

# Study of Dark Photons Using Future Electron-Positron Colliders Based on Machine Learning

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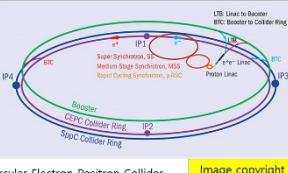
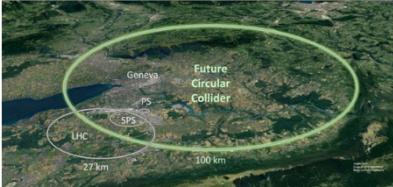
VI. Summary

# I. Introduction

## ■ Motivation and Objective

- The SM background is a significant problem in dark photon detection at collider experiments.
- To reduce the SM background events, we studied dark photons at future  $e^+e^-$  colliders based on ML.

# ■ Future electron-positron colliders

Accelerator/Detector	Type	$\sqrt{s}$ [GeV]	Circumference or length [km]
<b>CEPC/CEPC</b> (2030~, IHEP/China)	Circular	91 160 <b>240</b>	100
			
<b>FCC-ee/IDEA</b> (2038~, CERN/Switzerland)	Circular	91 160 250 <b>350</b>	97.75
			
<b>ILC/ILD</b> (2034~, Japan)	Linear	250 500 <b>1000</b>	20.5 31 40
			

## II. Motivation

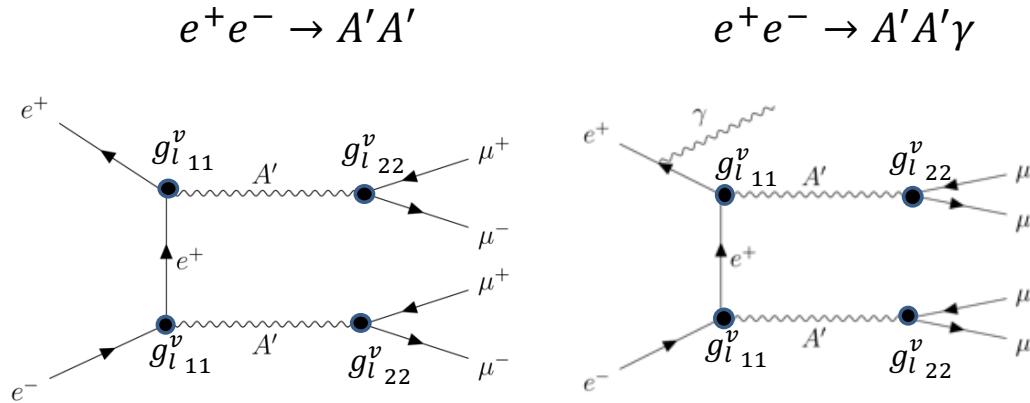
# ■ Signal modes

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



- Assumed that the dark photon ( $A'$ ) decay into muon pair [1, 2]
- Used a simplified model [3, 4]

<Feynman diagrams of signal modes>



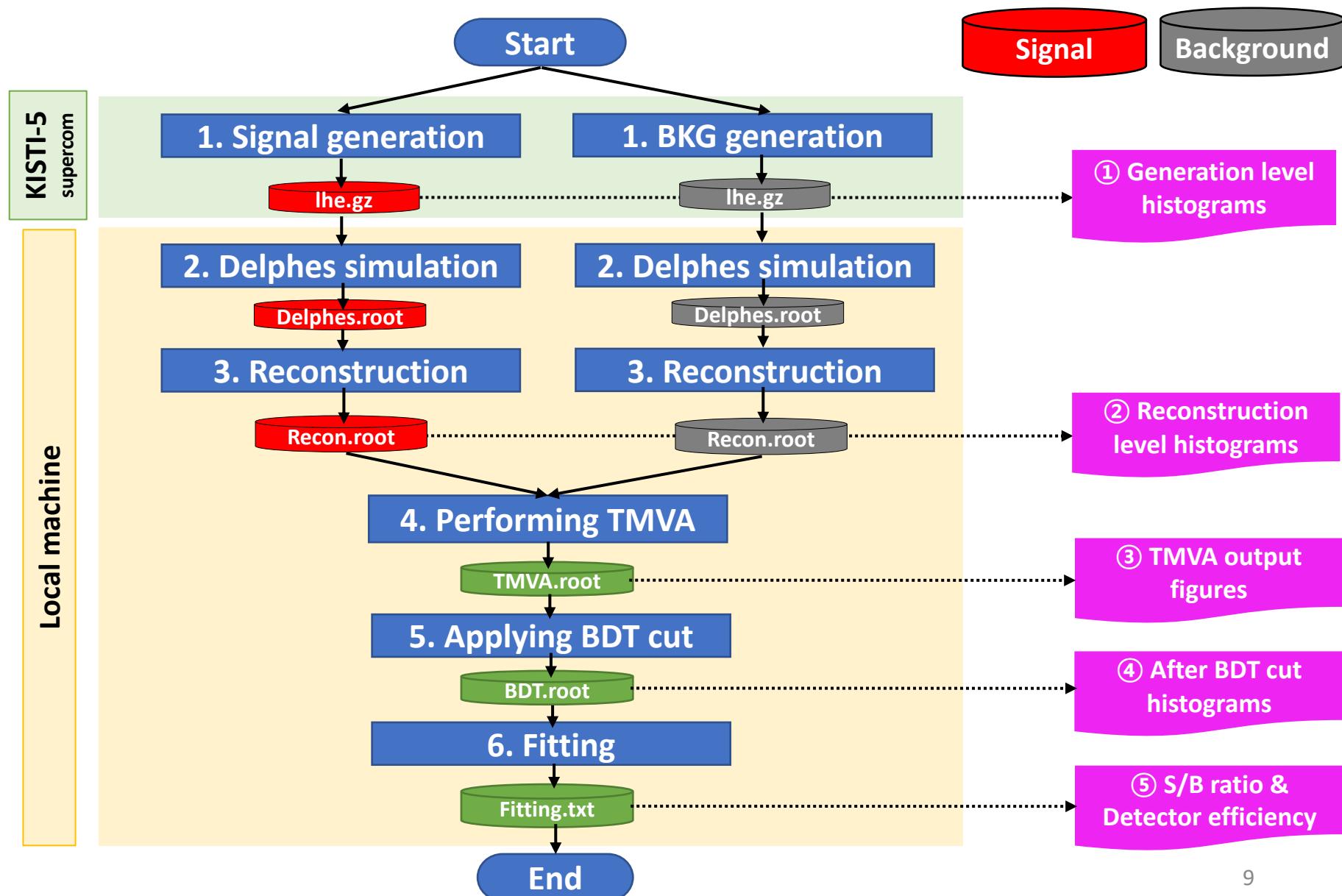
	Modes	Model
Signal	$e^+ e^- \rightarrow A'A'$	$e^+ e^- \rightarrow A'A'\gamma$ Simplified model
Background	$e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$	$e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^- \gamma$ The Standard model

- [1] I. Yeo and K. Cho, J. Astron. Space Sci. **35**(2), 67 (2018).  
[2] B. Shuve and I. Yavin, Phys. Rev. D. **89**, 113004 (2014).  
[3] J. Alwall *et al.*, JHEP **07**, 79 (2014).  
[4] J. Abdallah *et al.*, Phys. Dark Univ. **9-10**, 8 (2015).

## III. Methods

# Flowchart of the study

TMVA: Toolkit for Multivariate Data Analysis



# ■ Configuration of the study

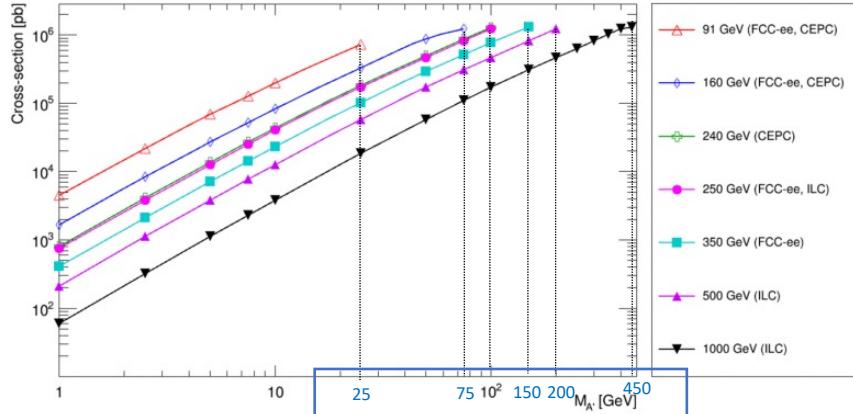
- Configuration of generation and machine learning.

Process	Parameters	Signal modes	Background modes
		$e^+e^- \rightarrow A'A'(\gamma)$	$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-(\gamma)$
	Event generator		MadGraph5 ver. 2.6.6
	Model	The simplified model	The Standard Model
	No. of events	1,000,000	~1,000,000
Generation	$\sqrt{s}$ [GeV]	91, 160, 240, 250, 350, 500, 1000	91, 160, 240, 250, 350, 500, 1000
	Decay width [GeV]	$6.7 \times 10^{-6}$	-
	Coupling constants $(g_l^\nu_{11}, g_l^\nu_{22})$	0.1	-
	Model	Boosted Decision Trees	
Machine learning		$p_{T\mu_1}, p_{T\mu_2}, p_{T\mu_3}, p_{T\mu_4}, \eta_{\mu_1}, \eta_{\mu_2}, \eta_{\mu_3}, \eta_{\mu_4},$ $\phi_{\mu_1}, \phi_{\mu_2}, \phi_{\mu_3}, \phi_{\mu_4}, m_{A'_1}, m_{A'_2}, p_{TA'_1}$ and $p_{TA'_2}$ (16 variables)	
(TMVA)	Input variables	<b>For <math>e^+e^- \rightarrow A'A'</math> and <math>e^+e^- \rightarrow A'A'\gamma</math></b>	
		$p_{T\gamma}, \eta_\gamma, \phi_\gamma$ and $E_\gamma$ (4 more variables for $\gamma$ -included decay modes)	
		<b>For <math>e^+e^- \rightarrow A'A'\gamma</math></b>	

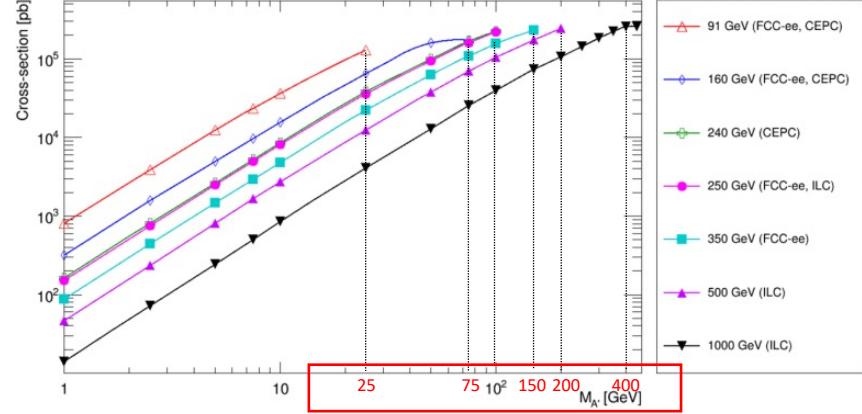
## IV. Preprocessing

- Cross-section depending on the dark photon mass

(a)

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

(b)

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

- Dark photon masses with the highest cross-section

Accelerator/Detector	$\sqrt{s}$ [GeV]	$m_{A'} [\text{GeV}]$	
		$e^+ e^- \rightarrow A' A'$	$e^+ e^- \rightarrow A' A'\gamma$
CEPC/CEPC	91	25	25
	160	75	75
	240	100	100
FCC-ee/IDEA	91	25	25
	160	75	75
	250	100	100
	350	150	150
ILC/ILD	250	100	100
	500	200	200
	1000	450	400

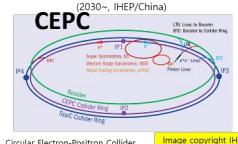
## IV. Results

1.  $e^+ e^- \rightarrow A' A'$  with  $A' \rightarrow \mu^+ \mu^-$

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

# 1. $e^+e^- \rightarrow A'A'$ with $A' \rightarrow \mu^+\mu^-$

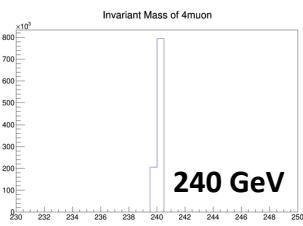
- Case I. CEPC at  $\sqrt{s} = 240$  GeV,  $m_{A'} = 100$  GeV



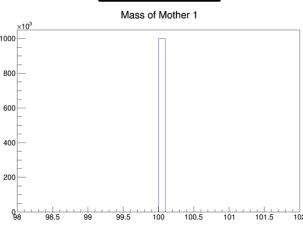
## ① Generation level

Signal	1,000,000
Background	972,739

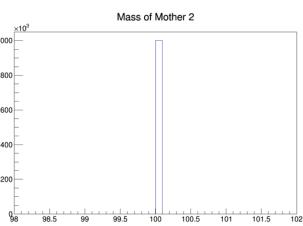
$M_{\mu^+\mu^-\mu^+\mu^-}$



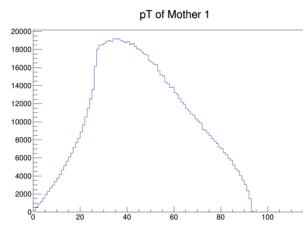
$M_{\mu^+\mu^-}$



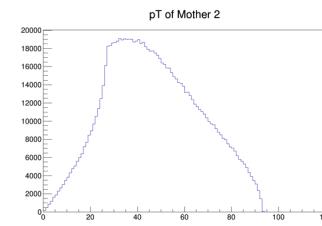
$M_{\mu^+\mu^-}$



$p_T \mu^+\mu^-$



$p_T \mu^+\mu^-$



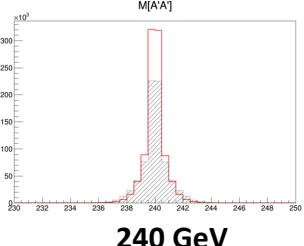
Signal

Background

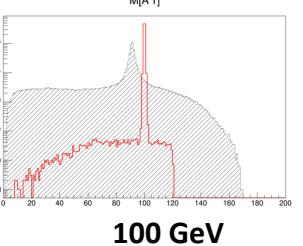
## ② Reconstruction level

Signal	944,310
Background	777,912

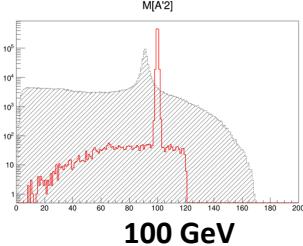
$M_{\mu^+\mu^-\mu^+\mu^-}$



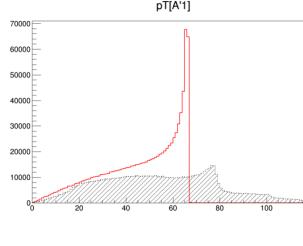
$M_{\mu^+\mu^-}$



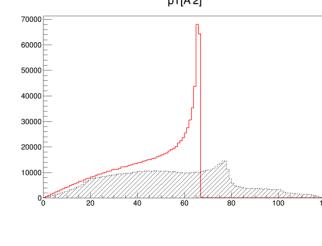
$M_{\mu^+\mu^-}$



$p_T \mu^+\mu^-$



$p_T \mu^+\mu^-$

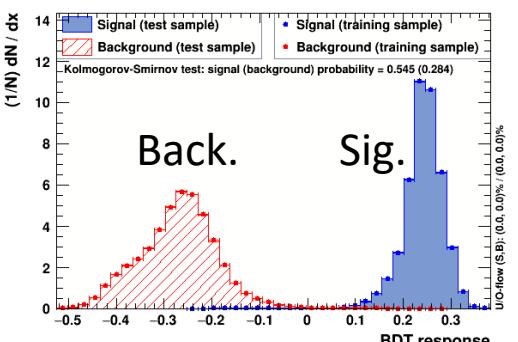


### ③ TMVA

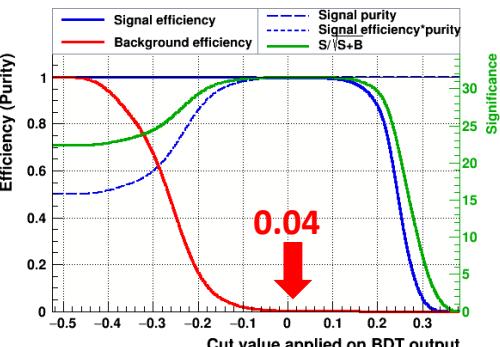
<Number of train and test data>

No. of data	Signal	Background
Train	472,155	388,956
Test	472,155	388,956
Total	944,310	777,912

