M^3:
Muon Missing Momentum

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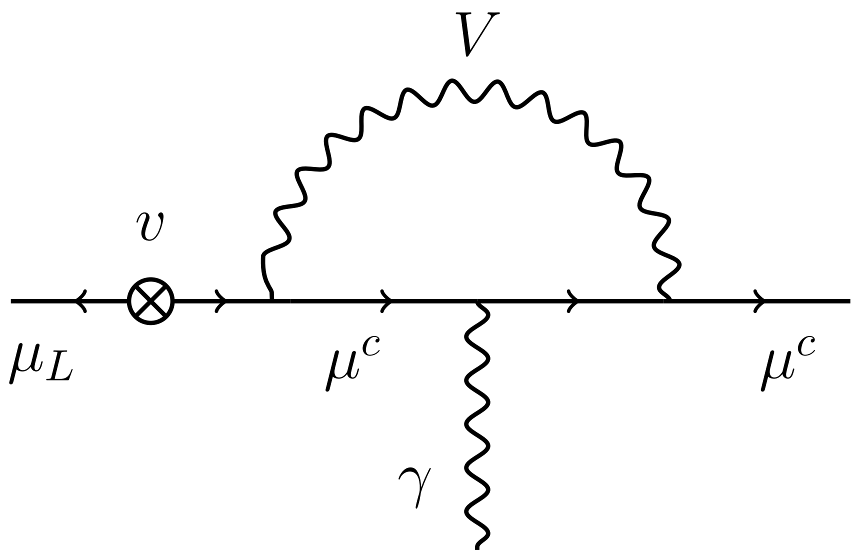
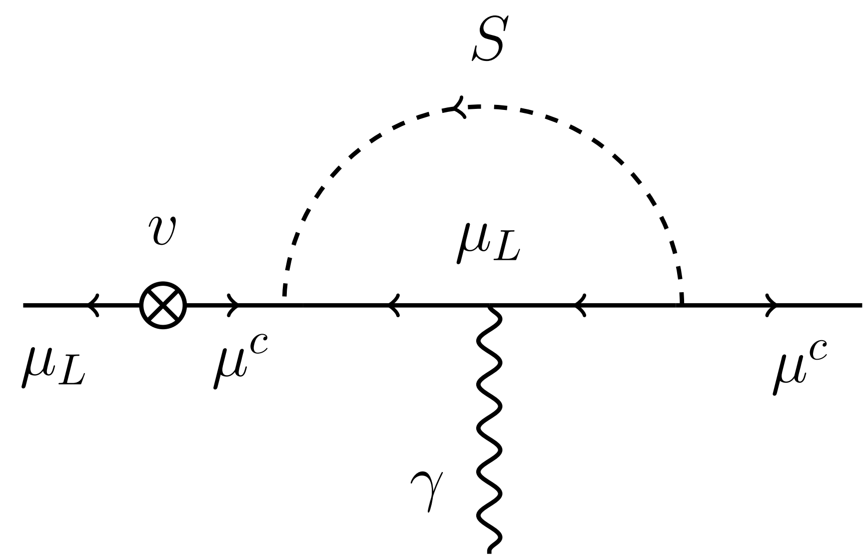
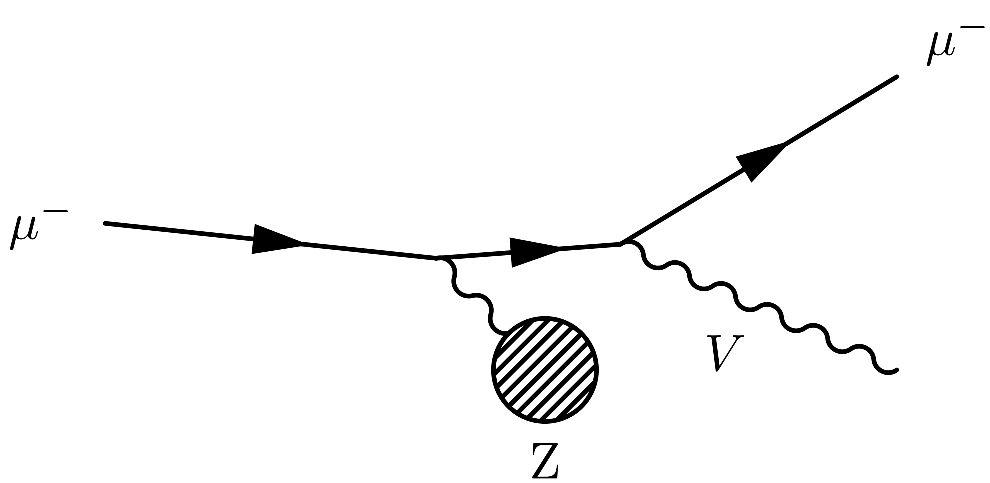
FNAL Muon Campus Workshop, 5/26/21

