Summary and Discussions of 48th General Meeting of ILC Physics Subgroup

Sept 10, 2016, KEK

Jacqueline Yan (KEK)

On behalf of the physics sub-group

Goal of BSM Study Group

Provide a clear vision on the potential of ILC physics

Higgs/EW　　Top　　BSM

<u>Particularly commenting on "BSM"</u>

- **Direct search for new particles**
  complementary to the LHC

- **indirect search through precision measurements of SM physics (Higgs boson and top quark couplings, 2-fermion processes)**
  a powerful approach guaranteed at the ILC

Many Contributions Today

Higgs/EW:
T. Ogawa: Anomalous HVV coupling
Y. Kato: BSM Search using Higgs to Invisible Decay

Top Physics:
Y. Kiyo: threshold effect in neutral Higgs decays
Y. Sato: top cross section and AFB

BSM:
J. Yan: Light Higgsinos from Natural SUSY at ILC $\sqrt{s}$=500GeV

Usually other talks as well, Higgs self Coupling, etc….

We plan to submit a document to the MEXT (ILC Advisory Panel) to demonstrate the potential for new physics discovery at the ILC

Follow up to the ICFA letter

A Report on

Prospects for New Particle Discovery Potential

From slides of K. Fujii

by the end of this summer

Contents: Prospects for new particle discoveries at ILC
Target: MEXT Expert Panel (official name: MEXT ILC Advisory Panel)
Length: ??
Deadline: Summer 2016
Purpose: Backup the short report with updates taking into account LHC Run II development (as recommended by MEXT)

Plan

Report to be based on a ILC-LHC comparison table of discovery potential

Structure of the table

Typical discovery scenarios in Y-axis

- SUSY (subdivision such as Bino-, Wino-, Higgsino-LSP, as needed)
- Minimal Composite Higgs Models (subdivision as needed)
- Dark matter particles

Discovery channel/method in X-axis

- Precision Higgs measurements
- Precision top measurements
- Indirect searches (other than H and t)
- Direct searches

Each cell

Prospects at ILC (depending on 13TeV LHC results)

Key message to deliver

There are other important kinds of discovery than new particle discovery!

From slides of K. Fujii

If Some New Physics Signal Seen at 13 TeV LHC

	Precision Higgs	Precision Top	Other Indirect Methods	Direct Searches
SUSY				
Compositeness				
DM				
...				

Completion of this table is the near future goal

New Physics Discovery at LHC ?
Prepare for both scenarios
(yes and no)

If new physics signals seen / not seen at 13 TeV LHC

	Precision Higgs	Precision Top	Other Indirect Methods	Direct Searches
SUSY				
Compositeness				
DM				
…				

Active participation from Asian team in many of these cells

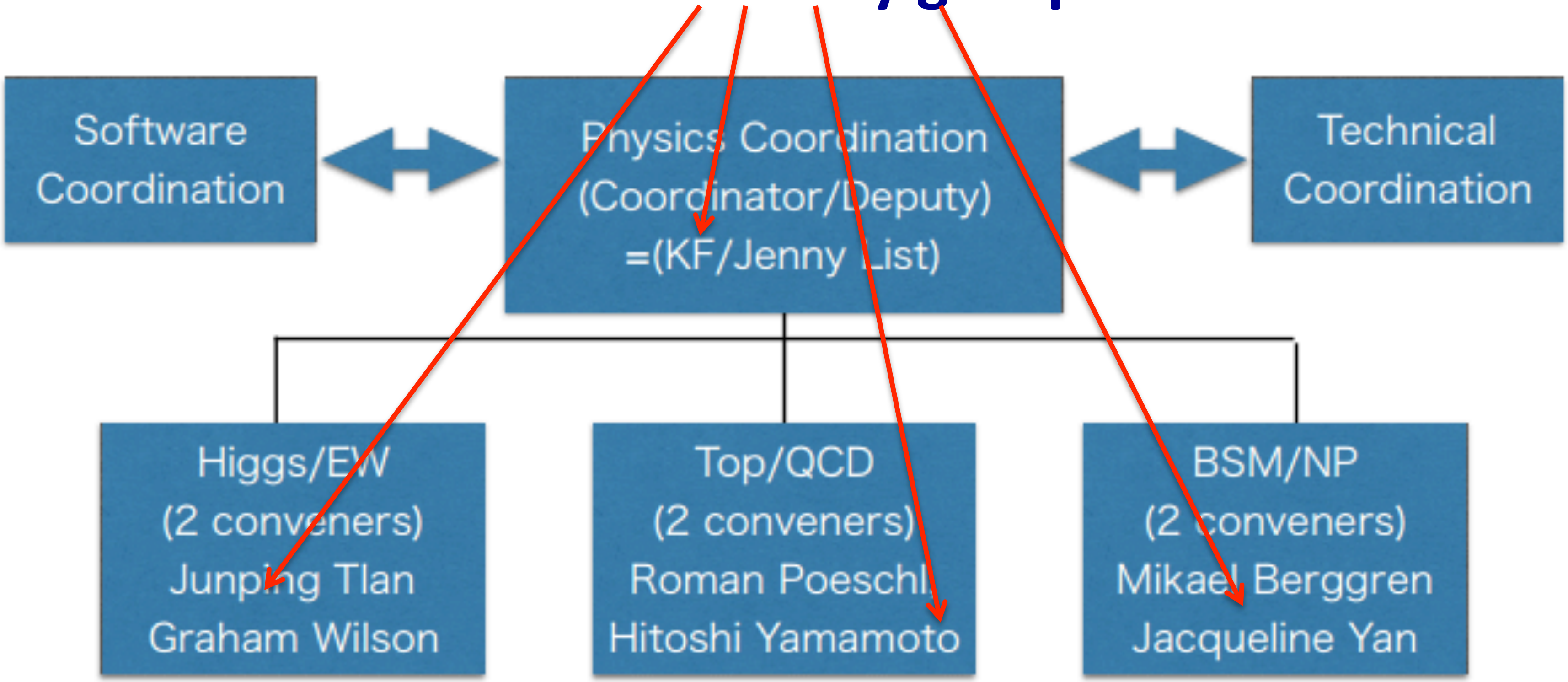
However much remains to be done (analysis, software, theoretic studies)

We need to start working here

We need physics studies that backup the table and make it fully convincing.

- **Form a team for each row (=discovery scenario)**
- **Prepare contents in each cell**
- **Combined (global) analyses of Higgs/Top/New Physics**
- **Involve theorists**

We have a convener from out Asian team for each of the three study groups



The structure and the members of the physics coordination team have been approved by IA.

We may add more subgroups as needed.

Major BSM Studies

Indirect Search

- Precision measurements of SM physics

  (Higgs and top couplings, 2 fermion processes)

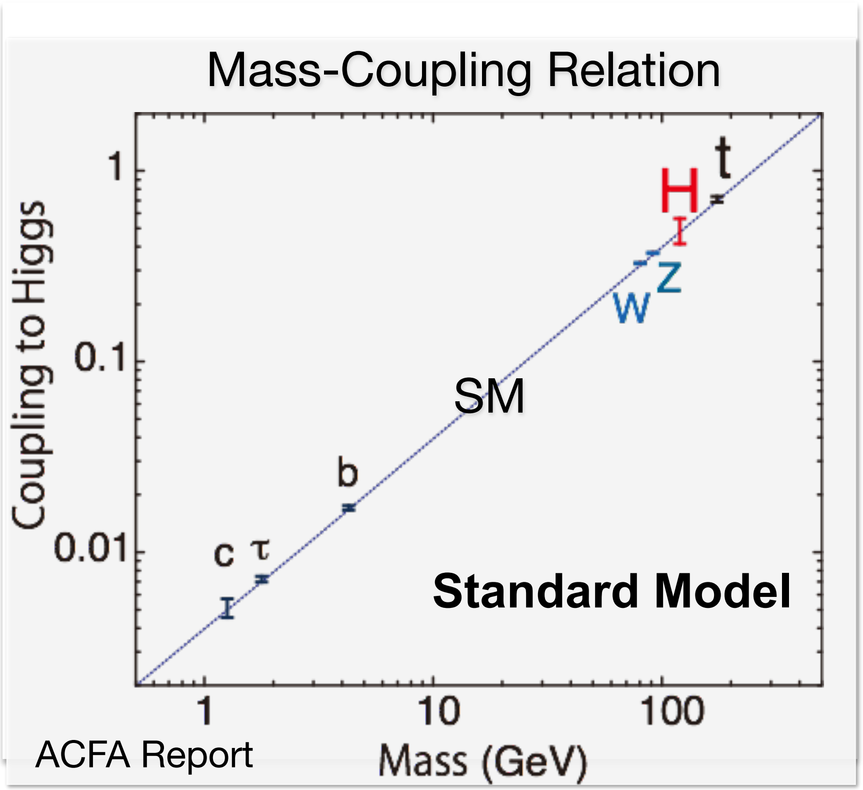
Direct Search

- Dark matter Search (mono-photon / using H→ invisible)
- Light Higgsinos from natural SUSY with compressed mass spectra
- Light Stau with compresses mass spectra

New Physics Search using Precise Measurement of Higgs Couplings

In SM, particle mass is proportional to coupling strength *is this really correct ?*

