MC4BSM2016 July 21, 2016

ILC Physics

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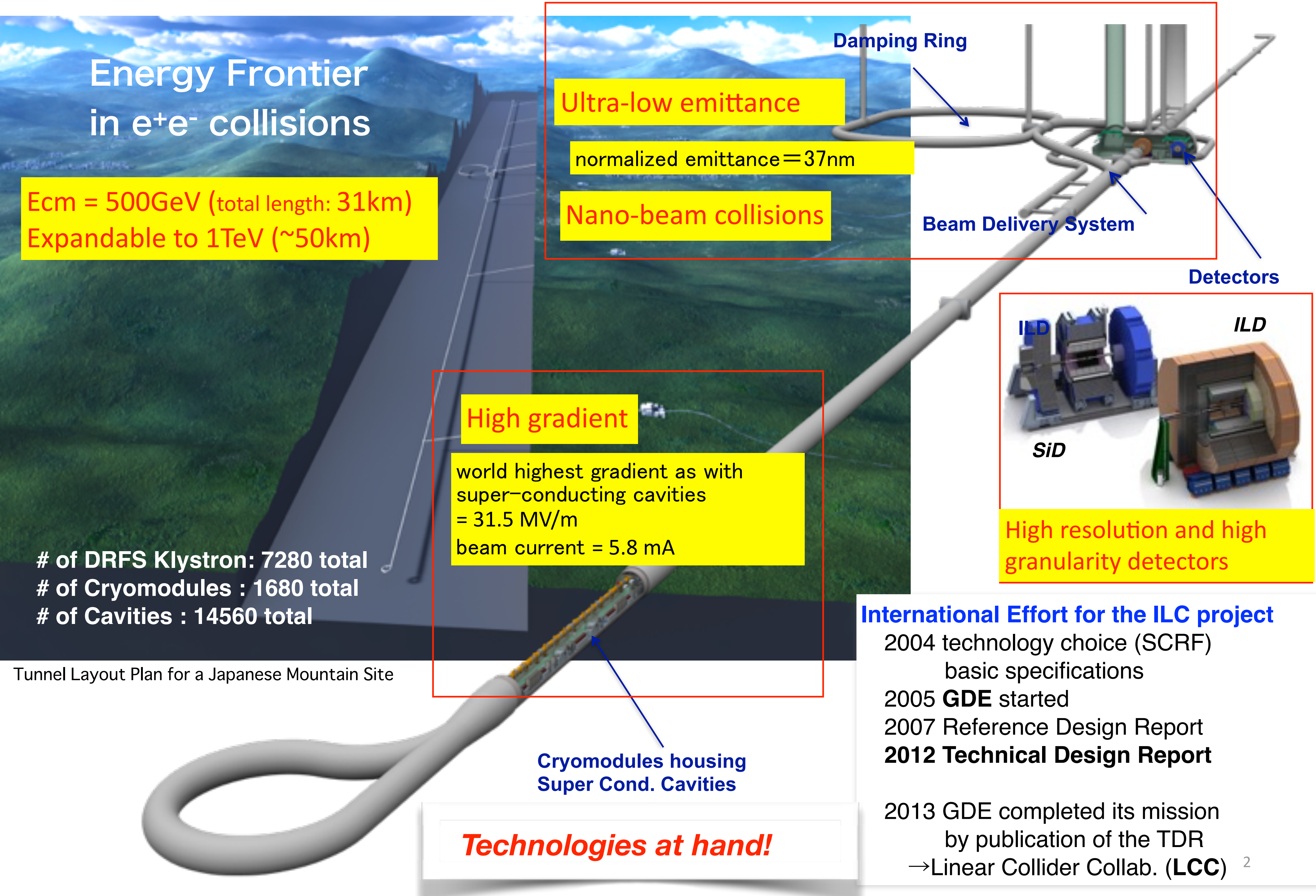
KEK

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

International Linear Collider (ILC)



Energy Frontier
in e^+e^- collisions

Ecm = 500GeV (total length: 31km)
Expandable to 1TeV (~50km)

Ultra-low emittance

normalized emittance＝37nm

Nano-beam collisions

High gradient

world highest gradient as with super–conducting cavities = 31.5 MV/m
beam current = 5.8 mA

High resolution and high granularity detectors

# of DRFS Klystron: 7280 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

Tunnel Layout Plan for a Japanese Mountain Site

Technologies at hand!

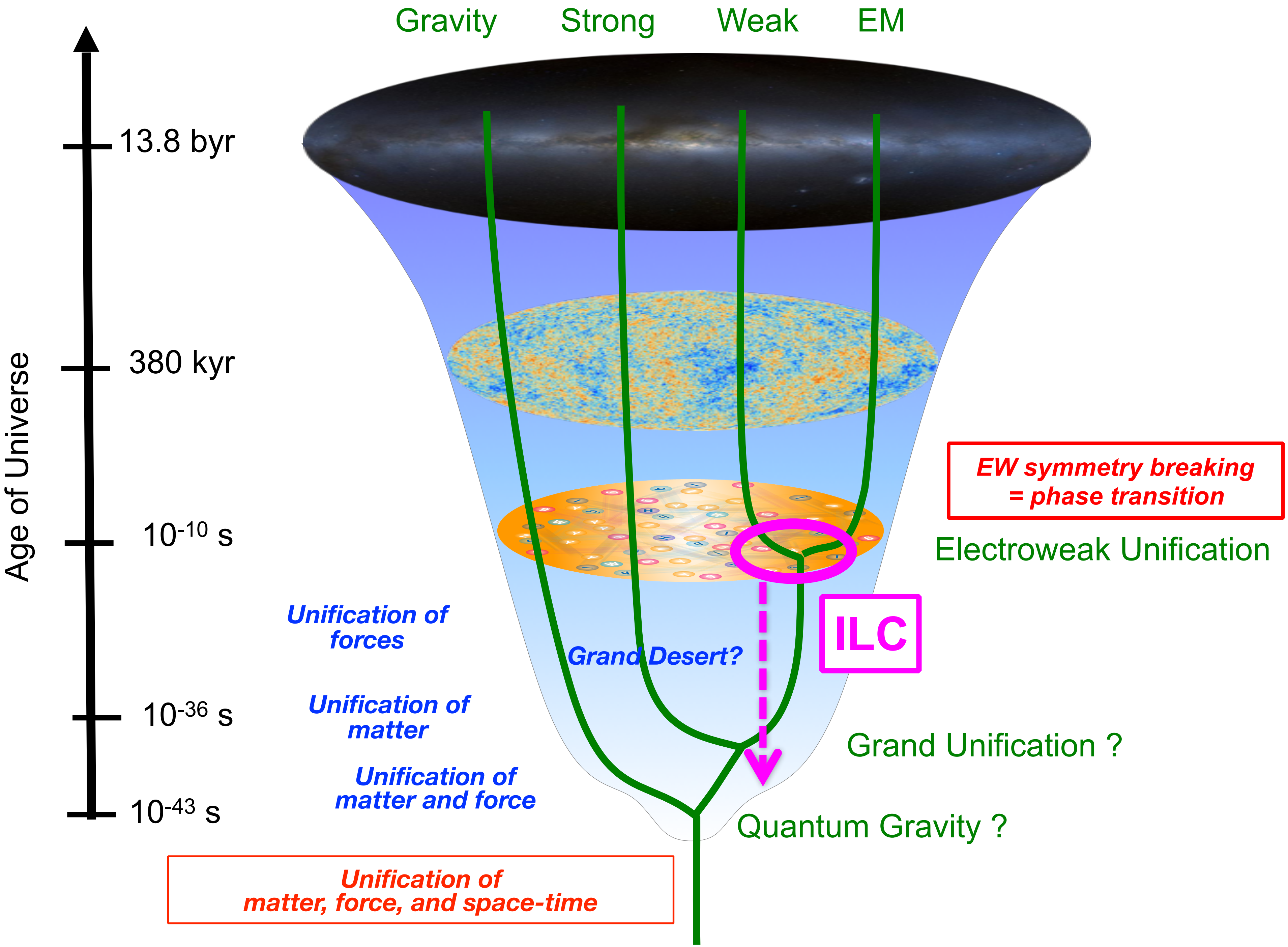
International Effort for the ILC project

2004 technology choice (SCRF)
basic specifications
2005 **GDE** started
2007 Reference Design Report
2012 Technical Design Report

2013 GDE completed its mission
by publication of the TDR
→Linear Collider Collab. (**LCC**)

Physics at ILC

Towards ultimate unification



Gravity Strong Weak EM

Age of Universe

13.8 byr

380 kyr

10^{-10} s

10^{-36} s

10^{-43} s

EW symmetry breaking
= phase transition

Electroweak Unification

ILC

Unification of forces

Grand Desert?

Unification of matter

Grand Unification ?

Unification of matter and force

Quantum Gravity ?

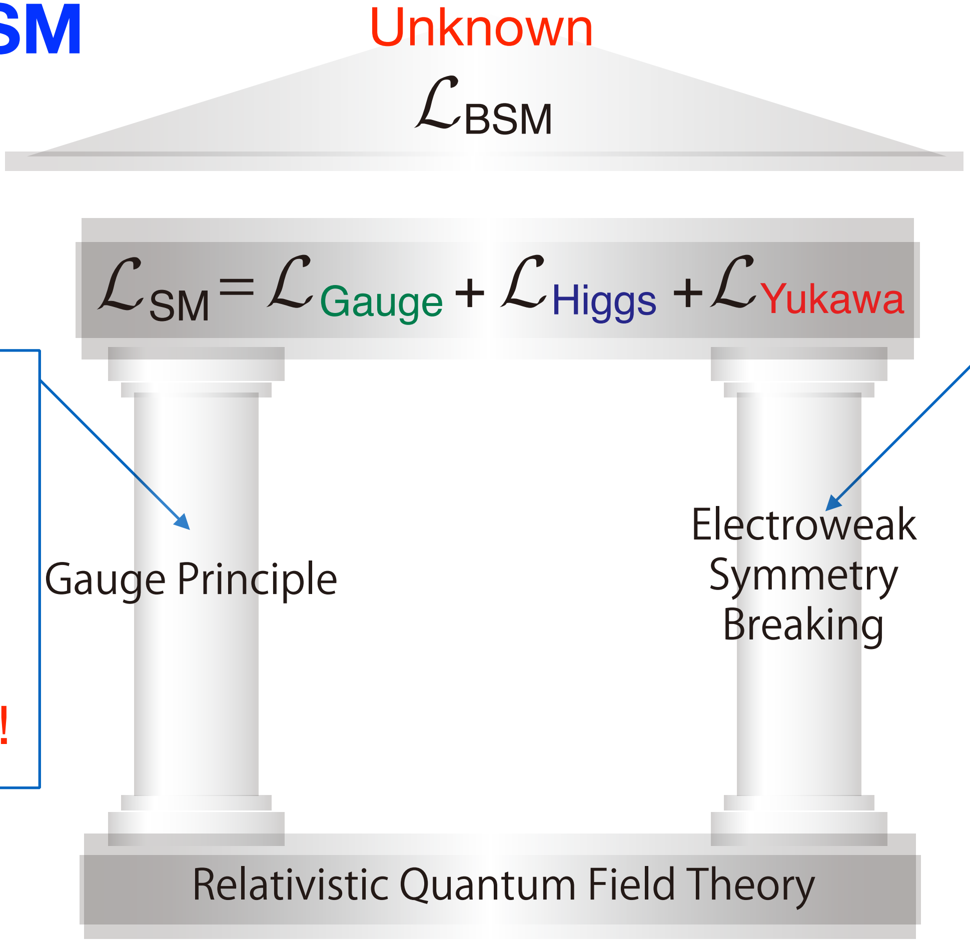
Unification of
matter, force, and space-time

Why is the EW scale so important ?

Why is the EW scale so important?

Mystery of something in the vacuum

2 Pillars of SM



Unknown

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

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

Gauge Principle

Electroweak Symmetry Breaking

Relativistic Quantum Field Theory

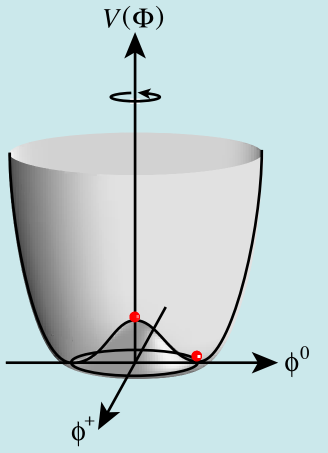
Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

Vacuum filled with weak charge (evidence: H125)

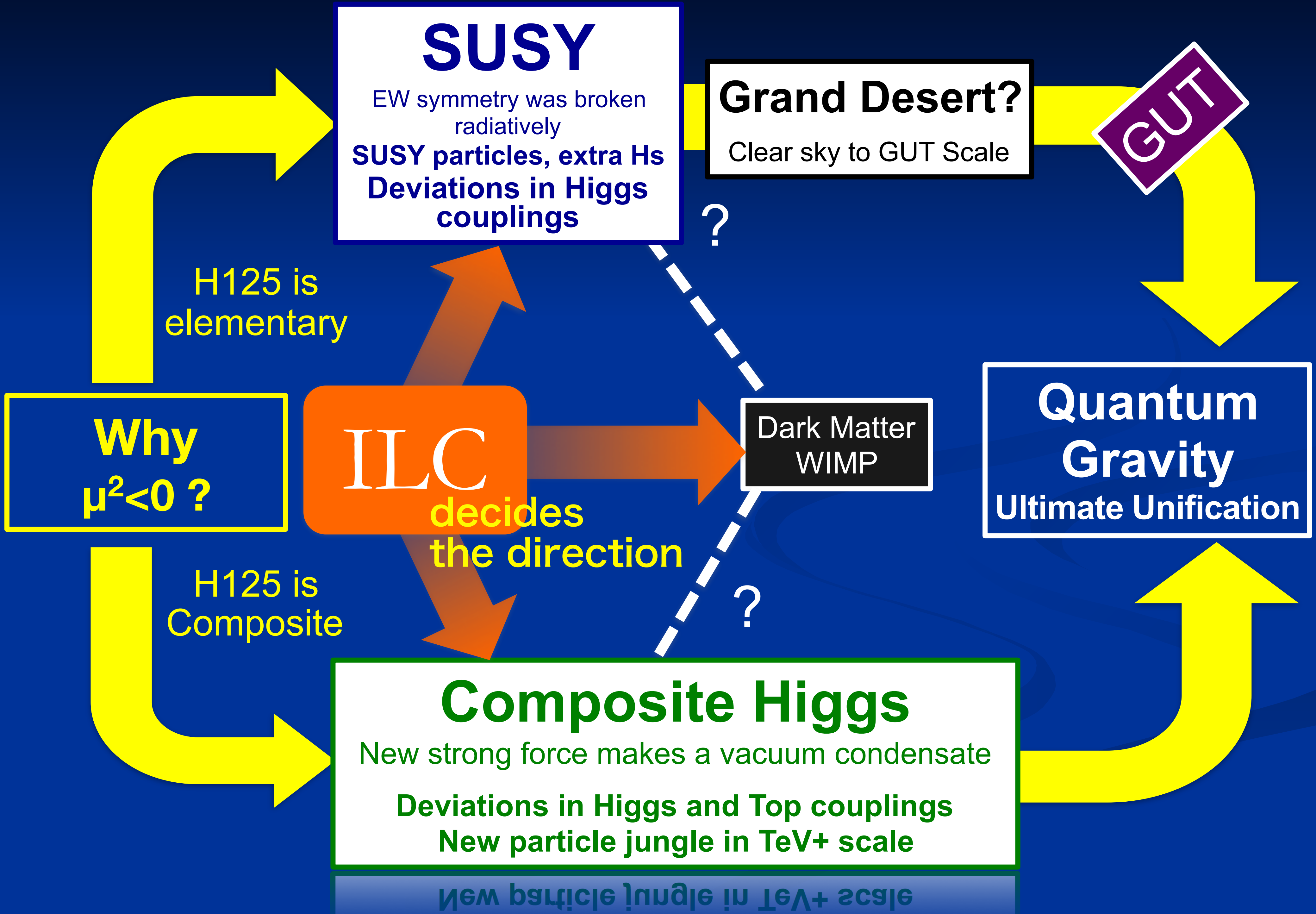
The nature of the Higgs field - its multiplet structure & dynamics behind it - is all unknown!

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



The SM does not explain **why the Higgs field 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



SUSY

EW symmetry was broken radiatively

SUSY particles, extra Hs

Deviations in Higgs couplings

Grand Desert?

Clear sky to GUT Scale

H125 is elementary

Why

$\mu^2<0$?

ILC

decides the direction

Dark Matter
WIMP

Quantum Gravity

Ultimate Unification

H125 is Composite

Composite Higgs

New strong force makes a vacuum condensate

Deviations in Higgs and Top couplings

New particle jungle in TeV+ scale

New particle jungle in TeV+ scale

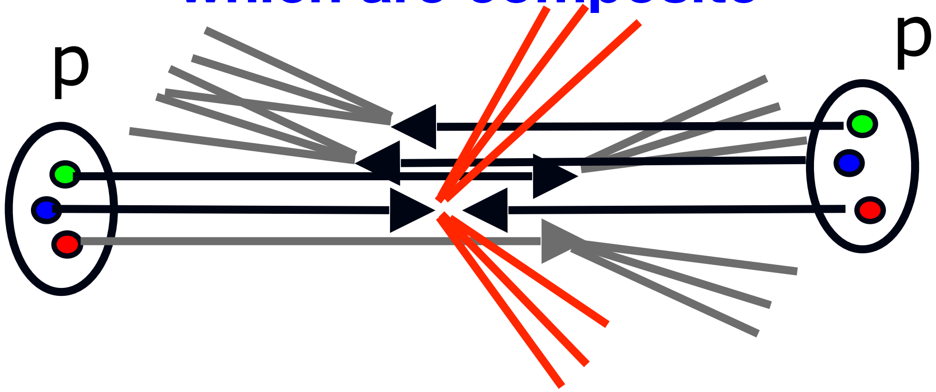
The 3 major probes for BSM at ILC:

Higgs, ***Top***, **and search for**

New Particles

3 Powerful Tools

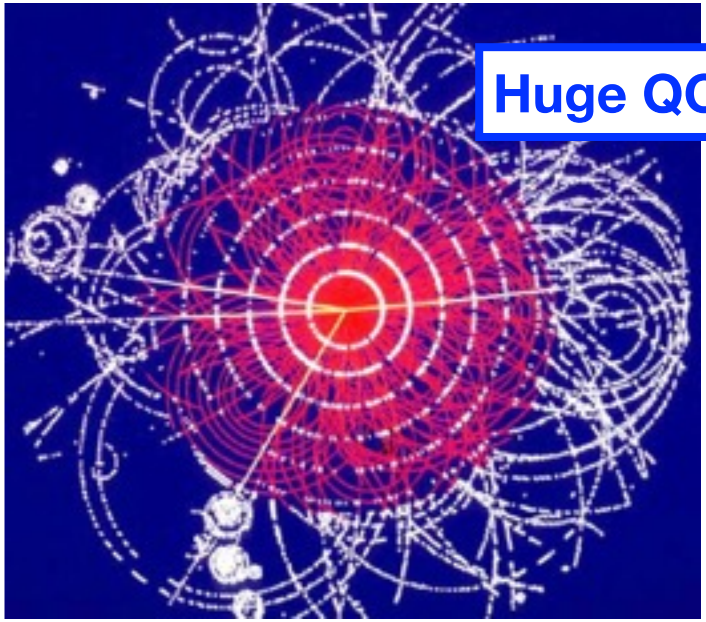
LHC: Collision of protons which are composite



Ecm 7-14 TeV

Pileup

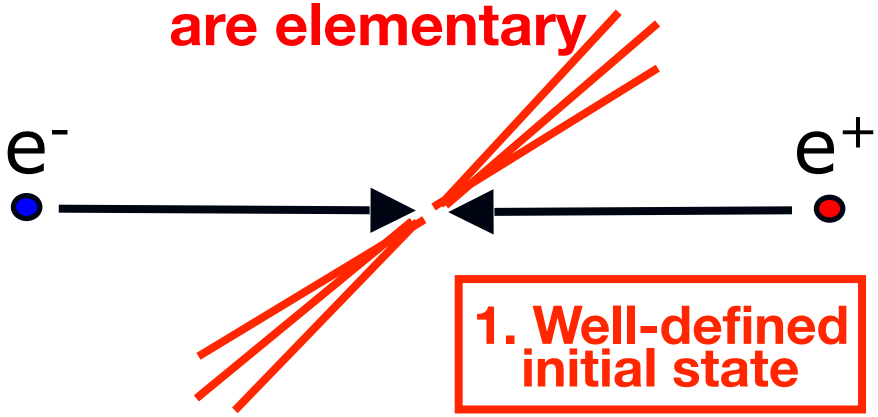
Initial state not very well defined



Huge QCD BG

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

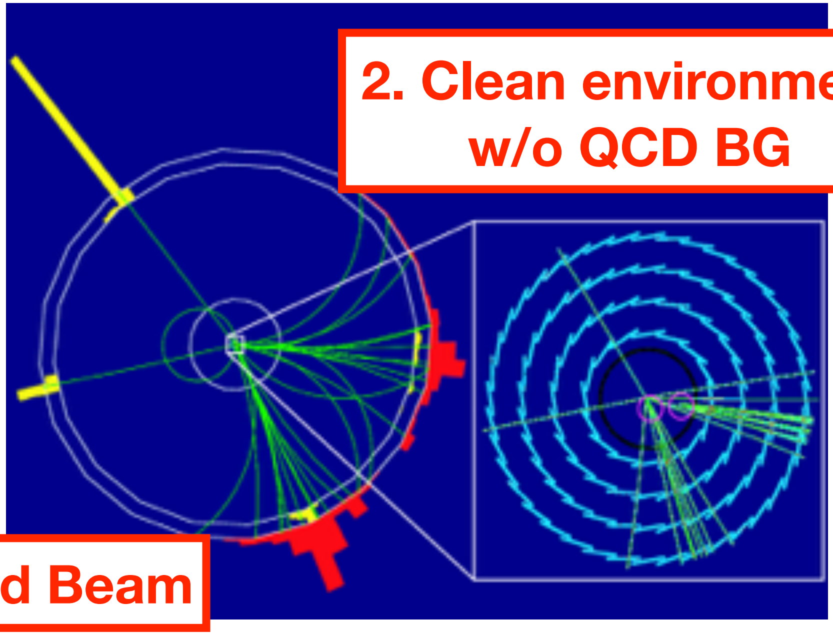
ILC: Collision of e^+e^- which are elementary



1. Well-defined initial state

Ecm 0.25-1 TeV

Lab. frame = CM frame



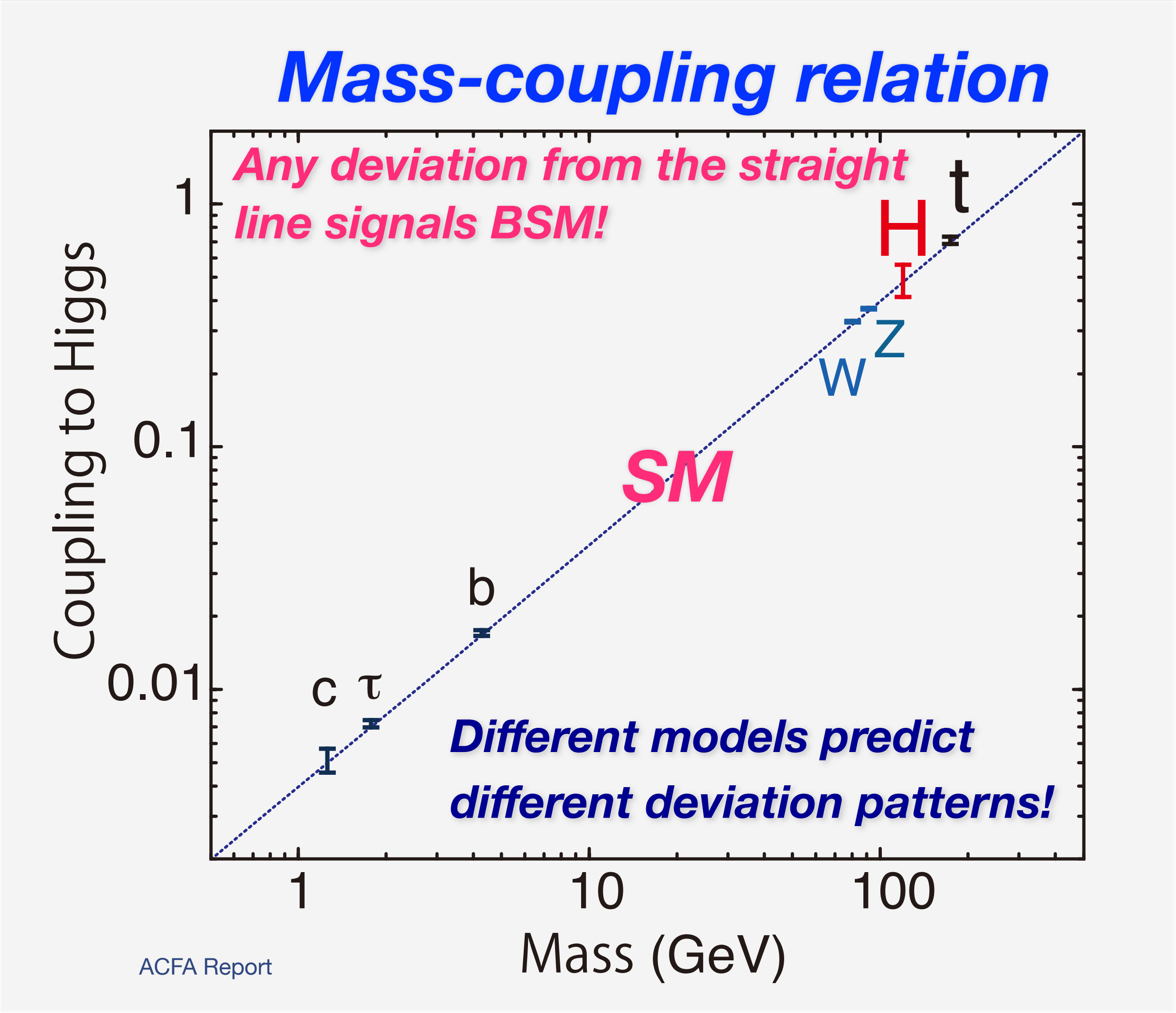
2. Clean environment w/o QCD BG

3. Polarized Beam

clean and and able to detect everything produced!

Higgs

Deviation in Higgs Couplings



Mass-coupling relation

Any deviation from the straight line signals BSM!

SM

Different models predict different deviation patterns!

ACFA Report

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

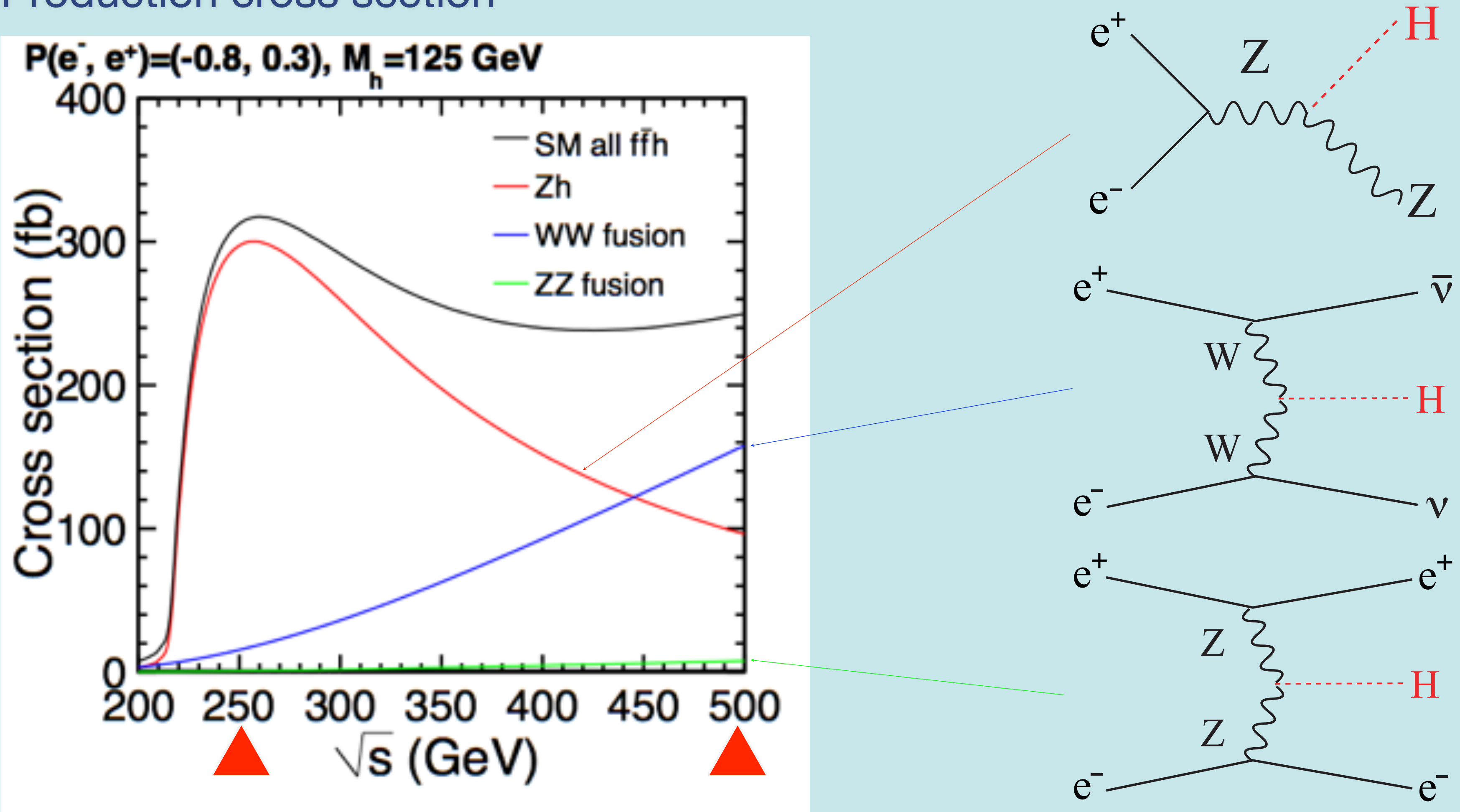
New physics at 1 TeV → **deviation is at most ~10%**

We ***need a %-level precision*** → LHC is not enough → ***ILC***

Main Production Processes

Single Higgs Production

Production cross section



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

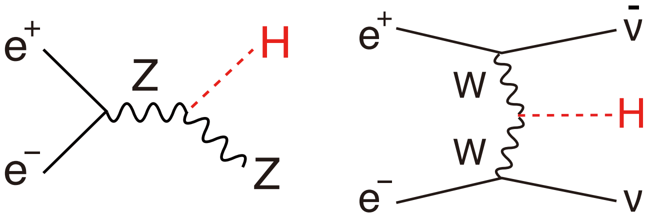
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

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

Key Point

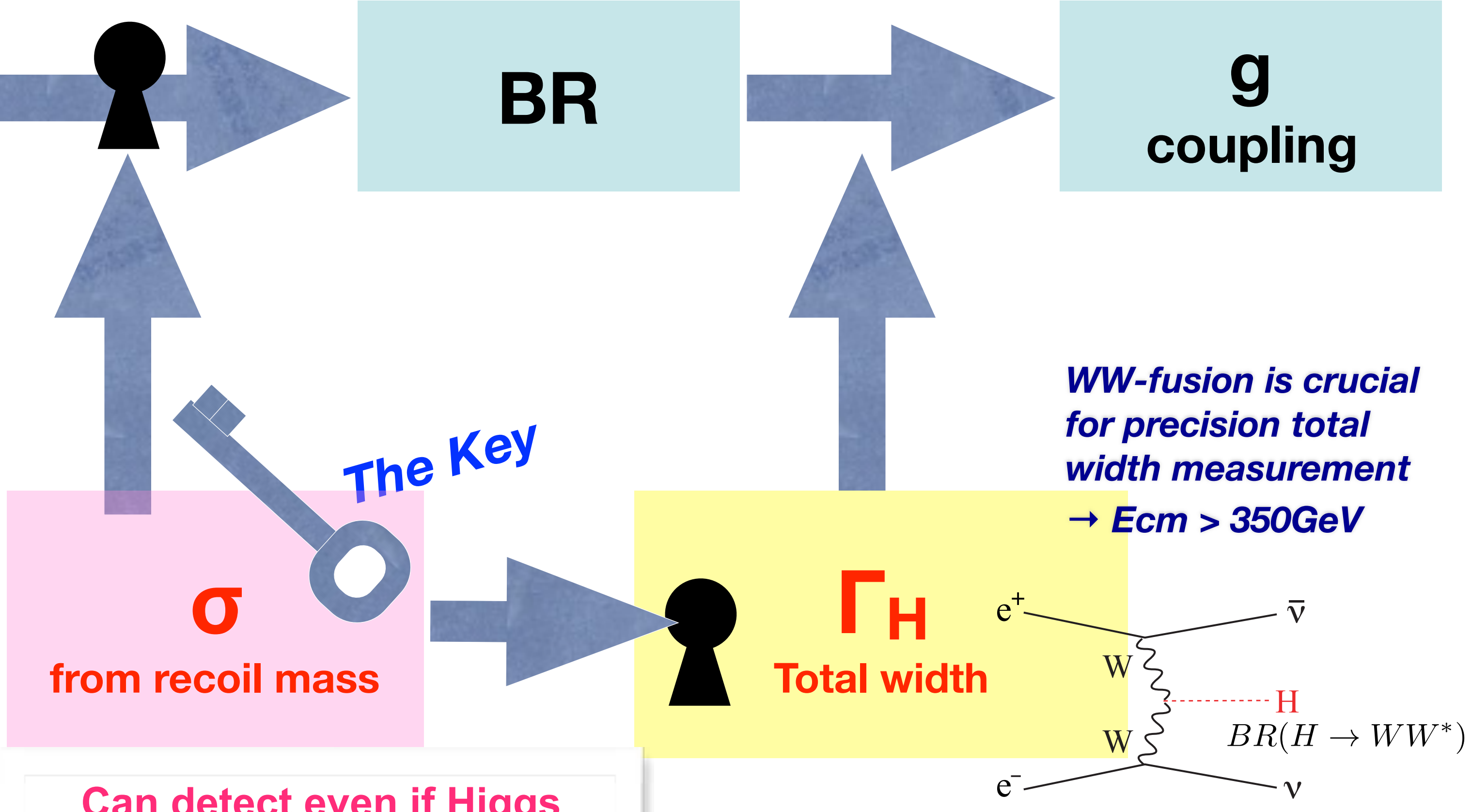
At LHC all the measurements are σ×BR measurements.

