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

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2019/September/3

ILD Group Meeting

$h \to \mu^+\mu^-$ Work: General Status

- DBD-paper: today’s topic
- LCWS2019: plan to go
- IDR note: PUBLISHED! (ILD-PHYS-PUB-2019-002, see at https://confluence.desy.de/display/ILD/ILD+notes)
- IDR ($h \to \mu^+\mu^-$ part only): made comments long time ago

Introduction: $h \to \mu^+\mu^-$

- Can be used for testing
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd fermions and 2nd lepton/quark
- Very challenging analysis: small branching ratio ($\mathrm{BR}(h \to \mu^+\mu^-)$ = 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 pol.; 2*2*2 = 8 channels

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

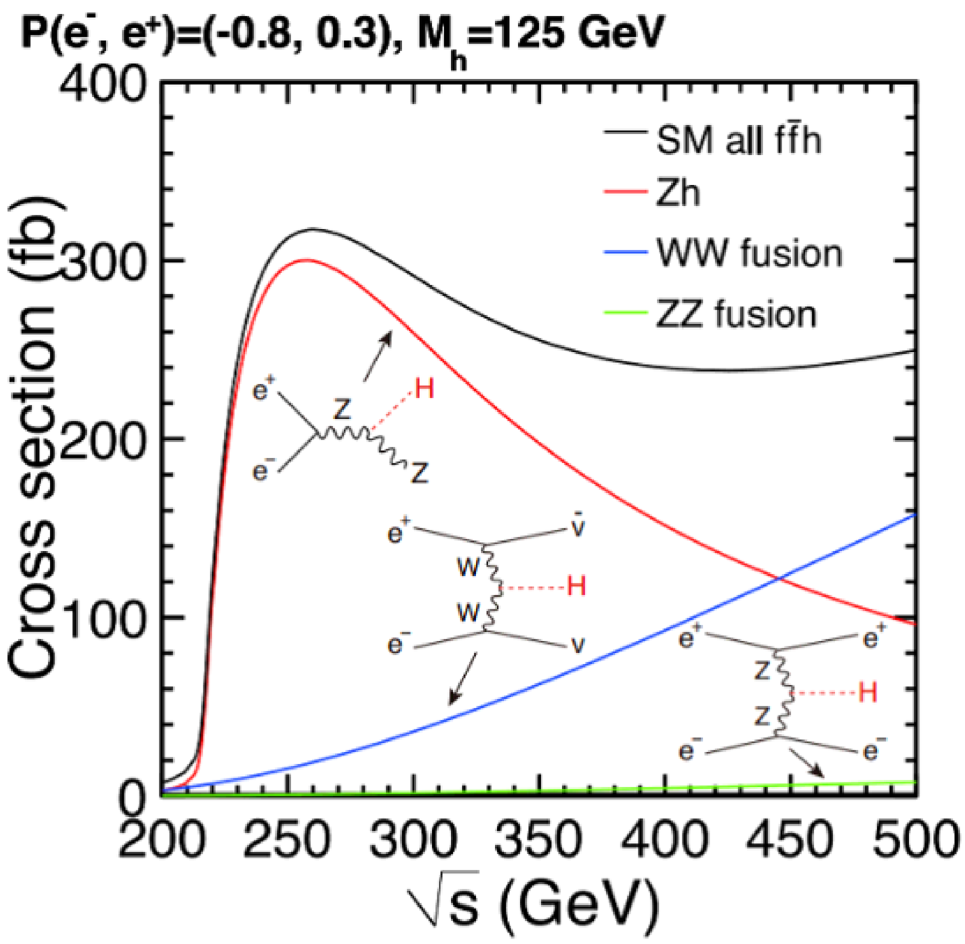


Table 2: The expected number of signal events N_{signal} for each channel, where $\int L dt$ is the integrated luminosity based on the running scenario [16–18].

channel	$\int L dt$ (ab^{-1})	N_{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

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

Summary of Analysis Procedure

- Select $h \to \mu^+\mu^-$ candidate
- Channel-specific reconstruction and preselection
- TMVA (BDTG) analysis
- Toy MC
  - Crystal Ball + Gaussian for signal modeling, 1st order polynomial for background modeling
  - 50000 times pseudo-experiments
  - optimization performed by changing BDTG score cut

Example of Modeling (qqh250-L)

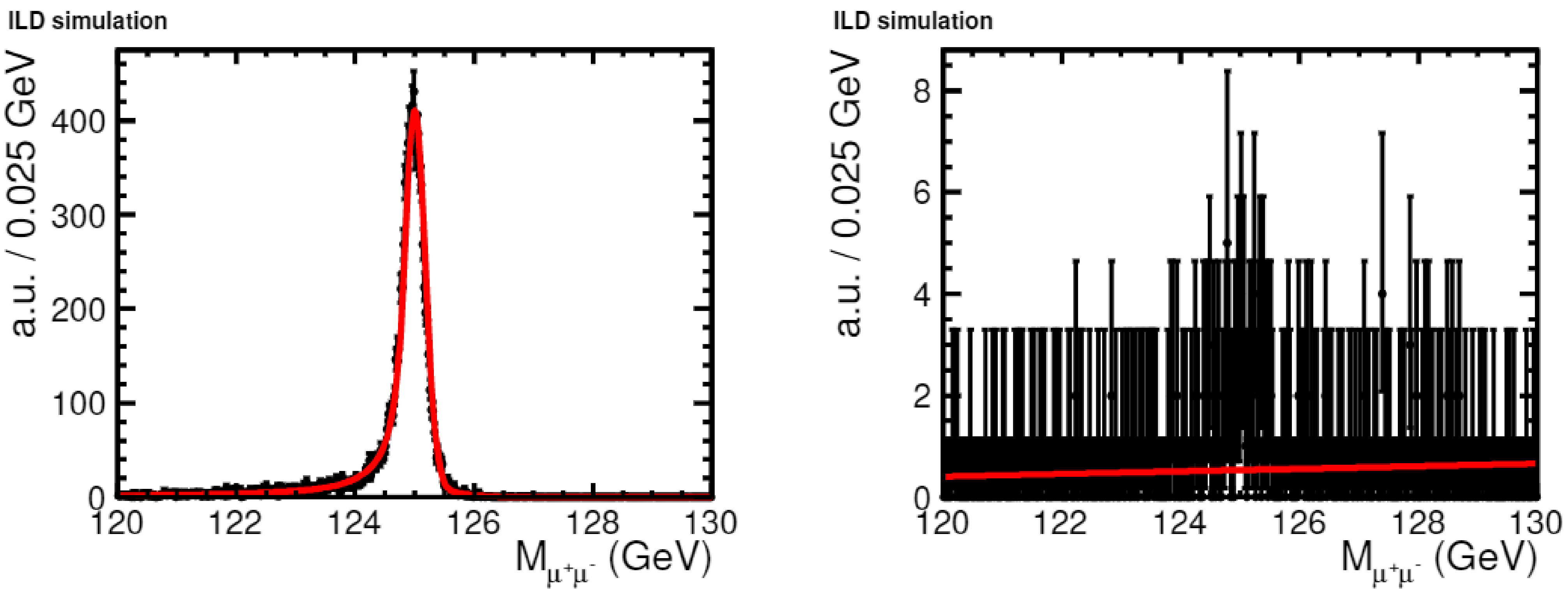


Figure 8: Modeling of $M_{\mu^+\mu^-}$ distribution after all cuts using modeling functions in qqh250-L. Left: signal process with the fitting result using f_S in the red curve. Right: background process with the fitting result using f_B in the red line.

