Perspectives on Future Supersymmetry at Colliders

Sunghoon Jung

Korea Institute for Advanced Study

The 4th KIAS Workshop on Particle Physics and Cosmology

Based on collaborations with

G.Barenboim, E.J.Chun, S.Gori, W.I.Park, L.T.Wang, J.D.Wells

1312.1802, 1404.2691, 1407.1218, 1410.6287

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Future collider

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

- Isn’t it simply a scaled-up version of previous studies?

- I will address in the “Future SUSY” framework.

Future SUSY

- Data driven. Overall heavy. Lighter fermions (gauginos, higgsinos) ~ a few 100-1000 GeV and heavier scalars.
- General futuristic SUSY spectrum that will exhibit generic features of future new physics models.

Future SUSY

- Data driven. Overall heavy. Lighter fermions (gauginos, higgsinos) ~ a few 100-1000 GeV and heavier scalars.

- General futuristic SUSY spectrum that will exhibit generic features of future new physics models.

- Many aspects of current SUSY analyses do 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 100 TeV collider say definitive about the Future SUSY?
  Or, what do we eventually need for that?

- Future SUSY vs. 100GeVish SUSY:
  Generic features that only appear in the Future SUSY.

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.
M.Ibe, 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. (gauge coupl unification, DM)
- Important mass scales: ~1 TeV Higgsino DM, ~3 TeV Wino DM.
  => Testing the 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 primary observable/variable of the Future SUSY.
- Gauginos are least model-dependent fields encoding SUSY breaking mediation info.

K.Choi, H.P.Nilles

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

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

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

Overview

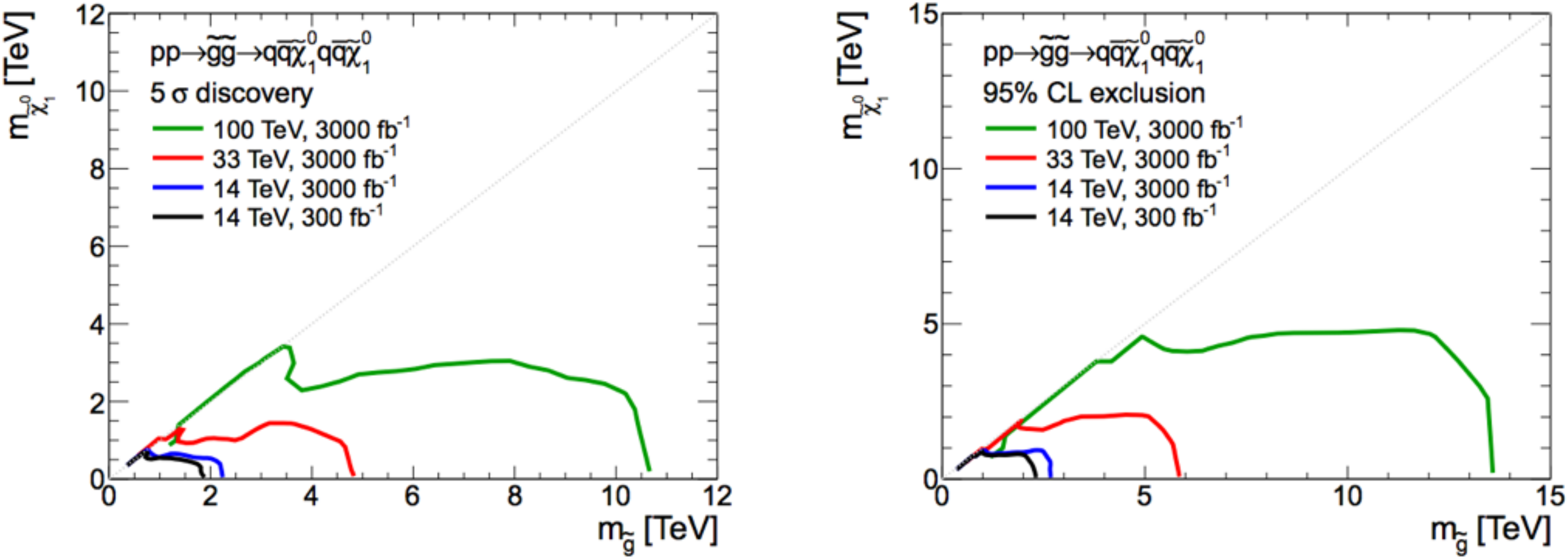
- 1. Gluino pair
  - Wino thermal DM, gaugino code, resummation.

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

1. Gluino pair

Wino thermal DM,
Gaugino code,
Resummation

Searches of guino pairs

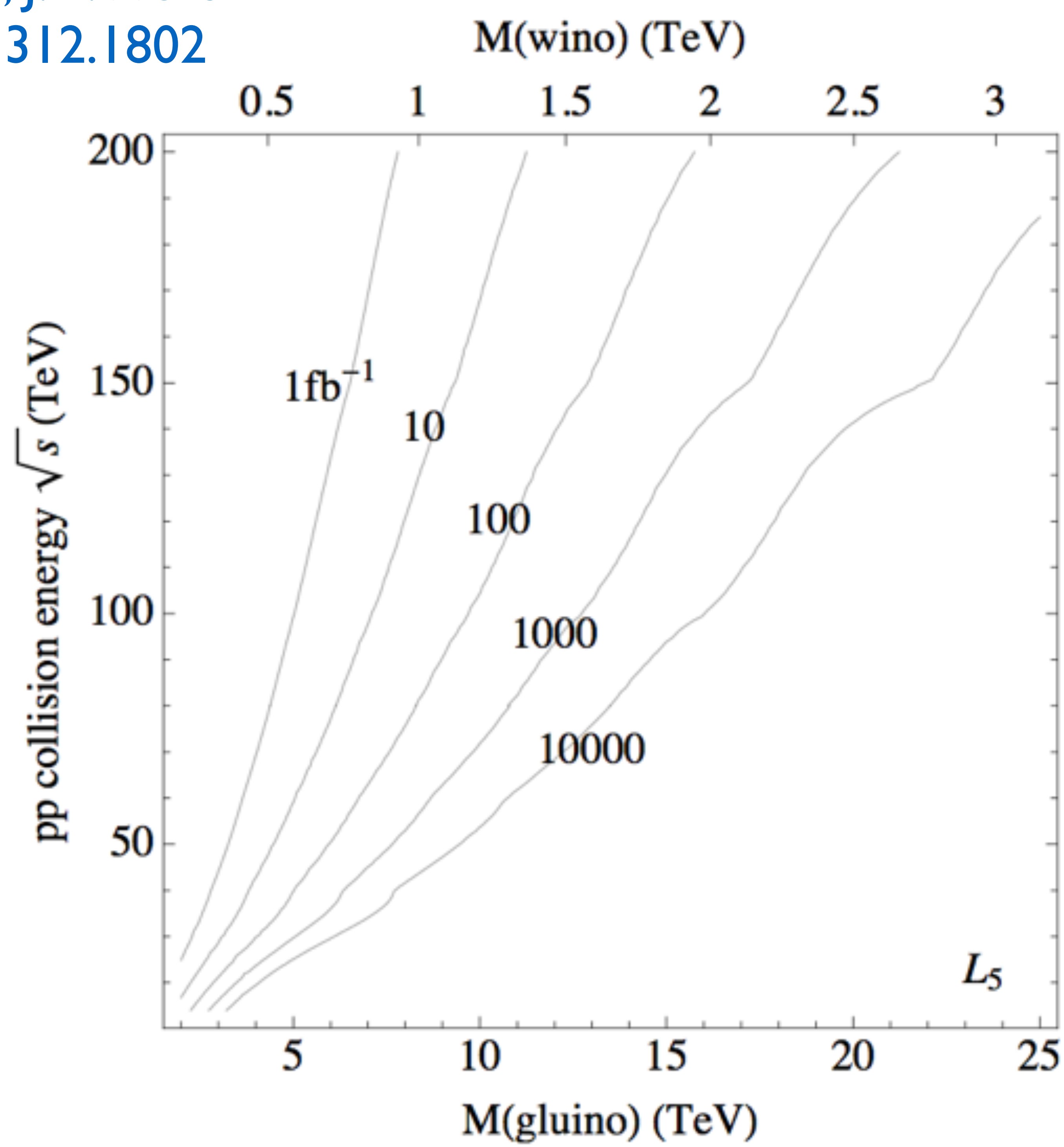


T.Cohen et. al.

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

Wino DM (AMSB)

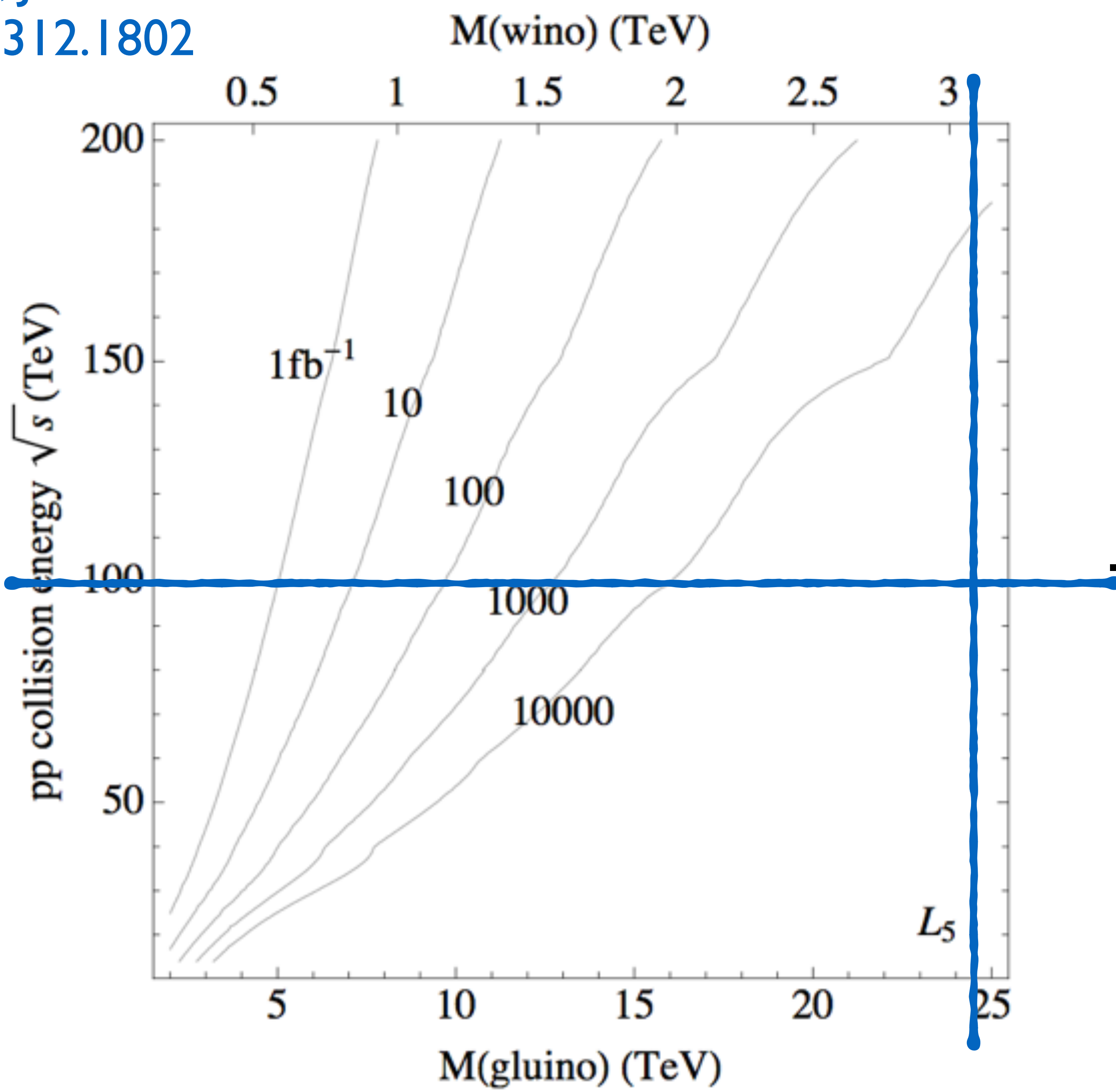
SJ, J.D.Wells
1312.1802



- m(gluino) / m(Wino) ~ 7 (largest hierarchy among Gaugino code makes AMSB most difficult for discovery)

