Top@LC 2017, CERN

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

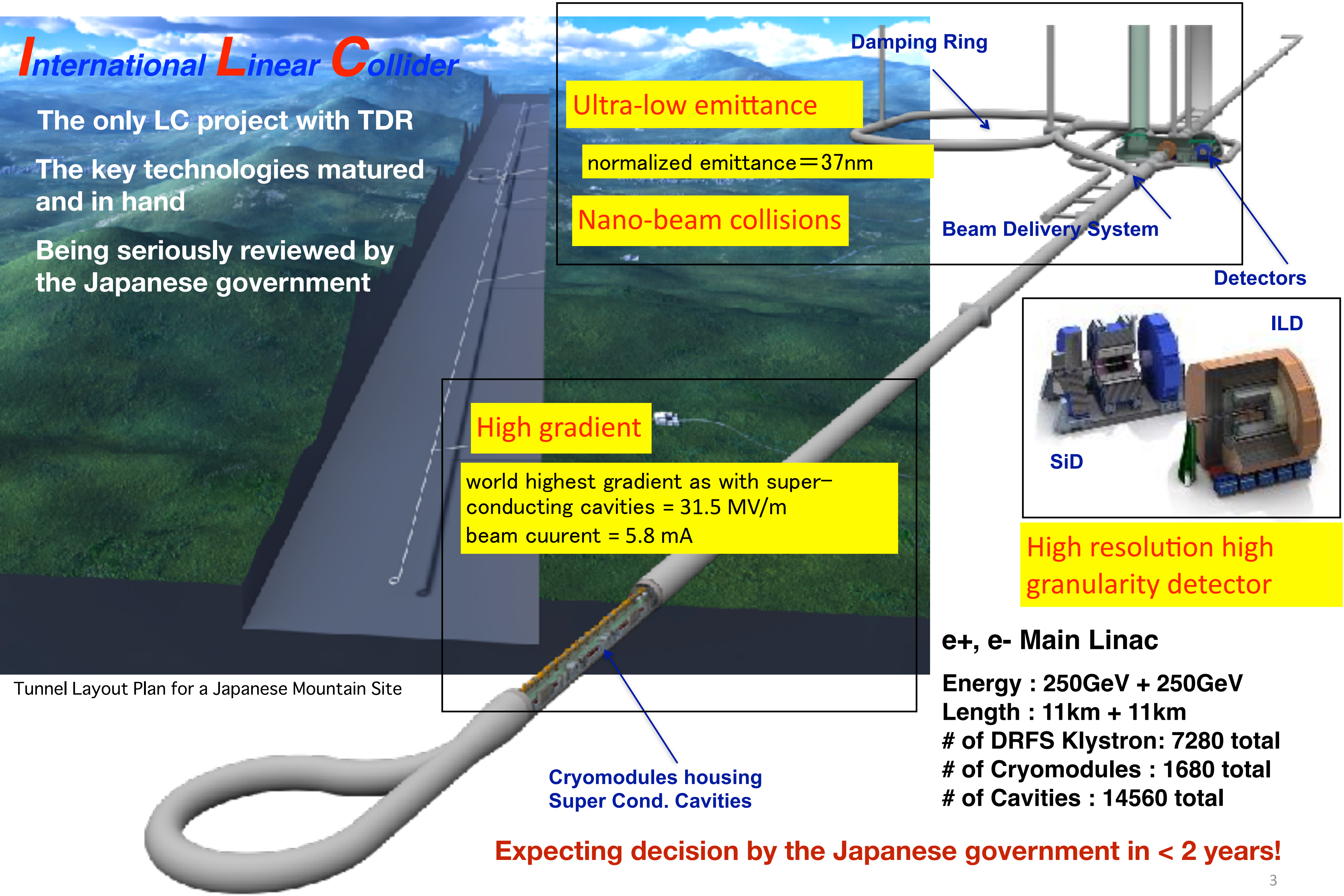
Keisuke Fujii (KEK)

June 8, 2017

Part I

ILC Project Status

Bird's Eye View of the ILC Accelerator



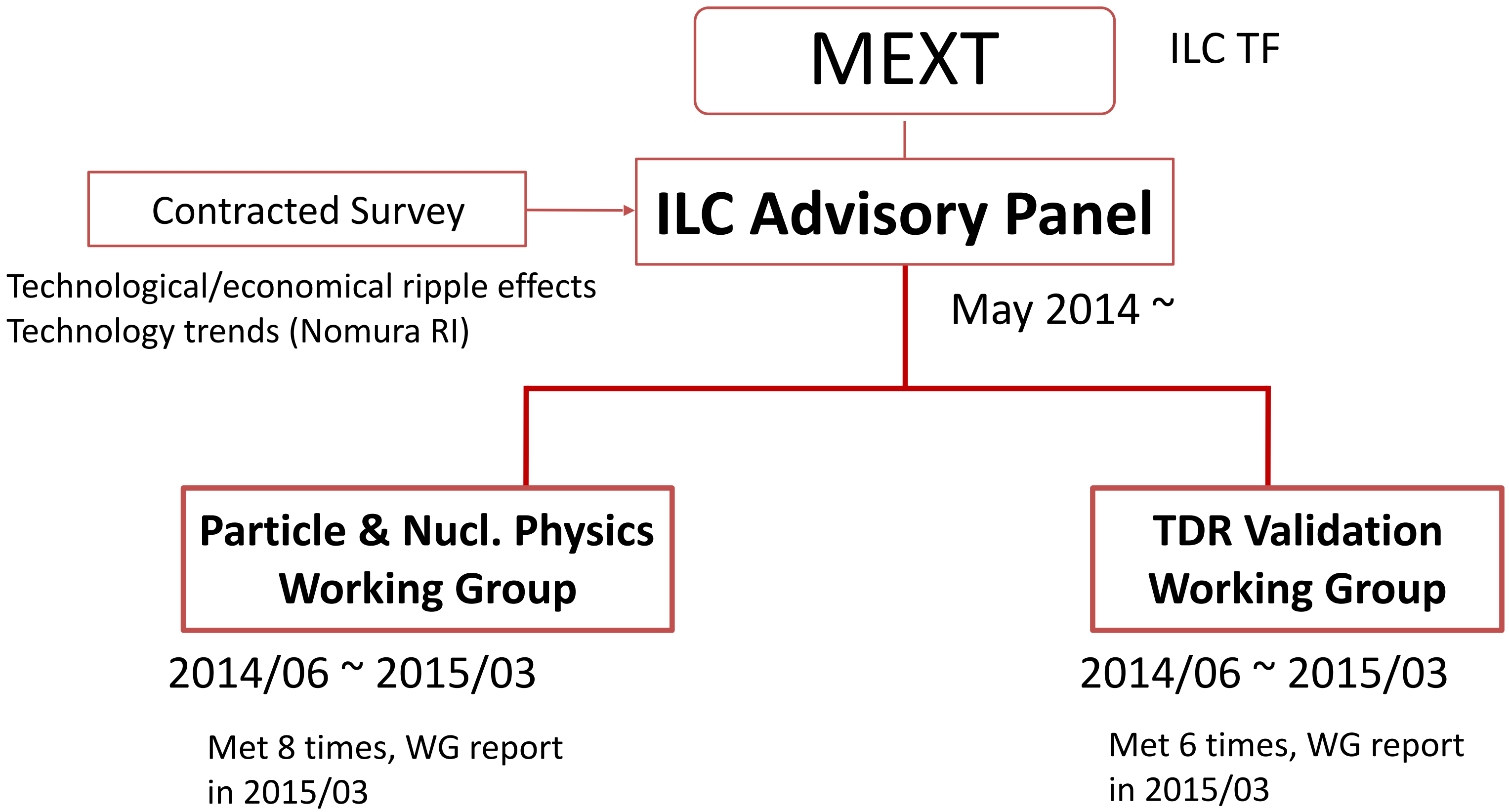
Expecting decision by the Japanese government in < 2 years!

MEXT's ILC Review

MEXT	=	Japan's **M**inistry of **E**ducation, **C**ulture, **S**ports, **S**cience and **T**echnology

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

The panel published an Interim Summary in 2015

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.
  - Investigate issues concerning necessary human resources

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  - Investigate issues concerning necessary human resources → **HR WG**

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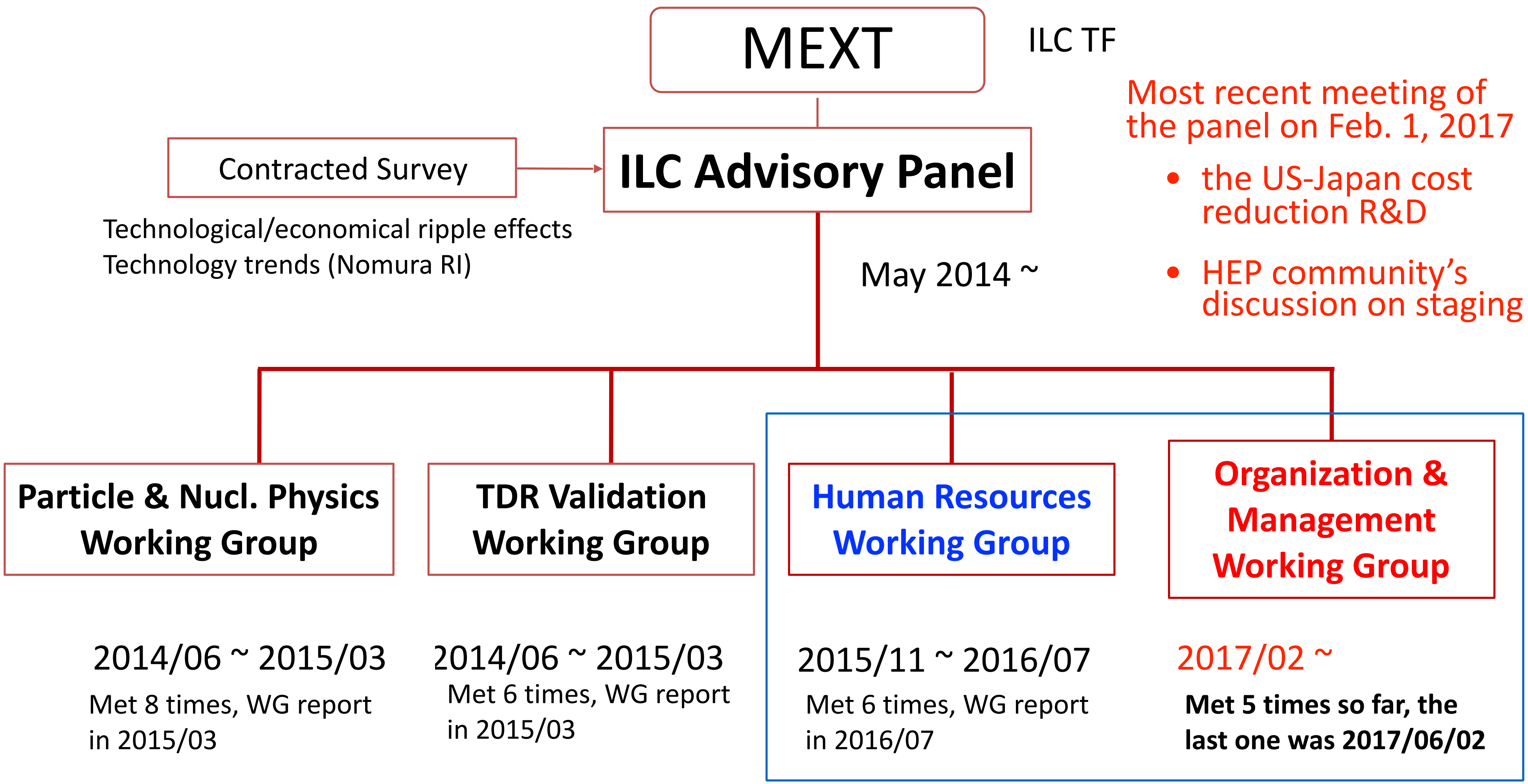

http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/index.htm

Linear Collider Collaboration (LCC)

is on working on issues raised in the Interim Summary

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

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→ **LCC** homework 1

→ **LCC** homework 2

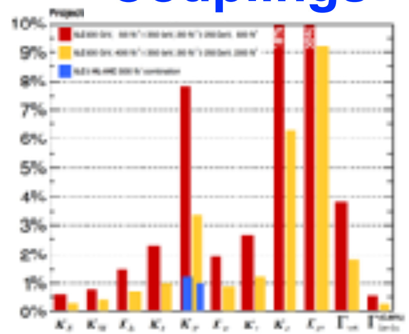
→ **LCC** homework 3

LCC Physics WG & Parameters WG

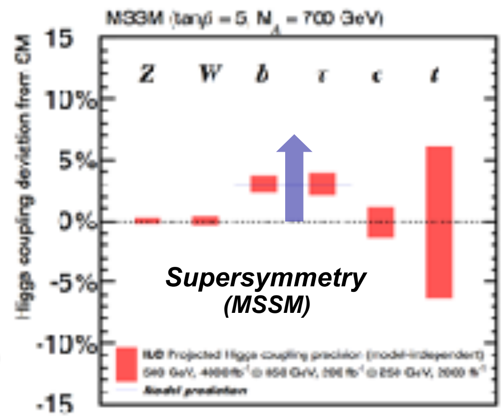
Physics Case for the ILC
arXiv: 1506.05992, Jun.19, 2015

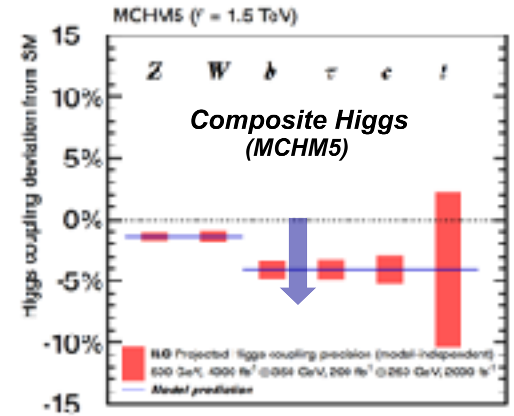
ILC Operating Scenarios
arXiv: 1510.05739, Oct.19, 2015

Higgs Couplings



Elementary v.s. Composite?



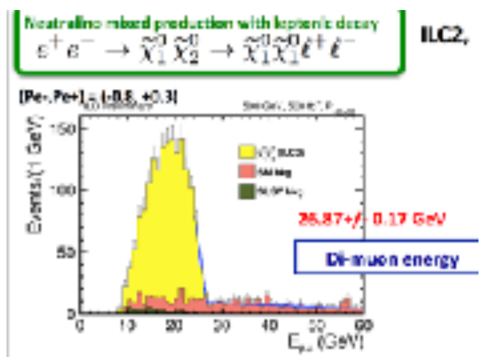


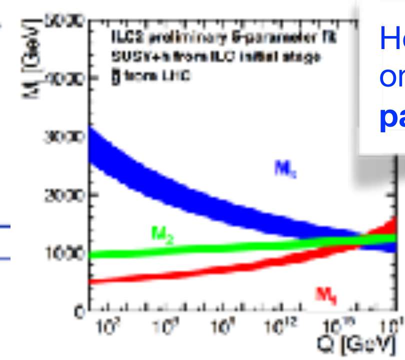
Implication of the 750 GeV γγ Resonance as a Case Study for the ILC
arXiv: 1607.03829, Jul. 31, 2016

X750 was found dead but the exercise proved ILC's capability to probe new physics operating behind a possible heavy new particle beyond its direct reach

Homework 2: **Monitor, analyze, and examine the development of LHC experiments.**

The Potential of the ILC for Discovering New Particles
arXiv: 1702.05333, Feb. 17, 2017





Homework 1: Provide a clear vision on **the discovery potential of new particles**

ILC Brochure
LCC communicators & phys. WG

Homework 3: Get **understanding from the general public** and other scientific communities.

Home works from MEXT ILC Panel

Interim Summary

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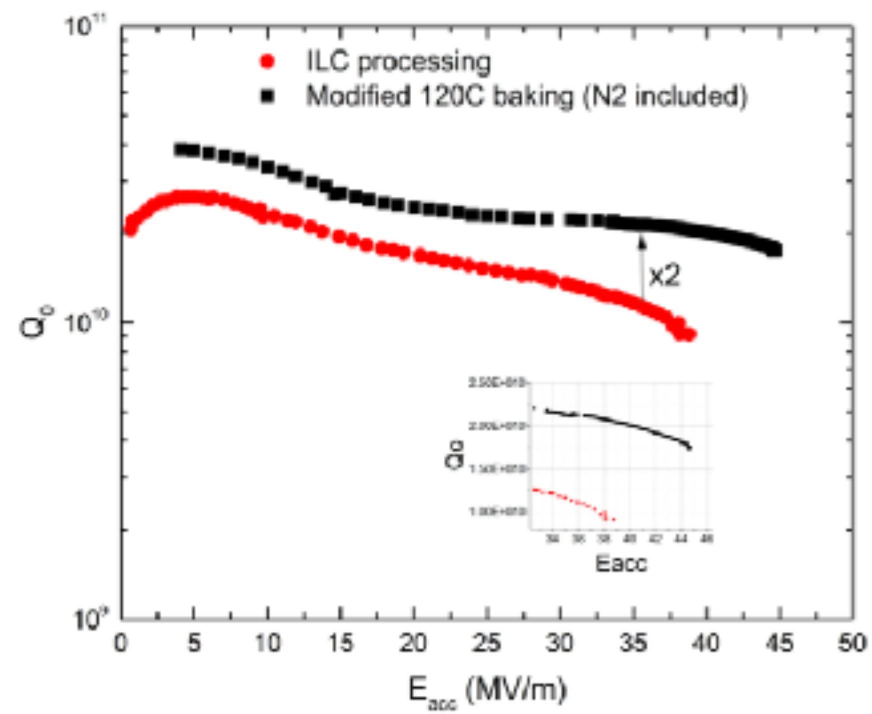
→ **US-J**

MEXT-DOE Discussion Group

- At the end of May 2016, high level officers from MEXT visited their DOE counter part 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 reduction in Nb material preparation
  - High-Q high-gradient SCRF cavity using nitrogen infusion



So we are doing our homework and MEXT is doing their homework very seriously!

Support from Diet Members and Industrial Sector in Japan

- ***Federation of Diet Members for the ILC*** (since 2008 with >150 members from both the governing and opposition parties)
- ***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. *Another one happened just recently.*

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)

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 of Part I

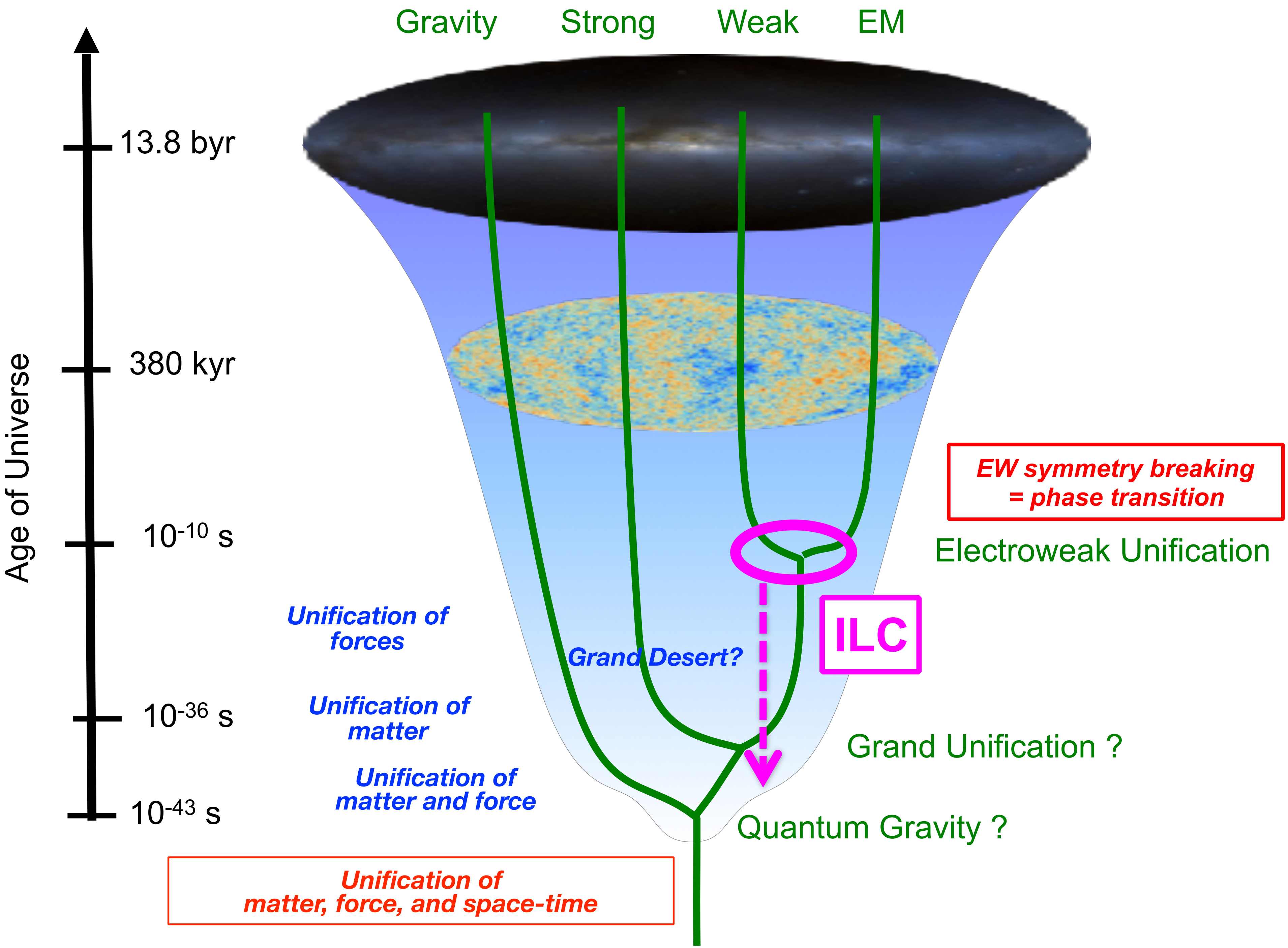
- ***MEXT is seriously investigating various issues to be solved to host the ILC in Japan.***
- KEK/JHEPC is taking ***various actions together with the LCC*** to address issues pointed out by the MEXT ILC Advisory Panel.
- ***MEXT-DOE joint discussion group*** started.
- ***US-Japan joint effort on cost reduction*** started.
- There are important ***political interactions happening also in Europe and Asia,*** which I had no time to cover today.
- Serious discussions on ***staging from 250 GeV*** started.
- As Hon. Kawamura said in LCWS 2016, ***2017-2018 will be a very important time for the ILC.***

Part II

ILC Physics

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?

