Muon Beam Fixed Target Phenomenology for $(g-2)_\mu$

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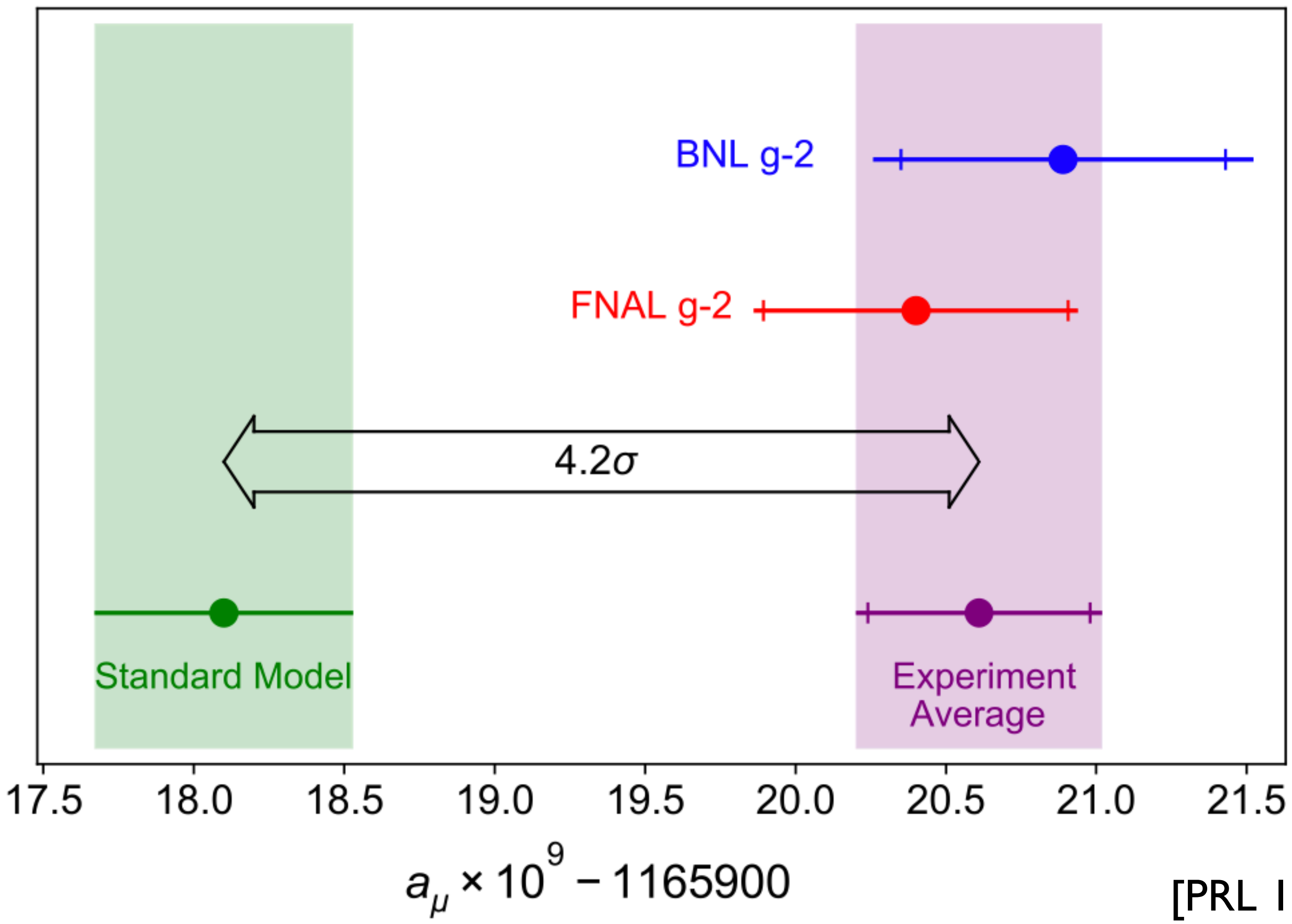
University of Pittsburgh

Discovering the new physics of $(g-2)_\mu$
with fixed target muon facilities at Fermilab
June 22, 2021

Fermilab Muon $g-2$ results



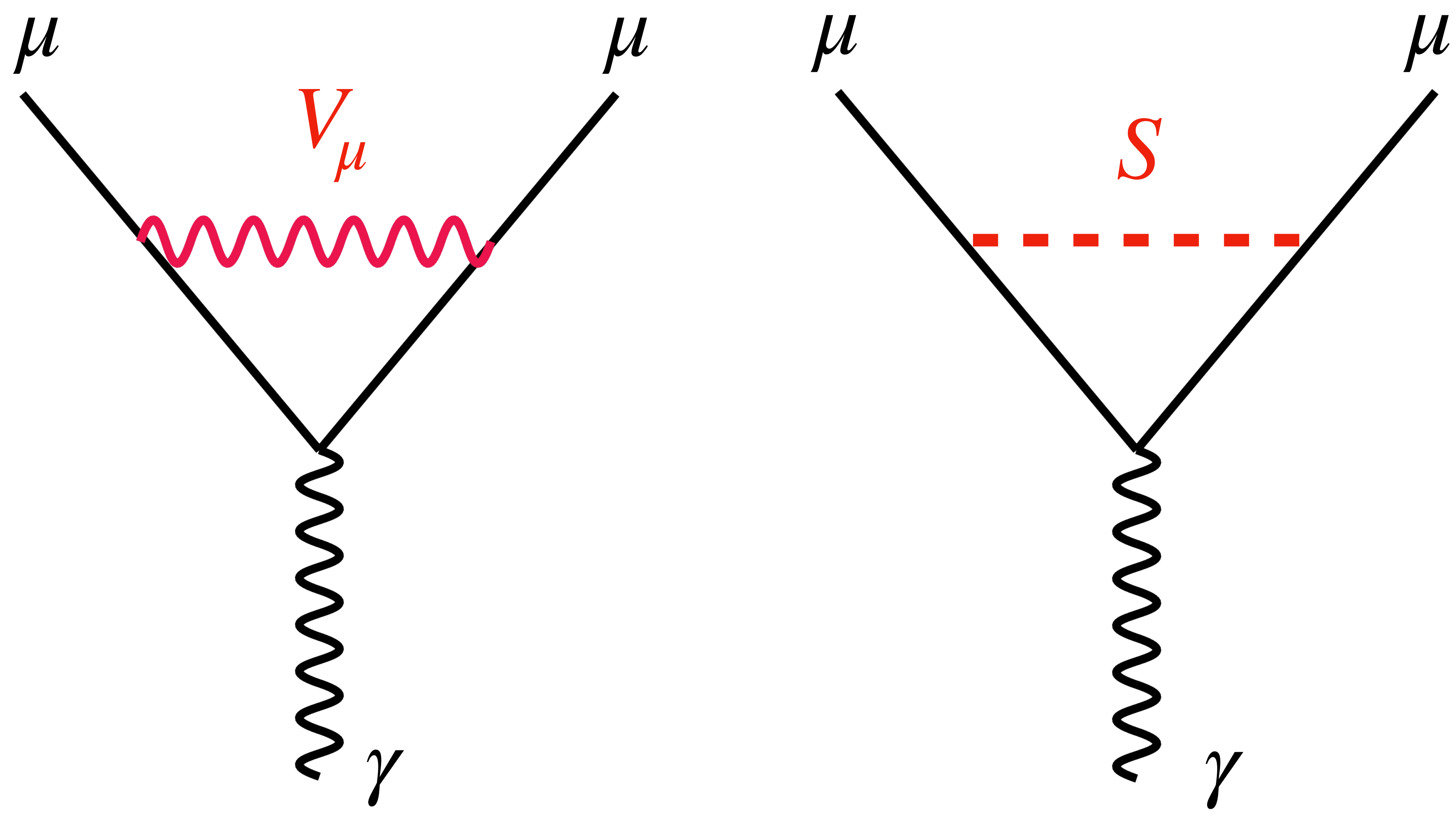
[PRL 126, 141801 (2021)]

Standard Model prediction: $a_\mu(\text{SM}) = 116\ 591\ 810(43) \times 10^{-11}$

Combined FNAL/BNL result: $a_\mu(\text{Exp}) = 116\ 592\ 061(41) \times 10^{-11}$

