Dark Photon Models for CMS

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CMS Working Subgroup

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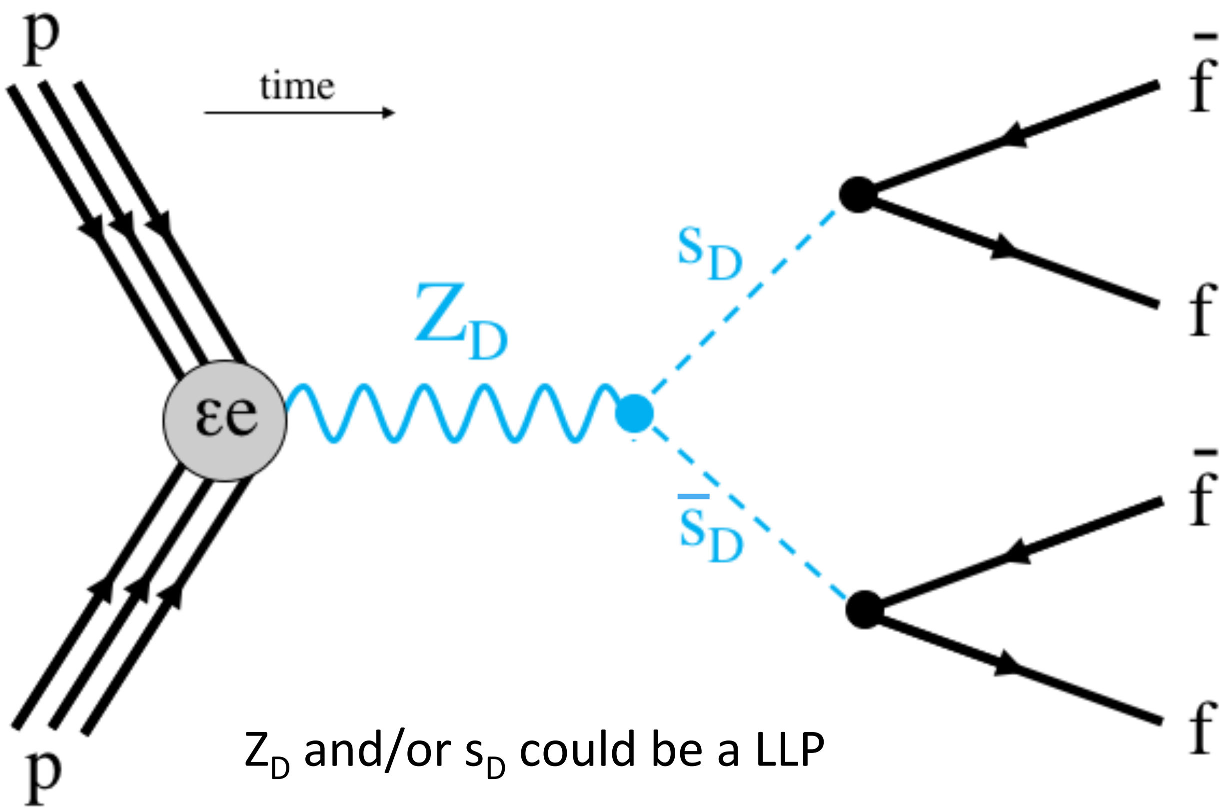
  Yongho Jeong

Disclaimer

- All plots are at Madgraph generator level
- No CMS simulation is used
- No CMS data are used or shown here

Dark Photon Coupling to Scalar Dark Matter Particles

Model 1:
Scalars



Z_D and/or s_D could be a LLP

Coupling Z_D to s_D could be larger than Z_D to f

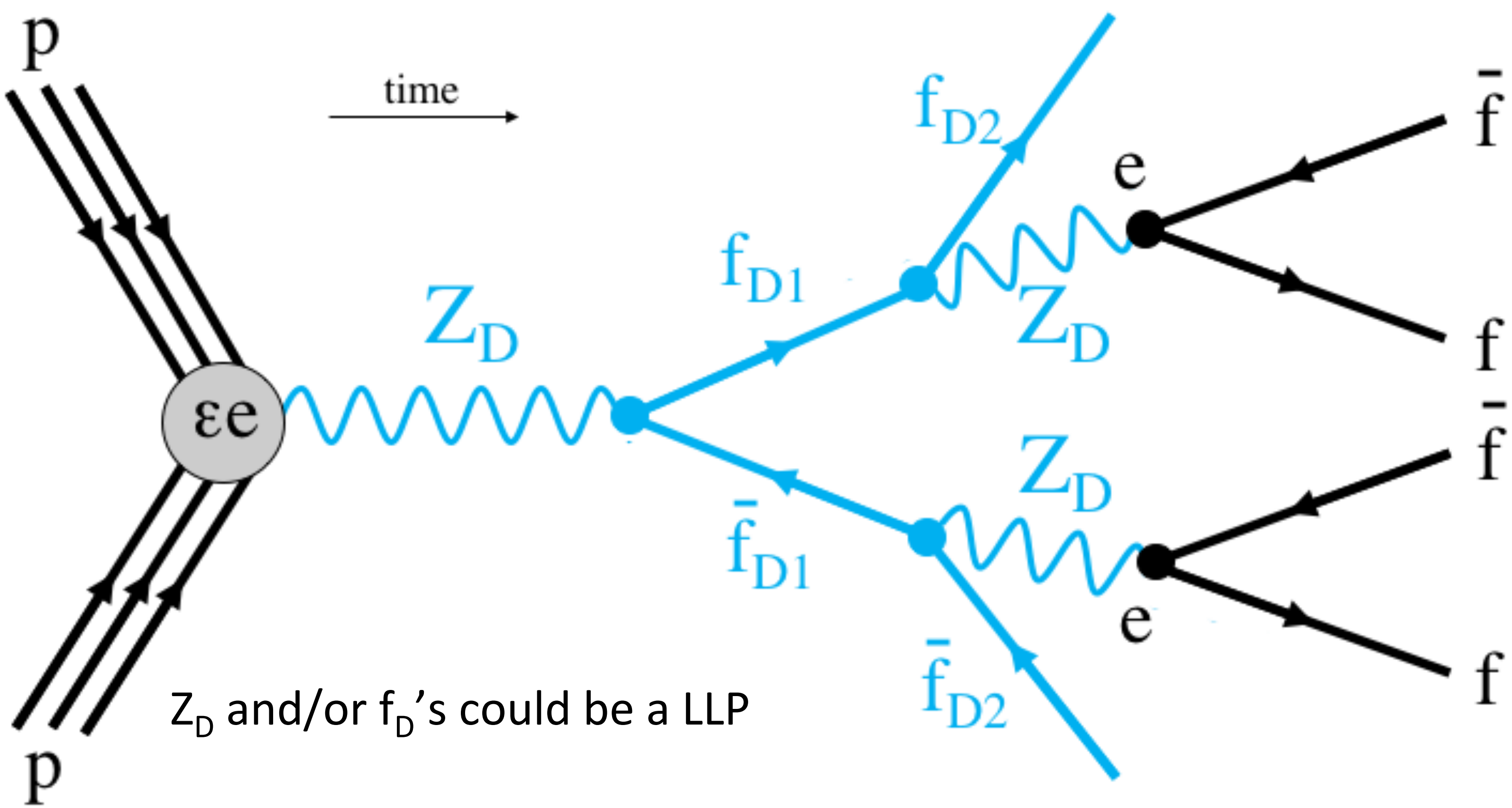
Note:
s_D is not taken as a self-conjugate scalar here; i.e. s_D and $\bar{s}_D$ are NOT the same particle.

Black: SM particles
Blue: DM particles

Dark Photon Coupling to Fermionic DM Particles

Model 2:
Fermions

f_D stable ➔ Missing E_T



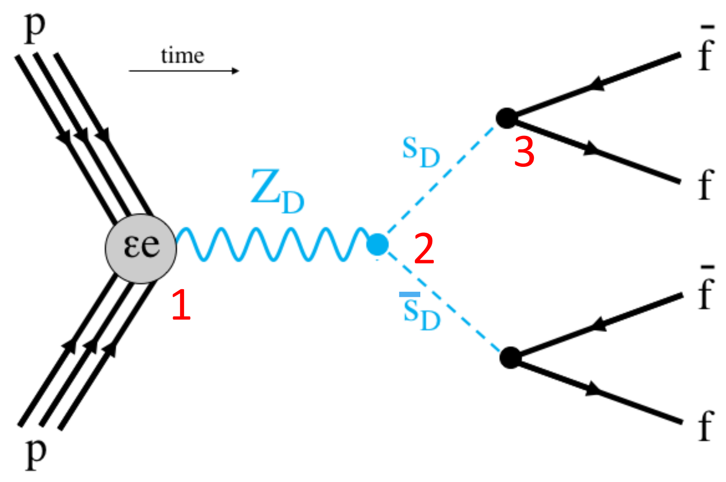
Z_D and/or f_D's could be a LLP

Coupling Z_D to f_D could be larger than Z_D to f

Black: SM particles
Blue: DM particles

Couplings Used in Dark Photon Model Lagrangians

Scalar model



Using Feynrules + MadGraph to generate events

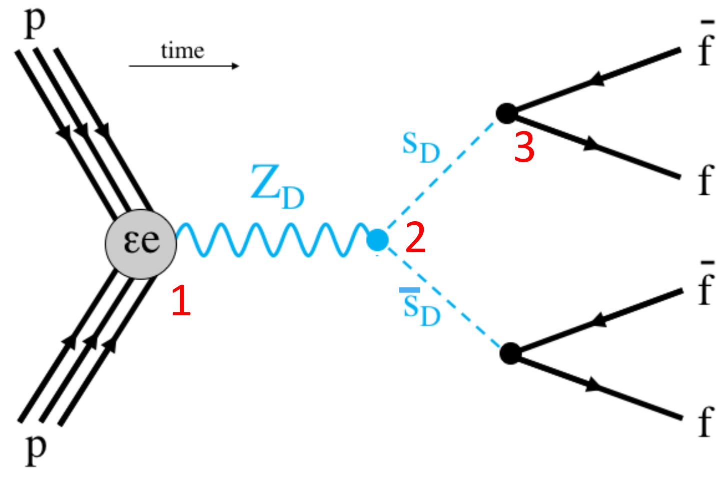
Using MadAnalysis to analyze and plot

- Dark Scalar is **NOT self-conjugate**
- 1. $\bar{q}\gamma^{\mu}(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$
- 2. $g_{Vs\gamma}^D(\overline{s_D}\partial^{\mu}s_D - s_D\partial^{\mu}\overline{s_D})\, Z_{D\mu}$
- 3. $g_{sl}^D\,\bar{\mu}\,\mu\, s_D$

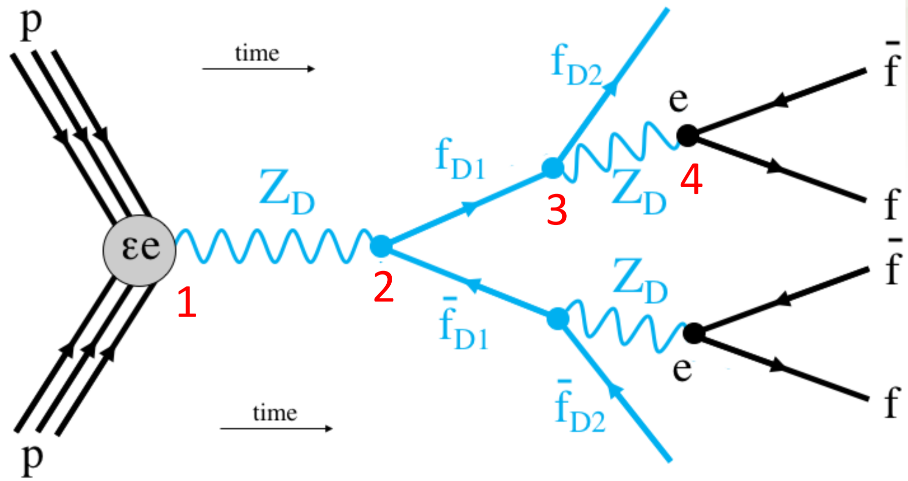
Three distinct couplings

Couplings Used in Dark Photon Model Lagrangians

Scalar model



Fermionic model



- Dark Scalar is **NOT self-conjugate**
- 1. $\bar{q}\gamma^{\mu}(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$
- 2. $g_{Vs\gamma}^D(\overline{s_D}\partial^{\mu}s_D - s_D\partial^{\mu}\overline{s_D})\, Z_{D\mu}$
- 3. $g_{sl}^D\, \bar{\mu}\, \mu\, s_D$

- Dark Fermions are **self-conjugate**
- 1. $\bar{q}\gamma^{\mu}(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$
- 2. $g_{Af\gamma}^D\, \overline{f_{D1}}\gamma^{\mu}\gamma^5 f_{D1}\, Z_{D\mu}$
- 3. $g_{Aff}^D\, \overline{f_{D1}}\gamma^{\mu}\gamma^5 f_{D2}\, Z_{D\mu}$
- 4. $\bar{\mu}\gamma^{\mu}(g_{Vl}^D + g_{Al}^D\gamma^5)\mu\, Z_{D\mu}$

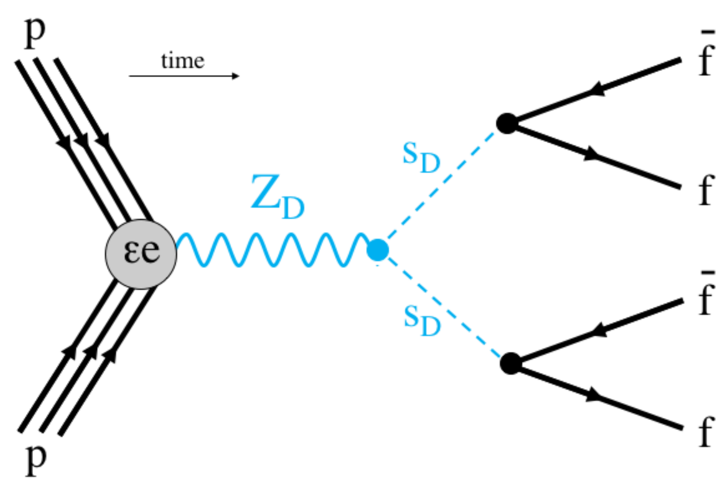
Four distinct couplings

Varying the Coupling Constants

Lagrangian	gV	gA	Does it work?
$\bar{q}\gamma^{\mu}(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$	0.25	0.25	
	0.25	0.001	
	0.001	0.25	
	0	0.25	
	0.25	0	
$\overline{f_{D1}}(g_V^D \pm g_A^D\gamma^5)f_{D1}\, Z_{D\mu}$	0	0.25	
	0.25	0.25	Mathematica error: Not hermitian
	0.25	0	Mathematica error: Not hermitian
$\overline{f_{D1}}(g_V^D \pm g_A^D\gamma^5)f_{D2}\, Z_{D\mu}$	0	0.25	
	0.25	0.25	Mathematica error: Not hermitian
	0.25	0	Mathematica error: Not hermitian
$\bar{\mu}\gamma^{\mu}(g_{Vl}^D + g_{Al}^D\gamma^5)\mu\, Z_{D\mu}$	0.25	0.25	
	0.25	0.001	
	0.001	0.25	
	0	0.25	
	0.25	0	

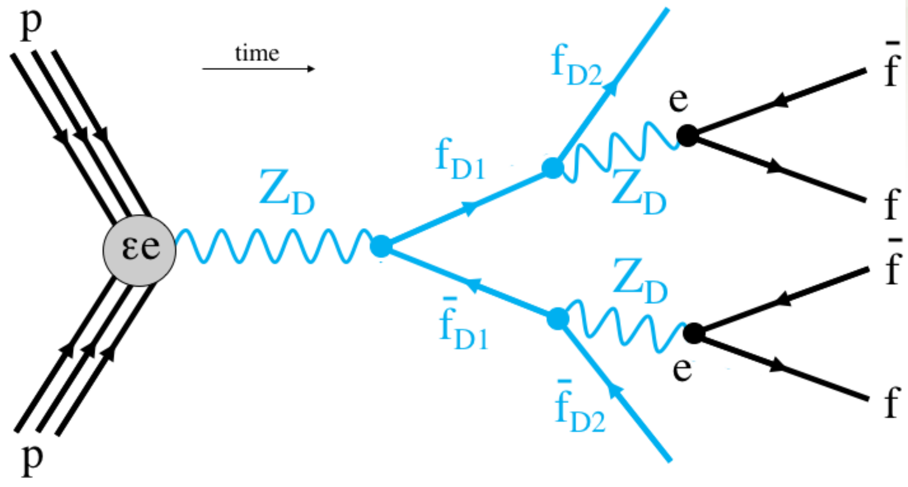
Masses-at-a-glance

Scalar model



Z_D(GeV)	s_D (GeV)
20	2
100	2
1000	2

Fermionic model



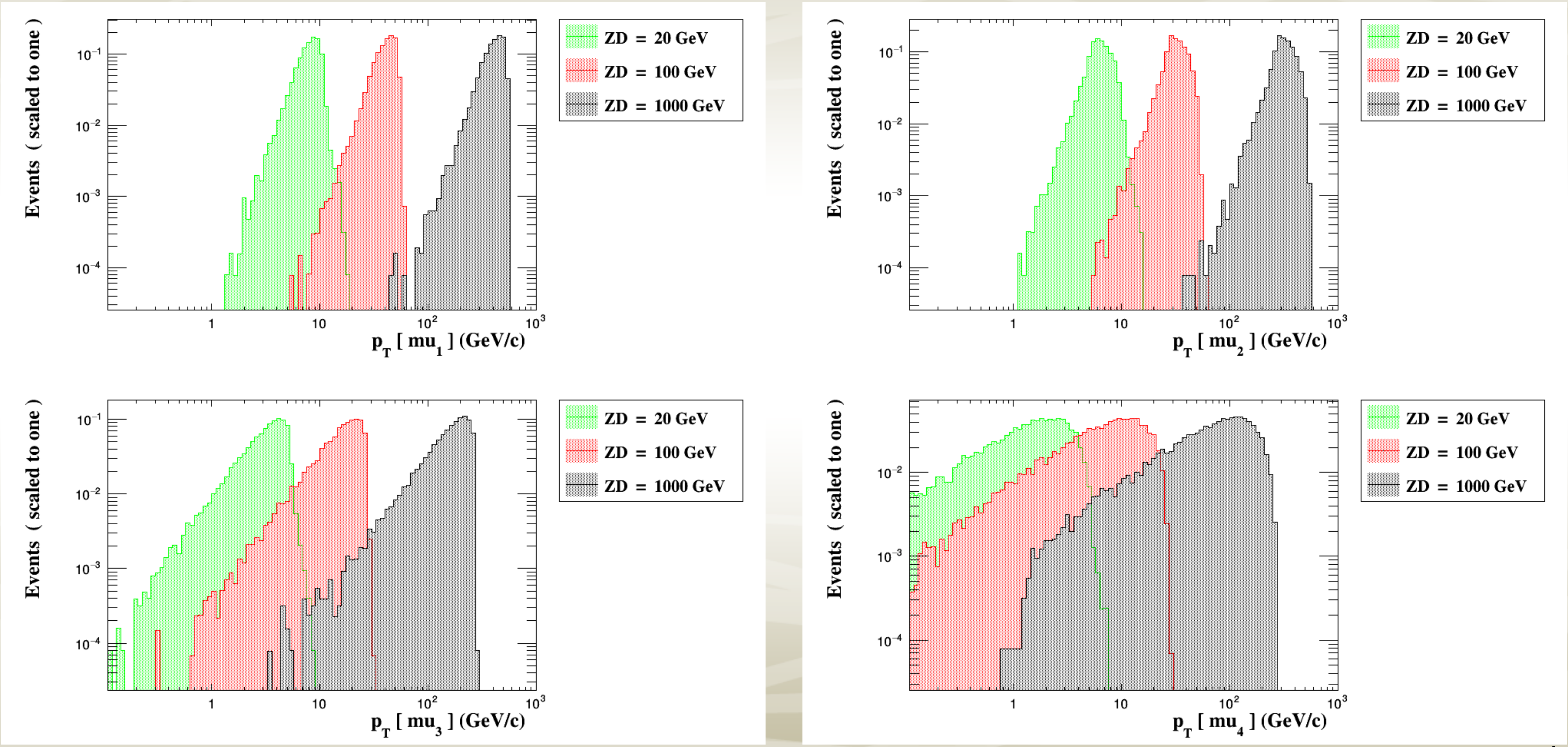
Z_D(GeV)	f_{D1}(GeV)	f_{D2}(GeV)
40	15	4
100	30	4
1000	30	4

Kinematics & Topology

Samples with Dimuon Final States – All plots at generator level

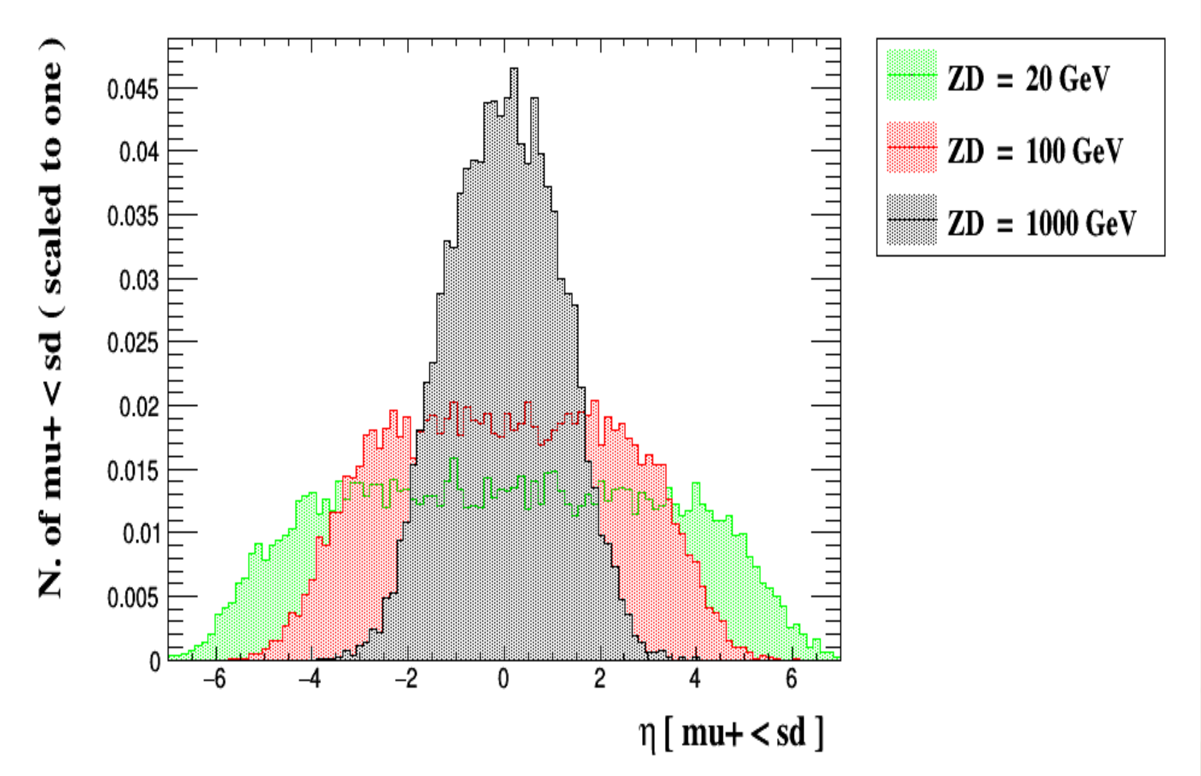
Scalar Model

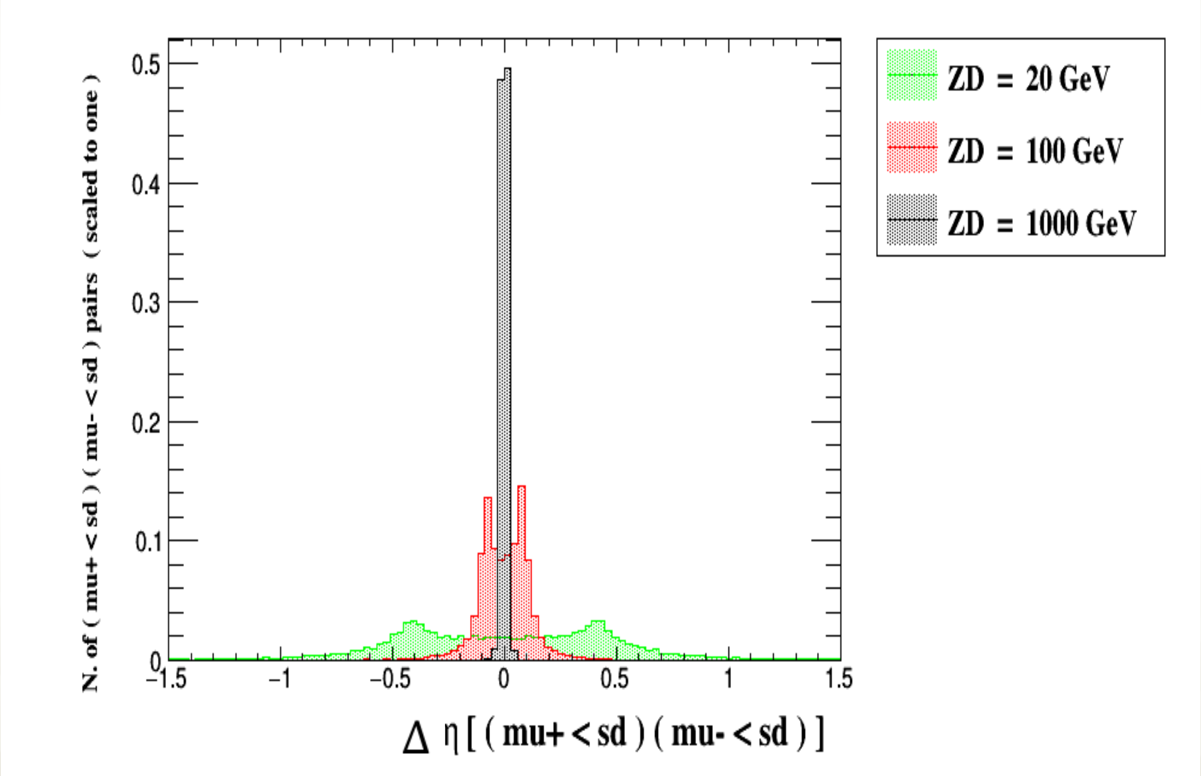
P_T of Leading, Subleading, 3rd, and 4th Muon



Scalar Model

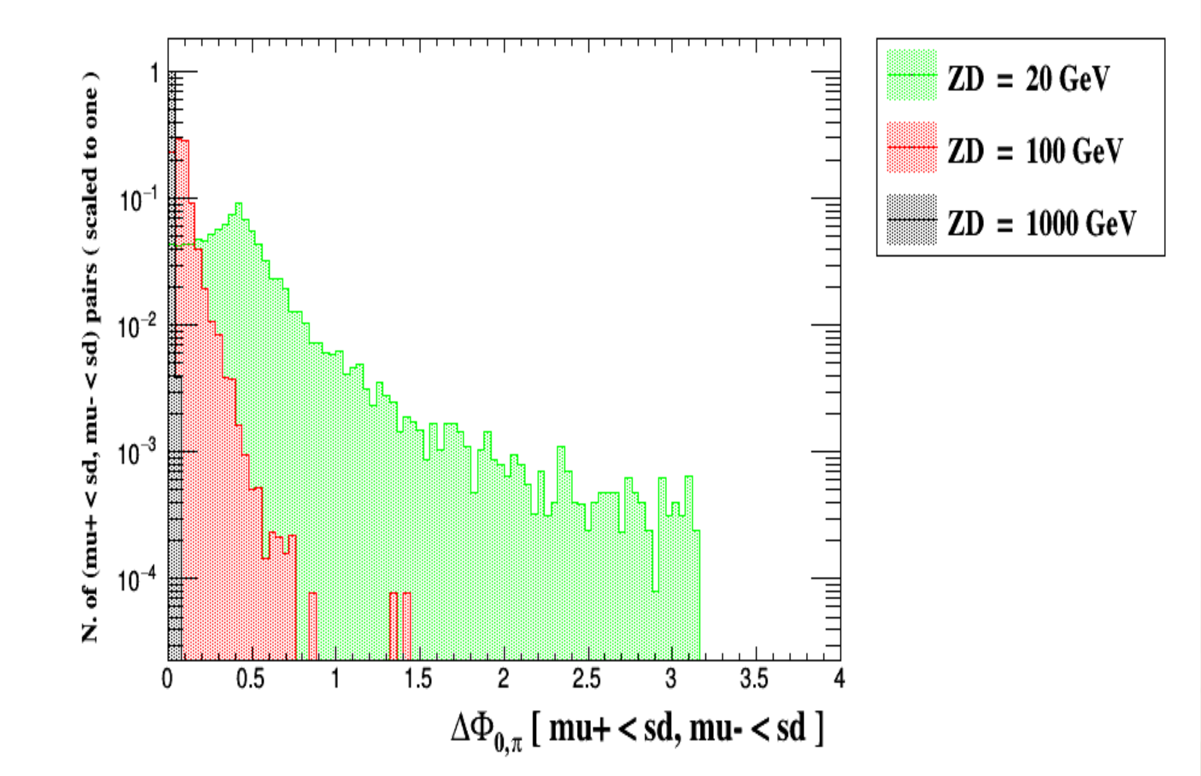
η of Muons and Δη between Muons from Same Vertex

