

# ILC as a SUSY discovery and precision instrument

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On behalf of the ILD Concept Group



## Chargino production at the ILC

M.T. Núñez Pardo de Vera<sup>1</sup>, M. Berggren<sup>1</sup>, J. List<sup>1</sup>

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arXiv:2002.01239 [hep-ph]

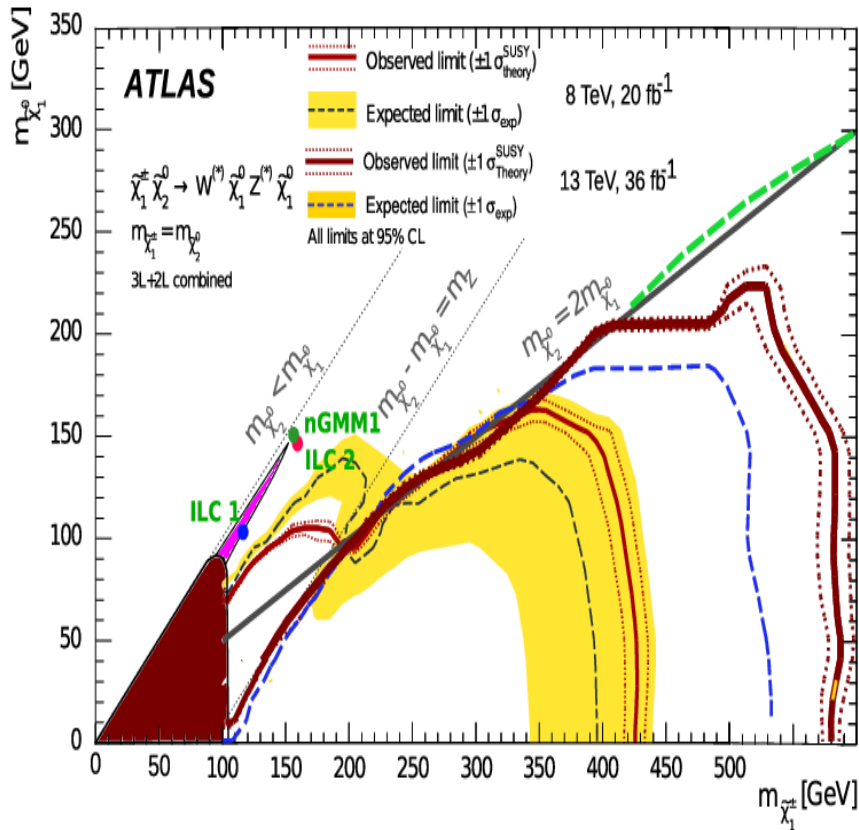
## From light Higgsinos to test of unification

H. Baer<sup>1</sup>, M. Berggren<sup>2</sup>, K. Fujii<sup>3</sup>, J. List<sup>2</sup>, S.-L. Lehtinen<sup>4,2</sup>, T. Tanabe<sup>5</sup>, J. Yan<sup>3</sup>

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# Introduction



- 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

# 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  $\sim 100$ -300 GeV

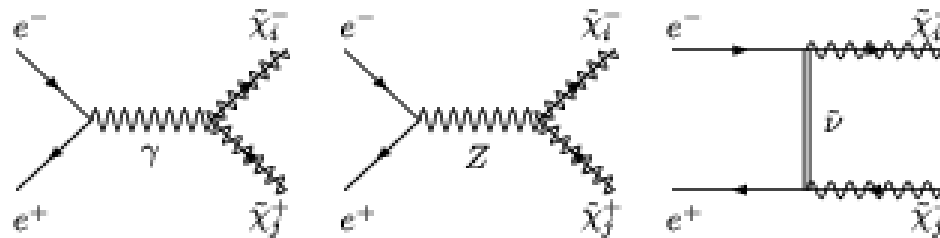
**Challenging for LHC if other sparticles are heavy... but not for ILC:**

- 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  $4\pi$  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)



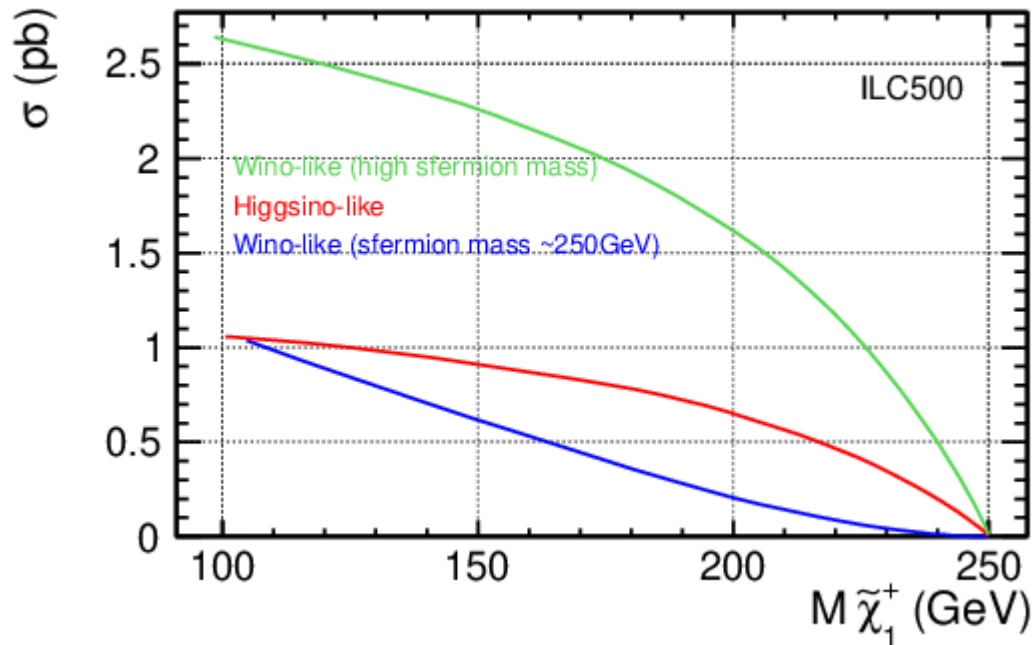
Cross section studies divided depending on:

- chargino mixing: Higgsino-like, Wino-like and Mixed charginos
- sneutrino mass scale: high ( $\sim 1\text{TeV}$ ), low (around kinematic limit)

# Chargino searches: cross sections

## Worst scenario for Wino and Higgsino-like charginos

Cross sections



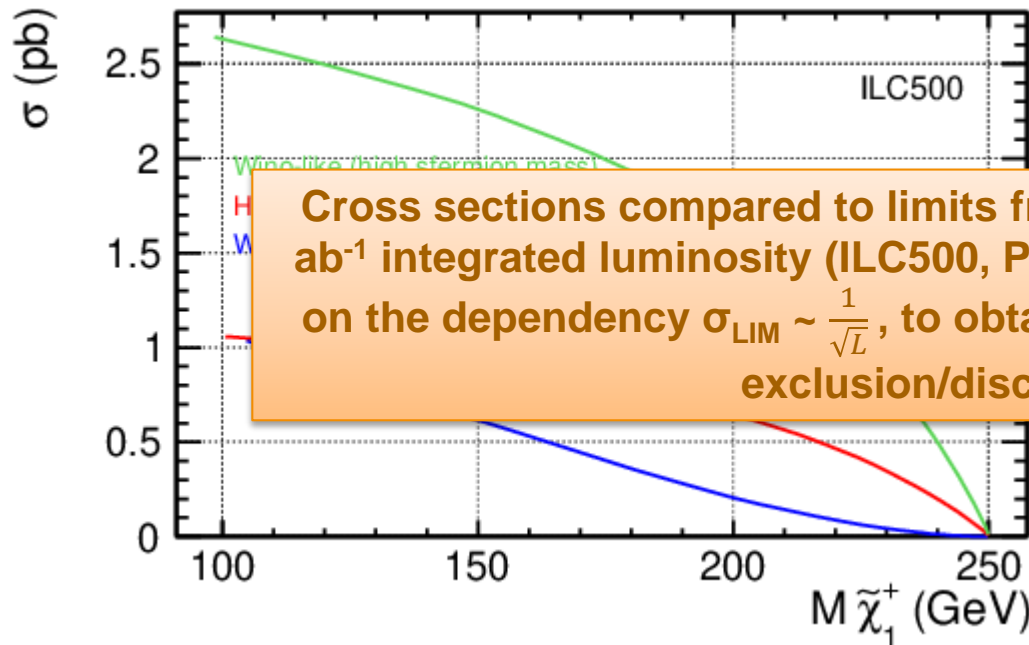
$P(e^-, e^+) = (-80\%, +30\%)$

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

# Chargino searches: cross sections

## Worst scenario for Wino and Higgsino-like charginos

Cross sections

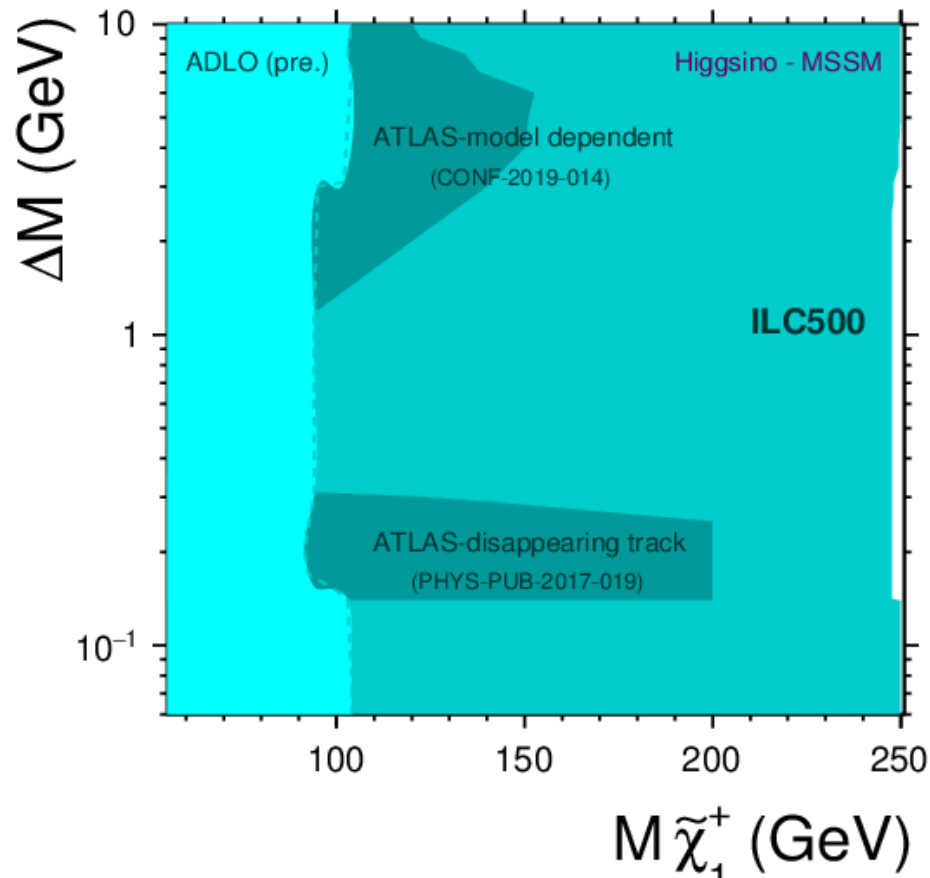


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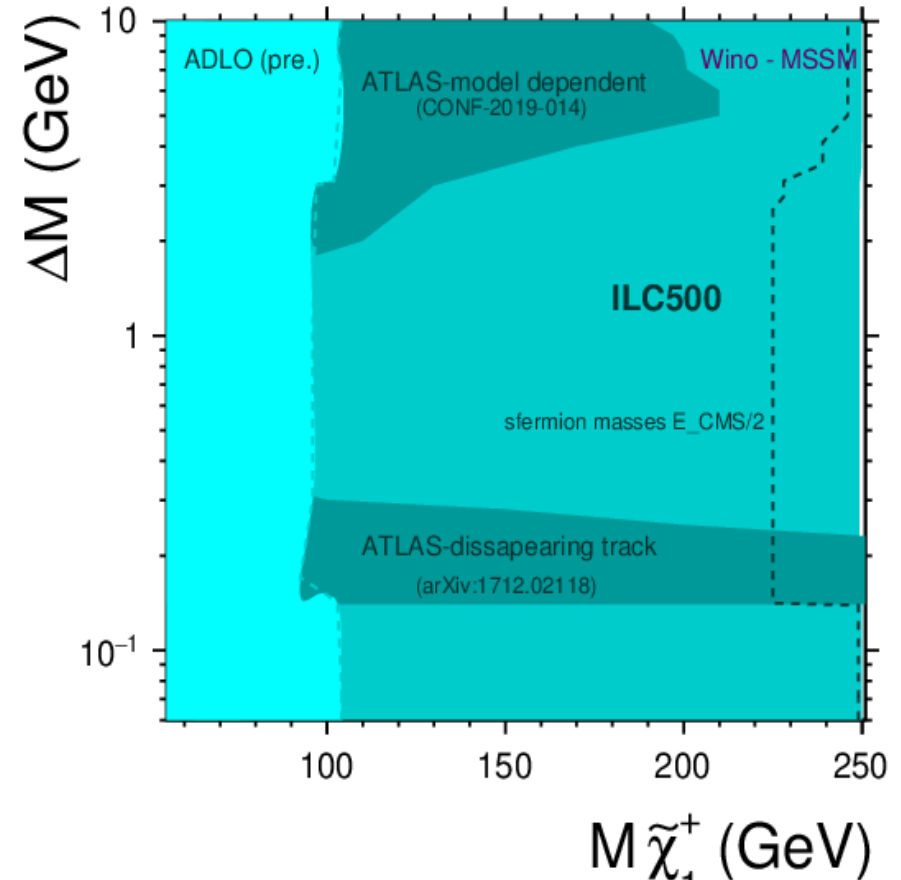
Lower efficiencies reached in Wino-like case with sfermions masses close to kinematic limit

