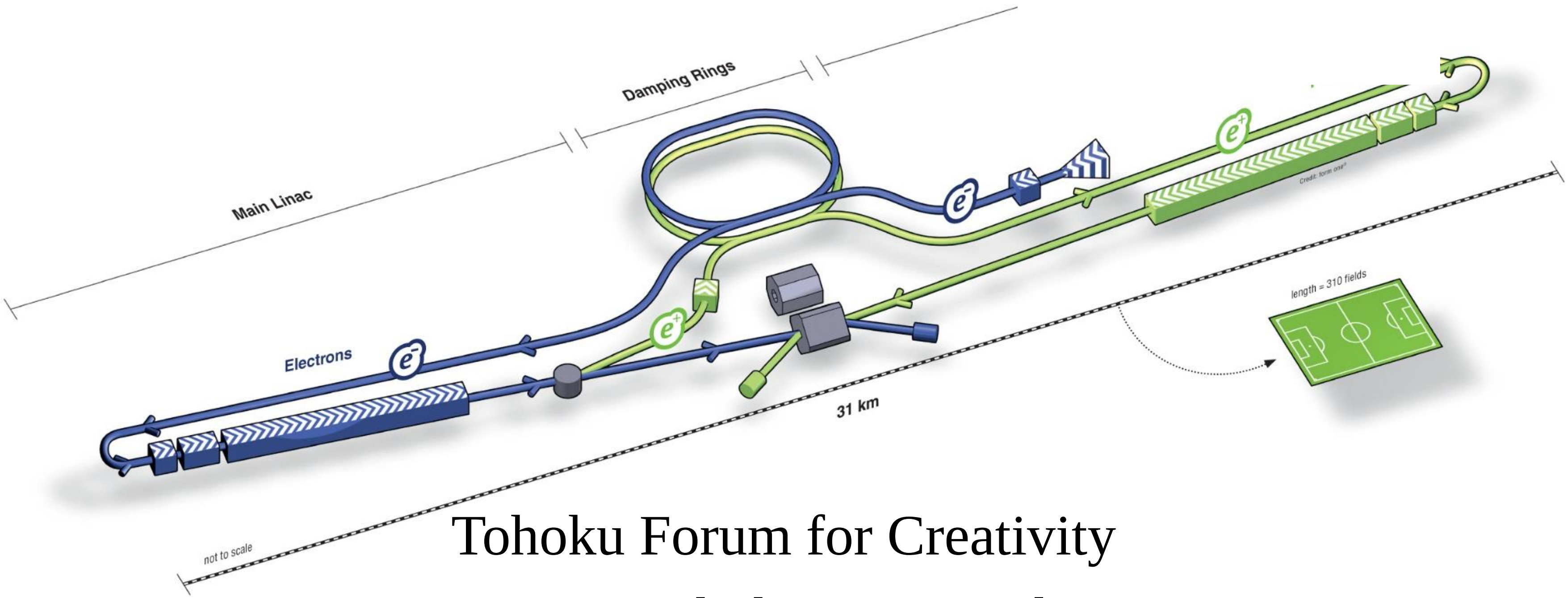
BSM searches at ILC



Tohoku Forum for Creativity

2013.10.22. Tohoku Univ. Eriko Kato

ILC Scheme | © www.form-one.de

New Physics at the TeV scale

Issues motivating physics study at **TeV scale:**

- **Naturalness**
  - Radiative correction to Higgs mass term has quadratic divergence
  - Require new physics / new particles in the TeV range to avoid excessive fine-tuning
    - e.g. Supersymmetry (SUSY), Composite Higgs, Extra Dimensions
- **Dark Matter (DM)**
  - WMAP relic density predicts O(100) GeV WIMP
  - New physics models predict natural DM candidates

➢ So far LHC8 hasn't observed any New Physics. What can be happening?

Possible scenarios for New Physics

- No NP found@LHC14
  - Within LHC kinematic reach, but cannot observe.
  - e.g. in many models $\tilde{q}, \tilde{g}$ are heavy. small $\sigma_{electroweak}$, large bkg
  - e.g. small visible energy. Contracted mass spectrum
  - e.g. purely hadronic decay

- No NP found @LHC14
  - Out of kinematic reach of LHC

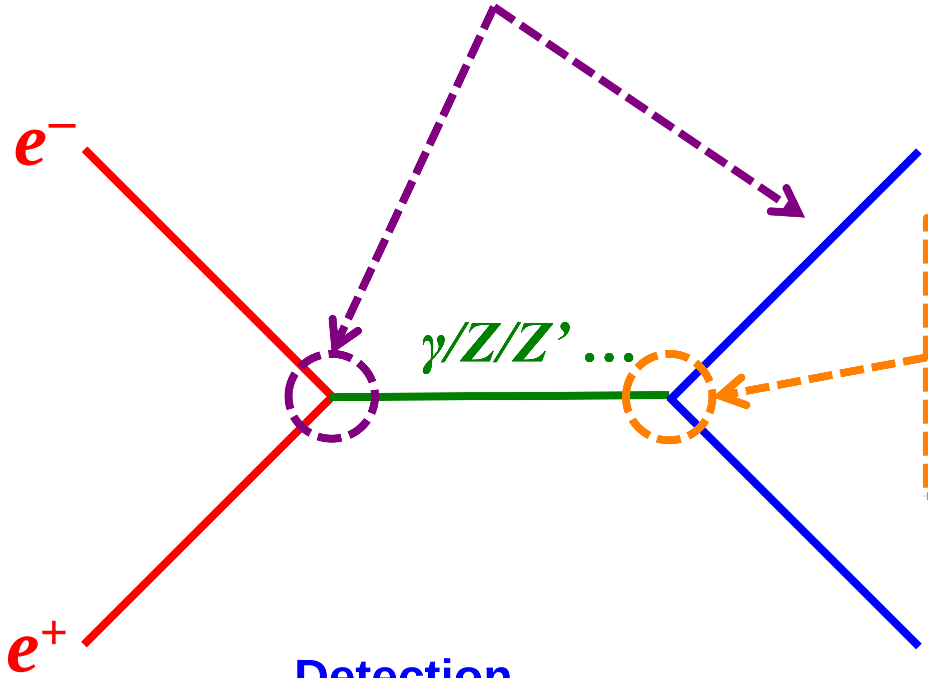
- NP found @LHC14!!
  - Found SM deviation

➢ Where can ILC contribute?

ILC characteristics

Elementary process
Well-understood at LEP
Theoretical uncertainty <1%

Beam
Tunable energy
(250GeV~1TeV)
Polarization
$P_{electron} = \pm 80\%$
$P_{positron} = \pm 30\%$



