上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

SJTU

首届SHINE缪子源及其应用研讨会 (SMS2025)

DREAMuS: Dark matter REsearch with Advanced Muon Source

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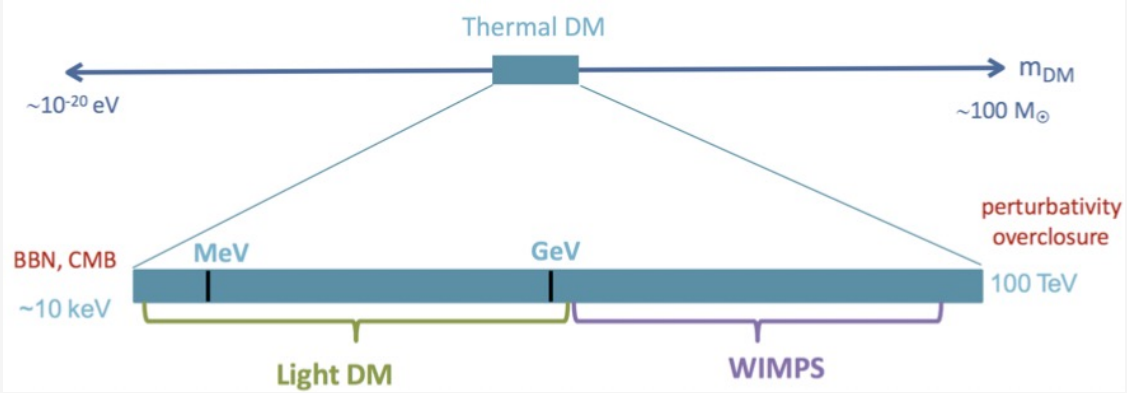
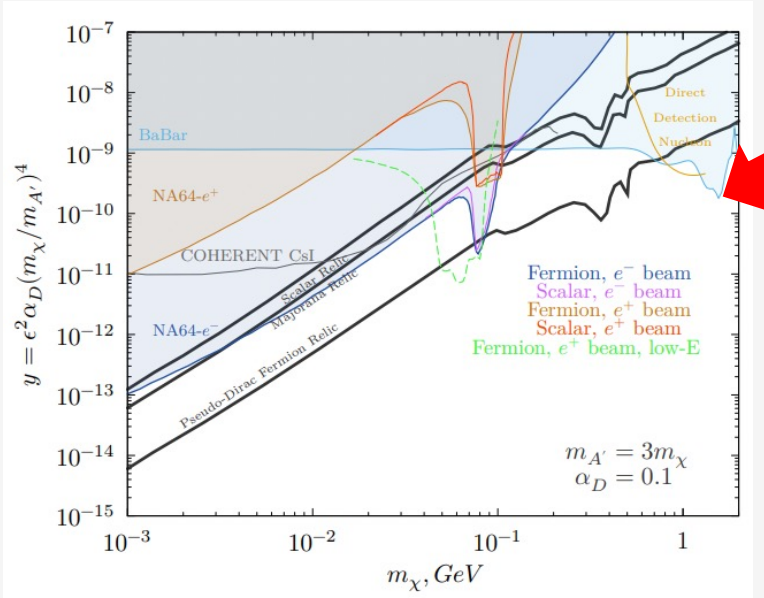
Dark Matter Search

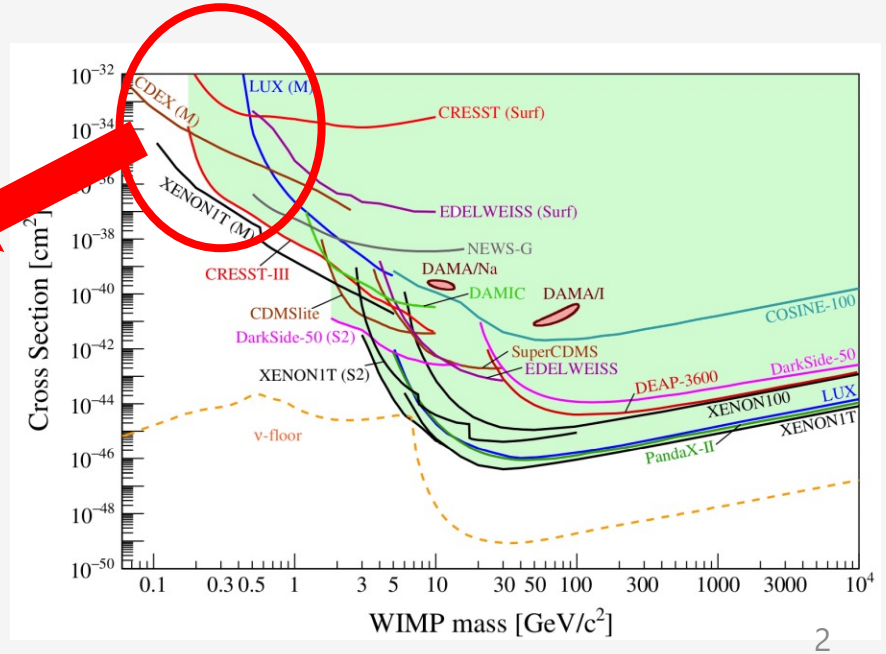
- According to the “freeze-out” mechanism, the mass of dark matter can be in MeV-GeV scale

- Muon is 200 times heavier than electron and more sensitive to new physics

- Post-WIMP era: fixed-target experiments have advantages in the low mass region

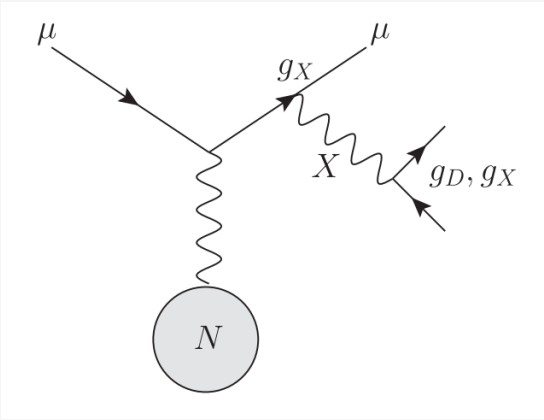




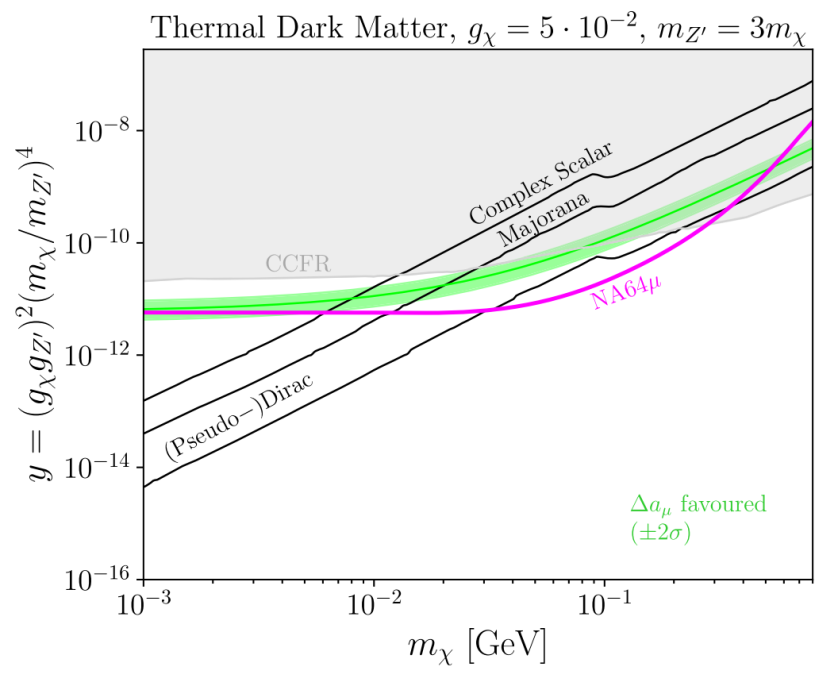


Light Dark Matter Search With Fixed-Target Experiments

- Various fix-target experiments with different kinds of beam
- Muon-filic dark matter search can be applied on muon beam
- Thermal Dark Matter with (Sub-)GeV Z' model
  - Lμ − Lτ boson Z' where Z' can decay to invisible particles, like neutrino or dark matter particles

