Characterizing Light Higgsinos from Natural SUSY at the ILC: from MZ to the GUT scale

S.-L. Lehtinen, M. Berggren, J. List (DESY)
H. Baer (Oklahoma), K. Fujii, J. Yan (KEK),
T.Tanabe (Tokyo)

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Outline

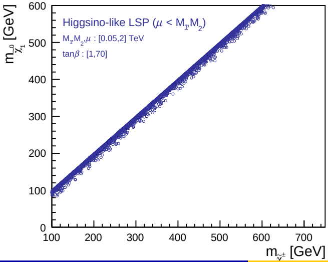
1. Light higgsinos: Motivation
2. The ILC
3. Measurements at the International Linear Collider
4. Probing the GUT-scale at ILC (& LHC)
   - Need to add the Higgs
   - Unification, Discrimination, Prediction
5. Conclusions

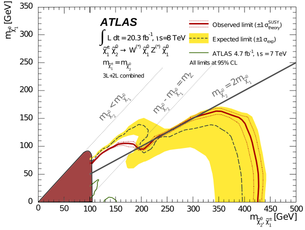
Why study light higgsinos

- 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 μ parameter at the EW scale:

$$m_Z^2 = 2\frac{m^2_{H_d}+\Sigma^d_d-(m^2_{H_u}+\Sigma^u_u)\tan^2\beta}{\tan^2\beta-1} - 2\mu^2$$

- μ small $\Rightarrow$ light higgsinos. Typical mass difference 10 - 20 GeV
- $\Rightarrow$ challenging for LHC if other sparticles are heavy even with new customised searches (ATLAS, in magenta)





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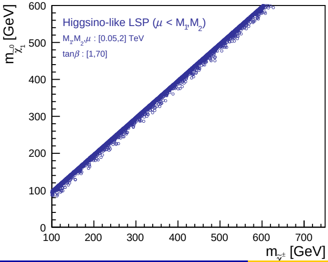
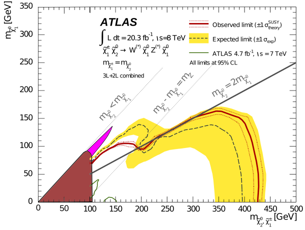
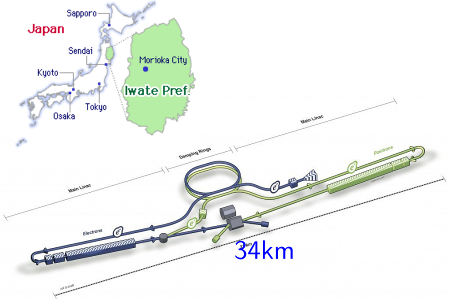




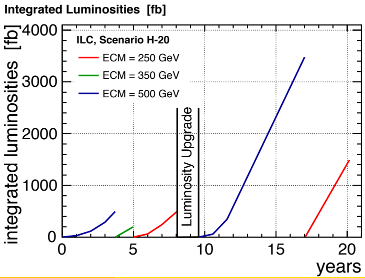
What is the International Linear Collider (ILC)

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



Typical 20yr running scenario

arXiv:1506.07830



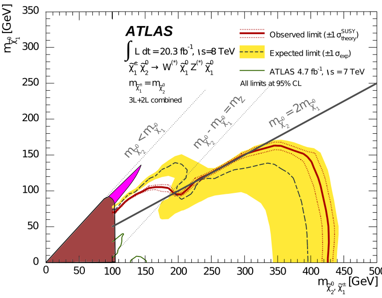
Benchmarks studied

- $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$ observable (in one benchmark $\tilde{\chi}^0_3$ 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

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



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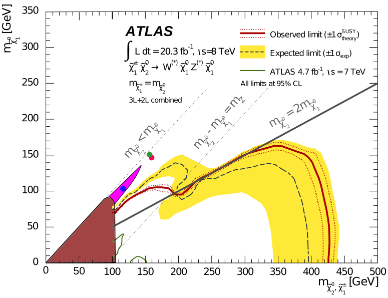
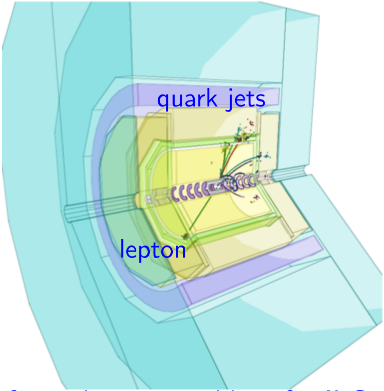


Cross sections for production in e^+e^- at $\sqrt{s} = 500$ GeV several hundred fb

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

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

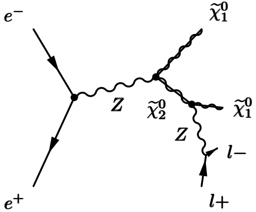


Soft tracks - no problem for ILC

- Full SM, Beam spectrum, ISR and $\gamma\gamma$ "pile-up" included
- Event generation `Whizard 1.95`, hadronisation `Pythia 6.422`
- Detailed ILD-specific software for simulation and reconstruction (`Mokka` (=`Geant4`) & `Marlin`)

