SUSY Parameter determination and dark matter phenomenology at future e+e- colliders

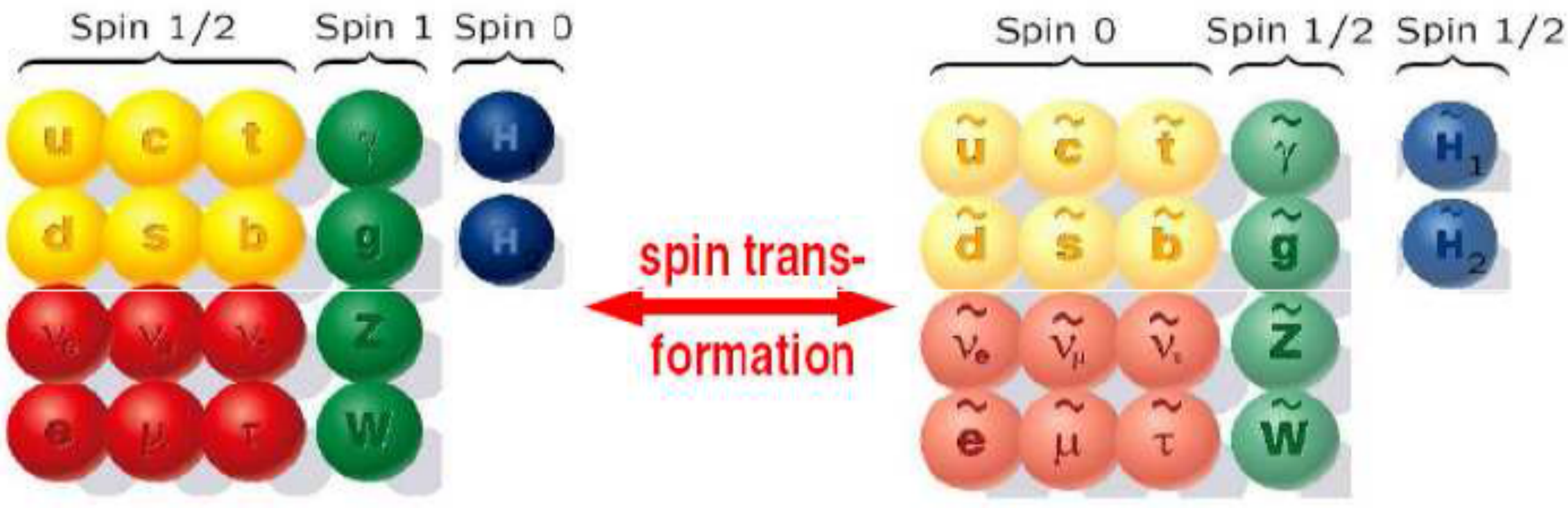
G. Moortgat-Pick (Uni Hamburg/DESY)
In coll. with J. Becks, M. Chakraborti, R. Heine, S. Heinemeyer, F. Lika, I. Saha

- **Short SUSY Intro&Strategy**
- **Scans**
- **Parameter determination**
- **Results on DM**
- **Conclusions**

LINEAR COLLIDER COLLABORATION

Supersymmetry - MSSM

- Symmetry between fermions and bosons



'The search for SUSY is one of the biggest adventures in present-day physics.' Ed Witten (1999)

- Large uncoloured / EW sector

charginos/neutralinos: M_1, M_2, μ, $\tan\beta$ $\Rightarrow$ Dark Matter candidate: $\tilde{\chi}_1^0$

Sleptons: $M_{\tilde{l}_L}$, $M_{\tilde{l}_R}$ (equal for all 3 generations, or different 1.2. vs. 3.)

Several options to embed dark matter

M. Chakraborti, S. Heinemeyer, I. Saha 20/21

A) wino/bino DM with chargino co-annihilation ($M_1 \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim 650(700)$ GeV

B/C) bino DM with slepton co-annihilation ($M_1 \lesssim M_2, \mu$)
relic DM density 100% fulfilled
$\Rightarrow$ two cases: all 3 generations degenerate vs. 3rd generation independent
$\Rightarrow m_{\text{(N)LSP}} \lesssim 550(600)$ GeV

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$ ($M_2 \lesssim M_1, \mu$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim 600$ GeV

SUSY and $(g\text{-}2)_\mu$

Feynman diagrams for MSSM 1L corrections:

– Diagrams with chargino/sneutrino exchange
– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}^\pm_i - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}^0_j - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

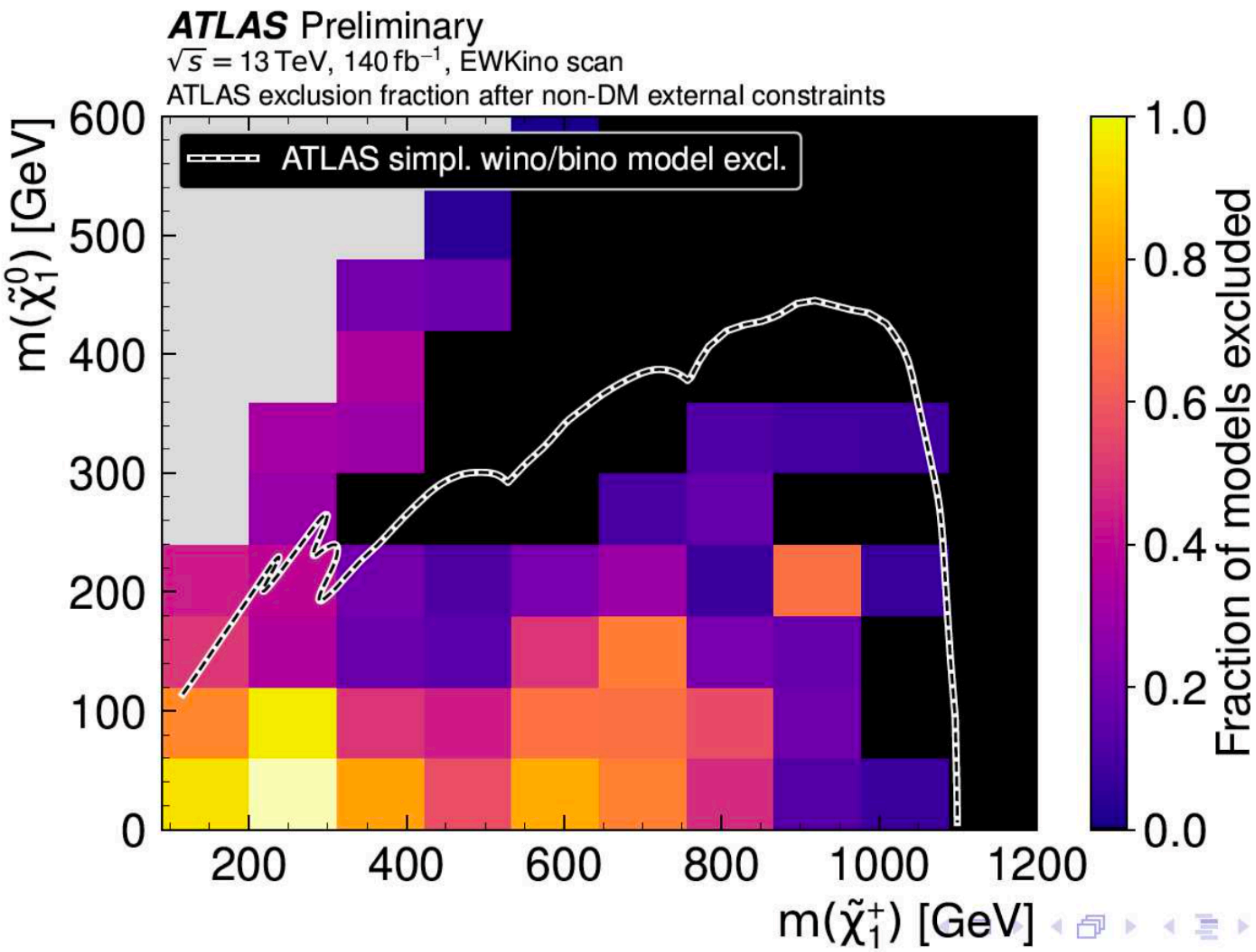
SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

$\Rightarrow$ slepton masses constrol the size of $\Delta a_\mu^{\text{MSSM}}$

Impact from LHC SUSY searches limits

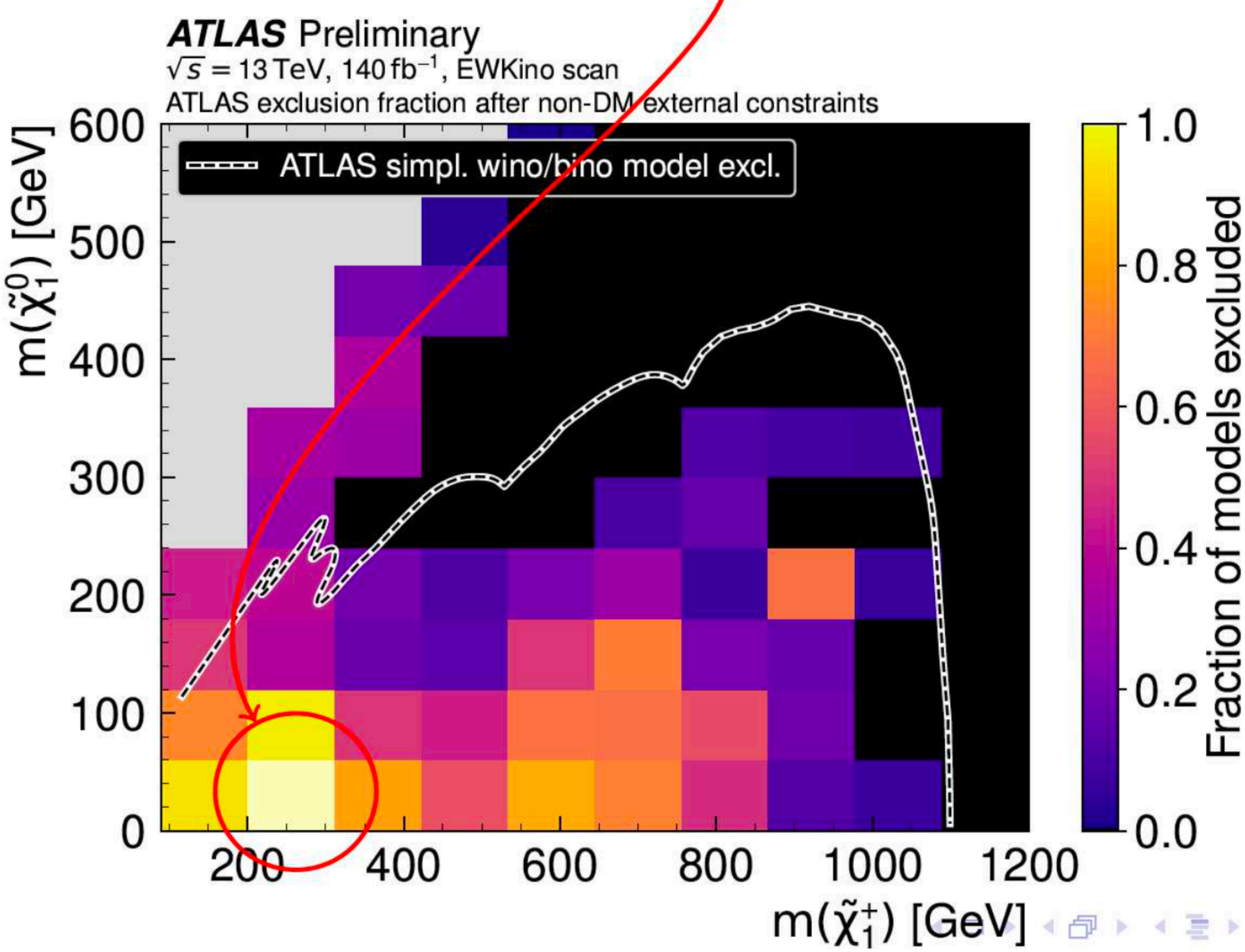
taken from M. Berggren 2023



Impact from LHC SUSY searches limits

taken from M. Berggren 2023

Only this one is actually excluded !



SUSY light dark matter range

⇒ Our "models" predict low chargino/neutralino masses

Possible search channels:

- $pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X$
- $pp \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + H/Z$
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 H/Z \; \tilde{\chi}_1^0 W^\pm$
- $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^+ \; \tilde{\chi}_1^0 W^-$
- ...

Possible kinematic situations:

- non-compressed spectra: on-shell decays to $H/Z, W^\pm$
- compressed spectra: off-shell decays to $Z, W^\pm$
- light sleptons that appear in the decay chains
- heavy sleptons that are absent from the decay chains
- ...

