Prospects of measuring Higgs boson decays into muon pairs at the ILC

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Introduction

Discovery of SM-like Higgs boson at the LHC 

But, still many open questions: 

- SM Higgs? BSM Higgs?
- dark matter, dark energy
- BSM (SUSY, composite...)
- ...

Precise measurement of Higgs boson

would be a key to answer the questions

- mass-coupling relation
- any deviation shows the existence of BSM
- typically small deviation

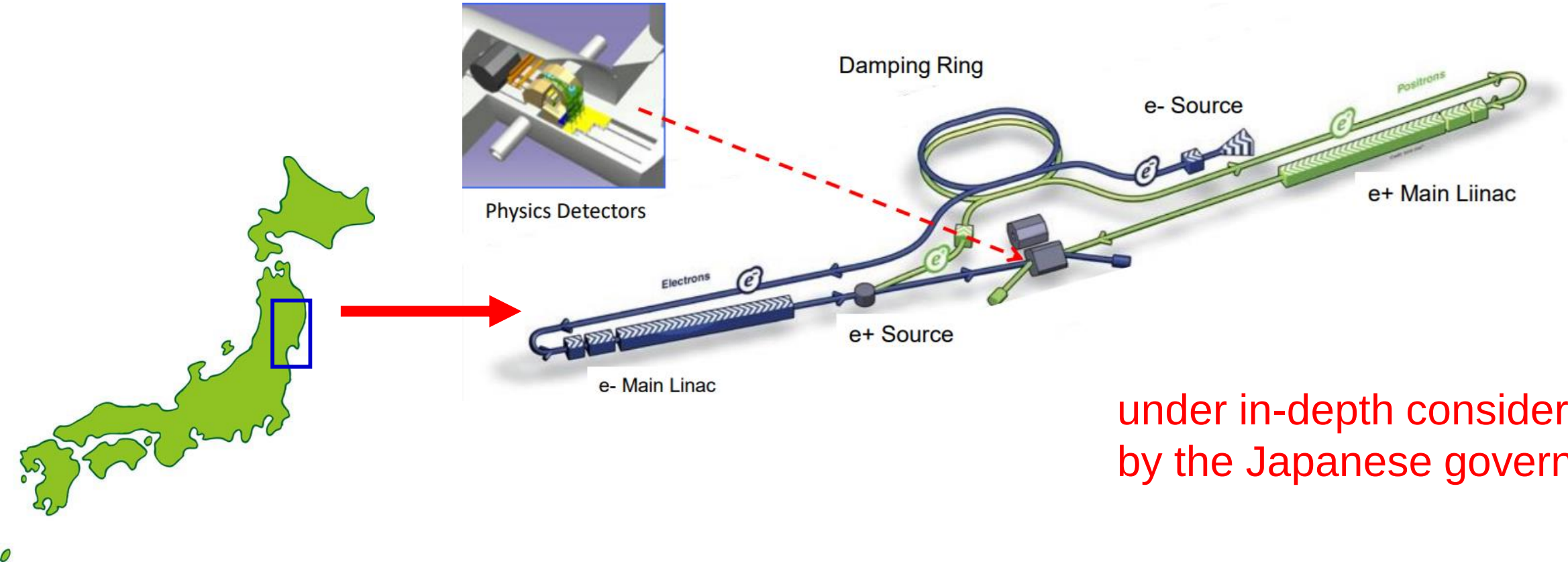
One example: Supersymmetry

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

arXiv:1306.6352

The International Linear Collider (ILC)

- e^+e^- collider, E_{CM} = 250 GeV (upgradable to 500 GeV, 1 TeV)
- polarized beam (e^-: ±80%, e^+: ±30%)
- clean environment, known initial state



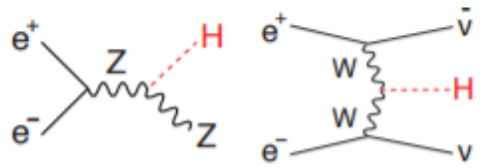
under in-depth consideration
by the Japanese government