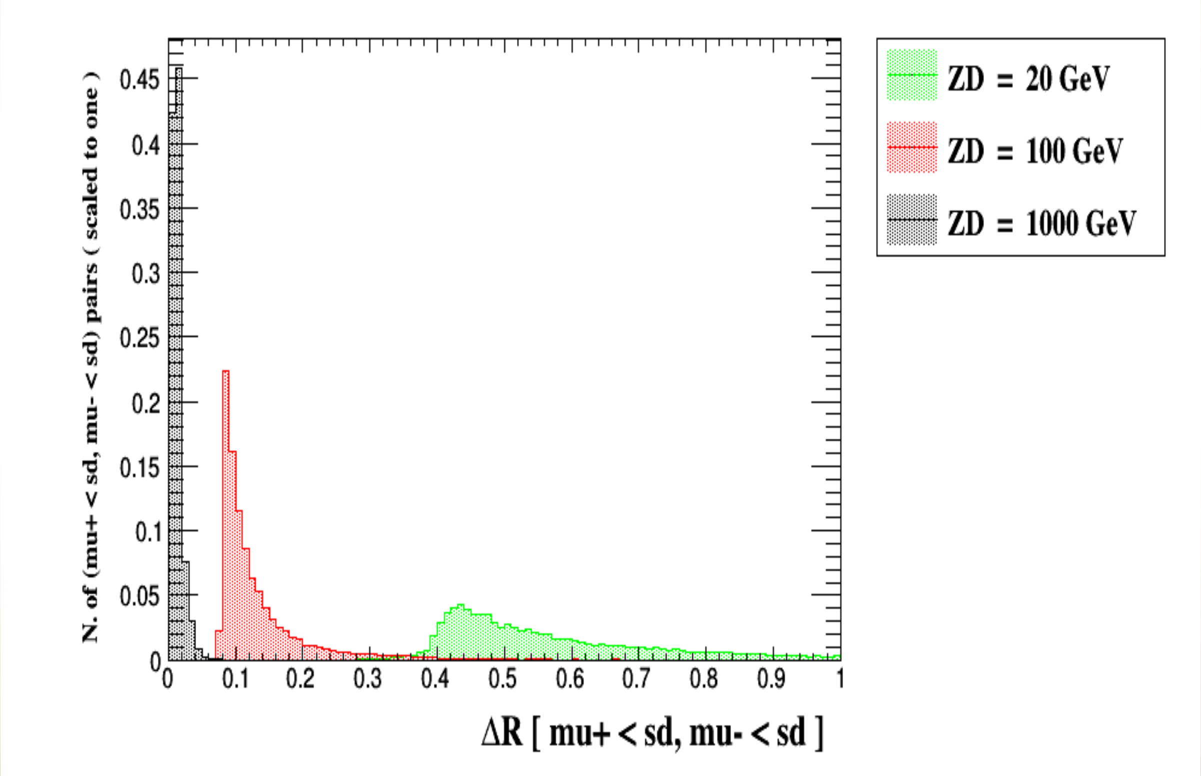




Scalar Model

Δφ and ΔR between Muons from Same Vertex





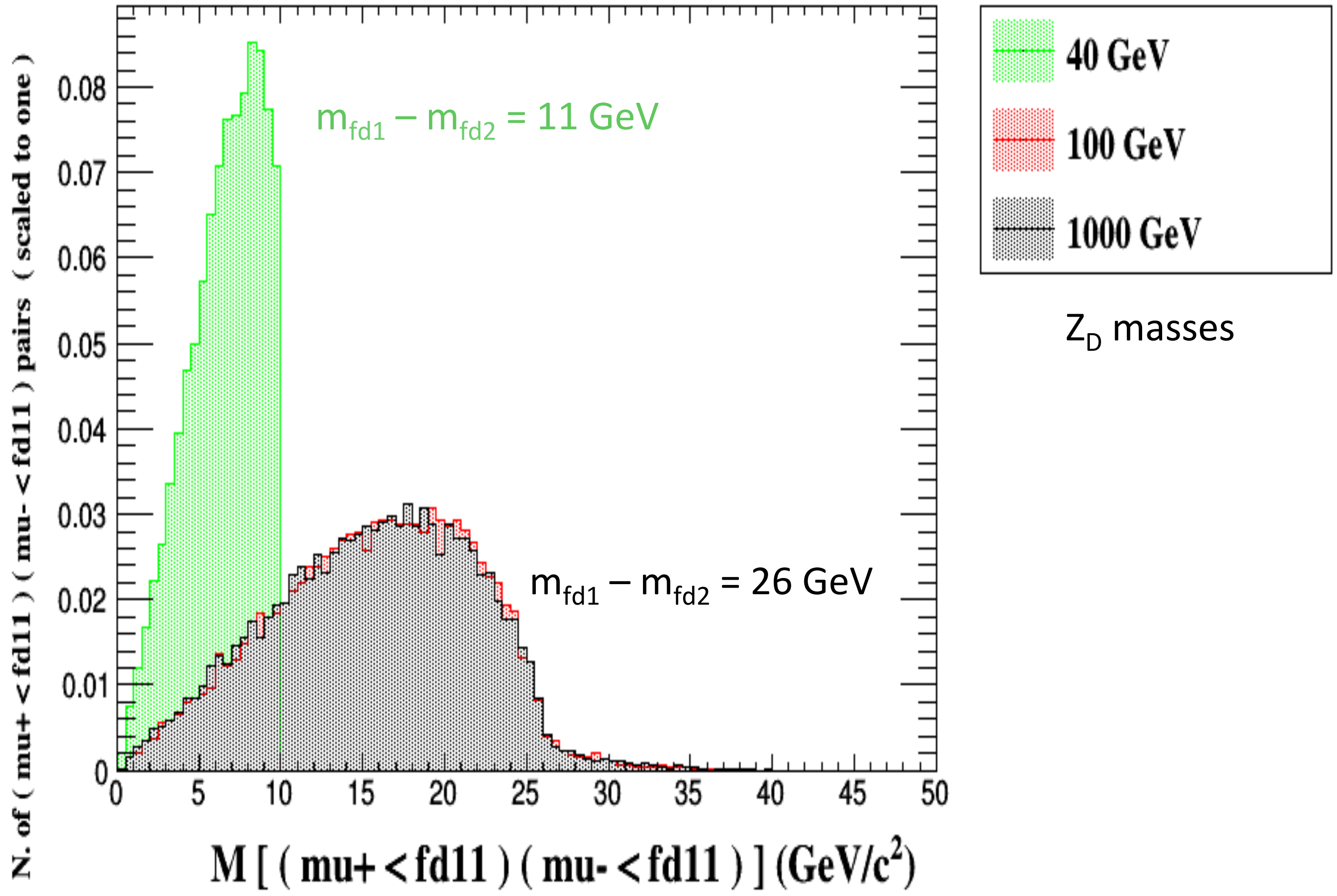
Scalar Model

Kinematics & Topology

Samples with Dimuon Final States – All plots at generator level

Fermionic Model

Invariant Mass of Muons from Same f_{d1}



Z_D masses

Fermionic Model

Summary & Plans

- Developing 2 models with decays of dark photons into scalar or fermionic dark matter particles with two dimuon pairs in final state
- Complementary to models with direct dark photon decays into dimuons (see Cristiano's and Teruki's talks)
- Investigating different coupling types & strengths with MadGraph
- Event kinematics & topology look reasonable at generator level
- Next:
  - Simulate and reconstruct events in CMS detector (in progress)
  - Connect with CMS searches for two displaced dimuon pairs
    - Look into reinterpreting 2016 dimuon pair results for these models
    - Full Run 2 analysis

The End

Backup slides

Event Generation

Feynrules

• Mathematica package that allows the calculation of Feynman rules in momentum space for *any* QFT physics mode which can then be used to implement the new physics model into MadGraph, see https://arxiv.org/pdf/1508.00564.pdf

MadGraph

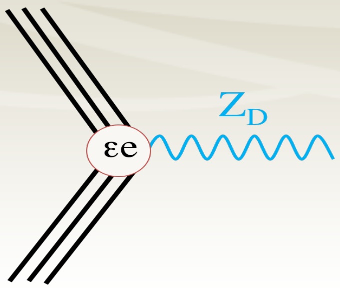
• Computation of cross sections; generation of hard scattering events

MadAnalysis

• Framework for phenomenological investigations at generator level which we use for analysis and producing plots.

Lagrangian Terms in MadGraph

- γ_D production from quarks
  - V ± A coupling: $\bar{q}\gamma^{\mu}(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$



Using Feynrules + MadGraph to generate events

Using MadAnalysis to analyze and plot events

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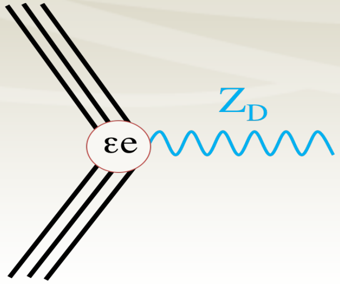
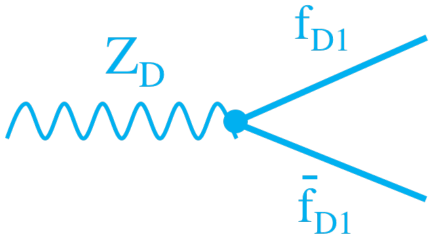


- Pure dark coupling of γ_D to dark fermions in pair production
  - axial coupling *only*: $g_{Af\gamma}^D\, \overline{f_{D1}}\gamma^{\mu}\gamma^5 f_{D1}\, Z_{D\mu}$



Lagrangian Terms in MadGraph

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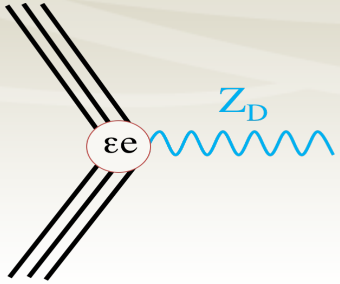

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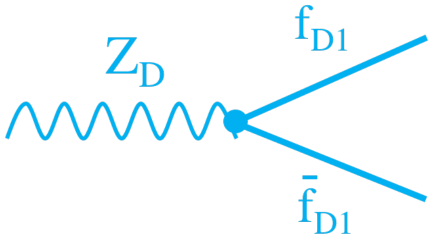
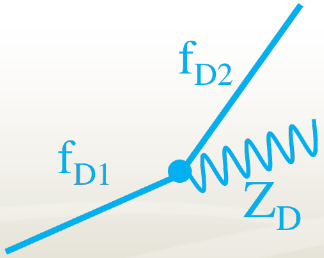
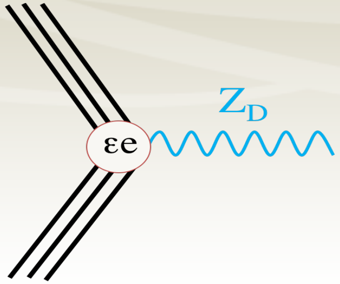


- Pure dark coupling of γ_D to dark fermions in decay
  - axial coupling *only*: $g_{Aff}^D\, \overline{f_{D1}}\gamma^{\mu}\gamma^5 f_{D2}\, Z_{D\mu}$

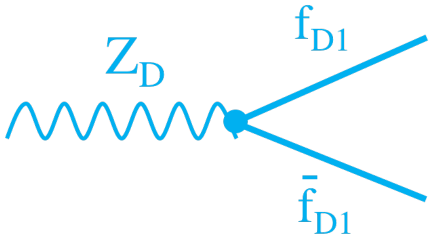


Lagrangian Terms in MadGraph

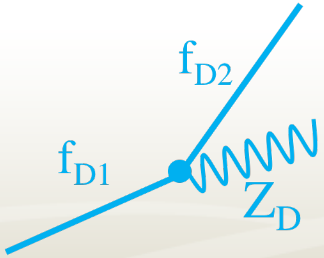
- γ_D production from quarks
  - V ± A coupling: $\bar{q}\gamma^\mu(g_V^D \pm g_A^D\gamma^5)q\, Z_{D\mu}$



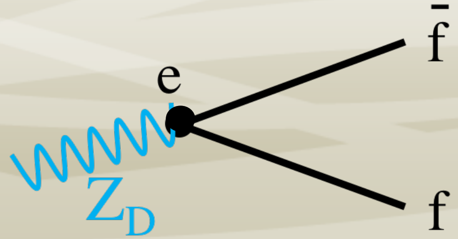
- Pure dark coupling of γ_D to dark fermions in pair production
  - axial coupling *only*: $g^D_{Af\gamma}\,\overline{f_{D1}}\gamma^\mu\gamma^5 f_{D1}\, Z_{D\mu}$



- Pure dark coupling of γ_D to dark fermions in decay
  - axial coupling *only*: $g^D_{Aff}\,\overline{f_{D1}}\gamma^\mu\gamma^5 f_{D2}\, Z_{D\mu}$

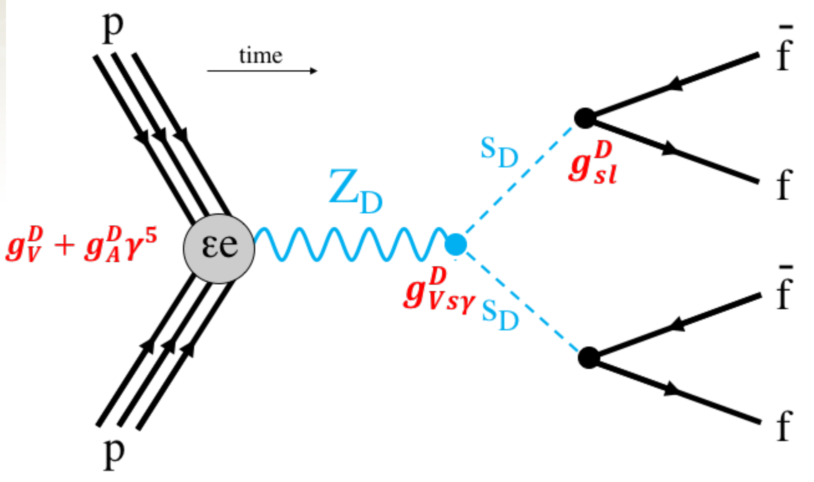


- Coupling of γ_D to muons
  - V ± A coupling: $\bar{\mu}\gamma^\mu(g^D_{Vl} + g^D_{Al}\gamma^5)\mu\, Z_{D\mu}$



Example for a Parameter Set

Scalar model

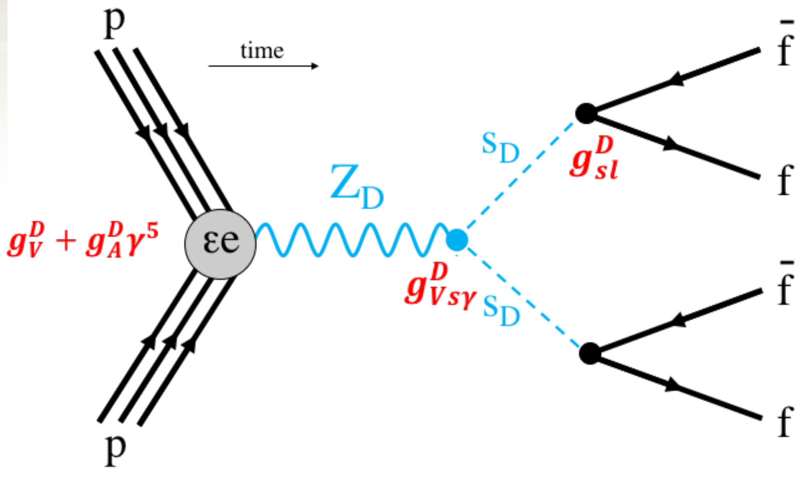


- $g_V^D = 0.25$
- $g_A^D = 0$
- $g_{Vs\gamma}^D = 10^{-3}$
- $g_{sl}^D = 0.25$

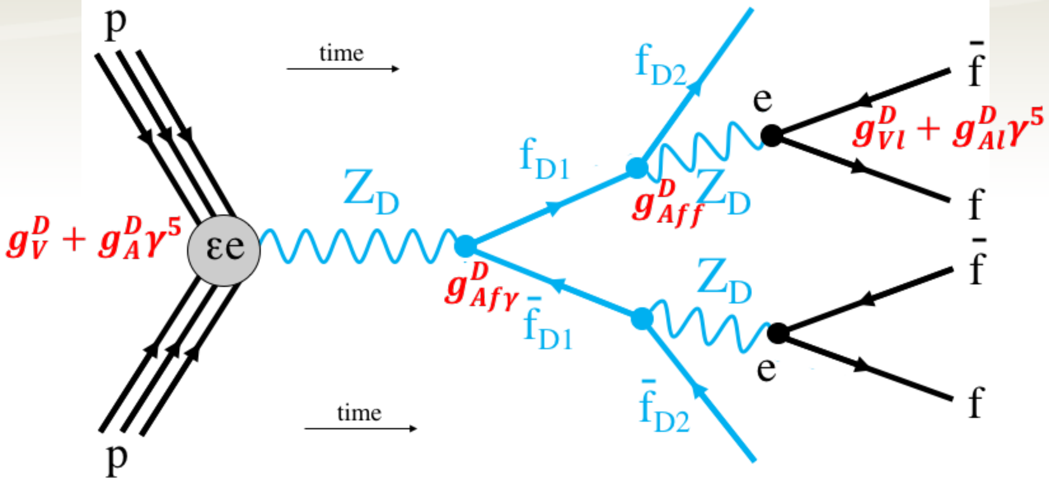
- $M_{ZD} = 20, 100, 1000\ GeV$
- $Width_{ZD} = 1\ GeV$
- $M_{sD} = 2\ GeV$
- $Width_{sD} = 0.00407\ GeV$

Example for a Parameter Set

Scalar model



Fermionic model



- $g^D_V = 0.25$
- $g^D_A = 0$
- $g^D_{Vs\gamma} = 10^{-3}$
- $g^D_{sl} = 0.25$

- $M_{ZD} = 20, 100, 1000\ GeV$
- $Width_{ZD} = 1\ GeV$
- $M_{sD} = 2\ GeV$
- $Width_{sD} = 0.00407\ GeV$

- $g^D_V = 0.25$
- $g^D_A = 0$
- $g^D_{Af\gamma} = 10^{-3}$
- $g^D_{Aff} = 0.25$
- $g^D_{vl} = 0.25$
- $g^D_{Al} = 10^{-3}$

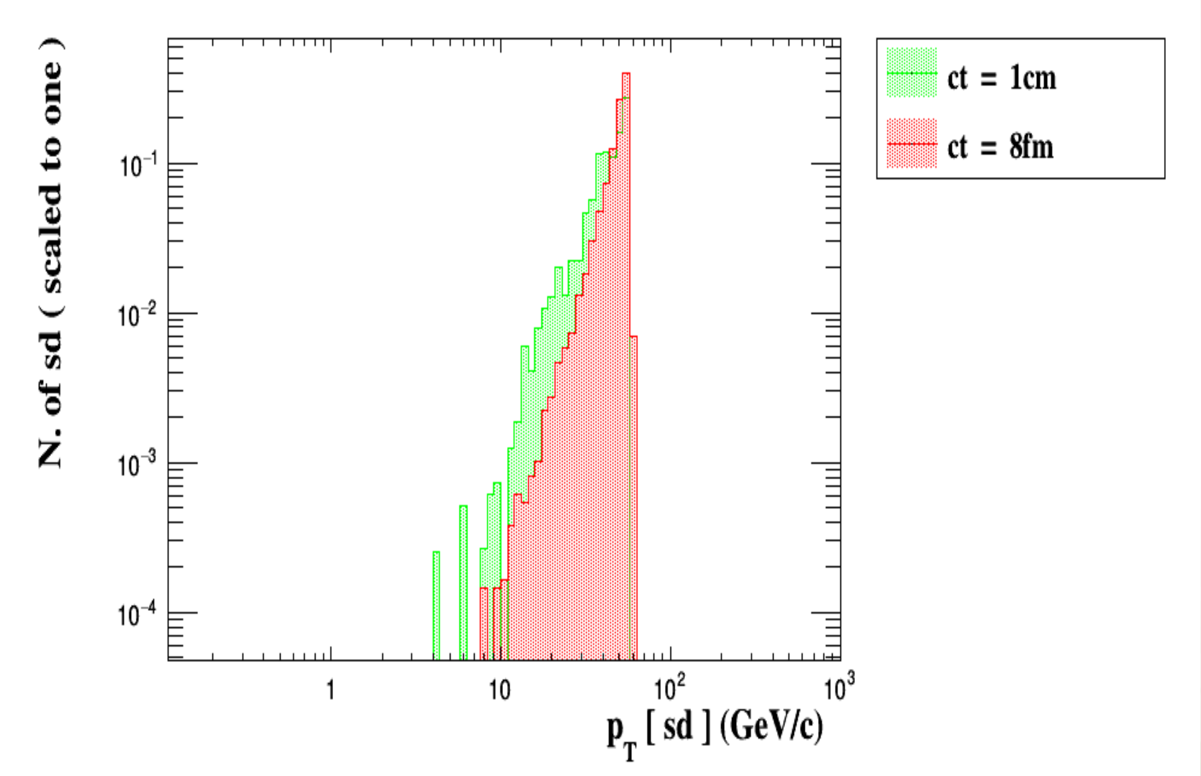
- $M_{ZD} = 40, 100, 1000\ GeV$
- $Width_{ZD} = 2\ GeV$
- $M_{fD1} = 30\ GeV$
- $M_{fD2} = 4\ GeV$
- $Width_{fD1} = 1\ GeV$
- $Width_{fD2} = 1\ GeV$

