Triple-Higgs coupling measurement at future e+e- colliders

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Higgs Coupling 2016, SLAC

Outline

- Introduction
- Indirect measurement of triple-Higgs coupling
- Direct measurement of triple-Higgs coupling
  - complementarity with LHC
- Model-independent extraction of the triple-Higgs coupling in EFT **[NEW!]**

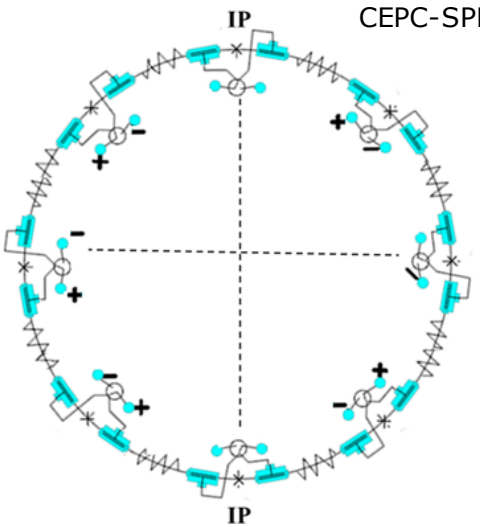
Circular Colliders

CEPC

Pre-CDR 2015

Circular Electron-Positron Collider

- Site: **China**
- CM energy: **90-240 GeV**
- Single main ring + booster ring
- Circumference: **50 km**
- # of IPs: **2**
- Precursor to 70 TeV pp collider (**SPPC**)

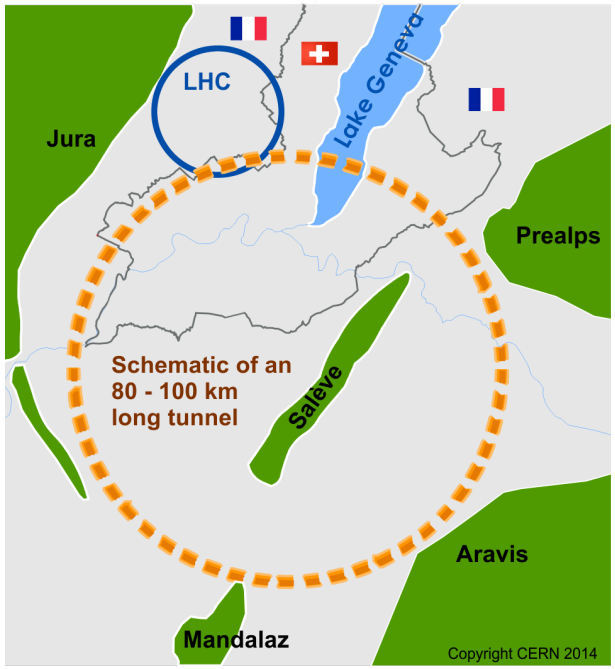


CEPC-SPPC PreCDR

FCC-ee

Future Circular Collider: e+e-

- Site: **CERN**
- CM energy: **90-350 GeV**
- Two main rings + booster ring
- Circumference: **100 km**
- # of IPs: **2-4**
- Possible precursor to 100 TeV pp collider (**FCC-hh**)



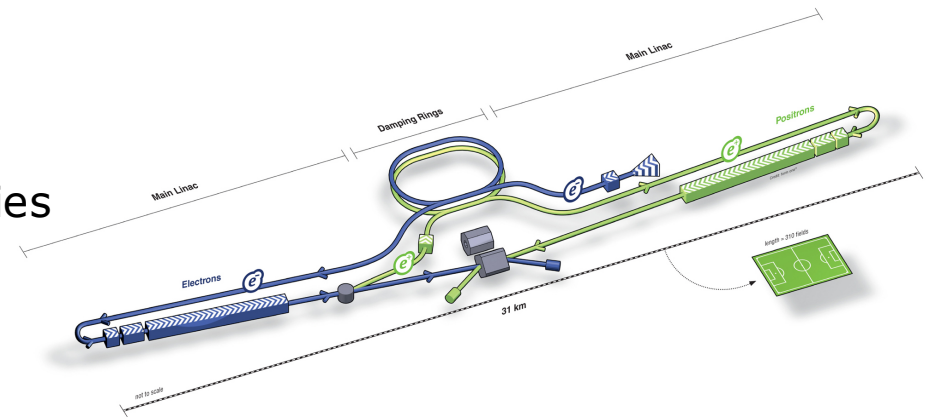
Linear Colliders

ILC

TDR 2013

International Linear Collider

- Based on superconducting RF cavities
- Potential site: **Japan**
- CM energy: **250-500 GeV**
  (upgradable to 1 TeV)
- Length: **34 km** (for 500 GeV)

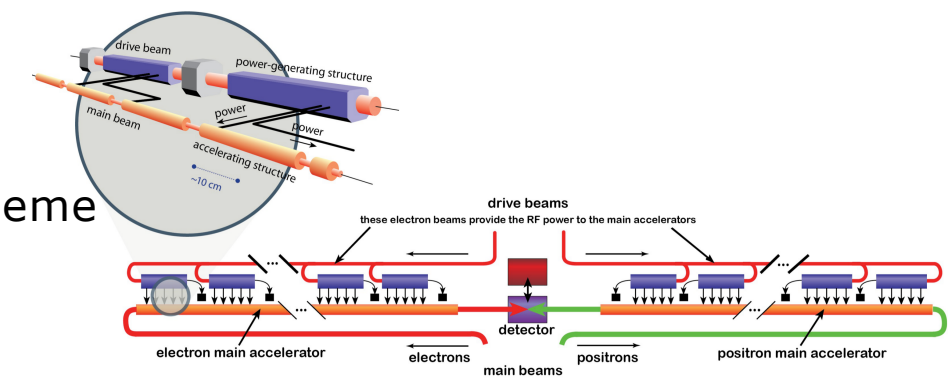


CLIC

CDR 2012

Compact Linear Collider

- Based on 2-beam acceleration scheme
- Site: **CERN**
- CM energy: **340 GeV → 3 TeV**
- Length: **50 km** (for 3 TeV)



