Muon g-2, Dark Matter and MSSM

Keisuke Yanagi
Univ. of Tokyo

Preliminary work with M. Endo, S. Iwamoto, and K. Hamaguchi

Physics beyond the SM

Many hints!

- Hierarchy problem
- Dark Matter
- Muon g-2 (> 3σ)
- Baryon asymmetry, neutrino mass, GUT, etc…

Supersymmetry

- Cancellation of loop correction
- Neutralino WIMP DM
- Neutralino/chargino - smuon loop

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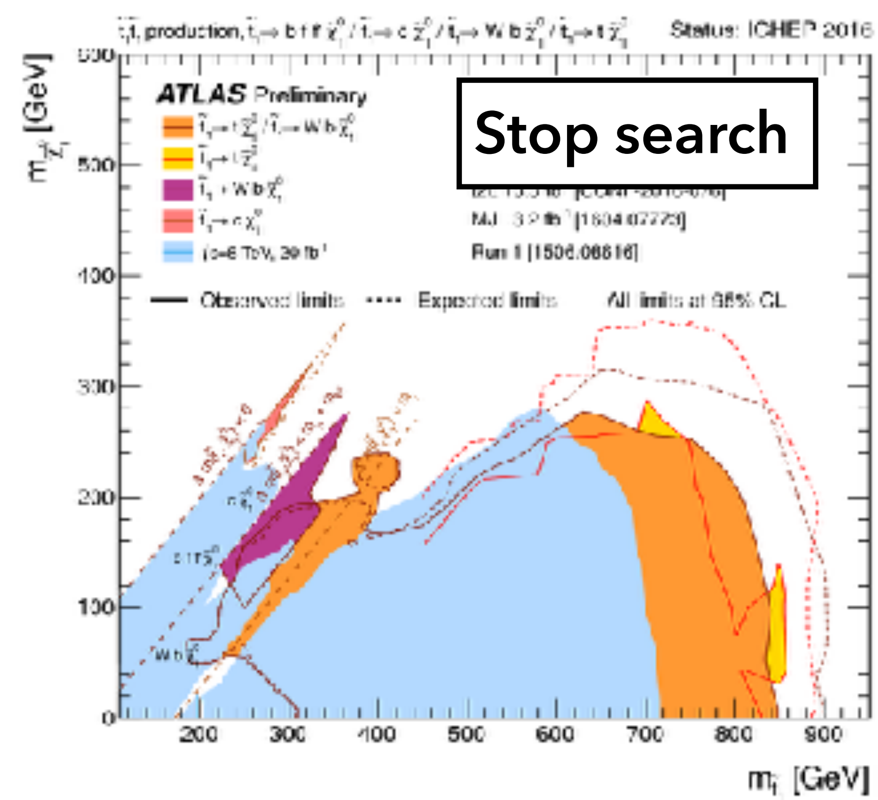
However, LHC found that…

- Colored superparticles > *O*(1) TeV
- MSSM cannot solve EW hierarchy

Little hierarchy problem



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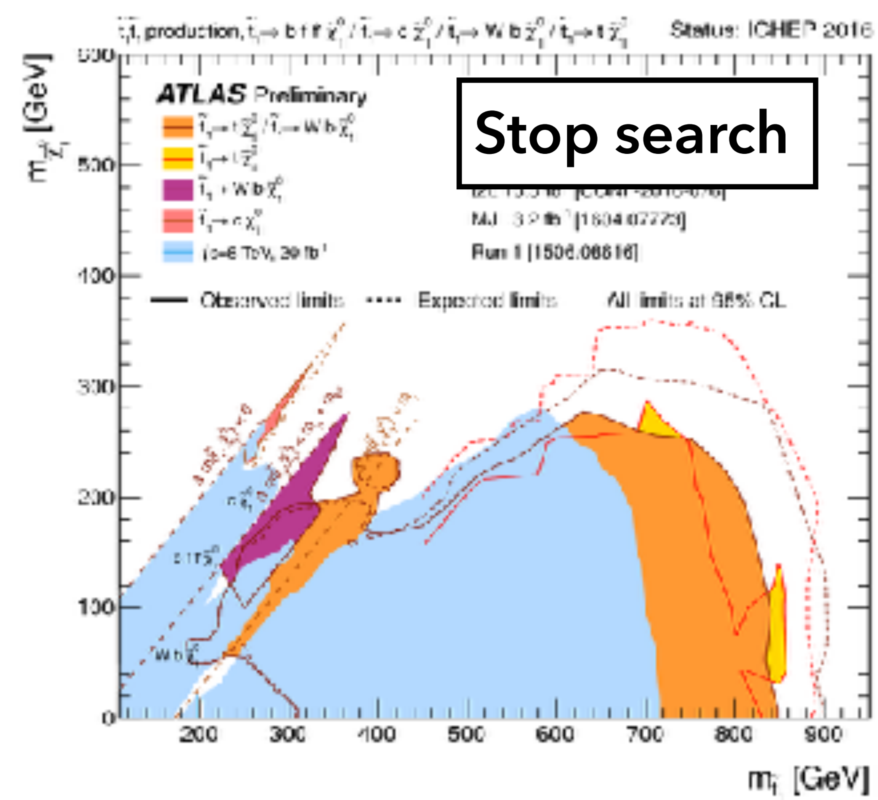


But still,

SUSY can solve DM and Muon g-2 anomaly

Phenomenologically, SUSY is still attractive!

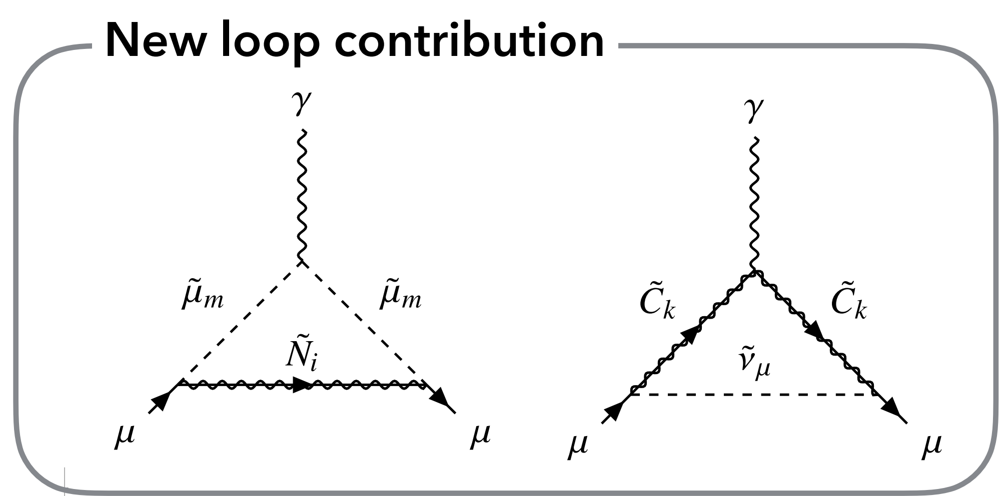
Muon g-2 and DM in MSSM

- 3σ discrepancy of muon g-2 between SM and the experiment

$$a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (261 \pm 80) \times 10^{-11}$$

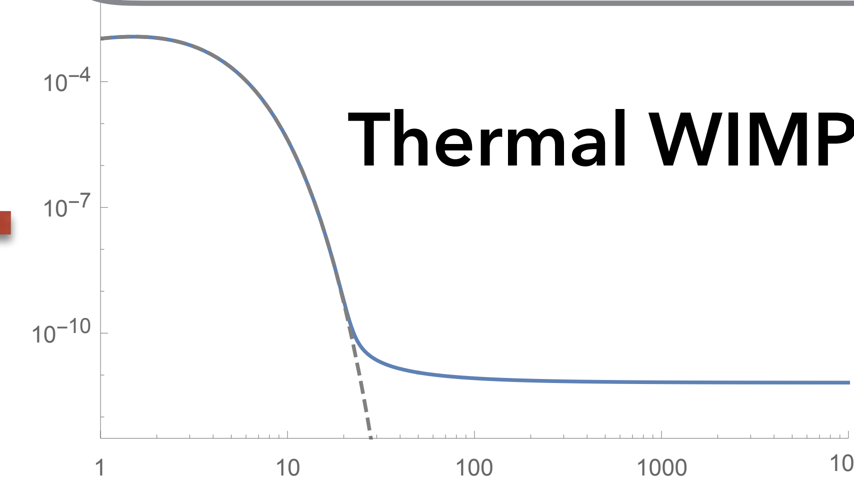
[Hagiwara et.al. 2011]

MSSM



- DM abundance today

$$\Omega_{DM}h^2 = 0.12$$



Thermal WIMP DM

100 GeV - 1 TeV neutralino/chargino and smuon is necessary

bounds are not so strict as colored ones

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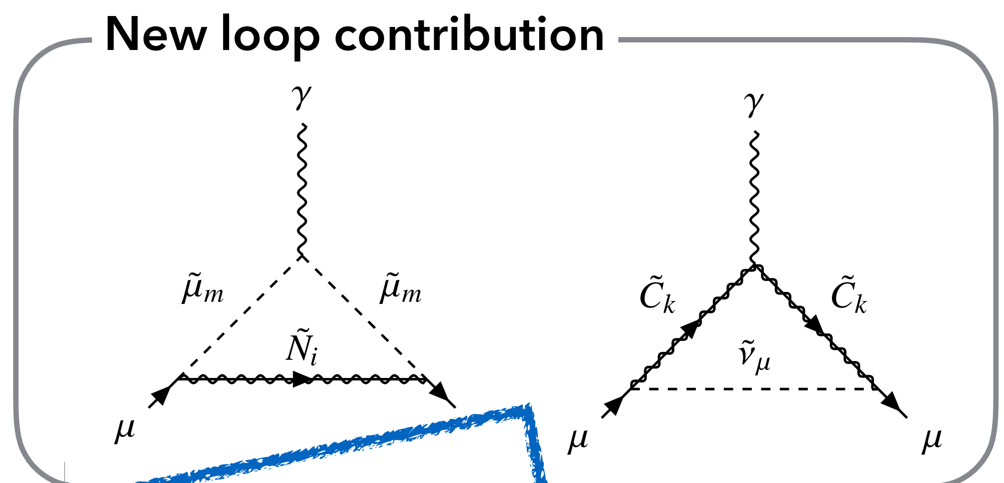

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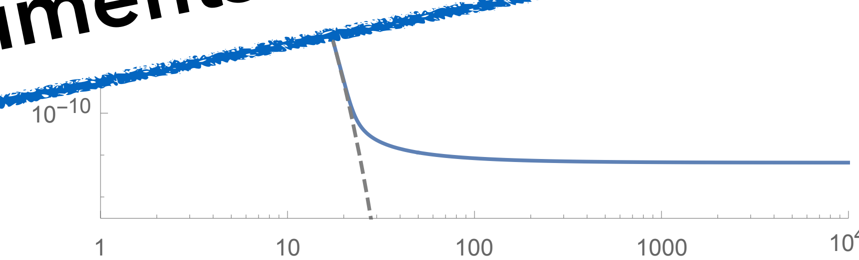

Consistent with current experiments?
Detectable by future experiments?

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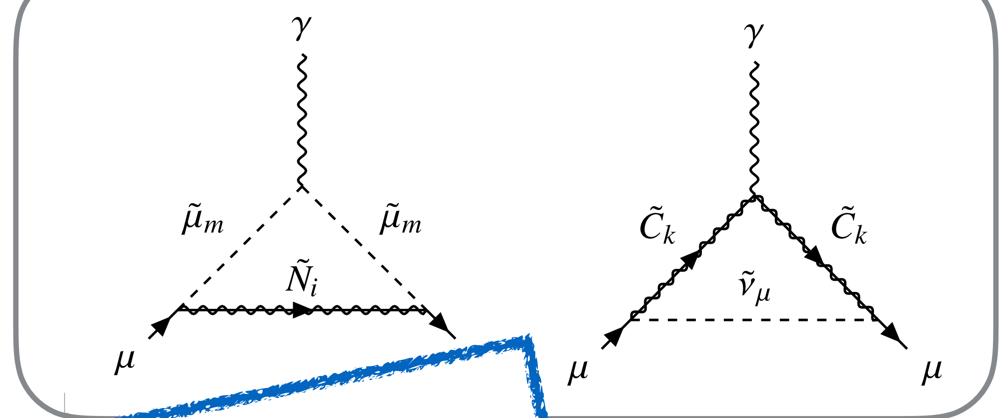
Muon g-2 and DM in MSSM

MSSM

New loop contribution



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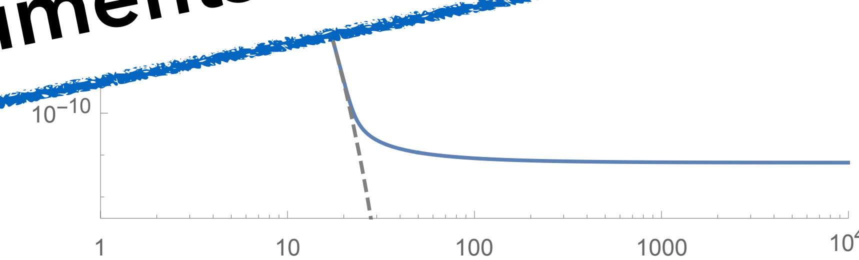

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Messages

LHC or DM direct detection are not enough to study the parameter space!

1. DM in each g-2 scenario
2. Experimental bounds (Direct detection, LHC, ILC)
3. Results

MSSM spectrum

Model-independent approach motivated by g-2 and DM

R-parity is conserved

- Slepton
- Bino, Wino
- Higgsino
- Squark
- Gluino
- Heavy Higgs

Bino, Wino, Higgsino } Neutralino DM

Slepton, Bino, Wino, Higgsino } Muon g-2

Squark, Gluino, Heavy Higgs } Irrelevant

$$m_{H^{0,\pm}}, m_{A^0}, m_{\tilde{g}}, m_{\tilde{q}}, \gg m_{\widetilde{N}}, m_{\widetilde{C}^{\pm}} m_{\tilde{l}}$$

We consider only slepton, bino, wino, Higgsino

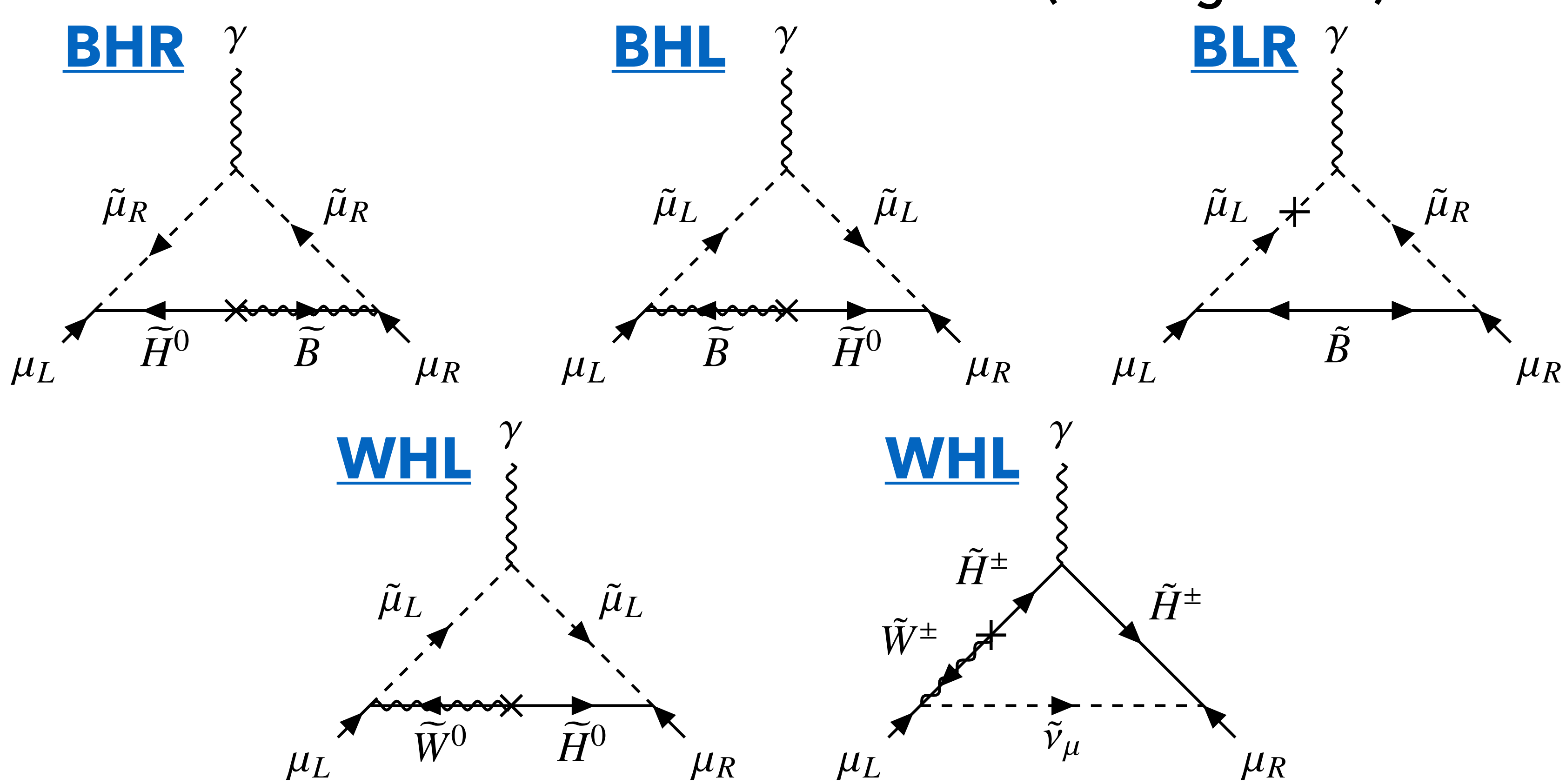
parameters: M_1, M_2, μ, m_L, m_R, $\tan\beta$

Our strategy

We classify SUSY contribution to g-2 into 4 scenarios

5 diagrams, 4scenarios in gauge eigenstates

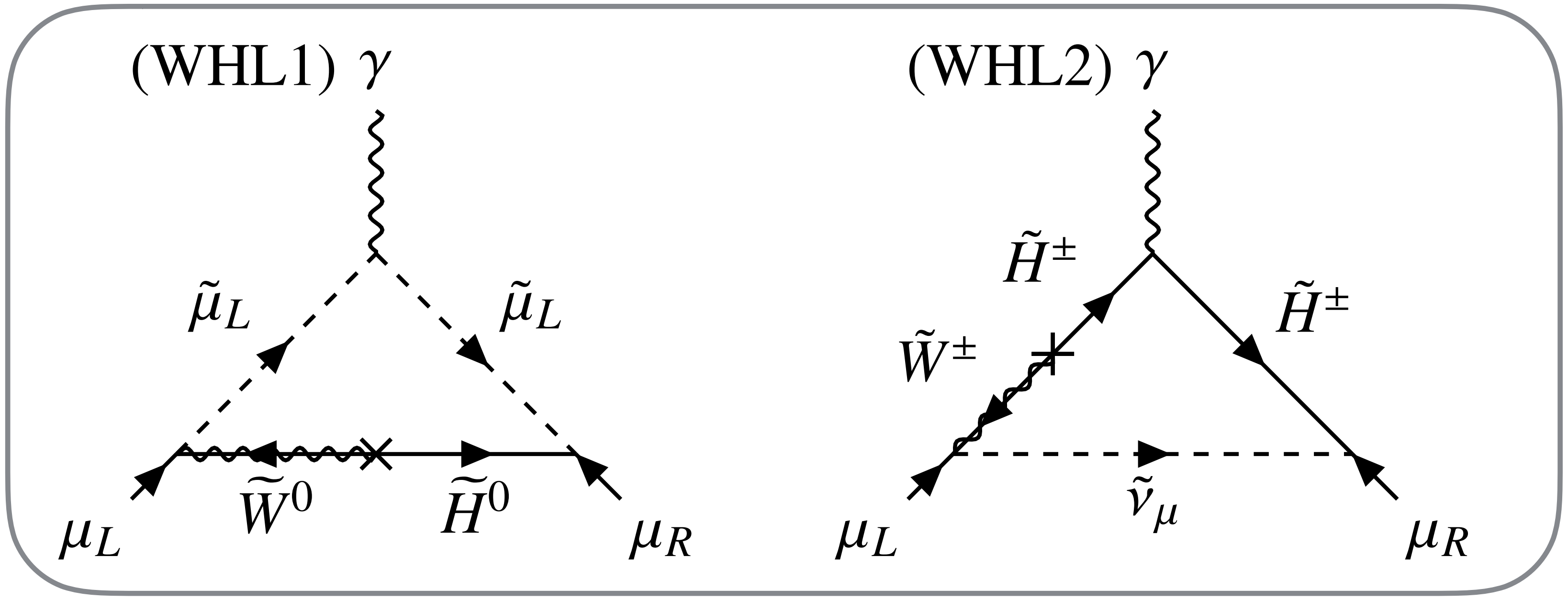
(for large tanβ)



Is it possible to obtain DM abundance $\Omega_{\mathrm{DM}}h^2 = 0.12$ in each scenario ??

