DREAMuS: Dark matter REsearch with Advanced Muon Source

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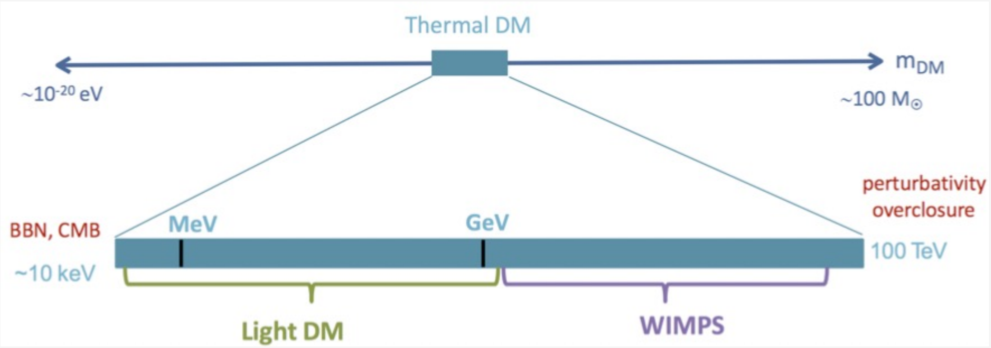
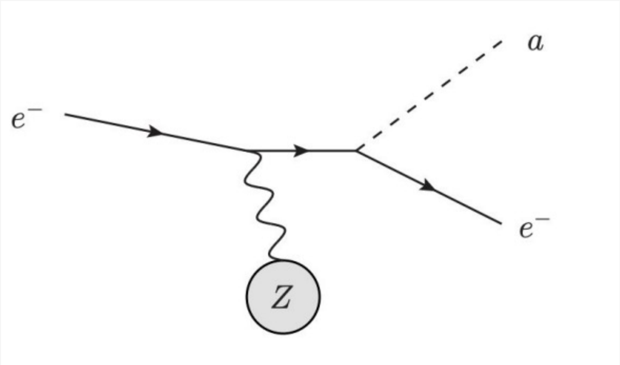
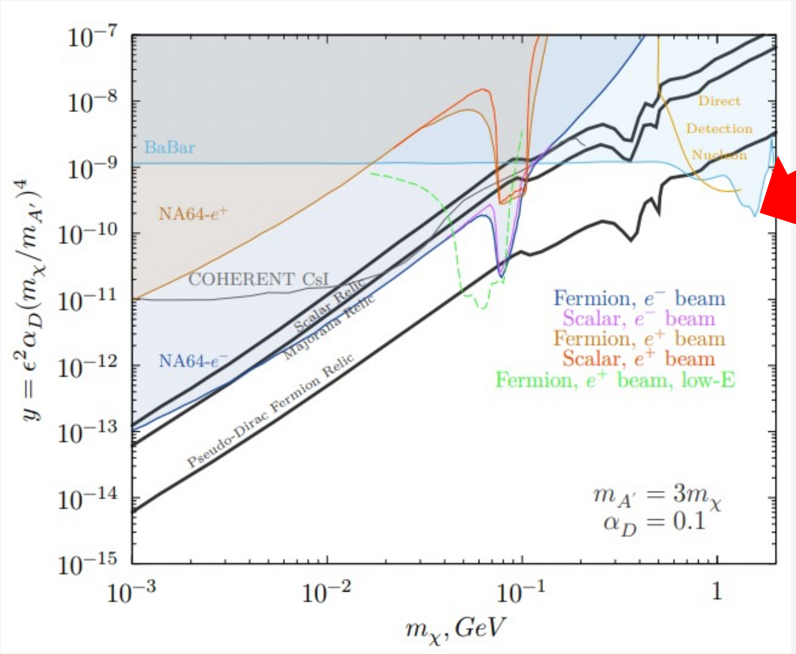
Arxiv: 2604.10257

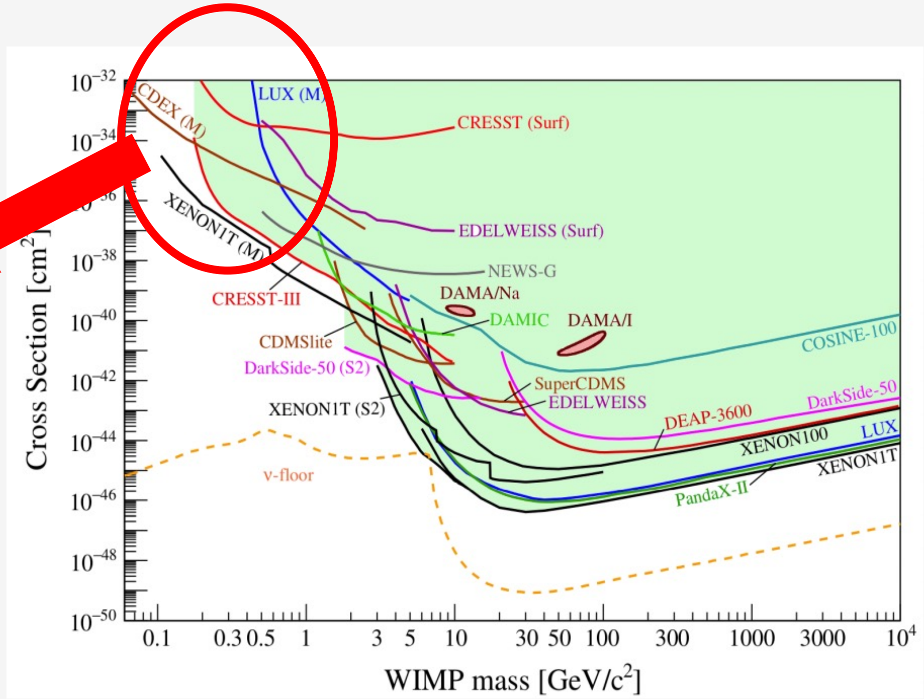
Light Dark Matter Search With Fixed Target

- 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









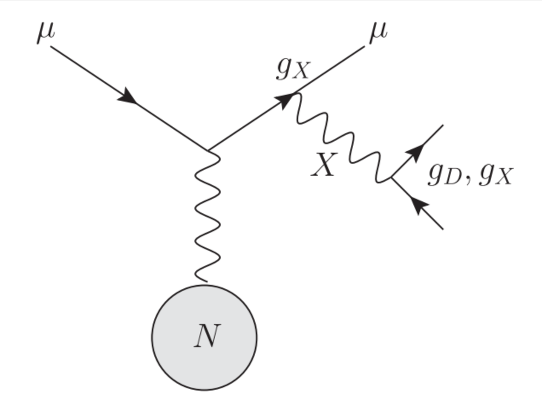
Phys. Rev. D **109**, L031103

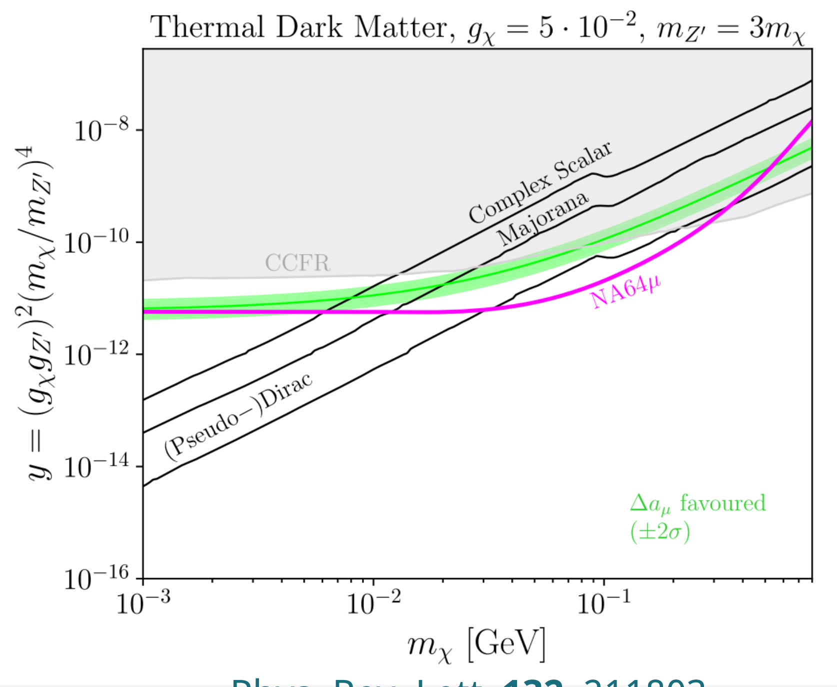
Muon Beam as a Probe of New Physics

- 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.

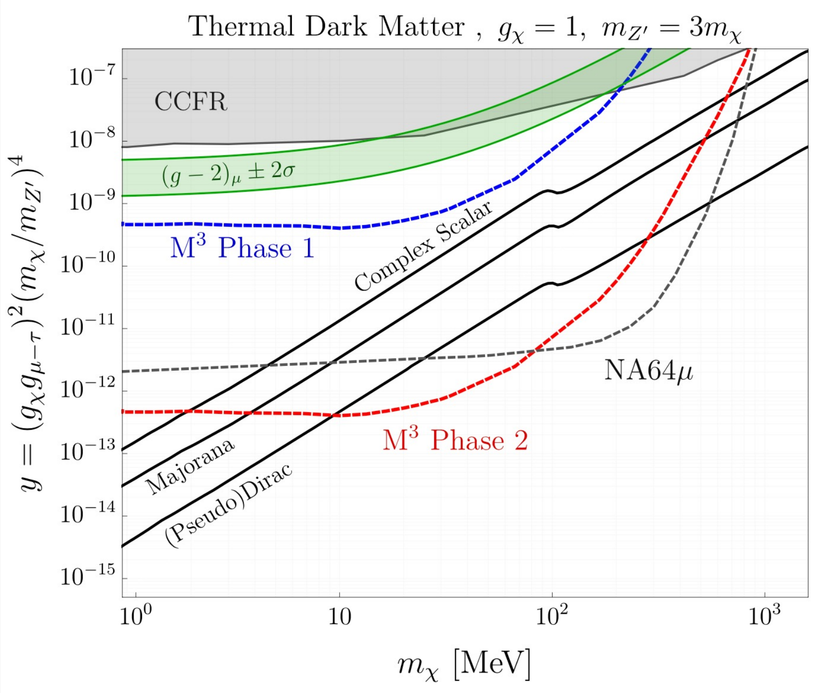
- Example: Thermal Dark Matter with (Sub-)GeV Z' model
- Lμ − Lτ boson Z' where Z' can decay to invisible particles, like neutrino or dark matter particles