Key Point

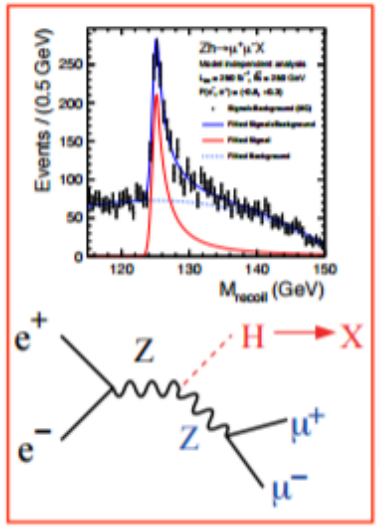
K. Fujii's talk, LCWS2014

LHC: all measurements are $\sigma \times \mathrm{BR}$

ILC: $\sigma \times \mathrm{BR}$ measurements + σ measurement



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



σ×BR

BR

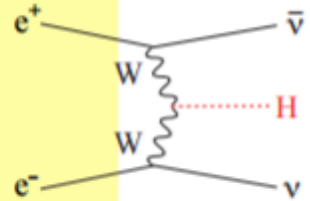
g coupling

The Key

σ from recoil mass

Γ_H total width

WW-fusion is crucial for precision total width measurement → Ecm > 350GeV



Z→qq is also usable.

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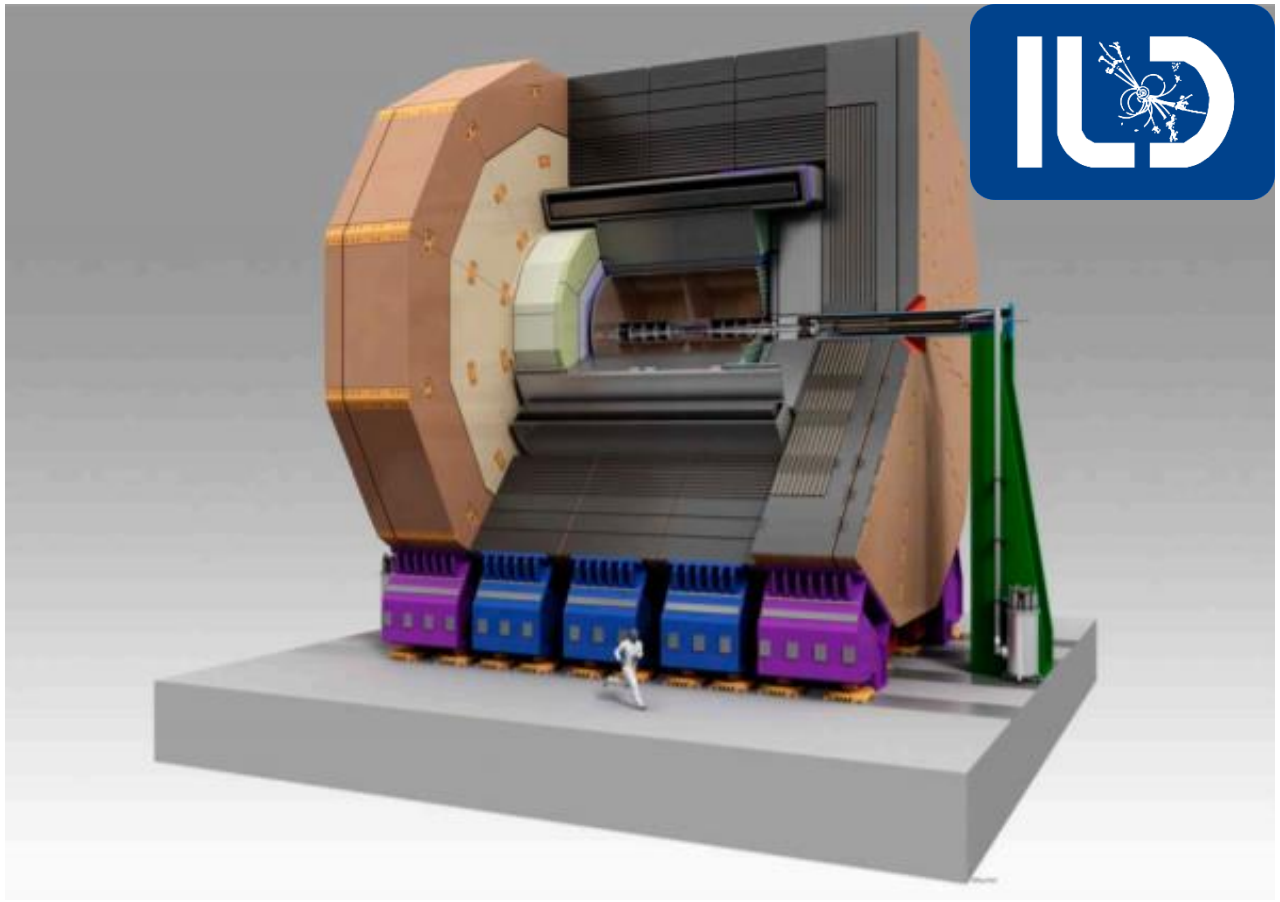
Detector Concept at the ILC

