SUSY Dark matter determination at future e+e- colliders (cont.)

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In coll. with J. Becks, S. Heinemeyer, L. Kriege

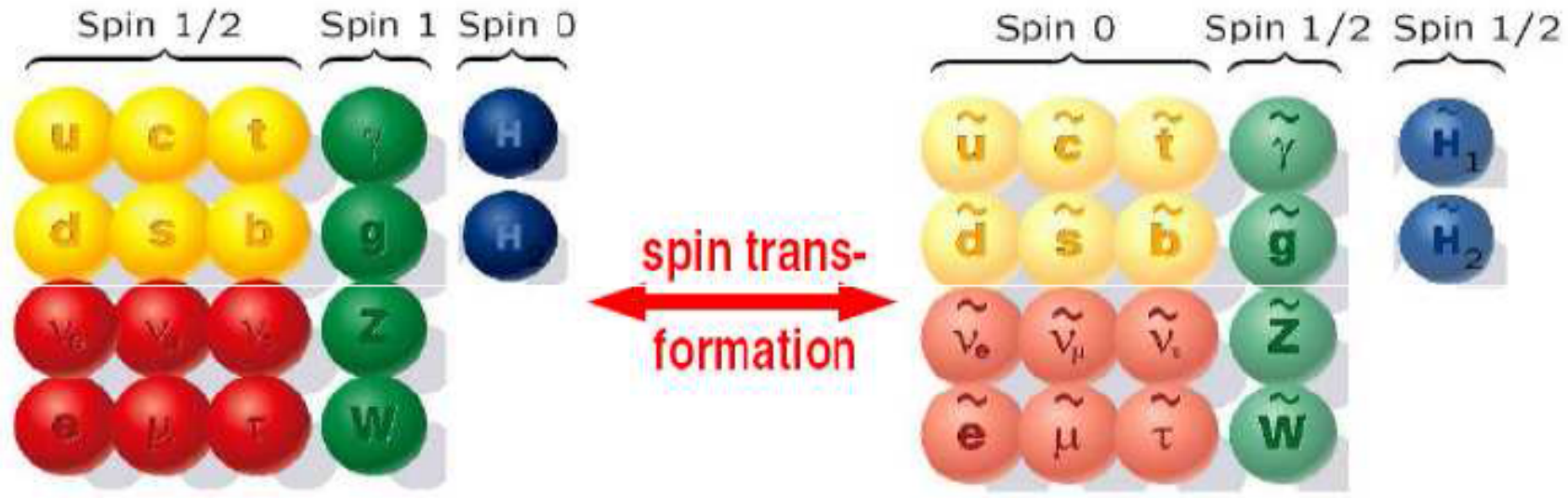
- **Short SUSY Intro&Strategy**
- **Scans**
- **Parameter determination**
- **Results on DM**
- **Conclusions**



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

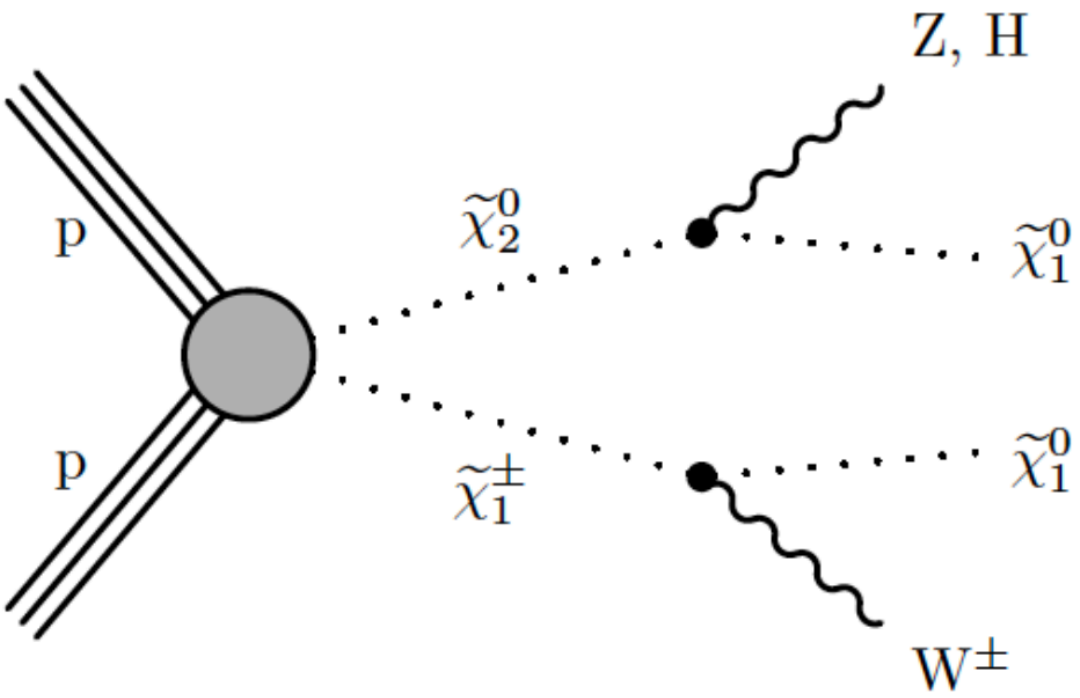
charginos/neutralinos: M_1, M_2, μ, $\tan\beta$ $\Rightarrow$ Dark Matter candidate: $\tilde{\chi}_1^0$