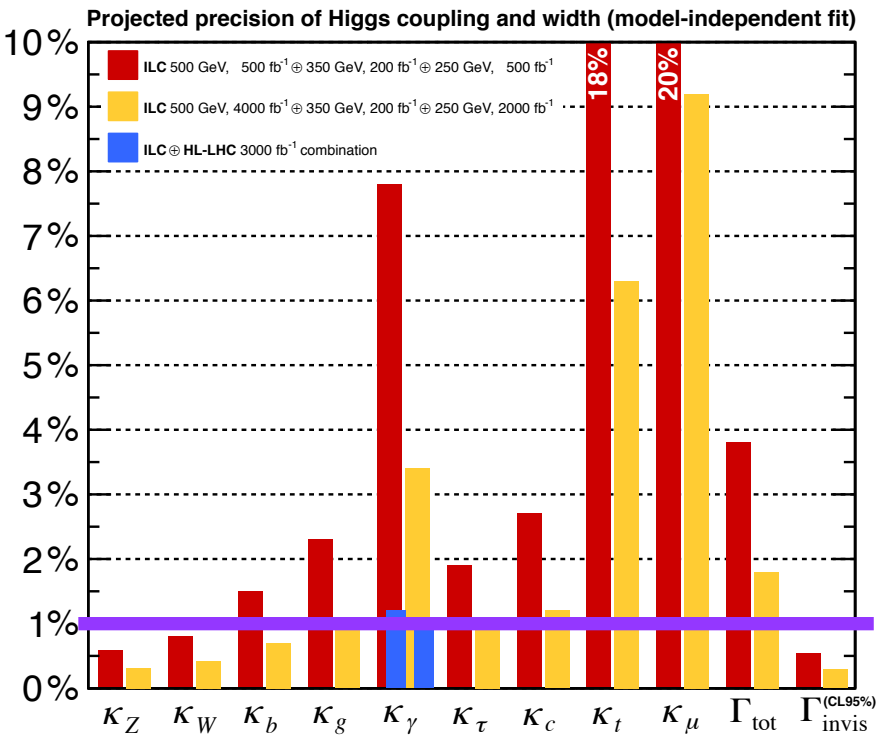
Higgs Couplings

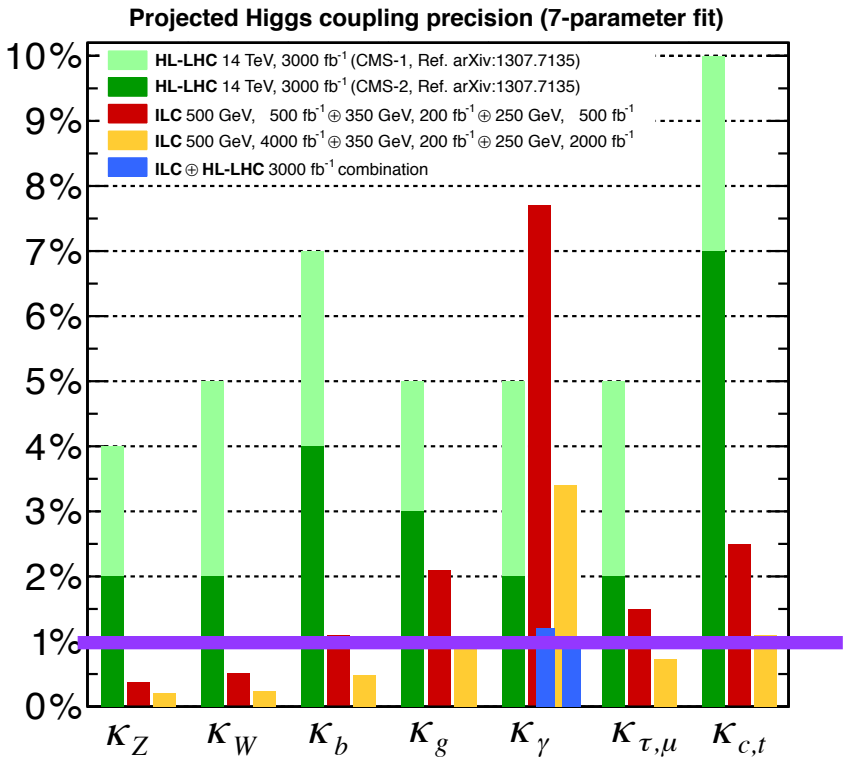
Example: ILC

Model-Independent:
Only possible at e+e-

Model-Dependent:
Compare with LHC

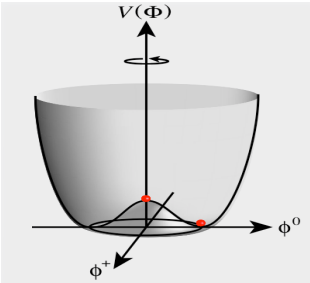
Includes systematic uncertainties [arXiv:1506.05992]



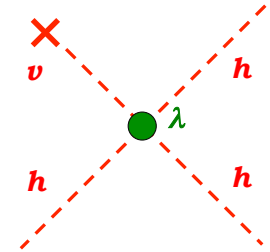


Sub-percent precision on most Higgs couplings with full ILC program

Motivation



$$V(\eta) = \frac{1}{2}m^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4$$

