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한국과학기술정보연구원 Korea Institute of Science and Technology Information

A study of dark photon at e^+e^- colliders using KISTI-5 supercomputer

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UST and KISTI

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Contents

1. Motivation

Motivation

- Dark Matter(DM) cannot be explained by the Standard Model(SM).
- Because DM has a small cross-section, a large amount of simulation data must be generated.
- Therefore, efficient research on HPC(High Performance Computing) is required.
- In the previous study, we have studied on CPU time consumed for simulation.
- Based on this result, we have effectively used the KISTI-5 supercomputer for HPC.
- We have studied double dark photons produced by e^+e^- colliders.
- Double dark photon mode is $\boldsymbol{e^+\, e^-} \rightarrow \boldsymbol{A'A'}$ and $\boldsymbol{A'A'\gamma}$ with each $\boldsymbol{A'}$ decays into dimuon.
- To know ISR effect, we have also included ISR photon for double dark photon mode.

Current and future e^+e^- colliders

Belle II
(2017~, KEK/Japan)

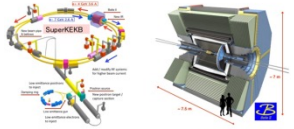
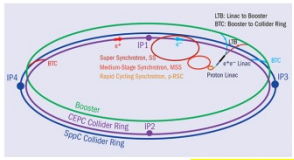


Image copyright Belle II

FCC-ee
(2038~, CERN/Switzerland)

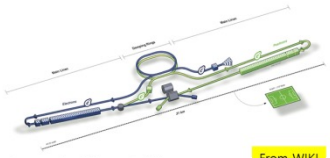
Future Circular Collider — Image copyright CERN

CEPC
(2030~, IHEP/China)



Circular Electron-Positron Collider — Image copyright IHEP

ILC
(2034~, Japan)



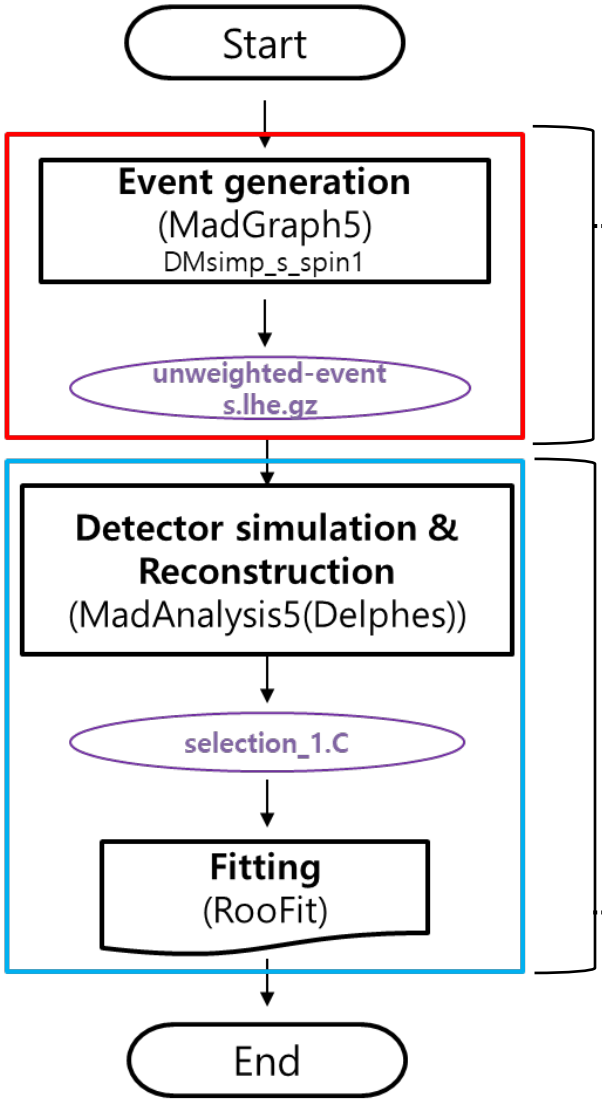
International Linear Collider — From WIKI

Experiments	Type	CM energy [GeV]	Circumference/ length [km]
Belle II	Circular	10.58 (e^+: 4, e^-: 7)	3.0116
FCC-ee (Future circular collider)	Circular	92 ($e^\pm$: 45.5)	97.75
		240 ($e^\pm$: 125)	
		366 ($e^\pm$: 175)	
CEPC (Circular electron positron collider)	Linear	92 ($e^\pm$: 45.5)	100
		240 ($e^\pm$: 120)	
ILC (International linear collider)	Linear	250 ($e^\pm$: 125)	20.5
		500 ($e^\pm$: 250)	31

PDG 2020

2. Flowchart

Flow chart of softwares and hardwares



Specification	KISTI-5 KNL	KISTI-5 SKL	Local machine
OS	CentOS 7.4	CentOS 7.4	Scientific Linux 6.5
Processor	Intel Xeon Phi 7250 1.4 GHz	Intel Xeon Skylake (Gold 6148) 2.4 GHz	Intel Xeon CPU X5560 2.8 GHz
Architecture	Many-core	Multicore	Multicore
Number of cores/CPU	68	20	4
Number of CPUs/node	1	2	8
Number of cores/node	68	40	32
Number of total nodes	8,305	132	1
Number of total cores	564,740	5,280	32

[1] Kihong Park and Kihyeon Cho, J. Astron. Space Sci. 38 (2021) 55-63.
[2] Kihong Park, Kyungho Kim, Kihyeon Cho, J. Astron. Space Sci. 39 (2022) 1-10.

Process of stand-alone frame analysis

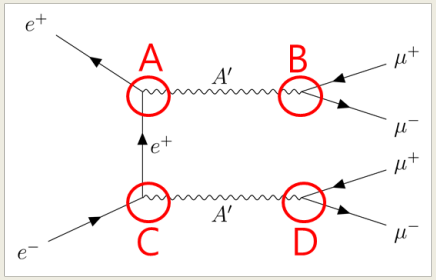
Processing	Software	Code	Input file	Output file
I. Event generation	MadGraph5	mg5_apap.mac	model: simplified model	unweighed_events.lhe.gz
II. Detector simulation	MadAnalysis5 (Delphes)	ma5_apap_rl.mac	unweighed_events.lhe.gz	cms_edited_0.3_ new.root
III. Reconstruction	MadAnalysis5		unweighed_events.lhe.gz (Parton level)	selection_1.C (histogram macros, etc)
IV. Fitting	RooFit	belle2_reco.c	selection_1.C (as data)	belle2_mass_reco.png

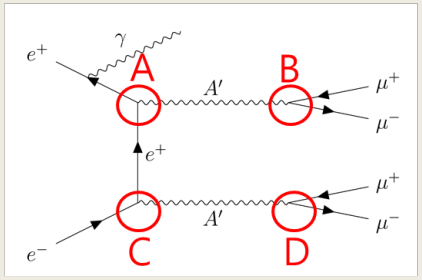
3. Theory

Theory

$e^+ e^- \rightarrow A'A'$ and $A'A'\gamma$ with $A' \rightarrow \mu^+\mu^-$

- **Feynman diagrams of double dark photon mode [3, 4]**

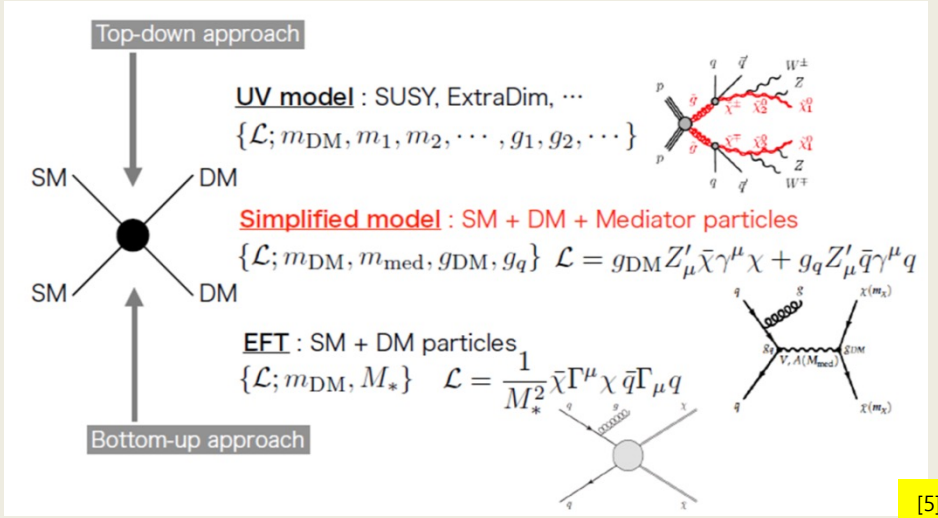




	Theory	MadGraph5	Default value	Description
A, C	$g^v_{l_{11}}$	gvl11	1	Electron-Y1 vector coupling
B, D	$g^v_{l_{22}}$	gvl22	1	Muon-Y1 vector coupling

[3] Insung Yeo and Kihyeon Cho, *J. Astron. Space Sci.* 35 (2018) 67-74.
[4] Shuve Brian and Itay Yavin, *Physical Review D* 89.11 (2014) 113004.

- **Simplified model [5, 6]**



- The SM particles + Dark Matter + Mediator particles (dark photon)
- A′: dark photon with spin1
- Imported in MadGraph5

[5] Daniele, et al., Alves, *Journal of Physics G*: Nuclear and Particle Physics, 39(10) (2012) 105005.
[6] Kentarou Mawatari's ppt (KAIST-KAIX workshop 07/15/19).

