

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

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CLUSTER OF EXCELLENCE  
QUANTUM UNIVERSE  
**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

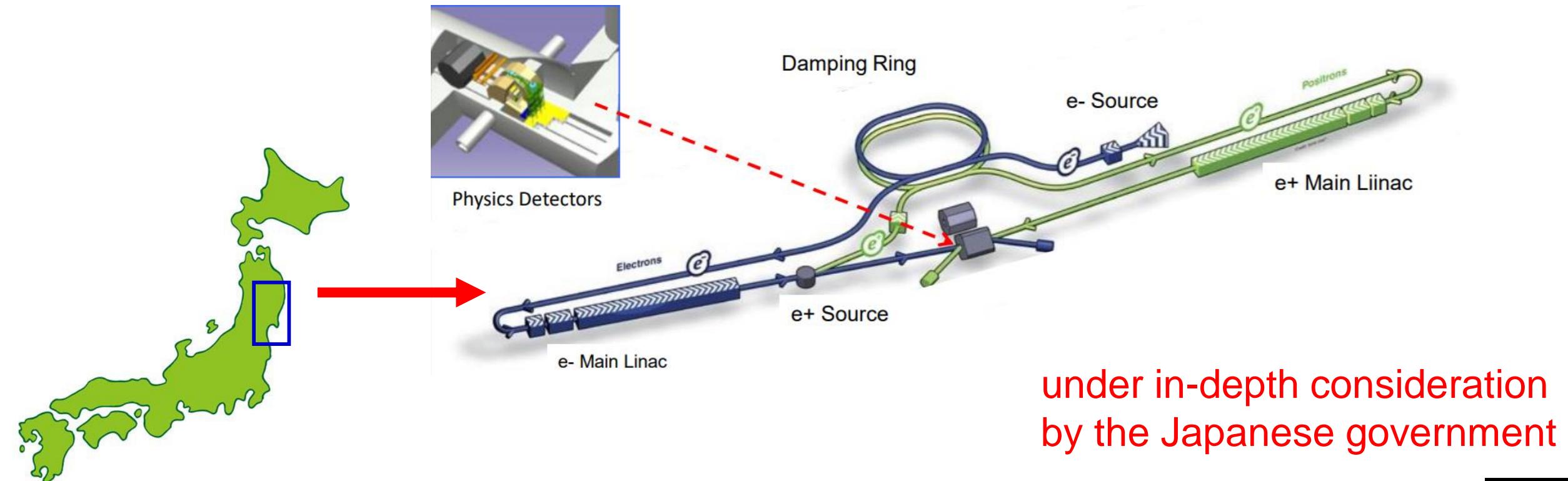
One example: Supersymmetry

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

arXiv:1306.6352

# The International Linear Collider (ILC)

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



# Key Point

LHC

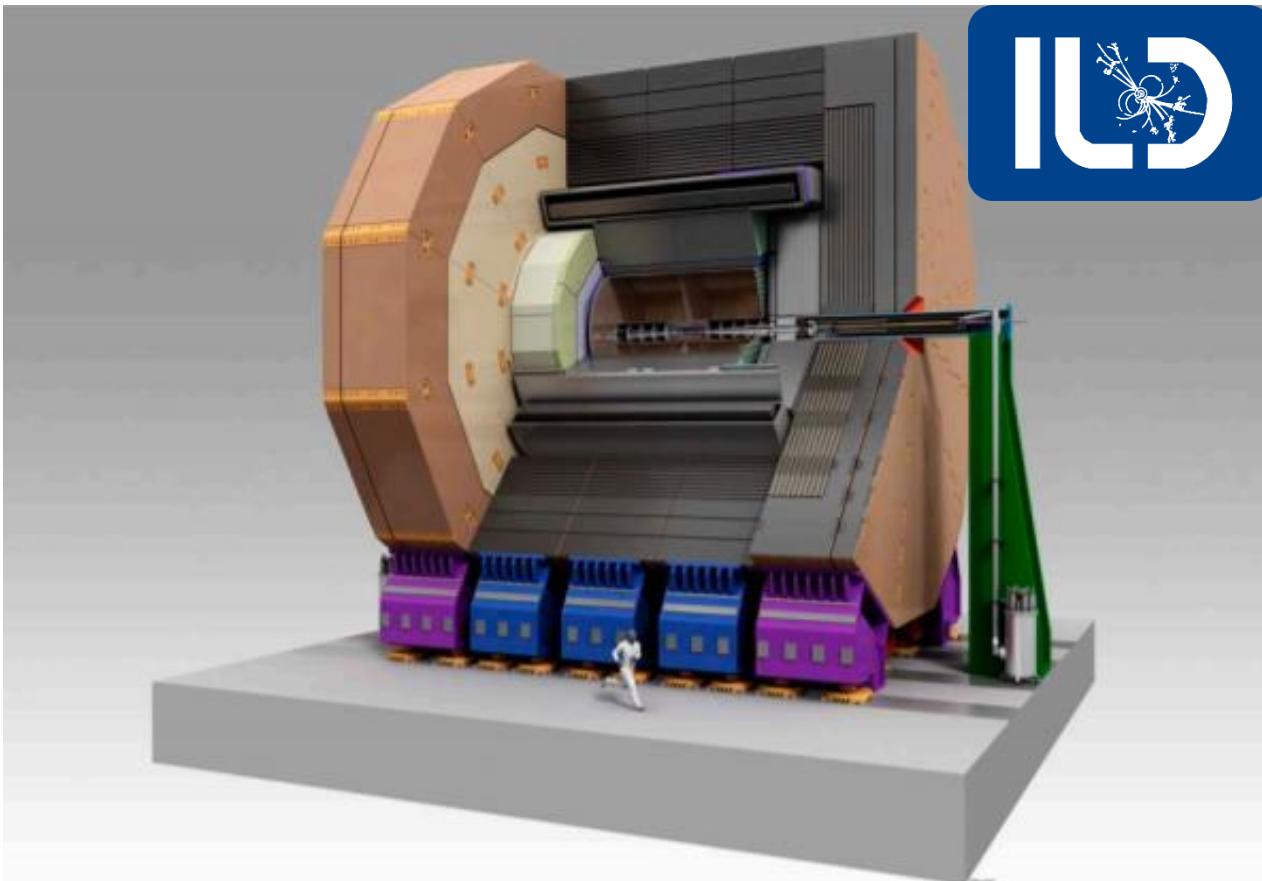
$\sigma \times \text{BR}$  measurements  
 $\sigma$  measurement impossible  
model-dependent

