ILC250
Higgs Factory in Japan

Hiroaki Aihara
The University of Tokyo

February 23, 2017
Summer Down Under

CoEPP Workshop 2017 @ Adelaide, Australia

Prerequisites

Machine basics

- Charged particles radiate photons when accelerated: Synchrotron radiation

$$P_s = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^2} \left[\left(\frac{d\mathbf{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{d\tau} \right)^2 \right]$$

(Covariant form of SR power)

τ : proper time

- Linear machine

$$P_s = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^2} \left(\frac{dE}{dx} \right)^2 \quad \left(P_s \approx 22\times10^{-17} \text{ watts for } \frac{dE}{dx} = 35\text{MeV/m} \right)$$

$$\eta \equiv \frac{P_s}{dE/dx} = \frac{\text{SR loss}}{\text{Energy gain}} \quad \left(\approx 12.8\times10^{-14} \quad \text{! completely negligible !} \right)$$

- Circular machine

$$P_s = \frac{e^2 c \gamma^2}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^2} \left(\frac{d\mathbf{p}}{dt} \right)^2 = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

$$\frac{P_s(\text{muon})}{P_s(\text{electron})} \approx 6\times10^{-10}$$

$$\frac{P_s(\text{proton})}{P_s(\text{electron})} \approx 10^{-13}$$

Machine basics (continued)

- Circular machine

$$\Delta E = \text{Energy loss per turn } = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4}\frac{E^4}{R}$$

$$= 88.5[\text{KeV}]\frac{E^4[\text{GeV}]^4}{R[\text{m}]} \quad \text{(for electrons)}$$

$$\approx \text{ 3 GeV for } E = 100 \text{ GeV, R=3 km}$$

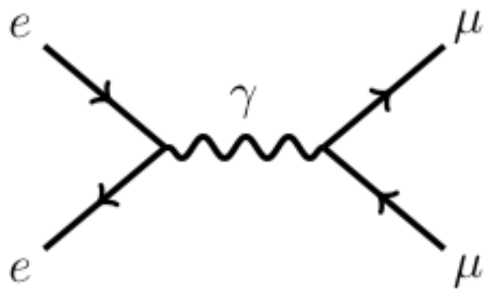
$$\approx \text{ 7.3 GeV for } E = 125 \text{ GeV}$$

$$\approx \text{ 1.88 TeV for } E = 500 \text{ GeV}$$

- As energy frontier accelerators, electron linear machines and/or muon circular machines are the choice.

Basics of e⁺e- collision

- s-channel cross section

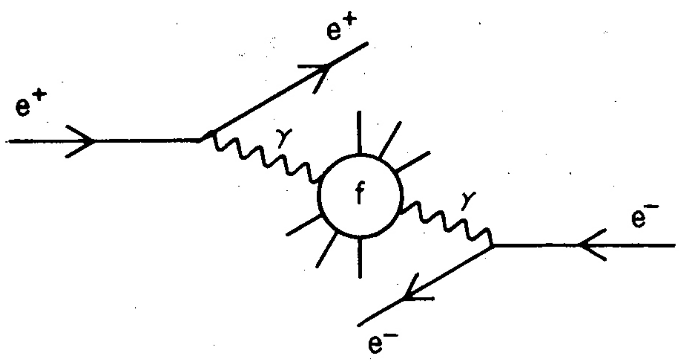


QED Tree diagram

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8[\text{fb}]}{\left(\sqrt{s}[\text{TeV}]\right)^2} \propto \frac{1}{s}$$

- t-channel cross section

photon- photon fusion process



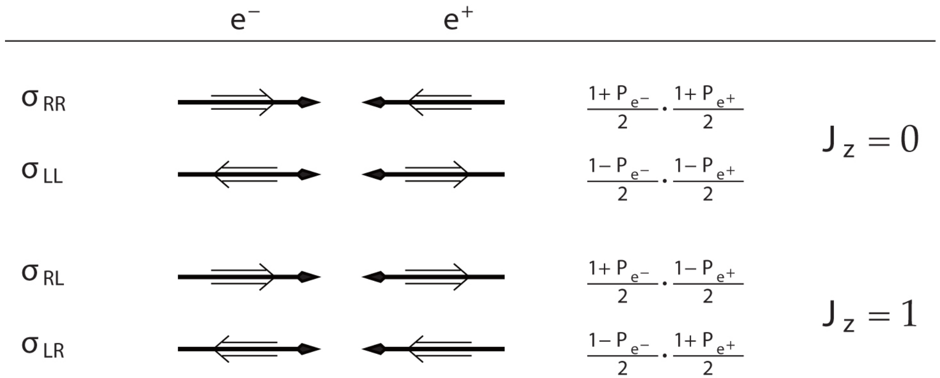
$$\sigma \propto \alpha^4 \ln\left(\frac{s}{m_f^2}\right)$$

t-channel log rise

Basics of e+e- collision (continued)

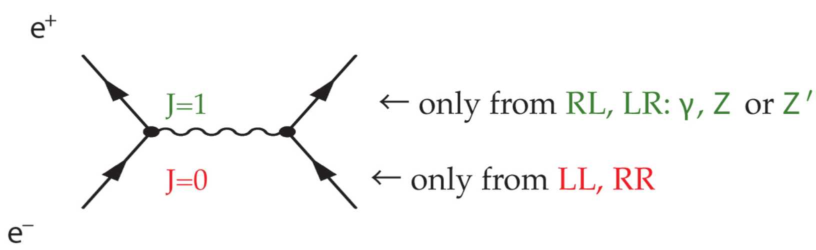
- Cross sections can be expressed, in terms of the longitudinal polarization of the beams, as: (*helicity amplitude formalism*)

$$\sigma_{P_-P_+} = \frac{1}{4}\left[(1+P_-)(1+P_+)\sigma_{\mathrm{RR}} + (1-P_-)(1-P_+)\sigma_{\mathrm{LL}} + (1+P_-)(1-P_+)\sigma_{\mathrm{RL}} + (1-P_-)(1+P_+)\sigma_{\mathrm{LR}}\right]$$

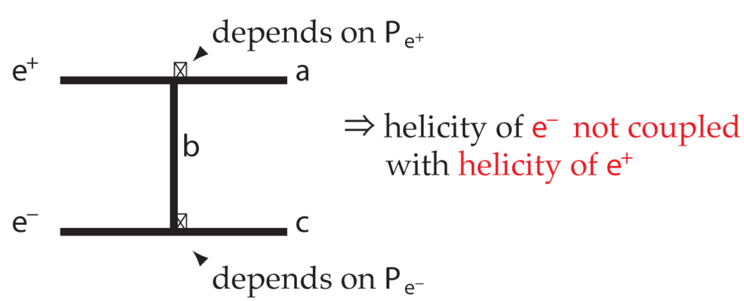


- Use beam polarization as a Feynman diagram selector

s-channel

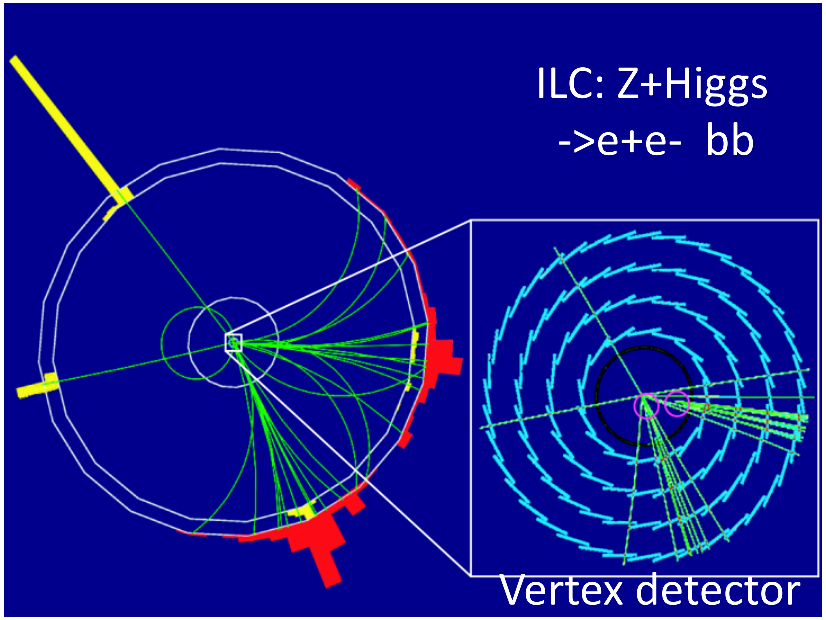


t-channel

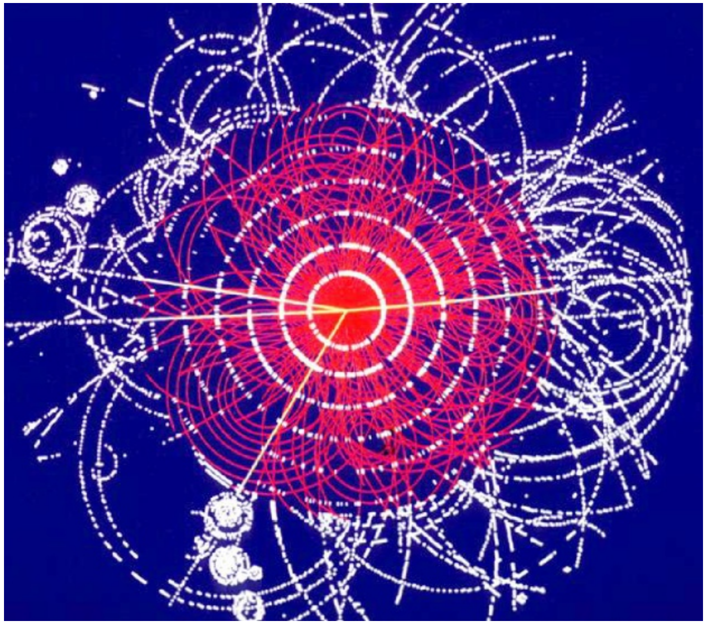


Why lepton colliders ?