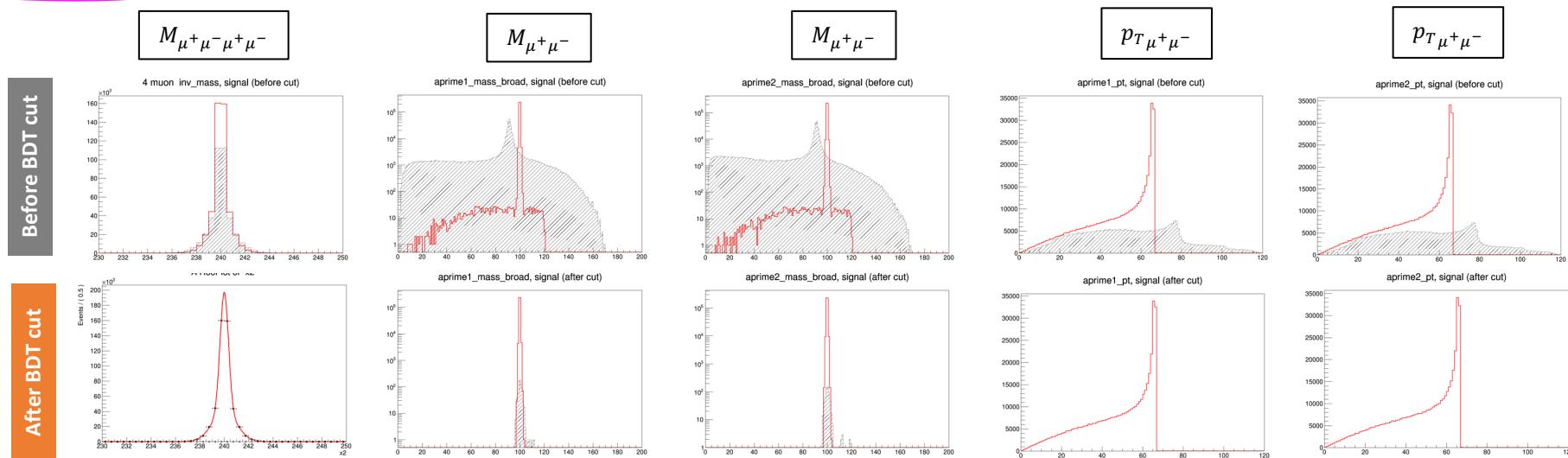
<BDT responses>



<Cut efficiencies>

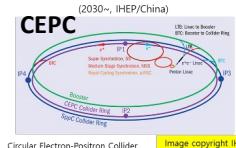


### ④ After BDT cut



<S/B improvement>

No. of data	Signal	Background	S/B
Before BDT cut	472,155	388,956	1.2
After BDT cut	470,580	596	789.6
S/B improvement	-	-	658.0





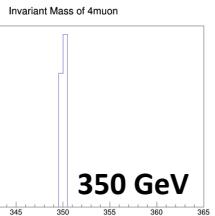
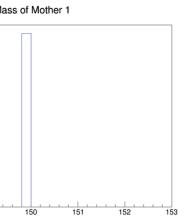
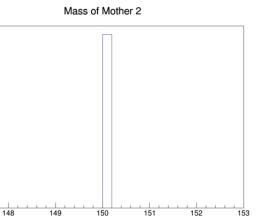
Future Circular Collider

Image copyright CERN

# ■ Case II. FCC-ee at $\sqrt{s} = 350 \text{ GeV}$ , $m_{A'} = 150 \text{ GeV}$

## ① Generation level

Signal	1,000,000
Background	967,667

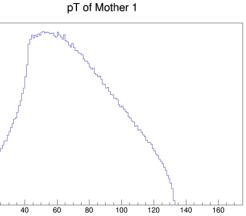
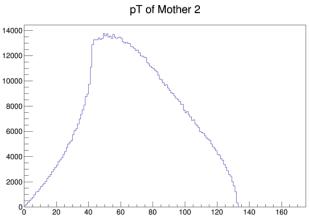
 $M_{\mu^+\mu^-\mu^+\mu^-}$  $M_{\mu^+\mu^-}$  $M_{\mu^+\mu^-}$ 

Signal

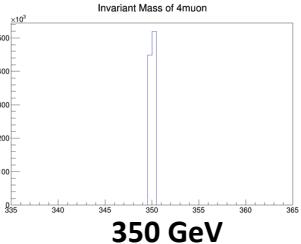
150 GeV

150 GeV

350 GeV

 $p_T \mu^+\mu^-$  $p_T \mu^+\mu^-$ 

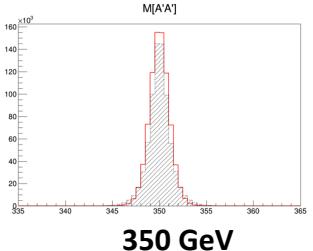
Background



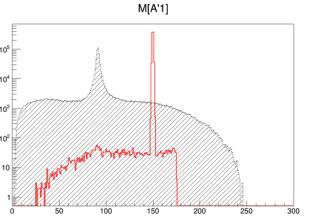
350 GeV

## ② Reconstruction level

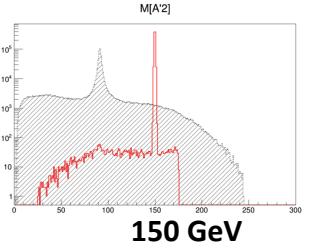
Signal	821,251
Background	739,877

 $M_{\mu^+\mu^-\mu^+\mu^-}$ 

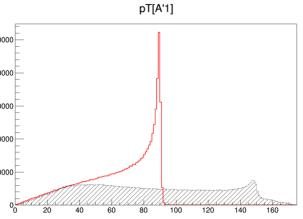
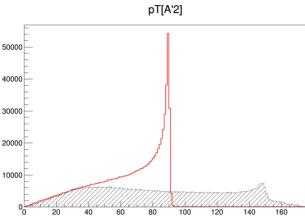
350 GeV

 $M_{\mu^+\mu^-}$ 

150 GeV

 $M_{\mu^+\mu^-}$ 

150 GeV

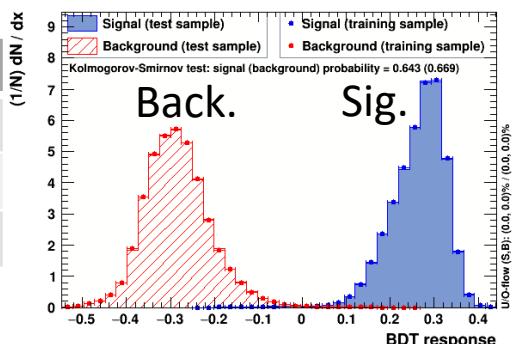
 $p_T \mu^+\mu^-$  $p_T[A'1]$  $p_T \mu^+\mu^-$  $p_T[A'2]$

### ③ TMVA

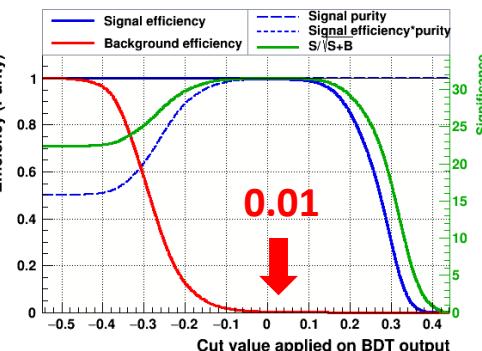
<Number of train and test data>

No. of data	Signal	Background
Train	410,625	369,938
Test	410,625	369,938
Total	821,251	739,877

<BDT responses>

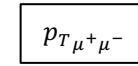
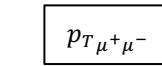
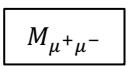
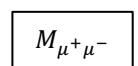
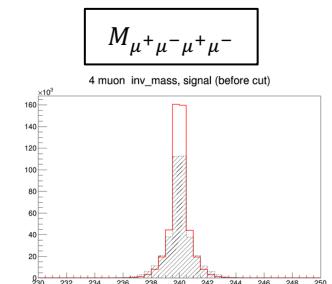


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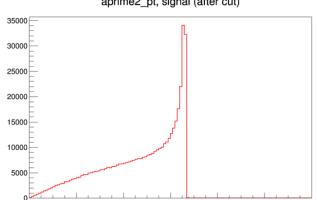
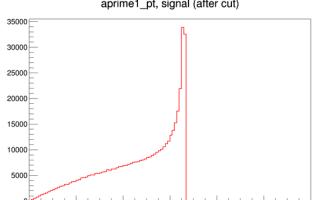
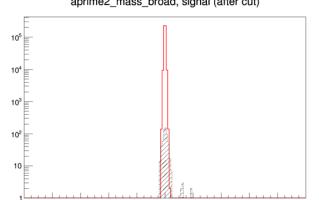
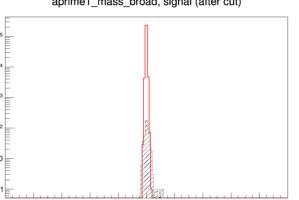
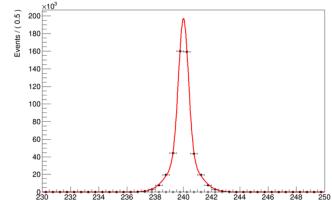


### ④ After BDT cut

Before BDT cut



After BDT cut



<S/B improvement>

No. of data	Signal	Background	S/B
Before BDT cut	410,625	369,938	1.1
After BDT cut	408,957	765	534.6
S/B improvement	-	-	486.0



# Case III. ILC at $\sqrt{s} = 1000 \text{ GeV}$ , $m_{A'} = 450 \text{ GeV}$

## ① Generation level

Signal	1,000,000
Background	913,321

$M_{\mu^+\mu^-\mu^+\mu^-}$

Invariant Mass of 4muon

1000 GeV

$M_{\mu^+\mu^-}$

Mass of Mother 1

450 GeV

$M_{\mu^+\mu^-}$

Mass of Mother 2

450 GeV

$p_T \mu^+\mu^-$

$p_T$  of Mother 1

$p_T \mu^+\mu^-$

$p_T$  of Mother 2

Signal

Background

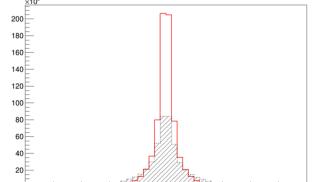
1000 GeV

## ② Reconstruction level

Signal	741,382
Background	496,638

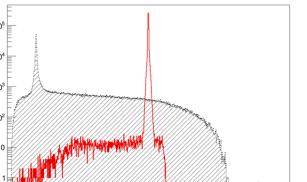
$M_{\mu^+\mu^-\mu^+\mu^-}$

$M[A'A']$



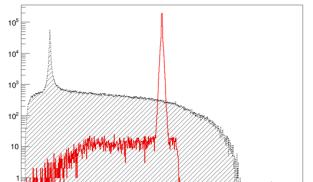
$M_{\mu^+\mu^-}$

$M[A'1]$



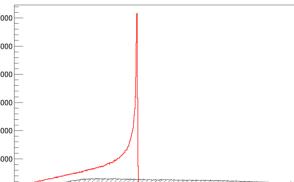
$M_{\mu^+\mu^-}$

$M[A'2]$



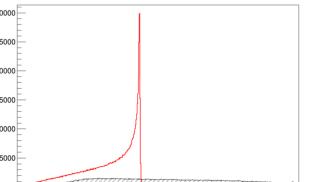
$p_T \mu^+\mu^-$

$p_T[A'1]$



$p_T \mu^+\mu^-$

$p_T[A'2]$



1000 GeV

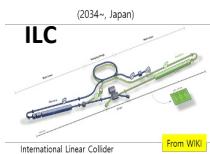
450 GeV

450 GeV

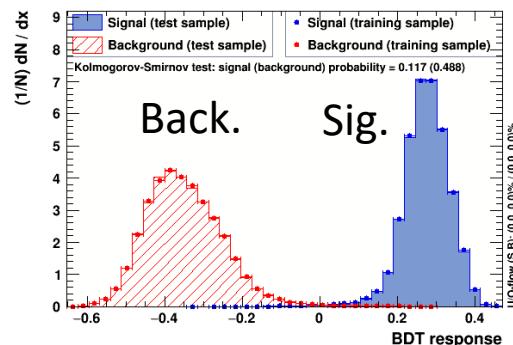
### ③ TMVA

<Number of train and test data>

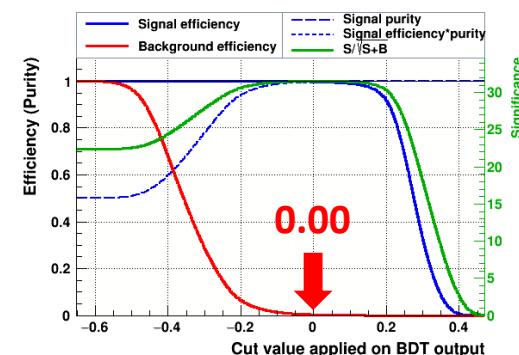
No. of data	Signal	Background
Train	370,691	248,319
Test	370,691	248,319
Total	741,381	496,368



<BDT responses>

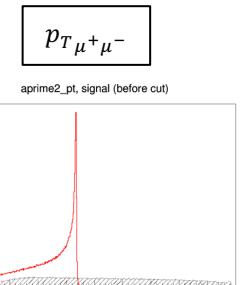
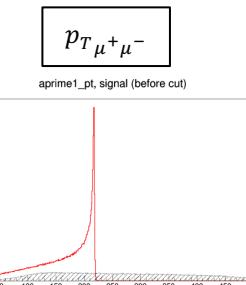
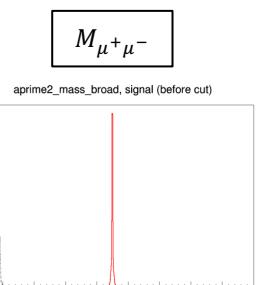
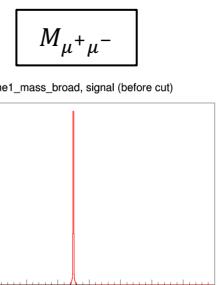
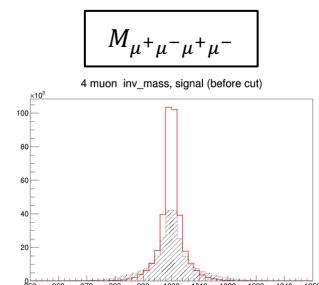


<Cut efficiencies>

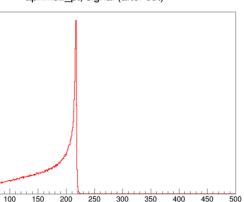
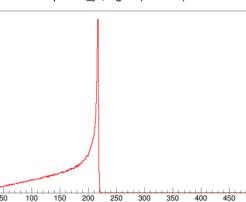
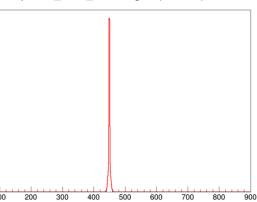
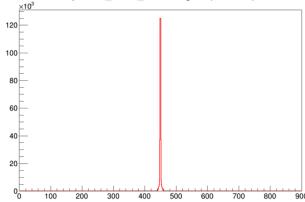
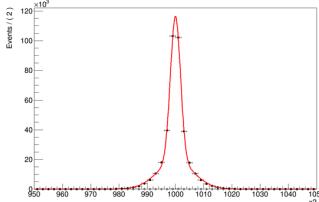