Production
New particles
Dark Matter
etc

Detection
Low background
hermetic
Highly granular sensors
Trigger free operation

Possible scenarios for New Physics

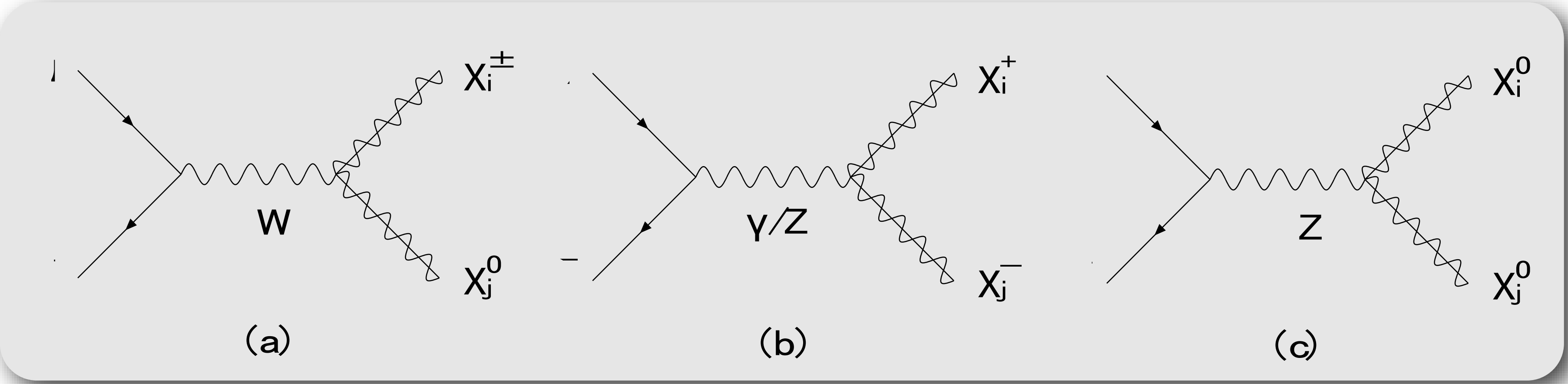
- No NP found@LHC14
  - Within LHC kinematic reach, but cannot observe.
  - e.g. in many models $\tilde{q}, \tilde{g}$ are heavy. small $\sigma_{electroweak}$, large bkg
  - e.g. small visible energy. Compressed mass spectrum
  - e.g. purely hadronic decay
- ➢ ILC strong point for discovery
- No NP found @LHC14
  - Out of kinematic reach of LHC
- ➢ ILC will probe NP though loop effects(electroweak precision meas.)
- NP found @LHC14!!
  - Found SM deviation
- ➢ ILC will disentangle complicated NP phenomenon's and conduct NP precision measurements.

Some examples….

(MOSTLY SUSY)

Electroweakino Direct Production

(Electroweakinos: collective name for gauginos and Higgsinos)



For LHC:

$$p\overline{p} \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 X,\ \tilde{\chi}_1^+ \tilde{\chi}_1^- X,\ \ldots$$

For ILC:

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-,\ \tilde{\chi}_2^+ \tilde{\chi}_2^-,\ \tilde{\chi}_1^0 \tilde{\chi}_2^0,\ \ldots$$

Decays:

$$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} \tilde{\chi}_1^0$$

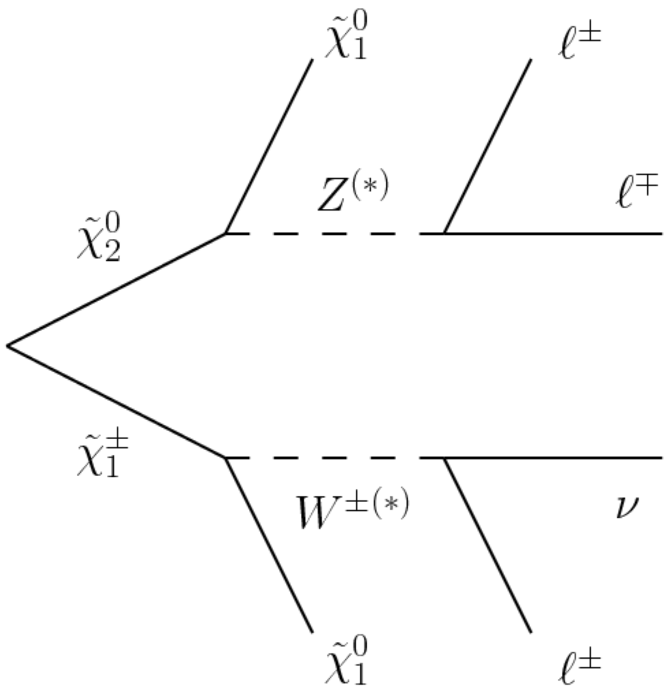
$$\tilde{\chi}_2^0 \rightarrow (Z/h) \tilde{\chi}_1^0$$

$$\ldots$$

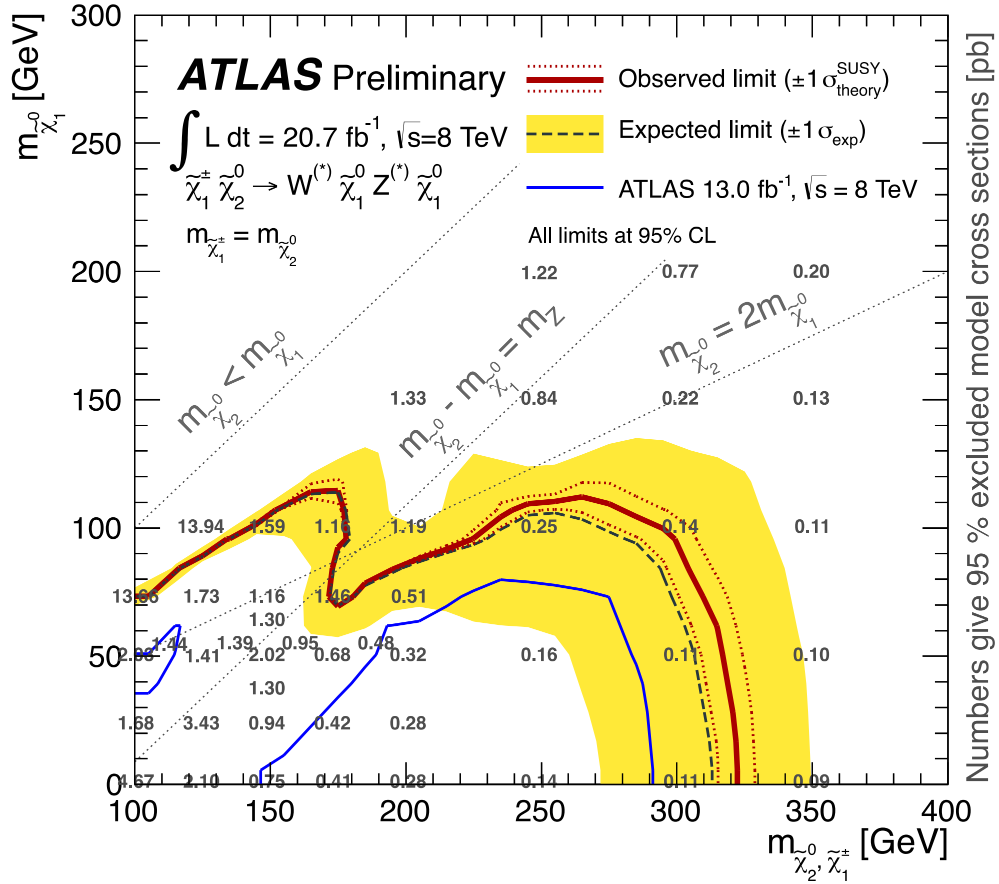
From LHC

Simplified model:

$\tilde{\chi}_1^0$ is bino, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are wino and degenerate