- Two elementary particles (e^+e^- or mu^+mu^-) collide with electromagnetic or weak interactions
  - No underlying/QCD event background
  - Signal can be clearly seen without hadronic noises
  - Helicity selector can be employed to separate diagrams



LHC Higgs



Caveat: Lepton colliders are not background free.
Beamstrahlung present in e^+e^- linear colliders, but can be contained.

Challenges with lepton colliders ?

- Two elementary particles (e^+e^- or mu^+mu^-) collide with electromagnetic or weak interactions
  - Cross section is small: s-channel cross section drops as 1/s
  - Cross section is 100 – 10 fb

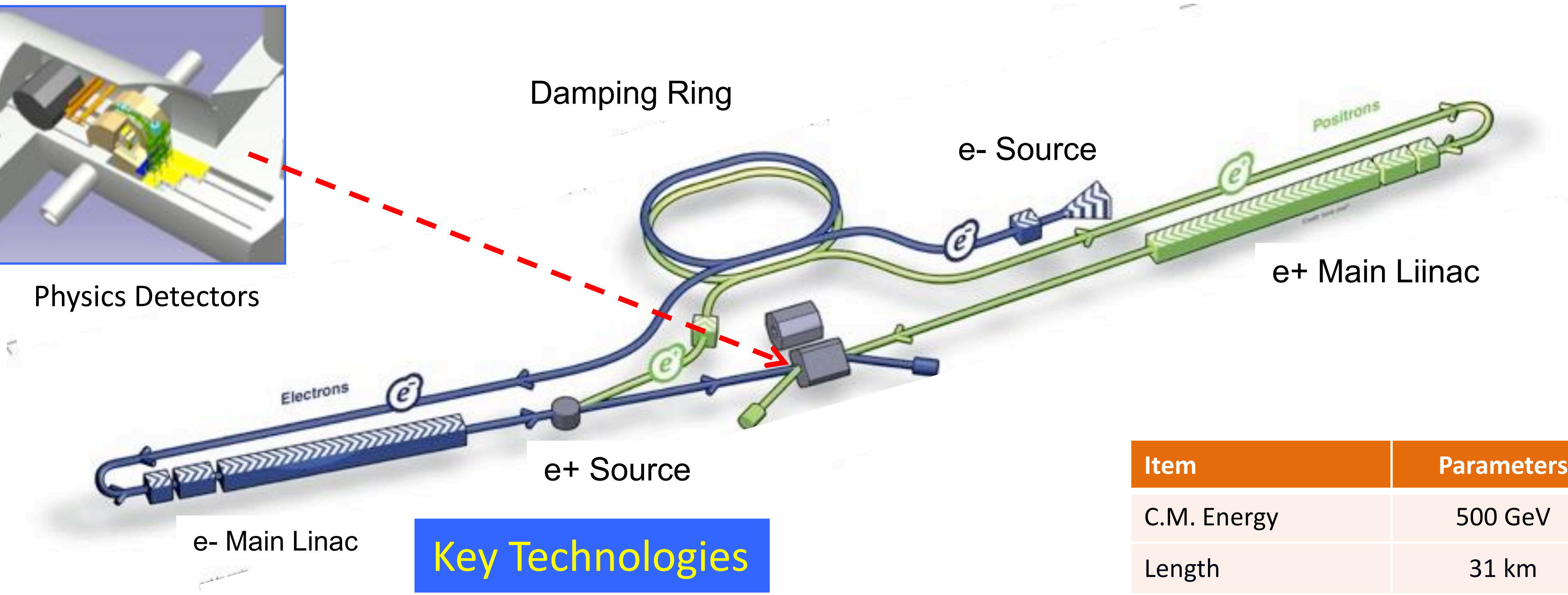
$$\sigma(1\text{fb}) \times Luminosity(10^{34}\text{cm}^{-2}\text{s}^{-1}) \times 1\text{yr}\ (10^7\text{s}) = 100\ \text{events}$$

  - High energy machine requires high luminosity machine.

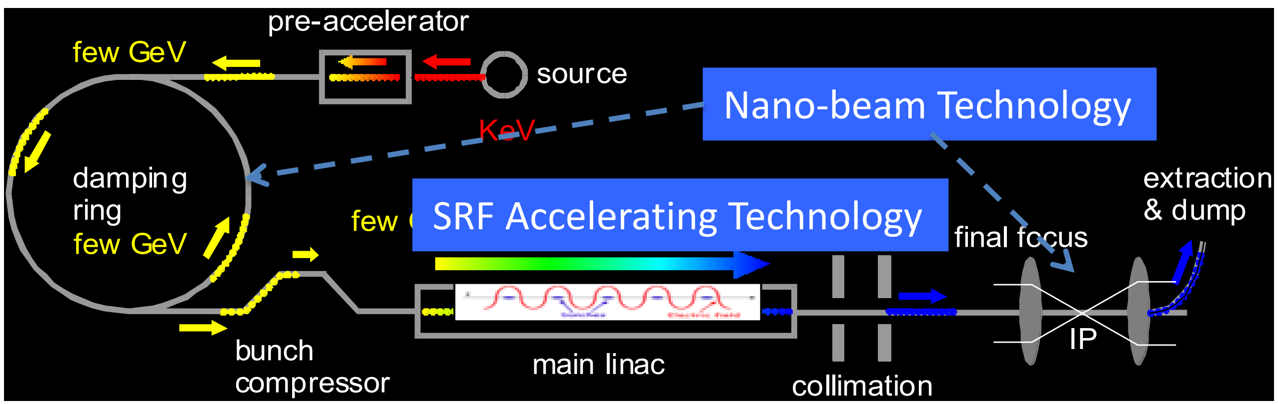
$$L = \frac{N^2}{4\pi\sigma_x\sigma_y} n_{\text{bunch}} f_{\text{rep}} \propto \frac{N}{\sigma_x}\frac{1}{\sigma_y}\eta P$$

  - For a total collider wall plug power *P* to be 100-200 MW, the (vertical) beam size σ_y needs to be 10-1 nm. Nano beams! (Note : 1 GW ~ 1 nuclear reactor)
  - Better have "target/new particles" and/or "resonances"
  - You do not want to be in the continuum desert.

ILC Acc. Design Overview (in TDR)



Key Technologies

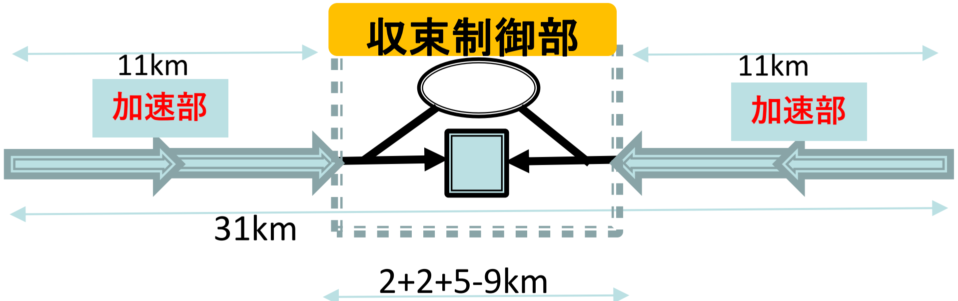


Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**5.9** nm
SRF Cavity G. Q_0	**31.5** MV/m Q_0 = 1x10^{10}

ILCステージング型（LCWS2016を経て）

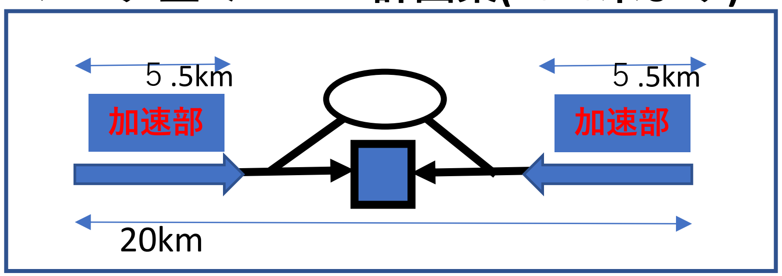
Sorry.
This slide in still in Japanese.