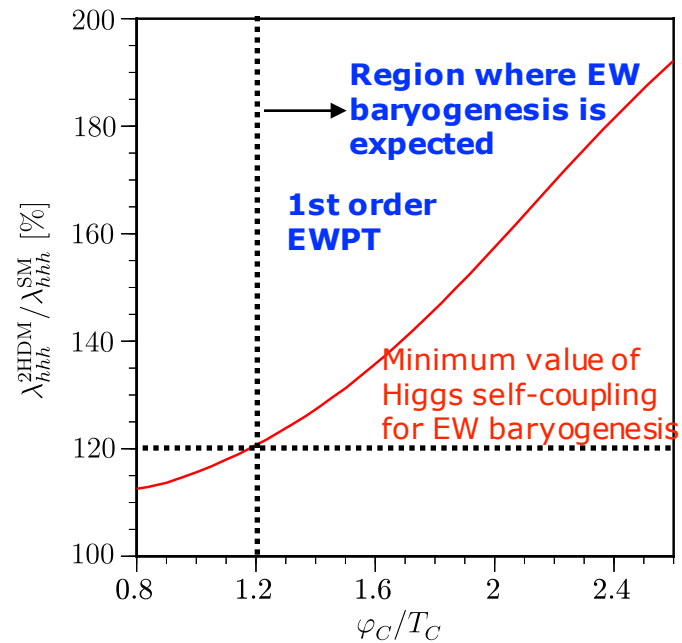


Motivation for measuring the triple-Higgs coupling:

1. Crucial test of electroweak symmetry breaking in the SM
   - Direct probe of the Higgs potential

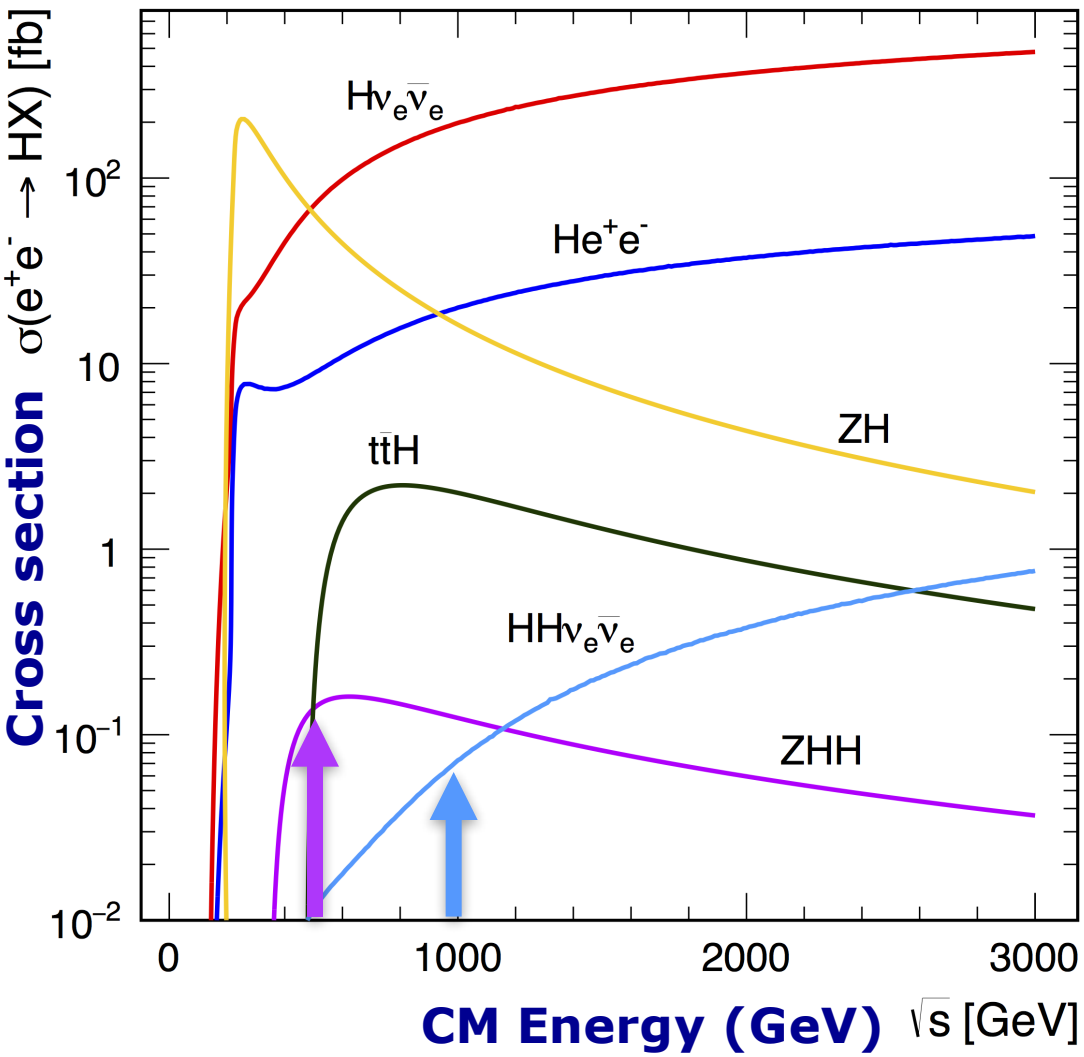
2. New Physics

- Deviations expected by new physics in the Higgs sector
- Predicted deviations are typically **large**
  - Grojean, Servant, Wells, PRD71, 036001
  - Hashino, Kanemura, Orikasa, 1508.03245
  - Fuyuto, Senaha, PLB747, 152
  - Perelstein, Katz, JHEP1407, 108