DM in WHL scenario

- **Wino, Higgsino, Left-handed smuon/sneutrino** $(\widetilde{W},\ \widetilde{H},\ \widetilde{\mu}_L,\ \widetilde{\nu}_\mu)$
- **Assume M_2, μ, m_L << M_1, m_R**



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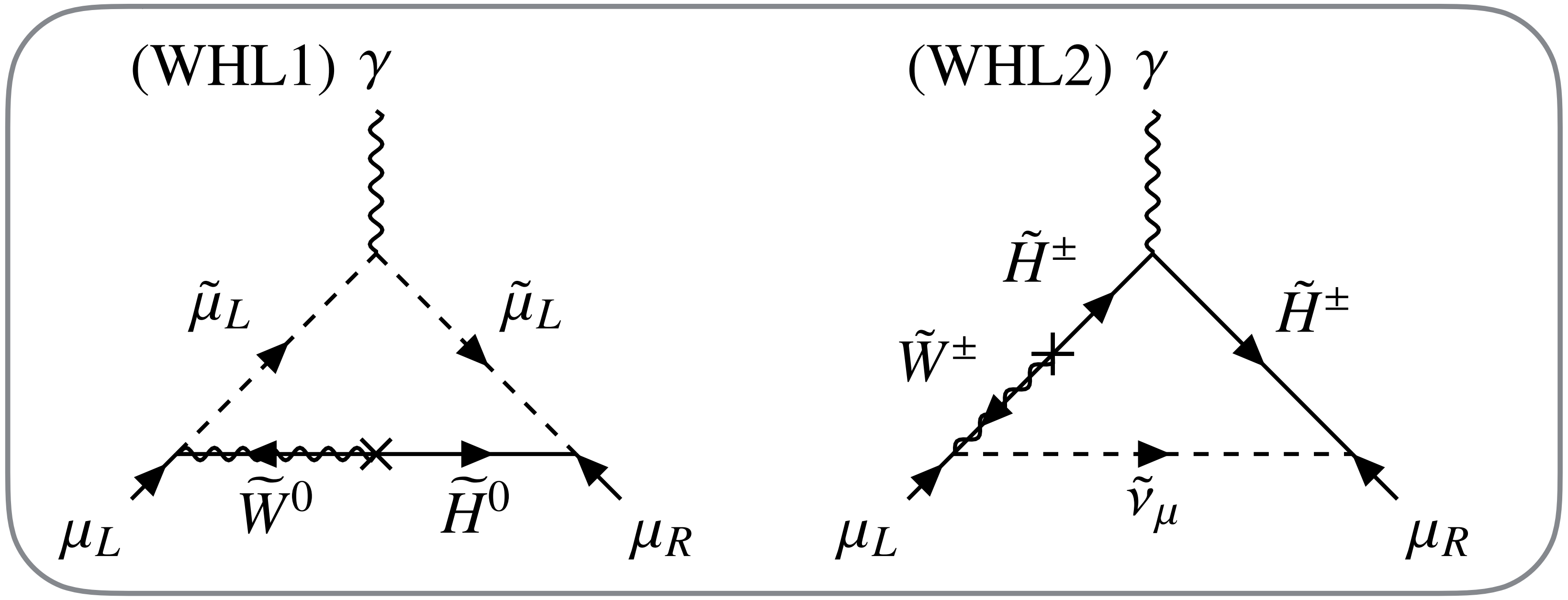


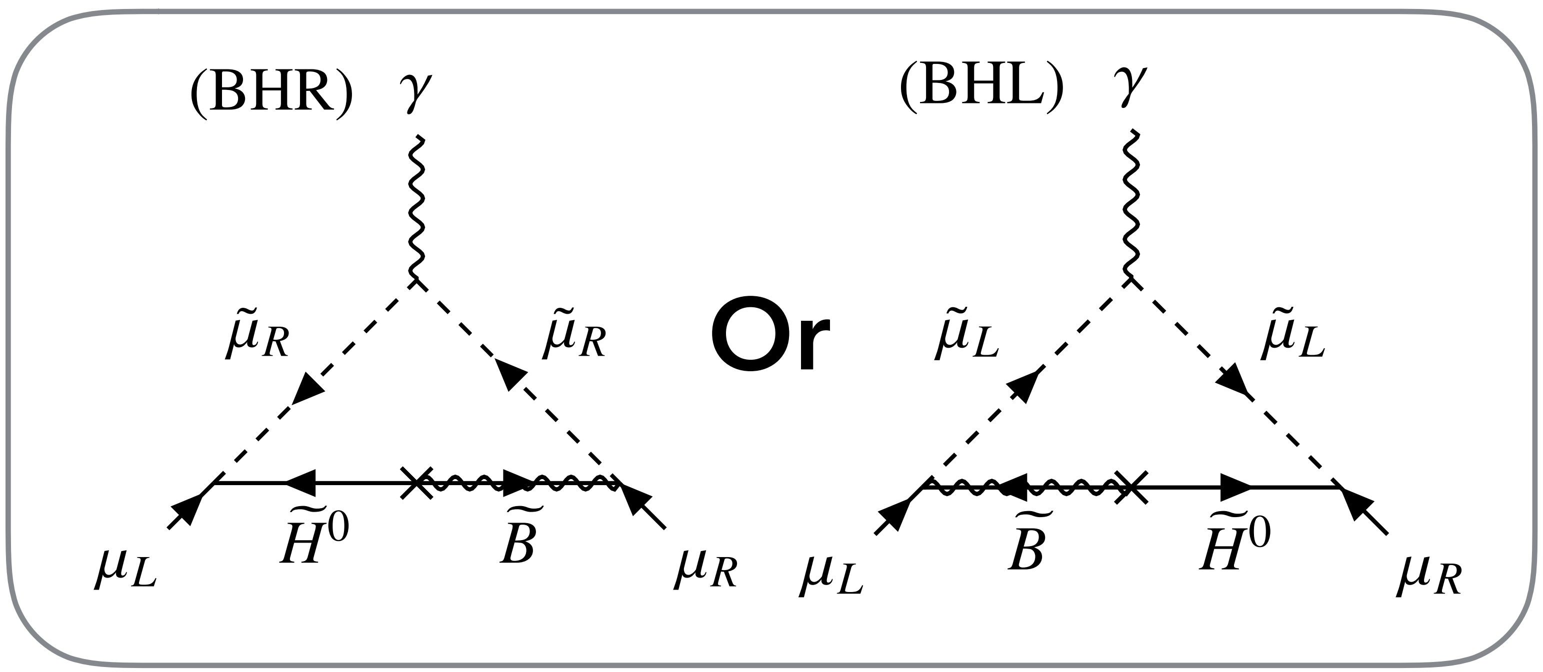
- For DM, M_2 ~ 3 TeV (Wino DM), or μ ~ 1 TeV (Higgsino DM)
- But then, a_μ(WHL) << δa_μ = 261 × 10^{-11}
- a_μ(WHL) = 5.6 × 10^{-11} (M_2 = μ = m_R = 3 TeV, tanß=40)

  a_μ(WHL) = 50 × 10^{-11} (M_2 = μ = m_R = 1 TeV, tanß=40)

No solution…

DM in BHR or BHL scenario

- **Bino, Higgsino, Right- or Left-handed smuon** $(\widetilde{B},\ \widetilde{H},\ \widetilde{\mu}_R)$ $(\widetilde{B},\ \widetilde{H},\ \widetilde{\mu}_L)$
- **M_1, μ, m_R << M_2, m_L (BHR)**
- **M_1, μ, m_L << M_2, m_R (BHL)**



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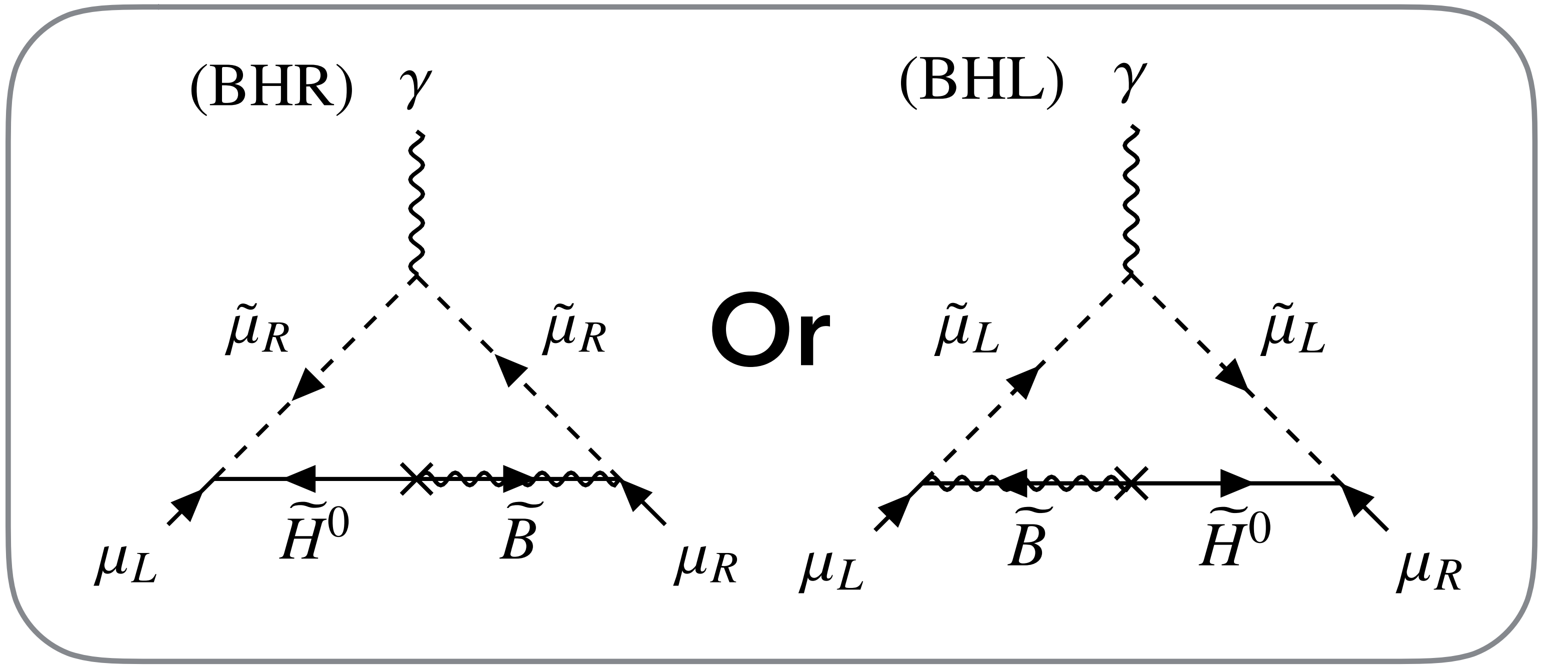
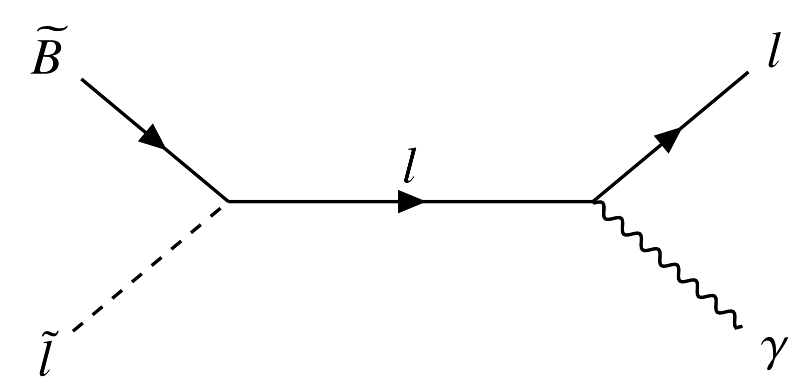


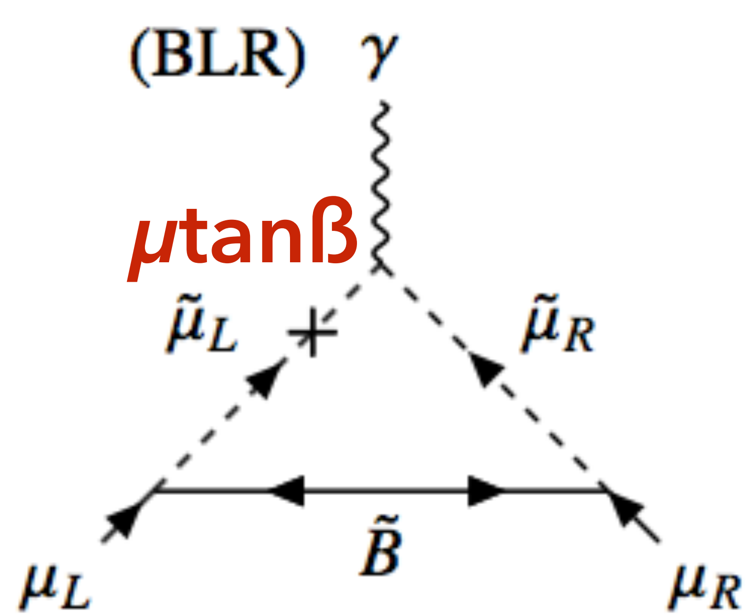
- **Bino DM is usually overproduced…**
- **Bino-slepton coannihilation gives $\Omega_{\mathrm{Bino}}h^2 = \Omega_{\mathrm{DM}}h^2$**

$$m_{\tilde{l}} - m_{\widetilde{B}} \sim 10\ \mathrm{GeV}$$



DM in BLR scenario

- Bino, Left- and right-handed smuon $(\widetilde{B},\ \widetilde{\mu}_L,\ \widetilde{\mu}_R)$
- Parameters: M_1, μ, m_L, m_R
- Looks similar to BHR or BHL



- a_μ(BLR) $\propto$ μtanβ
- Large μtanβ destabilize our vacuum
- Analysis becomes qualitatively different…

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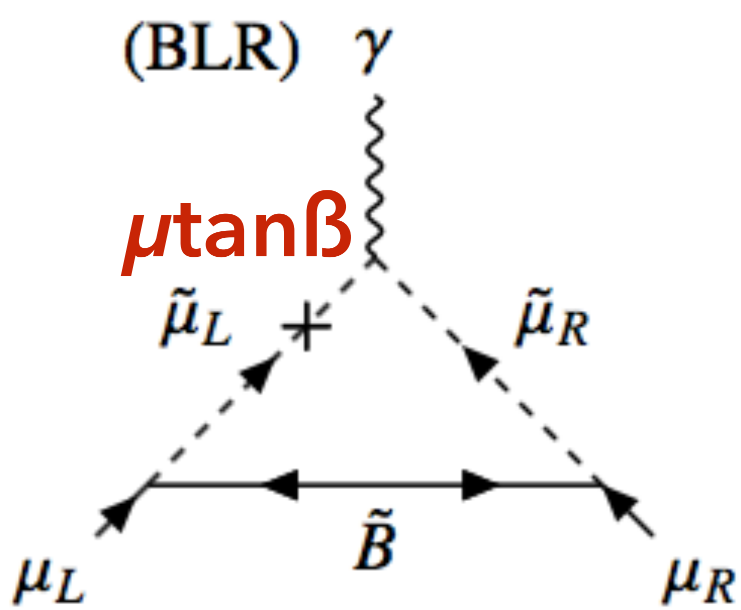

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Future work

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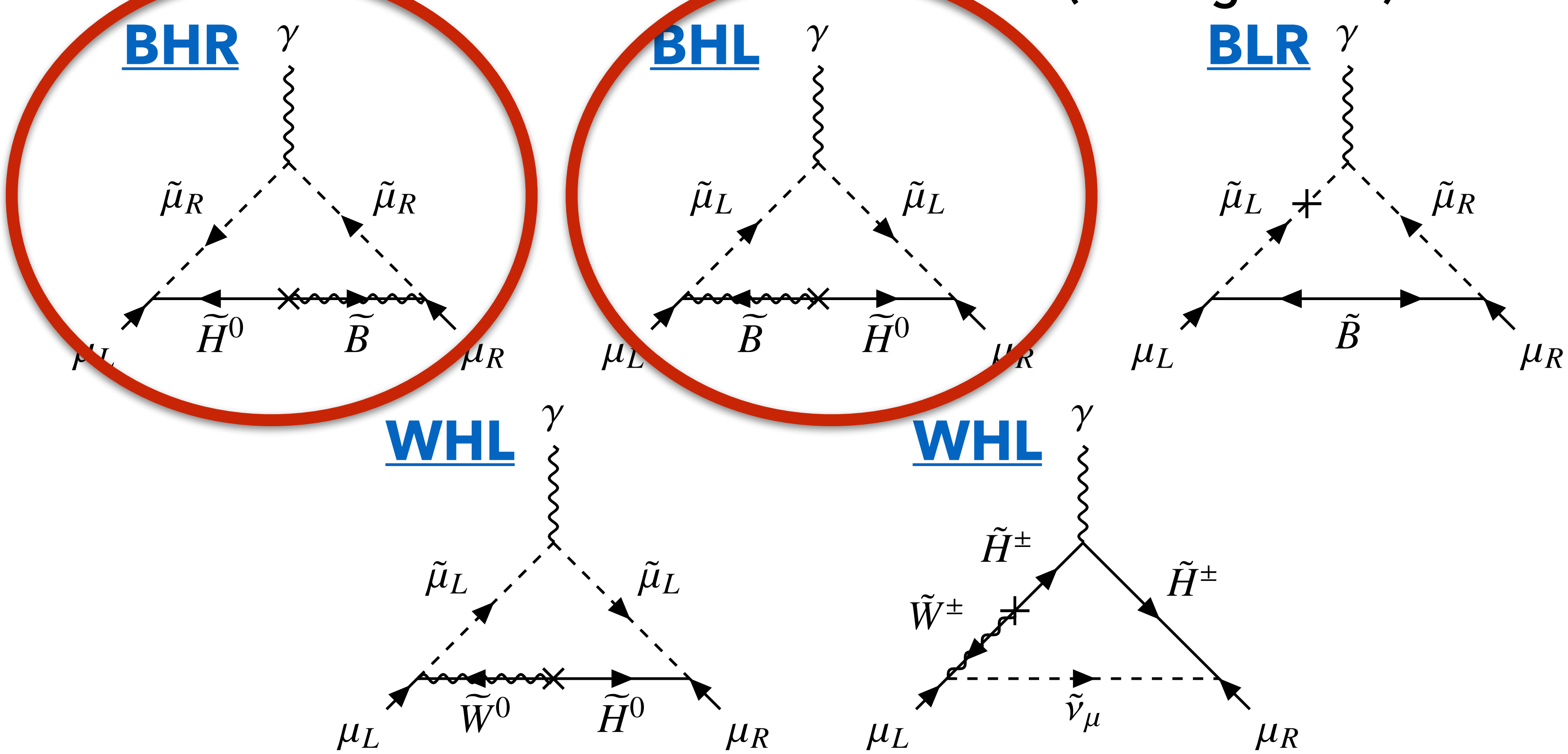

We focus on BHR and BHL scenarios

1. DM in each g-2 scenario
2. Experimental bounds (Direct detection, LHC, ILC)
3. Results

Various experimental inputs

DM direct detection

$(\widetilde{B},\ \widetilde{H},\ \widetilde{\mu}_R)$ $(\widetilde{B},\ \widetilde{H},\ \widetilde{\mu}_L)$

- Spin-independent scattering

LUX, XENON1T

- Spin-dependent scattering

Weaker bounds than spin-independent

LHC

- Slepton production
- Neutralino/chargino production
  - decay to slepton
  - decay to *WZ* or *Wh*

Small mass difference makes it difficult…

$m_{\widetilde{l}} - m_{\widetilde{B}} \sim 10\ \mathrm{GeV}$

Future high-luminosity LHC is important!

ILC

Environment is clean!

