TOHOKU
UNIVERSITY

Summary of Group C
ILC Physics Capability

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And all the participants to Group C

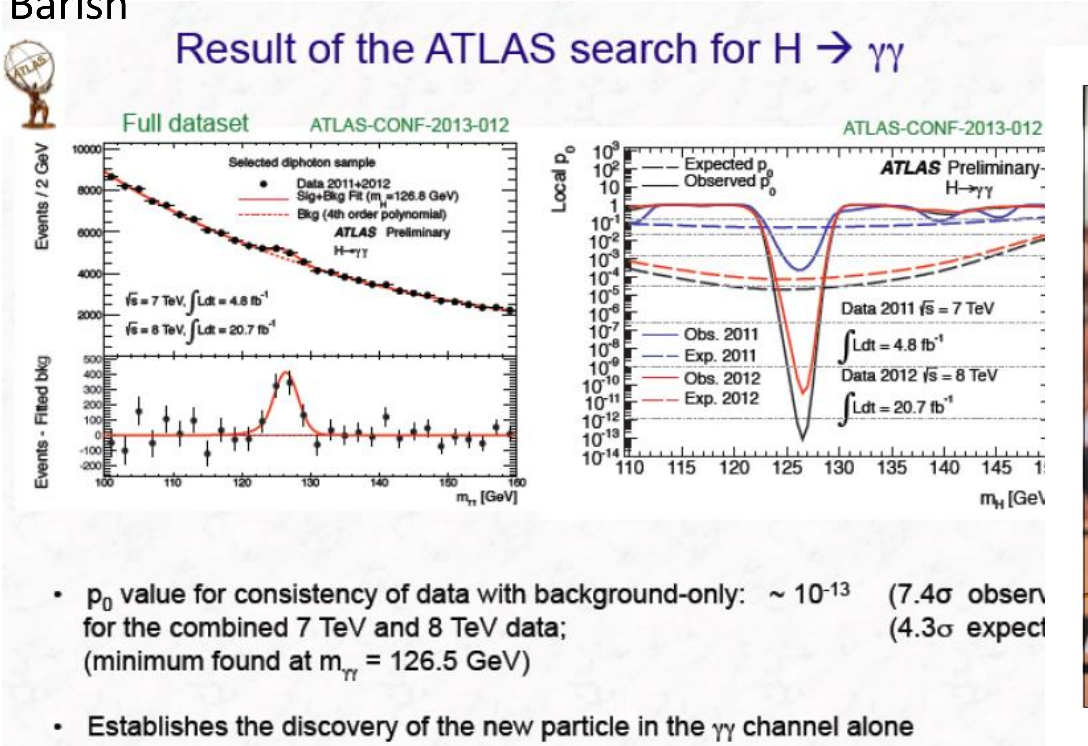
Particle Physics and Cosmology after the discovery of Higgs boson

Tohoku Forum for Creativity

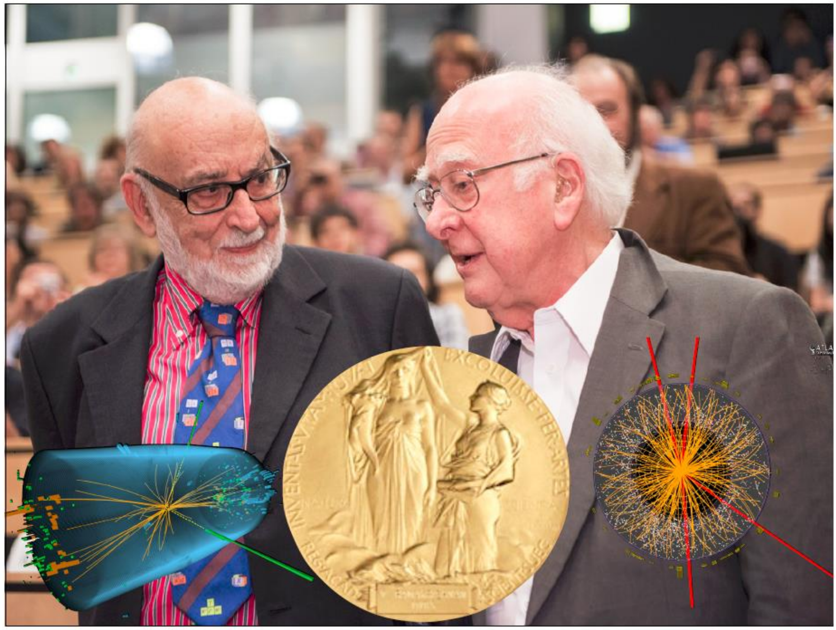
A Higgs Boson was Discovered

- First elementary scalar ??????????????????????????????
- We should measure the boson with ultimate precision!
- Who can do it? → ILC

Barish

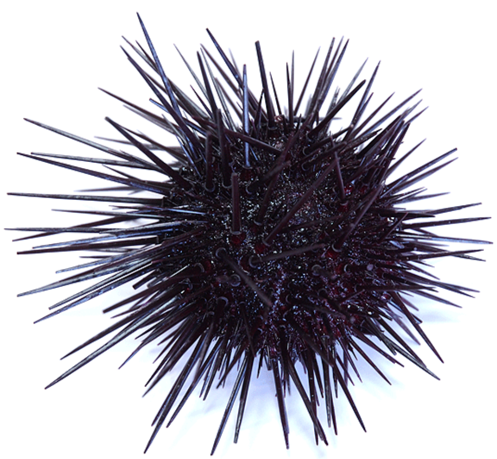


Gross



Other Mysteries in Our Uni-verse

- Dark Matter
- Dark Energy
- Baryogenesis/Leptogenesis
- Neutrino mass
- Inflation
- ….
- ILC might give answers/hints to the mysteries, or might not.