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



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

σ×BR



BR

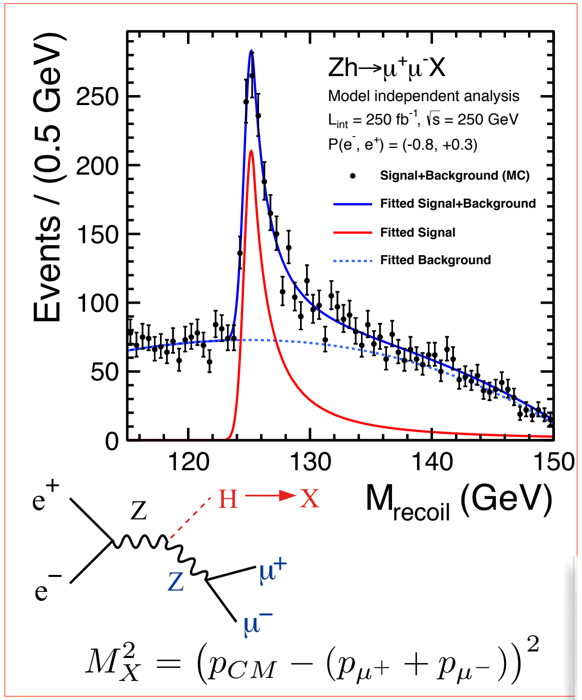
g
coupling

The Key

σ
from recoil mass

Γ_H
Total width

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

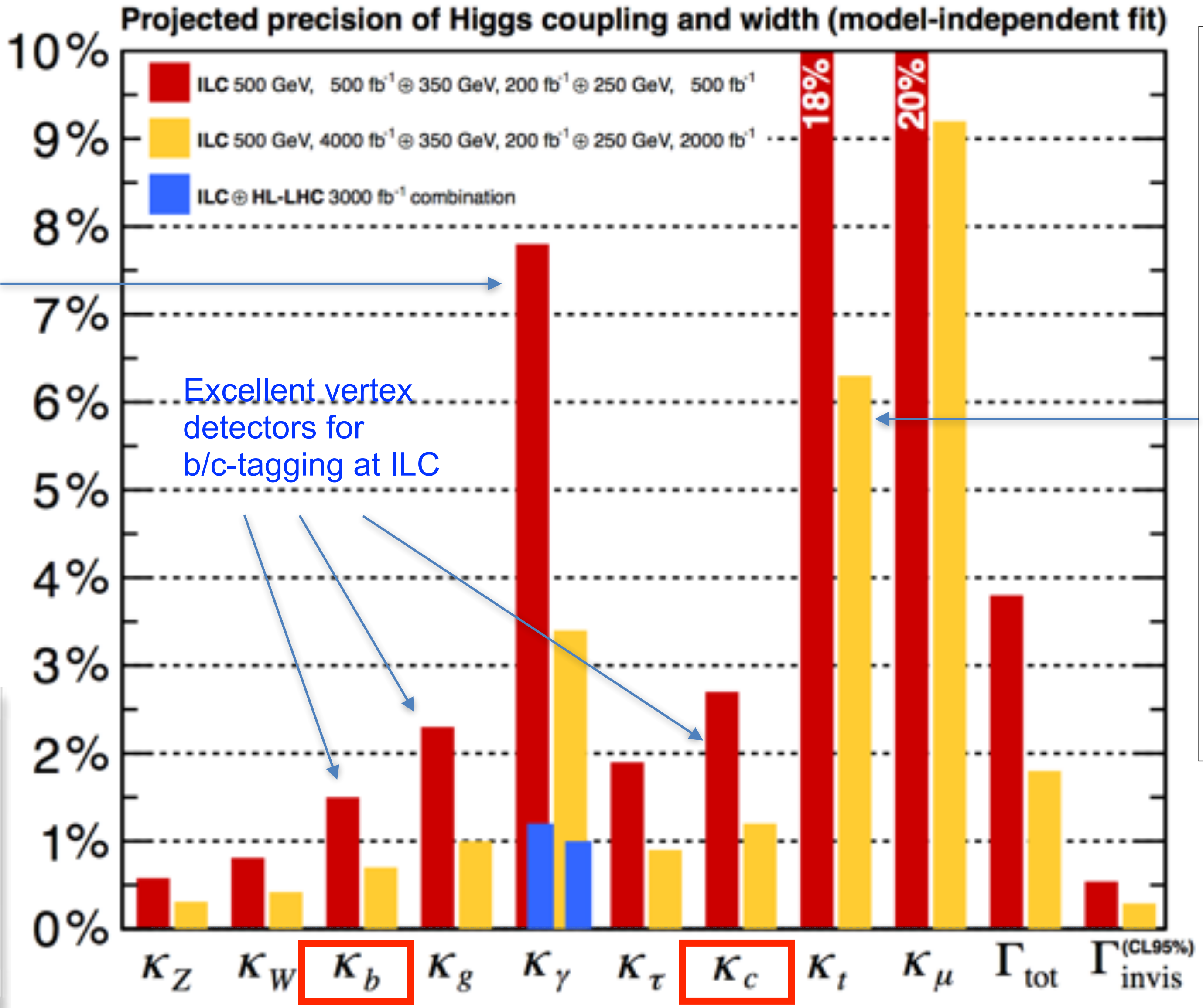
Better hγγ with LHC/ILC synergy

LHC can precisely measure

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

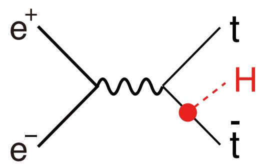
ILC can precisely measure ***K_Z***

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

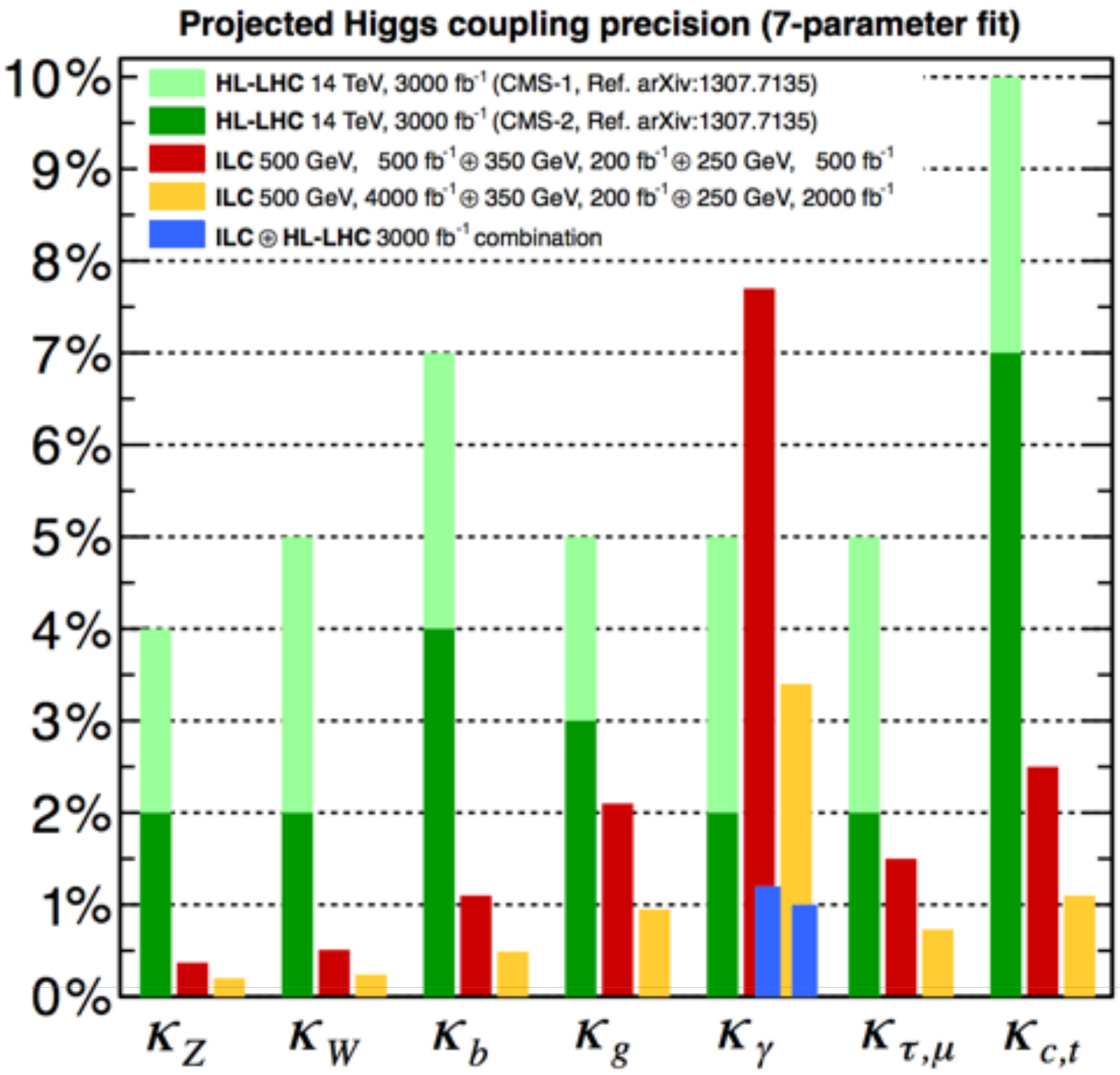
~1% or better for most couplings!

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

H20 Scenario

arXiv: 1506.05992
arXiv: 1506.07830

Σ_{SM} BR = 1



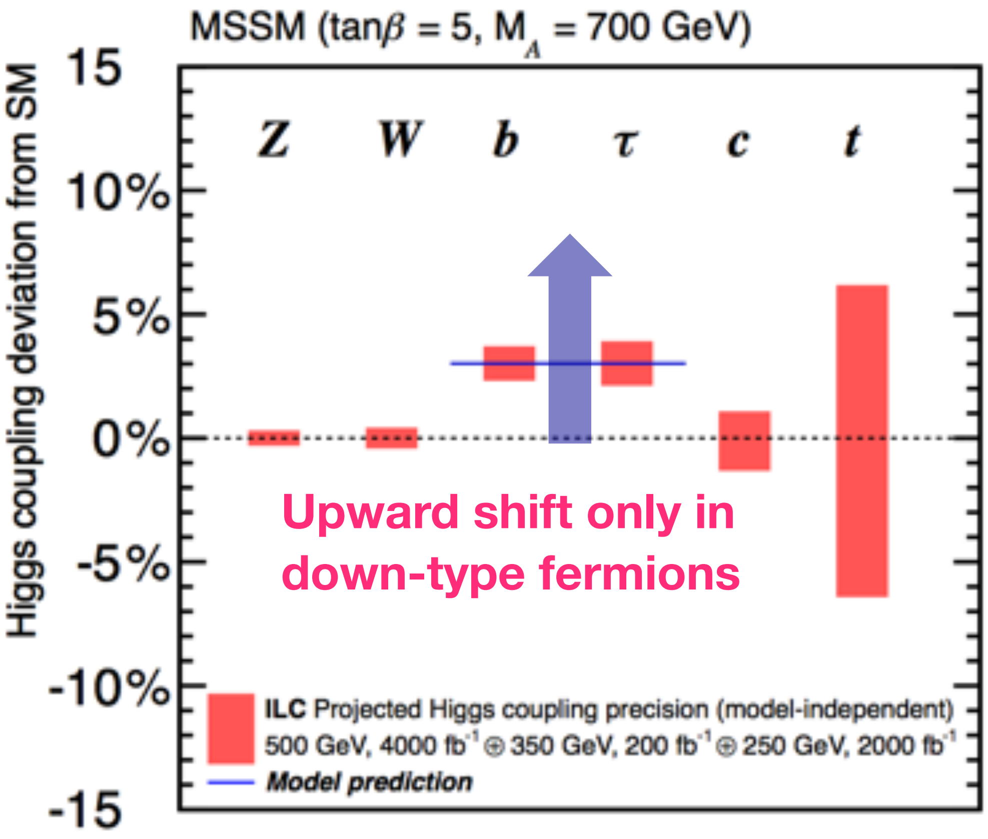
Possible to achieve precision far exceeding LHC!

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

Fingerprinting

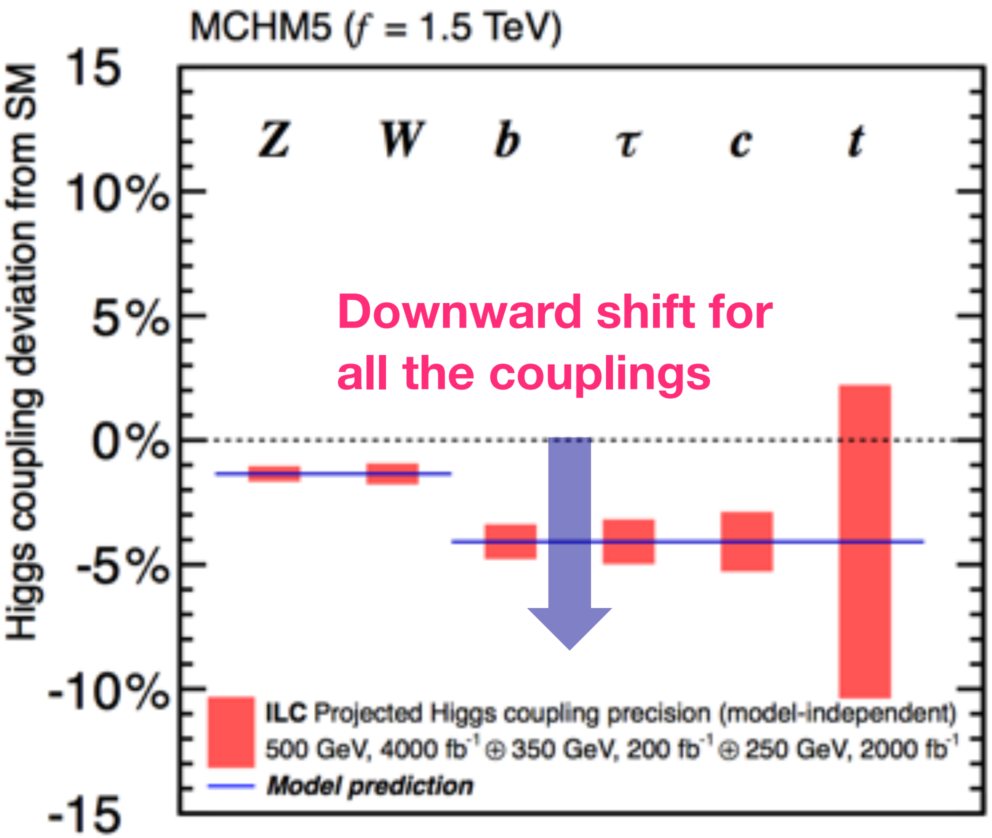
Elementary v.s. Composite?

Supersymmetry
(MSSM)



Upward shift only in down-type fermions

Composite Higgs
(MCHM5)



Downward shift for all the couplings

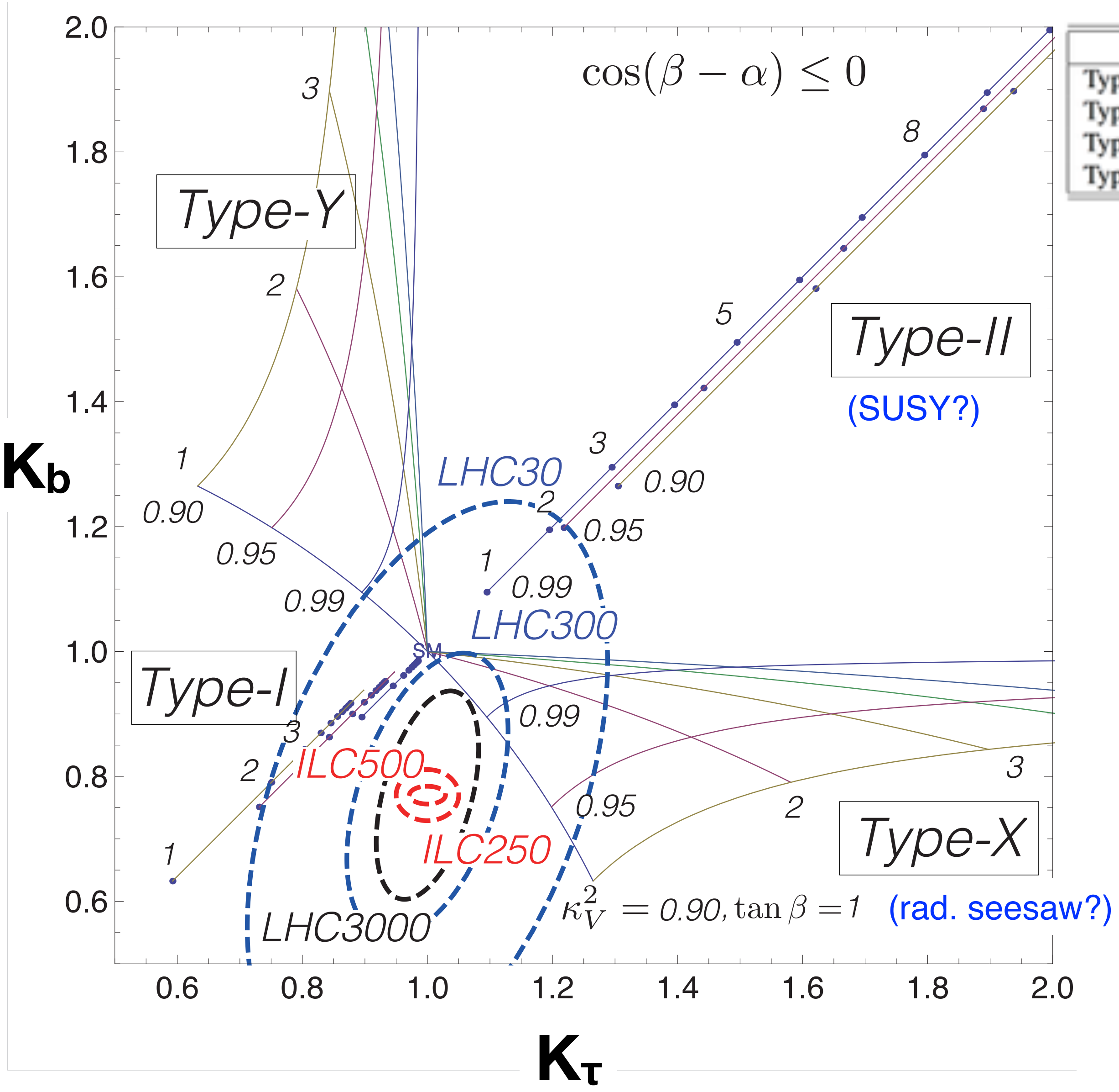
ILC 250+500 LumiUP

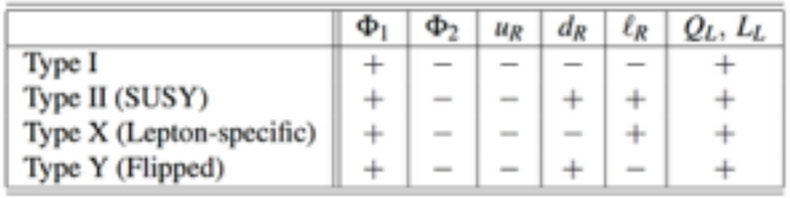
Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity far exceeds that of LHC!

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)

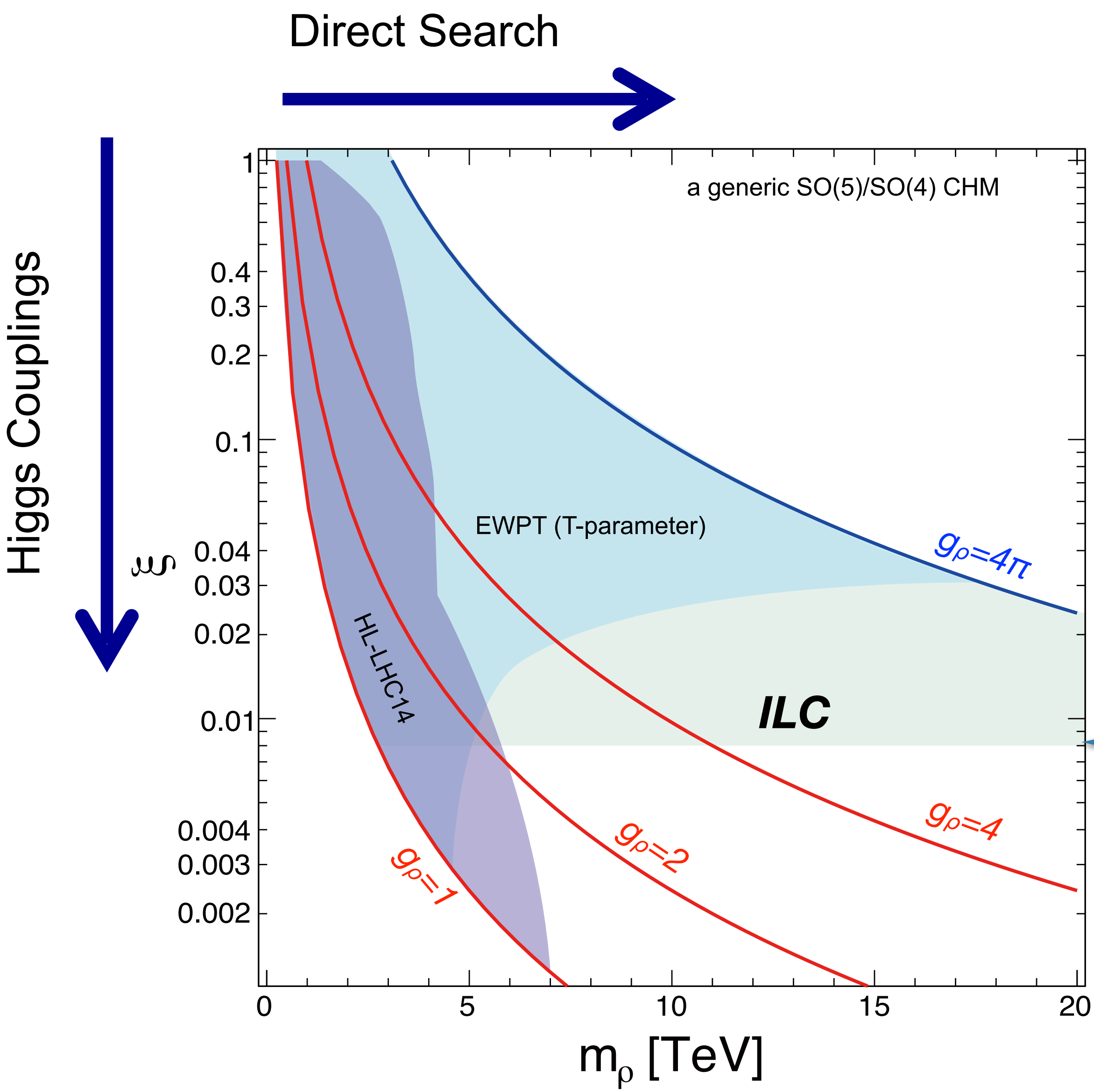
Kanemura et al (arXiv: 1406.3294)

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

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

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

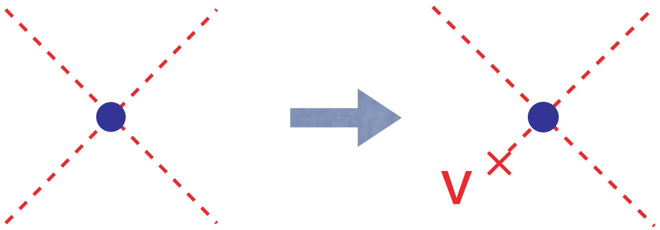
ILC (250+500 LumiUP)

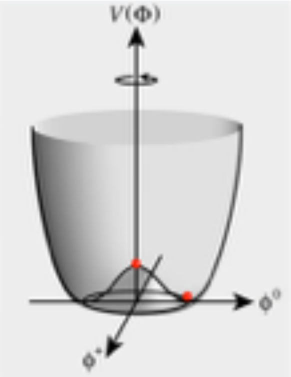
$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

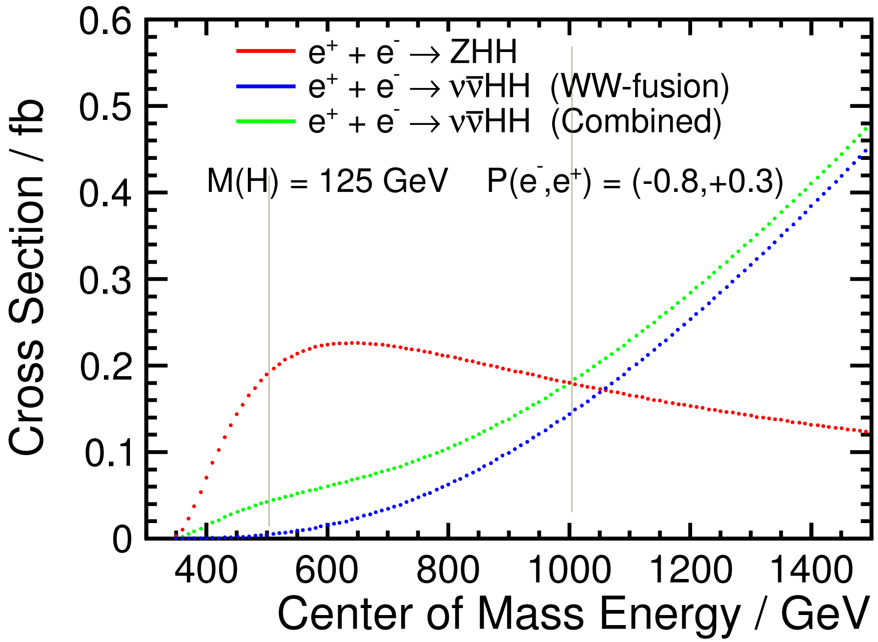
Higgs Self-coupling

Higgs Self-Coupling

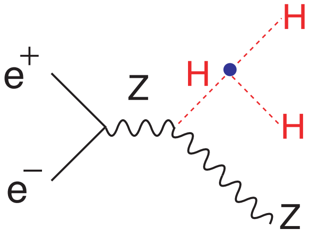
The ***Higgs 3-point self-coupling*** is at the heart of EWSB!

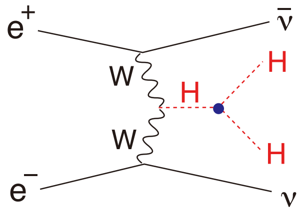






There are ***two ways to measure it*** at ILC





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%

27% (H20)

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

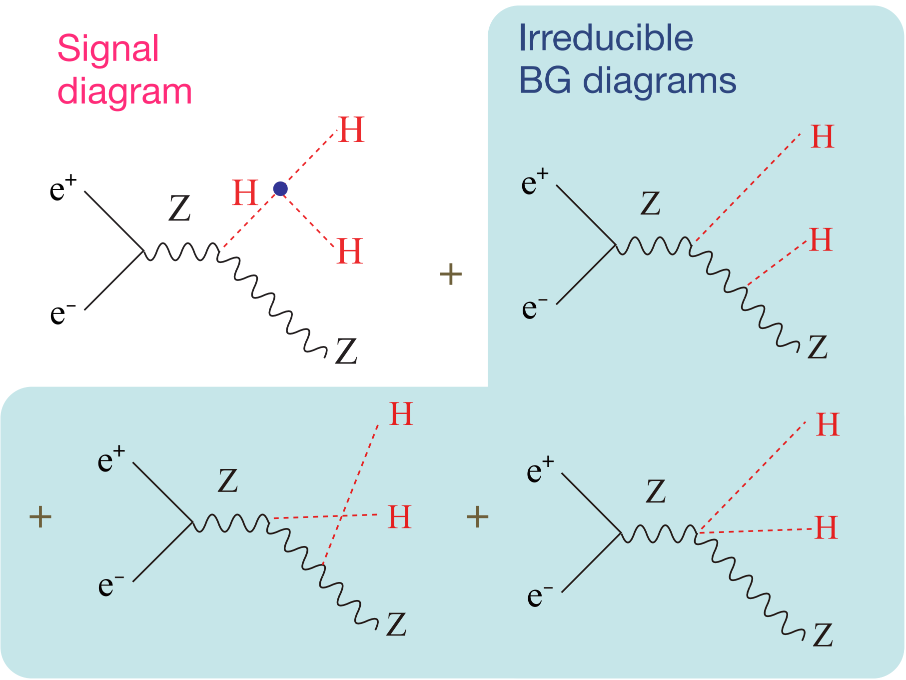
Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams***

CLIC (arXiv: 1307.5288)

