International Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP2025)

DREAMuS: Dark matter REsearch with Advanced Muon Source

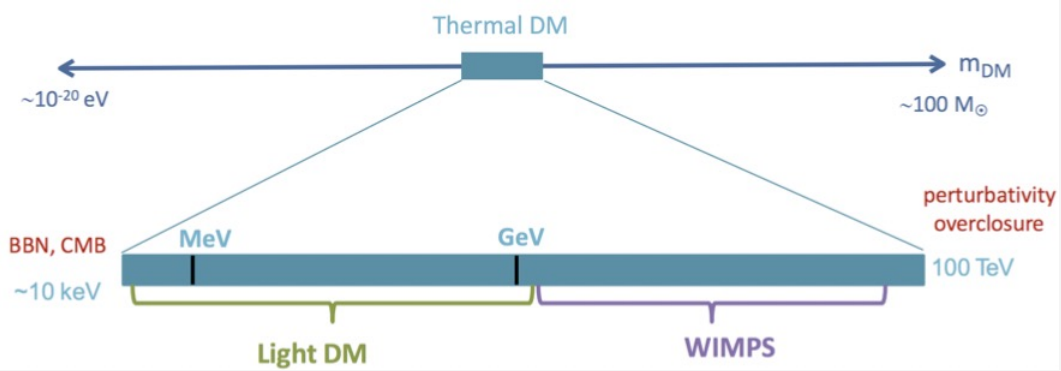
Xiang Chen, Jun Gao, Shaofeng Ge, Liang Li, Zejia Lu, Cen Mo, Yulei Zhang

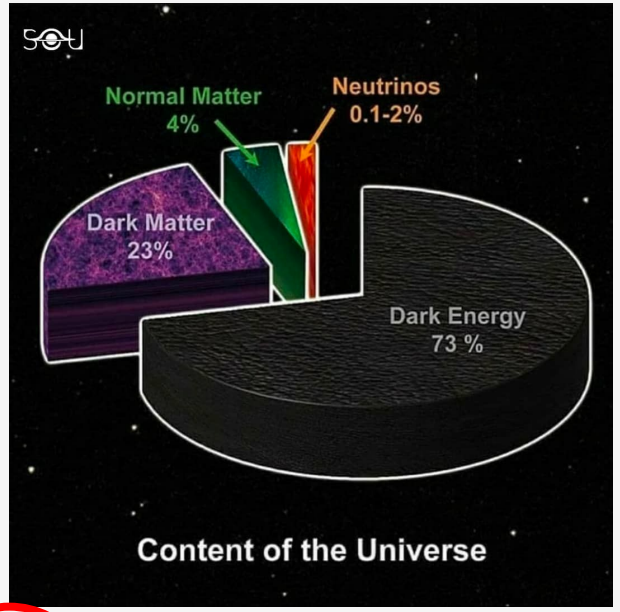
2025/05/17

Shanghai Jiao Tong University

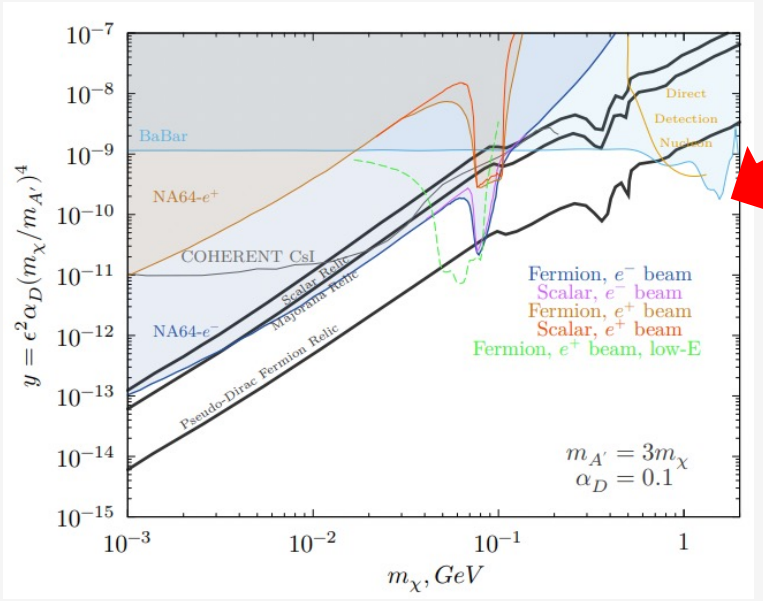
Dark Matter Searching

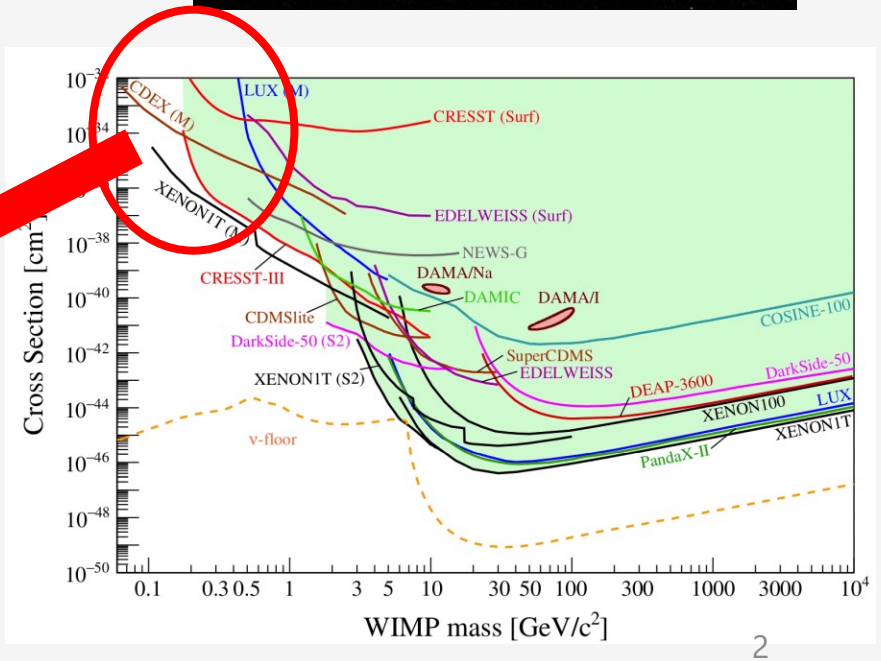
- According to the “freeze-out” mechanism, the mass of dark matter can be in MeV-GeV scale