Mission of Group C

- Estimate sensitivities of Higgs, top, EW and direct BSM searches at the ILC
- Give combined constraints on BSM models.
- Compare them with the (HL-)LHC

- This is too high target for one week program.
    - We need full 3 months program of Tohoku Forum for Creativity
- So I would summarize what ILC can do which LHC cannot from the talks and discussions.
- And then, I would summarize home works.

Talks

- Thank you very much for giving nice talks in Group C
  - Higgs in BSM Models -- Shinya Kanemura
  - Higgs Measurements at the ILC -- Junping Tian
  - BSM searches at the ILC – Eriko Kato
  - New physics at Colliders – Mihoko Nojiri
  - Top theory at e+e- colliders -- Hiroshi Yokoya
  - Top quark measurements at the ILC -- Akimasa Ishikawa
- And important talks in other groups, especially
  - Probing SUSY Contributions to Muon g-2 at LHC and ILC -- Motoi Endo
  - Energy Extendability of ILC – Kaoru Yokoya
  - SUSY+Beyond -- Ryuichiro Kitano

Pros of the ILC

- CM Energy is tunable/known.
  - Threshold scan to determine mass and spin
  - Endpoint analysis to determine the masses in the reactions with missing particles
- Beam polarization of P(e-,e+) = (+-80%, +-30%) is possible
  - Chiral structure
  - Distinguish hypercharge and weak isospin
- Model independent analysis
  - No assumptions on cross sections
  - All data are taken (triggerless operation)

We should make full use of above powerful weapons which LHC does not have

Energy Extendability of the ILC

Group D

- Natural extension to 1.5TeV with 67km.
- Aggressive extension scenario to 3.0TeV (not guaranteed)

Conclusion

K. Yokoya

- ILC can be certainly extended to ~1TeV by a natural extension of the present technology of niobium cavity
  - Can be 1.5TeV with full use of 67km site
- Even higher energy might be reached (3TeV?) using a new SC technology such as thin film
- Obviously, quantitative studies are needed including the luminosity estimation, etc.
- CLIC technology allows to reach ~3TeV in the prepared Kitakami site (~50km)
- Plasma accelerator technology may bring about even higher energy (after several tens of years)

Higgs

- Model independent precise measurements of Higgs couplings to vector bosons and fermions are possible (Tian).
- Coupling to vector bosons is the window of BSM (Kanemura).
- Finger printing of Higgs sector (Kanemura, Tian)
- Higgs self-coupling (Tian, Kanemura)

- Invisible Decays (Ishikawa)

Higgs to Vector Boson Coupling : κ_V

- If κ_V is less than unity, the energy scale of new scalar can be determined
- $\kappa_V^2 >$ 0.984@95%CL if $\kappa_V^2=1$.
  - $M_A >$ 600GeV (1.4TeV) for $\tan\beta$ = 7 (1) in 2HDM (type independent)
  - $M_S >$ 4TeV in additional singlet model

Kanemura

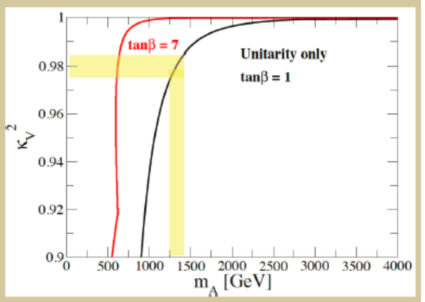
Unitarity bound in the 2HDM

$\kappa_V^2 = \sin^2(\beta-\alpha)$

If κ_V^2 is found to be less than 1, the upper bound on the mass of the second Higgs is obtained

Φ_1 *and* Φ_2 share v=246 GeV

$v_1^2+v_2^2 = v^2$

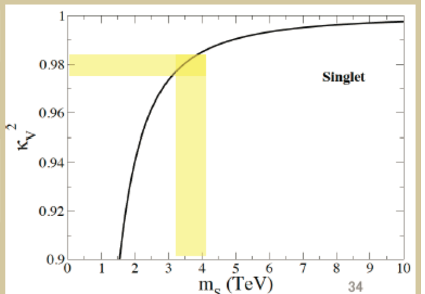


In Higgs Singlet model (Φ+S)

$\kappa_V^2 = \cos^2\theta$

Situation is similar, but the bound is much relaxed

S has the VEV but it does not share V (= 246 GeV)



