Naturalness and light higgsinos: why ILC is the right machine for SUSY discovery

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EPS-HEP 2017

7.7.2017

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A Graduate Education Program of Universität Hamburg in Cooperation with DESY

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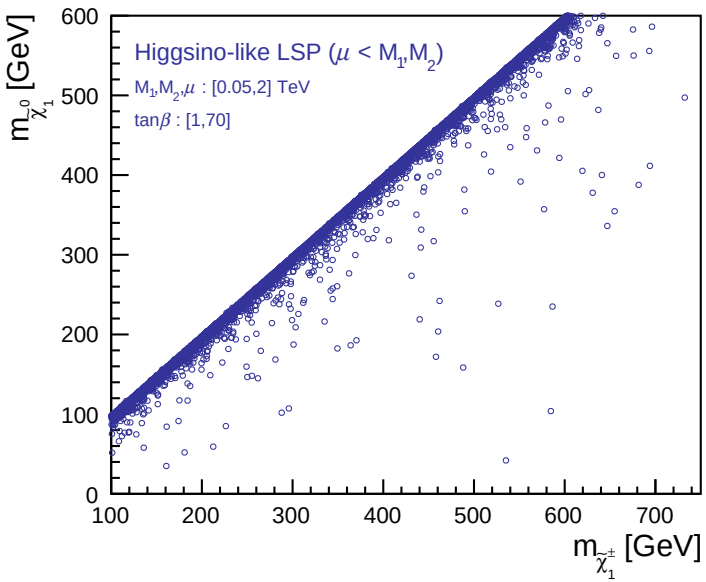
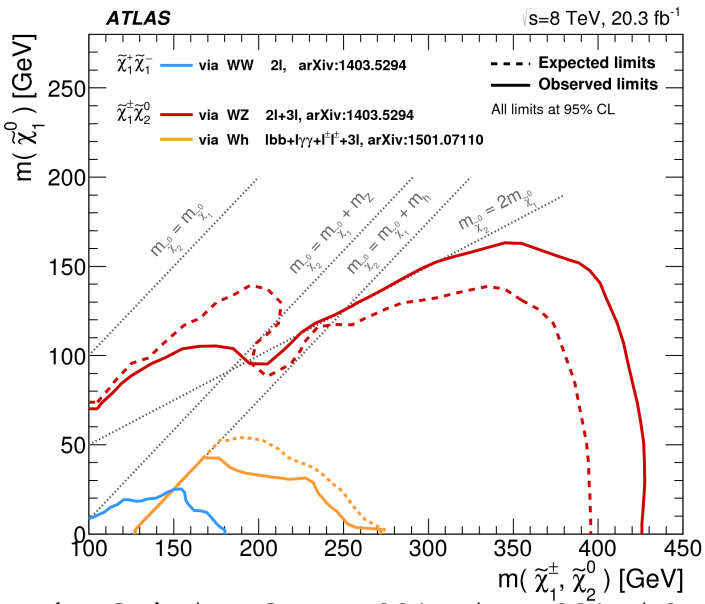
Why study light higgsinos

- Naturalness and small fine tuning requires μ parameter at the EW scale:

$$m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$$

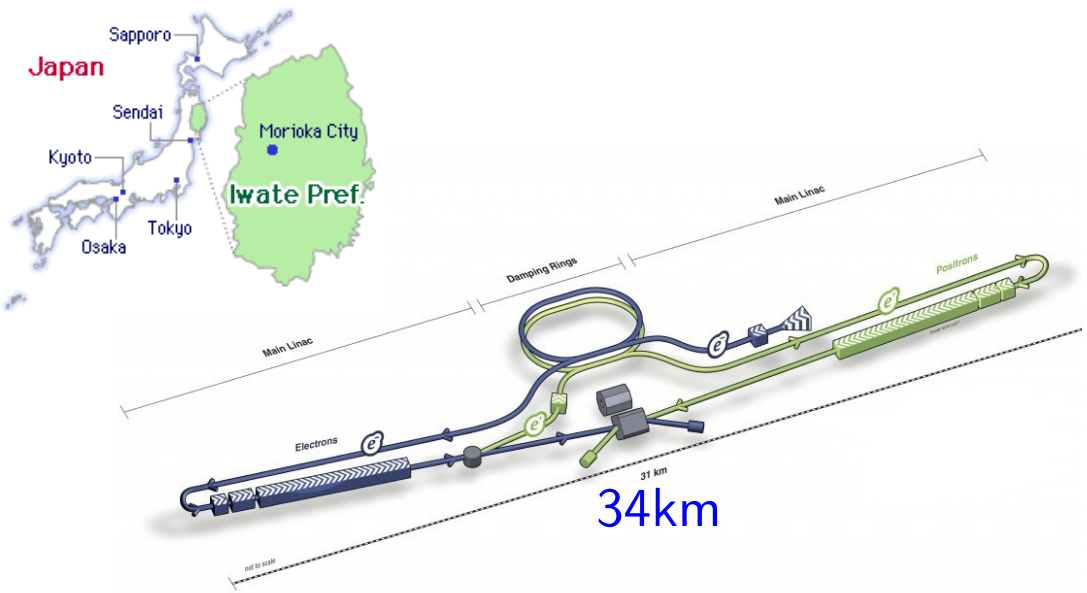
- μ small $\Longrightarrow$ light higgsinos
- Typical mass difference 10 - 20 GeV
  $\Longrightarrow$ challenging for LHC if other sparticles are heavy



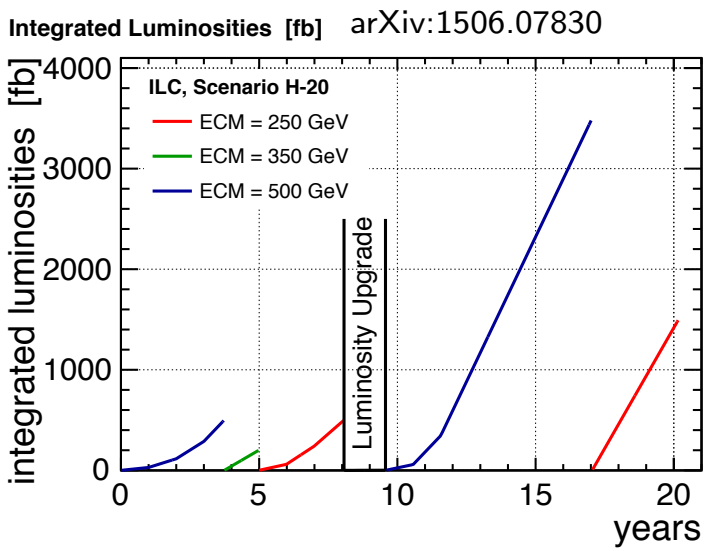


International Linear Collider (ILC)

