Study on High Energy Physics and Simulations on Dark Matter and the Standard Model

Report on the outcomes of 2019 summer internship at KISTI

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- Background knowledge
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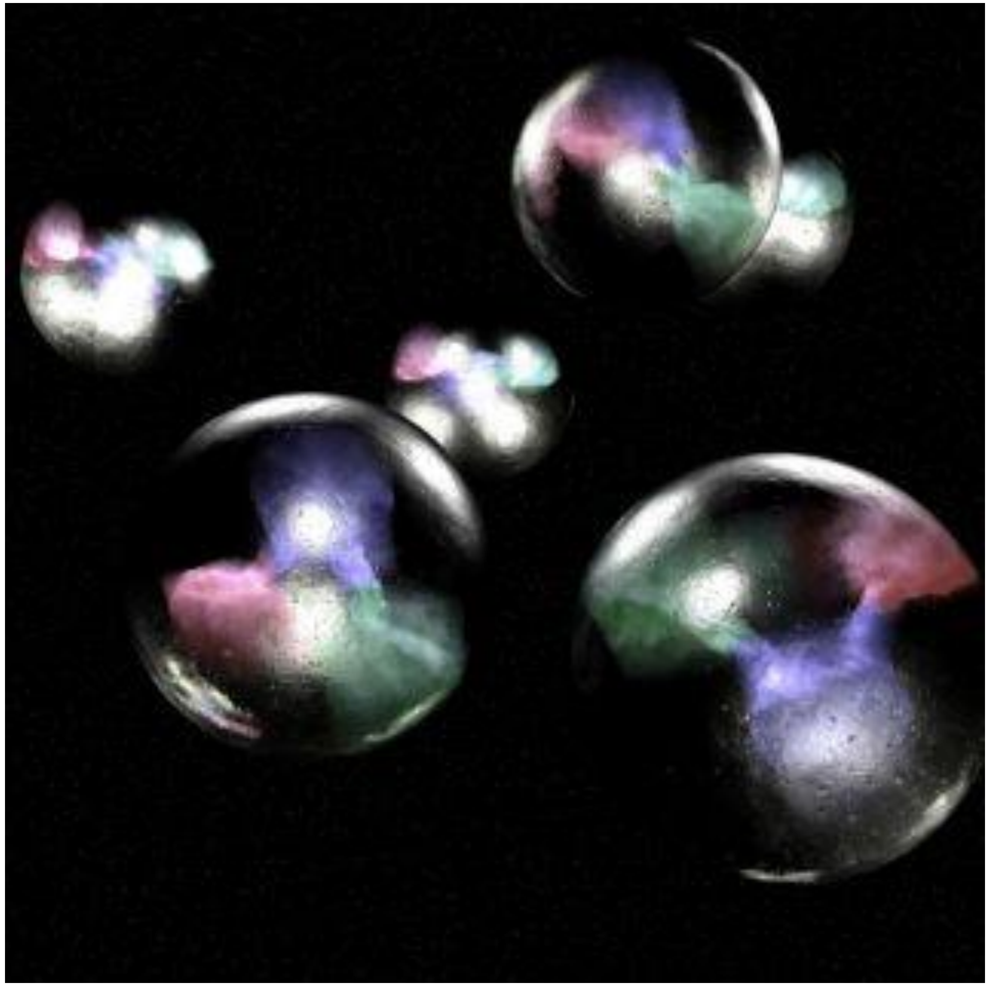
Introduction: High Energy Physics (HEP)

High Energy Physics is the study of the basic components of nature and the laws which govern them.

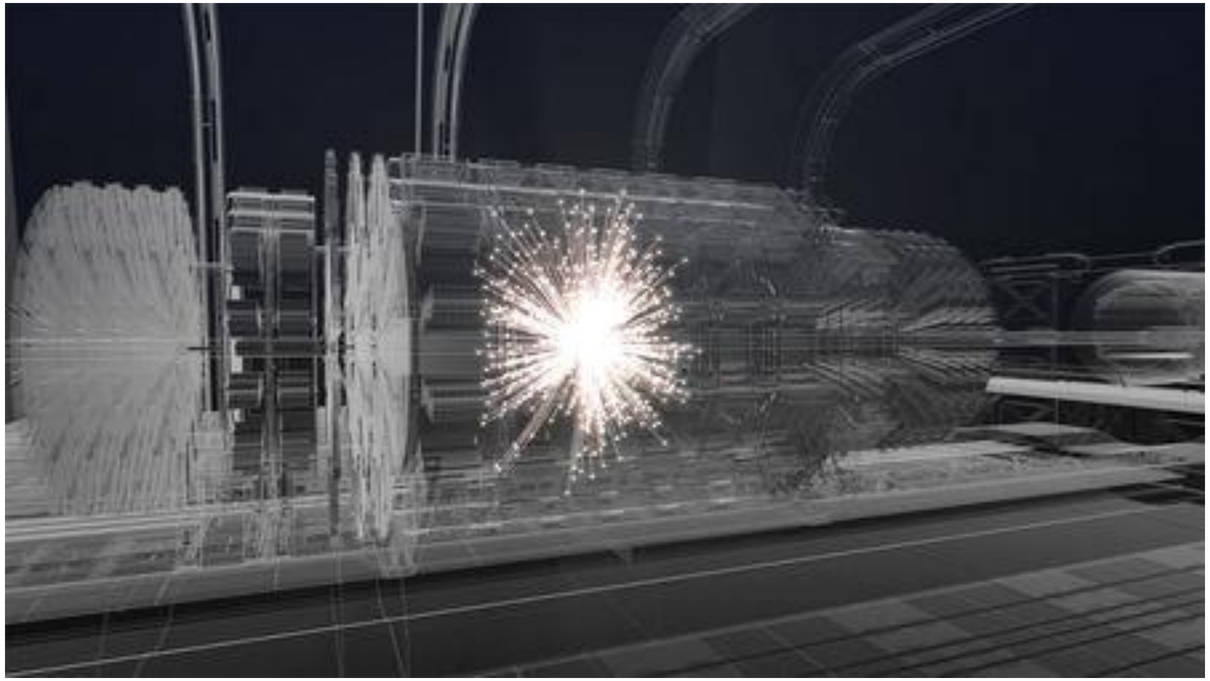
These components include particles of various kinds, therefor HEP involves Particle Physics.



Introduction: High Energy Physics (HEP)

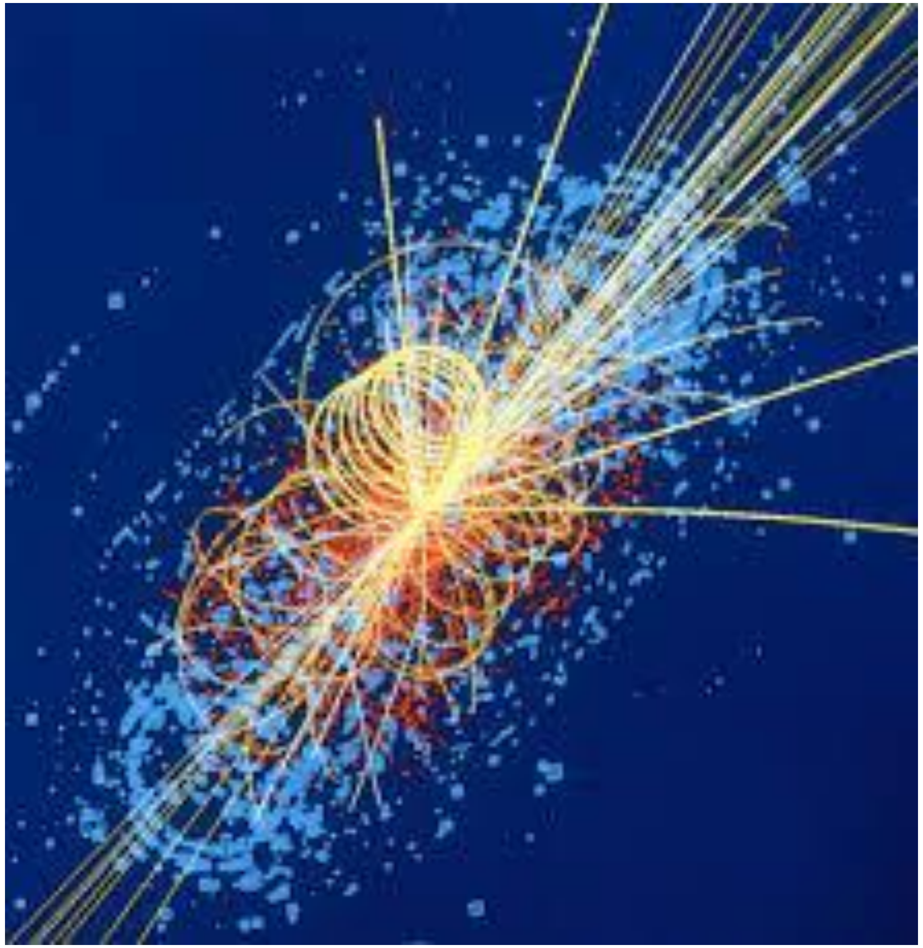
The study of Particles require high energies to inspect into minute lengths.

this is why we use particle colliders.



Introduction: High Energy Physics (HEP)

There is currently a large body of theoretical models to describe particle physics. We use computer simulations to translate the theory into predictions that we can test.



Introduction: High Energy Physics (HEP)

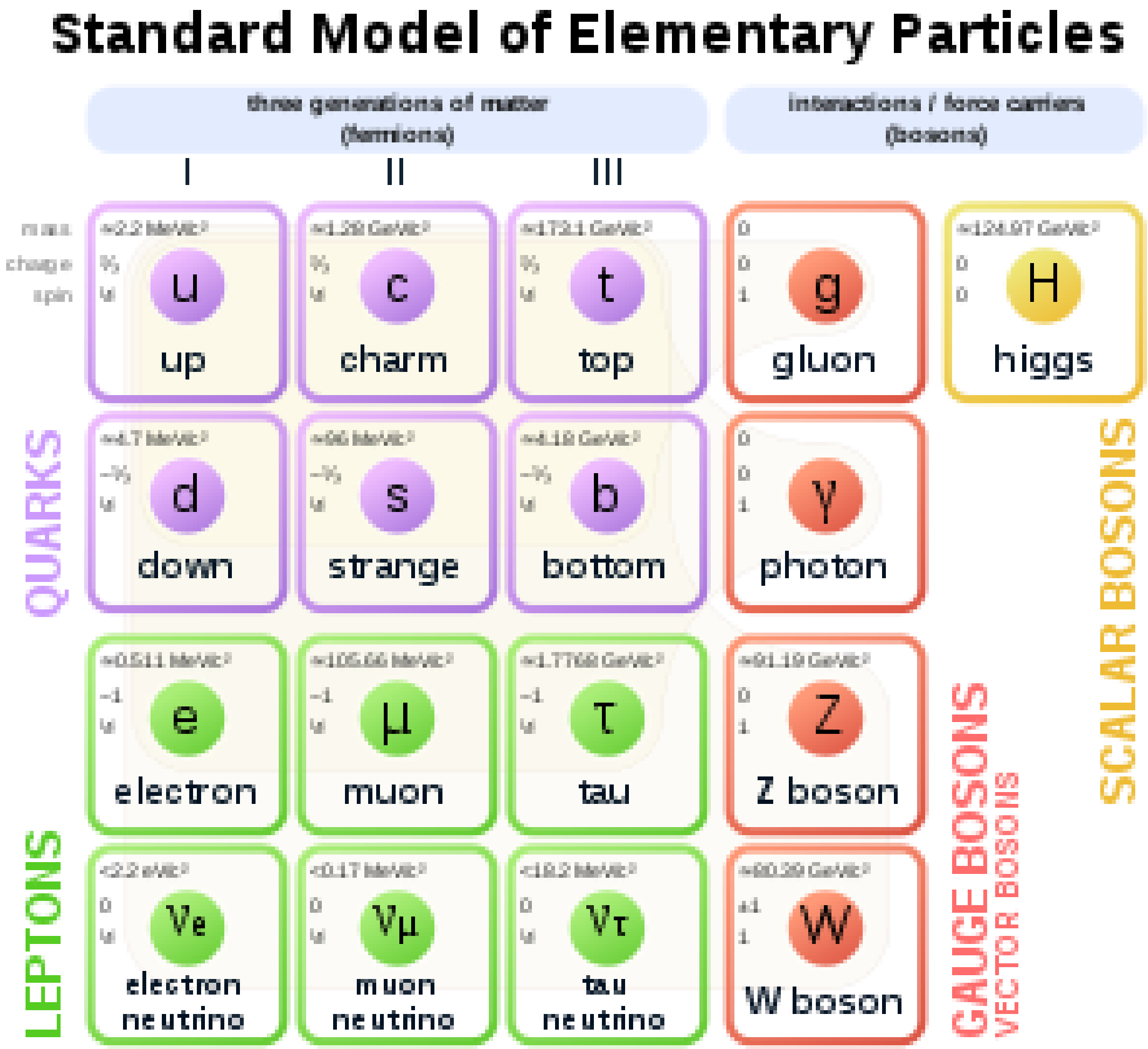
Right now, a lot of pressure is on experimental HEP to produce results to verify or falsify many existing theories.

These experiments require big data analysis.

Introduction: HEP research at KISTI

KISTI has the needed computational infrastructure for the study of HEP. At KISTI we use supercomputers to inspect the frontiers of HEP using simulations of theories and big data analysis. In other words, we use e-science to connect theory, experiment, and computation.

Background knowledge: Standard Model

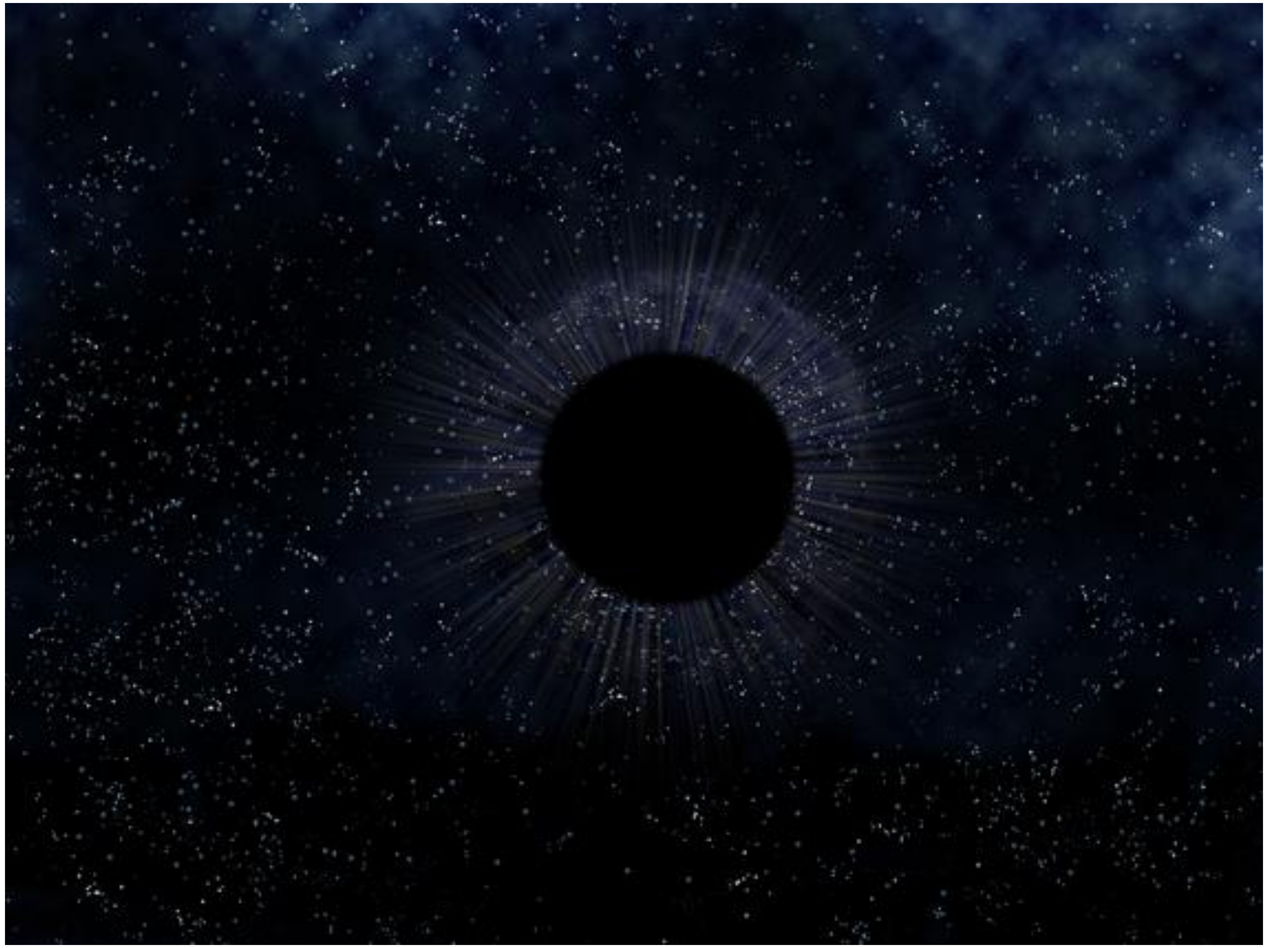


Background knowledge: Dark Matter

Dark Matter is not dark; we call it dark because we cannot see it, but what we should call it is transparent. It does not interact with light via electromagnetic forces as far as we can tell. In fact, it does not interact with anything via electromagnetism or nuclear forces.

