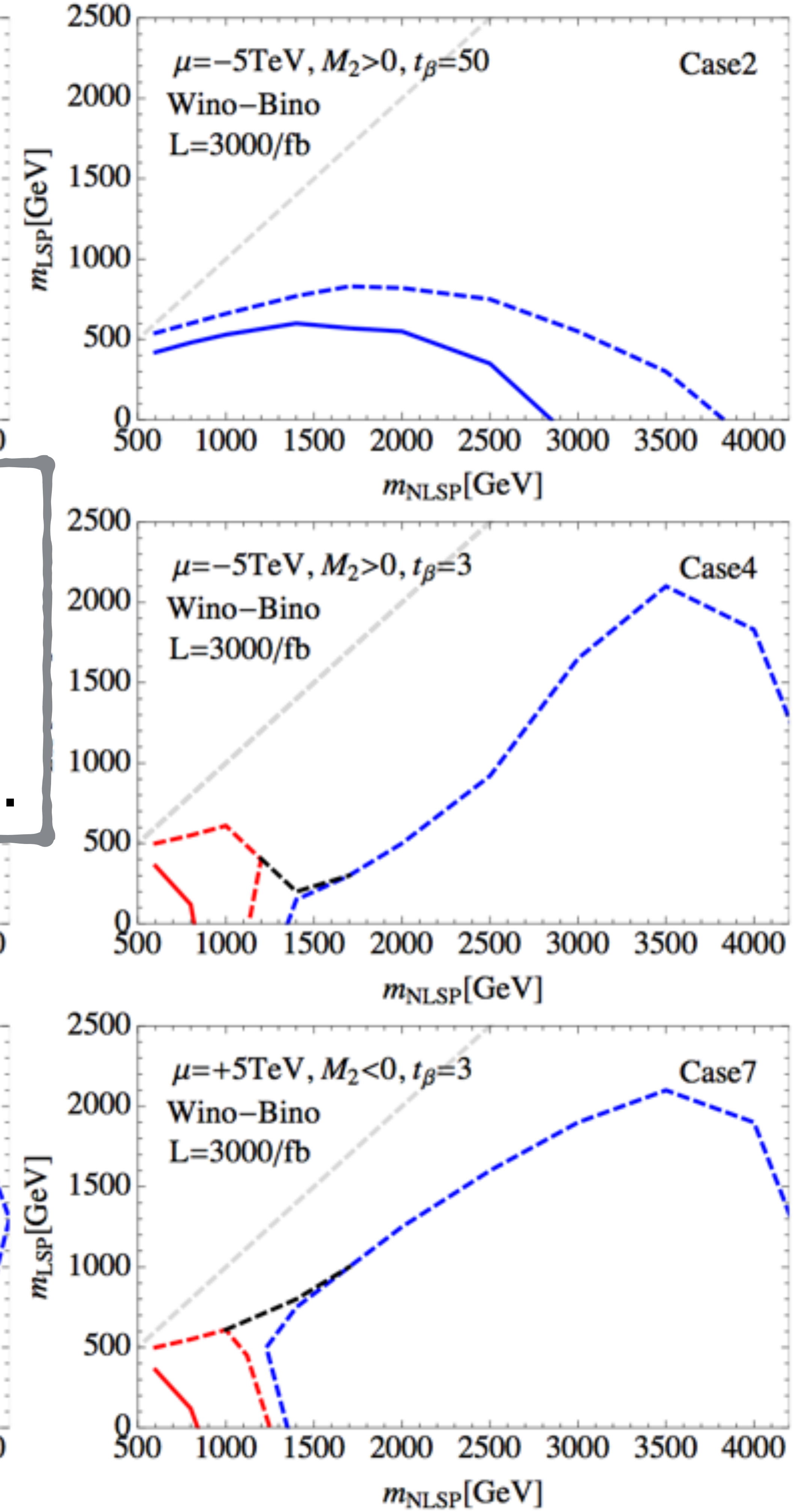
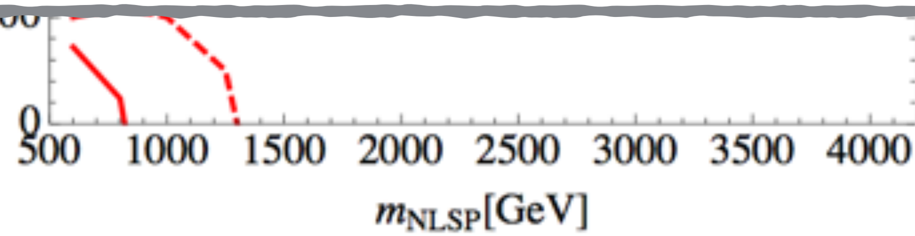
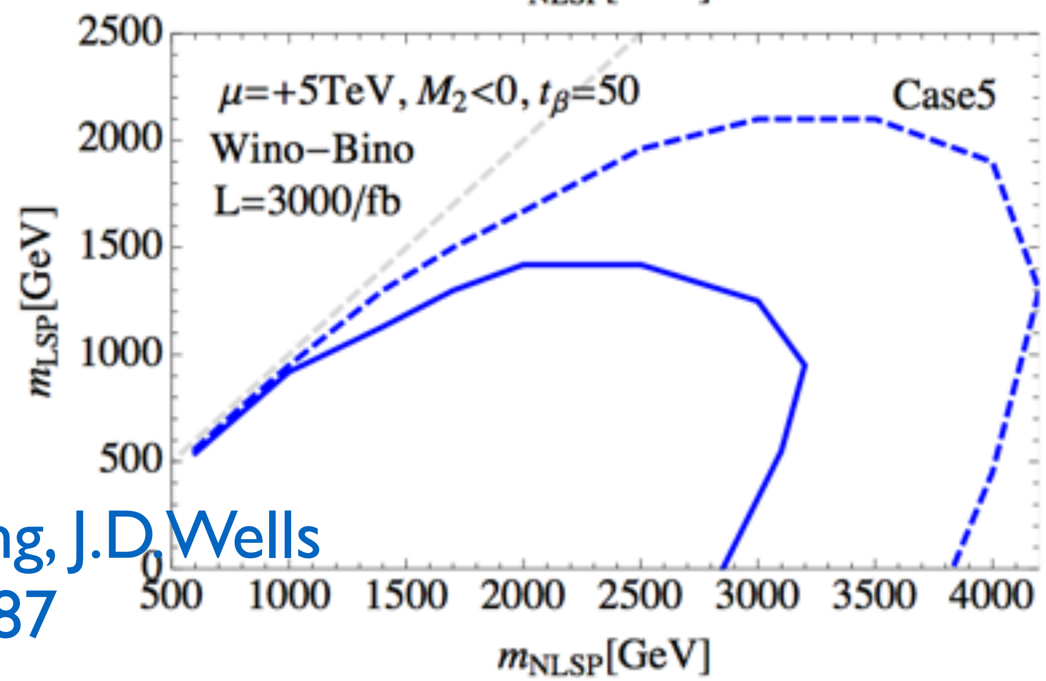




Still Wino-Bino model,
but various features appear
depending on
tan beta, sign(M1 M2), sign(mu M2).