Model independent

Tian

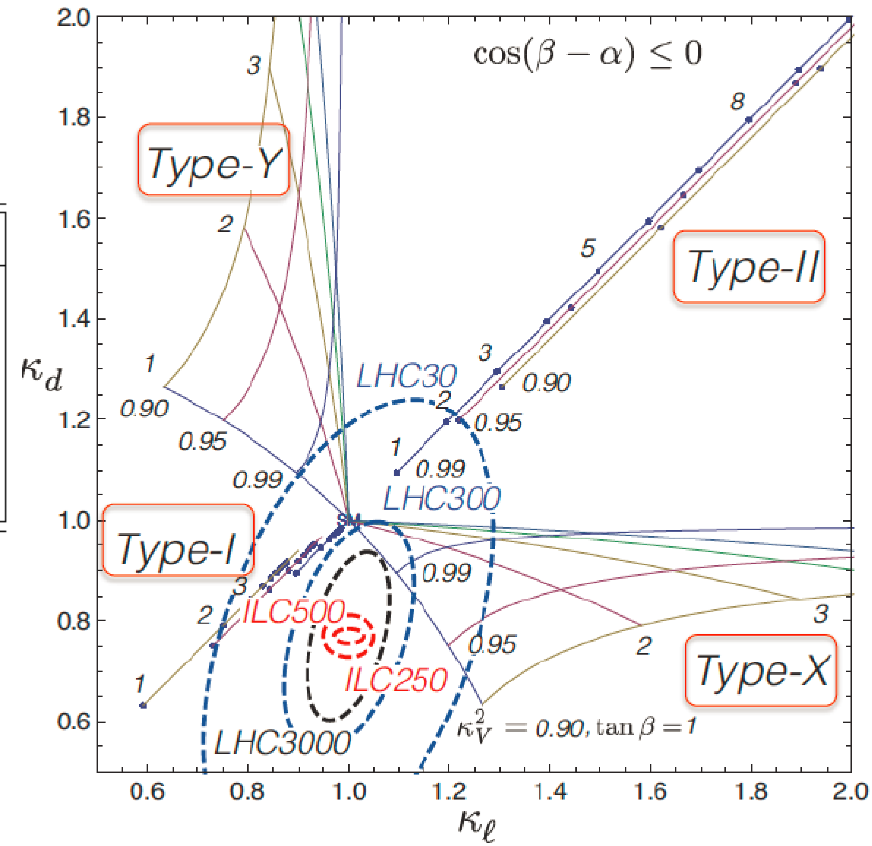
coupling $\Delta g/g$	Baseline 250 GeV	Baseline + 500 GeV	Baseline + 1 TeV	LumiUP 250 GeV	LumiUP + 500 GeV	LumiUP + 1 TeV
HZZ	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
HWW	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
Hbb	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
Hcc	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
Hgg	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
Hττ	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
Hγγ	18%	8.4%	4.0%	8.2%	4.5%	2.4%
Hμμ	-	-	16%	-	-	10%
Htt	-	14%	3.1%	-	7.8%	1.9%
Γ_0	11%	5.0%	4.6%	5.4%	2.5%	2.3%
Br(Inv)	<0.95%	<0.95%	<0.95%	0.44%	0.44%	0.44%
HHH	-	83%	21%	-	46%	13%

Yukawa Couplings

- Discrimination of type in 2HDM
  - H→bb VS H→ττ

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Kanemura



Higgs self-coupling

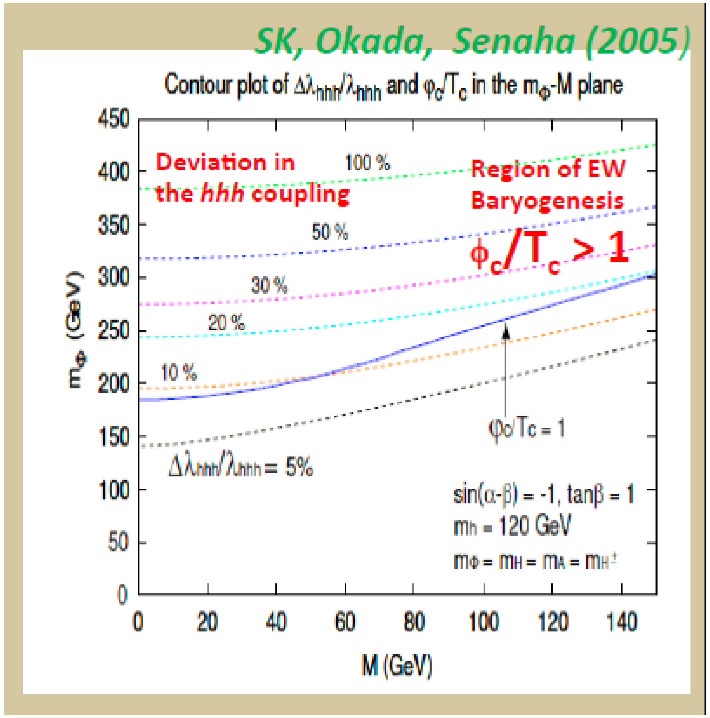
- Window to EW Baryogenesis
- 13% sensitivity at 1TeV.
- If deviation is 20%～30%, we can discriminate models

Tian

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV			500 GeV + 1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

Scenario A: HH-->bbbb, full simulation done
Scenario B: by adding HH-->bbWW*, full simulation ongoing, expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement, expected ~20% relative improvement (conservative)