### ④ After BDT cut

Before BDT cut



After BDT cut



<S/B improvement>

No. of data	Signal	Background	S/B
Before BDT cut	370,691	<b>248,319</b>	<b>1.5</b>
After BDT cut	369,881	<b>856</b>	<b>432.1</b>
S/B improvement	-	-	<b>288.1</b>

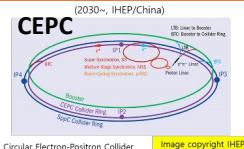
## ⑤ S/B & Detector efficiency

- Performed the same procedure to other cases
- S/B improved **a factor of 100~10000**
- Detector efficiency through high-purity signal events

Accelerator/Detector	$\sqrt{s}$ [GeV]	$m_{A'}$ [GeV]	S/B improvement	Detector efficiency [%]
CEPC/CEPC	91	25	847.3	$92.4 \pm 0.2$
	160	75	680.6	$94.3 \pm 0.2$
	240	100	658.0	$94.1 \pm 0.3$
FCC-ee/IDEA	91	25	11781.2	$87.7 \pm 0.1$
	160	75	876.3	$79.1 \pm 0.1$
	250	100	1455.8	$83.5 \pm 0.1$
	350	150	486.0	$81.8 \pm 0.1$
ILC/ILD	250	100	713.6	$71.0 \pm 0.3$
	500	200	709.6	$73.3 \pm 0.4$
	1000	450	288.1	$74.0 \pm 0.2$

# 2. $e^+e^- \rightarrow A'A'\gamma$ with $A' \rightarrow \mu^+\mu^-$

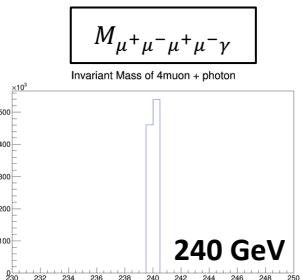
- Case I: CEPC at  $\sqrt{s} = 240$  GeV,  $m_{A'} = 100$  GeV



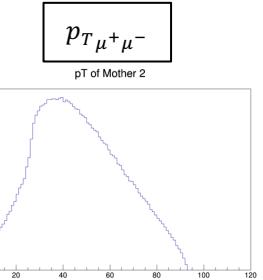
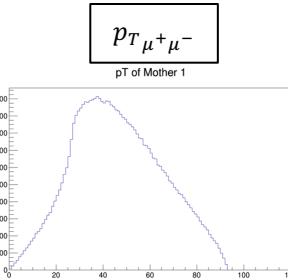
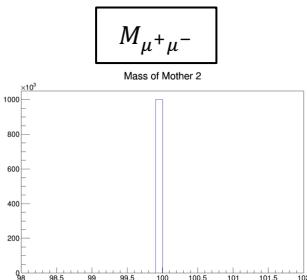
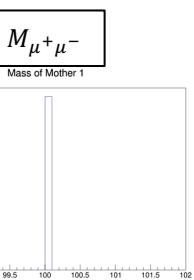
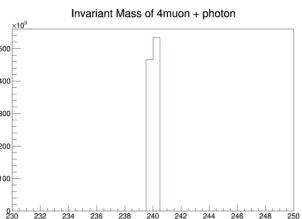
## ① Generation level

Signal	1,000,000
Background	1,000,000

Signal

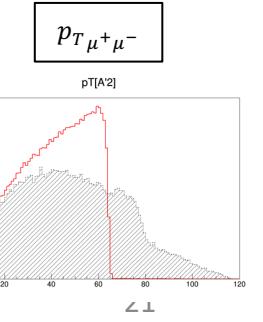
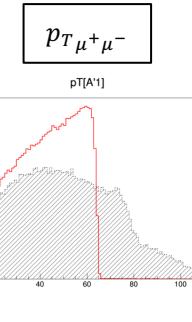
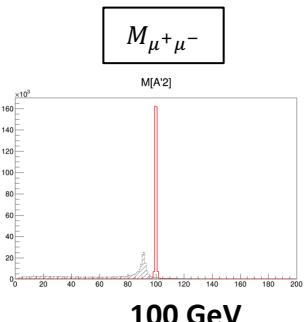
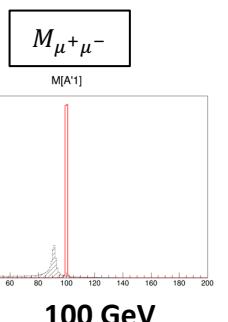
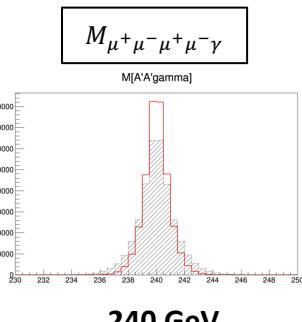


Background



## ② Reconstruction level

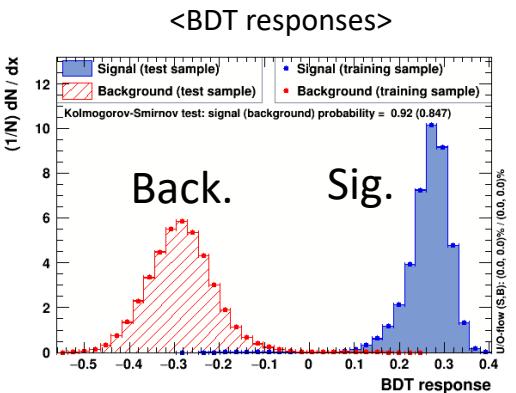
Signal	339,161
Background	341,995



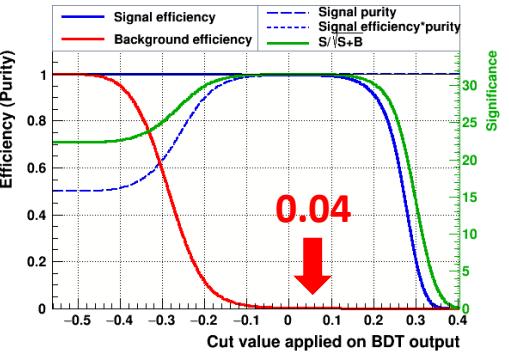
### ③ TMVA

<Number of train and test data>

No. of data	Signal	Background
Train	169,580	170,997
Test	169,580	170,997
Total	339,161	341,995

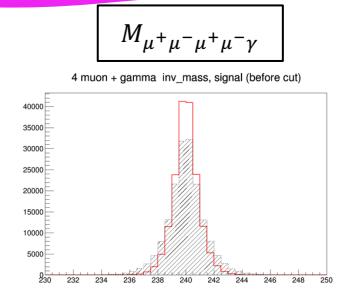


<Cut efficiencies>

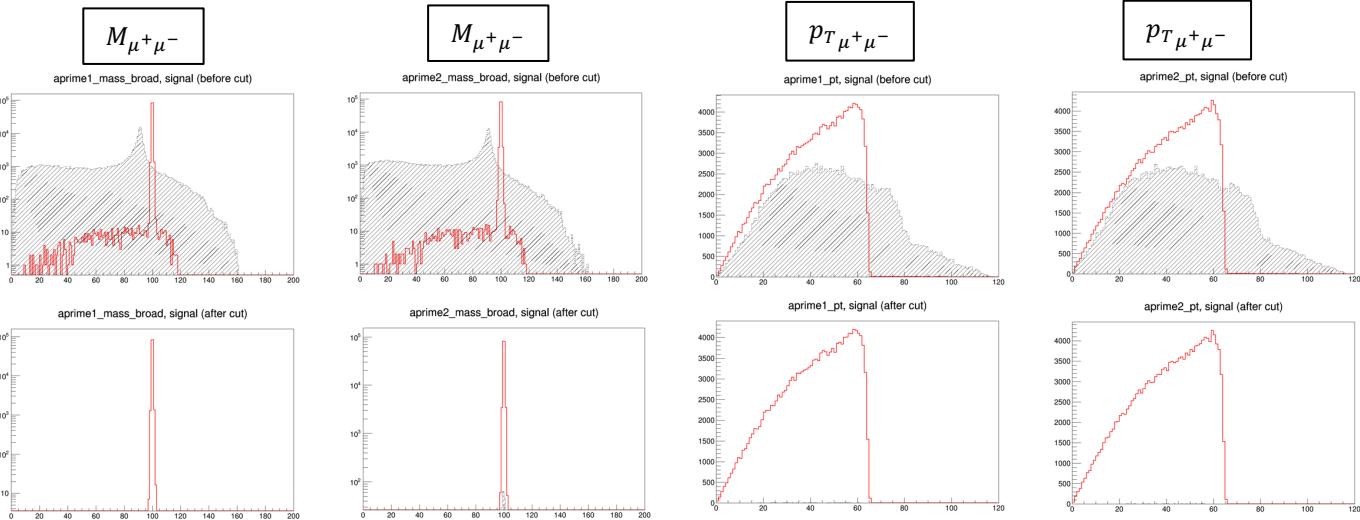
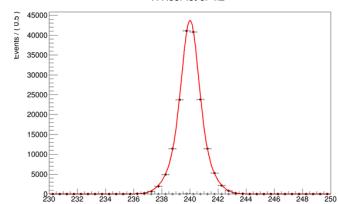


### ④ After BDT cut

Before BDT cut

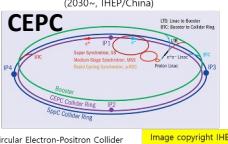


After BDT cut



<S/B improvement>

No. of data	Signal	Background	S/B
Before BDT cut	169,580	170,997	1.0
After BDT cut	168,879	238	709.6
S/B improvement	-	-	709.6





Future Circular Collider

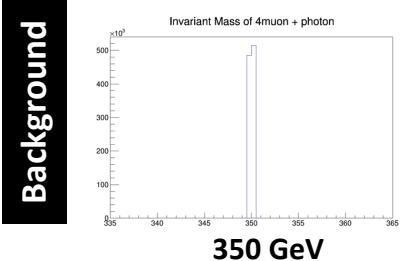
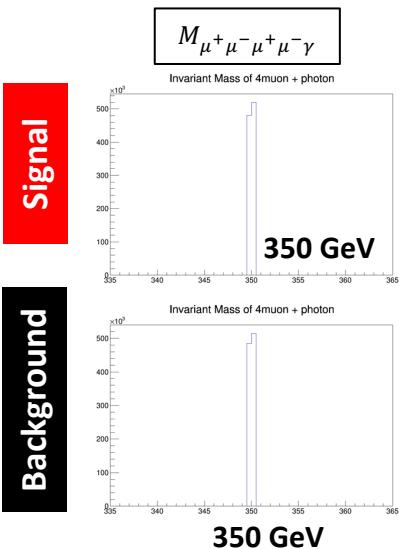
Image copyright CERN

## ■ Case II: FCC-ee at $\sqrt{s} = 350 \text{ GeV}$ , $m_{A'} = 150 \text{ GeV}$

### ① Generation level

Signal 1,000,000

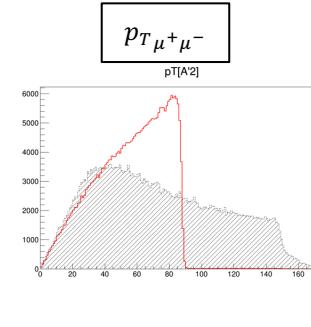
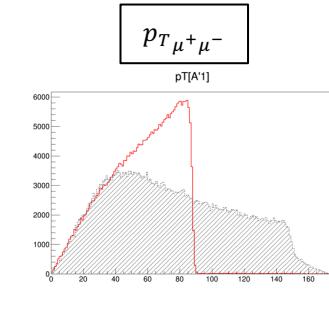
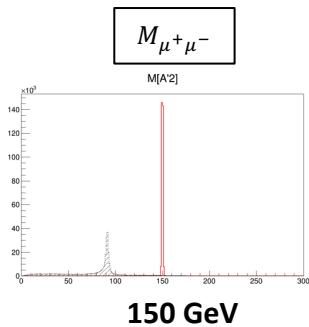
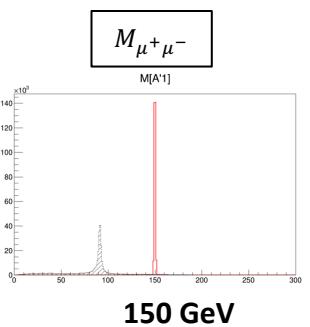
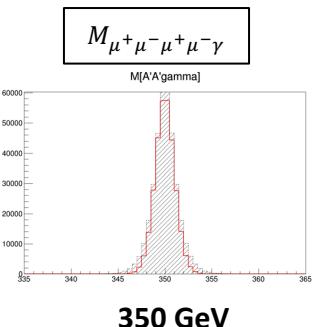
Background 1,000,000



### ② Reconstruction level

Signal 306,454

Background 357,941

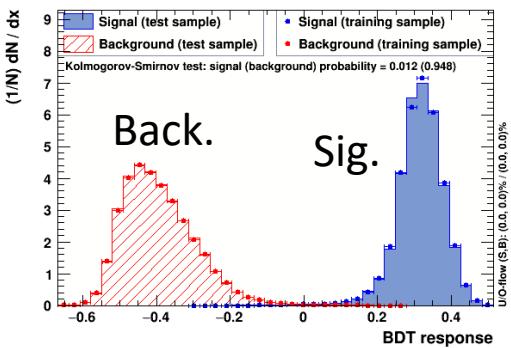


### ③ TMVA output

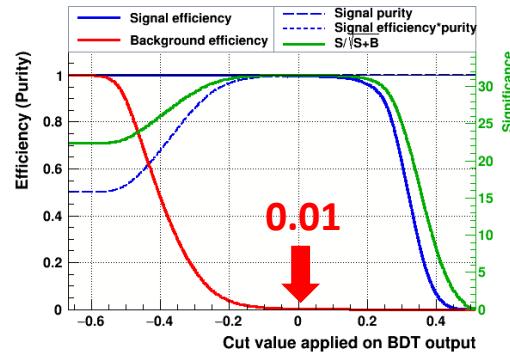
<Number of train and test data>

No. of data	Signal	Background
Train	153,227	178,970
Test	153,227	178,970
Total	306,454	357,941

<BDT responses>

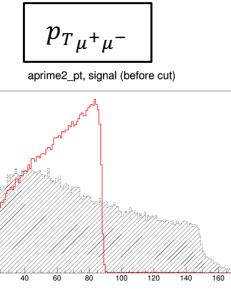
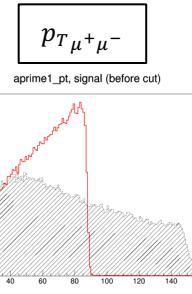
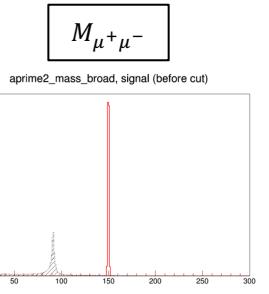
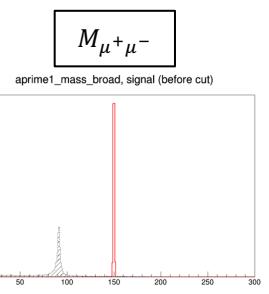
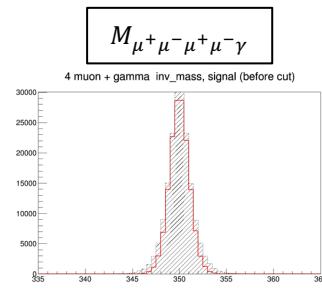


<Cut efficiencies>

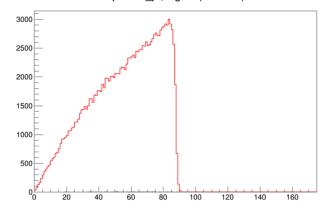
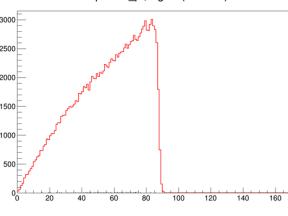
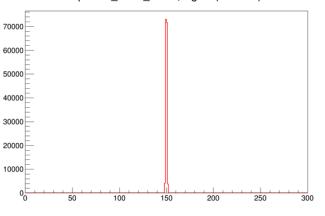
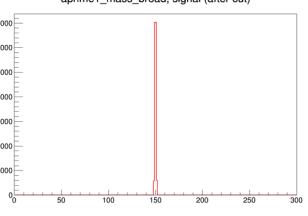
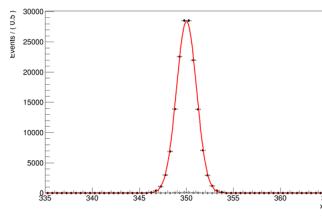


