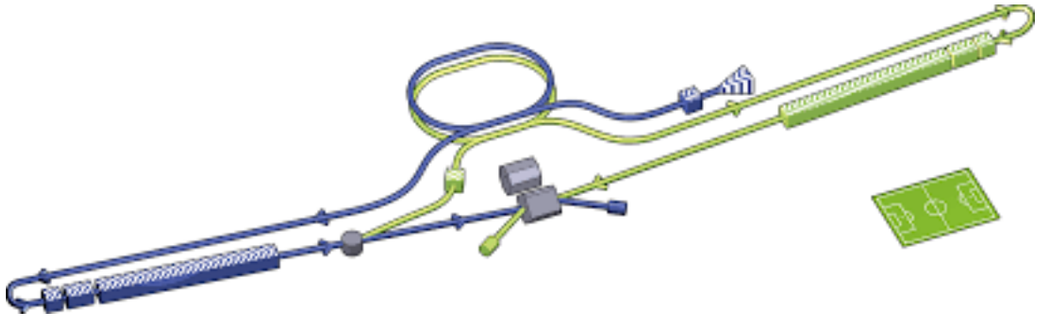
The potential of the ILC for discovering new particles– especially SUSY dark matter

Howard Baer
University of Oklahoma

Why

SUSY



Prologue:

Japan is deliberating on construction of International Linear e+e- Collider (ILC)

- stage 1: $\sqrt{s} = 250$ GeV Higgs factory: $e^+e^- \to Zh$
- stage 2: upgrade to $\sqrt{s} \sim 380 - 500$ GeV explore $t\bar{t}$ threshold
- $\sqrt{s} \sim 500$ GeV: $e^+e^- \to Zhh$ Higgs self-coupling
- then: operate above $t\bar{t}h$ threshold: top Yukawa coupling

A guaranteed program of exciting measurements!

BUT!

Important question from Japan MEXT committee:
given the prospect of no new physics beyond the SM at LHC,
what are prospects for new particle discovery at ILC?

Short reply to MEXT from ICFA:
backed up by lengthier Linear Collider Collaboration Physics Working Group report

DESY 17-012
KEK Preprint 2016-60
SLAC-PUB-16916
LAL 17-017
MPP-2017-5
IFT-UAM/CSIC-17-008

arXiv:1702.05333

The Potential of the ILC for Discovering New Particles

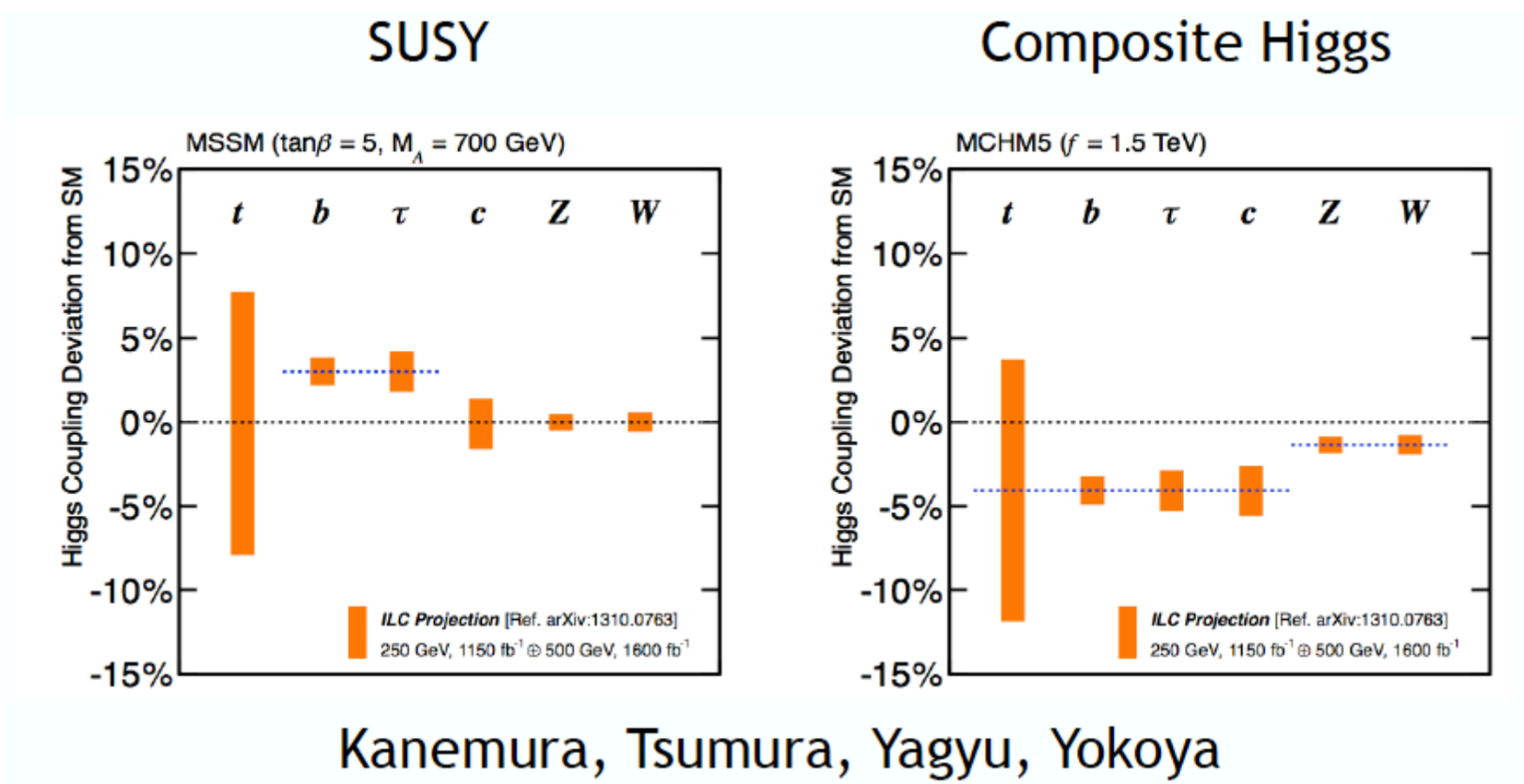
Document Supporting the ICFA Response Letter to the ILC Advisory Panel

LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3,4], Michael E. Peskin[5](conveners); Tim Barklow[5], Yuanning Gao[6], Shinya Kanemura[7], Hyungdo Kim[8], Jenny List[2], Mihoko Nojiri[1,9], Maxim Perelstein[10], Roman Pöschl[11], Jürgen Reuter[2], Frank Simon[12], Tomohiko Tanabe[13], James D. Wells[14], Jaehoon Yu[15]; Howard Baer[16], Mikael Berggren[2], Sven Heinemeyer[17], Suvi-Leena Lehtinen[2], Junping Tian[13], Graham Wilson[18], Jacqueline Yan[1]; Hitoshi Murayama[9,19,20], James Brau[21]