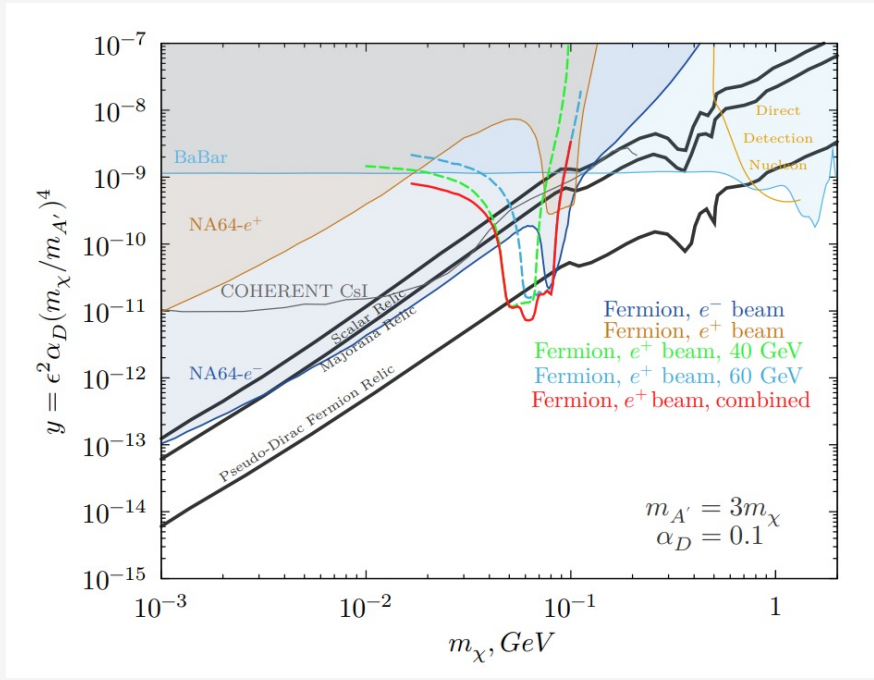


Muon beam



Phys. Rev. Lett. **132**, 211803

Electron beam

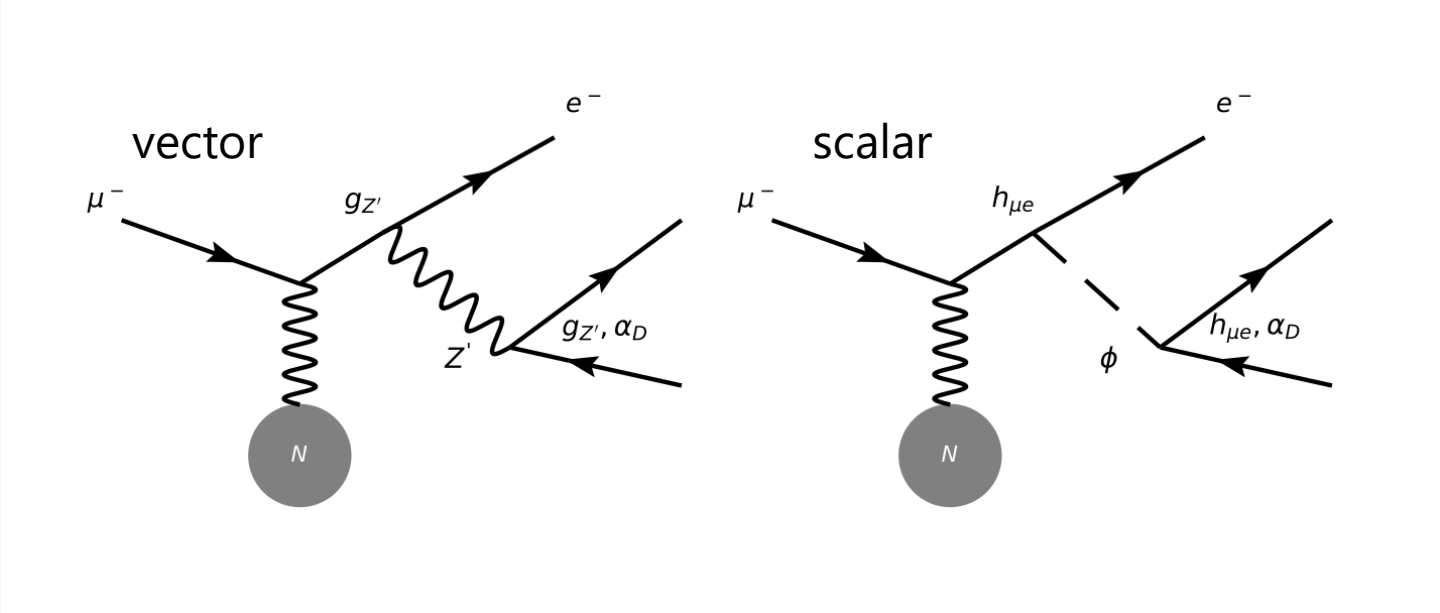


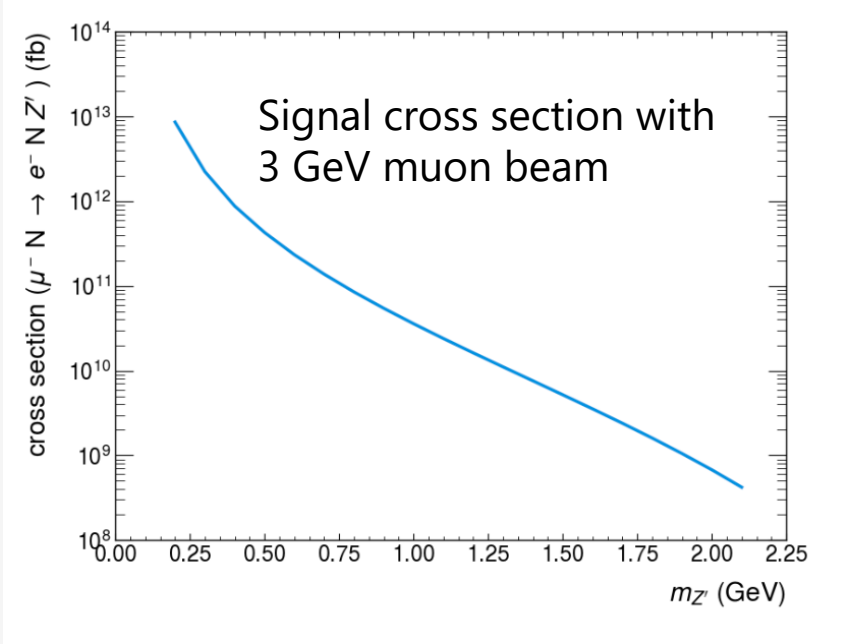
Phys. Rev. D **109**, L031103

DREAMuS: Dark matter REsearch with Advanced Muon Source

Dark matter search with fixed-target experiment using muon beam @ HIAF

- Dark matter (χ) from a flavor-violating **vector boson** Z′ or **scalar** boson ϕ
- 3 GeV muon interaction with 22cm lead target





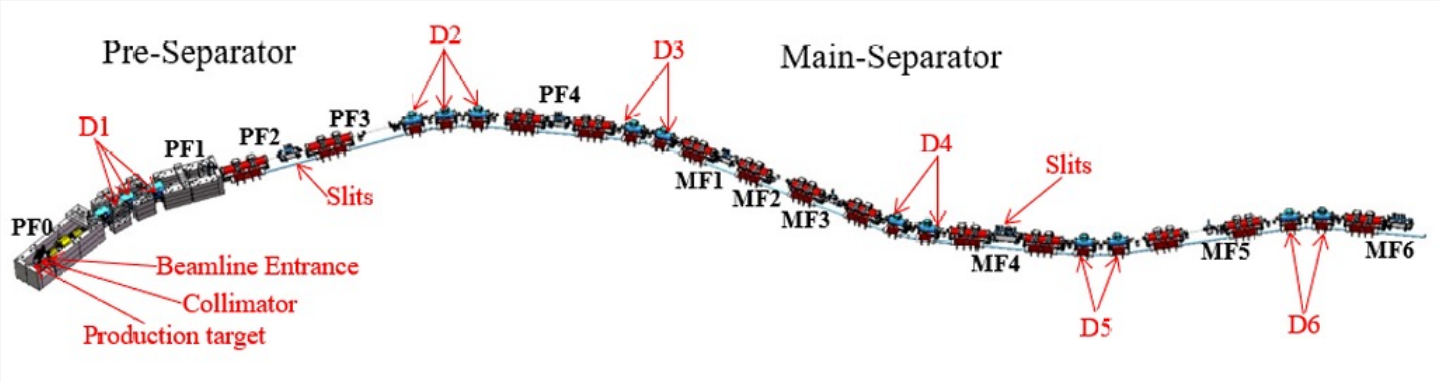
Single electron + large missing momentum/energy

High Intensity Heavy Ion Accelerator Facility

- First high intensity and high energy muon beam in China
  - GeV muon beam is provided with high intensity
  - HIAF beam: 0.5 – 7.5 GeV, 3-8*10^6 μ/s (Peak intensity)
  - CiADS beam: 0.5 – 0.6 GeV, 5*10^8 μ/s (Phase-I)

TABLE IV. The maximum muon flux intensities with proton, $^{18}O^{6+}$, and $^{78}Kr^{19+}$ projectiles, and the corresponding muon beam momenta and purities.

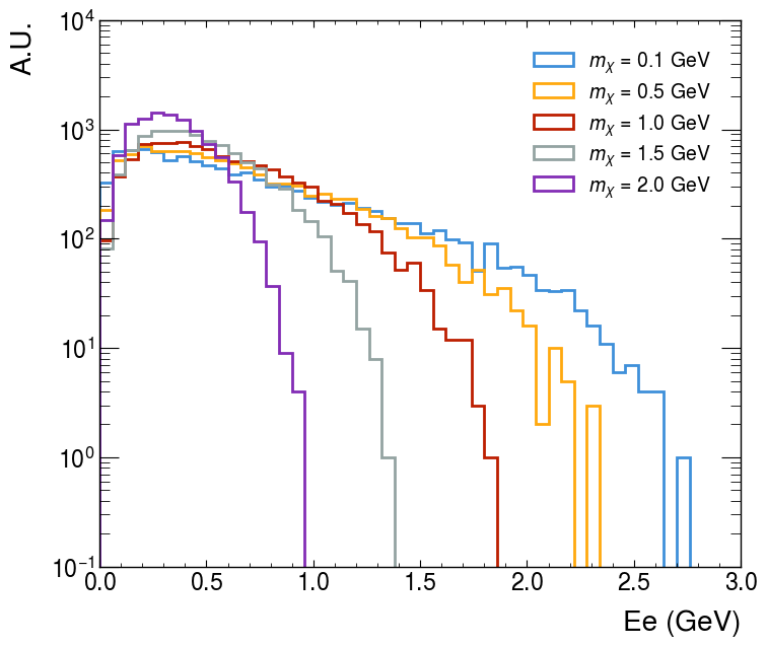
	Proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
μ^+ beam			
Momentum (GeV/c)	3.5	1.5	1.0
Flux intensity (μ^+/s)	8.2×10^6	3.5×10^6	1.8×10^6
Muon purity	2.0%	0.80%	0.60%
μ^- beam			
Momentum (GeV/c)	2.3	1.5	1.0
Flux intensity (μ^-/s)	3.8×10^6	4.2×10^6	1.6×10^6
Muon purity	13%	20%	23%