### ④ After BDT cut

Before BDT cut

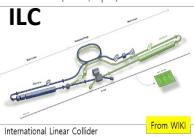


After BDT cut



<S/B improvement>

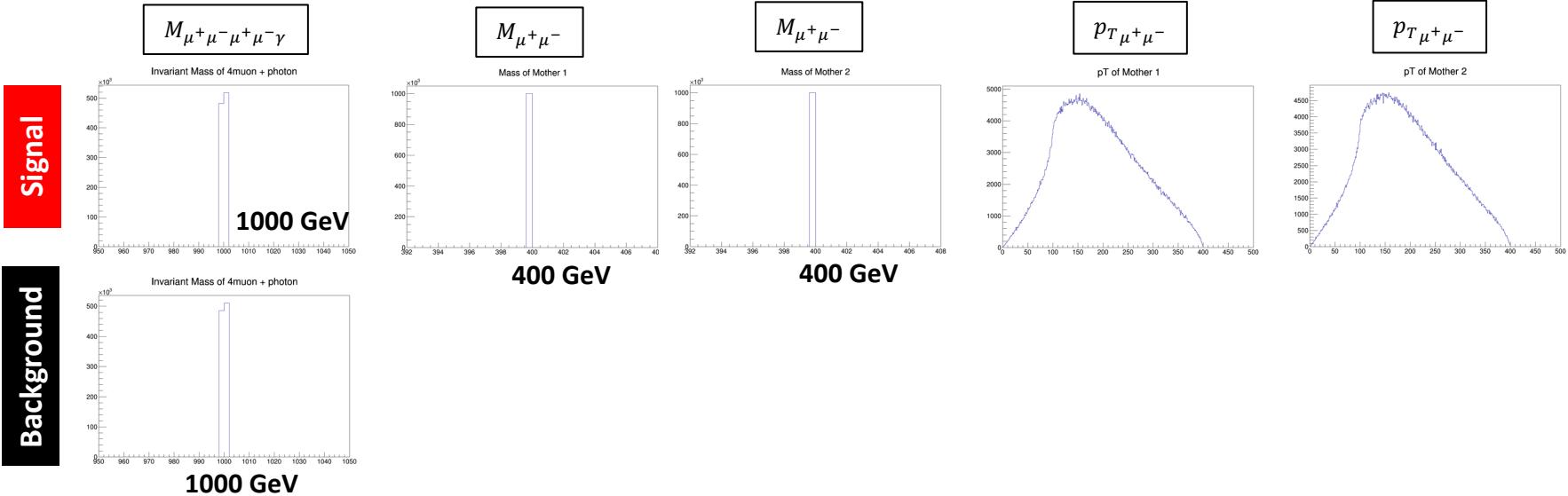
No. of data	Signal	Background	S/B
Before BDT cut	153,227	178,970	0.9
After BDT cut	152,557	419	364.1
S/B improvement	-	-	404.6



# ■ Case III. ILC at $\sqrt{s} = 1000 \text{ GeV}$ , $m_{A'} = 400 \text{ GeV}$

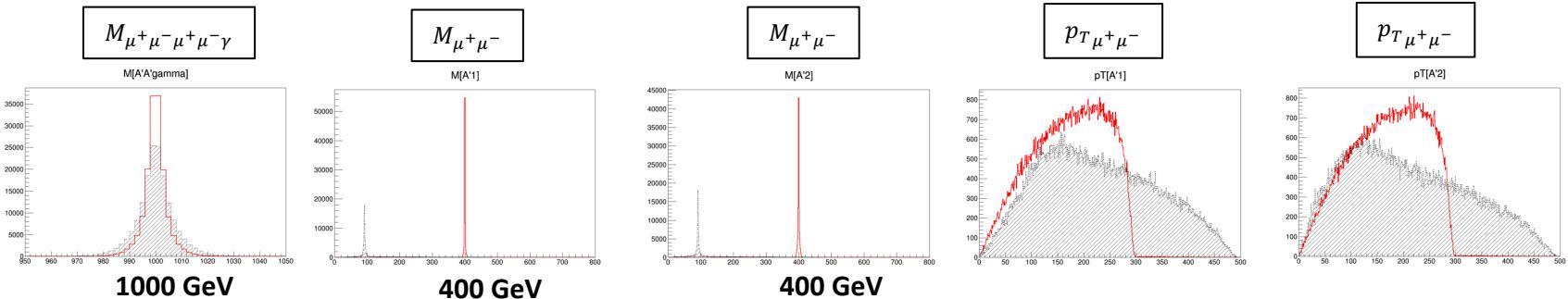
## ① Generation level

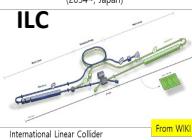
Signal	1,000,000
Background	1,000,000



## ② Reconstruction level

Signal	154,514
Background	165,443



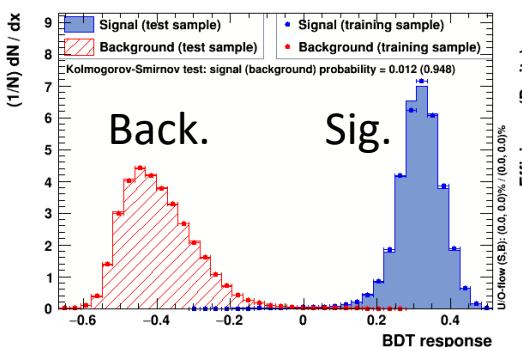


### ③ TMVA output

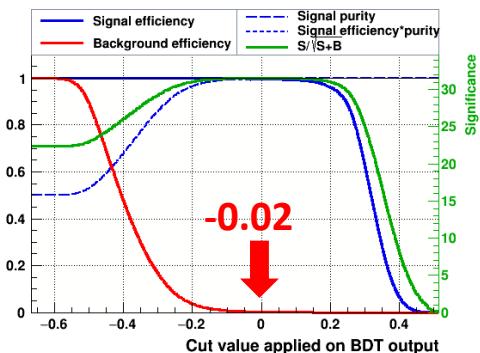
<Number of train and test data>

No. of data	Signal	Background
Train	77,257	82,721
Test	77,257	82,721
Total	154,514	165,443

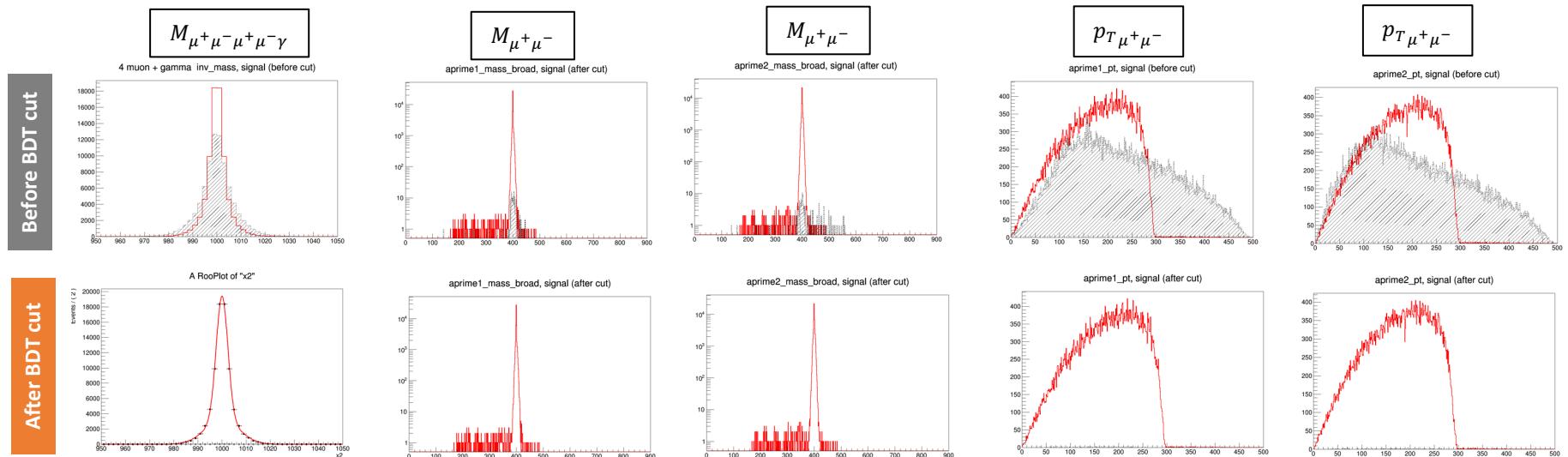
<BDT responses>



<Cut efficiencies>



### ④ After BDT cut



<S/B improvement>

No. of data	Signal	Background	S/B
Before BDT cut	77,257	82,721	0.9
After BDT cut	77,053	244	315.8
S/B improvement	-	-	350.9

## ⑤ S/B & Detector efficiency

- Performed the same procedure to other cases
- S/B improved **a factor of 100~1000**
- Detector efficiency through high-purity signal events

Accelerator/Detector	$\sqrt{s}$ [GeV]	$m_{A'}$ [GeV]	S/B improvement	Detector efficiency [%]
CEPC/CEPC	91	25	731.0	$32.4 \pm 0.9$
	160	75	717.1	$19.5 \pm 0.5$
	240	100	709.6	$33.8 \pm 0.5$
FCC-ee/IDEA	91	25	409.2	$30.3 \pm 0.1$
	160	75	1328.9	$16.2 \pm 0.1$
	250	100	3694.7	$31.0 \pm 0.1$
	350	150	404.6	$30.5 \pm 0.1$
ILC/ILD	250	100	727.9	$5.4 \pm 0.6$
	500	200	532.0	$10.4 \pm 0.2$
	1000	400	350.9	$15.4 \pm 0.1$

## VI. Summary

# ■ Summary

- To reduce the SM background
- Studied the ‘double dark photon modes’ at the future e+e- colliders based on machine learning
- S/B improved a factor of 100~10000
- Detector efficiencies through high-purity signal events
- Will help the search for the dark photons

# ACKNOWLEDGMENTS

- National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1F1A1064008)
- Major institutional R&D program, KISTI (No. K-24-L02-C04-S01)
- National Supercomputing Center with supercomputing resources including technical support (KSC-2023-CHA-0005)
- A. Sytov acknowledges support by the European Commission through the H2020-MSCA-IF TRILLION project (GA. 101032975)

**Thank you for listening. ☺**

kihong@kisti.re.kr

# Backups

- The configuration for the dark photon mass scan
- Dark photon selection
- More on reconstruction level
- More on machine learning results
- Delphes configuration
- Signal Feynman diagrams
- Background Feynman diagrams
- More on the simplified model
- More on the dark photon
- Cross-section study for signal processes
- Cross-section study for background processes
- CPU time

# The configuration for the dark photon mass scan

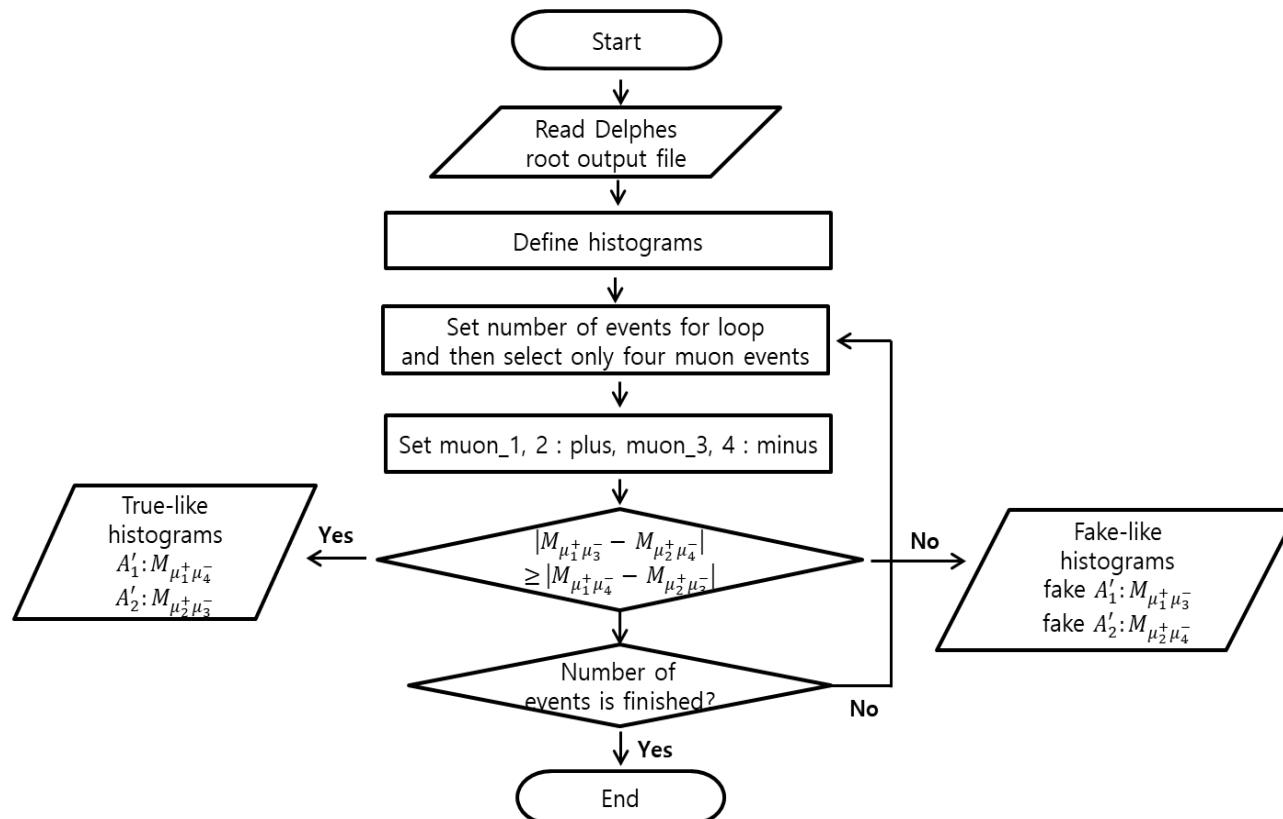
- We scanned the dark photon mass from 1.0 GeV to 500 GeV to find the highest cross-section.
- We used the KISTI-5 supercomputer for efficient scanning.

Configuration	$e^+e^- \rightarrow A'A'$	$e^+e^- \rightarrow A'A'\gamma$
Event generator		MadGraph5 ver. 2.6.6
Model		The simplified model
Machine		KISTI-5 supercomputer
Number of events	10,000	10,000
$\sqrt{s}$ [GeV]	91, 160, 240, 250, 350, 500, 1000	91, 160, 240, 250, 350, 500, 1000
$m_{A'}$ [GeV]	1.0, 2.5, 5.0, 7.5, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500	1.0, 2.5, 5.0, 7.5, 10, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500
Decay width [GeV]	$6.7 \times 10^{-6}$	$6.7 \times 10^{-6}$
Coupling constants $(g_{l1}^v, g_{l2}^v)$	0.1	0.1

# Dark photon selection

- The dark photon was reconstructed using the condition of the least dark photon mass difference.