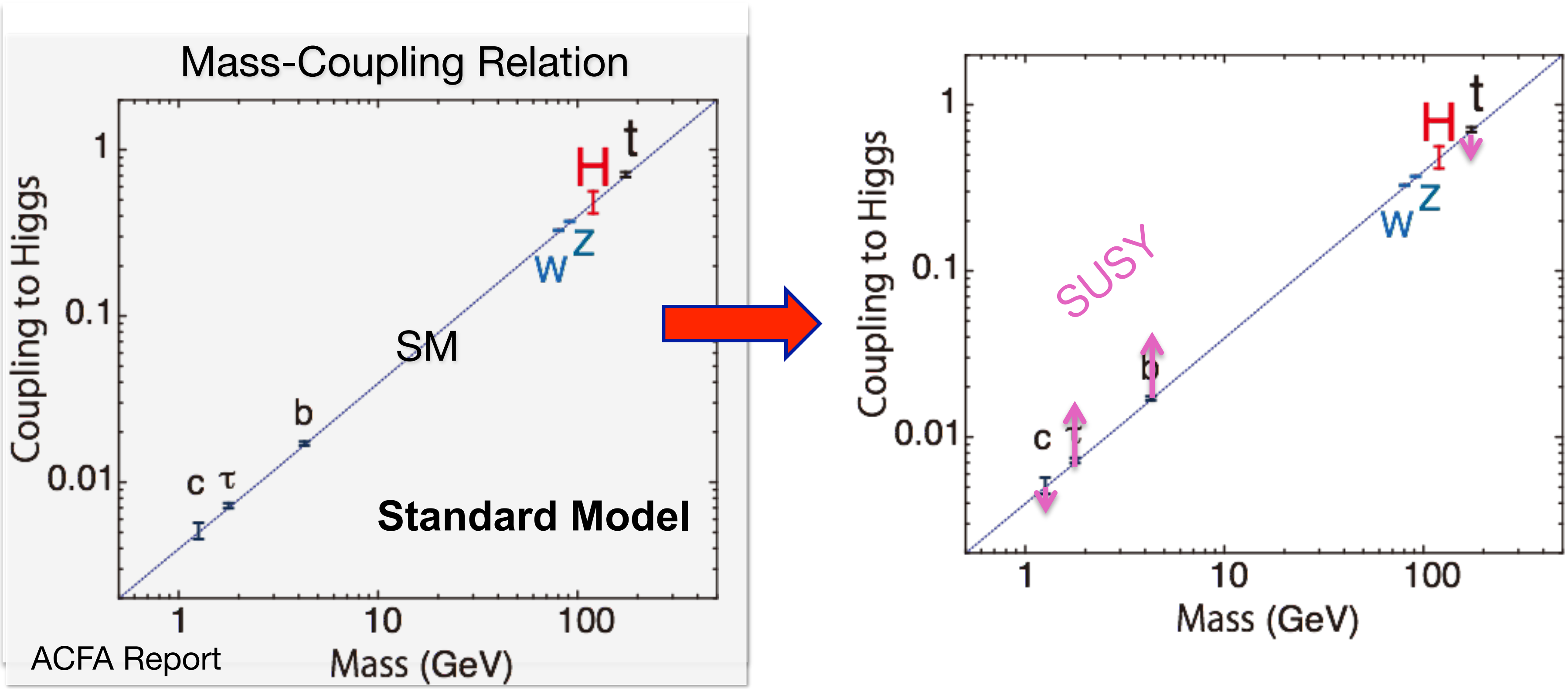
What will happen if there exists new physics ?



New Physics Search using Precise Measurement of Higgs Couplings

In SM, particle mass is proportional to coupling strength

New Physics ➔ deviation from straight line



Pattern / size of deviation depends on new physics model and energy scale

➔ precisely measure this to distinguish new physics models

Precision Higgs measurements are promised at the ILC
---- a powerful approach to new physics search ----

New Physics Search using Precise Measurement of Higgs Couplings

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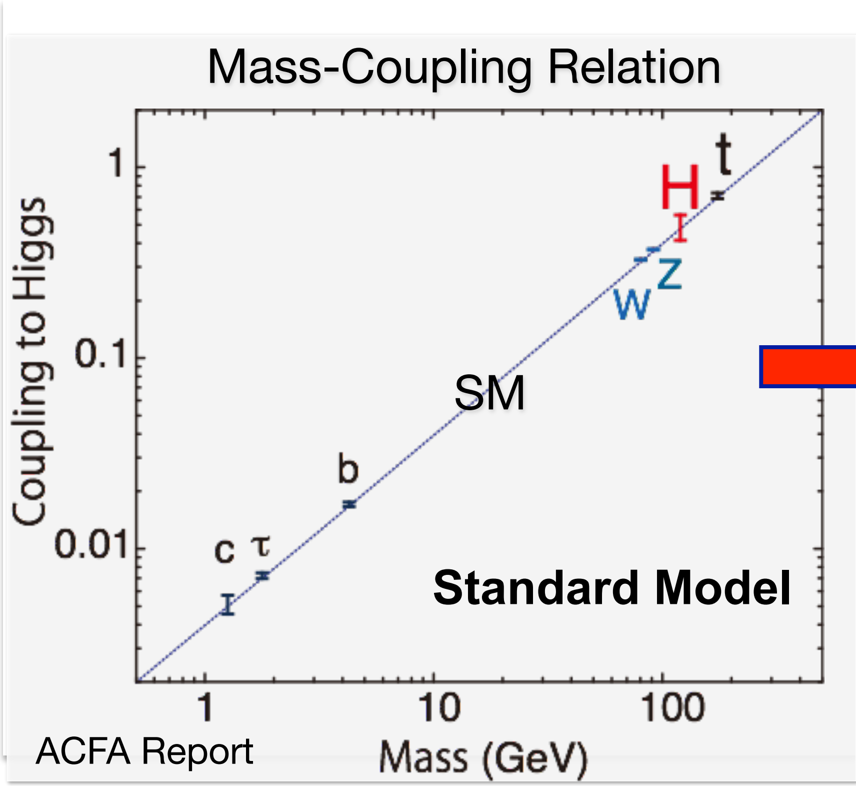
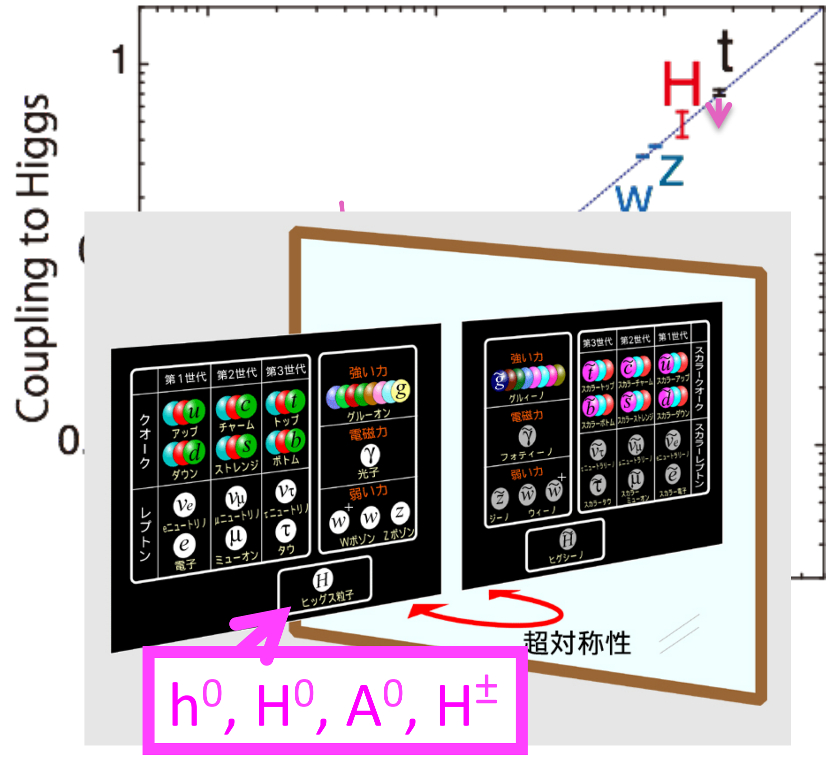




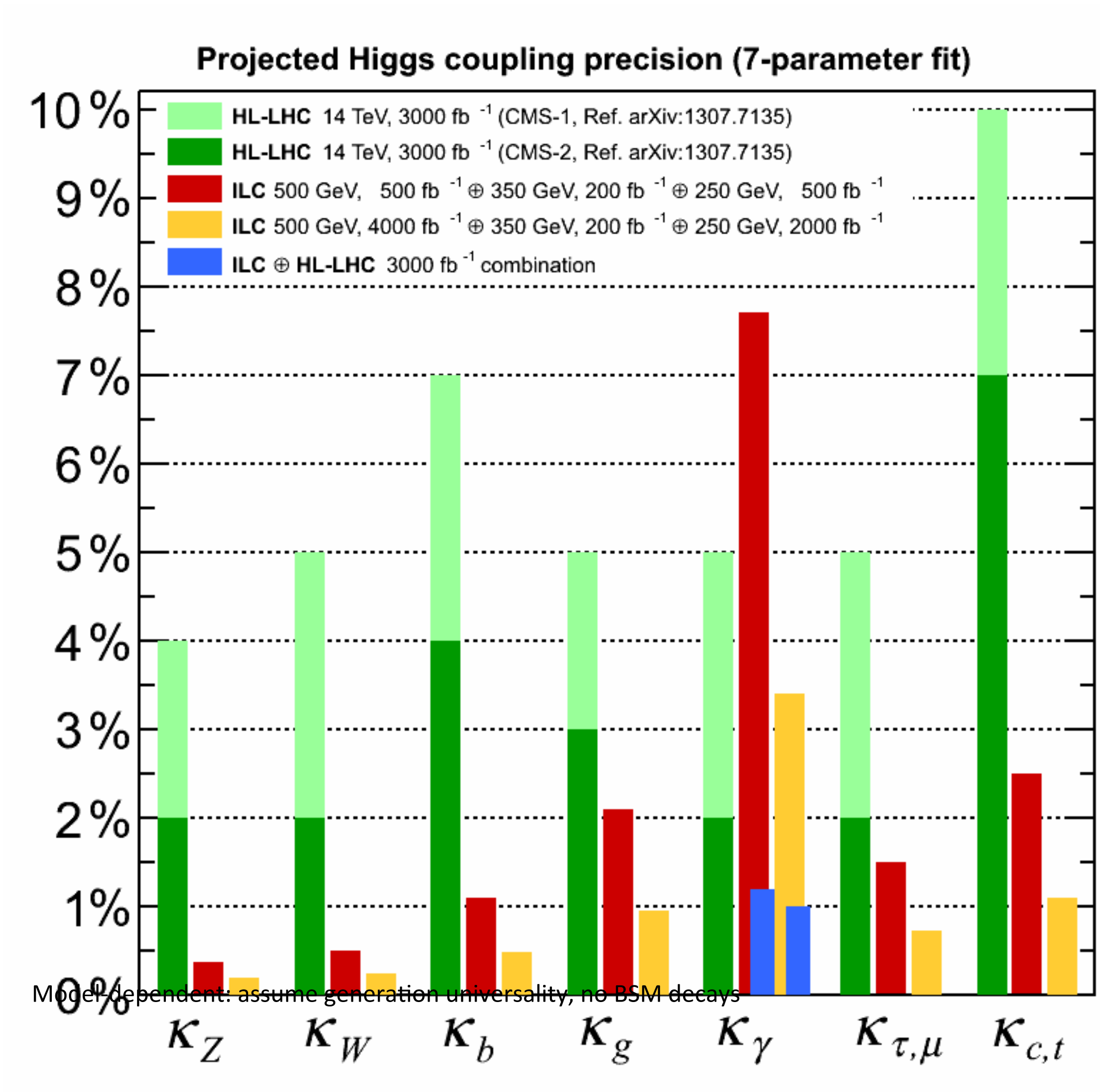
Pattern / size of deviation depends on new physics model and energy scale
➔ precisely measure this to distinguish new physics models

