Parasitic Strategies For Muon Facilities

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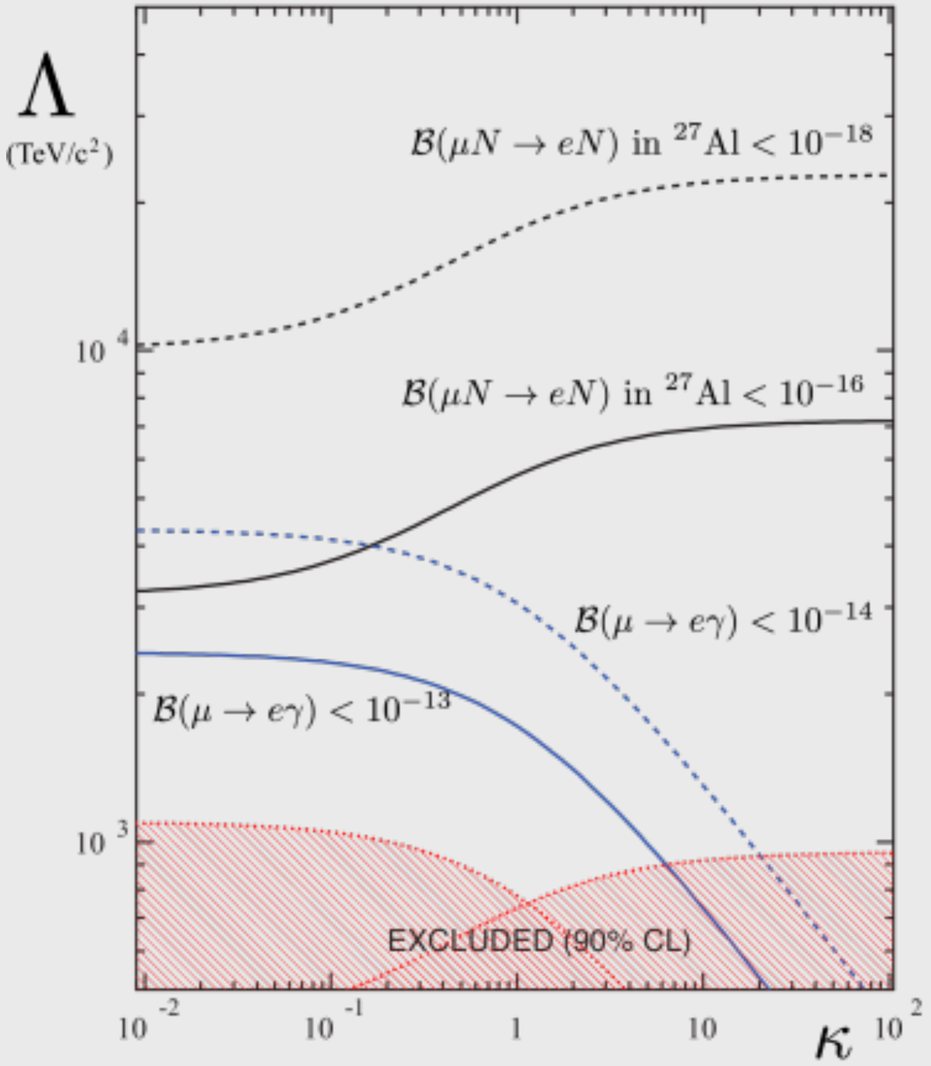
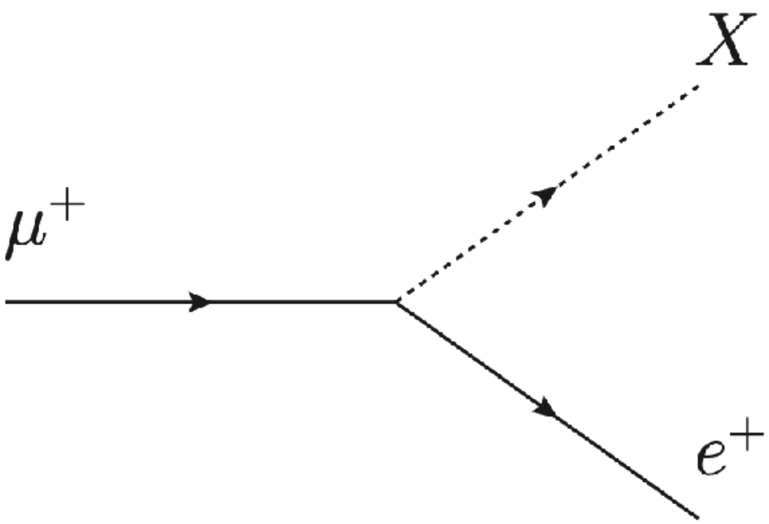
FUTURE MUON FACILITIES WORKSHOP | CALTECH | 2023

Probing High Scales With CLFV

- We typically think of muon facilities as probes of very high scales.
- The signatures are kinematically distinctive electrons/photons.
- **Strategy:** Cut out everything else.