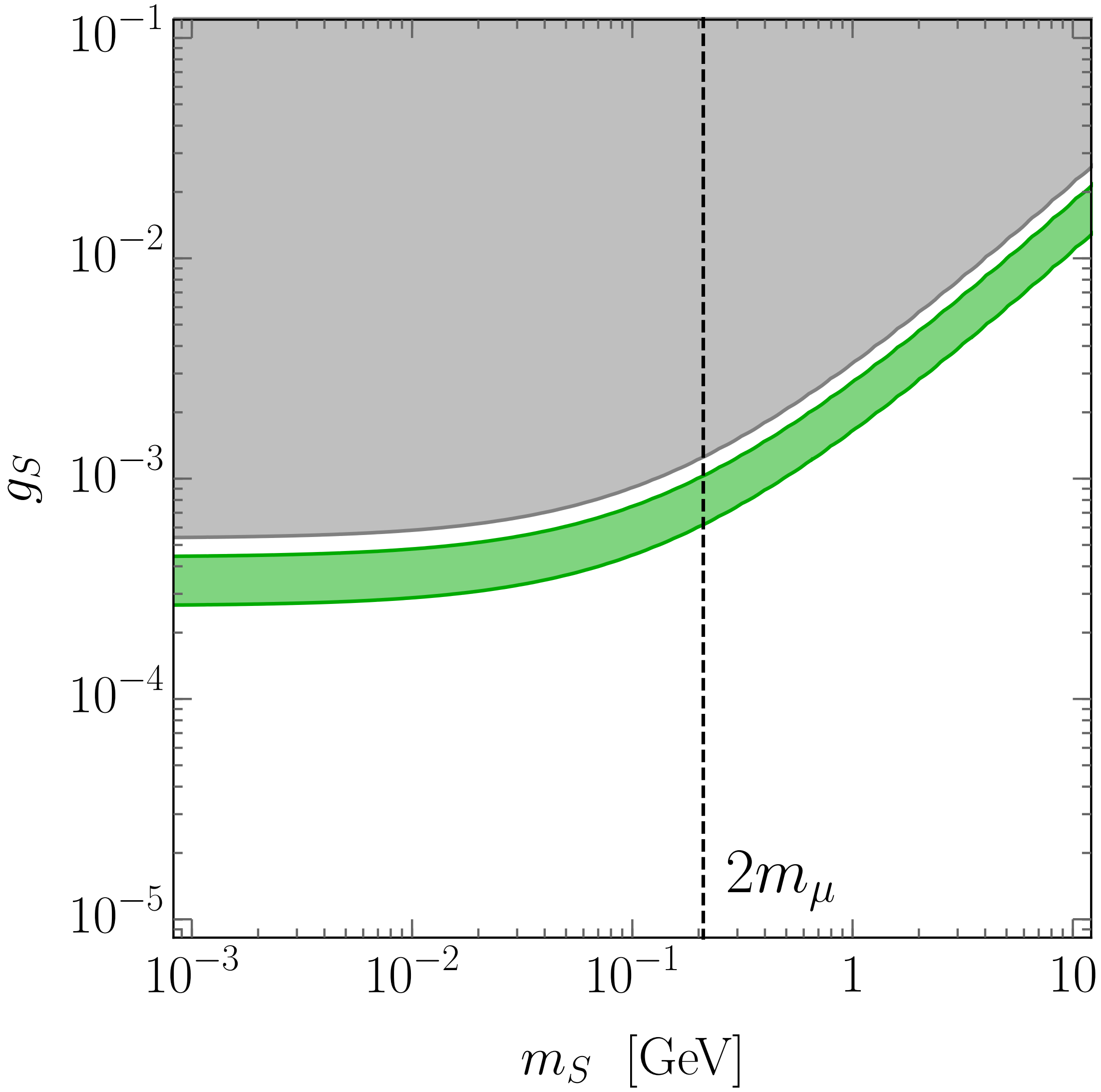
Discrepancy: $a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11} \quad (4.2\sigma)$

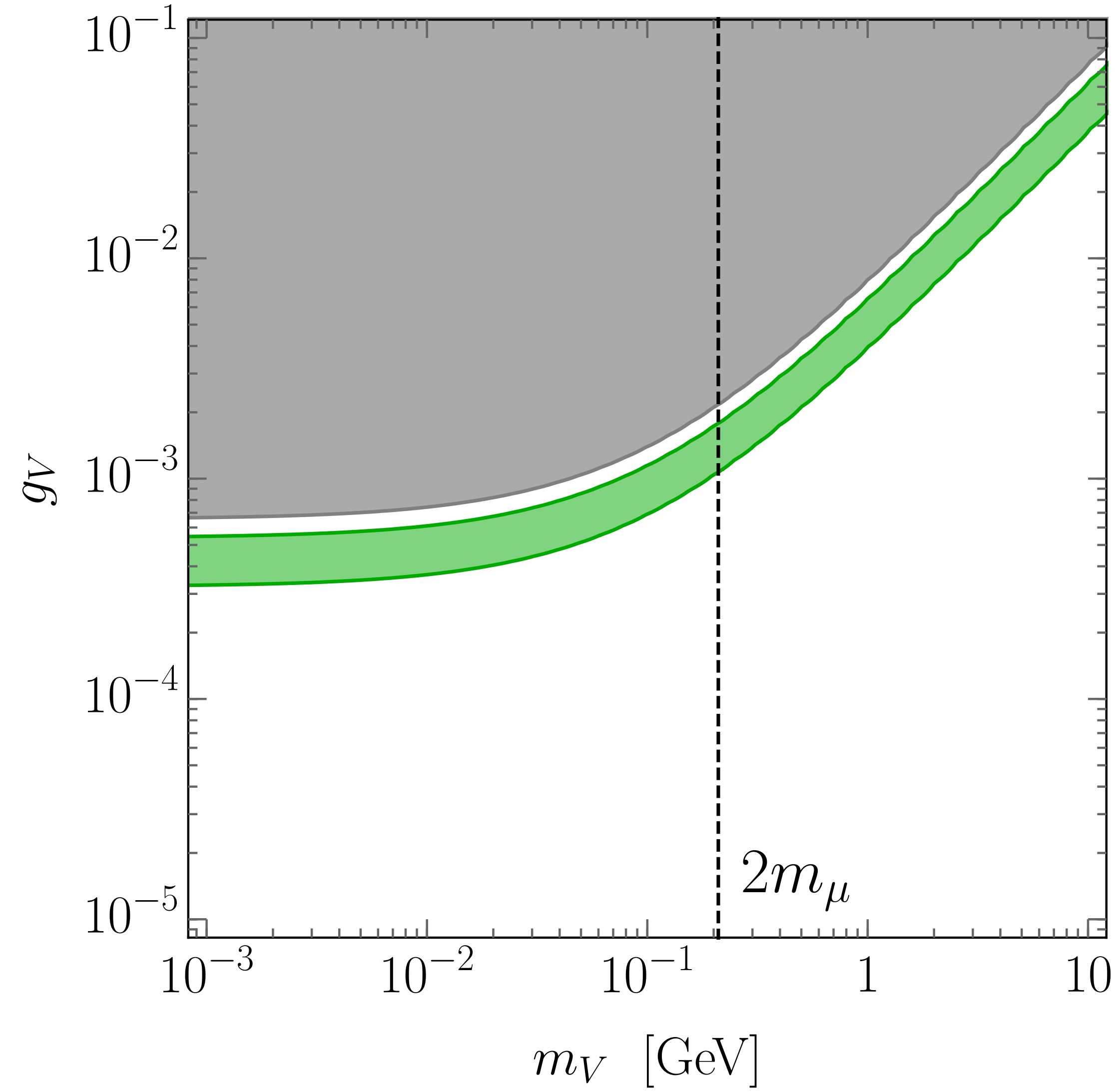
Muon-philic force and $(g-2)_\mu$



Muon beam fixed target experiments can directly search for the mediator!

