Sensitivity potential to a flavor-changing scalar boson with DUNE and NA64

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Muons in Minneapolis Workshop

Dec 6-8, 2023

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Outline

- Motivation
- Benchmark model: Charge Lepton Flavor violating scalar boson model
- Sensitivity potential at muon beam-dump experiments
  - NA64μ
  - DUNE
- DIS e/$\mu \to \tau$ conversion as possible BSM signal at NA64
- Conclusions

Motivation

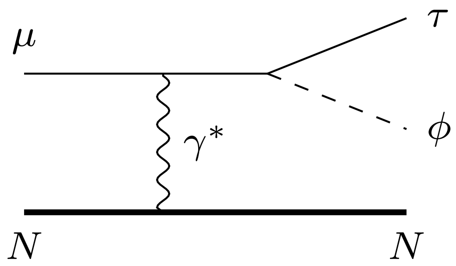
- Dark Sector physics could manifest in interactions with leptons:
  - Existing discrepancy between muon g-2 theory and experiment.
  - Lepton flavor is conserved with massless neutrinos.
  - Non-zero neutrino masses: neutrino oscillations motivate search for Lepton Flavor violations.
  - Charged Lepton flavor violation is heavily suppressed in the SM → sensitive test of new physics.
  - A lepton-flavor-violating interaction could be mediated by a Dark Sector particle, feebly coupling to SM.

Motivation

- Many experiments use e/muon beams to search for CLFV:
  - Muon-e-Gamma (MEG II, PSI): $\mu^+ \to e^+ + \gamma$
  - Mu3e experiment (PSI): $\mu^+ \to e^+e^+e^-$
  - Mu2e experiment (Fermilab): $\mu N \to eN$
  - COMET experiment (JPARC): $\mu N \to eN$
  - Belle (II) e^+e^- collider: tau decays to ℓ leptons, $\ell = e, \mu$
  - **NA64e, NA64μ:** e/μ-beam + target: missing energy/momentum technique
  - **DUNE**, HyperK: Proton dump experiments producing an intense muon beam as a “side product” + Near Detector suite
  - Others: M^3, SHADOWS, HIKE, ATLAS, SHIP,…

CLFV model

- Recent model put forward: Y. Ema, Z. Liu, K-F Lyu and M. Pospelov *JHEP* **135** (2023).
  - Flavor-changing scalar boson with accidental longevity



$$\mathcal{L}_{\mathcal{I}} = \phi\bar{\mu}(g_V + g_A\gamma^5)l + \phi^*\bar{l}(g_V^* - g_A^*\gamma^5)\mu$$

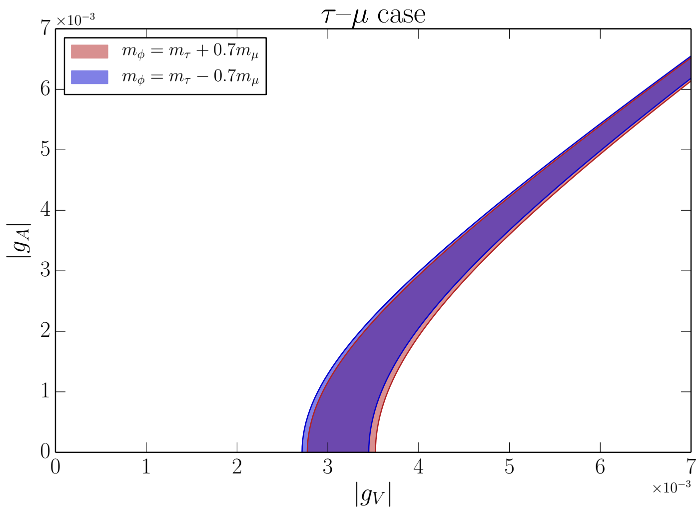
- $m_\phi < \ell_2 - \ell_1$: leads to prompt decay of l_2 (lepton lifetime)
- $m_\phi > \ell_2 + \ell_1$: prompt decay of ϕ (prompt decay searches)
- $|\ell_2 - \ell_1| < m_\phi < \ell_2 + \ell_1$: two-body decay not allowed, long lifetime

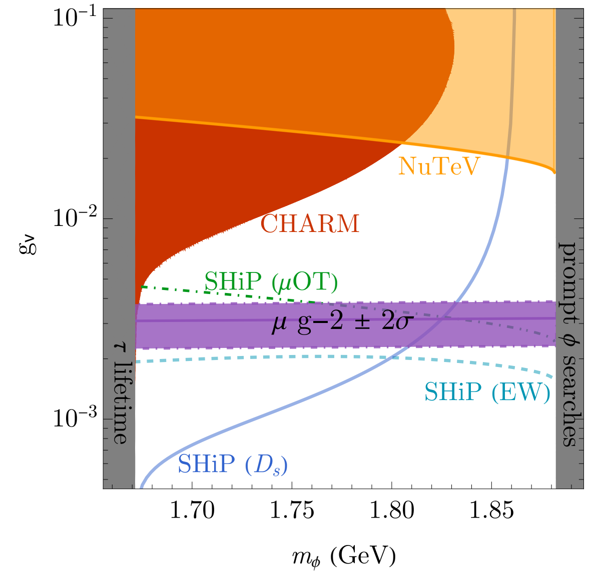
➡ Macroscopic propagation distance between production and decay

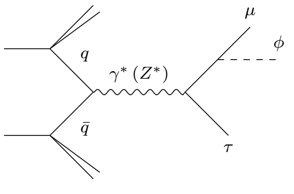
CLFV model target parameter

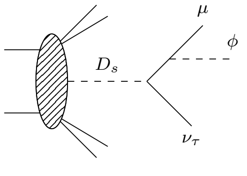
Y. Ema, Z. Liu, K-F Lyu and M. Pospelov *JHEP* **135** (2023).

