March 1, 2017 in Toyama

ILC, Project Status and Physics with Focus on Electroweak Symmetry Breaking

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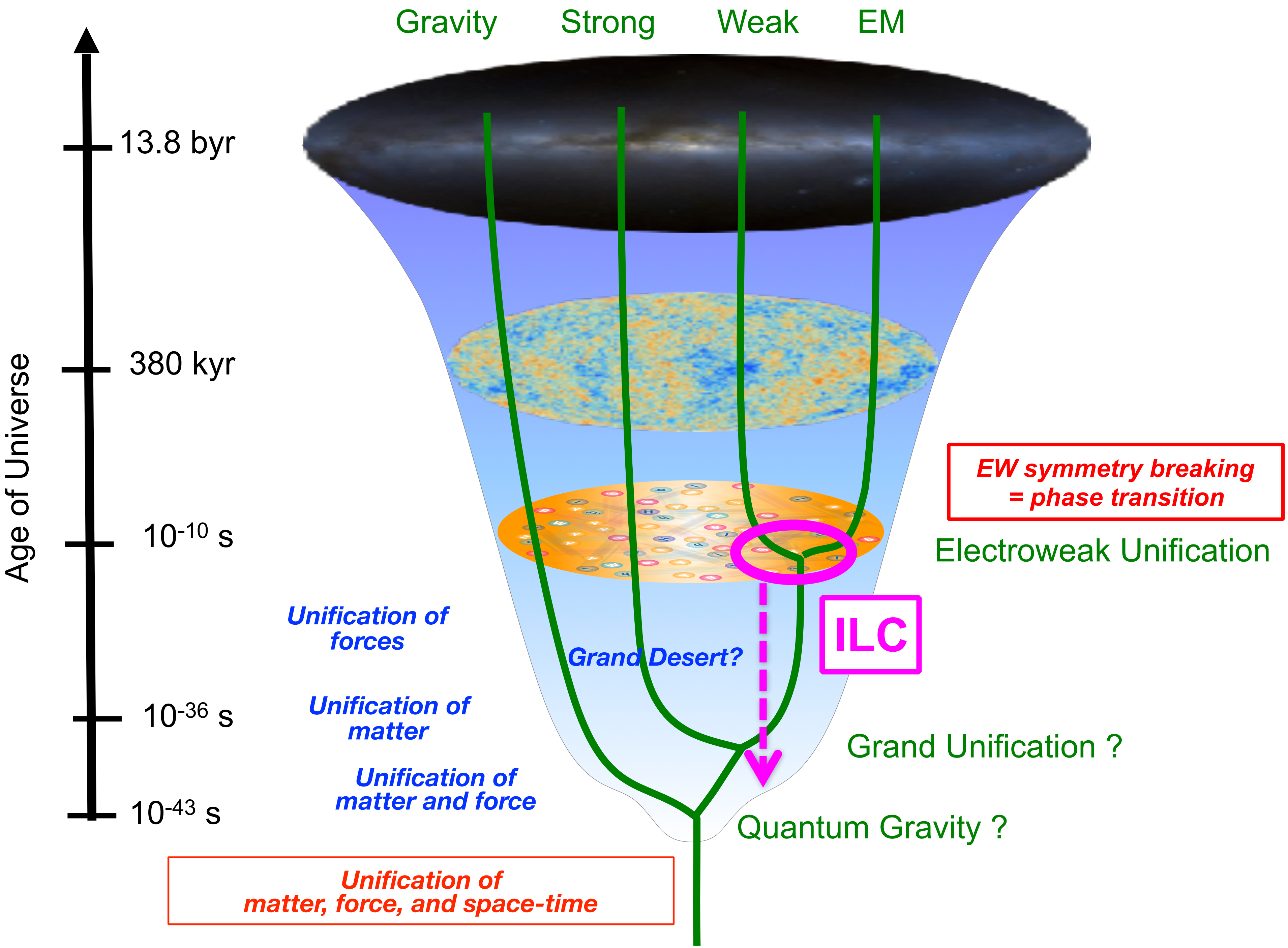
KEK

arXiv: 1506.05992 (ILC Physics Case)
arXiv: 1506.07830 (ILC Run Scenarios)
arXiv: 1306.6352 (ILC TDR: Physics)
EPJC (2015) 75:371 (LC Physics)
arXiv: 1702.05333 (ILC New Particles)

Towards ultimate unification

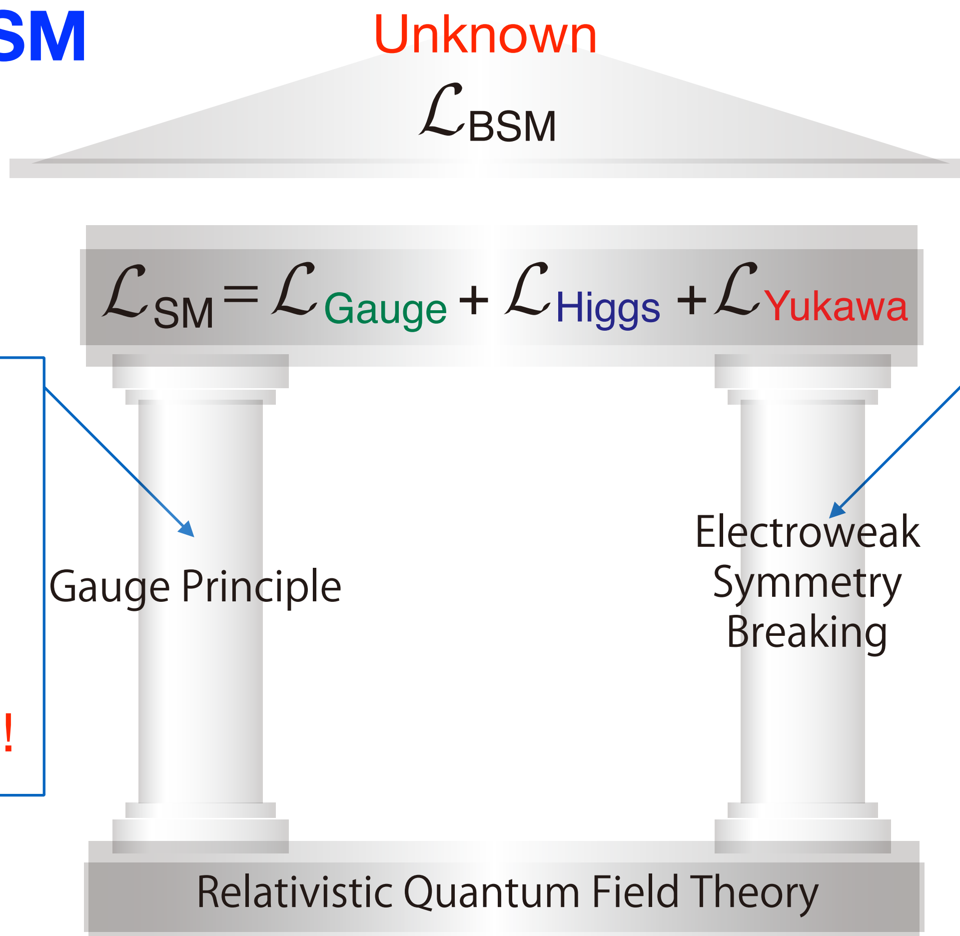


Why is the EW scale so important ?

Why is the EW scale so important?

Mystery of something in the vacuum

2 Pillars of SM

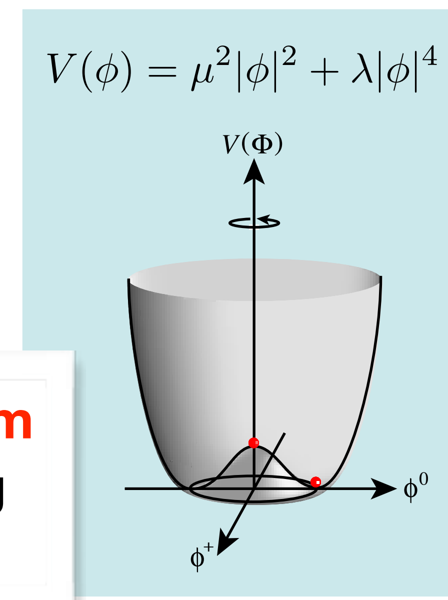


Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

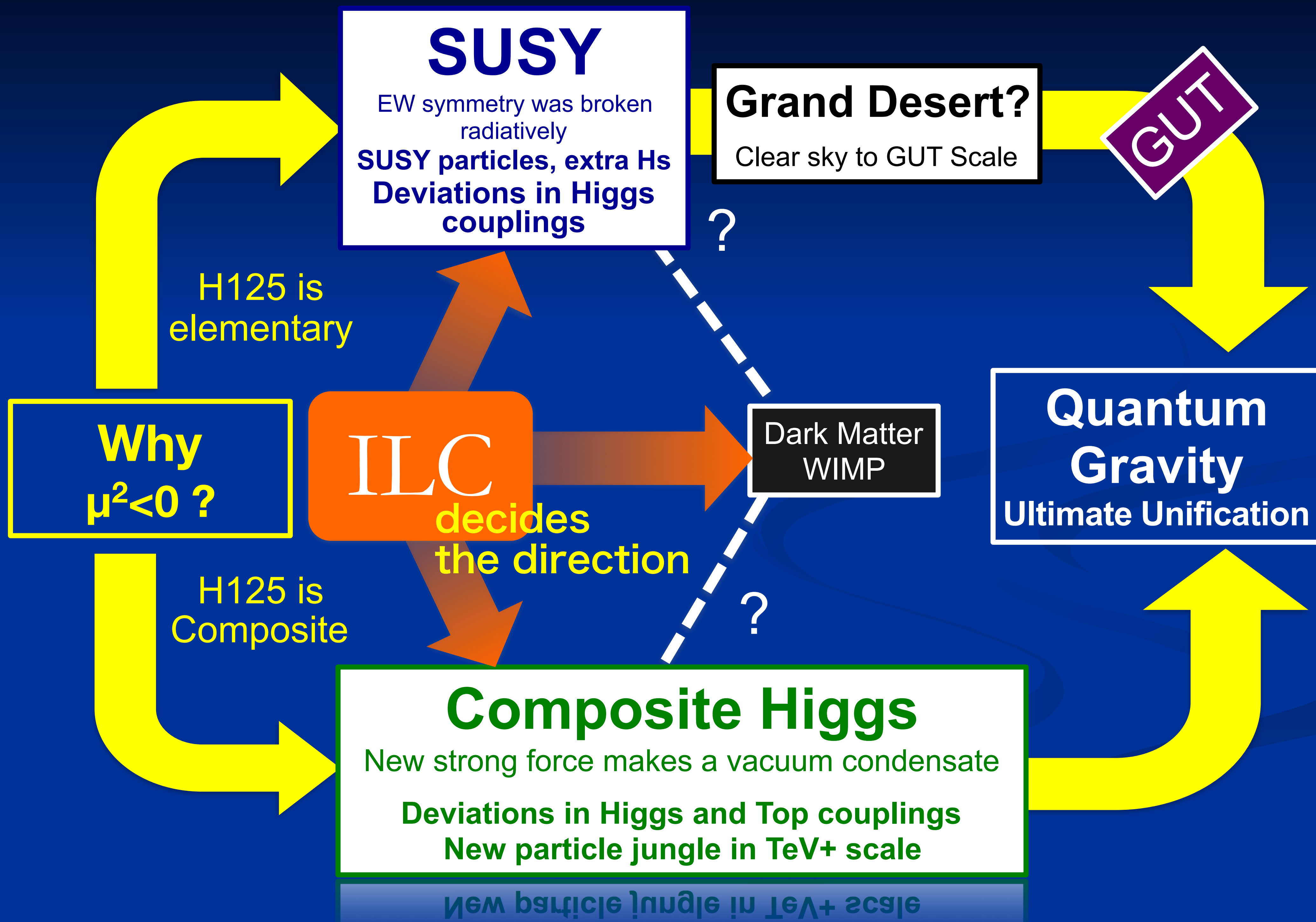
Vacuum filled with weak charge (evidence: H125)

The nature of the Higgs field - its multiplet structure & dynamics behind it - is all unknown!



The SM does not explain **why the Higgs field developed a vacuum expectation value** (***Why $\mu^2 < 0$?***)**! The answer forks depending on whether H125 is elementary or composite!**

Big Branching Point at the EW Scale

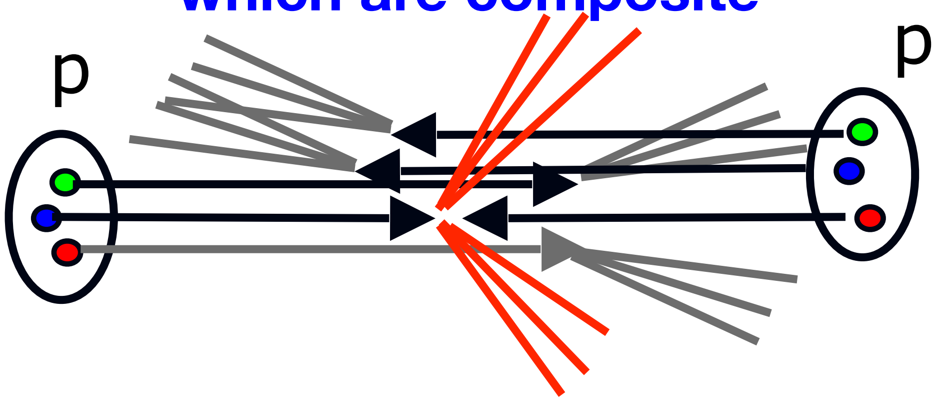


The 3 major probes for BSM at ILC:

Higgs, ***Top***, and search for ***New Particles***

3 Powerful Tools

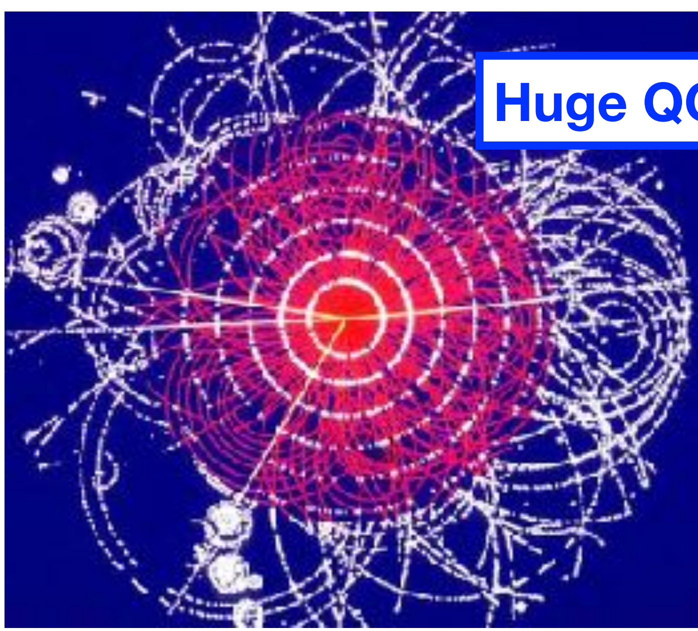
LHC: Collision of protons which are composite



Ecm 7-14 TeV

Pileup

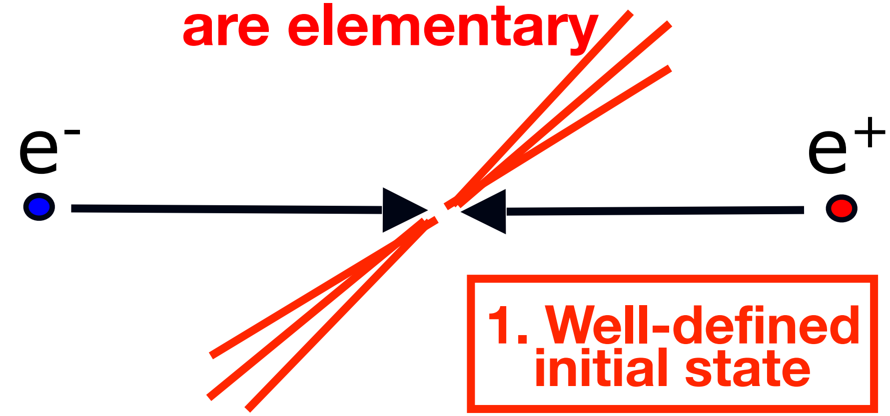
Initial state not very well defined



Huge QCD BG

proton is composite ⇒ events are complicated but
maximum reachable energy is high!

ILC: Collision of e^+e^- which are elementary

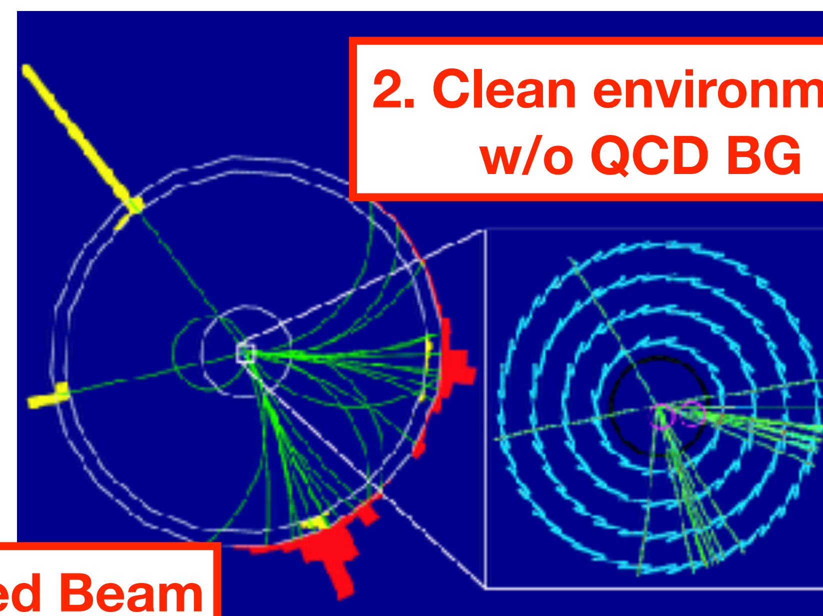


1. Well-defined initial state

Ecm 0.25-1 TeV

Lab. frame = CM frame

2. Clean environment w/o QCD BG



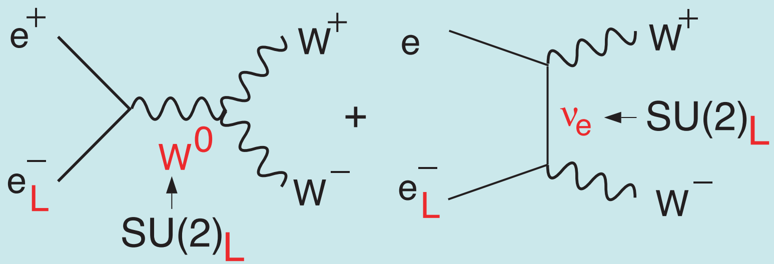
3. Polarized Beam

clean and and able to detect everything produced!

Power of Beam Polarization

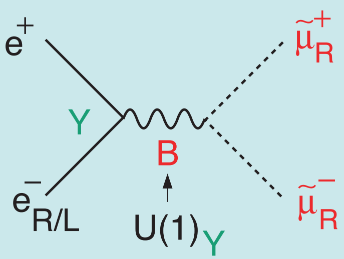
BG Suppression

W^+W^- *(Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

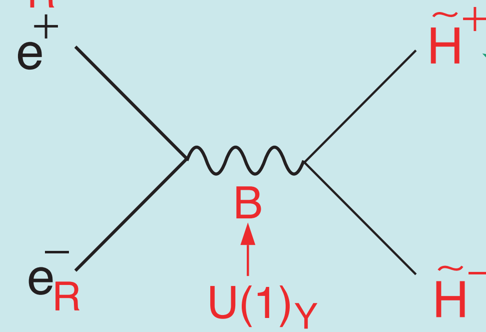


$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

Chargino Pair

e^-_R Beam



Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

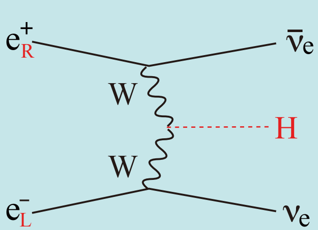
cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

Decomposition

WW-fusion Higgs Prod.



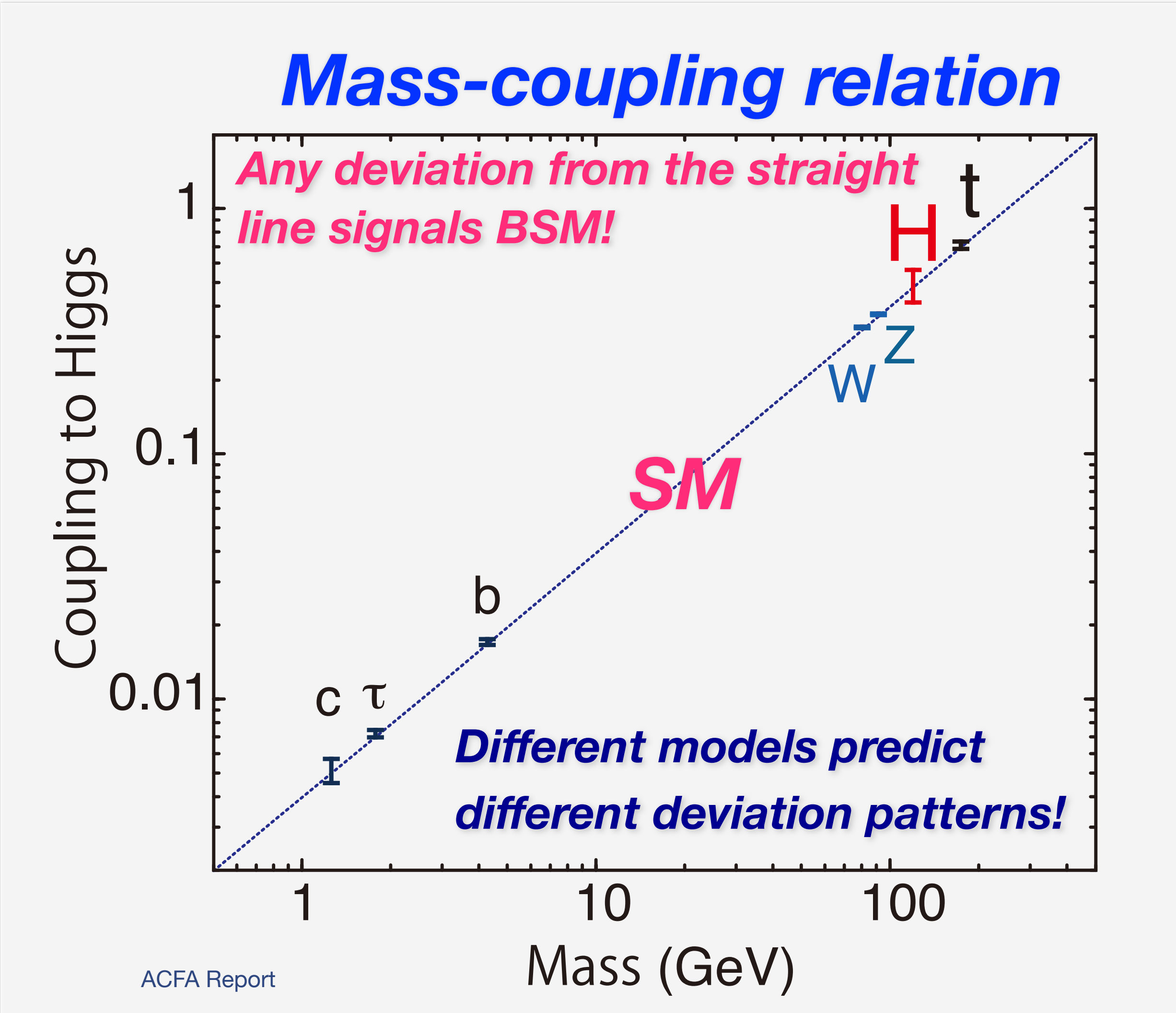
	ILC
Pol (e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement

Among three probes, today, we will focus on

Higgs

Deviation in Higgs Couplings



The size of the deviation depends on the new physics scale (Λ)!

Decoupling Theorem:
Λ↑ → SM

example 1: **Minimal SUSY**
(MSSM : tanβ=5, radiative correction factor ≈ 1)

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

heavy Higgs mass

example 2: **Minimal Composite Higgs Model**

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

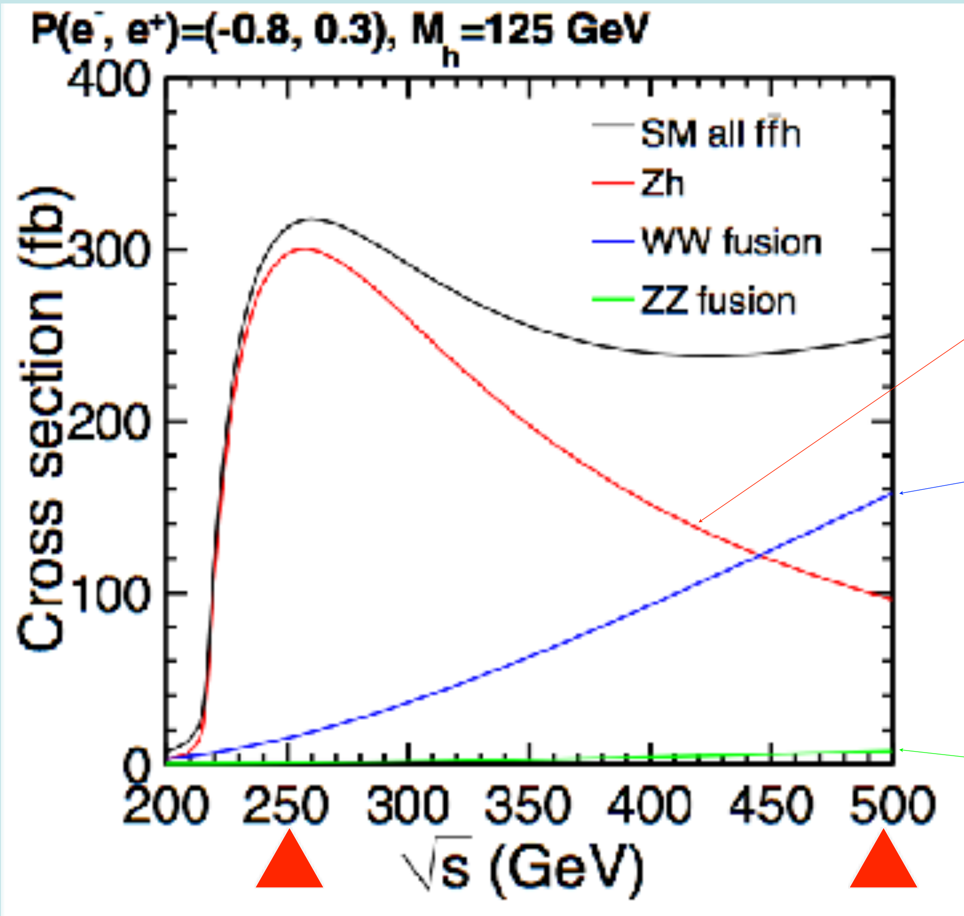
composite scale

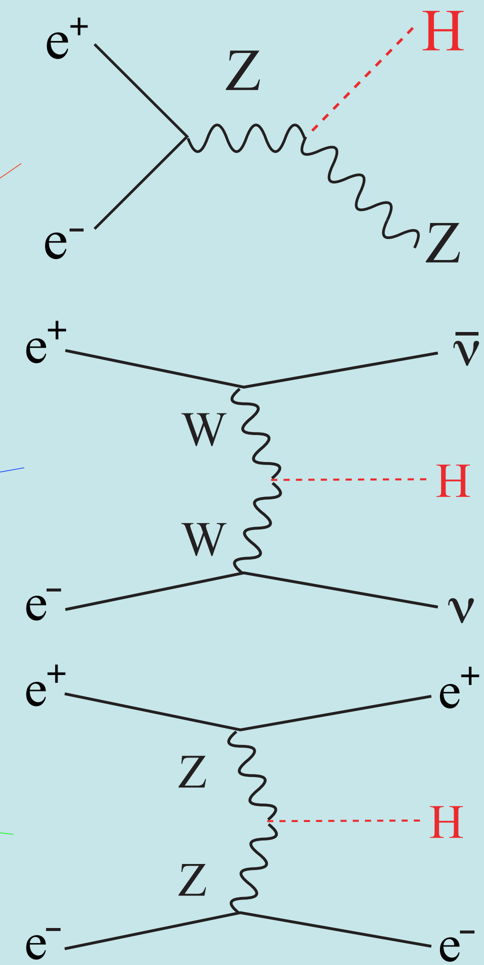
New physics at 1 TeV → **deviation is at most ~10%**
We ***need a %-level precision*** → ***ILC***

Main Production Processes

Single Higgs Production

Production cross section





ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

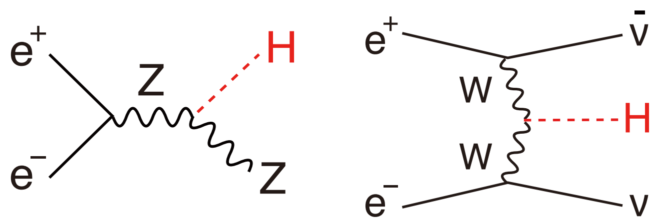
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

200k w/ TDR baseline, eventually >1M Higgs events!