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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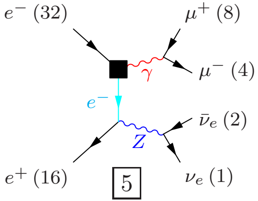
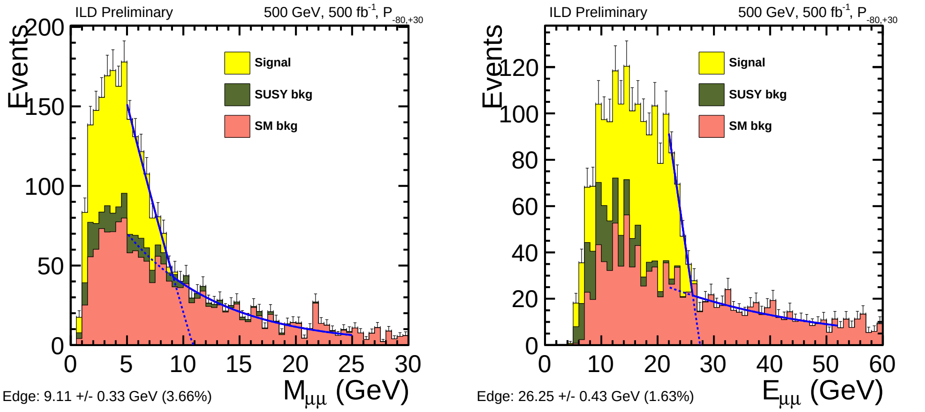


Background example

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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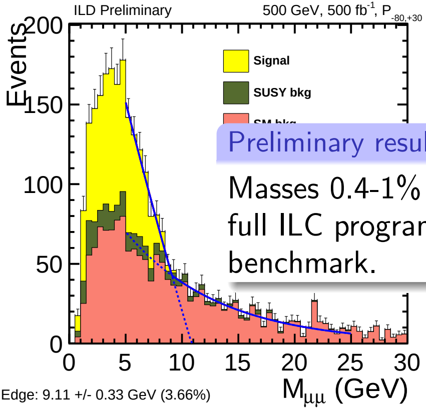
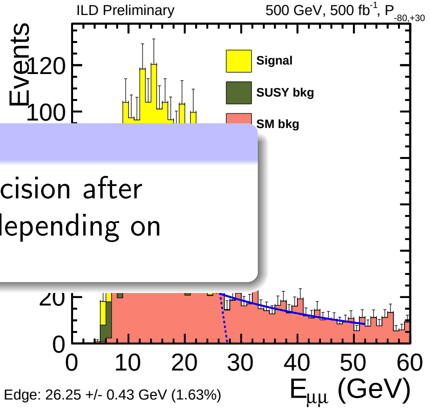


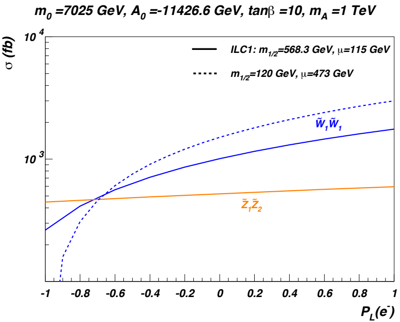


Preliminary result:

Masses 0.4-1% precision after full ILC program, depending on benchmark.

Cross section measurement

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



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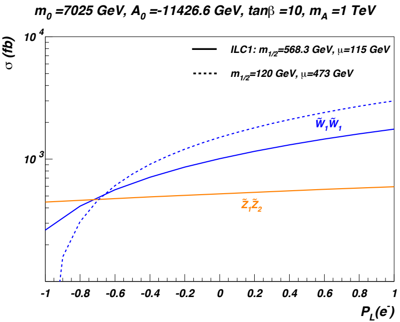

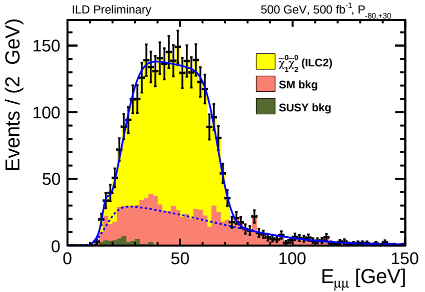

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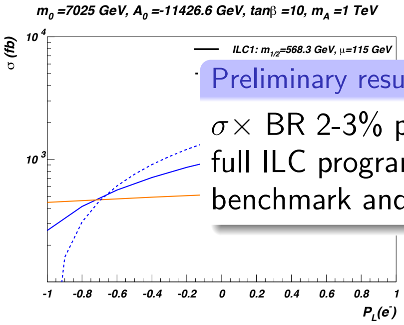
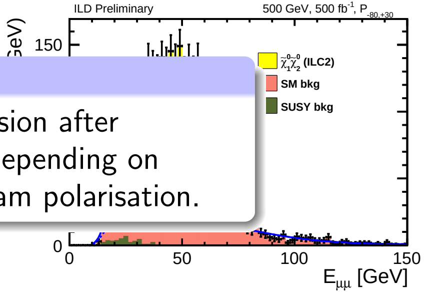


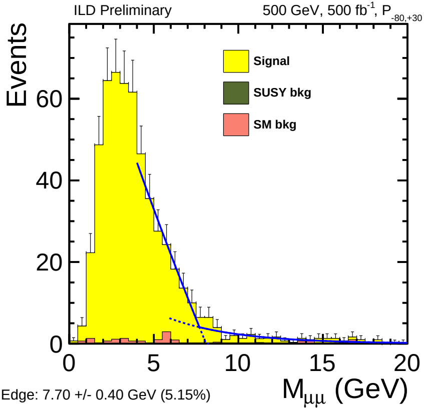


Preliminary result:

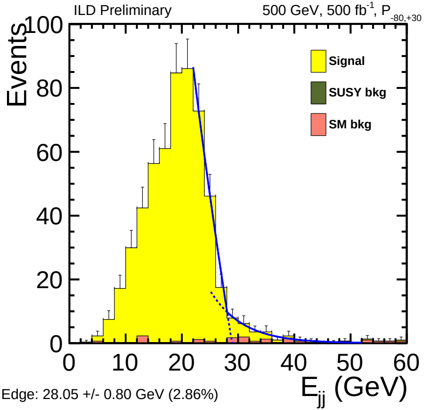
$\sigma \times$ BR 2-3% precision after full ILC program, depending on benchmark and beam polarisation.

