Prospects of chargino searches and measurements at the ILC

Teresa Núñez - DESY

On behalf of the ILD Concept Group

Chargino production at the ILC

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arXiv:2002.01239 [hep-ph]

From light Higgsinos to test of unification

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Photon-photon processes at the ILC and BSM signatures with small mass differences

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DESY-THESIS-2021-002

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SUSY 2021, 25-08-21

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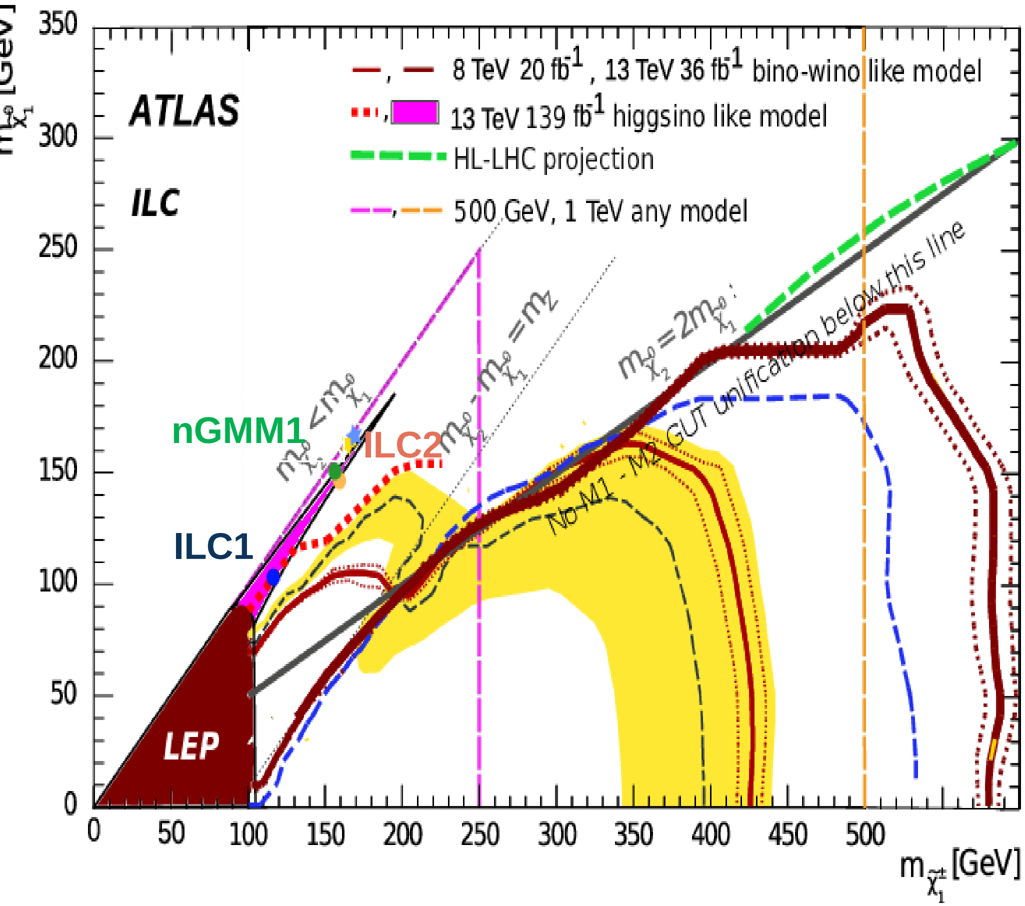
Introduction



ATLAS: Eur Phys J C78,995 (2018) [arXiv:1803.02762]
Phys Rev D101,052002 (2020) [arXiV:1911.12606]
arXix:2106.01676
ATLAS HL-LHC: ATL-PHYS-PUB-2018-048

- No evidence of SUSY in LHC data at 7, 8 and 13 GeV
- LHC SUSY exclusion/discovery limits are strongly model dependent
- Complementary nature of physics in e^+e^- colliders offers interesting scenarios where SUSY can be discovered …
- … and highly model independent exclusion/discovery limits can be obtained

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Motivation

Electroweak naturalness in simple SUSY models requires a cluster of four light Higgsinos

$\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0, \tilde{\chi}_2^0$ compressed spectrum (10-20 GeV) around ~ 100-300 GeV

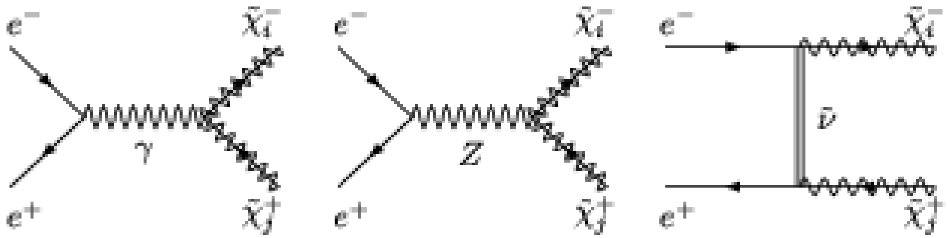
Challenging for LHC if other sparticles are heavy… but not for ILC:

- Electron-Positron collider at $\sqrt{s}$ = 250-500 GeV with energy upgradability (1TeV)
- Electrons (80%) and positrons (30%) polarisations
- Well defined initial state: 4-Momentum and spin configuration
- Clean and reconstructable final state
- Hermetic detectors (almost 4π coverage)
- Triggerless operation

Searches for Higgsinos or Winos (charginos) at small mass differences and evaluation of precision of model parameter measurements

Chargino searches

- Compute lighter chargino pair production cross sections in a wide SUSY parameter space (only using MSSM as model and R-parity conservation)
- Determine case with lowest production cross sections
- Compare to cross section detection limits extrapolated from LEP results (in the worst scenario)



Cross section studies divided depending on:

- chargino mixing: Higgsino-like, Wino-like and Mixed charginos
- sneutrino mass scale: high (~1TeV), low (around kinematic limit)

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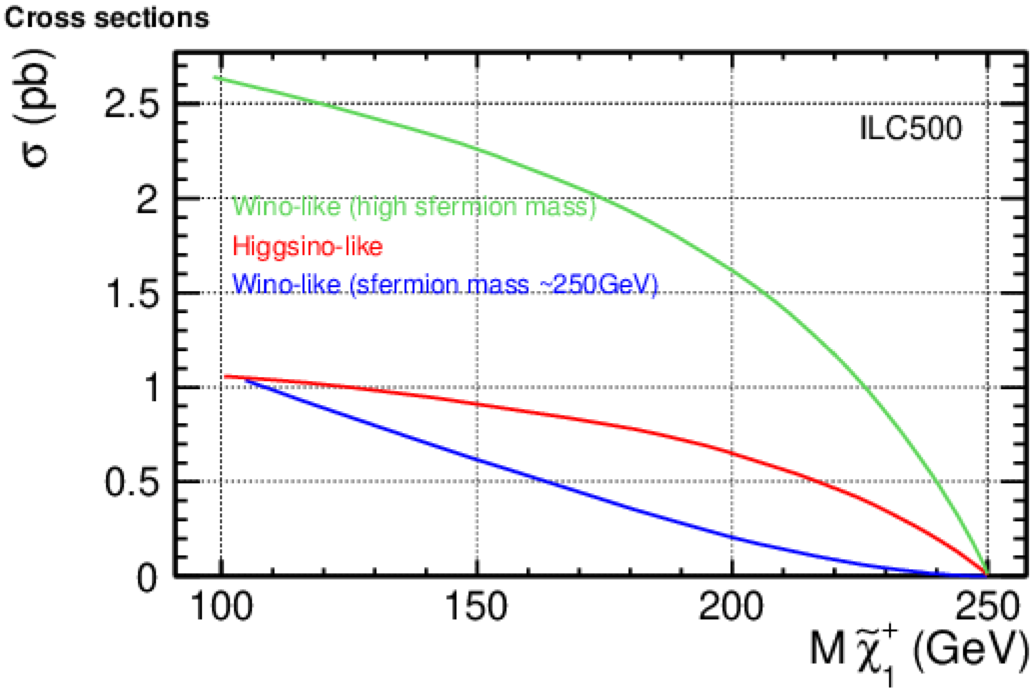
Chargino searches: cross sections

Worst scenario for Wino and Higgsino-like charginos



P(e-,e+)=(-80%,+30%)

Lower efficiencies reached in Wino-like case with sfermions masses close to kinematic limit

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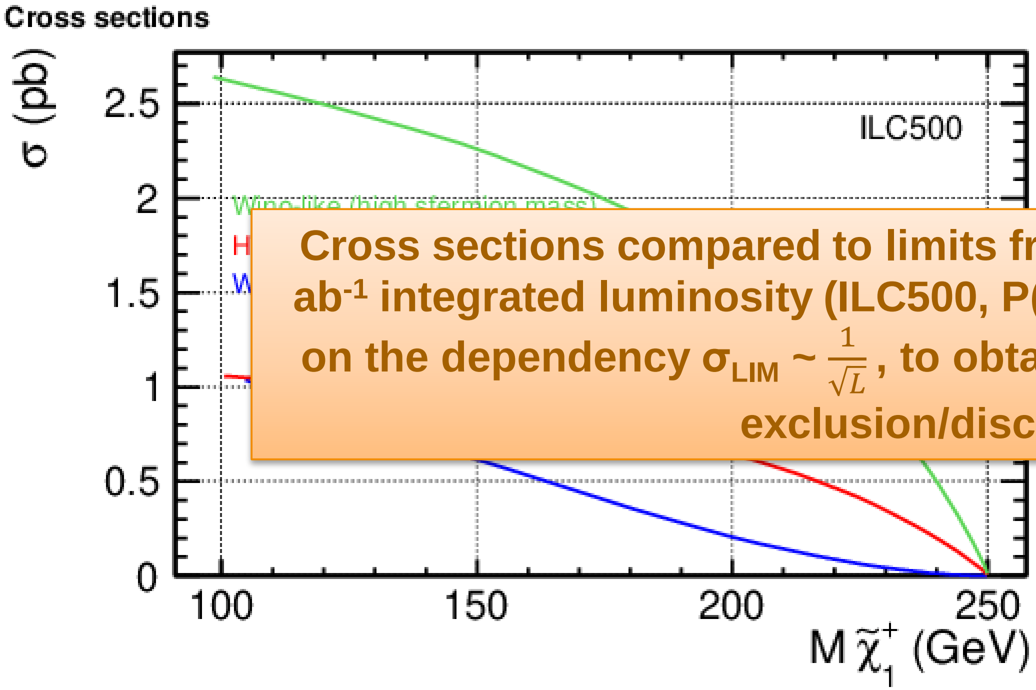
Chargino searches: cross sections

Worst scenario for Wino and Higgsino-like charginos



Cross sections compared to limits from LEP extrapolated to 1.6 ab^{-1} integrated luminosity (ILC500, P(e-,e+)=(-80%,+30%)), based on the dependency $\sigma_{LIM} \sim \frac{1}{\sqrt{L}}$, to obtain mass limits for chargino exclusion/discovery

P(e-,e+)=(-80%,+30%)

Lower efficiencies reached in Wino-like case with sfermions masses close to kinematic limit

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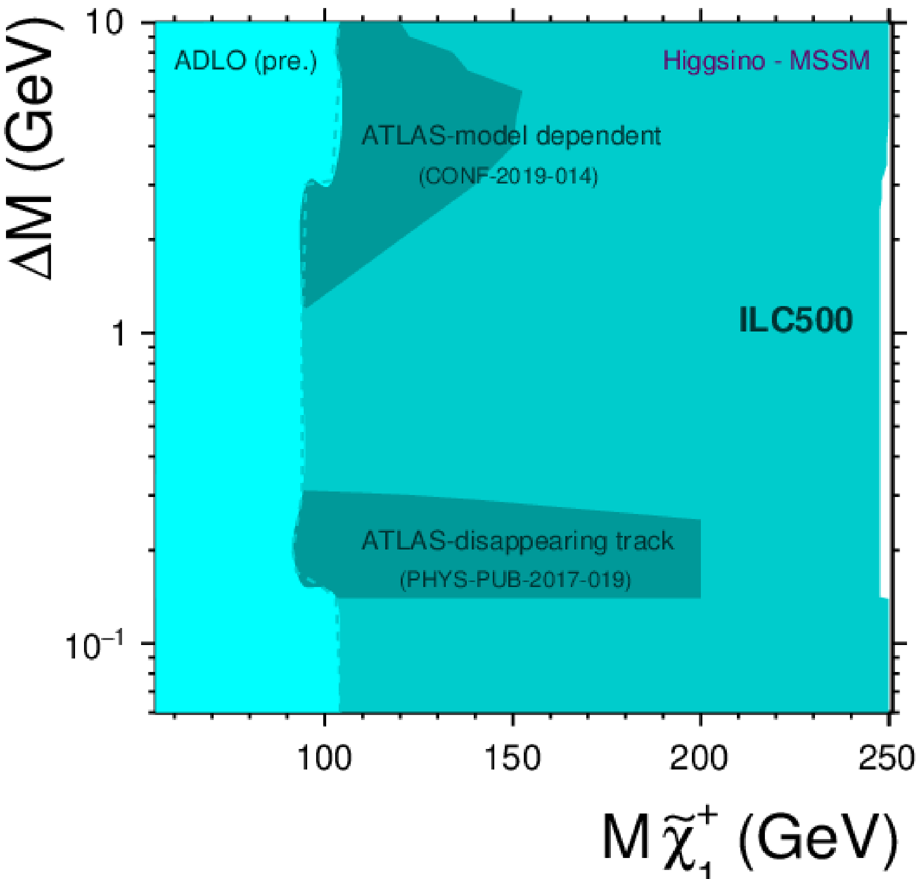
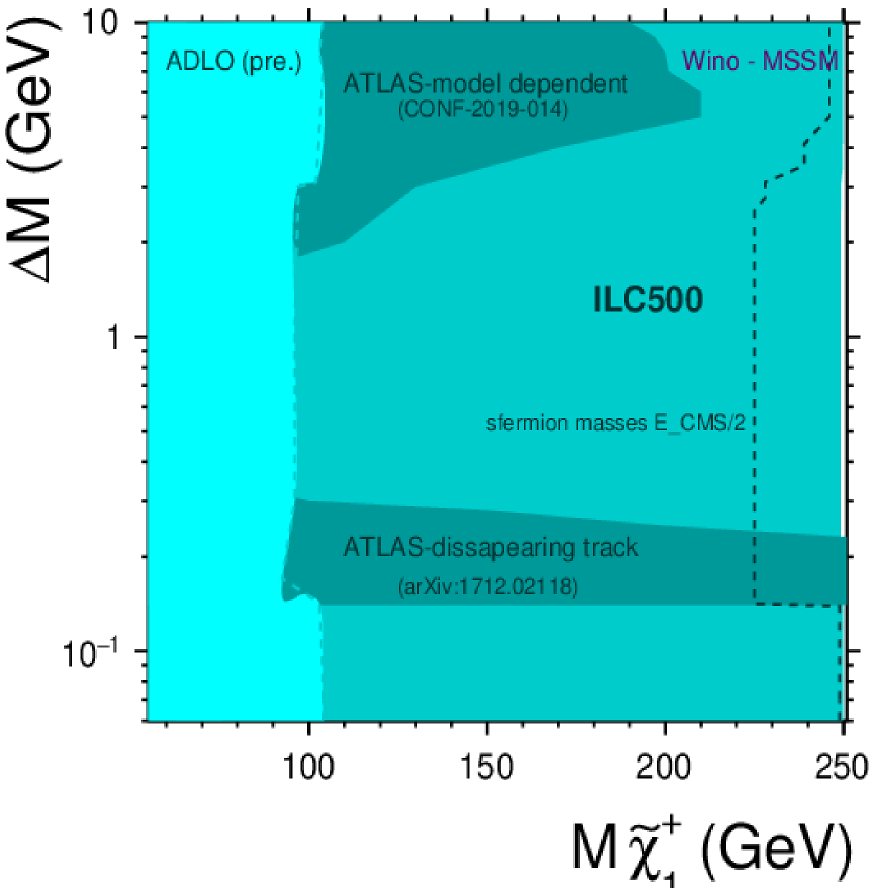
Chargino searches: mass exclusion limits

