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

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@ DESY

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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

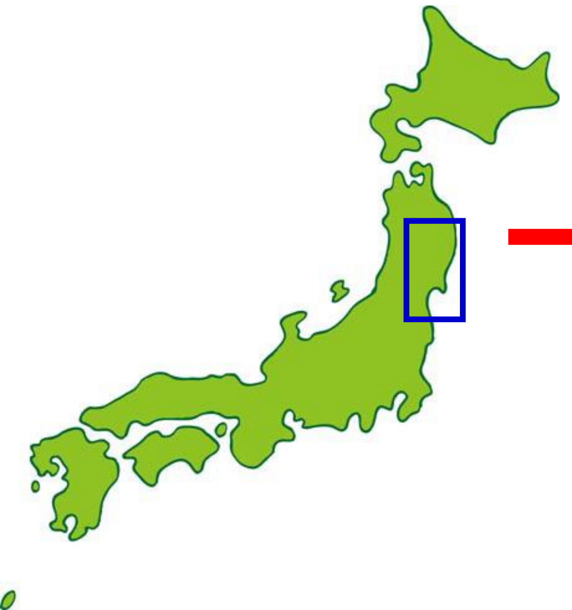
One example: Supersymmetry

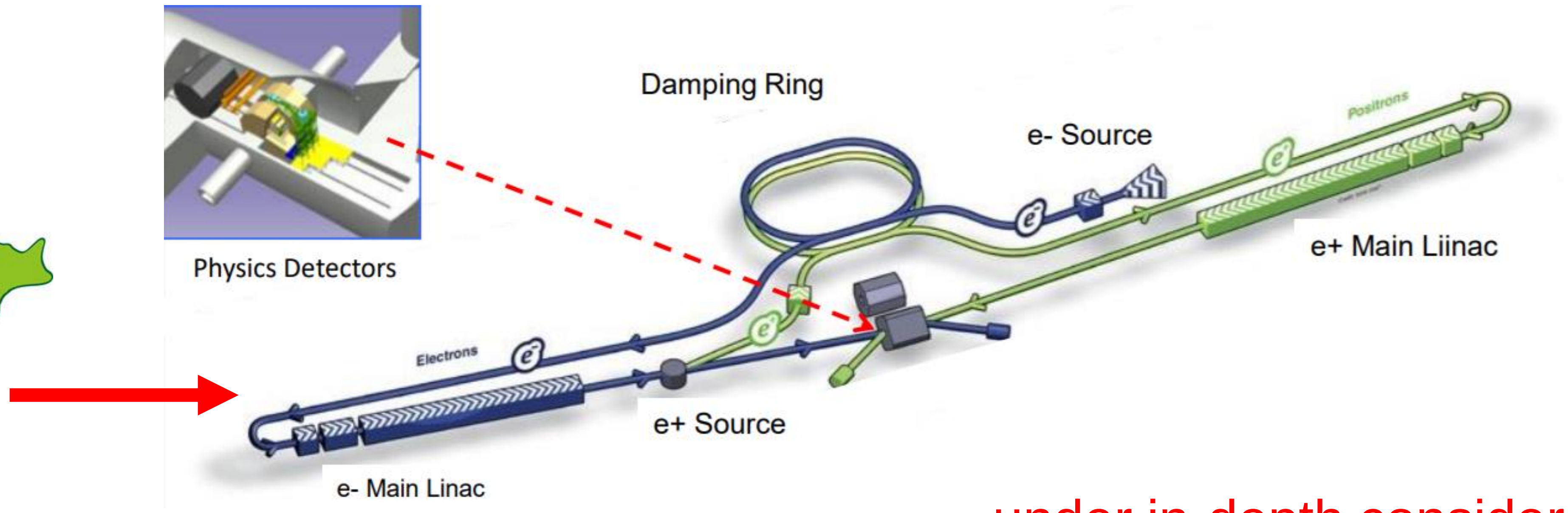
$$\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

arXiv:1306.6352

The International Linear Collider (ILC)