Bremsstrahlung-like process





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



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

DREAMuS: Dark matter REsearch with Advanced Muon Source

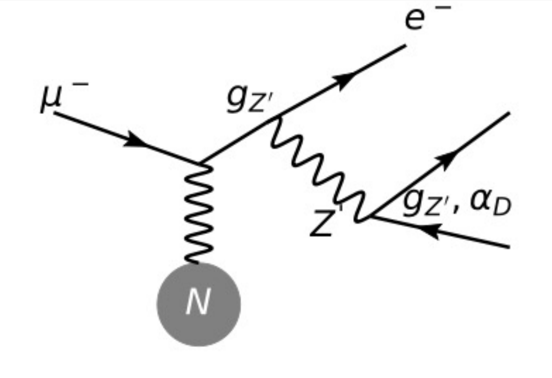
Dark matter search with fixed-target experiment using muon beam @ HIAF **Arxiv:2604.10257**

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

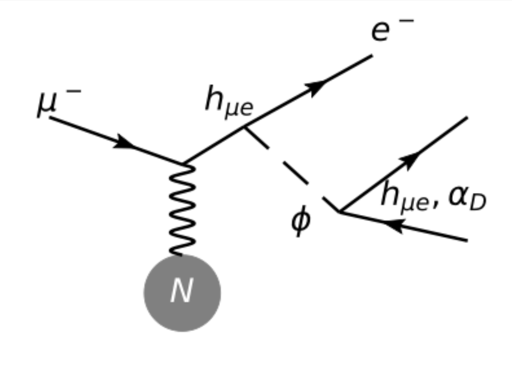
$$\mathcal{L} \supset g_\mu X \bar{f} \Gamma f + g_{e\mu} X \bar{e} \Gamma \mu + \text{h.c.},$$

Radiation Channel

vector



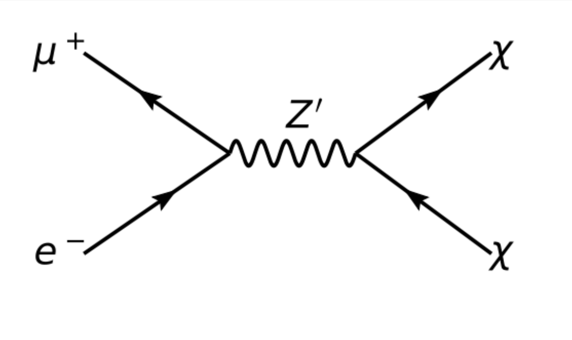
scalar



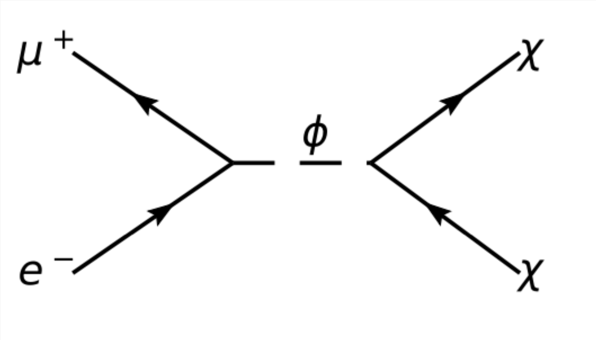
Single electron + large missing momentum/energy

Annihilation Channel

vector



scalar



No visible particle in the final state

High Intensity Heavy Ion Accelerator Facility

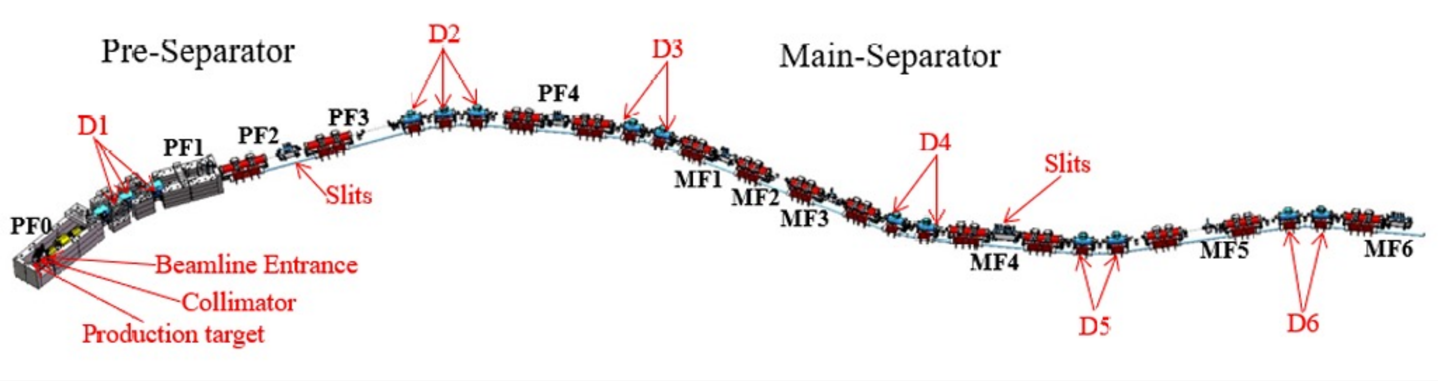
- First high intensity and high energy muon beam in China
  - GeV muon beam is provided with high intensity
  - HIRIBL on HIAF: 0.5 – 7.5 GeV, 3-8*10^6 μ/s (Peak intensity)
  - Continuous beam mode

Pulsed mode

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%

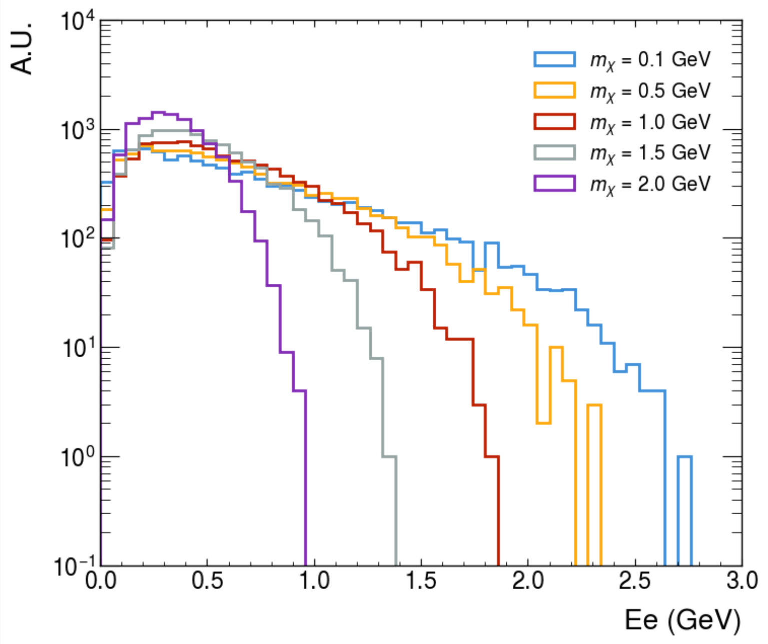
Beam background can be further reduced by the TOF detector