Higgsino



Wino



Chargino searches: mass exclusion limits

Higgsino

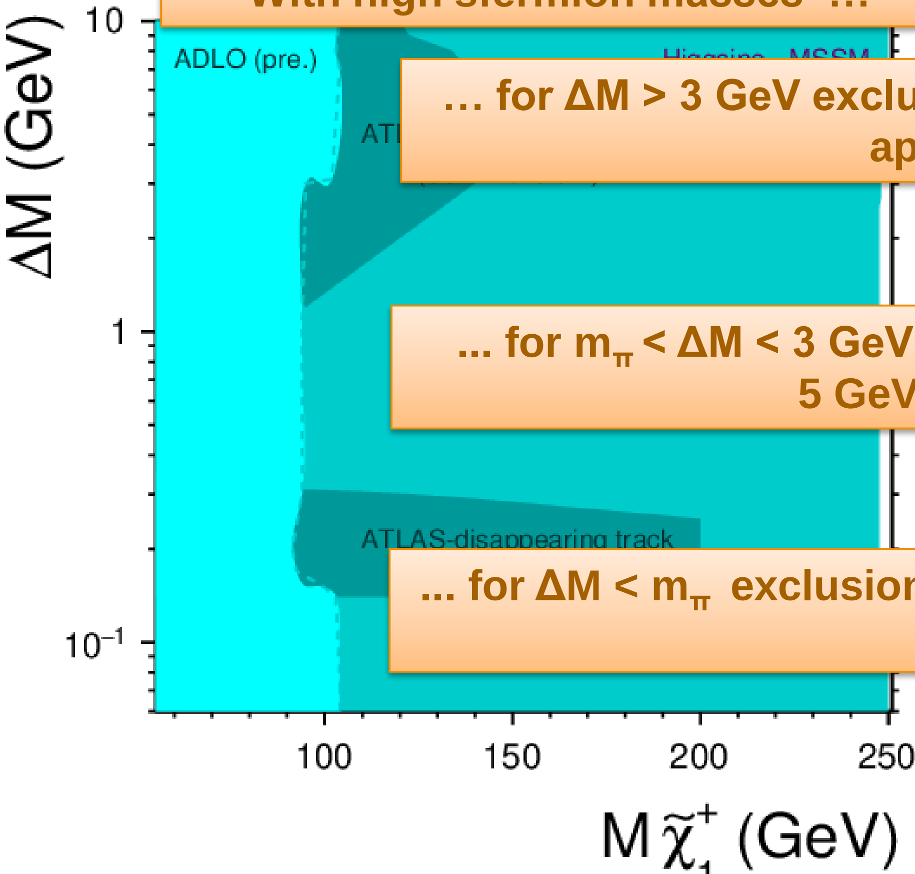
Wino

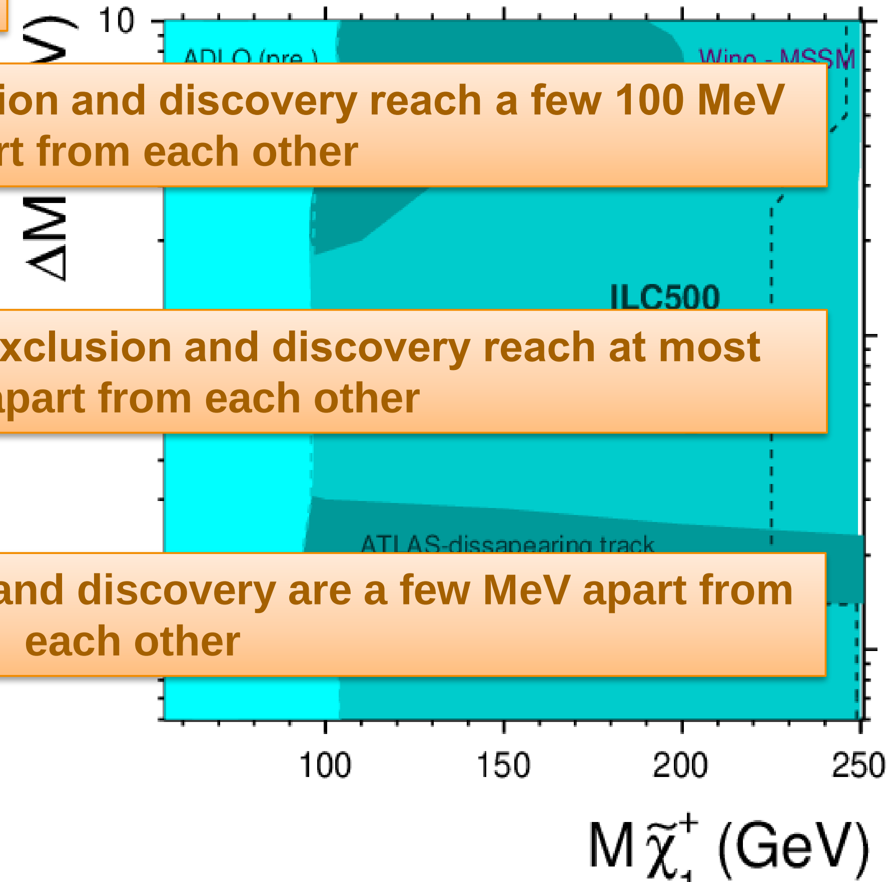
With high sfermion masses …

… for ΔM > 3 GeV exclusion and discovery reach a few 100 MeV apart from each other

... for m_π < ΔM < 3 GeV exclusion and discovery reach at most 5 GeV apart from each other

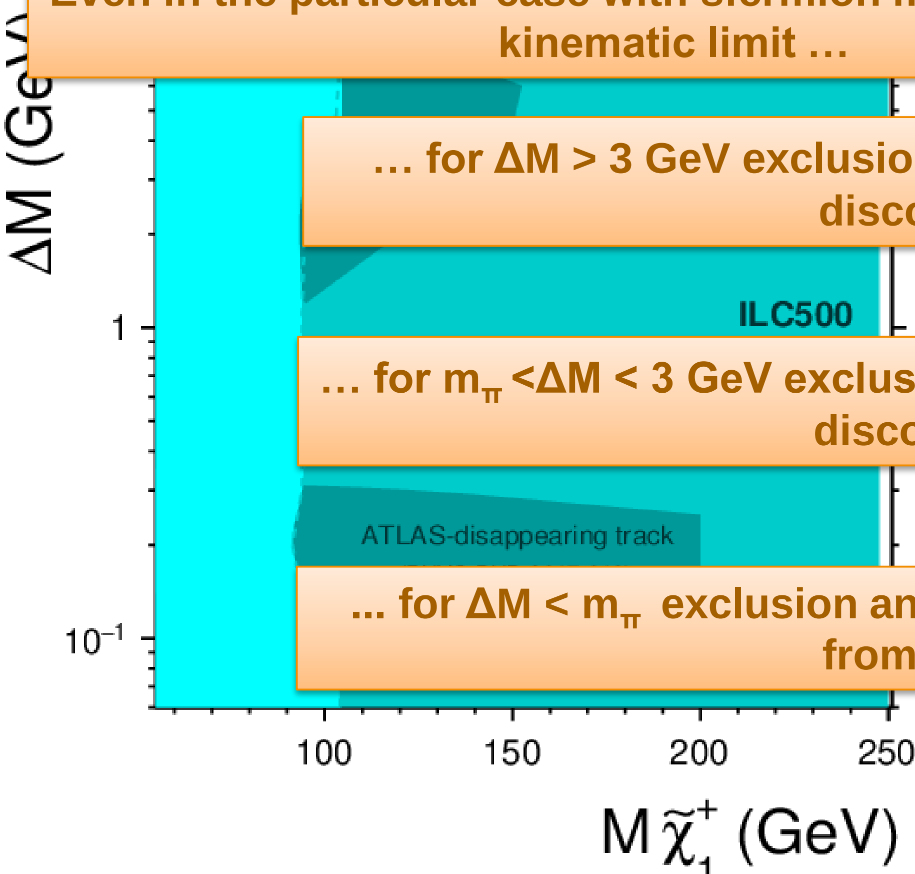
... for ΔM < m_π exclusion and discovery are a few MeV apart from each other



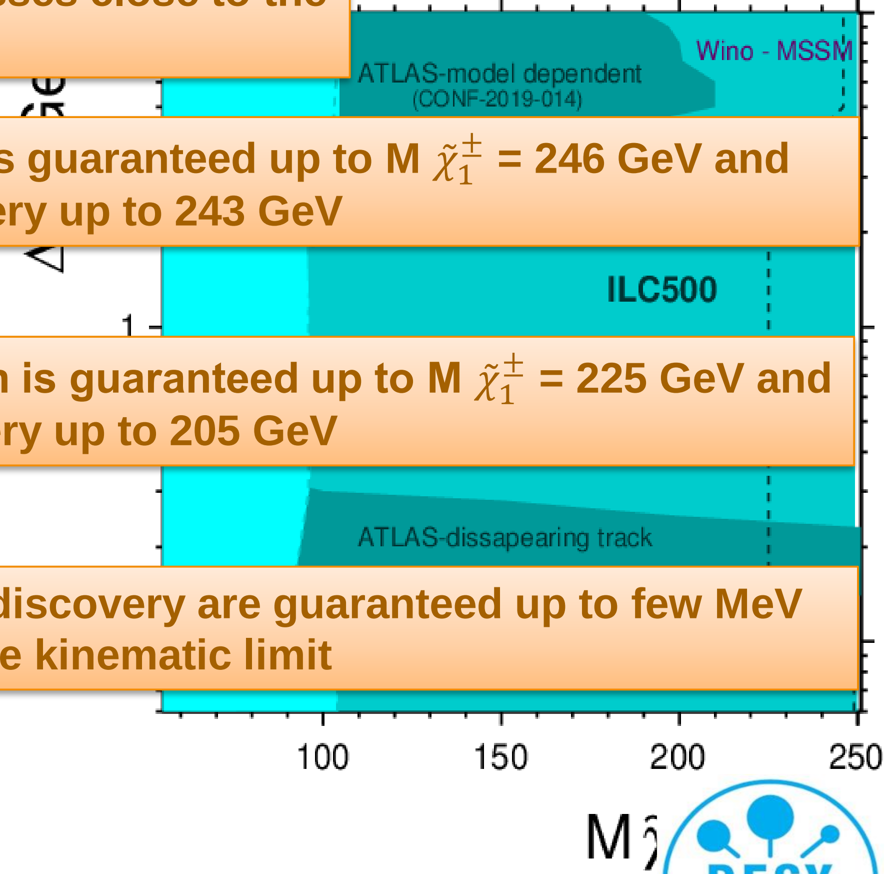


Chargino searches: mass exclusion limits

Higgsino



Wino



Even in the particular case with sfermion masses close to the kinematic limit …

… for ΔM > 3 GeV exclusion is guaranteed up to M $\tilde{\chi}_1^{\pm}$ = 246 GeV and discovery up to 243 GeV

… for m_π <ΔM < 3 GeV exclusion is guaranteed up to M $\tilde{\chi}_1^{\pm}$ = 225 GeV and discovery up to 205 GeV

... for ΔM < m_π exclusion and discovery are guaranteed up to few MeV from the kinematic limit

Chargino searches: Conclusions

Improvements at the ILC

- Polarisation (increases signal/background ratio)
- No trigger (increases detection efficiency and allows 'redundant' analysis) but …

  ISR needed for gamma-gamma background suppression
- Smaller beam size (increases detection efficiency by releasing ISR requests -> observation of decay length for soft events)

General comments

- Loop corrections are not included (chargino pair production cross sections can change up to 20%)
- Low sfermions masses not taken into account in LEP analysis, they would imply:

  - changes in chargino branching ratios and decay topology

  - sfermion production and possible discovery

  The drop in cross section due to sfermions masses depends on the beam energy, can be shifted.
- ISR request close to kinematic limits could cause unknown effects

From Light Higgsinos to test of unification

Examine the capability of the ILC to make precision measurements of superparticle properties offering the possibility to make important predictions of SUSY breaking and fundamental particle physics and providing insights int the nature of dark matter and cosmology

Three benchmark scenarios

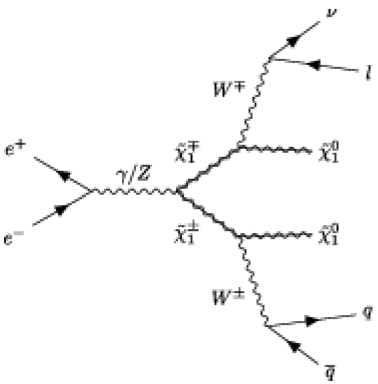
ILC1 & ILC2:

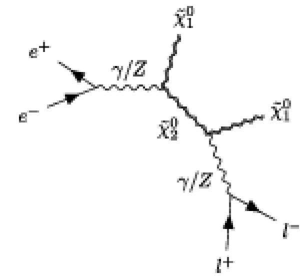
- Natural models from NUHM2
- Gaugino mass unification at GUT scale

nGMM1:

- Natural generalized mirage mediation model
- Gaugino mass unification at mirage scale

Two channels



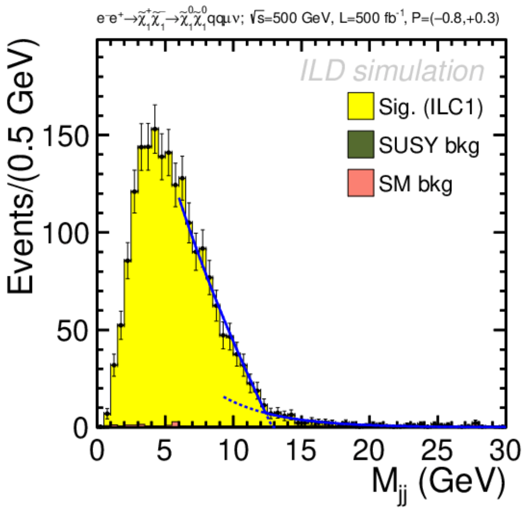


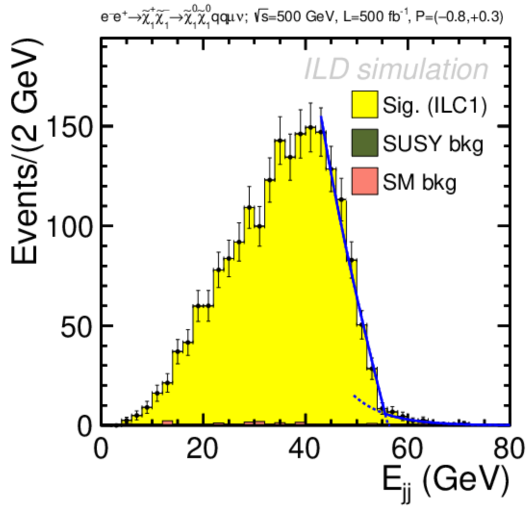
Light Higgsino masses ~150 GeV and mass differences 4-20 GeV