- 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 config.
- Clean and completely reconstructable final state
- Under political consideration in Japan



Typical 20yr running scenario



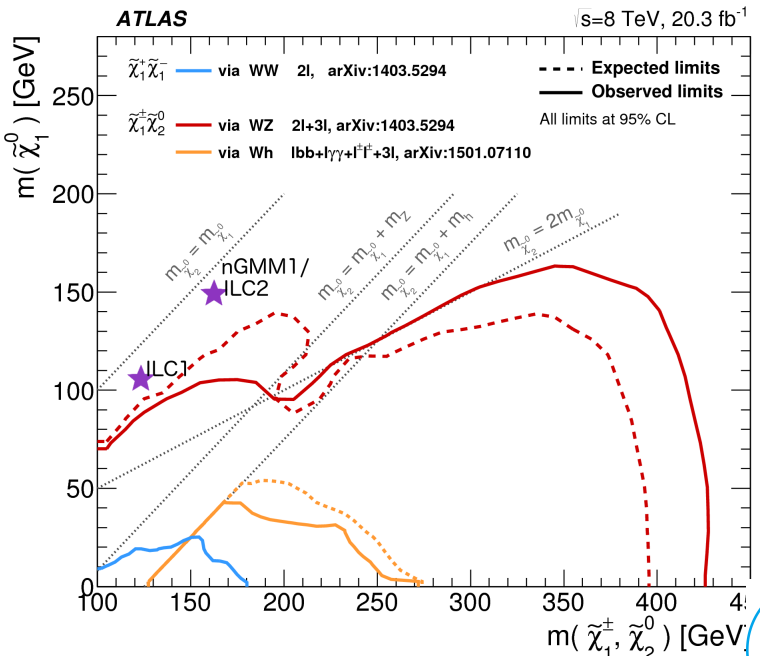
Benchmarks studied

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

Three specific benchmarks

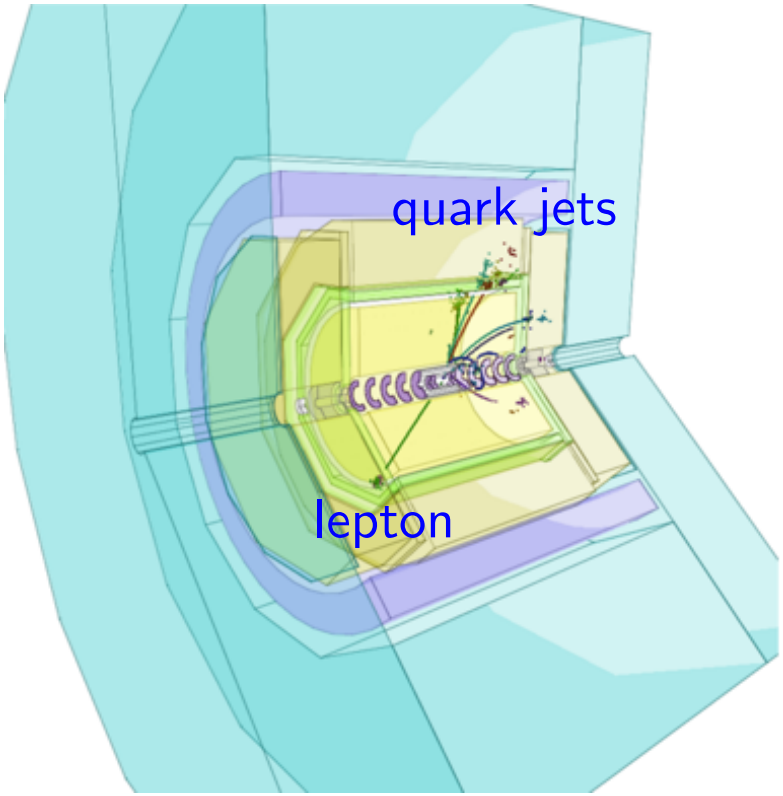
mass	ILC1	ILC2	nGMM1
$\widetilde{\chi}_1^\pm - \widetilde{\chi}_1^0$	14 GeV	10 GeV	7 GeV
$\widetilde{\chi}_2^0 - \widetilde{\chi}_1^0$	21 GeV	10 GeV	4 GeV
$\widetilde{g}$	1560 GeV	2830 GeV	2860 GeV

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



Detailed simulation: 500 GeV, 500 fb^{-1}, $\mathcal{P}(\pm 80\%, \mp 30\%)$

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

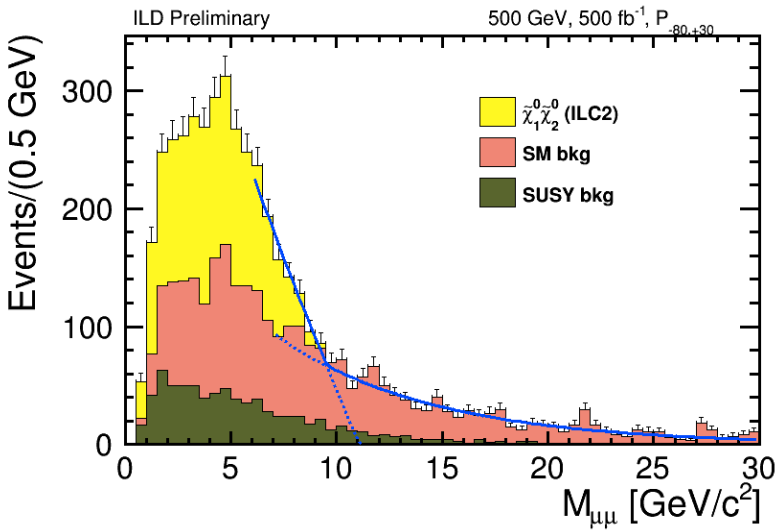


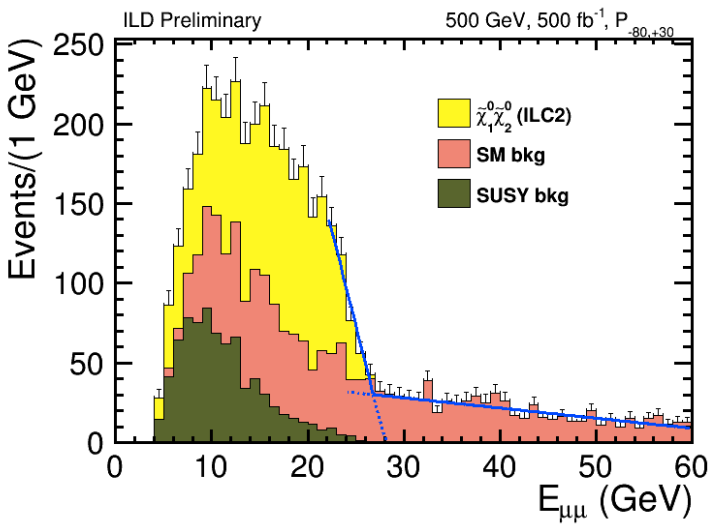
Soft tracks - no problem for ILC

- Event generation `Whizard 1.95`, hadronisation `Pythia 6.422`
- Detailed ILD-specific software for simulation and reconstruction (`Mokka` & `Marlin`)
- Beam spectrum and ISR included
- Analysis by Jacqueline Yan (KEK)