Mediator parameter space and $(g-2)_\mu$



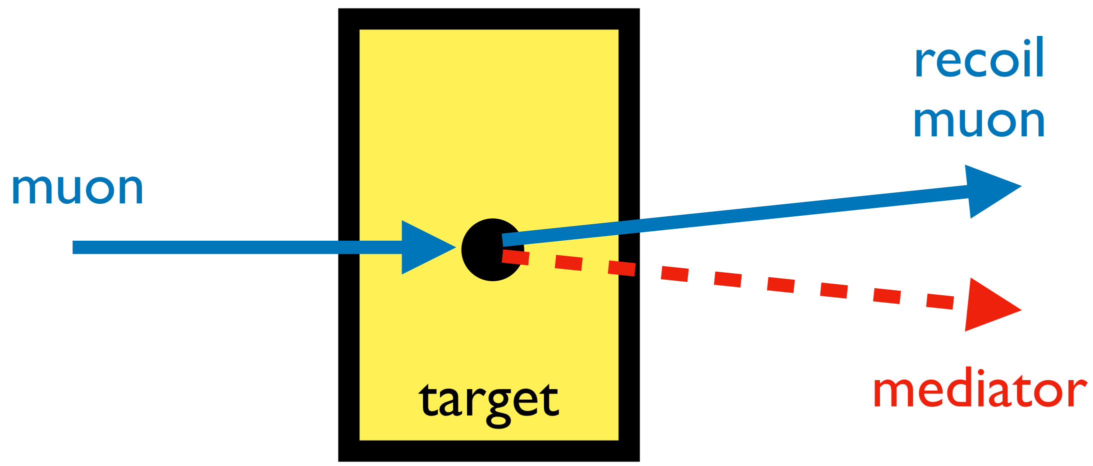


Substantial mediator coupling needed to explain $(g-2)_\mu$

➡ **Large production rates in muon beam experiments!**

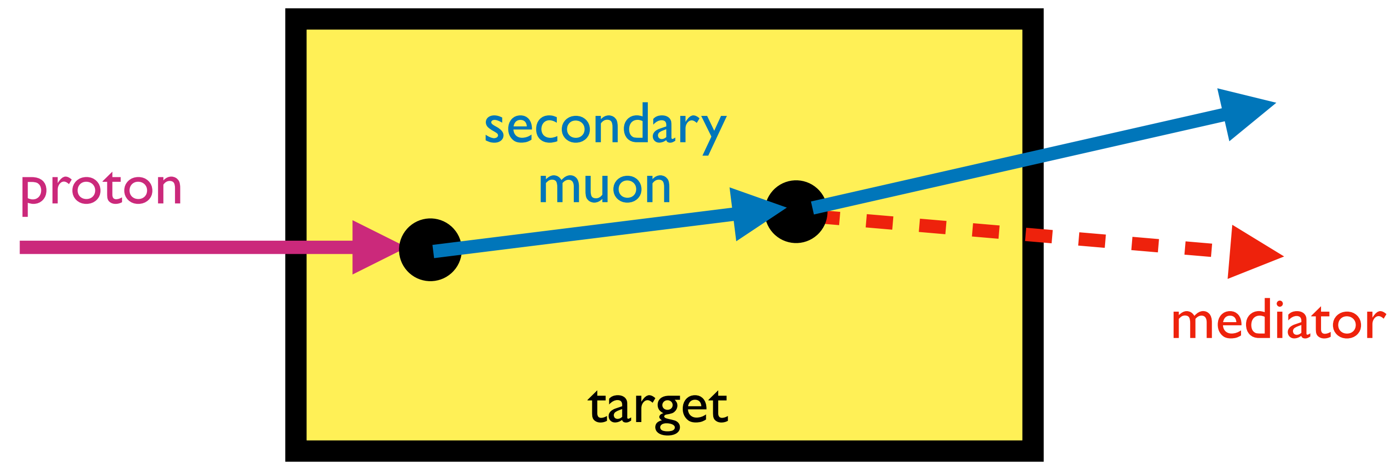
Mediator production and detection in muon and proton fixed target experiments

Muon Beam



See talks by C. Mantilla Suarez & Y. Zhong

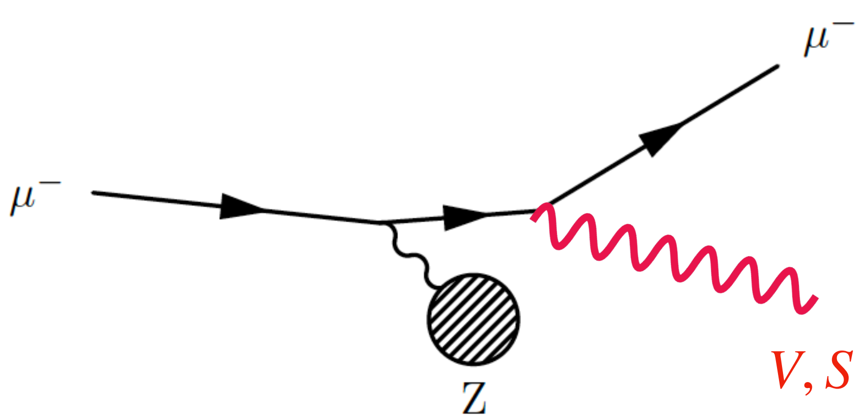
Proton Beam



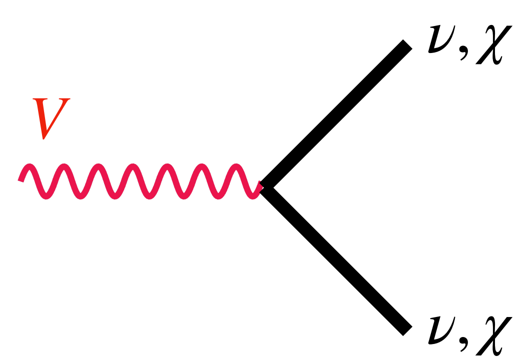
See talks by D. Sperka & P. Harris

Mediator Production and Detection

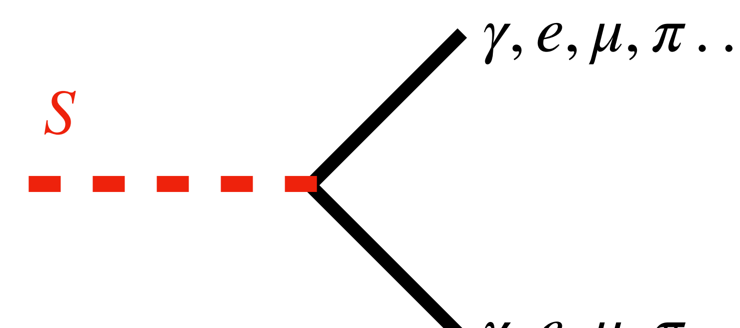
Mediator production via muon bremsstrahlung



Detect invisible decays via missing energy/momentum



Detect visible decays



Minimal signatures/mediators/models

	Invisible			Visible			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \ldots$
vector	no(?)	yes	yes	no	no(?)	yes* $(m_V > 2m_\mu)$	no(?)
	• $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM. (* $m_V > 2m_\mu$ constrained by dedicated *BABAR* search) • Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics)						
scalar	yes $(m_S < 2m_\mu)$	yes	yes	yes $(m_S < 2m_\mu)$	yes $(m_S < 2m_\mu)$	yes $(m_S > 2m_\mu)$	yes $(m_S > 2m_\pi)$
	• All minimal signatures can be realized in scalar simplified models. • UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle affect (g-2) • More phenomenological studies needed to chart the parameter space						
signature	missing momentum			prompt or displaced resonance			