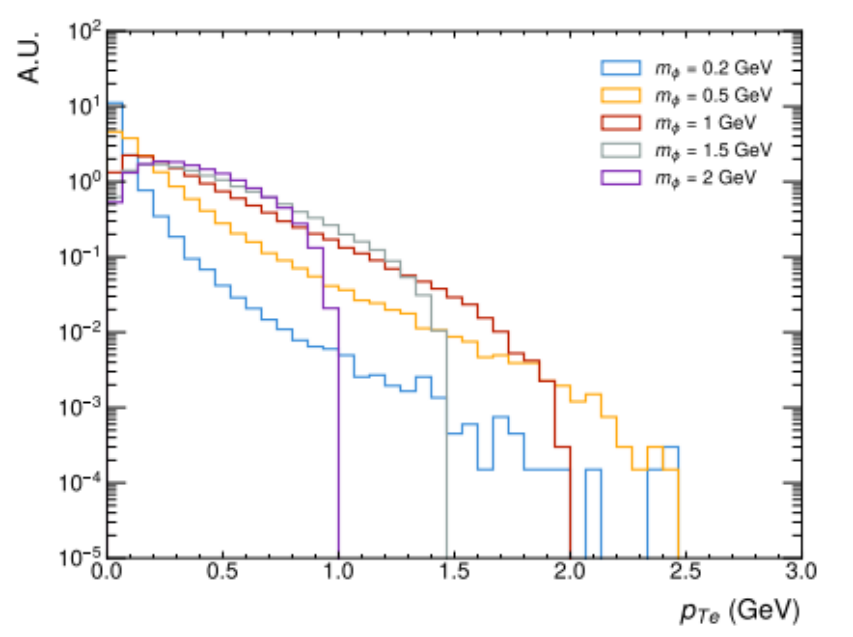


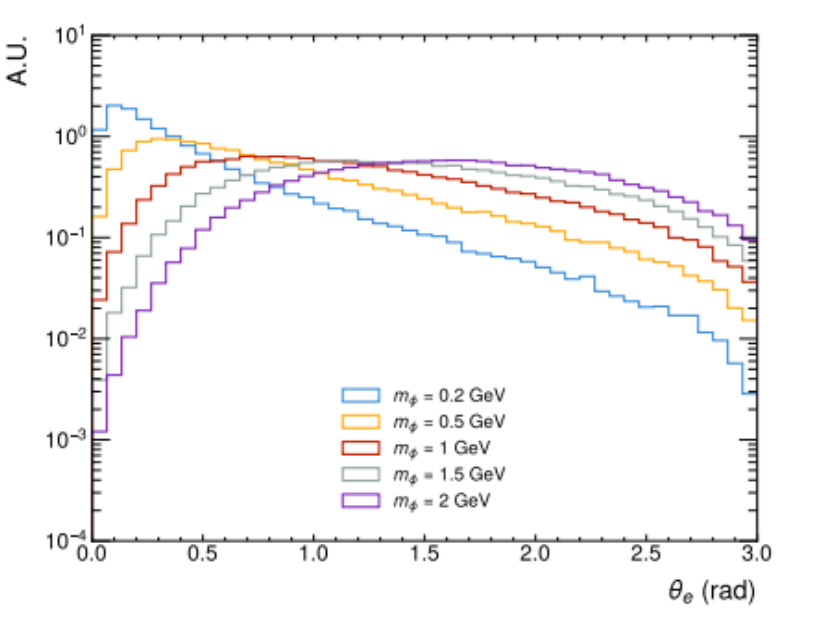
Phys. Rev. Accel. Beams **28**, 053401

Signal Kinematics

Z' and ϕ signals have the similar kinematics distribution







- Sizeable energy and pT for decayed electron
- Energy, pT and θ_e of decayed electron decreases as the m_Z, increases

Background Estimation

- Three main background categories for different final states
- Muon decay has the same final state
- Electron with large theta can be produced in muon ionization and electron pair production

Single electron

Muon decay
(Elastic scattering)
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_m$

Muon radiative decay
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma$

Muon electron scattering
$\mu^- e^- \rightarrow e^- \mu^- (\gamma)$

Muon bremsstrahlung +decay
$\mu^- N \rightarrow N e^- \bar{\nu}_e \nu_m \gamma$

Multiple electrons

Muon decay internal conversion
$\mu^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_m$

Muon decay +
photon external conversion
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma, \gamma N \rightarrow e^+ e^- N$

Electron pair production
$\mu^- N \rightarrow N \mu^- e^+ e^-$

Muon electron scattering + muon decay
$\mu^- e^- \rightarrow e^- \mu^- (\gamma)$, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m$

Hadrons

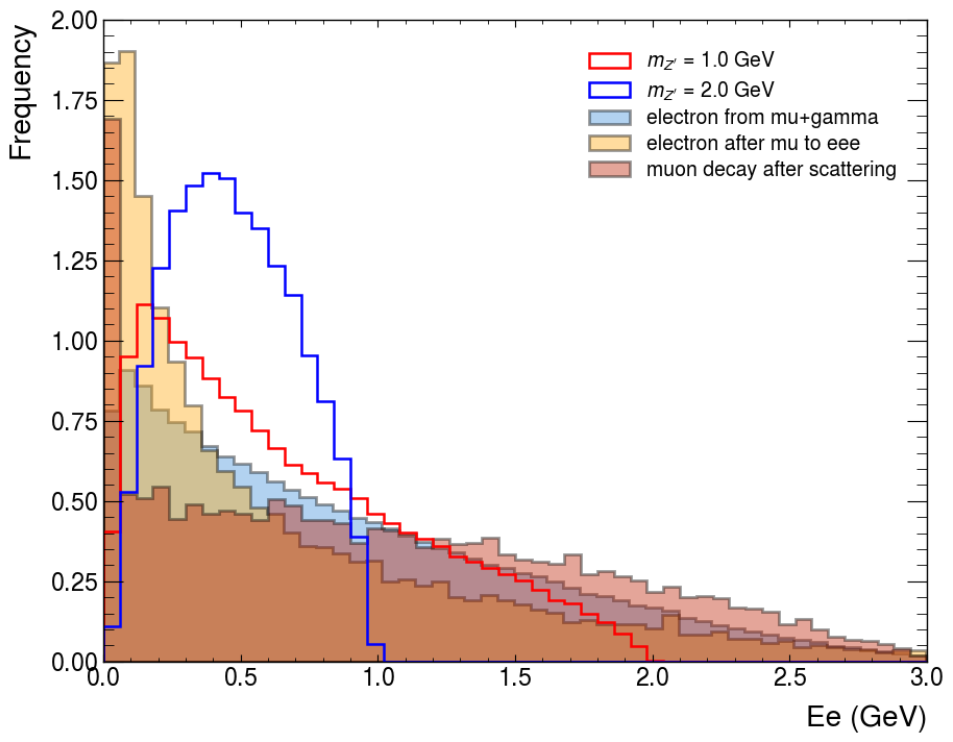
Muon decay+ muon nuclear
$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_m N' + hadron \ldots$

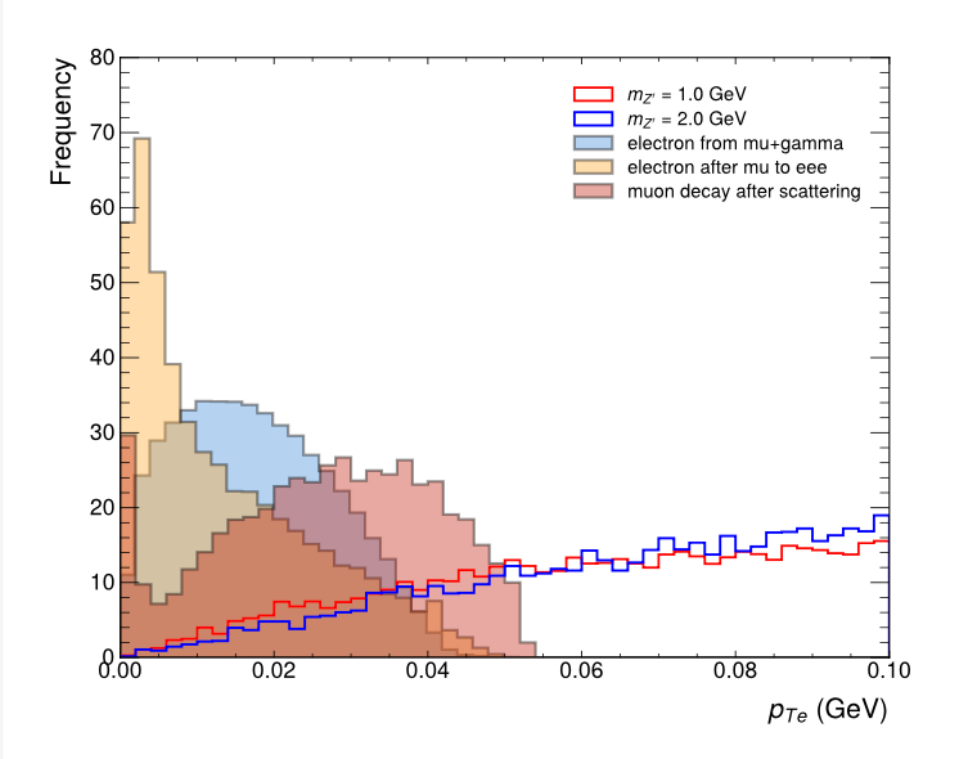
Muon ionization
$\mu^- N \rightarrow N' \mu^- e^- + hardron$