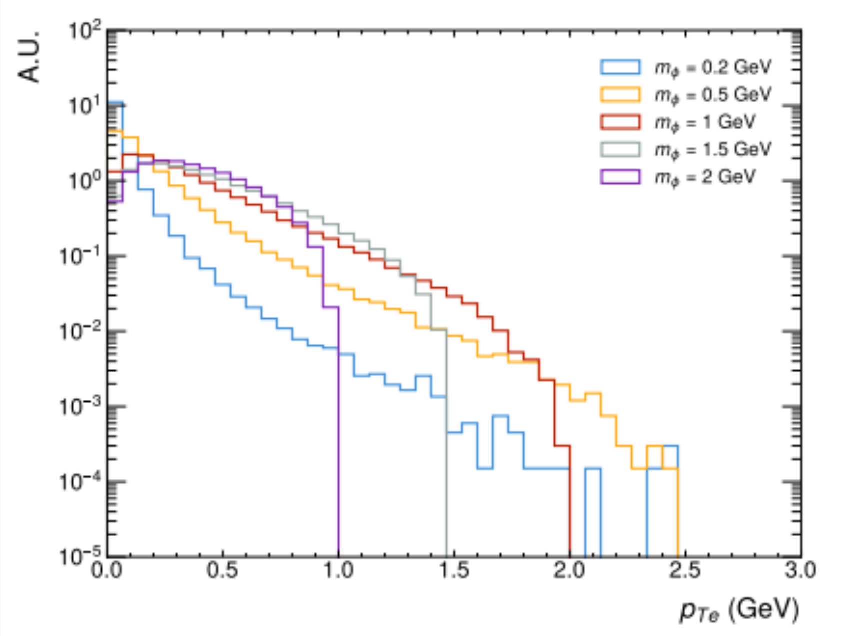


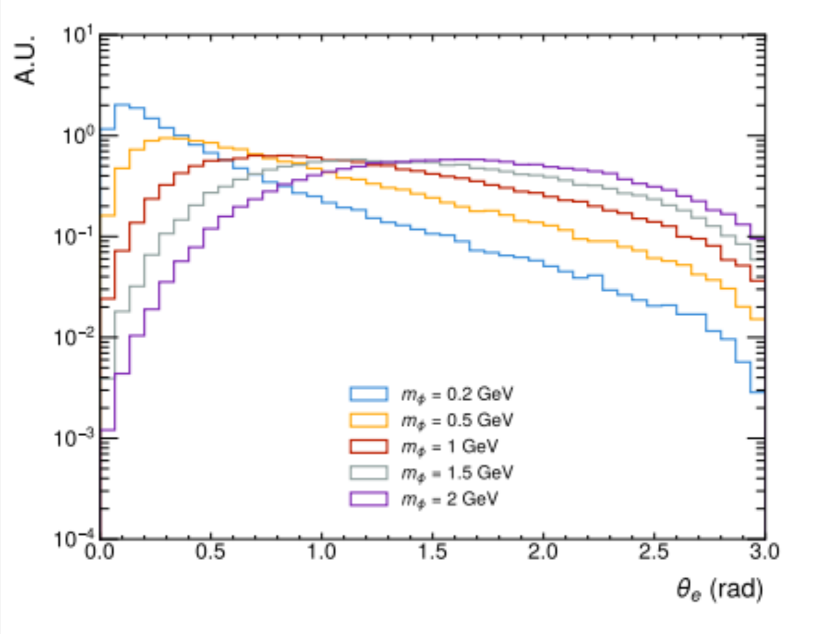
Phys. Rev. Accel. Beams **28**, 053401

Signal Kinematics

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



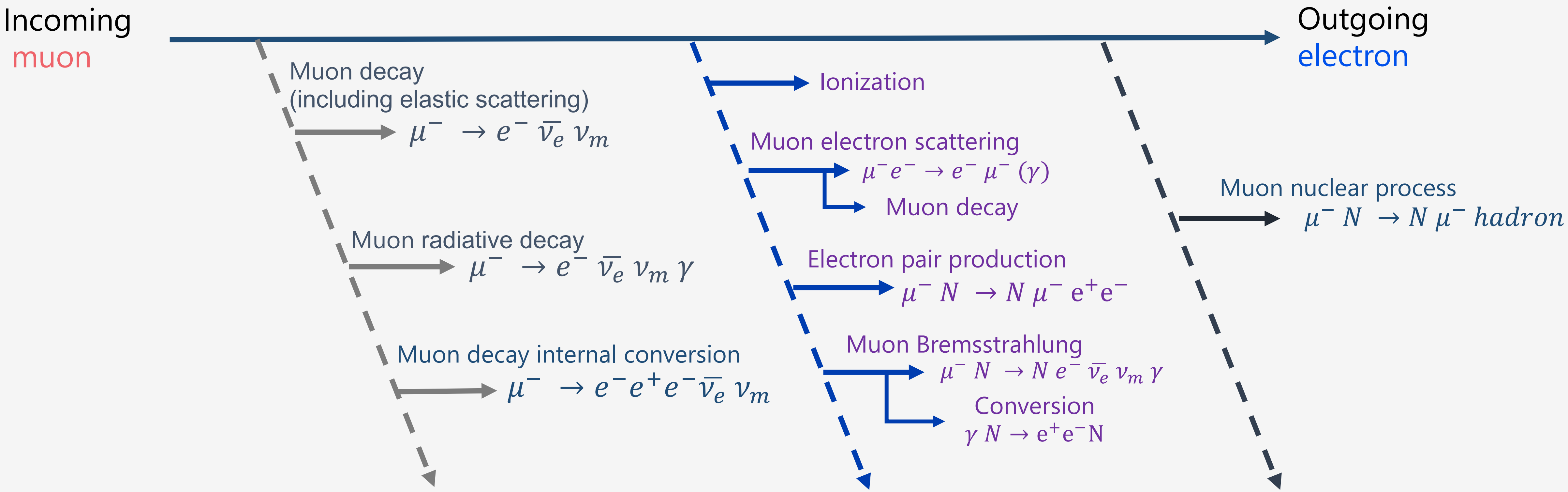




- Electron with sizeable transverse momentum
- Energy, pT and θ_e of decayed electron decreases as the m_X increases

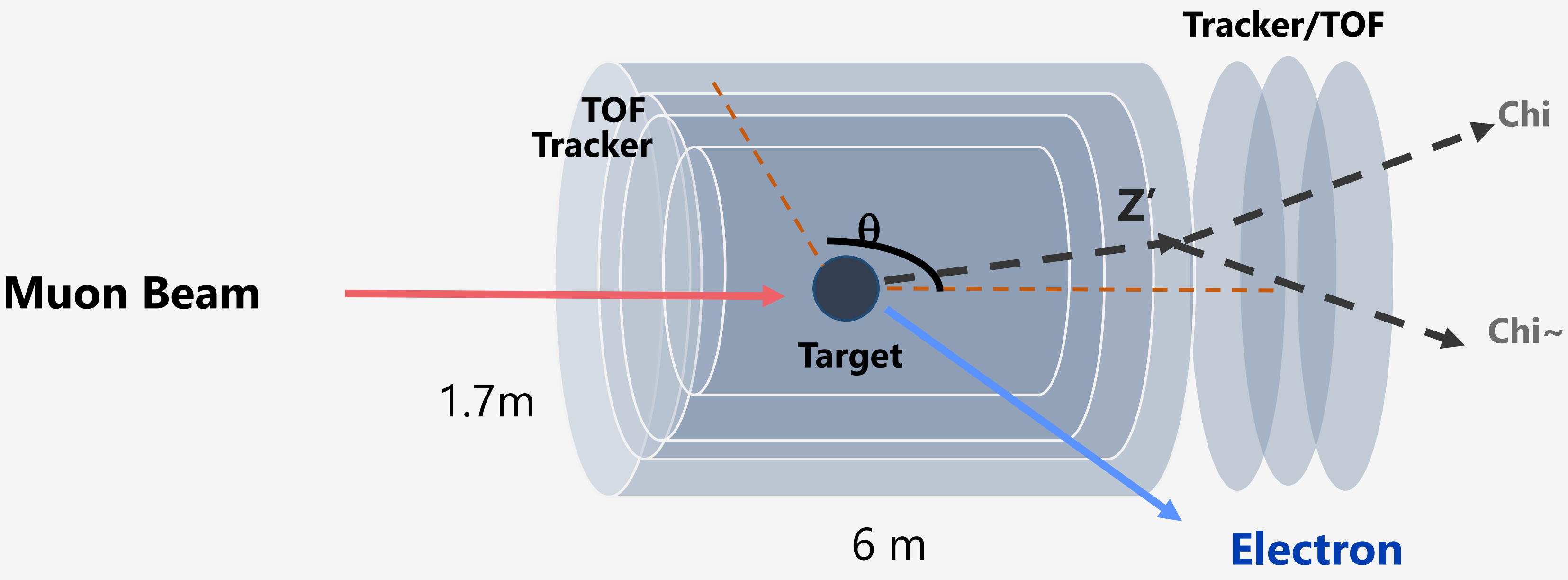
Background Estimation

- 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

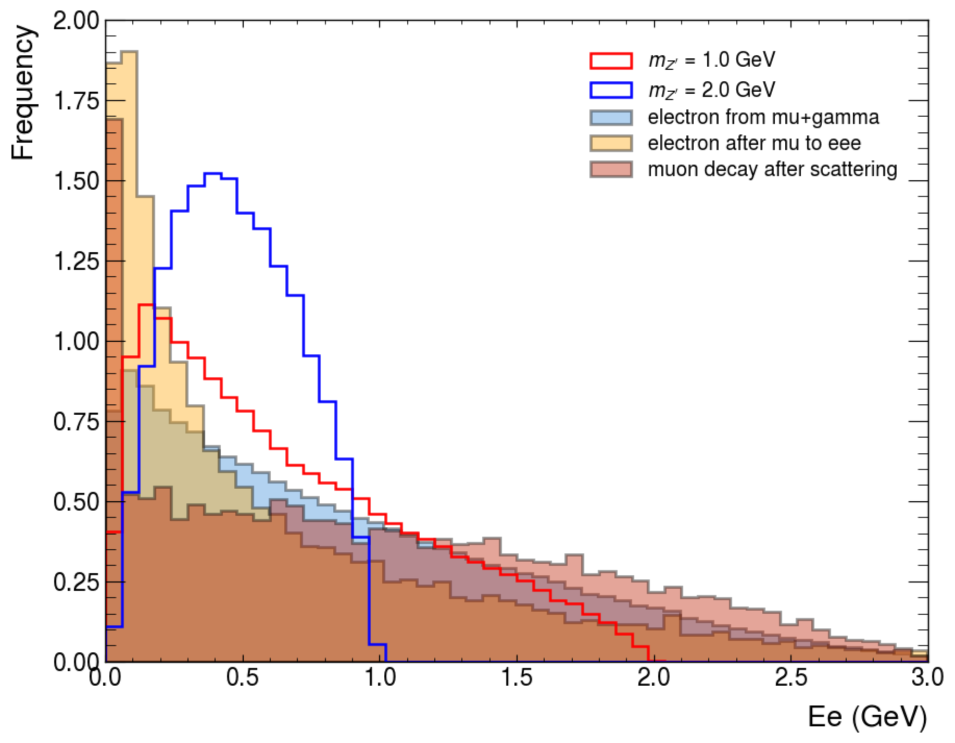
- The detector consists primarily of a tracking system and a TOF system
- Angular acceptance for charged particles up to scattering angles of roughly 120 degree
- Three additional standalone tracking and TOF stations along the beamline for beam remnant veto

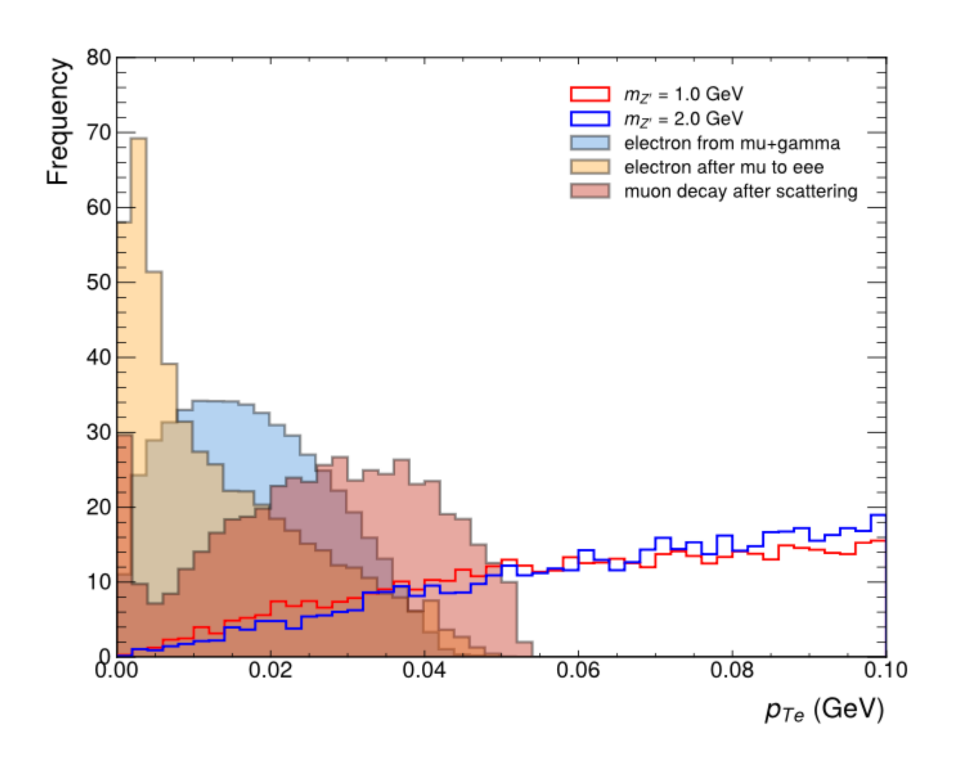


Background Estimation: Muon Decay

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

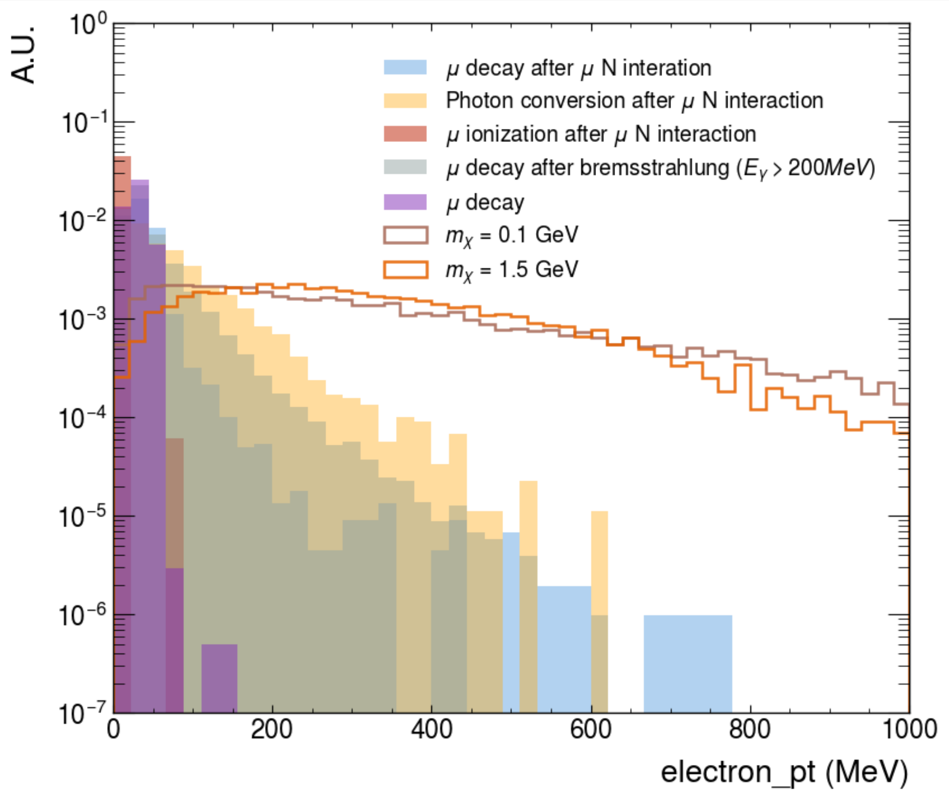
- Muon decay: $\mu^- \to e^- \bar{\nu}_e \nu_m$, taking into account of muon multiple scatterings
- Rare decay processed are simulated by McMule