ILC

$\sigma \times \text{BR}$  measurements  
 $\sigma$  measurement (recoil technique)  
highly model-independent

# 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:

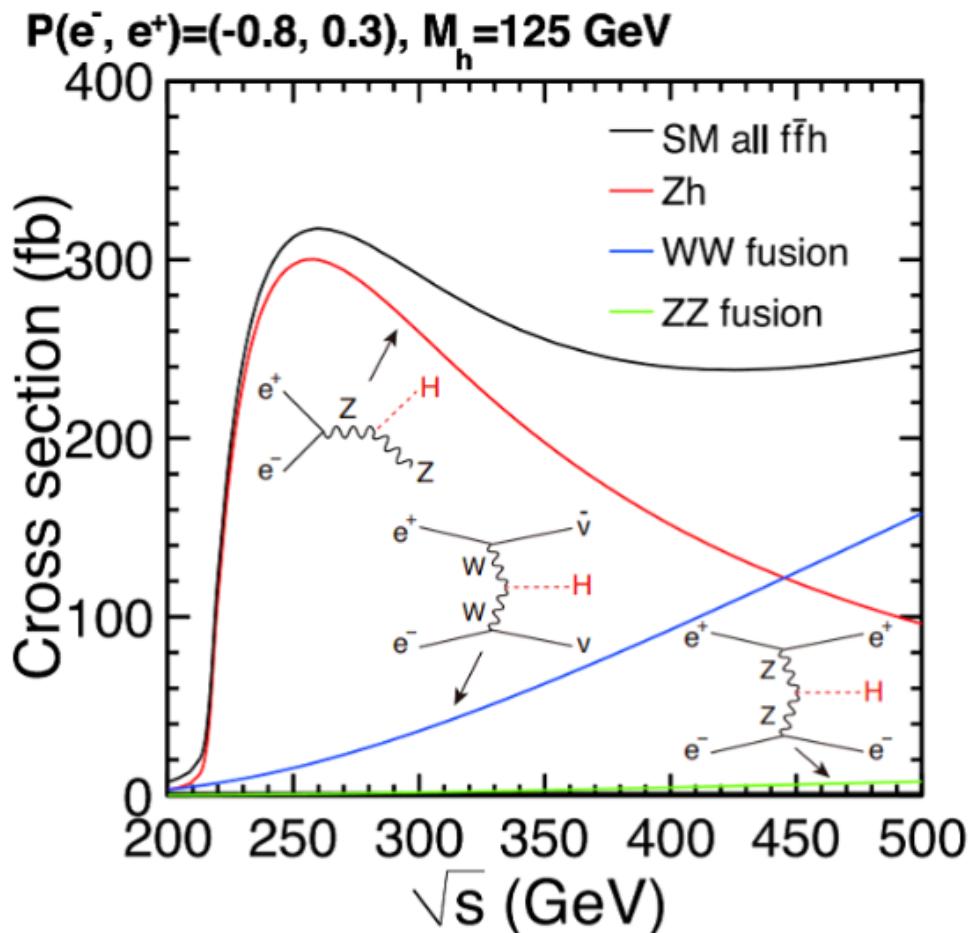
- Impact parameter resolution  
 $\sigma_{r\phi} < 5 \oplus \frac{10}{ps\sin^{3/2}\theta} \mu\text{m}$
- **Momentum resolution**  
 $\sigma_{1/p_T} < 2 \cdot 10^{-5} \text{ GeV}^{-1}$
- Energy resolution  
 $\sigma_E/E = 3 - 4\%$

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

- Can be used for testing:
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd leptons ( $\kappa_\mu/\kappa_\tau$ ) and 2nd lepton/quark ( $\kappa_\mu/\kappa_c$ )
- Challenging: tiny branching ratio ( $\text{BR}(h \rightarrow \mu^+ \mu^-) = \textcolor{red}{2.2*10^{-4}}$ )
- Previous studies: most of them performed at 1 TeV or higher
- This study: 250 GeV & 500 GeV,  $q\bar{q}h$  and  $\nu\bar{\nu}h$  final states, L/R beam polarization;  $2*2*2 = 8$  channels

# $h \rightarrow \mu^+ \mu^-$ Events at the ILC

Table 2: The expected number of signal events  $N_{\text{signal}}$  for each channel, where  $\int Ldt$  is the integrated luminosity based on the running scenario [16–18].



channel	$\int Ldt (\text{ab}^{-1})$	$N_{\text{signal}}$
qqh250-L	0.9	41.1
qqh250-R	0.9	28.1
nnh250-L	0.9	15.0
nnh250-R	0.9	8.4
qqh500-L	1.6	24.6
qqh500-R	1.6	16.5
nnh500-L	1.6	57.5
nnh500-R	1.6	7.9

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

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

# Analysis Settings

- **Geant4-based full detector simulation** with ILD model
- Included all available SM backgrounds
  - Number of total MC events =  $O(10^7)$  for each center-of-mass energy
  - (for specialist) Used DBD-world samples

# Summary of Analysis Procedure

- Select  $h \rightarrow \mu^+ \mu^-$  candidate
- Channel-specific reconstruction and preselection
- TMVA (BDTG) analysis
- Toy MC using  $M_{\mu^+ \mu^-}$ 
  - Crystal Ball + Gaussian for signal modeling  $f_S$ , first order polynomial for background modeling  $f_B$
  - 50000 times pseudo-experiments and fitting with  $f \equiv Y_S f_S + Y_B f_B$
  - optimization performed by changing BDTG score cut