これまでの基準計画案(2007-2016)



ILC250

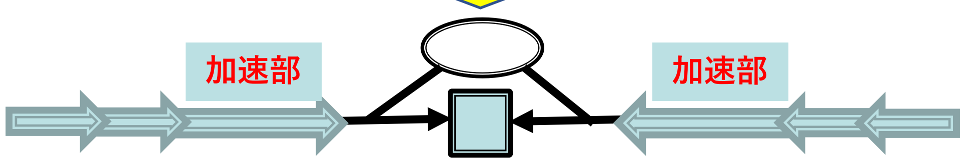
ステージング型ミニマム計画案(2016末より)



建設・運転コストダウン２大項目

1. **日米協力**（性能向上）⇒ ～10%削減
2. **ミニマム計画 (20km)** ⇒ ～30%削減

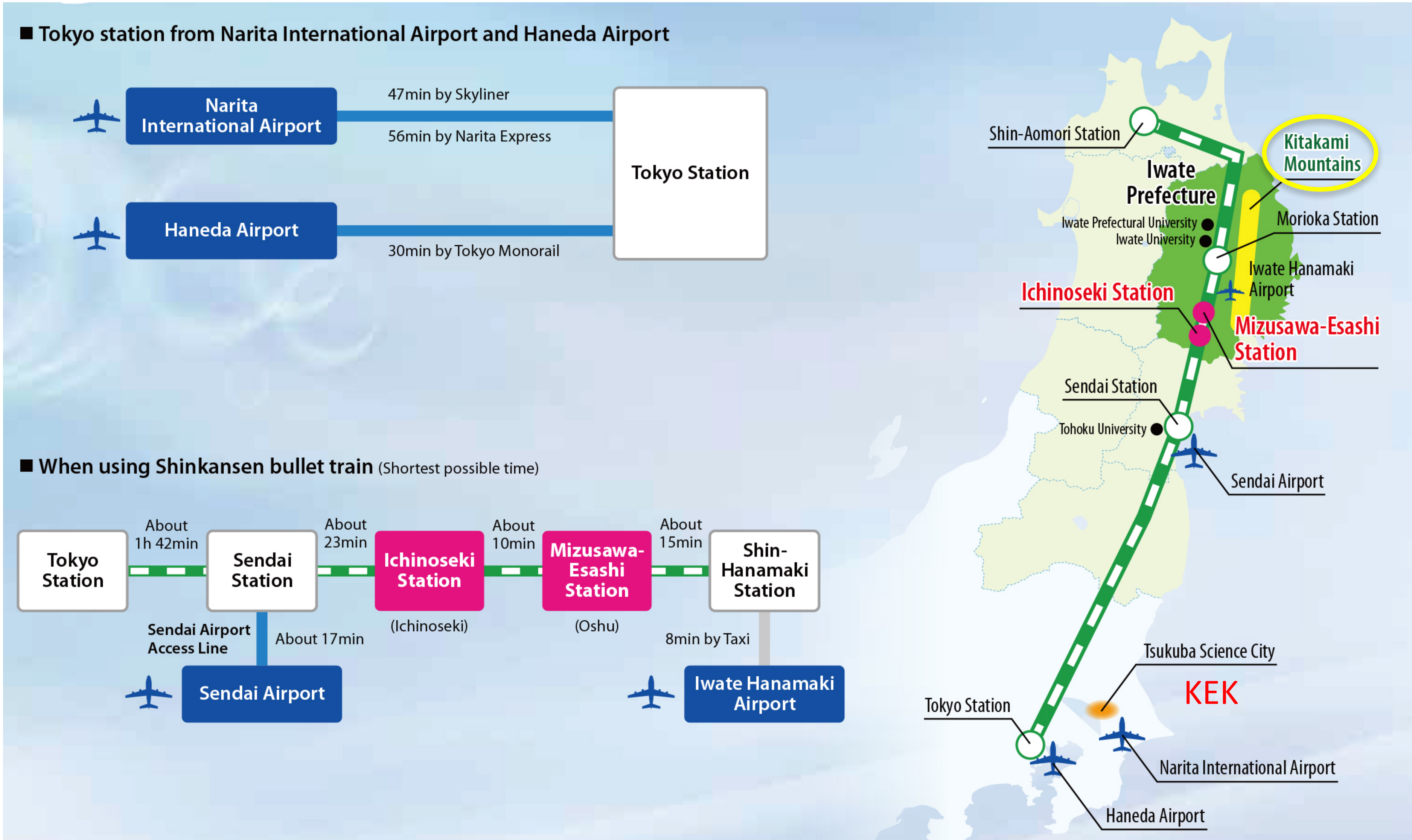
10年以上の最先端研究ののち



更に高度化（瞬発力向上）した加速部を**必要性と資金に合わせて段階的に継ぎ足して**いく（**数十年にわたる世界最先端拠点**）

確実な最重要研究対象	必要なエネルギー	直線 (ILC)	円形 (中国)
ヒッグス粒子	240 GeV	**20 km**	50~70 km
トップクォーク	350 GeV	24 km	100 km
２つのヒッグス同時生成	500 GeV	**30 km**	不可能
未知の領域	1000 GeV ~	50 km	不可能

ILC site in North Japan



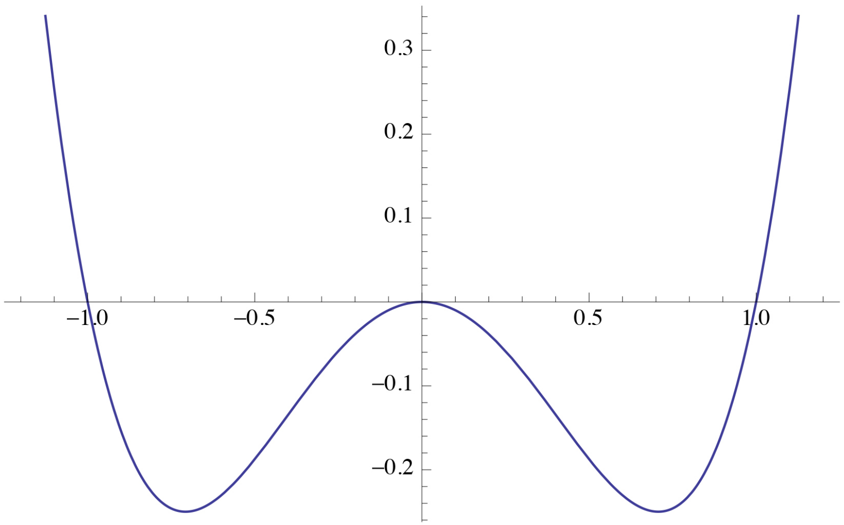
Committee on ILC250-Higgs Factory

- Japan HEP Committee (JHEPC) set up the committee to re-examine/assure physics case of ILC250 in view of the results being obtained at the 13 TeV LHC.
  - Composed largely of Japanese HEP physicists outside the ILC community
  - Final report to JHEPC by the end of this coming May
  - Sensitivity to new physics scale, concurrent running with HL-LHC
- Note:
  - Japan HEP Community already proposed ILC250 in October, 2012.
  - After the report by Science Council of Japan (SCJ) in 2013, the MEXT ILC Advisory Panel asked, in their 2015 Summary, for re-examination of ILC based on the results of the 13 TeV LHC through the end of 2017.

Precision Higgs Physics

The Standard Model Higgs primer

Higgs scalar potential: $V = -|\mu|^2 \Phi^+\Phi + \lambda\left(\Phi^+\Phi\right)^2$



A minimum away from zero field value causes (spontaneous) electroweak symmetry breaking

$$v^2 = \frac{|\mu|^2}{\lambda} = \frac{1}{\sqrt{2}G_F} = (246\ \mathrm{GeV})^2$$

$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} = \frac{1}{2v^2} \qquad m_H^2 = 2\lambda v^2 = 2|\mu|^2$$

Higgs Discovery By ATLAS & CMS

$$|\mu|^2 = \frac{m_H^2}{2} \approx \frac{(126\ \mathrm{GeV})^2}{2} \approx (89\ \mathrm{GeV})^2$$

$$\lambda = \frac{|\mu|^2}{v^2} = \frac{m_H^2}{2v^2} \approx \frac{(126\ \mathrm{GeV})^2}{2(246\ \mathrm{GeV})^2} \approx 0.13$$

Weak coupling !

Predicted BRs for 125GeV SM Higgs

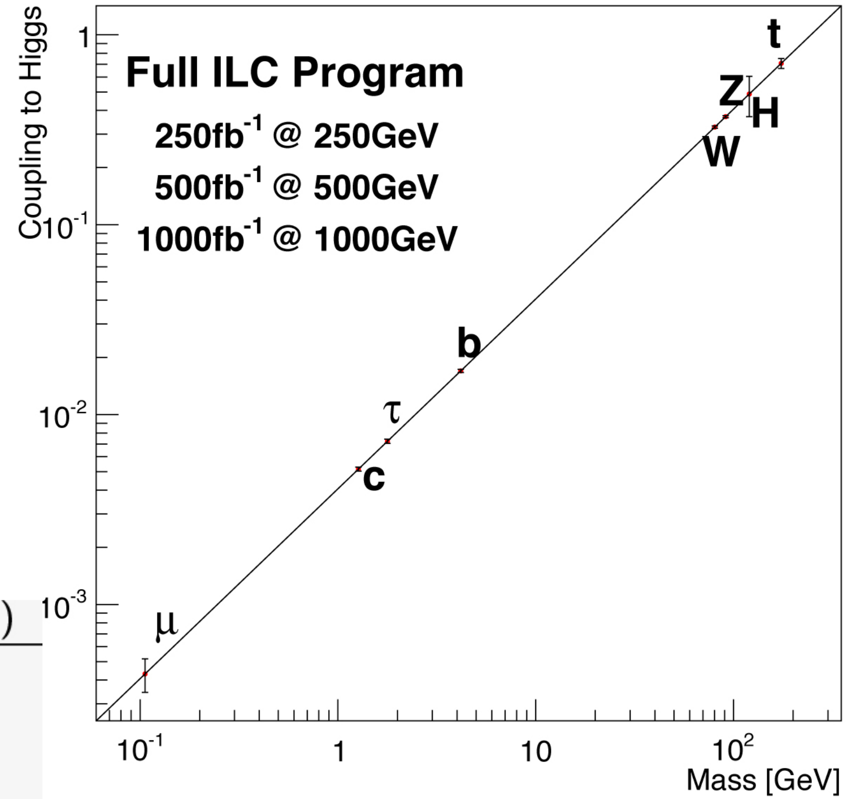
Decay mode	BR	Notes (as of early 2014)
$b\bar{b}$	58%	Observed at about 2σ at CMS
WW^*	22%	Observed at 4σ
gg	8.6%	
$\tau\tau$	6.3%	Observed at 1–2 σ
$c\bar{c}$	2.9%	
ZZ^*	2.6%	Discovery mode (in $ZZ^* \to 4\mu$, $2\mu 2e$, $4e$)
$\gamma\gamma$	0.23%	Discovery mode
$Z\gamma$	0.15%	
$\mu\mu$	0.022%	
Γ_{tot}	4.1 MeV	Total width