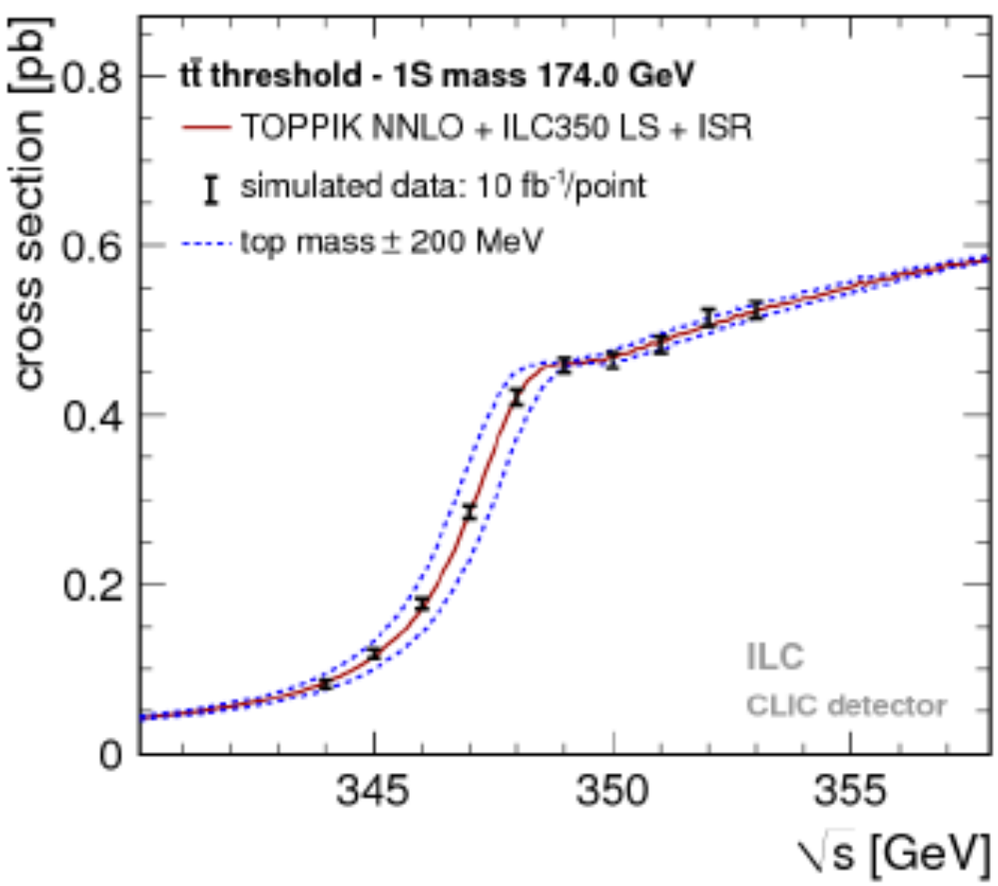
Stage 1: Higgs factory

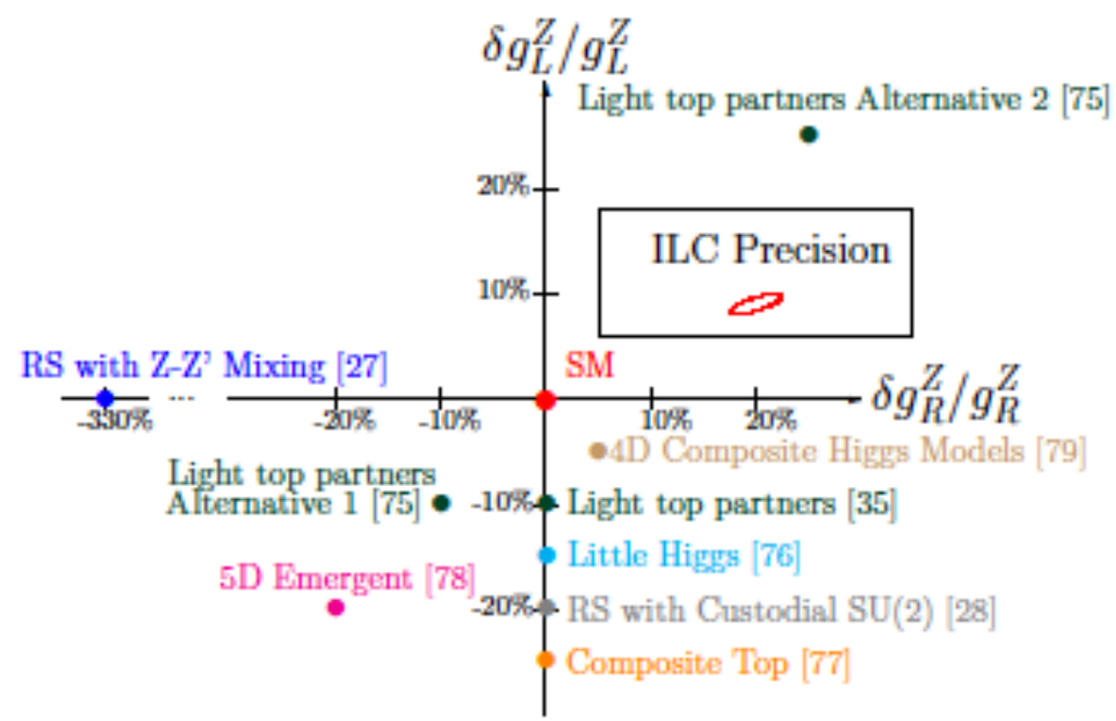
- At $\sqrt{s} = 250$ GeV, $e^+e^- \to Zh$ allows measurement of Higgs boson couplings to fermions/gauge bosons/invisibles to $< 1\%$ precision
- A program of Higgs fingerprinting: distinguish *e.g.* SUSY pattern from composite Higgs models
- at $\sqrt{s} = 500$ GeV, measure Higgs self coupling λ via Zhh
- ultimately measure top Yukawa coupling via $t\bar{t}h$ production



ILC as precision top factory:

- At $\sqrt{s} = 350 - 500$ GeV, $e^+e^- \to t\bar{t}$ allows precision scan of top pair production threshold
- measure m_t to 50 MeV precision
- using polarized beams: measure top quark left-/right- couplings to high precision
- test composite/ED models even if $Q(new\ physics) \sim 10$ TeV





ILC potential to discover new force particles: explore the multi-TeV range via real or virtual effects

$$e^+e^- \to \gamma, Z, Z' \to f\bar{f}$$

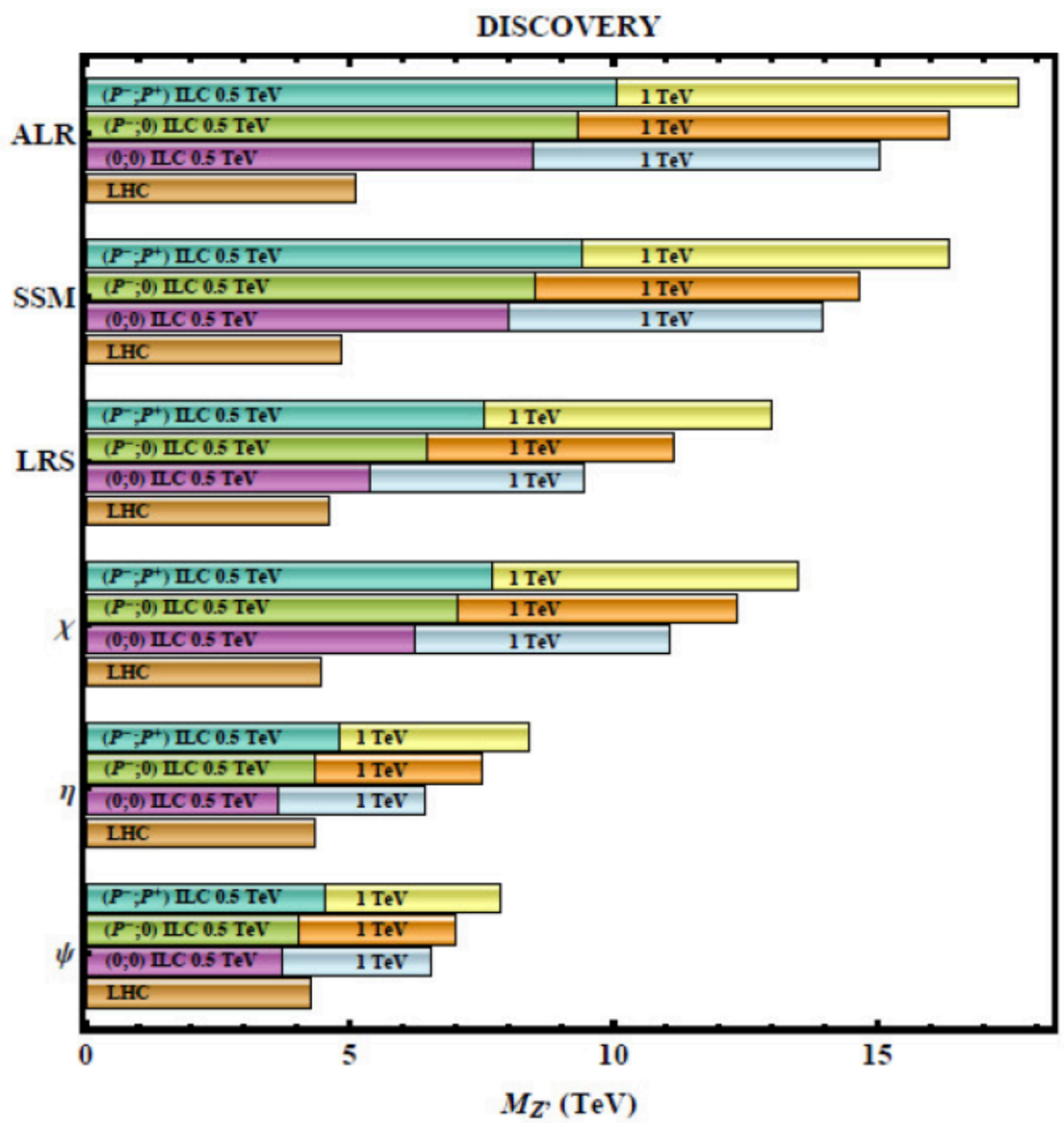


Fig. 120 Discovery reach of the ILC with $\sqrt{s} = 0.5$ (1.0) TeV and

While previous results are guaranteed testable,
can ILC weigh in on the biggest possibility:
the discovery of SUSY?