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

The Problem : BG diagrams dilute self-coupling contribution



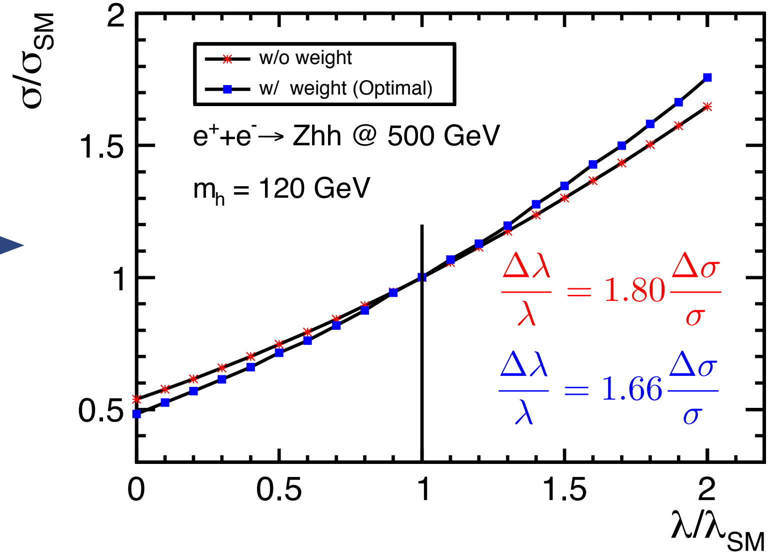
Signal diagram

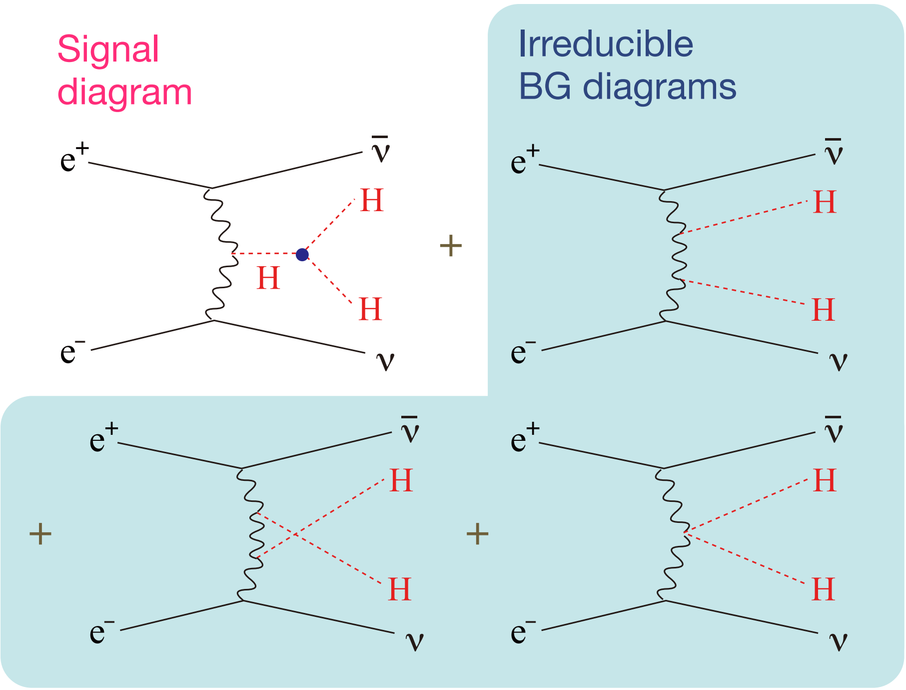
Irreducible BG diagrams

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

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

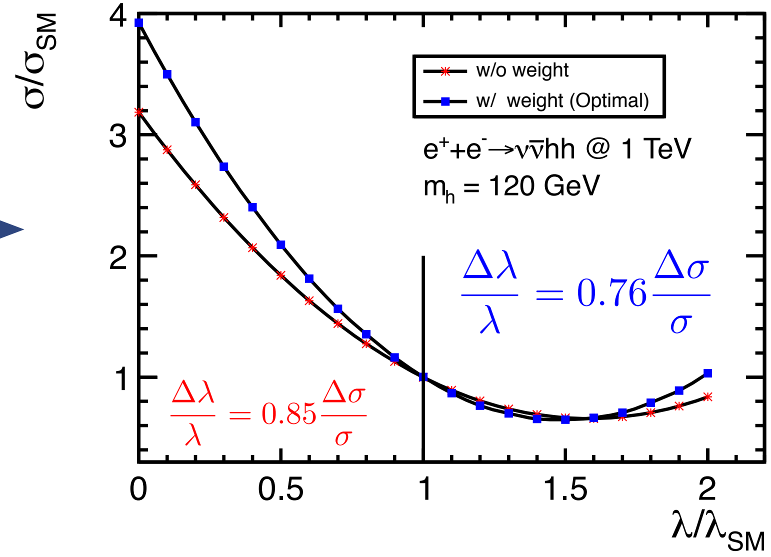
F=0.5 if no BG diagrams





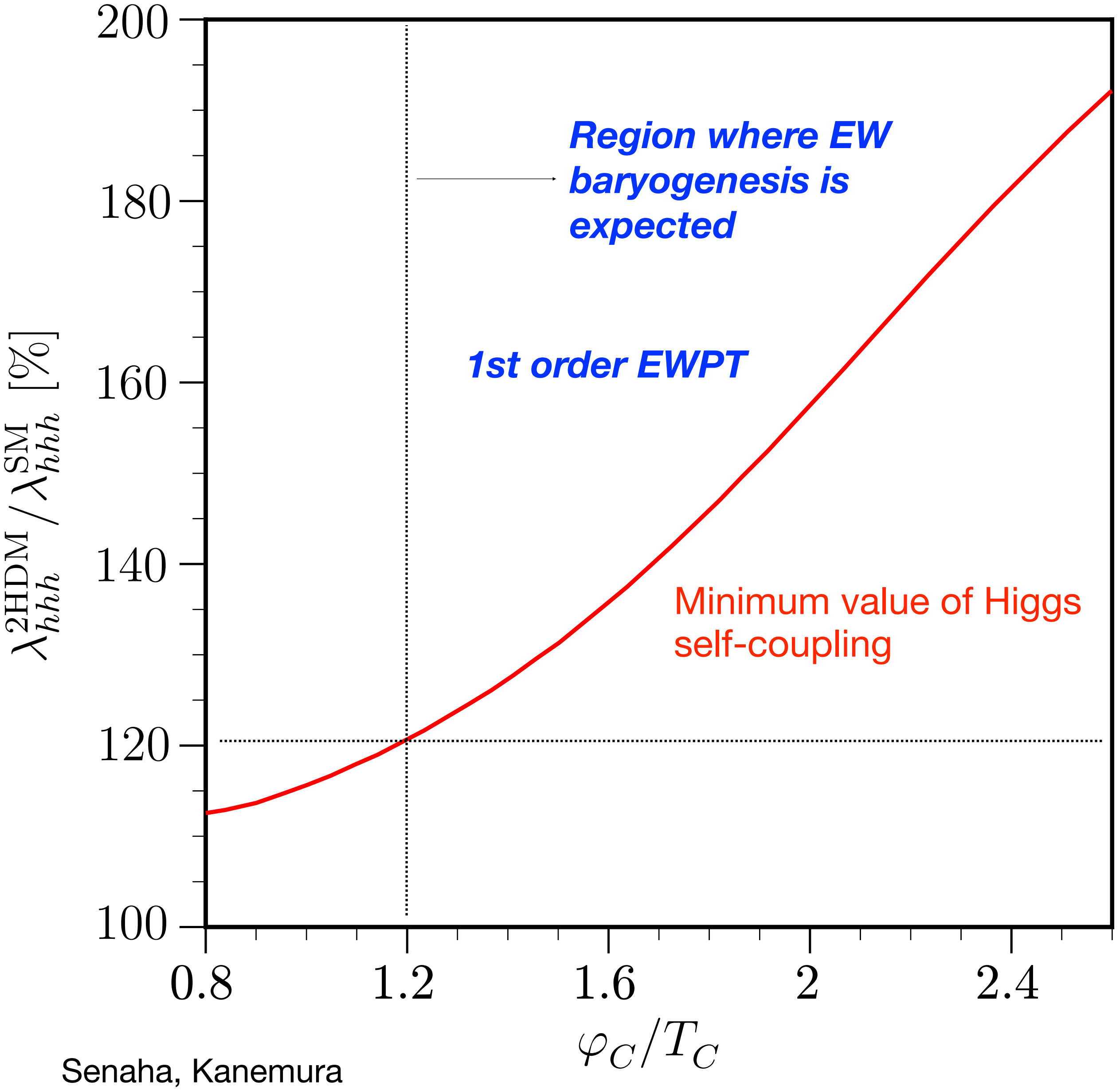
Signal diagram

Irreducible BG diagrams



Junping Tian LC-REP-2013-003

Electroweak Baryogenesis



Senaha, Kanemura

Example:

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***.

Top

Search for Anomalous tZZ Couplings

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

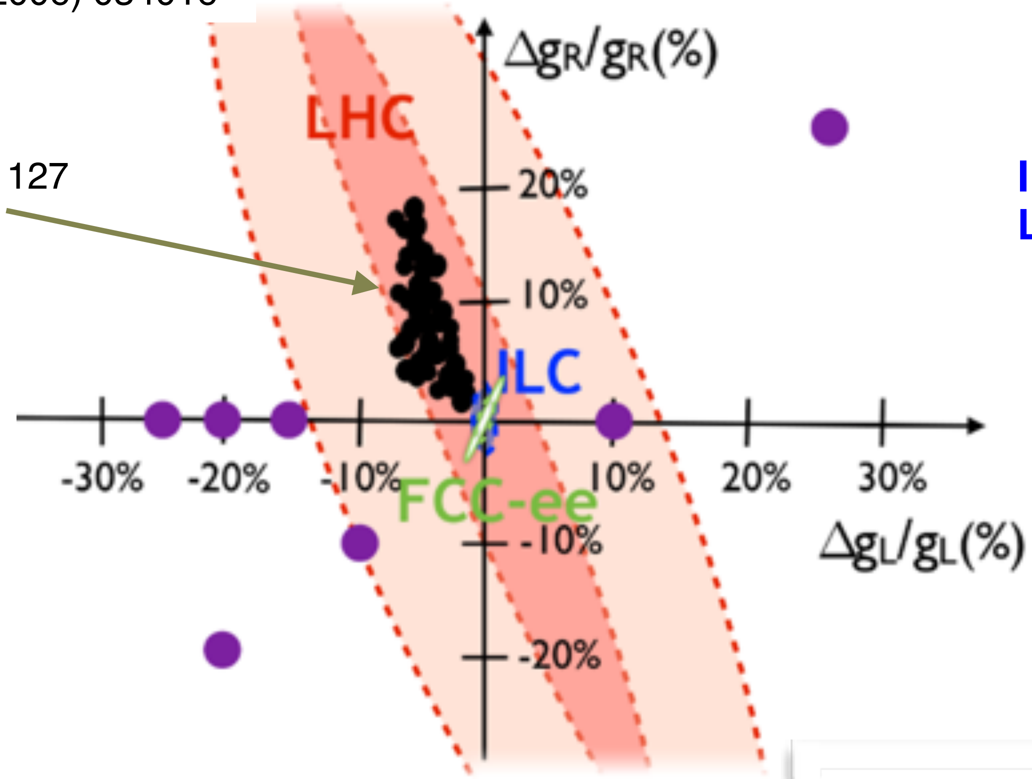
→ ***Specific deviation pattern*** *expected in* ***ttZ form factors*** *depending on new physics.*

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

Deviation in ttZ coupling of right-handed top quark

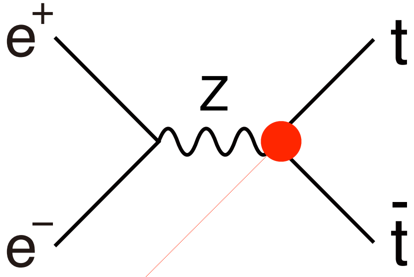
Phys.Rev.D73 (2006) 034016

4DCHM JHEP08 (2015) 127



ILC, √s = 500 GeV
Lumi = 500 fb^{-1}

Deviation in ttZ coupling of left-handed top quark



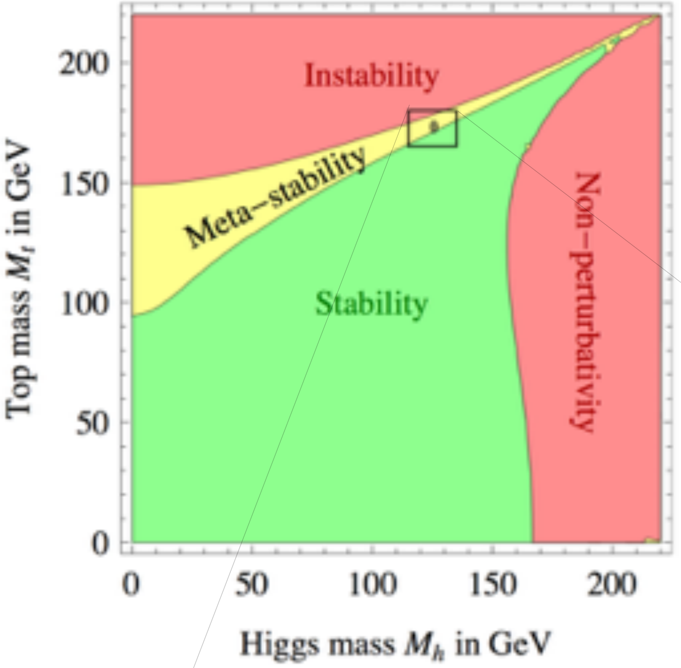
$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

Purple points: deviations expected for various new physics models (new physics scale ~1 TeV) compiled in arXiv:1505.06020

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

What if no deviation from the SM would be seen?

Clarify the Range of Validity of SM



Stability of SM Vacuum

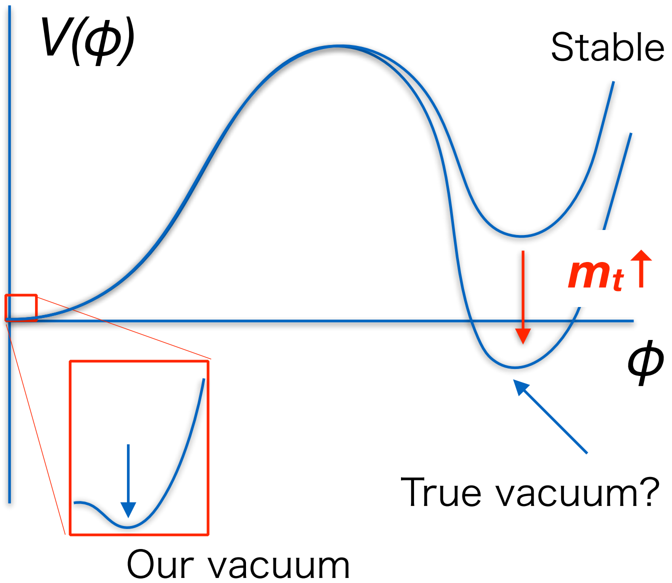
Top Yukawa coupling drives the 4-point Higgs coupling (λ) to negative!

The current values of mt and mh:

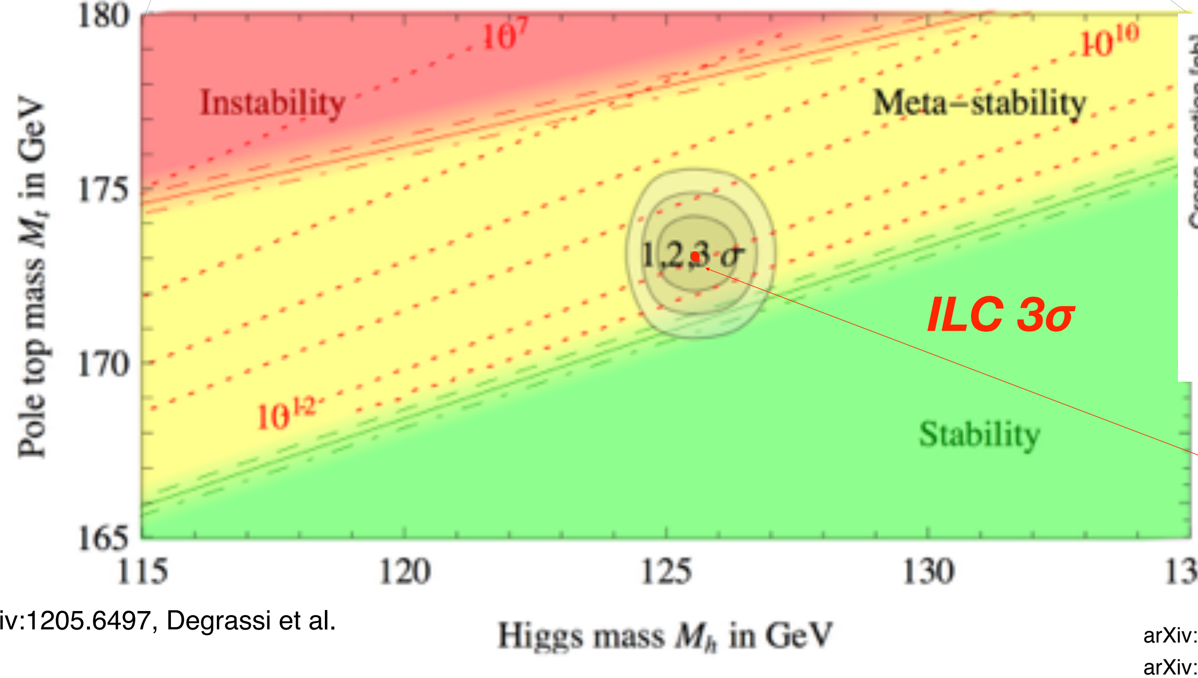
Subtle point of meta-stability!

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

To anser this, we need precision m_t measurement!

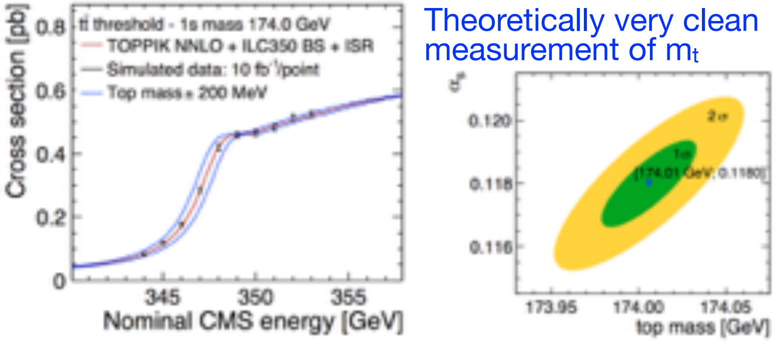


At LHC, theory error limits the precision to ~500MeV.



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

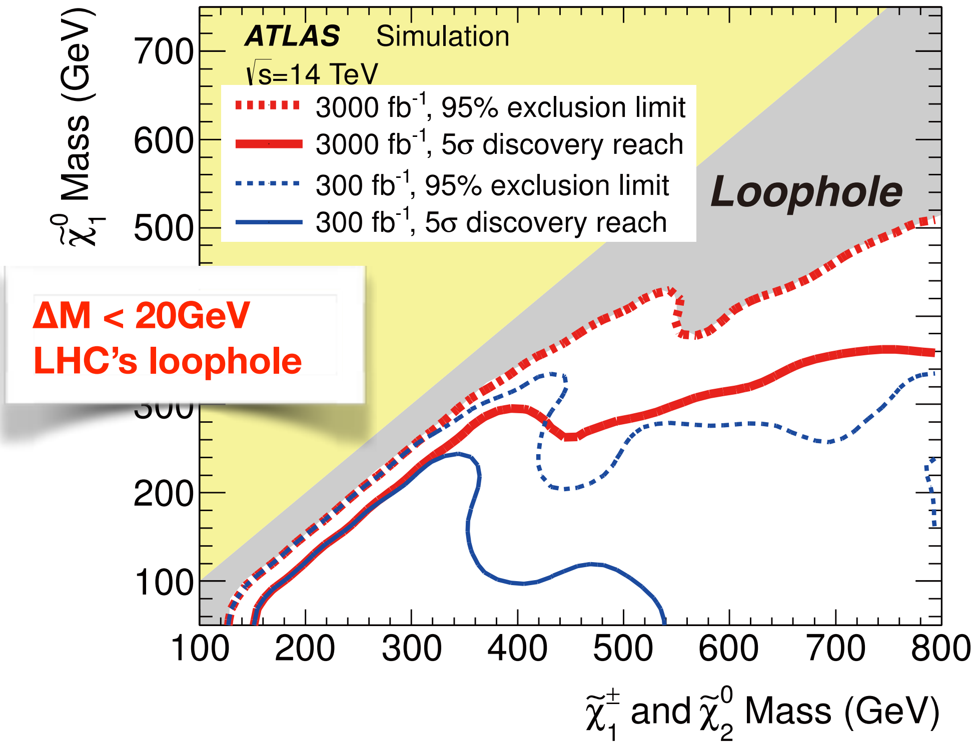
Direct Searches for New Particles

ILC, too, is an energy frontier machine!

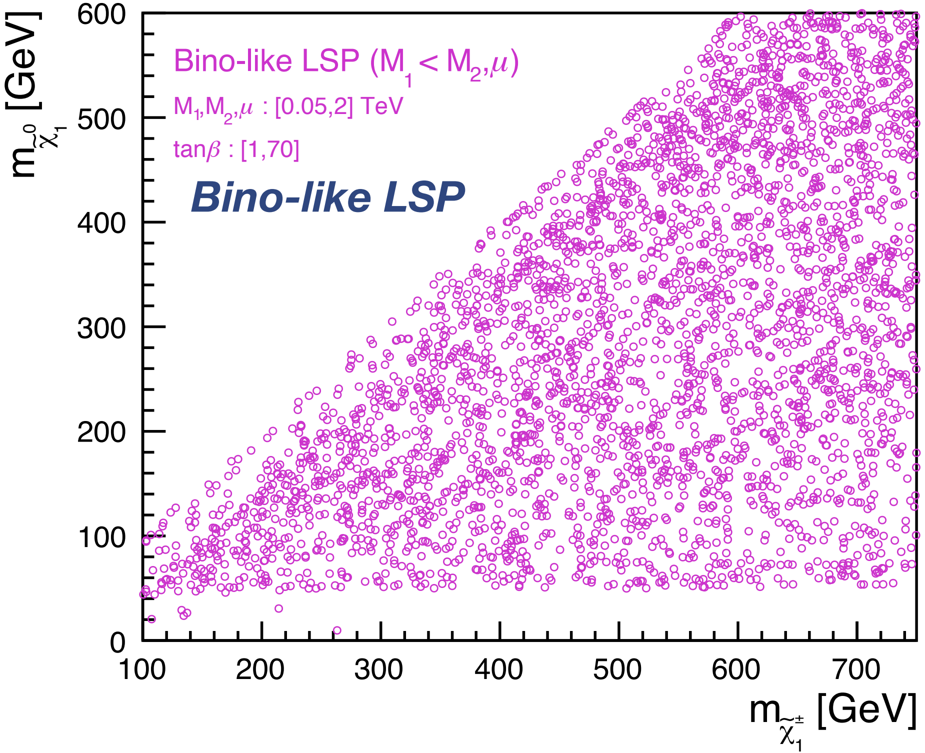
It will enter ***uncharted waters of e^+e^- collisions***

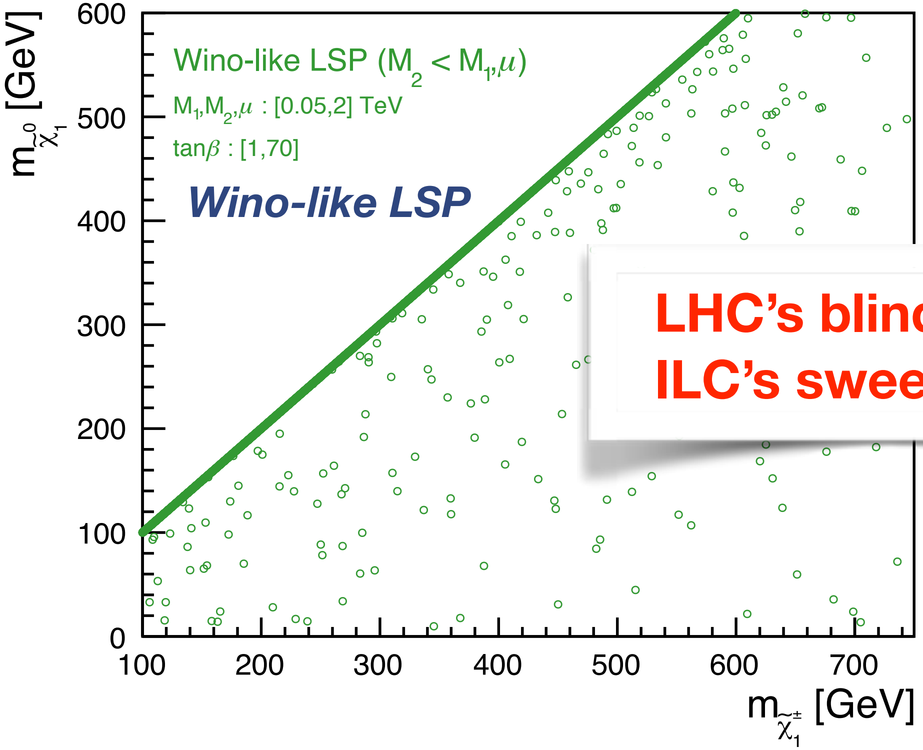
Thanks to well-defined initial states,
clean environment w/o QCD BG, and polarized beams
ILC can cover blind spots of LHC

Chargino Search

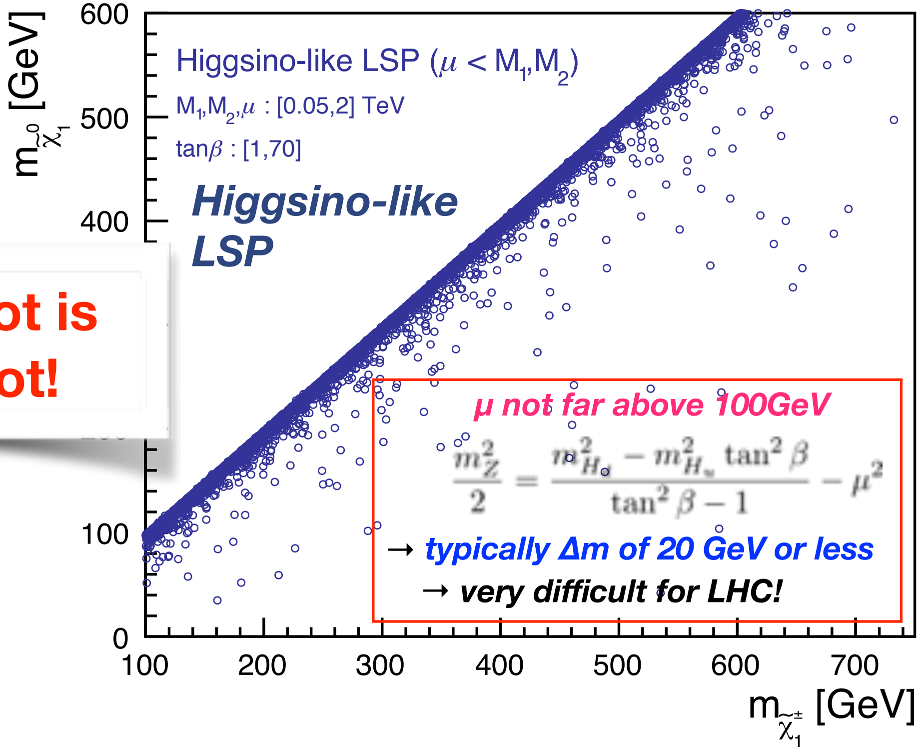


ΔM < 20GeV
LHC's loophole





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***

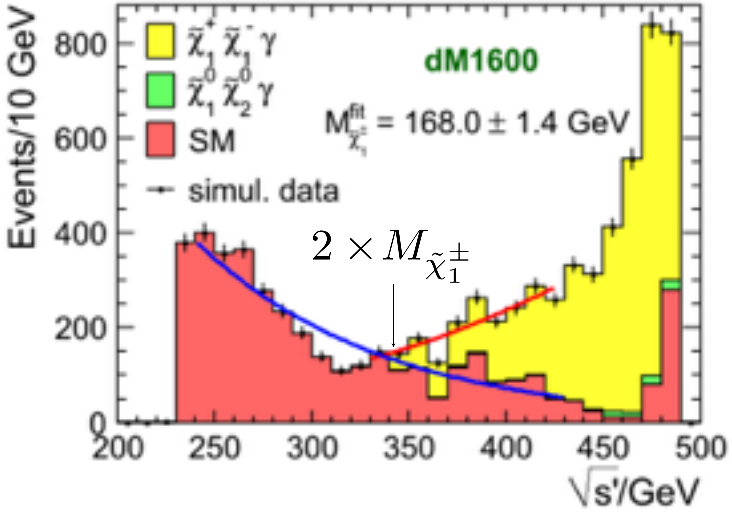
→ ***very difficult for LHC!***

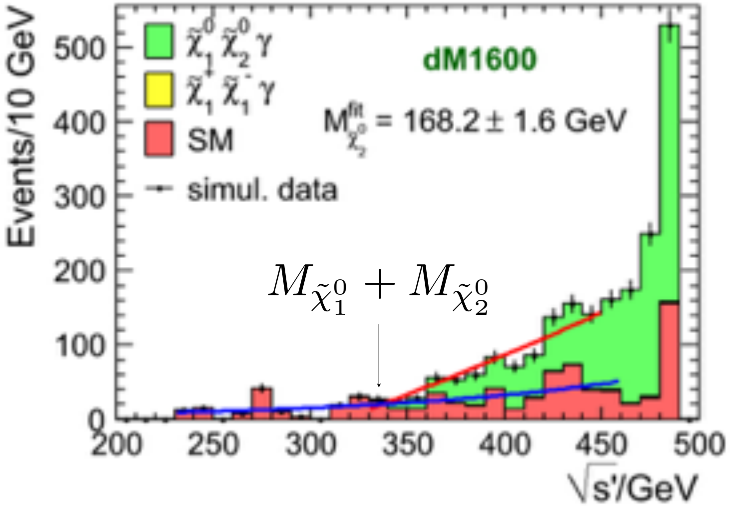
Higgsinos in Natural SUSY (ΔM<a few GeV)

ISR Tagging

ILC as a Higgsino Factory

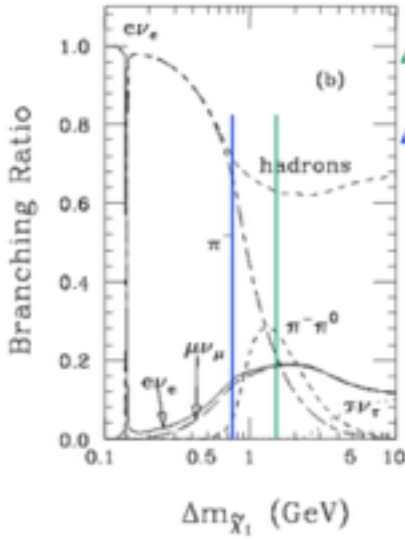
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$





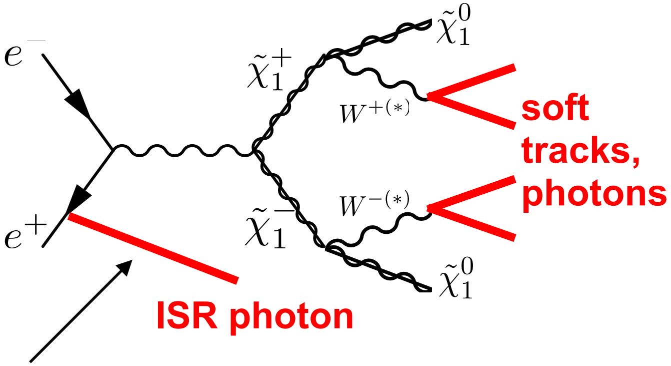
EPJC (2013) 73:2660

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



mh=124 GeV
ΔM = 1.59 GeV

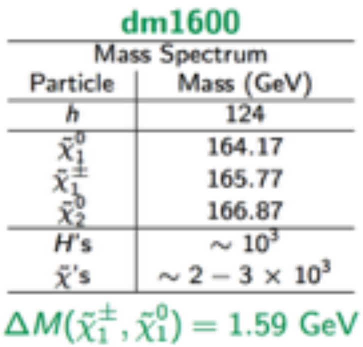
mh=127 GeV
ΔM = 0.77 GeV



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)



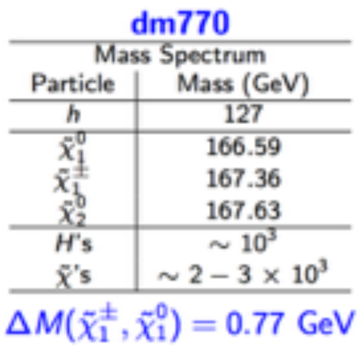
dm1600

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

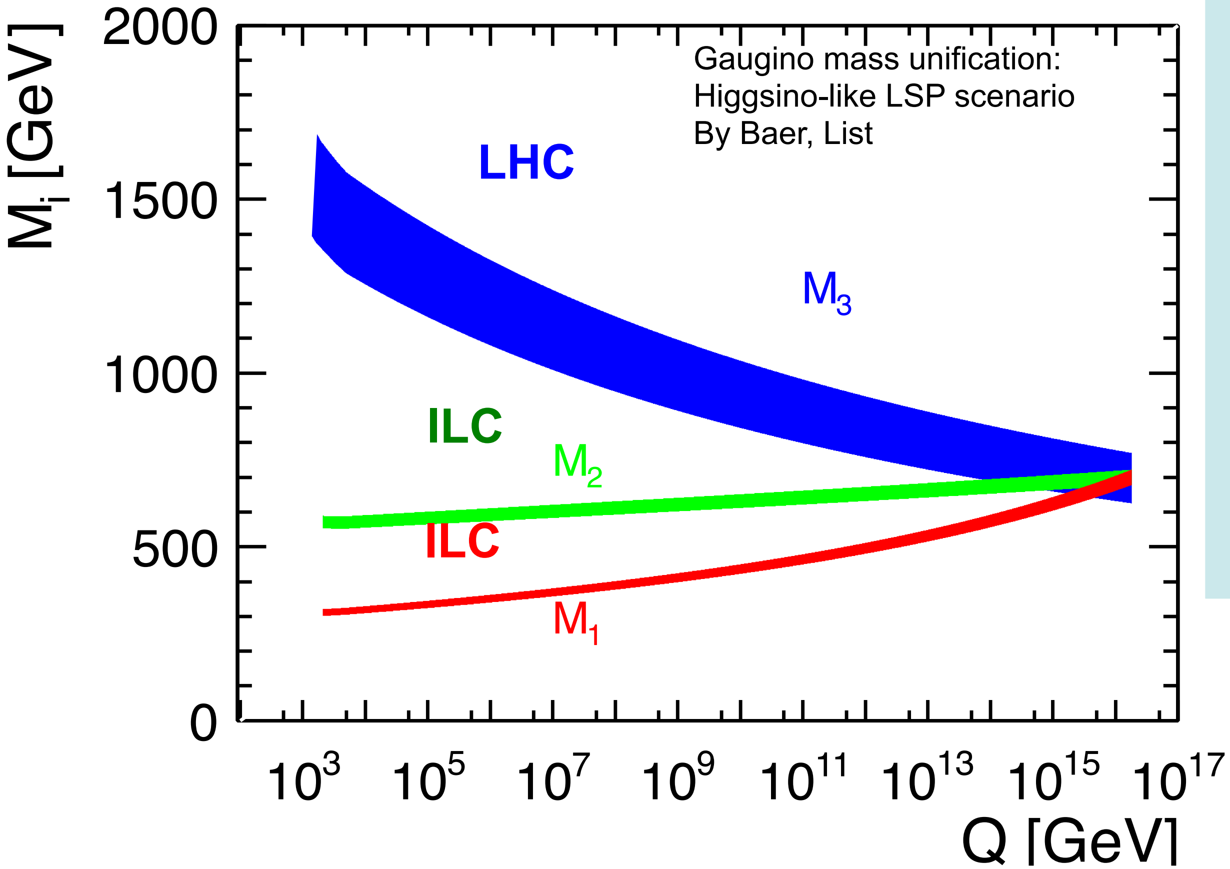
$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\mathrm{GeV}$$
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\mathrm{MeV}$$