Higgs coupling to particle

$$\text{SM Higgs: coupling} = \frac{m}{v}$$

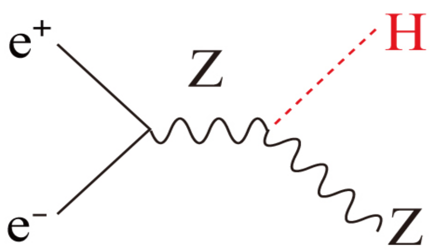
2013 estimates

Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$< 9\%$	< 0.44 %	< 0.30 %	< 0.26 %
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

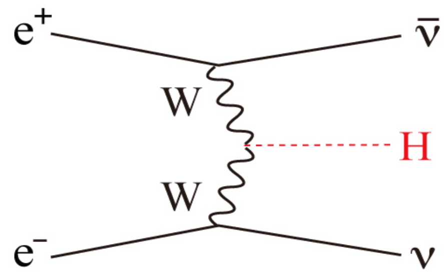


Model-independent determination of Higgs to particle couplings

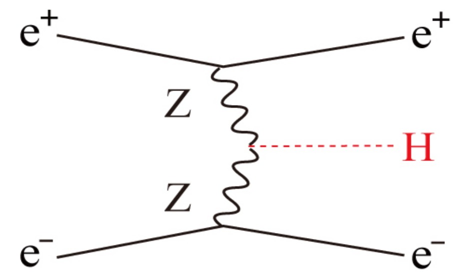
Higgs production at ILC



Higgs-strahlung



WW fusion



ZZ fusion

$$\sigma(e^+e^- \to ZH) = \frac{G_F^2 m_Z^4}{96\pi s}\left\{(-1+4\sin^2\theta_W)^2+1\right\}\lambda^{1/2}\frac{\lambda+12m_Z^2/s}{(1-m_Z^2/s)^2}$$

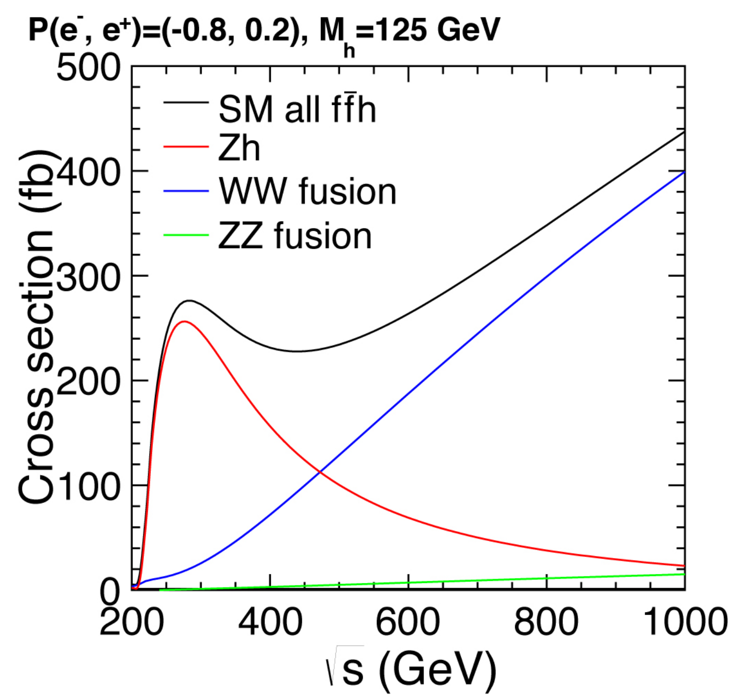
$$\lambda = (1-(m_H+m_Z)^2/s)(1-(m_H-m_Z)^2/s)$$

$$\sigma(e^+e^- \to \bar{\nu}_e\nu_e H) \approx \frac{G_F^3 m_W^4}{4\sqrt{2}\pi^3}\left[\left(1+\frac{m_H^2}{s}\right)\ln\frac{s}{m_H^2} - 2\left(1-\frac{m_H^2}{s}\right)\right]$$

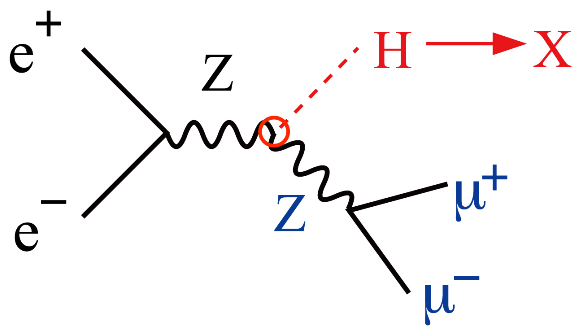
$$\to \frac{G_F^3 m_W^4}{4\sqrt{2}\pi^3}\ln\frac{s}{m_H^2} \qquad \text{(t-channel log rise)}$$

$$\sigma(ZZ\ \text{fusion}) \approx \sigma(WW\ \text{fusion}) \times 16\cos^4\theta_W$$

$$\approx \sigma(WW\ \text{fusion}) \times \frac{1}{9.5}$$



Precision Higgs mass and BR measurements at ILC250

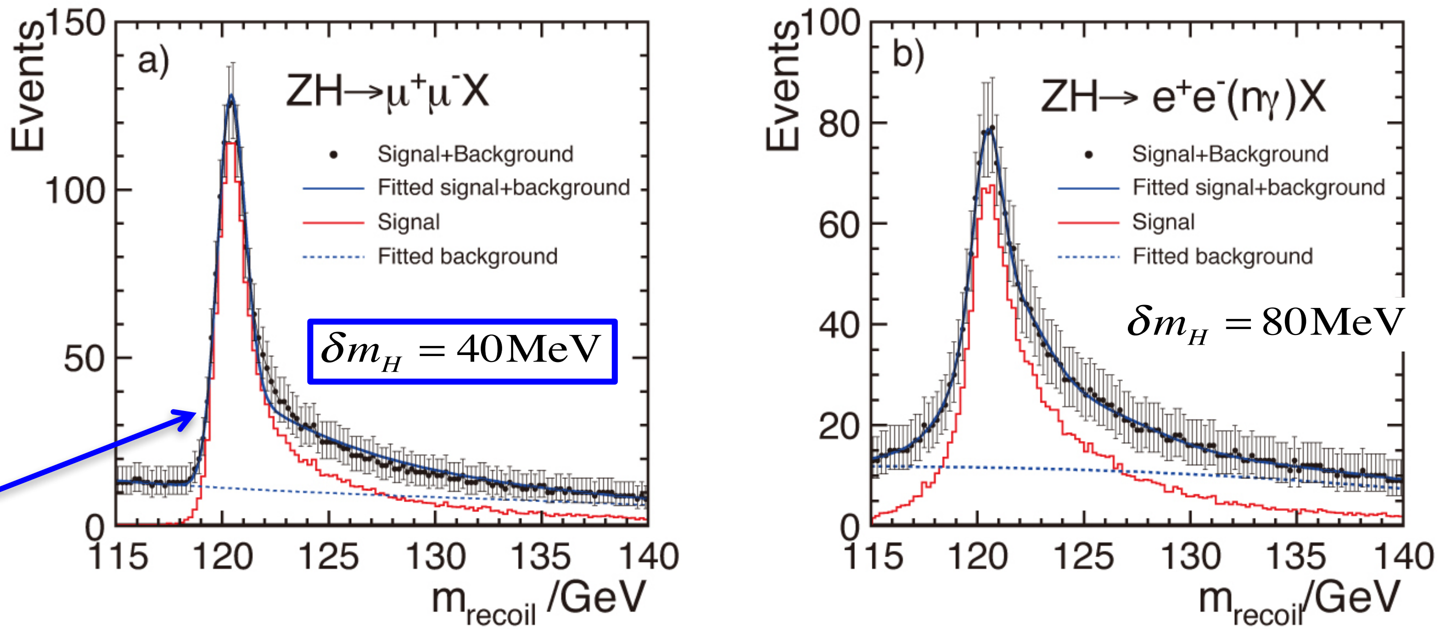


Recoil mass recosntruction technique

$$m^2_{\rm recoil} = \left(\sqrt{s} - E_{\ell^+} - E_{\ell^-}\right)^2 - \left|\mathbf{p}_{\ell^+} + \mathbf{p}_{\ell^-}\right|^2$$

Independent of X

Figure 2.8
Higgs recoil mass distribution in the Higgs-strahlung process $e^+e^- \to Zh$, with (a) $Z \to \mu^+\mu^-$ and (b) $Z \to e^+e^-(n\gamma)$. The results are shown for $P(e^+, e^-) = (+30\%, -80\%)$ beam polarization.



dominated by beam energy spread

$\Gamma_H \approx 4\text{MeV (SM)}$

- Inclusive ZH cross section measurement: $\Delta\sigma_{ZH} / \sigma_{ZH} \approx 2.5\%$
- Branching ratios by identifying X

- A measurement of the e+e- to *Zhiggs* cross section without any reference to the Higgs branching ratios.