Mass extraction e.g. $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\mu^+\mu^-$

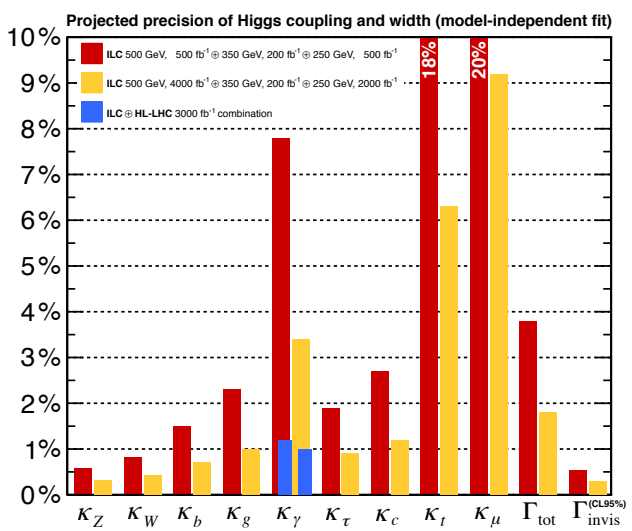
- Kinematics: Maximum invariant mass gives the mass splitting. Then maximum of di-electron energy gives the absolute masses since initial state known

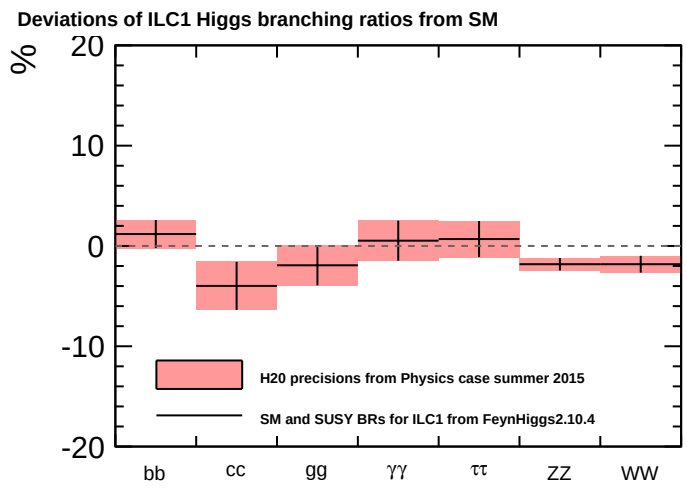




Summary of preliminary analysis results

- Mass precisions $\sim$ 0.2% after 20y (4 ab^{-1})
- Polarised $\sigma \times$BR for $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ decays with 0.5-2% precision depending on channel and polarisation
- Include Higgs mass (Δ=15 MeV) and branching ratios from ILC 20y operation
- Additional relaxable assumption: gluino mass from HL-LHC with 10% precision





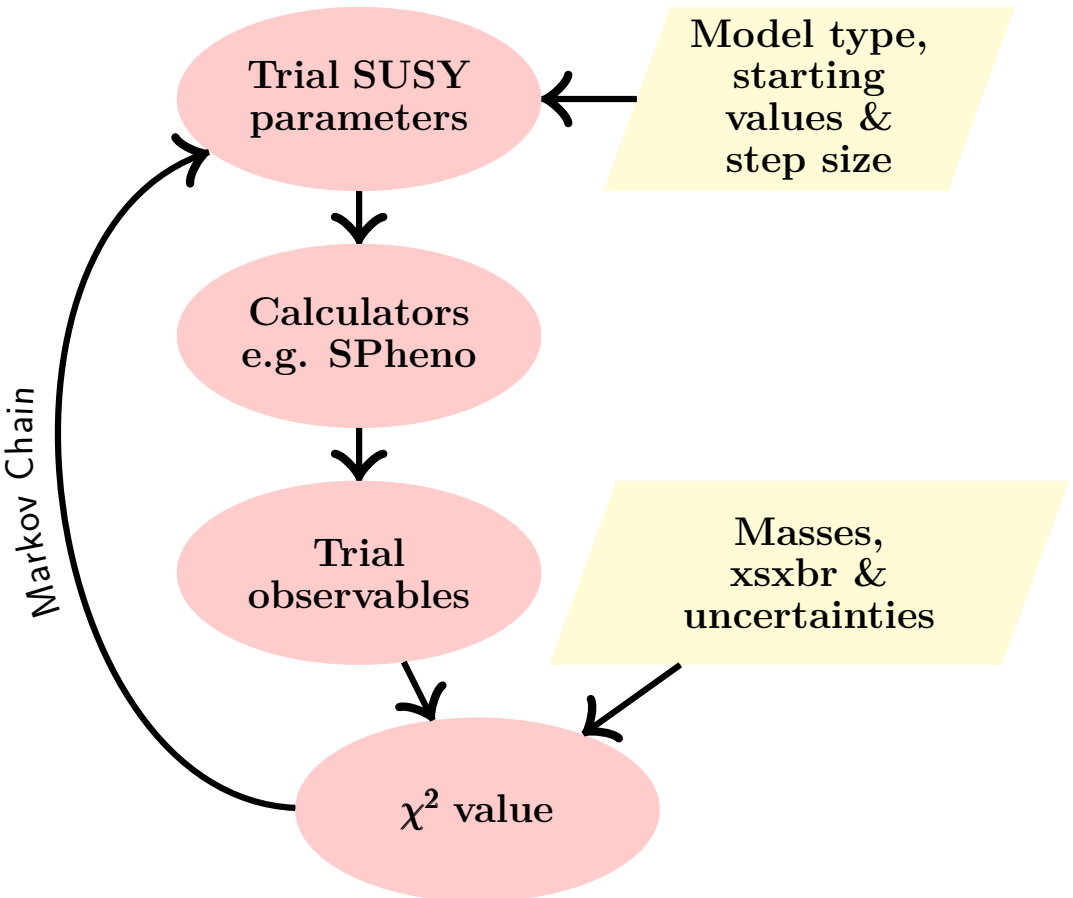
Fitting parameters to observables with Fittino

