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

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Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

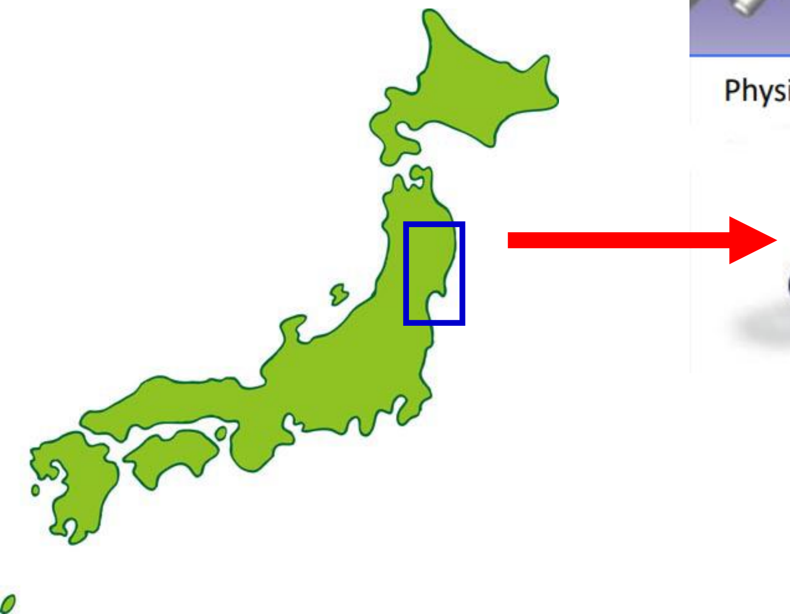
Introduction

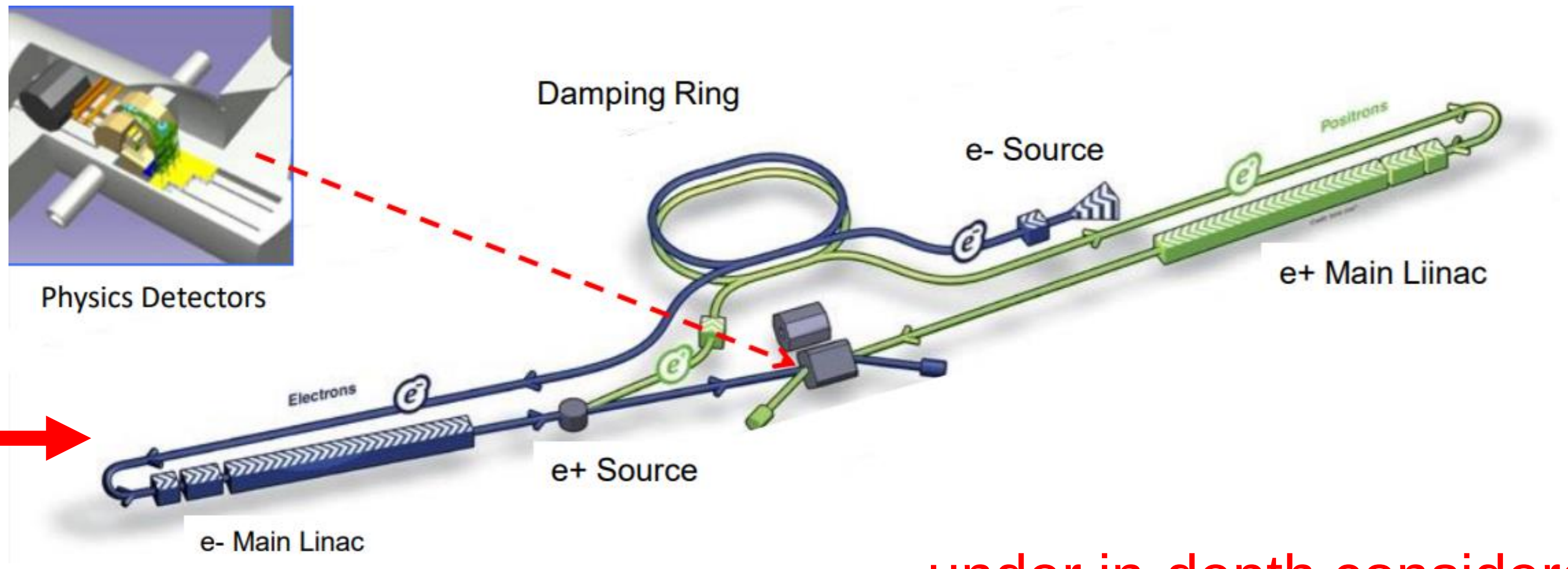
- Discovery of SM-like Higgs boson at the LHC 
- But, still limited knowledge about Higgs 

