
DREAMuS: Dark matter REsearch with Advanced Muon Source

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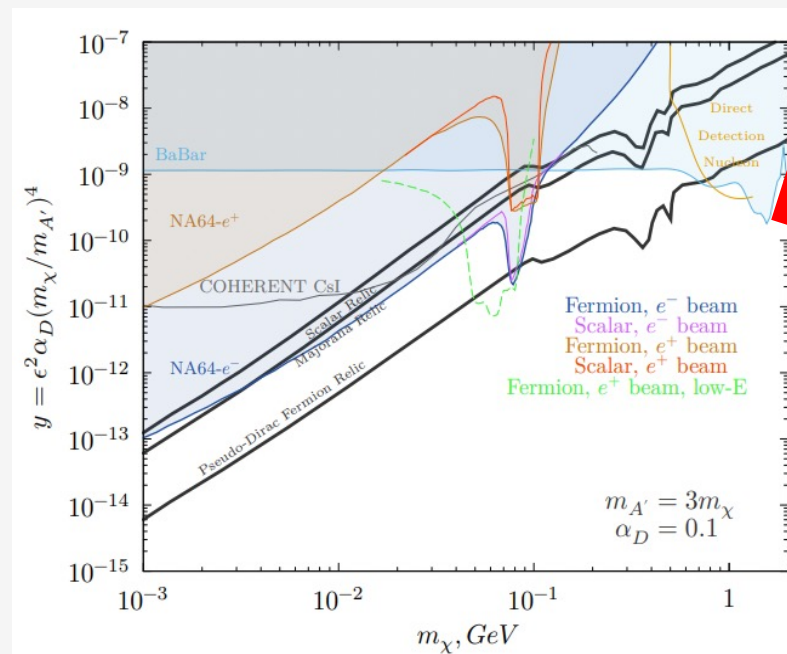
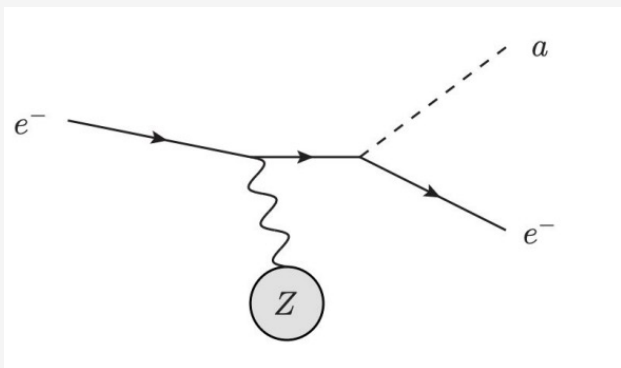
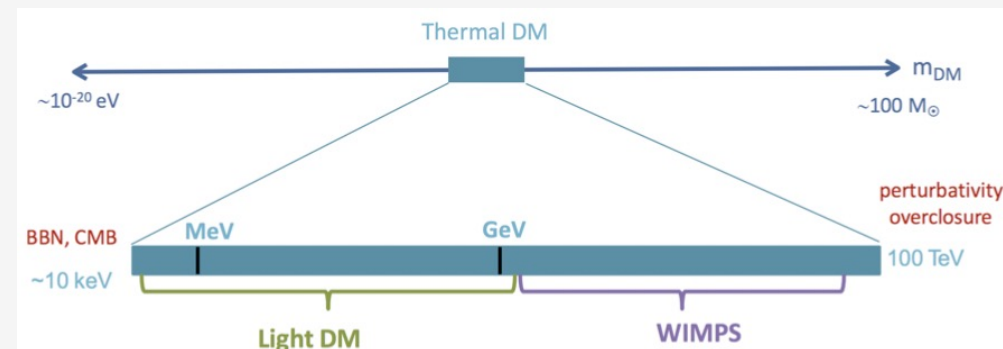
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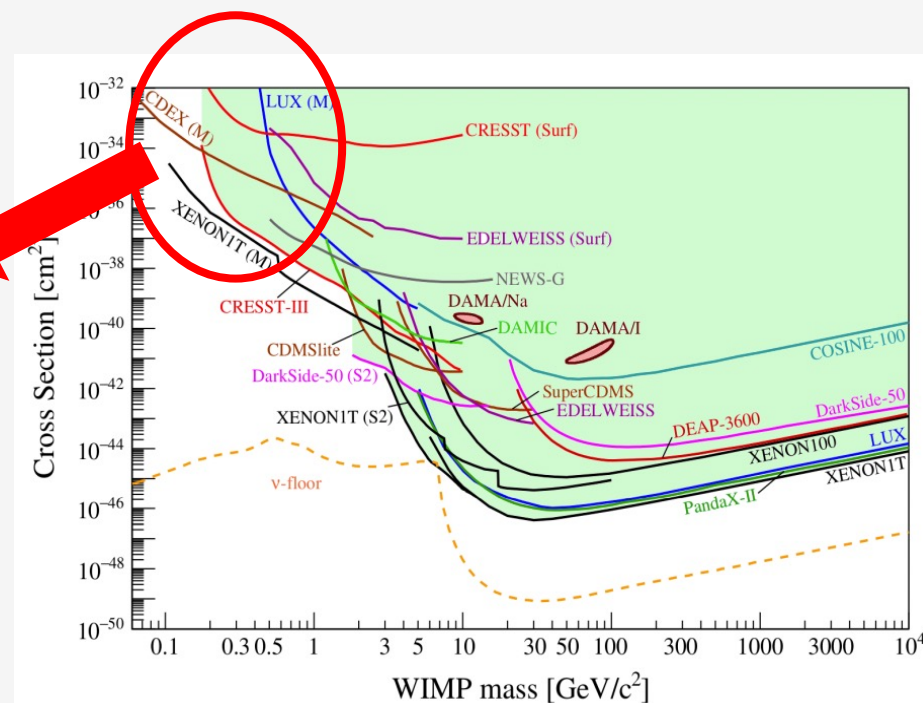
[Arxiv: 2604.10257](#)

Light Dark Matter Search With Fixed Target

- Thermal freeze-out motivates dark matter in the MeV–GeV mass range.
- Post-WIMP era: fixed-target experiments have advantages in the low mass region
- Various fix-target experiments with different kinds of beam



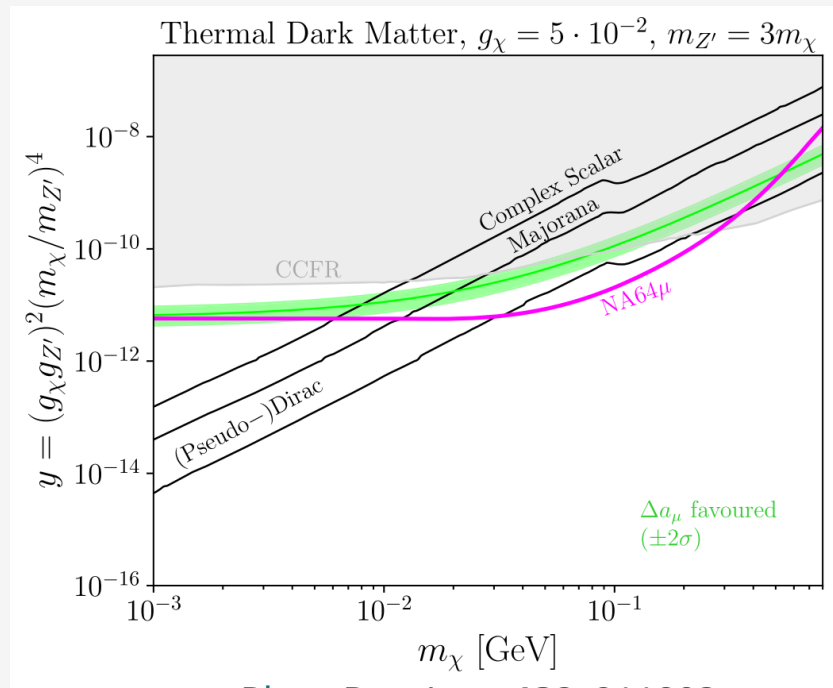
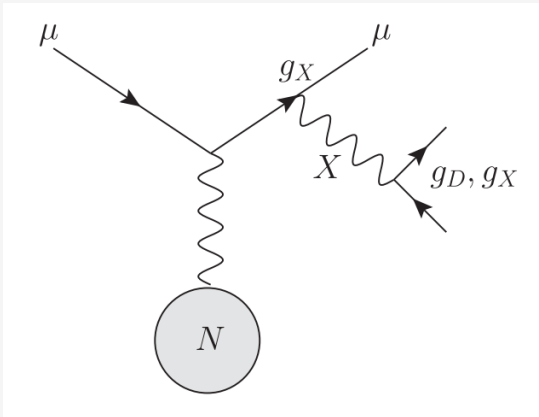
[Phys. Rev. D **109**, L031103](#)



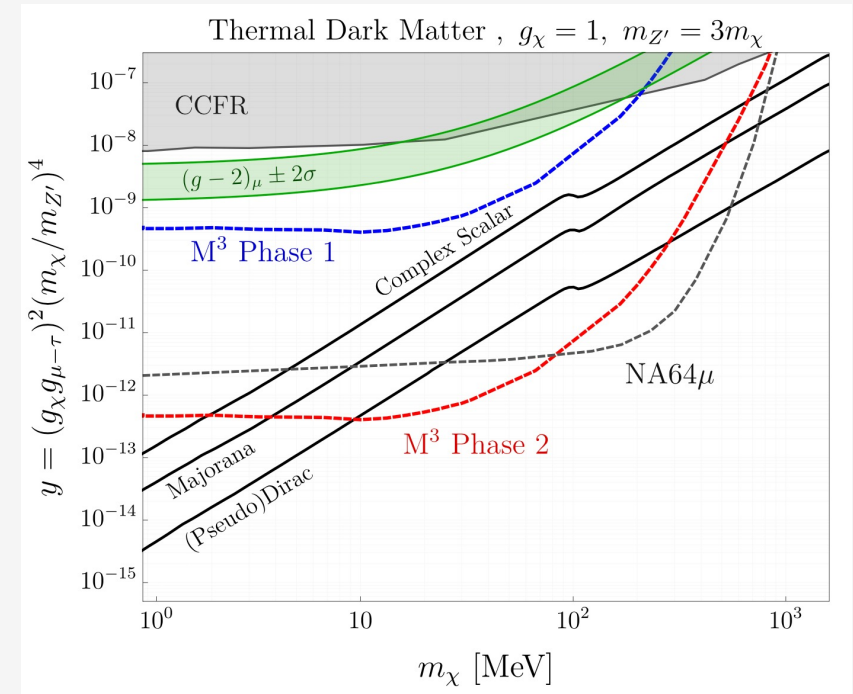
Muon Beam as a Probe of New Physics

- Muon is 200 times heavier than electron and more sensitive to new physics
- Muon beams are especially suited to probing muon-philic dark-sector models.
- Example: Thermal Dark Matter with (Sub-)GeV Z' model
- $L\mu - L\tau$ boson Z' where Z' can decay to invisible particles, like neutrino or dark matter particles