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





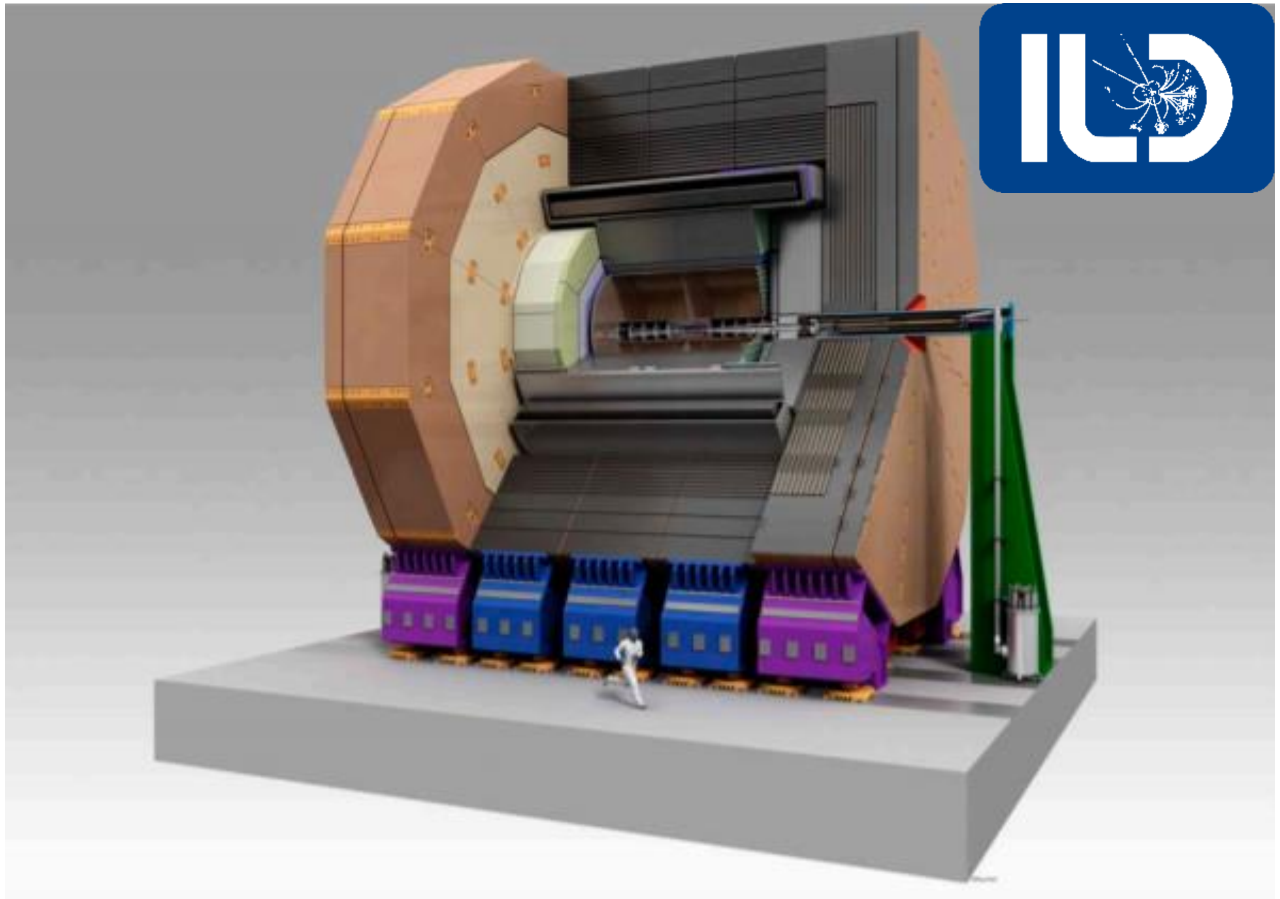
under in-depth consideration
by the Japanese government

Key Point

LHC	ILC
- $\sigma \times \mathrm{BR}$ measurements	- $\sigma \times \mathrm{BR}$ measurements
- σ measurement **impossible**	- σ measurement (recoil technique)
- model-dependent	- highly model-independent

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

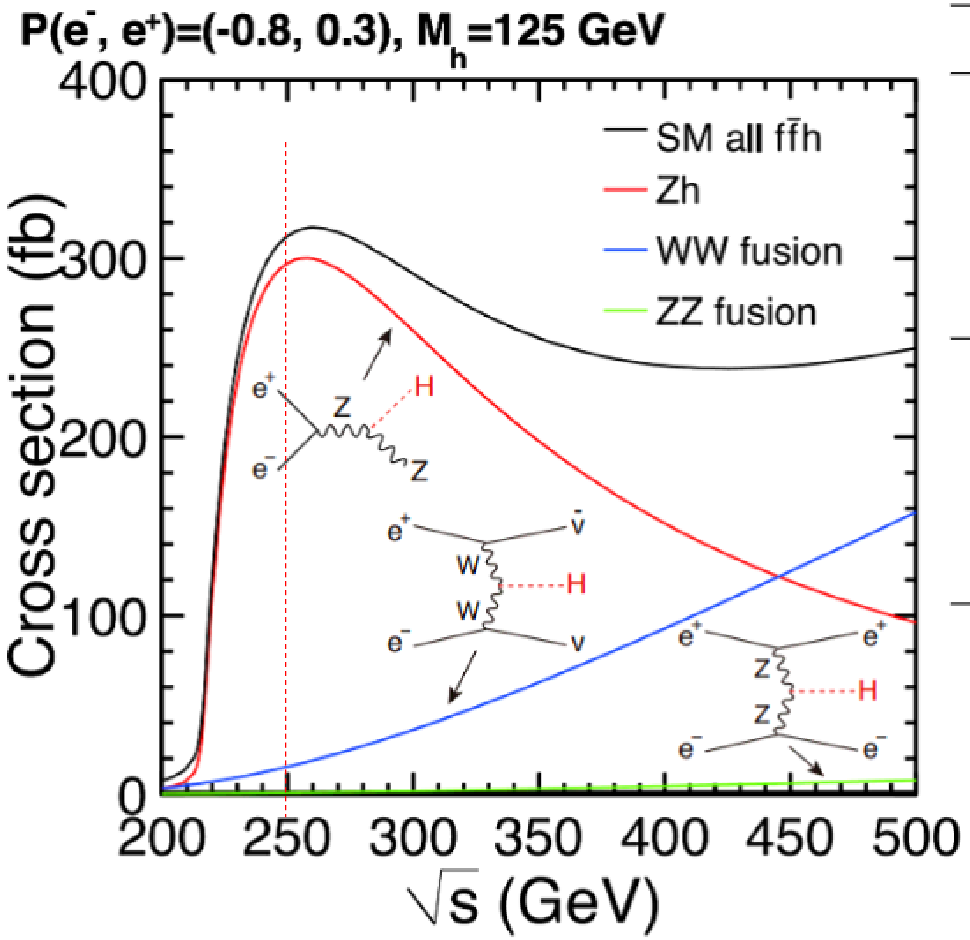
Requirements:

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

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

- 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($h \to \mu^+\mu^-$) = **2.2×10^{-4}**)
- Previous studies: mostly 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; $2 \times 2 \times 2 = 8$ channels