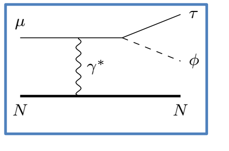
- Benchmark parameter target region to explain the muon g-2 anomaly
- Existing/projected limits from μ-on-target, direct EW production, heavy-meson decay











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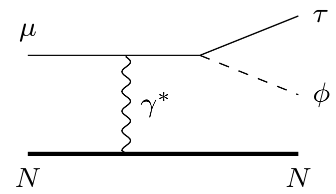
CLFV model and μ on target

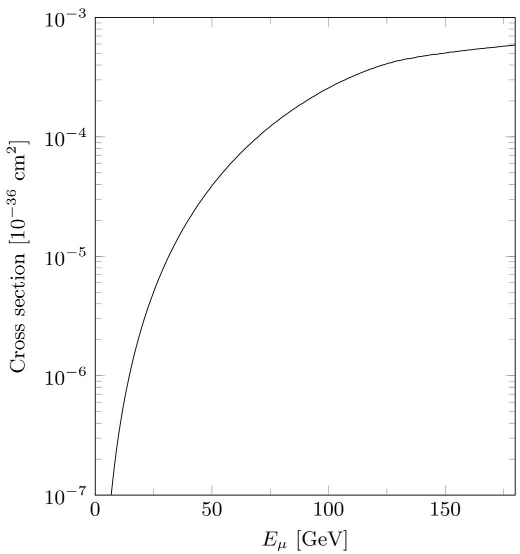
- Production cross section and lifetime:

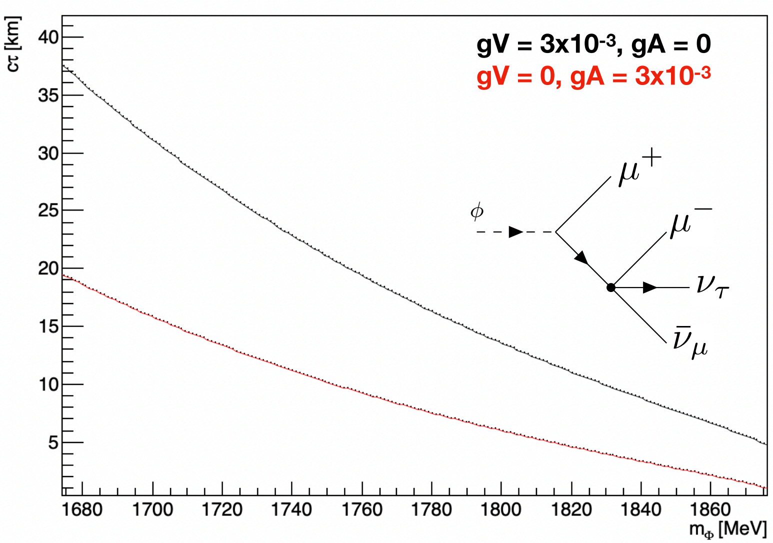


$$s > (\sum_x m_x)^2$$

$$m_\mu^2 + m_N^2 + 2E_\mu m_N > (m_\tau + m_N + m_\phi)^2$$

if $m_\phi \simeq m_\tau$ $\quad E_\mu > \dfrac{(2m_\tau + m_N)^2 - m_\mu^2 - m_N^2}{2m_N} \simeq 3.8\text{GeV}$





CLFV as a benchmark for μ-on-target experiments

- μ-on-target experiments are promising to detect new signals:
  - precisely measure incoming muon energies/distributions
  - measure outgoing particles and/or search for excess above Bg after dump
- Experimental scenarios:
  - **NA64μ**: High-intensity, 160 GeV/c muon beam at CERN SPS (Pb/W target)
  - **DUNE**: High-intensity, wide-energy muon beam produced as by-product from neutrino beam production (Steel target)

Signal yield at detector:

$$N_\phi = \int \mathrm{d}E_\phi \Phi_\phi(E_\phi) \times \frac{l_{\mathrm{det}}}{\gamma \beta c \tau_\phi}$$

Signal flux at production:

$$\Phi_\phi(E_\phi) = l_{\mathrm{target}} n_A \int dE\,\Phi_\mu(E) \times \int_0^{\theta_{\mathrm{det}}} \mathrm{d}\theta_\phi \sin\theta_\phi \frac{\mathrm{d}^2\sigma(E, E_\phi)}{\mathrm{d}E_\phi \mathrm{d}\cos\theta_\phi}$$

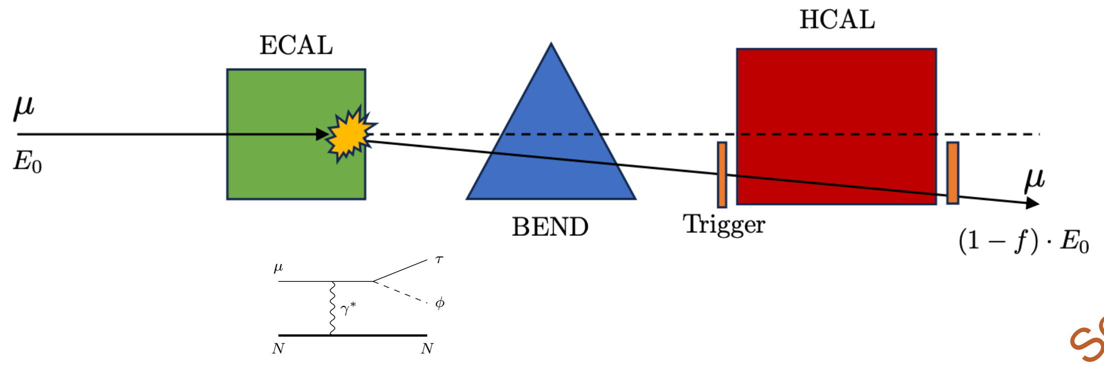
D. V. Kirpichnov et al. Phys. Rev. D 104 (2021)
https://doi.org/10.1103/PhysRevD.104.076012

General approach

- General approach to probe hidden sectors with muon beams on target
- Milicharged particle search: S. Gninenko et al. PRD 100 (2019) 035003
- Deep-inelastic e-τ, μ-τ conversion: S. Gninenko et al. PRD 98 (2018) 015007
- Vector portal interaction with light dark matter: S. Gninenko et al. Phys. Lett. B 796 (2019) 117
- Leptonic scalar as portal interaction: S. Gninenko et al. PRD 106 (2022) 015003
- Spin-0 mediators: H. Sieber et al. hep-ph:arXiv:2305.09015
- CLFV scalar: BR et al. EPJ C (2023) 83:775

NA64μ experiment

- NA64μ is a fixed-target experiment at CERN looking for DM portal interactions.
- The experiment uses the 160-GeV/c muon beam from CERN SPS.
- Beam scintillators, veto counters, low material-budget trackers, dipole magnets constrain the incoming beam momentum.
- Missing energy/momentum carried away by a New Particle leaves a scattered muon.
- Invisible-mode: muon final-state phase-space from the decaying τ used as a proxy

