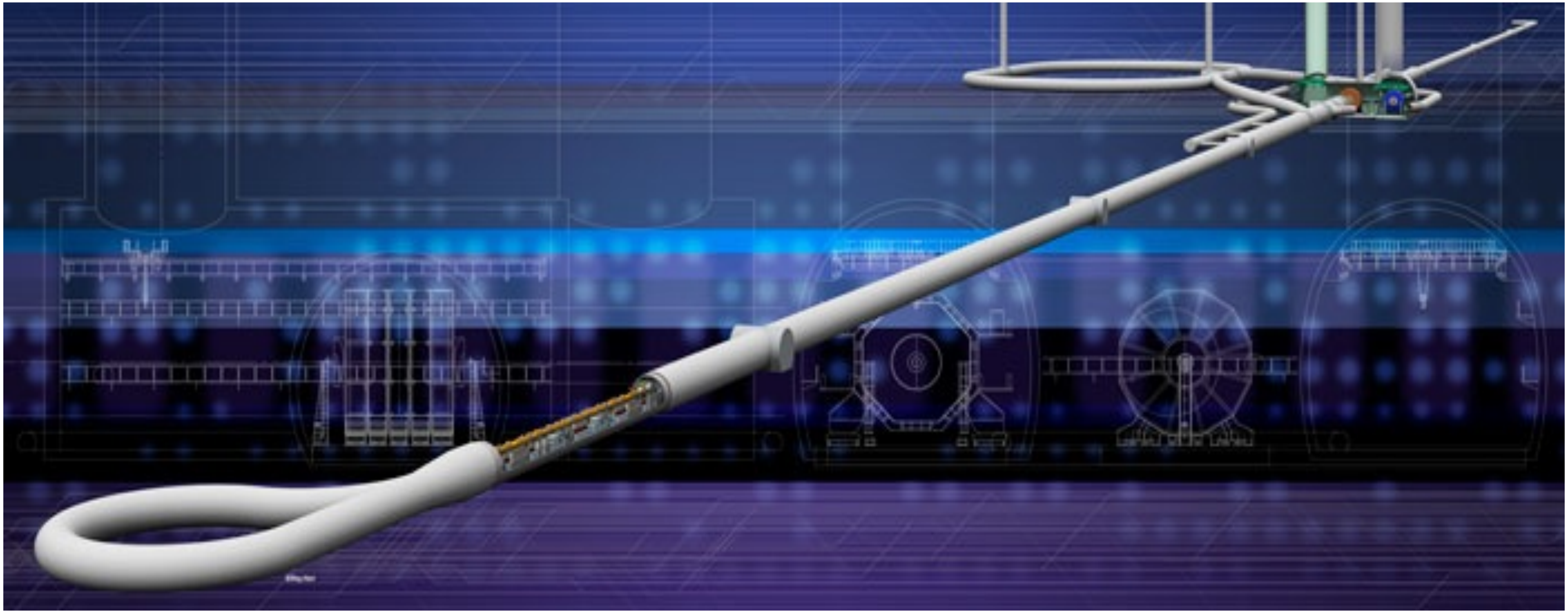
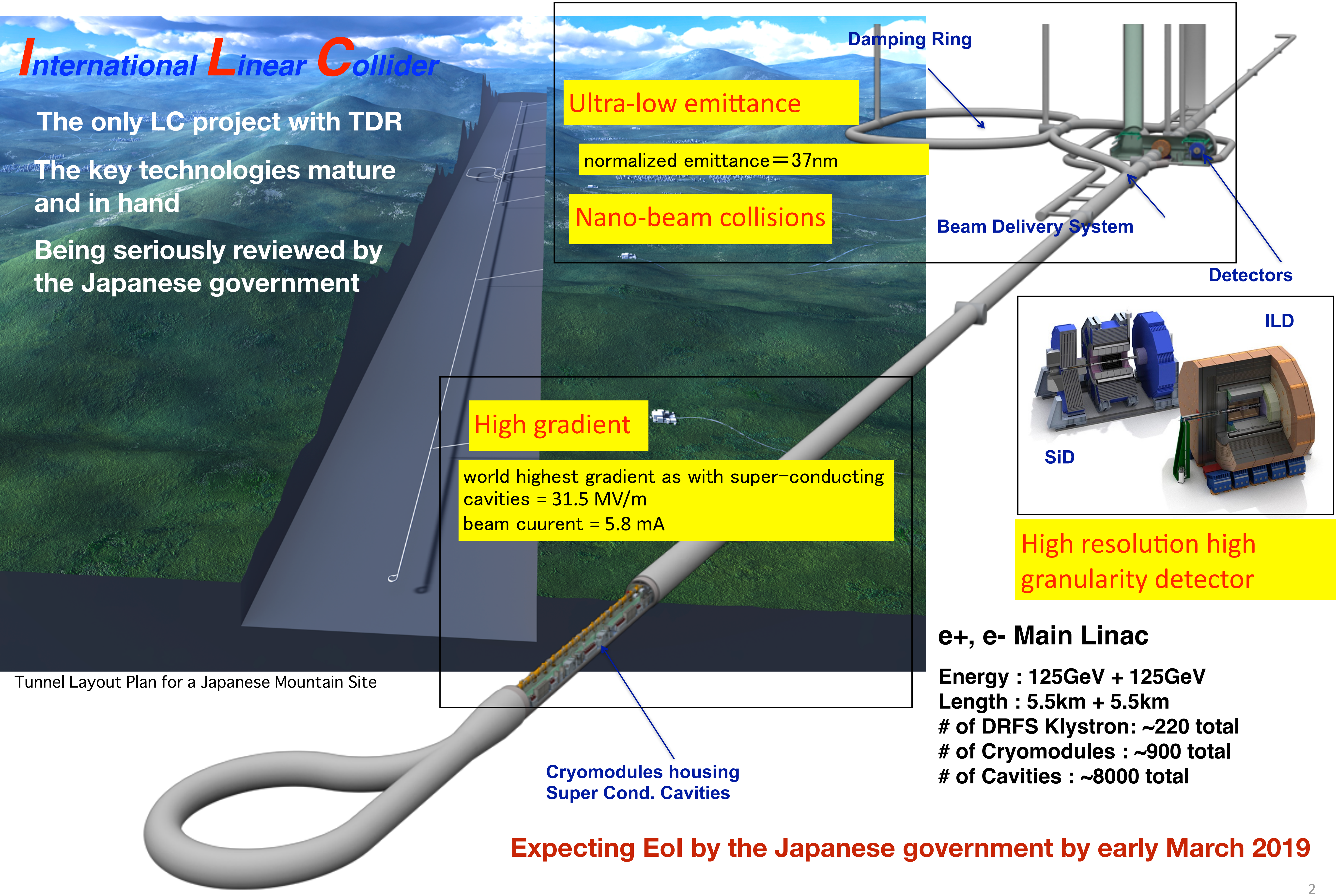
Physics at the ILC



Keisuke Fujii
KEK

Bird's Eye View of the ILC Accelerator



International Linear Collider

The only LC project with TDR

The key technologies mature and in hand

Being seriously reviewed by the Japanese government

Tunnel Layout Plan for a Japanese Mountain Site

Ultra-low emittance

normalized emittance＝37nm

Nano-beam collisions

High gradient

world highest gradient as with super−conducting cavities = 31.5 MV/m

beam cuurent = 5.8 mA

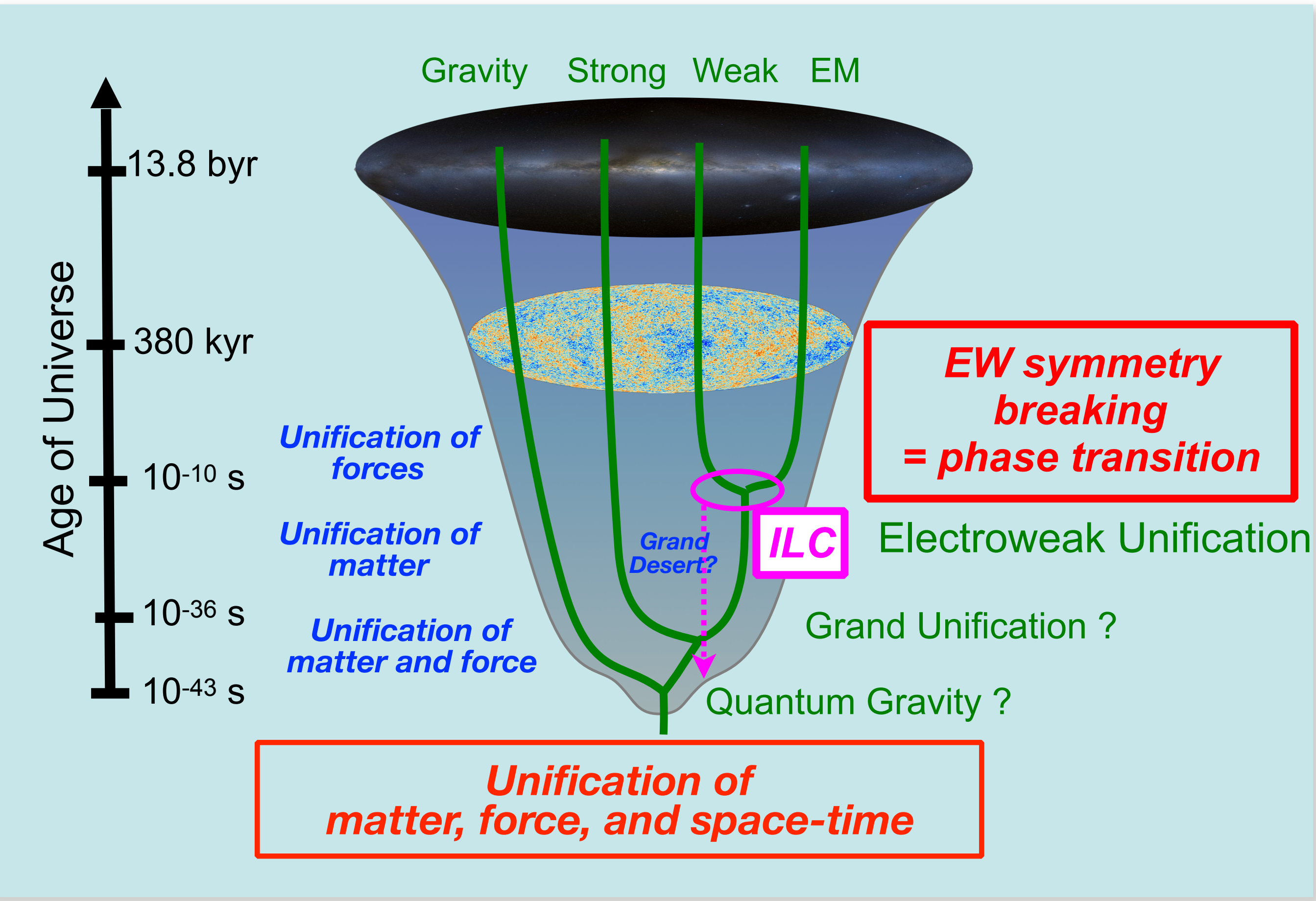
High resolution high granularity detector

e+, e- Main Linac

Energy : 125GeV + 125GeV
Length : 5.5km + 5.5km
# of DRFS Klystron: ~220 total
# of Cryomodules : ~900 total
# of Cavities : ~8000 total

Expecting EoI by the Japanese government by early March 2019

Towards Ultimate Unification



Our goal is to go back in time to the moment of creation (Planck Scale), when everything, matter, force, and space-time, was conceived to be unified.

Standard Model (SM)
=Summary of Our Current Understanding

Gauge Symmetry = SU(3)xSU(2)xU(1)

Matter Fields = Quarks & Leptons (3 Gen.)

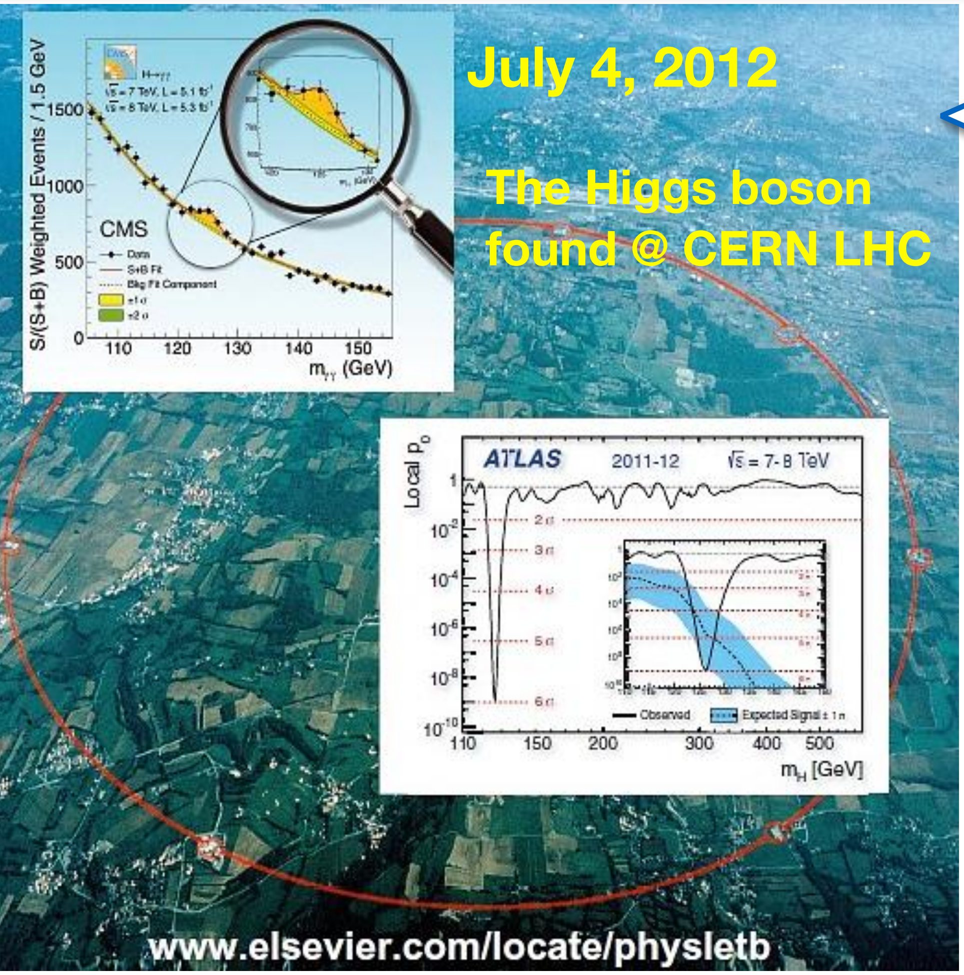
1995 Top discovery @ FNAL Tevatron
→3 generations of matter fields completed

Force Fields = Gauge Fields (γ,W/Z, g)

1983 W/Z discovery @ CERN SPPS
→ Gauge bosons for the 3 forces found

Symmetry Breaking Field = **Higgs Field (H)**

→ **2012 found @ LHC**: SM completed



July 4, 2012

The Higgs boson found @ CERN LHC

www.elsevier.com/locate/physletb

Beyond the SM

The SM has been extremely successful.

→ Yet, there remain a lot of mysteries (Dark Matter, Baryon Number Asymmetry, Neutrino Mass/Mixing, Dark Energy, ..)

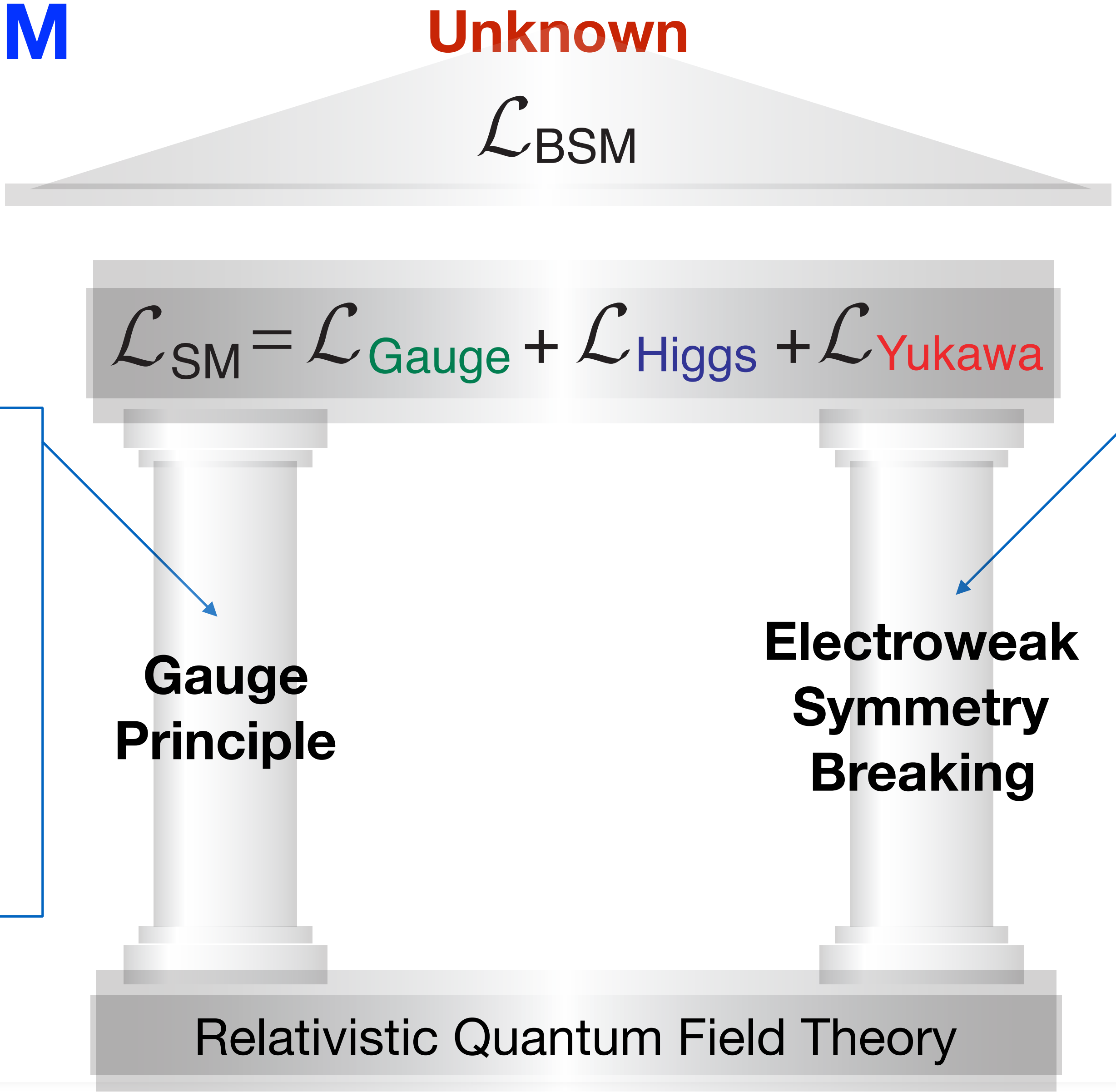
→ Start of new voyage to the Plank Scale: From the EW scale, there seems to be still a long way to go.

Why is the EW scale so important?

Why is the EW scale so important?