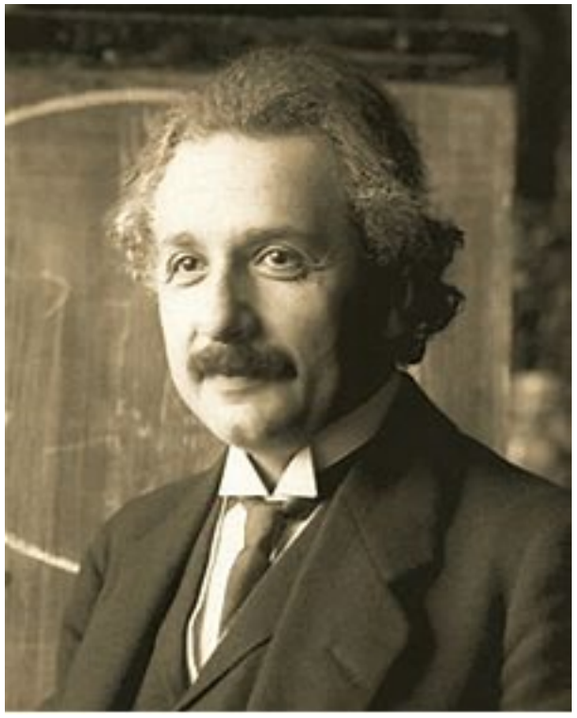
Or do recent LHC results, m(glno)>2 TeV, m(t1)>1 TeV
pre-empt any possibility?

So far, the bulk of LHC searches take place within
either unnatural or simplified models

What is the most natural, simplest version of SUSY?

SUSY motivation: simplicity and naturalness

``The appearance of fine-tuning in a scientific theory
is like a cry of distress from nature
complaining that something needs to be better explained"
S. Weinberg



``Everything should be made as simple as possible,
but not simpler"
A. Einstein

Needed: a natural theory which contains SM: the MSSM

MSSM+naturalness=> light higgsinos with mass~100-200 GeV

$$m_h^2 = \mu^2 + m_{H_u}^2 + mixing + rad.corr. \qquad \text{(MSSM)}$$

naturalness:
all independent contributions to some observable O
should be comparable to or less than O

otherwise:
if one contribution is >>O, then some other
must be fine-tuned to large opposite-sign to maintain O
at its measured value: this is unnatural
(i.e. highly implausible; likely wrong)

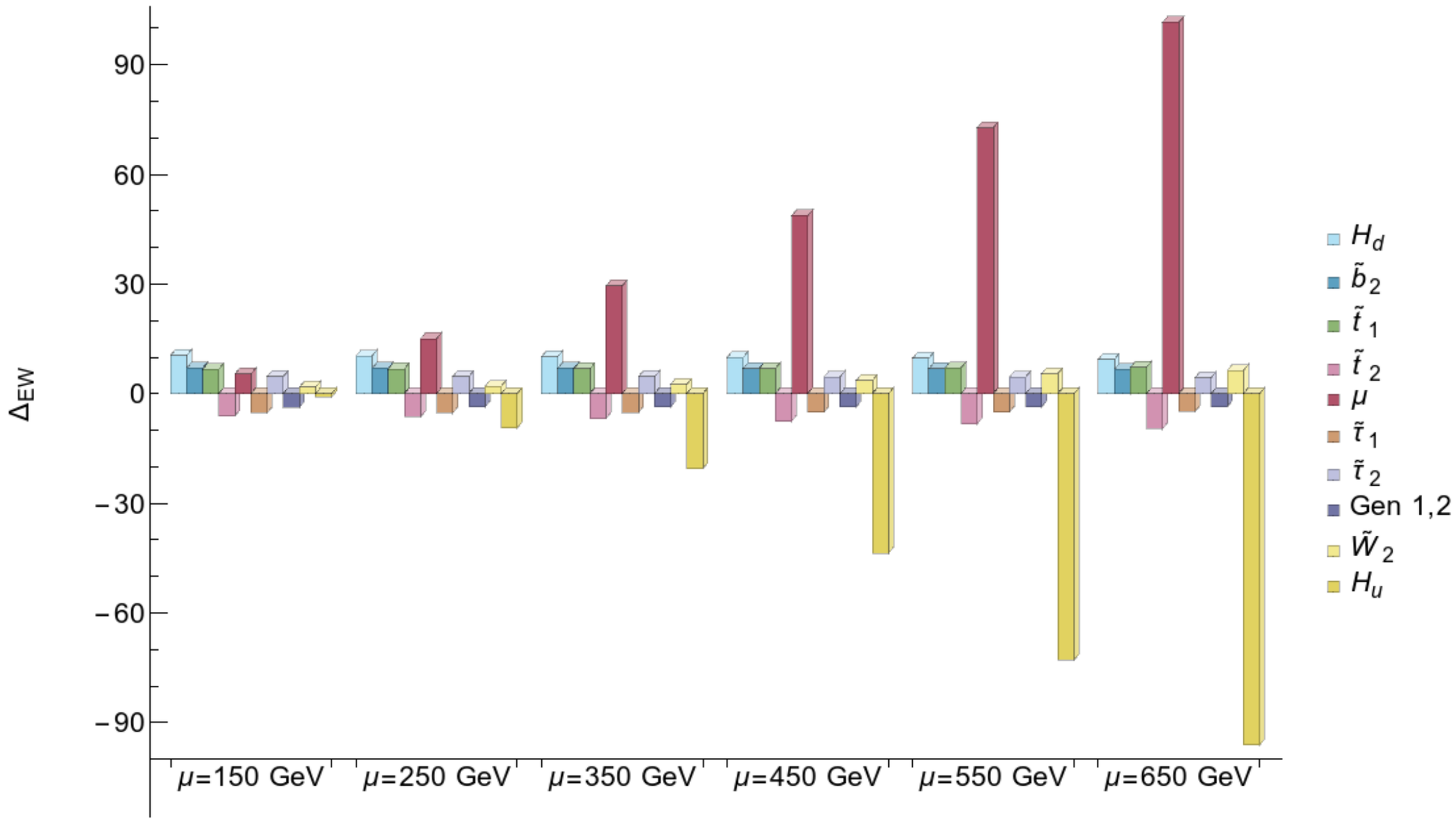
- $m_{H_u}^2$ is driven small negative (radiatively driven naturalness)
- Higgs/higgsino mass $\mu \sim 100 - 200$ GeV (the smaller the better)
- radiative corrections to m_Z^2 relation minimized for highly mixed TeV-scale top squarks

[m(glno)<~4-5 TeV; m(t1)<3 TeV at little cost to naturalness]

LHC has only begun to explore natural SUSY parameter space!

light higgsinos are difficult, perhaps impossible, to see at LHC

How much is too much fine-tuning?