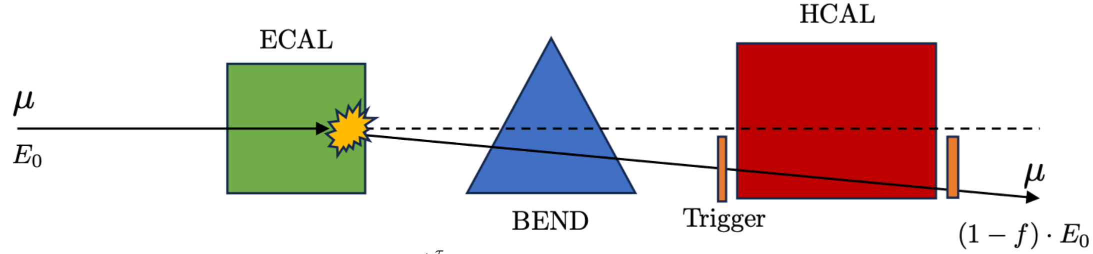


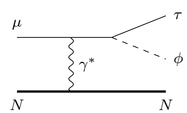
See more details on NA64 in Paolo Crivelli's talk

NA64μ experiment

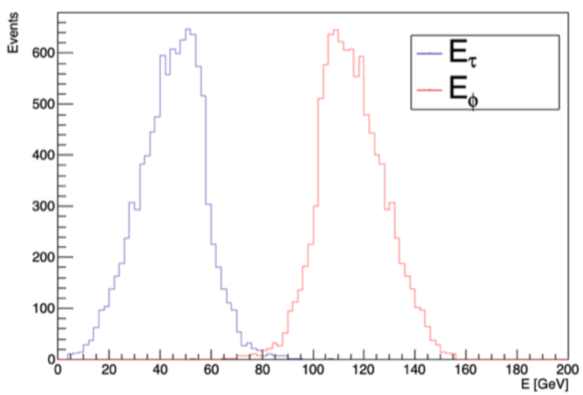
Initial state
Well-defined incoming μ with $\sim$ 160 GeV/c

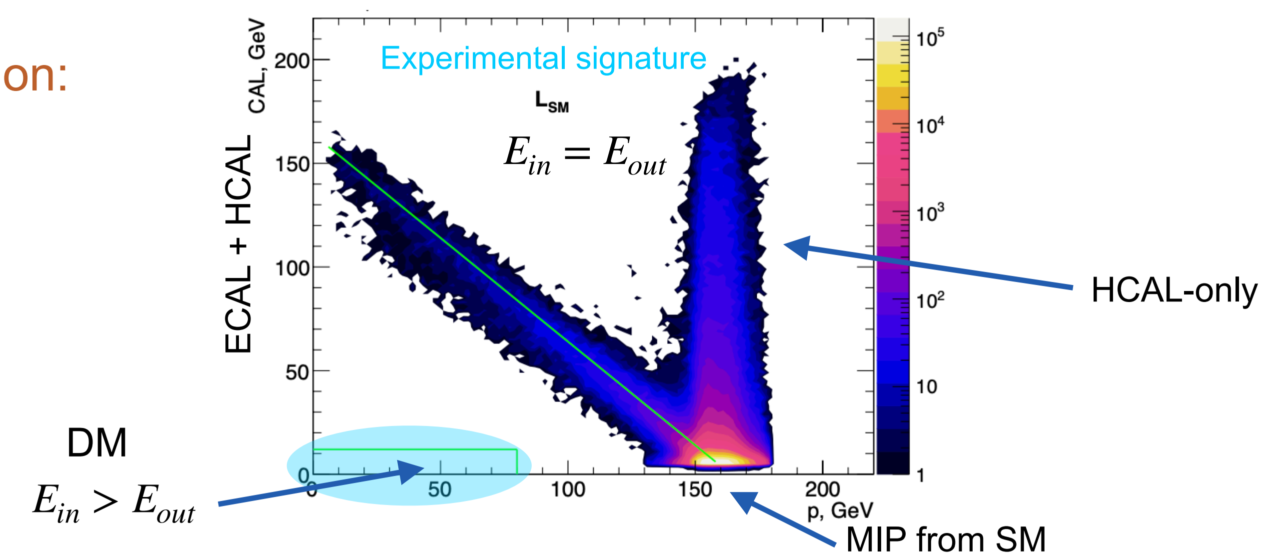
Final state
Single scattered μ with muon compatible energy deposit in the detector and momentum $\lesssim$ 80 GeV/c





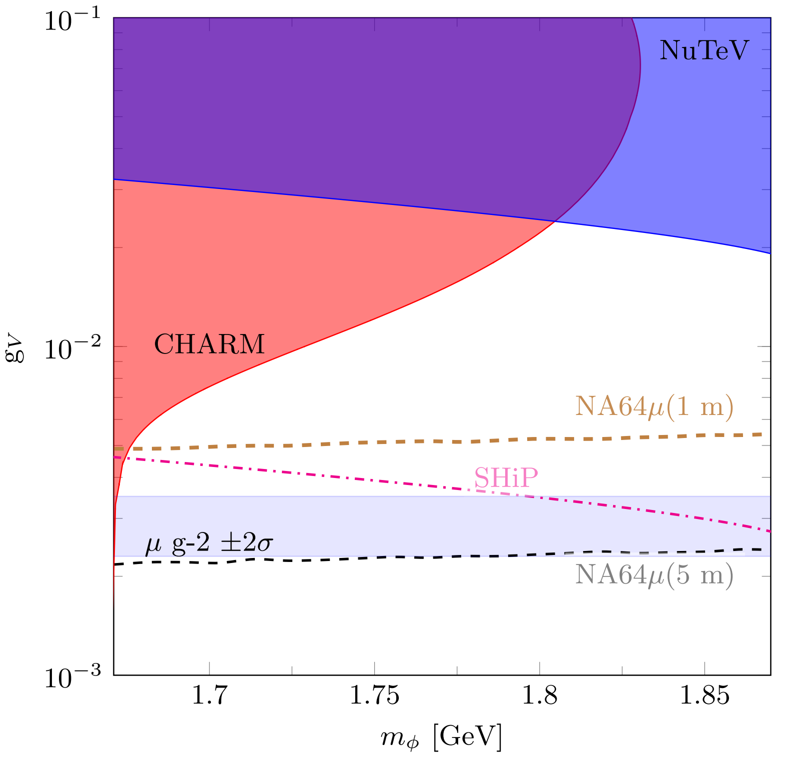
Sampling the diff. cross section:





NA64μ experiment

- Sensitivity study using an ideal scenario:
  - Assuming ~3 x 10^{13} MOT
  - Assuming a future optimized of target length/material (Pb/W)
  - No reconstruction, trigger effects
  - Both leptonic and hadronic decay modes allowed



BR, L. Molina-Bueno, L. Fields, H. Sieber, P. Crivelli EPJ C (2023) 83:775
https://doi.org/10.1016/j.cpc.2021.108129