ILD (**I**nternational **L**arge **D**etector)



Tracker: Vertex, TPC
Calorimeter: ECAL, HCAL
3.5T magnetic field
Yoke for muon, Forward system

Requirements:

- Impact parameter resolution

  $\sigma_{r\phi} < 5 \oplus \frac{10}{p\sin^{3/2}\theta}\ \mu\text{m}$

- **Momentum resolution**

  σ_{1/p_T} < 2*10^{-5} GeV^{-1}

- Energy resolution

  σ_E/E = 3 - 4%

In This Talk: $h \rightarrow \mu^+\mu^-$

- Can be used for testing:
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd leptons (κ_μ/κ_τ) and 2nd lepton/quark (κ_μ/κ_c)
- Challenging: tiny branching ratio (BR($h \rightarrow \mu^+\mu^-$) = **2.2*10^{-4}**)

Previous Studies

Everything performed at >= 1 TeV, or not realistic

Reference	E_{CM}	beam pol. $P(e^-, e^+)$	$\int Ldt$	$\frac{\Delta(\sigma \times BR)}{(\sigma \times BR)}$	comment
LC-REP-2013-006	1 TeV	(-0.8, +0.2)	500 fb^{-1}	44%	ILC/ILD
arXiv:1306.6329 [hep-ex]	1 TeV	(-0.8, +0.2)	1000 fb^{-1}	32%	ILC/SiD
arXiv:1603.04718 [hep-ex]	1 TeV	(-0.8, +0.2)	500 fb^{-1}	36%	ILC/ILD used TMVA
Eur. Phys. J. **C73**(2), 2290 (2013)	3 TeV	unpol.	2000 fb^{-1}	15%	CLIC_SiD M_h = 120 GeV used TMVA
Eur. Phys. J. **C75**, 515 (2015)	1.4 TeV	unpol.	1500 fb^{-1}	38%	CLIC_ILD used TMVA
		(-0.8, 0)		25%	
arXiv:0911.0006 [physics.ins-det]	250 GeV	(-0.8, +0.3)	250 fb^{-1}	91%	ILC/SiD M_h = 120 GeV