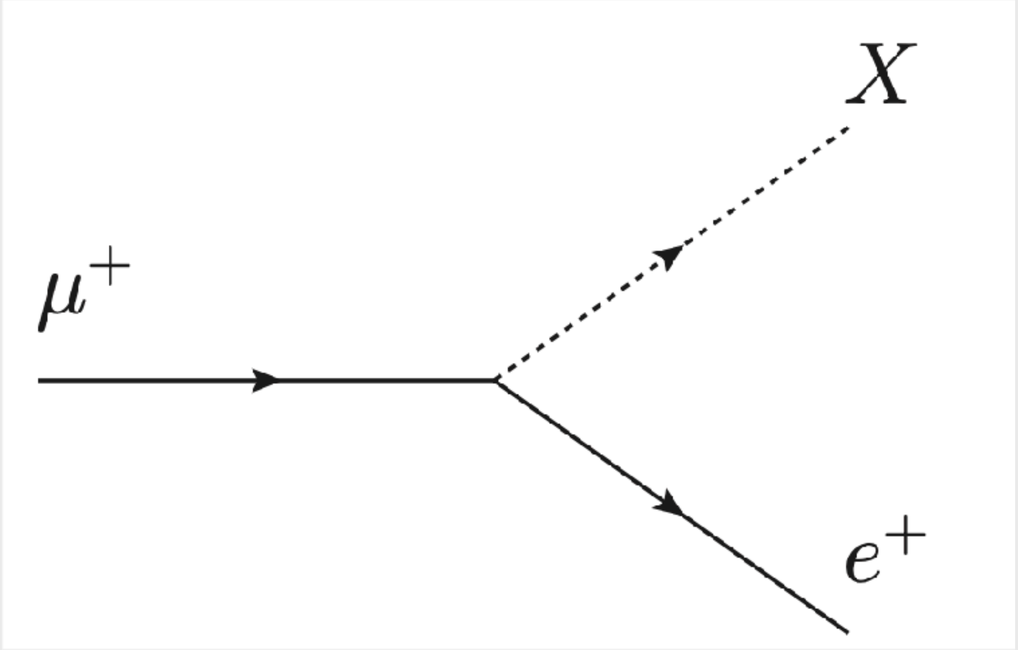


LIGHT NEW PHYSICS

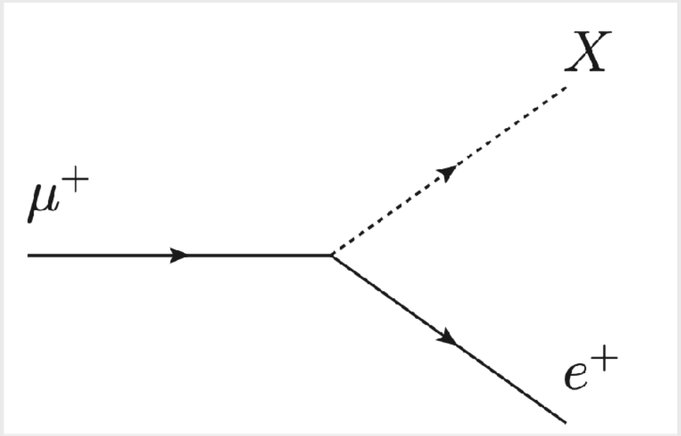
RARE BUT **KINEMATICALLY DISTINCTIVE**

Probing Low Scales With Muon Facilities

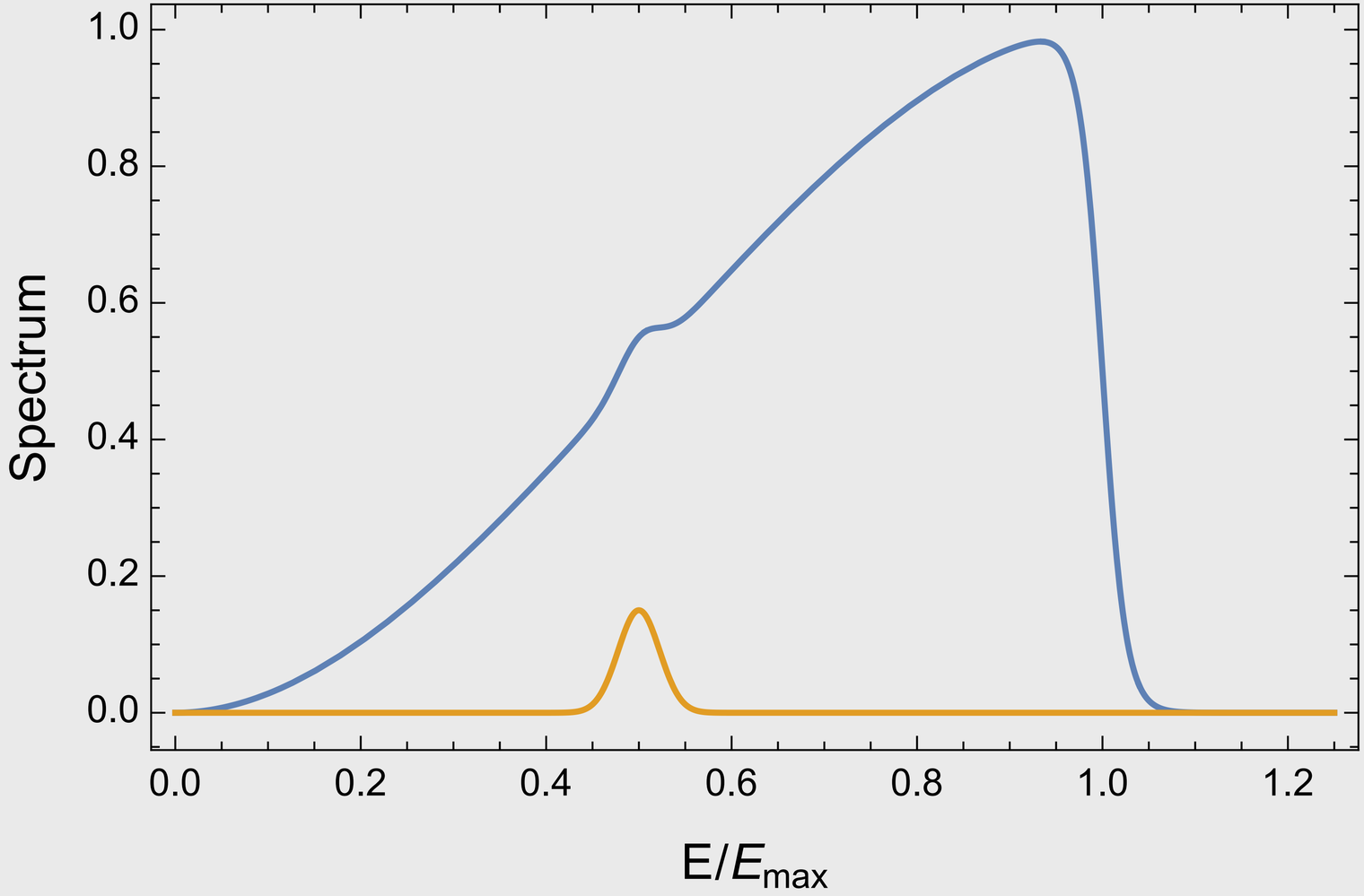
- High statistics: Attack weak coupling limit.
- Kinematically distinctive signatures.
- Generally outside the "central mission" of the facility.



Signals Below The Michel Edge

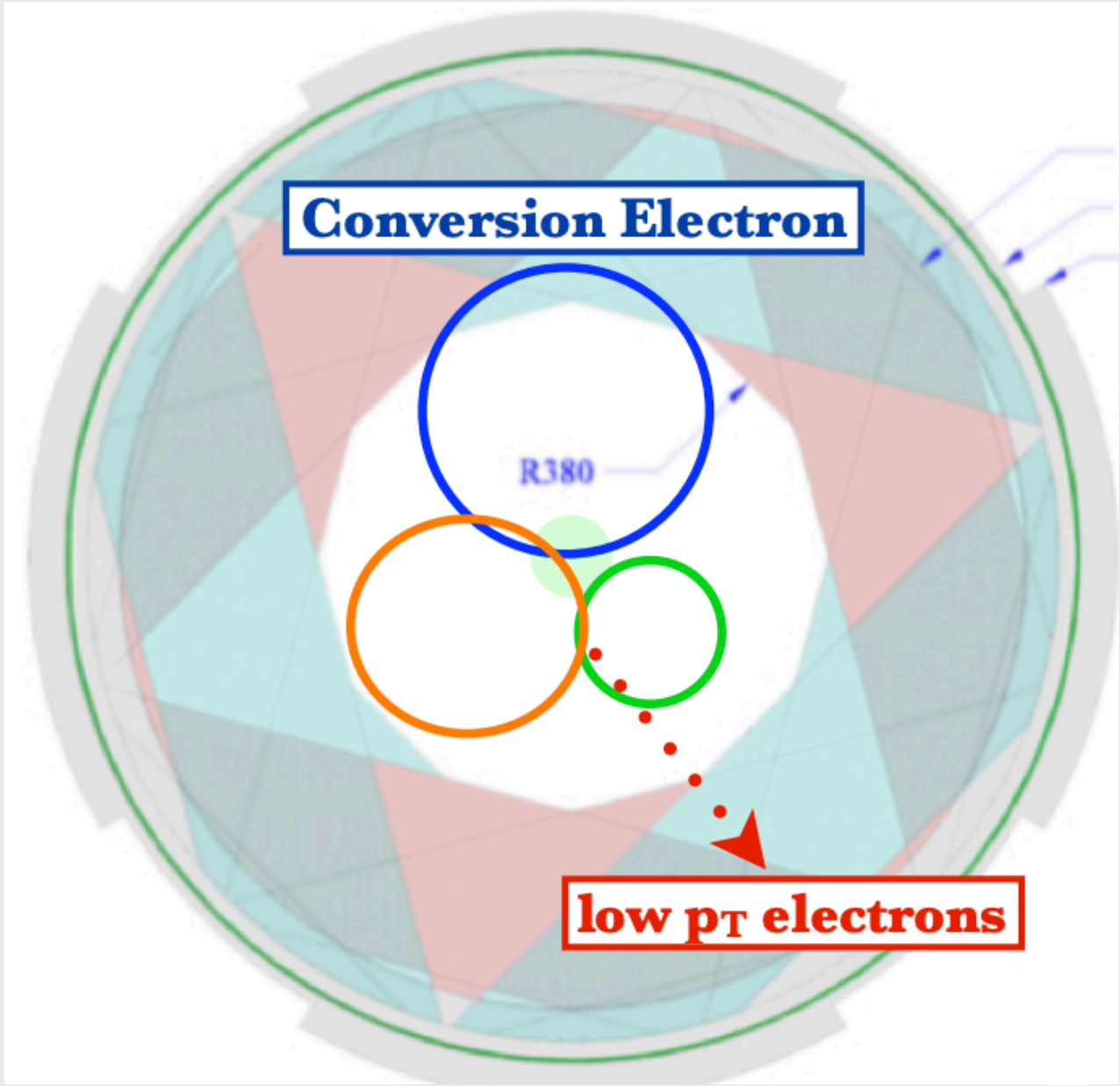


- Search for a mono-energetic positron.
- Look for a bump on the Michel spectrum.



Signal Is Invisible

- Tracker is designed to let Michel positrons pass through middle.
- Whole idea seems doomed from the outset.



PART 1

BE AN OPTIMIST

- Muon conversion facilities can be "hacked" to do new searches.
- There are certain "irreducible strengths".
- Huge muon statistics, high quality detectors.

PART 2

WHERE TO LOOK

- What kinds of models are well suited to searches.
- Opportunities with muons and pions.
- Positively vs negatively charged muons.

PART 3

AN EXAMPLE

- Using Mu2e to look for mono-energetic electrons.
- Illustration of "multi-tool" nature of experiment.
- How to use different parts/phases of experiment for physics.

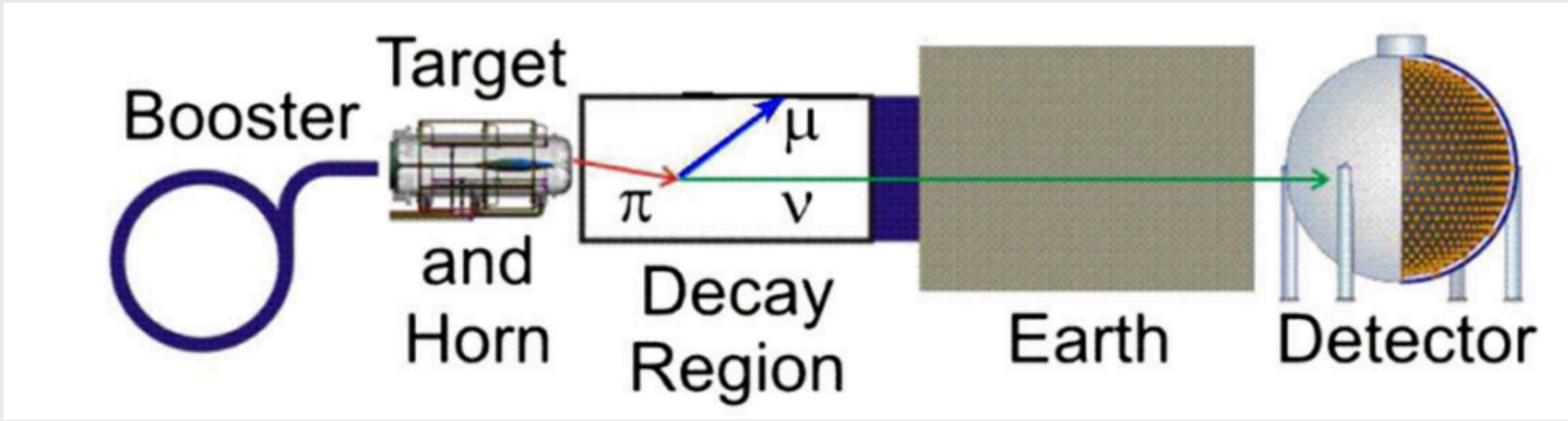
An Intensity Frontier Cousin

- Dark sector searches increasingly recognized as part of the neutrino program.