Direct measurement of masses and cross sections

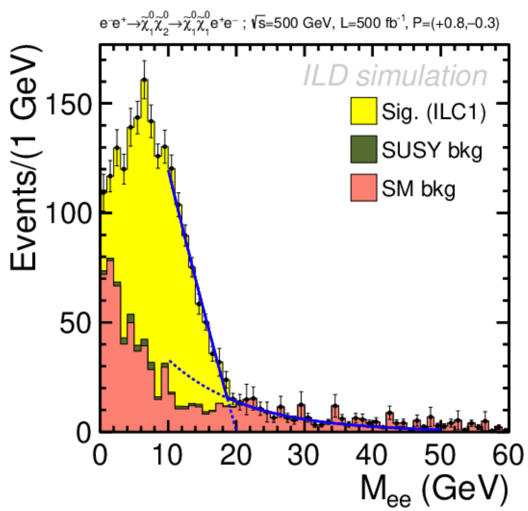
Extracted from kinematic distributions in both channels under study

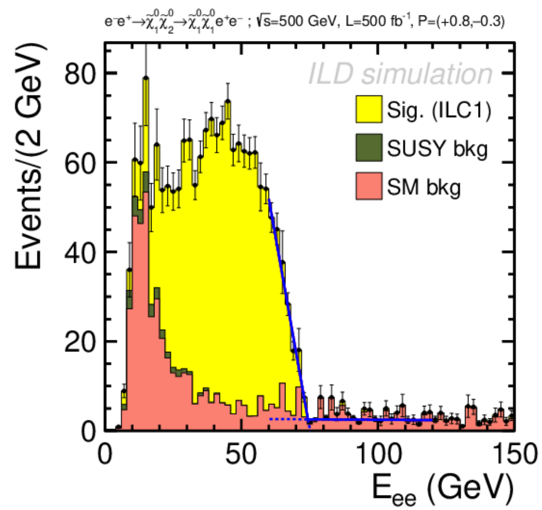
Chargino channel





Neutralino channel





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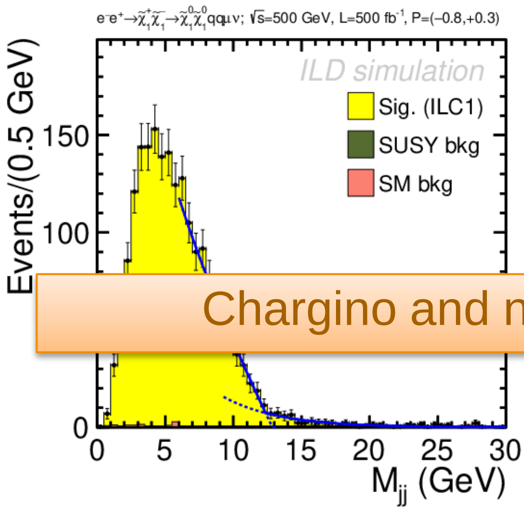
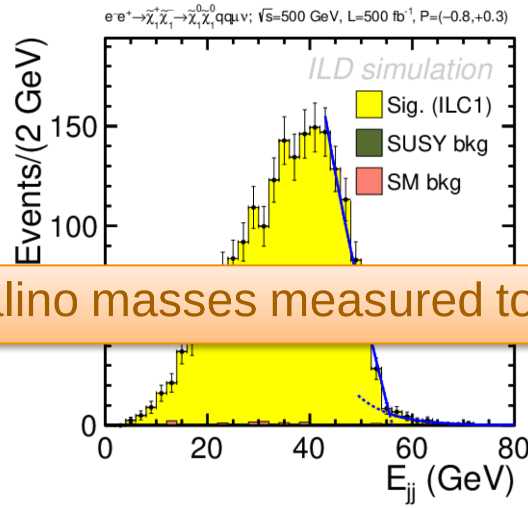
Direct measurement of masses and cross sections

Extracted from kinematic distributions in both channels under study

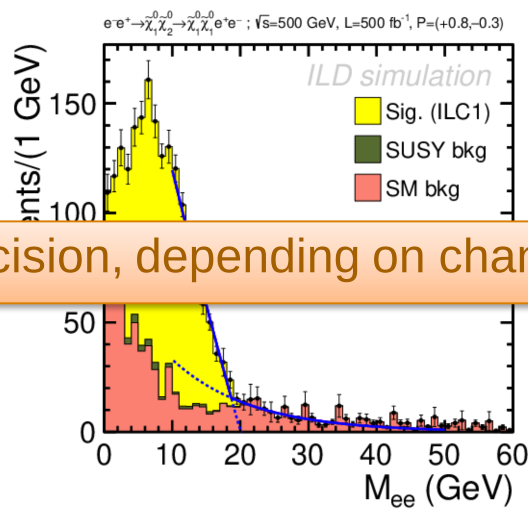


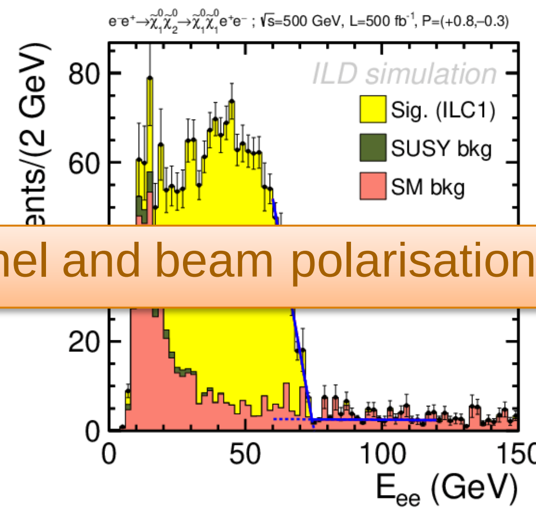


Chargino channel

Chargino and neutralino masses measured to less than 1% precision

Neutralino channel





σ x BR up to a few % precision, depending on channel and beam polarisation

Fitting fundamental parameters and testing gaugino mass unification

Extraction of both GUT-scale and weak-scale parameters with two different approaches (4 and 10 free parameters), extrapolation of these to the GUT-scale

Input parameters:

- Four Higgsino masses
- Four polarised total cross sections from chargino and neutralino
- Higgs observables with ILC precision:
  - > Mass of the lightest CP-even Higgs boson
  - > Higgs decay branching ratios

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Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

None of the benchmarks can be excluded as NUMH2 model

Not underlying models (NUHM1, CMSSM): interpretations ruled out at 95% CL with only 0.1% total integrated luminosity

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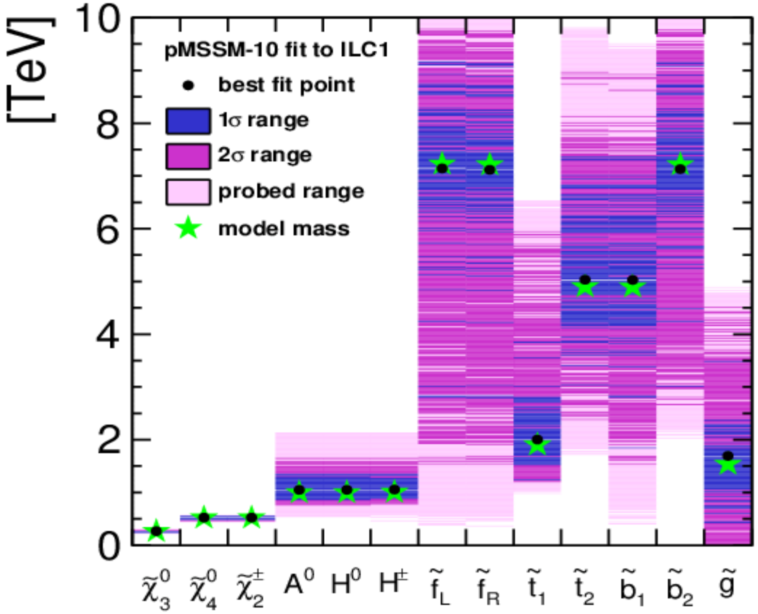
Fitting fundamental parameters: Weak scale

Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone

pMSSM-10 ILC1

Parameters entering Higgsino sector in tree and loop level



Clear electroweakinos and heavy Higgs bosons mass predictions

Changes in parameters entering at loop level the Higgsino sector do not affect heavier Higgsino predictions

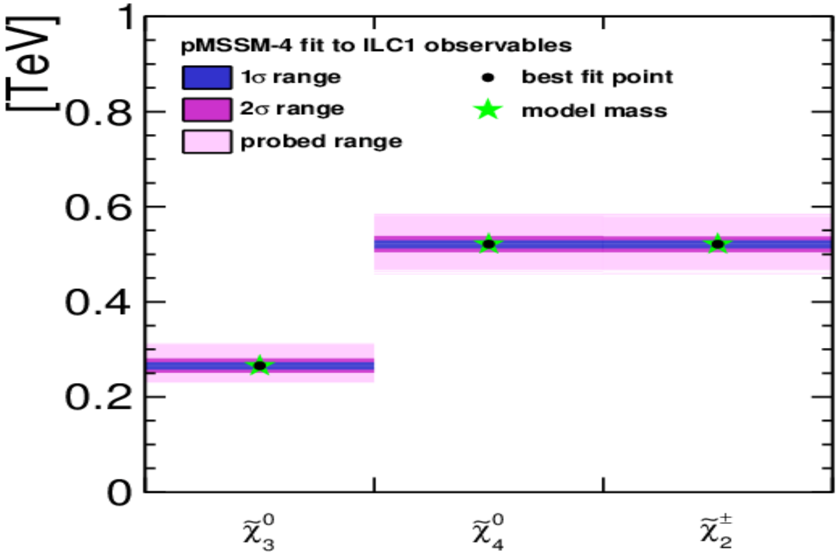
Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders

Fitting fundamental parameters: Weak scale

pMSSM-4 ILC1

Only tree level Higgsino sector parameters



Heavier electroweakinos mass precisions improved up to 1.6% - 3%

Changes in fixed parameters keeps predictions within 1σ uncertainties

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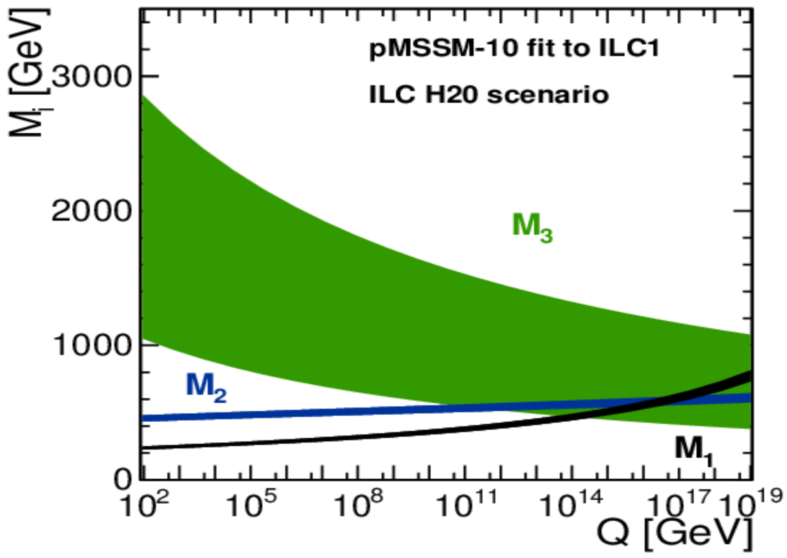
Testing gaugino mass unification

MSSM RGEs used to evolve fitted parameters to higher energy scales and check unification hypothesis

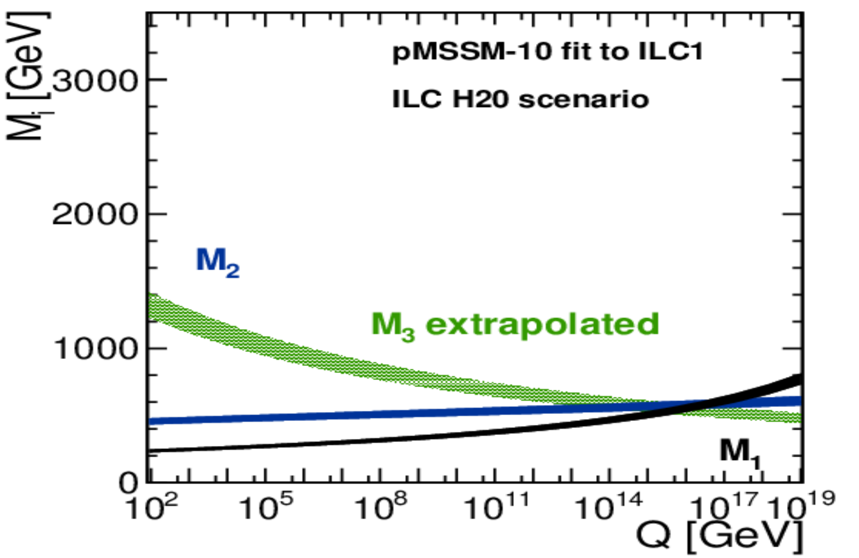
Test gaugino mass unification in different models
Study impact of experimental improvements

- pMSSM-10 weak scale parameters extracted at Q=10GeV
- Scan around extracted values using corresponding PDF within +/- 1σ
- Calculate running parameters at different energy scales

Testing gaugino mass unification: ILC1



Assuming NUHM2 model, prediction of physical gluino mass can be obtained: m_g = 1467 +/- 80 GeV



Q_{unif} and $M_{1/2}$ in agreement with GUT scale model fit (same for ILC2)

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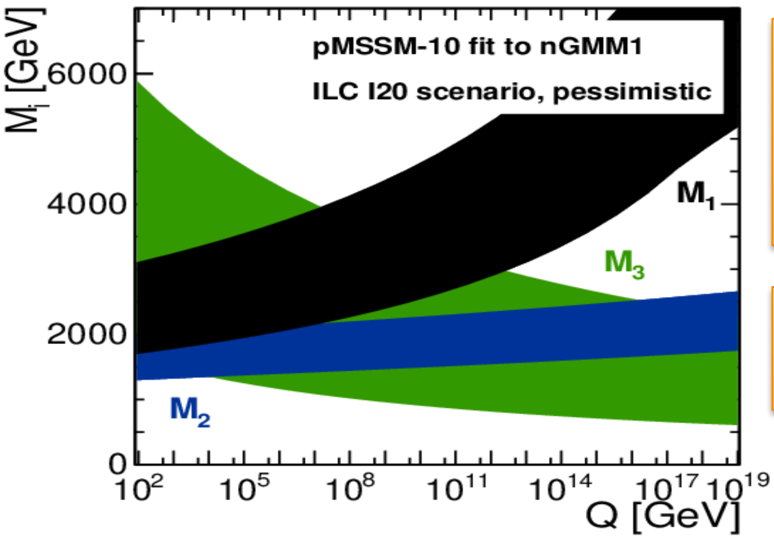
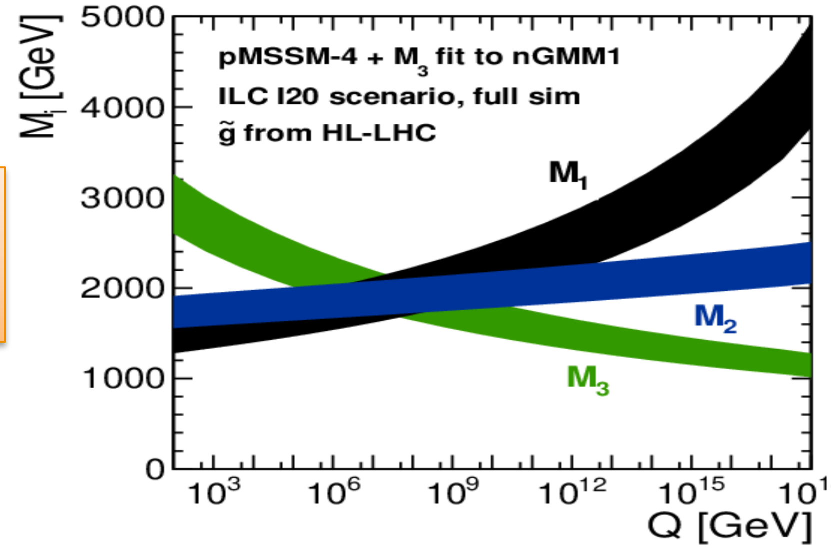
Testing gaugino mass unification: nGMM1



