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

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This talk is based on our paper
EPJC **80**:1186 (2020)

CLUSTER OF EXCELLENCE
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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Introduction

- Higgs boson has been discovered at the LHC, but we still have many open questions.
  - Higgs properties, dark matter, BSM, ...
  - In the European particle physics strategy, it is mentioned that an e^+e^- Higgs factory is the highest-priority next collider. One obvious mission is to understand full properties of Higgs boson.
- This talk will focus on coupling between Higgs and muon.
- ILC, CLIC, FCC-ee, CEPC, ...
  - This talk will focus on ILC which already published technical design report.

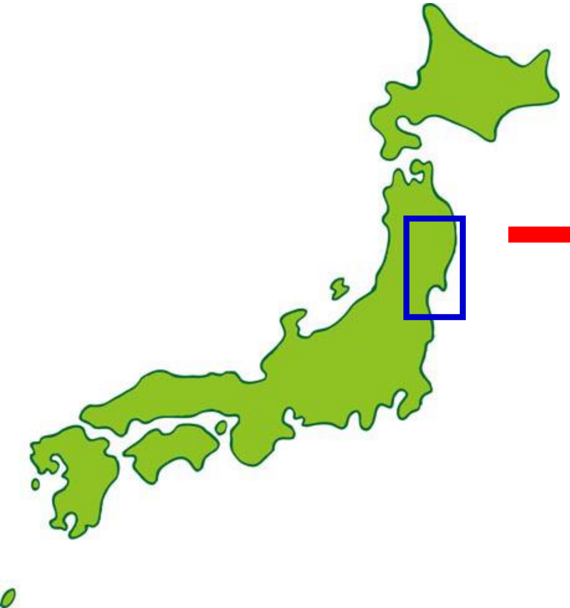
Why $H \to \mu^+\mu^-$ at ILC?

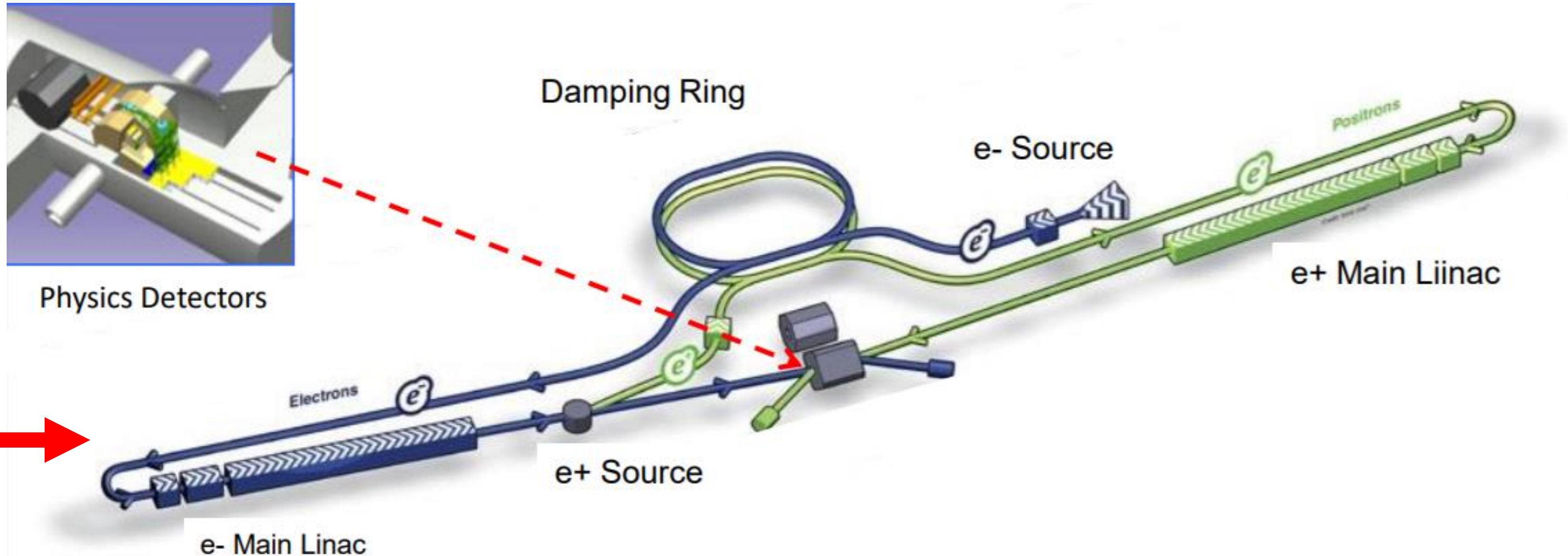
- Can be used for testing:
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd leptons (κ_μ/κ_τ) and 2nd lepton/quark (κ_μ/κ_c)

LHC	ILC (e^+e^- collider)
$\sigma \times \mathrm{BF}$ measurements	$\sigma \times \mathrm{BF}$ measurements
σ measurement impossible	σ measurement (recoil technique)
model-dependent	highly model-independent

The International Linear Collider (ILC)