- Slepton production

Various experimental inputs

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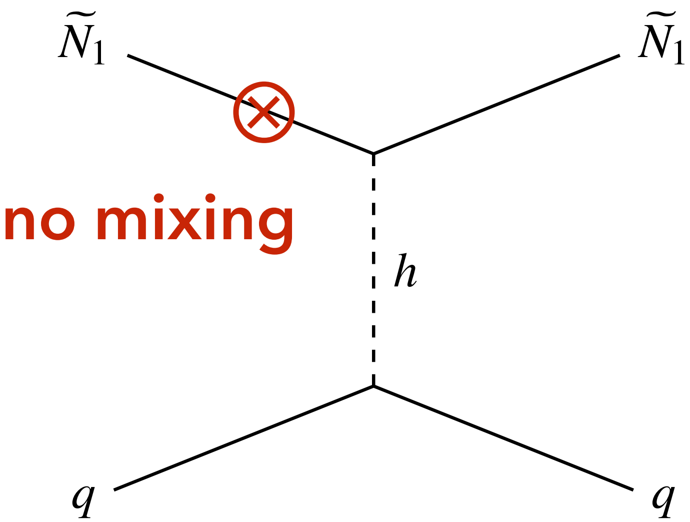
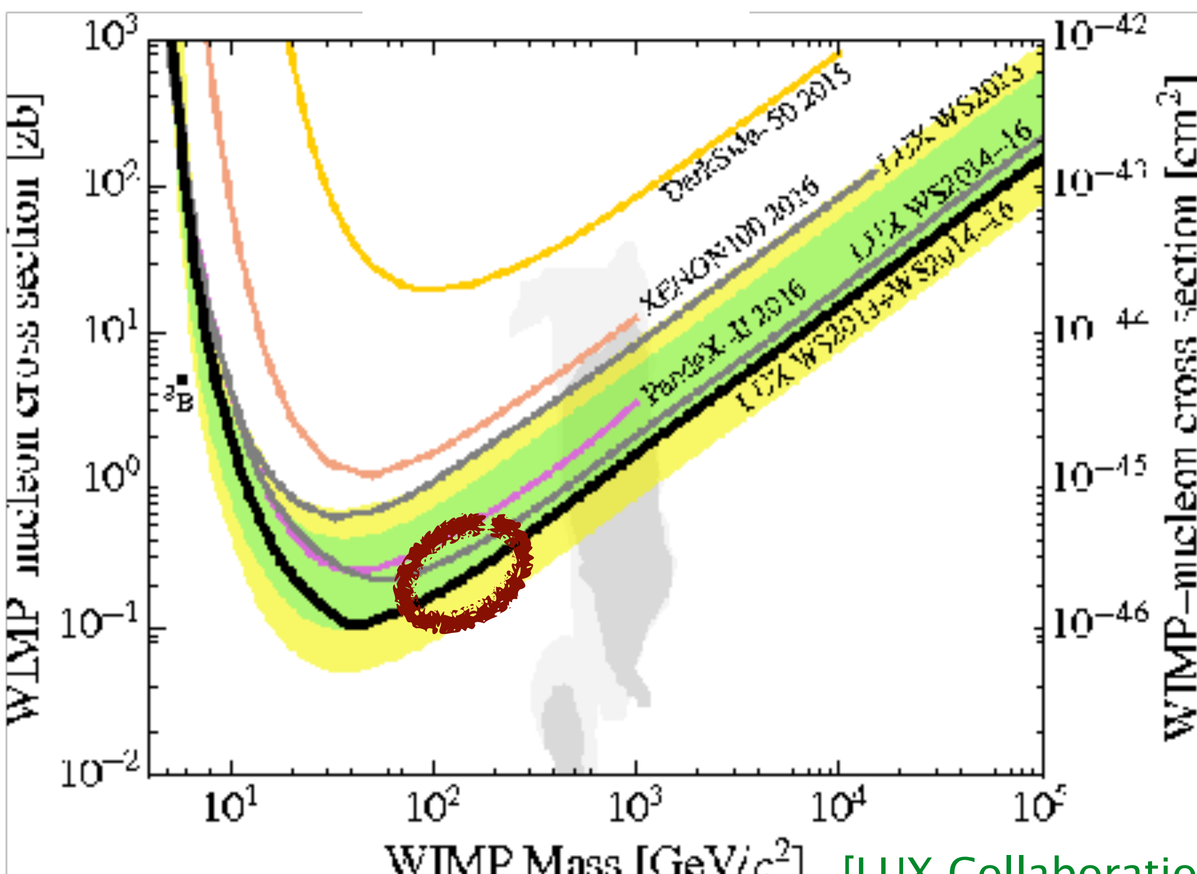


Bino-Higgsino mixing
$\sim 1/(\mu^2 - M_1^2)$

Muon g-2 favors M_1 = 100 - 200 GeV
in BHR or BHL scenario

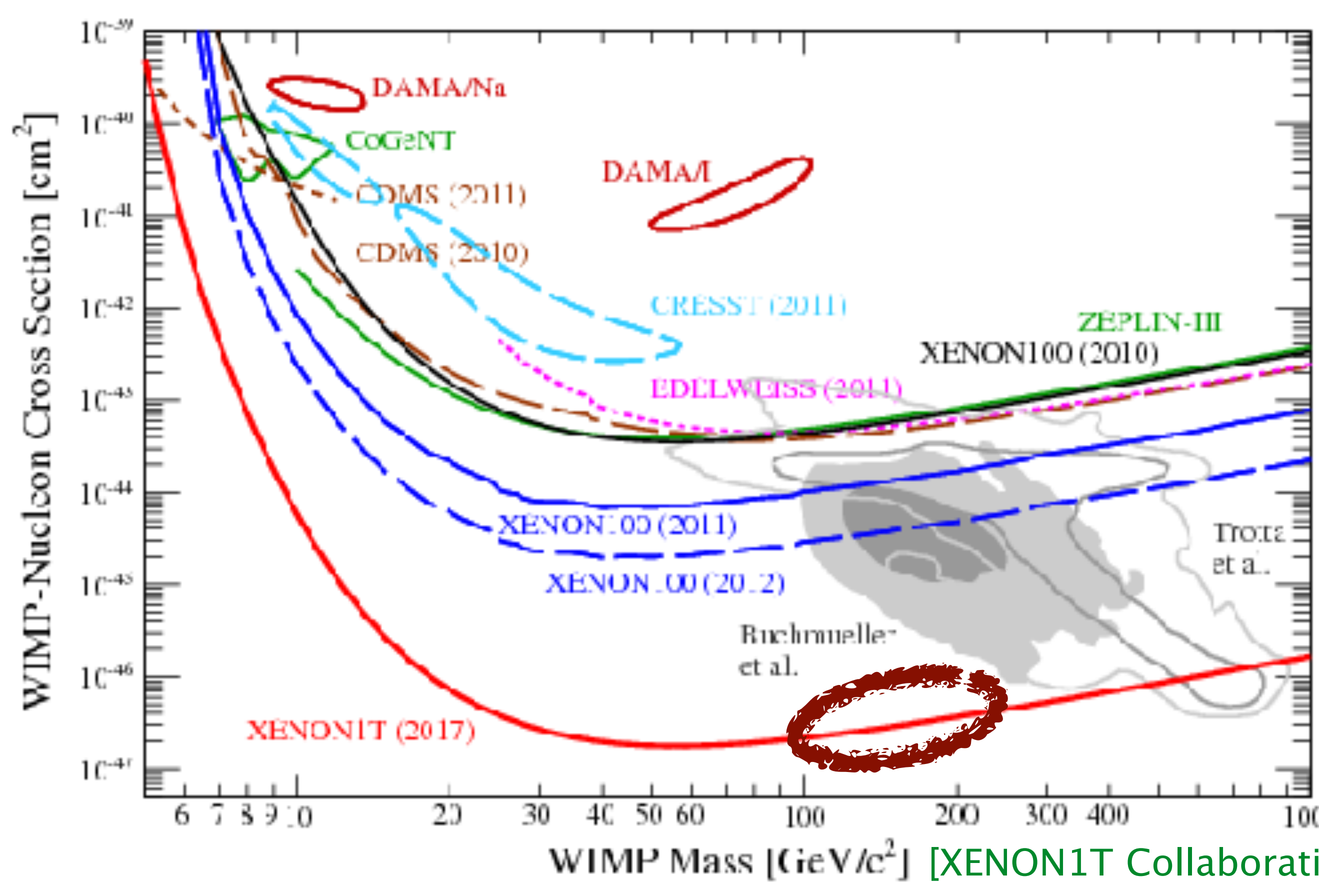
Latest LUX



[LUX Collaboration]

σ_{upper} = 0.2 - 0.3 zb

Future XENON1T

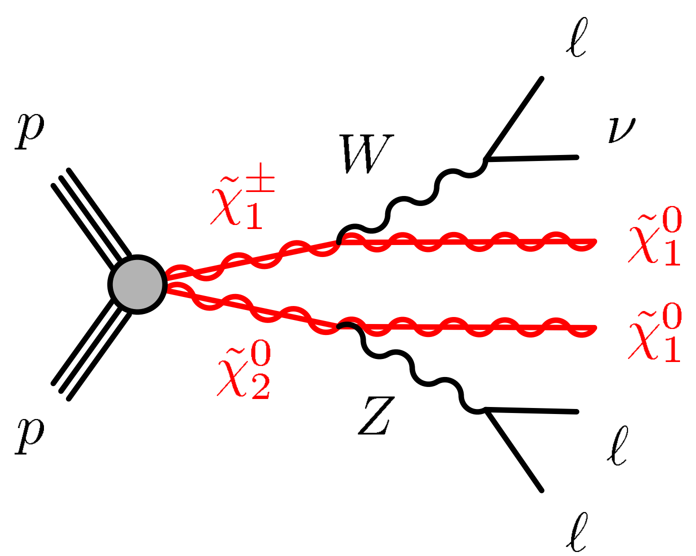


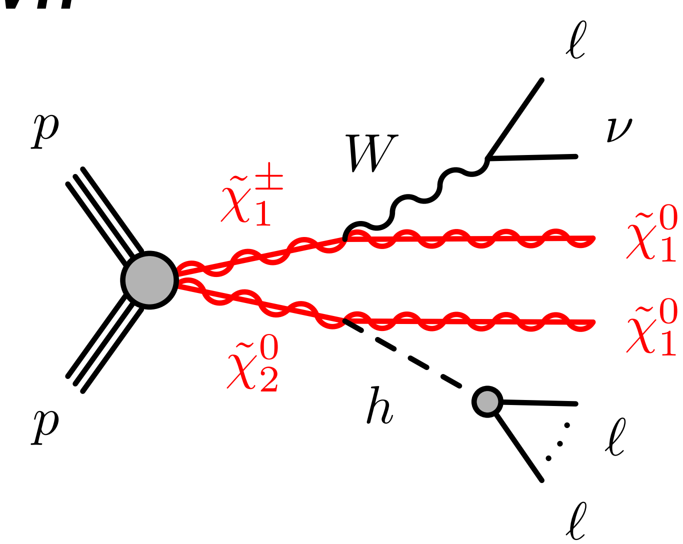
[XENON1T Collaboration]

σ_{upper} = 0.02 - 0.03 zb

High-Luminosity LHC

- **Future prospect:** $\sqrt{s} = 14\ \text{TeV}$ $\int \mathcal{L} = 3000\ \text{fb}^{-1}$
- **Higgsino pair production**
- **Decaying to 3 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$ via *WZ* or *Wh***





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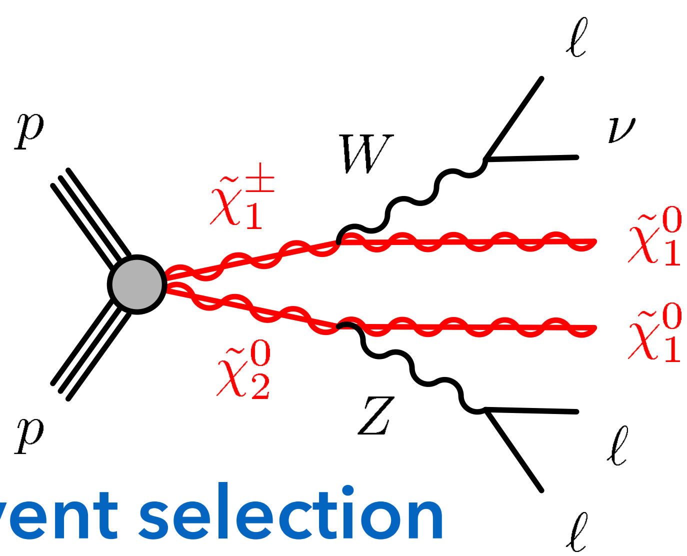

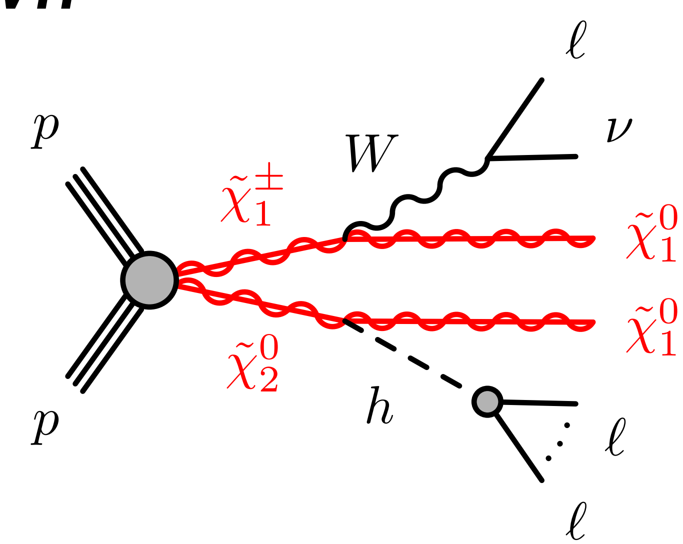

ATLAS's event selection

Selection	SRA	SRB	SRC	SRD
$\lvert m_{\mathrm{SFOZ}} - m_Z \rvert$[GeV]	< 10			
# of b-tagged jets	0			
lepton $p_T(1,2,3)$[GeV]	> 50			
$\not{E}_T$[GeV]	> 250	> 300	> 400	> 500
m_T[GeV]	> 150	> 200	> 200	> 200
$N_{95\mathrm{exp}}^{\mathrm{SRX}}$	111	38.8	17.8	9.6

Selection	SRE	SRF	SRG	SRH
SFOS pair	veto			
# of b-tagged jets	0			
$\not{E}_T$[GeV]	> 100			
$m_{\mathrm{OS}}^{\min\Delta R}$[GeV]	< 75			
$m_T(l_1)$[GeV]	> 200	> 200	> 300	> 400
$m_T(l_2)$[GeV]	> 100	> 150	> 150	> 150
$m_T(l_3)$[GeV]	> 100	> 100	> 100	> 100
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[ATL-PHYS-PUB-2014-010]

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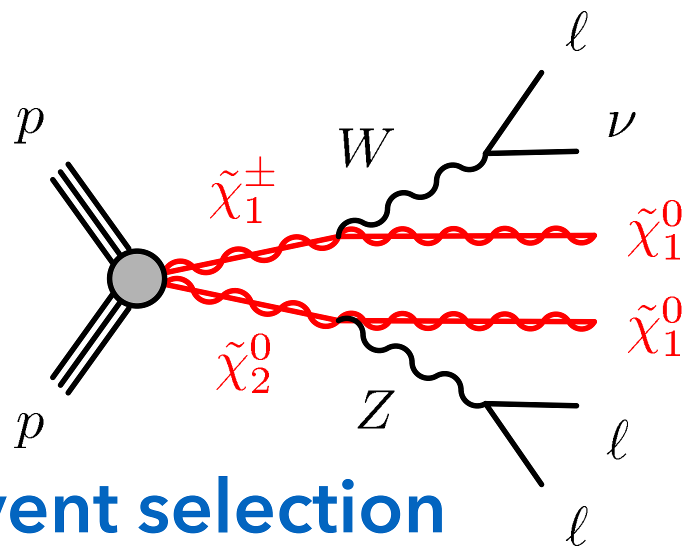

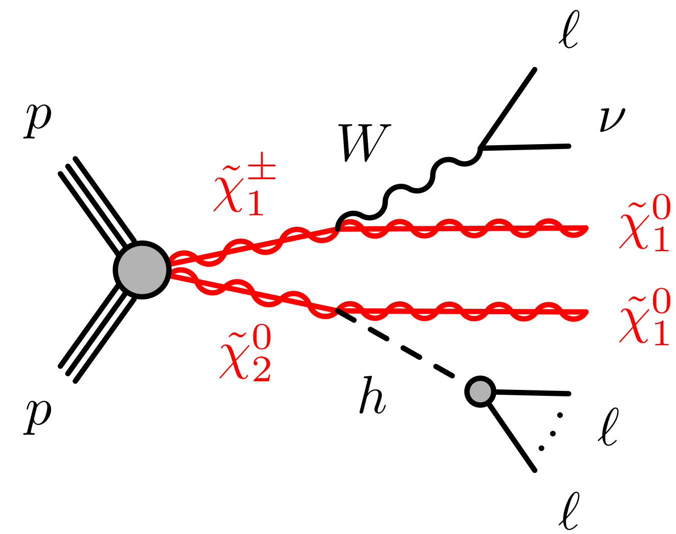

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[ATL-PHYS-PUB-2014-010]

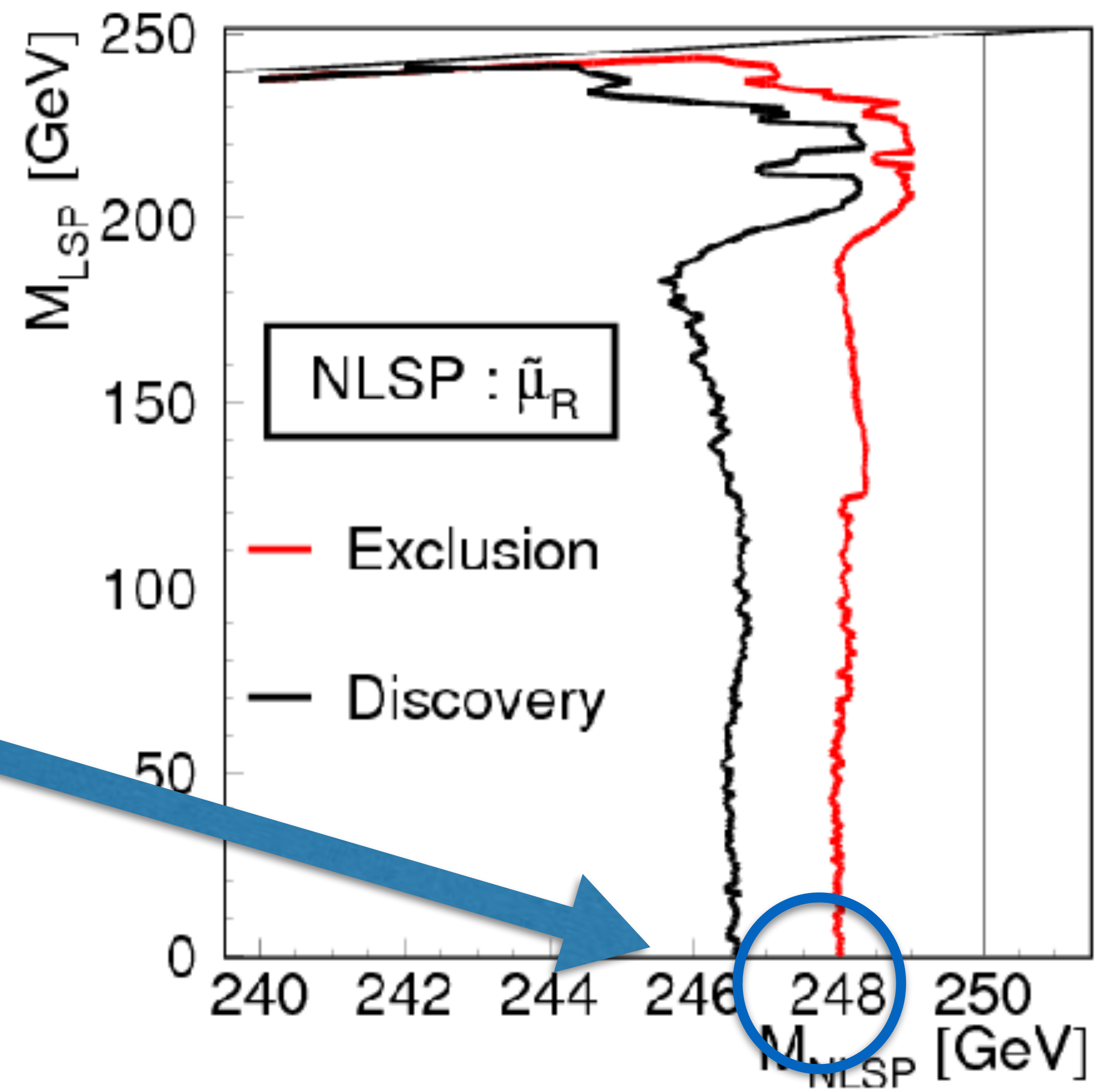
We compare these numbers to our SUSY simulation

ILC 500 GeV

Slepton production

$$e^+e^- \to \widetilde{l}^+\widetilde{l}^- \to l^+\widetilde{N}_1 l^-\widetilde{N}_1$$

- ILC can probe small mass deference!