# Chargino searches: mass exclusion limits

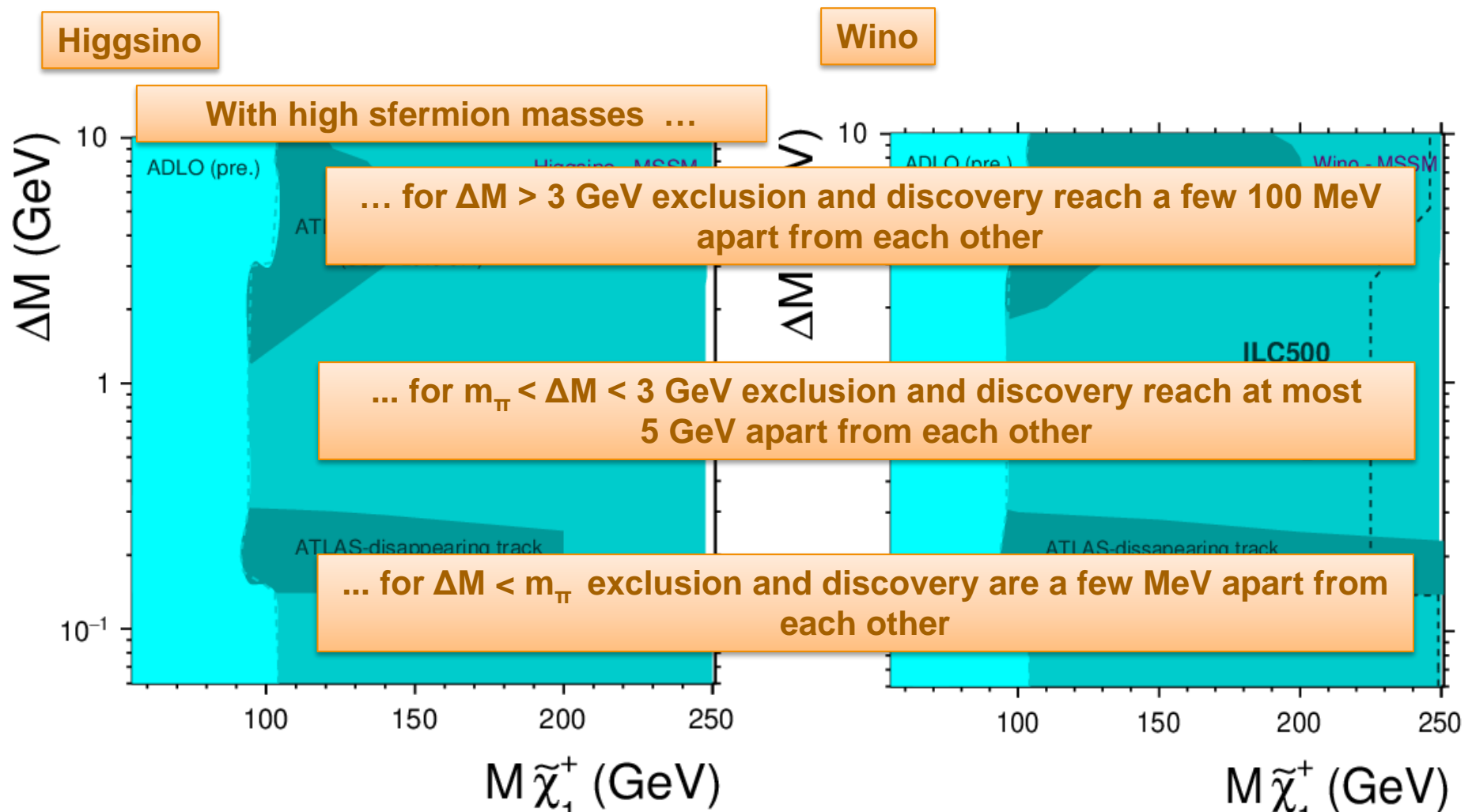
Higgsino



Wino



# Chargino searches: mass exclusion limits





# Chargino searches: mass exclusion limits

Higgsino

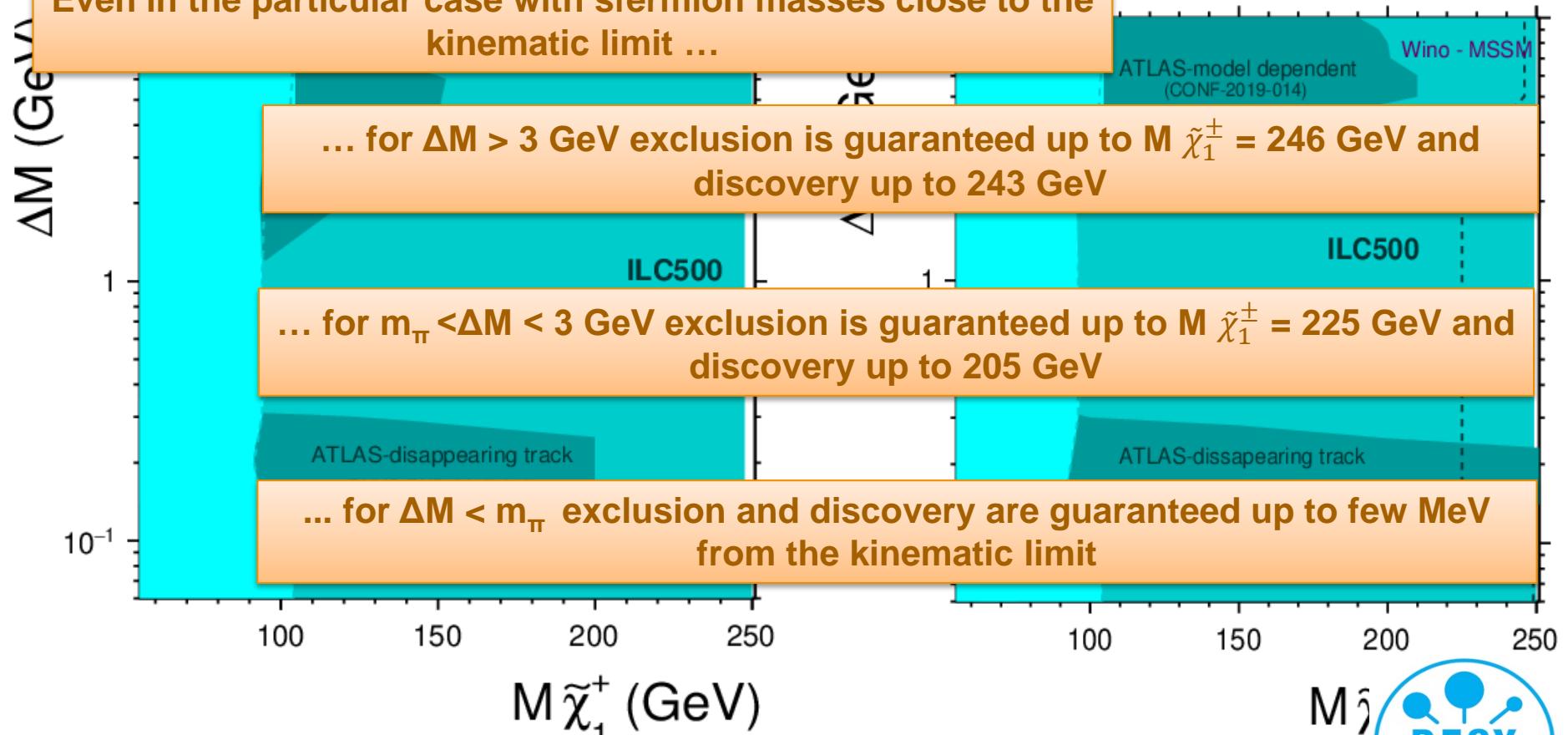
Wino

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

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

... for  $m_\pi < \Delta M < 3 \text{ GeV}$  exclusion is guaranteed up to  $M_{\tilde{\chi}_1^\pm} = 225 \text{ GeV}$  and discovery up to 205 GeV

... for  $\Delta M < m_\pi$  exclusion and discovery are guaranteed up to few MeV from the kinematic limit



$M_{\tilde{\chi}_1^\pm} \text{ (GeV)}$

$M_{\tilde{\chi}_1^\pm}$

# 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 (**increase chargino pair production cross sections**)
- 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 discoveryThe 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 into the nature of dark matter and cosmology

## Three benchmark scenarios

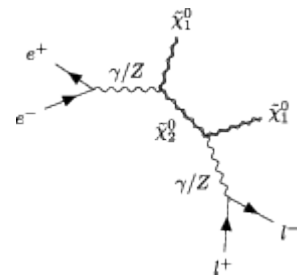
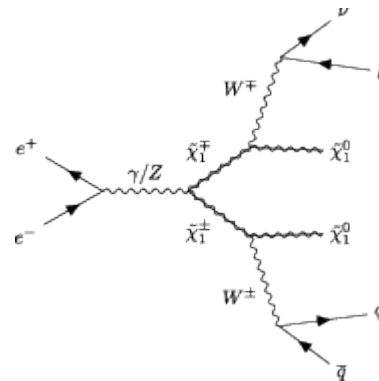
### ILC1 & ILC2:

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

### nGMM1:

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

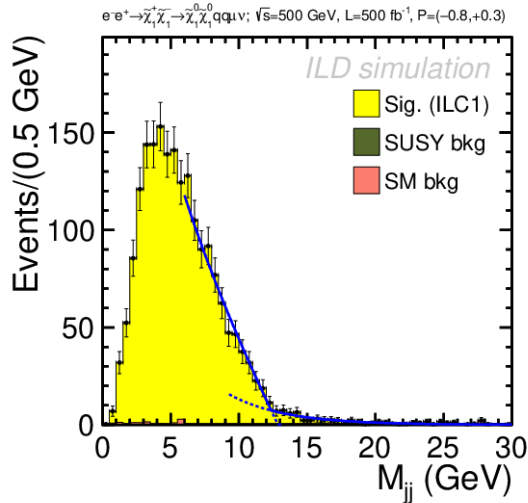
## Two channels



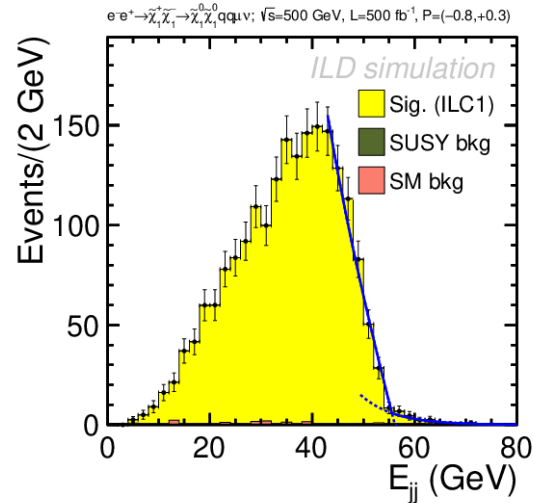
Light Higgsino masses  $\sim 150$  GeV and mass differences 4-20 GeV

# Direct measurement of masses and cross sections

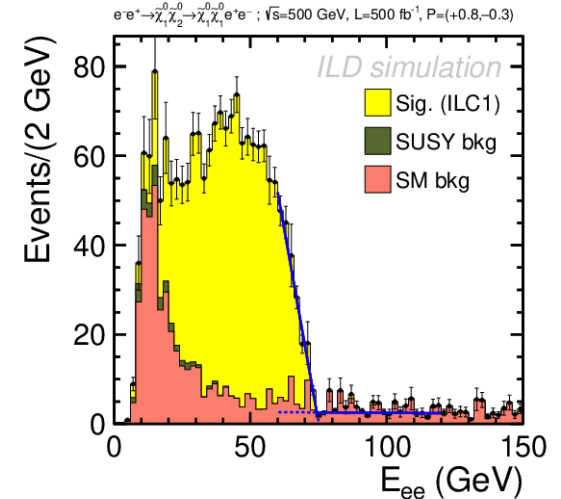
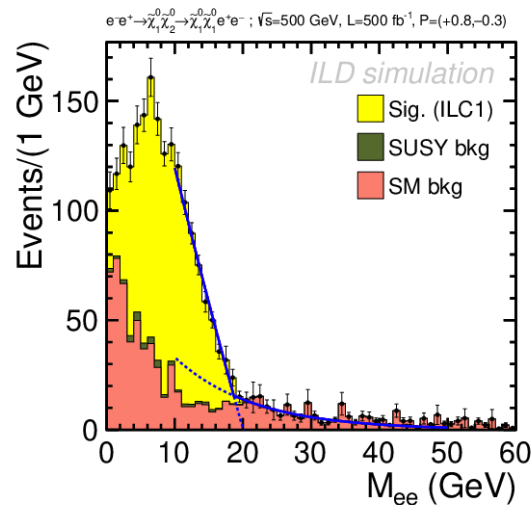
Extracted from kinematic distributions in both channels under study