Dark Sector Studies with Neutrino Beams

NF03 Contributed White Paper to Snowmass 2021

Brian Batell[*1], Joshua Berger[2], Vedran Brdar[3,4], Alan D. Bross[3], Janet M. Conrad[5], Patrick deNiverville[6], Valentina De Romeri[7], Bhaskar Dutta[8], Saeid Foroughi-Abari[9],



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MINIBOONE - DM

CLFV

- High intensity beam.
- Complicated nuclear targets.
- High statistics.

Neutrino

- High intensity beam.
- Complicated nuclear targets.
- High statistics.

CLFV

- High intensity beam.
- Complicated nuclear targets.
- High statistics.
- Selective detection
- Energy resolution.

Neutrino

- High intensity beam.
- Complicated nuclear targets.
- High statistics.
- Inclusive detection

CLFV | Neutrino

Main Idea

- Neutrino and CLFV facilities have a lot in common.
- The past 10 years have seen an increasing appreciation for parasitic BSM searches at neutrino facilities.
- There are clearly unexplored opportunities with muon facilities.

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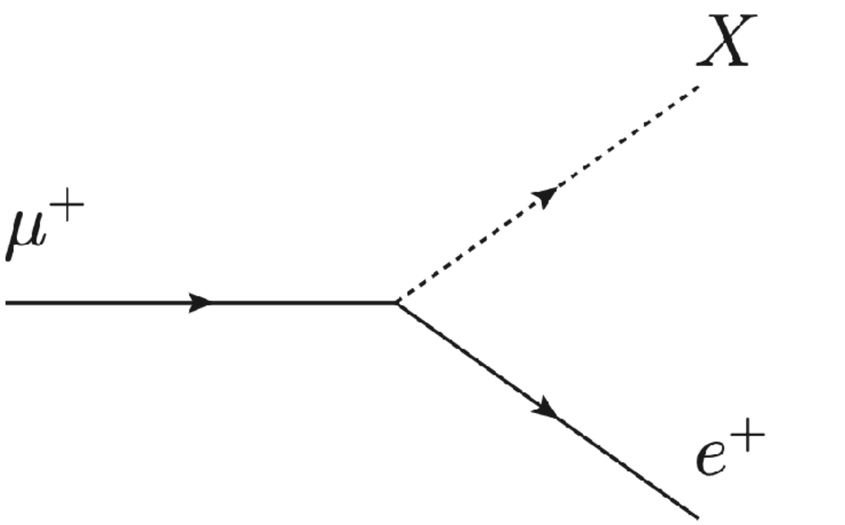


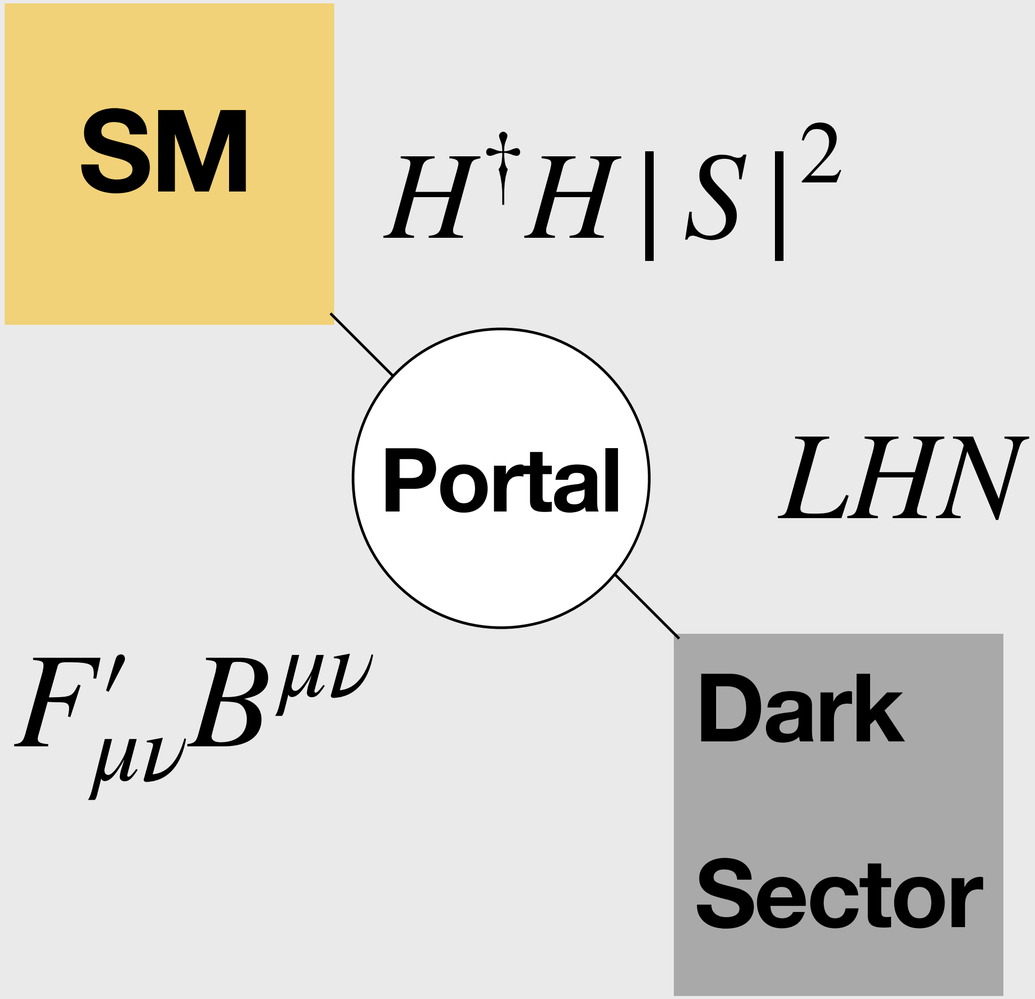
LIGHT NEW PHYSICS

RARE BUT **KINEMATICALLY DISTINCTIVE**

Motivation

- Dark matter strongly hints at the existence of dark sectors.
- A simple, model agnostic program exists.
- Focus on portals i.e. couplings that could talk to the SM.

Portals



Motivation

- Q: How many ways can light new physics couple to the SM?
- A: Not many once you restrict to low-dim operators!

$$\mathcal{O}^{[4]}_{\text{singlet}} = \phi^2 |H|^2 \quad \text{or} \quad LHN \quad \text{or} \quad B^{\mu\nu} B'_{\mu\nu}$$

Scalars **HNLs** **Z-Prime**

$$\mathcal{O}^{[5]}_{\text{singlet}} = \frac{1}{\Lambda} (\partial_\mu a)\, J^\mu + \dots$$

ALPs

Light New Physics

- Data demands that new physics be heavy, or weakly coupled

- What could we see in a ~100 MeV experiment?