[arXiv:1307.5248]

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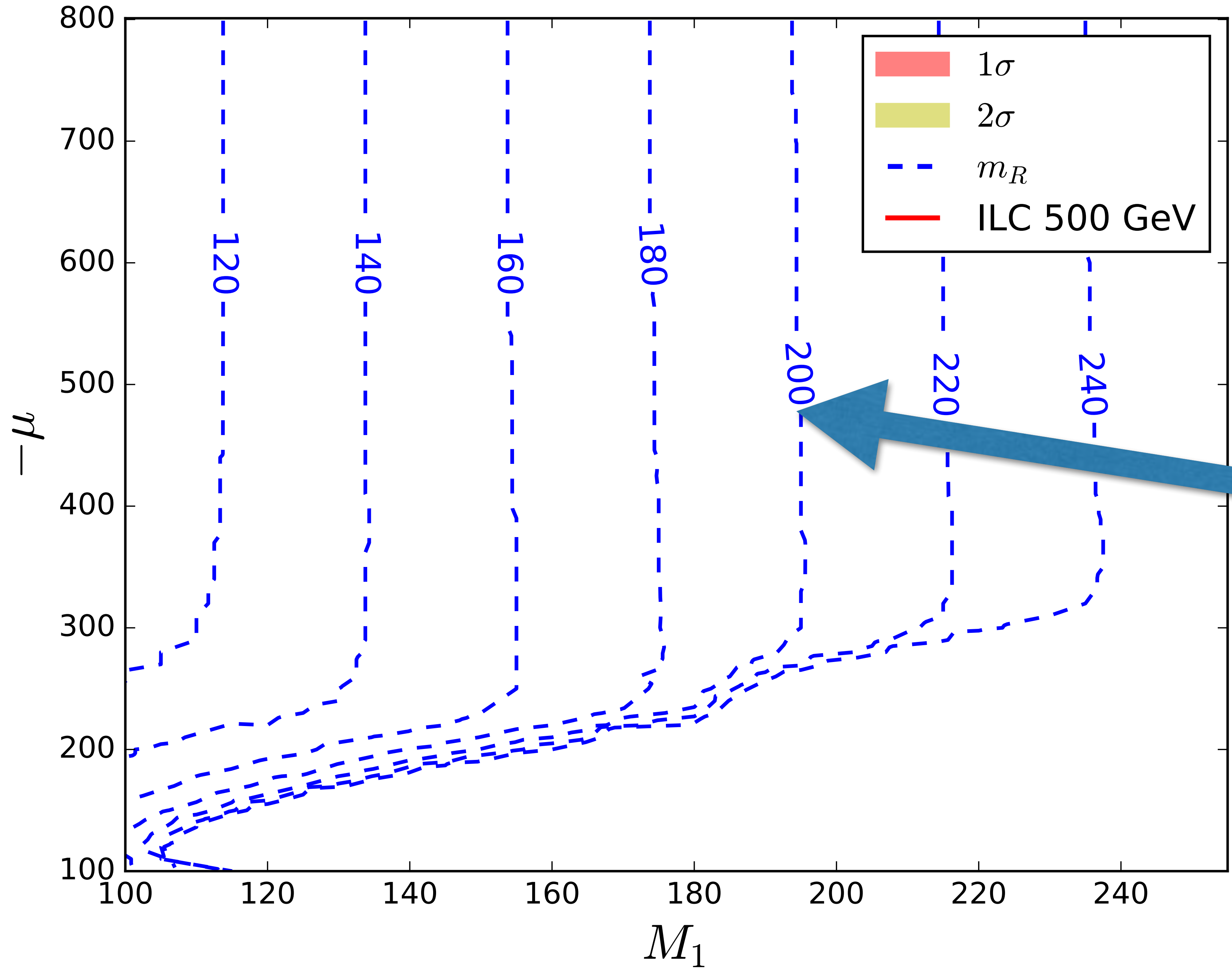
BHR scenario



Parameters:

M_1, μ, m_R, tanß=40

m_R that gives

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Bino-slepton coannihilation

[Preliminary]

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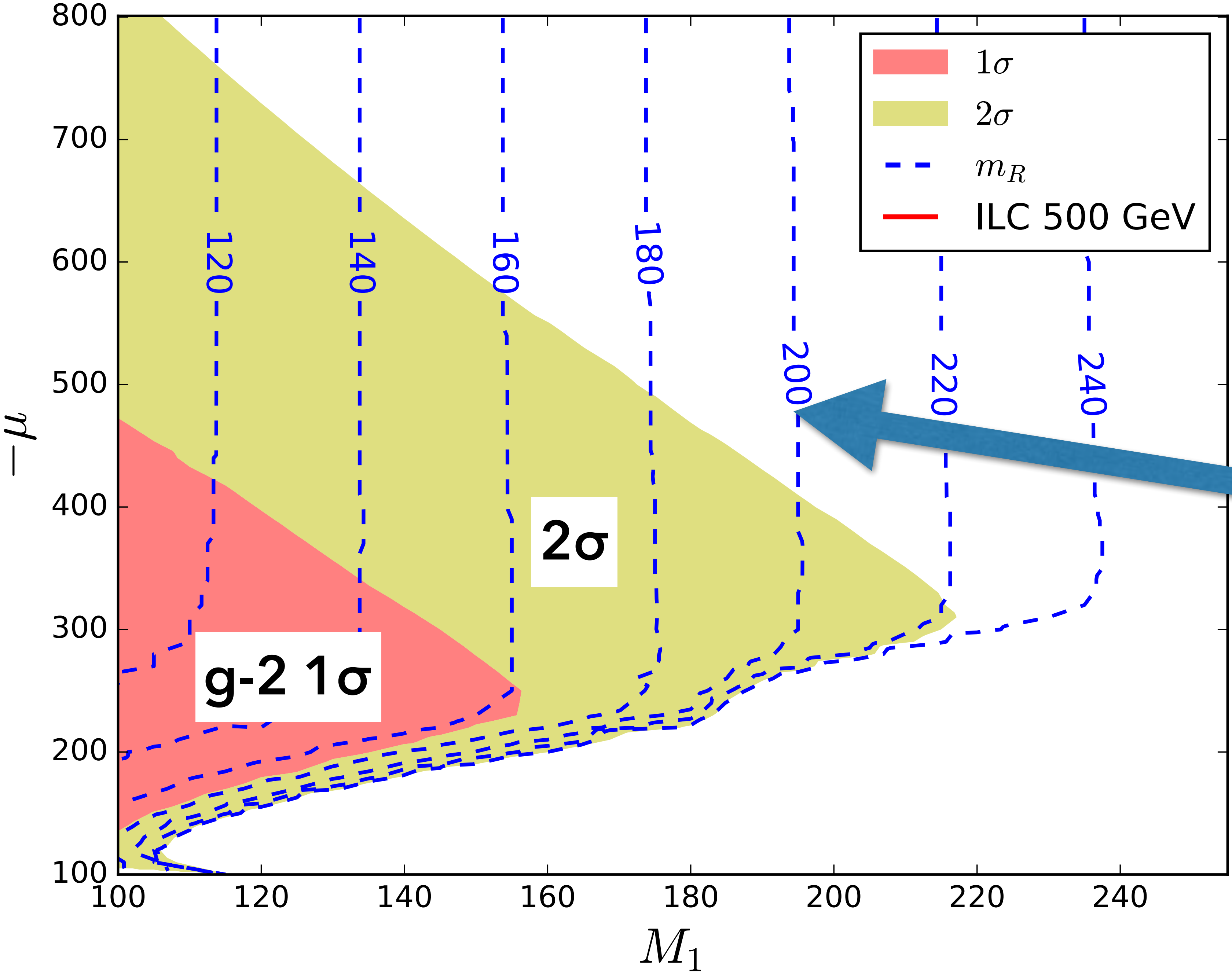

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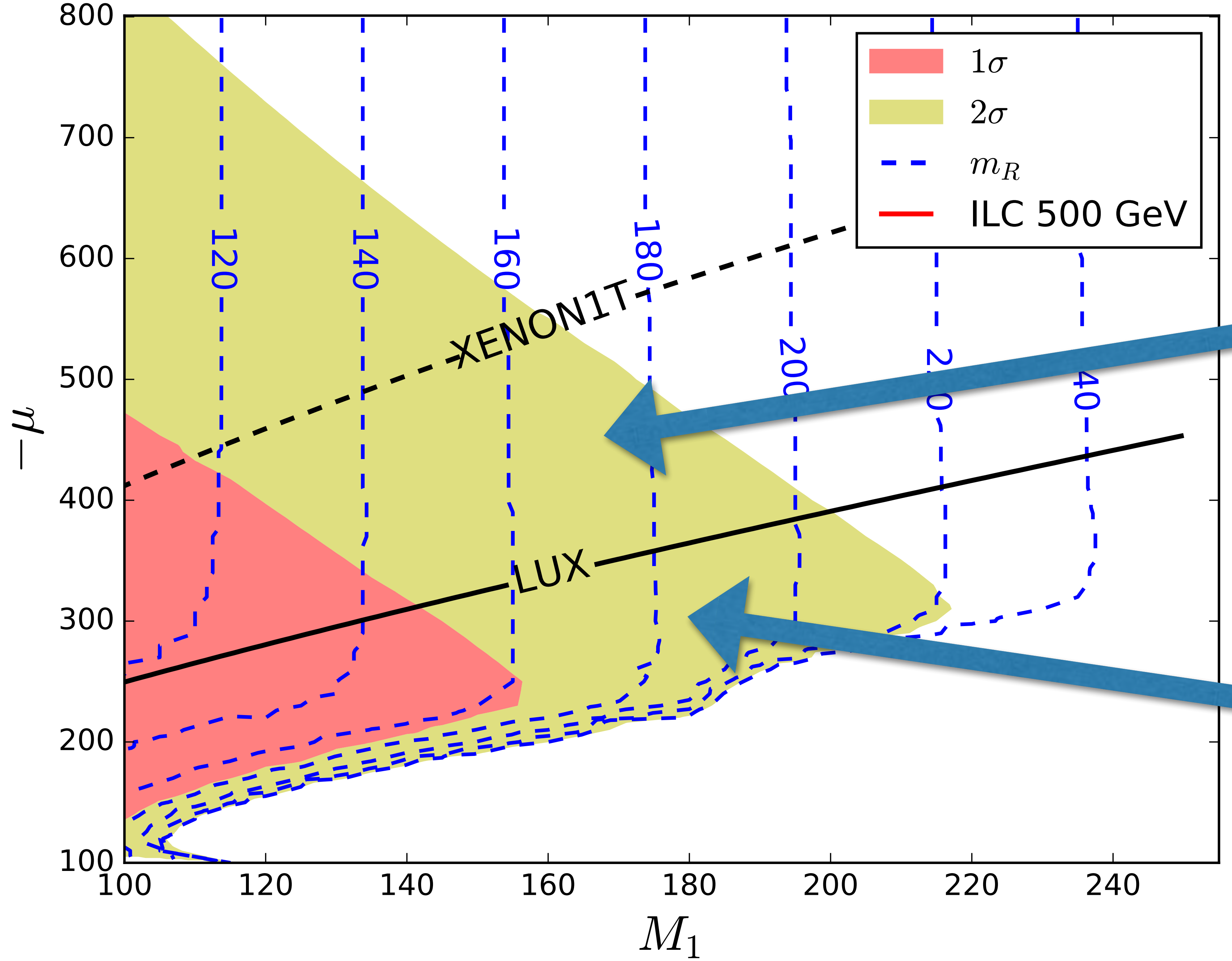
Bino-slepton coannihilation

We can calculate

$a_\mu(\mathrm{BHR}) = a_\mu(M_1, \mu, m_R)$

$\mu M_1 < 0$ is favored by g-2

BHR scenario



XENON1T will probe here (this year?)

Excluded by LUX

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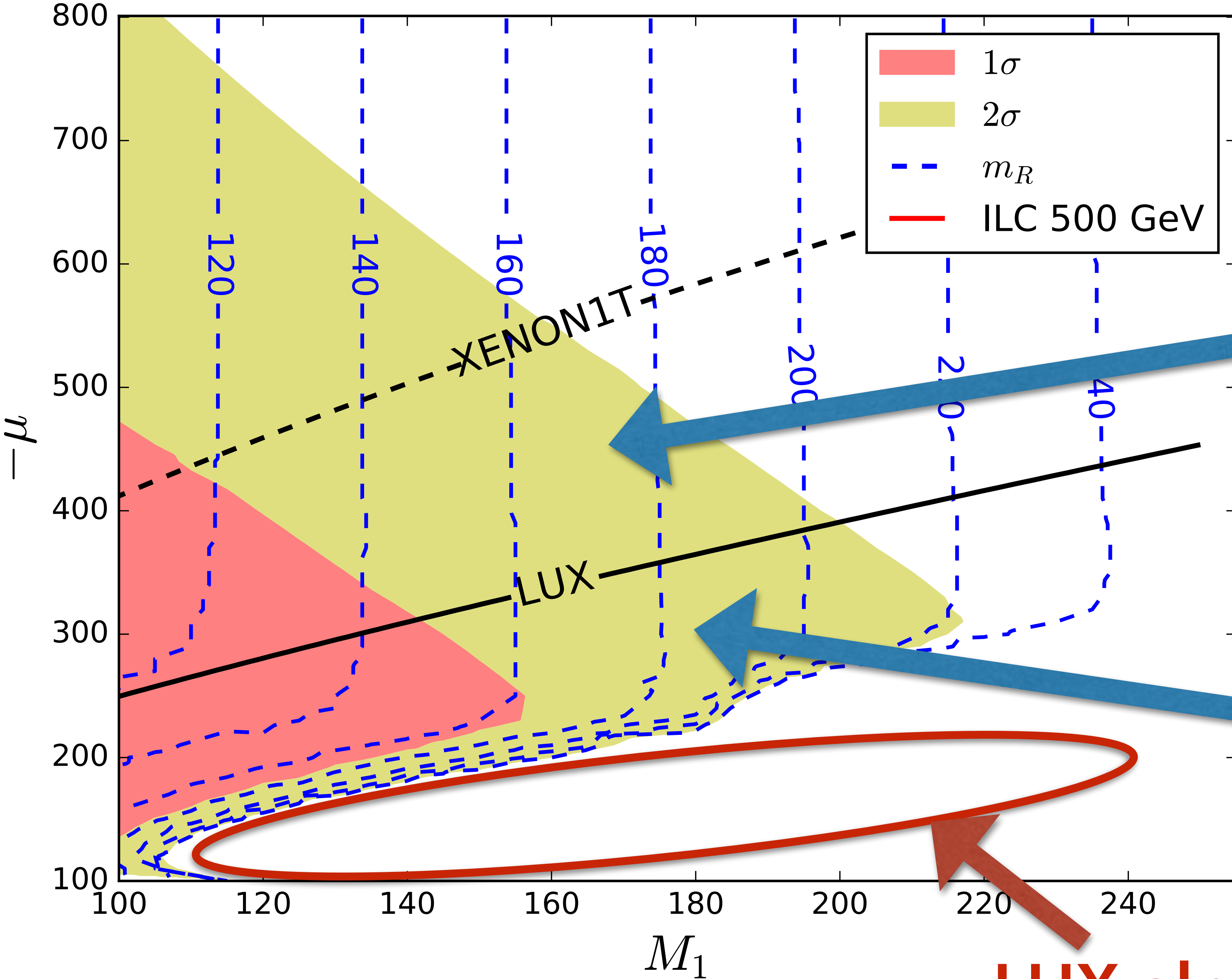

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LUX already excluded well-tempered bino-Higgsino in this scenario!

[Preliminary]

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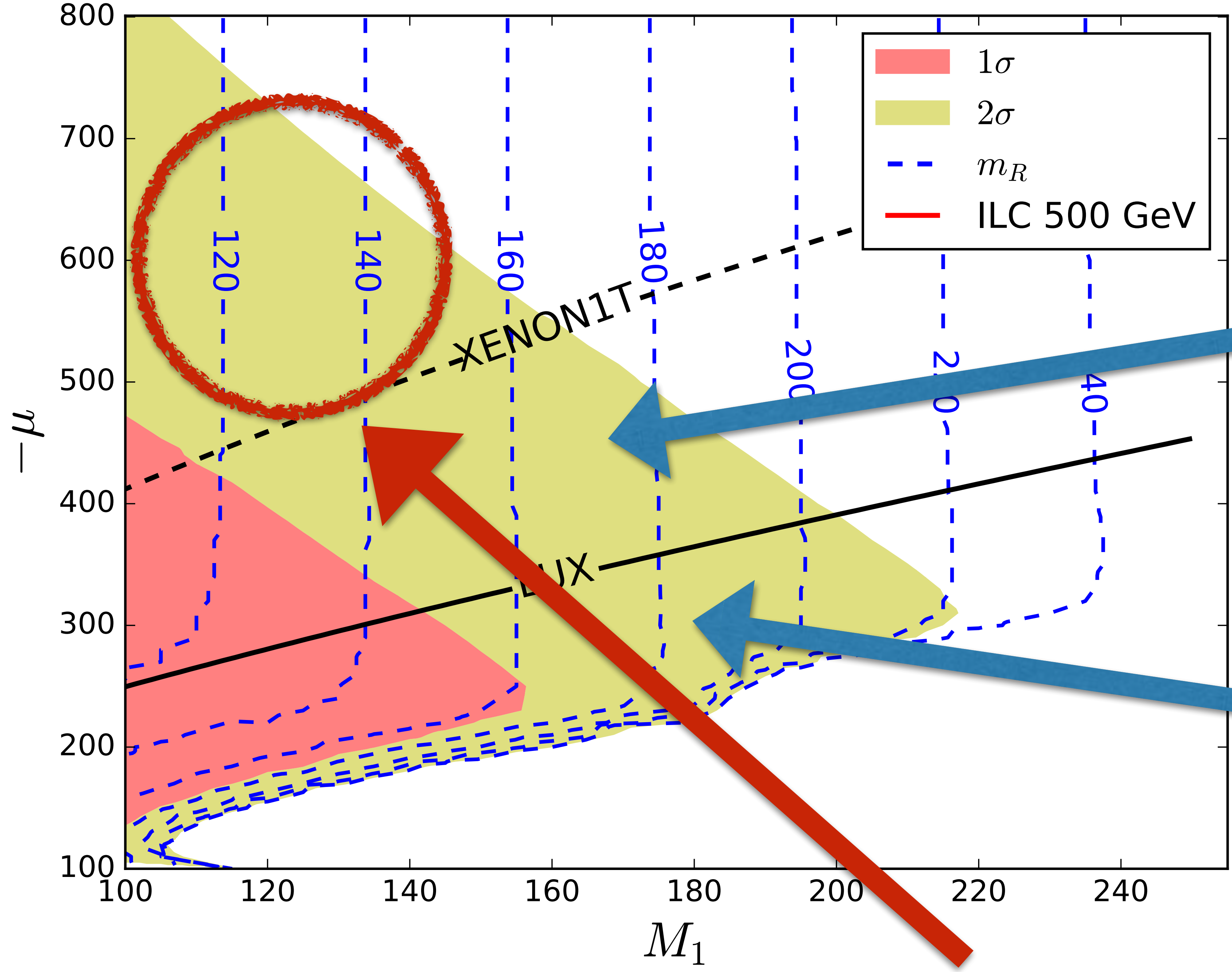

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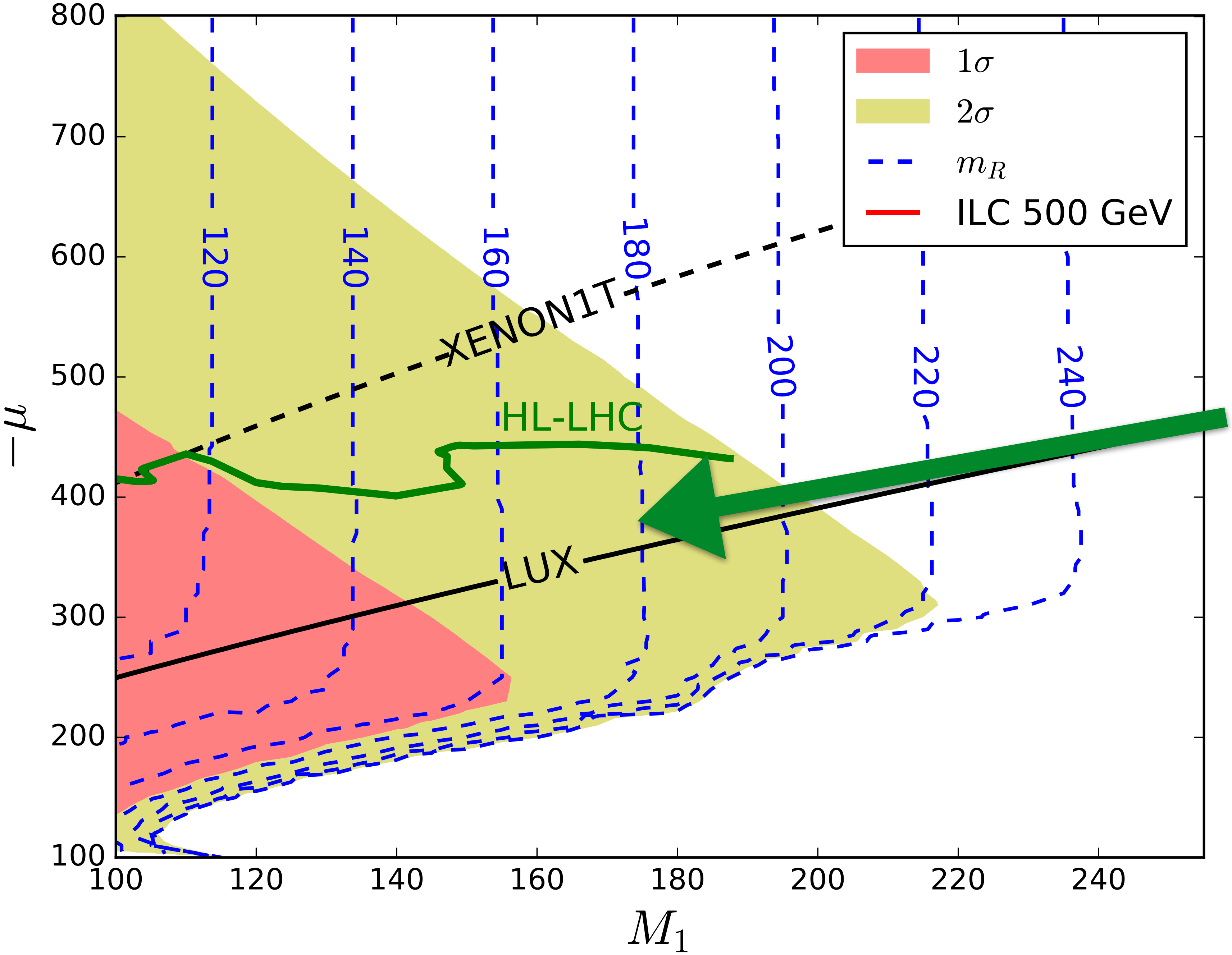
[Preliminary]

Can LHC probe here?

