# Natural SUSY at the ILC: from MZ to the GUT scale

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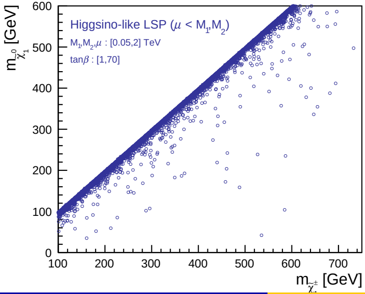
# Outline

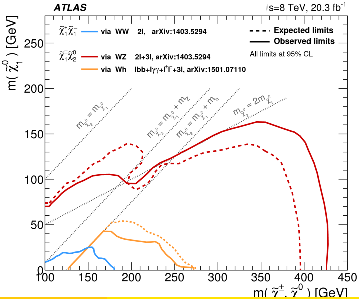
# Why study light higgsinos

- The superpartners of un-coloured SM bosons mix to $\tilde{\chi}^0_{1-4}$ and $\tilde{\chi}^{\pm}_{1-2}$, governed by $\mu, M_1, M_2, \tan\beta$.
- Naturalness and small fine tuning require $\mu$ parameter at the EW scale:

$$m_Z^2 = 2\frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$$

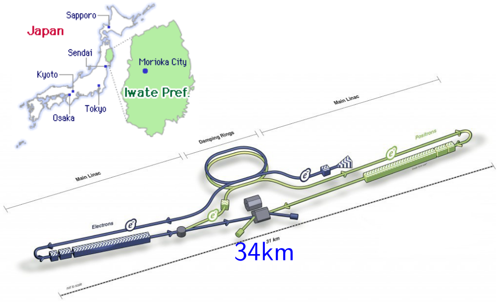
- $\mu$ small $\Rightarrow$ light higgsinos. Typical mass difference 10 - 20 GeV
- $\Rightarrow$ challenging for LHC if other sparticles are heavy



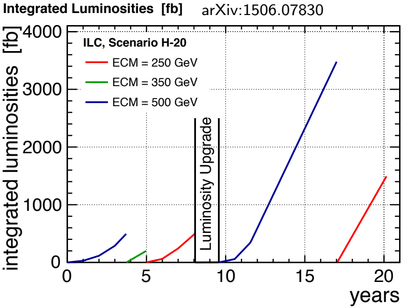



# What is the International Linear Collider (ILC)

- Electron-positron collider at $\sqrt{s} = 250 - 500\text{GeV}$ (1TeV)
- Polarisation of electrons 80%, positrons 30%
- Well-defined initial state: 4-momentum and spin configuration.
- Clean and completely reconstructable final state
- Almost $4\pi$ detector coverage. No trigger needed
- Under political consideration in Japan




Typical 20yr running scenario

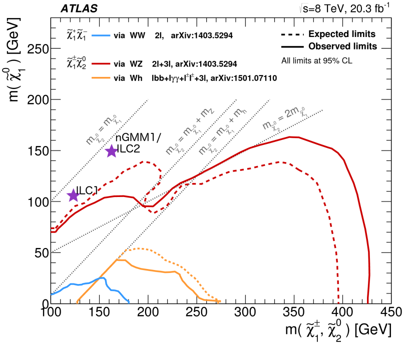


# Benchmarks studied

- $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$ observable, in ILC1 $\tilde{\chi}^0_3$ accessible with a small cross section
- Other sparticles heavy
- Mass gaps $\sim 10 - 20$ GeV $\Rightarrow$ higgsinos decay via a virtual Z/W