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

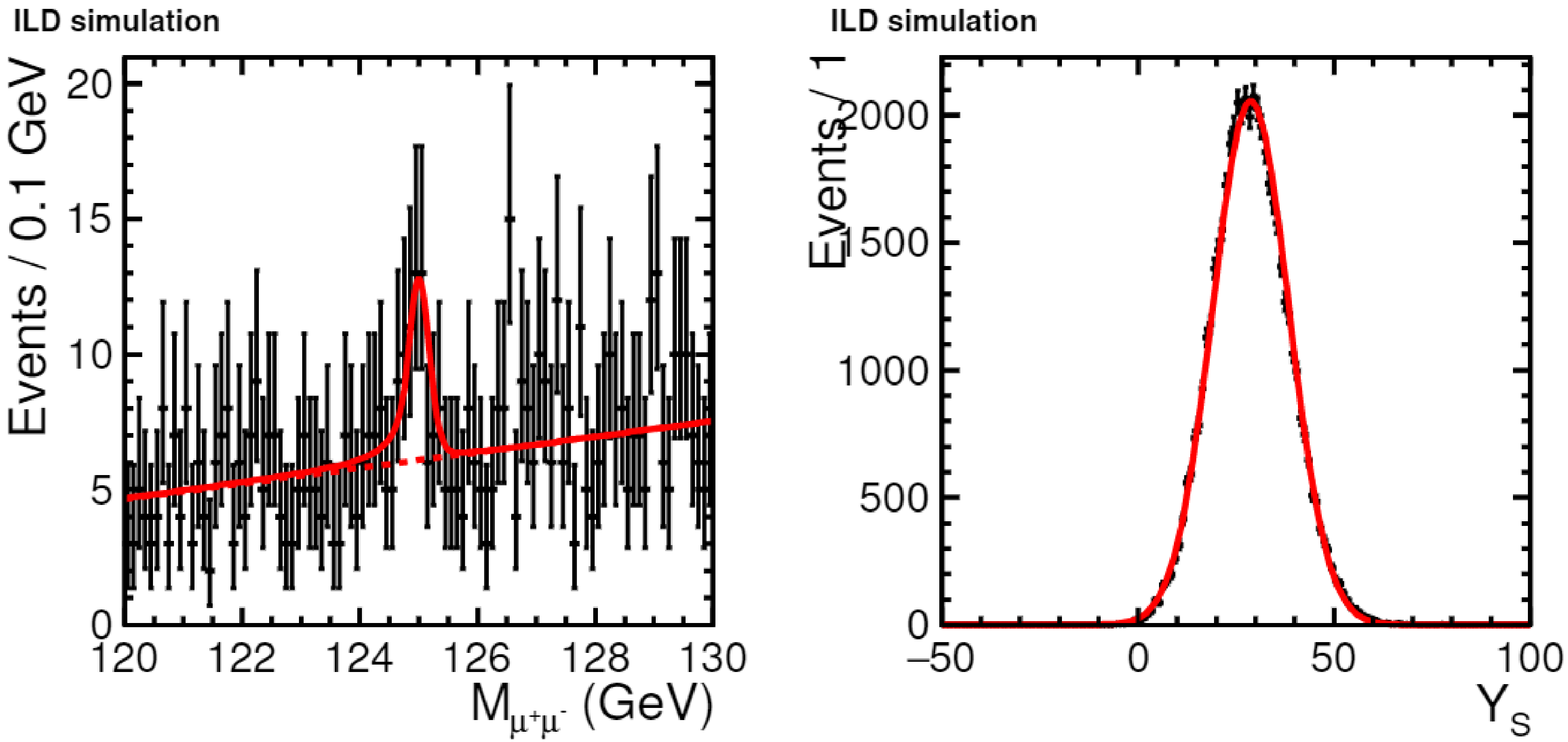


Figure 9: Left: an example of one pseudo-experiment in qqh250-L. Black dots are the pseudo-data. The solid red curve shows the unbinned fitting result using function $f \equiv Y_S f_S + Y_B f_B$ and the dotted red line shows its background component $Y_B f_B$. Right: the Y_S distribution after 50000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

Results

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	28.8(70.1%)	0.1	570.3	4.4
qqh250-R	> 0.90	16.4(58.4%)	~ 0	143.1	3.5
nnh250-L	> 0.95	4.2(28.2%)	~ 0	155.3	12.2
nnh250-R	> 0.70	4.5(53.3%)	~ 0	170.9	13.9
qqh500-L	> 0.60	13.1(53.5%)	4.2	113.8	8.9
qqh500-R	> 0.25	10.0(60.8%)	9.6	71.3	7.3
nnh500-L	> 0.50	30.8(53.5%)	~ 0	744.6	48.1
nnh500-R	> 0.35	3.8(48.1%)	0	90.1	1.0

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

$\sqrt{s} = 250$ GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	33.7%	116.8%
R	35.9%	111.8%
$\sqrt{s} = 500$ GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	42.9%	37.2%
R	48.9%	106.5%

ILC250: **23.5%**

ILC250+500: **16.7%**

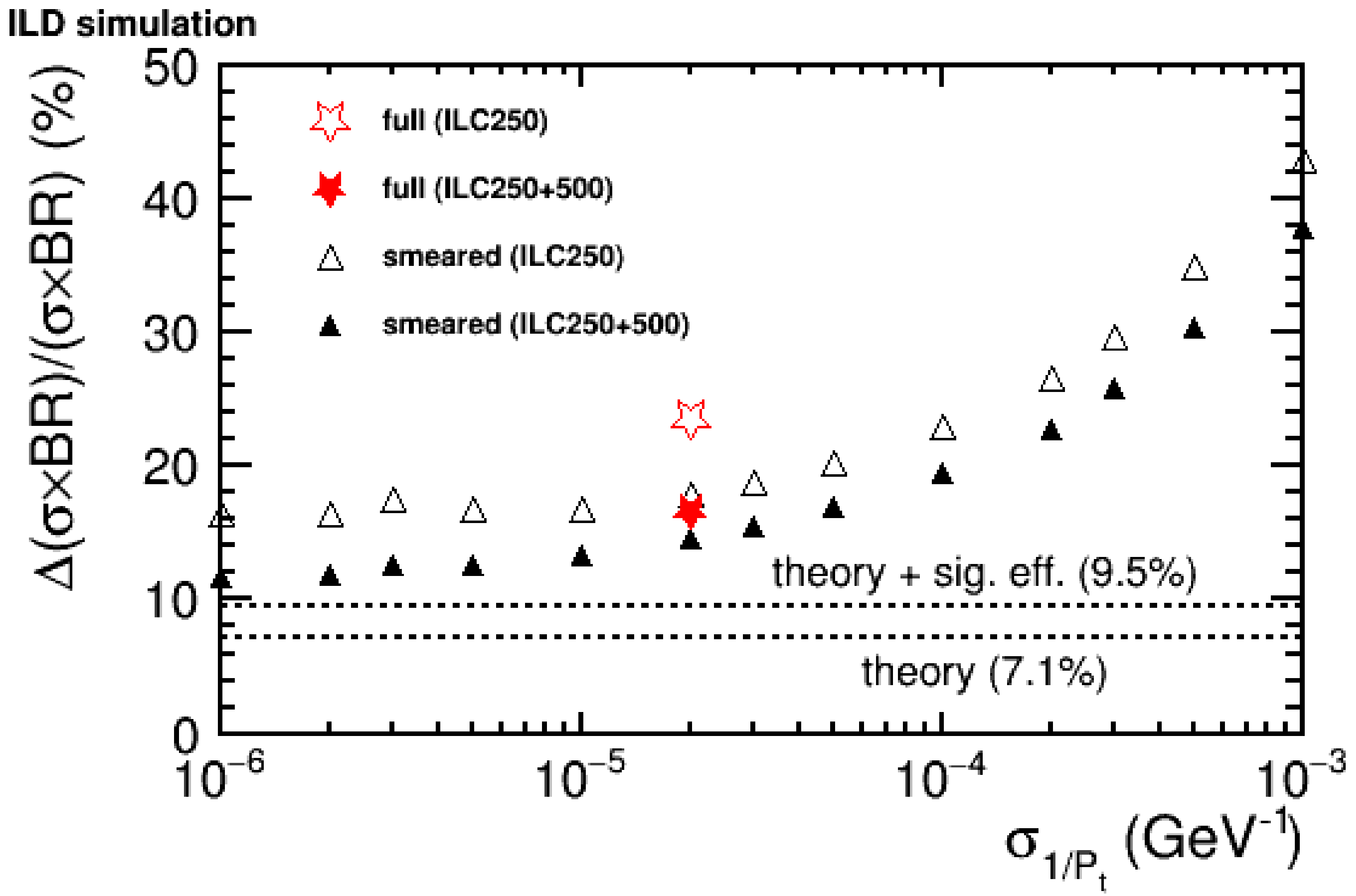
Discussion 1

- Factor 2.4 far from theory (100% sig. eff., no bkg, no det. eff.)
  - ILC250(ILC250+500) theory = 10.4%(7.1%)
- 2 major reasons: signal selection efficiency and “irreducible” background
    - $q\bar{q}\mu^+\mu^-$ for $q\bar{q}h$, $\nu\bar{\nu}\mu^+\mu^-$ for $\nu\bar{\nu}h$
- Worse than HL-LHC prospects (10-13%)
  - ~200 events vs O(10^4) events
  - possible improvement by adding 1 TeV data; ~11%
  - can extract absolute couplings under EFT framework at ILC