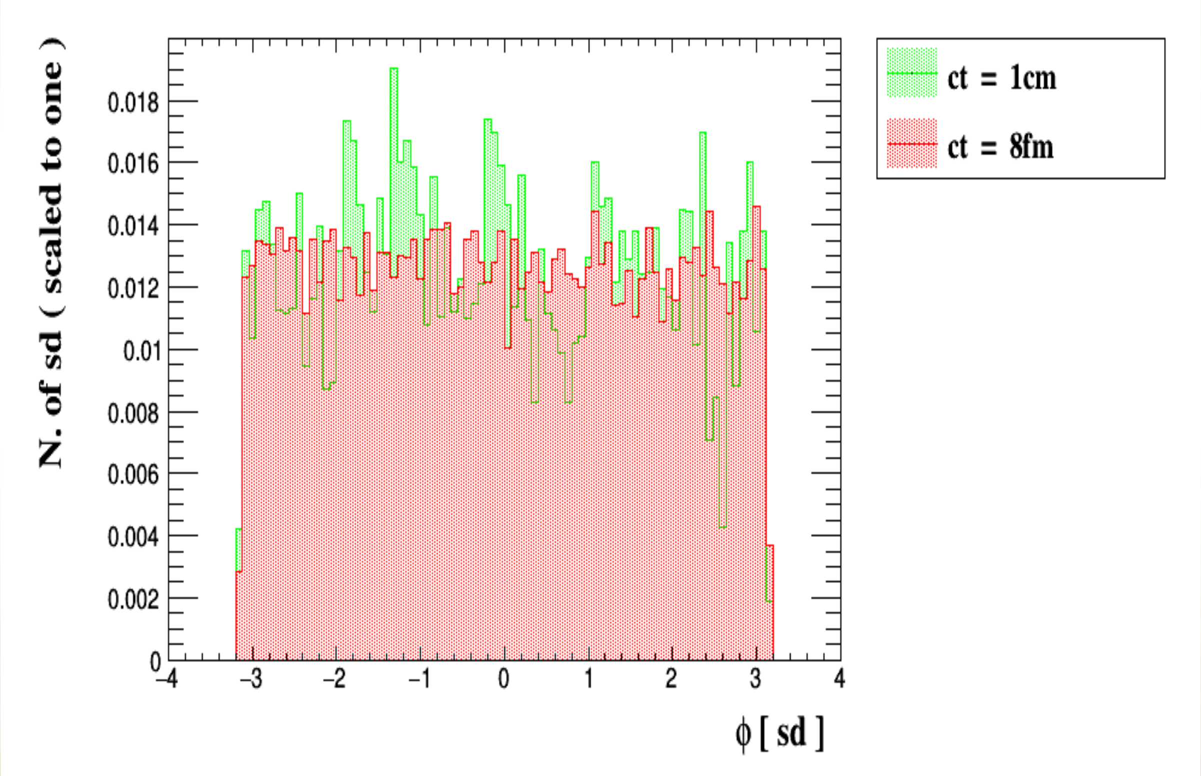
Long-lived s_D vs. Short-lived s_D

Samples with Dimuon Final States – All plots at generator level

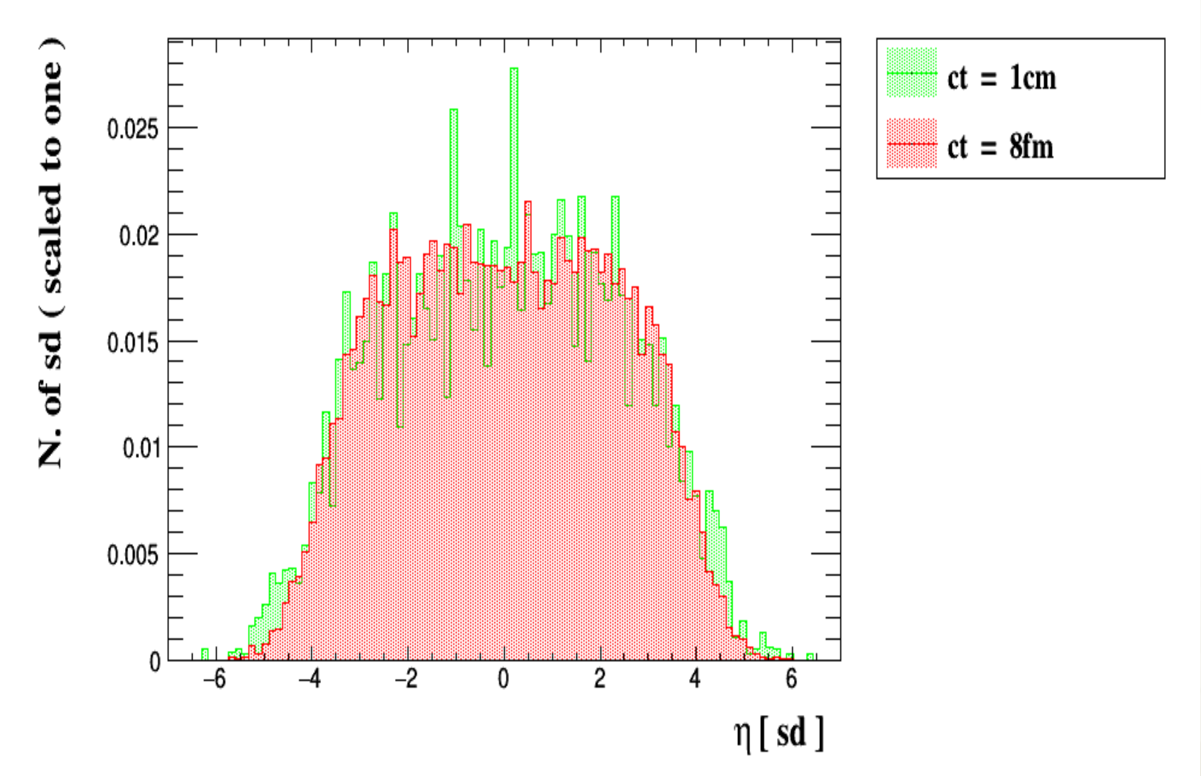
Scalar Model

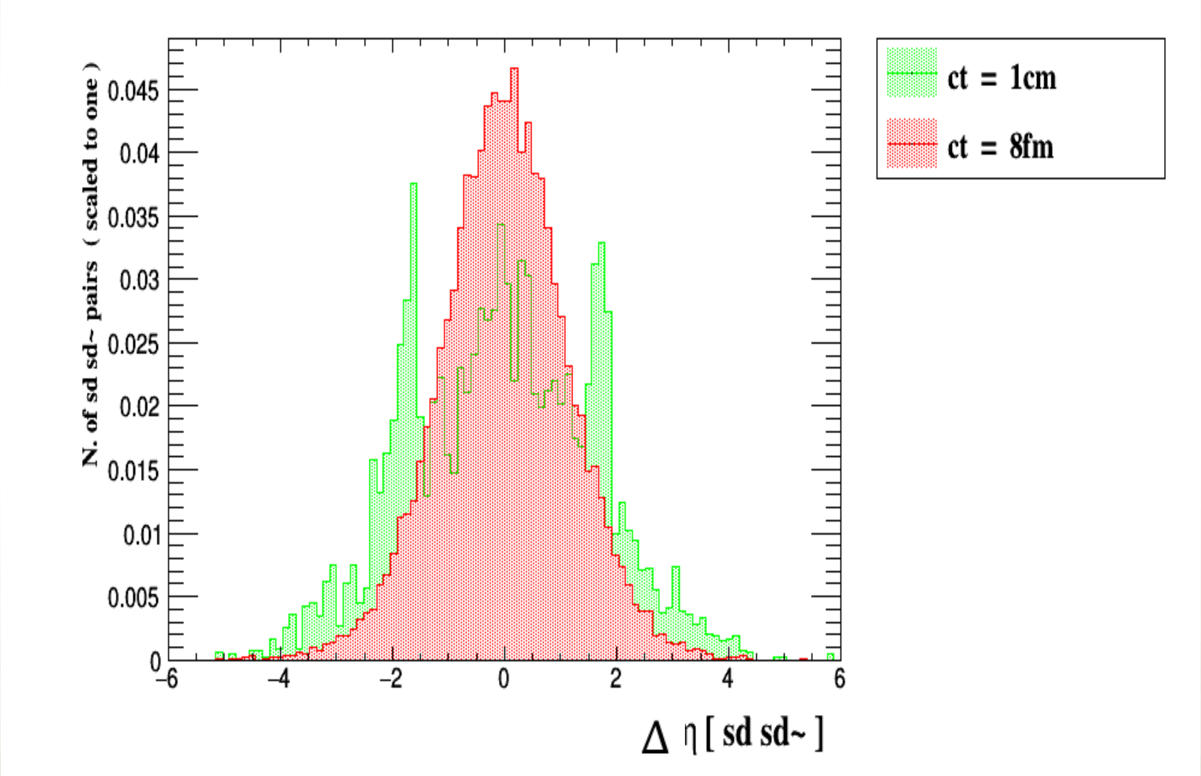
P_T & φ of s_D



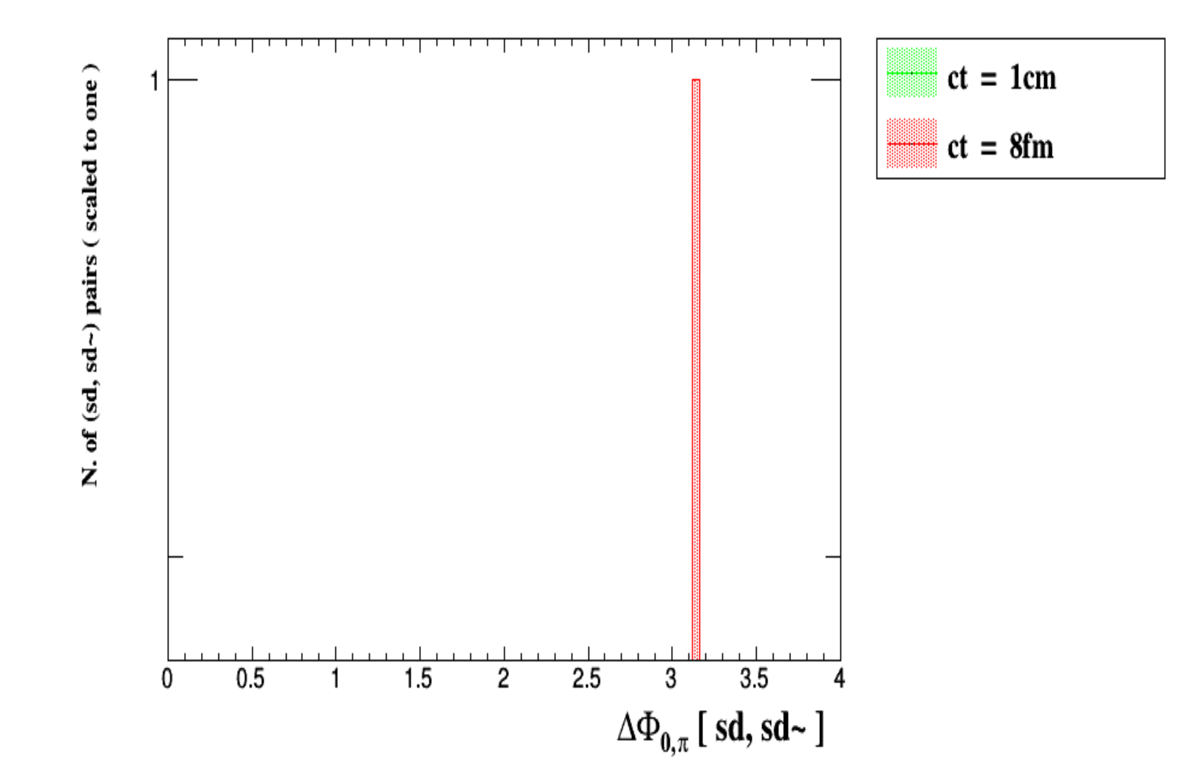


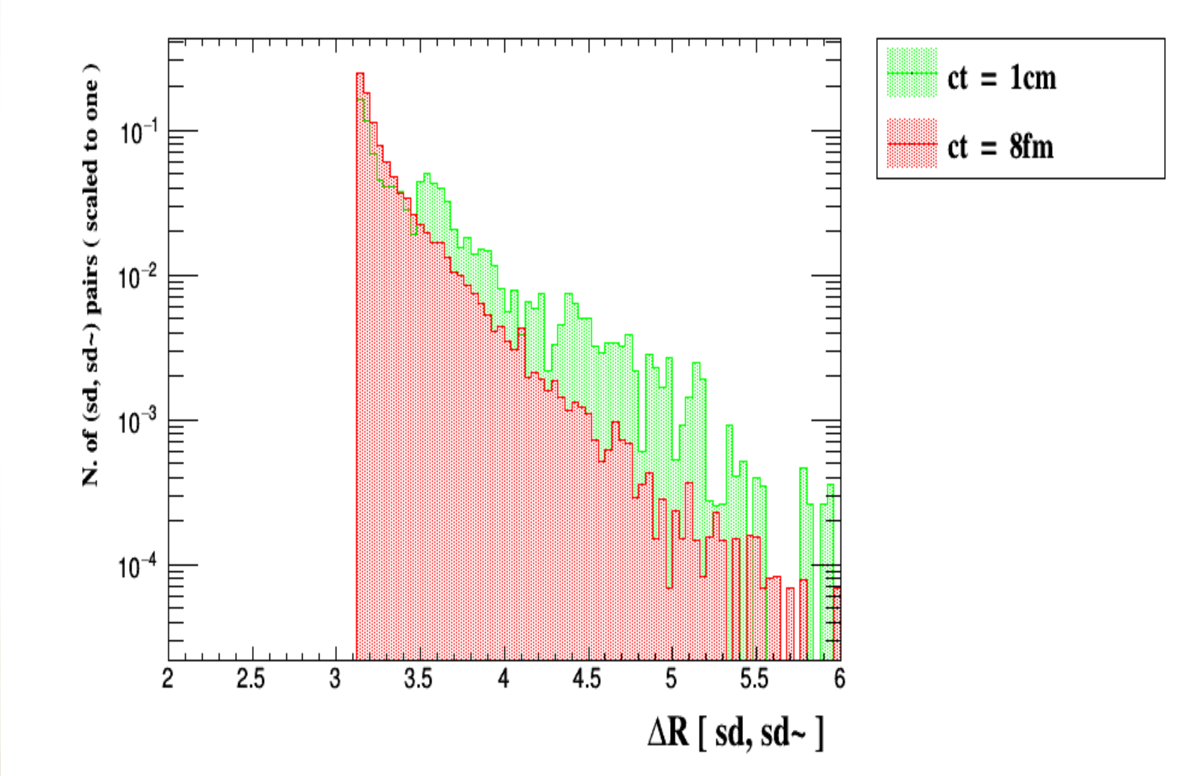
η & $\Delta\eta$ of s_D



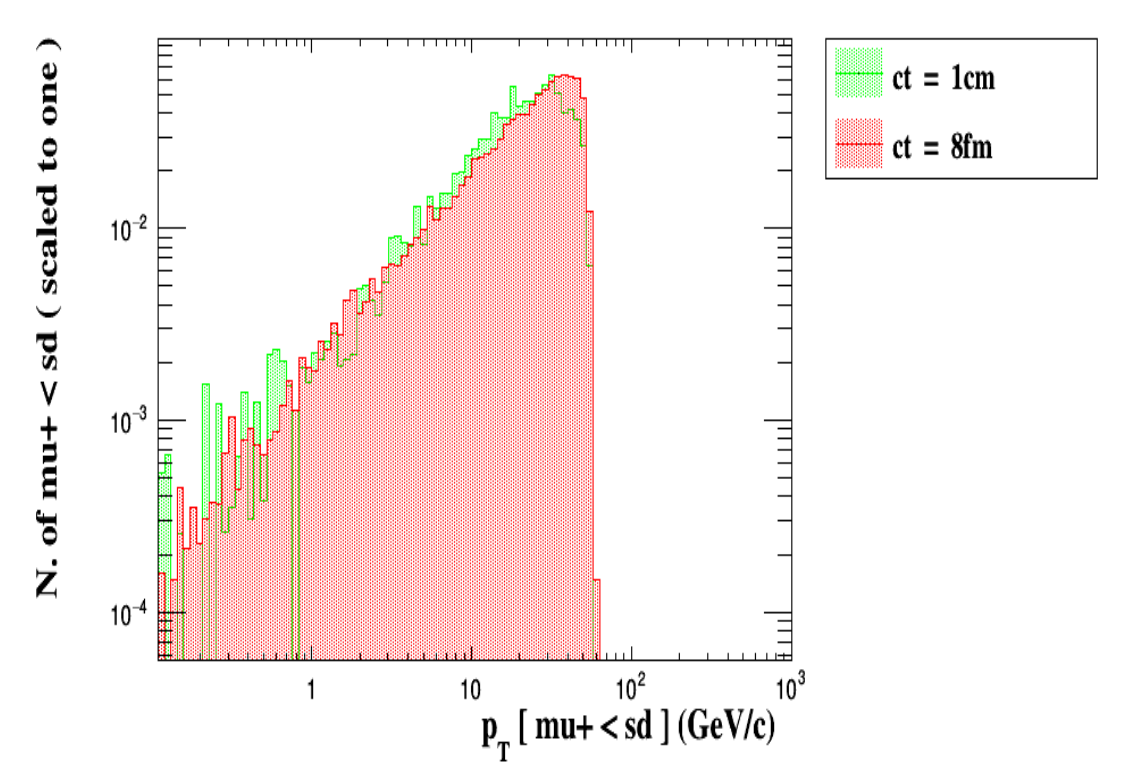


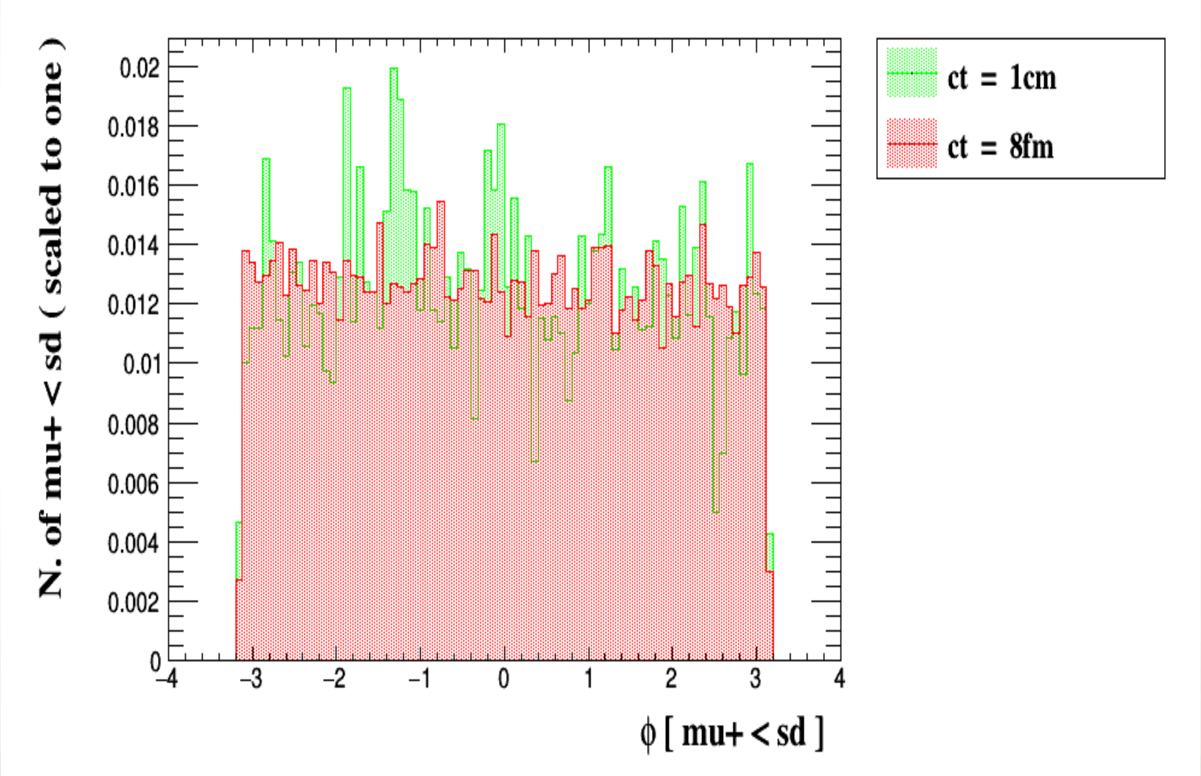
$\Delta\varphi$ & ΔR of s_D



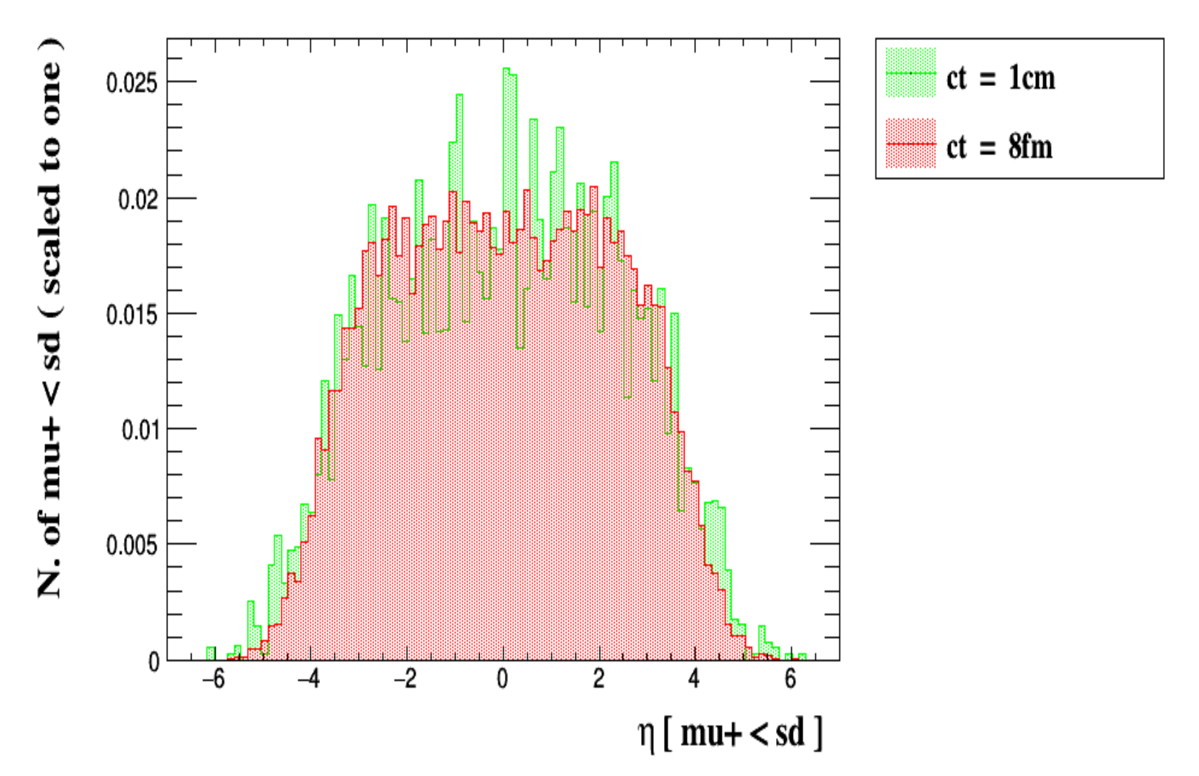


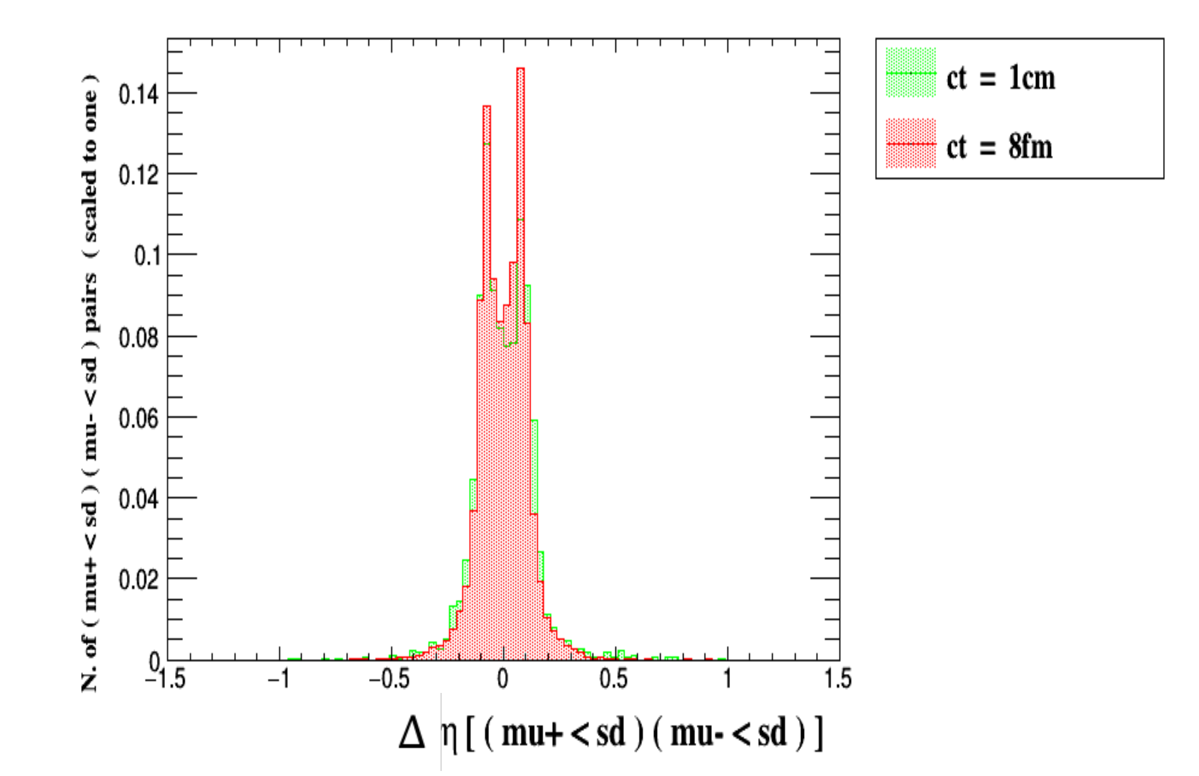
P_T & φ of μ



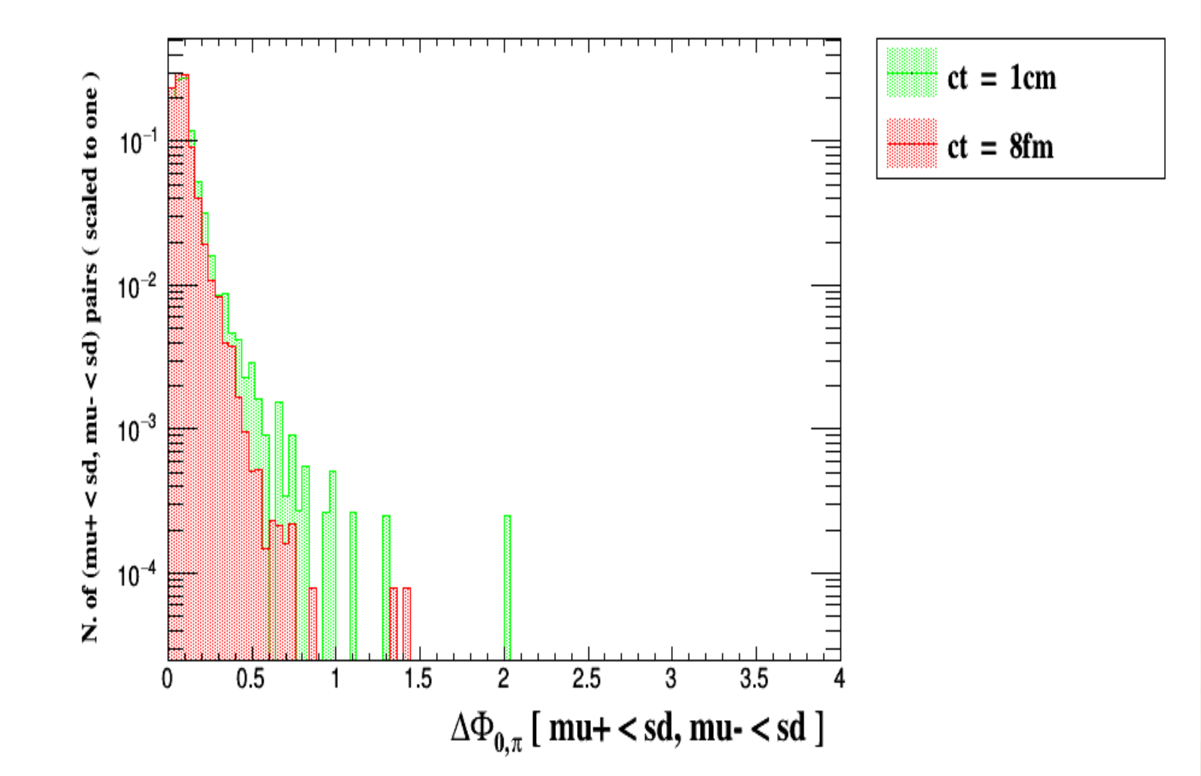


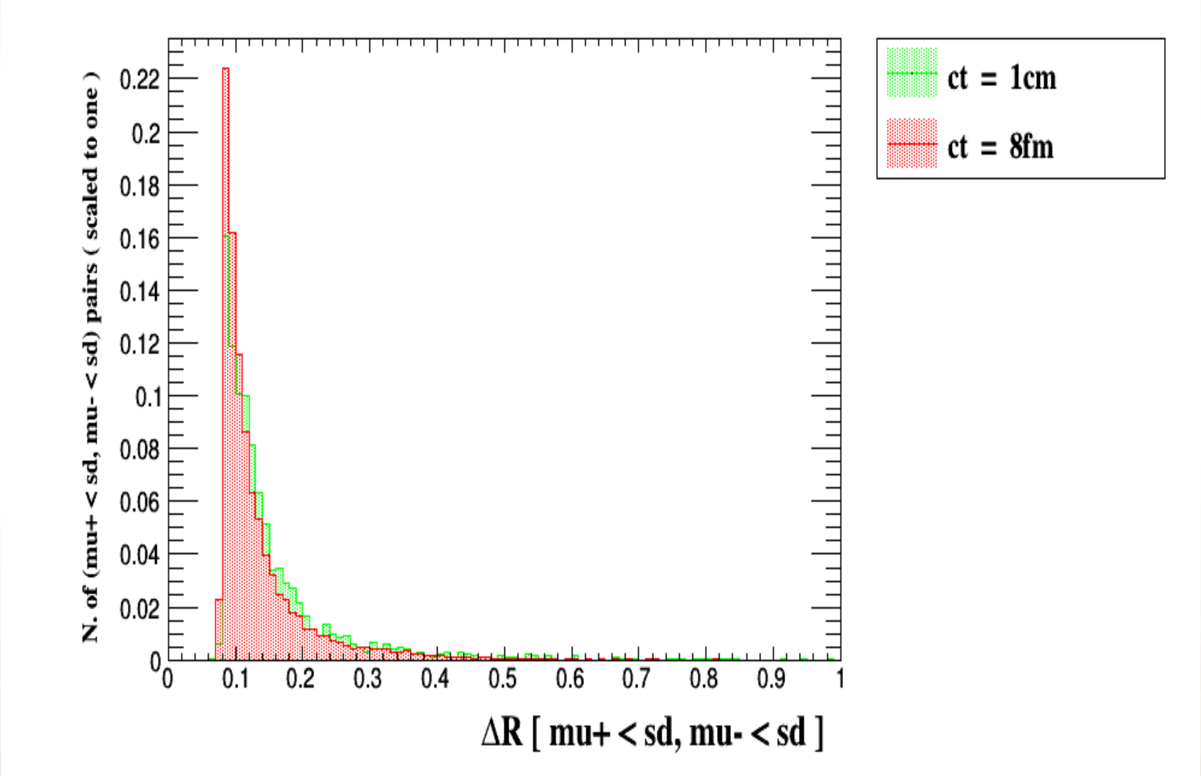
η & $\Delta\eta$ of μs



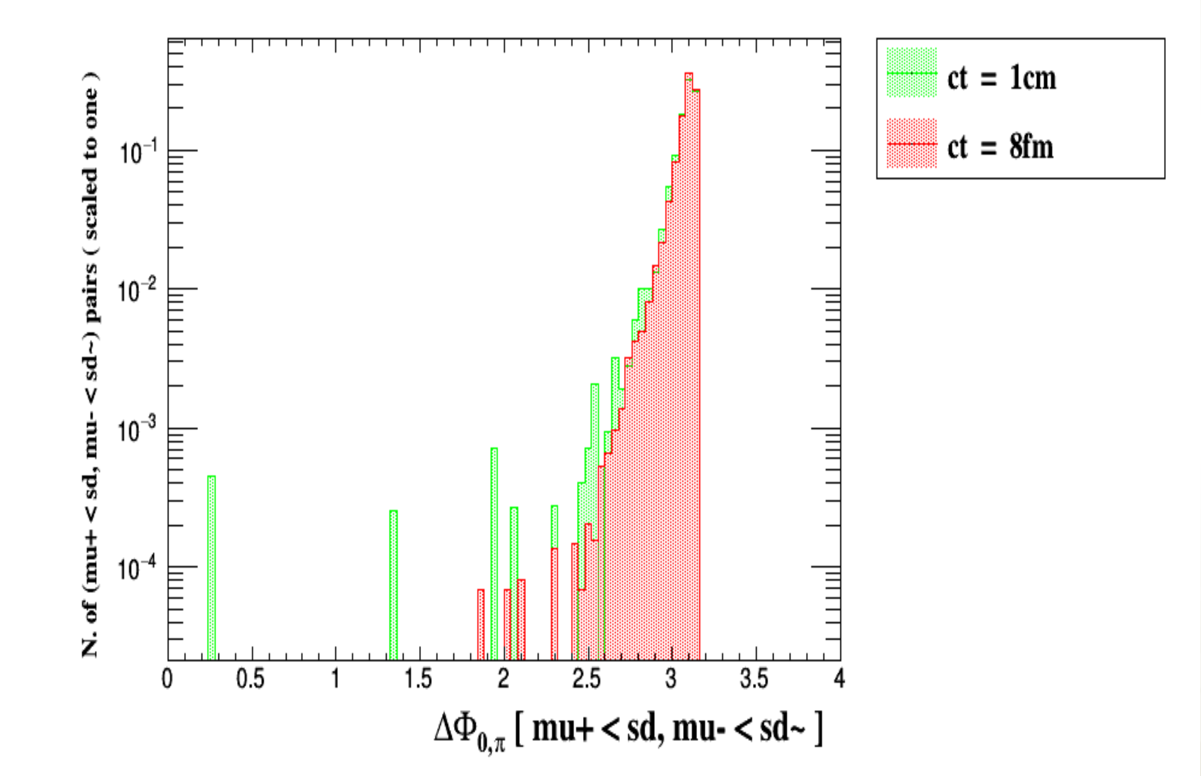


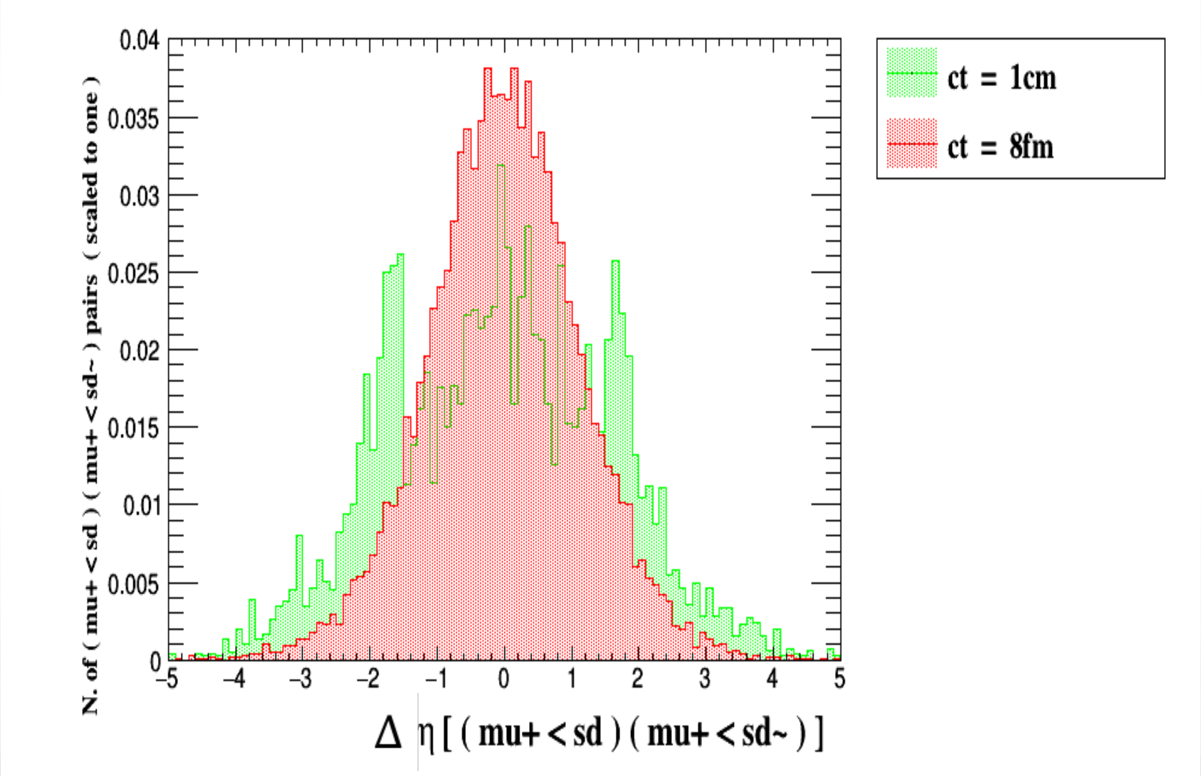
$\Delta\varphi$ & ΔR of μs



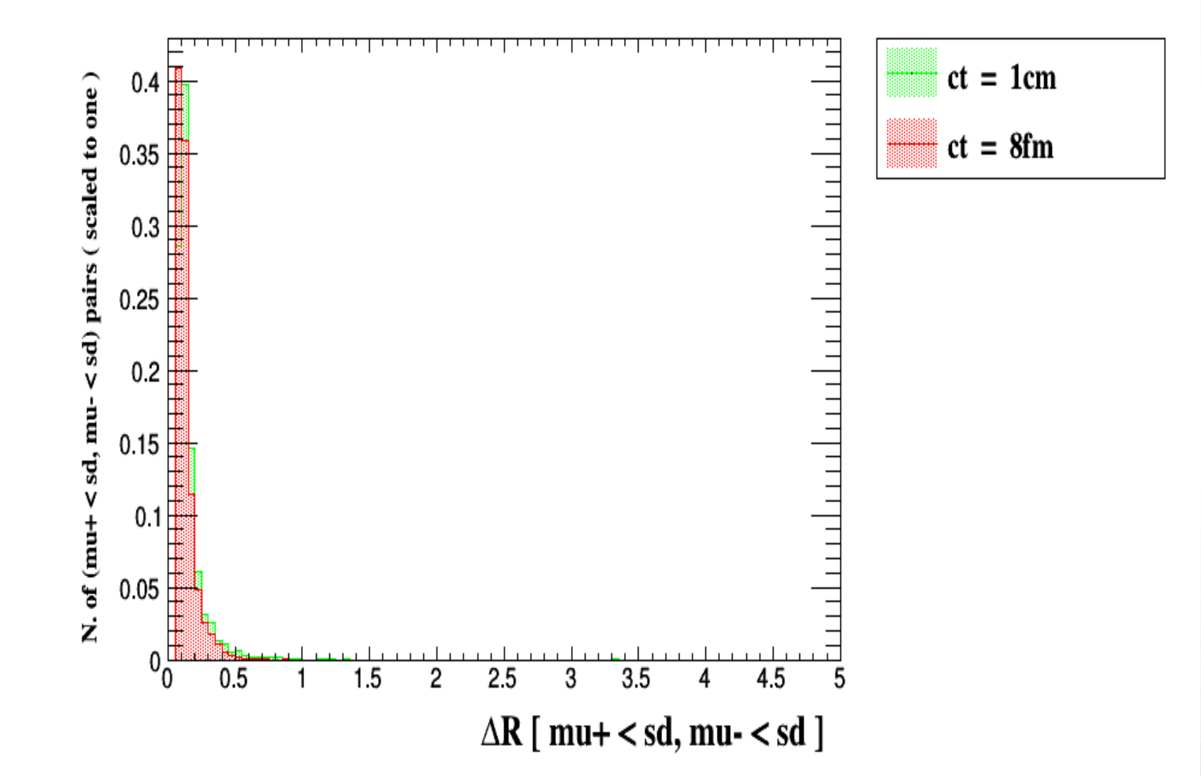


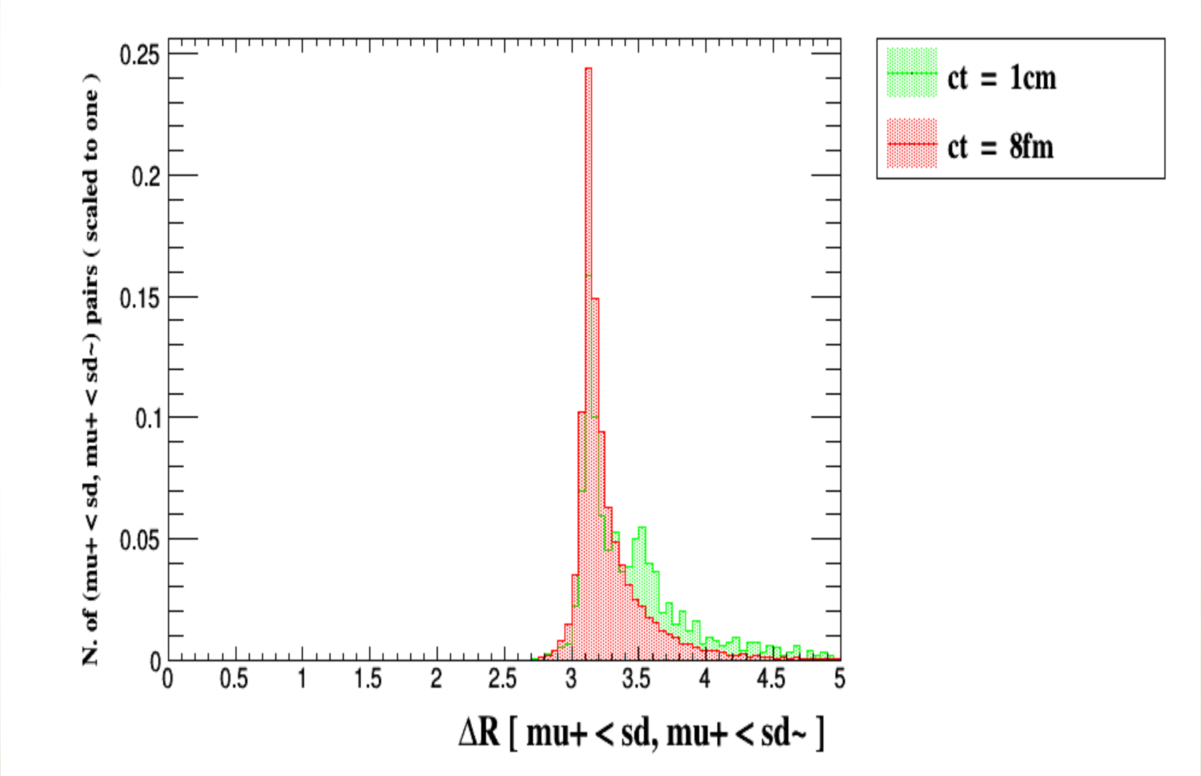
η & $\Delta\eta$ of μs



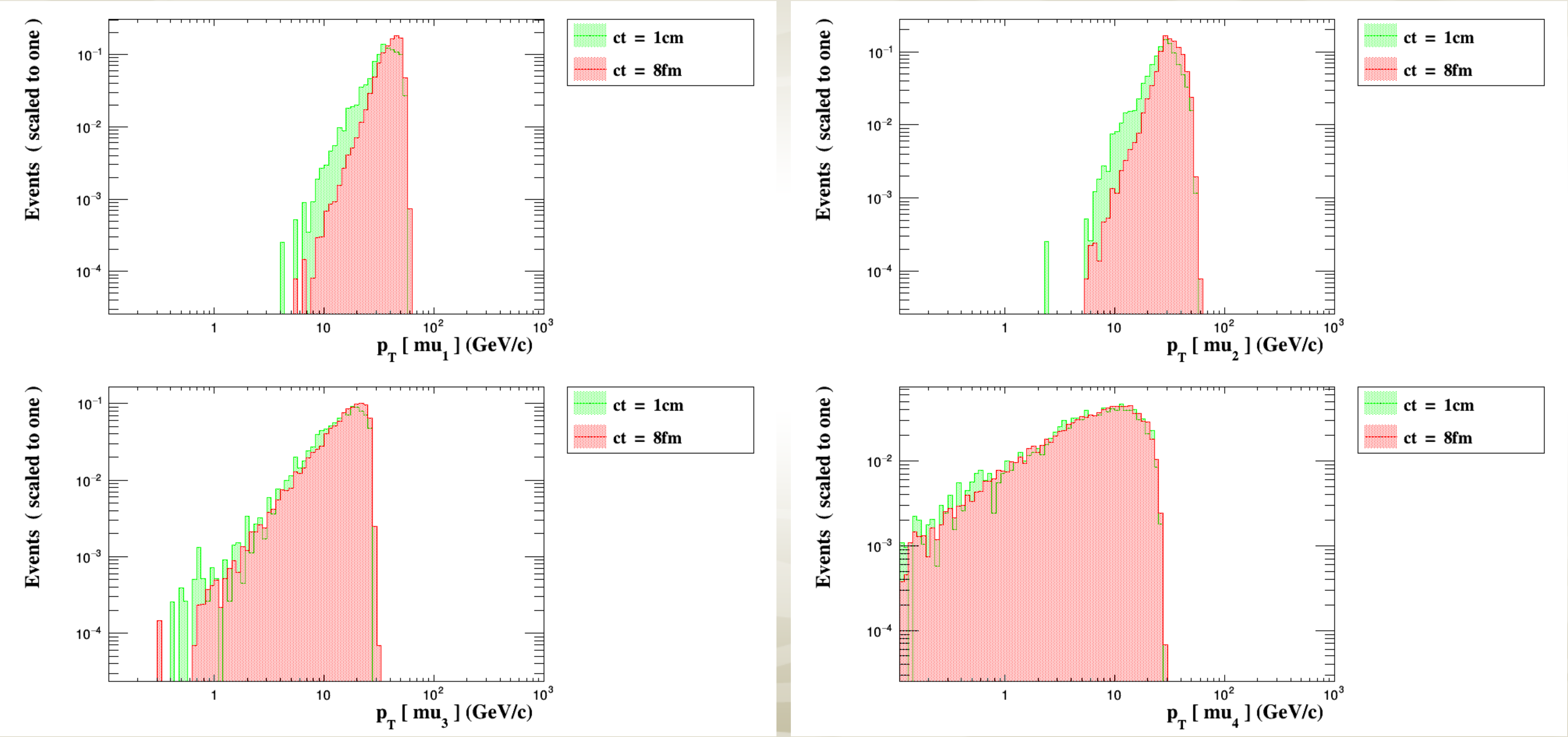


η & $\Delta\eta$ of μs (different vertices)





P_T of leading, sub-leading 3^{rd} and 4^{th} μs



Methodology – Feynrules

- A Mathematica package that allows the calculation of Feynman rules in momentum space for *any* QFT physics model.
- We provide FeynRules with the minimal information required to describe the our model, contained in the so-called model-file.
- This information is then used to calculate the set of Feynman rules associated with the Lagrangian.
- The Feynman rules calculated by the code can then be used to implement the new physics model into MadGraph.
- Implementation of our model with Feynrules is based *simplified dark Matter* model:
  - https://arxiv.org/pdf/1508.00564.pdf

Methodology – MadGraph

- MadGraph is a framework that aims at providing all the elements necessary for SM and BSM phenomenology.
- Computations of cross sections, the generation of hard events .
- Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes.
- Matrix elements at the tree- and one-loop-level can also be obtained.
- We use MadGraph to privately generate events for our models with different particle masses and life times.