Masses (GeV) in three benchmarks

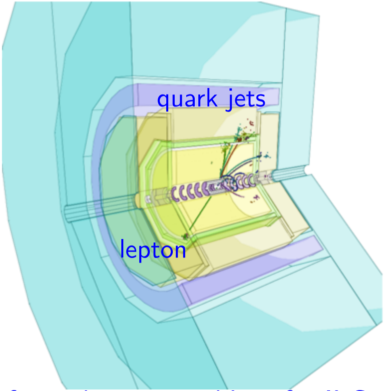
| | ILC1 | ILC2 | nGMM1 |
|---|---|---|---|
| $\tilde{\chi}^0_1$ | 103 | 148 | 151 |
| $\tilde{\chi}^\pm_1$ | 117 | 157.8 | 159 |
| $\tilde{\chi}^0_2$ | 124 | 158.3 | 156 |
| $\tilde{\chi}^0_3$ | 267 | 539 | 1530 |
| $\tilde{g}$ | 1560 | 2830 | 2860 |




Cross sections for production in $e^+e^-$ at $\sqrt{s} = 500$ GeV several hundred fb

# Detailed simulation study: 500 GeV, 500 fb$^{-1}$

$e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to \tilde{\chi}_1^0 q\bar{q}'\tilde{\chi}_1^0 e\nu_e$
in the International Large Detector

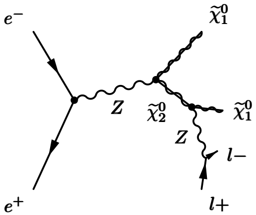



Soft tracks - no problem for ILC

- Event generation `Whizard 1.95`, hadronisation `Pythia 6.422`
- Detailed ILD-specific software for simulation and reconstruction (`Mokka` & `Marlin`)
- Beam spectrum, ISR and $\gamma\gamma$ "pile-up" included

# Neutralino measurement

- Neutralino signal: $e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 e^+e^-(\mu^+\mu^-)$
- Characterised by large missing energy and two fermions in the final state
- Main background 4-fermion processes $\nu\nu ll$

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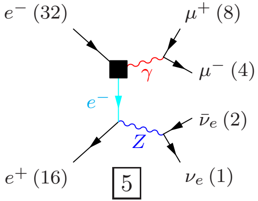
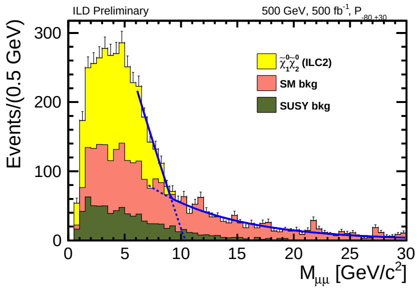
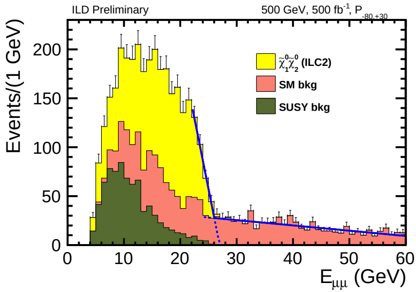



Background example

# Mass extraction

- Kinematics: Maximum invariant mass gives the mass splitting. Then maximum of di-lepton energy gives the absolute masses since initial state known



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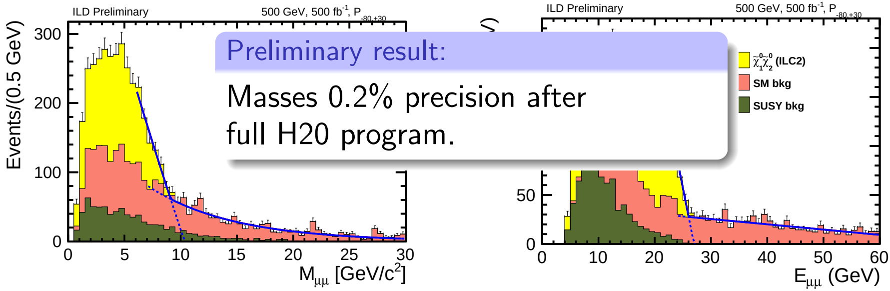
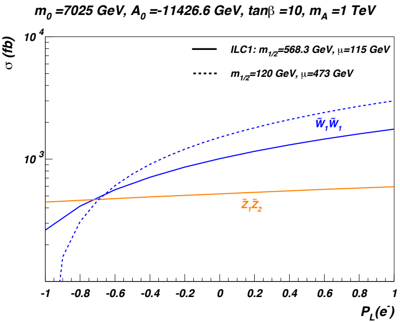



**Preliminary result:**

Masses 0.2% precision after full H20 program.