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

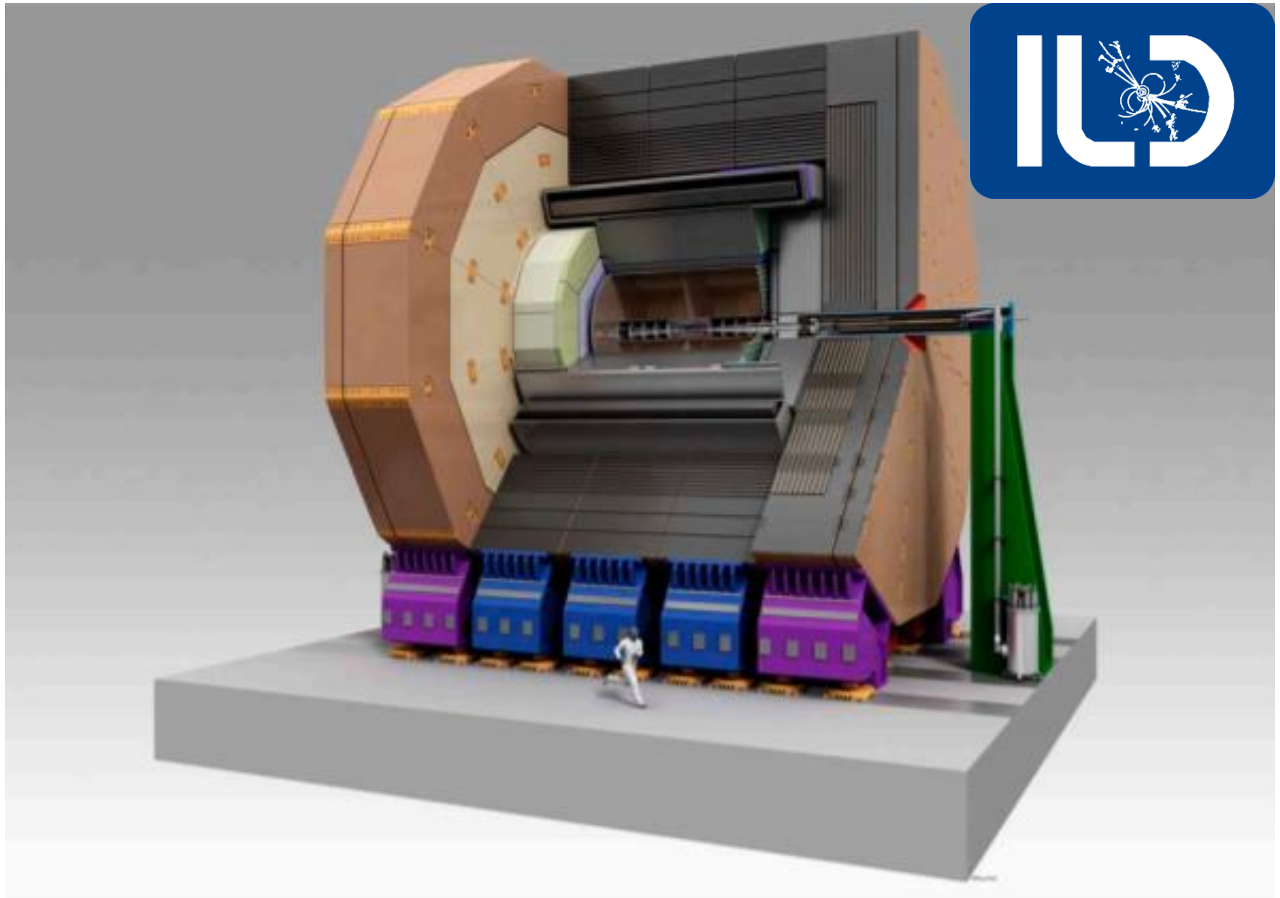




under in-depth consideration by the Japanese government

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
  $\sigma_{r\phi} < 5 \oplus \frac{10}{p\sin^{3/2}\theta}$ μm
- **Momentum resolution**
  $\sigma_{1/p_T} < 2*10^{-5}$ GeV^{-1}
  (@ high P_t)
- Energy resolution
  σ_E/E = 3 - 4%

This Talk: $H \to \mu^+\mu^-$

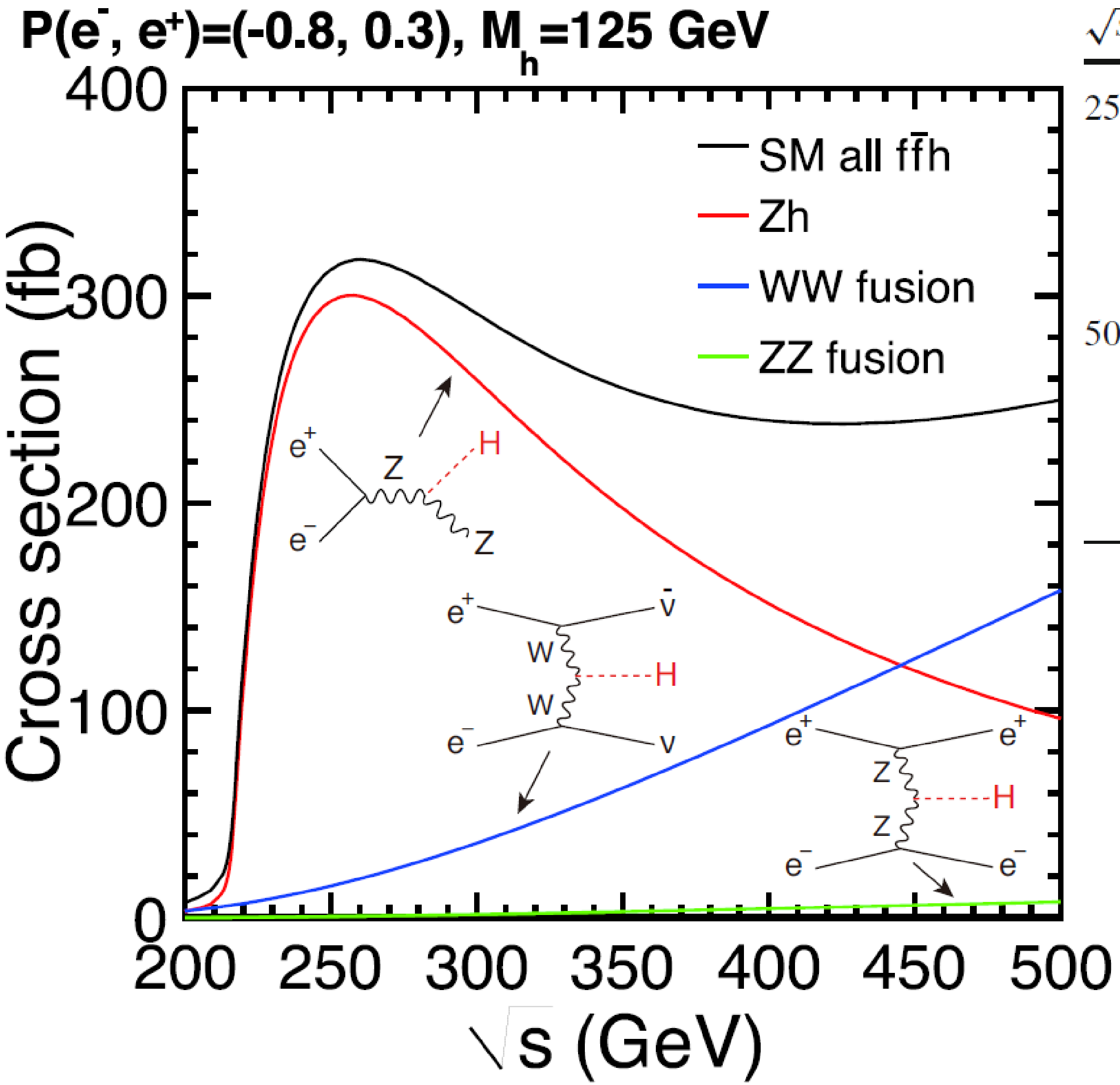
- Challenging: tiny branching fraction
  - BF($H \to \mu^+\mu^-$) = **$2.2*10^{-4}$**
- Previous studies: most of them performed at E_{CM} = 1 TeV or higher (next page)
- This study: E_{CM} = 250 GeV & 500 GeV, $q\bar{q}H$ and $\nu\bar{\nu}H$ final states, L/R beam polarization; 2*2*2 = 8 channels