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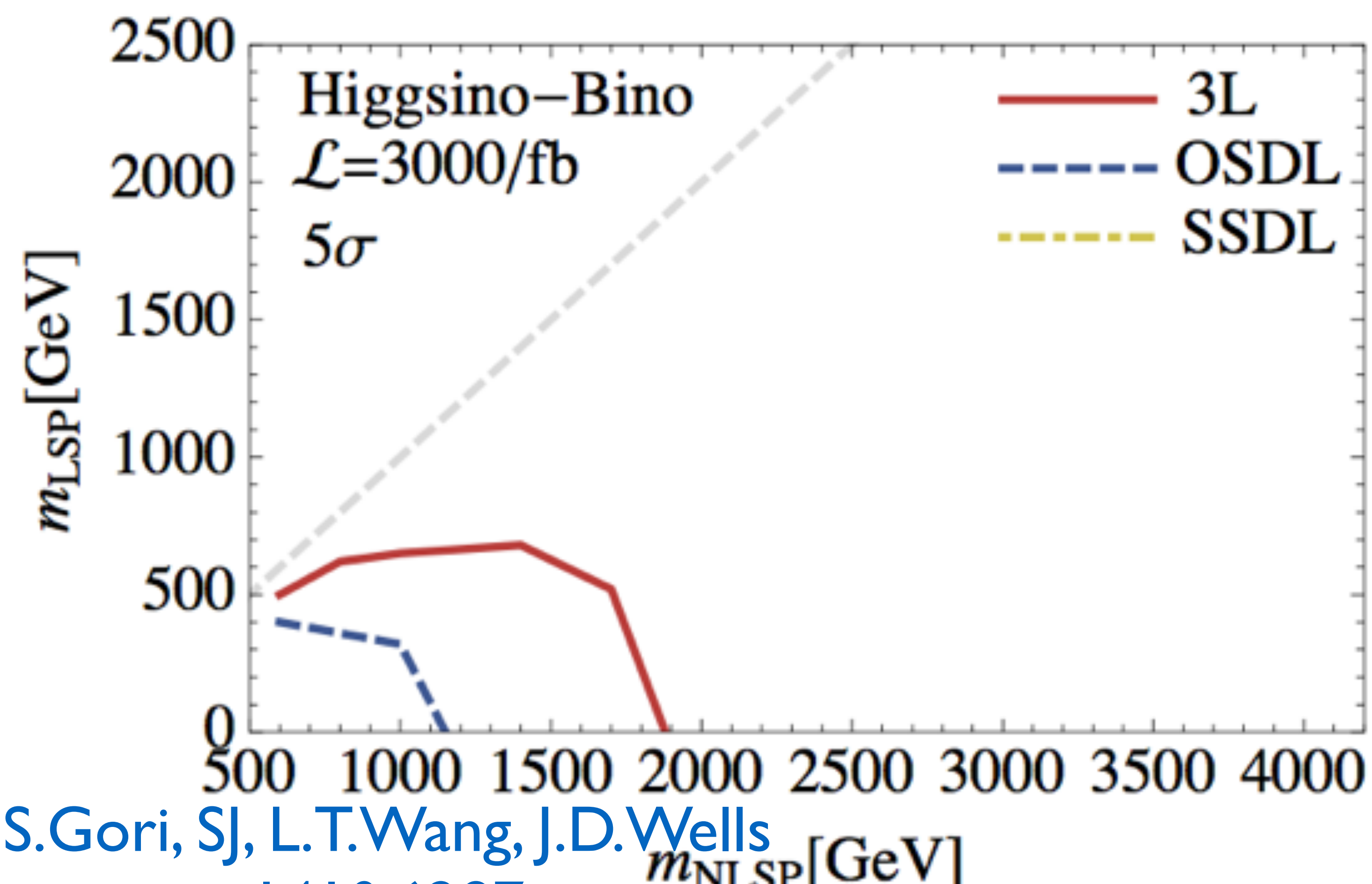
1410.6287

Higgsinos are special

SJ, 1404.2691

Always,
BR(NLSP -> LSP + Z)
= BR(NLSP -> LSP + h)

- If Higgsinos are LSPs or NLSPs, parameter dependences essentially vanish!



S.Gori, SJ, L.T.Wang, J.D.Wells
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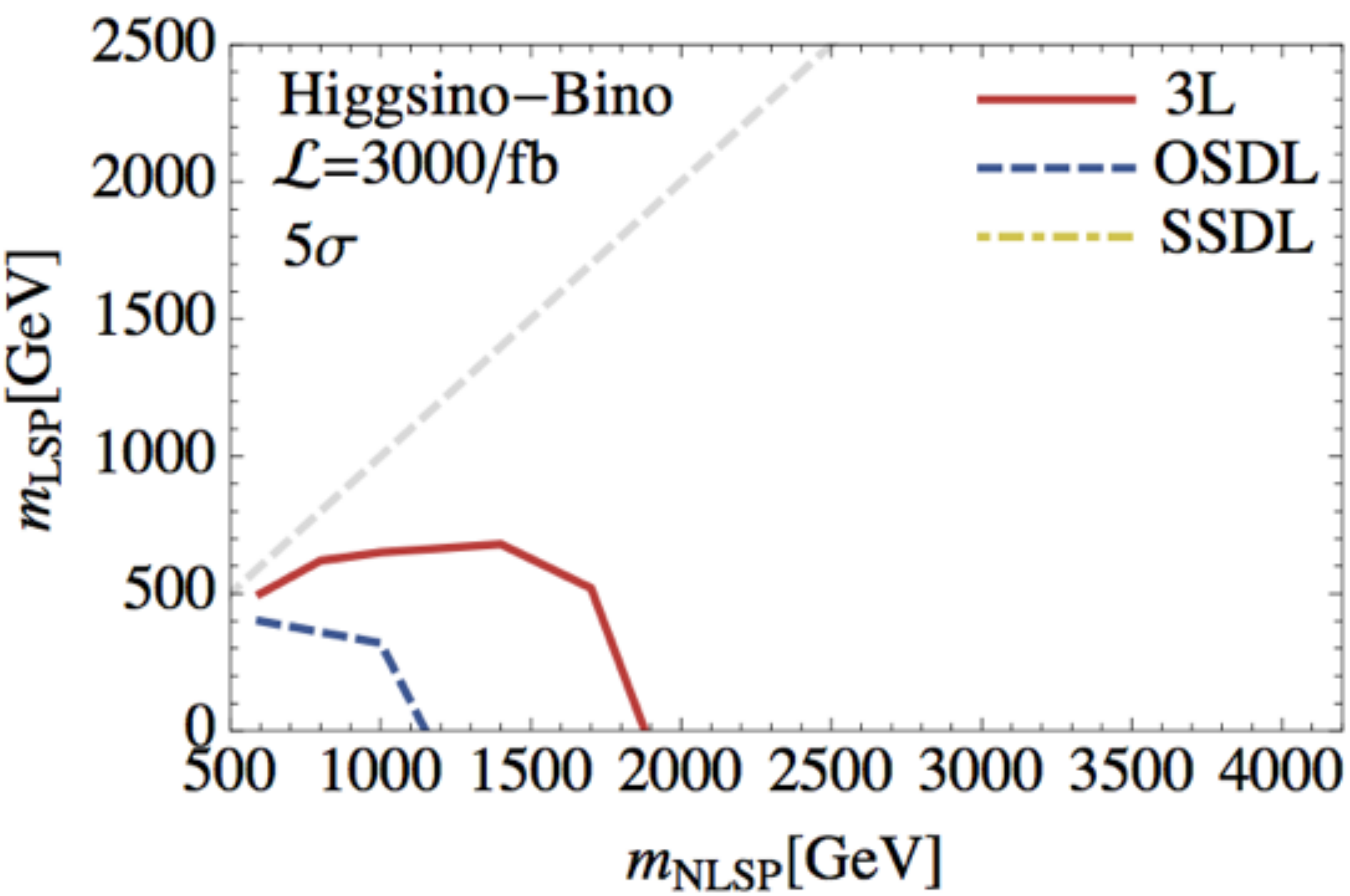


- Just one plot is all.