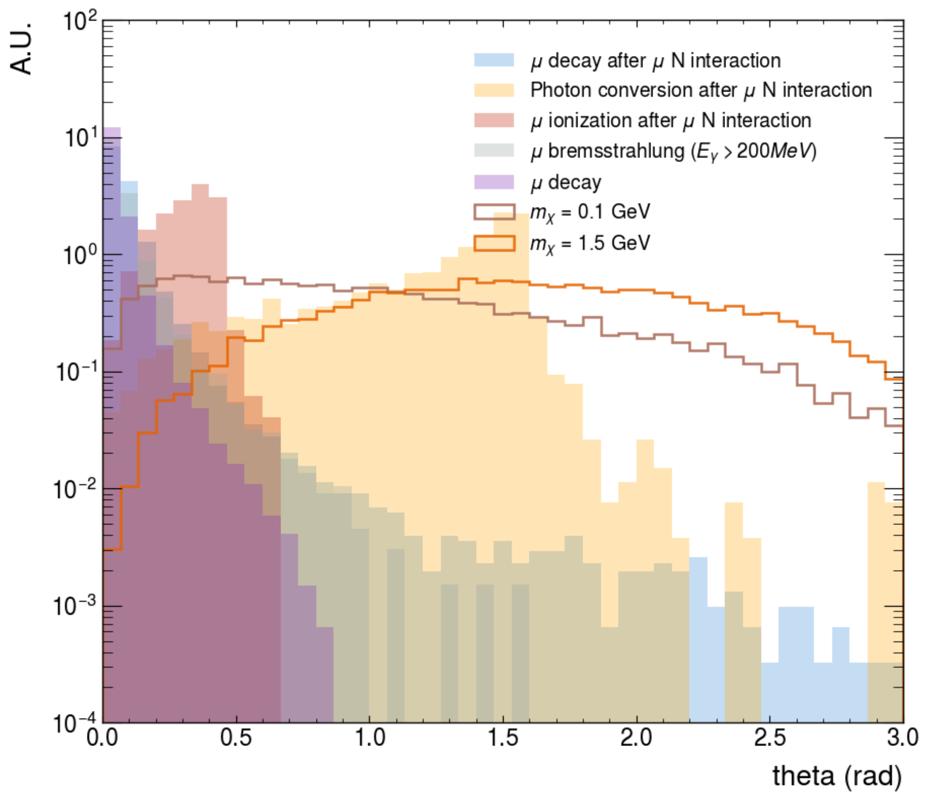




More Backgrounds

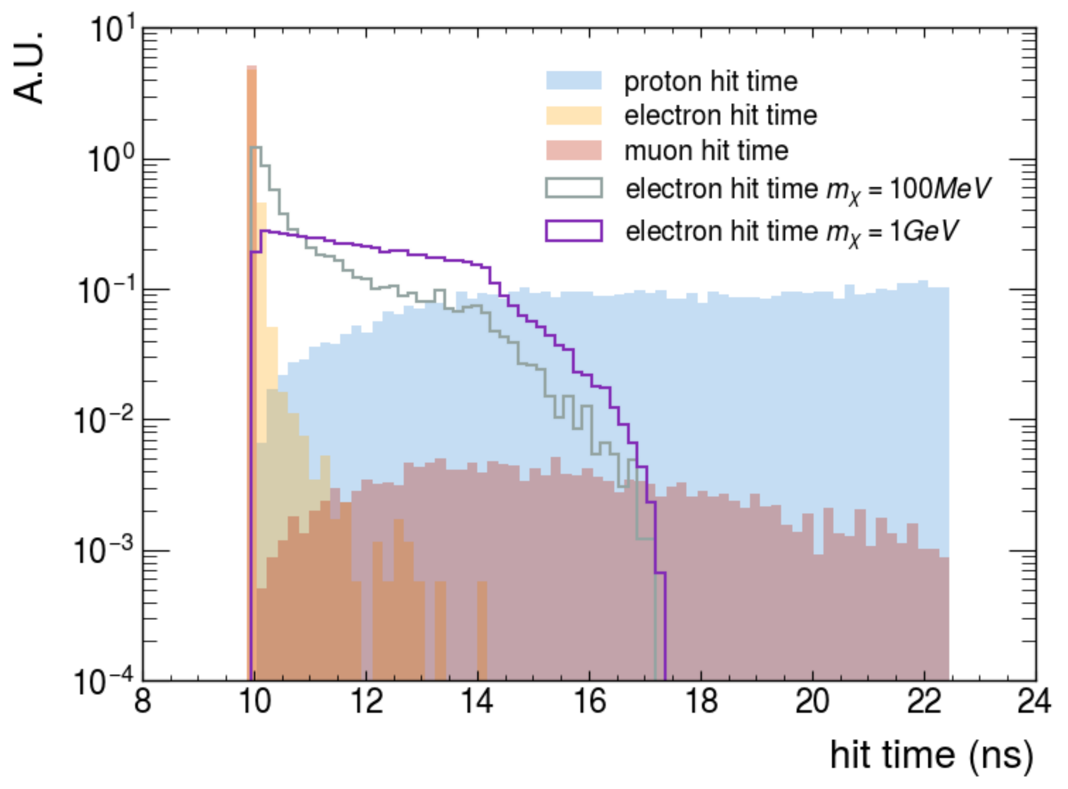
- Muon nuclear process ($N + \mu^- \rightarrow N + \mu^- + p.....$): produces charge particles such as protons, pions and muons with similar characters with those of signal process
  - μ-N interaction and μ bremsstrahlung processes may produce electrons with large pT
    - Hadrons can be identified and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