3 leptons + MET



<u>100% BR into W/Z assumed</u>

ATLAS-CONF-2013-035

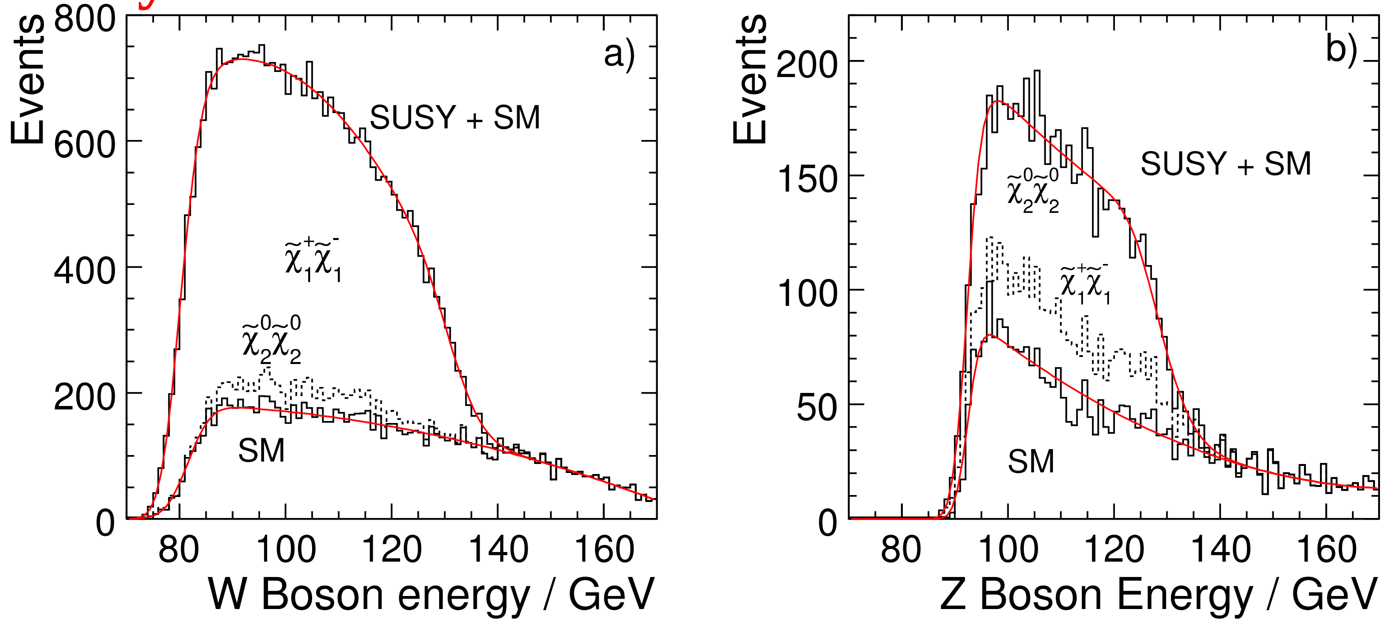
Gaugino pair production

- **ILC** can search for SUSY particles with **mass below √s/2**
- Consider pair production of $\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_1^{0}$ whose masses are close
  - $e^+ e^- \rightarrow \chi_1^+ \chi_1^- \rightarrow \chi_1^0 \chi_1^0 W^+ W^-$
  - $e^+ e^- \rightarrow \chi_2^0 \chi_2^0 \rightarrow \chi_1^0 \chi_1^0 Z^0 Z^0$

If soft jets → challenging signature

- **Discovery** + mass measurement via detection of **kinematic edges**:

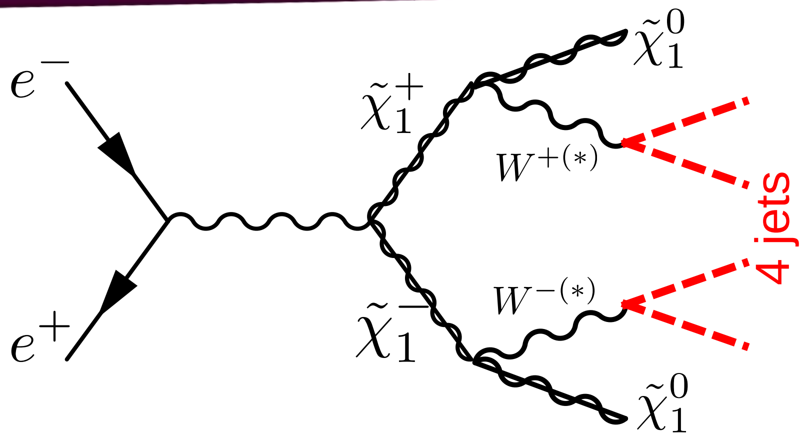
ILC 500 GeV



Suehara, List [arXiv:0906.5508]

Chargino / Neutralino can be discovered
+ studied with mass resolution O(1)%

4 jets + missing 4-momentum



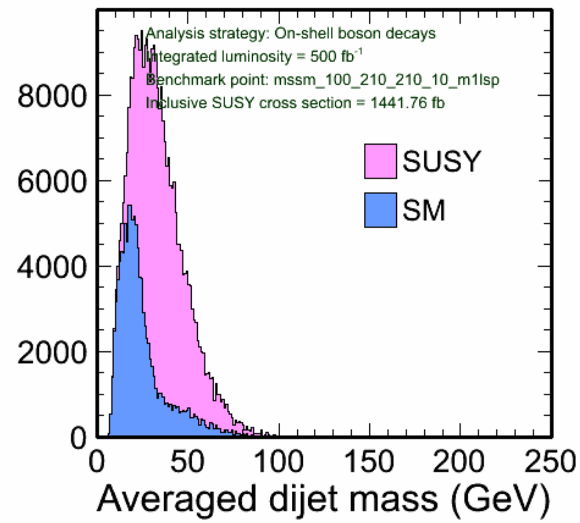
General strategy:

Reconstruct the hadronic decay of the chargino: **4 jets + missing 4-momentum** signature.

Choose jet combination most consistent with the same dijet mass.

Event selection based on:

- Number of particles
- Large missing energy
- Missing momentum ***not*** along the beam pipe
- Require minimum jet energy
- Jet finder transition values



$$M_{\tilde{\chi}_1^0} = 90.9 \text{ GeV}$$

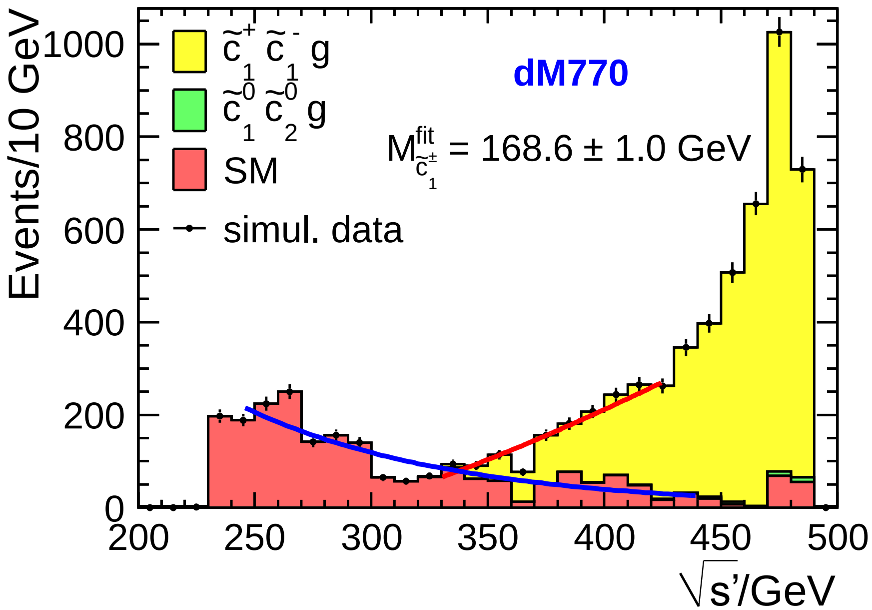
$$M_{\tilde{\chi}_1^\pm} = 165.9 \text{ GeV}$$