NA64μ experiment

- Challenges:
  - Assumed total collected data: ~3 x 10^{13} MOT
  - Muon beam intensity for NA64: CERN M2 can deliver 10^{12} POT per spill, 3500 spills/day, 2 x 10^{8} μ/spill (note: SHiP p beam intensity is expected to be higher)
    - Assuming 10^{11} MOT/day, 80% duty cycle, 3 x 10^{13} MOT is reachable in ~43 days…
    - Current NA64μ capable to operate at 10^{7} μ/spill
    - Planned updates during LS3 (2026-2028) to trigger, electronics, detectors to reach ~6 x 10^{7}
    - Beam induced background increases with higher intensity (pile-up, muon beam halo)
  - Trigger on downstream muon from τ leptonic decay: 17% decay BR
  - Other τ hadronic final states travel long due to cτ before decaying
  - Target several meters of heavy Z nuclear target… (W ECAL to be tested in 2024)

BR, L. Molina-Bueno, L. Fields, H. Sieber, P. Crivelli EPJ C (2023) 83:775
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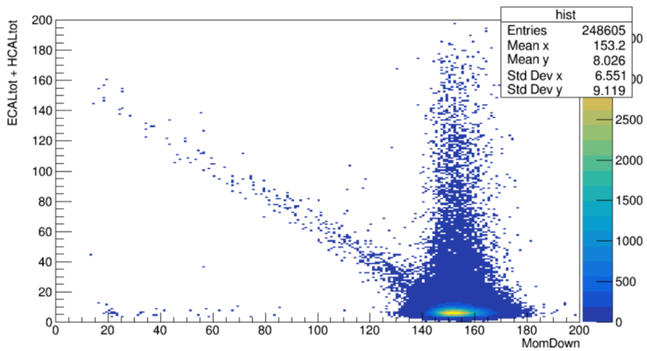
NA64μ experiment

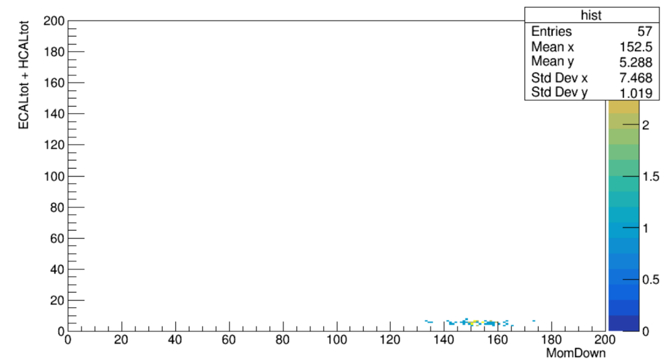
ETH group:
Claudine Felten
Benjamin B. Oberhauser
Henri Sieber

- Ongoing work: full Geant4 simulation using the DMG4* package

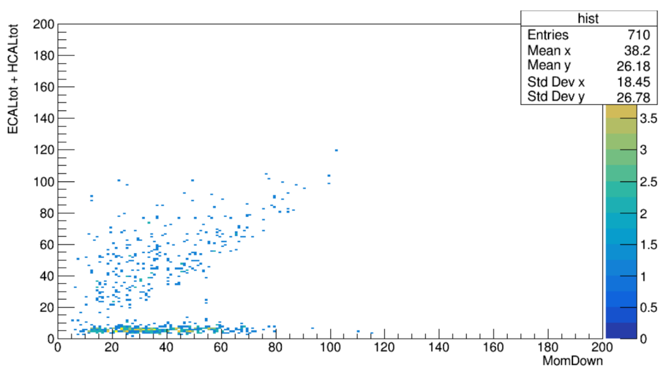
Beam quality cuts, high downstream muon fit quality, and low Veto calorimeter activity

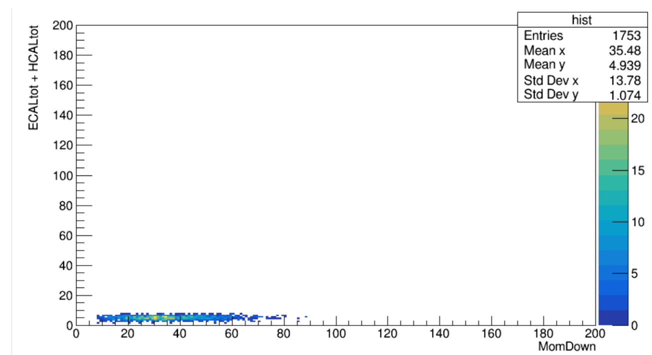
Require trigger and also MIP compatible events (different MOT)





SM





CLFV scalar signal

*M. Bondi et al. Comp. Phys. Comm. 269 (2021). https://doi.org/10.1016/j.cpc.2021.108129

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NA64μ experiment

ETH group:
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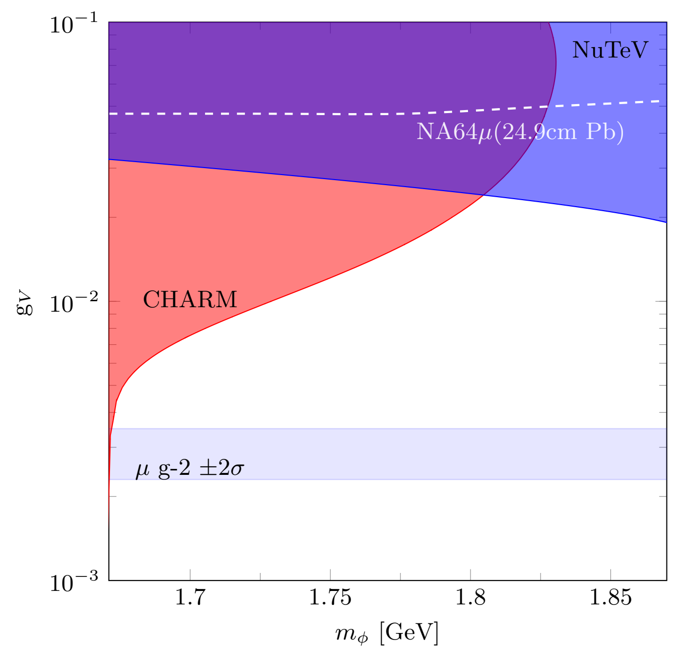
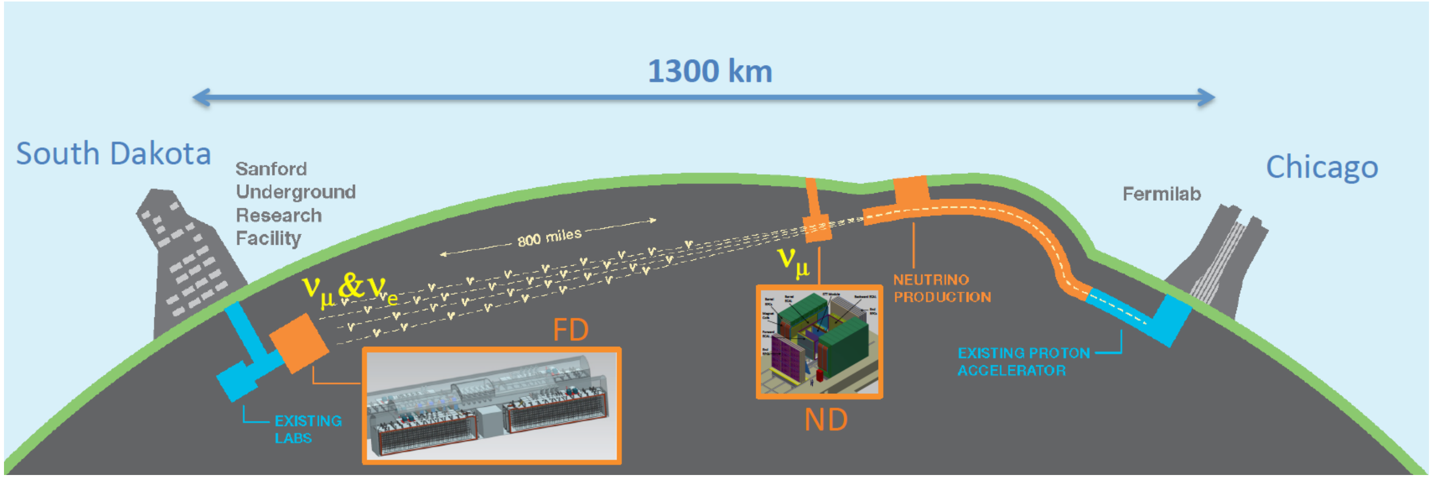
Henri Sieber