Background Estimation: Muon Decay

Considering muon decay (including elastic scattering) and two rare decay, muon radiative decay (RD, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma$) and internal conversion (IC, $\mu^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_m$):

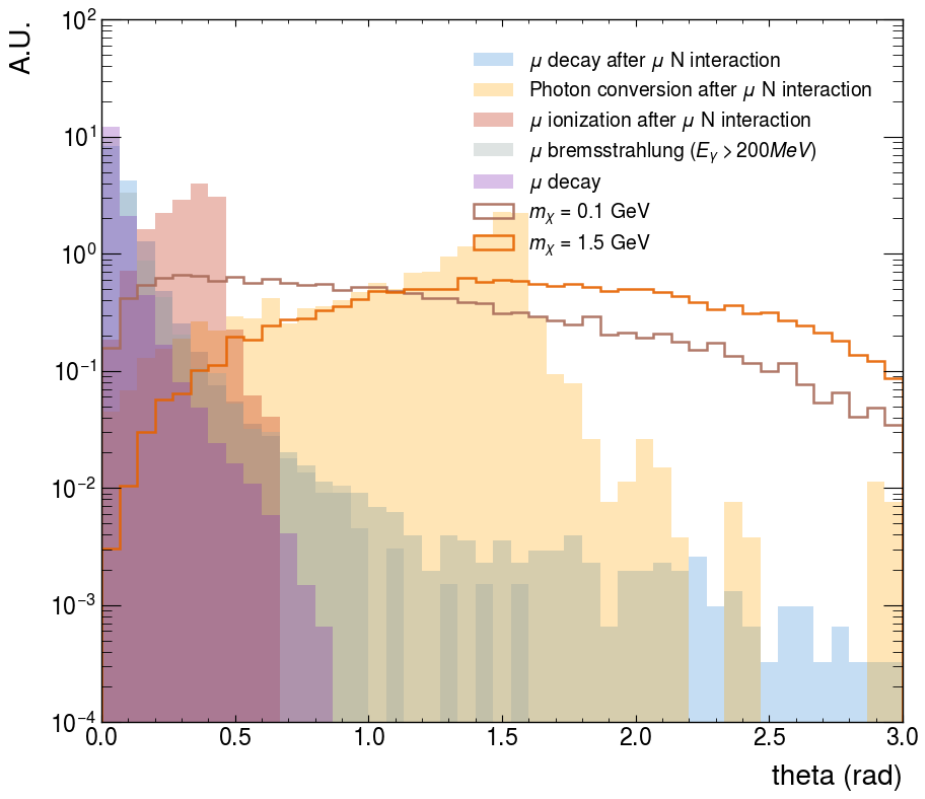
- Muon decay: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m$, taking into account of muon multiple scatterings
- Rare decay processed are simulated by McMule

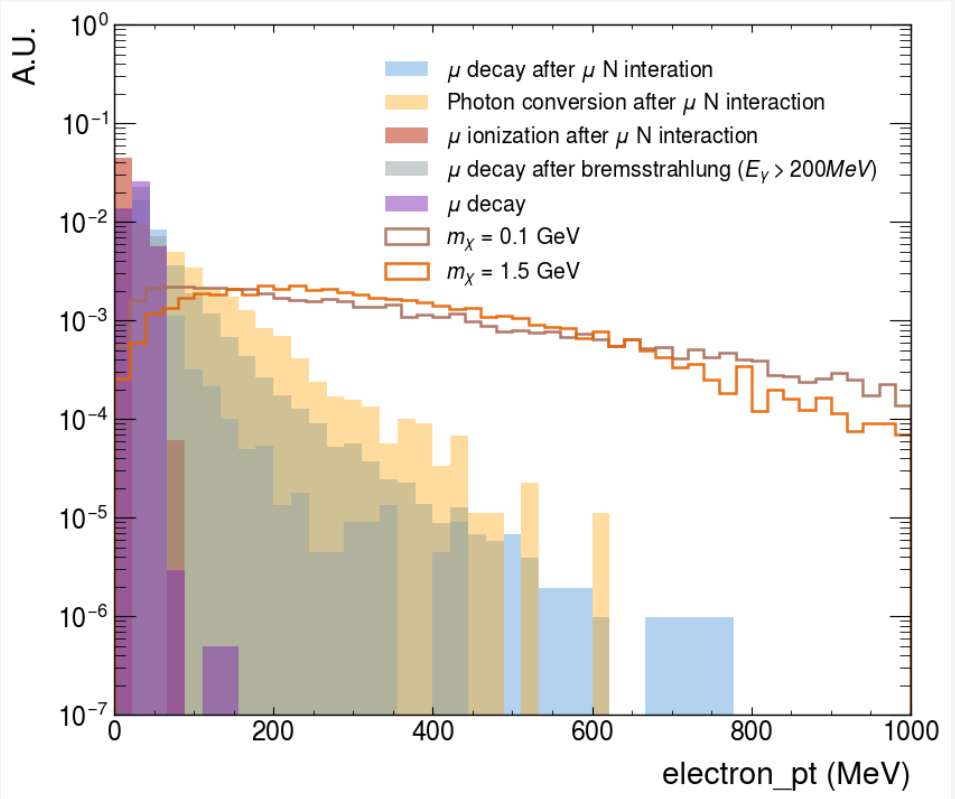




More Backgrounds

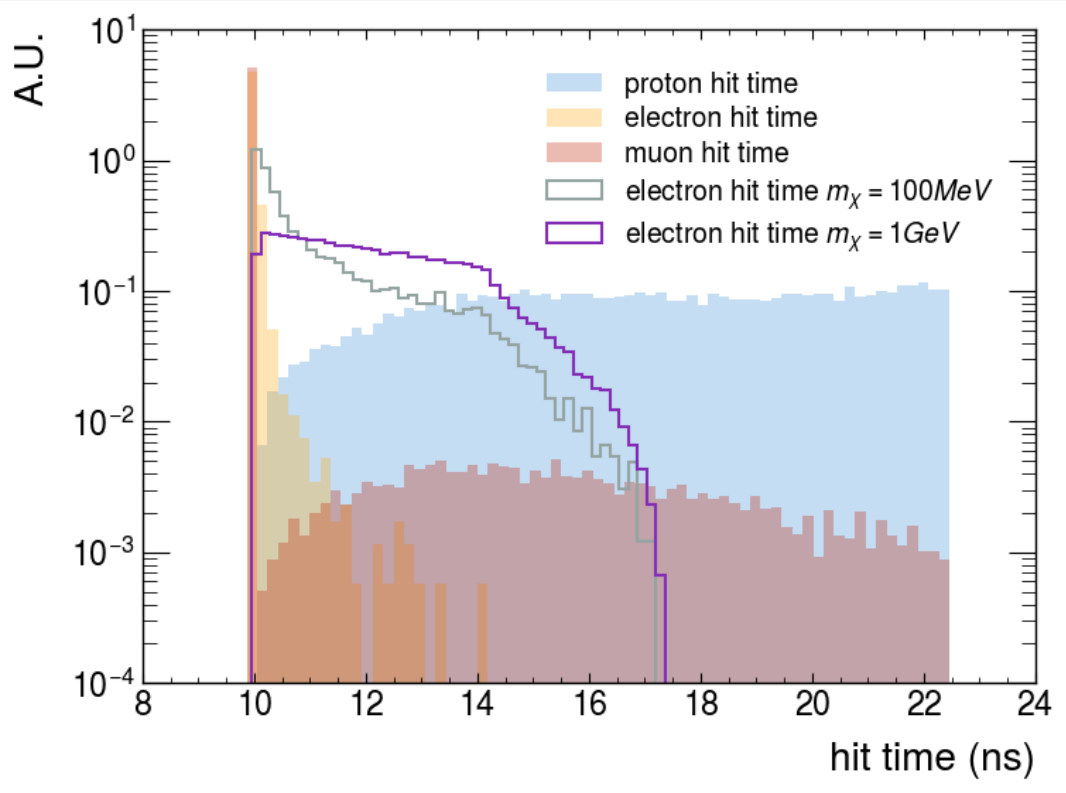
- Muon nuclear process (N + $\mu^- \rightarrow$ N + μ^- + p…..): produces charge particles such as protons, pions and muons with similar characters with those of signal process
  - μ-N interaction and μ bremsstrahlung processes may produce electrons with large pT
    - Hadrons can be identified and rejected by TOF detector
    - Photons can be rejected by gamma detector if needed