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

SUSY light dark matter range

⇒ Our "models" predict low chargino/neutralino masses

Golden mode at the LHC:

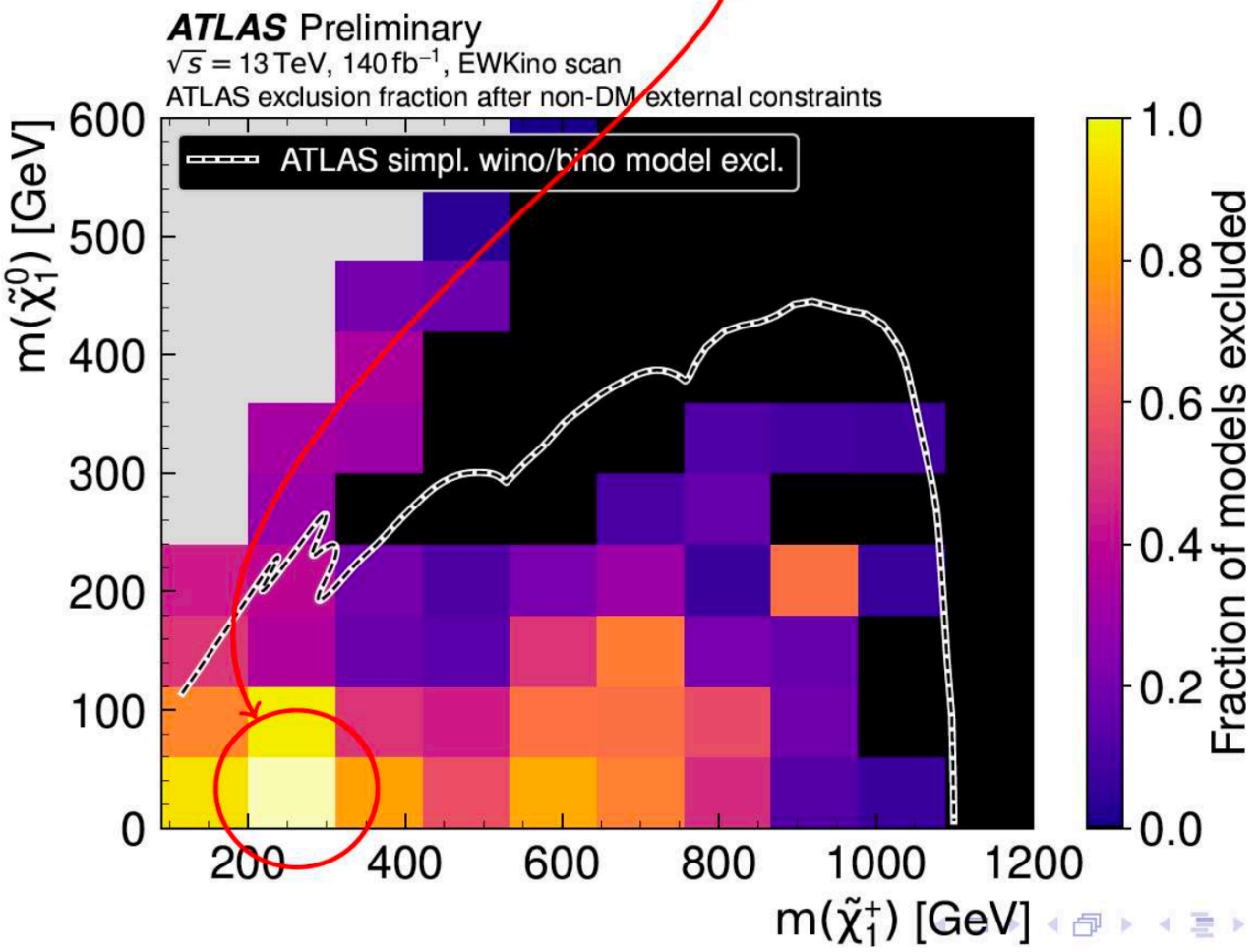


⇒ experimental results?