Z-Prime

$$\mathscr{L} \subset g' \bar{\mu} \Gamma_\mu e \, Z'^\mu$$

$$\mathscr{L} \subset \frac{1}{\Lambda} \bar{\mu} \Gamma_\mu e \, \partial^\mu a$$

Axions

HNLs

$$\mathscr{L} \subset U_{eN} \left[f_\pi G_F \left(\partial_\mu \pi \right) \bar{N} \gamma^\mu P_L e \right]$$

Probing Low Scales With Muon Facilities

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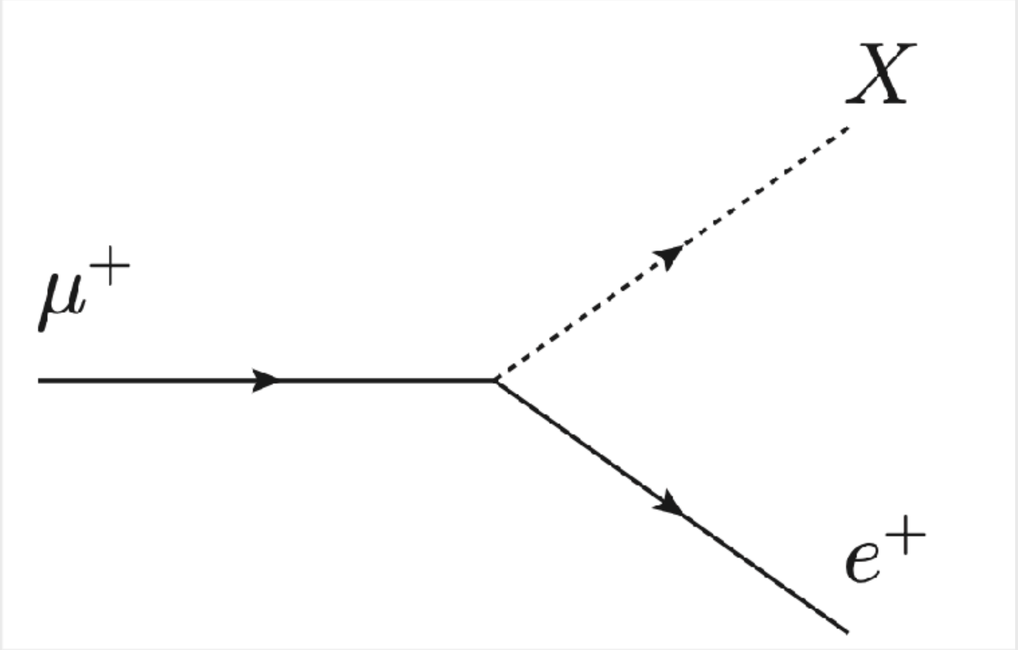
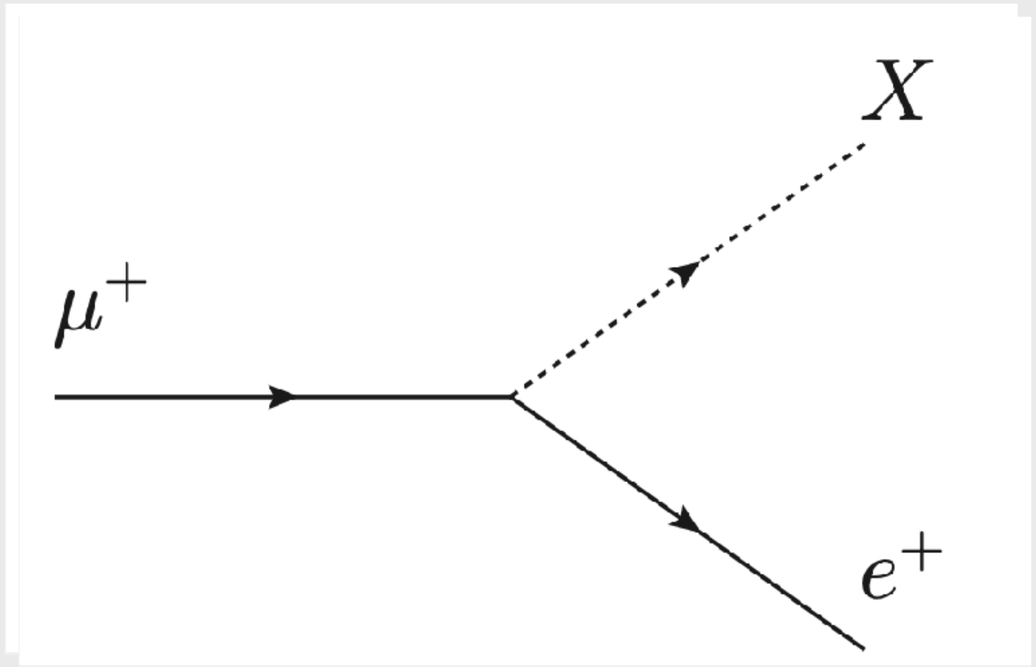
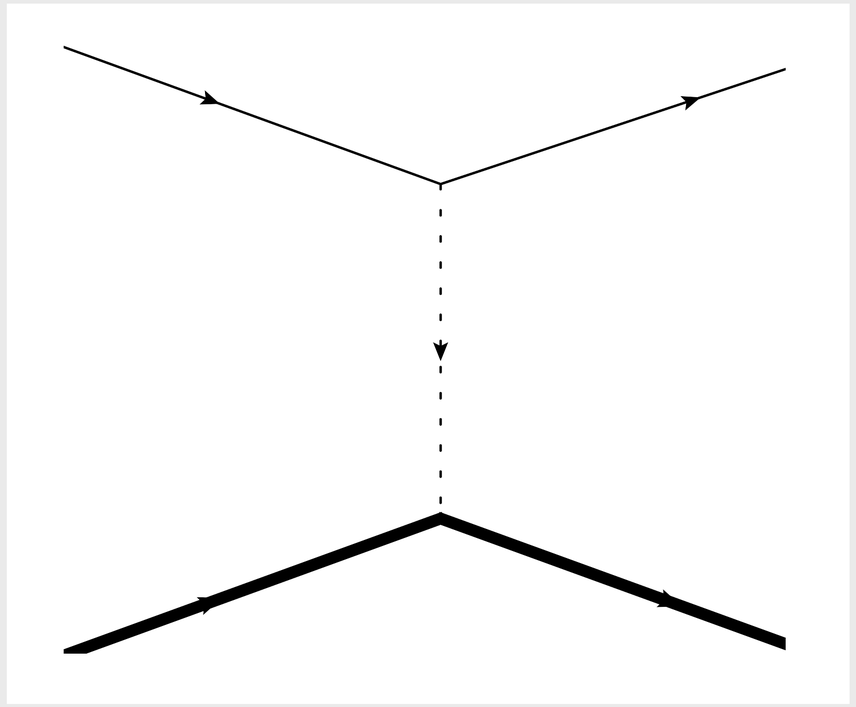


On-Shell Vs Off-Shell Processes



$$\Gamma \sim O(g^2)$$

THIS WINS



$$\Gamma \sim O(g^4)$$

Probing Low Scales With Muon Facilities

Main Idea

- Light new physics is well motivated. Portals are constrained by gauge group of SM.
- On-shell decays have much better reach than off-shell mediated processes
- This is the opposite of high-scale scenarios.

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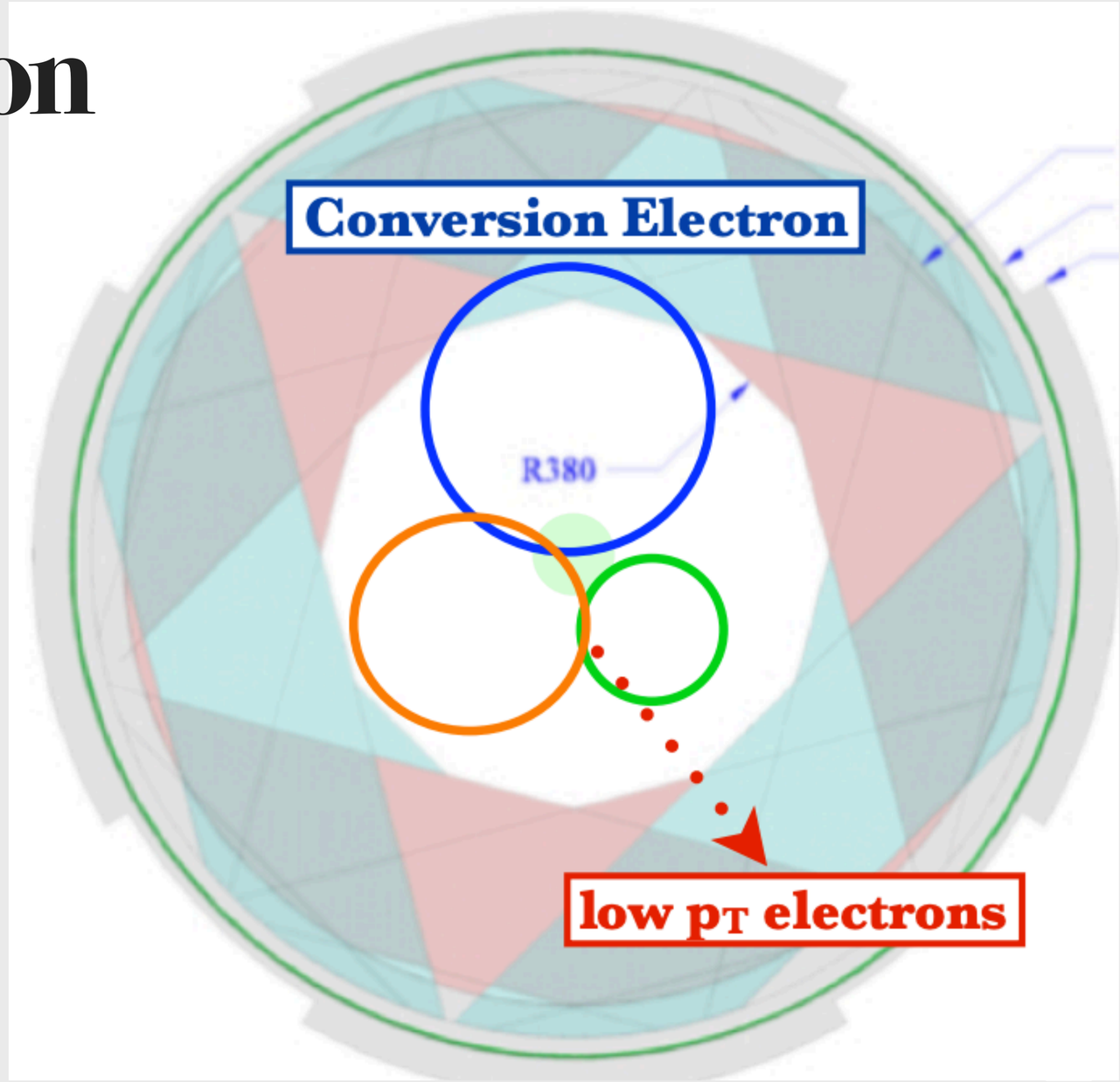
COLLABORATORS