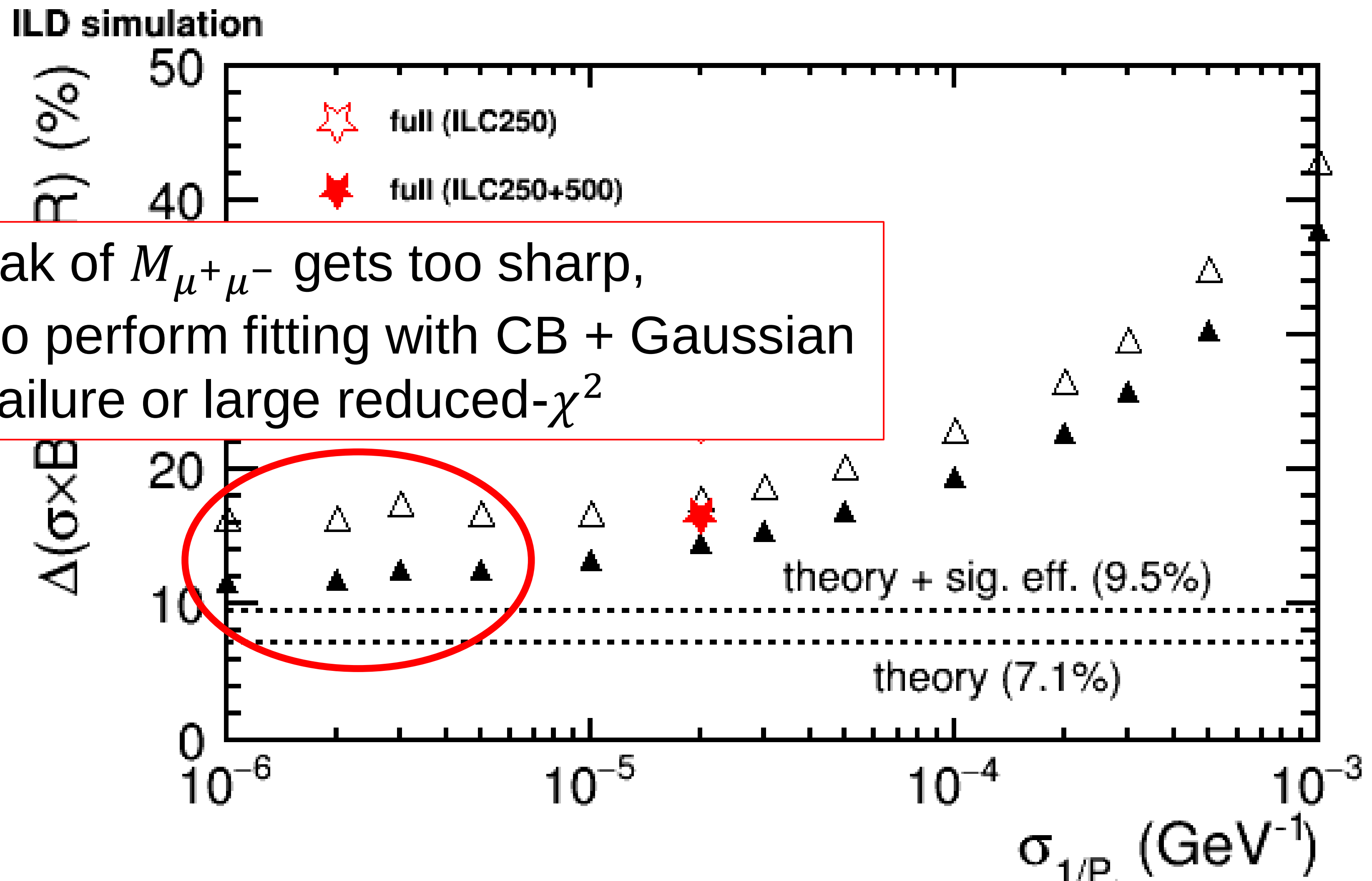
Impact of Transverse Momentum Resolution

- $M_{\mu^+\mu^-}$ is most important ---> 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}) with a Gaussian random number, apply smearing to MC truth momentum of $h \rightarrow \mu^+\mu^-$ candidate
  - found a mistake in previous analysis code (technical details in backup), causes some overestimation especially at 500 GeV

New Plot (ILC250+500)



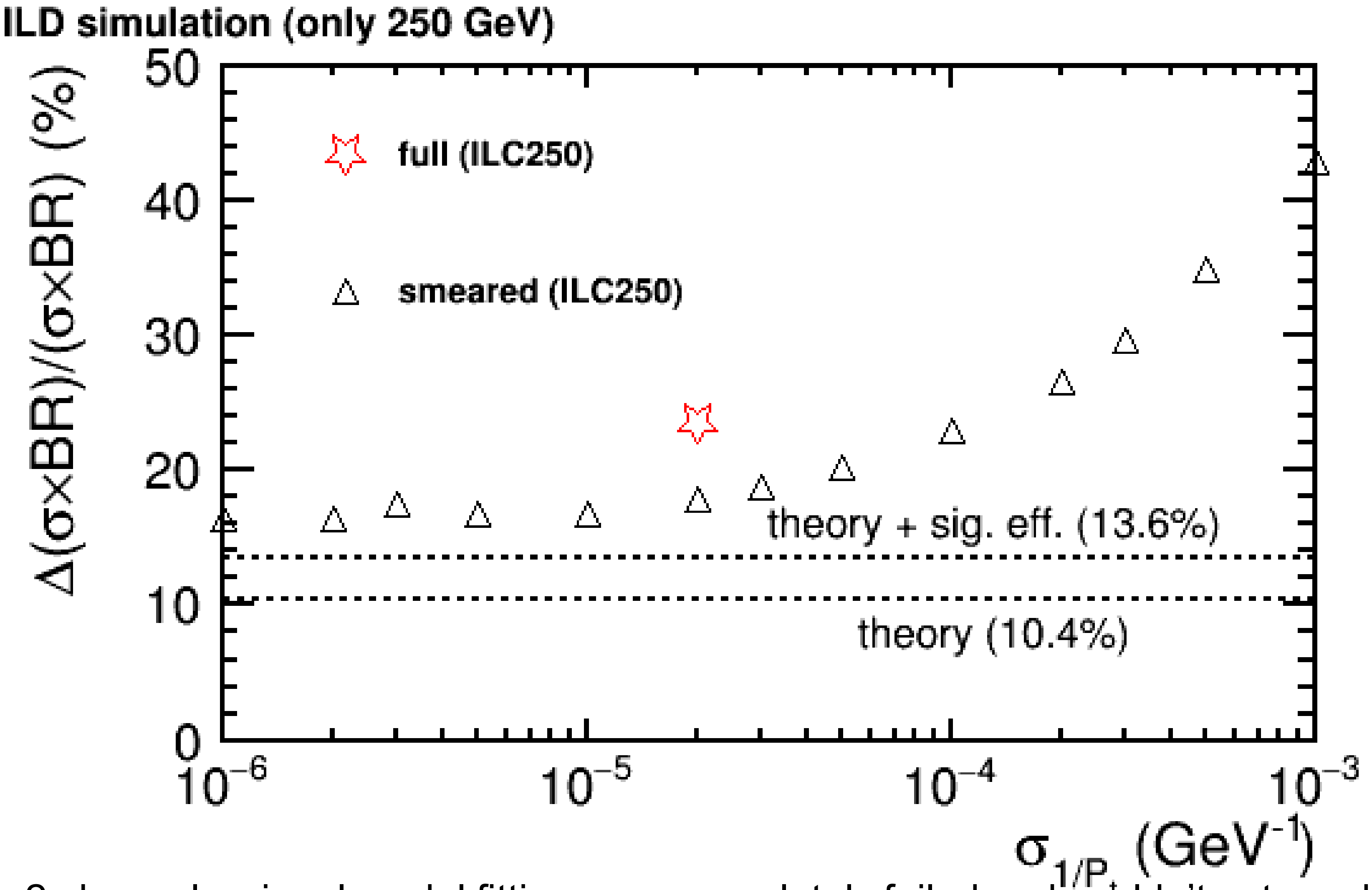
New Plot (ILC250+500)



since the peak of $M_{\mu^+\mu^-}$ gets too sharp,
it is difficult to perform fitting with CB + Gaussian
completely failure or large reduced-χ^2