Fittino minimises

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

(arXiv:hep-ph/0412012)

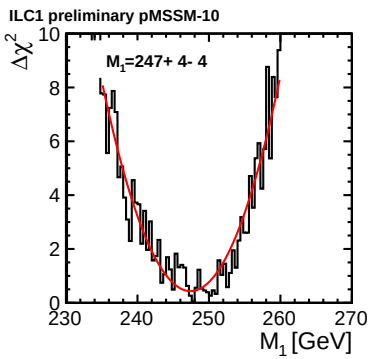
SUSY SPheno3.3.9beta,
Higgs mass and BRs
FeynHiggs2.10.2,
DM MicrOMEGAs and
Astrofit

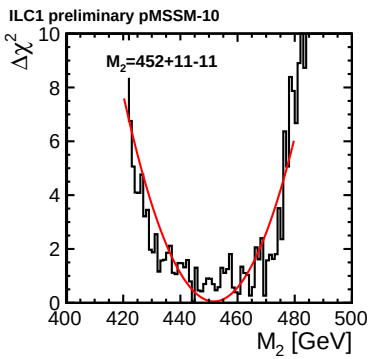


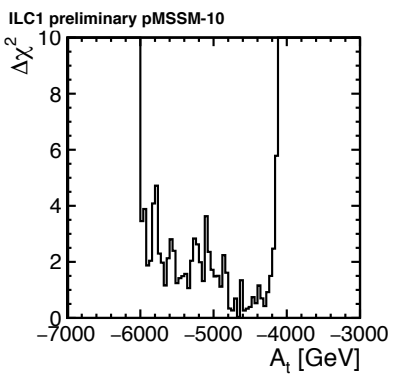
Fitted model and results: ILC1

- Underlying model GUT model (NUHM2)
- Fit 10-parameter pMSSM:

parameter	ILC1 pMSSM-10
M_1	250
M_2	463
M_3	1270
m_A	1000
μ	115
$\tan\beta$	10
$M_{\tilde{t}_L}$	4820
$M_{\tilde{t}_R}$	1670
$M_{\text{other sfermions}}$	7150
$A_{t=b=\tau}$	-4400

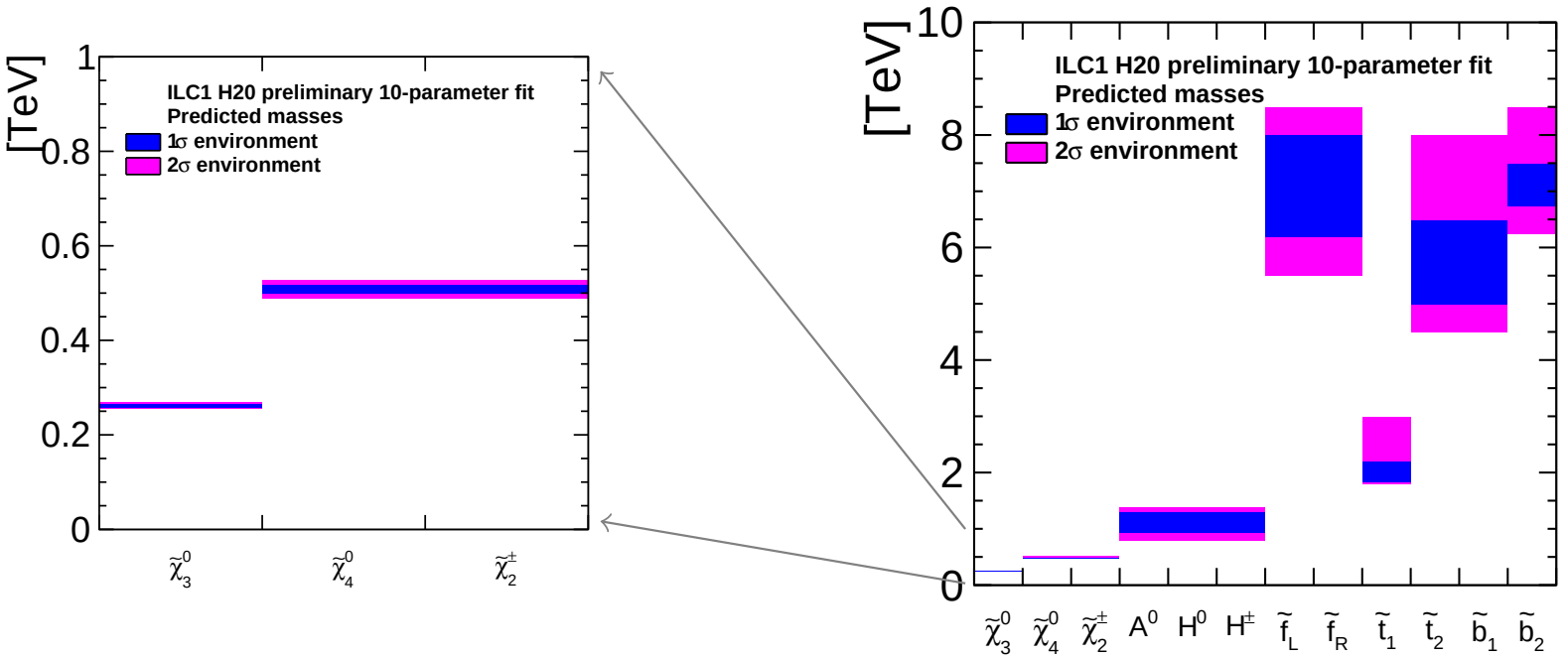






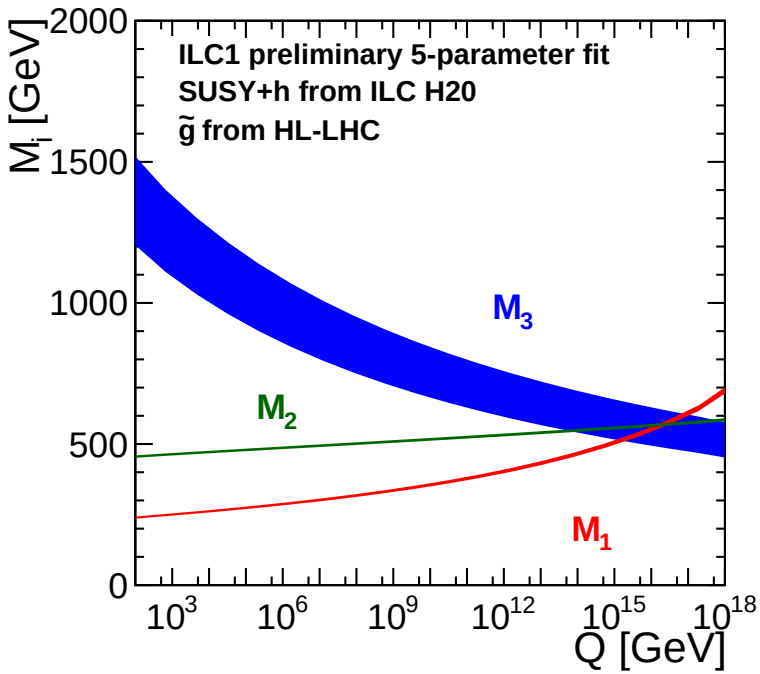
Predicted masses and dark matter relic density

