Branching ratio measurement of $h \to \mu^+\mu^-$ at the ILC

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ALCW2018 @ Fukuoka, Japan

2018/May/28 - June/1

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

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

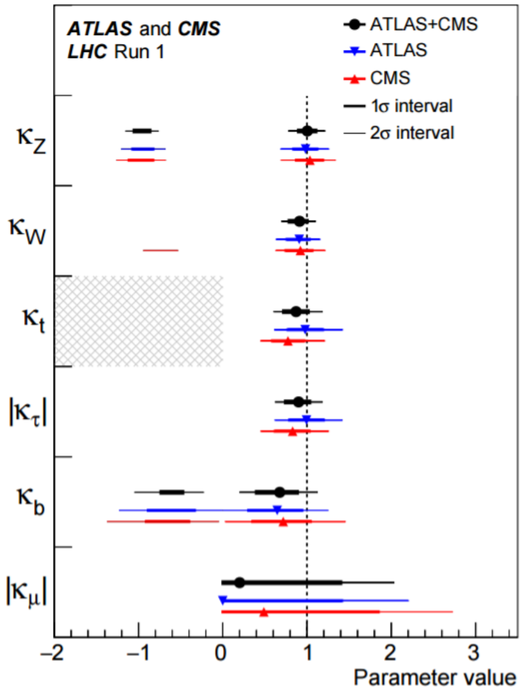
Introduction

Discovery of Higgs-like boson at the LHC
--> Last particle of SM? Or beyond SM?

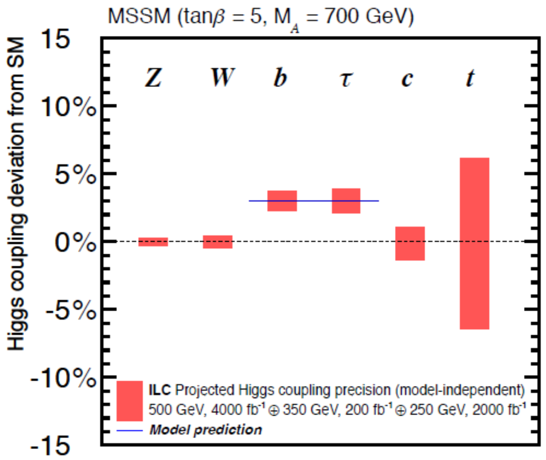
Goal: model-independent determination of
EWSB sector with precise measurements
- mass-coupling relation
- any deviation shows the existence of BSM

⇩

ILC



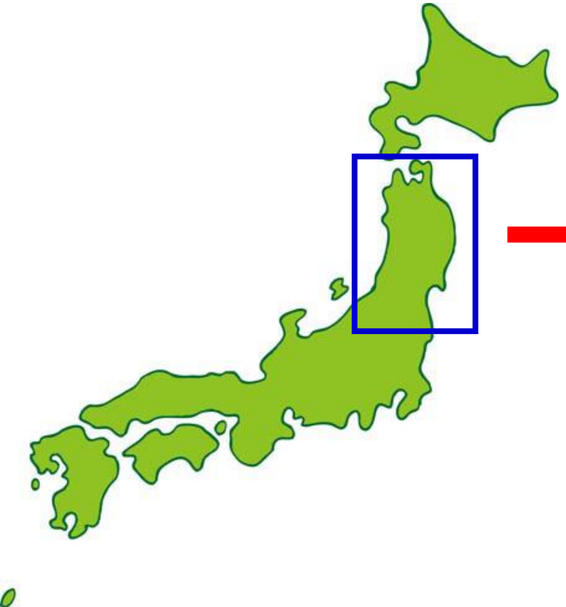
JHEP **08** (2016) 045

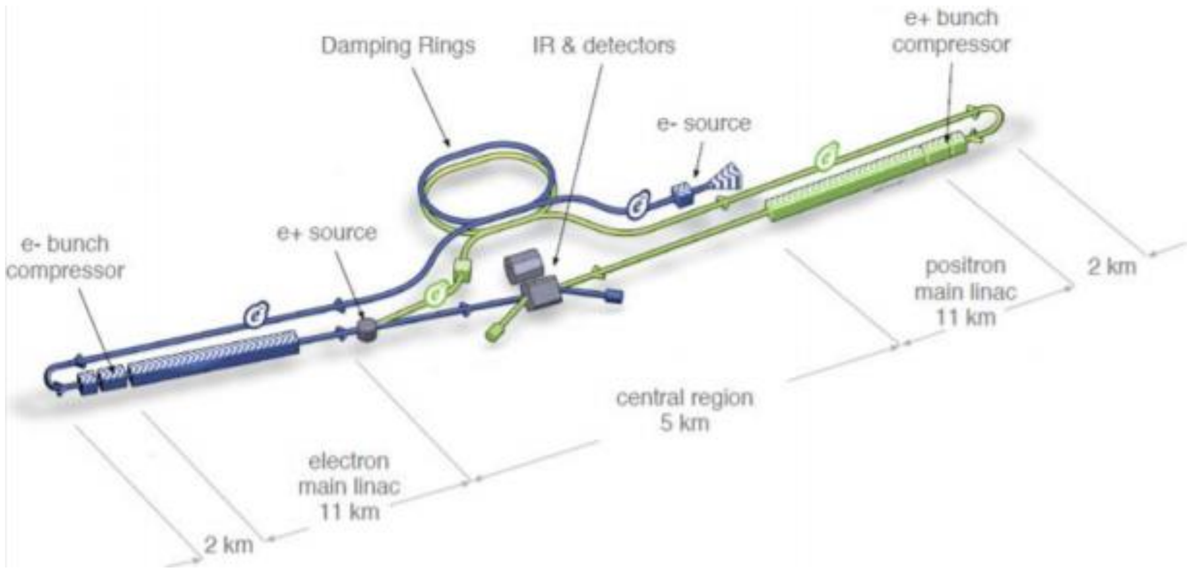


arXiv:
1506.05992
[hep-ex]