# Cross section measurement

- Measure with different polarisation combinations
- Polarisation dependence reveals higgsino nature
- Strategy: Fit overall shape to count events



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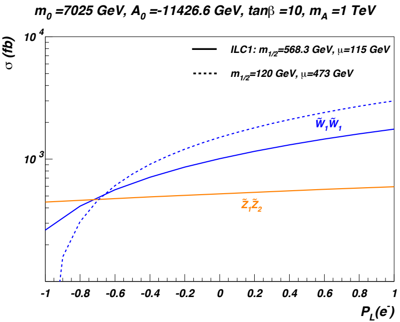


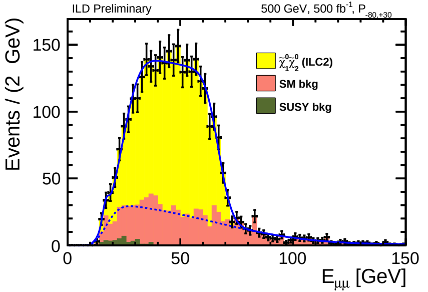

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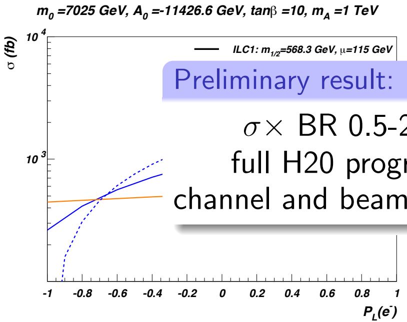


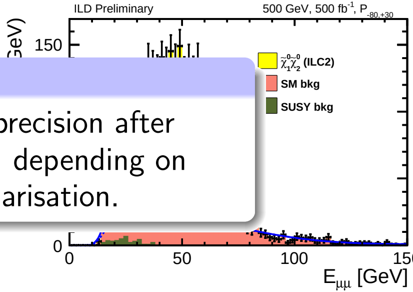


**Preliminary result:**

$\sigma \times$ BR 0.5-2% precision after full H20 program, depending on channel and beam polarisation.

# Chargino measurement

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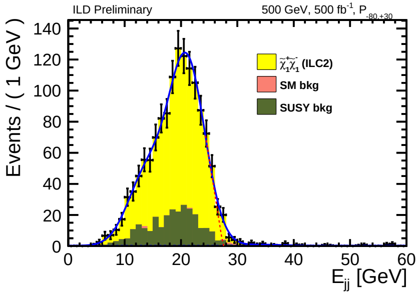


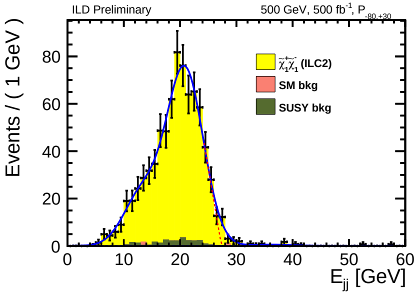

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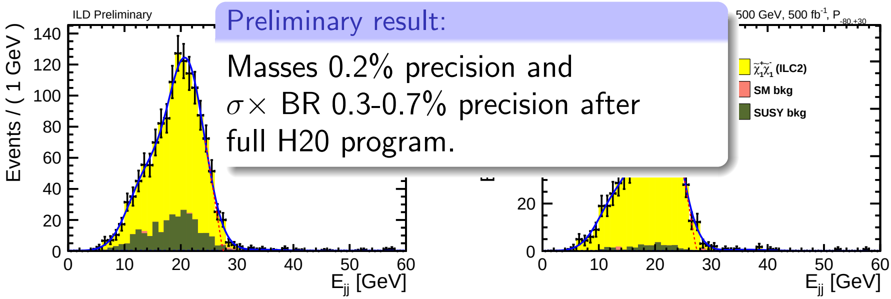


**Preliminary result:**

Masses 0.2% precision and $\sigma\times$ BR 0.3-0.7% precision after full H20 program.