Neutralino channel

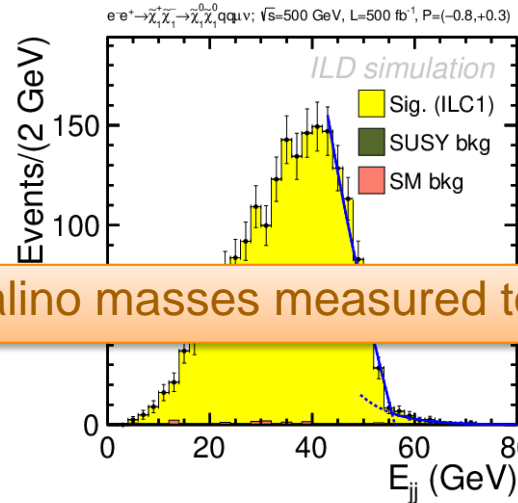
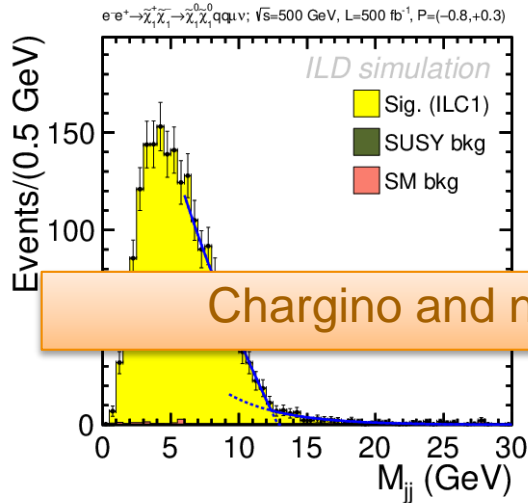


Chargino channel



# Direct measurement of masses and cross sections

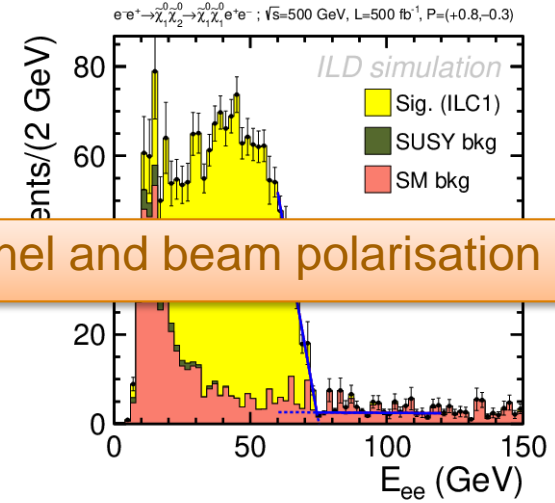
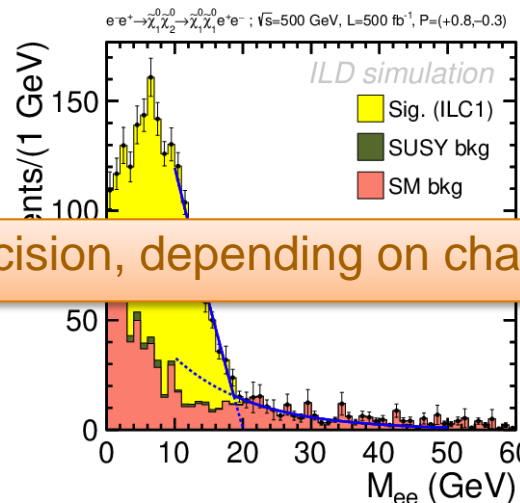
Extracted from kinematic distributions in both channels under study



Chargino channel

Chargino and neutralino masses measured to less than 1% precision

Neutralino channel



$\sigma \times$  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 and dark matter implications

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

# Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

**None of the benchmarks can be excluded as NUHM2 model**

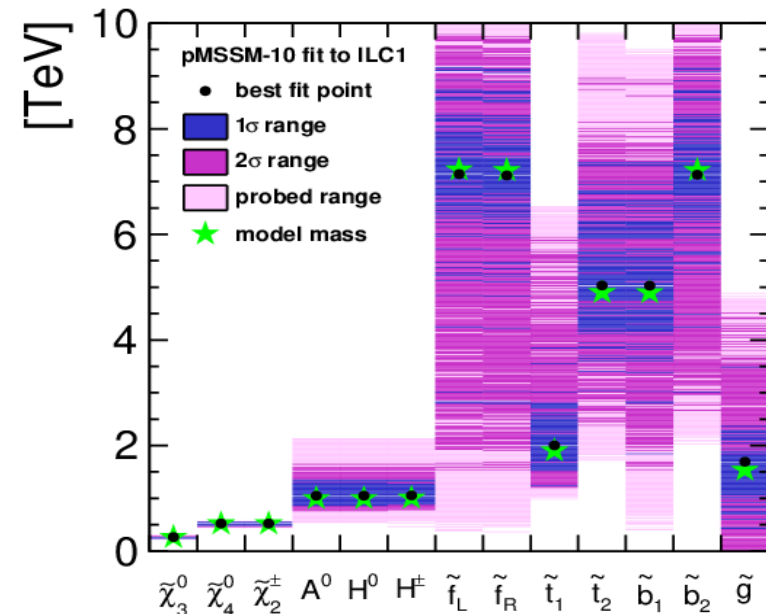
Not underlying models (NUHM1, CMSSM): interpretations ruled out at 95% CL with only 0.1 total integrated luminosity

# 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

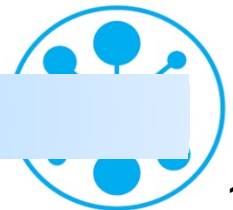
Parameters entering Higgsino sector in tree and loop level



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

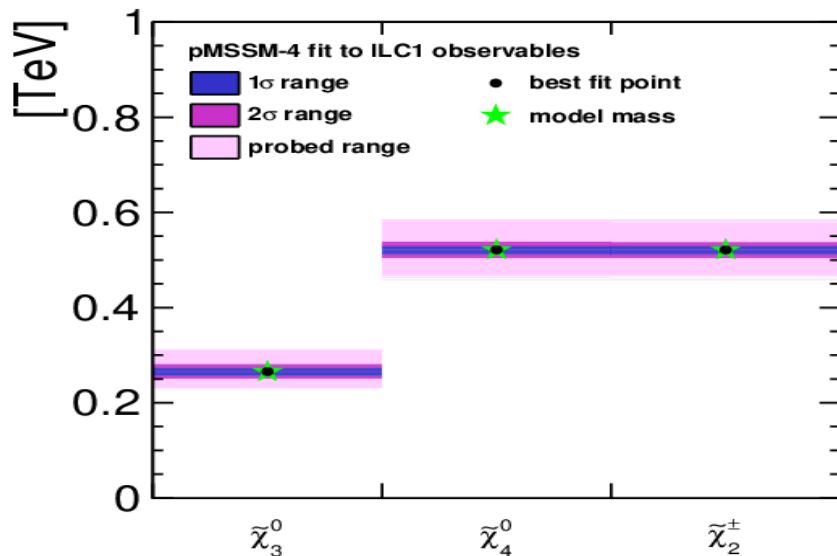




# Fitting fundamental parameters: Weak scale

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 1 $\sigma$  uncertainties

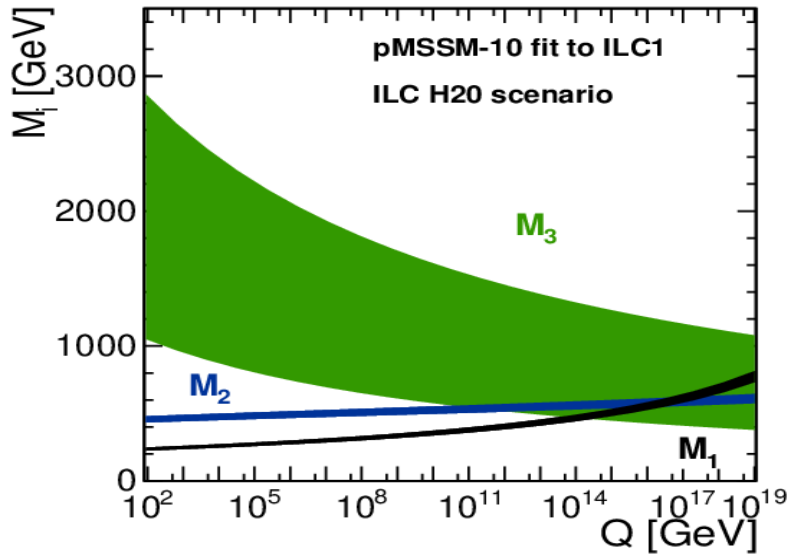
# Testing gaugino mass unification

**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

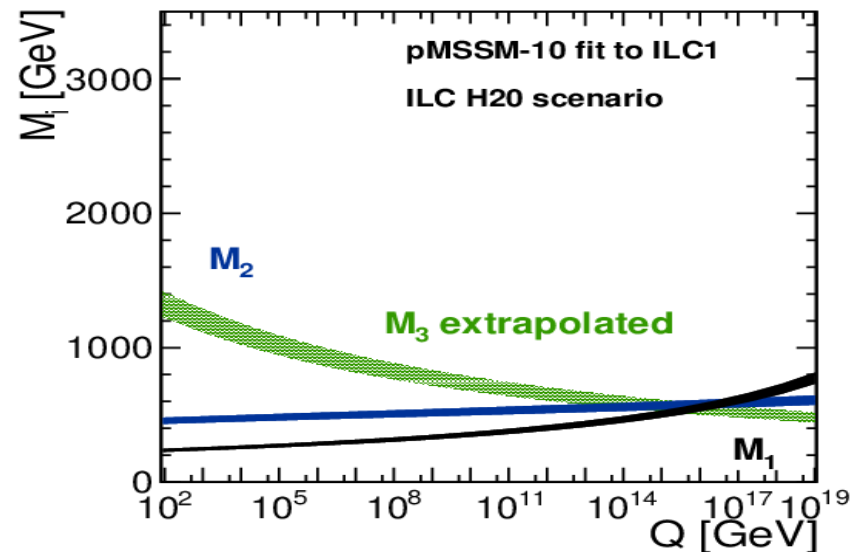
- pMSSM-10 weak scale parameters extracted at  $Q=10\text{GeV}$
- Scan around extracted values using corresponding PDF within  $\pm 1\sigma$
- Calculate running parameters at different energy scales

# Testing gaugino mass unification: ILC1

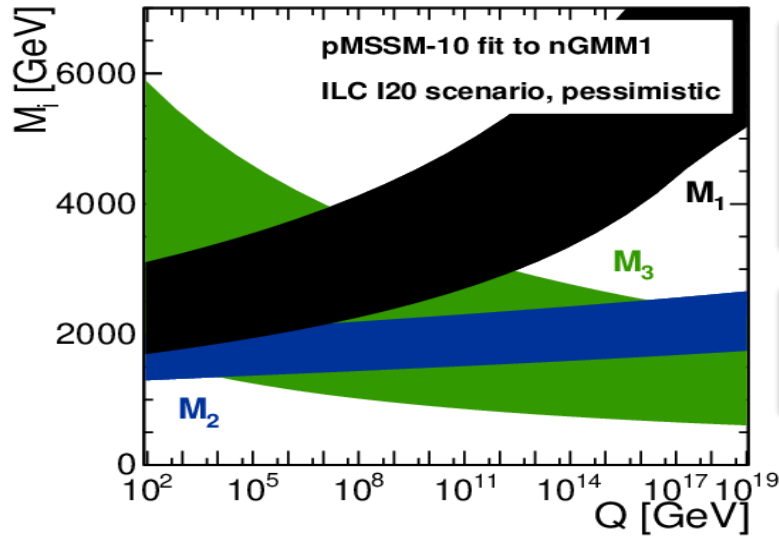


Assuming NUHM2 model, prediction of physical gluino mass can be obtained:  $m_g = 1467 \pm 80$  GeV

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



# Testing gaugino mass unification: nGMM1

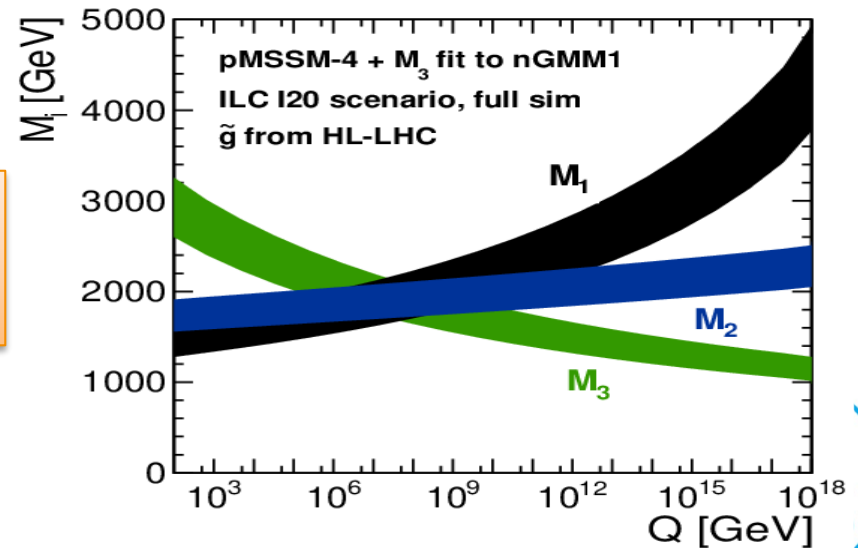


## Differences with ILC1 & ILC2:

- 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



# Conclusions

- It was shown the reach of the ILC for discovering 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 SUSY measurements can improve considerable the results of both analysis
- Interplay between ILC results and WIMP detection experiments can provide important information about the nature of dark matter and other dark matter related items