The International Linear Collider

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



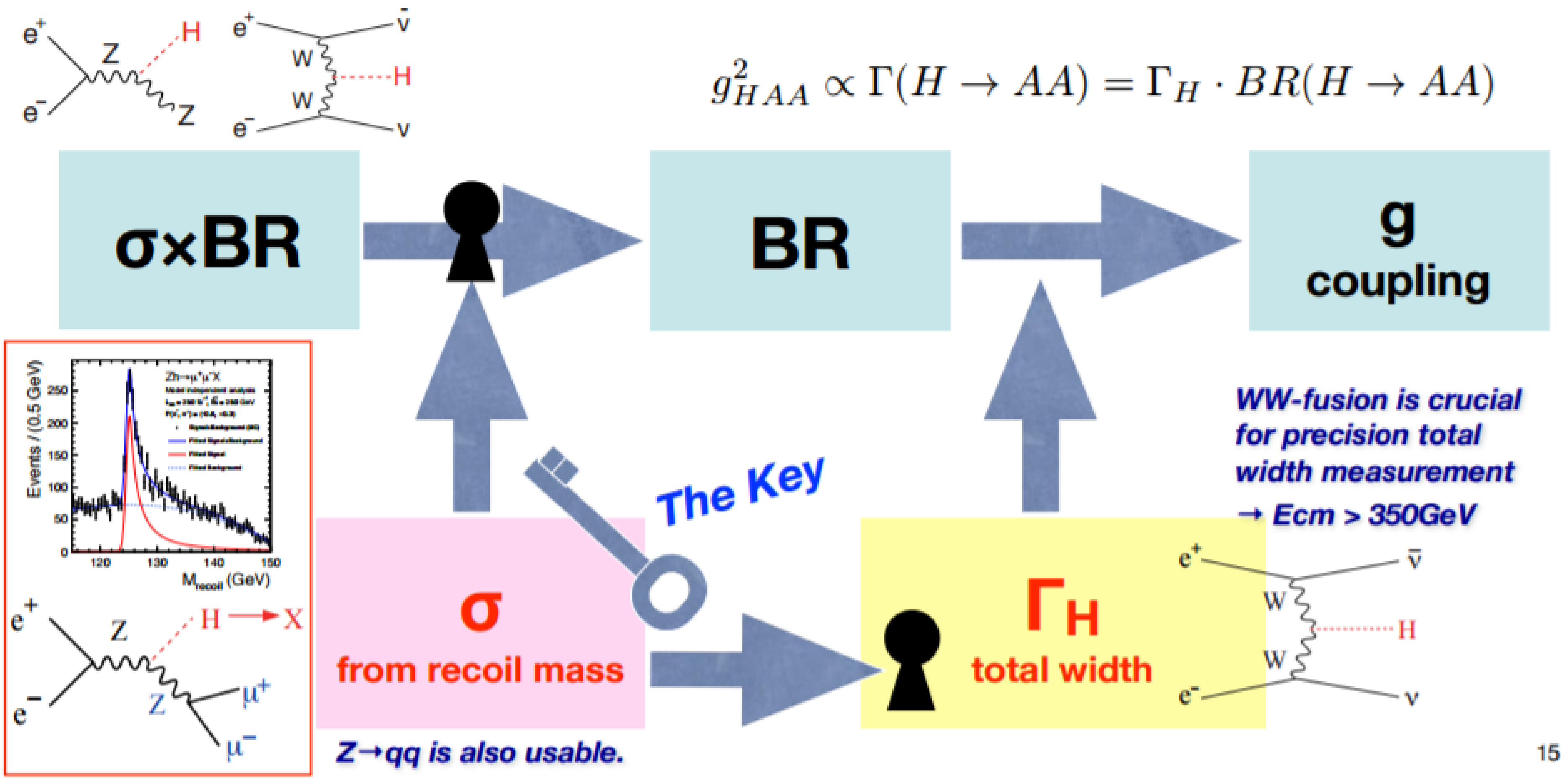


Key Point

K. Fujii's talk, LCWS2014

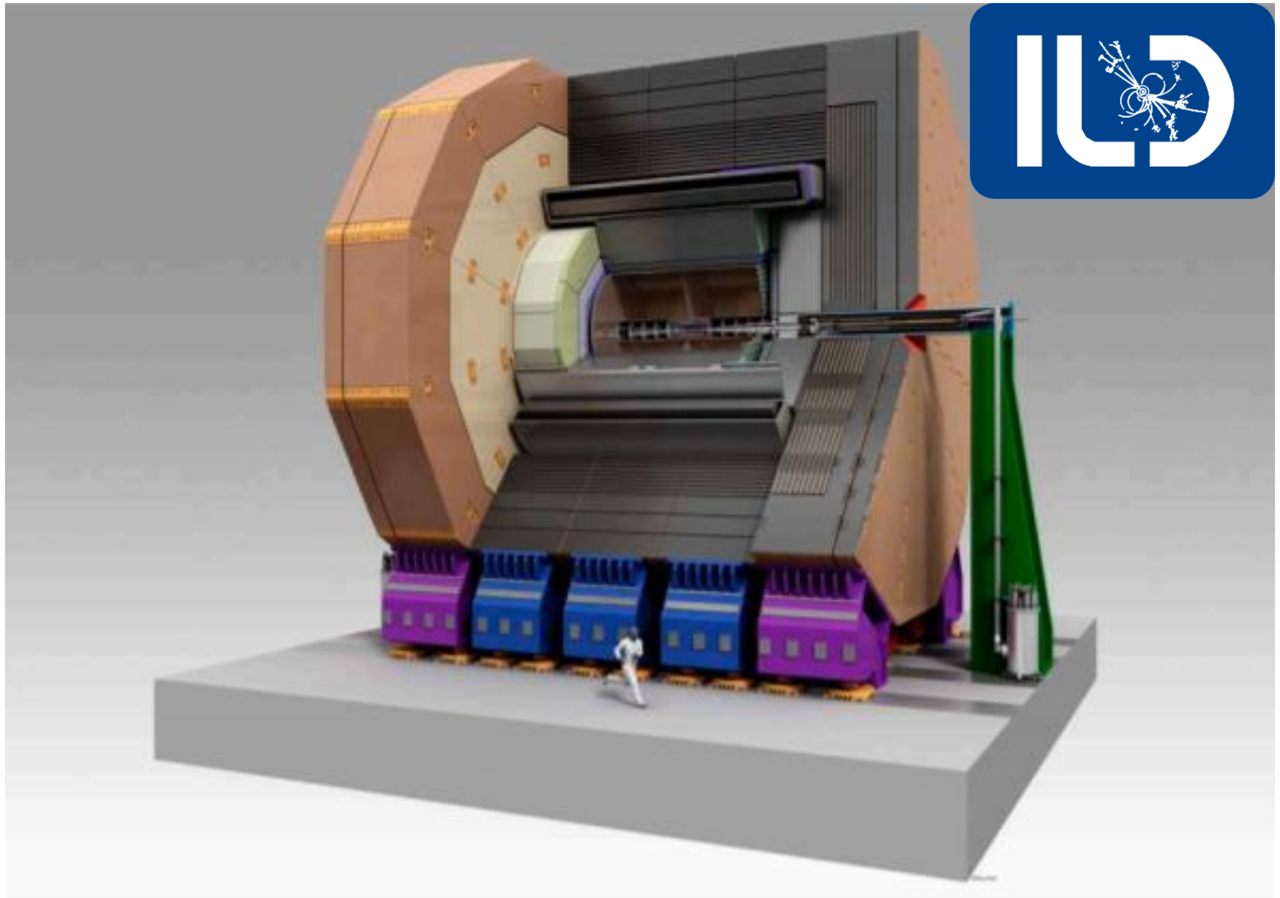
LHC: all measurements are $\sigma \times \mathrm{BR}$

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



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**
  $\sigma_{1/p_T} < 2 \times 10^{-5}\ \text{GeV}^{-1}$
- Energy resolution
  $\sigma_E/E = 3 - 4\%$

In 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)
- Good benchmark for detector optimization
- Challenging: tiny branching ratio (BR($h \to \mu^+\mu^-$) = **$2.2*10^{-4}$**)