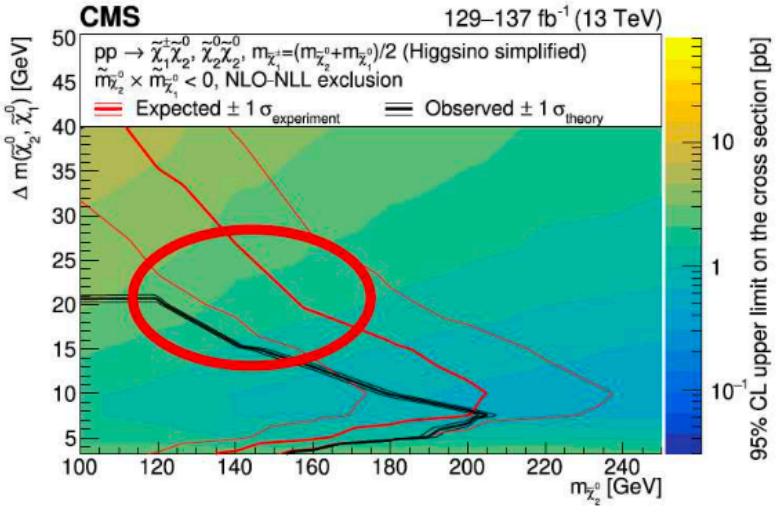
Impact from LHC SUSY searches limits

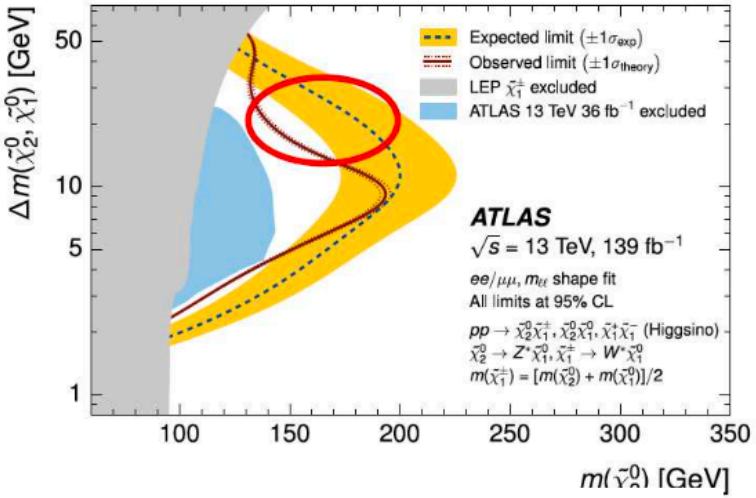
taken from M. Berggren 2023

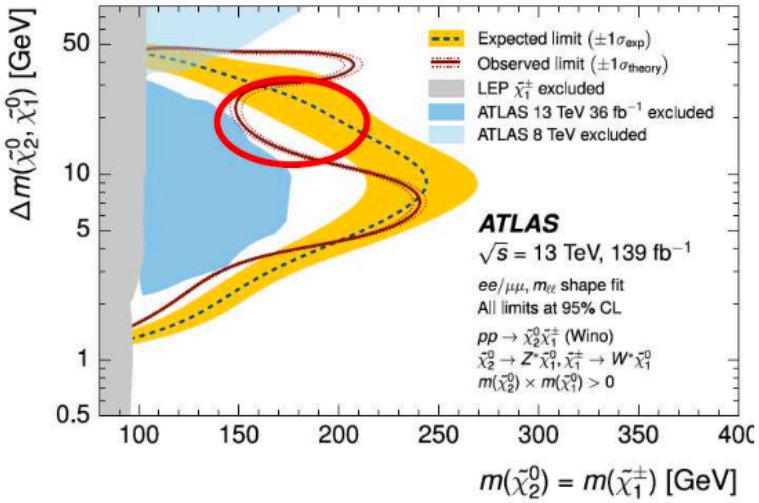
Only this one is actually excluded !

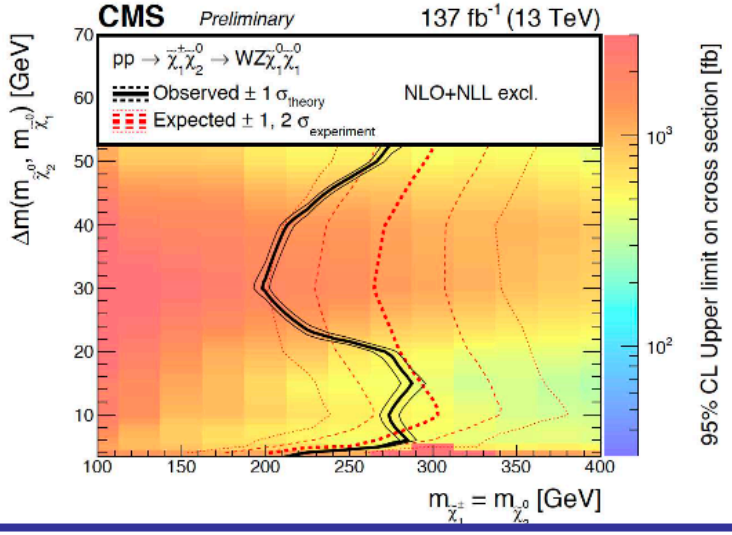


Results ‘compressed’ spectra w/ heavy sleptons









➡‘excess’ region: $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^{\pm}}$ $\Delta m := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 20$ GeV

Idea

- **Convert SUSY measurements into crucial dark matter test**
  - Turn LHC+LC measurements into precise SUSY parameters
  - Predict $\Omega_\chi h^2$ on basis of parameter determination
- **Studied process: e^+e^- $\chi^+\chi^-$**
  - Input : measured masses of $\chi^\pm$, χ^0, via continuum or threshold
  - Measured polarized cross setions at 350 and 500 GeV
  - Measured A_{FB} of this process
- **Determine fundamental parameters: M_1, M_2, μ, $\tan\beta$**
  - Fine, very accurate results …. <% level
  - Predict dark matter contribution
- **Advantages LC:**
  - more tools (e+& e- polarization, threshold scans, ISR method)
  - high precision (up to quantum level)

Several options to embed dark matter

$$\chi_i^0\ (i{=}1,2,3,4) = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

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 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