Invisible mediator

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<tr><td>final state/ mediator</td><td>Long-lived</td><td>neutrinos $\nu\nu$</td><td>DM $\chi\chi$</td><td>photons $\gamma\gamma$</td><td>electrons e^+e^-</td><td>muons $\mu^+\mu^-$</td><td>hadrons $\pi\pi, \ldots$</td></tr>
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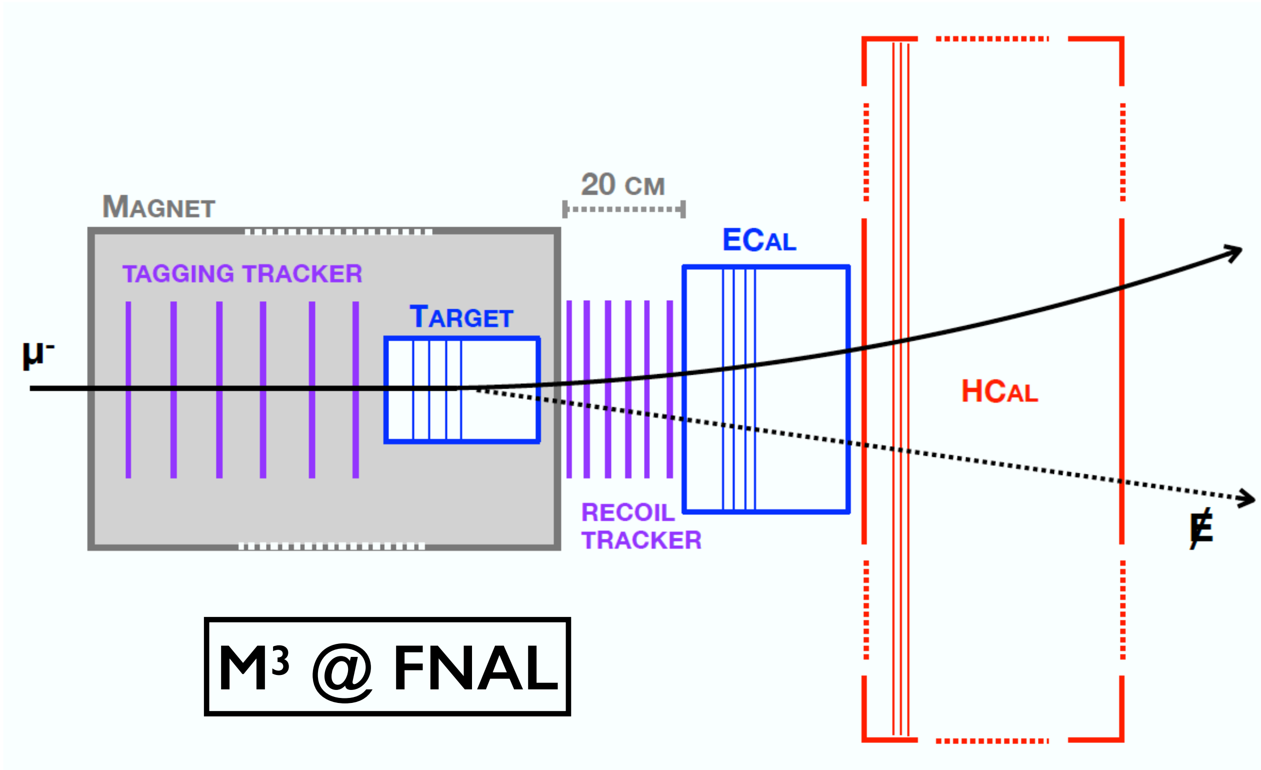
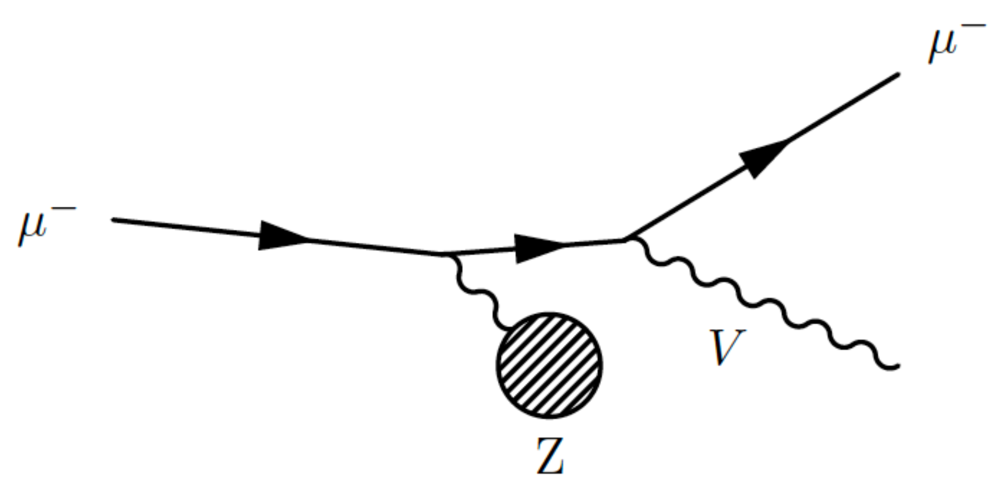
Invisible mediator

- Muon beam missing energy / momentum experiment

[Gninenko, Krasnikov, Matveev, '14]
[Kahn, Krnjaic, Tran, Whitbeck, '18]





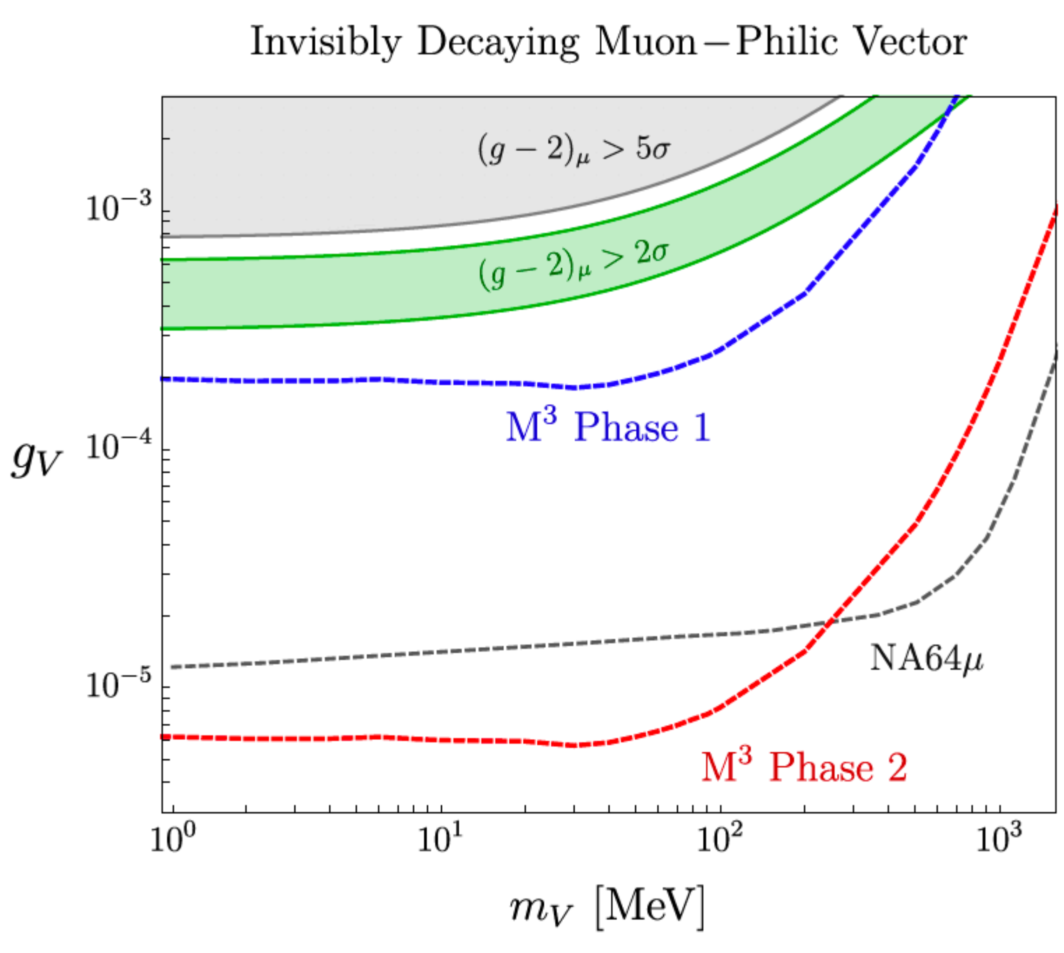
Mediator decays to DM, neutrinos, or is long-lived