- Heavier neutralino/chargino masses predicted with 2% uncertainty
  $\Longrightarrow$ Sets the scale for energy upgrade e.g. to $\sqrt{s} \sim 1$ TeV
- Dark matter relic density $\Omega_{ILC1}/\Omega_{Planck} = 0.054 \pm 0.001$
  $\Longrightarrow$ Strong hint that non-SUSY DM or non-thermal production exists



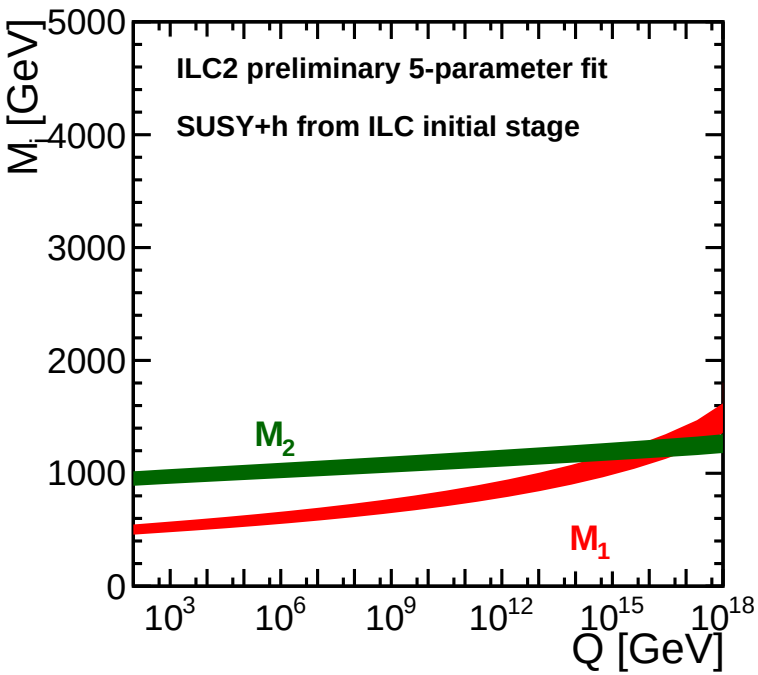
Test of gaugino mass M_i unification

- Take determined parameters at 1 TeV
- Run up to GUT scale with two-loop RGEs, but fix other parameters to model values
- Underlying theory is NUHM2 and indeed find unification of M_i at 10^{16} GeV



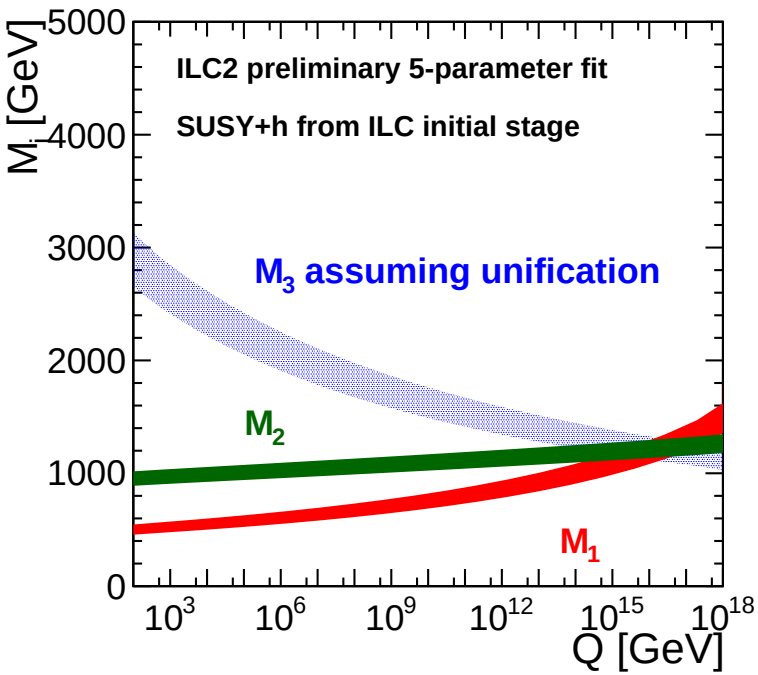
Extrapolation of M_3 assuming unification

- Drop assumption about gluino measurement $\rightarrow$ ILC2, plot precisions after 5y of ILC
- Find Q_U s.t. $M_1(Q_U) = M_2(Q_U)$



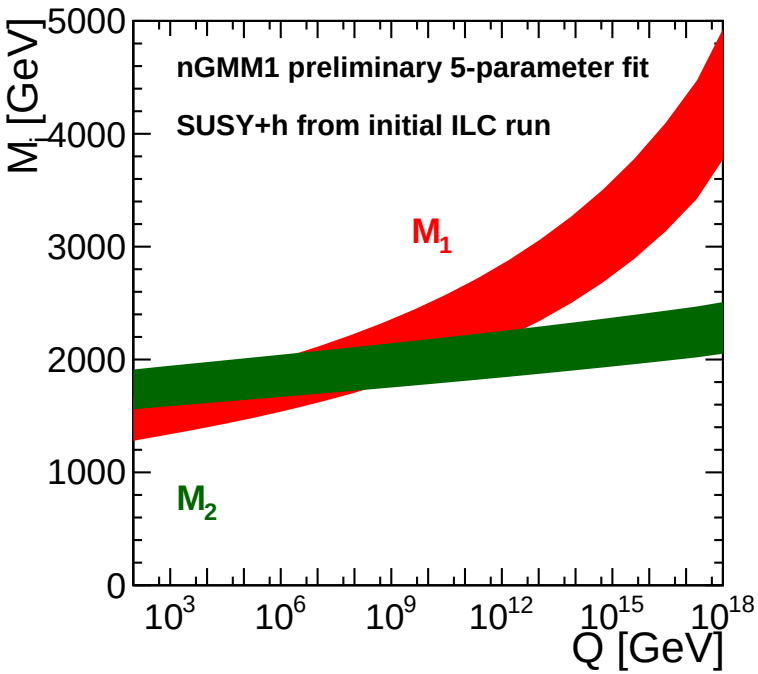
Extrapolation of M_3 assuming unification