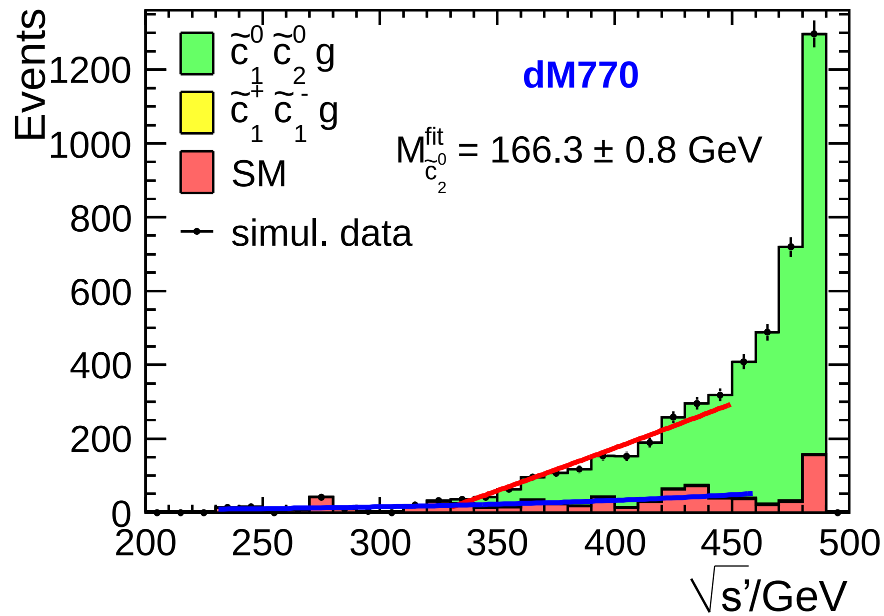
Higgsino pair production

Naturalness argument calls for light Higgsinos e.g. in the case of MSSM:

$$m_Z^2 = -2\left(m_{H_u}^2 + |\mu|^2\right) + \mathcal{O}(\cot^2\beta)$$

Higgsinos → small mass gaps

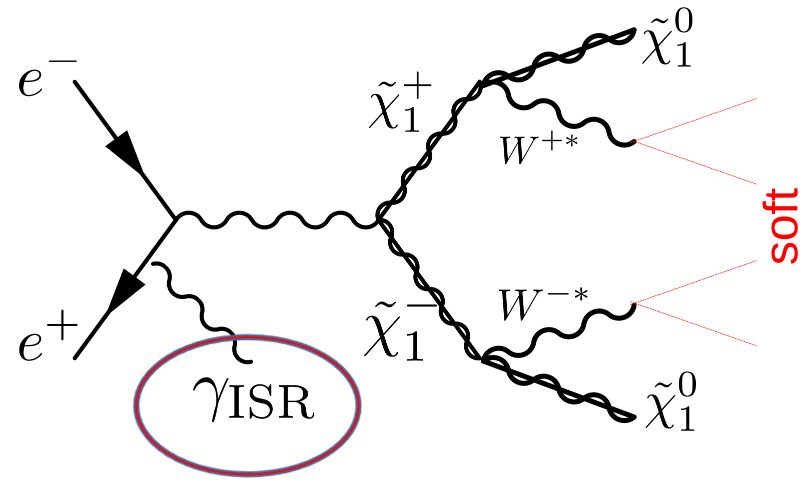




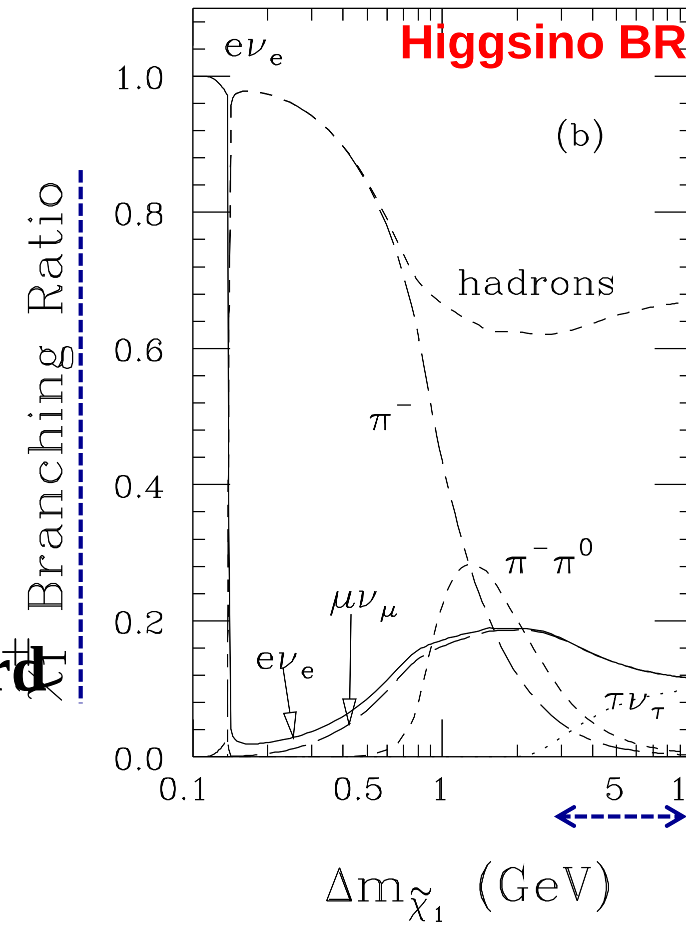
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert [arXiv:1307.3566]

Even for sub-GeV mass differences, the charginos/neutralinos can be discovered / measured to O(1)% in mass.

ISR photon + soft particles



The **ISR tag** is critical in reducing γ γ backgrounds by kicking the **hard forward electrons** into detector acceptance.



Chen, Drees, Gunion
[arXiv:hep-ph/9902309]

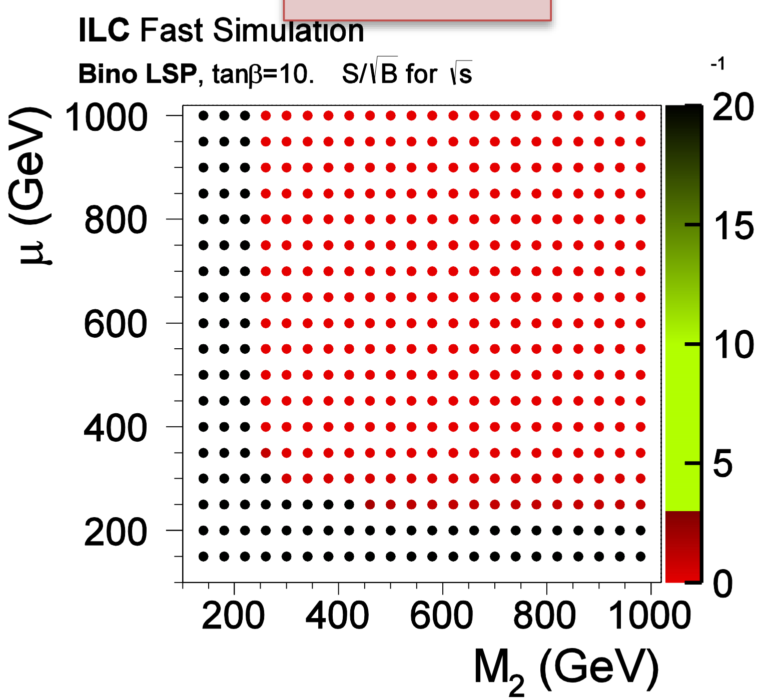
For the soft particles:

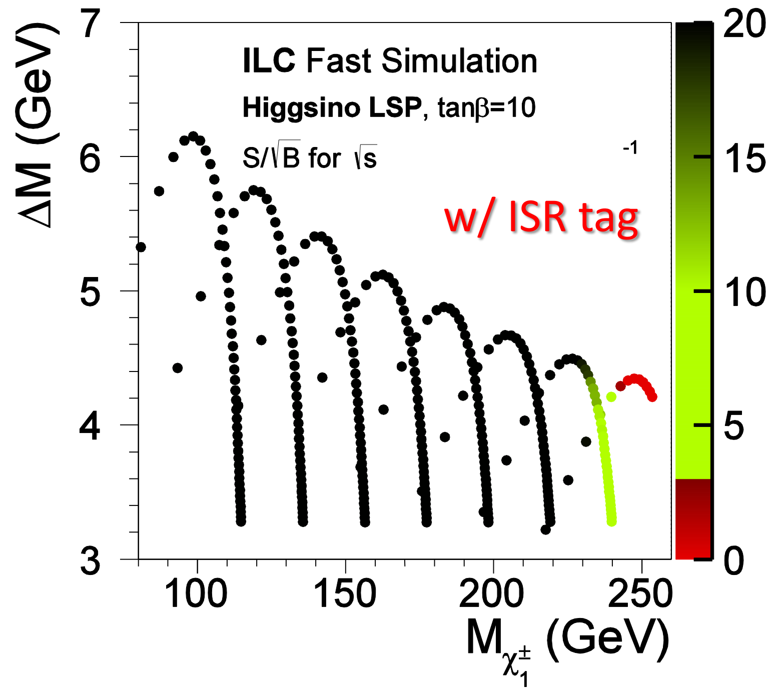
Choose characteristic signature, e.g.
lepton on one side + pions on the other side.