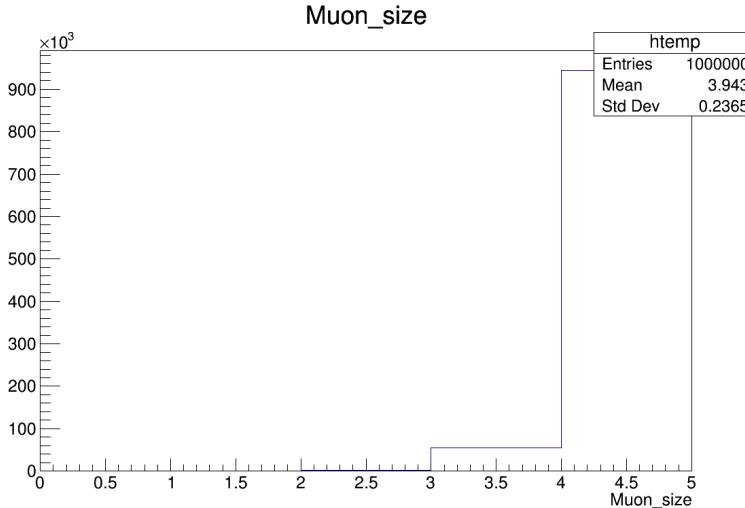
Flowchart of dark photon selection based on stand-alone frame



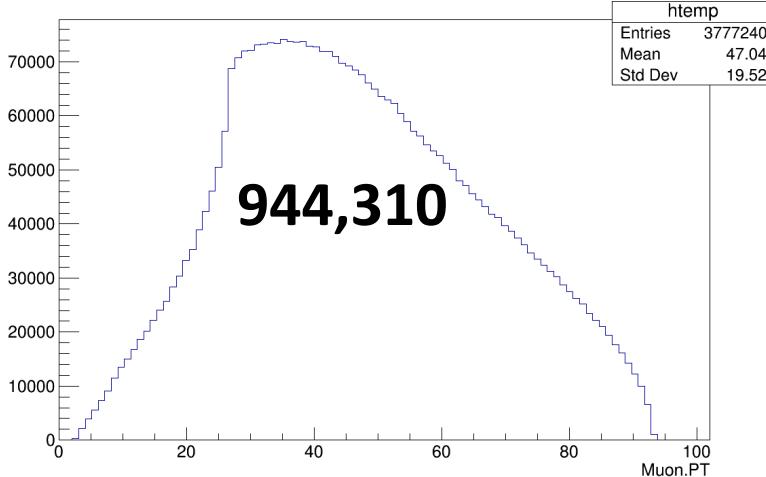
# More on reconstruction level

② Reconstruction level (1M)  $e^+e^- \rightarrow A'A'$ , CEPC  $\sqrt{s} = 240 \text{ GeV}$ ,  $m_{A'} = 100 \text{ GeV}$

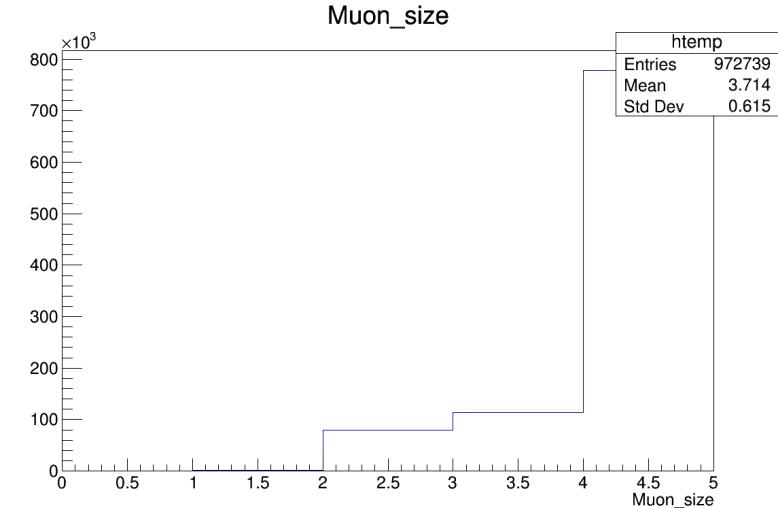
Signal



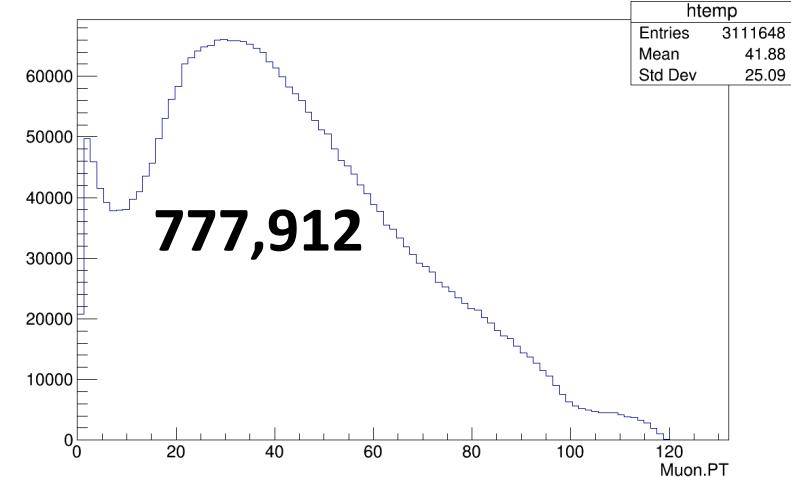
Muon.PT {Muon\_size == 4}



Background



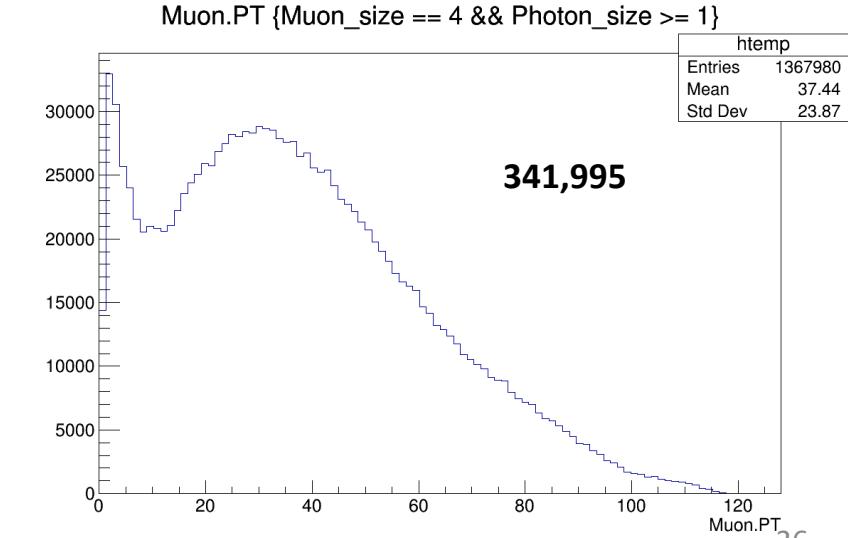
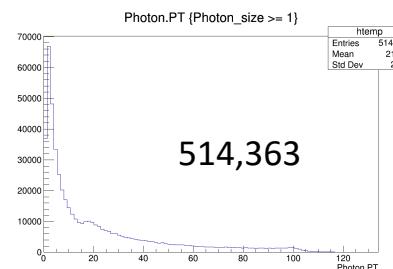
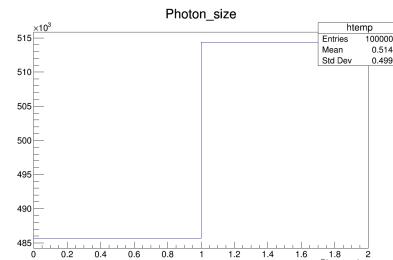
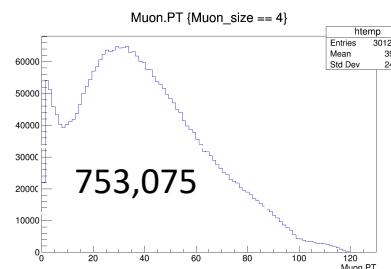
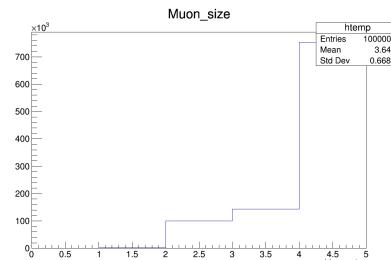
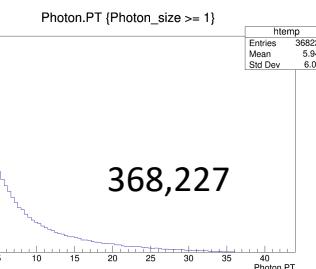
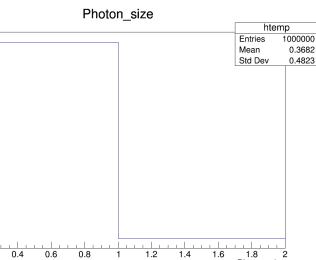
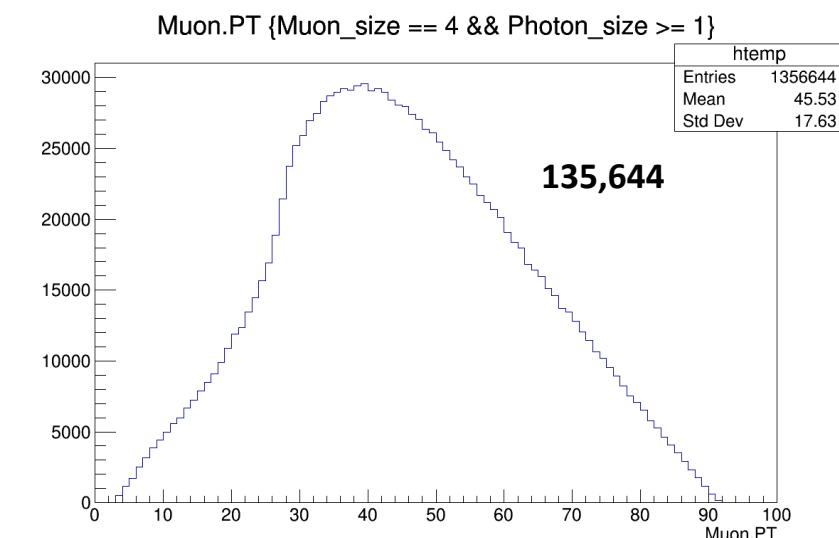
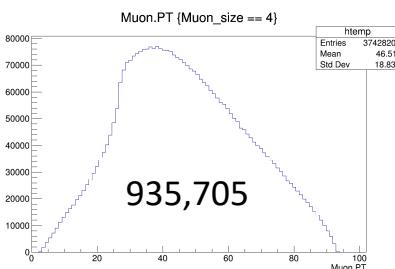
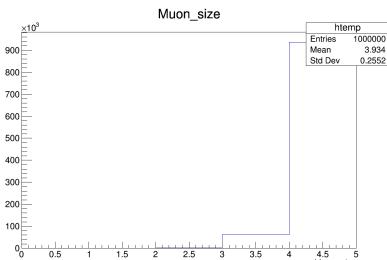
Muon.PT {Muon\_size == 4}



② Reconstruction level (1M)  $e^+e^- \rightarrow A'A'\gamma$ , CEPC  $\sqrt{s} = 240$  GeV,  $m_{A'} = 100$  GeV

Signal

Background

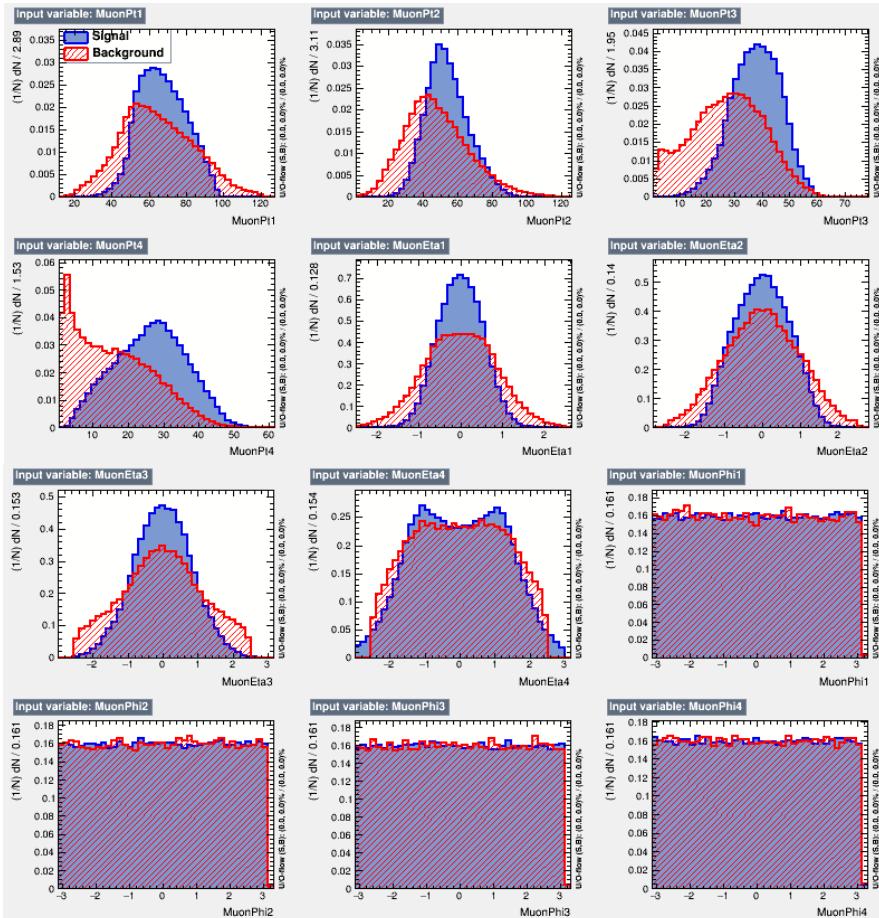


# More on machine learning results

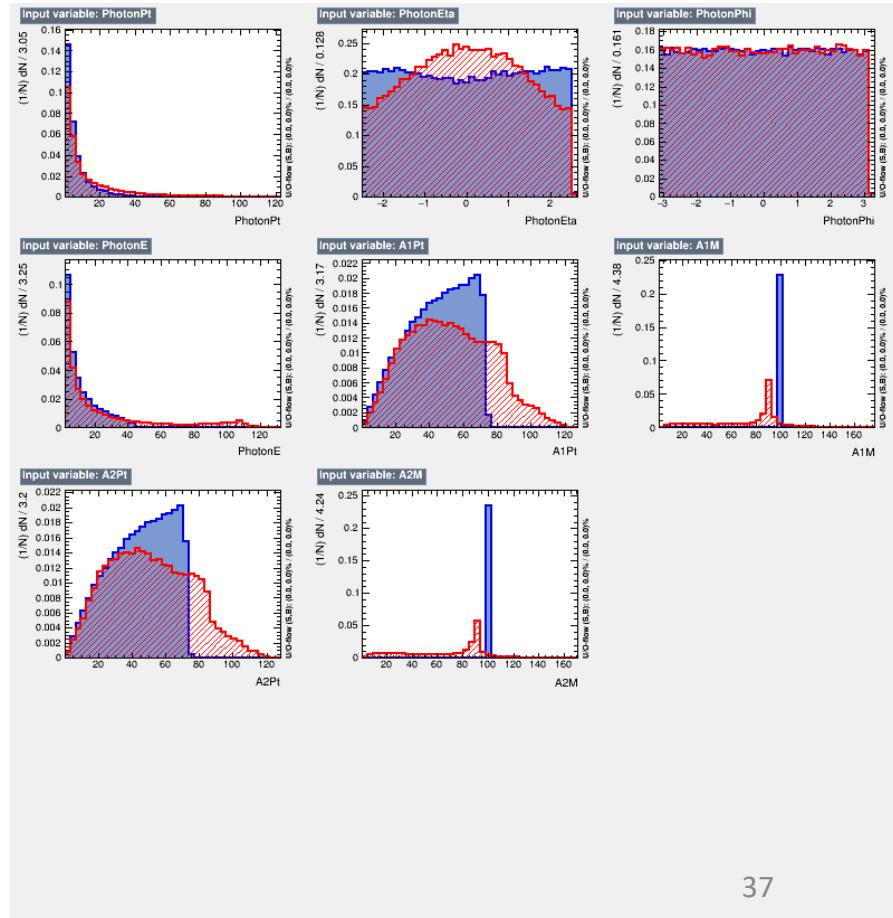
③ BDT: input variables  $e^+e^- \rightarrow A'A'\gamma$ , FCC-ee  $\sqrt{s} = 250$  GeV,  $m_{A'} = 100$  GeV