4. $A'A'$ and $A'A'\gamma$

Background(SM) mode

- We have used SM as a background.
- The background(SM) mode are $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^- \gamma$.

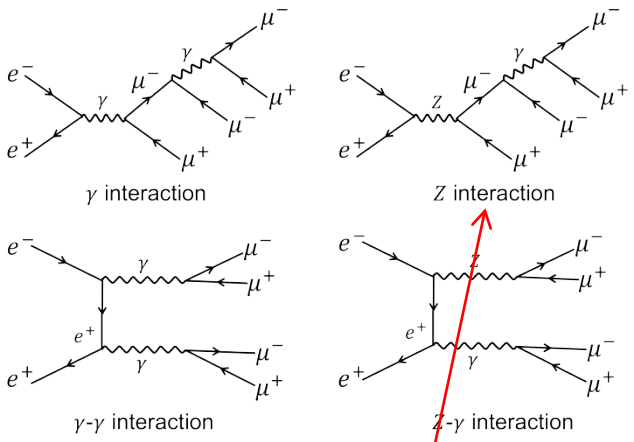
- Parameters of background(SM) mode

Specifications	$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$	$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-\gamma$
Machine	KISTI-5 supercomputer	
Simulation	MadGraph5 v2.6.6	
Importing model	The standard model (default)	
Command	generate e+ e- > mu+ mu- mu+ mu-	generate e+ e- > mu+ mu- mu+ mu- a
Condition	$p_{T,\mu} \geq 0.01\ GeV, p_{T,\gamma} \geq 0.01\ GeV$	
Number of generated events	10,000	
CM energy [GeV]	1, 2, …, 9, 10, 20, …, 490, 500, 600, 700, …, 2,900, 3,000	

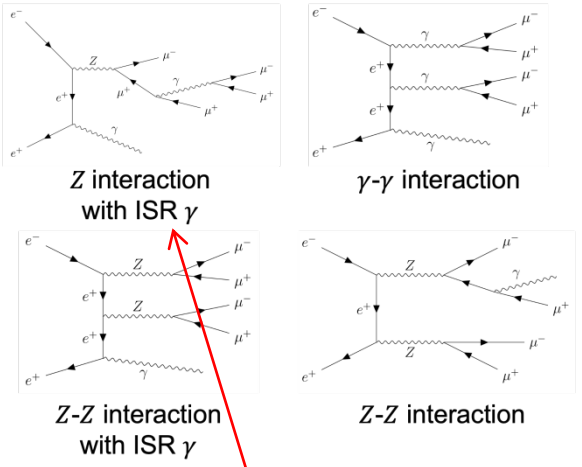
- The minimum transverse momentum cuts for photons and leptons are set to 0.01 in order to generate events at energies less than 40 GeV.

Dominant Feynman diagrams

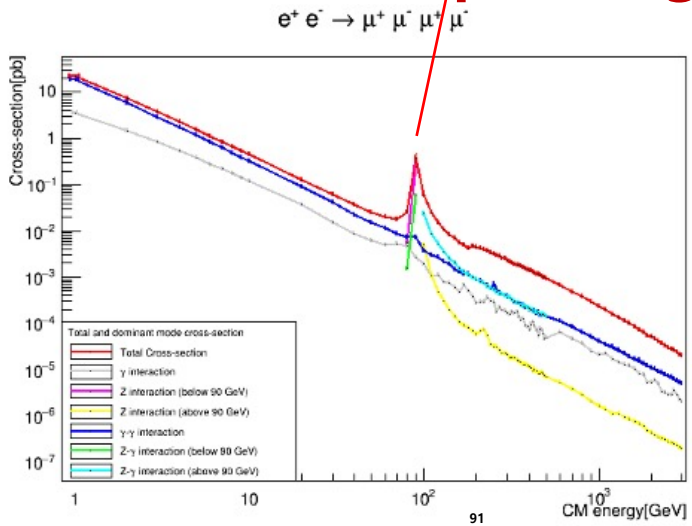
$$e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

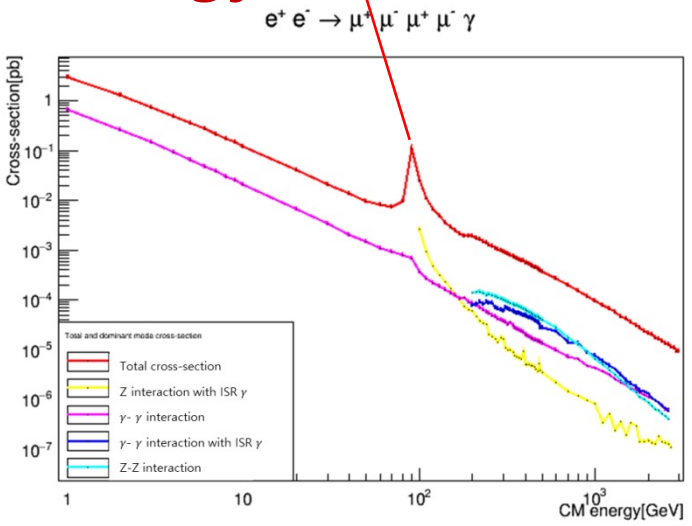


$$e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^- \gamma$$



Cross-section depending on CM energy





Double dark photon mode

- Double dark photon mode are $e^+e^- \rightarrow A'A'$ and $e^+e^- \rightarrow A'A'\gamma$ where each A' decays into dimuon.

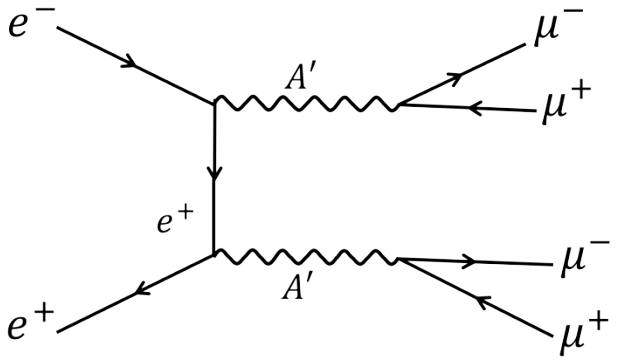
- Parameters of Double dark photon mode

Specifications	$e^+e^- \rightarrow A'A'$	$e^+e^- \rightarrow A'A'\gamma$
Machine	KISTI-5 supercomputer	
Simulation	MadGraph5 v2.6.6	
Importing model	Simplified model	
Command	generate e+e- > y1y1, y1 > mu+ mu-	generate e+e- > y1y1, y1 > mu+ mu- a
Condition	$p_{T,\mu} \geq 0.01\ GeV, p_{T,\gamma} \geq 0.01\ GeV$	
Number of generated events	10,000	
CM energy [GeV]	1, 2, …, 9, 10, 20, …, 490, 500, 600, 700, …, 2,900, 3,000	
Dark photon mass [GeV]	0.25, 0.5, 0.75, 1.0, 2.5, 5.0, 7.5, 10.0, 25.0, 50.0, 75.0, 100.0	
Dark photon decay width [GeV]	6.7×10^{-6}GeV	
Coupling constant	0.0001, 0.00025, 0.0005, 0.00075, 0.001, …, 0.1, 0.25, 0.5, 0.75, 1.0	

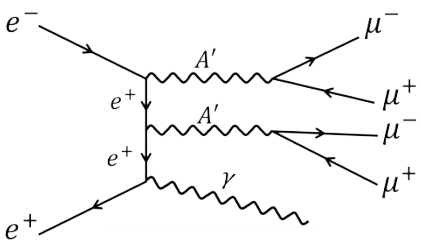
- The minimum transverse momentum cuts for photons and leptons are set to 0.01 in order to generate events at energies less than 40 GeV.