R. HILL, S. HUANG, D. KOLTICK, P. MURAT, J. ZUPAN

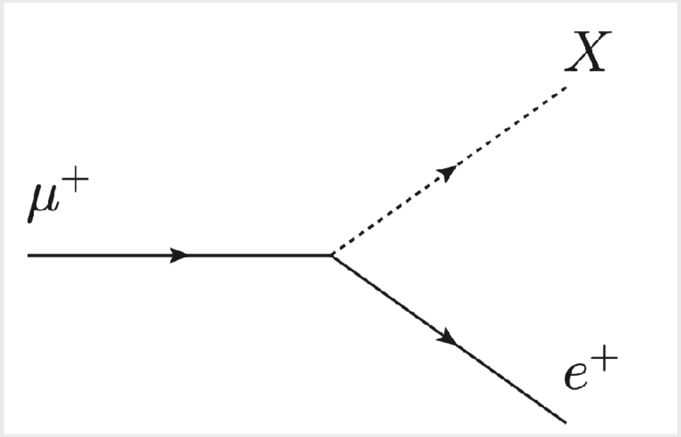
Potential μ^+ Calibration

- Tracker is designed to let Michel positrons pass through middle.
- Must lower B-field to 50%.
- Must operate at a lower beam intensity.



Search For $\mu^+ \rightarrow e^+X$ During Calibration

- Every challenge I described makes calibration difficult.
- There are already plans to use a μ^+ run for calibration.



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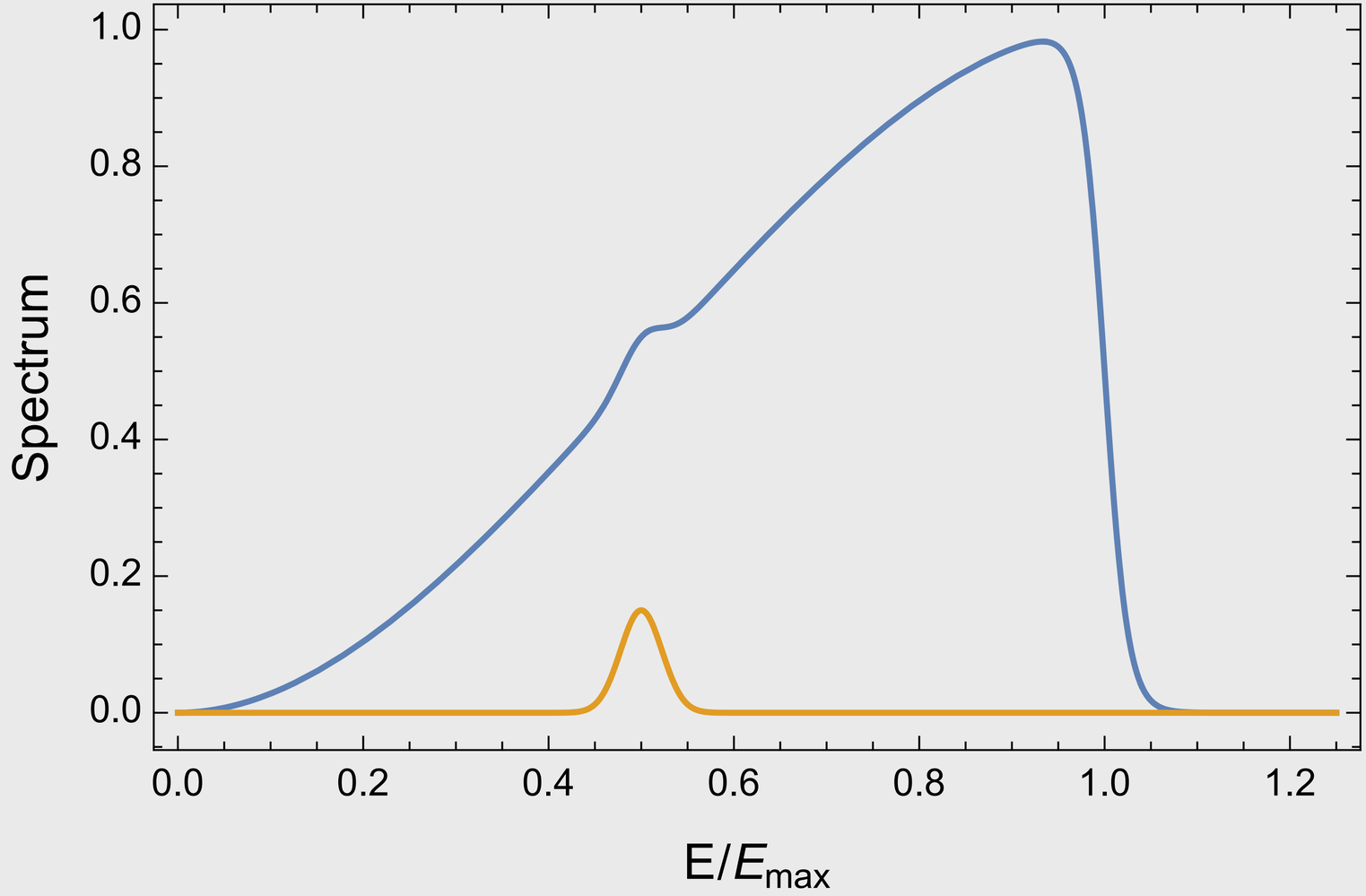
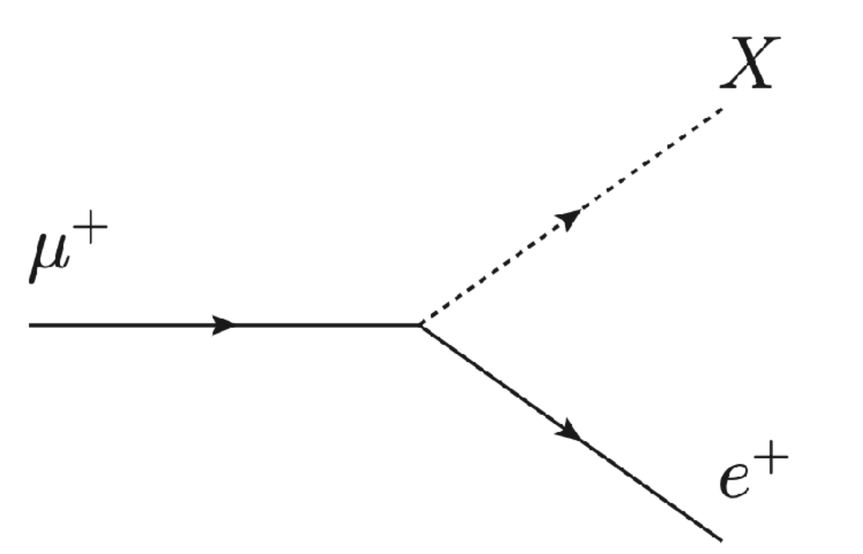


Positives And Negatives Of Muon Decay



- Clean mono-energetic positron.
- Must live below the Michel Edge.

- Complicated by atomic binding.
- Backgrounds are hard to control.
- Huge loss in signal rate.