Background knowledge: Dark Matter

Dark Matter might not even be matter. All we know is that there's something out there which is causing more gravity than there should be.



Background knowledge: Dark Matter

- Maybe it interacts just a little bit with matter. If it does then we should be able to generate it using colliders!
- Like good physicists, we make a model, and see what it predicts using simulations.

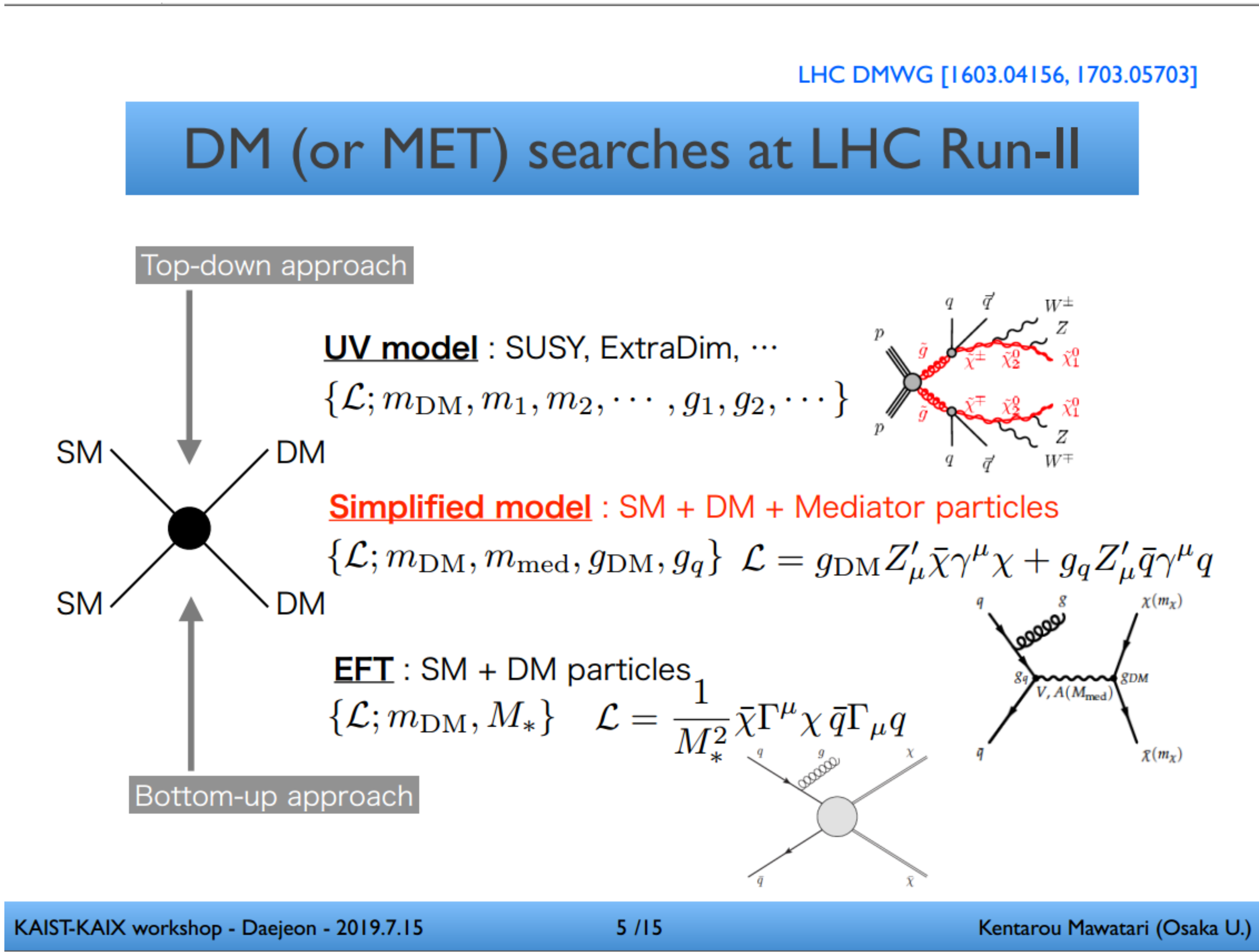
Background knowledge: Simplified Dark Matter model (SDM)

I used The Simplified Dark Matter model:

It has a simple Lagrangian form which is very practical for interaction between matter and dark matter via mediators.

it has been encoded as a model which runs on MadGraph (a software).

Reference: Kentarou Mawatari (Osaka U.). KAIST–KAIX workshop – Daejeon – 2019.7.15



Part 1: MadGraph (Standard Model Background)

MadGraph is a tool to generate particle physics processes, their Feynman diagrams and cross-sections.

The first thing I did is to test MadGraph on known processes.

e+ e- > mu+ mu-

e+ e- > e+ e-

e+ e- > ve ve~ a

e+ e- > a a a

e+: positron, e-: electron
mu-: muon, mu+: antimuon
ve: neutrino
a: photon
+ and – are charges
~ means anti

Part 1: MadGraph (Standard Model Background)
e+ e- > mu+ mu-

The process is colliding electrons and positrons to produce muons and anti-muons.

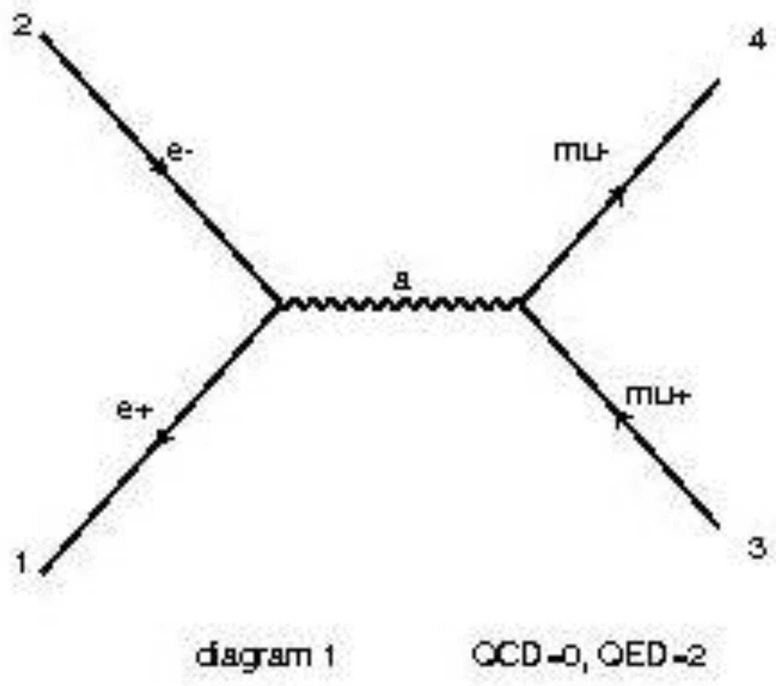
The purpose of this is to learn how the cross section of interaction changes as a function of the energies of the beams.

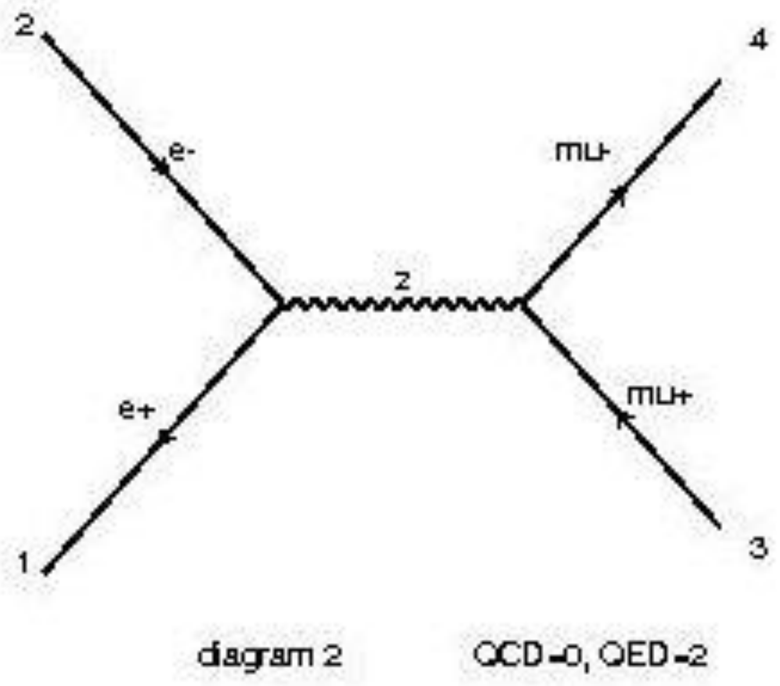
The cross section has the units of pb (picobarn). one barn = 10^{-28} m^2 which is approximately the cross-sectional area of a uranium nucleus. However, the cross section is best understood as a measure of the probability of interaction between the small particles.

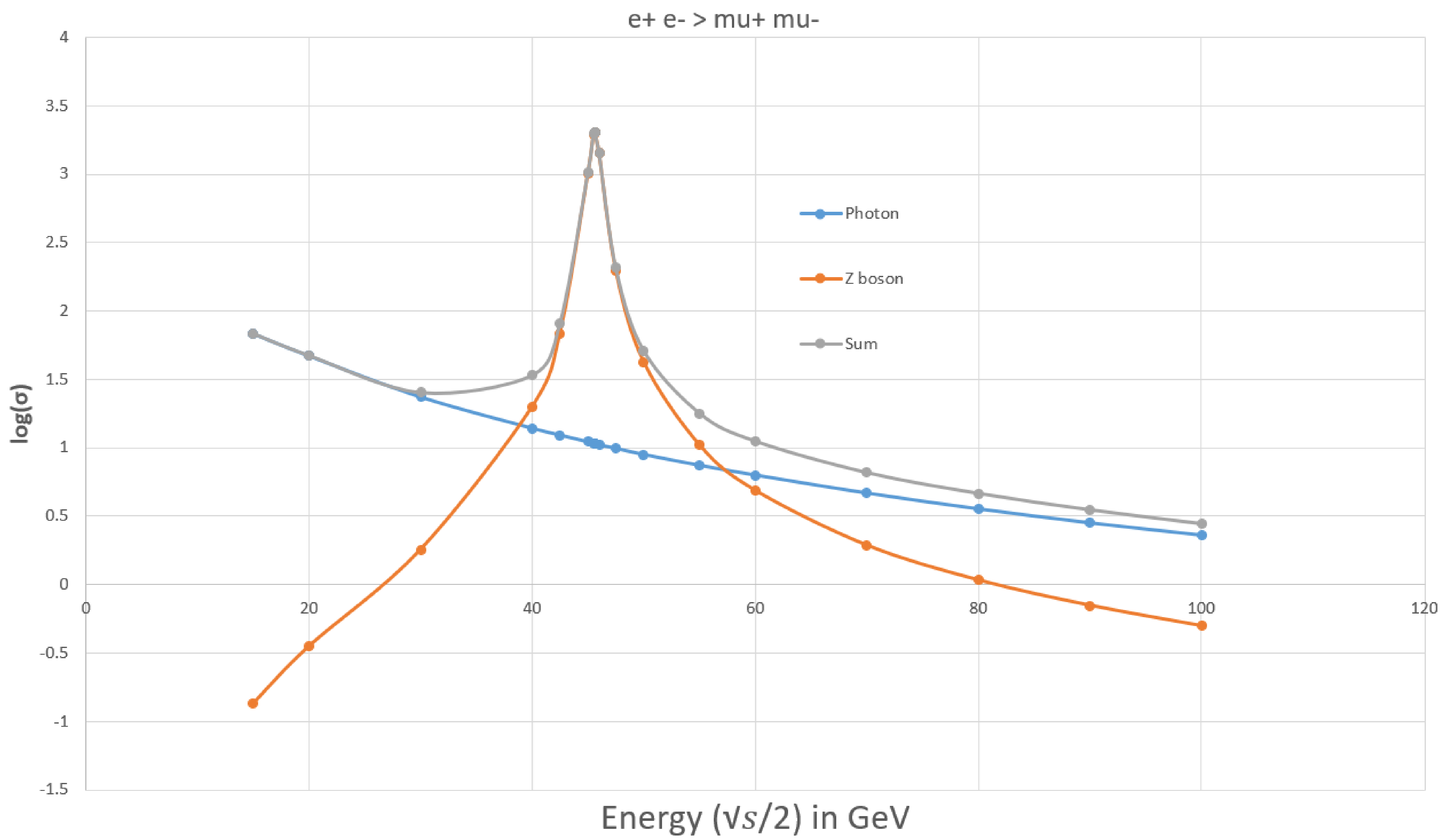
Part 1: MadGraph (Standard Model Background)

e+ e- > mu+ mu-

Two Feynman diagrams: two interactions: electromagnetic and weak via z boson $\sqrt{s}$