□ BDT 20 input variables

**Muons**



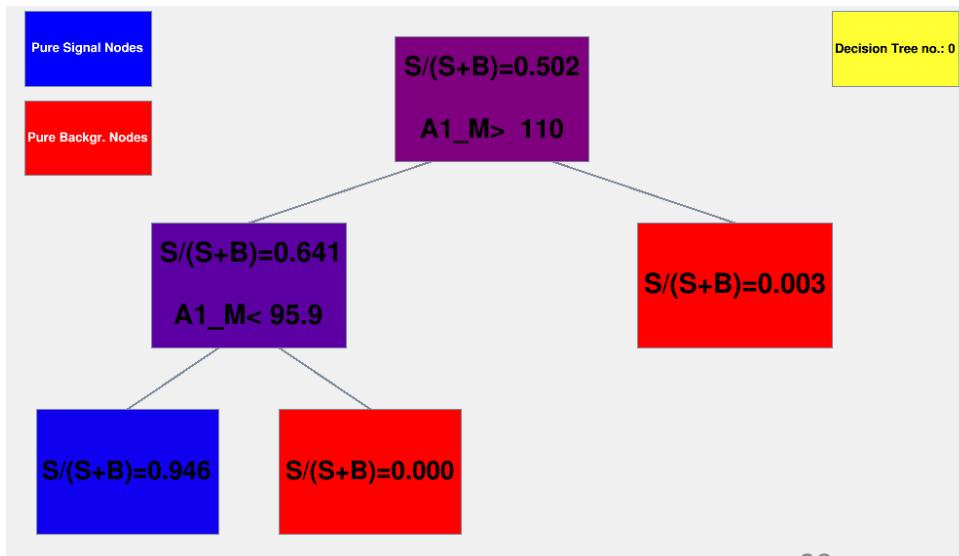
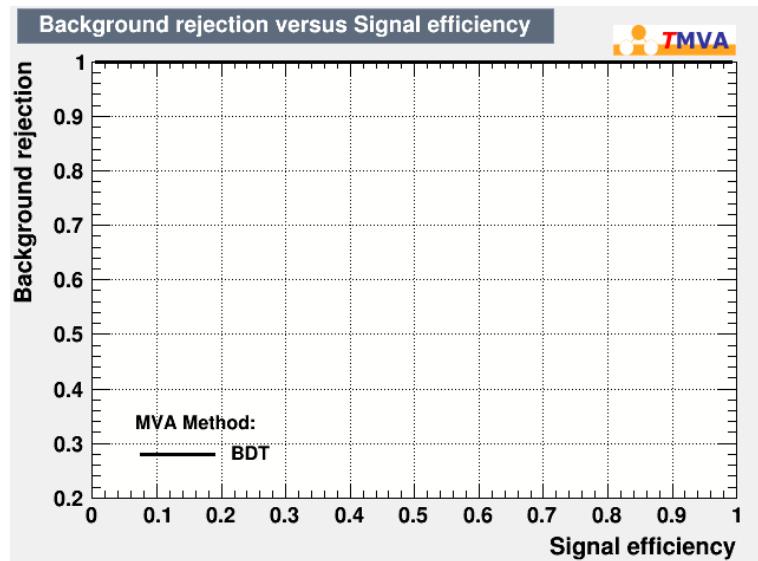
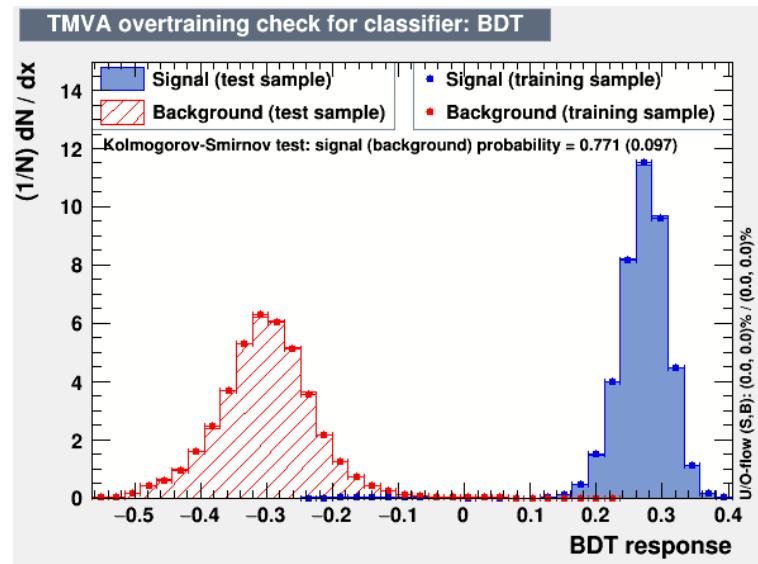
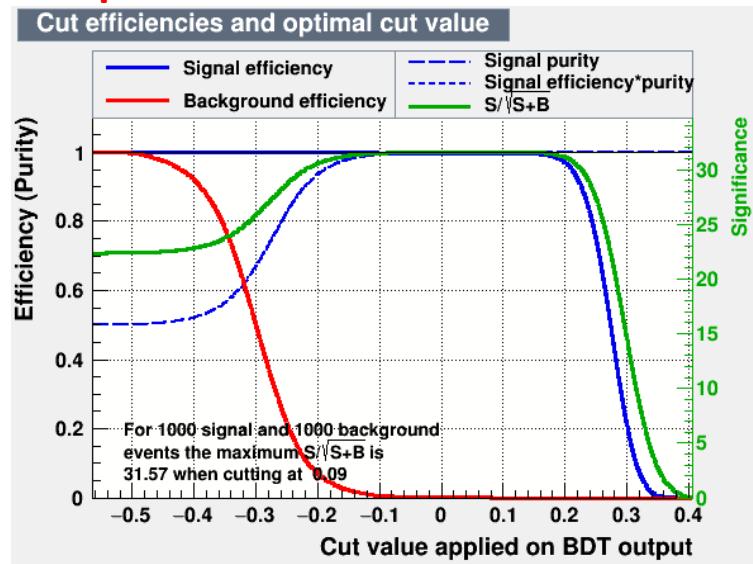
**Photon & Dark photon**



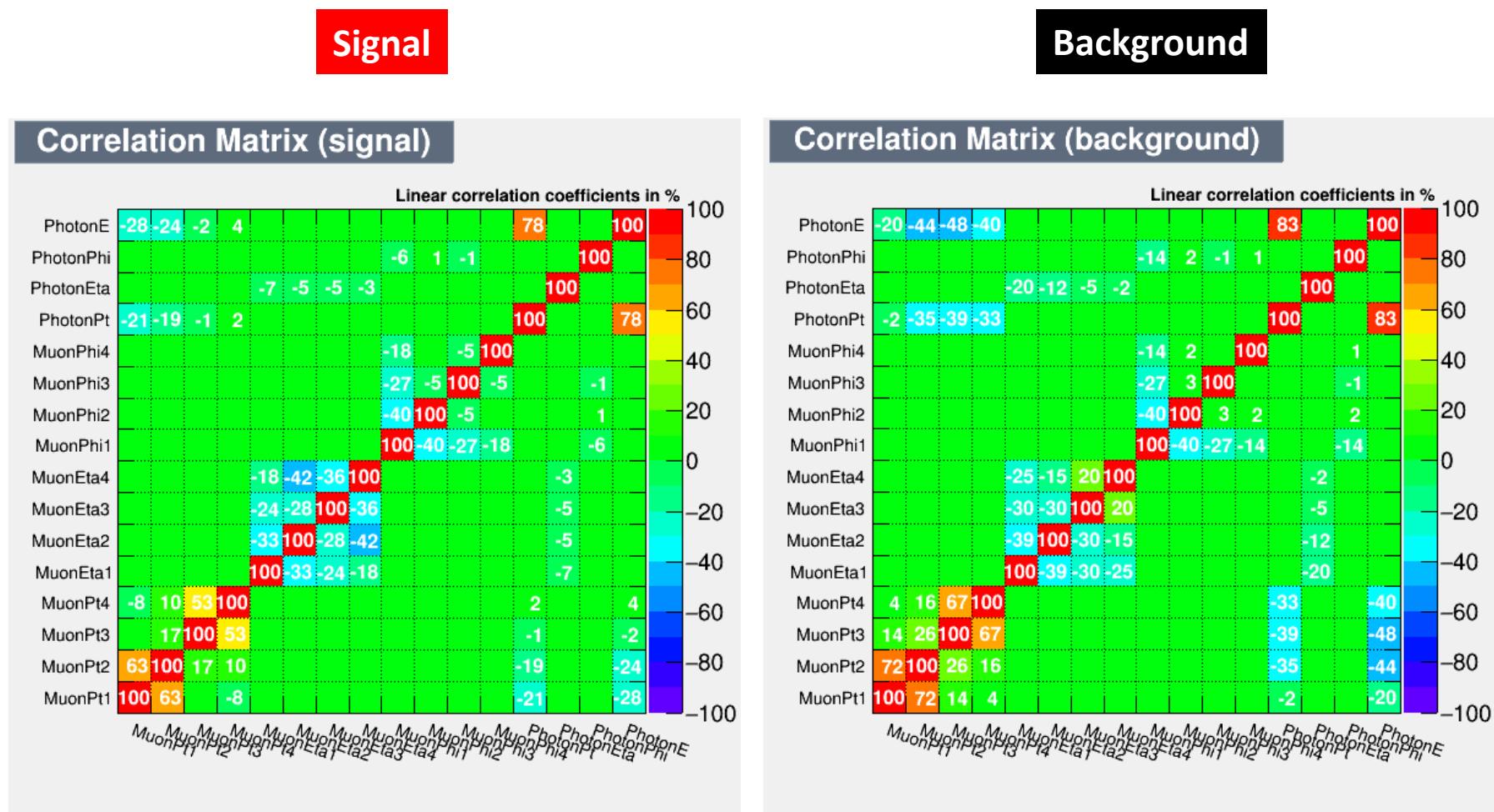
### ③ BDT: optimal cut $e^+e^- \rightarrow A'A'\gamma$ , FCC-ee $\sqrt{s} = 250$ GeV, $m_{A'} = 100$ GeV

#### □ BDT results figures

##### Optimal cut: 0.09



#### Correlation Matrix of signal and background



# Parameters of Delphes configuration cards

Accelerator/ Detector	CEPC/ CEPC	FCC-ee/ IDEA	ILC/ ILD
Magnetic field (B)			
Radius [m]	1.81	2.25	1.8
Half-length [m]	2.35	2.5	2.4
B [T]	3.5	2.0	3.5
Muon			
Tracking efficiency $\eta$	$ \eta  \leq 3.0$	$ \eta  \leq 3.0$	$ \eta  \leq 2.4$
Tracking efficiency $p_T$ [GeV]	$\geq 0.1$	-	$\geq 0.1$
Tracking efficiency E [GeV]	-	$\geq 0.3$	-
Efficiency $\eta$	$ \eta  \leq 3.0$	$ \eta  \leq 3.0$	$ \eta  \leq 2.4$
Efficiency $p_T$ [GeV]	-	-	$\geq 10.0$
Efficiency E [GeV]	$\geq 2.0$	$\geq 2.0$	-
Isolation DeltaRMaX	$\leq 0.5$	$\leq 0.5$	$\leq 0.5$
Isolation PTMin	$\geq 0.5$	$\geq 0.5$	$\geq 0.5$
Photon			
Efficiency $\eta$	$ \eta  \leq 3.0$	$ \eta  \leq 3.0$	$ \eta  \leq 2.5$
Efficiency $p_T$ [GeV]	-	-	$\geq 10.0$
Efficiency E [GeV]	$\geq 2.0$	$\geq 2.0$	-
Isolation DeltaRMaX	$\leq 0.5$	$\leq 0.5$	$\leq 0.5$
Isolation PTMin	$\geq 0.5$	$\geq 0.5$	$\geq 0.5$

# Signal Feynman diagrams (A'A')

❖ Total 2 diagrams

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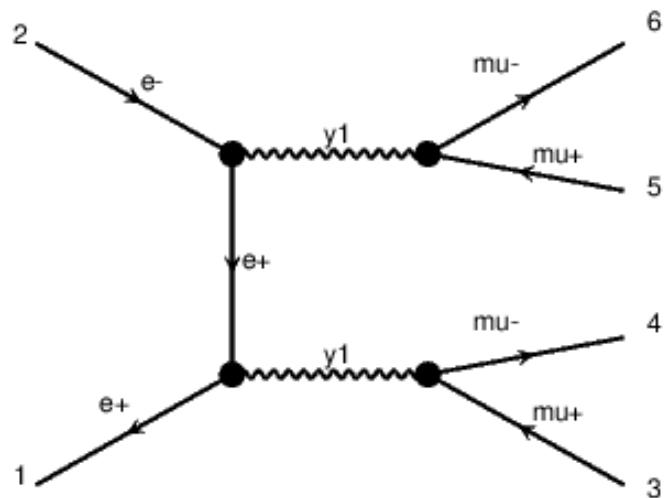


diagram 1

DMV=4, QCD=0, QED=0

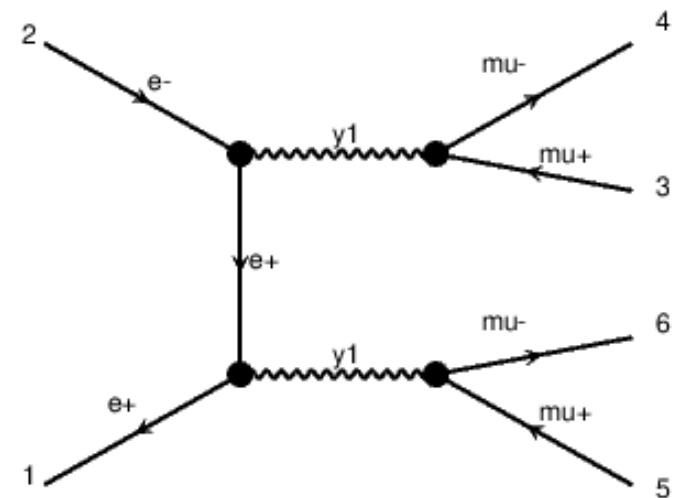


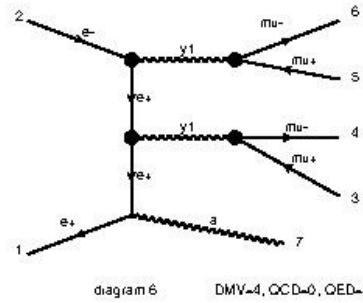
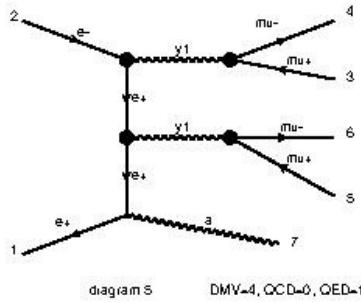
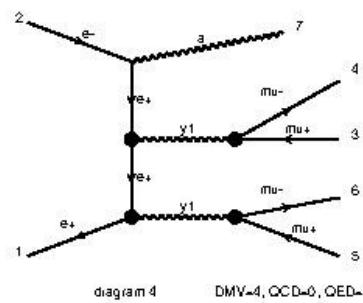
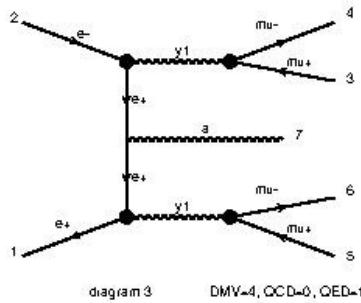
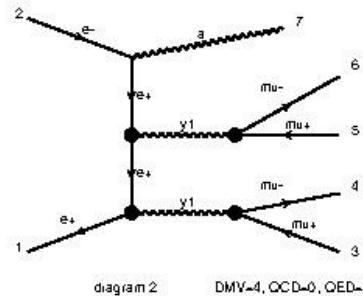
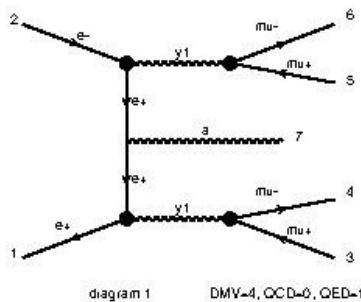
diagram 2