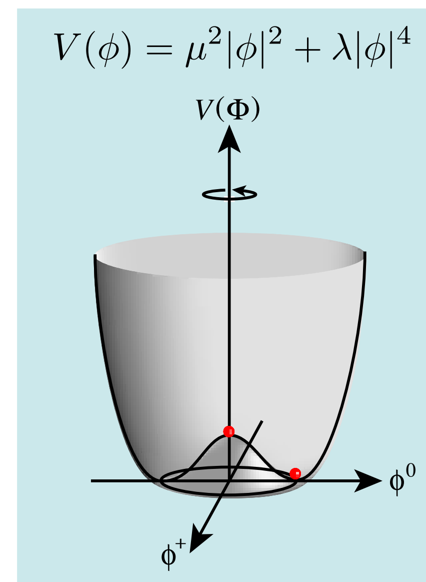
Mystery of something in the vacuum

With the discovery of H125 at LHC we know that ***our vacuum is filled with "something" having weak charge.*** This something is called ***the Higgs field,*** but we don't know its true character, its multiplet structure, or its underlying dynamics.

In particular, **the SM does not explain** ***why the Higgs field developed a vacuum expectation value.***

★ *In other words* ***the SM does not answer the question:***

Why $\mu^2 < 0$?

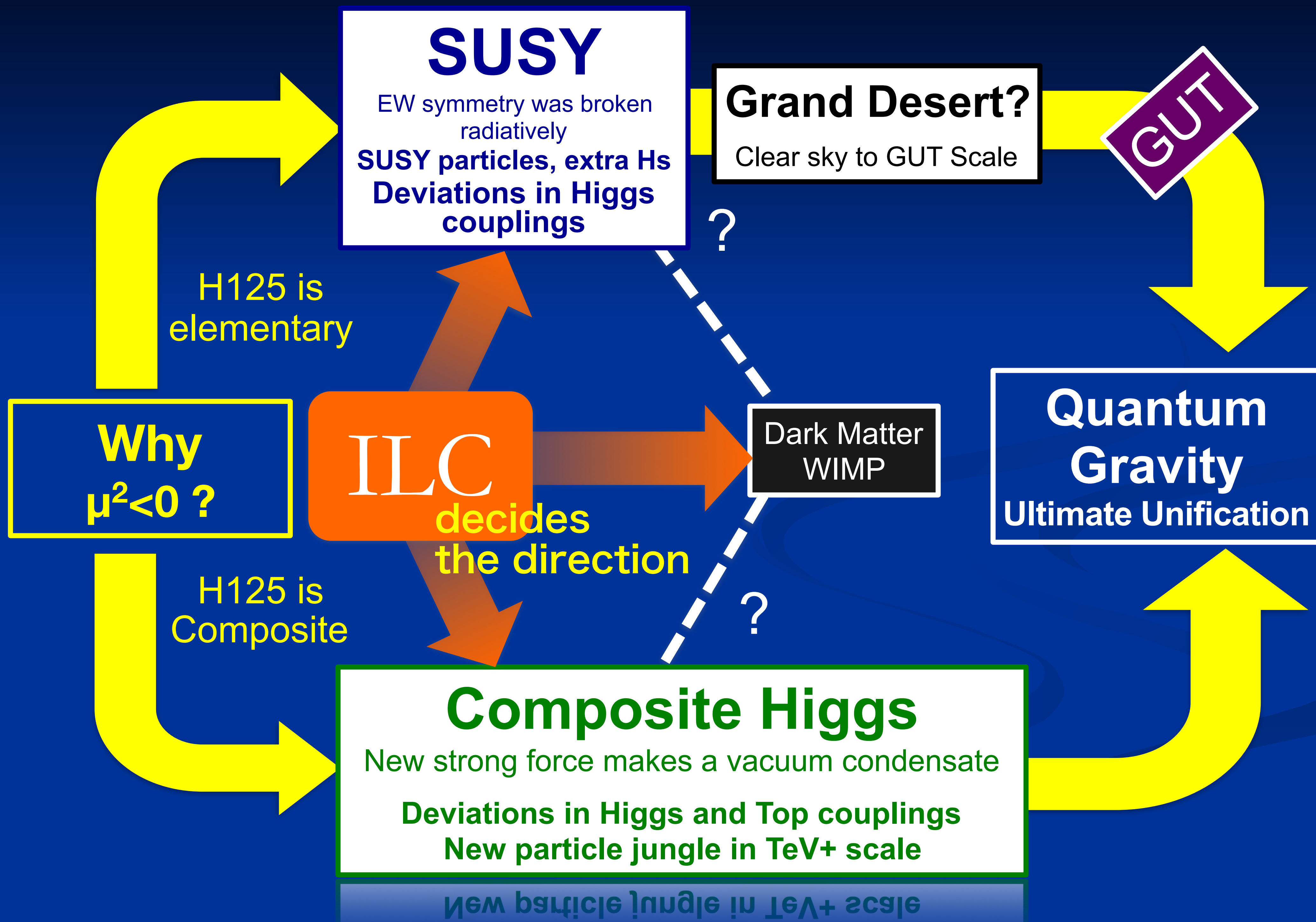


★ *To answer this question,*
we need to go beyond the Standard Model!

Big fork ahead of us

The answer forks depending on whether
H125 is elementary or composite!

Big Fork at the EW Scale



The 3 major probes for BSM at ILC:

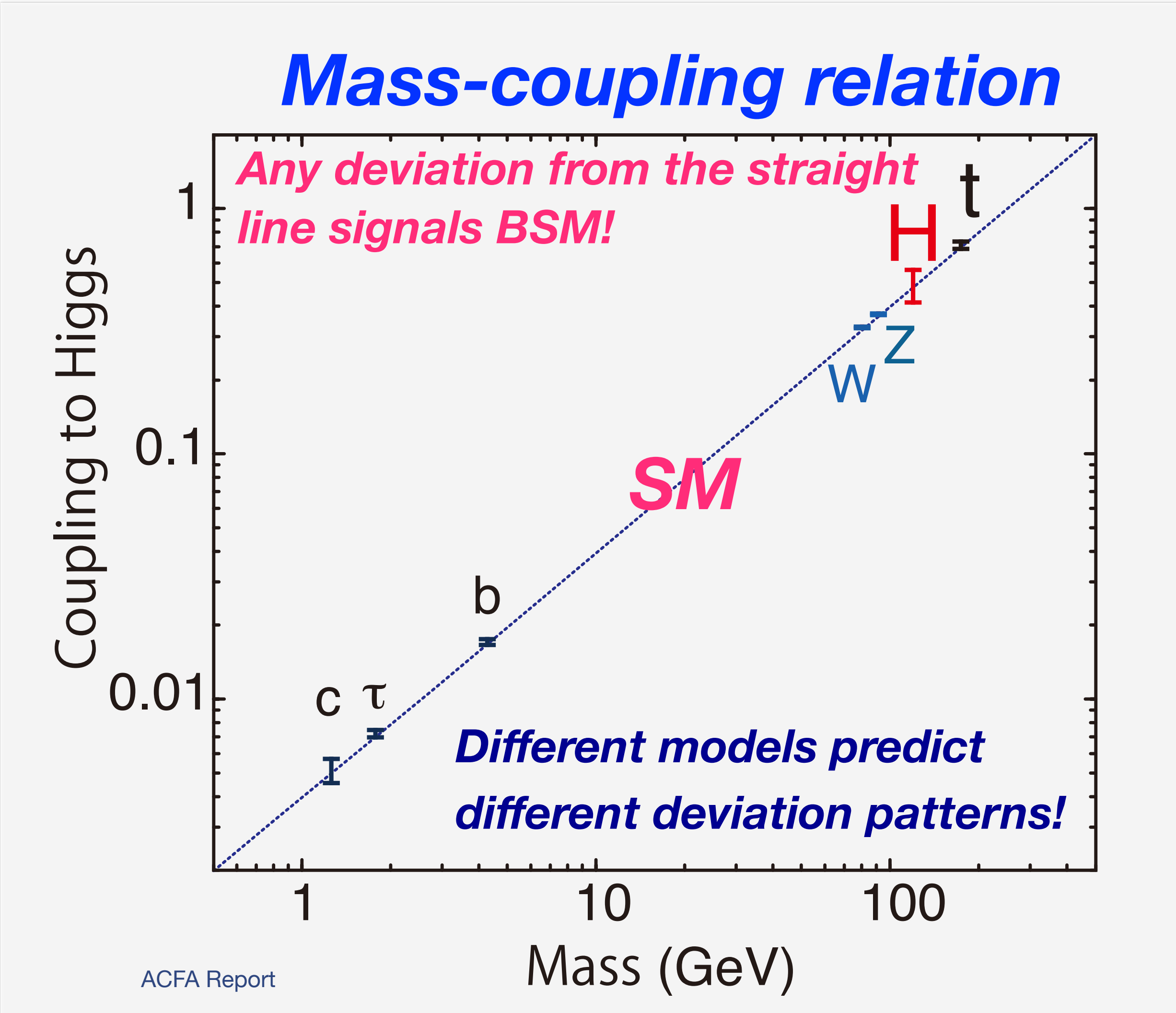
Higgs, *Top*, and search for *New Particles*

The 3 major probes for BSM at ILC:

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

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**

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

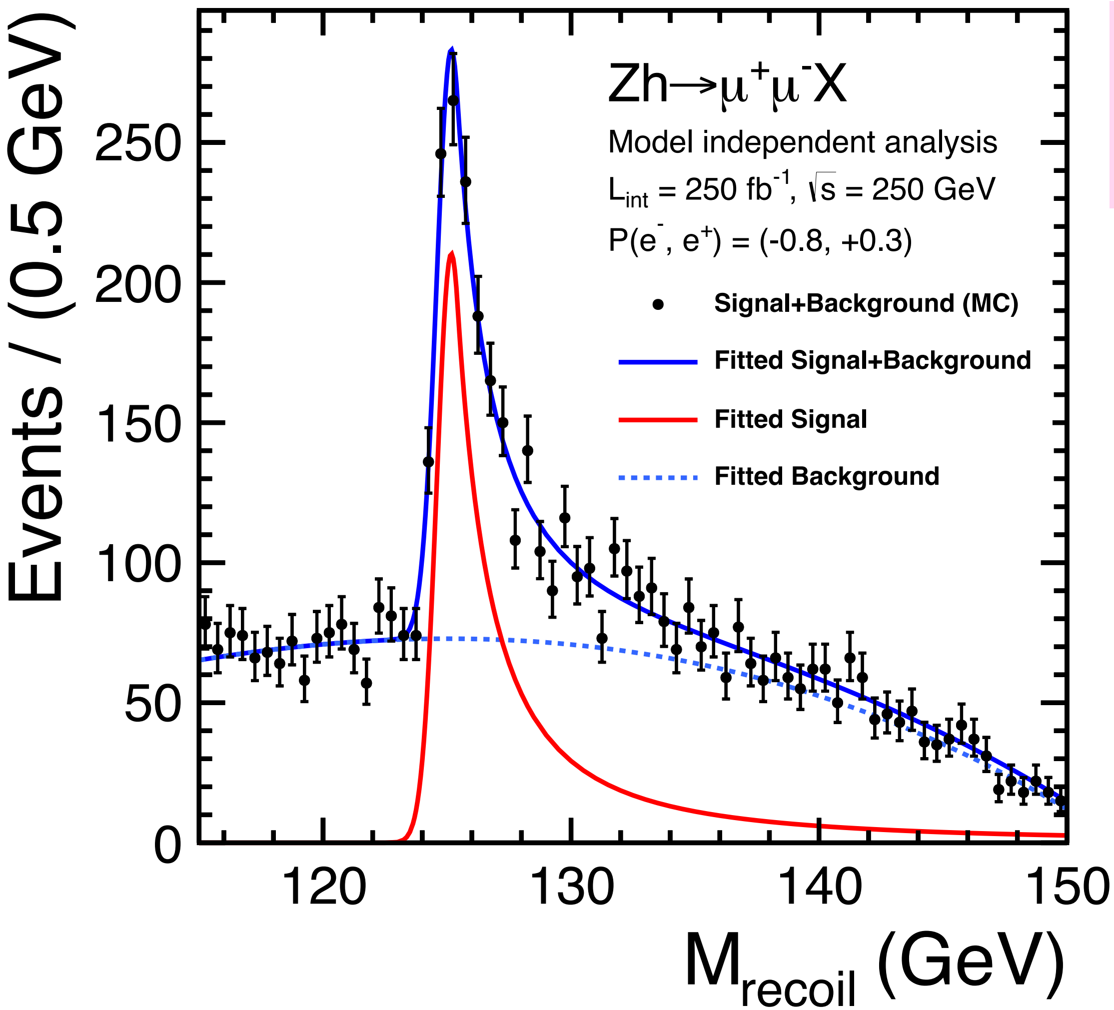
composite scale

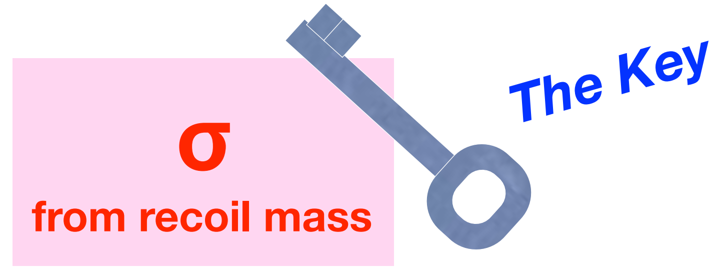
New physics at 1 TeV → **deviation is at most ~10%**

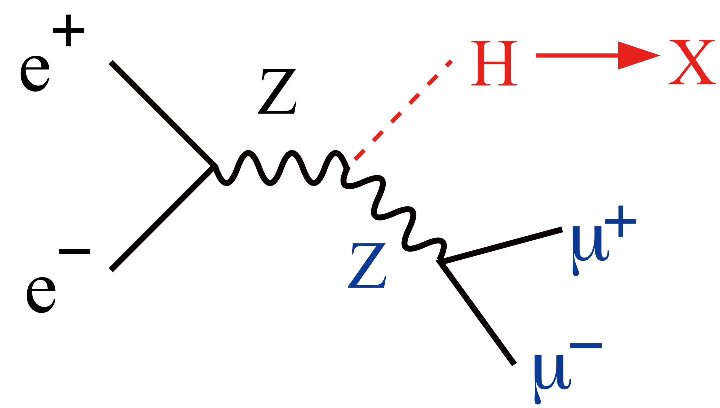
We ***need a %-level precision*** → ***ILC***

The Key

All the measurements are σ×BR measurements with one crucial exception, the σ measurement using recoil mass technique, that is the key to the model-independent determination of various Higgs couplings.







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

Can detect the Higgs without looking at it!

Higgs Couplings

***Model-independent* coupling fit, impossible at LHC**

H20 Scenario

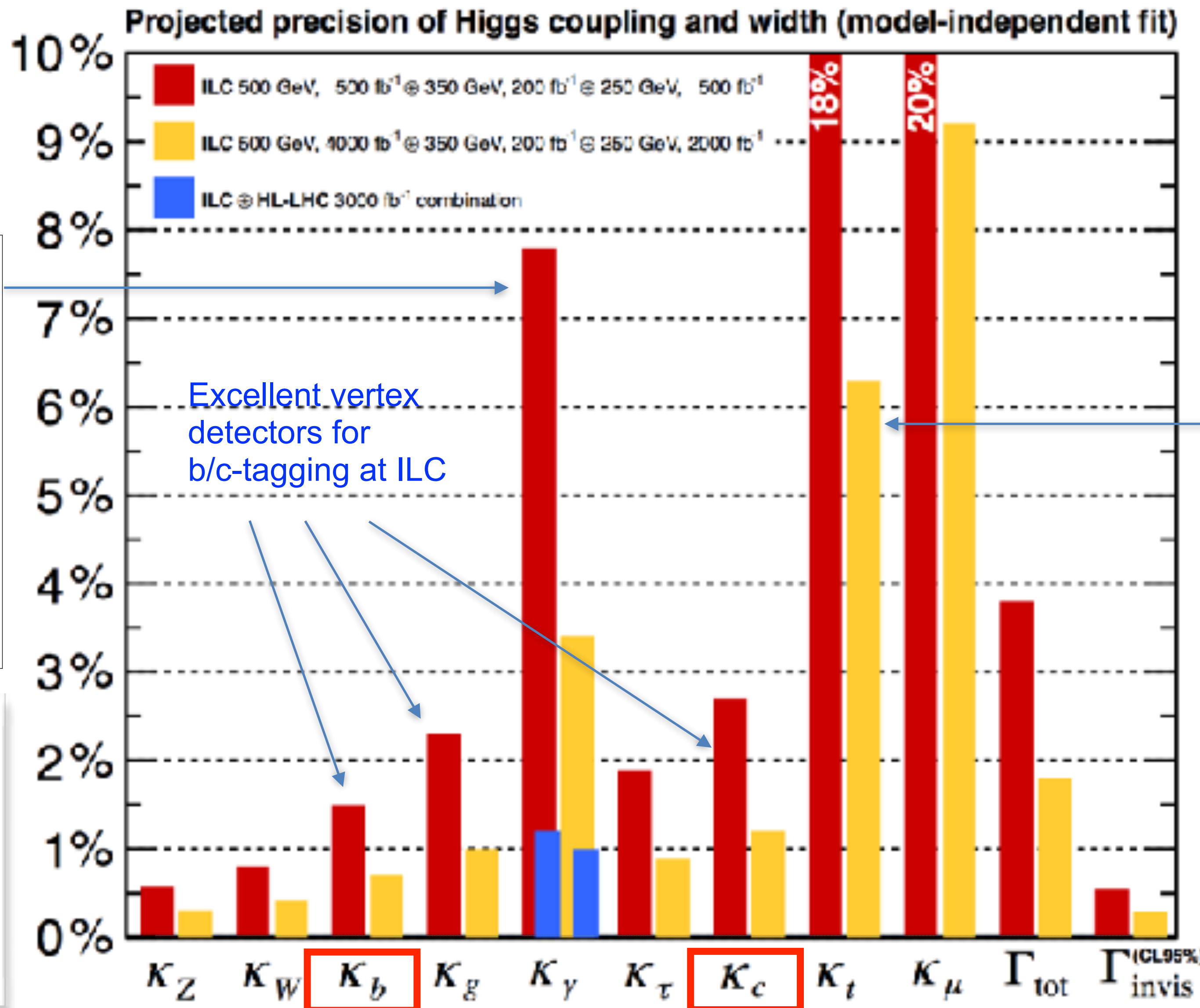
arXiv: 1506.05992
arXiv: 1506.07830

Better hγγ with LHC/ILC synergy

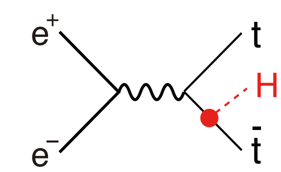
LHC can precisely measure
BR(h→γγ) / BR(h→ZZ*)
= $(K_\gamma / K_Z)^2$

ILC can precisely measure K_Z

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



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

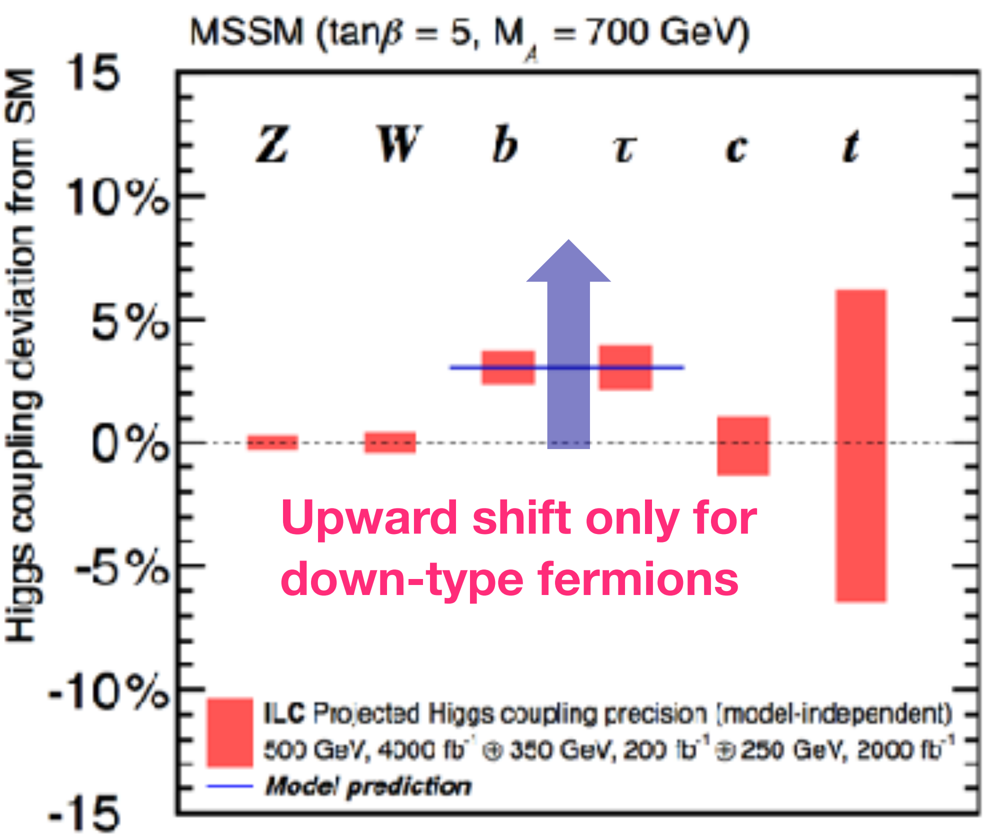
~1% or better for most couplings!