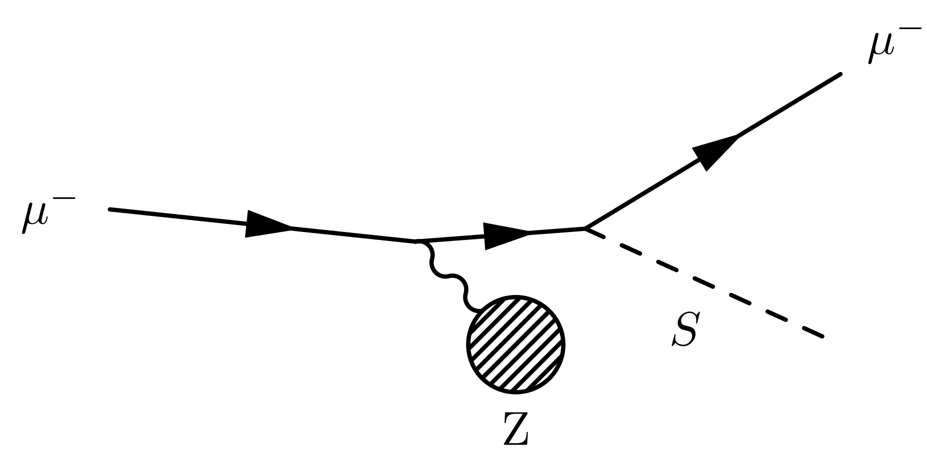
Motivation: light new physics for g-2





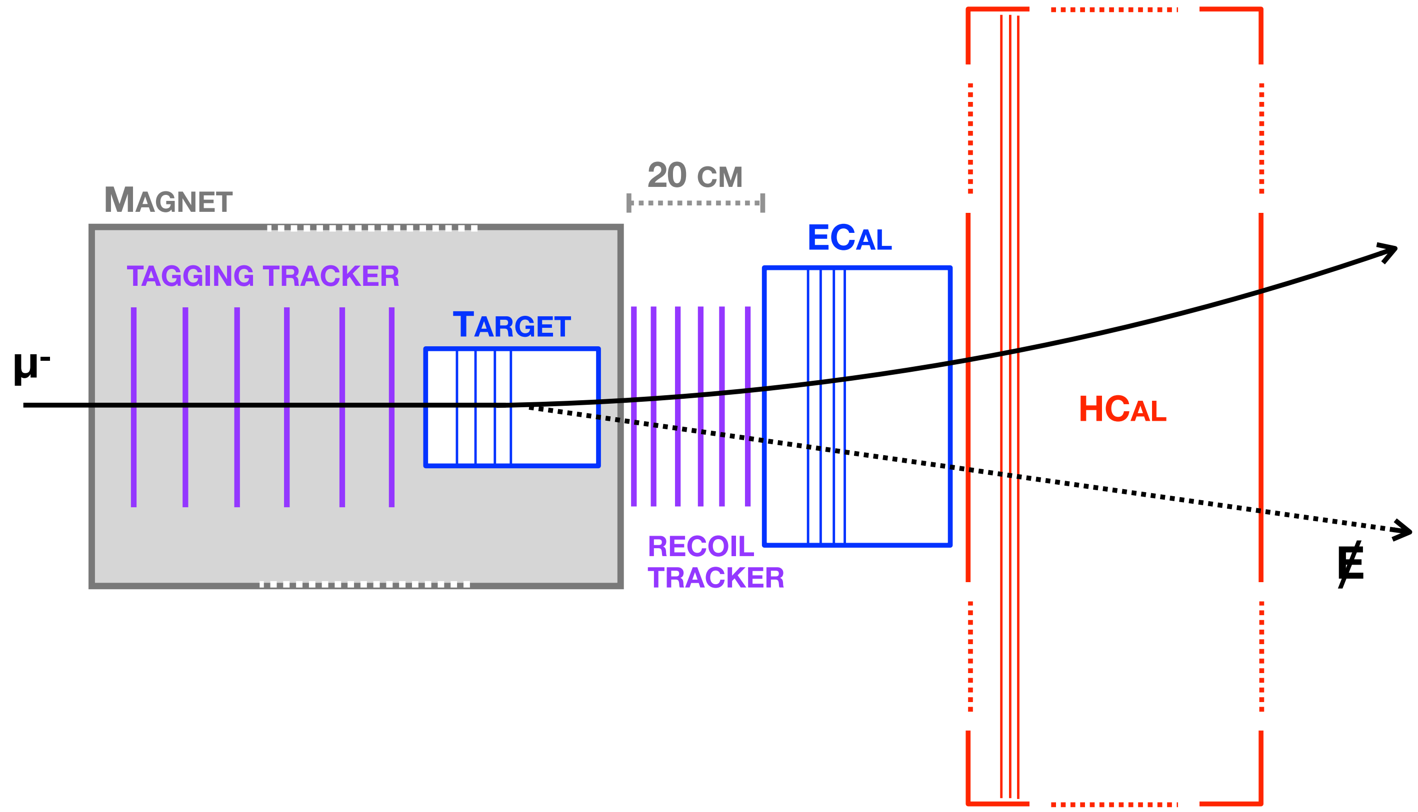
If it contributes to g-2, it couples to the muon!