Previous Studies

Everything performed at >= 1 TeV, or not realistic

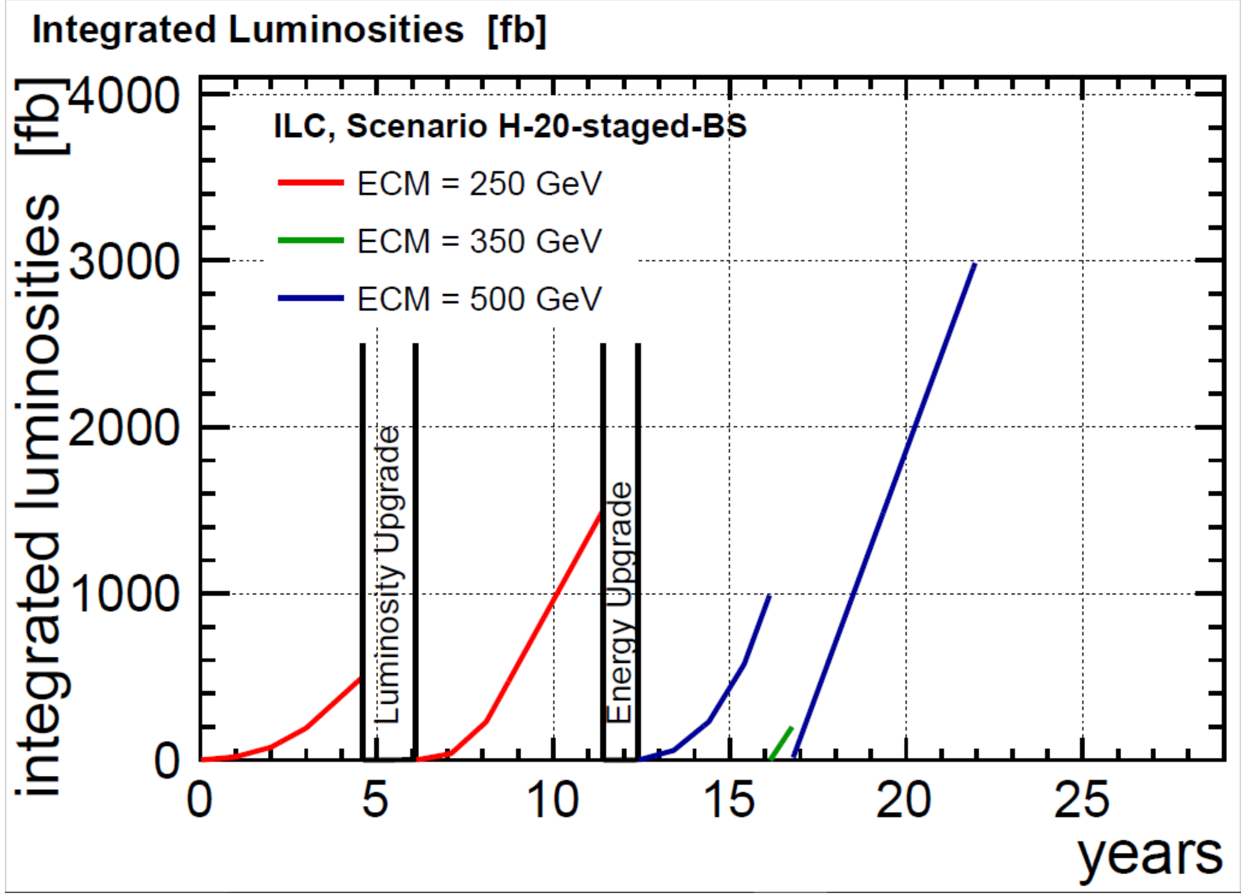
Reference	E_{CM}	beam pol. $P(e^-, e^+)$	$\int Ldt$	$\frac{\Delta(\sigma \times BR)}{(\sigma \times BR)}$	comment
LC-REP-2013-006	1 TeV	(-0.8, +0.2)	500 fb^{-1}	44%	ILC/ILD
arXiv:1306.6329 [hep-ex]	1 TeV	(-0.8, +0.2)	1000 fb^{-1}	32%	ILC/SiD
arXiv:1603.04718 [hep-ex]	1 TeV	(-0.8, +0.2)	500 fb^{-1}	36%	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

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

Single Higgs Production

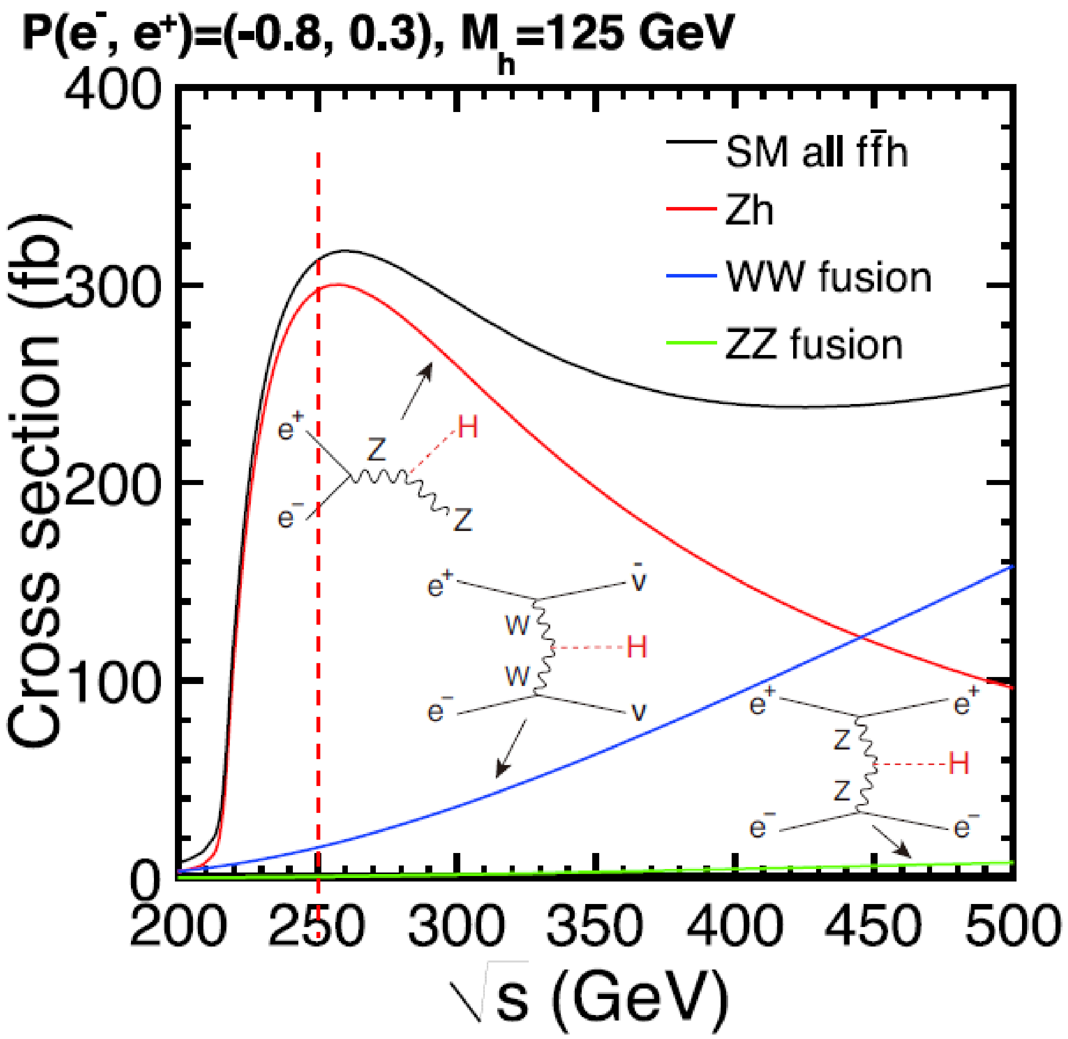
$\sqrt{s}$ = 250 GeV

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	58
		R	1600	8
	$q\bar{q}h$	L	1600	25
		R	1600	16
250	$\nu\bar{\nu}h$	L	900	28
		R	900	8
	$q\bar{q}h$	L	900	41
		R	900	15



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 possible SM backgrounds
  - Used DBD-style samples, a first look of newly generated MC samples will be given in Thursday (joint Sim/Rec/DetPerf/Vertex/Tracking)
  - Performed toy MC in the end to extract the precision, because some SM background processes have not enough MC statistics

