Perspectives on Future Supersymmetry at Colliders

Sunghoon Jung
Korea Institute for Advanced Study (KIAS)

High1 Joint Winter Conference

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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What my talk is about

1. Future collider prospects

2. Future SUSY, new features

3. Future standard searches of SUSY

1. Future collider

- Standard search prospects of a 100 TeV pp collider
- Is it good enough?
  How "well" can we do?
  How well do we "need" to do?
- Is it simply a scaled-up version of previous studies?
- I will address them in the Future SUSY framework focusing on the Wino/Higgsino thermal DM.

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My talk is also about

1. Future collider prospects
2. Future SUSY, new features
3. Future standard searches of SUSY

2. Future SUSY

- We focus on lightest superparticles: gauginos and higgsinos of a few 100-1000 GeV.
- A half of universe generically have lightest inos.
- Important mass scales: ~1 TeV Higgsino DM, ~3 TeV Wino DM.
- In general, gauginos and higgsinos are likely well-separated in mass and highly pure states… =>

Generic new features

- Pure gauginos and higgsinos.
  => Dirac Higgsino vs. Majorana gaugino. Gaugino code becomes a primary observable.

- Well-separated in mass.
  => Decays between them governed by Goldstone Equivalence Theorem (GET). New simplifying relations.

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

My talk is lastly about

1. Future collider prospects
2. Future SUSY, new features
3. Future standard searches of SUSY

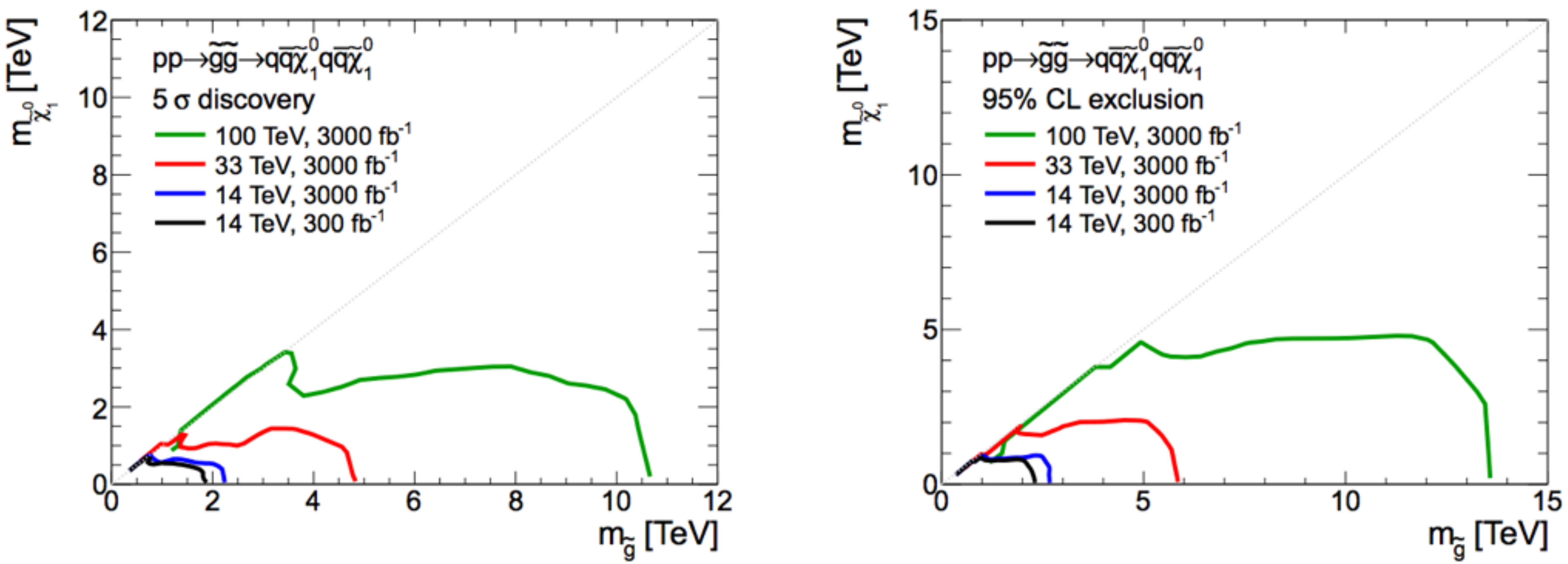
3. Future new searches

- Not yet standard, but very useful SUSY searches.
- Displaced decays
  - show up quite often.
- Resonance searches (not covered today)
  - filling inevitable gaps of current collider searches

1. Gluino pair

Wino thermal DM,
Gaugino code,
Resummation

Searches of guino pairs



T.Cohen et. al.

- Traditional Meff is good enough.

Searches of guino pairs

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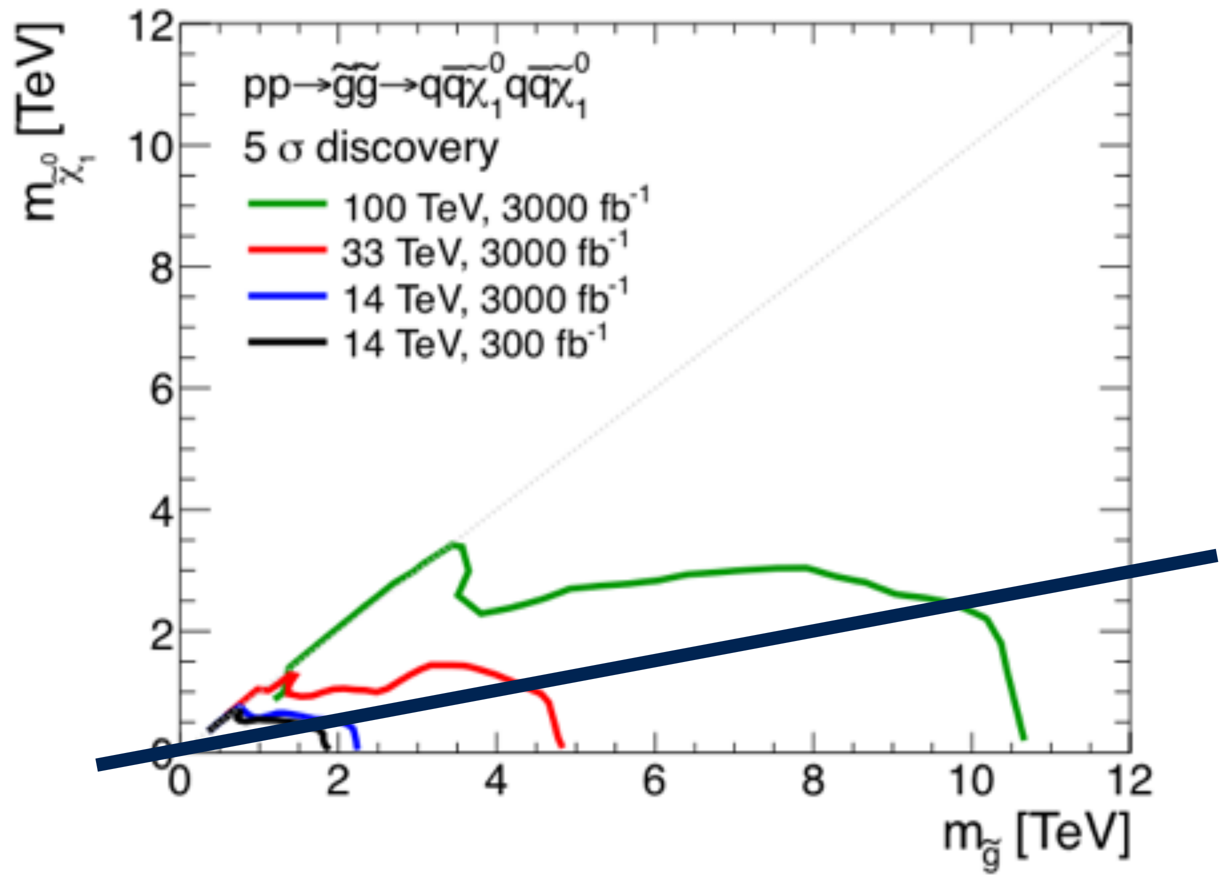
- Only the gluino mass matters when well split.



Wino DM (AMSB)