- May serve as an alternative true simplified model ! (BR(Z)=BR(h))

Indistinguishable Higgsinos

SJ, 1404.2691

- Higgsinos have two nearly degenerate, *indistinguishable* neutralinos.

$$\chi^0_{H_{1,2}} \simeq \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_d \pm \widetilde{H}^0_u\right) \qquad \frac{N_{H_1 3}}{N_{H_1 4}} = -\frac{N_{H_2 3}}{N_{H_2 4}}$$

$$\Gamma(\chi^0_i \to \chi^0_{H_1} Z) \simeq \Gamma(\chi^0_i \to \chi^0_{H_2} h),$$

$$\Gamma(\chi^0_i \to \chi^0_{H_1} h) \simeq \Gamma(\chi^0_i \to \chi^0_{H_2} Z),$$

(See also T.Han, S.Padhi, S.Su, 1309.5966)

Higgsino observables

SJ, 1404.2691

- Higgsinos have two nearly degenerate, *indistinguishable* neutralinos.

$$\chi^0_{H_{1,2}} \simeq \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_d \pm \widetilde{H}^0_u\right) \qquad \frac{N_{H_1 3}}{N_{H_1 4}} = -\frac{N_{H_2 3}}{N_{H_2 4}}$$

$$\Gamma(\chi^0_i \to \chi^0_{H_1} Z) \simeq \Gamma(\chi^0_i \to \chi^0_{H_2} h),$$

$$\Gamma(\chi^0_i \to \chi^0_{H_1} h) \simeq \Gamma(\chi^0_i \to \chi^0_{H_2} Z),$$

(See also T.Han, S.Padhi, S.Su, 1309.5966)

- Adding all, what we *observe* is the same # of h and Z.

$$\Gamma(\chi^0_i \to \chi^0_{H_1} Z) + \Gamma(\chi^0_i \to \chi^0_{H_2} Z) \simeq \Gamma(\chi^0_i \to \chi^0_{H_1} h) + \Gamma(\chi^0_i \to \chi^0_{H_2} h).$$

Runge Basis (Higgs basis)

SJ, 1404.2691

$$H_u = v_u + H_u^0 + iA_u^0$$
$$H_d^c = v_d + H_d^0 - iA_d^0$$

gauge eigenbasis

Runge rotation

$$H_{vev} = v + (H_u^0 s_\beta + H_d^0 c_\beta) + iG^0$$
$$H_\perp = 0 + (H_u^0 c_\beta - H_d^0 s_\beta) + iA^0$$

Runge basis

Only one doublet contains a whole vev and Goldstone.

Runge Basis + alignment

SJ, 1404.2691

$$H_u = v_u + H_u^0 + iA_u^0$$
$$H_d^c = v_d + H_d^0 - iA_d^0$$

gauge eigenbasis

↓ Runge rotation

$$H_{vev} = v + (H_u^0 s_\beta + H_d^0 c_\beta) + iG^0$$
$$H_\perp = 0 + (H_u^0 c_\beta - H_d^0 s_\beta) + iA^0$$

Runge basis

↓ alignment limit

$$H_{vev} = v + h^0 + iG^0$$
$$H_\perp = 0 + H^0 + iA^0$$

Mass eigenbasis

+ finally Goldstone Eq Thm

$$H_u = v_u + H_u^0 + iA_u^0$$
$$H_d^c = v_d + H_d^0 - iA_d^0$$

gauge eigenbasis

Runge rotation

$$H_{vev} = v + (H_u^0 s_\beta + H_d^0 c_\beta) + iG^0$$
$$H_\perp = 0 + (H_u^0 c_\beta - H_d^0 s_\beta) + iA^0$$

Runge basis

alignment limit

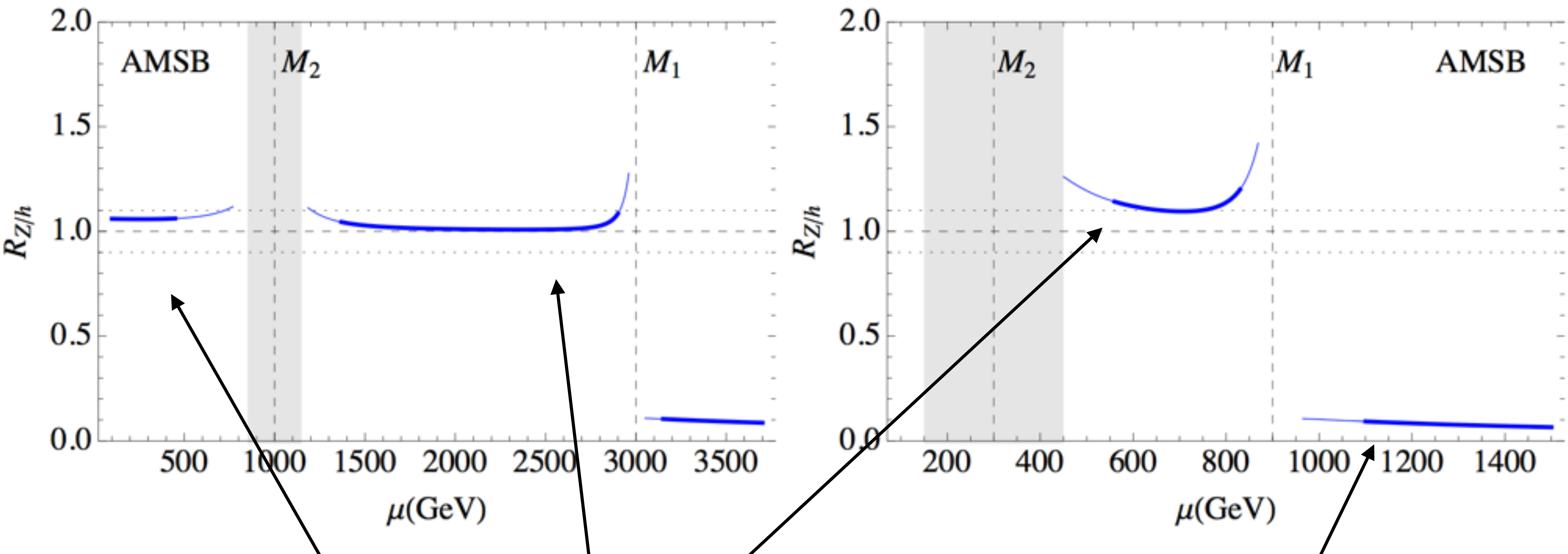
$$H_{vev} = v + h^0 + iZ$$
$$H_\perp = 0 + H^0 + iA^0$$

h and Z are in the same doublet!