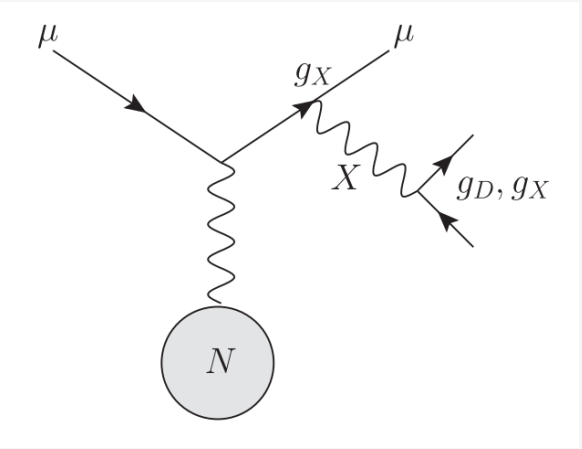
- Muon is 200 times heavier than electron and more sensitive to new physics
- Post-WIMP era: fixed-target experiments have advantages in the low mass region



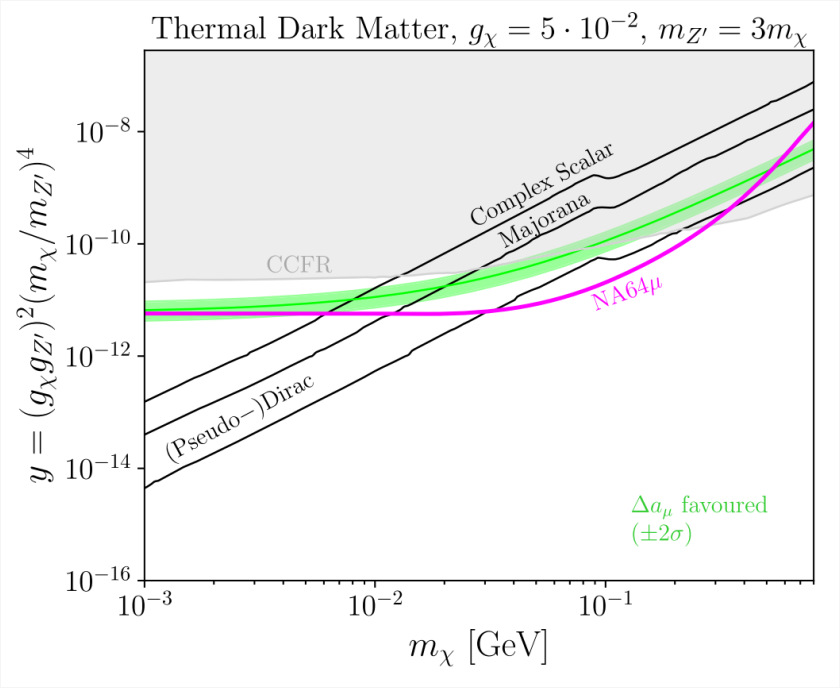


Dark Matter Search With Fixed-Target Experiment

- Various fix-target experiments with different kinds of 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

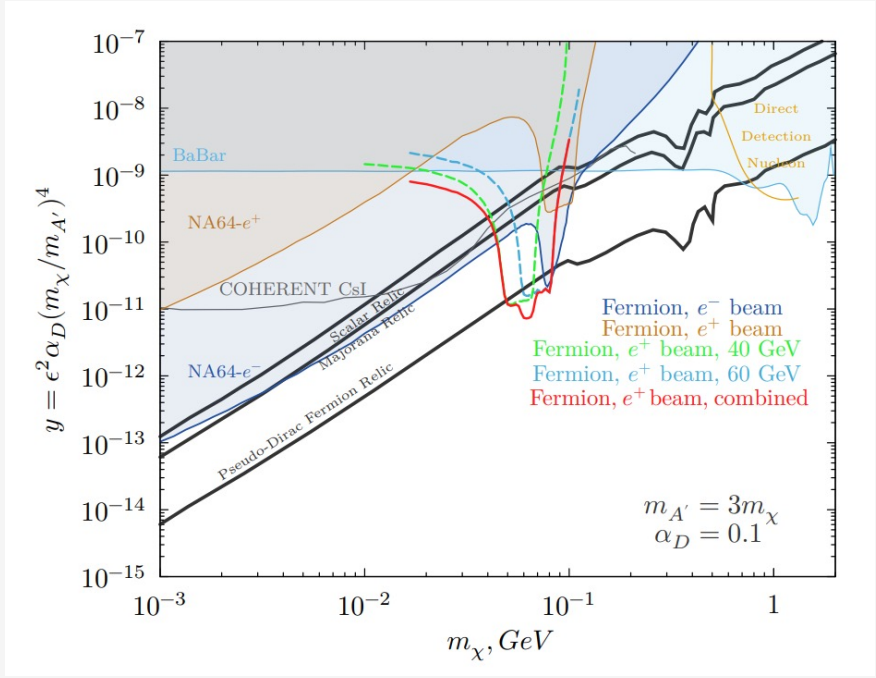


Muon beam



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

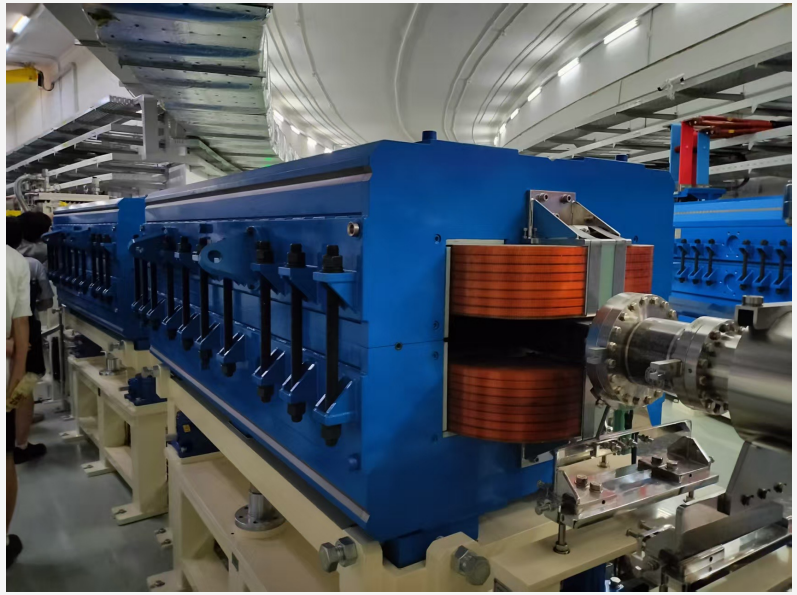
Electron beam



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

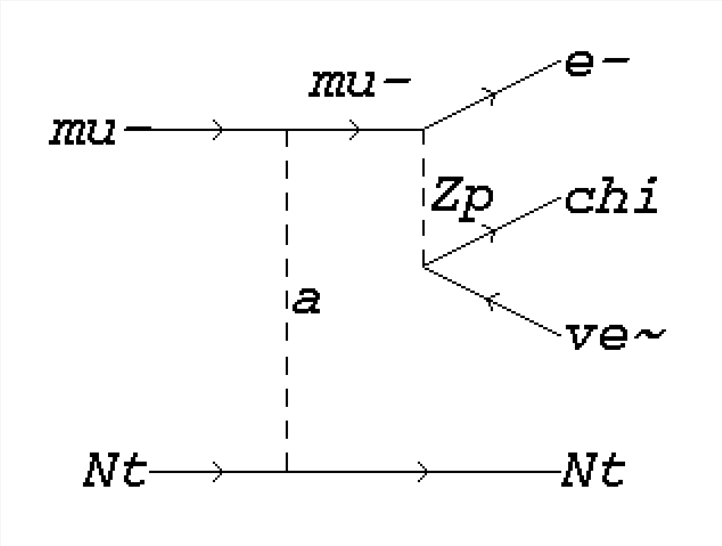
High Intensity Heavy Ion Accelerator Facility