Wino DM (AMSB)

SJ, J.D.Wells
1312.1802

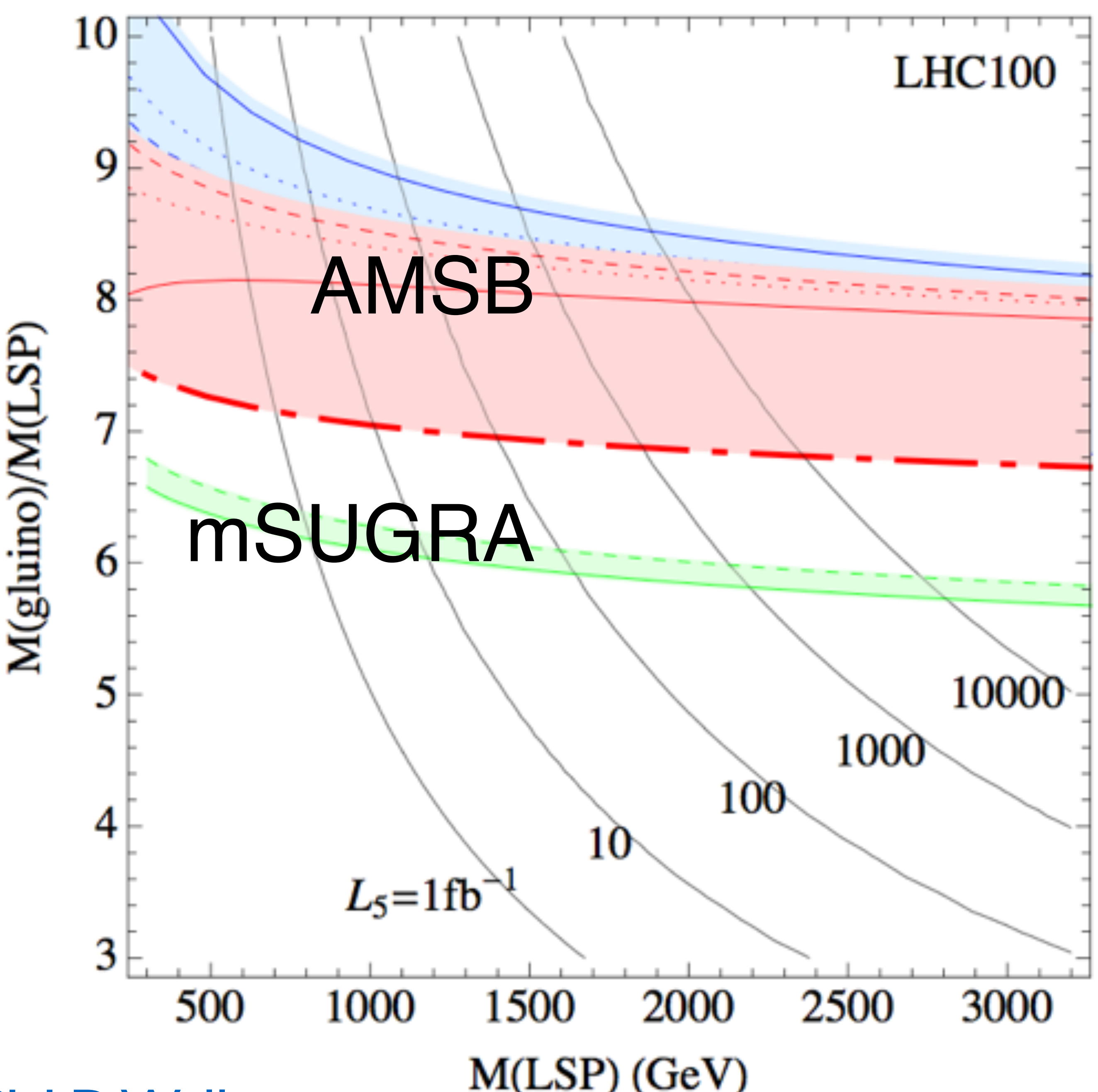


- m(gluino) / m(Wino) ~ 7 (largest hierarchy among Gaugino code makes AMSB most difficult for discovery)

- 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



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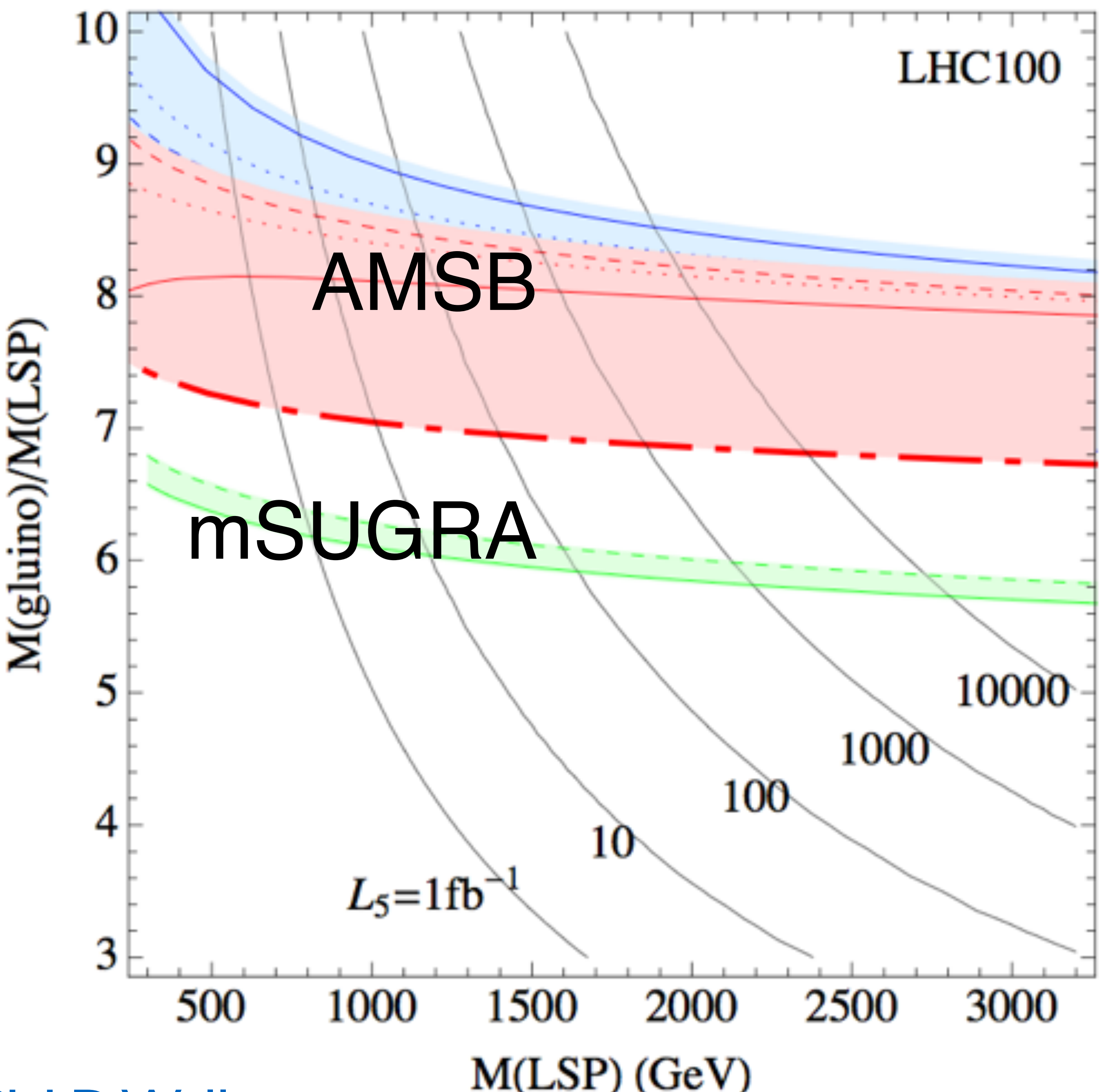
- Reach in the (gaug)ino mass ratio!
  (If gaugino code is such a fundamental observable and crucial for discovery)
- No definitive coverage of Higgsino DM here.

Reach in gaugino code



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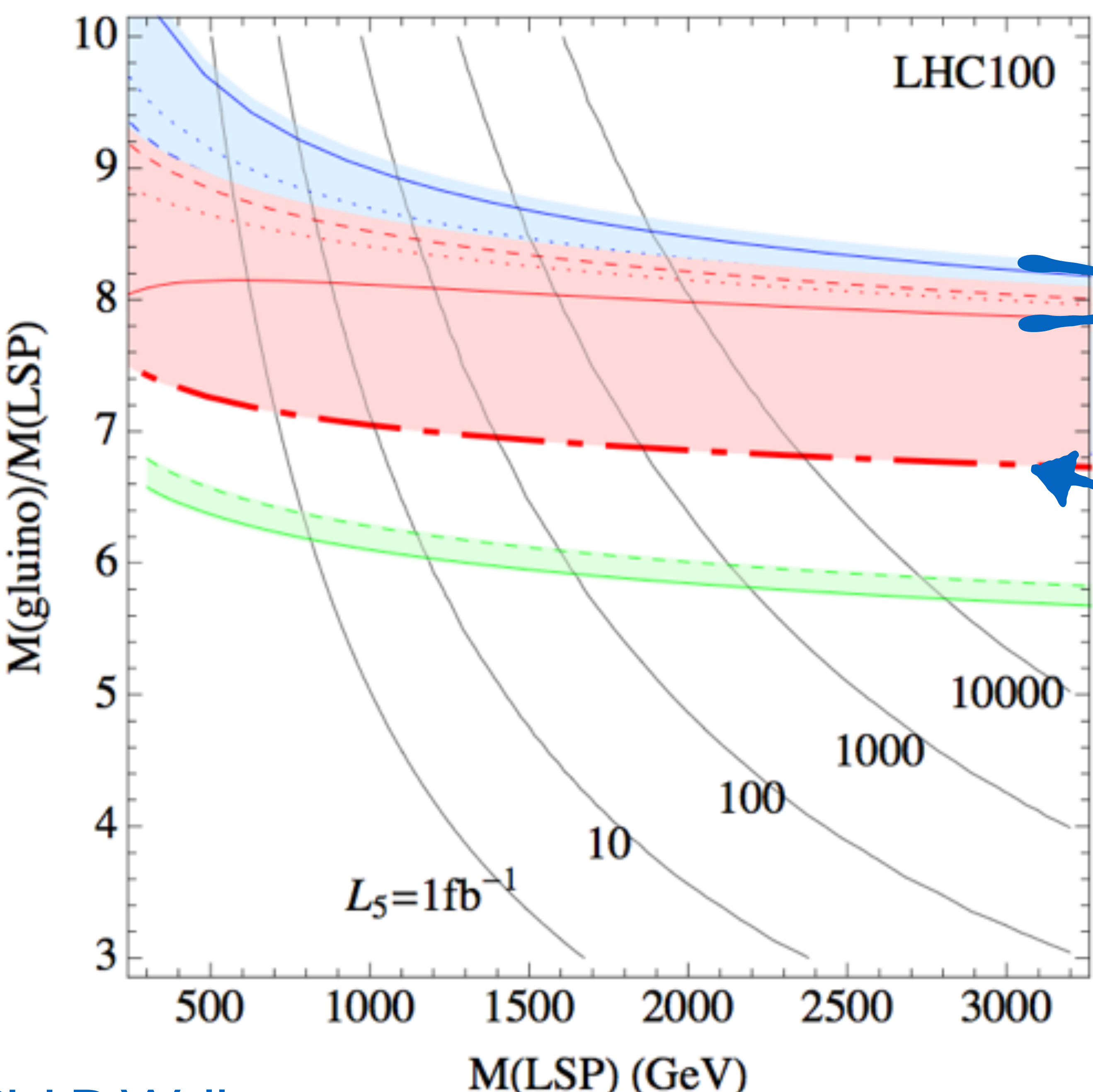
- Reach in the (gaug)ino mass ratio!
  (If gaugino code is such a fundamental observable and crucial for discovery)
- No definitive coverage of Higgsino DM here.