Precision Higgs measurements are promised at the ILC
---- a powerful approach to new physics search ----

Precision of ILC Higgs Coupling Measurements

compared to the LHC

HL-LHC : final data
ILC ~8 yrs run
ILC ~20 yrs run
ILC and LHC synergy



Model-dependent: assume generation universality, no BSM decays

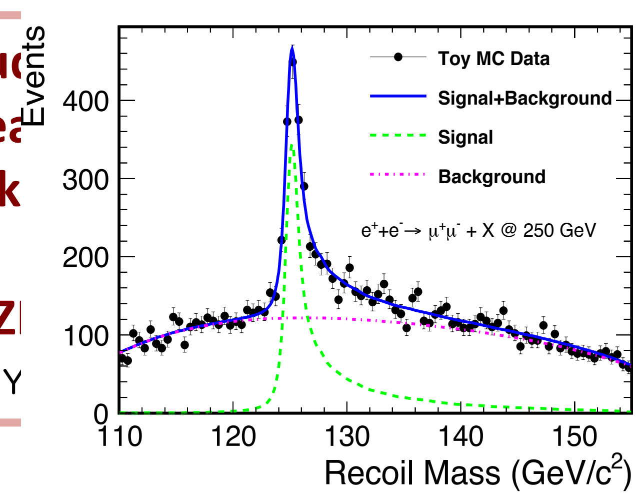
ILC is capable of 3-10 times higher precision than LHC
(almost all couplings better than 1%)

- **ILC is needed for detecting O(1)% deviation from SM**

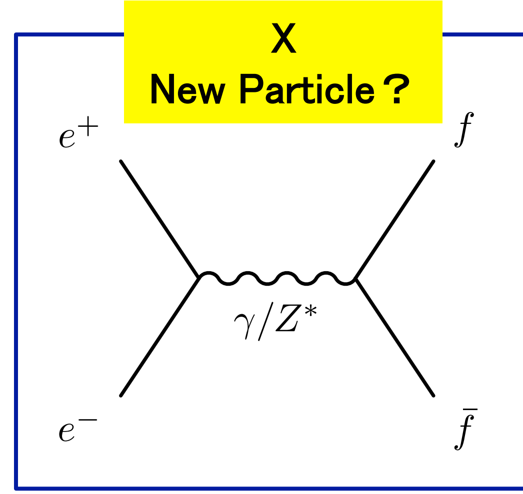
Stu
mea
talk

σZ

J.Y



Search for new interaction forces : 2–fermion processes and top precision measurements



Measure the effect of new forces on SM physics

e.g. heavy gauge boson Z'

LHC: direct search

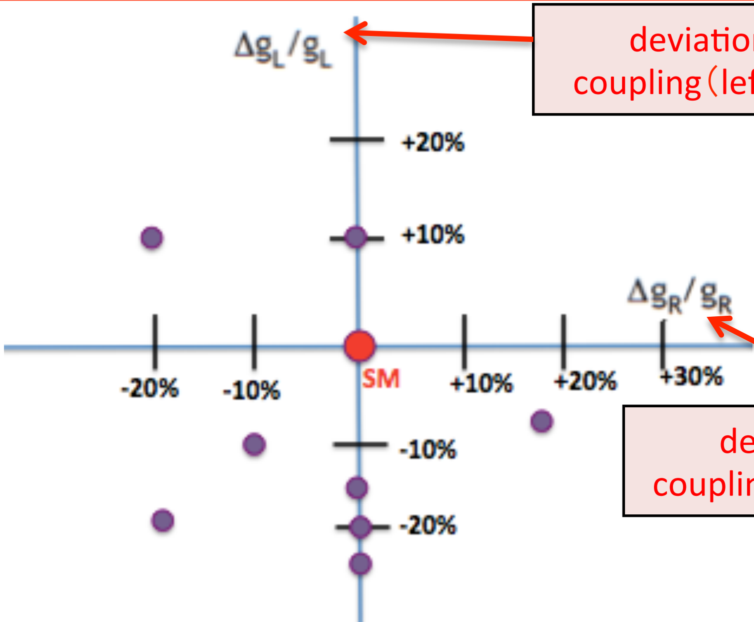
ILC: determine new physics model
using precise coupling measurements

f = top quark, leptons, etc..
X = Z′, KK graviton, etc…

example) **deviation of top quark coupling from SM signifies new physics**

Top coupling anomalies for various new physics models （energy〜1 TeV)

Beam polarization is a MUST

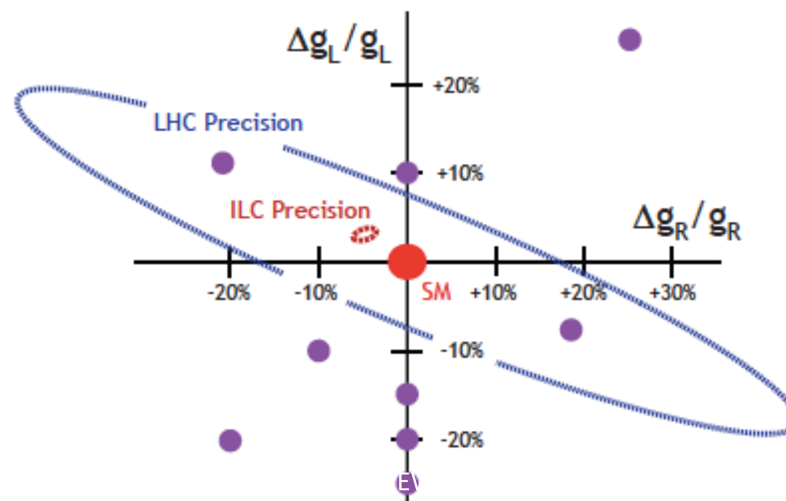


deviation of ttZ coupling（left-handed）

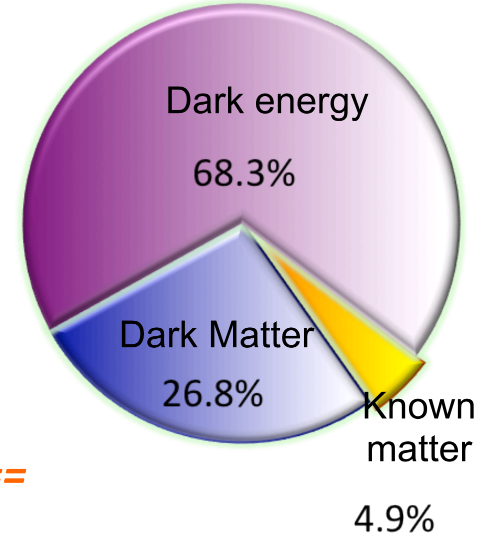
deviation of ttZ coupling（right-handed）

ttZ coupling measurement

ILC can exclude more models than LHC (68% CL)



Dark Matter Search at the ILC

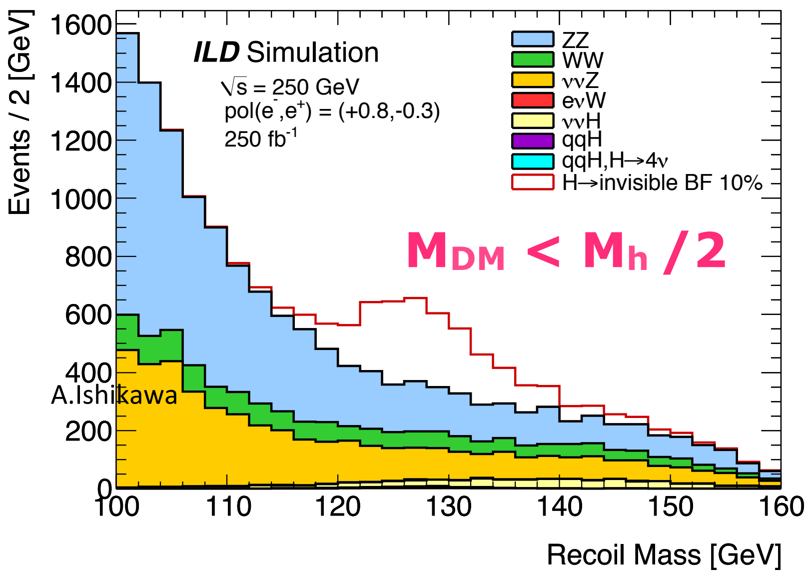


Production, discovery, and detailed study of DM (WIMP) is anticipated at the ILC

at ILC energy lightest SUSY particle is strong DM candidate
➔focus on SUSY signals (light Higgsinos, light stau)