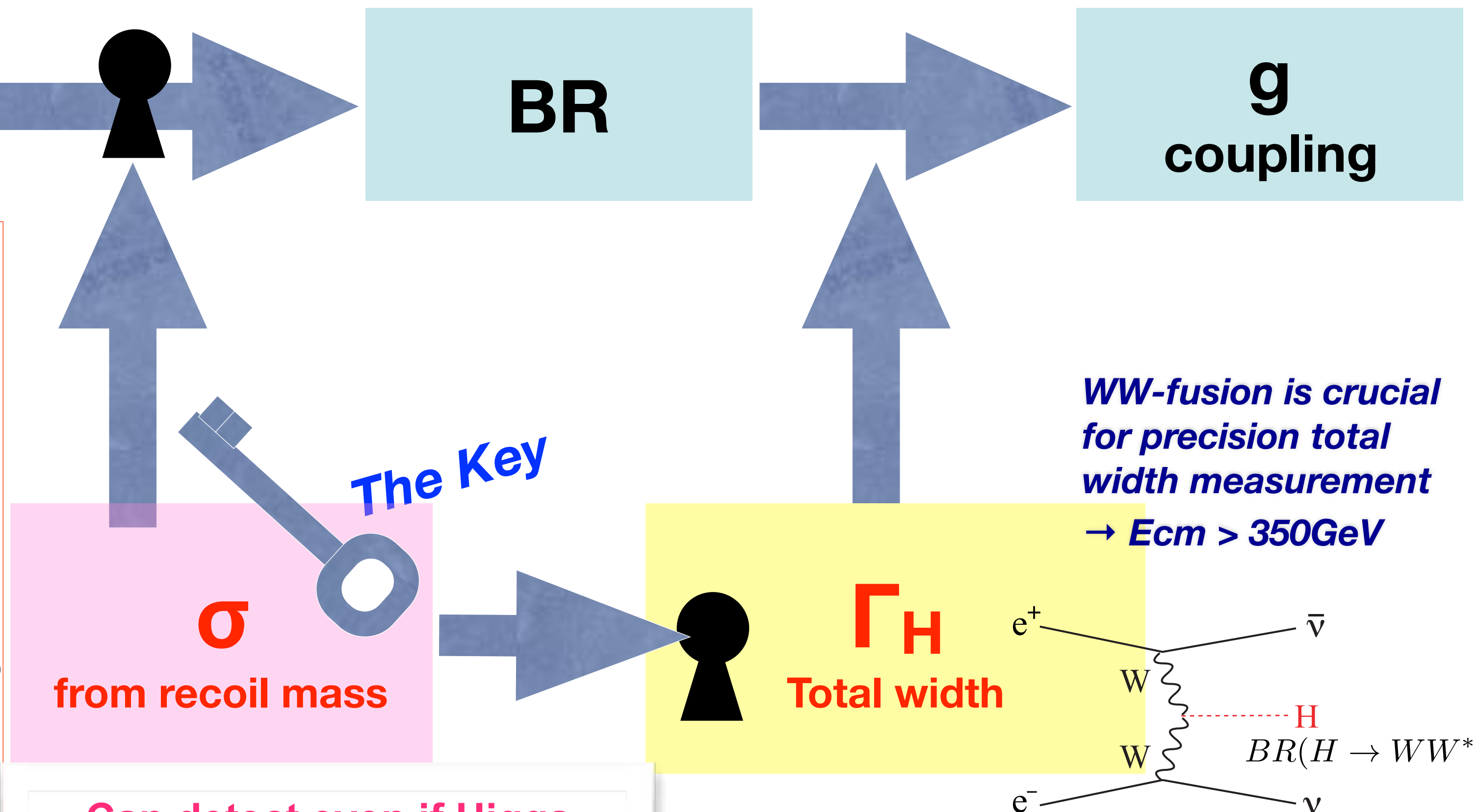
Key Point

At LHC all the measurements are σ×BR measurements.

At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.

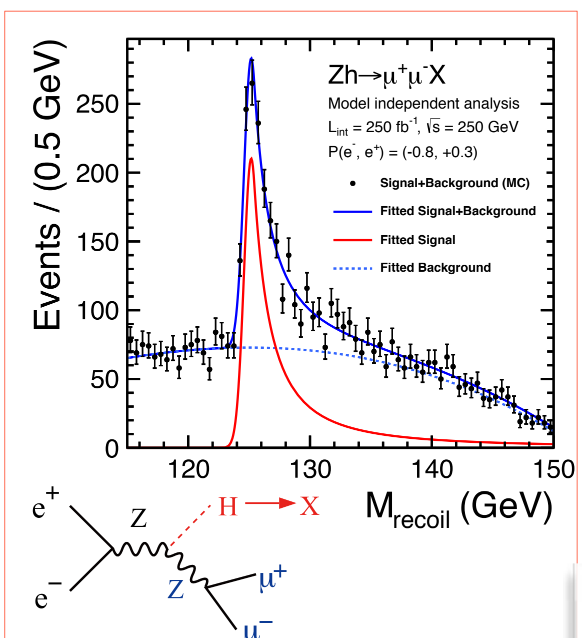


$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



WW-fusion is crucial for precision total width measurement

→ Ecm > 350GeV



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

Can detect even if Higgs decays invisibly!

Higgs Couplings

Model-independent coupling fit, impossible at LHC

H20 Scenario

arXiv: 1506.05992
arXiv: 1506.07830

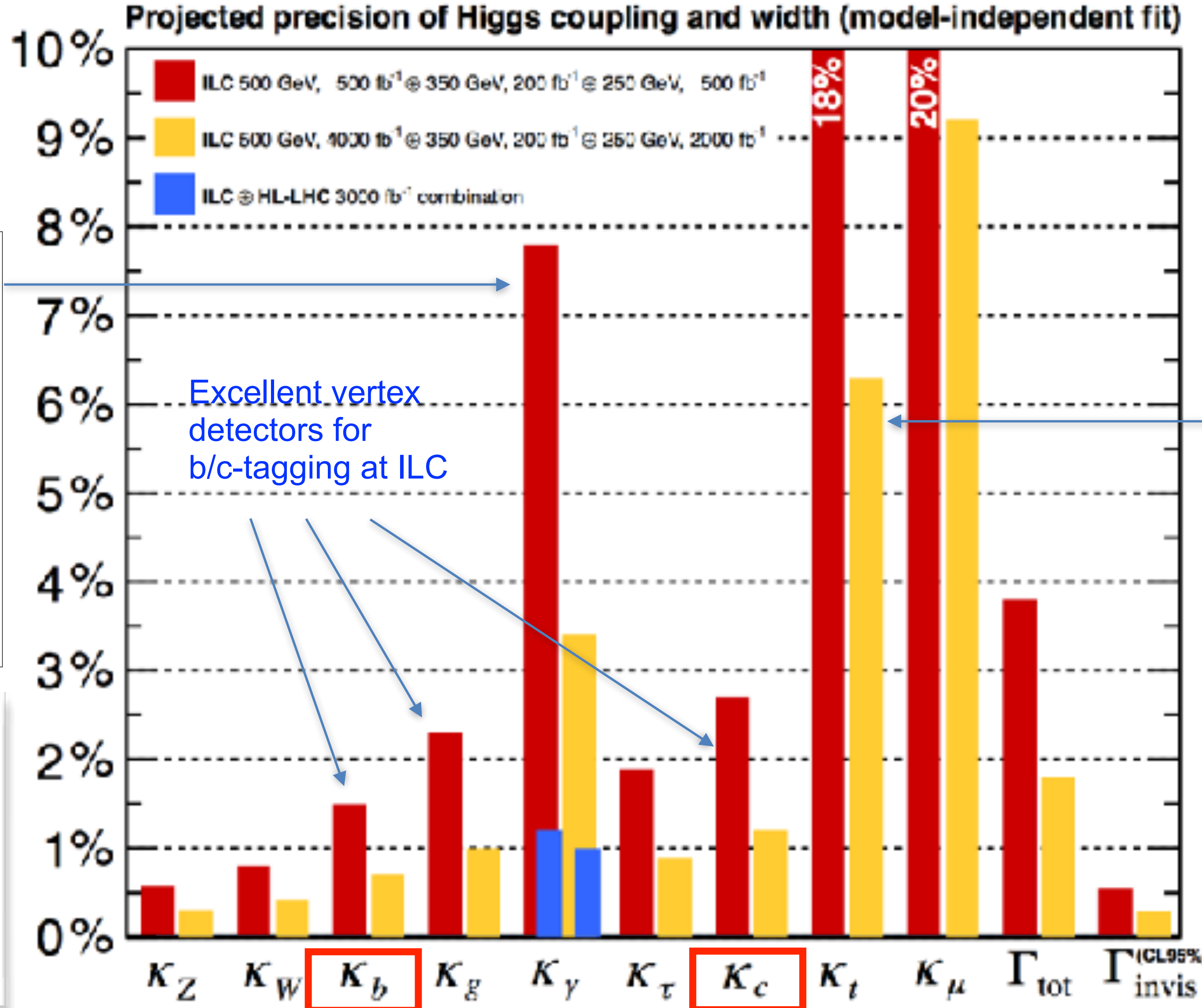
Better hγγ with LHC/ILC synergy

LHC can precisely measure

BR(h→γγ) / BR(h→ZZ*)
= (K_γ / K_Z)^2

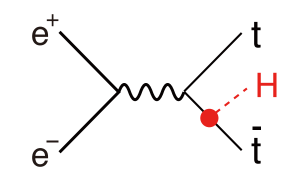
ILC can precisely measure ***K_Z***

All of major Higgs decay modes accessible at ILC with 250-500GeV!



Excellent vertex detectors for b/c-tagging at ILC

Top Yukawa improves by going to 550 GeV

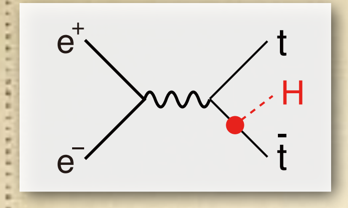


Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV

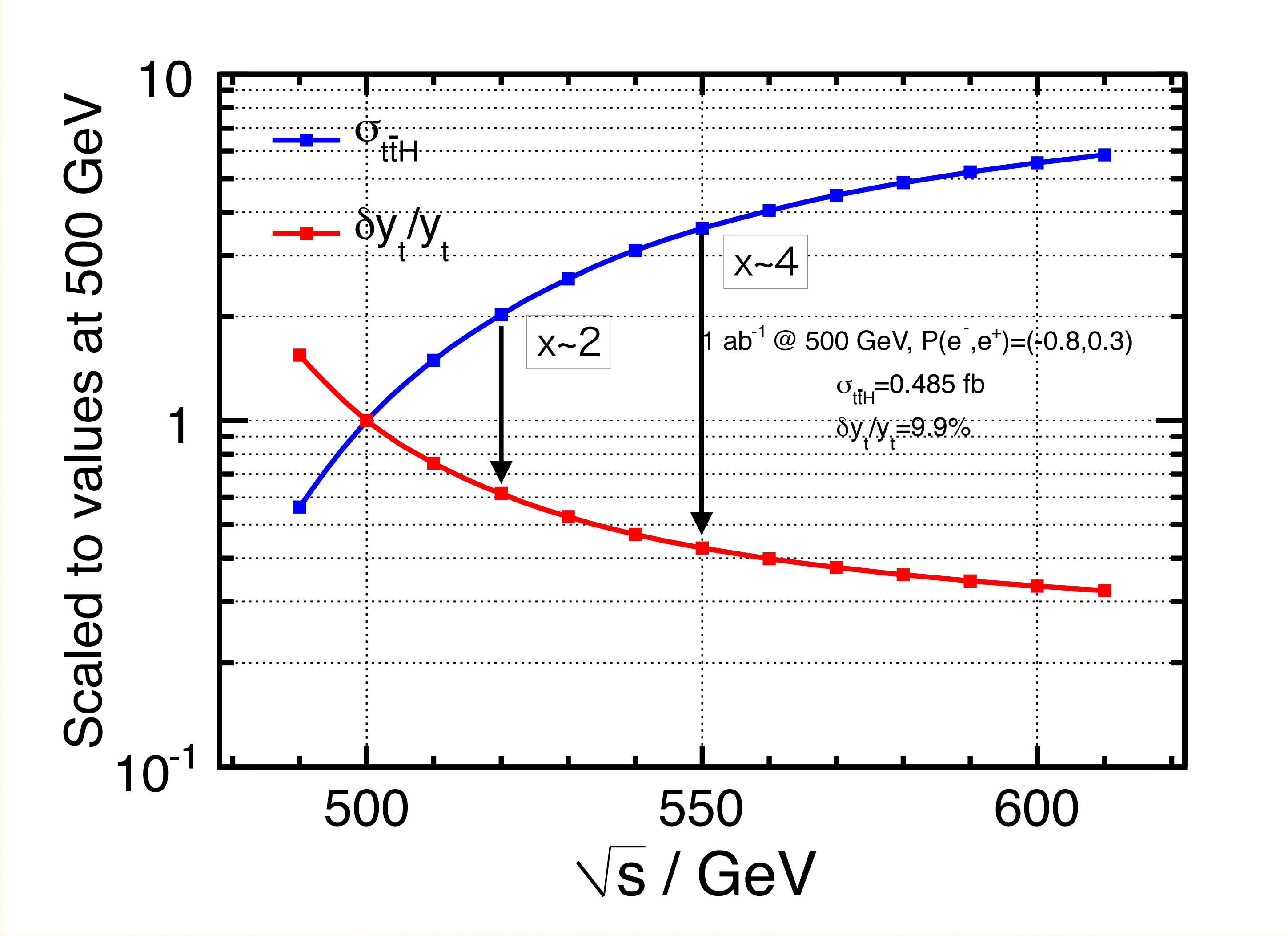
→ 3%

500 GeV already excellent except for K_t, K_μ, and K_γ

~1% or better for most couplings!



Top Yukawa coupling



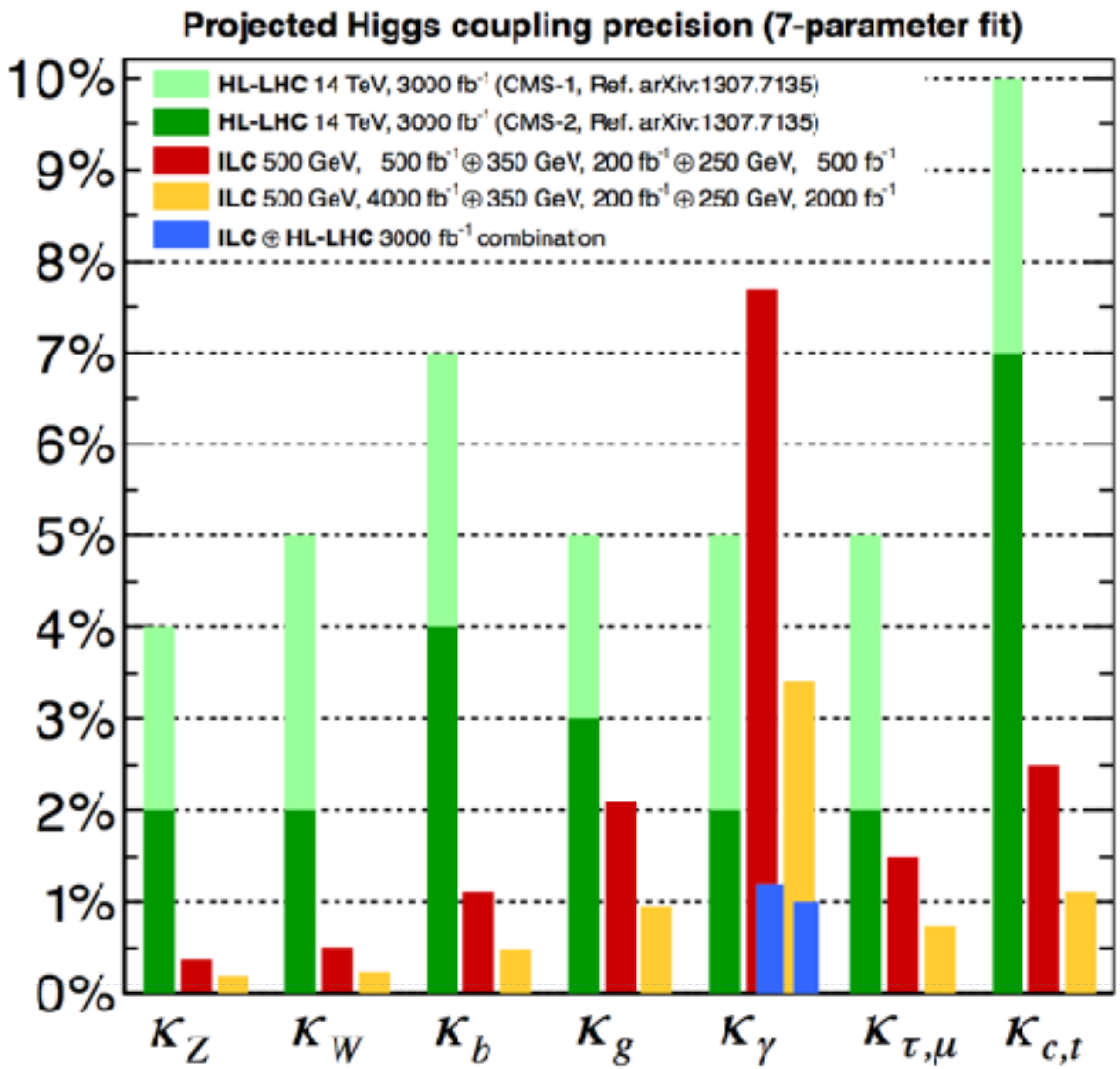
Y. Sudo

Slight increase of E_{max} is very beneficial!

Model-dependent ***coupling fit*** *(LHC-style 7-parameter fit)*

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

Σ_{SM} BR = 1



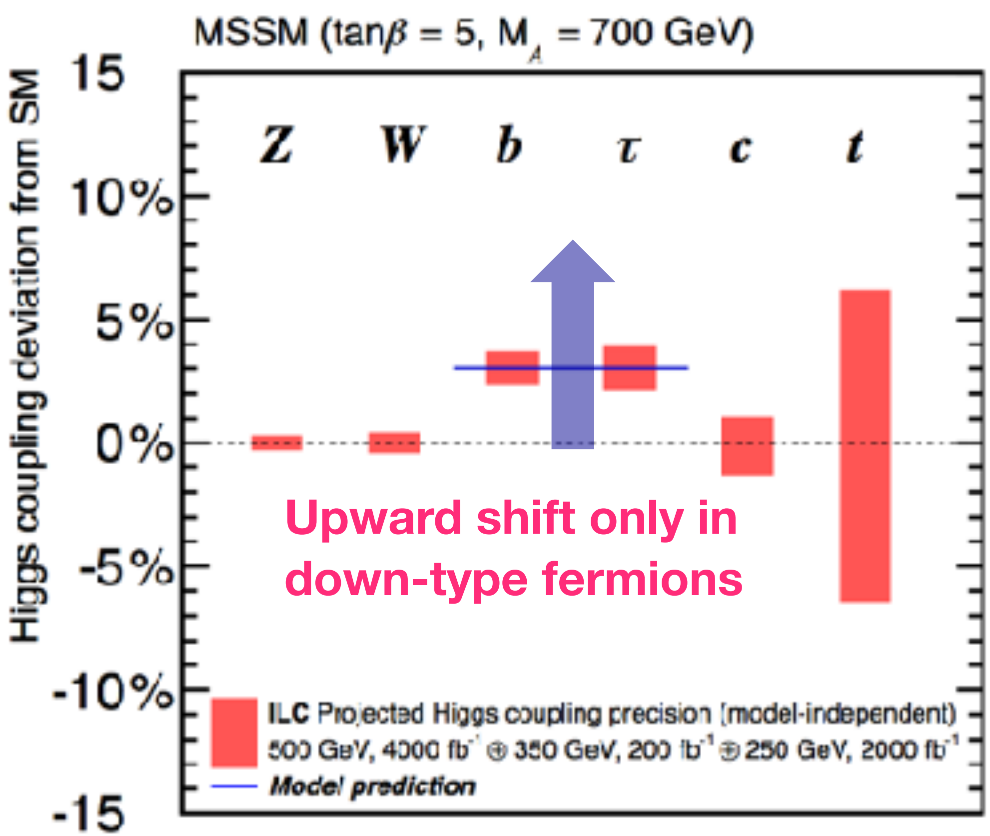
Possible to achieve precision far exceeding LHC!

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

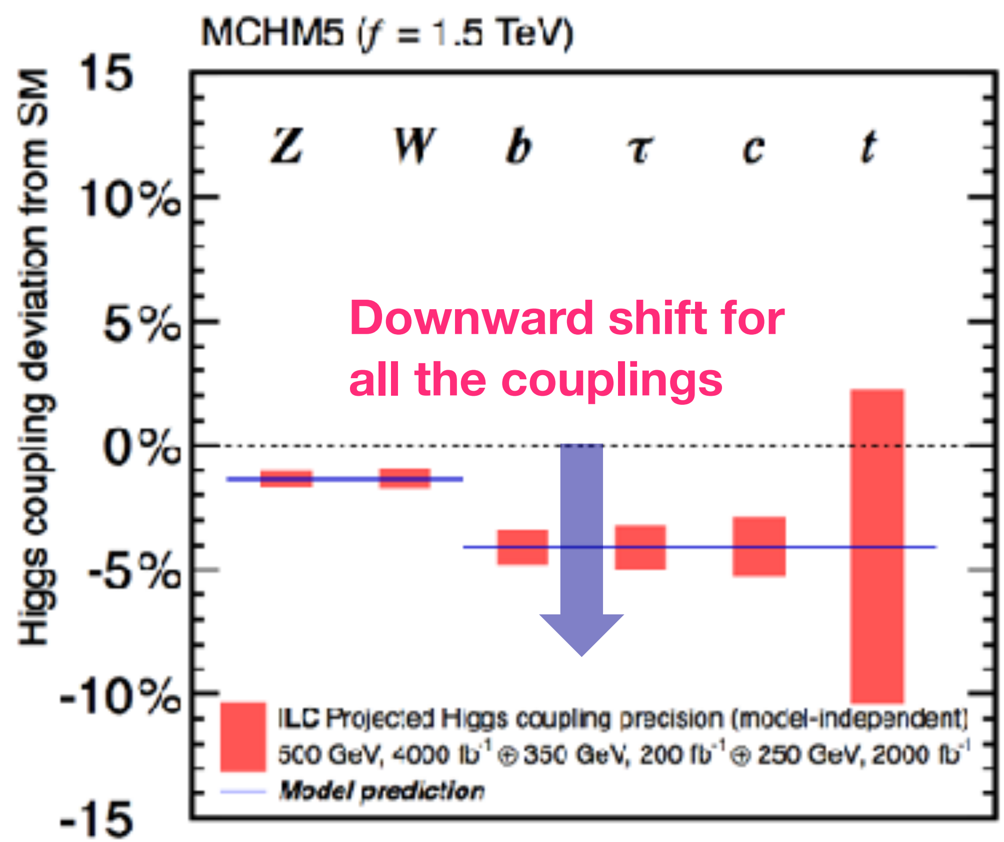
Fingerprinting

Elementary v.s. Composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



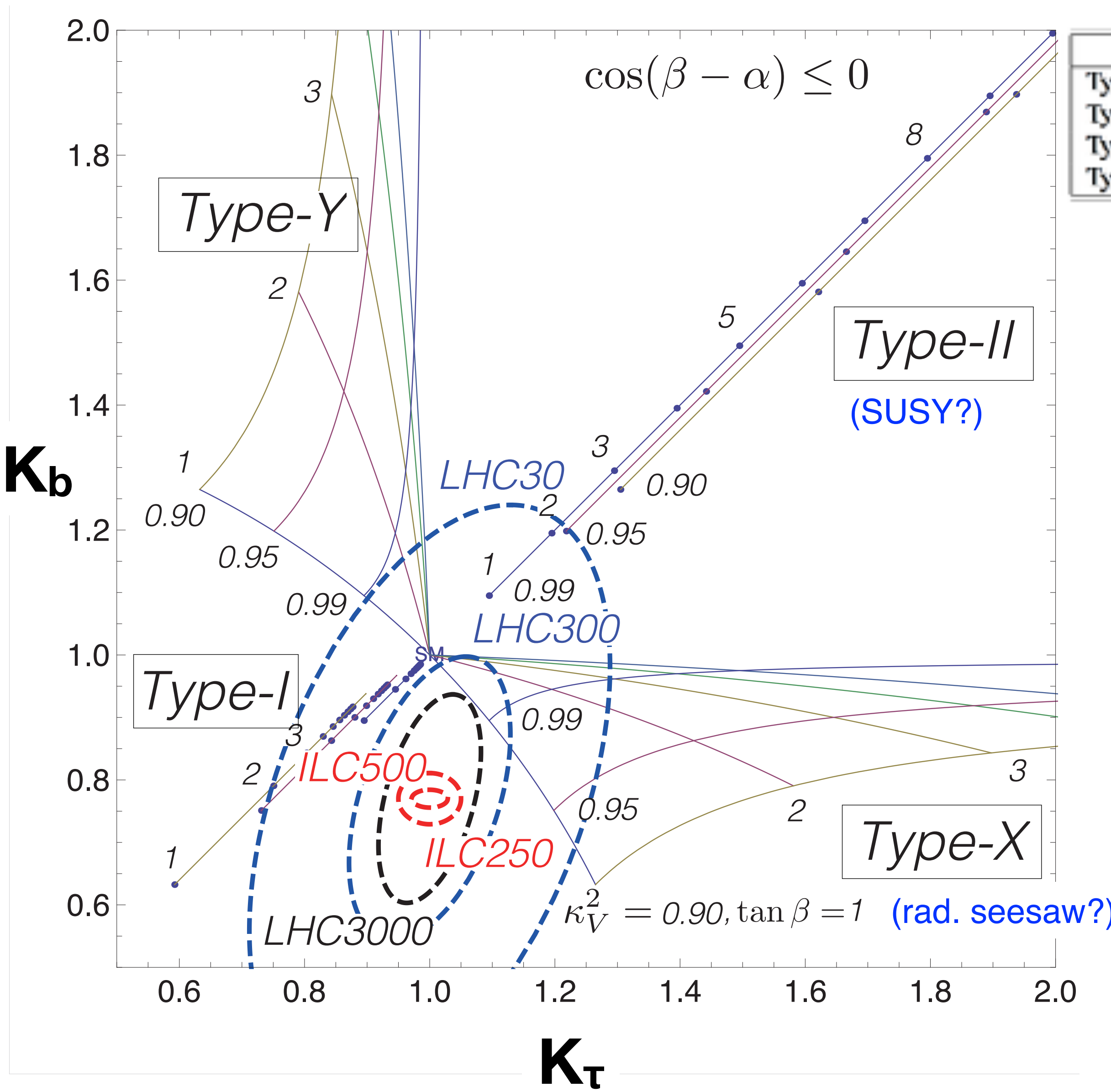
ILC 250+500 LumiUP

Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity far exceeds that of LHC!

Fingerprinting

2HDM

Multiplet Structure



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

*Given a deviation of the Higgs to Z coupling: **$\Delta K_V^2 = 1-K_V^2 = 0.01$** we will be able to **discriminate the 4 models!***

Model-dependent
7-parameter fit
ILC: Baseline lumi.