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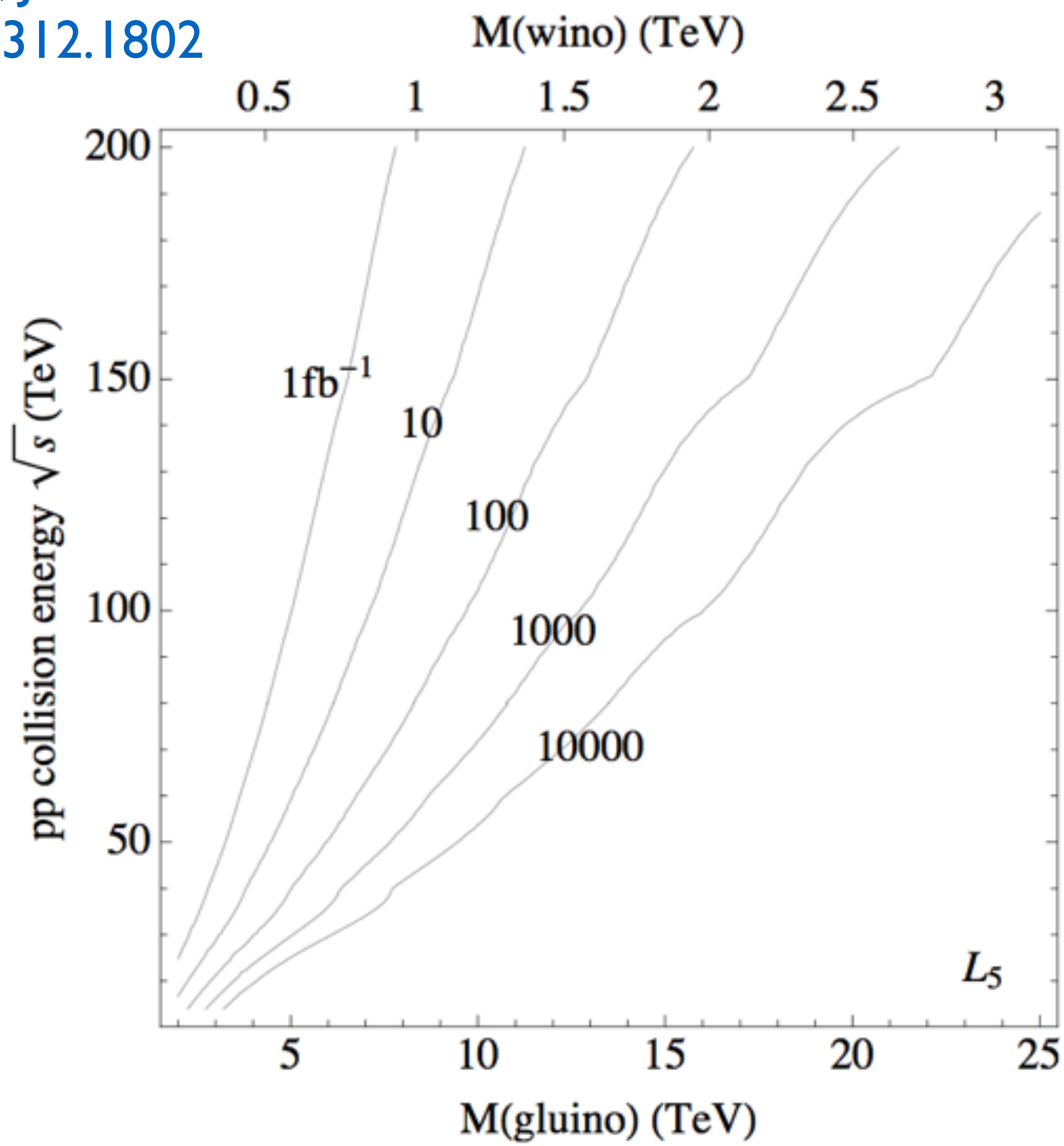

- m(gluino) / m(Wino) ~ 8 (largest hierarchy among Gaugino code)

Wino DM (AMSB)

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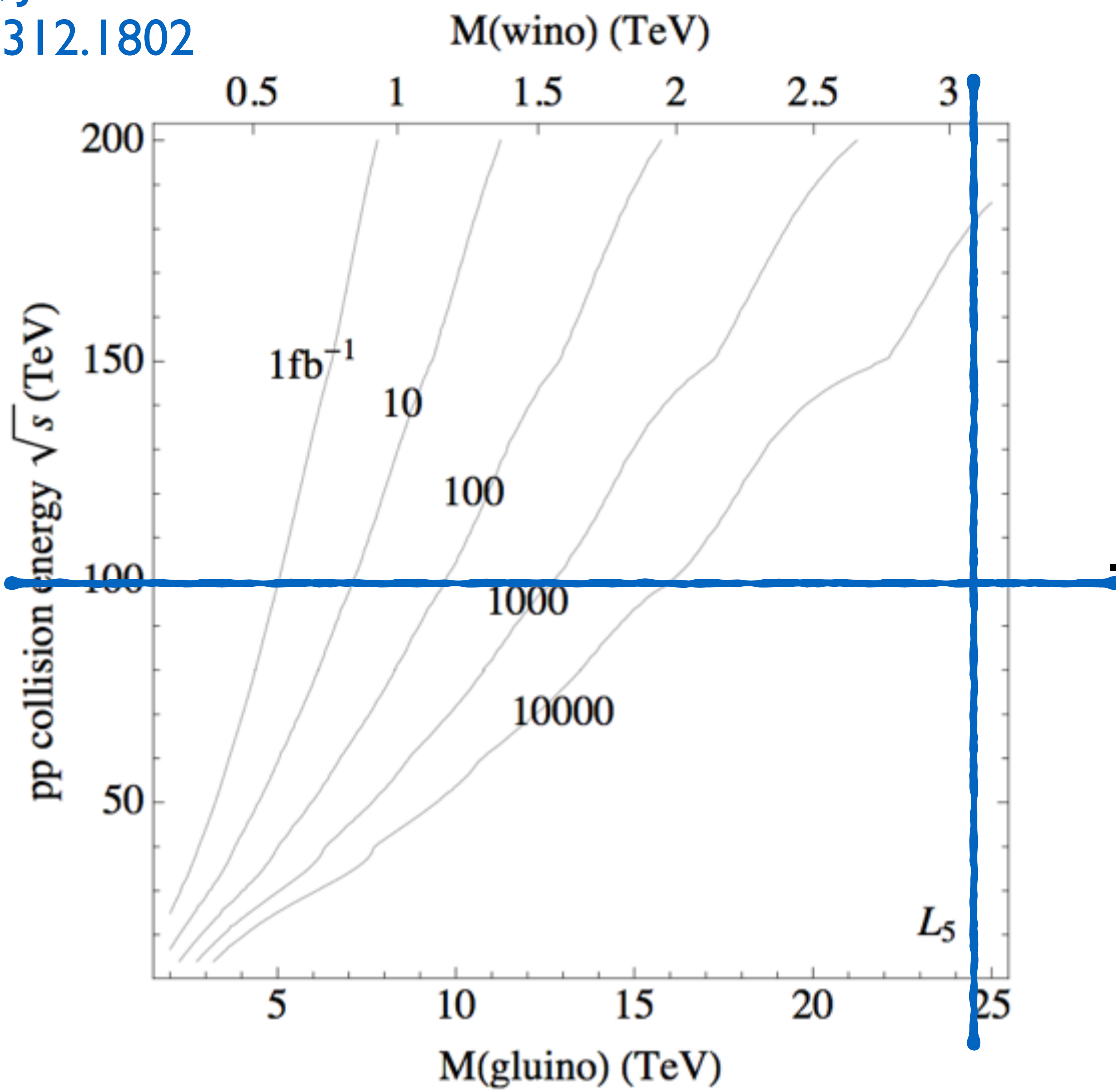
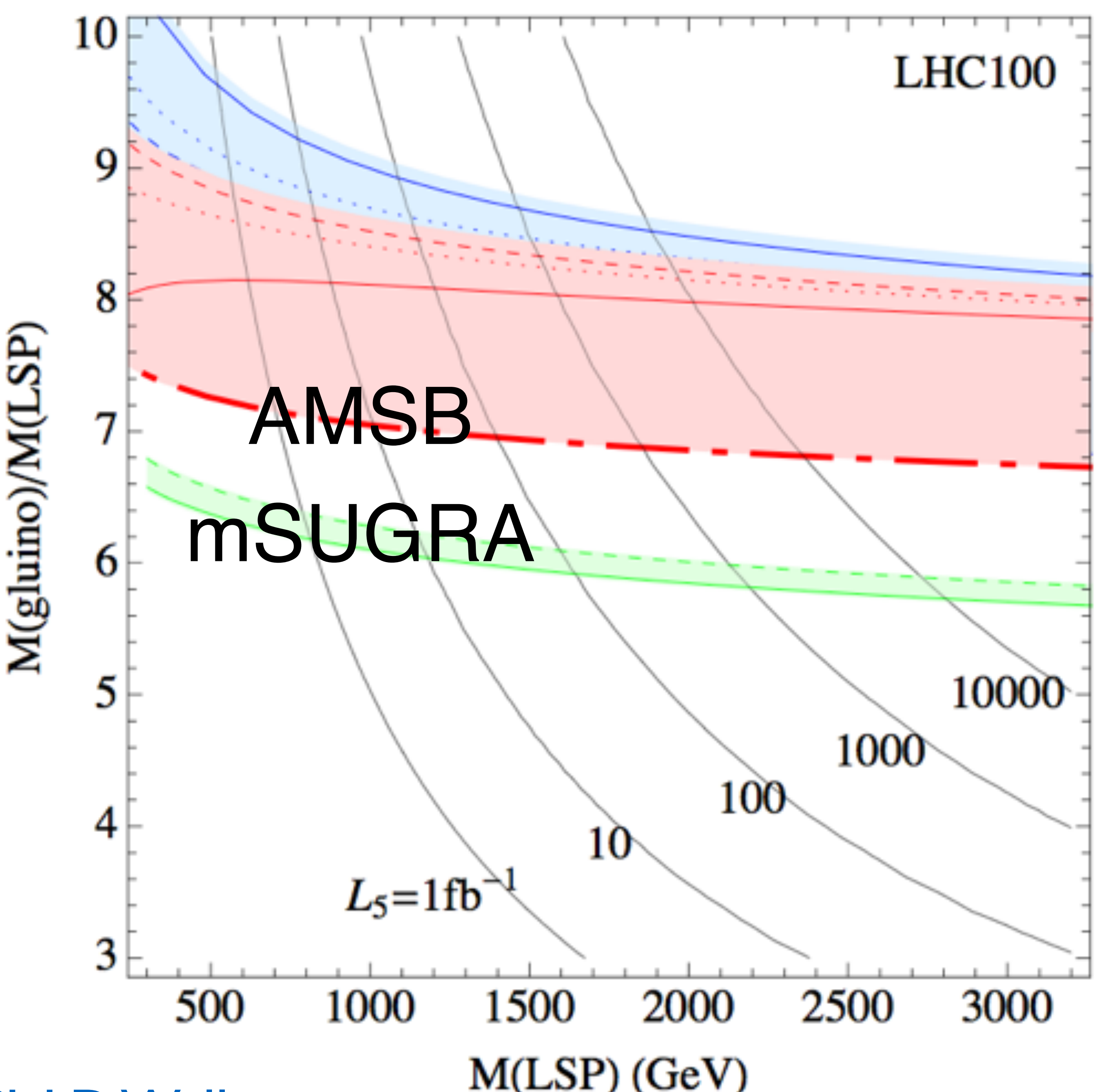