Strategy: detect missing momentum from emitted S/V

M^3 schematic



Similar in spirit to LDMX (electron beam missing momentum)

Main differences from LDMX:

- **thicker (50 X0) active target** (muon is a MIP)
- outgoing muon momentum measured **exclusively by recoil tracker** (ECal and HCal for veto only)

More advantages of muons

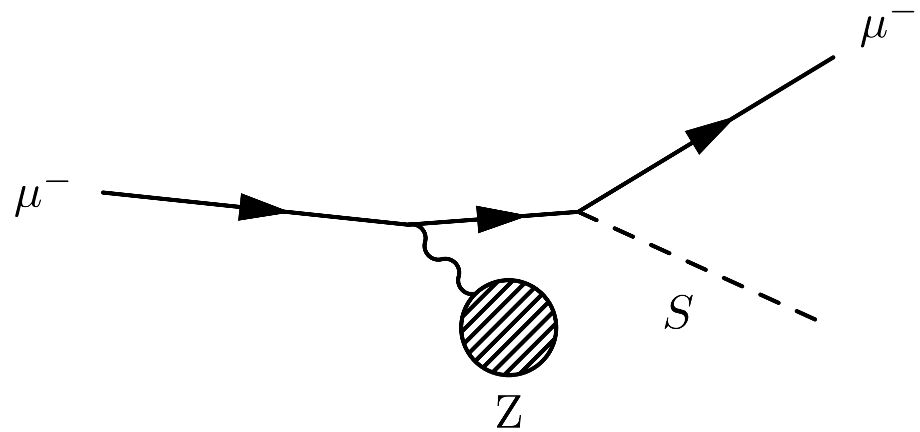
Theoretical:

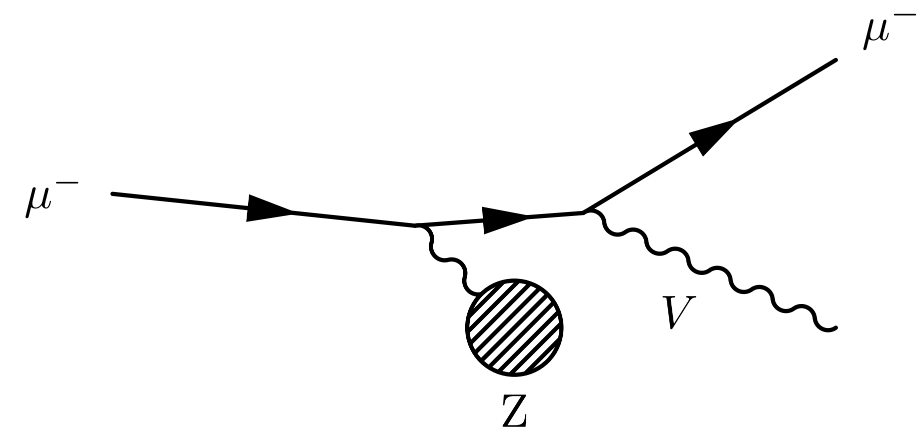
- This could be a discovery machine! Very plausible that g-2 is due to new < GeV particles
- Dark matter which only couples to muons could explain null results in direct and indirect detection

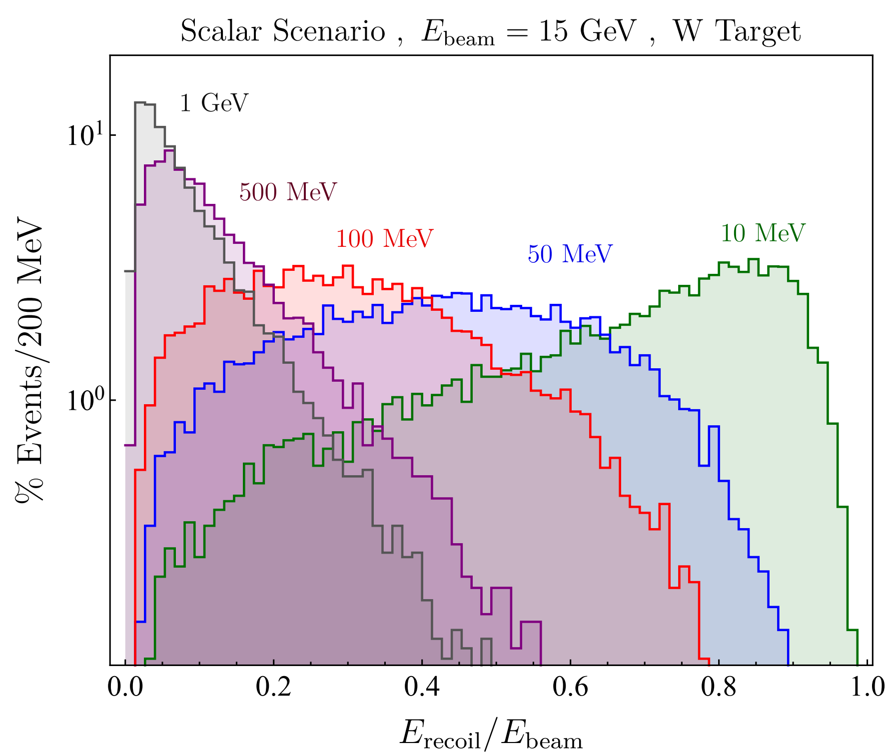
Practical:

- Heavier than electrons, brem less (lower QED-related backgrounds); better reach than electron beam for high-mass invisibles
- Only a few labs in the world have a sufficiently intense GeV-scale muon beam, and Fermilab is one of them!