ILC TDR

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Kanemura et al (arXiv: 1406.3294)

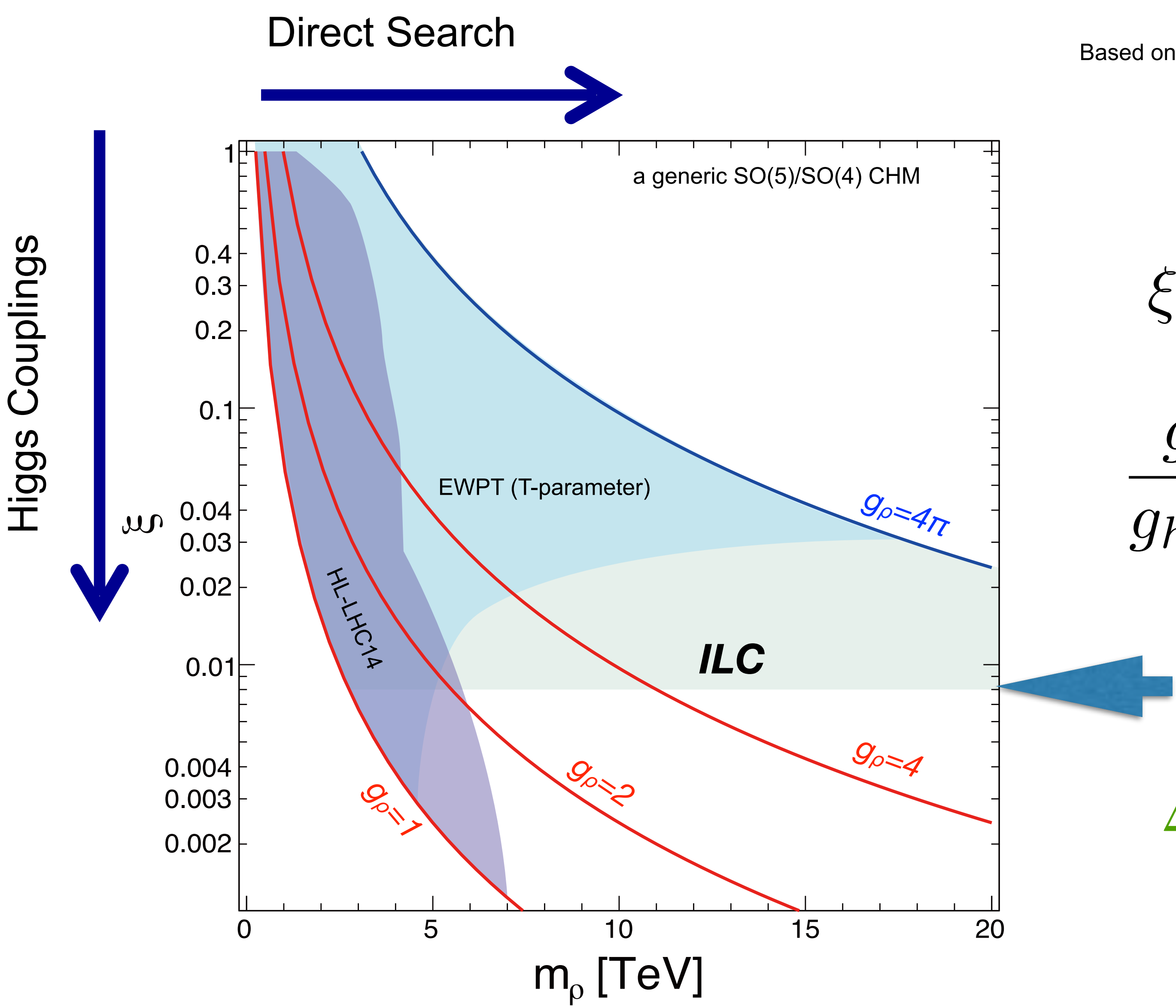
Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)

Based on Contino, et al, JHEP 1402 (2014) 006
Torre, Thamm, Wulzer 2014
Grojean @ LCWS 2014



$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2 = \frac{v^2}{f^2}$$

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \sqrt{1-\xi}$$

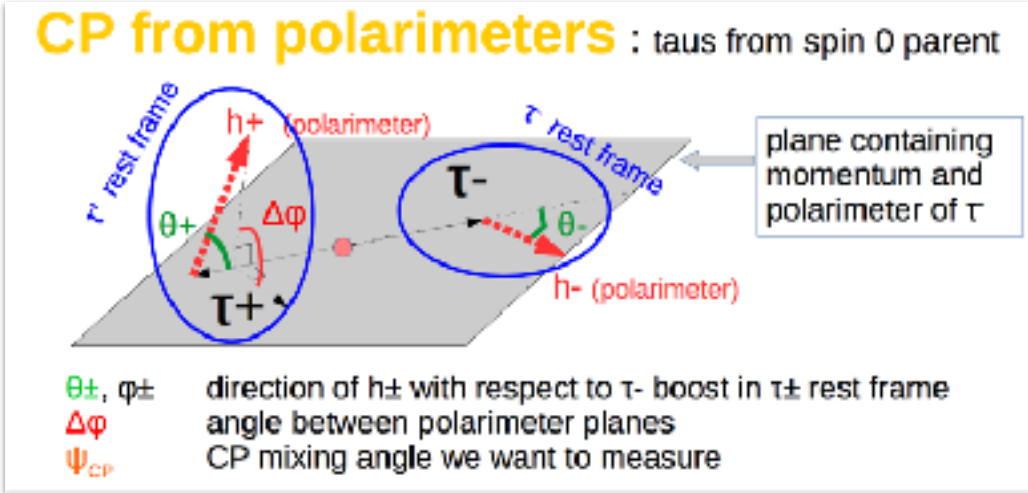
ILC (250+500 LumiUP)

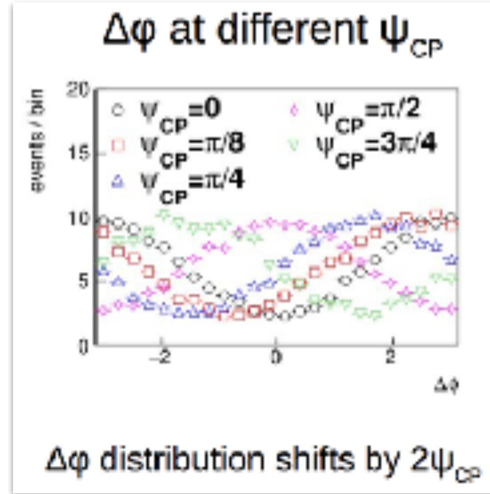
$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

LCWS2016 in Morioka: D. Jeans, "Measuring CP in $H \to \tau^+\tau^-$ at ILC"

CP Mixing $$\mathcal{L}_{h\tau\tau} = g\bar{\tau}\left(\cos\Psi_{CP} + i\gamma_5 \sin\Psi_{CP}\right)\tau\, h$$

250GeV





$2ab^{-1}$ @ 250 GeV

$$\langle \delta\Psi_{CP} \rangle \simeq 3.8^\circ$$
(preliminary)

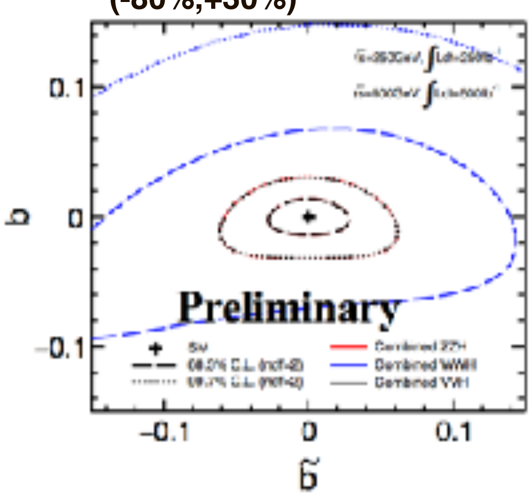
LCWS2016 in Morioka: T. Ogawa, "Full Simulation Study of Anomalous VVH Couplings at ILC"

$$\mathcal{L}_{VVh} = 2M_V^2 \frac{1}{\Lambda}\left(\frac{\Lambda}{v} + a\right) h\, V_\mu V^\mu + C_V \frac{b}{\Lambda} h\, V_{\mu\nu}V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} h\, V_{\mu\nu}\tilde{V}^{\mu\nu} \quad (C_W, C_Z) = (1, 1/2)$$

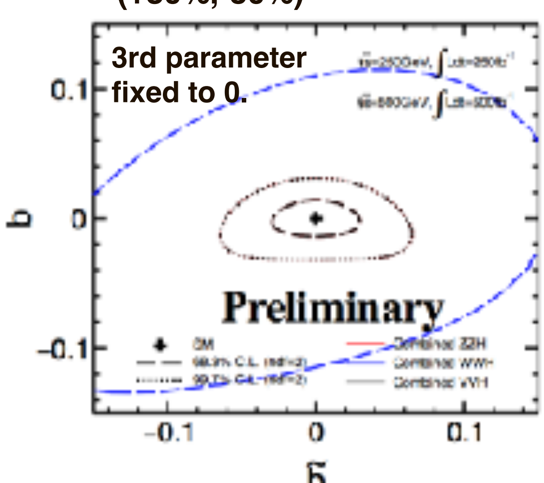
250+500GeV

Angular shape for ZZh (7 processes) + WWh (5 processes) + σ : $250fb^{-1}$@250 GeV and $500fb^{-1}$@500 GeV

(-80%,+30%)



(+80%,-30%)



Translation to Snowmass convention

$$f_{CP\tilde{b}} = (f_{\tilde{b}}/f_{a_4}) f_{CP}$$

$$\rightarrow \quad f_{CP\tilde{b}} \simeq 1.5 \times 10^{-5}$$
$$(\tilde{b} \simeq 0.07(3\sigma) @ \ 500\text{GeV})$$

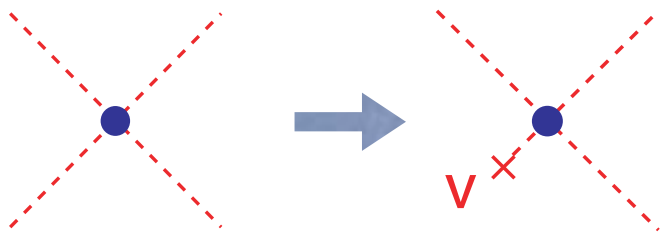
A factor of 2.5 better than Snowmass fast simulation results (arXiv: 1309.4819).

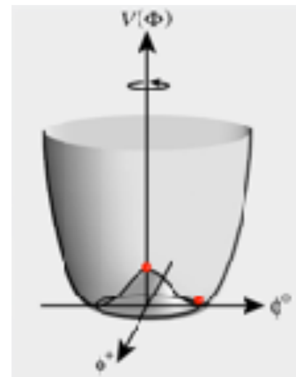
Further improvement expected for H20!

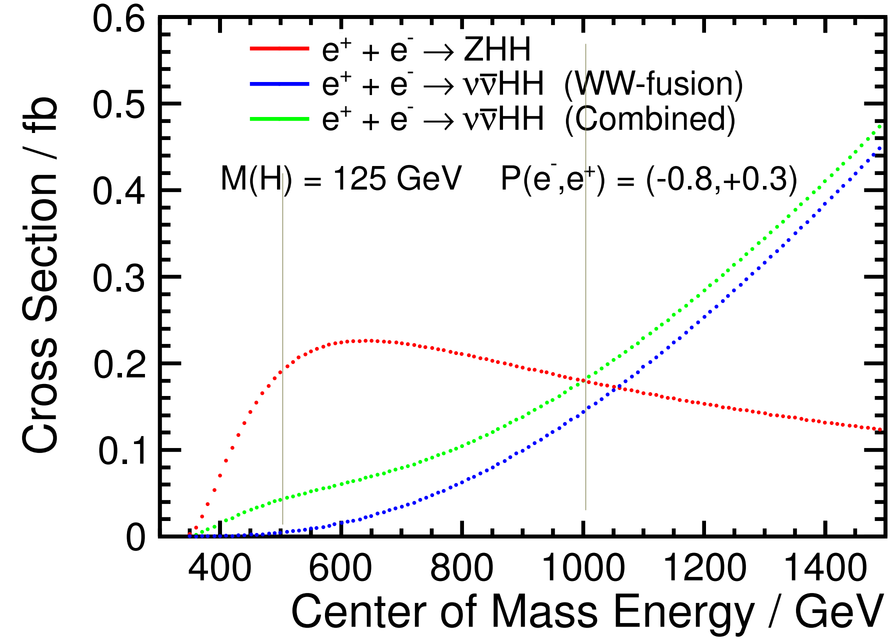
EW Phase Transition
1st order
or
2nd order ?

Higgs Self-Coupling

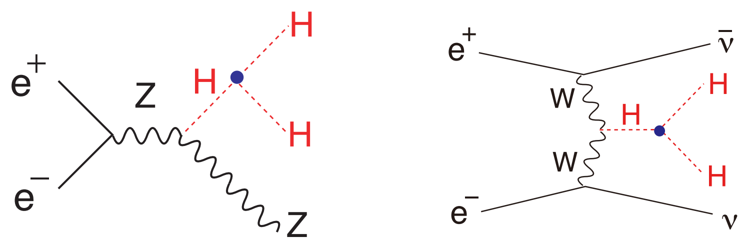
The ***Higgs 3-point self-coupling*** is at the heart of EWSB!







There are ***two ways to measure it*** at ILC



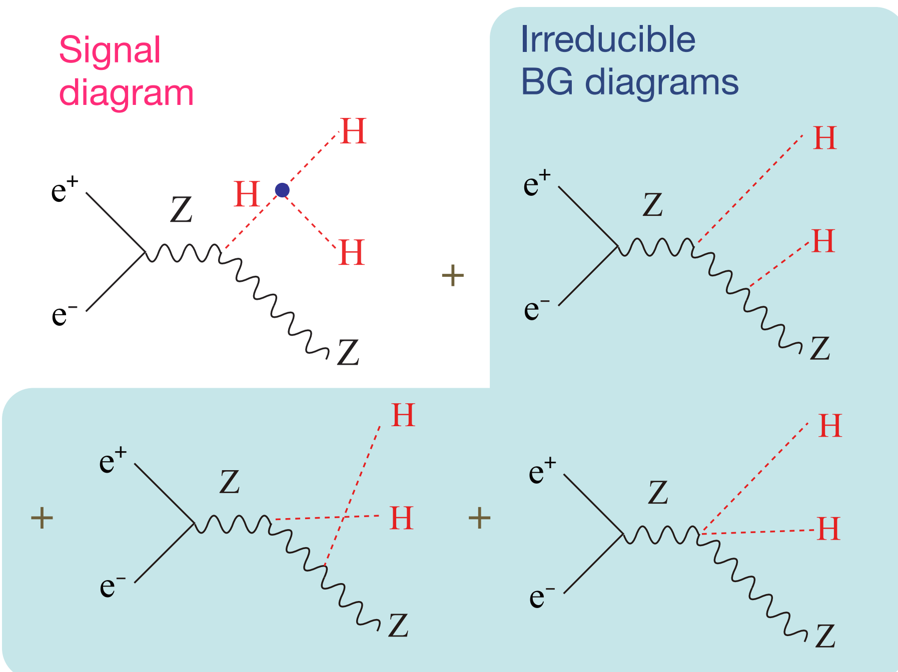
arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$
$P(e^-,e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

26% (H20)

Challenging even at ILC because of
- Small cross section
- ***Presence of irreducible BG diagrams***

Ongoing analysis improvements ***towards O(10)% measurement***

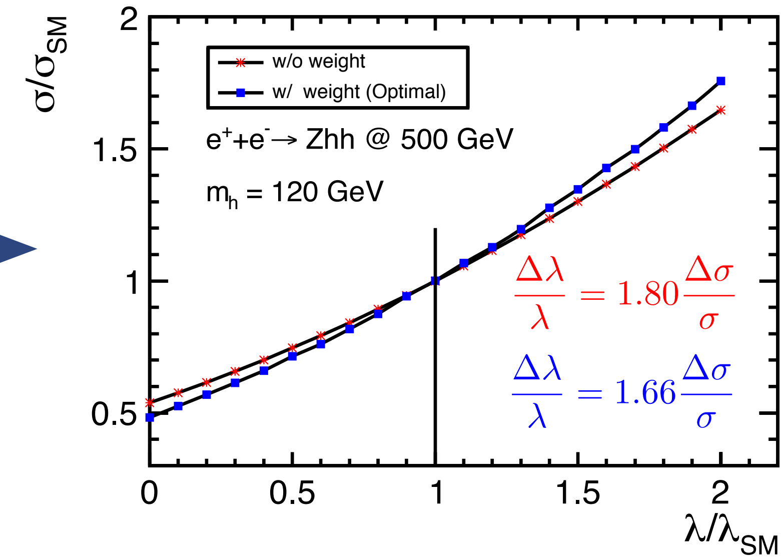
The Problem : BG diagrams dilute self-coupling contribution

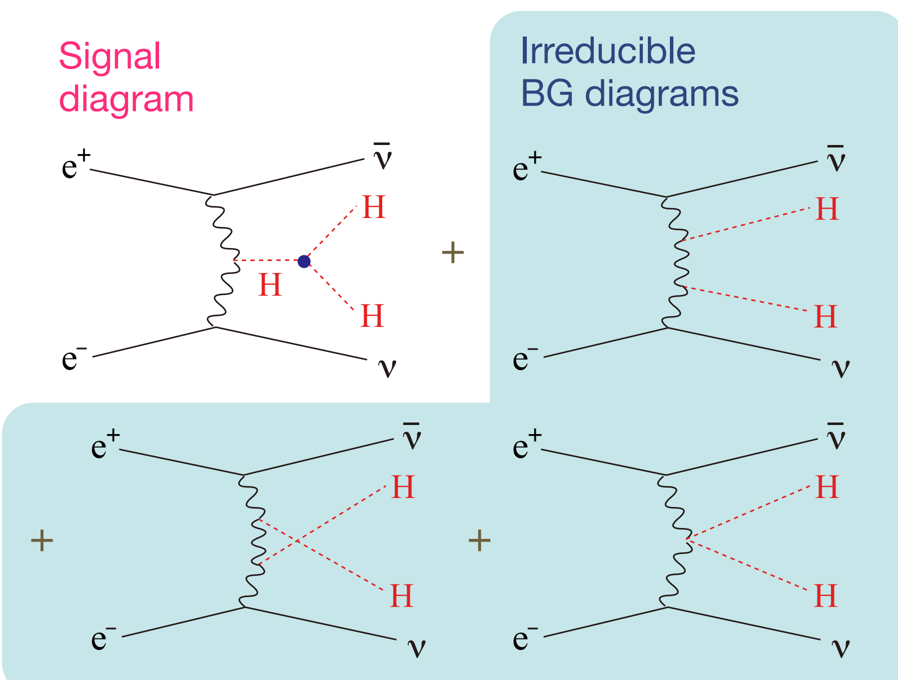


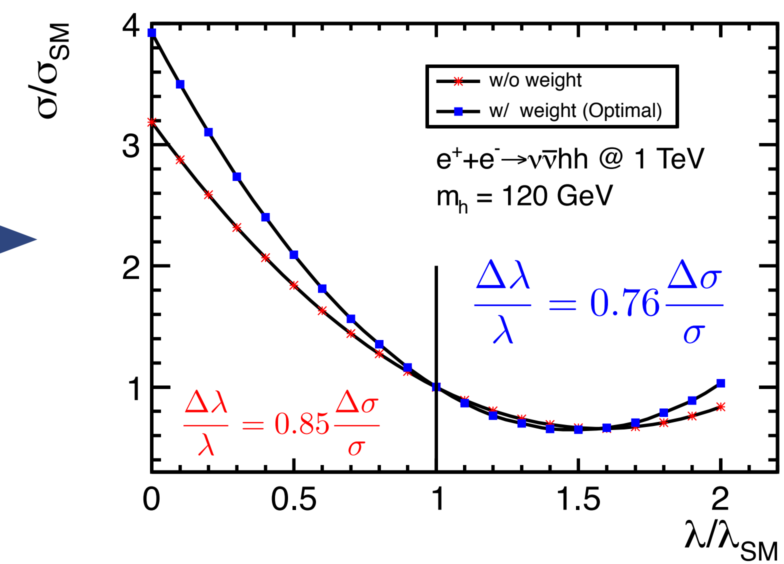
$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams

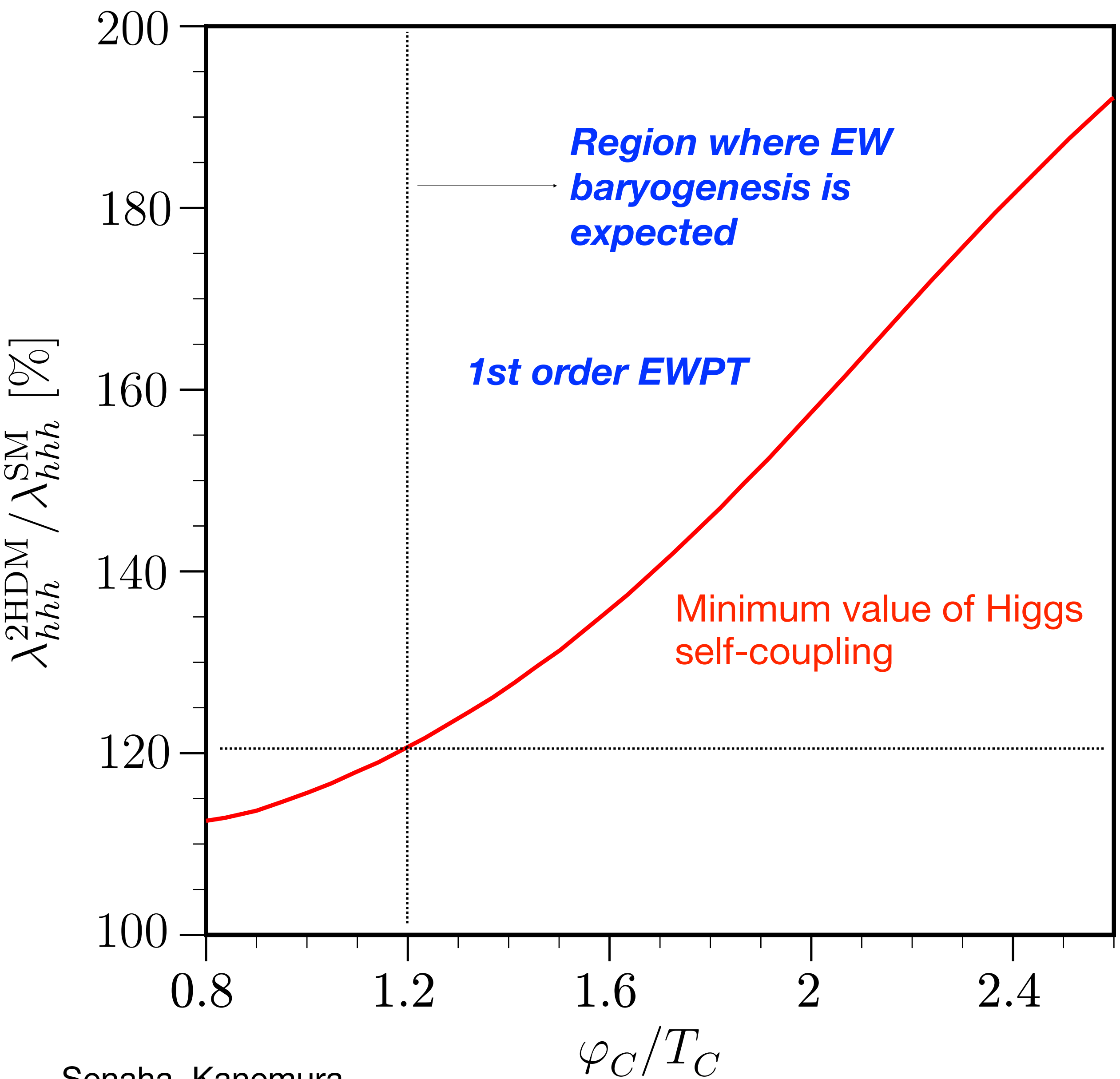






Junping Tian LC-REP-2013-003

Electroweak Baryogenesis



Senaha, Kanemura

<u>Example:</u>

Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling
→ ***1st order EW phase transition***
→ ***Out of equilibrium***

+ CPV in Higgs sector
→ ***EW baryogenesis possible***

Constructive interference between signal and BG diagrams:
→ ***if +100% deviation, then 14% precision expected on λ*** at 500GeV.

ILC can address the idea of ***baryogenesis occurring at the electroweak scale***.

Summary of Physics Part

- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** The discovery of H(125) completed the SM particle spectrum and taught us how the EW symmetry was broken. However, it does not tell us why it was broken. ***Why $\mu^2 < 0$?*** To answer this question we need to go beyond the SM.

- There is a big fork concerning the question: ***Is H(125) elementary or composite?*** There are ***two powerful probes*** in hand: ***H(125) itself and the top quark***. Different models predict different deviation patterns in Higgs and top couplings. ***ILC will measure these couplings with unprecedented precision.***

- This will open up a window to BSM and ***fingerprint BSM models***, otherwise it will set the energy scale for the E-frontier machine that will follow LHC and ILC.

- ***Cubic self-coupling measurement*** will decide whether the EWSB was strong 1st order phase transition or not. If it was, it will provide us the possibility of understanding ***baryogenesis at the EW scale***.

- ***The ILC is an ideal machine to address these questions*** (regardless of BSM scenarios) and we can do this ***model-independently***.

- Though I could not cover it today, It is also very important to stress that ***ILC, too, is an energy frontier machine.*** It will access the energy region never explored with any lepton collider. It is not a tiny corner of the parameter space that will be left after LHC. ***There is a wide and interesting region for ILC to explore.***

- Once a new particle is discovered, we can precisely determine its properties. In the SUSY case, for instance, we might even hope to probe GUT scale physics through RGE.

- ***In this way, ILC will pave the way to the moment of creation.***

ILC Project Status

ILC Promotion: Recent History

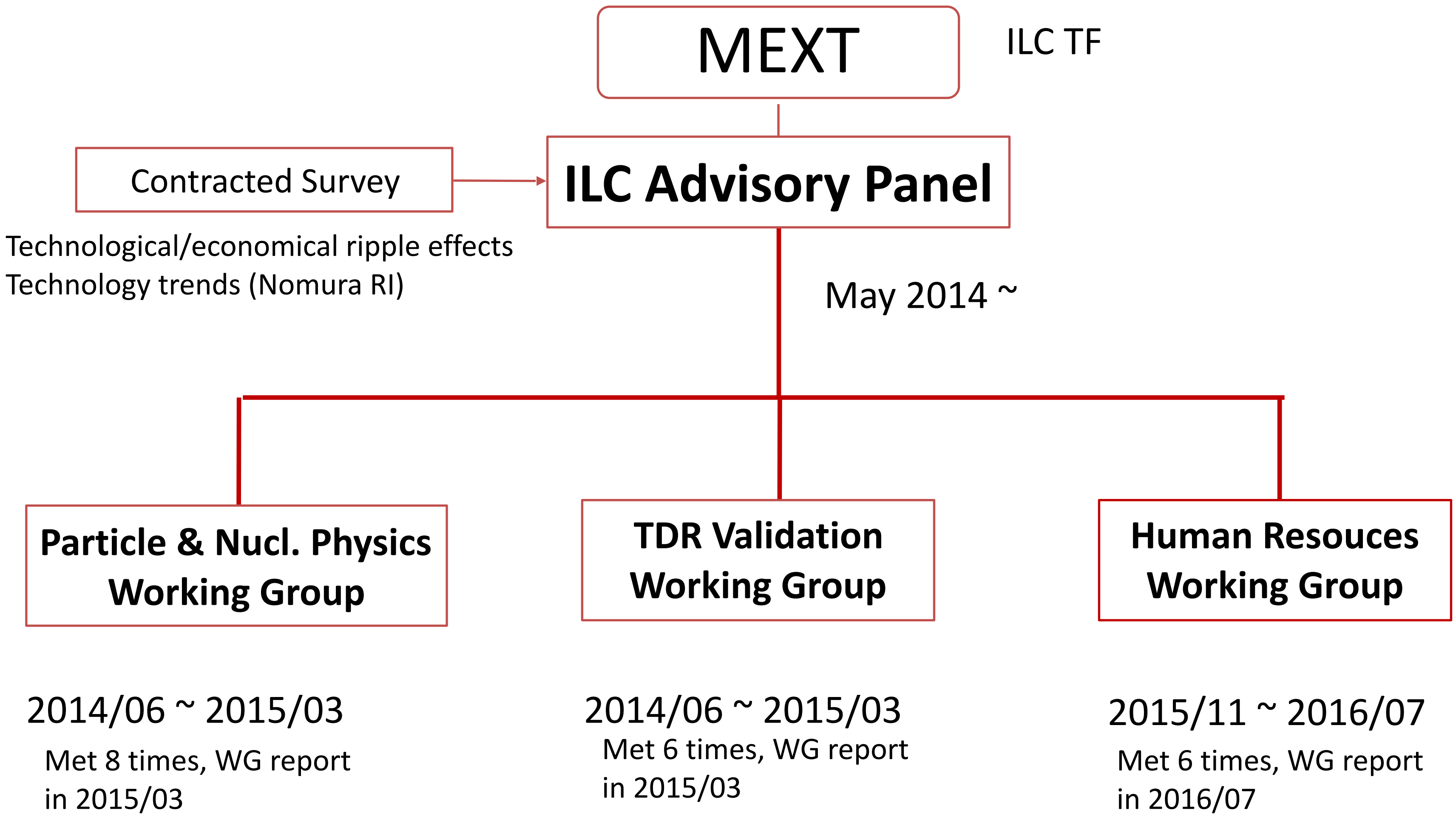
- Oct. 2013: Japanese HEP community proposed to host the ILC in Japan as a global project. “A Proposal for a Phased Execution of the ILC”.
- Statements on ILC hosted in Japan
  - The European Strategy for Particle Physics Update 2013
  - ACFA/AsiaHEP Statement on the ILC (Sep. 2013)
  - P5 Report (May 2014)
  - ICFA statements (Jan. & July 2014)
- Sep. 2013: Science Council of Japan (SCJ) sent report on the ILC project to MEXT.
- May 2014: MEXT set up ILC Advisory Panel.