- One can also use the Z-tagged sample to measure the Higgs BRs and directly look for unexpected, non-SM decays.

- For a Higgs mass of 125 GeV, the cross section e+e- to *Zhiggs* peaks at an CMS of 250 GeV.

Preliminaries from the ILC250 strategy study group

- highlights after initial run at 250 GeV ($\int L dt \sim 400\ fb^{-1}$)
- projections at the end of 250 GeV run ($\int L dt \sim 2000\ fb^{-1}$)
- projections with 500 GeV run and possible staging scenario

(exact $\int L dt$ to be defined later by LCC physics WG)

highlights after initial run

$\sqrt{s}$ = 250 GeV

$\int L dt \sim 400$ fb^{-1}

by courtesy of Junping Tian (Tokyo)

highlight 1: absolute Higgs couplings

ILC initial: $\delta g_{HZZ} = 0.83\%$

$$\Lambda > \sqrt{\frac{1\%}{\delta g_{HZZ}}} 1.74\mathrm{TeV}$$

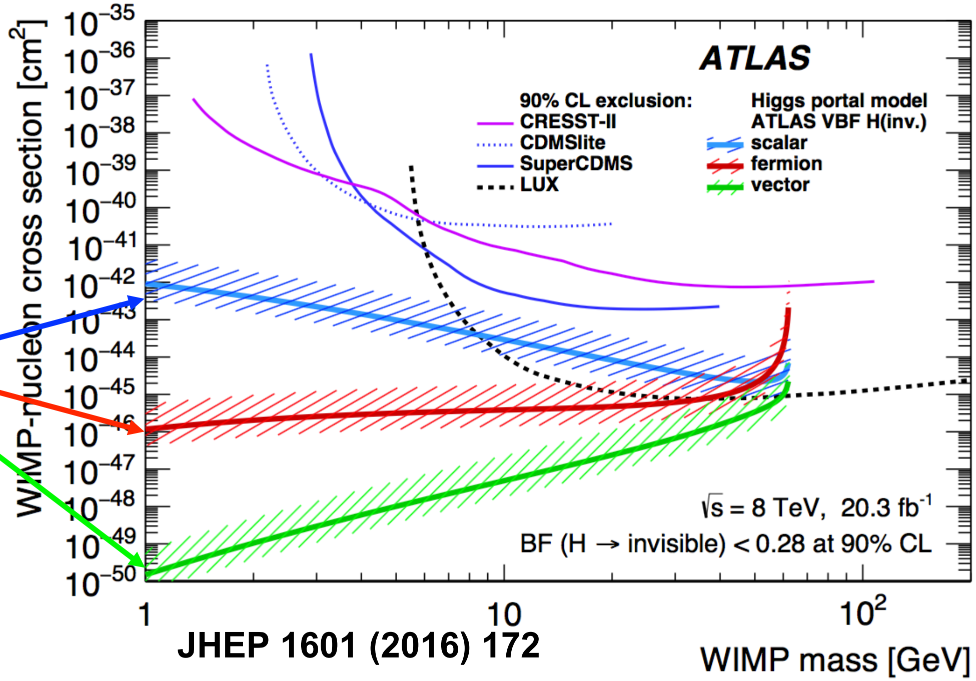
- model-independent measurement —> qualitative difference with coupling measurement @ LHC
- important to know absolute value of Higgs couplings —> Higgs branching ratios, or ratios of couplings, can remain unchanged in BSM models, e.g. some composite models
- with ~0.83% precision on HZZ coupling, composite scale Λ > 1.74TeV can be probed (cf talk by N.Craig @ LCWS16)
- together with κ_Z/κ_γ @ LHC —> ~1% precision on $H\gamma\gamma$ coupling

highlight 2: Higgs to invisible decay

ILC initial: BR(H—>inv.) < 0.64% (95% CL)

- a very powerful test for Higgs portal model —> could be more sensitive than other direct DM search experiments
- initial sensitivity is already more than one order of magnitude higher than expectation after HL-LHC

ILC initial
x50 lower



JHEP 1601 (2016) 172

Motivation

Is the 125 GeV Higgs a CP eigenstate ?

$$h_{125} = \cos\ \psi_{CP}\ h^{CPeven} + \sin\psi_{CP}\ A^{CPodd}$$

pure CP even: $\psi_{CP} = 0$

odd: $\psi_{CP} = \pi/2$

Does the Higgs sector provide the additional CP violation needed to explain our universe's baryon – anti-baryon asymmetry ?

Do Higgs couplings conserve CP ?

e.g. coupling to fermions:

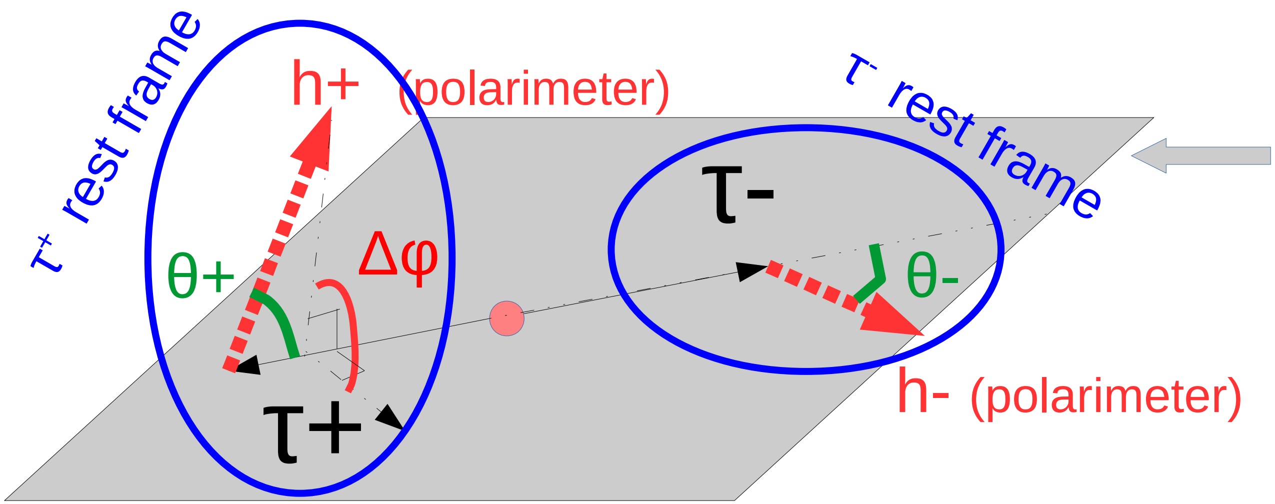
$$\mathcal{L} \sim g\,\bar{f}\,(\cos\psi_{CP} + i\,\gamma^5 \sin\psi_{CP})\,f\,H$$

CP conserving coupling $\psi_{CP} = 0$

maximally violating $\psi_{CP} = \pi/2$

Courtesy of Daniel Jeans
Tokyo

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

distribution of events in polarimeter space:

$$dN/(d\cos\theta^+ d\cos\theta^- d\phi^+ d\phi^-) \propto (1 + \cos\theta^+ \cos\theta^-) - \sin\theta^+ \sin\theta^- \cos(\Delta\phi - 2\psi_{CP}).$$

→ Δφ distribution sensitive to ψ_{CP} → **transverse spin components**

→ events with large contrast c = $\sin\theta^+ \sin\theta^- / (1 + \cos\theta^+ \cos\theta^-)$
event sensitivity depends on longitudinal spin components

highlight 3: Higgs CP mixing

- test CP-violating source in Higgs sector —> baryongenesis
- essential to understand structures of all Higgs couplings

through H—>τ⁺τ⁻

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP}) f$$

ILC initial: $\Delta\Phi_{CP} \sim 8^\circ$

D.Jeans @ LCWS16

through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + \underline{C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}}$$

(CP-odd)

ILC initial: $\Delta\tilde{b} \sim 0.01$ (for Λ=246GeV)

T.Ogawa @ LCWS16

highlight 4: Higgs mass and total width

ILC initial: Δm_H~30MeV, $\delta\Gamma_H$~10%

- Δm_H is one source of systematic errors for H—>WW*/ZZ* partial width calculation: 30MeV uncertainty would yield 0.2% error for HWW/HZZ coupling determination (arXiv:1404.0319)

- model-independent determination of Higgs total width —> one direct probe for existence of new large decay modes

highlight 5: Higgs decays to bb/cc/gg

ILC initial: $\delta BR_b \sim 1\%$

- precise measurement of BR(H—>bb), largest decay mode
- first direct measurement of Hcc coupling ~ 6%
- first direct measurement of Hgg coupling ~6%