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



$\sqrt{s}$	process	beam pol.	abbreviation	$\int L dt$ (ab^{-1})	N_{signal}
250 GeV	$q\bar{q}h$	L	qqh250-L	0.9	41.1
		R	qqh250-R		28.1
	$\nu\bar{\nu}h$	L	nnh250-L		15.0
		R	nnh250-R		8.4
500 GeV	$q\bar{q}h$	L	qqh500-L	1.6	24.6
		R	qqh500-R		16.5
	$\nu\bar{\nu}h$	L	nnh500-L		57.5
		R	nnh500-R		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

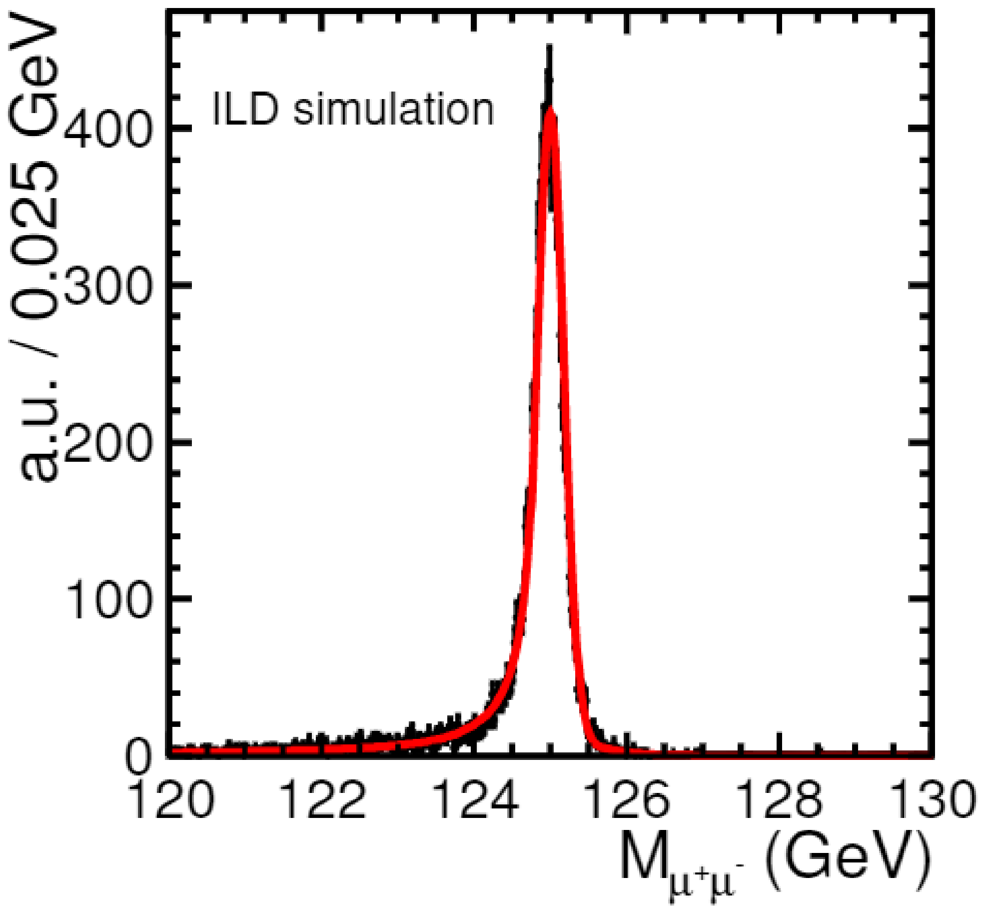
Analysis Settings

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

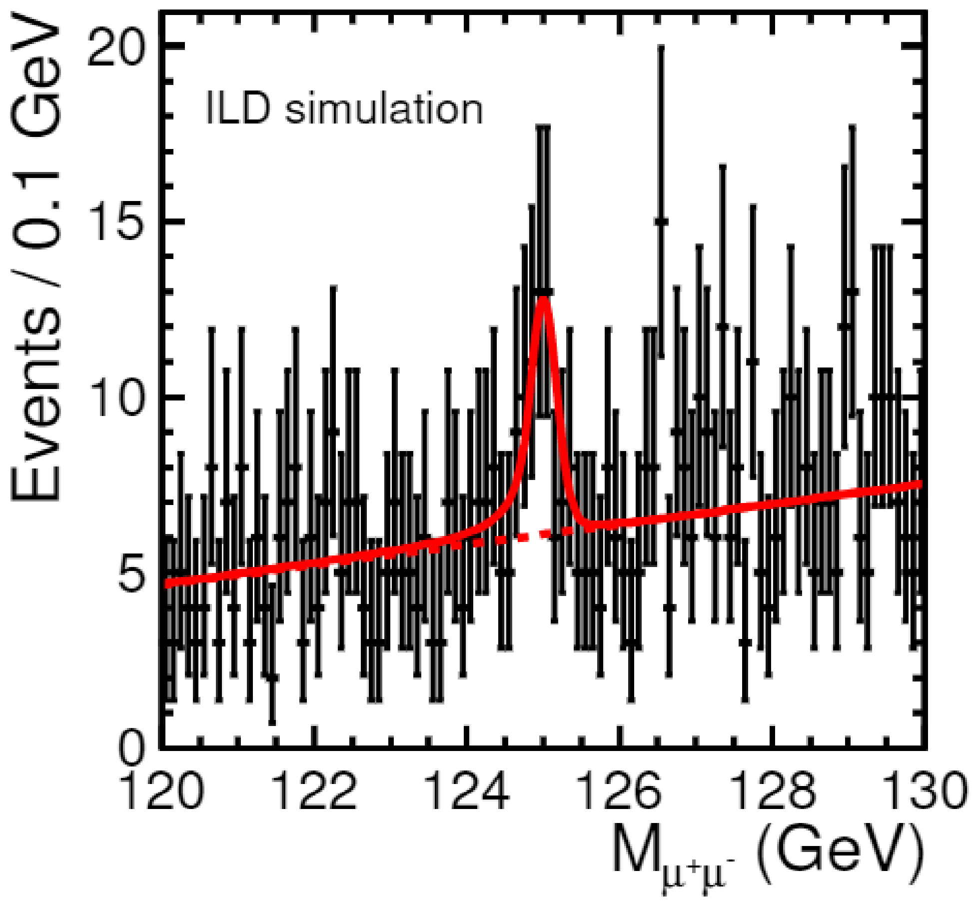
Summary of Analysis Procedure

- Select $h \to \mu^+\mu^-$ 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 Plots (qqh250-L)



Crystal Ball + Gaussian fit for signal



Example of one pseudo-experiment

Results (1)

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

Precision on $\frac{\Delta\left(\sigma\times\mathrm{BR}(h\to\mu^+\mu^-)\right)}{\left(\sigma\times\mathrm{BR}(h\to\mu^+\mu^-)\right)}$