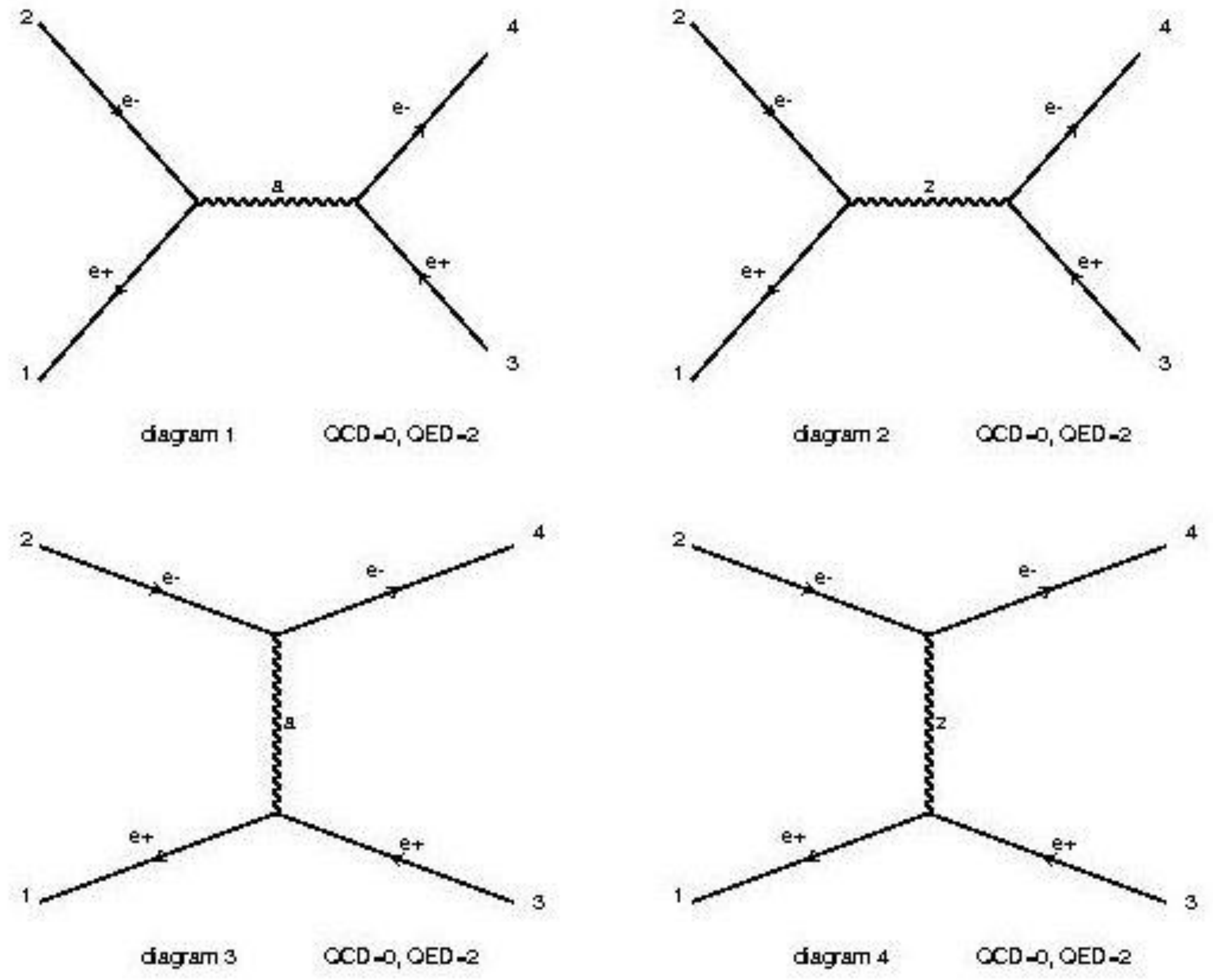



e+ e- > mu+ mu-
Photon
Z boson
Sum
log(σ)
Energy (√s/2) in GeV
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
20
40
60
80
100
120

Part 1: MadGraph (Standard Model Background)

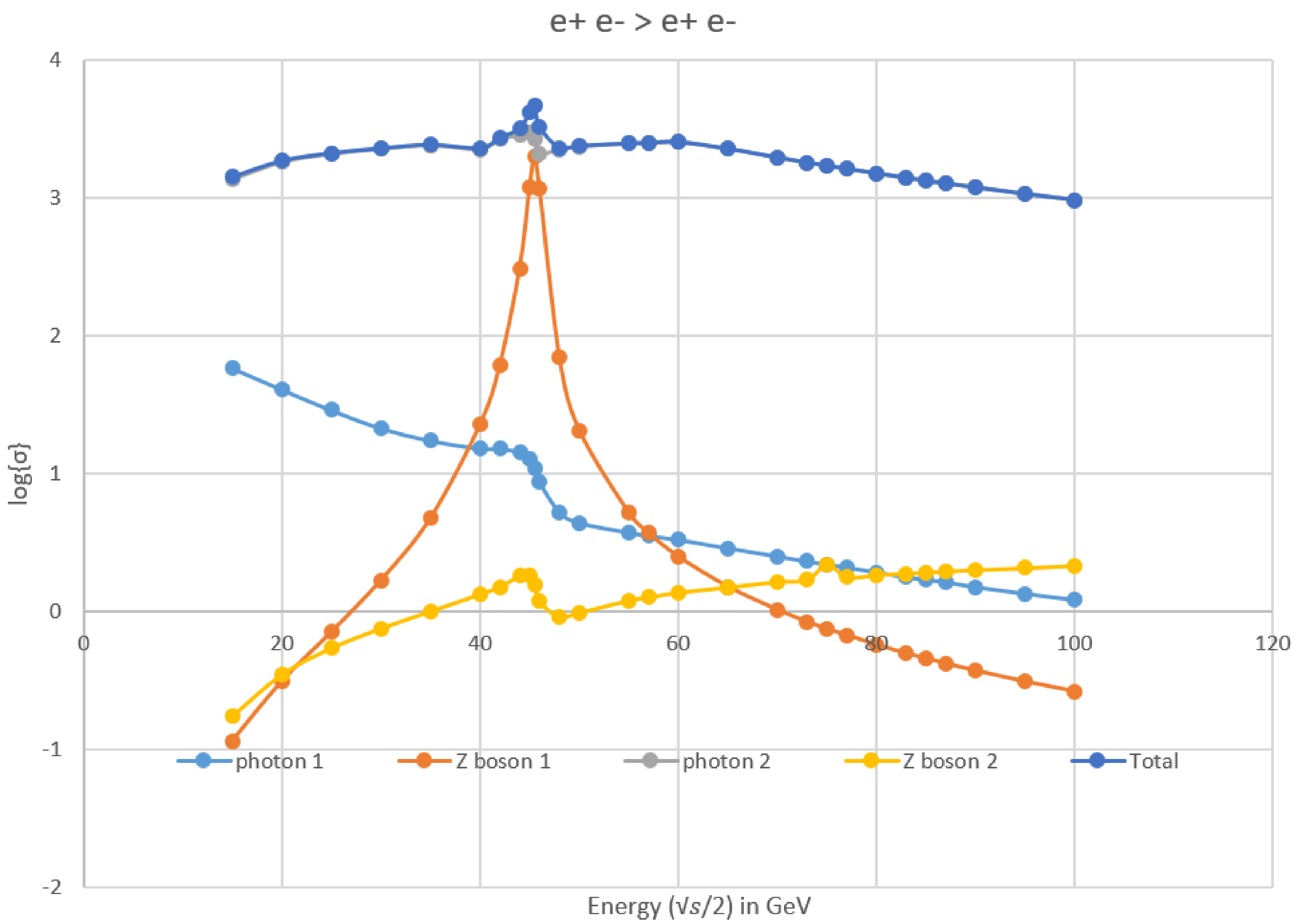
e+ e- > e+ e-

I also did e+ e- > e+ e-. For this there are 4 diagrams: 2 s channels and 2 t channels



Theoretical predictions for the cross section of this process have the same form as for e+ e- > mu+ mu-. Only replace Mu with e.

All together in log scale: t photon interaction dominates, apart from t channel z boson peak.



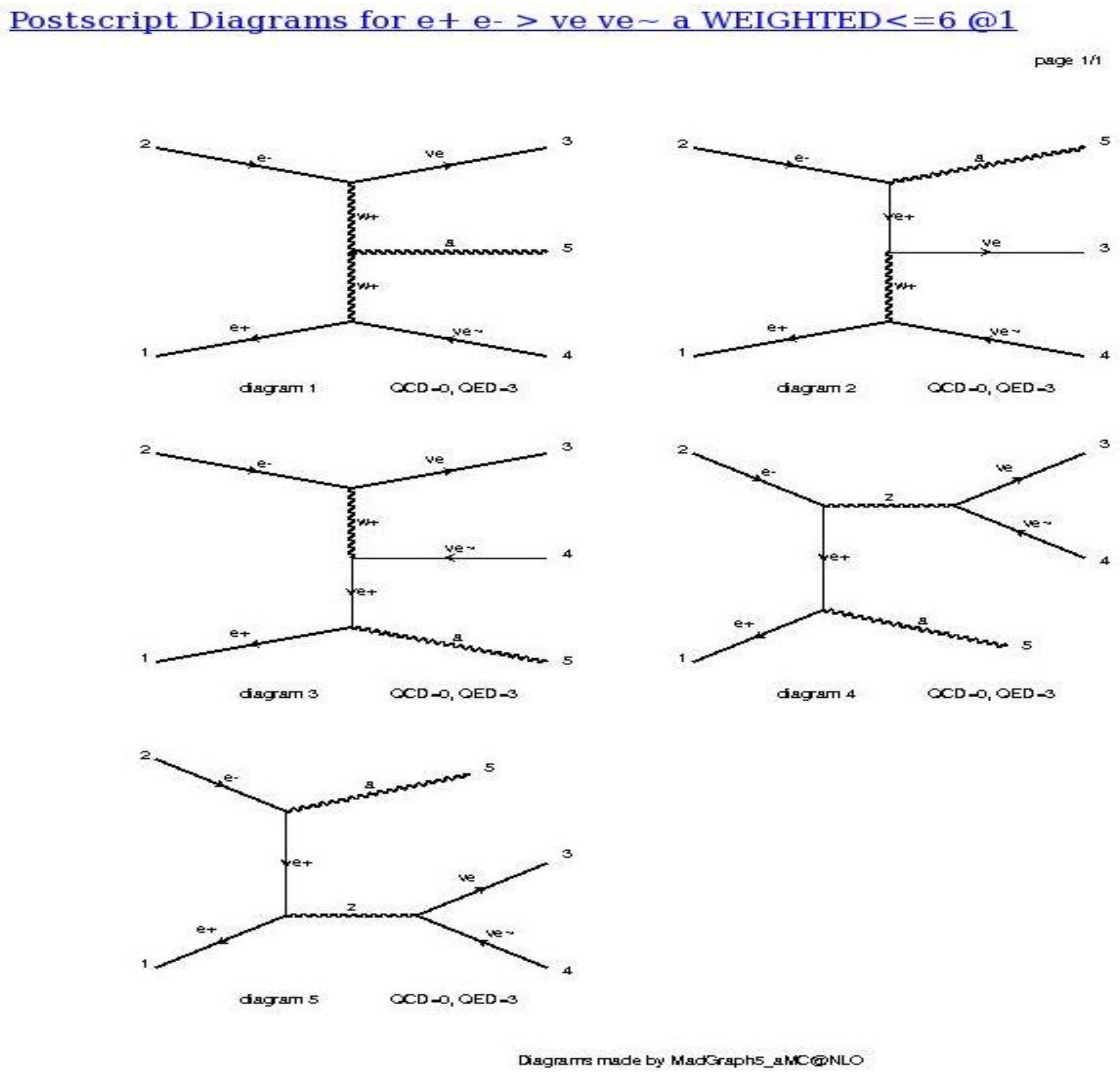
Part 1: MadGraph (Standard Model Background)

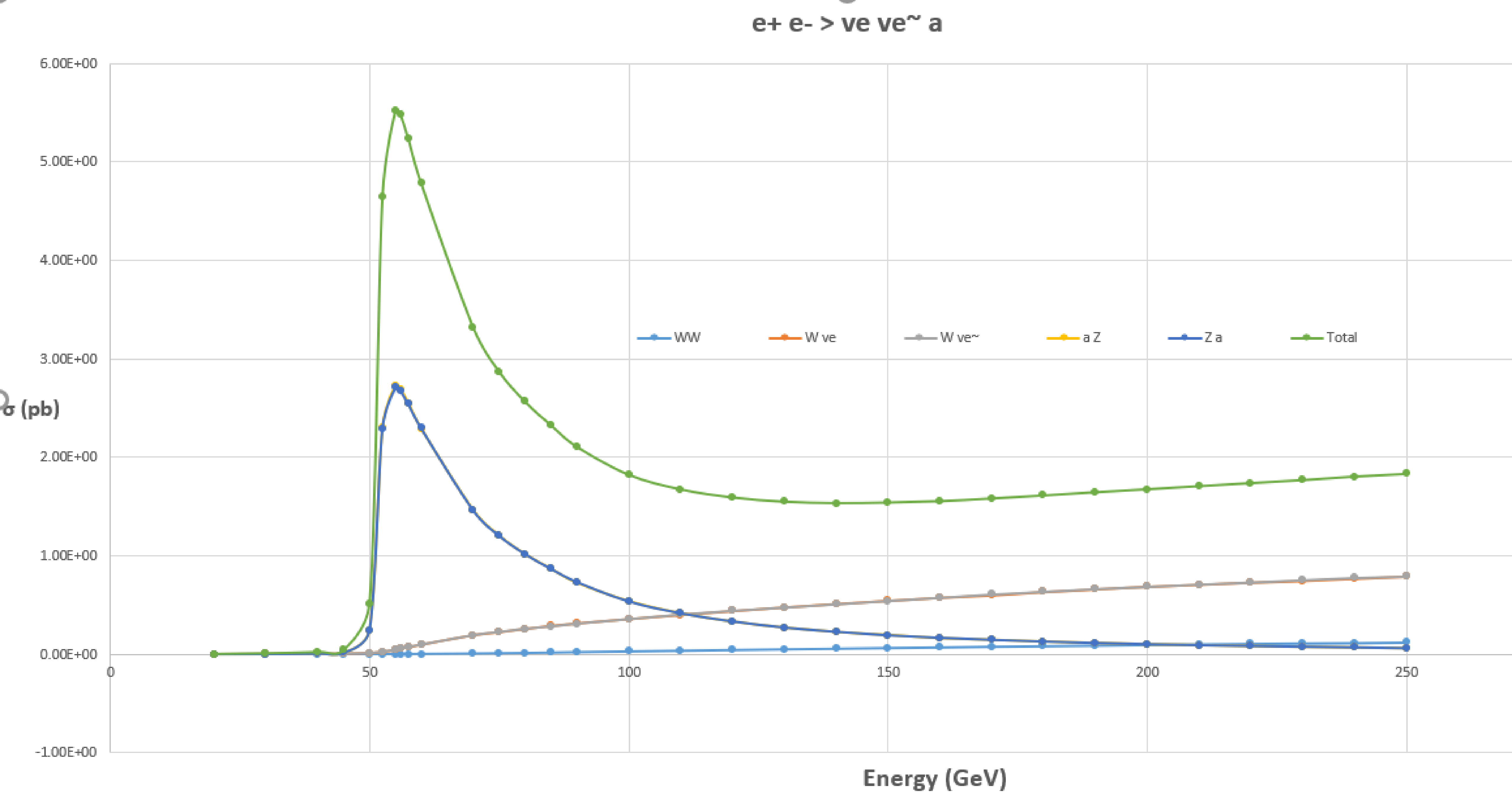
e+ e- > ve ve~ a

Another process that I've tried is
e+ e- > ve ve~ a

This process resembles the SDM process that we wish to study (e+ e- > xd xd~ a), and it's important to understand as a standard model interaction which is similar to the simple dark matter model interaction.

Next slide contains the results.
Legends are as follows:
WW: diagram 1
W ve: diagram 2
W ve~: diagram 3
aZ: diagram 4
Za: diagram 5
Total: sum of cross sections of all diagrams.