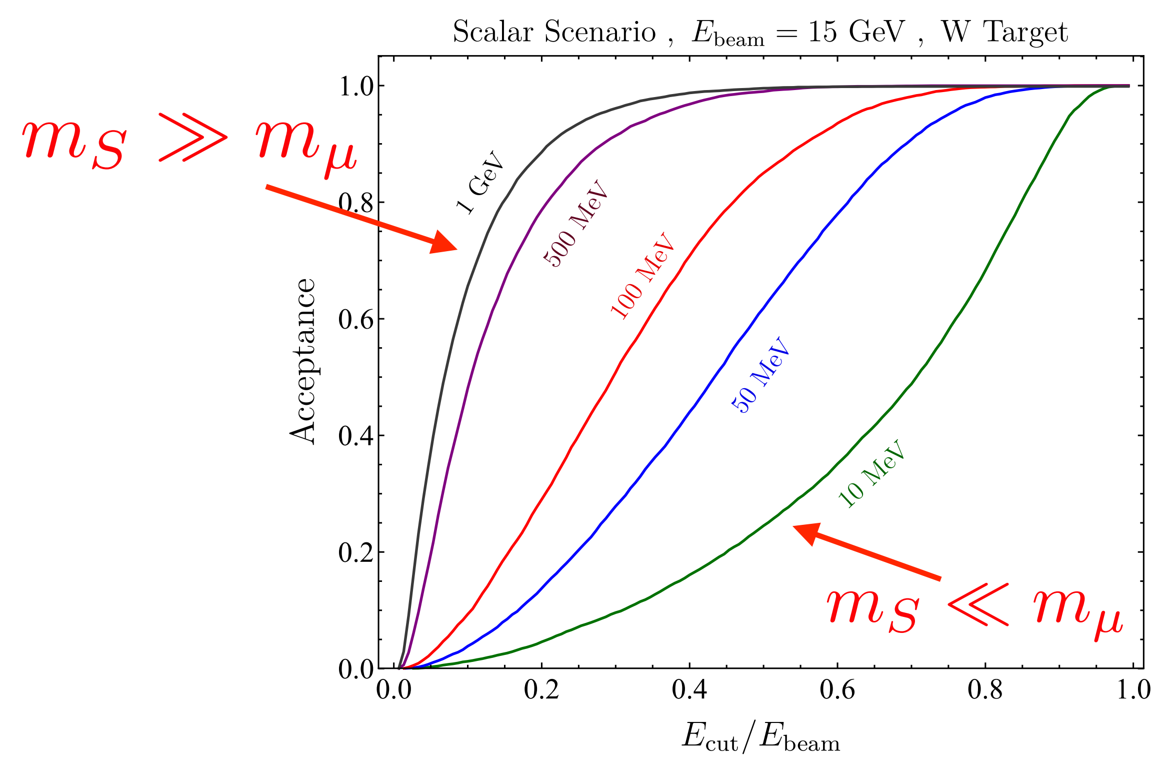
Setup







outgoing energy distribution

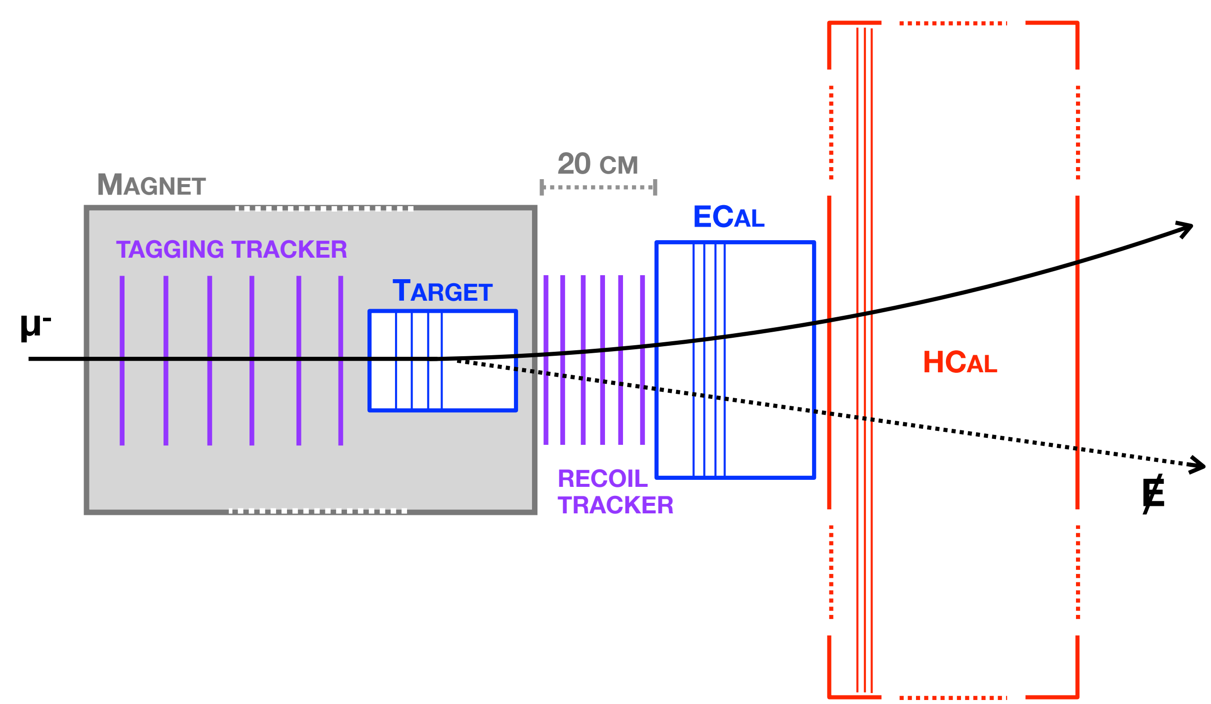


acceptance

Unlike electron beam, invisible particle doesn't take all the beam energy:
low-mass invisibles are QED-like (and hard to distinguish from background)