Numerical demonstration

SJ, 1404.2691

$$R_{Z/h} \equiv \frac{\sum_{i,j} \sigma(\chi_i) \times \mathrm{BR}(\chi_i \to \chi_j + Z)}{\sum_{i,j} \sigma(\chi_i) \times \mathrm{BR}(\chi_i \to \chi_j + h)}$$

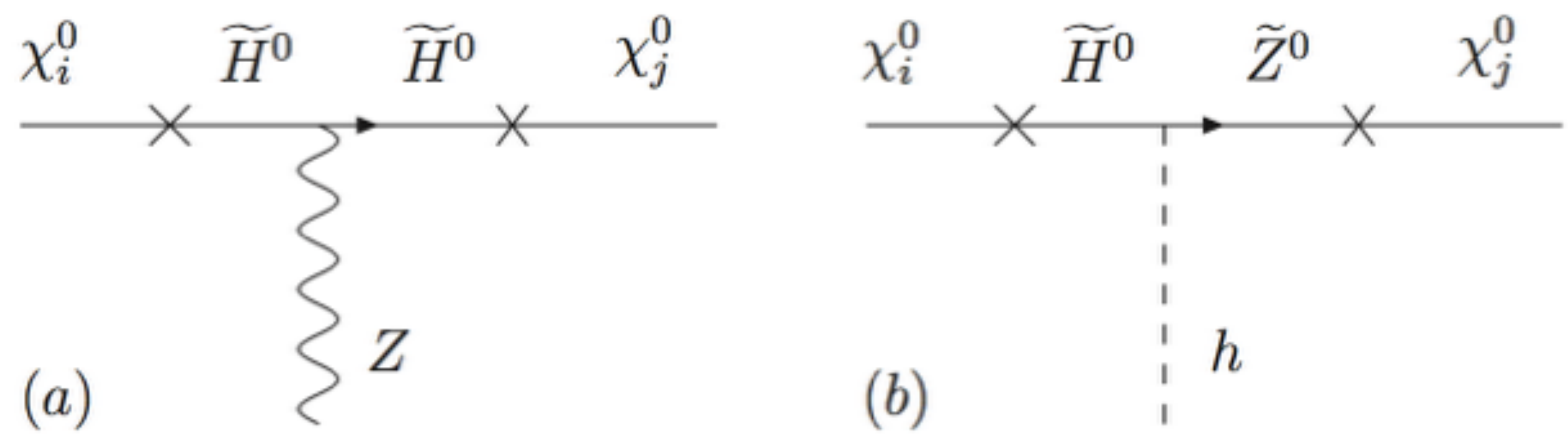


Higgsinos are LSPs or NLSPs.

Heavier Higgsinos

What GET implies

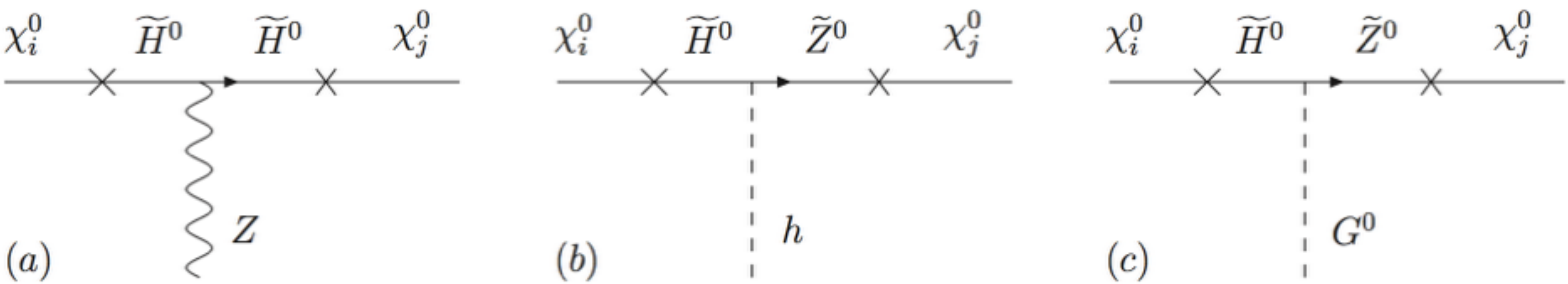
Suppose Higgsino decays to Zinos:



- (a) needs **one** small mixing insertion,
- (b) needs **no** small mixing insertion.
- Often (b) > (a) for Wino NLSPs, but not always.

What GET implies

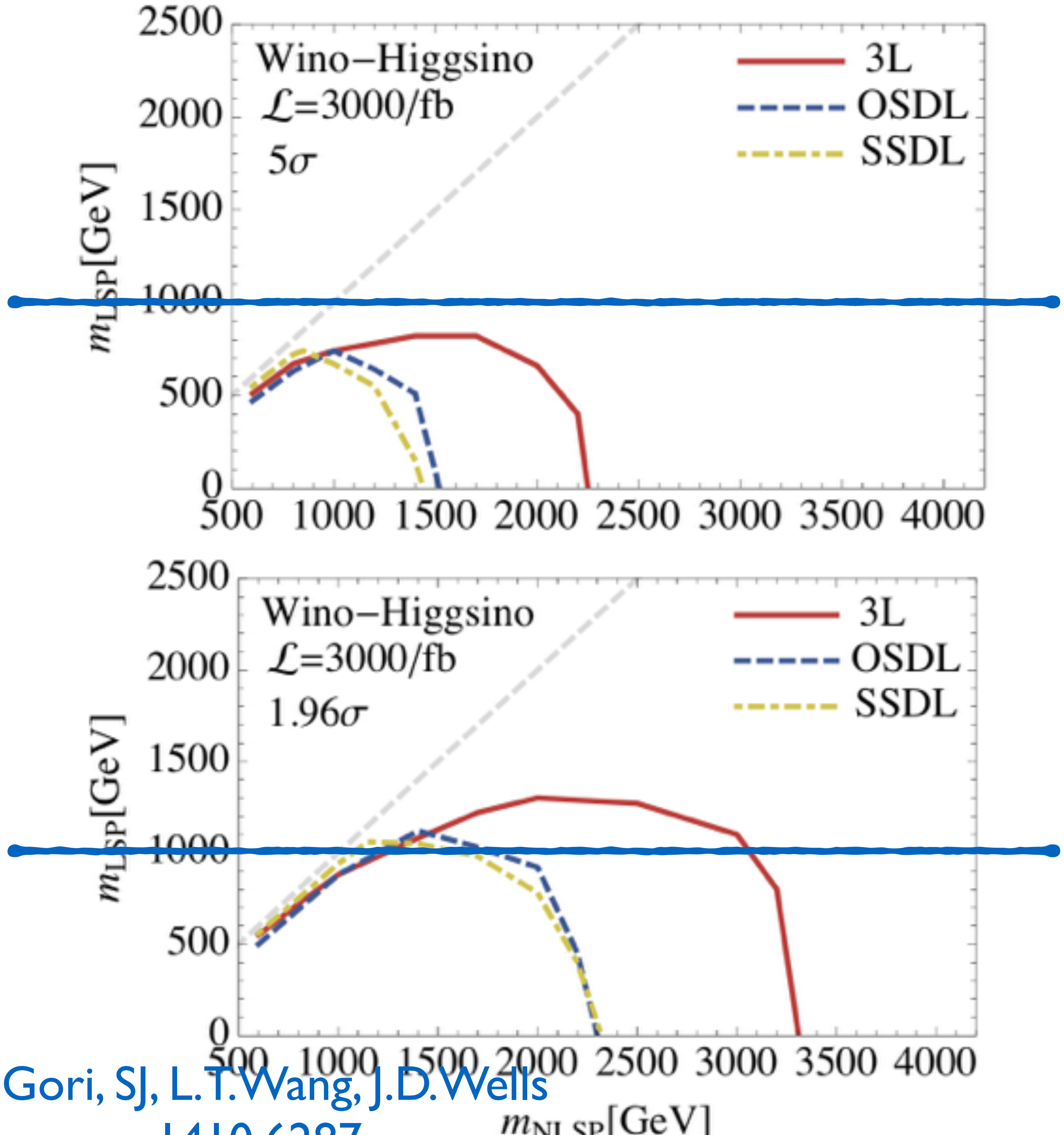
Suppose Higgsino decays to Zinos:



Think about (a) in terms of Goldstones (c).