GUT Scale Physics

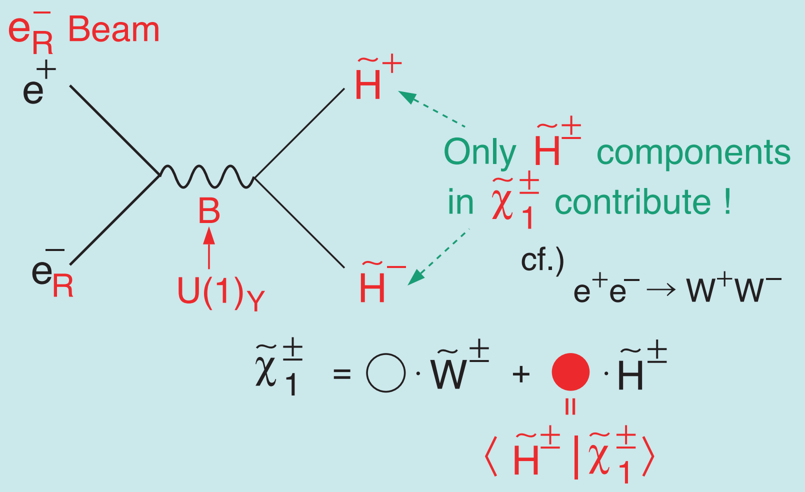
If we are lucky and the gluino is in LHC's mass reach and the lighter chargino and the neutralinos are in ILC's mass reach, ***we will be able to test the gaugino mass unification!***

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

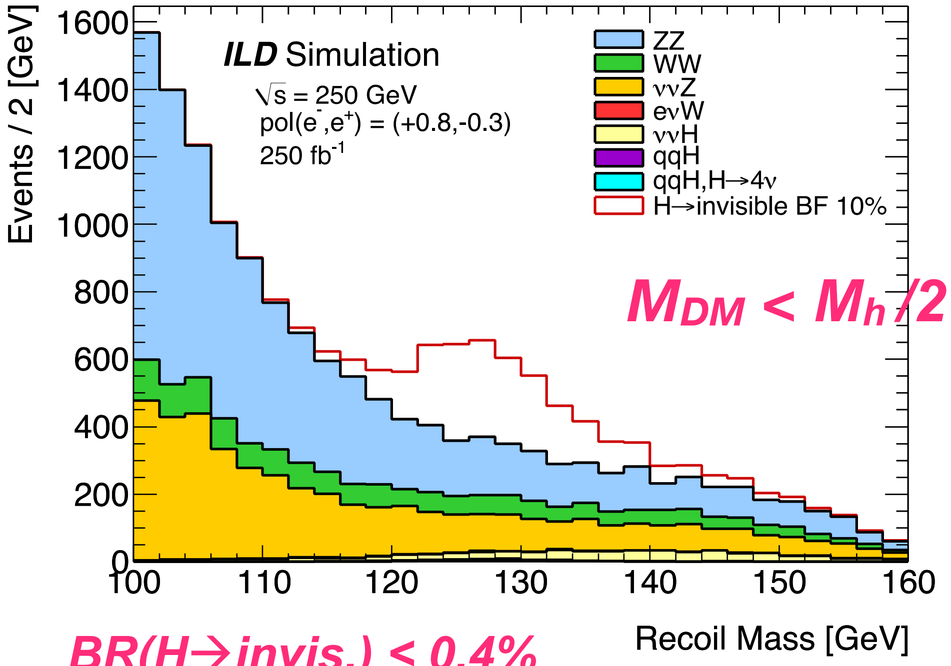
Decay of a new particle to Dark Matter (DM)

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

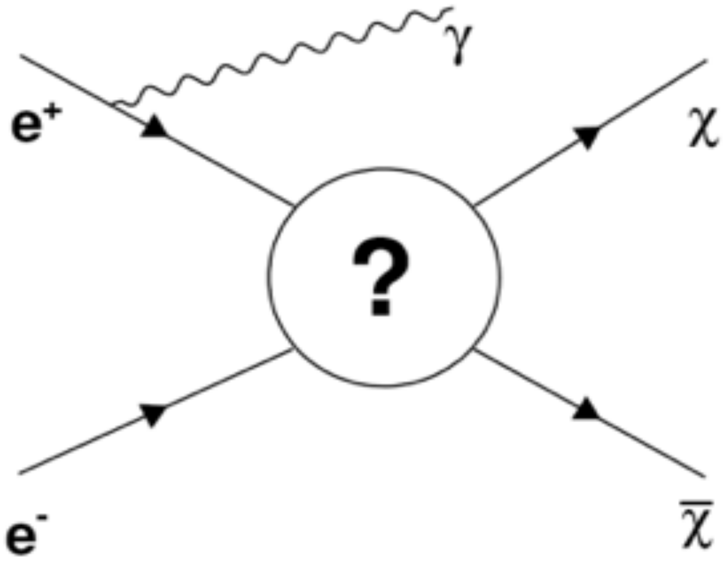


$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%

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

Mono-photon Search

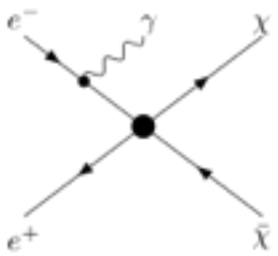


→ ***M_{DM} reach ~ $E_{cm}/2$***

Possible to access BR_{inv} to 0.4%!

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

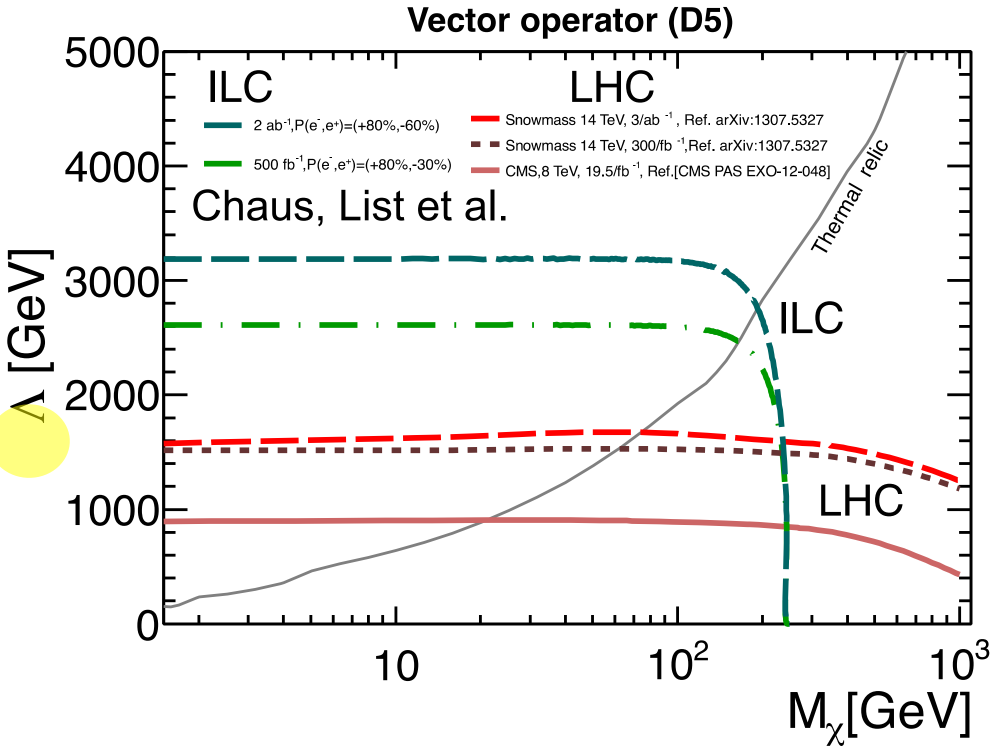
DM: Effective Operator Approach

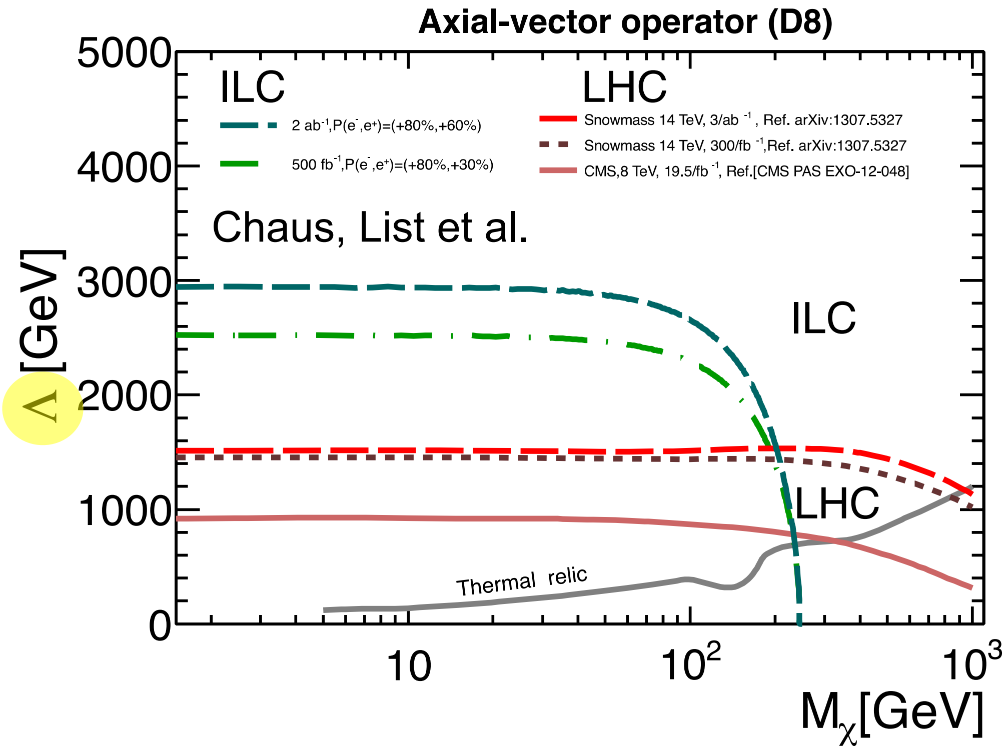


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

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

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


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!***

Summary

- 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 address this question we need to go beyond the SM.
- There is a big branching point 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 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 answer these questions*** (regardless of BSM scenarios) and we can do this ***model-independently***.
- 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 (eg. Natural SUSY).***
- Once a new particle is found at ILC, we can precisely determine its properties, making full use of ***polarized beams***. In the case of natural radiative SUSY scenario, we might even probe GUT scale physics using RGE.
- ***In this way, ILC will pave the way to BSM physics.***

Backup

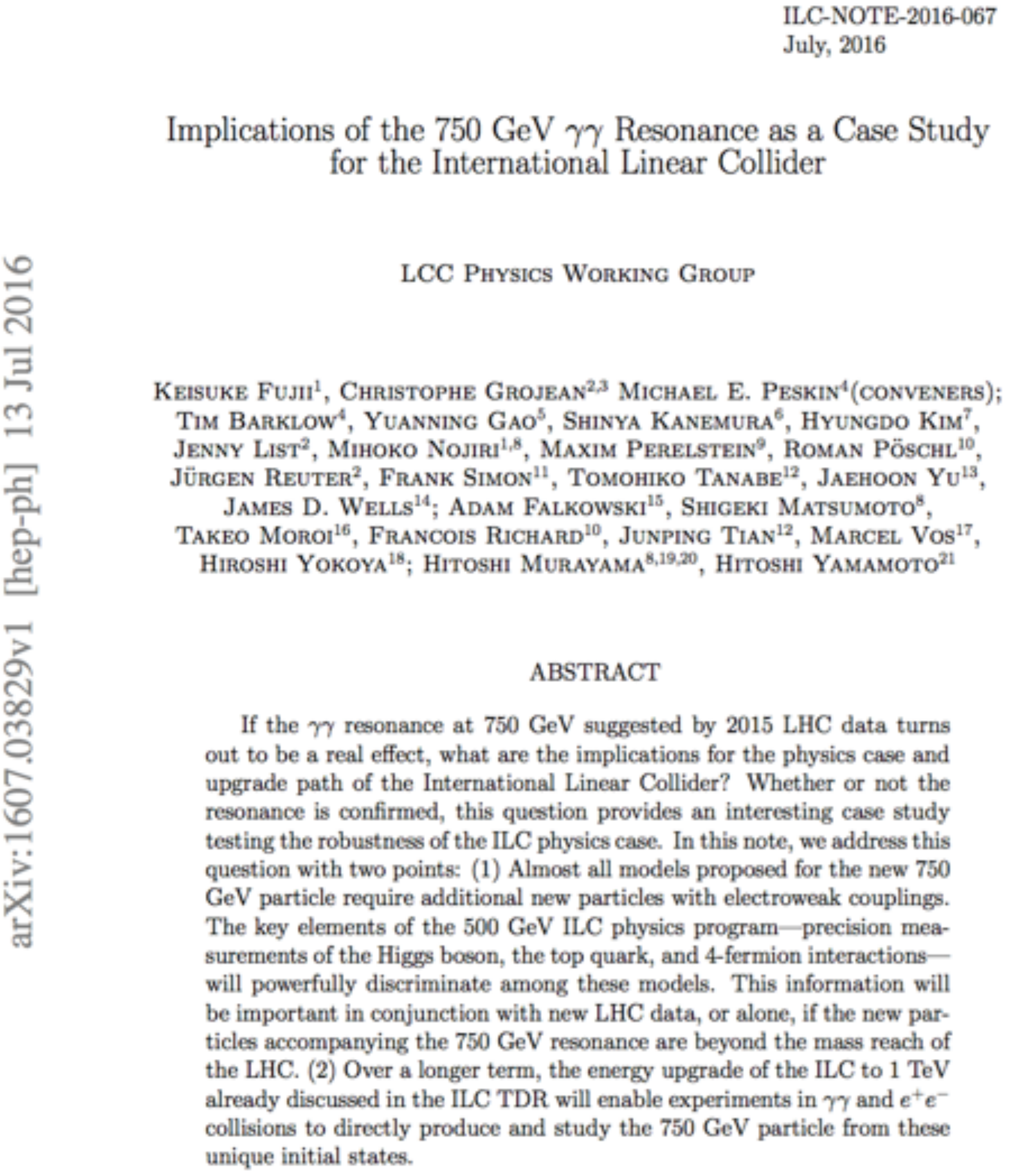
I strongly believe that **ILC is worth building regardless of what LHC is going to discover.**

But the MEXT ILC Advisory Panel recommended **to closely monitor, analyze, and examine the development of LHC experiments.**

X750

Our (=LCC Physics WG) Attitudes towards X750

1. It's too early to get excited,
2. but if it is real, it is ***a good example of case 3*** in the ICFA letter to MEXT's ILC Advisory Panel:
   case 3: LHC discovers relatively heavy new particles *(which cannot be directly produced at the 500 GeV ILC)*
3. Since the MEXT Panel recommended to ***closely monitor, analyze, and examine the development of LHC experiments***, this is ***a good opportunity to do exercise for case 3***. → motivation for this note
4. In LCC's letter to the panel, it is stated that "***While performing precision studies of the Higgs boson and the top quark, we will prepare for the energy upgrade of the ILC*** *taking advantage of energy expandability enabled by its linear shape.*"
5. *The note is intended to show*
   1. ***The 500 GeV ILC has a lot to say about X750 through precision measurements*** *plus* ***possible discovery of NPs associated with X750.***
   2. ***Possible energy upgrade with PLC option will open up even greater opportunities to uncover the new physics operating behind X750 together with LHC.***



ILC-NOTE-2016-067
July, 2016

arXiv:1607.03829v1 [hep-ph] 13 Jul 2016

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

LCC Physics Working Group

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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.

In this note X750 is called Φ

Questions addressed in the note

1. If Φ (=X750) is real, what would the implications be for the program of the ILC?
2. Will the ILC be able to shed light on this resonance or on accompanying new physics?

Caution

It might turn out that ***the Φ is a relatively minor player*** *in a new sector of physics that the LHC will begin to uncover in the next few years*.

For this reason, ***it is premature to discuss a new accelerator intended specifically to target the Φ*** or any other new particle that turns up in the early 13 TeV LHC data.

Properties of X750 (hereafter called Φ)

Φ →γγ means ***Φ = color singlet*** with ***J ≠ 1***

we assume J = 0

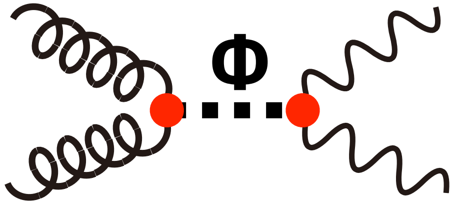
Φ is seen at 13 TeV but is much less apparent at 8 TeV

	gg	$b\bar{b}$	$d\bar{d}$	$u\bar{u}$	$\gamma\gamma$
$r_{p\bar{p}}$	4.8	5.7	2.7	2.6	1.9

$\mathcal{L}_{13\text{TeV}}/\mathcal{L}_{8\text{TeV}}$ preferes production via gg-fusion (or bb annihilation)

Assume production via gg:

$$\sigma(pp \to \Phi \to \gamma\gamma) = 5\ \text{fb} \Longrightarrow \Gamma(\Phi \to \gamma\gamma) \geq 0.5\ \text{MeV}$$



Effective Lagrangian

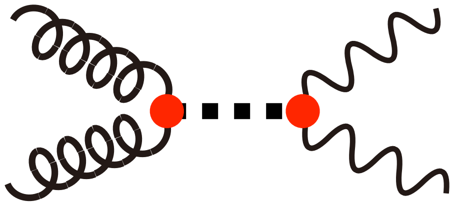
Underlying BSM physics must respect SU(3) x SU(2) x U(1)

→ γ must be a mixture of neutral SU(2) and U(1) gauge bosons

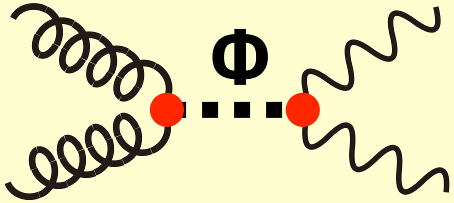
$$\boxed{\mathcal{L} = \frac{\alpha_s}{4} A_3\, \Phi\, G_{\mu\nu} G^{\mu\nu} + \frac{\alpha_w}{4} A_2\, \Phi\, W_{\mu\nu} W^{\mu\nu} + \frac{\alpha'}{4} A_1\, \Phi\, B_{\mu\nu} B^{\mu\nu}}$$

Typical Models and Effects

Effective Couplings



Φ=RS radion

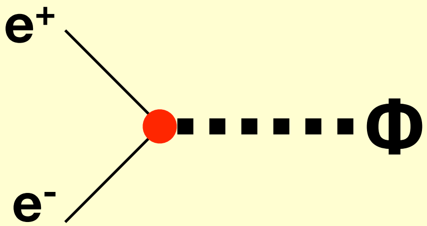


KK-loop correction

→ hWW, hZZ

~8% deviation expected for 5 TeV KK gluon.

Φ=RS gravition J=2

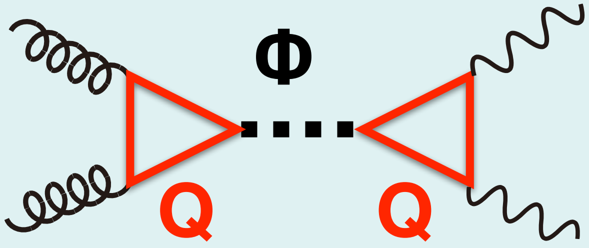


direct coupling to e^+e^-

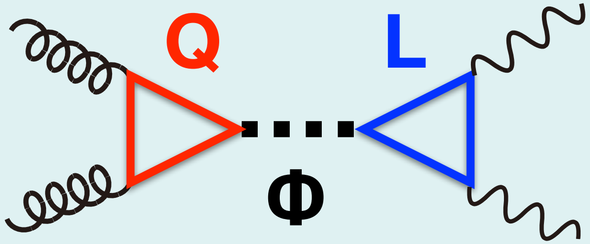
→ s-channel Φ production

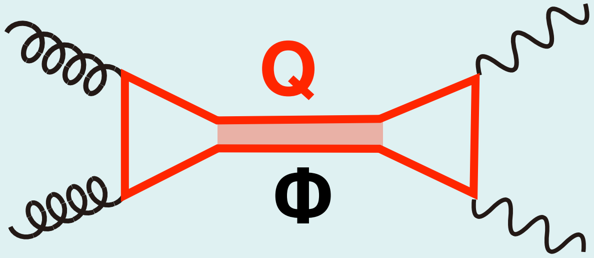
still not completely excluded.

Elementary Scalar



New vector-like fermions in the loops

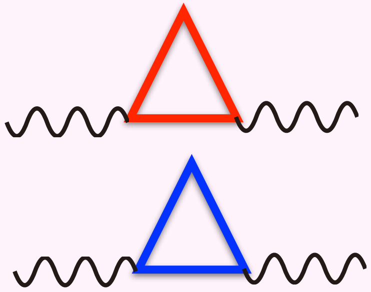




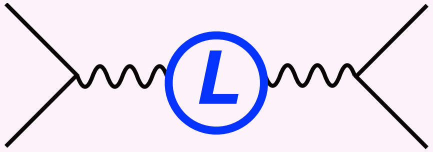
Resonance/pNGB

might be accompanied by DM within ILC's reach

Oblique Corrections



→ 2-to-2 processes



with $\delta\sigma/\sigma=0.1\%$, ILC sensitivity exceeds LHC

Mixings

Q-t mixing → ttZ

L-τ mixing

Φ-h mixing

→ $h\gamma\gamma$, hgg

→ hWW, hZZ

a few % deviation expected

→ well within H20 target

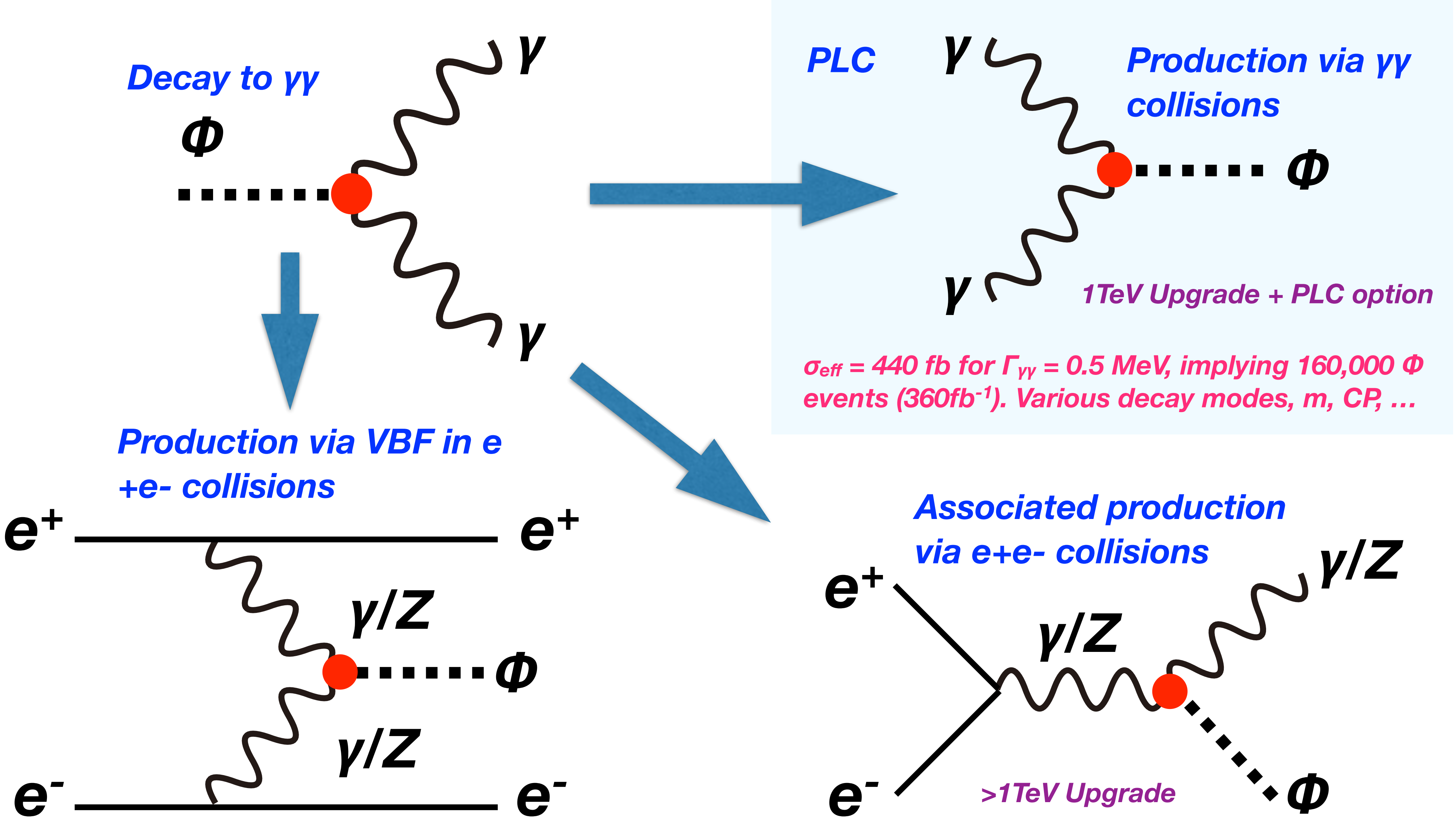
	hWW hZZ	$hb\bar{b}$ $h\tau\tau$	$h\gamma\gamma$ hgg	$ht\bar{t}$	$h \rightarrow$ invis.	$h\tau\mu$	$t\bar{t}Z$	$ee \rightarrow ee, \mu\mu$	$ee \rightarrow \gamma+$ invis.
Vectorlike fermions		X	X	X			X	X	
2 Higgs doublet	X	X	X	X					
Higgs singlet	X	X		X			X		
NMSSM	X	X	X	X	X				X
Flavored Higgs	X	X	X			X			
NR bound state		X		X				X	
Pion of new forces		X	X	X	X		X	X	X
RS radion	X	X	X	X			X		
RS graviton	X	X		X			X		

Table 2: Anomalies in precision measurements expected to be visible at the ILC for the models of the Φ discussed in this section.

Direct observation of the Φ in e^+e^- and $\gamma\gamma$ collisions

Observation of Φ in e^+e^- and γγ collisions

$\Phi \to \gamma\gamma$ means there is a ***Φγγ coupling*** which implies



Decay to γγ

PLC

Production via γγ collisions

1TeV Upgrade + PLC option

σ_{eff} = 440 fb for $\Gamma_{\gamma\gamma}$ = 0.5 MeV, implying 160,000 Φ events (360fb^{-1}). Various decay modes, m, CP, …

Production via VBF in e+e- collisions

>1TeV Upgrade

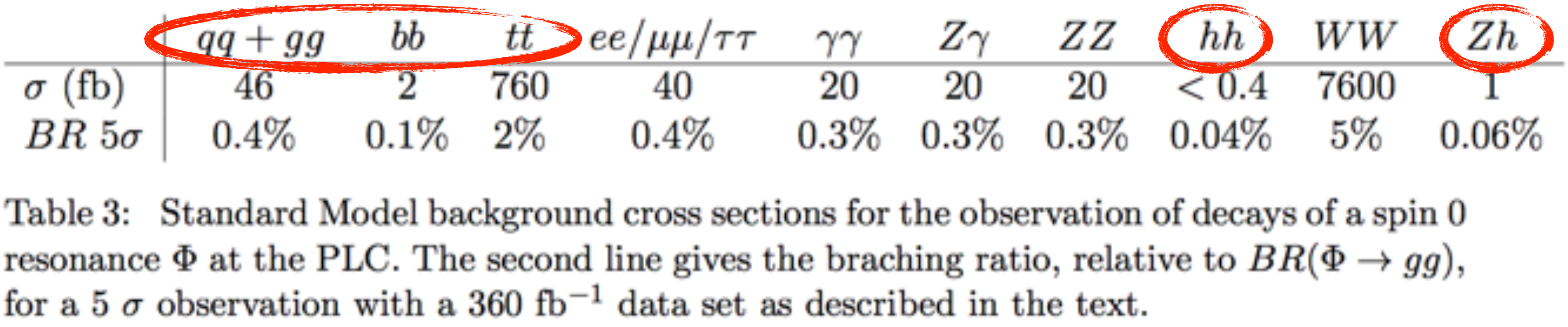
$\sigma_{ee\Phi}$ too small to be useful for $\Gamma_{\gamma\gamma}$ = 0.5MeV

Associated production via e+e- collisions

>1TeV Upgrade

$\sigma_{\Phi V}$ small for $\Gamma_{\gamma\gamma}$ = 0.5MeV, but potentially contain a lot of information: m, Γ_Φ, Γ_f, J, CP, R, …

PLC: Production via γγ collisions



	$qq+gg$	bb	tt	$ee/\mu\mu/\tau\tau$	$\gamma\gamma$	$Z\gamma$	ZZ	hh	WW	Zh
σ (fb)	46	2	760	40	20	20	20	< 0.4	7600	1
$BR\ 5\sigma$	0.4%	0.1%	2%	0.4%	0.3%	0.3%	0.3%	0.04%	5%	0.06%

Table 3: Standard Model background cross sections for the observation of decays of a spin 0 resonance Φ at the PLC. The second line gives the braching ratio, relative to $BR(\Phi \to gg)$, for a 5 σ observation with a 360 fb^{-1} data set as described in the text.

The capability for direct observation of the gg decay and the sensitivity to bb, tt, and Higgs modes far exceed what will be possible at the LHC.

Properties to be measured at PLC

$\Gamma_{\gamma\gamma}$ x $BR(\Phi\to gg)$	
J	*(from decay angular distribution)*
CP	*(from transversely polarized initial photons)*
$R:=A_2/A_1$	*(from ratios of rates to different decay modes)*
Γ_Φ	*(directly from the mass spectrum if it is 10s of GeV as suggested by ATLAS)*

1. *The note is intended to show*
    - ***The 500 GeV ILC has a lot to say about X750 through precision measurements*** *plus* ***possible discovery of NPs associated with X750****.*
    - ***Possible energy upgrade with PLC option will open up even greater opportunities to uncover the new physics operating behind X750 together with LHC****.*

2. ***Our strategy stated in the ICFA letter to MEXT's ILC Advisory Panel is intact****:*
   While performing precision studies of the Higgs boson and the top quark, we will prepare for the energy upgrade of the ILC *taking advantage of energy expandability enabled by its linear shape.*

Caution

It might turn out that ***the Φ is a relatively minor player*** *in a new sector of physics that the LHC will begin to uncover in the next few years*.

For this reason, ***it is premature to discuss a new accelerator intended specifically to target the Φ*** or any other new particle that turns up in the early 13 TeV LHC data.

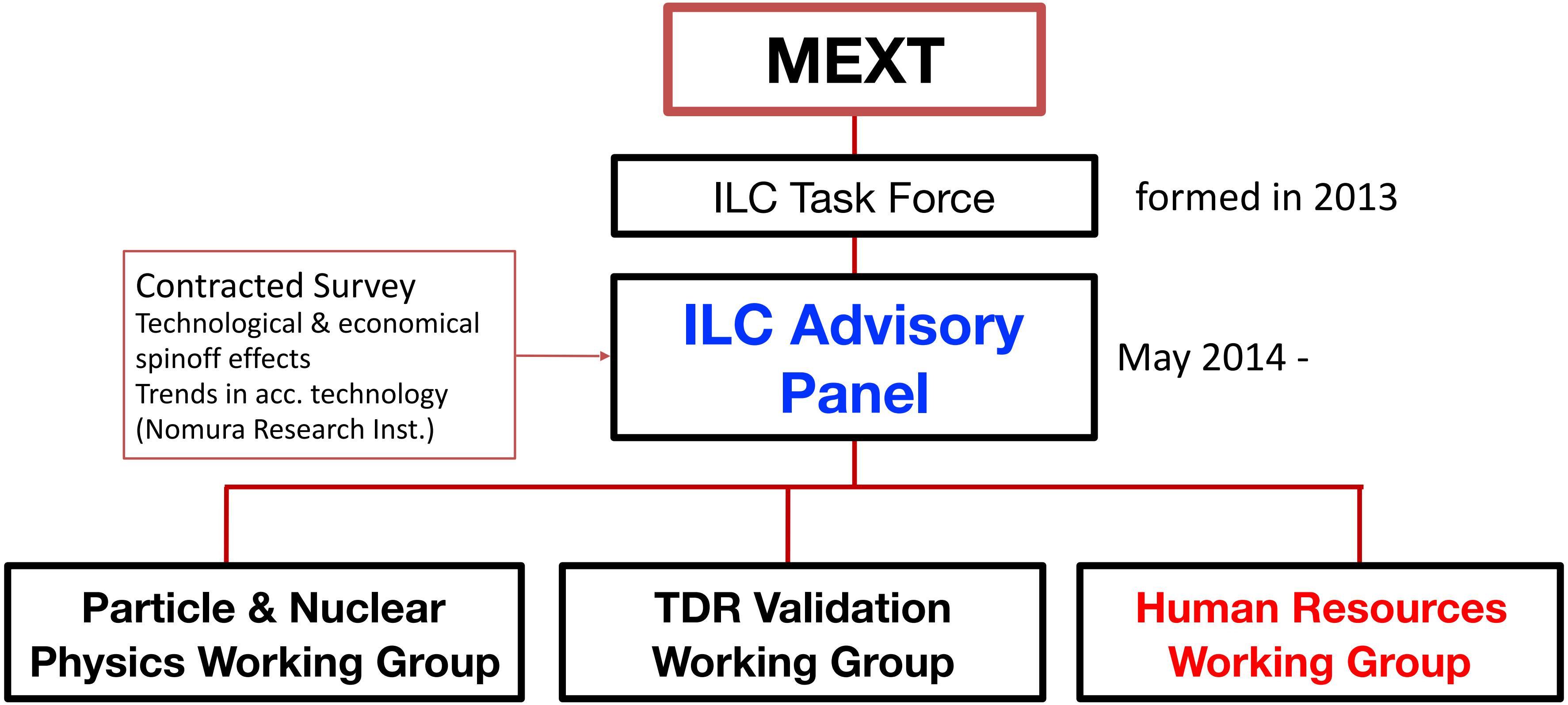
ILC Project Status

MEXT’s ILC Review

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

MEXT's ILC Review

In May, 2014 MEXT setup the ILC Advisory Panel for discussion on various issues concerning ILC construction in Japan. **ILC is now officially being studied.**



MEXT

ILC Task Force

formed in 2013

Contracted Survey
Technological & economical spinoff effects
Trends in acc. technology
(Nomura Research Inst.)