Beam requirements

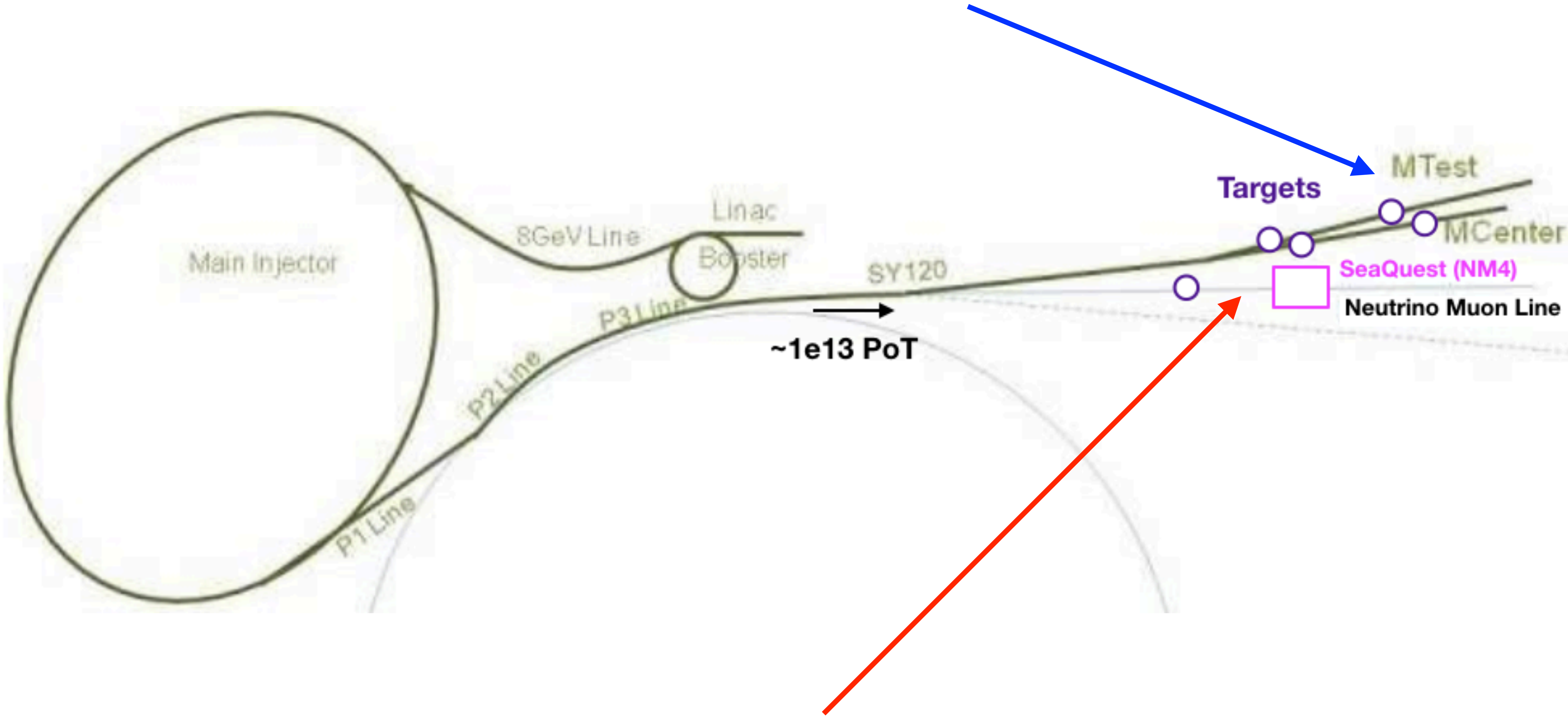
- Need a lot of muons on target (MoT), i.e. high rep rate
- Need to individually identify and track each one so that we know they lost a significant amount of momentum $(p_{\rm out} \lesssim 0.5\, p_{\rm in})$
- Pion contamination = bad (esp. pions decaying in target). Estimate 10^{-6} will suffice for g-2 search
- $p_{\rm in}$ > ~several GeV - 10s of GeV:
  - lower boundary: need significant amount of lost momentum above detector thresholds to detect bkg processes
  - upper boundary: high momentum beam requires more B field lever arm, makes for a big and expensive detector with poor coverage