- m(gluino) / m(Wino) ~ 8 (largest hierarchy among Gaugino code)

- 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



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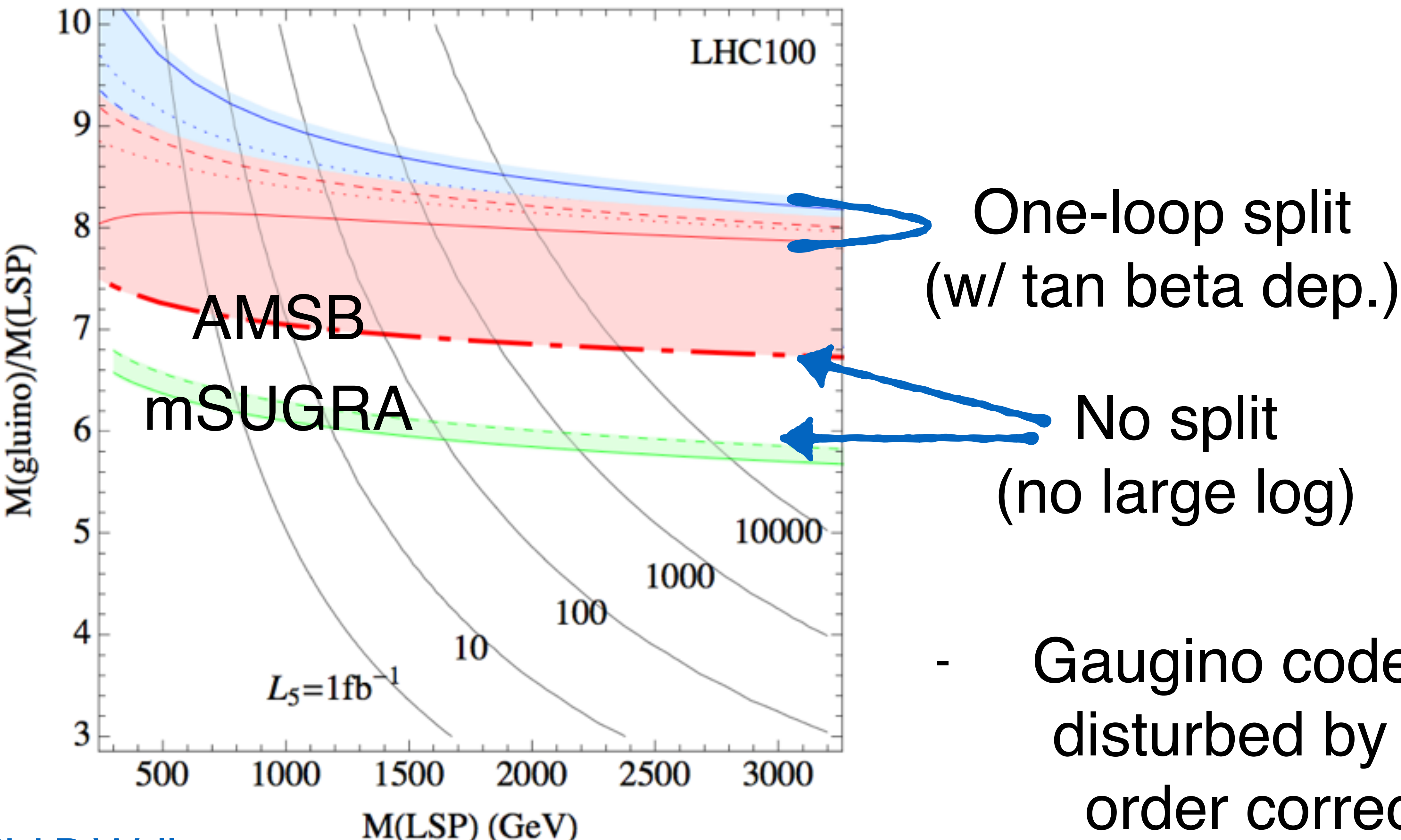
- If gaugino code is such a useful observable…

  this plot must be a very useful one.

Reach in gaugino code



- Gaugino code can be disturbed by higher-order corrections.

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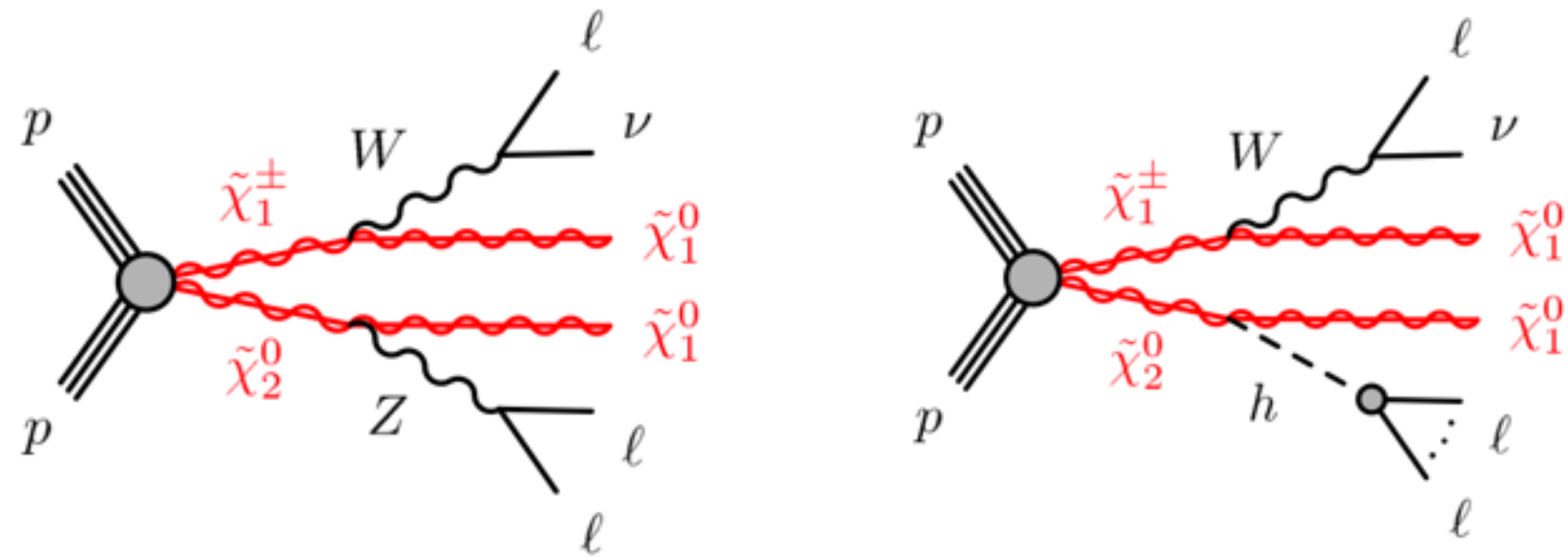
2. EWino NLSP pair

Higgsino thermal DM,
Higgsino relations from GET

EWino NLSP searches



- EWinos decay always via gauge/Higgs bosons.

- They are inherently related by Goldstone Eq Thm.

- Multilepton + MET are representative signatures.