ILC Advisory Panel

May 2014 -

Particle & Nuclear Physics Working Group

2014/06 - 2015/03

Met 8 times, WG report submitted in March 2015

TDR Validation Working Group

2014/06 - 2015/03

Met 6 times, WG report submitted in March 2015

Human Resources Working Group

2015/11 -

Met 6 times, WG submitted in July 2016

Interim Report

ILC Advisory Panel released “Summary of Discussions” in Aug., 2015 and clarified issues to be addressed in their recommendations:

Recommendation 1: The ILC project requires huge investment that is so huge that a single country cannot cover, thus ***it is indispensable to share the cost internationally.*** From the viewpoint that the huge investments in new science projects must be weighed based upon the scientific merit of the project, ***a clear vision on the discovery potential of new particles as well as that of precision measurements of the Higgs boson and the top quark has to be shown*** so as to bring about novel development that goes beyond the Standard Model of the particle physics.

ICFA letter & its followup

Recommendation 2: Since the specifications of the performance and the scientific achievements of the ILC are considered to be designed based on the results of LHC experiments, which are planned to be executed through the end of 2017, it is necessary to ***closely monitor, analyze and examine the development of LHC experiments.*** Furthermore, it is necessary to ***clarify how to solve technical issues and how to mitigate cost risk*** associated with the project.

X750 note

Recommendation 3: While presenting the total project plan, including not only the plan for the accelerator and related facilities but also the plan for other infrastructure as well as efforts pointed out in Recommendations 1 & 2, it is important to ***have general understanding on the project by the public and science communities.***

ILC brochure

Recent International Move

US-Japan Political Leader's Forum on Advanced Science and Technology

February 11 and 12, 2016, Washington DC

The 4th visit by representatives of Federation of Diet Members for ILC (Formed in the Japanese Diet in 2008, More than 150 members).
The forum is hosted by the Hudson Institute and Advanced Accelerator Association Promoting Science and Technology of Japan (AAA), and attended by Scientists, Industrial people, and DOE and MEXT officials.

- 1st day: "Forum on Enhancing US-Japan Alliance Through Science and Technology"
- 2nd day: "US-Japan ILC Technical Session"
- Japanese Diet members visited several key persons in US Congress and Senate to discuss US-Japan cooperation for the ILC project.
- Diet members plan to continue this forum to establish stronger cooperation with US Congresspersons and Senators

Feb 11, 2016
Rayburn House Office Building

Feb 12, 2016
Hudson Institute

Recent AsiaHEP/ACFA Statement

AsiaHEP/ACFA Statement on the ILC & Circular Electron Positron Collider

- AsiaHEP and ACFA reassert their **strong endorsement of the ILC**, which is in a mature state of technical development. The aim of ILC is to explore physics beyond the Standard Model by unprecedented precision measurements of the Higgs boson and top quark, as well as searching for new particles which are difficult to discover at LHC. The Higgs studies at higher energies are especially important for measurement of WW fusion process, to fix the full Higgs decay width, and to measure the Higgs self-coupling. In continuation of decades of world-wide coordination, **we encourage redoubled international efforts at this critical time to make the ILC a reality in Japan.** The past few years have seen growing interest in a large radius circular collider, first focused as a “Higgs factory", and ultimately for proton-proton collisions at the high energy frontier. **We encourage the effort lead by China in this direction, and look forward to the completion of the technical design in a timely manner**.

June 1, 2016: Executive Meeting of Federation of Diet Members for ILC

Attending executive members:
7 Diet members (executive members)
From MEXT:
Yayoi KOMATSU (Director, Research Promotion Bureau),
Hiroshi IKUKAWA (Deputy Director-General, Research Promotion Bureau),
Masami WATANABE (Director, Basic Research Promotion Division, Research Promotion Bureau),
Sadahiro HAGIWARA (Director for Particle and Nuclear Physics Promotion Office, Basic Research Promotion Division, Research Promotion Bureau) +others
Scientists: Sakue Yamada, Toshinori Mori, Tadashi Ishikawa, Tomohiko Tanabe
AAA: Jun-ichi NISHIYAMA

Agenda

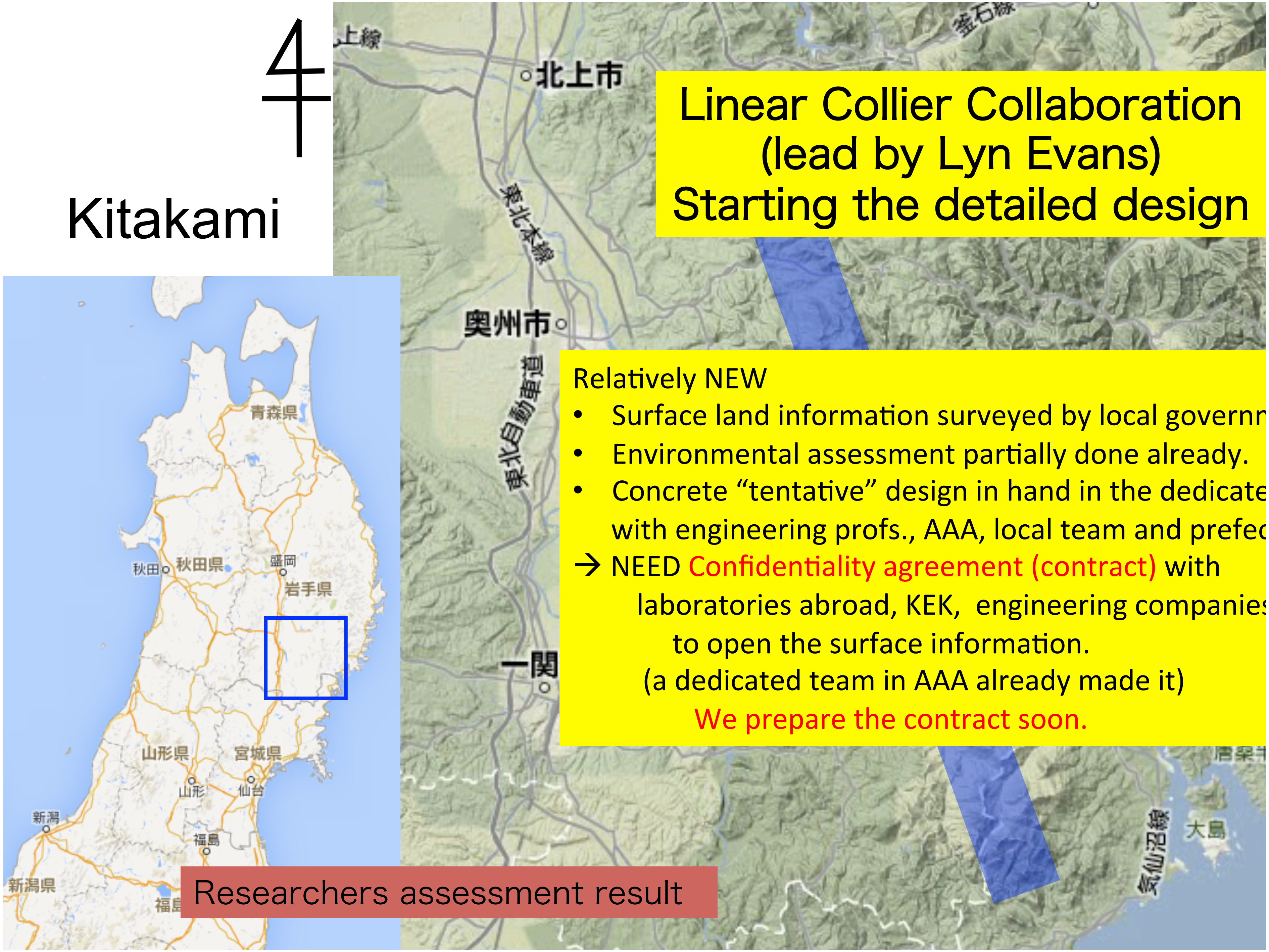
- **Report by MEXT on MEXT-DOE meeting on May 25**
- Discussions and recommendations by Diet members
- Remarks by scientist (Toshinori Mori, as P5 committee member)

Confirming and Conclusions of the meeting

- **The next meeting of the MEXT-DOE Discussion Group should be held in July/August.**
- **By October this year, items on joint research should be identified and concluded, in time for the next round of budget request (Japan JFY2017, US FY2018)**
- **Discussion Group’s planning should include researchers and industry for concrete R&D planning.**

Local Support

Kitakami



Linear Collier Collaboration (lead by Lyn Evans) Starting the detailed design

Relatively NEW

- Surface land information surveyed by local governn
- Environmental assessment partially done already.
- Concrete “tentative” design in hand in the dedicate with engineering profs., AAA, local team and prefec

→ NEED Confidentiality agreement (contract) with laboratories abroad, KEK, engineering companie to open the surface information.

(a dedicated team in AAA already made it)

We prepare the contract soon.

Researchers assessment result

Satoru Yamashita, ECFA LCWS 2016 in Santander


Oshu City


Ichinoseki Station


Morioka


Tohoku tourism ad seen on Tokyo Metro

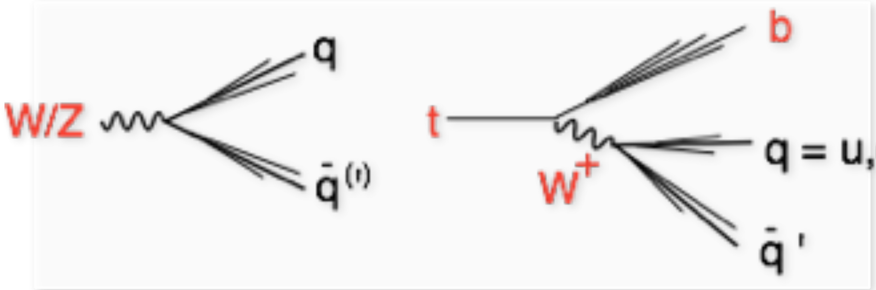

Posters and “Toy ILC” by school children of Oshu City welcoming international workshop on ILC

ILC Detectors

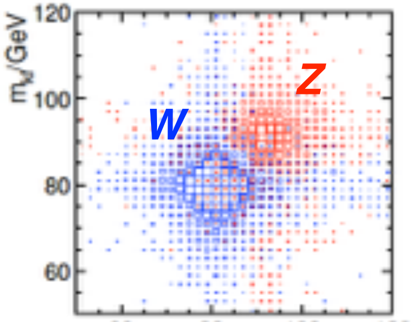
New Paradigm :

View events as viewing a Feynman diagram

Reconstruct final states in terms of fundamental particles (quarks, leptons, gauge bosons, and Higgs bosons)



Identify W/Z/top/Higgs with their jet invariant mass: $M_{\rm jets}$

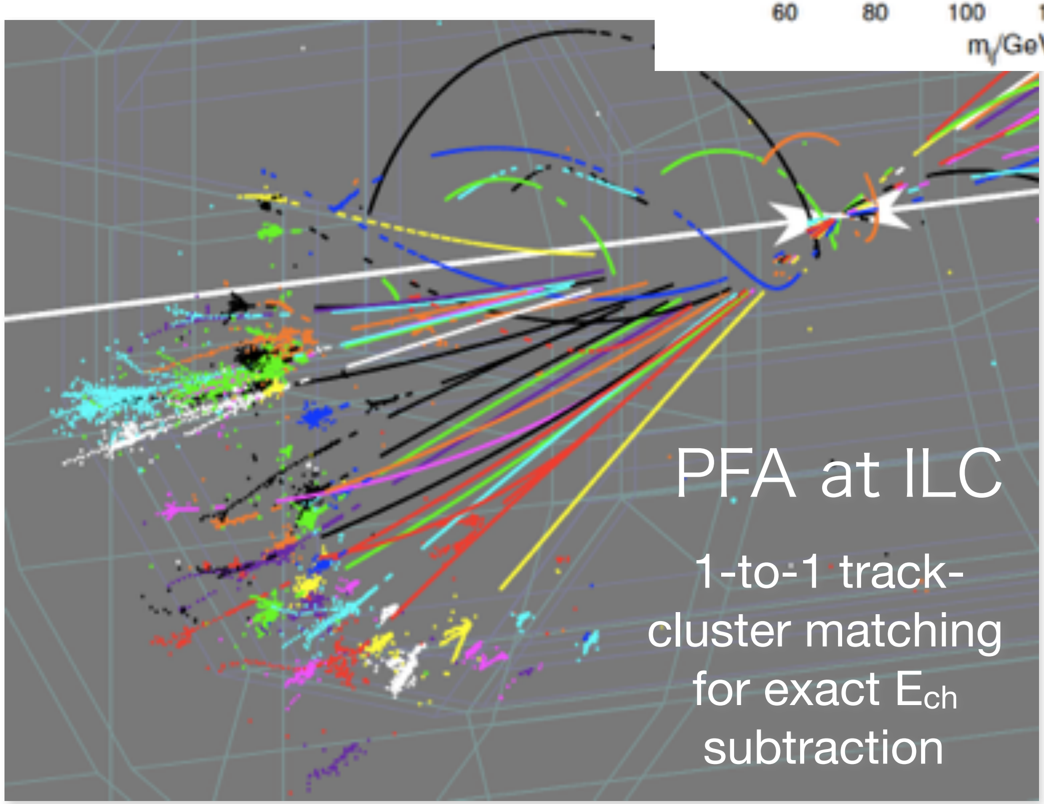


Particle Flow Analysis

PFA is the key to achieve excellent jet invariant mass resolution comparable to the natural width of the weak boson:

$$\sigma_{M_{\rm jets}} \simeq \Gamma_Z$$

Use tracker for charged particles, use CAL only for neutral particles, removing energy deposits by charged particles (E_{ch}) in CAL by 1-to-1 track to CAL cluster matching



PFA at ILC

1-to-1 track-cluster matching for exact E_{ch} subtraction

1-to-1 matching requires

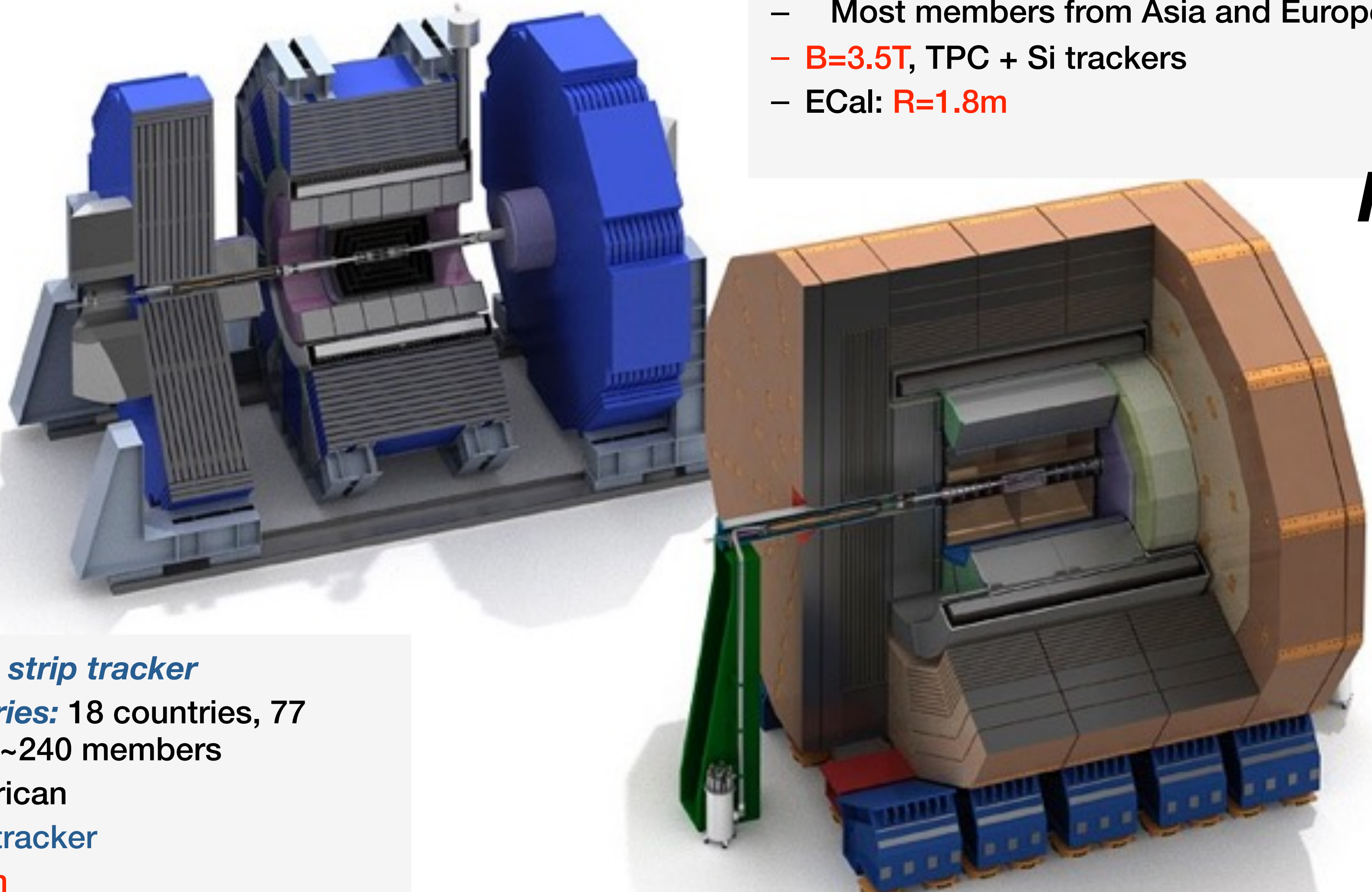
High resolution tracking

High granularity calorimetry

Detailed Baseline Design (TDR vol.4)

arXiv: 1306.6329

- Large R with ***TPC tracker***
  - ***LOI signatories:*** 32 countries, 151 institutions, ~700 members
  - Most members from Asia and Europe
  - B=3.5T, TPC + Si trackers
  - ECal: R=1.8m



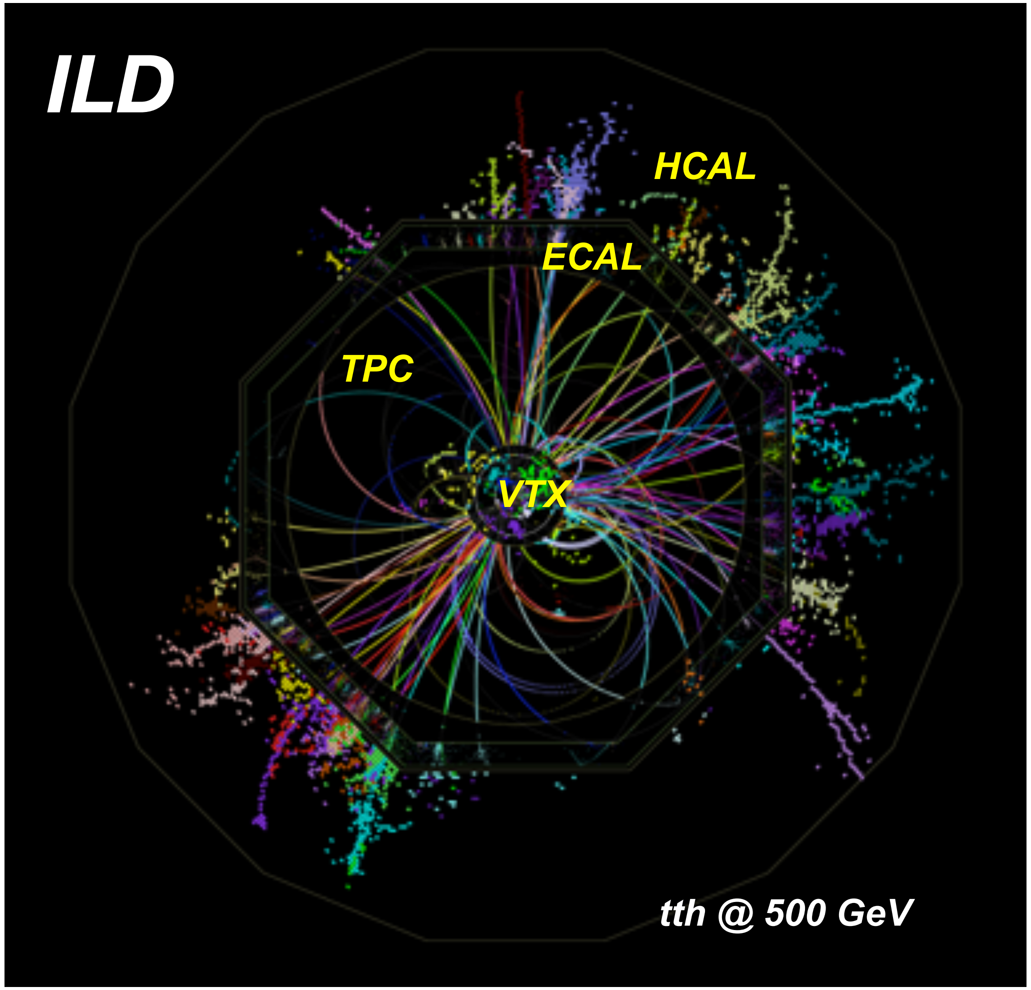
- High B with ***Si strip tracker***
  - ***LOI signatories:*** 18 countries, 77 institutions, ~240 members
  - Mostly American
  - B=5T, Si only tracker
  - ECal : R=1.27m

Both detector concepts are optimized for

Particle Flow Analysis

Features of ILC Detectors

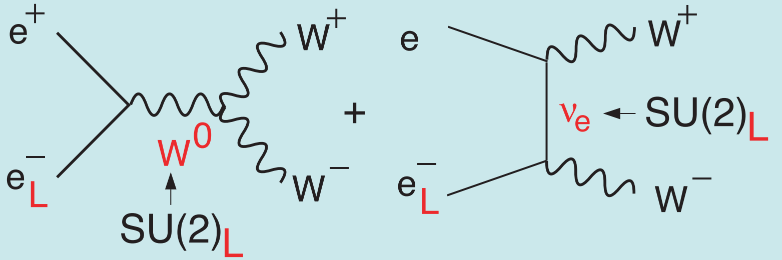
- Compared with LHC detectors, ILC detectors have **~10 times better momentum resolution and 100~1000 times finer granularity.**
- This performance **can be achieved only in the clean environment of the ILC**, and cannot be achieved in the LHC environment.



tth @ 500 GeV

Power of Beam Polarization

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

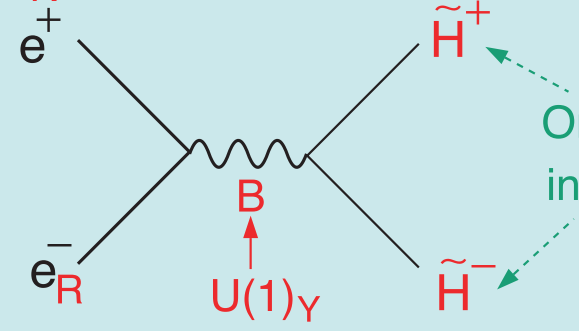


In the symmetry limit, $\sigma_{WW} \to 0$ for e_R^- !

BG Suppression

Chargino Pair

e_R^- Beam



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

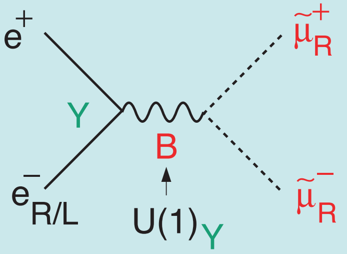
cf.) $e^+e^- \to W^+W^-$

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

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

Decomposition

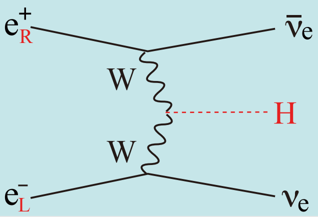
Slepton Pair



$Y_L = -1/2$: 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

Higgs

Why 500 GeV?

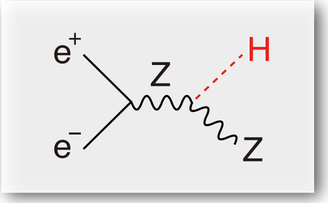
Higgs-related Physics at Ecm ≲ 500 GeV

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)

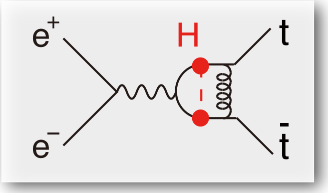
→Higgs couplings (other than top)

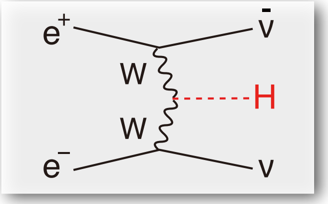


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- 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



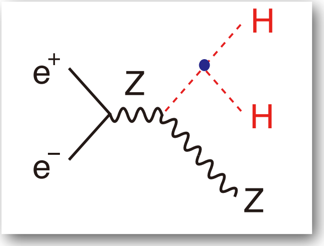


vvH @ 350 - 500GeV :

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

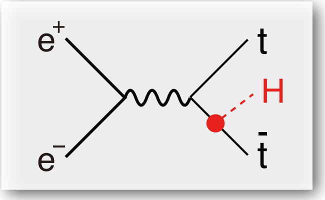
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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)

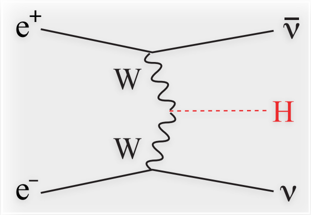
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

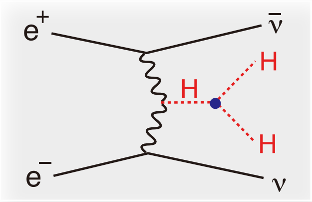
vvHH @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

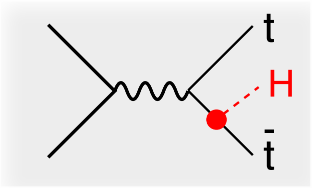
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

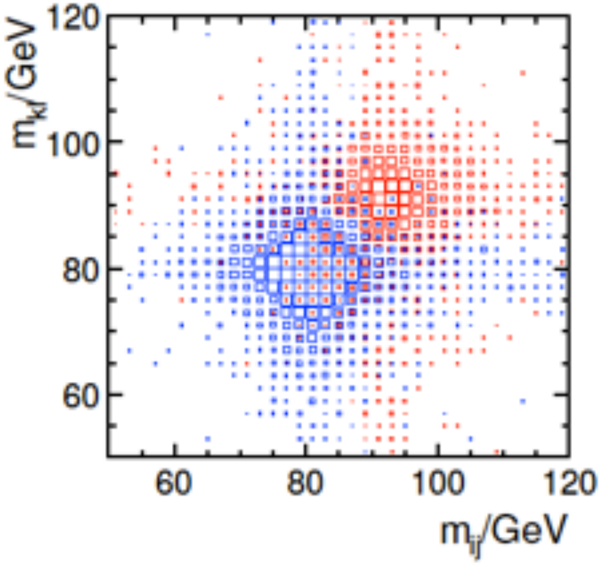
ttbarH @ 1TeV : 1ab^{-1}

- 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!

Model-independent Global Fit for Couplings

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

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

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

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

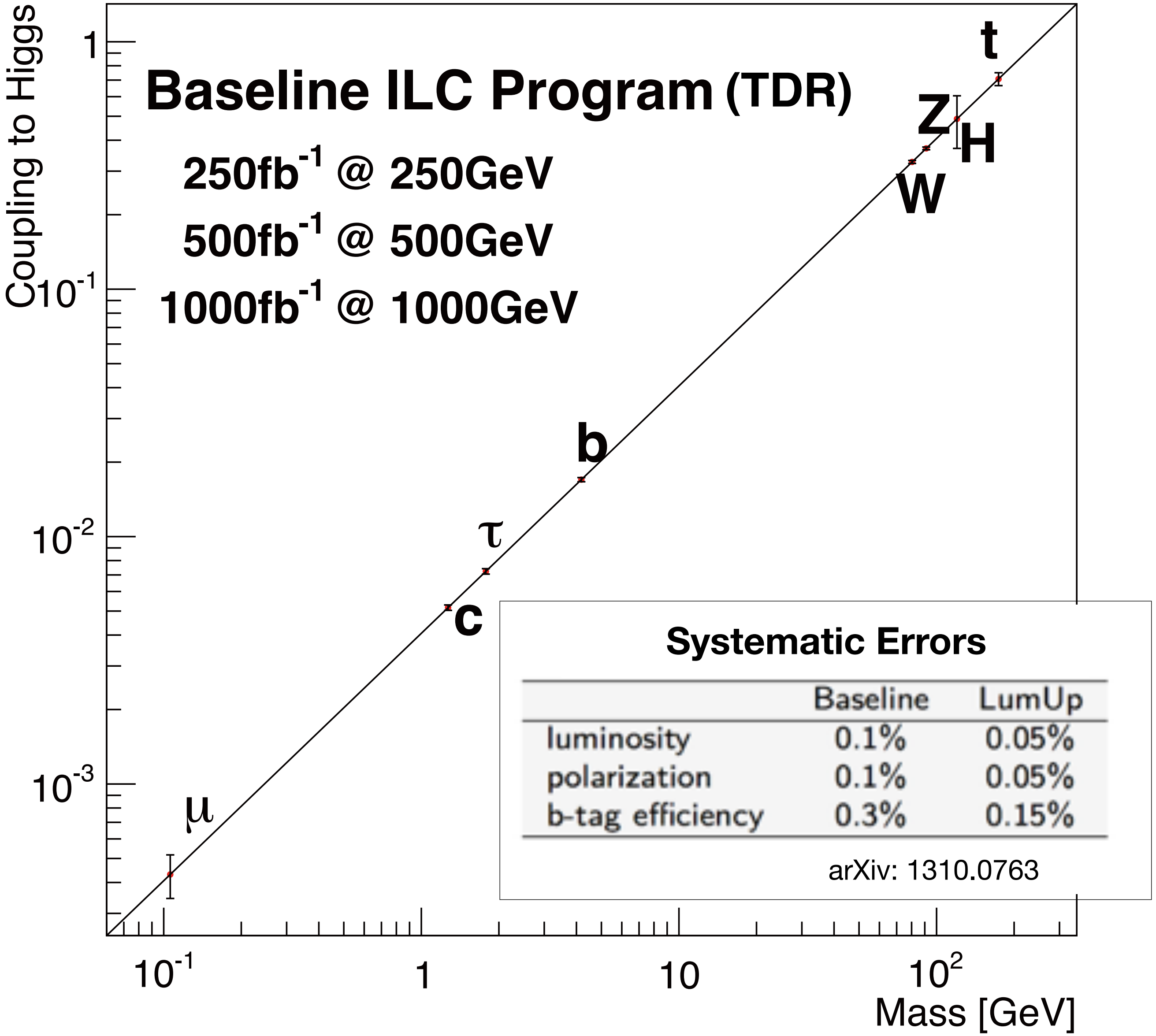
$(A_i = Z, W, t)$

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

$$F_i = S_i\, G_i$$

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

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



Baseline ILC Program (TDR)

250fb^{-1} @ 250GeV

500fb^{-1} @ 500GeV

1000fb^{-1} @ 1000GeV

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!