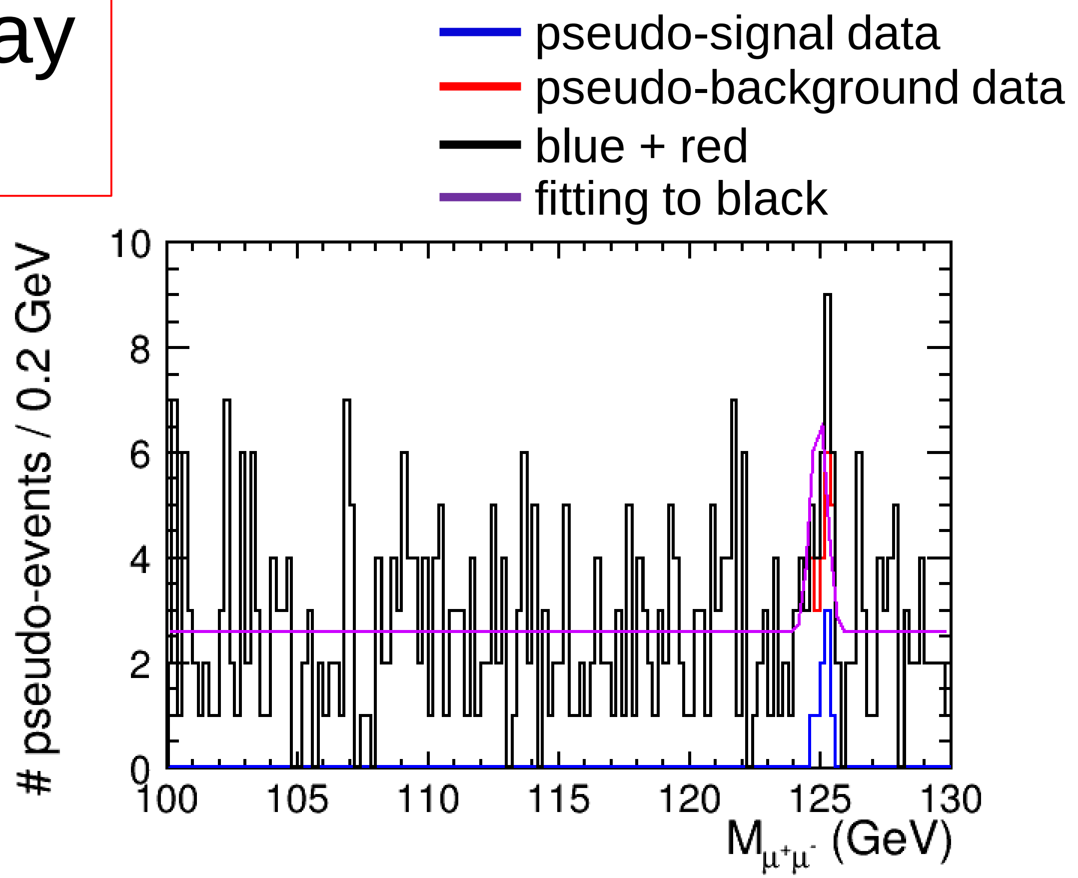
E_{CM}	# total MC events
500 GeV	$1.4*10^7$
250 GeV	$7.1*10^7$

arXiv:1801.07966 [hep-ex]
(LCWS2017 proceedings)

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. toy MC with $M_{\mu^+\mu^-}$
   - extract final precision
   - (for experts) 200 MeV/bin -> 2 MeV/bin



Results

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

250 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	27.6%	97.5%
R	32.9%	94.7%

500 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	38.4%	27.8%
R	53.9%	92.5%

ILC250 combined = 20.2% (“theoretical limit” = 10.4%)
ILC250+500 combined = **14.3%** (“theoretical limit” = 7.1%)
HL-LHC: 10-21%

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

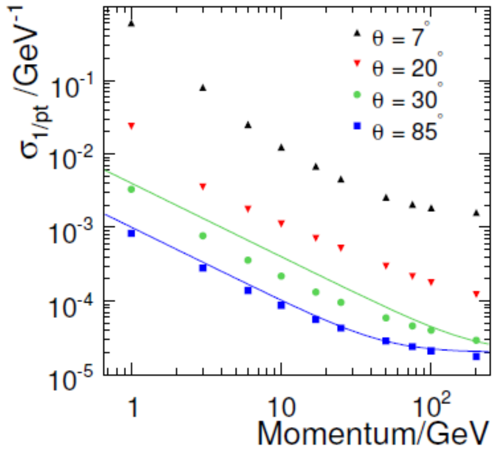
Impact of Momentum Resolution

- 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. On average, this is still good approximation.
  - replace $M_{\mu^+\mu^-}$ to $M_{\mu^+\mu^-}^{\text{smear}}$ in toy MC
  - (for specialist) 200 MeV/bin -> 2 MeV/bin



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

arXiv:1306.632 [physics.ins-det]

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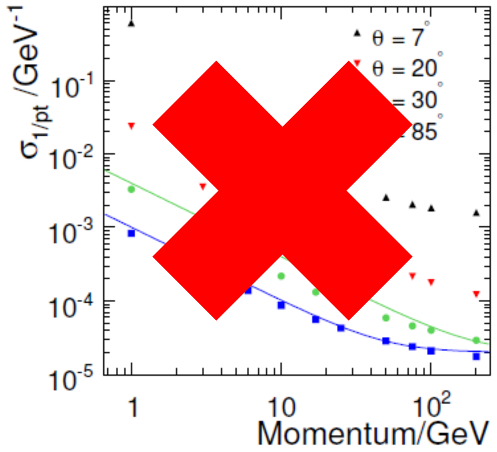
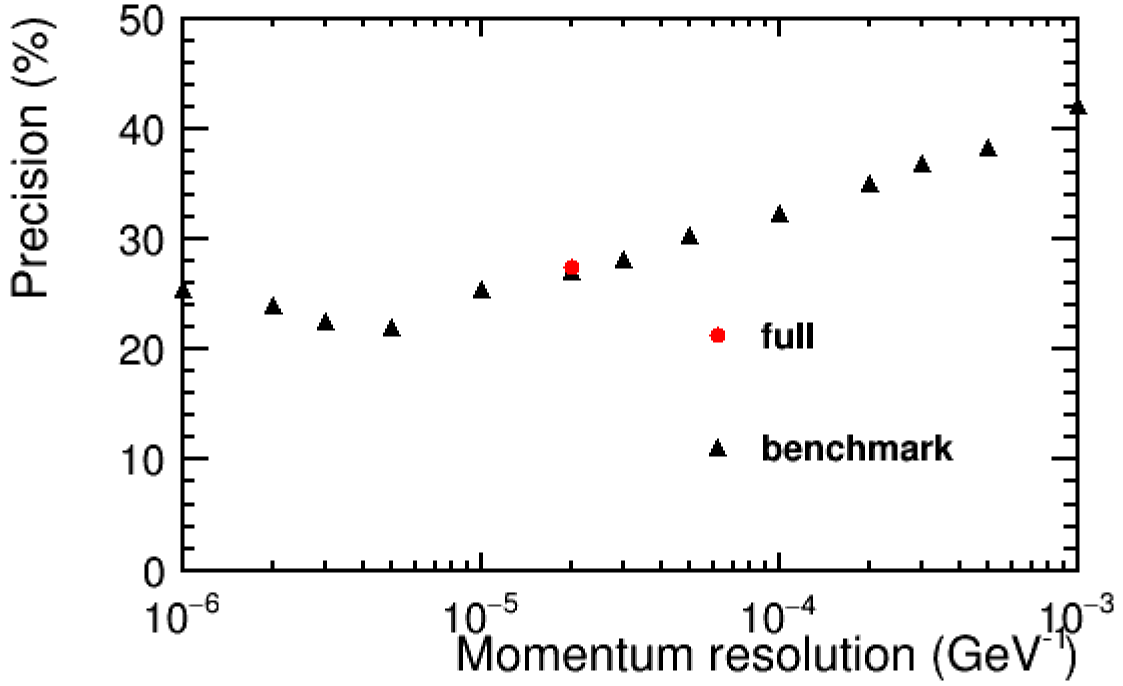
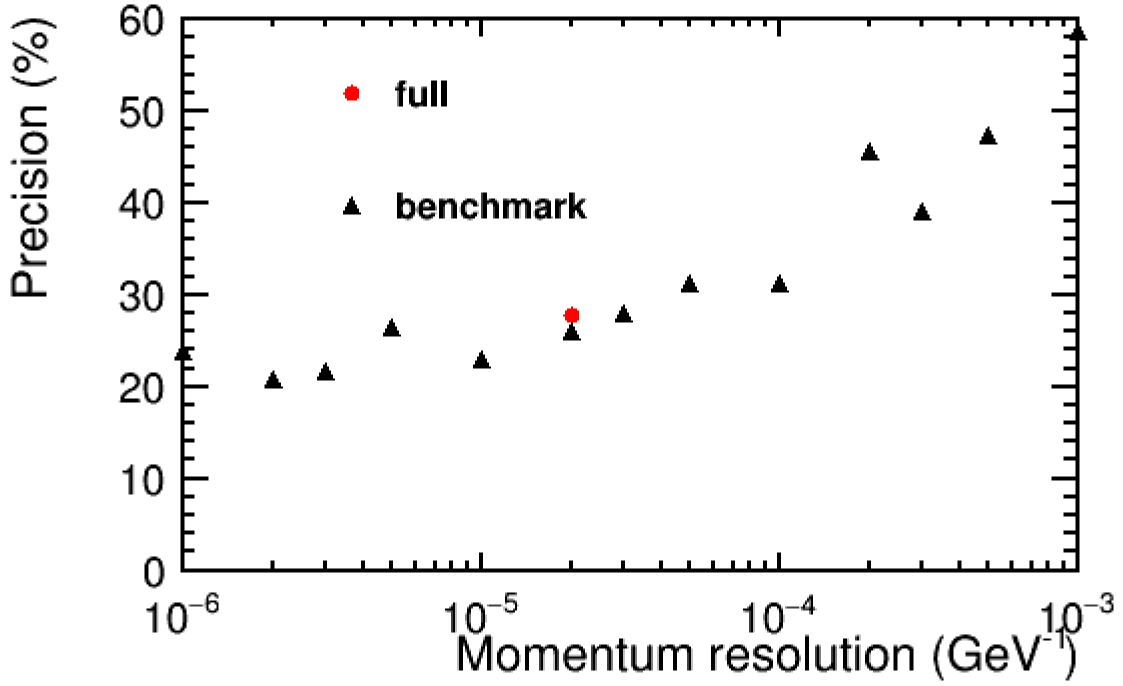