# Probing the GUT scale

So, we have three masses and four cross-section (two processes $\times$ two beam-polarisations), with permil to percent precision.

- What can we say about SUSY parameters based on these observables?
- Which parameters are determined and how accurately?
- Can we test the SUSY model type?
- Can we make predictions about the unobserved part of the spectrum?
- Is there more to be used from the ILC data?

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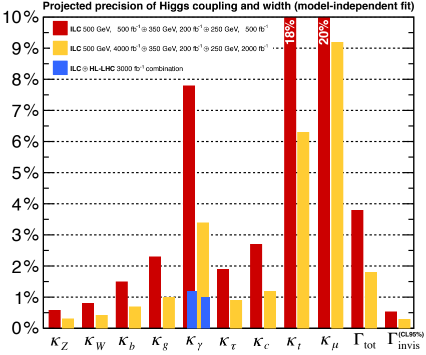
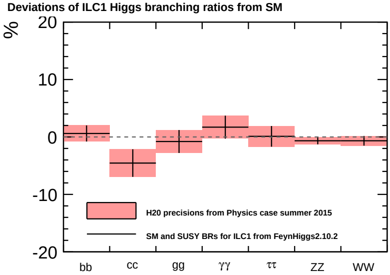
# Probing the GUT scale: Higgs is important!

- Assume ILC will measure $m_h$ to 15 MeV precision
- No deviation from SM BRs but still important for the fit



# What does the model type mean?

Model type: which are the parameters of the model

- Two types of model: GUT scale and weak scale
- GUT scale model assumes a specific cause of SUSY breaking $\Longrightarrow$ few parameters (4-6)
- Weak scale model does not assume knowledge about the cause of SUSY breaking $\Longrightarrow$ lots of parameters
  - But some violate lepton number, violate CP in new ways, increase rates of FCNC...
  - Thus usually use only 10-19 parameters
- A priori do not know it is a GUT model so fit weak scale pMSSM-5 or 10 (at 1 TeV)

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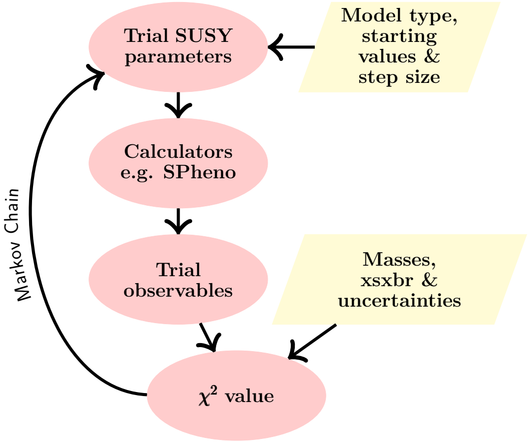
# Probing the GUT scale: Fitting SUSY parameters

Fittino minimises

$$\chi^2 = \left(\frac{\mathcal{O}(ILC) - \mathcal{O}(theory)}{\Delta\mathcal{O}(ILC)}\right)^2$$

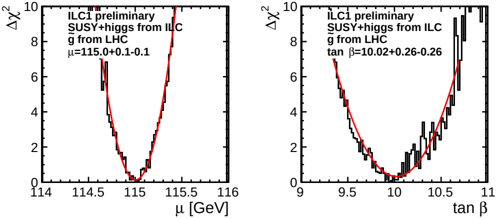
(arXiv:hep-ph/0412012)

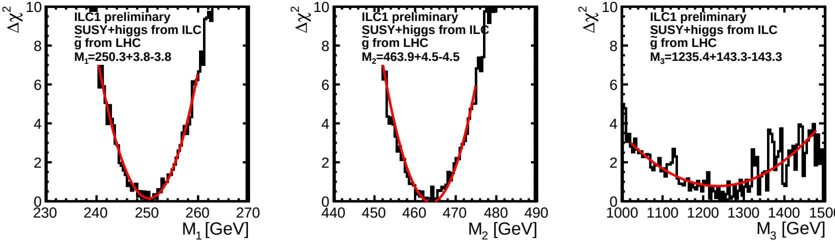
SPheno 3.3.9beta,
Higgs mass and BRs
FeynHiggs2.10.2