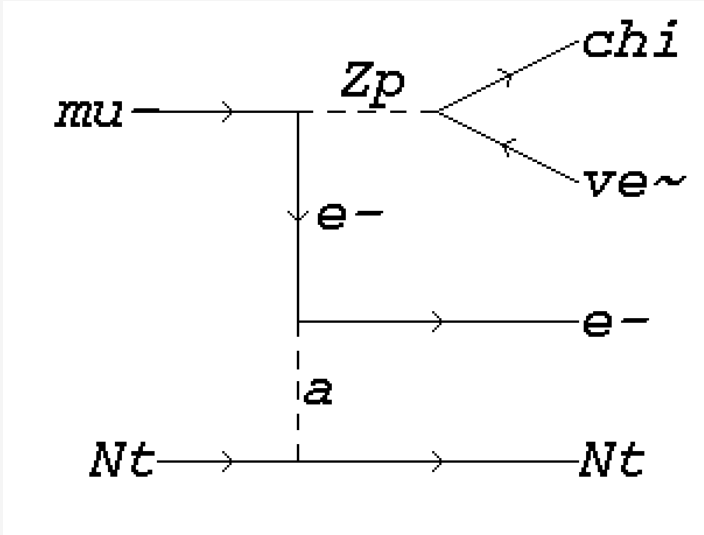
- First high intensity and high energy muon beam in China
  - GeV muon beam is provided with high intensity
  - HIAF beam: 0.5 – 7.5 GeV, 3-8*10^6 μ/s (Peak intensity)
  - CiADS beam: 0.5 – 0.6 GeV, 5*10^8 μ/s (Phase-I)



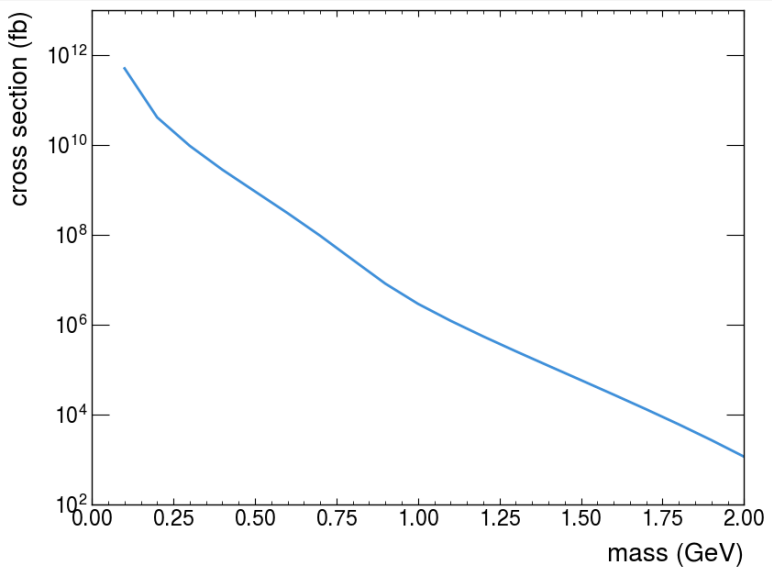
Dark Matter Search With Fixed Target Experiment

- Dark matter search with fixed-target experiment using muon beam @ HIAF
  - Dark matter (χ) from a heavy, flavor-violating Z′
  - 3 GeV muon interaction with 350 μm tungsten target