Mystery of the Higgs field filling the universe

2 Pillars of SM



Unknown

$\mathcal{L}_{\text{BSM}}$

$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$

Gauge Principle

Electroweak Symmetry Breaking

Relativistic Quantum Field Theory

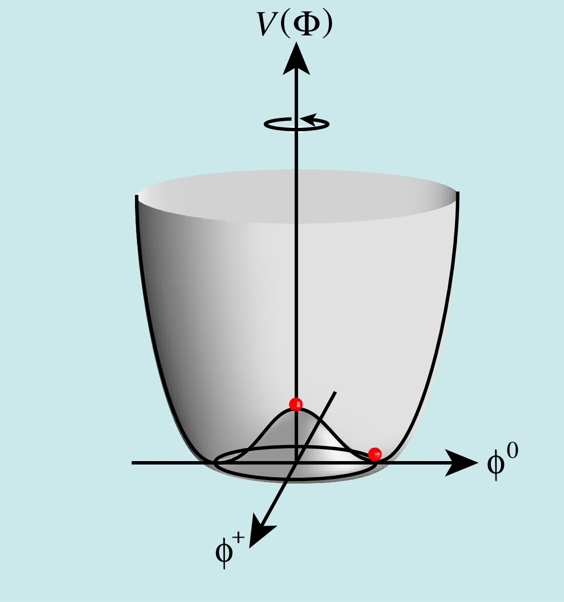
Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

Vacuum filled with weak charge (evidence: H125)

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

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

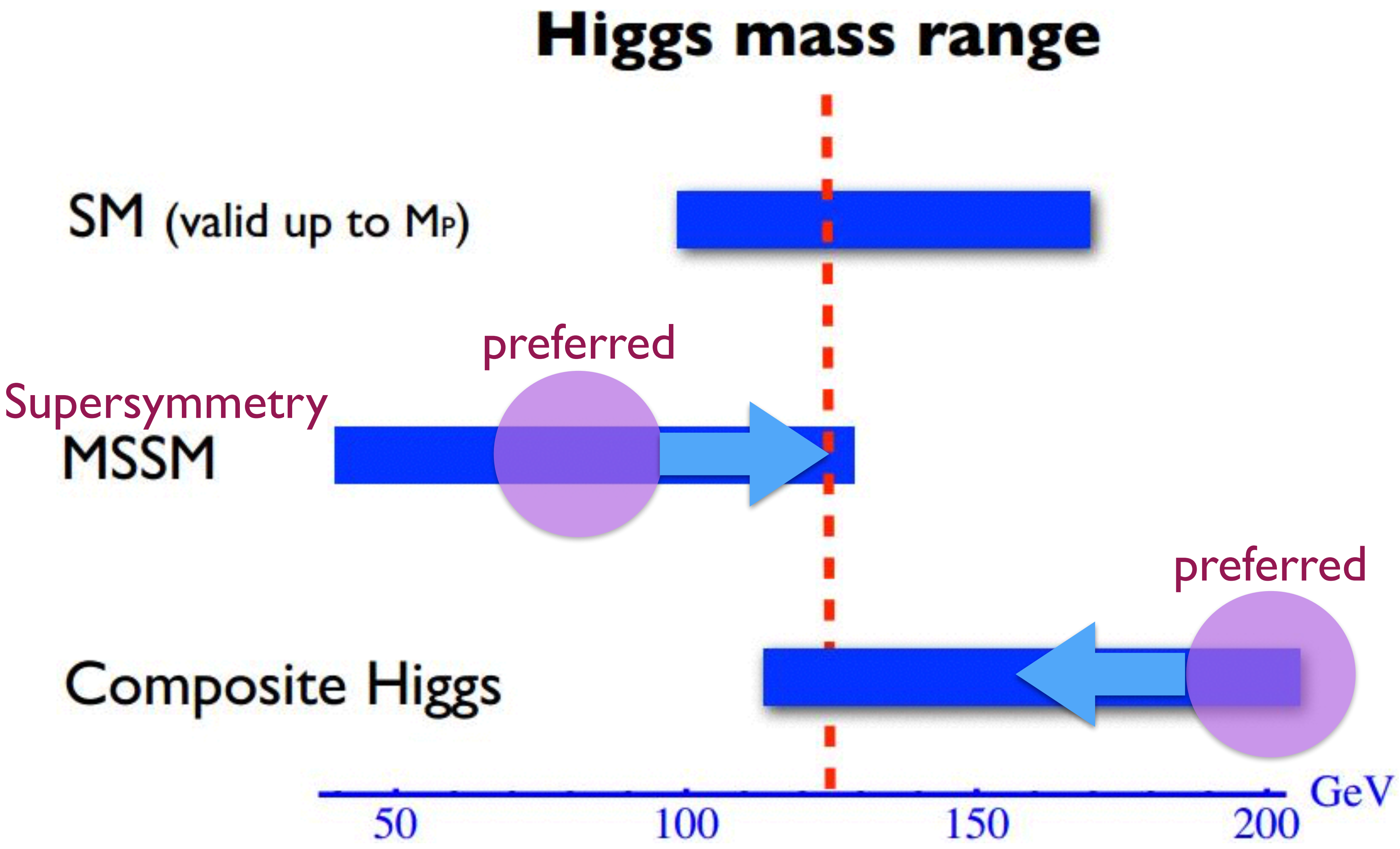


The SM does not explain **why the Higgs field filled the universe:**

Why $\mu^2 < 0$?

The EW scale is the key to answer this question.

Before the Higgs discovery, we were hoping that the Higgs mass would tell us the answer.



By A Pomarol

Hyung Do Kim

The Higgs mass turned out to be at a very subtle point

Why did the Higgs field fill the universe and why at the EW scale?

Our future forks in three ways

depending on the answer

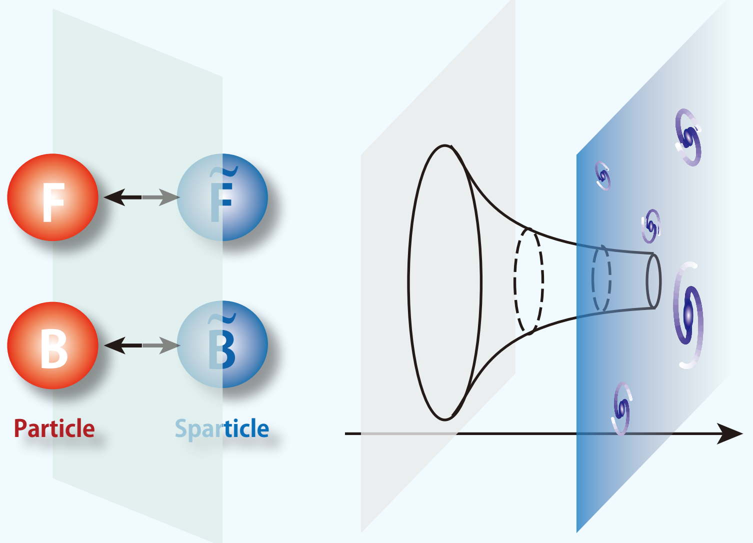
Extension of Space-Time

SUSY / Extra-dimensions

Key = Precision Higgs and Top couplings
SUSY particle discovery

Fermionic Extra -dim. = SUSY

Bosonic Extra -dim. = RS (ADD)

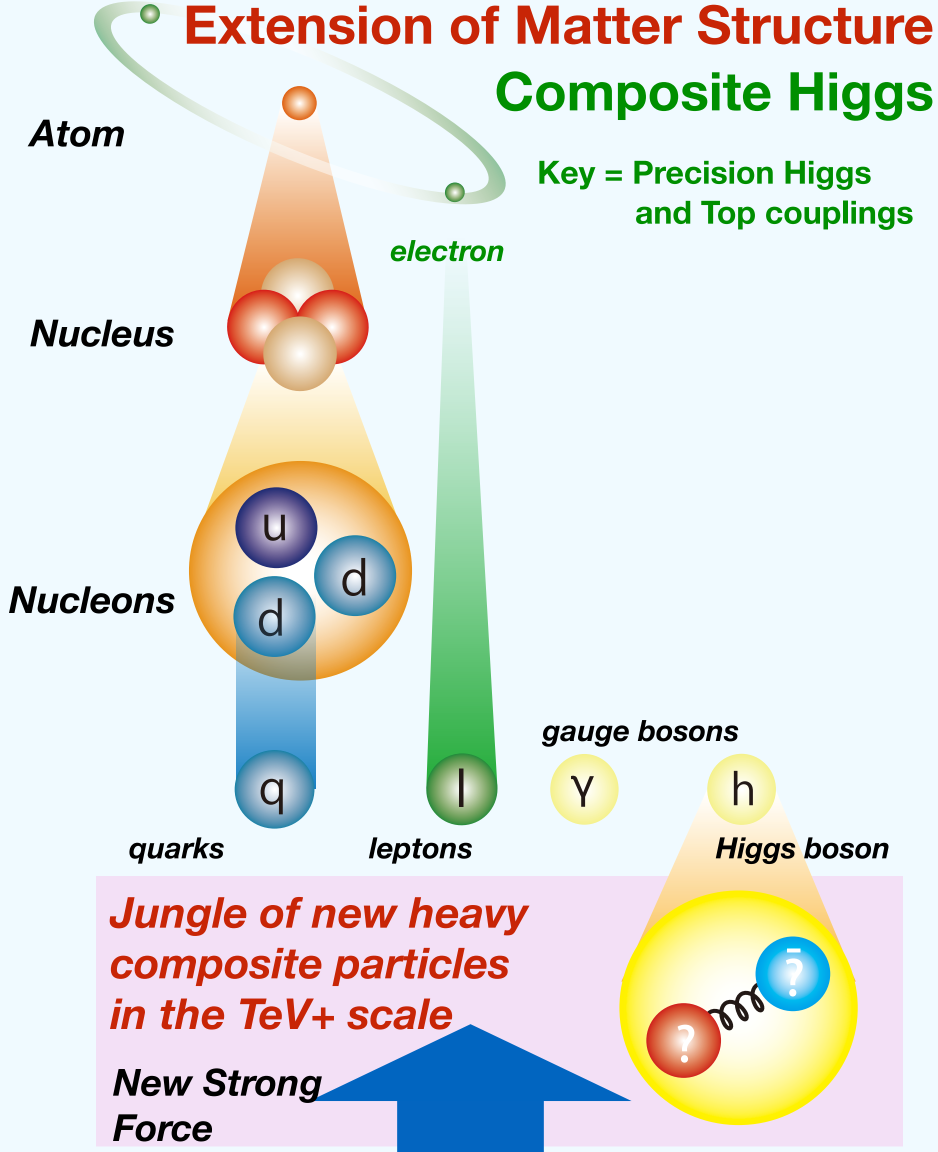


Big step towards ultimate unification

Extension of Matter Structure

Composite Higgs

Key = Precision Higgs and Top couplings



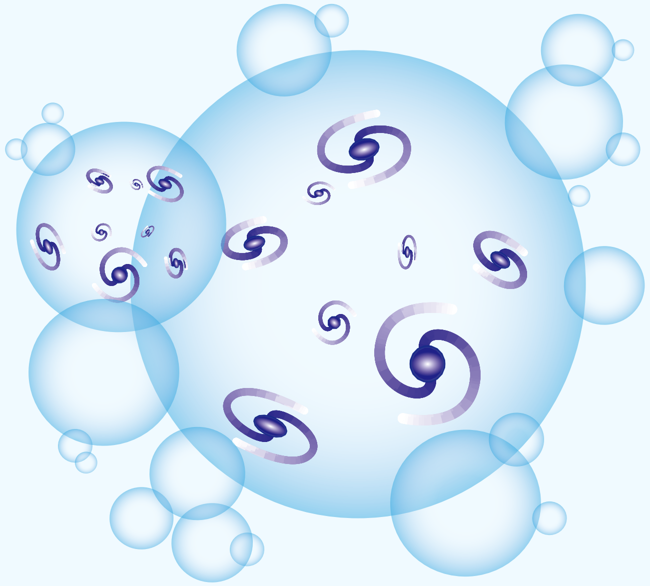
Jungle of new heavy composite particles in the TeV+ scale

New Strong Force

Completely New Principle

Multiverse + Anthropic Principle ?

Key = precision m_t and m_h measurements



The 1st Road: Existence of *another dimension*

The 2nd Road: Existence of *a new stratum of Nature*

No deviation from SM

The 3rd Road: Existence of *a myriad of universes ?*

We are
here

Depending on which way to go, the answers to other big questions like dark matter, baryon asymmetry of the universe, neutrino masses/mixings, dark energy, … also change.

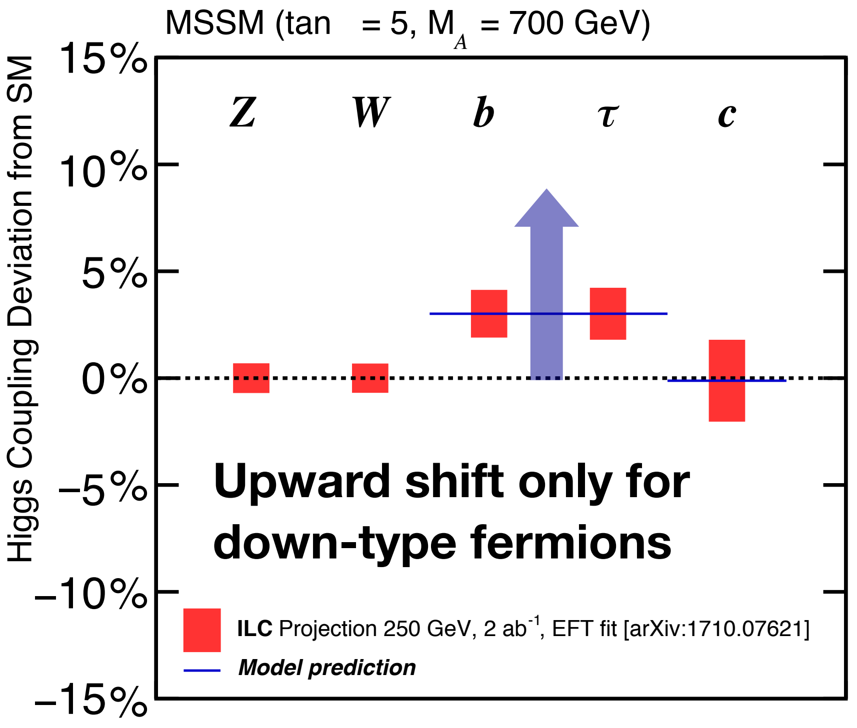
We need to know which way to go to answer these big questions!

Which way to go?

Decide the way by fingerprinting models with Precision Higgs Measurements

Supersymmetry

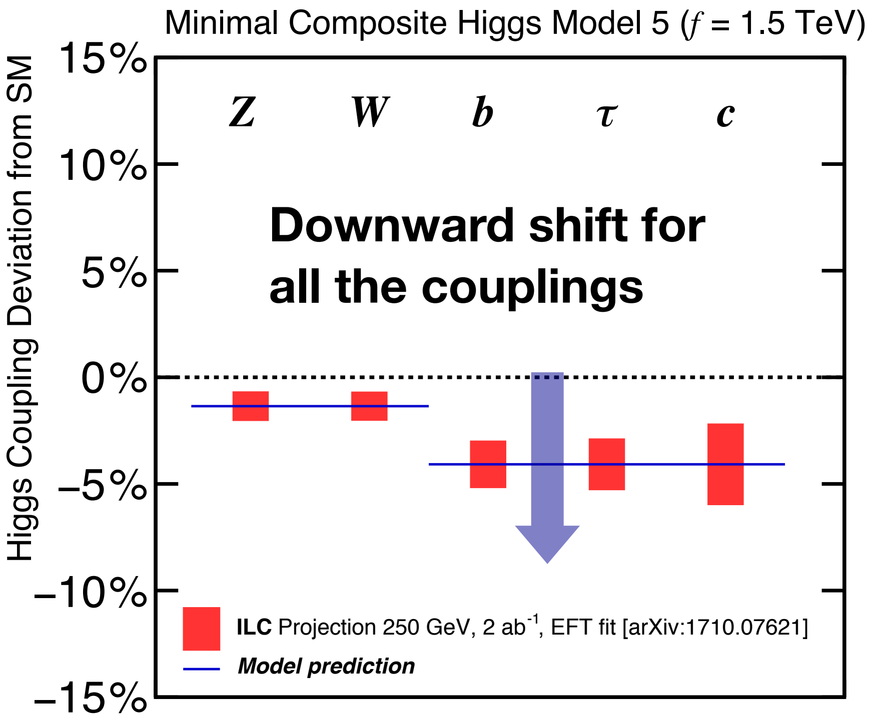
(MSSM)



Upward shift only for down-type fermions

Composite Higgs

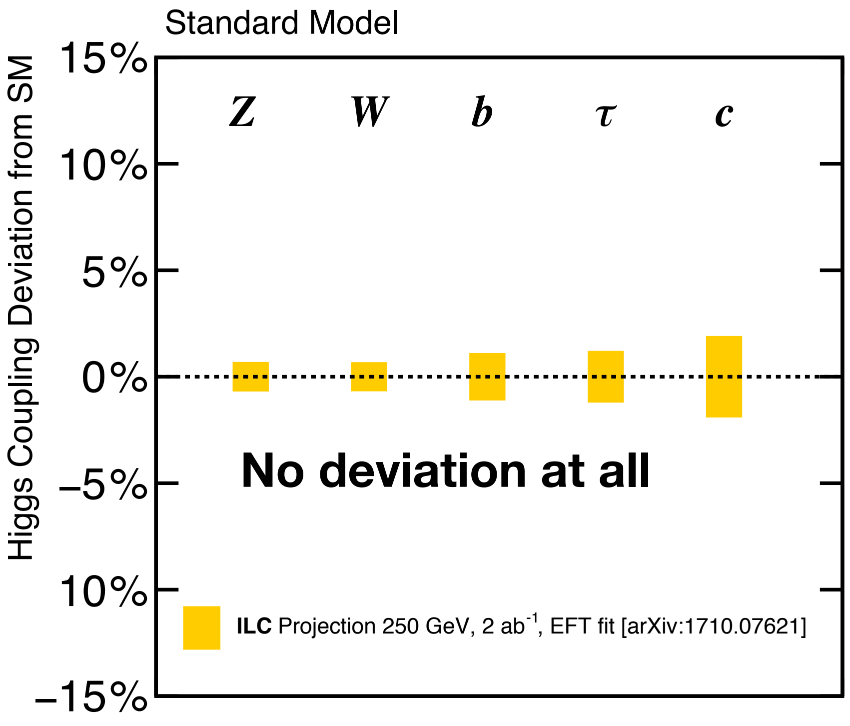
(MCHM5)



Downward shift for all the couplings

Multi-verse?

(Standard Model)



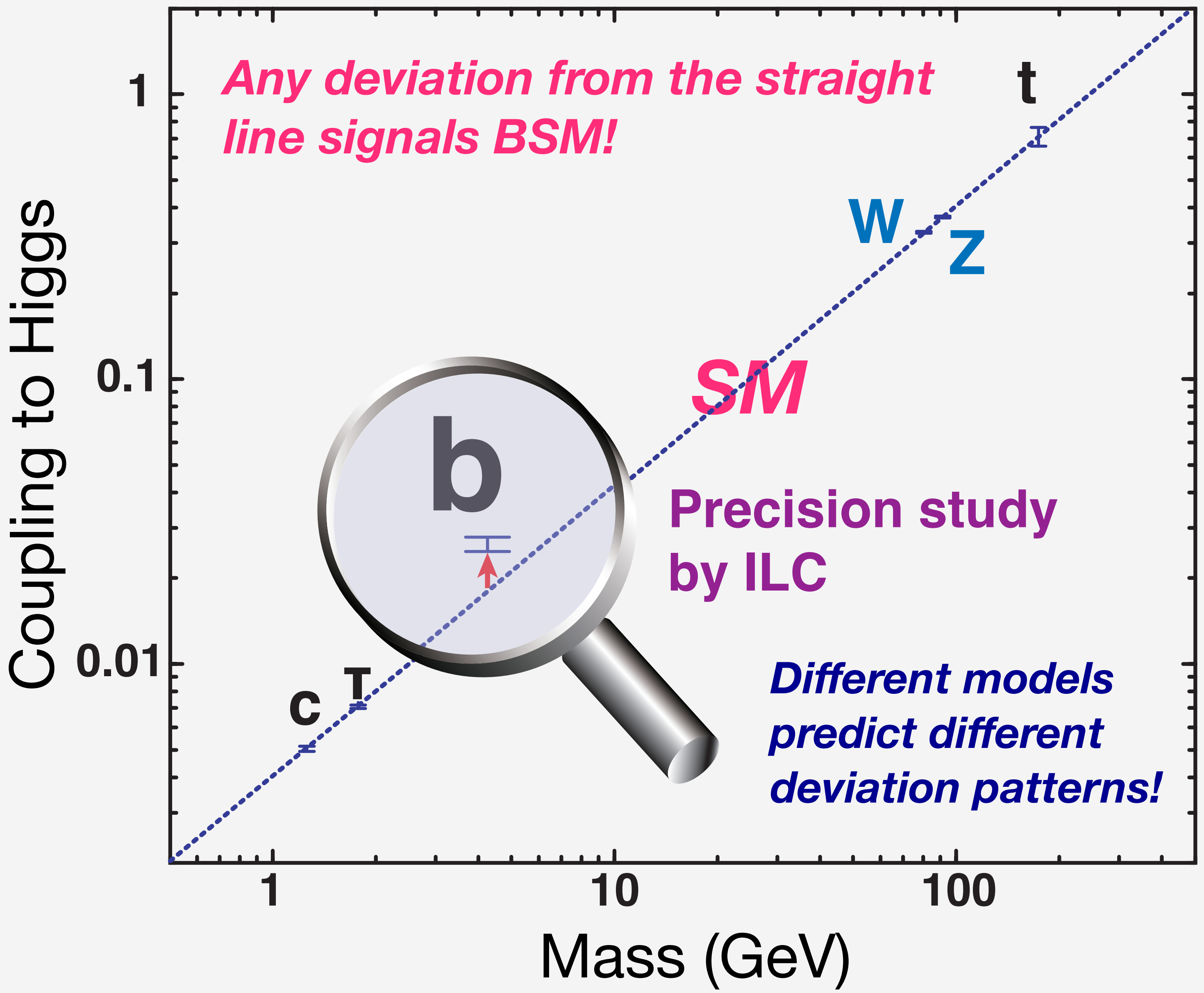
No deviation at all

Different models predict different deviation patterns
→ Deviation pattern tells us which way to go.

Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity goes beyond that of LHC.

Deviation in Higgs Couplings

Mass-coupling relation



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)

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

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***

Precision Higgs coupling study *is* ***a torch***

to shed light on our way ahead.

LHC Run II saw no clear signal of physics beyond the Standard Model.