Differences with ILC1 & ILC2:
- Underlying model unifies at intermediate scale
- M_1 and M_2 determination at weak scale much less accurate

Even in pessimistic scenario gaugino mass unification at GUT scale can be rejected



Improving precision and using hypothetical gluino mass shows unification at intermediate scale

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Effect of $\gamma\gamma \rightarrow$ low p_T hadron overlay on Higgsino analysis

e+e- beams are accompanied by real and virtual photons

At = 500 GeV 1.05 low pt hadron events/Bunch crossing expected

- A new developed track grouping algorithm facilitates an effective separation of signal and overlay tracks (based on impact parameter)
- Event selection criteria were adapted
- Key observables like the chargino mass and polarized cross section can be measured with few percent uncertainty
- Even with statistical uncertainties worsening due to presence of overlay to about ~3%, the obtained results are highly precise

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Conclusions

- We show the ILC discovering reach for SUSY in the chargino channel within the worst scenario and in very conservative conditions. Mass limits up to few GeV below the kinematic limit have been found
- The capability of the ILC for measuring SUSY observables with precision enough to make relevant SUSY related predictions has been studied and confirmed
- Improvement on the experimental results are clearly reflected on the predictions
- The predictions extracted from direct SUSY measurements can have an important role in future accelerator designs and upgrades
- The interplay between ILC and LHC/HL-LHC SUSY measurements can improve considerably the results of both analysis
- Light Higgsinos can be measured at the ILC even in the presence of $\gamma\gamma \rightarrow$ low p_T hadron overlay

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Backup slides

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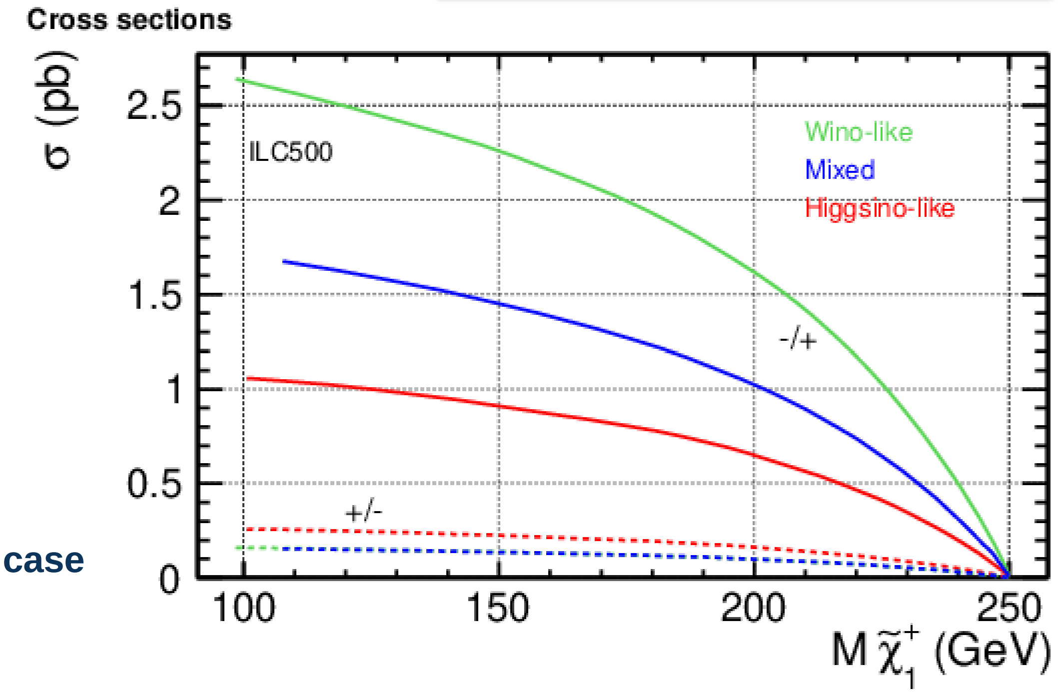
Chargino searches: cross sections

High sfermion masses

$\sqrt{s}$ = 500 GeV, ISR photon

ILC experimental conditions



Lower cross sections for Higgsino-like case

+/- → P(e-,e+)=(-80%,+30%)
-/+ → P(e-,e+)=(+80%,-30%)

P(e-,e+)=(-80%,+30%) with $\mathcal{L}$ = 1.6 ab^{-1} will be used for the study

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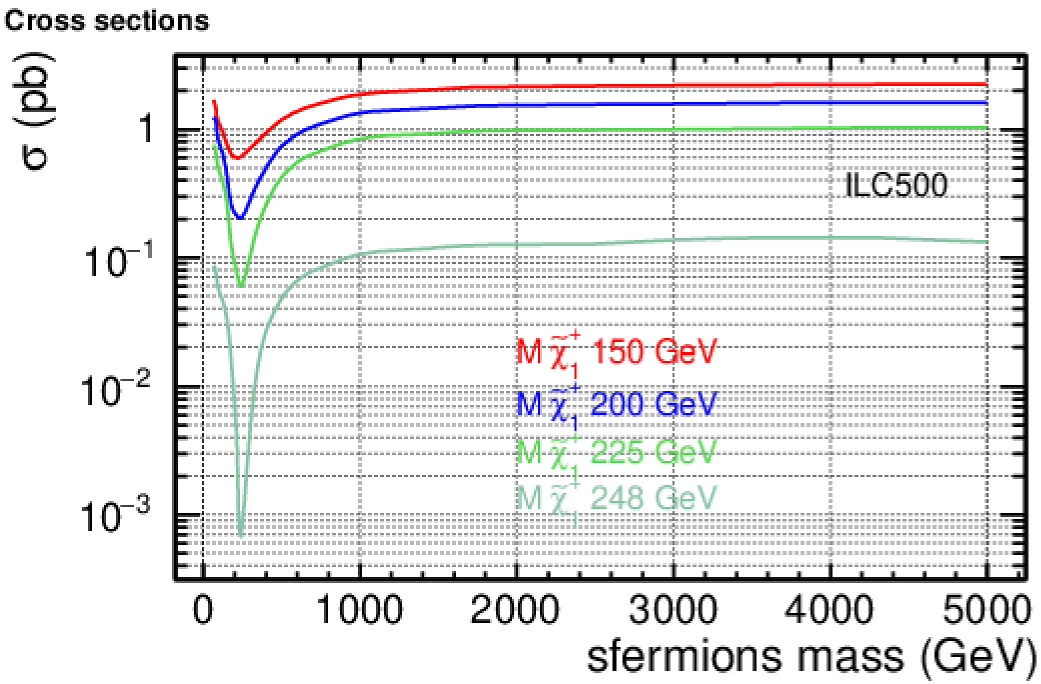
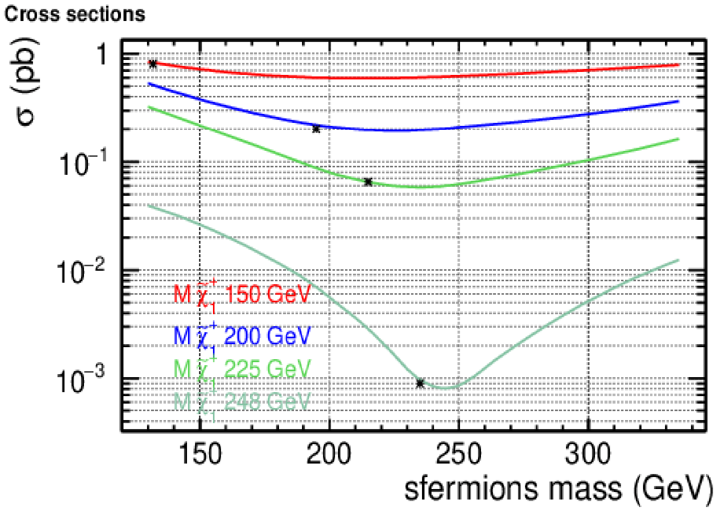
Chargino searches: cross sections

Low sfermion masses



Wino-like charginos

- **Affects Wino case via destructive interference of t-channel**
- **No effect on Higgsino due to weakly coupling to sneutrino**



⋆ **Limit selectron mass < M$\tilde{\chi}_1^{\pm}$**

P(e-,e+)=(-80%,+30%)

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Chargino searches: extrapolated data

Combined LEP chargino studies

- Data taken at up to ~208 GeV center-of-mass energy, accumulated luminosity ~800 pb^{-1}
- No signal found, limits derived at 95%CL in the context of MSSM (R parity conservation) focused in the region with small $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{LSP}$
- Two cases considered:
  - Higgsino-like
  - Wino-like (high sfermion masses)
- Three topologies for the analysis of chargino decays:
  - prompt decays into leptons, leptons + jets, jets via W* (ΔM > 3GeV)
  - soft decays with a ISR requested on trigger (π mass < ΔM < 3GeV)
  - events with tracks displaying kinks, impact parameters offset or heavy stable charged particles (ΔM < π mass)

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- No signal found, limits derived at 95%CL in the context of MSSM (R parity conservation) focused in the region with small $\Delta M = M_{\tilde{\chi}_1^{\pm}} - M_{LSP}$
- Two cases considered:
  - Higg
  - Win

Cross sections compared to limits from LEP extrapolated to 1.6 fb^{-1} integrated luminosity (ILC500, P(e-,e+)=(-80%,+30%)) based on the dependency $\sigma_{LIM} \sim \frac{1}{\sqrt{L}}$

- Three topologies for the analysis of chargino decays:
  - prompt decays into leptons, leptons + jets, jets via W* ($\Delta M > 3$GeV)
  - soft decays with a ISR requested on trigger (π mass < ΔM < 3GeV)
  - events with tracks displaying kinks, impact parameters offset or heavy stable charged particles (ΔM < π mass)

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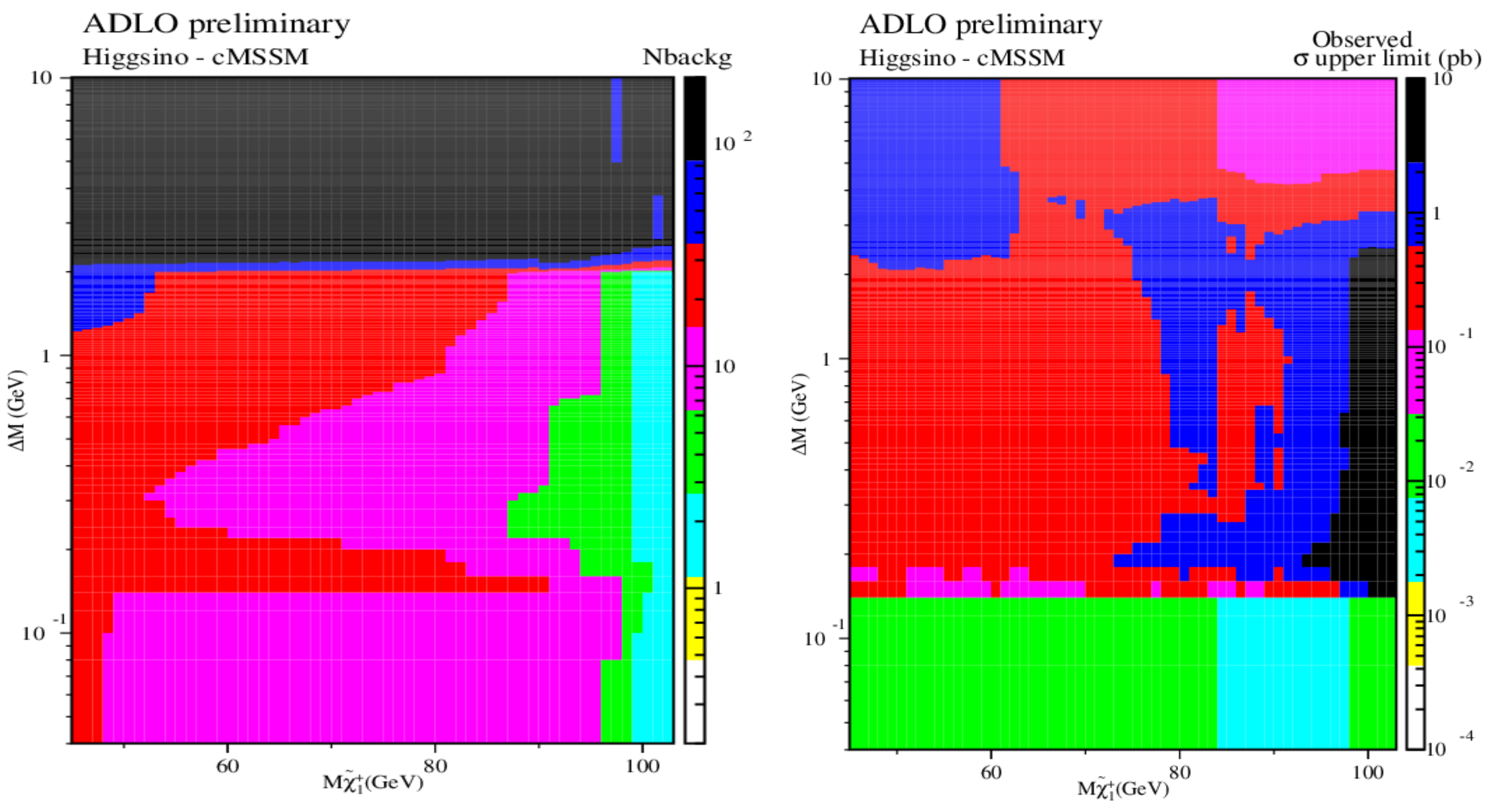
Chargino searches:

Comparison to extrapolated limits



Low efficiency in π mass < DM < 3 GeV region due to ISR trigger requirement

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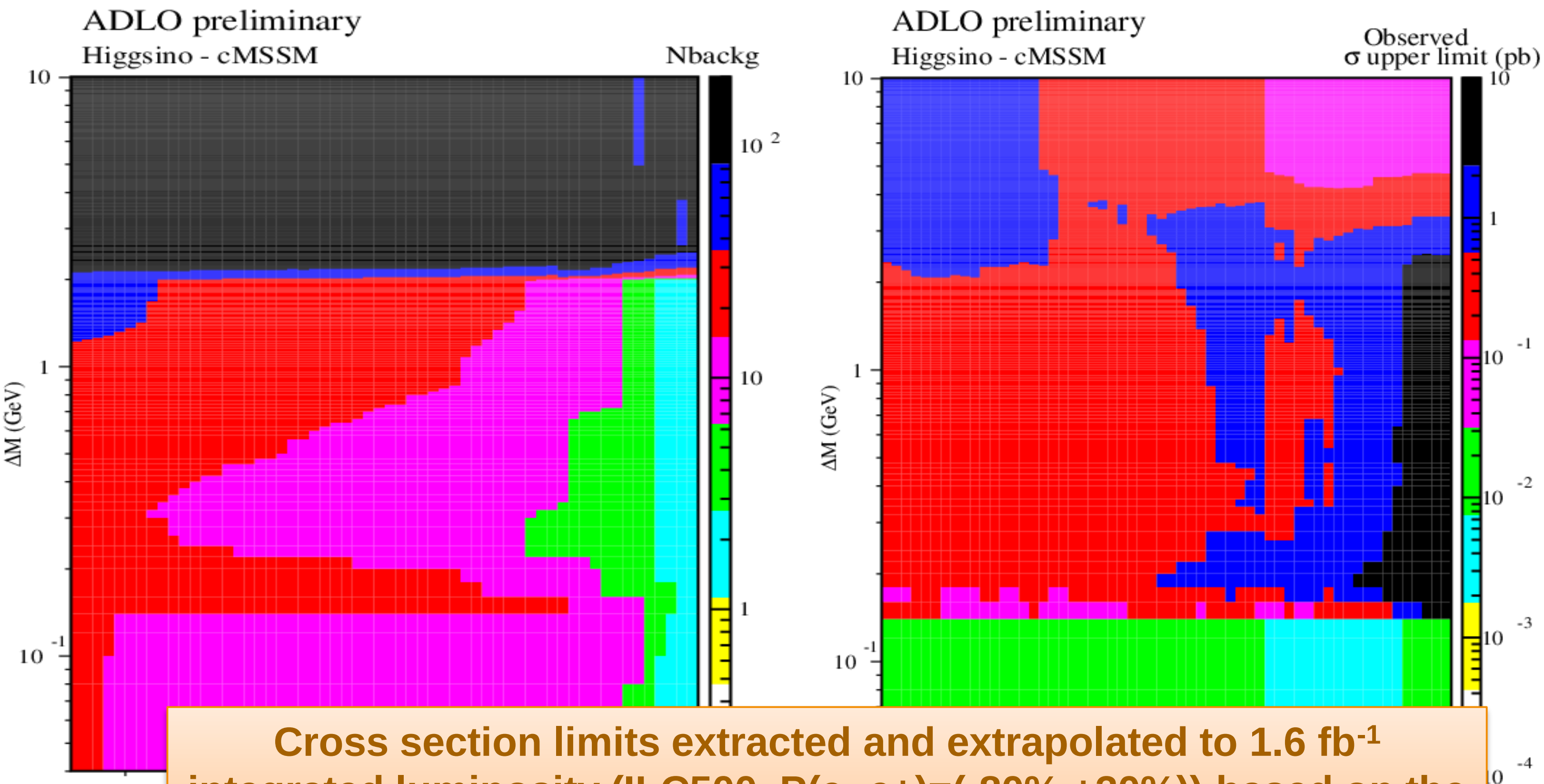
Chargino searches:

Comparison to extrapolated limits



Cross section limits extracted and extrapolated to 1.6 fb^{-1} integrated luminosity (ILC500, P(e-,e+)=(-80%,+30%)) based on the dependency $\sigma_{LIM} \sim \frac{1}{\sqrt{L}}$

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Benchmark scenarios

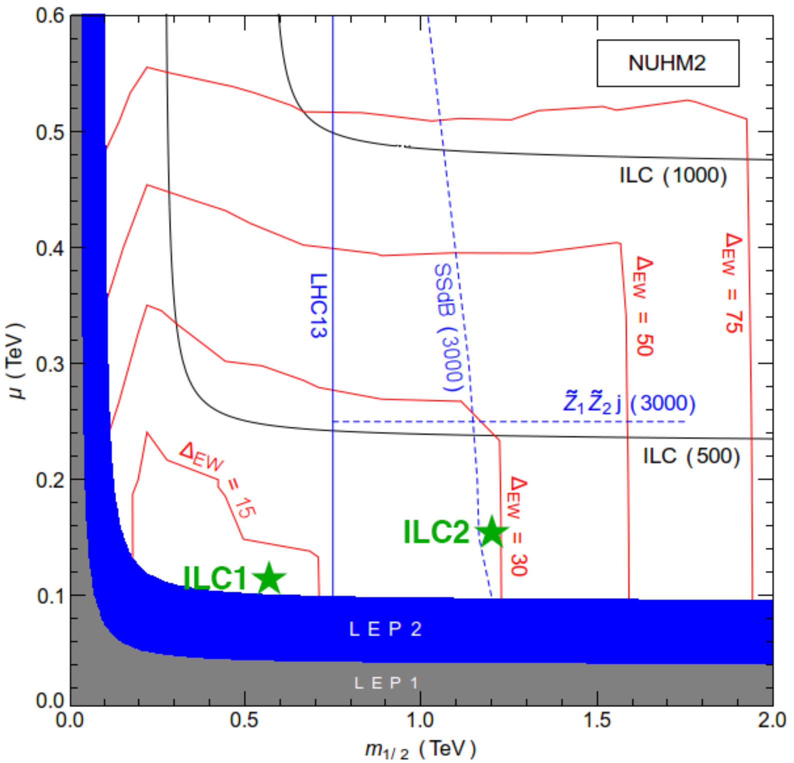
ILC1 & ILC2:

- Natural models from NUHM2
- Gaugino mass unification at GUT scale

nGMM1:

- Natural generalized mirage mediation model
- Gaugino mass unification at mirage scale (between EW and GUT scales)

Masses (GeV)	ILC1	ILC2	nGMM1
neu1	103	148	151
Chi1+-	117	157.8	159
Neu2	124	158.3	156
Neu3	267	539	1530
Gluino	1560	2830	2860



Cross sections at $\sqrt{s} = 500\ GeV$ several hundreds fb

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Software tools and observables

- Whizard1.95 for event generation
- ILD-specific software based on Geant4 for simulation and reconstruction
- Beam spectrum, ISR and γγ "pile-up" included
- $\sqrt{s}$ = 500 GeV and $\mathcal{L}$ = 500 fb^{-1} simulation results scaled to operation scenarios

- Processes studied:

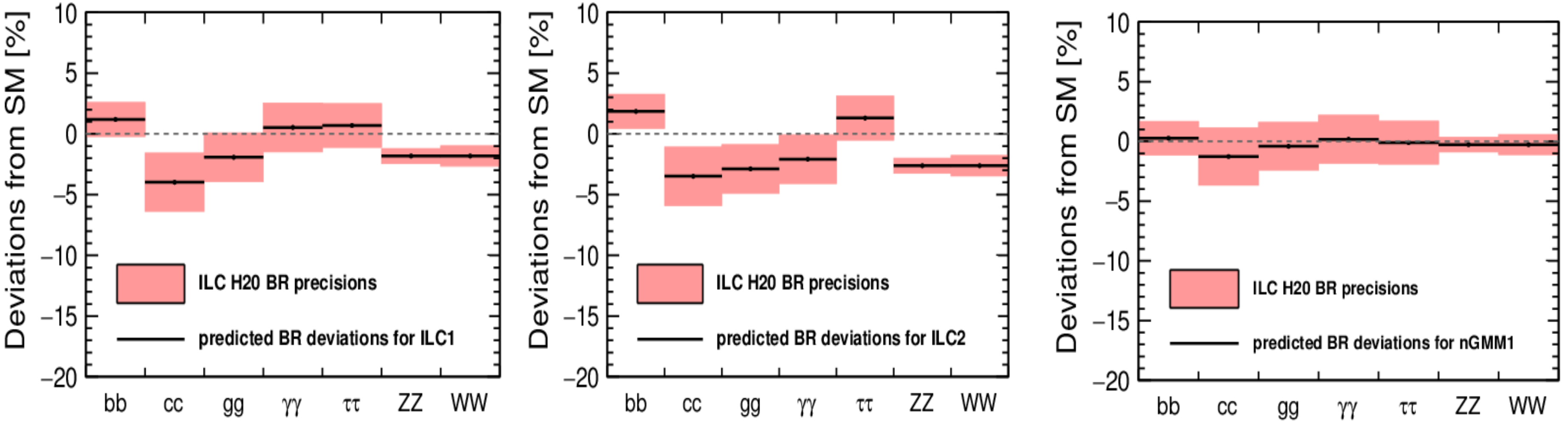
$$e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 q\bar{q}\ \tilde{\chi}_1^0\ e\ \nu_e\ (\mu\nu_\mu)$$

$$e^+ e^- \rightarrow \tilde{\chi}_1^0\ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ \tilde{\chi}_1^0\ e^+ e^-\ (\mu^+ \mu^-)$$

- Observables:
  - three masses ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$)
  - four cross sections
- Masses from kinematical distributions (maximum invariant mass -> mass splittings, maximum dilepton/dijet energy -> absolute masses)
- Cross sections from counting events after fitting overall shape

Chargino and neutralino channels studied independently

Higgs branching rations



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Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

Fit to NUMH2 model

	ILC1 best fit (true)	ILC2 best fit (true)	nGMM1 best fit
$M_{1/2}$	556.7 (568.3)	1194 (1200)	2407
μ	105.3 (115.0)	150.7 (150.0)	155.6
$\tan\beta$	11.4 (10.0)	16.0 (15.0)	10.0
m_A	968 (1000)	1008 (1000)	1603
M_0	7685 (7025)	4788 (5000)	3422
A_0	-11064 (-10427)	-7663 (-8000)	-7409
X^2	0.0011 (0.0013)	0.02848 (0.0007)	0.233

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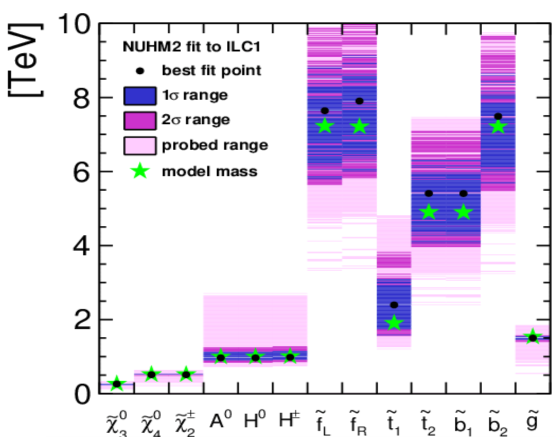
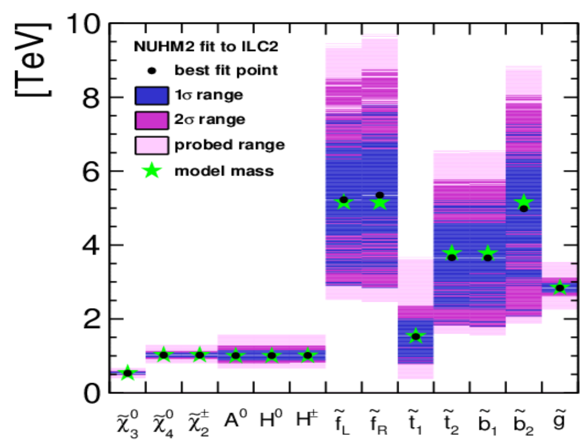
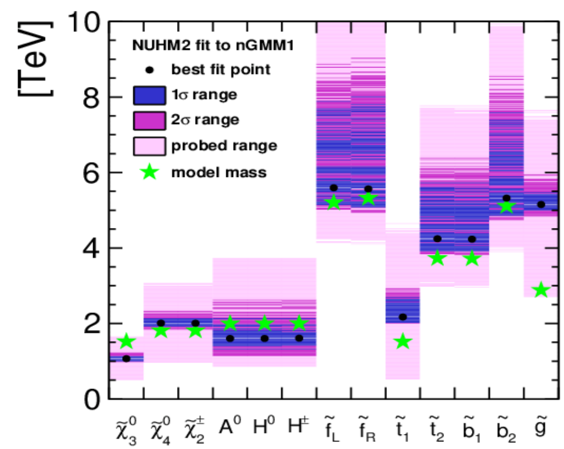
Fitting fundamental parameters: predicting SUSY spectrum

Clear electroweakinos and heavy Higgs bosons mass predictions (ILC1 & ILC2)







gluino mass firmly predicted (GUT check)

Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders

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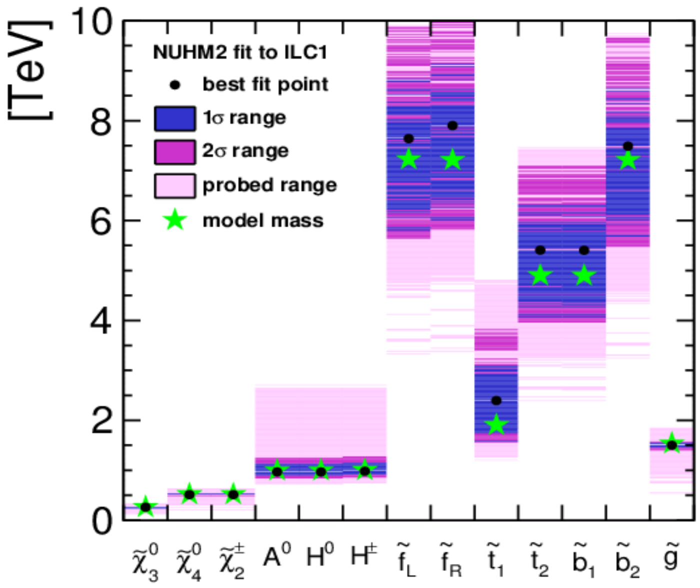
Fitting fundamental parameters: predicting SUSY spectrum

ILC1 (GUT-scale fit)



Clear electroweakinos and heavy Higgs bosons mass predictions

gluino mass firmly predicted (GUT check)

Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders

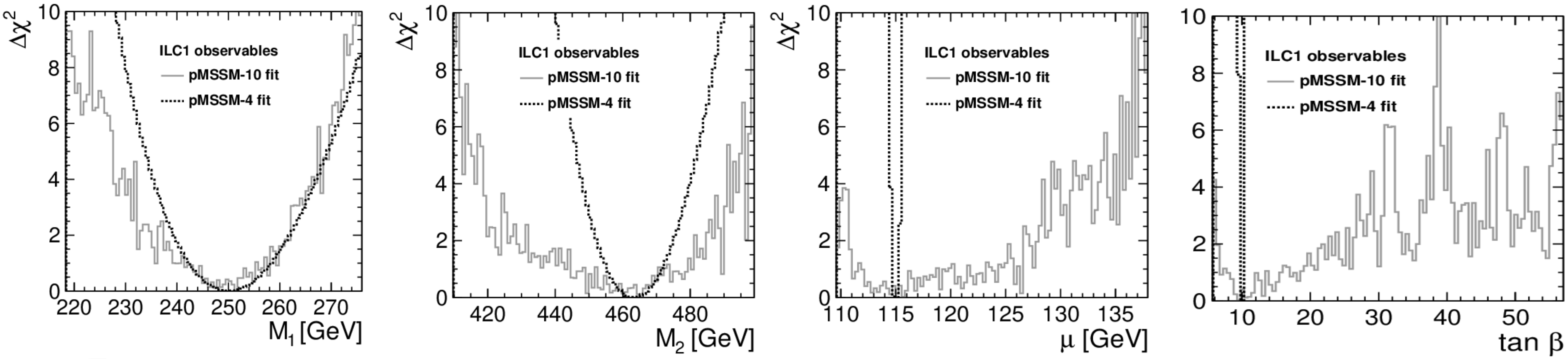
Fitting fundamental parameters: Weak scale

- Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone
- Study influence of parameters in which Higgsino sector enters at loop level
- Investigate precision achievable when fitting only tree level Higgsino parameters