Fermilab beam facilities

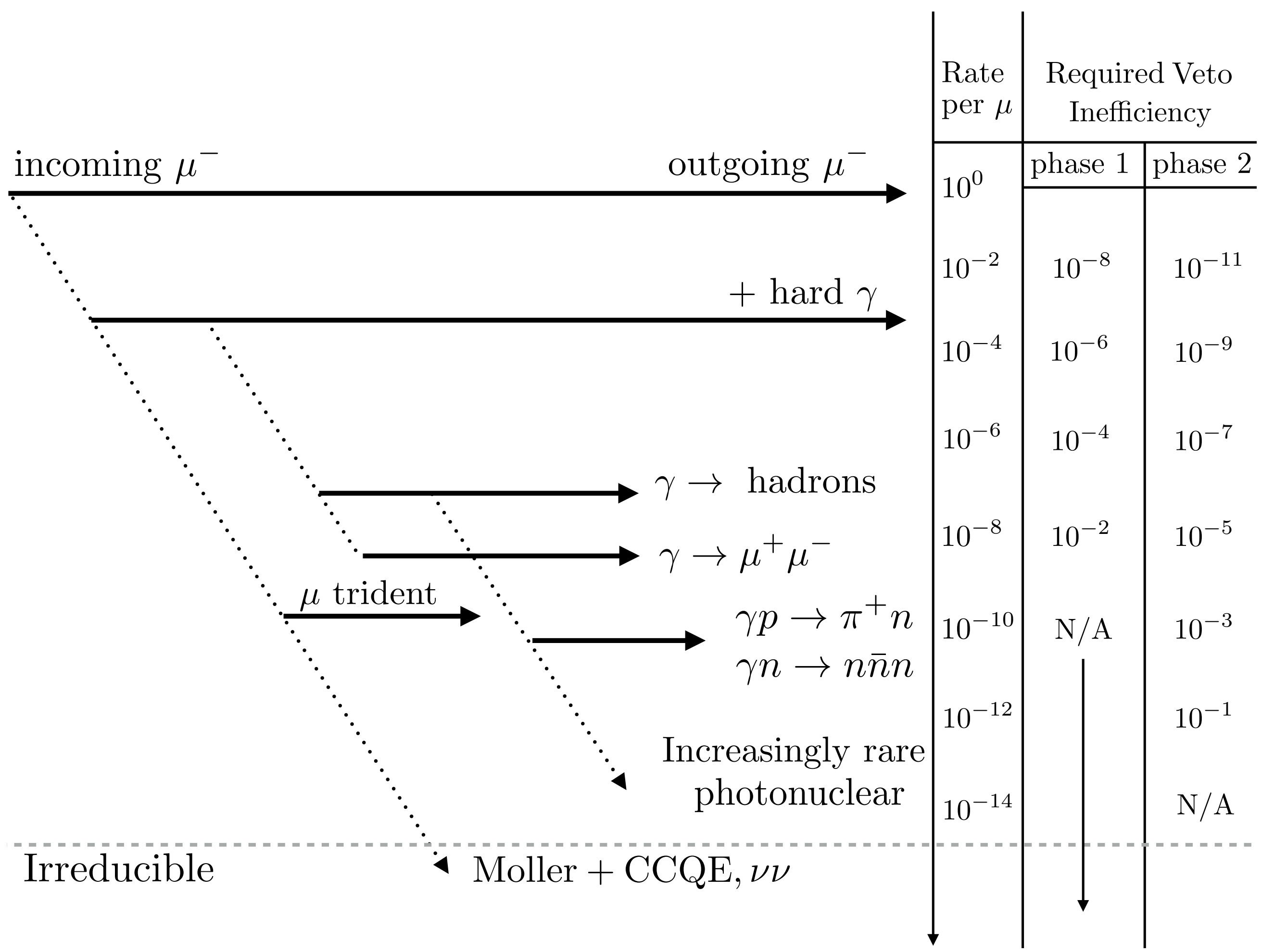
(At least) two possibilities for a 15 GeV muon beam:

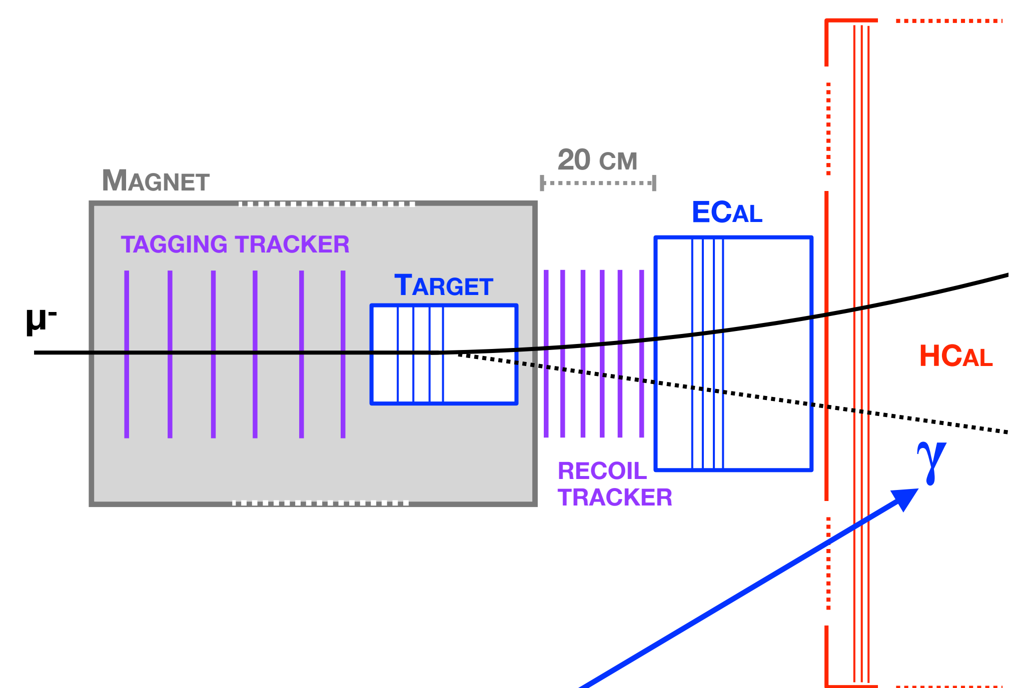
Phase 1: 10^{10} MOT at MCenter



Phase 2: 10^{13} MOT (NM4 beam line with modifications)