- This talk: $h \rightarrow \mu^+\mu^-$ at E_{CM} = 250/500 GeV at the ILC
  - Model-independent measurement ---> see F. Simon's talk
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd leptons (κ_μ/κ_τ) and 2nd lepton/quark (κ_μ/κ_c)
  - challenging: tiny branching ratio (BR($h \rightarrow \mu^+\mu^-$) = **$2.2*10^{-4}$**)

The International Linear Collider (ILC)

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



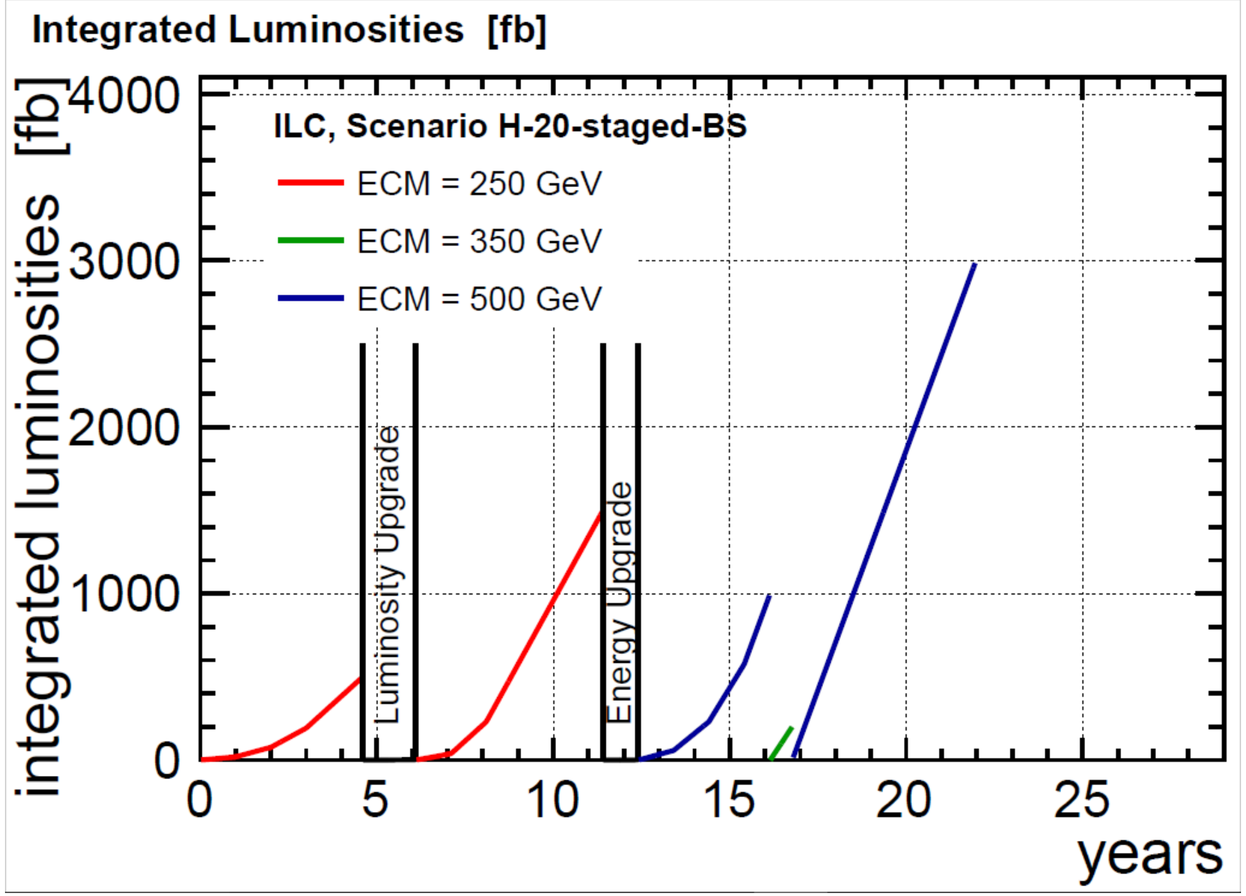


under in-depth consideration
by the Japanese government

ILC Running Scenario

optimized scenario with considering Higgs/Top/New physics

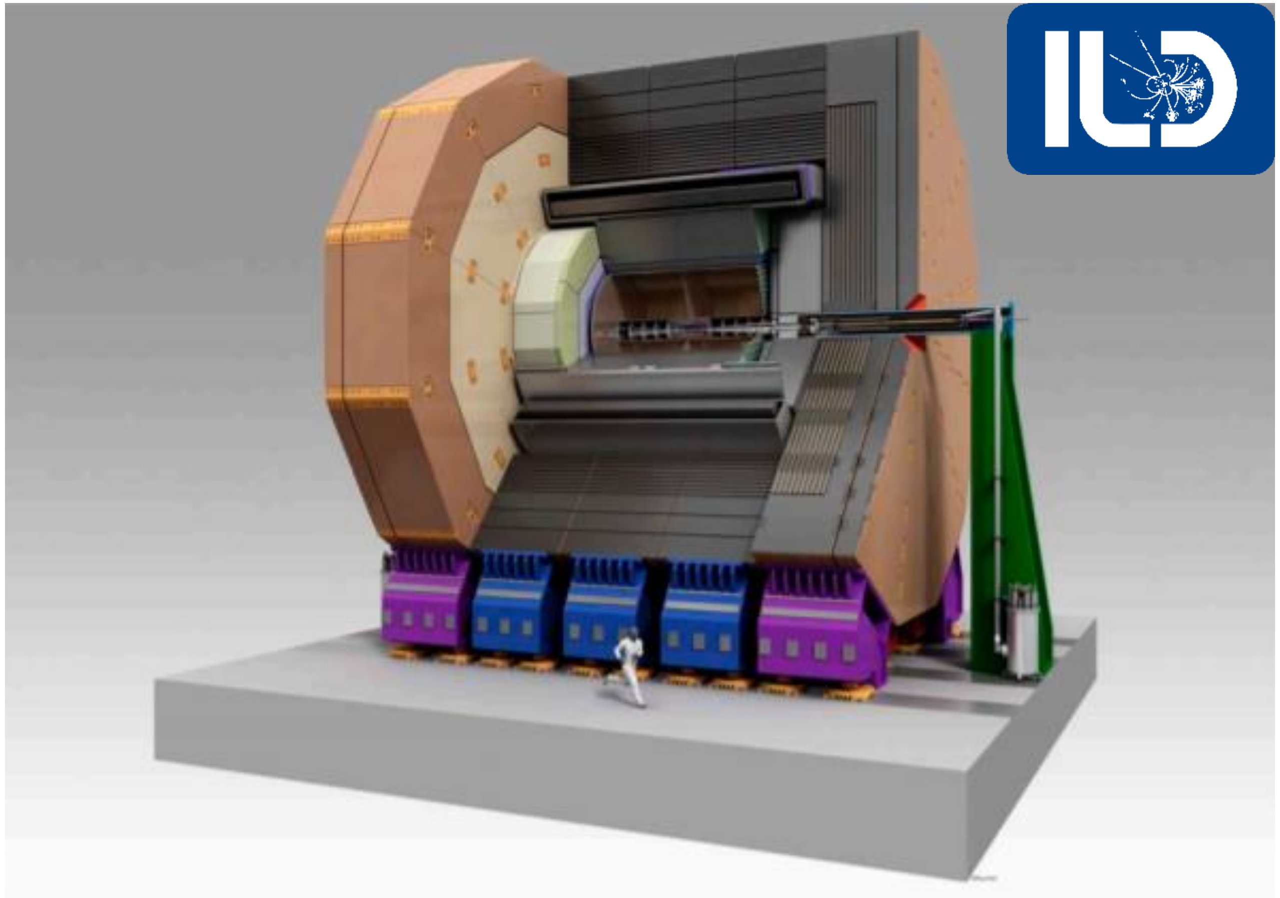
~20 years running with energy range [250-500] GeV, beam polarization sharing



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

Detector Concept at the ILC

ILD (**International Large Detector**)