MEXT's ILC Review

MEXT = Japan's
Ministry of
Education,
Culture, **S**ports, **S**cience and
Technology

ILC Advisory Panel

Set up in May 2014 under MEXT ILC Task Force to investigate various issues concerning the possibility of hosting the ILC in Japan



http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/index.htm

Interim Summary

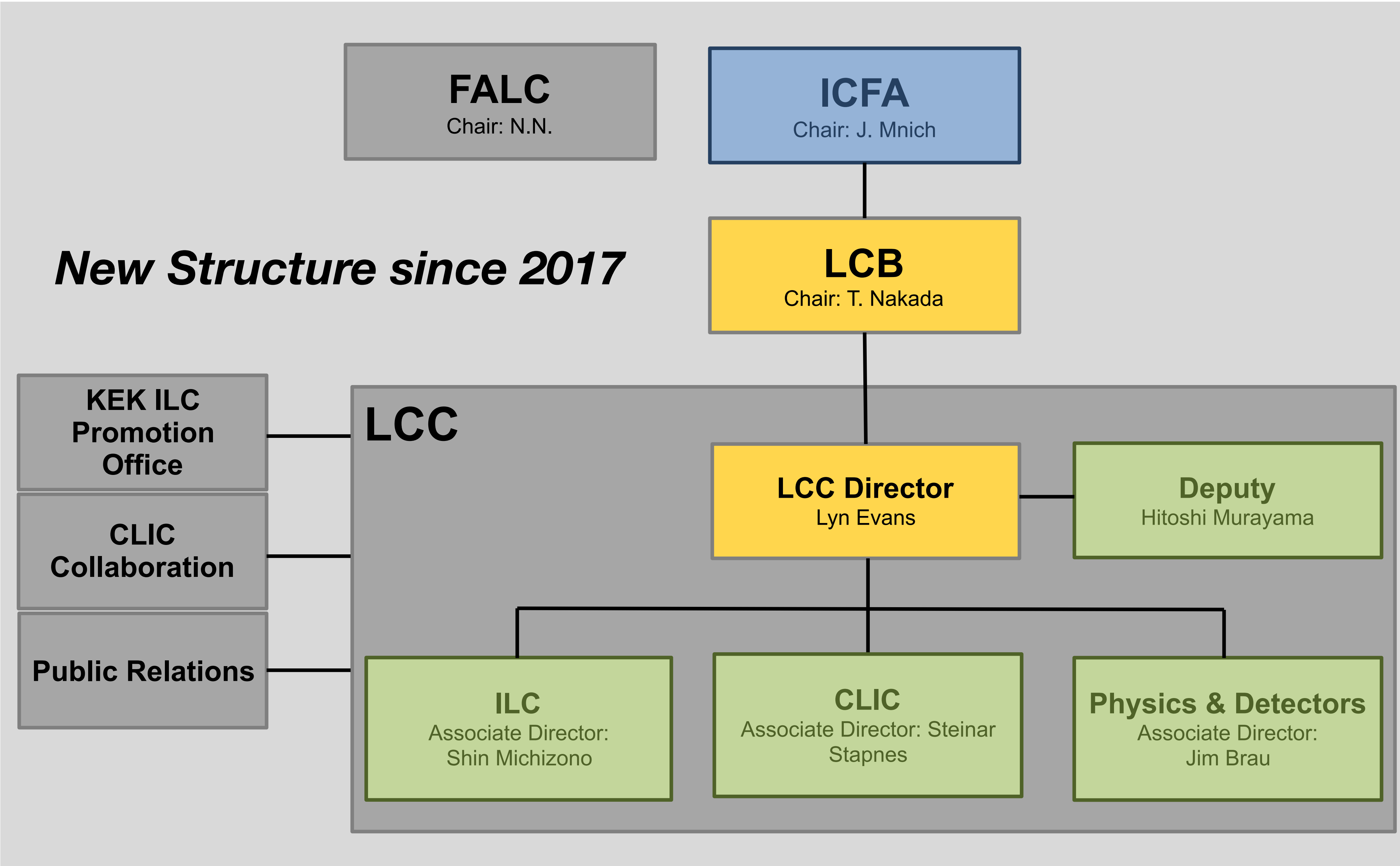
http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/gaiyou/1360593.htm

- ILC Advisory Panel published an interim summary of their discussions based on the reports from the two working groups (Particle & Nuclear Physics WG and TDR Validation WG).
- The interim summary pointed out the following issues
  - Obtain clear vision for international cost sharing
  - **Make clear scientific merits (not only precision studies of Higgs and top but also possibilities of new particle discoveries) that match the investment**
  - **Monitor, analyze, and examine the development of LHC experiments.**
  - Solve remaining technological issues and **mitigate cost risk**.
  - Get **understanding from the general public** and other scientific communities.

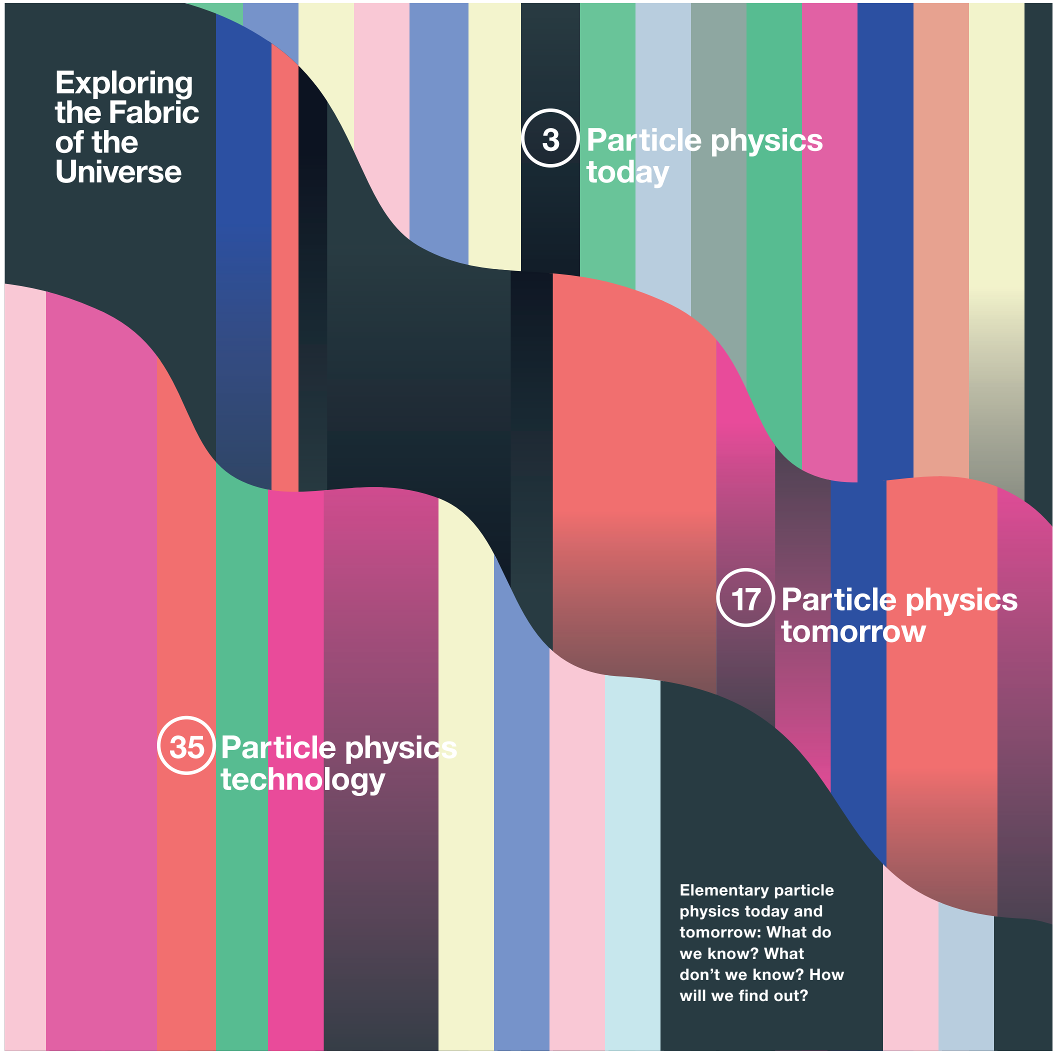
Linear Collider Collaboration (LCC)

international collaboration
to address these issues

LCB/LCC Organization 2017



ILC Brochure



ILC communicators with consultation by LCC Physics WG

Essentially completed → to be publicized soon!

And did the homework following MEXT's recommendation

ILC–NOTE–2016–067
DESY 16–145, IPMU16-0108
KEK Preprint 2016–9, LAL 16–185
MPP–2016–174, SLAC–PUB–16751

July, 2016

Implications of the 750 GeV $\gamma\gamma$ Resonance as a Case Study for the International Linear Collider

LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3] Michael E. Peskin[4](conveners); Tim Barklow[4], Yuanning Gao[5], Shinya Kanemura[6], Hyungdo Kim[7], Jenny List[2], Mihoko Nojiri[1,8], Maxim Perelstein[9], Roman Pöschl[10], Jürgen Reuter[2], Frank Simon[11], Tomohiko Tanabe[12], Jaehoon Yu[13], James D. Wells[14]; Adam Falkowski[15], Shigeki Matsumoto[8], Takeo Moroi[16], François Richard[10], Junping Tian[12], Marcel Vos[17], Hiroshi Yokoya[18]; Hitoshi Murayama[8,19,20], Hitoshi Yamamoto[21]

ABSTRACT

If the $\gamma\gamma$ resonance at 750 GeV suggested by 2015 LHC data turns out to be a real effect, what are the implications for the physics case and upgrade path of the International Linear Collider? Whether or not the resonance is confirmed, this question provides an interesting case study testing the robustness of the ILC physics case. In this note, we address this question with two points: (1) Almost all models proposed for the new 750 GeV particle require additional new particles with electroweak couplings. The key elements of the 500 GeV ILC physics program—precision measurements of the Higgs boson, the top quark, and 4-fermion interactions—will powerfully discriminate among these models. This information will be important in conjunction with new LHC data, or alone, if the new particles accompanying the 750 GeV resonance are beyond the mass reach of the LHC. (2) Over a longer term, the energy upgrade of the ILC to 1 TeV already discussed in the ILC TDR will enable experiments in $\gamma\gamma$ and e^+e^- collisions to directly produce and study the 750 GeV particle from these unique initial states.

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[1,6], 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]

Abstract

This paper addresses the question of whether the International Linear Collider has the capability of discovering new particles that have not already been discovered at the CERN Large Hadron Collider. We summarize the various paths to discovery offered by the ILC, and discuss them in the context of three different scenarios: 1. LHC does not discover any new particles, 2. LHC discovers some new low mass states and 3. LHC discovers new heavy particles. We will show that in each case, ILC plays a critical role in discovery of new phenomena and in pushing forward the frontiers of high-energy physics as well as our understanding of the universe in a manner which is highly complementary to that of LHC.

For the busy reader, a two-page executive summary is provided at the beginning of the document.

ILC Advisory Panel

Set up in May 2014 under MEXT ILC Task Force to investigate various issues concerning the possibility of hosting the ILC in Japan

MEXT

ILC TF

Most recent meeting of the panel on Feb. 1, 2017

- the US-Japan cost reduction R&D
- HEP community's discussion on staging

Contracted Survey

Technological/economical ripple effects
Technology trends (Nomura RI)

ILC Advisory Panel

May 2014 ~

Particle & Nucl. Physics Working Group

2014/06 ~ 2015/03

Met 8 times, WG report in 2015/03

TDR Validation Working Group

2014/06 ~ 2015/03

Met 6 times, WG report in 2015/03

Human Resouces Working Group

2015/11 ~ 2016/07

Met 6 times, WG report in 2016/07

Organization & Management Working Group

2017/02 ~

1st meeting scheduled in 2017/03

http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/index.htm

Support from Diet Members and Industrial Sector in Japan

- ***Federation of Diet Members for the ILC*** (since 2008 with >150 members)
- ***Advanced Accelerator Association*** *Promoting Science & Technology* (AAA) (since 2008 with 100 companies and 40 universities and research institutions)
- Event in Washington DC on Feb. 2016 coordinated by Hudson Institute and AAA. 4th visit to Washington by Diet members with MEXT officials.

From LC NEWSLINE

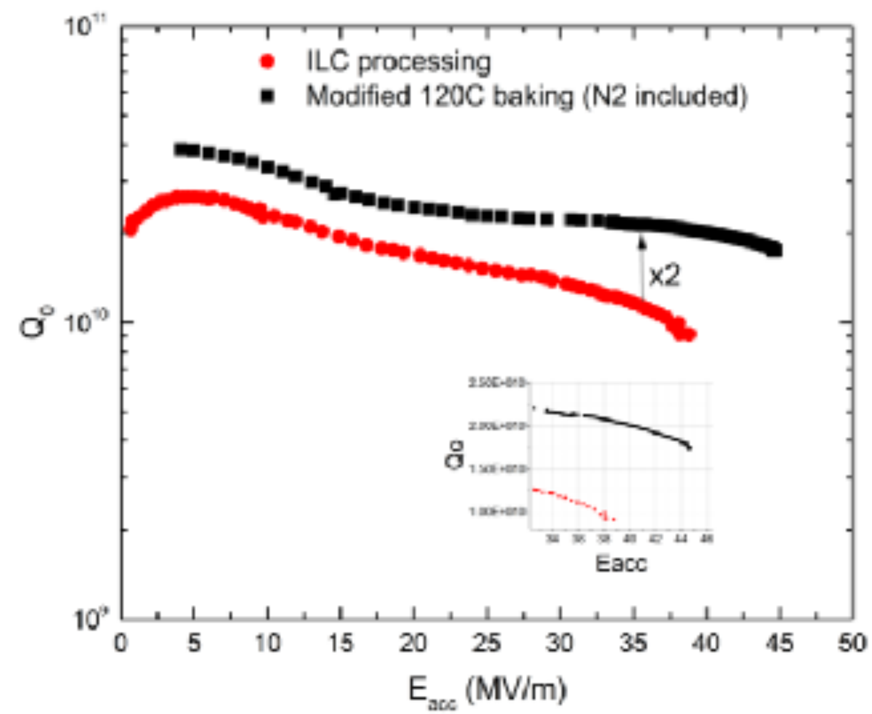
http://newsline.linearcollider.org/2016/03/03/us-japan-symposium/

Hon. Shionoya is recommending the Kasoku Kids cartoon book to the roundtable discussion chaired by Dr. William Schneider, Jr. (Hudson Institute)

MET-DOE Discussion Group

- High level officers from MEXT visited their DOE counter part at the end of May and it was agreed to start a US-Japan discussion group co-chaired by Director of Office of Science of DOE and a corresponding level officer in MEXT. They decided to meet every 2-3 months.

- In their Oct. 2016 meeting, it was agreed to start ***US-Japan collaborative research for ILC cost reduction:*** aiming at 10-12% cost reduction of the ILC machine construction cost.
  - Cost reduction in Nb material preparation
  - High-Q high-gradient SCRF cavity using nitrogen infusion



Science First with the ILC- Keynote speech by Takeo Kawamura *from LC NEWSLINE*

http://newsline.linearcollider.org/2016/12/08/science-first/

Hon. Takeo Kawamura giving a keynote speech at the LCWS2016 in Morioka, japan. Image: LCWS2015 LOC

In his keynote at LCWS2016, former MEXT Minister Takeo Kawamura stressed that while fundamental research may have application in the long run, it's the science that is most important.

LCWS2016 in Morioka, japan.

Standing ovations for Hon. Takeo Kawamura's speech by LCWS2016 participants. Image: LCWS2016 LOC

Staging Discussion

- In LCWS 2016, Nov. in Morioka, it was agreed to start seriously considering a staging scenario of the ILC ***to significantly reduce the initial construction cost***.
  - 1st stage as a Higgs factory
  - and later stages taking advantage of flexible energy expandability of a linear collider.
- LCB/LCC started working on possible staging scenarios to build consensus among the worldwide HEP community.

Summary

- MEXT is seriously investigating various issues to be solved to host the ILC in Japan.
- KEK/JHEP is taking various actions together with the LCC to address issues pointed out by the MEXT ILC Advisory Panel.
- MEXT-DOE joint discussion group started.
- US-Japan collaborative research on cost reduction started.
- There are important political interactions happening also in Europe and Asia.
- Serious discussions on staging started.
- As Hon. Kawamura said in LCWS 2016, 2017-2018 will be a very important time for the ILC.

Backup

The Current Official Operation Scenario: H20

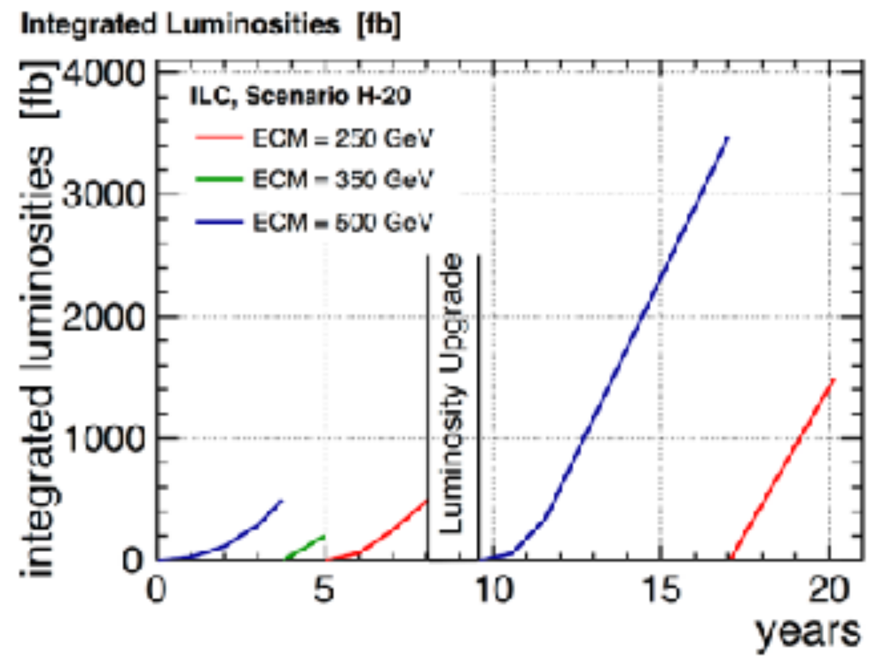
J. Brau : ICHEP2016

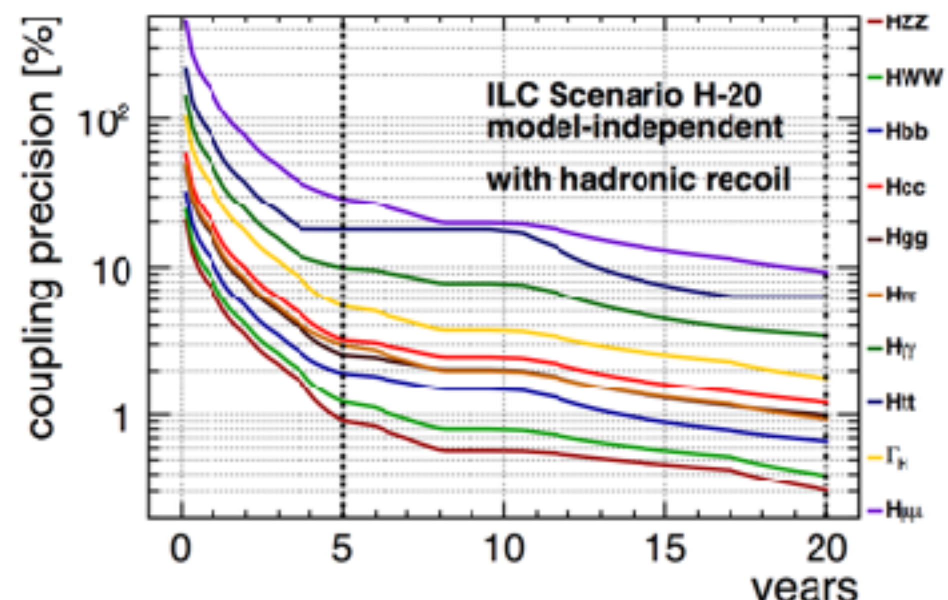
ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• gHWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision W couplings	✔	✔	
• precision search for Z'	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔

Figure 1: ILC Physics Goals.

Δm_h = 20MeV
→ 0.2% coupling uncertainty
for hWW and hZZ

High luminosity 250GeV run will be needed anyway, and the 250GeV stage alone can produce significant physics outputs, but, of course, the full program needs higher energy running.





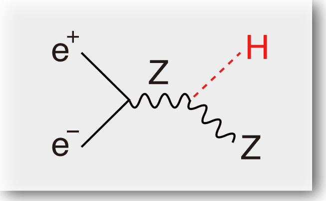
Higgs-related Physics at Ecm ≲ 500 GeV

Three well know thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (***recoil mass***)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

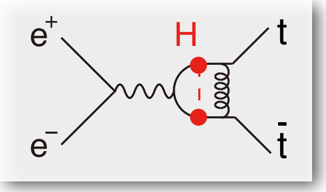
→Higgs couplings (other than top)



ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

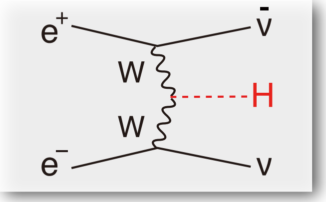
- Threshold scan --> theoretically clean ***mt*** measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of ***top Yukawa*** coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



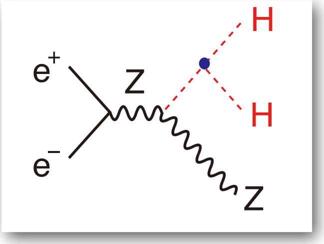
vvH @ 350 - 500GeV :

- ***HWW coupling*** -> ***total width*** --> absolute normalization of Higgs couplings



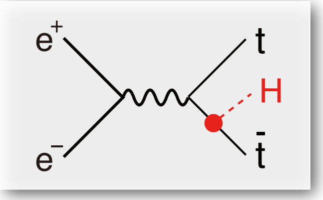
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> ***Higgs self-coupling***



ttbarH @ 500GeV (~2mt+M_H+30GeV) :

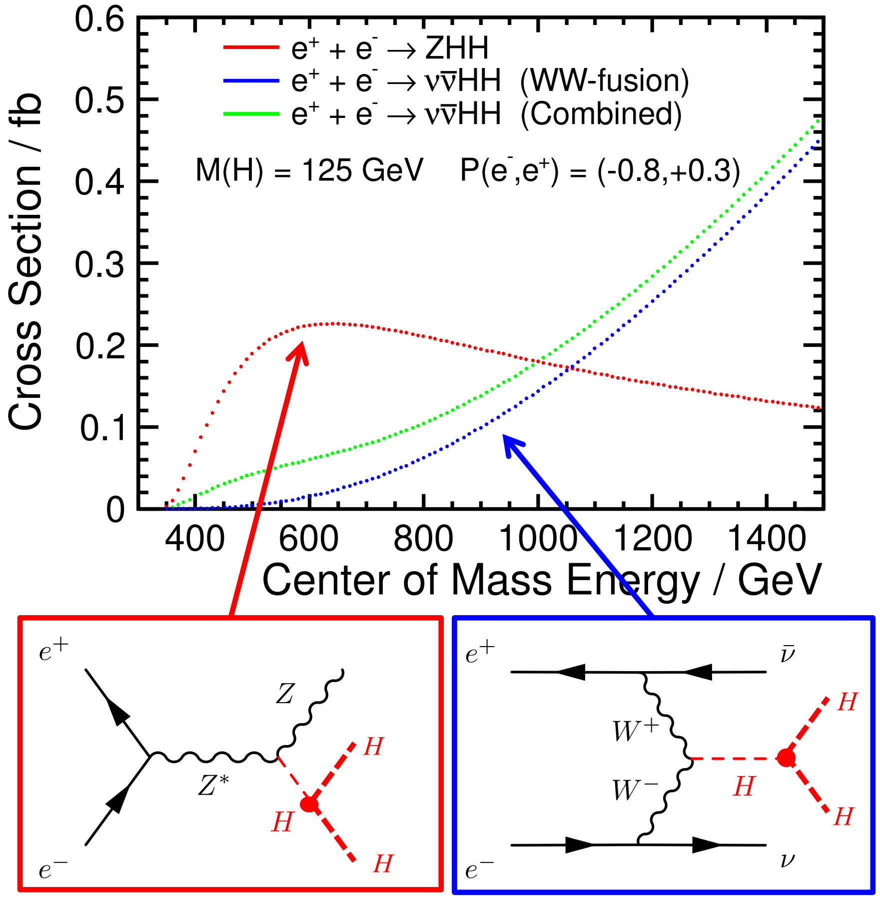
- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> ***top Yukawa*** measurable at 500GeV concurrently with the self-coupling



We can access all the relevant Higgs couplings at ~500GeV for the mass-coupling plot!

Direct Measurement

Cross section vs CM energy (e+e-)



Diagrams with triple-Higgs coupling

Expected precision based on
full detector simulation studies:

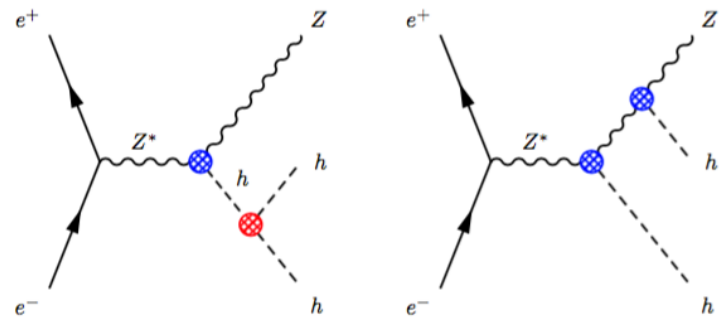
ILC	ILC
500 GeV, 4 ab-1 **δλ = 27%**	500 GeV, 4 ab-1 & 1 TeV, 8 ab-1 **δλ = 10%**

References:
J. Tian, LC-REP-2013-003
M. Kurata, LC-REP-2014-025
C. Duerig, Ph.D. thesis at DESY, 2016
HH→bbbb, bbWW* combination

CLIC	CLIC
1.4 GeV, 1.5 ab-1 **δλ = 21%**	1.4 TeV, 1.5 ab-1 & 3 TeV, 2 ab-1 **δλ = 10%**

References:
arXiv: 1307.5288
HH→bbbb only, upgrade in progress including bbWW*

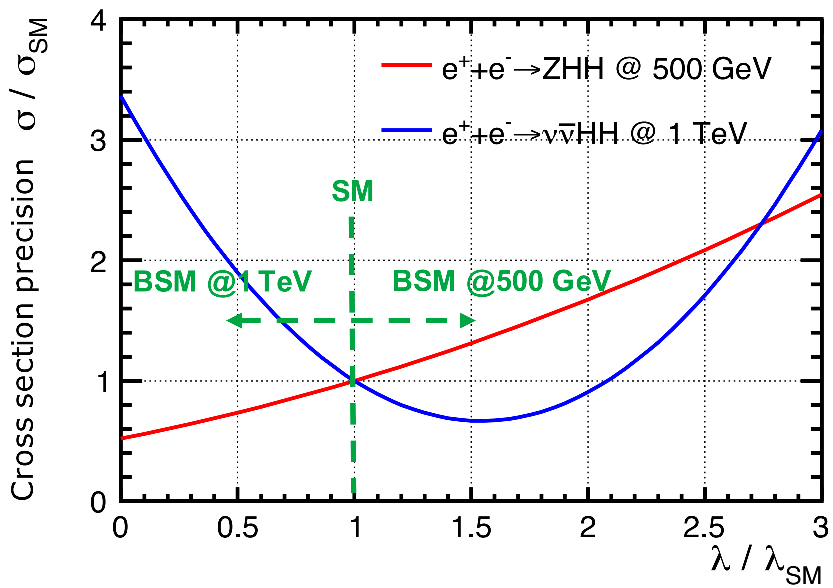
Triple-Higgs coupling with BSM

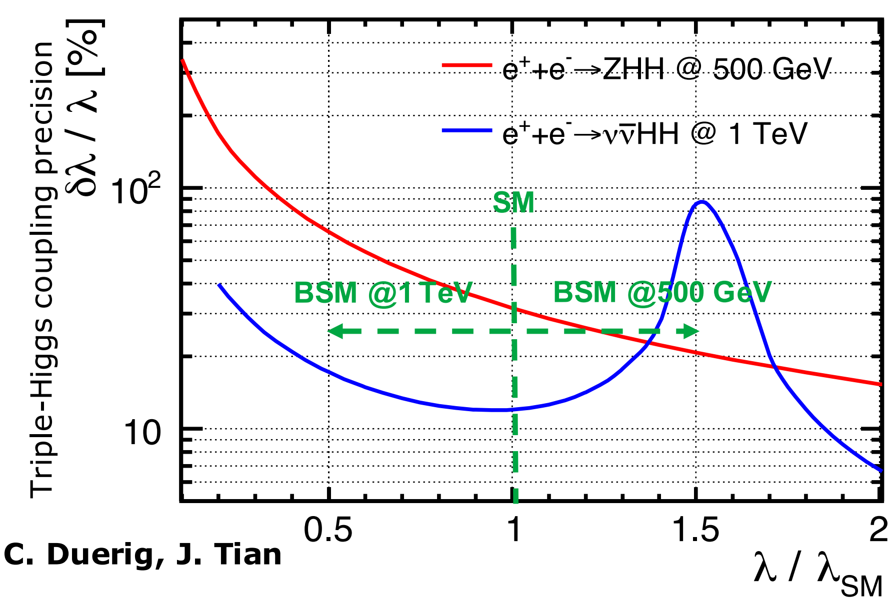


BSM can modify the triple-Higgs coupling. What effect does it have on the total cross section?