========== Activities by Asian groups ==========

Higgs Invisible Decay

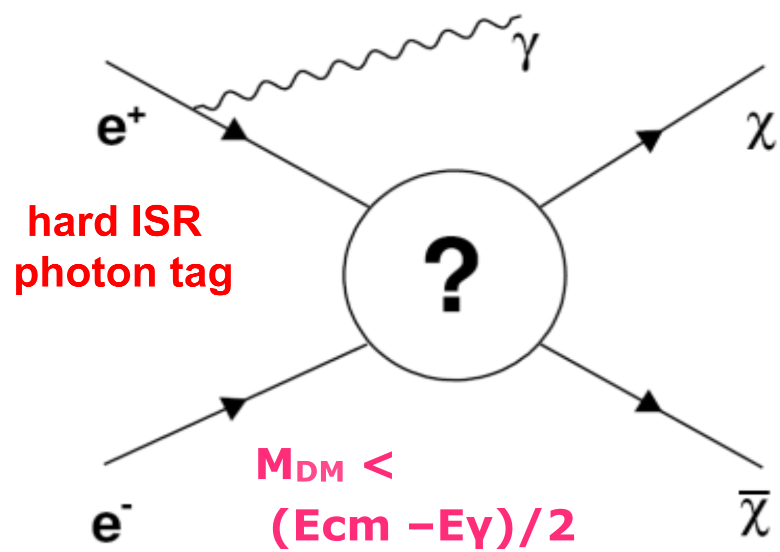


A. Ishikawa, J. Tian et al

If BR(H->invis) deviate from SM →BSM

BR(H→invis.) < 0.4% at 250 GeV, 1150 fb^{-1}

Monophoton Search

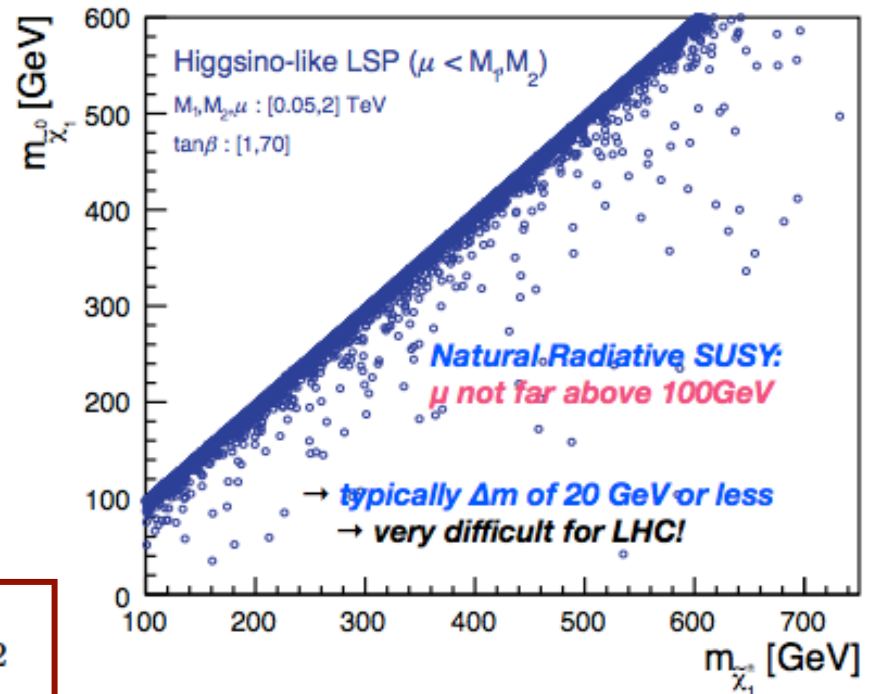


T. Tanabe et al

Motivation for Searching Light Higgsinos with Small ΔM

❖ From experimental point of view:

- LHC already excluded large regions with large ΔM = M(NLSP) – M(LSP)
- Remaining region with compressed spectrum
  very small visible energy release,
  near impossible to probe at LHC
  ➔ **ILC is essential**



❖ From theoretical point of view:

Compressed Higgsino spectra related to naturalness [e.g. arXiv:1212.2655, arXiv:1404.7510]

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- To maintain **small electroweak fine tuning ΔEW (<∼3%)**, all contributions on right-hand-side should be comparable to M(Z) ➔ requires **μ ∼ 100–300 GeV**

  top and bottom squarks in the few TeV regime, gluino mass 2−4 TeV,
  1st, 2nd generation squarks and sleptons in the 5−30 TeV regime

- μ feeds mass to both SM (W, Z, h) and SUSY particles (Higgsinos)
- Higgsino masses not too far from masses of W, Z, h (∼100 GeV)

Summary / To-DO

- ❖ We aim to provide a **clear vision on the potential of ILC physics**
  Particularly urgent is discovery potential of new physics at the ILC
  ➔ follow up document to ICFA letter (~Dec 2016)

- ❖ **need more physics studies to make it fully convincing.**
- **Asian groups are actively participating**
- **However much remains to be done (analysis, software, theoretic studies) ➔ form a team for each study topic**

- **dedicated conveners for each working group will provide support for newcomers and ongoing studies**
- **2 fermion process**
- **Higgsino related studies (e.g. alternative energies and benchmarks)**
- **Dark matter search**

and others.....

- **Call for more active participation in weekly / biweekly meetings**
- **Encourage newcomers**
- **Increase publications on ILC physics analysis**

If new physics signals seen / not seen at 13 TeV LHC

	Precision Higgs	Precision Top	Other Indirect Methods	Direct Searches
SUSY				
Compositeness				
DM				
...				

Active participation from Asian team in many of these cells

However much remains to be done (analysis, software, theoretic studies)

Please join ongoing analysis !

We need to start working here

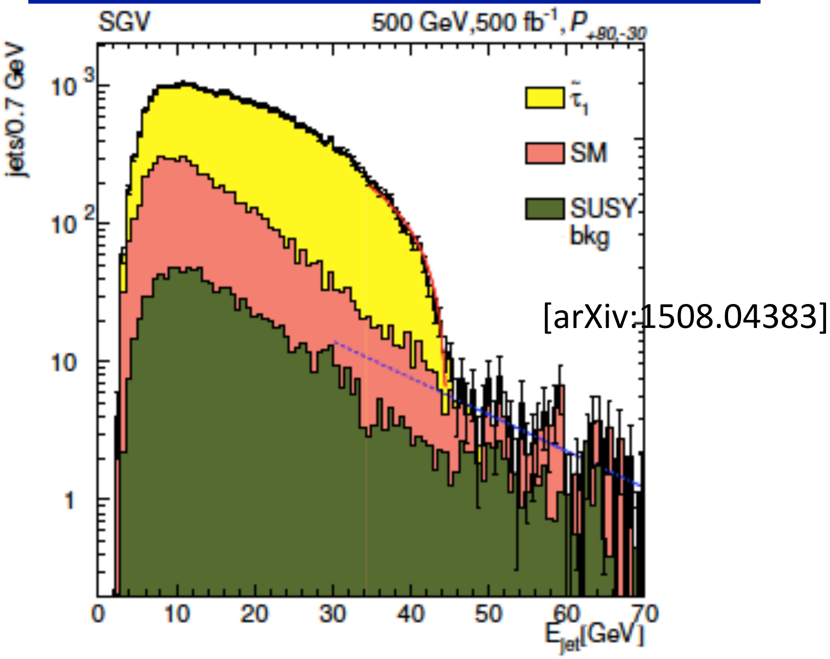
New Ideas are welcome !

There are a variety of studies newcomers can choose from

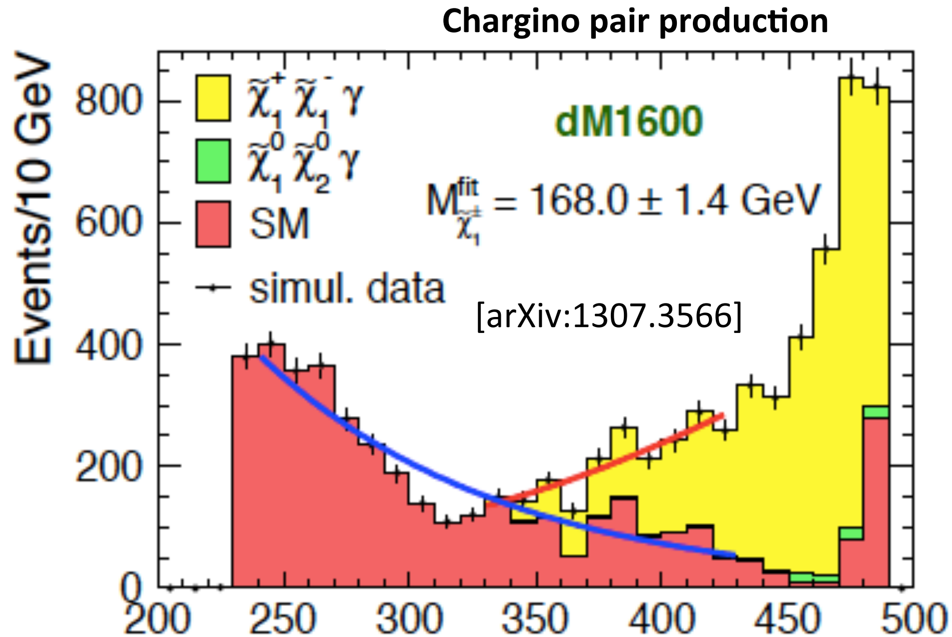
We anticipate your participation to make the ILC physics case as strong as possible!

Additional Material

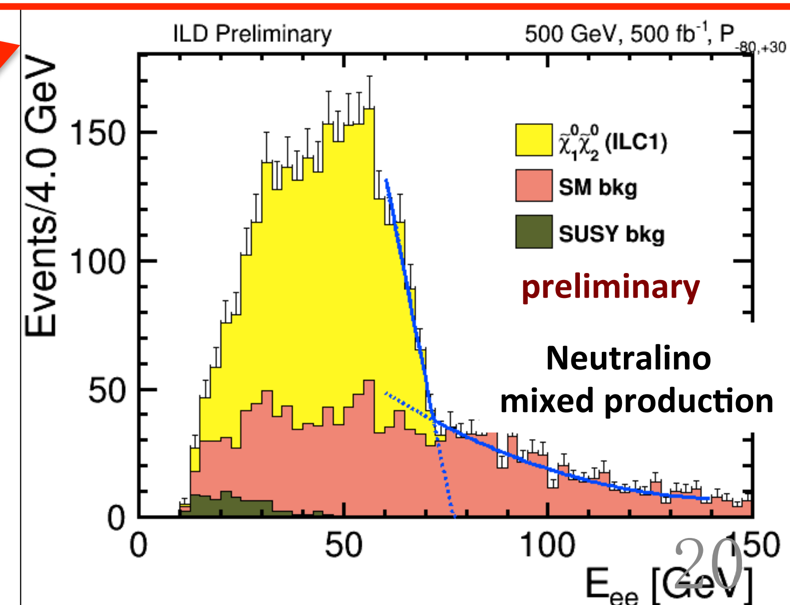
Light stau, ΔM=10 GeV, √s = 500 GeV



Light Higgsino, ΔM=1.6 GeV, √s = 500 GeV



Light Higgsino, ΔM=21 GeV, √s = 500 GeV



Ongoing study in Asian group

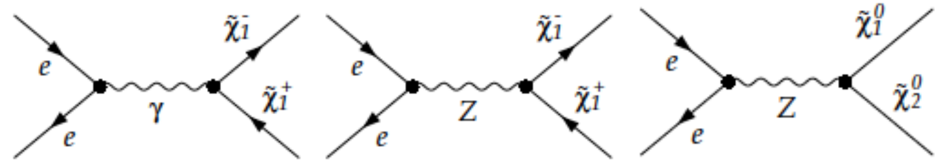
J. Yan (KEK) and T. Tanabe (U. of Tokyo)

We still have yet to pursue other variations of this study:

- **Higgsinos with masses close to √s / 2**
- **Threshold scan at lower √s**
  → **precise mass determination**

etc …….