$\sqrt{s} = 250$ GeV	$q\bar{q}h$	$\nu\bar{\nu}h$	ILC250	ILC250+500
L	34%	117%	24%	
R	36%	112%		
$\sqrt{s} = 500$ GeV	$q\bar{q}h$	$\nu\bar{\nu}h$	ILC500	17%
L	43%	37%	24%	
R	49%	107%		

ILC250: ~100 events

ILC250+500: ~200 events

Discussion (1)

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

factor ~2.4 above theory (100% sig. eff. and no backgrounds)
factor ~1.7 above theory + sig. eff. (theory but sig. eff. from full)

signal selection efficiency

~50% in full

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

"irreducible" background

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

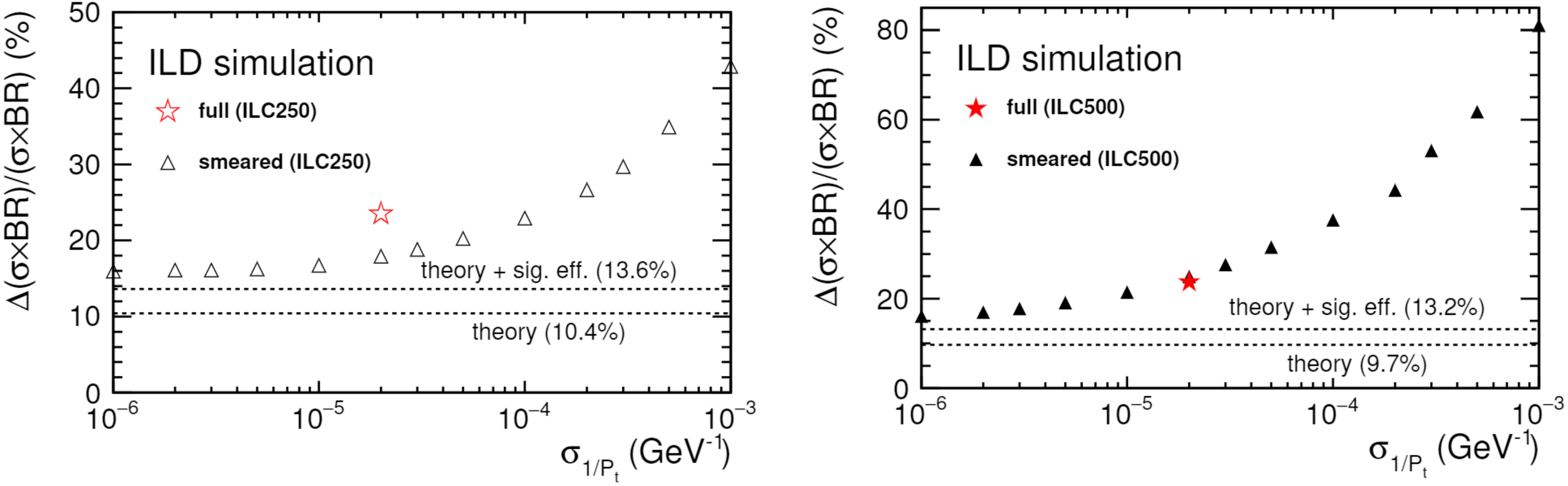
same final state ---> difficult to suppress

almost no τ 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 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 $h \to \mu^+\mu^-$ candidate

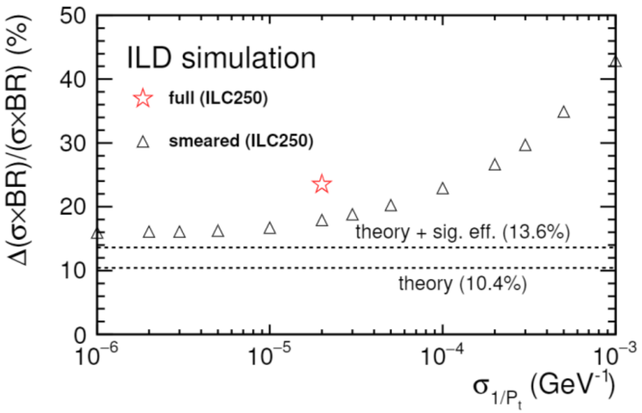
Results (2)