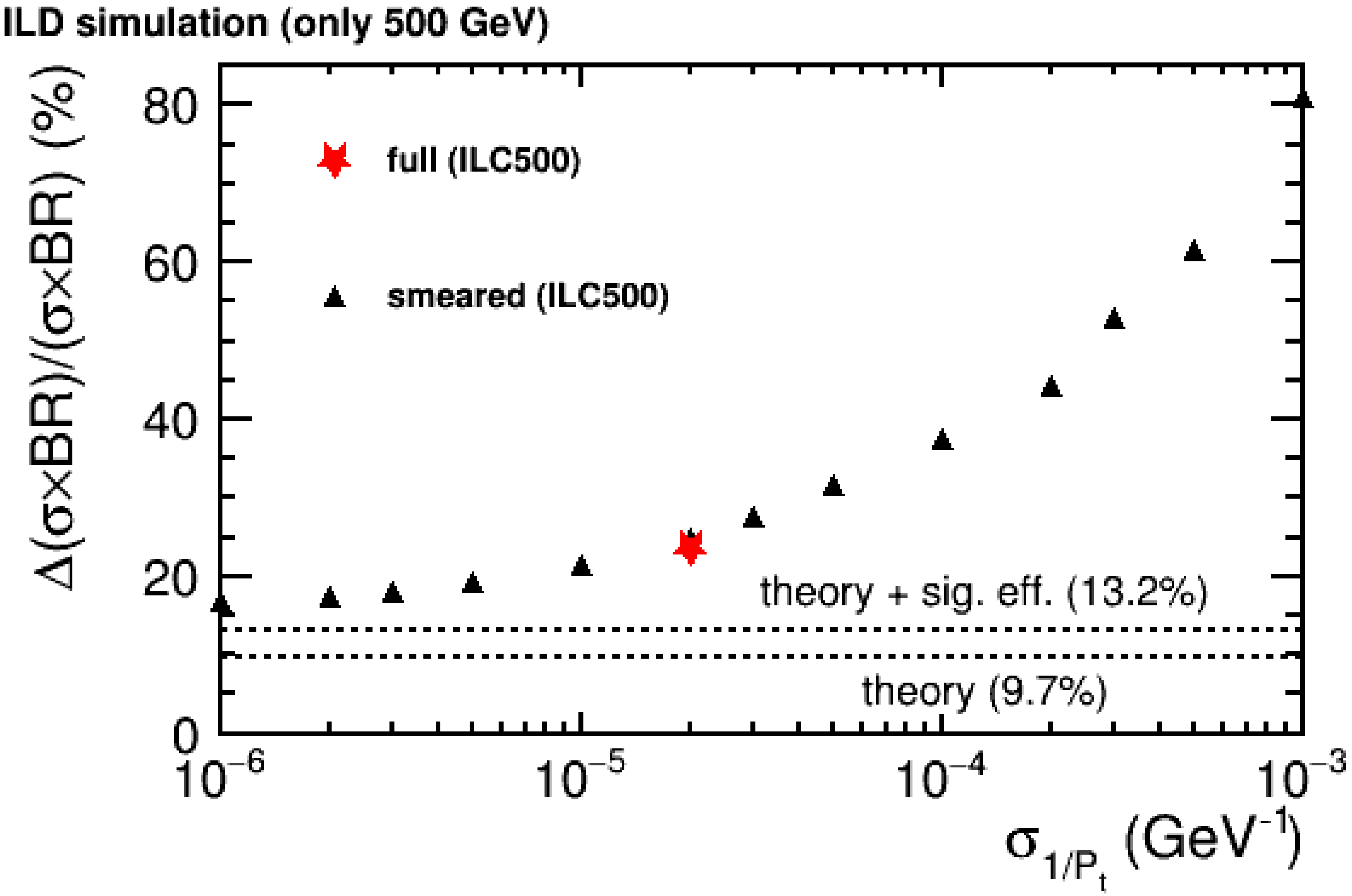
※In 2 channels, signal model fitting were completely failed and couldn't get numbers.
In the plot, some interpretation has been made at $5*10^{-6}$. (see backup)

New Plot (ILC250 only)



※In 2 channels, signal model fitting were completely failed and couldn't get numbers.
In the plot, some interpretation has been made at $5*10^{-6}$. (see backup)

New Plot (ILC500 only)



Discussion 2

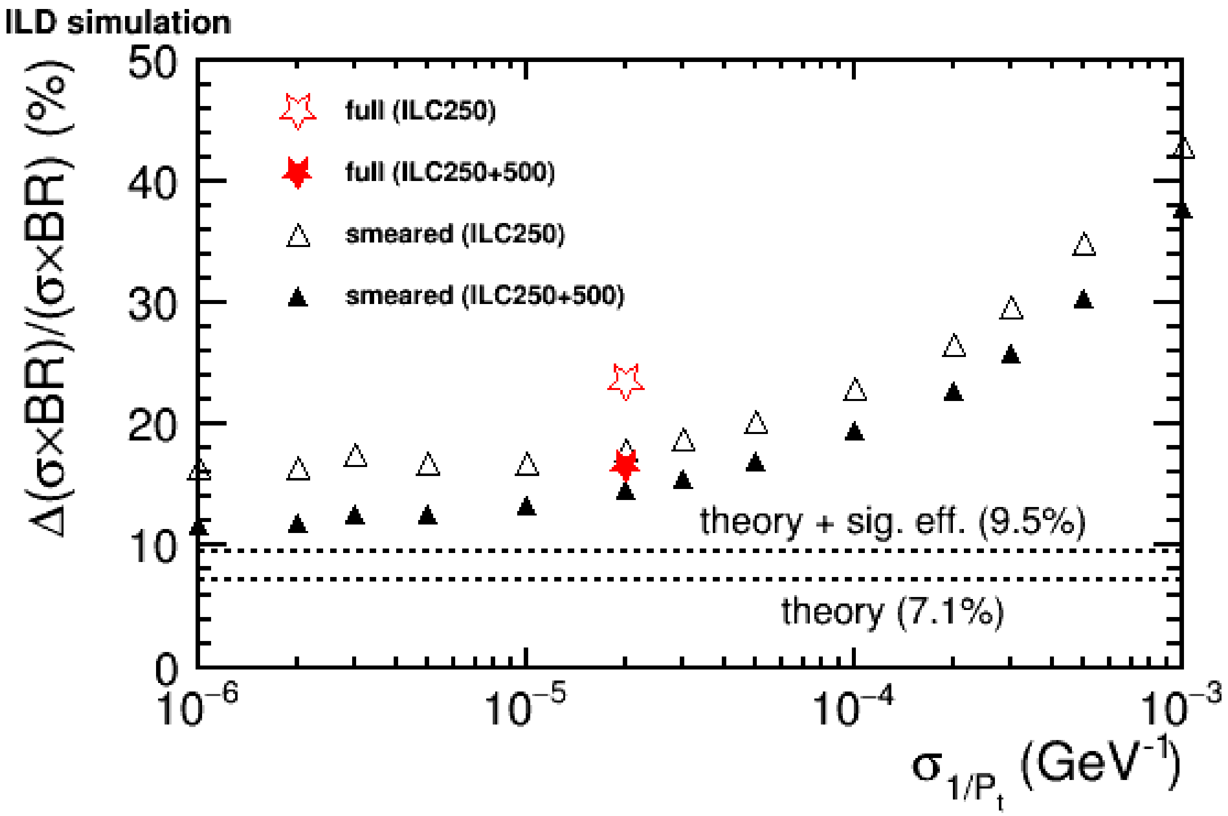
- CB + Gaussian signal modeling works perfectly until certain resolution but will not work in extremely good resolution cases, because the shape of $M_{\mu^+\mu^-}$ gets like Breit-Wigner function (+ FSR tail).
- It is important archive ILD goal for transverse momentum resolution for this analysis.
- Developing ultimate precision detector system and more proper modeling function will not improve the results. It will reach to the limit (dotted-lines).
- Possible limiting factor for this analysis is listed up (next page).