DMV=4, QCD=0, QED=0

# Signal Feynman diagrams ( $A'A'\gamma$ )

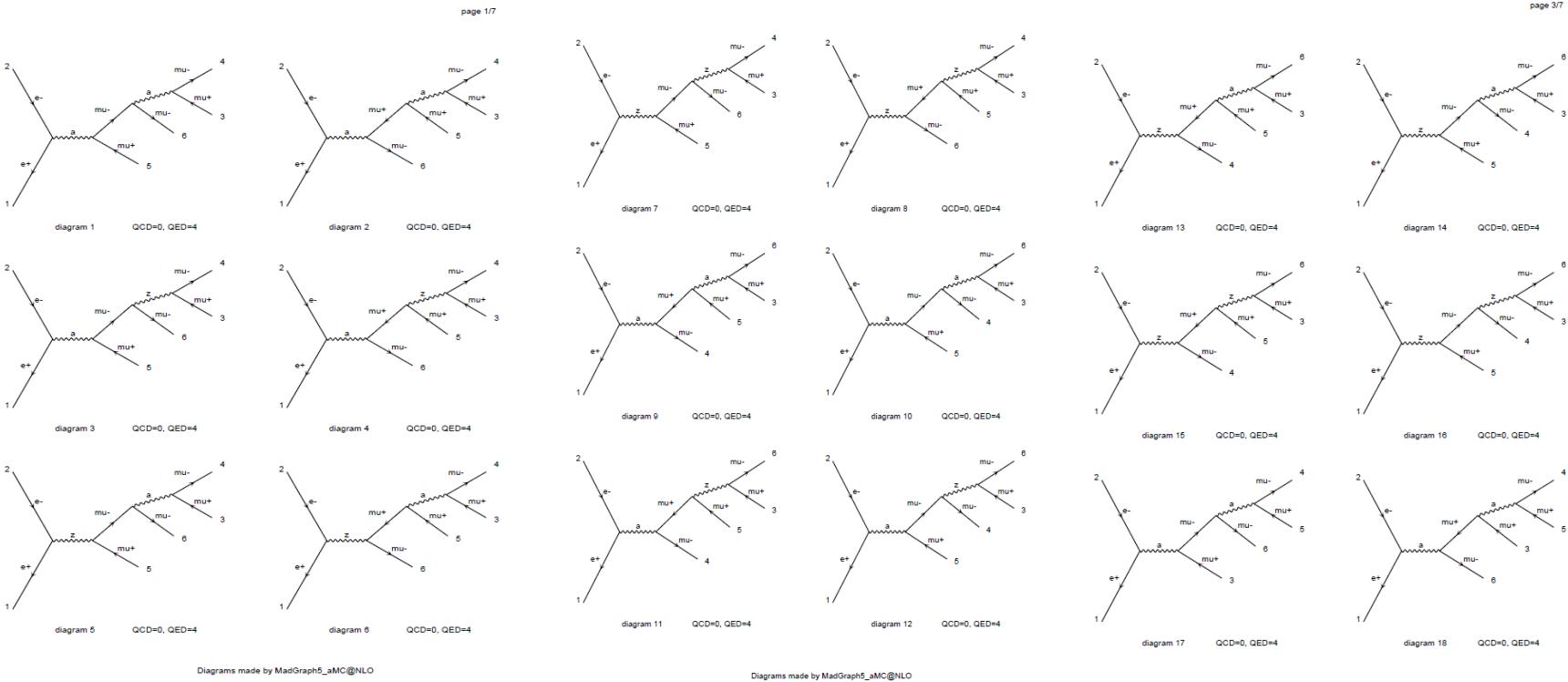
❖ Total 6 diagrams

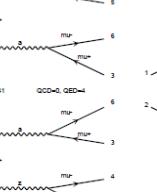
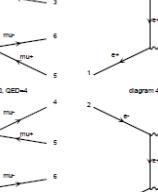
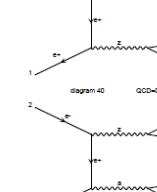
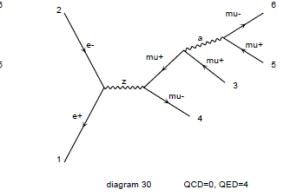
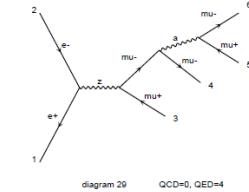
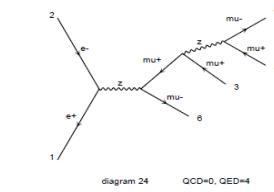
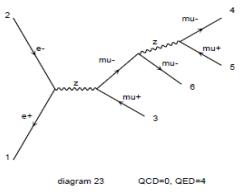
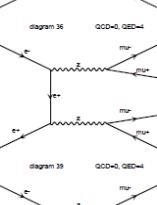
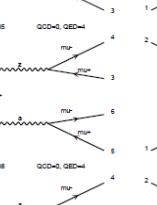
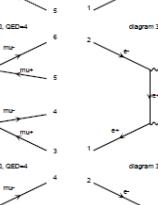
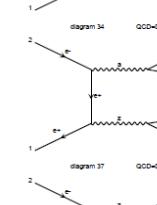
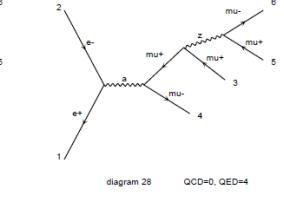
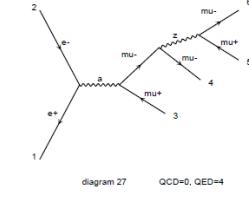
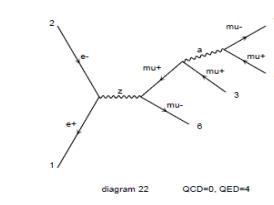
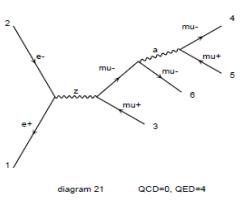
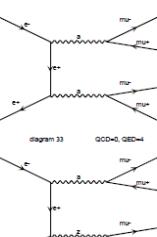
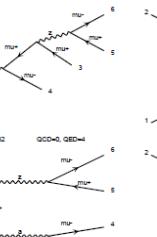
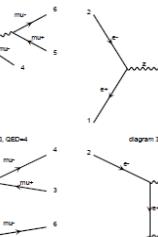
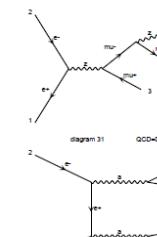
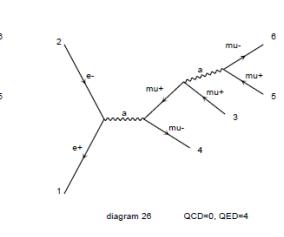
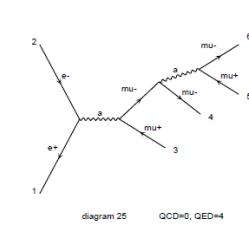
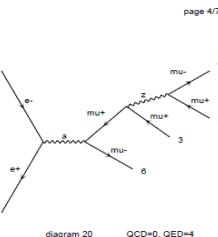
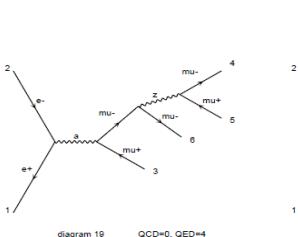
page 1/1



# Background Feynman diagrams (A'A')

❖ Total 48 diagrams

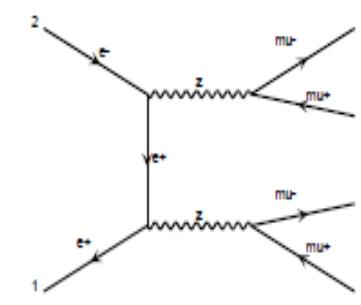
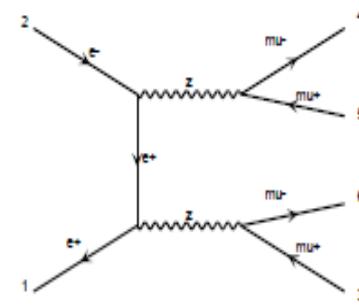
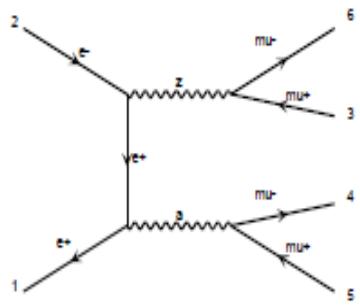




Diagrams made by MadGraph5\_aMC@NLO

Diagrams made by MadGraph5\_aMC@NLO

Diagrams made by MadGraph5\_aMC@NLO



# Background Feynman diagrams ( $A'A'\gamma$ )

❖ Total 336 diagrams (Parts)

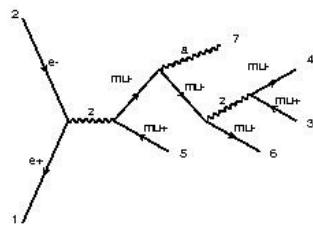


diagram 7    QCD=0, QED=5

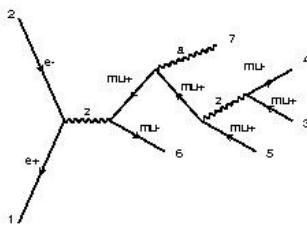


diagram 8    QCD=0, QED=5

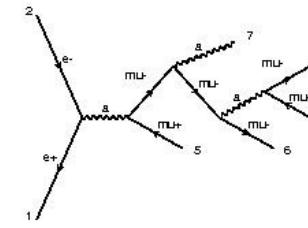


diagram 1    QCD=0, QED=5

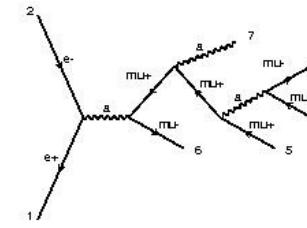


diagram 2    QCD=0, QED=5

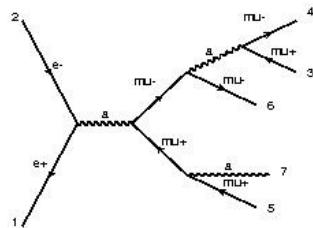


diagram 9    QCD=0, QED=5

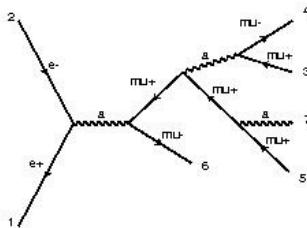


diagram 10    QCD=0, QED=5

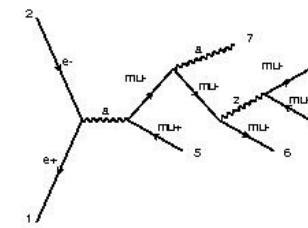


diagram 3    QCD=0, QED=5

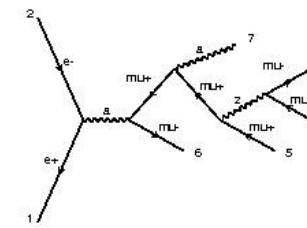


diagram 4    QCD=0, QED=5

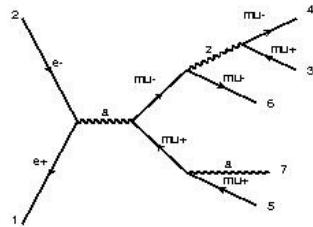


diagram 11    QCD=0, QED=5

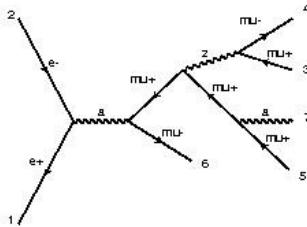


diagram 12    QCD=0, QED=5

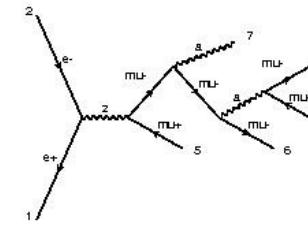


diagram 5    QCD=0, QED=5

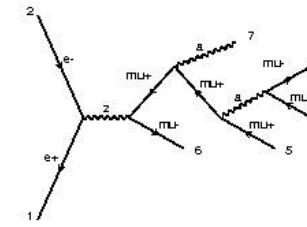


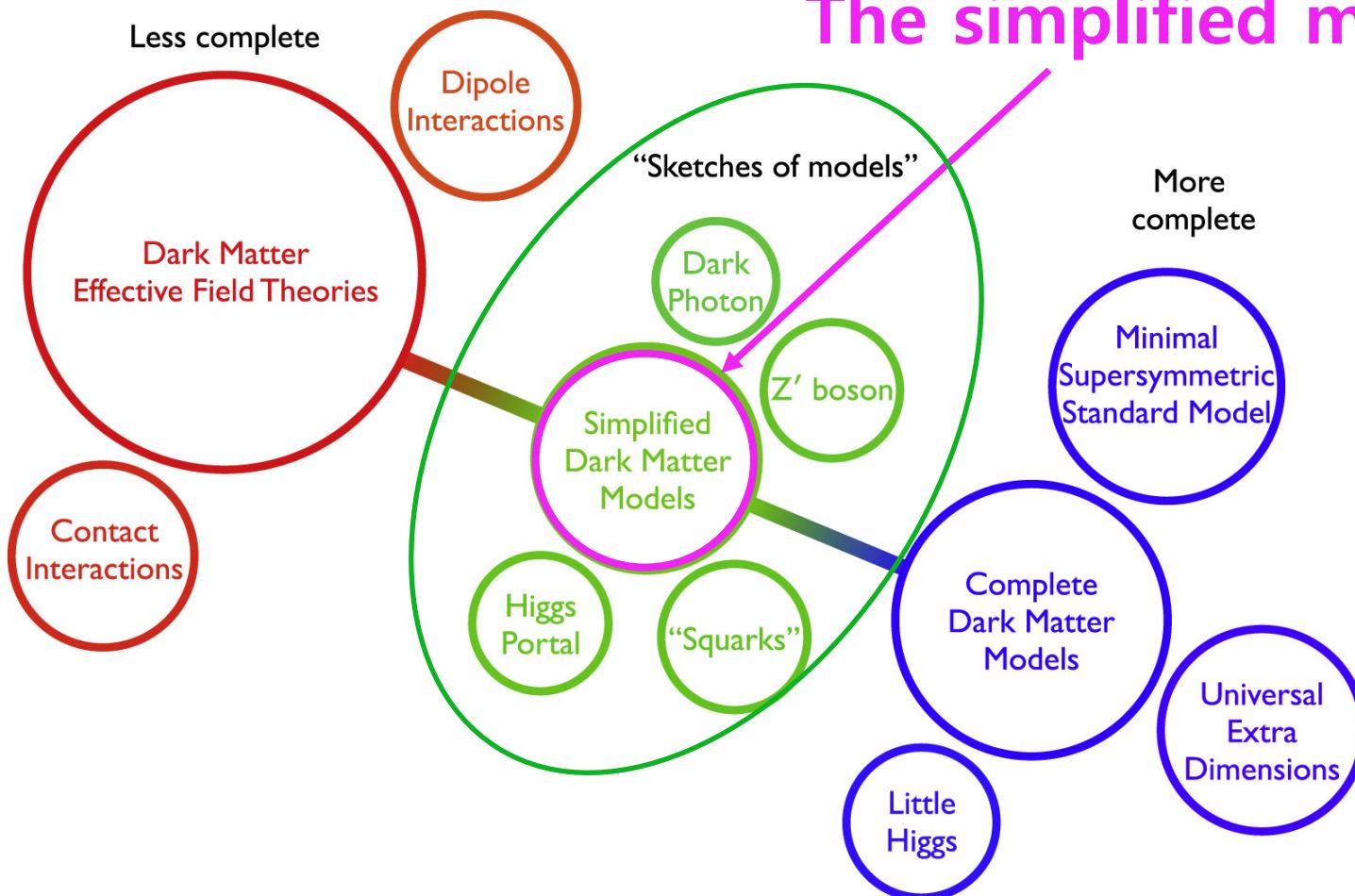
diagram 6    QCD=0, QED=5

Diagrams made by MadGraph5\_aMC@NLO

Diagrams made by MadGraph5\_aMC@NLO

# More on the simplified model

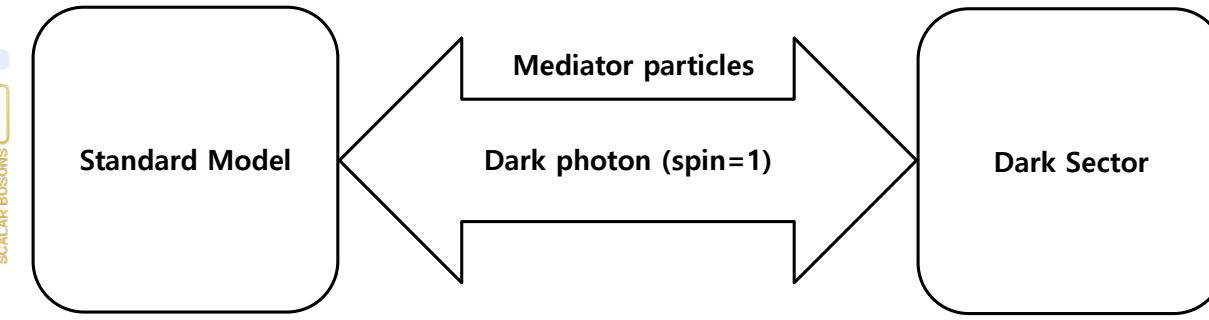
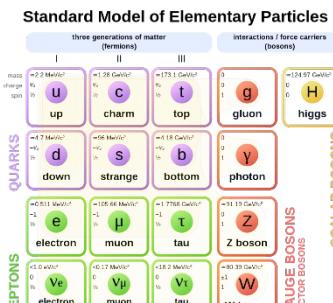
## The simplified model