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 — model independent at O(alpha^2) due to gaugino screening theorem and one-loop exact anomaly.

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

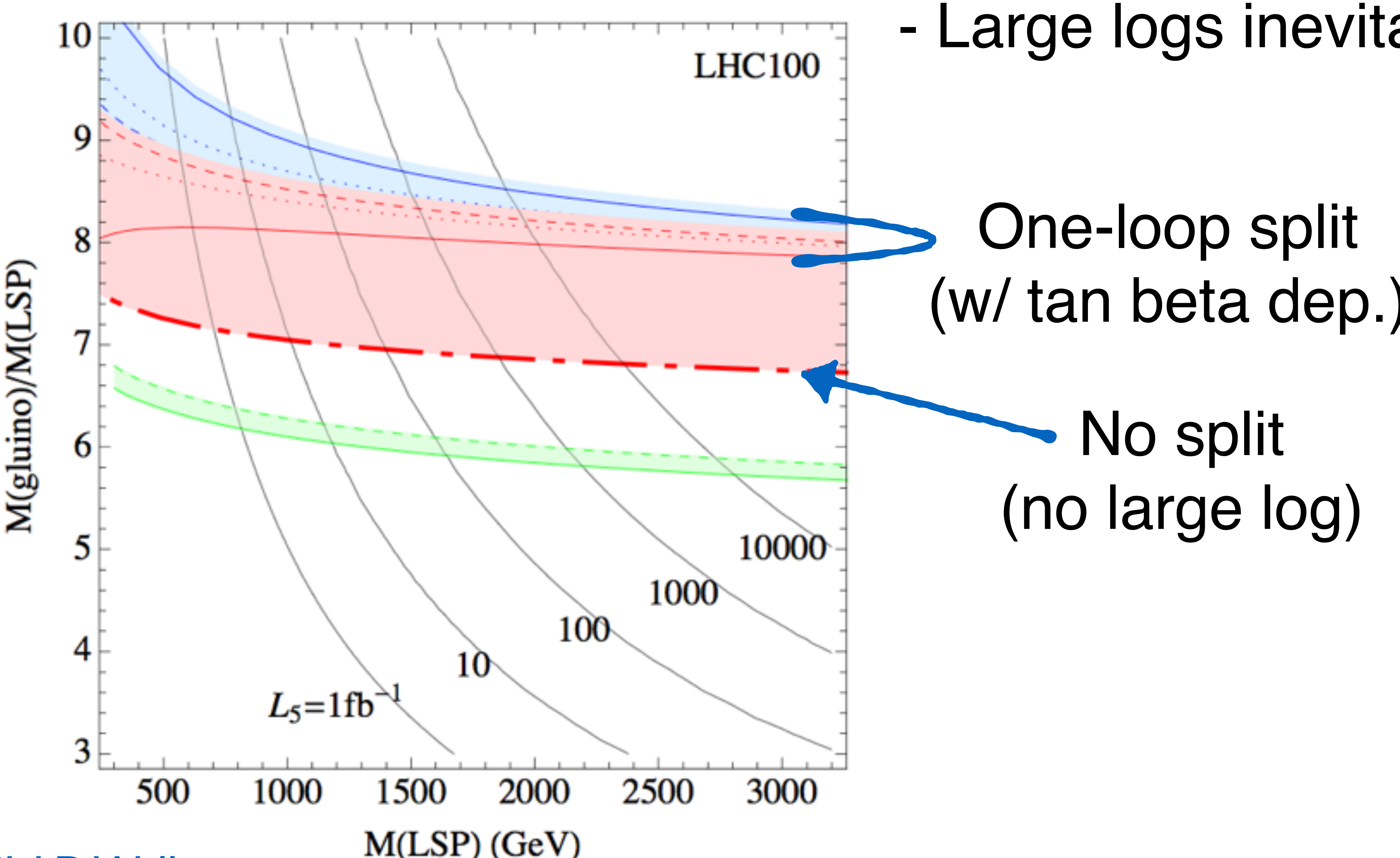
Arkani-Hamed, Giudice, Luty, Rattazzi

- 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.

Resumming the split hierarchy



- Large logs inevitable.

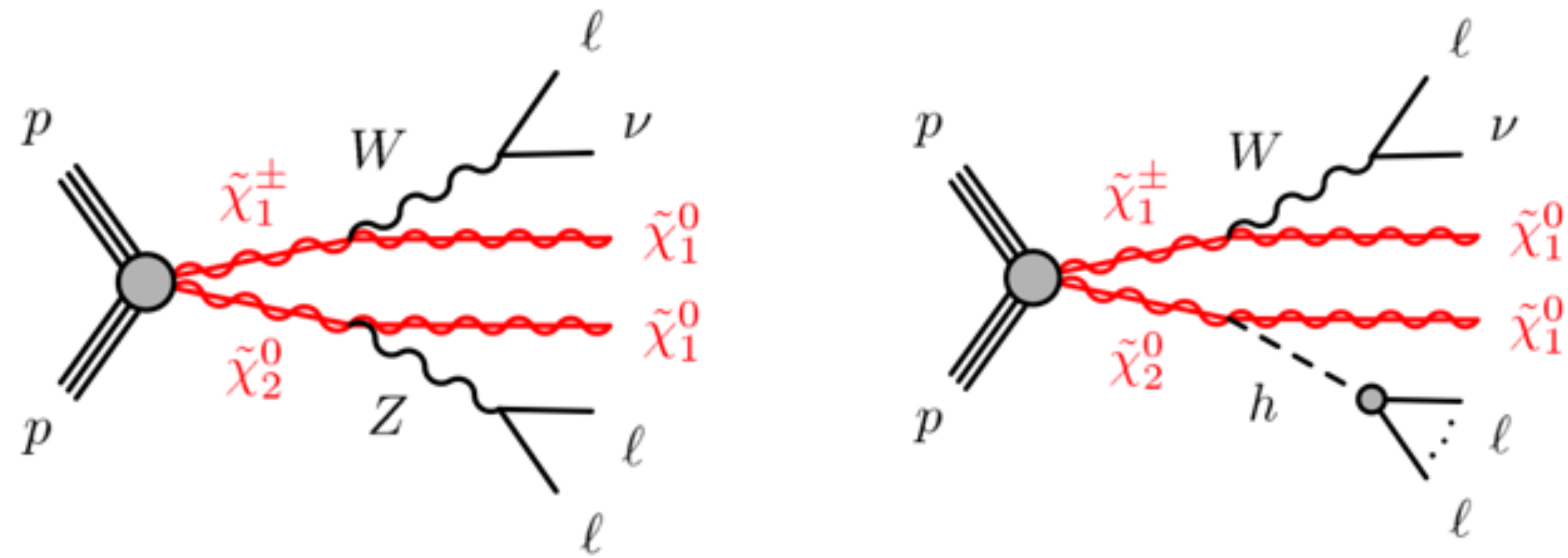
SJ, J.D.Wells
1312.1802

4 TeV Higgsino

2. EWino pair

Higgsino thermal DM,
Higgsino relations from GET,
Inverse Problem

EWino NLSP searches



- EWinos decay always via gauge/Higgs bosons.

- Multileptons are representative signatures.