arXiv:1306.632 [physics.ins-det]

Results (Major Channel)

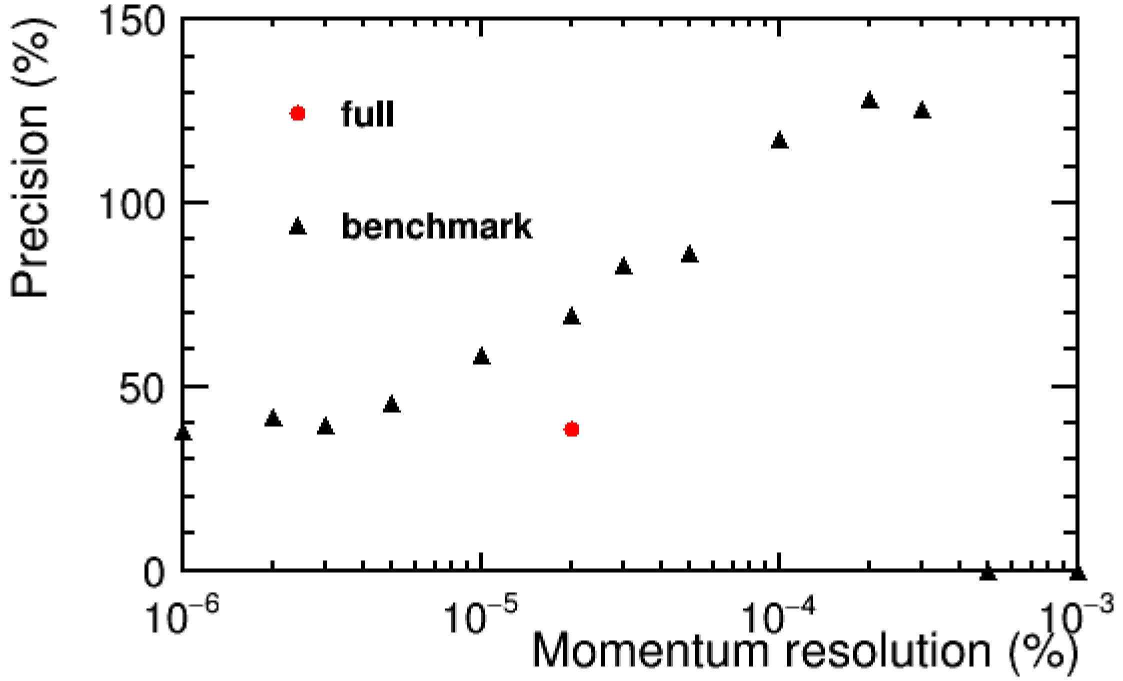




qqh250-L
full: 27.6%

nnh500-L
full: 27.8%

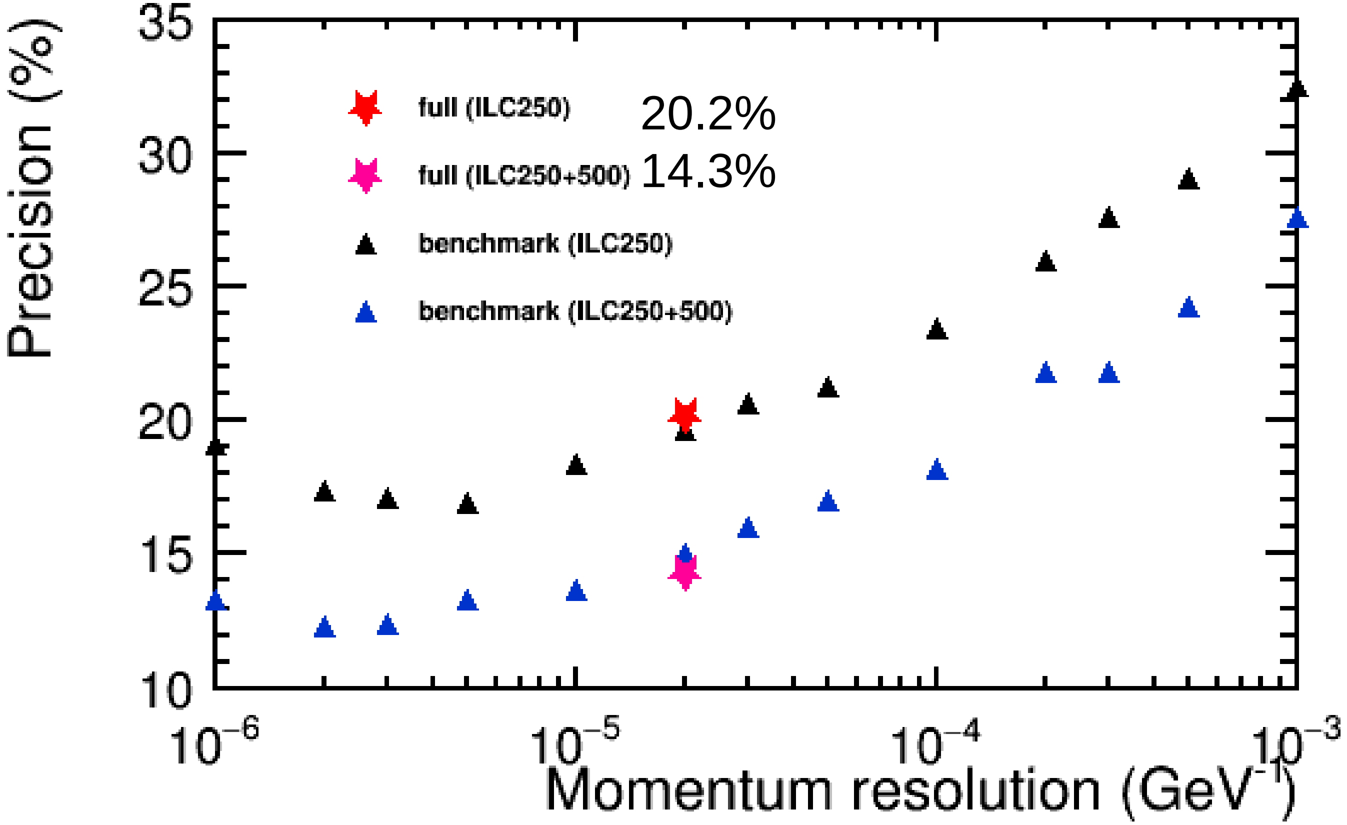
Results (???)



qqh500-L
full: 38.4%

- Fittings are failed many times
- Probably related too small number of events, or too small number of bkg MC events after all cuts.
- Smearing is applied signal and bkg.
- Planning to test: fix bkg, and smear only signal