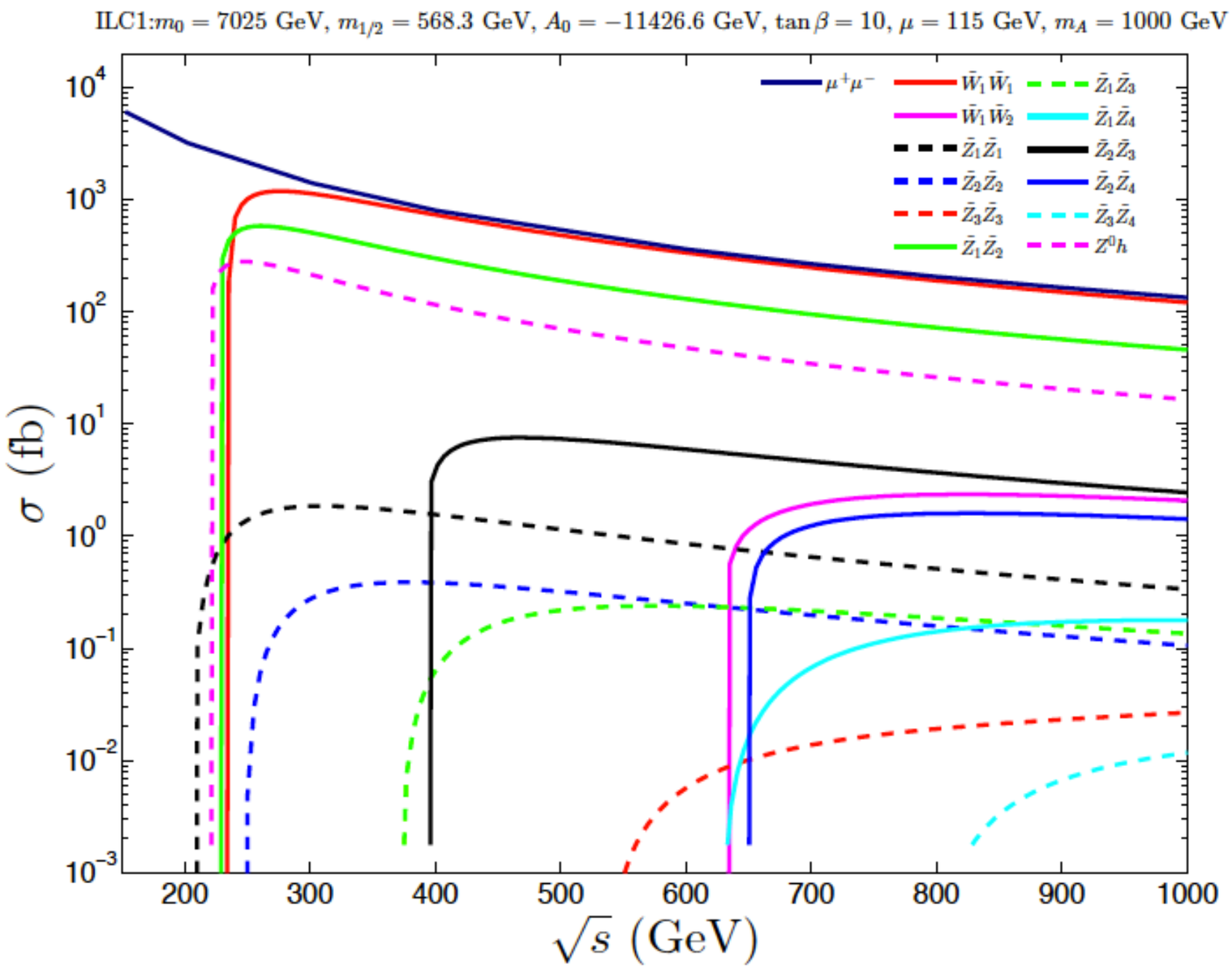
HB, Barger, Savoy

Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

Nature is natural $\Rightarrow \Delta_{EW} < 20 - 30$ (take 30 as conservative)

Smoking gun signature: light higgsinos at ILC:

ILC is Higgs/higgsino factory!



$$\sigma(higgsino) \gg \sigma(Zh)$$

3-15 GeV higgsino mass gaps no problem in clean ILC environment

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

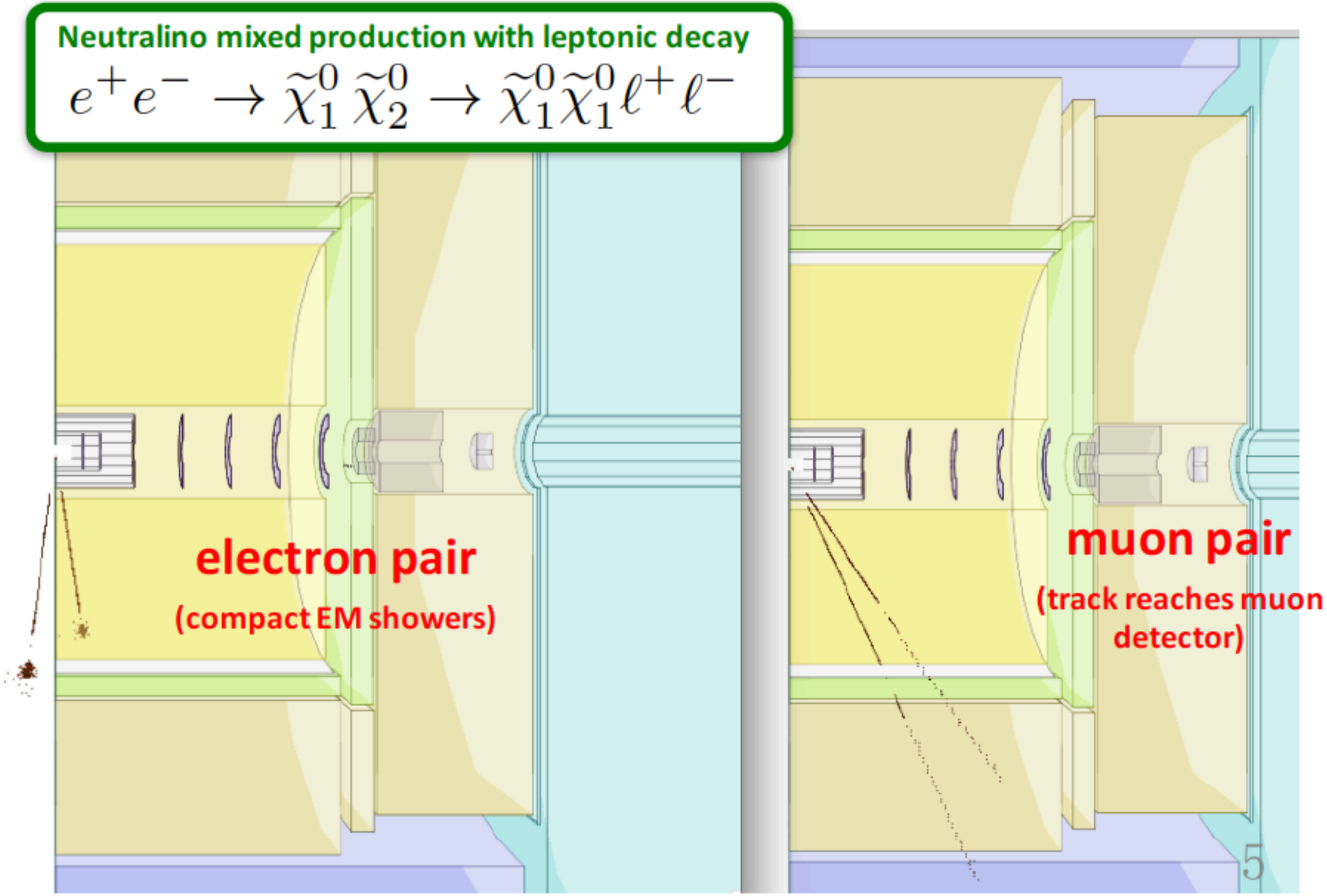
ILC either sees light higgsinos or natural MSSM dead

How do these signals look in the detector? (1)

√s =500 GeV

Neutralino mixed production with leptonic decay

$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$



Mass Extraction

$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

Mass extraction is done separately for each channel (N1N2 and C1C1)