Backgrounds and signal selection

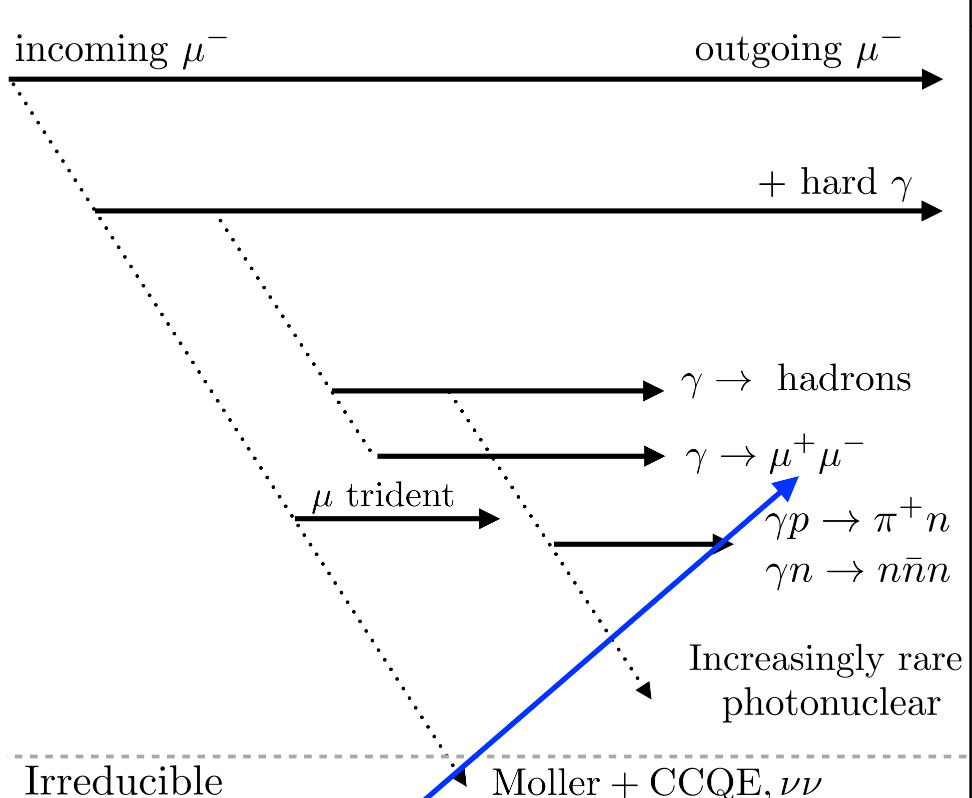




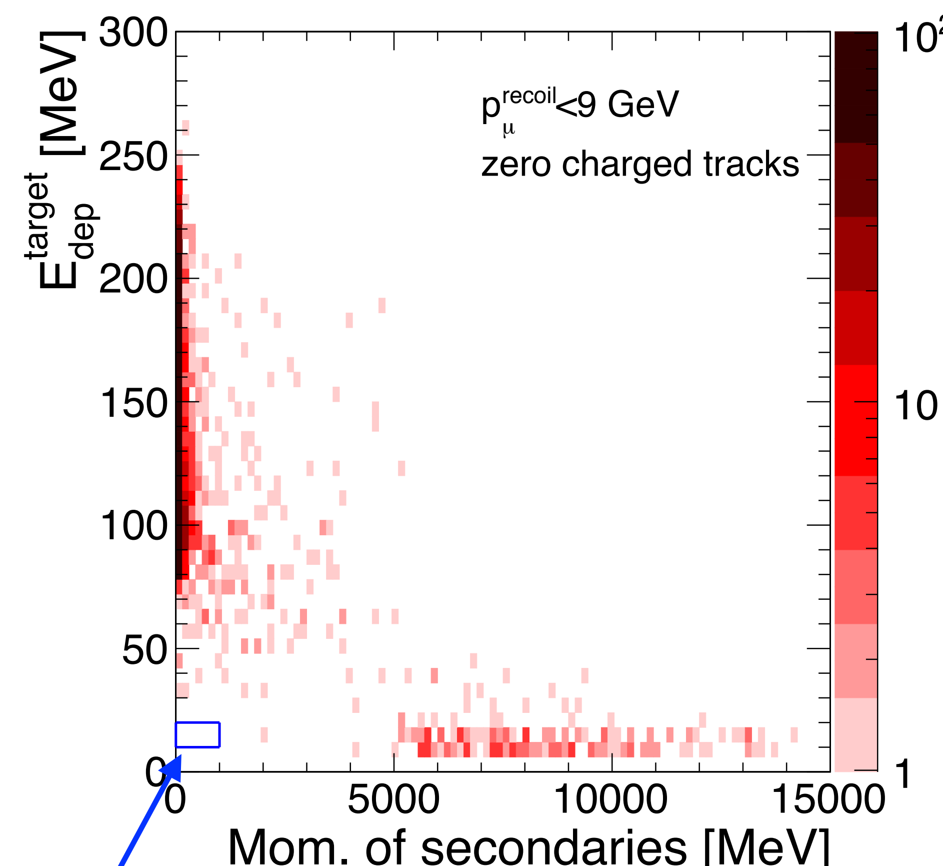
Main missing momentum background from undetected brem photon: either lost in target or downstream in a hadronic or conversion process