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

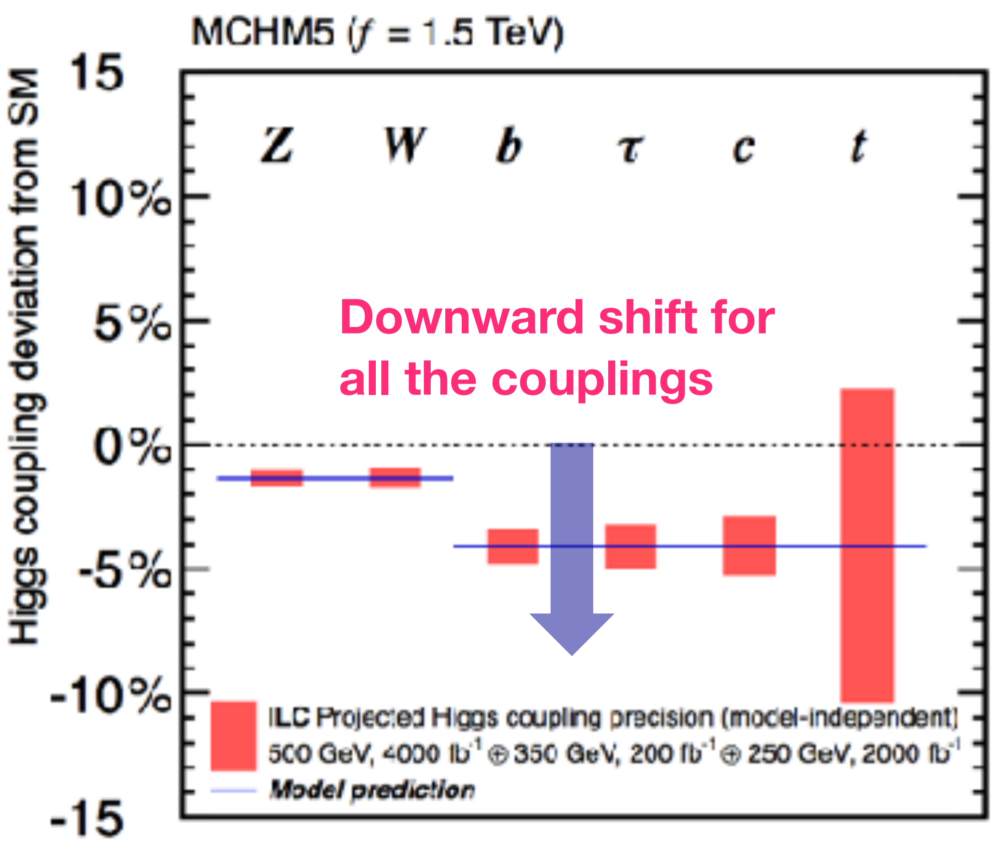
Fingerprinting

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 goes well beyond that of LHC!

Since now the focus is on the 250 GeV initial stage, we need to re-optimize our strategy for the precision coupling measurements.

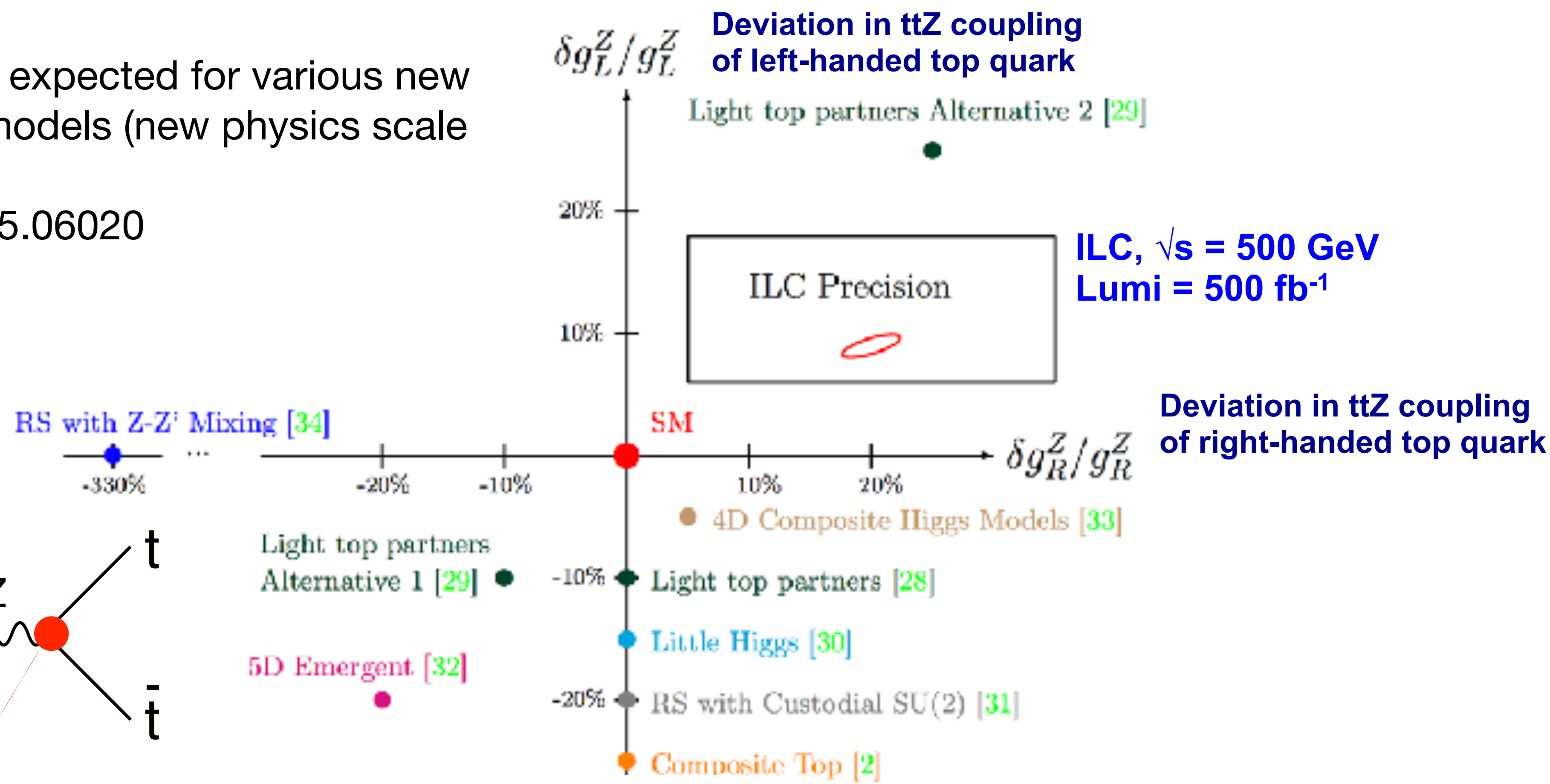
→New strategy based on *EFT* → Michael's talk

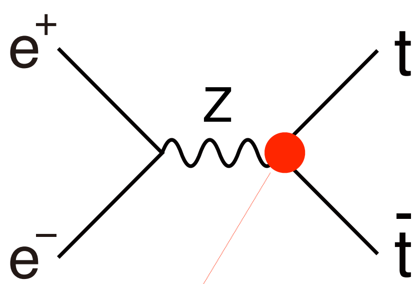
Top

Search for Anomalous ttZ Couplings

Top: **Heaviest in SM**→Must couple **strongly to the EWSB 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)***

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





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

→EFT: Martin Perello's talk

→MEM: Yo Sato's talk

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

250 GeV is below ttbar threshold, so at the initial stage, we need to use something else.

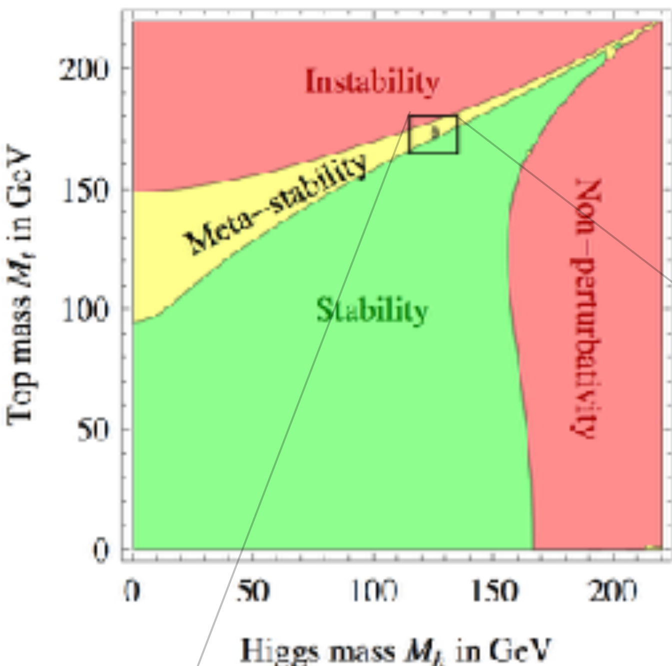
→Use bbar instead

→Sviatoslav's talk yesterday

→Francois's talk tomorrow

What if we could see no deviation from the SM in Higgs and Top couplings?

Clarify the Range of Validity of SM



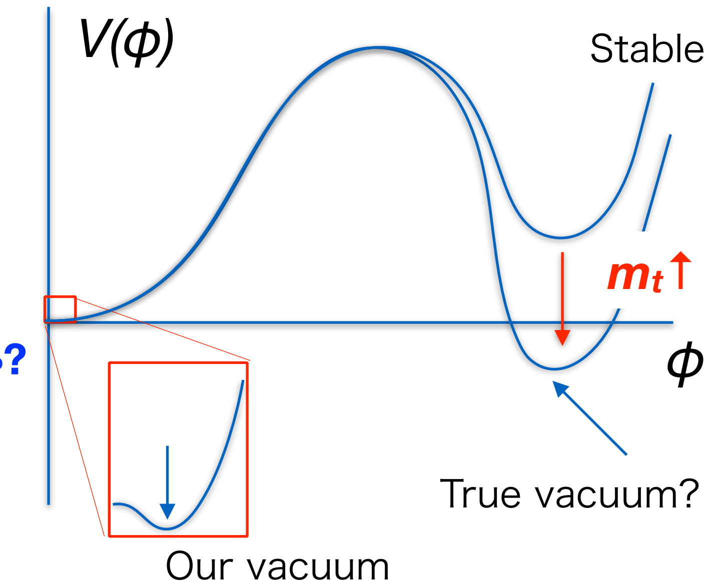
Stability of SM Vacuum

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

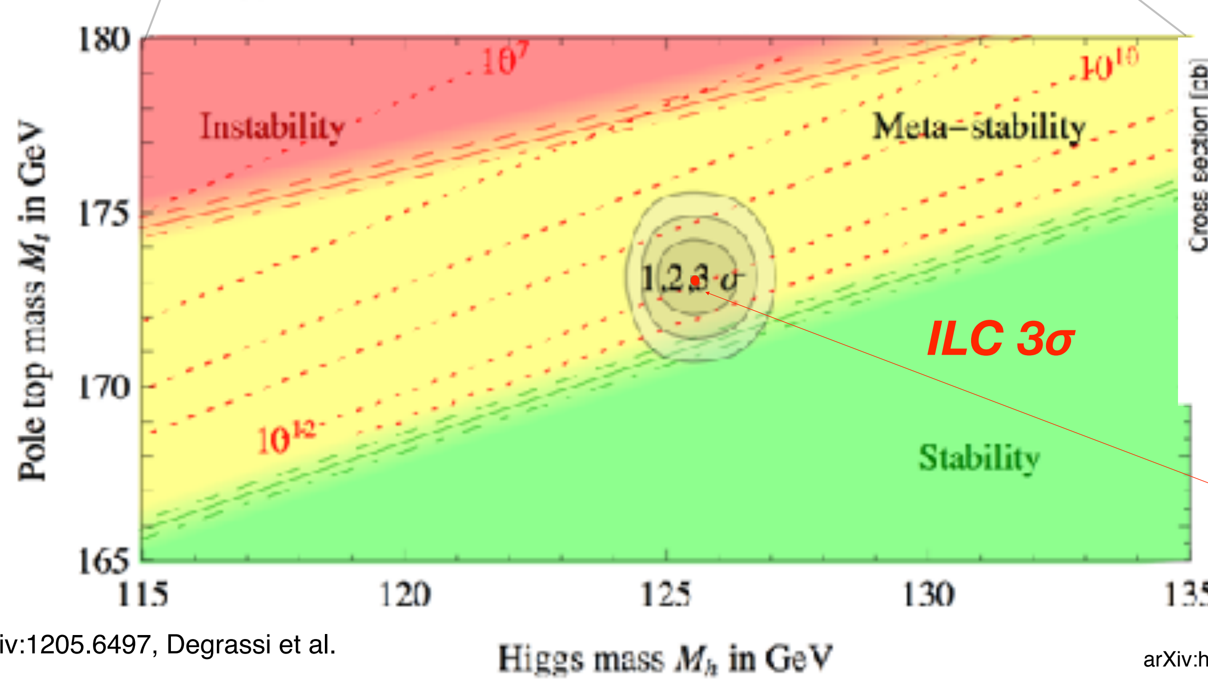
The current values of mt and mh:
Subtle point of meta-stability!

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

To answer this, we need precision m_t measurement!

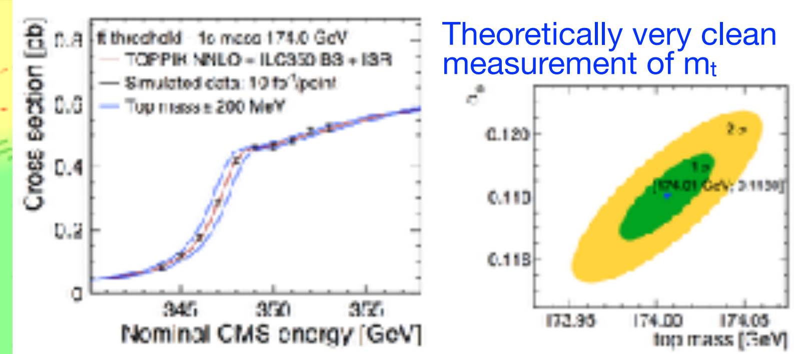


At LHC, theory error limits the precision to ~250MeV.



arXiv:1205.6497, Degrassi et al.

TTbar Threshold Scan @ILC



Theoretically very clean measurement of m_t

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

$$\Delta m_H = 15\,\mathrm{MeV}$$

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

What if we could see no deviation from the SM?

We need to go

to the ttbar threshold!

We are re-reformulating our strategy to BSM in the framework of staging from 250 GeV

Summary

- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** ***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 energy upgrade or the next machine.
  In this way, ***ILC will pave the way towards the moment of creation.***
- ***MEXT is seriously investigating various issues to be solved to host the ILC in Japan.***
- ***MEXT-DOE joint discussion group*** started.
- ***US-Japan joint effort on cost reduction*** started.
- There are important ***political interactions happening also in Europe and Asia.***
- Serious discussions on ***staging from 250 GeV*** started.
- As Hon. Kawamura said in LCWS 2016, ***2017-2018 will be a very important time for the ILC.***

Science First with ILC!

Backup

The Current Official Operation Scenario: H20

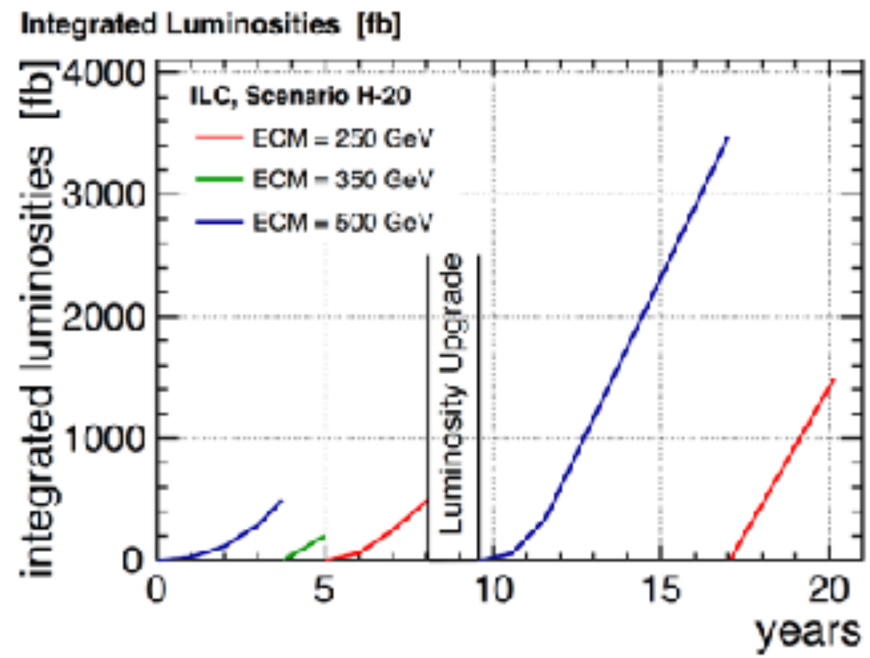
J. Brau : ICHEP2016

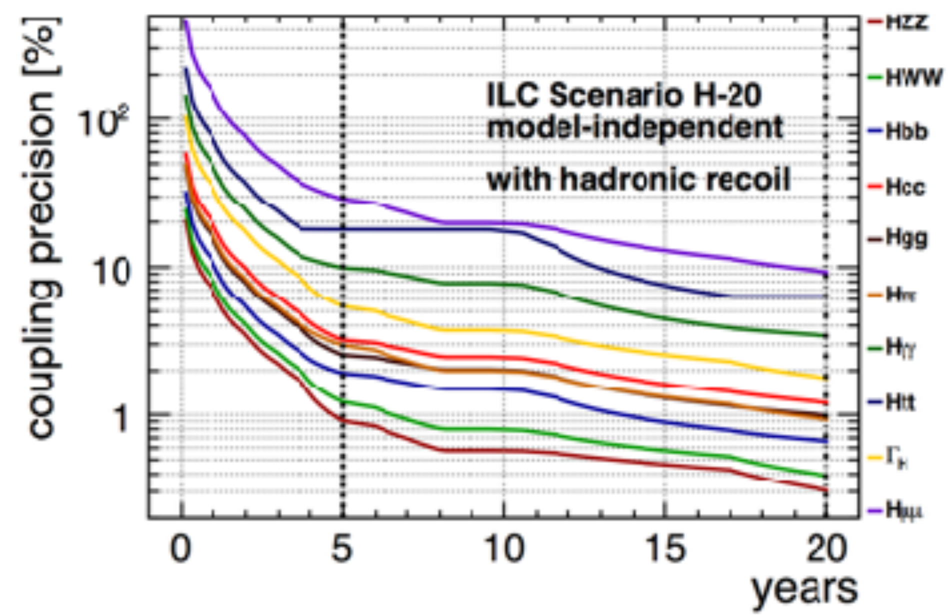
ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• gHWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak 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.





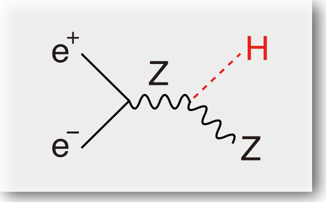
Higgs-related Physics at Ecm ≲ 500 GeV

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)

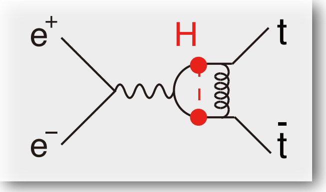
→Higgs couplings (other than top)

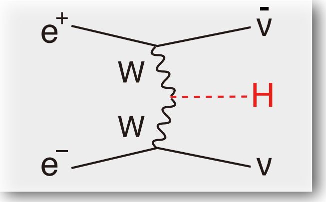


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- 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



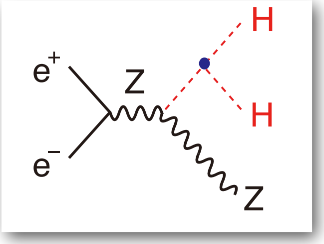


vvH @ 350 - 500GeV :

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

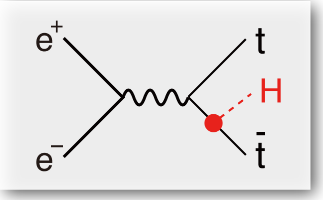
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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

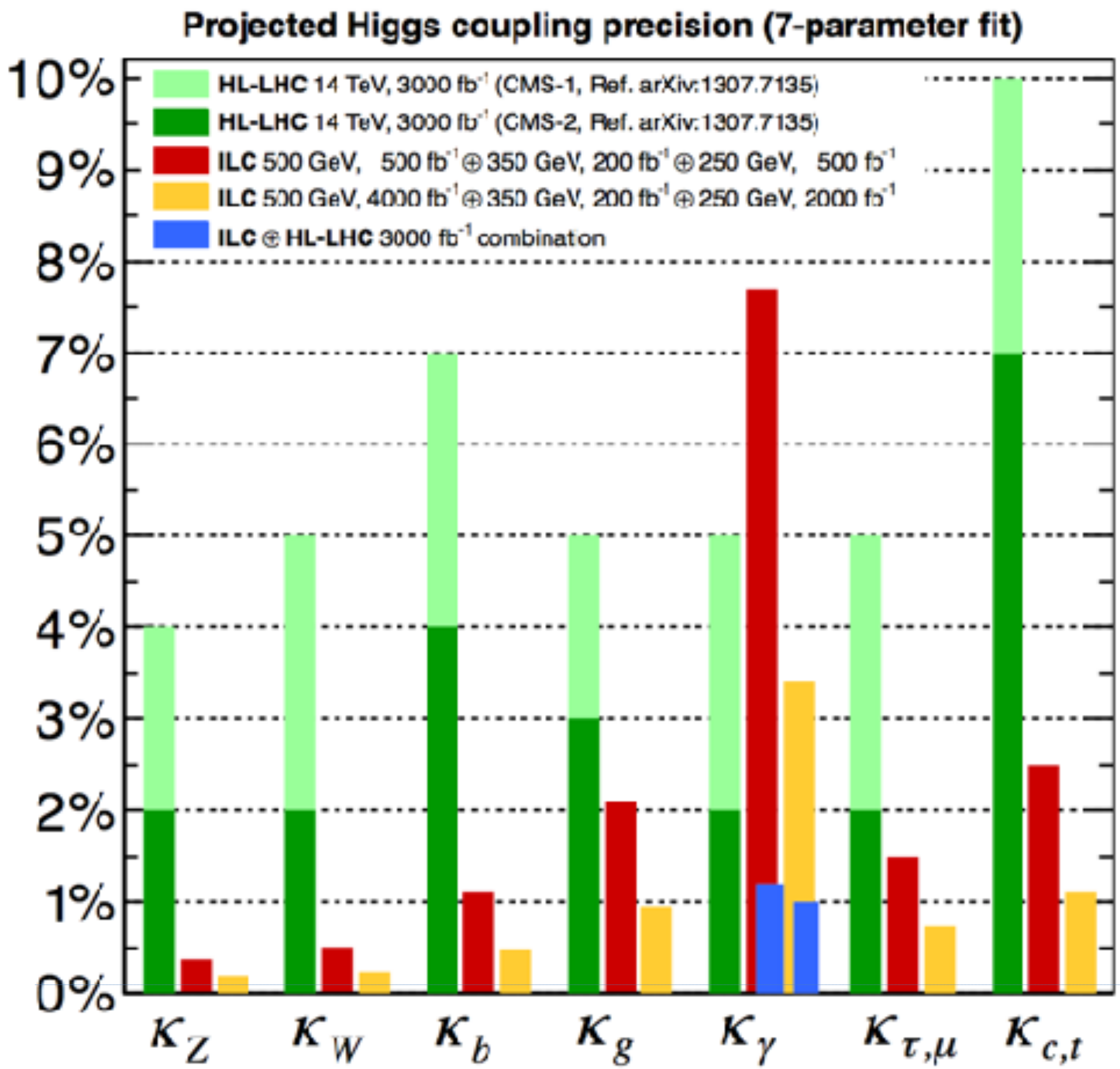


We can access all the relevant Higgs couplings at ~500GeV for the mass-coupling plot!