- Drop assumption about gluino measurement $\rightarrow$ ILC2, plot precisions after 5y of ILC
- Find Q_U s.t. $M_1(Q_U) = M_2(Q_U)$
- If assume $M_{1/2} = M_3$ and take NUHM2
- Then $M_3 = 2630 \pm 220$ GeV at 1 TeV
- And prediction for gluino mass $m_{\tilde{g}} = 2870 \pm 210$ GeV



Distinguishing between SUSY breaking scenarios

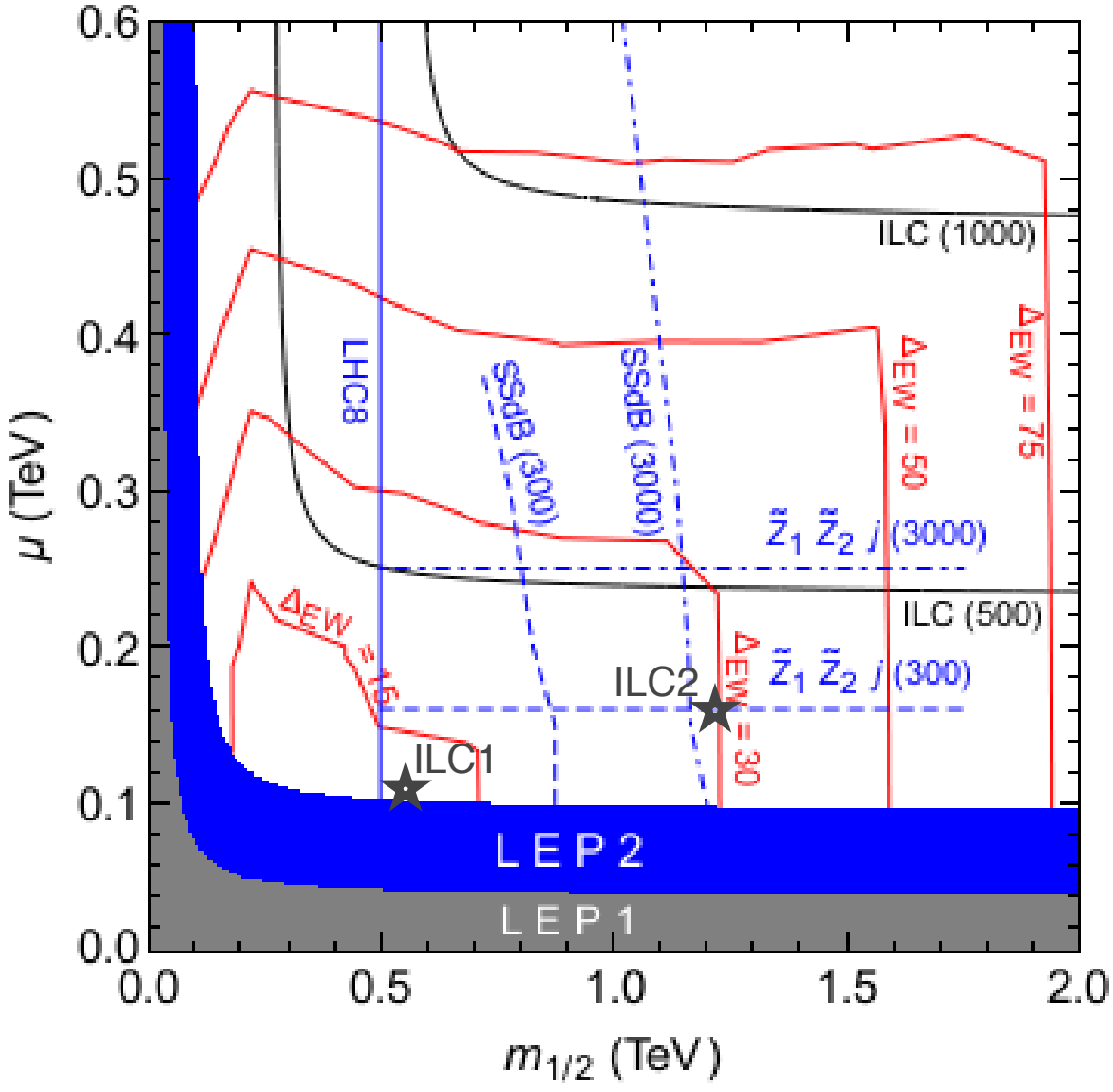
- Motivation for mirage breaking scenario Baer et al 1610.06205
- Gaugino mass parameter unification scale $\mu_{mir} = M_{GUT} e^{-8\pi^2/\alpha}$
- Analysis of scenario with mass gaps ~ 5 GeV ongoing
- Here: expected 4-5y ILC run precisions, clear difference to ILC1 scenario
- Prediction for gluino mass is possible