Previous Studies

Everything performed at >= 1 TeV, or not realistic

Reference	**E_{CM}**	**beam pol.** $P(e^-, e^+)$	$\int Ldt$	$\frac{\Delta(\sigma \times \mathrm{BF})}{(\sigma \times \mathrm{BF})}$	**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**

$H \to \mu^+\mu^-$ Events at the ILC



$\sqrt{s}$ (GeV)	Process	Beam pol.	Abbreviation	$\int L dt$ (ab^{-1})	N_{signal}
250	$q\bar{q}H$	L	qqH250-L	0.9	41.1
		R	qqH250-R	0.9	28.1
	$\nu\bar{\nu}H$	L	nnH250-L	0.9	15.0
		R	nnH250-R	0.9	8.4
500	$q\bar{q}H$	L	qqH500-L	1.6	24.6
		R	qqH500-R	1.6	16.5
	$\nu\bar{\nu}H$	L	nnH500-L	1.6	57.5
		R	nnH500-R	1.6	7.9

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

in total **~200** events at ILC
cf: $O(10^4)$ at HL-LHC
already ~1500 events at LHC-Run2

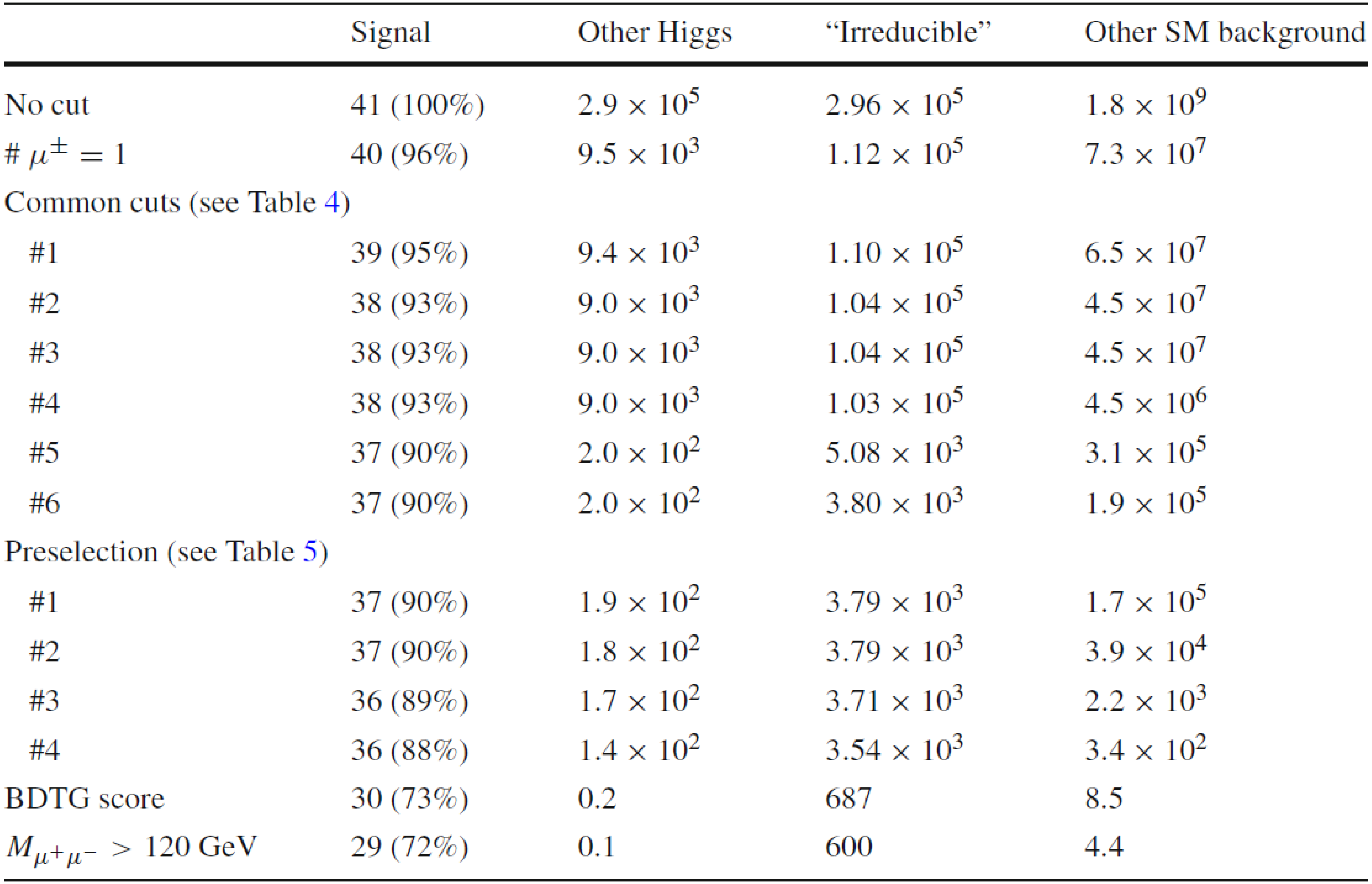
Summary of Analysis

- **Geant4-based full detector simulation** with ILD model
- Included all relevant SM backgrounds
  - Number of total MC events = O(10^7) for each center-of-mass energy
  - (for specialist) Used DBD-world samples
- Event reconstruction and selection (next page)
- Toy MC using $M_{\mu^+\mu^-}$
  - Crystal Ball + Gaussian for signal modeling f_S, first order polynomial (straight line) for background modeling f_B
  - 20000 times pseudo-experiments and fitting with $f \equiv Y_S f_S + Y_B f_B$
  - optimization performed by changing BDTG score cut

Event Selection (example: qqH250-L)