# Probing the GUT scale: Weak scale fits

- Purpose to test gaugino mass unification
- Input Higgs and SUSY obs. (incl $\tilde{g}$ fr. LHC).
- $M_1$, $M_2$, $M_3$, $\tan\beta$, and $\mu$ can be determined



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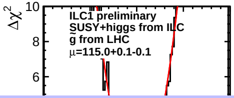
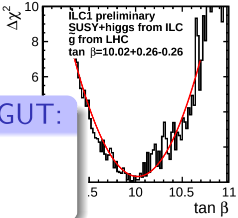
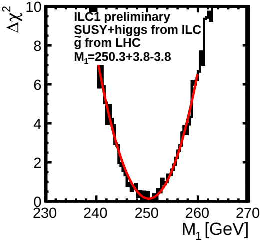
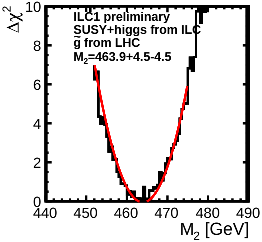


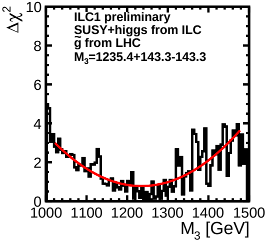




**Most importrant result for testing GUT:**

$\delta(M_1) \approx 4$ GeV, $\delta(M_2) \approx 11$ GeV, $\delta(M_3) \approx 130$ GeV.



# Probing the GUT-scale: Unification?

- This is at the 1 TeV scale.
- SUSY parameters change w/ scale governed by a system of coupled differential equations, the renormalisation group equataions (RGEs).
- What happens if one inputs the fitted values and precisions into the RGEs for $M_{1,2,3}$ ?
  - Do gaugino masses unify?
  - Yes ...
  - ... and also $M_3$: in ILC1 LHC will see the $\tilde{g}$.
  - ... or, conversely -in ILC2 - predict the gluino mass after just 5 years of ILC data: $m_{\tilde{g}} = 2870 \pm 210\mathrm{GeV}$

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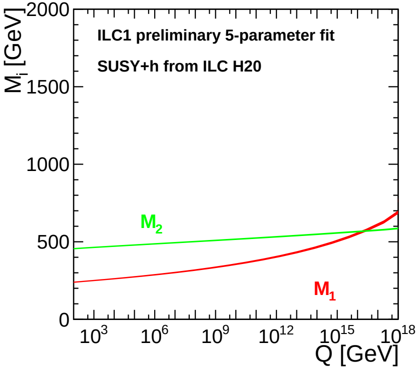

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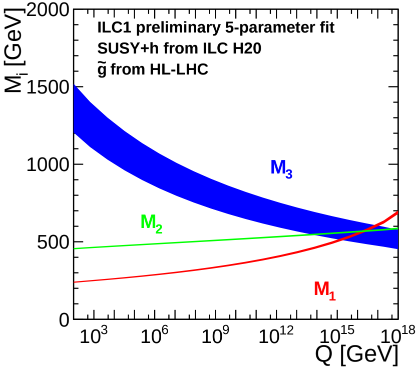

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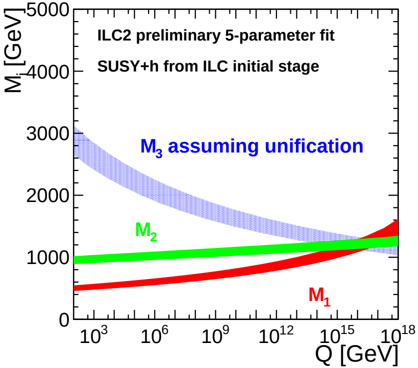

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- Compare results from ...
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- Clearly distinguishable!