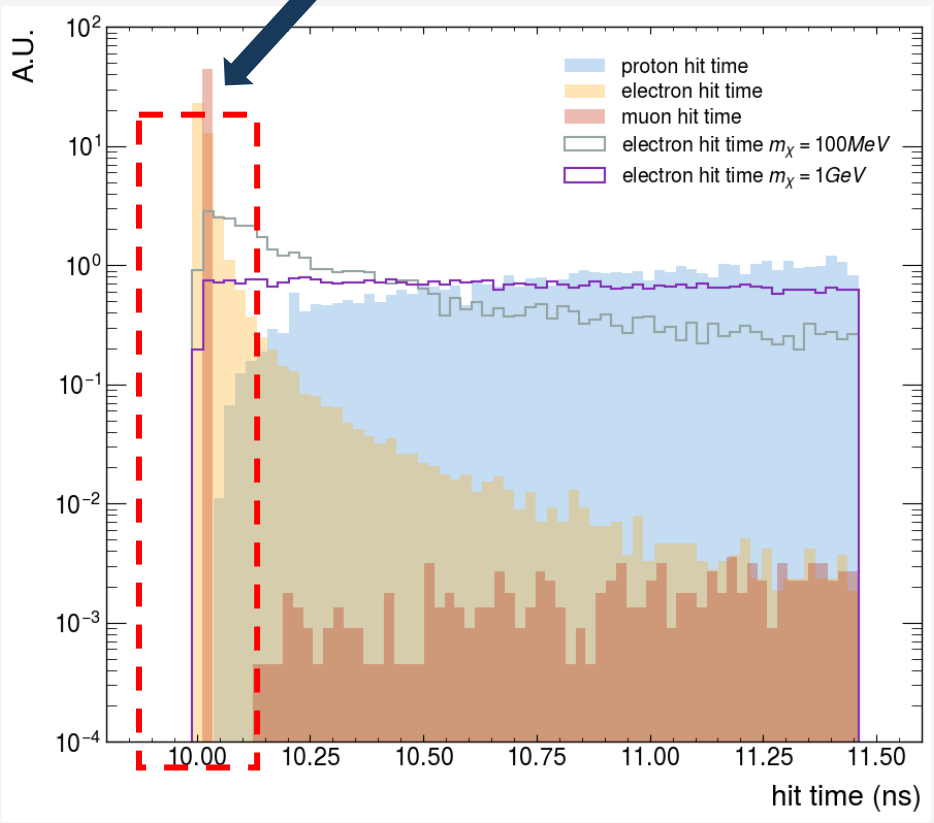


Proton and Muon Veto

- Time of flight (TOF) for protons, muons can be used as a veto
  - Particles travelling between two TOF detectors with distance L = 3 m
- TOF time selection [11ns, 14ns]
  - Remove most protons/hadrons since most electrons arrive < 14 ns
  - Remove muon beam remnant and non-decayed muons > 11ns
  - Good TOF timing resolution at 20-30 ps



TOF for different particles

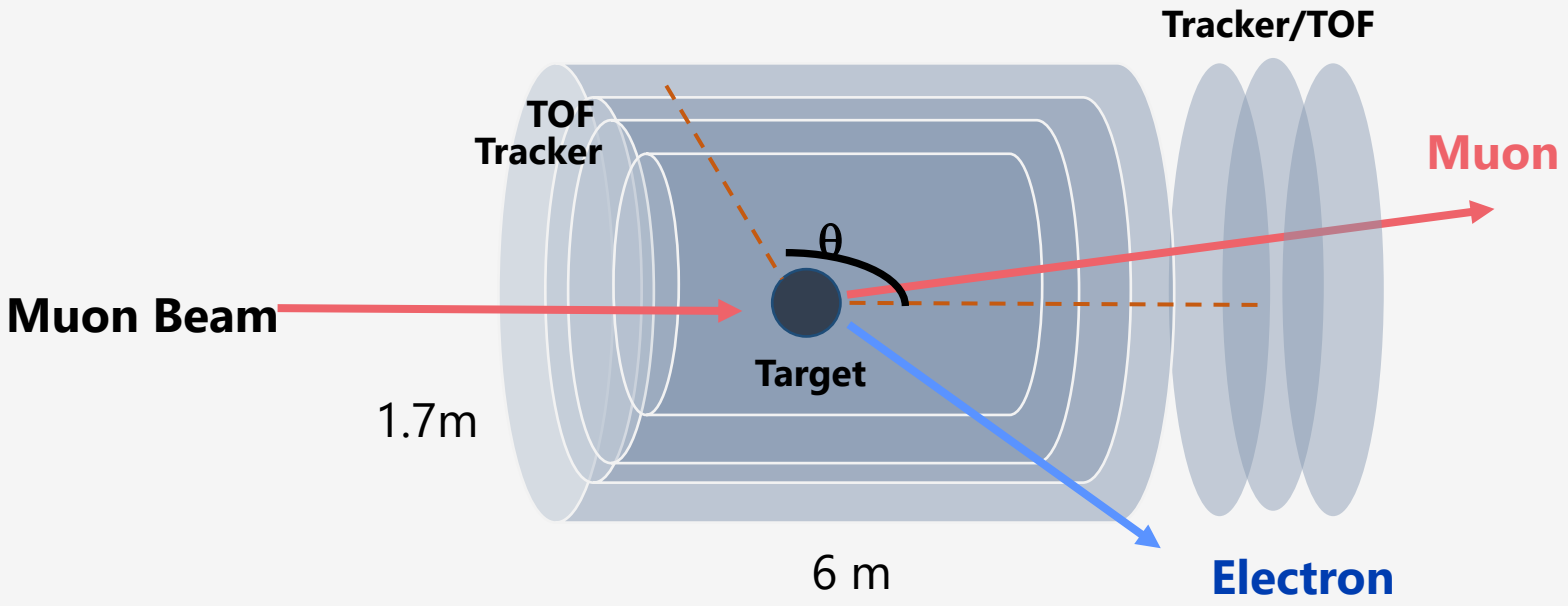


Signal Selection and Background Rejection

- Particle (veto) detector
  - Muon veto : **TOF > 11 ns**
    - Remove muon beam remnant
  - Proton veto : **TOF < 14 ns**

- Single track with Tracker/TOF
  - **Number of track = 1**
  - Tracking efficiency: 99%

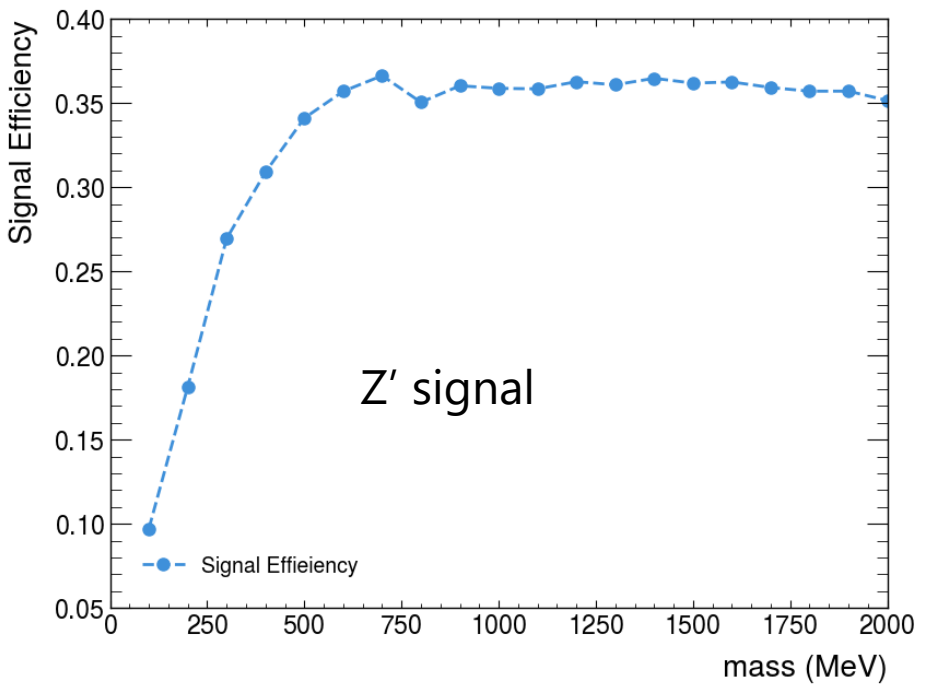
- Geometry acceptance:
  Electron θ acceptance: | θ | < 120°
- Electron pT selection:
  pT > 20 MeV
- Electron θ selection:
  | θ | > 0.75 radian (43 °)

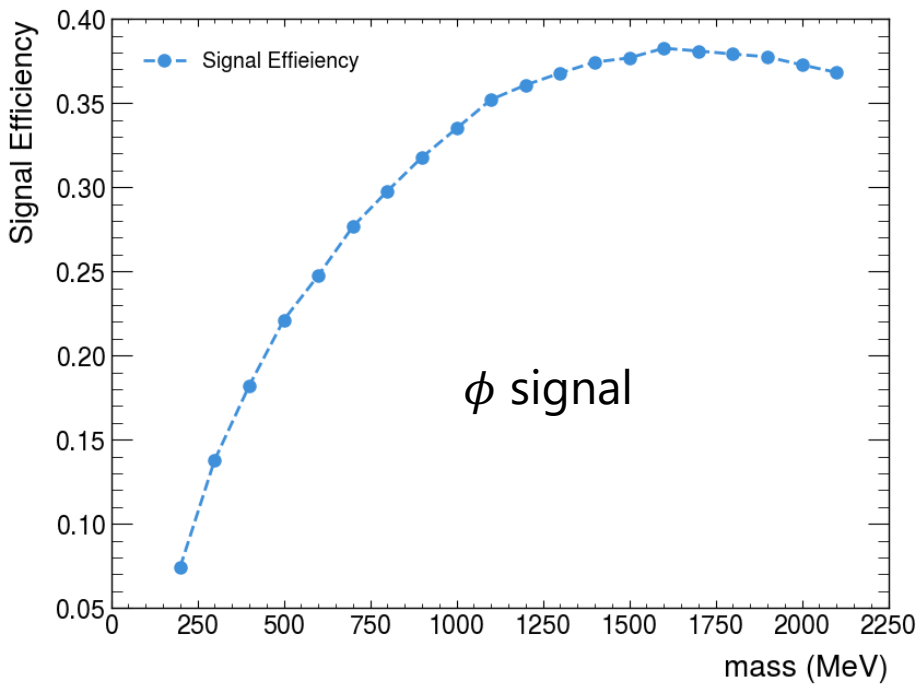


Signal Efficiency after Selection

- The signal efficiency ranges from 10% to 35%
- Geometry acceptance accounts for the efficiency drop in low mass region