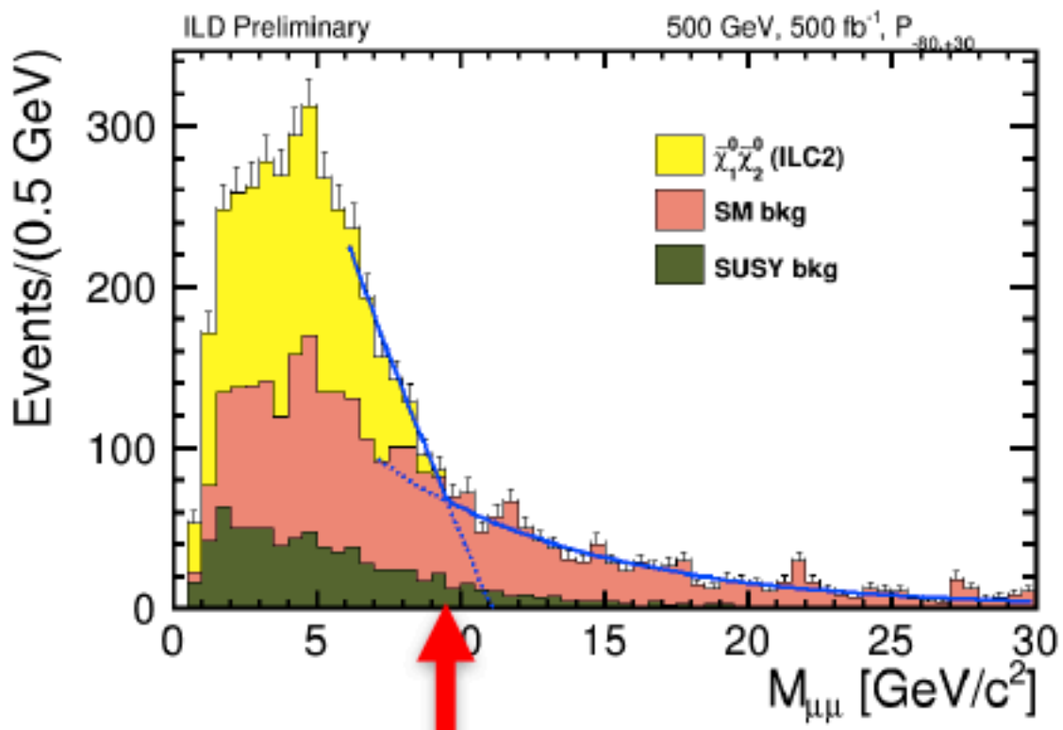
Example for N1N2 channel:

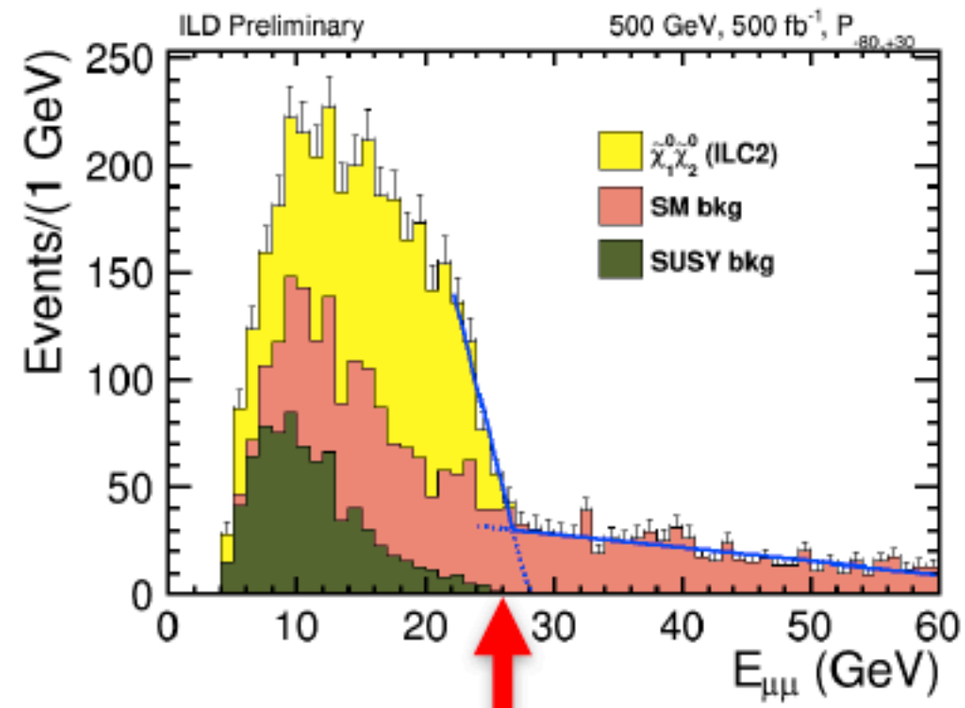
The maximum invariant mass gives mass splitting ΔM=**M(N2)-M(N1)**

The maximum di-lepton energy is a function of **M(N1)** and **M(N2)**

→ Solve for **M(N1)** and **M(N2)**

ILC2, (Pe-,Pe+) = (-0.8, +0.3), N1N2 dimuon final state





Edge extraction is key

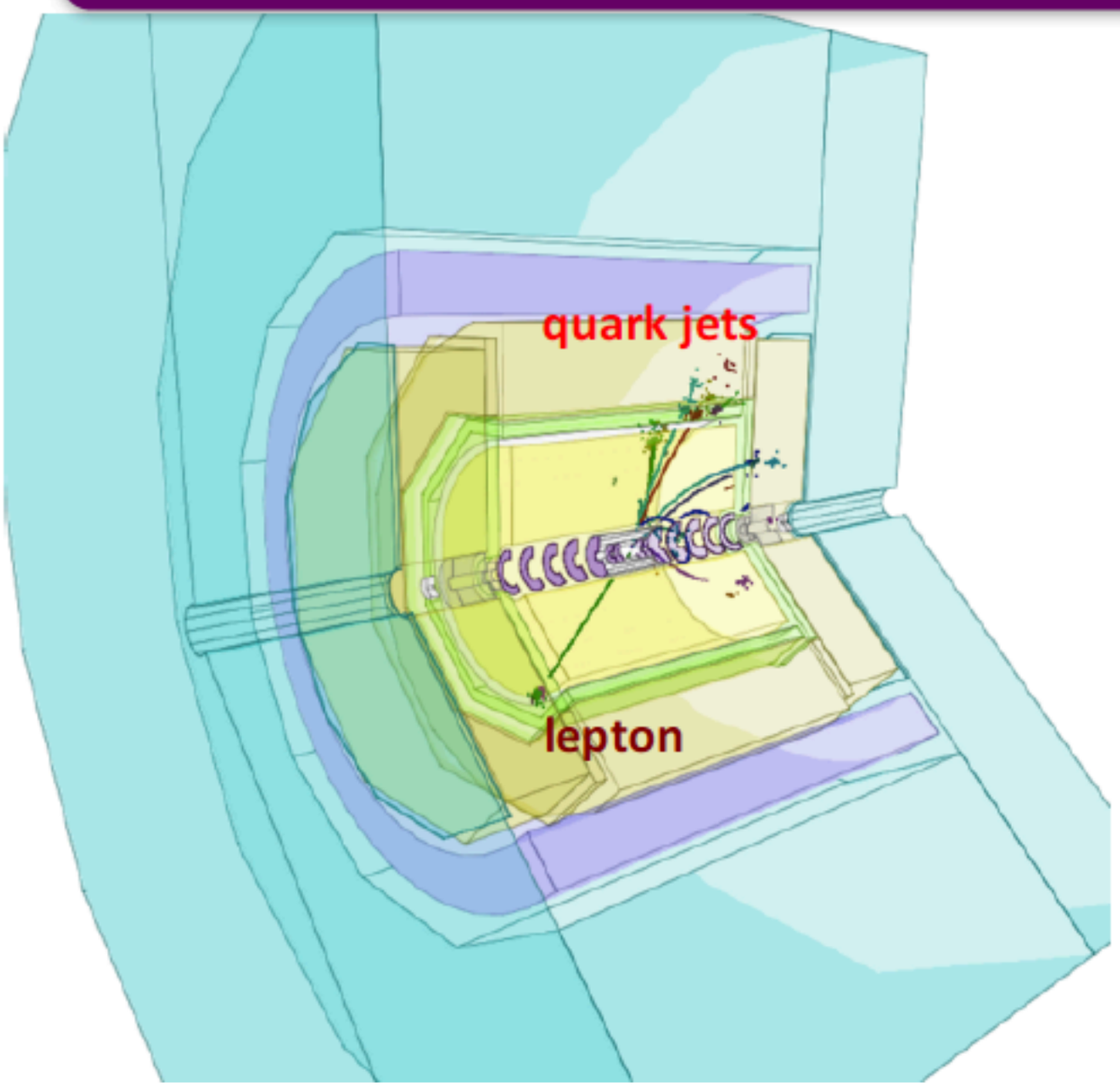
M(N1), M(N2) can be extracted at the 1% level