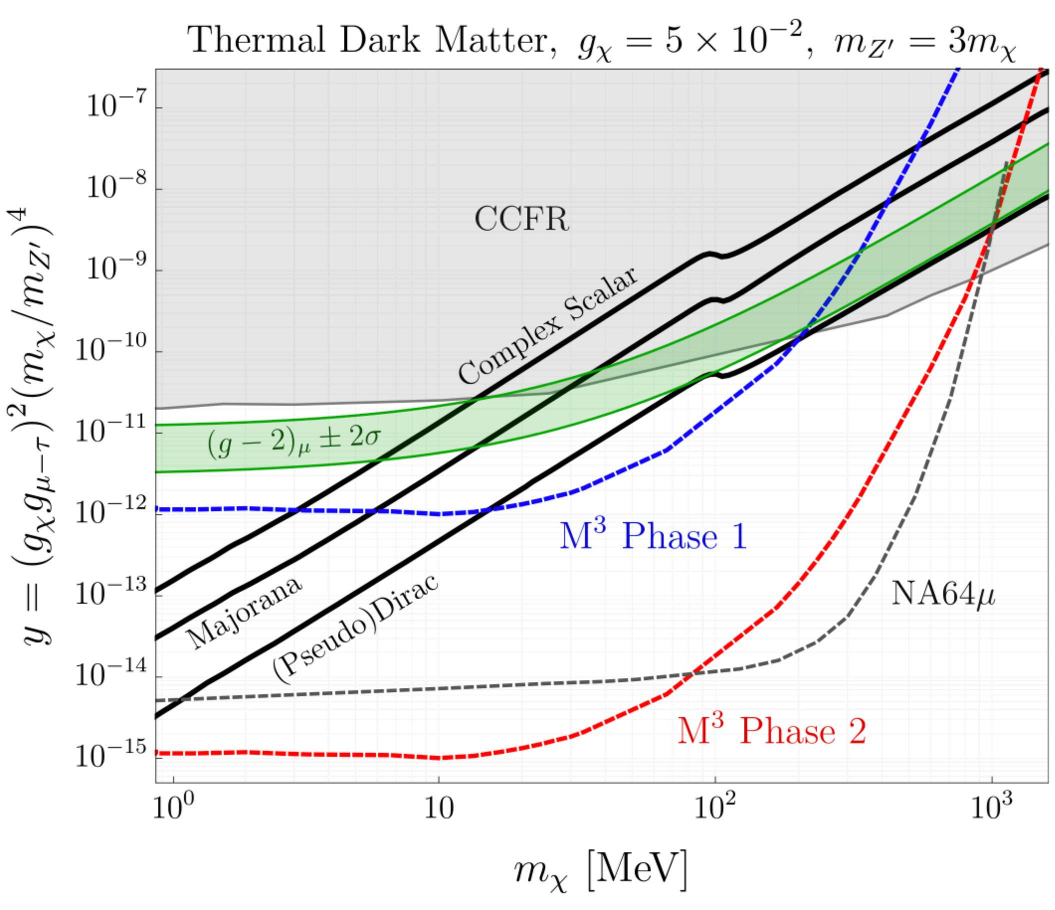
- Muon beam impinges on a thick target
- Mediator inherits significant fraction of beam energy
- Signal is a recoil muon with momentum measured by recoil tracker
- ECAL and HCAL used to veto backgrounds
- Experiment can be done with muon beams at FNAL!

See talk by C. Mantilla Suarez

- M^3 Phase 1 with ~ 10^{10} muons on target can cover most of the light mediator parameter space that explains $(g-2)_\mu$

- M^3 Phase 2 with ~ 10^{13} MOT can also test well-motivated models of muon-philic thermal dark matter





See talk by C. Suarez

Scalar mediator decay to photons

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Muon-philic scalar

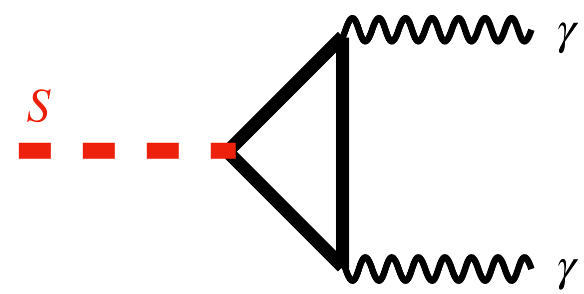
[Chen, Davoudiasl, Marciano, Zhang, '15]
[Chen, Pospelov, Zhong, '17]
[BB, Freitas, Ismail, McKeen, '17]

- Model

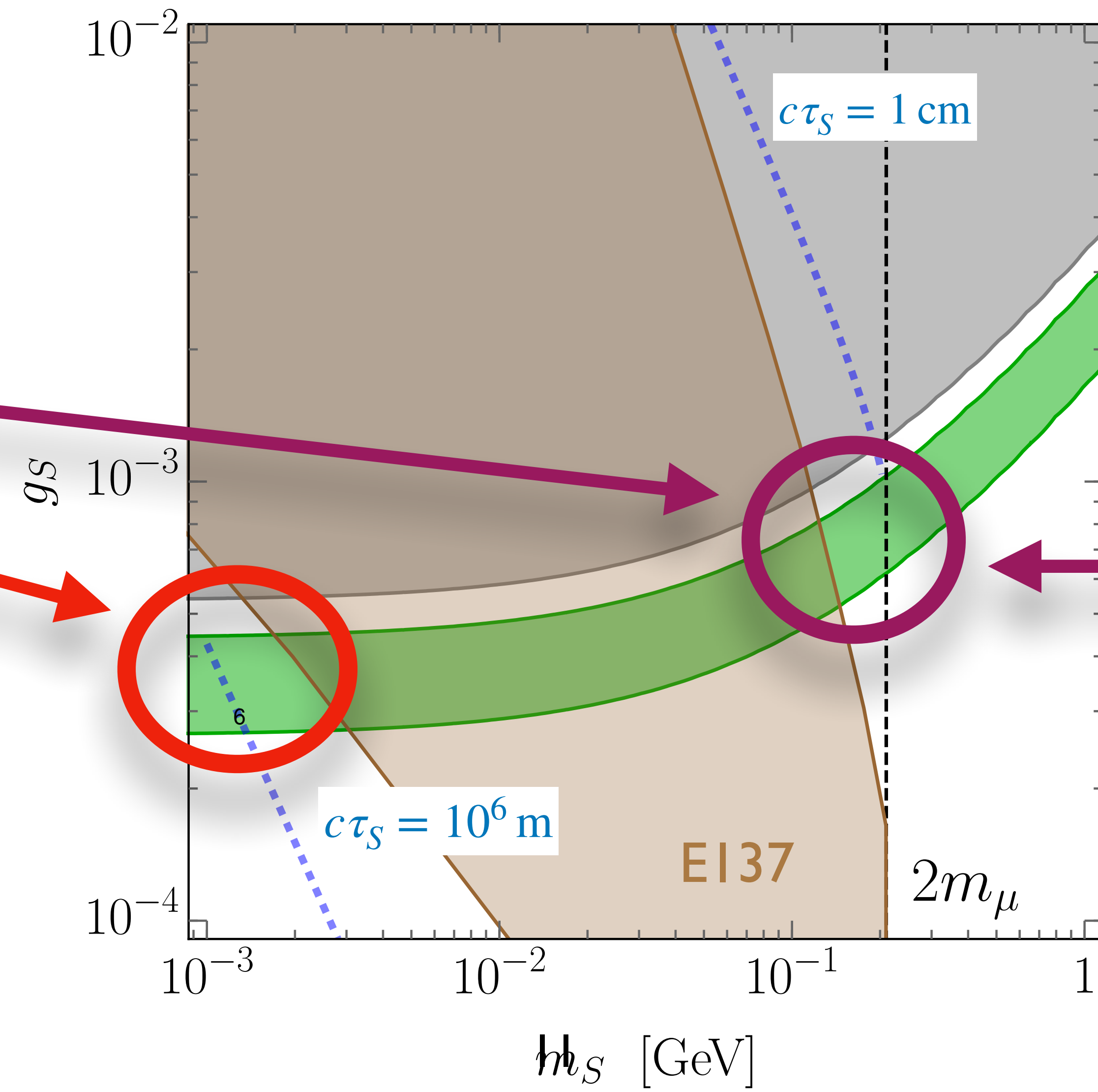
$$\mathcal{L} = -g_S\, S\, \overline{\mu}\mu - \frac{1}{4\Lambda} S F_{\mu\nu} F^{\mu\nu}$$

- Below the dimuon threshold, the scalar decays to photons with macroscopic decay length

- Minimal scenario: photon coupling generated at one loop from the muon coupling:



$$\frac{1}{4\Lambda} \sim \frac{g_S\, \alpha}{4\pi m_\mu}$$



Muon missing momentum search can be performed in both open regions

Blue dotted line indicates scalar decay length

Search for displaced diphoton resonance below diumon threshold

Scalar mediator decay to electrons

	Invisible			Visible			
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signature	missing momentum			displaced resonance			

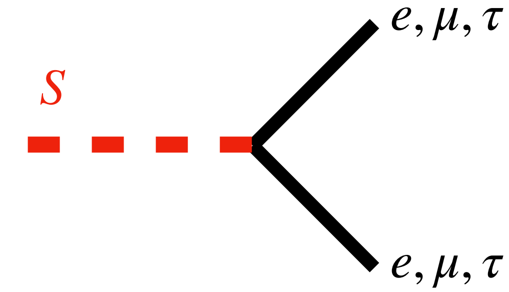
Lepto-philic scalar

[BB, Lange, McKeen, Pospelov, Ritz, '16]