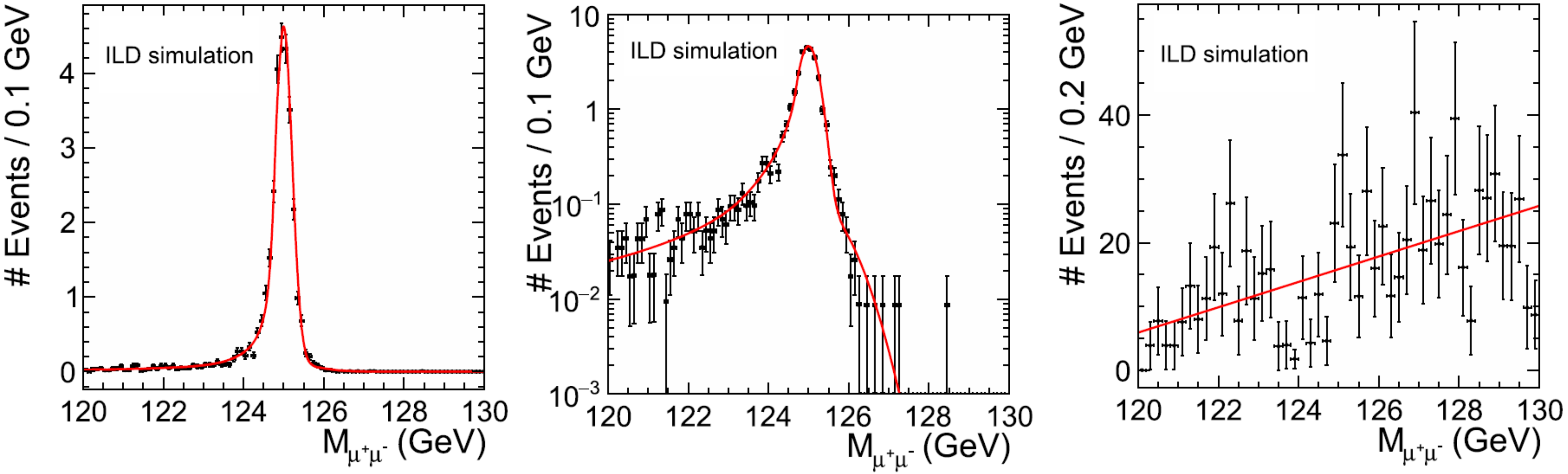
selection for $H \to \mu^+\mu^-$
- impact parameter cut
- di-muon mass cut
- ...

channel specific
- di-jet mass cut
- number of particles
- ...



	Signal	Other Higgs	"Irreducible"	Other SM background
No cut	41 (100%)	2.9×10^5	2.96×10^5	1.8×10^9
$\# \mu^\pm = 1$	40 (96%)	9.5×10^3	1.12×10^5	7.3×10^7
Common cuts (see Table 4)				
#1	39 (95%)	9.4×10^3	1.10×10^5	6.5×10^7
#2	38 (93%)	9.0×10^3	1.04×10^5	4.5×10^7
#3	38 (93%)	9.0×10^3	1.04×10^5	4.5×10^7
#4	38 (93%)	9.0×10^3	1.03×10^5	4.5×10^6
#5	37 (90%)	2.0×10^2	5.08×10^3	3.1×10^5
#6	37 (90%)	2.0×10^2	3.80×10^3	1.9×10^5
Preselection (see Table 5)				
#1	37 (90%)	1.9×10^2	3.79×10^3	1.7×10^5
#2	37 (90%)	1.8×10^2	3.79×10^3	3.9×10^4
#3	36 (89%)	1.7×10^2	3.71×10^3	2.2×10^3
#4	36 (88%)	1.4×10^2	3.54×10^3	3.4×10^2
BDTG score	30 (73%)	0.2	687	8.5
$M_{\mu^+\mu^-} > 120$ GeV	29 (72%)	0.1	600	4.4

Example of Modeling (nnH500-L)

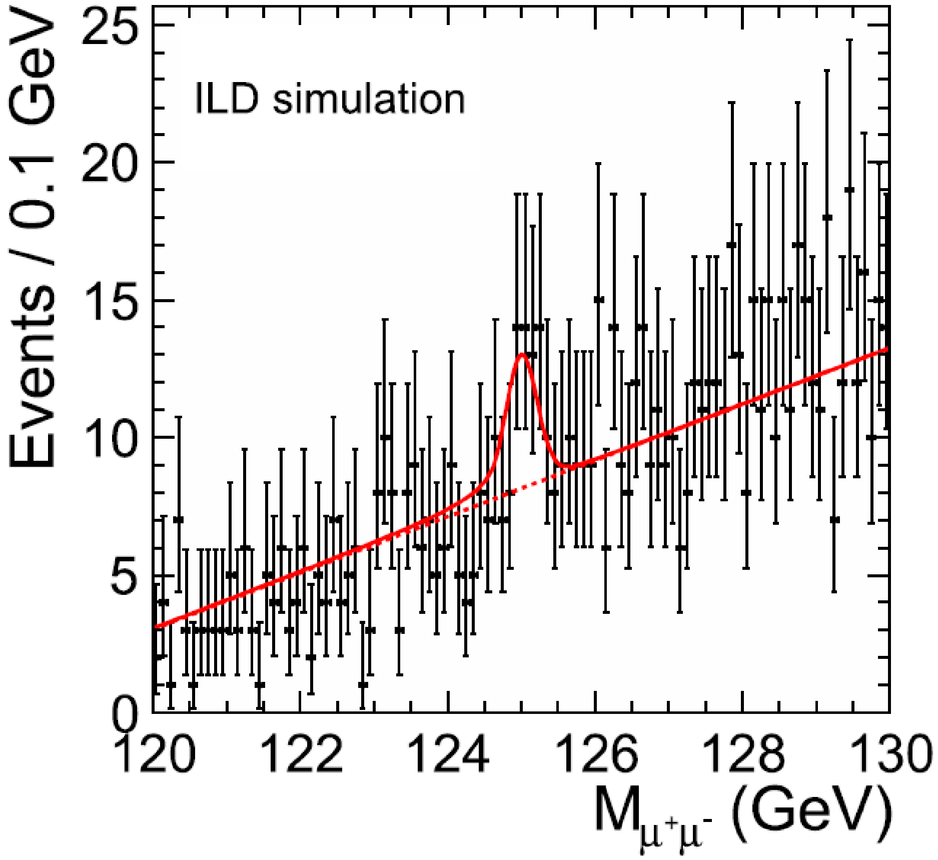


(a) Signal with result of f_S fit. **(b)** Logarithmic plot of (a). **(c)** Background with result of f_B fit.