Bremsstrahlung-like process



[Phys. Rev. Lett. **132**, 211803](#)



[J. High Energy. Phys. 2018, 153 \(2018\).](#)

DREAMuS: Dark matter REsearch with Advanced Muon Source

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

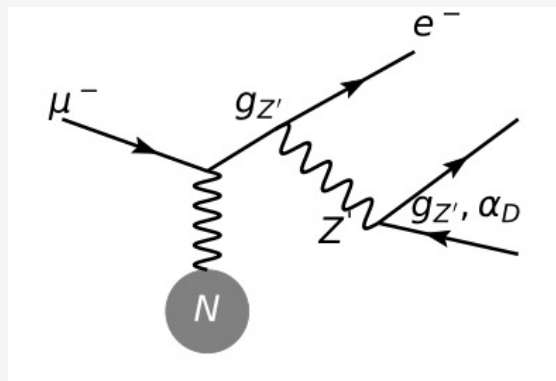
[Arxiv:2604.10257](https://arxiv.org/abs/2604.10257)

- Signal process: $\mu^- N \rightarrow e^- N X$
- Dark matter (χ) from a **flavor-violating** vector boson Z' or scalar boson ϕ
- 3 GeV muon interaction with 22cm lead target

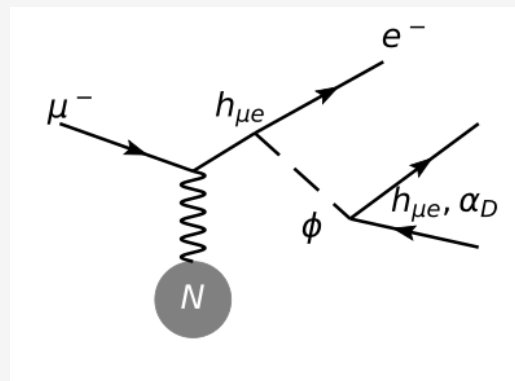
$$\mathcal{L} \supset g_\mu X \bar{f} \Gamma f + g_{e\mu} X \bar{e} \Gamma \mu + \text{h.c.},$$

Radiation Channel

vector



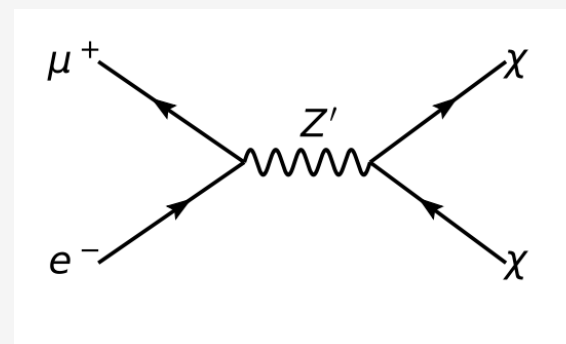
scalar



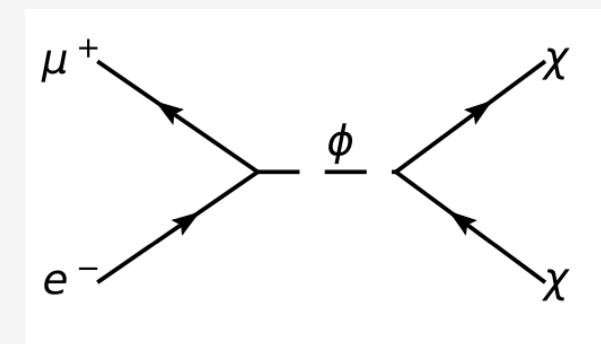
Single electron + large missing momentum/energy

Annihilation Channel

vector



scalar



No visible particle in the final state

High Intensity Heavy Ion Accelerator Facility

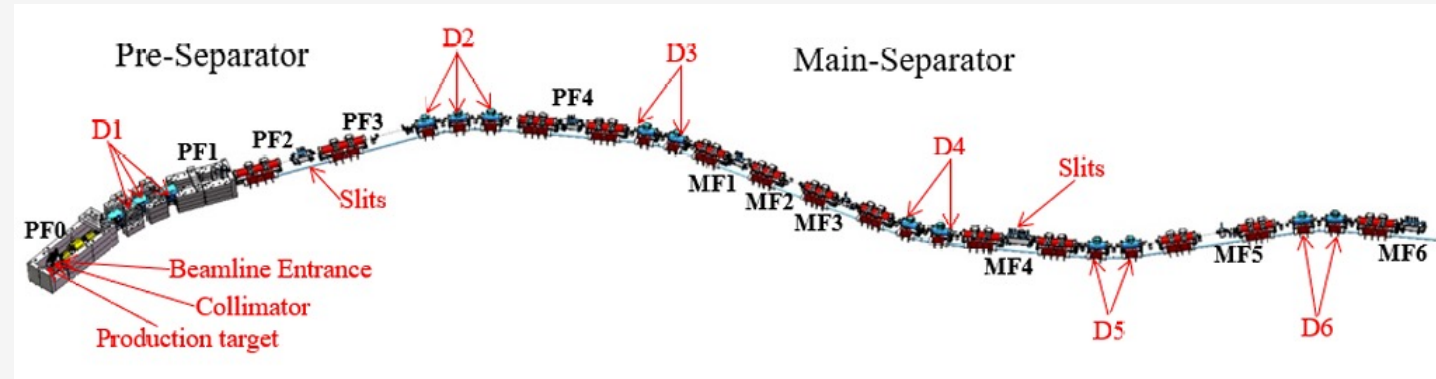
- First high intensity and high energy muon beam in China
 - GeV muon beam is provided with high intensity
 - HIRIBL on HIAF: 0.5 – 7.5 GeV, $3\text{--}8 \times 10^6 \mu/\text{s}$ (Peak intensity)
 - Continuous beam mode



Pulsed mode

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

	Proton	$^{18}\text{O}^{6+}$	$^{78}\text{Kr}^{19+}$
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%

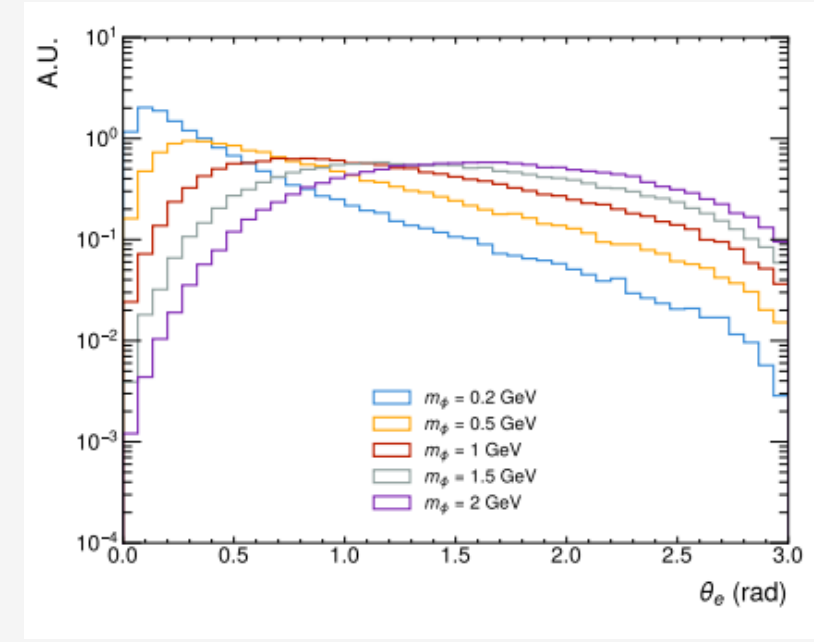
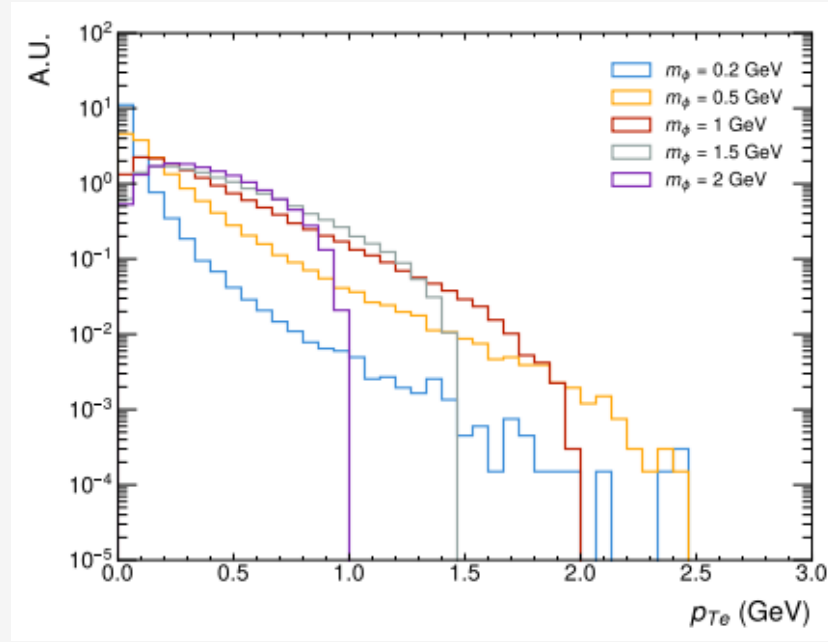
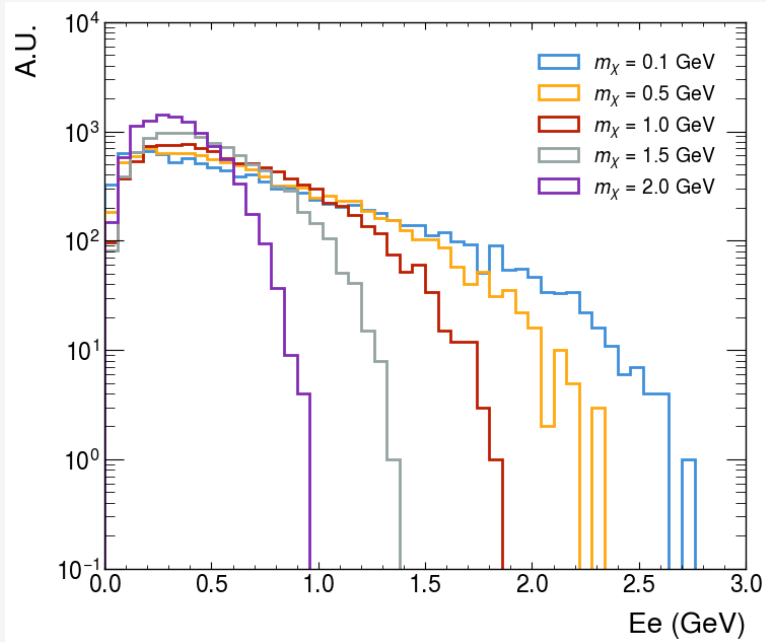