Chargino measurement

- Chargino signal: $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 q\bar{q}' \tilde{\chi}_1^0 e\nu_e(\mu\nu_\mu)$
- Characterised by large missing energy, two jets from one W* and a lepton from the other W*



Edge: 7.70 +/- 0.40 GeV (5.15%)



Edge: 28.05 +/- 0.80 GeV (2.86%)

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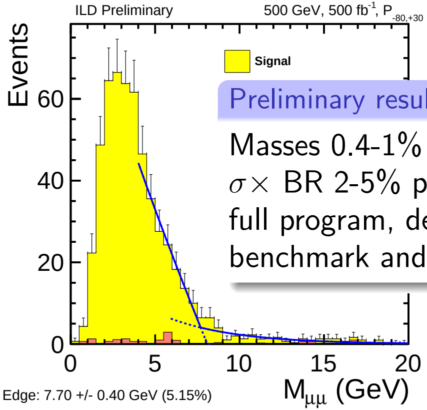

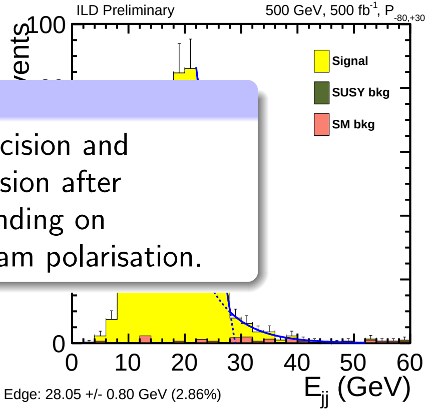

Preliminary result:

Masses 0.4-1% precision and $\sigma\times$ BR 2-5% precision after full program, depending on benchmark and beam polarisation.

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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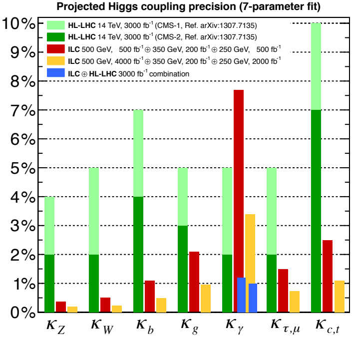
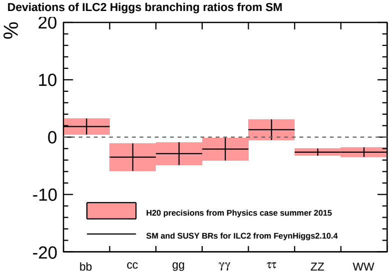
Probing the GUT scale: Higgs is important!

- Assume ILC will measure m_h to 15 MeV precision
- No large 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-4 or 10 (at 1 TeV)
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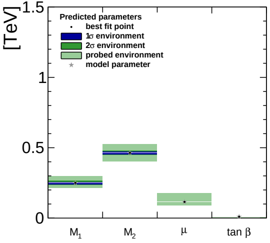
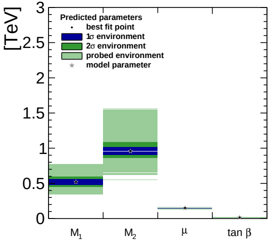
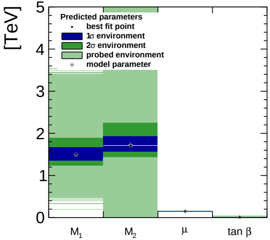
Probing the GUT scale: Weak scale fits

- Input Higgs and SUSY obs.
- M_1, M_2, $\tan\beta$, and μ can be determined w/ 4-parameter fit.
- 10-parameter fit gives constraints on rest of the parameters. .







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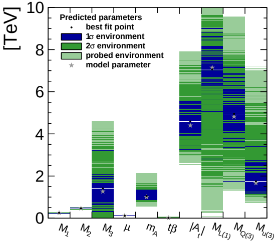

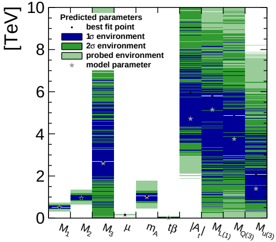

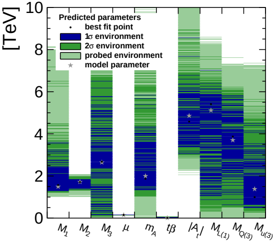

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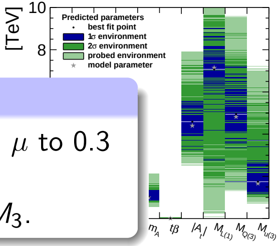
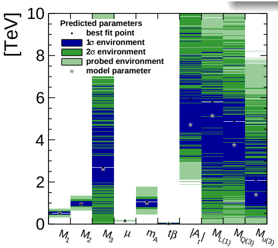
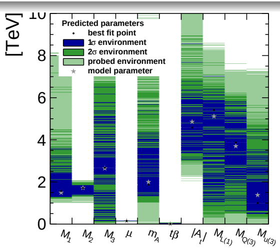


Most important results:

M_1 to 3-10 %, M_2 to 2-12 %, μ to 0.3 %, and $\tan\beta$ to 1-4%.