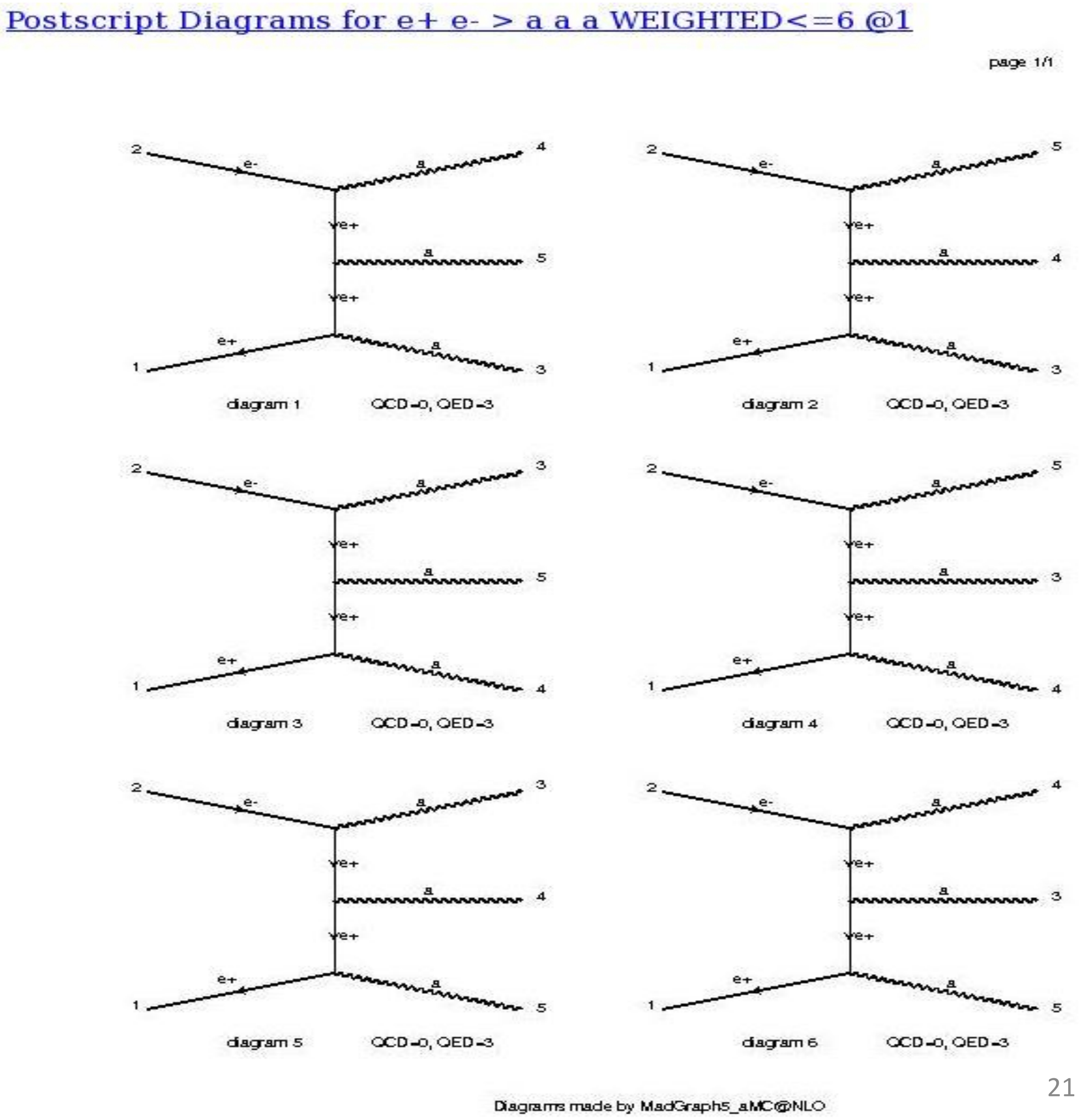



e+ e- > ve ve~ a
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
-1.00E+00
σ (pb)
WW
W ve
W ve~
a Z
Z a
Total
0
50
100
150
200
250
Energy (GeV)

Peak: 56 GeV

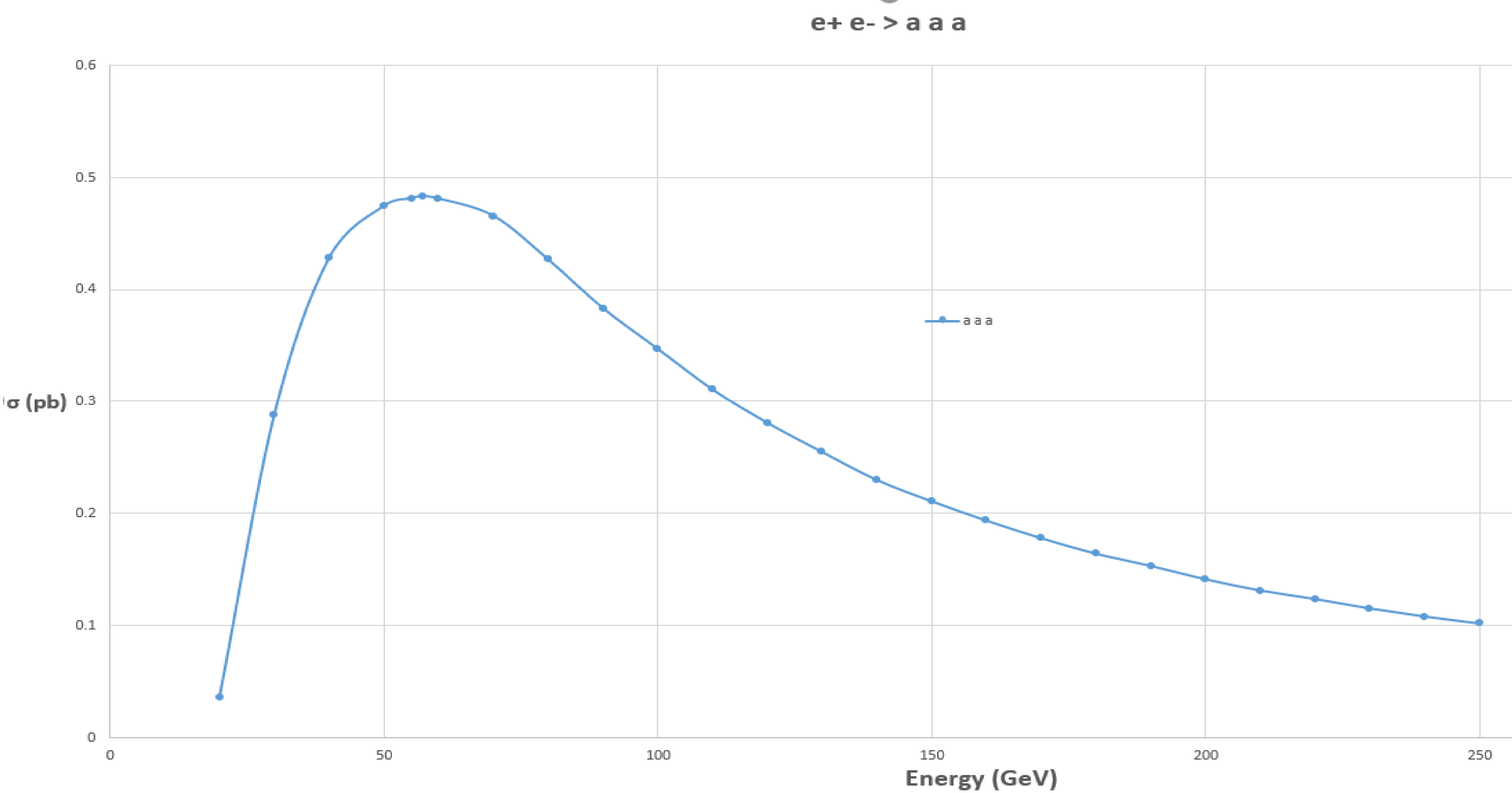
Part 1: MadGraph (Standard Model Background)

e+ e- > a a a



One last process that I've tried as an example is e+ e- > a a a

It has 6 diagrams but all of them are symmetrically equivalent. They are simply the 6 arrangements of the 3 outcoming photons. This means that their cross sections are the same, and so we're only interested in the total.



Peak: 57 GeV

Part 2: Asymmetry Collisions

First, I needed to see how Asymmetric colliders behave. Belle II collider for example gives the positrons 4 GeV of energy and the electrons 7 GeV.

I did the following processes:

e+ e- > ve ve~ a

e+ e- > a a a

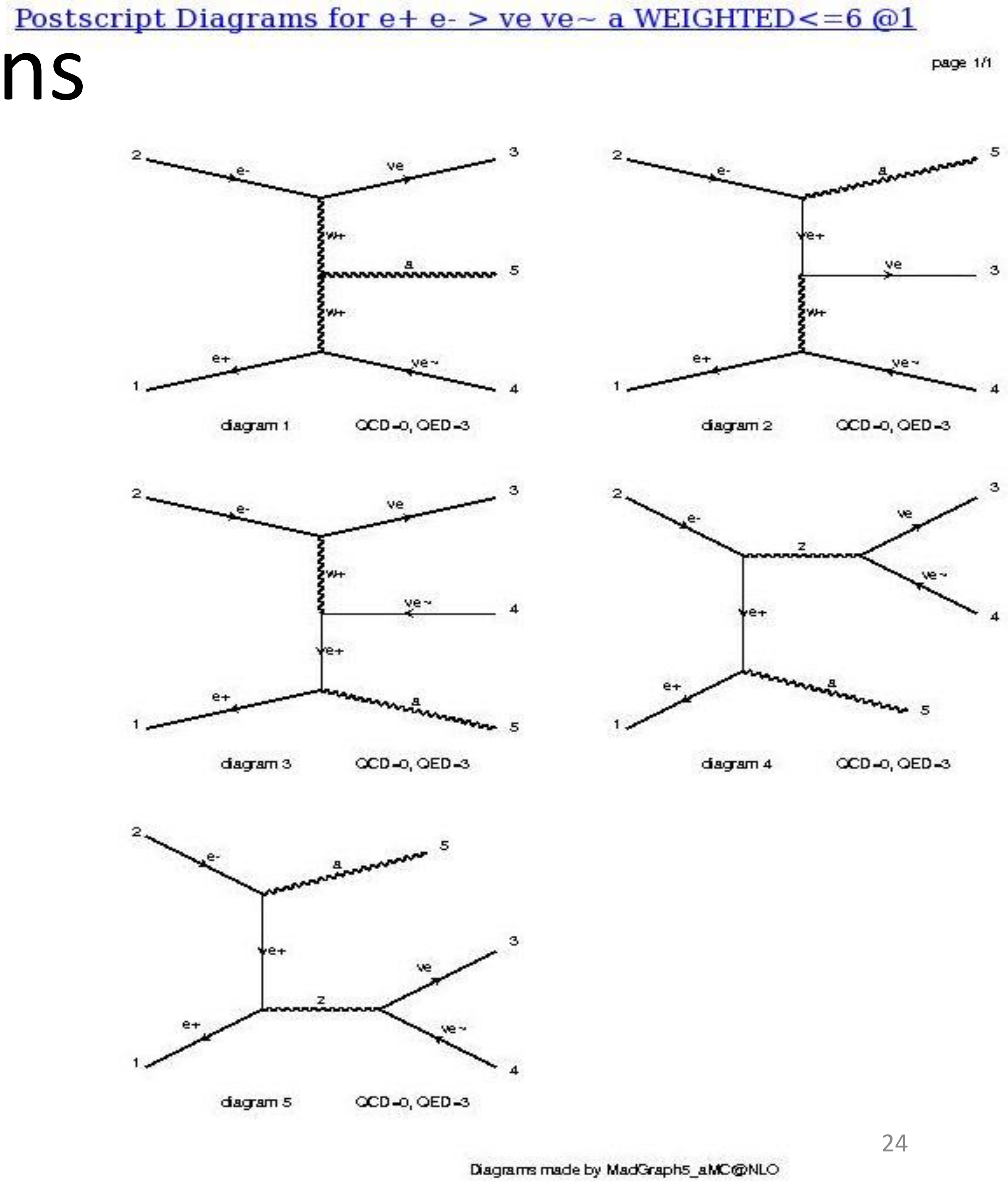
I test this for e+:e- energy ratios: 1:9, 2:8, 3:7, 4:6, 5:5, 6:4, 7:3, 8:2, 9:1.