[Phys. Rev. Accel. Beams **28**, 053401](#)

Beam background can be further reduced by the TOF detector

Signal Kinematics

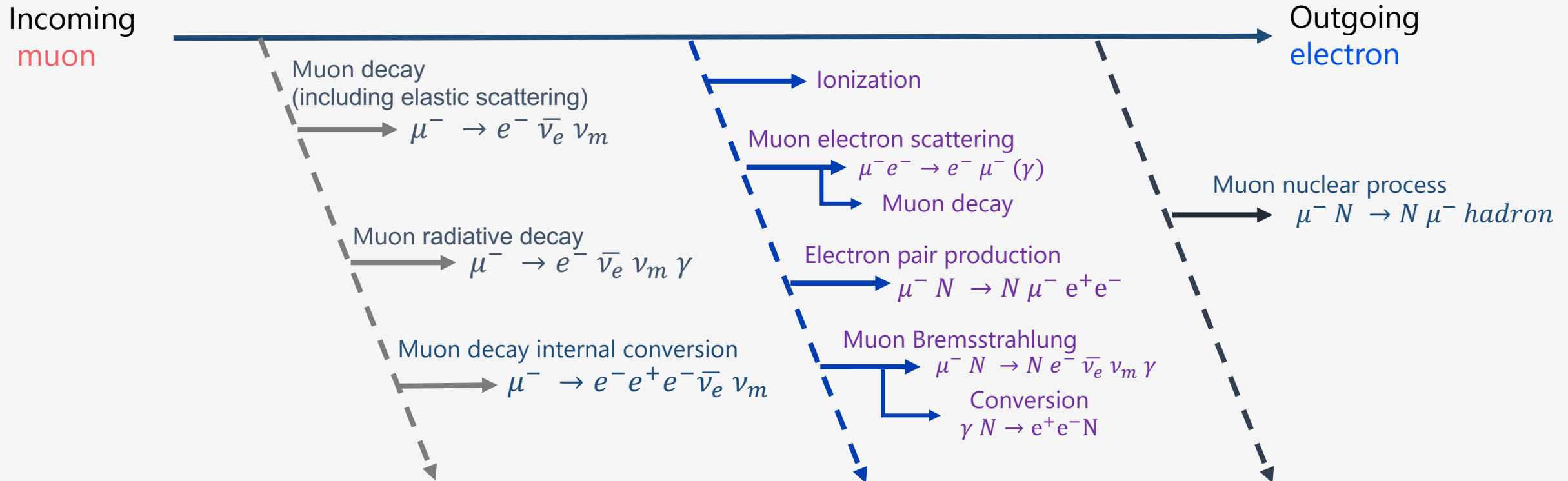
- Generated by Calchep
- Z' and ϕ signals have the similar kinematics distribution



- Electron with sizeable transverse momentum
- Energy, pT and θ_e of decayed electron decreases as the m_X increases

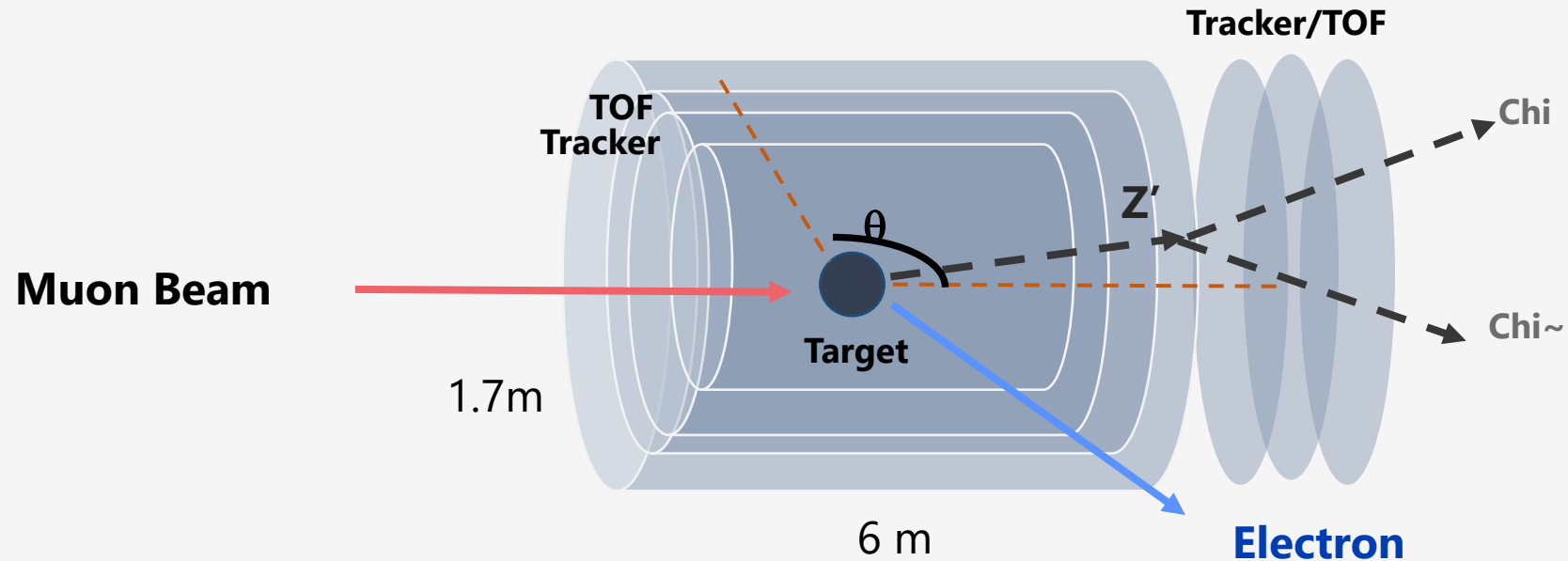
Background Estimation

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



DREAMuS Detector Concept

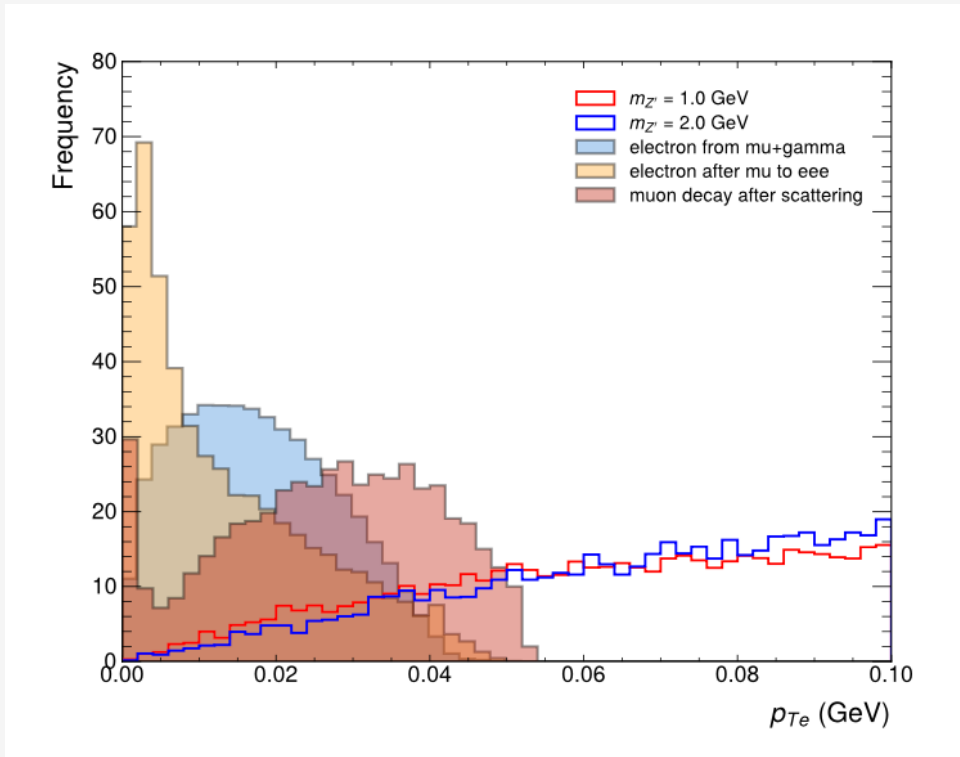
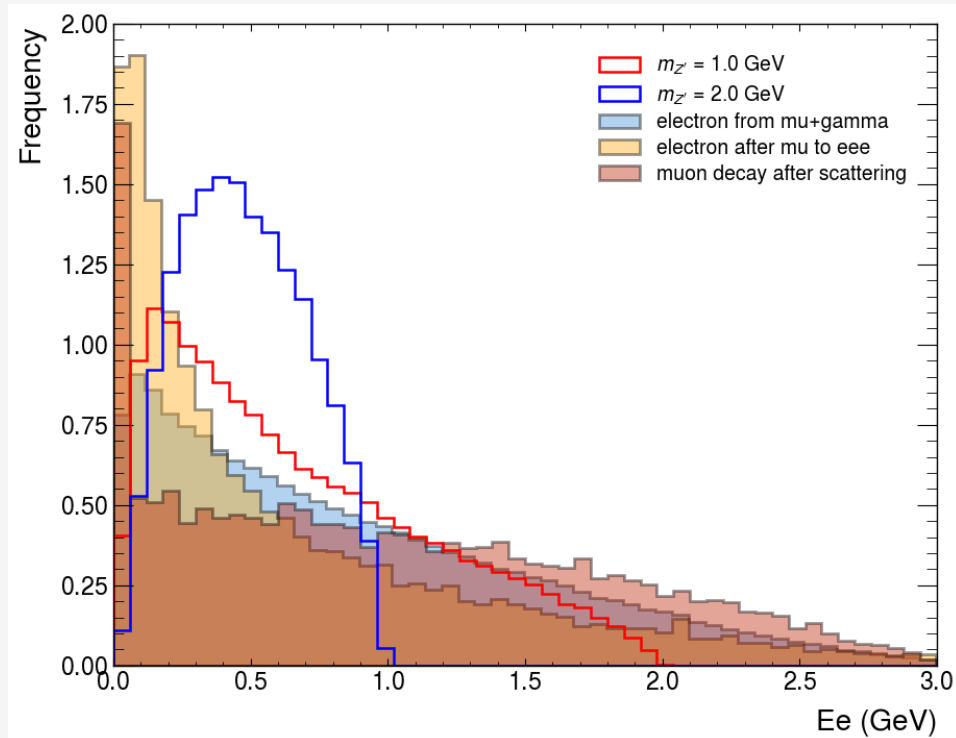
- The detector consists primarily of a tracking system and a TOF system
- Angular acceptance for charged particles up to scattering angles of roughly 120 degree
- Three additional standalone tracking and TOF stations along the beamline for beam remnant veto