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Wino NLSP - Bino LSP

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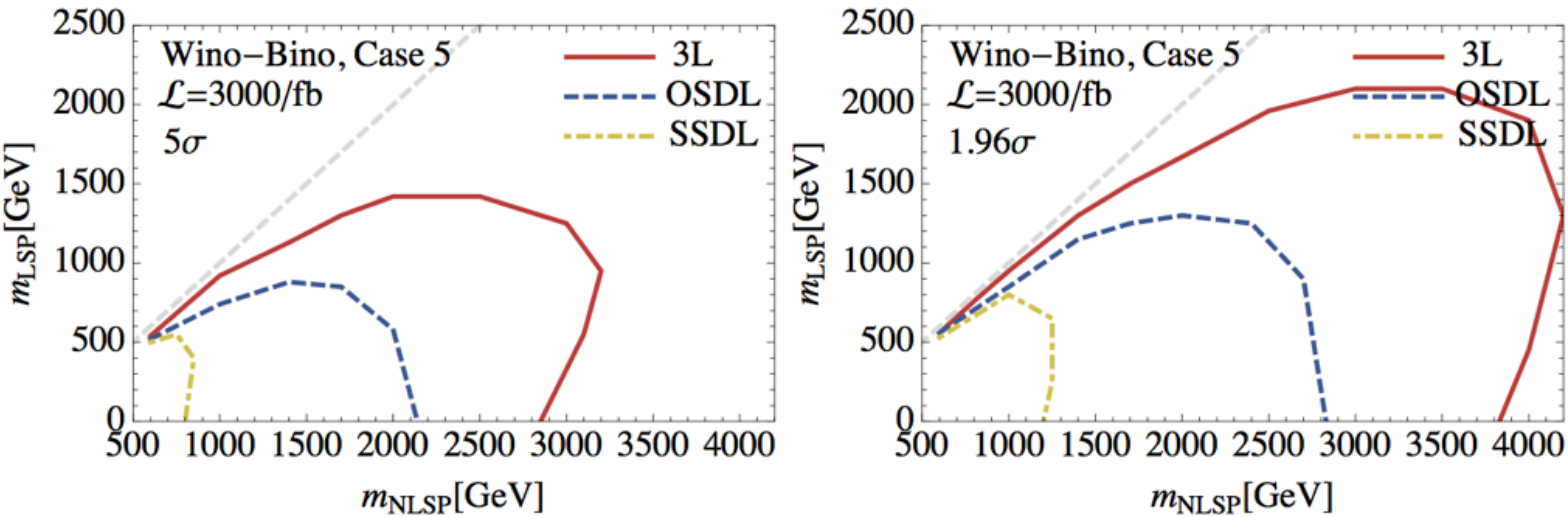
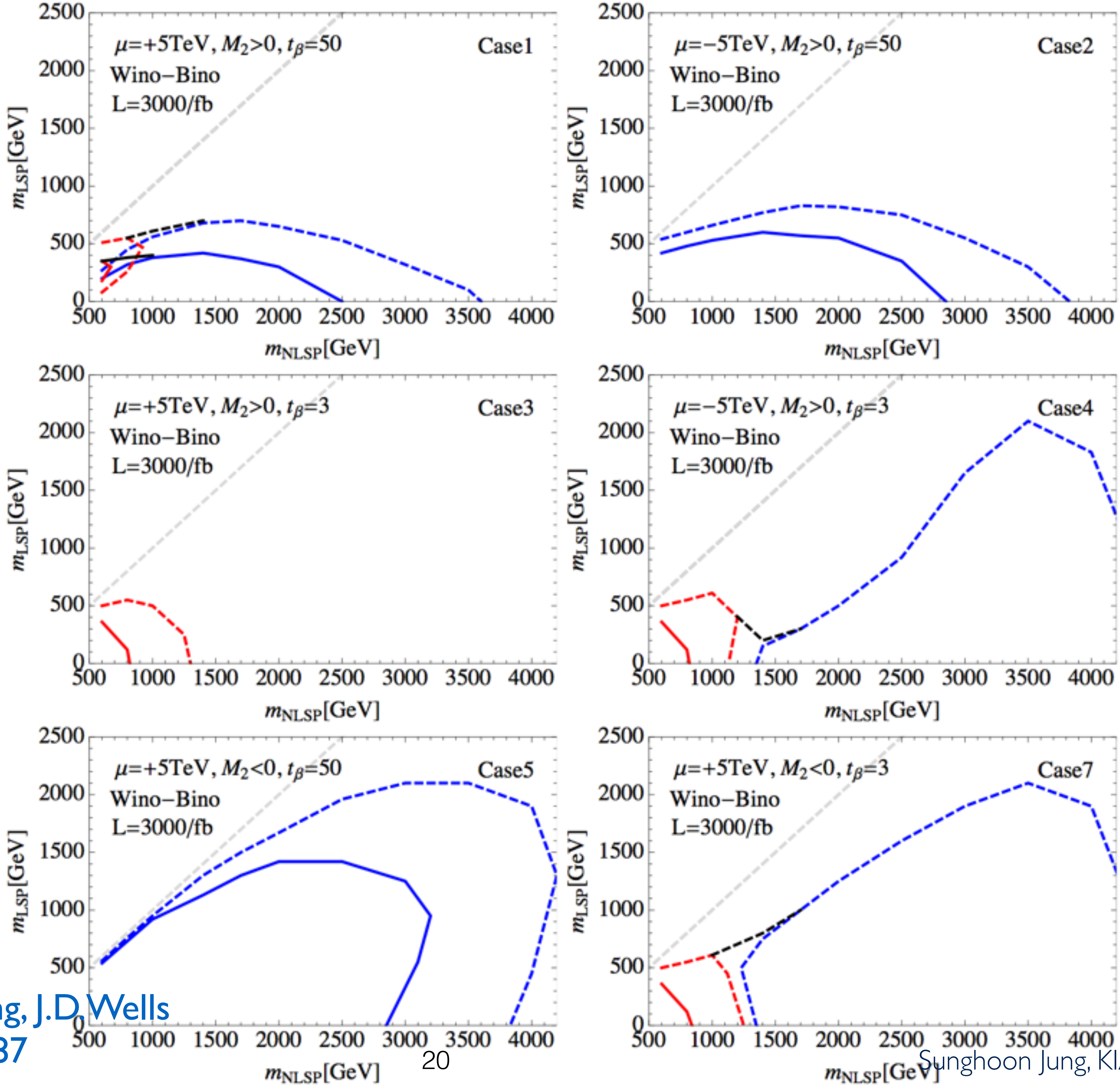
@ 100 TeV



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

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



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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.

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

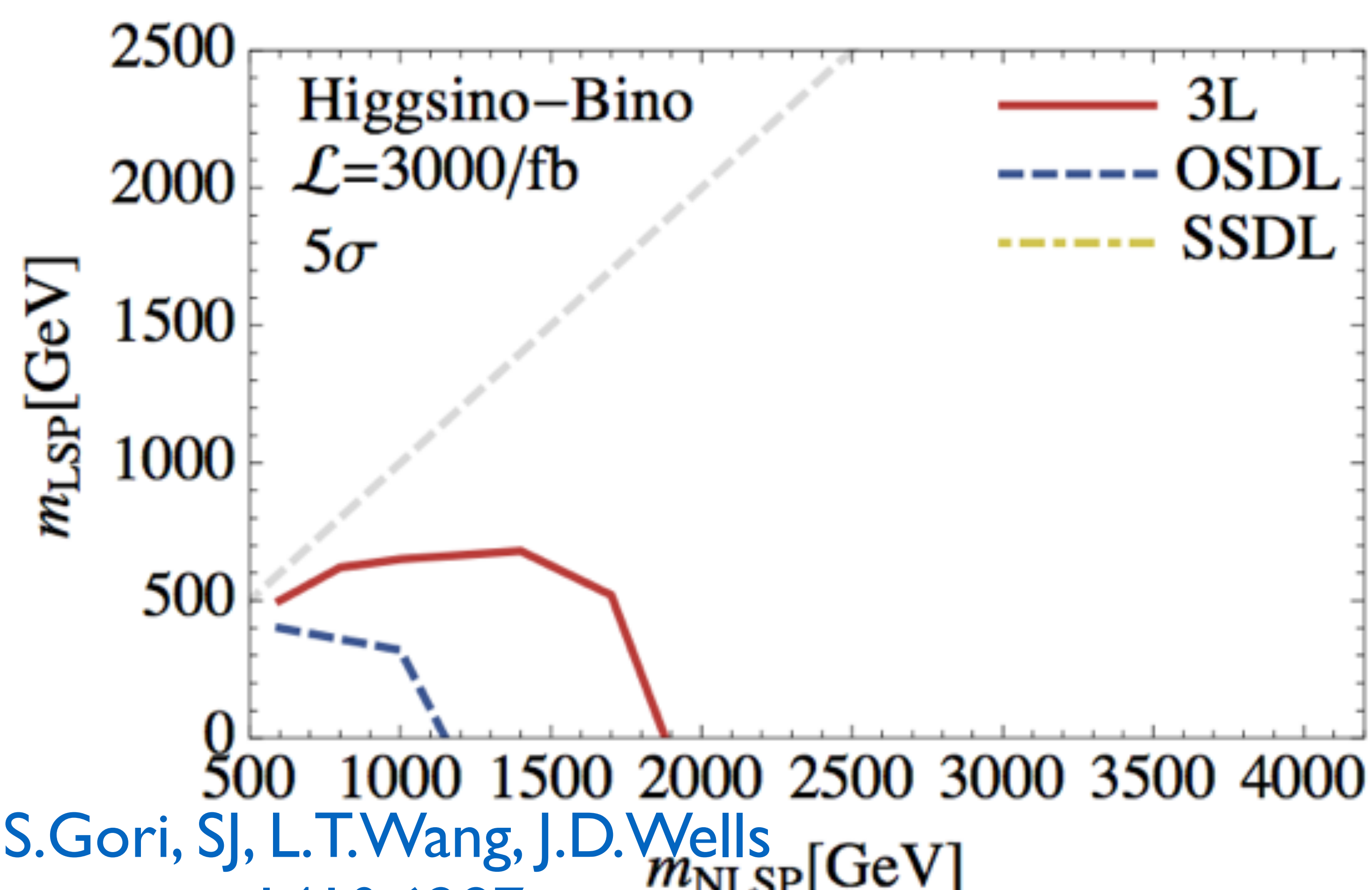
The slide from ATLAS speaker Frank Wurthwein's talk

Higgsinos are special

SJ, 1404.2691

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

- If Higgsinos are the LSP or the NLSP, parameter dependences essentially vanish!