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

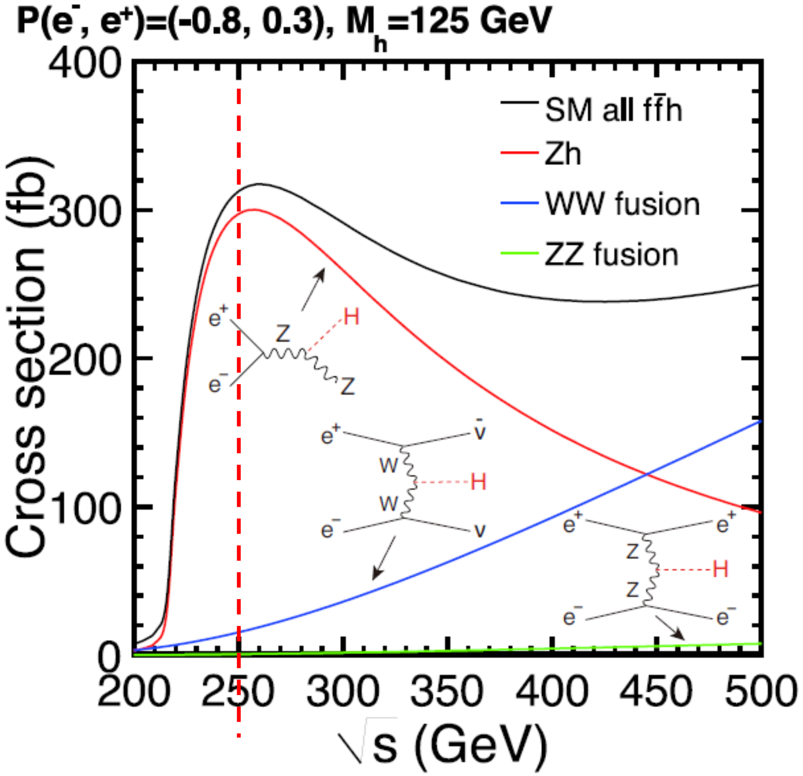
Requirements:

- Impact parameter resolution
  $\sigma_{r\phi} < 5 \oplus \frac{10}{p\sin^{3/2}\theta}\ \mu\mathrm{m}$
- **Momentum resolution**
  $\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$
- Jet energy resolution
  σ_E/E = 3 - 4%

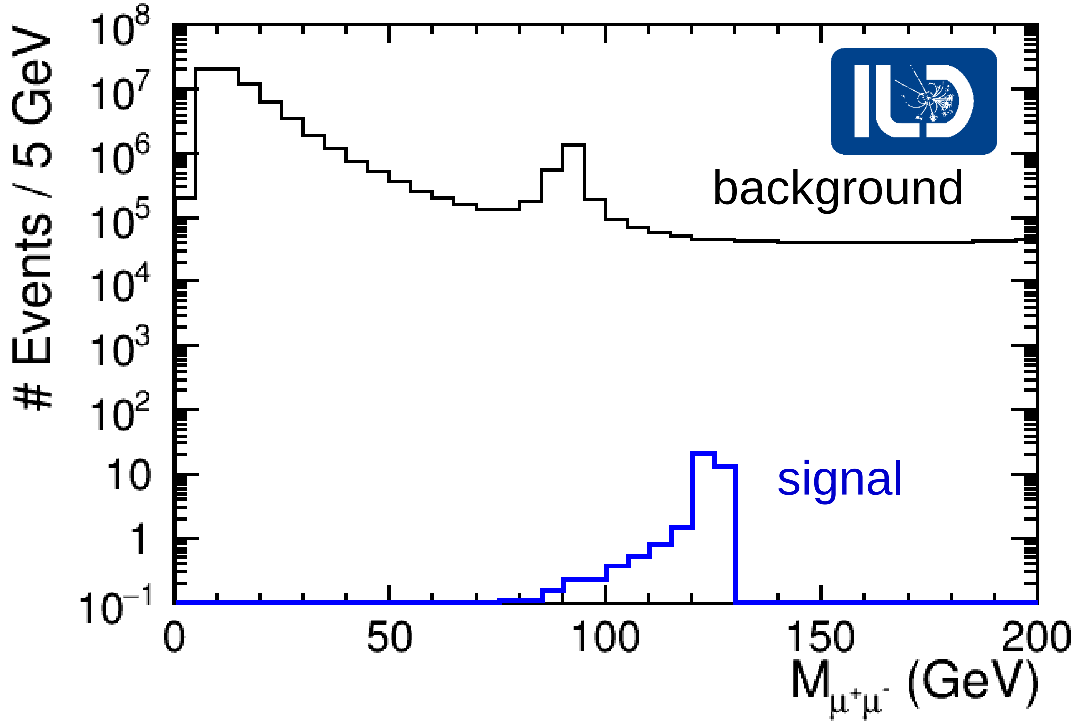
Higgs Production & Analysis Channel

$\sqrt{s}$ = 250 GeV
Higgs-strahlung (Zh) dominant

$\sqrt{s}$ = 500 GeV
WW-fusion dominant



Two channels analyzed:
$e^+e^- \to q\bar{q}h$ and $e^+e^- \to \nu\bar{\nu}h$
Two beam polarization considered