Feynman diagrams of Double dark photon mode

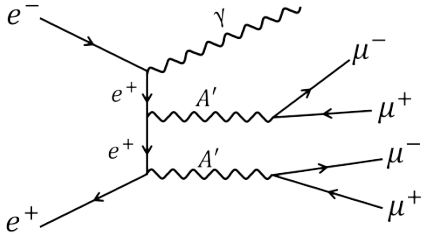
$e^+ e^- \rightarrow A'A'$



$e^+ e^- \rightarrow A'A'\gamma$

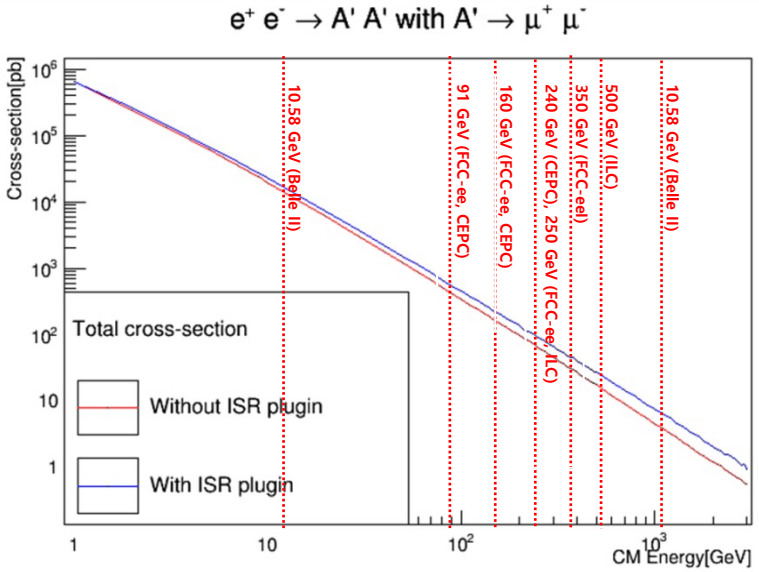


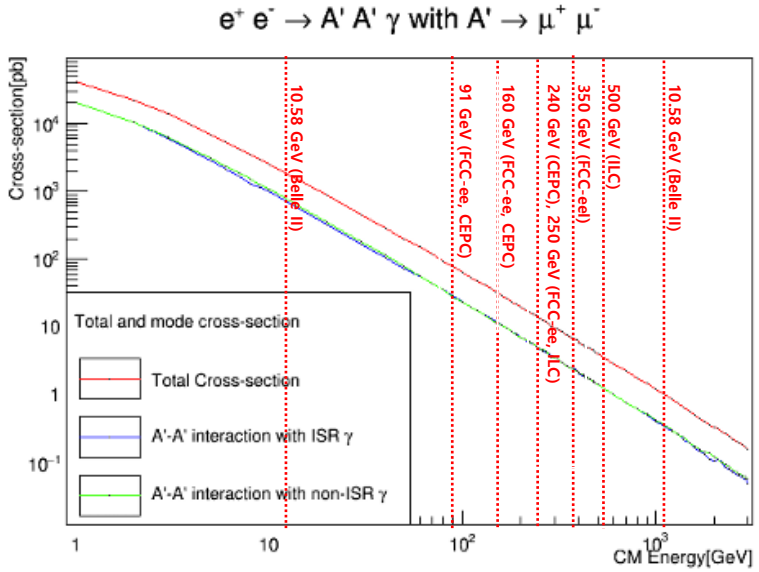
ISR photon mode



Non-ISR photon mode

Cross-section depending on CM energy

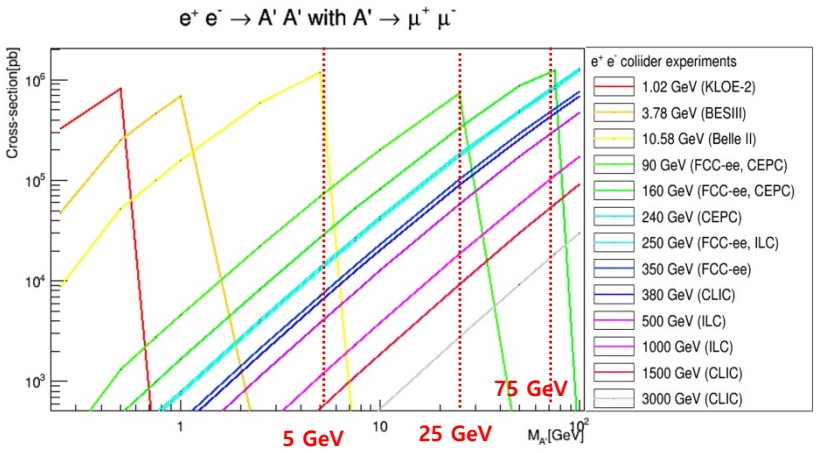




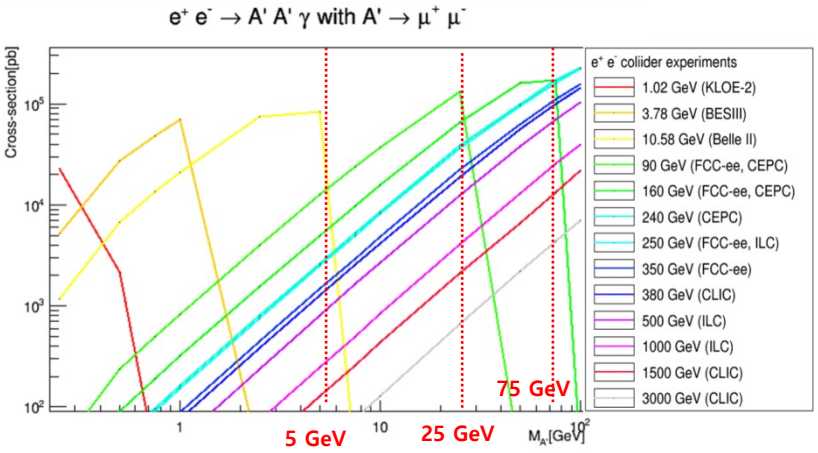
- Red vertical lines denote CM energy of experiments.
- We applied these CM energies to reconstruction for both $e^+ e^- \rightarrow A'A'$ and $e^+ e^- \rightarrow A'A'\gamma$.

Cross-section depending on dark photon mass

$$e^+ e^- \rightarrow A'A'$$

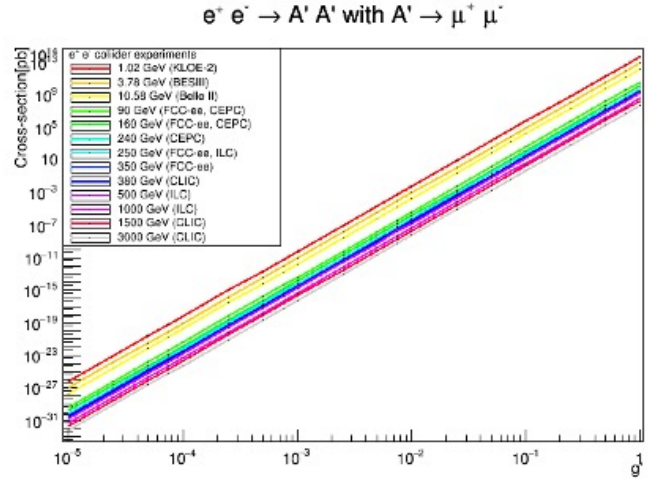


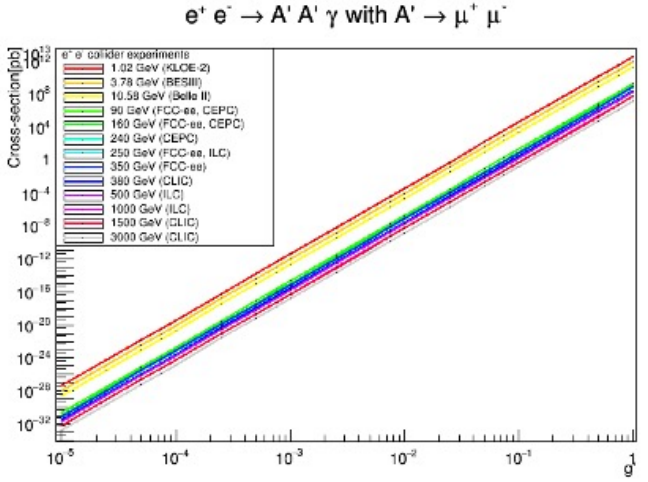
$$e^+ e^- \rightarrow A'A'\gamma$$



- Red vertical lines show dark photon masses which have the maximum cross-section.
- We have applied these dark photon masses to reconstruction in order to estimate the maximum expected number of double dark photon events.

Cross-section depending on coupling constant





5. Results

Reconstruction

- In order to fine the best CM energy for $e^+ e^- \rightarrow A'A'$ and $e^+ e^- \rightarrow A'A'\gamma$. we have studied the detector efficiency.
- Delphes was used to perform detector simulation.
- MadAnlaysis5 was used for reconstruction.

- Parameters of reconstruction

Specifications	Details
Number of generated events	1,000,000
Machine	Local Linux machine
Simulation tool kit	Delphes, MadAnalysis5
Condition	$p_{T,\mu} \geq 0.01\ GeV, p_{T,\gamma} \geq 0.01\ GeV$
Coupling constant	0.1
Fitting (function)	RooFit (2 Gaussian + 1th order polynomial) for $e^+ e^- \rightarrow A'A'$ RooFit (2 Bifurgaussian + 1th order polynomial) for $e^+ e^- \rightarrow A'A'\gamma$

- The minimum transverse momentum cuts for photons and leptons are set to 0.01 in order to generate events at energies less than 40 GeV.

Reconstructed parameters of $e^+ e^- \rightarrow A'A'$ and $e^+ e^- \rightarrow A'A'\gamma$

Belle II
(2017~, KEK/Japan)

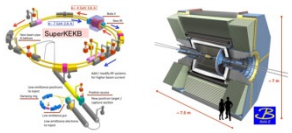
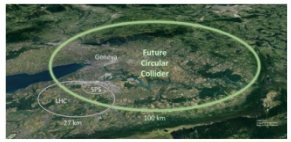


Image copyright Belle II

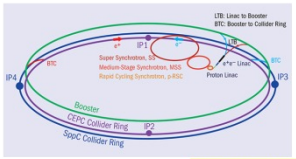
FCC-ee
(2038~, CERN/Switzerland)



Future Circular Collider

Image copyright CERN

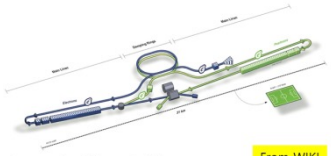
CEPC
(2030~, IHEP/China)



Circular Electron-Positron Collider

Image copyright IHEP

ILC
(2034~, Japan)