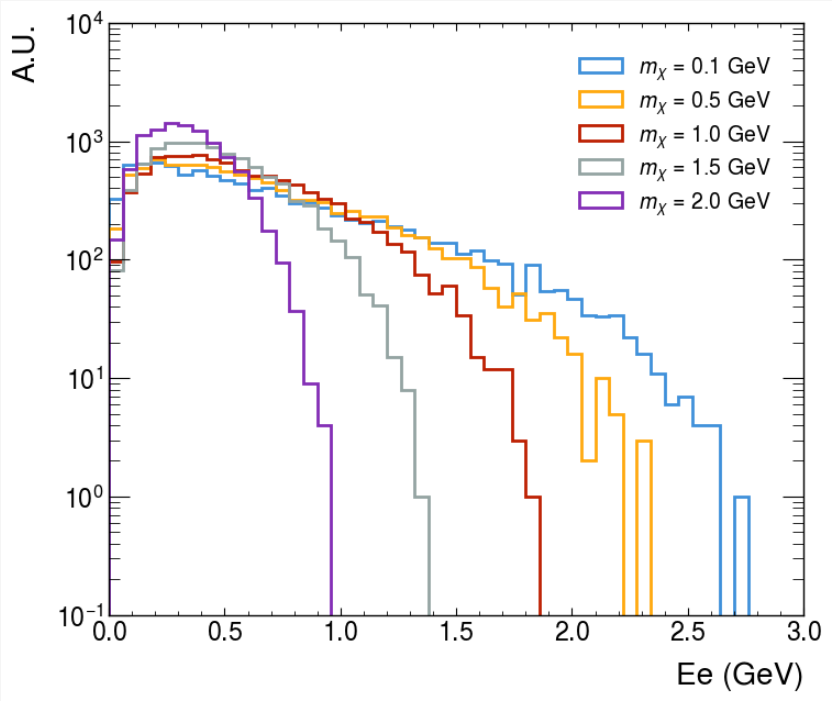


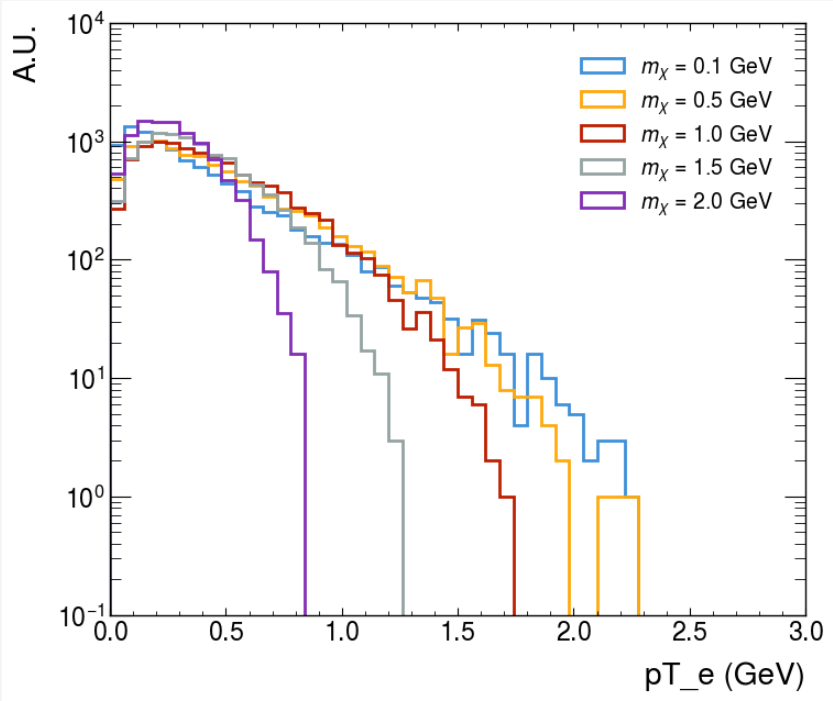
Dark Matter Production with Muon Beam

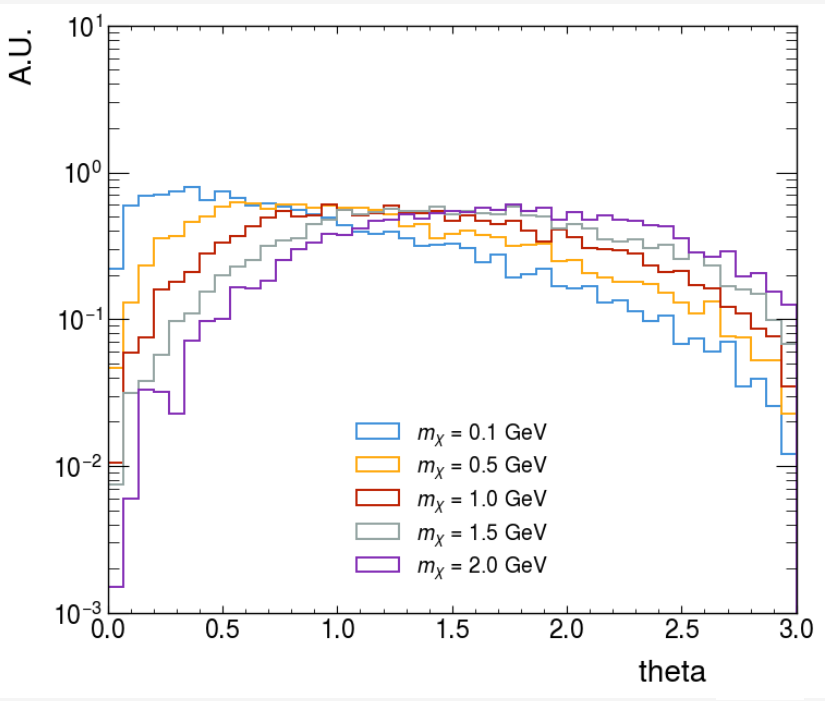


Signal cross section vs. m_χ

Signal Kinematics







- Sizeable energy and pT for decayed electron
- Energy and pT of decayed electron decreases as the m_χ increases

Background Estimation

- Three main background categories for different final states
  - Single electron, multiple electrons and hadrons

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

- Cross section estimation given by Geant4
- Muon decay is included in all processes

$$\text{Events} = \sigma_{per\ atom} * thickness * density * MOT$$

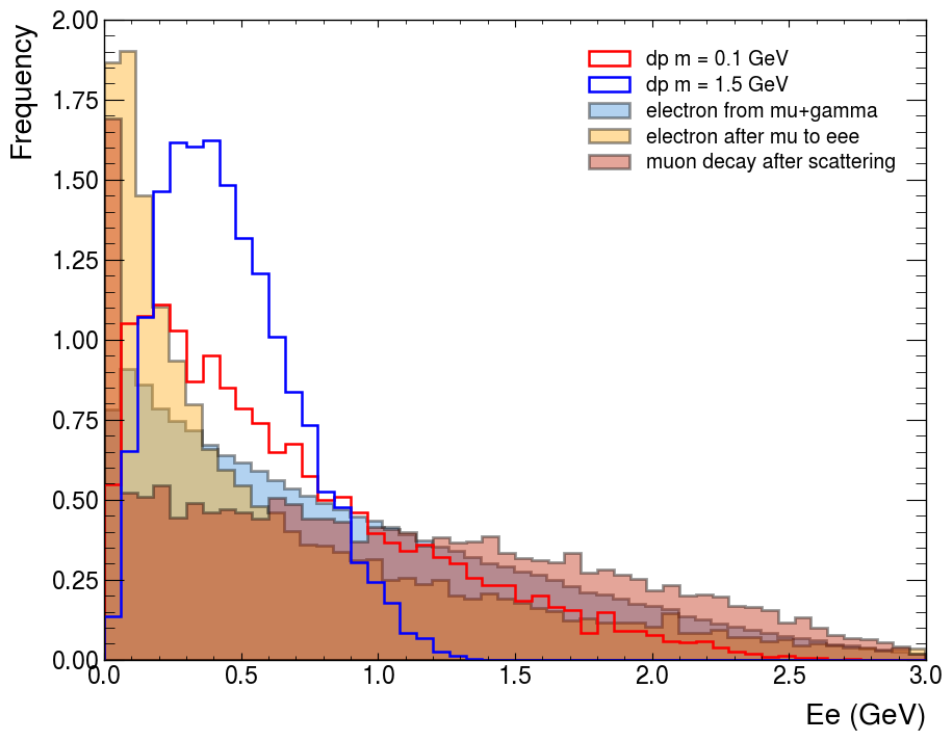
Process1	Muon bremsstrahlung	Elastic scattering	Muon electron scattering	Electron pair production + photon ext. conversion	Muon-nuclear interaction	Muon Ionization
Cross section	35 mb	217 mb	~1mb	~75 mb	~10 mb	1.7 b
Expected Events	$4*10^8$	$1*10^9$	$2*10^7$	$\sim 9*10^8$	$\sim 5*10^9$	$2.9*10^{11}$