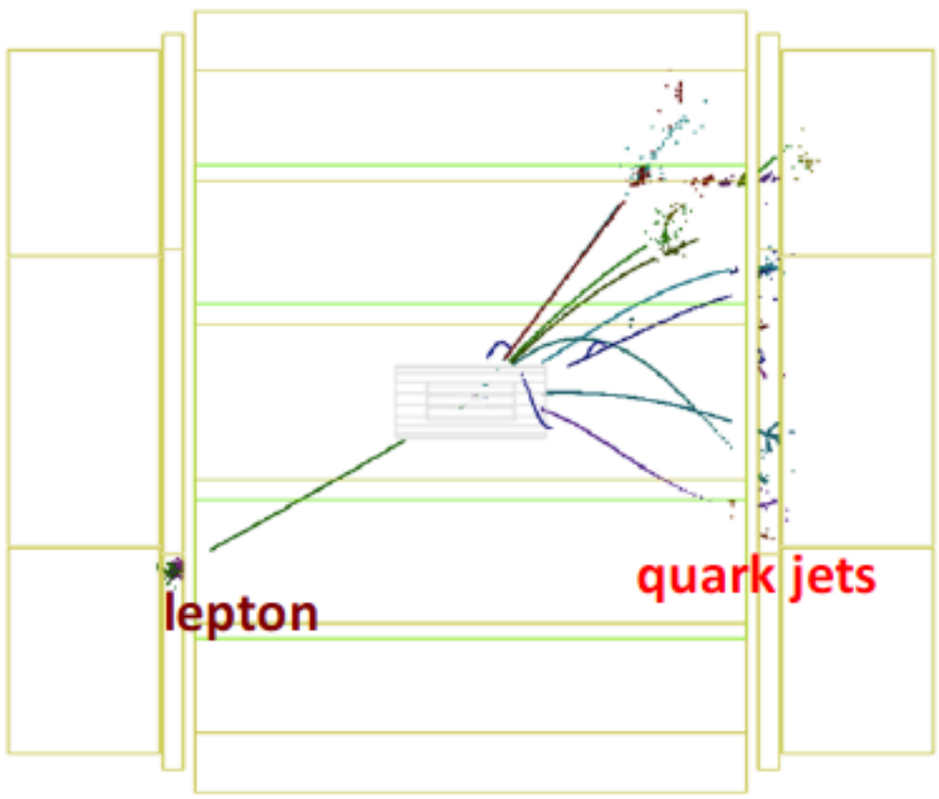
How do these signals look in the detector? (2)

√s =500 GeV

Chargino pair production with semileptonic decay

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 q q' \ell \nu$$





Mass Extraction

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 qq' \ell\nu$$

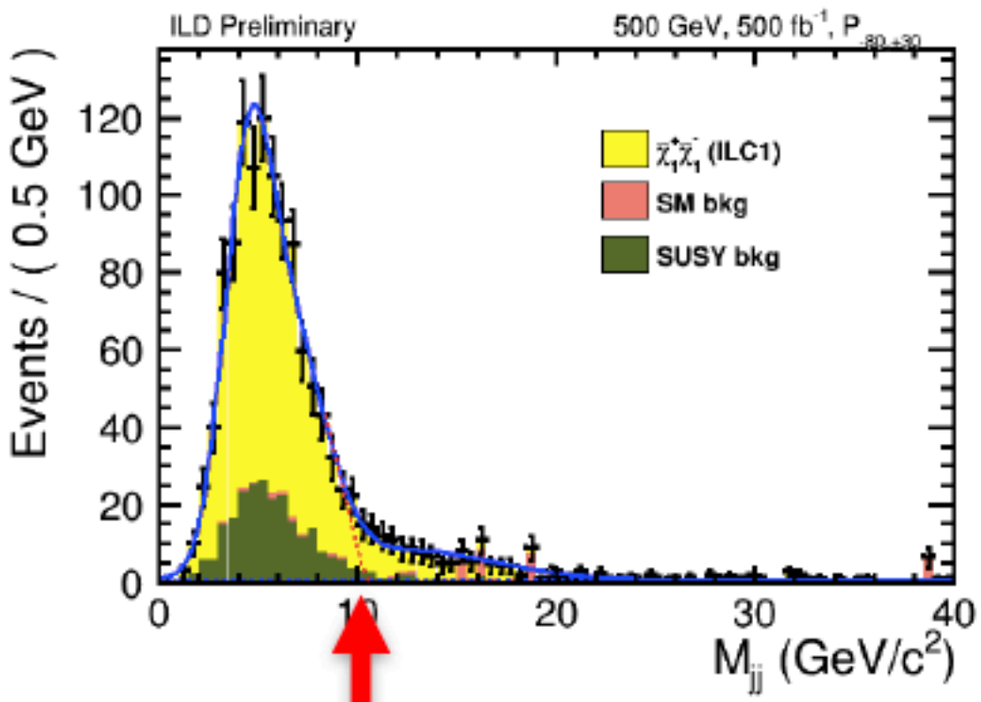
Mass extraction is done separately for each channel (N1N2 and C1C1)
Example for C1C1 channel:

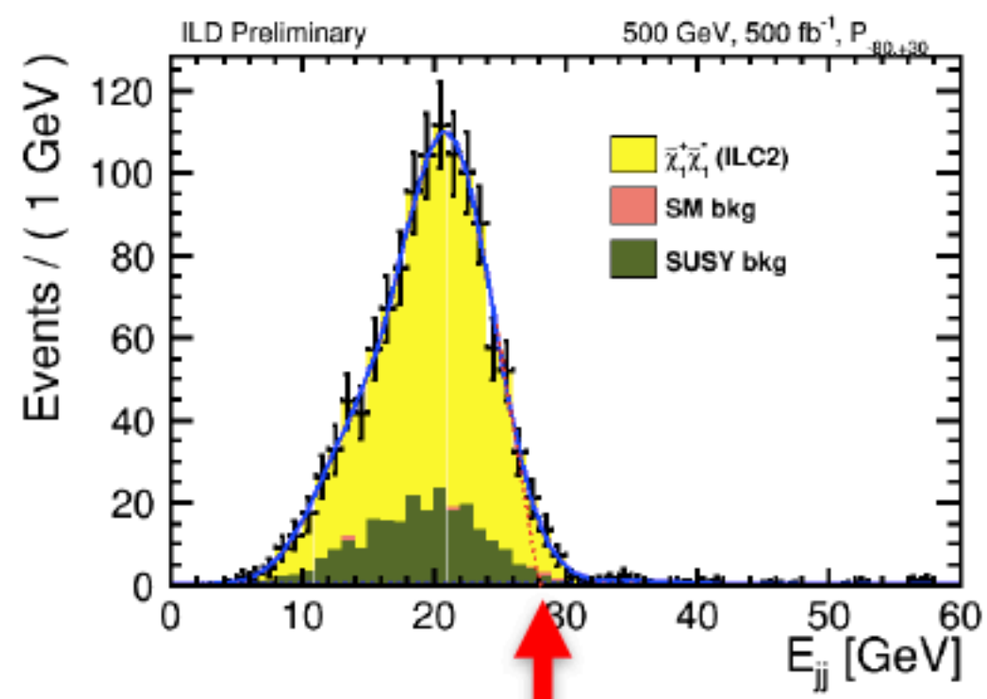
The maximum invariant mass gives mass splitting ΔM'=**M(C1)-M(N1)**

The maximum di-lepton energy is a function of **M(N1)** and **M(C1)**

→ Solve for **M(N1)** and **M(C1)**

ILC2, (Pe-,Pe+) = (-0.8, +0.3), C1C1 semi-muonic final state





Edge extraction is key

M(N1), M(C1) can be extracted at the 1% level

Probing the GUT scale

Input

(1) Observables (our analysis)
- 3 masses: M(N1), M(N2), M(C1),
- 4 cross sections: 2 processes (N1N2, C1C1) × 2 beam polarizations

(2) Exploit precision Higgs observables
- Higgs mass
- Higgs couplings

Output

- How well can we extract the underlying SUSY parameters?
- Can we discriminate the different SUSY models?
- What can we say about the unobserved part of the spectrum?