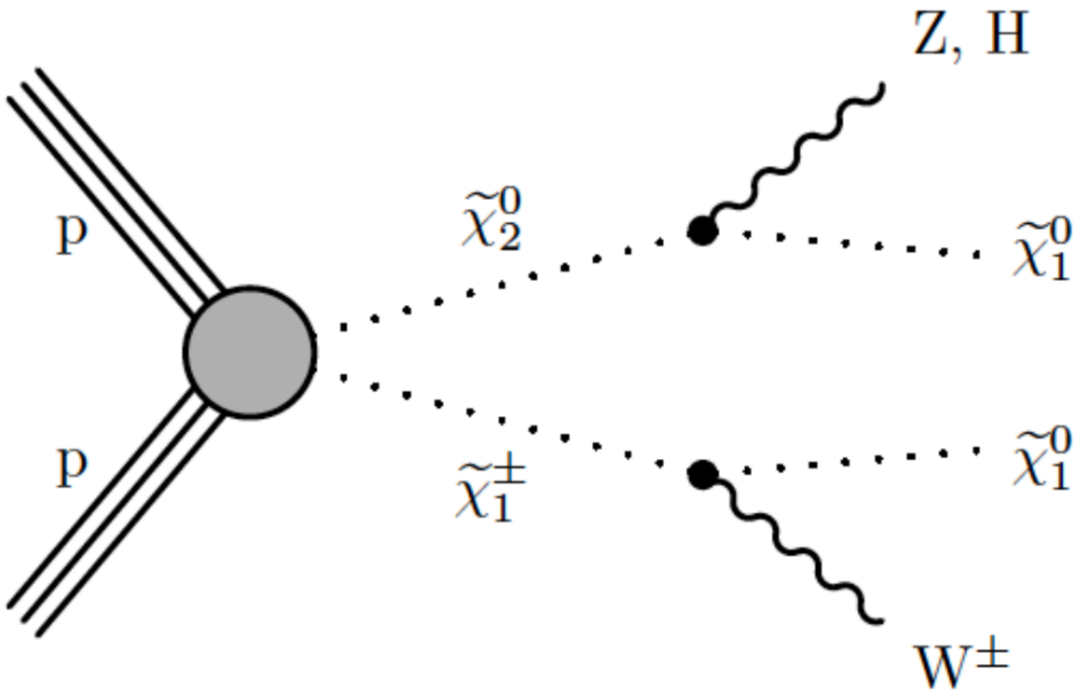
⇒ only one of these can be realized

⇒ only one of them should show up in the LHC searches

SUSY light dark matter range

⇒ Our "models" predict low chargino/neutralino masses

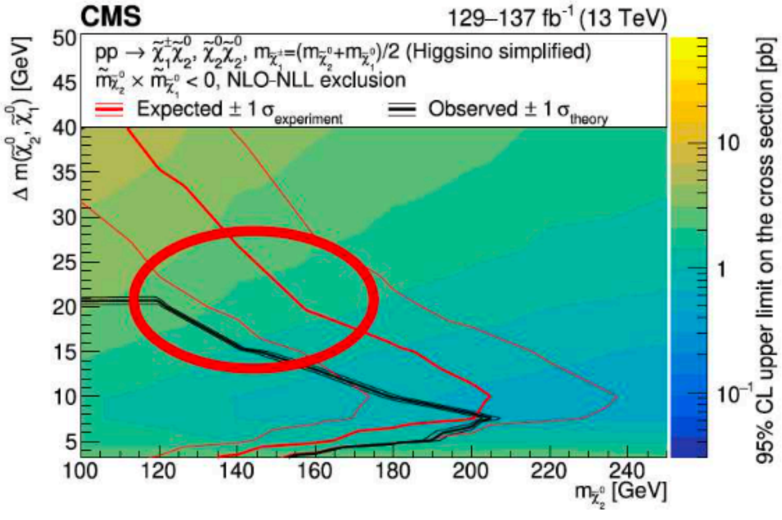
Golden mode at the LHC:

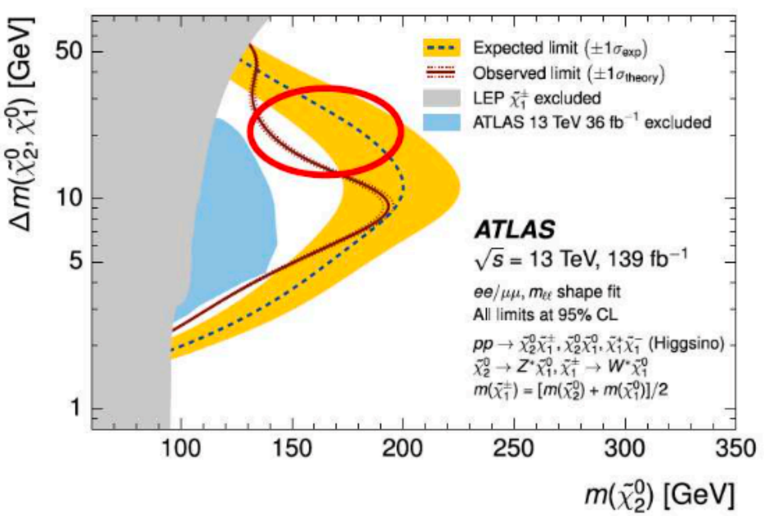


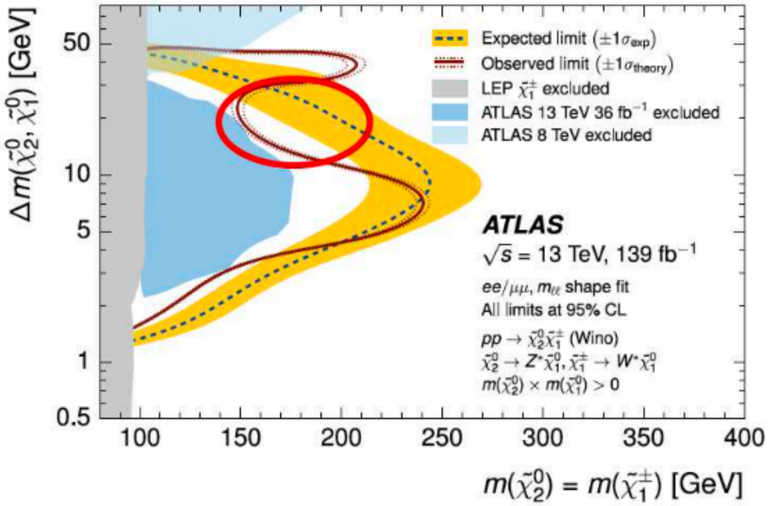
⇒ experimental results?

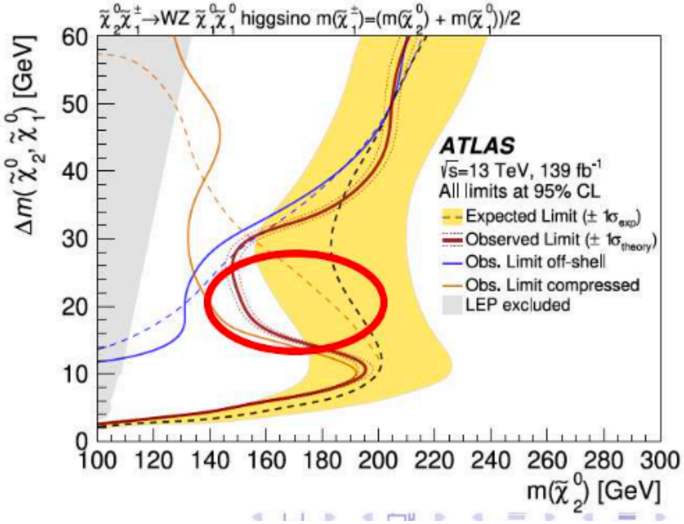
Results ‘compressed’ spectra w/ heavy sleptons

taken from M. Berggren 2023



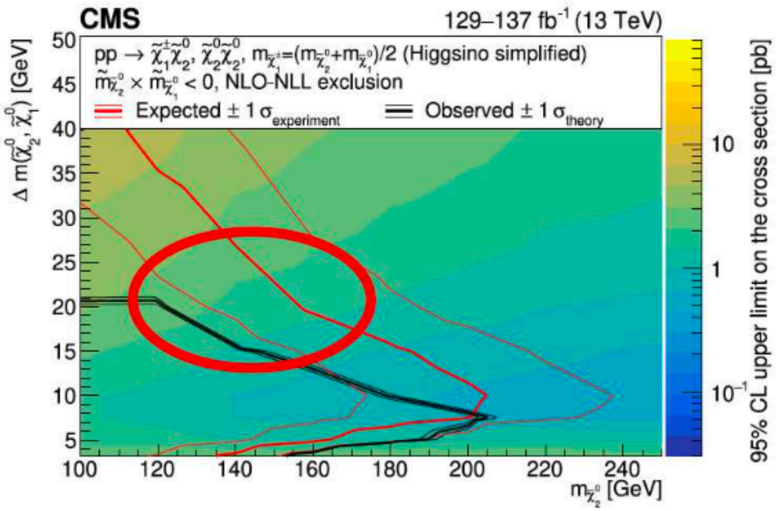


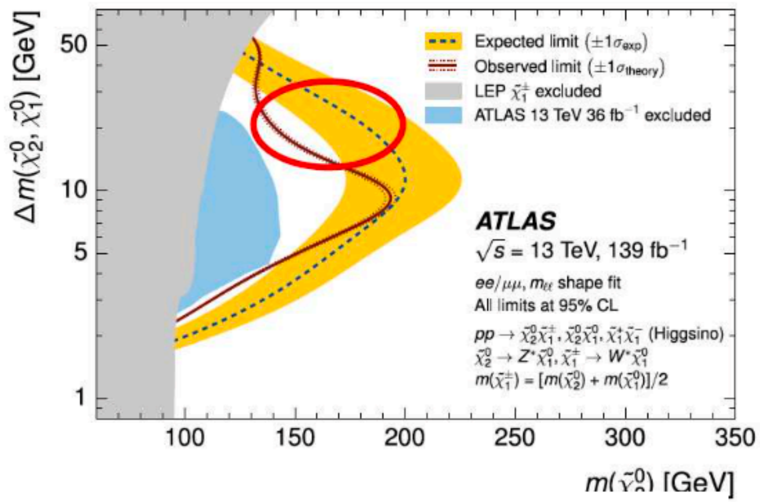


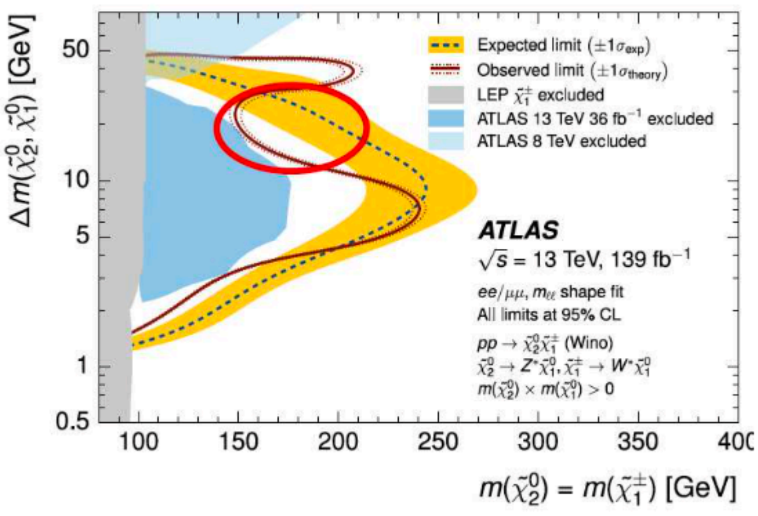


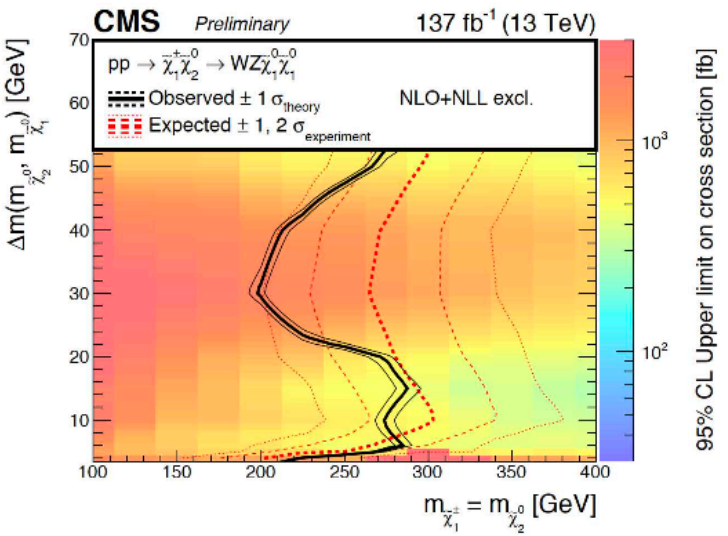
Results ‘compressed’ spectra w/ heavy sleptons

one more cms analysis









Focus on two scenarios: wino/bino vs higgsino

– $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm}$
– $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}\,(20\text{ GeV})$

A) wino/bino DM with chargino co-annihilation ($|M_1| \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim 650(700)$ GeV

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim |M_1|, M_2$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim 500$ GeV

$\Rightarrow$ can they fit the excesses?