Goal of Light Higgsino Study



Demonstrate measurement precision of Higgsino masses and production cross sections

Masses and cross sections as input →

Determine SUSY parameters
e.g. **M_1, M_2, μ, tanβ**

Why?
- **To get info about unobserved sparticles**
- **To test GUT-scale models**

How?
- **Global χ^2 fit of to observables**

- **Study dependence of cross section on beam polarization**
  → Determine mixing ratio
  Higgsino vs. Bino vs. Wino

Study input parameters and required precision for parameter extraction; interplay with Higgs precision measurements

Existing studies

(1) "Tackling light higgsinos at the ILC", M. Berggren et al. [arXiv:1307.3566]
- √s= 500 GeV, ΔM ∼1 GeV → use ISR tag, , Based on full ILD simulation

(2) "Physics at a Higgsino Factory", H. Baer et al. [arXiv:1404.7510]
- √s= 250 (340) GeV for ILC1 (ILC2), ΔM = 10-20 GeV, detector effects based on resolution formula

Ongoing studies

Asian group

Light Higgsinos with ΔM= 10 – 20 GeV , J. Yan, T. Tanabe et al
√s= 500 GeV, ΔM ∼10-20 GeV , Based on full ILD simulation

BSM Search Strategy at ILC

Focus on three cases based on the results of the (HL)-LHC:

Case 1: No discovery at LHC

- SUSY: Discovery anticipated for light SUSY particles (e.g. Higgsino)
- Dark Matter: Discovery anticipated for DM that can be seen at the ILC
- Precision measurements might give first discovery of new BSM interactions

Case 2: LHC discovers light new particles (can be seen at the ILC)

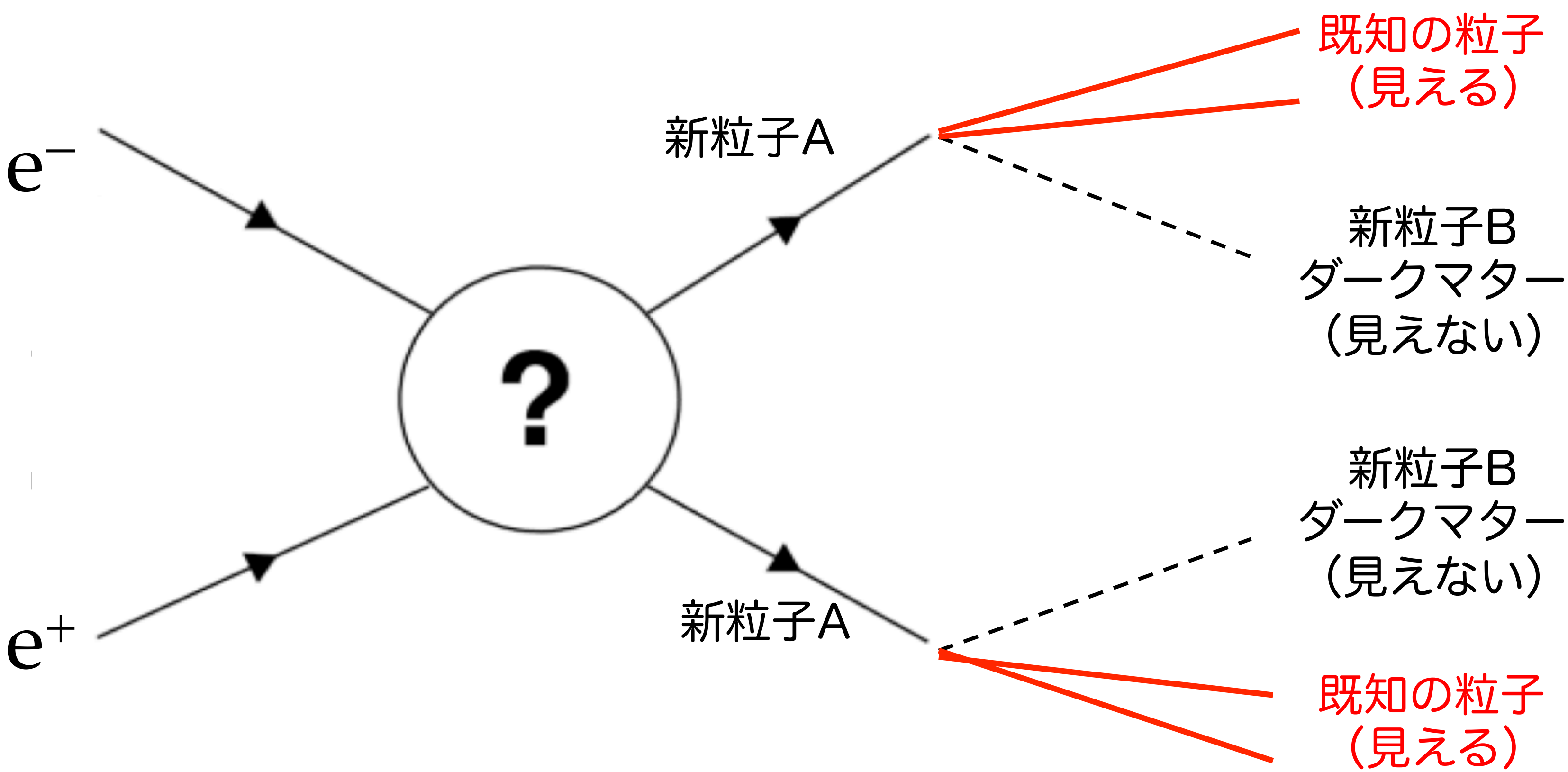
- SUSY: ILC will probe the new particles in detail; may discover more.
- Dark Matter: ILC will address the question of whether any of the new discovered particles is DM
- Precision measurements sensitive to heavy particles beyond LHC reach.

Case 3: LHC discovers heavy new particles

- SUSY: It is probable that ILC will discover new light particles.
- Dark Matter: Same as in Case 2, via measurements of the new light particles.
- Precision measurements test if there are additional heavy particles beyond the LHC reach.

From slides of T. Tanabe

ダークマターへ崩壊する新粒子探索



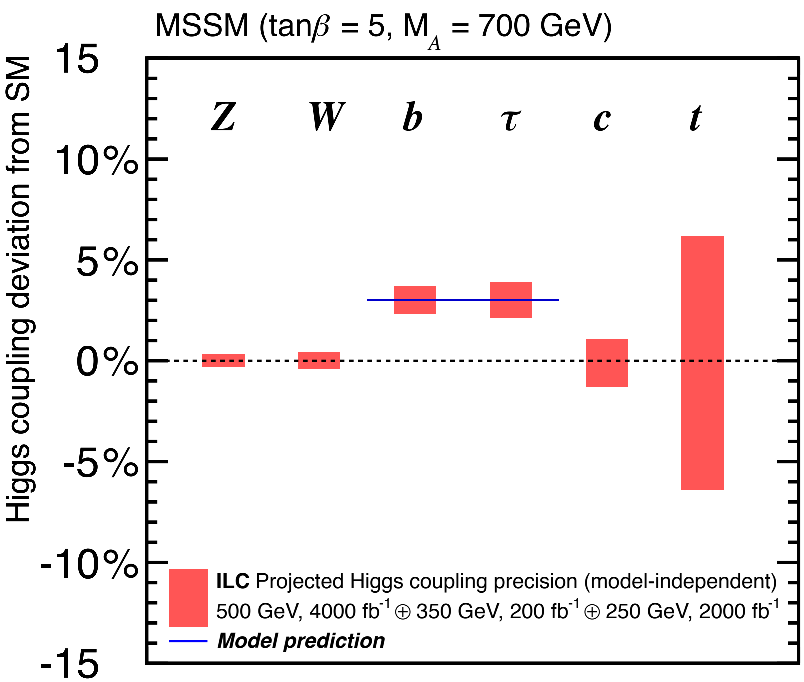
AとBの質量の差が小さいと見えるエネルギーも小さい

ILCなら発見可能（ILC測定器がすごい）

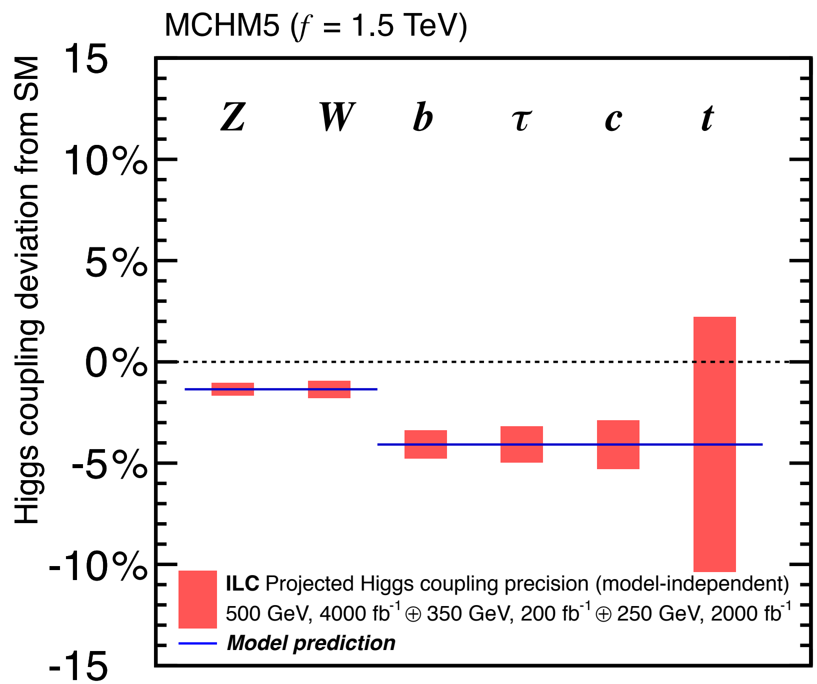
Fingerprinting

Higgs boson: elementary or composite?

Supersymmetry (MSSM)



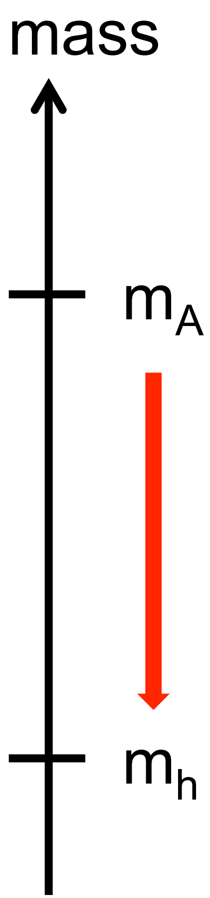
Composite Higgs (MCHM5)



→ Capability to distinguish models exhibiting specific patterns

Deviation in Higgs Couplings

Size of the deviation depends on the scale of new physics.