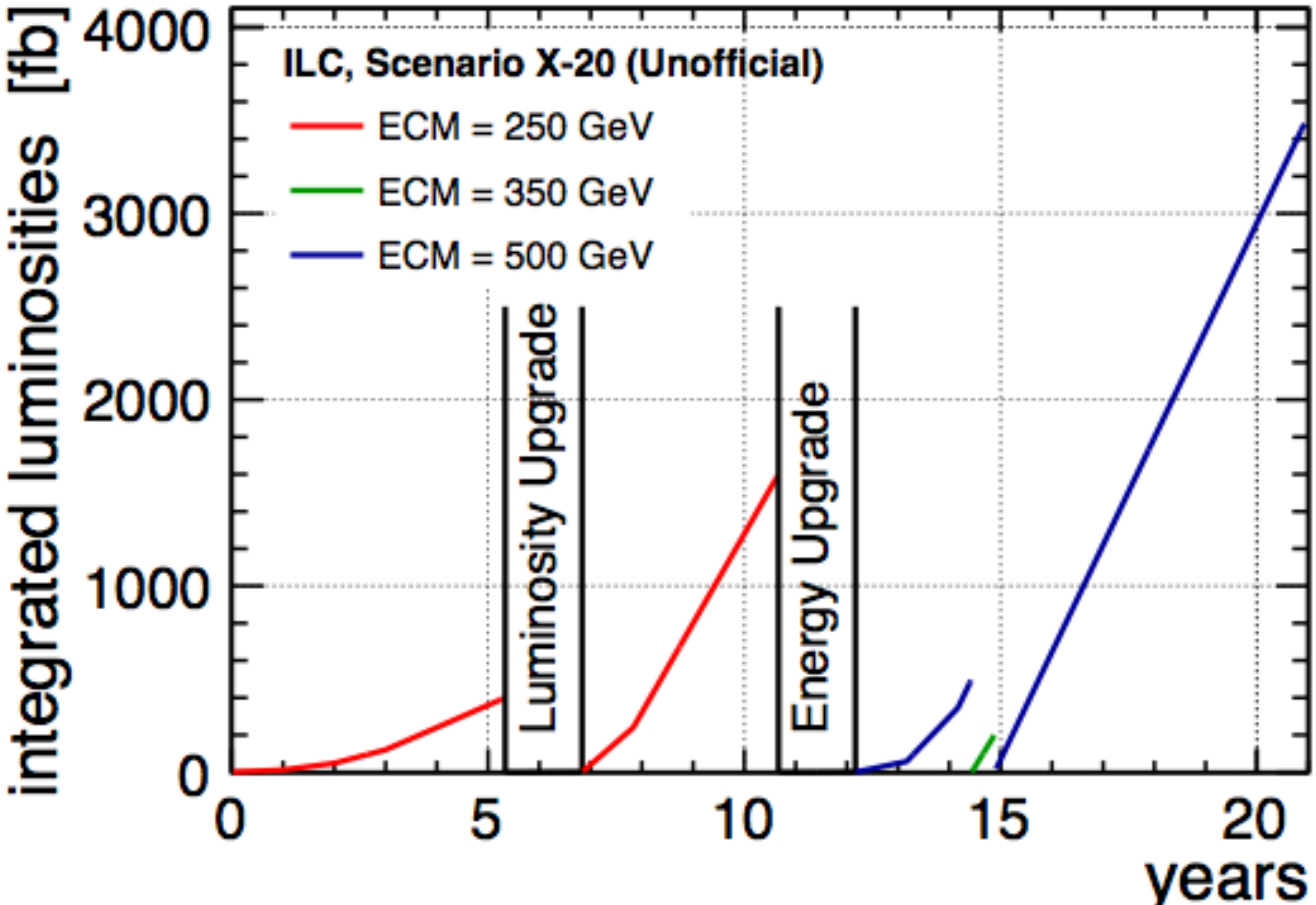
- projections with full integrated luminosities

$\int L dt \sim 2000\ fb^{-1}$ $\sqrt{s} = 250$ GeV

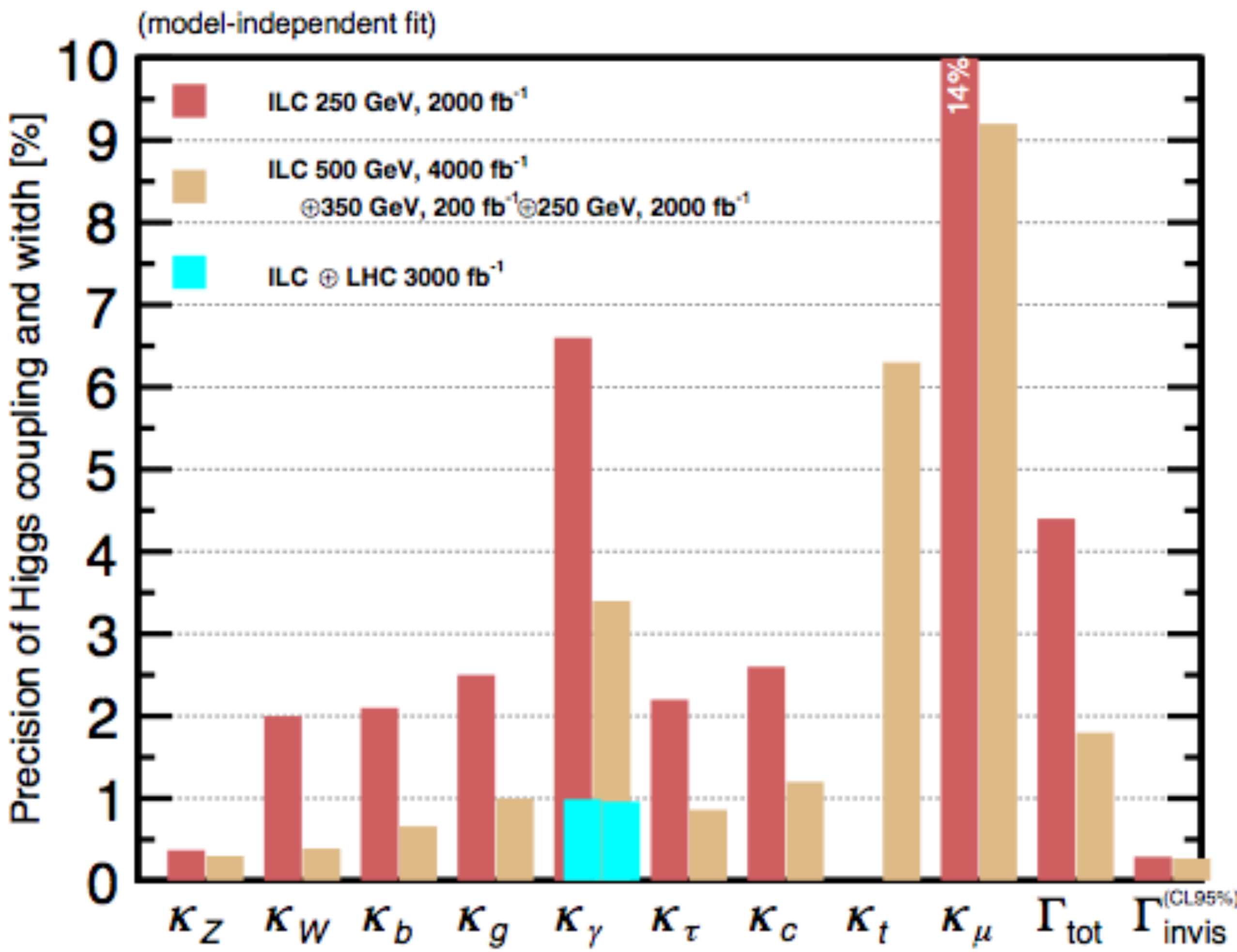
$\int L dt \sim 200\ fb^{-1}$ $\sqrt{s} = 350$ GeV