- (c) now also needs no mixing insertion.
- (b) and (c), hence (b) and (a), can be comparable.

Back to Higgsino DM…



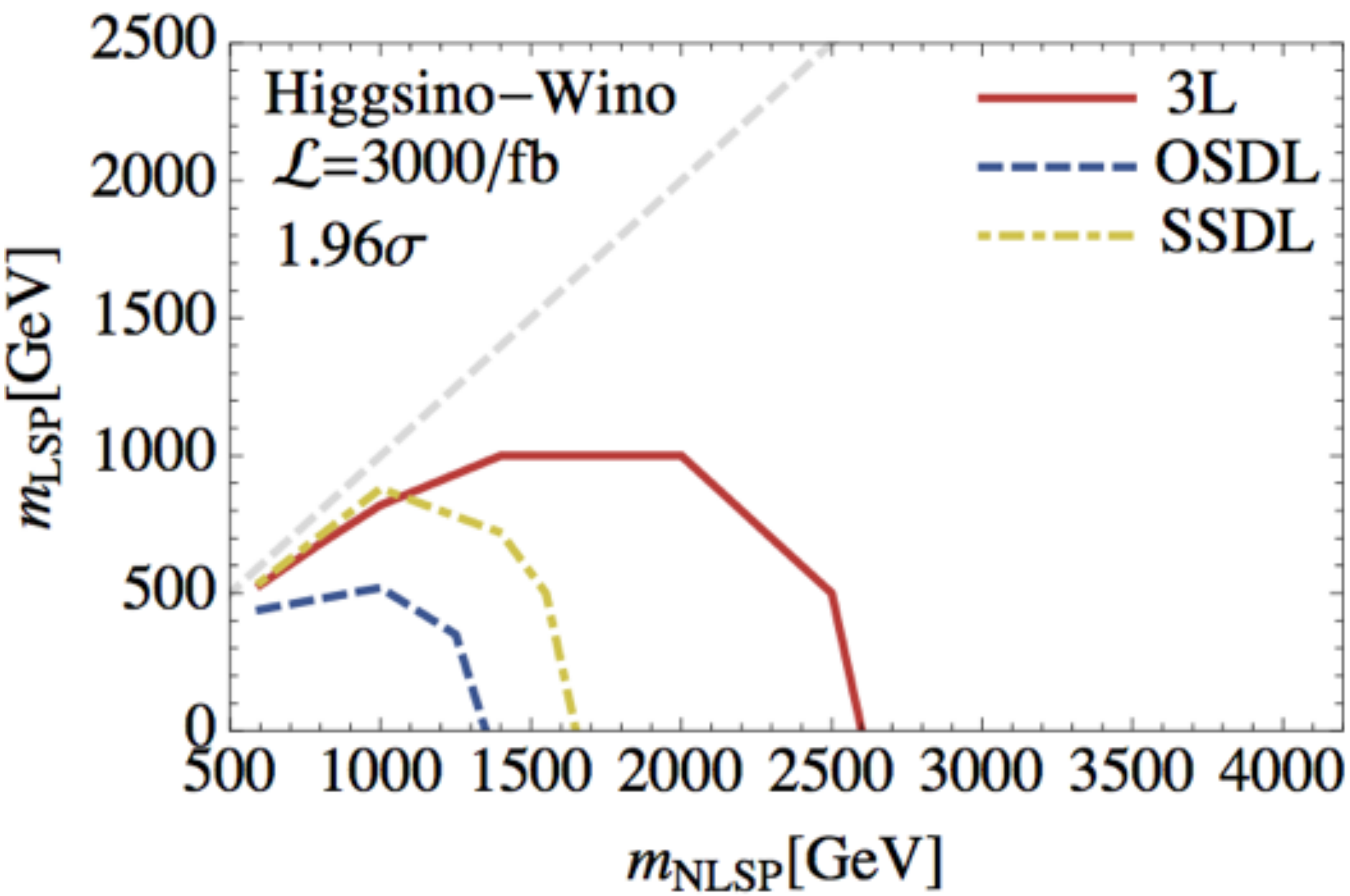
- Higgsino LSPs discovery prospects maybe highest in this channel benefit from large Wino productions.

- 1 TeV Higgsino DM is perhaps excludable, but not discoverable.