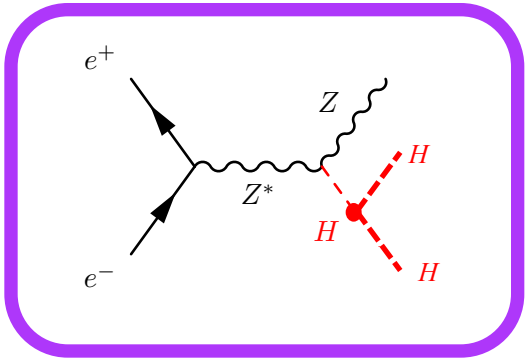
Kanemura, Senaha, Shindou, Yamada
Adapted from JHEP1305, 066

Higgs Production (e+e-)

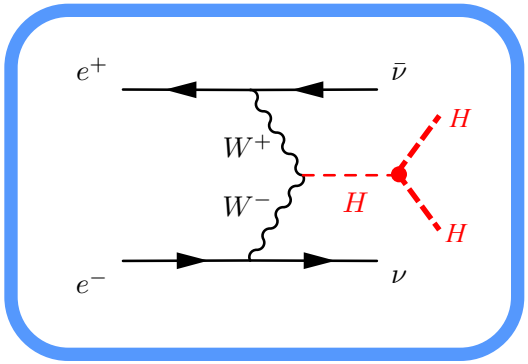


Double Higgs Production:

e+e- → ZHH



e+e- → ννHH

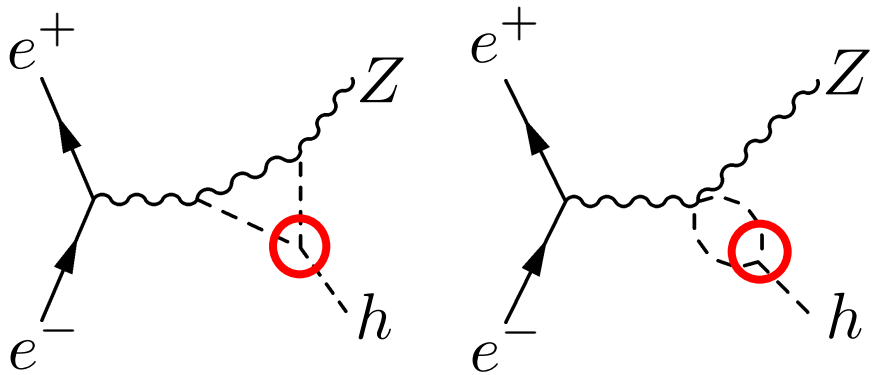


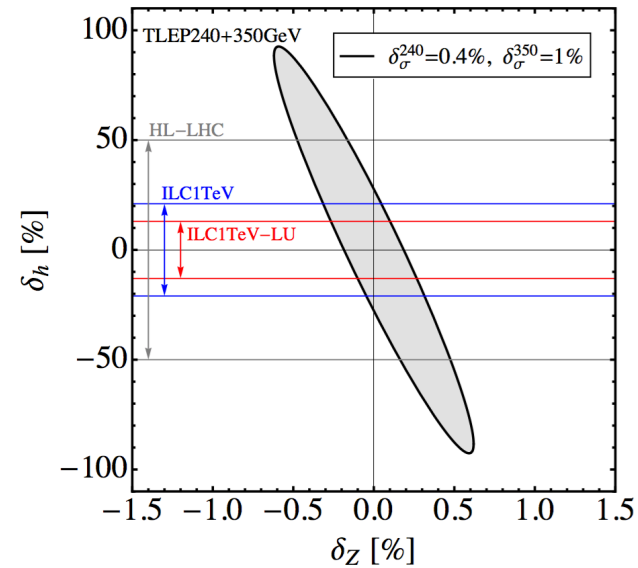
Require at least ~500 GeV for the direct measurement of the triple-Higgs coupling via double Higgs production.

Indirect Measurement

[McCullough, 1312.3322]

Use ZH process (e.g. 250 GeV):



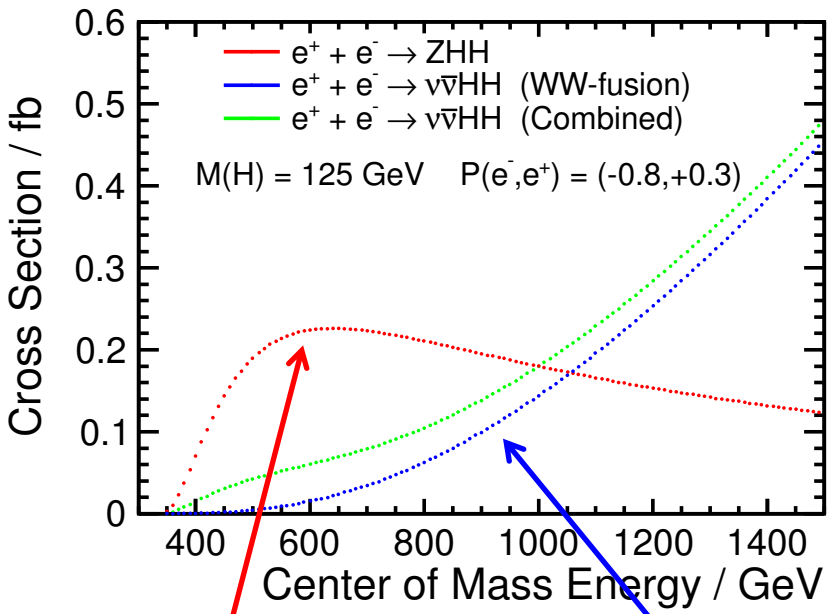


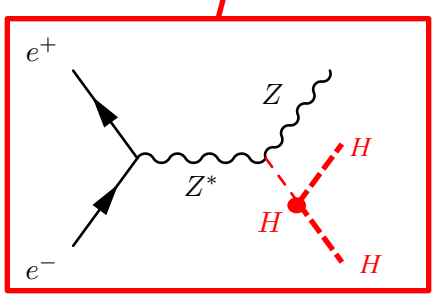
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