In addition: Upper limits on M_3.





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 !
  - Conversely, we could predict the gluino mass assuming unification:
    - In ILC1: LHC will see the $\tilde{g}$!
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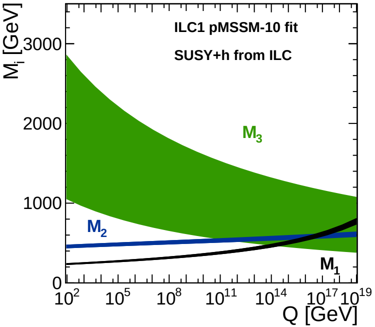

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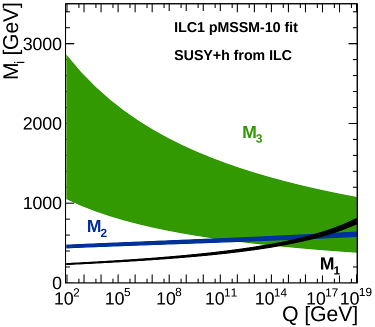

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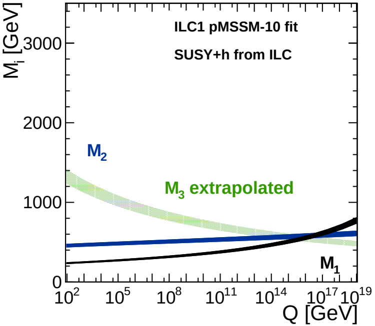

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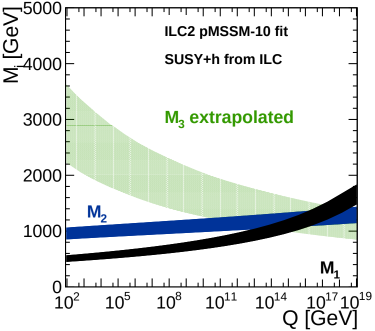

Probing the GUT-scale: Model discrimination?

- Can we see the difference between models ?
- Compare results from ...
  - ILC1 = radiatively driven natural SUSY, with ...
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- Clearly distinguishable!

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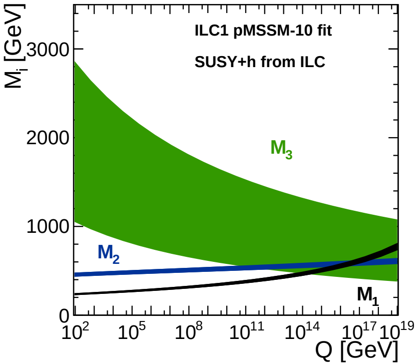

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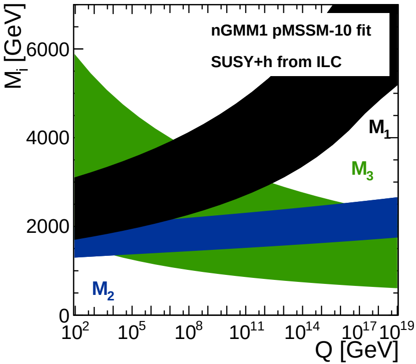
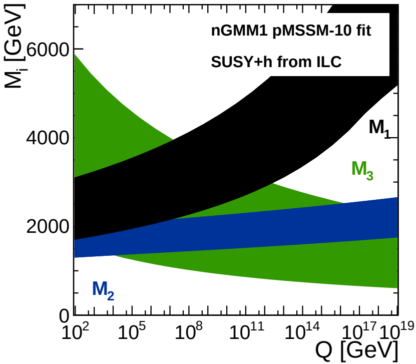


Probing the GUT-scale: Model discrimination?

- Can we see the difference between models ?
- Compare results from ...
  - ILC1 = radiatively driven natural SUSY, with ...
  - nGMM1 = mirage unification.
- Clearly distinguishable!



Probing the GUT-scale: Predict rest of spectrum?

- Heavier neutralino/chargino masses
  - $m_{\tilde{\chi}^0_3}$ to 5-12 %
  - $m_{\tilde{\chi}^0_4} = m_{\tilde{\chi}^\pm_2}$ to 4-14 %
  - Masses varies from 250 GeV to 1800 GeV (ILC1 $\tilde{\chi}^0_3$ to nGMM1 $\tilde{\chi}^\pm_2$)
    $\Longrightarrow$ Motivation for ILC energy upgrade/CLIC/FCChh !
- Rough ranges for all other masses

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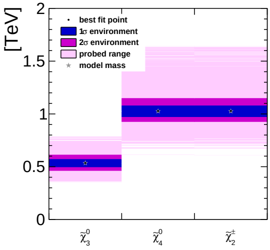

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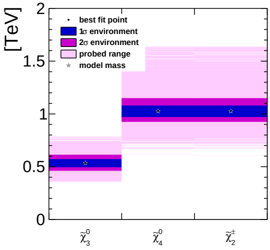

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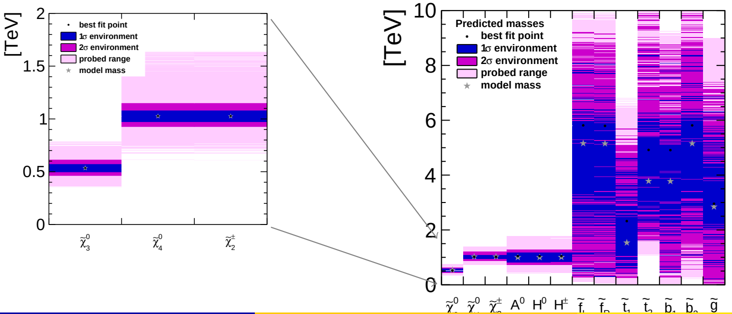