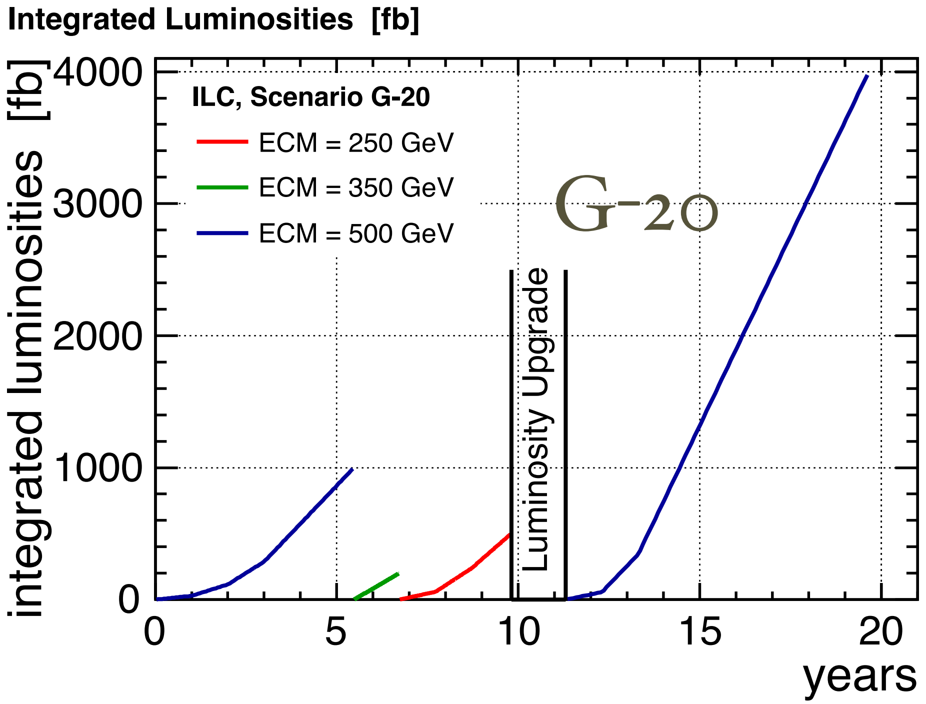
Independent Higgs Measurements at ILC

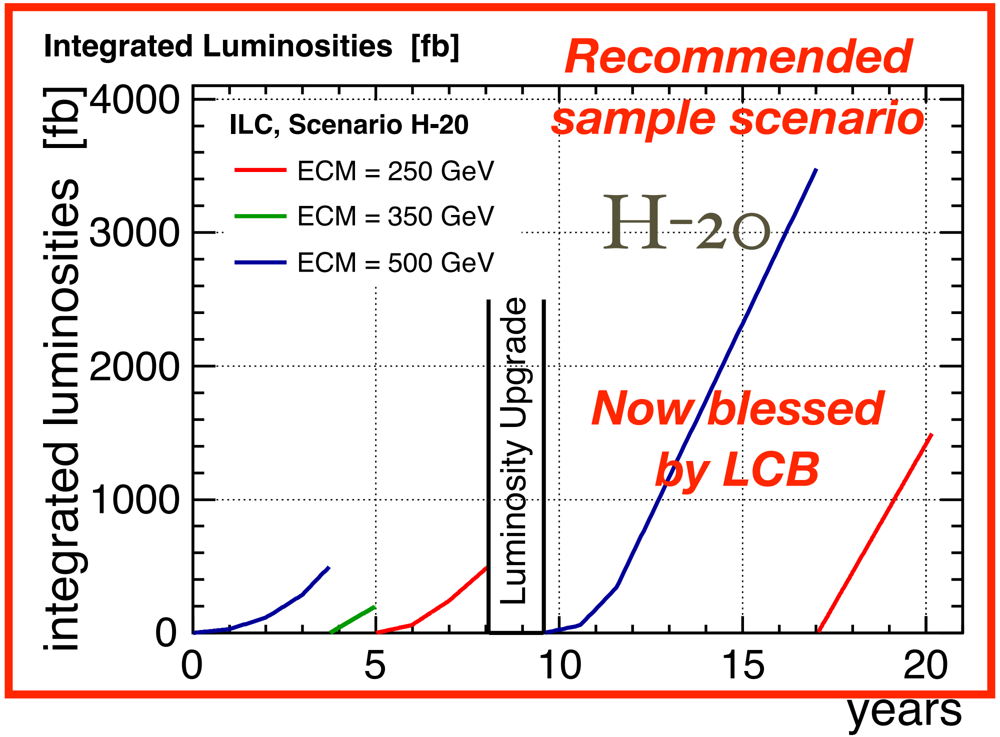
Baseline (=TDR) ILC program

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

($M_H = 125$ GeV)

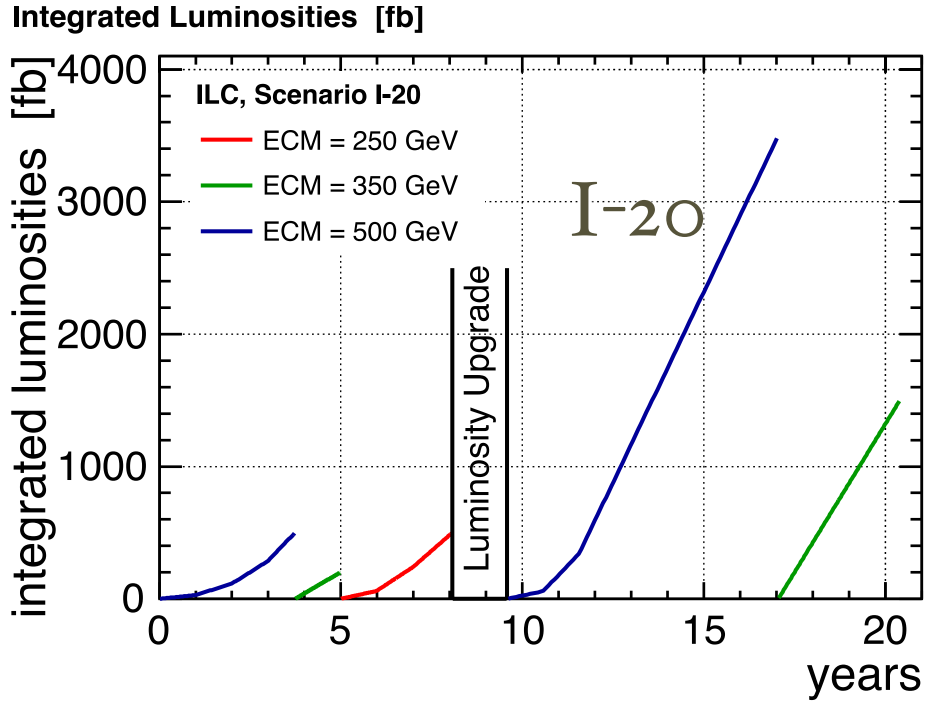
Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb^{-1}]	250		500		1000
polarization (e^-,e^+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	ννH(fusion)	ZH	ννH(fusion)	ννH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
$H\to bb$	1.2%	10.5%	1.8%	0.66%	0.32%
$H\to cc$	8.3%		13%	6.2%	3.1%
$H\to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

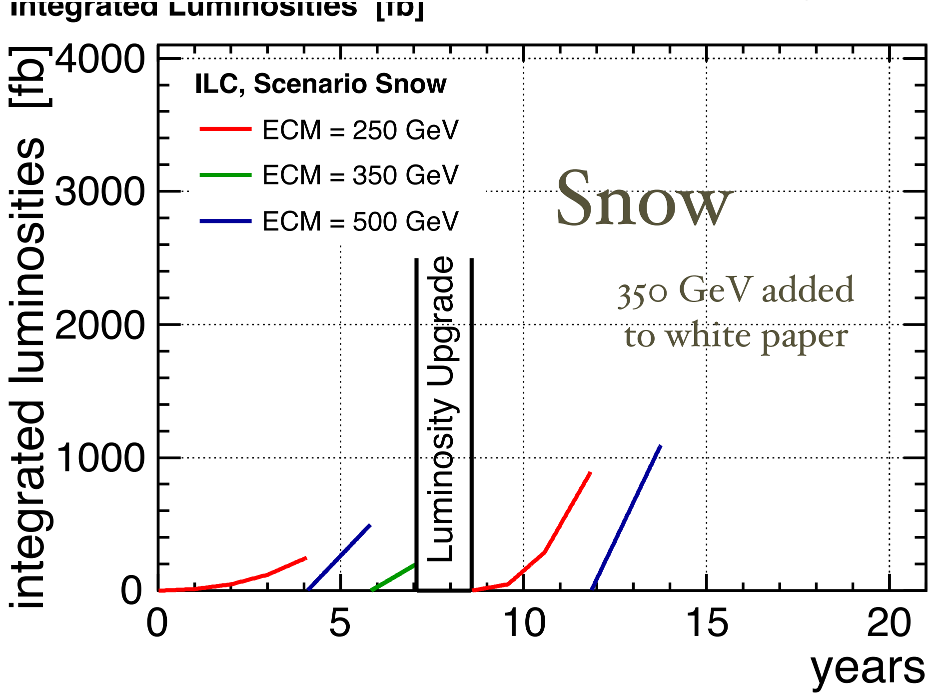




Recommended sample scenario

Now blessed by LCB

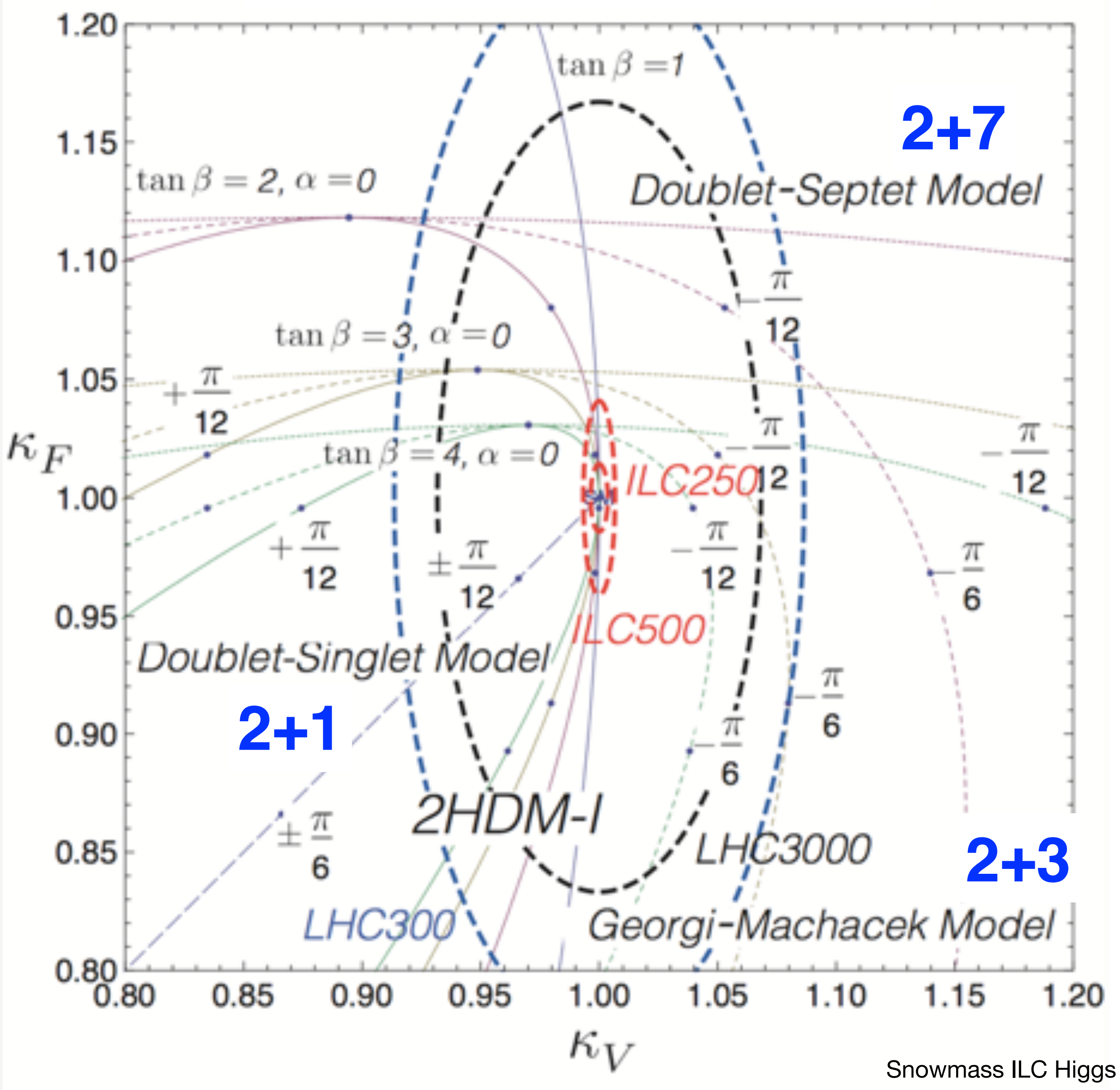




350 GeV added to white paper

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)]

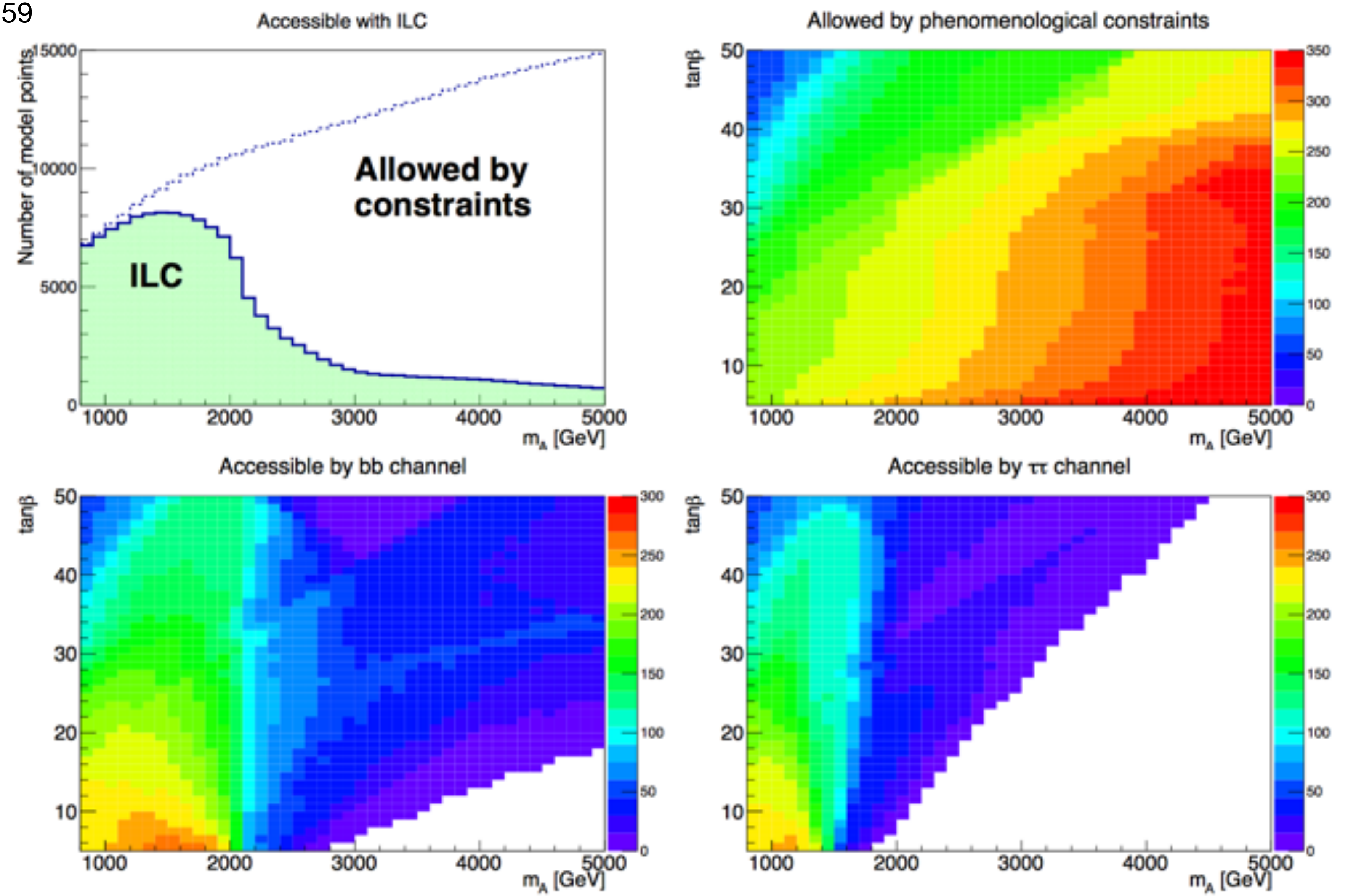


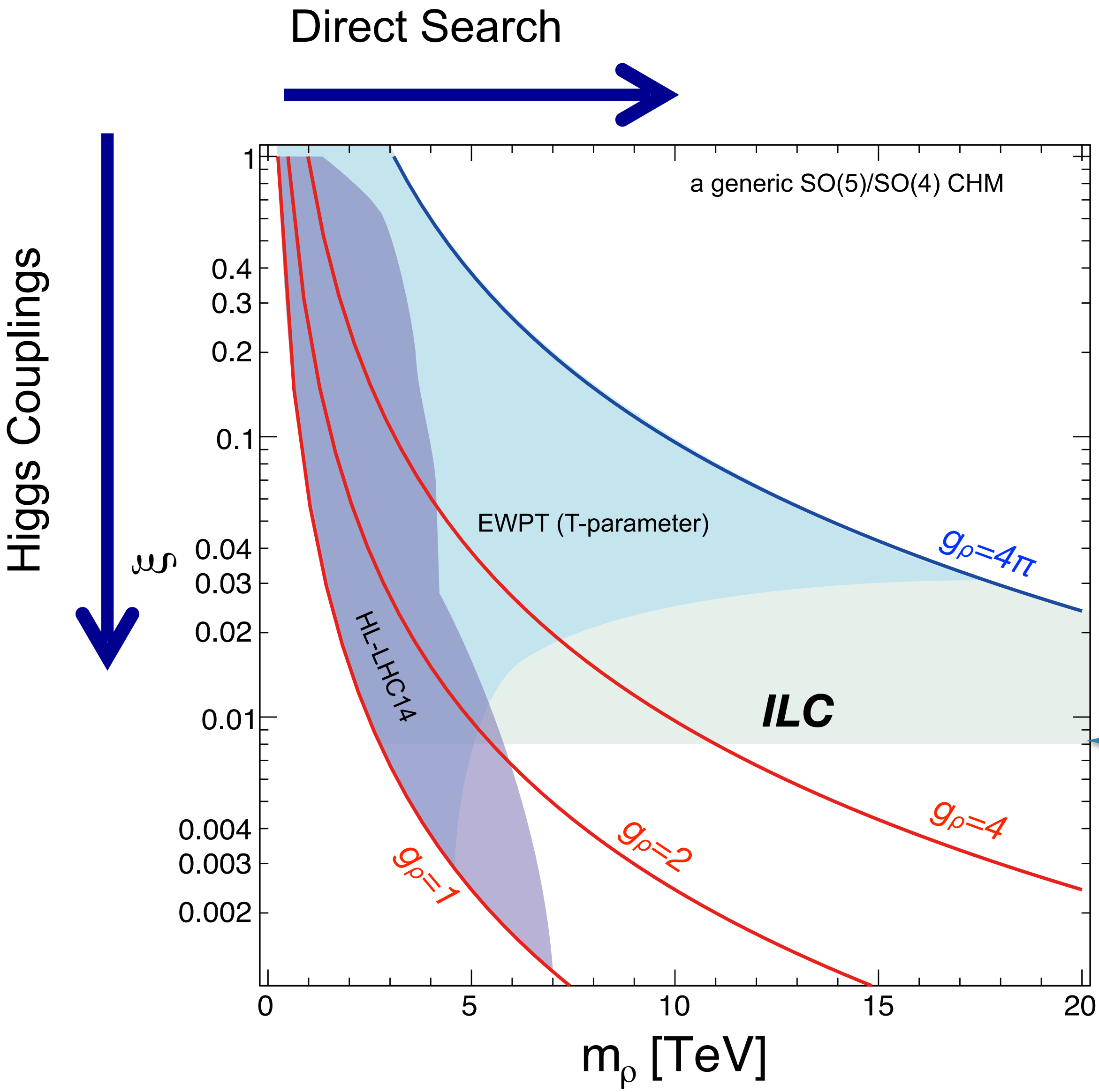
Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological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

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

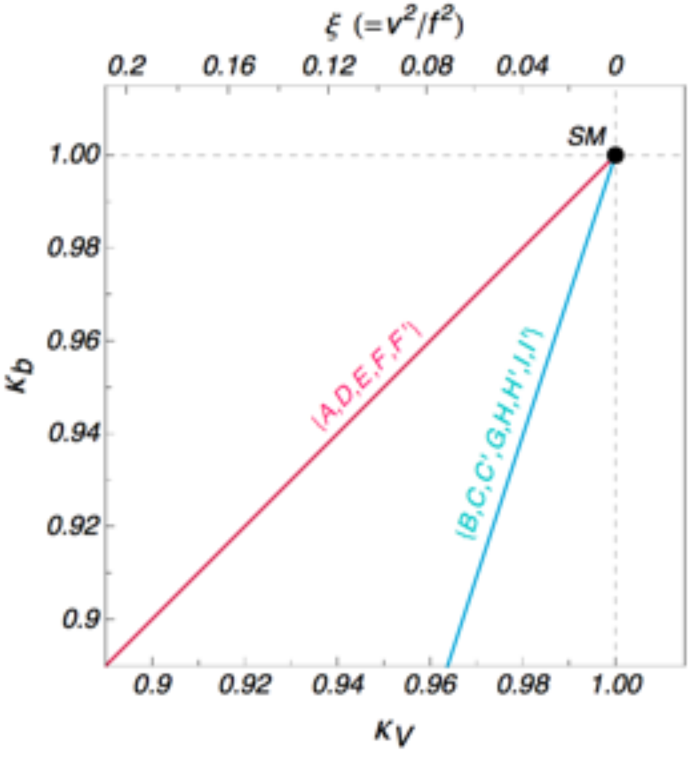
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \sqrt{1-\xi}$$

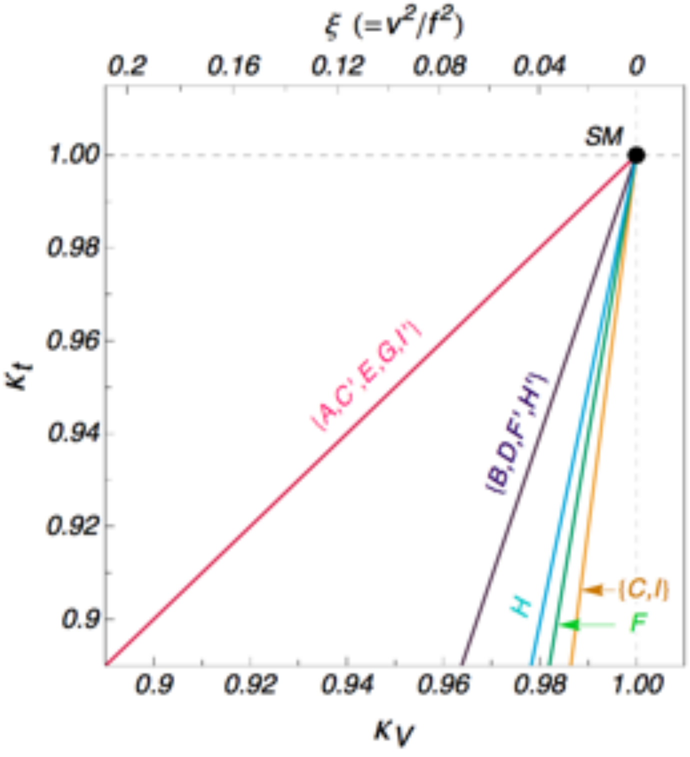
ILC (250+500 LumiUP)

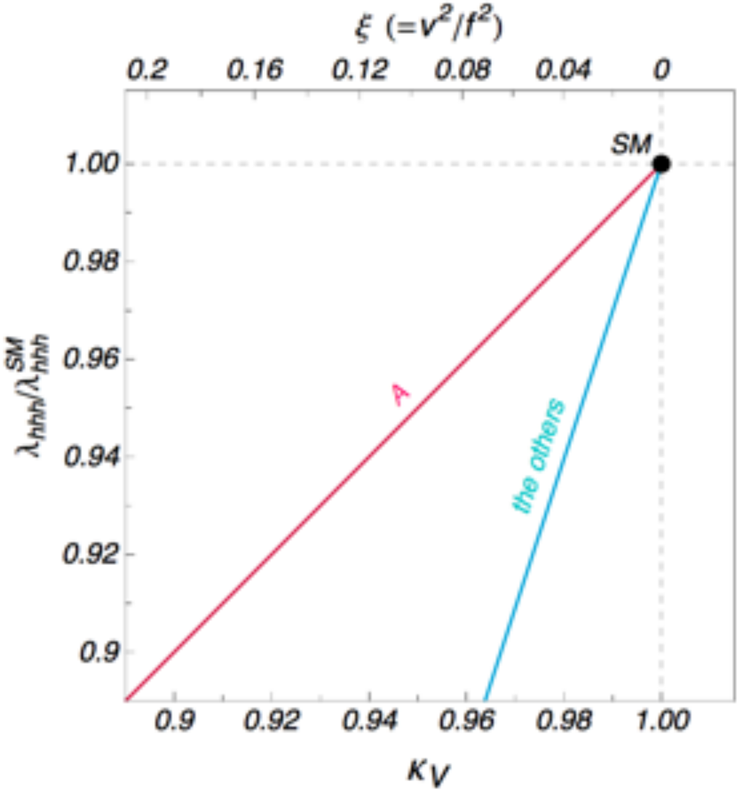
$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

New resonance scale and fingerprint identification in minimal composite Higgs models

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







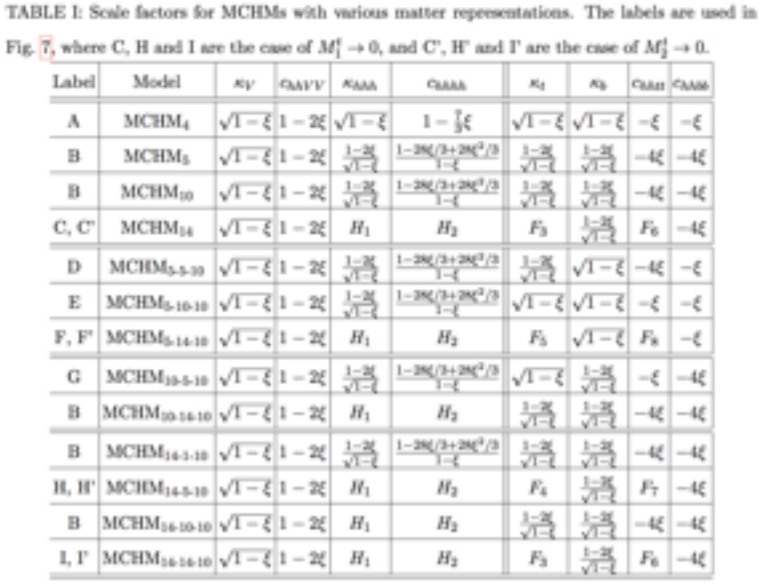


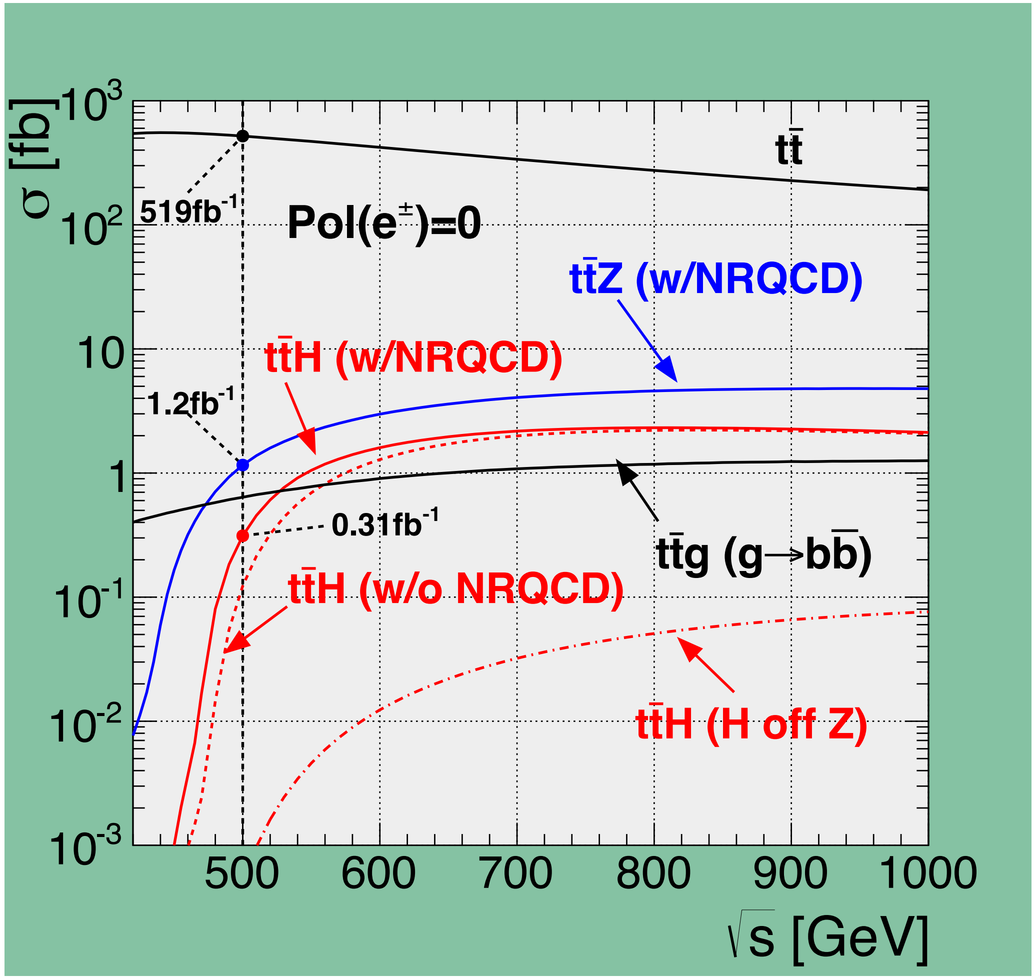
TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. 7, where C, H and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_2^t \to 0$.