International Linear Collider

From WIKI

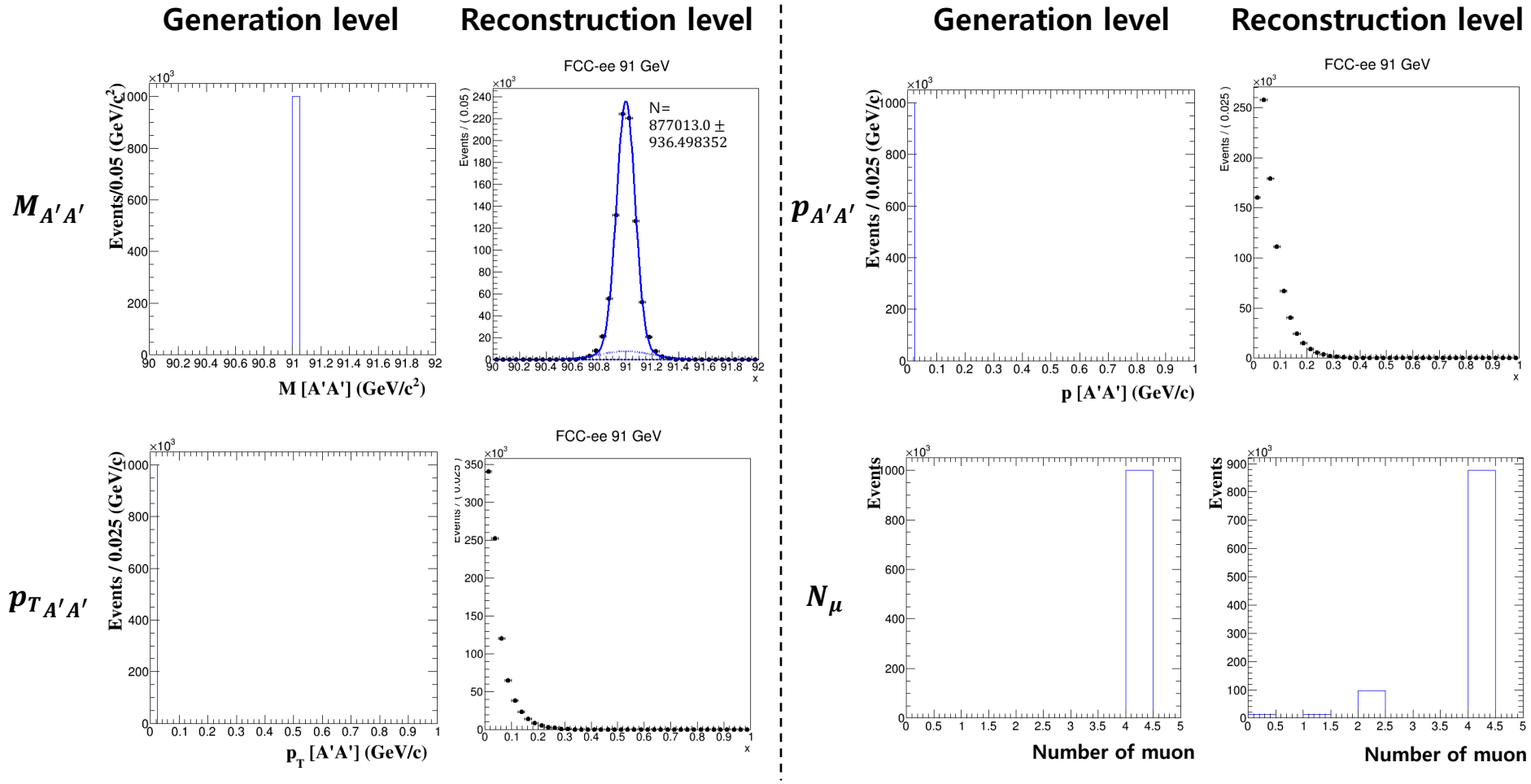
Experiments	CM energy [GeV]	Dark photon mass (width) [GeV]	Detector η cut	Delphes card
Belle II	10.58 (e^+: 4, e^-: 7)	5 (6.7×10^{-6})	$-1.317 \leq \eta \leq 1.901$	delphes_card_CMS.tcl (η cut for Belle II)
FCC-ee (Future circular collider)	91 ($e^{\pm}$: 45.5)	25 (6.7×10^{-6})	$-3.0 \leq \eta \leq 3.0$	delphes_card_IDEA.tcl
	160 ($e^{\pm}$: 80)	75 (6.7×10^{-6})		
	250 ($e^{\pm}$: 125)	100 (6.7×10^{-6})		
	350 ($e^{\pm}$: 175)	100 (6.7×10^{-6})		
CEPC (Circular electron positron collider)	91 ($e^{\pm}$: 45.5)	25 (6.7×10^{-6})	$-3.0 \leq \eta \leq 3.0$	delphes_card_CEPC.tcl
	160 ($e^{\pm}$: 80)	75 (6.7×10^{-6})		
	240 ($e^{\pm}$: 120)	100 (6.7×10^{-6})		
ILC (International linear collider)	250 ($e^{\pm}$: 125)	100 (6.7×10^{-6})	$-2.4 \leq \eta \leq 2.4$	delphes_card_ILD.tcl
	500 ($e^{\pm}$: 250)	100 (6.7×10^{-6})		
	1000 ($e^{\pm}$: 500)	100 (6.7×10^{-6})		

- Dark photon masses are selected where it has the maximum cross-section (p15).

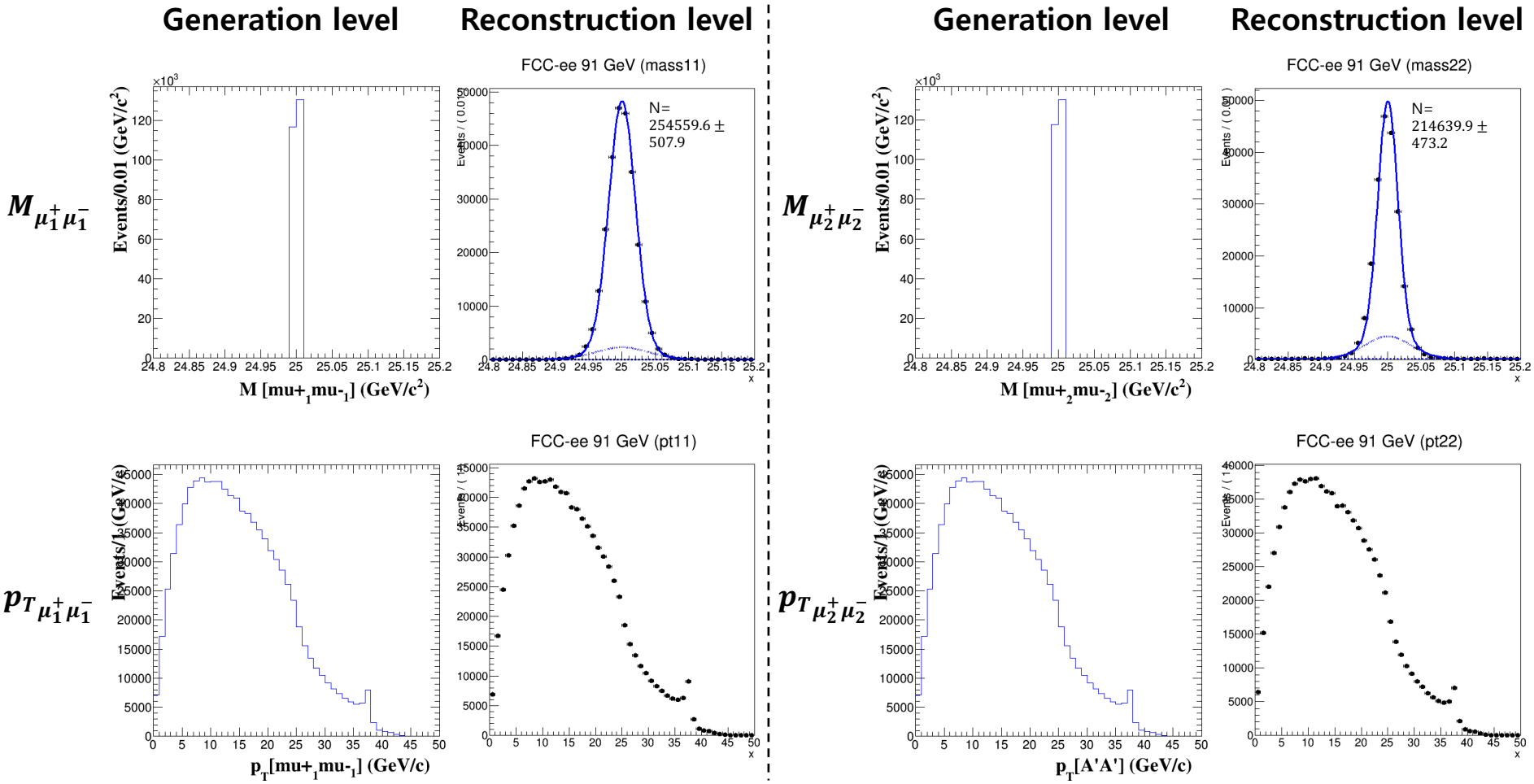
https://cp3.irmp.ucl.ac.be/projects/delphes/browser/git/cards