Methodology – MadAnalysis

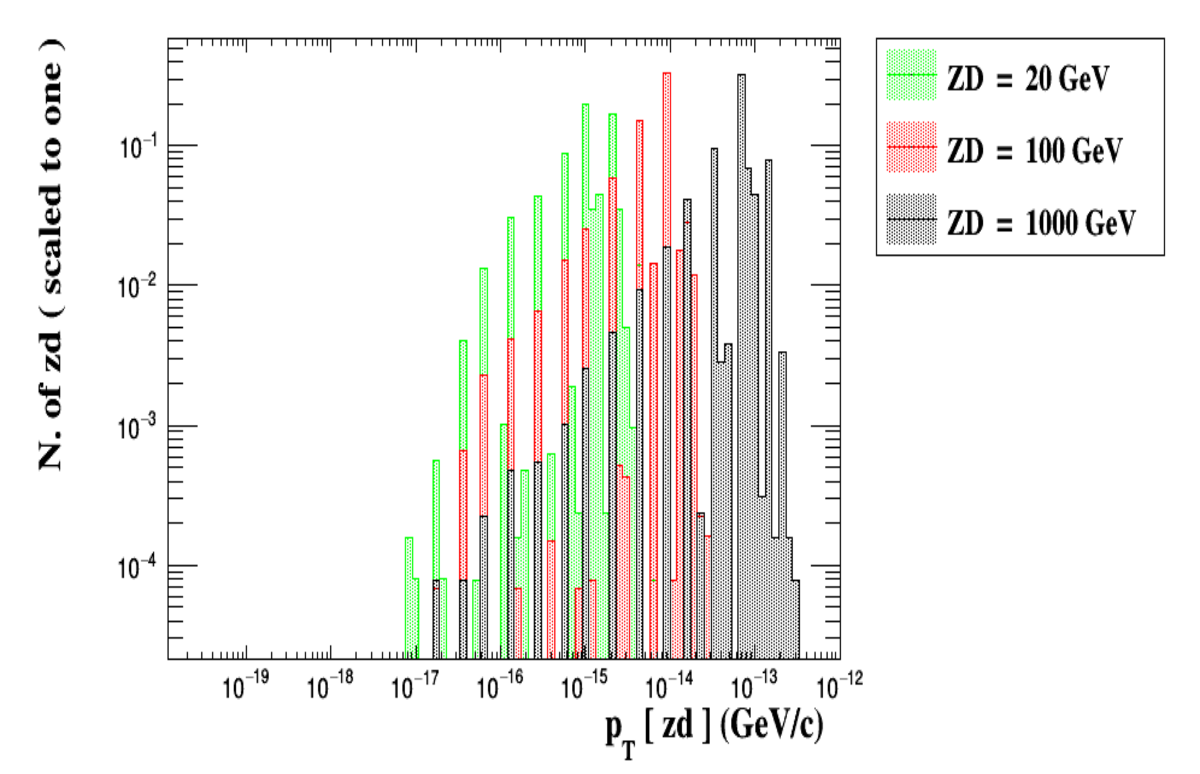
- MadAnalysis is a framework for phenomenological investigations at particle colliders.
- Based on a C++ kernel, this program allows to efficiently perform, in a straightforward and user-friendly fashion, sophisticated physics analyses of event files such as those generated a large class of Monte Carlo event generators.
- We are using MadAnalysis to analyze our and produce plots for our parton level events.

Lots more kinematics and topology plots

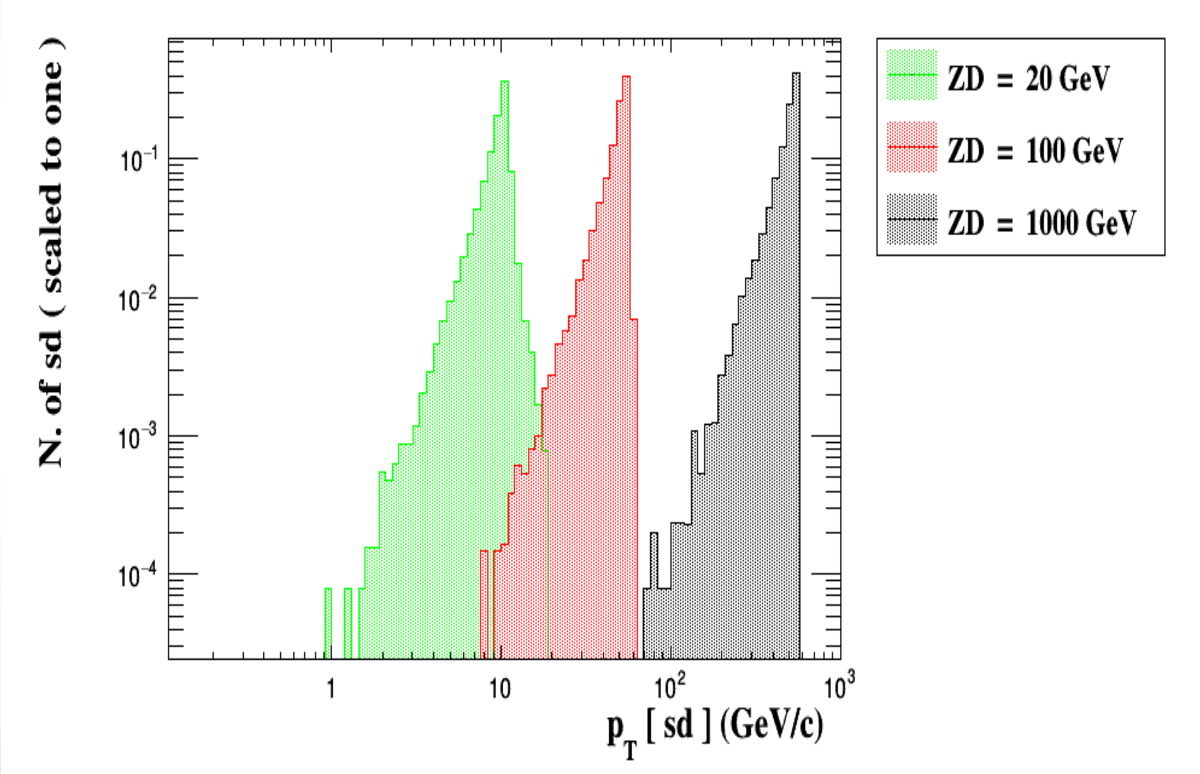
Samples with Dimuon Final States – All plots at generator level

Scalar

P_T plots

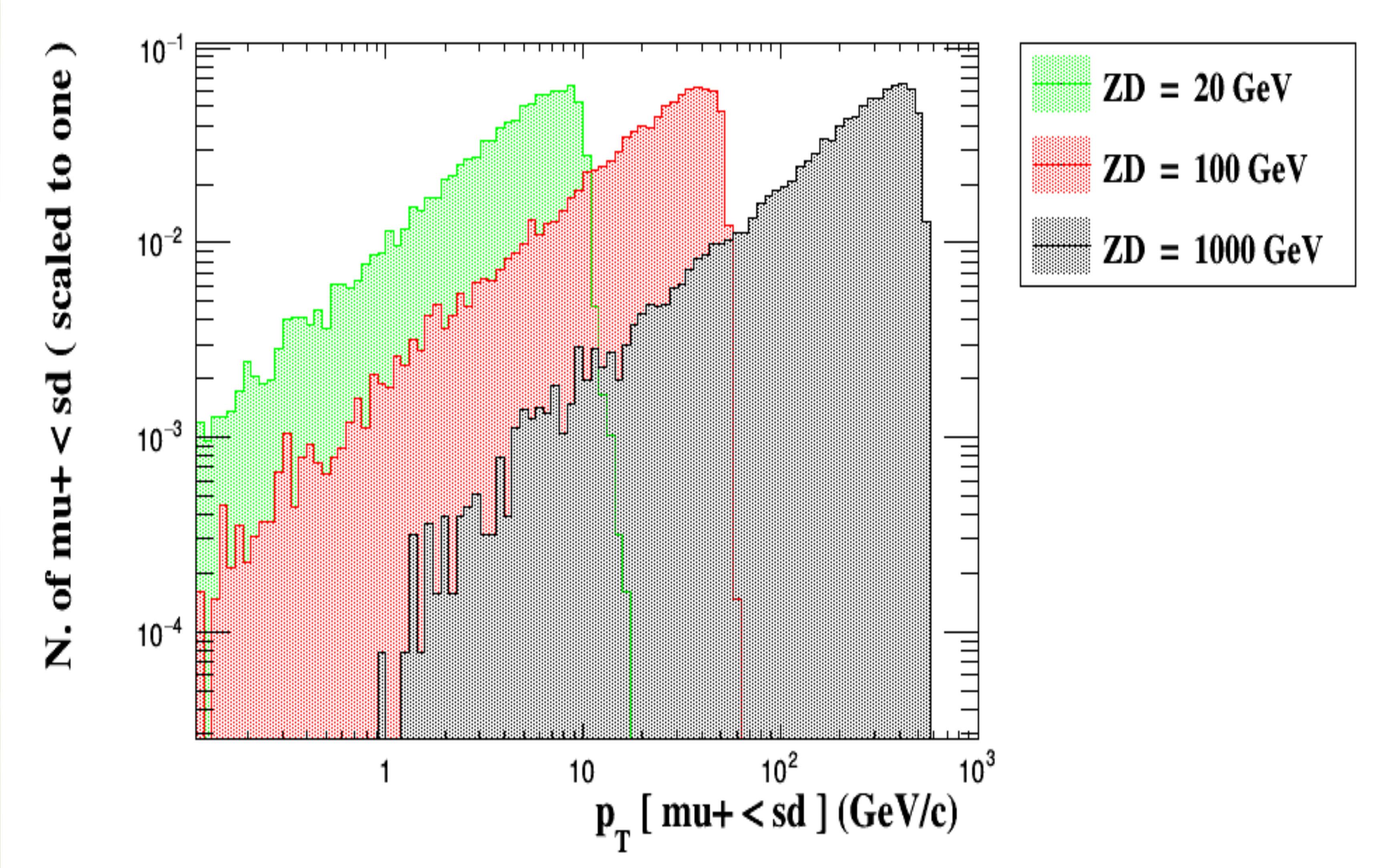


N. of zd (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12}
p_T [zd] (GeV/c)
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV



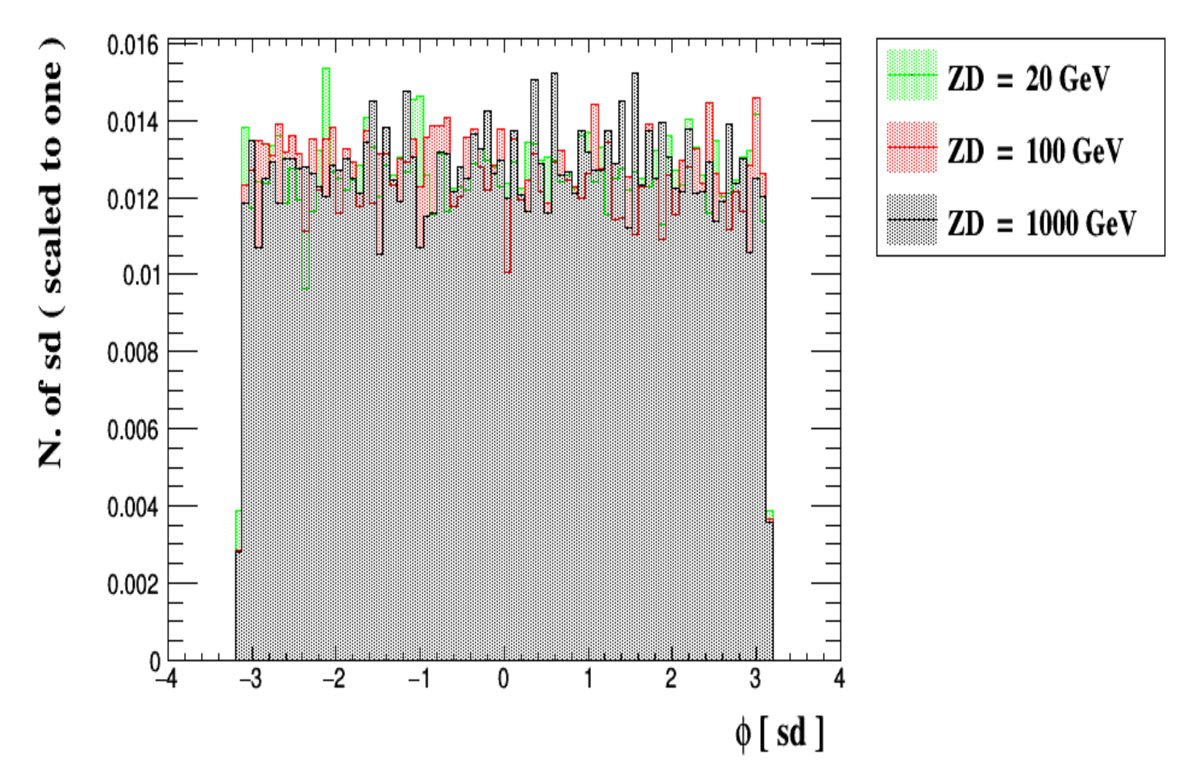
N. of sd (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1 10 10^2 10^3
p_T [sd] (GeV/c)
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV

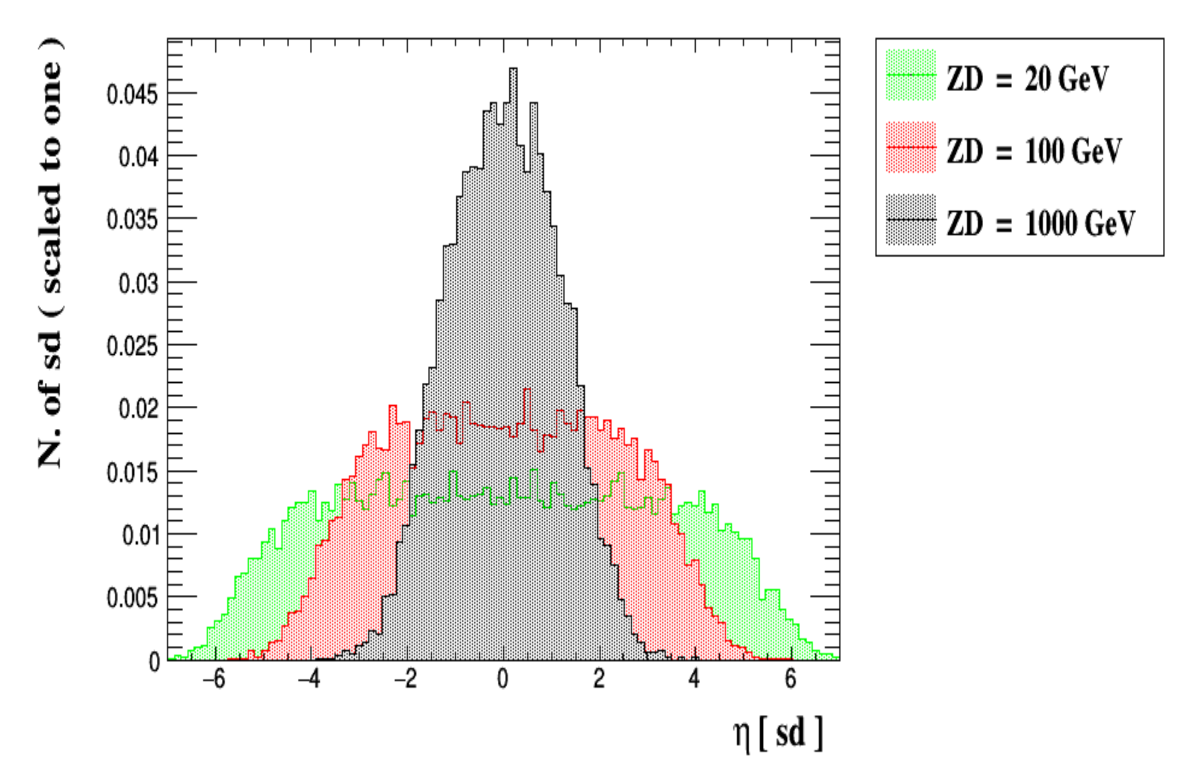
P_T of Muons



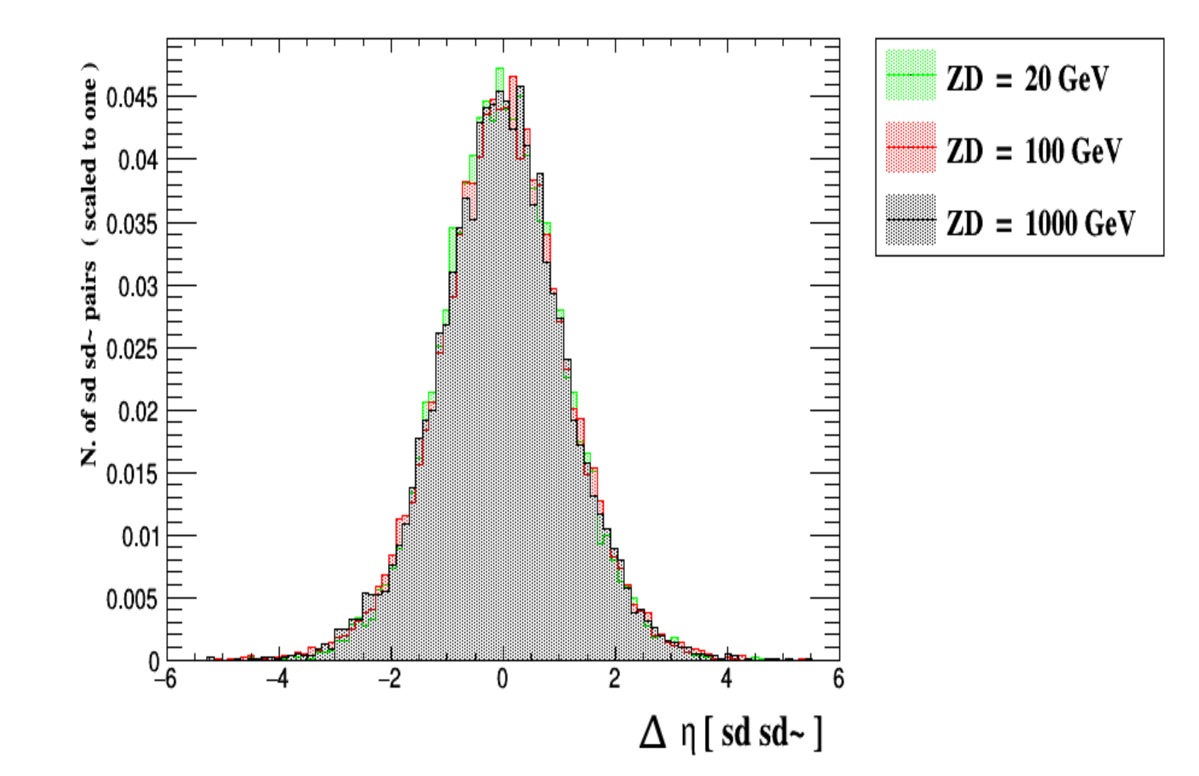
N. of mu+ < sd (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
p_T [mu+ < sd] (GeV/c)
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV

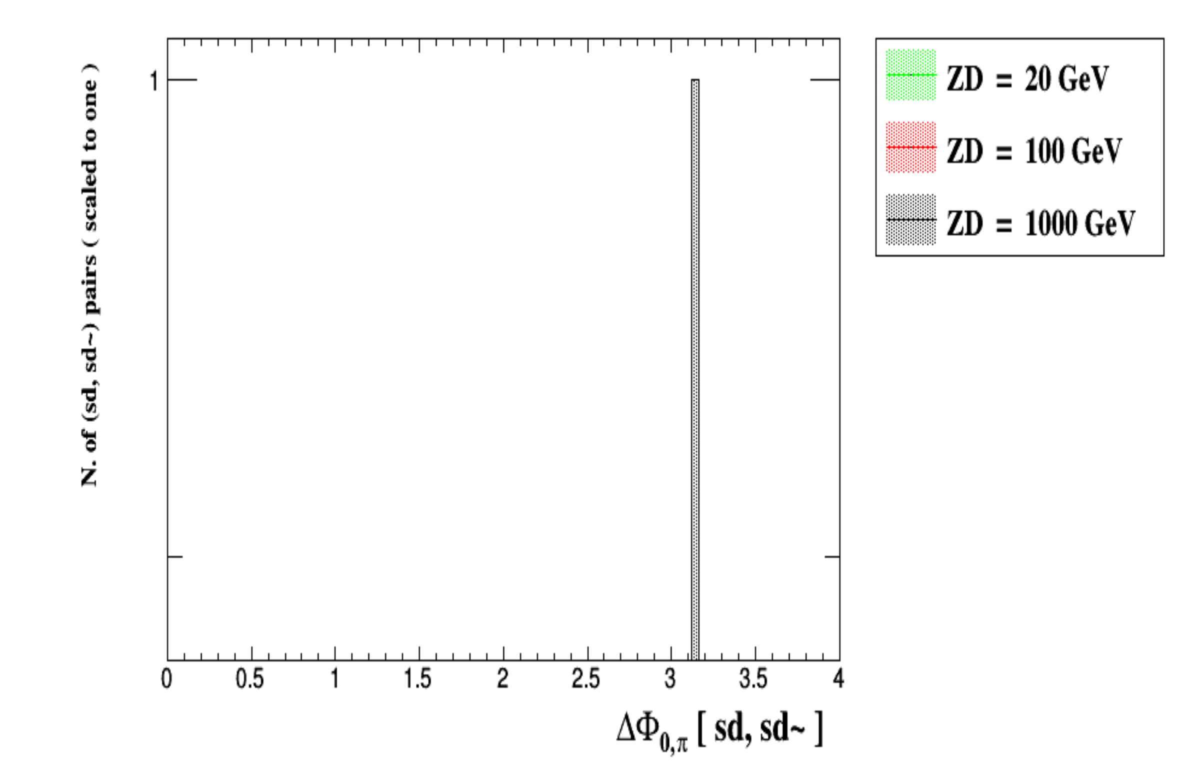
φ & η of s_D

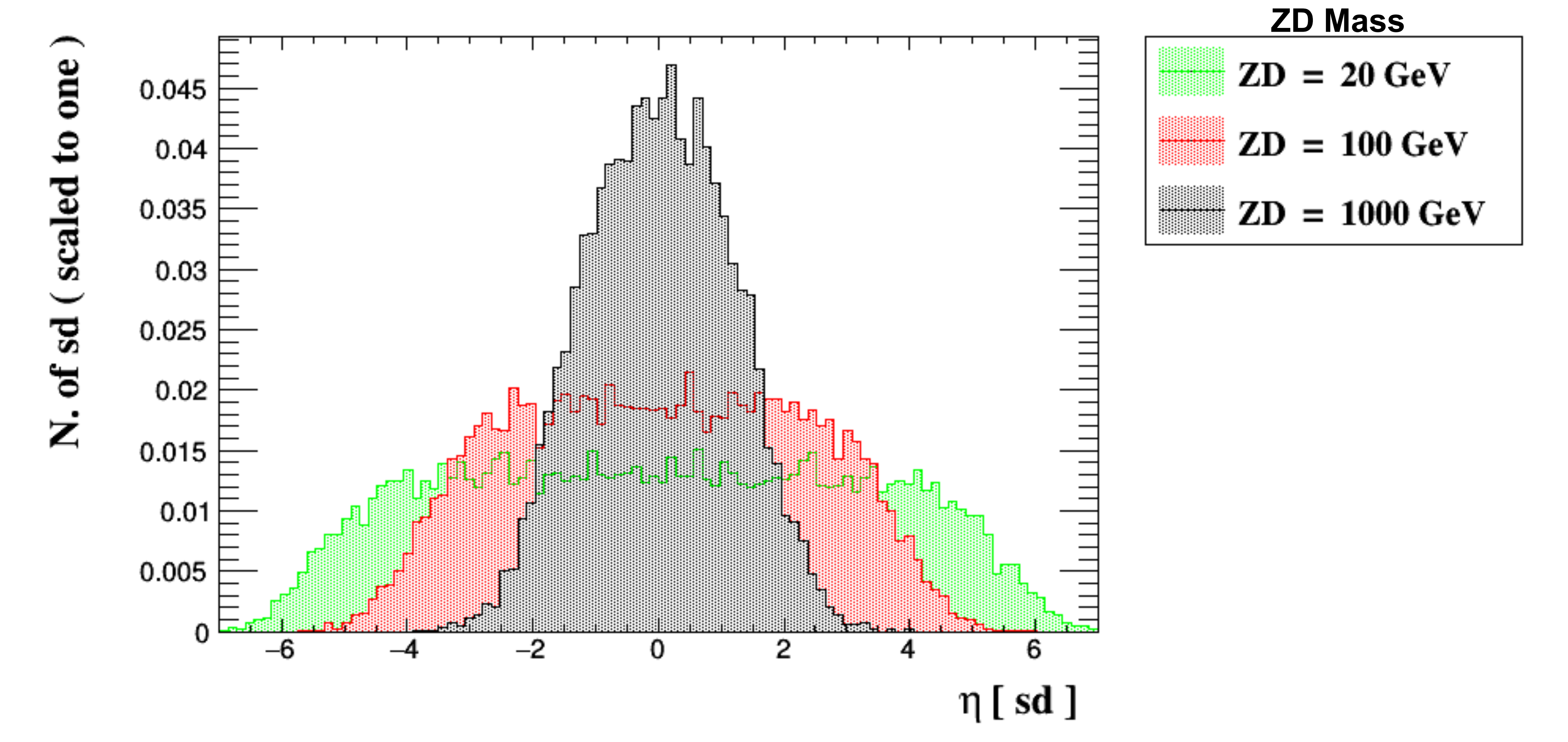


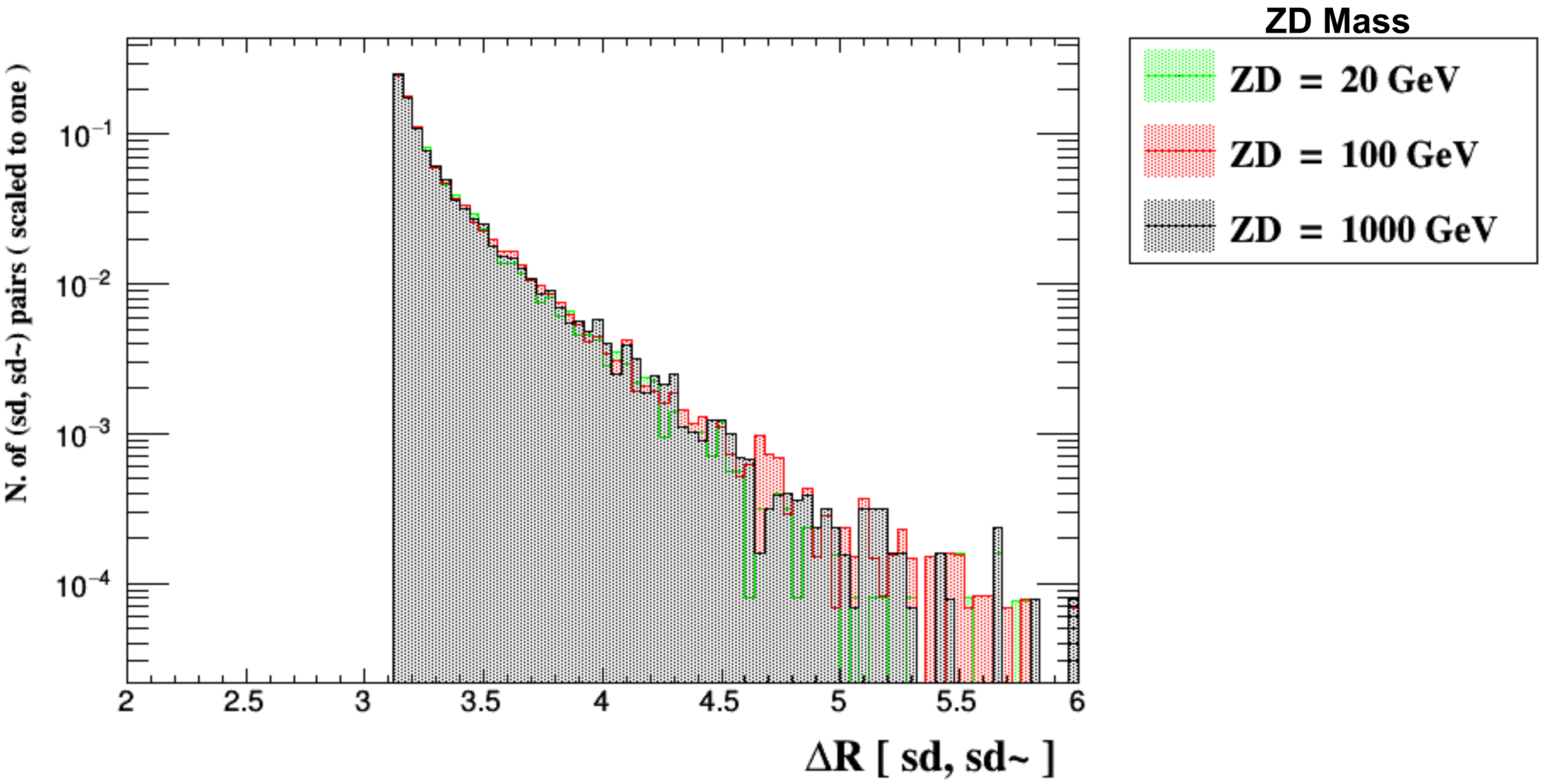


$\Delta\varphi$ & $\Delta\eta$ of the $s_D\ \overline{s_D}$

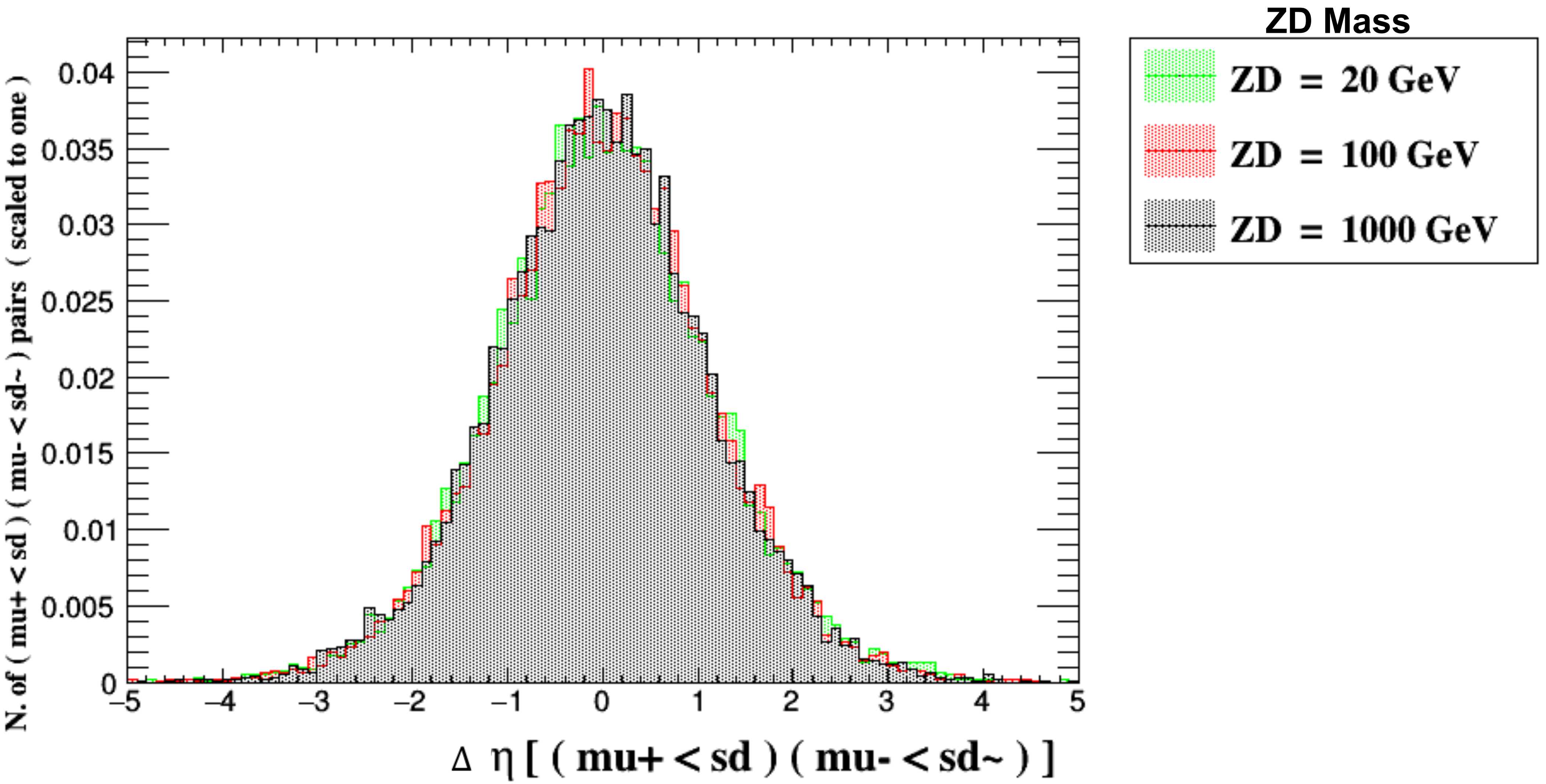


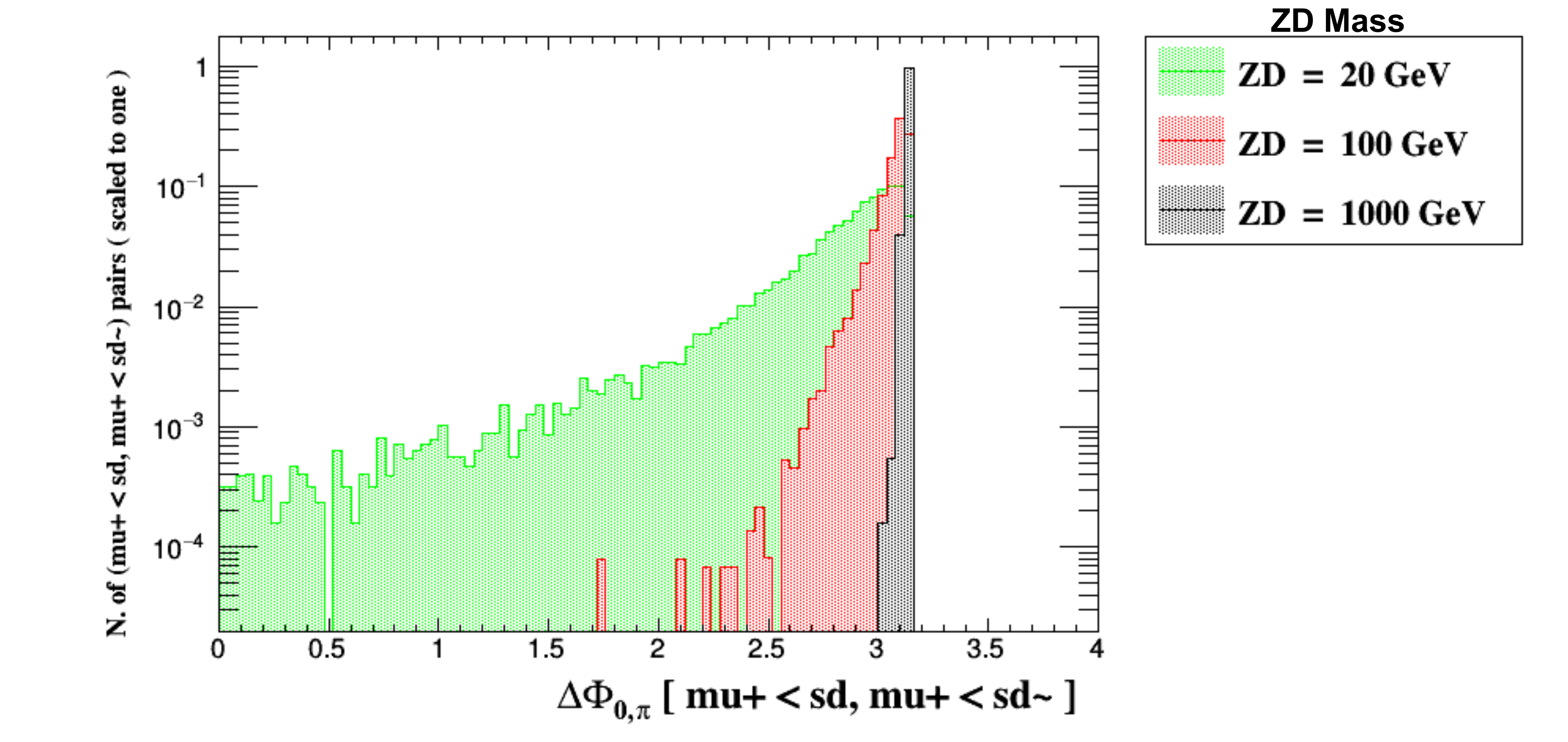


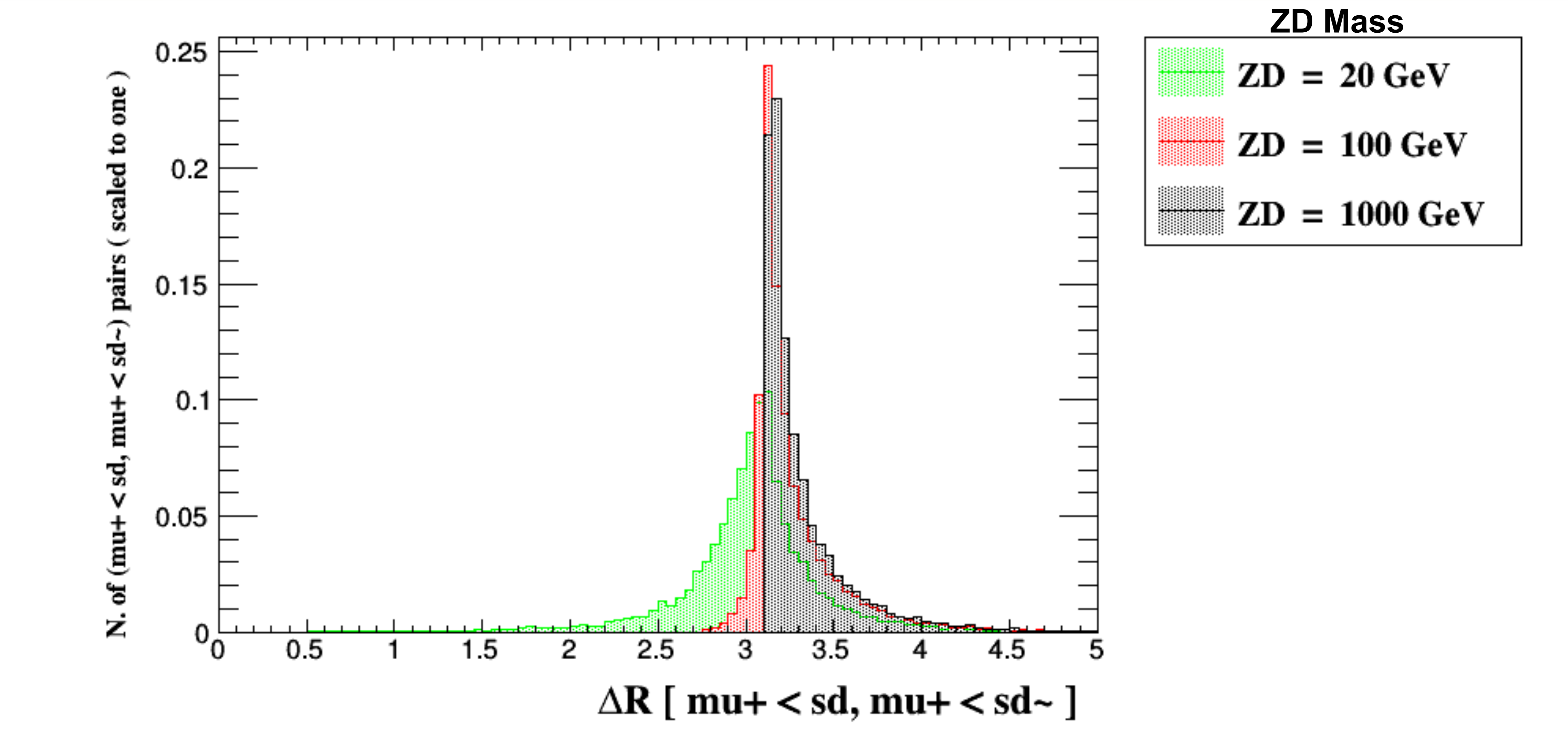

N. of sd (scaled to one)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−6
−4
−2
0
2
4
6
η [sd]
ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV

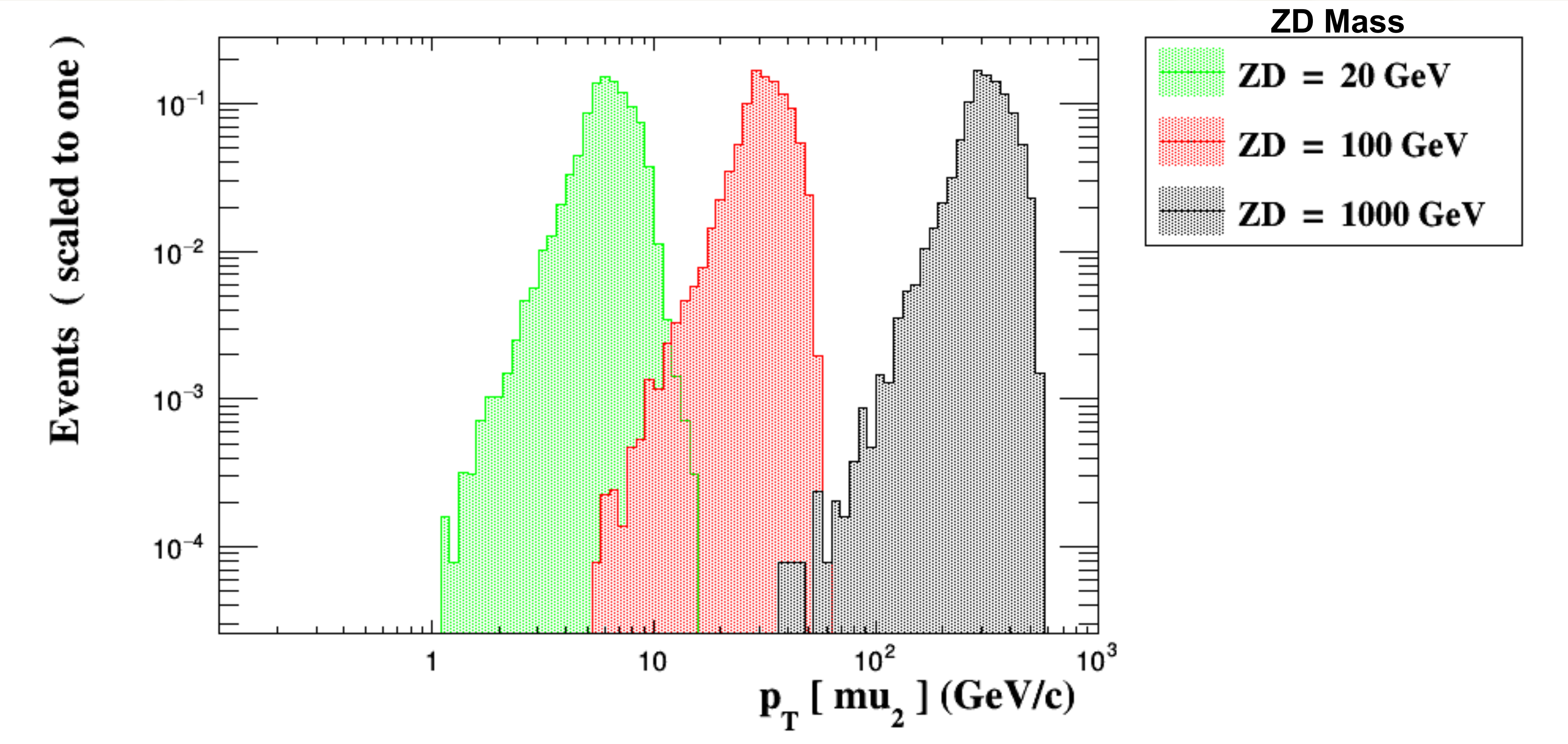


ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
N. of (sd, sd~) pairs (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2
2.5
3
3.5
4
4.5
5
5.5
6
ΔR [sd, sd~]

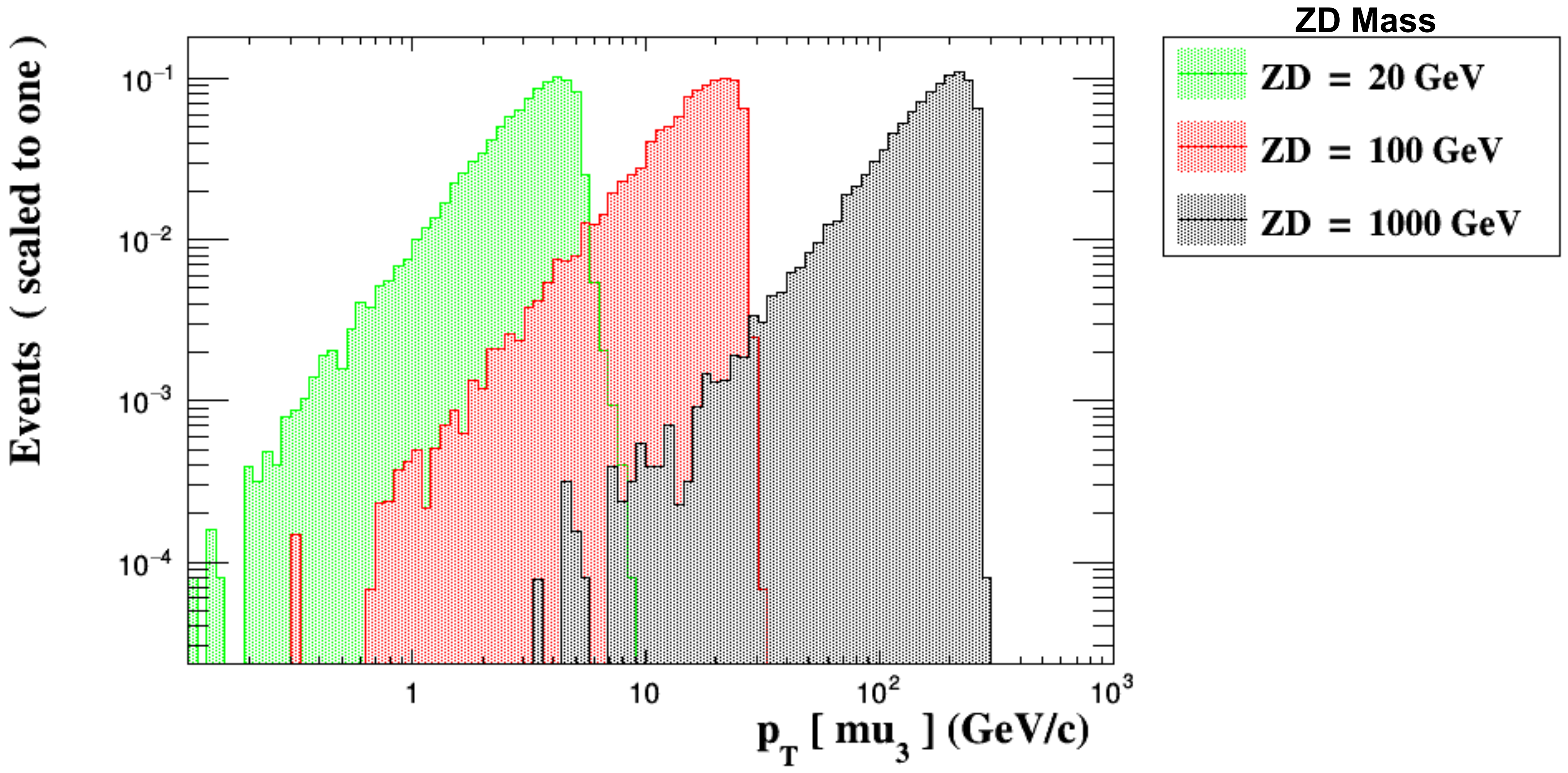

ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
N. of (mu+ < sd) (mu- < sd~) pairs (scaled to one)
Δ η [(mu+ < sd) (mu- < sd~)]
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−5
−4
−3
−2
−1
0
1
2
3
4
5


ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
N. of (mu+ < sd, mu+ < sd~) pairs (scaled to one)
ΔΦ0,π [mu+ < sd, mu+ < sd~]
1
10−1
10−2
10−3
10−4
0
0.5
1
1.5
2
2.5
3
3.5
4

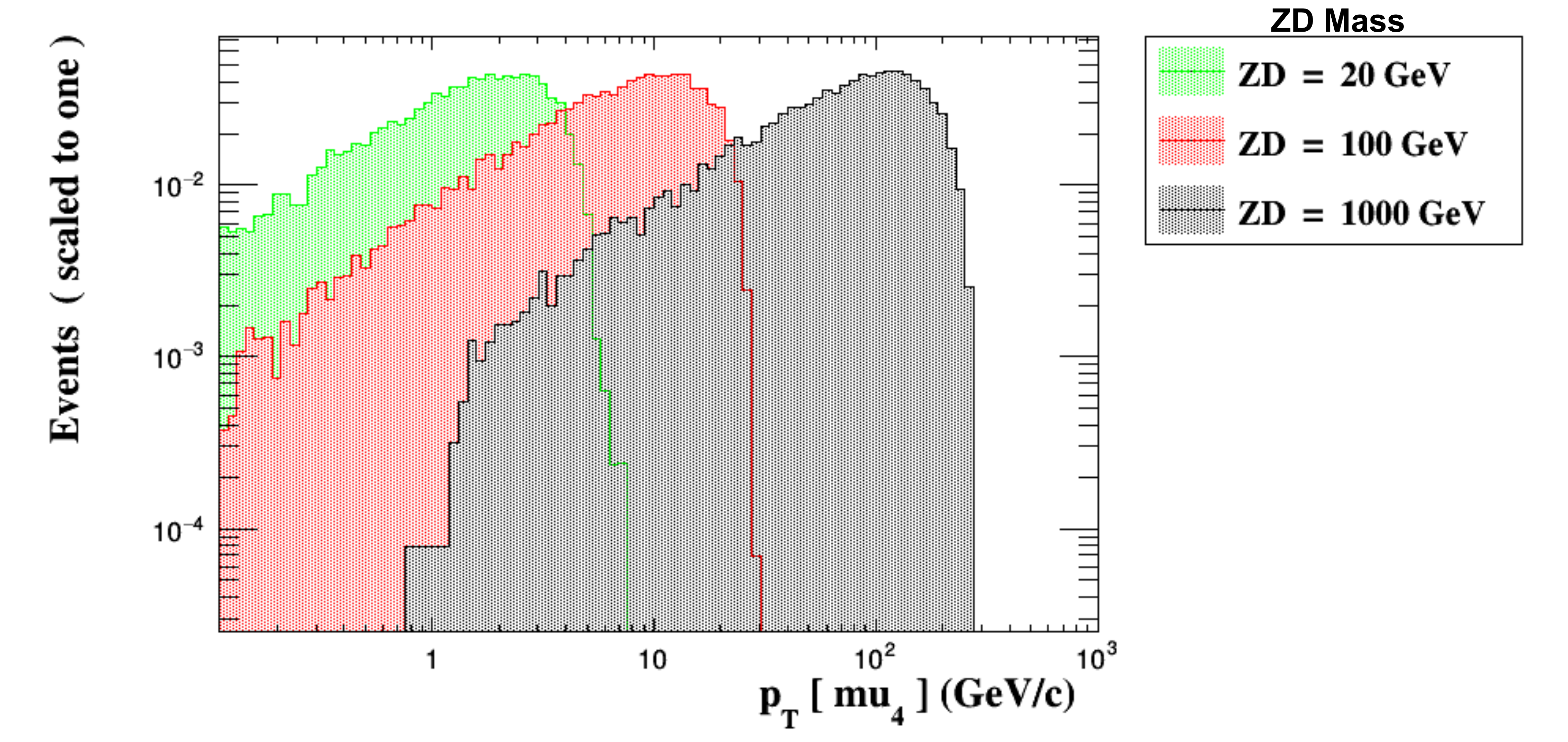

ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
N. of (mu+ < sd, mu+ < sd~) pairs (scaled to one)
ΔR [mu+ < sd, mu+ < sd~]
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Events (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
p_T [mu_2] (GeV/c)
ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV



ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
Events (scaled to one)
p_T [mu_3] (GeV/c)
10^-1
10^-2
10^-3
10^-4
1
10
10^2
10^3



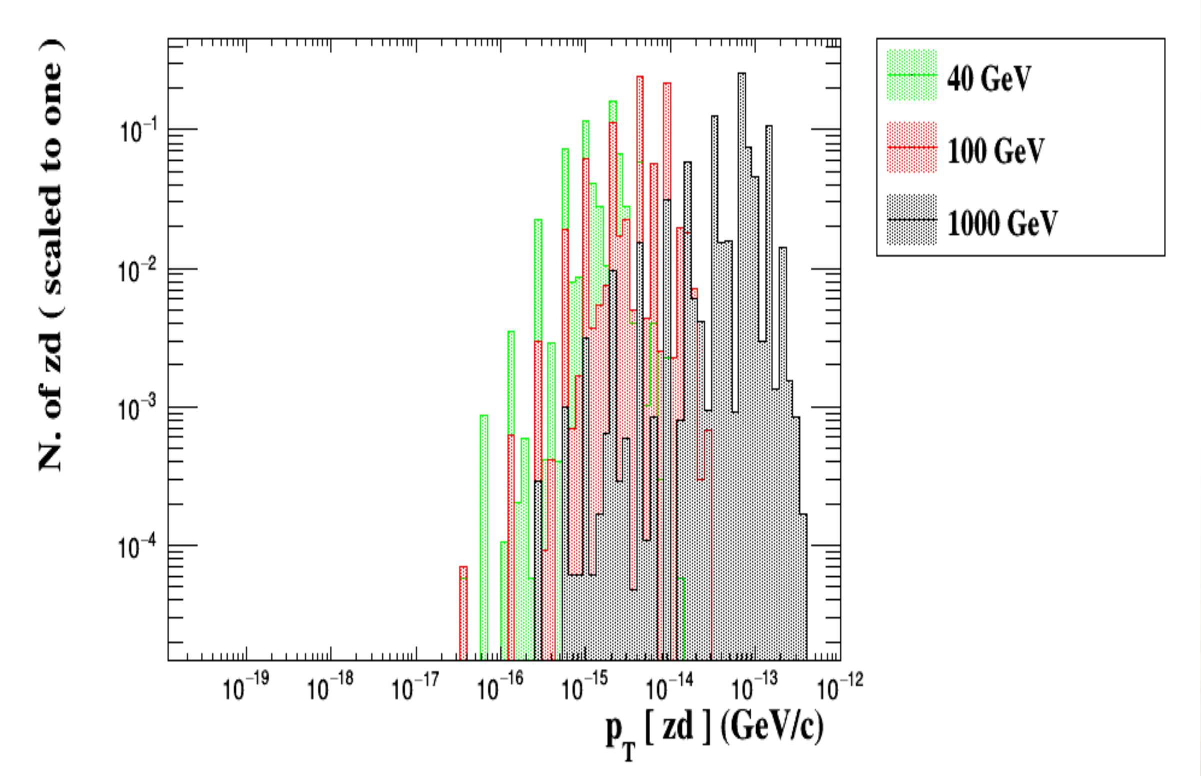
ZD Mass
ZD = 20 GeV
ZD = 100 GeV
ZD = 1000 GeV
Events (scaled to one)
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
p_T [mu_4] (GeV/c)

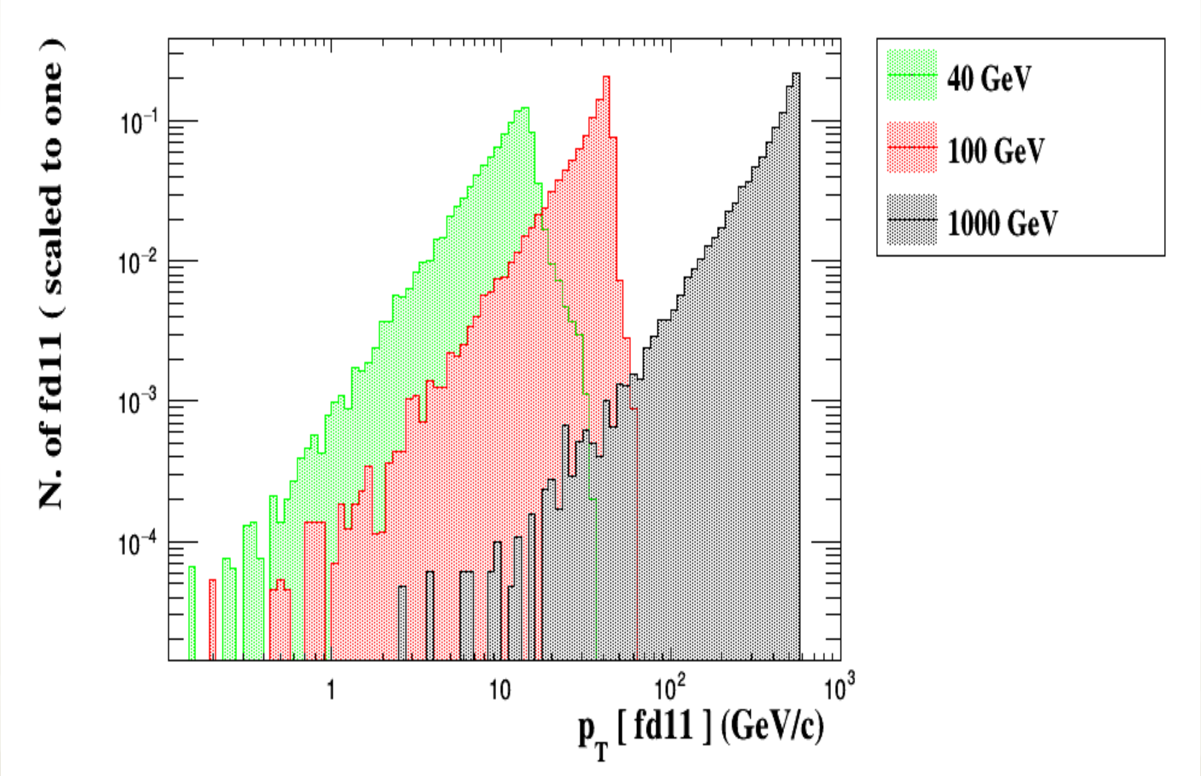
Lots more kinematics and topology plots

Samples with Dimuon Final States – All plots at generator level

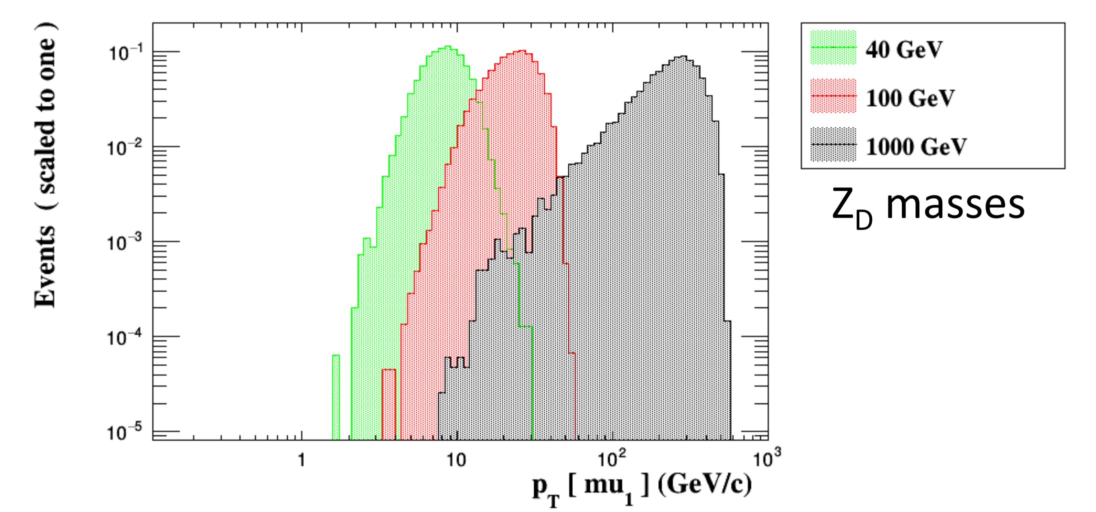
Fermionic

P_T Plots

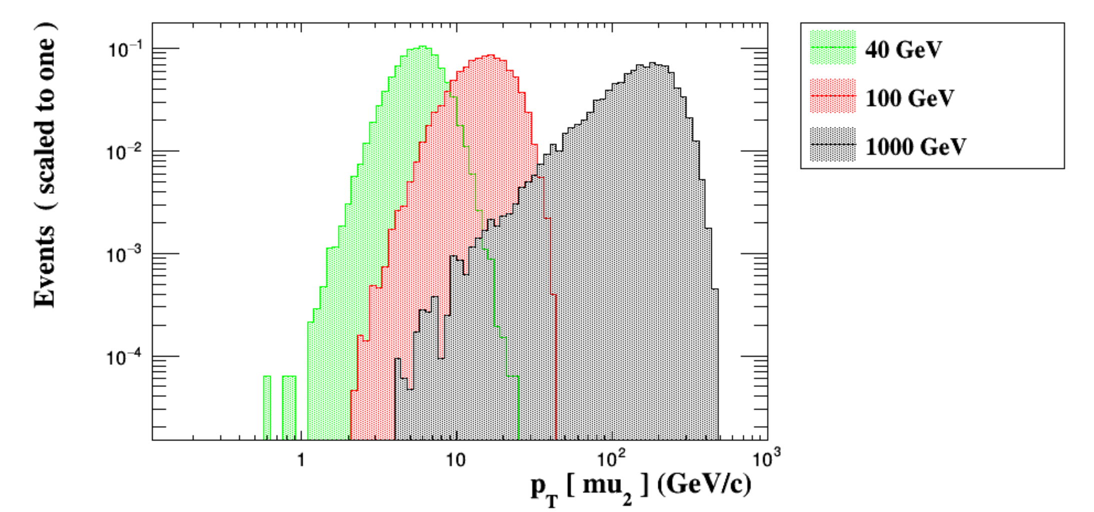

N. of zd (scaled to one)
40 GeV
100 GeV
1000 GeV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12}
p_T [zd] (GeV/c)