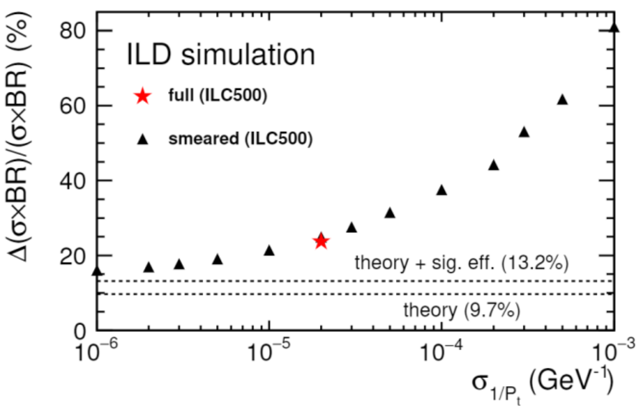


worse resolution = worse results on precision

Important to achieve ILD goal for σ_{1/P_t}

250 GeV



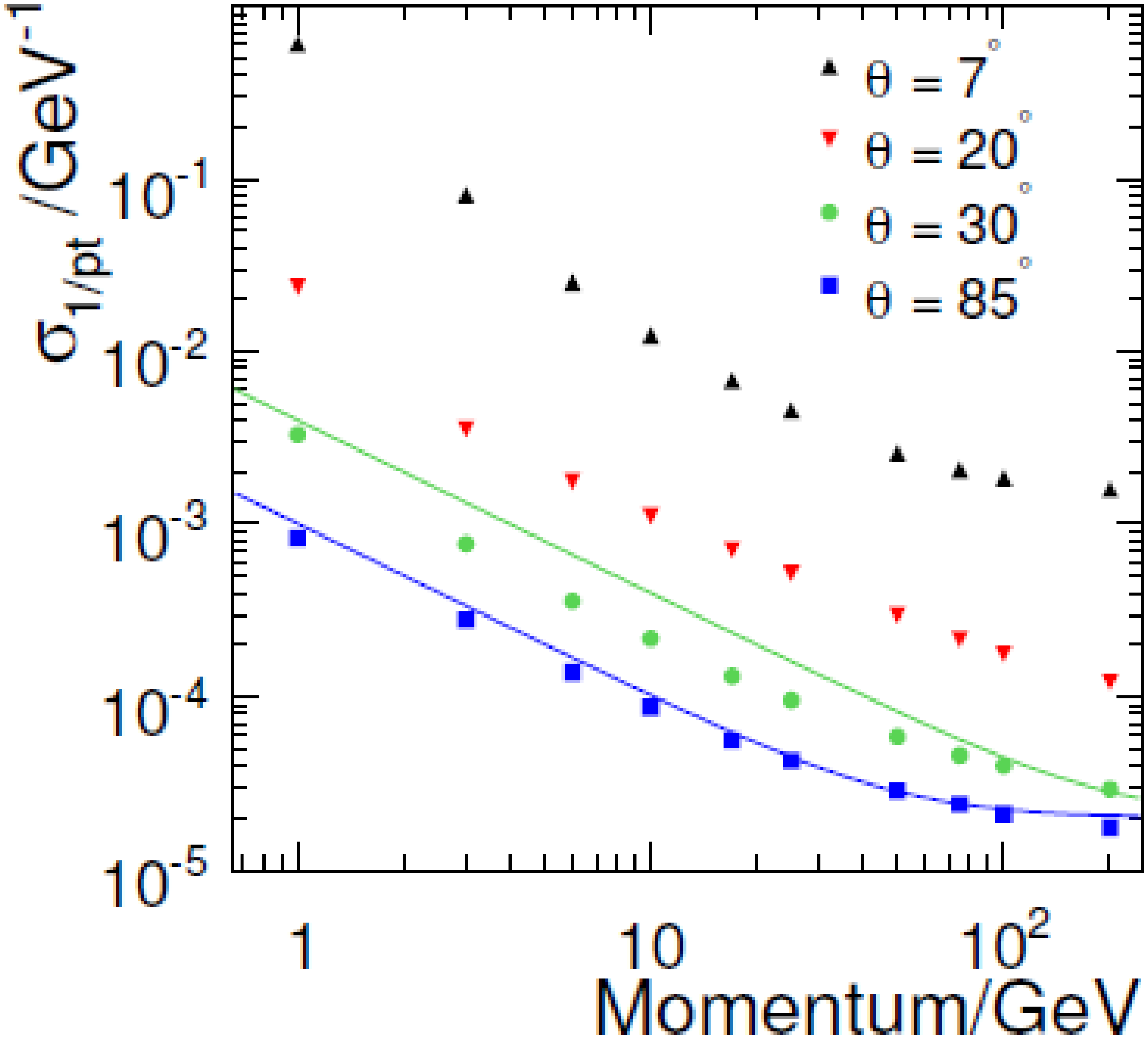


500 GeV

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

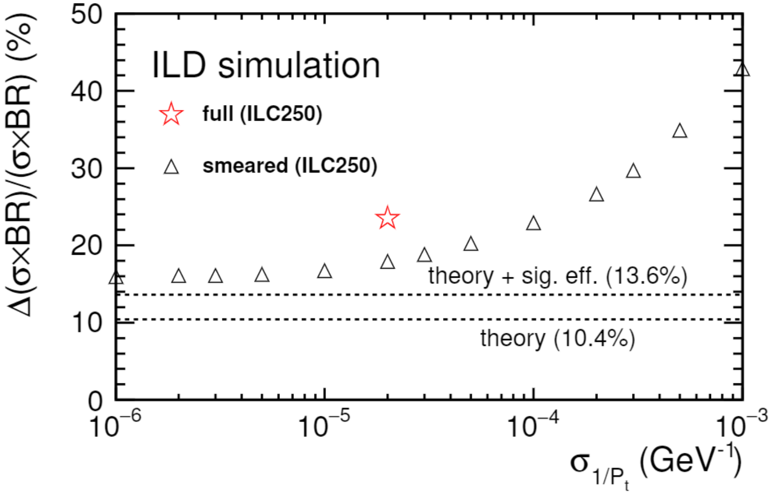
no significant improvement beyond 10^{-5} (will be capped ~16%)
medium momentum muons
---> effective resolution ~ 10^{-4}
---> important to keep or even improve resolution for medium momentum muons
---> material budget/distribution