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

Wino NLSP – Bino LSP

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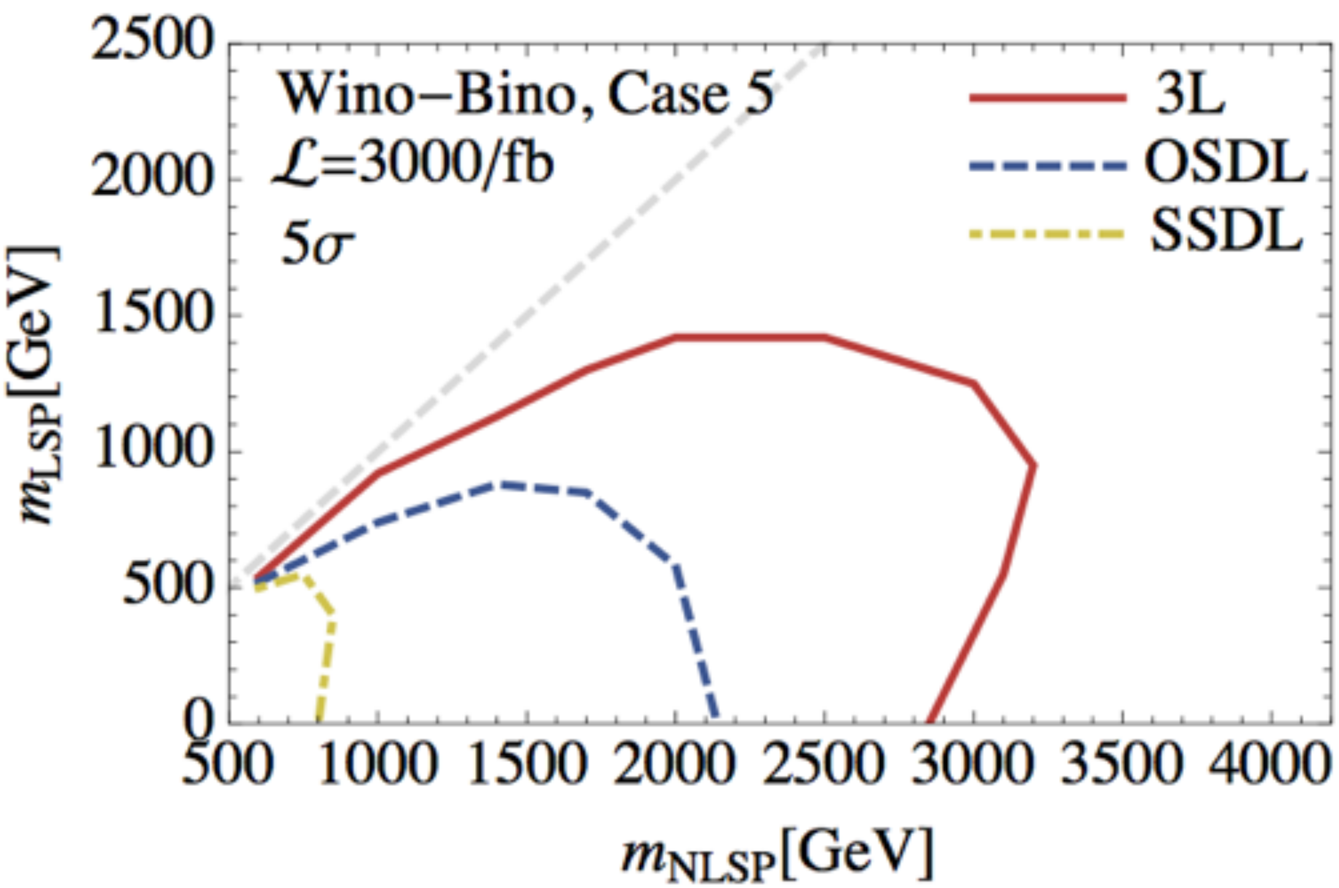
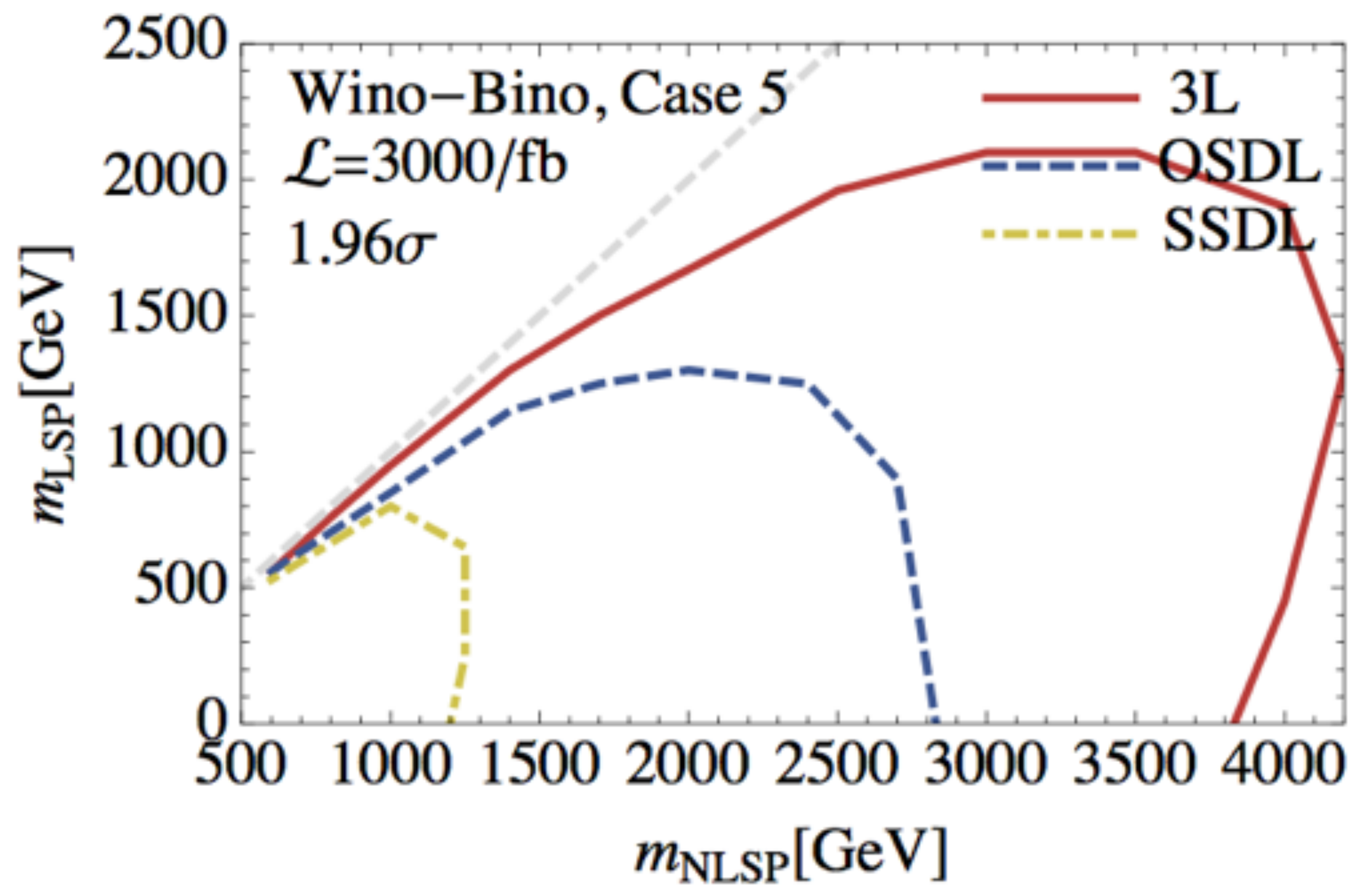
1410.6287





tan beta = 50, mu = +5 TeV > |M2| > 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)	26% X+ to Z X+
2.49797977E-01	2	1000022	24	# BR(~chi_2+ -> ~chi_10 W+)	50% X+ to W X0
2.59870362E-01	2	1000023	24	# BR(~chi_2+ -> ~chi_20 W+)	
2.31701044E-01	2	1000024	25	# BR(~chi_2+ -> ~chi_1+ h)	23% X+ to h X+

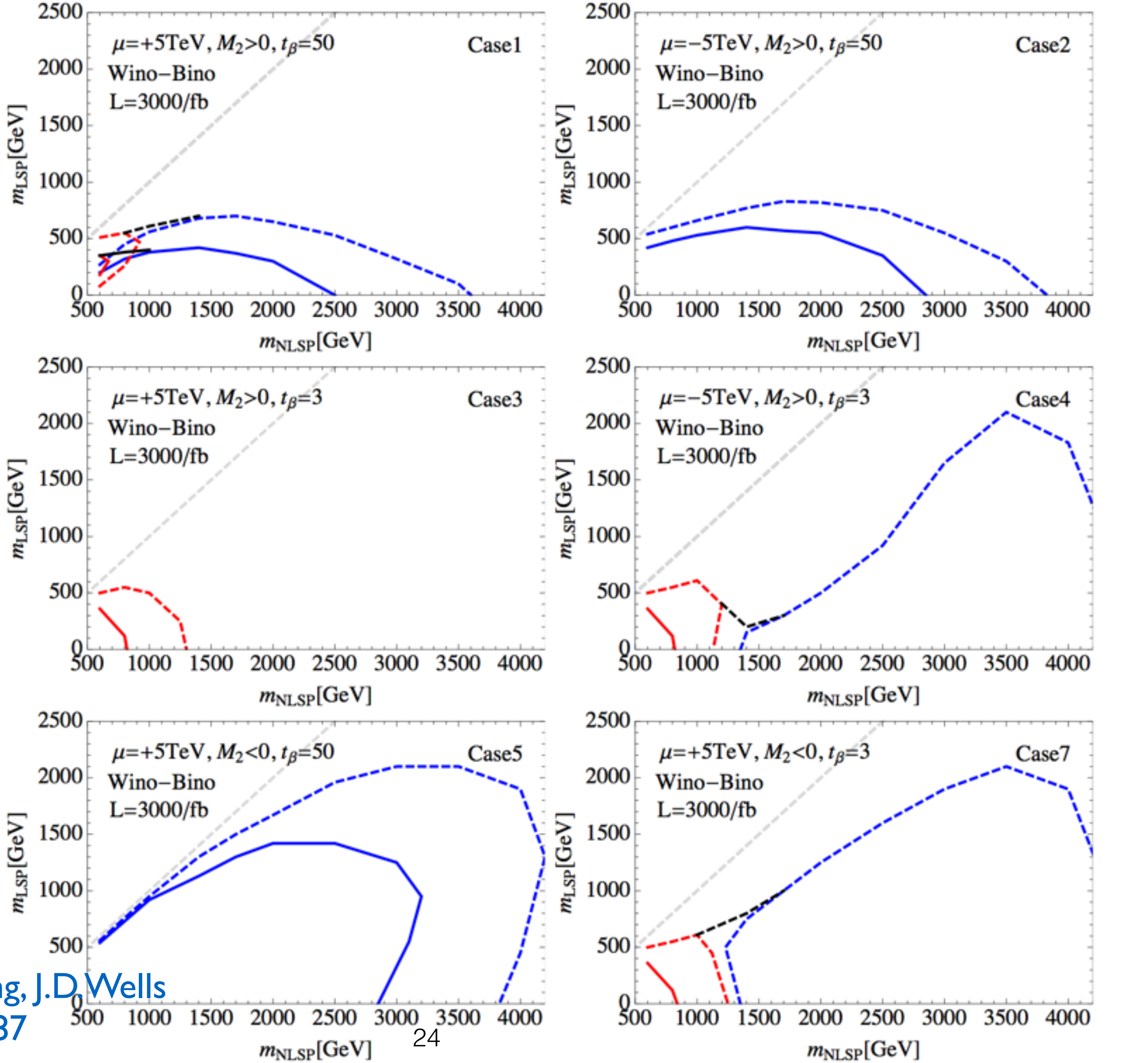
DECAY	1000025	5.33171141E+00	# neutralino3 decays		
# BR	NDA	ID1	ID2		
3.88604156E-02	2	1000022	23	# BR(~chi_30 -> ~chi_10 Z)	25% X0 to Z X0
2.11792763E-01	2	1000023	23	# BR(~chi_30 -> ~chi_20 Z)	
2.68240565E-01	2	1000024	-24	# BR(~chi_30 -> ~chi_1+ W-)	53% X0 to W X+
2.68240565E-01	2	-1000024	24	# BR(~chi_30 -> ~chi_1- W+)	
1.80468356E-01	2	1000022	25	# BR(~chi_30 -> ~chi_10 h)	21% X0 to h X0
3.23973361E-02	2	1000023	25	# BR(~chi_30 -> ~chi_20 h)	