Conclusions

- 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
- ILC would measure properties of higgsinos to percent-level precision.
- Precise measurements allow for extracting GUT and weak scale parameters and predicting mass scales of unobserved sparticles

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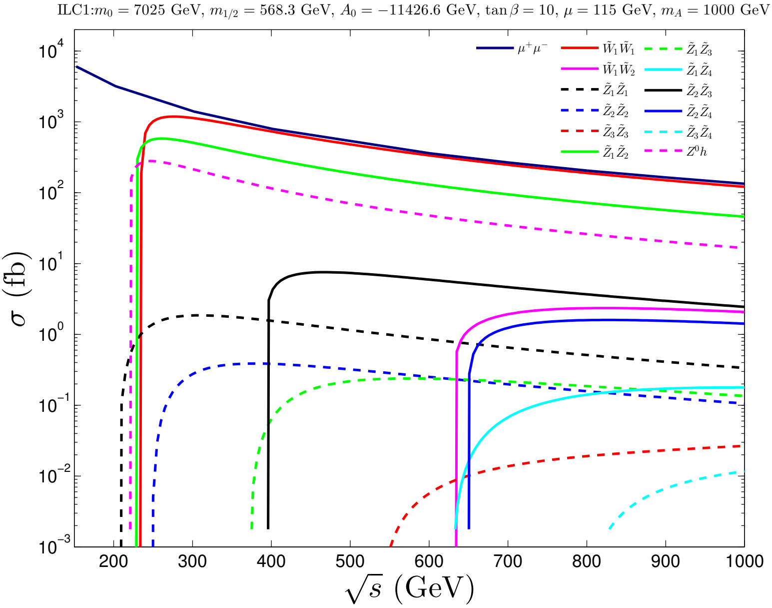
These results

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

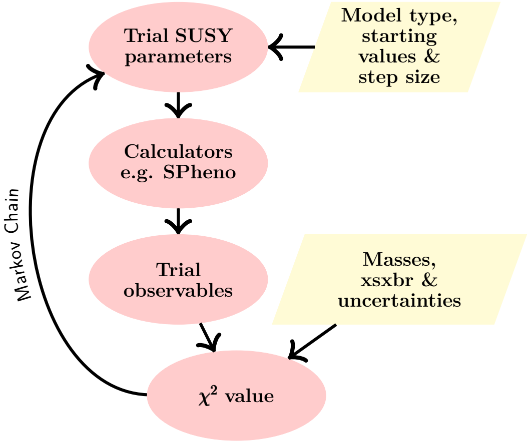
Probing the GUT scale: Fitting SUSY parameters

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

parameter	ILC1 pMSSM true	pMSSM-4 best fit point	pMSSM-4 1σ CL	pMSSM-4 2σ CL	pMSSM-10 best fit point	pMSSM-10 1σ CL	pMSSM-10 2σ CL
M_1	250	250.2	$^{+8.2}_{-7.7}$	$^{+17.1}_{-15.1}$	251.3	$^{+8.6}_{-15.7}$	$^{+17.2}_{-23.7}$
M_2	463	463.3	$^{+8.0}_{-8.1}$	$^{+16.2}_{-14.9}$	465.8	$^{+24.2}_{-23.0}$	$^{+31.4}_{-49.8}$
μ	115.0	115.0	$^{+0.2}_{-0.2}$	$^{+0.3}_{-0.3}$	115.7	$^{+10.9}_{-4.7}$	$^{+20.3}_{-6.1}$
$\tan\beta$	10.0	10.0	$^{+0.1}_{-0.1}$	$^{+0.2}_{-0.2}$	9.7	$^{+8.8}_{-3.0}$	$^{+45.3}_{-3.5}$
m_A	1000				1050	$^{+310}_{-180}$	$^{+607}_{-296}$
M_3	1270				1412	$^{+1791}_{-1104}$	$^{+1411}_{-2843}$
$M_{L(3)}$	7150				7063	$^{+2029}_{-4311}$	$^{+2645}_{-5632}$
$M_{U(3)}$	1670				1751	$^{+2414}_{-628}$	$^{+4498}_{-740}$
$M_{Q(3)}$	4820				4951	$^{+2324}_{-3226}$	$^{+3858}_{-3226}$
$A_{t=b=\tau}$	−4400				−4591	$^{+1371}_{-973}$	$^{+1647}_{-2949}$
χ^2		0.0011			0.1360		

Table: Fitted parameters in ILC1 pMSSM-4 and pMSSM-10, after 1m. points. All units in GeV except for $\tan\beta$ and χ^2.

Fitted parameters of ILC2

		pMSSM-4			pMSSM-10		
parameter	ILC2 pMSSM true	best fit point	1σ CL	2σ CL	best fit point	1σ CL	2σ CL
M_1	520.3	520.7	$^{+38.6}_{-37.6}$	$^{+79.1}_{-71.0}$	502.1	$^{+91.3}_{-32.9}$	$^{+130.1}_{-71.7}$
M_2	957.2	959.42	$^{+55.4}_{-53.1}$	$^{+124.1}_{-100.1}$	941.0	$^{+145.4}_{-71.7}$	$^{+229.2}_{-130.9}$
μ	150.0	150.0	$^{+0.4}_{-0.4}$	$^{+0.7}_{-0.8}$	154.4	$^{+24.7}_{-7.3}$	$^{+36.6}_{-8.2}$
$\tan\beta$	15.0	15.0	$^{+0.7}_{-0.6}$	$^{+1.7}_{-1.2}$	14.8	$^{+38.4}_{-7.8}$	$^{+48.2}_{-9.0}$
m_A	1000				1043	$^{+135}_{-203}$	$^{+240}_{-325}$
M_3	2607				2684	$^{+4990}_{-2585}$	$^{+5670}_{-2682}$
$M_{L(3)}$	5146				5797	$^{+2402}_{-5359}$	$^{+3511}_{-5544}$
$M_{U(3)}$	1395				2073	$^{+3518}_{-1805}$	$^{+4716}_{-1805}$
$M_{Q(3)}$	3757				4871	$^{+3680}_{-3933}$	$^{+5030}_{-4608}$
A_t	-4714				-5948	$^{+2734}_{-3387}$	$^{+3250}_{-4050}$
χ^2		0.0026			0.1627		