Combined Results



ILC250:
~17-20% precision
ILC250+500:
~12-15% precision

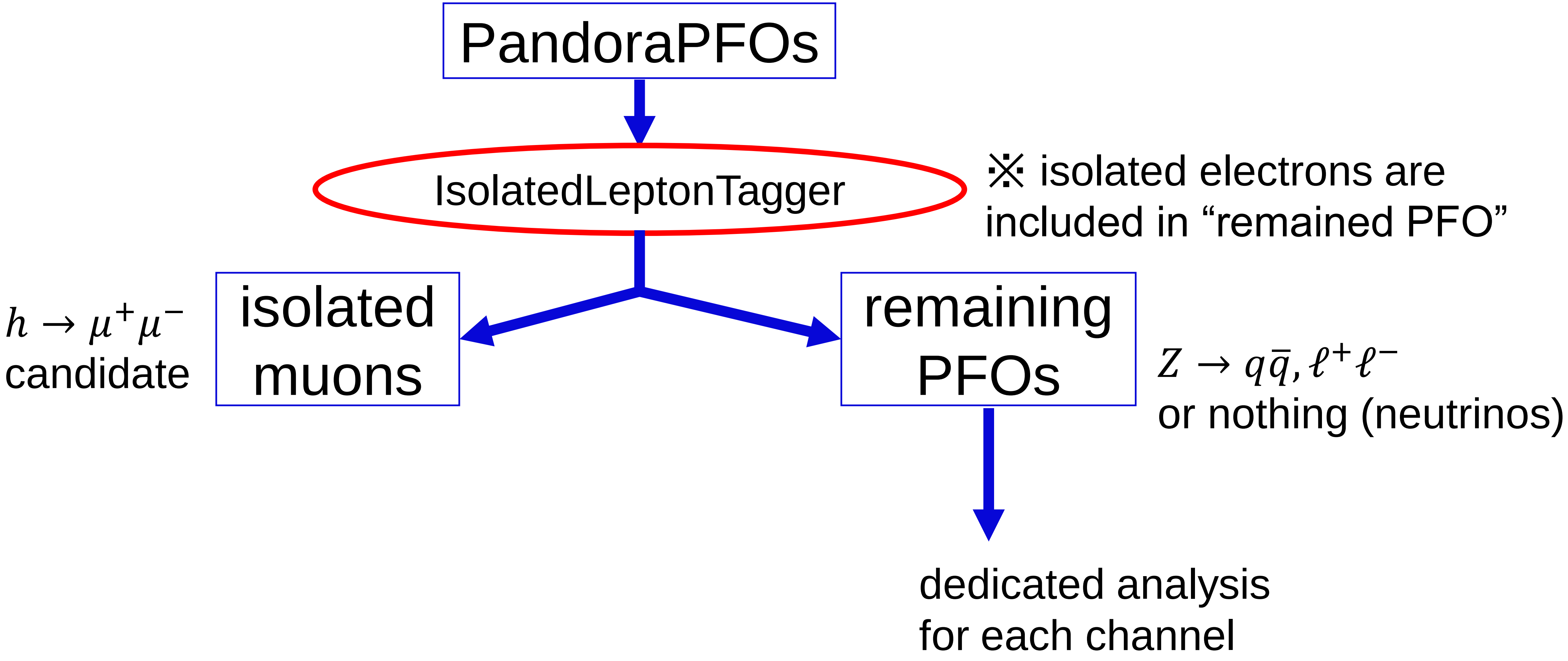
- ➢ relatively up to ~15% better results compare to full
- ➢ not drastic differences among better resolution cases

Summary

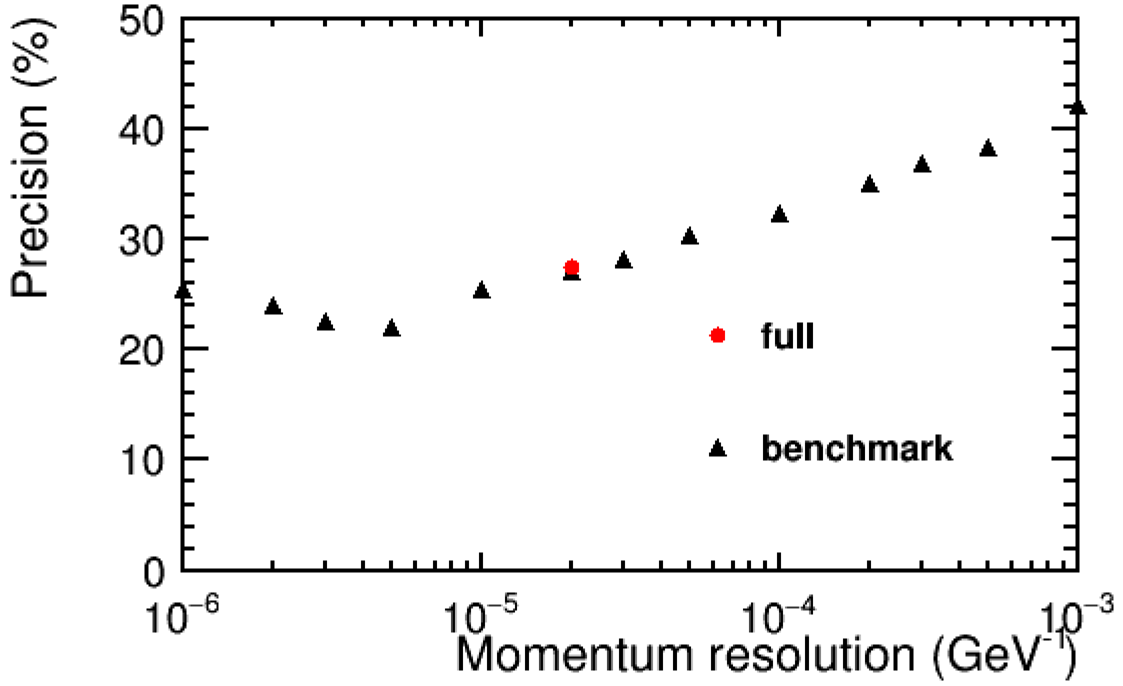
- Precise measurements and extracting absolute Higgs couplings are possible at the ILC
- Studied $h \to \mu^+\mu^-$ channel with E_{CM} = 250/500 GeV at the ILC
  - Can reach 14.3% combined precision for $\frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})}$
- Studied the impact of momentum resolution
  - Precision will not change dramatically around ~$1*10^{-5}$ momentum resolution
  - More studies needed