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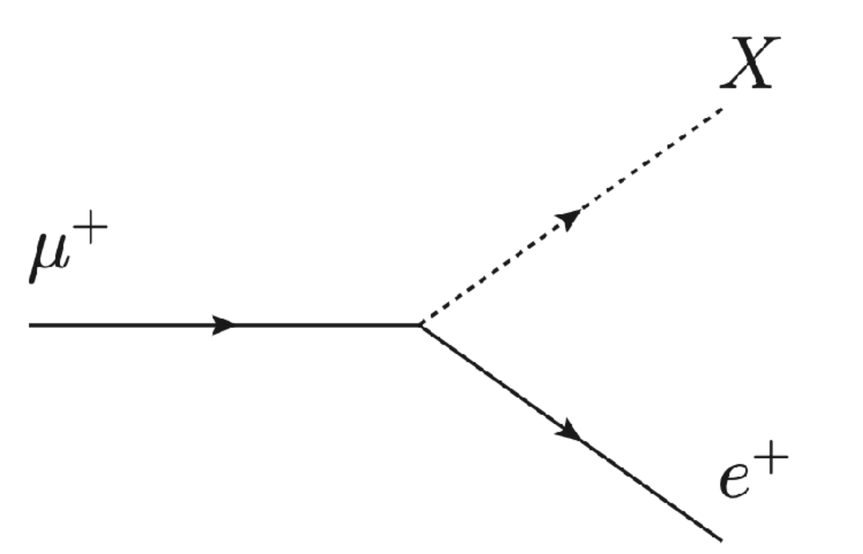

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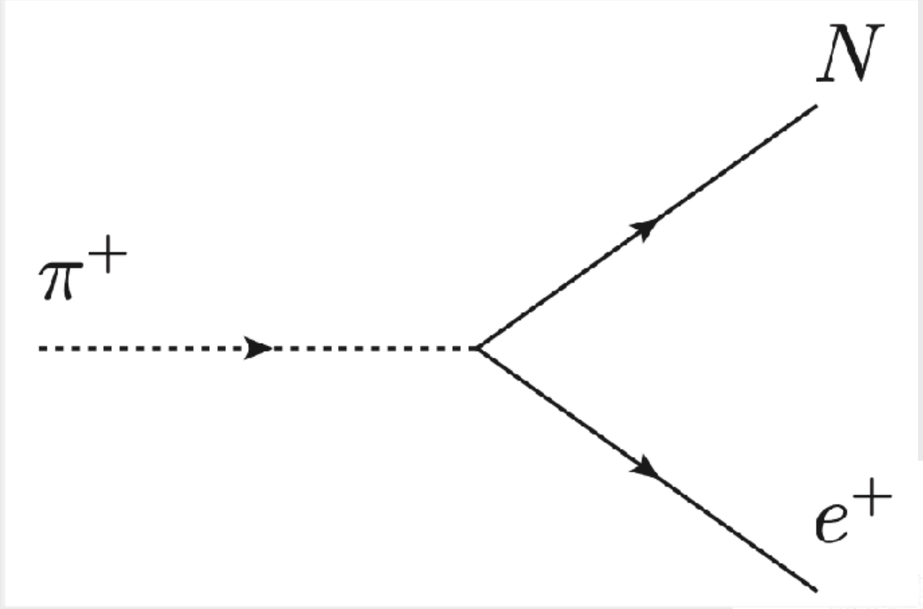
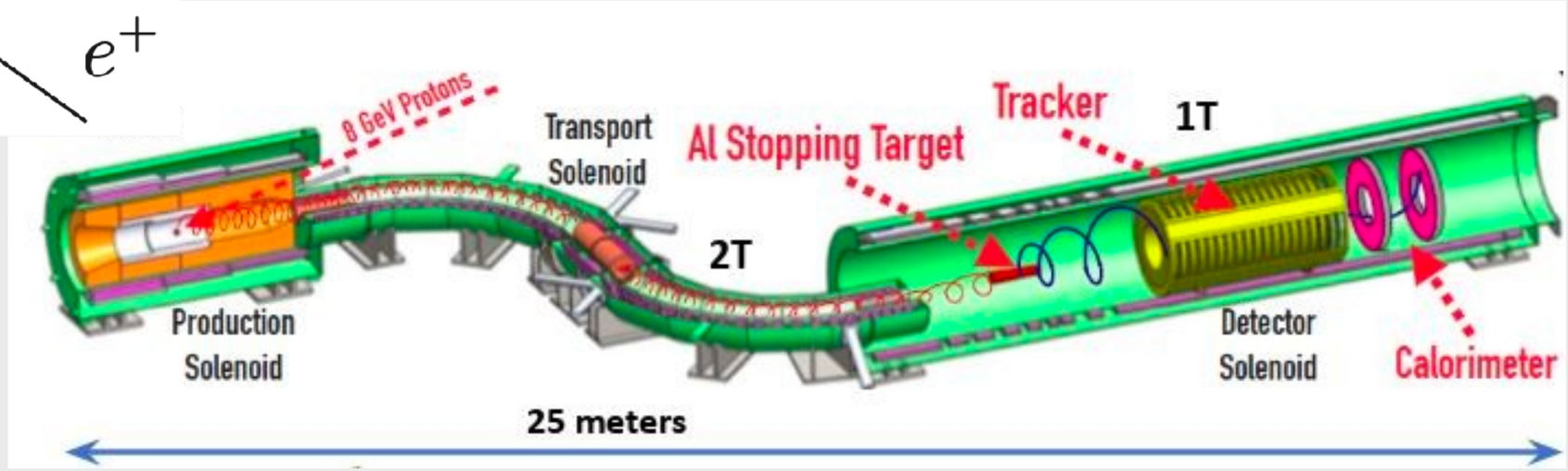
Heavy Neutral Leptons And π-Dar

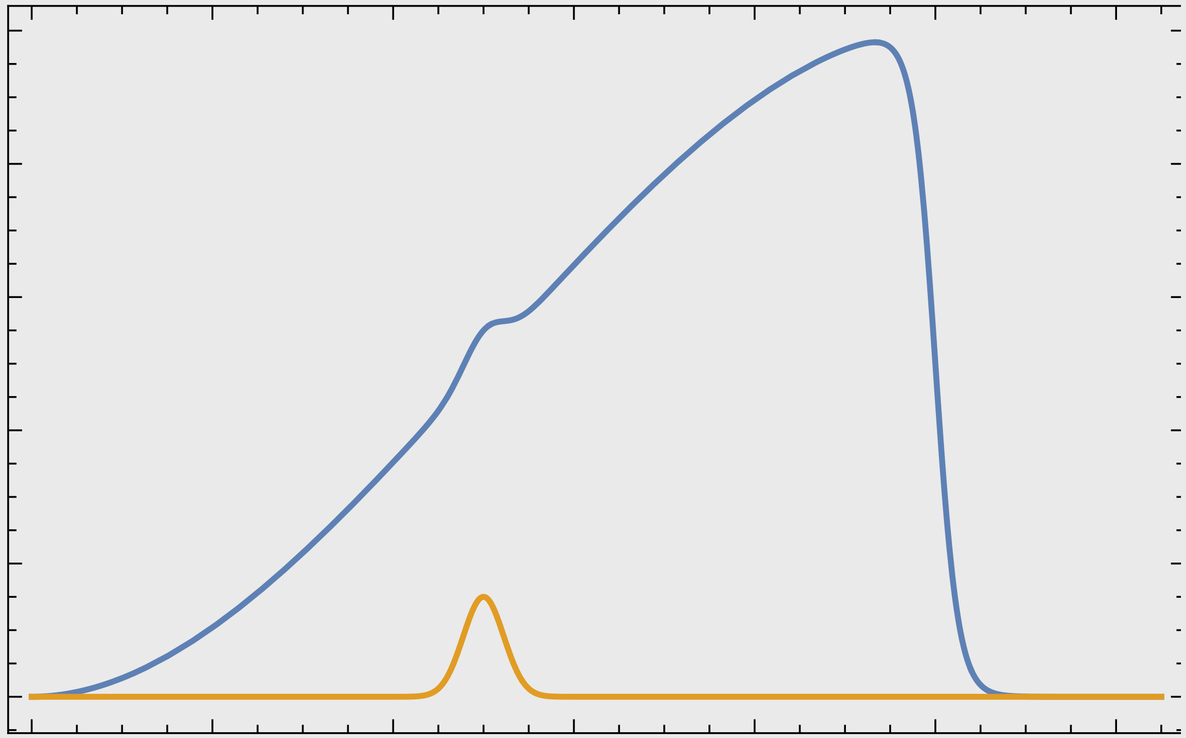


- With μ^+ comes a sample of π^+.
- Offers 2-body decay for HNL.
- Positron signal is in the ~65 MeV regime.