$$e^+ e^- \rightarrow A' A' \text{ with } A' \rightarrow \mu^+ \mu^-$$

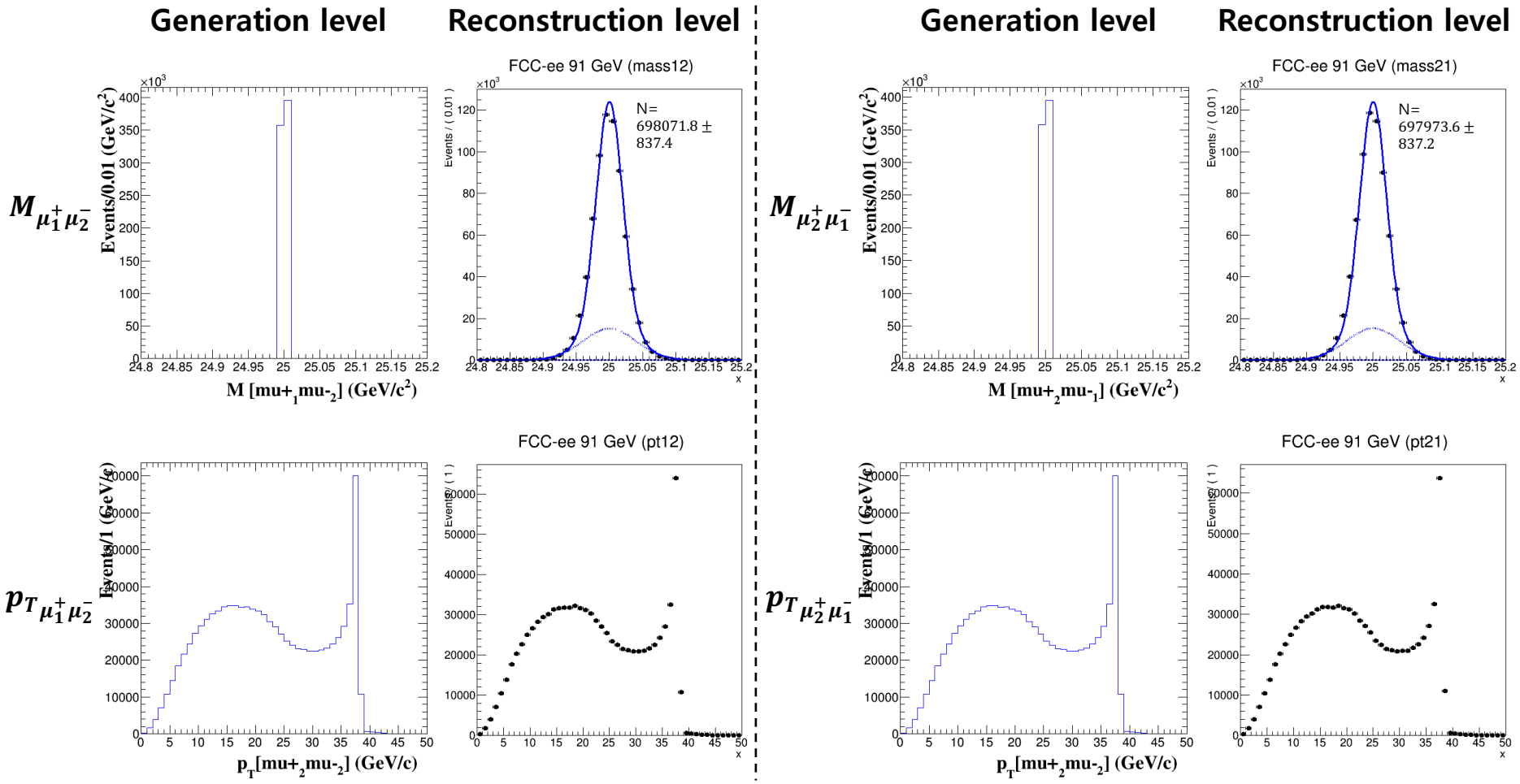
$e^+ e^- \rightarrow A'A'$ at FCC-ee 91 GeV (1/3)



$e^+ e^- \rightarrow A'A'$ at FCC-ee 91 GeV (2/3)



$e^+ e^- \rightarrow A'A'$ at FCC-ee 91 GeV (3/3)

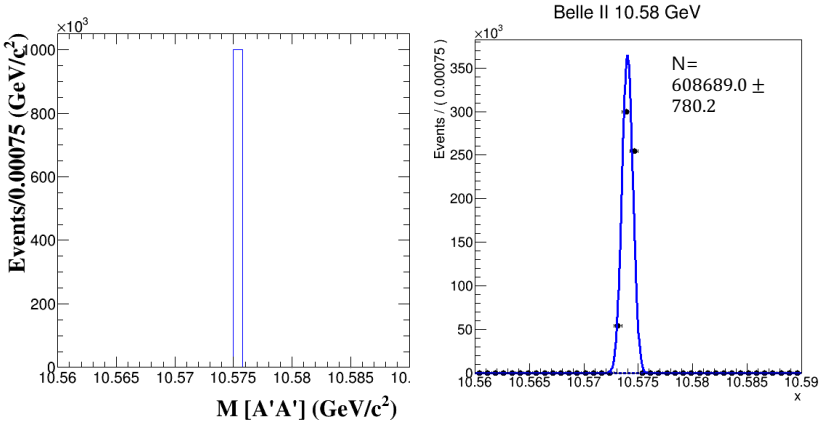


Signal events of $e^+ e^- \rightarrow A'A'$ (1/3)

Generation level | Reconstruction level

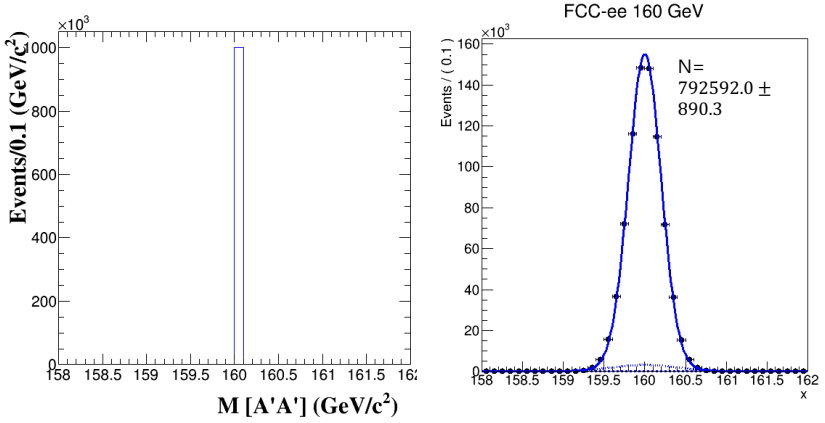
Belle II

10.58 GeV



FCC-ee

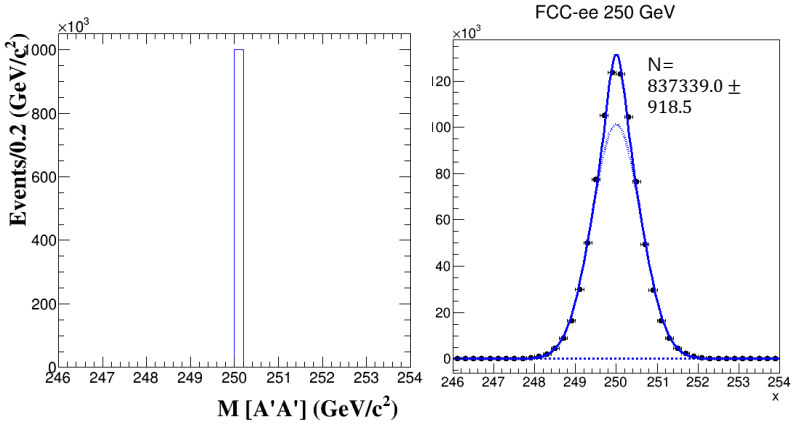
160 GeV



Generation level | Reconstruction level

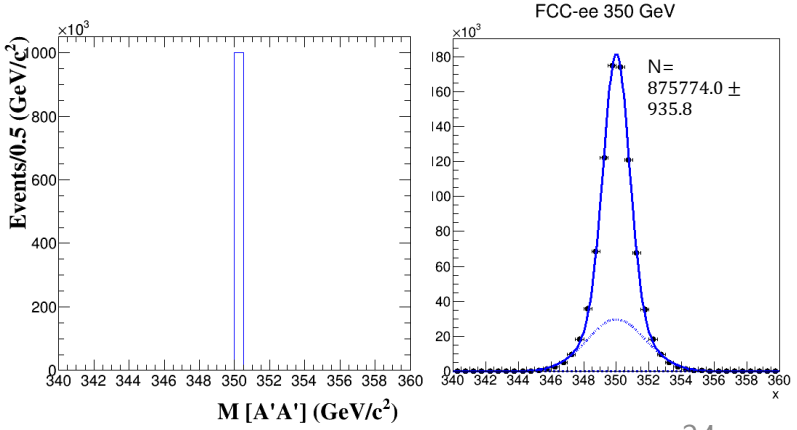
FCC-ee

250 GeV



FCC-ee

350 GeV

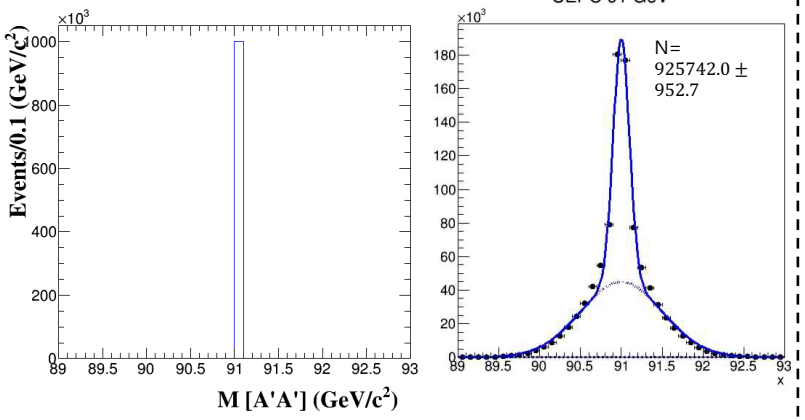


Signal events of $e^+ e^- \rightarrow A'A'$ (2/3)