$\int L dt \sim 4000\ fb^{-1}$ $\sqrt{s} = 500$ GeV

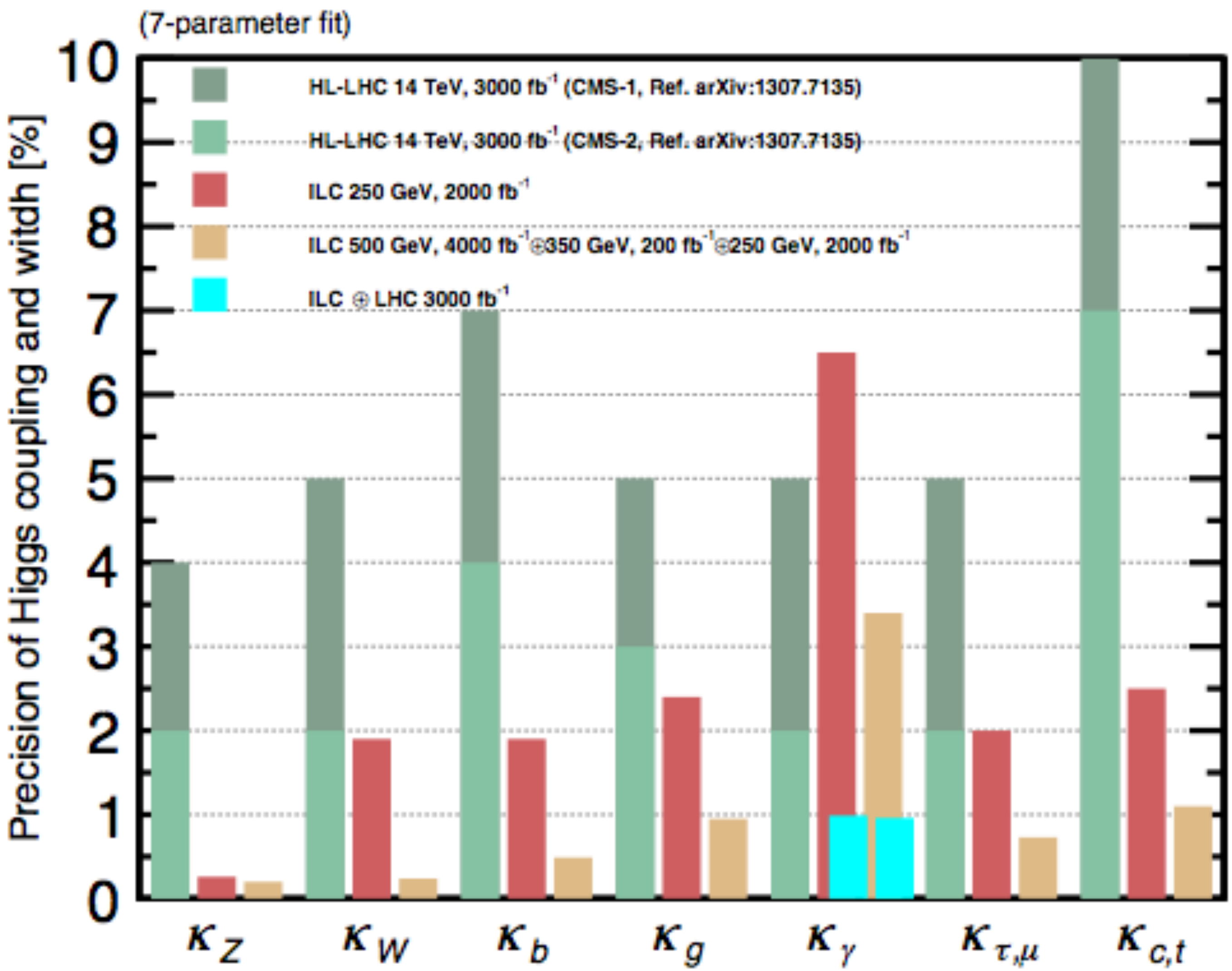
possible staging scenario: X-20



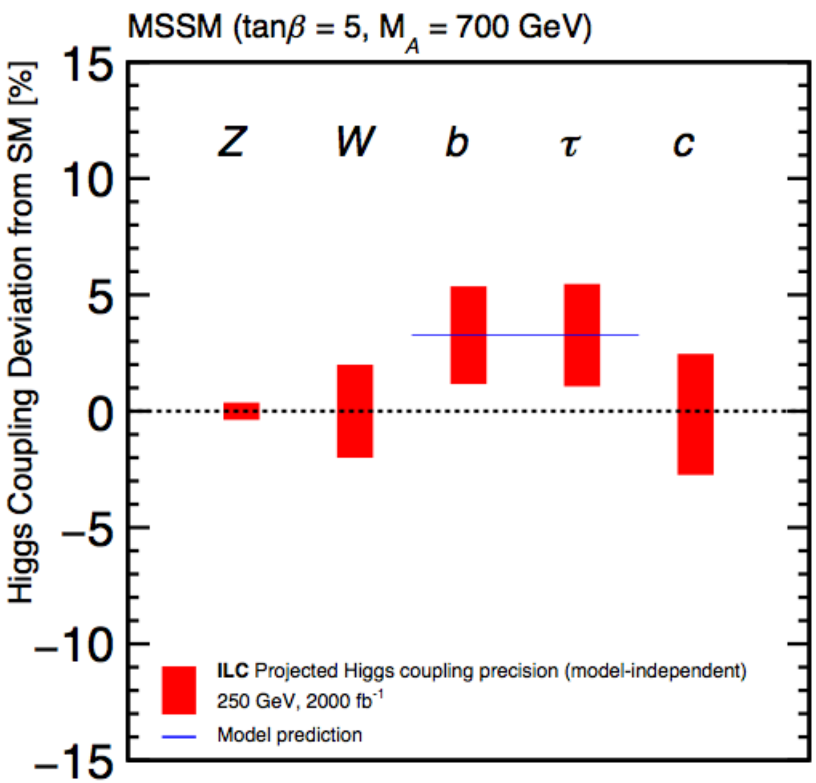
precision of coupling and width (model-independent fit)

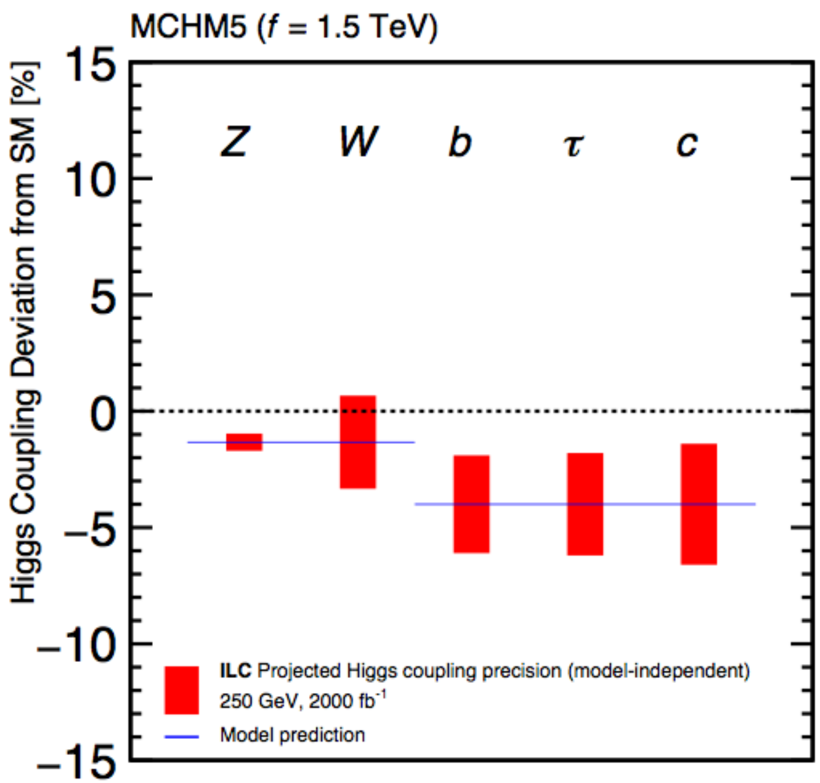


comparison with HL-LHC

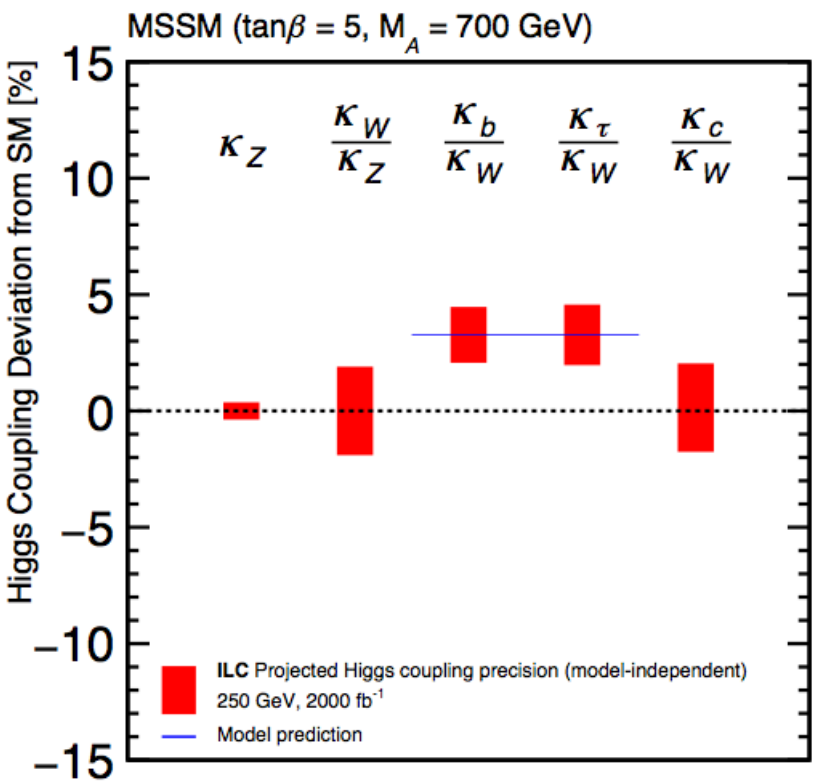


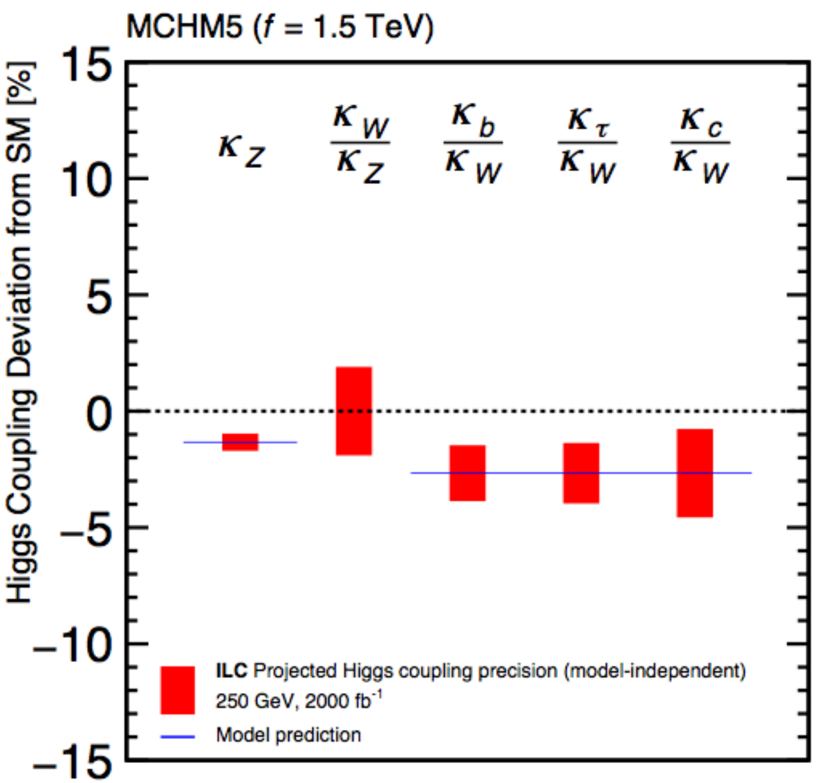
fingerprinting: SUSY or Composite (end of 250 GeV run)