Two models used: pMSSM-10, pMSSM-4

Fit parameters Higgsino sector

ILC1



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Fitting fundamental parameters: Weak scale

Weak-scale parameters

- **Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone**
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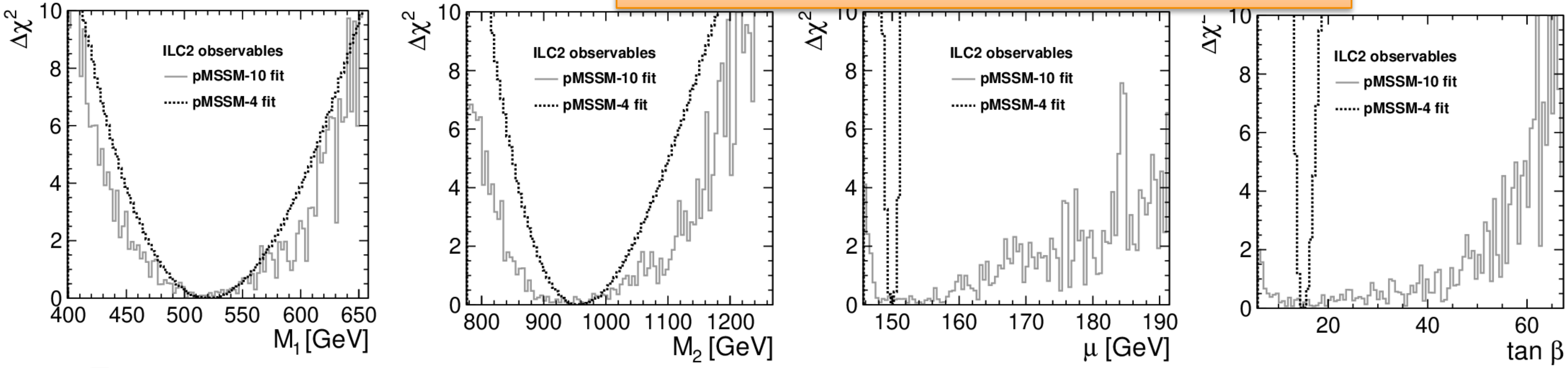
Two models used: pMSSM-10, pMSSM-4

Fit parameters Higgsino sector

ILC2

ILC2 shows same behaviour



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Hypothetical gluino mass from LHC (11% precision)

Fitting fundamental parameters: Weak scale

Weak-scale parameters

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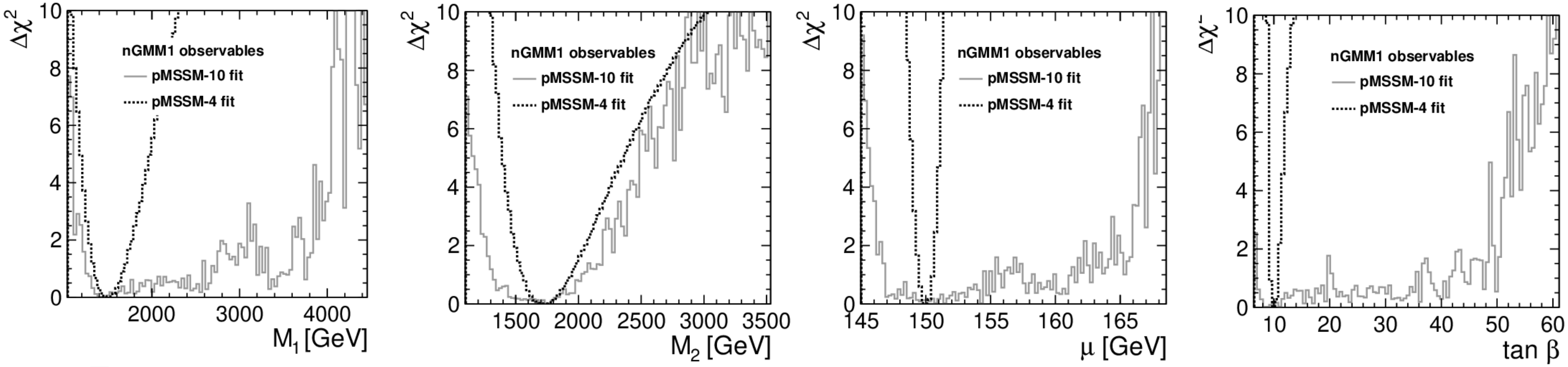
nGMM1



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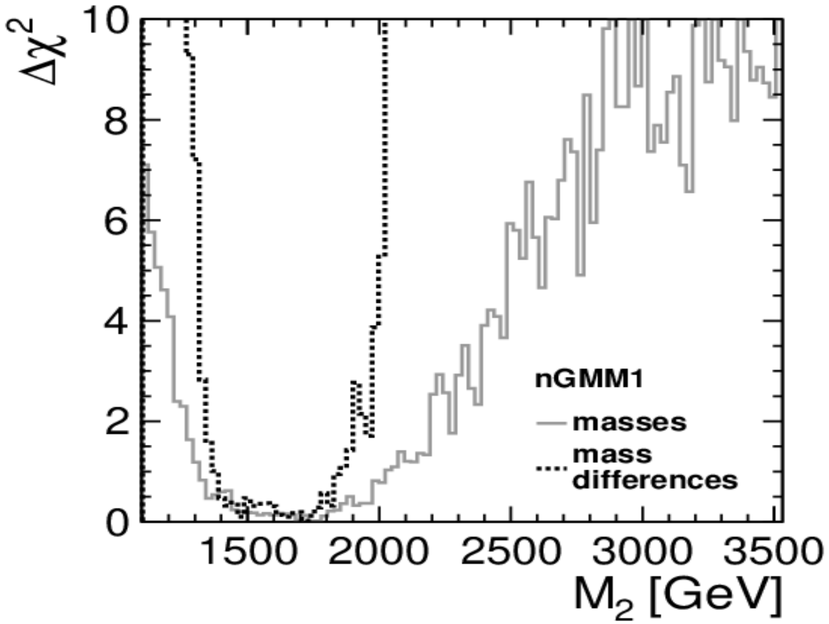
nGMM1 constrains less M1 and M2 due to worse experimental resolution and larger M1 and M2 absolute values

Fitting fundamental parameters: Weak scale

Improvement fit parameters by using mass differences

pMSSM-10 nGMM1



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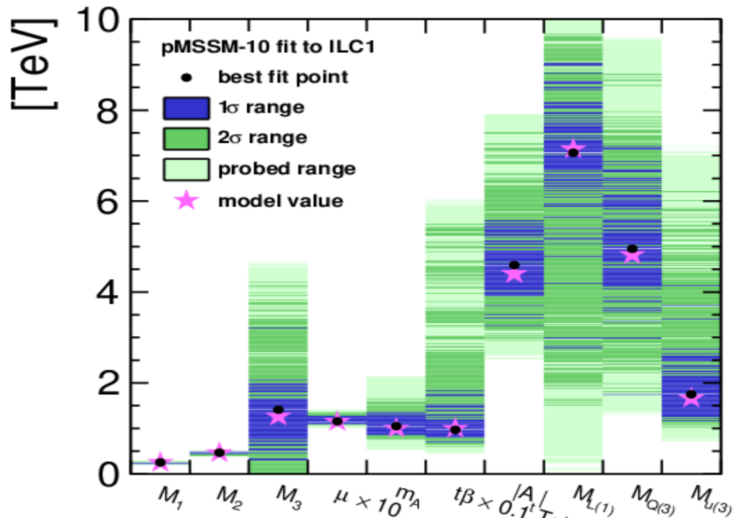
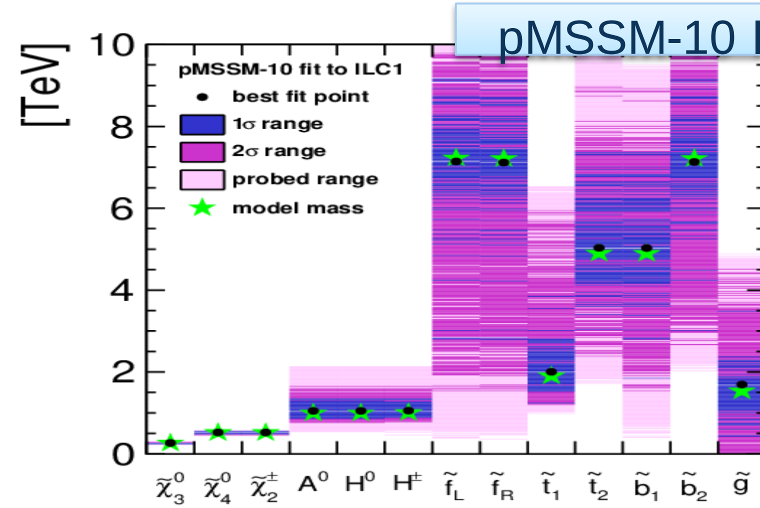
Hypothetical gluino mass from LHC (11% precision)

Fitting fundamental parameters: Weak scale

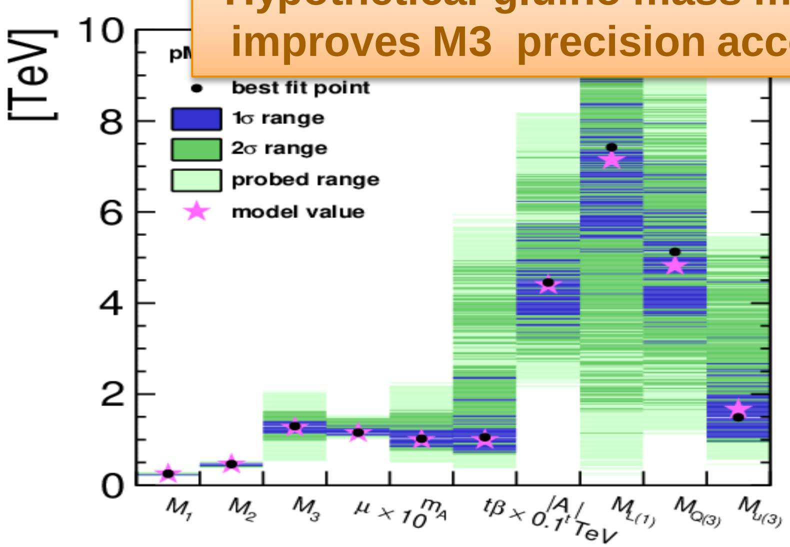
Constraints for parameters of colored sector can be obtained

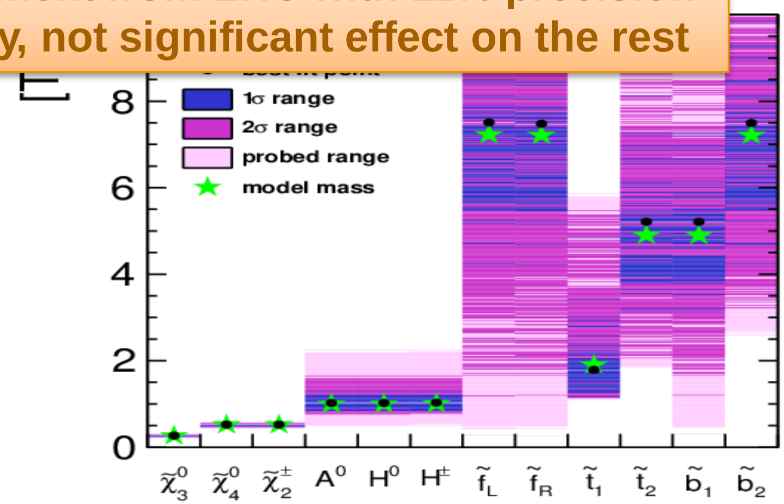
pMSSM-10 ILC1





Hypothetical gluino mass measurement from LHC with 11% precision improves M3 precision accordingly, not significant effect on the rest

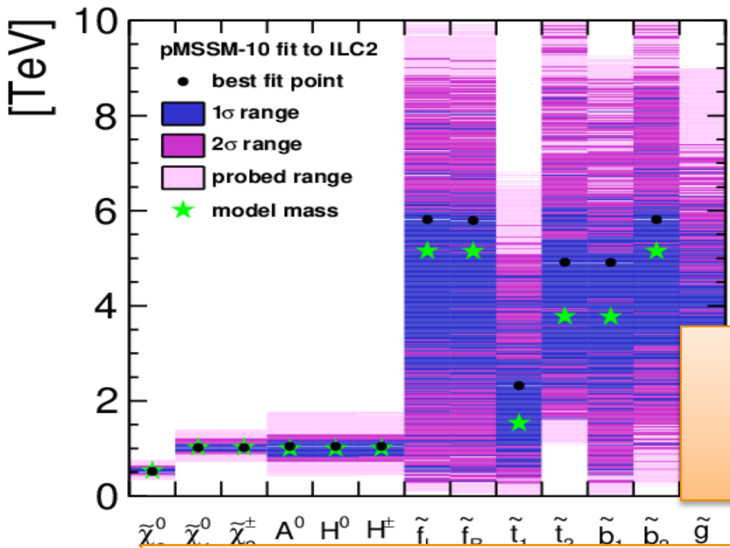


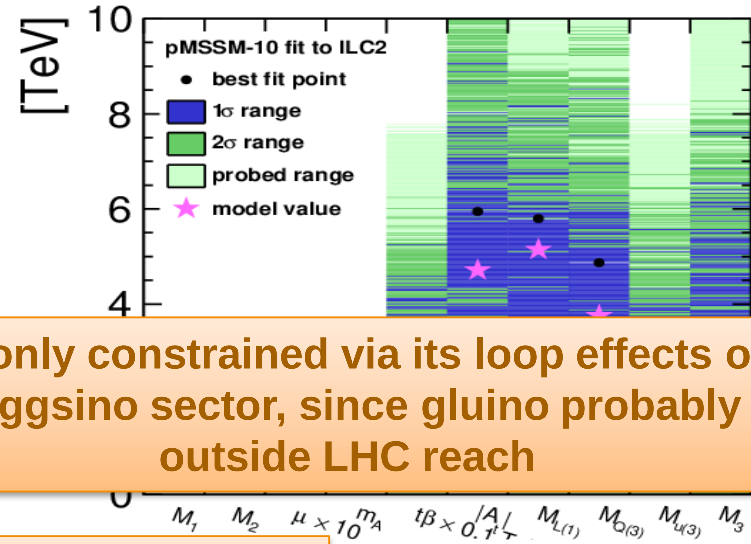


Fitting fundamental parameters: Weak scale

ILC2 predictions overestimate sfermions masses but still within 1σ

pMSSM-10 ILC2

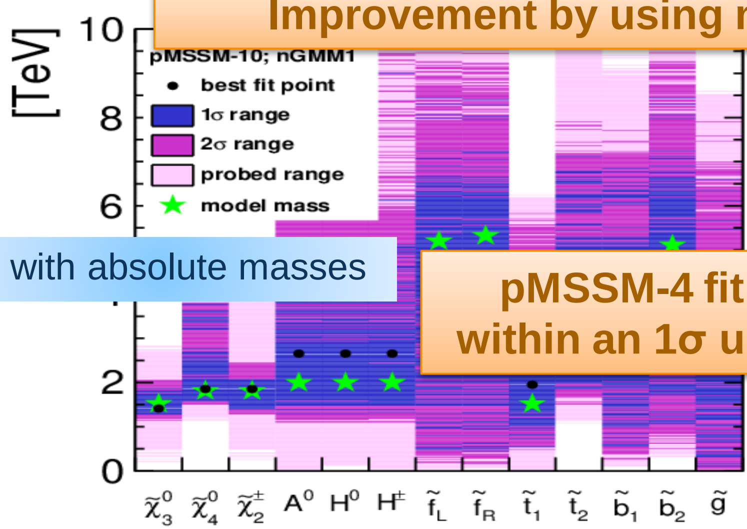


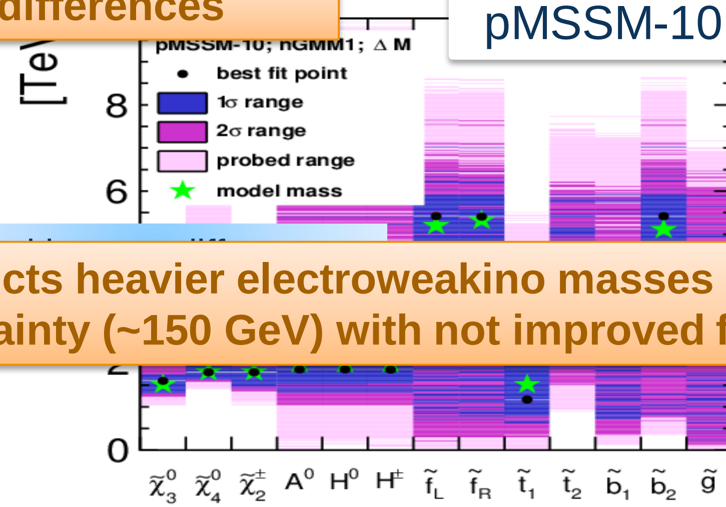


M3 only constrained via its loop effects on Higgsino sector, since gluino probably outside LHC reach