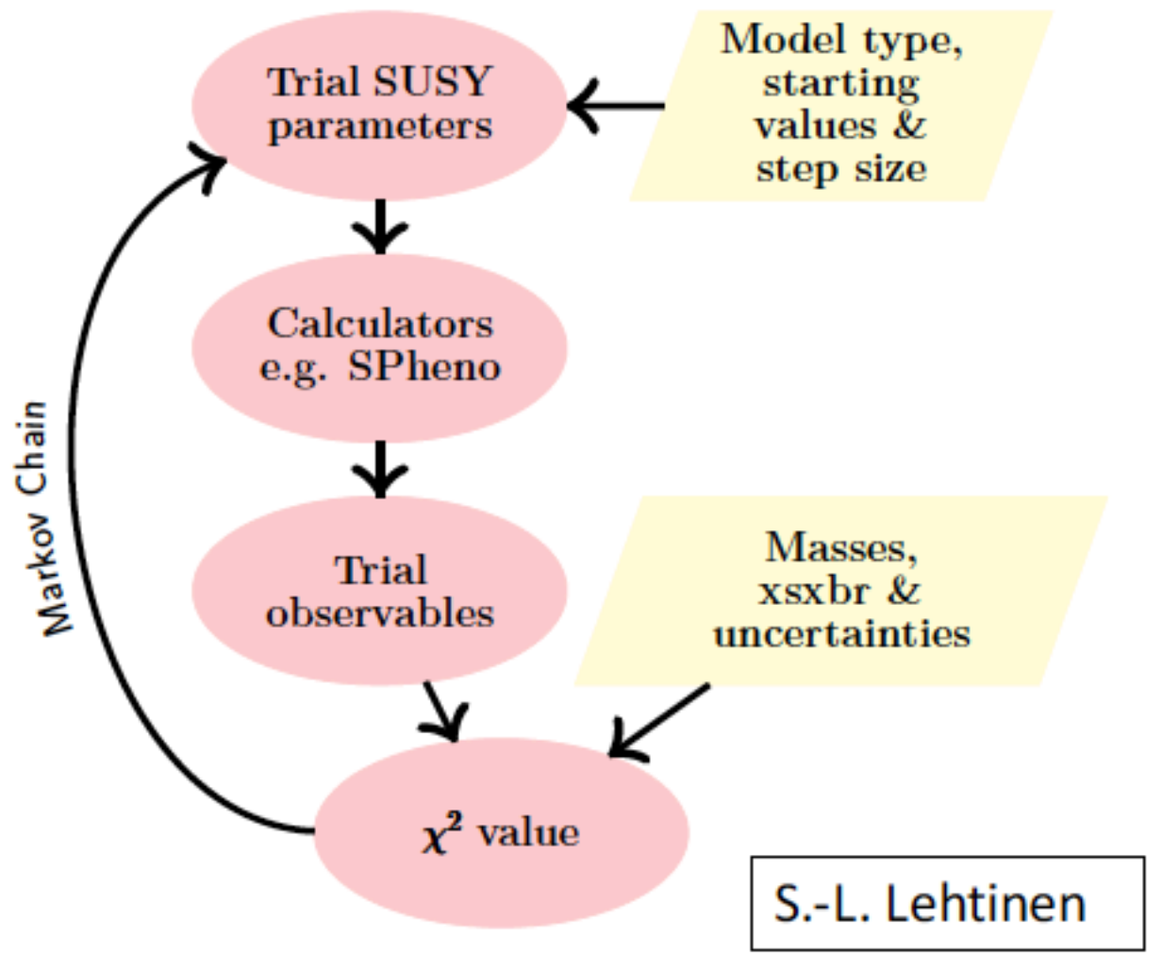
SUSY Parameter Fit

Chi-square (χ^2) value constructed from experimental observables and theory predictions
→ Uncertainty is taken from experimental observables
Finding SUSY parameters which give predictions that minimize χ^2
The range of values that fall within $\Delta\chi^2 = [0,1]$ gives the uncertainty

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,
FeynHiggs2.10.2 for Higgs,
MicrOMEGAs and
AstroFit for DM

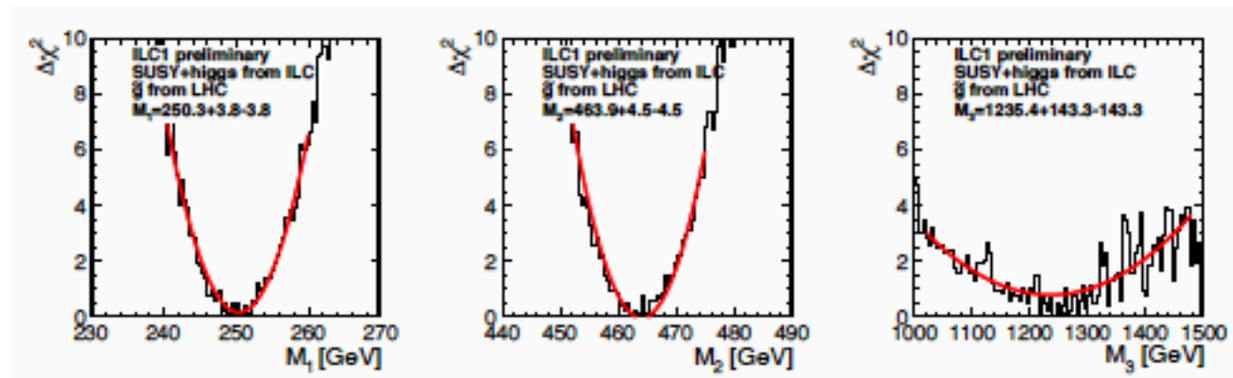
S.-L. Lehtinen

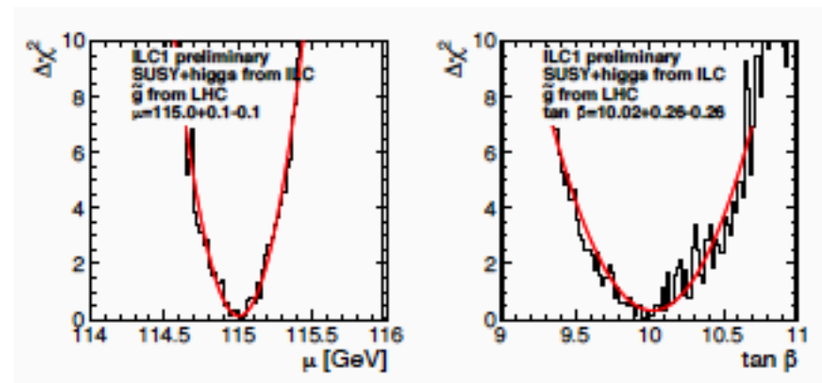
SUSY Parameter Fit: Results

5-parameter fit results, for ILC1 H20 observables

$$\Delta M_1 = 1.5\%$$
$$\Delta M_2 = 1.0\%$$
$$\Delta M_3 = 11.6\%$$
$$\Delta \mu = 0.1\%$$
$$\Delta \tan\beta = 2.5\%$$