- Model

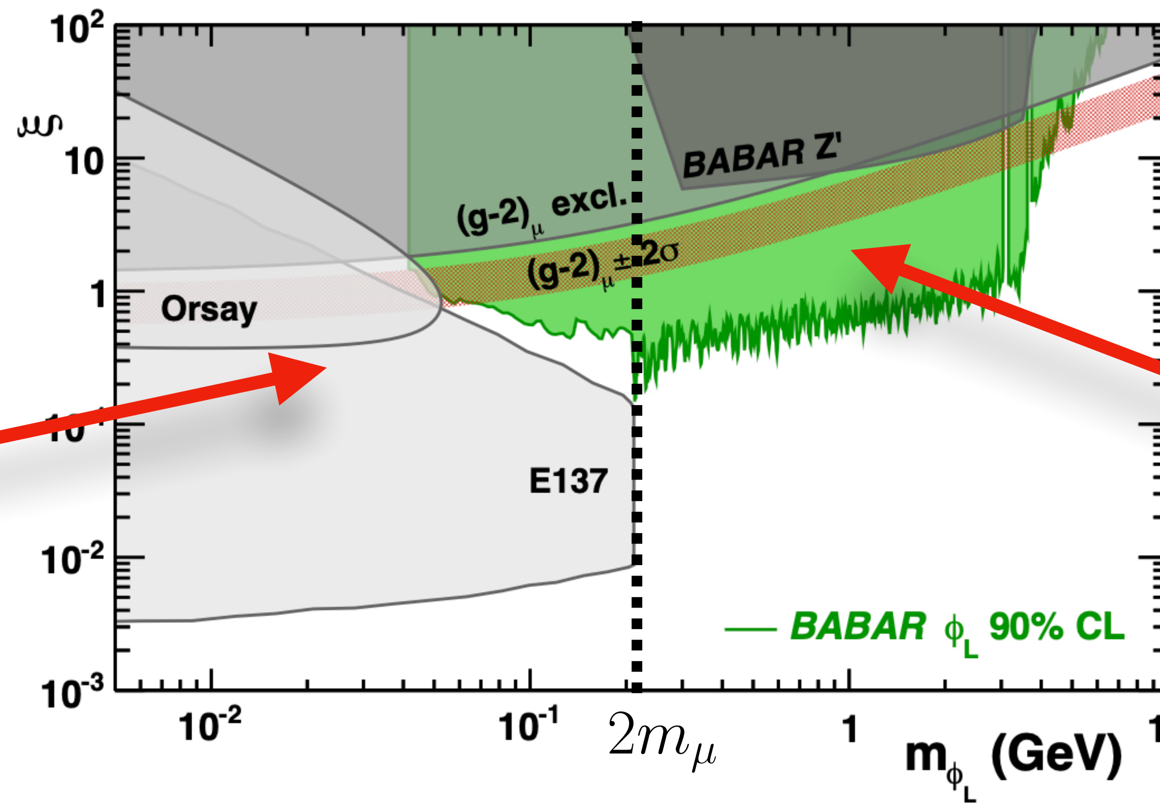
$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} S \bar{\ell} \ell$$

- Scalar inherits leptonic couplings from Higgs, couples in proportion to lepton mass



$$g_\ell = -\xi \frac{m_\ell}{v}$$

- This scenario is essentially ruled out for (sub-)GeV mass mediators (small region still allowed)



BABAR Collaboration, PRL 125, 181801 (2020)

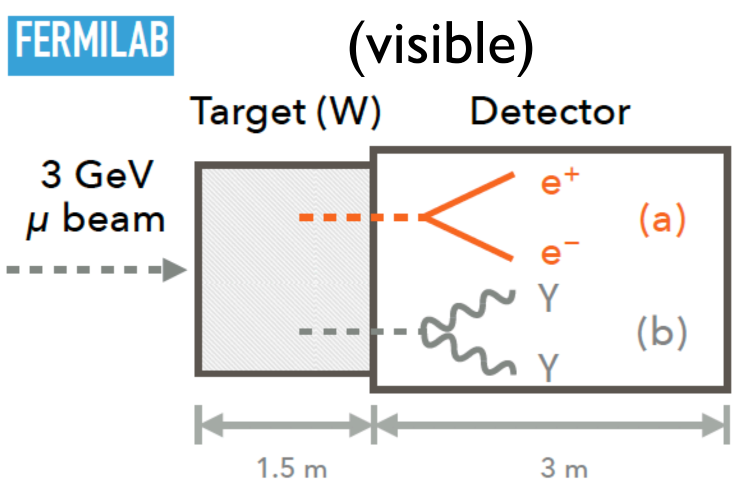
Electron beam dumps (rely on electron coupling)

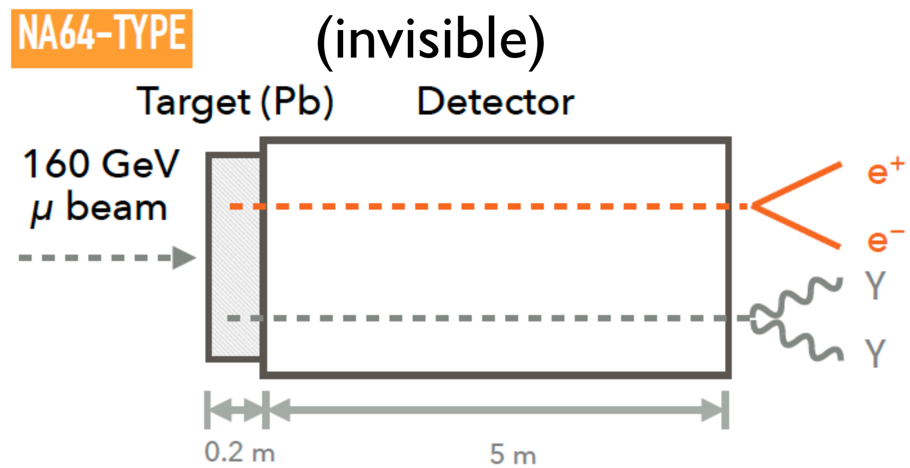
BABAR search, $e^+e^- \to \tau^+\tau^- S, S \to \ell^+\ell^-$ (relies on coupling to τ)

- If the scalar coupling to τ is suppressed, the BABAR constraint will not apply

- Muon fixed target experiments can probe unexplored regions in both muon-philic and leptophilic scalar models

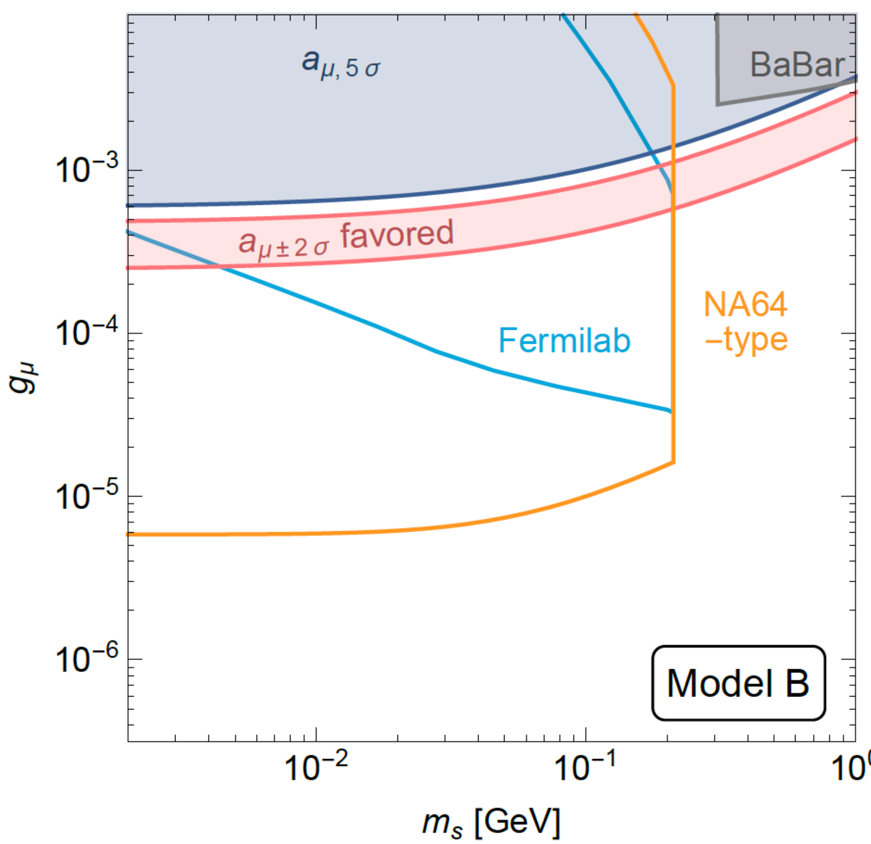
[Chen, Pospelov, Zhong, ’17]