Focus on two scenarios: wino/bino vs higgsino

A) Wino/bino DM with chargino co-annihilation

Parameter scan:

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$$100\ \text{GeV} \leq |M_1| \leq 400\ \text{GeV}\ ,$$

$$|M_1| \leq M_2 \leq 1.1|M_1|\ ,$$

$$1.1|M_1| \leq \mu \leq 10|M_1|,$$

$$2 \leq \tan\beta \leq 60,$$

$$100\ \text{GeV} \leq m_{\tilde{L}} \leq 1.5\ \text{TeV},$$

$$m_{\tilde{R}} = m_{\tilde{L}}\ .$$

(latter condition only to make the analysis simpler, no relevant effect)

wino/bino(+): $M_1 \times \mu > 0$

wino/bino(−): $M_1 \times \mu < 0$

relic DM density can be 100% fulfilled

$\Rightarrow m_{\text{(N)LSP}} \lesssim 600(650)$ GeV

(original scan assuming a $5\,\sigma$ deviation in $(g-2)_\mu$)

wino/bino

wino/bino(+): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:

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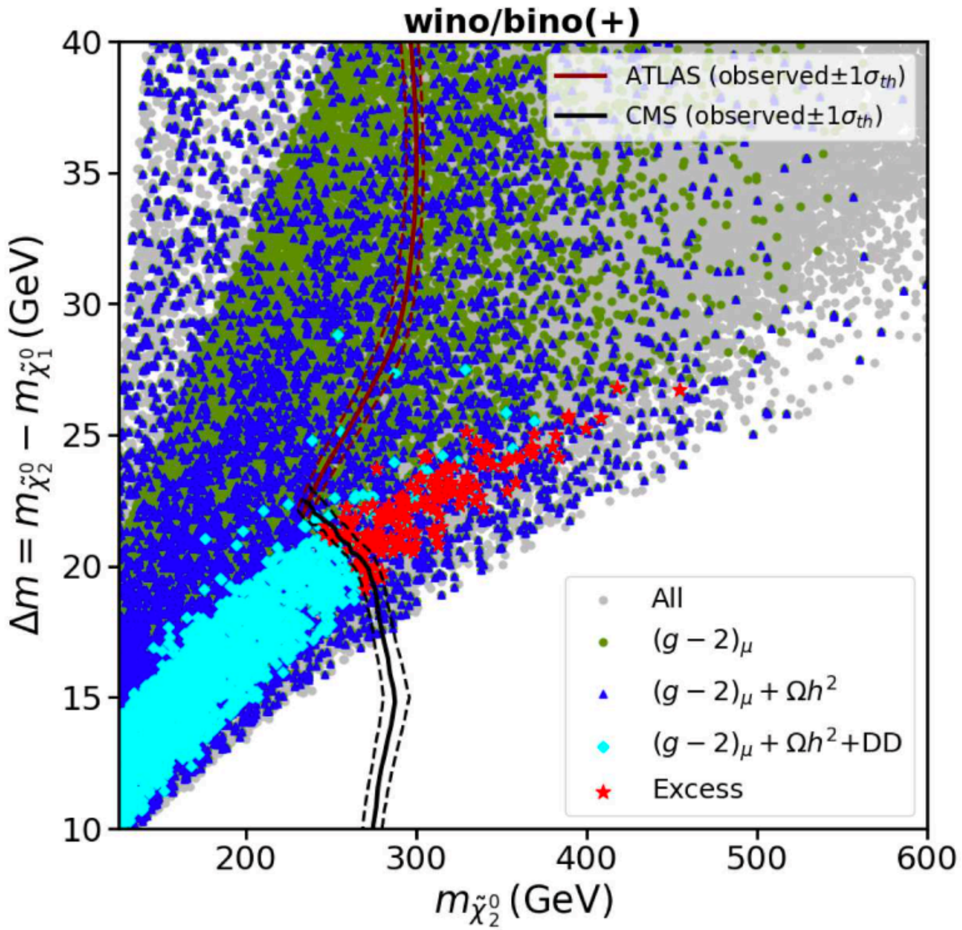

$\Rightarrow$ excesses not fully at the same Δm . . .

$\Rightarrow$ but many "good points" at $\Delta m \sim 20$ GeV

wino/bino

wino/bino(+): limits on slepton masses:

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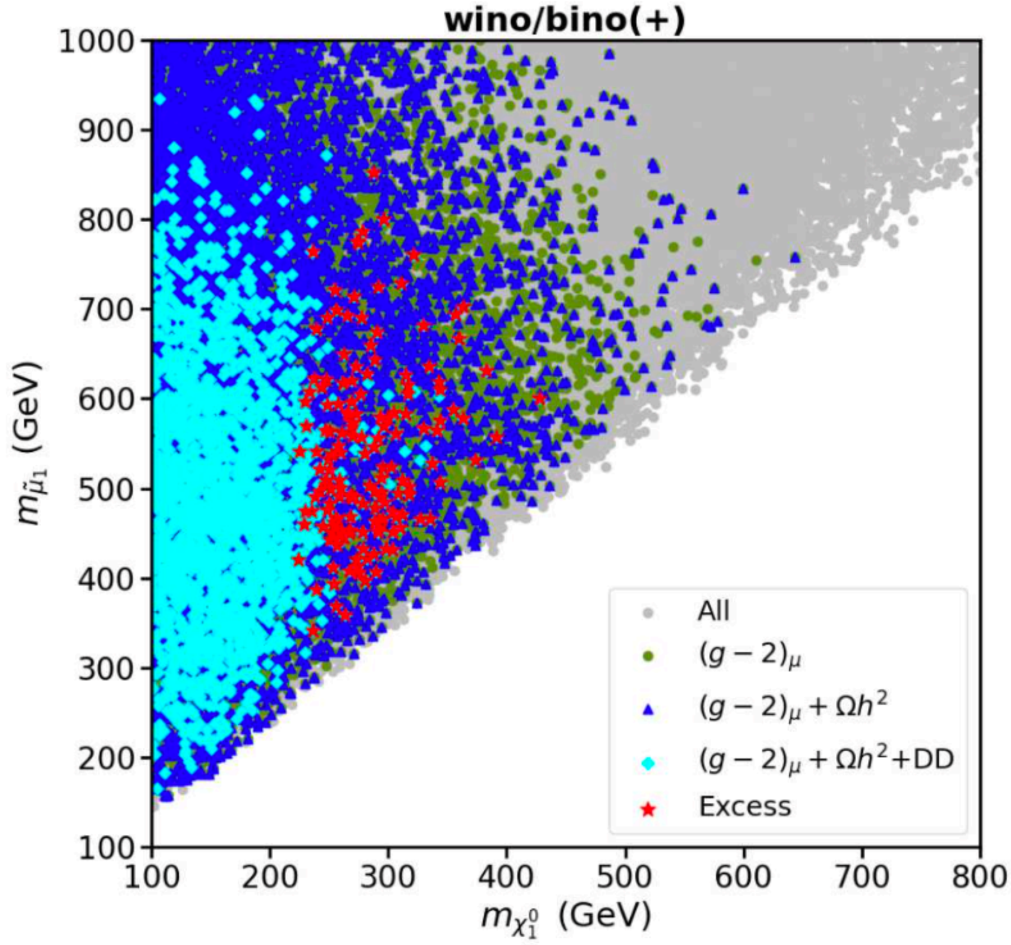

$\Rightarrow$ no limits on slepton masses (as expected)

wino/bino

wino/bino(+): LHC cross sections:

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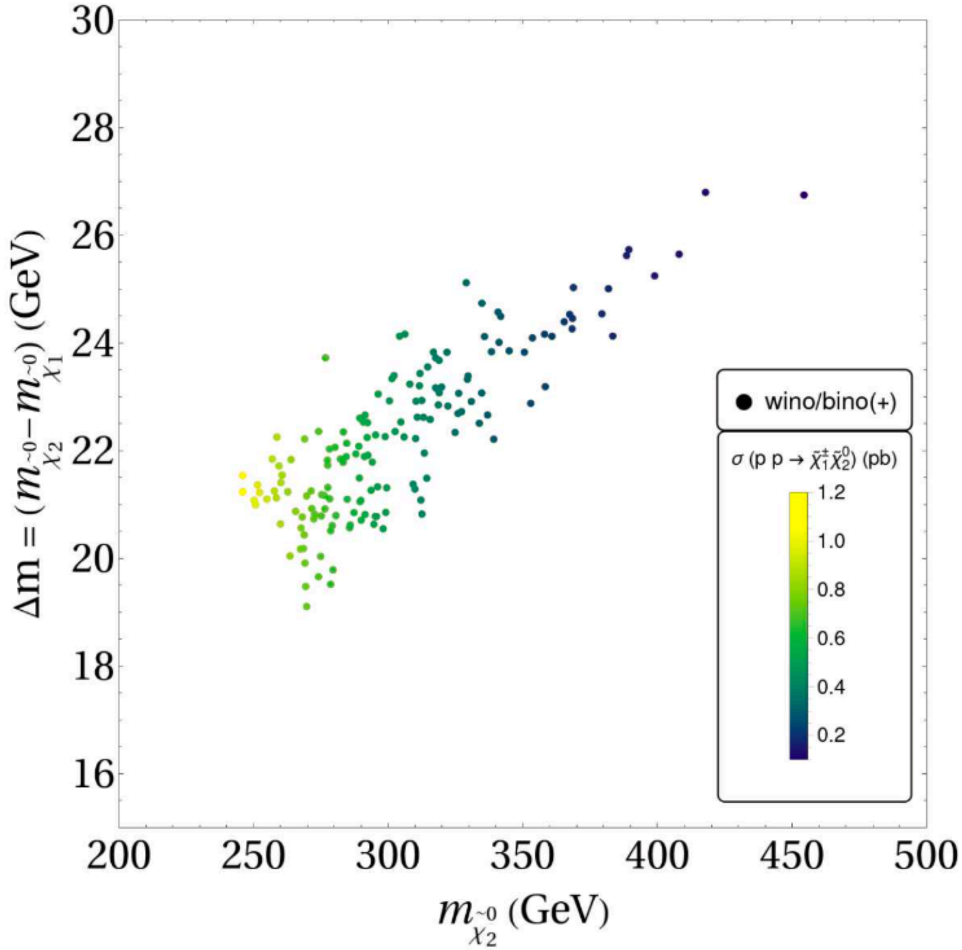

⇒ for lower massess XS have roughly the size required by excesses

wino/bino

wino/bino(+): $\sigma(e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$:

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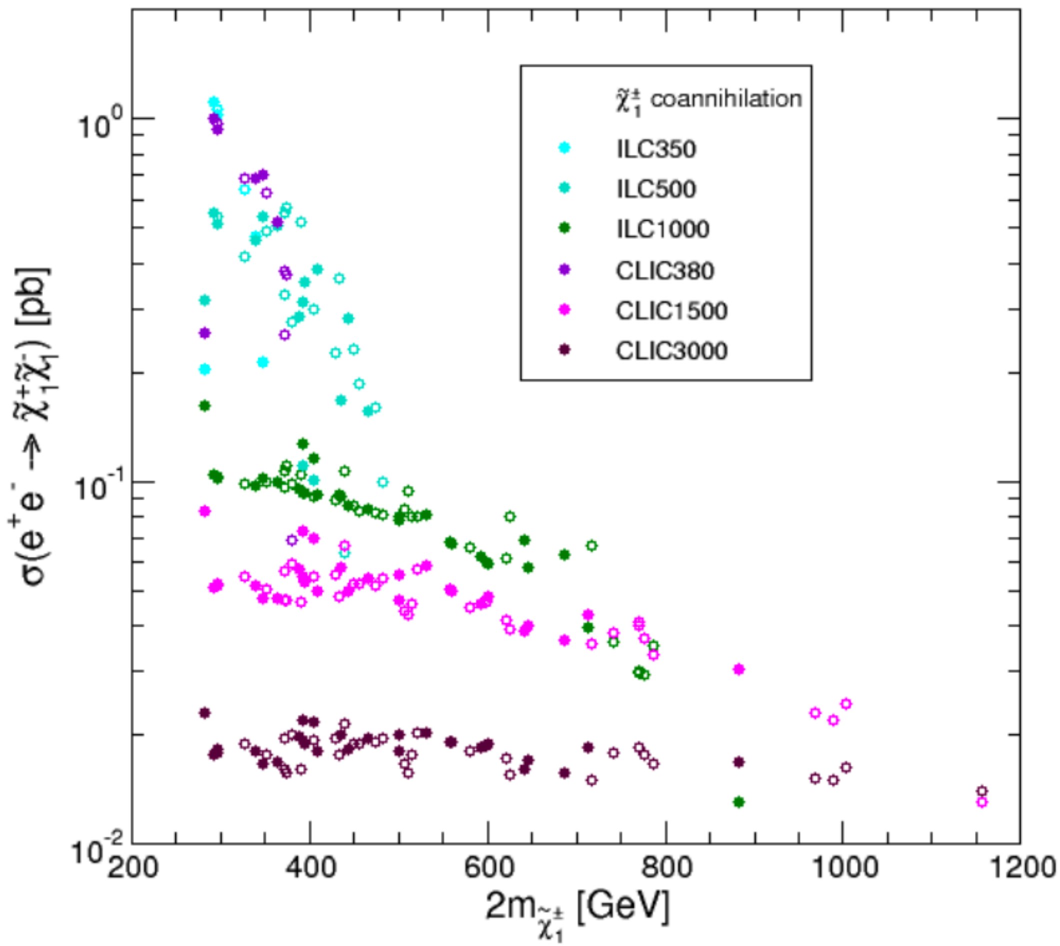
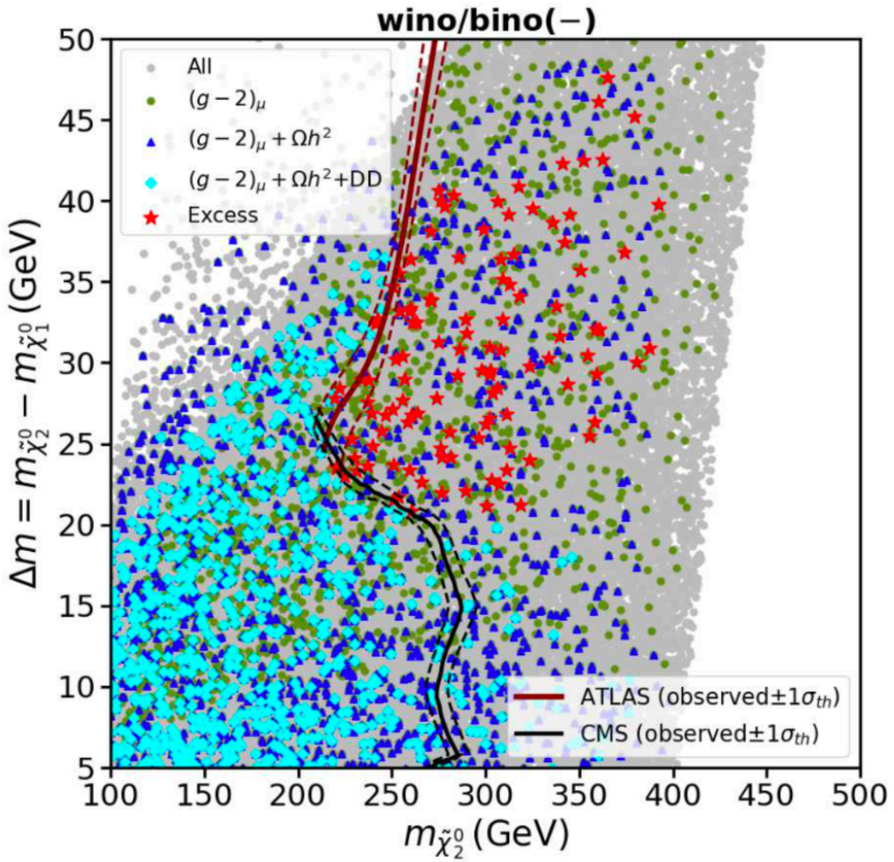