Limiting Factor For This Analysis

Limiting Factor	Reason	How To Improve
small # signal events	- physics - analysis	- more luminosity and more money - keep high signal efficiency
remaining background $q\bar{q}\mu^+\mu^-$ for $q\bar{q}h$ $\nu\bar{\nu}\mu^+\mu^-$ for $\nu\bar{\nu}h$	- physics - analysis	- develop more advanced technique - keep high background rejection rate
momentum resolution σ_{1/p_T}	- detector (hardware) - algorithm (software)	- more developments (only be the problem when σ_{1/p_T} is very bad)
FSR	- physics - analysis	- develop more sophisticated technique (only be the problem when σ_{1/p_T} is very good)

Discussion 3

Almost same conclusion with CLIC physics (1.4 TeV)



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

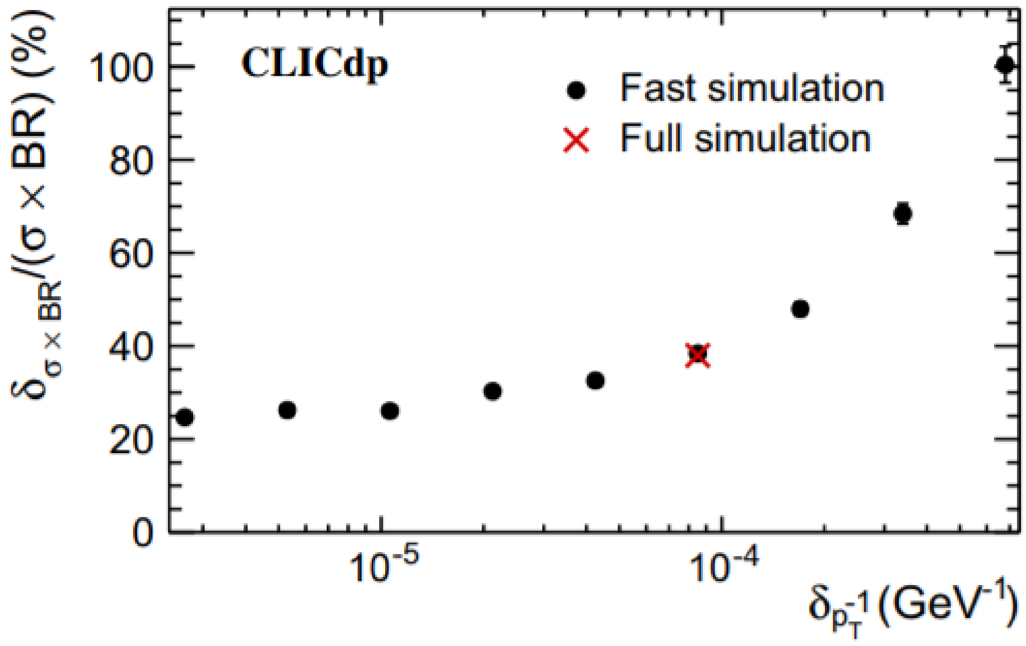


Fig. 11 Dependence of the relative statistical uncertainty of the $\sigma(H\nu\bar{\nu}) \times BR(H \to \mu^+\mu^-)$ on the transverse momentum resolution, δ_{1/p_T}, averaged over the signal sample in the whole detector

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 $H \to \mu^+\mu^-$ decay. (EPJC (2015) 75:515)

DBD-Paper Full Draft: How It Looks Like

Prospects of measuring Higgs boson decays into muon pairs at the International Linear Collider

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Abstract

We study the prospects for measuring the branching ratio of $h \to \mu^+\mu^-$ at the International Linear Collider (ILC). The study is performed at center-of-mass energies ($\sqrt{s}$) of 250 GeV and 500 GeV based on a full detector simulation of the International Large Detector (ILD) concept. For both $\sqrt{s}$ cases, the two final states $q\bar{q}h$ and $\nu\bar{\nu}h$ have been analyzed. For an integrated luminosity of 2 ab^{-1} at $\sqrt{s} = 250$ GeV and 4 ab^{-1} at $\sqrt{s} = 500$ GeV, the combined precision on the cross section times branching ratio of $h \to \mu^+\mu^-$ is estimated to be 16.7%. The impact of the transverse momentum resolution for this analysis is also studied. It is very important to achieve the detector requirement of the ILD for the transverse momentum resolution, but an ultimate resolution will not improve the results anymore, and the results will be limited by other factors.

Summary

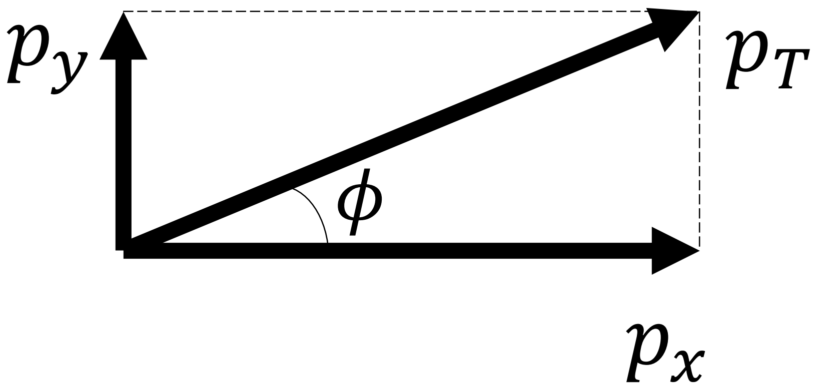
- DBD-analysis is done.
  - Obtained expected performance for precision on $\sigma \times \mathrm{BR}(h \to \mu^+\mu^-)$
  - Studied the impact of transverse momentum resolution σ_{1/p_T}
  - Almost same conclusion with CLIC 1.4 TeV analysis
  - Identified possible limiting factors and rooms for improvement
- DBD-paper: full draft will available in soon, and will start discussion with supervisors/referees

- Additional work: proceedings of EPS-HEP 2019 (deadline Oct./15, LCC Higgs Physics Talk)

BACKUP

Before Smearing

(from $h \to \mu\mu$ candidate)
μ MC-truth 4-momentum
(p_x, p_y, p_z, E)



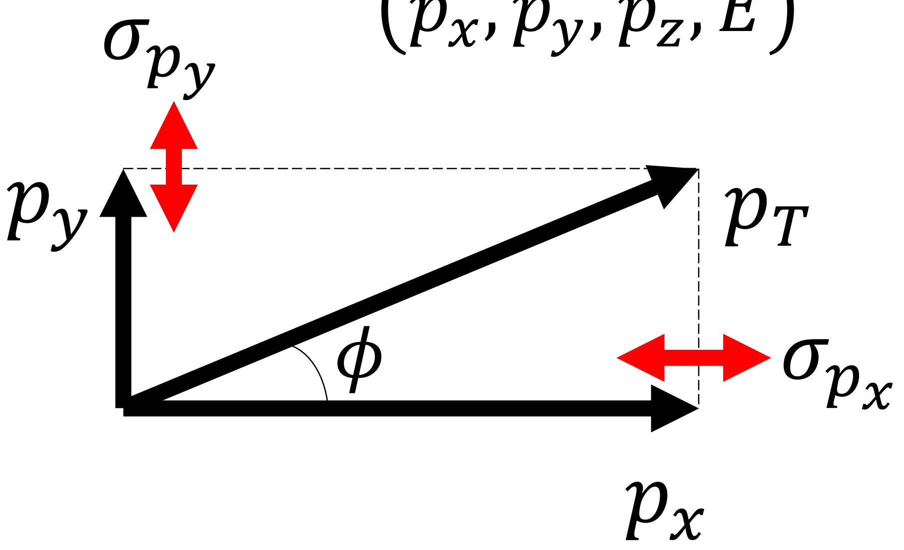
master formula

$$\sigma_{p_T} = \sigma_{1/p_T} \times p_T^2$$

σ_{1/p_T} is just a constant

Previous (1)