Note, “NA64-type” can also be done at FNAL (i.e., M3)

Muon-philic scalar



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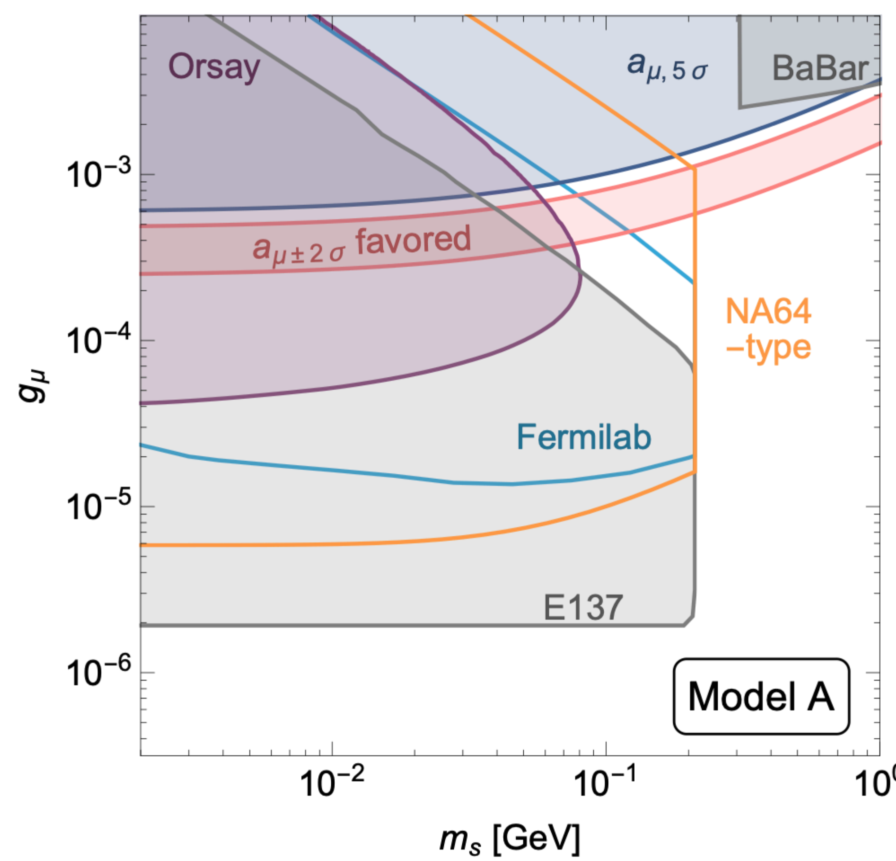
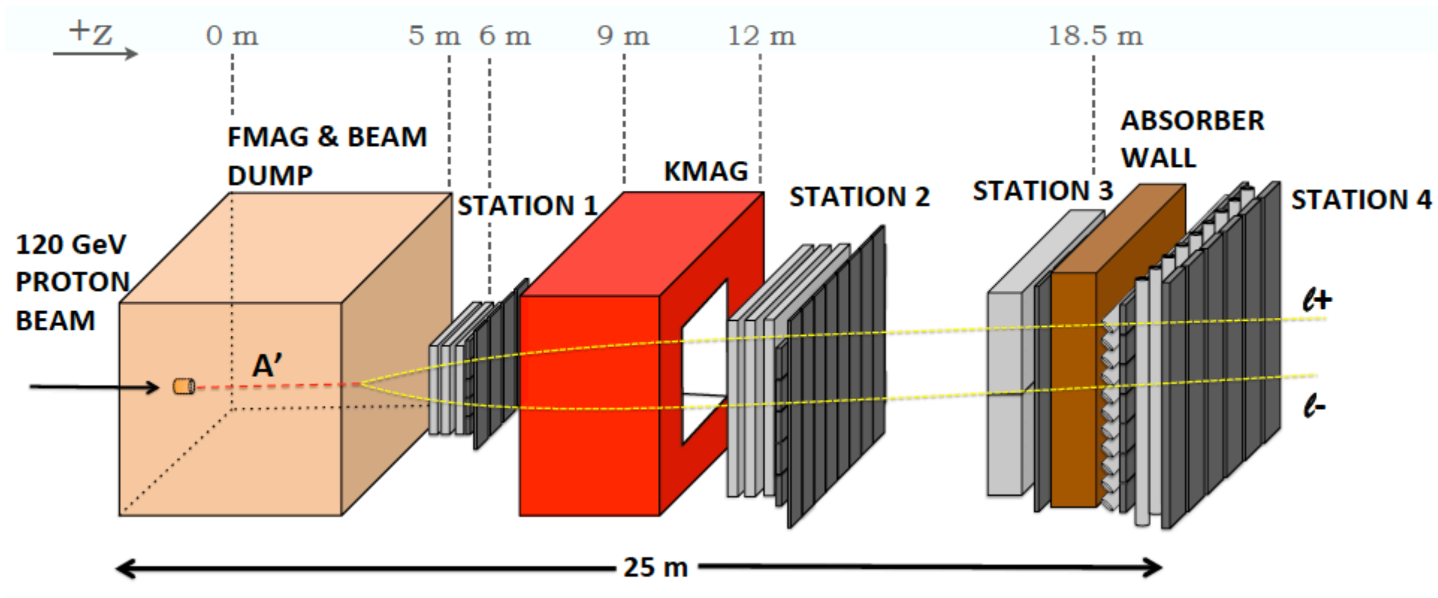


Right below dimuon threshold, both visible and invisible signals can be seen; important handle for model discrimination