S.Gori, SJ, L.T.Wang, J.D.Wells
1410.6287

not optimal for Wino DM

3.1 TeV Wino LSP is way up here.



- EWino NLSP pair is not optimal for Wino LSP

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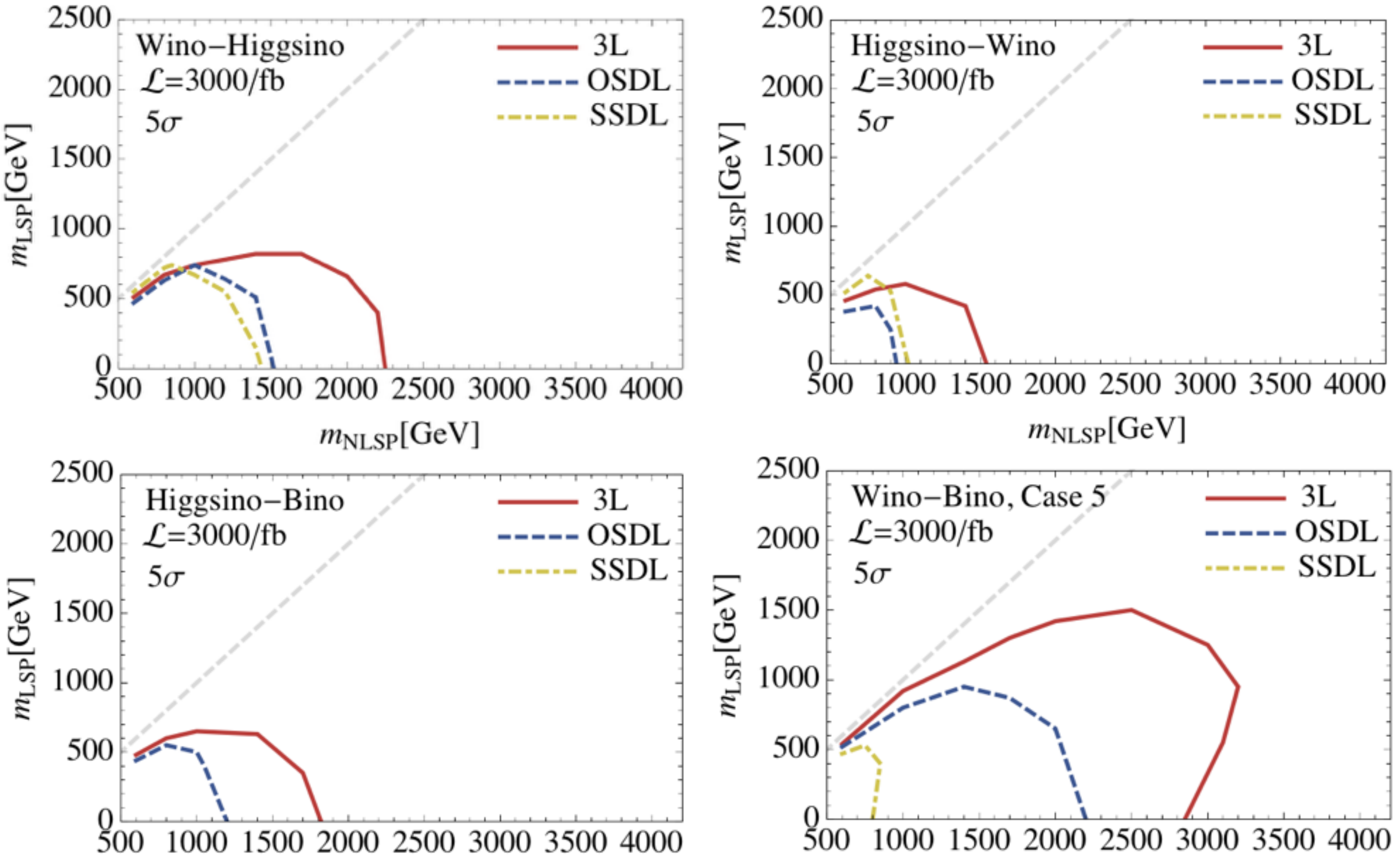
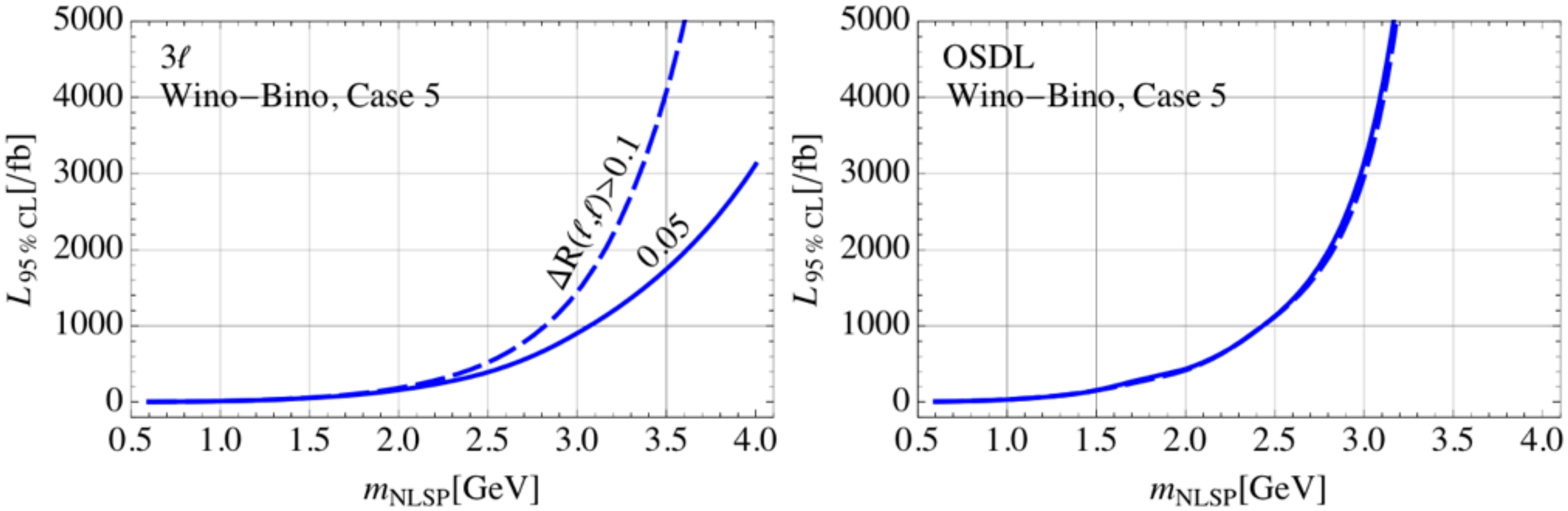
1410.6287

Summary of EWino searches



Lepton collimation



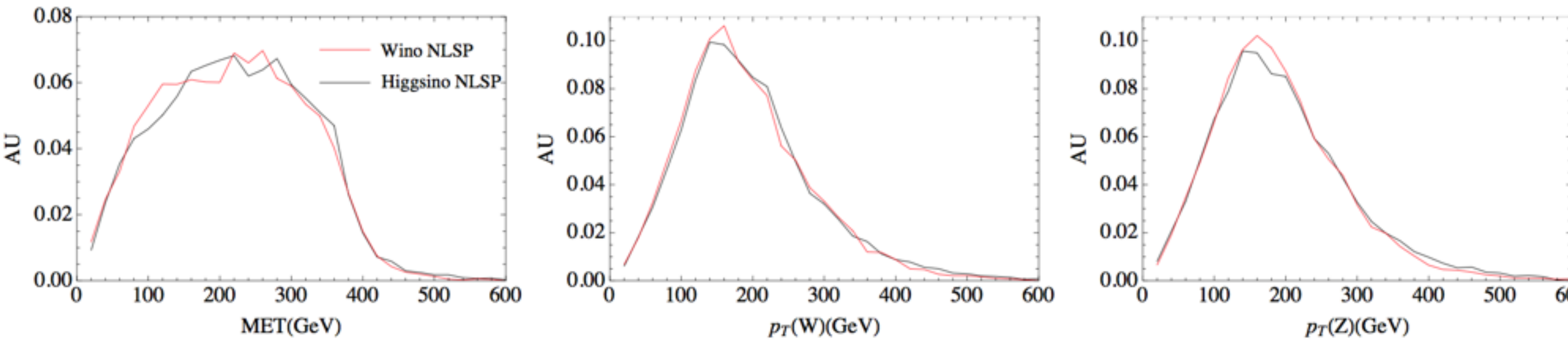
- Boosted physics is more relevant at future collider.

S.Gori, SJ, L.T.Wang, J.D.Wells
1410.6287

N.Arkani-Hamed, et. al.