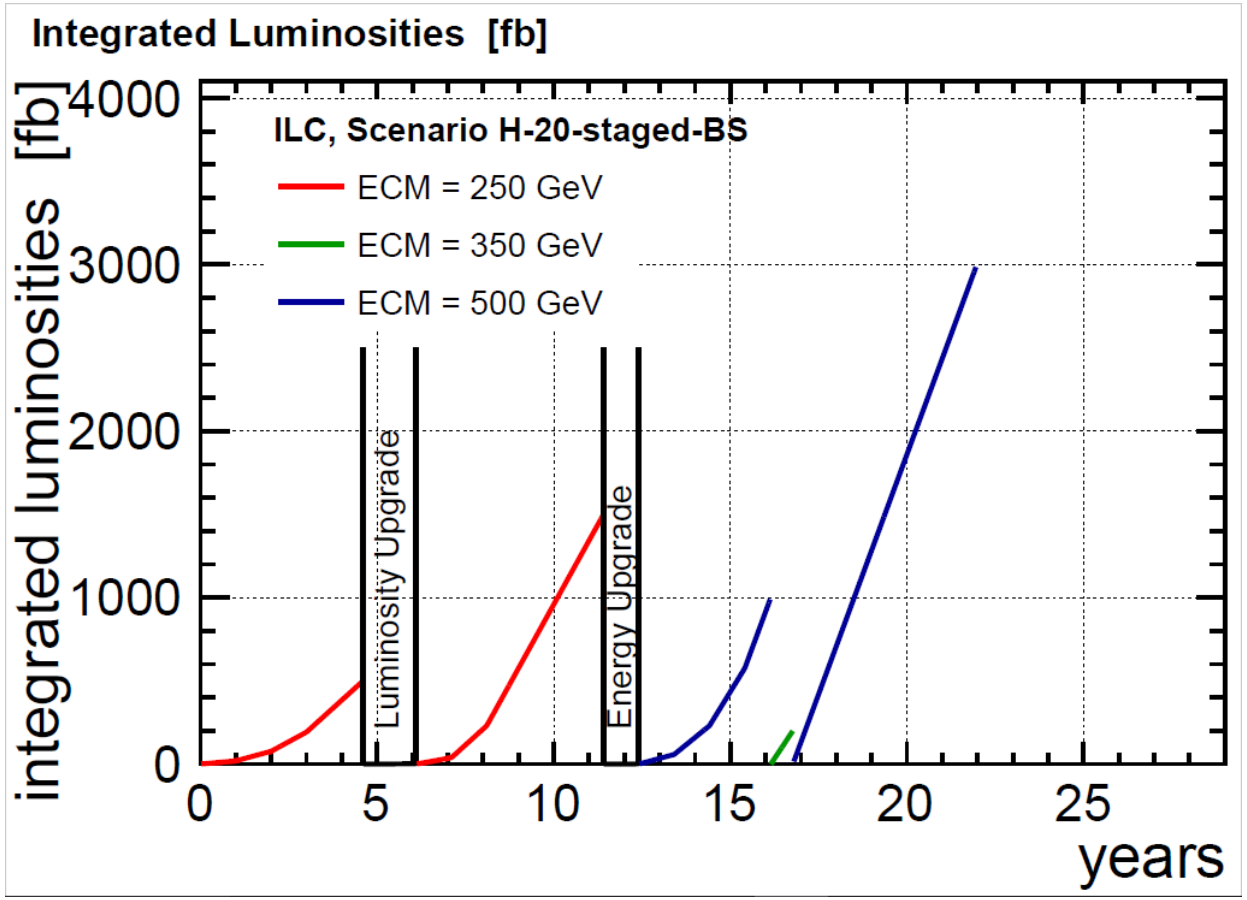
arXiv:1710.07621 [hep-ex]

ILC Running Scenario

optimized scenario with considering
- Higgs precise measurements
- Top physics
- New physics search

~20 years running with
energy range [250-500] GeV,
beam polarization sharing
---> then possible 1 TeV upgrade

preferred scenario:
2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV



staging running scenario

arXiv:1506.05992 [hep-ex]