3 GeV Muon beam
Flux rate: 3.5*10^6 μ/s
Beam time: 400 hours
Total events: 5*10^{12} MOT





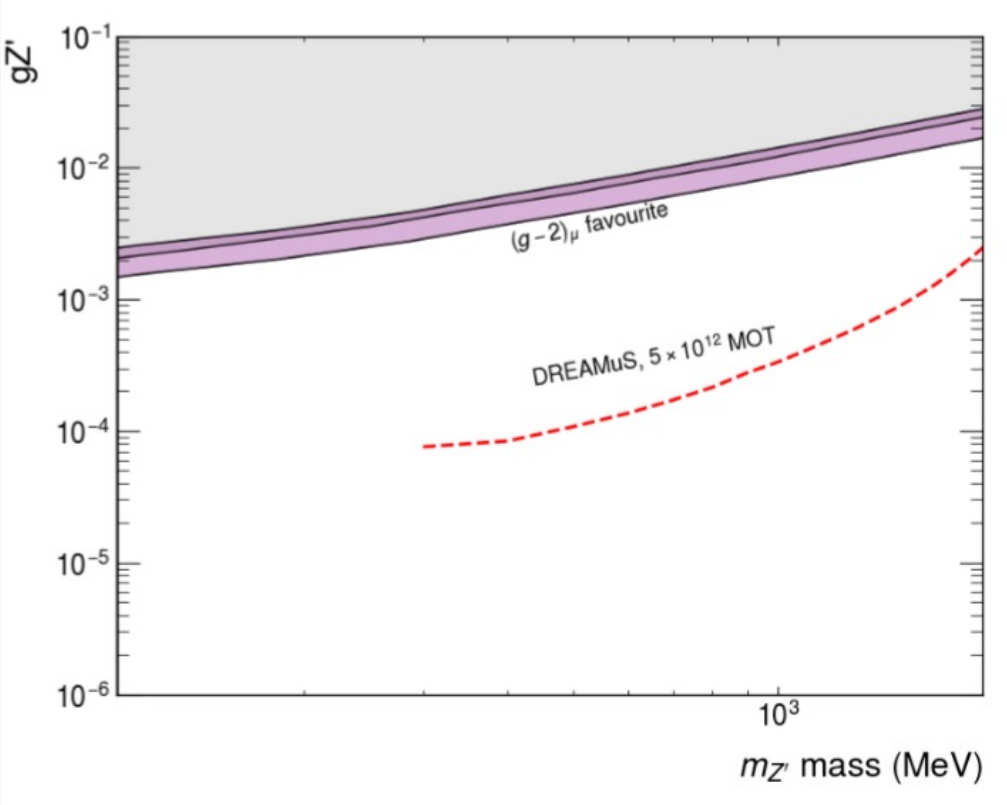
Background Removal

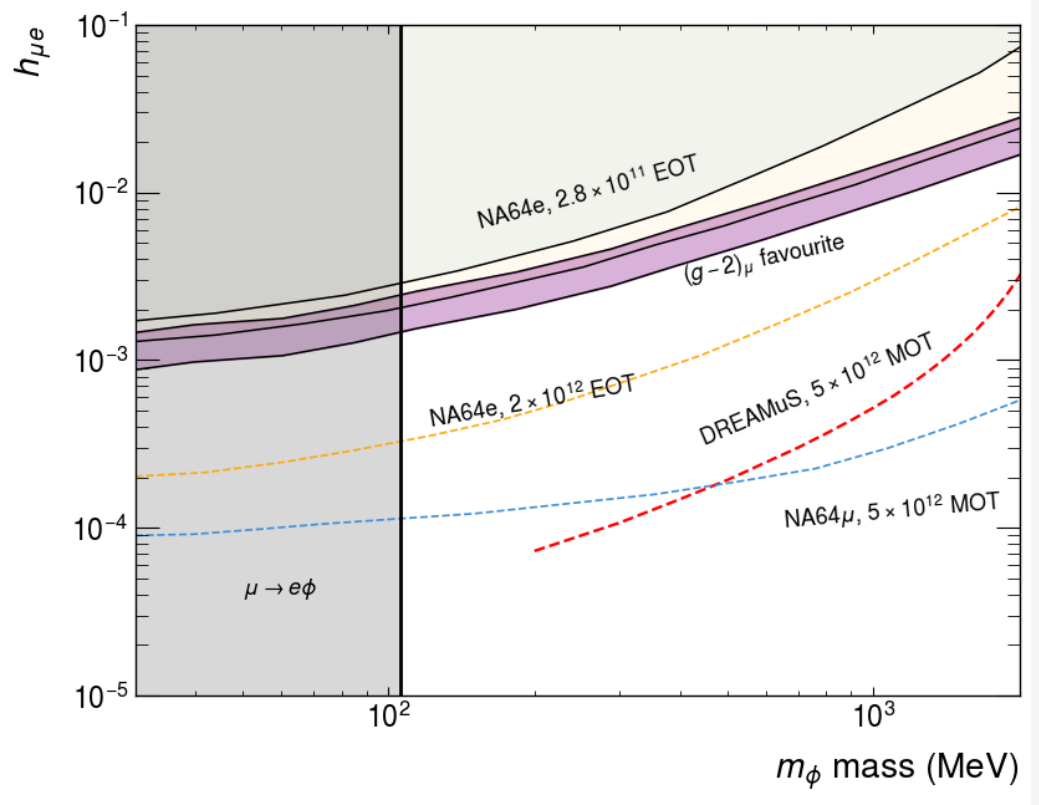
- Muon and proton veto can remove most backgrounds
- Electron pT and θ selection to further suppress backgrounds

Process	Muon electron scattering	Muon Ionization	Muon bremsstrahlung	Electron pair production + photon conversion	Elastic scattering	Muon-nuclear interaction
	10000	63089	164411	99281	113936	167120
Single track	358	2263	135506	138	88917	144
11 ns < TOF < 14 ns	0	84	314	0	37	3
Electron θ >43°	0	0	0	0	20	2
Electron pT> 20 MeV	0	0	0	0	0	0

Search Sensitivity with HIAF

- Stringent limit on flavor violating Z' model
  - 5*10^{12} MOT with background free assumption, $m_{Z'} = 3m_{\chi}$
  - 90% C.L. limit on $g_{Z'}$: ~ 10^{-4} - 10^{-5}



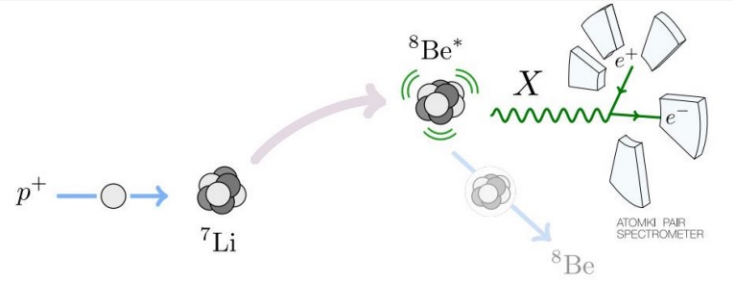


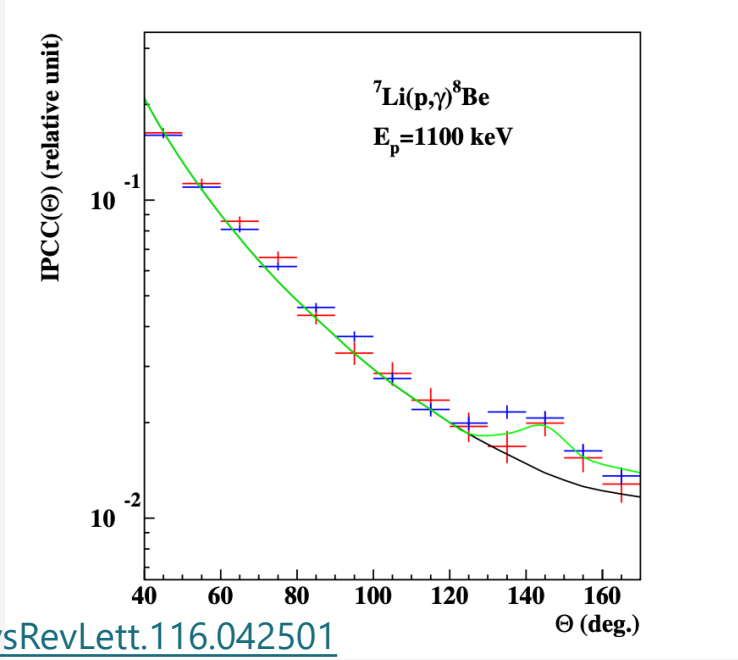
Best limit on flavor violating scalar ϕ model in the low mass region