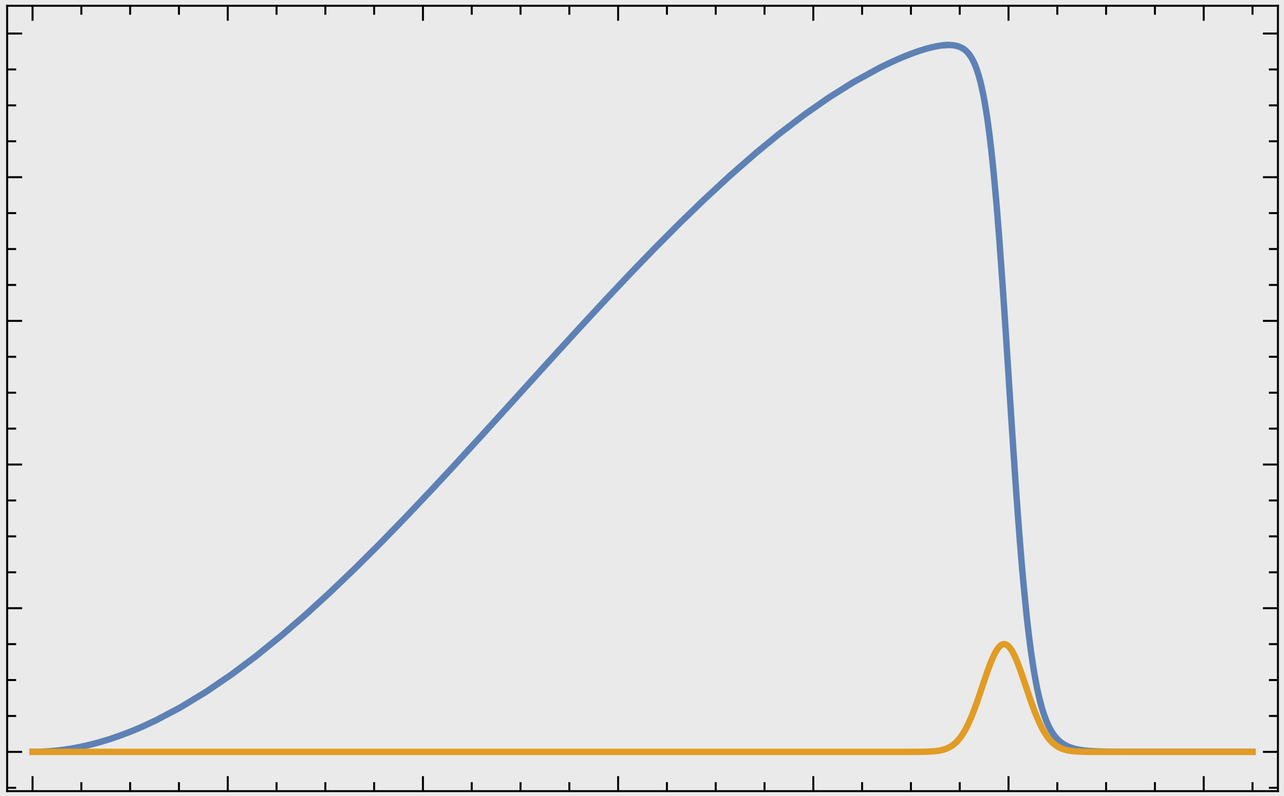
Search For $\mu^+ \rightarrow e^+X \quad m_N > 20$ MeV

- When peak is removed from edge background estimate is data driven.

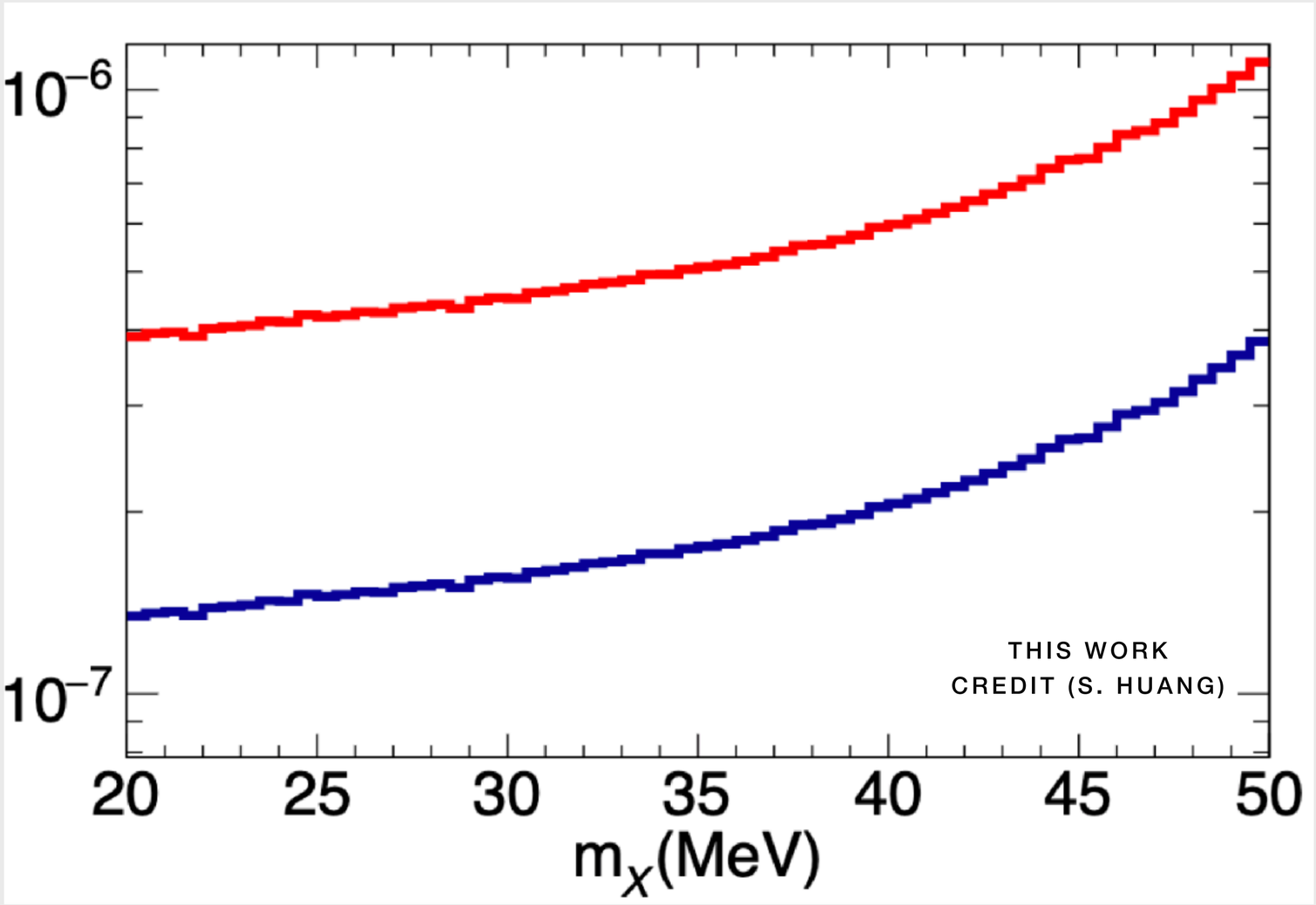


Search For $\mu^+ \to e^+ X$ $m_N \lesssim 20$ MeV

- When peak overlaps with Michel edge analysis is significantly complicated.
- Search is likely to be systematics limited.
- Still working to establish floor



Estimates For $\mu^+ \to e^+X \quad m_X > 20$ MeV



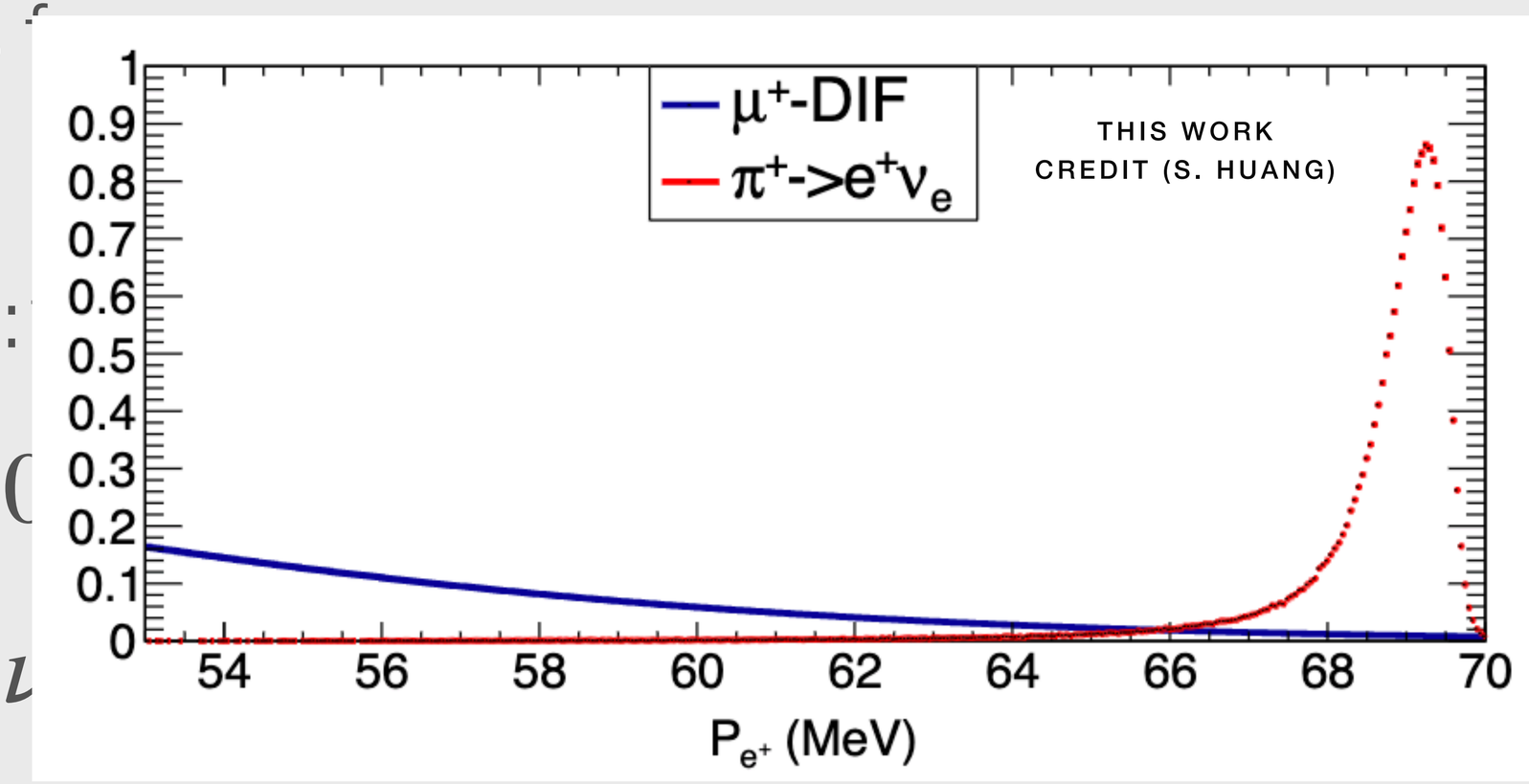
- Estimates with 2 weeks of data taking.
- Improve on world leading limit by a factor of 40.
- Constrains LFV models with ALPs, and Z’.