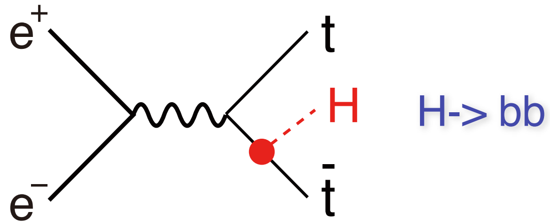
Label	Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
A	MCHM$_4$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	MCHM$_5$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-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_6	-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$_{5\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	MCHM$_{5\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
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$_{14\text{-}1\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
H, H'	MCHM$_{14\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	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

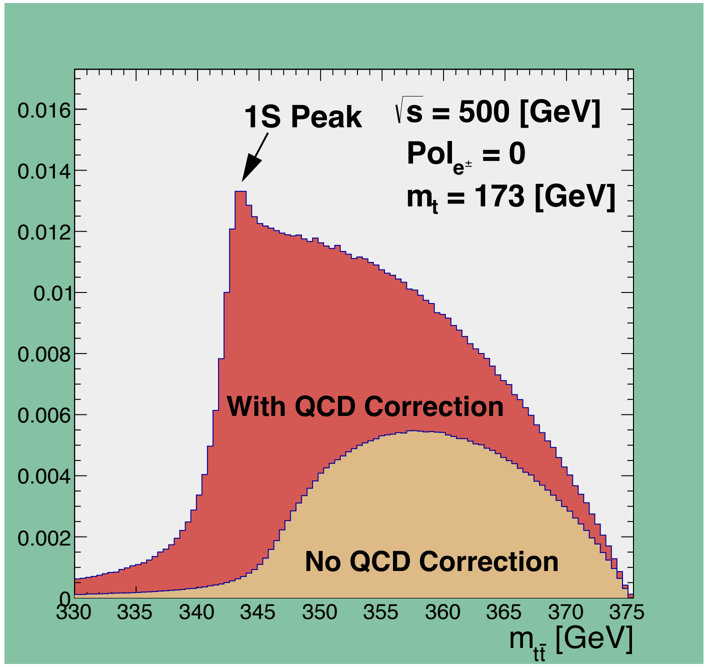
arXiv 1410.8413

Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed







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

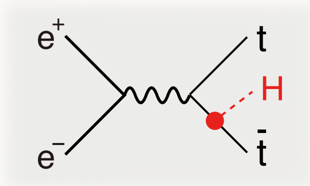
$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

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

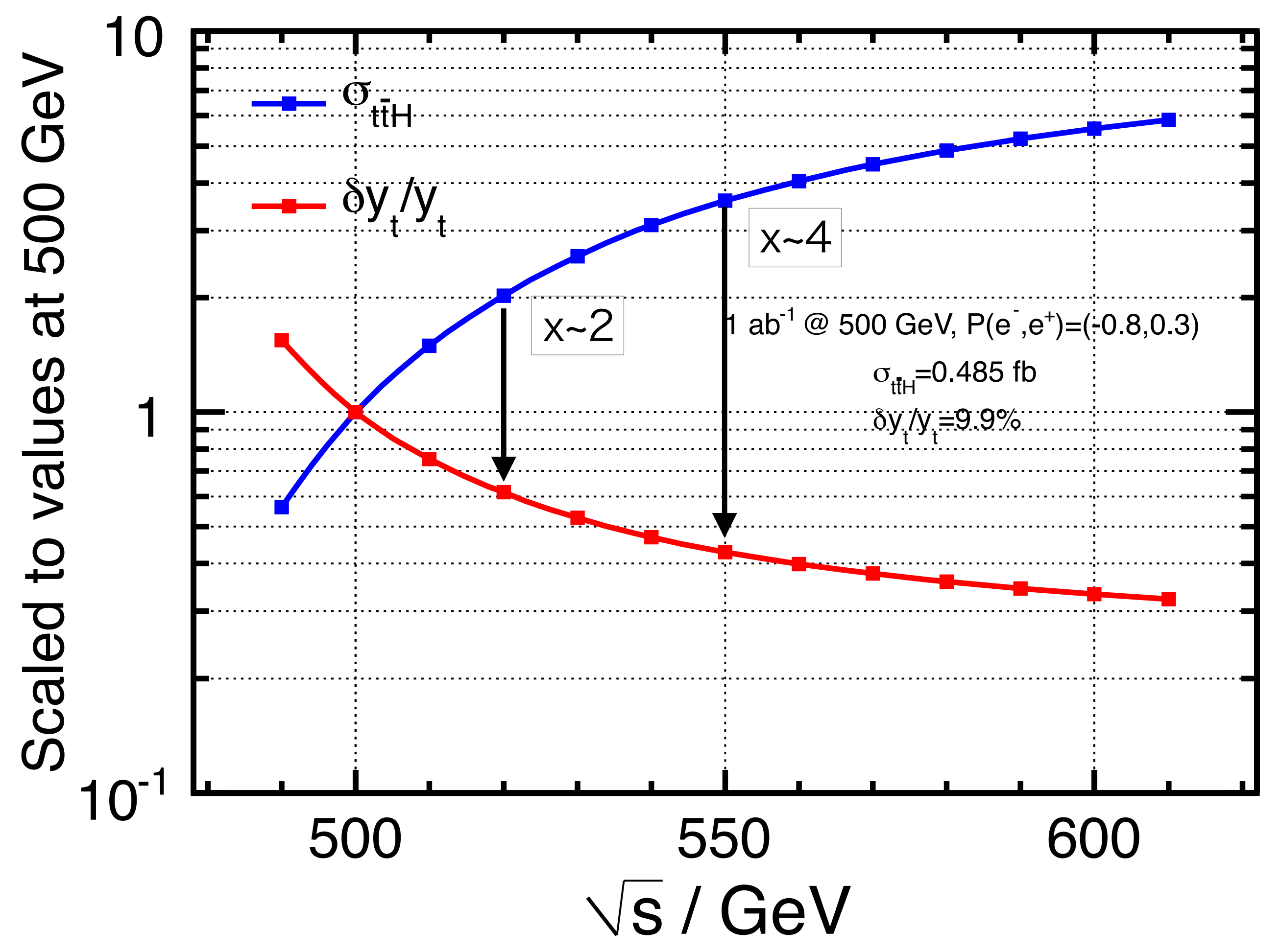
Tony Price, LCWS12

scaled from mH=120 GeV

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



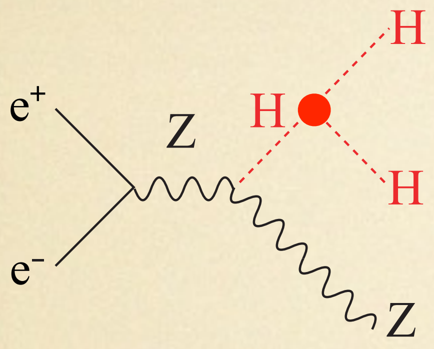
Top Yukawa coupling

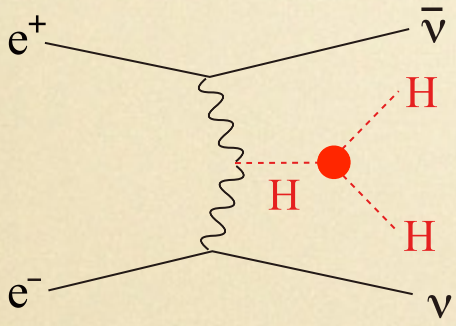


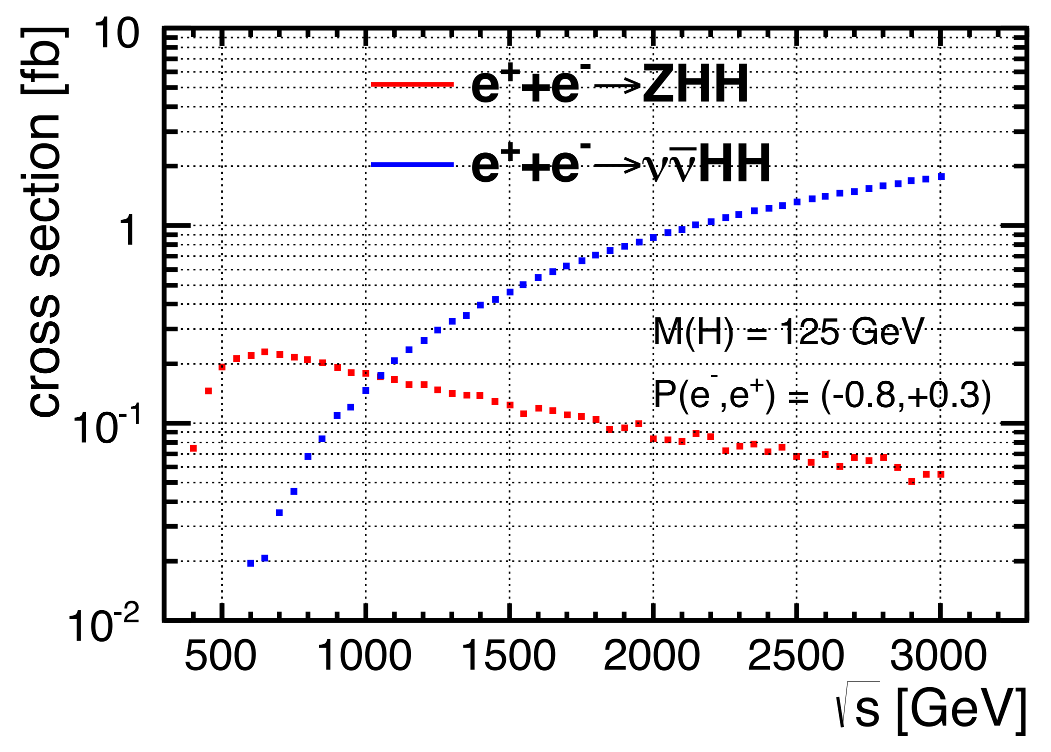
Y. Sudo

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%

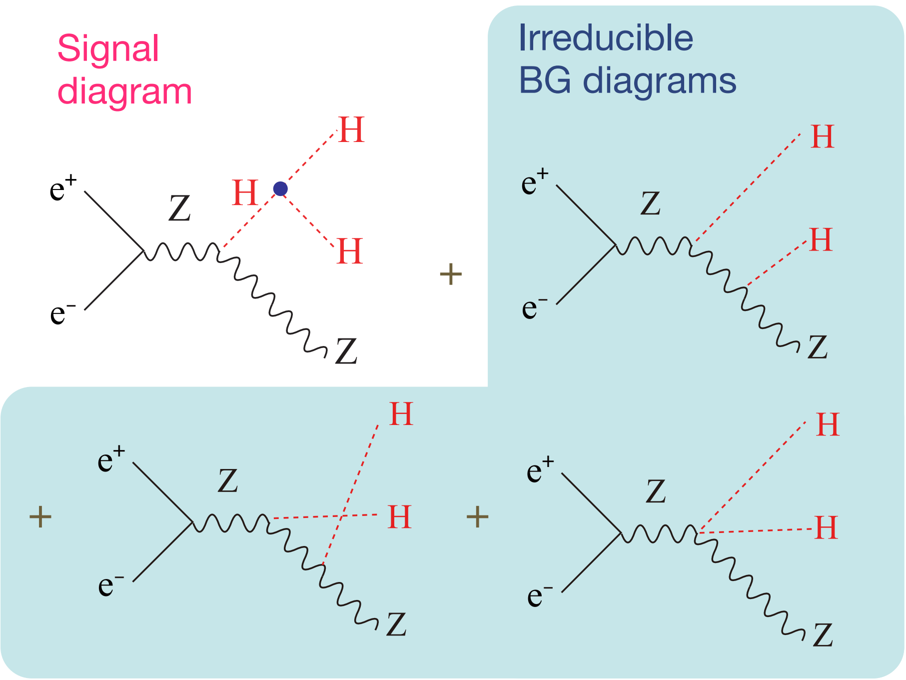
(arXiv: 1307.5288)

J. Tian, LC-REP-2013-003

C. Dürig @ ALCW15

M. Kurata, LC-REP-2014-025

The Problem : BG diagrams dilute self-coupling contribution

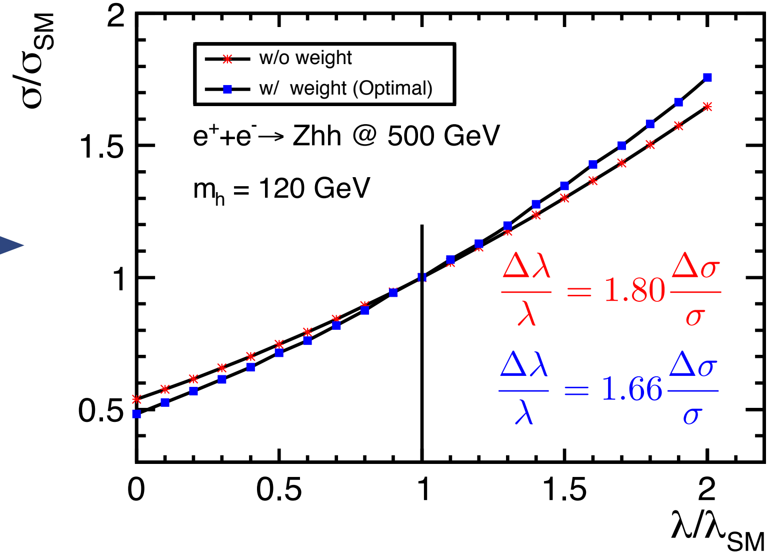

Signal diagram

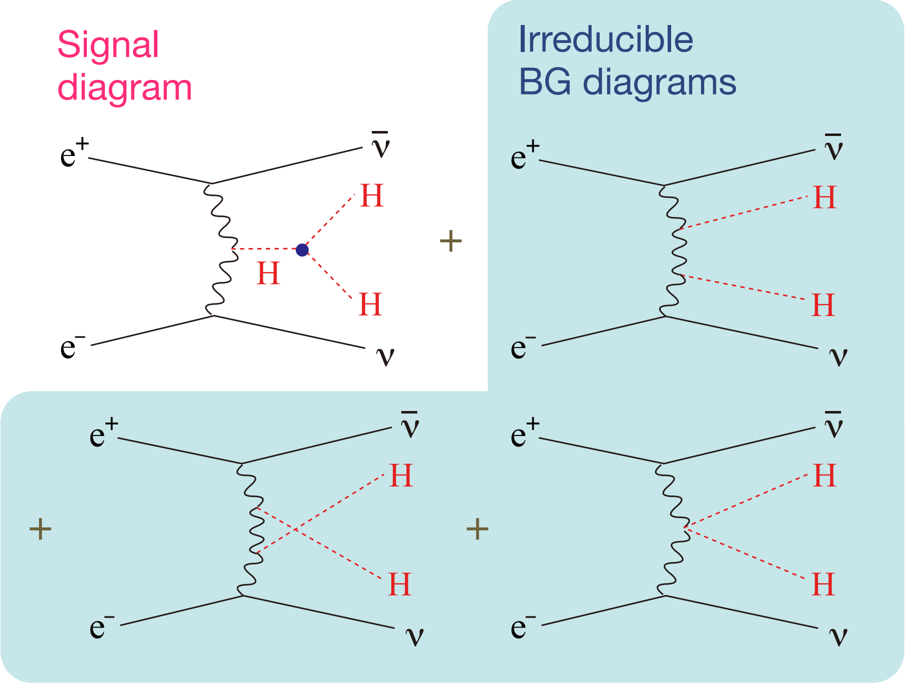
Irreducible BG diagrams

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

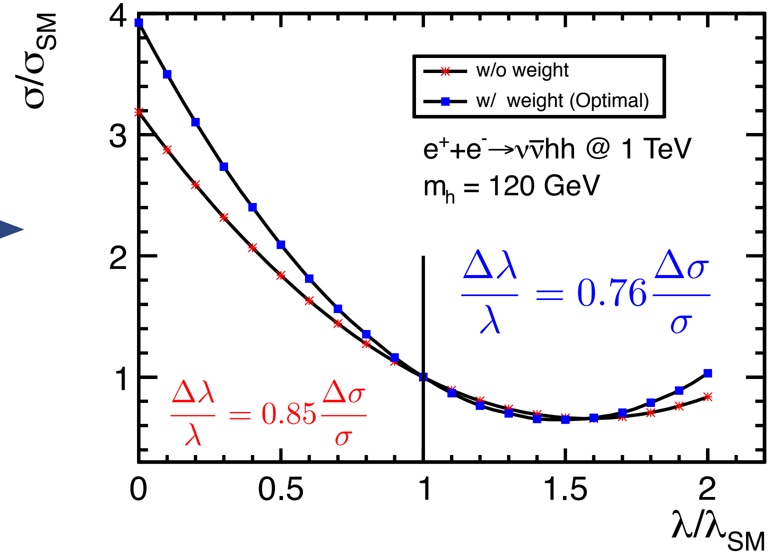
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams



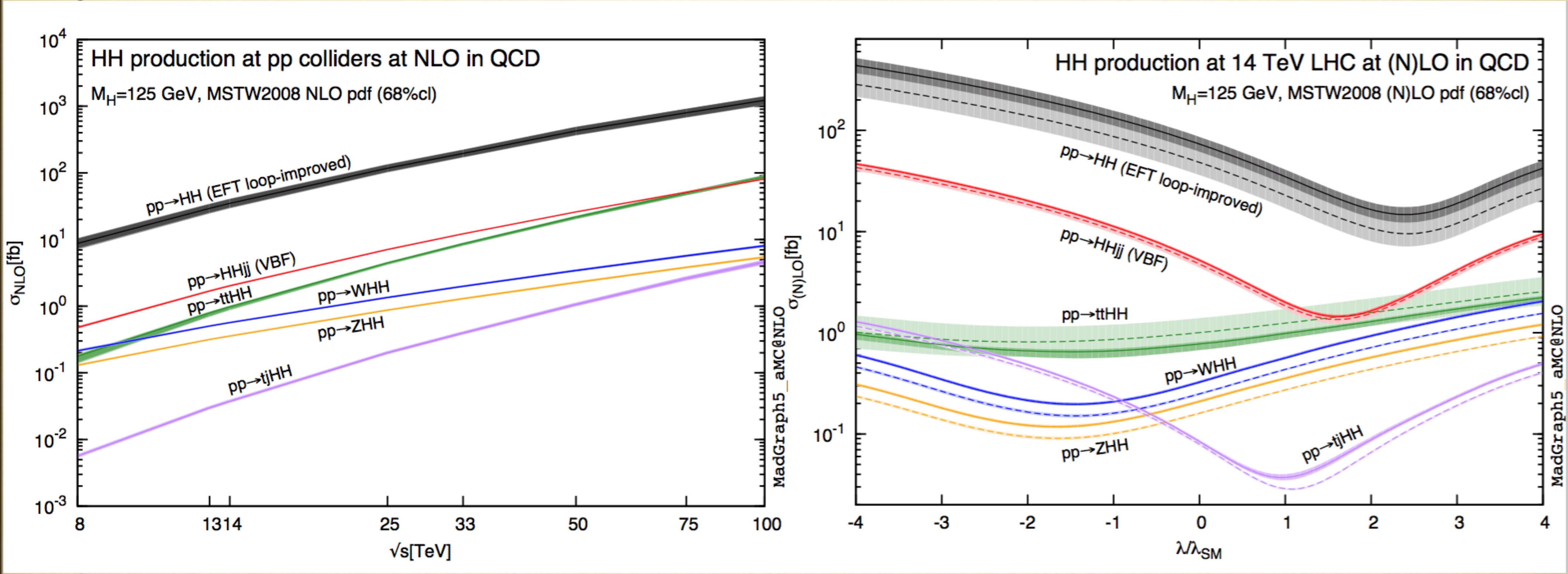

Signal diagram

Irreducible BG diagrams



Junping Tian LC-REP-2013-003

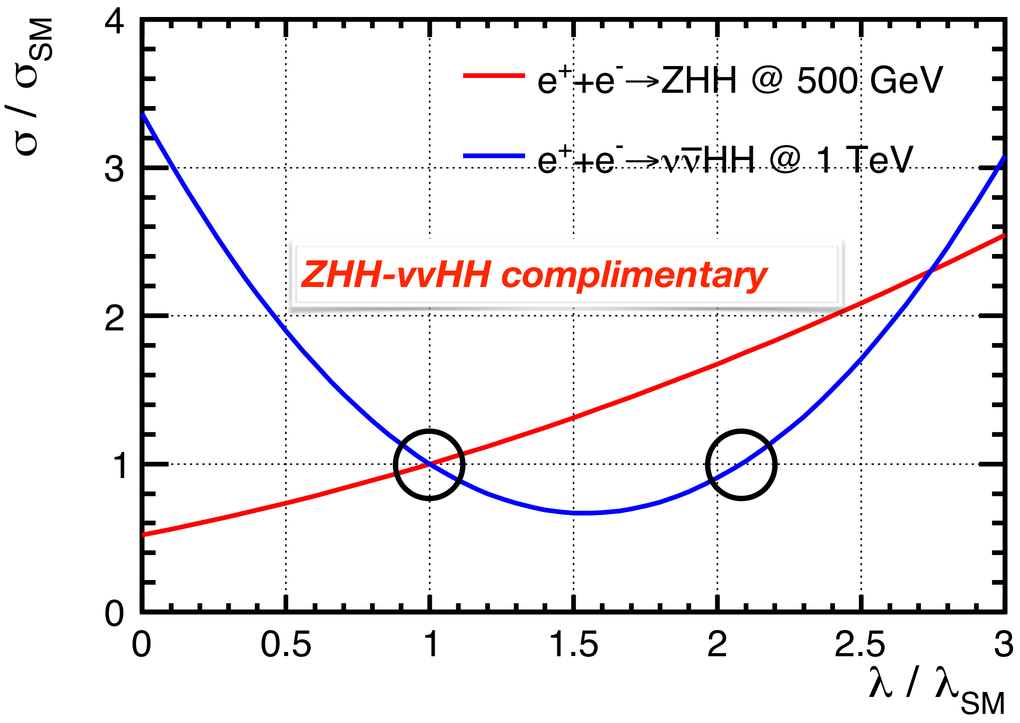
What if $\lambda \neq \lambda_{SM}$? @ LHC



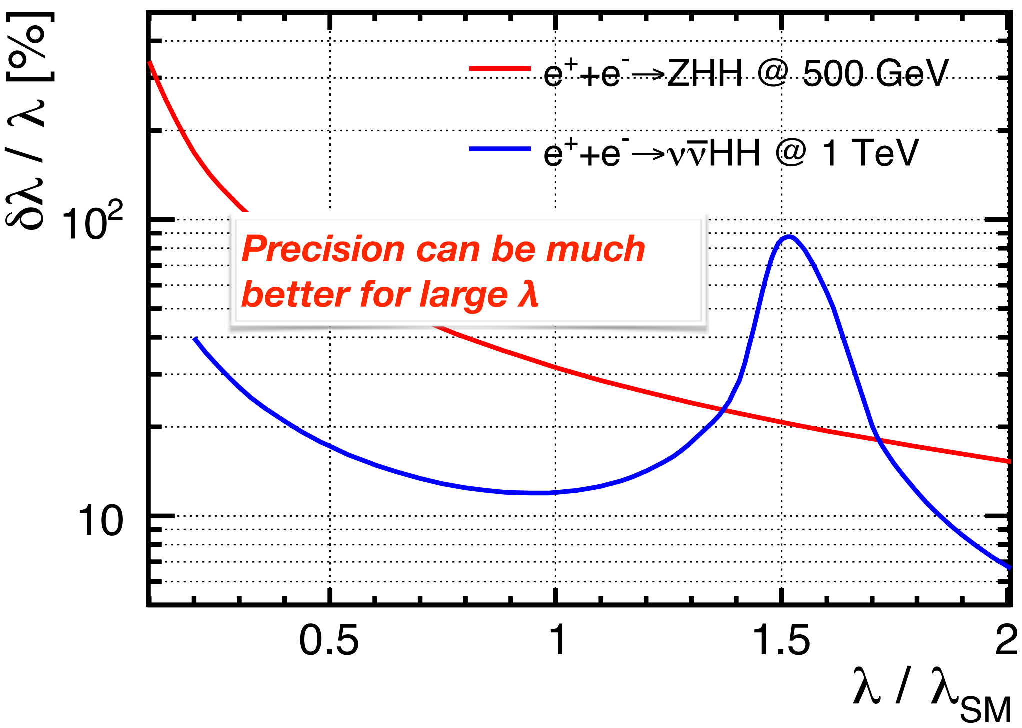
arXiv:1401.7304

- 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)

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



ZHH-vvHH complimentary



Precision can be much better for large λ

- for ZHH, interference is constructive, enhanced λ will increase σ, and improve sensitivity factor as well, e.g. if $\lambda = 2\lambda_{SM}$, σ increases by 60%, F reduced by 1/2, $\delta\lambda/\lambda$ ~15%
  → we may finish the λ story at 500 GeV ILC !
  In EWSB models with classical conformal symmetry (Hashino,Kanemura,Orikasa, arXiv:1508.03245)

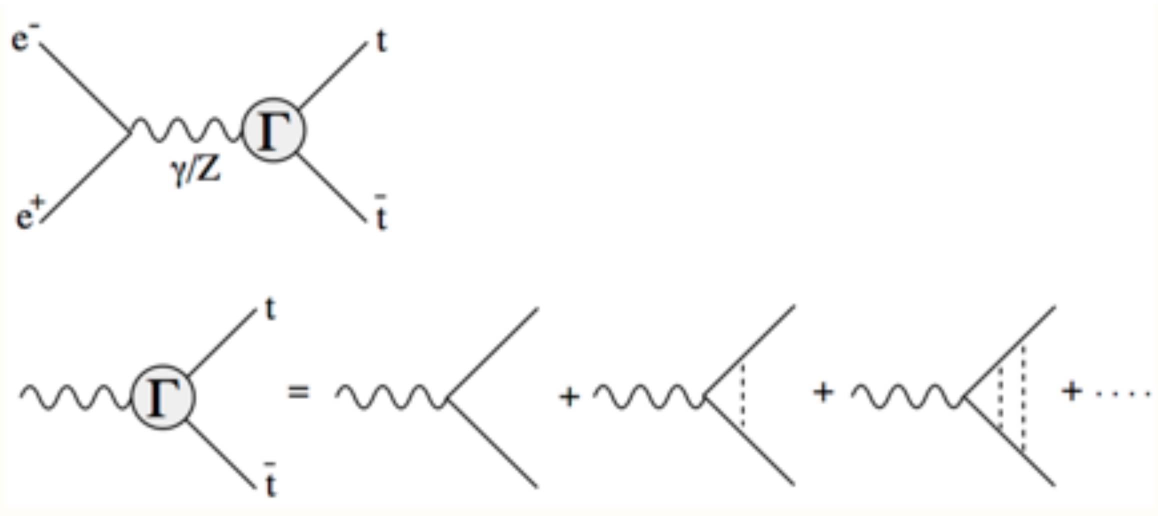
$$\Gamma_{hhh}^{\mathrm{CSI}} = \frac{5m_h^2}{v} = \frac{5}{3} \times \Gamma_{hhh}^{\mathrm{SMtree}}.$$

- for νvHH, interference is destructive, enhanced λ will decrease σ, minimum when λ~$1.5\lambda_{SM}$, $\delta\lambda/\lambda$ degrades significantly if $\lambda/\lambda_{SM} \in (1.3, 1.7)$
- but if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely more on ννHH
- two channels are complementary in terms of λ measurement in BSM

Top

Top Quark

Threshold Region



At threshold both the top quark and the anti-top quark are slow and stay close to each other, allowing multiple exchange of Coulombic gluons.

⇒ Leading contribution

The threshold correction factor (bound-state effect) denoted by Γ satisfies the Bethe-Salpeter equation which reduces to Schroedinger's equation:

$$\left[H - \left(E + \frac{i}{2}\Gamma_\Theta\right)\right] G = 1$$

in the non-relativistic limit. The operator G is related to Γ through

$$\Gamma_V^k \simeq -\left(\frac{1}{D_t} + \frac{1}{D_{\bar{t}}}\right) \cdot \tilde{G}(\boldsymbol{p}; E) \cdot \gamma^k$$

$$\tilde{G}(\boldsymbol{p}; E) \equiv \langle \boldsymbol{p} \,|\, G \,|\, \boldsymbol{x} = \boldsymbol{0} \rangle$$

for vector part

$$\Gamma_A^k \simeq -\left(\frac{1}{D_t} + \frac{1}{D_{\bar{t}}}\right) \cdot \left(\frac{\tilde{F}^l(\boldsymbol{p}; E)}{m_t}\right) \cdot \sigma^{kl}\gamma^5$$

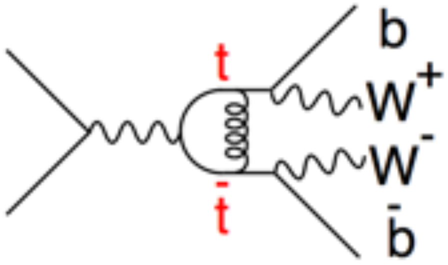
$$\tilde{F}^l(\boldsymbol{p}; E) \equiv \langle \boldsymbol{p} \,|\, G \cdot \hat{p}^l \,|\, \boldsymbol{x} = \boldsymbol{0} \rangle$$

for axial vector part

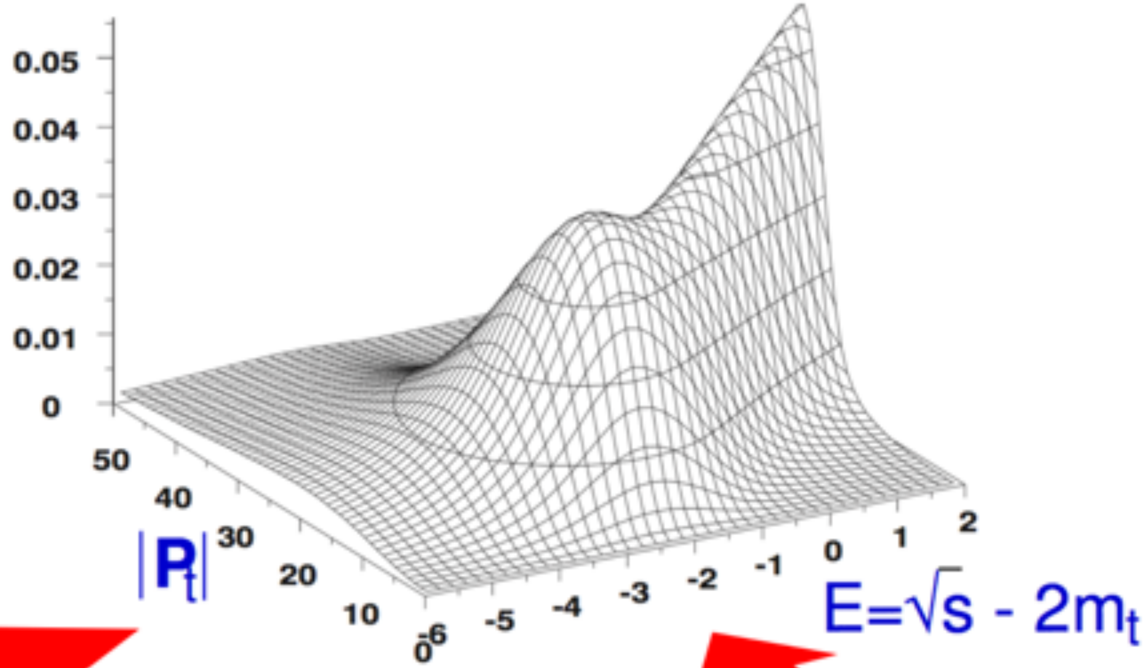
Top Quark

Threshold Region

How to access G experimentally



$p_{top} = p_{bW} = p_{3jets}$



Momentum Dist.

$$\frac{d\sigma_{t\bar t}}{d|\mathbf{p}|} \propto |\langle \mathbf{p}\,|\,G\,|\,\mathbf{x}=\mathbf{0}\,\rangle|^2 \simeq \left|\sum_n \frac{\phi_n(\mathbf{p})\Psi_n^*(\mathbf{0})}{E-E_n+i\Gamma_n/2}\right|^2$$

momentum space wave fun.

Threshold Scan

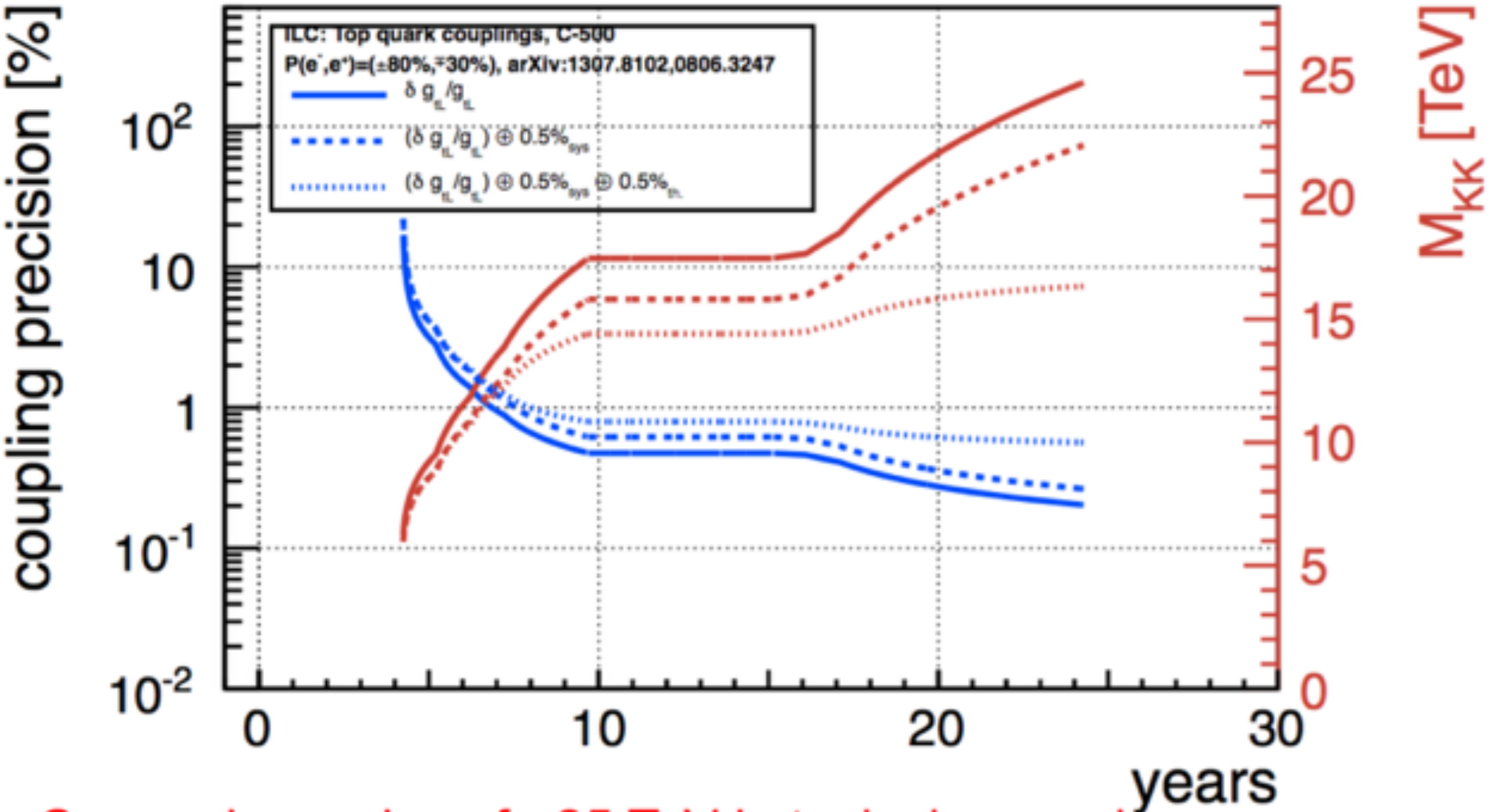
$$\sigma_{t\bar t} \propto Im\,\langle\,\mathbf{x}=\mathbf{0}\,|\,G\,|\,\mathbf{x}=\mathbf{0}\,\rangle \simeq Im\sum_n \frac{|\Psi_n(\mathbf{0})|^2}{E-E_n+i\Gamma_n/2}$$

wave function at origin

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

Comparison to FCC-ee

Recent publication assesses potential of FCC-ee

P. Janot, arXiv:1503.01325, arXiv:1510.09056

- run right above threshold; study assumes 2.4 ab^{-1} at √s = 365 GeV

  (theory systematics close to threshold to be evaluated)

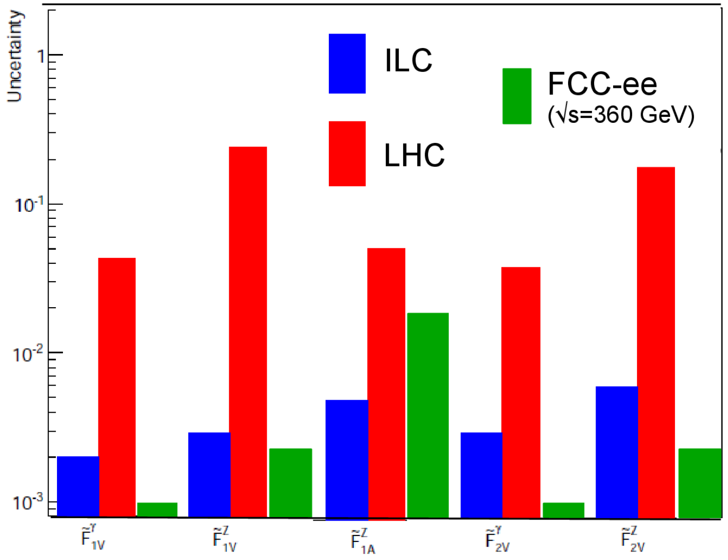
- no beam polarization, use final-state polarization instead

  (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:

- similar precision to ILC for Z couplings, except F1AZ
- significantly better than ILC for photon couplings

Complementarity



Good to see interest in this measurement
Full study needed to understand systematics

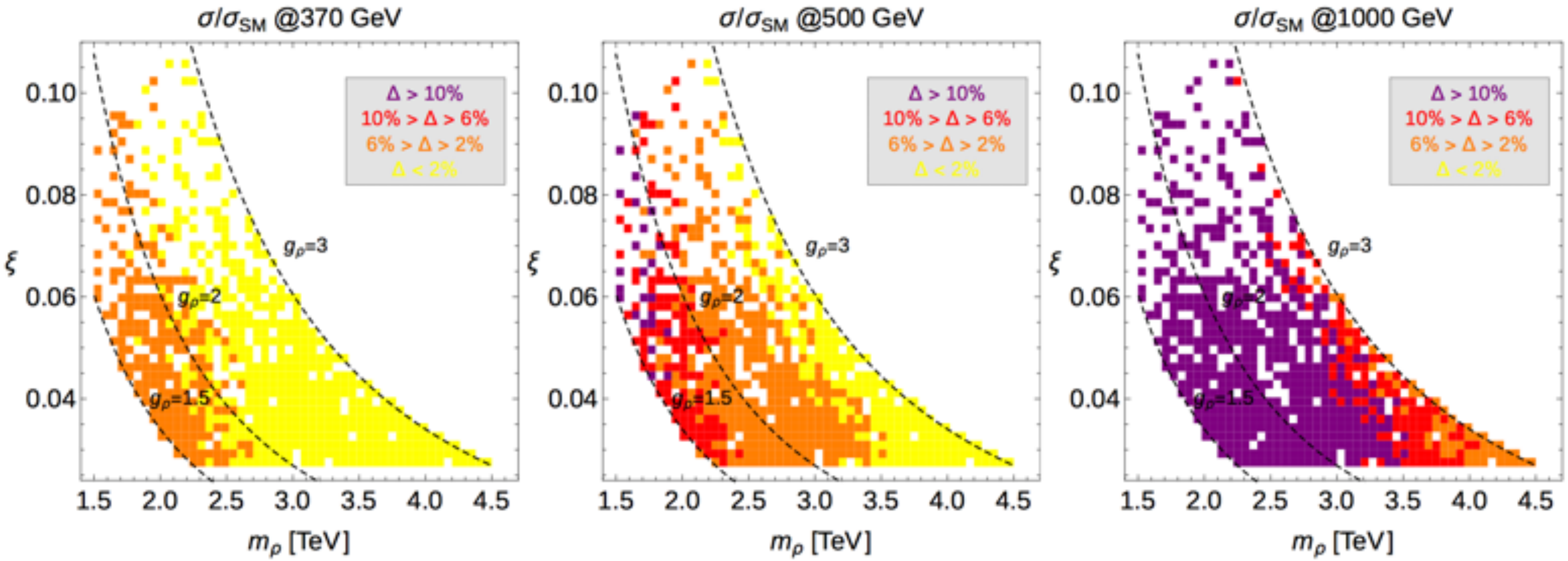


Figure 5. Predicted deviations for the cross section of the process $e^+e^- \to t\bar{t}$ at 370, 500, 1000 GeV in the 4DCHM compared with the SM as functions of $m_\rho = fg_\rho$ and $\xi = v^2/f^2$. For each point we have selected the configuration yielding the maximal deviation defined as $\Delta = (\sigma^{\rm 4DCHM} - \sigma^{\rm SM})/\sigma^{\rm SM}$. The points correspond to $f = 0.75 - 1.5\,\text{TeV}$, $g_\rho = 1.5 - 3$. Bounds on the masses of the extra fermions are the same as in figure 2.