(from $h \to \mu\mu$ candidate)
μ MC-truth 4-momentum
(p_x, p_y, p_z, E)



master formula

$$\sigma_{p_T} = \sigma_{1/p_T} \times p_T^2$$

σ_{1/p_T} is just a constant

I interpreted as:

$$\sigma_{p_x} = \sqrt{\sigma_{p_T}}, \sigma_{p_y} = \sqrt{\sigma_{p_T}}$$

and simulate each with gRandom->Gaus(0, $\sqrt{\sigma_{p_T}}$).

Obtain $\sigma_{p_x}(\mathrm{sim})$ and $\sigma_{p_y}(\mathrm{sim})$.

Smearing vector is:

$$\left(\sigma_{p_x}(\mathrm{sim}), \sigma_{p_y}(\mathrm{sim}), 0, 0\right)$$

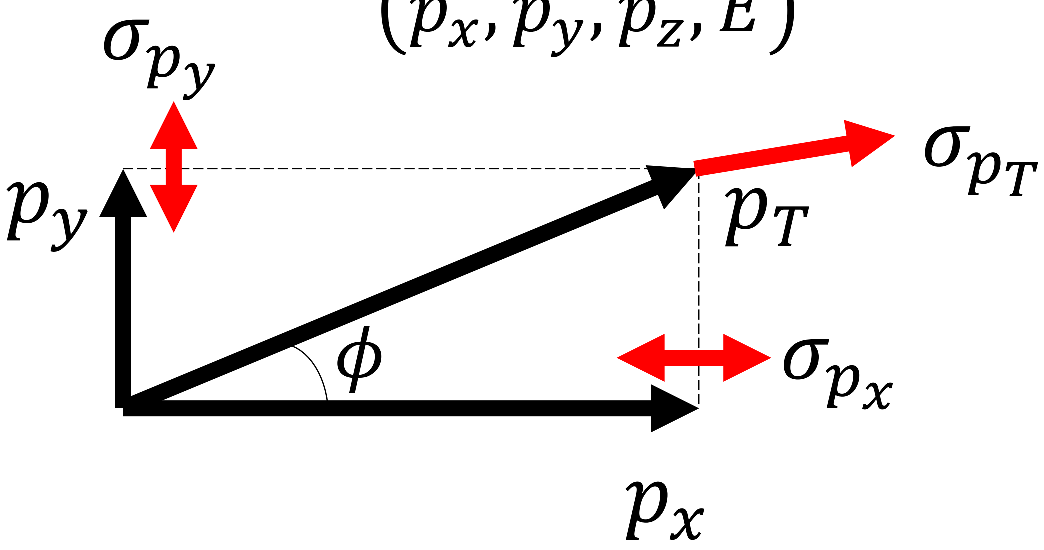
Previous (2)

master formula

$$\sigma_{p_T} = \sigma_{1/p_T} \times p_T^2$$

σ_{1/p_T} is just a constant

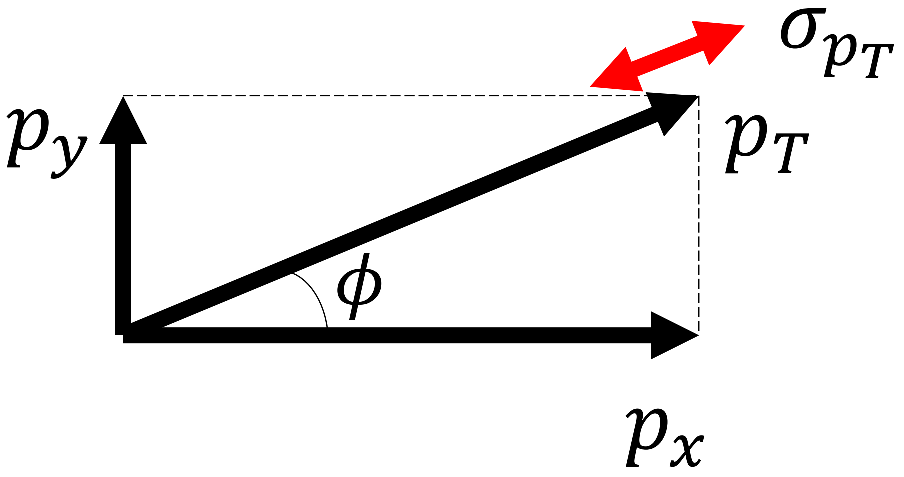
(from $h \rightarrow \mu\mu$ candidate)
μ MC-truth 4-momentum
(p_x, p_y, p_z, E)



However:
(1) σ_{p_T}-vector will not parallel to p_T-vector
(2) simulating not correct variable
-> can overestimate $\sigma_{p_T}(\text{sim})$ up to factor $\sqrt{2}$
-> more terrible in 500 GeV because higher p_T

Now (1)

(from $h \to \mu\mu$ candidate)
μ MC-truth 4-momentum
(p_x, p_y, p_z, E)



master formula

$$\sigma_{p_T} = \sigma_{1/p_T} \times p_T^2$$

σ_{1/p_T} is just a constant

simulate σ_{p_T} directly with gRandom->Gaus(0, σ_{p_T}), obtain $\sigma_{p_T}(\mathrm{sim})$.

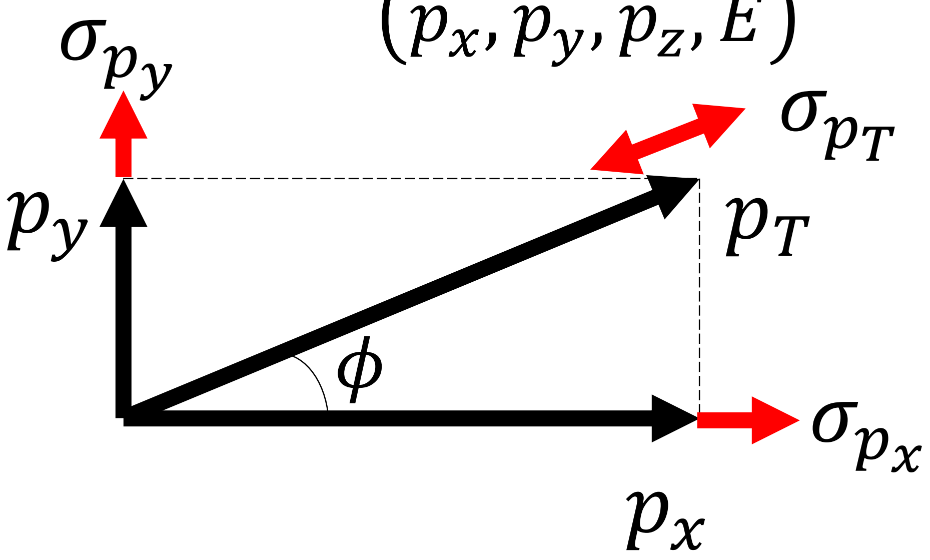
Then the smearing vector is:

$$\sigma_{p_x}(\mathrm{sim}) = \sigma_{p_T}(\mathrm{sim}) \times \cos\phi$$

$$\sigma_{p_y}(\mathrm{sim}) = \sigma_{p_T}(\mathrm{sim}) \times \sin\phi$$

Now (2)

(from $h \to \mu\mu$ candidate)
μ MC-truth 4-momentum
(p_x, p_y, p_z, E)