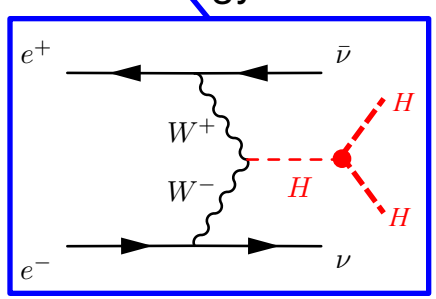
- **NLO** vertex correction has triple-Higgs coupling
- Take advantage of high luminosity (e.g. circular colliders)
  - If $\delta\sigma_{ZH}$ = 0.4%, then **δλ=28%**, assuming SM ZZH coupling; **δλ is larger for modified ZZH**.
- Important consistency check of the SM; offers complementary measurement (cf. direct measurement) about the loop process (**model-dependent**)

Direct Measurement

Cross section vs CM energy (e+e-)







Diagrams with triple-Higgs coupling

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

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

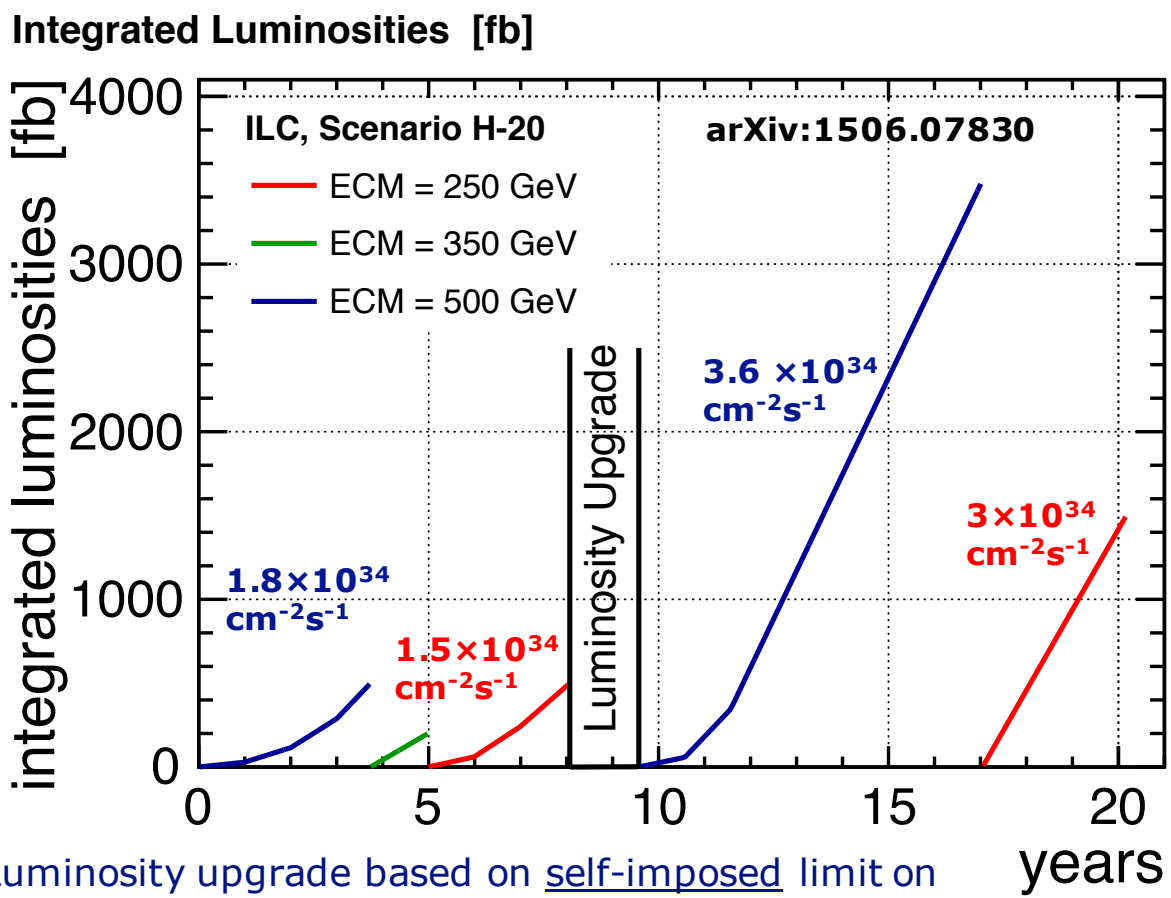
References:
J. Tian, LC-REP-2013-003
M. Kurata, LC-REP-2014-025
C. Duerig, Ph.D. thesis at DESY, 2016
HH→bbbb, bbWW* combination

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

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

Strawman Running Scenario for ILC

- **500 GeV:** General purpose Higgs & top physics, **triple-Higgs coupling**, top Yukawa, BSM
- **350 GeV:** Top threshold scan
- **250 GeV:** Dedicated Higgs measurements (mass, CP, …)



Total integrated luminosities:

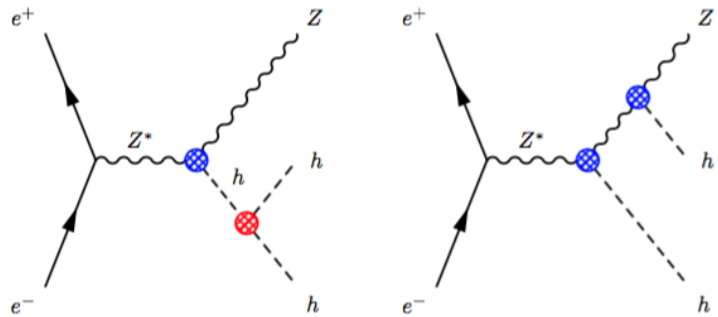
$\sqrt{s}$	$\int \mathcal{L}\, dt$
250 GeV	2000 fb^{-1}
350 GeV	200 fb^{-1}
500 GeV	**4000 fb^{-1}**

Reasonable assumption on integrated luminosities

Luminosity upgrade based on <u>self-imposed</u> limit on the power consumption of 200 MW.