Single Higgs Production

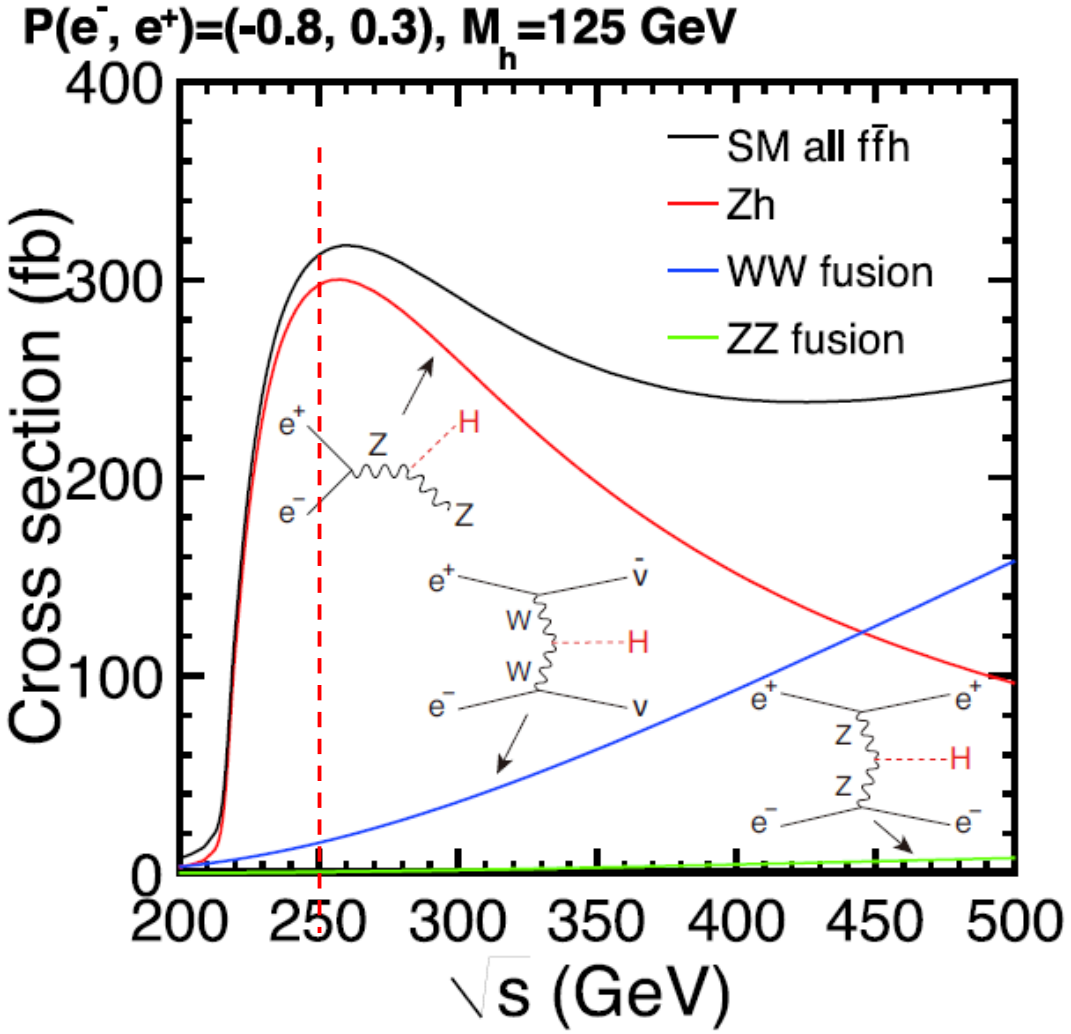
$\sqrt{s}$ = 250 GeV

Higgs-strahlung (Zh) dominant

$\sqrt{s}$ = 500 GeV

WW-fusion dominant

E_{CM}	process	beam pol.	$\int Ldt$ (fb^{-1})	# events
500	$\nu\bar{\nu}h$	L	1600	57.5
		R	1600	7.9
	$q\bar{q}h$	L	1600	24.6
		R	1600	16.5
250	$\nu\bar{\nu}h$	L	900	15.0
		R	900	8.4
	$q\bar{q}h$	L	900	41.1
		R	900	28.1



L: (e^-, e^+) = (-0.8, +0.3)

R: (e^-, e^+) = (+0.8, -0.3)

Analysis Settings

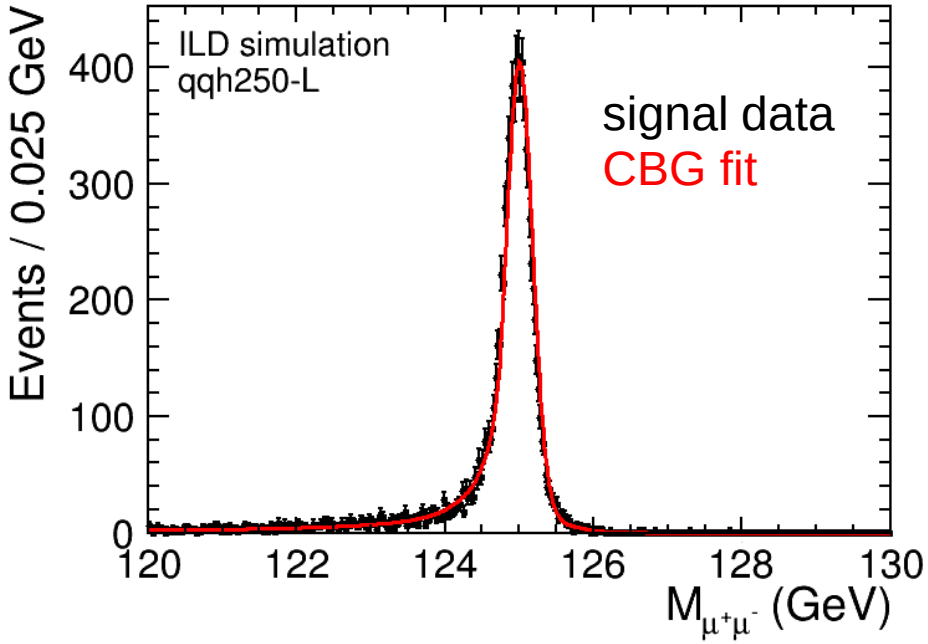
- Geant4-based full detector simulation with ILD model
- Included all available SM backgrounds
  - (for specialist) Used DBD-world samples
  - Performed toy MC in the end to estimate the precision