Improvement by using mass differences

pMSSM-10 nGMM1





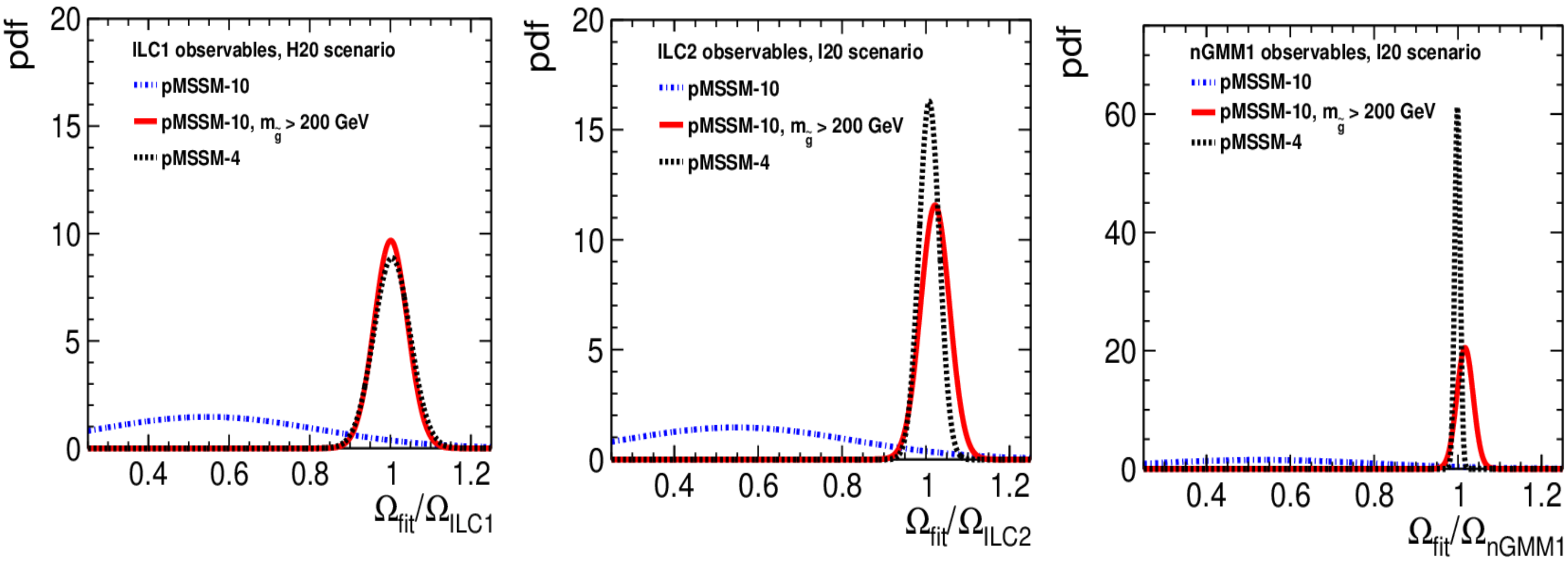
Fit with absolute masses

pMSSM-4 fit predicts heavier electroweakino masses within an 1σ uncertainty (~150 GeV) with not improved fit

Dark Matter in Higgsino fits

Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

Thermally produced WIMP relic density



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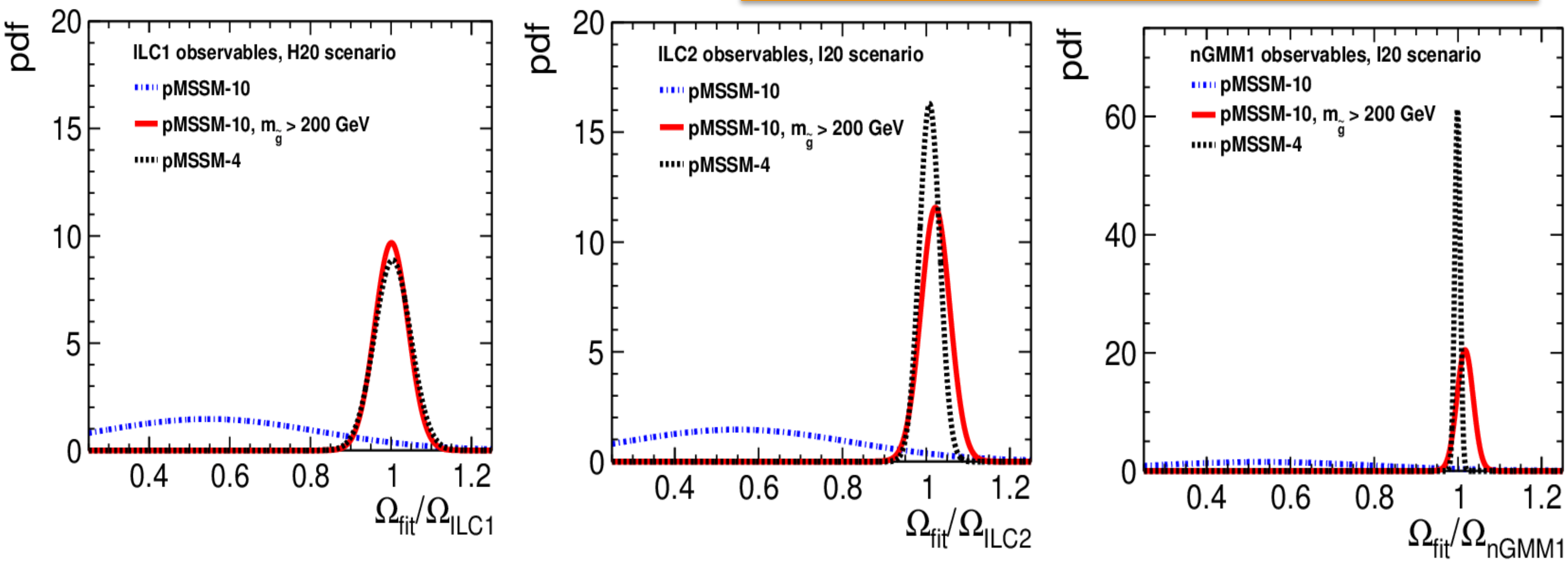
Dark Matter in Higgsino fits

Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

Thermally produced WIMP relic density

Agreement model with fit values



Such measurement would confirm possible underabundance of Higgsino-like WIMPs

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Dark Matter in Higgsino fits

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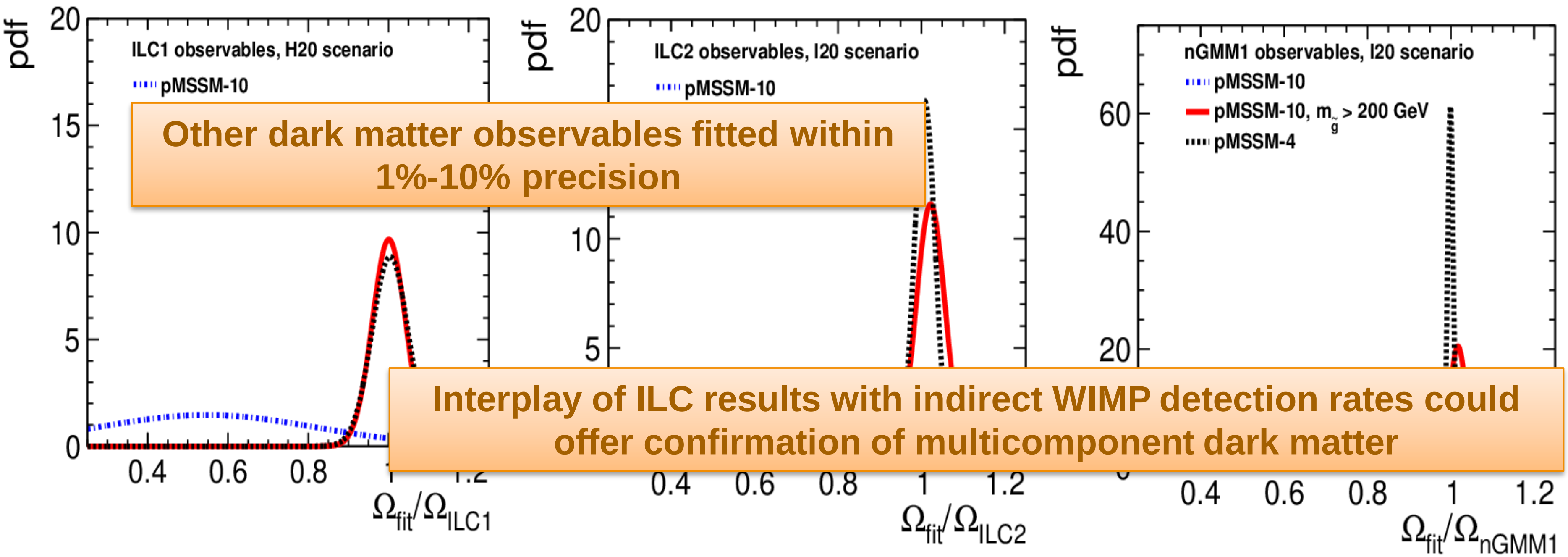

Other dark matter observables fitted within 1%-10% precision

Interplay of ILC results with indirect WIMP detection rates could offer confirmation of multicomponent dark matter

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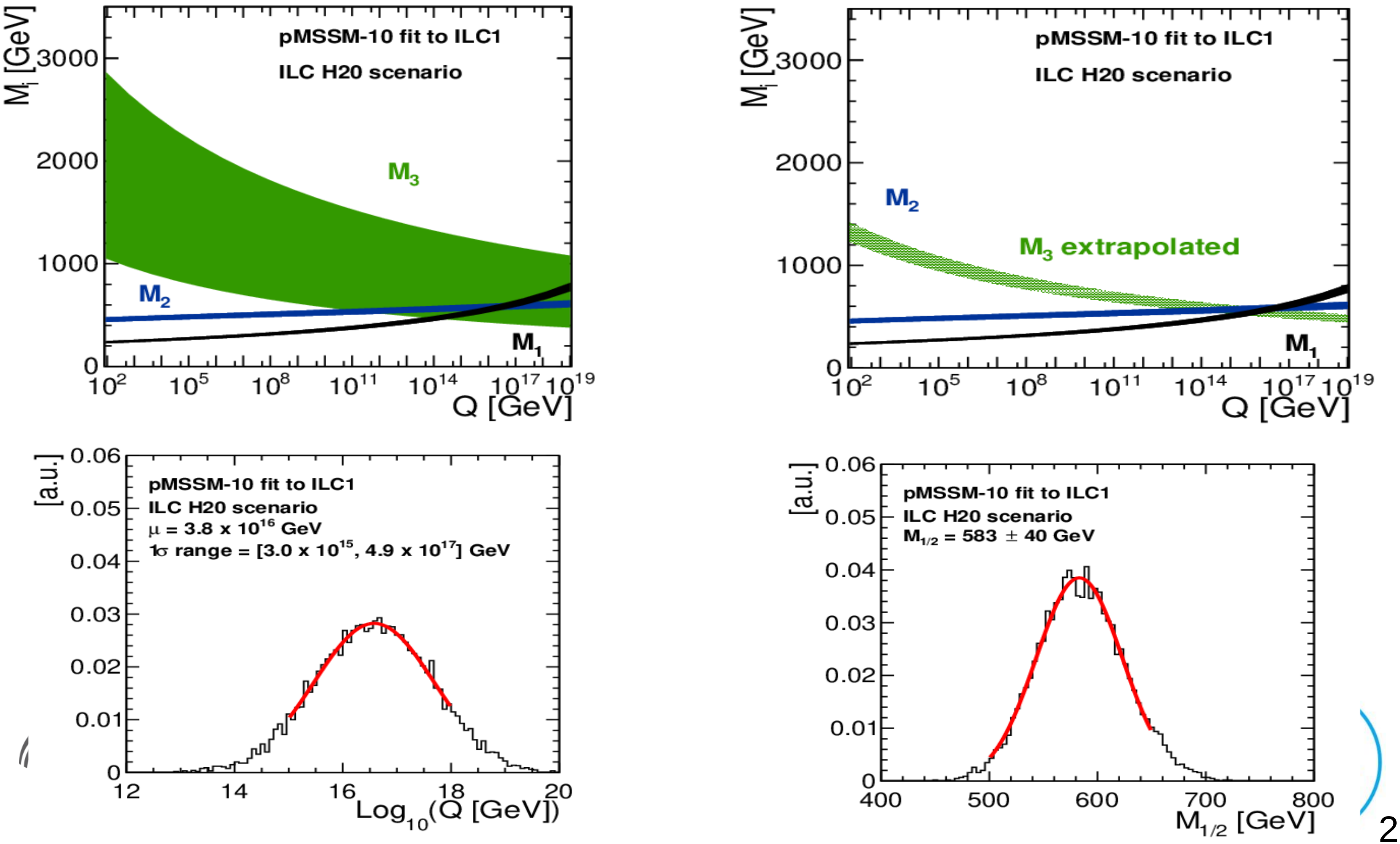
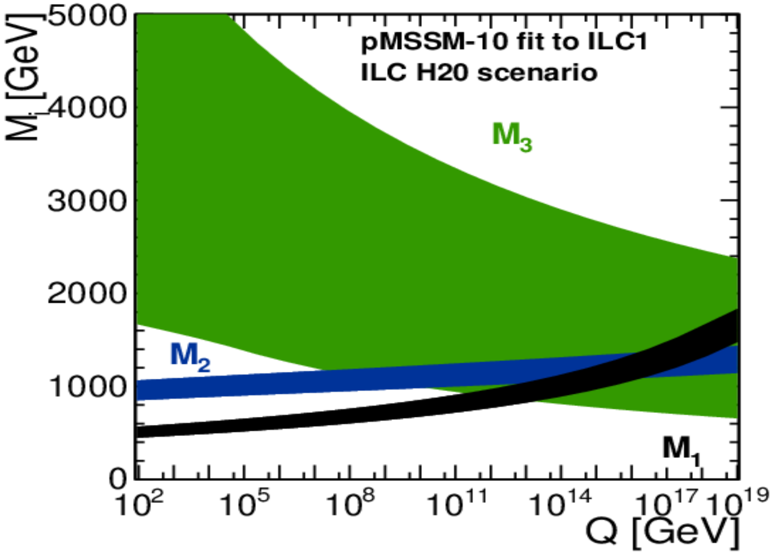
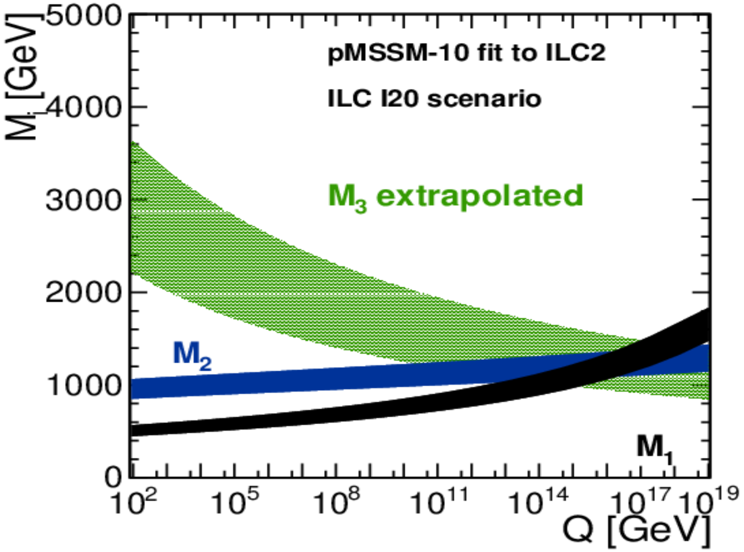
Testing gaugino mass unification: ILC1