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

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

Σ_{SM} BR = 1

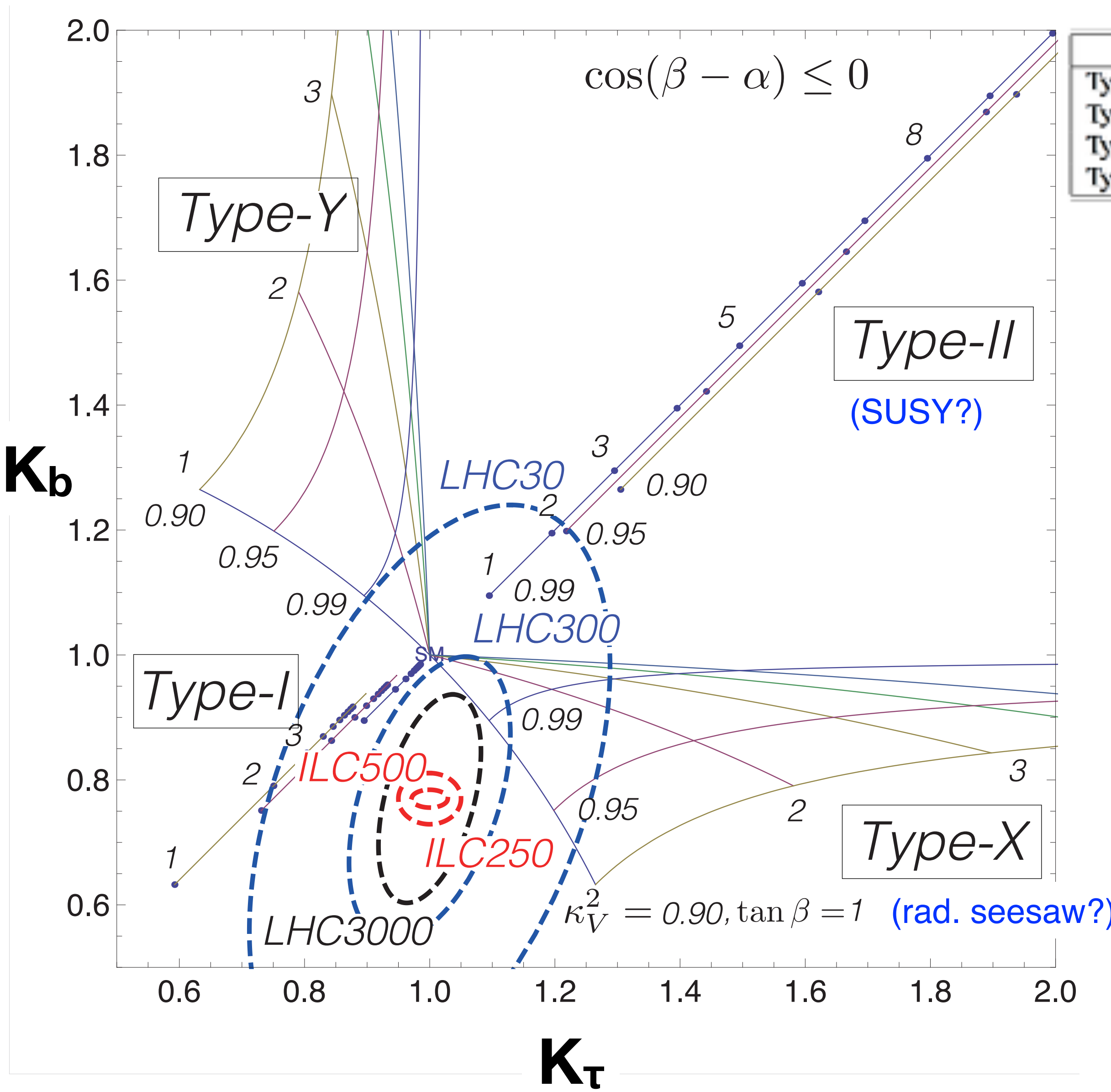


Possible to achieve precision far exceeding LHC!

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

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

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.

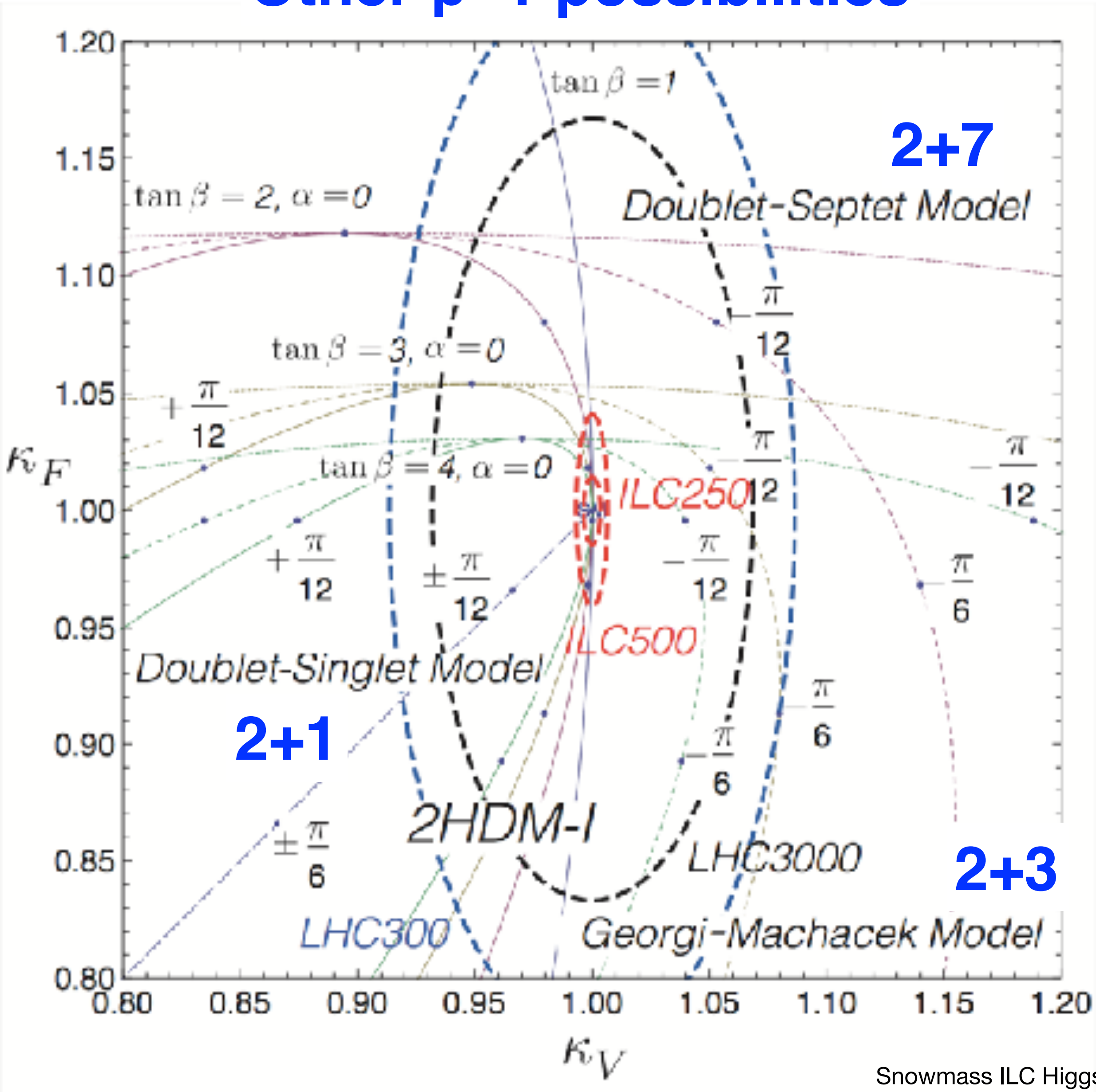
ILC TDR

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]

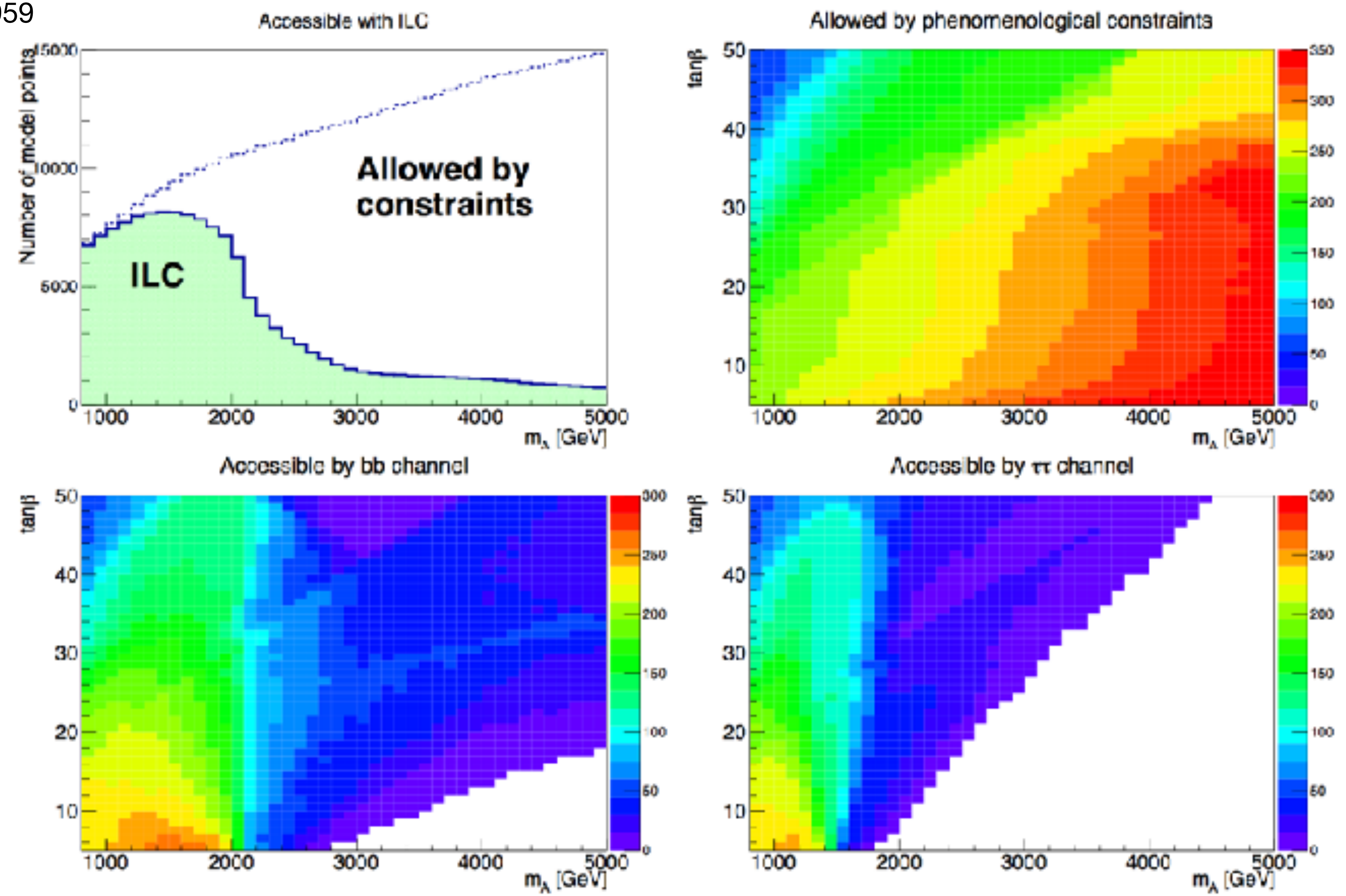


Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological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

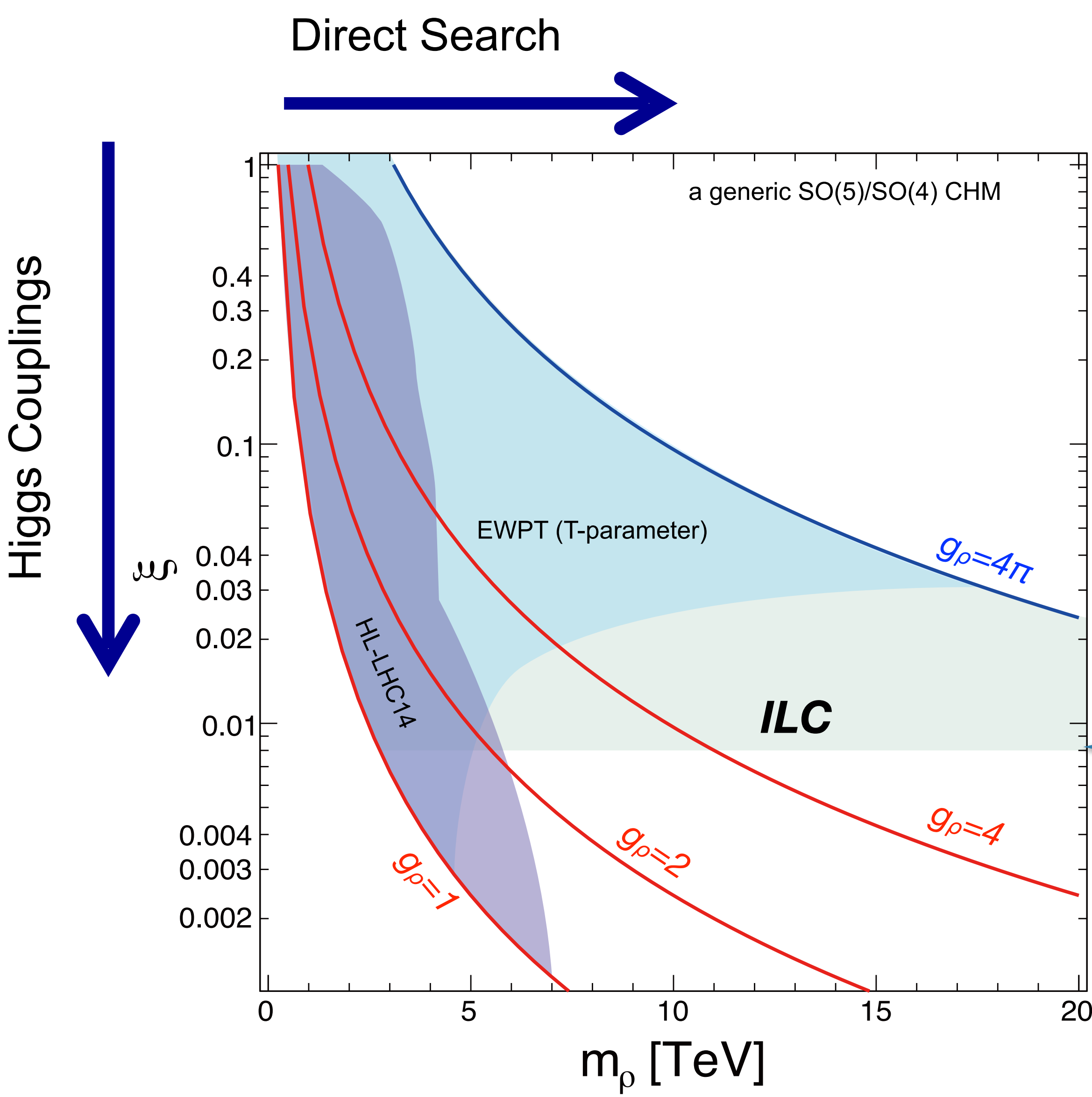
Composite Higgs: Reach

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



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

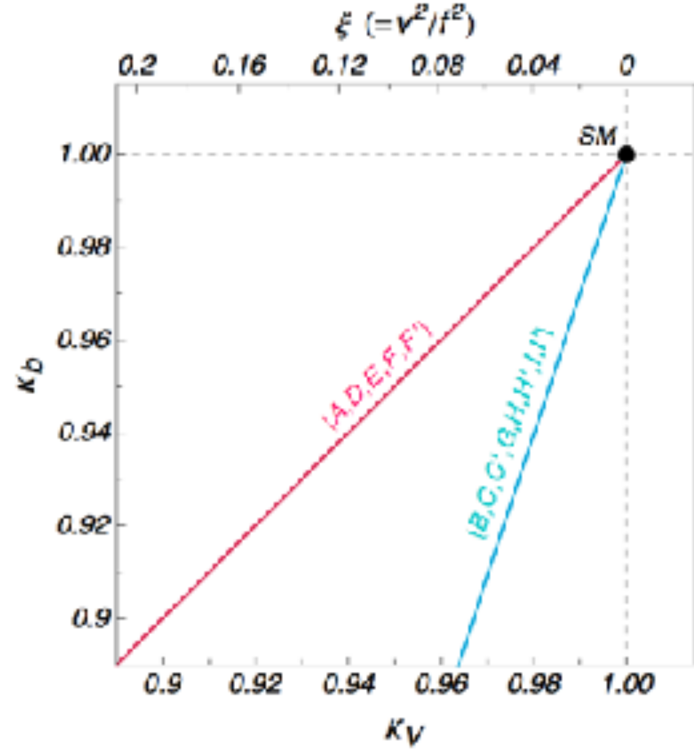
$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

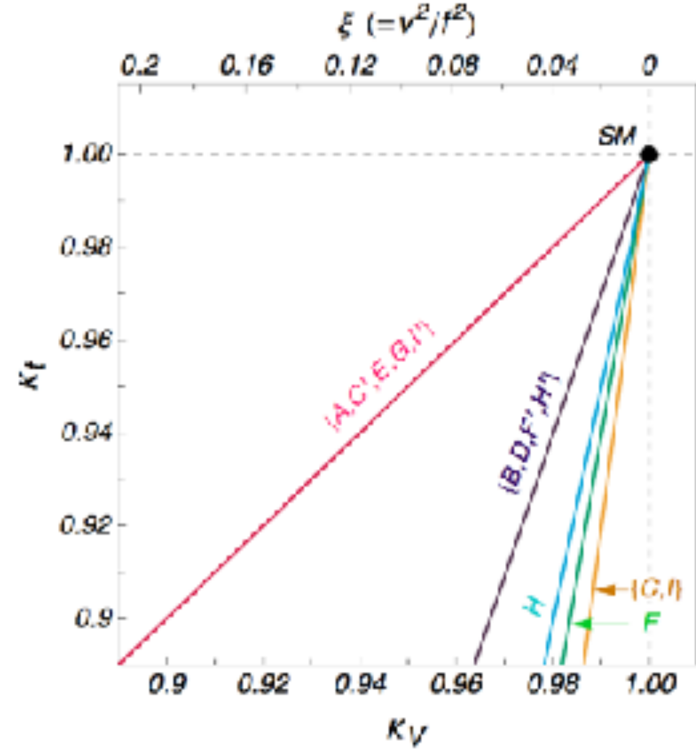
ILC (250+500 LumiUP)

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

New resonance scale and fingerprint identification in minimal composite Higgs models

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





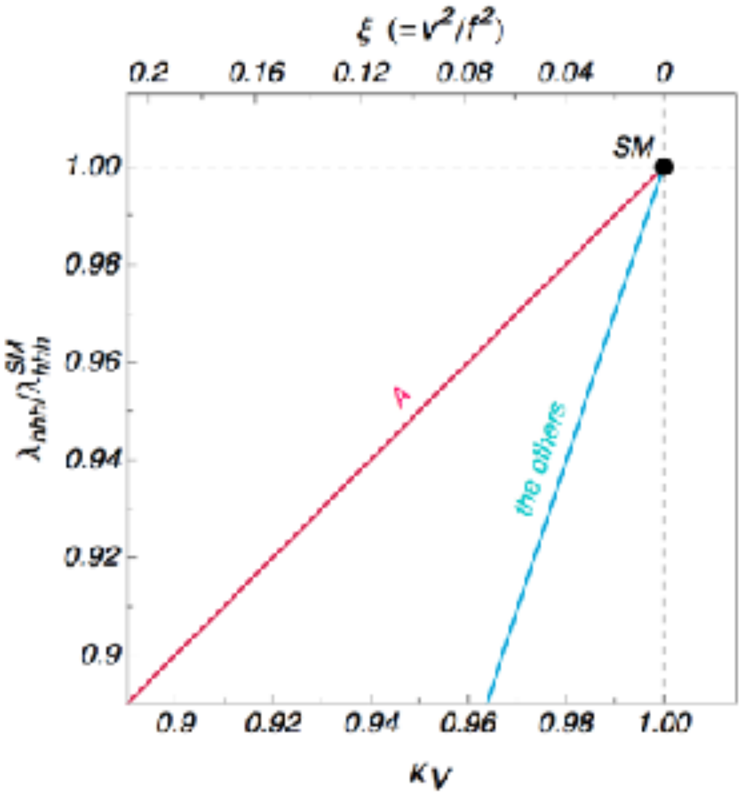


TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. ?, where C, E and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_5^t \to 0$.