Kanemura

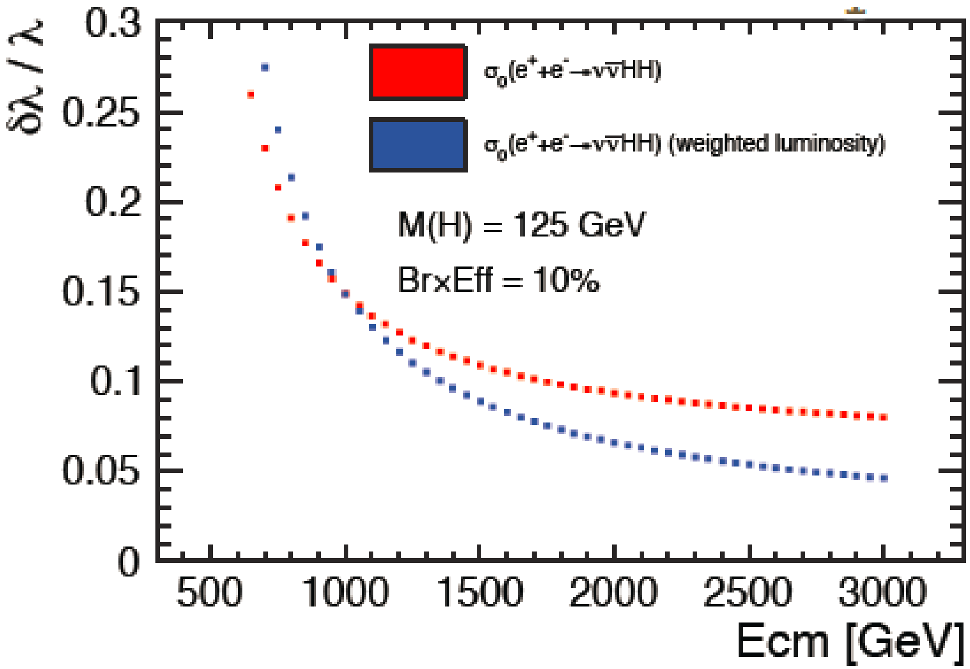


If *hhh* can be measured by O(10) %, the scenario of EW Baryogenesis can be tested

Higgs self-coupling at Energy Extended ILC

- 13% sensitivity at 1TeV.
- 8.5% at 1.5TeV
  - 10% if luminosity at 1.5TeV is the same as 1.0TeV

Tian

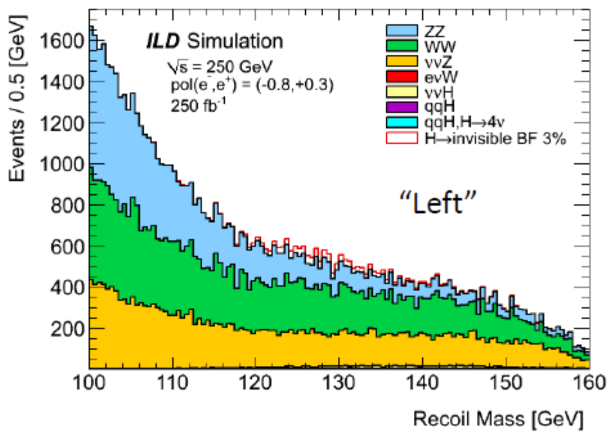


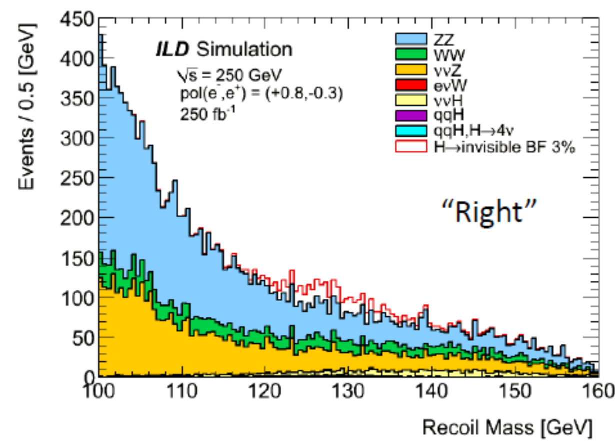
Invisible Higgs Decays

- Higgs Portal Dark Matter?
- Dark Radiation?

- If BF(H→invisible) = 3%
  - Signal is clearly seen for “Right” polarization

Ishikawa





The results with $250fb^{-1}$

- “Left” polarization : BF (H→invisible) < 0.95% @ 95% CL
- “Right” polarization : BF (H→invisible) < 0.69% @ 95% CL
  - The invisible does not include a H→ZZ*→4ν final state.
- If $1150fb^{-1}$ data is accumulated, 0.44% and 0.32% for “Left” and “Right”

From a crude toy MC scan, 5σ observation down to 2.8% and 2.0% for “Left” and “Right”, respectively.