Cosme, Lopes, Penedones: JHEP08 (2015) 127

DM

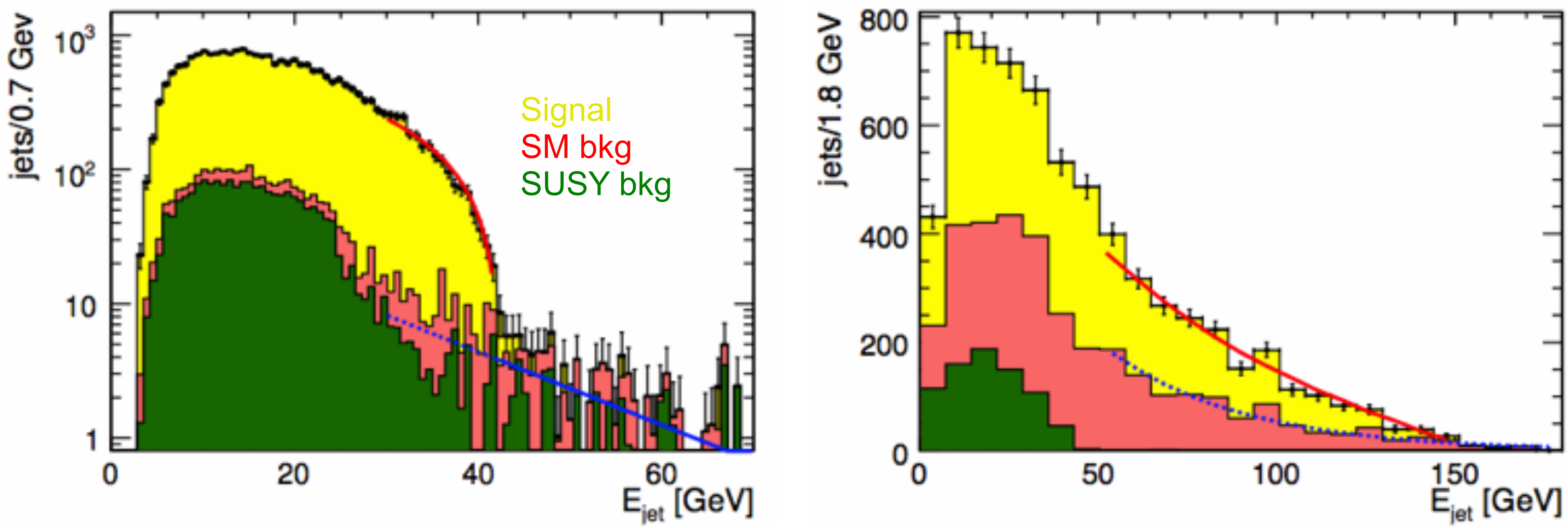
Slepton decays to DM with small mass differences

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)

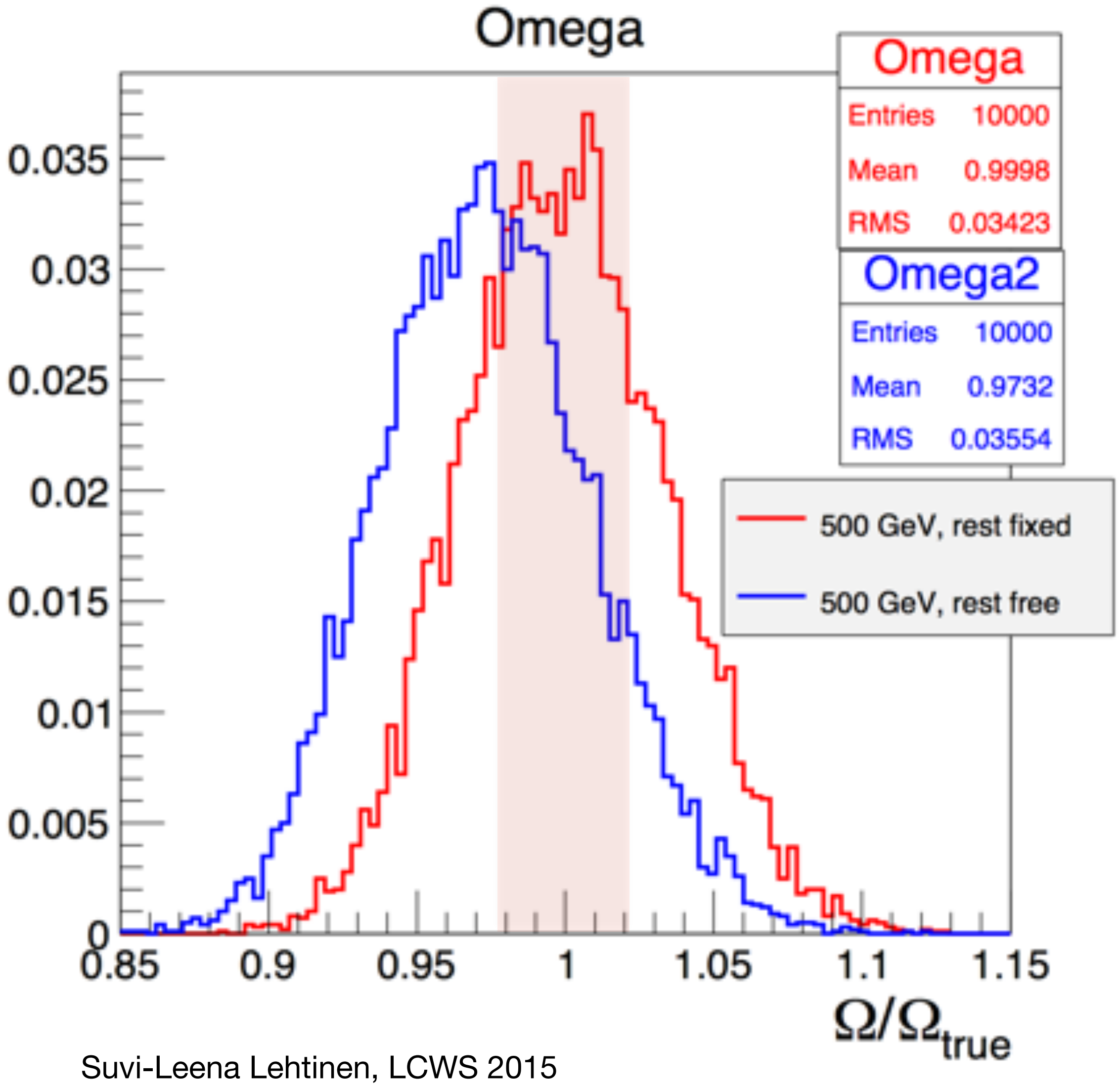


√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)
Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

DM Relic Abundance

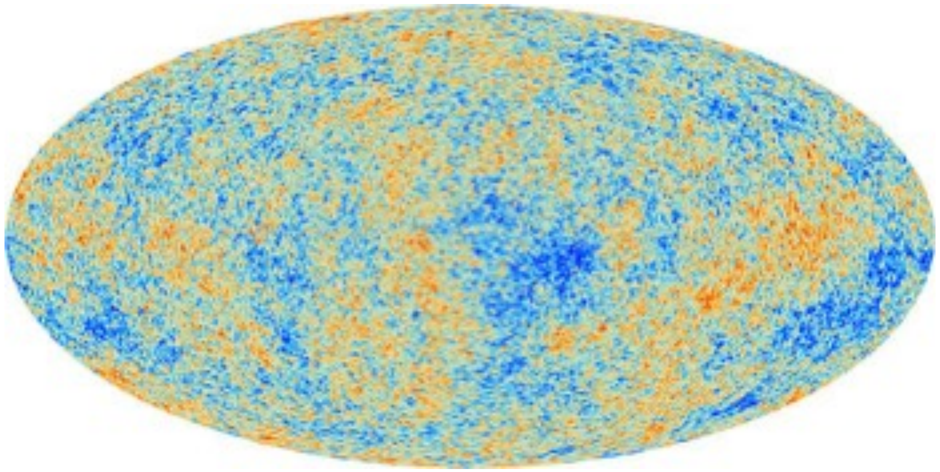
WMAP/Planck (68% CL)

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



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

Other Probes

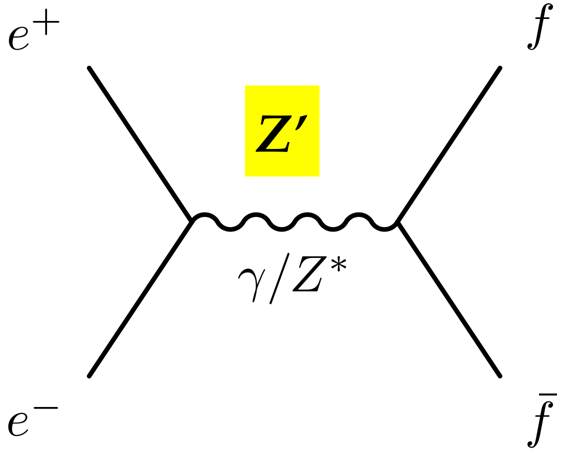
Z’

Z' : Heavy Neutral Gauge Bosons

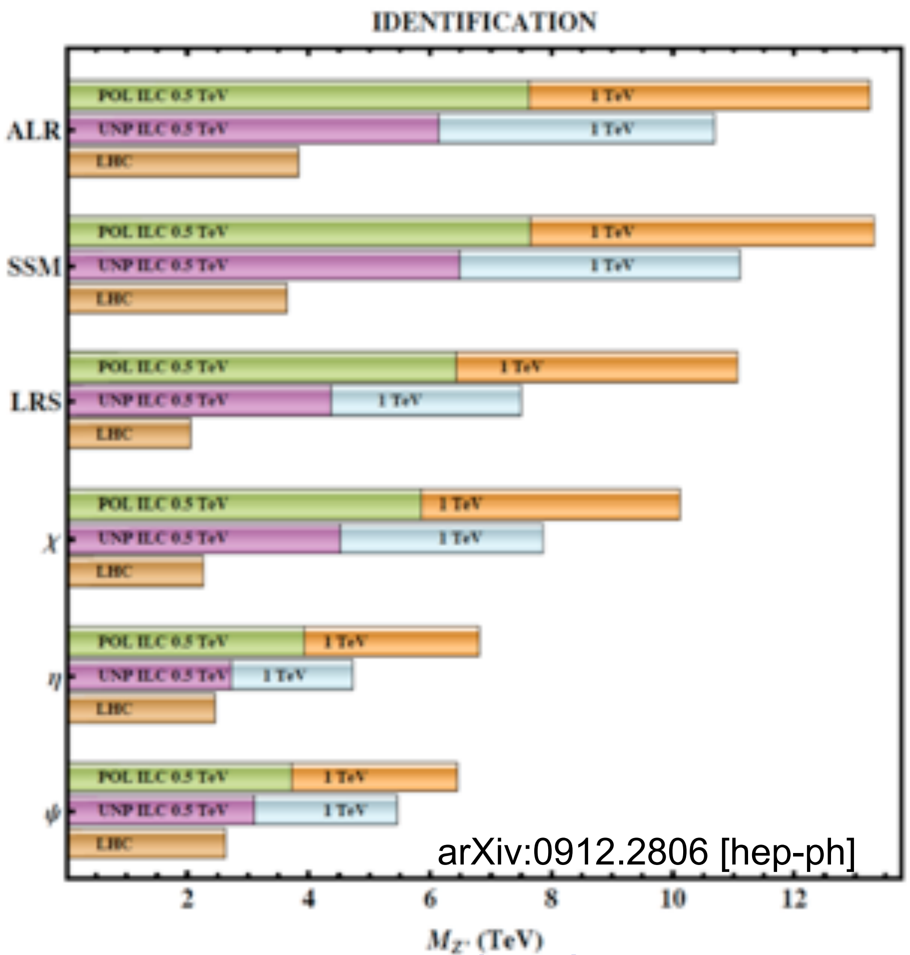
New gauge forces imply existence of heavy gauge bosons (Z')

Complementary approaches LHC/ILC

- LHC: Direct searches for Z' (mass determination)
- ILC: Indirect searches via interference effects (coupling measurements and model discrimination) – beam polarizations improve reach and discrimination power

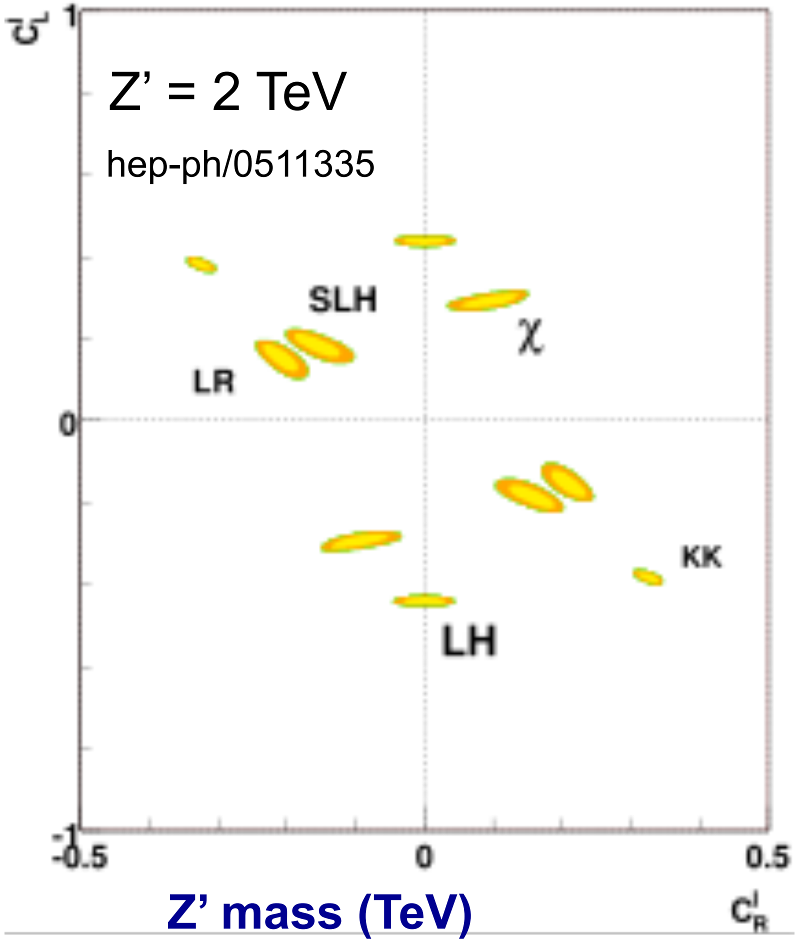


Models with Z' boson



arXiv:0912.2806 [hep-ph]

Z' mass (TeV)



Z' = 2 TeV

hep-ph/0511335

Z' mass (TeV)

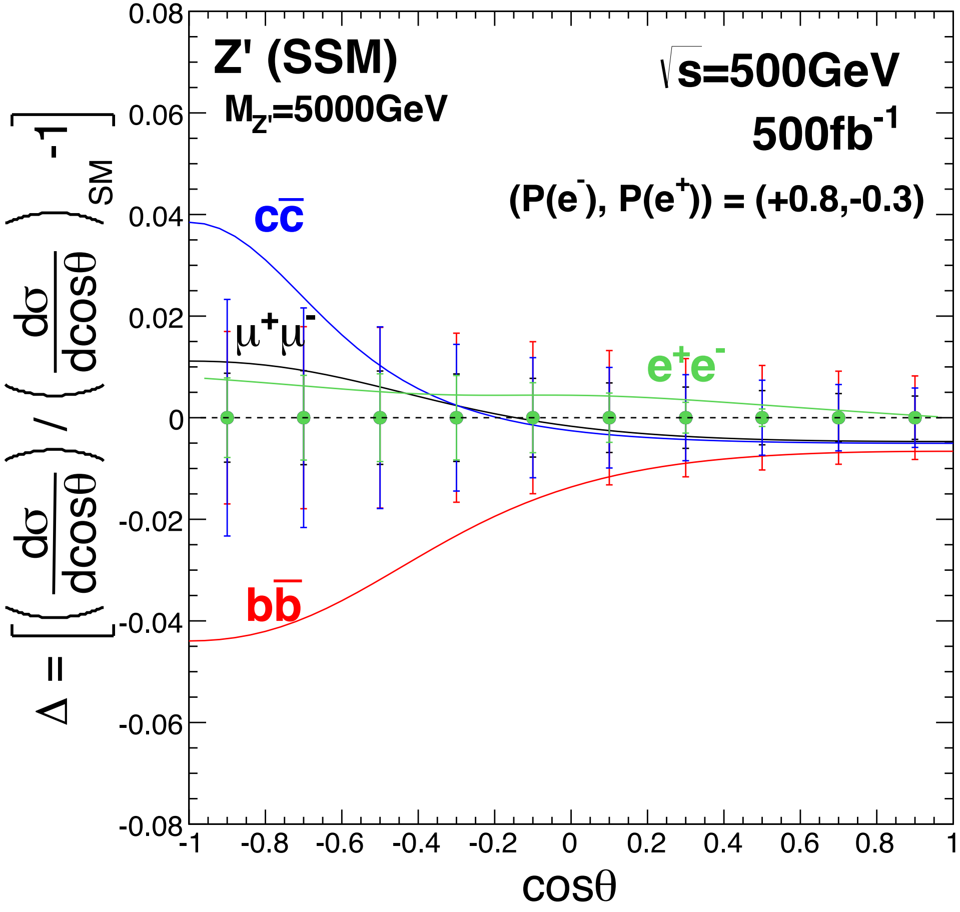
Two-Fermion Processes

Z' Search / Study

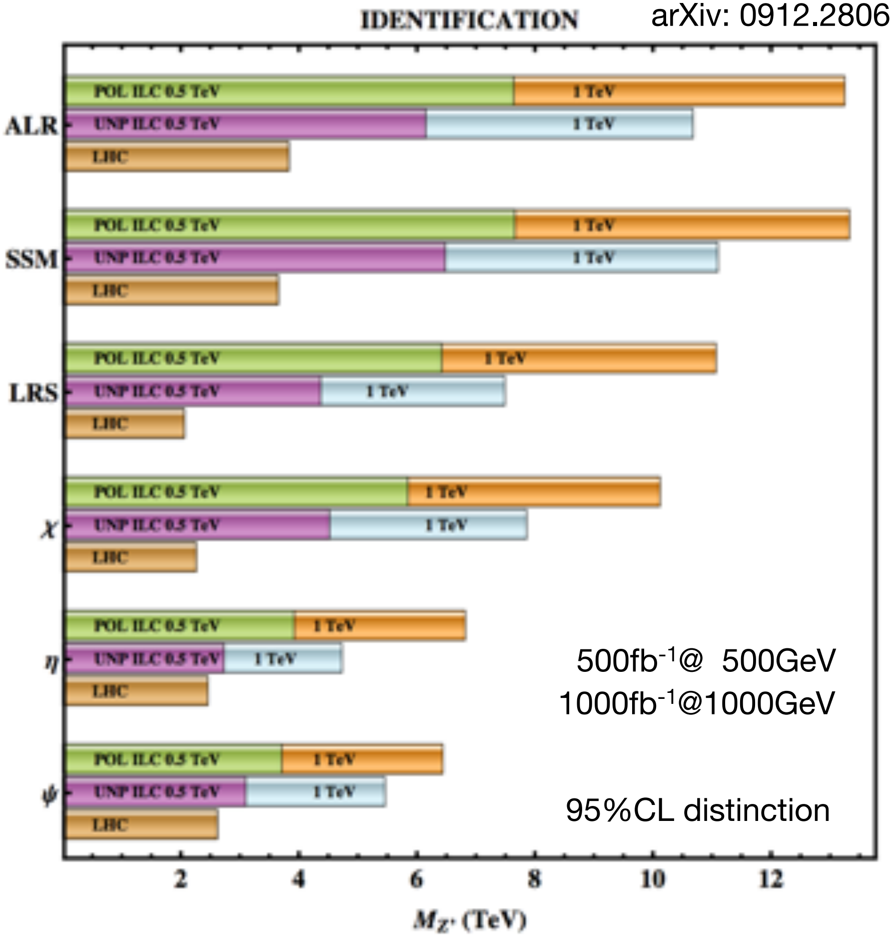
Observables: dσ(P-,P+)/d cosθ

$$\chi^2 = \sum_{f} \sum_{P-,P+} \sum_{i\in \text{bins}} \frac{|n_i(SM+Z') - n_i(SM)|^2}{\Delta n_i} \qquad (f=e,\mu,\tau,c,b)$$

Example: Sequential SM-like Z'



arXiv: 0912.2806



500fb^{-1}@ 500GeV
1000fb^{-1}@1000GeV

95%CL distinction

Two-Fermion Processes

Z’ Search / Study

arXiv:0912.2806 [hep-ph]

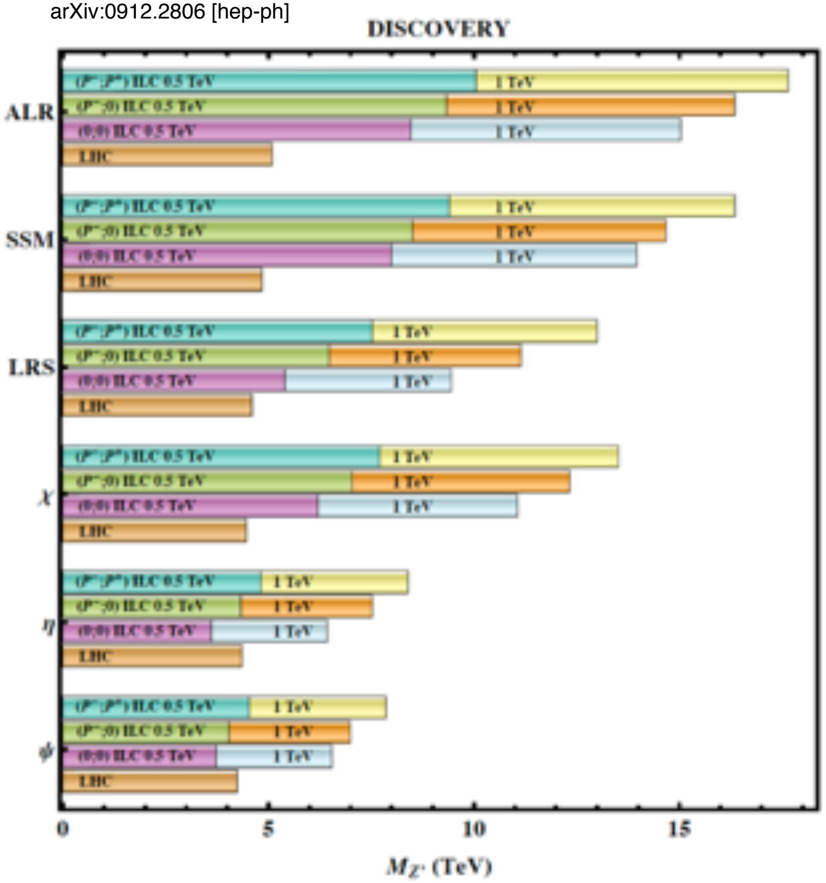
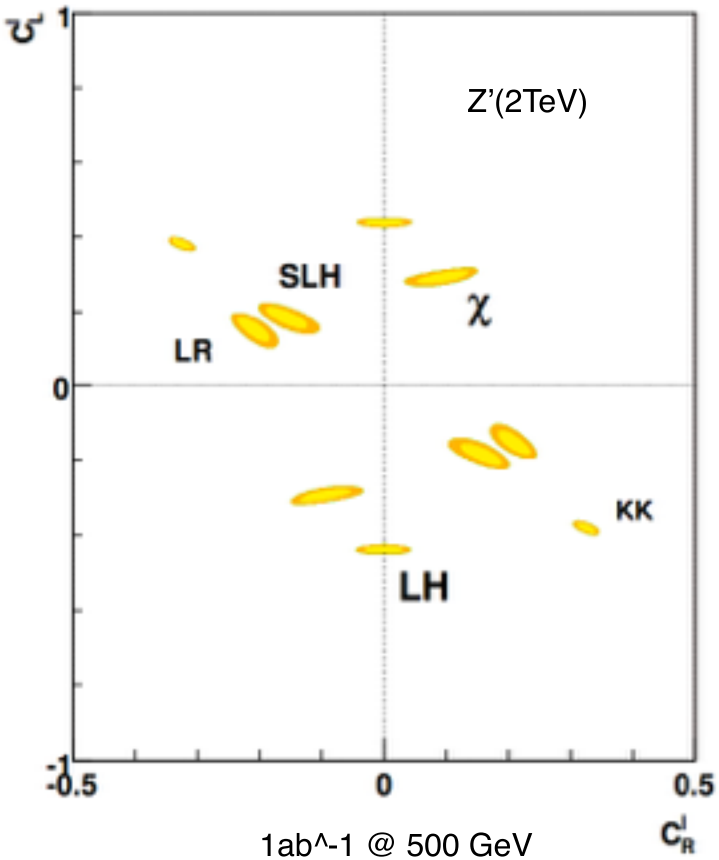


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335



1ab^-1 @ 500 GeV

ILC’s Model ID capability is expected to exceed that of LHC even if we cannot hit the Z’ pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007

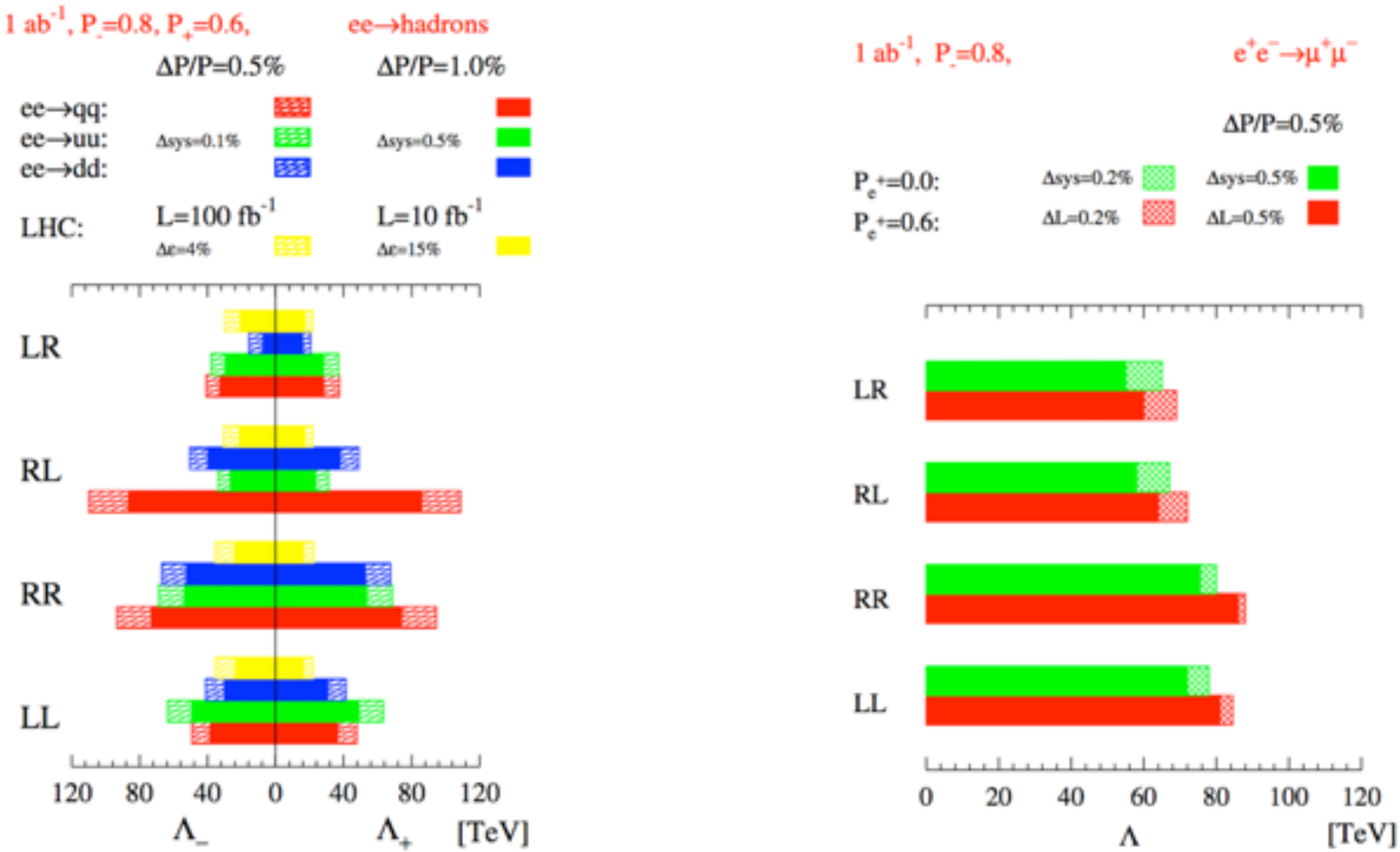


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \rightarrow$ hadrons (left) and $e^+e^- \rightarrow \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.