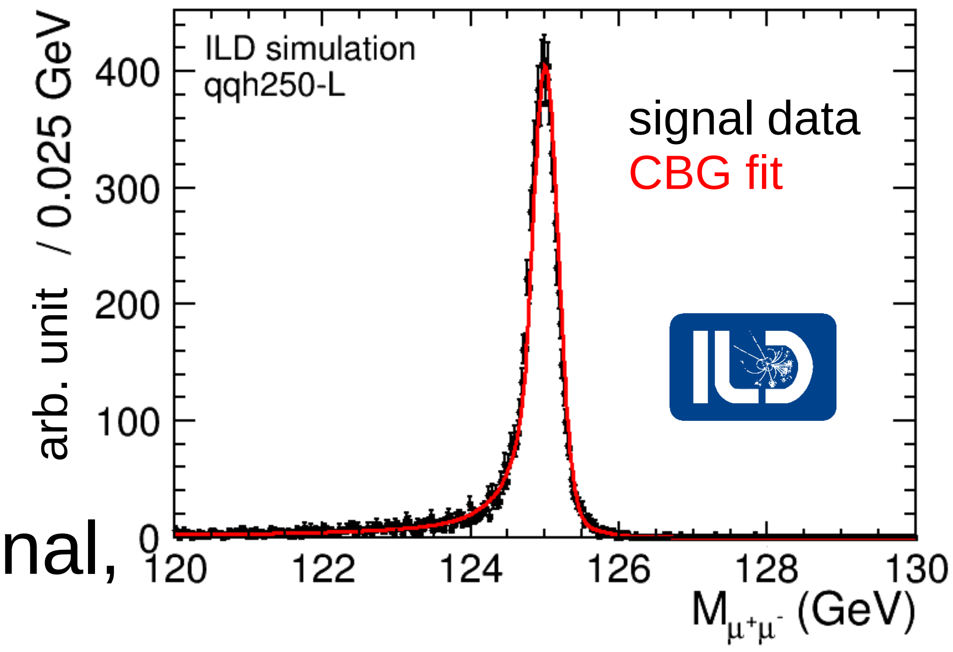


$q\bar{q}h$ channel @ 250 GeV

Brief Summary of Analysis

- MC samples are fully-simulated with Geant4
- Realistic reconstruction algorithm
- 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
   - Crystal Ball + Gaussian (CBG) for signal, 1st order polynomial for background



Results

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

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

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

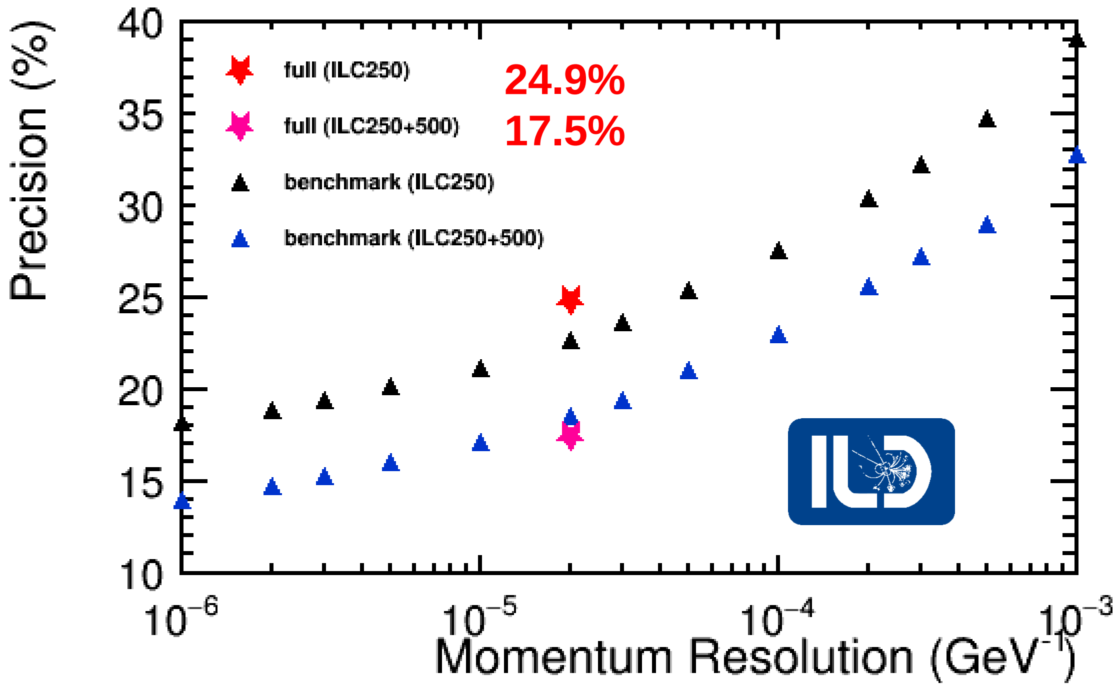
500 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	43.8%	37.9%
R	54.2%	108.8%

signal selection efficiency ~ 50%
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