→ ***No new particle in the LHC's range or it is in the LHC's blind spot.***

→ **Importance of precision Higgs measurements has been greatly enhanced.**

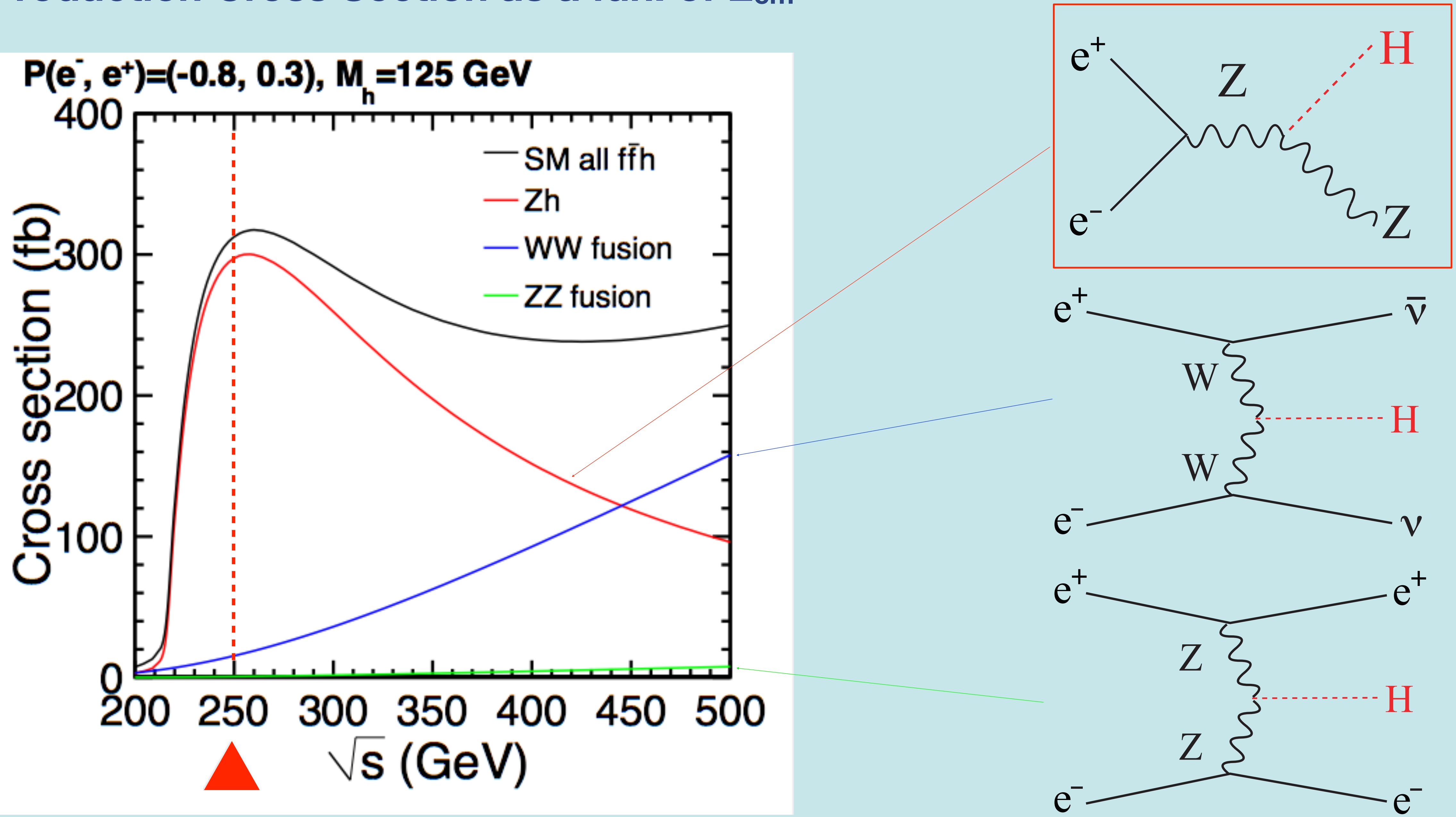
Mass-produce Higgs bosons and study them in detail

250 GeV ILC
as a Higgs Factory

250 GeV is a Special Energy

Single Higgs production cross section maximum

Production Cross Section as a fun. of E_{cm}



250 GeV: cross section maximum (~0.5 Million events for 2 ab^{-1})

Mass-produce Higgs bosons and study them in detail.

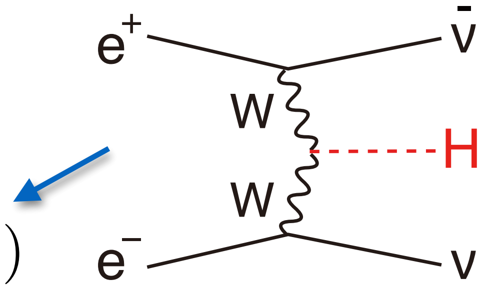
Recent Development: EFT Analysis

Potential drawback:

It has been said that Γ_h (Higgs total width) necessary for absolute coupling normalization requires >350GeV.

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$



cross section: small@250GeV

Solution: *EFT (Effective Field Theory)*

to relate **hZZ** and **hWW** couplings

LHC Run II results suggest that **250 GeV** is likely **in the validity range of the EFT**

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

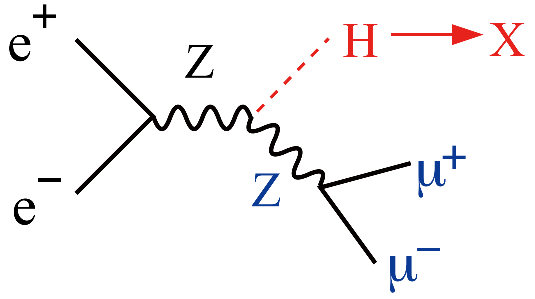
SU(2)xU(1) inv.
dim.6 operators

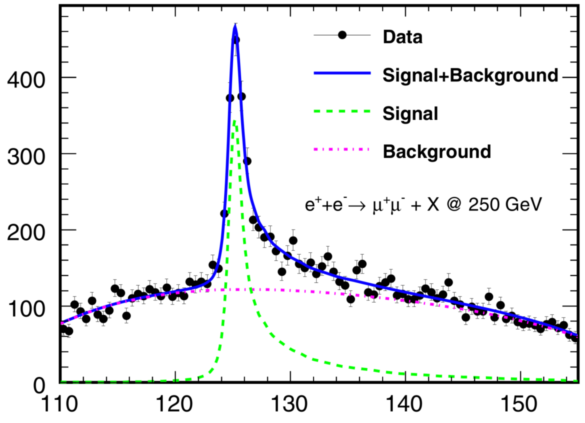
 # EFT coefficients to decide: 17 @ ILC

This ILC number is quite tractable.

Beam polarization doubles the number of usable observables.

The importance of ***the σ_{Zh} measurement by recoil mass technique*** remains the same.

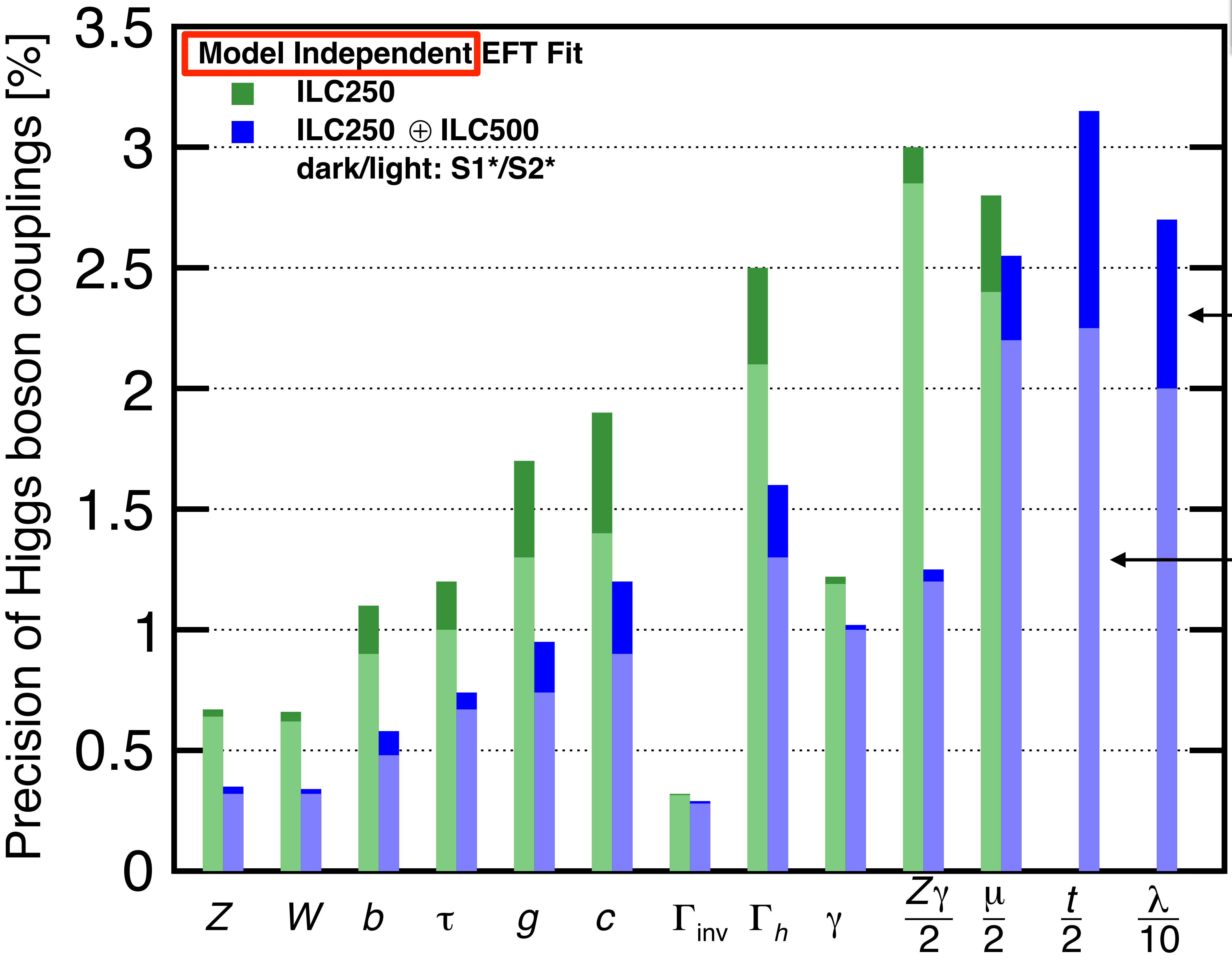


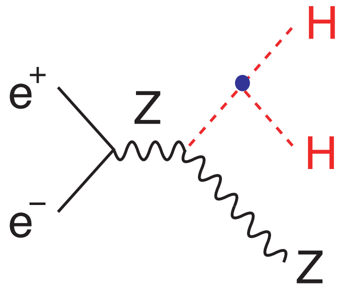


W_L and Z_L are NGBs from the Higgs sector. can use all the SM processes with W and Z to constrain the EFT coefficients.

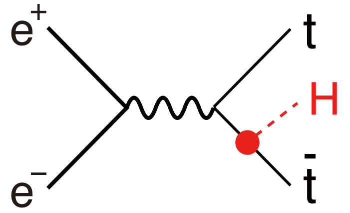
Absolute and model-independent Higgs coupling measurements possible with the 250 GeV data alone.

arXiv: 1901.09829





Self-coupling
Not accessible at 250 GeV.
Can reach 26% at 500 GeV.

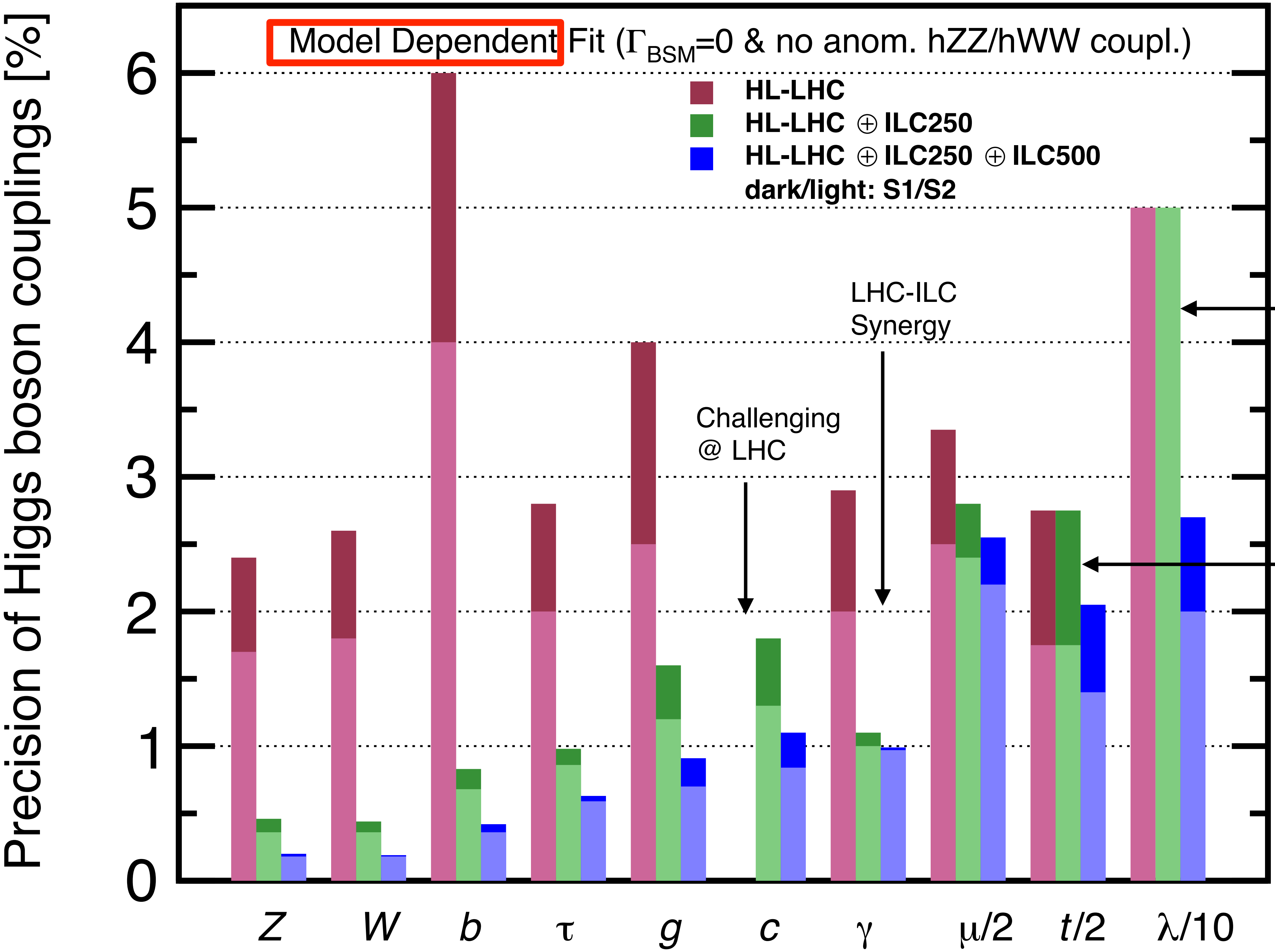


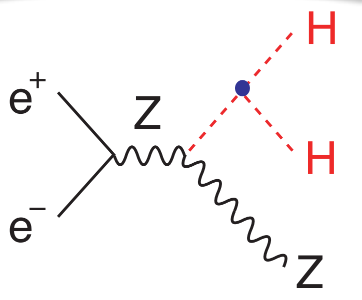
Top Yukawa
Not accessible at 250 GeV.
Can reach 3% at 550 GeV.

FIG. 2. Projected Higgs boson coupling uncertainties for the ILC program at 250 GeV and an energy upgrade to 500 GeV, using the highly model-independent analysis presented in [3]. This analysis makes use of data on $e^+e^- \rightarrow W^+W^-$ in addition to Higgs boson observables and also incorporates projected LHC results, as described in the text. Results are obtained assuming integrated luminosities of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV. All estimates of uncertainties are de- rived from full detector simulation. Note that the projected uncertainties in the Higgs couplings to Zγ, μμ, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot. The scenario S1* refers to analyses with our current understanding; the scenario S2* refers to more optimistic assumptions in which experimental errors decrease with experience. A full explanation of the analysis and assumptions underlying these estimates is given in [6].

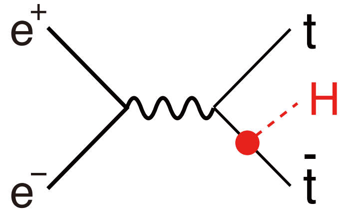
ILC allows model-independent fit to extract all the major Higgs couplings !

arXiv: 1901.09829





Self-coupling
Not accessible at 250 GeV.
Can reach 26% at 500 GeV.

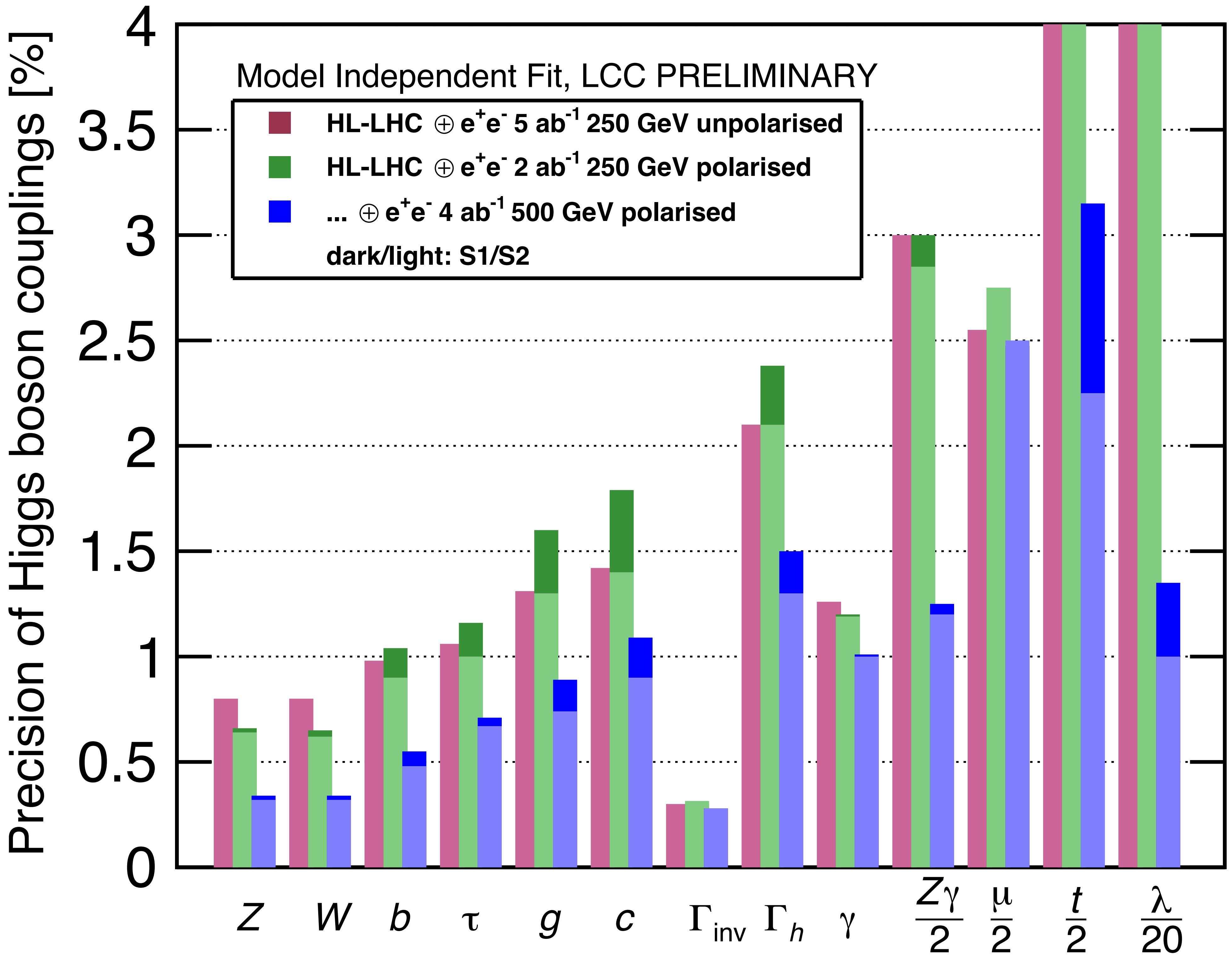


Top Yukawa
Not accessible at 250 GeV.
Can reach 3% at 550 GeV.

FIG. 1. Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. The dark- and light-red bars represent the projections in the scenarios S1 and S2 presented in [9, 10]. The scenario S1 refers to analyses with our current understanding; the scenario S2 refers to more optimistic assumptions in which experimental errors decrease with experience. The dark- and light-green bars represent the projections in the ILC scenarios in similar S1 and S2 scenarios defined in [6]. The dark- and light-blue bars show the projections for scenarios S1 and S2 when data from the 500 GeV run of the ILC is included. The same integrated luminosities are assumed as for Figure 2. The projected uncertainties in the Higgs couplings to μμ, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot.