Inverse Problem

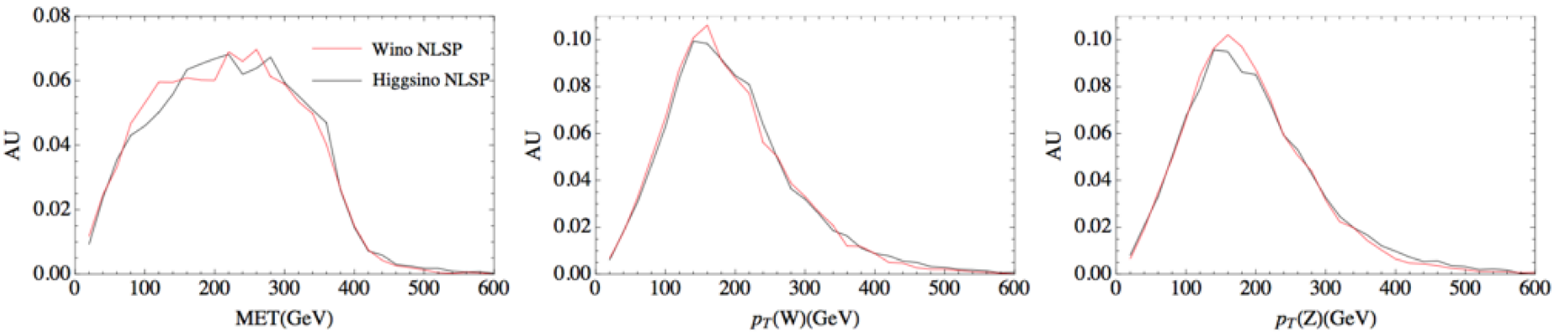
SJ, 1404.2691



Model	parameters (M_1, M_2, μ, t_β)	$\sigma(W^+W^-)$	$\sigma(W^\pm Z)$	$\sigma(ZZ)$
Wino-NLSP	0.5 TeV, 1.0 TeV, −2.0 TeV, 4.3	0.60 fb	1.1 fb	0 fb
Higgsino-NLSP	0.2 TeV, 2.0 TeV, 0.8 TeV, 2.0	0.61 fb	1.1 fb	0.02 fb

Inverse Problem

SJ, 1404.2691

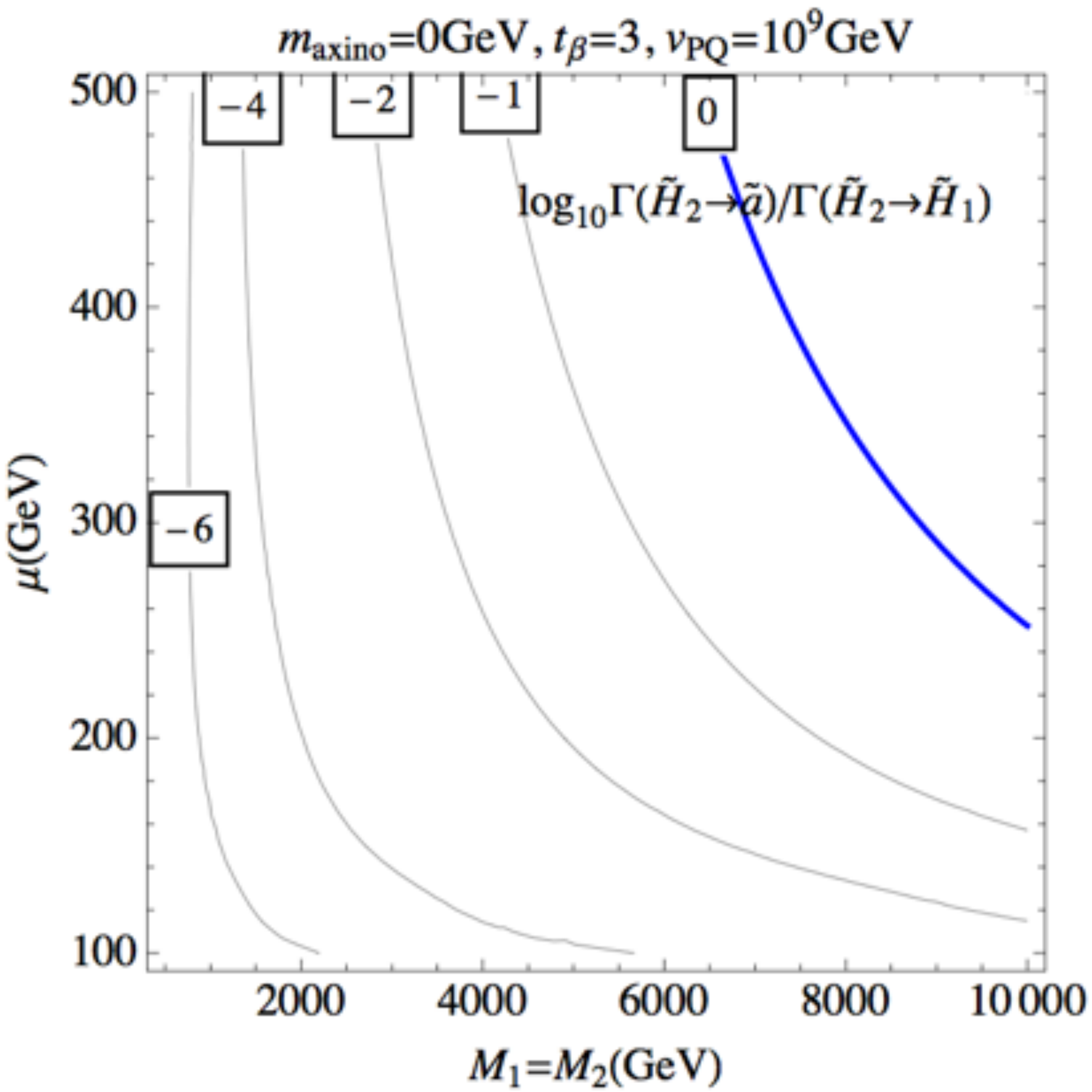


Model	parameters (M_1, M_2, μ, t_β)	$\sigma(W^+W^-)$	$\sigma(W^\pm Z)$	$\sigma(ZZ)$
Wino-NLSP	0.5 TeV, 1.0 TeV, −2.0 TeV, 4.3	0.60 fb	1.1 fb	0 fb
Higgsino-NLSP	0.2 TeV, 2.0 TeV, 0.8 TeV, 2.0	0.61 fb	1.1 fb	0.02 fb

- h/Z = 1.03 (second case) while h/Z = 5.35 (first case)

Aside: Exceptions from axino LSP

G.Barenboim, SJ, E.J.Chun, W.I.Park, 1407.1218



Higgsinos

Axinos

- Heavier Higgsinos dominantly decay to the lightest Higgsino.
- Essentially only lightest Higgsino pair productions.
- No summation of Higgsinos,,, and no Z/h=1 any more.