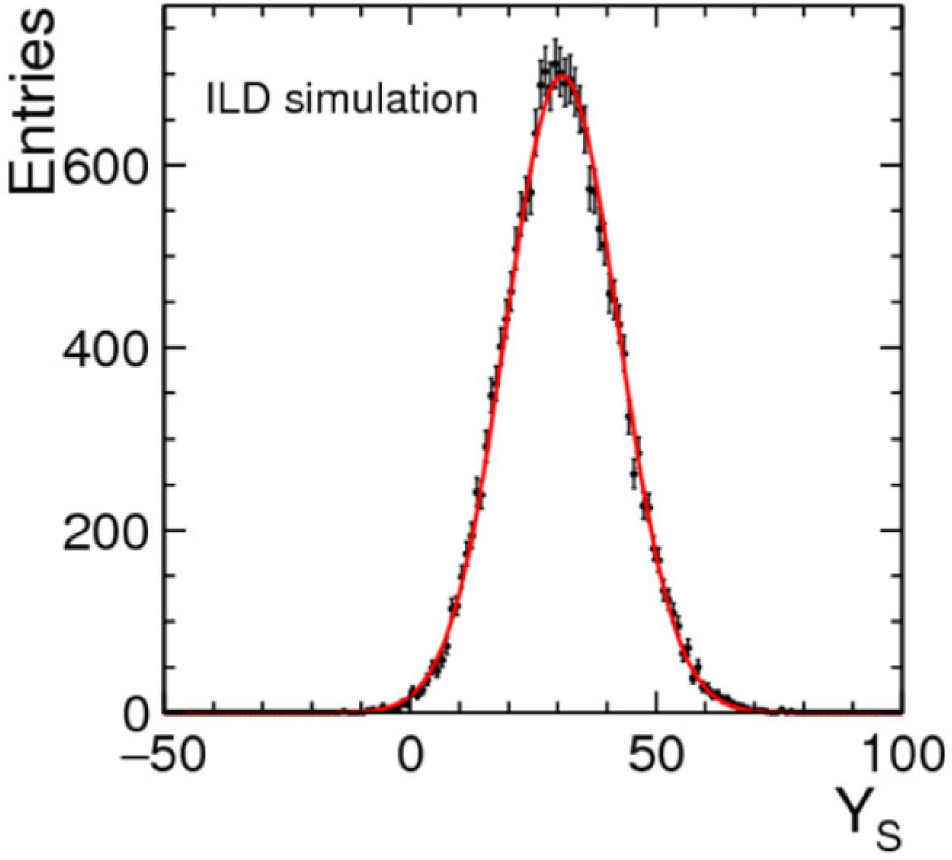
f_S: Crystal Ball + Gaussian

f_B: straight line

Example of Pseudo-Experiment and Extracting Precision (nnH500-L)

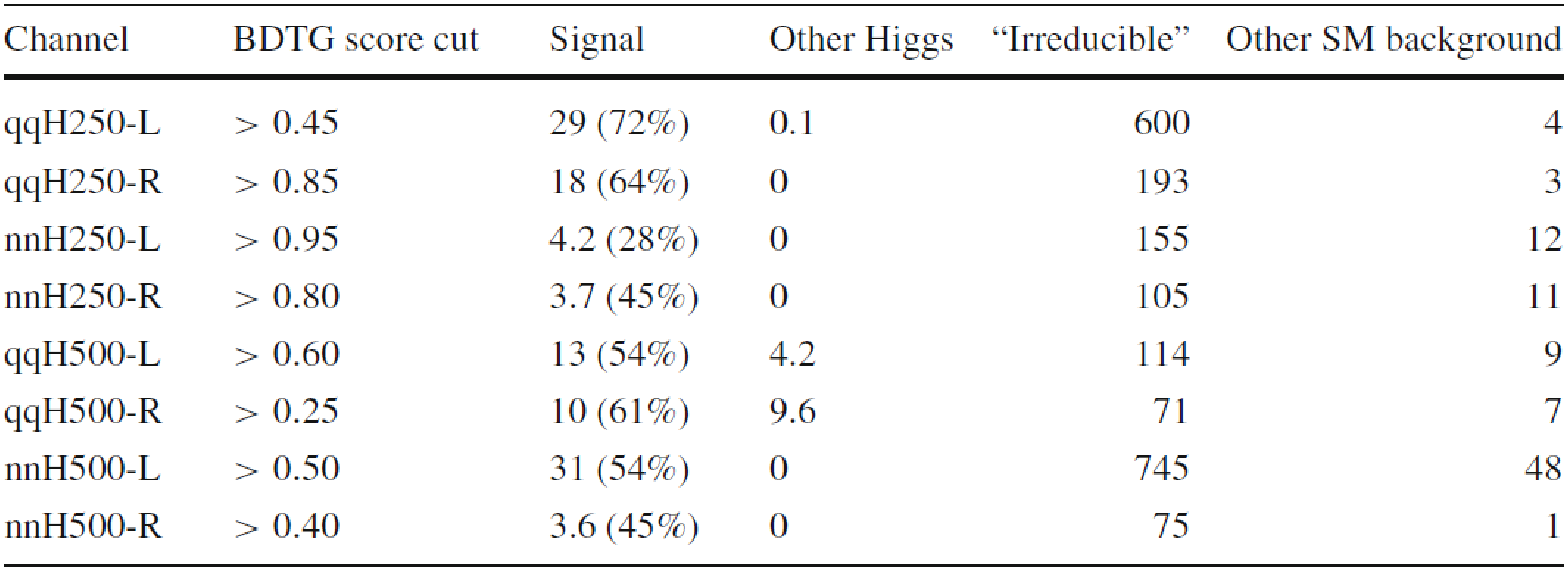


(a) Example of one pseudo-experiment.



(b) Distribution of yield of signal events Y_S from 2×10^4 pseudo-experiments.