BHR scenario



[Preliminary]

HL-LHC can probe here
Weaker than XENON1T!

$$\mathrm{Br}(\widetilde{H} \to \widetilde{\tau} + \tau(\nu_\tau))$$
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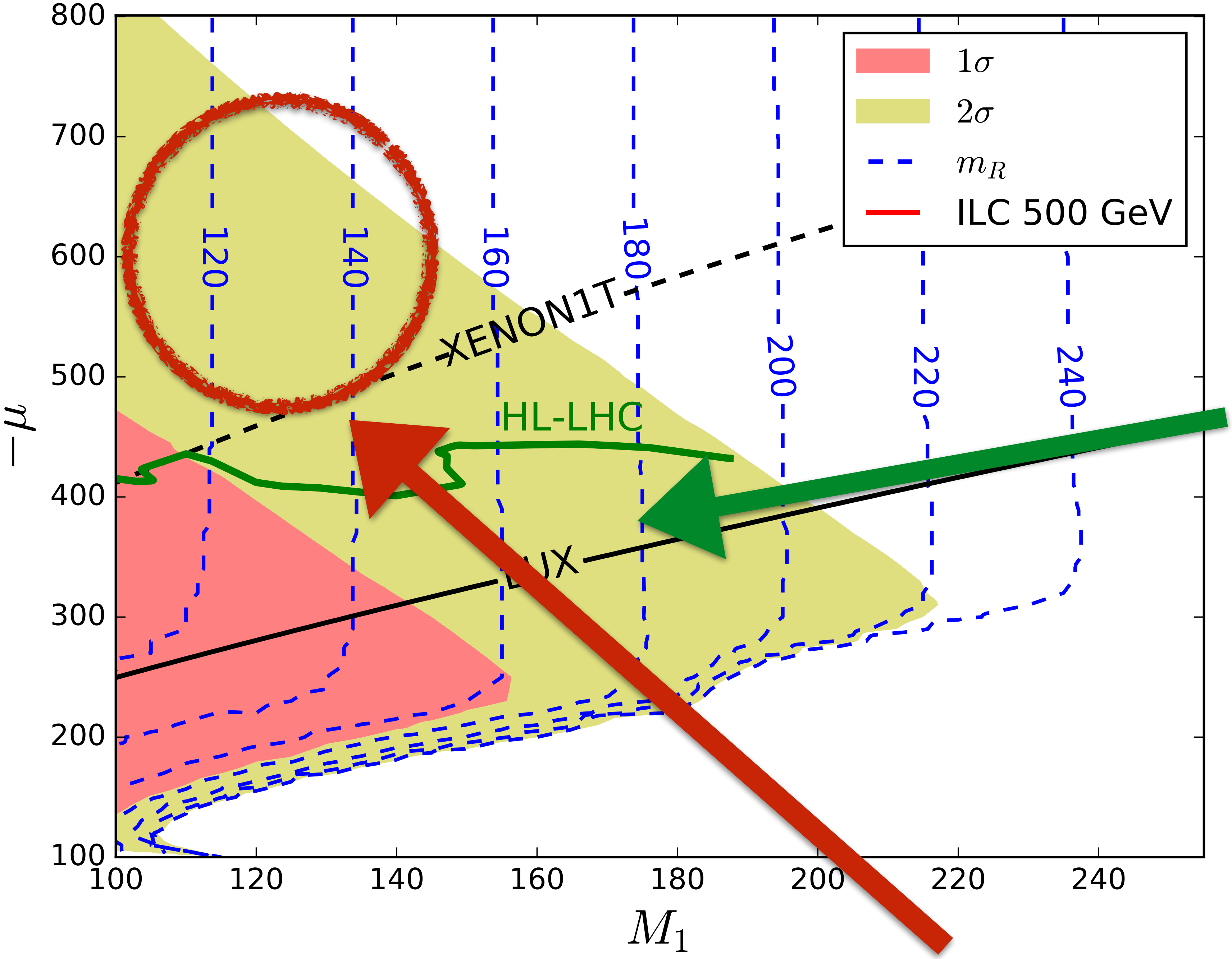
BHR scenario



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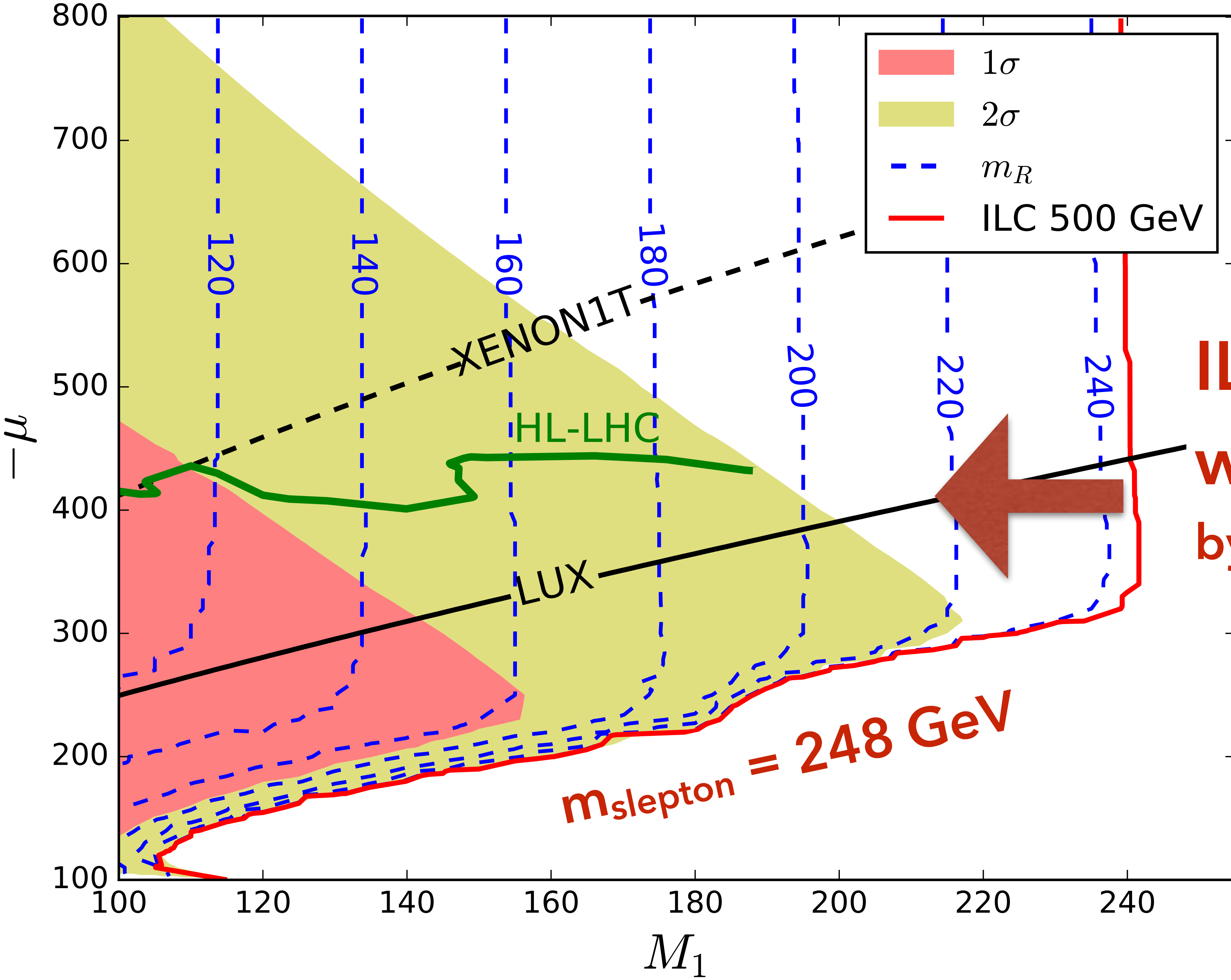
This region cannot be studied!

BHR scenario

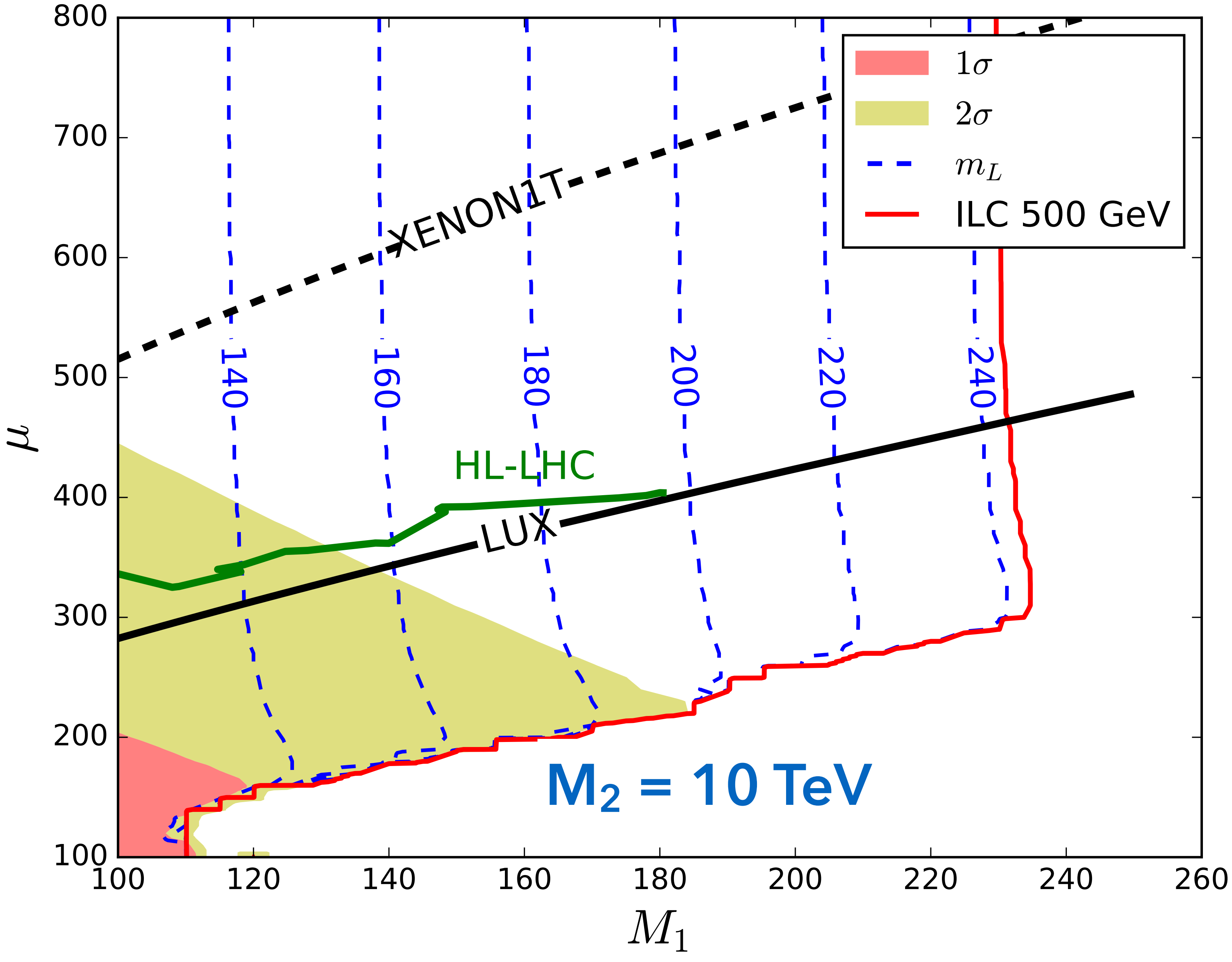


ILC 500 GeV can probe whole parameter space!

by slepton production

[Preliminary]

BHL scenario



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But M_2 is important since WHL contribution is large

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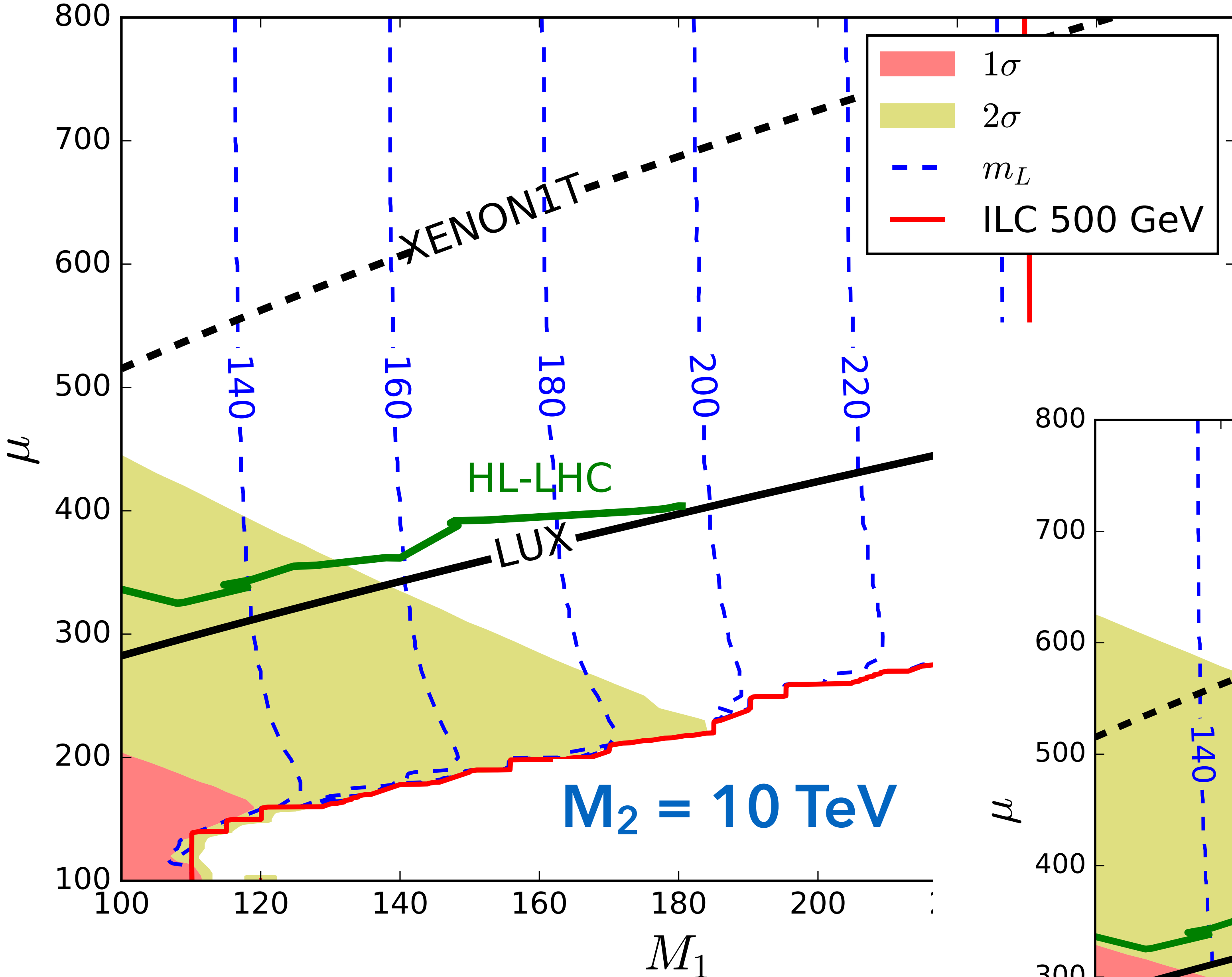