Generation level Reconstruction level

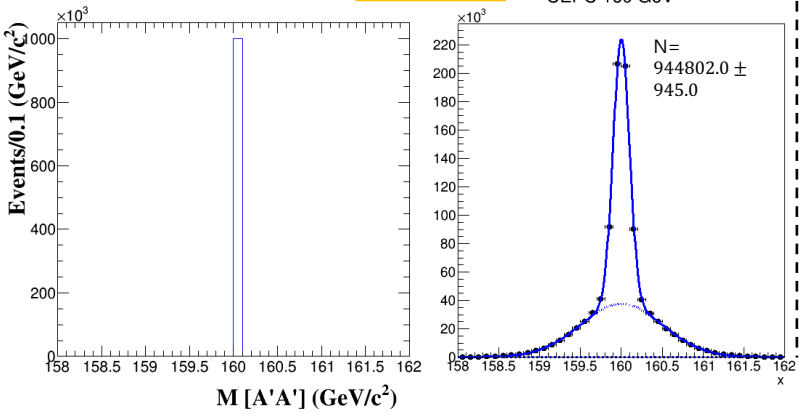
91 GeV

CEPC



160 GeV

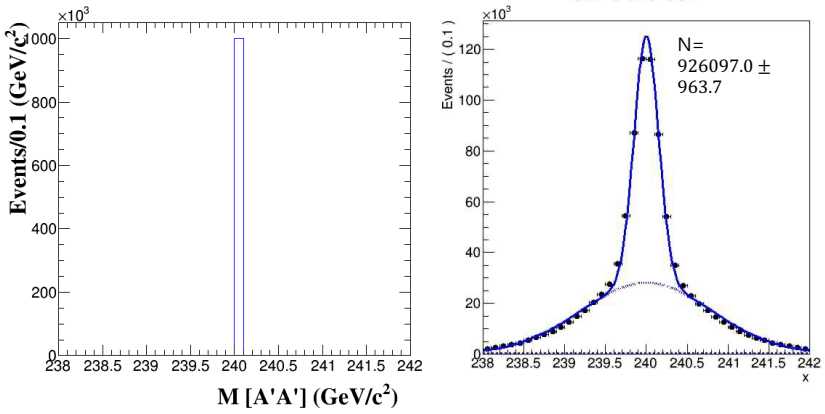
CEPC



Generation level Reconstruction level

240 GeV

CEPC

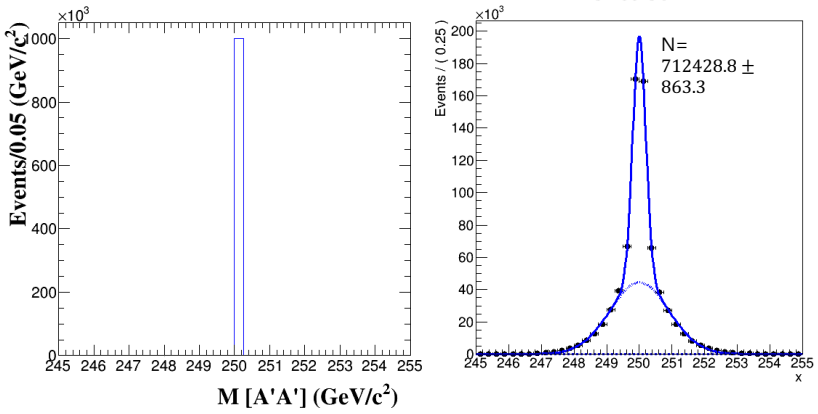


Signal events of $e^+ e^- \rightarrow A'A'$ (3/3)

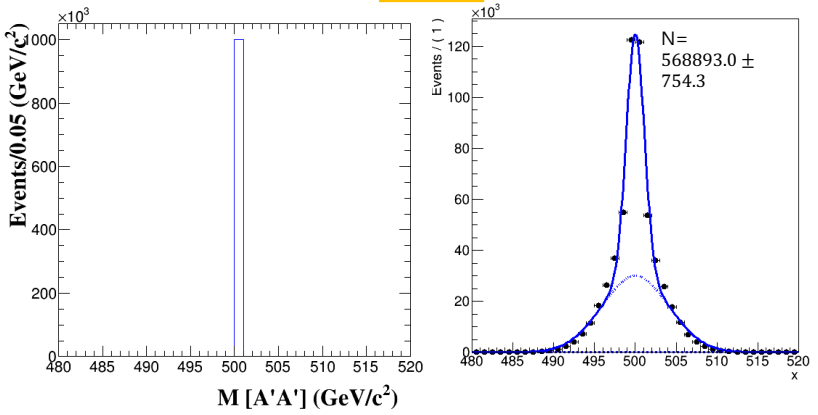
Generation level Reconstruction level

ILC

250 GeV



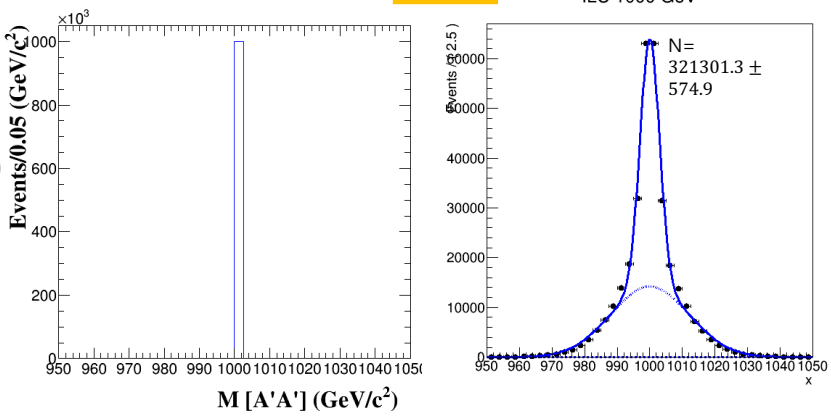
500 GeV



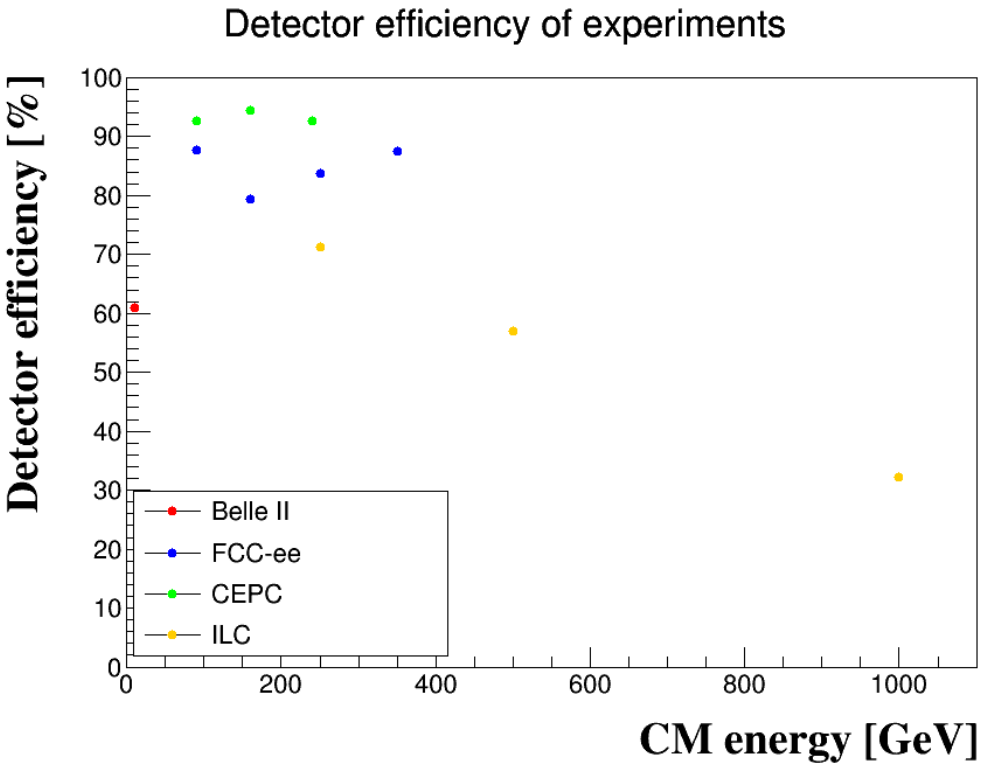
Generation level Reconstruction level

ILC

1000 GeV



Detector efficiency of $e^+ e^- \rightarrow A'A'$



Experiments	CM energy [GeV]	Detector efficiency [%]
Belle II	10.58 (e^+: 4, e^-: 7)	60.826 ± 0.078
FCC-ee	91 ($e^\pm$: 45.5)	87.701 ± 0.094
	160 ($e^\pm$: 80)	79.259 ± 0.089
	250 ($e^\pm$: 125)	83.733 ± 0.092
	350 ($e^\pm$: 175)	84.898 ± 0.091
CEPC	91 ($e^\pm$: 45.5)	92.059 ± 0.148
	160 ($e^\pm$: 80)	93.595 ± 0.140
	240 ($e^\pm$: 120)	93.398 ± 0.161
ILC	250 ($e^\pm$: 125)	70.706 ± 0.142
	500 ($e^\pm$: 250)	56.764 ± 0.134
	1000 ($e^\pm$: 500)	31.837 ± 0.101

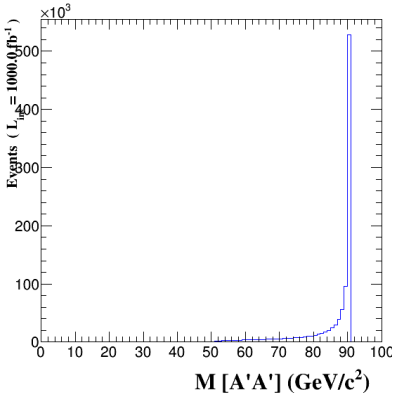
- In this $e^+ e^- \rightarrow A'A'$ mode, CEPC shows the highest detector efficiency among experiments.