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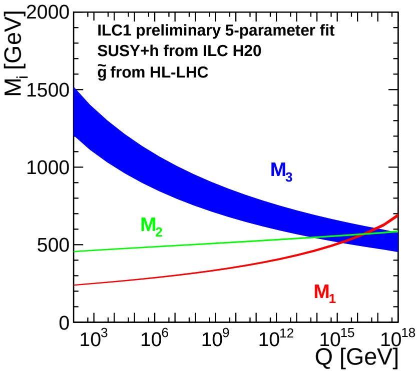

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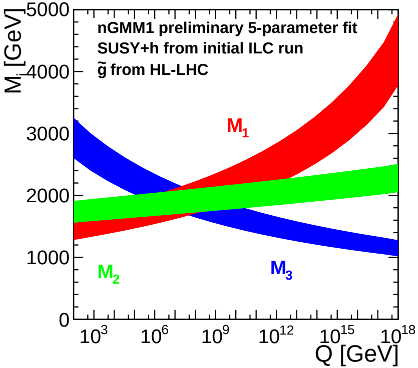

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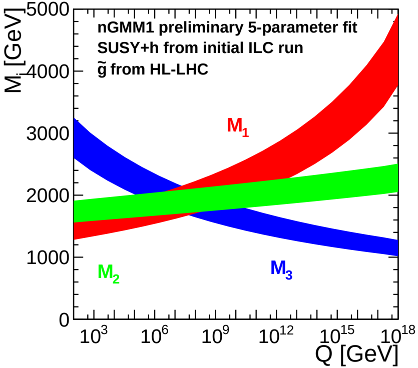

# Probing the GUT-scale: Predict rest of spectrum?

- Heavier neutralino/chargino masses
  - $m_{\tilde{\chi}_3^0} = 263 \pm 4\mathrm{GeV}$
  - $m_{\tilde{\chi}_4^0} = 509 \pm 10\mathrm{GeV}$, $m_{\tilde{\chi}_2^\pm} = 509 \pm 10\mathrm{GeV}$

    $\Longrightarrow$ Motivation for ILC energy upgrade e.g. to $\sqrt{s} \sim 1$ TeV
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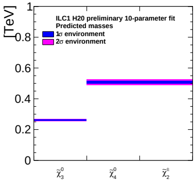

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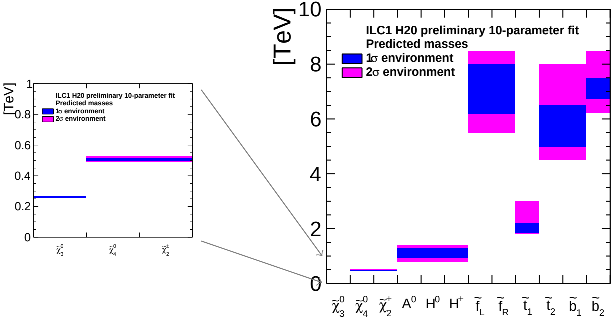