Label	Model	κ_V	κ_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
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_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_5	-4ξ
D	$MCHM_{5\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
E	$MCHM_{[illegible]}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	$MCHM_{[illegible]}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\sqrt{1-\xi}$	F_5	$-\xi$
G	$MCHM_{10\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
B	$MCHM_{10\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	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'	$MCHM_{[illegible]}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
B	$MCHM_{14\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
I, I'	$MCHM_{14\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ

arXiv 1410.8413

Composite Higgs: Reach

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}	2.9%
$e^-_R e^+_L$	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%

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

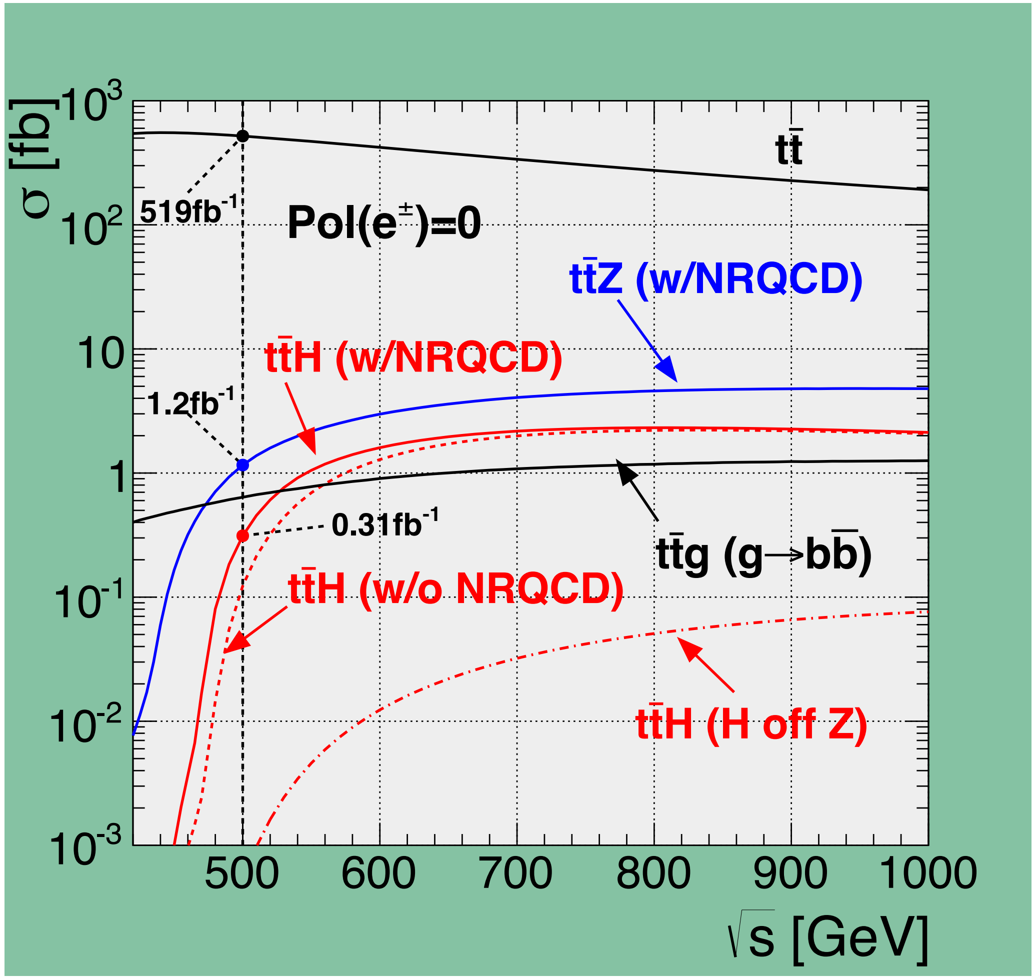
$\Lambda > 2.6\,\mathrm{TeV}$ (c_H =1)

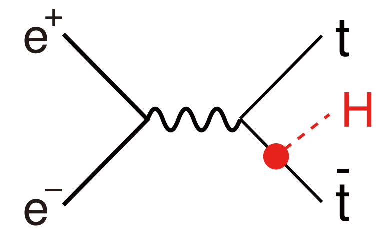
"r_H< 0.076 am"

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

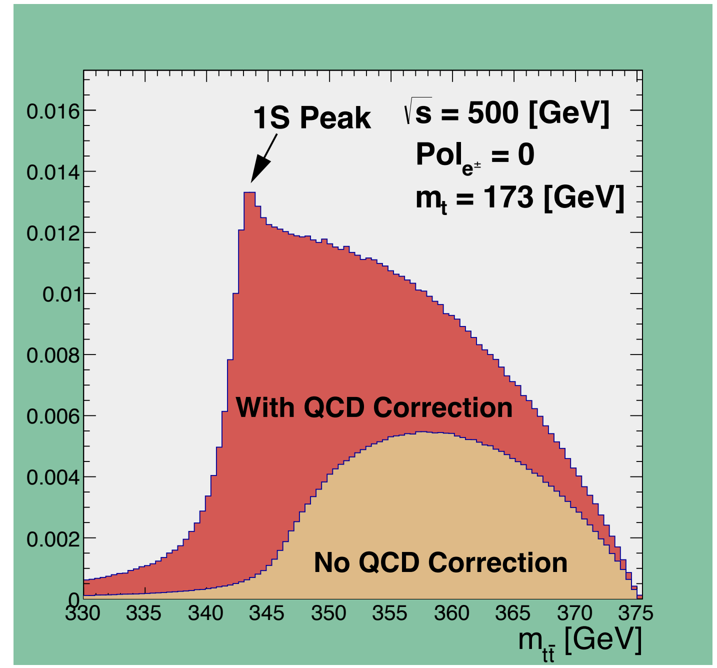
Top Yukawa Coupling

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

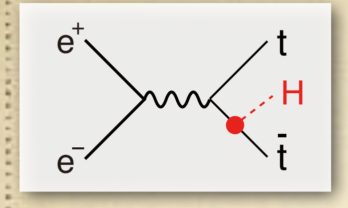
DBD Full Simulation

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

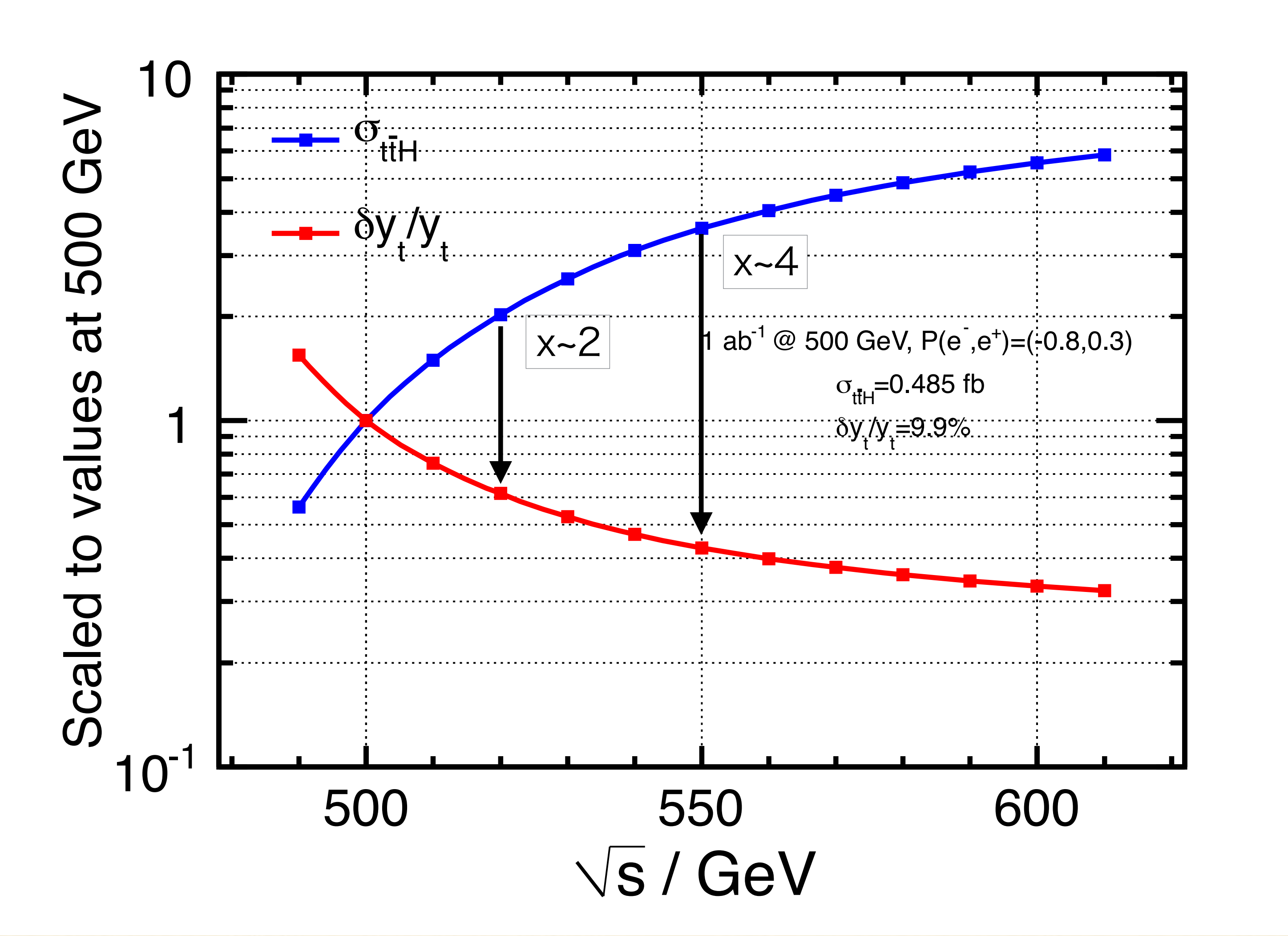
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

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

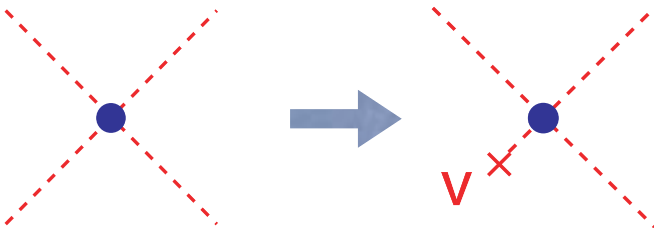
Slight increase of E_{max} is very beneficial!

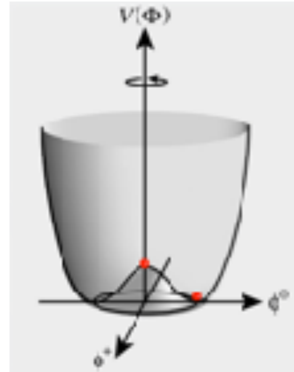
Higgs Self-Coupling

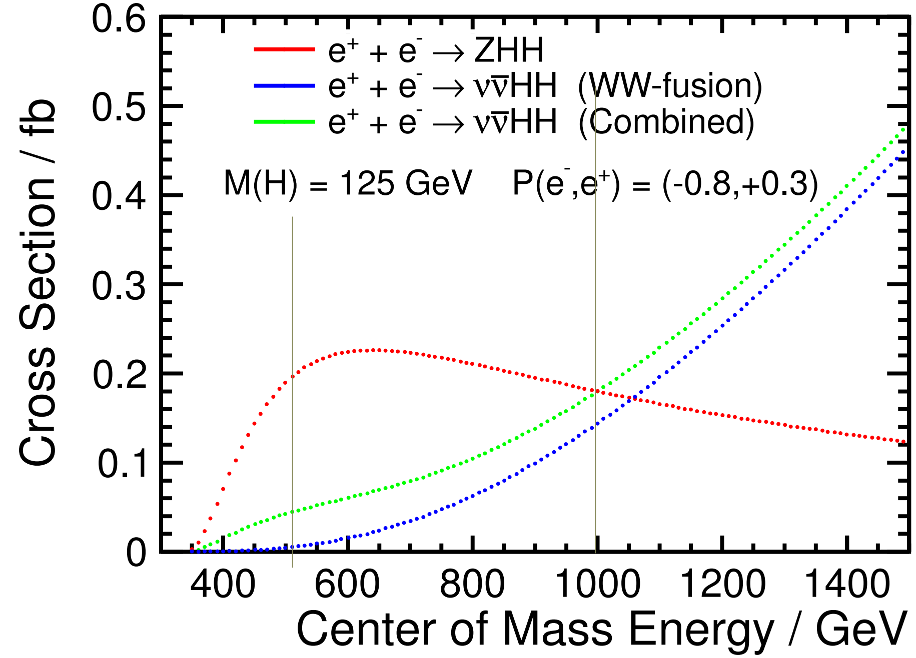
This could be the only coupling with significant deviation from the SM!

Higgs Self-Coupling

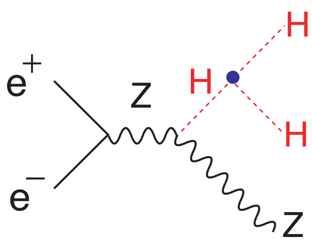
The ***Higgs cubic self-coupling*** is at the heart of EWSB, so should be measured in its own right!

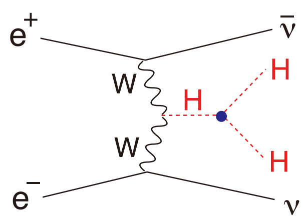






There are ***two ways to measure it*** at ILC





Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams that dilute the self-coupling contribution!***

ILC

	500 GeV	+ 1 TeV
Snowmas	46%	13%
H20	**26%**	10%

H20 arXiv: 1506.07870

J. Tian, LC-REP-2013-003

C. Dürig @ ALCW16

M. Kurata, LC-REP-2014-025

CLIC

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

(arXiv: 1307.5288)

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

Is EW Baryogenesis Posssible?

The answer is no in the Standard Model.

Strong 1st order EW phase transition

to bring the universe out of equilibrium

→ Large deviation of Higgs cubic self-coupling

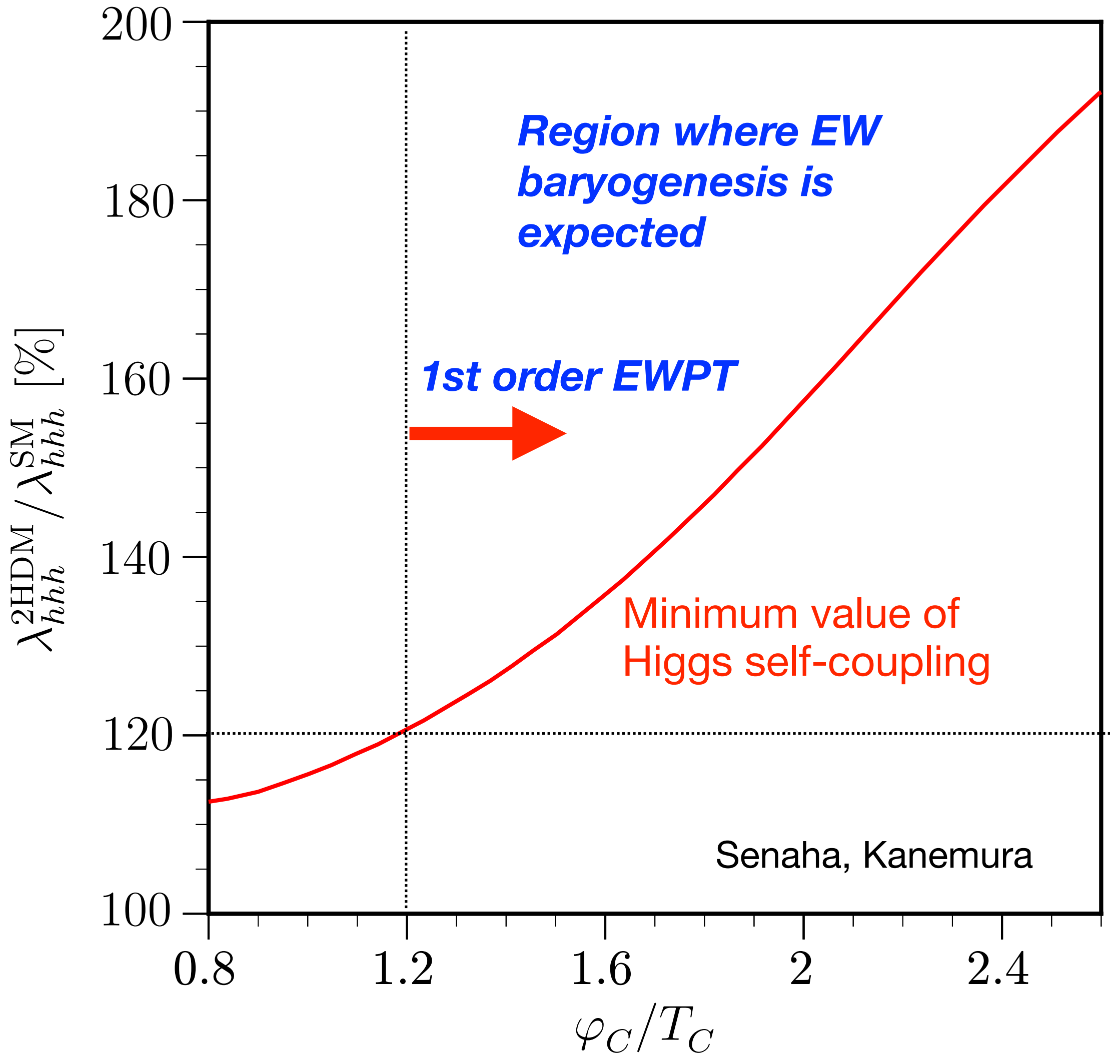
Enough CPV (δ_{KM} too small)

→ CPV source in Higgs sector

→ Extended Higgs sector

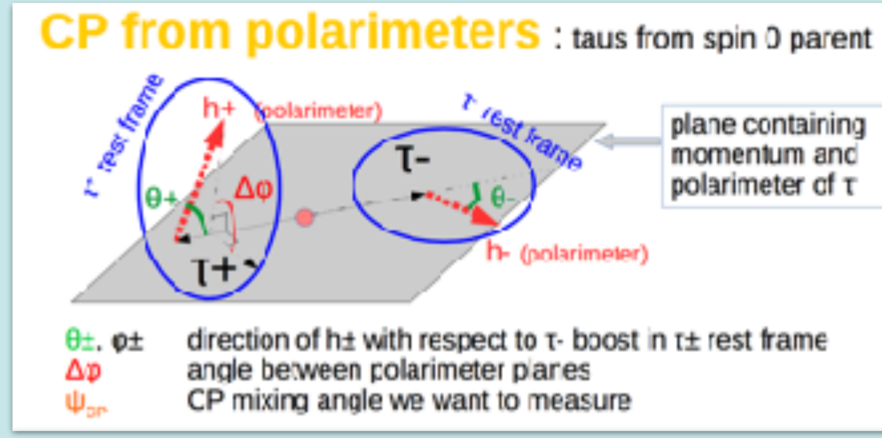
Electroweak Baryogenesis?