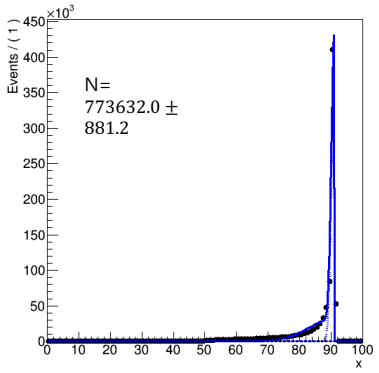
$$e^+ e^- \rightarrow A' A' \gamma \text{ with } A' \rightarrow \mu^+ \mu^-$$

$e^+ e^- \rightarrow A'A'\gamma$ at FCC-ee 91 GeV

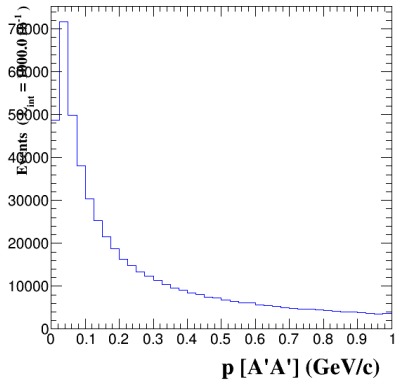
Generation level | Reconstruction level | Generation level | Reconstruction level

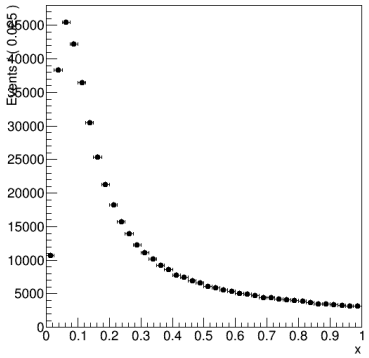
$M_{A'A'}$



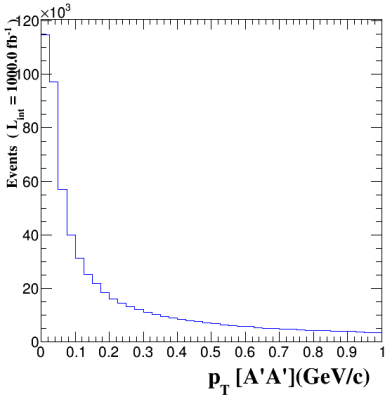


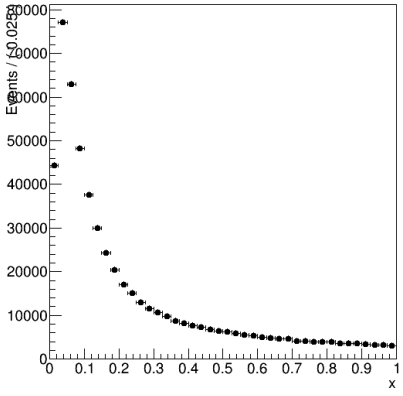
$p_{A'A'}$



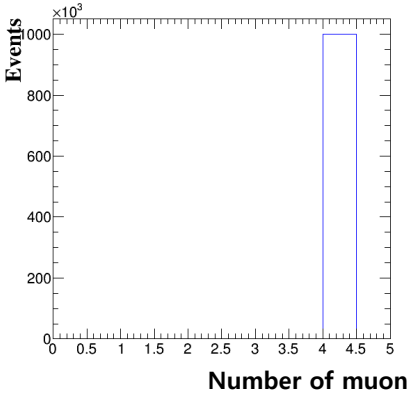


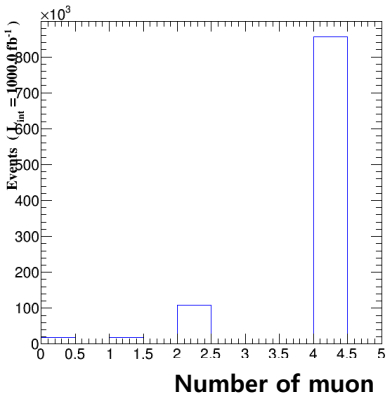
$p_{T_{A'A'}}$





N_μ



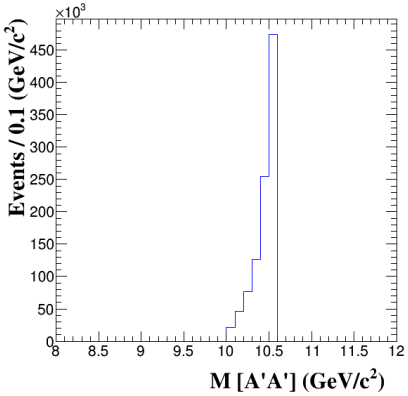


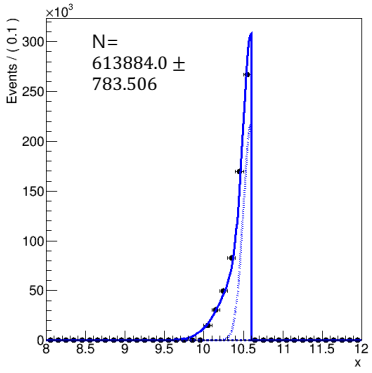
Signal events of $e^+ e^- \rightarrow A'A'\gamma$ (1/3)

Generation level Reconstruction level

Belle II

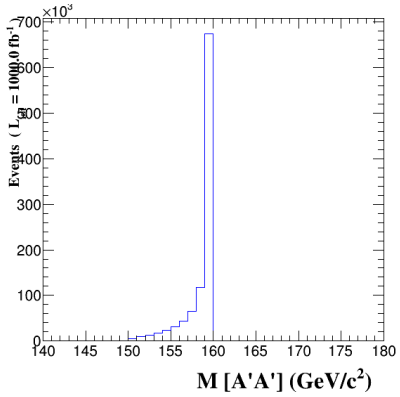
10.58 GeV

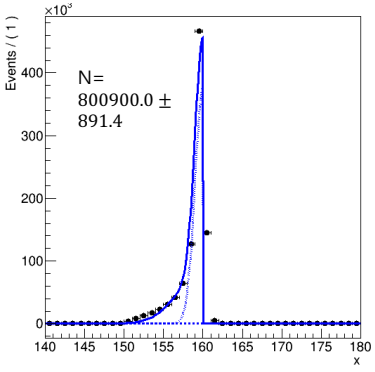




FCC-ee

160 GeV

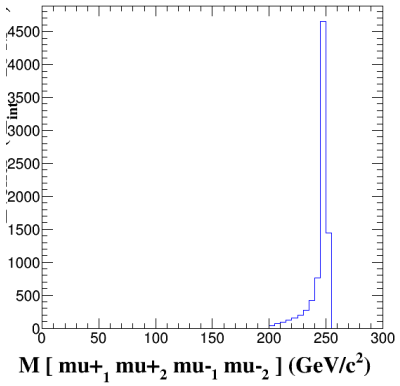


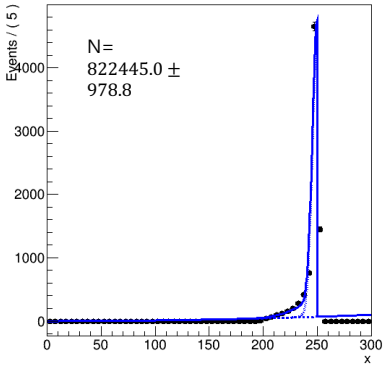


Generation level Reconstruction level

FCC-ee

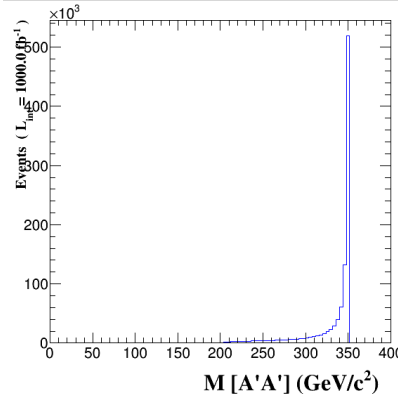
250 GeV

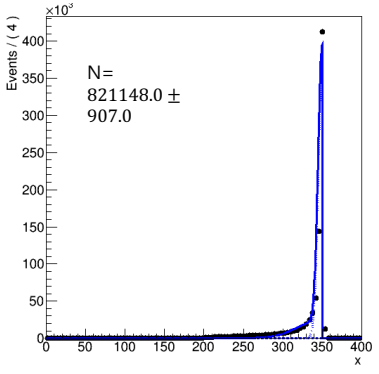




FCC-ee

350 GeV



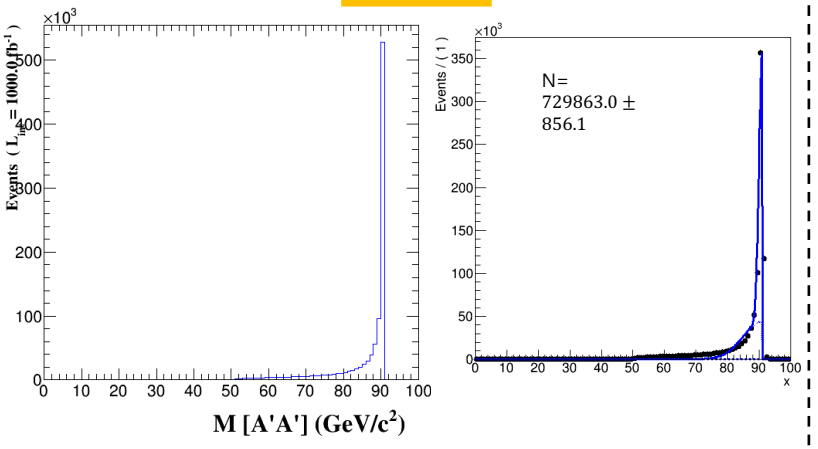


Signal events of $e^+ e^- \rightarrow A'A'\gamma$ (2/3)