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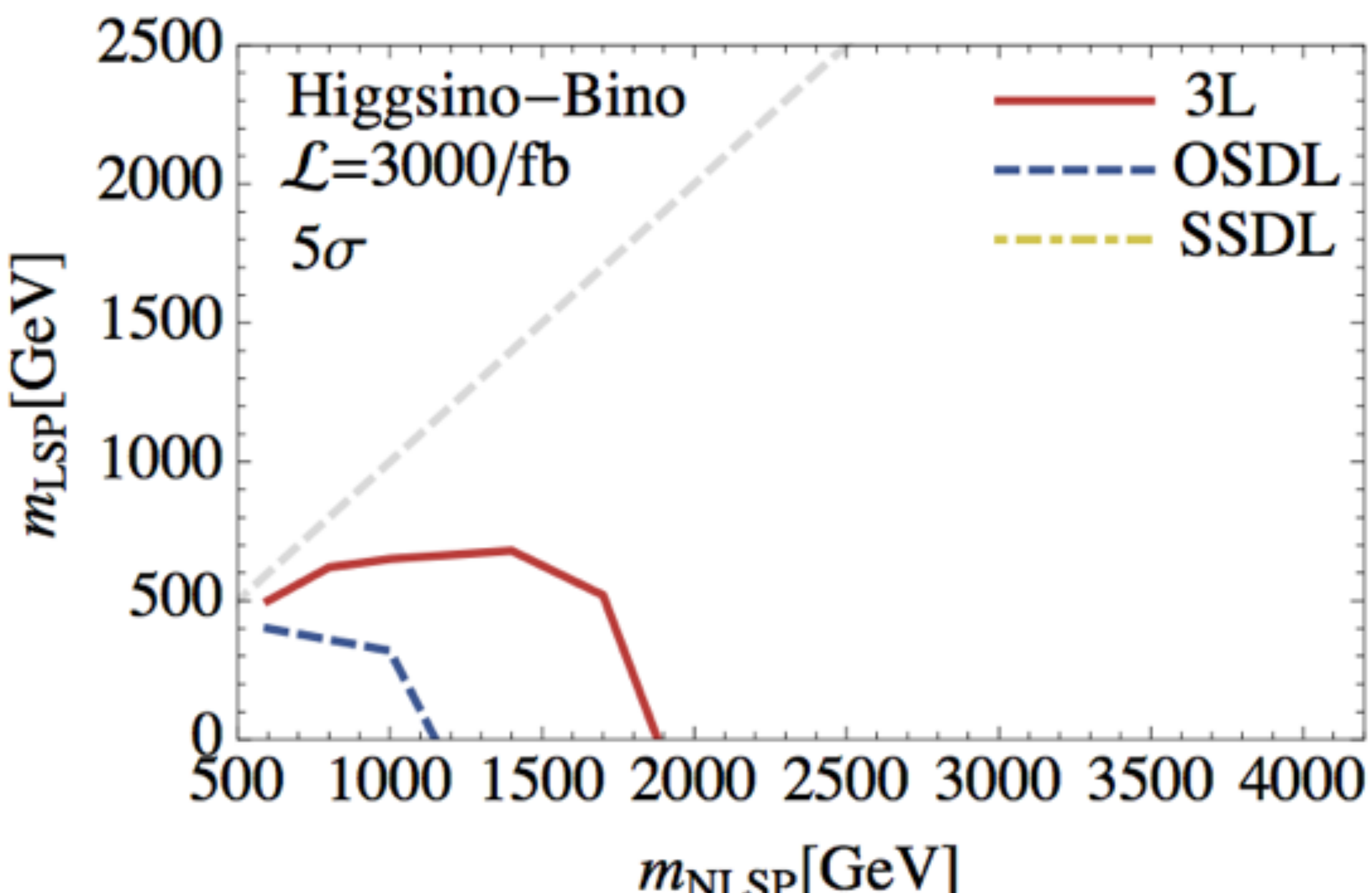

- Just one plot is all.

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

Higgsino observables

SJ, 1404.2691

- Higgsinos have two nearly degenerate, *indistinguishable* neutralinos, each of which has different BR(h) and BR(Z).

$$\chi^0_{H_{1,2}} \simeq \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_d \pm \widetilde{H}^0_u\right)$$

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

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

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NLSP BR Z vs. Higgs

SJ, 1404.2691

It was easiest to derive the relation using GET.

$$\Gamma(\chi_i^0 \to \chi_j^0 Z) \simeq \frac{g^2\, m_{\chi_i^0}}{16\pi c_W^2} \lambda^{1/2} \cdot \underline{\left|\mathcal{O}''^L_{ij}\right|^2} \, \frac{1}{r_Z}$$

$$\Gamma(\chi_i^0 \to \chi_j^0 h) \simeq \frac{g^2\, m_{\chi_i^0}}{16\pi} \lambda^{1/2} \cdot \underline{\left|D'^L_{hij}\right|^2} \left(1 + 2\sqrt{r_j}\right)$$

$$D'^L_{hij} = \frac{1}{2}\left(N^*_{j2} - t_W N^*_{j1}\right)\,\left(N^*_{i4} s_\beta - N^*_{i3} c_\beta\right)$$

$$\mathcal{O}''^L_{ij} = -\frac{1}{2}\left(N^*_{i3} N_{j3} - N^*_{i4} N_{j4}\right)$$

NLSP BR Z vs. Higgs

SJ, 1404.2691

It was easiest to derive the relation using GET.

$$\Gamma(\chi_i^0 \to \chi_j^0 Z) \simeq \frac{g^2\, m_{\chi_i^0}}{16\pi c_W^2} \lambda^{1/2} \cdot \left| \mathcal{O}_{ij}^{\prime\prime L} \right|^2 \frac{1}{r_Z} \simeq \frac{g^2\, m_{\chi_i^0}}{16\pi} \lambda^{1/2} \cdot \underline{\left| D_{Gij}^{\prime L} \right|^2} \left(1 - 2\sqrt{r_j}\right)$$

$$\Gamma(\chi_i^0 \to \chi_j^0 h) \simeq \frac{g^2\, m_{\chi_i^0}}{16\pi} \lambda^{1/2} \cdot \underline{\left| D_{hij}^{\prime L} \right|^2} \left(1 + 2\sqrt{r_j}\right)$$

For Higgsino LSPs or NLSPs:

$$\frac{\Gamma(\chi_i^0 \to \chi_j^0 Z)}{\Gamma(\chi_i^0 \to \chi_j^0 h)} \simeq \frac{|c_\beta N_{H_k 3} + s_\beta N_{H_k 4}|^2}{|c_\beta N_{H_k 3} - s_\beta N_{H_k 4}|^2}$$

Generally true

SJ, 1404.2691

The relation is valid with
Higgsino + many non-MSSM neutralinos.

If the electroweakino-Higgsinos are LSP and/or NLSP

$$\frac{\Gamma(\chi_i^0 \to \chi_j^0 Z)}{\Gamma(\chi_i^0 \to \chi_j^0 h)} \simeq \frac{|c_\beta N_{H_k 3} + s_\beta N_{H_k 4}|^2}{|c_\beta N_{H_k 3} - s_\beta N_{H_k 4}|^2}$$

If the axino-Higgsinos are LSP and/or NLSP

$$\frac{\Gamma(\chi_i^0 \to \chi_j^0 Z)}{\Gamma(\chi_i^0 \to \chi_j^0 h)} \simeq \frac{|s_\beta N_{H_k 3} - c_\beta N_{H_k 4}|^2}{|s_\beta N_{H_k 3} + c_\beta N_{H_k 4}|^2}$$

If the gravitino-Higgsinos are LSP and/or NLSP

$$\frac{\Gamma(\chi_i^0 \to \chi_j^0 Z)}{\Gamma(\chi_i^0 \to \chi_j^0 h)} \simeq \frac{|c_\beta N_{H_k 3} - s_\beta N_{H_k 4}|^2}{|c_\beta N_{H_k 3} + s_\beta N_{H_k 4}|^2}$$