Actual profile will depend on new physics, funding, and other projects.

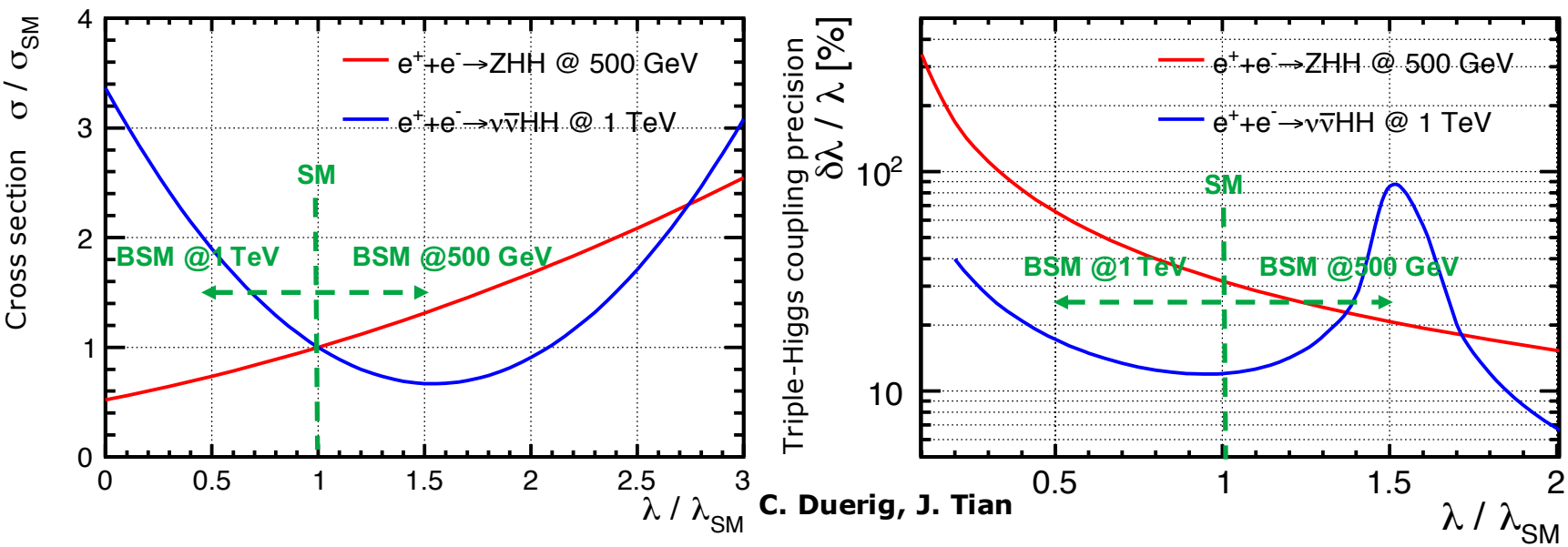
Triple-Higgs coupling with BSM



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

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

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

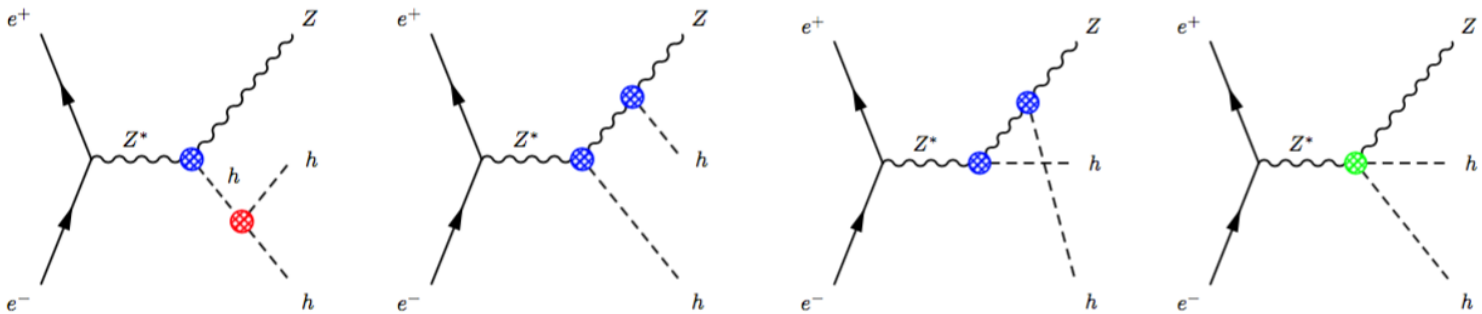


C. Duerig, J. Tian

500 GeV has unique sensitivity to larger triple-Higgs coupling

Model-independent extraction with EFT (1)

[Barklow, Fujii, Jung, Peskin, Tian]



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

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

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

Model-independent extraction with EFT (2)

[Barklow, Fujii, Jung, Peskin, Tian]

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

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

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

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

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

*These are issues for any double Higgs production process.