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

8/3/14 US-ATLAS Physics Workshop 2014 51

The slide from ATLAS speaker Frank Wurthwein's talk

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



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1410.6287

Blue:
WZ -> 3lep
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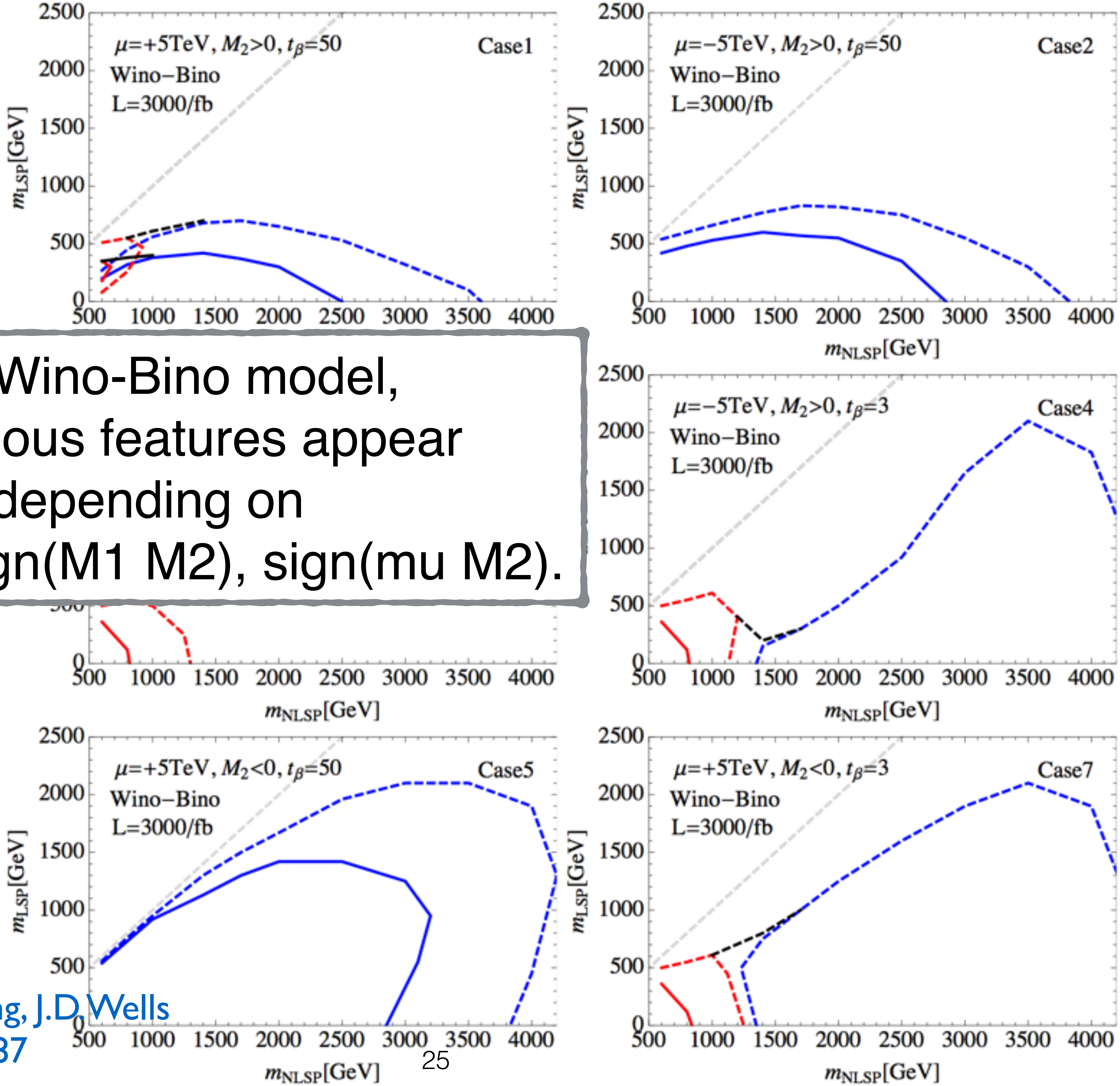

Still Wino-Bino model,
but various features appear
depending on
tan beta, sign(M1 M2), sign(mu M2).

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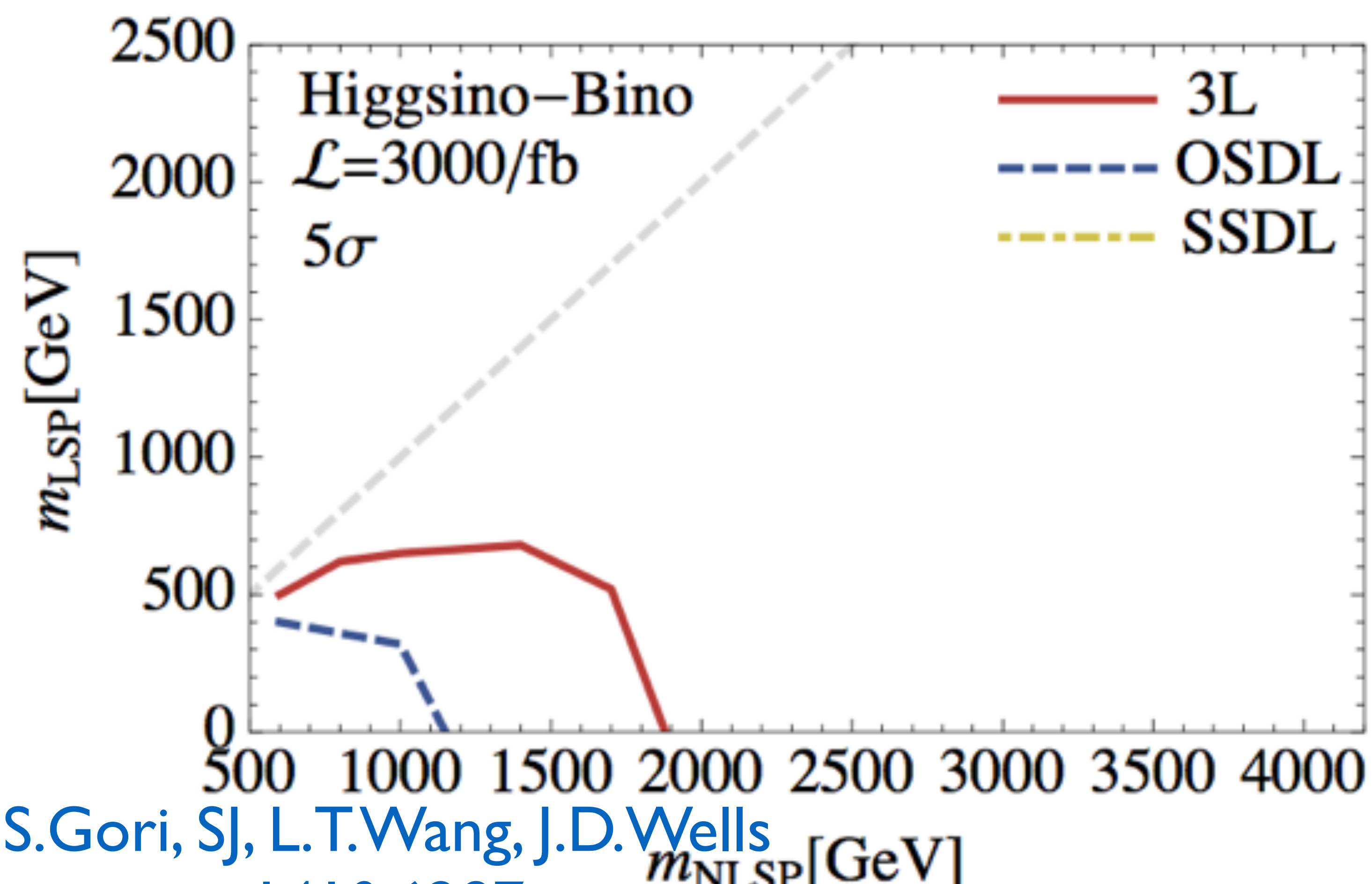
1410.6287

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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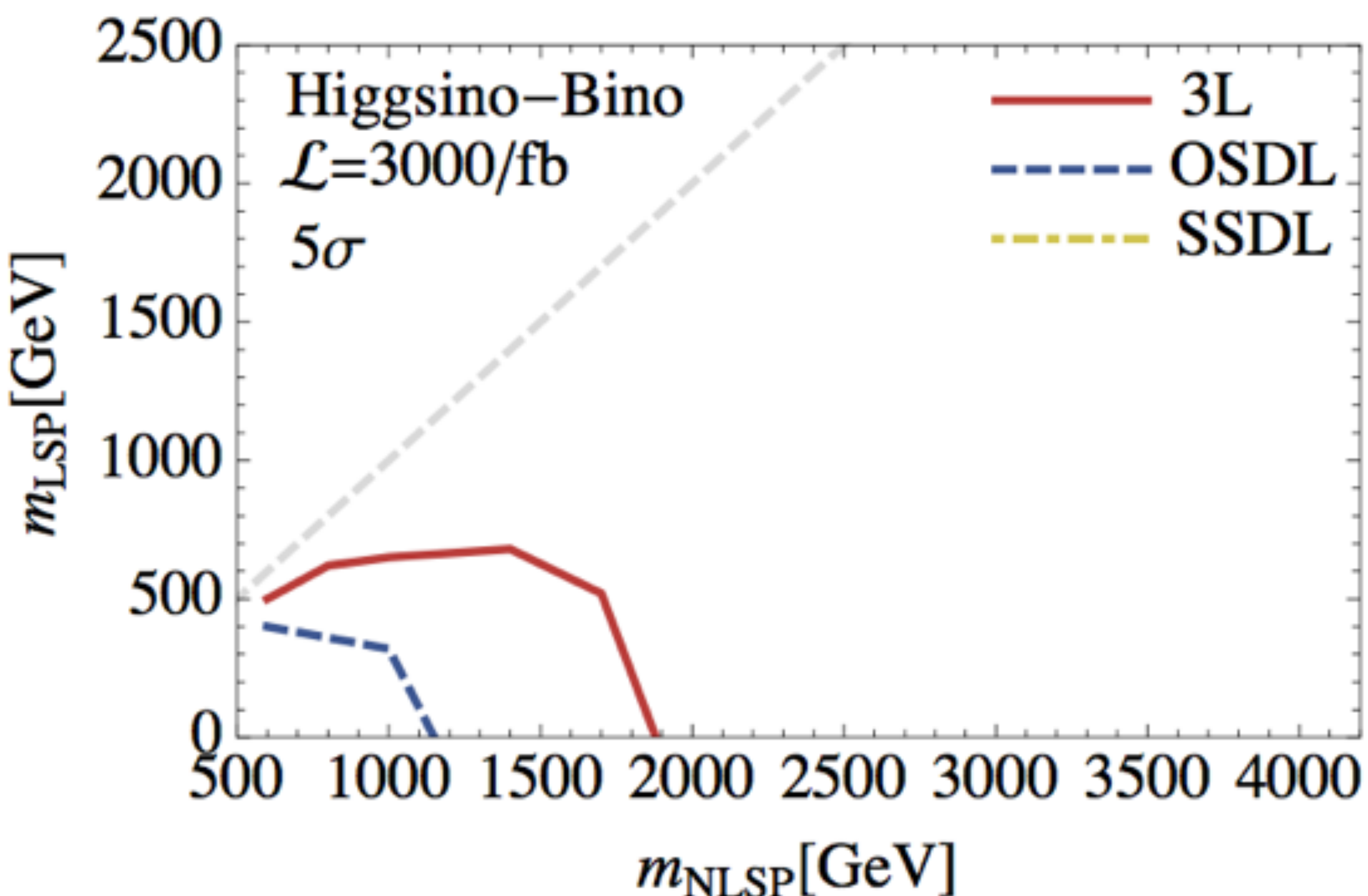


- Just one plot is all.