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

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

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

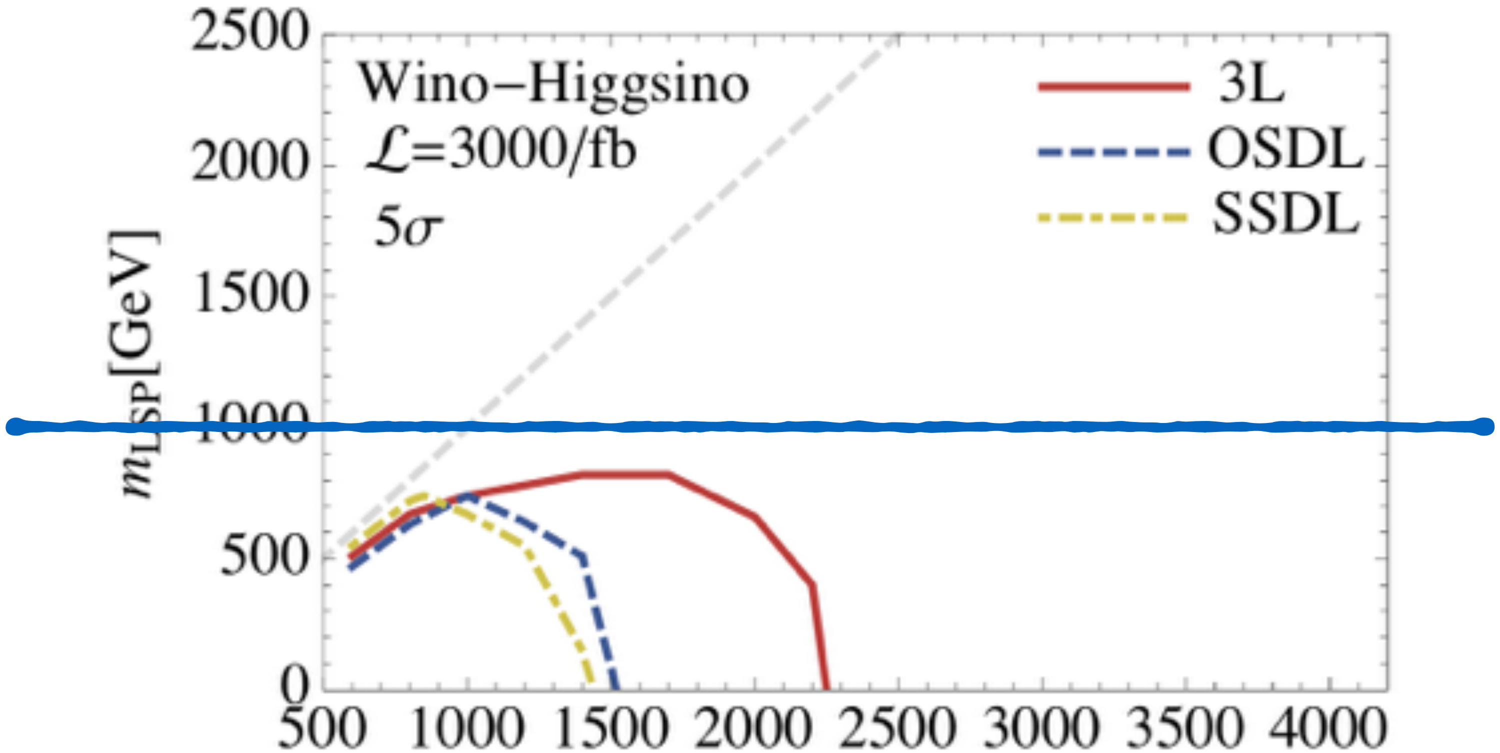
Runge basis

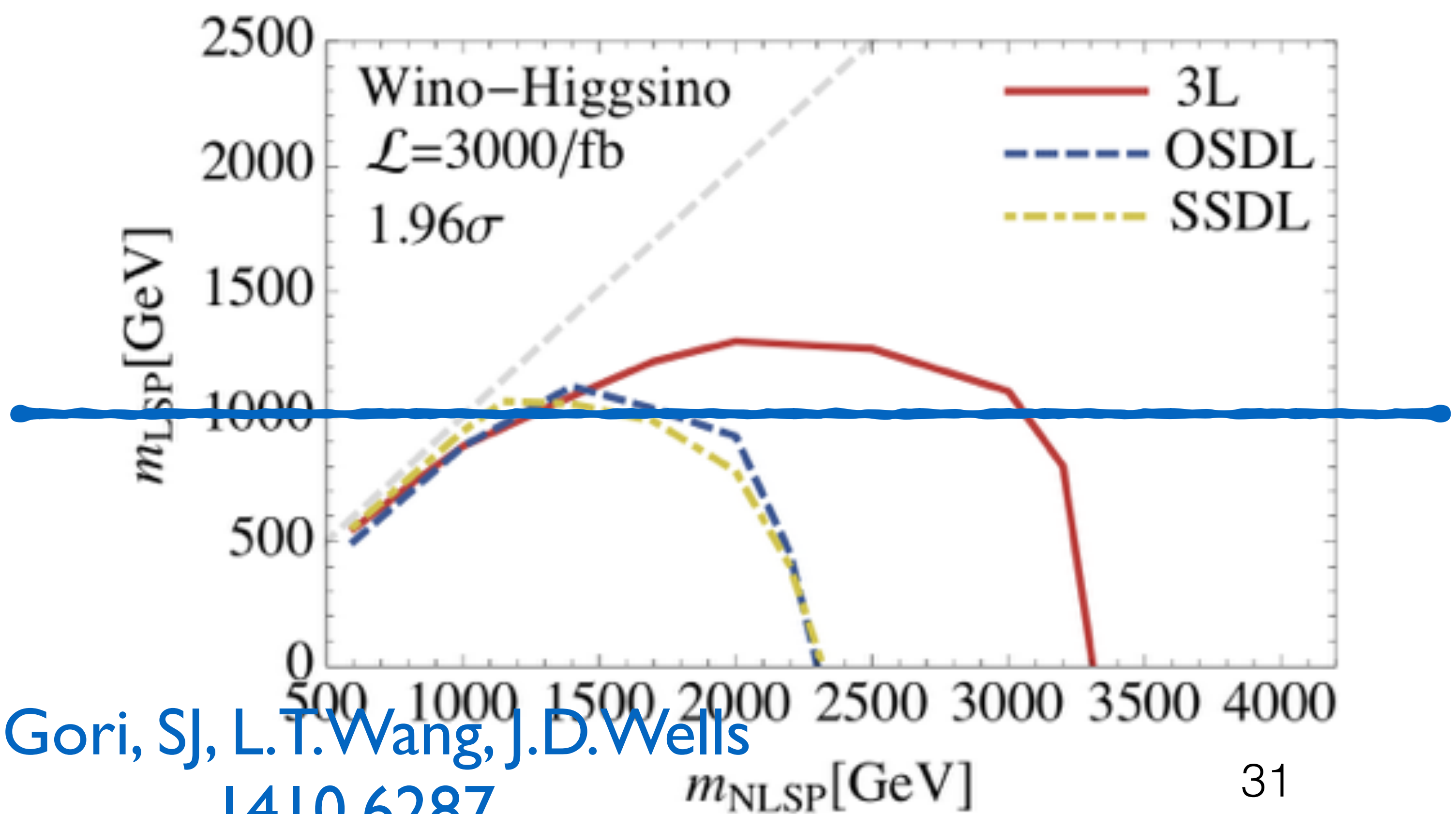
↓ alignment limit

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

h and Z are in the same doublet.

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

3. Displaced decays

axino LSP

Very weak interactions

- SUSY models often contain very weakly interacting particles (as the LSP) that can lead to displaced decays:
  Axinos/axions, gravitinos, small RPV, …