BSM

- Small mass splitting (Kato, Nojiri)
- Slepton (Kato, Endo)
- Higgsino and stop (Kato, Kitano)
- Model discrimination by angular analysis (Kato)

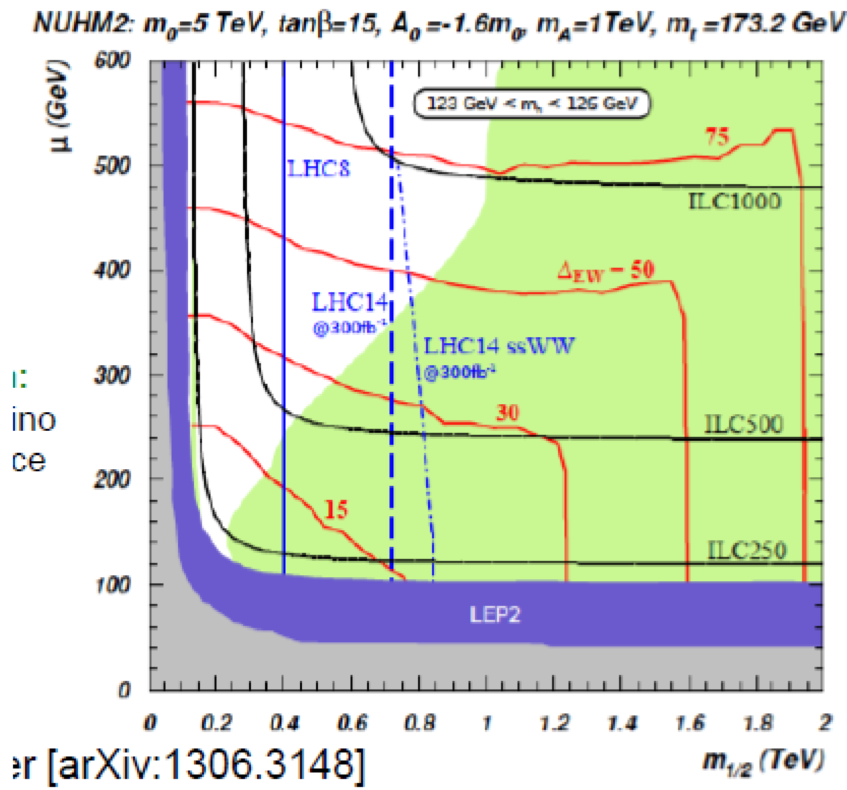
- Other than SUSY (Fujii)
  - Composite models
  - Z’ and ρ_T tails

Small Mass Splitting Case

Kato

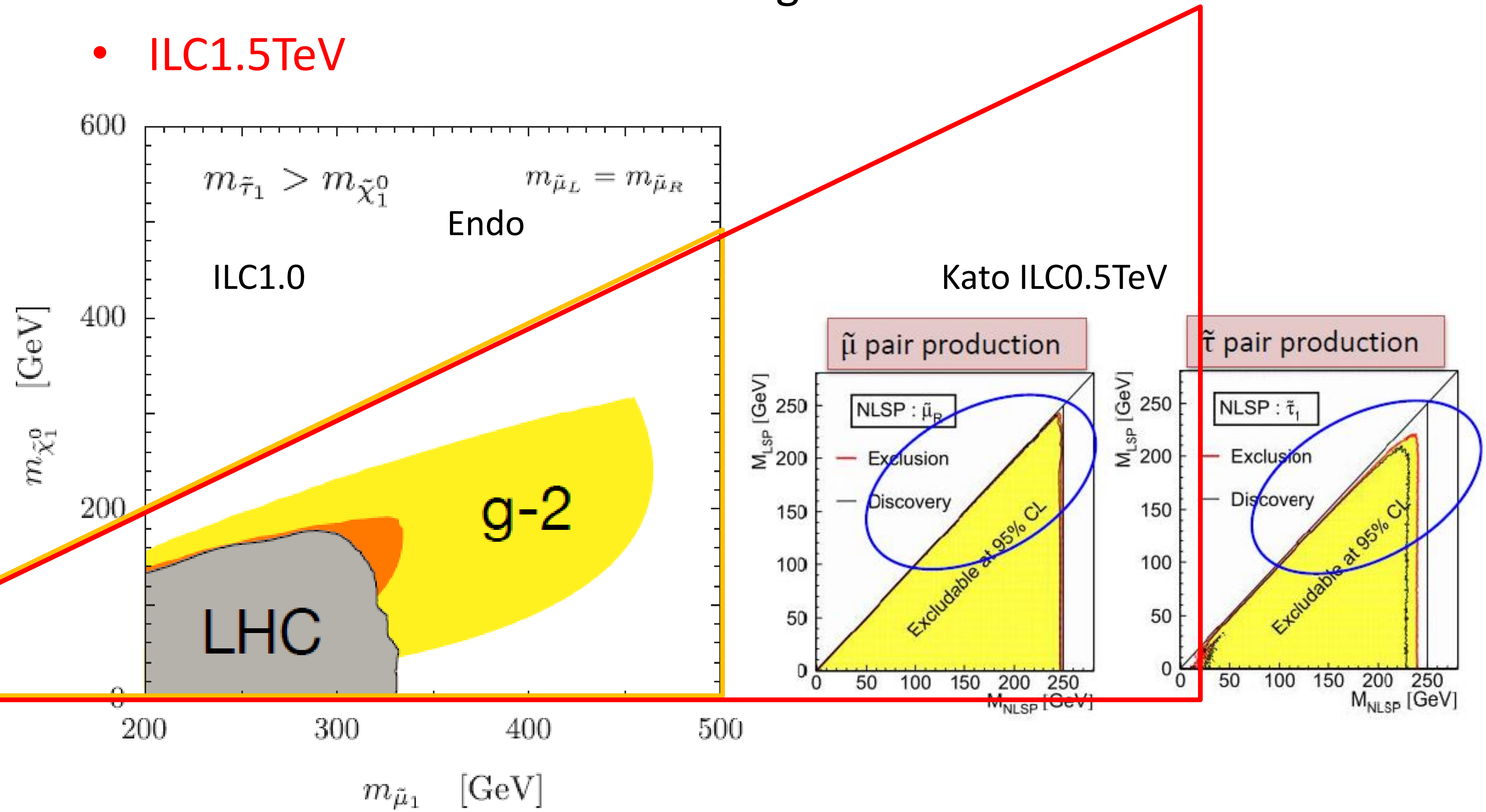
- Small mass splitting
  - Even the splitting is Sub-GeV
  - Higgsino LSP
    - Naturalness strategy
  - Wino LSP
    - Anomaly mediation
  - Stop NLSP, Bino LSP
  - UED
  - Wino/Higgsino discrimination using polarization
- Mass reach is about √s/2