ILC significantly improves LHC precisions → Much higher sensitivity to BSM !

Power of Polarization



Polarized 2 ab^{-1} is roughly equivalent to unpolarized 5 ab^{-1}!

Sensitivity of EFT Analysis

to sample new physics scenarios

arXiv: 1710.07621

9 sample models and expected deviations (%)

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [37]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [38]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [38]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [38]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

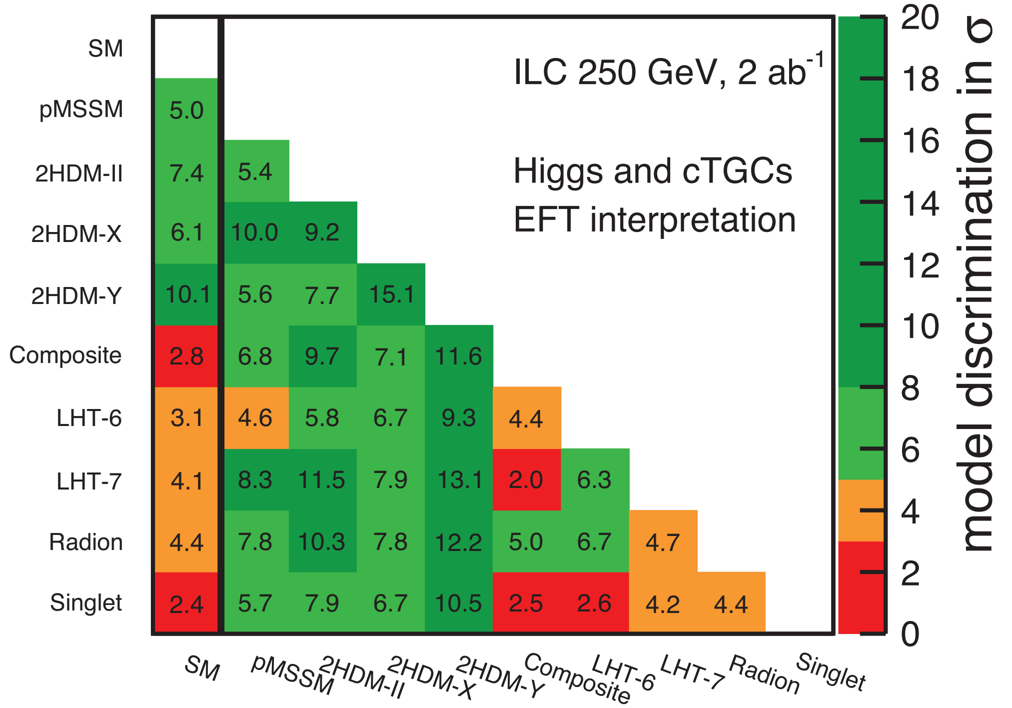
All new particles outside the projected reach of the HL-LHC
→ The only probe would be precision measurements of the Higgs couplings

Expected deviations are at most 10% or so
Needs high precision to see the deviations

→ Different new physics models predict different deviation patterns

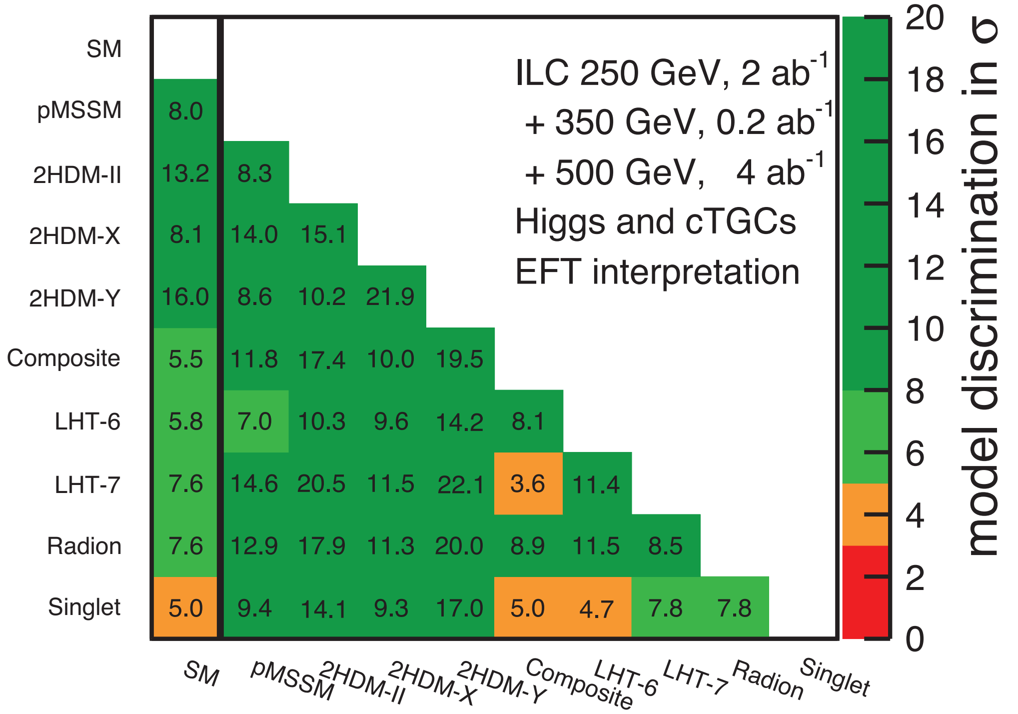
→ We can discriminate the models !

Discrimination power in σs



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

> 3σ sensitivities to most models @ 250 GeV



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

> 4σ sensitivities to almost all models @ 500 GeV

$$n \simeq \sqrt{\chi^2}$$

Depending on which way to go, the answers to other big questions like dark matter, baryon asymmetry of the universe, neutrino masses/mixings, dark energy, … also change.

We need to know which way to go to answer these big questions!

Depending on which way to go, the answers to other big questions like dark matter, baryon asymmetry of the universe, neutrino masses/mixings, dark energy, … also change.

250 GeV ILC decides the future direction of particle physics.

Though this is a Higgs conference, I cannot help but point out this.

250 GeV ILC
is a new particle
discovery machine!

Direct New Particle Searches

- >10^3 higher luminosity than LEP2
- beam polarizations
- much better detectors

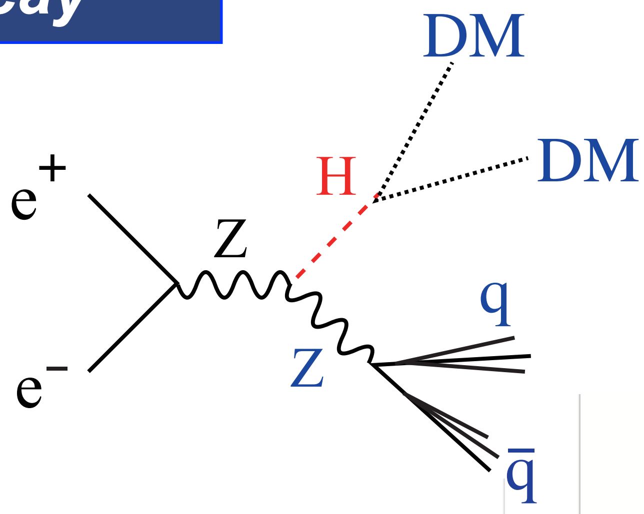
enhance sensitivities to regions with small cross sections and compressed mass spectrum, which are challenging at LHC

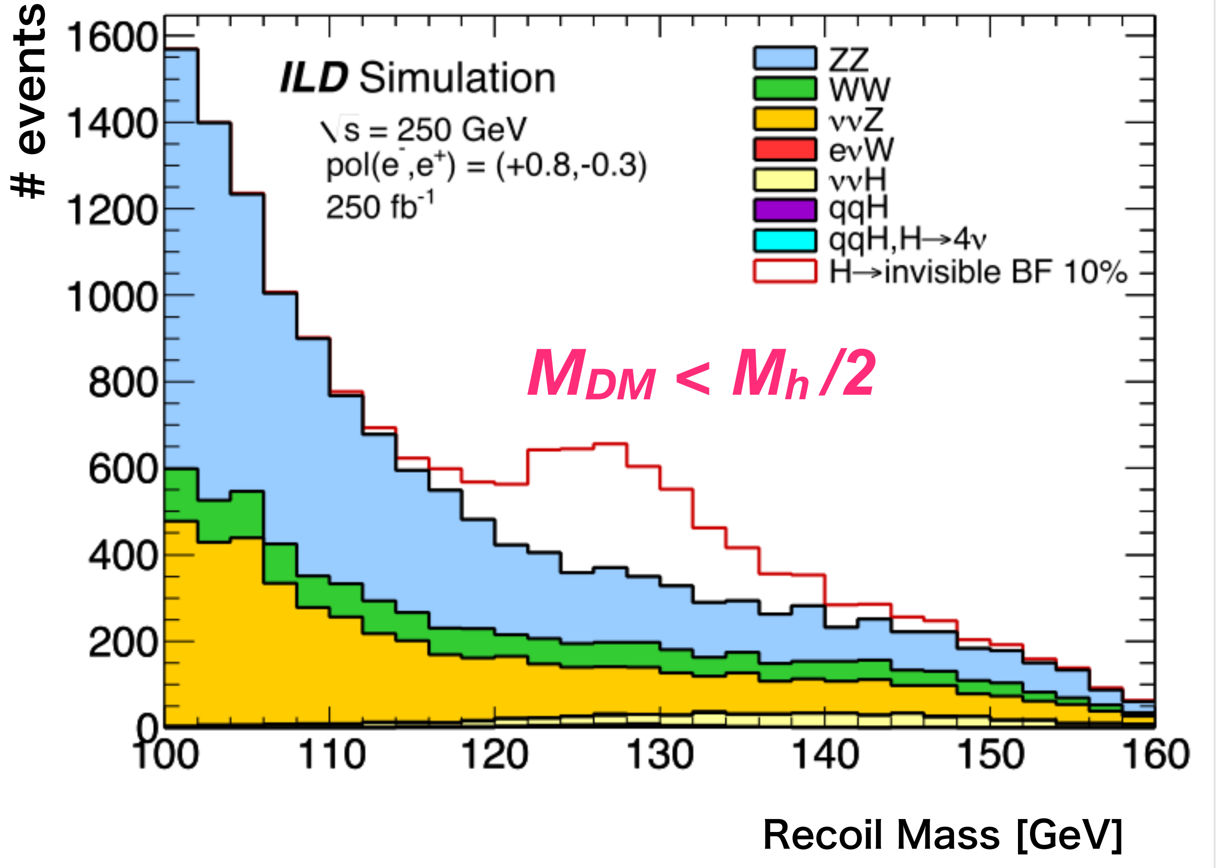
WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson





$M_{DM} < M_h/2$

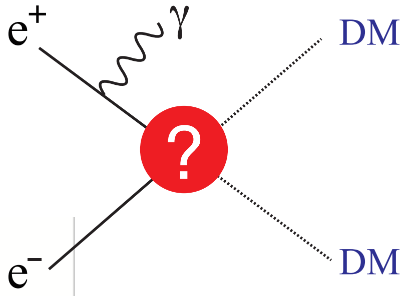
Possible to access BR_{inv} to 0.3%!

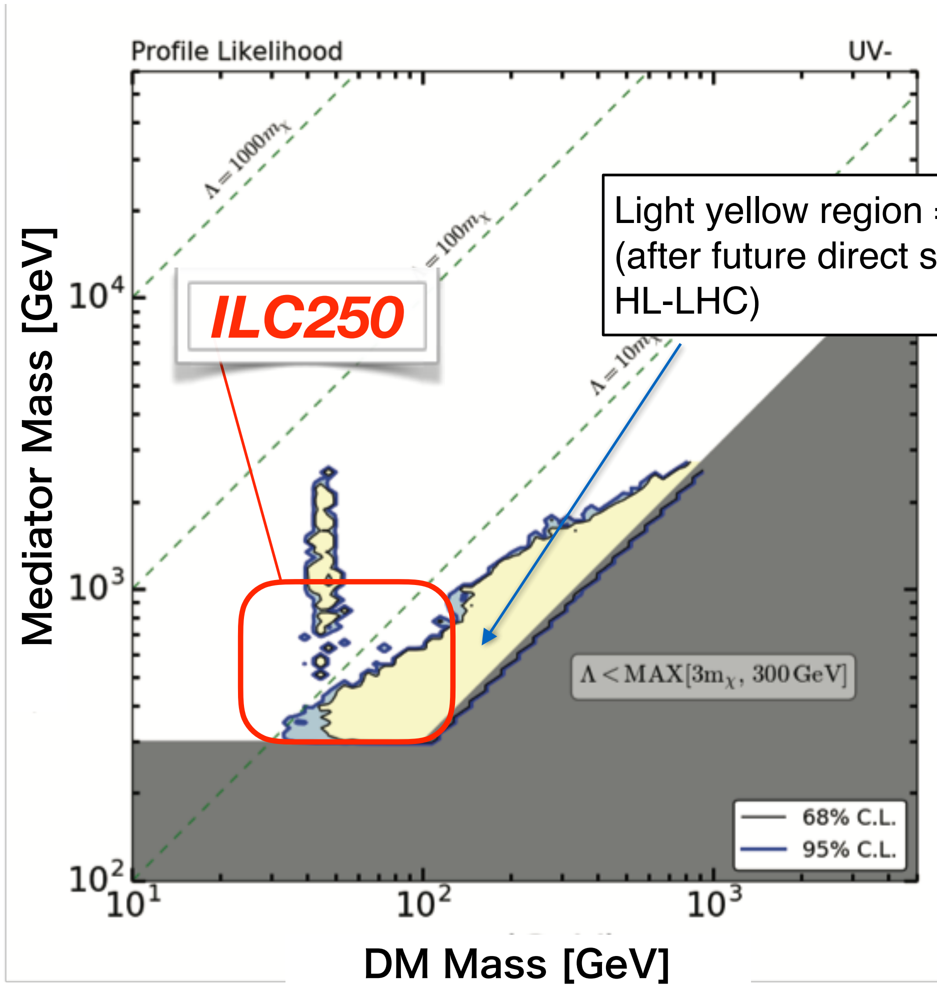
O(10) more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.





Light yellow region = to be left for ILC (after future direct searches including HL-LHC)

Significant chunk of region remains for ILC250!

※: HL-LHC = High Luminosity LHC

Summary

- Given the situation that LHC Run II has seen no new particles other than H125, the importance of precision Higgs measurements has been enhanced significantly.

- Recent analysis improvements made precision measurements of absolutely normalized Higgs couplings possible at the 250 GeV ILC alone.

- The 250 GeV ILC will show us the future direction of particle physics, by fingerprinting the deviation pattern of these precisely measured Higgs couplings.

- By adding experiments at higher energies (not covered today) in future which allow precision top studies and a measurement of the cubic Higgs self-coupling, we will be able to further narrow down viable new physics models.

- In this way the ILC will pave the way to unified understanding of Nature. The 250 GeV ILC will be its first step.

Backup

Linear vs Circular Discussion

Political support: ILC has been considered in depth over a number of years by the government of Japan, which is soon expected to make **an Expression of Interest to host the project**.

Politicians, governments, and funding agencies in Japan have been discussing the ILC with their counterparts in Europe and the US for a number of years, and have been encouraged by these discussions.

Other large collider projects have not yet reached a similar stage.

Technical maturity:

The RDR (CDR equivalent) for the ILC was published in 2007 and the **TDR in 2013**.

Circular collider projects have only recently published their CDRs.

The ILC's quoted performance and costs are deeply understood and thus reliable.

Timeline: Given a go-ahead, the ILC will very soon be ready to start construction. First collisions can occur within around 15 years from now.

According to current run plans, the ILC will complete its 2 ab-1 250 GeV run at about the time FCCee begins its ZH run.

Physics: Beam polarization is a powerful tool not available at high energy circular colliders.

When measuring Higgs couplings, **polarization compensates for the lower integrated luminosity at 250 GeV compared to FCCee (2 vs 5 ab-1)** not just by the increased rates but also by its power to remove some correlations among different EFT operators.

In the case that ILC observes new phenomena other than in the Higgs couplings, polarization will play an essential role in determining their chiral properties.

Polarization will also allow **systematic uncertainties** on many measurements **to be significantly reduced**.

Upgradeability: The ILC's collision energy can be readily upgraded to 500 GeV and above.

A technical design for a 500 GeV stage exists.

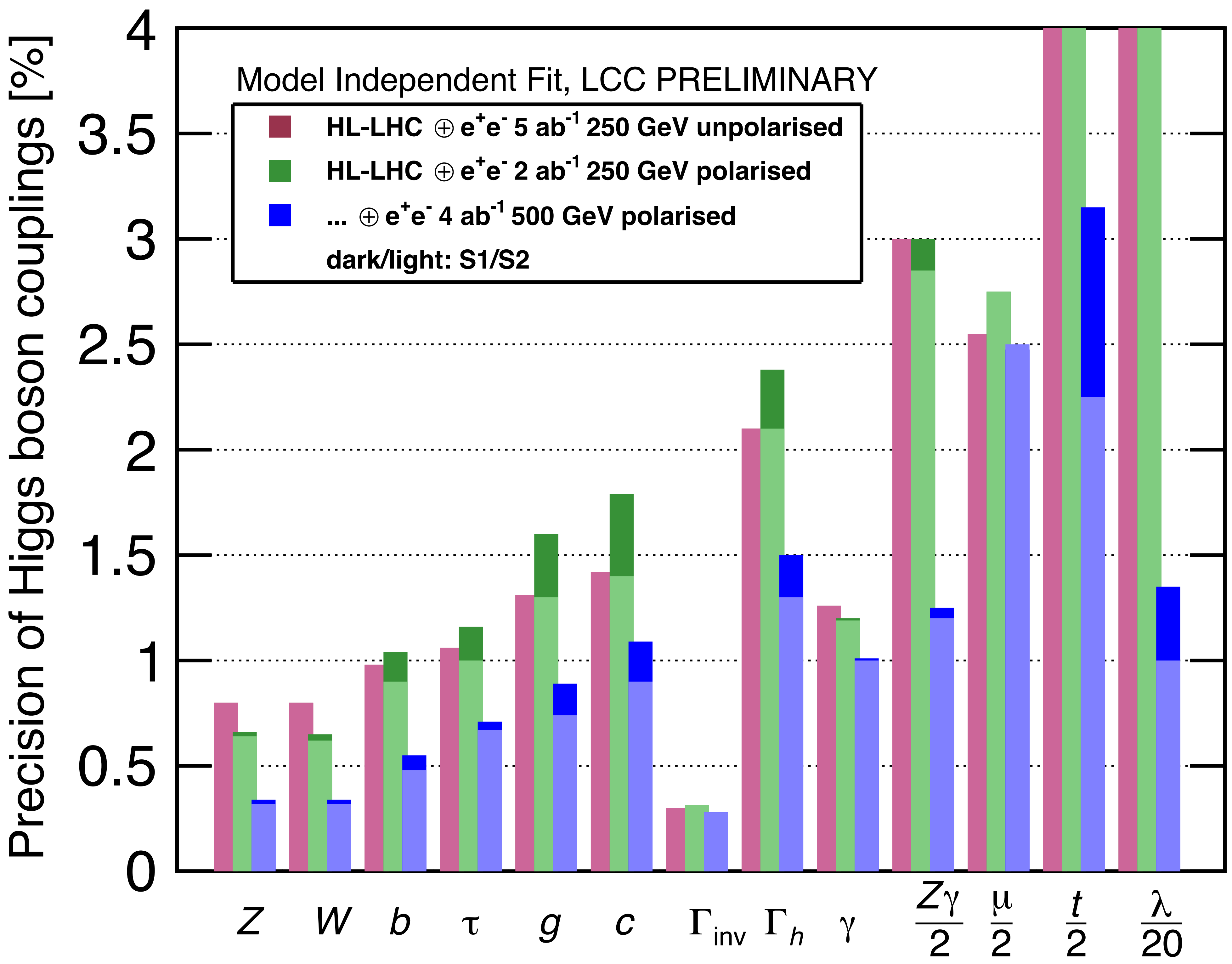
Likewise, **a technical design exists for upgrading the luminosity:**

- by a factor 2 by doubling the number of bunches per pulse,

- another factor 2 by doubling the repetition rate.

The ILC250 infrastructure is reusable. It provides long-term perspectives beyond current technologies (e.g. a plasma-based accelerator).

Power of Polarization



Polarized 2 ab-1 is roughly equivalent to unpolarized 5 ab-1!