- 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
EJ.Chun, SJ, P.Sharma

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

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
EJ.Chun, SJ, P.Sharma

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

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

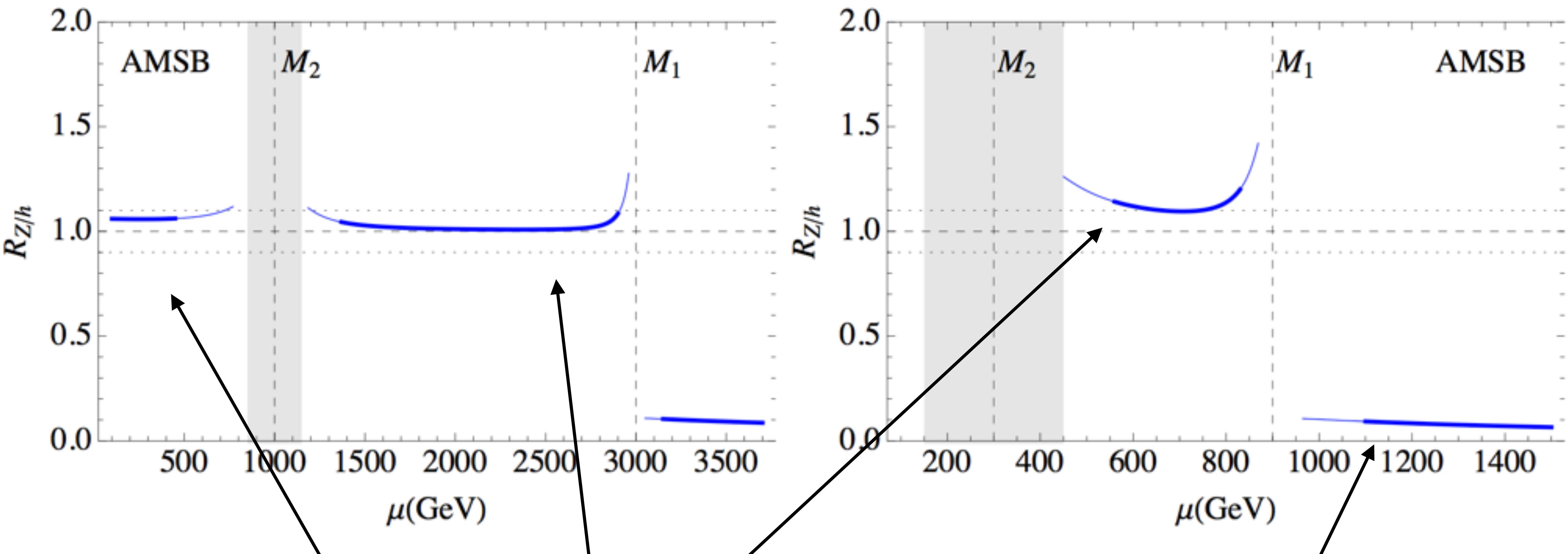
$$H_{vev} = v + h^0 + iZ$$
$$H_\perp = 0 + H^0 + iA^0$$

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.