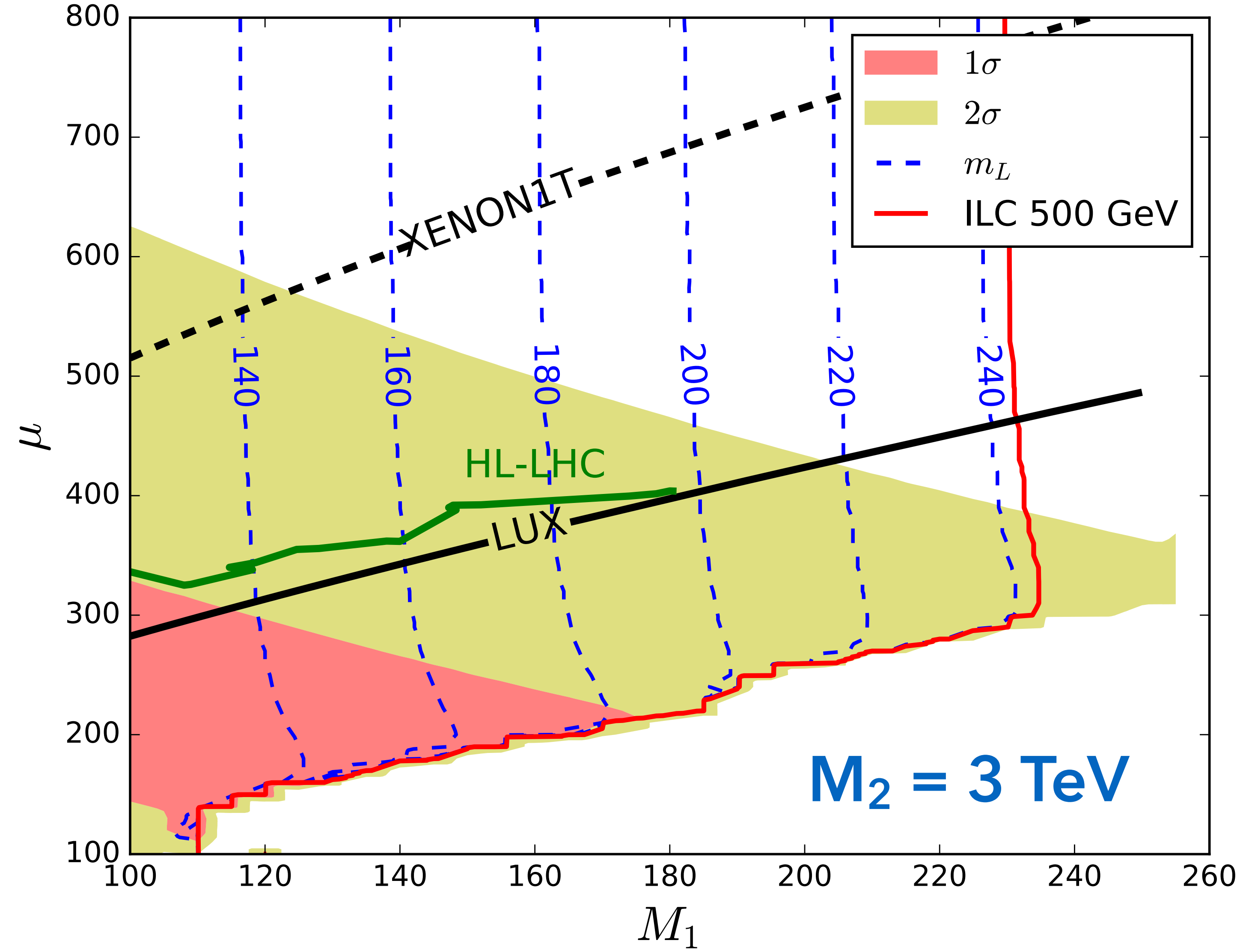

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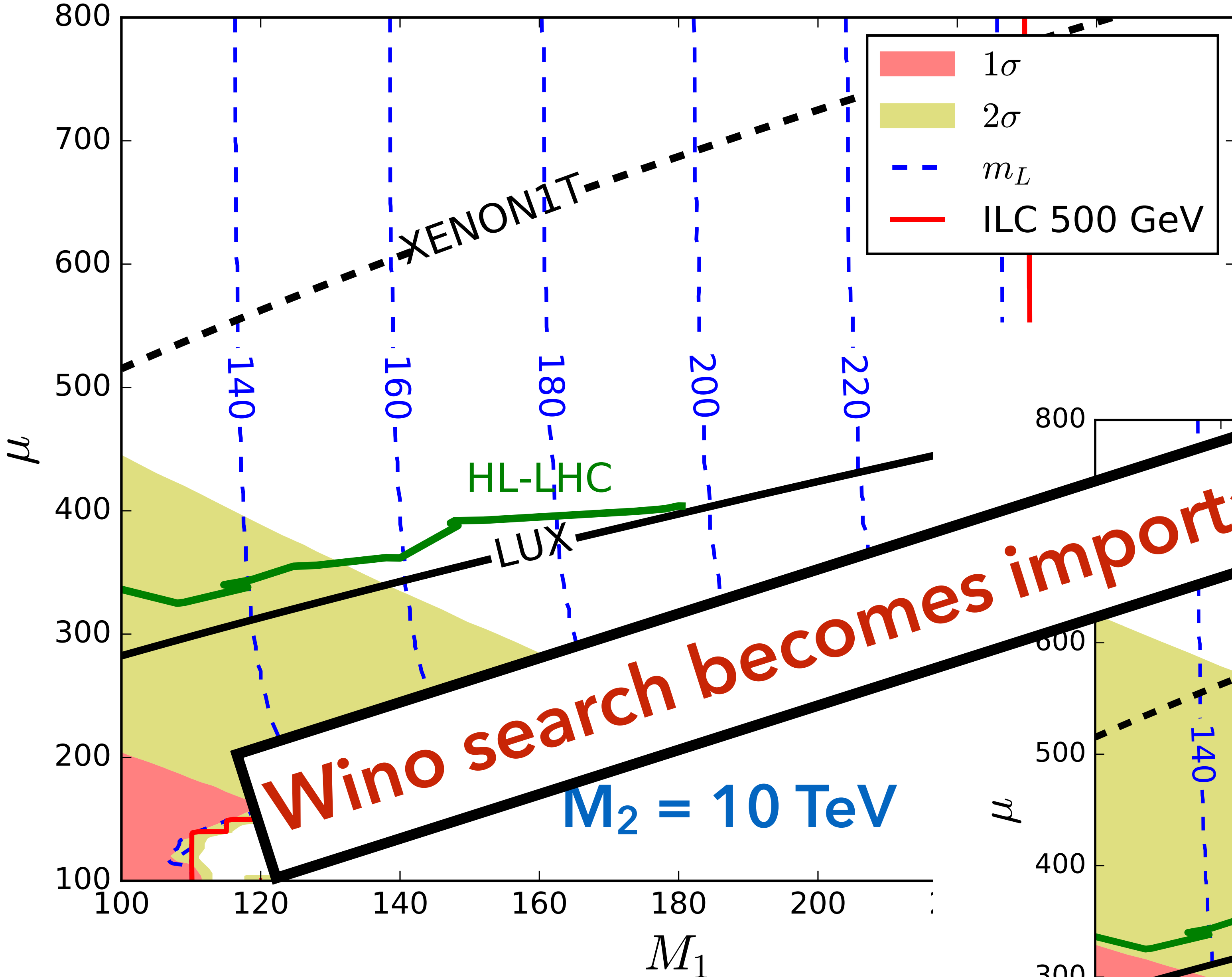
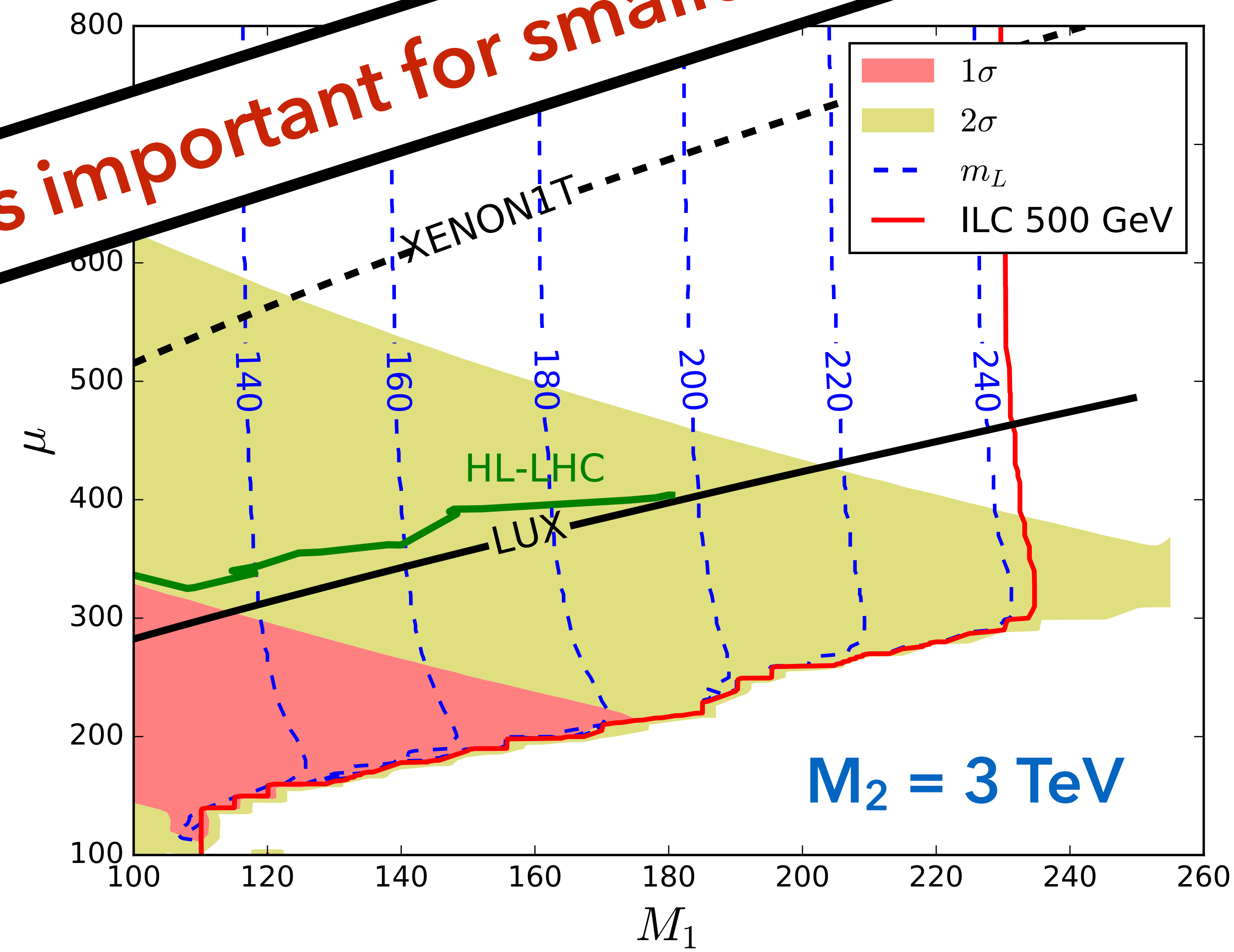
Looks similar to BHR scenario

But M_2 is important since WHL contribution is large





Wino search becomes important for smaller M_2!!

[Preliminary]

Summary

- MSSM can solve both the DM and muon g-2 anomaly
- We classify MSSM contributions into 4 scenarios
- BHR scenario cannot be covered even at the HL-LHC
- ILC is important!

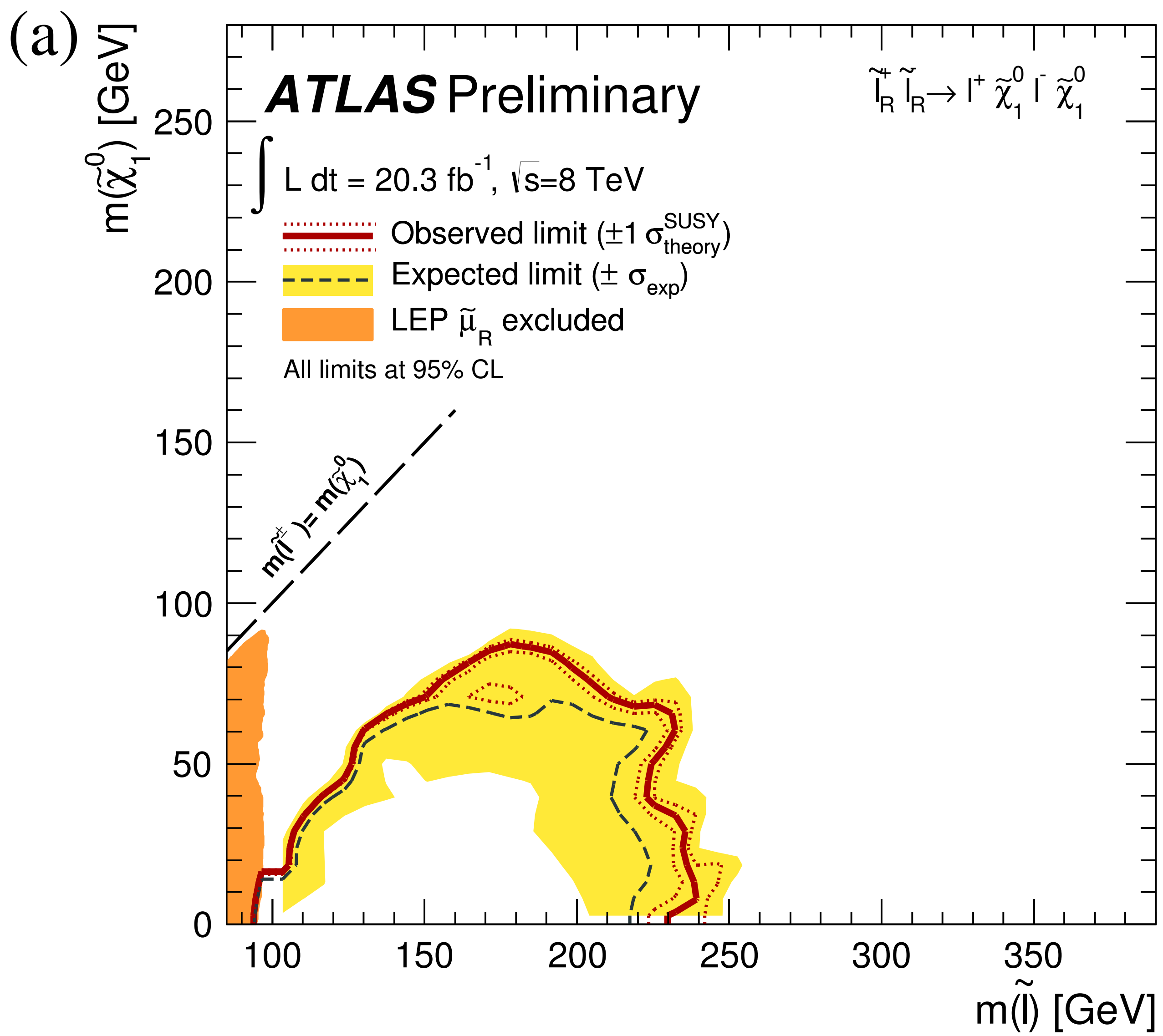
Backup

8 TeV: 2l + E_T^{miss}

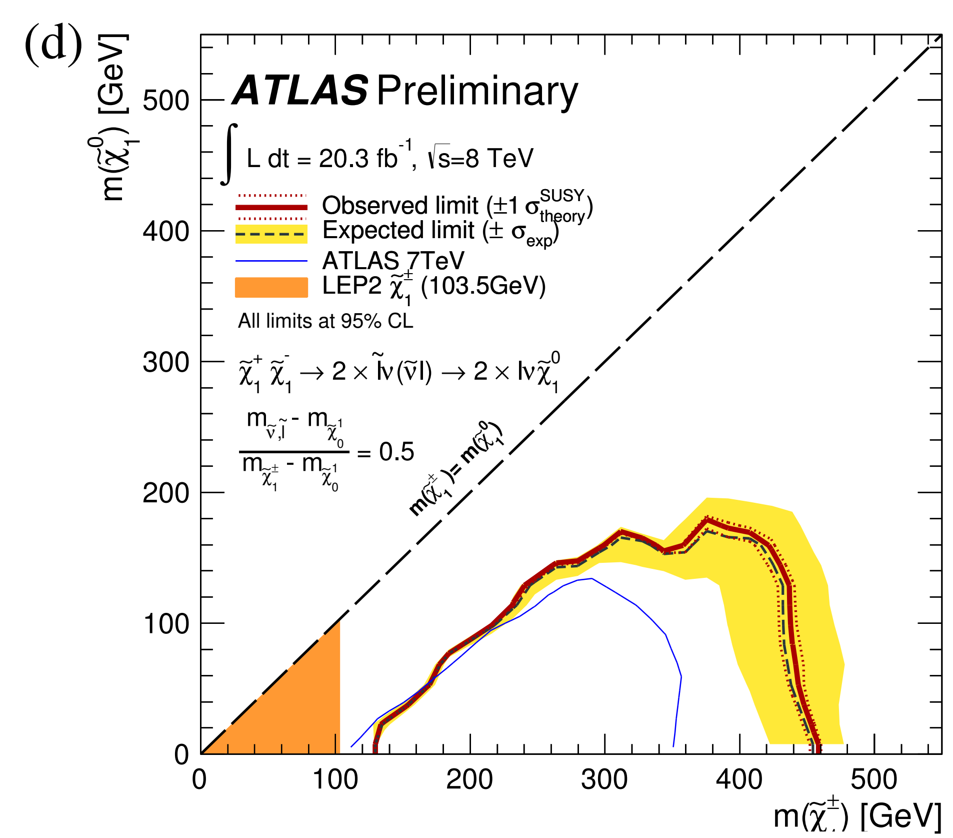
Slepton production

Mass bounds on bino-like LSP is ~100 GeV

Difficult to probe small mass difference



From chargino decay??

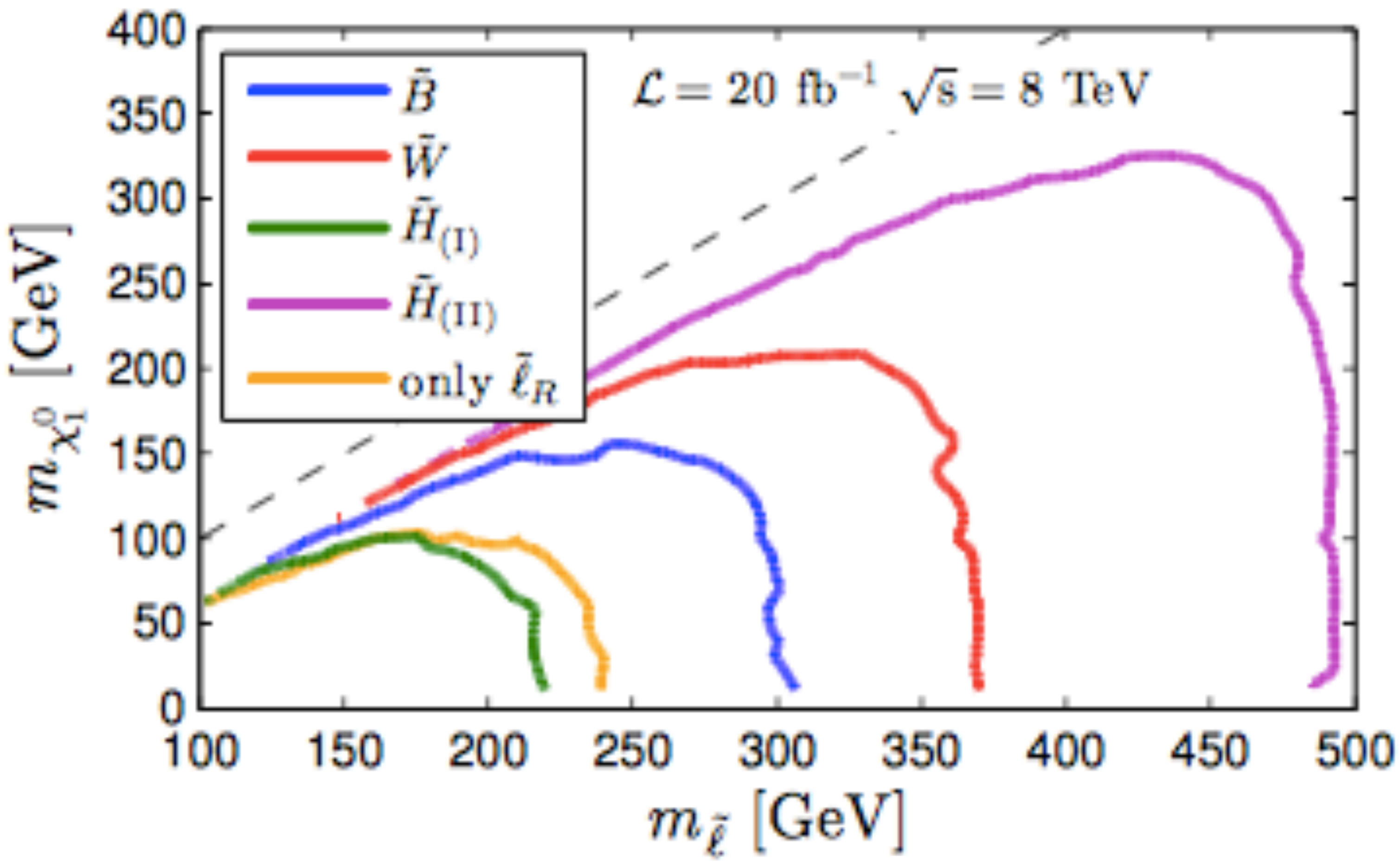


[ATLAS-CONF-2013-049]