Electroweakino parameter scan

Scan over M_1, M_2, μ (fix 1 as LSP, scan over the two parameters)
The squark/slepton sectors are decoupled.

Bino LSP $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0} + W$ **Higgsino LSP**





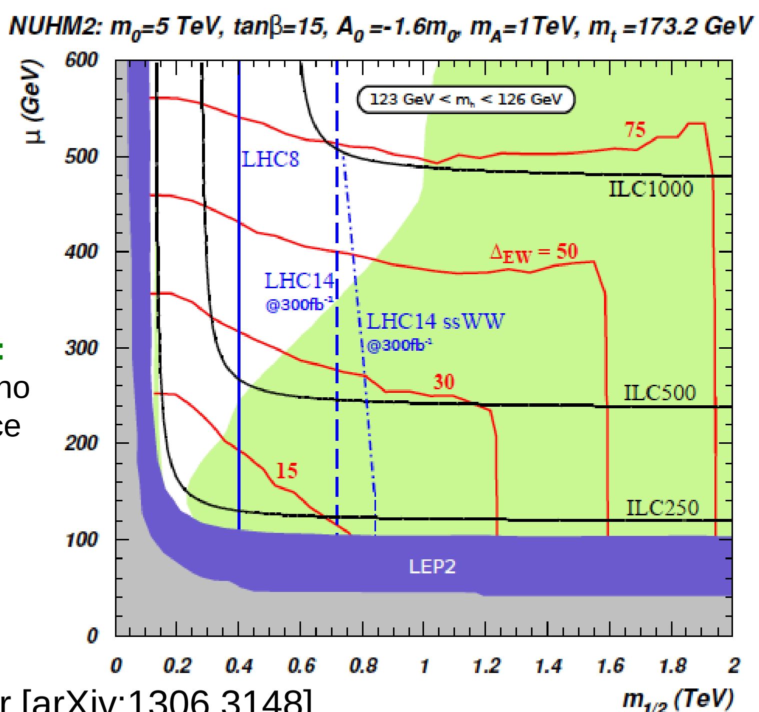
Benchmark: even able to measure sub-GeV mass difference

Berggren, Han, List, Padhi, Su, Tanabe

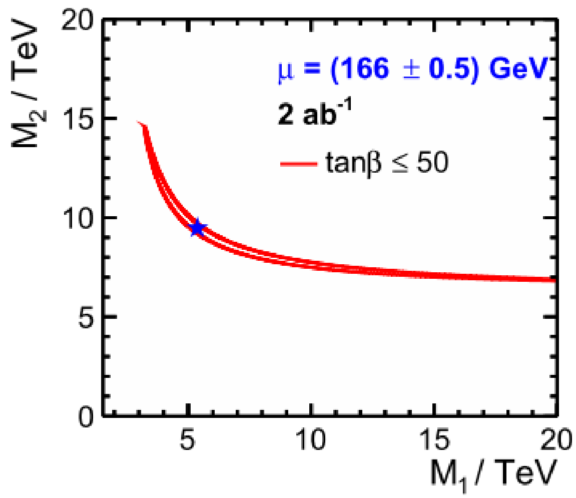
LHC/ILC Complementarity

- SUSY electroweak naturalness prefers light Higgsinos
  - Compressed mass spectrum
  - μ~100-300GeV
  - ILC higgsino factory!

Green region: thermal higgsino relic abundance $\Omega_h h^2 < 0.12$



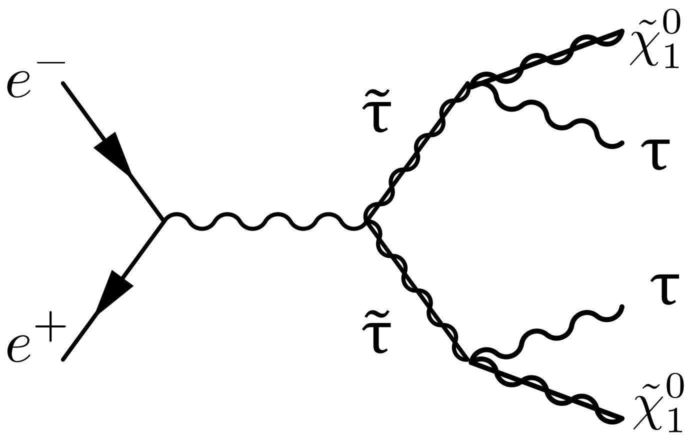
Baer, Barger [arXiv:1306.3148]

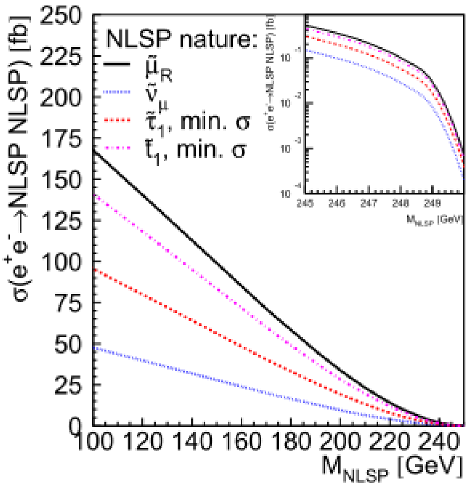


$\Delta(M\tilde{\chi}^{\pm} - M\tilde{\chi}^{0})$ as small as 770 MeV can be measured

Either discover Higgsinos or rule out SUSY electroweak naturalness

NLSP pair production





NLSP→LSP + X. no long decay chains. Simple.
If assume SUSY, σ is determined only by √s & mass

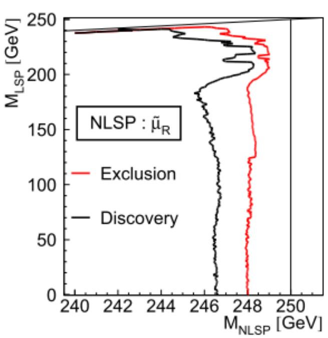
Systematically search for signals for all possible NLSP's , the entire space of models that are within the kinematic reach of the ILC can be covered.