Example 1: MSSM (tanβ=5, radiative corrections ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

composite scale

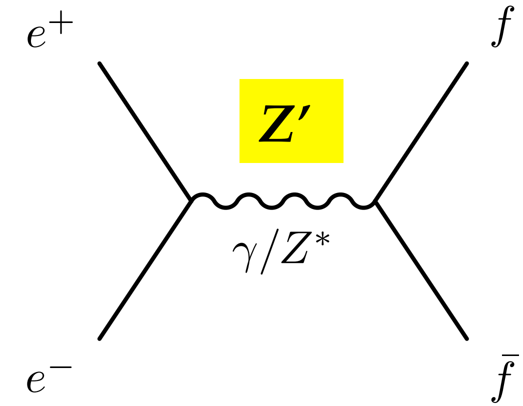
New physics at 1 TeV gives only **a few percent** deviation.
We need **%-level precision** to see such a deviation → **ILC**

Z' : Heavy Neutral Gauge Bosons

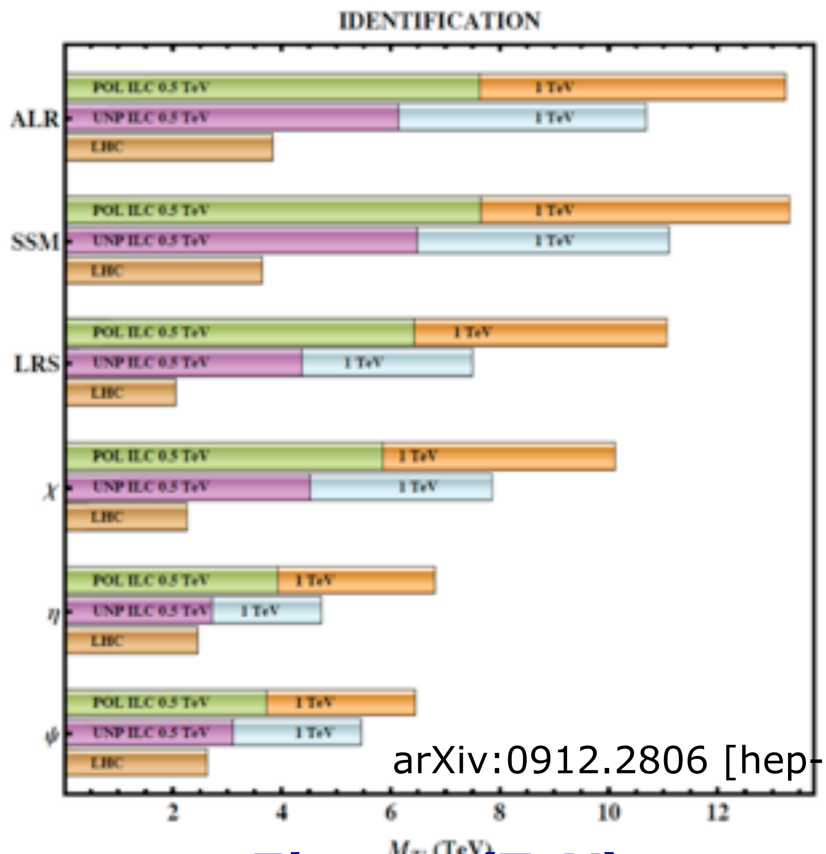
New gauge forces imply existence of heavy gauge bosons (Z')
LHC/ILC synergy:

- **LHC discovery** → determine mass of Z'
- **ILC measurements** → indirect access to couplings

Allows model discrimination
ILC: Beam polarizations improve reach and discrimination power

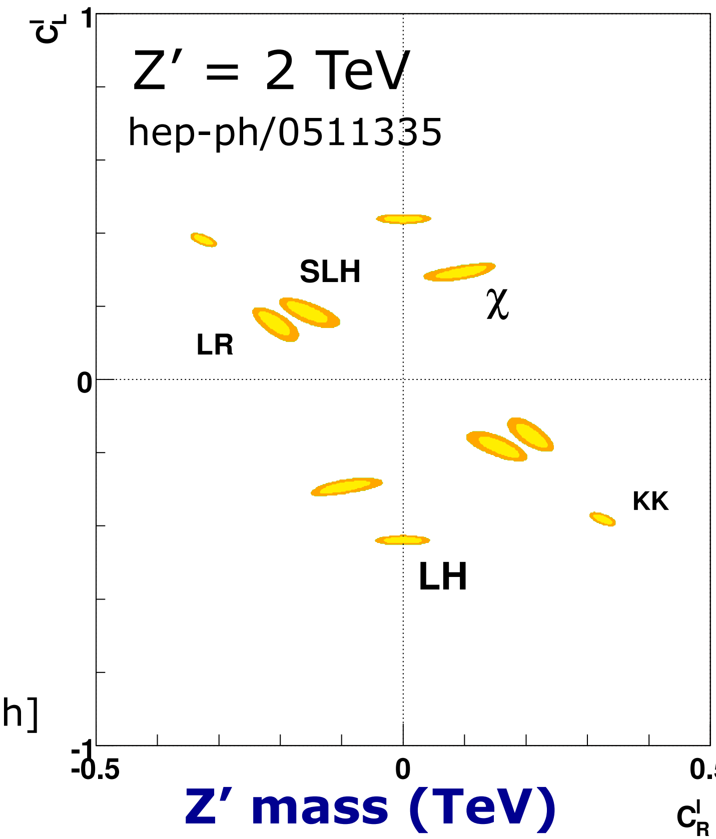


Models with Z' boson



arXiv:0912.2806 [hep-ph]

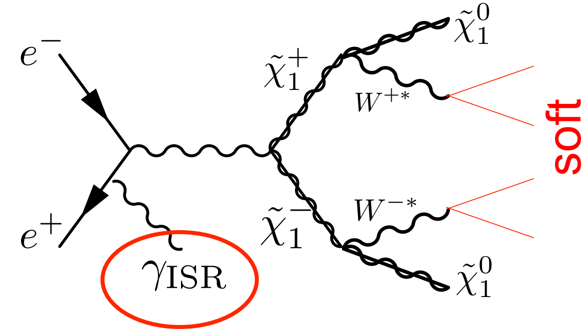
Z' mass (TeV)



Z' mass (TeV)

Higgsino decays to DM

with small mass differences



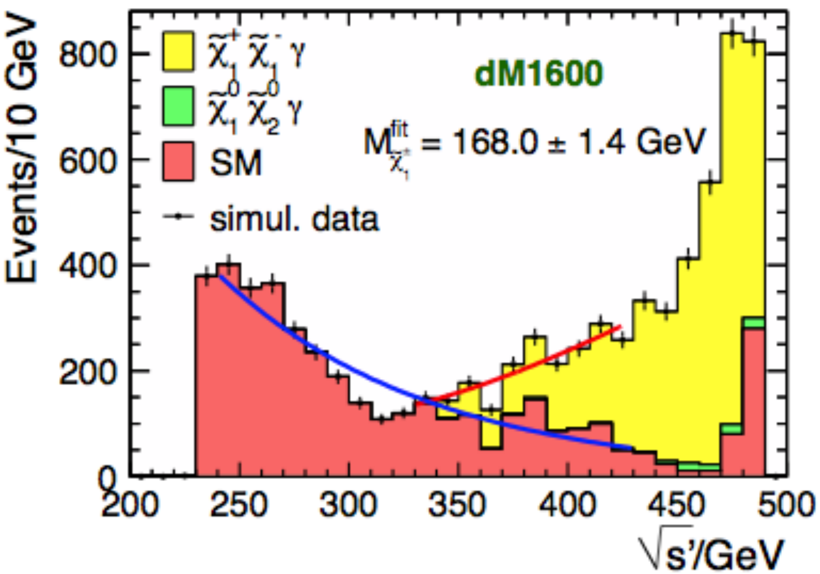
Study of Higgsino pair production, with ISR tag

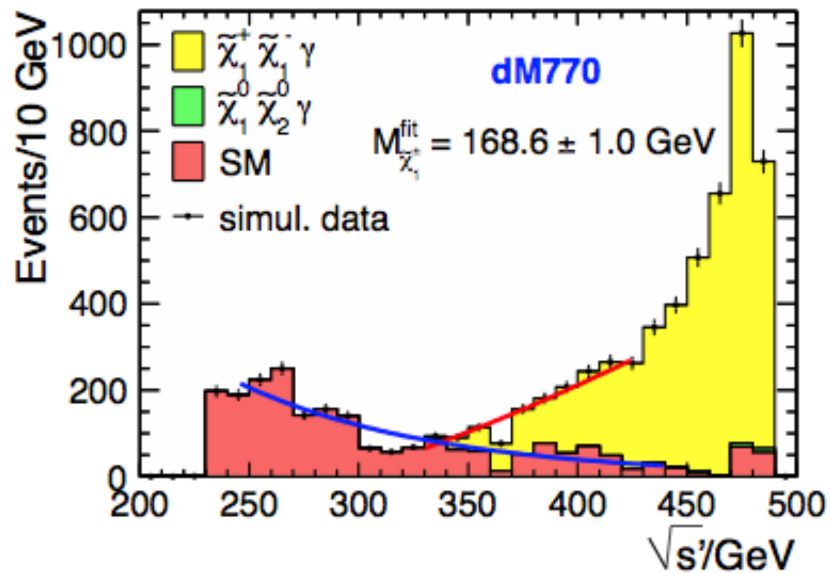
Benchmark models with
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \mathrm{fb}$$

$$\Delta M = 1.60\ (0.77)\ \mathrm{GeV}$$

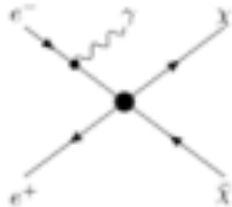
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert,
EPJ C73 (2013) 2660 [arXiv:1307.3566]





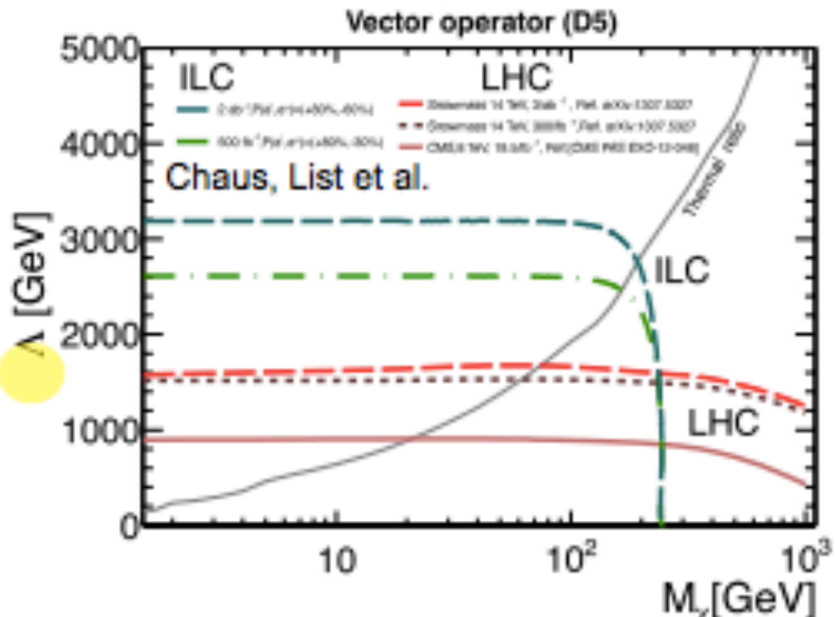
√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(-0.8,+0.3)
LSP mass resolution ~1%