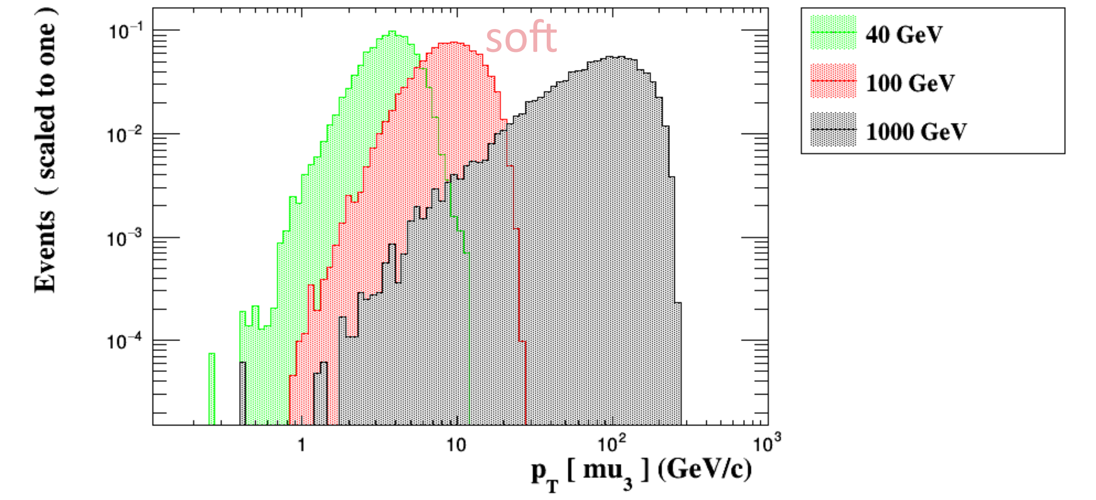

N. of fd11 (scaled to one)
40 GeV
100 GeV
1000 GeV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1 10 10^2 10^3
p_T [fd11] (GeV/c)

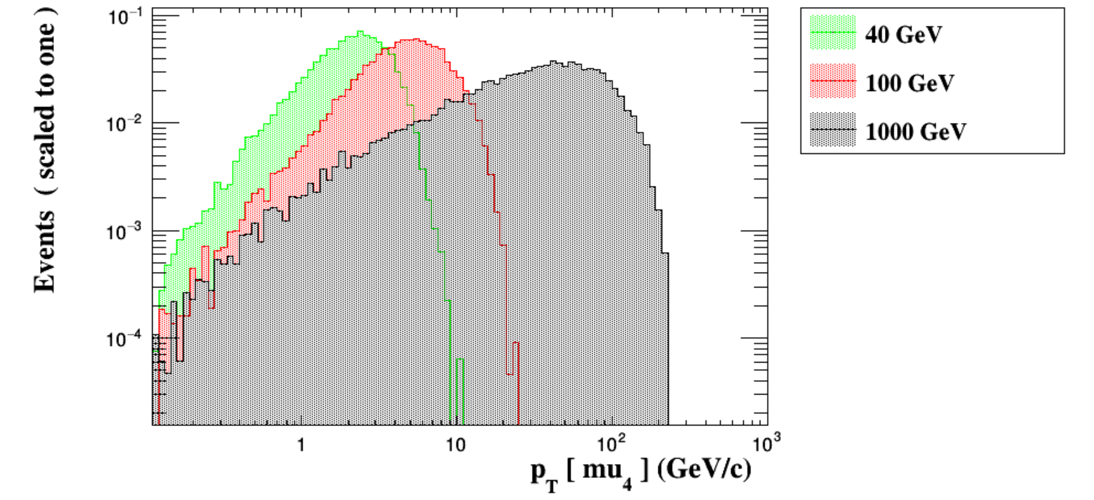
P_T of Leading, Subleading, 3rd, and 4th Muon



Z_D masses

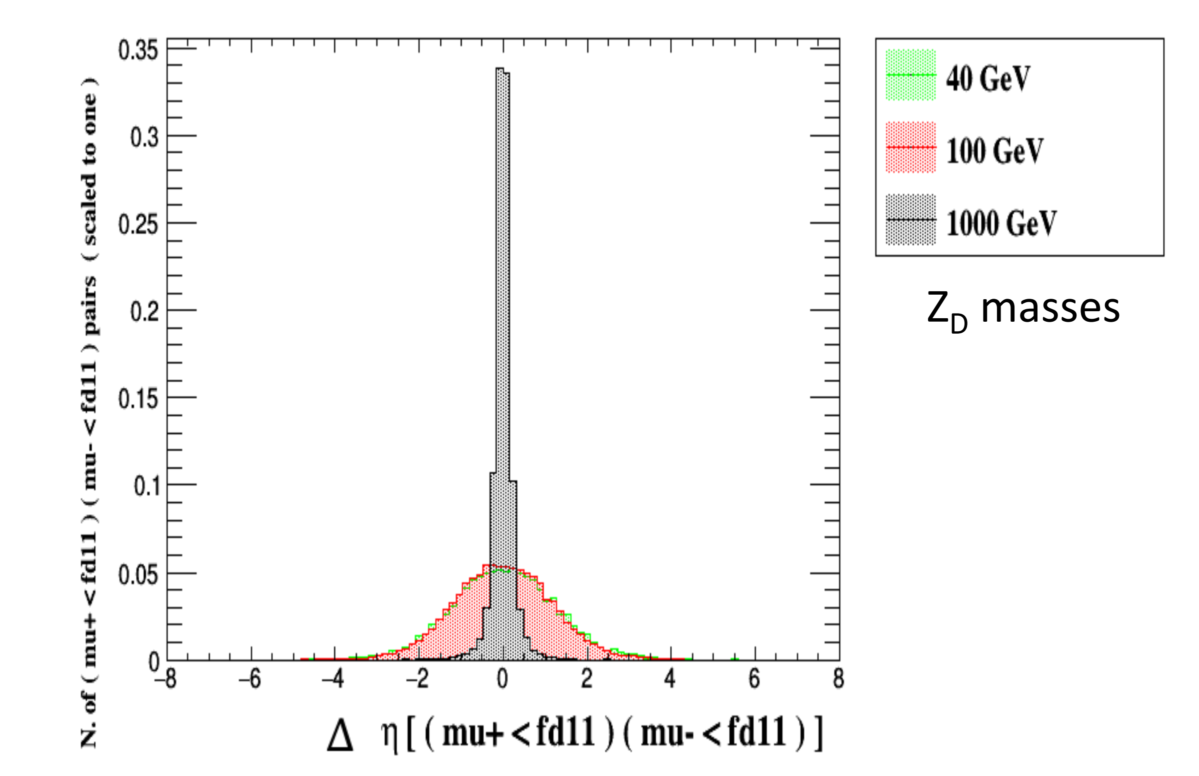




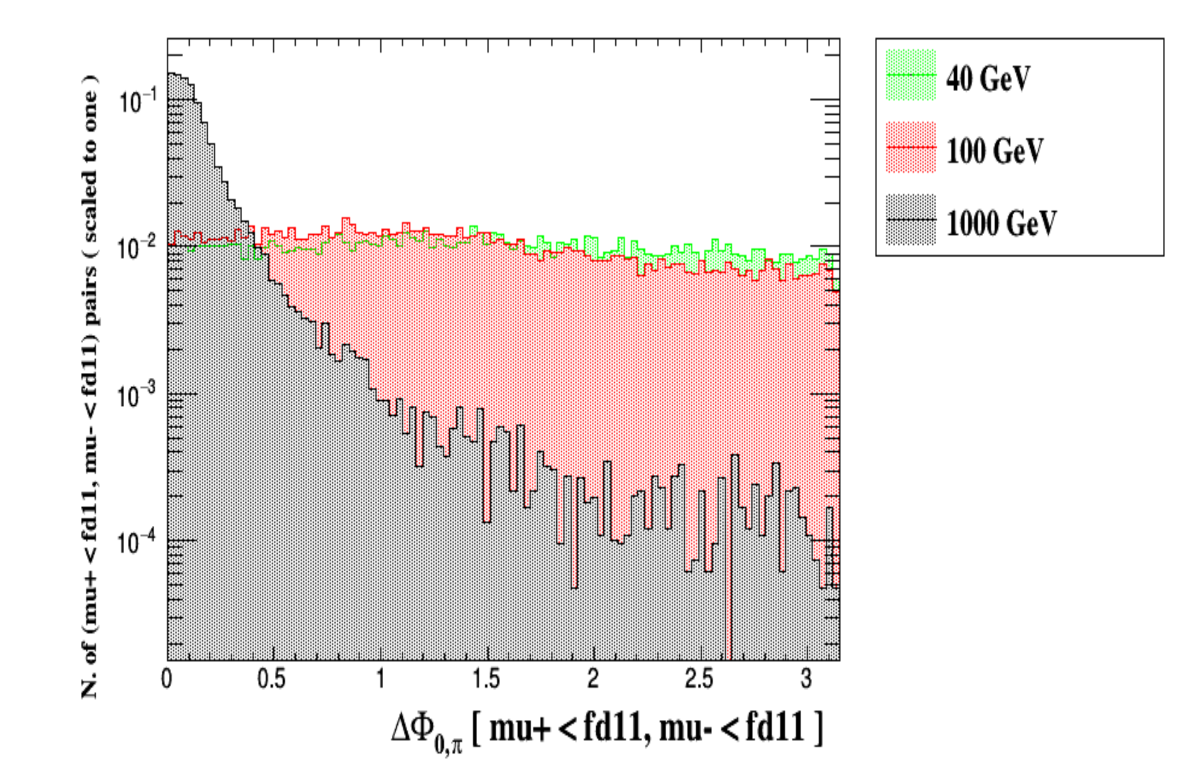


Fermionic Model

Δη and Δφ between Muons from Same Vertex

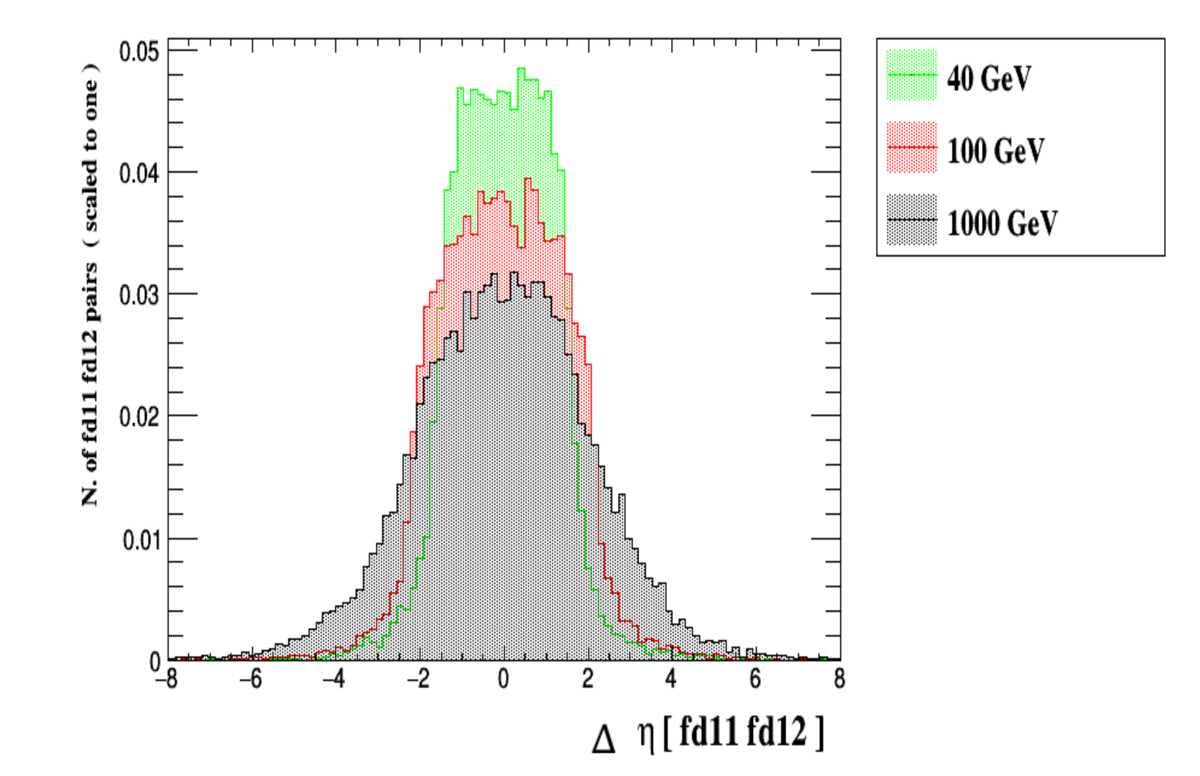


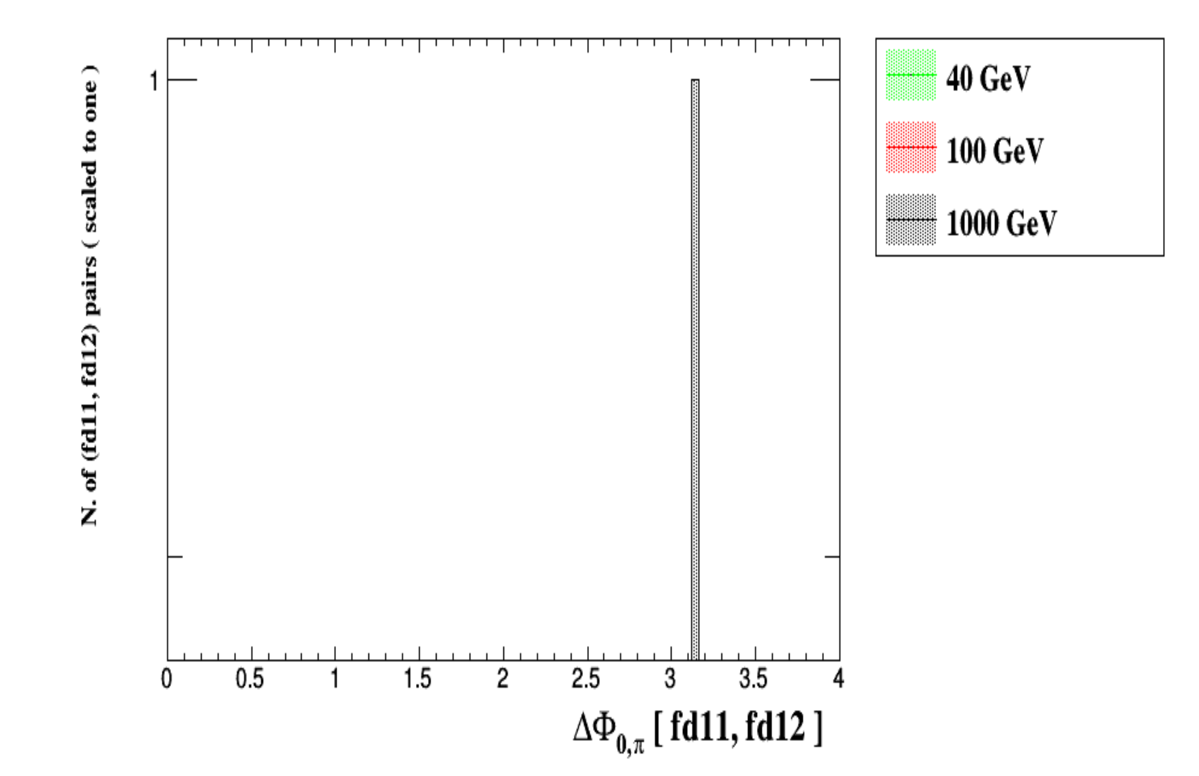
Z_D masses



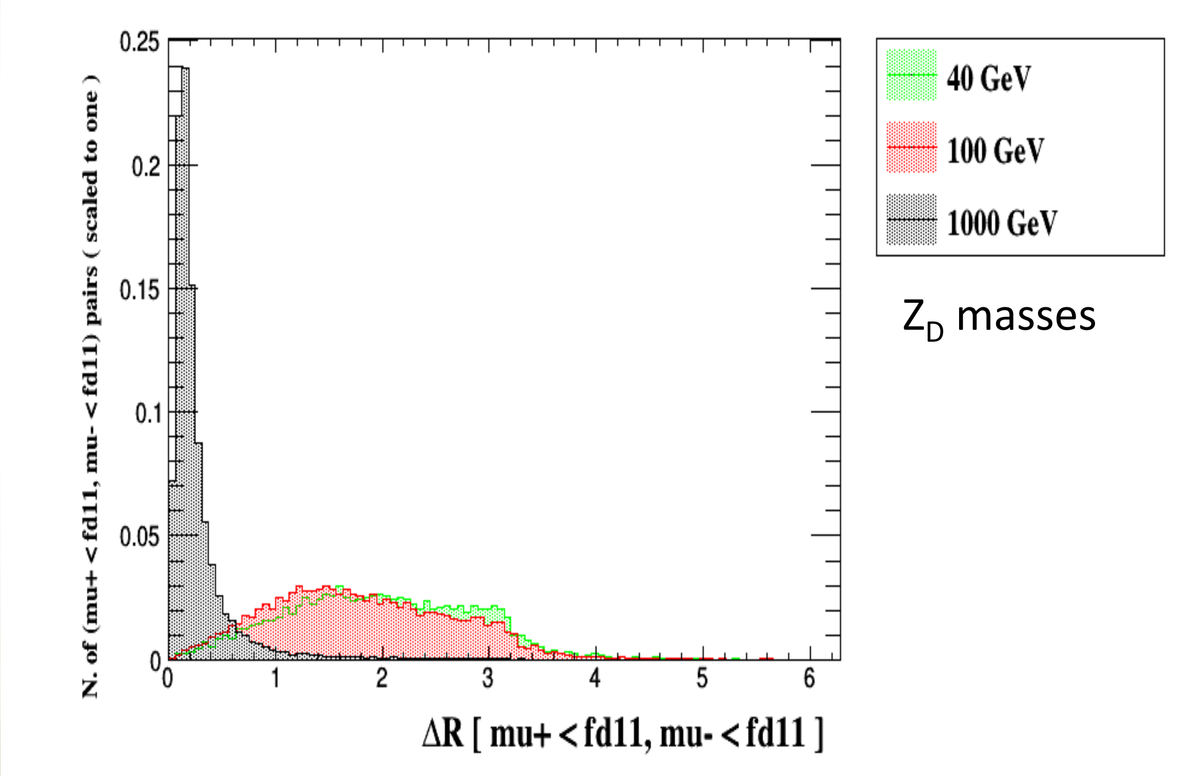
Fermionic Model

$\Delta\varphi$ & $\Delta\eta$ of $f_{d1}s$



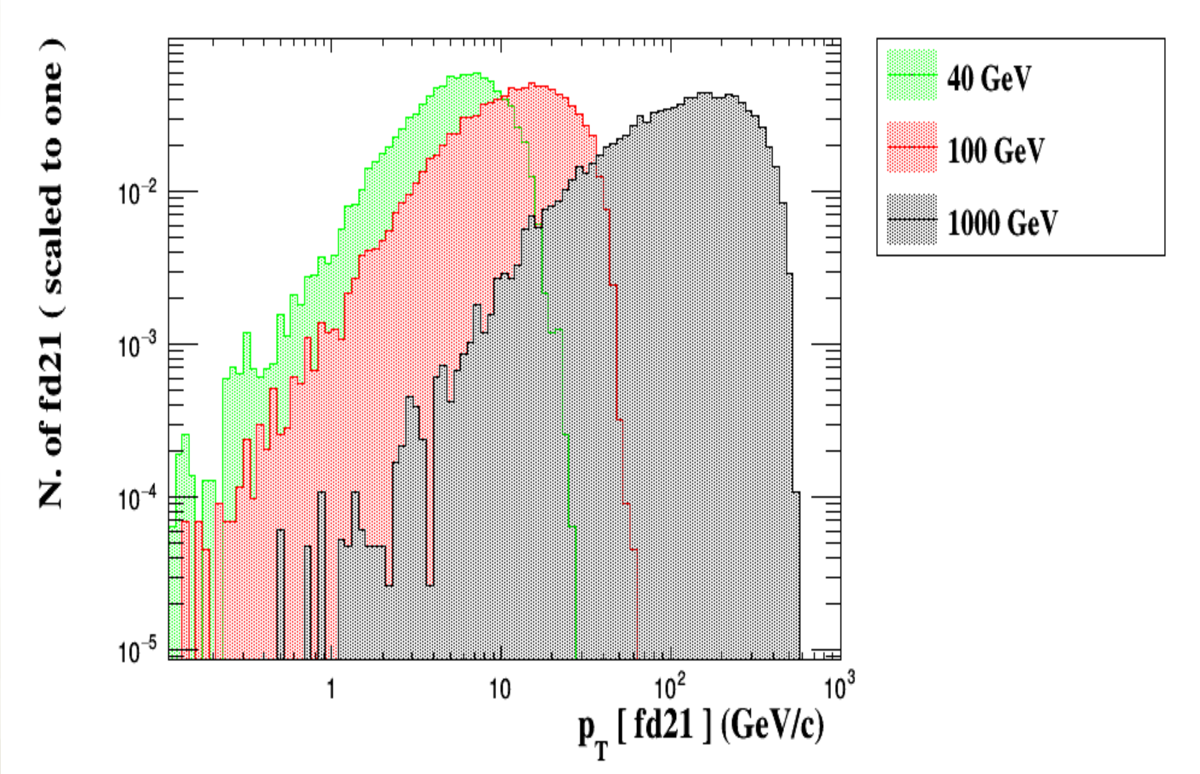


ΔR of μs



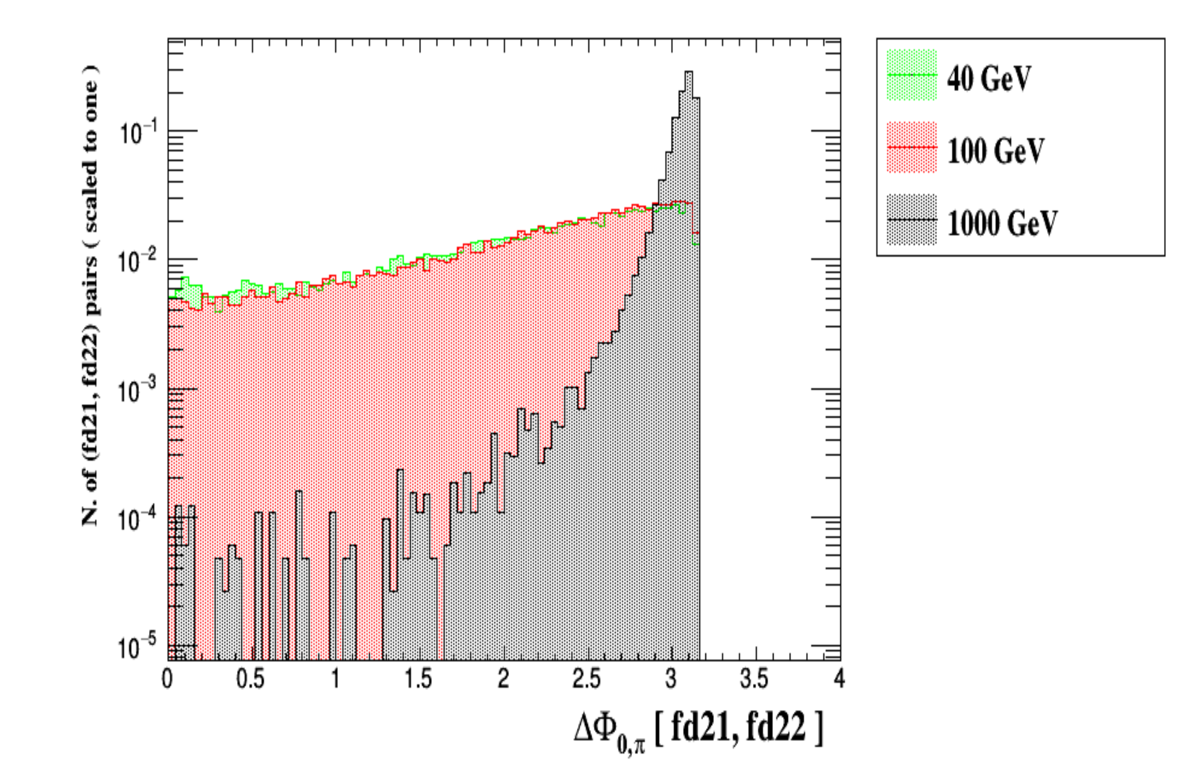
Z_D masses

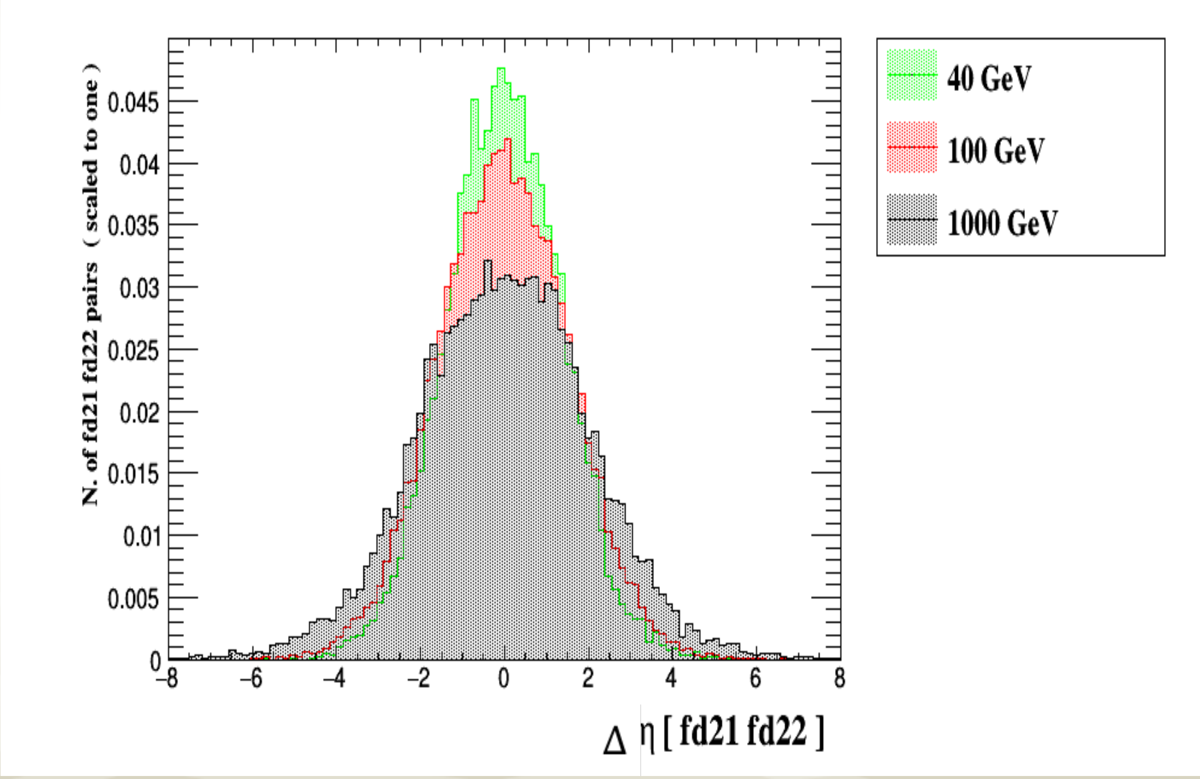
P_T of f_{d2}



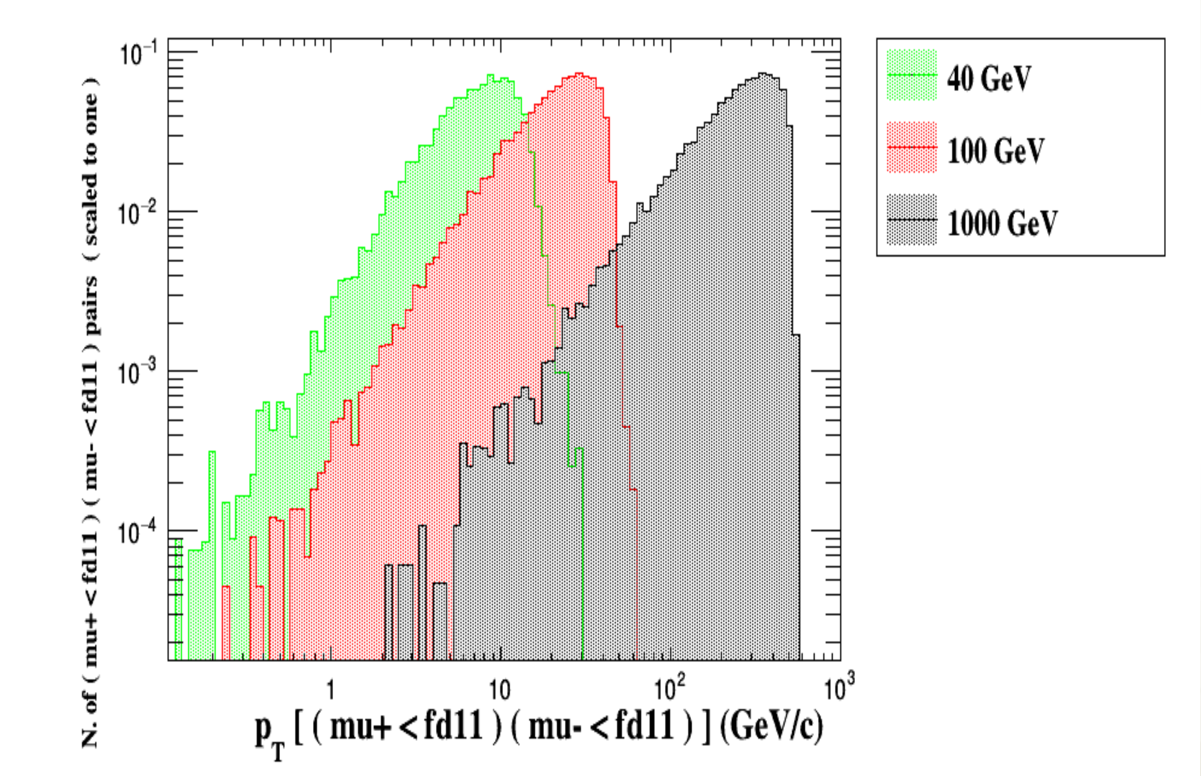
N. of fd21 (scaled to one)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
10^2
10^3
p_T [fd21] (GeV/c)
40 GeV
100 GeV
1000 GeV