$M_{\mu^+\mu^-}$ is most important for this analysis
---> momentum resolution (σ_{1/p_T}) has a crucial role



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

Summary

- Precise and model-independent measurements of Higgs boson are possible at the ILC
- Studied $h \rightarrow \mu^{+}\mu^{-}$ 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; reaching ILD goal is important

#ILCsupporters

BACKUP

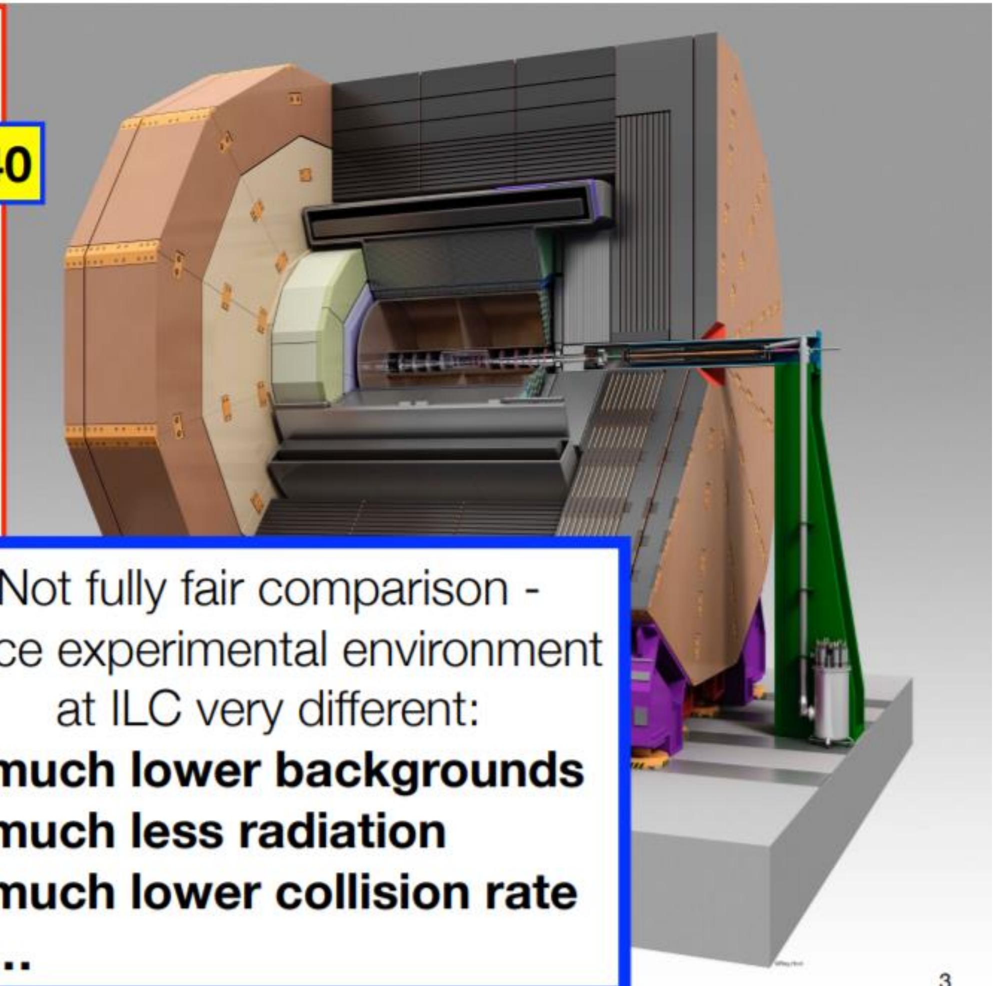
The ILD Concept

From key requirements from **physics**:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
  ≈ CMS / 40
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$
  ≈ CMS / 4
- **jet energy resolution** 3-4%
  ($H \rightarrow$ invisible)
  ≈ ATLAS / 2
- **hermeticity** θ_{min} = 5 mrad
  ($H \rightarrow$ invis, BSM)
  ≈ ATLAS / 3

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Not fully fair comparison - since experimental environment at ILC very different:

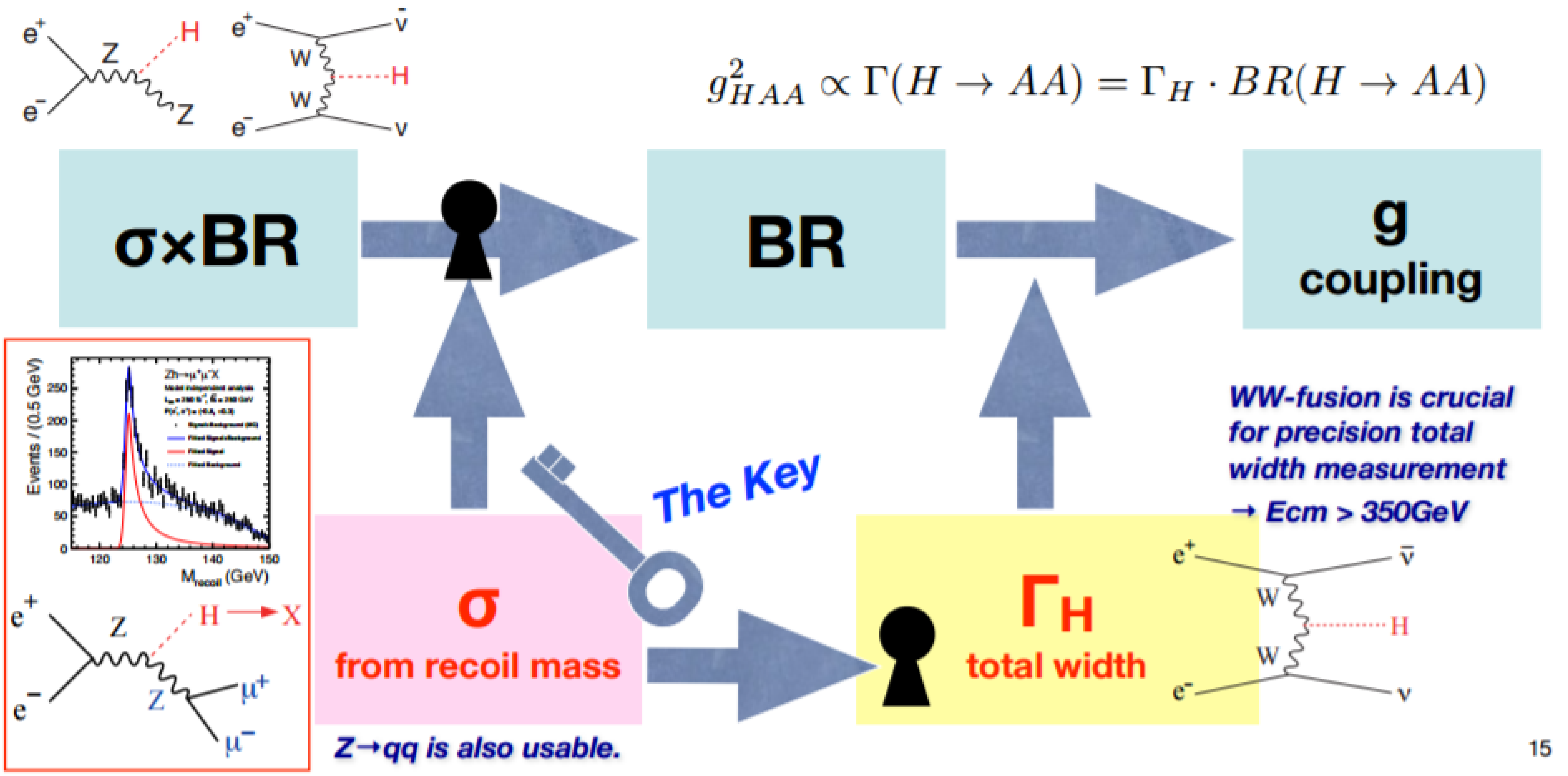
- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**
- **...**