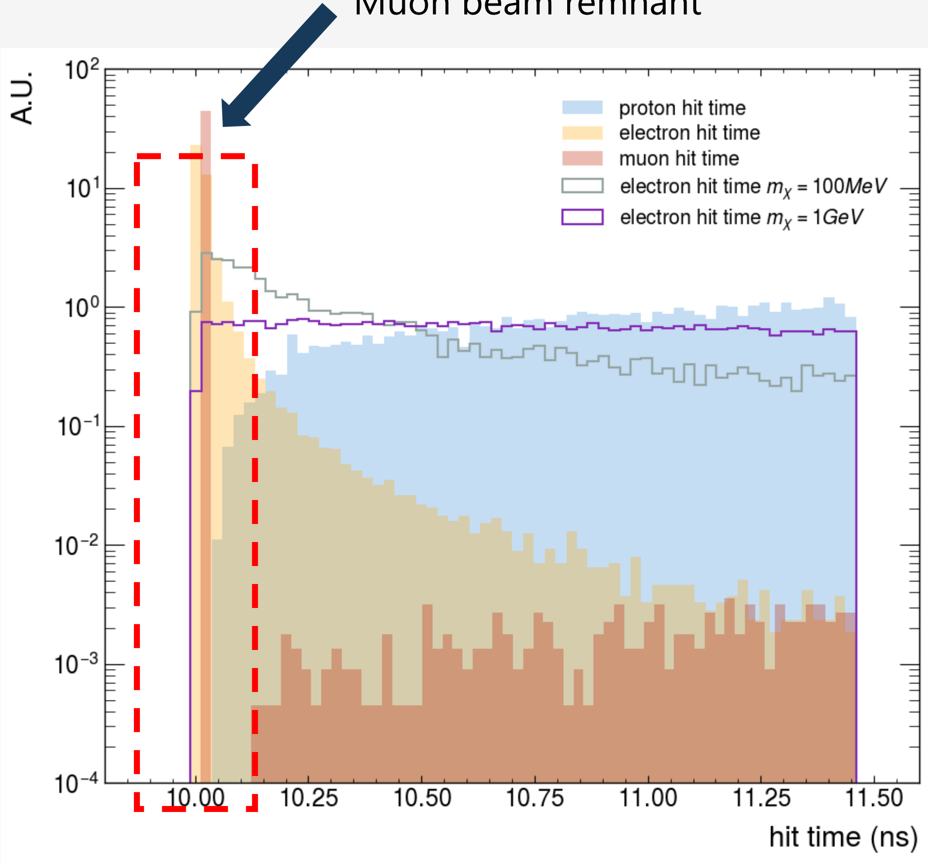
Proton and Muon Veto

- 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

Muon beam remnant

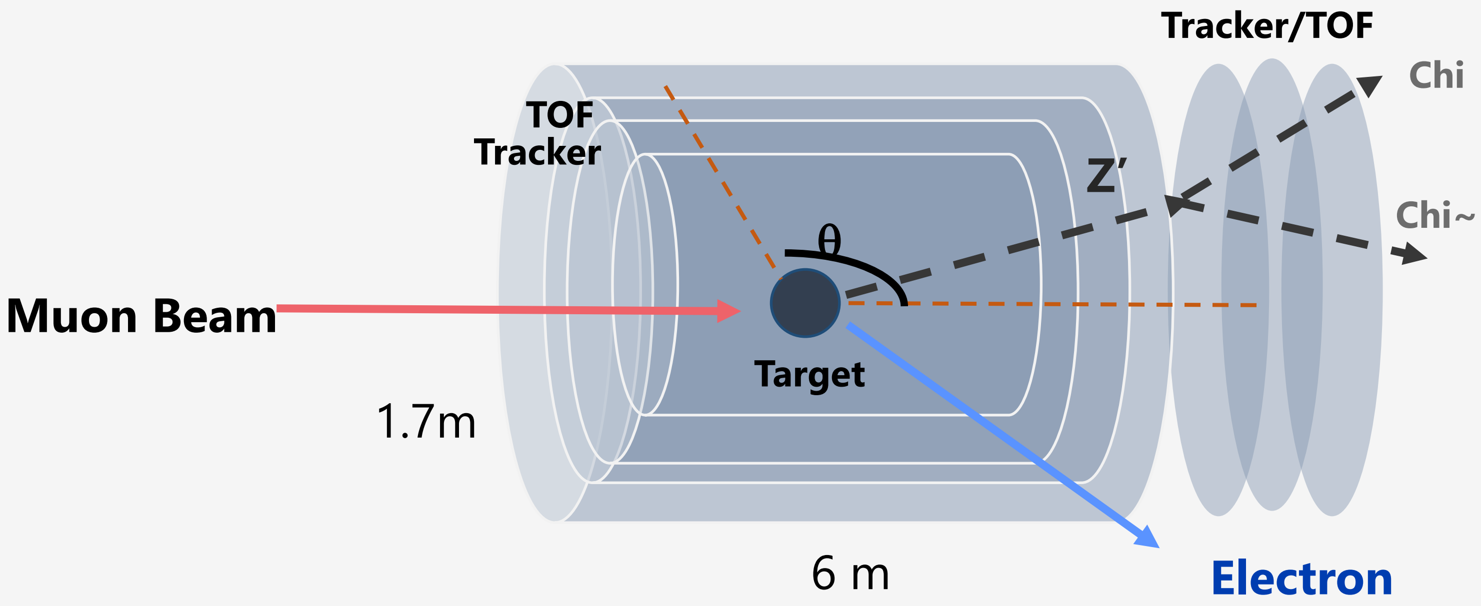


Signal Selection and Background Rejection

- 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 °)



- The signal efficiency ranges from 10% to 30%

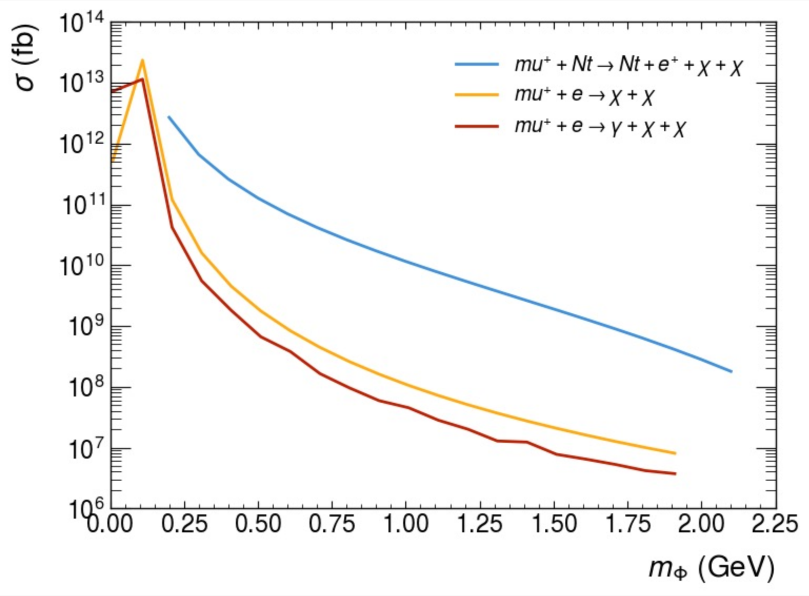
Signal Efficiency and Background Rejection

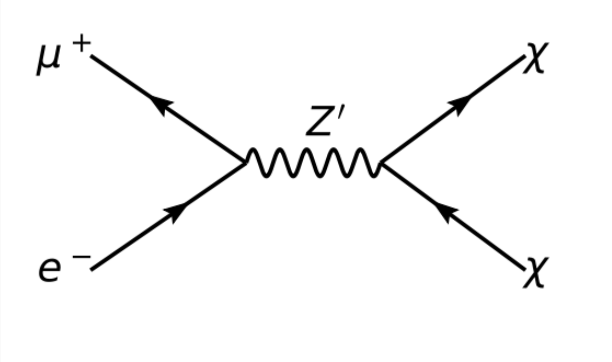
- Geant4 is used for background modelling
- Muon and proton veto can remove most backgrounds
- Electron pT and θ selection to further suppress backgrounds

Process	Generated	Single track	TOF	$\theta_e > 43^\circ$	$p_T^e > 20$ 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

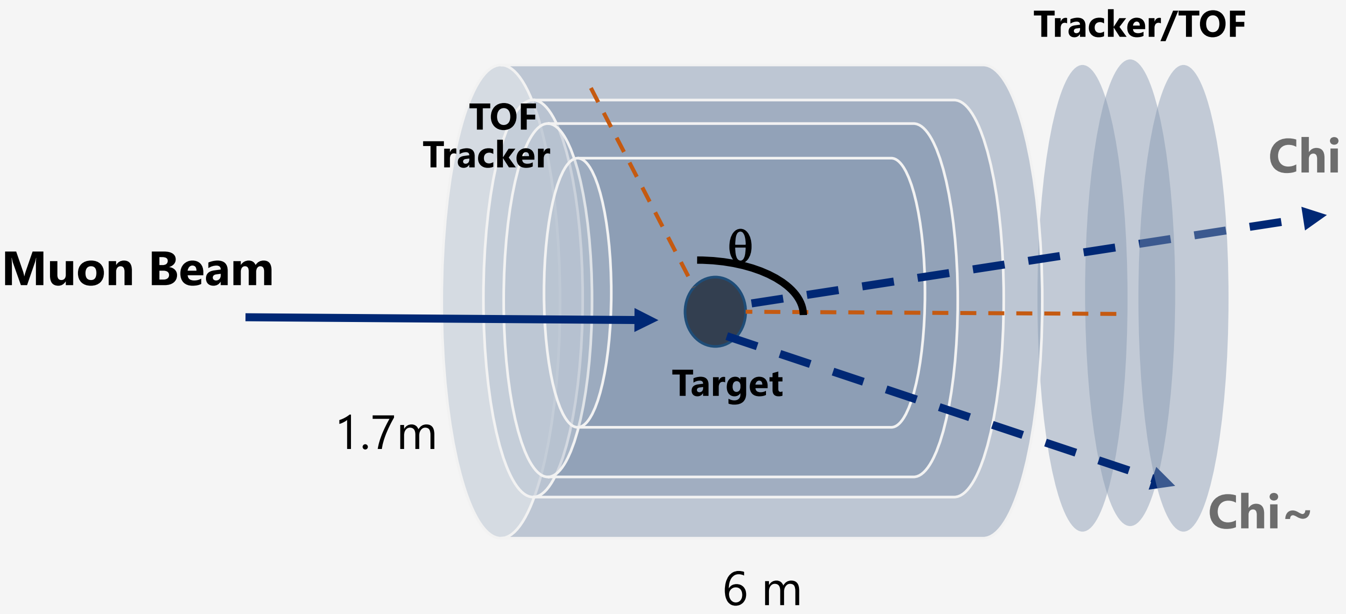
Annihilation Channel

- 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



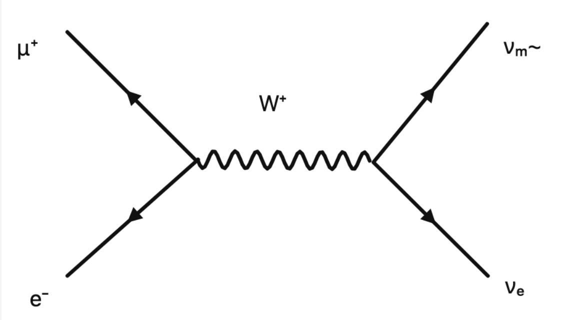


$$\sigma(s) \sim \frac{g_l g_D}{(s - M_W^2)^2 + M_W^2 \Gamma_W^2}$$



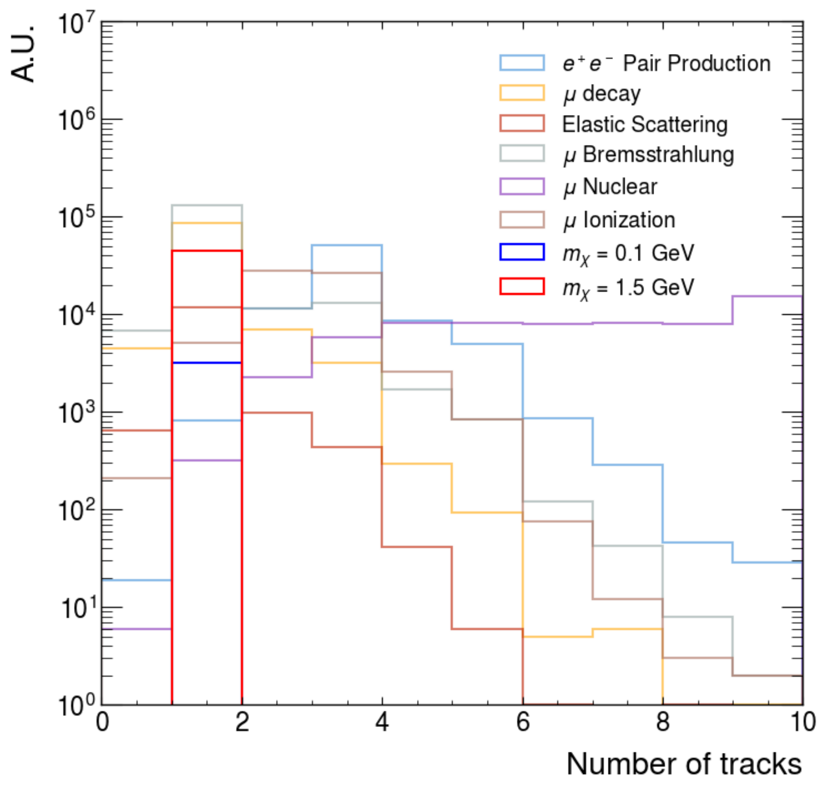
Background Estimation in Annihilation Channel

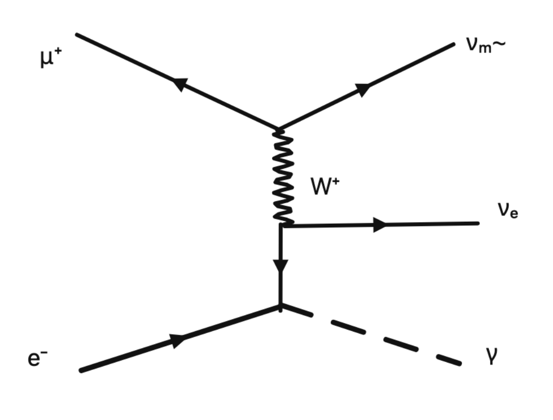
- **SM process**: Irreducible background with neutrino final state
- The cross section is very small, yielding 0.2 events with $5*10^{12}$ MOT for 22 cm lead target