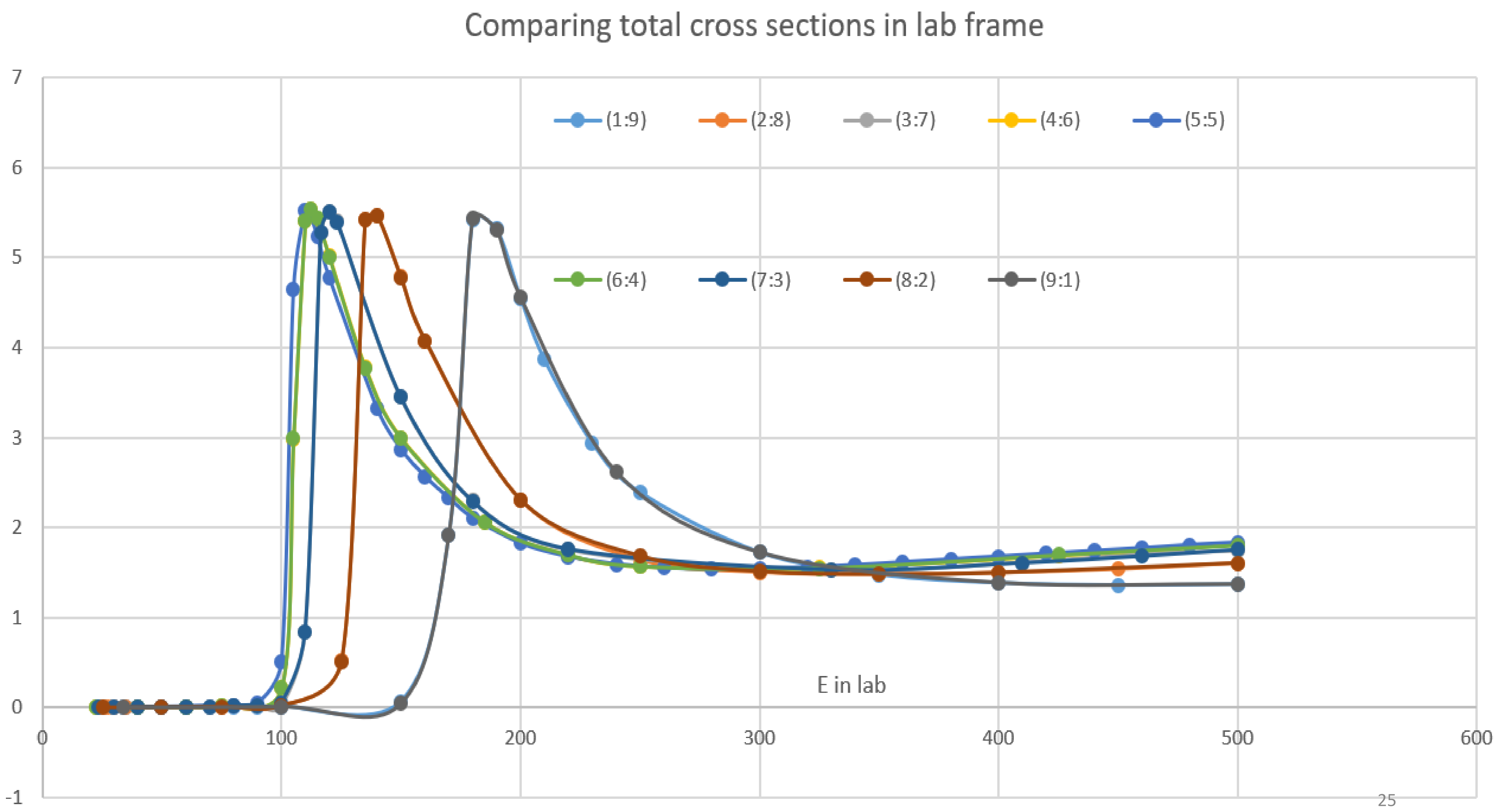
Part 2: Asymmetry Collisions

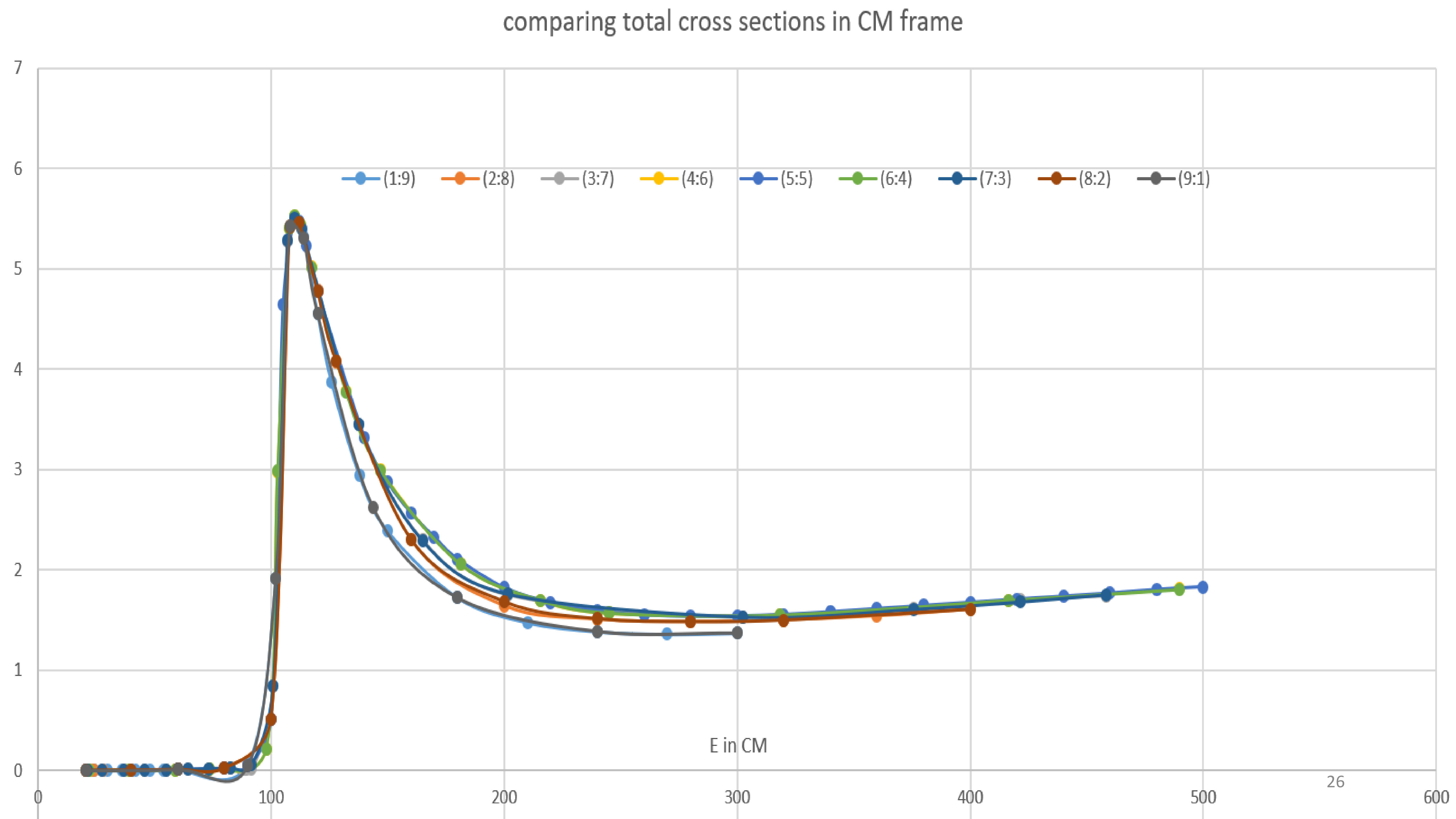
e+ e- > ve ve~ a

Diagrams for e+ e- > ve ve~ a

These are referenced in the following charts



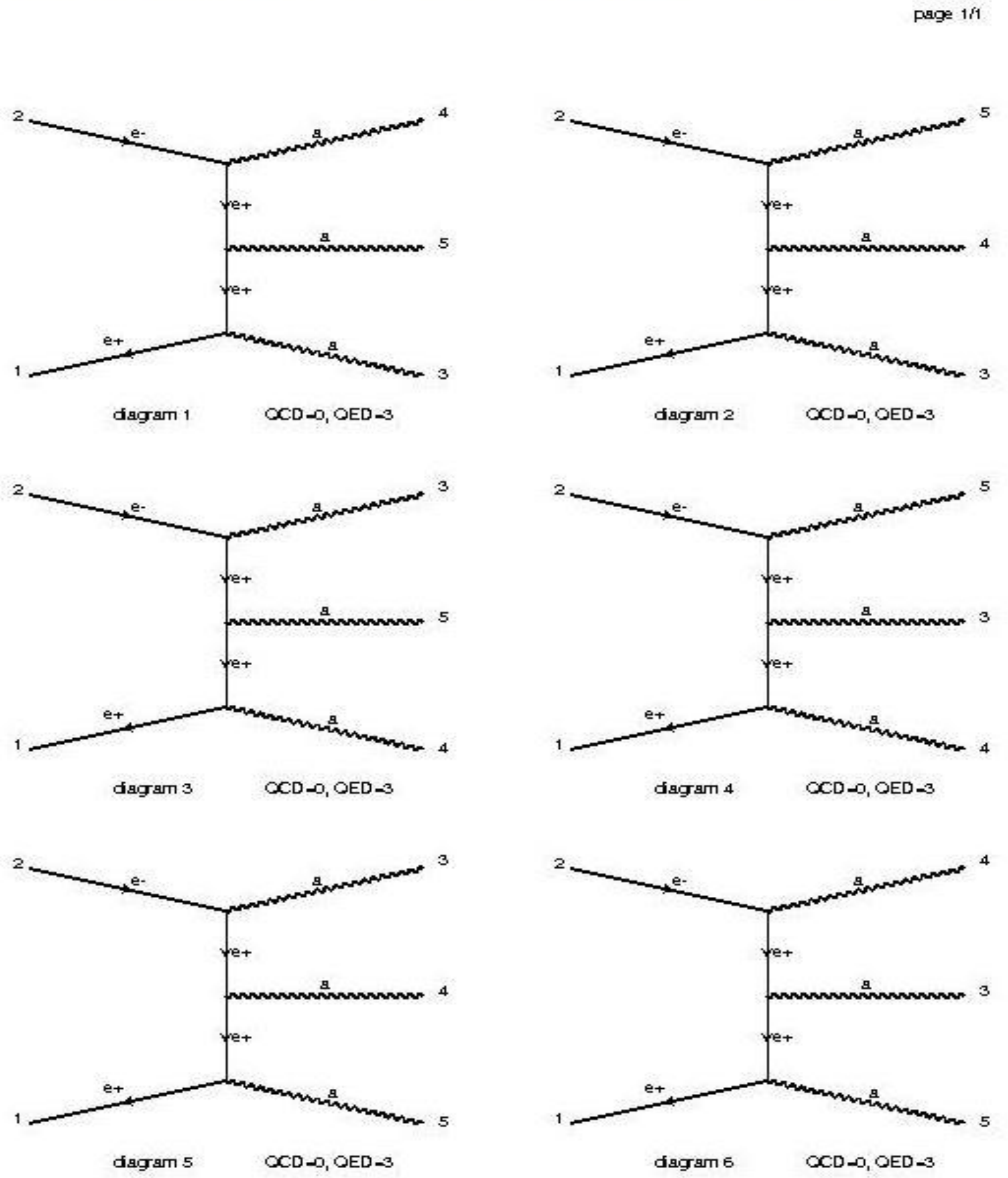

Comparing total cross sections in lab frame
(1:9)
(2:8)
(3:7)
(4:6)
(5:5)
(6:4)
(7:3)
(8:2)
(9:1)
E in lab
7
6
5
4
3
2
1
0
-1
0
100
200
300
400
500
600


comparing total cross sections in CM frame
7
6
5
4
3
2
1
0
(1:9)
(2:8)
(3:7)
(4:6)
(5:5)
(6:4)
(7:3)
(8:2)
(9:1)
E in CM
0
100
200
300
400
500
600

Part 2: Asymmetry Collisions

e+ e- > a a a

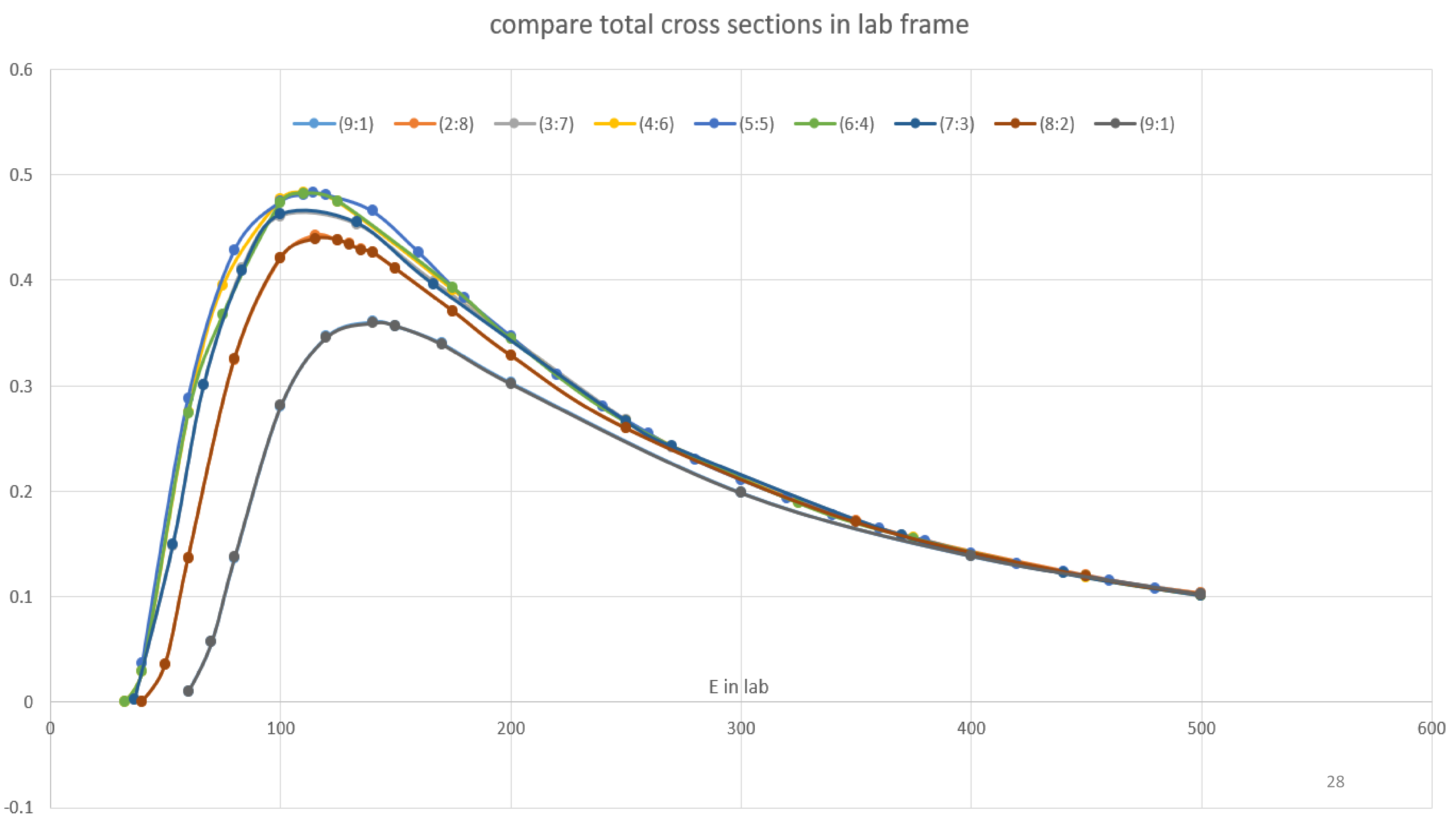
Postscript Diagrams for e+ e- > a a a WEIGHTED<=6 @1



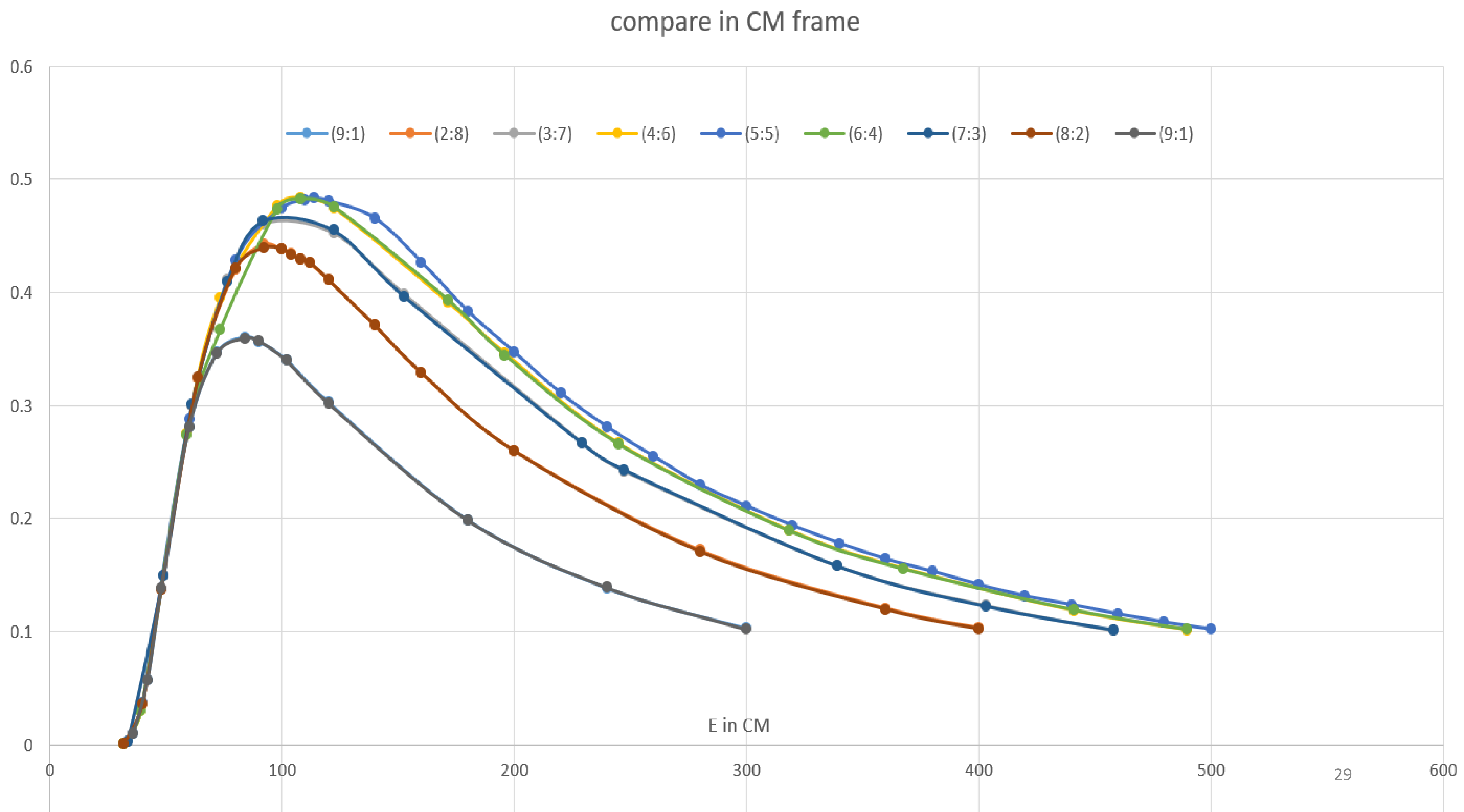
Diagrams made by MadGraph5_aMC@NLO

Diagrams for e+ e- > a a a

They are physically equivalent



compare total cross sections in lab frame
(9:1)
(2:8)
(3:7)
(4:6)
(5:5)
(6:4)
(7:3)
(8:2)
(9:1)
E in lab
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
100
200
300
400
500
600



compare in CM frame
(9:1)
(2:8)
(3:7)
(4:6)
(5:5)
(6:4)
(7:3)
(8:2)
(9:1)
E in CM
0
0.1
0.2
0.3
0.4
0.5
0.6
0
100
200
300
400
500
600