At 500 GeV, the cross section **increases** with increasing λ.

At 1 TeV, the cross section **decreases** with increasing λ. **[Same as LHC]**



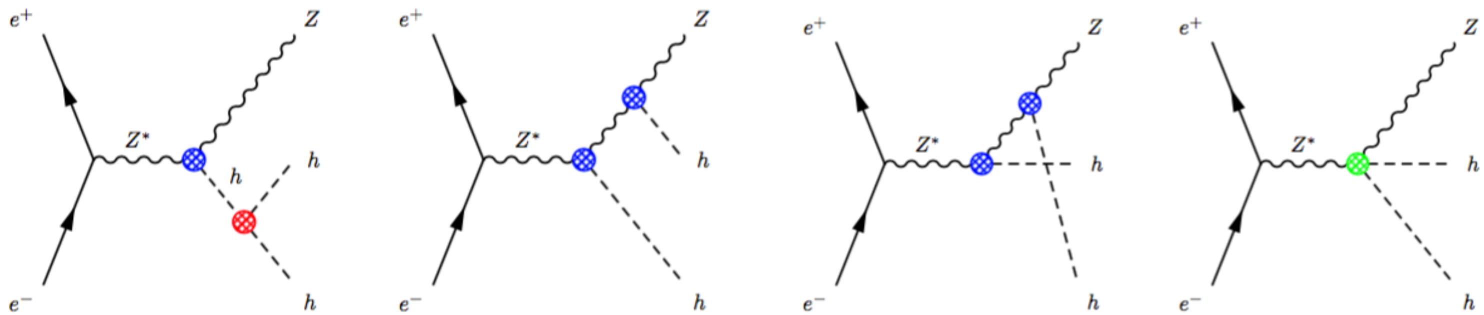


C. Duerig, J. Tian

500 GeV has unique sensitivity to larger triple-Higgs coupling

Model-independent extraction with EFT (1)

[Barklow, Fujii, Jung, Peskin, Tian]



- The authors ask the question: **If there is a deviation from the SM cross section, how to interpret this as a shift of the Higgs potential?**
- EFT analysis with dimension 6 operators: goal is to extract the parameter $\mathbf{c_6}$ in

$$\Delta\mathcal{L} = -c_6 \frac{\lambda}{v^2} (\Phi^\dagger \Phi)^3$$

- **9 additional dimension 6 coefficients** contribute to the double Higgs production. Of which:
  - **3** are determined by **precision electroweak** data
  - **3** are determined by measurement of **e+e- → W+W-**
  - **1** combination is constrained by the **small size of h→γγ**
- **Need 2 more constraints → will be provided by e+e- → Zh**

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Model-independent extraction with EFT (2)

[Barklow, Fujii, Jung, Peskin, Tian]

- Estimates of e+e- → Zh for the ILC program [Ogawa, Fujii, Tian]:
  - $\delta(c_H) = 1\%$ $\delta(16 c_{WW}) = 0.25\%$ (highly correlated)

- The effect of these parameters on the double Higgs cross section is

$$\frac{\sigma(e^+e^- \to Zhh)}{\sigma_{SM}} = 1 - \underline{3.6\, c_H} + \underline{7.4\,(16 c_{WW})} + 0.56\, c_6$$

Higgs wavefunction renormalization & new vertex $\Delta\mathcal{L} = \frac{c_H}{v_0} h \partial_\mu h \partial^\mu h$

dim-6 vertices enhanced by (s/m_Z^2)

*These are issues for any double Higgs production process.

For e+e- → Zhh, precision measurement of single-Higgs process brings these effects under control at the **10% level in c_6.** Within this uncertainty, the extraction of c_6 is completely **model-independent**.

Conclusions

on triple-Higgs coupling at future e+e- colliders

- **Indirect measurement** at the **30%-level** may be possible with high luminosity (e.g. circular colliders)
  - Provides complementary (but model-dependent) information about the loop process.

- For **direct measurement**, expected precision is **$\delta\lambda/\lambda$=27% at 500 GeV**, and **$\delta\lambda/\lambda$=10% combining 1 TeV**. These numbers are supported by studies with full detector simulation.
  - **500 GeV** has unique sensitivity when **$\lambda>\lambda_{SM}$**.
  - This condition is theoretically well-motivated.
  - This is complementary to 1 TeV and LHC, which are sensitive for $\lambda<\lambda_{SM}$.

- Based on EFT analysis, a **model-independent** extraction of the coefficient **c_6** is possible at the **10% level**.

Top

Top

Reference

arXiv:1604.08122

Report from workshop at IFIC Valencia (July 2015)

An up-to-date summary with an extensive bibliography

Top physics at high-energy lepton colliders

Summary of TopLC15, IFIC Valencia, 30th June - 2nd July, 2015

M. Vos (IFIC, editor)
Attendants of the workshop:
G. Abbas (IFIC), M. Beneke (TUM), S. Bilokin (LAL), M.J. Costa (IFIC), S. de Curtis (U. & INFN Firenze), K. Fujii (KEK), J. Fuster (IFIC), I. Garcia Garcia (IFIC), P. Gomis (IFIC), A. Hoang (U. Vienna), A. Irles (DESY), Y. Kiyo (Juntendo), M. Kurata (Tokyo), L. Linssen (CERN), J. List (DESY), M. Nebot (Lisboa), M. Perello (IFIC), R. Pöschl (LAL), N. Quach (KEK), J. Reuter (DESY), F. Richard (LAL), G. Rodrigo (IFIC), Ph. Roloff (CERN), E. Ros (IFIC), F. Simon (MPI Munich), J. Tian (KEK), A.F. Żarnecki (Univ. of Warsaw)

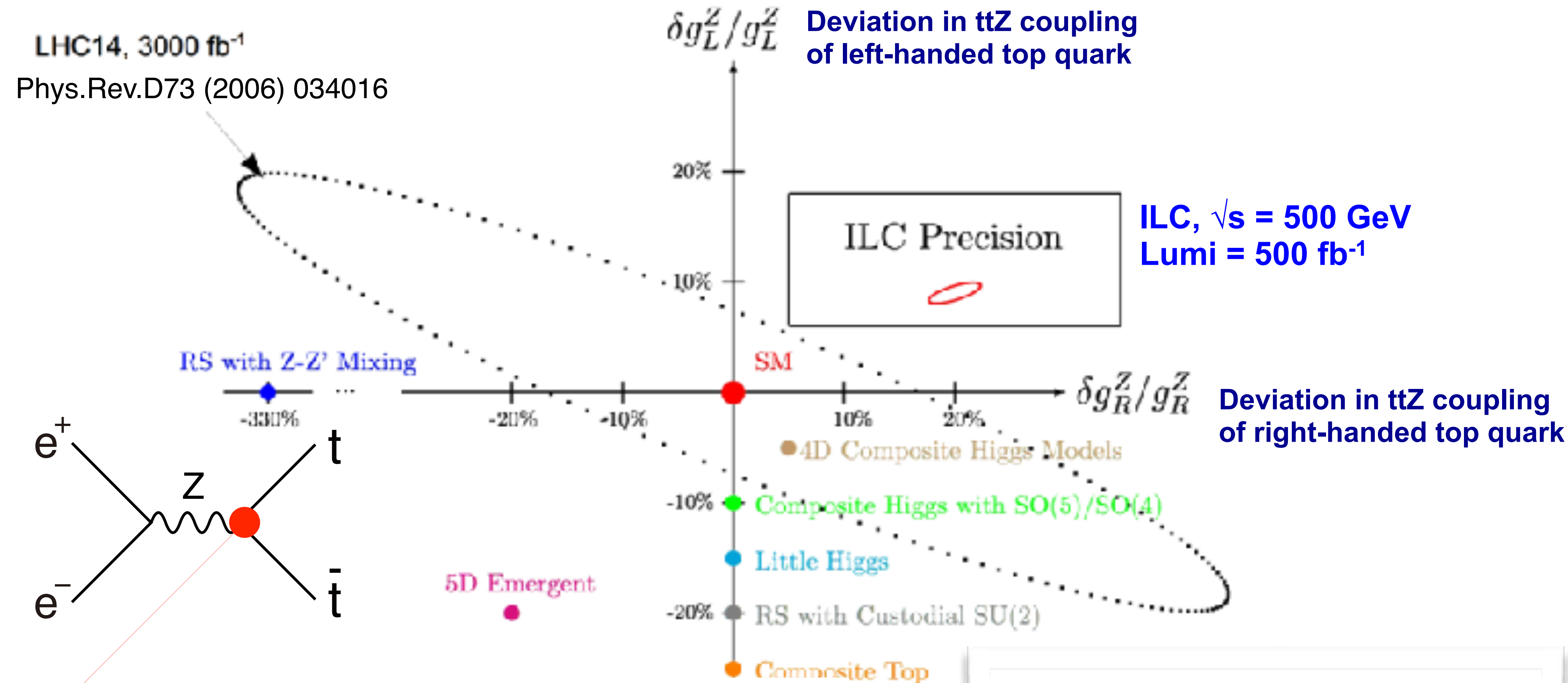
Corresponding author: M. Vos, IFIC (UVEG/CSIC), Edificios de Investigacion, c./ Catedratico Jose Beltran 2, E-46980 Paterna, Valencia, SPAIN (marcel.vos@ific.uv.es)

Search for Anomalous tZZ Couplings

Top: **Heaviest in SM**→Must couples **strongly to EW breaking sector (source of $\mu^2<0$)!**

→ ***Specific deviation pattern*** *expected in* ***ttZ form factors*** *depending on new physics.*

→ ***Beam polarization essential*** ***to separate L- and R-couplings (Strength of ILC)***



$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\tilde{F}_{1V}^X(k^2) + \gamma_5 \tilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\tilde{F}_{2V}^X(k^2) + \gamma_5 \tilde{F}_{2A}^X(k^2)\right)\right\}$$

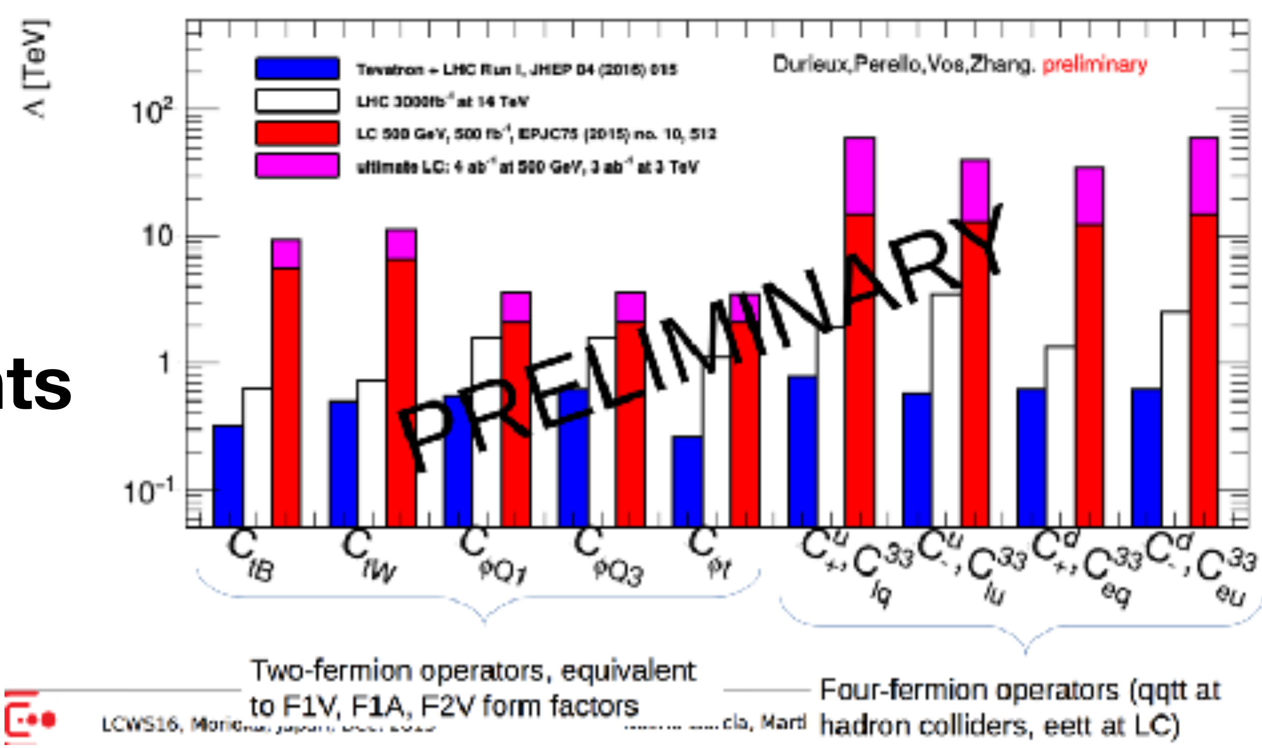
Deviation expected for various new physics models (new physics scale ~1 TeV)
arXiv:1505.06020

ILC is sensitive to ***M_{KK} up to ~25TeV*** for typical RS scenarios (even up to ~80 TeV in extreme cases)!

Top/QCD Talks from ILD at LCWS 2016

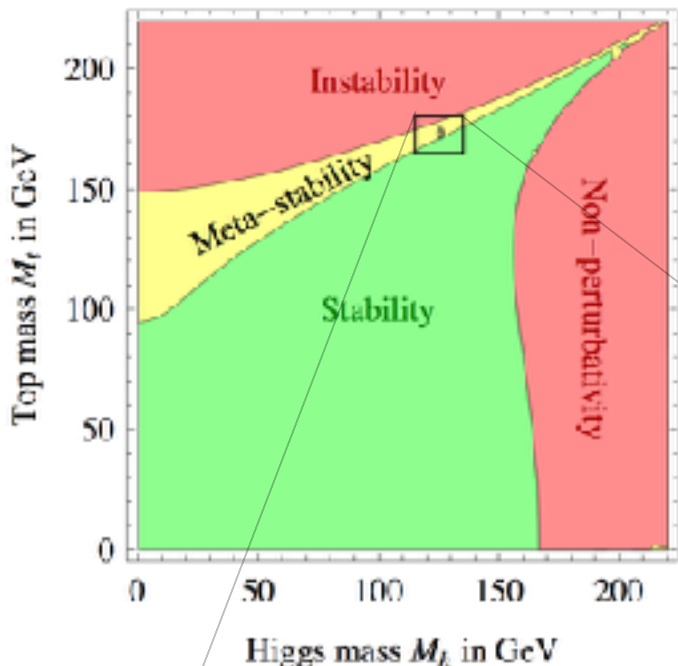
1. e+e- → tt : semi-leptonic (Sviatslav Bilokin)
2. **e+e- → bb (Sviatslav Bilokin)** →Dec.6 (R.Poeschl)
3. **e+e- → tt : bbμ+μ-νν: MEM (Yo Sato)** →Dec.7
4. mt reconstruction at 1TeV or higher (Nacho Garcia, Martin Perello, Philipp Roloff, Rickard Strom) with CLICdp →Dec.8 (R.Strom)
5. **mt using radiative return to threshold (Marça Boronat and Pablo Gomis)** →Dec.8 (M.Vos)
6. **Global fit with D6 EFT (Martin Perello, et al.)** →Dec.6 (M.Vos)

Form factors
→ EFT coefficients



What if no deviation from the SM would be seen?

Clarify the Range of Validity of SM



Stability of SM Vacuum

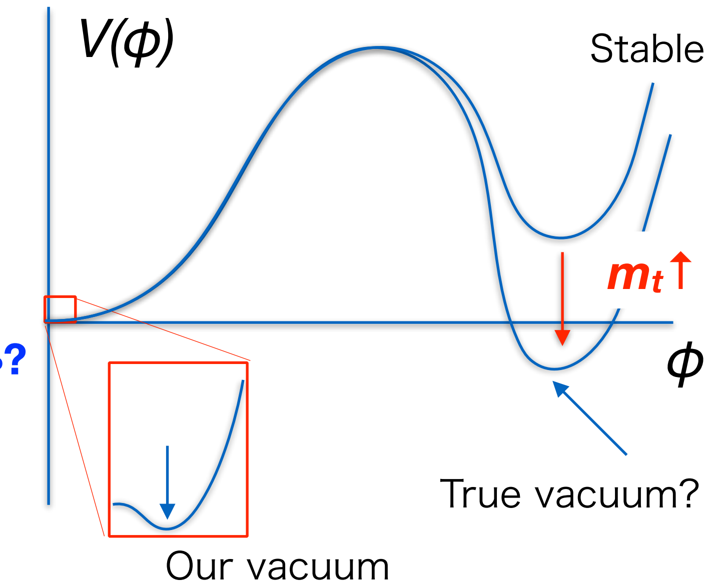
Top Yukawa coupling drives the 4-point Higgs coupling (λ) to negative!

The current values of mt and mh:

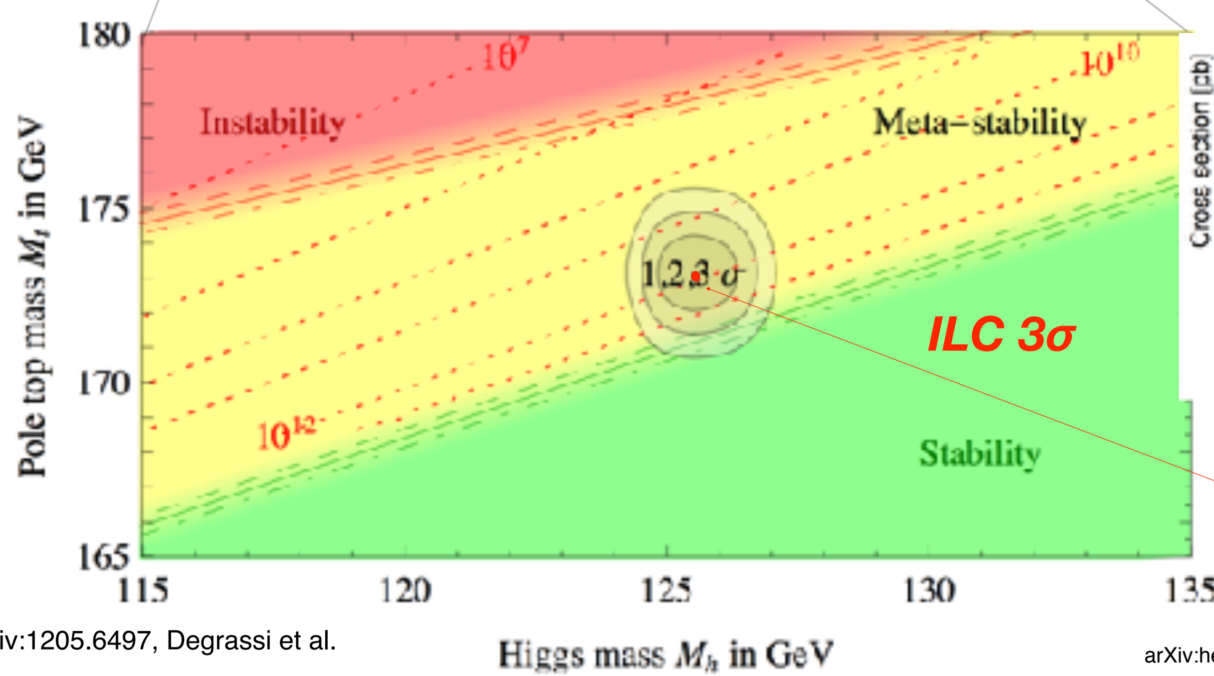
Subtle point of meta-stability!

Does λ go to negative below Λ_P? or $\lambda(\Lambda_{Pl}) = 0$?

To answer this, we need precision m_t measurement!

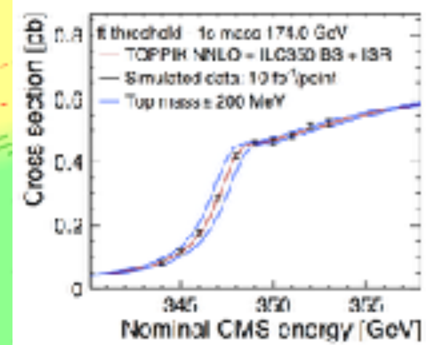


At LHC, theory error limits the precision to ~500MeV.

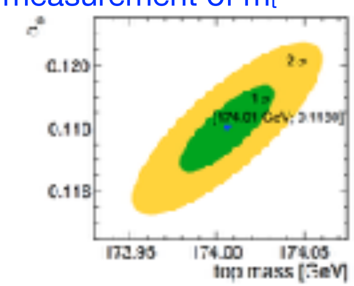


arXiv:1205.6497, Degrassi et al.

TTbar Threshold Scan @ILC



Theoretically very clean measurement of m_t



$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

ILC pinpoints the vacuum location

arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order
arXiv:hep-ph/1506.06864: NNNLO QCD
arXiv:hep-ph/1506.06542: possibility of MSbar mass to 20MeV

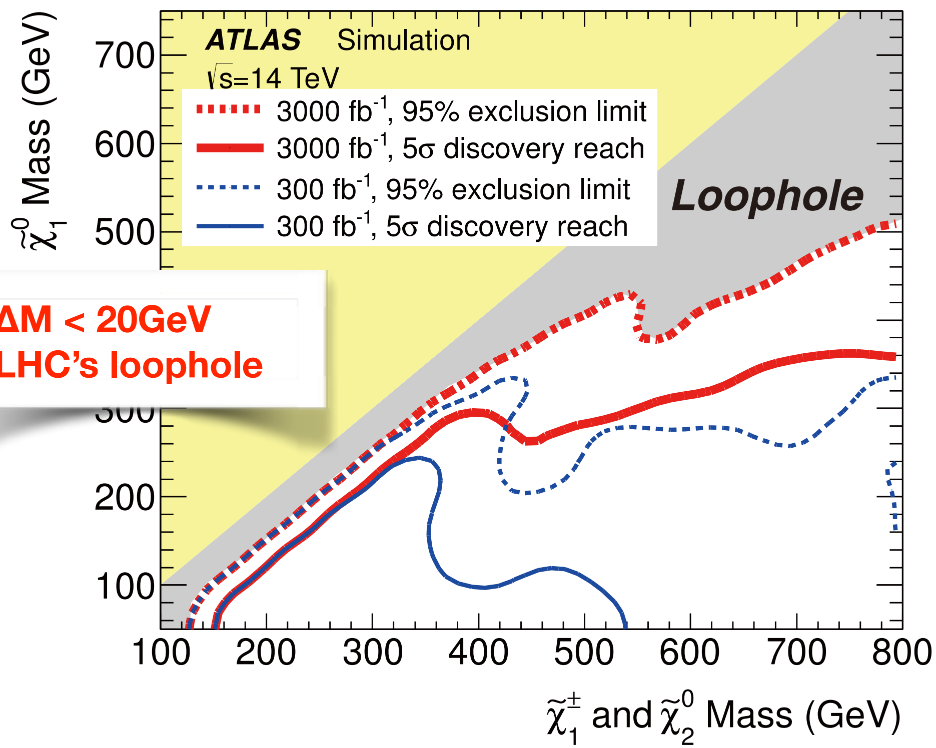
Direct Searches for New Particles

ILC, too, is an energy frontier machine!

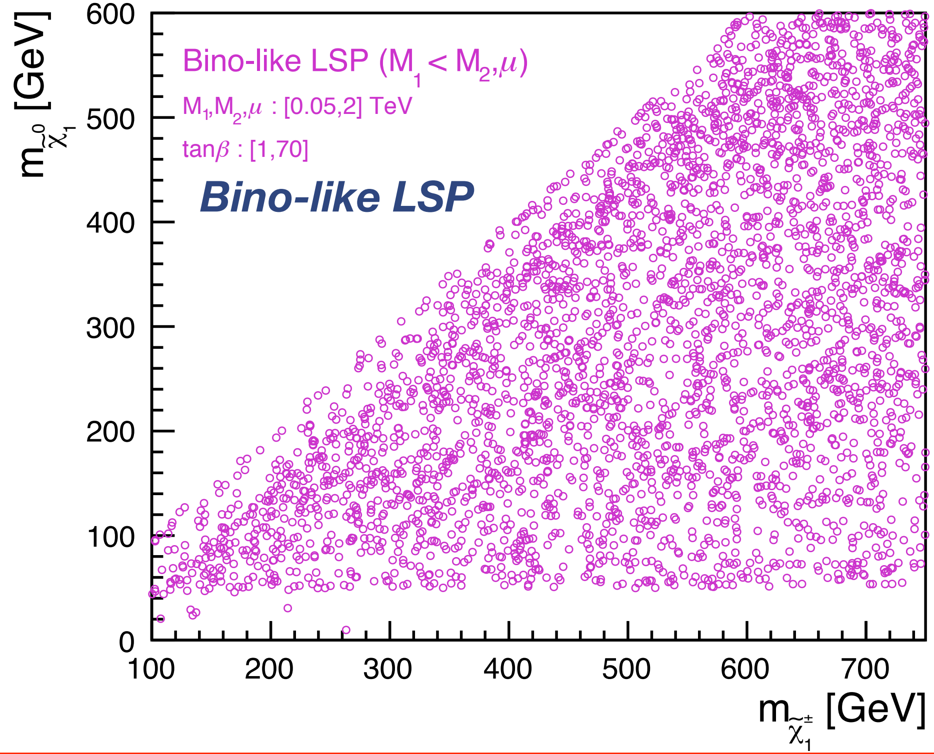
It will enter ***uncharted waters of e^+e^- collisions***

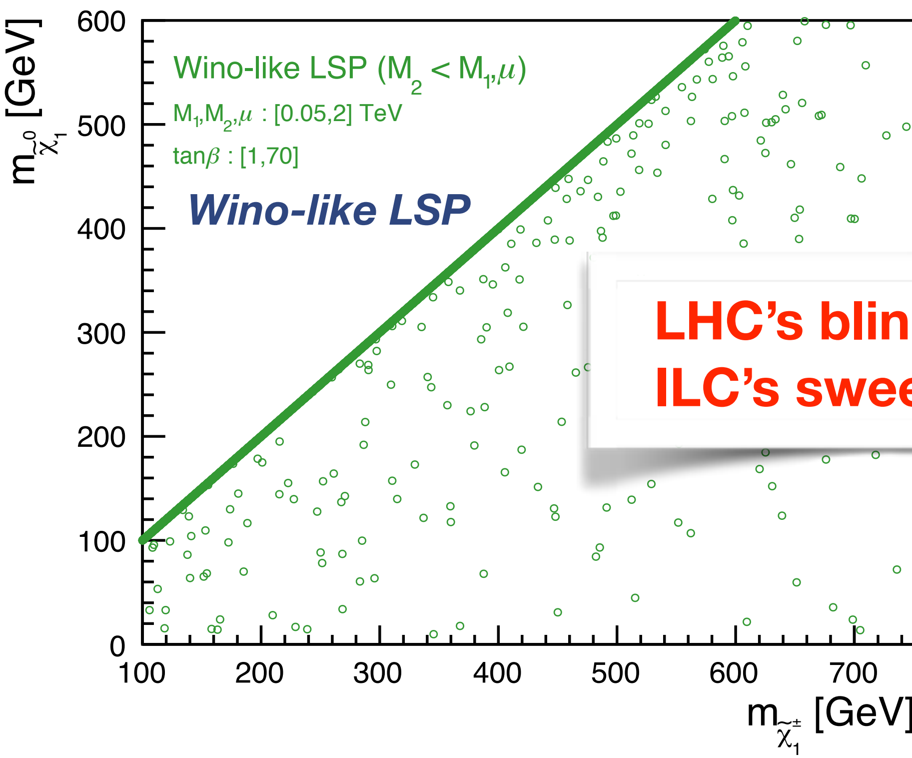
Thanks to well-defined initial states,
clean environment w/o QCD BG, and polarized beams
ILC can cover blind spots of LHC

Chargino Search

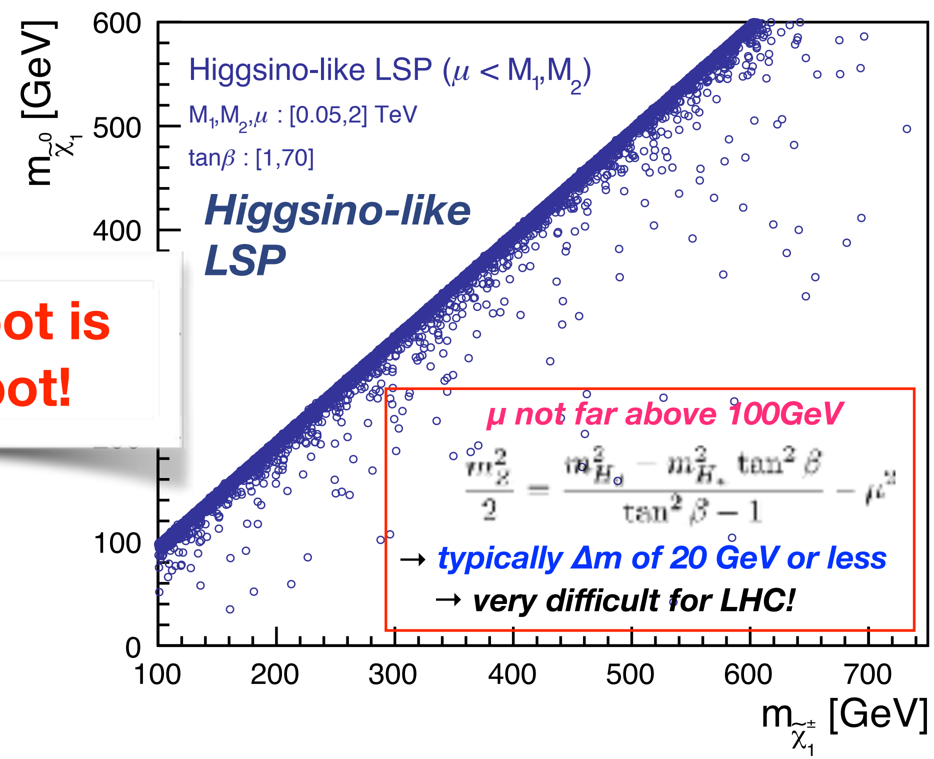


ΔM < 20GeV
LHC's loophole





LHC's blind spot is ILC's sweet spot!