3. gluino
vs.
stop, EWino

The question

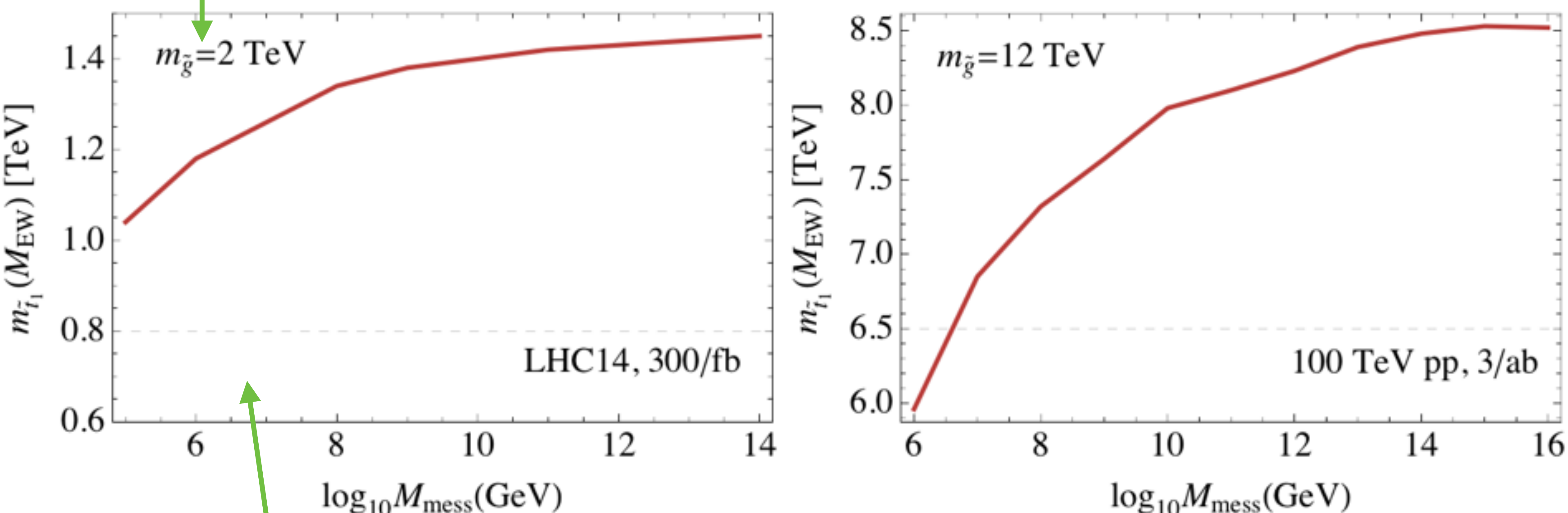
- If gluinos are nearby in mass with other sparticles, gluino pair is typically the easiest discovery channel.
- Can a gluino be *undiscoverably* heavy while stops or EWinos are *discoverably* light?

NB: Compared to usual questions of whether stops
can be light enough for natural EWSB,
our question is more practical and objective.

Stop vs. gluino

SJ, B.S.Kyae
in progress

Undiscoverably heavy gluinos



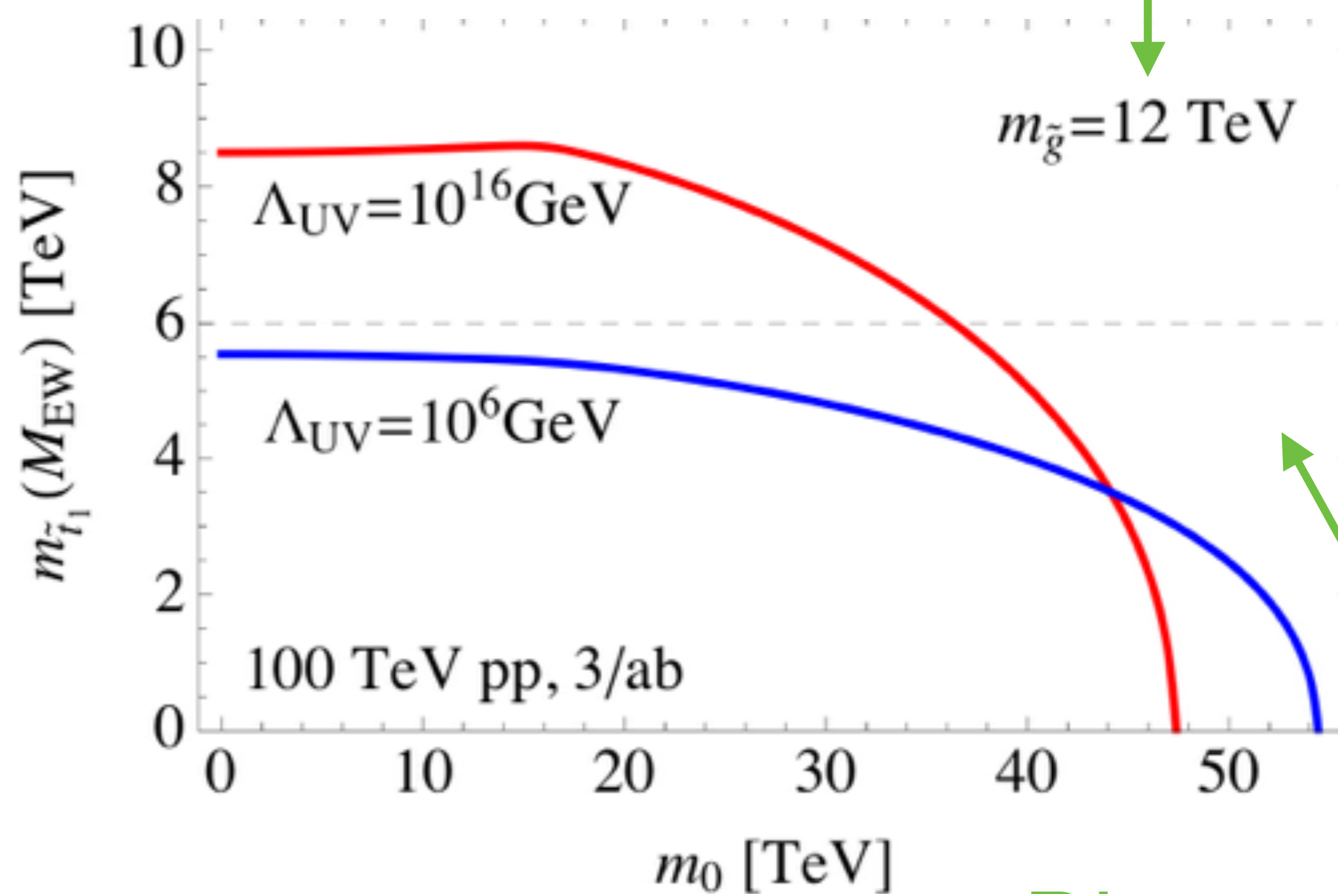
Discoverably light stops

- In most models, stops are efficiently RG-driven up to near gluinos. => Gluino pair is typically easier discovery channel.

Heavy squark 2-loop effects

SJ, B.S.Kyae
in progress

Undiscoverably heavy gluinos



Discoverably light stops

- Squarks ~3-4 times heavier than gluinos can lead to light enough stops. O(1-10) fine-tuning.

EWino vs. gluino

S.Gori, SJ, L.T.Wang, J.D.Wells
1410.6287

mSUGRA (M1:M2:M3=1:2:6)

M3=12 TeV

M2=4 TeV

M1=2 TeV

Undiscoverably heavy gluinos

discoverably light Wino NLSP

AMSB (M1:M2:M3=3:1:8)

M3=12 TeV

M1=4.5 TeV

M2=1.5 TeV

mu<1 TeV

- AMSB with Higgsino LSP can be discovered earlier via EWinos than gluinos.

Summary of prospects

- Gluino pairs @ 100 TeV does not definitely cover Wino or Higgsino DM scenarios. 200 TeV collider may probe Wino DM.

- 1 TeV Higgsino DM can perhaps be excludable (but not discoverable) via multilepton NLSP Wino productions @ 100 TeV.

- Stops with heavy squarks or AMSB with Higgsino LSP can be better searched via stops and EWino pair productions than gluing pairs.

Summary of future SUSY

- Results can be usefully presented for ino mass ratios. The resummation of scale hierarchy introduces 20-30% err. Better calc with eff thy.

- Goldstone Eq Thm is generically applied now and light Higgsino pheno especially simplified. BR(Z)=BR(h) always.

- Infamous Inverse Problem can be partially resolved based on such new relations.