Scans of available parameter points

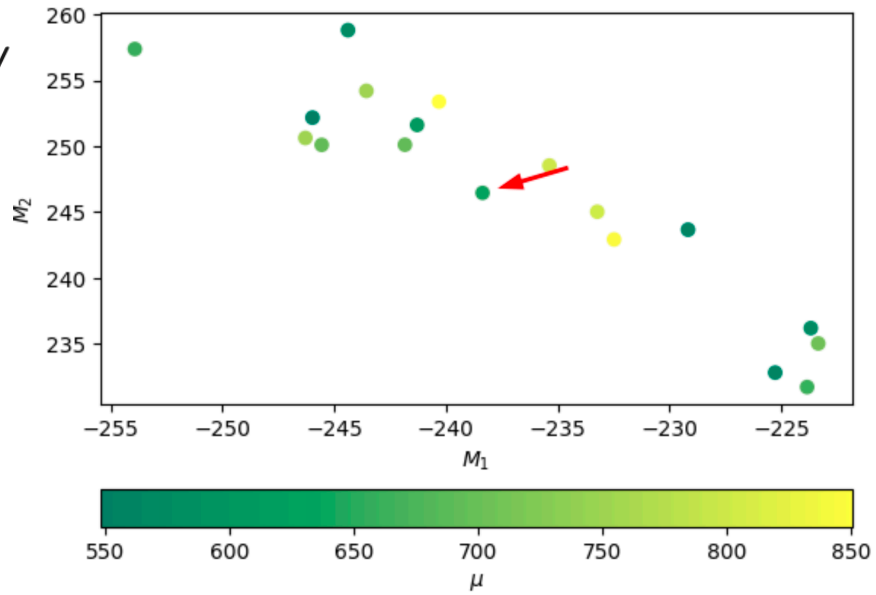
A) Wino/bino DM with chargino co-annihilation

M. Chakraborti, S. Heinemeyer, I. Saha 24

Parameter scan:

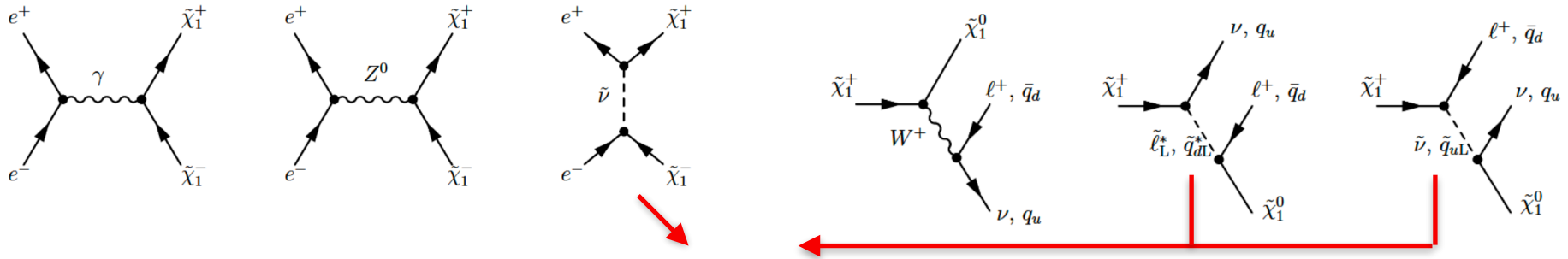
$$100\ \text{GeV} \leq |M_1| \leq 400\ \text{GeV}\ ,$$
$$|M_1| \leq M_2 \leq 1.1|M_1|\ ,$$
$$1.1|M_1| \leq \mu \leq 10|M_1|,$$
$$2 \leq \tan\beta \leq 60,$$
$$100\ \text{GeV} \leq m_{\tilde{L}} \leq 1.5\ \text{TeV}$$

➡ **Take all allowed points that describe the excess !**



Reconstruction of parameters

- **Light Chargino production & decay:**



also ν, e_L enter!

- so far tree-level analysis
- to be extended including full one-loop corrections
- leads to more involved parameter dependencies

A. Bharucha et al. '13, '16

- **Example point:**

$m_{\tilde{\chi}_1^0}$	204.94 GeV
$m_{\tilde{\chi}_2^0}$	233.94 GeV
$m_{\tilde{\chi}_1^\pm}$	258.28 GeV

all other masses ≥500 GeV

Reconstruction of parameters

Main idea:

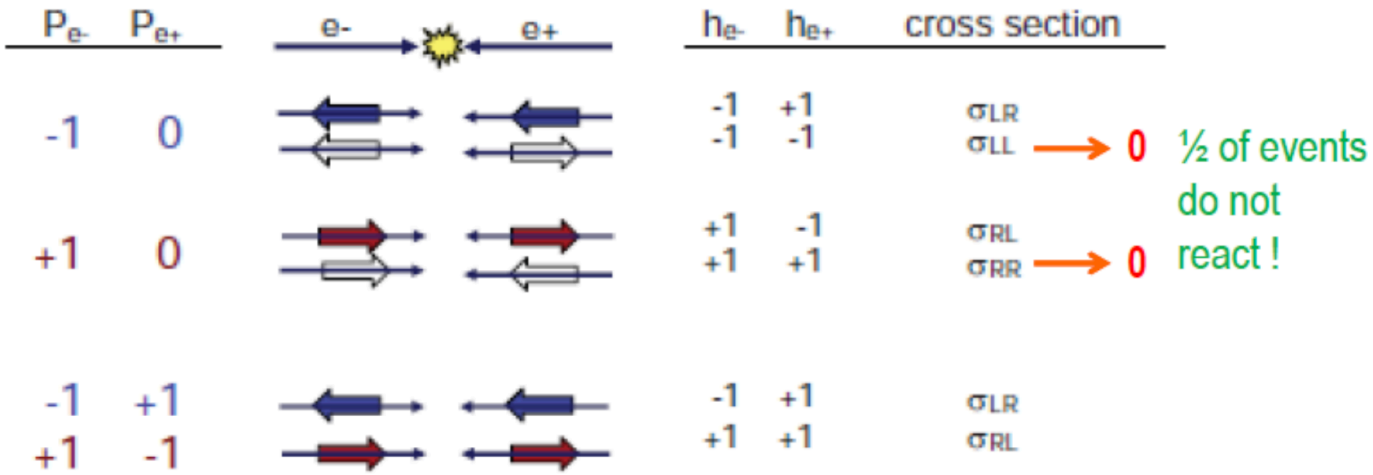
- **Measure cross sections at 2 different energies and masses, inversion into parameters ….as done in the past:** *e.g. K. Desch et al. hep-ph/ 0312069*