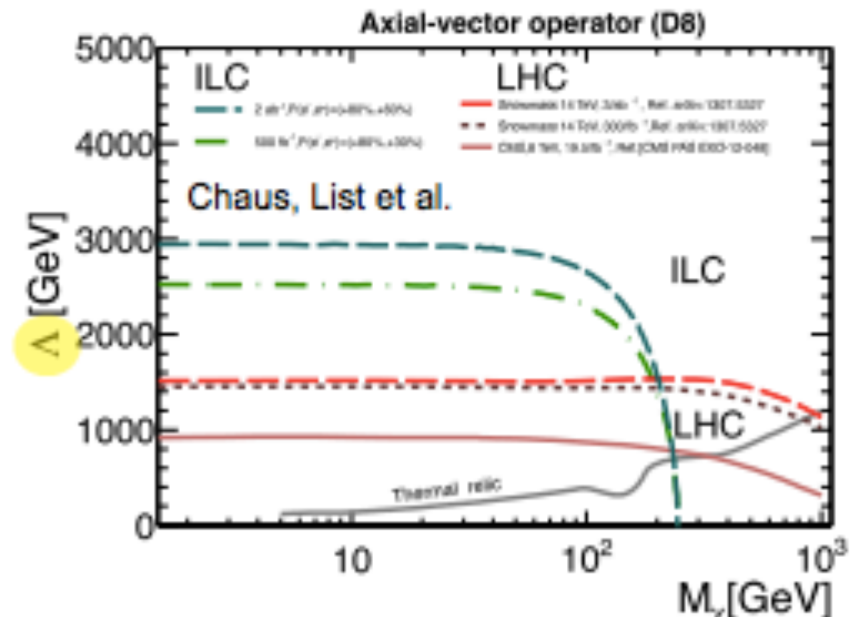
DM: Effective Operator Approach



$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

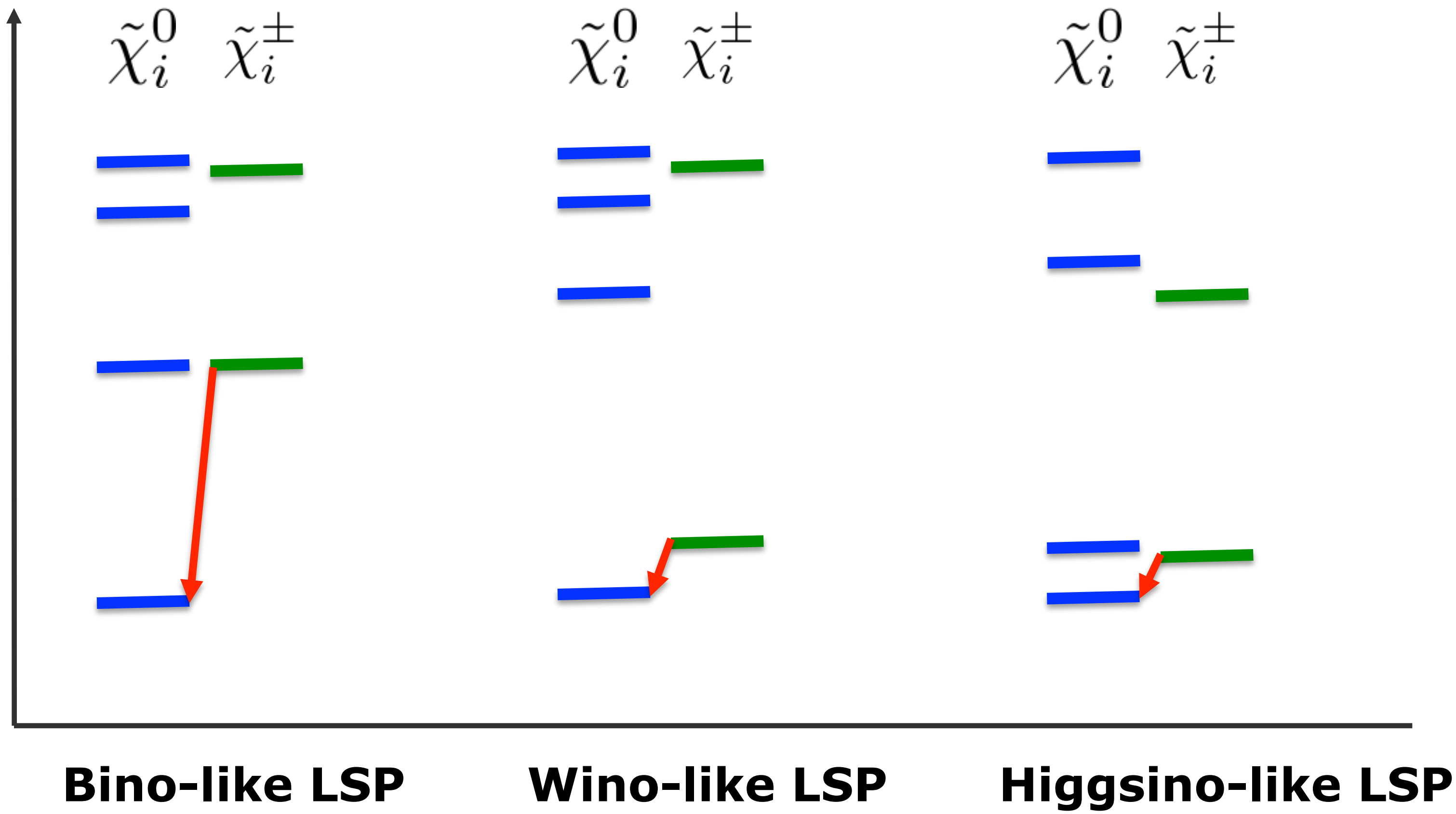
$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$





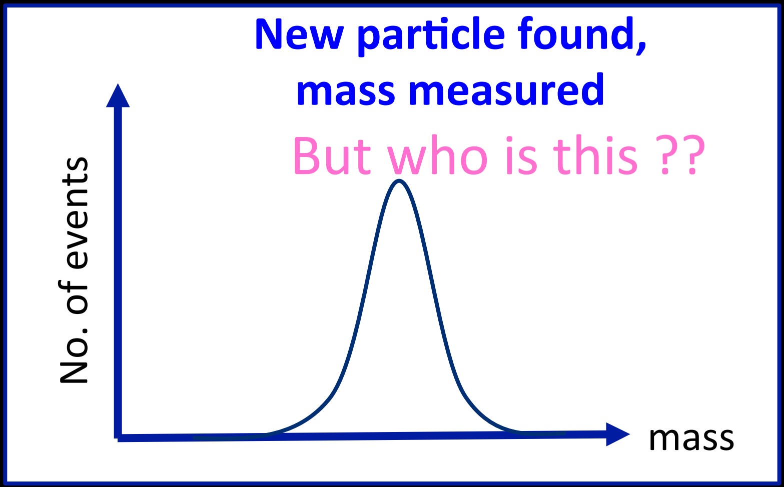
LHC sensitivity: Mediator mass up to Λ~1.5 TeV for **large DM mass**
ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~√s/2***

⇨ ***LHC-ILC synergy!***



LSP/NLSP typically degenerate
(depends on mixing)

Unique Capability 4



The Ultimate Power of Beam Polarization

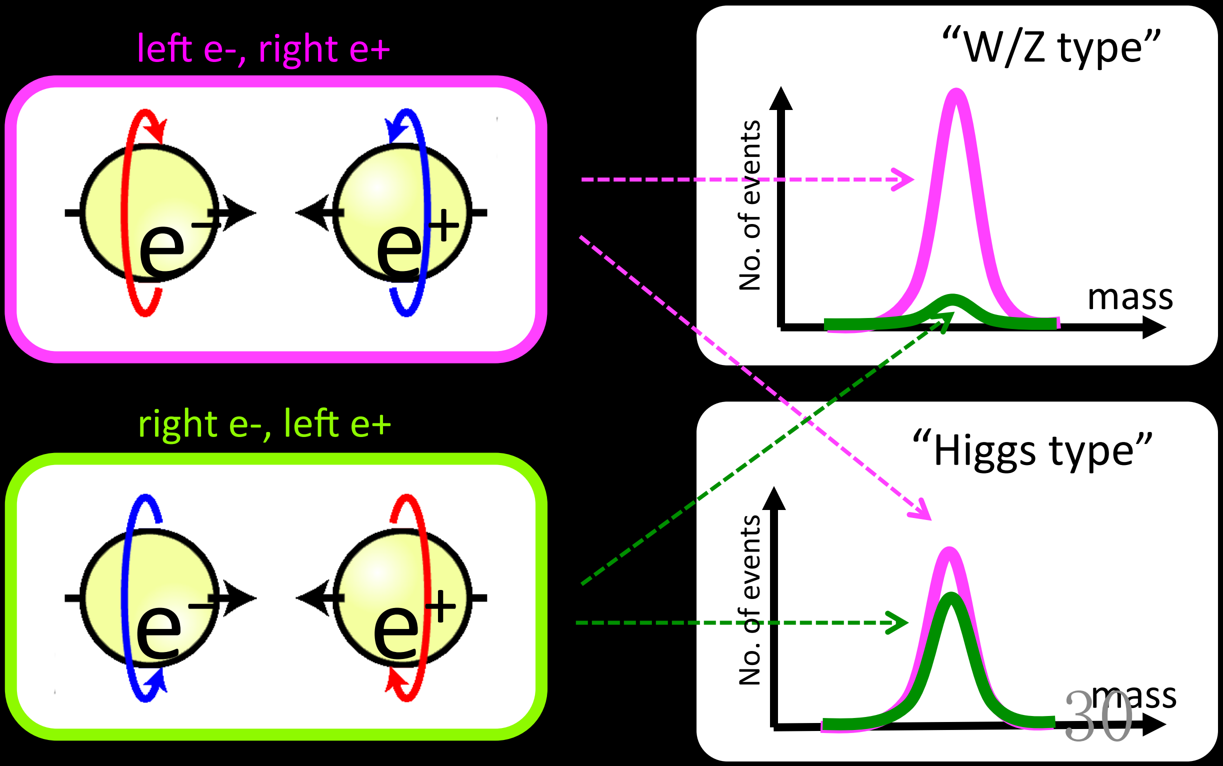
It enables us to distinguish new particles !