Results & Discussion (1)



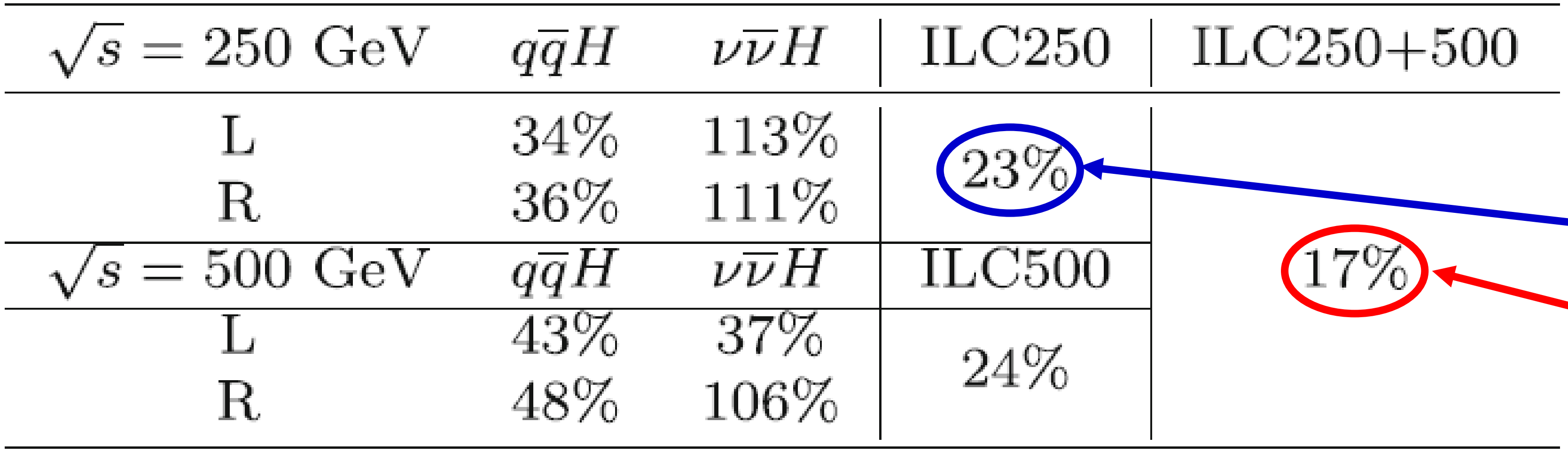
Channel	BDTG score cut	Signal	Other Higgs	“Irreducible”	Other SM background
qqH250-L	> 0.45	29 (72%)	0.1	600	4
qqH250-R	> 0.85	18 (64%)	0	193	3
nnH250-L	> 0.95	4.2 (28%)	0	155	12
nnH250-R	> 0.80	3.7 (45%)	0	105	11
qqH500-L	> 0.60	13 (54%)	4.2	114	9
qqH500-R	> 0.25	10 (61%)	9.6	71	7
nnH500-L	> 0.50	31 (54%)	0	745	48
nnH500-R	> 0.40	3.6 (45%)	0	75	1

Signal selection efficiency
~50% in most channel

S/B ratio
around 1/10 - 1/20 in most channel
only due to irreducible background

irreducible background
$qq\mu^+\mu^-$ for qqH channel
$\nu\nu\mu^+\mu^-$ for nnH channel
(almost no τ events,
purely irreducible)

Results & Discussion (2)



$\sqrt{s} = 250$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC250	ILC250+500
L	34%	113%	23%	17%
R	36%	111%		
$\sqrt{s} = 500$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC500	
L	43%	37%	24%	
R	48%	106%		

Expected precisions on BF($H \to \mu^+\mu^-$)

ILC250: 23%

ILC250+500: 17%

2 ab^{-1} @ 250 GeV

4 ab^{-1} @ 500 GeV

Comparison

ILC

- 17% precision on BF($H \to \mu^+\mu^-$) with **~200** events
- highly model-independent measurement
- will reach 11% precision up to ILC1000 (arXiv:1603.04718, 1506.07830)