# Example of Modeling (qqh250-L)

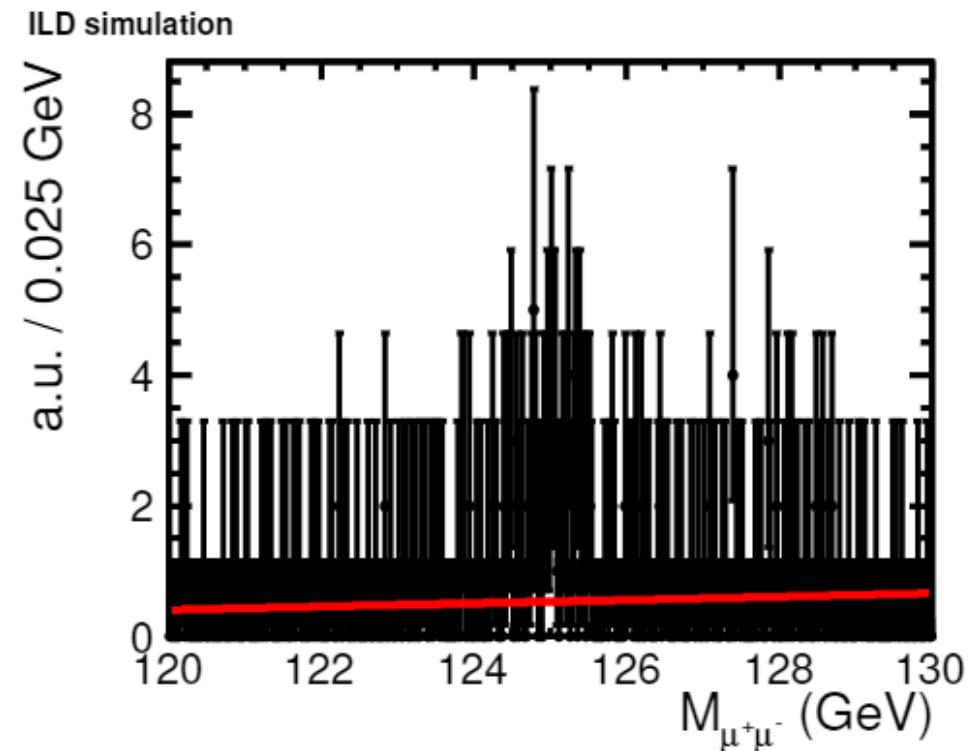
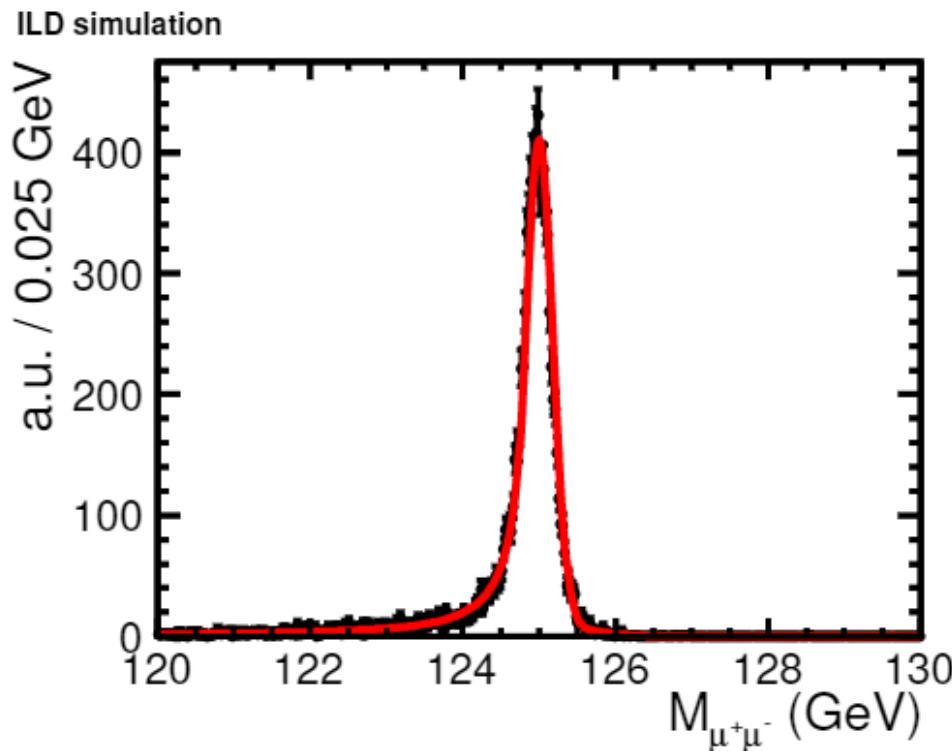


Figure 8: Modeling of  $M_{\mu^+\mu^-}$  distribution after all cuts using modeling functions in qqh250-L. Left: signal process with the fitting result using  $f_s$  in the red curve. Right: background process with the fitting result using  $f_B$  in the red line.