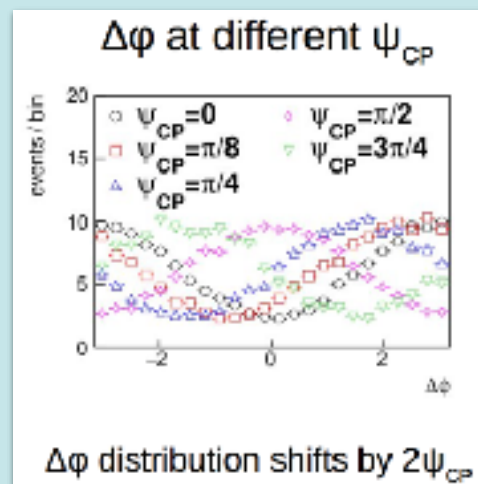
Example: ***2 Higgs Doublet Model (2HDM)***



Measuring CP in H → τ⁺τ⁻ at ILC

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





2ab⁻¹ @ 250 GeV

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

D. Jeans, LCWS16

Self-coupling Measurement at ILC

Constructive interference between signal and BG diagrams @500GeV

→ ***if +100% deviation, then Δλ/λ=14% expected!***

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

Strong 1st Order Phase Transition

Example: ***Doublet-Singlet Mixing Model (HSM)***

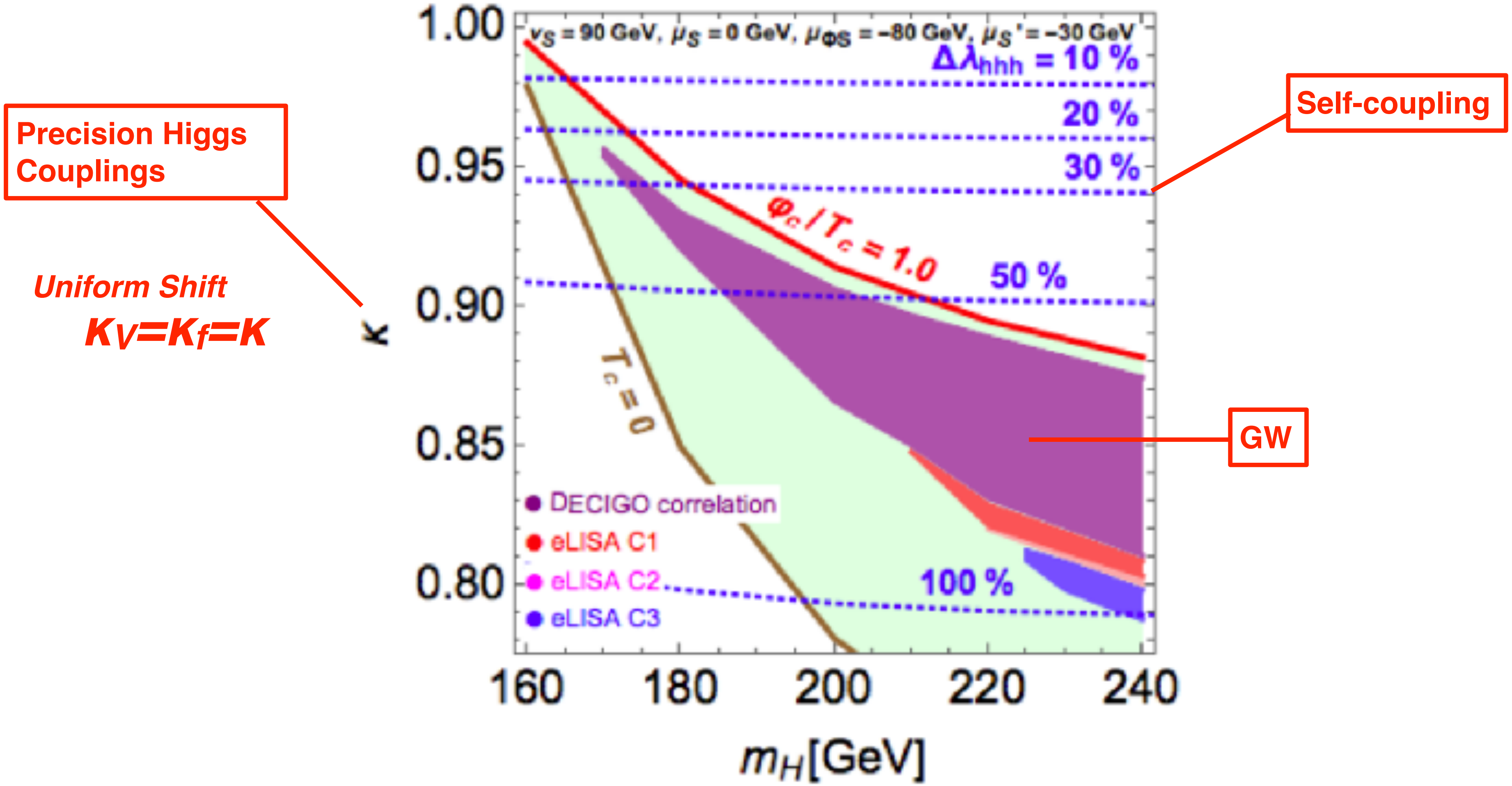
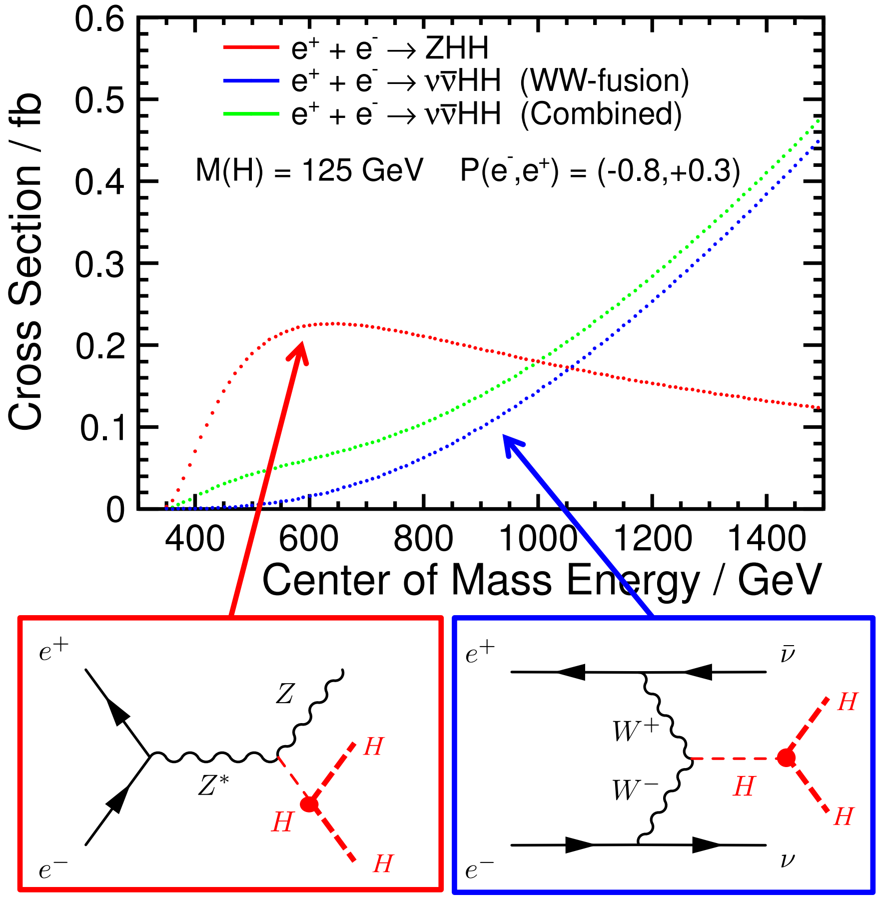


FIG. 2: The detectability of GWs and the contours of the deviations in the hhh coupling $\Delta\lambda_{hhh}$ in the m_H-κ plane. The projected region of a higher sensitive detector design is overlaid with that of weaker one. The region which satisfies both $\varphi_c/T_c > 1$ and $T_c > 0$ is also shown for a reference. The input parameters and legends are same as in Fig. 1

Fuyuno, Senaha: arXiv: 1406.0433
Hashino, Kakizaki, Kanemura, Matsui, Ko: arXiv 1609.00297

Direct Measurement

Cross section vs CM energy (e+e-)



Diagrams with triple-Higgs coupling

Expected precision based on **full detector simulation** studies:

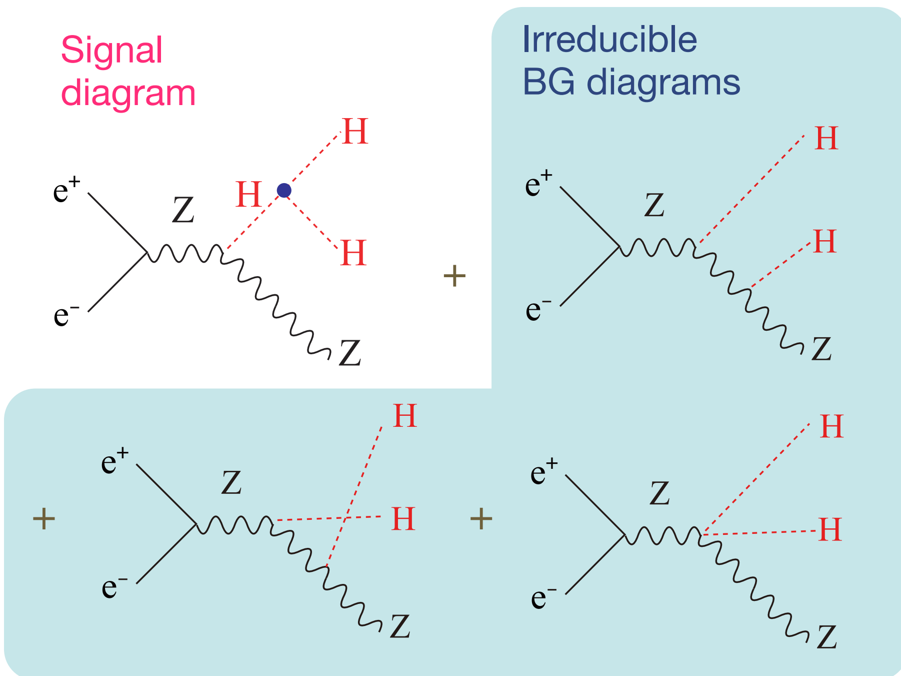
ILC	ILC
500 GeV, 4 ab-1 **δλ = 27%**	500 GeV, 4 ab-1 & 1 TeV, 8 ab-1 **δλ = 10%**

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*

The Problem : BG diagrams dilute self-coupling contribution

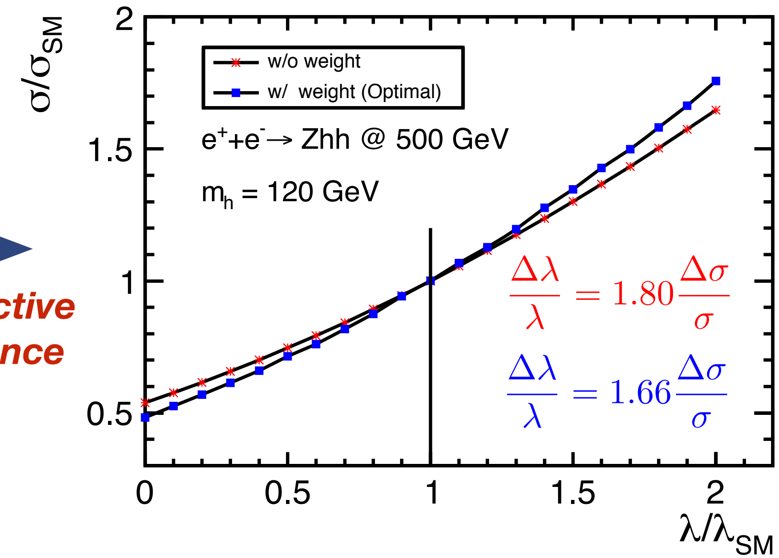


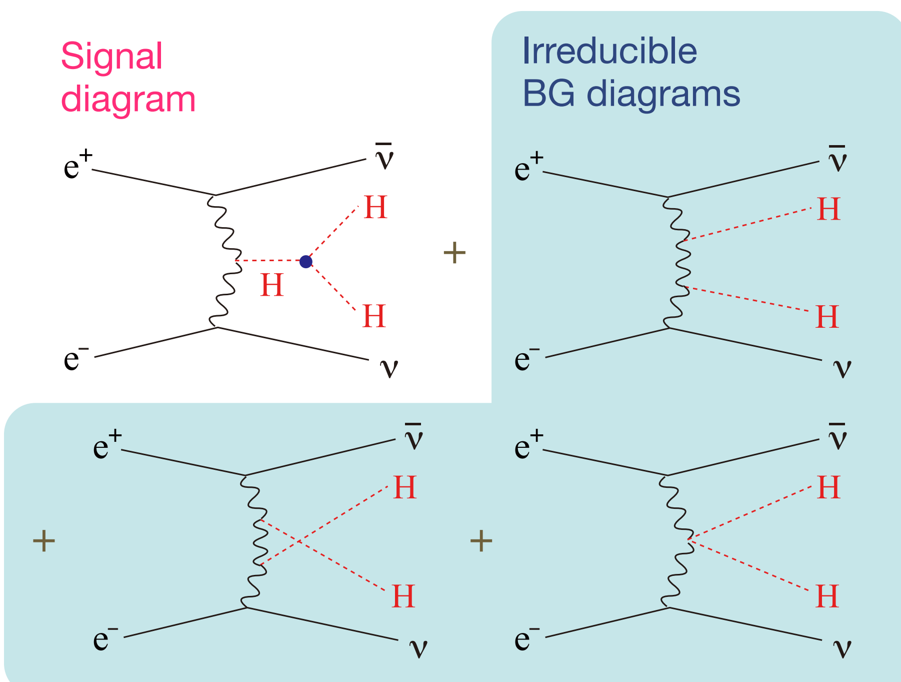
$$\sigma = \lambda^2 S + \lambda I + B$$

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

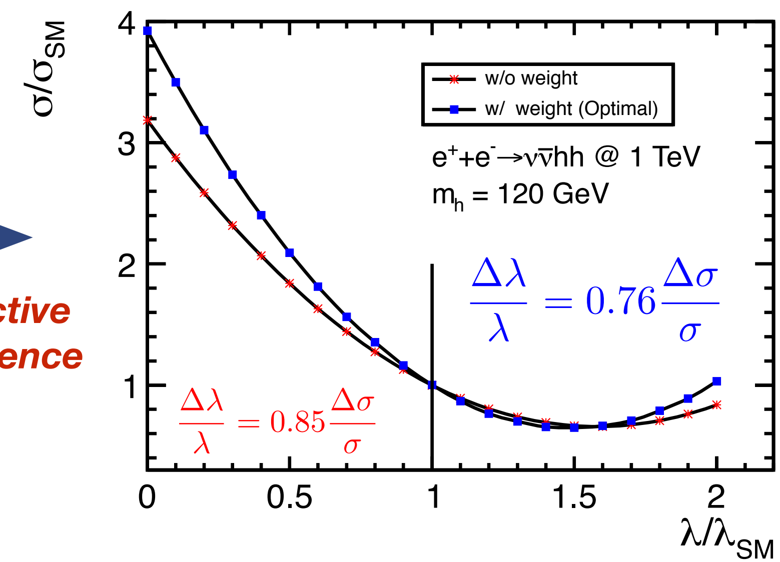
F=0.5 if no BG diagrams

Constructive interference





Destructive interference



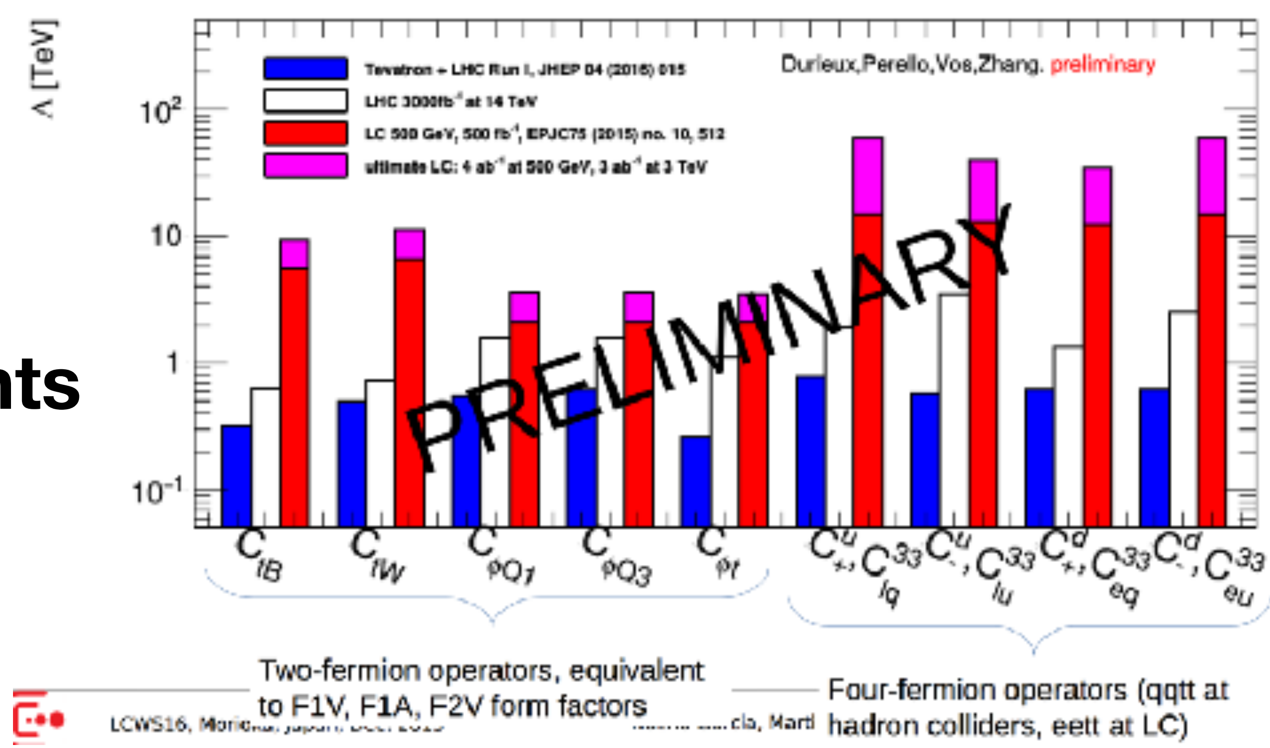
Junping Tian LC-REP-2013-003

Top

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)

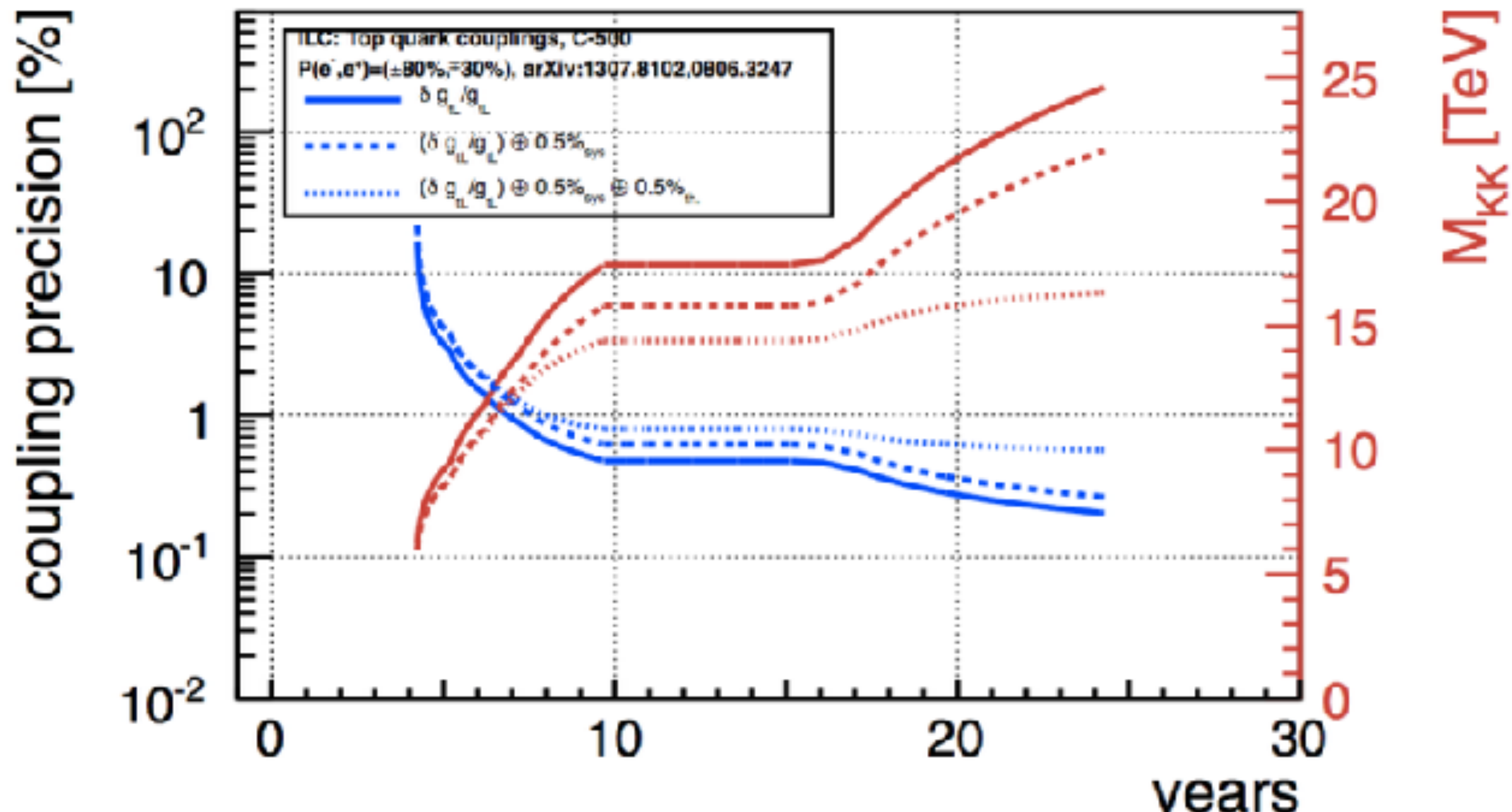
Form factors
→ EFT coefficients



Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 GeV for extreme scenarios)