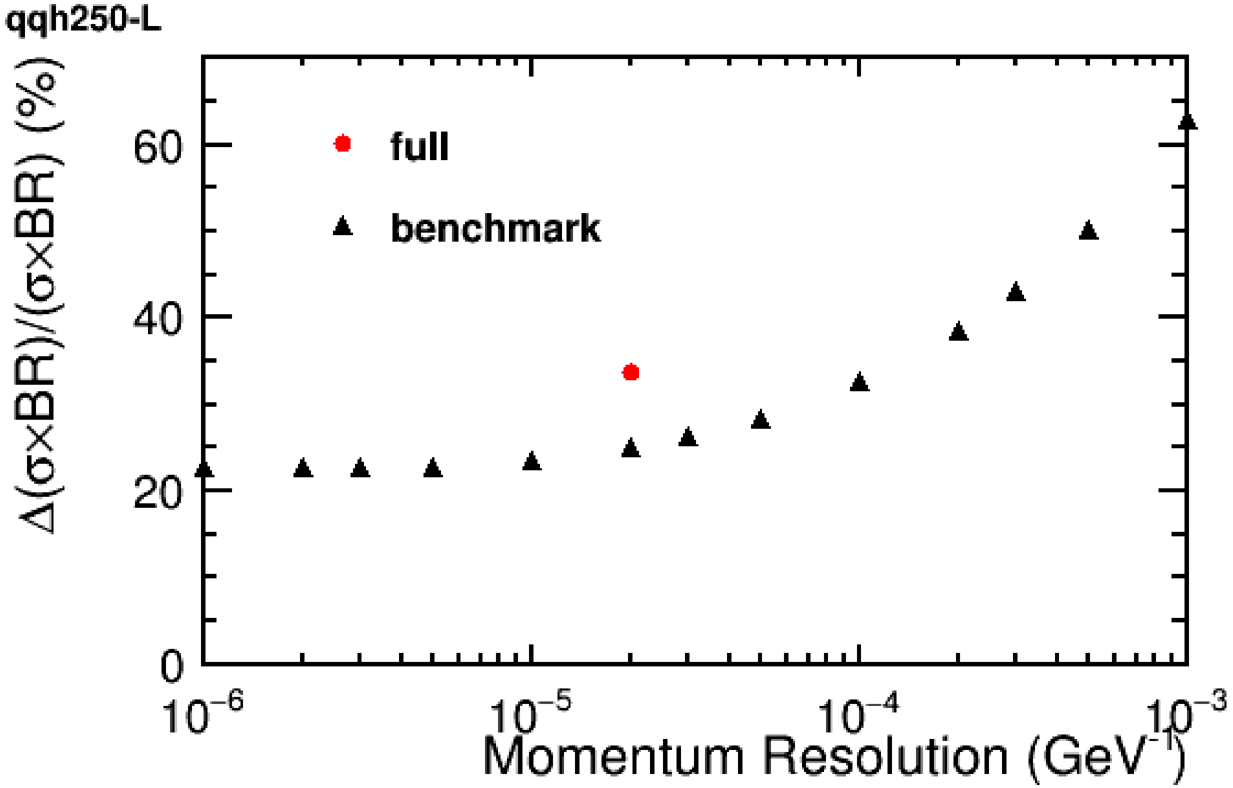
master formula

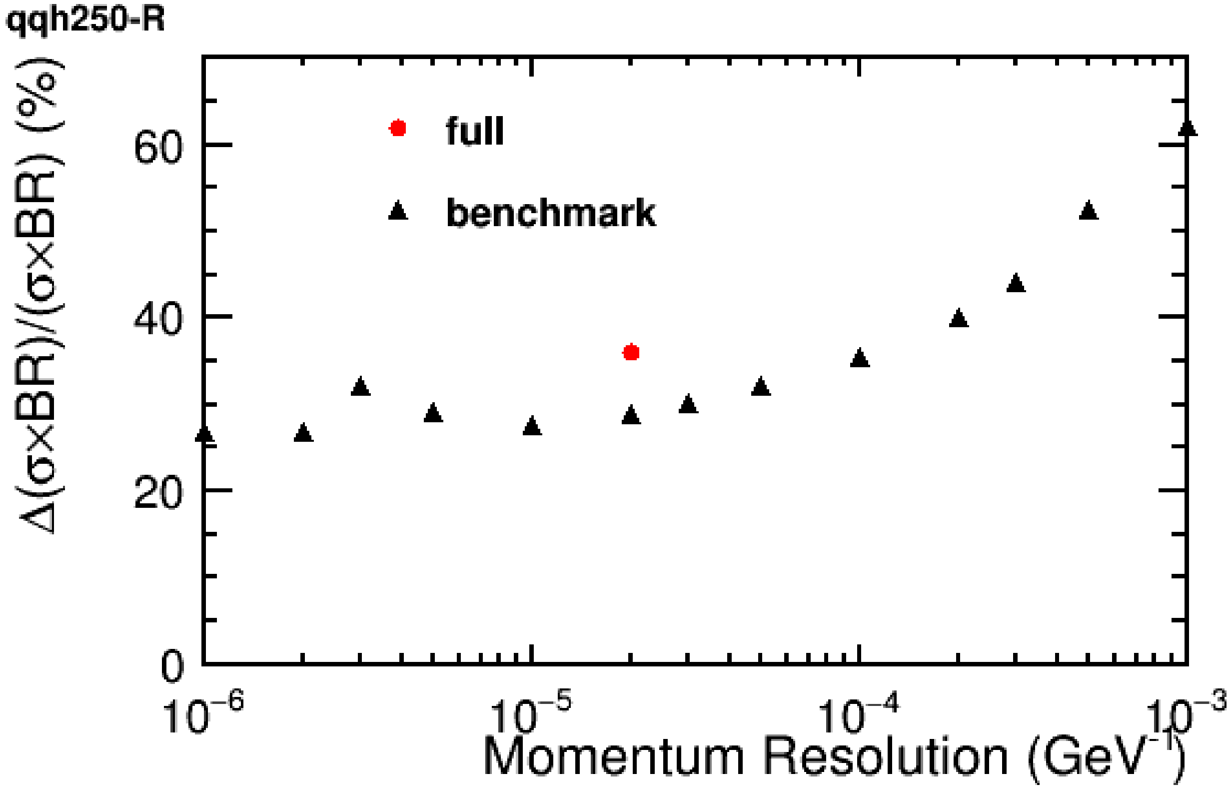
$$\sigma_{p_T} = \sigma_{1/p_T} \times p_T^2$$

σ_{1/p_T} is just a constant

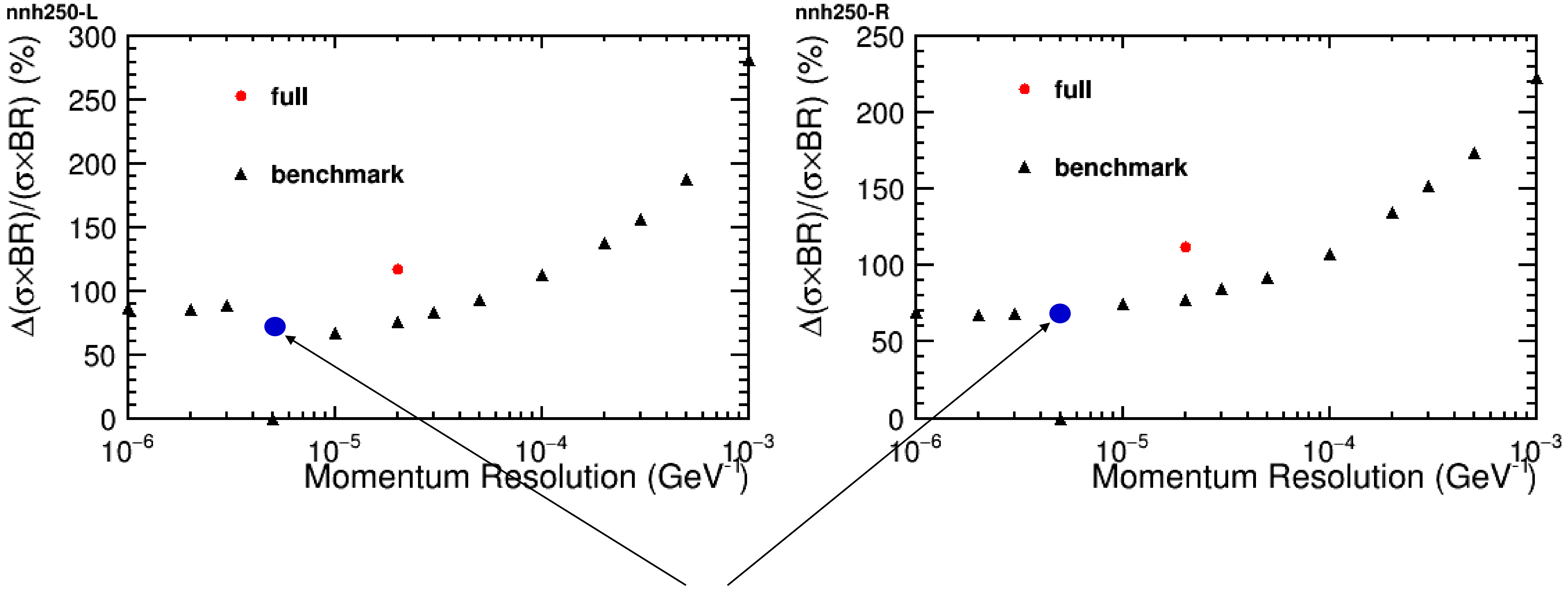
(1) keep parallel $p_T \parallel \sigma_{p_T}$
(2) no overestimating anymore