# Example of Pseudo-Experiment and Extracting Precision (qqh250-L)

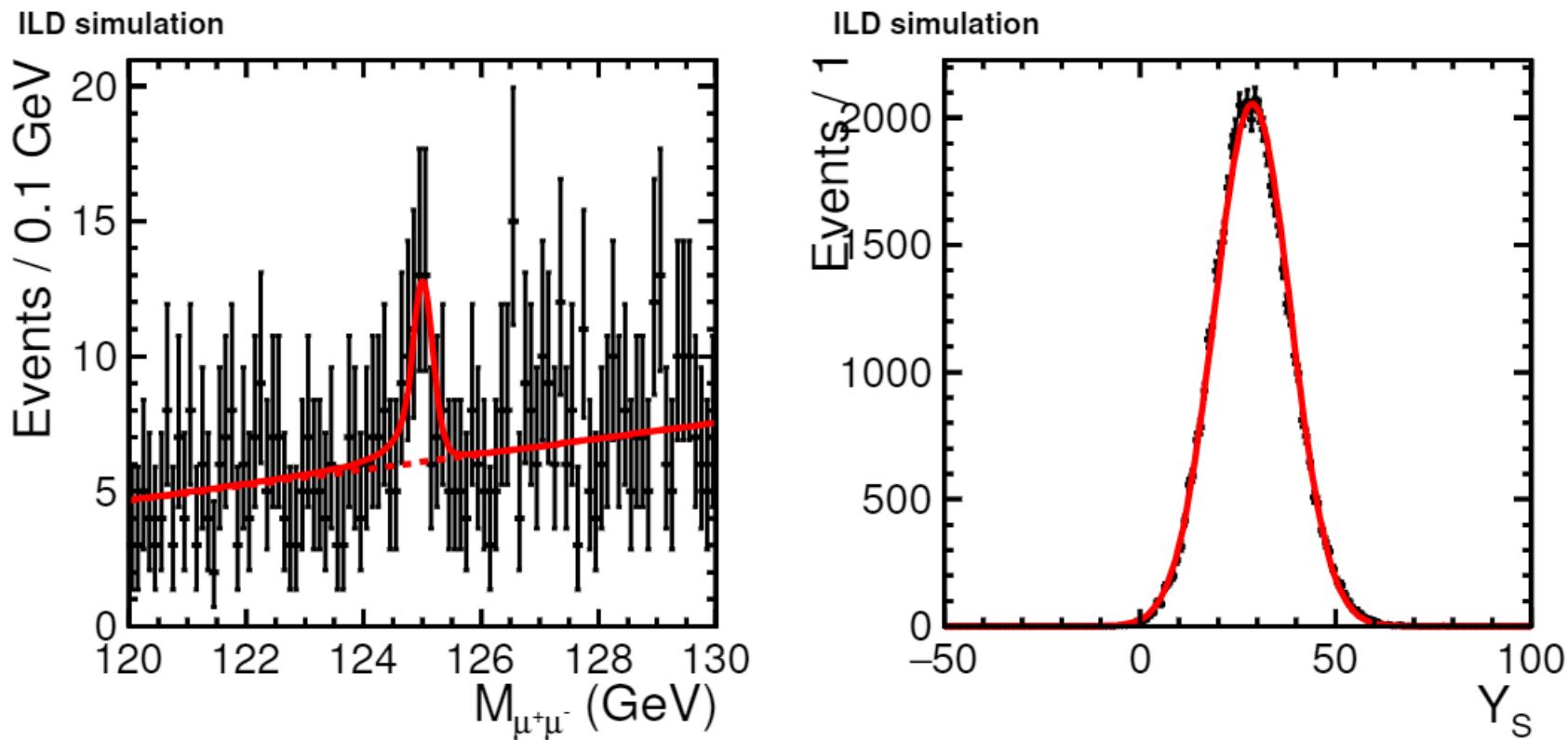


Figure 9: Left: an example of one pseudo-experiment in qqh250-L. Black dots are the pseudo-data. The solid red curve shows the unbinned fitting result using function  $f \equiv Y_S f_S + Y_B f_B$  and the dotted red line shows its background component  $Y_B f_B$ . Right: the  $Y_S$  distribution after 50000 times pseudo-experiments, together with Gaussian fitting in the red curve (qqh250-L).

# Results (1)

Table 10: Similar to Table 8, but after all cuts. The optimum cut on the BDTG score is also summarized.  
Numbers in brackets show the signal selection efficiency.

channel	BDTG score cut	signal	other Higgs	“irreducible”	other SM background
qqh250-L	> 0.50	29 (70.1%)	0.1	570	4
qqh250-R	> 0.90	16 (58.4%)	0	143	4
nnh250-L	> 0.95	4.2 (28.2%)	0	155	12
nnh250-R	> 0.70	4.5 (53.3%)	0	171	14
qqh500-L	> 0.60	13 (53.5%)	4.2	114	9
qqh500-R	> 0.25	10 (60.8%)	9.6	71	7
nnh500-L	> 0.50	31 (53.5%)	0	745	48
nnh500-R	> 0.35	3.8 (48.1%)	0	90	1

Table 11: Summary of the precision on  $\sigma \times \text{BR}(h \rightarrow \mu^+ \mu^-)$ .

$\sqrt{s} = 250 \text{ GeV}$	$q\bar{q}h$	$v\bar{v}h$		
L	34%	117%	<b>ILC250: 24%</b>	<b>ILC250+500: 17%</b>
R	36%	112%		
$\sqrt{s} = 500 \text{ GeV}$	$q\bar{q}h$	$v\bar{v}h$		
L	43%	37%		
R	49%	107%		

# Discussion (1)

	ILC250	ILC250+500
full	24%	17%
theory	10.4%	7.1%
theory + sig. eff.	13.6%	9.5%

factor ~2.4 far from theory (100% sig. eff. and no backgrounds)

factor ~1.7 far from theory + sig. eff. (theory but sig. eff. from full)