Testing gaugino mass unification: ILC2



Assuming NUHM2 model and that M3 unifies, prediction of physical gluino mass can be obtained: m_g = 2872 +/- 605 GeV



Possible to verify that M_1 and M_2 unify at GUT scale

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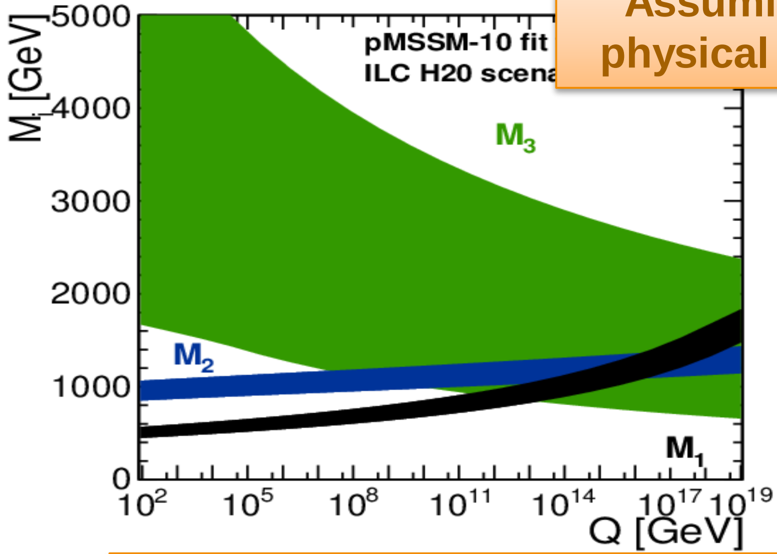

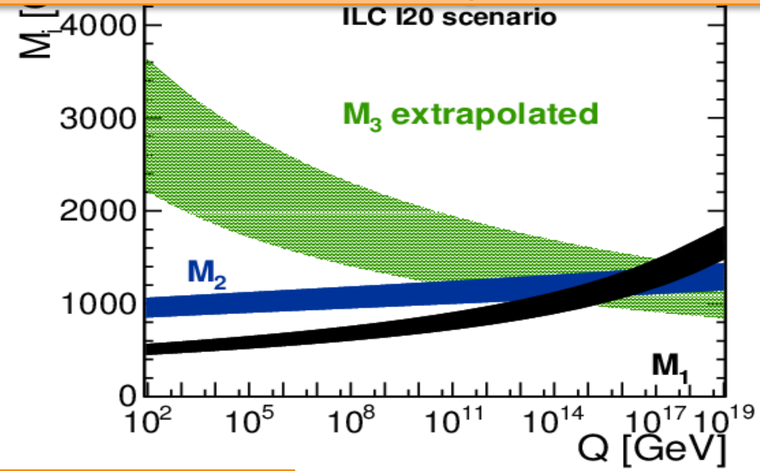

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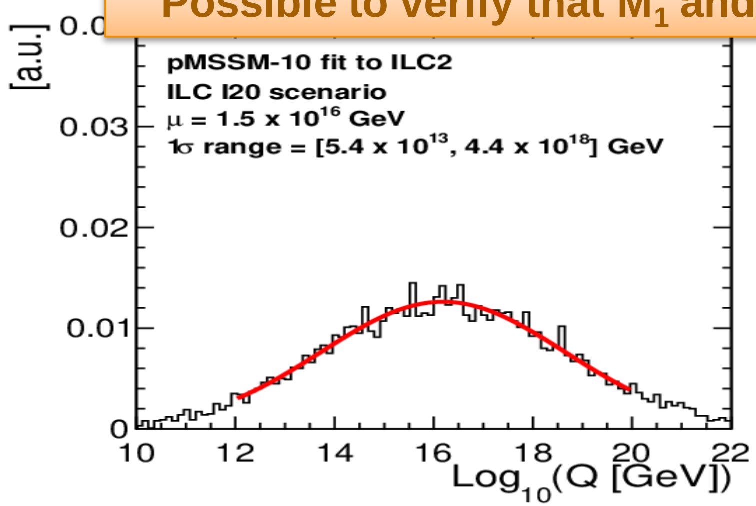
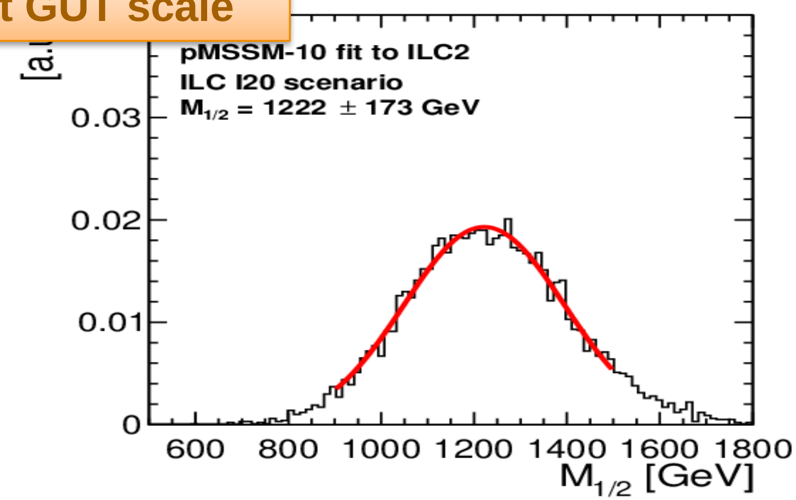
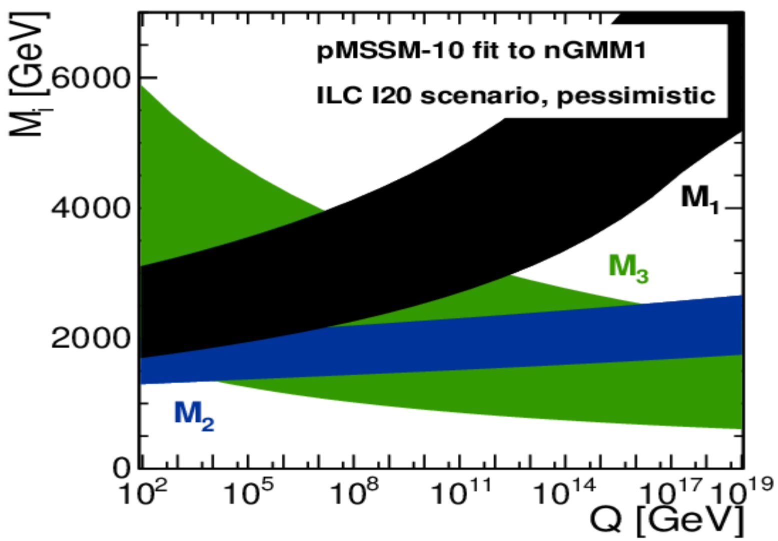
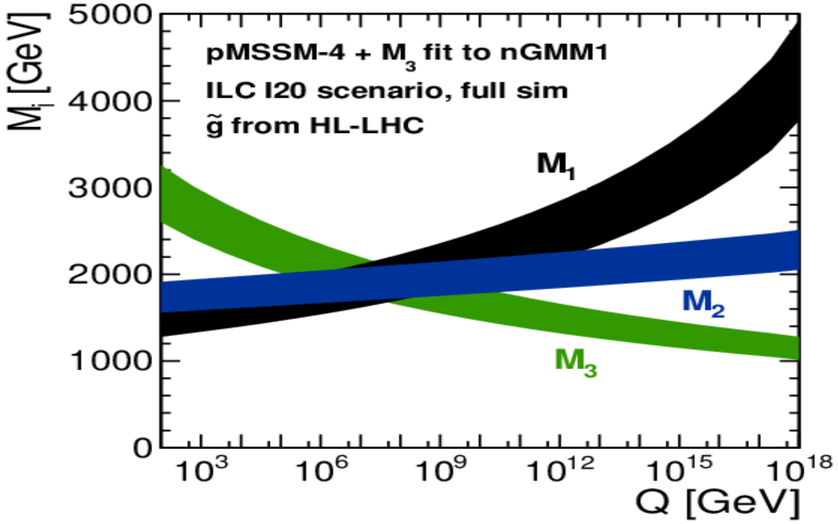
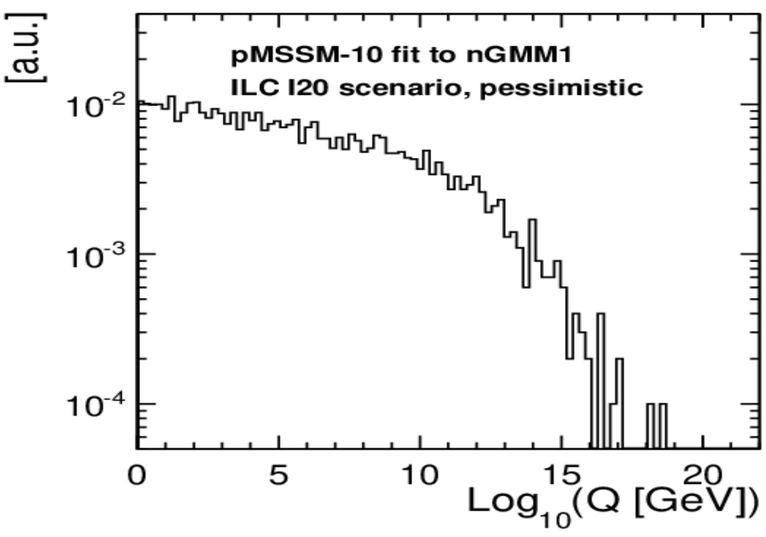


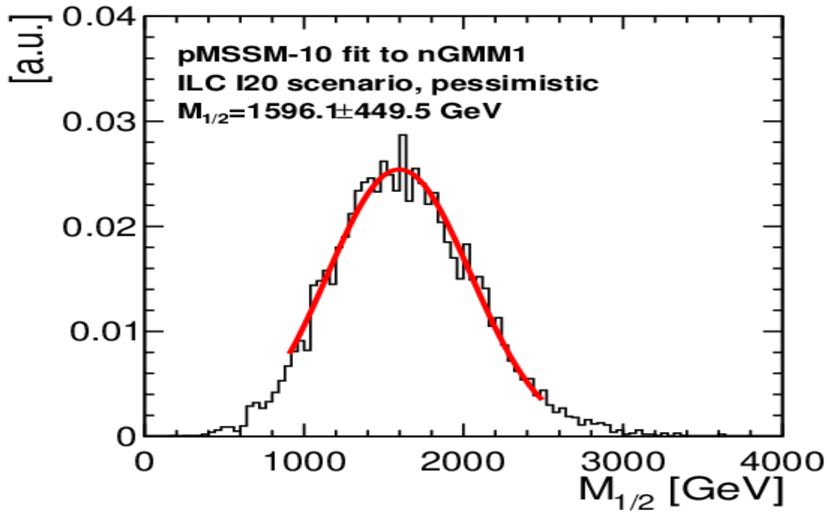


Testing gaugino mass unification: nGMM1

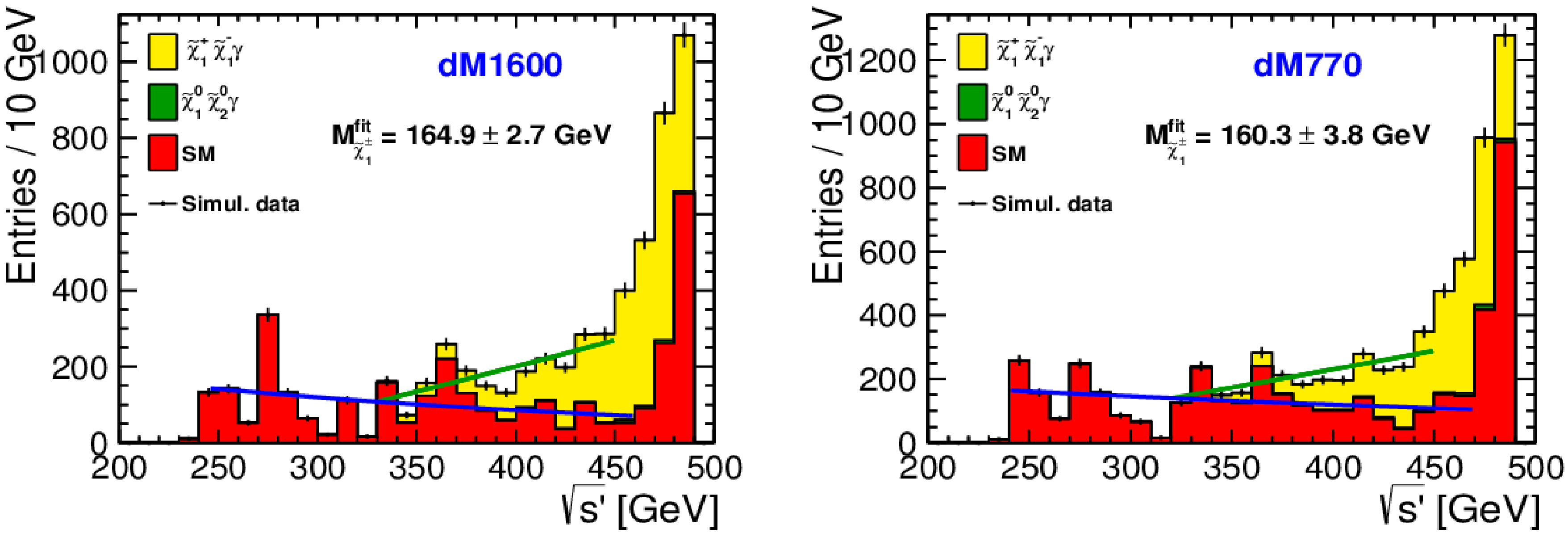








Effect of $\gamma\gamma \rightarrow$ low p_T hadron overlay on Higgsino analysis



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