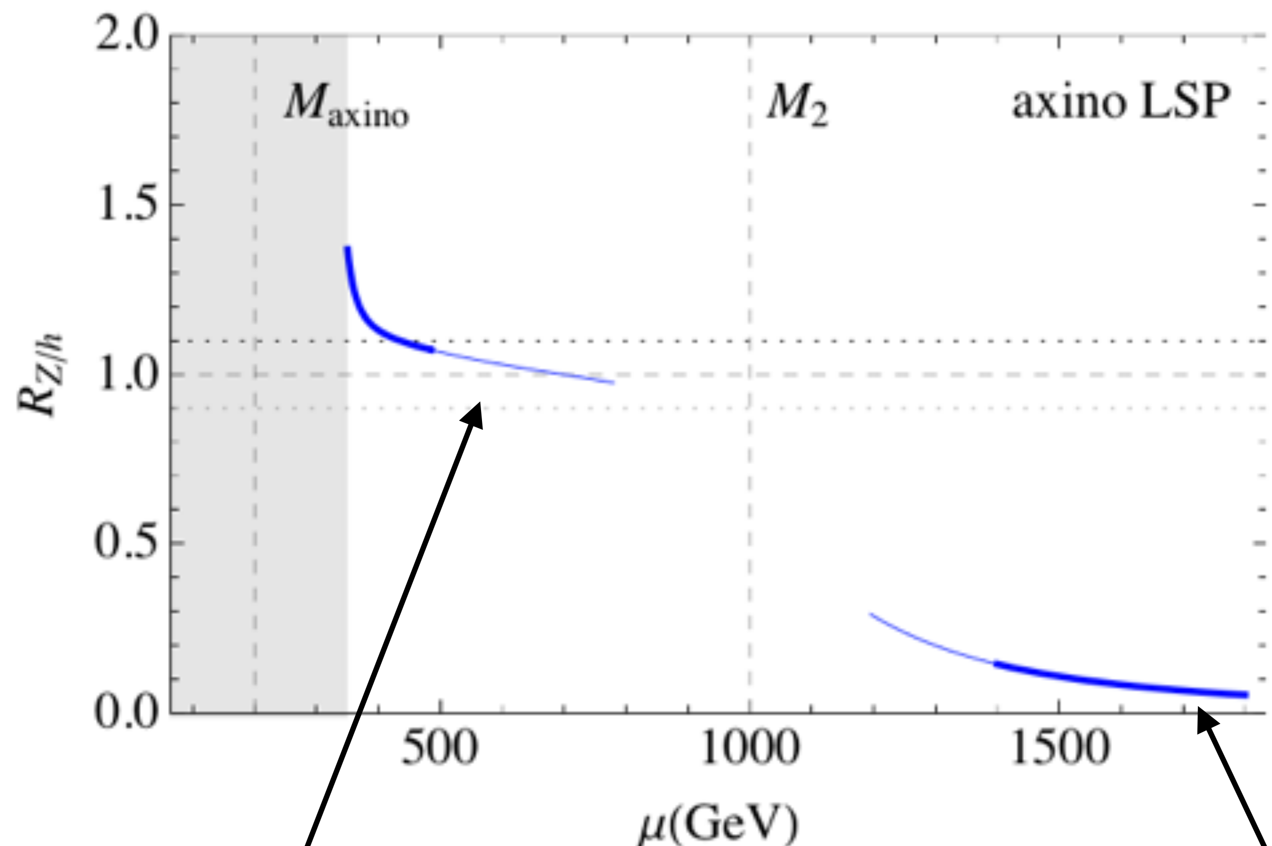
Heavier Higgsinos

Numerical demonstration

SJ, 1404.2691

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

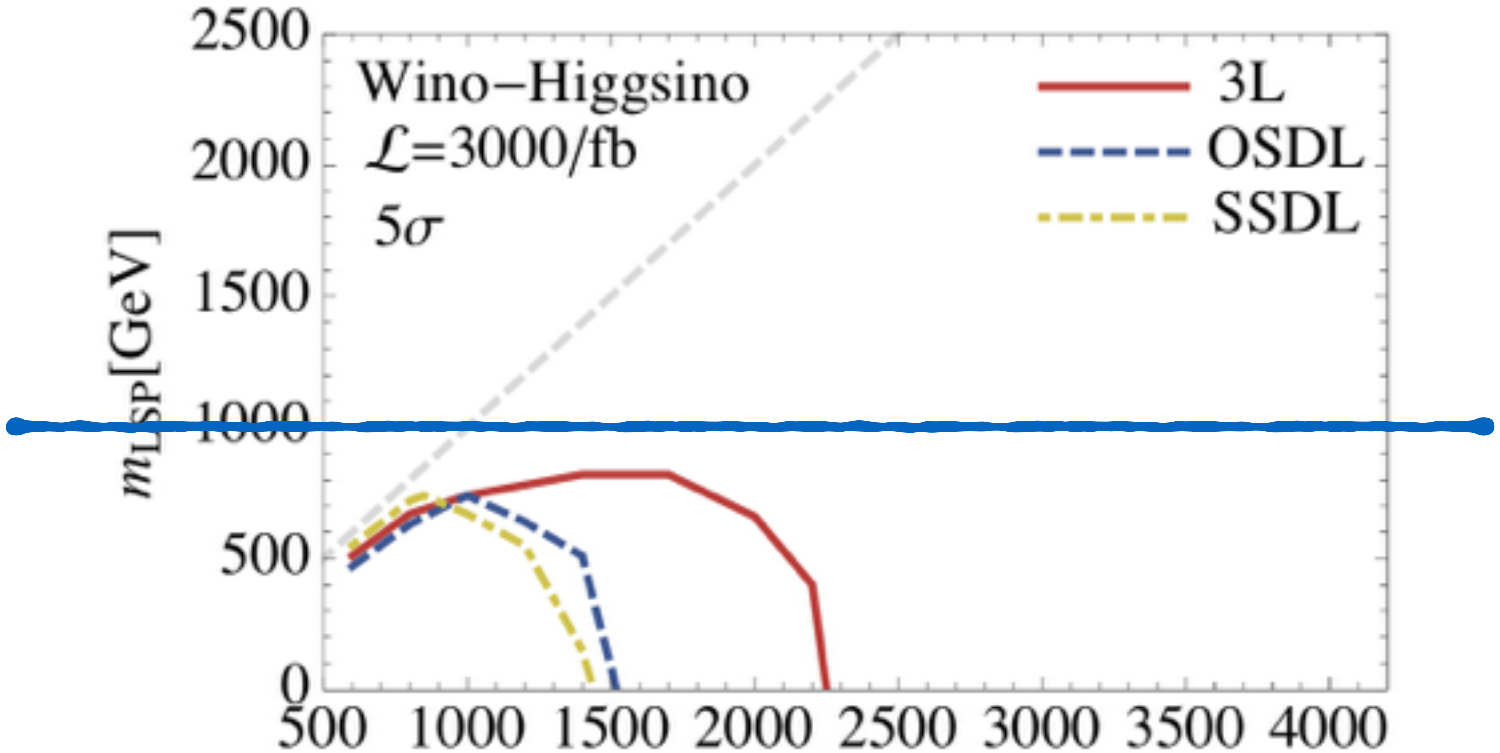
Even true with axinos or gravitinos



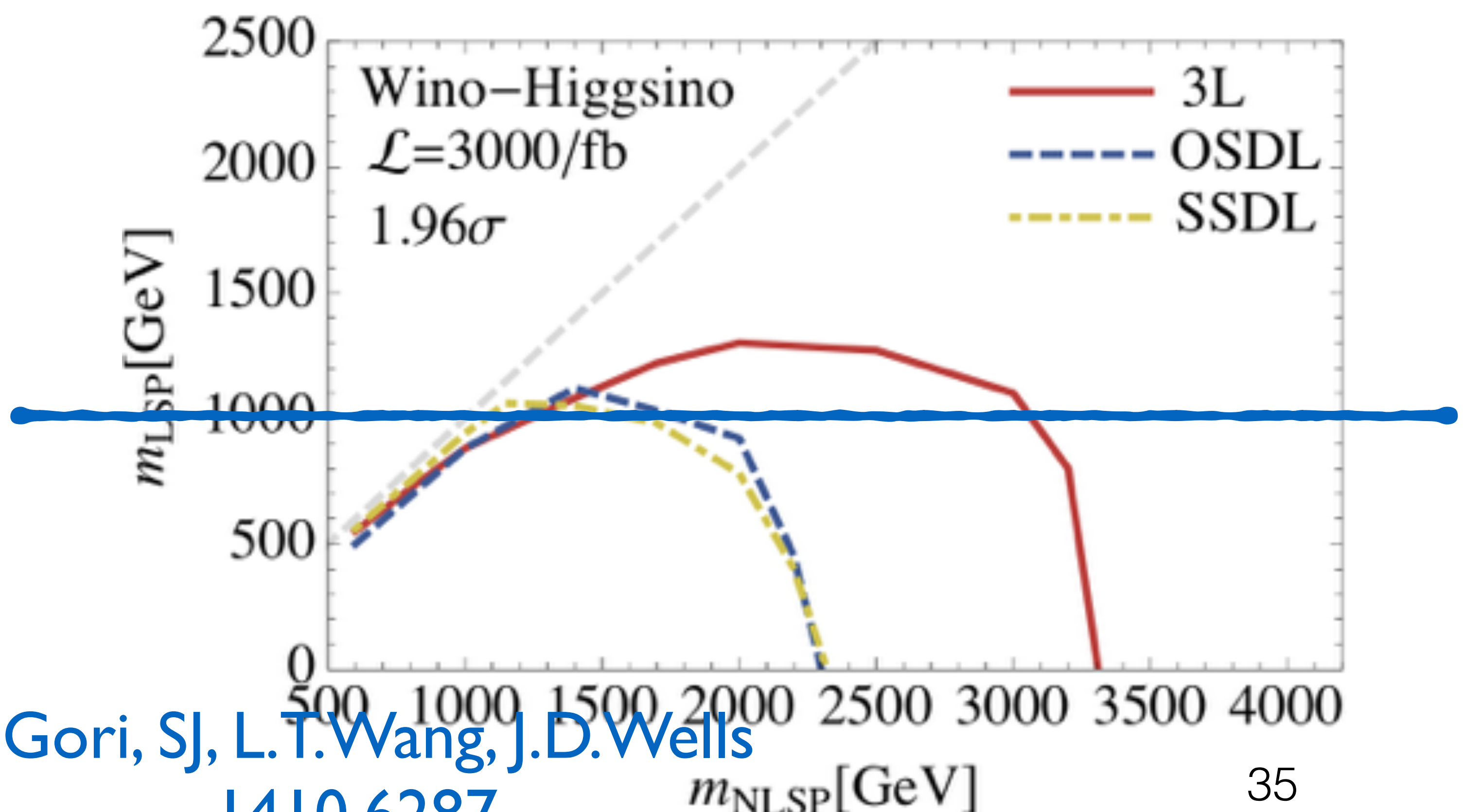
Higgsinos are LSPs or NLSPs.

Heavier Higgsinos

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.

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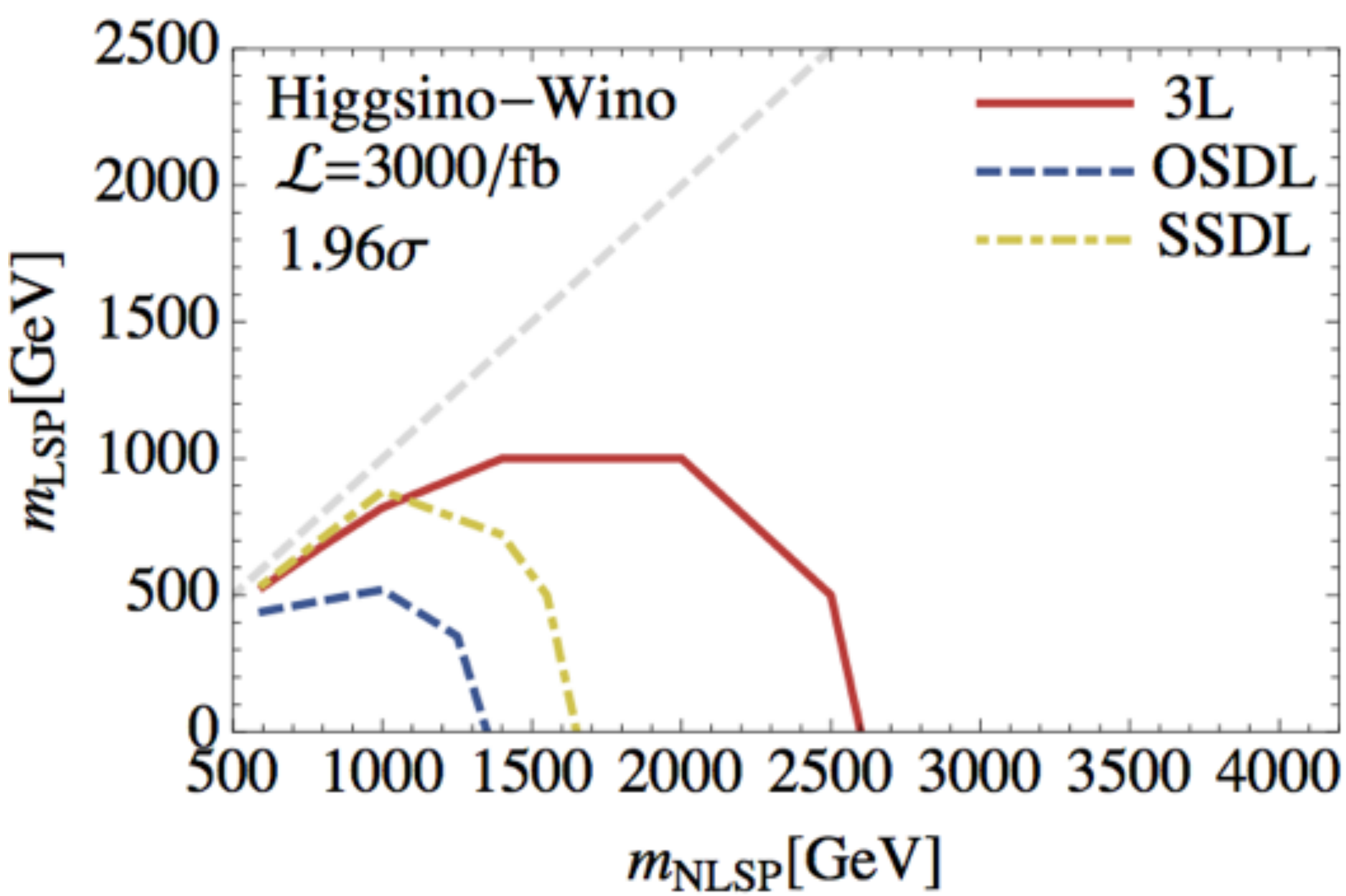
1410.6287

not optimal for Wino DM

3.1 TeV Wino LSP is way up here.



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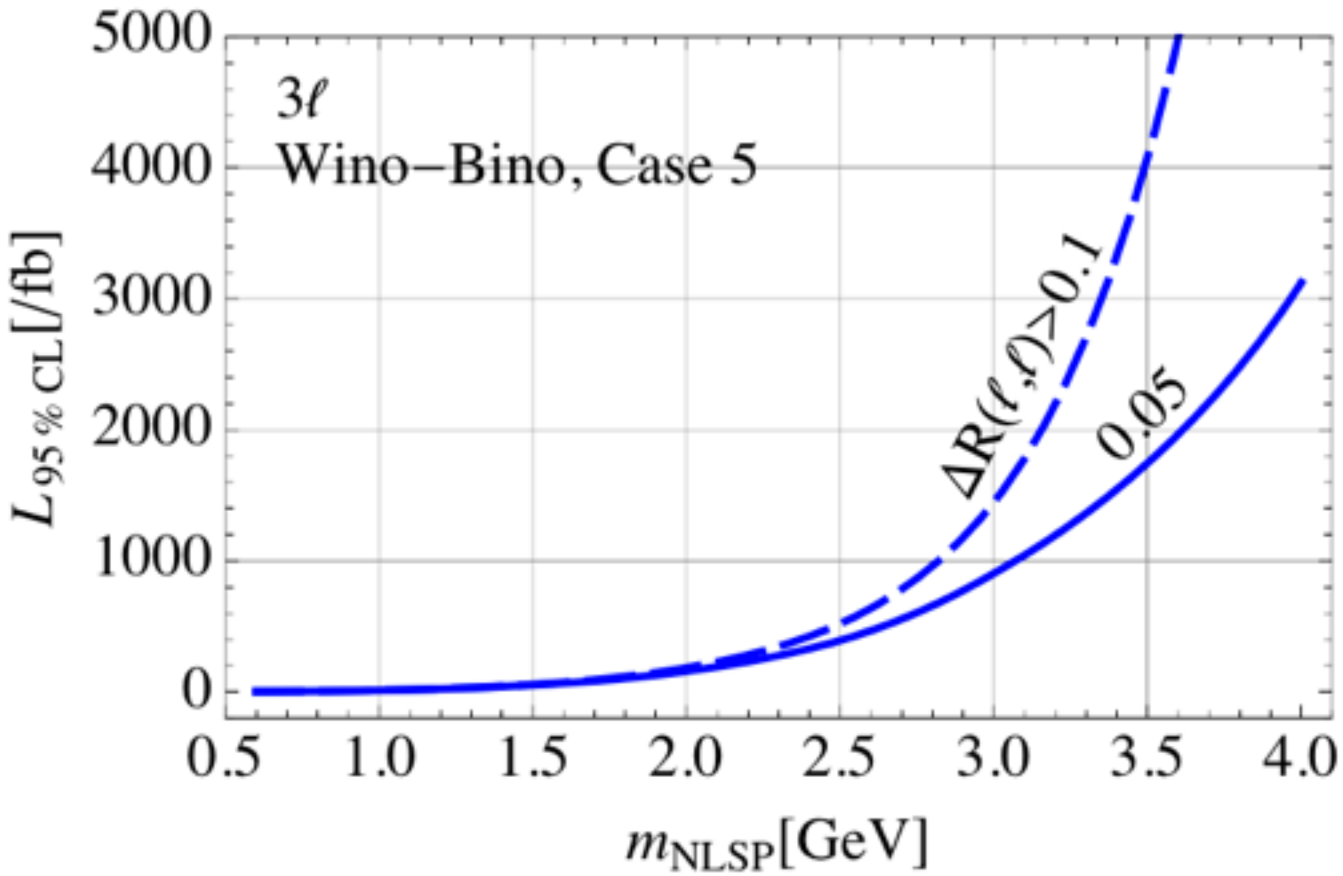
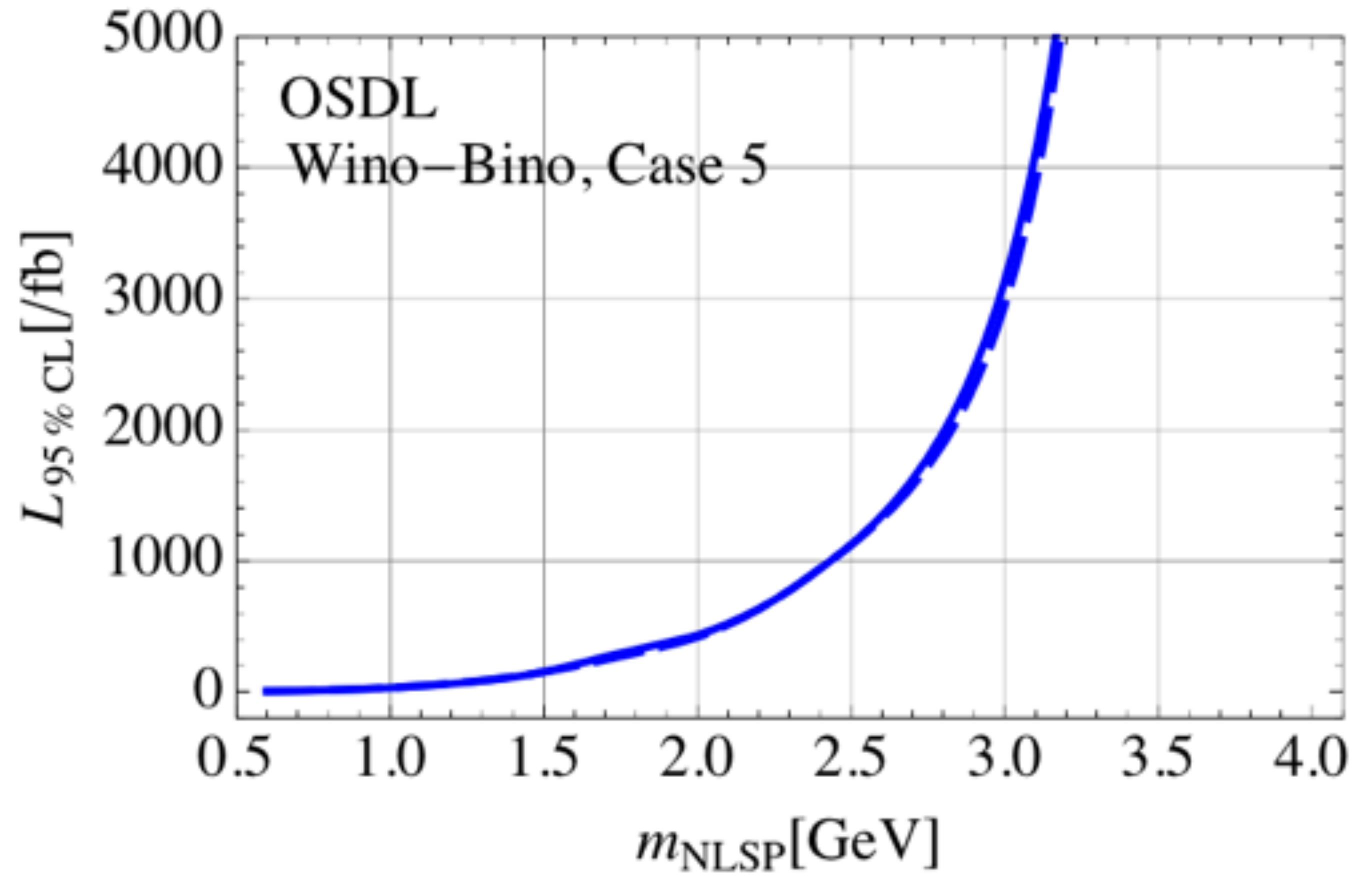
1410.6287