Background Estimation: Muon Decay

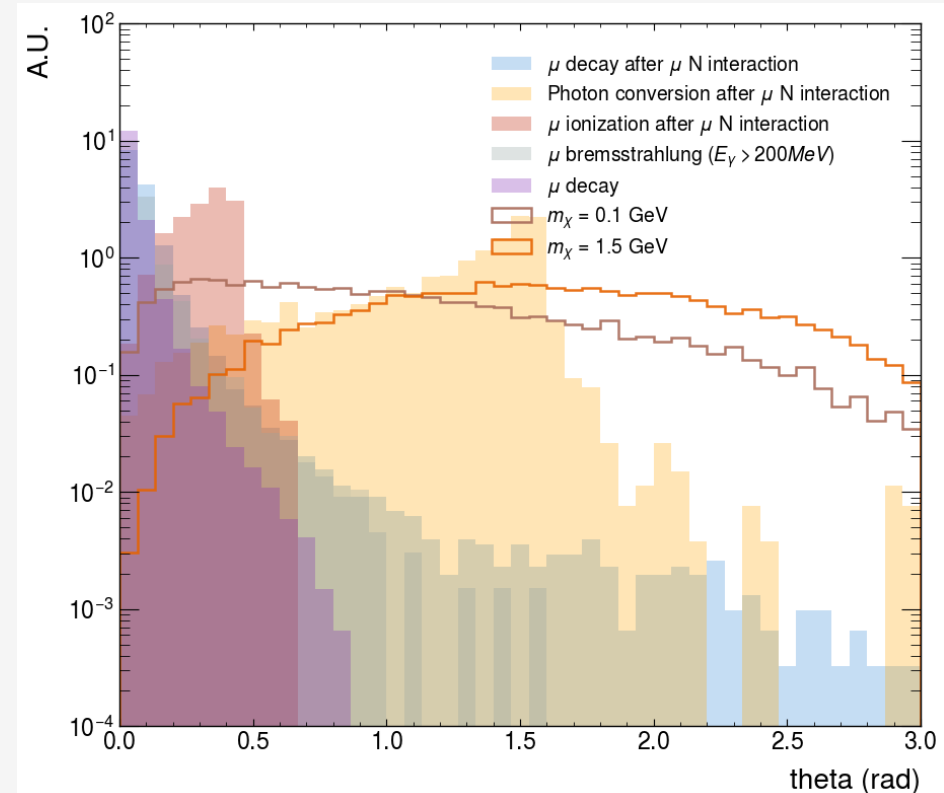
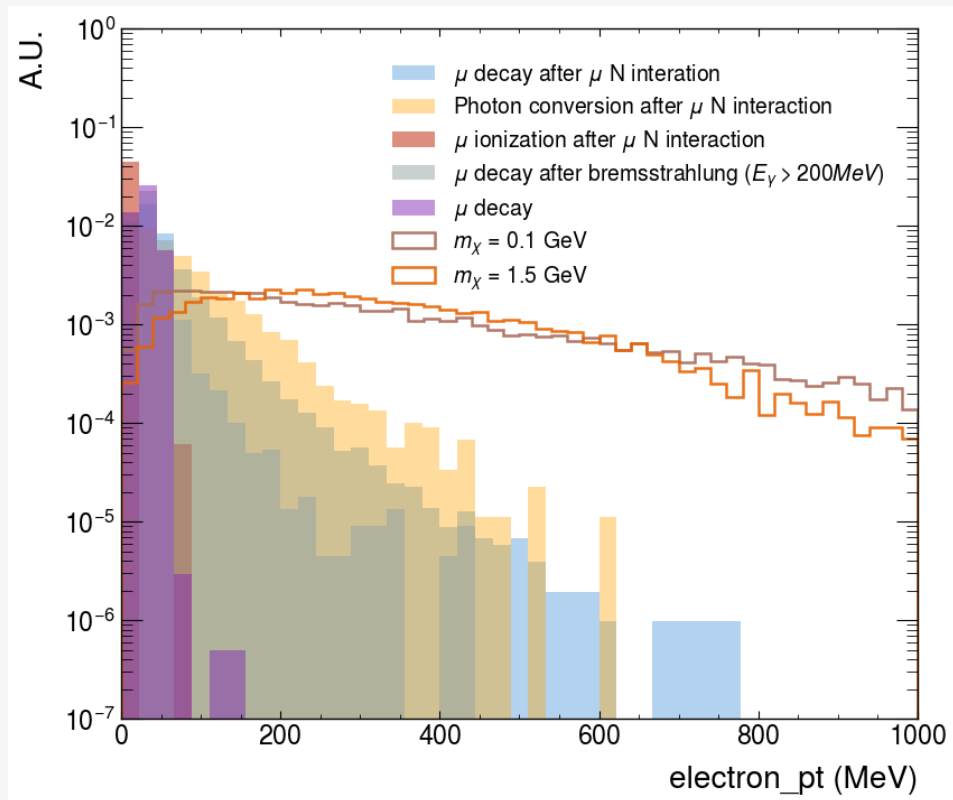
Considering muon decay (including elastic scattering) and two rare decay, muon radiative decay (RD, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma$) and internal conversion (IC, $\mu^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_m$):

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



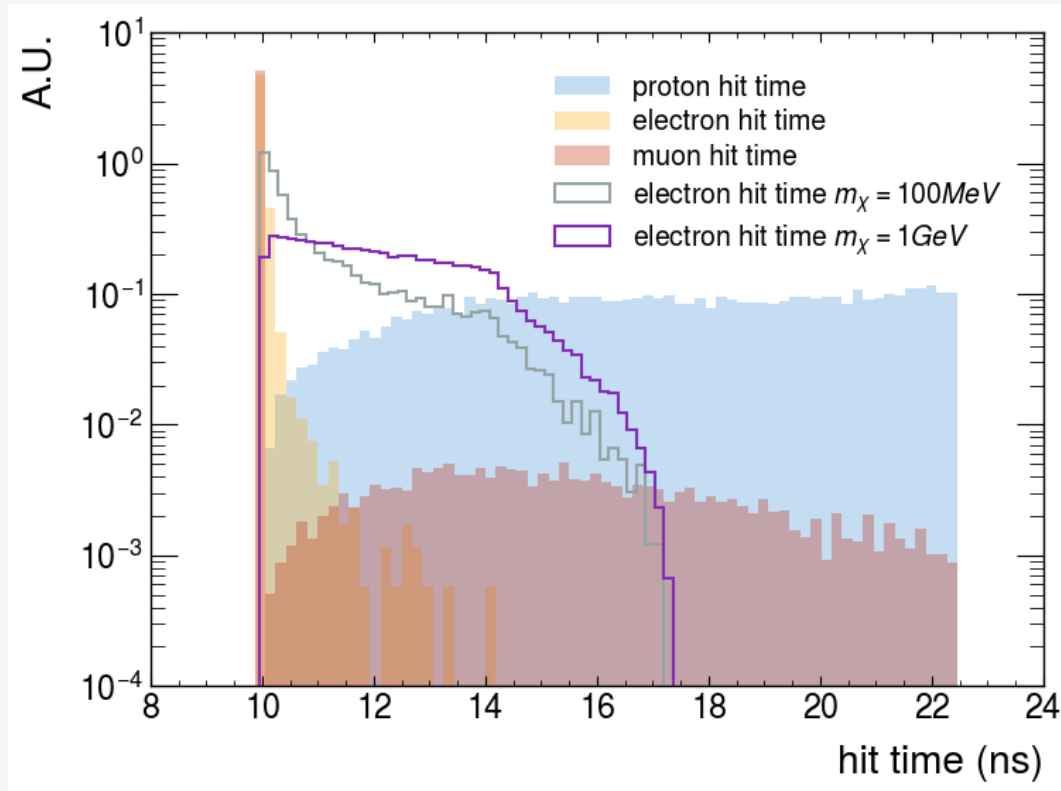
More Backgrounds

- Muon nuclear process ($N + \mu^- \rightarrow N + \mu^- + p \dots$): 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

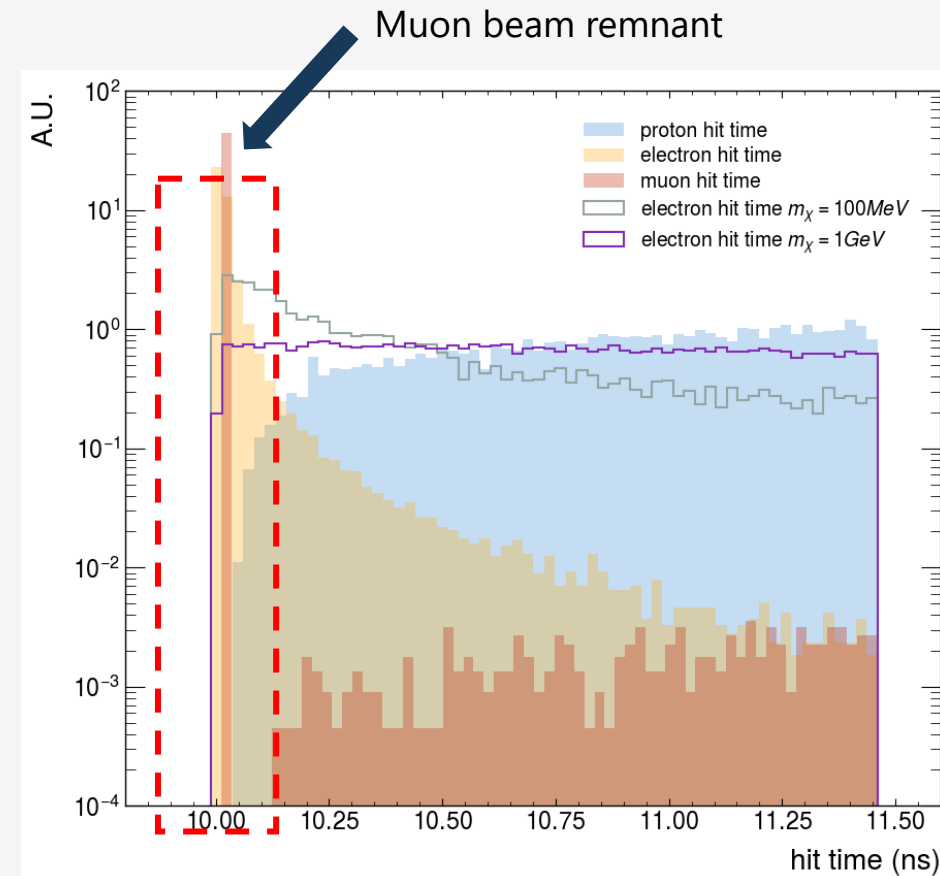


Proton and Muon Veto

- 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 > 11 ns
 - Good TOF timing resolution at 20-30 ps