M_1 and M_2 essentially the same in a 10-parameter fit and without gluino





S.-L. Lehtinen

Extrapolation to GUT-scale

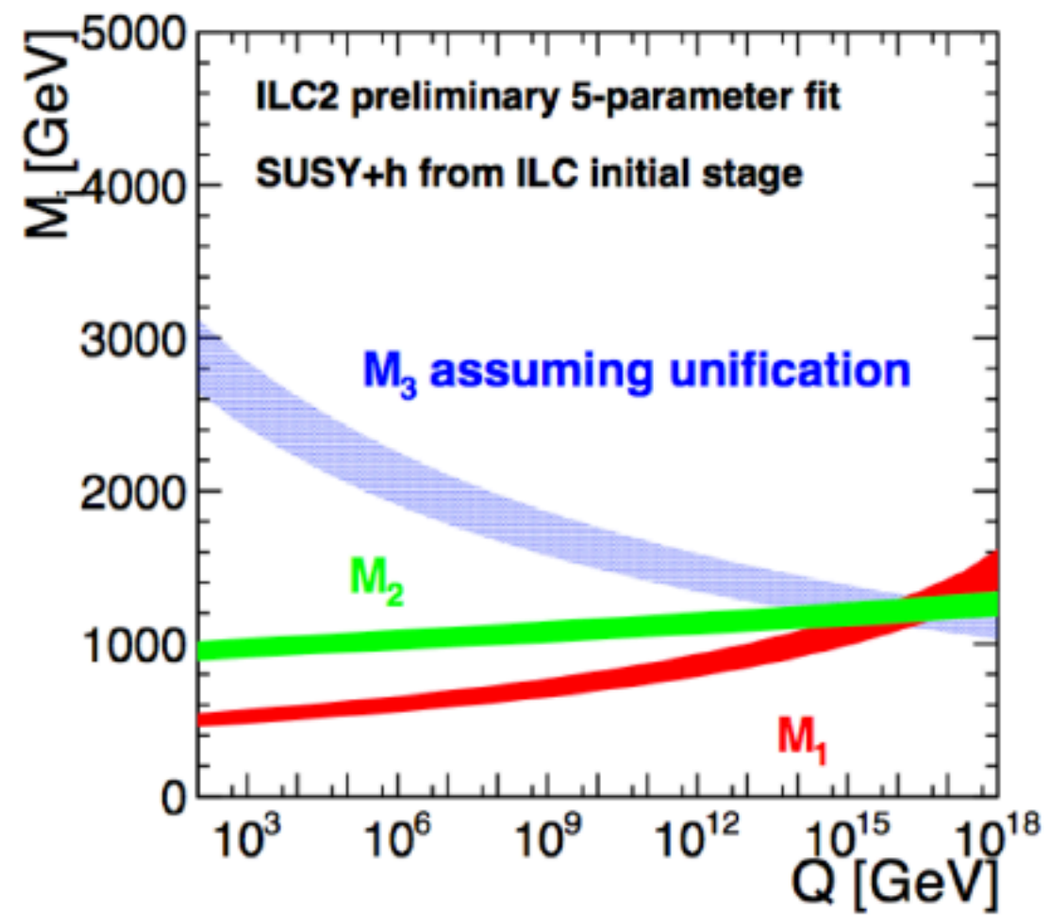
S.-L. Lehtinen

Example: ILC2, ILC initial stage lumi.

Take determined parameters at 1 TeV
Run up to GUT scale with two-loop RGEs
Fix other parameters to model values

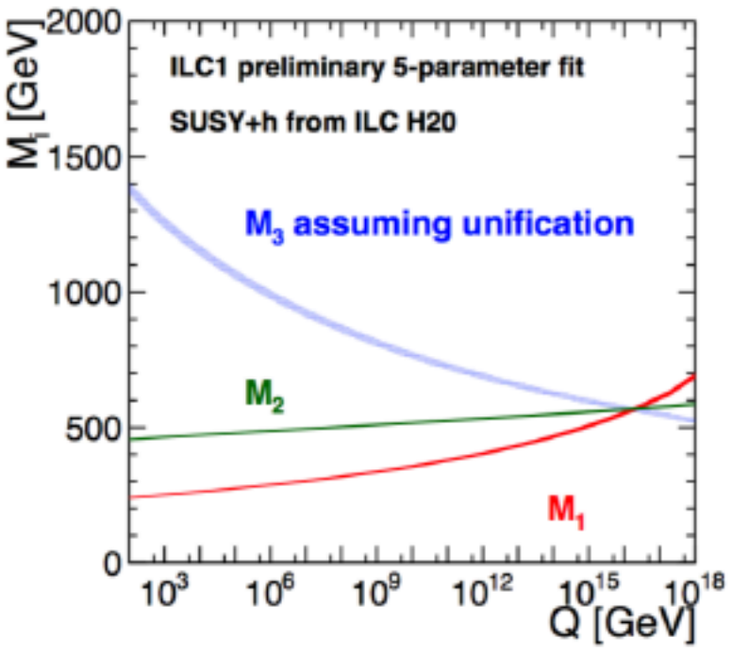
Can be used to predict gluino mass (M_3) assuming gaugino mass unification

→ **Sets the scale for next hadron collider**

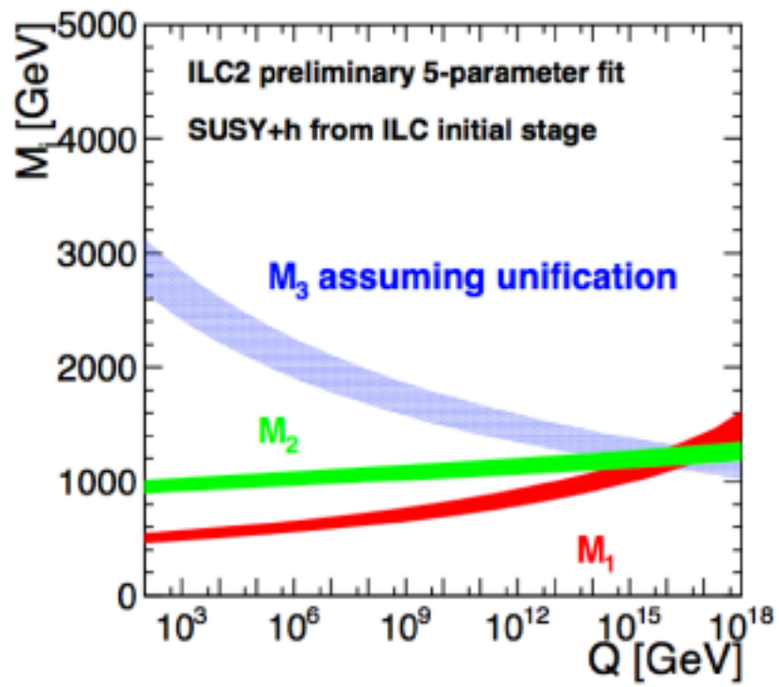


Model Discrimination

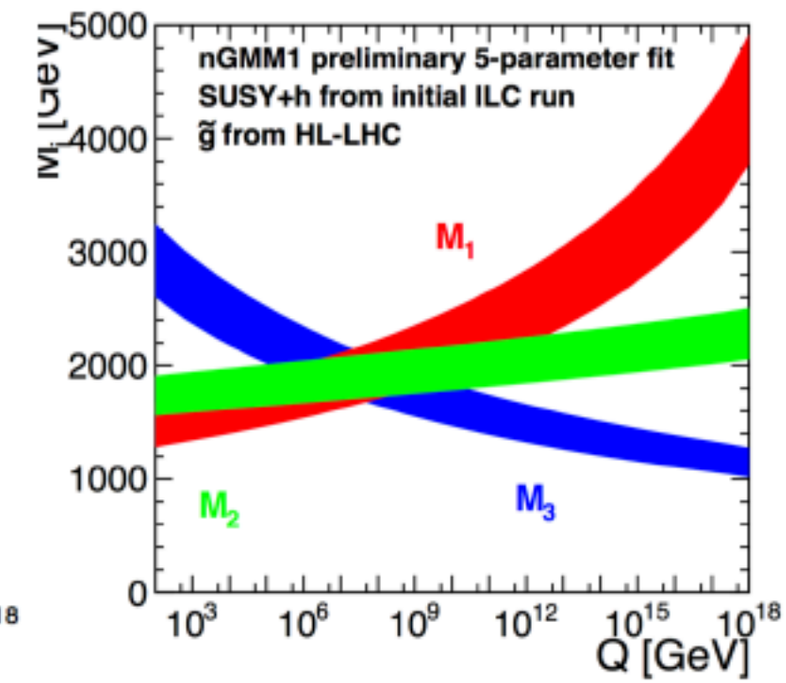
S.-L. Lehtinen



ILC1 (ILC H-20)



ILC2 (ILC initial stage)



nGMM1 (ILC initial stage)

The three scenarios are clearly distinguishable with the ILC alone

→ Gives insight into underlying SUSY breaking mechanism

Conclusions

- ILC stage 1: Higgs factory, Higgs fingerprinting
- ILC as precision top factory
- new forces: Z’
- simplest, most natural SUSY=> light higgsinos
- ILC should be a higgsino factory as well!
- lightest Higgsino is WIMP: but only part of DM (with axion?)
- precision measurements at ILC can test nature of higgsino-like WIMP and probe e.g. SUSY GUTs vs. stringy mirage mediation models