# More on the dark photon

- Dark portals between SM and DS depending on mediator
  - Vector portal (kinetic mixing, spin 1)
    - *Dark photon A', Dark Z', ...*
  - Pseudo-scalar portal (spin 0)
    - *Axion, ALP, ...*
  - Scalar portal (Higgs portal, spin 0)
    - *Dark Higgs, Dark scalar, ...*
  - Neutrino portal (Fermion portal, spin 1/2)
    - *Sterile neutrinos, ...*

## Knowns



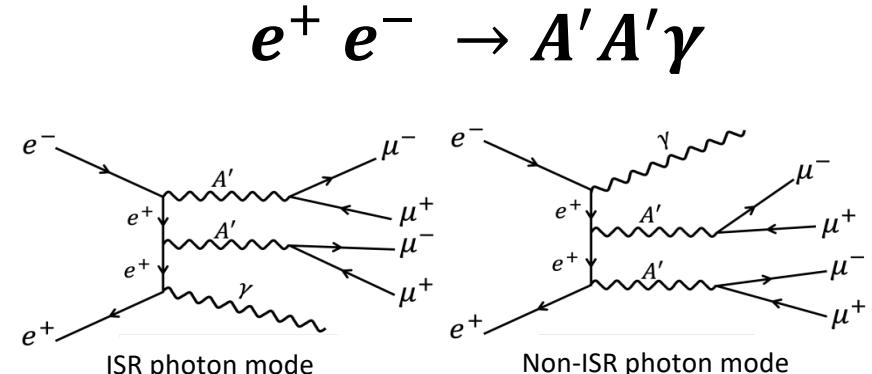
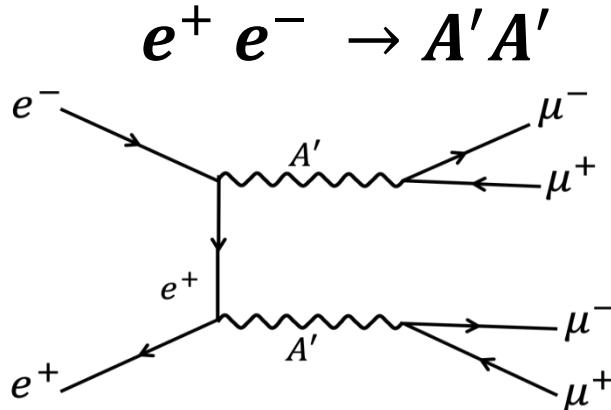
WIKI

## Unknowns

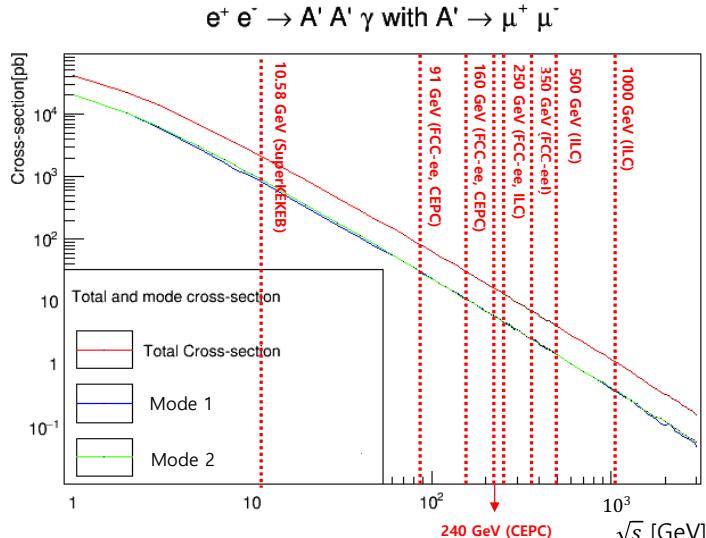
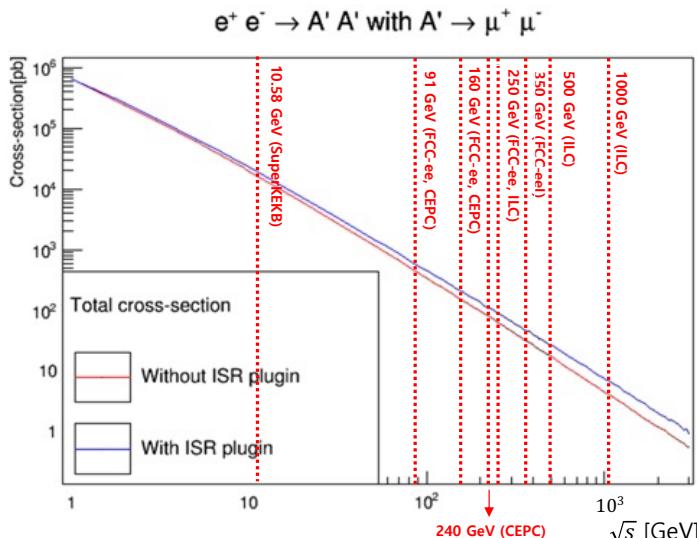
Dark matter  
Dark photon  
...

# Cross-section study of the signal processes

- Feynman diagrams of Double dark photon mode



- Cross-section depending on CM energy

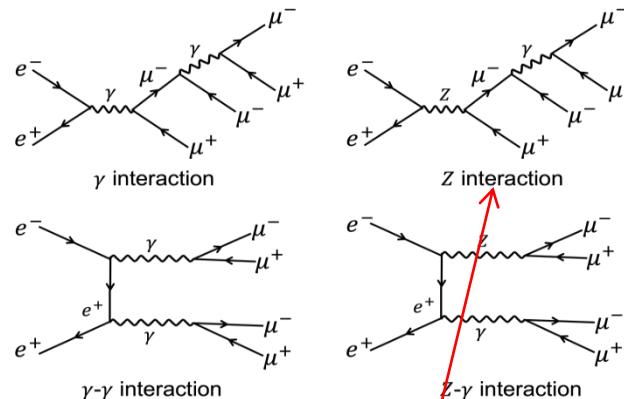


- Red vertical lines denote CM energy of experiments.
- We applied these CM energies to reconstruction for both  $e^+ e^- \rightarrow A' A'$  and  $e^+ e^- \rightarrow A' A' \gamma$ .

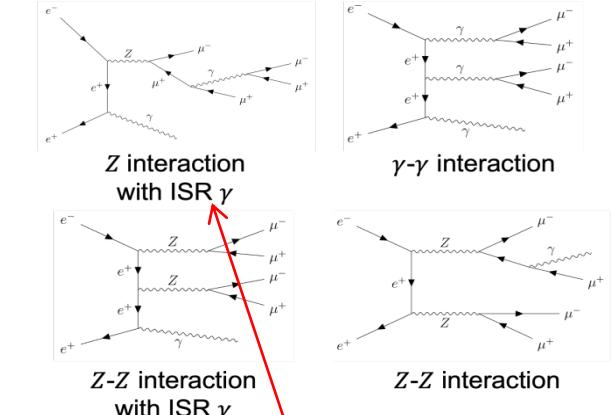
# Cross-section study of the background processes

- Dominant Feynman diagrams

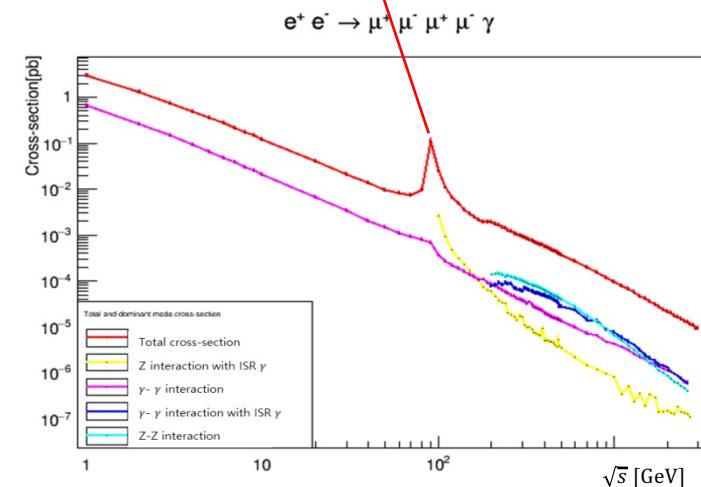
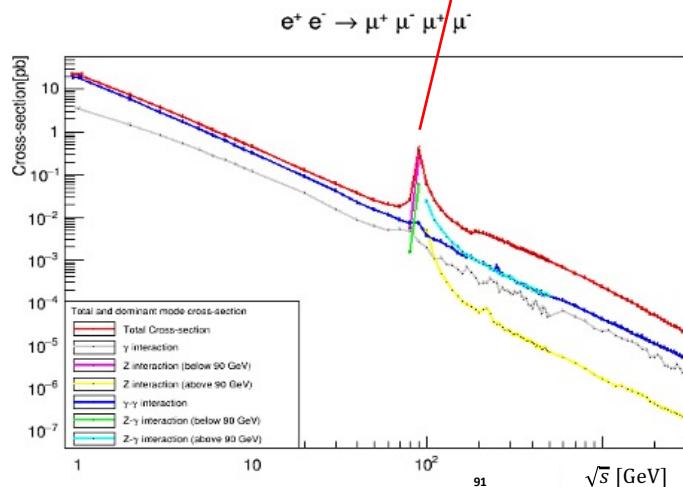
$$e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$



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



- Cross-section depending on CM energy



# CPU time (A'A')

e+e- -> A'A'

Event generation

			① Events generation														
			Signal						Background								
Mode	CM energy [GeV]	A' mass [GeV]	Walltime	Machine(Queue)	PBS JOB Id	Target	Results	xsection [pb]	Walltime	Machine(Que ue)	PBS Job Id	Events/run	Multi runs	iseed	Target	Results	xsection [pb]
e+e- → A'A', A' → μ+μ-	91	25	22m 4s	Nurion(norm_skl)	13615979	1,000,000	1,000,000	727100	24m 1s	norm_skl	13297352	500	20	1~20	1,000,000	1000000	
	160	75				1,000,000	1,000,000	1225000	1h 45m 16s	norm_skl	13297354	500	20	1~21	1,000,000	921471	
	240	100				1,000,000	1,000,000	1280000	1h 36m 20s	norm_skl	13297356	500	20	1~22	1,000,000	972739	
	250	100				1,000,000	1,000,000	1226000	2h 20m 6s	norm_skl	13297358	500	20	1~23	1,000,000	981396	
	350	150				1,000,000	1,000,000	1306000	1h 40m 46s	norm_skl	13297359	500	20	1~24	1,000,000	967667	
	500	200				1,000,000	1,000,000	1226000	3h 4m 54s	norm_skl	13297361	500	20	1~25	1,000,000	990118	
	1000	450				1,000,000	1,000,000	1312000	3h 28m 24s	norm_skl	13297363	500	20	1~26	1,000,000	913321	

			② Delphes simulation				③ TMVA		④ Histograms (fitting)		
Accelerator/Deteotor	CM energy [GeV]	A' mass [GeV]	Wall time (sig)	Wall time (bkg)	Machine	Wall time	Machine	Wall time	Machine	Wall time	Machine
CEPC	91	25	8m 44s	6m 59s	hepph	582s	hepph	34s	hepph	34s	
	160	75	12m 30s	7m 51s		889s		36s		36s	
	240	100	12m 32s	8m 47s		986s		36s		36s	
FCC-ee	91	25	11m 24s	8m 39s	hepph	531s	hepph	36s	hepph	36s	
	160	75	11m 19s	9m 43s		762s		37s		37s	
	250	100	11m 24s	10m 48s		950s		38s		38s	
	350	150	12m 41s	10m 38s		869s		37s		37s	
ILC	250	100	9m 37s	8m 32s		730s		36s		36s	
	500	200	9m 46s	8m 54s		790s		36s		36s	
	1000	450	9m 51s	8m 16s		712s		36s		36s	

# CPU time (A'A'gamma)

Event generation			Signal							
Mode	CM energy [GeV]	A' mass [GeV]	Walltime	Machine(Queue)	PBS JOB Id	Target	Results	xsection [pb]		
$e+e^- \rightarrow A'A'\gamma, A' \rightarrow \mu^+\mu^-$	91	25	22m 4s	Nurion(norm_skl)	13615979	1,000,000	1,000,000	727100		
	160	75				1,000,000	1,000,000	1225000		
	240	100				1,000,000	1,000,000	1280000		
	250	100				1,000,000	1,000,000	1226000		
	350	150				1,000,000	1,000,000	1306000		
	500	200				1,000,000	1,000,000	1226000		
	1000	400				1,000,000	1,000,000	1312000		
Background										
Walltime	Machine(Qu eue)	PBS Job I d	Events/ru n	Multi runs	Cores	Nodes(jobs)	iseed	Target	Results	xsection [pb]
11:57:14	norm_skl	1.3E+07	500	20	10	10	1~20	1,000,000	1,000,000	
5:09:21	norm_skl	1.3E+07	500	20	10	10	1~21	1,000,000	921,471	
5:42:28	norm_skl	1.3E+07	500	20	10	10	1~22	1,000,000	972,739	
	norm_skl	1.3E+07	500	20	10	10	1~23	1,000,000	981,396	
9:08:11	norm_skl	1.3E+07	500	20	10	10	1~24	1,000,000	967,667	
13:25:45	norm_skl	1.3E+07	500	20	10	10	1~25	1,000,000	990,118	
	norm_skl	1.3E+07	500	20	10	10	1~26	1,000,000	913,321	

Accelerator/Deteotor	CM energy [GeV]	A' mass [GeV]	② Delphes simulation			③ TMVA		④ Histograms (fitting)	
			Wall time (sig)	Wall time (bkg)	Machine	Wall time	Machine	Wall time	Machine
CEPC	91	25	10m 10s	7m 43s	hepph	236s	hepph	41s	hepph
	160	75	12m 39s	9m 12s		309s		40s	
	240	100	12m 3s	9m 58s		740s		45s	
FCC-ee	91	25	12m 32s	9m 52s	hepph	213s	hepph	39s	hepph
	160	75	12m 0s	11m 31s		261s		41s	
	250	100	12m 18s	12m 3s		423s		43s	
	350	150	12m 27s	12m 16s		448s		42s	
	250	100	10m 9s	9m 6s		73s		39s	
ILC	500	200	10m 26s	9m 23s		141s		41s	
	1000	400	10m 21s	9m 36s		213s		41s	