μ not far above 100GeV

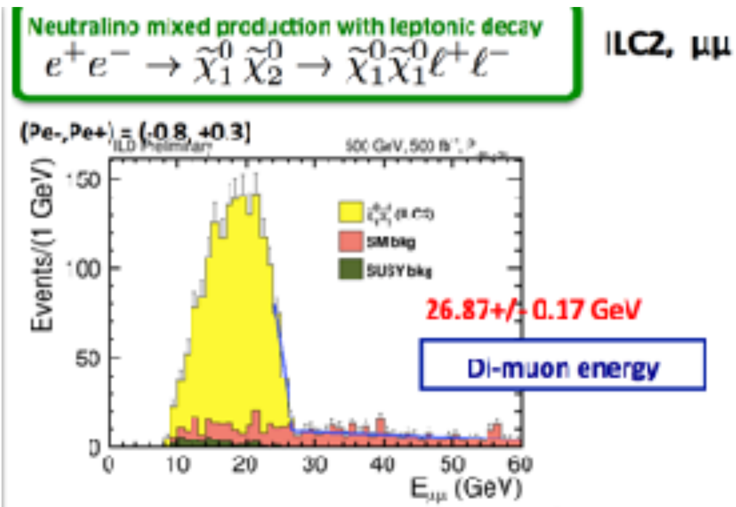
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

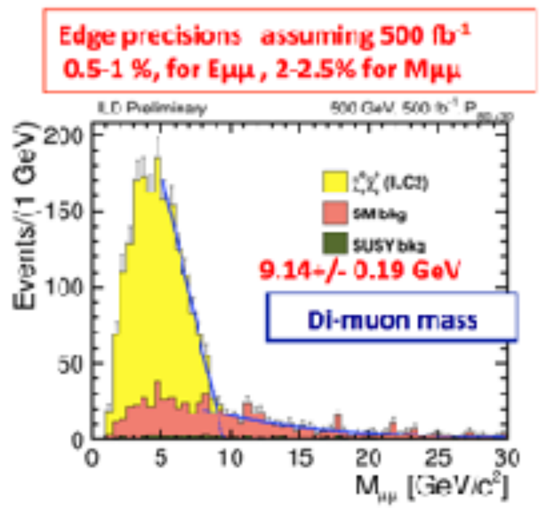
→ *typically Δm of 20 GeV or less*

→ ***very difficult for LHC!***

BSM Talks from ILD at LCWS 2016

1. **Generic WIMP searches (Moritz Habermehl)** → Dec.8 (T. Tanabe)
2. **SUSY co-annihilation (Mikael Berggren)** → Dec.8
3. **Higgsinos (Jacqueline Yan)** → Dec.8
4. **SUSY parameters from Higgsinos (Suvi-Leena Lehtinen)** → Dec.8





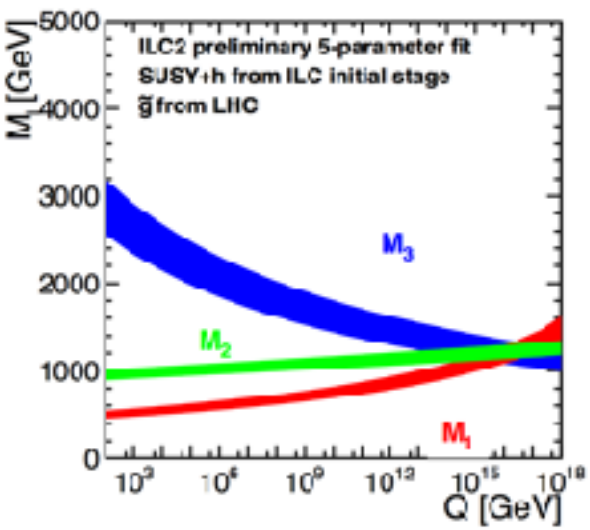
J. Yan : LCWS2016

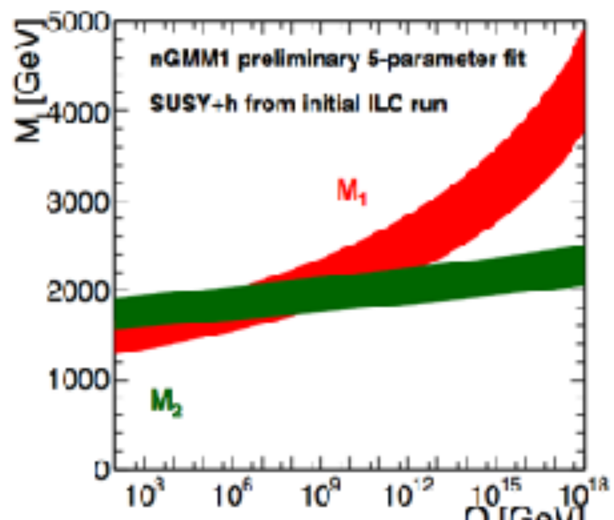
End points → M_X

"ILC2 benchmark": ΔM～ 10 GeV
σ_M / M < 1% (H20)

500GeV → ***ILC1: 250GeV*** ***ILC2: 350GeV***

Probing very high scale physics





S. Lehtinen : LCWS2016

Left: Test of gaugino mass unification

Right: Select SUSY breaking models (gravity mediated SUSY breaking vs mirage unification)

WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

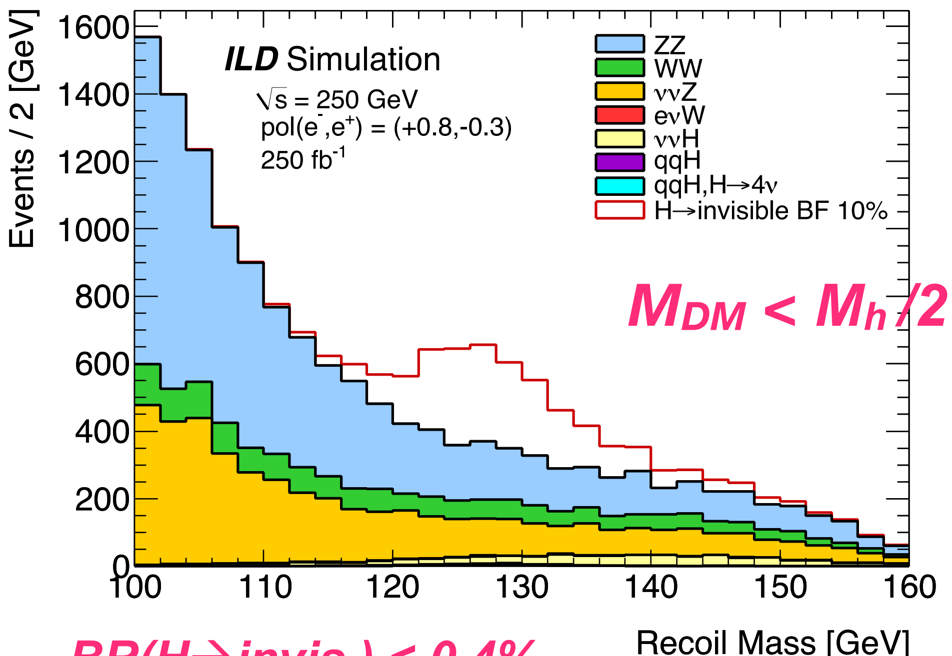
Decay of a new particle to Dark Matter (DM)

DM has a charged partner in many new physics models.

SUSY: The Lightest SUSY Particle (LSP) = DM → Its partner decays to a DM.

- Events with missing Pt (example: light chargino: see the previous page)

Higgs Invisible Decay

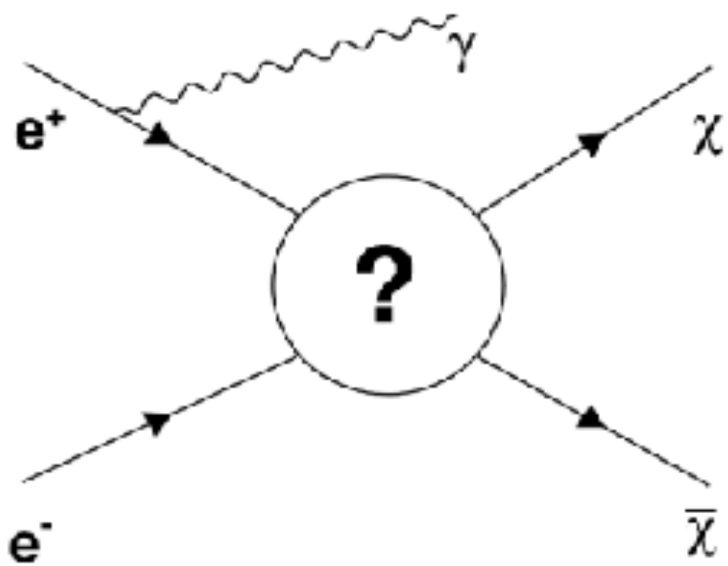


BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1} ***(<0.3% at 95%CL: H20)***

Possible to access BR_{inv} to 0.4%!

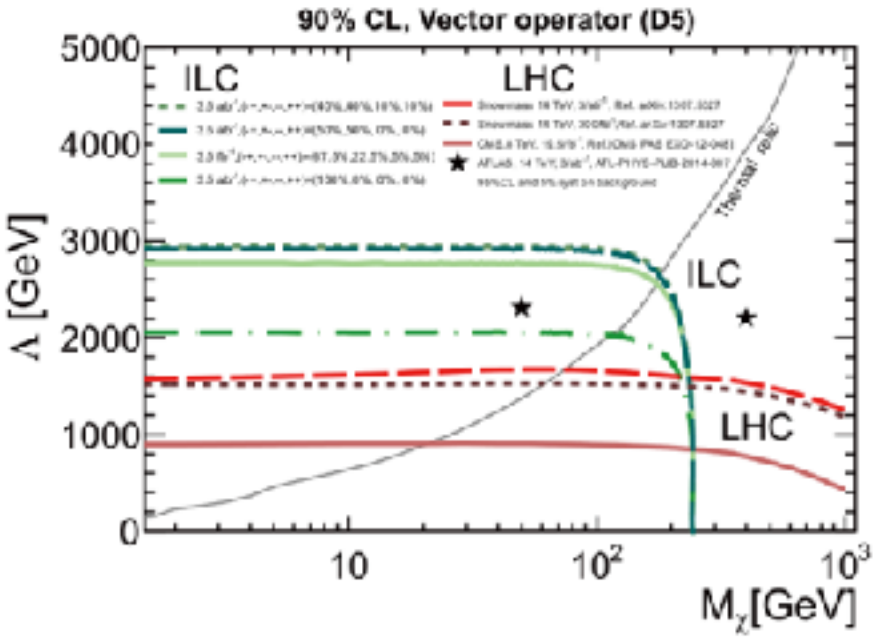
Mono-photon Search



→ ***M_{DM} reach ~ $E_{cm}/2$***

Possible to access DM to ~$E_{cm}/2$!

DM: WIMP Searches

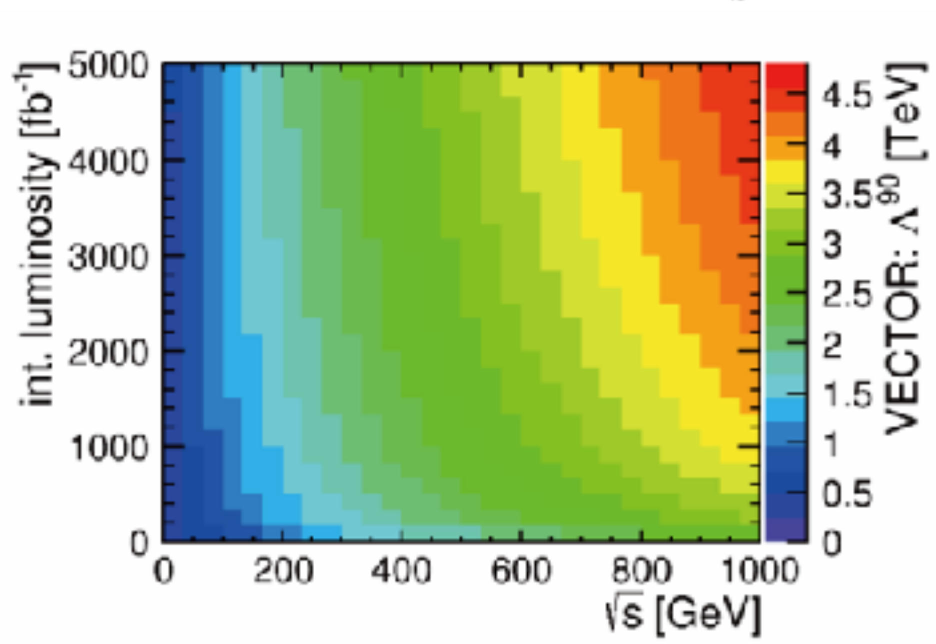


Previous result

LHC-ILC Comparison
[A. Chaus]

Example: Vector operator

- LHC sensitive to higher mass
- ILC sensitive to higher Λ



Recent result

Extrapolation to other √s
[M. Habermehl]

- ILC reach of Λ at different CM energies and integrated luminosities
- for small M_χ (< 100 GeV)
- Allows study of run scenarios

ILC’s H20 run scenario allows us to access Λ up to 3 ~ 4 TeV

Additional Slides

Higgs

Why 500 GeV?

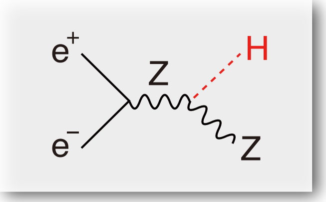
Higgs-related Physics at Ecm ≲ 500 GeV

Three well know thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (***recoil mass***)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

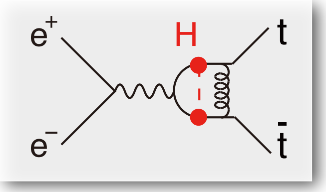
→Higgs couplings (other than top)

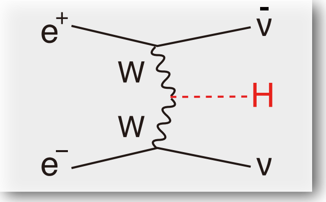


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> theoretically clean ***mt*** measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  - --> test stability of the SM vacuum
  - --> indirect meas. of ***top Yukawa*** coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



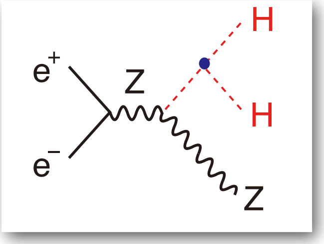


vvH @ 350 - 500GeV :

- ***HWW coupling*** -> ***total width*** --> absolute normalization of Higgs couplings

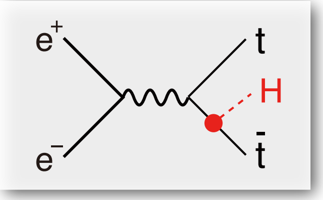
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> ***Higgs self-coupling***



ttbarH @ 500GeV (~2mt+M_H+30GeV) :

- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> ***top Yukawa*** measurable at 500GeV concurrently with the self-coupling



We can access all the relevant Higgs couplings at ~500GeV for the mass-coupling plot!

Higgs Physics at Higher Energy

Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

vvH @ at >1TeV : > 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

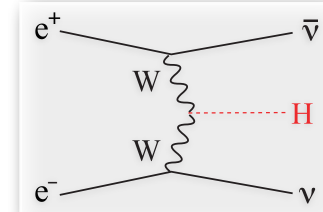
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

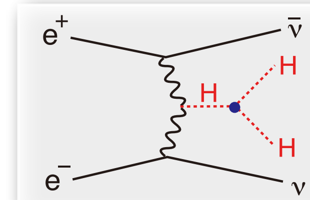
vvHH @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

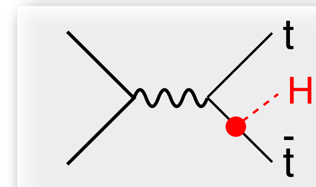
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

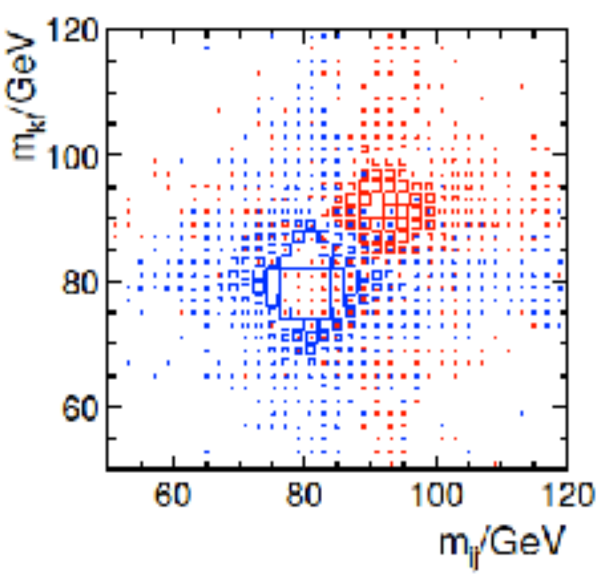
ttbarH @ 1TeV : 1ab^{-1}

- Prod. cross section becomes maximum at around 800GeV.
- CP mixing of Higgs can be unambiguously studied.









Obvious but most important advantage of higher energies in terms of Higgs physics is, however, its higher mass reach to other Higgs bosons expected in extended Higgs sectors and higher sensitivity to $W_L W_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!

Total Width and Coupling Extraction

One of the major advantages of the LC

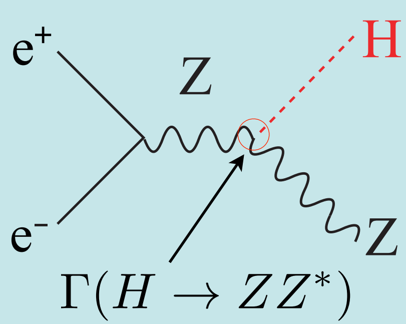
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

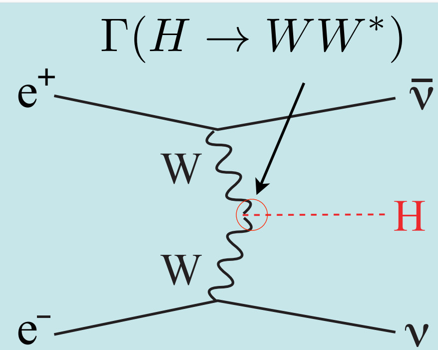
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 20\%$



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

Model-independent Global Fit for Couplings

33 σxBR measurements (Y_i) and σ_{ZH} ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2$$

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0}$$

$(i = 1, \cdots, 33)$

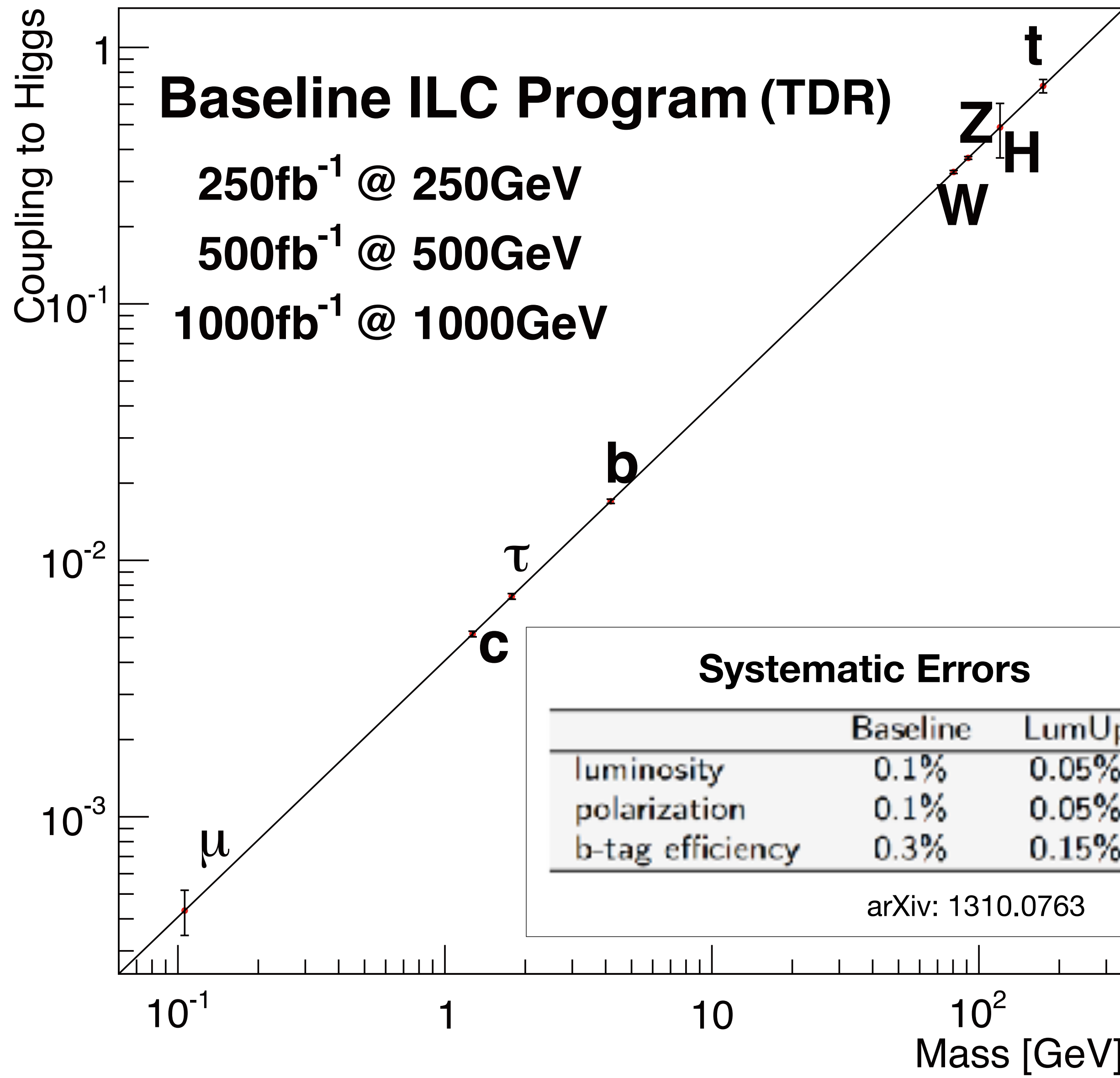
$(A_i = Z, W, t)$

$(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$

$$F_i = S_i\, G_i$$

$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

$$S_i = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$$



Systematic Errors

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

arXiv: 1310.0763

ILC's precisions will eventually reach sub-% level!

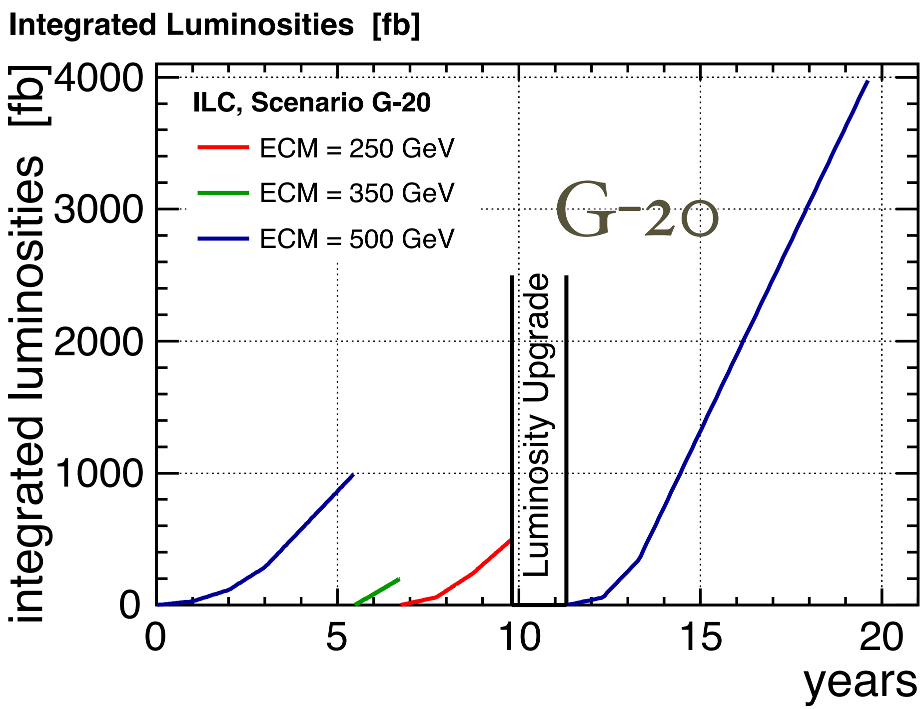
Independent Higgs Measurements at ILC

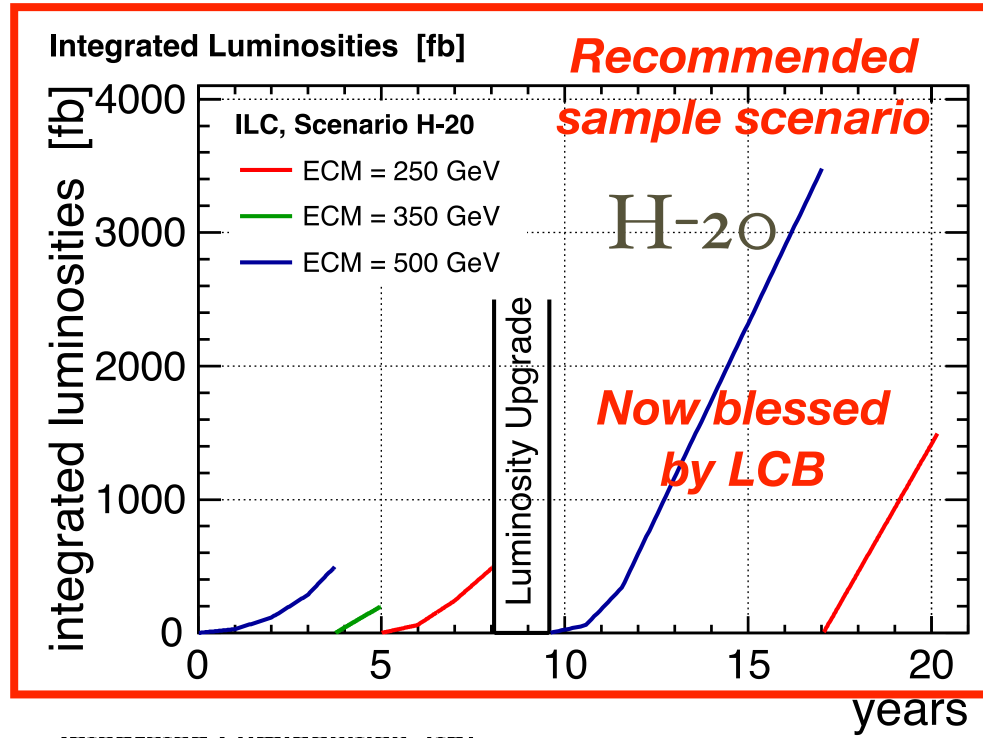
Baseline (=TDR) ILC program

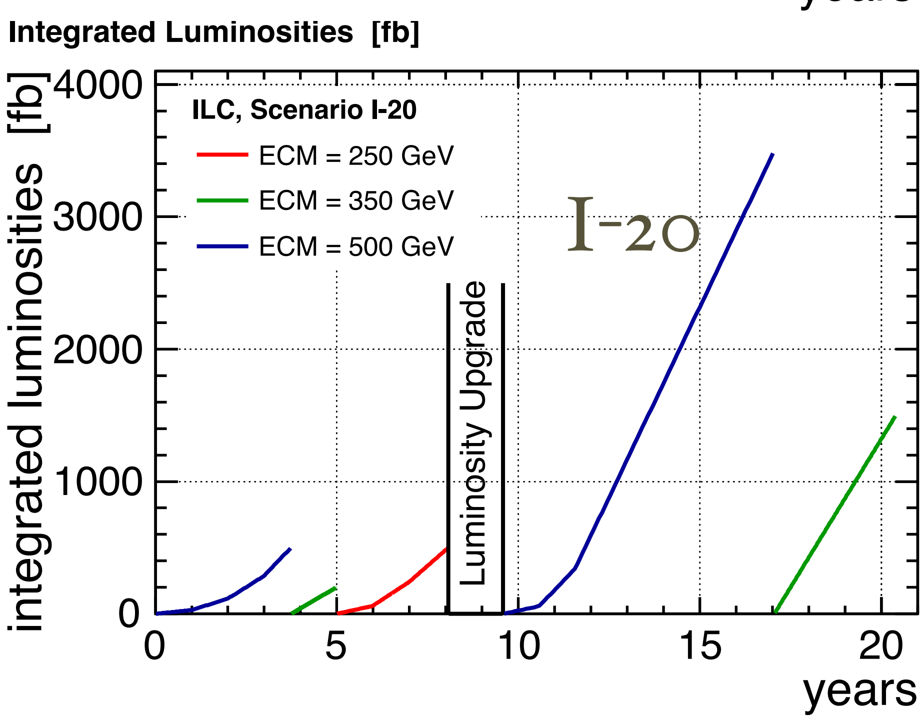
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