NLSP pair production

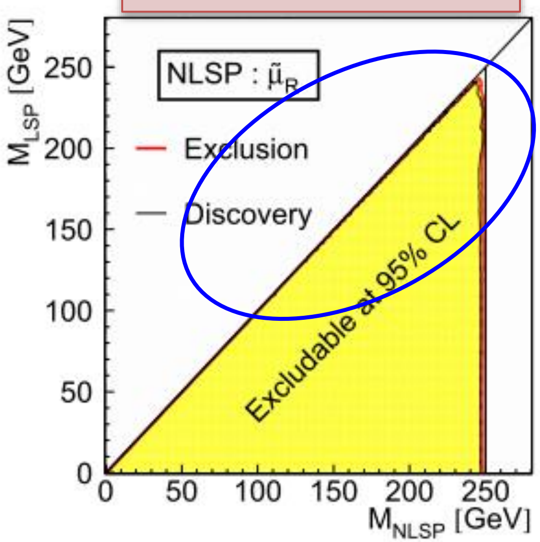
- No loopholes

ILC is especially sensitive to regions of small Mass difference
Difficult to trigger @ LHC

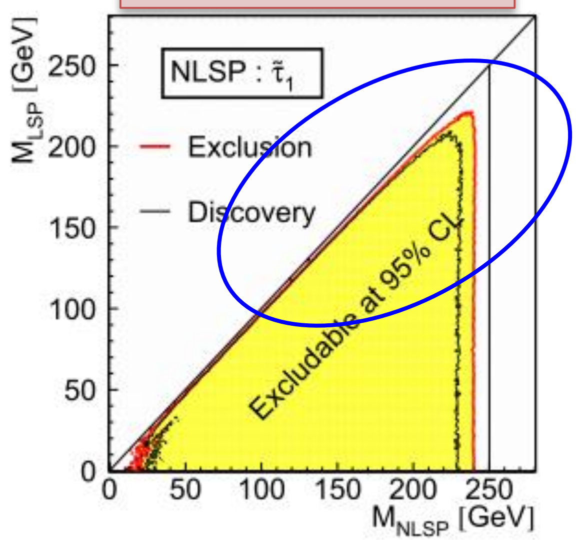
$\tilde{\mu}$ plot enlarged



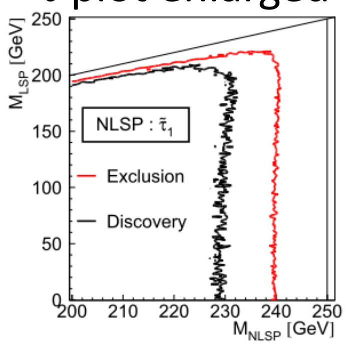
$\tilde{\mu}$ pair production



$\tilde{\tau}$ pair production

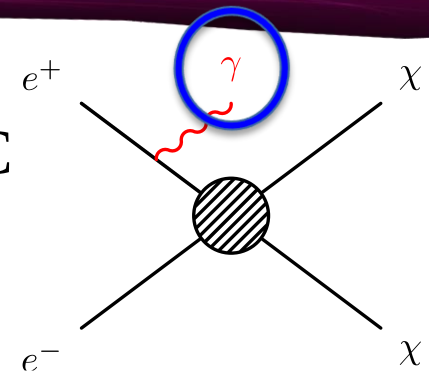


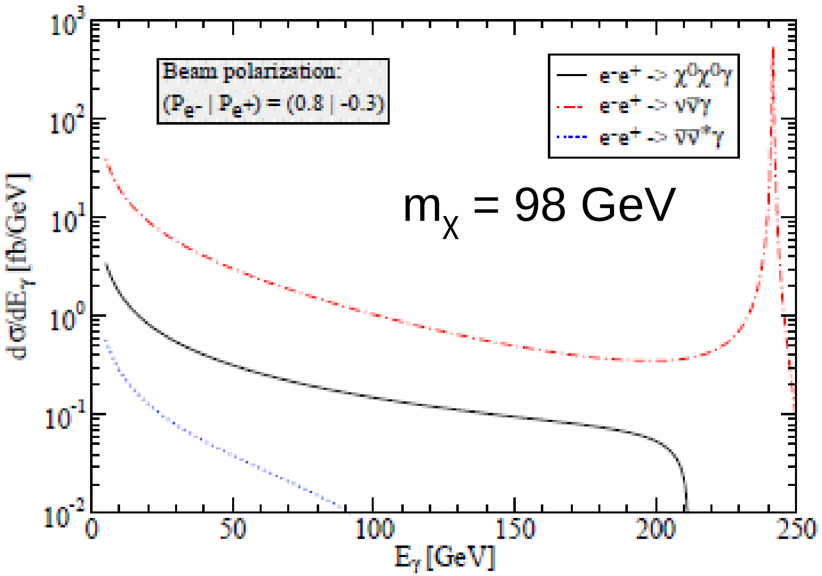
$\tilde{\tau}$ plot enlarged

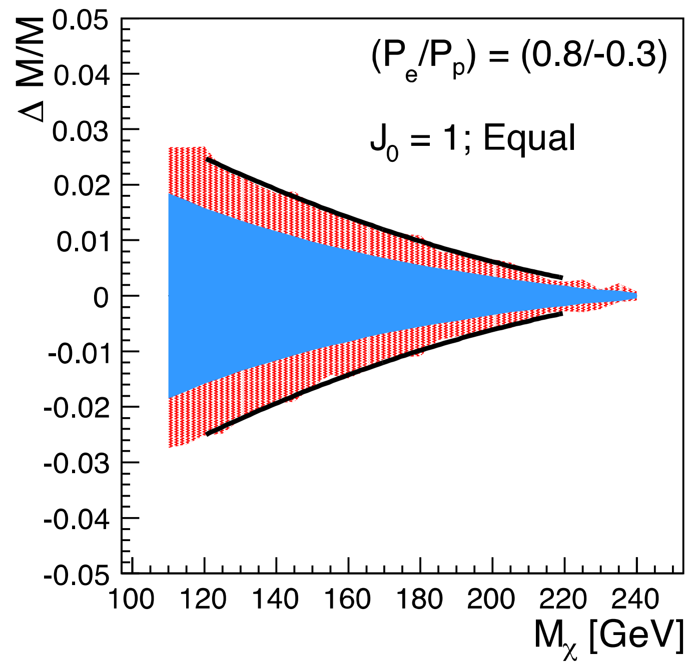


DM with Single Photons

Consider the case where only DM is accessible at ILC
→ Can still discover it with **single photons**







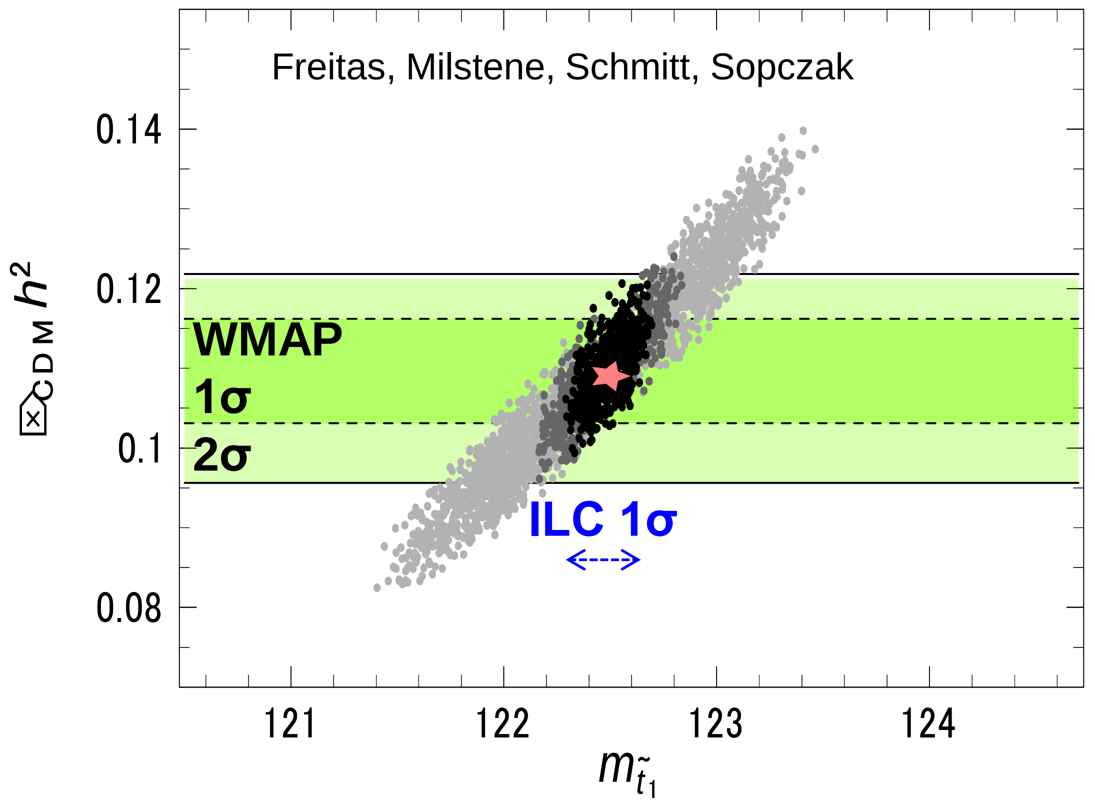
Bartels, List [arXiv:0901.4890]