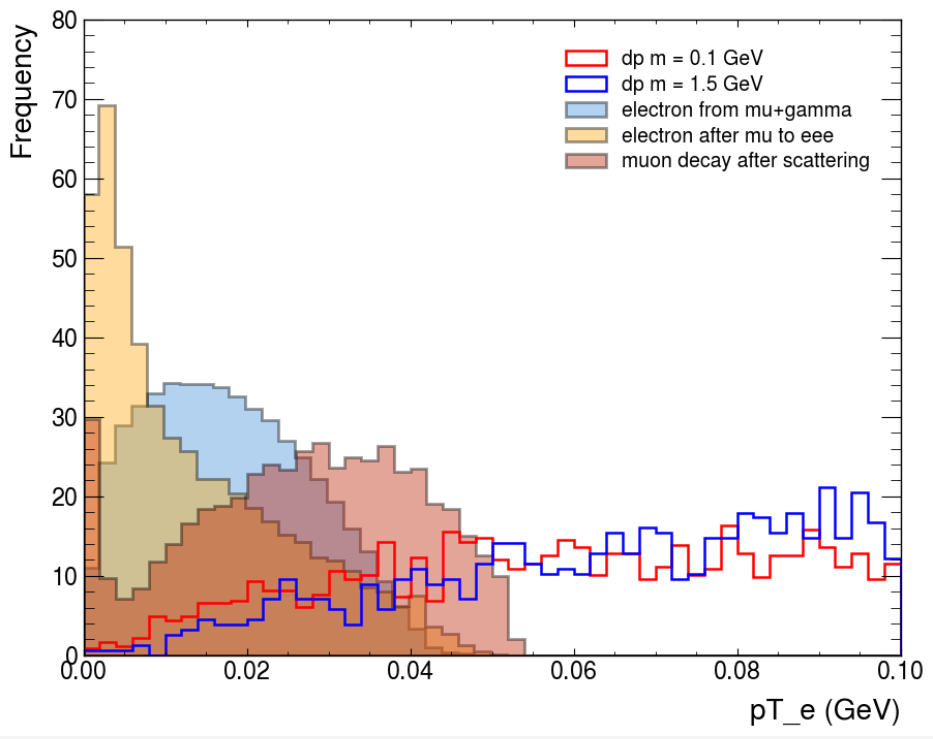
MOT: $6*10^{12}$ muons on target, 600 beam hours (30 days) with HIAF @ 3GeV.

arXiv:2502.20915

Background Estimation: Muon Decay

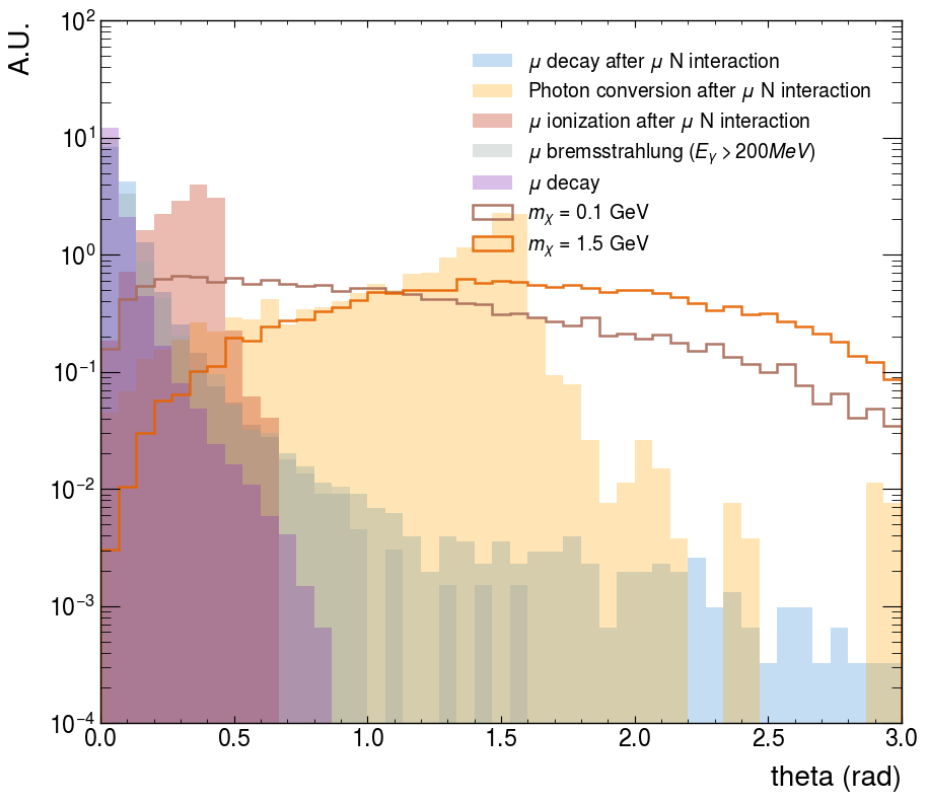
- Major backgrounds come from the muon decay (elastic scattering) and internal conversion:
  - Muon decay: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m$
    - Simulated by GEANT4, taking into account of muon multiple scatterings
  - Muon radiative decay (RD) and internal conversion (IC):
    - $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma$: simulated by McMule
    - $\mu^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_m$: simulated by McMule