- 90% C.L. limit on $h_{\phi e}$: ~ 10^{-4} - 10^{-5}

X_{17} Dark Matter Search

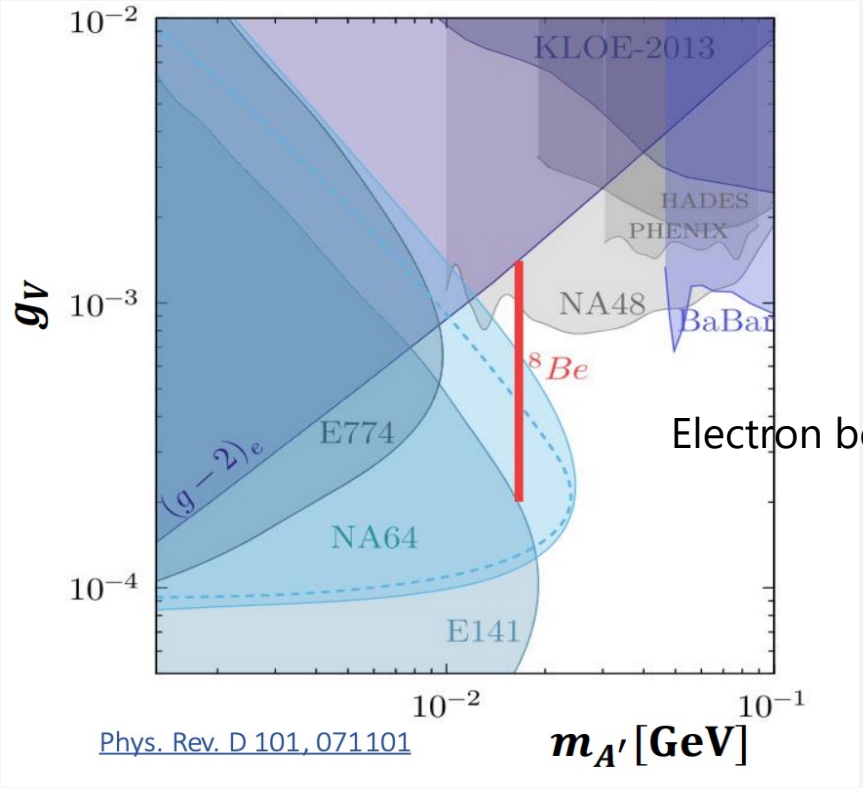
Anomalous excesses in angular correlation of ^{8}Li and ^{4}He couples are observed by the ATOMKI collaboration





PhysRevLett.116.042501

NA64 searched the X_{17} dark matter using 100 GeV electron beam and excluded certain X_{17} parameter space for dark photn explaination

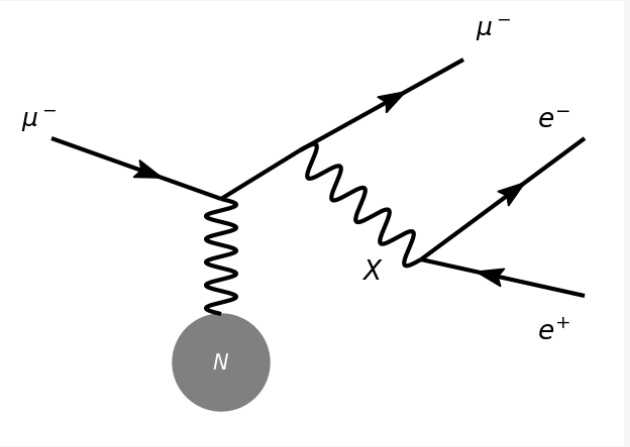


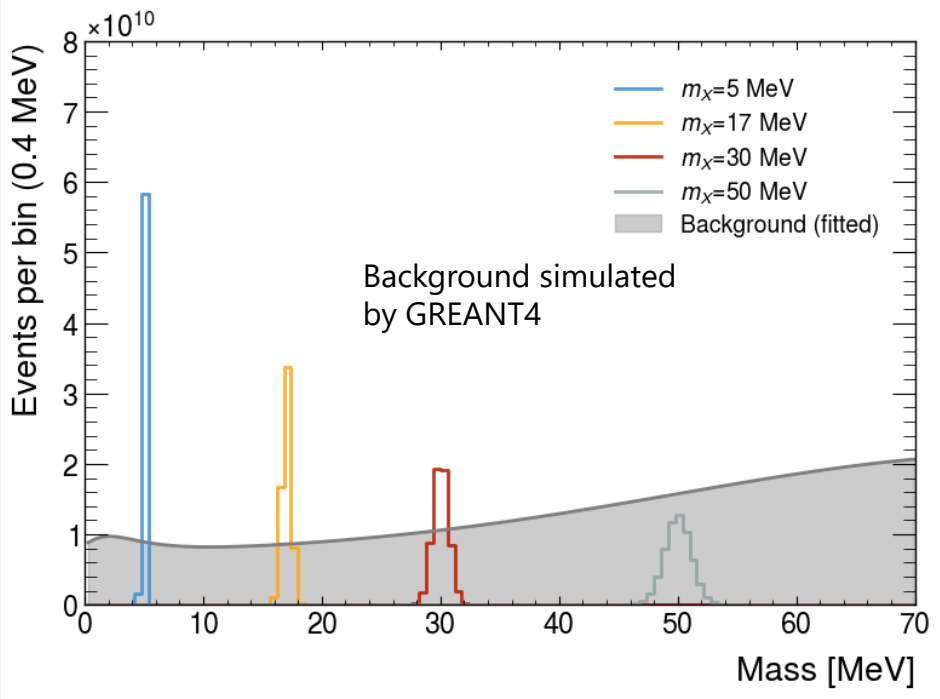
Phys. Rev. D 101, 071101

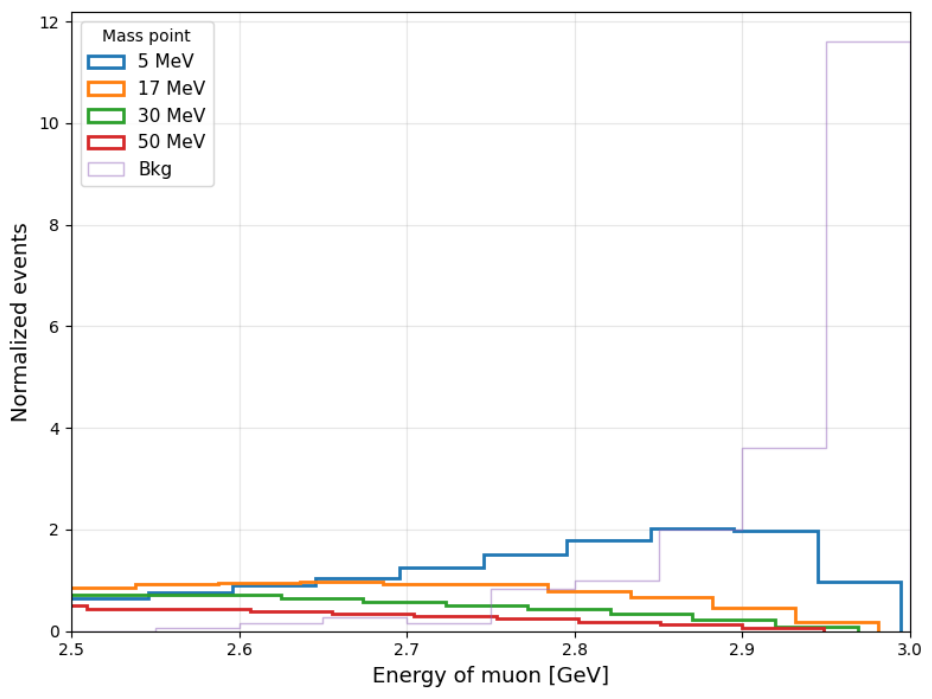
Electron beam

X_{17} Dark Matter Search at DREAMuS

- **Invariant mass method**: scaning the invariant mass distribution to find the mass peak of X_{17}
- Adding ECAL to measure the energy of electron pairs
- Require momemtum transfer larger than 300 MeV
- Main background: electron pair production by muon



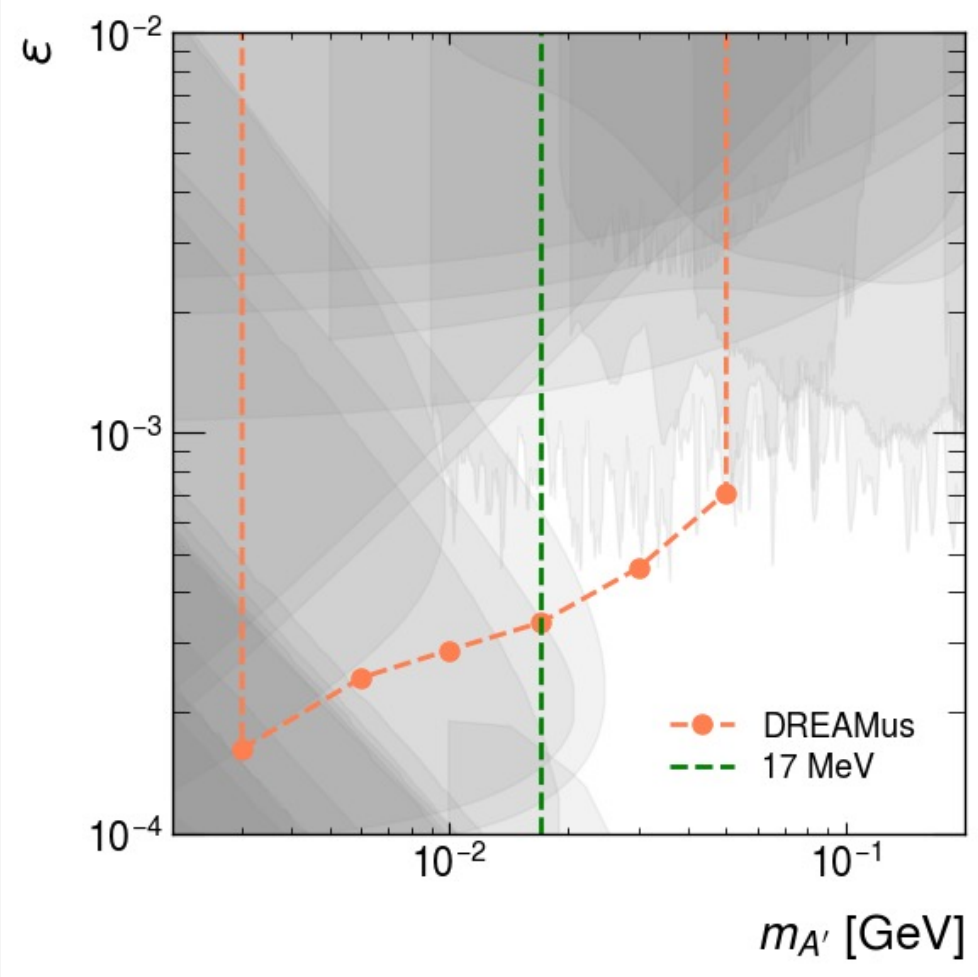




X_{17} Dark Matter Search at DREAMuS

- Signal mass at 3 MeV, 6 MeV, 10 MeV, 17 MeV, 30 MeV and 50 MeV are simulated using 3 GeV muon hitting on 22 cm lead target
- 90% C.L limit is derived and it can exclude the X17 region with $6*10^{13}$ MOT for 1 year run
- DREAMuS benefits from thicker target ($40X_0$) and backgroud modelling comparing with electron beam