$$\sigma^{\pm}\{ij\} = c_1 \cos^2 2\Phi_L + c_2 \cos 2\Phi_L + c_3 \cos^2 2\Phi_R + c_4 \cos 2\Phi_R + c_5 \cos 2\Phi_L \cos 2\Phi_R + c_6$$

  - **determine mixing angles Φ_L,Φ_R , mX^+_1, mX^0_1 ⟶ M_1, M_2, μ, tanβ**

- **But this time, √s>500 GeV needed……..**
- **We assume 1st stage ILC √s=550 GeV (for Di-Higgs required at least!)**
  - **no further energy stage!**
  - **but polarized electron & positron beams…**
  - **and include the decay to measure asymmetries via final leptons**
- **But have to exploit all 4 possible beam polarization configurations!**

Influence of e- & e+ beam polarization



- **Often only LR and RL applied…!**
  - **since no 100% polarization…..also LL and RR provide events**
  - **possible running scenario:**

LCvision, C. Balazs, arXiv: 2503.19983

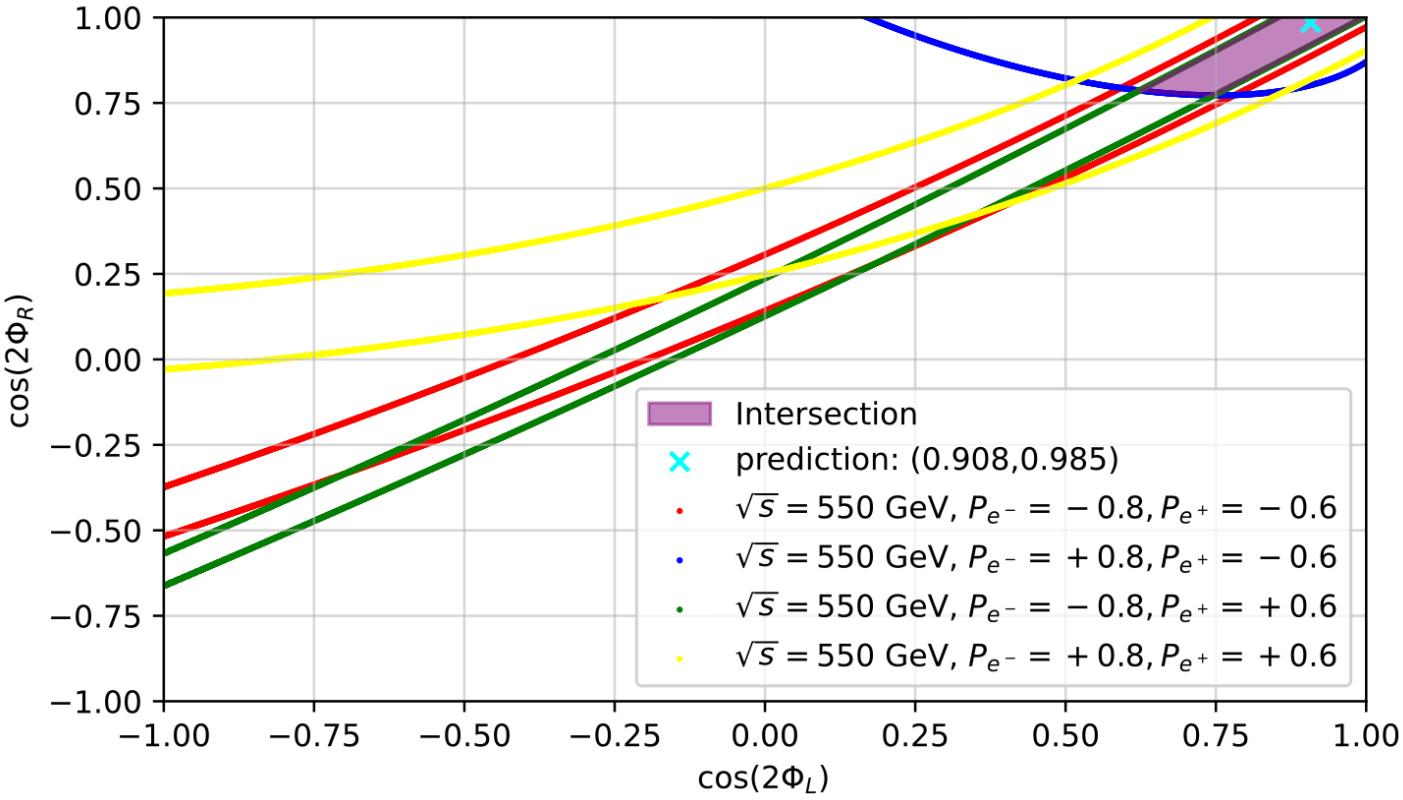
	91 GeV	250 GeV	350 GeV	550 GeV	1-3 TeV
$\int \mathcal{L}$ (ab^{-1})	0.1	3	0.2	8	8
beam polarisation (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(−+, −−, ++, +−) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)