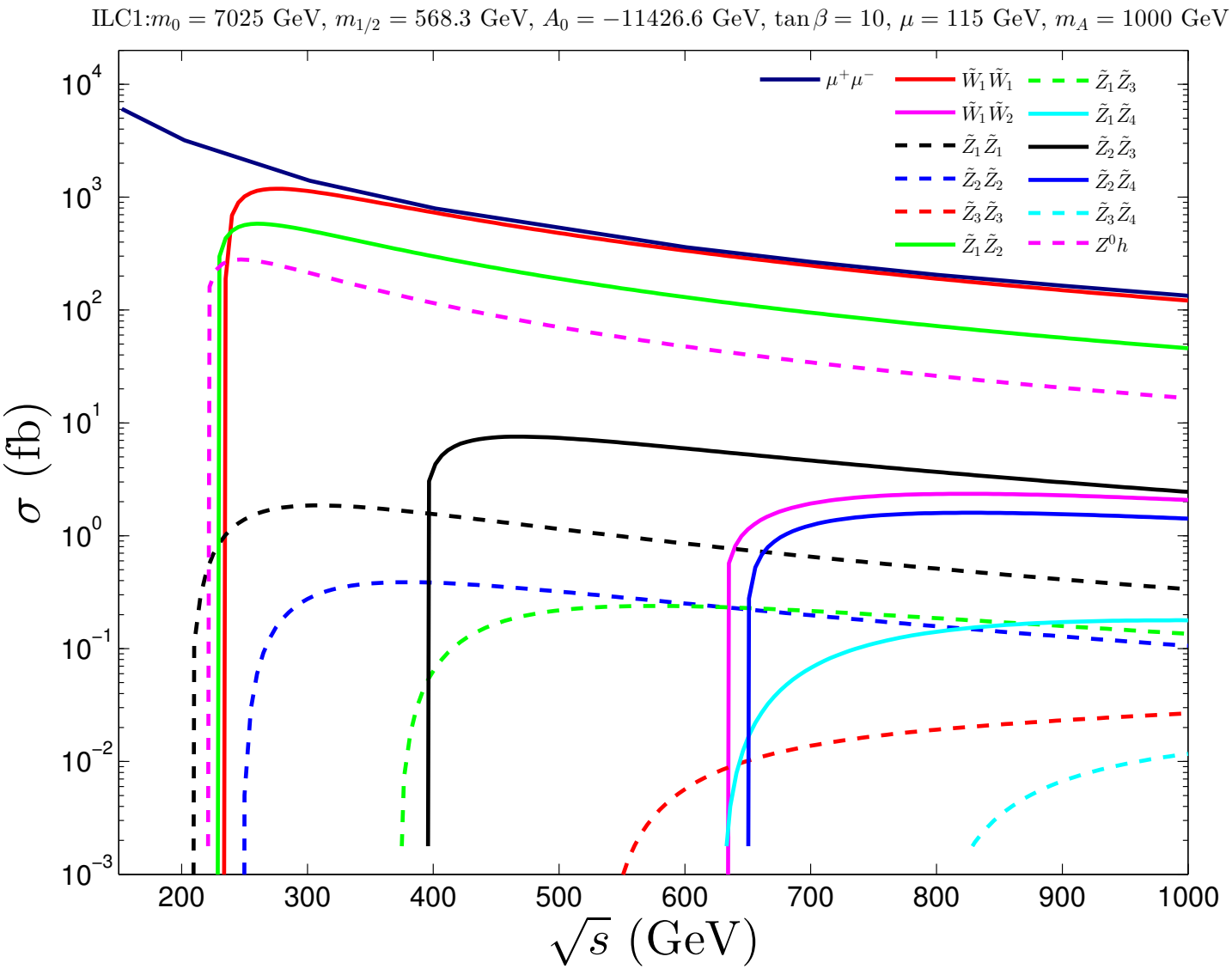
Summary

- ILC would measure properties of higgsinos to percent-level precision, with 20-year ILC run / threshold scans to sub-% precision in the ILC1 benchmark
- These precise measurements allow for extracting some weak scale parameters, in particular the bino and wino mass parameters with a few % uncertainty after 20 years
- Can obtain predictions for unobserved sparticles, motivating building future lepton and hadron colliders
- Would get a strong hint of the existence of non-SUSY DM
- Can have sensitivity to GUT unification hypotheses

BACKUP


0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
μ (TeV)
m1/2 (TeV)
ILC (1000)
ILC (500)
LHC8
SSdB (300)
SSdB (3000)
ΔEW = 75
ΔEW = 50
ΔEW = 30
ΔEW = 15
z̃1 z̃2 j (3000)
z̃1 z̃2 j (300)
ILC1
ILC2
LEP2
LEP1

ILC1 unpolarised cross sections

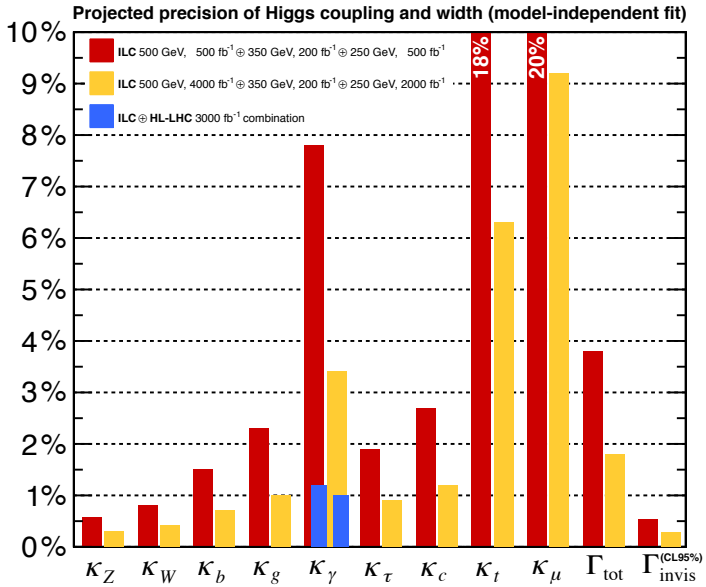


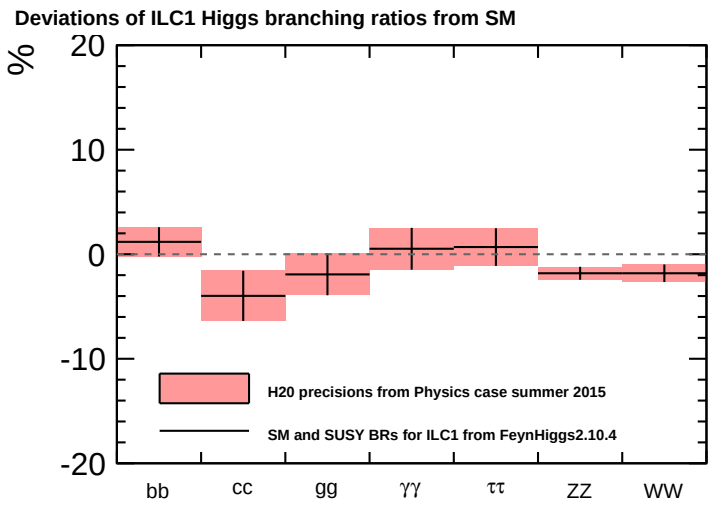
Fit observables

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

Higgs mass and BR measurements from ILC

- ILC will measure m_h to 25 MeV (15 MeV) precision in initial (H20) run
- Precision Higgs measurements included in the fit





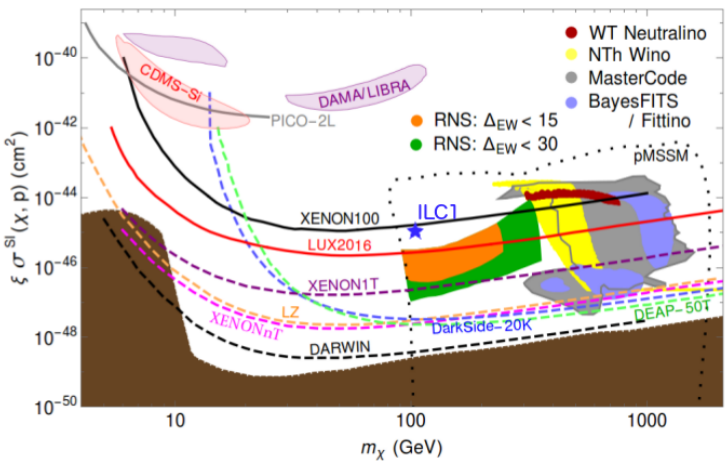
($h \to \gamma\gamma$ from LHC+ILC)