Use polarization to observe characteristics of new particles

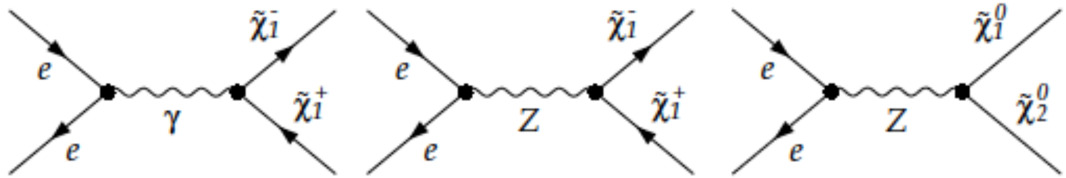
ex) : SUSY discovery

Count event rate while switching polarization

➔ distinguish particle type (according to theoretical predictions)



Benchmarks in this Study



RNS model (Radiatively-driven natural SUSY)

- **4 light Higgsinos:** $\tilde{\chi}_1^0$ (LSP) $\tilde{\chi}_2^0$ $\tilde{\chi}_1^+$ $\tilde{\chi}_1^-$

- **ΔM about 10-20 GeV complies with naturalness** (ISR tag not needed)

This study: **√s = 500 GeV**
Full detector simulation

Currently studying ILC1 benchmark

(Pe-, Pe+)	(-1.0,+1.0)	(+1.0,-1.0)
$\sigma(\chi_1^+\chi_1^-)$ [fb]	1800	335
$\sigma(\chi_1^0\chi_2^0)$ [fb]	491	379

BR($\chi_1^+ \rightarrow \chi_1^0 qq'$)	67%
BR($\chi_1^+ \rightarrow \chi_1^0 l\nu$) (l=e,μ)	22%
BR($\chi_2^0 \rightarrow \chi_1^0 qq'$)	58%
BR($\chi_2^0 \rightarrow \chi_1^0 ll$) (l=e,μ)	7.4%

NUHM2 model parameters [arXiv:1404.7510]

Benchmark	ILC1	ILC2
M_0 [GeV]	7025	5000
$M_{1/2}$ [GeV]	568.3	1200
A_0 [GeV]	-10427	-8000
tanβ	10	15
μ [GeV]	115	150
M_A [GeV]	1000	1000
$M(\chi_1^0)$ [GeV]	102.7	148.1
$M(\chi_1^\pm)$ [GeV]	117.3	158.3
$M(\chi_2^0)$ [GeV]	124.0	157.8
$M(\chi_3^0)$ [GeV]	267.0	538.8

Higgs precision measurements useful for parameter determination

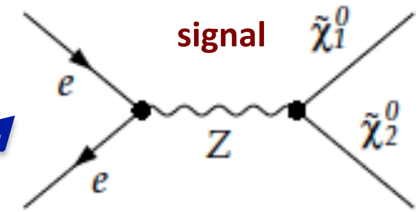
Defined at GUT scale
Defined at weak scale
Observables

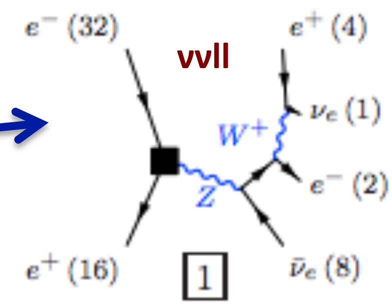
Event Selection

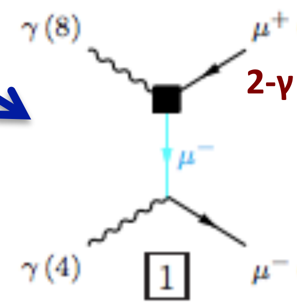
Neutralino mixed production with leptonic decay

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

- Reconstruct **two leptons (ee or μμ) which originate from Z^* emission in decay of χ_2^0 to χ_1^0**
- Major residual bkg. are 4f processes accompanied by large missing energy (ννll)
- 2-γ processes are removed by BeamCal veto, cuts on lepton track p_T, and coplanarity





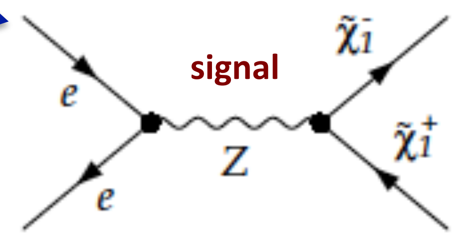


Chargino pair production with semileptonic decay

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

- Reconstruct **two jets which originate from W^* emission in decay of $\chi_1^\pm$ to χ_1^0**
- Use lepton (e or μ) from the other chargino as tag
- BeamCal veto, cuts on missing p_T, # of tracks, # of leptons, and coplanarity remove almost all bkg.

  (signal significance > 100)



SUSY Parameter Determination

[S.-L. Lehtinen]

Why?

- To get information about unobserved sparticles
- To test GUT-scale models

How?

- Global χ^2 fit of SUSY parameters to observables using Fittino [hep-ph/0412012]
- Fit GUT scale (NUHM2) parameters

Reminder:

Benchmark	ILC2
M_0 [GeV]	5000
$M_{1/2}$ [GeV]	1200
A_0 [GeV]	-8000
tanβ	15
μ [GeV]	150
M_A [GeV]	1000

Defined at GUT scale
Defined at weak scale

Observables and assumed precision for ILC2 benchmark

observable	value	uncertainty
mass $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$	$\sim$ 160 GeV	0.2 GeV
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)$	0.106	0.1
$BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\bar{q})$	0.590	0.1
$BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}')$	0.671	0.1
$BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l\nu_l)$	0.329	0.1
$\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)$, 4 polarisations	140 – 300 fb^{-1}	1%
$\sigma(\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp)$, 4 polarisations	200 – 970 fb^{-1}	1%

- Uncertainty to be updated with results from simulation study
- Study required precision that allows for full parameter determination

Fits of NUHM2 Parameters

[S.-L. Lehtinen]

ILC2

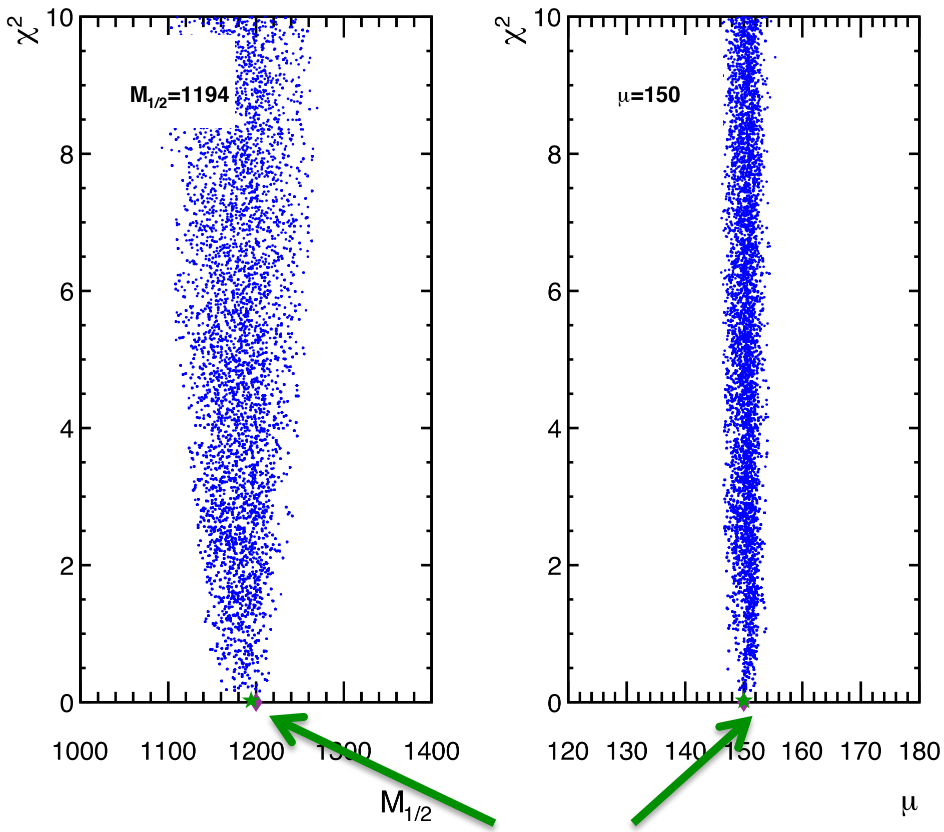
All 6 parameters are simultaneously varied. Initial values are set to be near the model values.

Each blue point corresponds to a set of parameter values. The χ^2 value is computed for each point.

Using the χ_1^0, χ_2^0, $\chi_1^\pm$ masses and production cross sections, $\mathbf{M_{1/2}}$ can be determined.

Adding Higgs mass and BR as measured at the ILC fixes μ and possibly constrains other parameters

In addition, if χ_3^0 can be observed in $\chi_2^0\chi_3^0$, $\tan\beta$ can be constrained as well. (ILC1)



Diamond = model point

Star = best fit point

Outlook

- **Test gaugino mass unification by fitting weak scale parameters M_1 and M_2**

ILC1

Cross sections (pure beam polarizations)
$\sqrt{s}$=500 GeV with TDR beam parameters

(Pe-, Pe+)	(-1.0,+1.0)	(+1.0,-1.0)
$\sigma(\chi_1^+ \chi_1^-)$ [fb]	1800	335
$\sigma(\chi_1^0 \chi_2^0)$ [fb]	491	379
$\sigma(\chi_2^0 \chi_3^0)$ [fb]	11.0	8.42
$\sigma(\chi_1^0 \chi_1^0)$ [fb]	2.03	1.56
$\sigma(\chi_2^0 \chi_2^0)$ [fb]	0.53	0.41
$\sigma(\chi_1^0 \chi_3^0)$ [fb]	0.28	0.20

Branching ratios

BR($\chi_1^+ \rightarrow \chi_1^0 qq'$)	67%
BR($\chi_1^+ \rightarrow \chi_1^0 l\nu$) (l=e,μ)	22%
BR($\chi_2^0 \rightarrow \chi_1^0 qq'$)	58%
BR($\chi_2^0 \rightarrow \chi_1^0 ll$) (l=e,μ)	7.4%