- **We use in the ff 80%,60% with same lumi than +-, -+.**

Reconstruction of parameters

$\sigma_{-,-}$	148.6034 fb
$\sigma_{+,-}$	15.9516 fb
$\sigma_{-,+}$	591.0757 fb
$\sigma_{+,+}$	63.9902 fb

statistical uncertainty	$\sigma_{\text{stat}} = \frac{\sqrt{\sigma L}}{L}$
polarisation uncertainty	$\delta P_{e^+} = \pm 0.5\%$ $\delta P_{e^-} = \pm 0.5\%$
mass uncertainty	$\delta m_{\tilde{\chi}} = 0.005 m_{\tilde{\chi}}$



Involving A_{FB} of the final leptons

$$\bullet\ |T|^2 = |\Delta_{f_1}|^2 |\Delta_{f_2}|^2 \sum_{fin.sp.} \overbrace{(P^{\lambda_{f_1}\lambda_{f_2}} P^{*\lambda'_{f_1}\lambda'_{f_2}})}^{\text{spin-density matrix}} \times \overbrace{(Z_{\lambda_{f_1}} Z^*_{\lambda'_{f_1}})}^{\text{decay matrix}} \times \overbrace{(Z_{\lambda_{f_2}} Z^*_{\lambda'_{f_2}})}^{\text{decay matrix}}$$

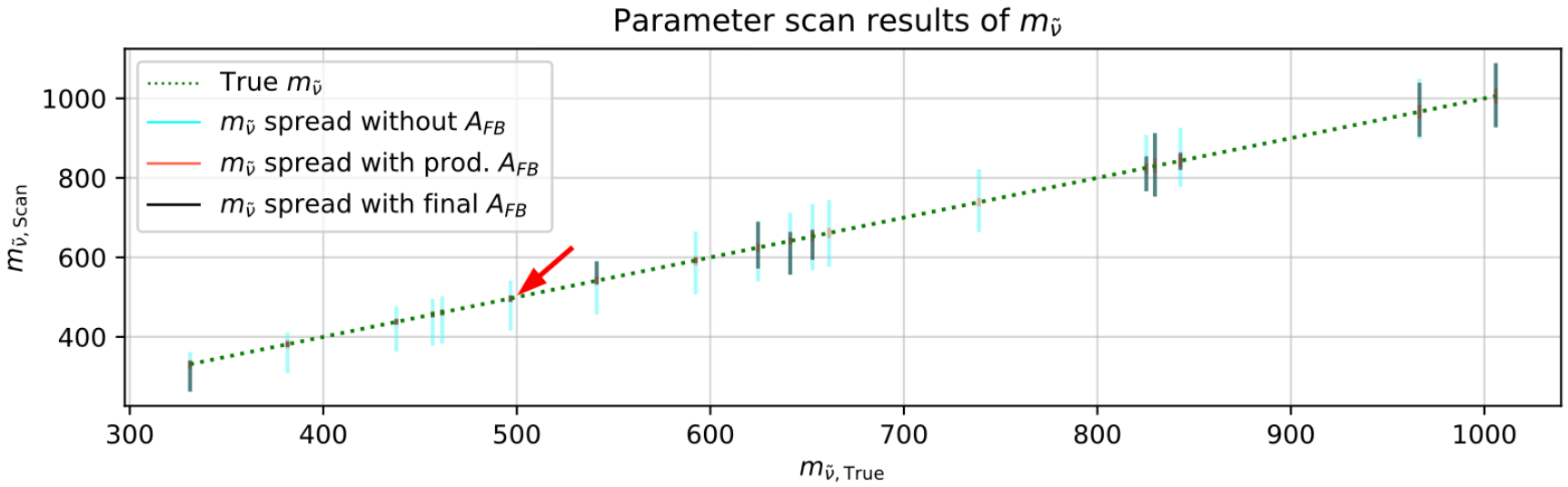
$$|T|^2 \sim \mathcal{P}(p_{f_1}, \overbrace{s_{f_1}, p_{f_2}, \underbrace{s_{f_2}}_{\text{spin correlations}}) \mathcal{D}(p_{f_2}, s_{f_2})}^{\text{spin correlations}} \otimes \mathcal{D}(p_{f_1}, s_{f_1})$$

- Leads to NEW contributions compared to only the cross section!
- Including stat. uncertainty from AFB via

$$\Delta A_{\rm FB}^{\rm stat} = 4\sqrt{\frac{\epsilon(1-\epsilon)}{N\,\Gamma}}$$

➡ allows to determine no the parameters including mν, that is to heavy to be produced directly!