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

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





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

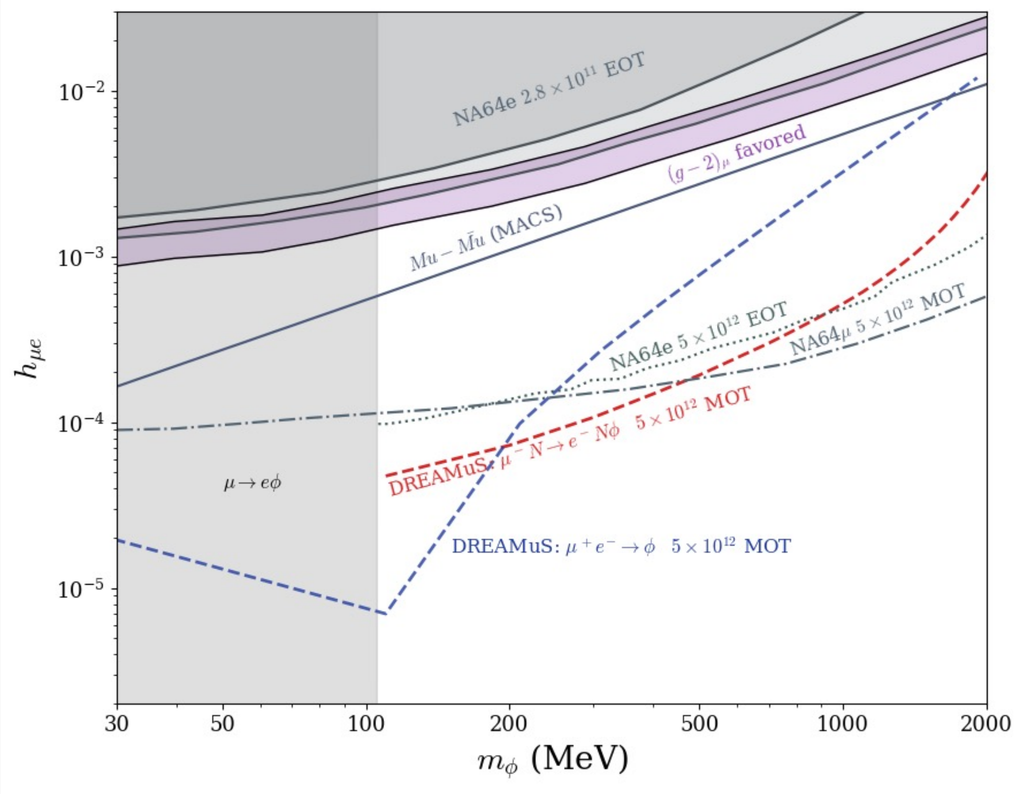
Annihilation Channel: Background Rejection

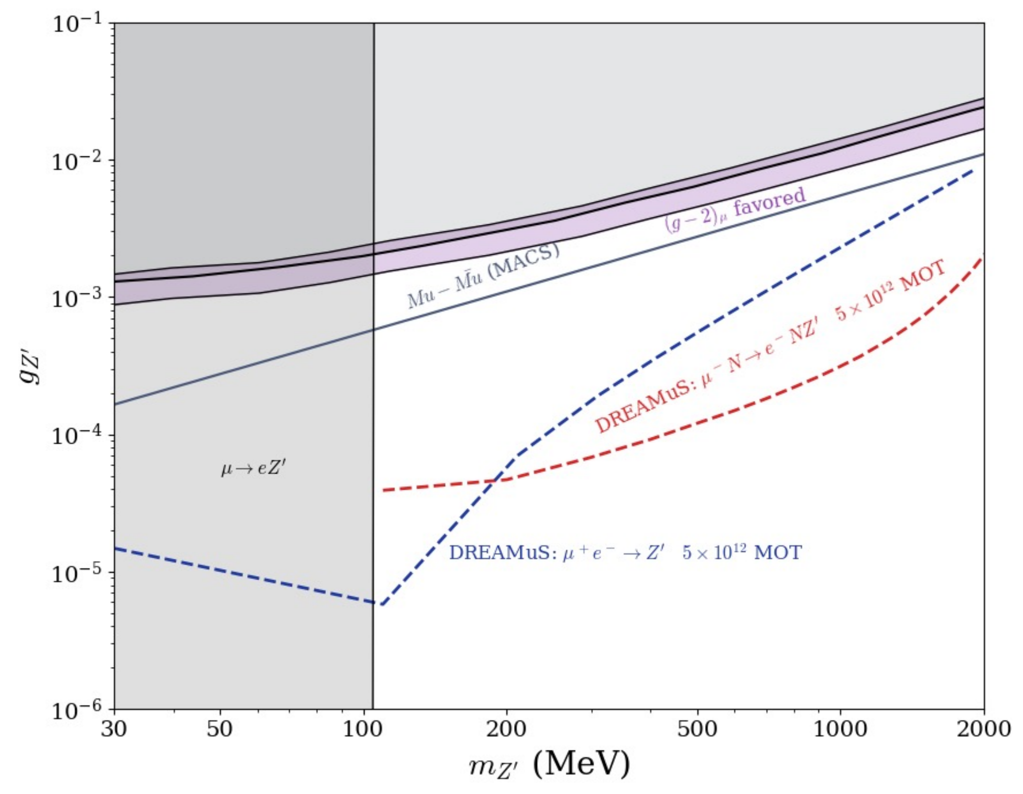
- For muon electron annihilation, the signal efficiency is almost 100% after background rejecton
- Charged-particle veto: Events with reconstructed downstream charged tracks are rejected. The assumed tracking efficiency is 99%
- Tracker veto: Events with any additional hits in the downstream tracker 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, $m_{Z'} = 3m_\chi$
  - 90% C.L. limit on the coupling constant: ~ 10^{-4} - 10^{-5}

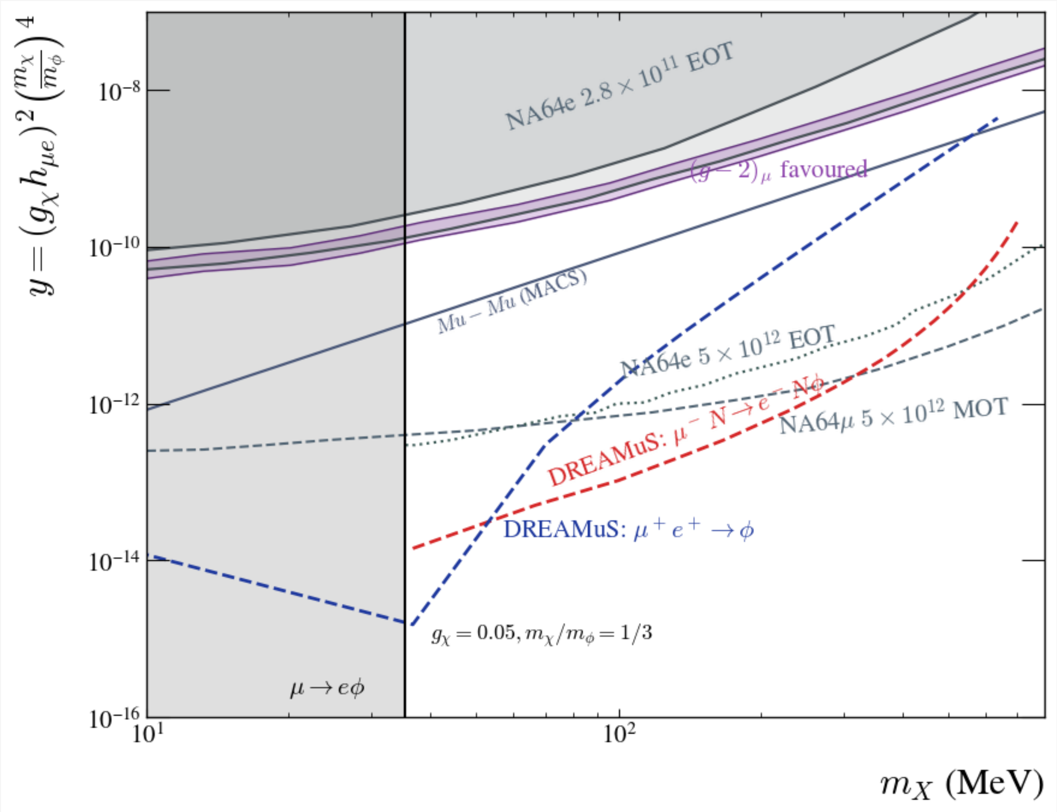


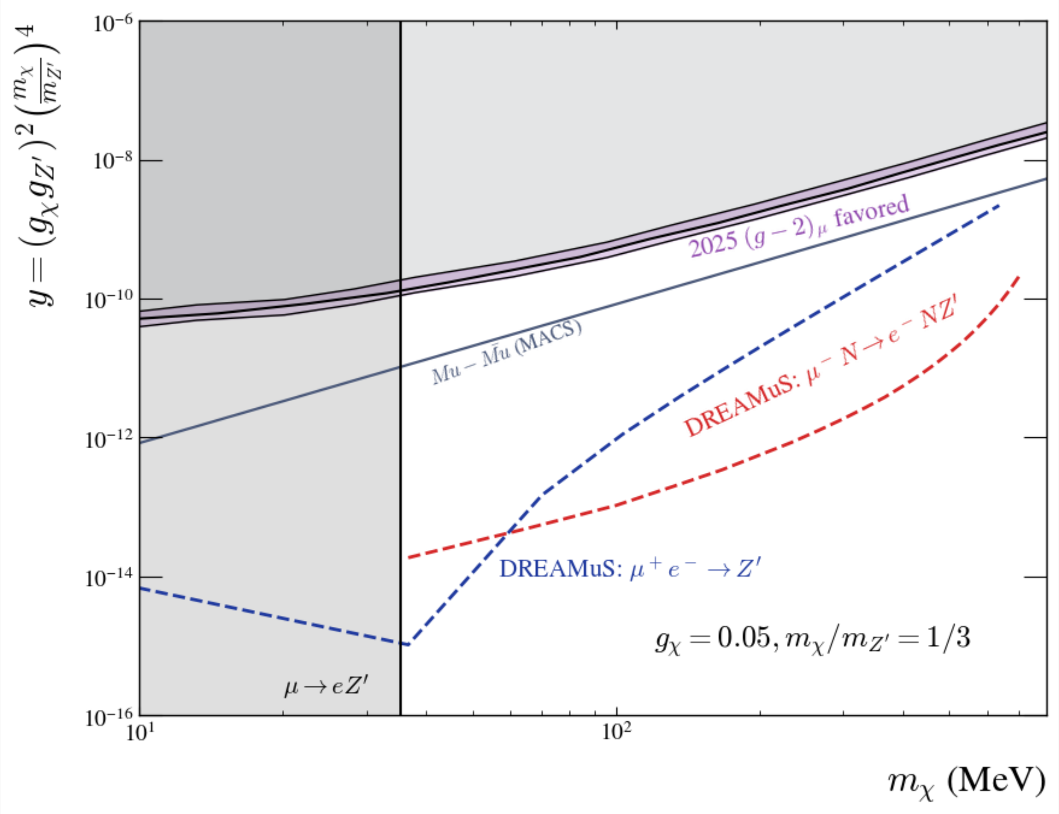


Comparing to muon beam results, 90% C.L. limit reaches ~10^{-6} , an order of magnitude better in 100MeV -200 MeV region for the annihilation channel

Search Sensitivity with HIAF for Dark Matter Particle

- Assuming the dark matter coupling factor gχ =0.05 and $m_X = 1/3 m_{Z'}$
- Constructing the factor $y \backsim (g\chi h_{e\mu})^2$ and $y \backsim (g\chi g_{Z'})^2$
- DREAMuS can yield best limit for the dark matter mass in the Sub-GeV region.