Discovery of DM w/ mass precision $\Delta m(\chi^0_1)/\chi^0_1$ ~ 3% or better

SUSY / DM Connection

Neutralino LSP with light scalar top with small mass difference can provide cross sections consistent with WMAP data $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \lesssim 30\ \text{GeV}$

Decay modes: $\tilde{t}_1 \to b\tilde{\chi}_1^+ \quad \tilde{t}_1 \to c\tilde{\chi}_1^0$



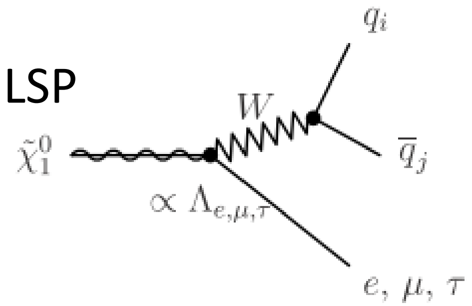
Scalar top discovery + Precision mass measurements

→ **Can establish neutralino as WIMP dark matter**

Neutrino physics @ ILC

- What is the origin of neutrino mass?
  - e.g. Seesaw→induces flavor violating decay of sleptons
  - e.g. Bilinear R-parity violation(RPV)

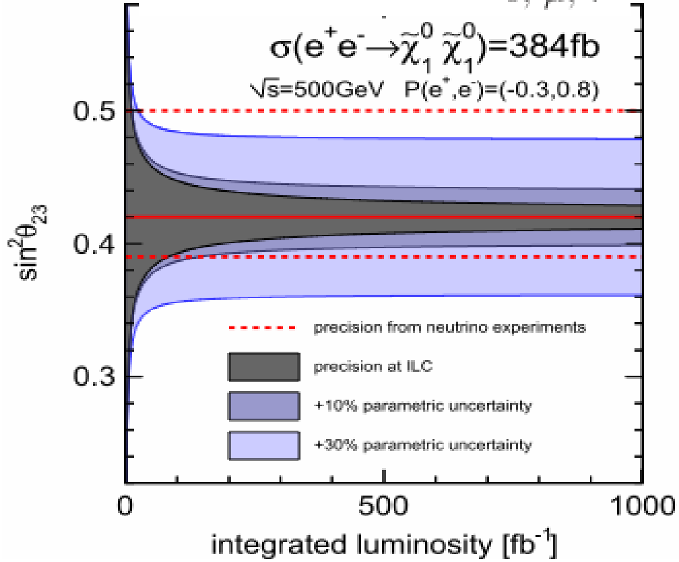
LSP



$$\Psi^{0T} = \left(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \nu_e, \nu_\mu, \nu_\tau\right)$$

$$\mathcal{L} = -\frac{1}{2}\left(\Psi^0\right)^T \mathbf{M}_N \Psi^0 + c.c.,$$

$$\frac{Br(\tilde{\chi}_1^0 \to W\mu)}{Br(\tilde{\chi}_1^0 \to W\tau)} \cong \tan^2\theta_{atm}$$



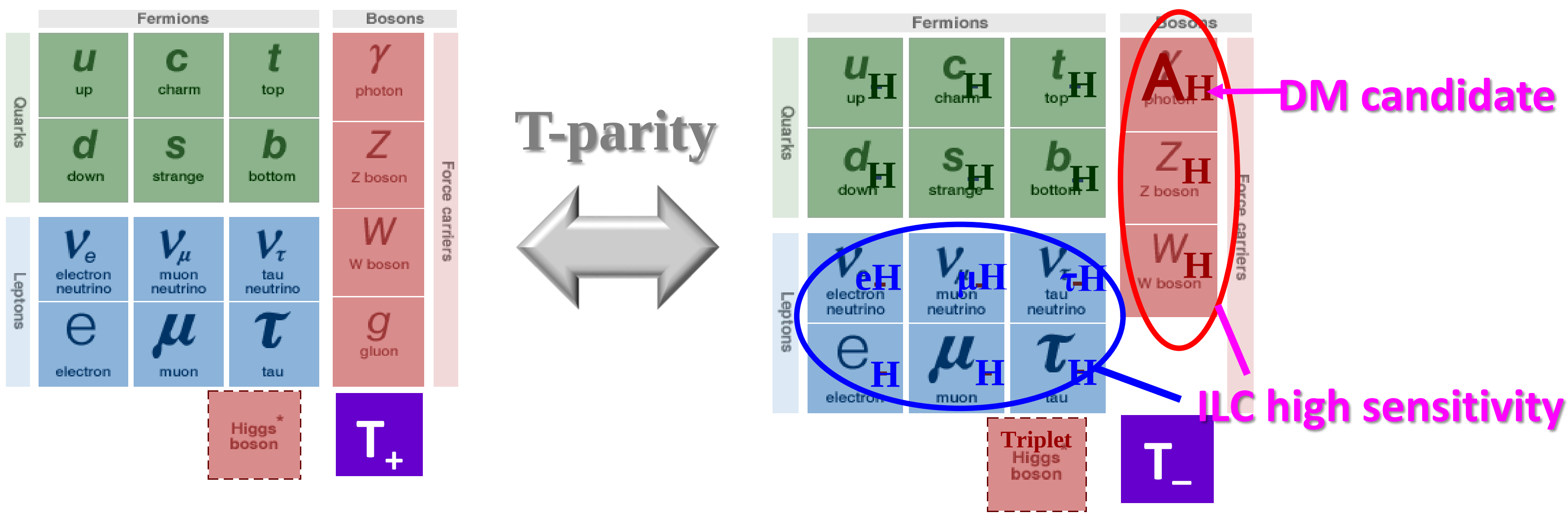
- By comparing with neutrino experiment results, ILC can test if neutrino mixing and mass generation is introduced by RPV

Alternative BSM theories

- Little Higgs models
  - Explains naturalness problem, dark matter
  - e.g. Littlest Higgs model with T-Parity

Global Symmetry : SU(5) → ($f \sim 1$ TeV) → SO(5)

subgroup : $[SU(2)_L \times U(1)_Y]^2$ → $SU(2)_L \times U(1)_Y$ → ($v \sim \langle h \rangle$) → $U(1)_Y$

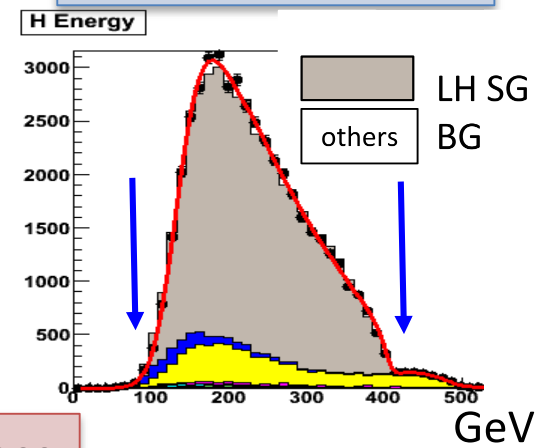


➢ **Quadratic divergent terms in Higgs mass cancel at 1-loop order**

Powerful ILC tools e.g. Little higgs models

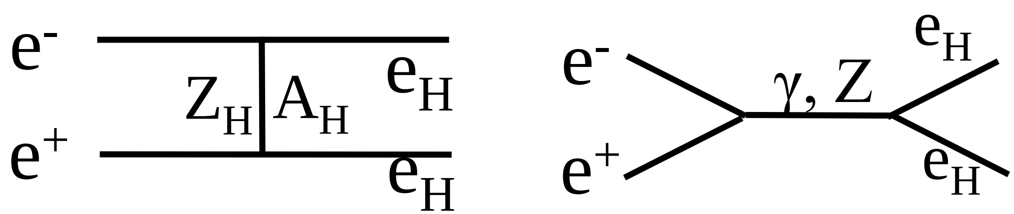
- Model independent mass measurements
  - *e.g.* $e^+ e^- \rightarrow Z_H Z_H \rightarrow A_H A_H HH$
  - Model parameter extraction (vev f, Yukawa coupling κ)