Part 3: Dark Matter simulations

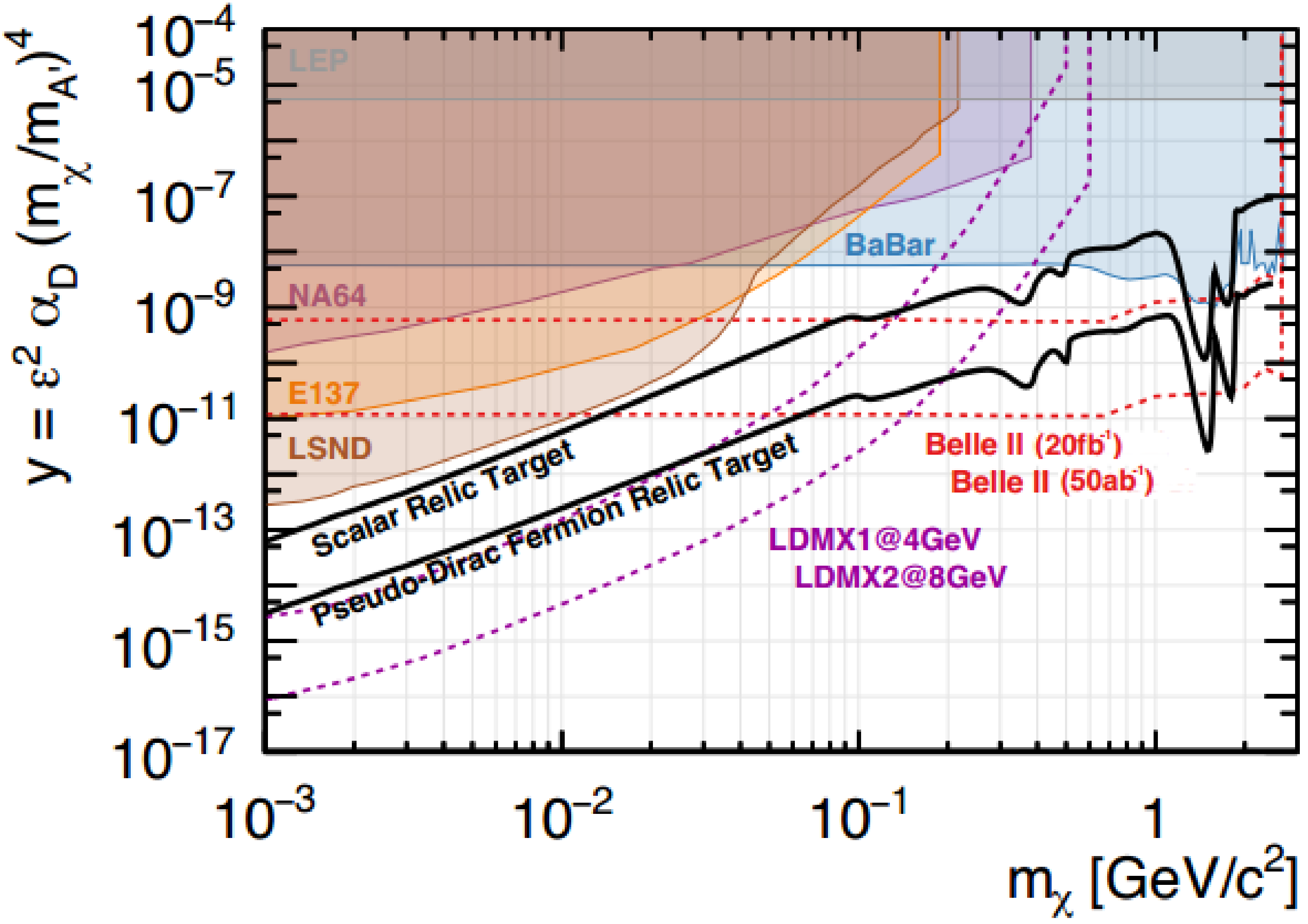
GOAL: To see how e+ e- colliders can generate dark matter

I delved into the Dark Matter Simulations using the Simplified Dark Matter Model (SDM). Here's a quick summary of what I did:

- I imported SDM spin1 and spin0 models and tested on known processes (xd is a dirac dark matter particle):
  p p > xd xd~ a   and   p p < xd xd~
- I started the desired processes: e+ e- collisions
- I had to automate inputting parameters so I learned bash code and wrote a loop file
- I used the two models on two processes:
  spin1 model for   e+ e- > xd xd~   and   e+ e- > xd xd~ a
  spin0 model for   e+ e- > xd xd~   and   e+ e- > xd xd~ a

Part 3: Dark Matter simulations
p p process

As needed for Belle II experiments, we adjust the dark matter masses and the dark mediator masses and calculate the cross sections, making a 2D surface graph.

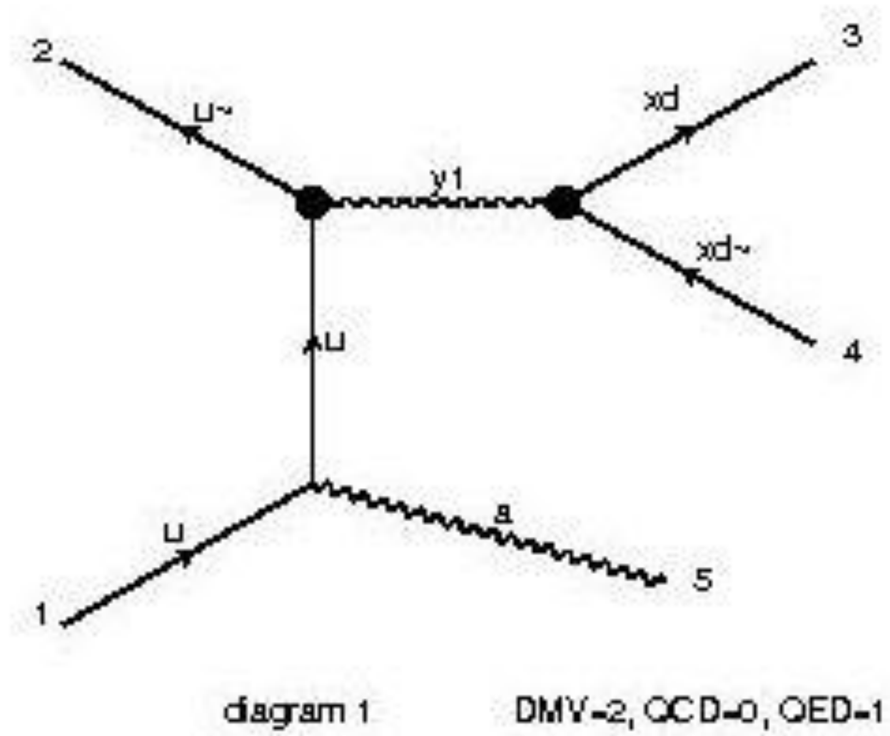


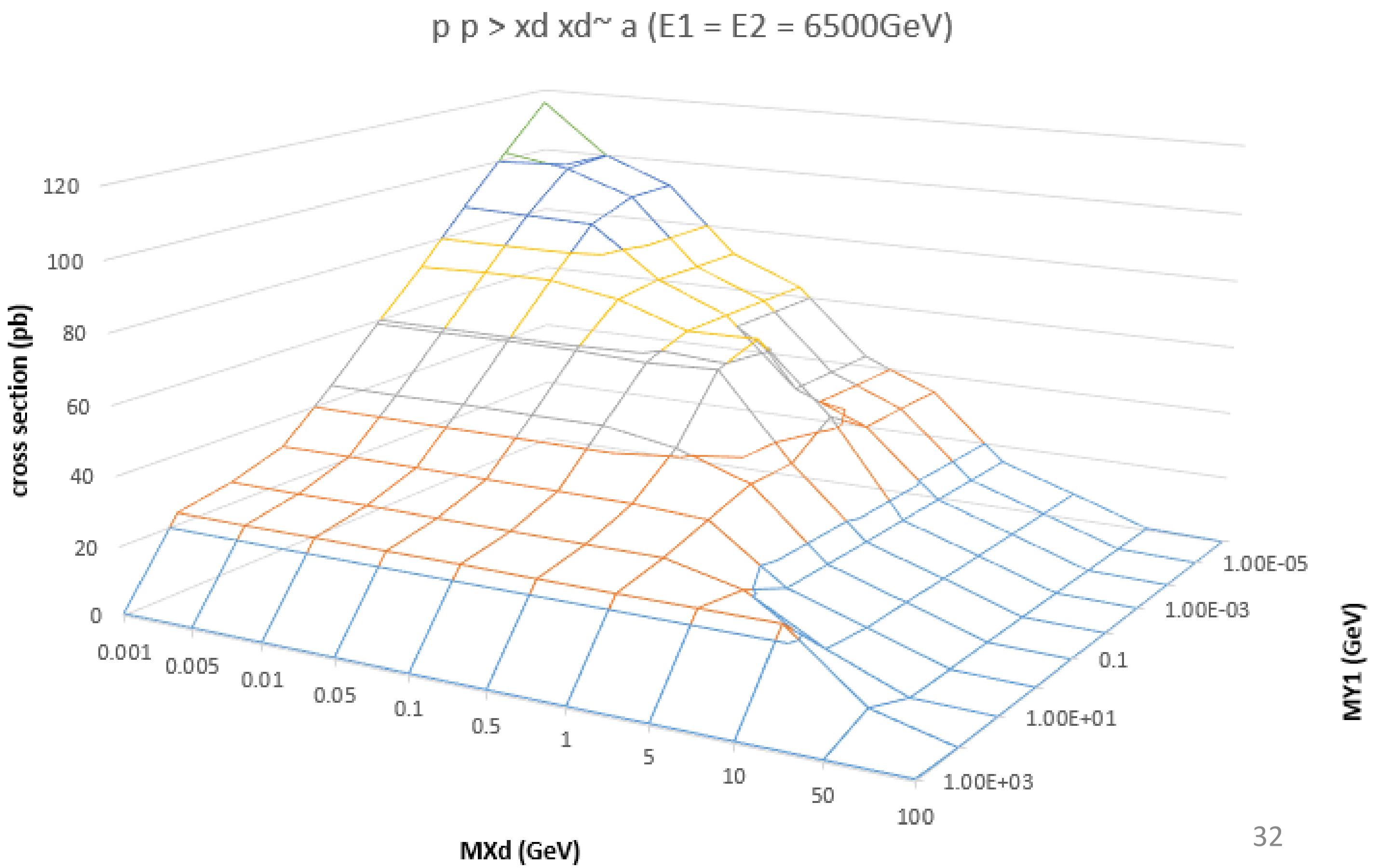
Reference: Kihyeon Cho (KISTI). DARK SECTOR WITH BELLE II

Part 3: Dark Matter simulations
p p > xd xd~ a

E(CM) = 13 TeV
Cross sections are very high for the range chosen:
MXd: (0.001 to 100) GeV
MY1: (1E-6 to 1E+3) GeV
Dominant for lower MXd and lower MY1

	1.00E+03	1.00E+02	1.00E+01	1	0.1	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06
0.001	0.5982	23.41	26.35	31.33	44.8	59.11	72.78	88.14	102.3	115.9
0.005	0.5971	23.35	26.22	31.54	44.73	59.01	73.48	87.63	98.97	99.93
0.01	0.5984	2.35E+01	26.39	31.52	44.96	59.21	73.46	87.04	91.84	91.96
0.05	0.5979	23.46	26.36	31.49	44.83	59.07	70.06	71.8	71.65	71.73
0.1	0.5973	23.54	26.28	31.45	44.92	58.33	62.94	63.11	63.15	63.16
0.5	0.5943	23.38	26.29	31.33	41.49	59.17	63.22	43.04	43.2	43.16
1	0.5955	23.33	26.29	30.44	34.39	34.49	42.82	34.2	34.43	34.43
5	0.5988	23.39	21.38	14.92	14.92	14.86	14.93	14.89	14.93	14.94
1.00E+01	0.5976	23.44	9.36E+00	7.883	7.892	7.875	7.889	7.942	7.901	7.869
50	0.5969	5.829	0.609	0.6034	0.6006	0.6045	0.6013	0.6032	0.6022	0.6052
100	0.5978	0.1581	0.1197	0.1195	0.1199	0.1191	0.1193	0.1194	0.1191	0.1185