E_{CM}	# total MC events
500 GeV	$1.4*10^7$
250 GeV	$7.1*10^7$

Brief Summary of Analysis

Analysis is structured in the same way for all channels.

1. select $h \to \mu^+\mu^-$ candidate
2. channel-specific analysis
3. multivariate analysis
4. modeling and toy MC with $M_{\mu^+\mu^-}$
   - ➢ extract final precision
   - ➢ (for experts) Crystal Ball + Gaussian (CBG) for signal, pol1 for background



ATLAS-PHYS-PUB-2018-006
CERN-LHCC-2015-10

Results

precision for $\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$

250 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	36.2%	122.4%
R	38.0%	105.1%

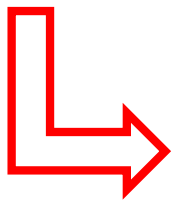
500 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	43.8%	37.9%
R	54.2%	108.8%

ILC250 combined = 24.9% (“theoretical limit” = 10.4%)
ILC250+500 combined = **17.5%** (“theoretical limit” = 7.1%)
HL-LHC: 10-13%

※theoretical limit = 100% efficiency, no backgrounds, no detector effects

Impact of Momentum Resolution

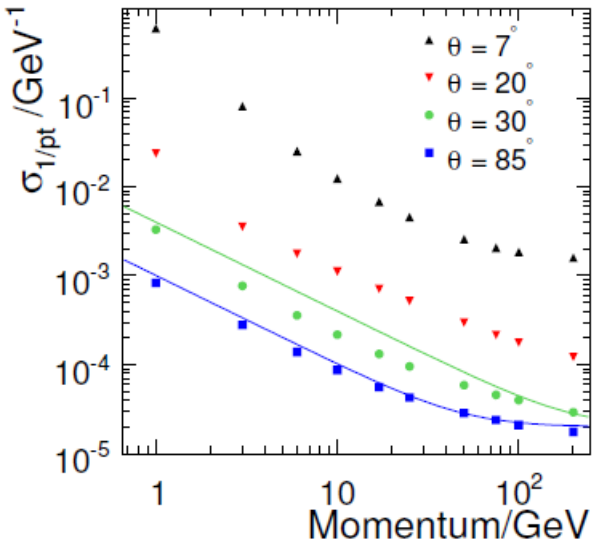
- The variable $M_{\mu^+\mu^-}$ is most important and essential for this analysis. Thus, the momentum resolution (P_t resolution) has a crucial role.
- Studied what will happen when we change the momentum resolution artificially
  - 13 benchmark points



Resolution (GeV^{-1})			
$1*10^{-3}$	$5*10^{-4}$	$5*10^{-5}$	$5*10^{-6}$
	$3*10^{-4}$	$3*10^{-5}$	$3*10^{-6}$
	$2*10^{-4}$	$2*10^{-5}$	$2*10^{-6}$
	$1*10^{-4}$	$1*10^{-5}$	$1*10^{-6}$