8 TeV: 2l + E_T^{miss}

Slepton production

In the case of left-handed slepton,
It depends on the character of the LSP

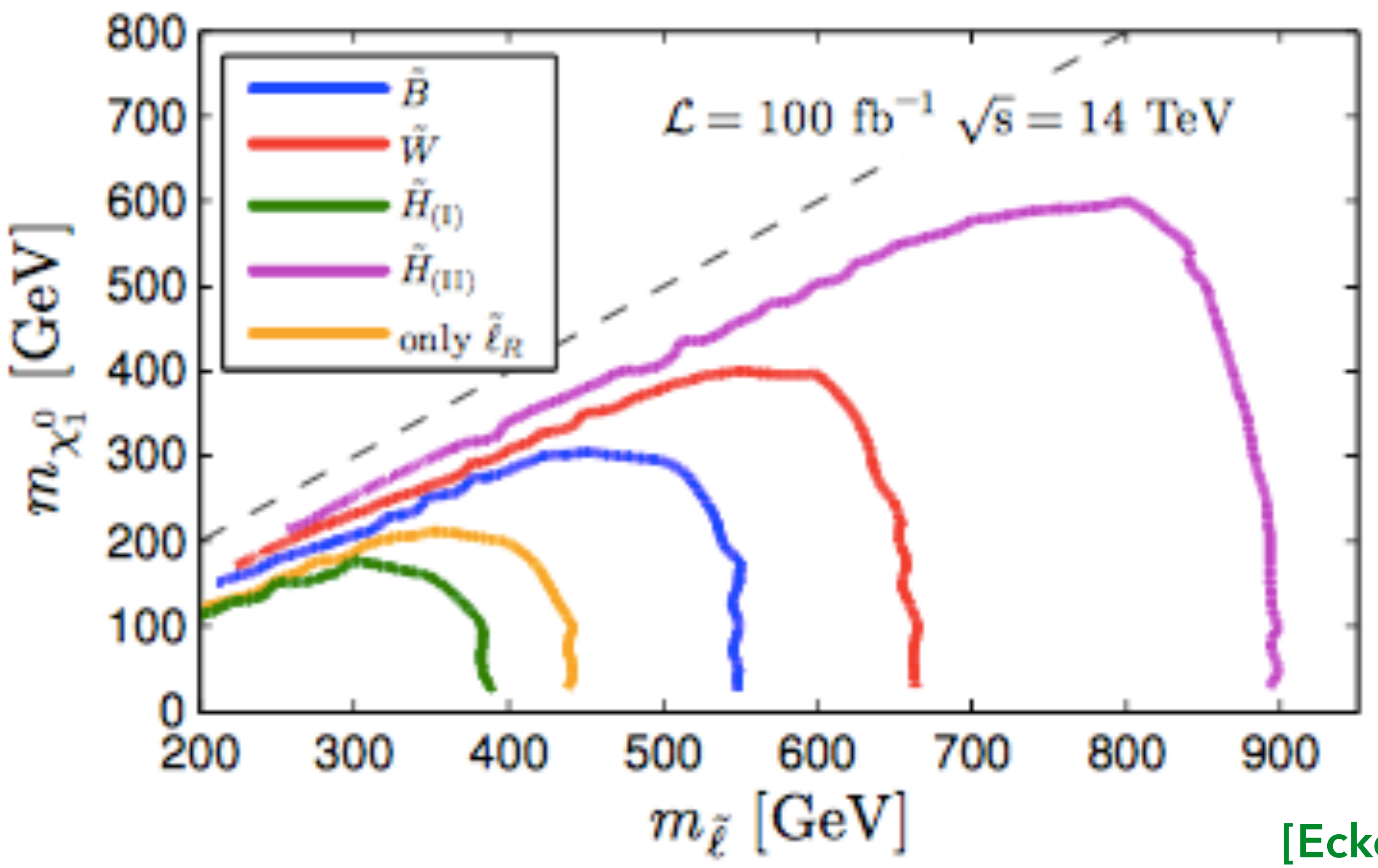


[Eckel et.al., 1408.2841]

14 TeV: 2l + E_T^{miss}

Slepton priduction

Even at 14 TeV, it is difficult to probe small mass difference



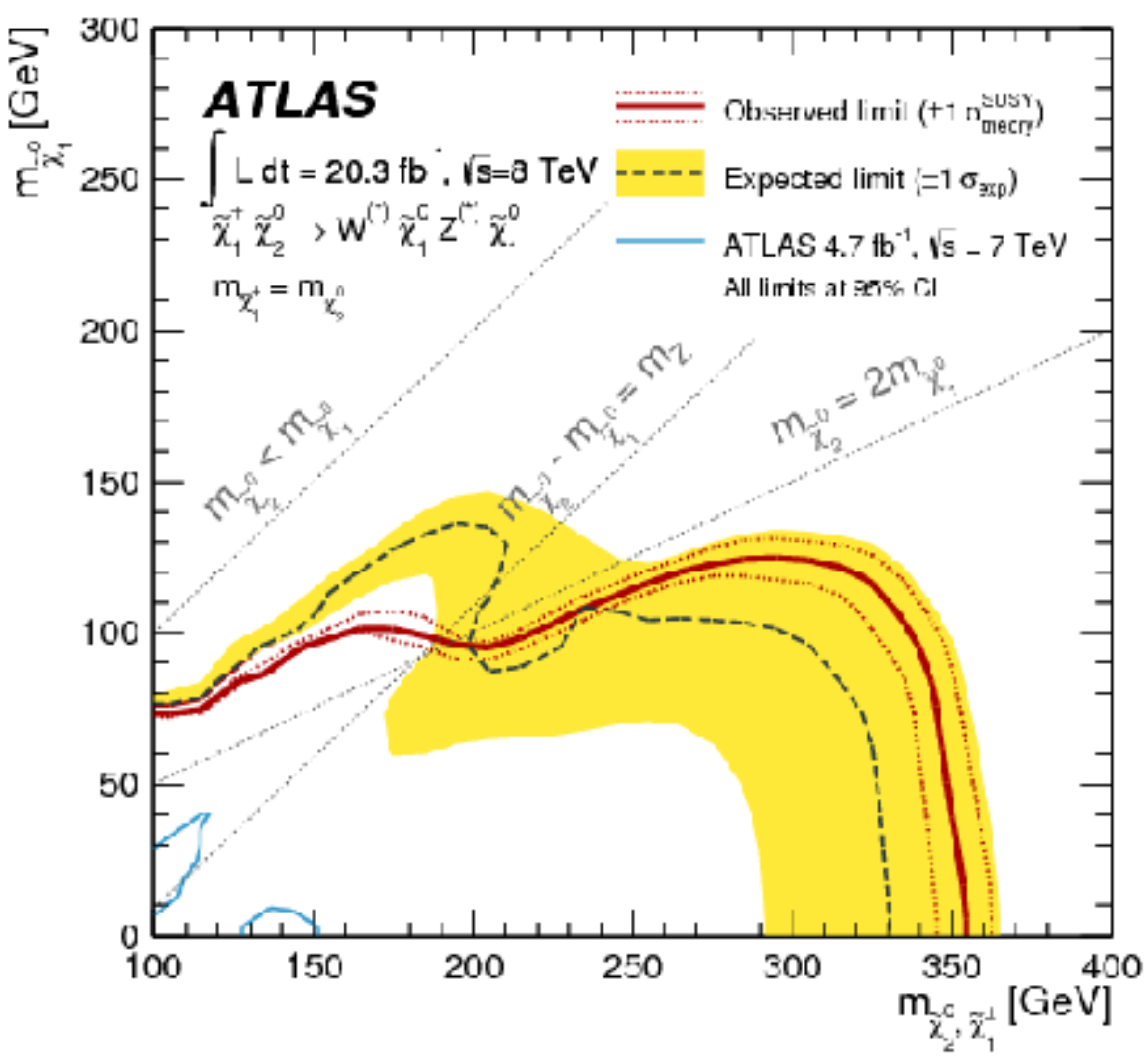
[Eckel et.al., 1408.2841]

8 TeV: 3l + E_T^{miss}

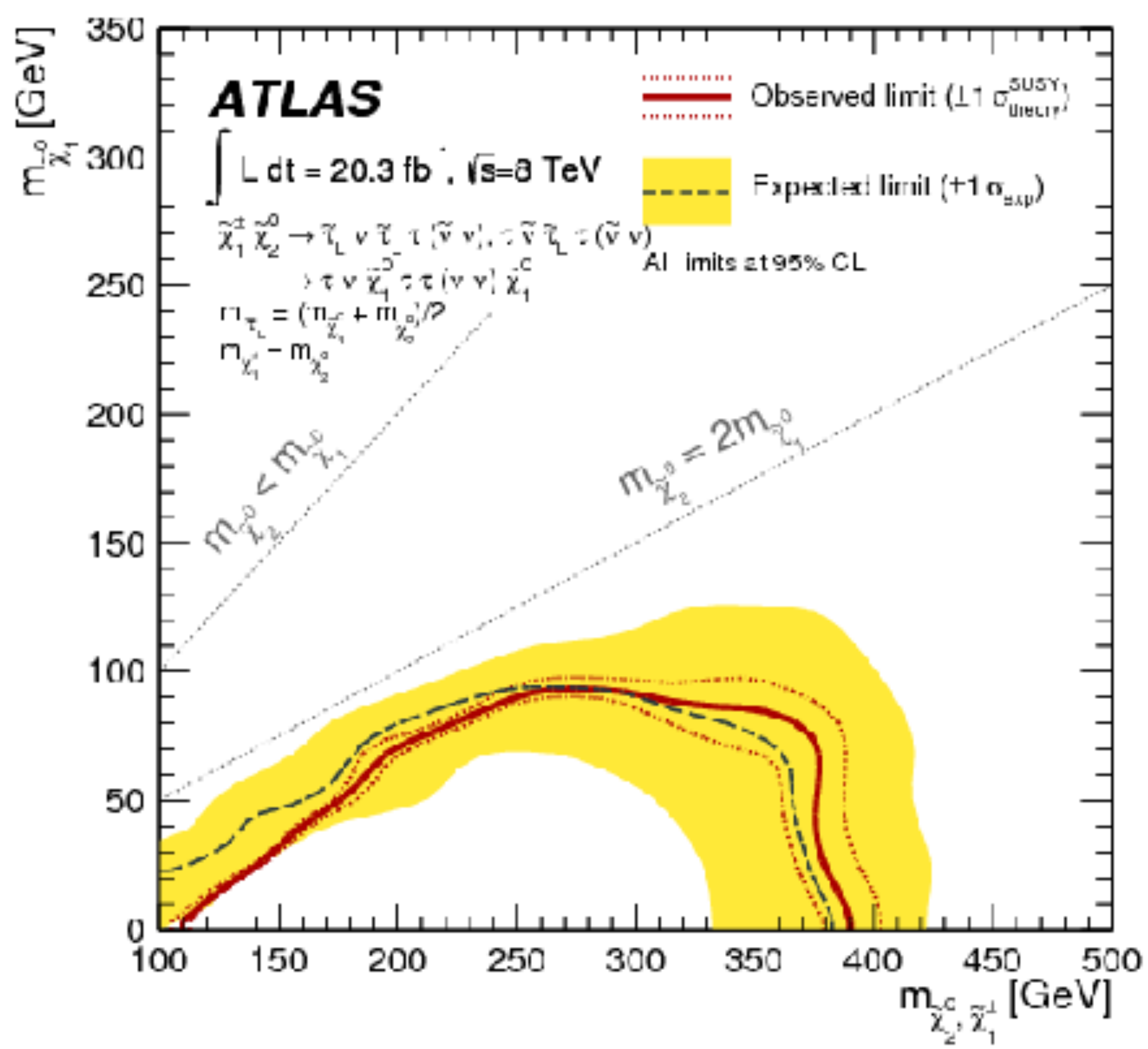
Neutralino/chargino production

In BHR or BHL scenario, neutralino/chargino decay to WZ, Wh, or stau

WZ



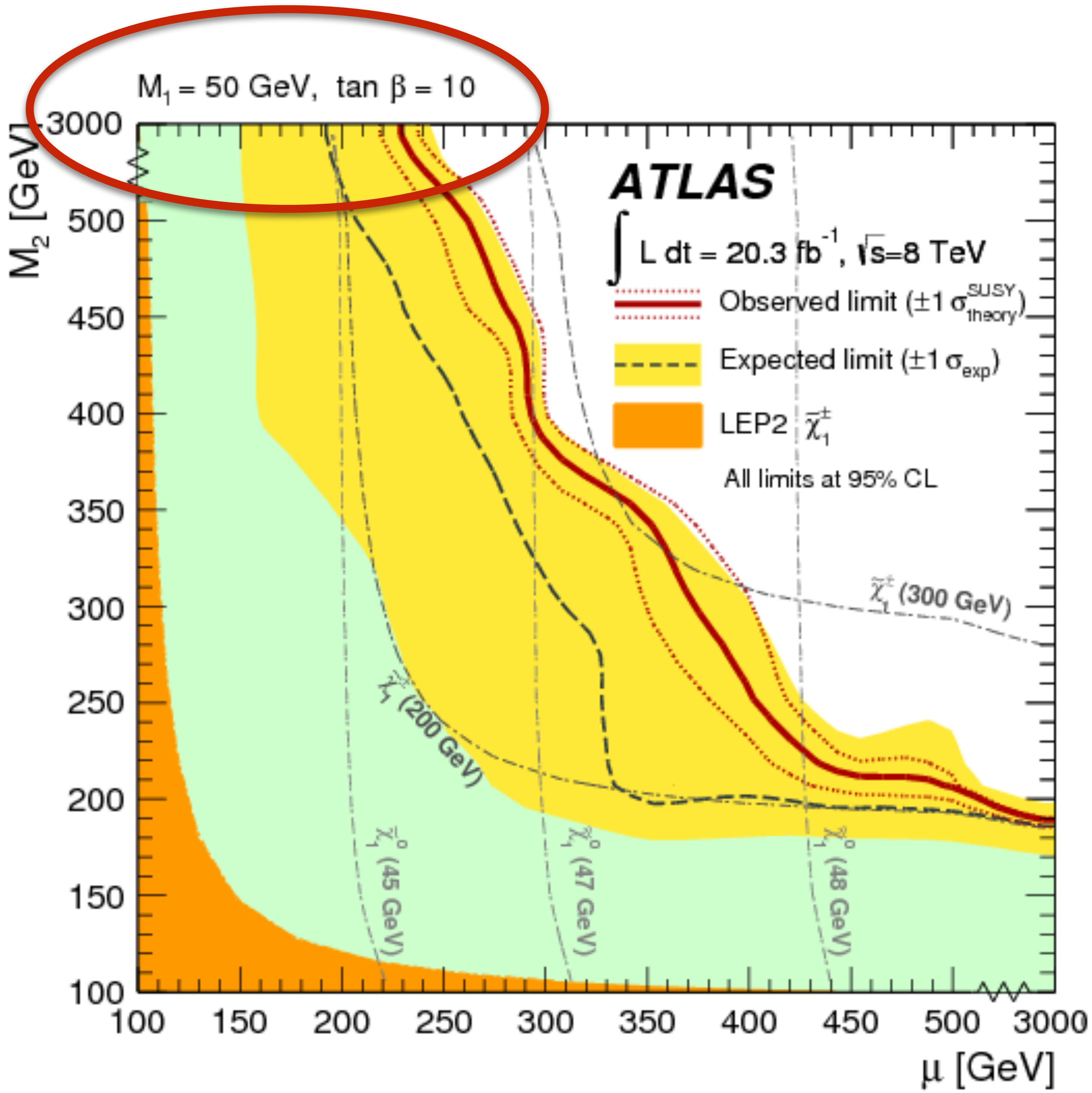
Stau



Mass bounds on LSP is ~100 GeV

8 TeV: 3l + E_T^{miss}

Neutralino/chargino production
Highly depends on the spectrum…

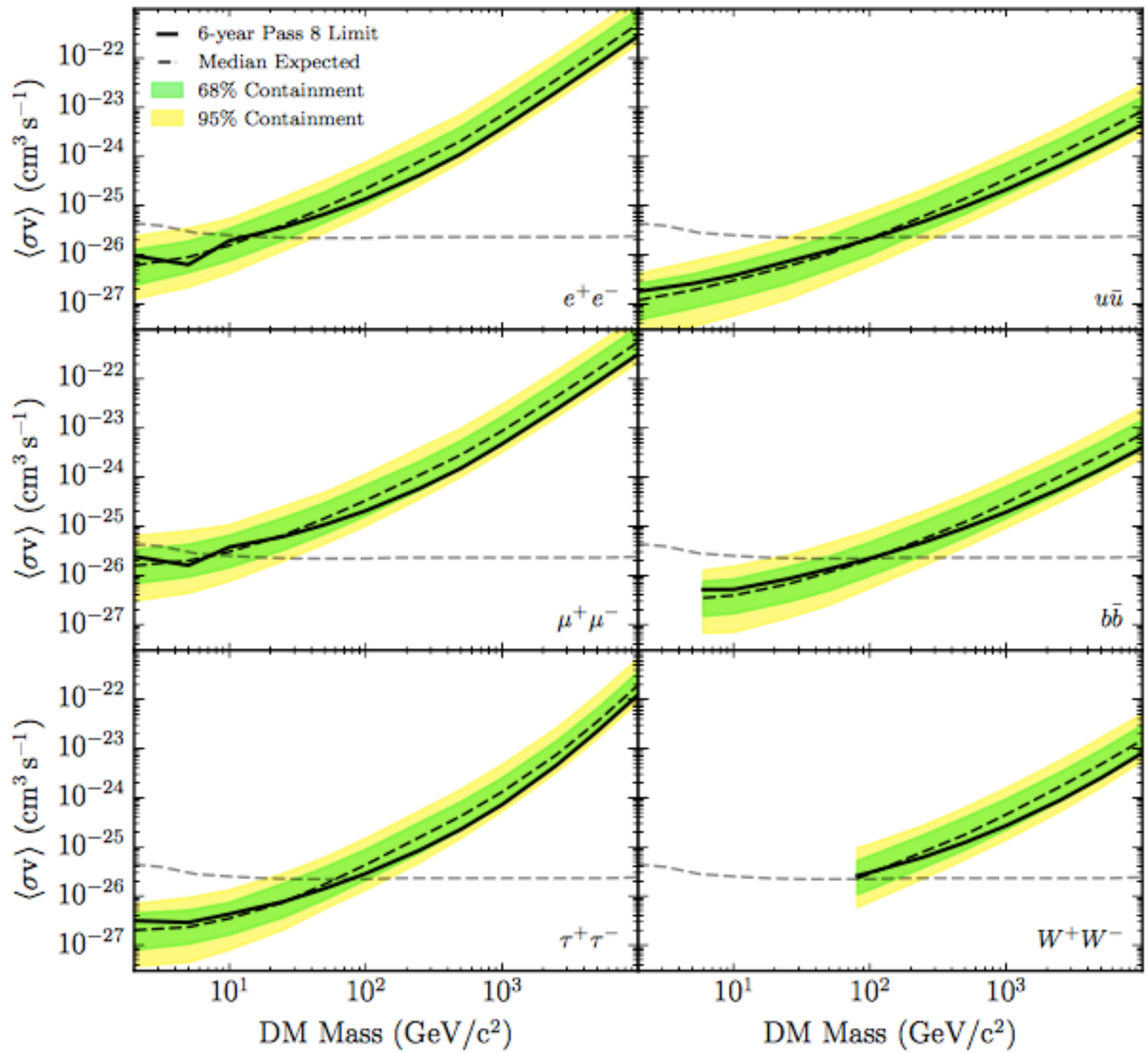


DM Indirect search

Annihilation
is p-wave suppressed

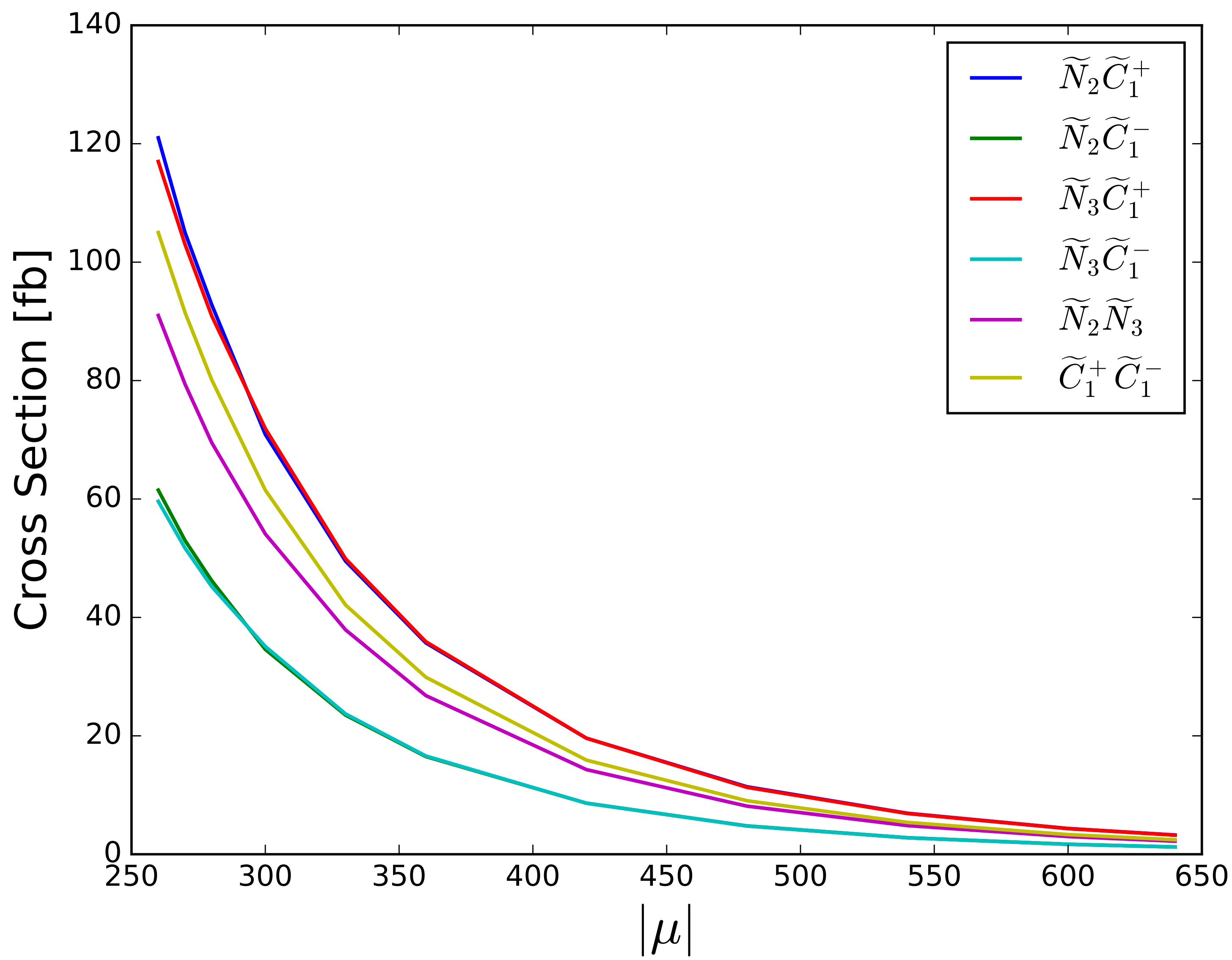
No bounds

Fermi-LAT



Production cross section of Higgsino-like neutralino/chargino

NLO production cross section of $pp \to \widetilde{N}_{2,3}\widetilde{C}_1^{\pm}$