Discussion ILC talks presented at ICHEP 2020 (Jul 31, 16:00 MESZ)

<https://stanford.zoom.us/j/99671238654?pwd=M2V2RCtYbTFrVi9Ub01kckh3WFVoZz09>

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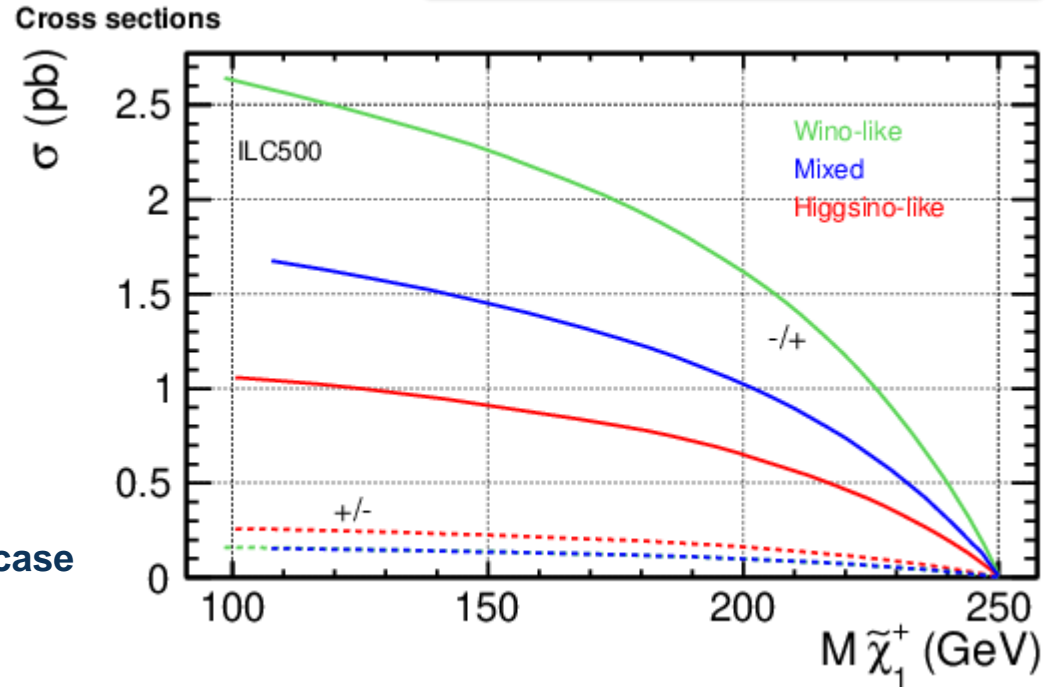
# Backup slides

# Chargino searches: cross sections

High sfermion masses

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

Lower cross sections for Higgsino-like case



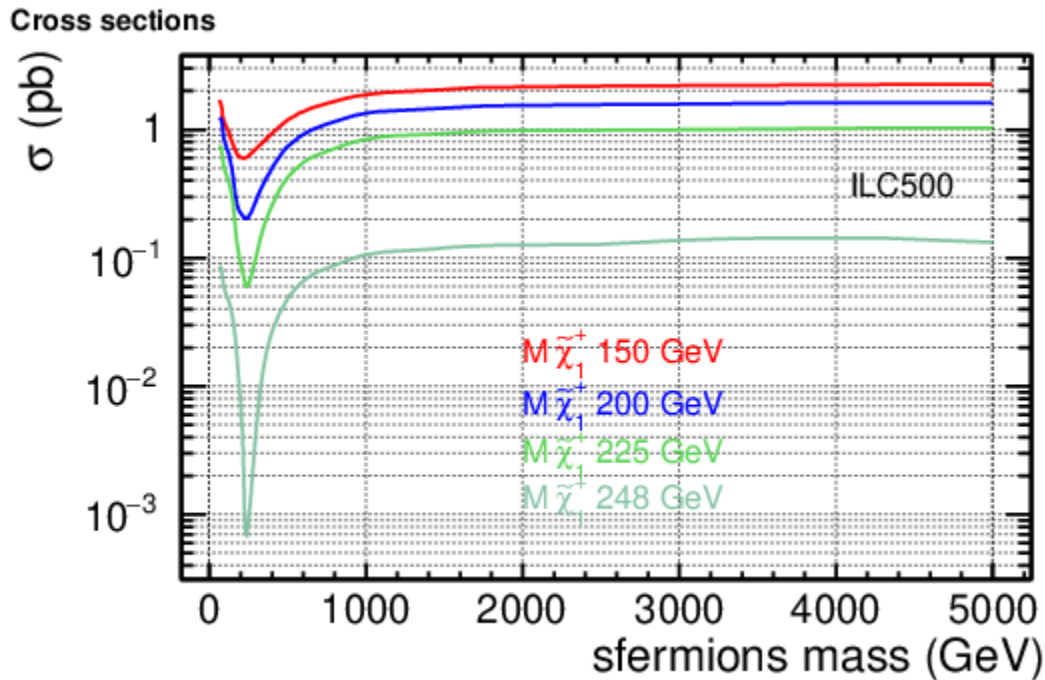
+/-  $\rightarrow$   $P(e^-,e^+) = (-80\%, +30\%)$

-/+  $\rightarrow$   $P(e^-,e^+) = (+80\%, -30\%)$

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

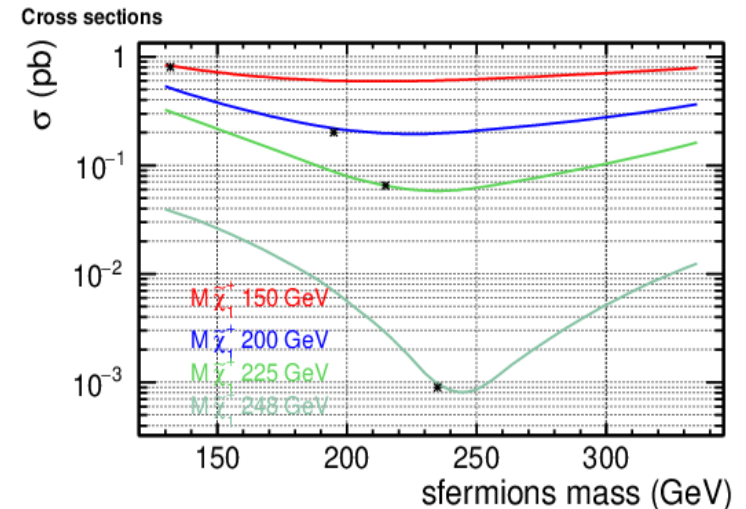
# Chargino searches: cross sections

## 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





# Chargino searches: extrapolated data

## Combined LEP chargino studies

- Data taken at up to  $\sim 208$  GeV center-of-mass energy, accumulated luminosity  $\sim 800 \text{ pb}^{-1}$
- No signal found, limits derived at 95%CL in the context of MSSM (R parity conservation) focused in the region with small  $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{\text{LSP}}$
- 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  $W^*$  ( $\Delta M > 3\text{GeV}$ )
  - soft decays with a ISR requested on trigger ( $\pi \text{ mass} < \Delta M < 3\text{GeV}$ )
  - events with tracks displaying kinks, impact parameters offset or heavy stable charged particles ( $\Delta M < \pi \text{ mass}$ )

# Chargino searches: extrapolated data

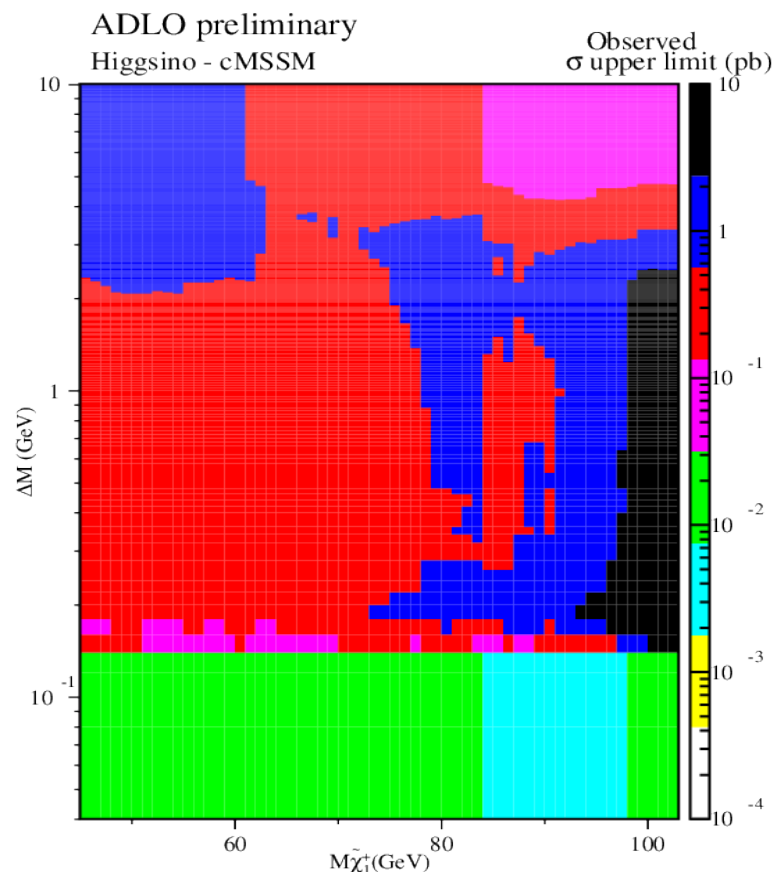
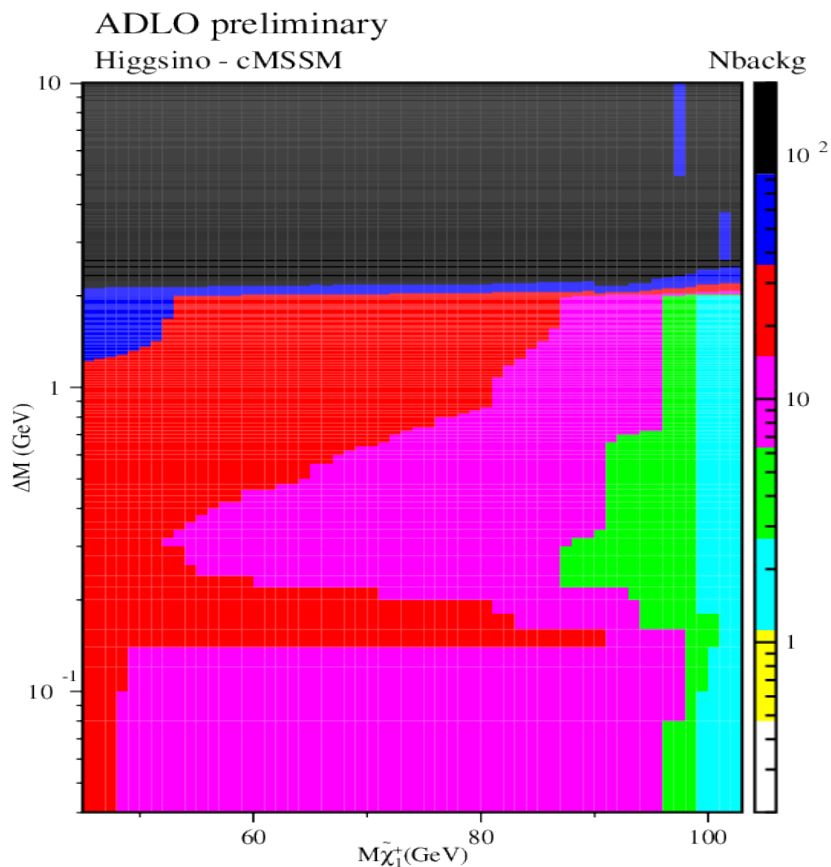
## Combined LEP chargino studies