$\Delta\varphi$ & $\Delta\eta$ of $f_{d2}s$

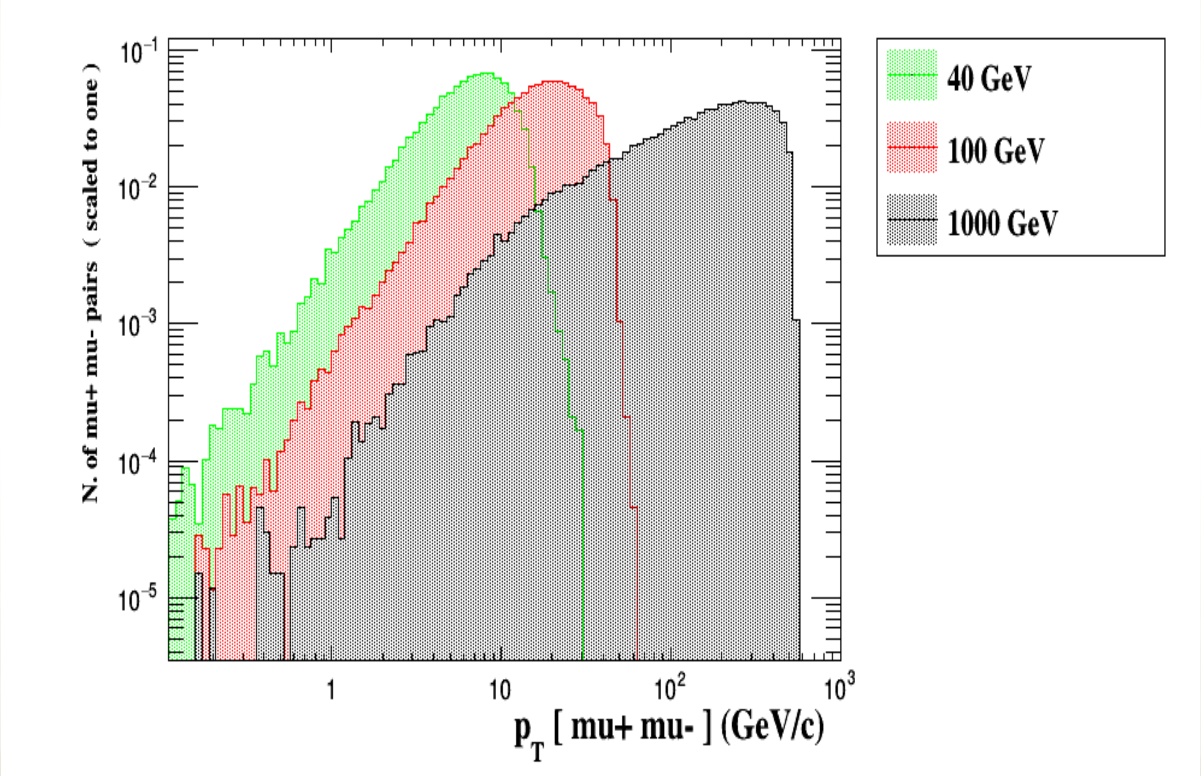




P_T of μs

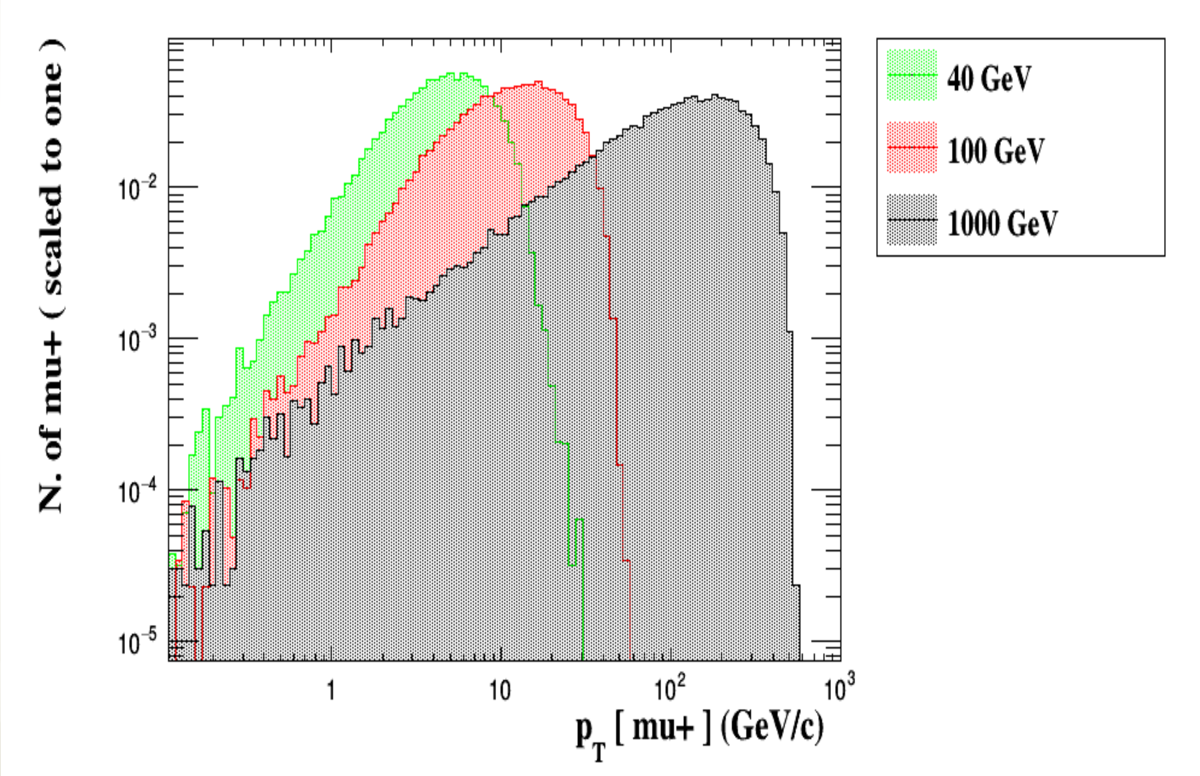


N. of (mu+ < fd11) (mu- < fd11) pairs (scaled to one)
p_T [(mu+ < fd11) (mu- < fd11)] (GeV/c)
40 GeV
100 GeV
1000 GeV



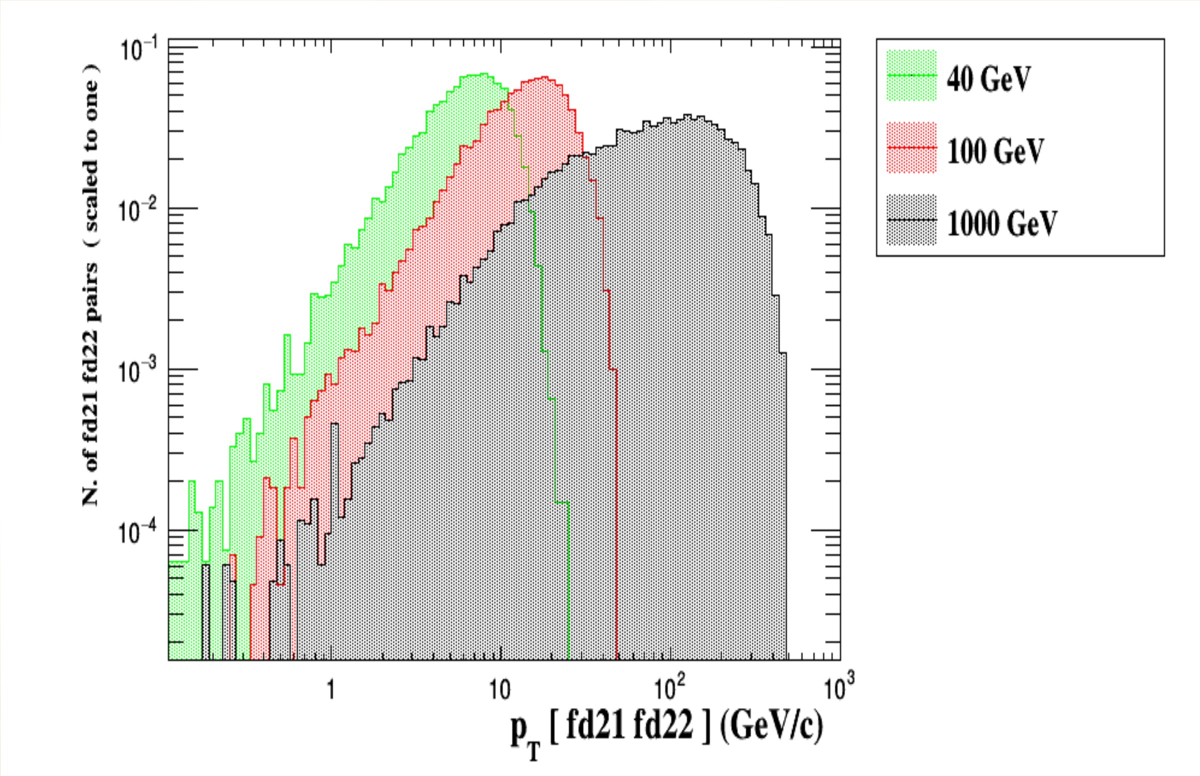
N. of mu+ mu- pairs (scaled to one)
p_T [mu+ mu-] (GeV/c)
40 GeV
100 GeV
1000 GeV

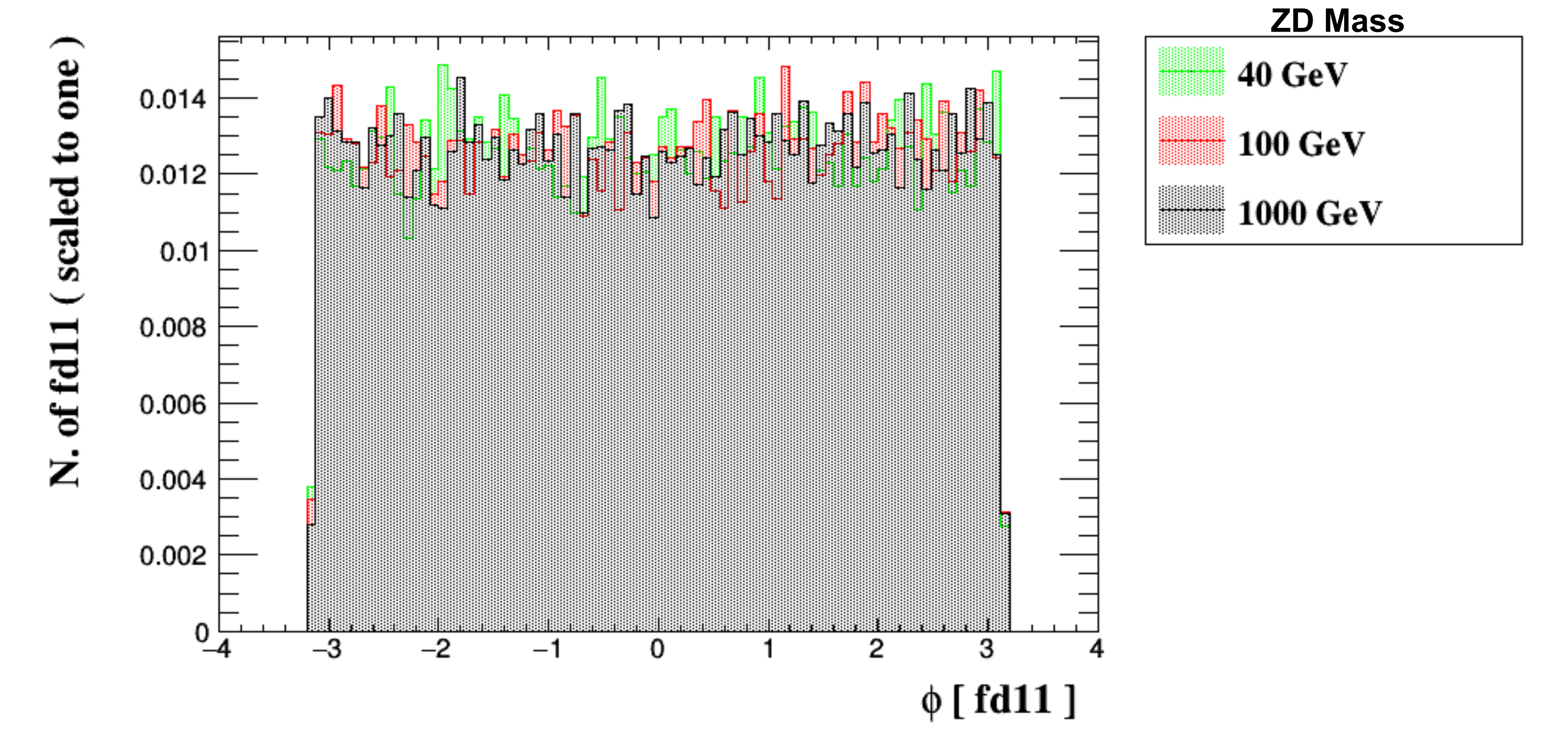
P_T of μ^+



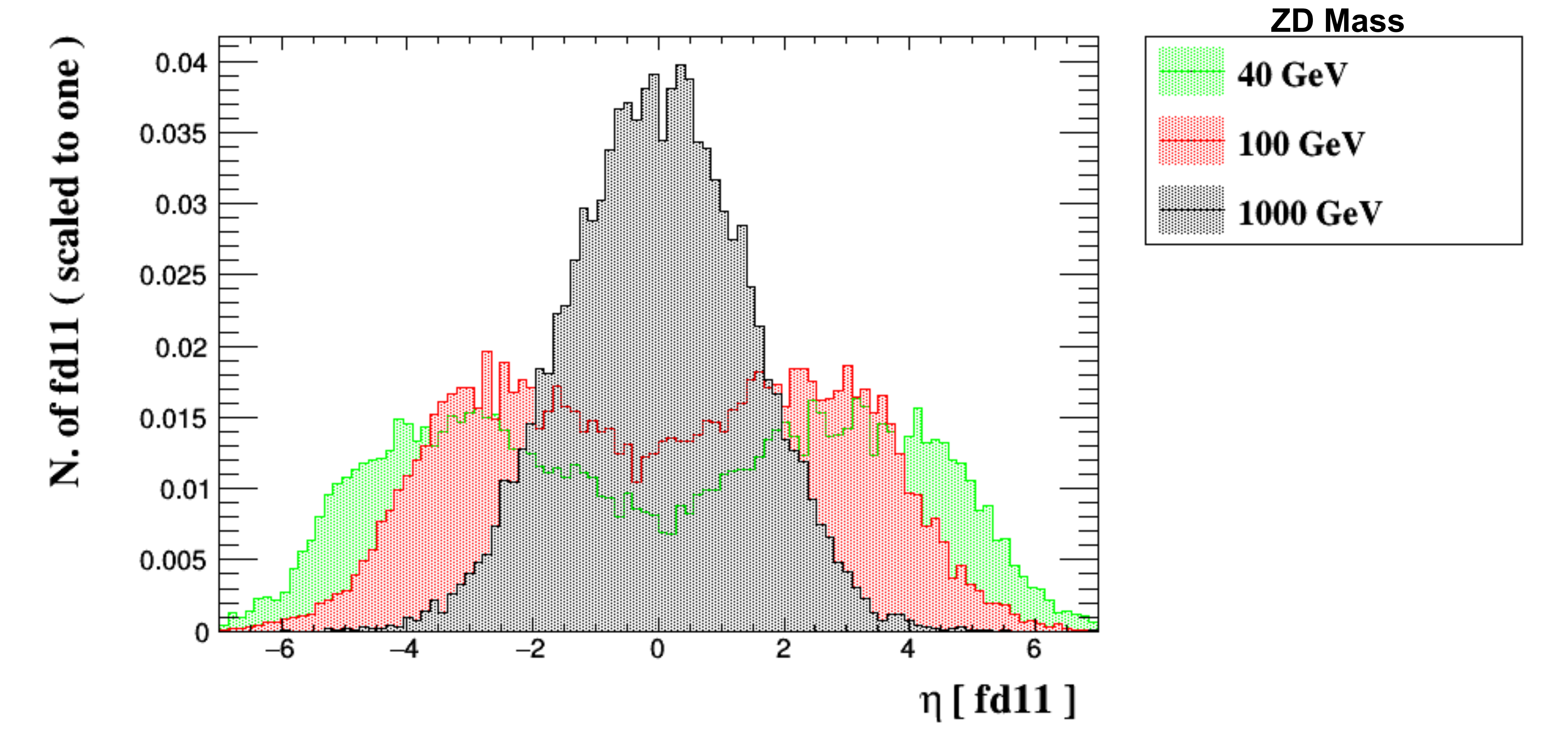
N. of mu+ (scaled to one)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
10^2
10^3
p_T [mu+] (GeV/c)
40 GeV
100 GeV
1000 GeV

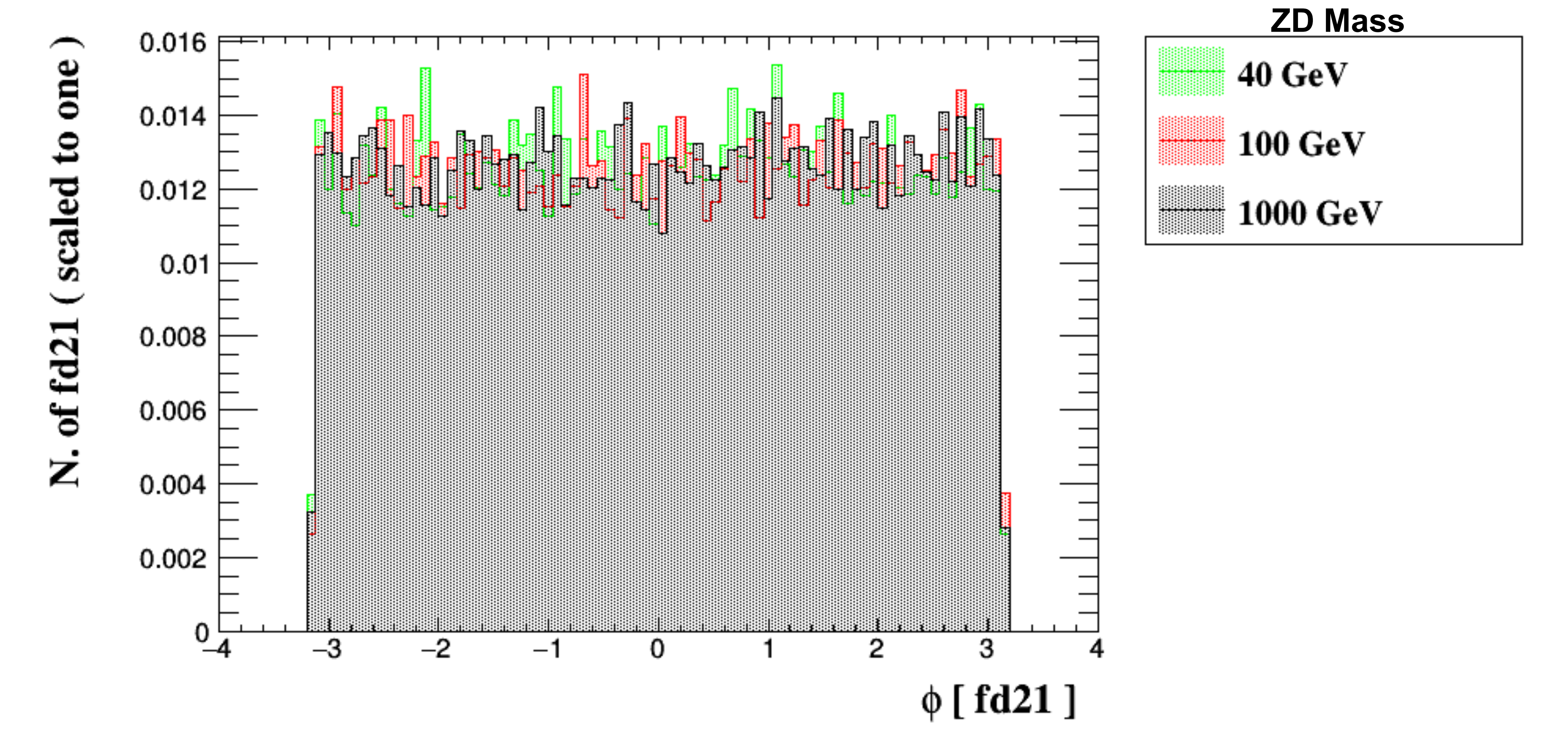
Missing momentum



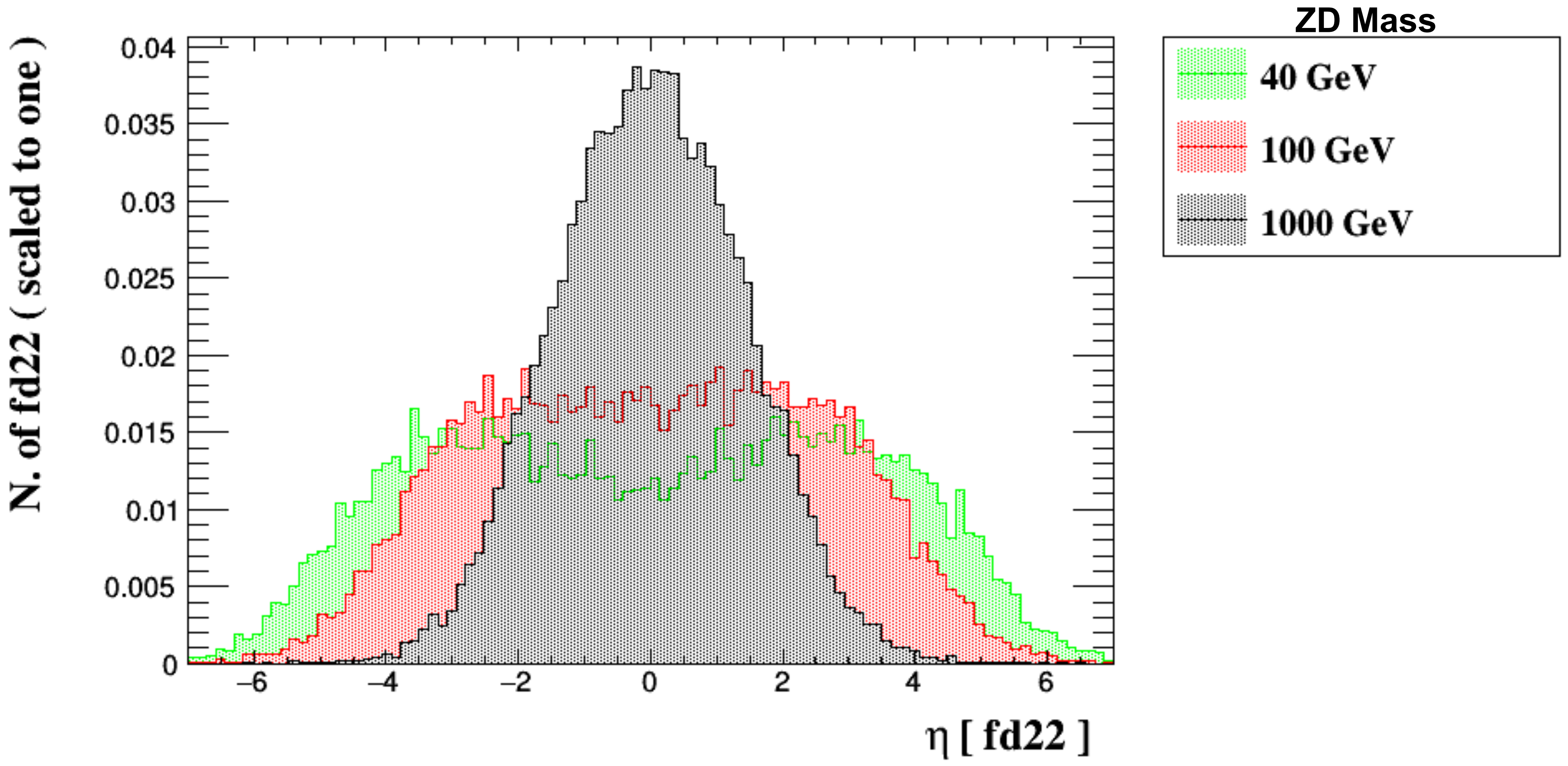


ZD Mass
40 GeV
100 GeV
1000 GeV
N. of fd11 (scaled to one)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
−4
−3
−2
−1
0
1
2
3
4
ϕ [fd11]

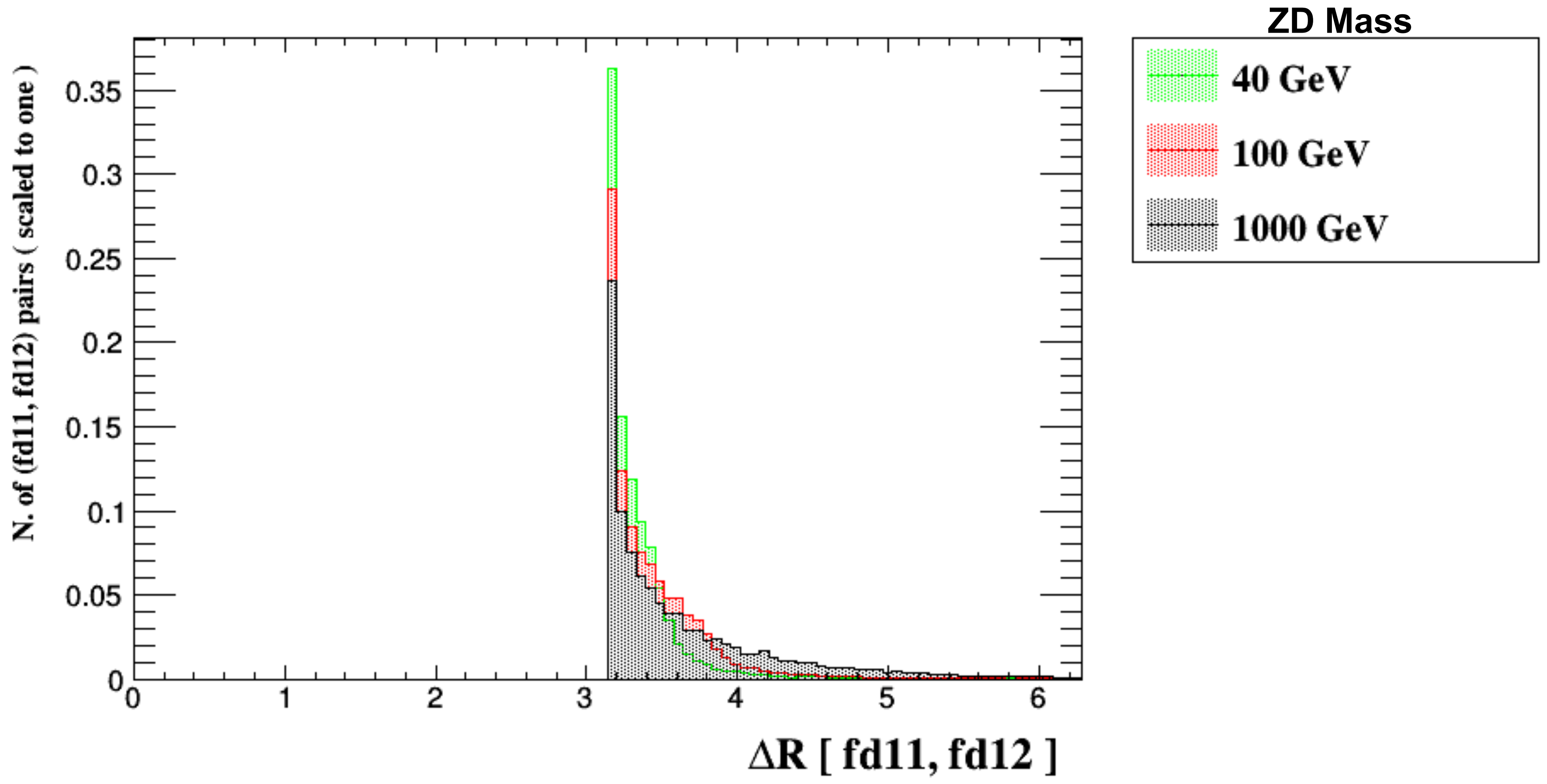

ZD Mass
40 GeV
100 GeV
1000 GeV
N. of fd11 (scaled to one)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−6
−4
−2
0
2
4
6
η [fd11]



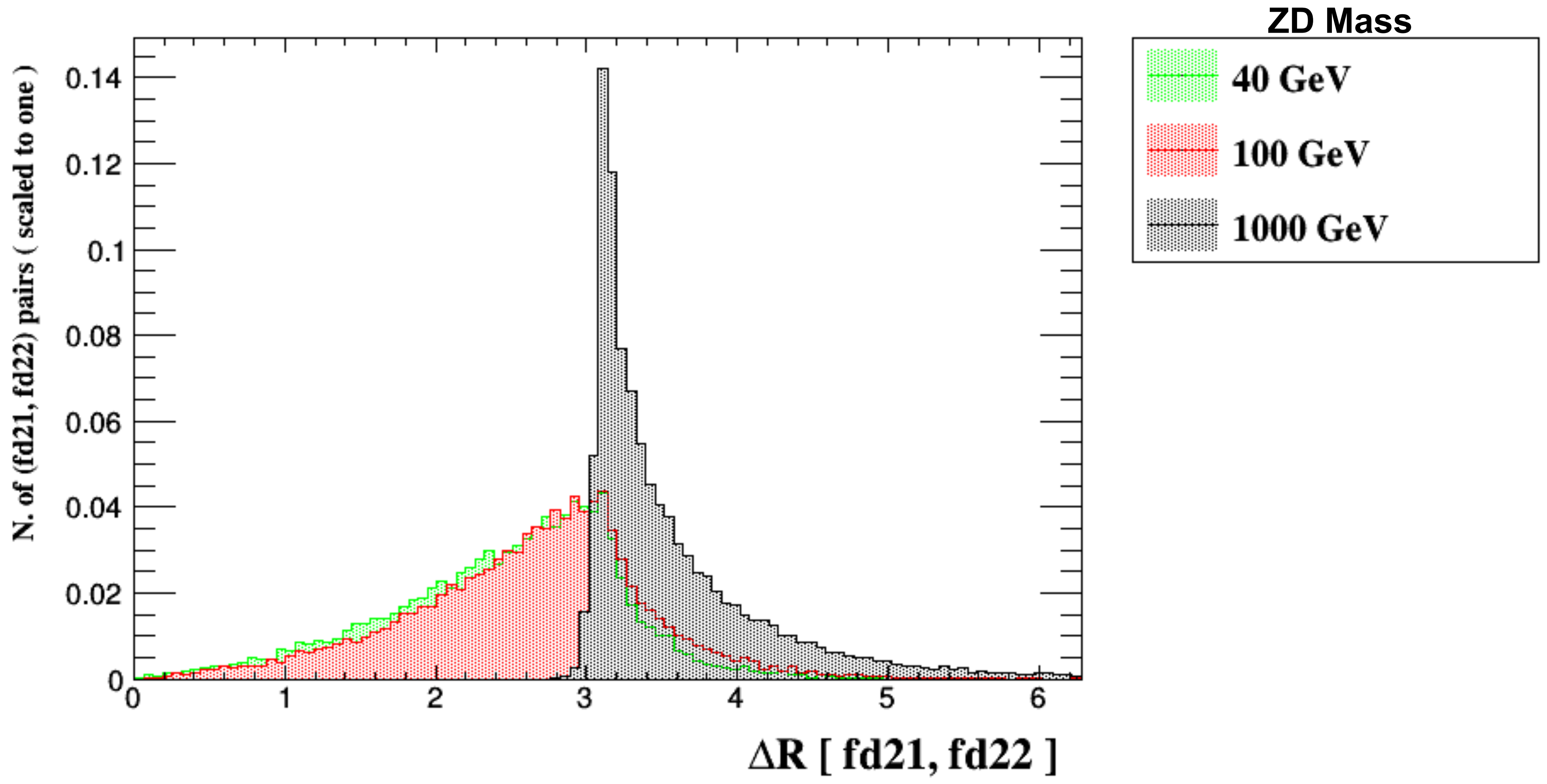
ZD Mass
40 GeV
100 GeV
1000 GeV
N. of fd21 (scaled to one)
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
−4
−3
−2
−1
0
1
2
3
4
φ [fd21]

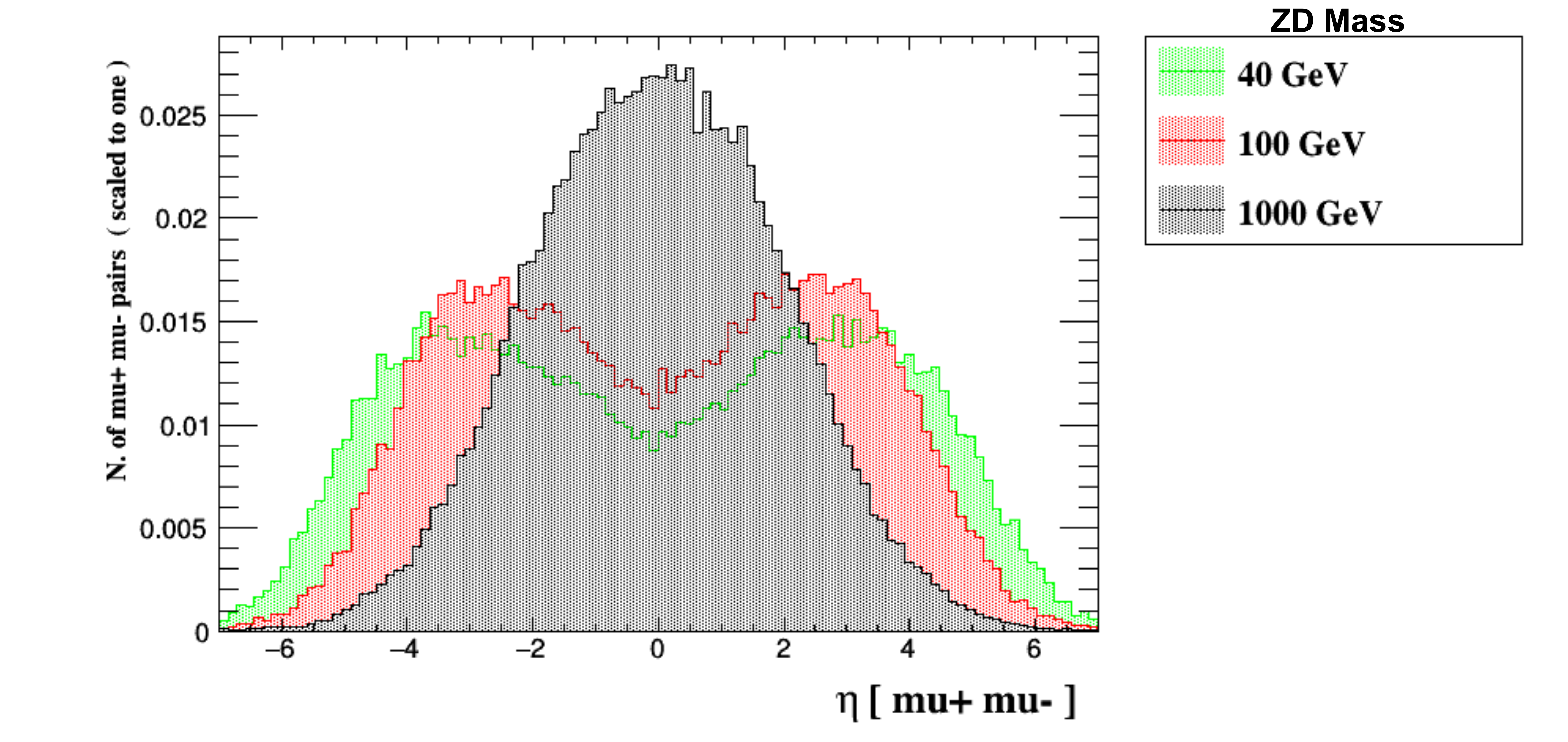


ZD Mass
40 GeV
100 GeV
1000 GeV
N. of fd22 (scaled to one)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−6
−4
−2
0
2
4
6
η [fd22]