⇒ easy for ILC500/ILC1000 :-)

wino/bino

wino/bino(−): results in the $m_{\tilde{\chi}_2^0}$-Δm plane:

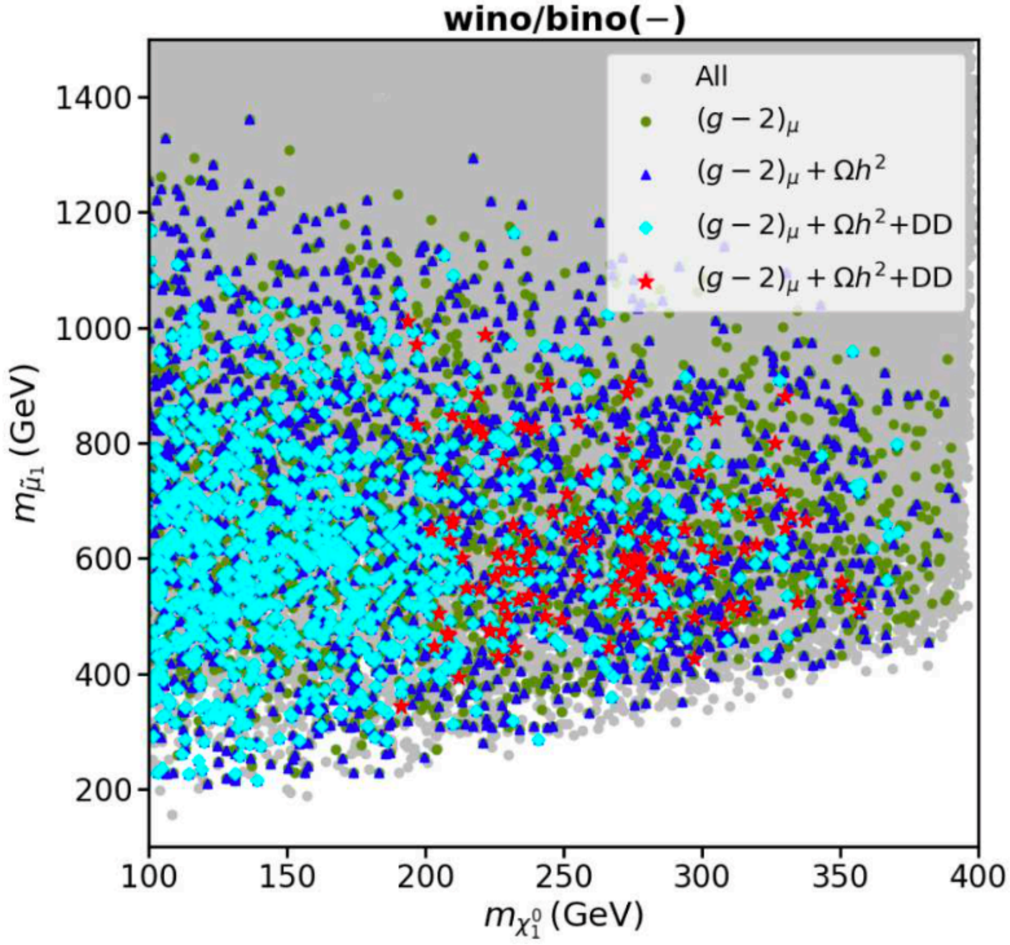


⇒ ATLAS/CMS excesses agree better in Δm than for wino/bino(+)

⇒ but many "good points" at $\Delta m \sim 25$ GeV

wino/bino

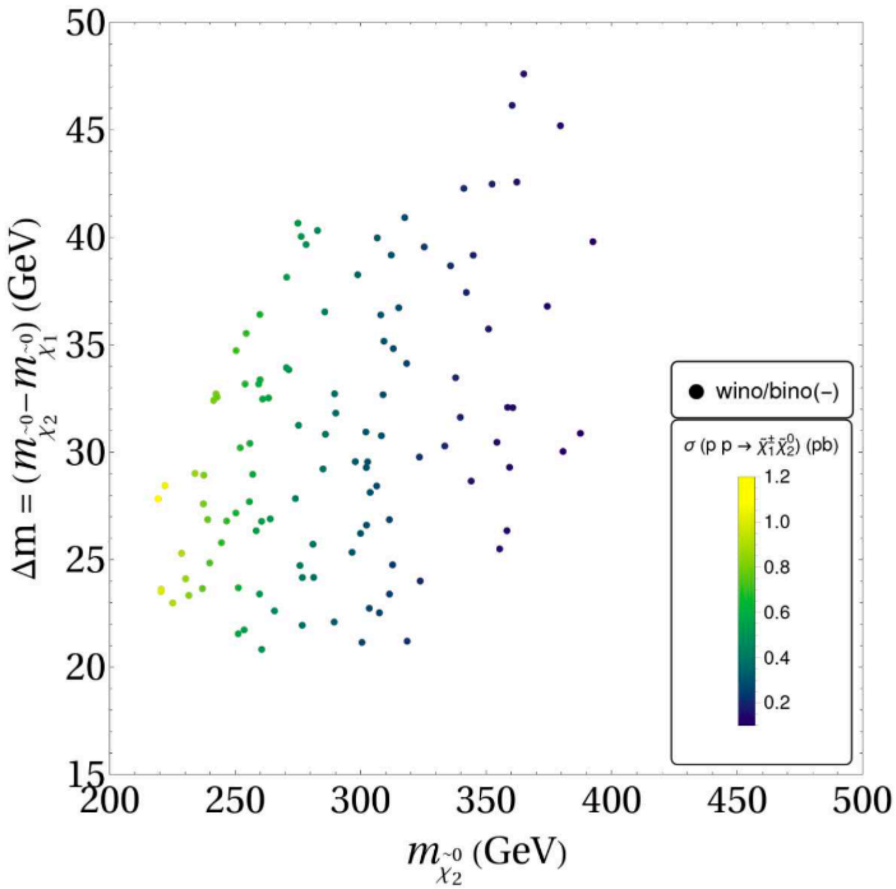
wino/bino(−): limits on slepton masses:



⇒ no limits on slepton masses (as expected)

wino/bino

wino/bino(−): LHC cross sections:



⇒ for lower masses XS have roughly the size required by excesses

⇒ prospects for $\sigma(e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp})$ similar as in wino/bino(+)

higgsino

D) Higgsino DM

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Original parameter scan: $(M_1 \times \mu > 0)$

$$100\ \text{GeV} \le \mu \le 1.2\ \text{TeV}\ ,$$

$$1.1\mu \le M_1 \le 10\mu\ ,$$

$$1.1 M_2 \le \mu \le 10\mu\ ,$$

$$5 \le \tan\beta \le 60,$$

$$100\ \text{GeV} \le m_{\tilde{L}}, m_{\tilde{R}} \le 2\ \text{TeV},$$

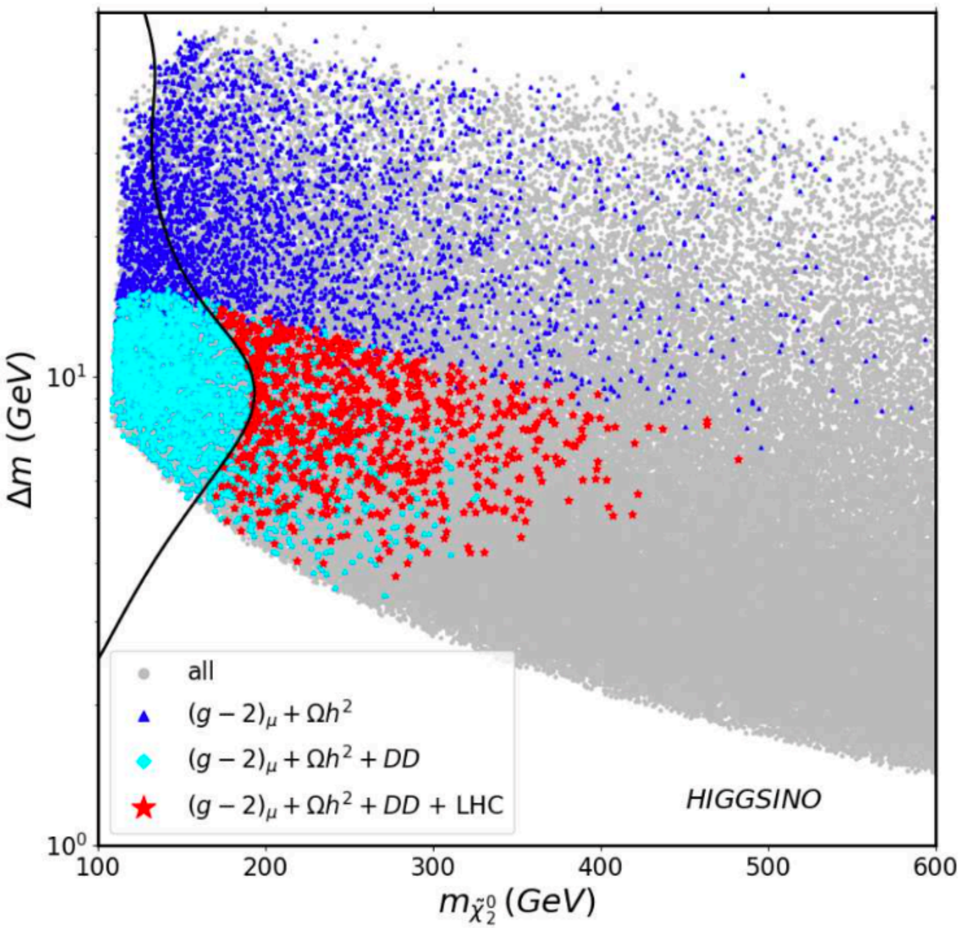
$\Rightarrow m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$

Full DM relic density reached only for $m_{\tilde{\chi}_1^0} \sim 1$ TeV
$\Rightarrow$ incompatible with a $5\,\sigma$ deviation in $(g-2)_\mu$
$\Rightarrow m_{(\text{N})\text{LSP}} \lesssim 500$ GeV

higgsino

Results in the $m_{\tilde{\chi}_2^0}$-Δm plane with old DD bound:

M. Chakraborti, S. Heinemeyer, I. Saha 2021



$\Rightarrow$ direct detection is the limiting factor on Δm

higgsino

New scan with $M_1 \times \mu < 0$

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$$-190 \text{ GeV} \leq M_1 \leq -1500 \text{ GeV}$$

$$M_2 = 2 \text{ TeV}$$

$$\mu = \frac{-2M_1 \tan\beta}{4 + x_1 \tan^2\beta}, \quad x_1 = \frac{m_h^2}{m_H^2}$$

$$5 \leq \tan\beta \leq 50$$

$$190 \leq M_A \leq 1200$$

$$2M_1 \leq m_{\tilde{l}_L}, m_{\tilde{l}_R} \leq 1500 \text{ GeV}$$

Condition on μ and M_1: exact blind spot conditions

relaxed blind spot condition: scan up to $\mu/|M_1| < 1$

higgsino

New scan with $M_1 \times \mu < 0$

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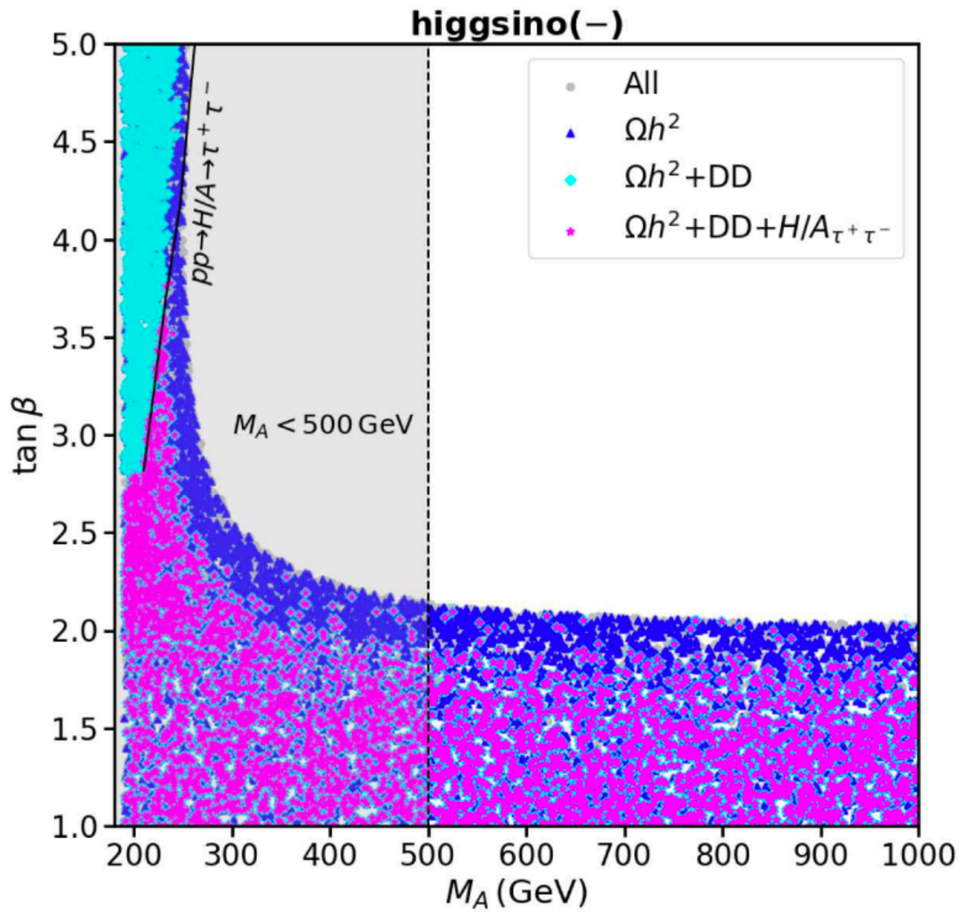