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

# Chargino searches:

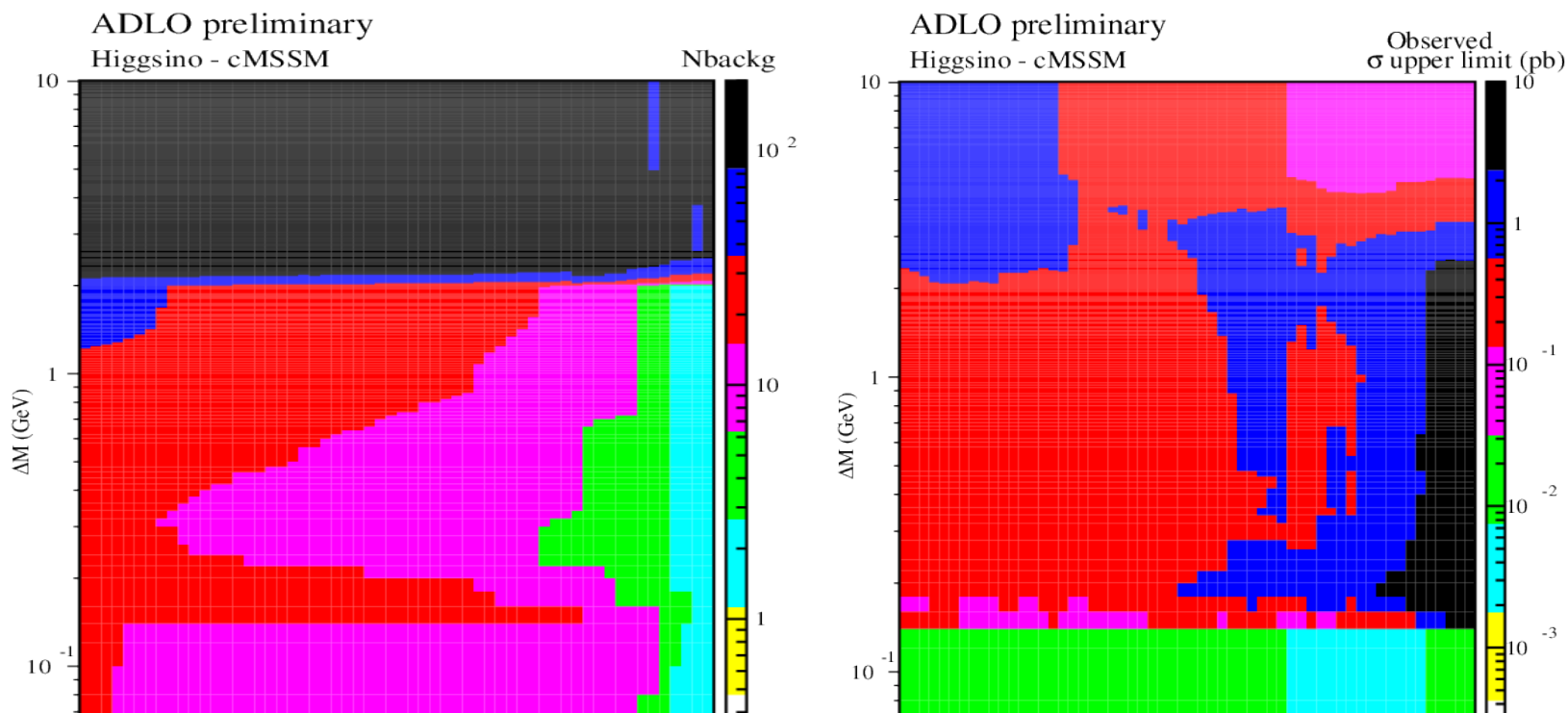
## Comparison to extrapolated limits



Low efficiency in  $\pi$  mass  $< \Delta M < 3$  GeV region due to ISR trigger requirement

# Chargino searches:

## Comparison to extrapolated limits



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

# Benchmark scenarios

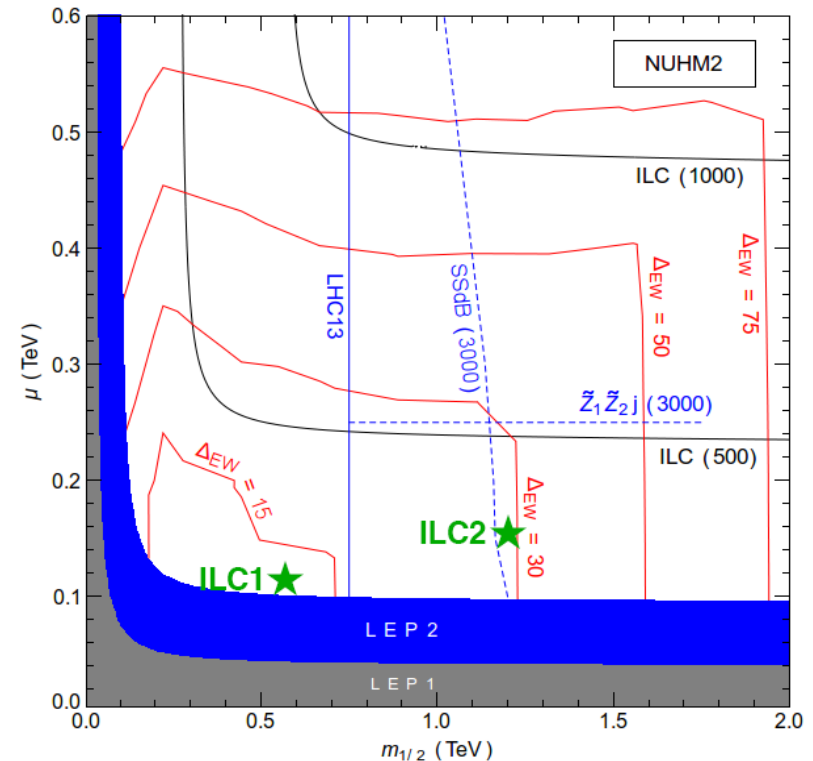
## ILC1 & ILC2:

- 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  $\sqrt{s} = 500 \text{ GeV}$   
several hundreds fb

# Software tools and observables

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

- Processes studied:

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

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

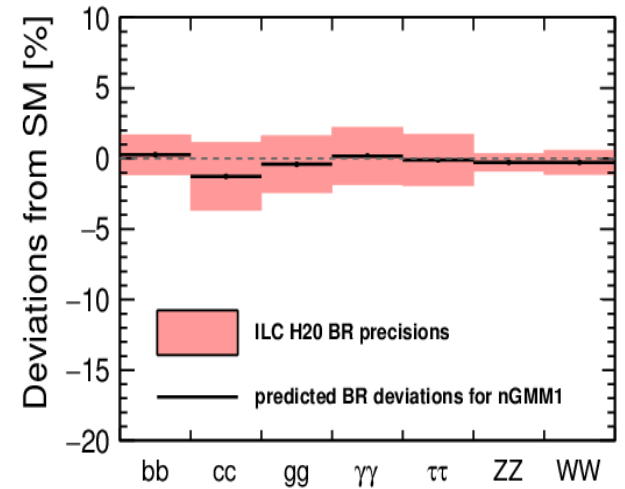
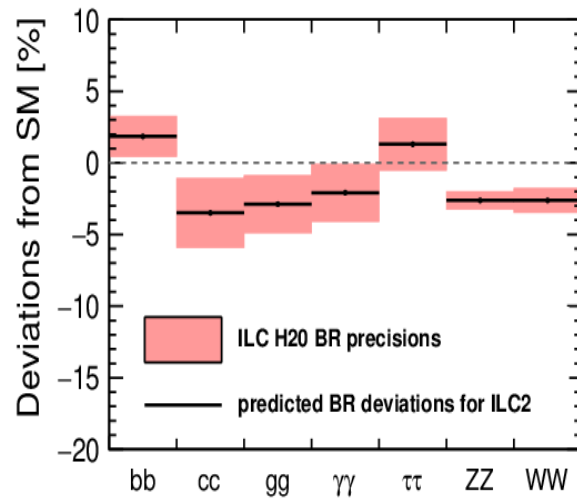
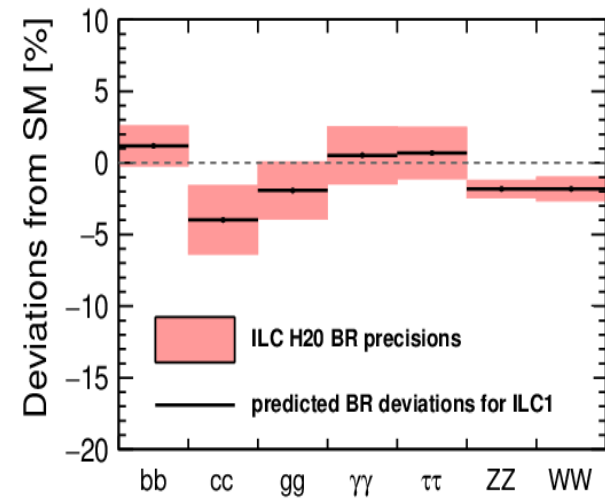
- Observables:

- 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

# Higgs branching ratios



# Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

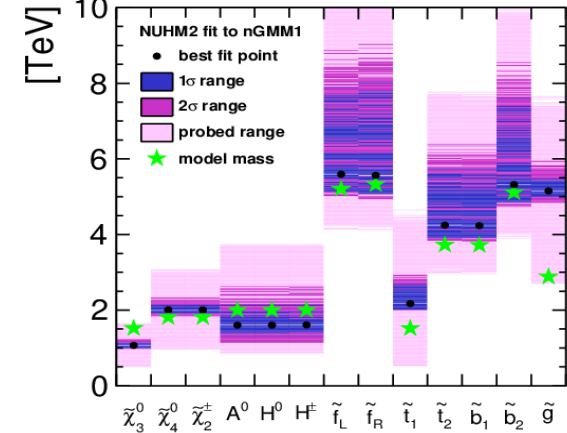
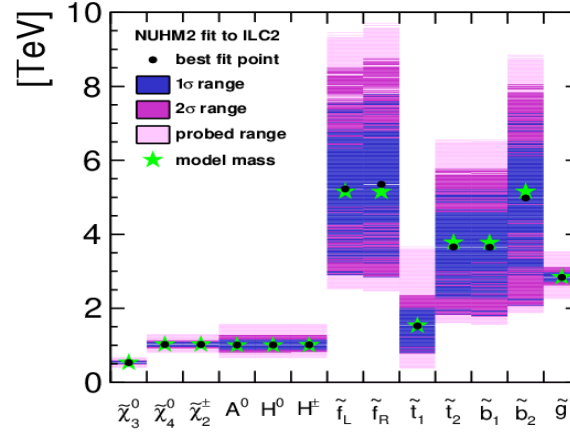
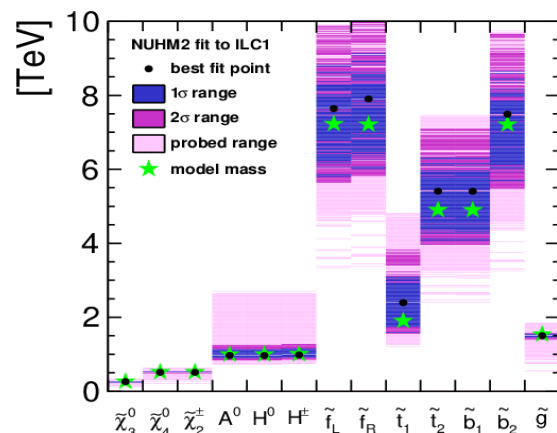
Fit to NUMH2 model

	ILC1 best fit (true)	ILC2 best fit (true)	nGMM1 best fit
$M_{1/2}$	556.7 (568.3)	1194 (1200)	2407
$\mu$	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
$\chi^2$	0.0011 (0.0013)	0.02848 (0.0007)	0.233



# Fitting fundamental parameters: predicting SUSY spectrum

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



gluino mass firmly predicted (GUT check)

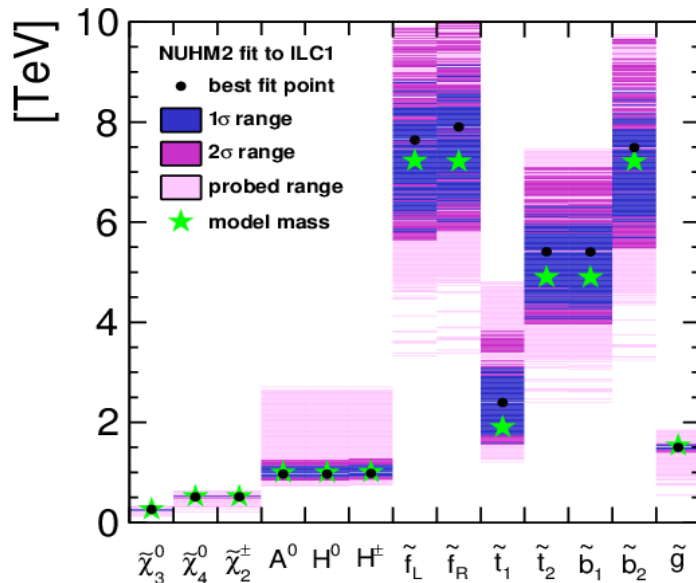
Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders



# Fitting fundamental parameters: predicting SUSY spectrum

ILC1 (GUT-scale fit)



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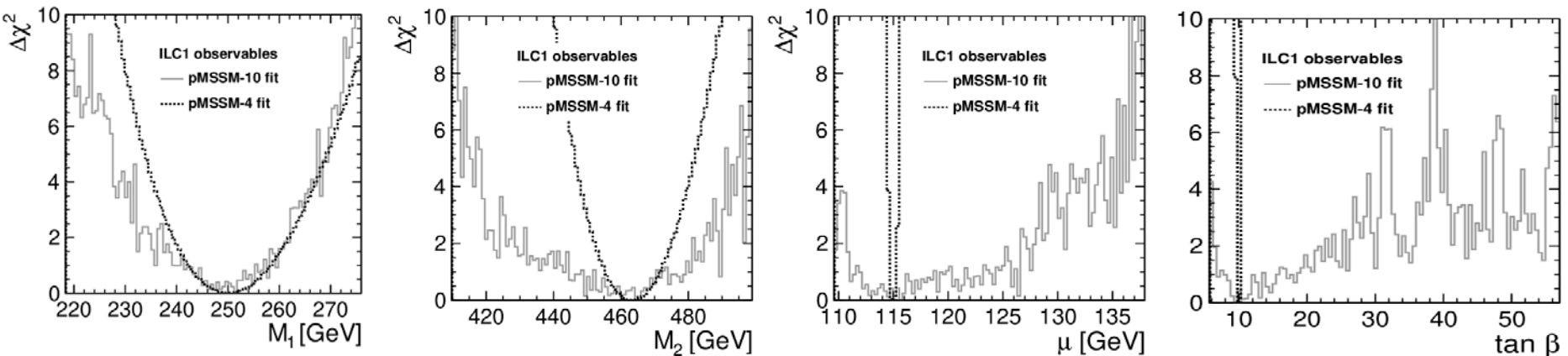
# Fitting fundamental parameters: Weak scale