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
  - Economic no calorimeter design
  - 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

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
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_m \gamma, \gamma N \rightarrow \mathrm{e}^+\mathrm{e}^-\mathrm{N}$

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

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

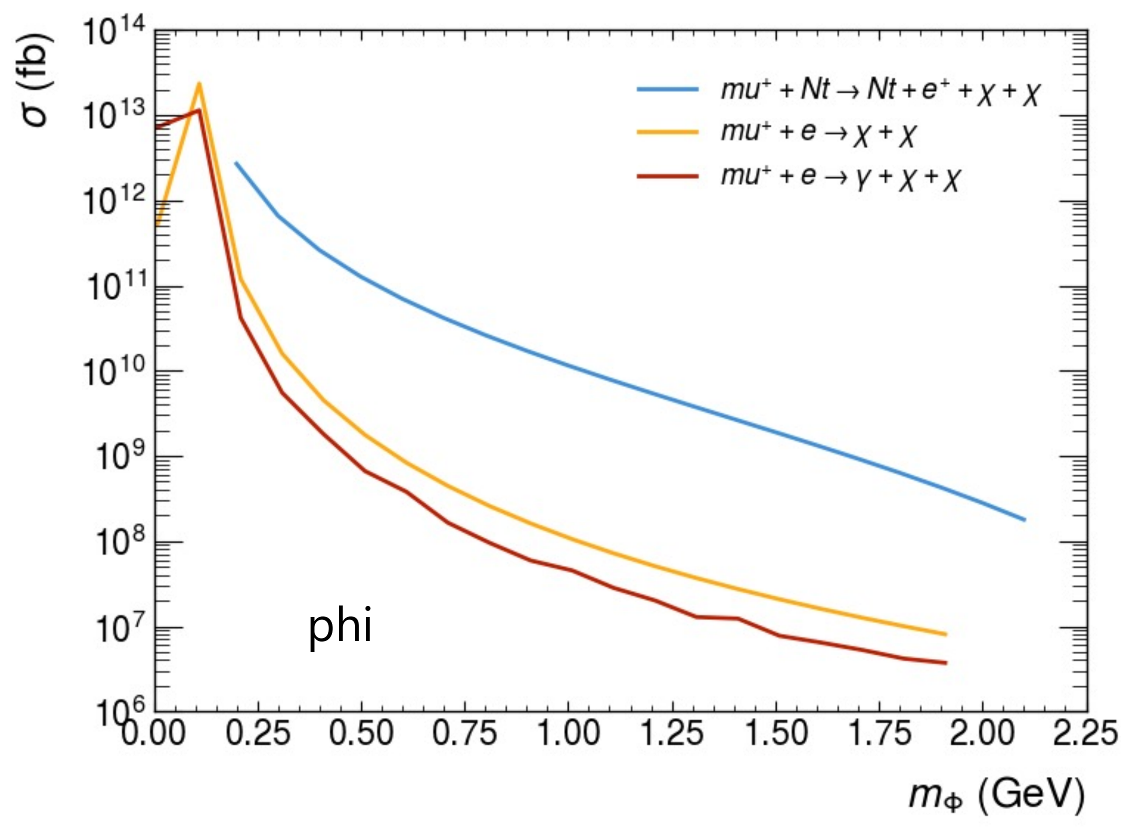
Hadrons

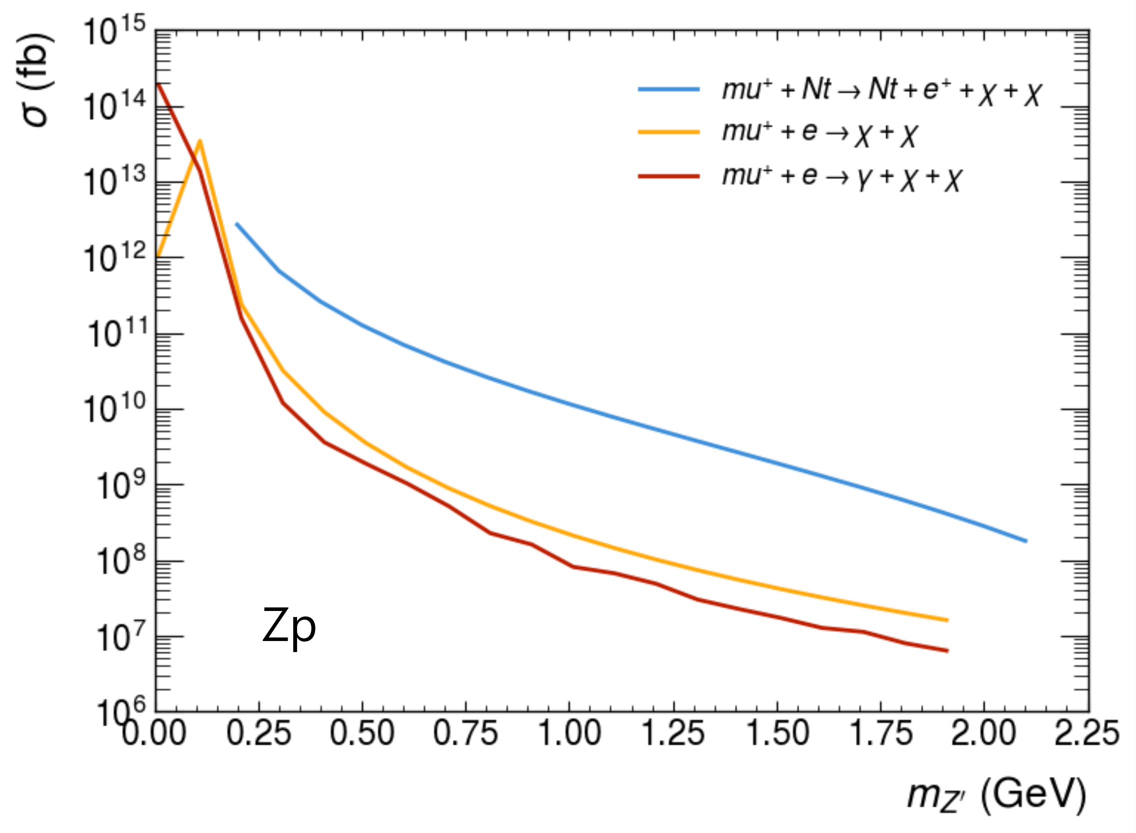
Muon decay+ muon nuclear
$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_m N' + hadron ...$

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

Anti-muon Electron Annihilation

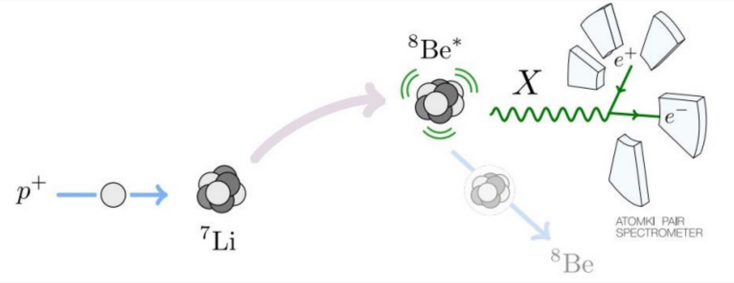
- The peak in the cross section estimation

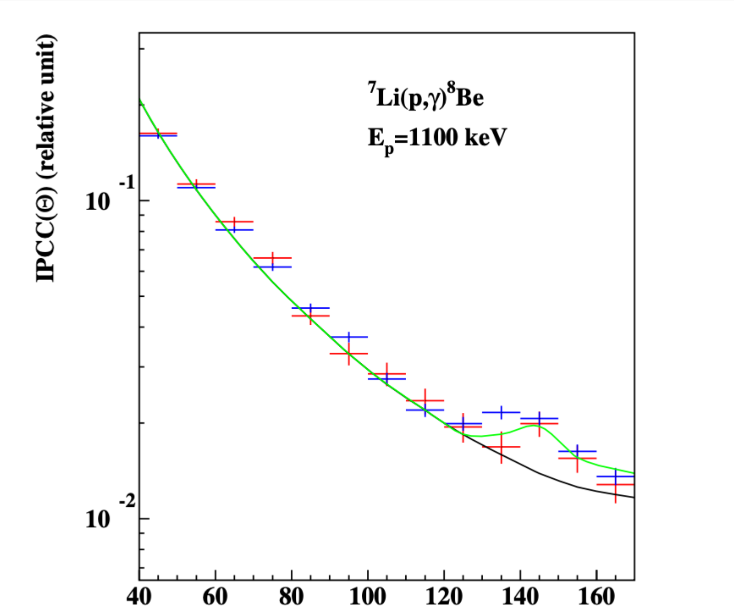




X_{17} Dark Matter Search

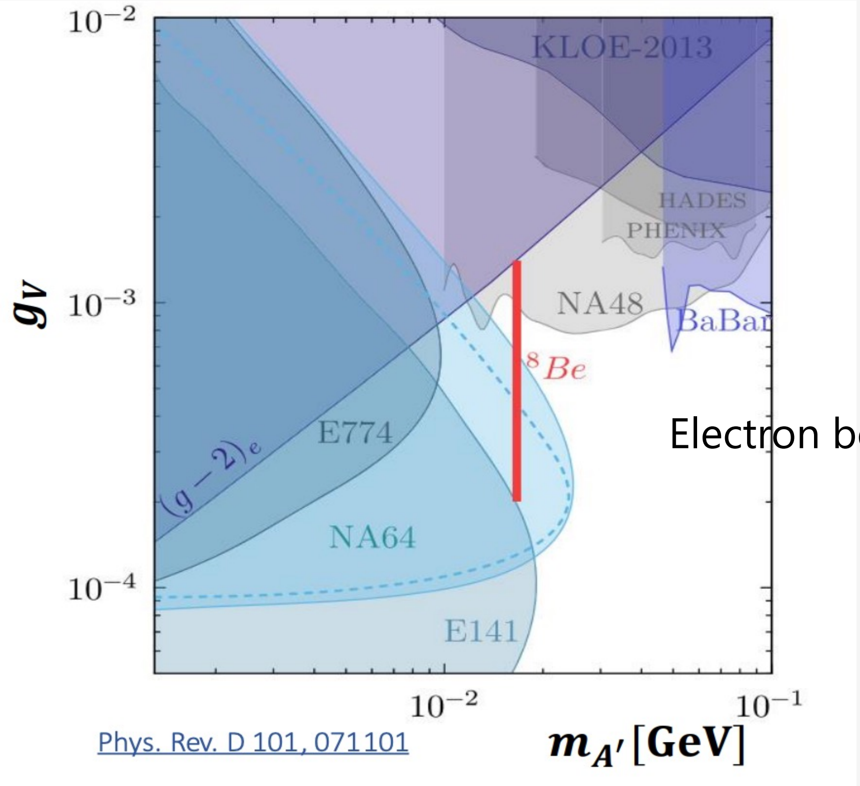
Anomalous excesses in angular correlation of ^{8}Li and ^{4}He couples are observed by the ATOMKI collaboration