BACKUP

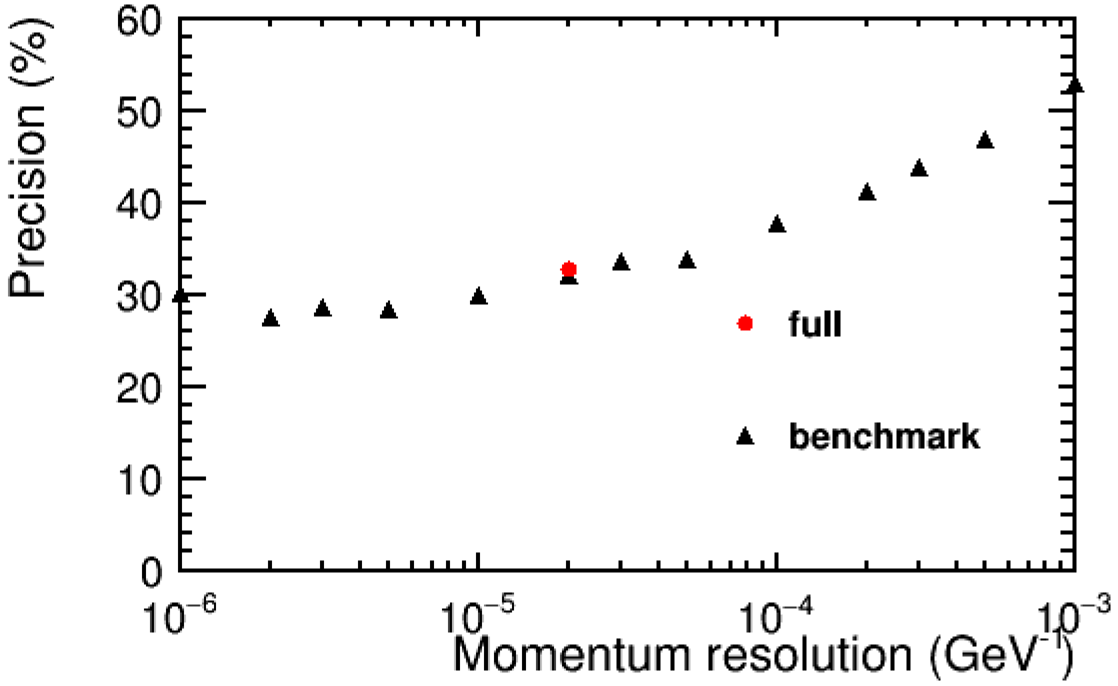
General Event Reconstruction



Results: qqh250

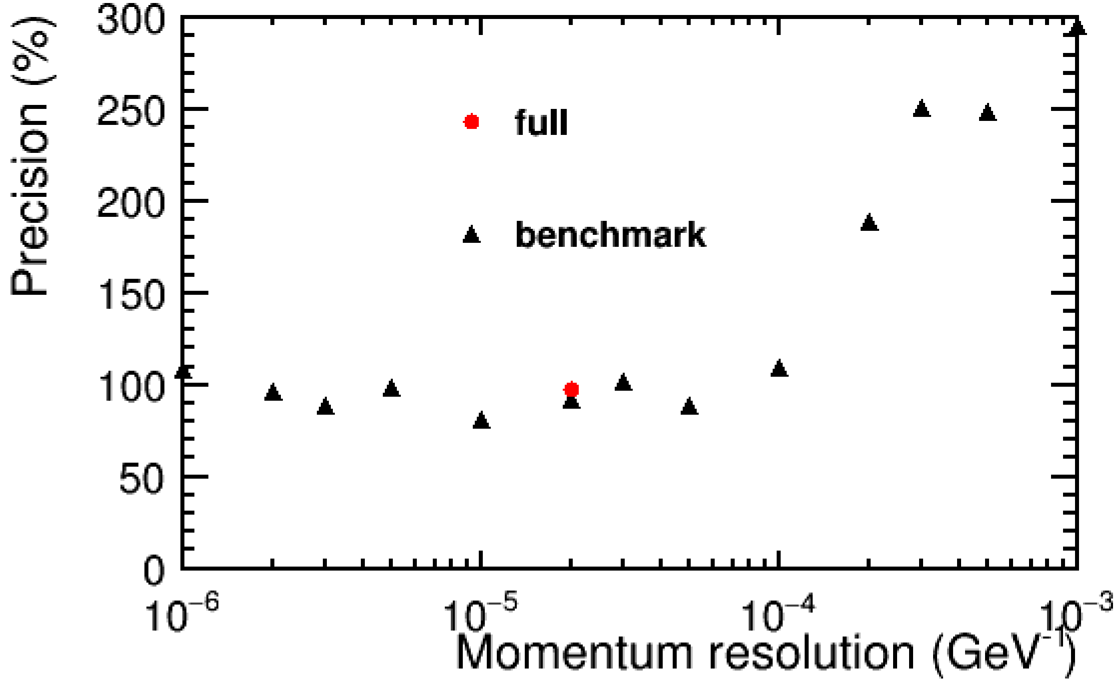


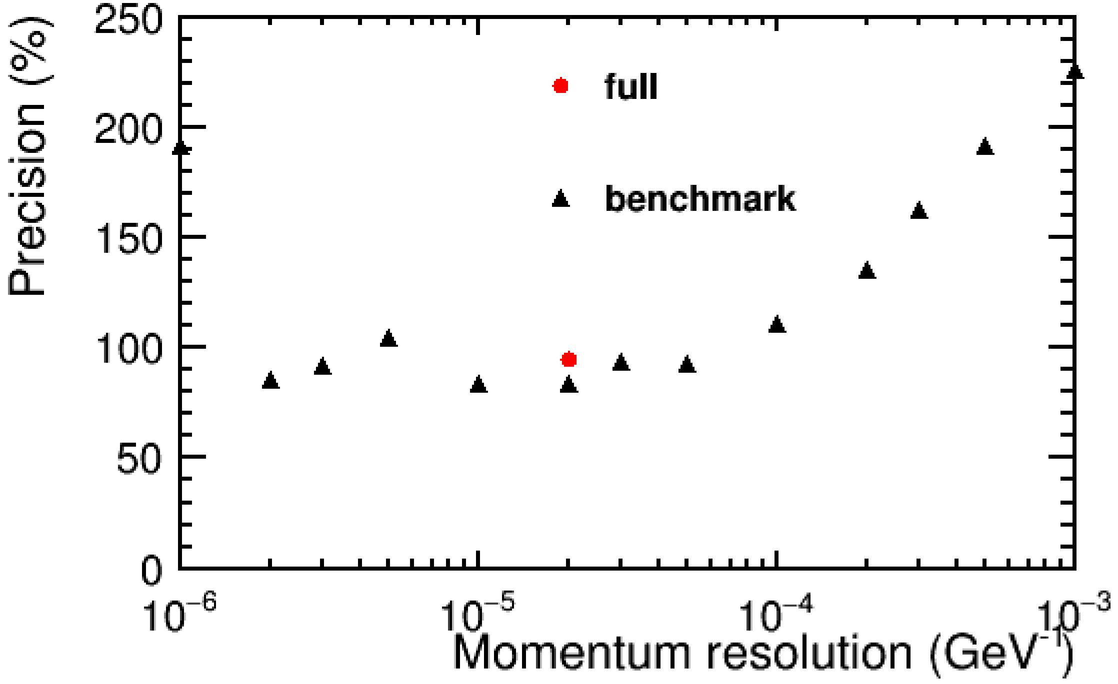
qqh250-L
full: 27.6%



qqh250-R
full: 32.9%

Results: nnh250

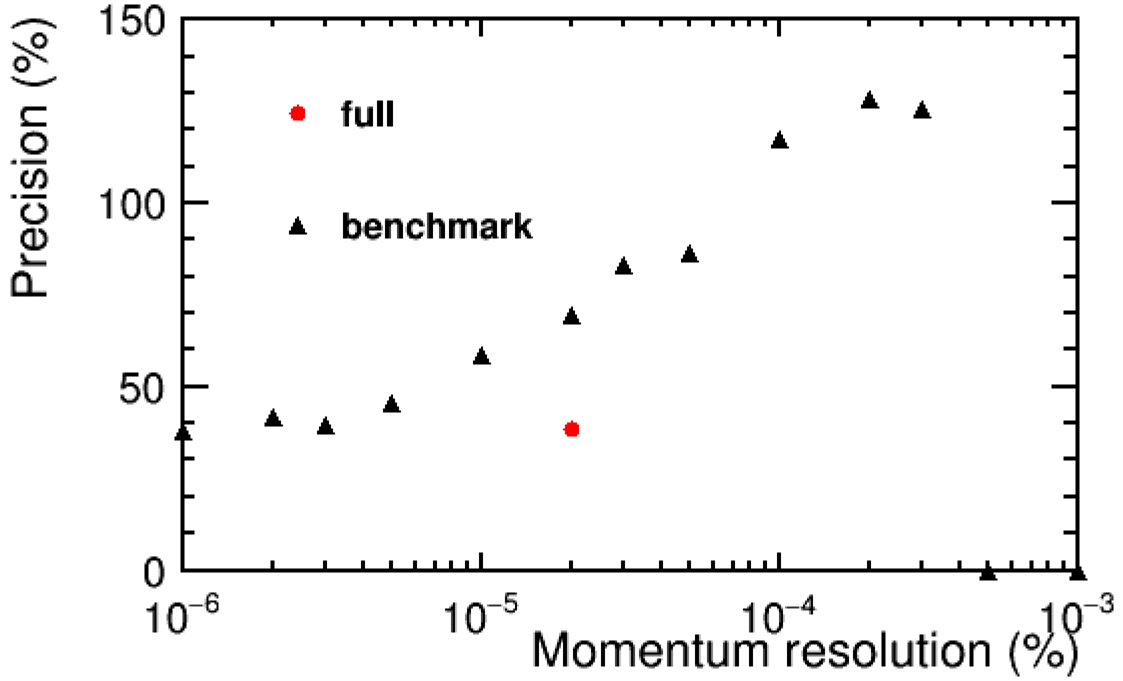