Individual Channel Plot (qqh250-L/R)



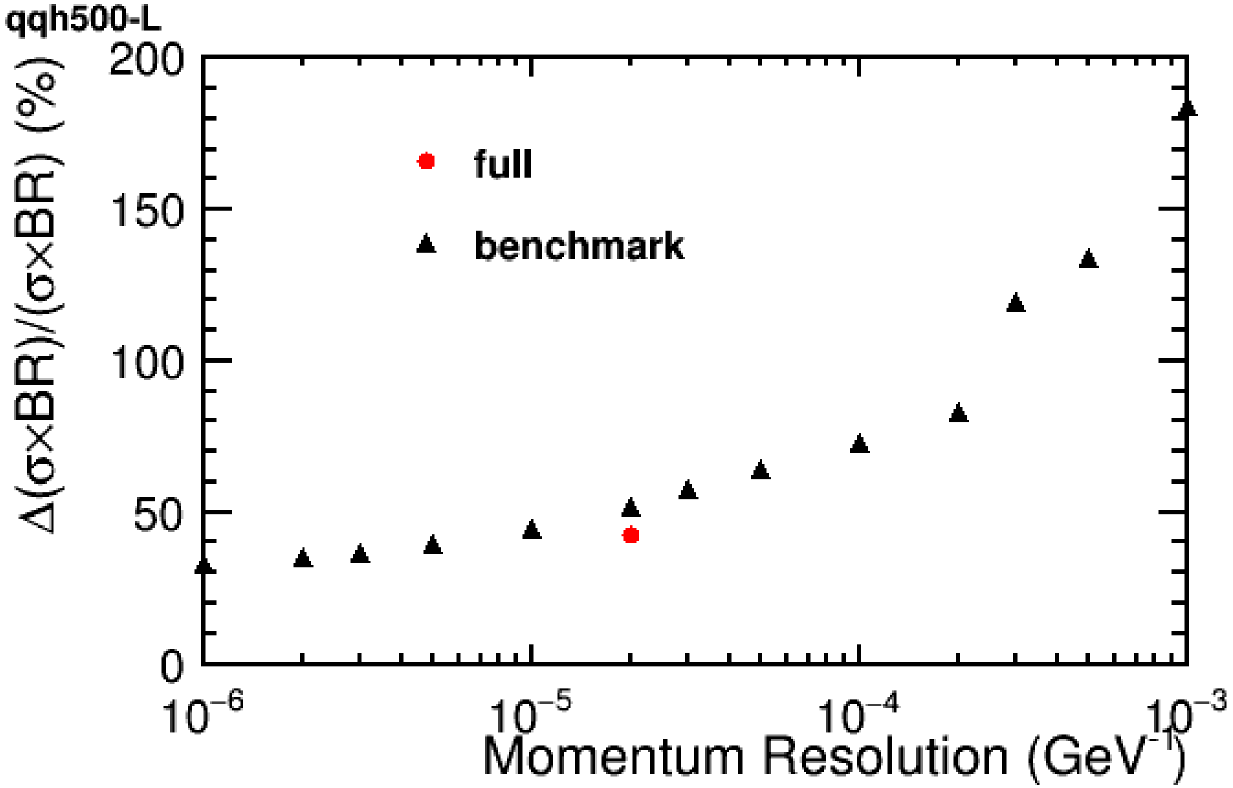


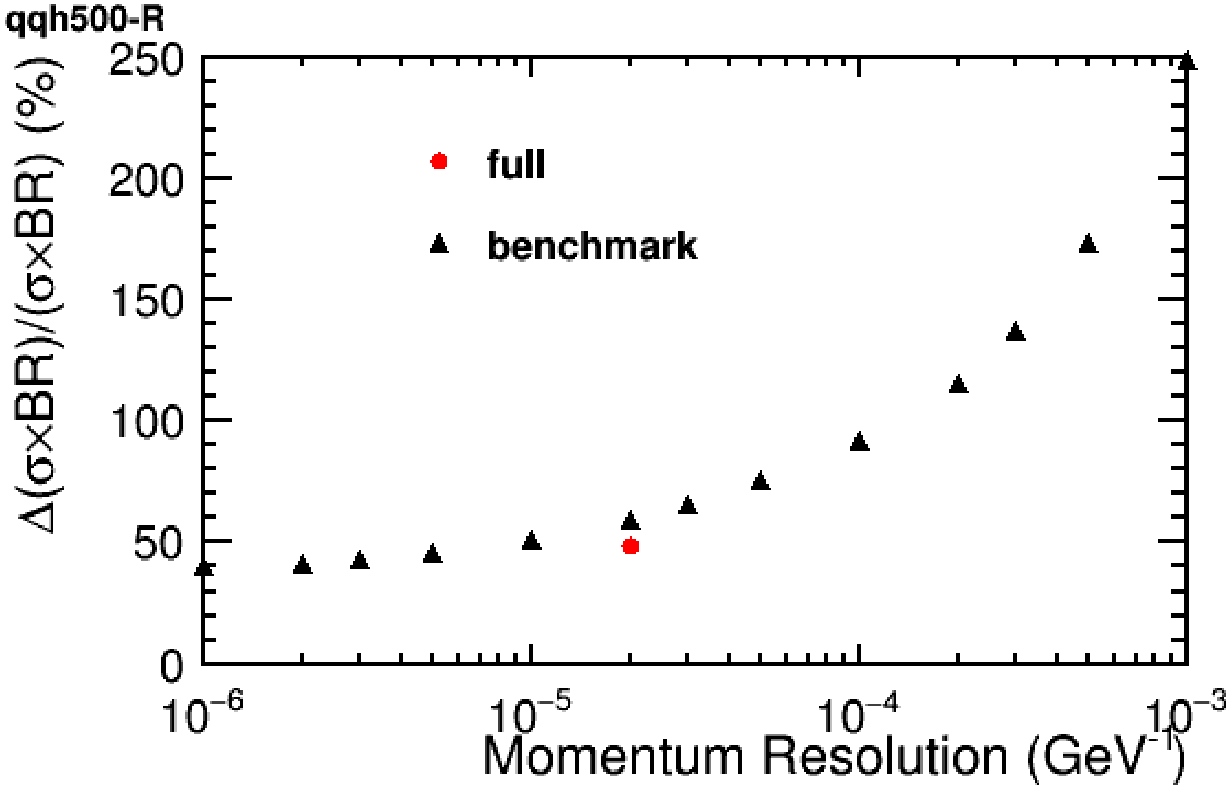
Individual Channel Plot (nnh250-L/R)



interpreted points because fitting failed completely

Individual Channel Plot (qqh500-L/R)





Individual Channel Plot (nnh500-L/R)