2018/10/21

Design Luminosity

Lumi-Up = # bunches x 2

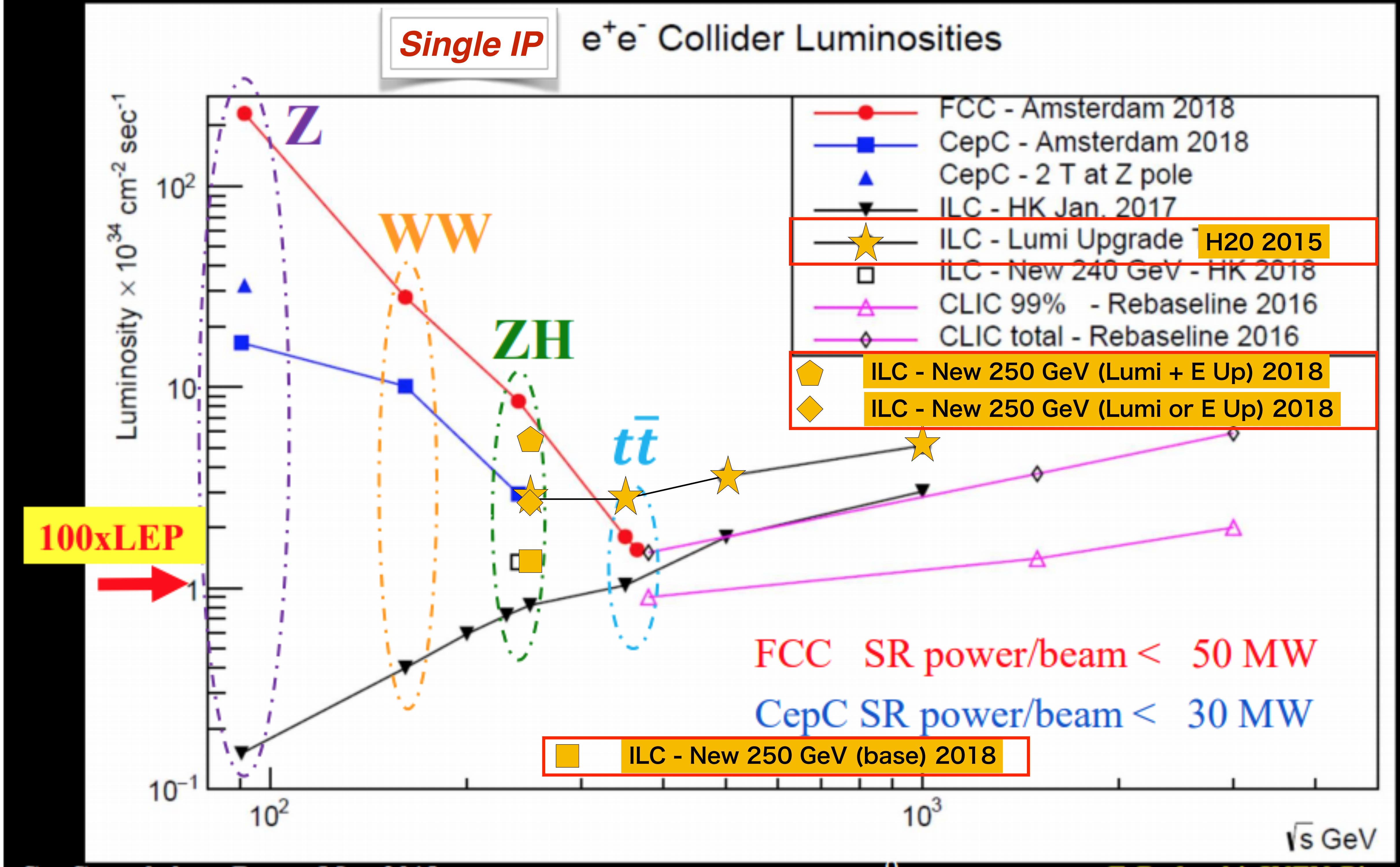
E-Up = E-Up to 500 GeV

	Base Line 1312 bunches (5 Hz)	Lumi-Up 2625 bunches (5 Hz)	(Lumi+E-Up) 2625 bunches (High Rep)
250 GeV (H20)	0.82×10^{34} (5 Hz)	1.64×10^{34} (5 Hz)	3.28×10^{34} (10 Hz)
350 GeV (H20)	1.0×10^{34} (5 Hz)	2.0×10^{34} (5 Hz)	2.8×10^{34} (7 Hz)
500 GeV (H20)	1.8×10^{34} (5 Hz)	3.6×10^{34} (5 Hz)	—
250 GeV (New)	1.35×10^{34} (5 Hz)	2.7×10^{34} (5 Hz)	5.4×10^{34} (10 Hz)

H20 numbers from arXiv: 1506.07830 with revision according to Change Request 5 (approved by Change Control Board in 2015)

250 GeV (New) numbers based on arXiv: 1711.00568

CepC, FCC, ILC, CLIC luminosity comparison



FCC SR power/beam < 50 MW

CepC SR power/beam < 30 MW

Beyond 250 GeV

What we can do at higher energies

Precision EW coupling measurement of Top
Precision Top mass measurement
Direct measurement of Top Yukawa coupling

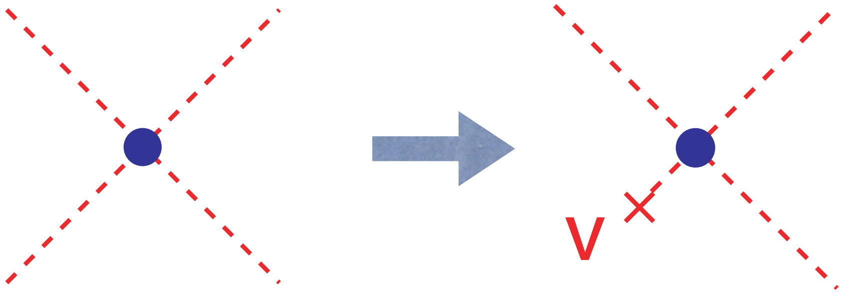
Measurement of 3-point Higgs self-coupling

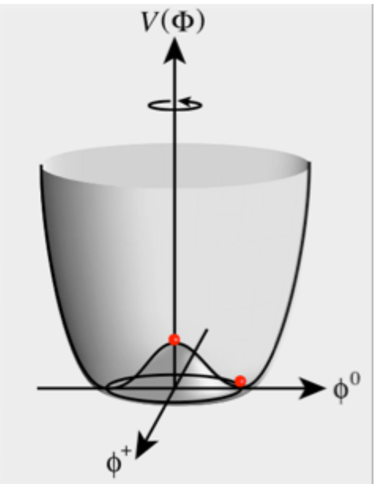
Expansion of search region of new particles

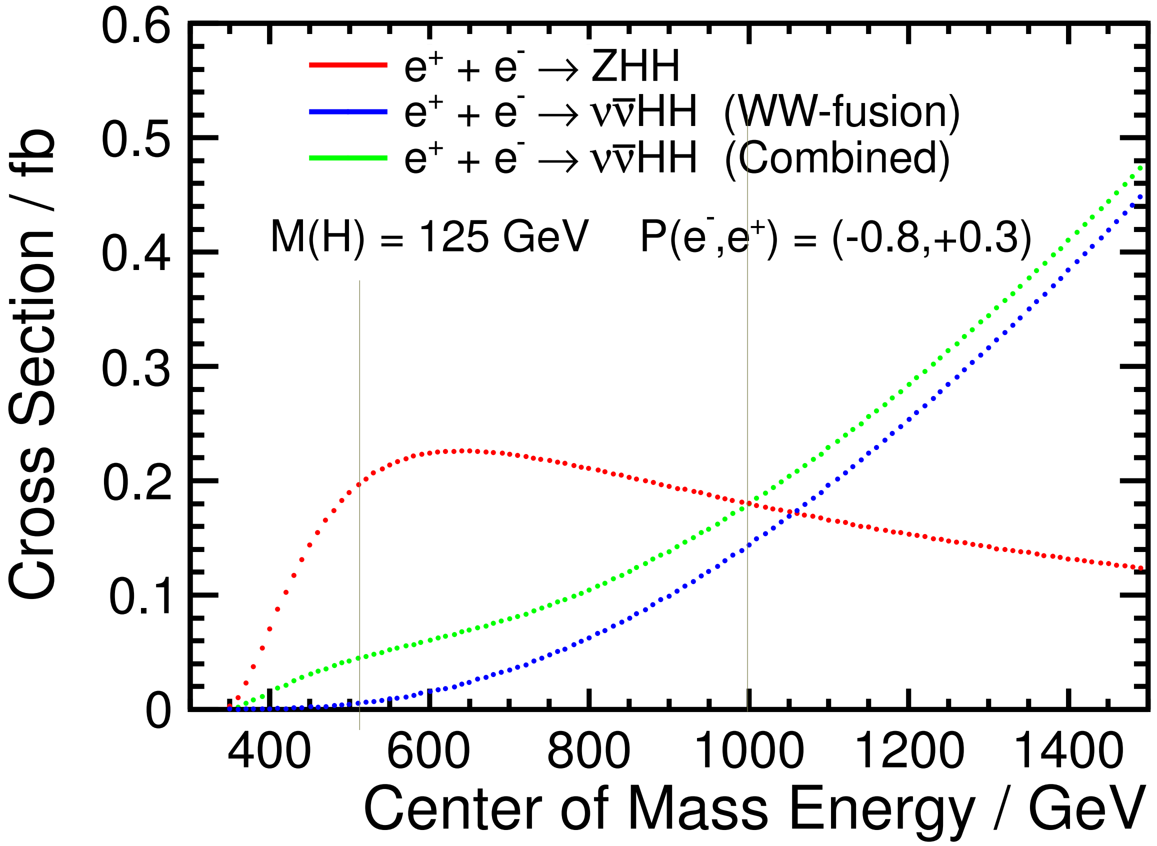
If no deviations at all would be seen?

Higgs Self-Coupling

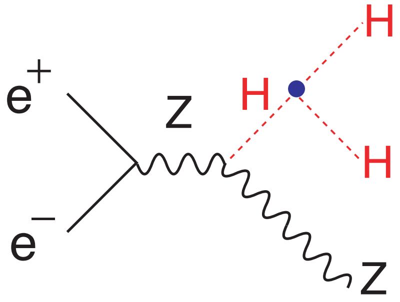
The ***Higgs cubic self-coupling*** is at the heart of EWSB, so should be measured in its own right!

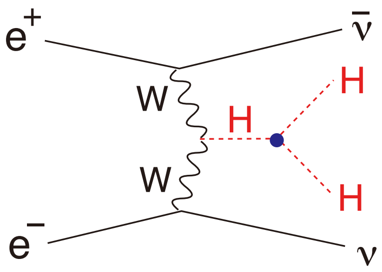






There are ***two ways to measure it*** at ILC





Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams that dilute the self-coupling contribution!***
- ***Separation of BSM effects that appear other than in self-coupling (possible in EFT: same impossible at LHC)***

ILC

	500 GeV	+ 1 TeV
Snowmass	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%

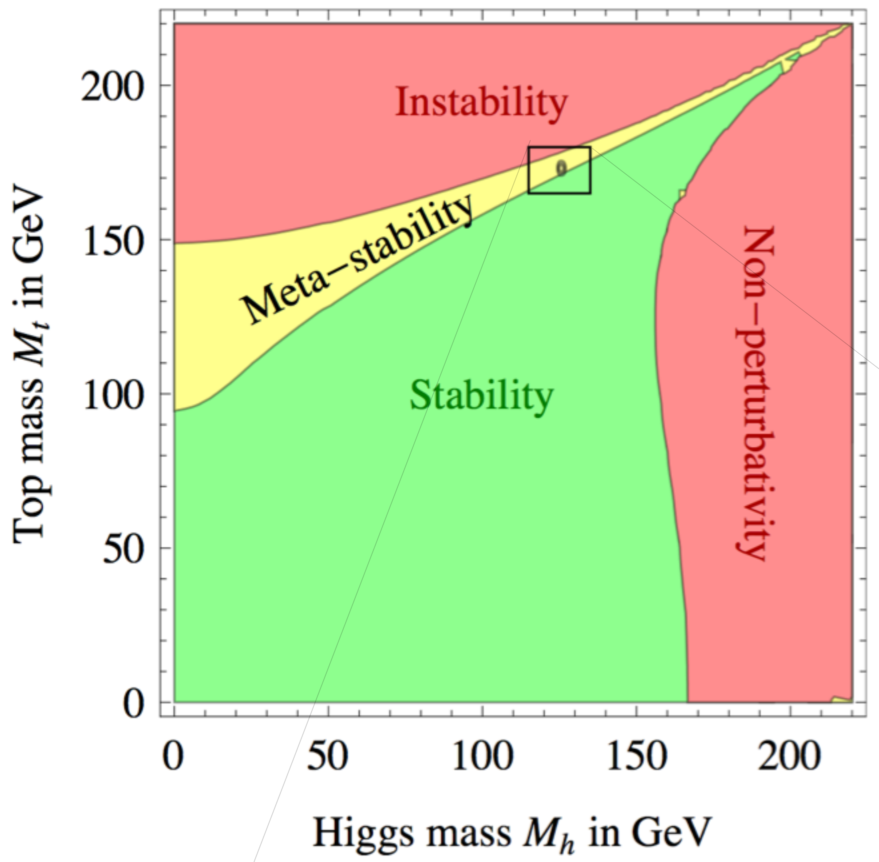
(arXiv: 1307.5288)

Ongoing effort ***towards O(10)% measurement***

If +100% deviation as possible in EWBG scenario, Δλ/λ=14%!

Clarify the Range of Validity of SM

Stability of SM Vacuum

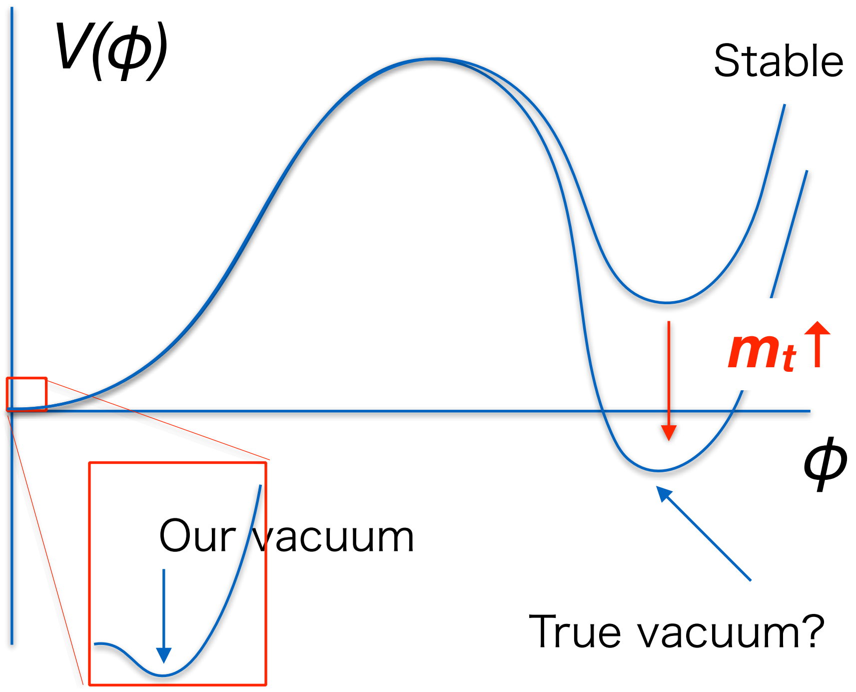


Top Yukawa coupling drives the 4-point Higgs coupling (λ) to negative!
→ The true vacuum could be somewhere else at a high ϕ value.

The current values of mt and mh seem to be in **subtle point of meta-stability!**

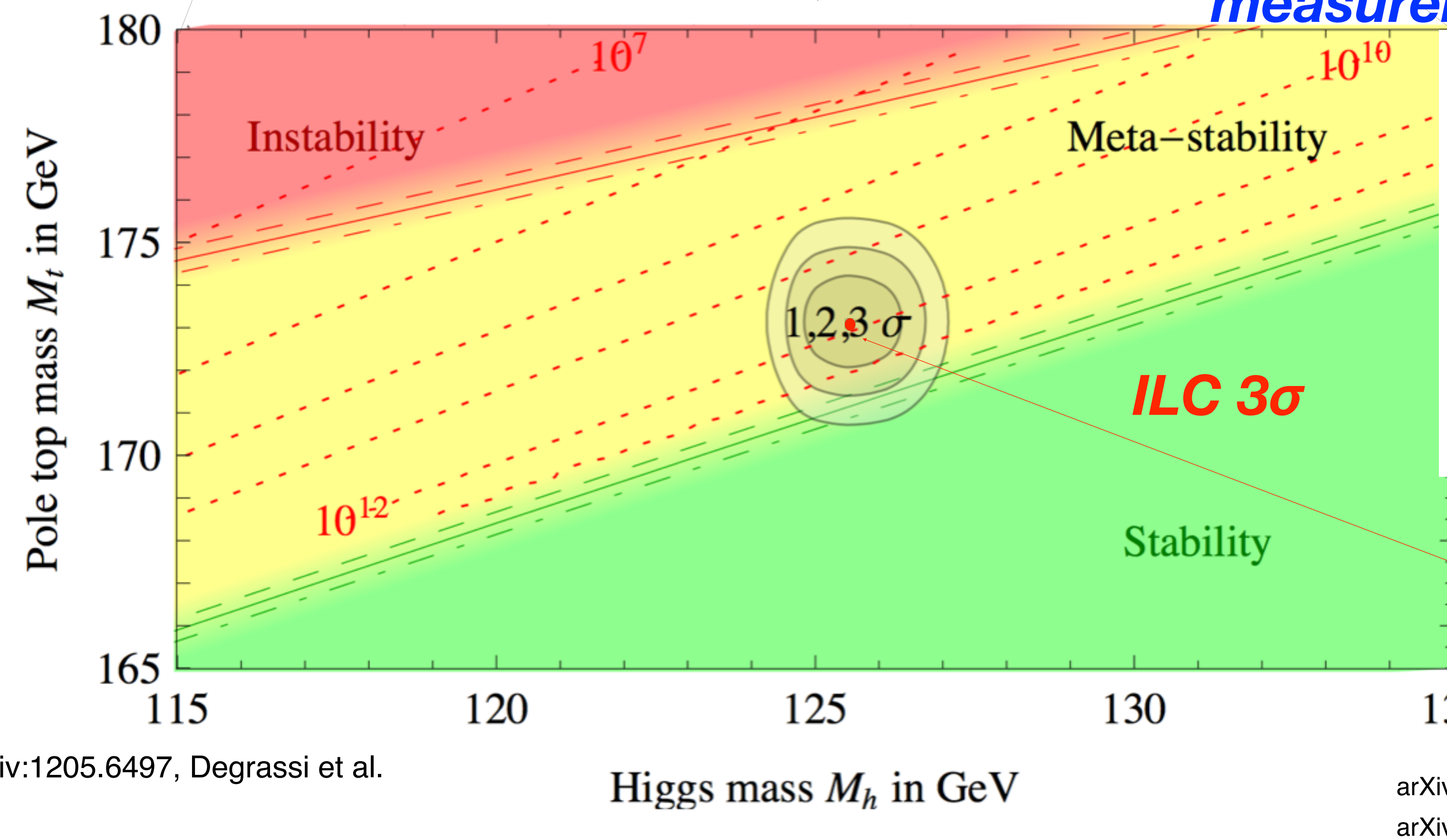
Does λ go to negative below Λ_P?
or $\lambda(\Lambda_{Pl}) = 0$ (suggesting new principle) ?

To answer this, we need precision m_t measurement!

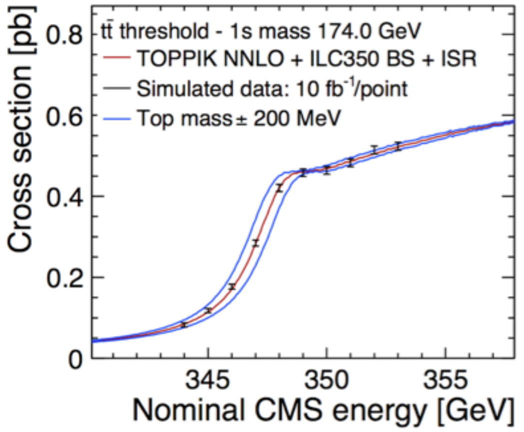


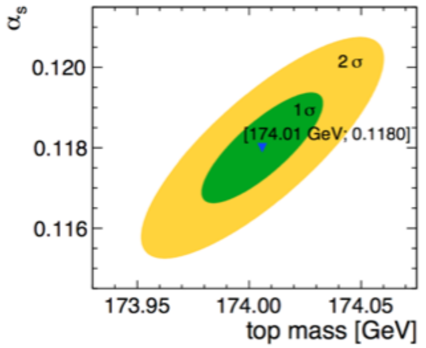
At LHC, theory error limits the precision to ~500MeV.

TTbar Threshold Scan @ILC allows very clean measurement of theoretically well defined mt



arXiv:1205.6497, Degrassi et al.





$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$
$$\Delta m_H = 14\,\mathrm{MeV}$$

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

EW Baryogenesis?