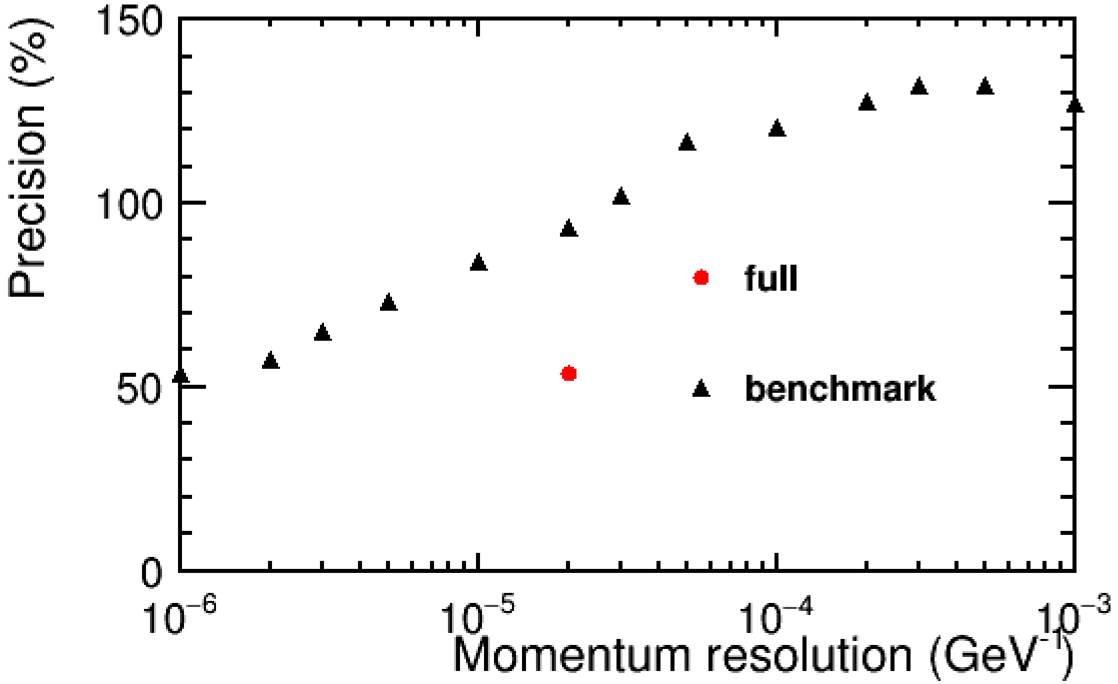
nnh250-L
full: 97.5%

nnh250-R
full: 94.7%

Results: qqh500

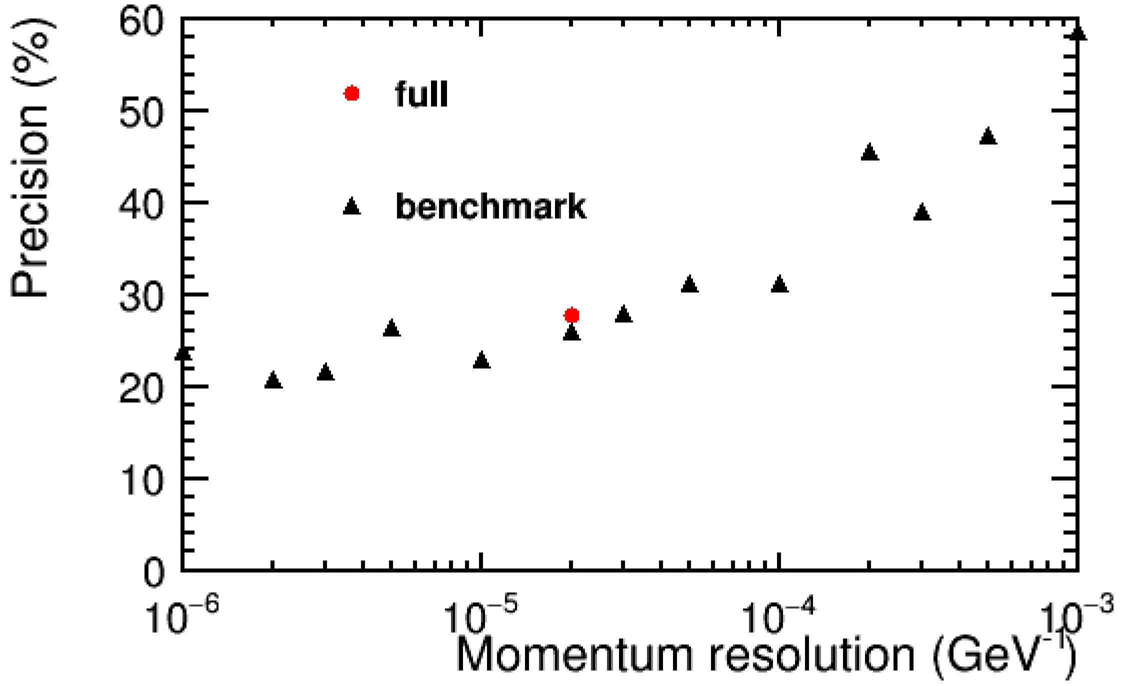


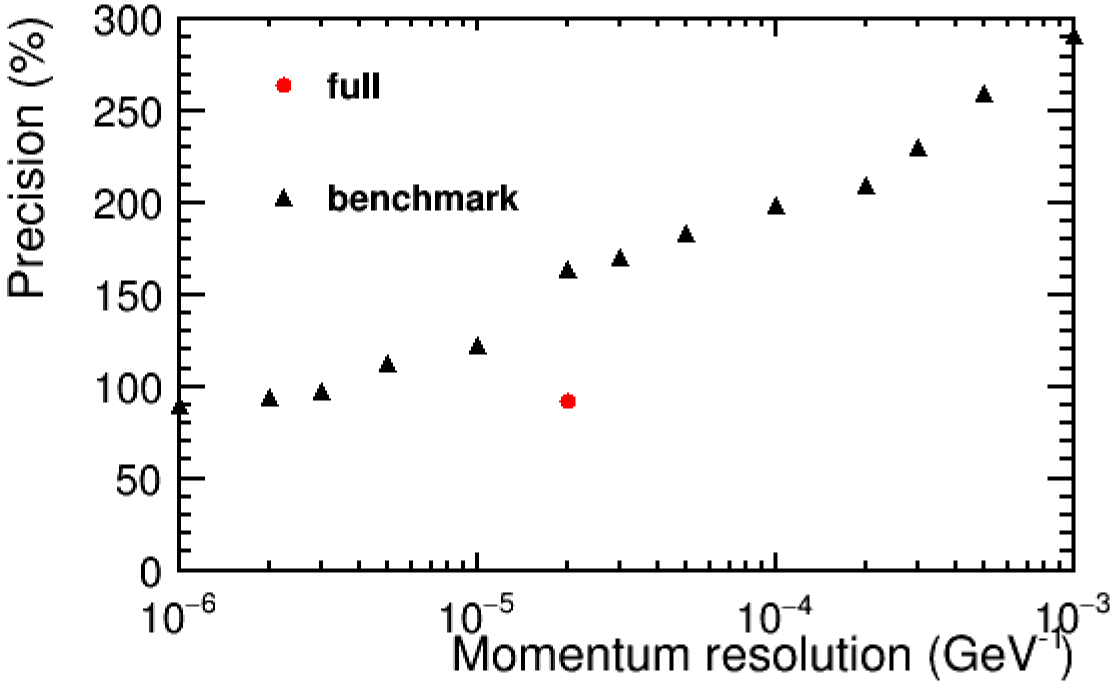
qqh500-L
full: 38.4%



qqh500-R
full: 53.9%

Results: nnh500





nnh500-L
full: 27.8%

nnh500-R
full: 92.5%