# Conclusions

- Light higgsinos motivated by naturalness, and are not excluded by LHC.
- ILC would probe higgsinos complementary to LHC reach
  - Either exclude masses up to $\sqrt{s}/2 = 500$ GeV for 1 TeV upgrade $\rightarrow$ wide coverage of natural SUSY scenarios
  - or discover regardless of mass scale of heavier states
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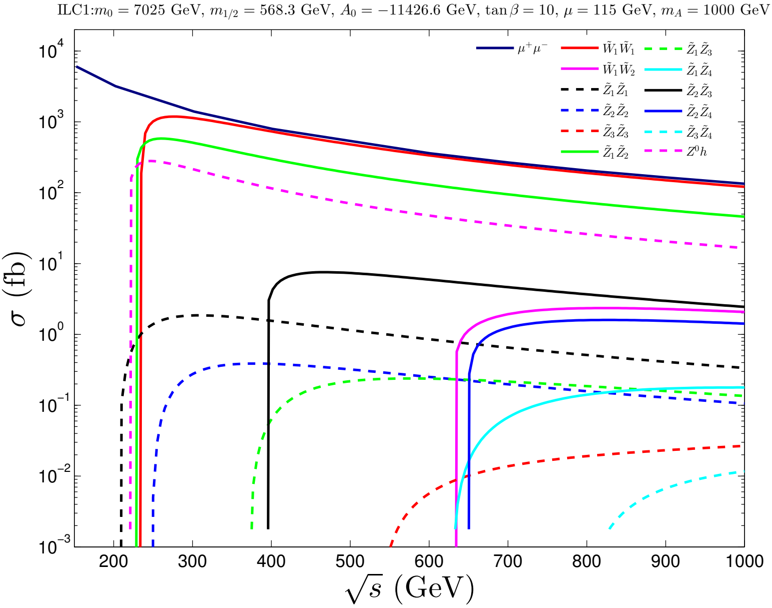
**These results**

would provide clear motivation for ILC 1 TeV upgrade or other, even higher energy colliders

Thank You !

BACKUP

# ILC1 unpolarised cross sections



Fit observables

- mass $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$ (1%)
- xsxbr of $\widetilde{\chi}^+_1 \widetilde{\chi}^-_1 \to q\bar{q}' l \nu_l$ (l=e, mu) (3%)
  for $\mathcal{P}(e^- = \mp 80\%, e^+ = \pm 30\%)$
- xsxbr of $\tilde{\chi}^0_1 \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 ll$ (l=e, mu) (3%)
  for $\mathcal{P}(e^- = \mp 80\%, e^+ = \pm 30\%)$
- Higgs mass $\Delta = 30$ MeV
- Higgs BRs $h \to bb, h \to cc,\ h \to \tau\tau, h \to gg,\ h \to \gamma\gamma,$
  $h \to ZZ^*, h \to WW^*$

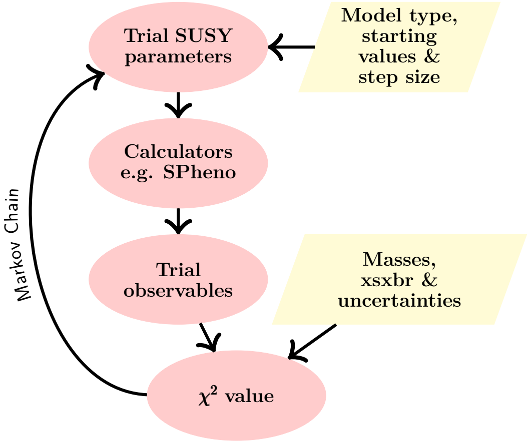
# Probing the GUT scale: Fitting SUSY parameters

Fittino minimises

$$\chi^2 = \left(\frac{\mathcal{O}(ILC) - \mathcal{O}(theory)}{\Delta\mathcal{O}(ILC)}\right)^2$$

(arXiv:hep-ph/0412012)

SPheno 3.3.9beta,
Higgs mass and BRs
FeynHiggs2.10.2



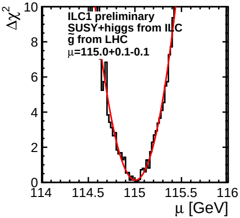
# Fitted parameters of ILC1

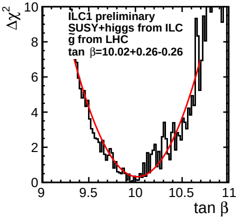
- Underlying theory is a 6-parameter GUT model (NUHM2)
- A priori do not know it is a GUT model so fit weak scale pMSSM-10 (at 1 TeV)