Impossible in SM

EW Phase Transition = Strong 1st Order

Necessary to deviate from equilibrium

→ Shifts in HXX couplings

Expect a large deviation in the HHH coupling

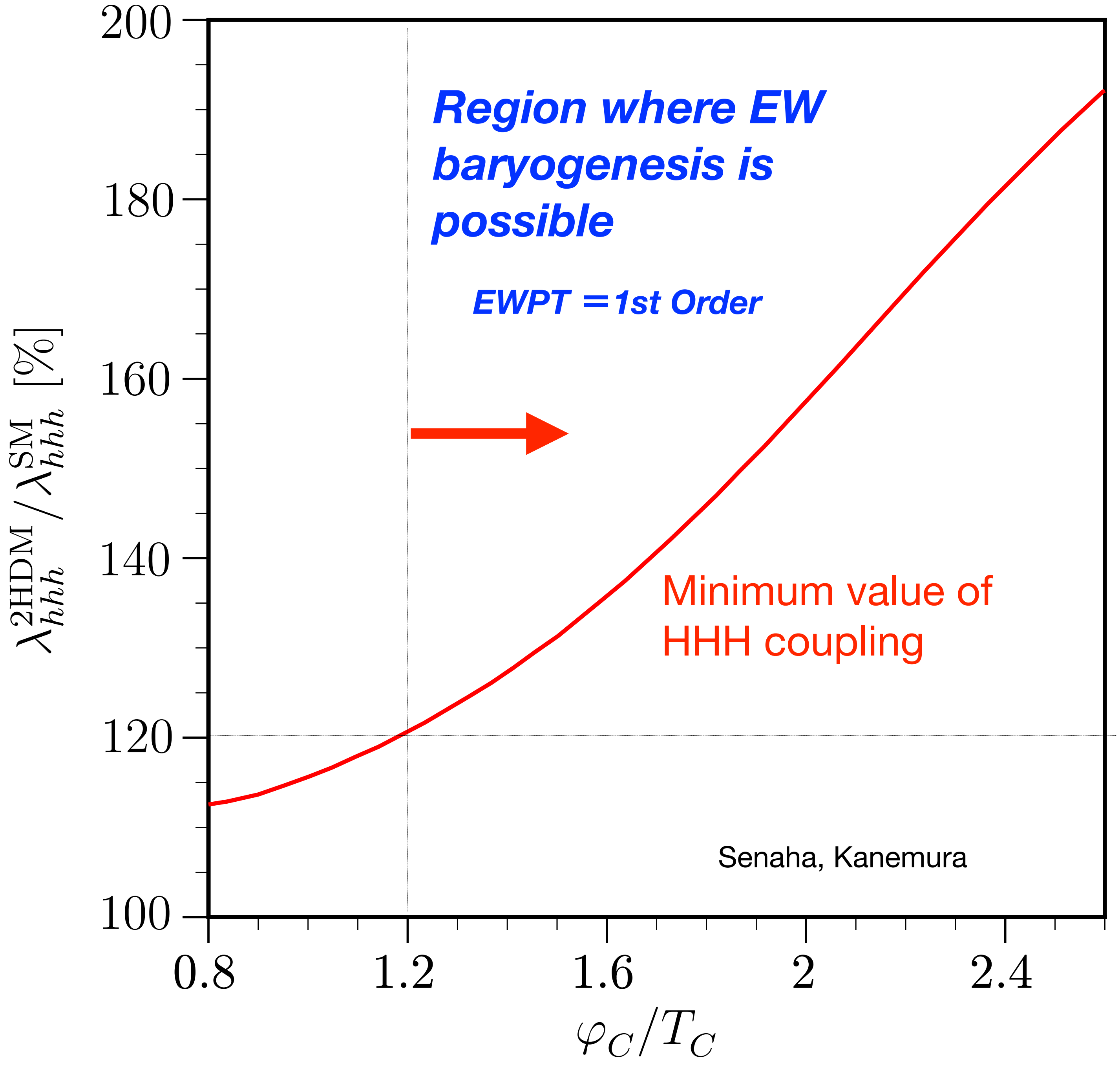
Big enough CP violation (δ_{KM} too small) at the bubble wall

→ CP violation in the Higgs sector

→ Extended Higgs Sector

EW Baryogenesis?

e.g.: ***2 Higgs Doublet Model (2HDM)***



Region where EW baryogenesis is possible

EWPT =1st Order

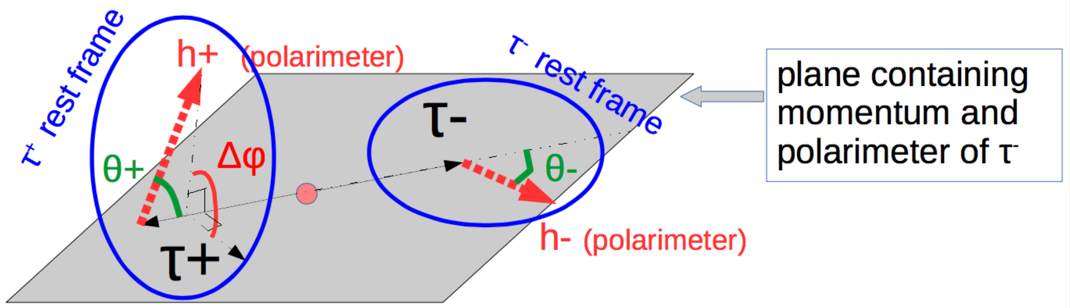
Minimum value of HHH coupling

Senaha, Kanemura

Measuring CP in H → $\tau^+\tau^-$ at ILC

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

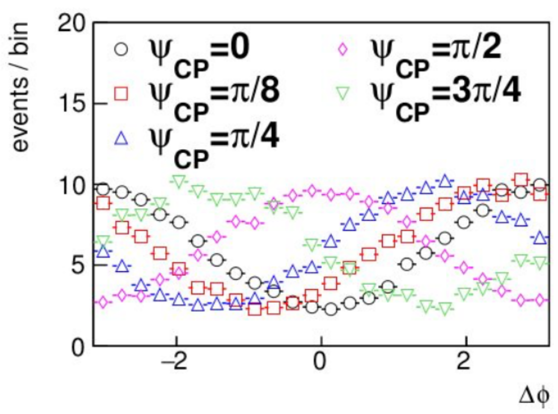
CP from polarimeters : taus from spin 0 parent



plane containing momentum and polarimeter of τ^-

θ±, φ±	direction of h± with respect to τ- boost in τ± rest frame
Δφ	angle between polarimeter planes
ψ_{CP}	CP mixing angle we want to measure

Δφ at different ψ_{CP}



Δφ distribution shifts by $2\psi_{CP}$

2ab^{-1} @ 250 GeV

$$\delta\Psi_{CP} \simeq 4^\circ$$

D. Jeans 2018

Measurement of HHH coupling at ILC

At 500 GeV signal and background diagrams constructively interfere.強め合う

→ ***If there is 100% upward shift→ Δλ/λ=14%***

ILC will test EW baryogenesis.

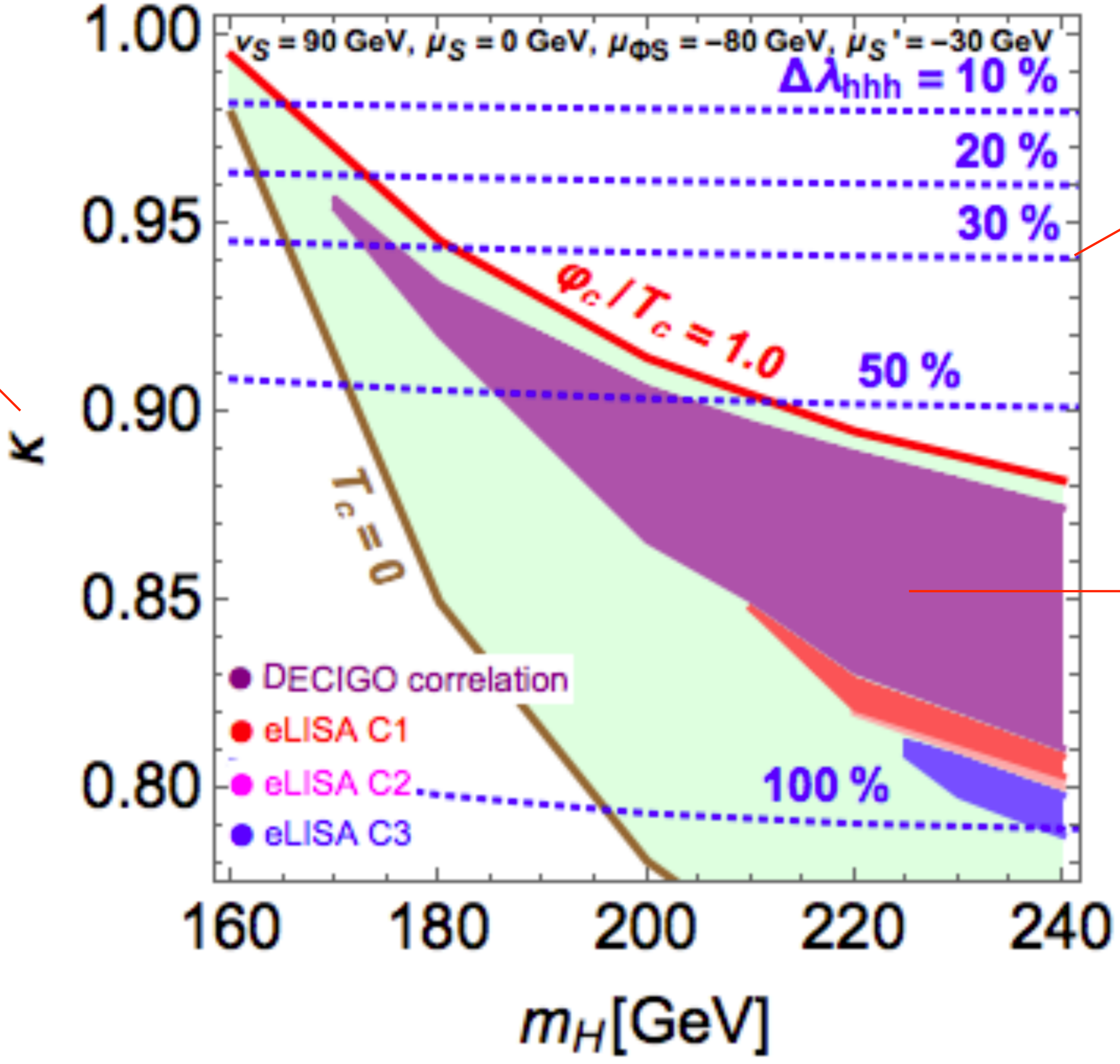
Strong 1st Order EW Phase Transition

e.g.: ***Doublet-Singlet Mixing Model (HSM)***

Precision Higgs Coupling Measurements

Uniform Shift

$\kappa_V=\kappa_f=\kappa$



g_{HHH} shift

Gravitational Wave

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

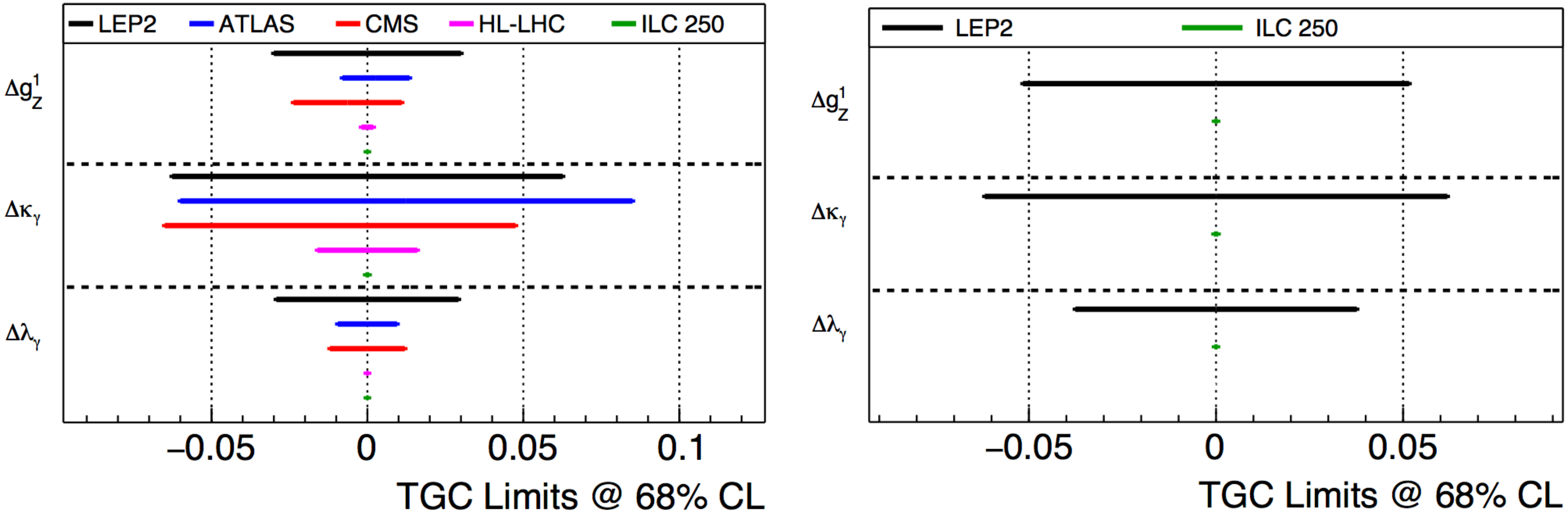
Fuyuno, Senaha: arXiv: 1406.0433

Hashino, Kakizaki, Kanemura, Matsui, Ko: arXiv 1609.00297

Higgs Studies

Example of Non-Higgs Process that plays an important role in the EFT fit

$e^+e^- \to W^+W^-$ (**T**riple **G**auge **C**ouplings)



(a) (b)

Figure 11: TGC precisions for LEP 2, Run1 at LHC, HL-LHC and the ILC at $\sqrt{s} = 250$ GeV with 2000 fb^{-1} luminosity (ILC 250) using one parameter fits (a) and for LEP 2 and ILC 250 using three parameter fits (b).

Significant improvements from HL-LHC and LEP2 !

coupling	current	S1*	S1	S2*	S2
hZZ - LHC	11.		2.5		1.7
- ILC 250		0.67	0.46	0.64	0.36
- ILC 500		0.35	0.20	0.32	0.18
hWW - LHC	15.		3.0		2.1
- ILC 250		0.66	0.44	0.62	0.36
- ILC 500		0.34	0.19	0.32	0.18
hbb - LHC	29.		5.5		4.0
- ILC 250		1.1	0.83	0.90	0.68
- ILC 500		0.58	0.42	0.48	0.36
$h\tau\tau$ - LHC	17.		3.6		2.8
- ILC 250		1.2	0.98	1.0	0.86
- ILC 500		0.74	0.63	0.67	0.59
hgg - LHC	15.		4.0		2.8
- ILC 250		1.7	1.6	1.3	1.2
- ILC 500		0.95	0.91	0.74	0.70
hcc - LHC	-		-		-
- ILC 250		1.9	1.8	1.4	1.3
- ILC 500		1.2	1.1	0.9	0.84
$h\gamma\gamma$ - LHC	15.		3.6		2.8
- ILC 250		1.2	1.1	1.2	1.0
- ILC 500		1.0	0.99	1.0	0.97
$h\mu\mu$ - LHC	70.		7.6		7.0
- ILC 250		5.6	5.6	5.5	5.5
- ILC 500		5.1	5.1	5.0	5.0
htt - LHC	14.		5.5		3.6
- ILC 250		-	5.5	-	3.6
- ILC 500		6.3	4.1	4.5	2.8
hhh - LHC			80		60
- ILC 500		-	80	-	60
- ILC 500		27	27	20	20
Γ_{tot} - ILC 250		2.5	1.3	2.1	1.1
- ILC 500		1.6	0.69	1.3	0.59
Γ_{inv} - ILC 250		0.32	-	0.32	-
- ILC 500		0.29	-	0.28	-

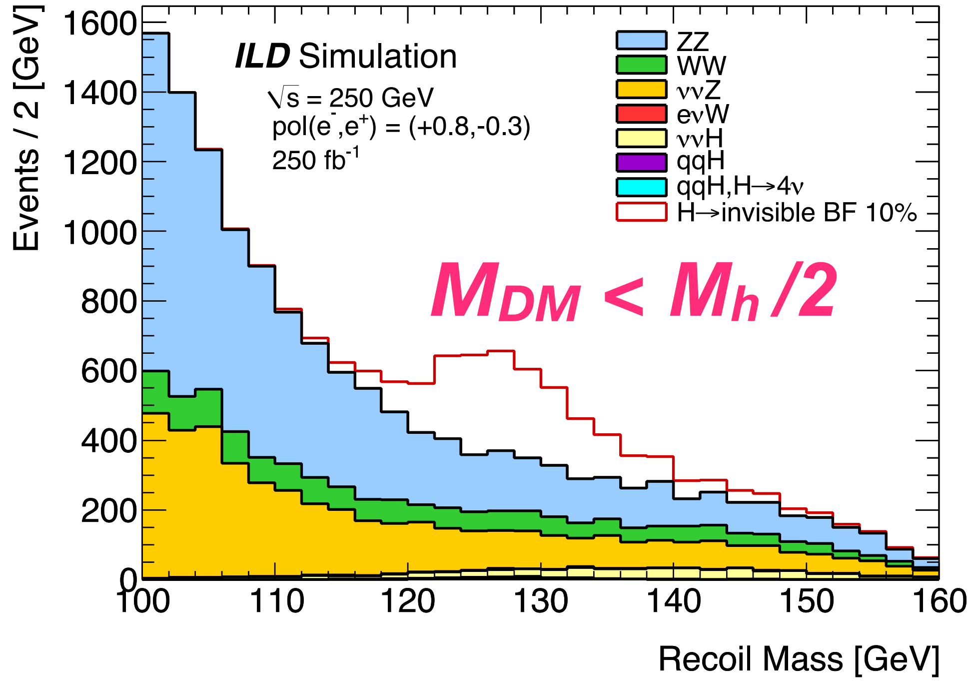
TABLE XV: Projected uncertainties in the Higgs boson couplings for LHC and for and for ILC at 250 GeV, with precision LHC input, in various scenarios. All values are given in percent (%). The values labeled "current" are taken from Table 8 of the CMS publication [240]. The LHC S1 and S2 values are taken from [239]. The ILC scenarios are as described in this paper. We also include our S1* and S1 projections including the full ILC data set with running at 250 GeV and 500 GeV. The ILC at 250 GeV only does not have direct sensitivity to the *htt* and *hhh* couplings; thus no model-independent values are given in these lines. The bottom lines give, for reference, the projected uncertainties in the Higgs boson total width and the 95% confidence limits on the Higgs boson invisible width. One should remember that one of the assumptions in the model-dependent S1/S2 fits is that the Higgs boson has no invisible or other exotic decay models. We believe that the comparison of the S1 values gives the sharpest comparison between the capabilities of LHC alone and the capabilities after adding the ILC measurements.