- Sensitivity using current NA64μ setup:
  - Assuming ~3 x 10^{13} MOT
  - Full Geant4 simulation
  - Including det acceptance, tracking reconstruction, quality cuts
  - Current eff. 24.9 cm Pb ECAL target
  - ~17% leptonic decay mode
  - (Signal cuts still being optimized)



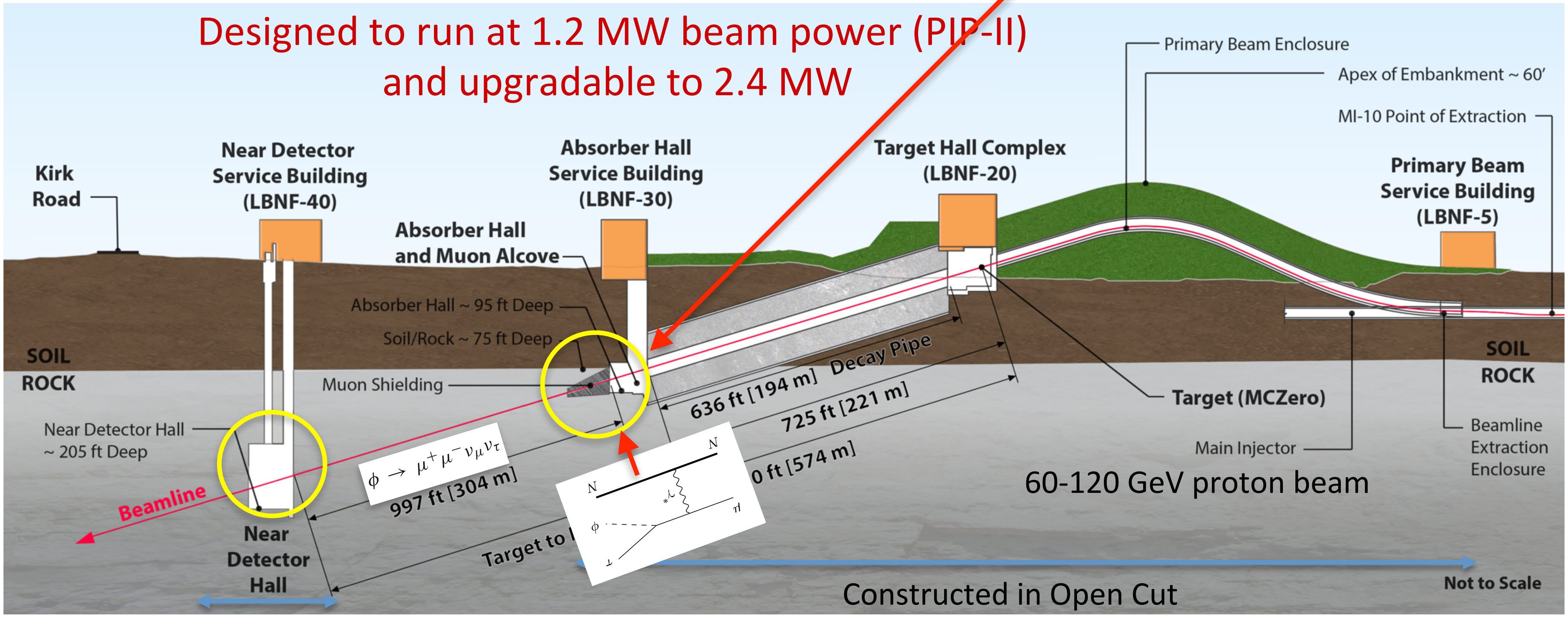
DUNE experiment

- LBNF (Long-Baseline Neutrino Facility) and DUNE (Deep Underground Neutrino Experiment):
  - Neutrinos from high-power proton beam: 1.2 MW, upgradable to 2.4 MW
  - Near Detector to characterize the neutrino beam
  - Far Detector: 40 kton Liquid Argon underground detectors



DUNE experiment

- Neutrino beam: 60-120 GeV p-beam hitting graphite target
- Hadrons decay to leptons, neutrinos in 220-m long decay pipe
- 30-m long stainless steel acts as a **muon beam dump**