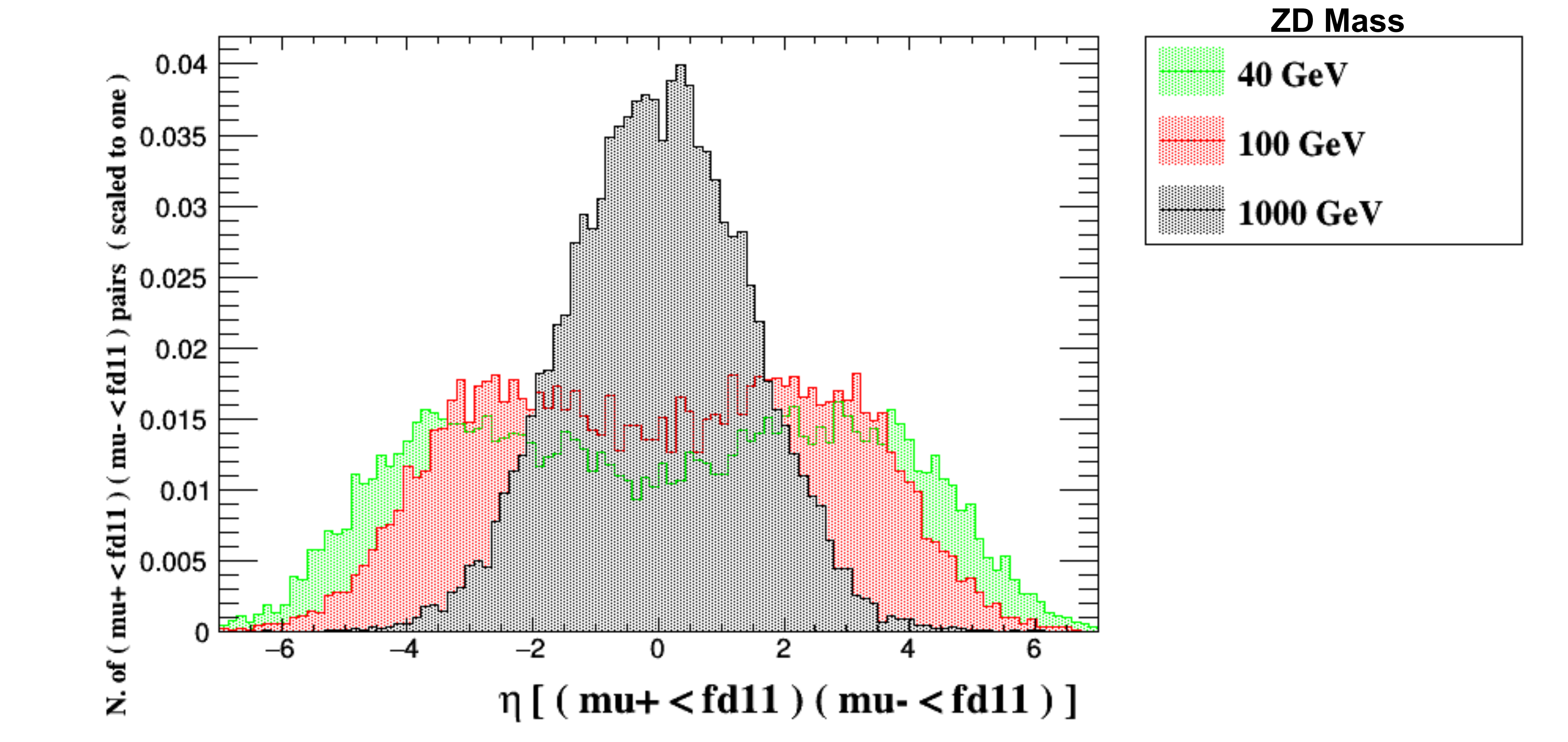


N. of (fd11, fd12) pairs (scaled to one)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
ΔR [fd11, fd12]
ZD Mass
40 GeV
100 GeV
1000 GeV

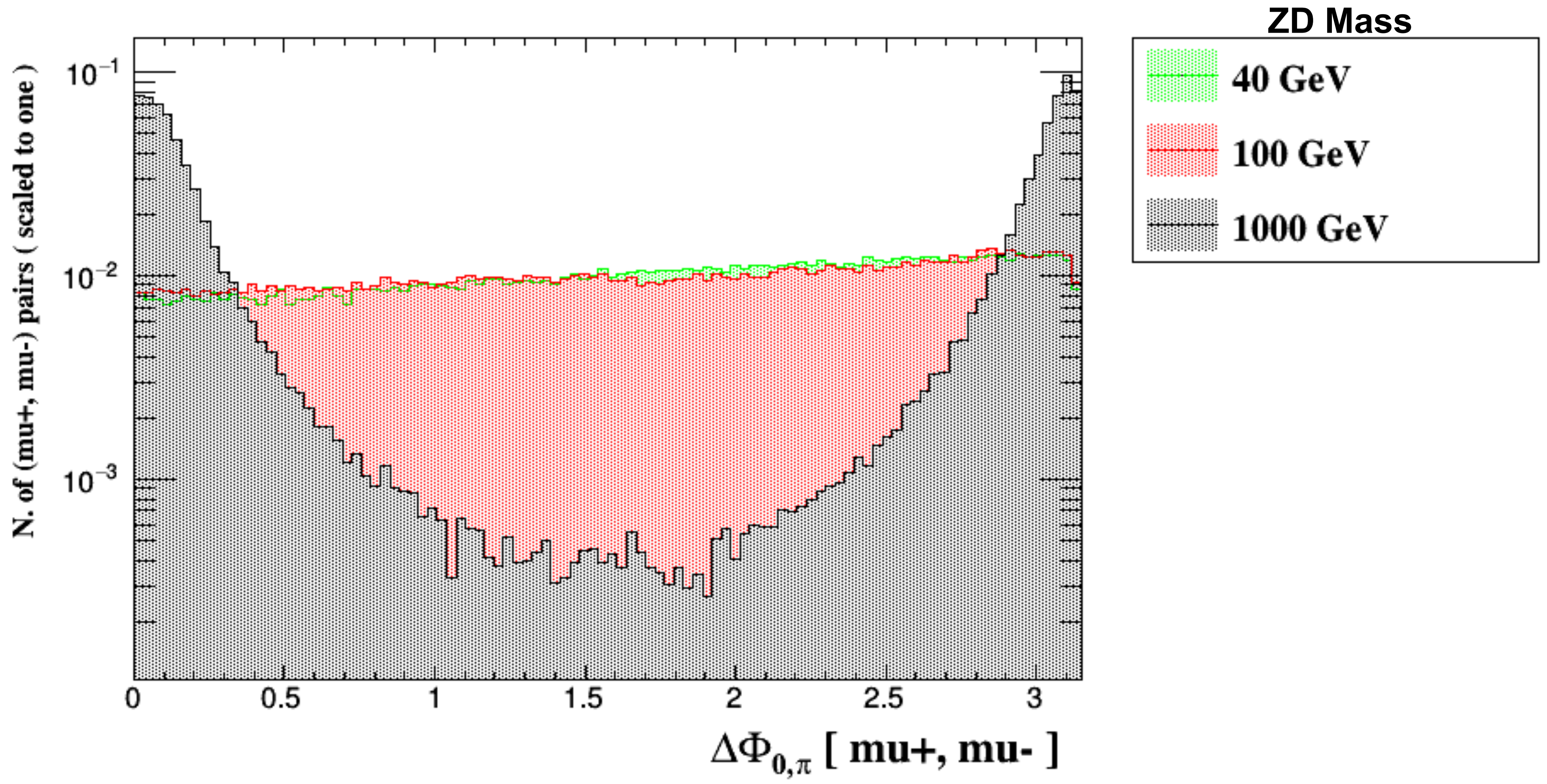

ZD Mass
40 GeV
100 GeV
1000 GeV
N. of (fd21, fd22) pairs (scaled to one)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
ΔR [fd21, fd22]

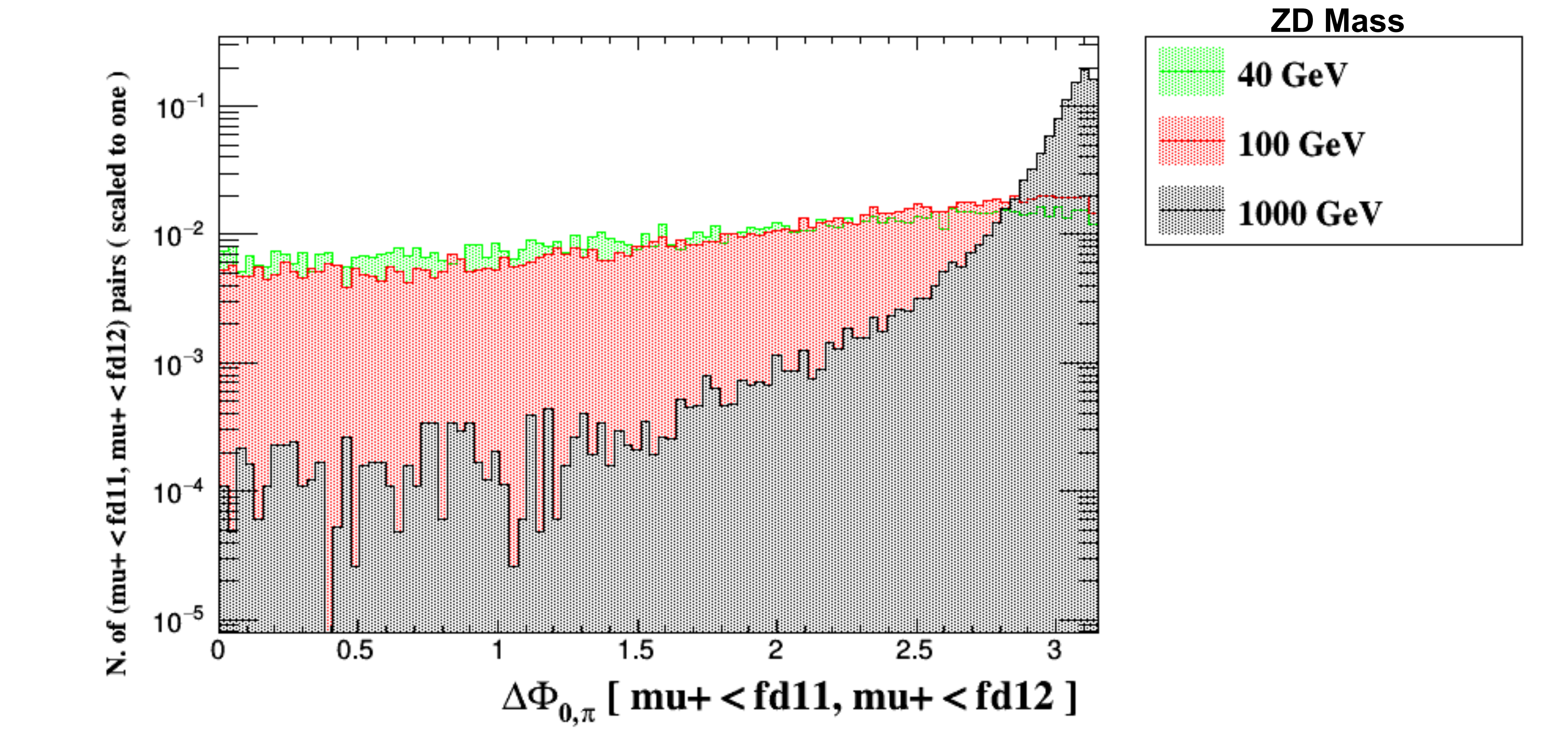


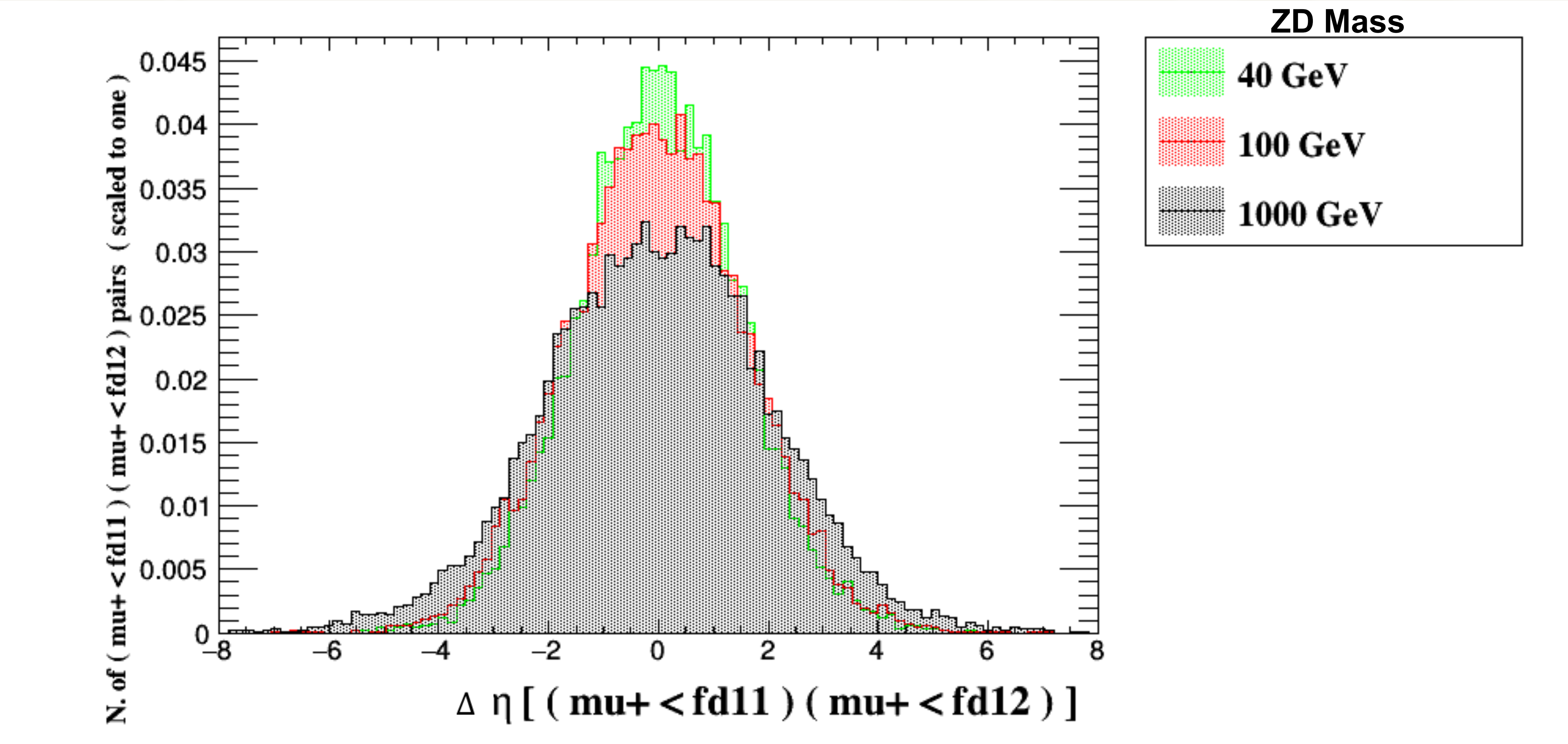
ZD Mass
40 GeV
100 GeV
1000 GeV
N. of mu+ mu- pairs (scaled to one)
0.025
0.02
0.015
0.01
0.005
0
−6
−4
−2
0
2
4
6
η [mu+ mu-]



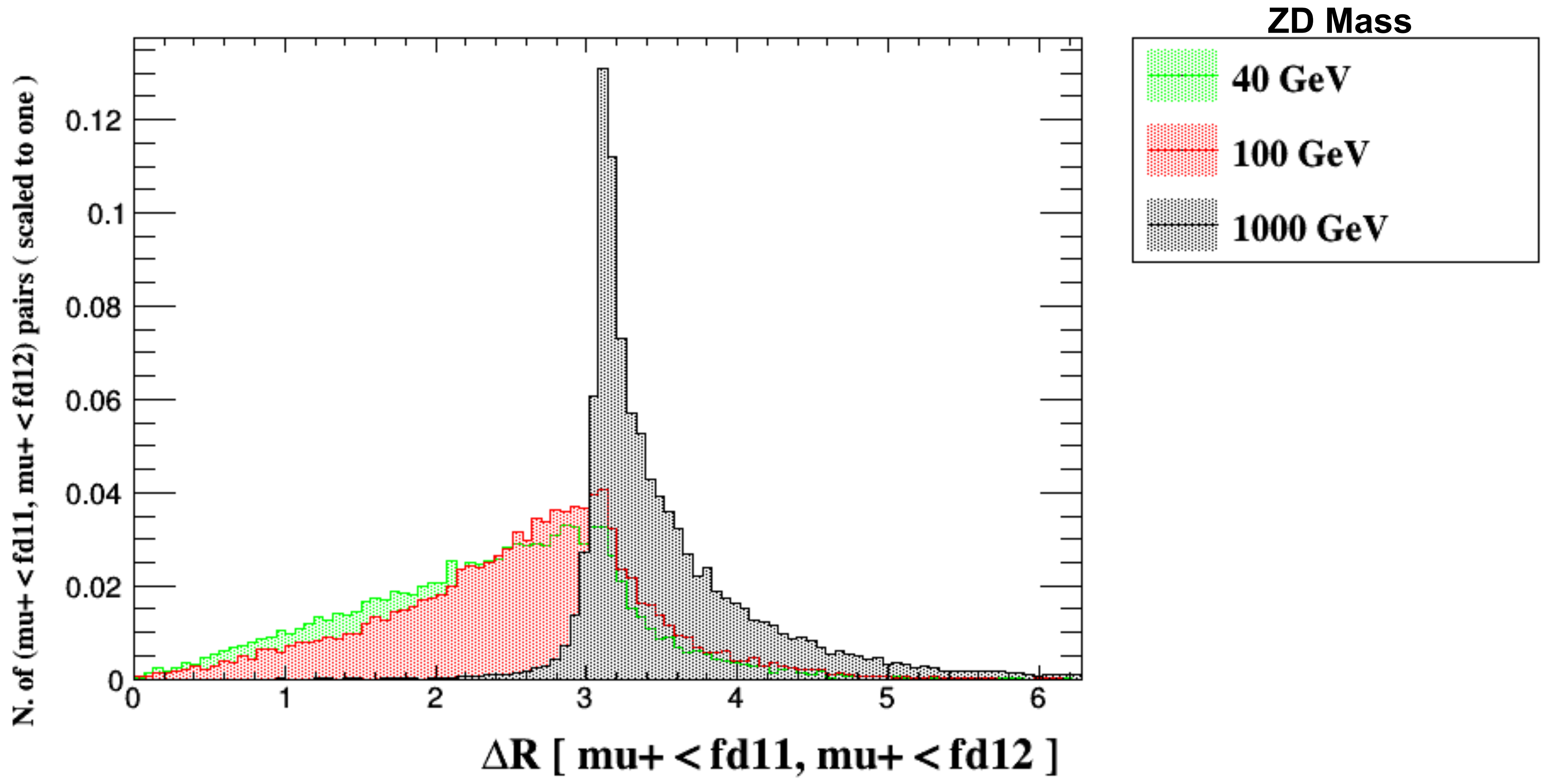
ZD Mass
40 GeV
100 GeV
1000 GeV
N. of (mu+ < fd11) (mu- < fd11) pairs (scaled to one)
η [(mu+ < fd11) (mu- < fd11)]
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−6
−4
−2
0
2
4
6


ZD Mass
40 GeV
100 GeV
1000 GeV
N. of (mu+, mu-) pairs (scaled to one)
10^{-1}
10^{-2}
10^{-3}
0
0.5
1
1.5
2
2.5
3
$\Delta\Phi_{0,\pi}$ [mu+, mu-]

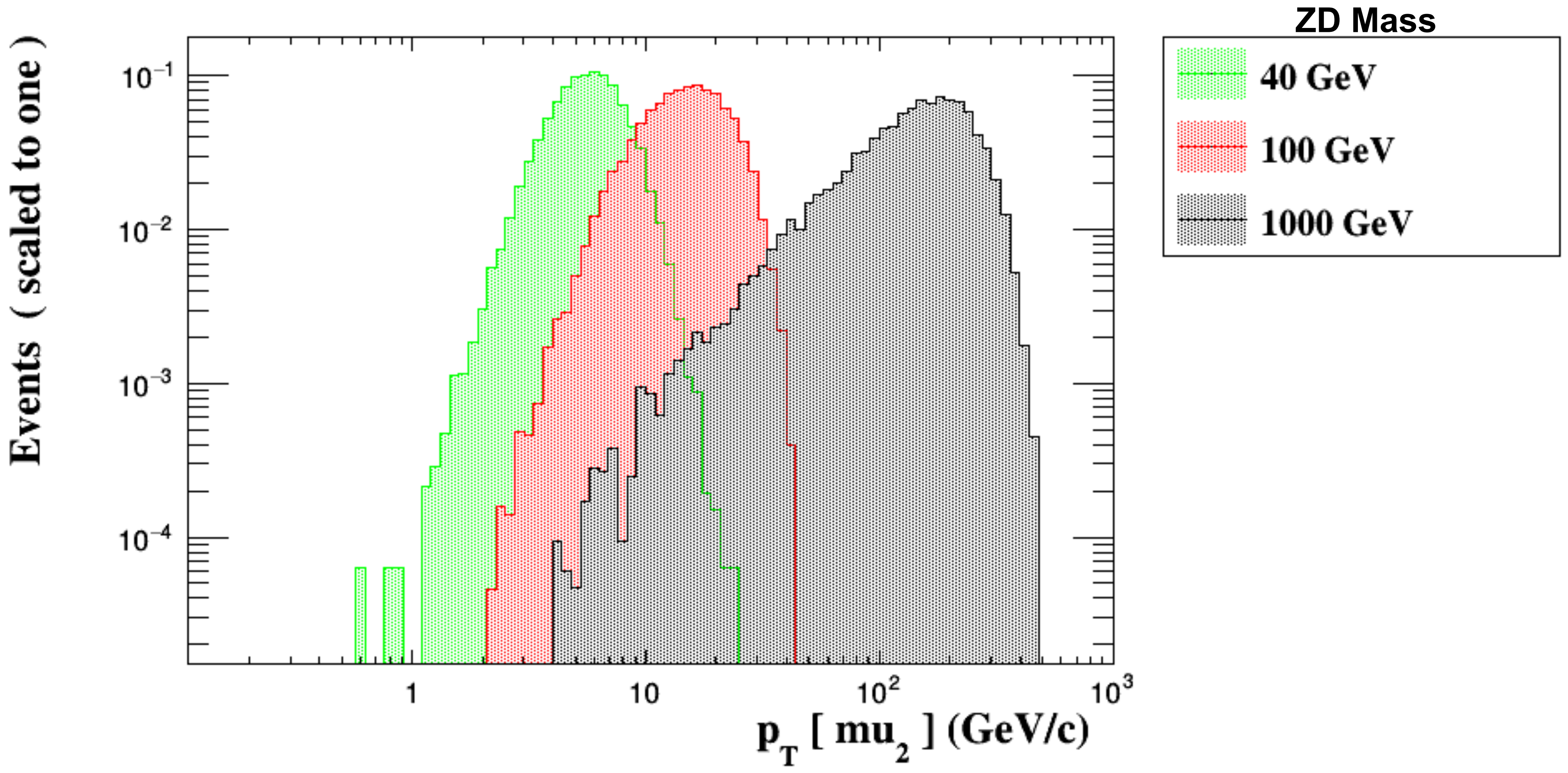

ZD Mass
40 GeV
100 GeV
1000 GeV
N. of (mu+ < fd11, mu+ < fd12) pairs (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.5
1
1.5
2
2.5
3
$\Delta\Phi_{0,\pi}$ [mu+ < fd11, mu+ < fd12]

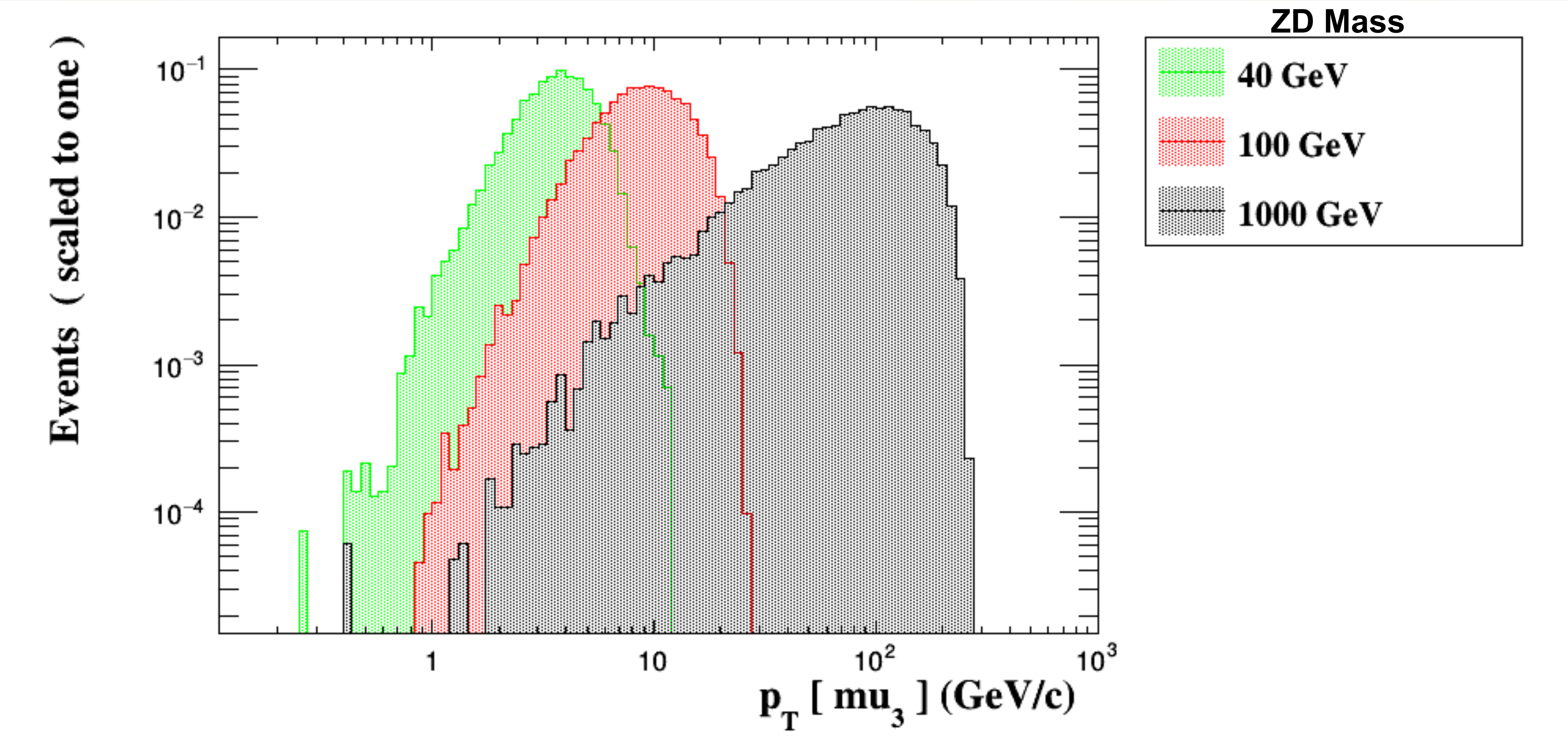


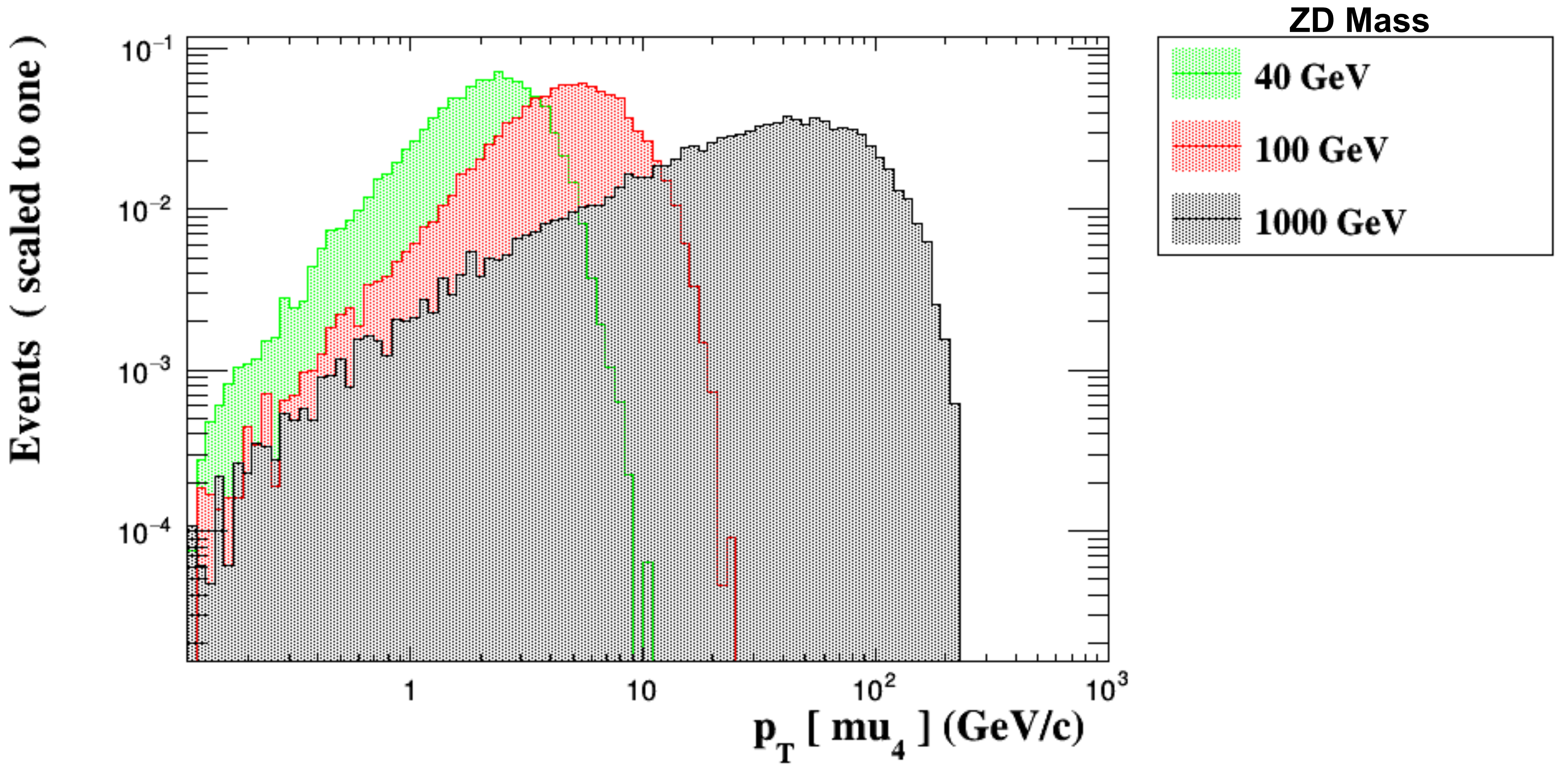
ZD Mass
40 GeV
100 GeV
1000 GeV
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
−8
−6
−4
−2
0
2
4
6
8
N. of (mu+ < fd11) (mu+ < fd12) pairs (scaled to one)
Δ η [(mu+ < fd11) (mu+ < fd12)]



ZD Mass
40 GeV
100 GeV
1000 GeV
N. of (mu+ < fd11, mu+ < fd12) pairs (scaled to one)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
1
2
3
4
5
6
ΔR [mu+ < fd11, mu+ < fd12]


ZD Mass
40 GeV
100 GeV
1000 GeV
Events (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
p_T [mu_2] (GeV/c)


Events (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
p_T [mu_3] (GeV/c)
ZD Mass
40 GeV
100 GeV
1000 GeV


ZD Mass
40 GeV
100 GeV
1000 GeV
Events (scaled to one)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^{2}
10^{3}
p_T [mu_4] (GeV/c)