## signal selection efficiency

~50% in full

$h \rightarrow \mu^+ \mu^-$  is rare event ---> crucial

## “irreducible” background

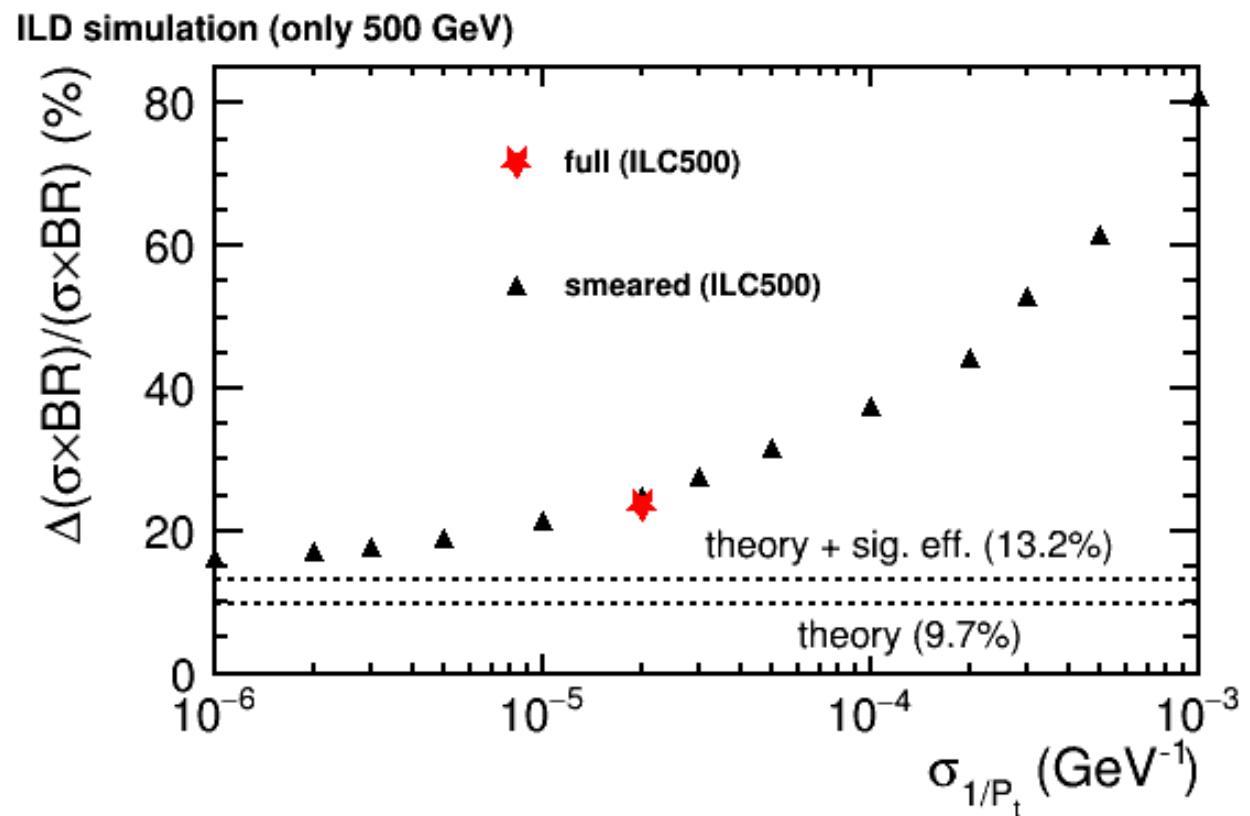
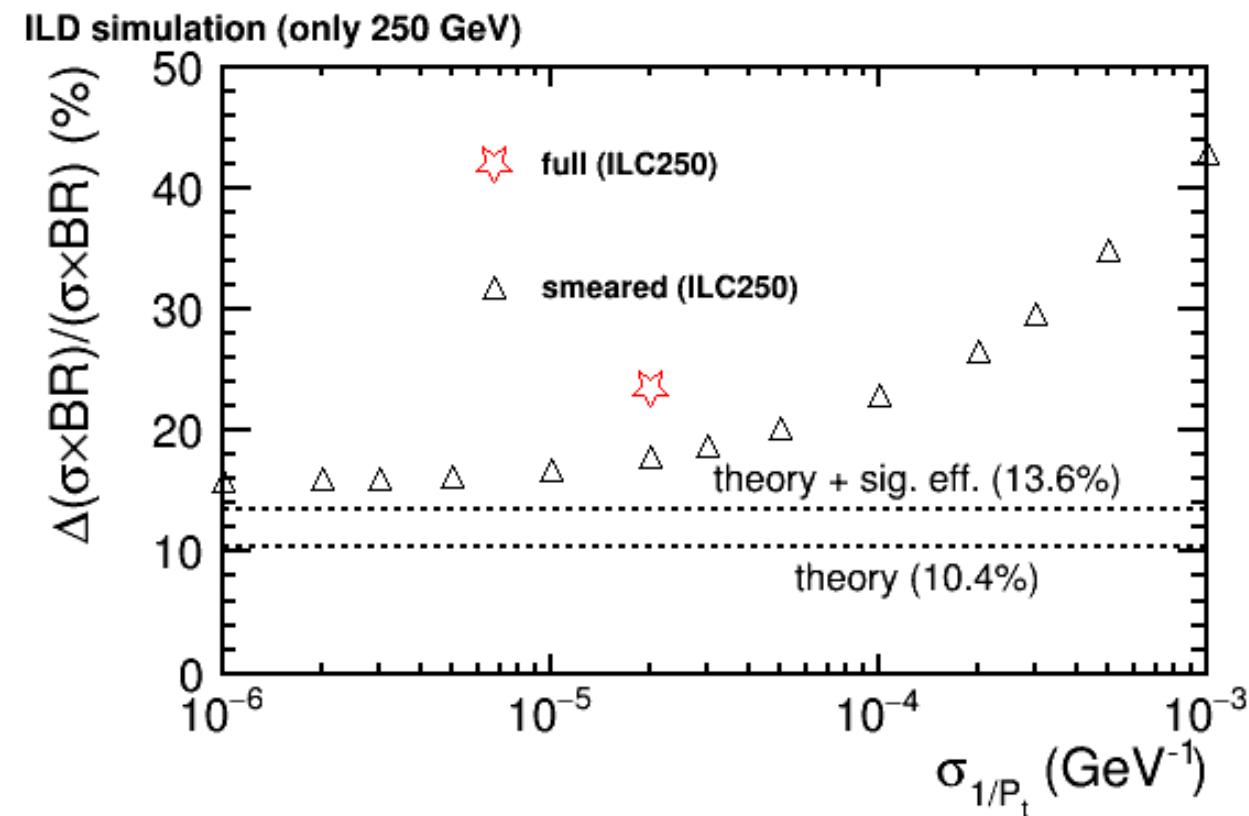
$q\bar{q}\mu^+\mu^-$  for  $q\bar{q}h$ ,  $\nu\nu\mu^+\mu^-$  for  $\nu\bar{\nu}h$

same final state ---> difficult to suppress  
almost no  $\tau$  events ---> “pure” same final state

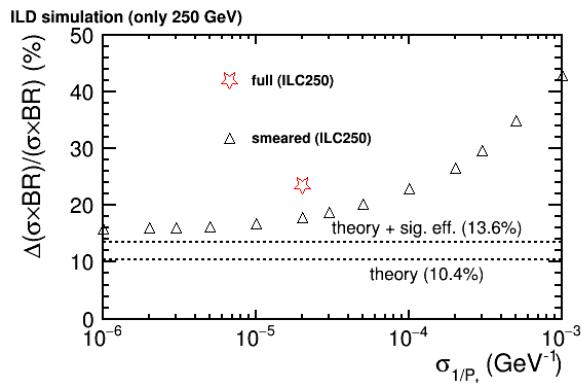
# Impact of Transverse Momentum Resolution

- $M_{\mu^+\mu^-}$  is most important because this is final observable to distinguish signal and background ---> measuring muon track has a crucial role ---> can be discussed with transverse momentum resolution  $\sigma_{1/P_t}$
- study performed by smearing
  - assume constant number of  $\sigma_{1/P_t}$  (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

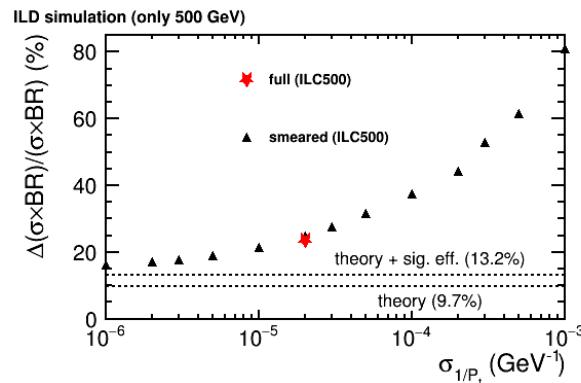
# Results (2)