Impact of Momentum Resolution

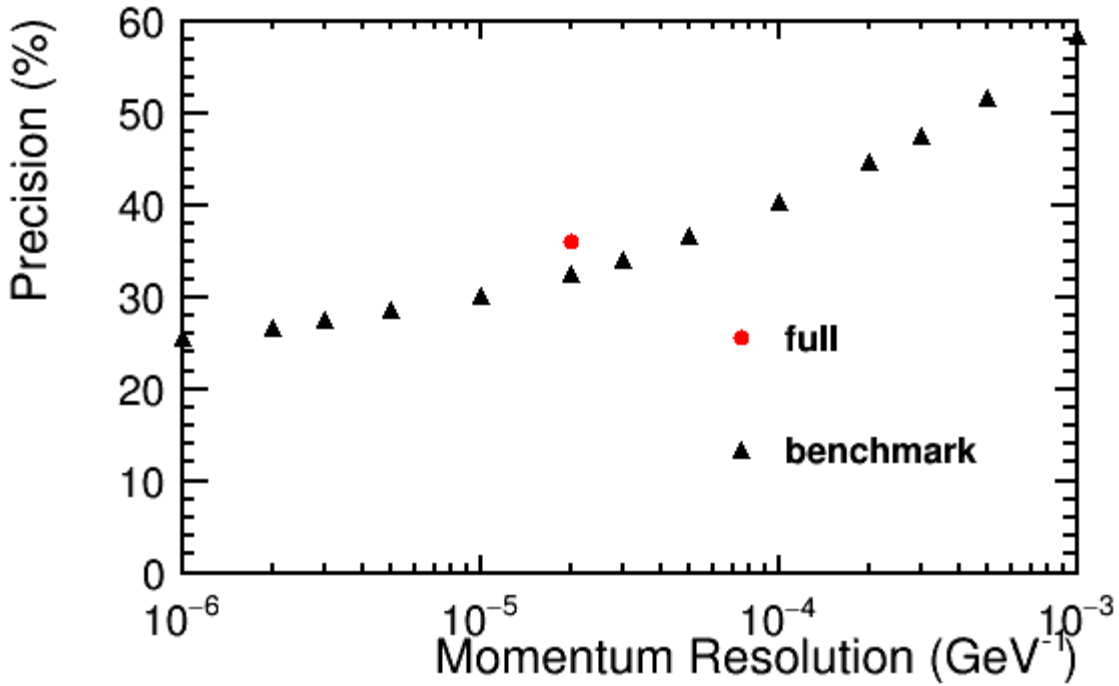
- smeared MCParticle momentum of $h \to \mu^+\mu^-$ candidate
  - Gaussian-smeared with **constant number**
    - no momentum/angular dependencies
    - Not 100% correct, but muons will fly everywhere and rather high momentum. On average, this is still good approximation.
  - replace $M_{\mu^+\mu^-}$ to $M^{\mathrm{smear}}_{\mu^+\mu^-}$ in toy MC