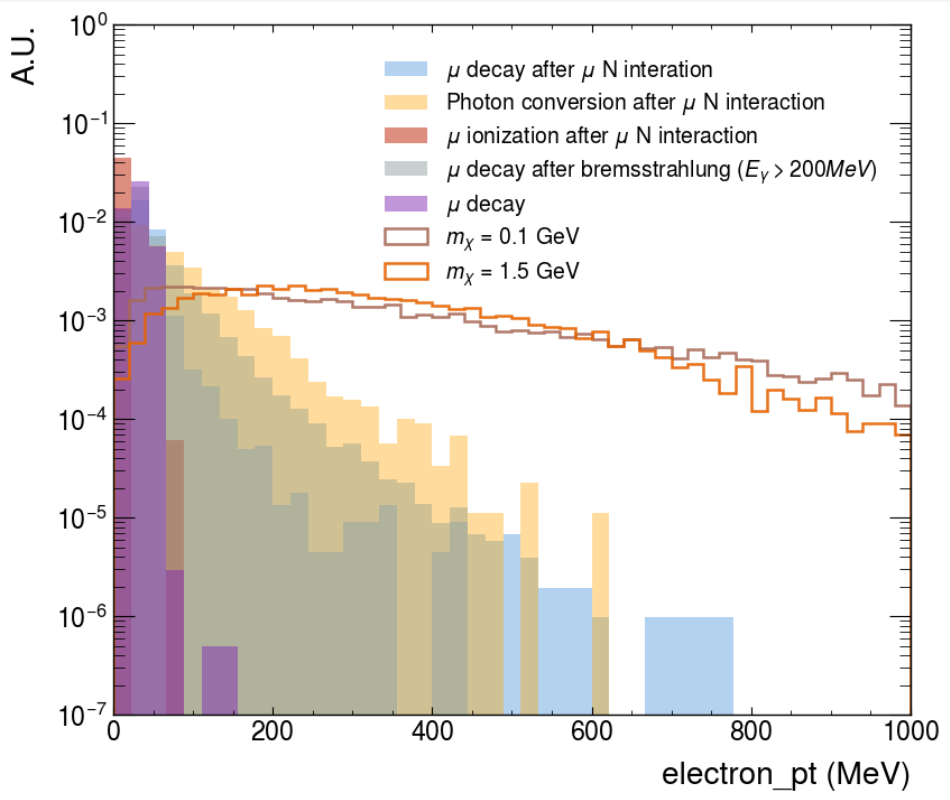




More Backgrounds

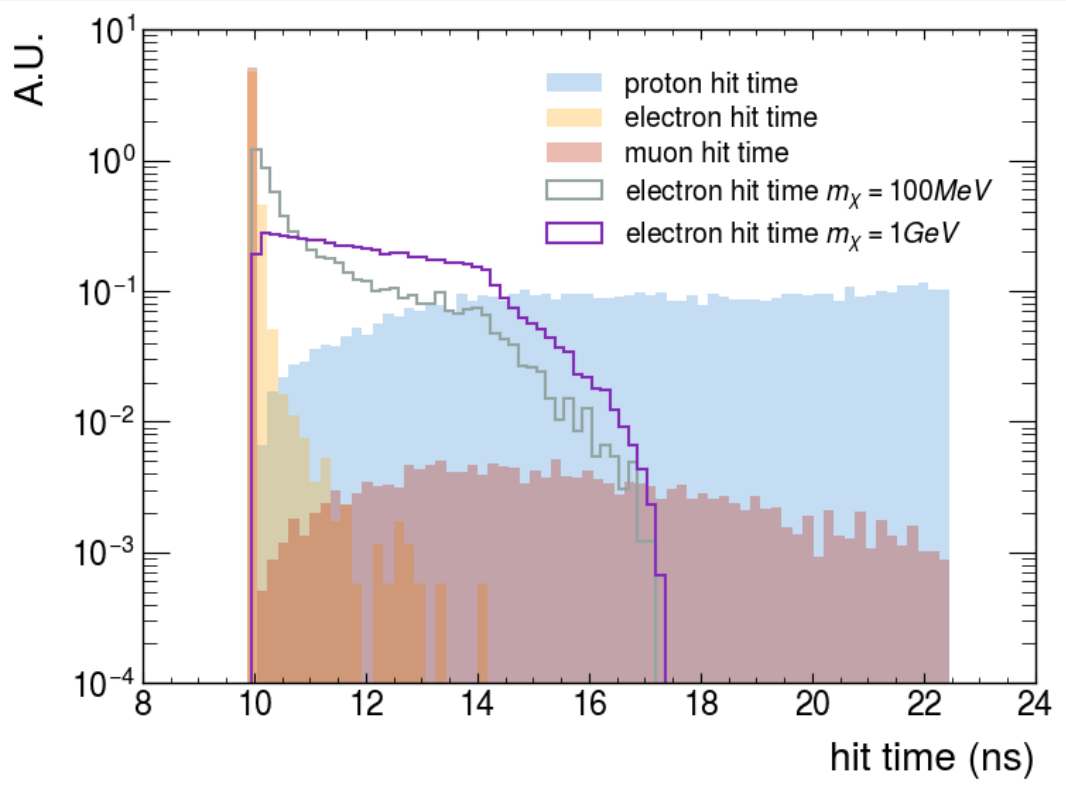
- Muon nuclear process (N + μ^- → N + μ^- + p…..): produces protons, pions and muons etc.
  - μ-N interaction and μ bremsstrahlung processes may produce electrons with large pT
    - Hadrons can be identified and rejected by TOF detector
    - Photons can be rejected by gamma detector if needed



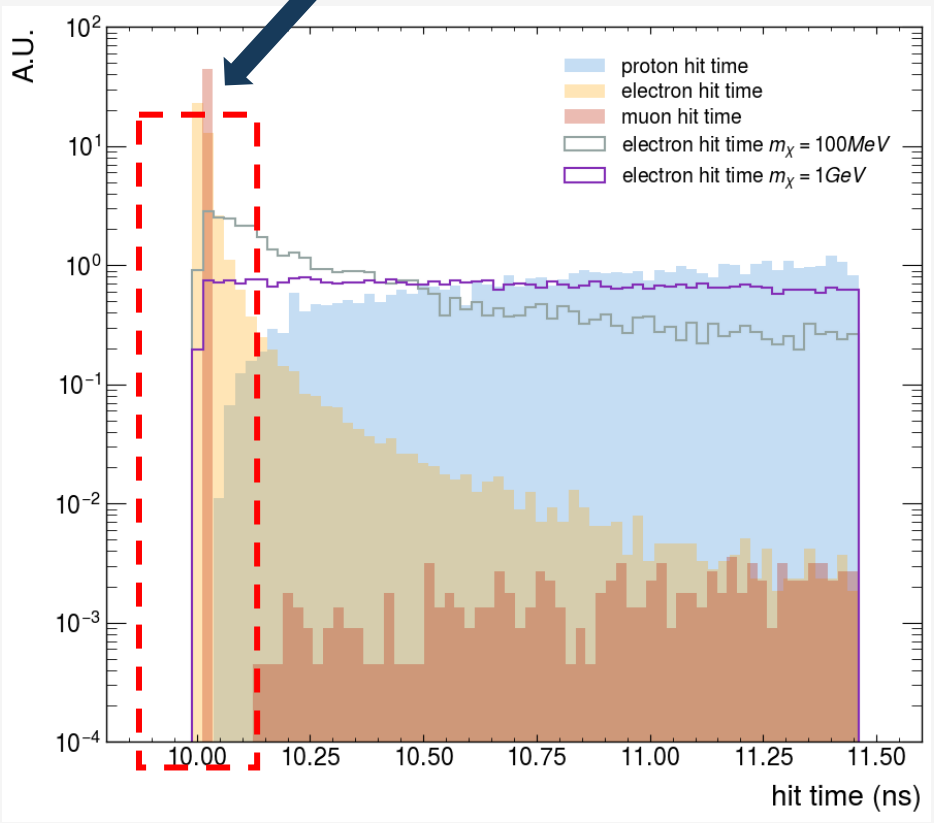


Proton and Muon Veto

- Time of flight (TOF) for protons, muons can be used as a veto
  - Particles travelling between two TOF detectors with distance L=3000 mm
- 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