Higgsino LSP case



Slepton Searches

- ILC1.0TeV can cover the muon g-2 motivated smuon.
- ILC1.5TeV



Smuon Mixing

- Smuon mixing is related to stau mixing

$$m^2_{\tilde{\mu}LR} = \frac{m_\mu}{m_\tau} m^2_{\tilde{\tau}LR}, \quad m^2_{\tilde{\tau}LR} = \frac{1}{2}(m^2_{\tilde{\tau}1} - m^2_{\tilde{\tau}2}) \sin 2\theta_{\tilde{\tau}}$$

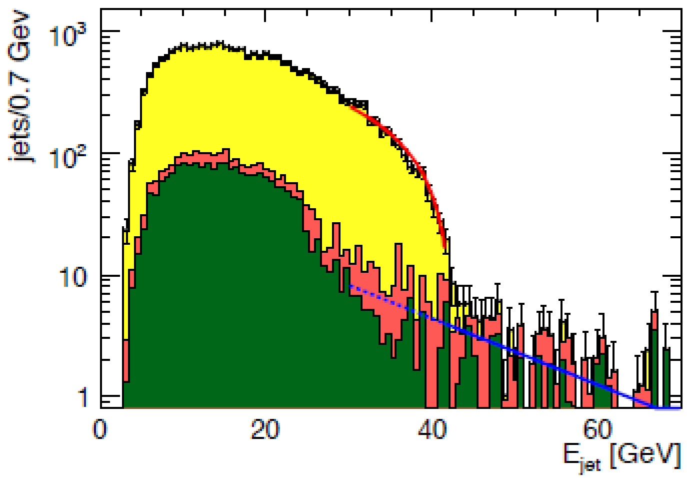
- Mass reconstruction of stau1 and stau2 from pair production
- Mixing is from σ(e+e→stau1stau1)