Invisible/Exotic※1 Higgs Decays

By making maximum use of Z-tagged Higgs bosons,
all kinds of invisible/exotic decays can be searched
for with high sensitivity

Invisible Higgs Decay

※1: exotic decays = non−SM decays



$M_{DM} < M_h/2$

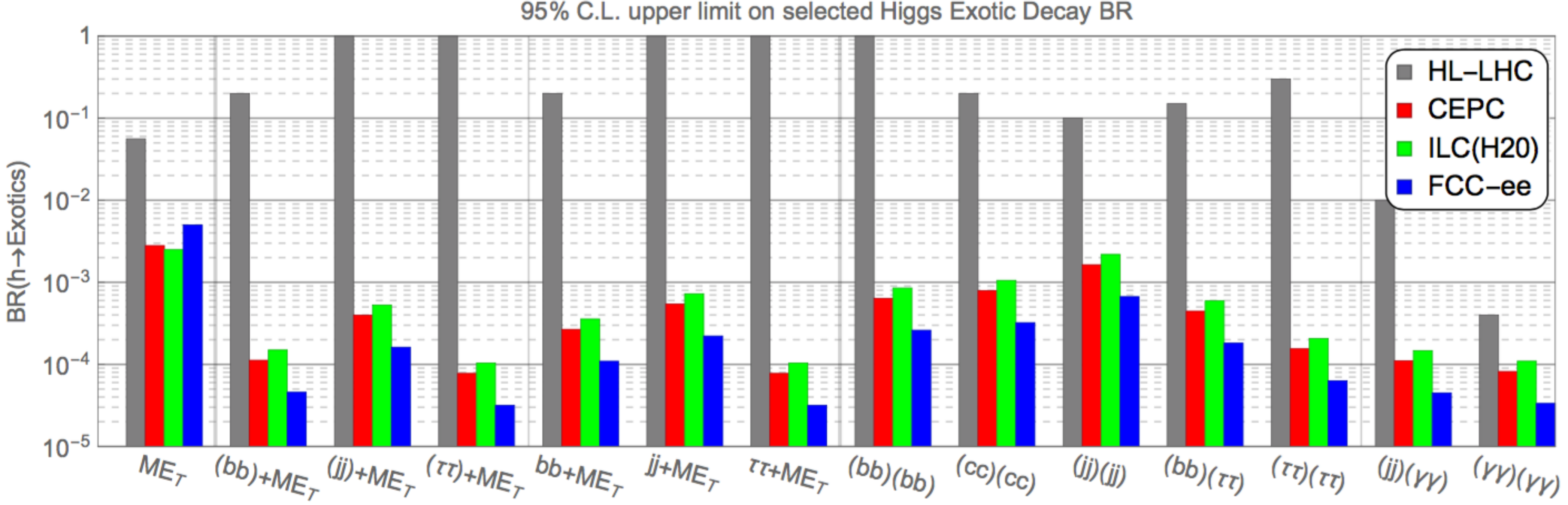
BR(H→invis.) < 0.3% at 95%CL
$2ab^{-1}$@ 250GeV

An attractive way to build a model of Dark Matter
= to assume a "Hidden Sector"

Invisible / Exotic Higgs Decays
= ideal hunting ground for

Higgs Portal	Neutrino Portal
$\epsilon\vert\varphi\vert^2\vert\hat{S}\vert^2$	$\epsilon\, L^\dagger\cdot\varphi\hat{N}$

Exotic Higgs Decays



Liu, Wang, Zhang
arXiv: 1612.09284

BR= 0.1%
→ >500 events
$2ab^{-1}$@ 250GeV

EFT Lagrangian Before EW Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

$$\begin{aligned}
\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .
\end{aligned}$$

Manifestly SU(2)xU(1) gauge invariant

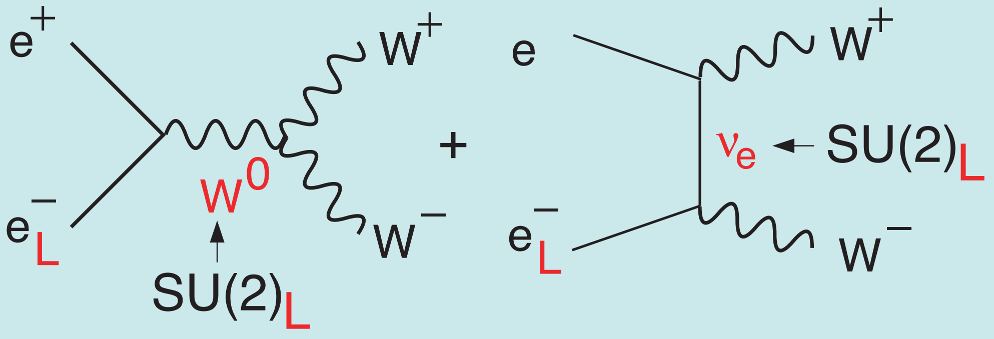
$$+\frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\tilde{B}^{\mu\nu}$$

10 parameters of which C_6 only affects Higgs self-coupling analysis.
5 parameters to account for Higgs coupling to b, c, τ, μ, g.
\+ **2** parameters to account for invisible and exotic Higgs decays.
\+ **4** parameters to account for the shifts of g, g’, v, and λ
\+ **2** parameters (CHL-type) to shift W, Z widths.

Direct/Indirect Searches

Power of Beam Polarization

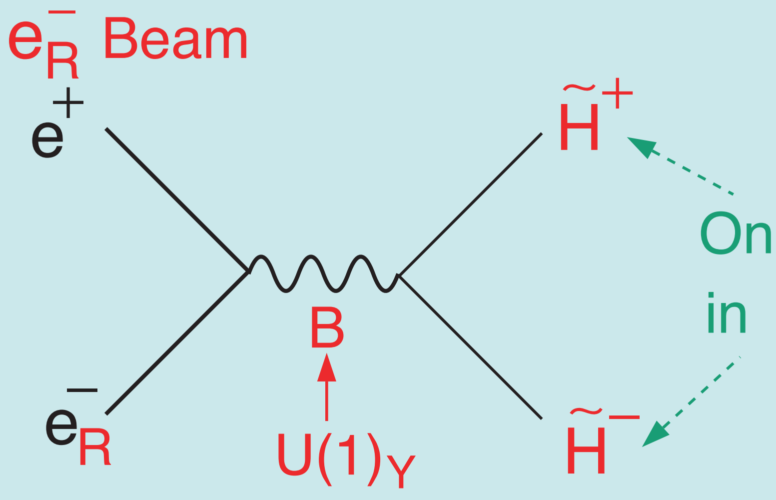
W^+W^- *(Largest SM BG in SUSY searches)*



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

BG Suppression

Chargino Pair



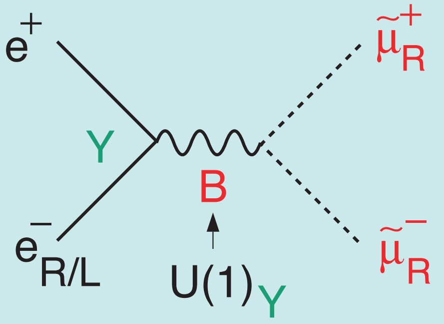
Only $\tilde{H}^{\pm}$ components in $\tilde{\chi}^{\pm}_1$ contribute !

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

$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \underset{\langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle}{\underset{\parallel}{\bullet}} \cdot \tilde{H}^{\pm}$$

Decomposition

Slepton Pair

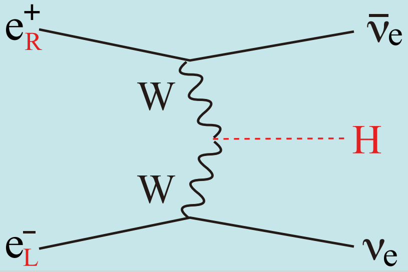


$Y_L = -1/2$: e^-_L

$Y_R = -1$: e^-_R

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

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

3. Higgsino Search

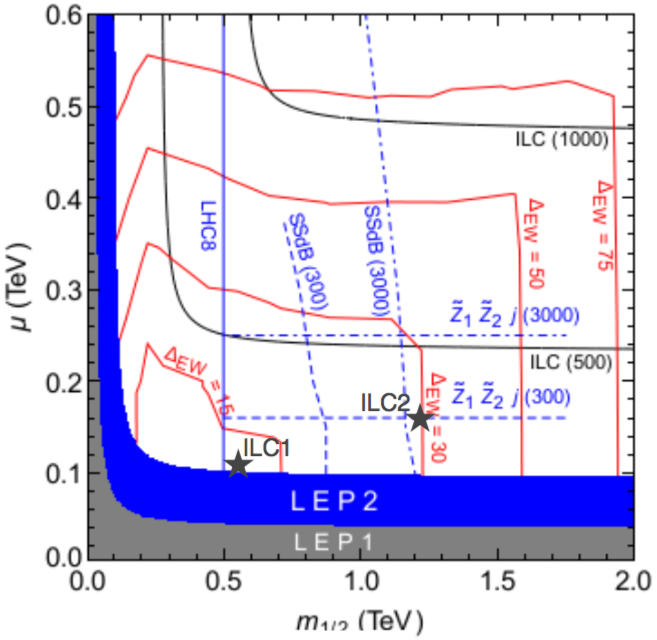
Radiatively driven Natural SUSY

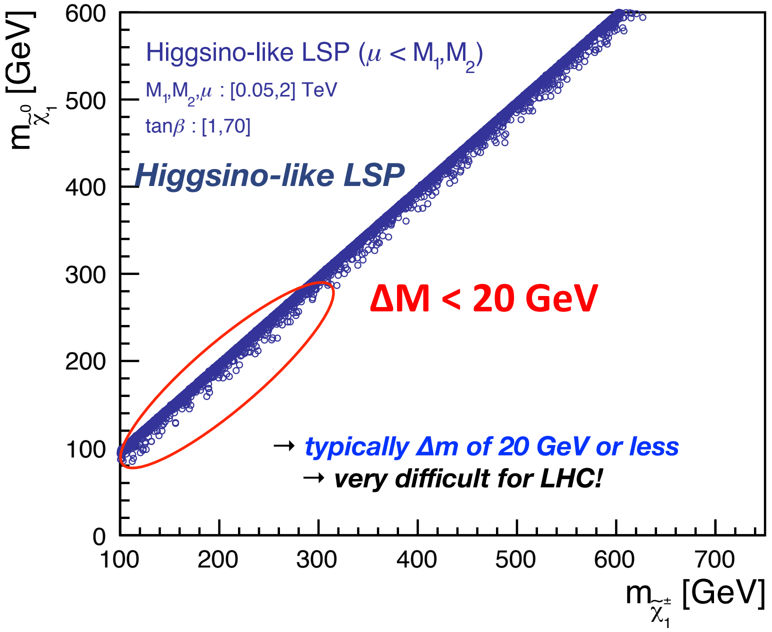
μ not far above 100GeV

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

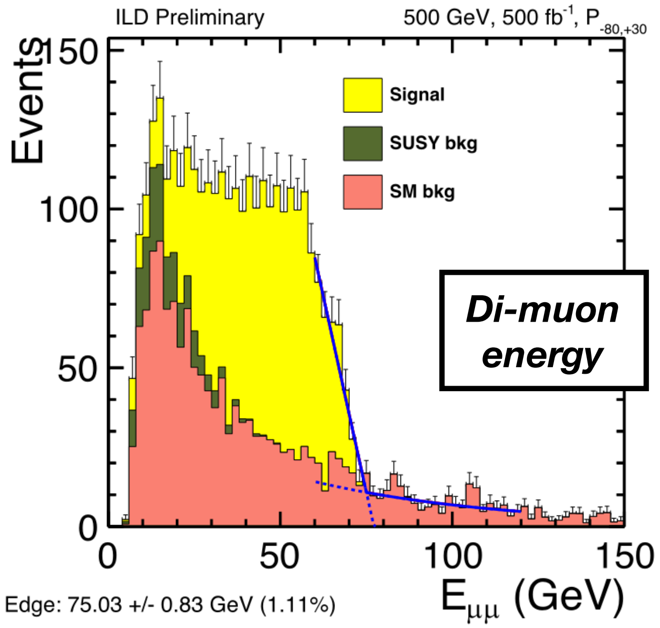
Chargino & neutralino production (ILC1)

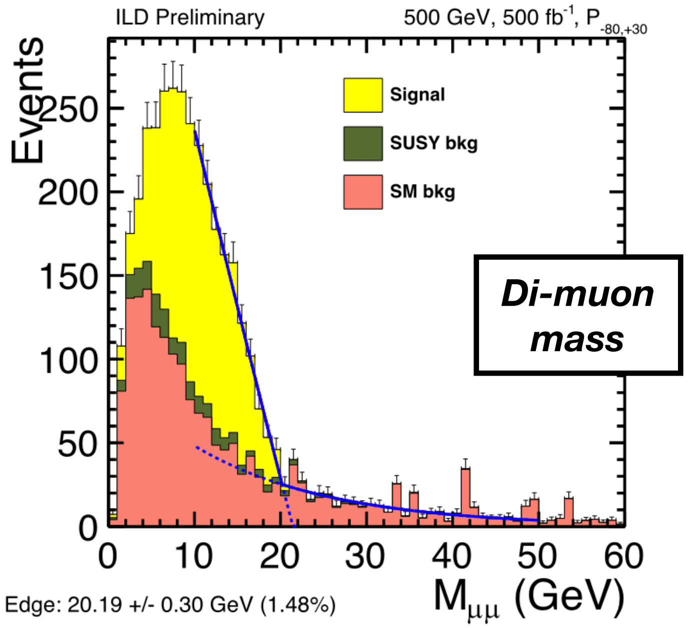
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$





T. Tanabe: LCWS2017





cross section and mass measurements

Kinematical edges→ M_X

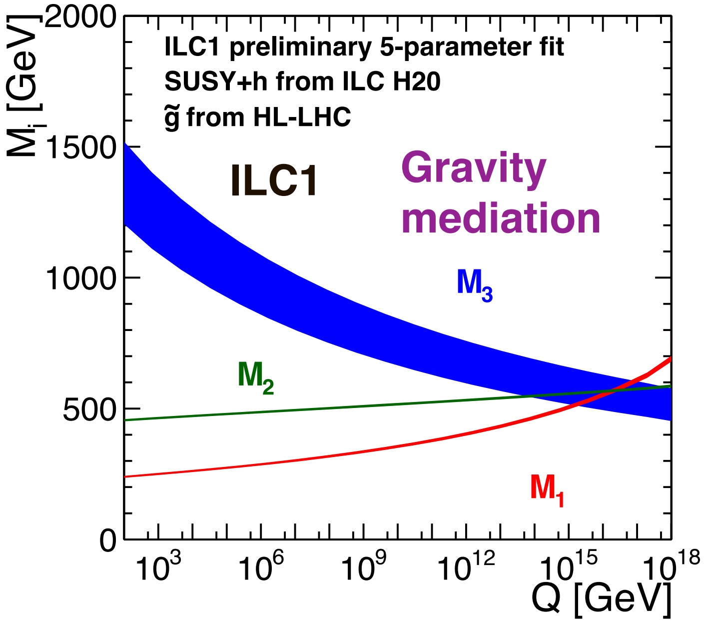
"ILC1 benchmark": ΔM∼ 20GeV

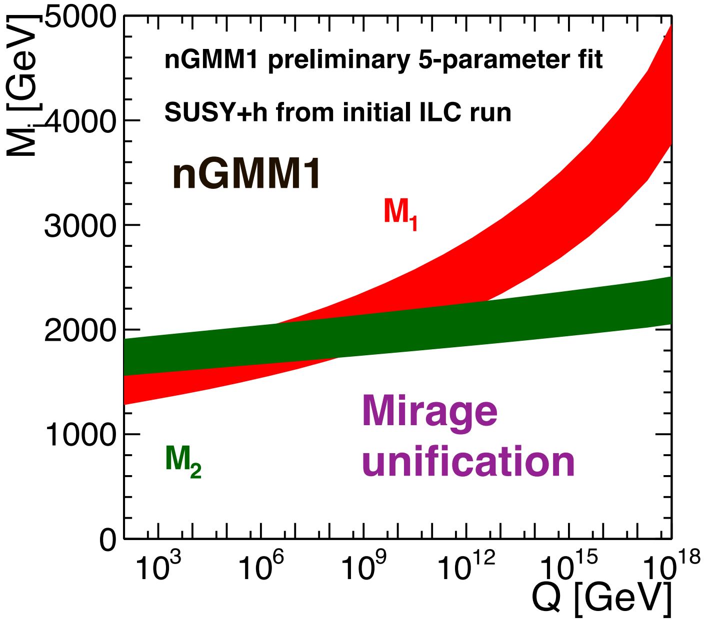
σ_M to ~2% M to ~1% (H20)

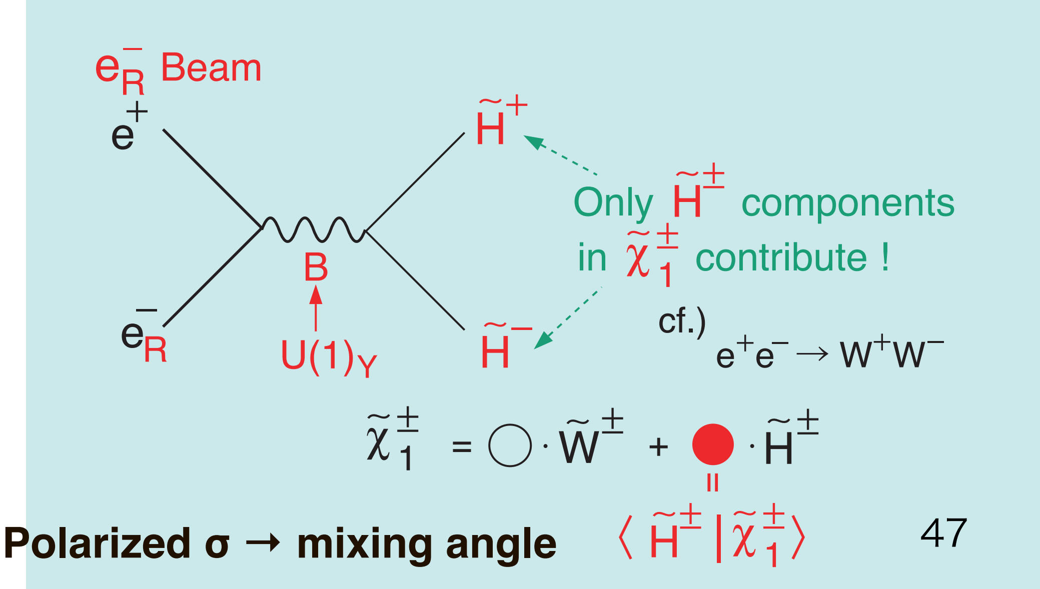
Power of beam polarization

→ Higgsino/gaugino decomposition

Test of gauging mass unification







Only $\tilde{H}^\pm$ components in $\tilde{\chi}_1^\pm$ contribute !

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

$$\tilde{\chi}_1^\pm = \bigcirc\cdot\tilde{W}^\pm + \bullet\cdot\tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$$

Polarized σ → mixing angle

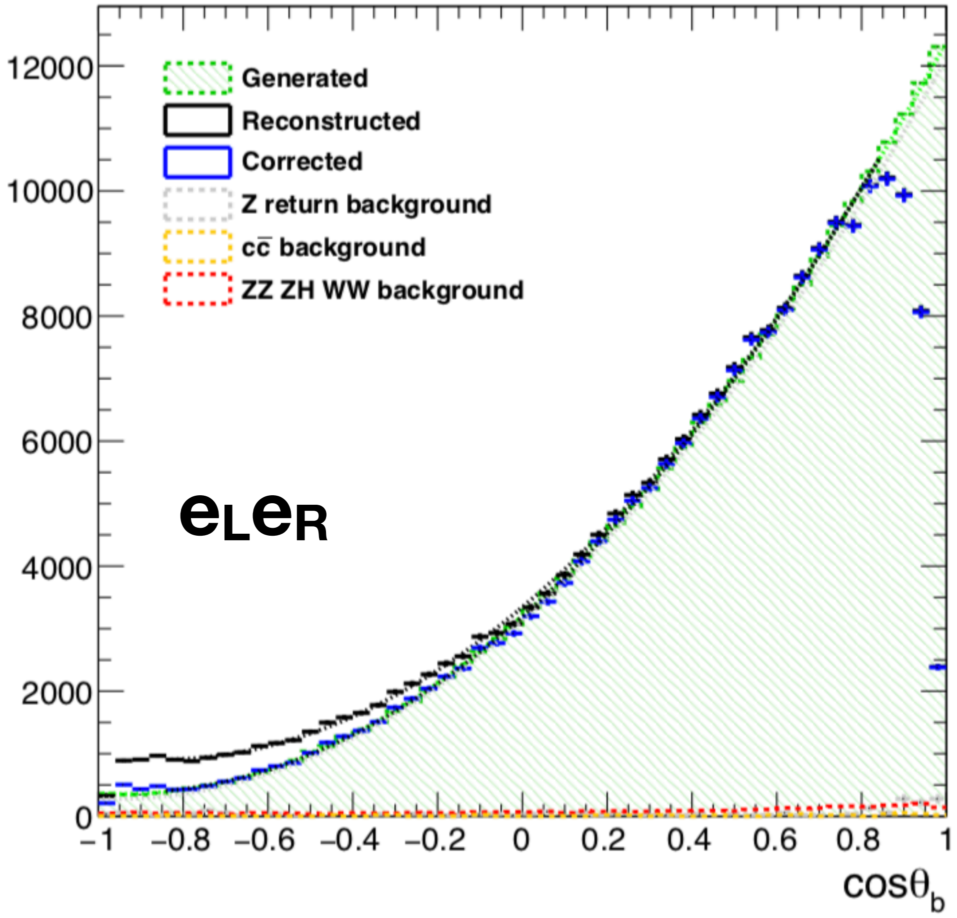
500GeV → ***ILC1: 250GeV***
ILC2: 350GeV

b-quark EW Form Factors

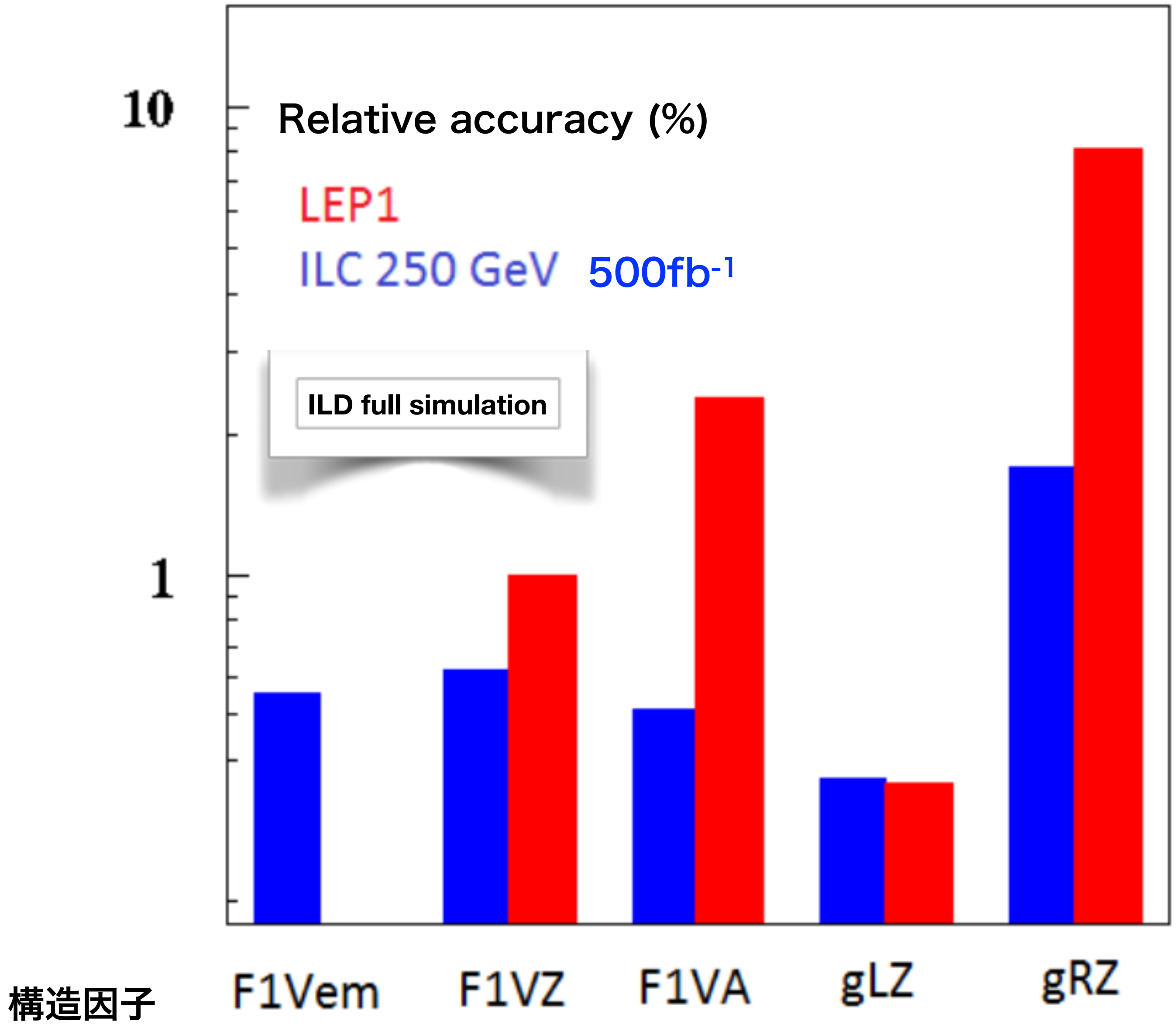
$$e^+e^- \to b\bar{b}$$

arXiv: 1709.04289

Vertex charge + K ID with dE/dx



Bilokhin, Poeschl, Richard



ILC has
- **10^3 times higher luminosity**
- **much improved detectors**
- **polarized beams**