Search For $\pi^+ \rightarrow e^+X$ During Calibration

- Every challenge I described makes calibration difficult.
- There are already plans to use a μ^+ run for calibration.

Potential π^+ Calibration

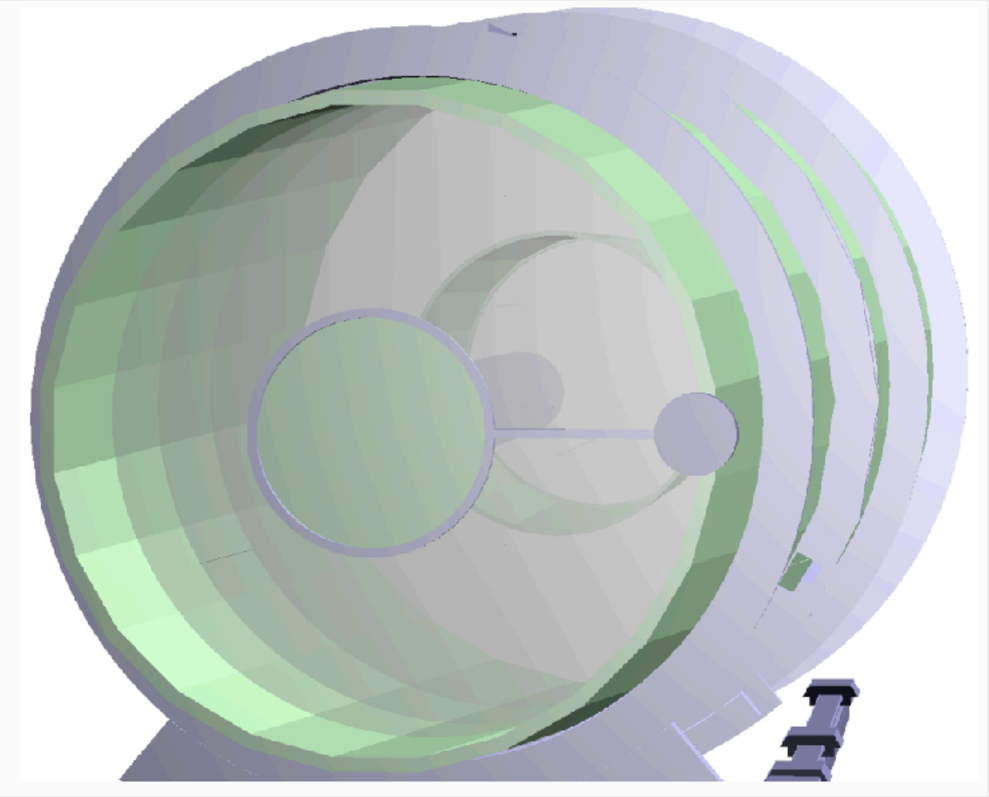
- The μ^+ beam comes f
  sample of π^+.
- Ratio is roughly 1000:
- But there are stil ~ 10
- Plan is to use $\pi^+ \rightarrow \nu$
  a calibration tool.



Momentum Degrader For π^+

- The μ-DIF background can be supressed.
- Model effect of momentum degrader

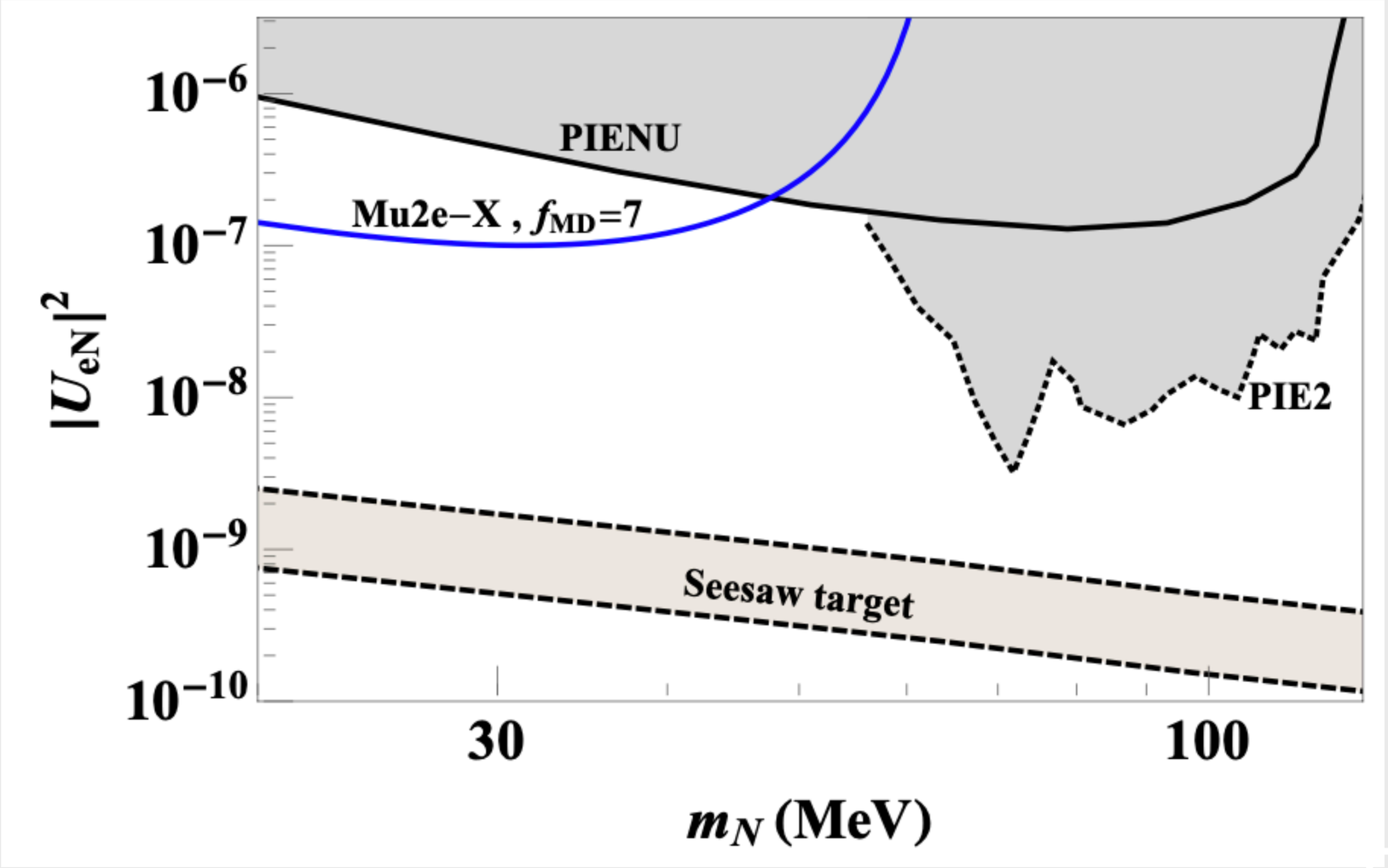
$$f_{\mathrm{MD}} = \left[\frac{N_{\pi-\mathrm{stop}}}{\sqrt{N_{\mu-\mathrm{DIF}}}}\right]_{\mathrm{MD}} \Bigg/ \left[\frac{N_{\pi-\mathrm{stop}}}{\sqrt{N_{\mu-\mathrm{DIF}}}}\right]_{\text{no MD}}$$



More $\pi-$ stops
Slows μ^+

Results For Heavy Neutral Leptons

- No planned experiment will probe the region of parameter space sketched here.



Conclusions

- **An obvious point:** Muon facilities have a lot of muons.
- Facilities tend to be specialized but even "sub-optimal" configurations can offer world leading sensitivity.
- Every piece of instrumentation is useful. What seems like a detail/footnote for one search can be crucial for another.