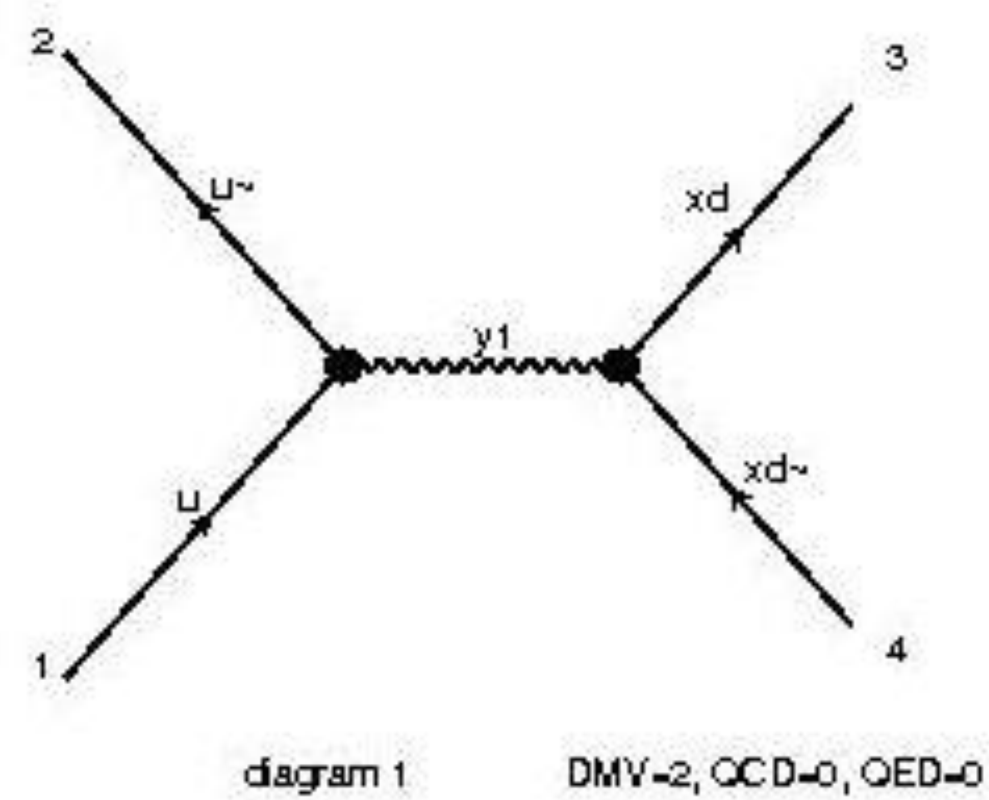




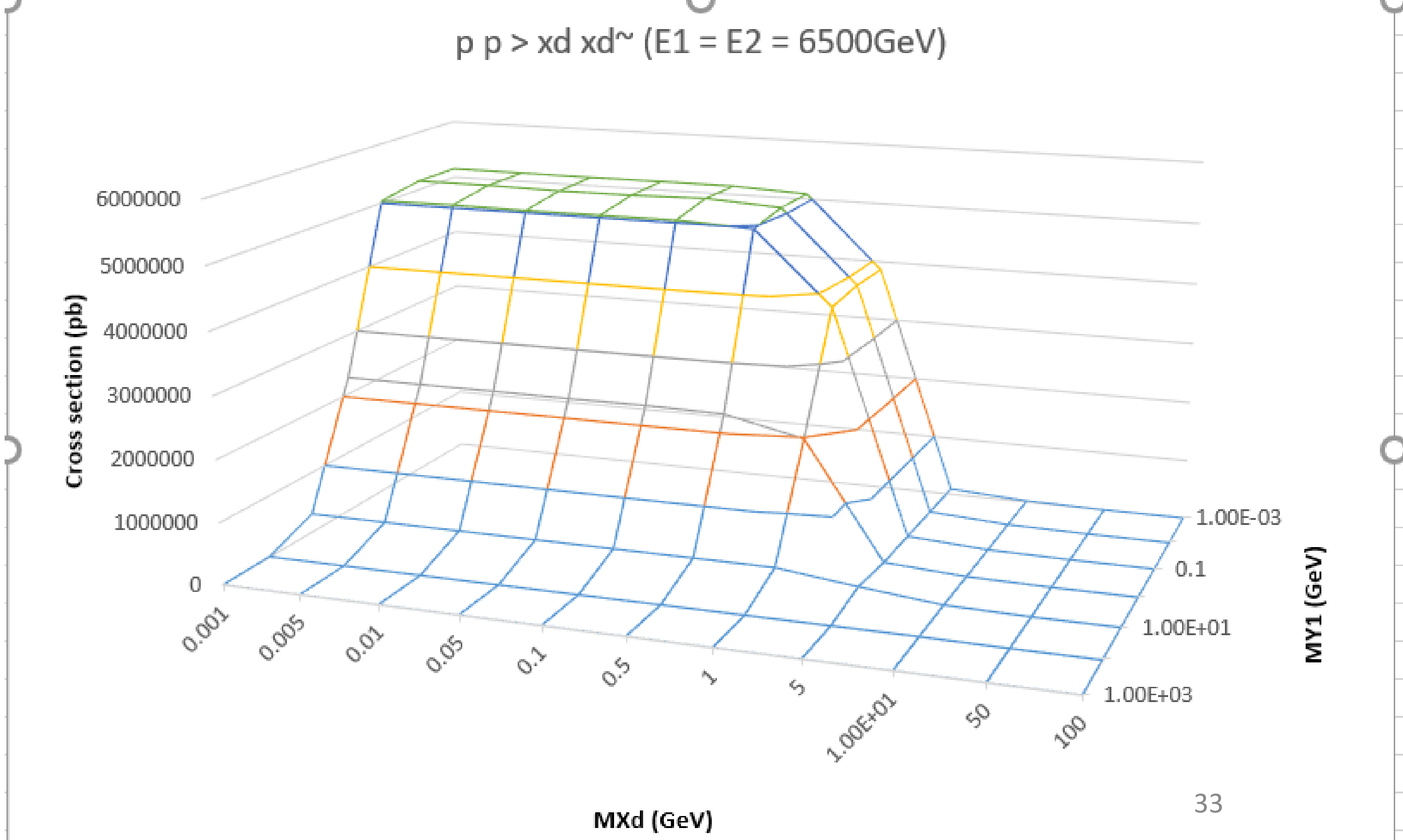
p p > xd xd~ a

E(CM) = 13 TeV

Much higher cross sections that p p > xd xd~ a
Cross sections are extremely high for the range chosen:
MXd: (0.001 to 100) GeV
MY1: (1E-3 to 1E+3) GeV
Dominant for lower MXd and lower MY1



	1.00E+03	1.00E+02	1.00E+01	1	0.1	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06
0.001	45.52	1.19E+04	3.08E+05	2.28E+06	5.04E+06	5.15E+06	5.15E+06			
0.005	45.5	1.19E+04	3.09E+05	2.28E+06	5.05E+06	5.15E+06	5.15E+06			
0.01	45.43	1.19E+04	3.08E+05	2.28E+06	5.03E+06	5.13E+06	5.15E+06			
0.05	45.6	1.19E+04	3.08E+05	2.27E+06	5.04E+06	5.14E+06	5.15E+06			
0.1	45.49	1.19E+04	3.08E+05	2.28E+06	5.04E+06	5.16E+06	5.15E+06			
0.5	45.56	1.19E+04	3.08E+05	2.26E+06	4.98E+06	5.09E+06	5.09E+06			
1	45.51	1.19E+04	3.06E+05	1.98E+06	3.80E+06	3.87E+06	3.86E+06			
5	45.55	1.19E+04	1.56E+05	9.55E+04	9.49E+04	9.50E+04	9.40E+04			
1.00E+01	45.54	1.19E+04	2.25E+04	1.76E+04	1.76E+04	1.76E+04	1.75E+04			
50	45.48	2.45E+03	186.6	185.1	184.9	184.9	185			
100	45.31	2.73E+01	20.04	19.93	19.93	19.97	20.01			



Part 3: Dark Matter simulations
e+ e- process

- The goal is to understand how lepton colliders can be used to detect dark matter. We study two processes:
- e+ e- > xd xd~ a
- e+ e- > xd xd~

- We cannot detect xd or xd~ directly (they are dark matter), but we can detect the photon a.

Part 3: Dark Matter simulations
spin1 e+ e- > xd xd~
Feynman Diagram generated by MG

Postscript Diagrams for e+ e- > xd xd~ DMV<=2 WEIGHTED<=4 @1

page 1/1

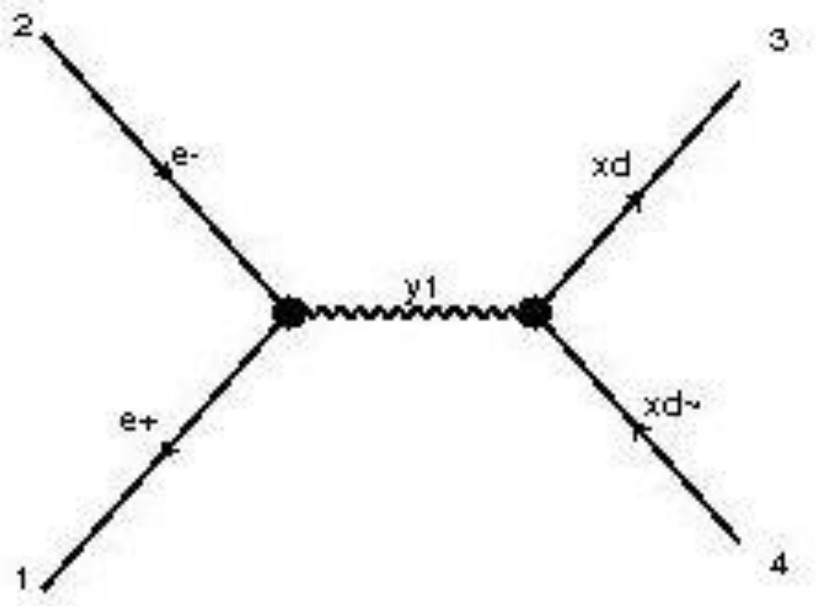


diagram 1 DMV=2, QCD=0, QED=0

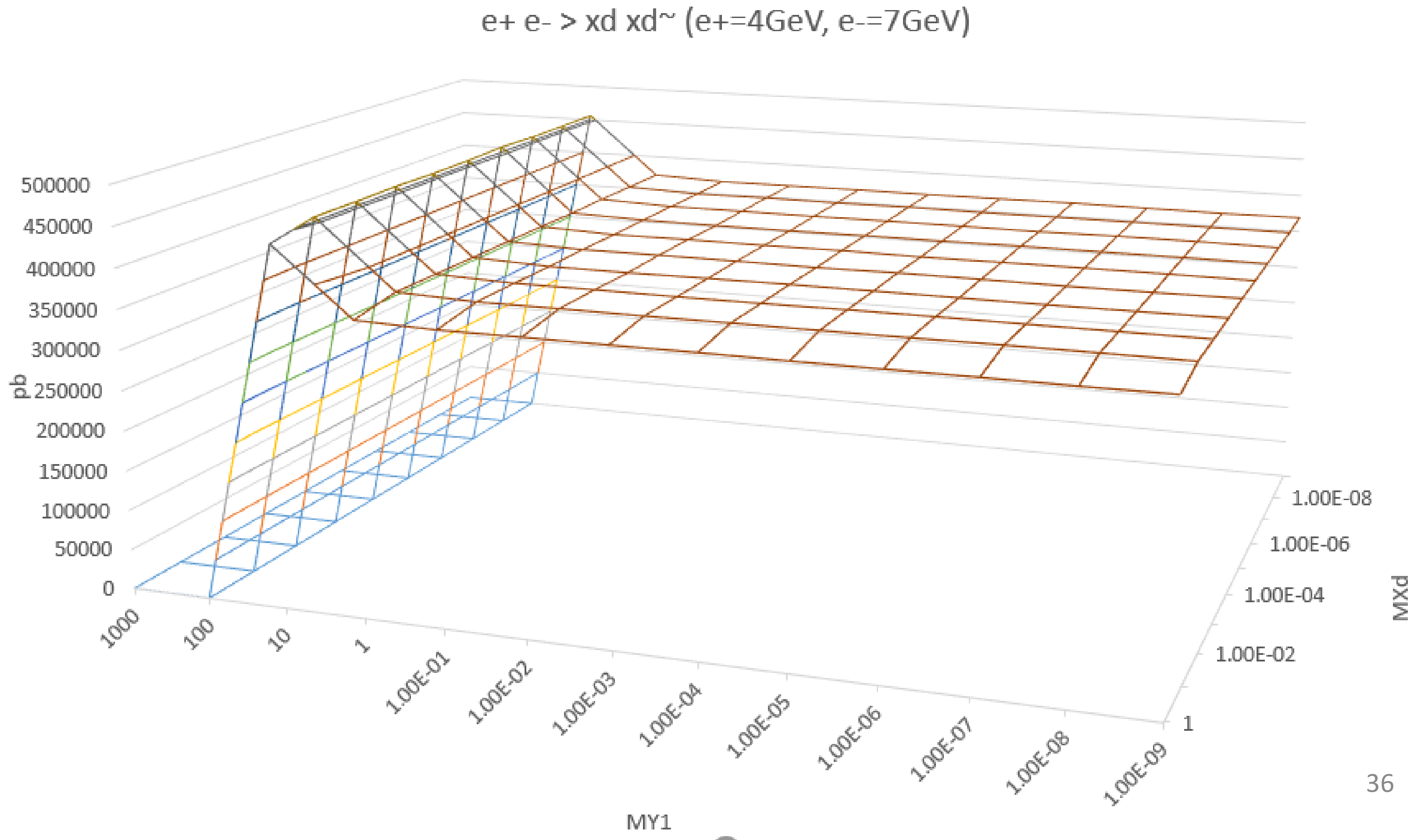
Part 3: Dark Matter simulations
spin1 e+ e- > xd xd~

Results

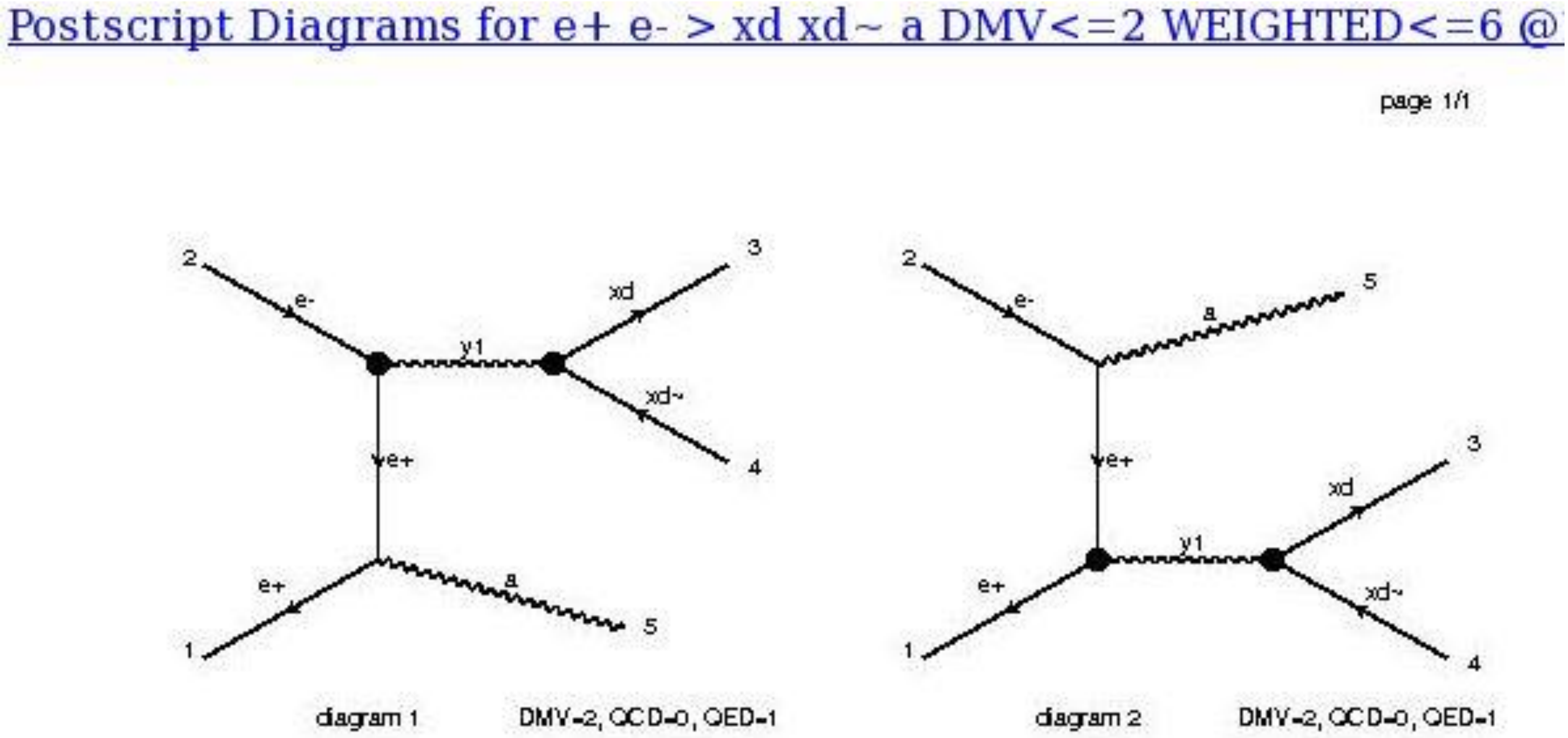
MXd:
Mostly uniform, a little lower cross-section for 1 GeV