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



# Fitting fundamental parameters: Weak scale

## Weak-scale parameters

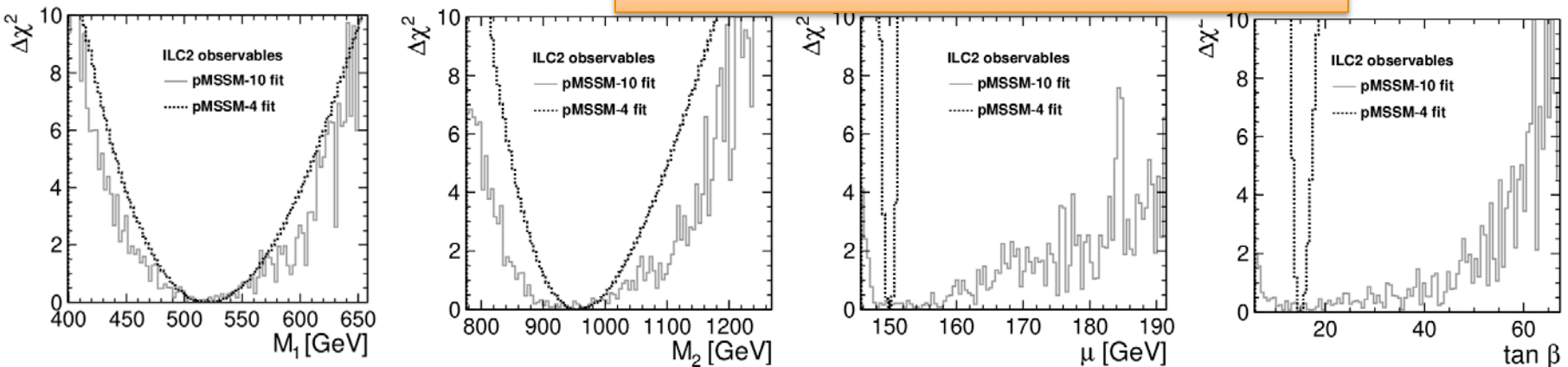
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Fit parameters Higgsino sector

ILC2

ILC2 shows same behaviour



# Fitting fundamental parameters: Weak scale

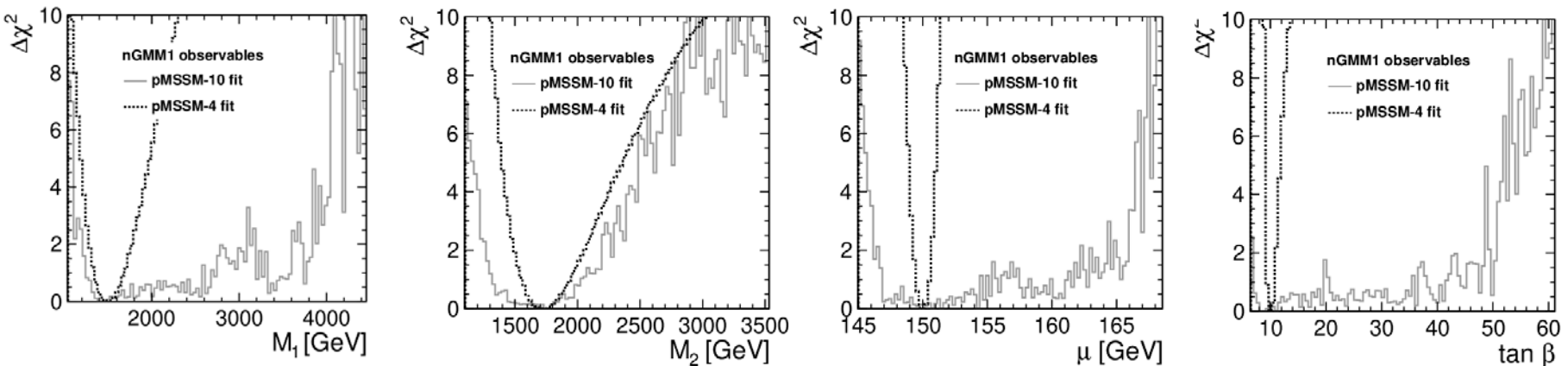
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Fit parameters Higgsino sector

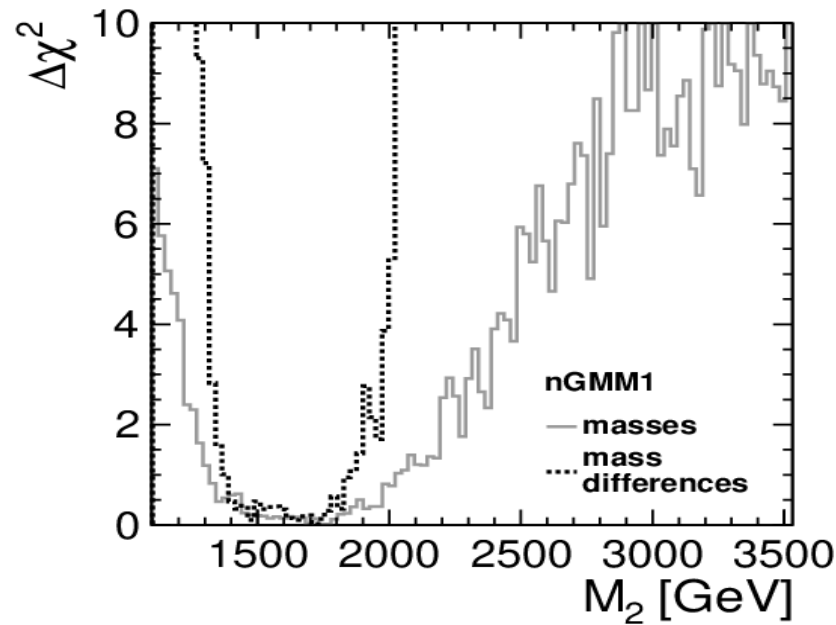
nGMM1



# Fitting fundamental parameters: Weak scale

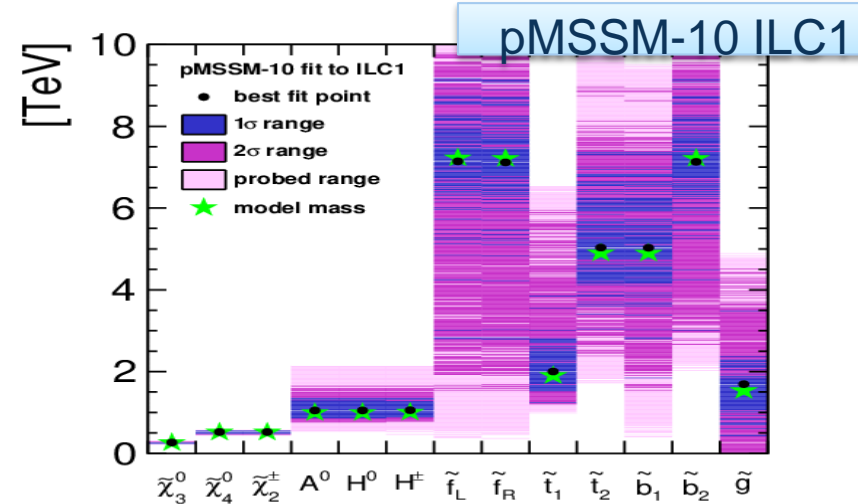
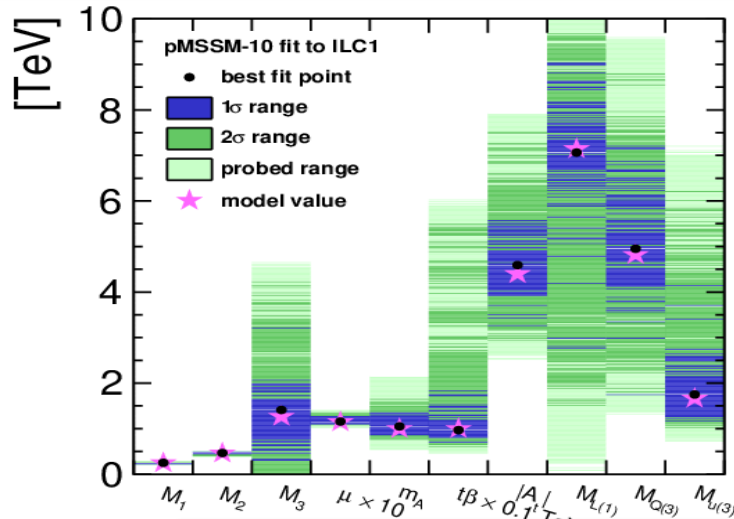
Improvement fit parameters by using mass differences

pMSSM-10 nGMM1

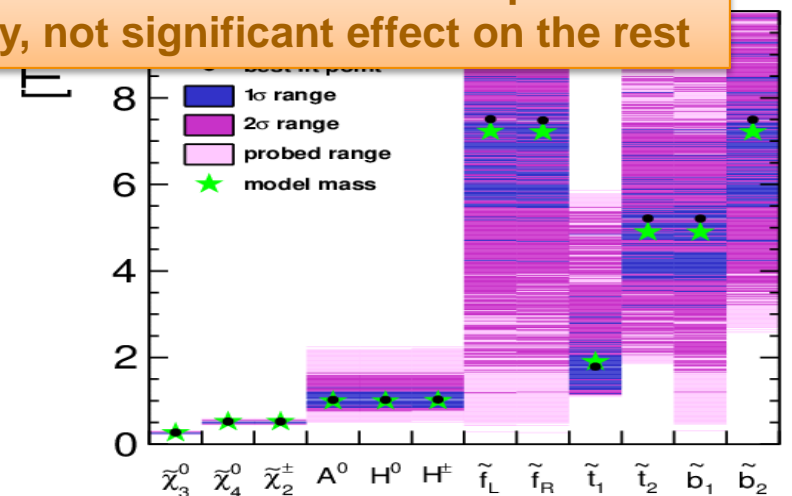
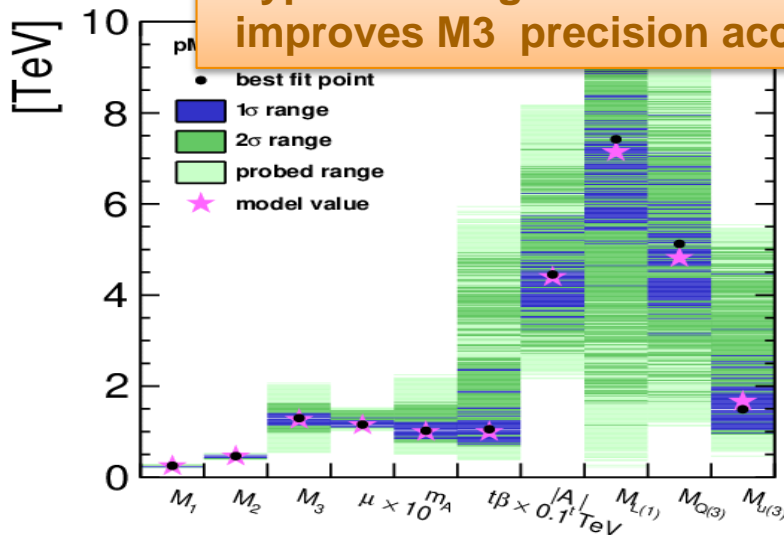


# Fitting fundamental parameters: Weak scale

Constraints for parameters of colored sector can be obtained



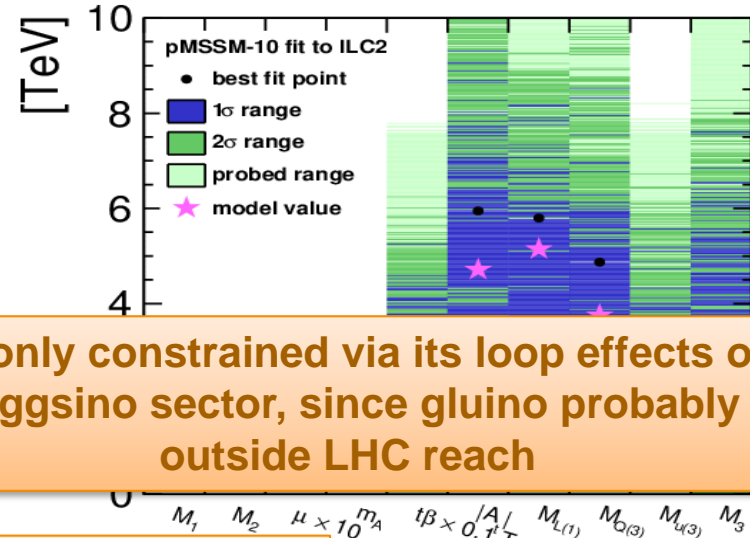
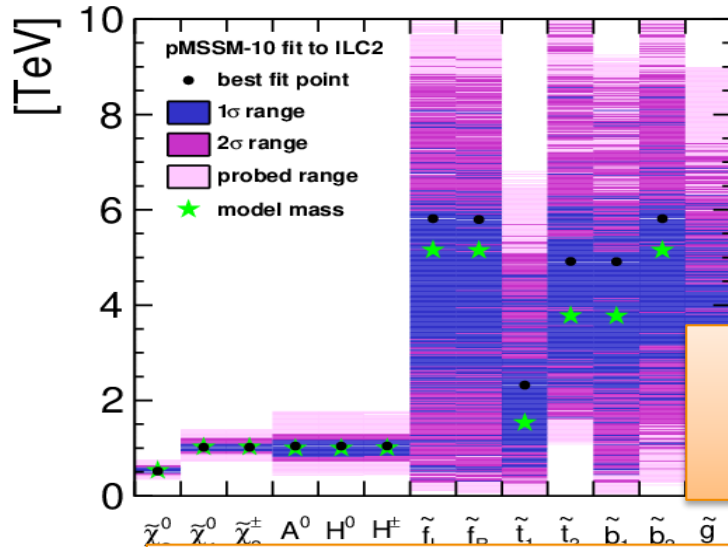
Hypothetical gluino mass measurement from LHC with 11% precision improves M3 precision accordingly, not significant effect on the rest