$$\delta \sin 2\theta_{\tilde{\tau}} / \sin 2\theta_{\tilde{\tau}} = 9\,\%$$

at $\sin 2\theta_{\tilde{\tau}} = 0.67$

$\sqrt{s} = 500\,\text{GeV}, \ \mathcal{L} = 500\,\text{fb}^{-1}$

$(P_{e+}, P_{e-}) = (-0.3, +0.8)$



$$\delta m^2_{\tilde{\mu}LR} / m^2_{\tilde{\mu}LR} = 12\,\%$$

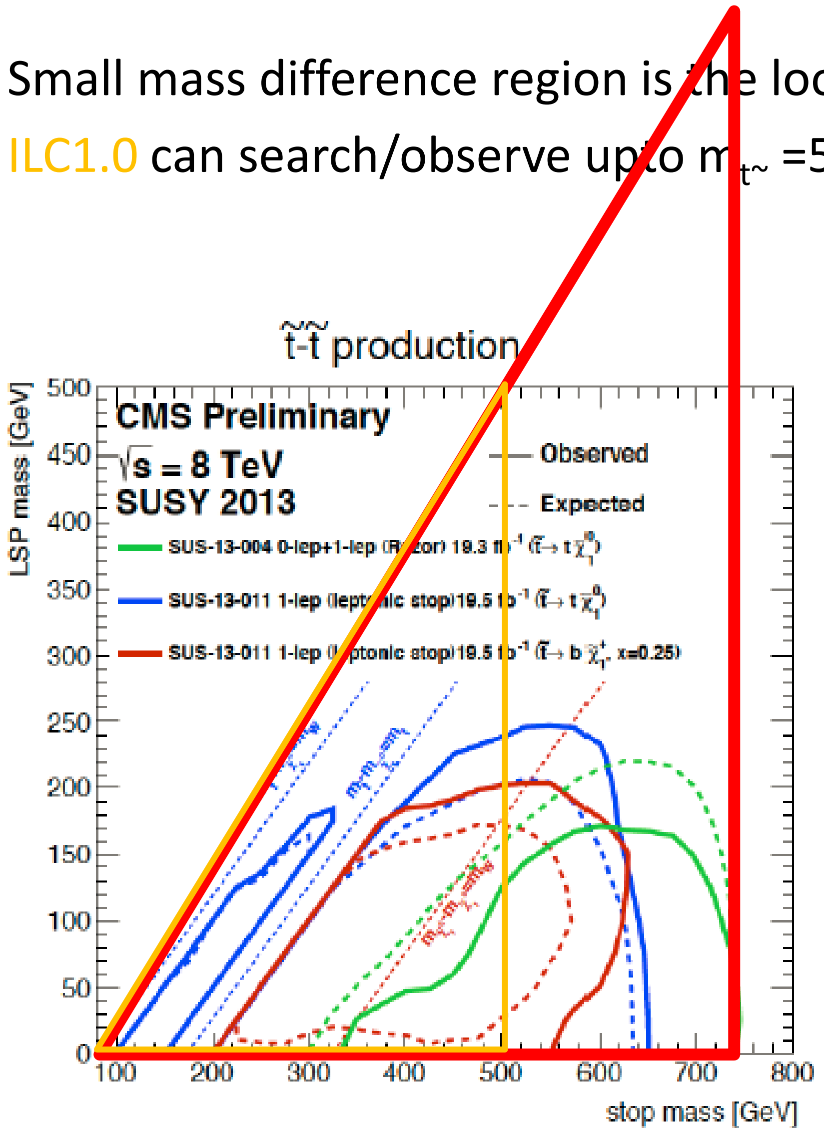
Note that $\sigma(e^+e^- \to \tilde{\tau}_1\tilde{\tau}_2)$ is very sensitive to mixing, though there is no study

Our home work

Light Stop

Kitano

- Small mass difference region is the loop hole of the LHC
- ILC1.0 can search/observe upto $m_{\tilde{t}}$ =500GeV



ILC1.0

ILC1.5

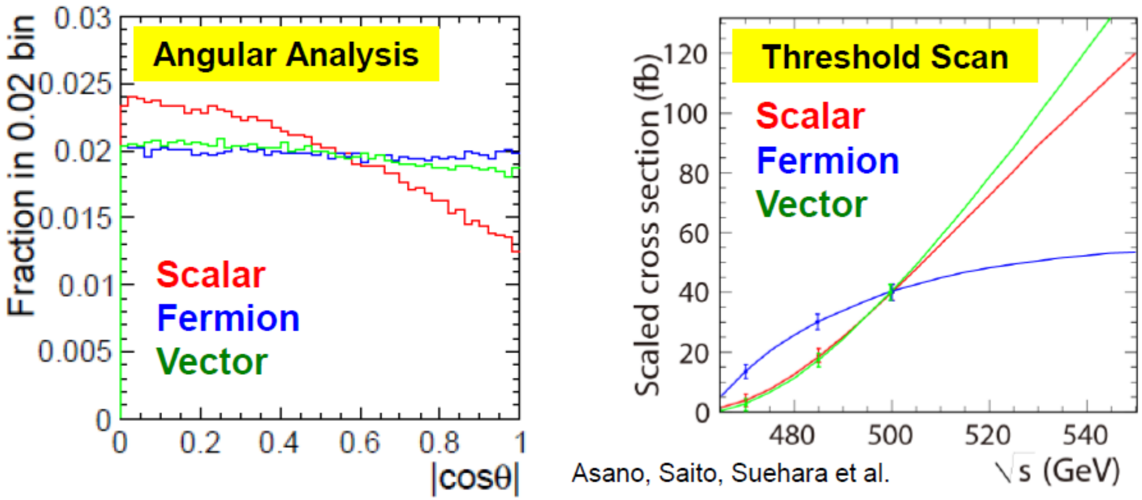
Model Discrimination

- Full use of polarization

Kato

Model Discrimination

- Phenomenology: $X^+ + X^- \rightarrow W^+ + \mathbf{DM} + W^- + \mathbf{DM}$
- 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**

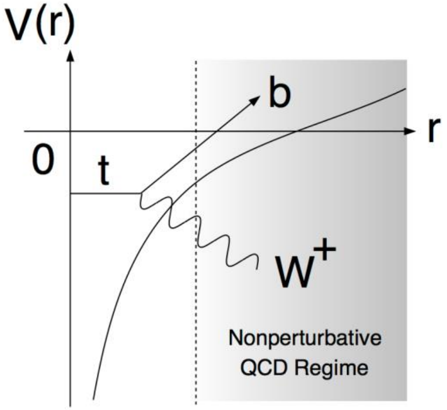


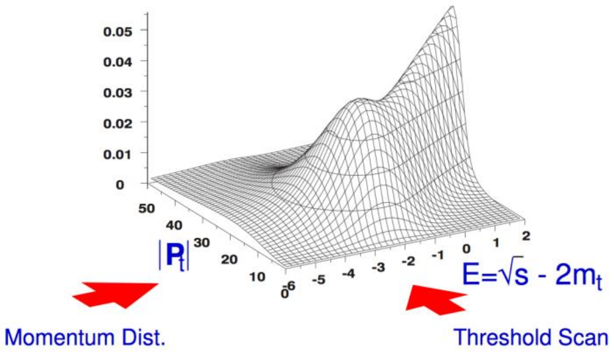
Asano, Saito, Suehara et al.