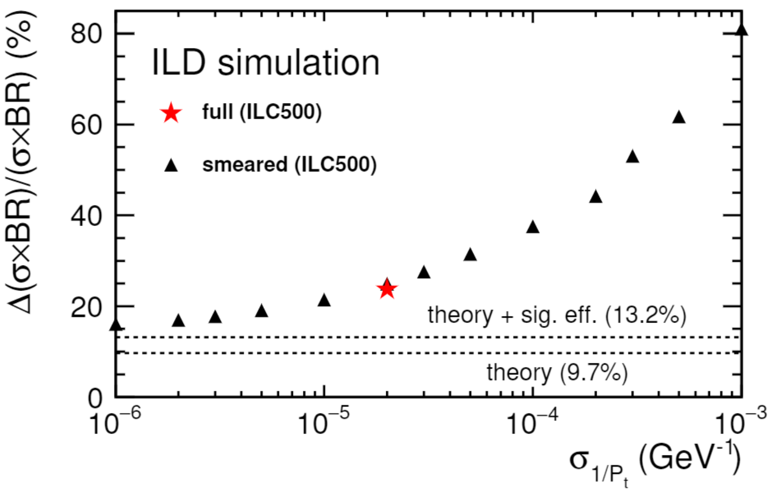
precision continues to improve down to smallest studied σ_{1/P_t} resolution
high momentum muons
---> effective resolution ~ $2*10^{-5}$
---> hard to improve, but important to keep ILD resolution
---> size, B field, point resolution, alignment SET...



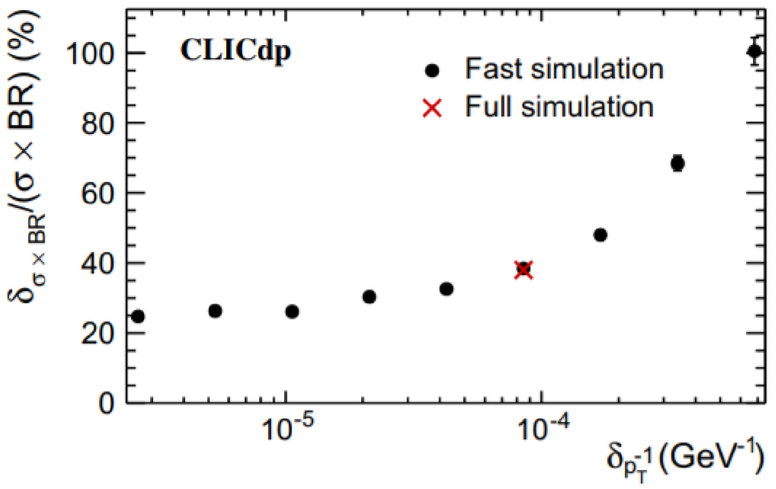
$\sigma_{1/pt}$ /GeV^{-1}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
10^2
Momentum/GeV
$\theta = 7^\circ$
$\theta = 20^\circ$
$\theta = 30^\circ$
$\theta = 85^\circ$