# Fitting fundamental parameters: Weak scale

ILC2 predictions overestimate sfermions masses but still within  $1\sigma$

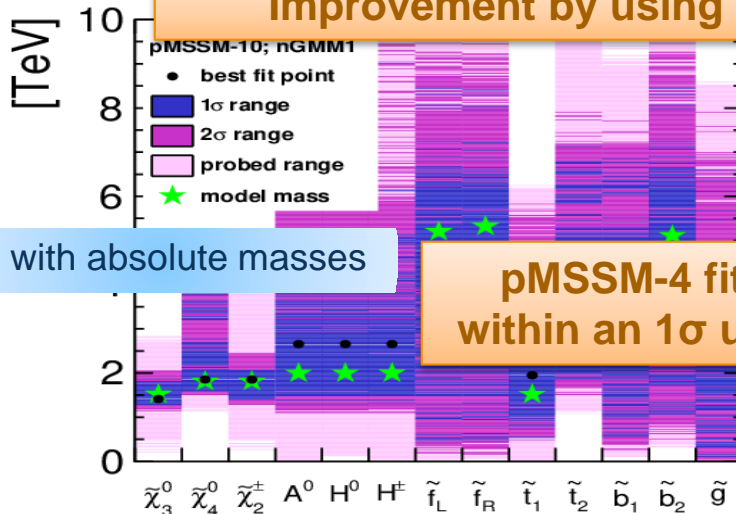
pMSSM-10 ILC2



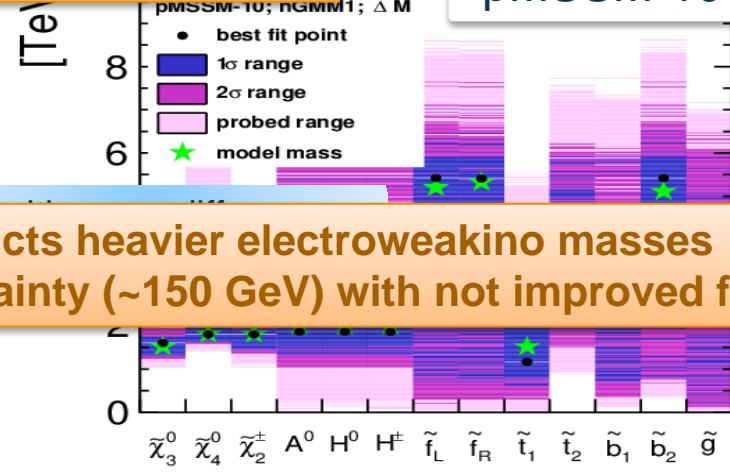
M3 only constrained via its loop effects on Higgsino sector, since gluino probably outside LHC reach

Improvement by using mass differences

pMSSM-10 nGMM1



Fit with absolute masses



pMSSM-4 fit predicts heavier electroweakino masses within an  $1\sigma$  uncertainty ( $\sim 150$  GeV) with not improved fit

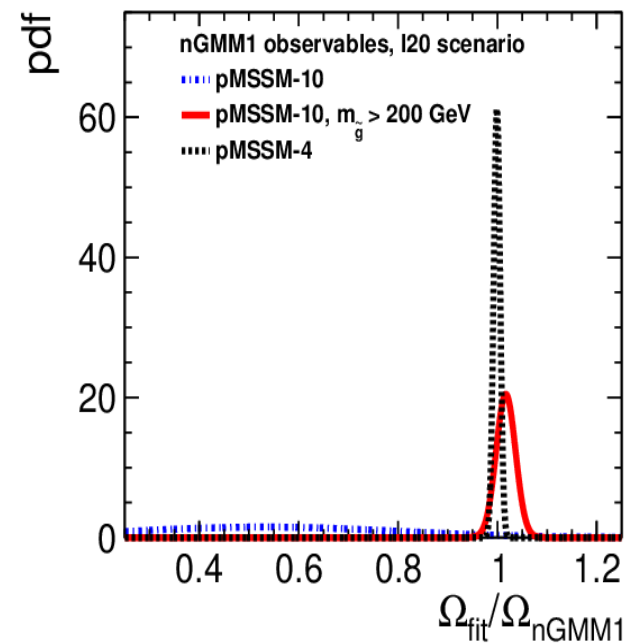
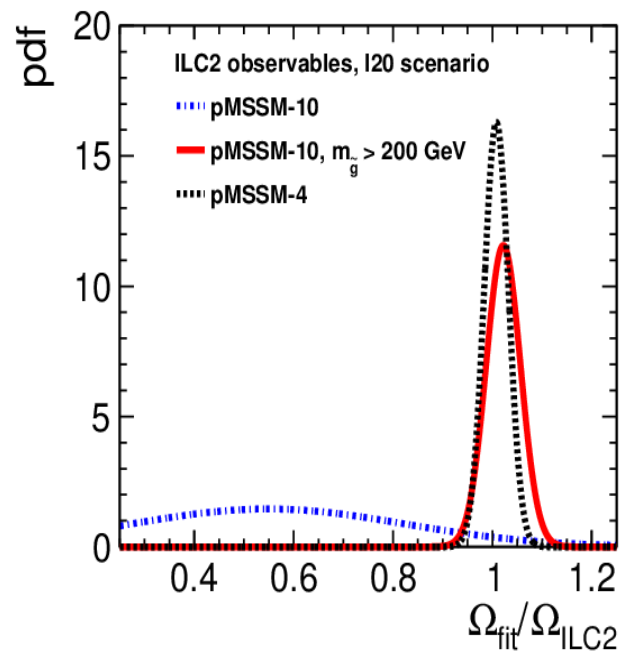
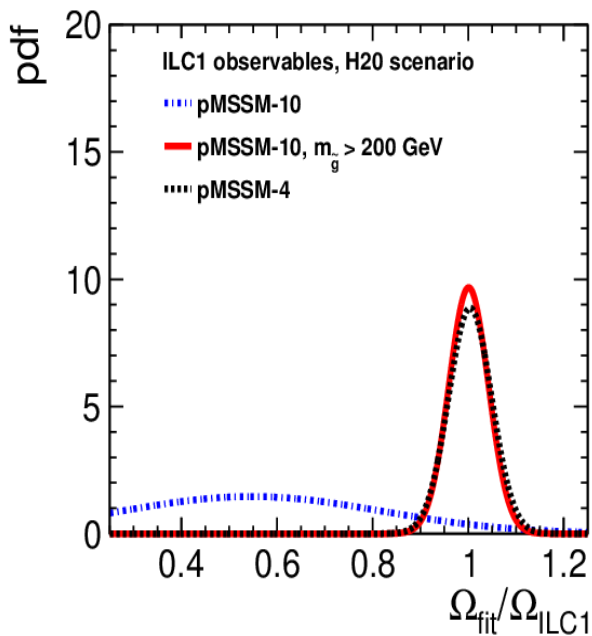