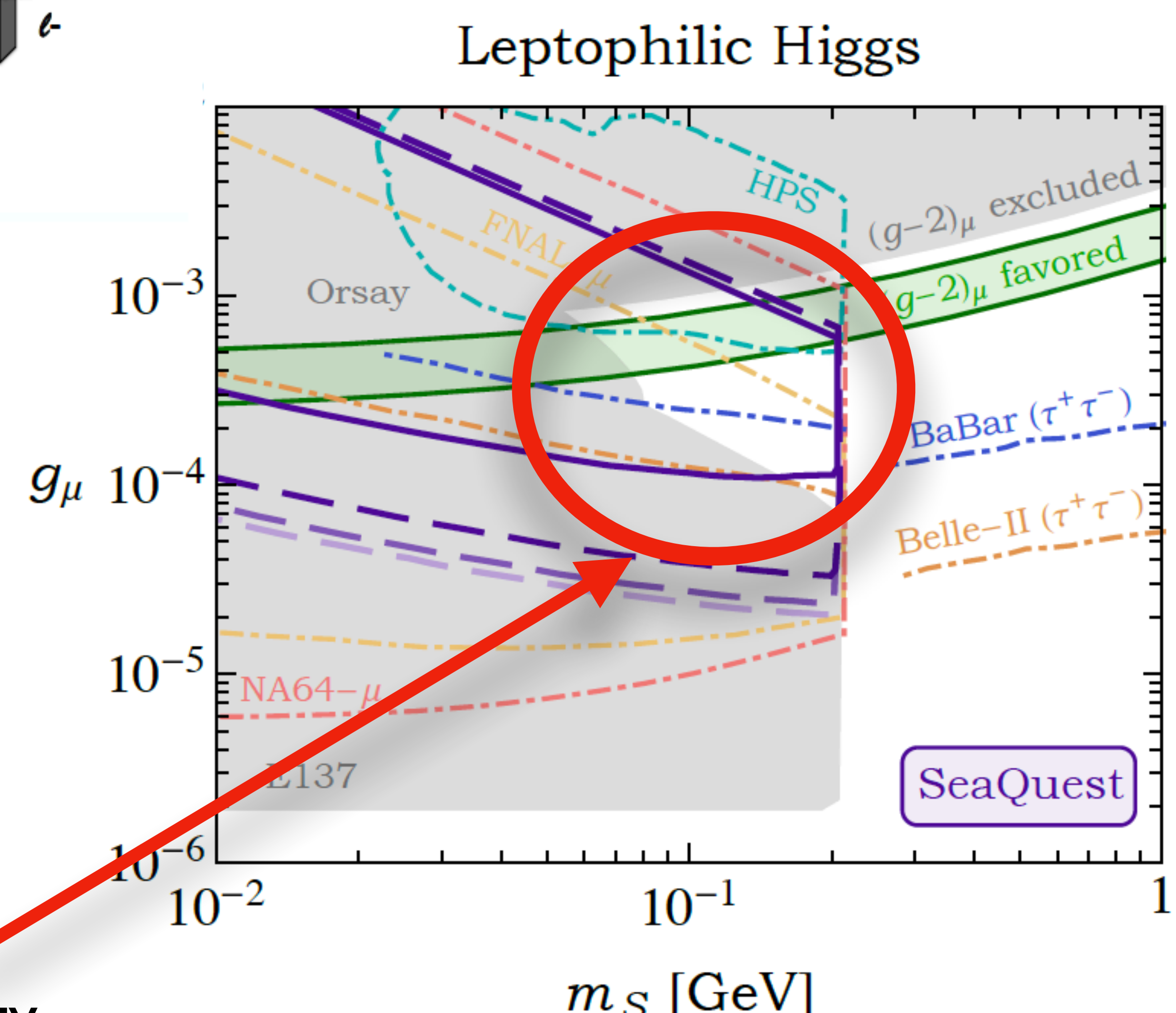
See talk by Y. Zhong

- Proton beam dump experiments, such as SeaQuest/SpinQuest/DarkQuest/LongQuest, can also probe leptophilic mediators

[Berlin, Gori, Schuster, Toro, '18]



- A large secondary flux of muons is produced in the primary proton-target collisions.
- Subsequent collisions of these muons in the dump can produce mediators



SeaQuest sensitivity
to di-electron channel

See talks by D. Sperka and P. Harris

Scalar mediator decay to muons

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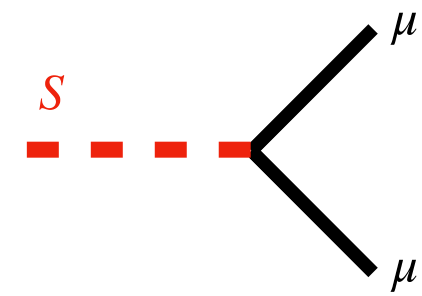
Muon-philic scalar

- Model

$$\mathcal{L} = -g_S\, S\, \overline{\mu}\mu$$

- Production and decay of scalar mediator tied to same coupling relevant for $(g-2)_\mu$

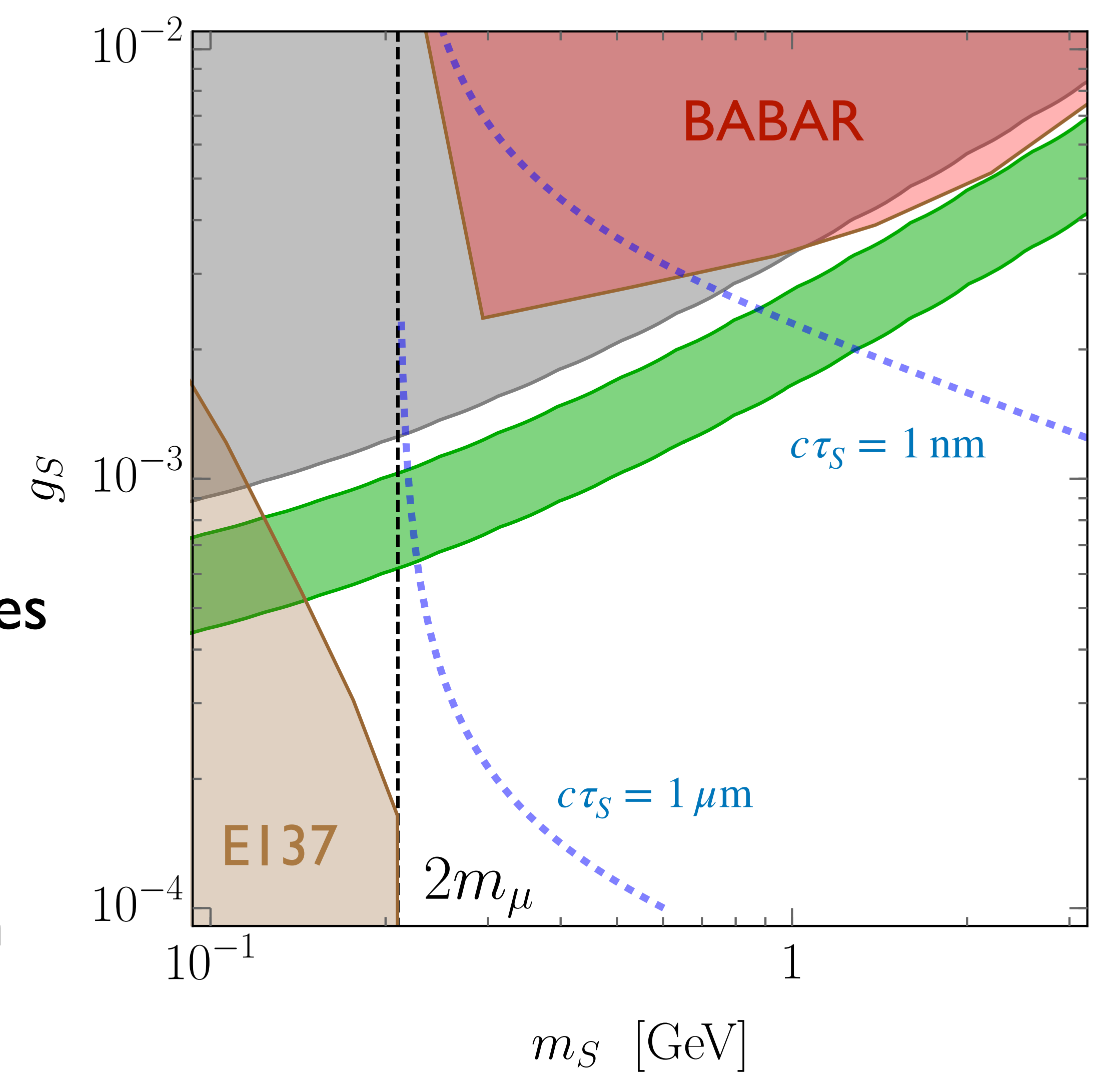


- Above the dimuon threshold, the scalar decays promptly to muons

- At muon beam fixed target experiments, strategy would be a dimuon resonance search

- No studies in the literature yet - feasibility study needed!

  [Forbes, Herwig, Kahn, Krnjaic, Mantilla Suarez, Tran, Whitbeck, to appear]



- It would also be worth considering opportunities at proton beam dump experiments

- Similar comments apply to scalars decaying hadronically. If such decays are to compete with the dimuon channel, they must be prompt.

Beyond the minimal models and signatures

Broader simplified model studies

- In the simplified scalar models, there is a broader parameter space than has been studied thus far.
- One can vary the coupling of the scalar to neutrinos, electrons, photons, quarks, and DM freely.
- Existing constraints and prospects at muon fixed target experiments depend in detail on such couplings.
- More phenomenological studies along these lines would be valuable.

[Forbes, Herwig, Kahn, Krnjaic, Mantilla Suarez, Tran, Whitbeck, to appear]

Complex final states

- Beyond the minimal visible decay channels discussed in this talk, one can envision more complex cascade decays with multiple visible particles plus missing invisible particles.
- Complex final states can often appear in models connecting to other outstanding problems (e.g., dark matter, neutrino masses, …) — important to explore these connections!
- In most cases it makes sense for experimental studies to prioritize the simple minimal final states and signatures.

Outlook

- Muon and proton beam fixed target experiments at Fermilab can provide powerful near-term probes of muon-philic forces explaining $(g-2)_\mu$

- A range of experimental signatures are needed to cover the simplest models:
  - Missing momentum, displaced resonance, $\ldots$
  - Some conceptual studies still needed (e.g., prompt dimuon resonance searches)

- More phenomenological studies of simplified model parameter space are warranted, and it is worth further exploring theoretical connections between $(g-2)_\mu$ and other outstanding puzzles.

- Minimal models and signatures provide a good first target. These can be broadly probed with experiments at Fermilab!