Comparison with CLIC 1.4 TeV Analysis





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



ILC: 250/500 GeV, two final states,
L/R beam polarization

CLIC: 1.4 TeV, one final state,
no beam polarization

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

BACKUP

Previous Studies

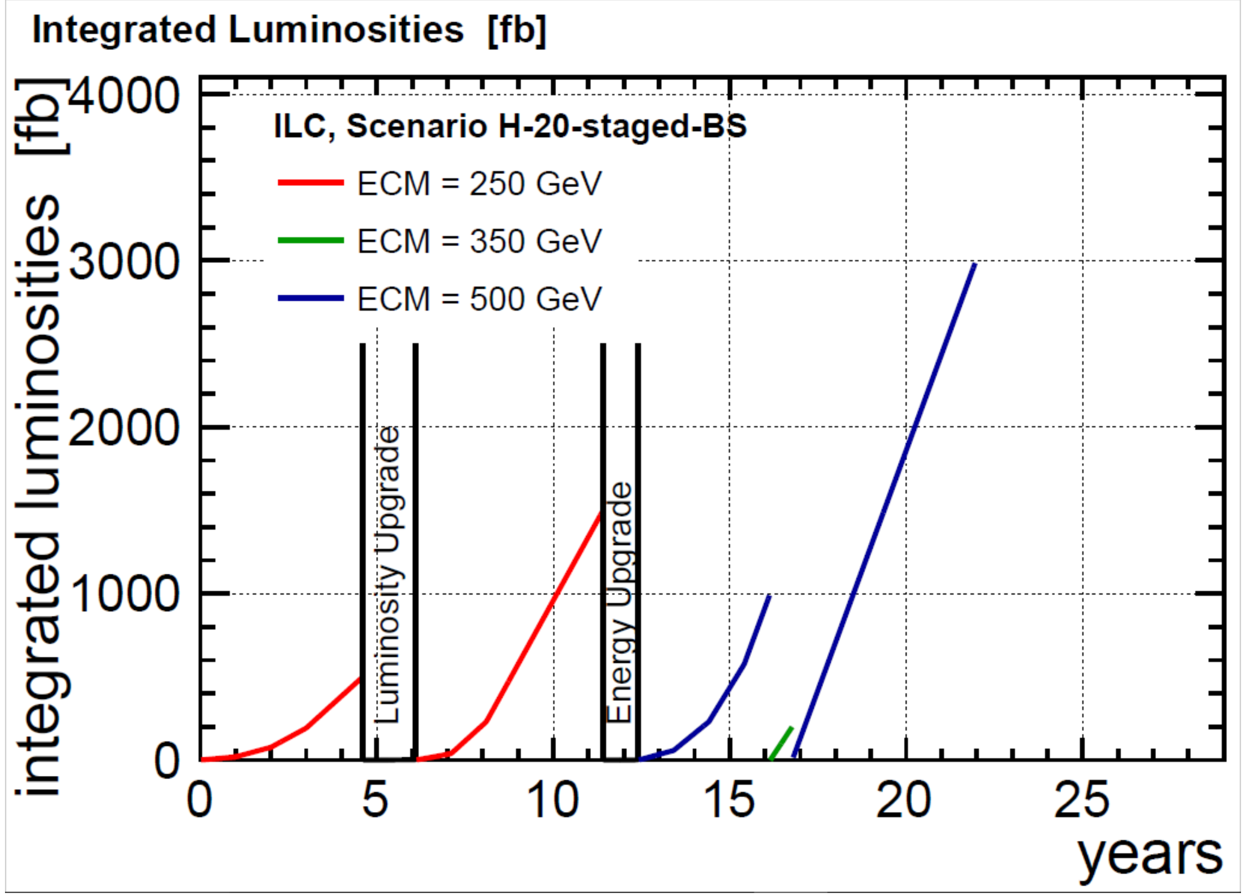
Everything performed at >= 1 TeV, or not realistic