# Dark Matter in Higgsino fits

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

Thermally produced WIMP relic density

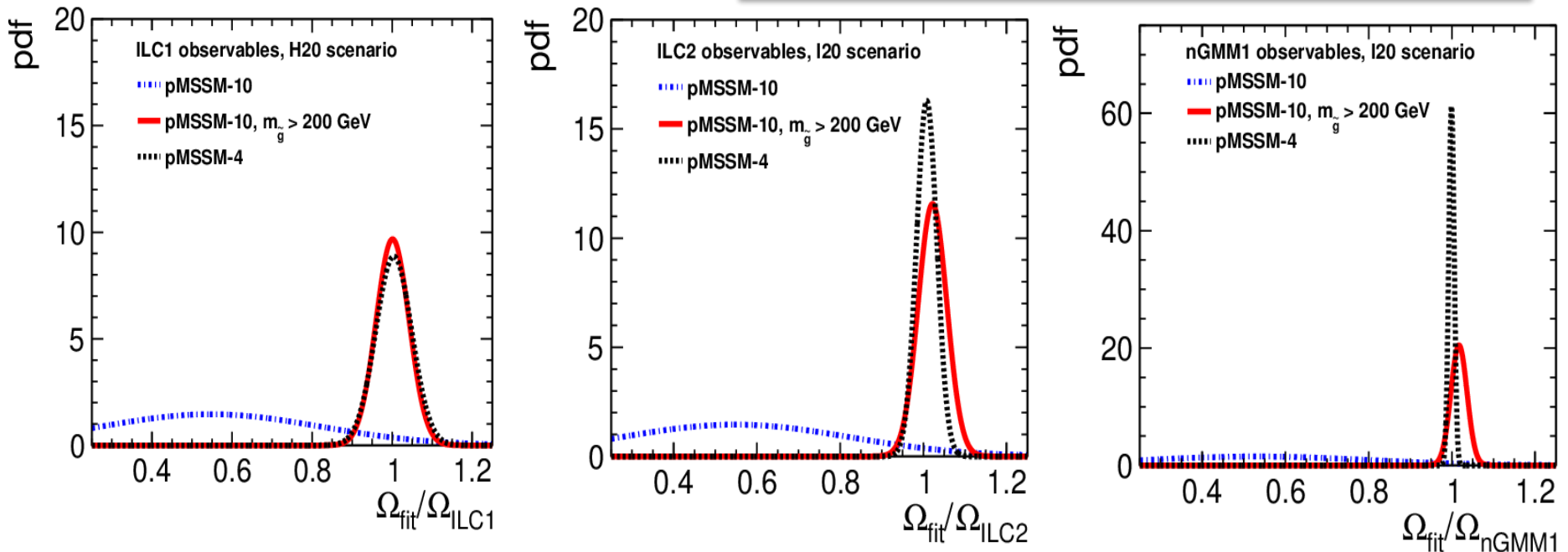


# Dark Matter in Higgsino fits

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

Thermally produced WIMP relic density

Agreement model with fit values

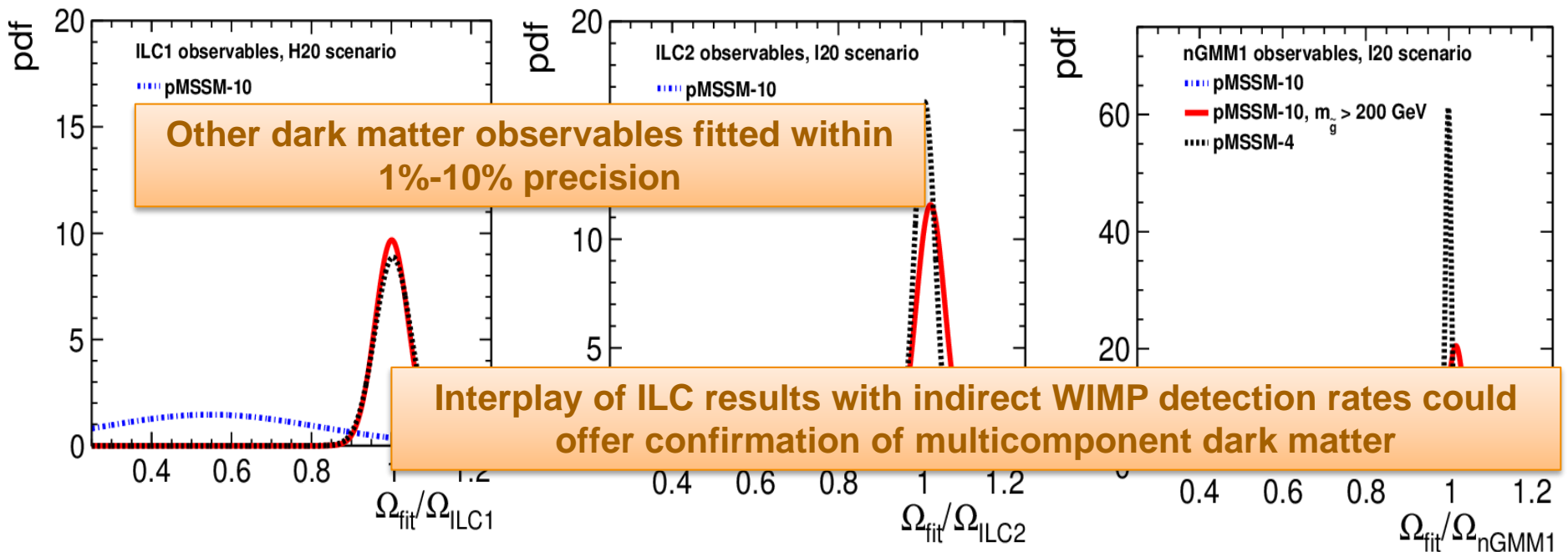


Such measurement would confirm possible underabundance of Higgsino-like WIMPs

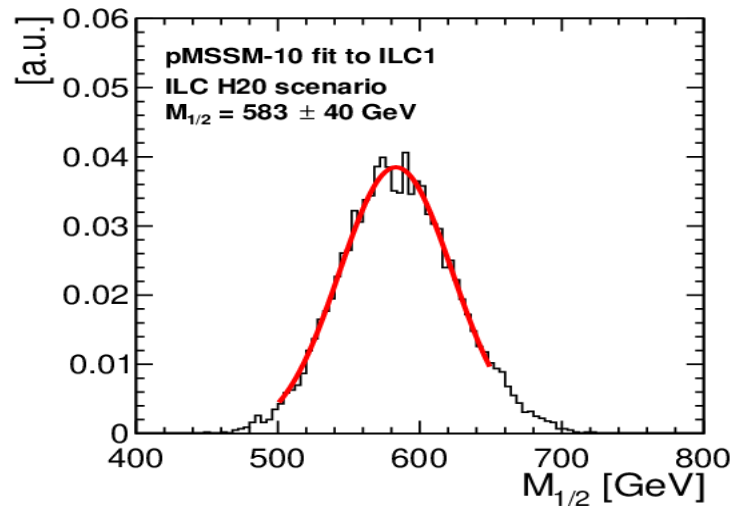
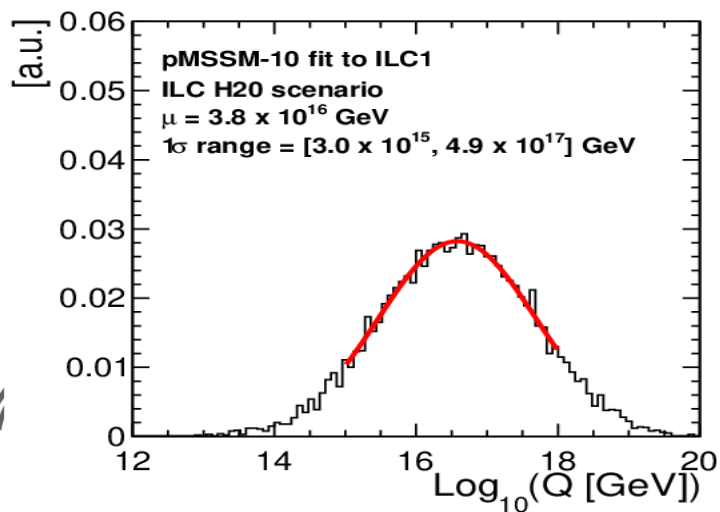
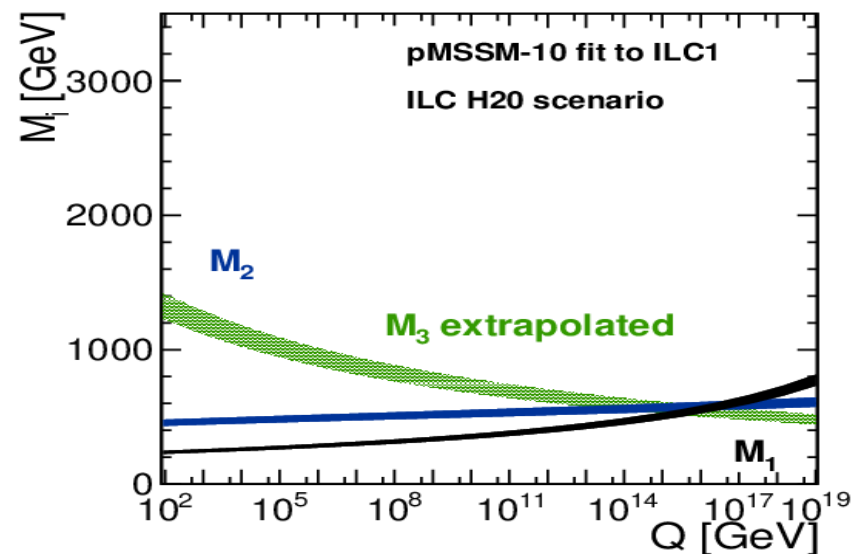
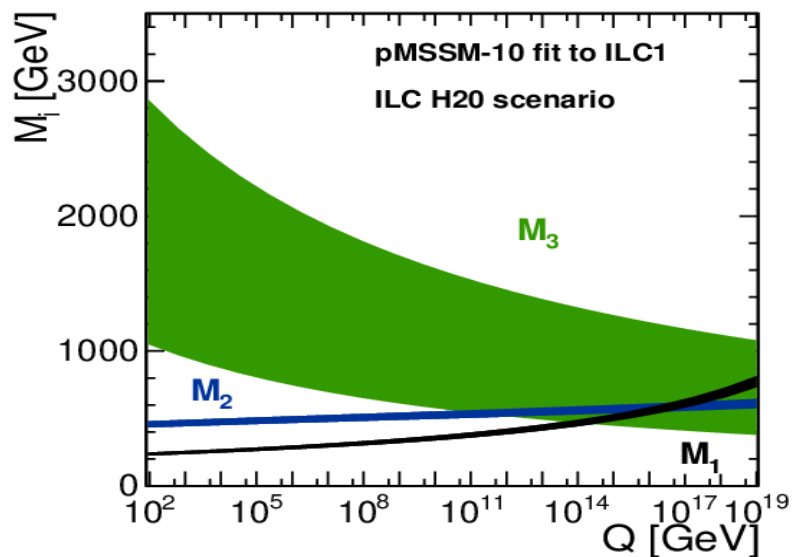
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Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

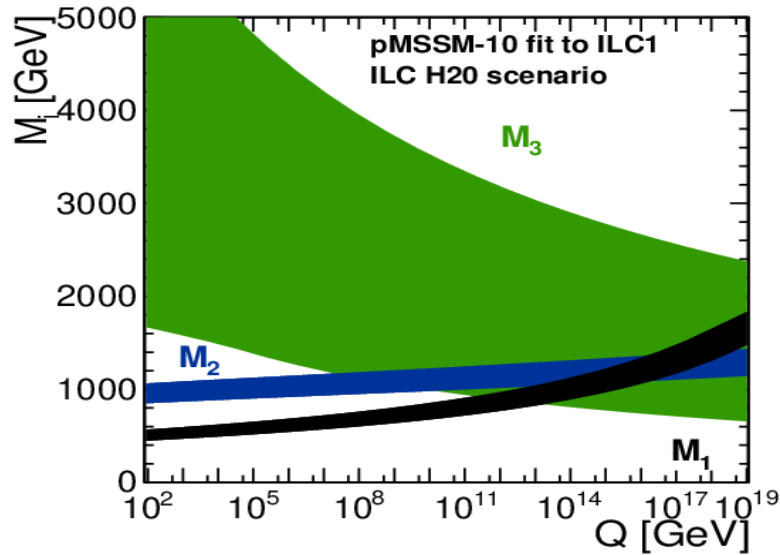
Thermally produced WIMP relic density



# Testing gaugino mass unification: ILC1

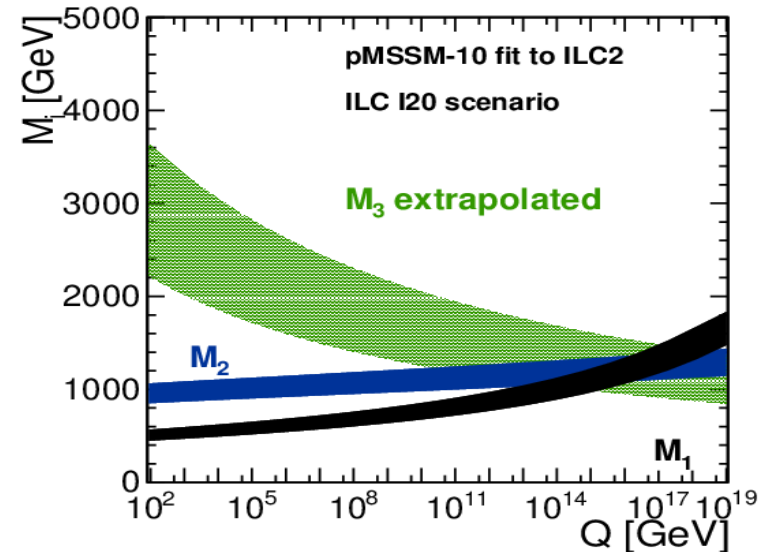


# Testing gaugino mass unification: ILC2



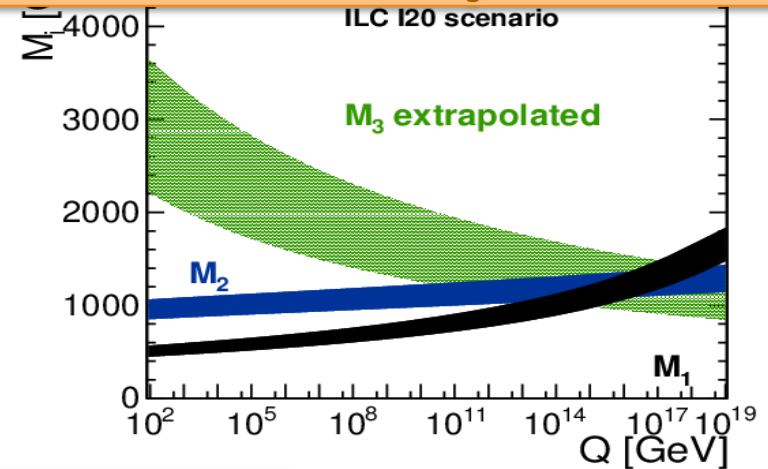
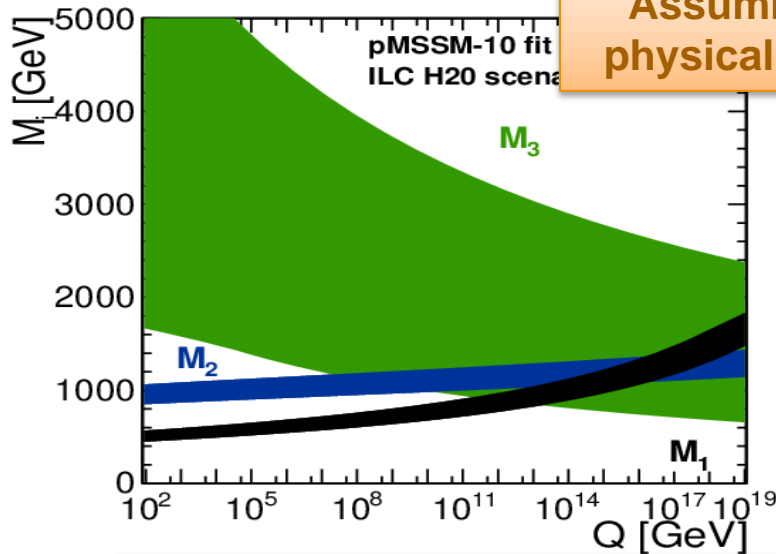
Assuming NUHM2 model and that  $M_3$  unifies, prediction of physical gluino mass can be obtained:  $m_g = 2872 \pm 605$  GeV

Possible to verify that  $M_1$  and  $M_2$  unify at GUT scale

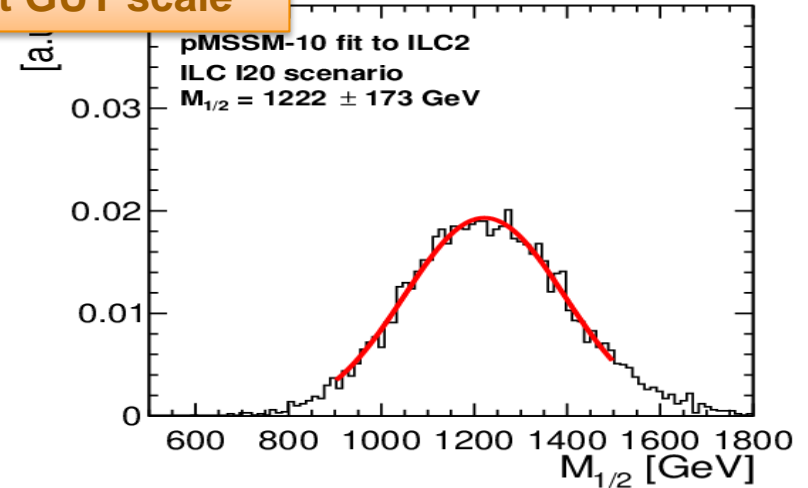
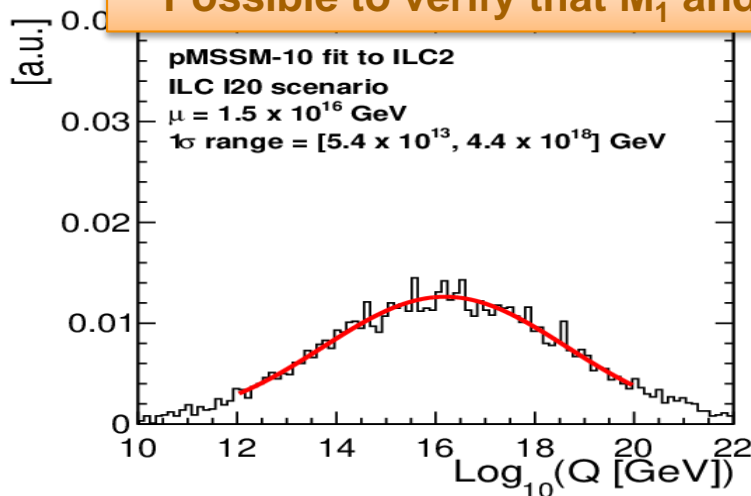


# Testing gaugino mass unification: ILC2

Assuming NUHM2 model and that  $M_3$  unifies, prediction of physical gluino mass can be obtained:  $m_g = 2872 \pm 605$  GeV



Possible to verify that  $M_1$  and  $M_2$  unify at GUT scale



# Testing gaugino mass unification: nGMM1