=> Important guidance for e.g. 100 TeV pp-collider

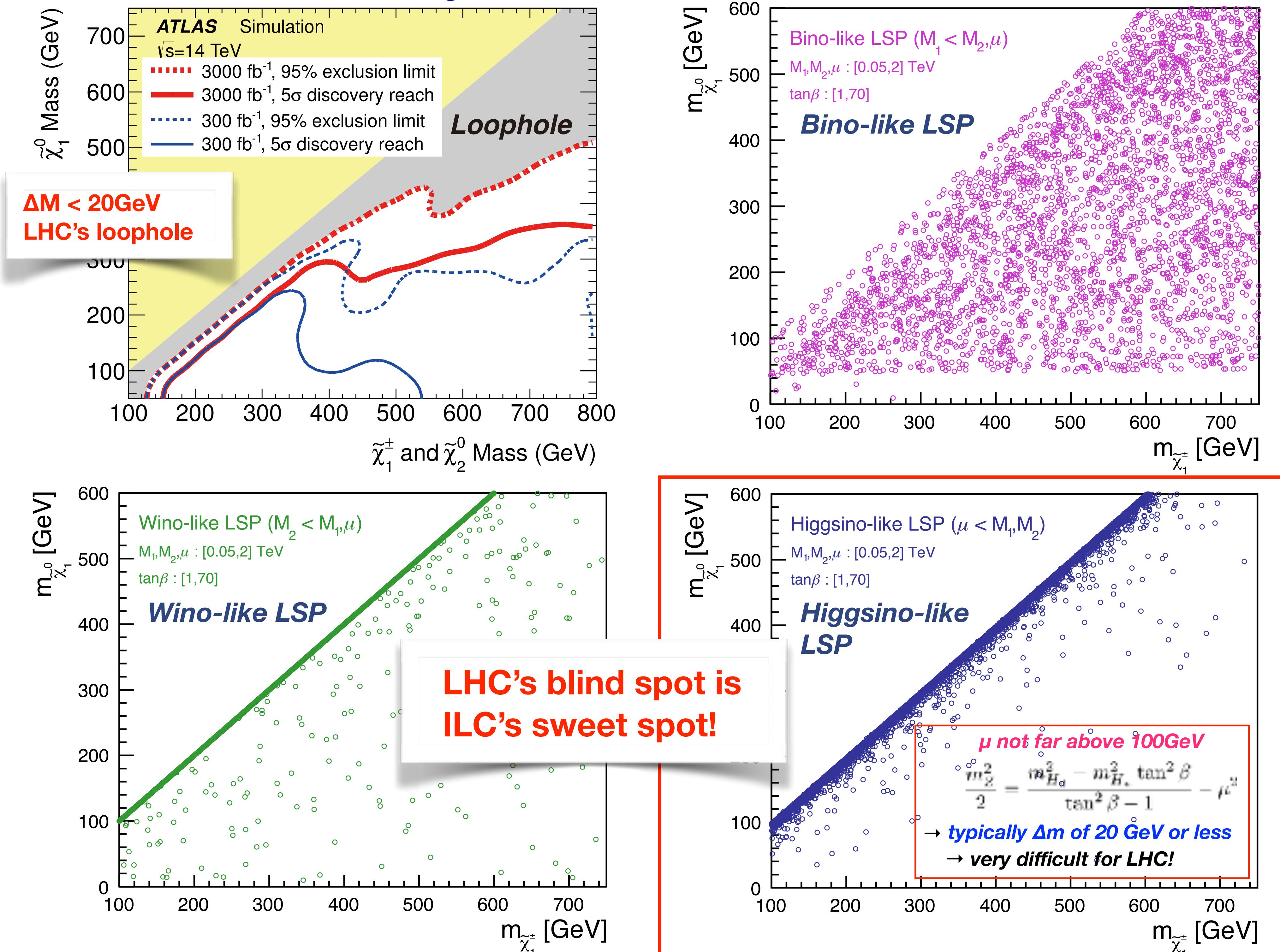
Direct Searches for New Particles

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 / Neutrarino Searches

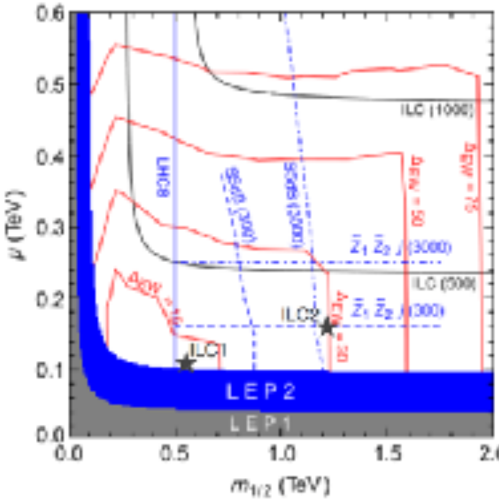


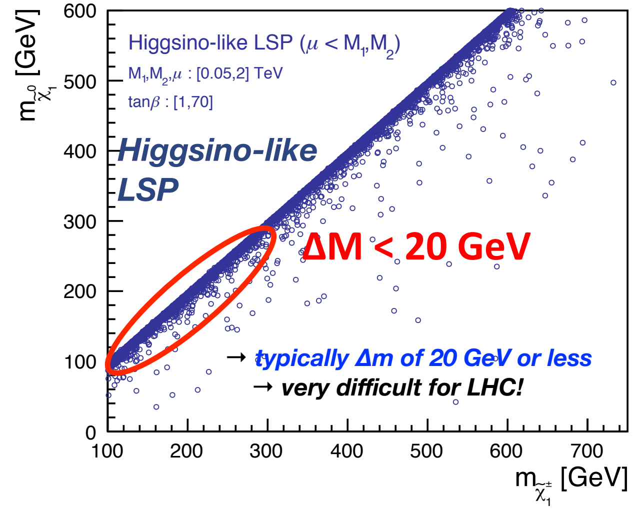
Higgsinos

Radiatively driven Natural SUSY

μ not far above 100GeV

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





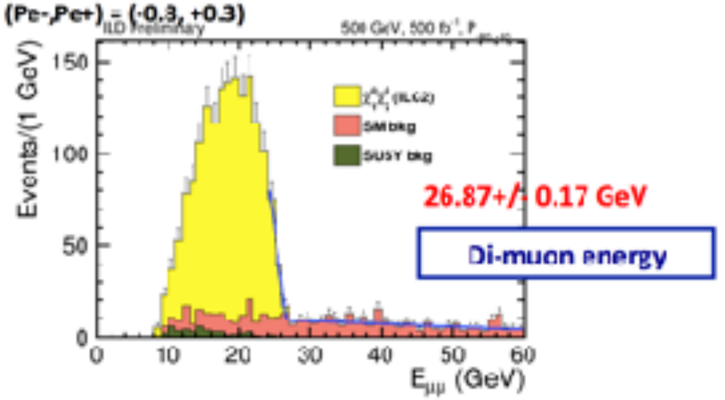
Chargino & Neutralino Productions

Neutralino mixed production with leptonic decay

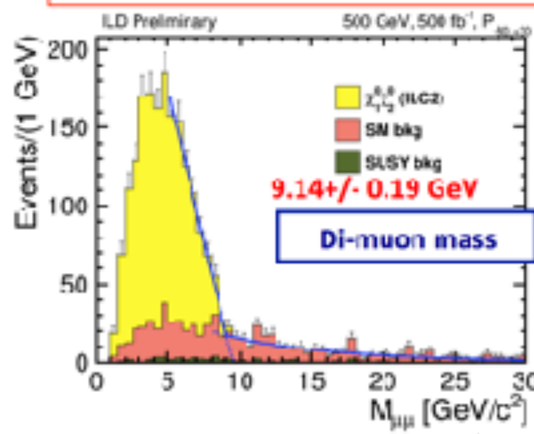
$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+\ell^-$

ILC2, μμ

(Pe-,Pe+) = (-0.3, +0.3)



Edge precisions assuming 500 fb^{-1}
0.5-1 %, for Eμμ , 2-2.5% for Mμμ

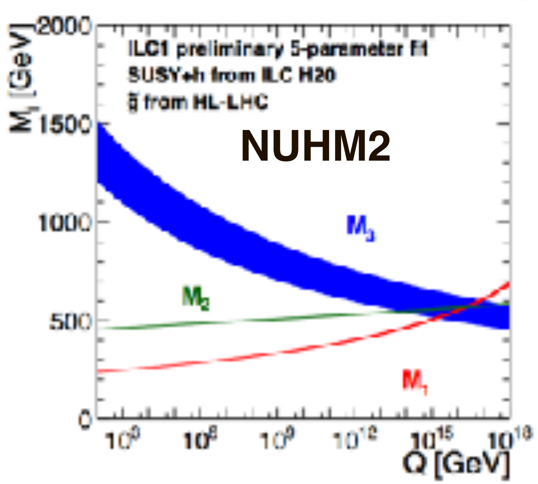


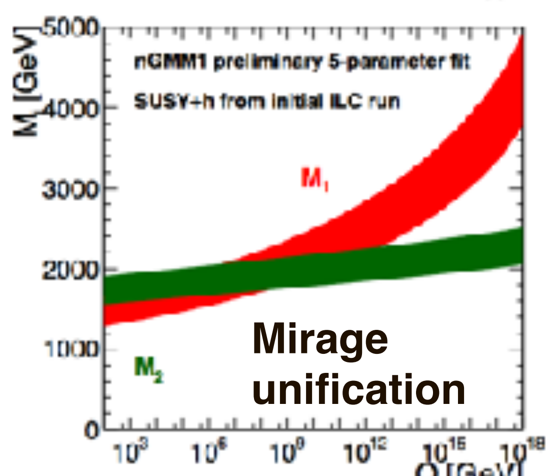
J. Yan : LCWS2016

End points → M_X

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

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





S. Lehtinen : LCWS2016

Power of Beam Polarization for Higgsino-Gaugino decomposition

Left: **Test of gaugino mass unification**

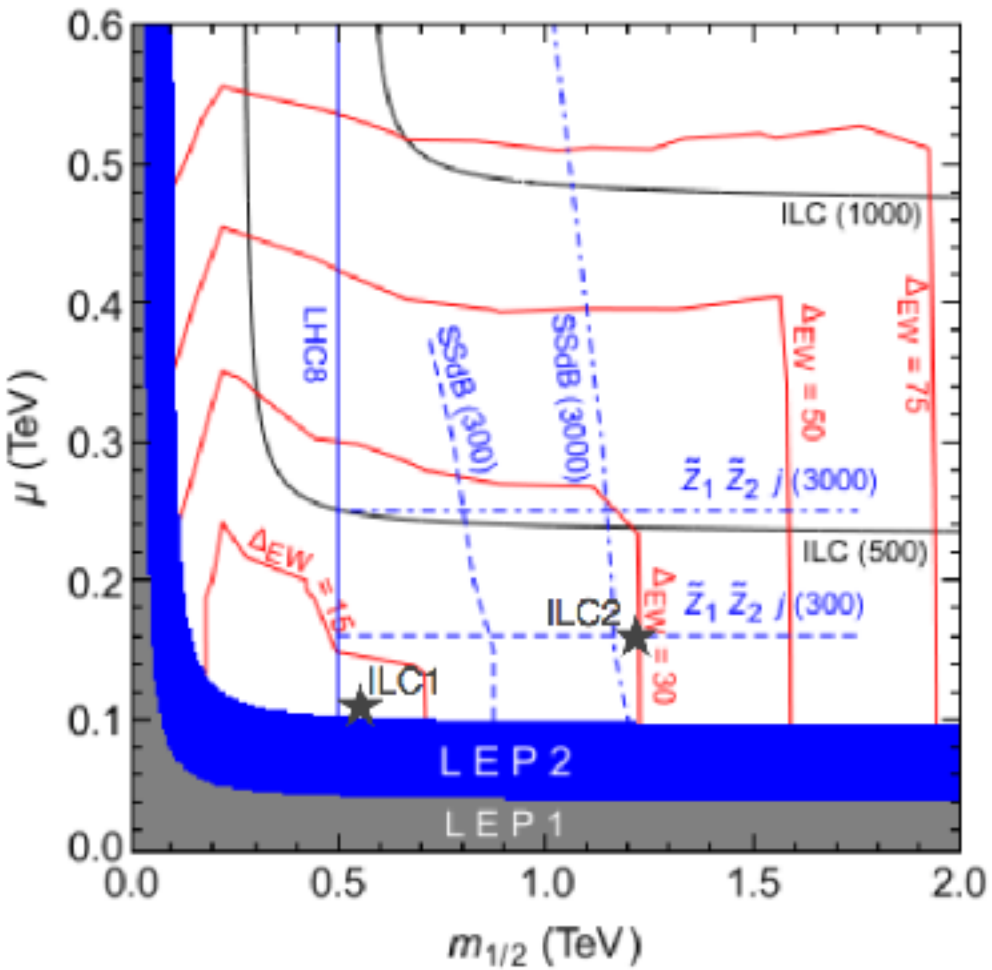
Right: **Select SUSY breaking models** (gravity mediated SUSY breaking vs mirage unification)

Higgsinos

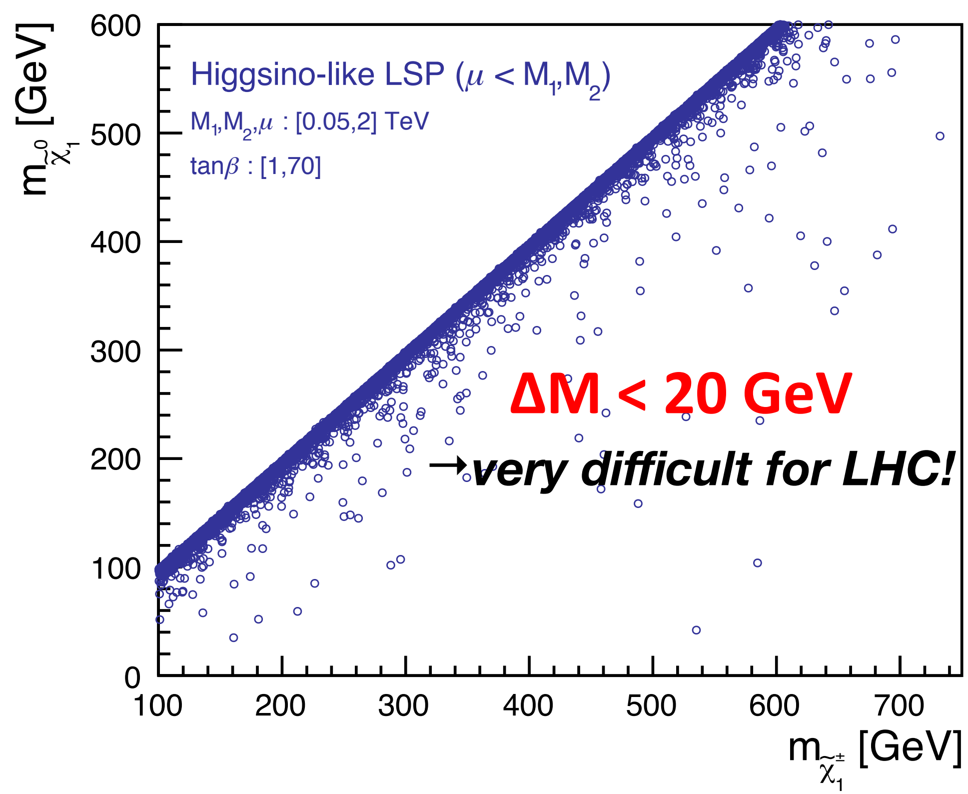
R**adiatively driven **N**atural **SUSY

μ not far above 100GeV

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



Higgsino-like LSP

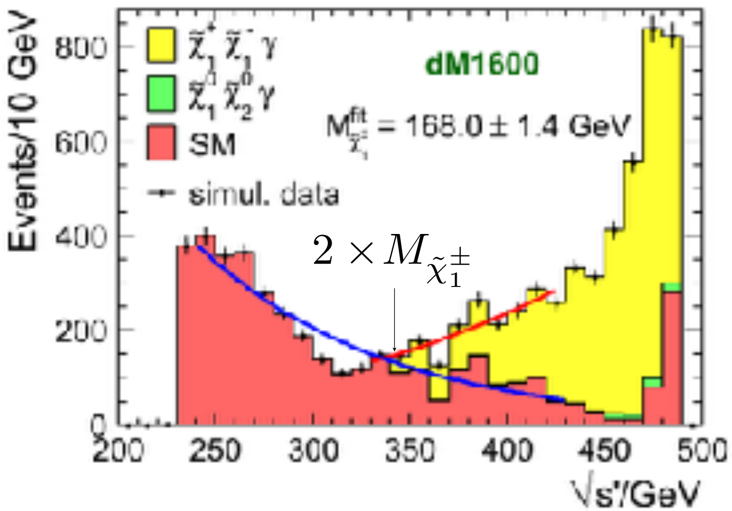


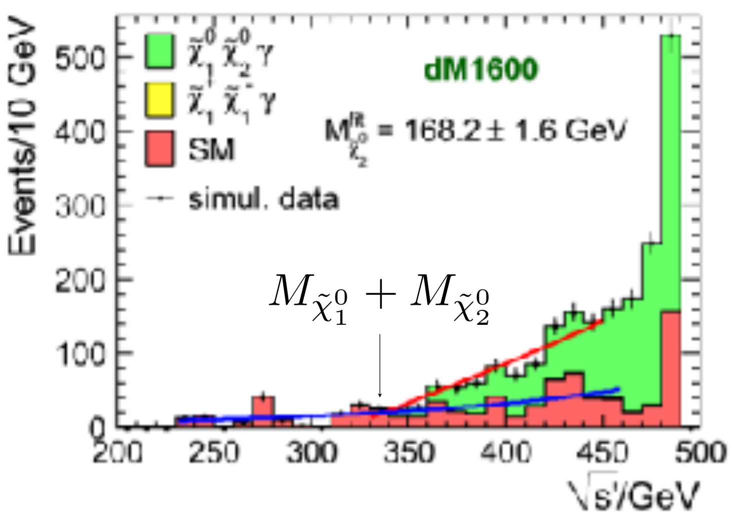
Higgsinos in Natural SUSY (ΔM<a few GeV)

ISR Tagging

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$

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

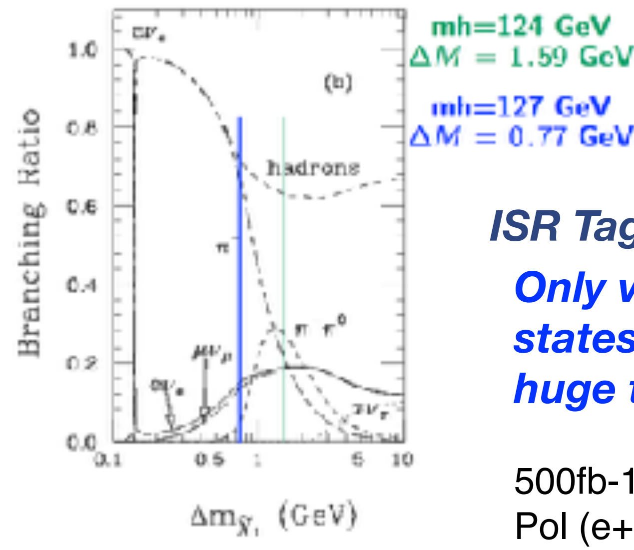


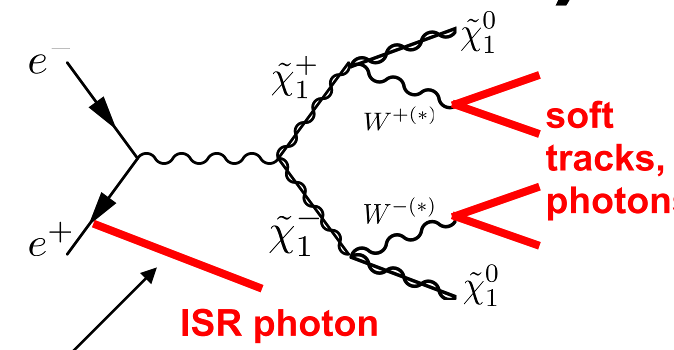


EPJC (2013) 73:2660

ILC as a Higgsino Factory

Ref: C.-H. Chen et al. hep-ph:9512230





ISR Tagging

Only very soft particles in the final states → Require a hard ISR to kill huge two-photon BG!

500fb-1 @ Ecm=500GeV
Pol (e+,e-) = (+0.3,-0.8) and (-0.3,+0.8)

dm1600

Mass Spectrum	
Particle	Mass (GeV)
h	124
$\tilde{\chi}_1^0$	164.17
$\tilde{\chi}_1^\pm$	165.77
$\tilde{\chi}_2^0$	166.87
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3 \times 10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.59$ GeV

$$\delta(\sigma \times BR) \simeq 3\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\mathrm{GeV}$$
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 70\,\mathrm{MeV}$$

dm770

Mass Spectrum	
Particle	Mass (GeV)
h	127
$\tilde{\chi}_1^0$	166.59
$\tilde{\chi}_1^\pm$	167.36
$\tilde{\chi}_2^0$	167.63
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3 \times 10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.77$ GeV

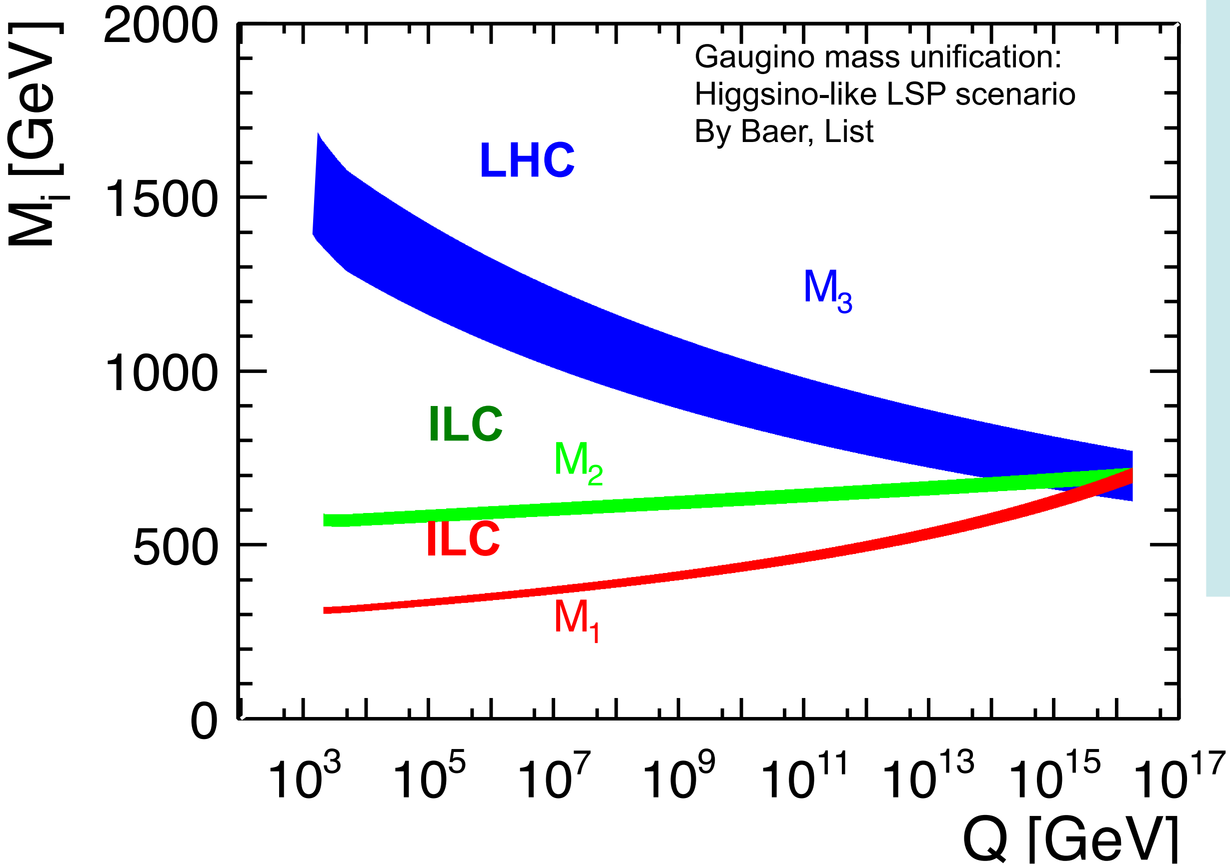
$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\mathrm{GeV}$$
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\mathrm{MeV}$$