Generation level | Reconstruction level | Generation level | Reconstruction level

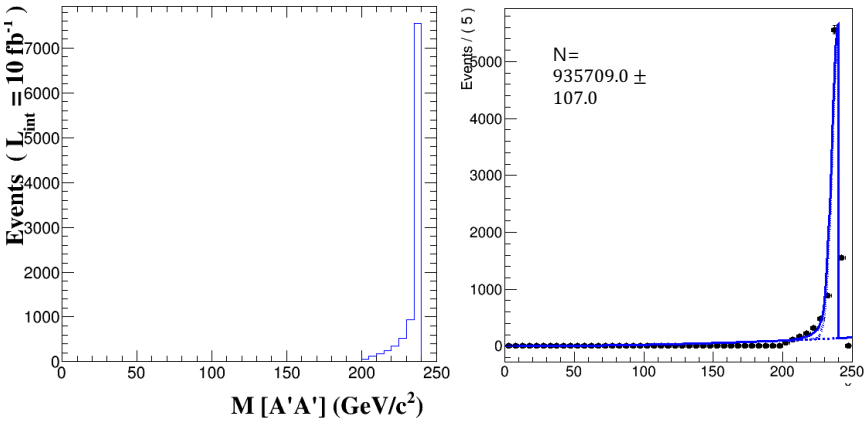
CEPC

91 GeV



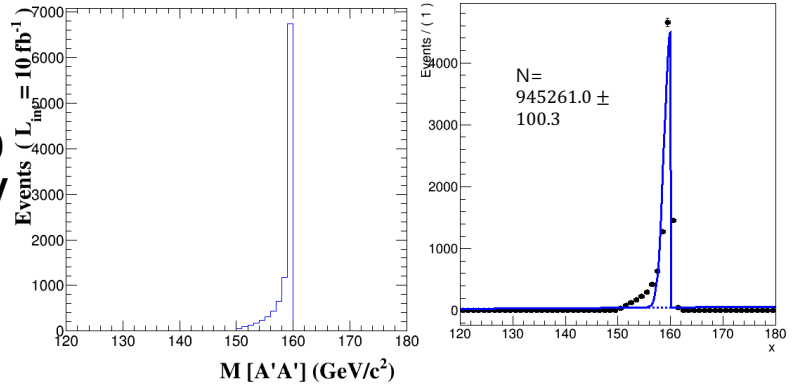
CEPC

240 GeV



CEPC

160 GeV

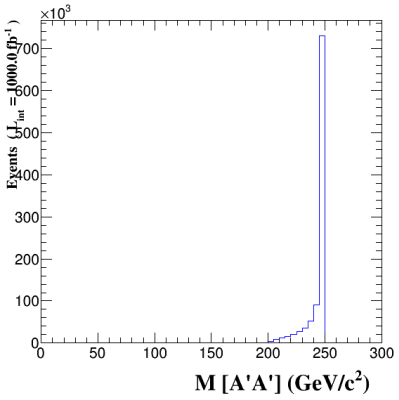


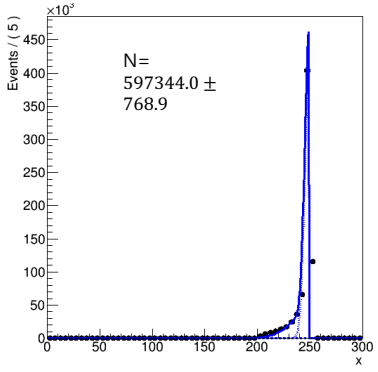
Signal events of $e^+ e^- \rightarrow A'A'\gamma$ (3/3)

Generation level | Reconstruction level | Generation level | Reconstruction level

ILC

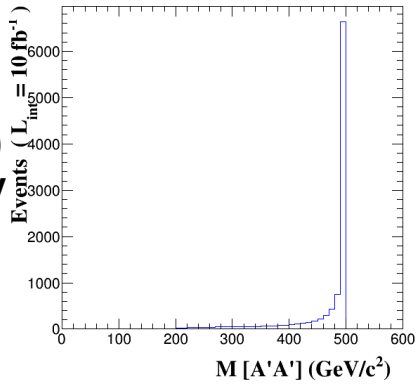
250 GeV

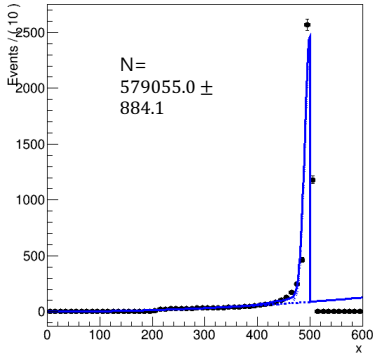




ILC

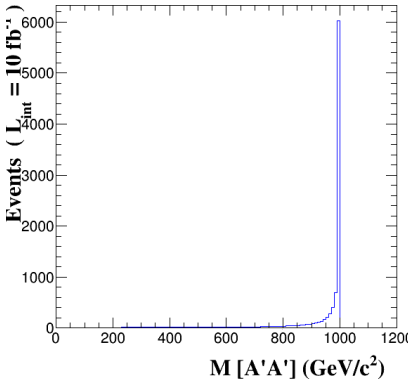
500 GeV

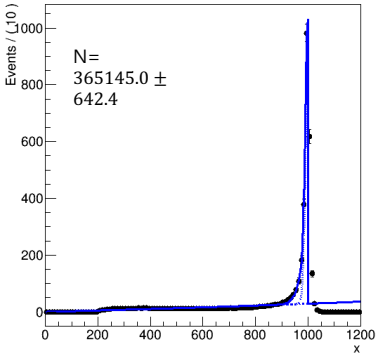




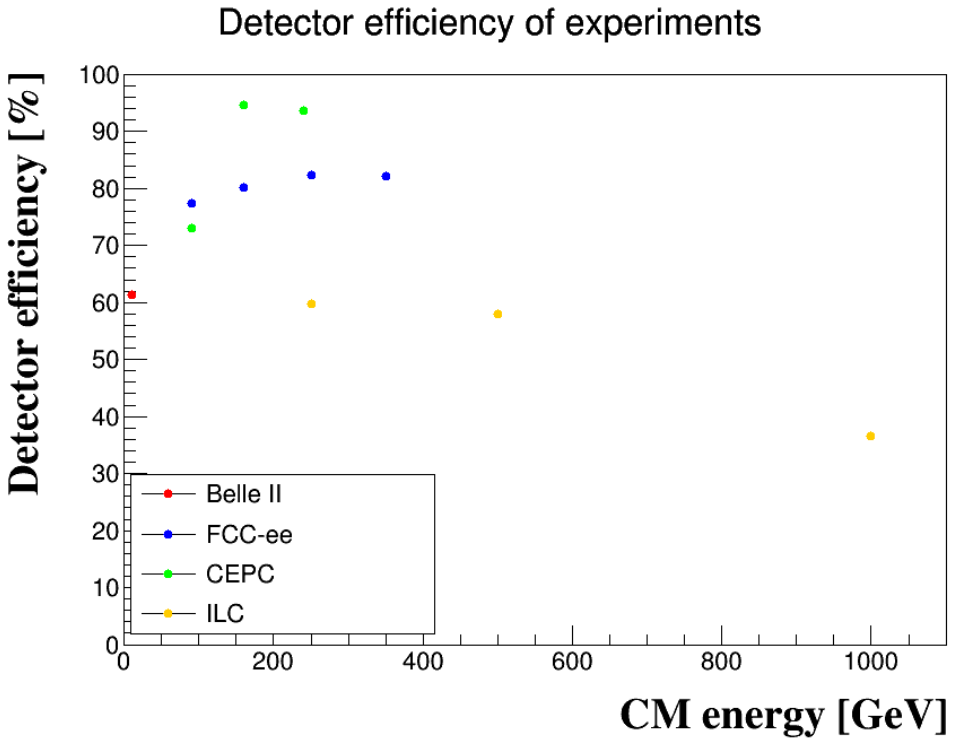
ILC

1000 GeV





Detector efficiency of $e^+ e^- \rightarrow A'A'\gamma$



Experiments	CM energy [GeV]	Detector efficiency [%]
Belle II	10.58 (e^+: 4, e^-: 7)	61.388 ± 0.0784
FCC-ee	91 ($e^\pm$: 45.5)	77.363 ± 0.088
	160 ($e^\pm$: 80)	80.090 ± 0.089
	250 ($e^\pm$: 125)	82.245 ± 0.098
	350 ($e^\pm$: 175)	82.115 ± 0.091
CEPC	91 ($e^\pm$: 45.5)	72.986 ± 0.086
	160 ($e^\pm$: 80)	94.526 ± 0.010
	240 ($e^\pm$: 120)	93.571 ± 0.011
ILC	250 ($e^\pm$: 125)	59.734 ± 0.077
	500 ($e^\pm$: 250)	57.905 ± 0.088
	1000 ($e^\pm$: 500)	36.515 ± 0.064

- In this $e^+ e^- \rightarrow A'A'\gamma$ mode, CEPC shows the highest detector efficiency among experiments.

6. Summary

Summary

- DM research requires a large amount of computing resources to process big data and simulations.
- In the previous study, we had researched a single dark photon using HPC so that we found the optimization for it.
- Based on this information, we have effectively studied double dark photons produced by e^+e^- colliders for using HPC.
- In order to search for double dark photons at e^+e^- colliders, we have reported the expected number of events considering detector efficiency.
- The results will help to explore double dark photon events for various e^+e^- colliders.

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