$\Rightarrow M_A \gtrsim 500$ GeV and $\tan\beta \lesssim 2$ allowed

higgsino

New scan with $M_1 \times \mu < 0$

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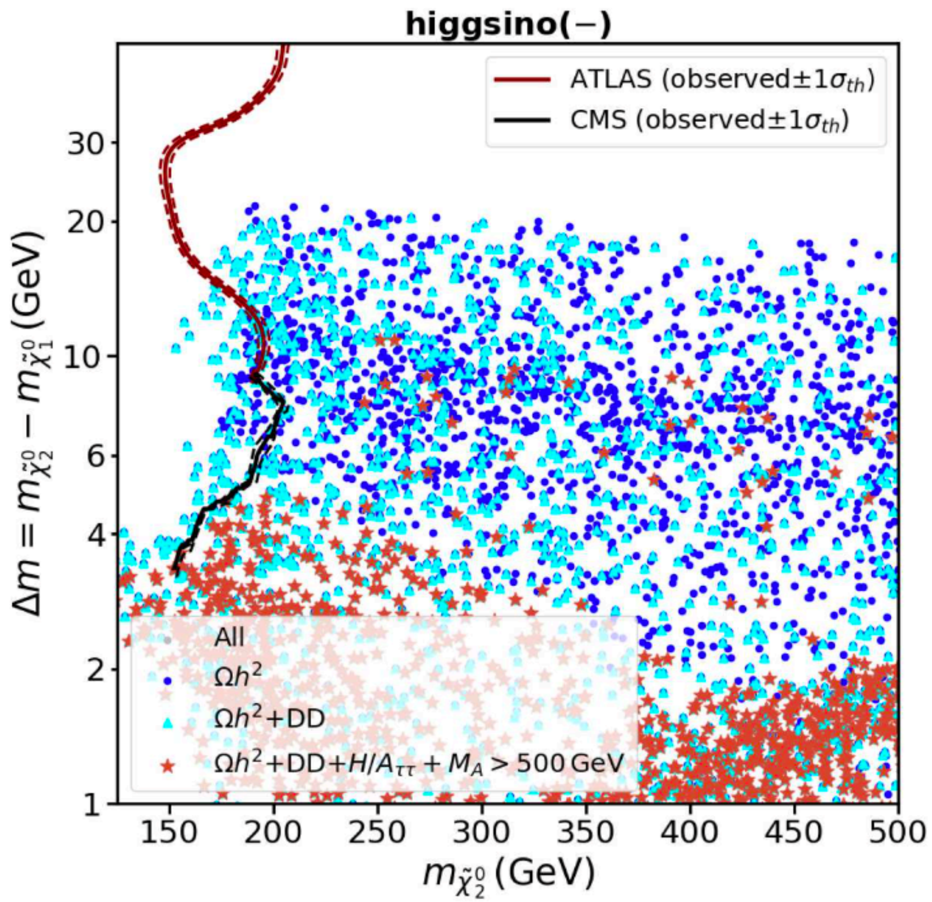

⇒ restrictions still cut away the "good parameter space"

⇒ higgsino(−) does not work (in the MSSM)

Interpretation combination

Compressed spectra at current and future colliders

Higgsino, wino and bino/wino DM:

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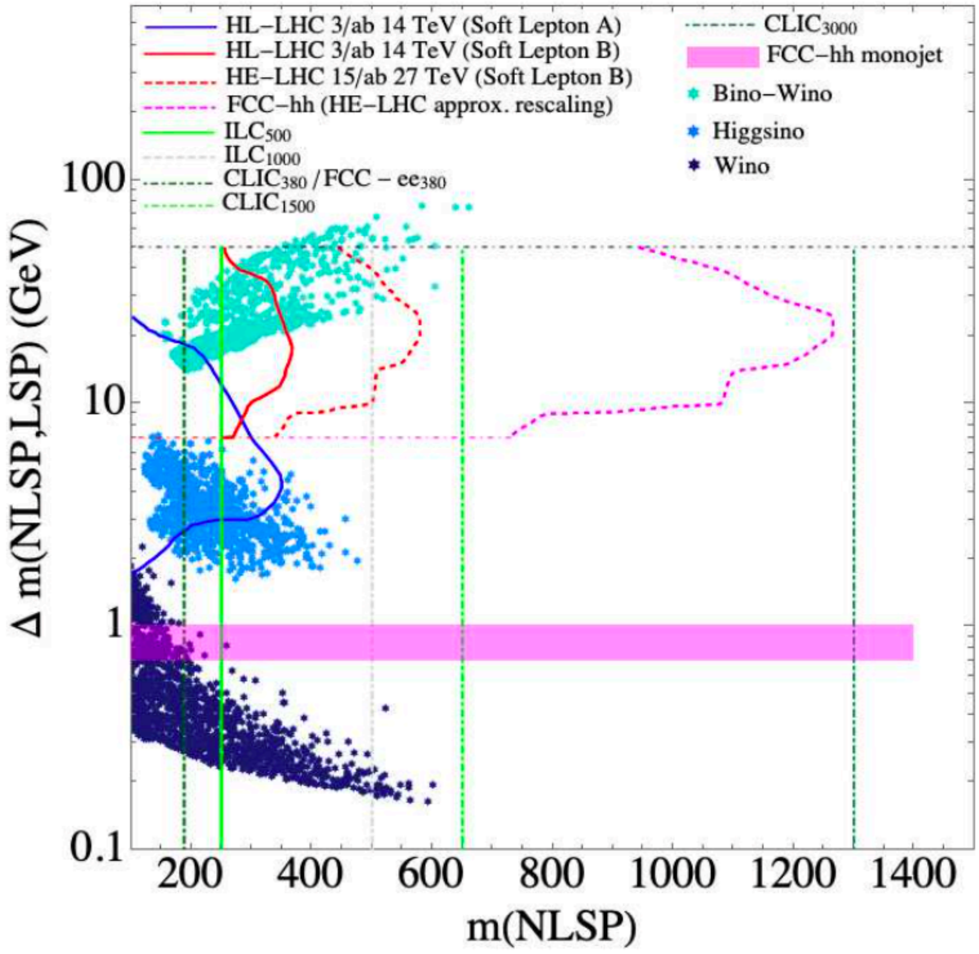


⇒ excesses can be covered "in any case" at the ILC500/ILC1000

Reconstruction of parameters

The main idea:

1. Assume that (low-mass) wino-bino DM ($\tilde{\chi}_1^{\pm}$-coannihilation) is realized: $M_1 \lesssim M_2 \ll \mu$ (but for now $M_1 \times \mu > 0$).

2. At the ILC500 we measure $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^{\pm}}$ and $\sigma(e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp})$.
   XS measurement with two (good) polarizations and at $\sqrt{s} = 400, 500$ GeV.

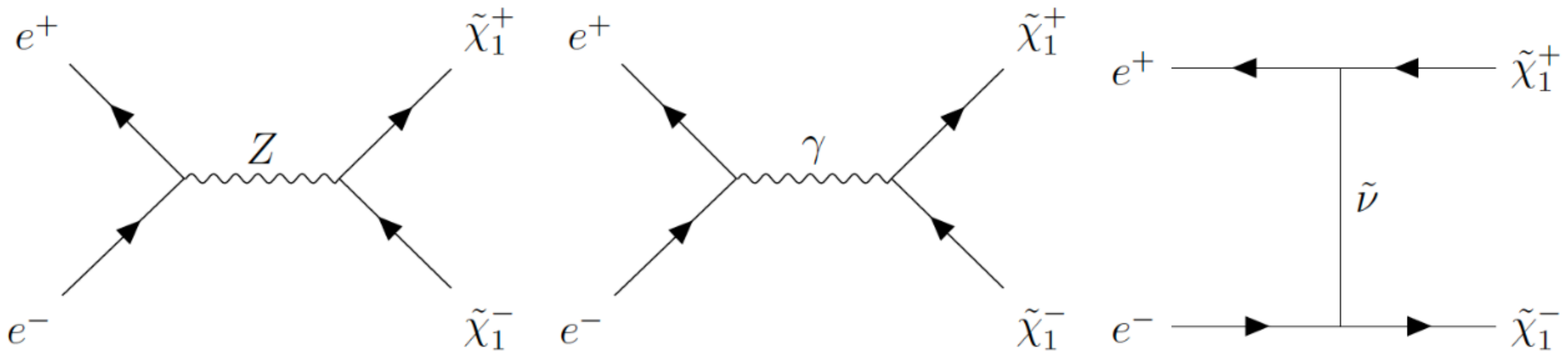
3. This allows (in principle) to reconstruct M_1, M_2, μ, $m_{\tilde{\nu}_e}$, ... – with uncertainties.
   $\tan\beta$ assumed to be roughly known from other measurements.

4. With these parameters $\Omega_\chi h^2$ can be calculated – with uncertainties.

5. Comparison of $\Omega_\chi h^2$ with astrophysically measured value constitutes an important test of the model.

Reconstruction of parameters

The Feynman diagrams:



$\Rightarrow m_{\tilde{\nu}_e}$ enters

– so far tree-level analysis

– to be repeated including full one-loop corrections

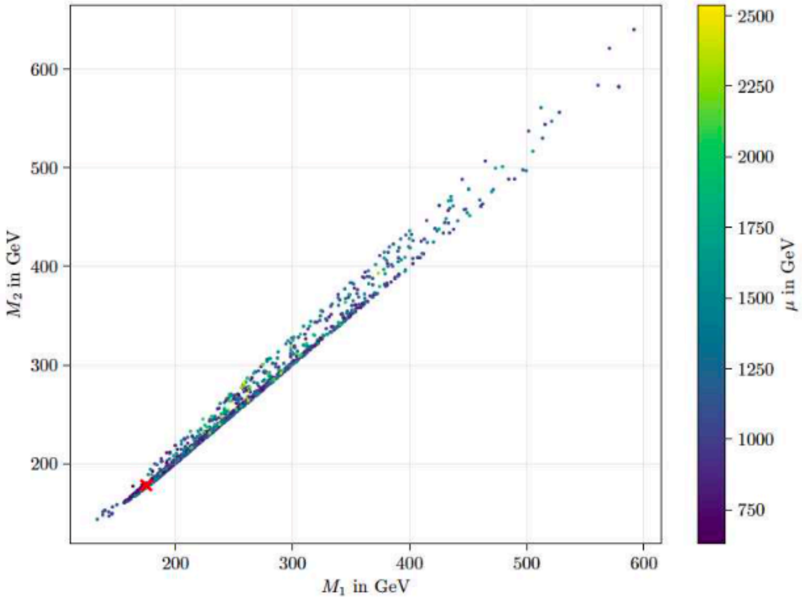
A. Bharucha et al. '13, '16

– more involved parameter dependences

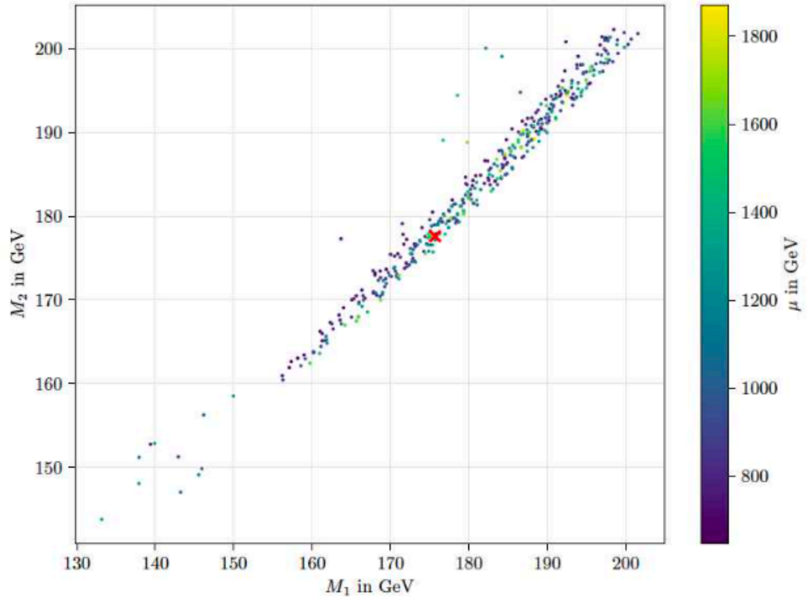
Reconstruction of parameters

The parameter points:

full (original) set



accessible set

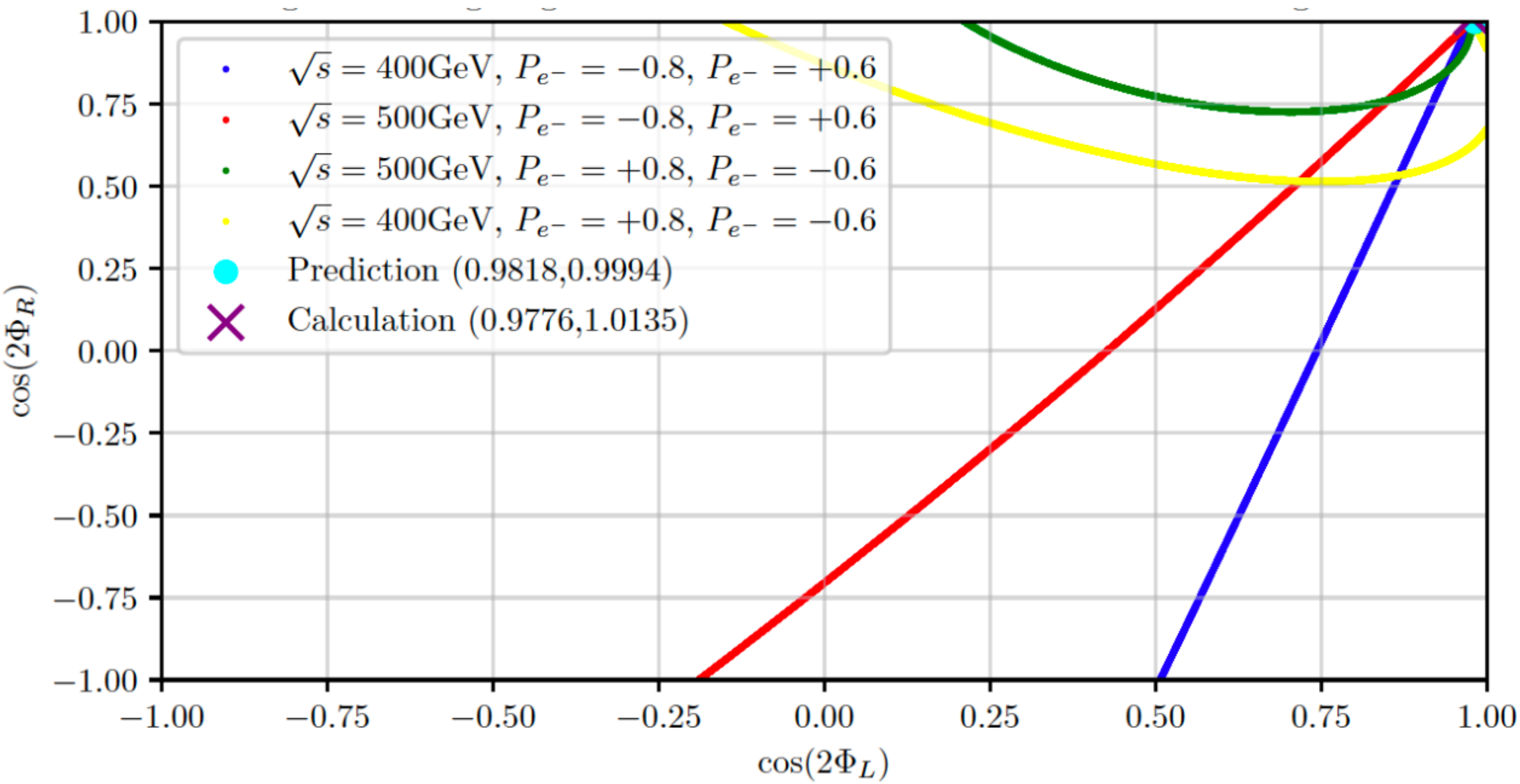


⇒ only lower masses accessible

⇒ interesting points corresponding to the excesses covered . . .
(red star: example point)

Reconstruction of parameters

Ellispses of four XS measurements:

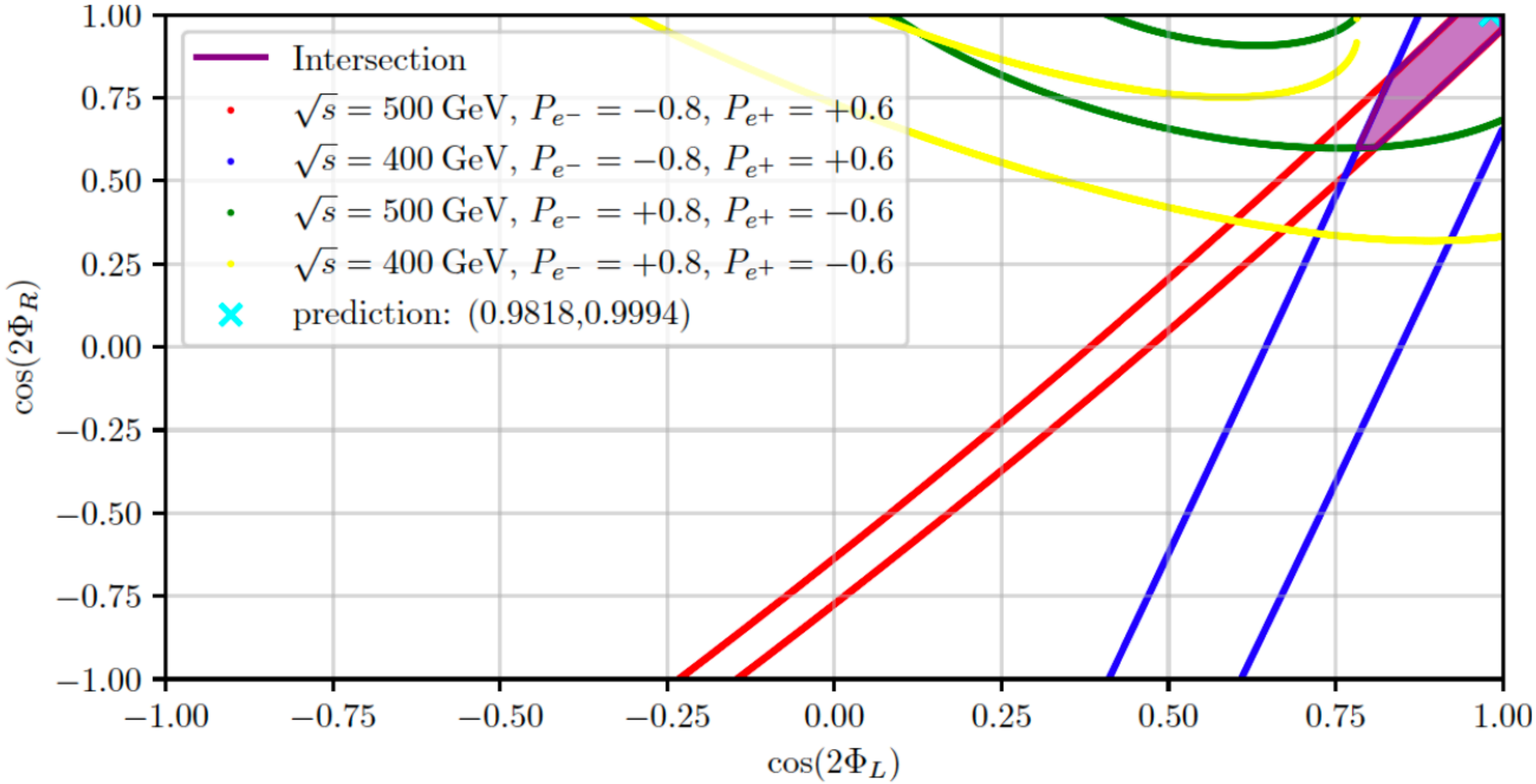


➡ $X^+_1X^-_1$ parametrized by 2 mixing angles

⇒ four ellipses must meet – and they do!

Reconstruction of parameters

Ellispses of four XS measurements with uncertainties:

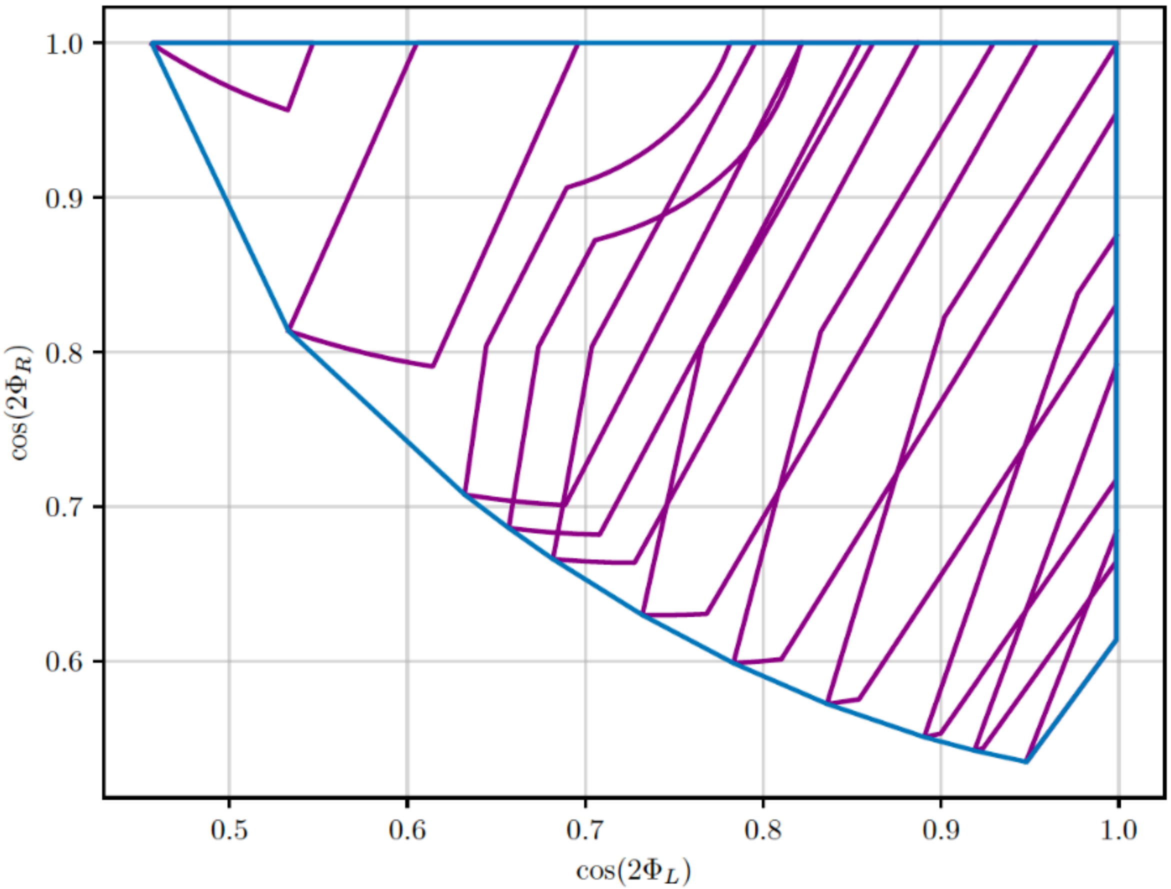


⇒ uncertainties lead to overlap region

So far used: correct, but unknown $m_{\tilde{\nu}_e}$ (too heavy for ILC500)

Reconstruction of parameters

Variation of $m_{\tilde{\nu}_e}$:

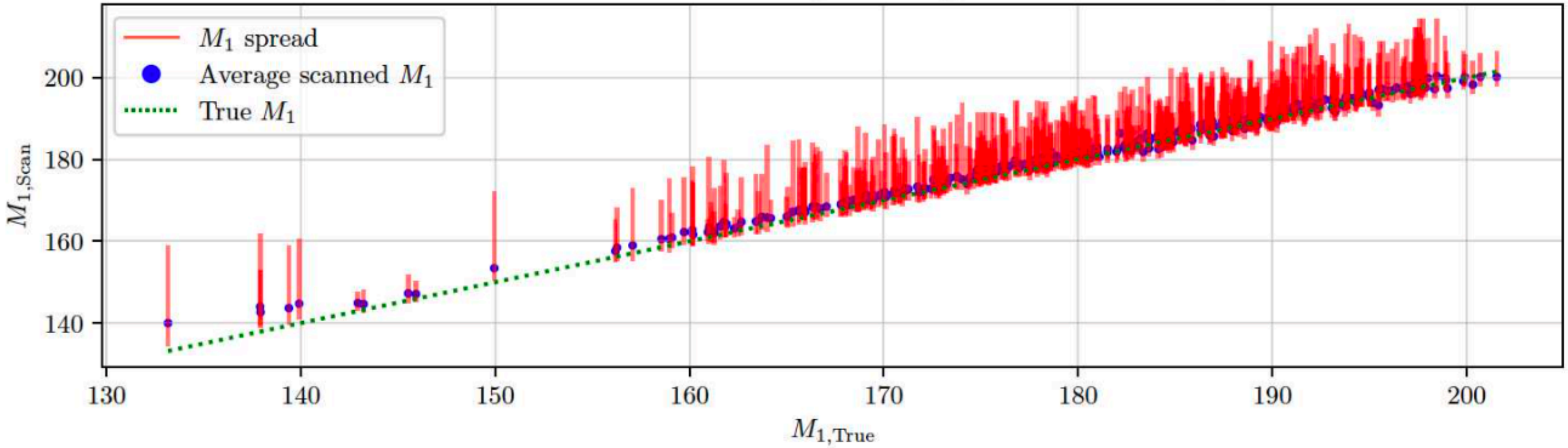


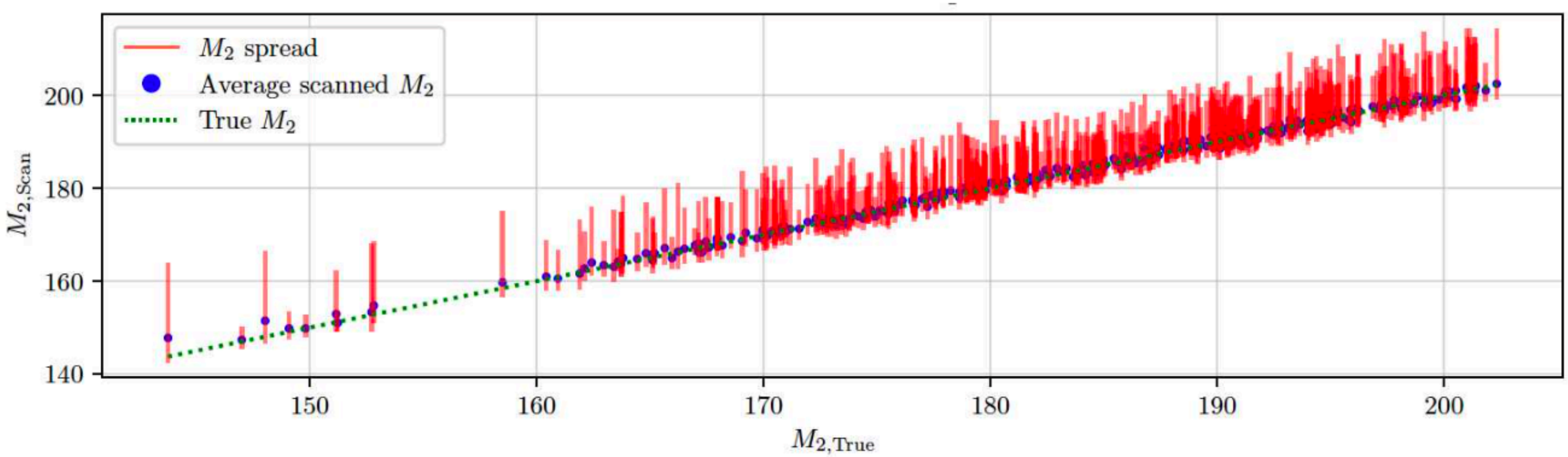
⇒ overlap region smeared out

⇒ indirect determination of $m_{\tilde{\nu}_e}$ (within $\lesssim \pm 100$ GeV)