Energy distribution

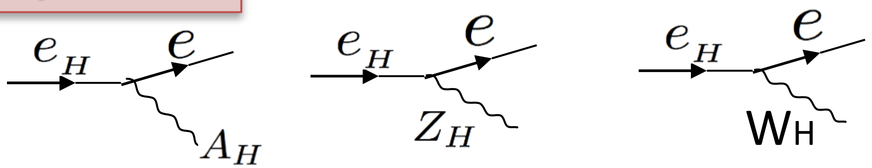


- Many observables
  - Cross section
  - Angular distribution
  - Polarization etc.

Example of a decay process



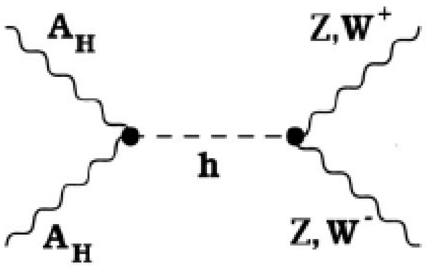
Decay branch

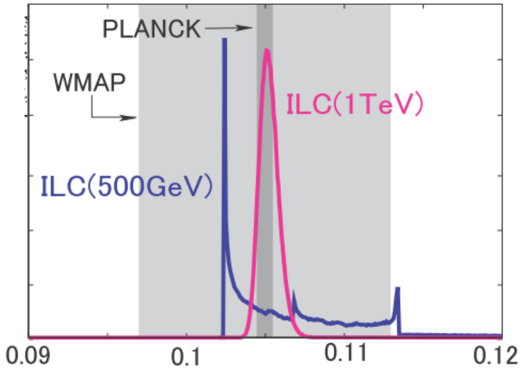


➢ Able to disentangle and measure almost all introduced couplings

What we can test e.g. Little higgs models

- Mass hierarchy
  - Evidence of little higgs mass generation mechanism
- Dark matter relic density
  - Lightest T-parity odd particle is a dark matter candidate
  - Global symmetry vev(f) determines Ωh^2
- ➢ Is LTP indeed the DM filled in the universe?



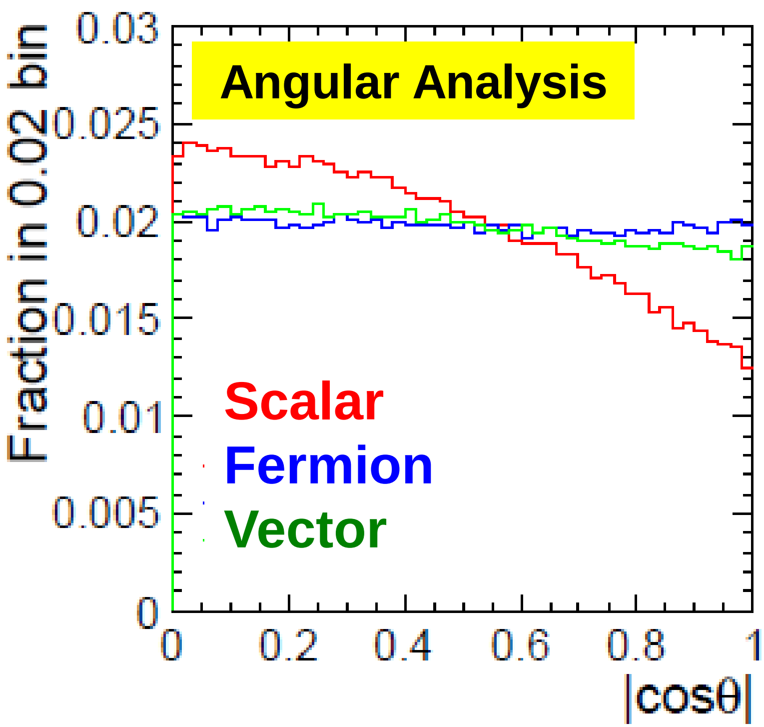


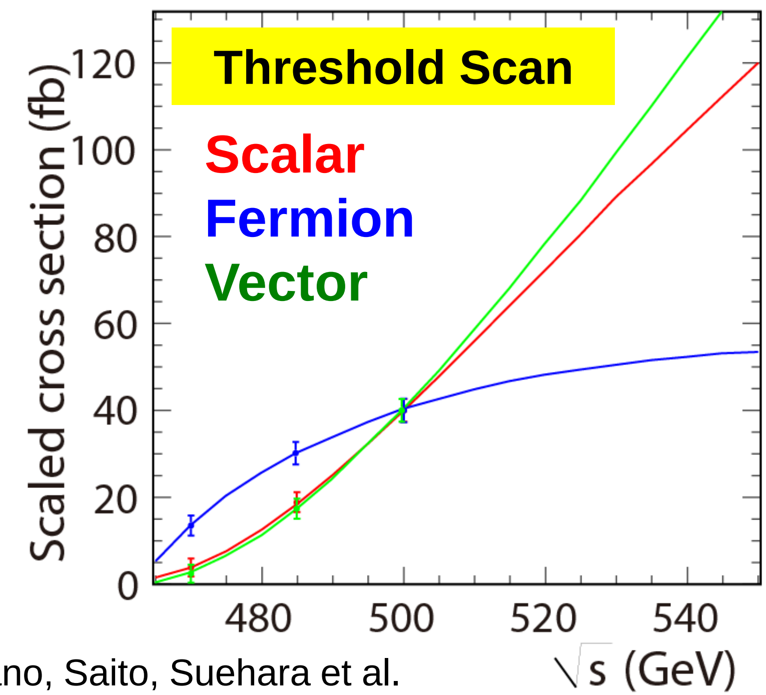
Dark matter relic density Ωh

- Test various coupling relationships
  - Global symmetry should include gauged subsets.
- ➢ Measure the structure of the Little Higgs

Model Discrimination

- Phenomenology: **X**$^+$ + **X**$^-$ → W$^+$ + **DM** + W$^-$ + **DM**
- How to discriminate different physics models?
  - **Spin of X**: e.g. Inert Higgs (0), SUSY (1/2), Little Higgs (1)
- **Angular analysis** of **X production** + **Threshold Scan**





Asano, Saito, Suehara et al.

→ Model Discrimination with spin information

Summary

- There are strong physics cases where the LHC might not be sensitive to NP but the ILC is.
- If LHC14 where to find some NP..
  - ILC's mission will to disentangle NP and do precision measurements to make predictions for higher energy.
- We gave examples..
  - light higgsinos
  - Comprehensive bottom up coverage of NLSP-LSP combinations for slepton, squark, chargino and neutralino
  - Bilinear R-parity violation for neutrino physics
  - Generic WIMP searches
  - Non SUSY models. e.g. Little Higgs models

BACKUP

SUSY is a special case. There is a potentially large positive contribution to the Higgs mass term that must be cancelled.

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

No large cancellations:

$\mu \lesssim 200\ \mathrm{GeV}$	Higgsino mass
$m(\widetilde{t}) \lesssim 1\ \mathrm{TeV}$	stop mass
$m(\widetilde{g}) \lesssim 3\ \mathrm{TeV}$	gluino mass

Optimistically, we will get there at HL-LHC.

M. Peskin, CSS2013

→ If this is the case, ILC will be a Higgsino factory!