GUT Scale Physics

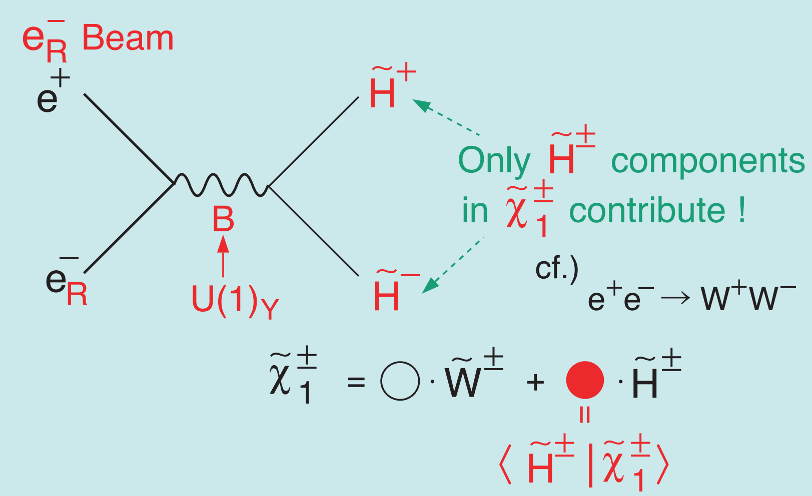
If we are lucky and the gluino is in LHC's mass reach and the lighter chargino and the neutralinos are in ILC's mass reach, ***we will be able to test the gaugino mass unification!***

LHC: gluino discovery
→ mass determination

ILC: Higgsino-like EWkino discovery
→ M1, M2 via mixing between Higgsino and Bino/Wino



Chargino decomposition



***Beam polarization is essential** to decompose the EWkinos to bino, wino, and higgsino and extract M_1 and M_2.*

WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

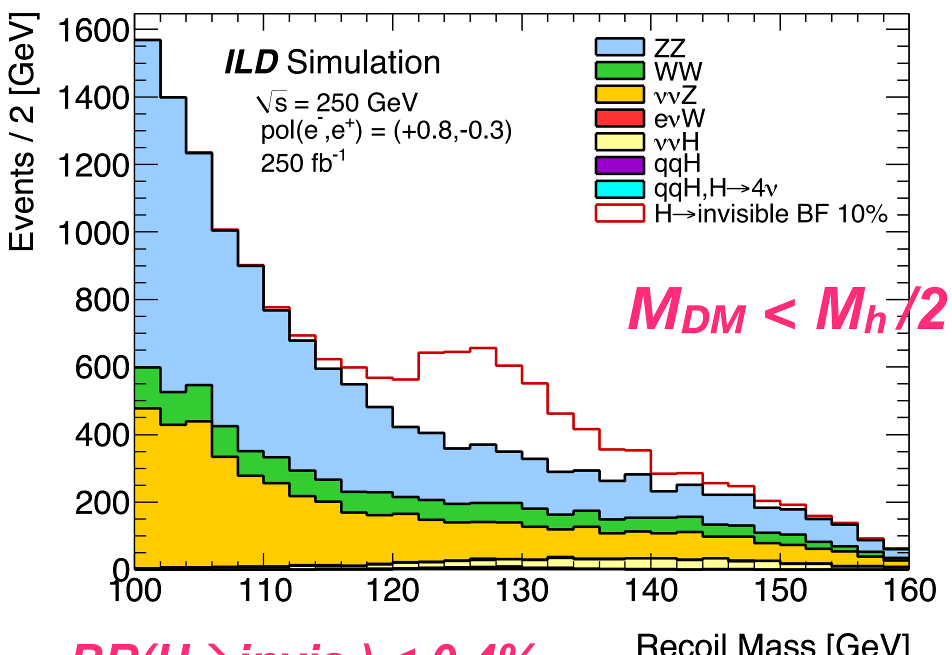
1. Decay of a new particle to Dark Matter (DM)

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)

2. Higgs Invisible Decay



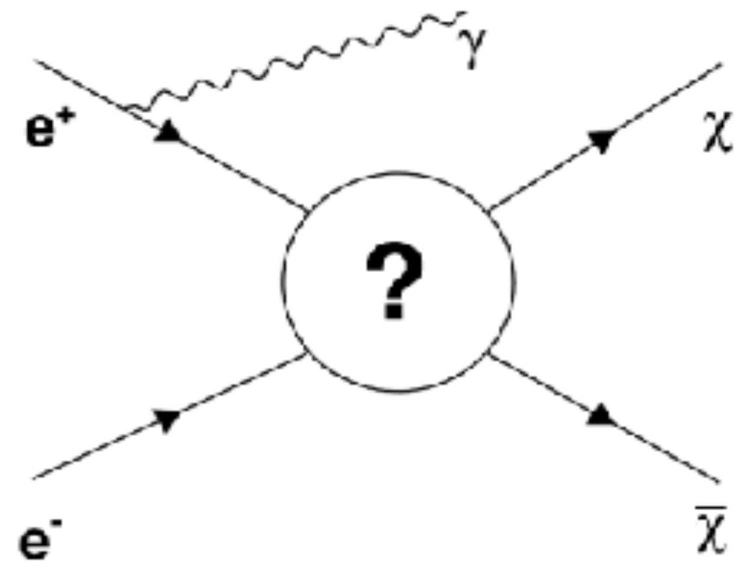
$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%

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

Possible to access BR_{inv} to 0.3%!

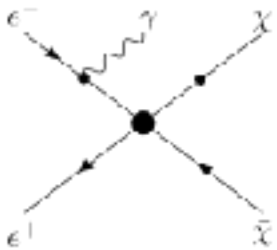
3. Mono-photon Search



→ ***M_{DM} reach ~ $E_{cm}/2$***

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

DM: Effective Operator Approach

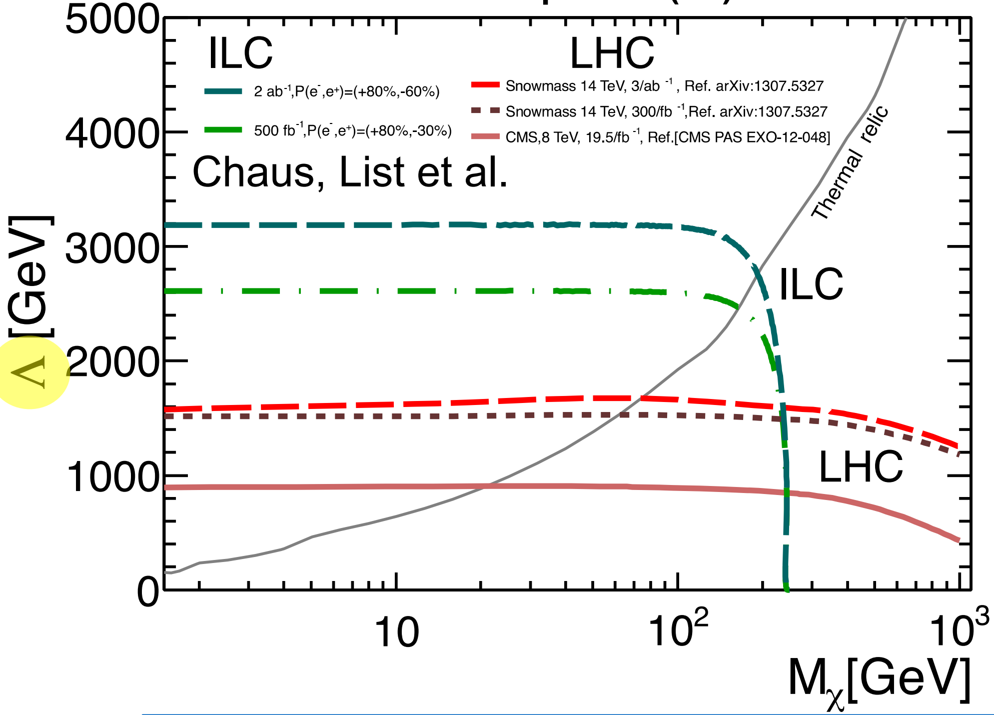


$$\mathcal{L}_{\mathrm{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

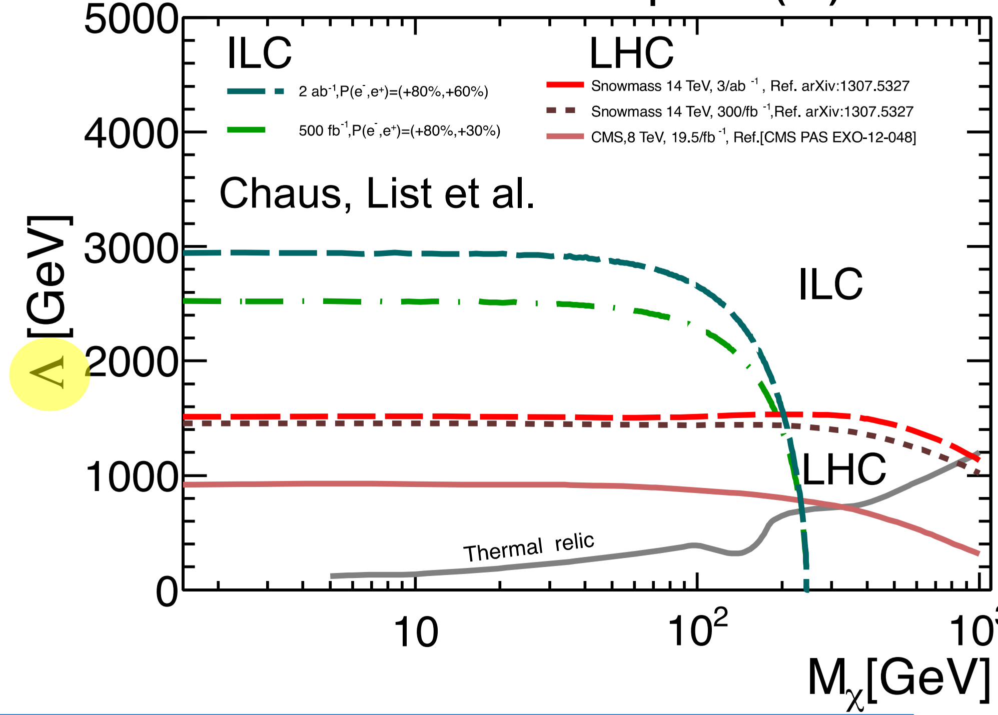
$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)$$

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

Vector operator (D5)



Axial-vector operator (D8)

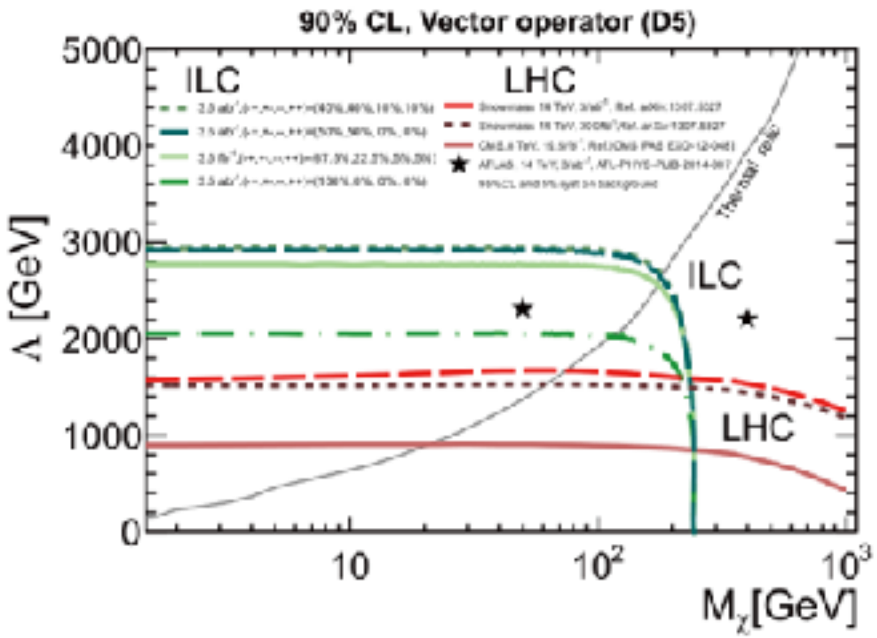


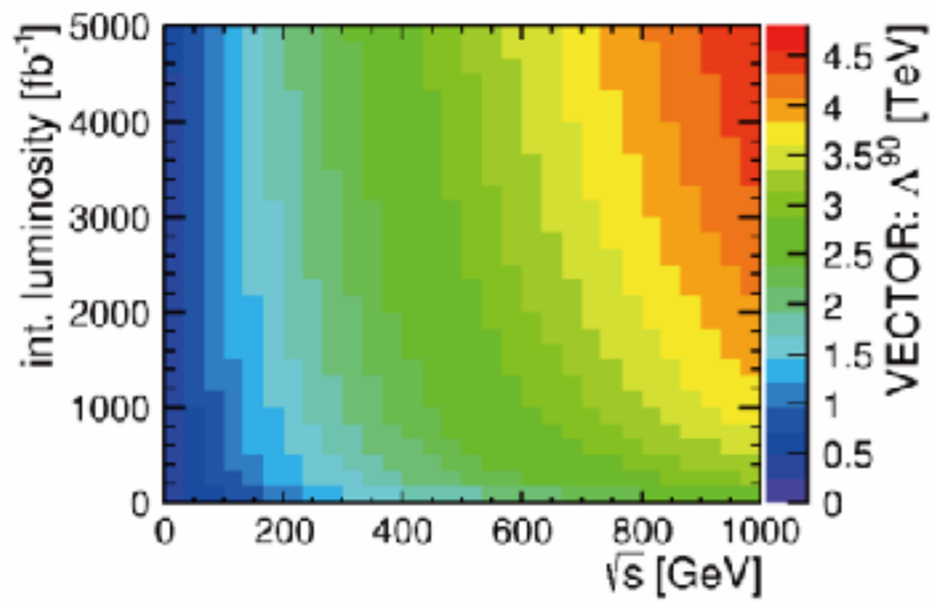
LHC sensitivity: Mediator mass up to Λ~1.5 TeV for **large DM mass**

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

LHC-ILC synergy!

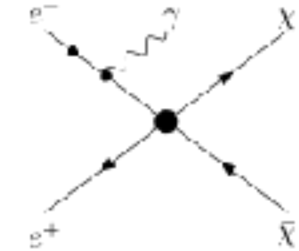
DM: Effective Operator Approach





T. Tanabe, LCWS16

Previous result



LHC-ILC Comparison [A. Chaus]

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

Example: Vector operator

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

LHC-ILC synergy!

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

Slepton decays to DM with small mass differences

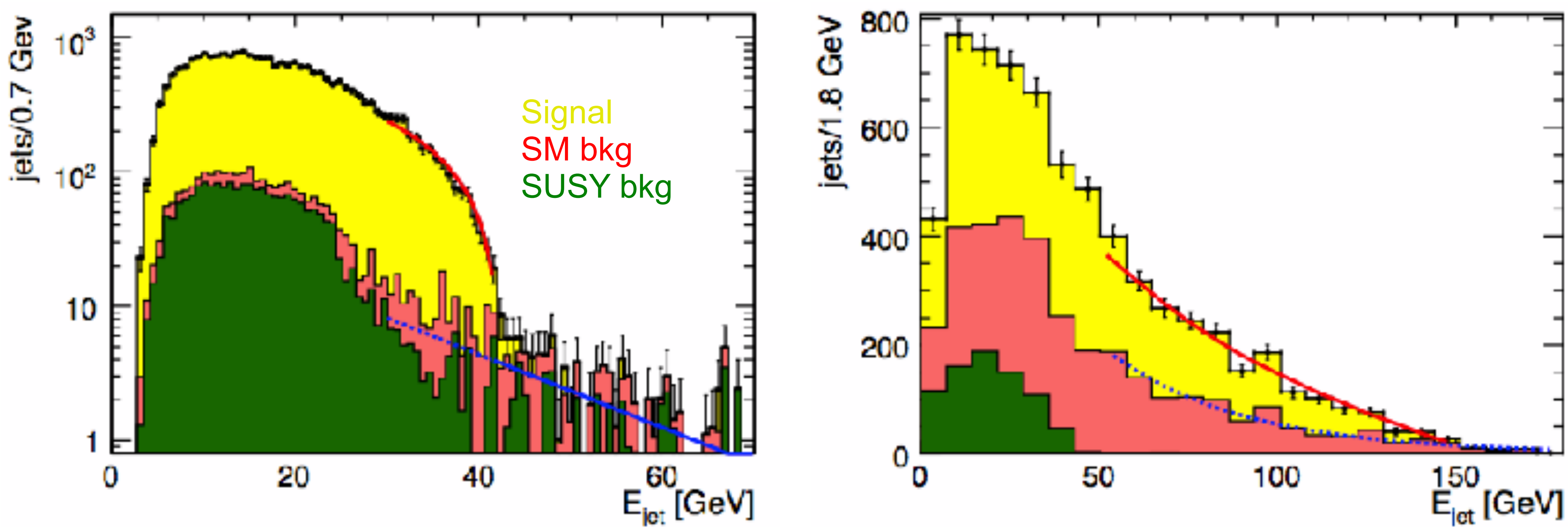
Study of stau pair production at the ILC

Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

$$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-) = 158 \text{ fb}$$
$$\sigma(e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-) = 18 \text{ fb}$$

Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



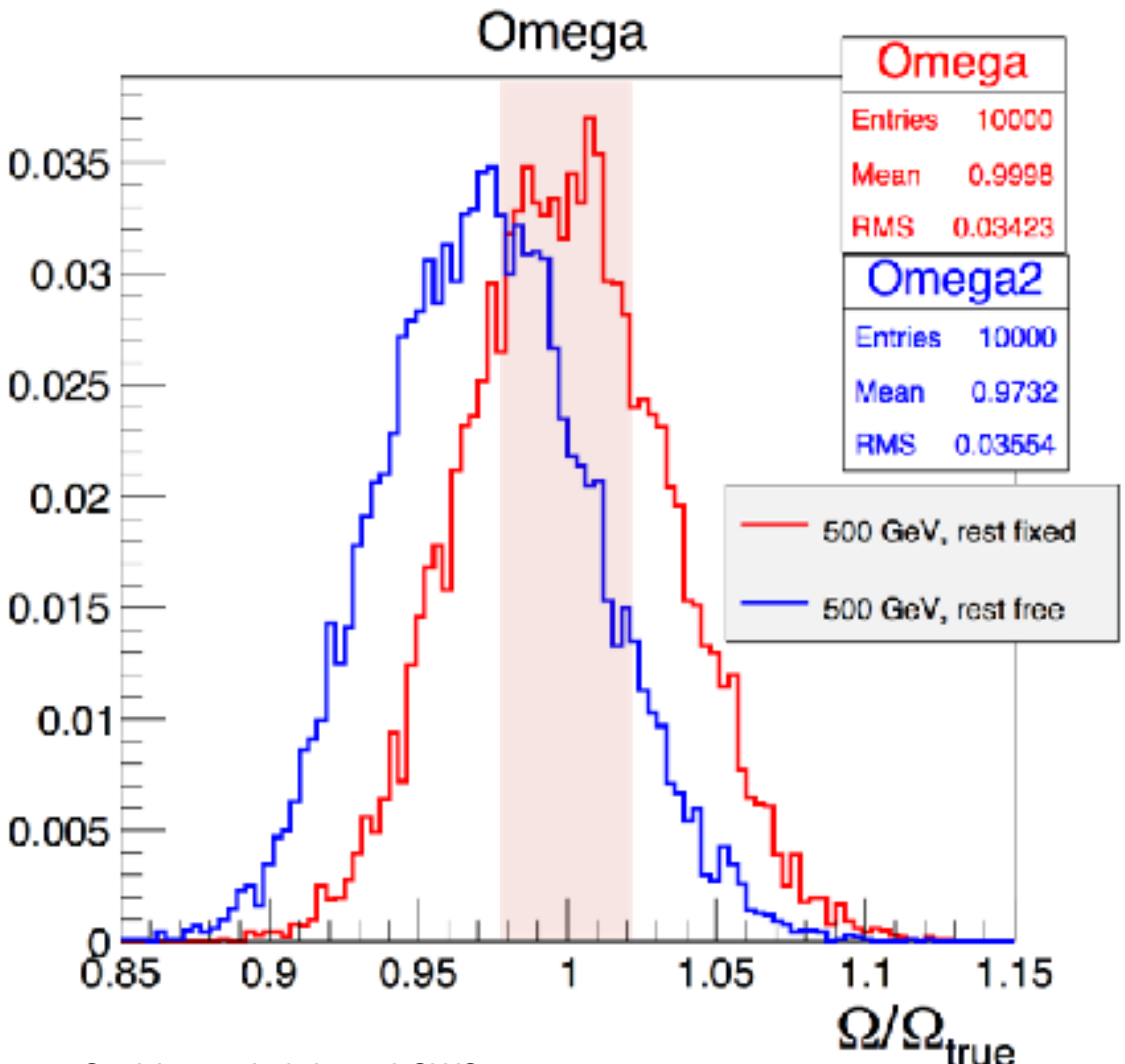
√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)

Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

DM Relic Abundance

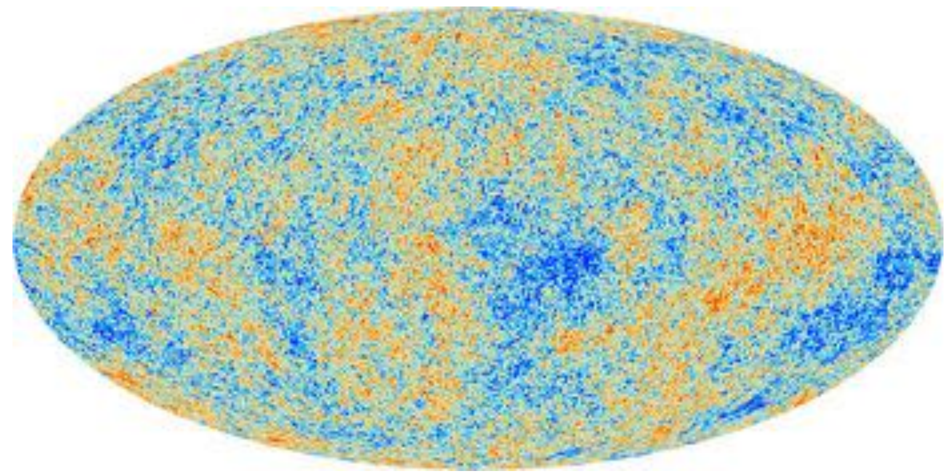
WMAP/Planck (68% CL)

$$\Omega_c h^2 = 0.1196 \pm 0.0027$$



Suvi-Leena Lehtinen, LCWS 2015

ESA/Planck



Once a DM candidate is discovered, crucial to check the consistency with the measured DM relic abundance.

Mass and couplings measured at ILC
→ DM relic density to compare with the CMB data