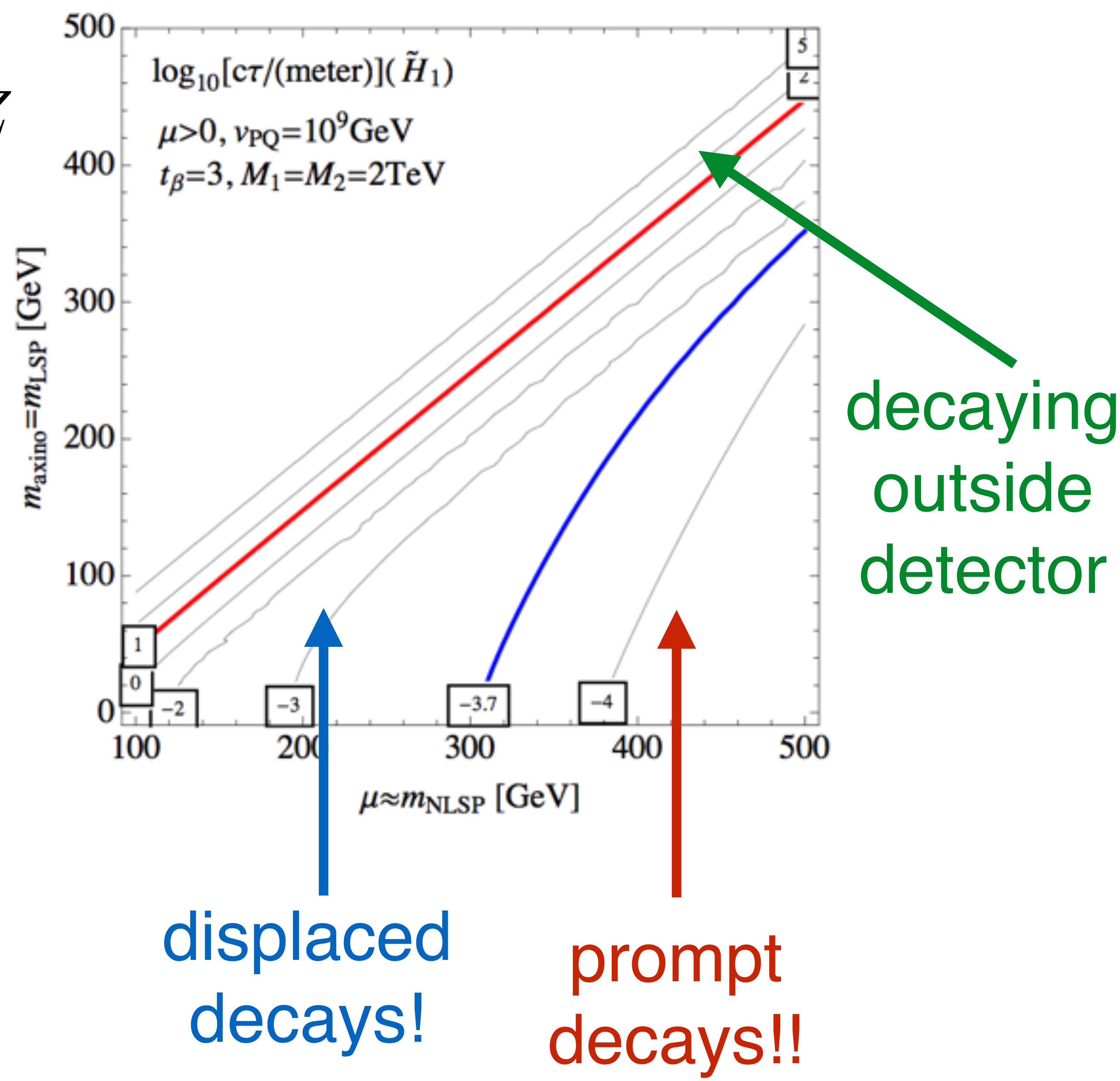
- Focus on Axino LSP + Higgsino NLSP

$$W = c_H \frac{\mu}{v_{PQ}} A H_u H_d$$

Lightest Higgsino decays

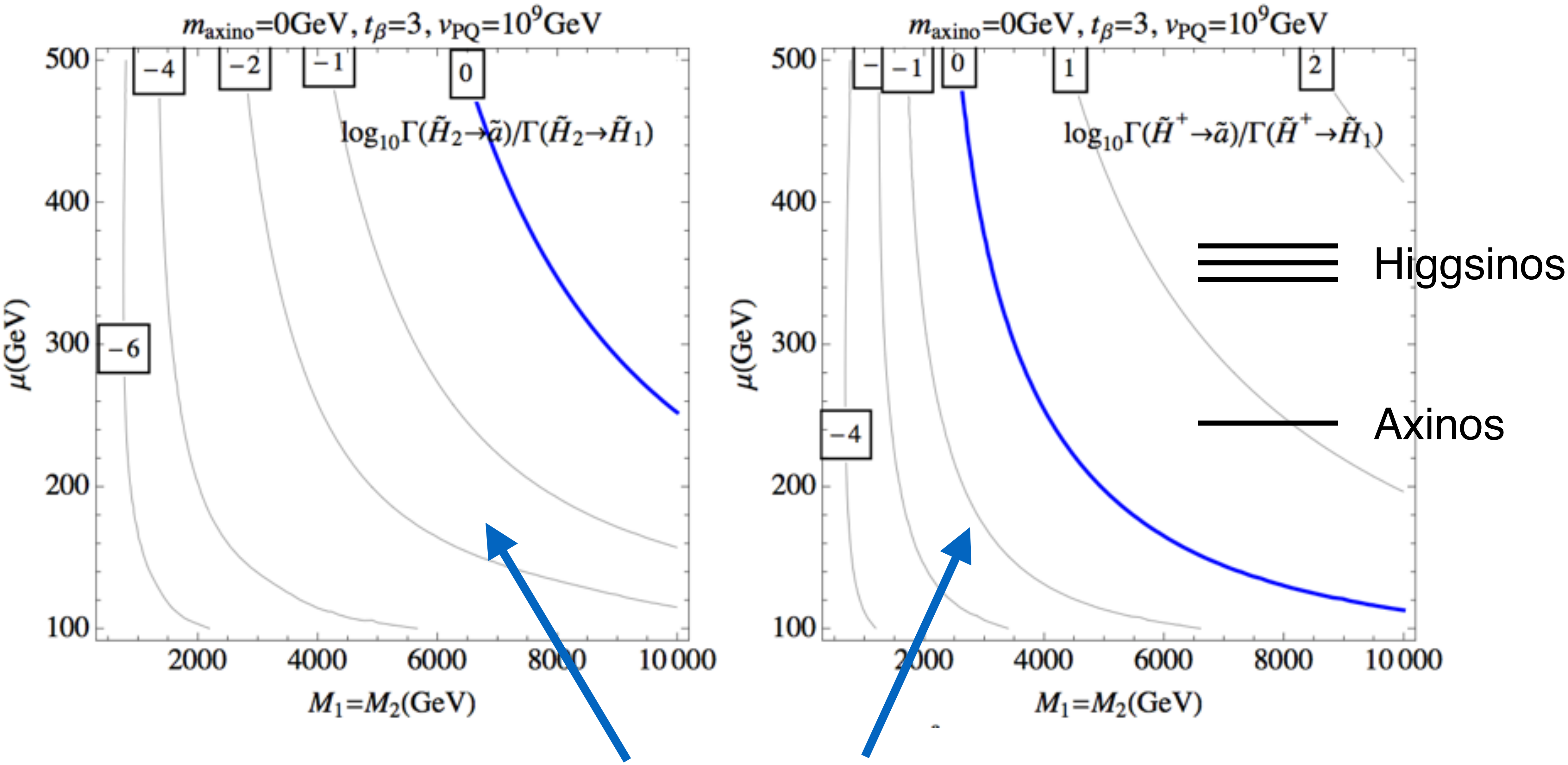
Barenboim, Chun, SJ, Park, 1407.1218

$$\widetilde{H}_1^0 \to \widetilde{a} + h/Z$$



Heavier Higgsino decays

$\widetilde{H}_2^0 \to \widetilde{a} + h/Z,\ \widetilde{H}_1^0 + Z^*$ $\widetilde{H}^+ \to \widetilde{a} + W,\ \widetilde{H}_1^0 + W^*$



Heavier Higgsinos dominantly decay to lightest Higgsinos rather than to the axino LSPs directly.

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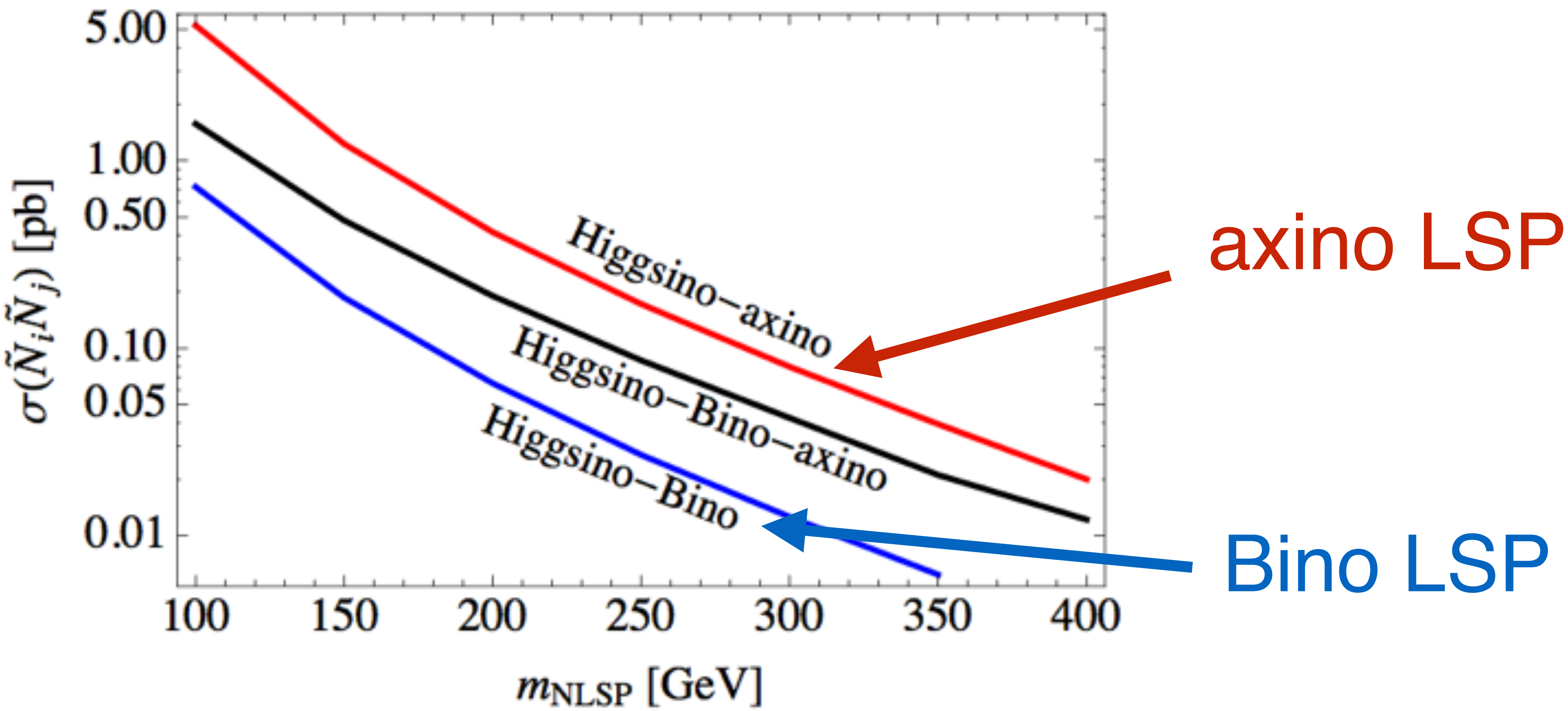
Effectively enhanced lightest Higgsino productions

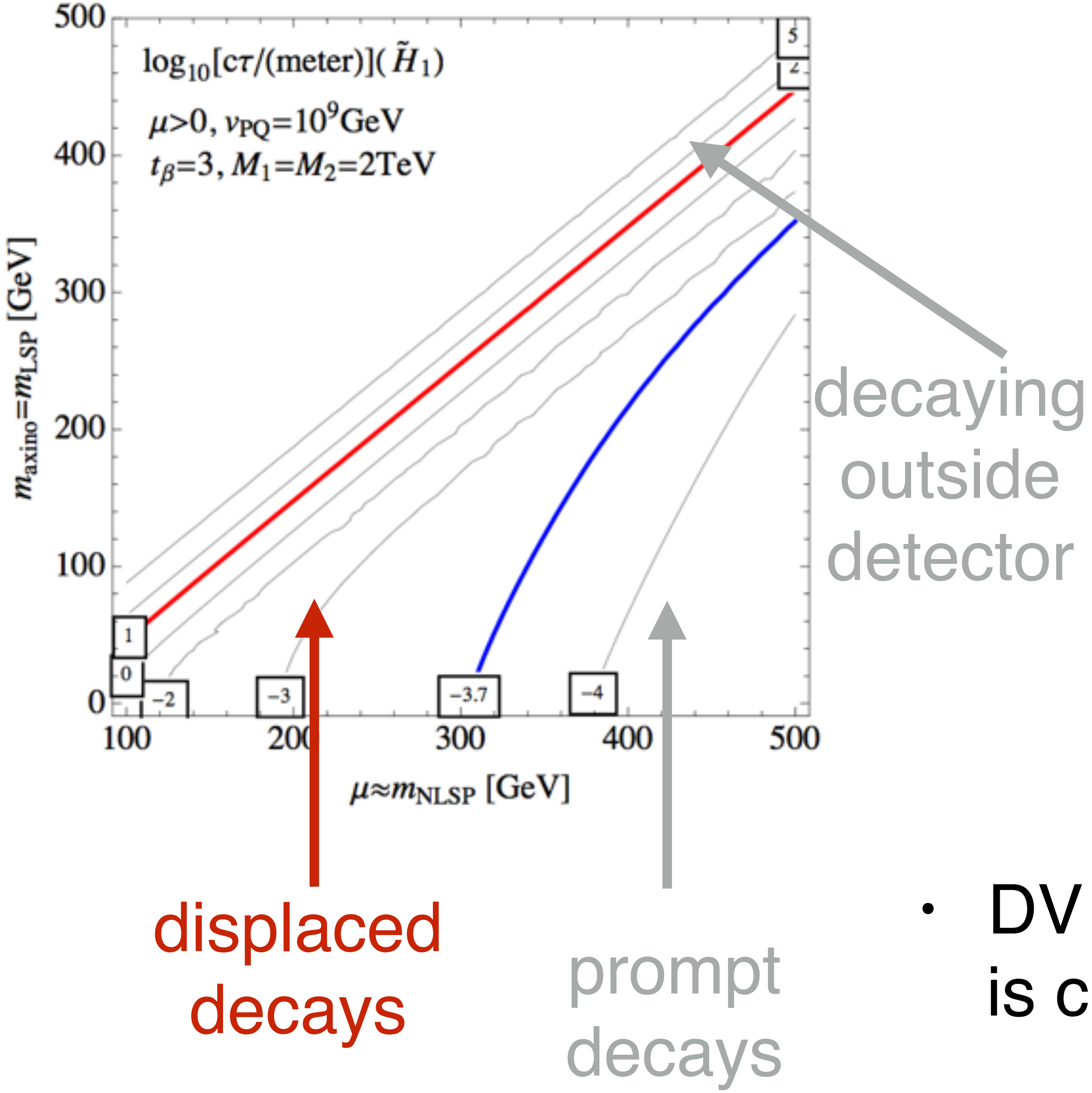
$$\widetilde{H}^0_1\widetilde{H}^0_2,\ \widetilde{H}^\pm\widetilde{H}^\mp,\ \widetilde{H}^0_{1,2}\widetilde{H}^\pm \to \widetilde{H}^0_1\widetilde{H}^0_1$$



Effective neutral NLSP pair production
is 7~8 times enhanced in Higgsino-axino model.