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

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

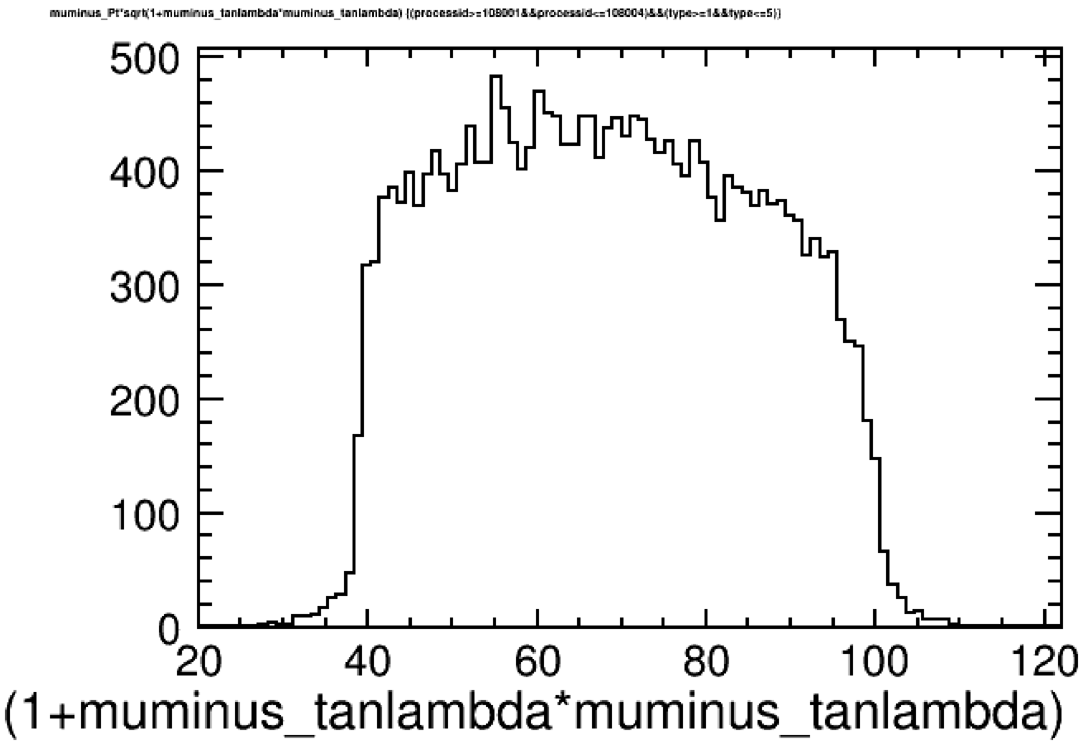


staging running scenario

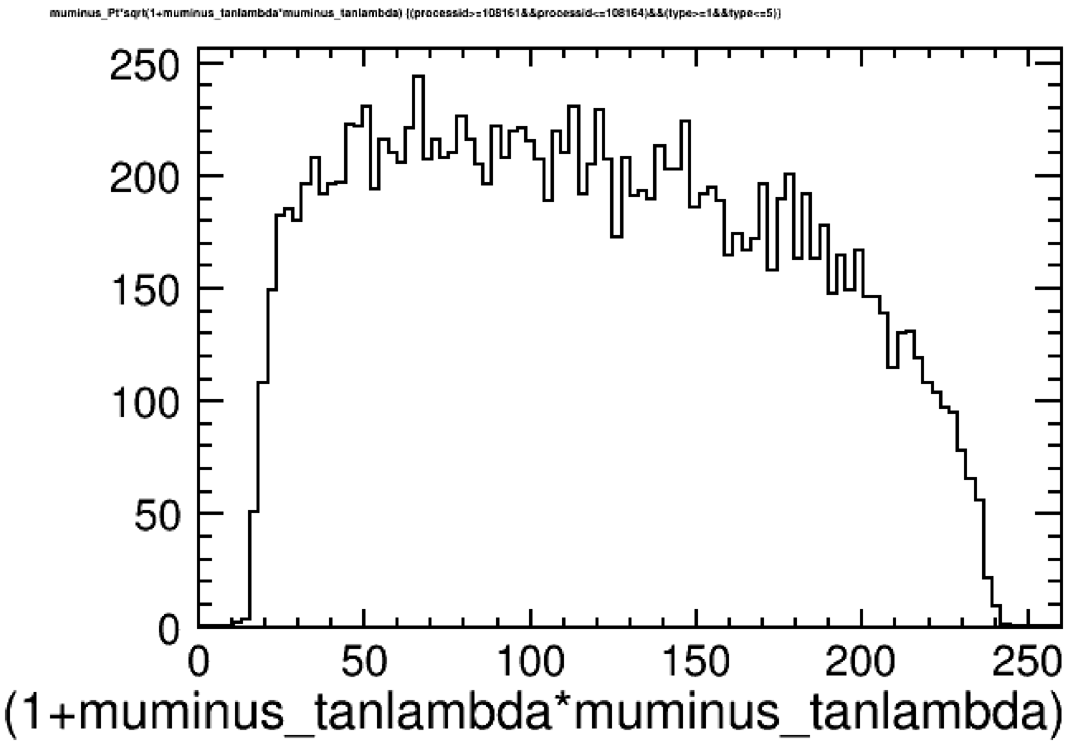
preferred scenario:
2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV

Actual Magnitude of Momentum

qqh250-L



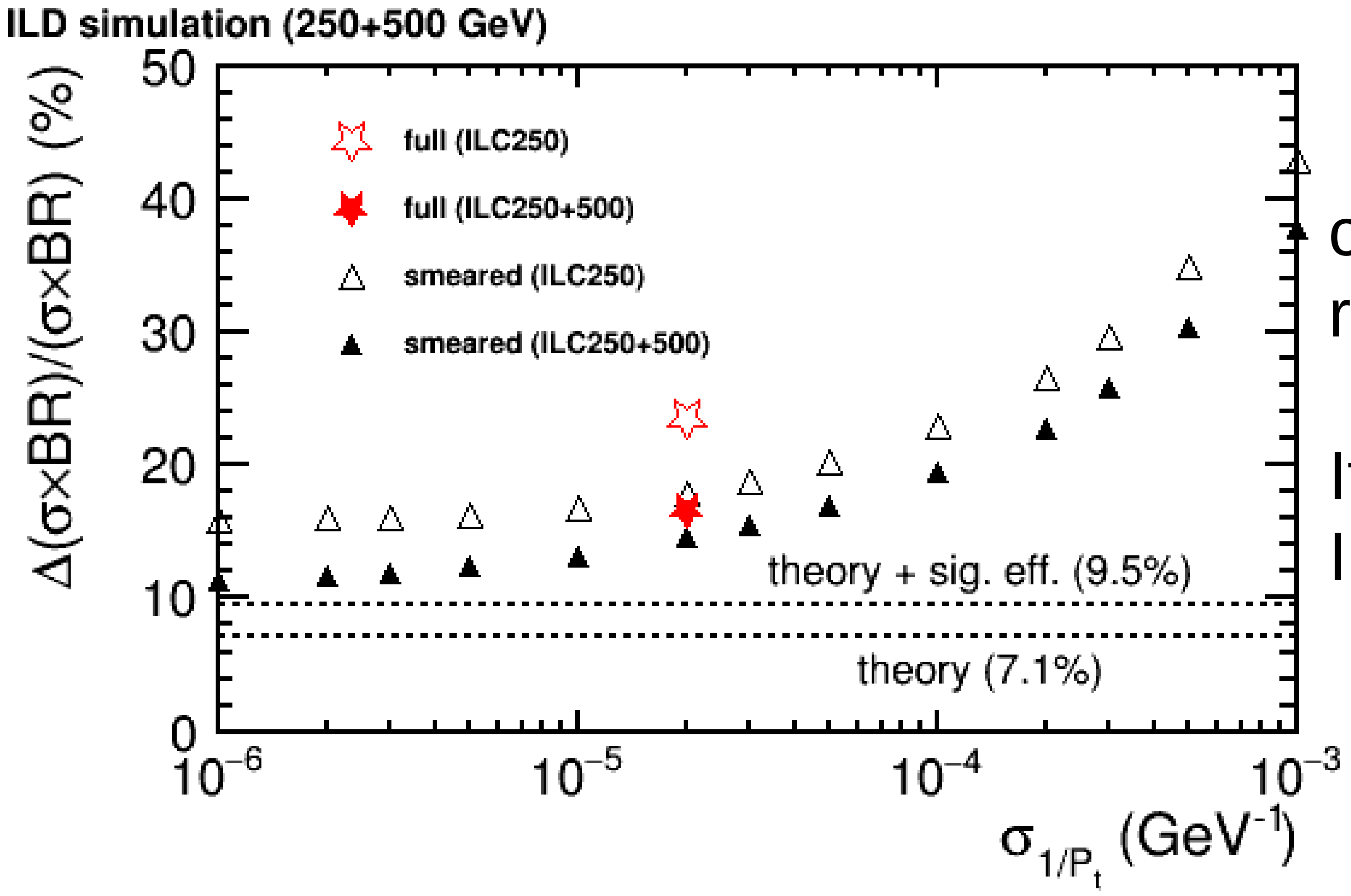
qqh500-L



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

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

Combined Results



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

It is very important to achieve ILD goal for σ_{1/p_T}.

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)