Sets requirements for detection capabilities of target and downstream ECal and HCal

Backgrounds and signal selection



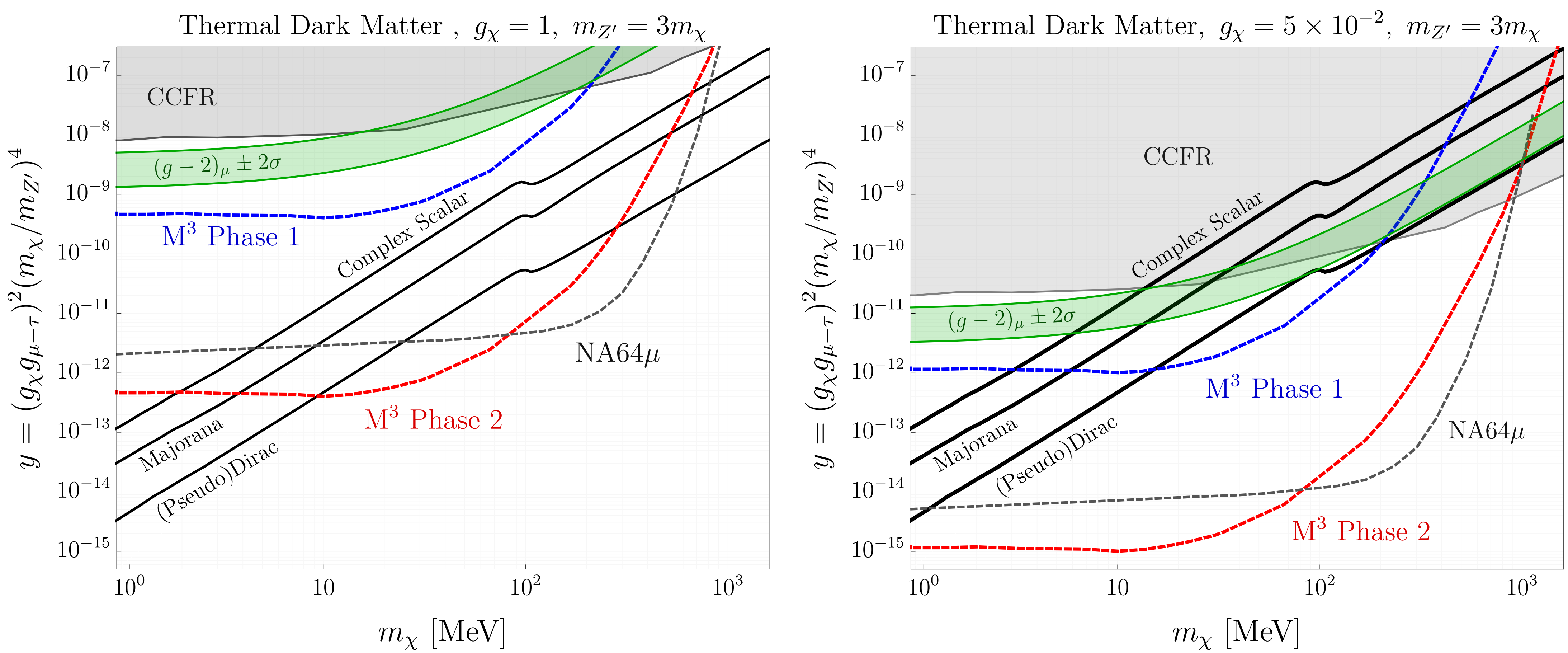
Rate per μ	Required Veto Inefficiency phase 1	Required Veto Inefficiency phase 2
10^{0}		
10^{-2}	10^{-8}	10^{-11}
10^{-4}	10^{-6}	10^{-9}
10^{-6}	10^{-4}	10^{-7}
10^{-8}	10^{-2}	10^{-5}
10^{-10}	N/A	10^{-3}
10^{-12}		10^{-1}
10^{-14}		N/A



signal region

Key takeaway: phase 1 is (nearly) **QED backgrounds only**
(zero events in signal region for 10^7 MOT GEANT simulation)

Reach



Phase 1: **complete coverage of g-2 region** for any invisibly-decaying particle lighter than the muon

Phase 2: can probe large parts of well-motivated DM parameter space

NA64 is a potential competitor at CERN:
let's do this experiment at Fermilab!

In progress: M^4 (Minimal M^3)

What is the minimal (cost, infrastructure, MOT, etc) experiment required to have complete coverage of g-2 region for sub-GeV states?

- Visible decays of S? $S \to \mu^+\mu^-, \pi^+\pi^-,\ \pi^0\pi^0,\ \ e^+e^-,\ \gamma\gamma$
- Do we actually need an ECal, or are photonuclear backgrounds small enough? (Careful study in progress)
- Define realistic beam expectations: How much beam can be delivered to MCenter per spill? What's the bunch structure/ occupancy? What's the pion contamination? What's the expected beam energy and transverse spread?

Full study expected to be completed this fall; workshop planned for late June