Reconstruction of parameters



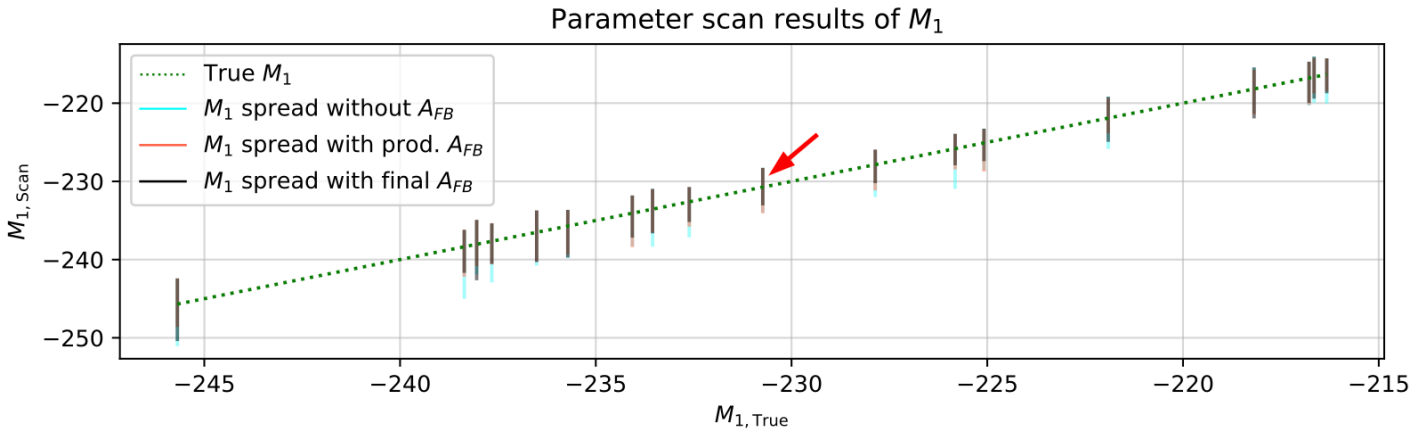
- Determination of msneutrino possible, although too heavy to be producted directly

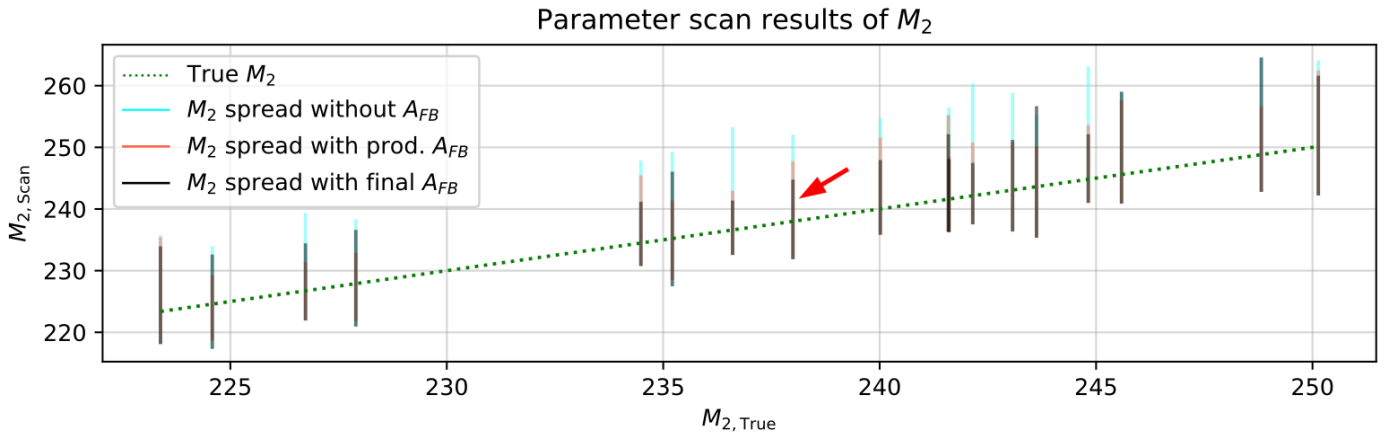
- Even indirect prediction of mselL (SU(2) relation

➡ consistency check

Reconstruction of parameters

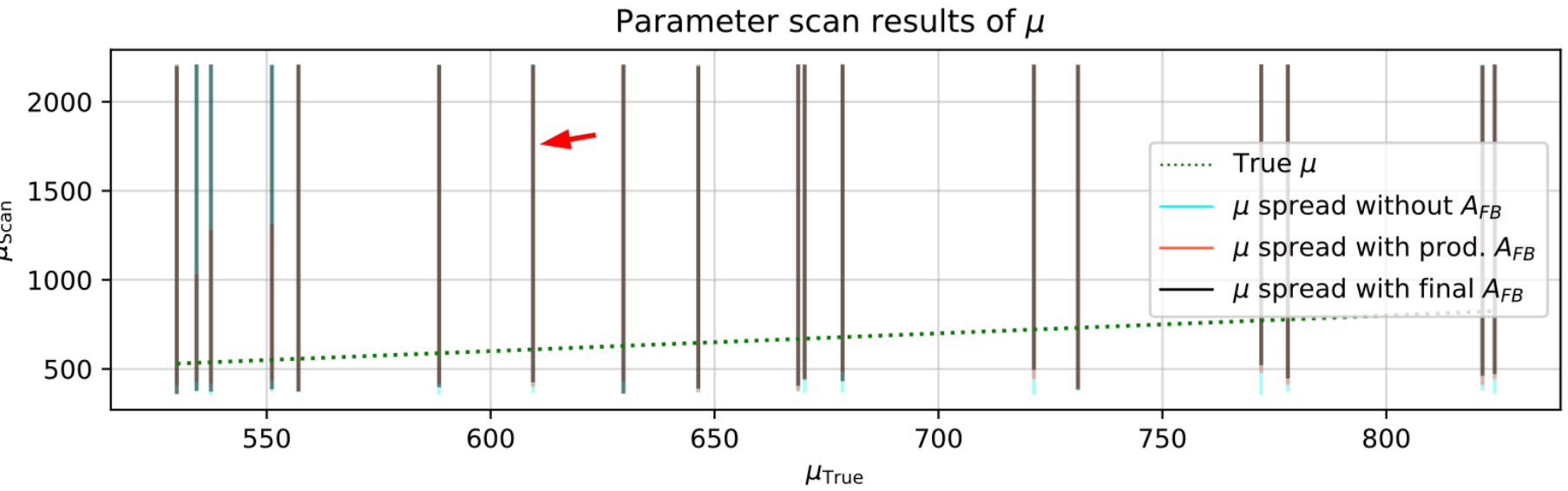
- Precise determination of gaugino parameters