Reconstruction of parameters

Reconstruction of M_1 and M_2:

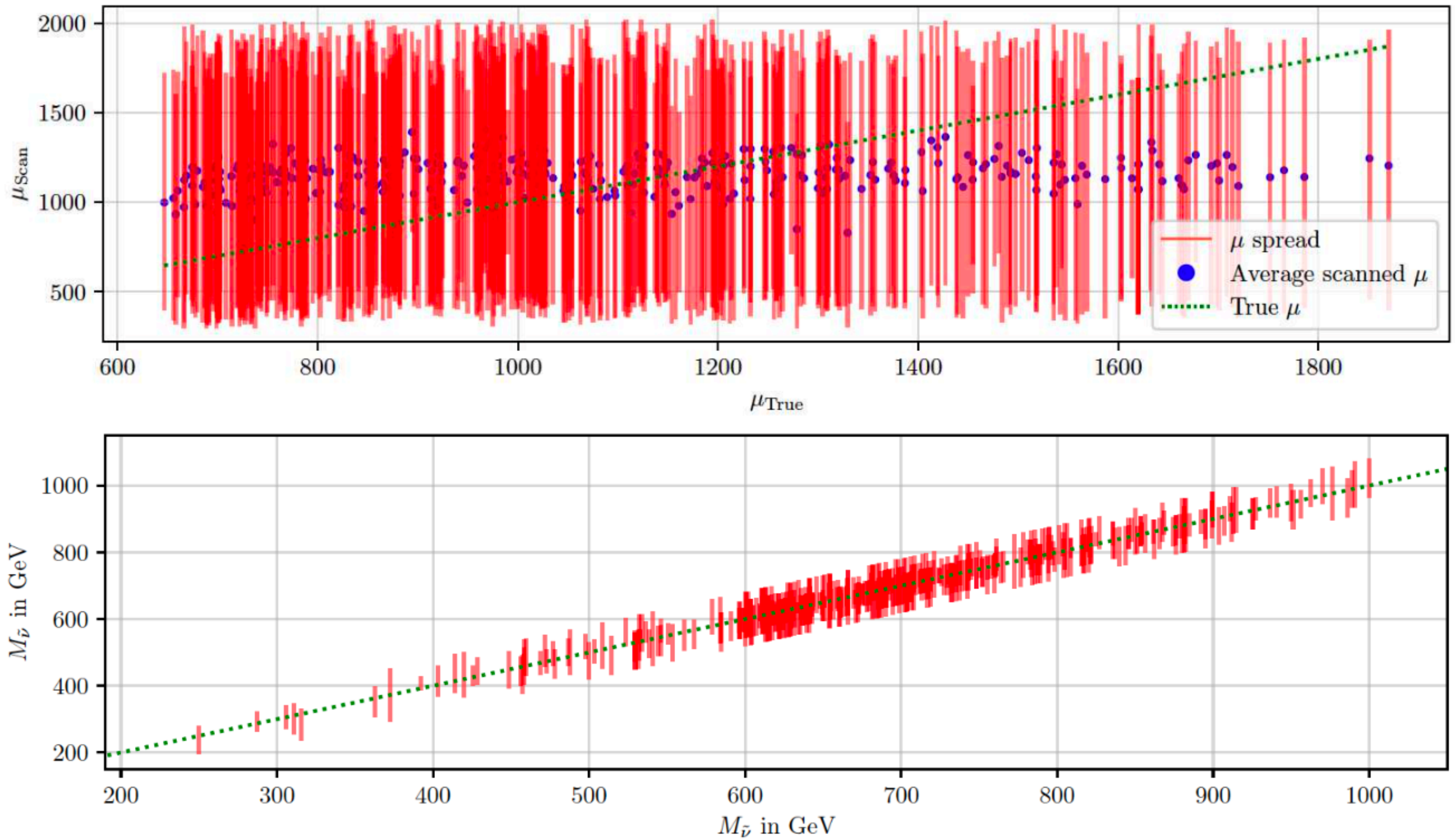




$\Rightarrow$ good reconstructions possible

Reconstruction of parameters

Reconstruction of μ and $m_{\tilde{\nu}_e}$:

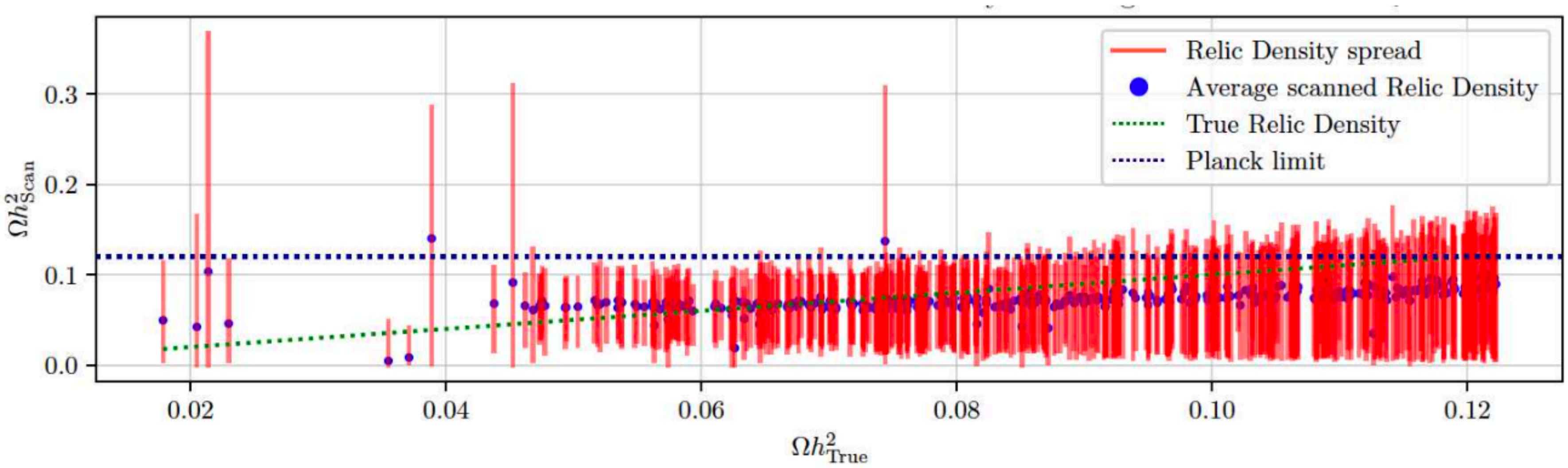


⇒ bad reconstruction of μ, good reconstruction of $m_{\tilde{\nu}_e}$

⇒ no problem, since μ is not very relevant in this scenario

Relic density

Reconstruction of $\Omega_\chi h^2$:



⇒ often large uncertainties - but not too bad either

⇒ reason: experimental uncertainties in M_1 and M_2

⇒ possible improvement: optimized $\sqrt{s}$

Conclusions

- For the first time consistent excesses in ATLAS and CMS in SUSY searches have been observed.

- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 Z^* \; \tilde{\chi}_1^0 W^*$
  with $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \gtrsim 250$ GeV, $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV

- Best-fit explanation in the MSSM: wino/bino DM with $M_1 \times \mu < 0$

Nearly ideal situation for ILC500(+): or the HALHF upgrade

- $\Omega_\chi h^2$ reconstruction at ILC500:
  - scenario: wino/bino DM with $M_1 \times \mu > 0$
  - measurement of $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm}$ and $\sigma(e^+ e- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$
  - XS measurement with two polarizations and at $\sqrt{s} = 400, 500$ GeV
  - reconstruction of M_1, M_2, μ, $m_{\tilde{\nu}_e}$ (ind.!), . . . – with uncertainties
  - calculation of $\Omega_\chi h^2$ – with uncertainties

  $\Rightarrow$ "agreement" with astrophysical measurement

Further SUSY facts

- Low energy experiments, $(g\text{-}2)_\mu$:
  - favours rather low SUSY masses in electroweak sector:

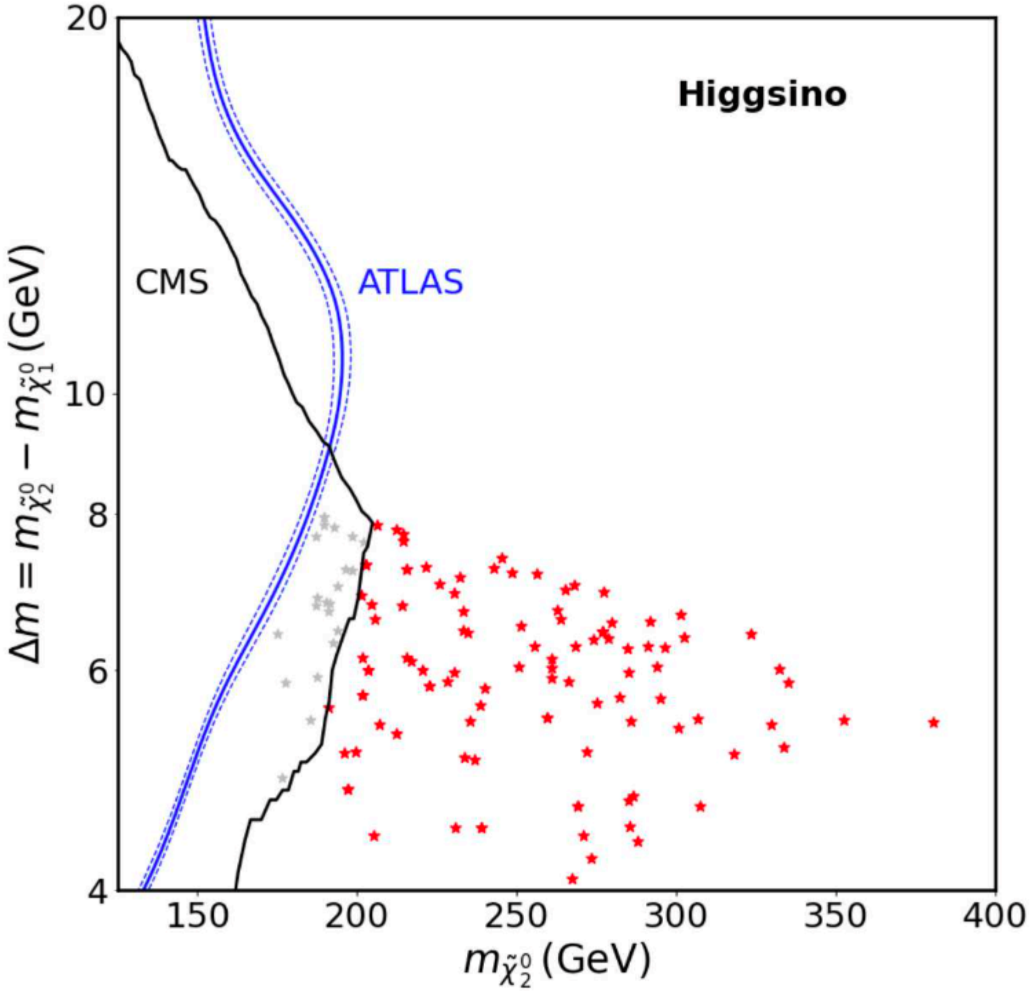
$$\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$

    - C very model dependent, SUSY/ED ~ O(α/4π …)
  - LHC results prefer rather heavy coloured sector in 1st +2nd generation
  - Way out: rather simple
    - Decouple uncoloured and coloured sector and/or take hybrid models of SUSY breaking
    - Just leave out the constrained minimal models, that's all

Remember: Minimal SUSY contains 105 new parameter… why should nature be too simple ?