→ Model Discrimination with spin information

Top Quark

- Precise mass determination with tiny QCD uncertainty for the test of vacuum stability in the SM (Lykken, H. Yokoya, Ishikawa).
- Search for CP Violating couplings (H. Yokoya)
- Forward-backward Asymmetry and top momentum measurements (Fujii)
  - QCD potential in ttbar resonance





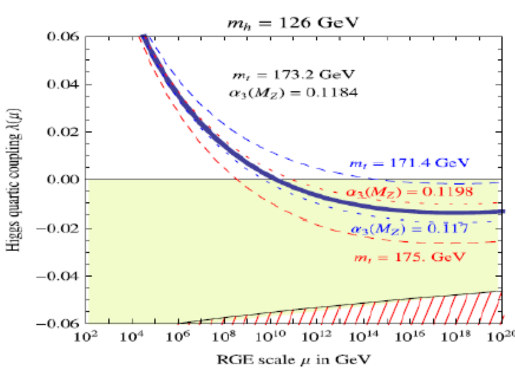
Vacuum Stability

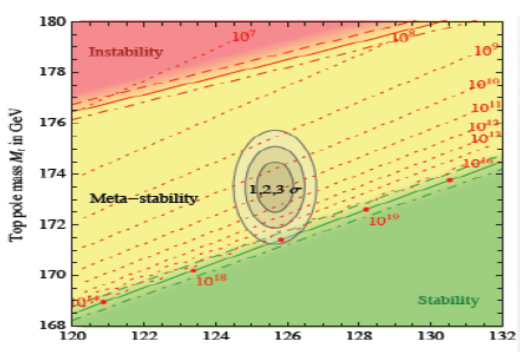
- Top mass measurement in running mass scheme is quiet important for the fate of our universe (in the SM)

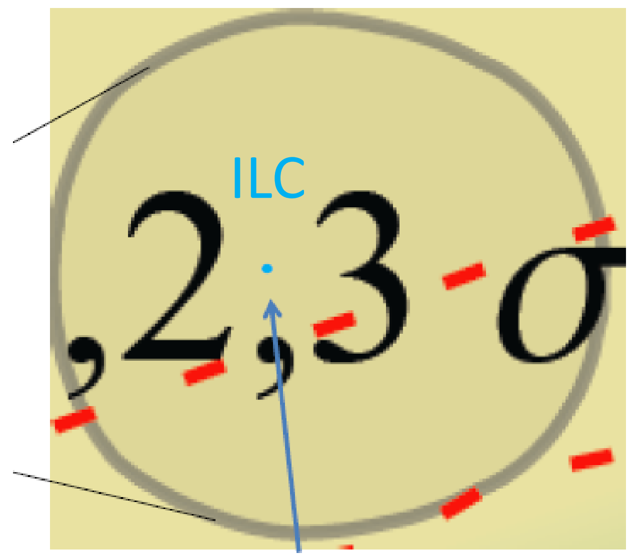
SM vacuum stability

- RGE of Higgs quartic coupling $16\pi^2\mu\frac{d\lambda}{d\mu} = 24\lambda^2 - 6y_t^4 + \cdots$

Top-quark mass is crucial for higher-scale behavior of the SM vacuum
Is it accidental or not? We need more accurate input of the top-quark mass







$\Delta M_H = \pm 37$ MeV
$\Delta m_t^{pole} = \pm 17$MeV

Only Stat error.

Electroweak

- This is missing item in Group C.

- Two fermion (ee → ff) measurements at ILC from 250GeV to 1TeV and beyond.
- Vector boson scattering at energy extended ILC.
  - Longitudinal component
- Runnings at WW threshold and Z pole.

Homework

- Higgs
  - CP mixture by ttH, H→$\tau\tau$, and ZH
  - Higgs coupling theoretical calculation in one loop level in BSM models
- BSM
  - Stau1stau2 pair production for stau mixing measurement
  - Light stop and LSP masses for relic abundance
- Top
  - Momentum distribution and A_{FB} for QCD potential in ttbar resonance
  - Measurement of luminosity spectrum for threshold studies (also for EW)
  - Top CP violating coupling by CP odd observables in top production and decay
  - Theoretical calculation of vacuum instability.
- EW
  - W mass at WW threshold, Weinberg angle at Z pole, and others.
  - Can ILC run at WW threshold and Z pole with reasonable luminosity and polarization? (Group D)
- Theory
  - Reduction of theory uncertainty, Higgs, top

Summary

- ILC
  - CM Energy is tunable/known.
  - Beam polarization possible
  - Model independent analysis
- Reconfirmed that even after the LHC, ILC can perform many theoretically motivated BSM searches that LHC cannot do.
  - Direct or/and indirect observation of BSM?
- Energy extendability is one of the key issues for
  - BSM searches
  - Higgs self-coupling
  - $W_L W_L$ scattering to test elementary/composite Higgs.
- We need ILC.

Creativity of Japanese Cuisine