# 250 GeV



# 500 GeV



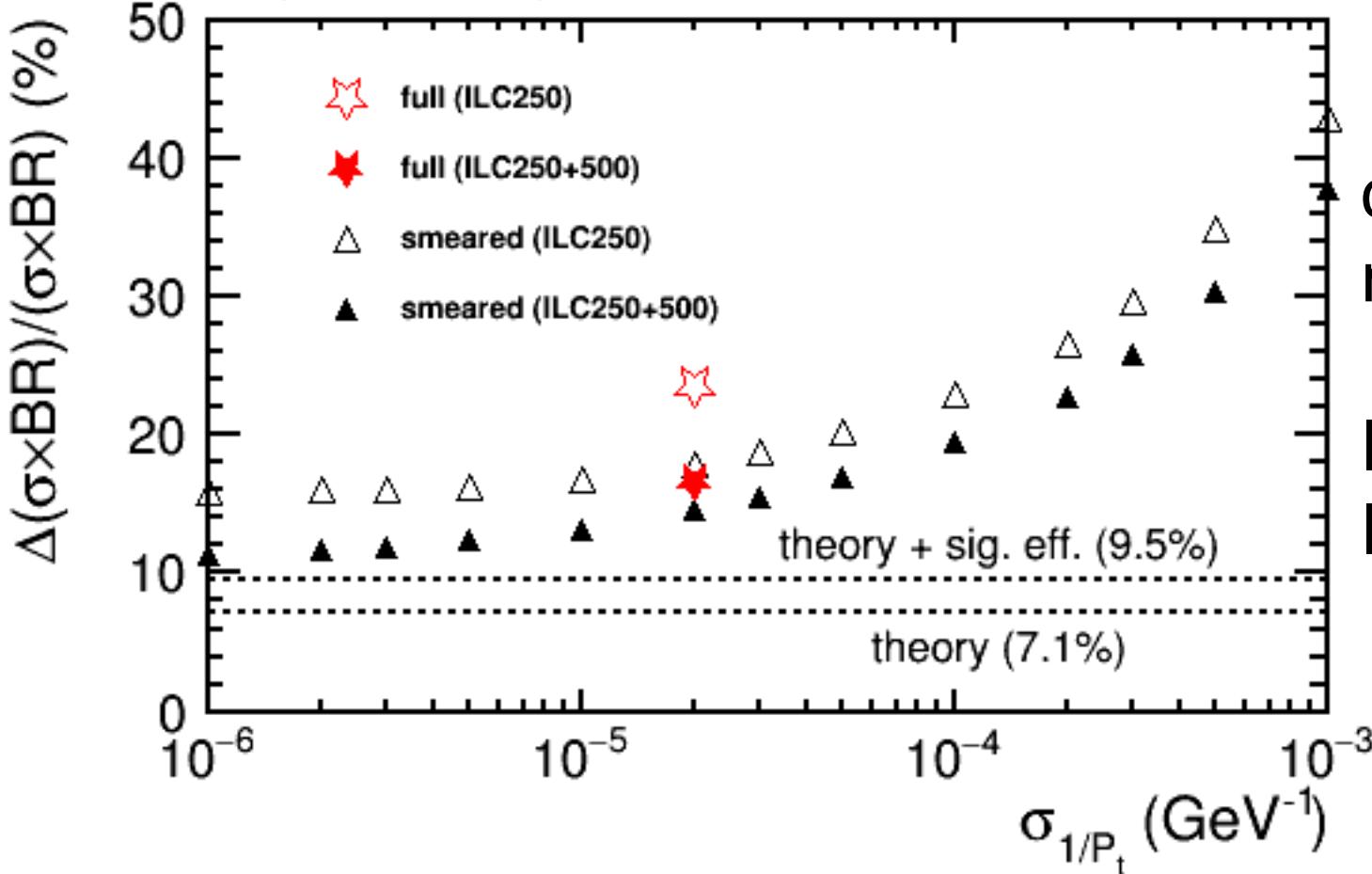
Both cases could improve up to 10% (absolute) by better  $\sigma_{1/P_t}$  resolution.

no significant improvement beyond  $10^{-5}$   
(will be capped ~16%)  
medium momentum muons  
---> effective resolution  $\sim 10^{-4}$   
---> important to keep or even improve  
resolution for medium momentum muons  
---> material budget/distribution

precision continues to improve down to  
smallest studied  $\sigma_{1/P_t}$  resolution  
high momentum muons  
---> effective resolution  $\sim 2 \cdot 10^{-5}$   
---> hard to improve, but important to  
keep ILD resolution  
---> size, B field, point resolution,  
alignment SET...

# Combined Results

ILD simulation (250+500 GeV)