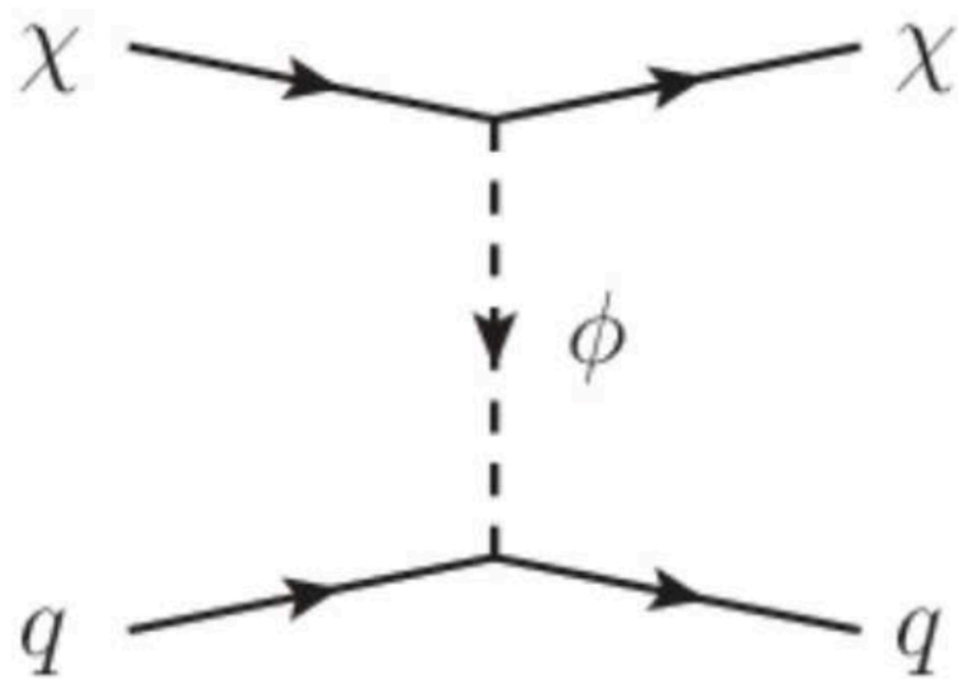
Results in the $m_{\tilde{\chi}_2^0}$-Δm plane

[PRELIMINARY]



$\Rightarrow$ excess not fitted :-($\Rightarrow$ DD cuts away the "good points"

Problematic diagram for higgsino DM DD:

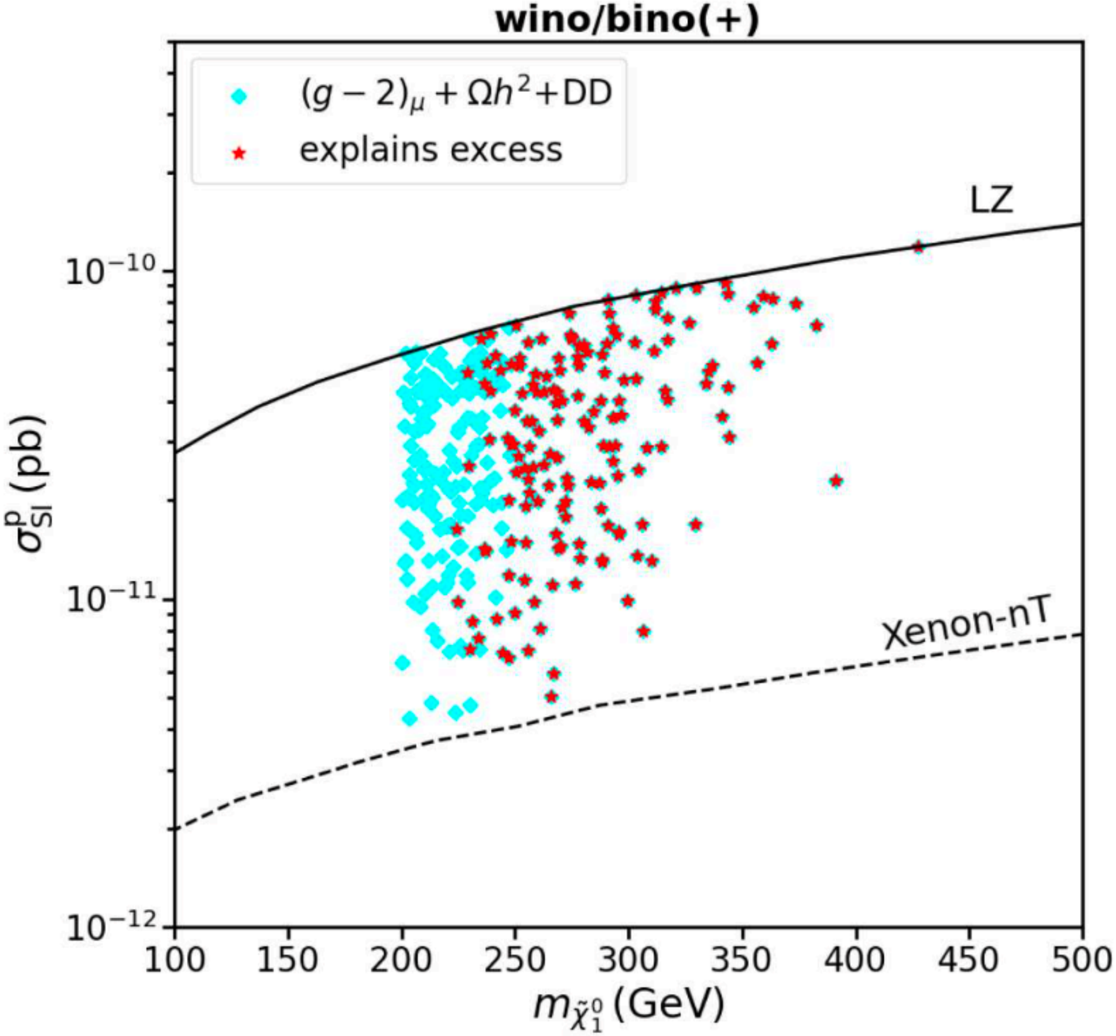


$\phi = h, H$

⇒ cancellation possible for $\mu \times M_1 < 0$ ("blind spots")

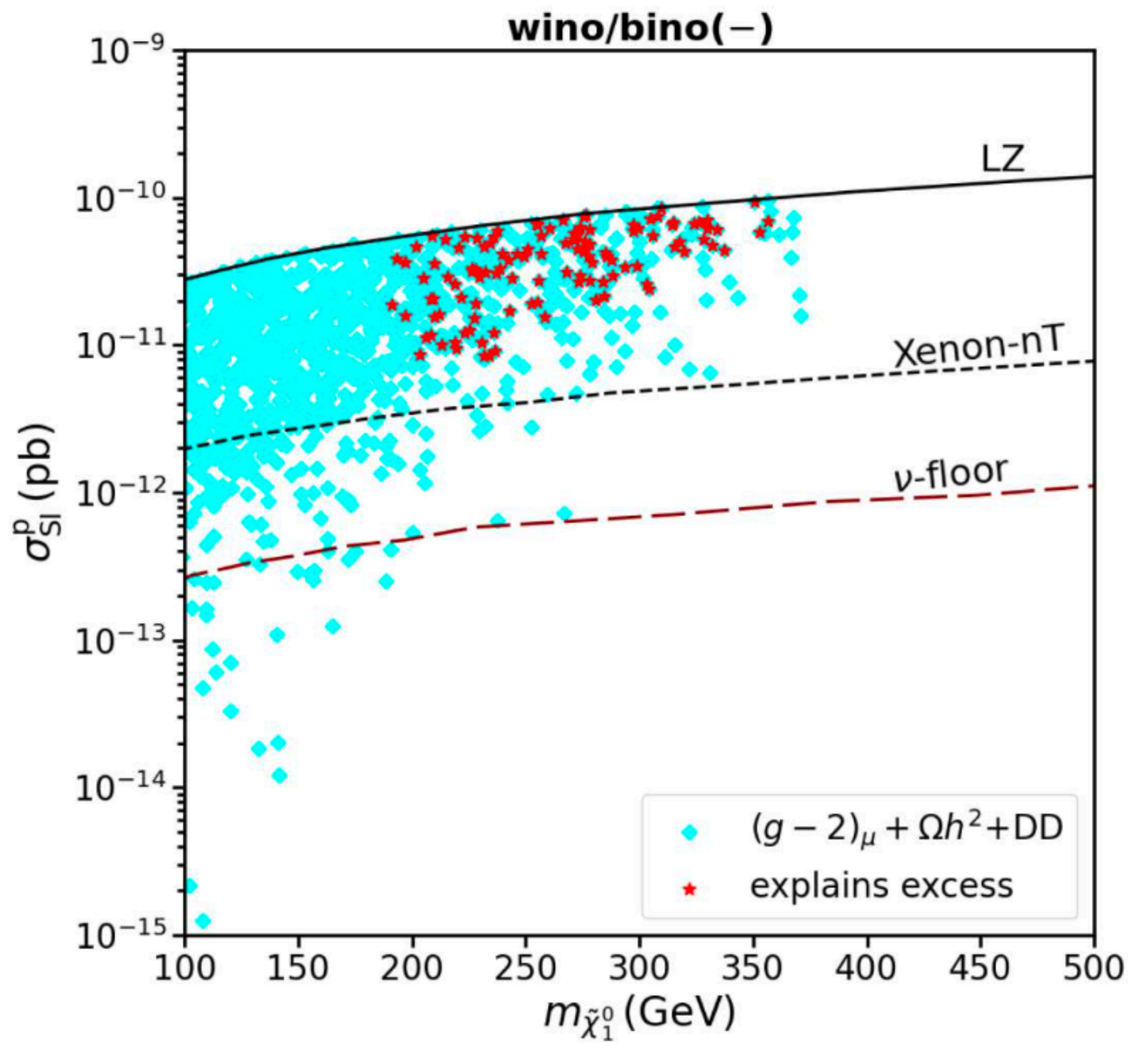
⇒ new scan with $M_1 < 0$

wino/bino(+): direct detection prospects:



$\Rightarrow$ wino/bino(+)/$\tilde{\chi}^\pm_1$ co-annihiliation will be covered by XENON-nT/LZ

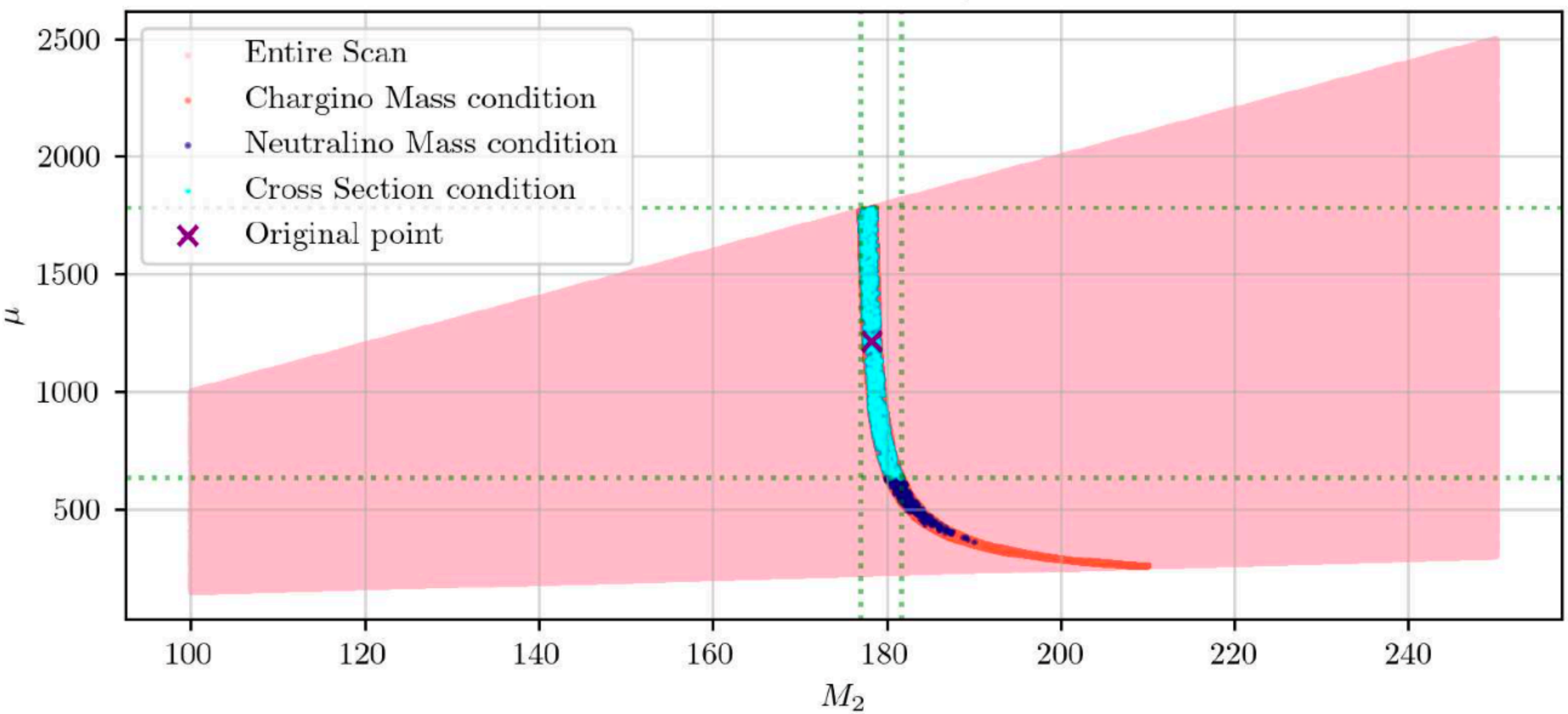
wino/bino(−): direct detection prospects:



⇒ wino/bino(−)/$\tilde{\chi}_1^{\pm}$ co-annihiliation will be covered by XENON-nT/LZ

⇒ low mass points now excluded ⇒ would have been a problem for DD

MSSM parameter determination:



- XS measurement very important
- M_2 well determined
- μ poorly determined (not very relevant in this scenario)