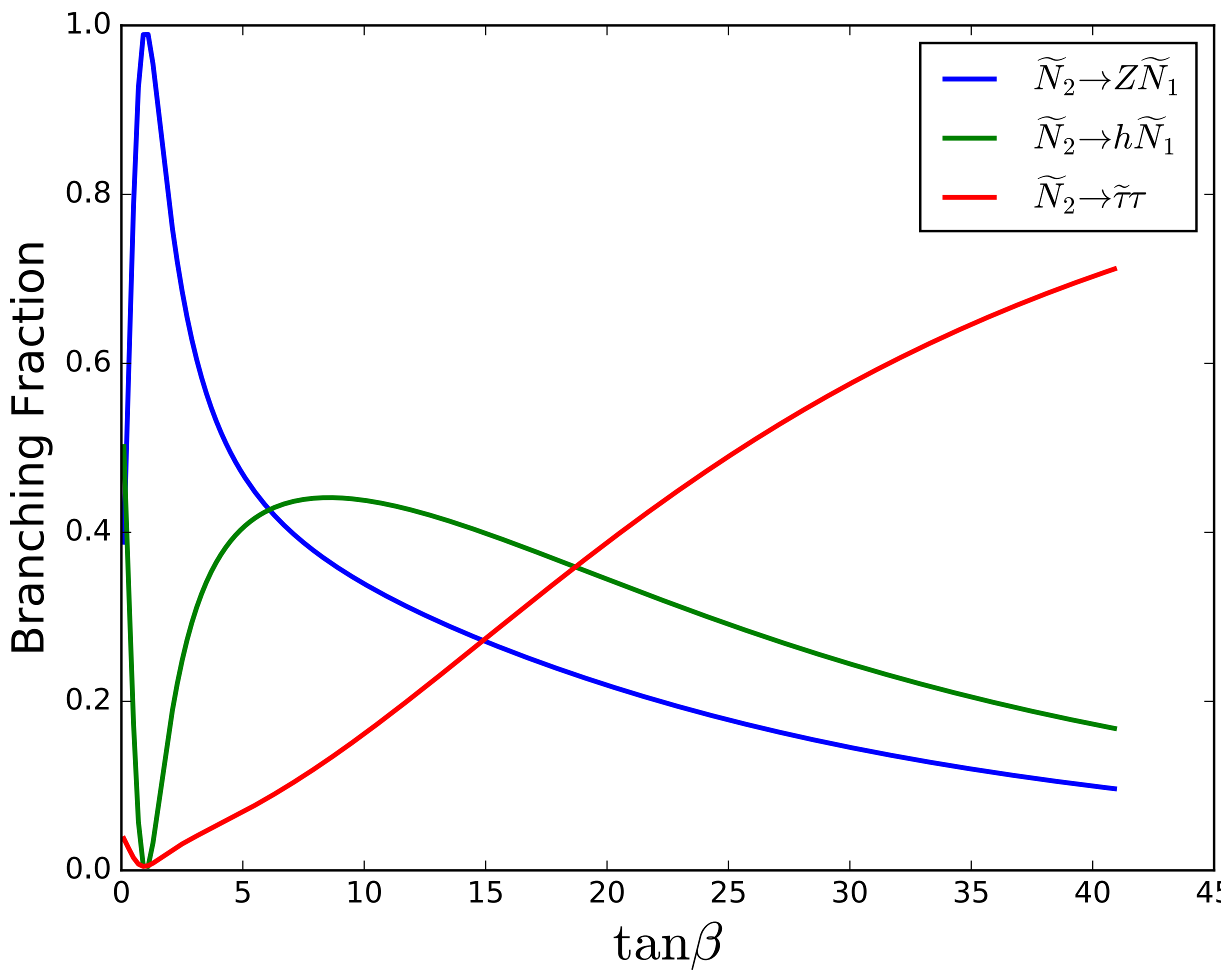


(Computed by Prospino 2)

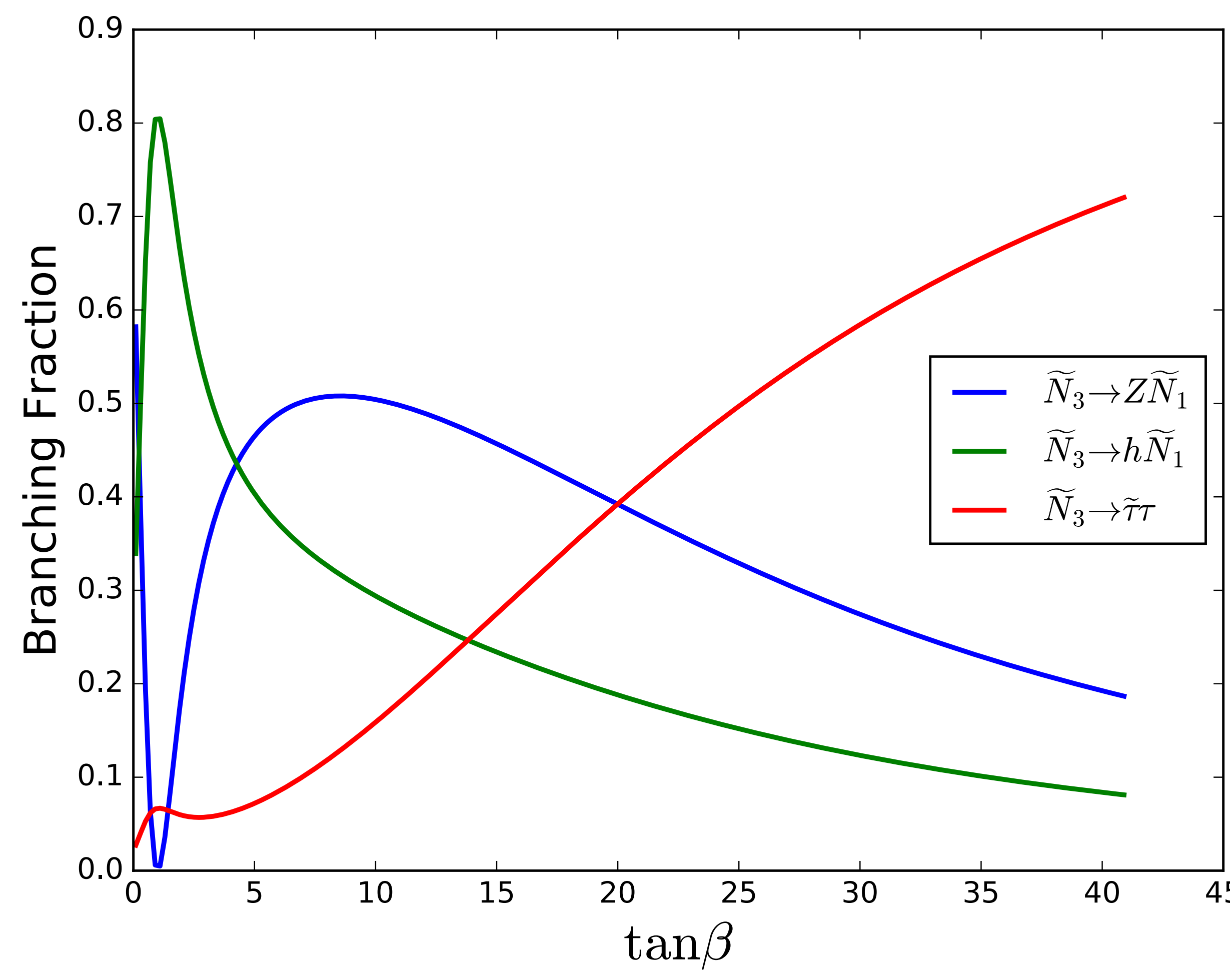
M_1 = 100 GeV, $\mu<0$

Branching fractions of Higgsino-like neutralinos

N_2



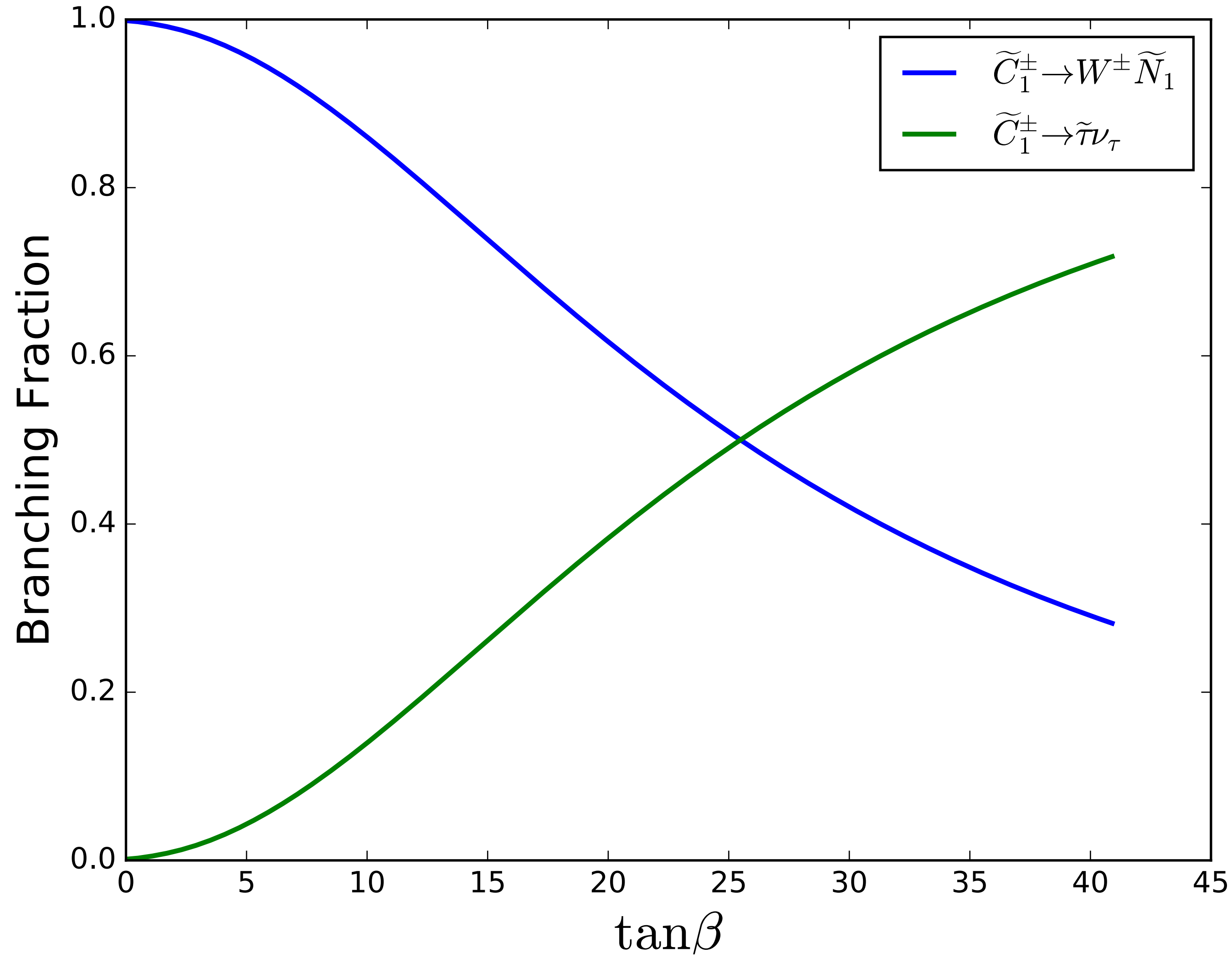
N_3



- M_1 = 100 GeV, μ=-500 GeV, m_R = 110 GeV (which give $\Omega_{DM}h^2 = 0.12$)
- The Higgsino coupling to stau is Yukawa: $y_\tau = m_\tau / v\cos\beta$
- Braching fraction to stau is enhanced for large tanß

Branching fractions of Higgsino-like charginos

$C_1^{\pm}$



The Higgsino coupling to stau is Yukawa: $y_{\tau} \sim m_{\tau} / v\cos\beta$

Enhanced for large $\tan\beta$

LHC simulation

- Generate 50000 events fot each neutralino/chargino production channel by Herwig++
- Their decay modes are restricted to *WZ* or *Wh*
- Detector simulation and event selection are done by CheckMATE

Acceptance is obtained for each neutralino/chargino, each decay mode, and each signal region

$$A_{i,\pm}^{Z,\mathrm{SRX}} = \frac{\text{\# of events which pass the cuts of SRX}}{\text{\# of generated events in } pp \to \widetilde{N}_i \widetilde{C}_1^{\pm} \to W\widetilde{N}_1 Z\widetilde{N}_1},$$

$$A_{23}^{Z,\mathrm{SRX}} = \frac{\text{\# of events which pass the cuts of SRX}}{\text{\# of generated events in } pp \to \widetilde{N}_2 \widetilde{N}_3 \to Z\widetilde{N}_1 Z\widetilde{N}_1}.$$

Expected number of events and evaluation

Expected number of events for each signal region

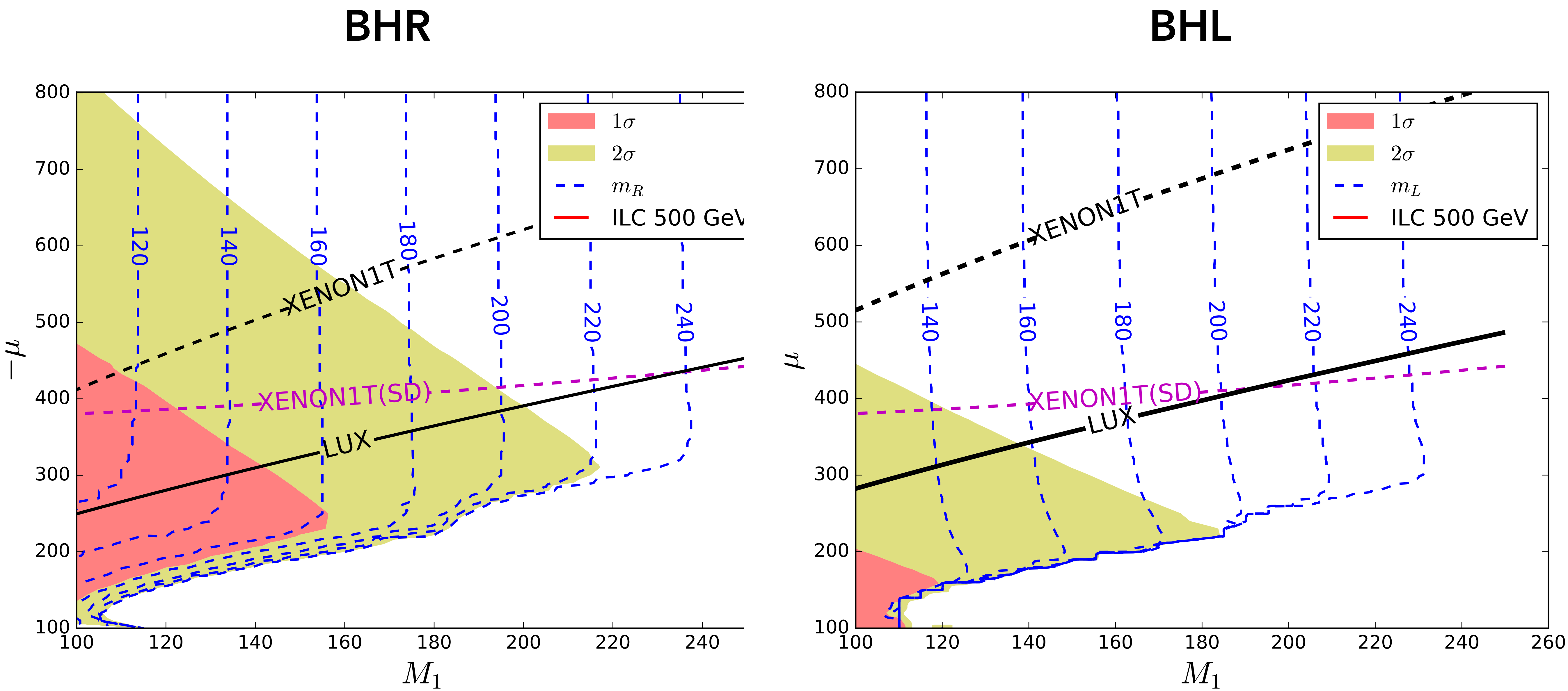
$$
\begin{aligned}
N_{i,\pm}^{\mathrm{SRX}} &= \int \mathcal{L} \cdot \sigma(pp \to \widetilde{N}_i \widetilde{C}_1^{\pm}) \cdot \mathrm{Br}(\widetilde{N}_i \to Z\widetilde{N}_1) \cdot \mathrm{Br}(\widetilde{C}_1^{\pm} \to W^{\pm}\widetilde{N}_1) \cdot A_{i,\pm}^{Z,\mathrm{SRX}} \\
&+ \int \mathcal{L} \cdot \sigma(pp \to \widetilde{N}_i \widetilde{C}_1^{\pm}) \cdot \mathrm{Br}(\widetilde{N}_i \to h\widetilde{N}_1) \cdot \mathrm{Br}(\widetilde{C}_1^{\pm} \to W^{\pm}\widetilde{N}_1) \cdot A_{i,\pm}^{h,\mathrm{SRX}}, \\
N_{23}^{\mathrm{SRX}} &= \int \mathcal{L} \cdot \sigma(pp \to \widetilde{N}_2 \widetilde{N}_3) \cdot \mathrm{Br}(\widetilde{N}_2 \to Z\widetilde{N}_1) \cdot \mathrm{Br}(\widetilde{N}_3 \to Z\widetilde{N}_1) \cdot A_{23}^{Z,\mathrm{SRX}} \\
&+ \int \mathcal{L} \cdot \sigma(pp \to \widetilde{N}_2 \widetilde{N}_3) \cdot \mathrm{Br}(\widetilde{N}_2 \to h\widetilde{N}_1) \cdot \mathrm{Br}(\widetilde{N}_3 \to h\widetilde{N}_1) \cdot A_{23}^{h,\mathrm{SRX}},
\end{aligned}
$$

$$
N^{\mathrm{SRX}} \equiv \textstyle\sum_{\mathrm{ch}} N_{\mathrm{ch}}^{\mathrm{SRX}}
$$

$$
r^{\mathrm{SRX}} \equiv \frac{N^{\mathrm{SRX}} - 1.96\Delta N^{\mathrm{SRX}}}{N_{95\mathrm{exp}}^{\mathrm{SRX}}},
$$ **is used for evaluation**

If $r_{\max} \equiv \max_{\mathrm{SR}}\{r^{\mathrm{SRX}}\} > 1$ **the model point is excluded at 95% CL.**

Spin-dependent scattering



Weaker expected limits than spin-independent
No limits from XENON100