TOF for different particles



Signal Selection and Background Rejection

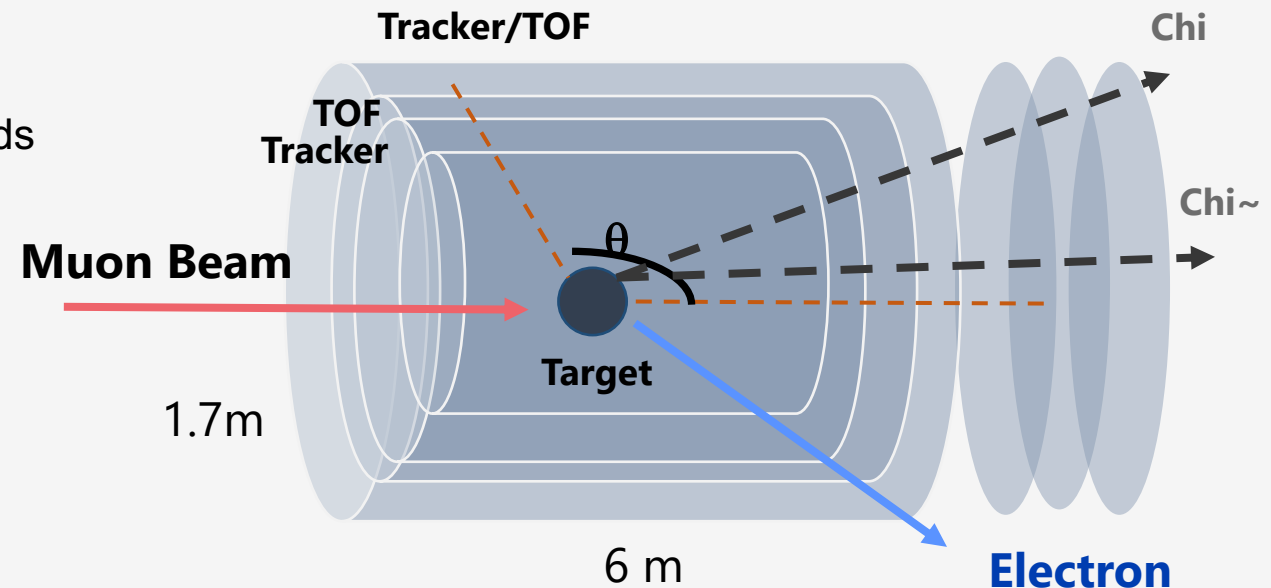
- Particle (veto) detector
 - Muon veto : **TOF > 11 ns**
 - Remove muon beam remnant
 - Proton veto : **TOF < 14 ns**
- Single track with Tracker/TOF
 - Number of track = 1**
 - Tracking efficiency: 99%

- Geometry acceptance:
 - Electron θ acceptance: $|\theta| < 120^\circ$**
- Electron pT selection:
 - $p_T > 20 \text{ MeV}$**
- Electron θ selection:
 - $|\theta| > 0.75 \text{ radian } (43^\circ)$**

- The signal efficiency ranges from 10% to 30%

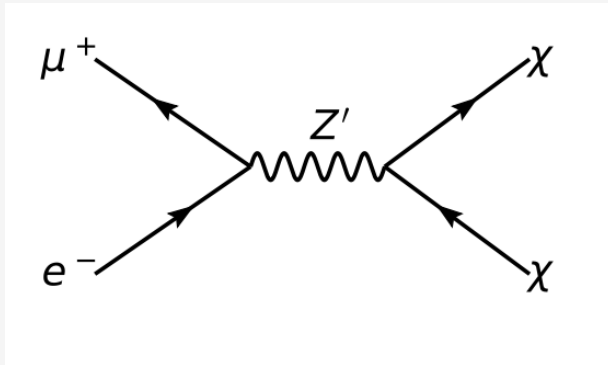
- Fast simulation is used for background modelling
- Muon and proton veto can remove most backgrounds
- Electron pT and θ selection to further suppress backgrounds

Process	Generated	Single track	TOF	$\theta_e > 43^\circ$	$p_T^e > 20 \text{ MeV}$
μ -e Scattering	50000	264	0	0	0
μ Ionization	63089	2263	84	0	0
μ Bremsstrahlung	164411	135506	314	0	0
e Pair-production	99281	138	0	0	0
Elastic Scattering	113936	88917	37	20	0
μ -N Interaction	167120	144	3	2	0

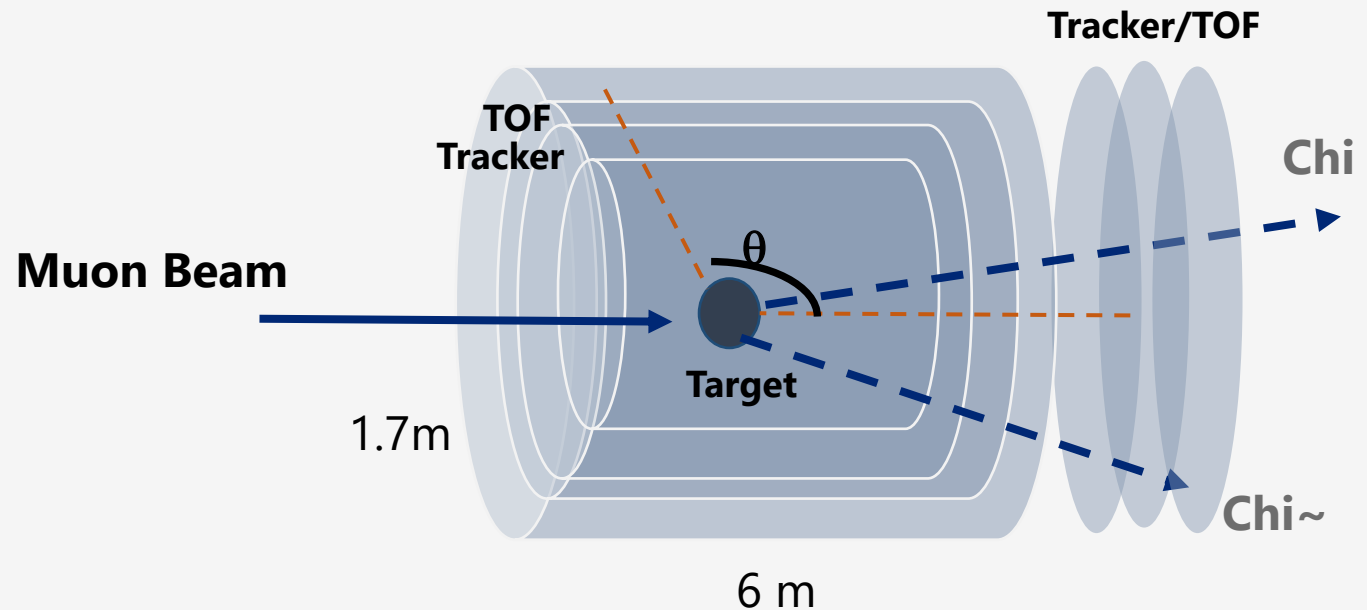
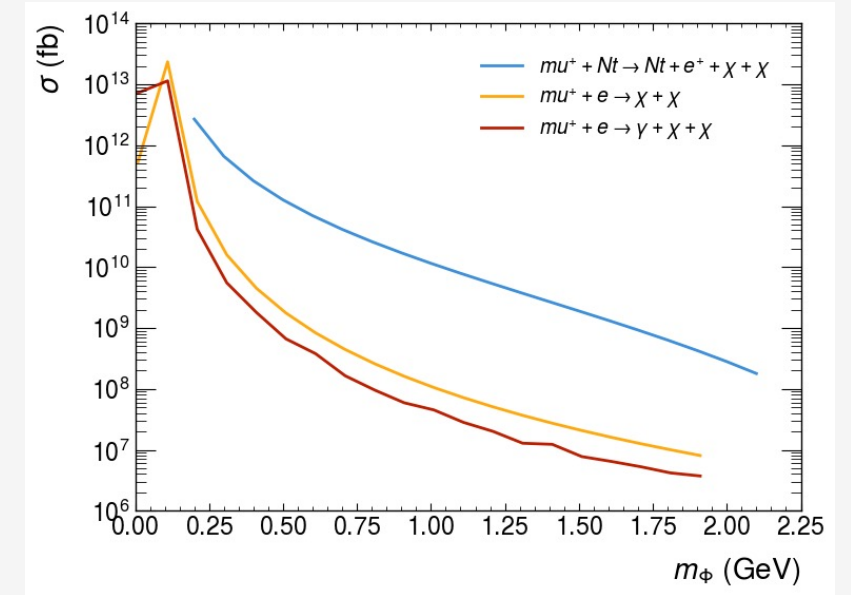


Annihilation Channel

- HIAF can produce positive muon with higher flux rate
- For the muon with 3 GeV muon beam hit on electron in the target, the center of mass is around 199 MeV
- **Signal signature: no any charge particles in the final state**