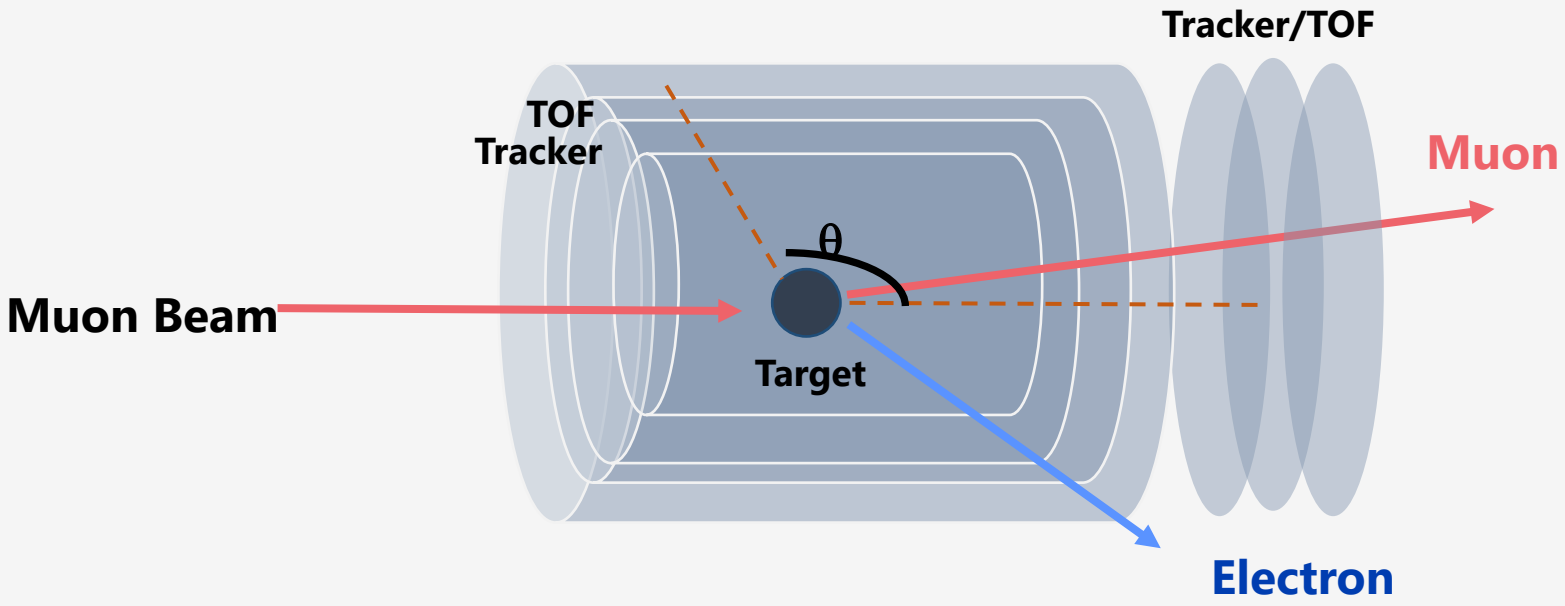


Signal Selection and Background Rejection

- 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 °)



Background Removal

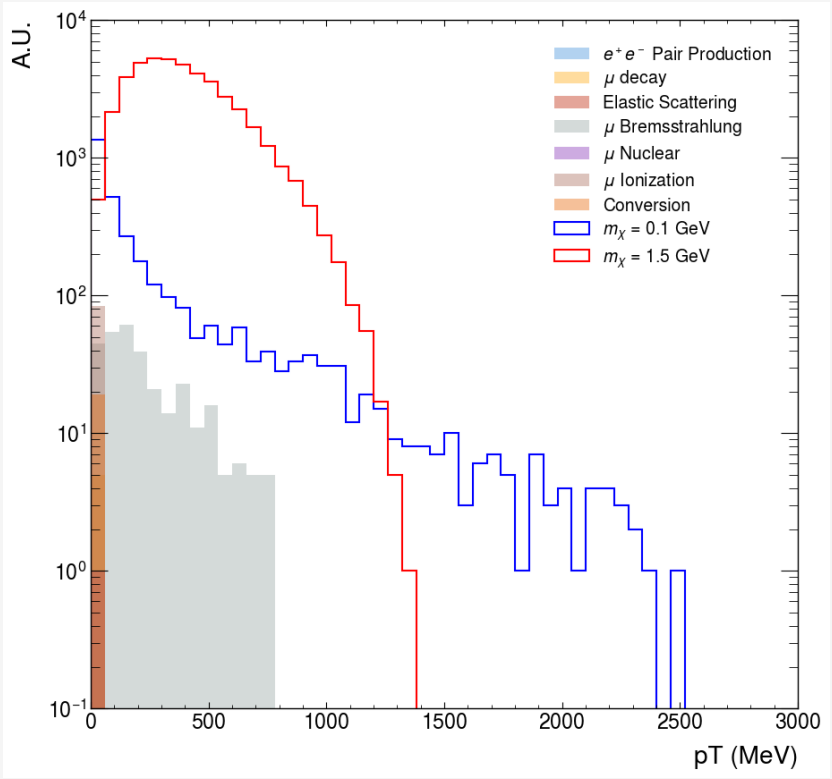
- Muon and Proton veto can remove most backgrounds
- Electron pT and θ selection to further suppress backgrounds