MY1:
Low cross-section below 100 GeV
Peak near 10 GeV
Uniform below 1 GeV

	1000	100	10	1	1.00E-01	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08	1.00E-09
1	0.0045	45.65	4.44E+05	3.62E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05	3.59E+05
1.00E-01	0.00462	46.7	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05
1.00E-02	0.00462	46.8	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.68E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05
1.00E-03	0.00463	46.84	4.57E+05	3.73E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05
1.00E-04	0.00465	46.84	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05
1.00E-05	0.00463	46.99	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05
1.00E-06	0.00463	47.02	4.58E+05	3.72E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05
1.00E-07	0.00464	46.81	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.68E+05	3.69E+05	3.69E+05	3.69E+05
1.00E-08	0.00463	47	4.56E+05	3.73E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.68E+05
1.00E-09	0.00462	46.94	4.56E+05	3.72E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.69E+05	3.70E+05	3.69E+05	3.69E+05	3.69E+05



Part 3: Dark Matter simulations
spin1 e+ e- > xd xd~ a
(Feynman diagram in MG for spin 1 model)



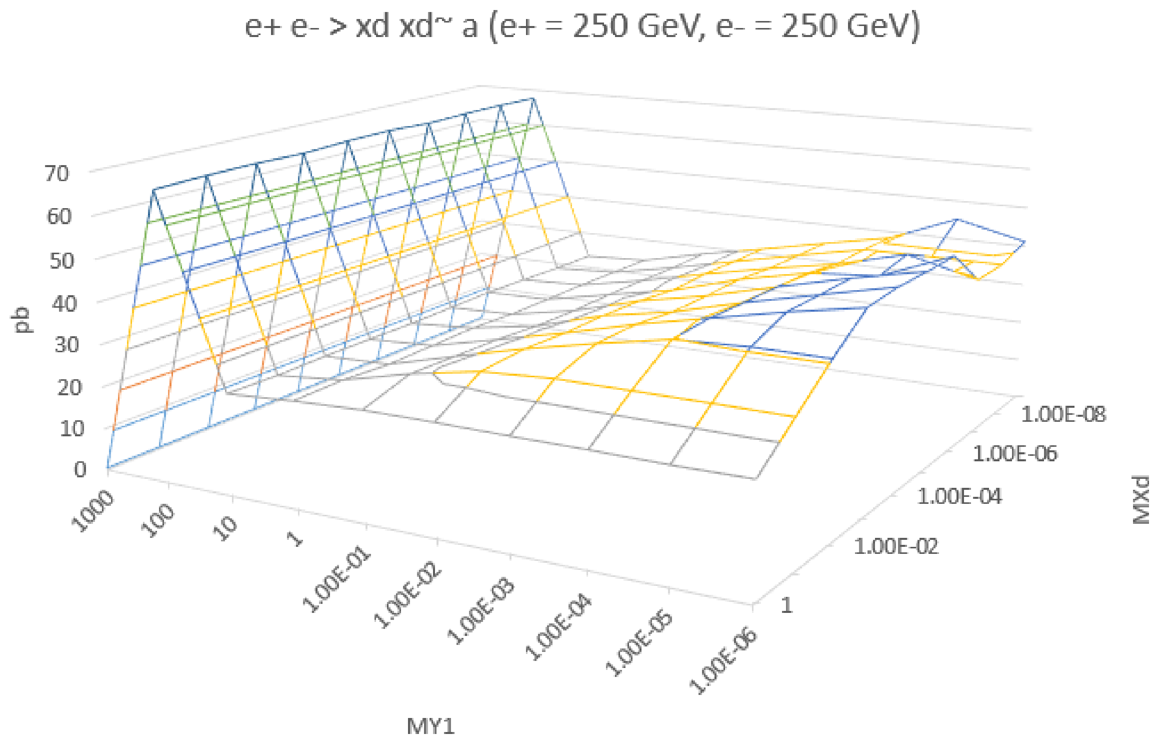
Part 3: Dark Matter simulations
spin1 e+ e- > xd xd~ a

Energy:
e+ = 250 GeV, e- = 250 GeV

Mass range:
MY1: 1000 GeV to 1e-6 GeV
MXd: 1 GeV to 1e-9 GeV

results analysis:
In MY1: cross section starts low at high MY1, then there's a peak about 100 GeV, then it increases steadily as MY1 decreases
in MXd: cross section is mostly uniform for high MY1, begins to show changes for low MY1: as MXd decreases, it starts low then increases, then decreases again.

	1000	100	10	1	1.00E-01	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06
1	0.4943	67.63	23.76	24.81	25.54	25.63	25.55	25.57	25.46	25.61
1.00E-01	0.4933	67.95	23.47	24.96	29.01	32.11	33.11	33.15	33.2	33.13
1.00E-02	0.4929	67.98	23.68	24.25	28.65	32.85	36.53	39.87	40.66	40.64
1.00E-03	0.4943	67.66	23.66	24.48	28.4	32.36	36.73	40.48	44.17	47.4
1.00E-04	0.4938	68.11	23.54	24.75	27.63	32.47	35.67	40.17	44.13	48.11
1.00E-05	0.4876	68.24	23.75	24.27	27.46	32.18	35.66	40.05	44.24	47.93
1.00E-06	0.4903	67.68	23.97	24.28	27.75	31.07	36	39.74	41.12	47.95
1.00E-07	0.4953	67.89	23.71	24.44	27.75	31.64	35.19	38.37	42.82	38.58
1.00E-08	0.4902	67.91	23.37	24.3	27.63	31.41	35.09	38.61	38.76	38.78
1.00E-09	0.4946	67.63	23.31	24.13	27.96	31.36	34.92	38.35	45.2	41.2



Part 3: Dark Matter simulations spin0 e+ e- > xd xd~

- MG reports that no process is possible for e+ e- > xd xd~

```
MG5_aMC>generate e+ e- > xd xd~
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=4: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=5: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=6: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=7: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=8: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=9: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=10: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying coupling order WEIGHTED<=11: WEIGTHED IS 2*DMS+2*QED+QCD
INFO: Trying process: e+ e- > xd xd~ DMS<=2 WEIGHTED<=12 @1
Command "generate e+ e- > xd xd~" interrupted with error:
NoDiagramException : No amplitudes generated from process Process: e+ e- > xd xd~ DMS=2 WEIG
HTED=12 @1. Please enter a valid process
MG5_aMC>
```

Part 3: Dark Matter simulations spin0 e+ e- > xd xd~ a

Postscript Diagrams for e+ e- > xd xd~ a DMS<=2 WEIGHTED<=6 @1

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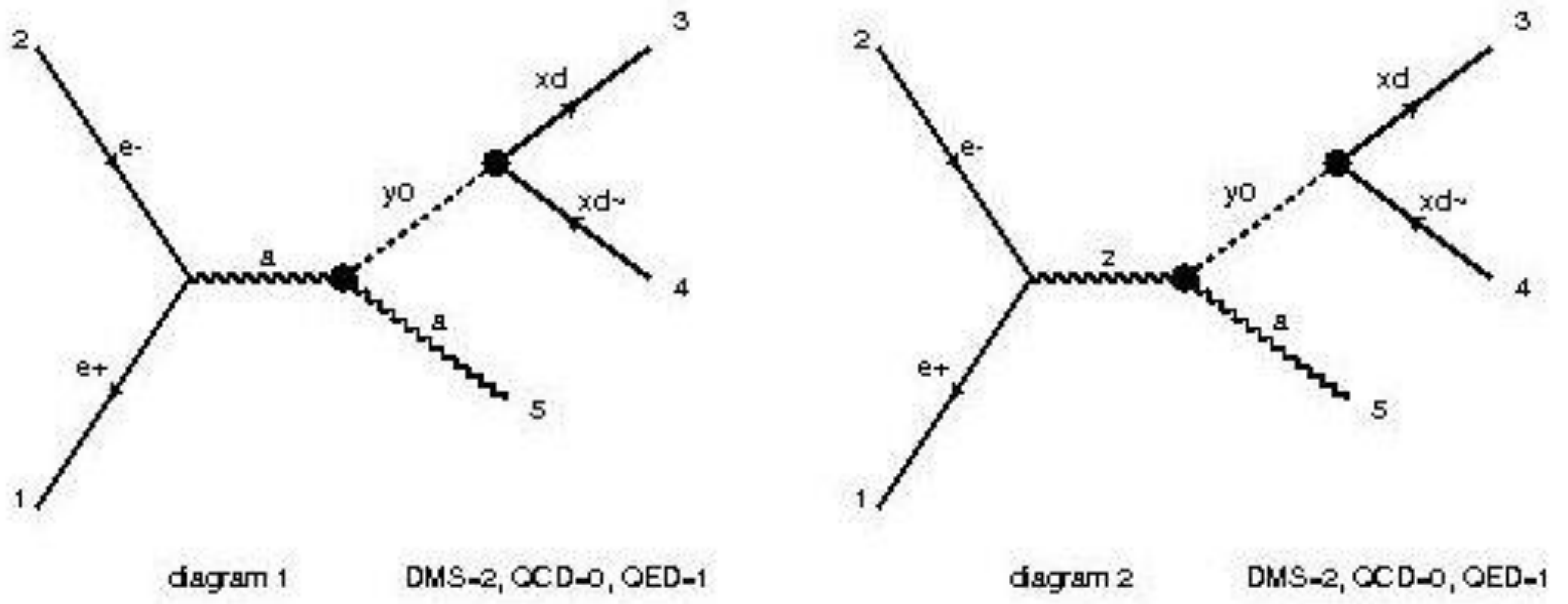
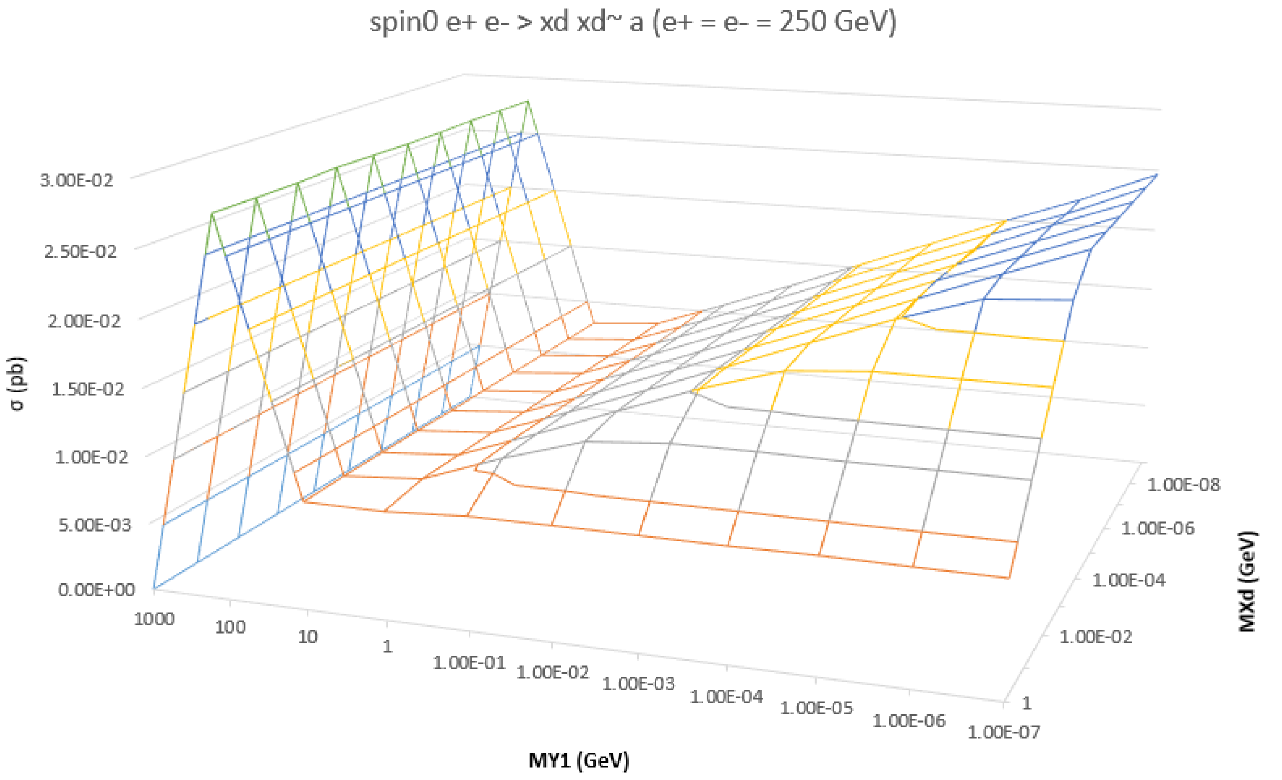


Part 3: Dark Matter simulations spin0 e+ e- > xd xd~ a

	1000	100	10	1	1.00E-01	1.00E-02	1.00E-03	1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08	1.00E-09
1	3.77E-06	0.02795	0.007956	0.007937	0.008288	0.008325	0.008326	0.008314	0.008384	0.00834	0.008328	0.008313	0.00833
1.00E-01	3.78E-06	0.02792	0.008035	0.008478	0.01064	0.01246	0.01295	0.01299	0.01293	0.01297	0.01296	0.01296	
1.00E-02	3.77E-06	0.02792	0.008055	0.008495	0.0107	0.013	0.01522	0.01707	0.01757	0.01759	0.01759	0.01763	
1.00E-03	3.78E-06	0.02804	0.008061	0.008516	0.01069	0.01297	0.01531	0.01762	0.01985	0.02178	0.0222	0.02223	
1.00E-04	3.79E-06	0.02796	0.008005	0.008485	0.01067	0.01297	0.01528	0.01758	0.01997	0.02227	0.0245	0.02677	
1.00E-05	3.77E-06	0.0279	0.00806	0.008518	0.01065	0.01295	0.01533	0.01764	0.02003	0.02225	0.02457	0.02685	
1.00E-06	3.78E-06	0.02789	0.008046	0.008534	0.01069	0.013	0.01528	0.01762	0.01997	0.02225	0.02457	0.02678	
1.00E-07	3.77E-06	0.02796	0.008041	0.008521	0.01068	0.01296	0.01529	0.01762	0.0199	0.02233	0.02458	0.02681	
1.00E-08	3.77E-06	0.02793	0.00805	0.008513	0.01068	0.01297	0.01532	0.01769	0.01997	0.0221	0.02462	#256	
1.00E-09	3.77E-06	0.0279	0.008059	0.00855	0.01073	0.01298	0.01531	0.01761	0.01996	0.02215	0.02464		

- Energies:
  (e+ = 250 GeV, e- = 250 GeV)
- Mass ranges:
  MY1= (1e-10 GeV to 1e-19 GeV)
  MXd = (1e-10 GeV to 1e-19 GeV)



Summary

- Learned important theoretical background for particle physics.
- Studied Important electron-positron interactions in standard model background and how the cross section depends on the beams energy.
- Studied the effects of asymmetric collisions and how the cross sections depend of the ratio between beam energies.
- Implemented the Simplified Dark Matter models spin1 and spin0 to study how electron-positron collisions can generate dark matter. Studied how the cross section changes for various ranges of dark masses.