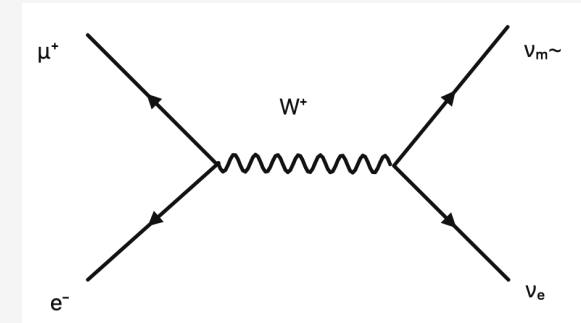
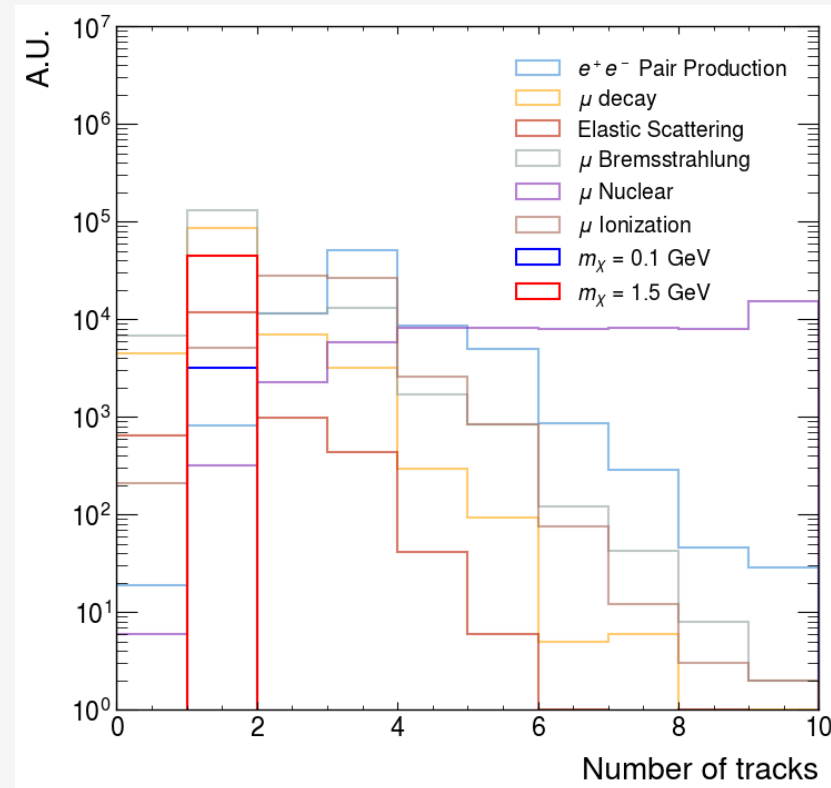
$$\sigma(s) \sim \frac{g_l g_D}{(s - M_W^2)^2 + M_W^2 \Gamma_W^2}$$



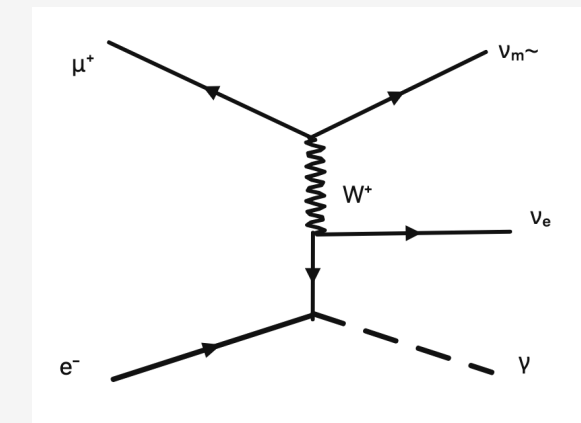
Background Estimation in Annihilation Channel

- **SM process:** Irreducible background with neutrino final state
- The cross section is very small, yielding 0.2 events with $5 \cdot 10^{12}$ MOT

- **Missing track:** tracks which are not well reconstructed (1%)
- Especially for muon bremsstrahlung and muon decay process



$$\sigma = 5.5 \cdot 10^{-2} \text{ fb}$$



$$\sigma = 2.5 \cdot 10^{-3} \text{ fb}$$

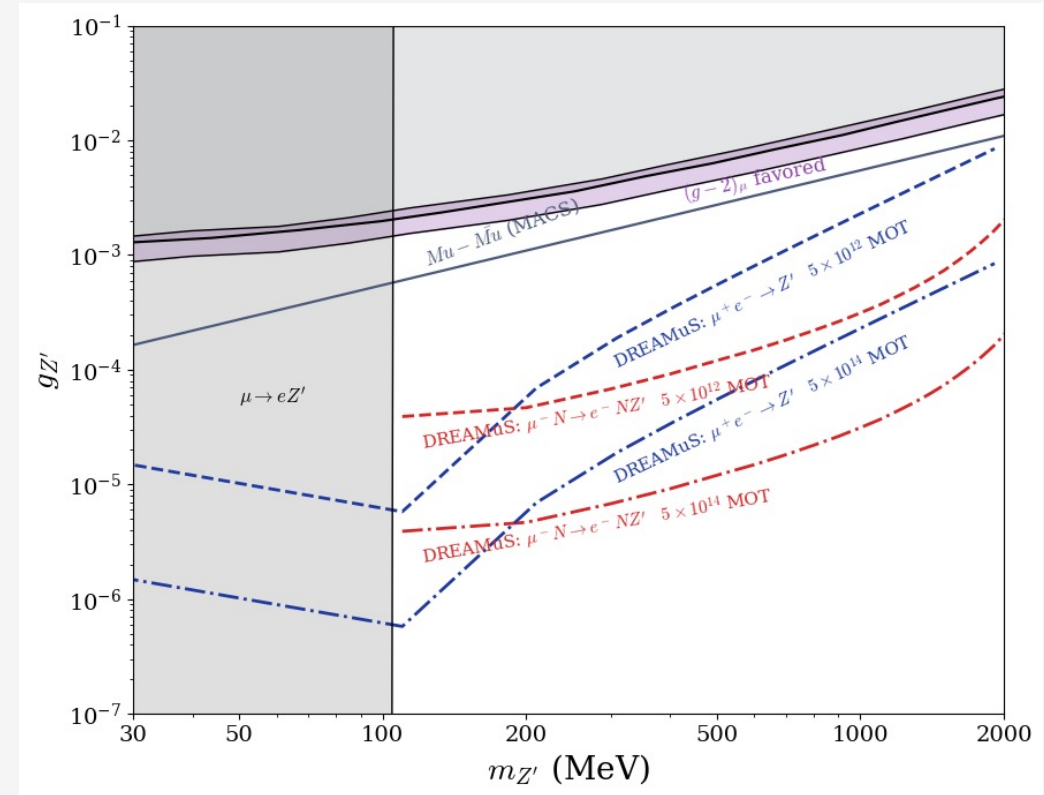
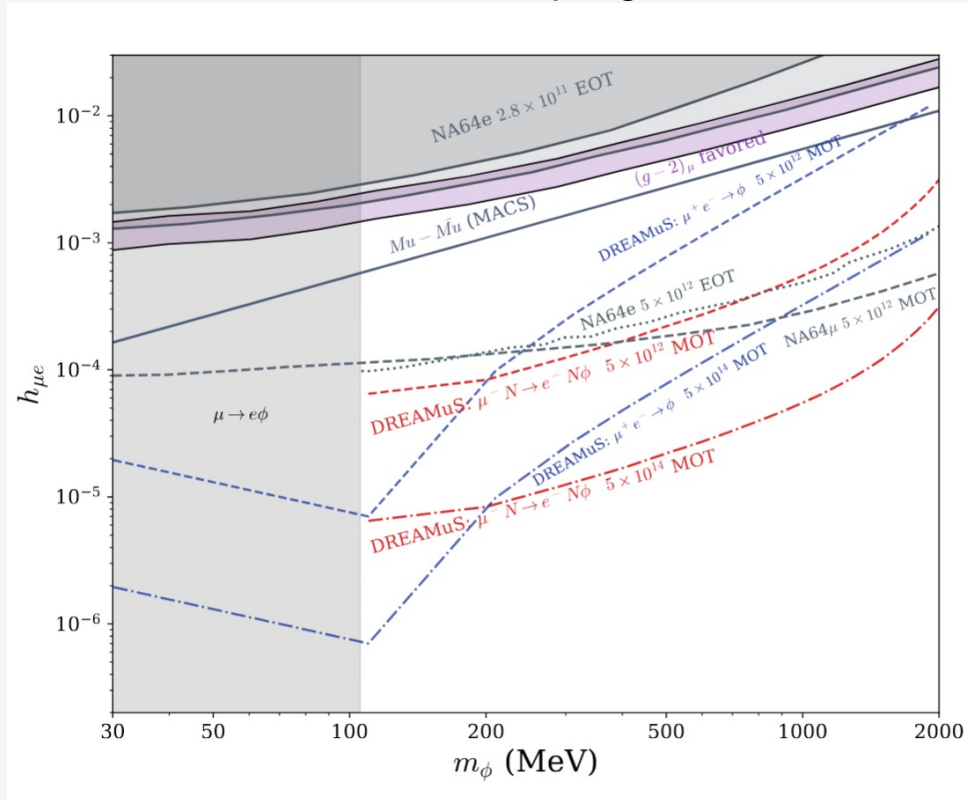
Annihilation Channel: Background Rejection

- For muon electron annihilation, the signal efficiency is almost 100% after background rejection
- Charged-particle veto: Events with reconstructed downstream charged tracks are rejected. The assumed tracking efficiency is 99%
- Tracker veto: Events with any additional hits in the downstream tracker are rejected

Process	Generated events	No track	No hits on tracker
μ Decay	200000	1800	0
μ -e Scattering	63089	26	0
μ Bremsstrahlung	328806	2806	0
e Pair-production	9999973	609	0
Elastic Scattering	13936	118	0
μ -N Interaction	167120	4	0

Search Sensitivity with HIAF

- Stringent limit on flavor violating Z' model
- Best limit on flavor violating scalar ϕ model in the low mass region
 - 5×10^{12} MOT for 4000 (2000) hours for $\mu^- (\mu^+)$ with background free assumption
 - 90% C.L. limit on the coupling constant: $\sim 10^{-4} - 10^{-5}$



Comparing to muon beam results, 90% C.L. limit reaches $\sim 10^{-6}$, **an order of magnitude better** in 100MeV -200 MeV region for the annihilation channel