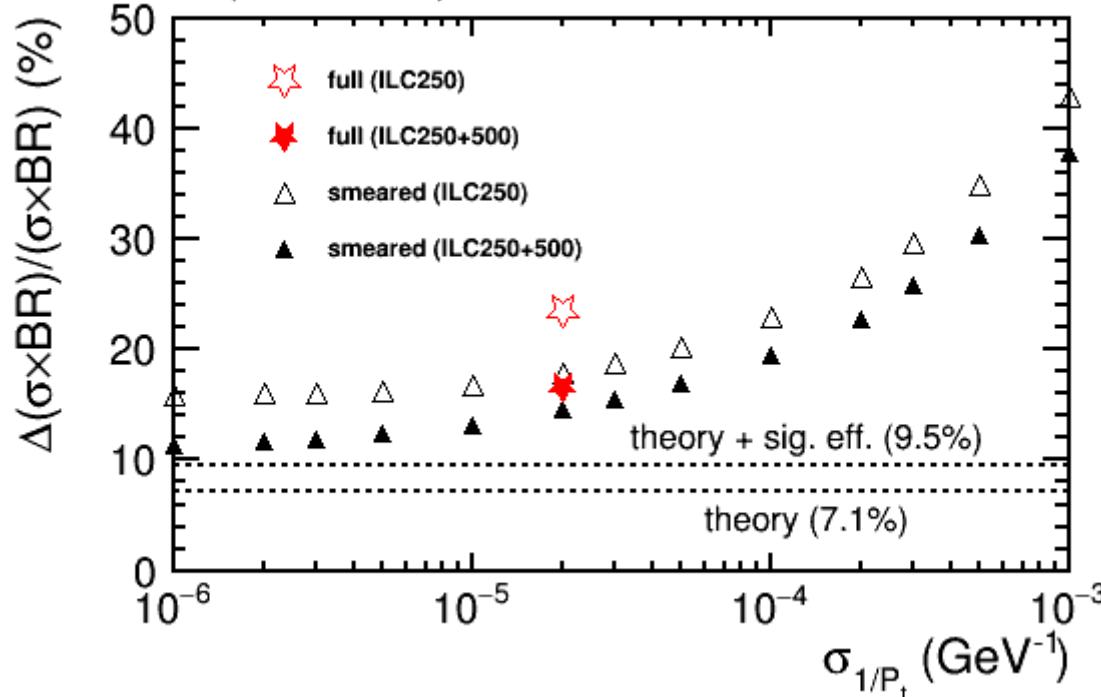


combined full result: 17%  
results will be capped at ~10%

It is very important to achieve  
ILD goal for  $\sigma_1/p_T$ .

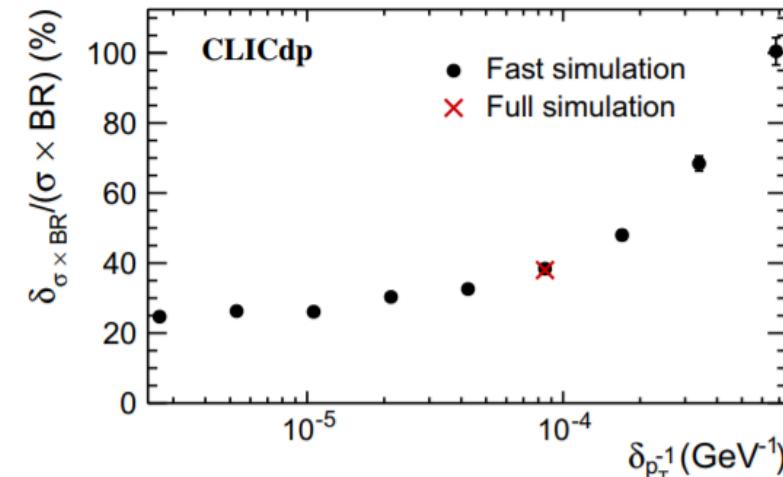
# Comparison with CLIC 1.4 TeV Analysis

ILD simulation (250+500 GeV)



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

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,  $\delta_{1/p_T}$ , averaged over the signal sample in the whole detector

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
- Studied  $h \rightarrow \mu^+ \mu^-$  channel with  $E_{CM} = 250/500$  GeV at the ILC
  - Can reach 17% combined precision for  $\frac{\Delta(\sigma \times BR)}{(\sigma \times BR)}$
- Studied the impact of transverse momentum resolution  $\sigma_{1/P_t}$ 
  - Important to achieve the ILD goal for  $\sigma_{1/P_t}$

# BACKUP



# Previous Studies

Everything performed at  $\geq 1 \text{ TeV}$ , or not realistic

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

# 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

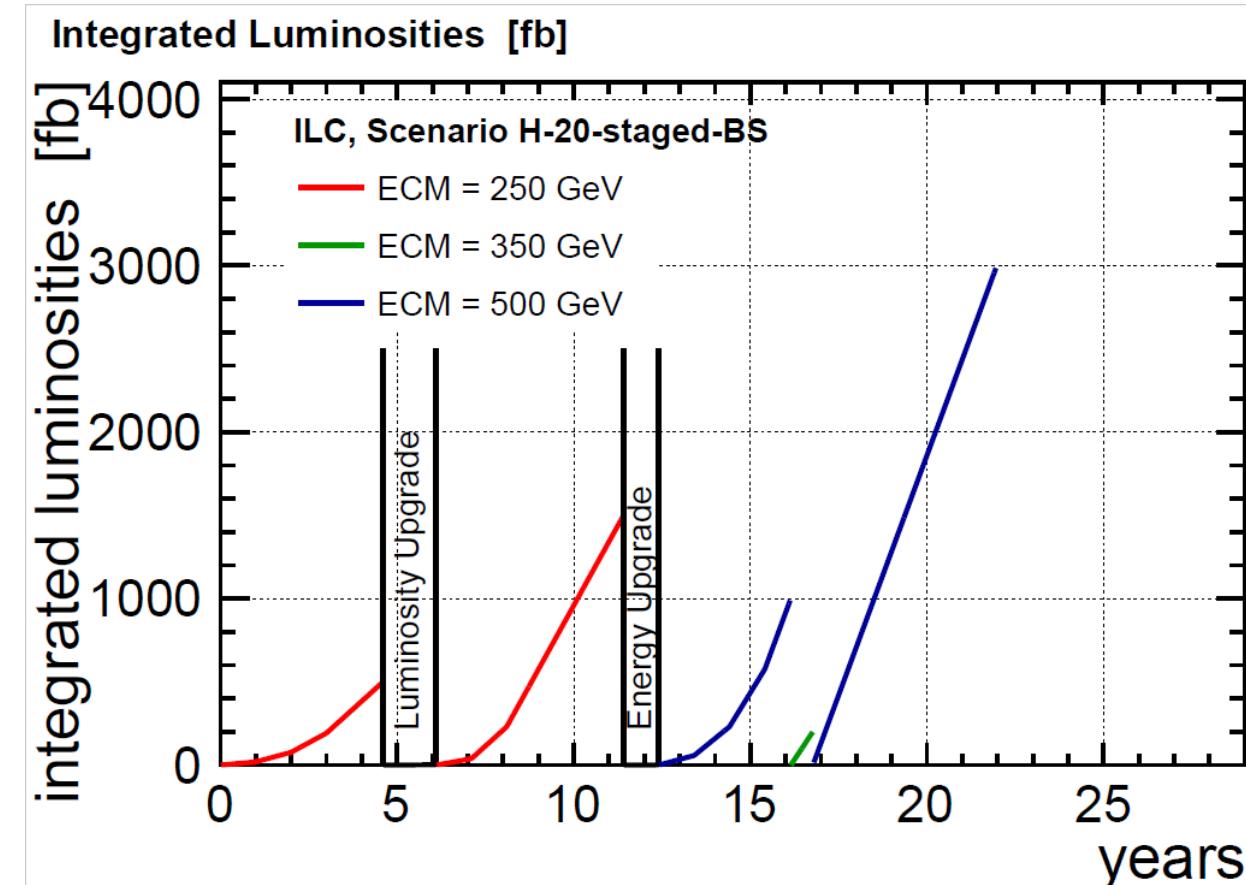
- > then possible 1 TeV upgrade

preferred scenario:

$2000 \text{ fb}^{-1}$  @ 250 GeV

$200 \text{ fb}^{-1}$  @ 350 GeV

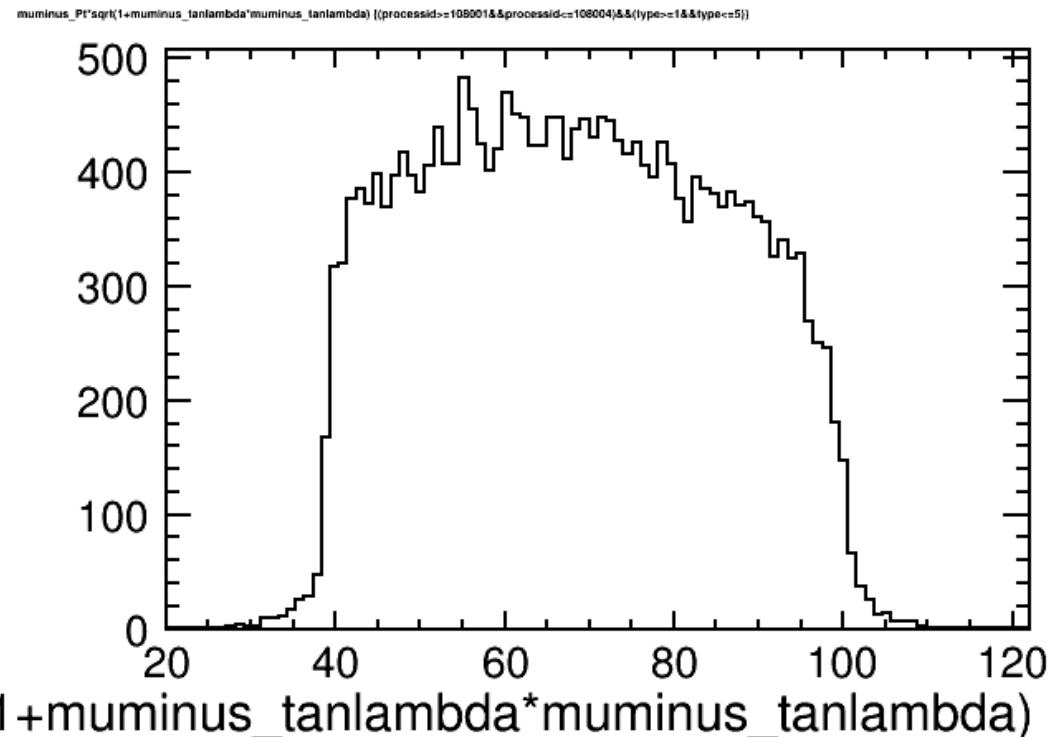
$4000 \text{ fb}^{-1}$  @ 500 GeV



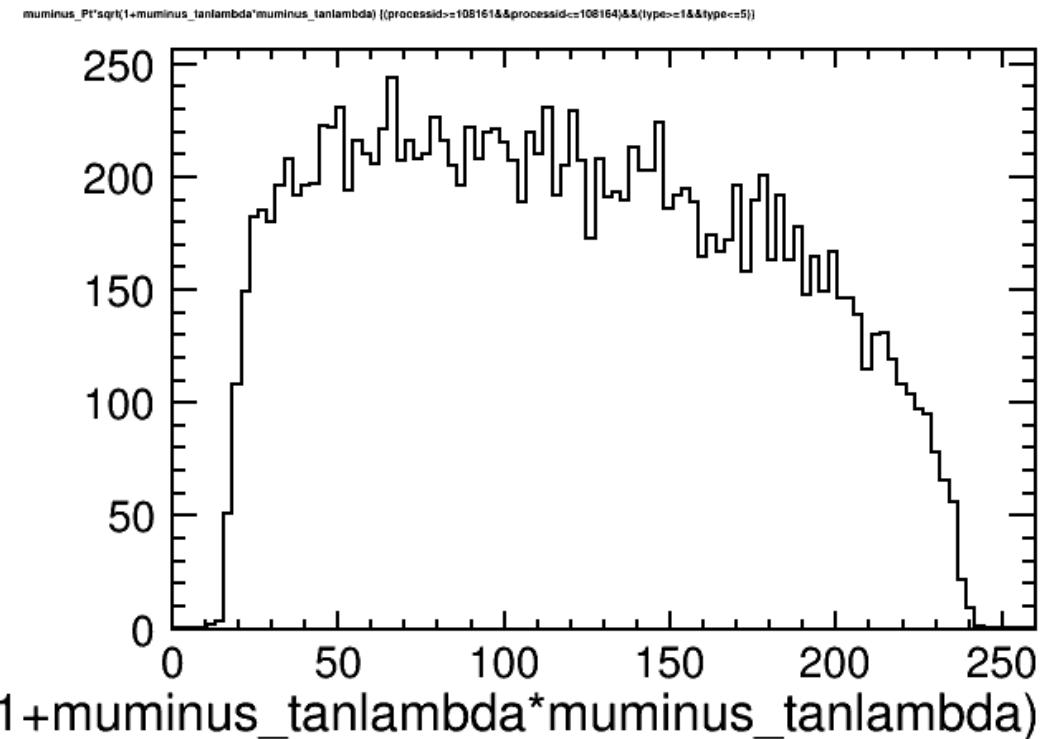
staging running scenario

# Actual Magnitude of Momentum

qqh250-L



qqh500-L



plotted  $p(\mu^-) = P_t \sqrt{1 + \tan^2 \lambda}$

full sim. events, not lumi-weighted, before BDTG cut

# CLIC Conclusion

- Even a large improvement of the muon momentum resolution would result in only a moderate improvement of the statistical uncertainty of the measured product of the Higgs production cross-section and the branching ratio for the  $H \rightarrow \mu^+ \mu^-$  decay.  
(EPJC (2015) 75:515)