- EWino NLSP pair is not optimal for Wino LSP

Lepton collimation





- Boosted physics is more relevant at future collider.

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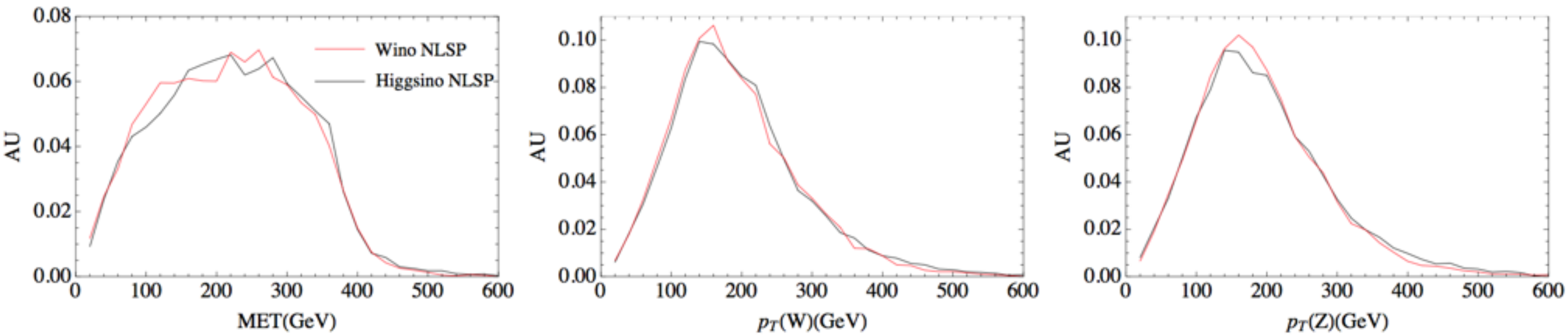
1410.6287

Inverse Problem

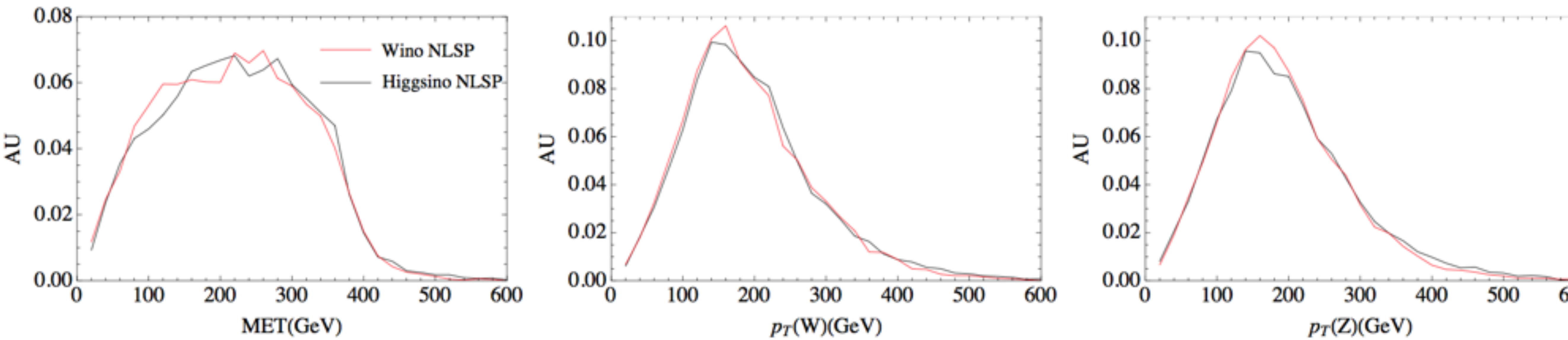
SJ, 1404.2691



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

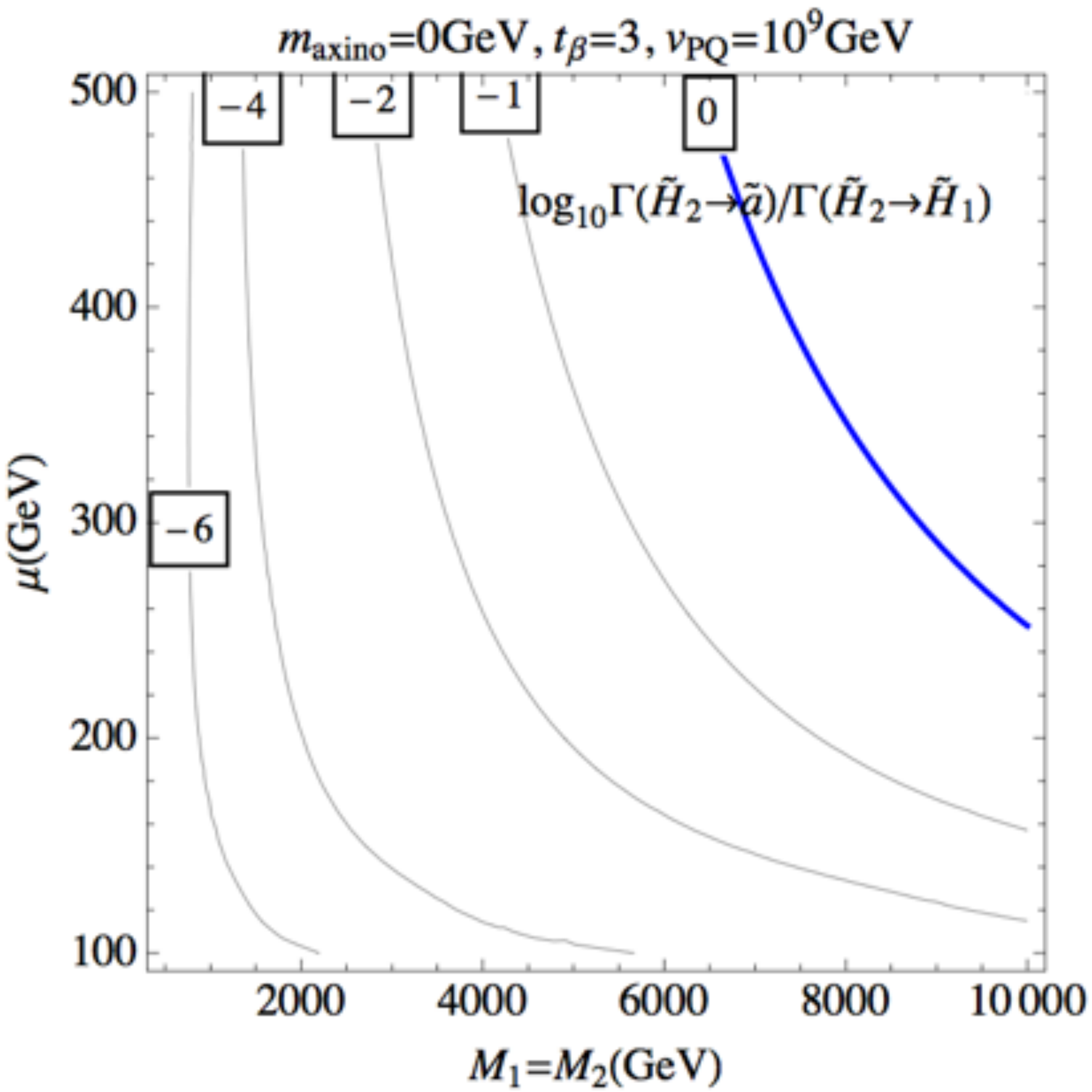


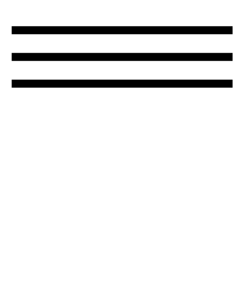
Model	parameters (M_1, M_2, μ, t_β)	$\sigma(W^+W^-)$	$\sigma(W^\pm Z)$	$\sigma(ZZ)$
Wino-NLSP	0.5 TeV, 1.0 TeV, −2.0 TeV, 4.3	0.60 fb	1.1 fb	0 fb
Higgsino-NLSP	0.2 TeV, 2.0 TeV, 0.8 TeV, 2.0	0.61 fb	1.1 fb	0.02 fb

- 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.

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.

Summary of future SUSY

- Results can be usefully presented for ino mass ratios. The resummation of scale hierarchy still leaves 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.