Summary

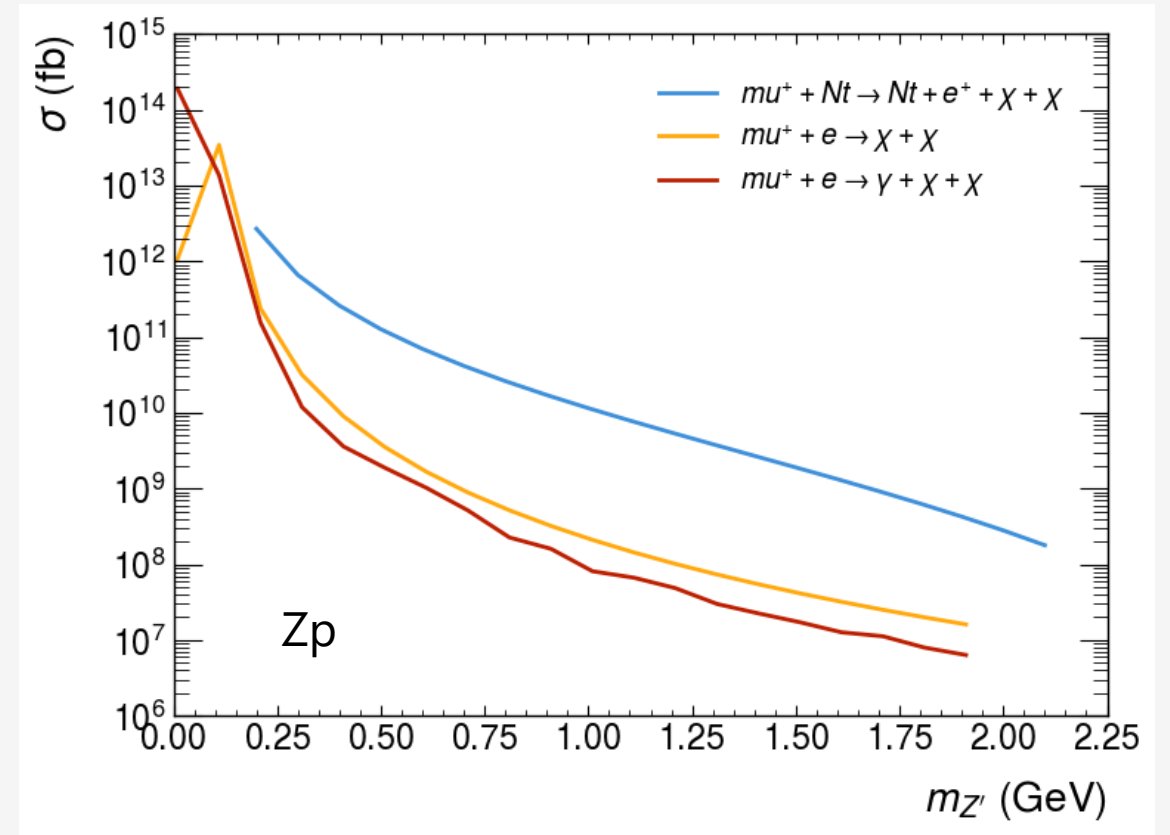
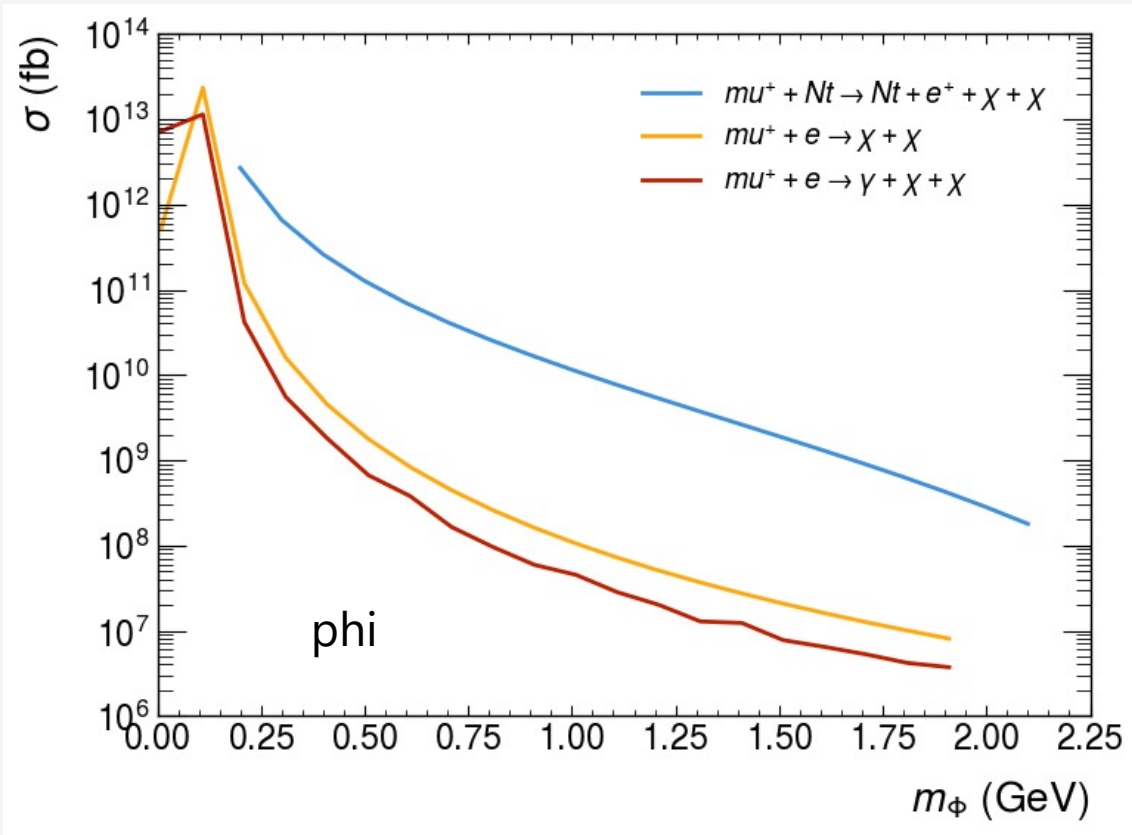
- **World's best sensitivity limits on flavor violating models**
 - 90% C.L. limit on the vector boson model reaches 10^{-5}
 - Most stringent constrain on flavor violating scalar ϕ model in the low mass region
 - Positive muon beam can enhance the sensitivity by an order of magnitude in 100MeV to 200 MeV
- **Cost-effective design: < 5 M CNY**, including inner silicon tracker + 2 outer layer TOF/Tracker (barrel + endcap) + Mechanical + DAQ + Shielding + Target
 - Cost can be further reduced via synergy with other experiments
- **Rich physics opportunities:**
 - Dark matter search: muon-philic dark matter
 - Light scalar/vector boson and axion search
 - X17 and LLPs searches
- **Synergy with other experiments at HIAF: LUNE, PKMuon etc..**
- **Welcome for collaboration!**



Backups

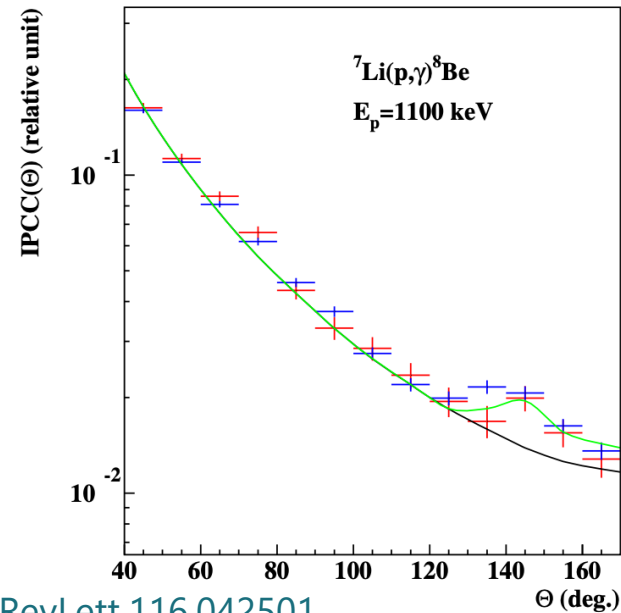
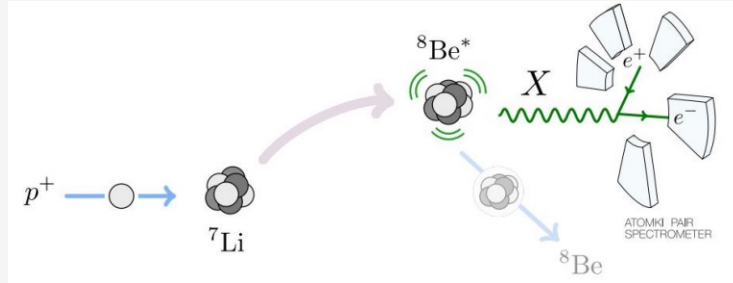
Anti-muon Electron Annihilation

Ⓢ The peak in the cross section estimation



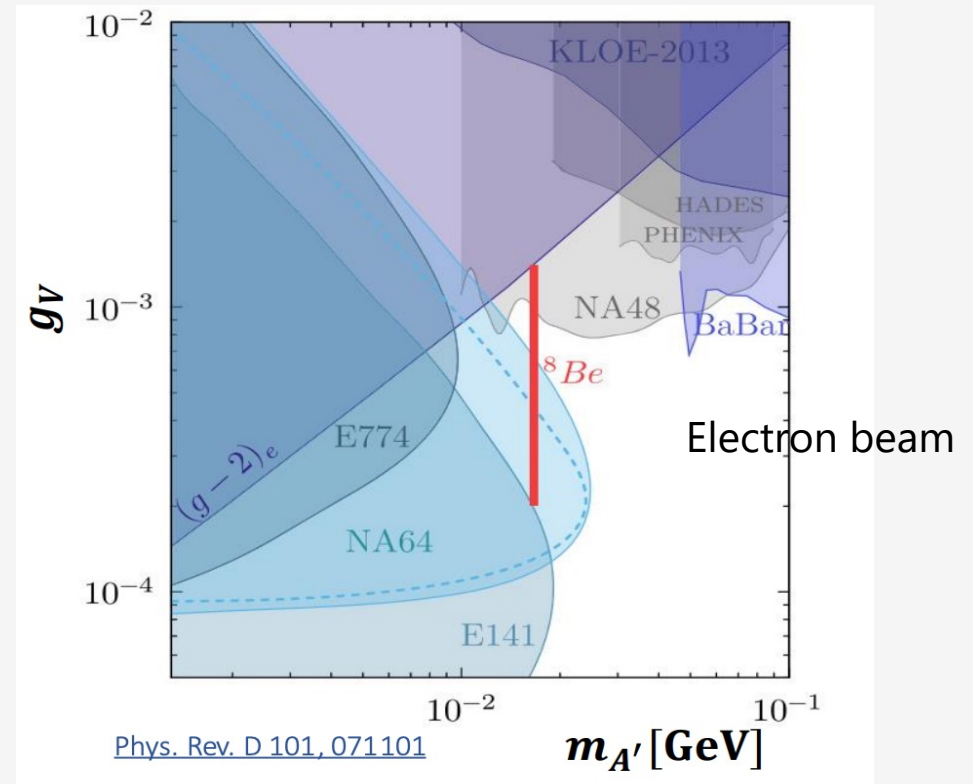
X_{17} Dark Matter Search

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



[PhysRevLett.116.042501](https://arxiv.org/abs/1604.042501)