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

Conclusions

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

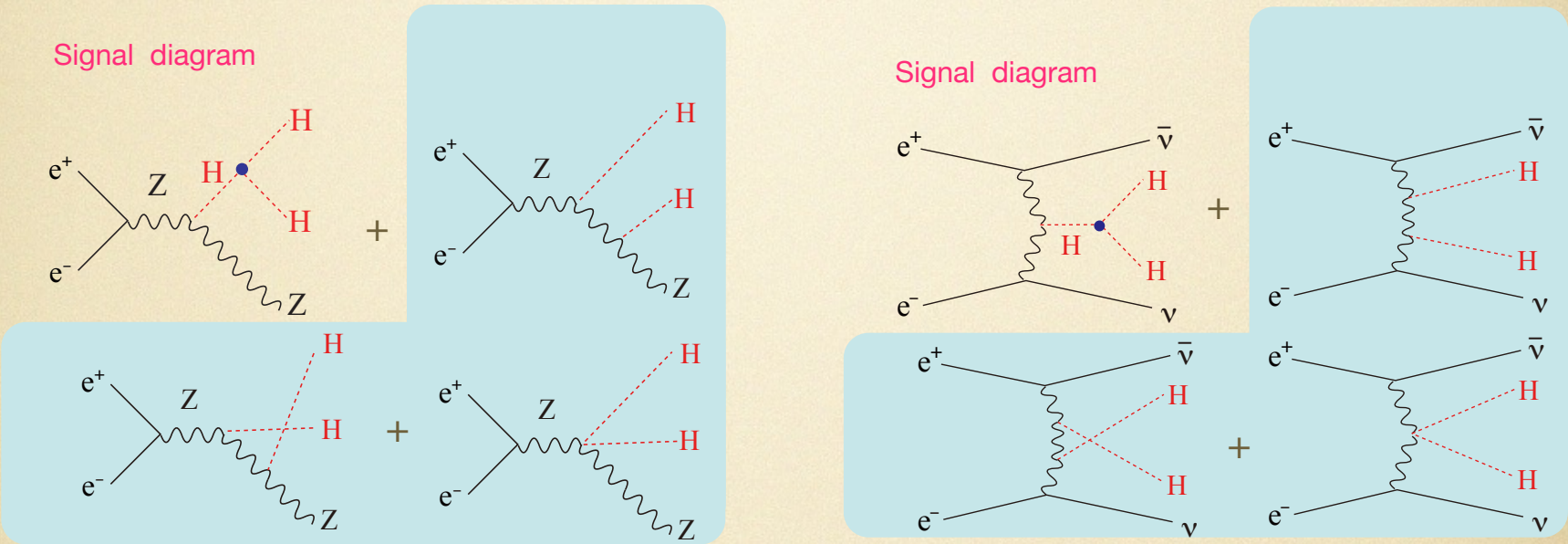
- **Indirect measurement** at the **30%-level** may be possible with high luminosity (e.g. circular colliders)
  - Provides complementary (but model-dependent) information about the loop process.

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

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

Additional Slides

physics issues: diagrams for double Higgs production



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

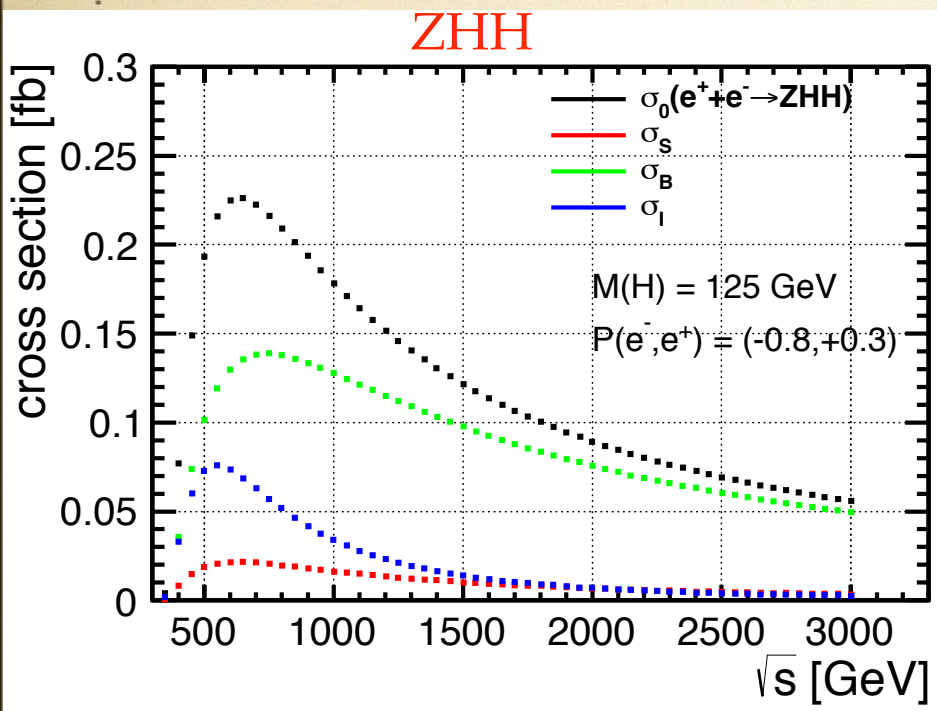
(signal diagram) (interference) (background diagram)