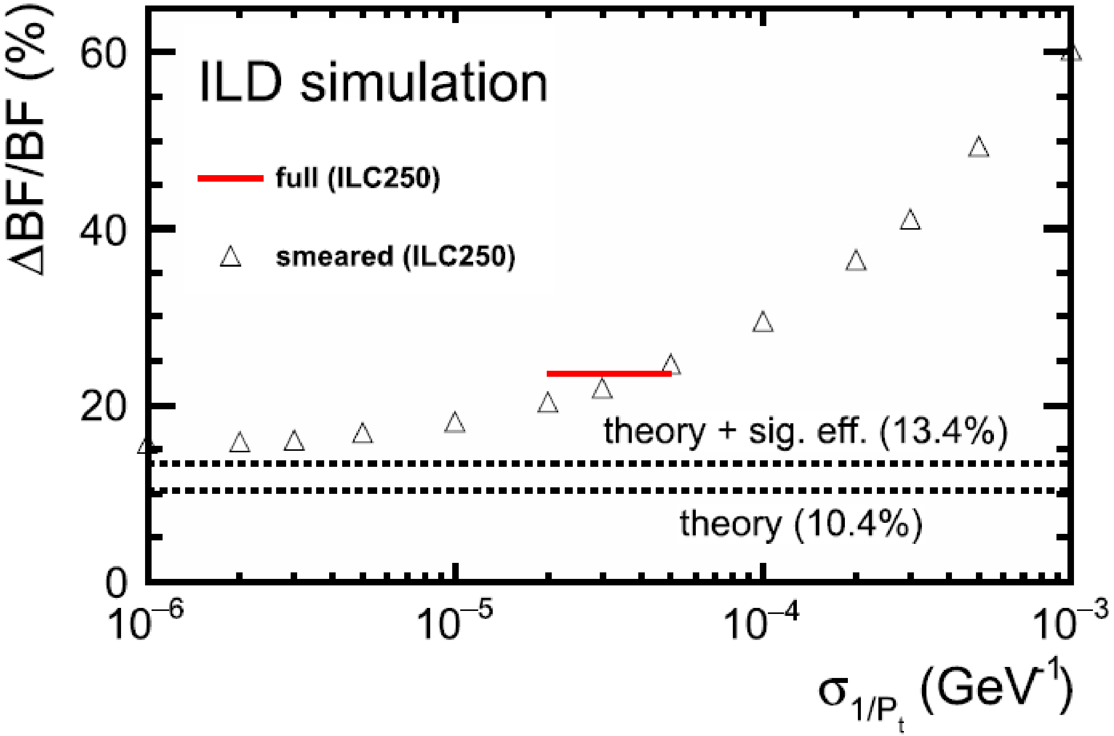
HL-LHC

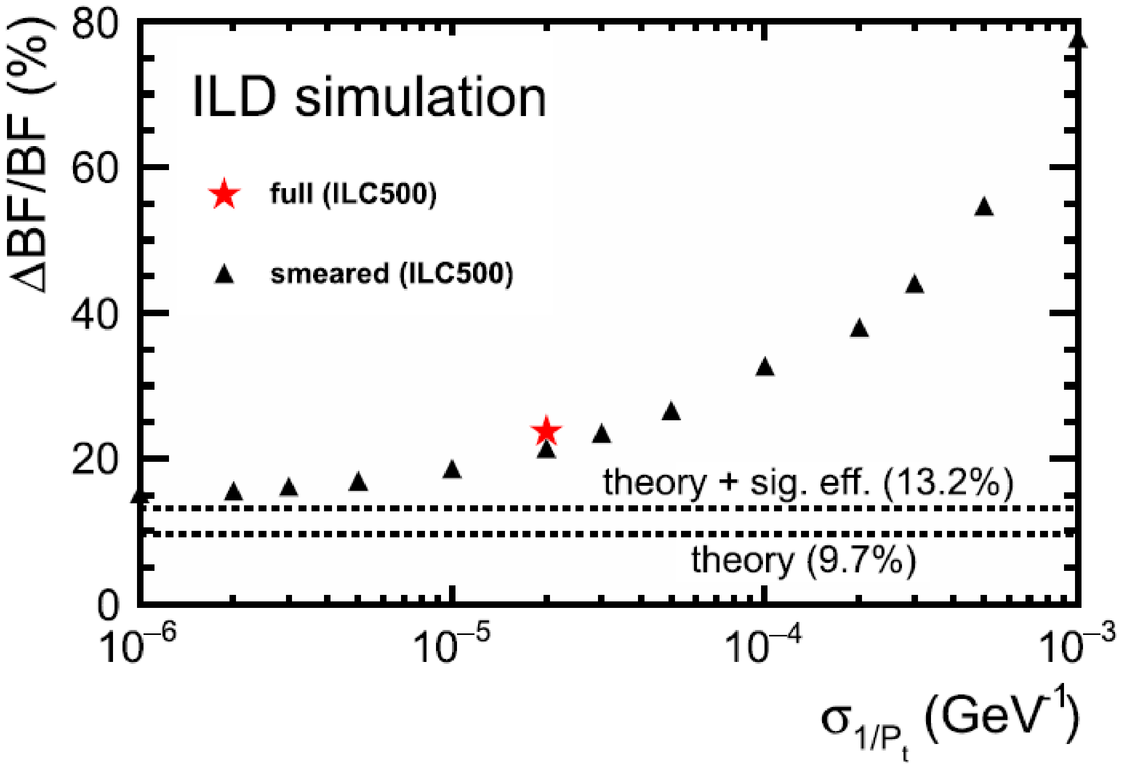
- 13%/10% precision on signal strength with ATLAS/CMS HL-LHC run, **$\sim 10^4$** events
- extraction of BF($H \to \mu^+\mu^-$) is model-dependent

Impact of Transverse Momentum Resolution

- Measuring muon track has a crucial role for this analysis because $M_{\mu^+\mu^-}$ is the most important variable to distinguish signal and background.
- This point can be discussed with transverse momentum resolution σ_{1/P_t}.
- study performed by smearing
  - assume constant number of σ_{1/P_t} (from 10^{-3} to 10^{-6} GeV^{-1}) with a Gaussian random number (ignore dependencies of angle/momentum), apply smearing to MC truth momentum of $H \rightarrow \mu^+\mu^-$ candidate

Impact of σ_{1/P_t}: ILC250 & ILC500



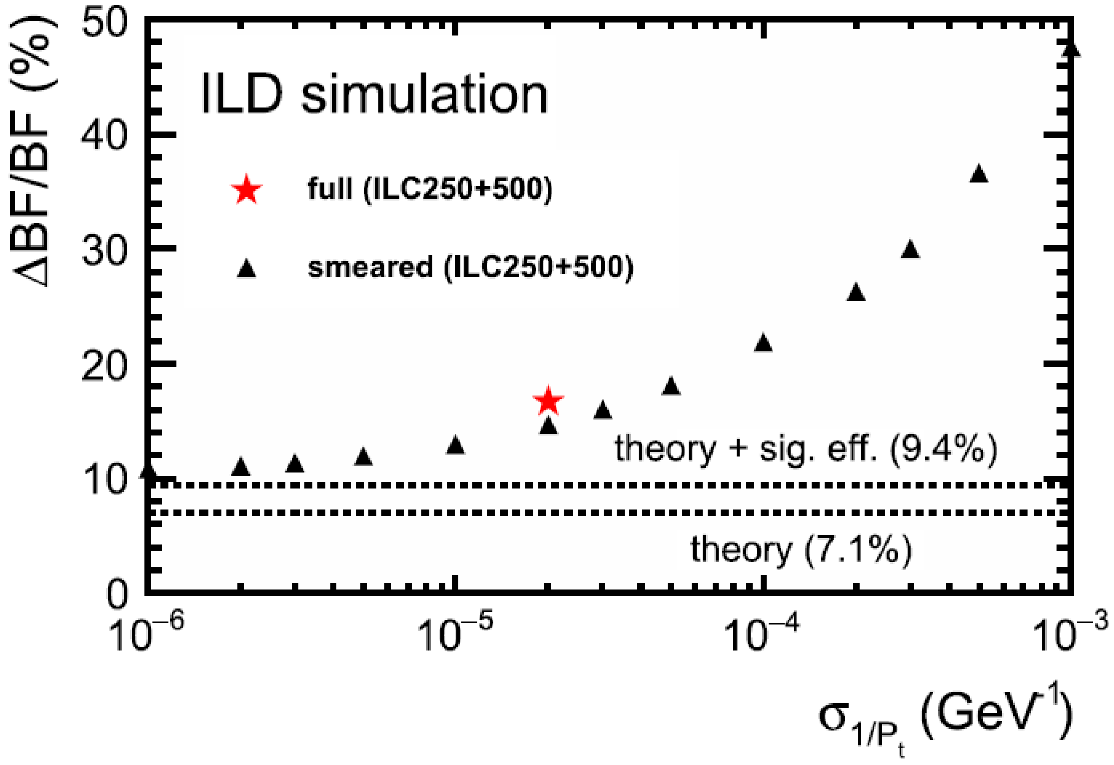


Very important to achieve ILD goal ($\sigma_{1/P_t} \lesssim 2 \times 10^{-5}$ GeV^{-1})

worse σ_{1/P_t} : precision gets drastically worse

better σ_{1/P_t} : will reach ~15% precision, realistically very difficult to develop