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



[Phys. Rev. D 101, 071101](https://arxiv.org/abs/1604.042501)

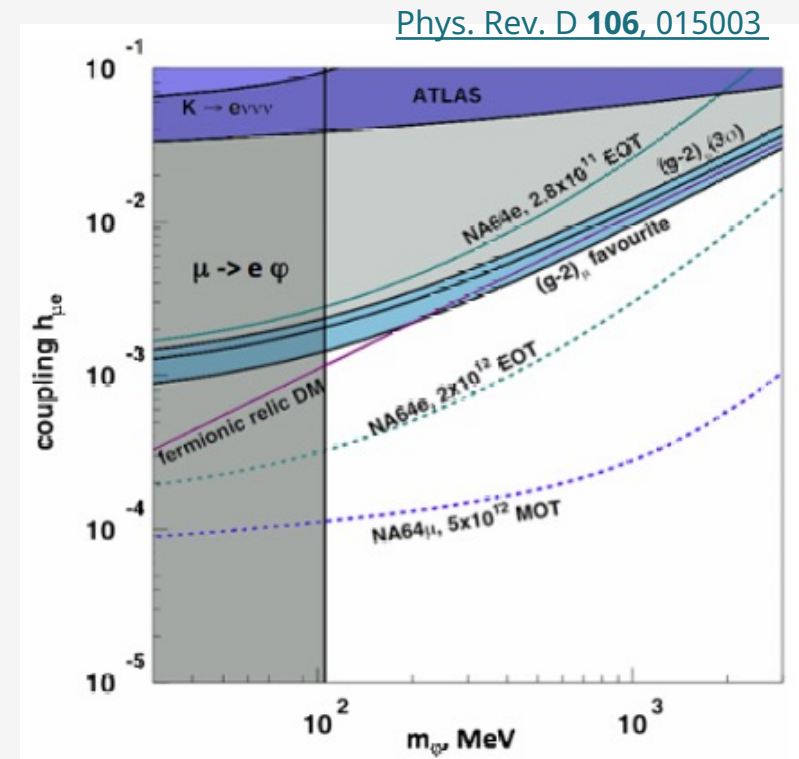
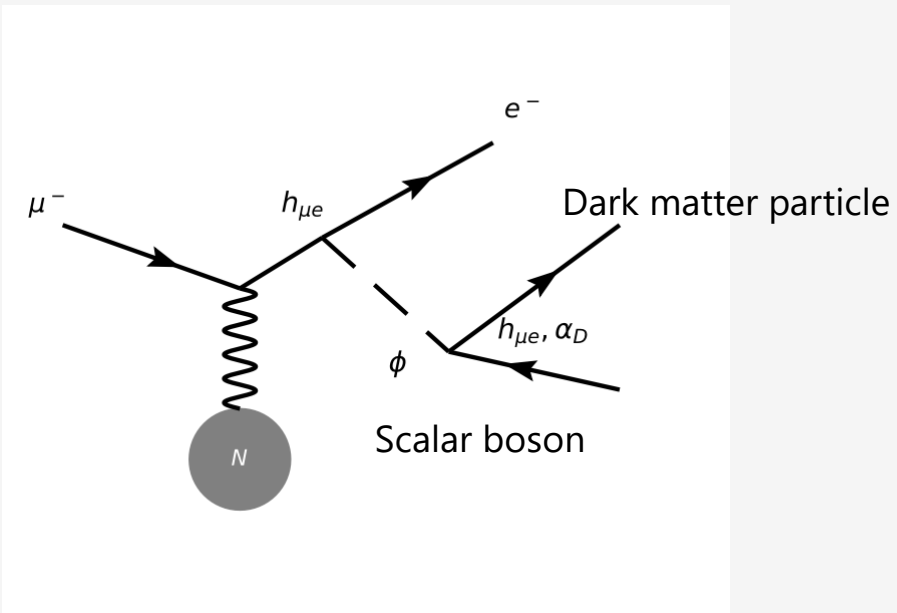
Flavor Violation Boson Search

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

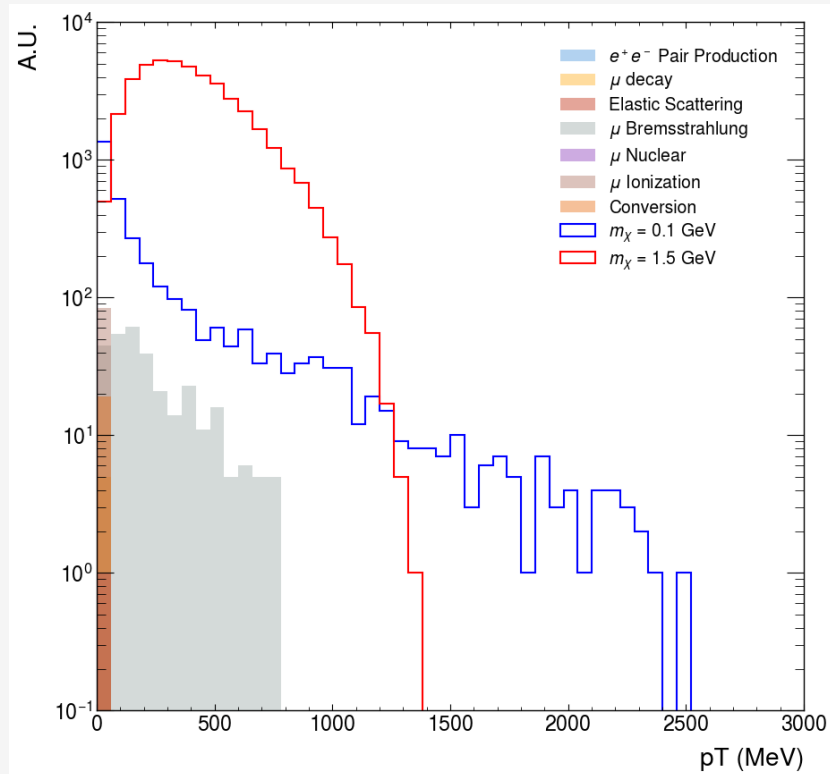
$$L_{\phi\mu e} = -h_{\mu e}\bar{e}_L\mu_R\phi + \text{H.c.},$$

Dark Matter Production with Muon Beam

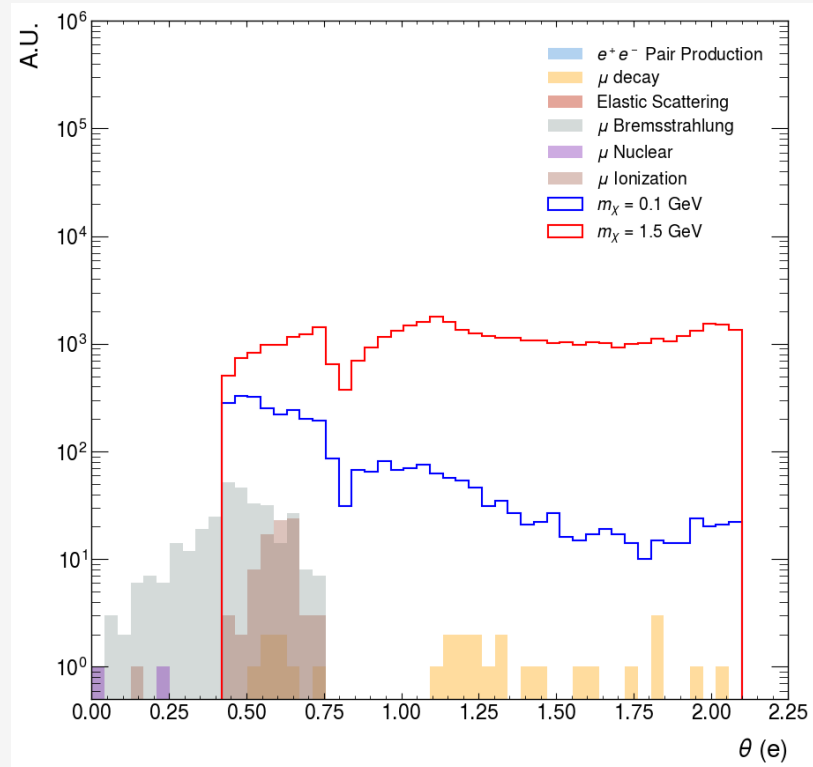


Electron p_T and θ Distributions

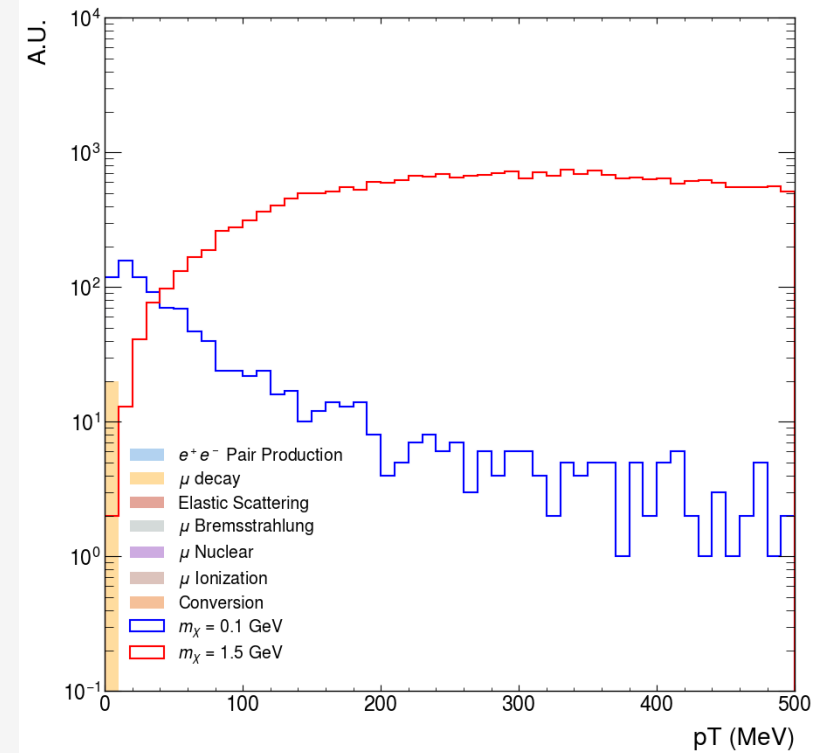
p_T after TOF selection



θ after TOF selection



p_T after θ selection



X₁₇ 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 $6 \cdot 10^{13}$ MOT
- DREAMuS benefits from thicker target ($40X_0$) and background modelling comparing with electron beam

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