90% C.L. limit on ε: ~ 10^{-3} - 10^{-4}



Summary

- **Dark Matter Research with Advanced Muon Source (DREAMuS)**
  - A proposal for fixed-target experiment to search for dark matter with HIAF beam
  - Preliminary signal and background study with a tracker + TOF detector
- **World's best sensitivity limits on flavor violating models**
  - Signal characteristics: electron with large pT and θ
  - **90% C.L. limit on the vector boson model reaches 10^{-5}**
  - **Strongest constrain on flavor violating scalar ϕ model in the low mass region**
- **X_{17} BSM particle search at DREAMuS**
  - **Discover or exclude X_{17} particle around 17 MeV**
- More physics opportunities at DREAMuS
  - Potential use of anti-muon beam to enhance the sensitivity and expand the physics search

Backups

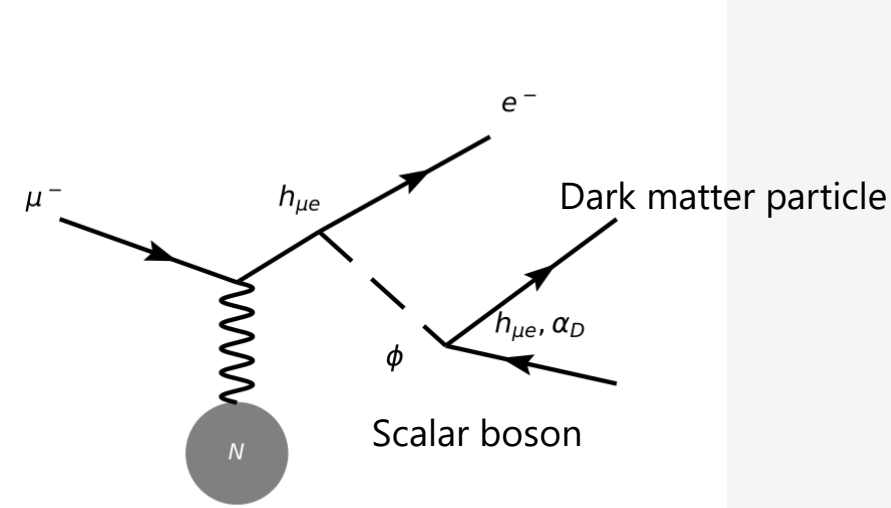
Flavor Violation Boson Search

Dark matter (χ) from a heavy, flavor-violating scalar boson ϕ

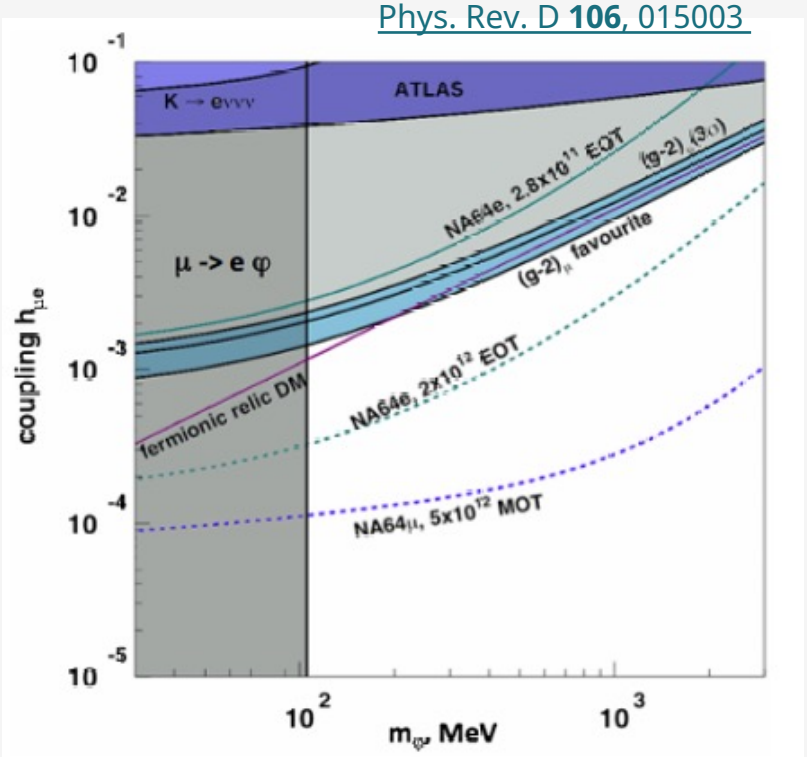
- Using the GeV level muon beam to hit the high–density target to generate flavor violation process
- For example, NA64@cern can shield upper limit on ϕ mass and the coupling

$$L_{\varphi\mu e} = -h_{\mu e}\bar{e}_L\mu_R\varphi + \text{H.c.},$$

Dark Matter Production with Muon Beam

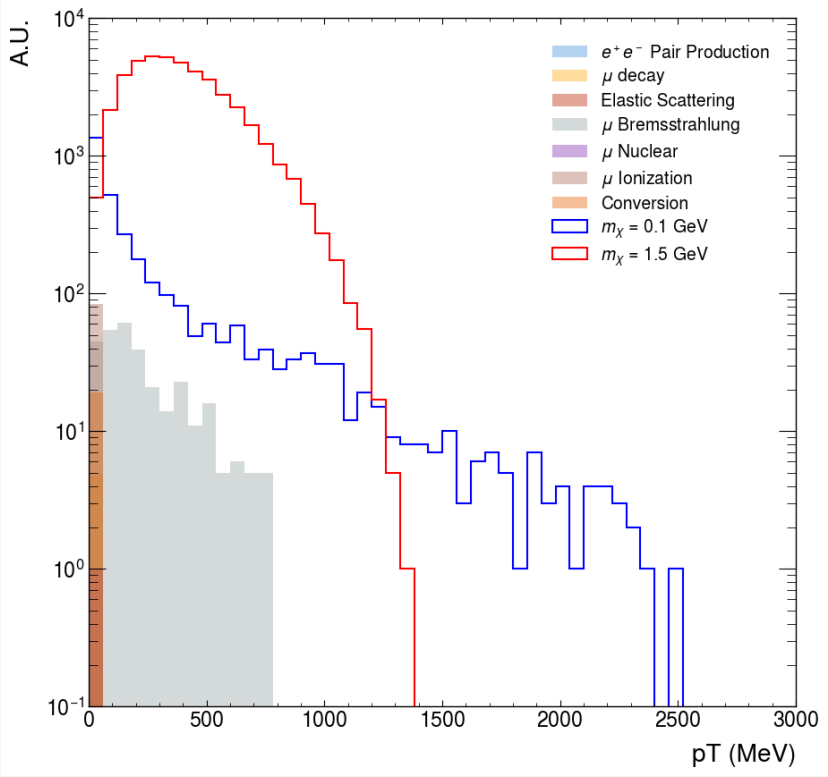


Phys. Rev. D **106**, 015003

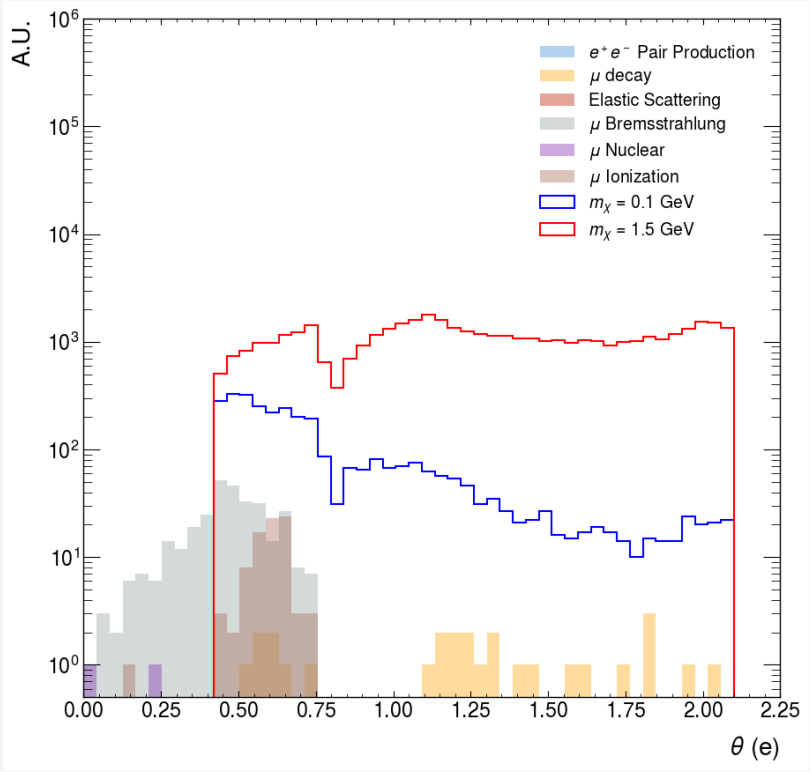


Electron pT and θ Distributions

p_T after TOF selection



θ after TOF selection



p_T after θ selection