Displaced dijet vertex

Barenboim, Chun, SJ, Park, 1407.1218



$$\widetilde{H}_1^0\widetilde{H}_1^0 \to \widetilde{a}\widetilde{a}ZZ$$

$$Z \to jj$$

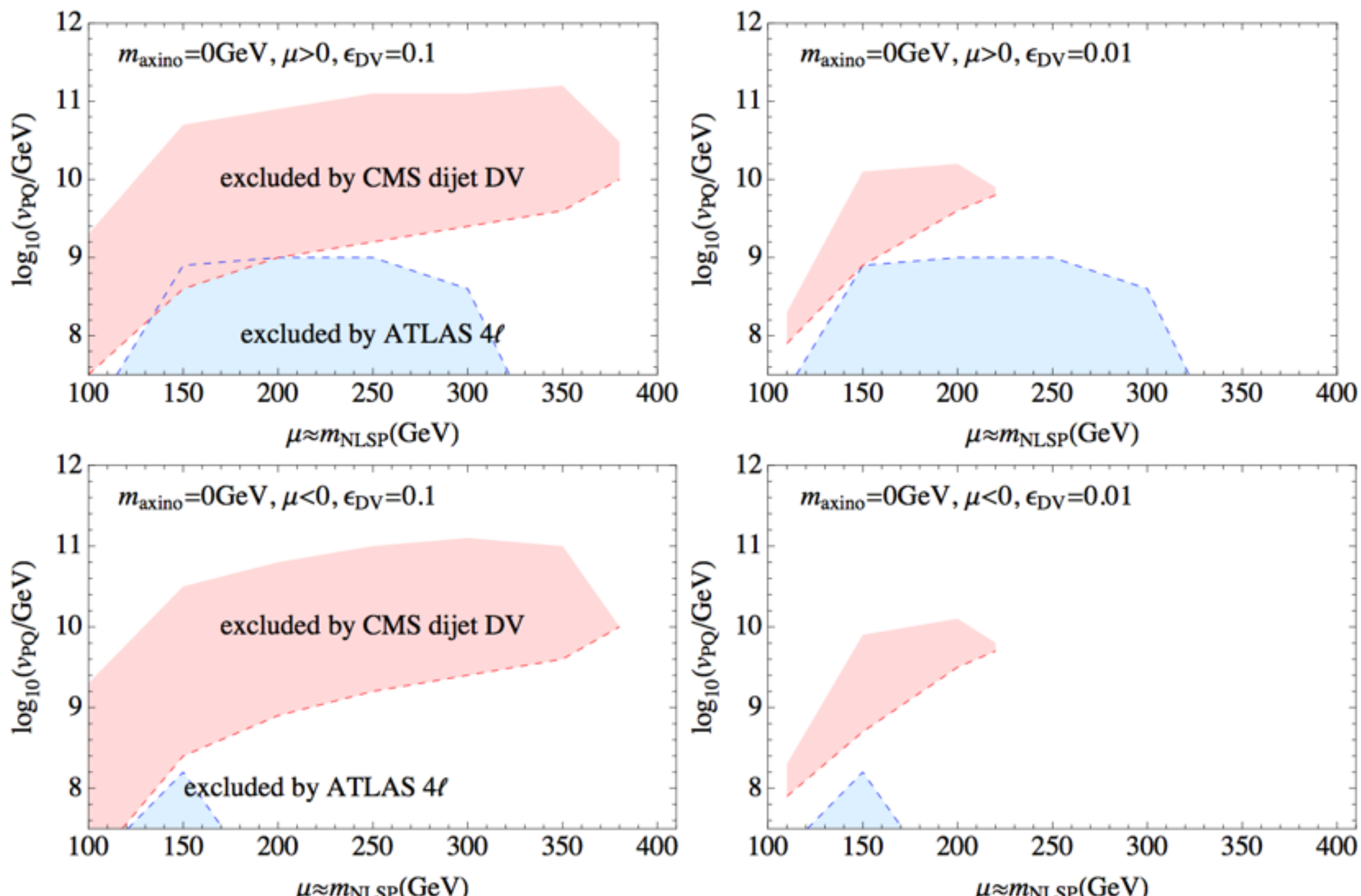
- 2 jets meeting at DV
  $300\mu m \leq d_\perp \leq 60cm$
  $p_T > 60\,\mathrm{GeV}$ and $|\eta| < 2$;
- HT>600 GeV
- DV reconstruction efficiency is critical. We assume either
  $\epsilon_{DV} = 0.1,\ 0.01$

Collider bounds on axinos

Barenboim, Chun, SJ, Park, 1407.1218

DV reconstruction worse →

↓ BR(4l) smaller



Collider bounds on axinos

Barenboim, Chun, SJ, Park, 1407.1218

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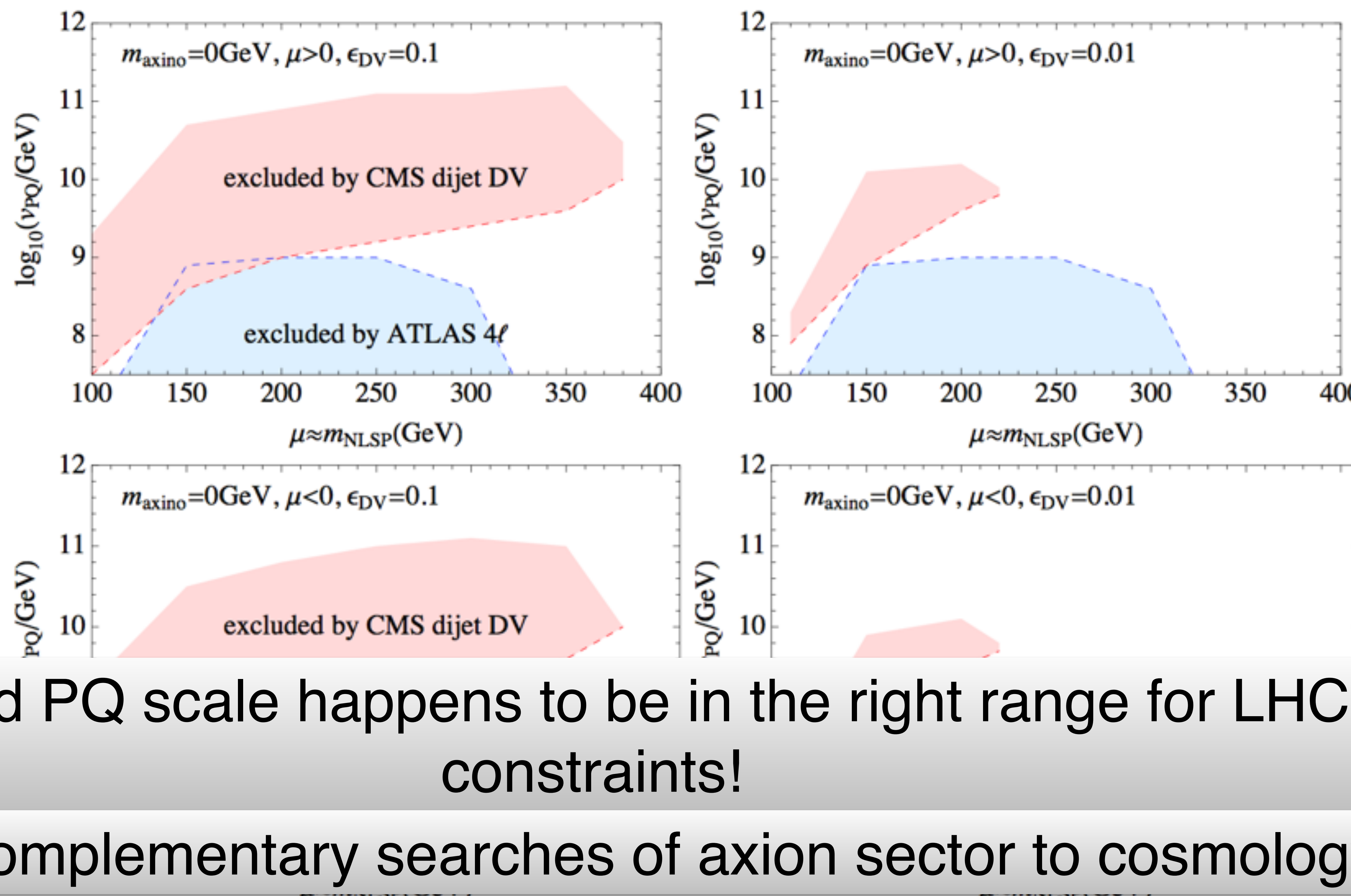

↓ BR(4l)

s

Allowed PQ scale happens to be in the right range for LHC constraints!

Nice complementary searches of axion sector to cosmology.

Summary of prospects

- Gluino pairs @ 100 TeV do not definitely cover Wino or Higgsino DM scenarios.
- 1 TeV Higgsino DM can perhaps be excludable (but not discoverable) via multilepton decays of Wino.
- Displaced decay searches can often provide useful complementary information.

Summary of future SUSY

- Bound interpretation in terms of ino mass ratios.
- Better resummation needed for gaugino code.
- Goldstone Eq Thm is generically applied; and light Higgsino pheno especially simplified. BR(Z)=BR(h) always.

Thank you for your attention.