Combined Results & Comparison with CLIC



Eur. Phys. J. C (2015) 75:515

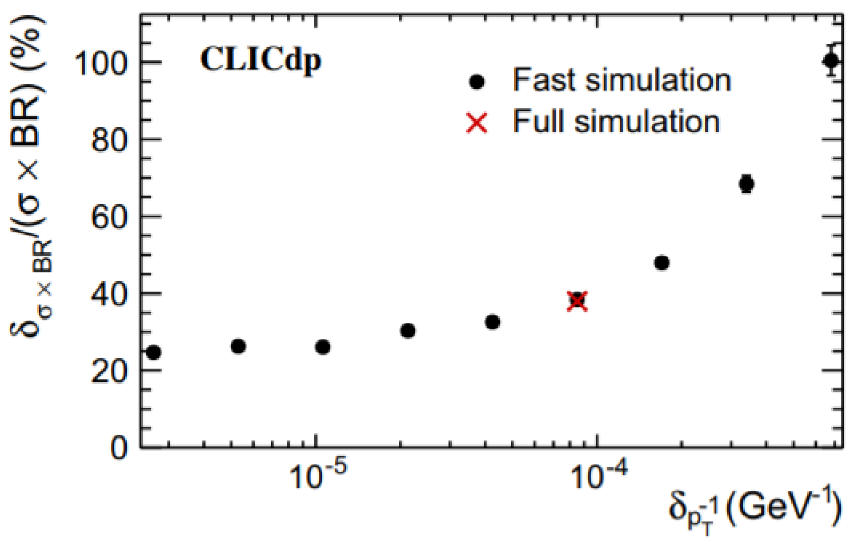


Fig. 11 Dependence of the relative statistical uncertainty of the $\sigma(H\nu\bar{\nu}) \times BR(H \rightarrow \mu^+\mu^-)$ on the transverse momentum resolution, δ_{1/p_T}, averaged over the signal sample in the whole detector

ILC: 250/500 GeV, two final states,
L/R beam pol. (combined)

CLIC: 1.4 TeV, one final state,
no beam pol.

Different setups, the same conclusions.

Summary

- Precise measurements and extracting absolute Higgs couplings are possible at the ILC in a highly model-independent way
- Comprehensive full simulation study of $H \rightarrow \mu^{+}\mu^{-}$ with E_{CM} = 250/500 GeV at the ILC
    - Can reach the combined precision of 17% for BF($H \rightarrow \mu^{+}\mu^{-}$)
- Studied the impact of transverse momentum resolution σ_{1/P_t}
    - Important to achieve the ILD goal for σ_{1/P_t}

BACKUP

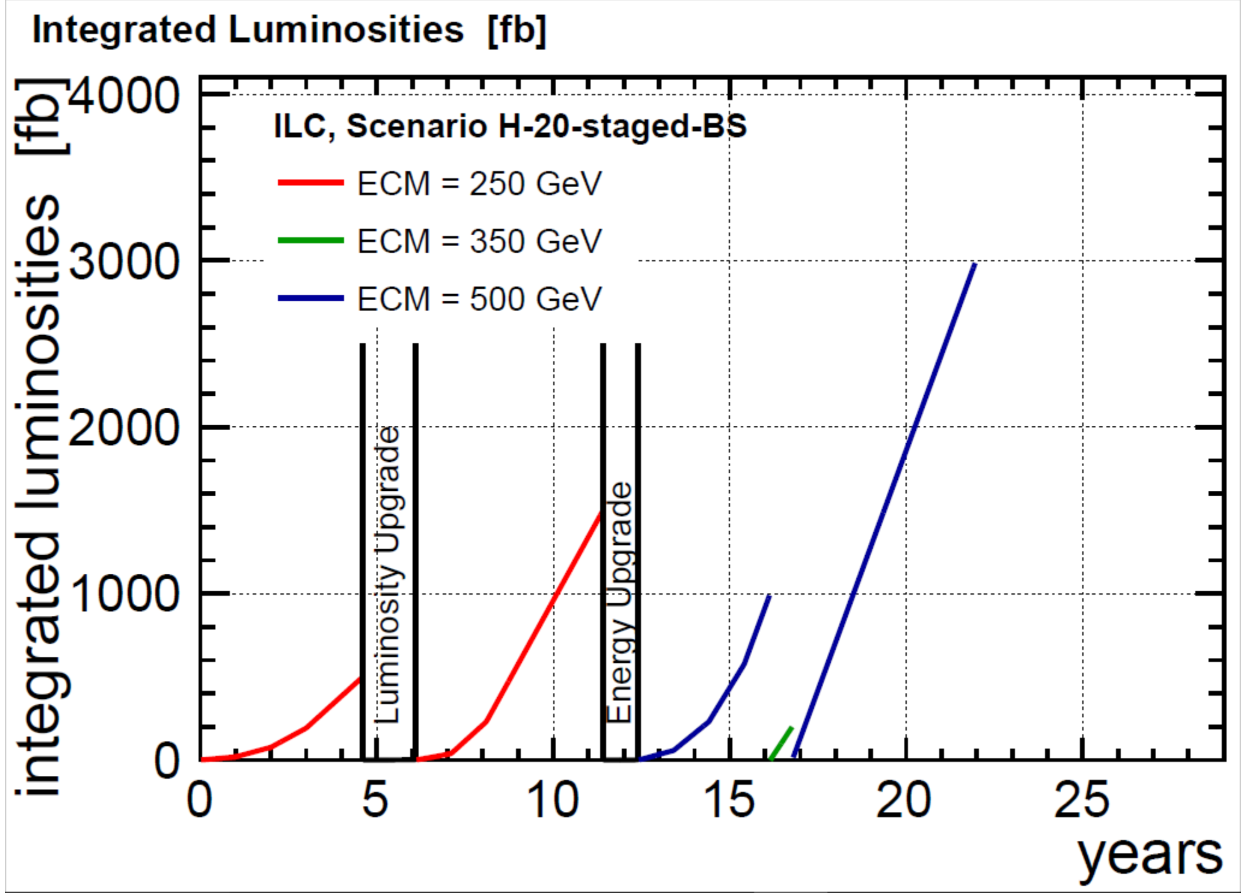
arXiv:1710.07621 [hep-ex]

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