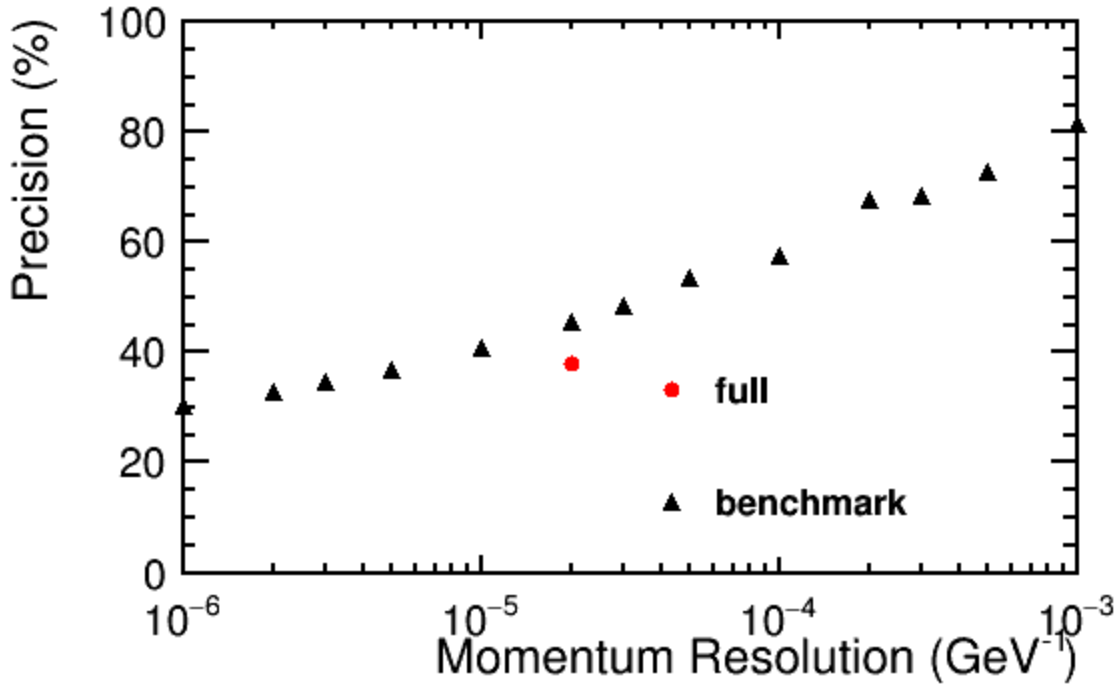
arXiv:1306.6329

Studied the impact to final number: $\frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})}$ in this study

Results (Major Channel)

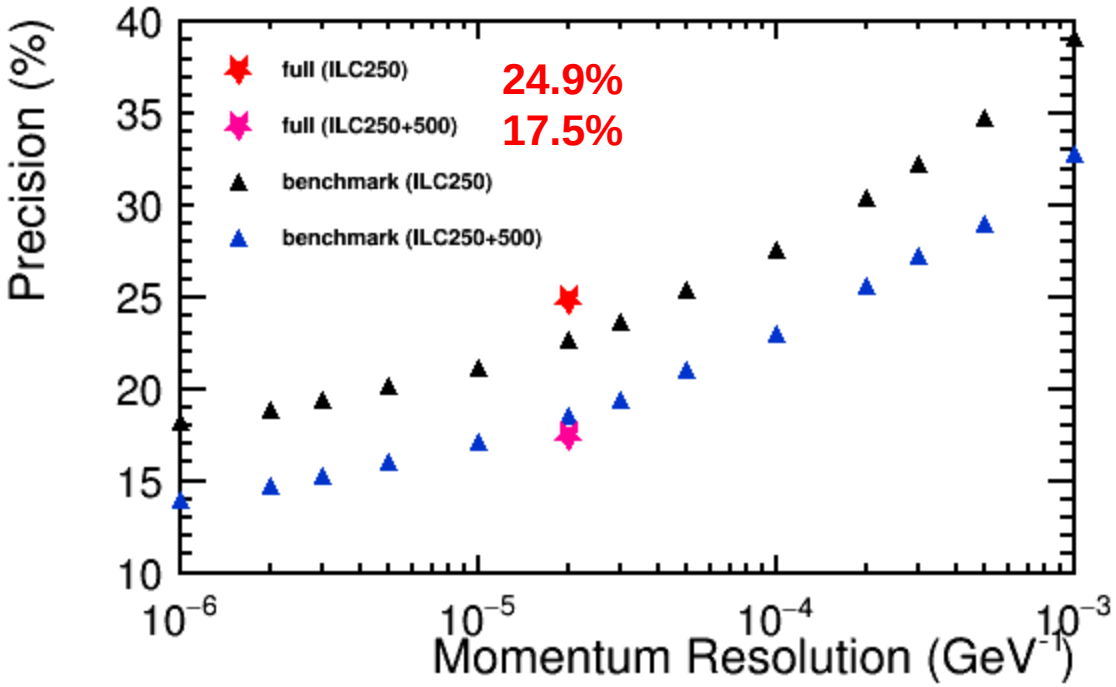


qqh250-L
full: 36.2%



nnh500-L
full: 37.9%

Combined Results



- better resolution gives better result
- relative improvement is ~20% when resolution is factor 10 better
- relative ~40% worse when resolution is factor 10 worse

ILC250: ~18-23%
ILC250+500: ~14-18%

Summary

- Precise measurements and extracting absolute Higgs couplings are possible at the ILC
- Studied $h \to \mu^+\mu^-$ channel with E_{CM} = 250/500 GeV at the ILC
  - Can reach 17.5% combined precision for $\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$
- Studied the impact of momentum resolution
- Now summarizing into a full paper: ongoing
- (for specialist) IDR analysis has just started