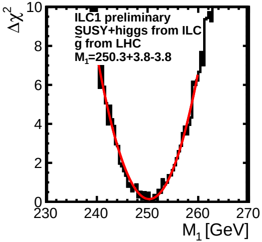
| parameter | ILC1 pMSSM-10 | Fitted values (higgsinos, Higgs, $m_{\tilde{g}}$) |
|---|---|---|
| $M_1$ | 250 | $247 \pm 4\mathrm{GeV}$ |
| $M_2$ | 463 | $452 \pm 11\mathrm{GeV}$ |
| $M_3$ | 1270 | $1280 \pm 130\mathrm{GeV}$ |
| $\mu$ | 115 | $[115, 122]\mathrm{GeV}$ |
| $\tan\beta$ | 10 | $[8, 18]$ |
| $M_{\tilde{t}_L}$ | 4820 | $[4500, 8000]\mathrm{GeV}$ |
| $M_{\tilde{t}_R}$ | 1670 | $[1500, 2000]\mathrm{GeV}$ |
| $M_{\text{other sfermions}}$ | 7150 | $[5500, 8500]\mathrm{GeV}$ |
| $A_{t=b=\tau}$ | $-4400$ | $[-6600, -4200]\mathrm{GeV}$ |
| $m_A$ | 1000 | $1110 \pm 116\mathrm{GeV}$ |

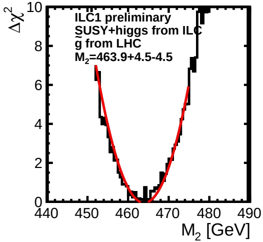
# Probing the GUT scale: Weak scale fits

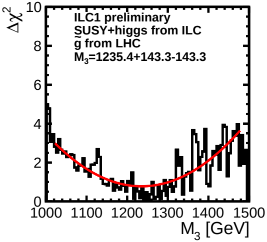
- Purpose to test gaugino mass unification
- Input Higgs and SUSY obs. (incl $\tilde{g}$ fr. LHC).
- $M_1$, $M_2$, $M_3$, $\tan\beta$, and $\mu$ can be determined



# Probing the GUT-scale: Predict rest of spectrum?

- Can we predict more from these data ?
- Do 10-parameter fit of ILC1 SUSY+higgs.
- Measurements/predictions for all of SUSY.
  - Quite precise for the rest of the gauginos.
  - Very preliminary 95% CL ranges:
    - $\sim$ 1 TeV predictions for the others higgses.
    - $\gg$ 1 TeV predictions for $\tilde{f}$s
- Once again: Clearly Yes.

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Predicted masses of states beyond ILC reach

| State | Mass |
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| $\tilde{\chi}_4^0$ | $524 \pm 8$ |
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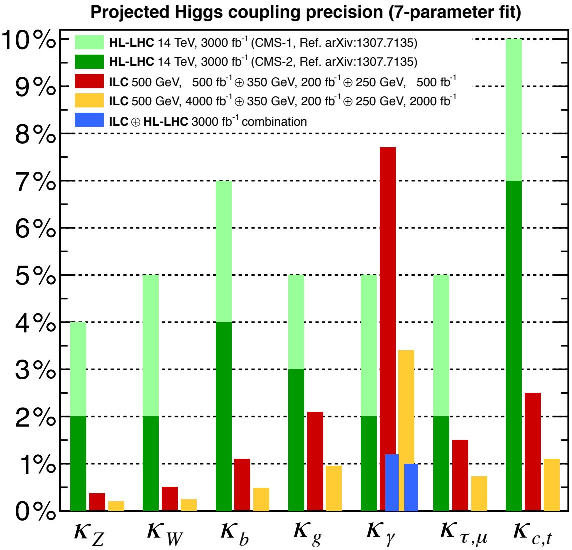
# Model *dependent* Higgs measurements at ILC and LHC



# Dark matter predictions

- Dark matter relic density $\Omega_{ILC1}/\Omega_{Planck} = 0.054 \pm 0.001$
  $\implies$ Strong hint that non-SUSY DM or non-thermal production of higgsinos exists
- Spin-independent WIMP-nucleon scattering cross section
  $\sigma^{SI} = 1.5 \times 10^{-8}$ pb
- WIMP annihilation cross section
  $< \sigma v >= 2.6 \times 10^{-25}$ cm$^3$s$^{-1}$