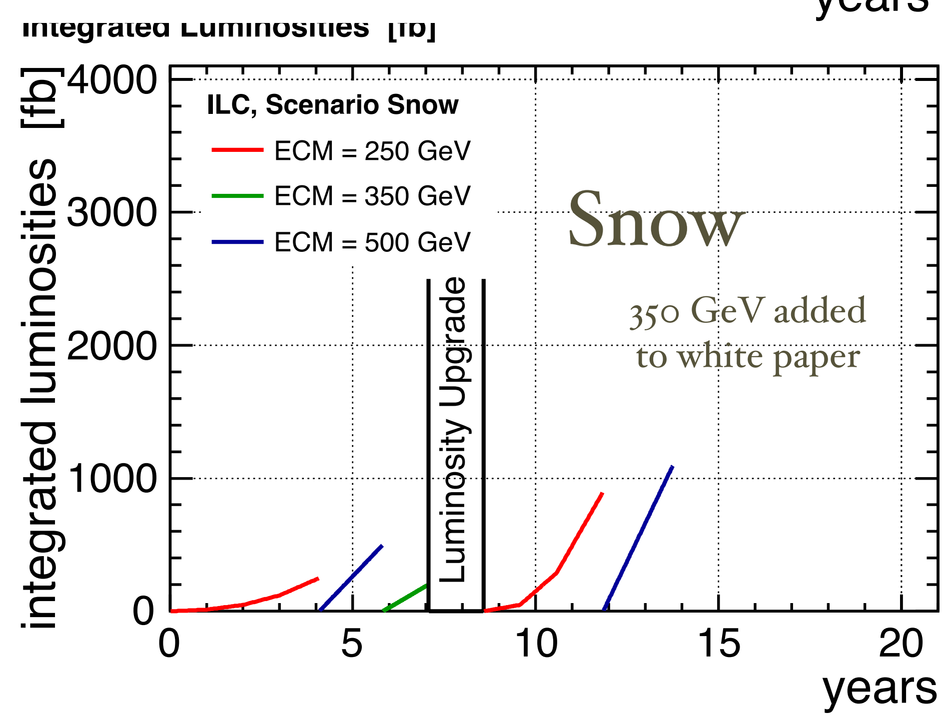
(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb^{-1}]	250		500		1000
polarization (e^-,e^+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	ννH(fusion)	ZH	ννH(fusion)	ννH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.32%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	3.2%		5.4%	9%	3.1%
H→ZZ*	19%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	72%	-	88%	72%	31%
tth/H→bb	-		28% (12%@550GeV)		6.2%


Integrated Luminosities [fb]
ILC, Scenario G-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
G-20
Luminosity Upgrade
integrated luminosities [fb]
4000
3000
2000
1000
0
0
5
10
15
20
years


Integrated Luminosities [fb]
Recommended
sample scenario
ILC, Scenario H-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
H-20
Now blessed
by LCB
Luminosity Upgrade
integrated luminosities [fb]
4000
3000
2000
1000
0
0
5
10
15
20
years

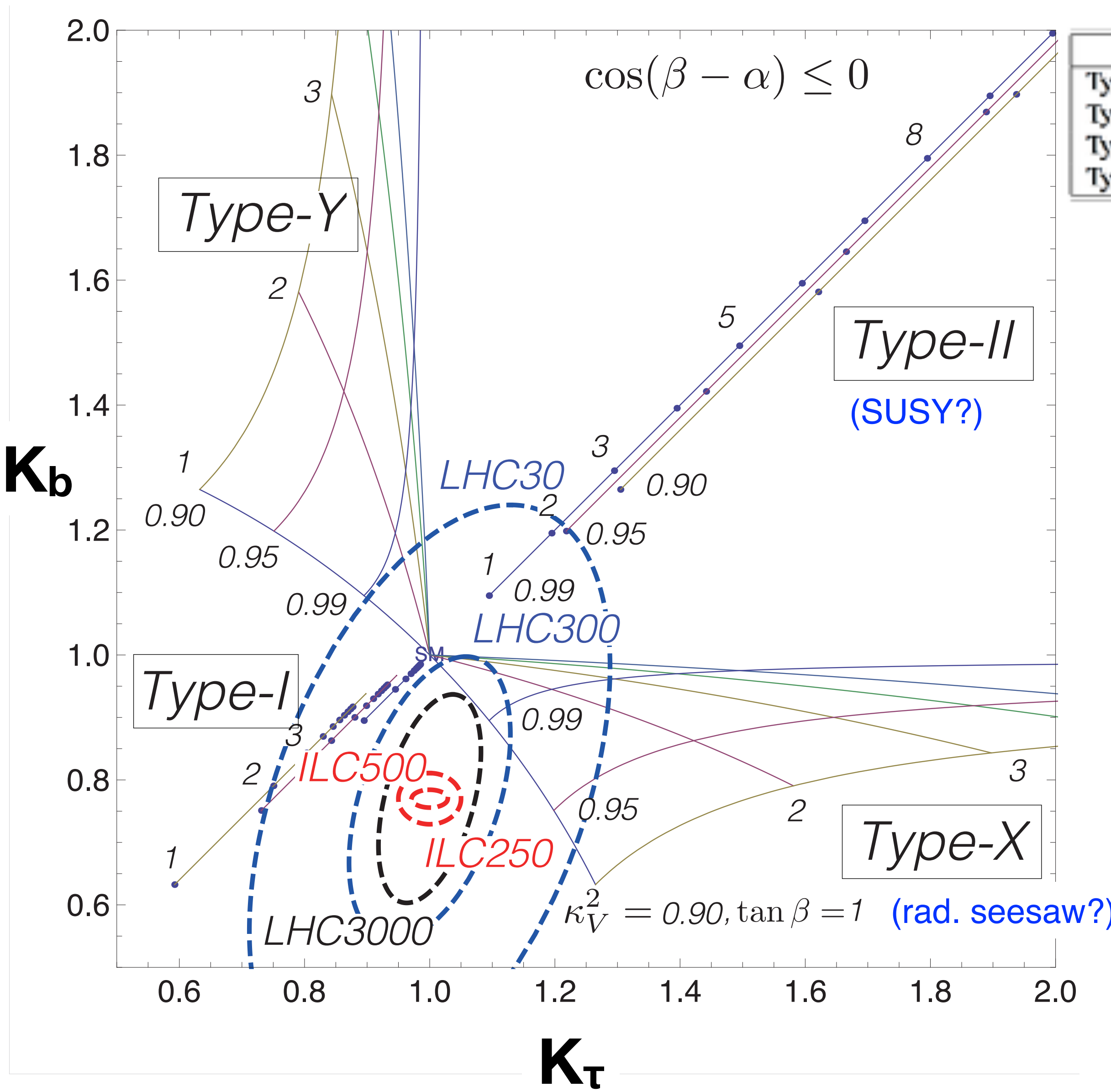

Integrated Luminosities [fb]
ILC, Scenario I-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
I-20
Luminosity Upgrade
integrated luminosities [fb]
4000
3000
2000
1000
0
0
5
10
15
20
years


Integrated Luminosities [fb]
ILC, Scenario Snow
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
Snow
350 GeV added
to white paper
Luminosity Upgrade
integrated luminosities [fb]
4000
3000
2000
1000
0
0
5
10
15
20
years

Fingerprinting

2HDM

Multiplet Structure



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

Given a deviation of the Higgs to Z coupling: ***$\Delta K_V^2 = 1 - K_V^2 = 0.01$*** *we will be able to* ***discriminate the 4 models!***

Model-dependent
7-parameter fit
ILC: Baseline lumi.

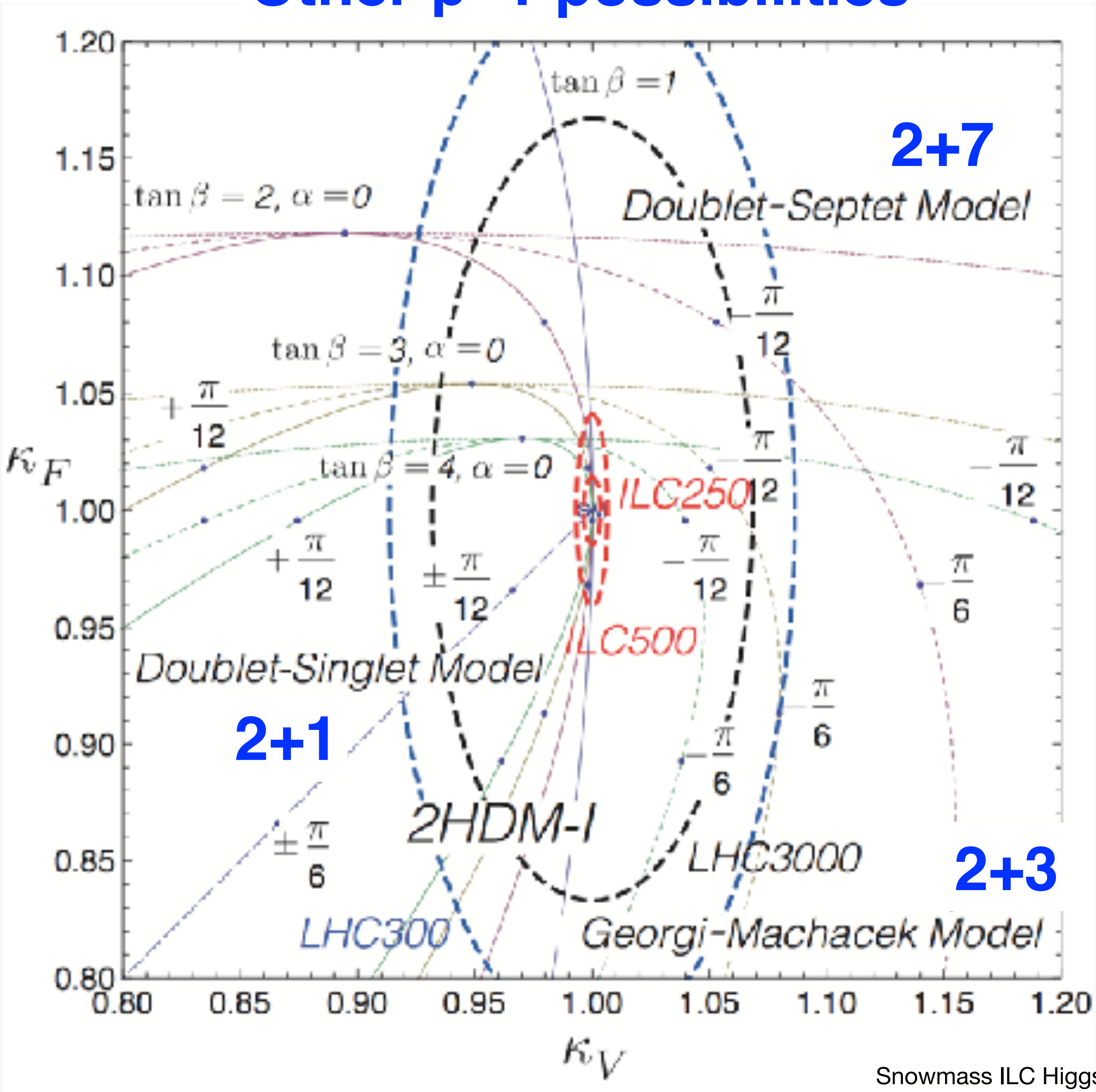
ILC TDR

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Kanemura et al (arXiv: 1406.3294)

Multiplet Structure

Other ρ=1 possibilities



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Kanemura et al (arXiv: 1406.3294)

Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

arXiv 1502.03959

Footprints of Supersymmetry on Higgs Decay

Motoi Endo[a,b], Takeo Moroi[a,b], and Mihoko M. Nojiri[b,c,d]

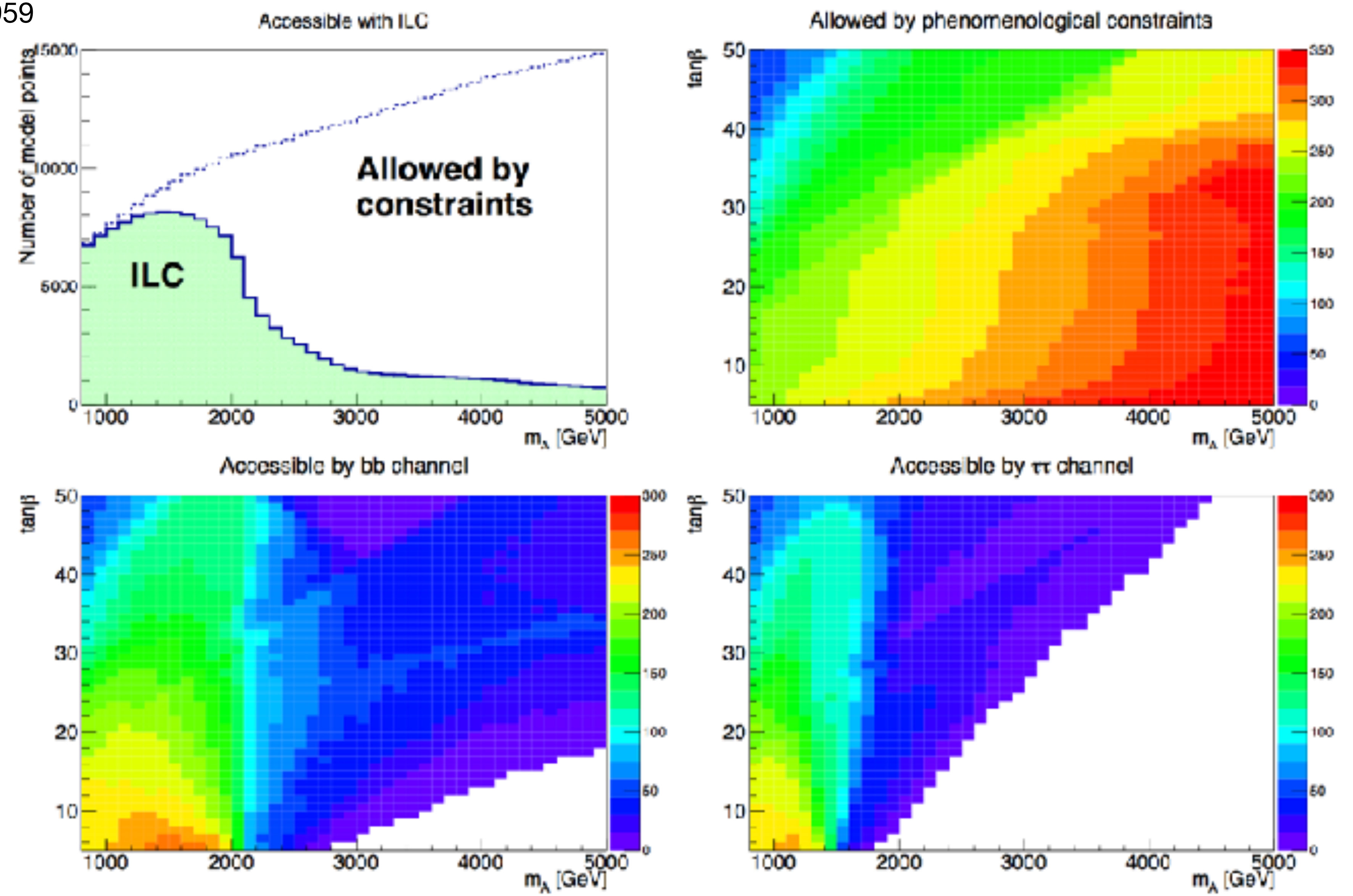


Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological constraints on m_A vs. $\tan\beta$ plane. Lower-left: The number of model points accessible with ILC by $h \to \bar{b}b$. Lower-right: The number of model points accessible with ILC by $h \to \bar{\tau}\tau$.

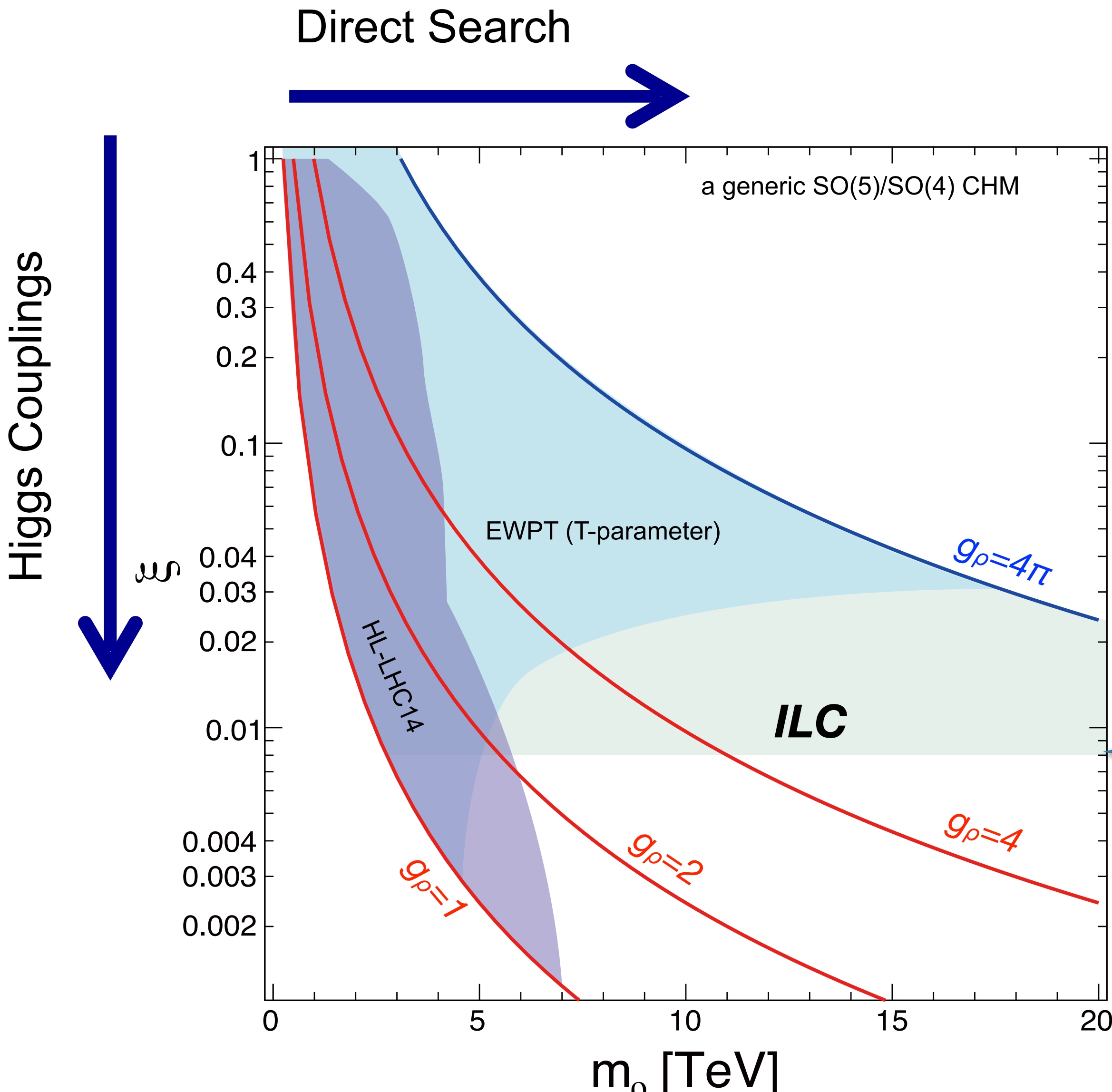
Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)

Based on Contino, et al, JHEP 1402 (2014) 006
Torre, Thamm, Wulzer 2014
Grojean @ LCWS 2014



$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2 = \frac{v^2}{f^2}$$

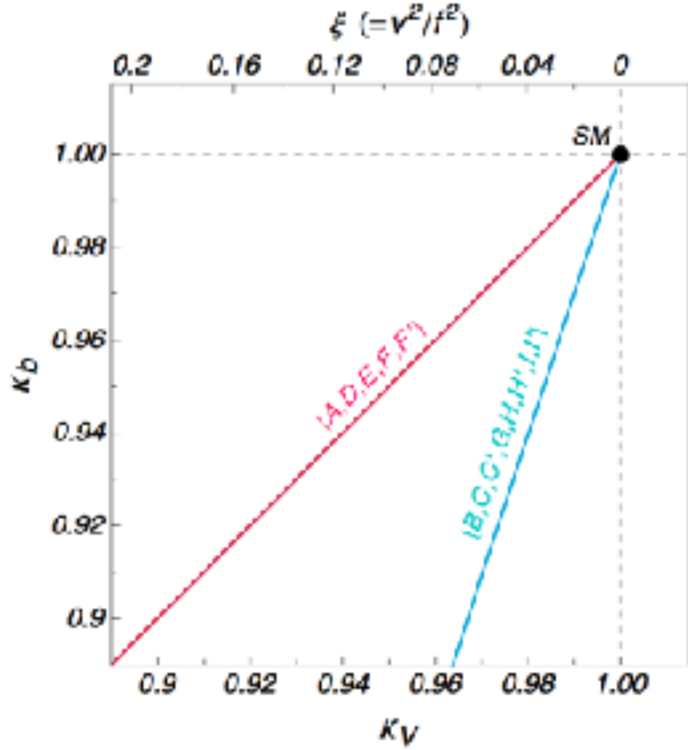
$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

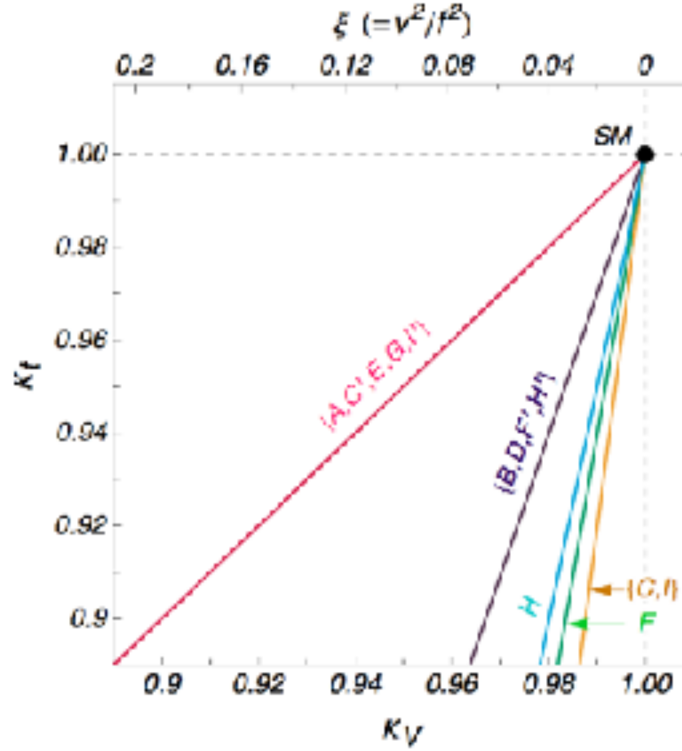
ILC (250+500 LumiUP)

$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

New resonance scale and fingerprint identification in minimal composite Higgs models

Shinya Kanemura,[1] Kunio Kaneta,[2] Naoki Machida,[1] and Tetsuo Shindou[3]





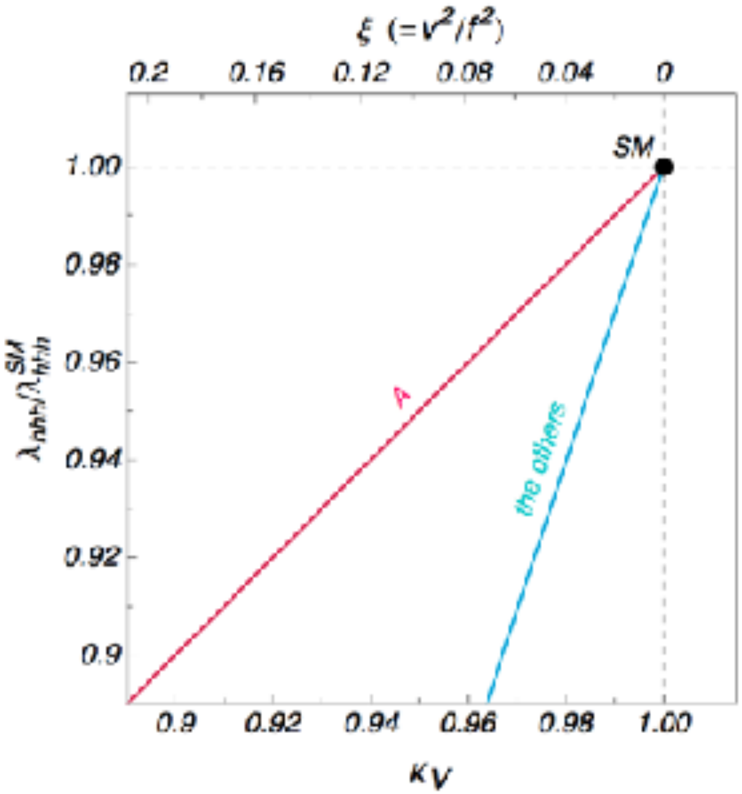


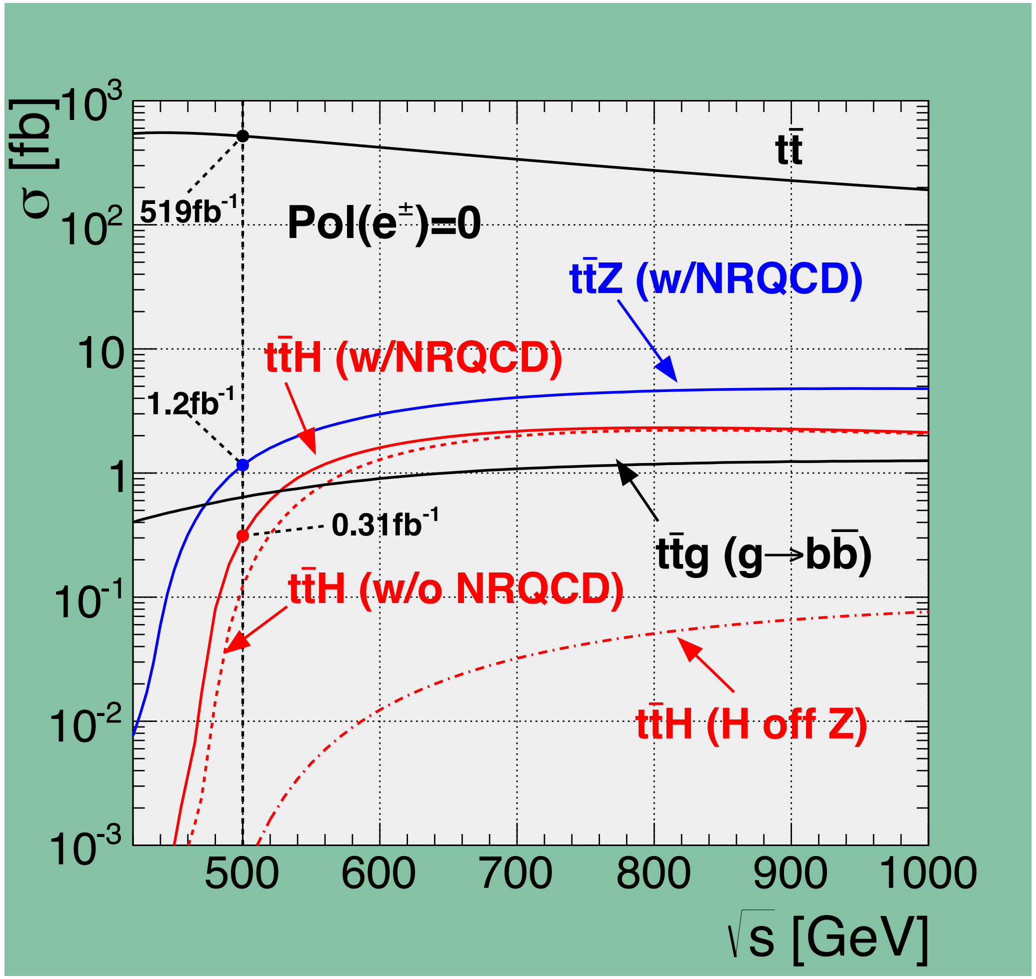
TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. ?, where C, E and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_5^t \to 0$.