Key Point

K. Fujii's talk, LCWS2014

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

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



Single Higgs Production

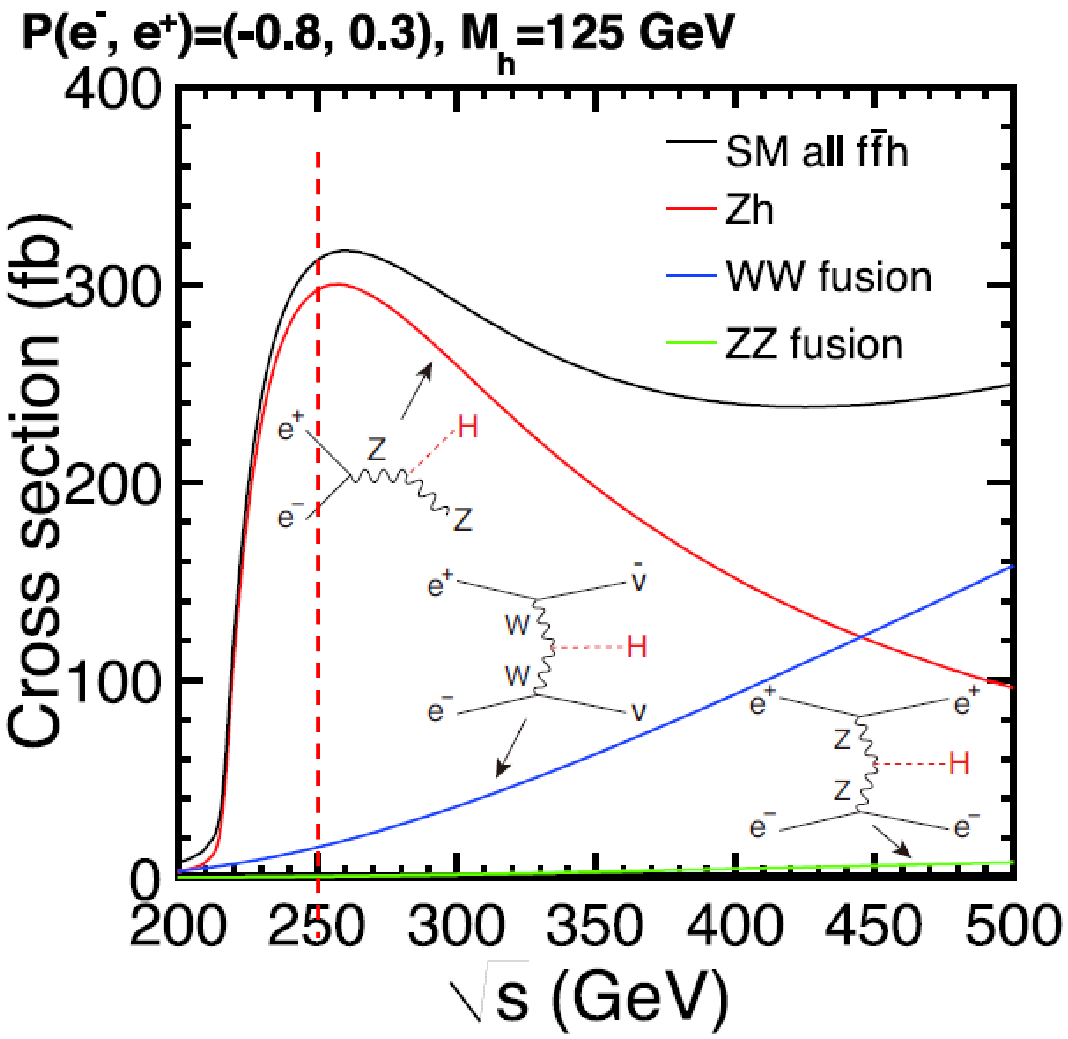
$\sqrt{s}$ = 250 GeV

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)

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

Analysis Settings

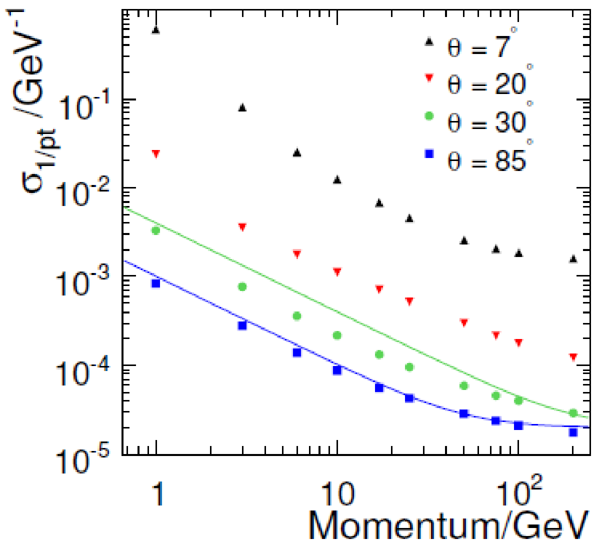
- Geant4-based full detector simulation with ILD model
- Included all available SM backgrounds
  - (for specialist) Used DBD-world samples
  - Performed toy MC in the end to estimate the precision

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

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 $M_{\mu^+\mu^-}^{\text{smear}}$ in toy MC

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



arXiv:1306.6329