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

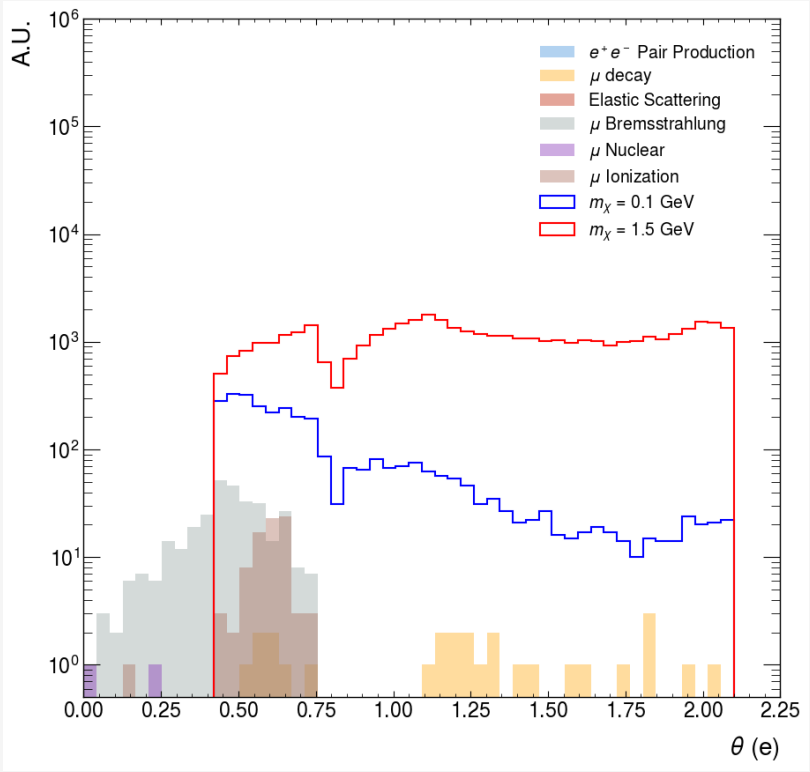
Signal efficiency: ~ 35%

Electron pT and θ Distributions

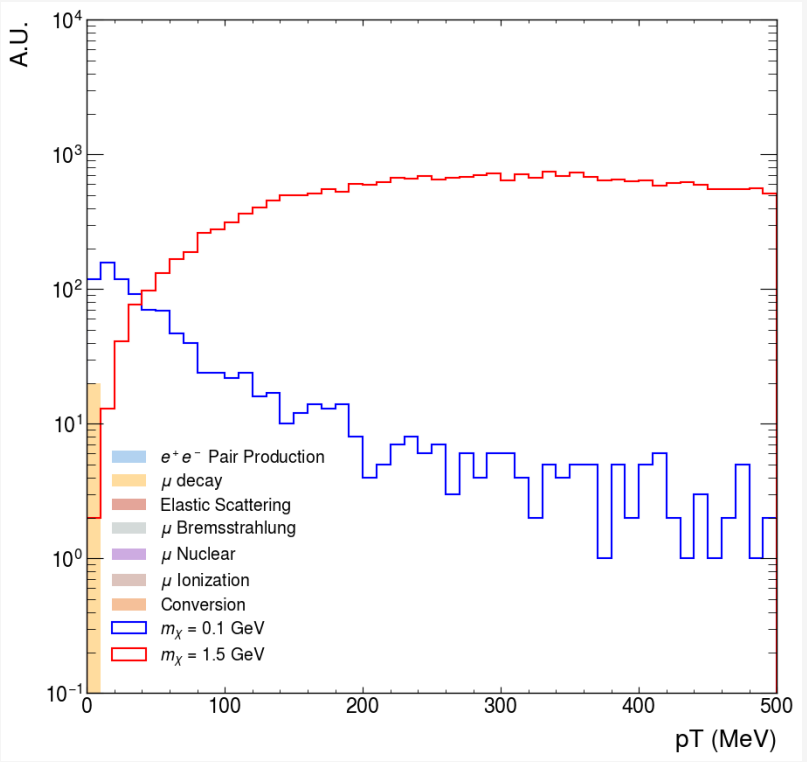
p_T after TOF selection



θ after TOF selection

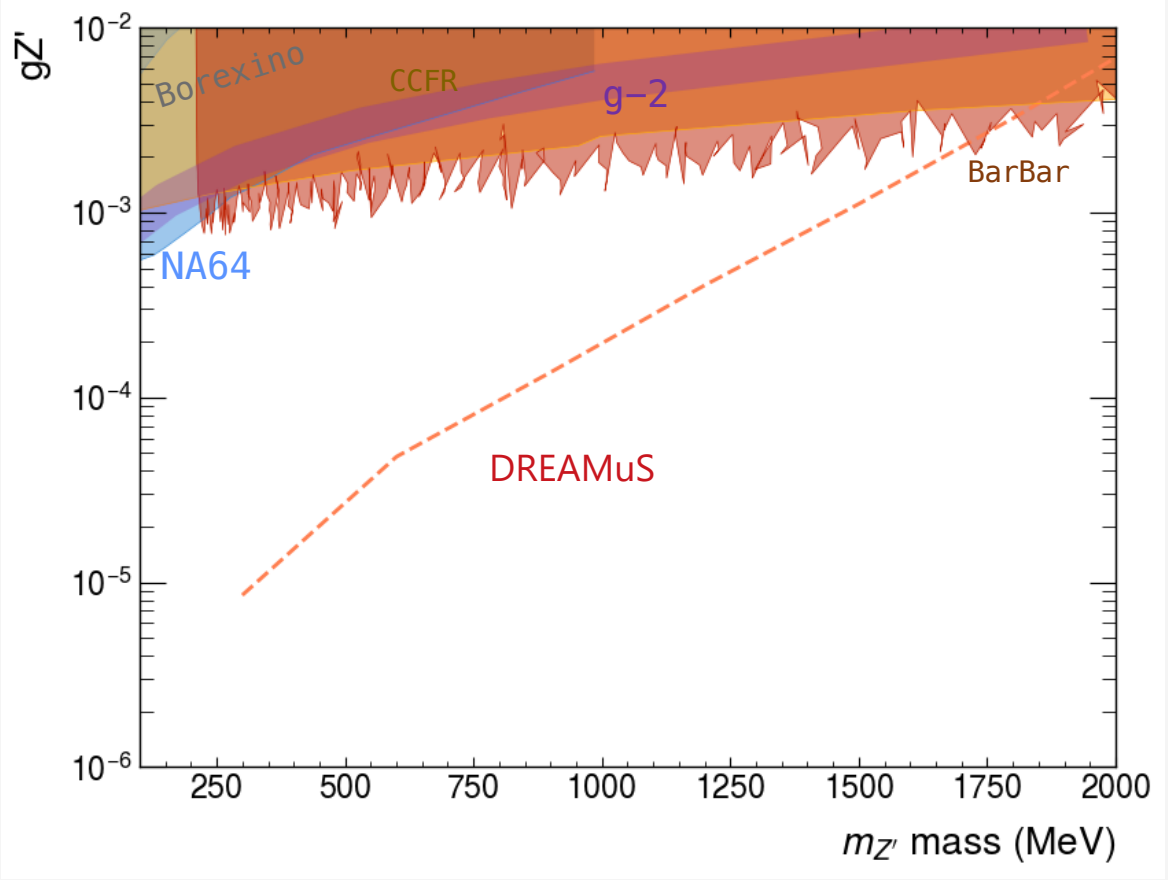


p_T after θ selection



Signal Sensitivity

- $6*10^{12}$ MOT with background free assumption, $m_{Z'} = 3m_{\chi} > 3m_{\mu}$
- Best limit on the flavour violating Z' model
  - 90% C.L. limit on $g_{Z'}$: ~10^{-5}
  - In comparison with L_{tau} -L_{u} "vanila" model



Summary

- **Dark Matter Research with Advanced Muon Source (DREAMuS)**
  - Proposal for fixed-target experiment to search for dark matter with HIAF beam
- Preliminary signal and background study with basic detector setup
  - Signal selection: single track and electron pT and θ selection
  - Muon and proton veto to reject most backgrounds
  - Effective and affordable detector design: tracker + TOF
- **World's best sensitivity limit on flavor violating Z'**
  - **90% C.L. limit on $g_{Z'}$ reaches 10^{-5}**
  - May expand search strategy to include other signal models
- Synergy with other muon physics programs at HIAF/CiADS
  - PKMu-HFRS
  - Muon-Proton Scattering
  - …

Abundant Collaboration Opportunities — Joint Efforts Are Highly Encouraged!

Backup