Parameter Determination

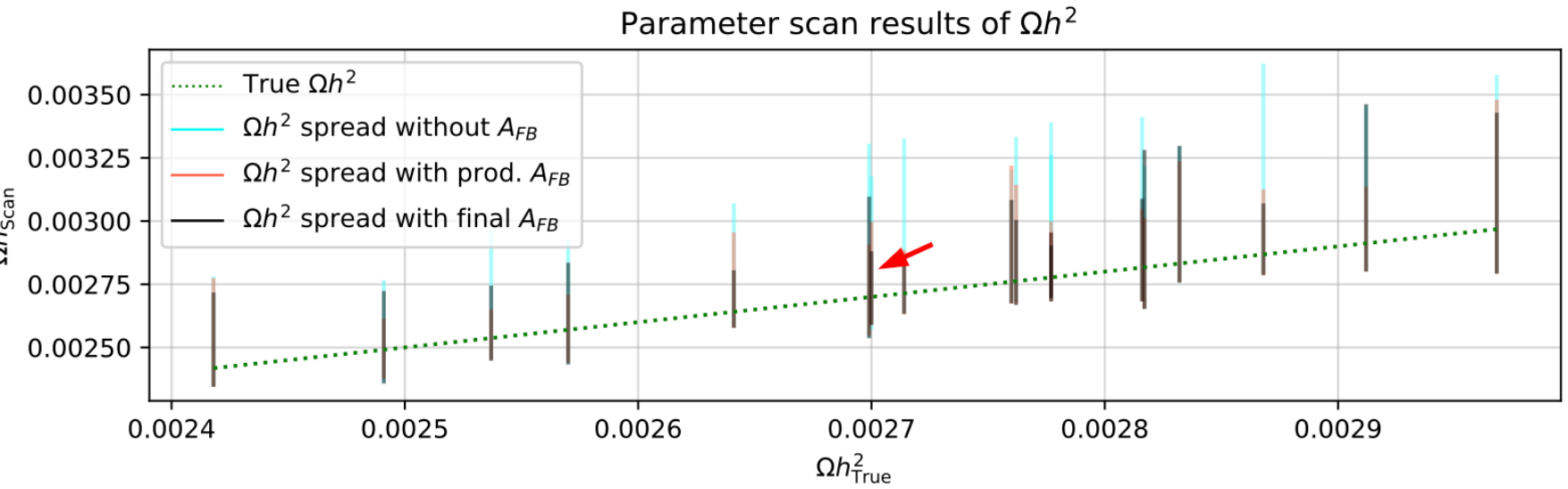
- Less recise determination of the higgsino parameter



…….since we studied a gaugino scenario.…clear from the beginning

Relic Density

- The important message is: we can predict the corresponding relic density rather accurately:



……about 10 % -level, that's complementary to inpout from cosmology

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 $M_1 \times \mu < 0$

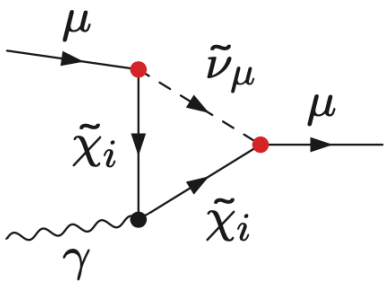
Nearly ideal situation for ILC500(+): or the HALHF upgrade

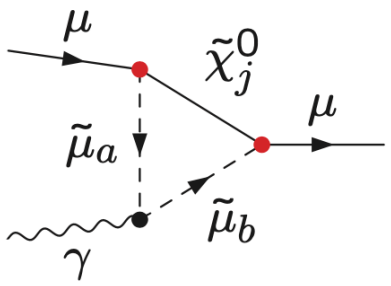
- $\Omega_\chi h^2$ reconstruction at ILC500:
  - scenario: gaugino-like, in concordance with current excesses
  - measurement of $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm}$ and $\sigma(e^+e- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$
    - polarization of both beams essential for exploiting even e.g. RR configurations, if only one energy stage is available
  - 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

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:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \;:\; \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \;:\; \sim m_\mu \tan\beta$$

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

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

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