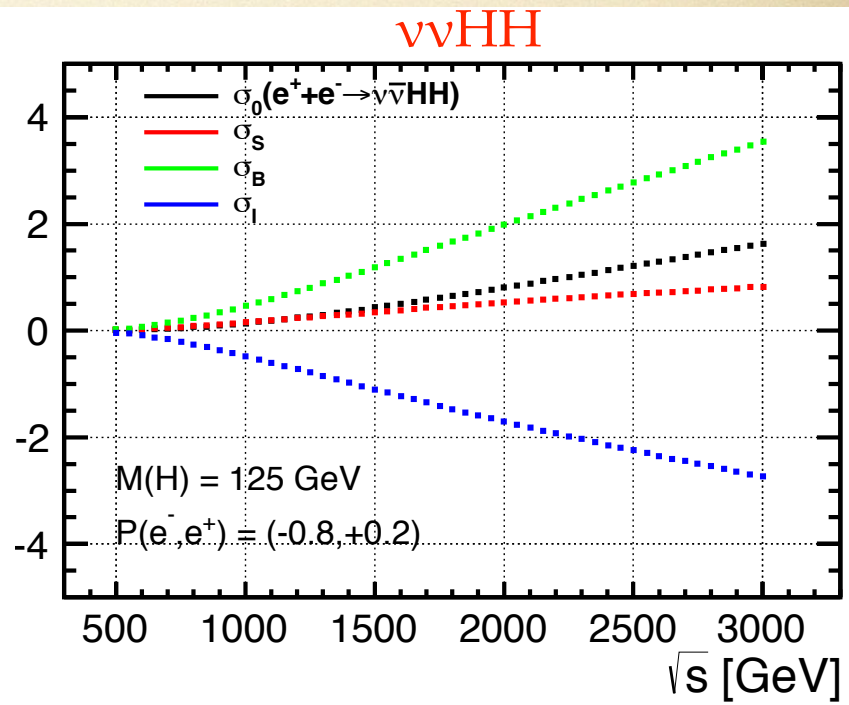
- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

Junping Tian

breakdown of σ to S, I and B terms

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

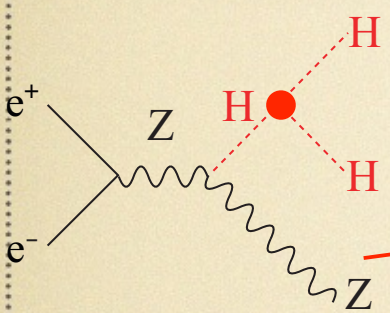


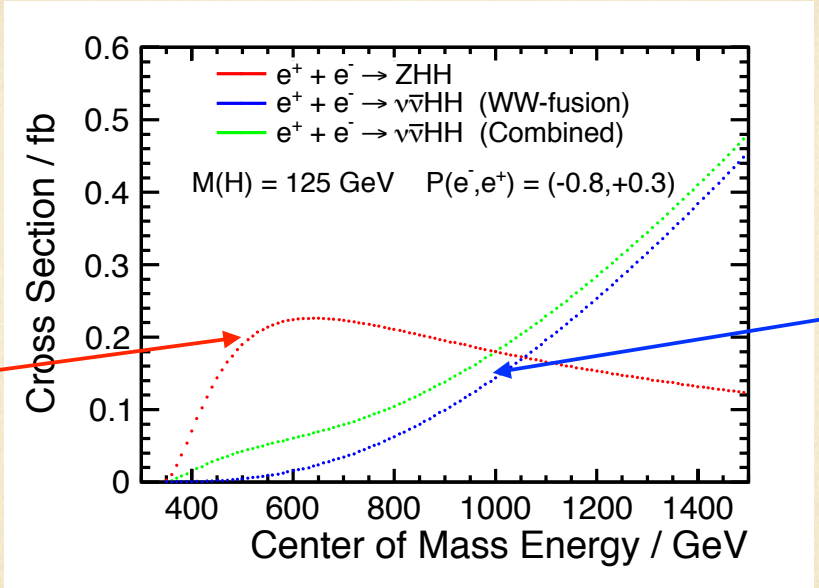


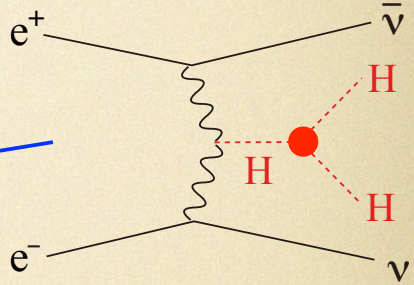
- B term (green) >> S term (red) —> more difficult than expected
- interference I term (blue) plays an crucial role in both cases; larger I term for νν̄HH indicates potential better sensitivity in νν̄HH than ZHH
- For ZHH: clearly ~500-600 GeV is preferred; peak positions of I or S term are smaller than that of B term and the apparent total σ (black)
- For νν̄HH: dependence on ecm, S term < apparent σ < B term ≈ I term

how we measure it at ILC and analysis strategy

Junping Tian







searching mode and main backgrounds: $e^+ + e^- \to ZHH$ @ 500 GeV

- llHH: llbb (ZZ, γZ, bbZ), lνbbqq (tt-bar), llbbbb (ZZZ/ZZH)
- ννHH: bbbb (ZZ, γZ, bbZ), τνbbqq (tt-bar), ννbbbb (ZZZ/ZZH)
- qqHH: bbbb (ZZ, γZ, bbZ), bbqqqq (tt-bar), qqbbbb (ZZZ/ZZH)

event selection:

$B/S \sim 10^{3\text{-}4}$

- isolated-lepton selection or rejection
- jet clustering and flavor tagging
- missing energy or visible energy requirement
- event reconstructed as from signal and dominant background
- each dominant background is suppressed by training a neural-net

status of full simulation analysis @ ILC

- ☑ DBD full simulation analyses (mH=125 GeV): ZHH @ 500 GeV, ννHH @ 1 TeV
- ☑ SGV fast simulation analysis: ννHH @ 1 TeV (consistent with full simulation)

- updating analysis with mH=125 GeV
- impact of beam background from γγ->hadrons
- impact of beam polarisations
- improving analysis technique / strategy
  - isolated lepton tagging
  - kinematic fitting
  - optimize cuts for coupling instead of cross section
  - matrix element method and color-singlet-jet-clustering

J. Tian, LC-REP-2013-003 C. Dürig @ ALCW15 M. Kurata, LC-REP-2014-025