Table: Fitted parameters in ILC2 pMSSM-4 and pMSSM-10, after 1m. points. All units in GeV except for $\tan\beta$ and χ^2.

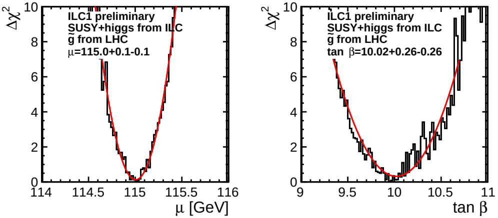
Fitted parameters of nGMM1

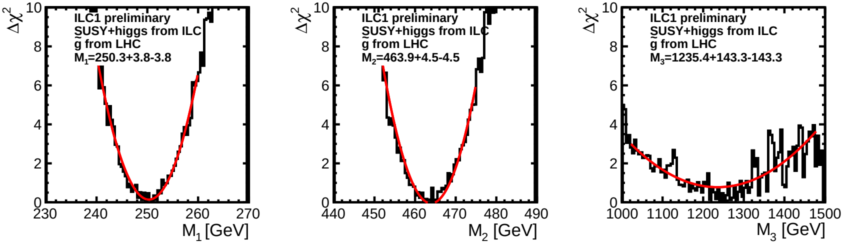
parameter	true	pMSSM-4 best fit point	pMSSM-4 1σ CL	pMSSM-4 2σ CL	pMSSM-10 best fit point	pMSSM-10 1σ CL	pMSSM-10 2σ CL	pMSSM-10 with mass differences best fit point	pMSSM-10 with mass differences 1σ CL	pMSSM-10 with mass differences 2σ CL
M_1	1493	1501	$^{+173}_{-149}$	$^{+411}_{-280}$	1386	$^{+2386}_{-145}$	$^{+2830}_{-282}$	1573	$^{+2091}_{-282}$	$^{+5650}_{-344}$
M_2	1720	1711	$^{+220}_{-158}$	$^{+530}_{-279}$	1768	$^{+254}_{-451}$	$^{+717}_{-549}$	1710	$^{+137}_{-313}$	$^{+277}_{-394}$
μ	150.0	150.0	$^{+0.4}_{-0.4}$	$^{+0.9}_{-0.9}$	154.2	$^{+7.4}_{-8.7}$	$^{+12.9}_{-8.3}$	149.9	$^{+11.5}_{-3.4}$	$^{+15.3}_{-4.2}$
$\tan\beta$	10.0	10.0	$^{+0.5}_{-0.3}$	$^{+1.2}_{-0.6}$	8.3	$^{+41.9}_{-1.3}$	$^{+44.6}_{-1.9}$	11.2	$^{+32.5}_{-3.4}$	$^{+63.9}_{-4.2}$
m_A	2000				2655	$^{+6493}_{-1449}$	$^{+11492}_{-1596}$	1868	$^{+4018}_{-567}$	$^{+6423}_{-867}$
M_3	2646				3173	$^{+4229}_{-3168}$	$^{+5347}_{-3168}$	2677	$^{+3892}_{-2541}$	$^{+4550}_{-2614}$
$M_{L(3)}$	5115				4781	$^{+3589}_{-4077}$	$^{+4630}_{-4456}$	5412	$^{+1629}_{-4581}$	$^{+2319}_{-5118}$
$M_{U(3)}$	1381				1774	$^{+2384}_{-1086}$	$^{+4826}_{-1214}$	996	$^{+3540}_{-500}$	$^{+4686}_{-741}$
$M_{Q(3)}$	3701				4011	$^{+3254}_{-3535}$	$^{+3982}_{-3697}$	3874	$^{+1983}_{-3245}$	$^{+2356}_{-3370}$
A_t	−4857				−6766	$^{+3698}_{-509}$	$^{+4012}_{-1702}$	−4582	$^{+1558}_{-4006}$	$^{+1750}_{-4390}$
χ^2		0.0138			0.0927			0.0668		

Table: Fitted parameters in nGMM1: pMSSM-4, pMSSM-10 and pMSSM-10 with mass differences fitted using 1m. points each. All units in GeV except for $\tan\beta$ and χ^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 μ can be determined