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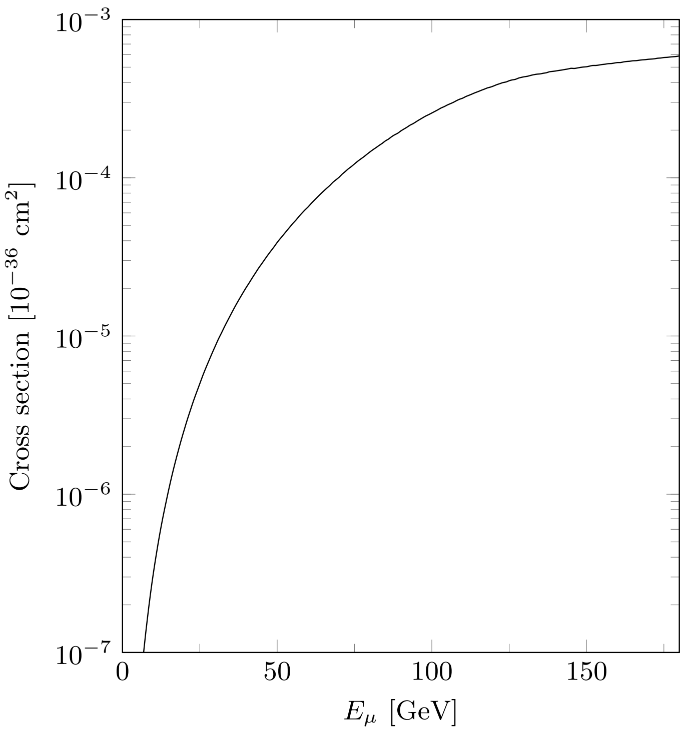
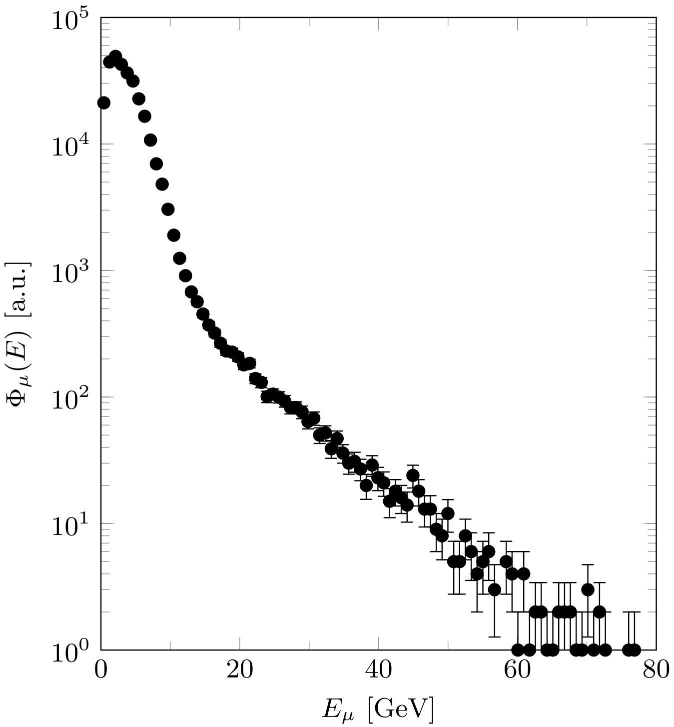
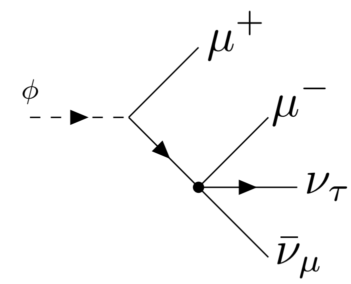
DUNE experiment

- Full simulation of LBNF beam by DUNE beam group
- Extract muon flux at the end of the decay pipe
- Estimated integrated muon flux $\Phi_\mu \sim 5 \times 10^{19}$ per 1×10^{21} POT (1 year of operation)
- Cross-section steeply rising: tail of the muon flux enhances production

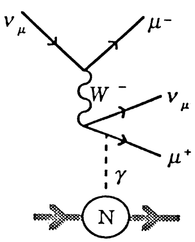


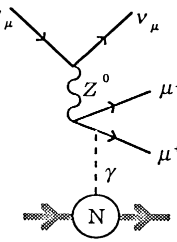


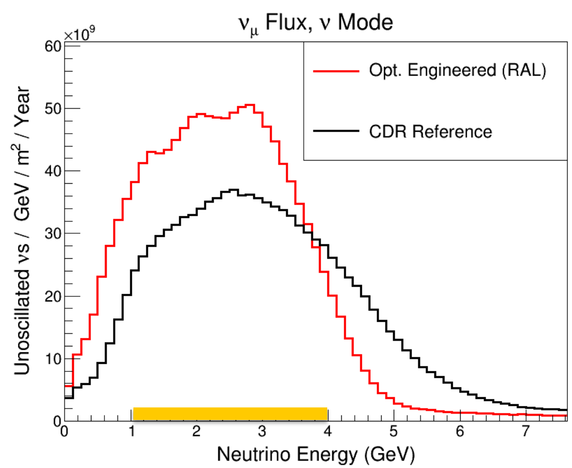
DUNE experiment



- Assume visible mode: CLFV boson decays before/within the LArTPC Near Detector
- Signature: look for $\mu^+\mu^-$ pair without any other activity
- Possible backgrounds:
  - Neutrino trident production (Investigation w/ GENIE v3)
    - Small cross section at $E_\nu \sim$ 1-10 GeV neutrino energy
    - $M_{\mu\mu}$ invariant mass distribution steeply falling at low mass
  - Neutrino-Ar quasi-elastic, Resonant, and DIS scattering with meson production + decay (GENIE v3)
    - additional hadronic activity in the final state
- Discriminating for low-multiplicity events and no hadronic activity, and using $M_{\mu\mu}$ invariant mass cut, could eliminate backgrounds
- GENIE v3: simulated comprehensive neutrino-Argon interactions with LBNF beam, low multiplicity cut eliminated all backgrounds
- Full detector simulation to be done







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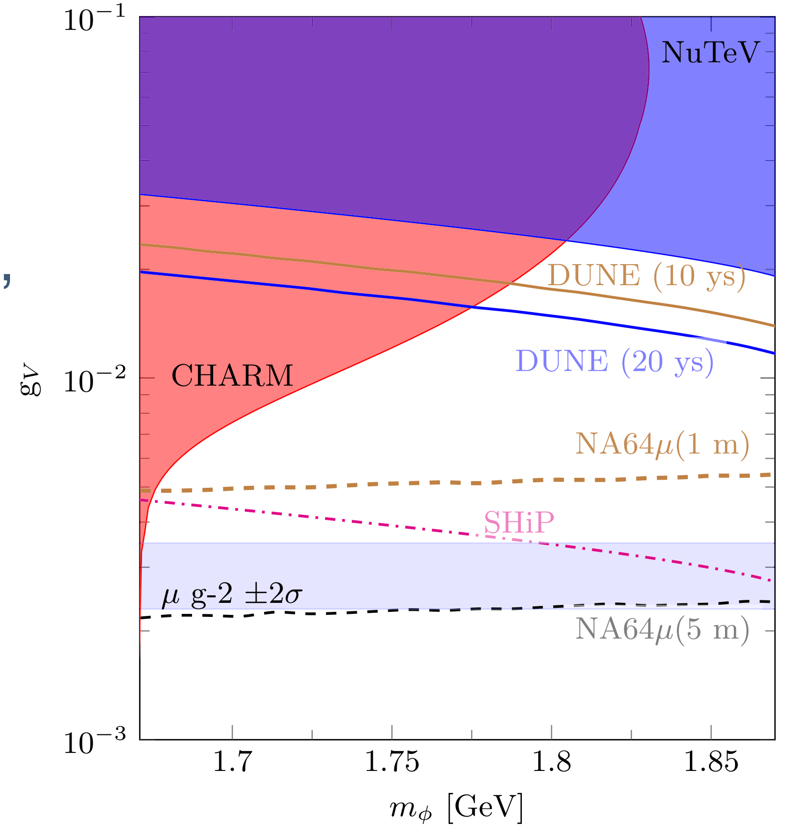
DUNE experiment