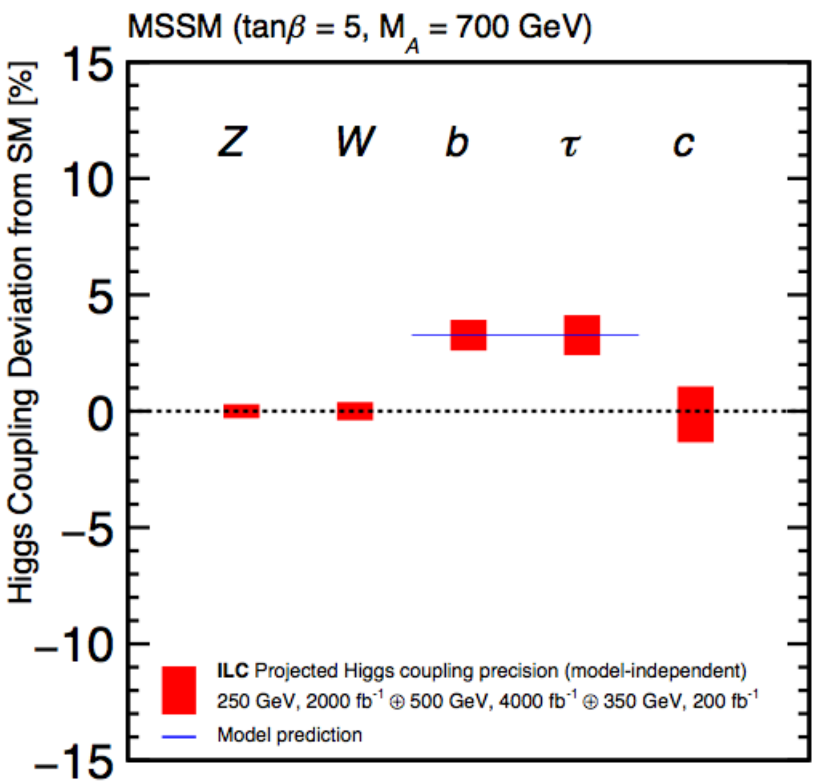


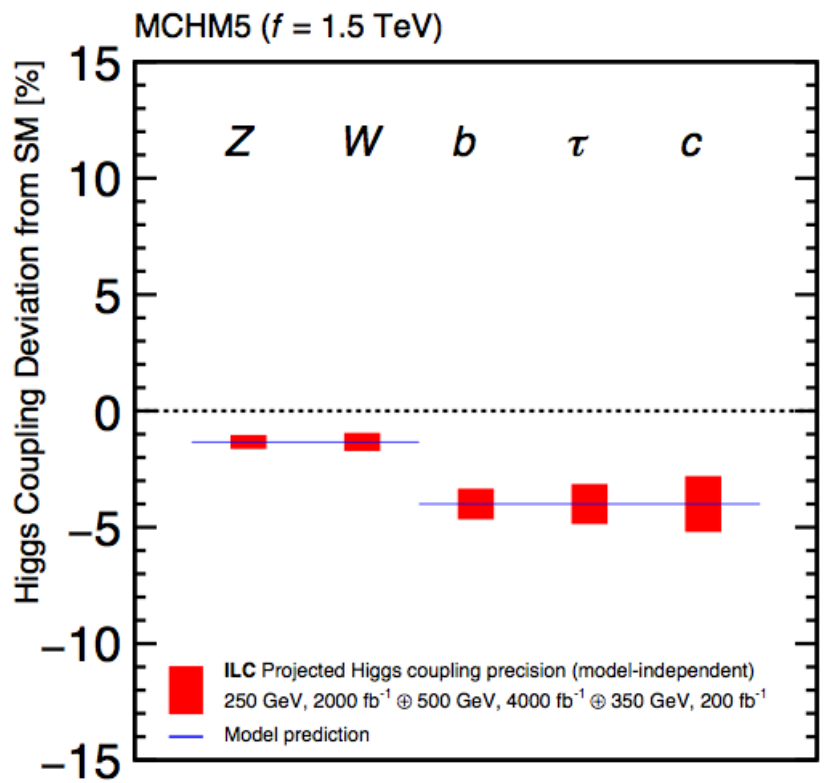
fingerprinting: SUSY or Composite (end of 250 GeV run; using coupling ratio)



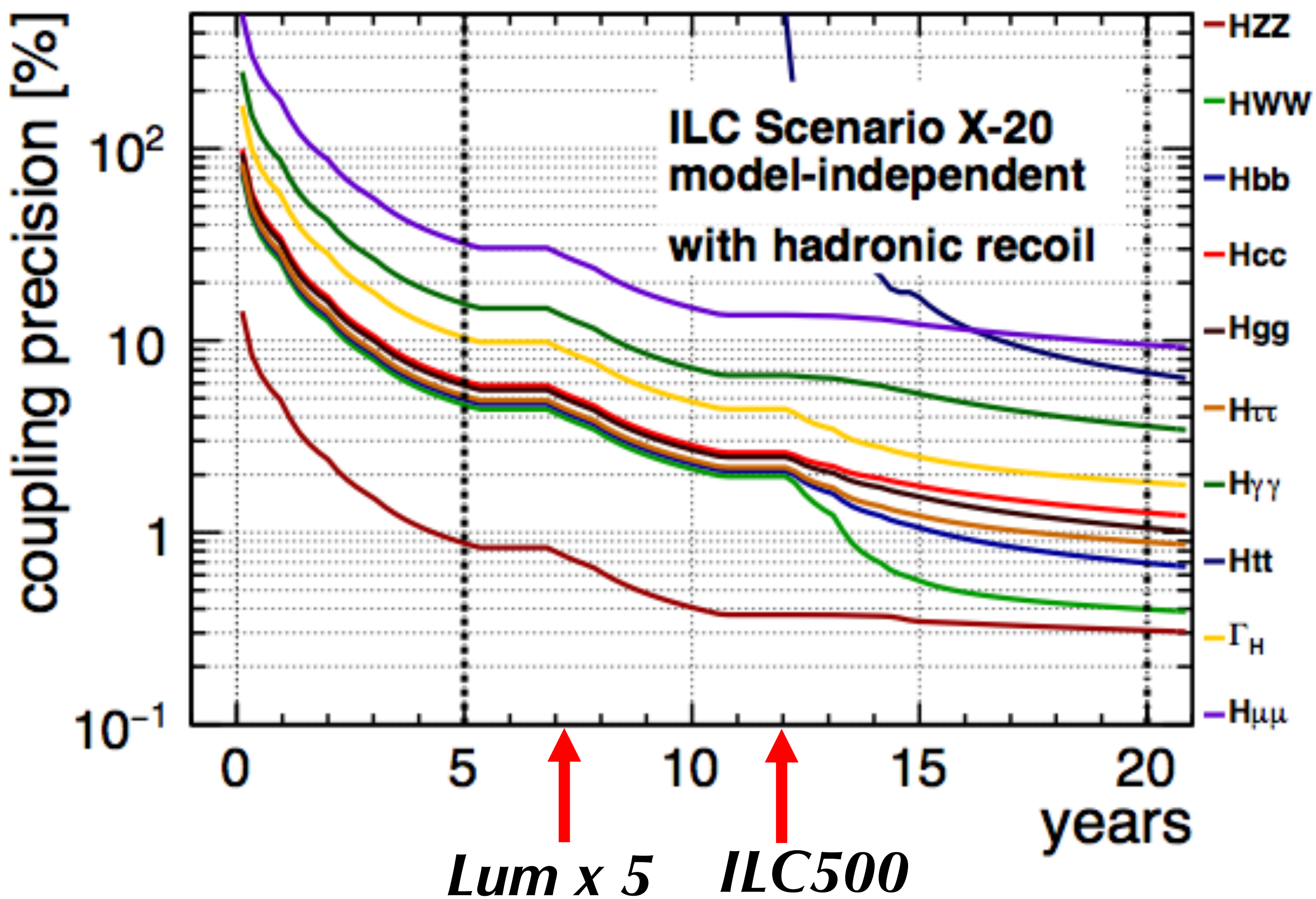


fingerprinting: SUSY or Composite (end of 500 GeV run)





evolution of coupling precision



Conclusion

- ILC250 is a Higgs factory.
- Confirm the importance/significance of Higgs physics – a window to a new world
  - Continue to drive potential to probe energy scale of new physics

- *Build/design to cost.*
- *Build it soon or never.*

Design Strategies

- SiD
  - High B field (5 Tesla)
  - Small ECAL ID
  - Small calorimeter volume
    - Finer ECAL granularity
  - Silicon main tracker
- ILD
  - Medium B field (3.5 Tesla)
  - Large ECAL ID
    - Particle separation for PFA
  - Redundancy in tracking
  - TPC for main tracker