Fitted masses ILC1

prediction	ILC1 All SUSY+h		
	best fit	1σ CL	2σ CL
$m_{\tilde{\chi}_3^0}$	267	$^{+8}_{-16}$	$^{+16}_{-26}$
$m_{\tilde{\chi}_4^0}$	524	$^{+20}_{-26}$	$^{+26}_{-55}$
$m_{\tilde{\chi}_2^\pm}$	524	$^{+19}_{-26}$	$^{+25}_{-55}$
m_{H_0}	1050	$^{+310}_{-190}$	$^{+610}_{-290}$
m_{A_0}	1050	$^{+310}_{-190}$	$^{+610}_{-290}$
$m_{H^\pm}$	1056	$^{+304}_{-176}$	$^{+604}_{-276}$
$m_{\tilde{u}_L}$	7143	$^{+2037}_{-4343}$	$^{+2657}_{-5603}$
$m_{\tilde{u}_R}$	7117	$^{+2023}_{-4337}$	$^{+2643}_{-5577}$
$m_{\tilde{t}_1}$	2003	$^{+1857}_{-763}$	$^{+3957}_{-803}$
$m_{\tilde{t}_2}$	5033	$^{+2347}_{-1993}$	$^{+3947}_{-2653}$
$m_{\tilde{b}_1}$	5028	$^{+2352}_{-3188}$	$^{+3912}_{-3488}$
$m_{\tilde{b}_2}$	7130	$^{+2030}_{-4310}$	$^{+2650}_{-4470}$
$m_{\tilde{g}}$	1693	$^{+1807}_{-1273}$	$^{+2827}_{-1693}$

Table: ILC1 fitted masses, pMSSM-10 fit with AllSUSY+h observables, 1×10^6 points

Fitted masses ILC2

prediction	ILC2 All SUSY+h		
	best fit	1σ	2σ
$m_{\tilde{\chi}^0_3}$	518	$^{+72}_{-34}$	$^{+110}_{-74}$
$m_{\tilde{\chi}^0_4}$	1018	$^{+82}_{-76}$	$^{+190}_{-134}$
$m_{\tilde{\chi}^\pm_2}$	1018	$^{+82}_{-76}$	$^{+190}_{-134}$
m_{H_0}	1043	$^{+137}_{-223}$	$^{+257}_{-323}$
m_{A_0}	1043	$^{+137}_{-223}$	$^{+257}_{-323}$
$m_{H^\pm}$	1045	$^{+135}_{-205}$	$^{+255}_{-325}$
$m_{\tilde{u}_L}$	5814	$^{+2286}_{-5474}$	$^{+3406}_{-5534}$
$m_{\tilde{u}_R}$	5795	$^{+2285}_{-5495}$	$^{+3385}_{-5495}$
$m_{\tilde{t}_1}$	2322	$^{+2318}_{-1902}$	$^{+3378}_{-2062}$
$m_{\tilde{t}_2}$	4917	$^{+3663}_{-3277}$	$^{+4983}_{-3317}$
$m_{\tilde{b}_1}$	4911	$^{+3189}_{-4471}$	$^{+3869}_{-4631}$
$m_{\tilde{b}_2}$	5814	$^{+2766}_{-4734}$	$^{+4086}_{-5254}$
$m_{\tilde{g}}$	2955	$^{+3925}_{-2735}$	$^{+4445}_{-2935}$

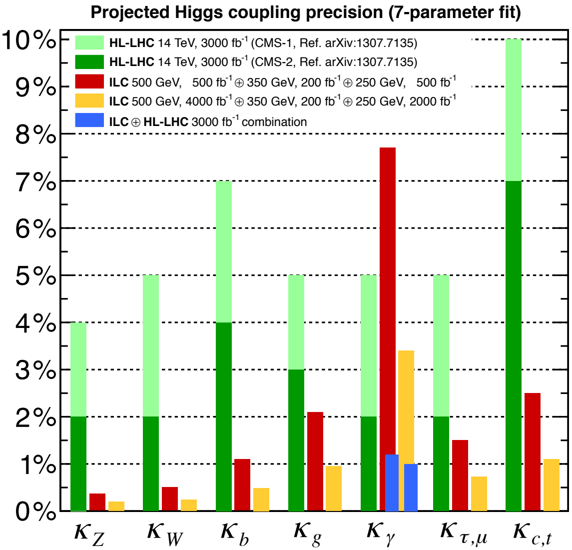
Table: ILC2 fitted masses, pMSSM-10 fit with AllSUSY+h observables, 1×10^6 points