- Sensitivity study using ideal scenario:
  - Assuming beam time: 10 years, 20 years (10^{19} MOT/year)
  - Decay branching ratio of 17%
  - Background free
  - 5 m x 5 m LAr Near Detector



BR, L. Molina-Bueno, L. Fields, H. Sieber, P. Crivelli EPJ C (2023) 83:775
https://doi.org/10.1016/j.cpc.2021.108129

DIS e(μ)→τ conversion at NA64

$$e(\mu) + (A,Z) \to \tau + X$$

- High-energy-scale BSM physics could contribute to CLFV at low-energy via universal effective LFV operators that can be tested at NA64e,μ.
- Possible Dim-6 operators specified in paper by S. Gninenko at el (2018).
- Existing limits on S, V-operators from ZEUS and from rare meson decays.
- But missing limits on T-operators: $\mu\to\tau$ DIS conversion, and multiple other quark flavor combinations.
- NA64 is an inclusive mode experiment: all possible quark flavor combinations are summed up.

$$\tau \to \ell + M^0\,,$$
$$B \to \ell + \tau\,,$$
$$B \to \ell^\pm + \tau^\mp + M$$

$$e^- + q_i \to \tau^- + q_f\,, \quad \mu^- + q_i \to \tau^- + q_f$$

$$\mathcal{L}_{\ell\tau} = \sum_{I,if,XY} \left(\Lambda^{\ell\tau}_{I_{if,XY}}\right)^{-2} \mathcal{O}^{\ell\tau}_{I_{if,XY}} + \text{H.c.}\,, \quad \ell = e, \mu\,,$$

$$\begin{aligned}
\mathbf{S}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{S_{if,XY}} = (\bar\tau P_X l)(\bar q_f P_Y q_i)\,,\\
\mathbf{V}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{V_{if,XY}} = (\bar\tau \gamma^\mu P_X l)(\bar q_f \gamma_\mu P_Y q_i)\,,\\
\mathbf{T}-\text{type:} \quad & \mathcal{O}^{\ell\tau}_{T_{if,XX}} = (\bar\tau \sigma^{\mu\nu} P_X l)(\bar q_f \sigma_{\mu\nu} P_X q_i)
\end{aligned}$$

$$i, f = u, d, s, c, b, t$$
$$X, Y = L, R$$

S. Gninenko et al. PRD 98 (2018) 015007
https://doi.org/10.1103/PhysRevD.98.015007

DIS e(μ)→τ conversion at NA64

$$e(\mu) + (A, Z) \to \tau + X$$

- Synergy with CLFV scalar boson: mean energy for τ depends on the type of operator, but similarly boosted τ in the final state.
- Both cases fall into the sensitivity range of NA64 (see tables below). Final-state tau energy is similar to the CLFV scalar boson final-state.
- Backgrounds (dominated by bremsstrahlung) are expected to be suppressed by a minimal cut on the final-state energy 10-30 GeV. $\sigma(\ell + A \to \ell + X) \approx \sigma_{BS}(\ell + A \to \ell + X)$
- We are in the process of implementing this into the full simulation of NA64 and DMG4.

Mean τ energy
e-beam, E = 100 GeV

Operator	$\langle E_\tau \rangle_I$
S operators	25
V operators	57
T operators	62

Mean τ energy
μ-beam, E = 150 GeV

Operator	$\langle E_\tau \rangle_I$
S operators	38
V operators	86
T operators	93

S. Gninenko et al. PRD 98 (2018) 015007
https://doi.org/10.1103/PhysRevD.98.015007

Summary

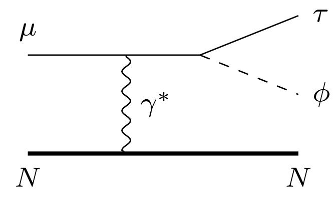
- Charged lepton flavor violating signature could be a sensitive test of New Physics.
- Benchmark: scalar CLFV boson with longevity.
- Considered two μ beam-dump experiments: NA64μ and DUNE
- Both experiments have potential to explore the parameter space - although both are challenging.
- The techniques used are general and other DM and Portal Interaction scenarios could be tested at NA64.
- DIS e/μ $\rightarrow \tau$ conversion that could hint at New Physics operators suppressed at low-energy.
- Other ideas for μ-on-target tests are welcome!

Thank you for the attention!

Backup

CLFV model

- Production:



$$\frac{d\sigma(p+q\to p'+k)}{d(p\cdot k)}=\frac{|\bar{\mathcal{A}}_{2\to 2}|^2}{8\pi s^2}$$

2->2

$$\mu\gamma \to \tau\phi$$

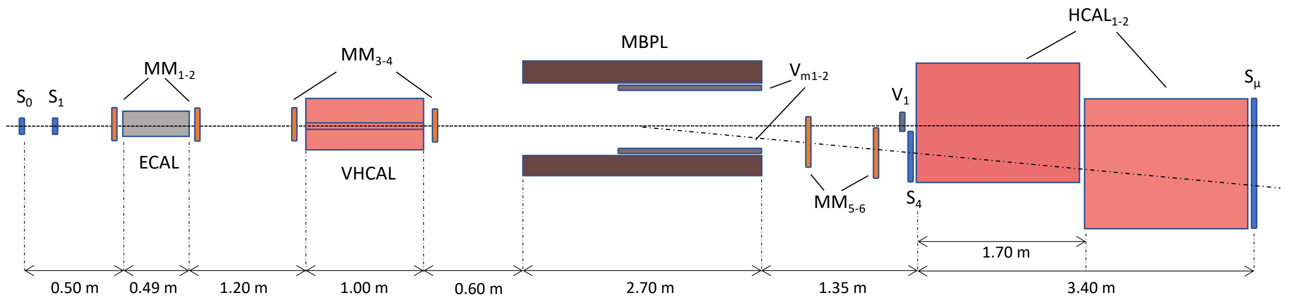
- Feyncalc:

$$|\bar{\mathcal{A}}_{2\to 2}|^2 = -\frac{e^2 m_\mu m_\tau (g_A g_A^* - g_V g_V^*)}{(m_\mu^2 - s)^2 (m_\tau^2 - u)^2}\times$$
$$\times\,[m_\mu^4(m_\phi^2+u)+2m_\mu^3(m_\tau^3-m_\tau u)$$
$$+\,m_\mu^2\left(m_\tau^4-2m_\phi^2 s-2m_\tau^2 u+u(u-2s)\right)$$
$$+\,2m_\mu m_\tau s(u-m_\tau^2)+s\left(m_\phi^2 s+m_\tau^4-2m_\tau^2 u+u(s+u)\right)]$$

$$x=E_\phi/E_\mu \qquad s=(p+q)^2\simeq m_\mu^2-\frac{u-m_\tau^2}{1-x}$$

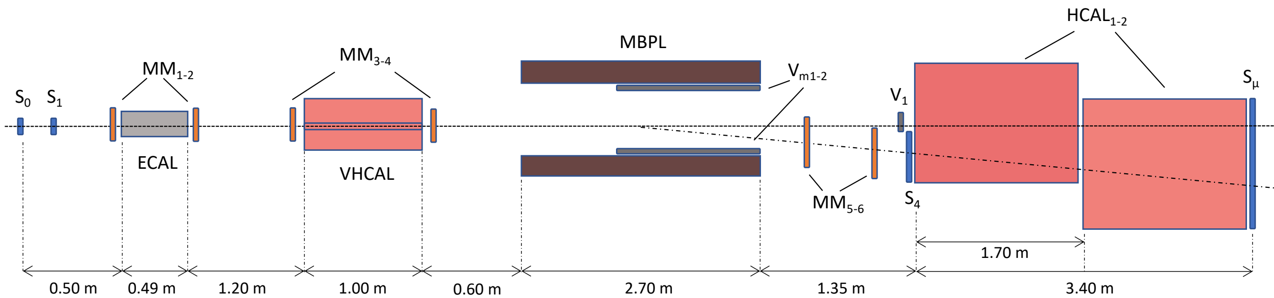
$$u=(p-k)^2\simeq -E_\mu x\theta_\phi^2-\frac{1-x}{x}m_\phi^2+(1-x)m_\mu^2$$

NA64μ experiment

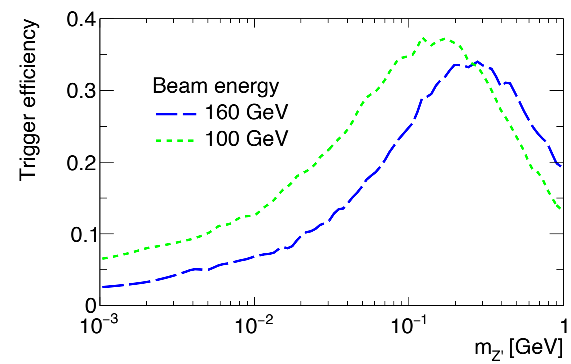


- Scattered muon carries away $E_\mu' = fE_\mu$, DM $(1-f)E_\mu$, Emiss $= E_\mu - E_\mu'$
- 40X0 ECAL (Pb-Scint),
- VHCAL (Cu-Scint) to veto charged secondaries by upstream muon interactions.
- HCAL modules, 7.5λ_I Steel-Scint,
- 2nd magnetic spectrometer with 1.4 T*m, 6 MM detectors for tracking

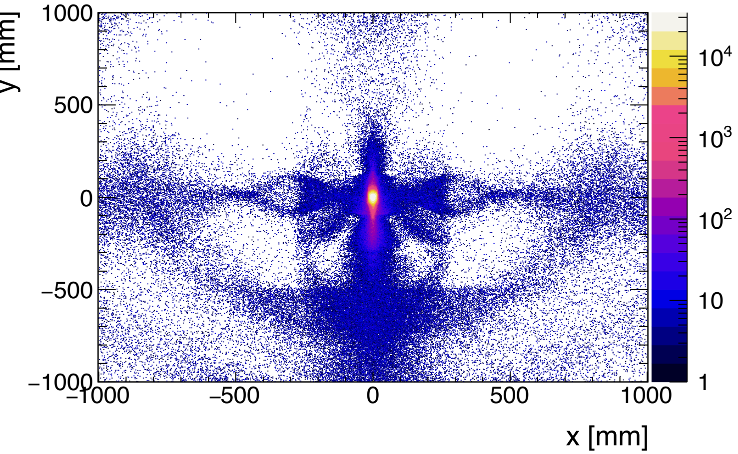
NA64μ experiment

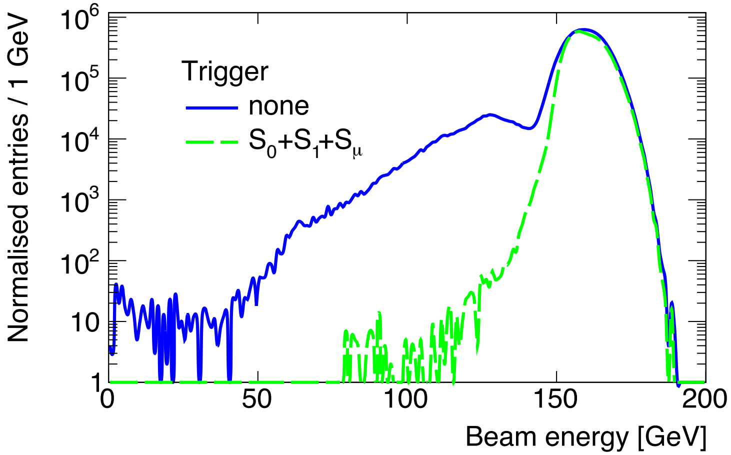


- Initial muon tag:S0 x S1 x S_μ
- S4 shifted from beam axis
- Combined trigger eff for S0 x S1 x S4 x S_μ
- Additional veto in V1 x $V_{m1\text{-}2}$ gives trigger eff. of 0.1%
- Cuts:
  - Initial beam momentum [140, 180] GeV/c
  - Single downgoing track with with < 80 GeV/c (10^{-12})
  - No energy deposit in VHCAL,
  - No deposit in HCAL (MIP)



Muon beam profile





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