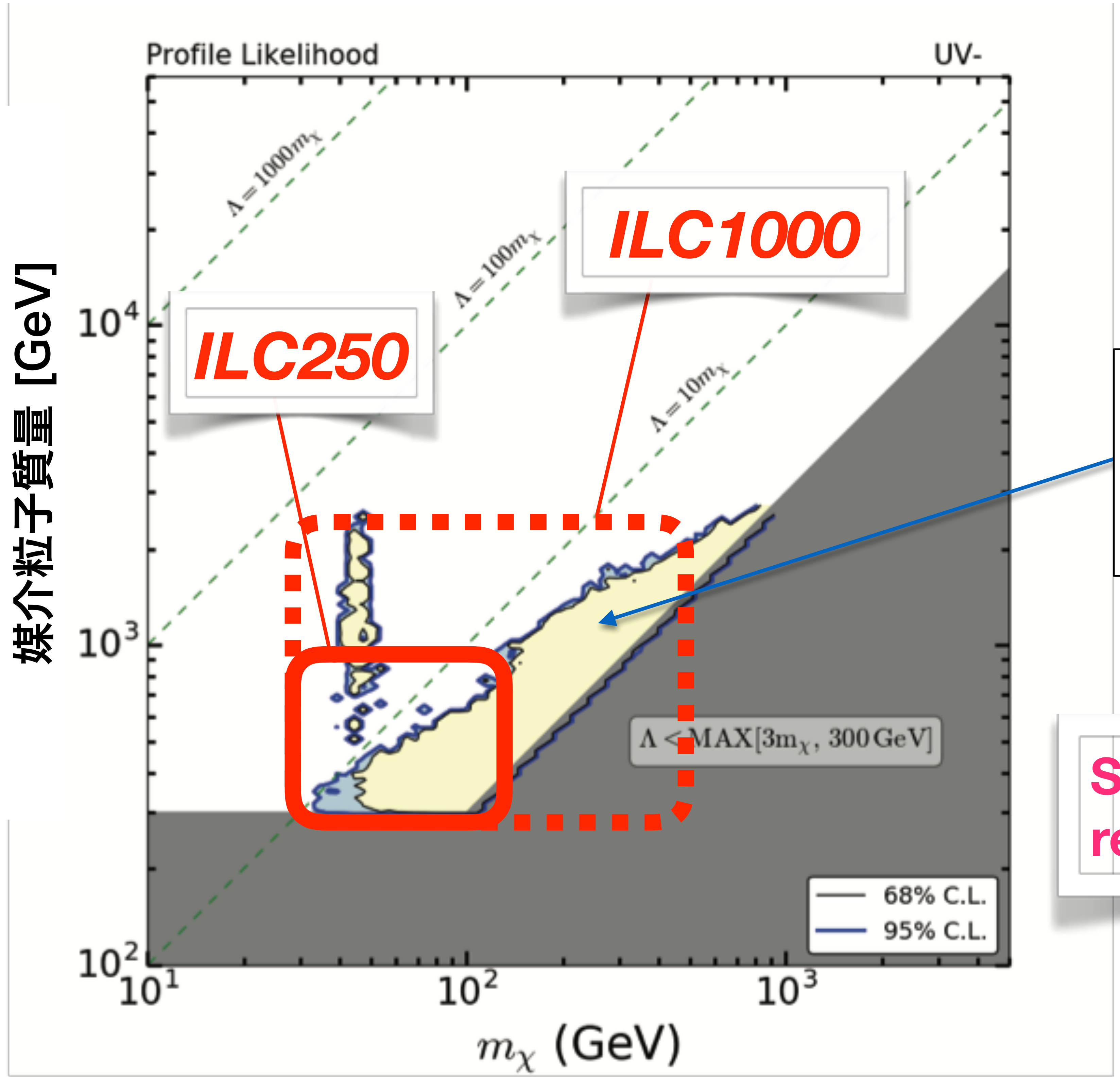
as compared to LEP

ILC will put a period to long outstanding LEP A_{FB}(b) anomaly.
Once confirmed → BSM study

WIMP Search

Mono-photon search

arXiv: 1702.05377

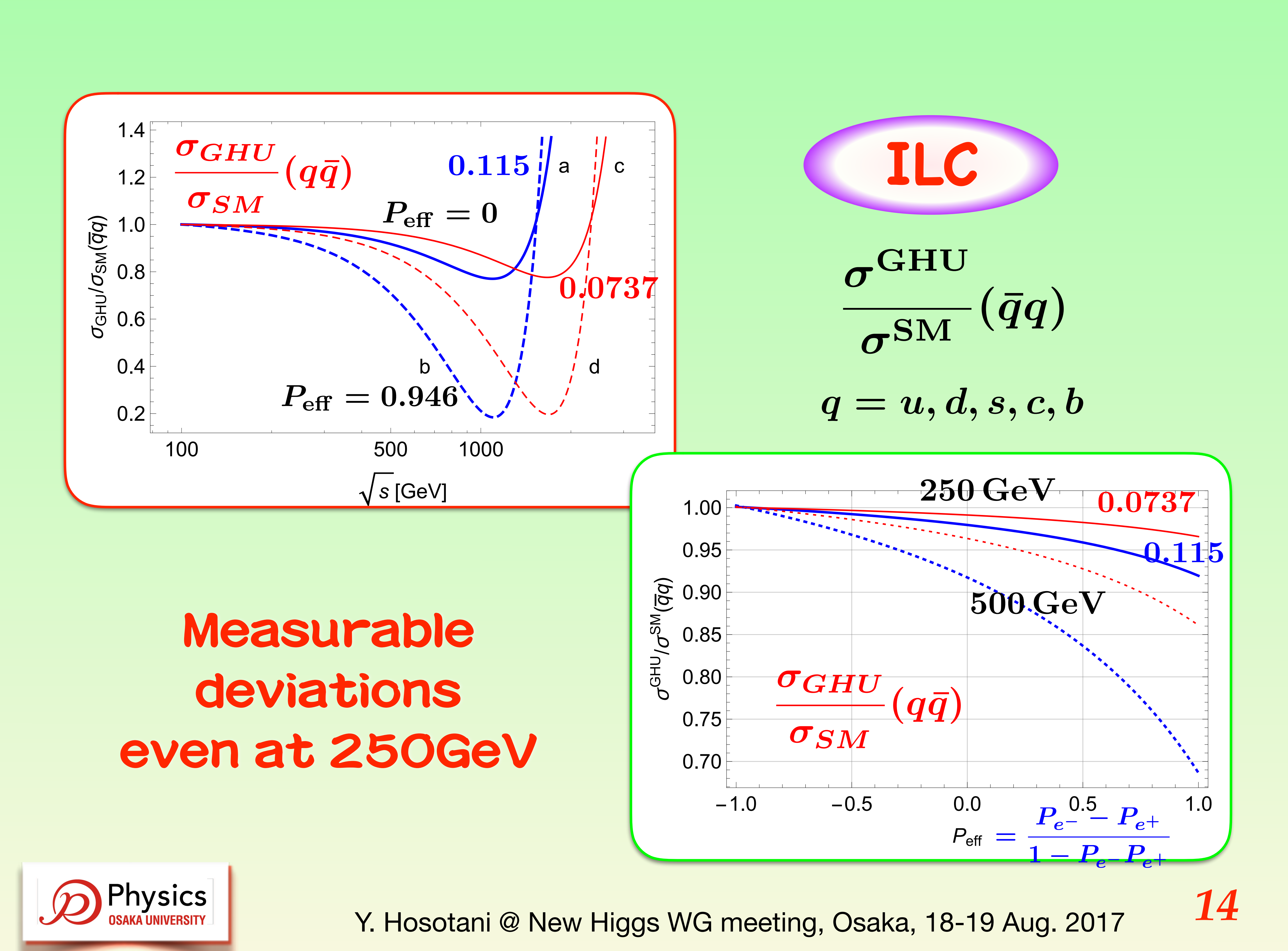


Light yellow region
= to be left for ILC
(after future direct searches
including HL-LHC)

Significant chunk of region remains for ILC250!

Gauge Higgs Unification

PL B 775 (2017) 297 (arXiv:1705.05282) : Funatsu, Hatanaka, **Hosotani**, Orikasa



ILC

$$\frac{\sigma^{\rm GHU}}{\sigma^{\rm SM}}(\bar{q}q)$$

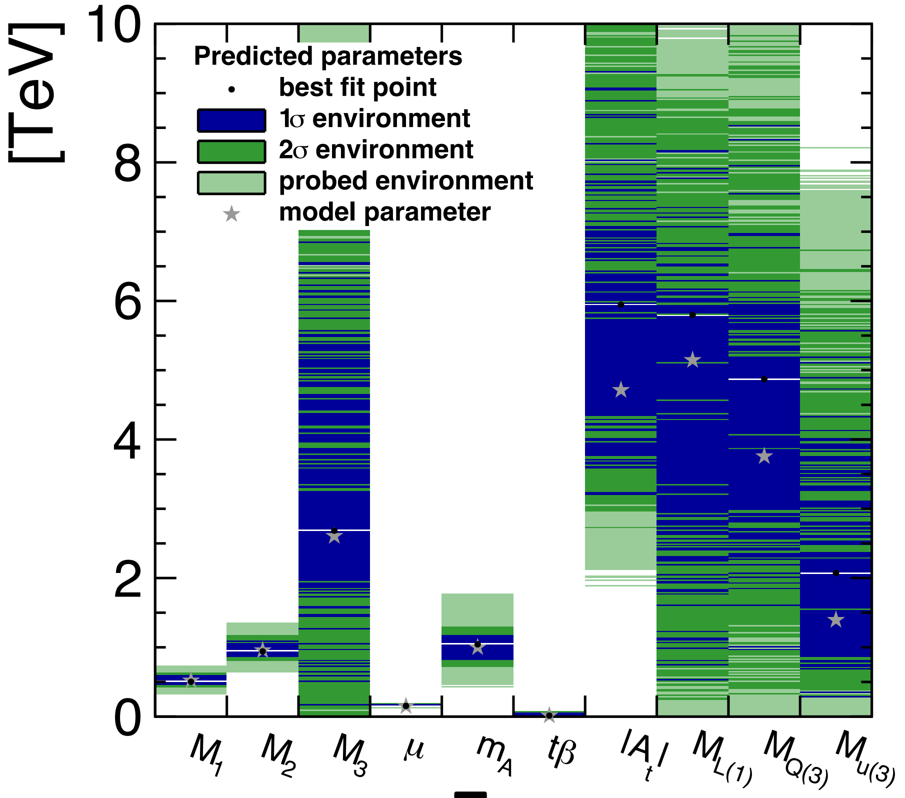
$$q = u, d, s, c, b$$

Measurable deviations even at 250GeV

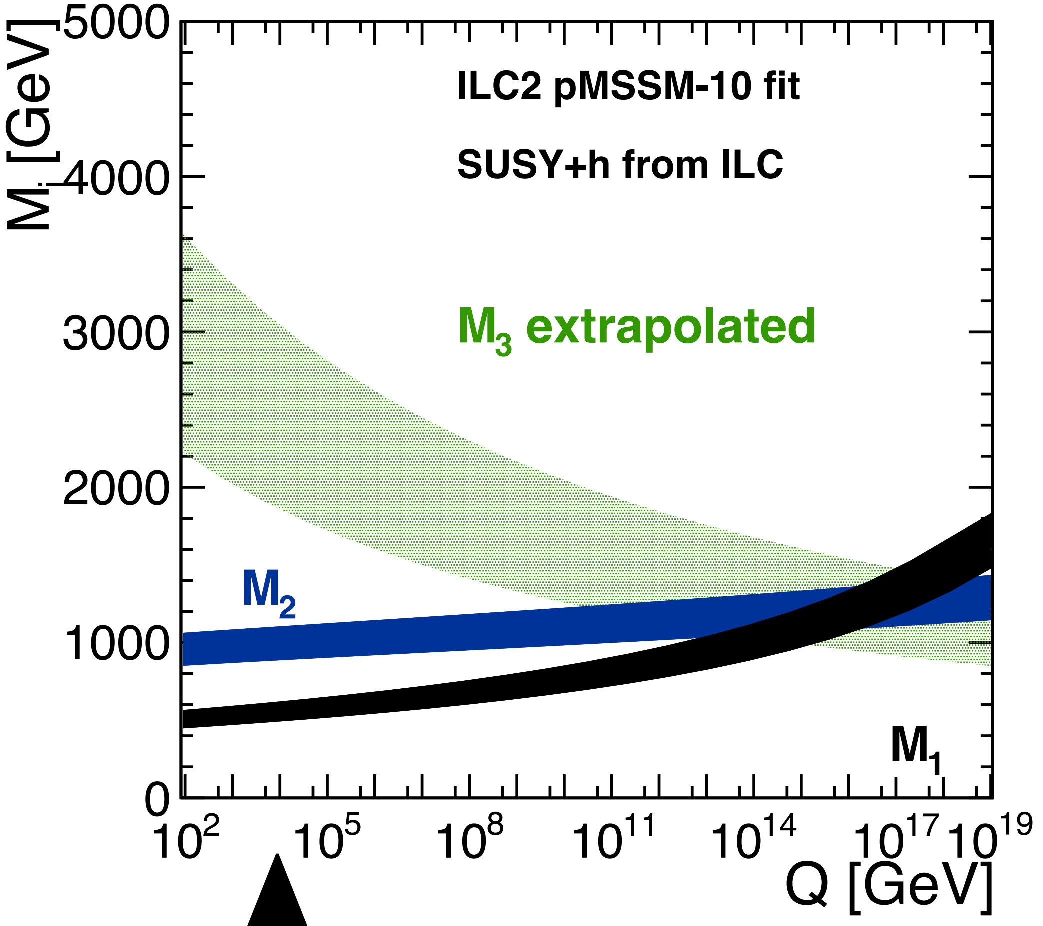
Y. Hosotani @ New Higgs WG meeting, Osaka, 18-19 Aug. 2017

14

Example: ILC2: *10-parameter* Fit (H20)

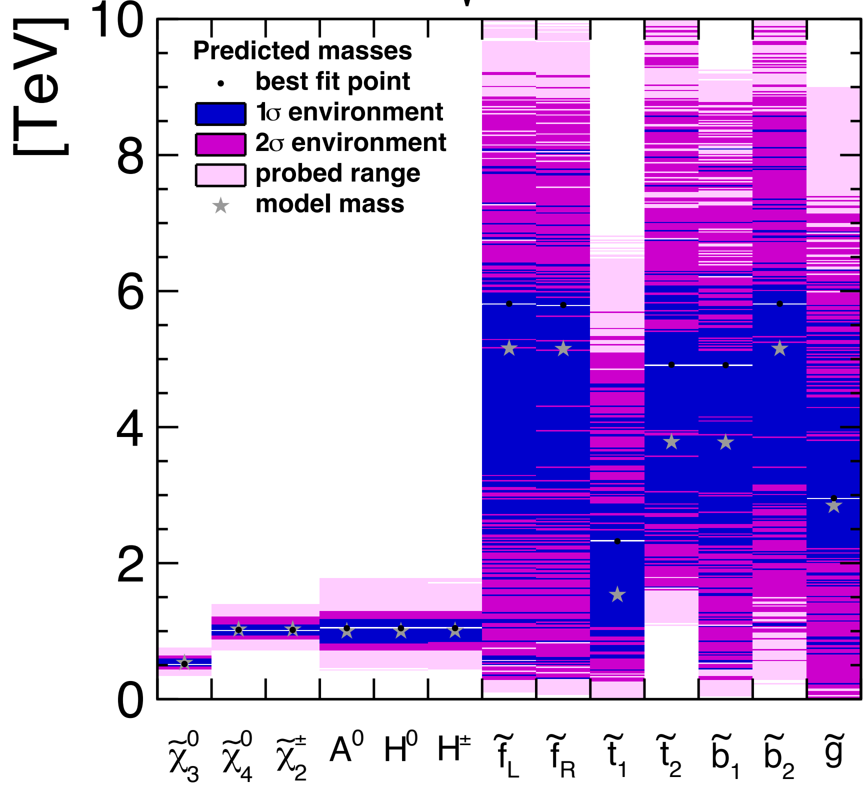


Assuming GUT relation, predict M3 at the EW scale



Or, if a gluino found at LHC, we can test Gaugino mass unification

Prediction of heavy states



N2, N4, C2 masses to ~10%

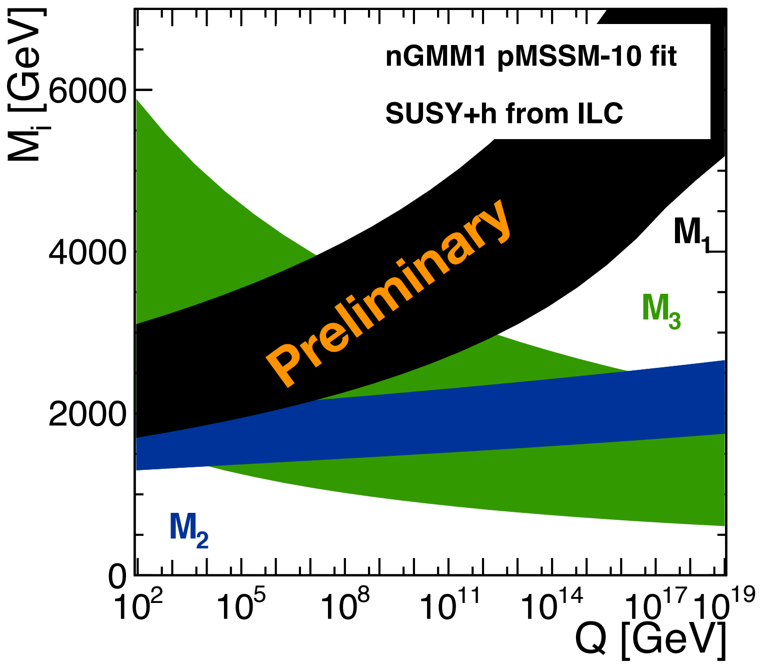
A, H, H+/- masses to ~20%

Sets the target for ILC E-upgrade

Upper limit on stop, other sfermions and gluino

Sets the Energy for next machine?

Distinguish different SUSY breaking scenarios



Can exclude standard GUT-scale unification

nGMM1