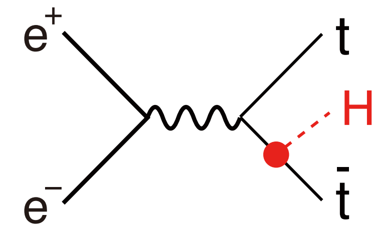
Label	Model	κ_V	κ_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{htt}	c_{hbb}
A	$MCHM_4$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	$MCHM_5$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	$MCHM_{10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
C, C'	$MCHM_{14}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
D	$MCHM_{5-5-10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
E	$MCHM_{5-14-10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	$MCHM_{5-14-10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_6	$-\xi$
G	$MCHM_{10-5-10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
B	$MCHM_{10-14-10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	MCHM[illegible]	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
H, H'	$MCHM_{14-5-10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_6	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
B	$MCHM_{14-10-10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
I, I'	$MCHM_{14-14-10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_8	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_9	-4ξ

arXiv 1410.8413

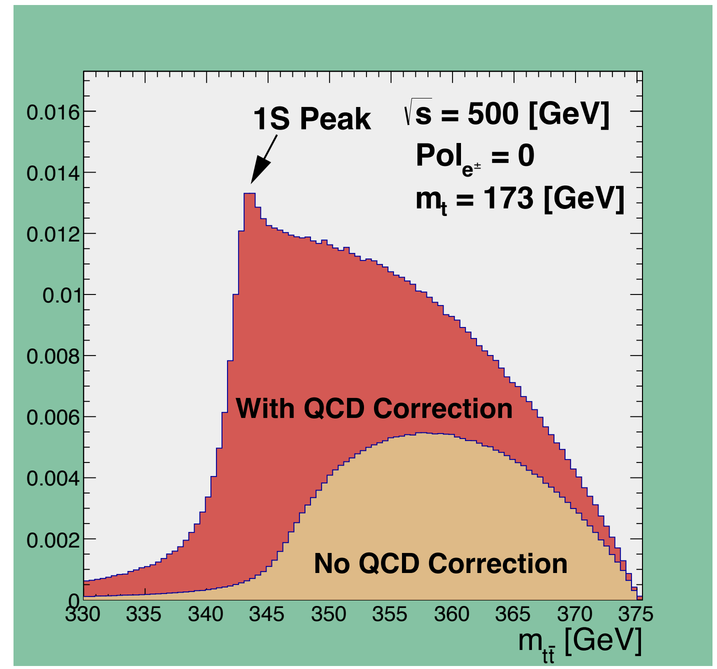
Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

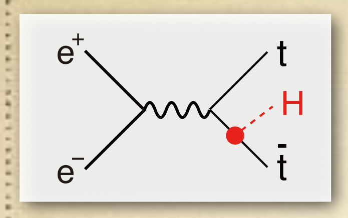
DBD Full Simulation

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

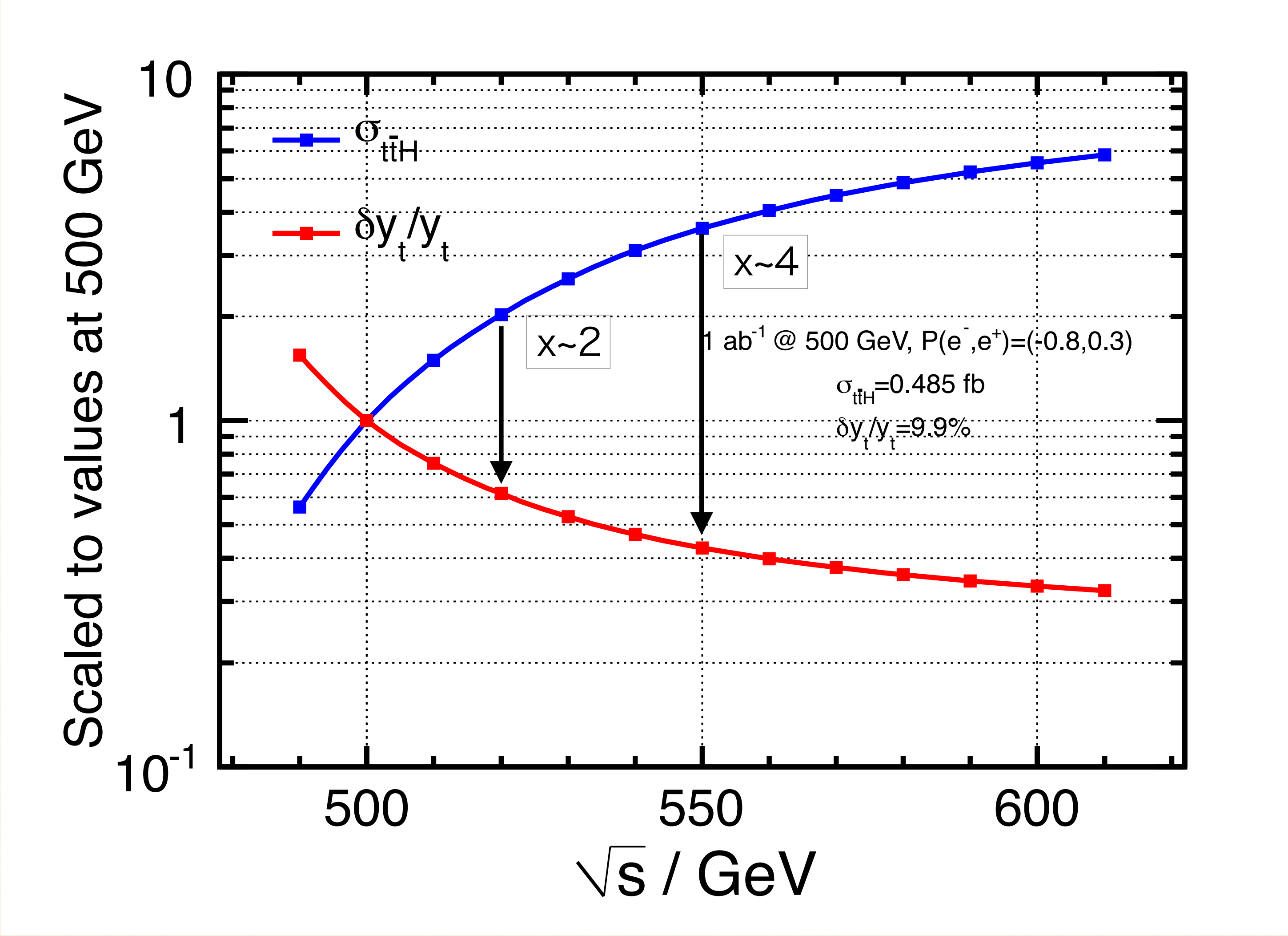
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!



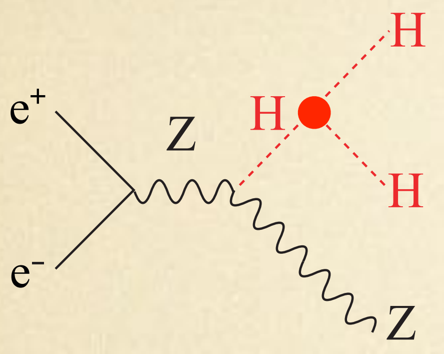
Top Yukawa coupling

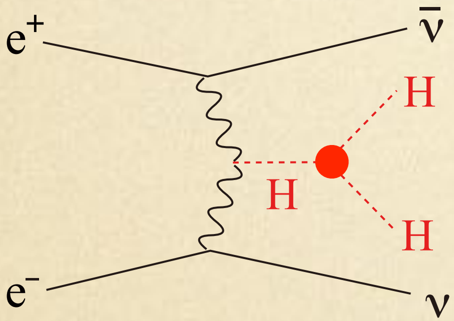


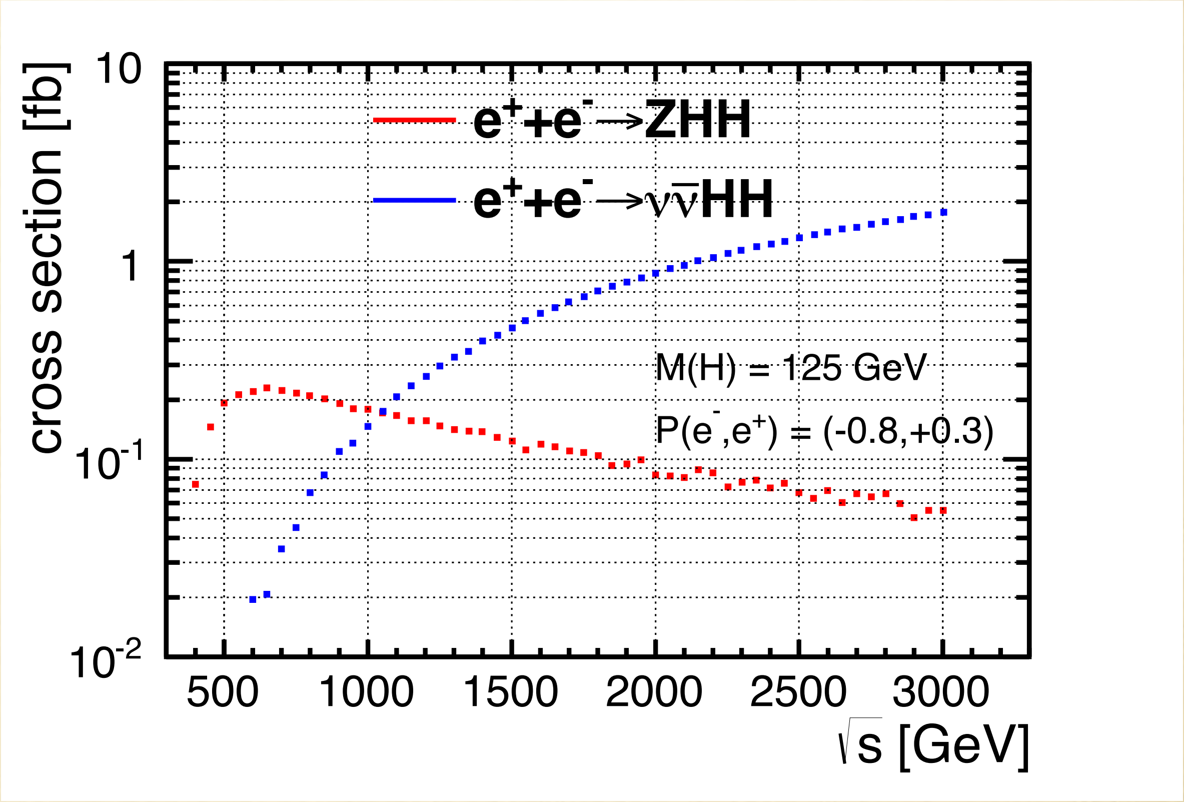
Y. Sudo

Slight increase of E_{max} is very beneficial!

prospects of Higgs self-coupling @ linear colliders







prospects from full simulation studies:

ILC

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	27%	10%

(ref. H20 arXiv: 1506.07870)

CLIC

1.4 TeV (1.5 ab^{-1})	+3 TeV (2 ab^{-1})
21%	10%

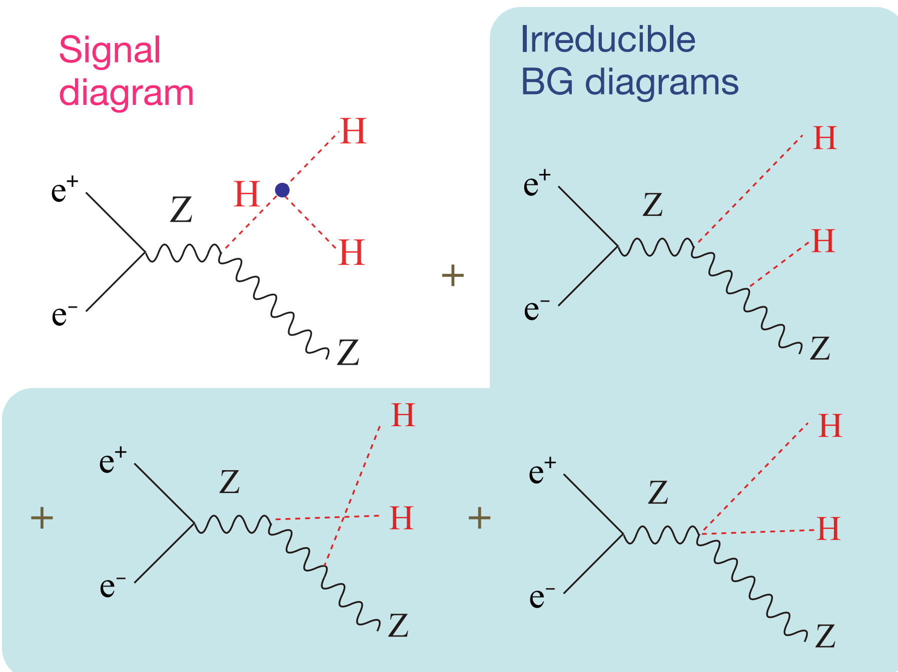
(arXiv: 1307.5288)

J. Tian, LC-REP-2013-003

C. Dürig @ ALCW15

M. Kurata, LC-REP-2014-025

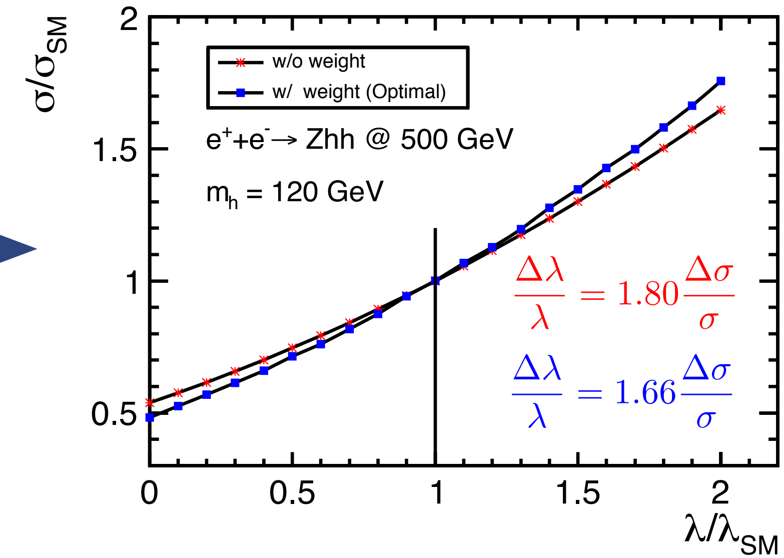
The Problem : BG diagrams dilute self-coupling contribution

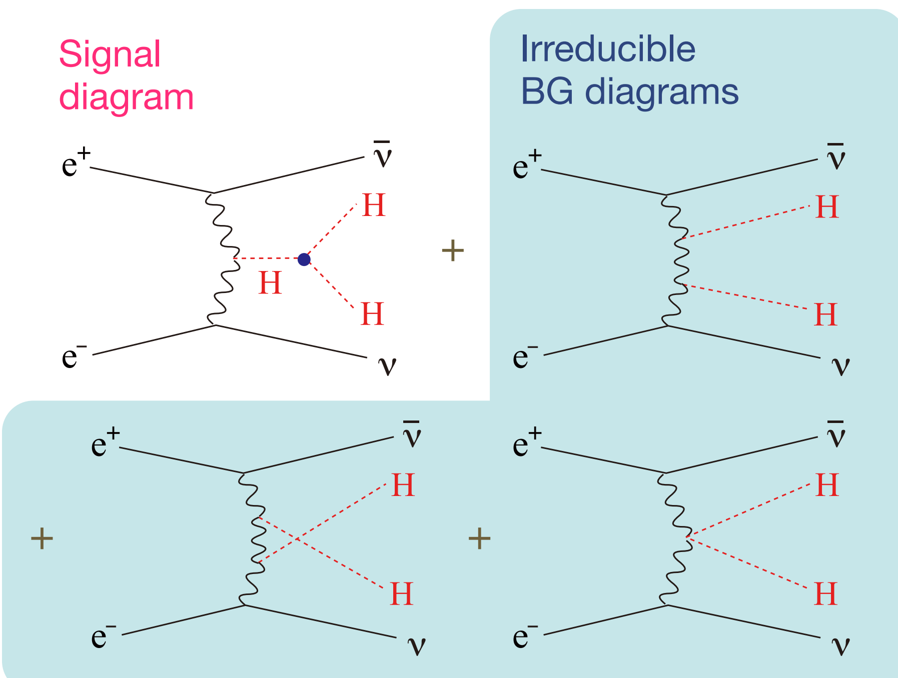


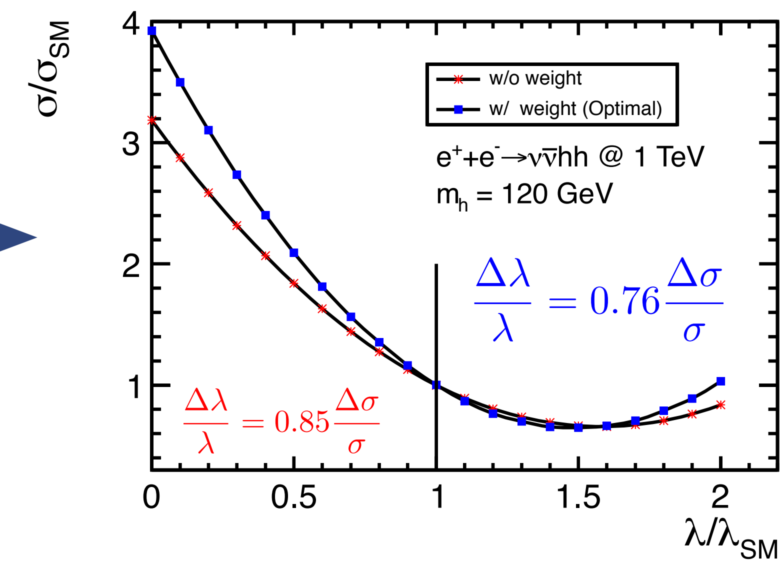
$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams

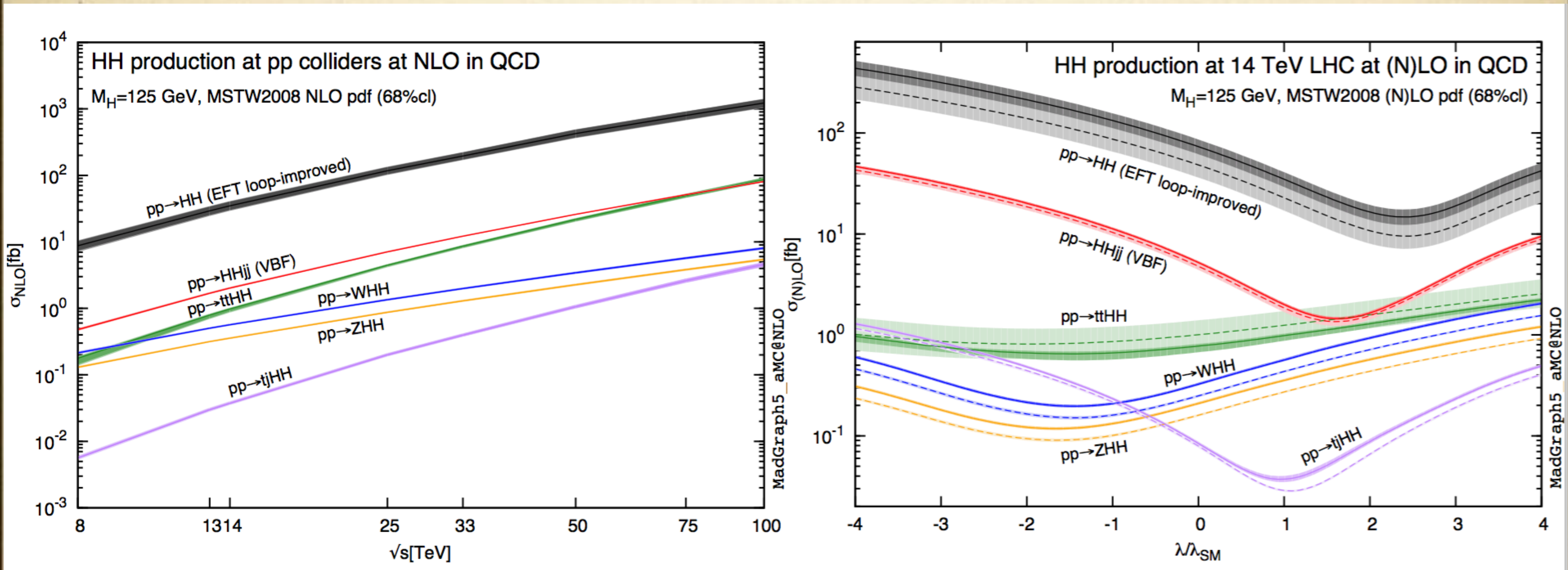






Junping Tian LC-REP-2013-003

What if $\lambda \neq \lambda_{SM}$? @ LHC

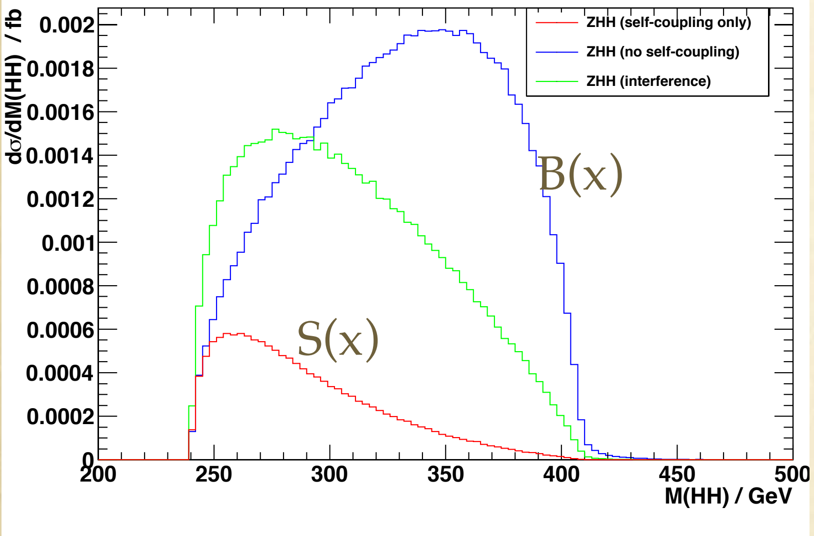


arXiv:1401.7304

- interference is destructive, σ minimum at $\lambda \sim 2.5\lambda_{SM}$; if λ is enhanced, it's going to be very difficult (from snowmass study by 3000 fb-1 @ 14 TeV, significance of double Higgs production is only ~ 2σ, if cross section decreases by a fact of 2~3, very challenging to observe pp—>HH)

a new general method to improve the sensitivity of λ

differential cross-section



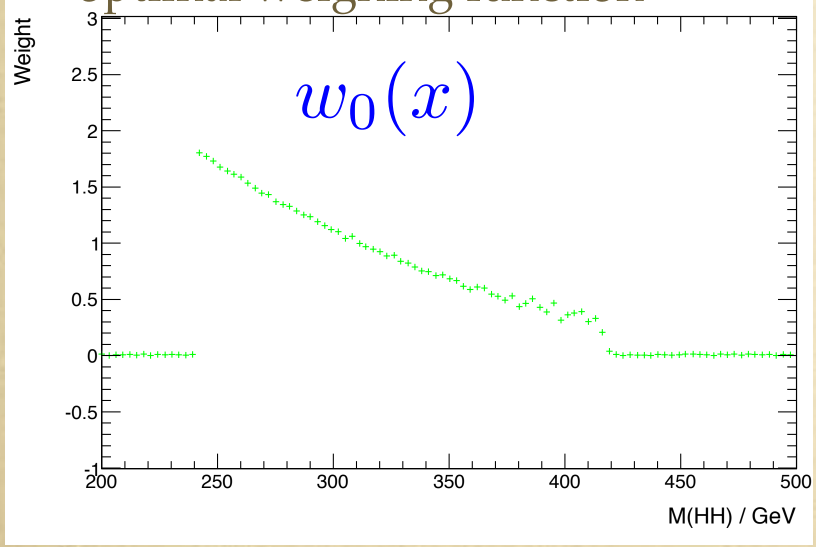
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x)\mathrm{d}x$$

optimal weighing function



equation of the optimal w(x) (variance principle):

$$\sigma(x)w_0(x)\int (I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int \sigma(x)w_0^2(x)\mathrm{d}x$$

general solution:

$$w_0(x) = c \cdot \frac{I(x)+2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

LCWS2016 in Morioka: N. Craig, “Higgs precision physics at linear and circular e+e- colliders”

σ_{Zh} in EFT → Composite Scale

The size comes from the scale of an EFT operator:

$$\mathcal{L} \supset \left(\frac{c_H}{\Lambda^2}\right)\frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

$$\rightarrow \left(\frac{2C_H v^2}{\Lambda^2}\right)\frac{1}{2}\left(\partial_\mu h\right)^2$$

250GeV

ILC direct Zh

(Yan et al. 1604.07524)

$\sqrt{s}$	250 GeV		350 GeV		500 GeV	
	$\int \mathcal{L}dt$	$\Delta\sigma_{Zh}/\sigma_{Zh}$	$\int \mathcal{L}dt$	$\Delta\sigma_{Zh}/\sigma_{Zh}$	$\int \mathcal{L}dt$	$\Delta\sigma_{Zh}/\sigma_{Zh}$
$e^-_L e^+_R$	1350 fb^{-1}	1.1%	115 fb^{-1}	5.0%	1600 fb^{-1}	2.5%
$e^-_R e^+_L$	450 fb^{-1}	2.2%	45 fb^{-1}	9.8%	1600 fb^{-1}	3.1%

My naive ILC combo: $\delta\sigma_{Zh}/\sigma_{Zh}$=0.88%

$$c_H \frac{v^2}{\Lambda^2} < 0.0044$$

$\Lambda > 2.6\,\text{TeV}$ ($c_H = 1$)

“r_H< 0.076 am”

This requires the absolute value, not ratio. → **recoil mass technique essential** → e^+e^- colliders.

LCWS2016 in Morioka: C. Deurig, “Measureing the Higgs Self-coupling at the ILC”

The current state of the art

Kinematic fit, optimized event selection, leading to 10% relative improvement.

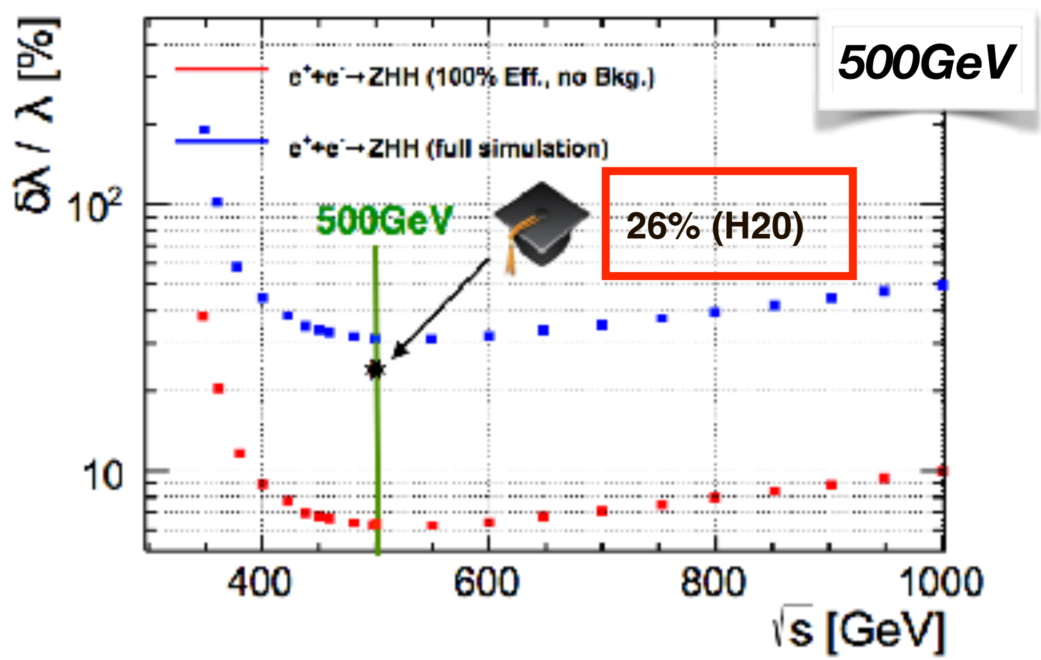
- for HH → bbbb

$$\frac{\Delta\sigma(ZHH)}{\sigma(ZHH)} = 21.1\% \rightarrow 5.9\sigma \text{ discovery}$$

- combined with HH → bbWW*

$$\frac{\Delta\sigma(ZHH)}{\sigma(ZHH)} = 16.8\% \rightarrow 8.0\sigma \text{ discovery}$$

- results in 26.6% precision on λ_{SM}



Note: $\delta\lambda/\lambda$ = 13% (H20) if $\lambda = 2\,\lambda_{SM}$