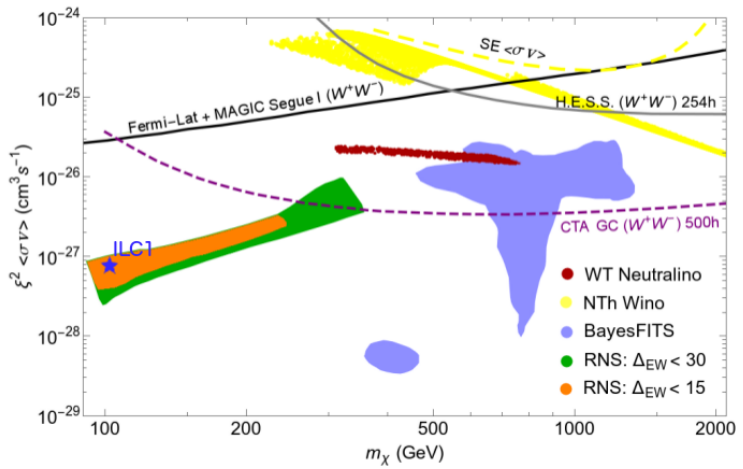
ILC1 pMSSM-10 preliminary fit results

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

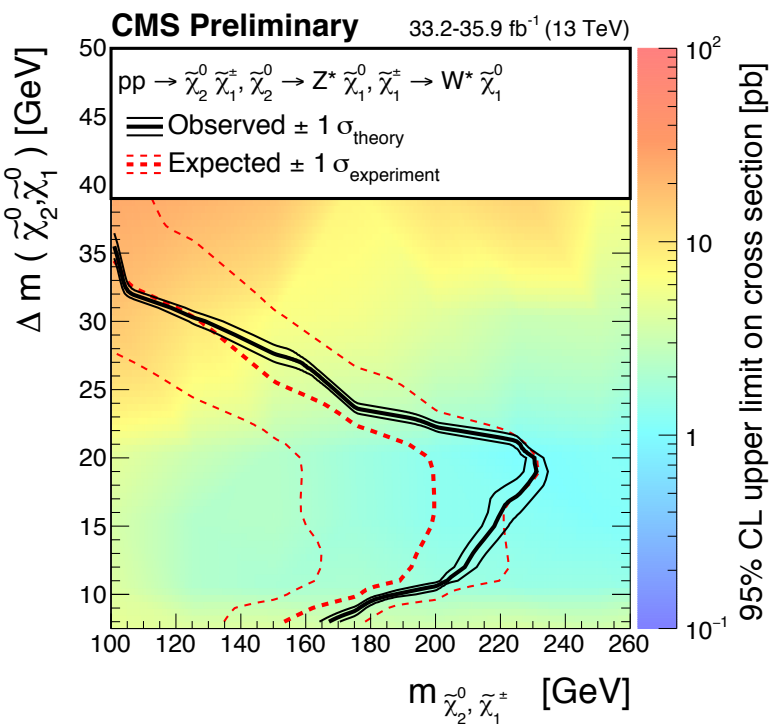
Dark matter predictions

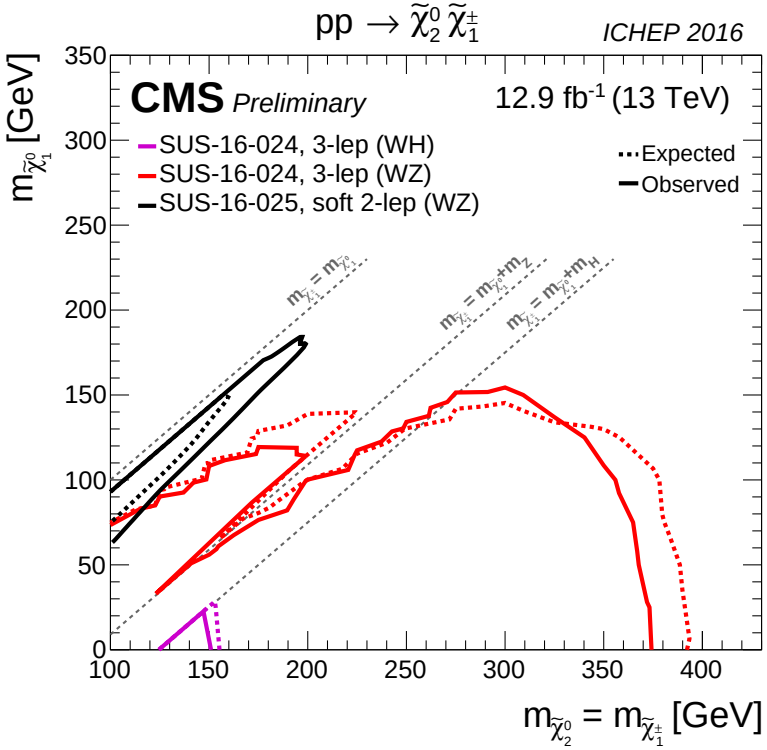
- Dark matter relic density $\Omega_{ILC1}/\Omega_{Planck} = 0.054 \pm 0.001$
  $\Longrightarrow$ Strong hint that non-SUSY DM or non-thermal production exists
- Spin-independent WIMP-nucleon scattering cross section
  $\sigma^{SI} = 1.5 \times 10^{-8}$ pb
- WIMP annihilation cross section
  $< \sigma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





Figures from 1609.06735


CMS Preliminary
33.2-35.9 fb-1 (13 TeV)
pp → χ̃20 χ̃±1, χ̃20 → Z* χ̃01, χ̃±1 → W* χ̃01
Observed ± 1 σtheory
Expected ± 1 σexperiment
Δ m (χ̃20,χ̃01) [GeV]
m χ̃20, χ̃±1 [GeV]
95% CL upper limit on cross section [pb]


pp → χ̃20 χ̃±1
ICHEP 2016
CMS Preliminary
12.9 fb-1 (13 TeV)
SUS-16-024, 3-lep (WH)
SUS-16-024, 3-lep (WZ)
SUS-16-025, soft 2-lep (WZ)
Expected
Observed
mχ̃01 [GeV]
mχ̃20 = mχ̃±1 [GeV]