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

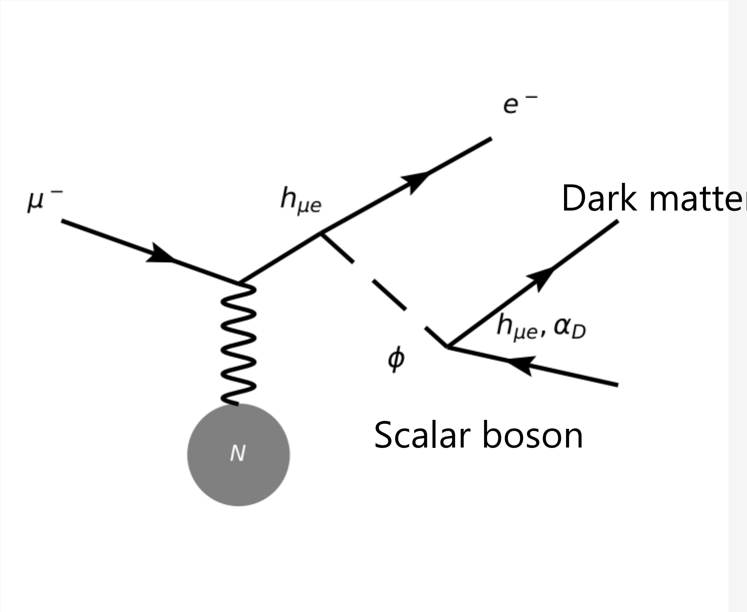
Flavor Violation Boson Search

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

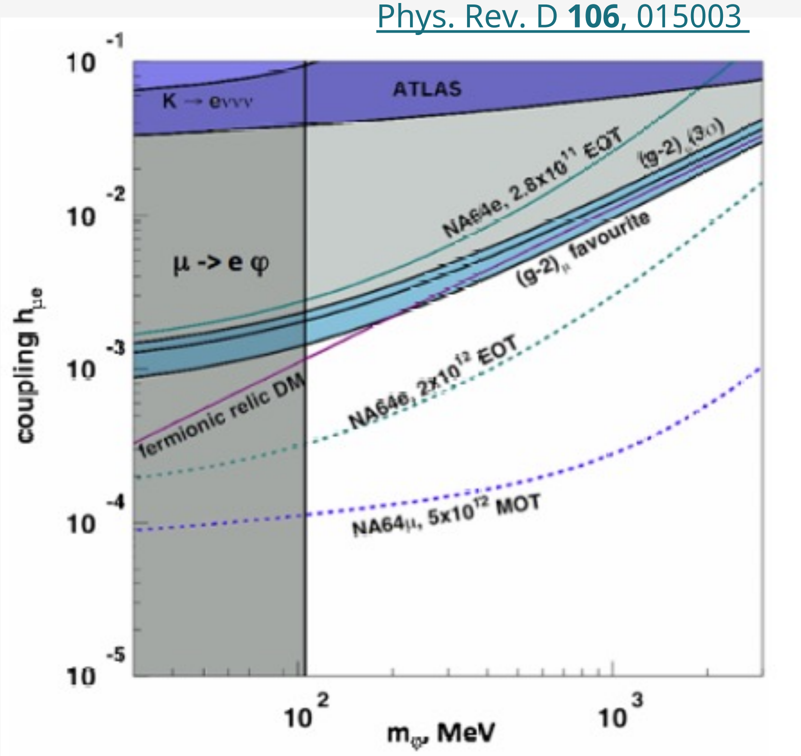
- Using the GeV level muon beam to hit the high–density target to generate flavor violation process
- For example, NA64@cern can shield upper limit on ϕ mass and the coupling

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

Dark Matter Production with Muon Beam

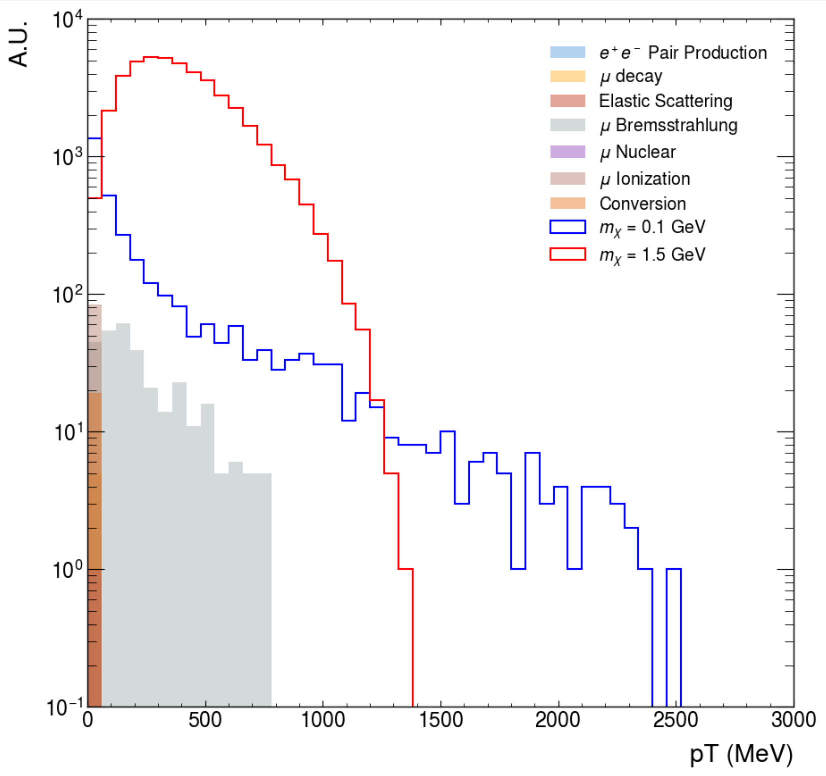


Phys. Rev. D **106**, 015003

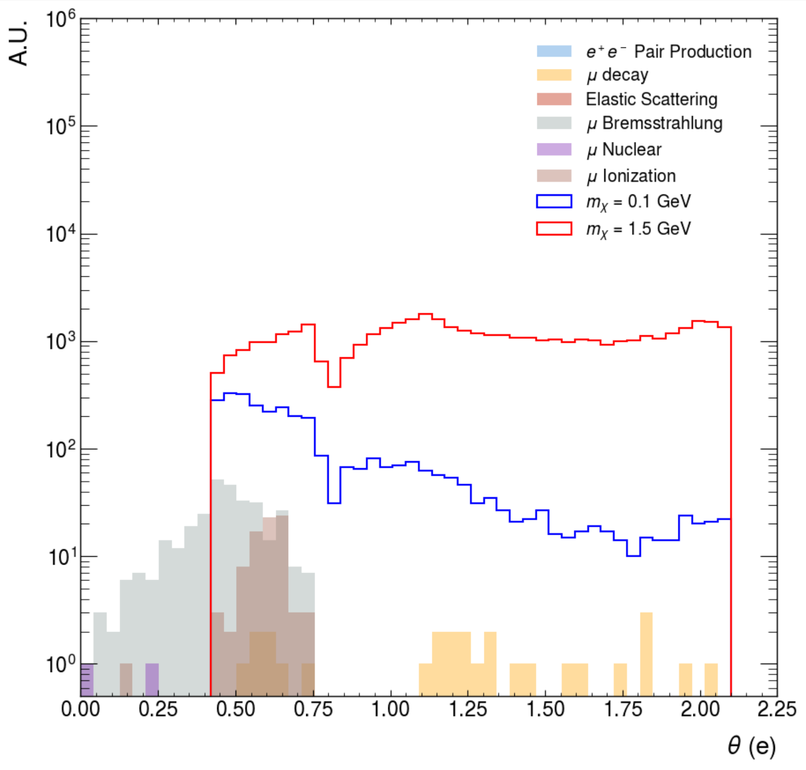


Electron pT and θ Distributions

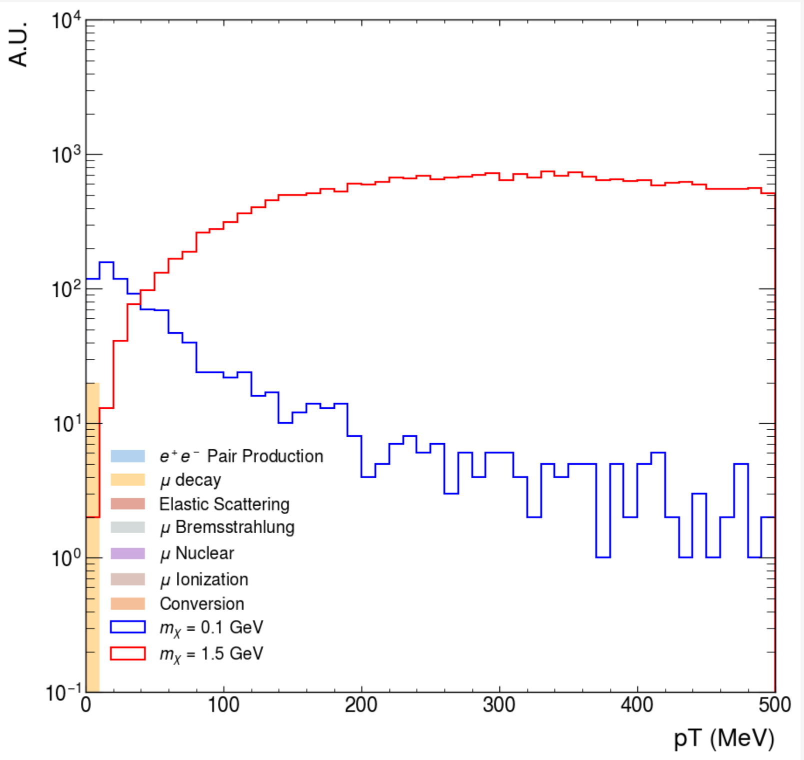
p_T after TOF selection



θ after TOF selection



p_T after θ selection



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
- DREAMuS benefits from thicker target ($40X_0$) and backgroud modelling comparing with electron beam

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