Fitted masses nGMM1

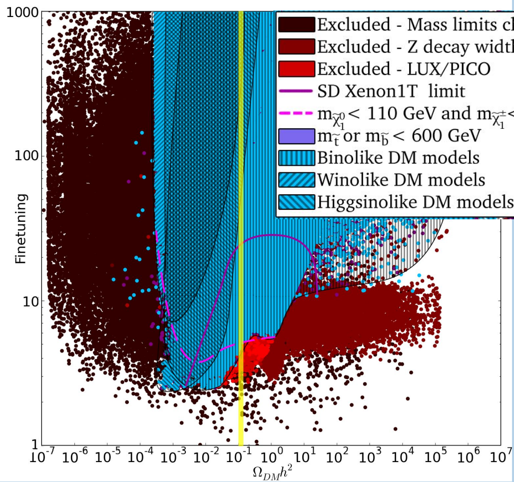
prediction	nGMM1 All SUSY + h			nGMM1 All SUSY mass diff + h		
	best fit	1σ	2σ	best fit	1σ	2σ
$m_{\tilde{\chi}_3^0}$	1412	$^{+454}_{-134}$	$^{+640}_{-260}$	1603	$^{+149}_{-283}$	$^{+347}_{-349}$
$m_{\tilde{\chi}_4^0}$	1854	$^{+1920}_{-264}$	$^{+2364}_{-336}$	1802	$^{+1834}_{-146}$	$^{+2710}_{-218}$
$m_{\tilde{\chi}_2^\pm}$	1853	$^{+229}_{-443}$	$^{+601}_{-557}$	1801	$^{+137}_{-349}$	$^{+275}_{-433}$
m_{H_0}	2655	$^{+6365}_{-1355}$	$^{+7125}_{-1555}$	1868	$^{+3992}_{-528}$	$^{+6372}_{-828}$
m_{A_0}	2655	$^{+6365}_{-1355}$	$^{+7125}_{-1555}$	1868	$^{+3992}_{-528}$	$^{+6372}_{-828}$
$m_{H^\pm}$	2656	$^{+6364}_{-1336}$	$^{+7124}_{-1556}$	1863	$^{+3997}_{-523}$	$^{+6377}_{-823}$
$m_{\tilde{u}_L}$	4762	$^{+3698}_{-4282}$	$^{+4718}_{-4582}$	5421	$^{+1619}_{-4721}$	$^{+2239}_{-5221}$
$m_{\tilde{u}_R}$	4754	$^{+3666}_{-4294}$	$^{+4706}_{-4594}$	5408	$^{+1612}_{-4708}$	$^{+2232}_{-5108}$
$m_{\tilde{t}_1}$	1951	$^{+1549}_{-1411}$	$^{+3889}_{-1471}$	1168	$^{+3332}_{-548}$	$^{+3332}_{-868}$
$m_{\tilde{t}_2}$	4029	$^{+3120}_{-2160}$	$^{+3900}_{-2520}$	3894	$^{+2026}_{-2014}$	$^{+2326}_{-2394}$
$m_{\tilde{b}_1}$	4008	$^{+2852}_{-3448}$	$^{+3712}_{-3748}$	3888	$^{+2032}_{-3168}$	$^{+2232}_{-3528}$
$m_{\tilde{b}_2}$	4763	$^{+3697}_{-3703}$	$^{+4717}_{-4263}$	5419	$^{+1621}_{-4599}$	$^{+2241}_{-4739}$
$m_{\tilde{g}}$	3361	$^{+3259}_{-3261}$	$^{+4559}_{-3361}$	2924	$^{+2976}_{-2684}$	$^{+3556}_{-2804}$

Table: nGMM1 fitted masses, pMSSM-10 fit with AllSUSY+h observables and pMSSM-10 fit with the higgsino mass differences replacing $M_{\tilde{\chi}_2^0}$ and $M_{\tilde{\chi}_1^\pm}$ as observables. The fit length was 10^6 Markov Chain points in each case.

Model *dependent* Higgs measurements at ILC and LHC

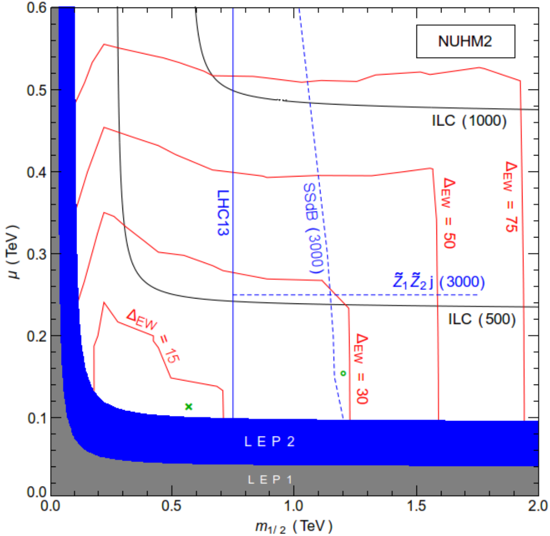


Naturalness



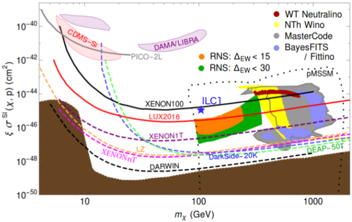
[1612.06333]

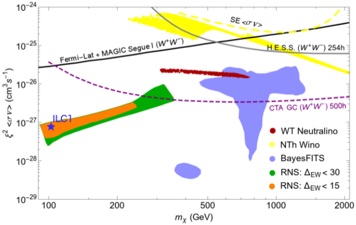
Naturalness



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}





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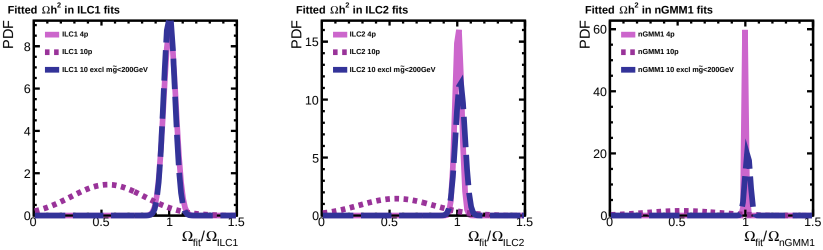
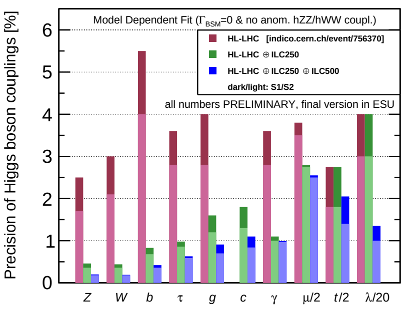
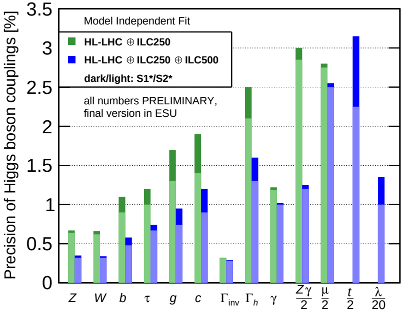


Latest higgs couplings (preliminary)





Recent ATLAS exclusions