Other Opportunities with Muon Beams

Cari Cesarotti - MIT CTP-LI → CERN-TH

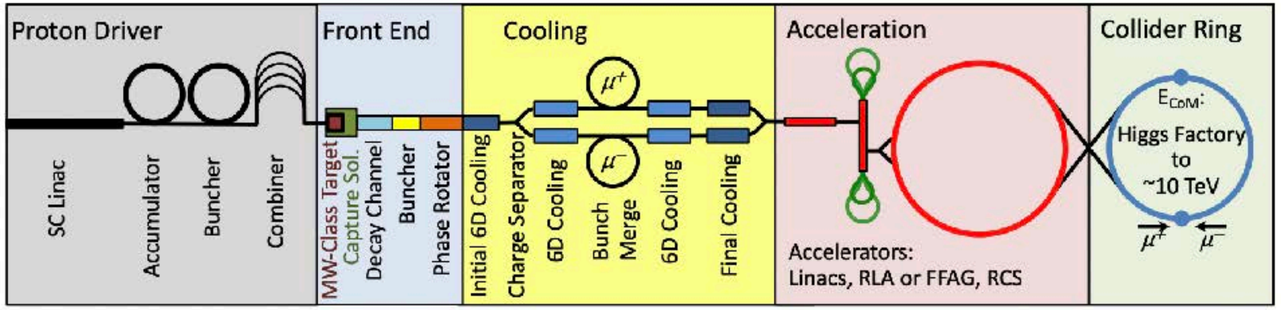
USMCC Second Annual Meeting

University of Chicago, August 8 2025

Physics with Muon Beams

Before we *collide* muons, we *accelerate* them.

Why is this interesting?



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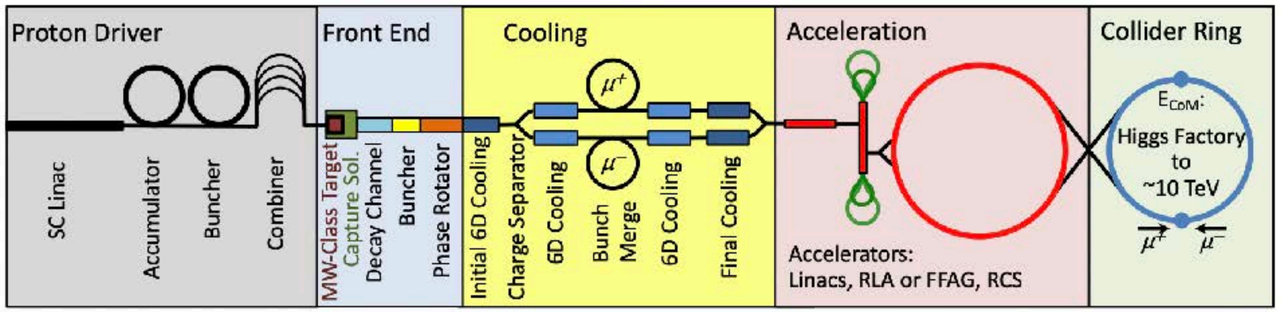

Reason 1: A high-energy & intense beam of muons has never been realized

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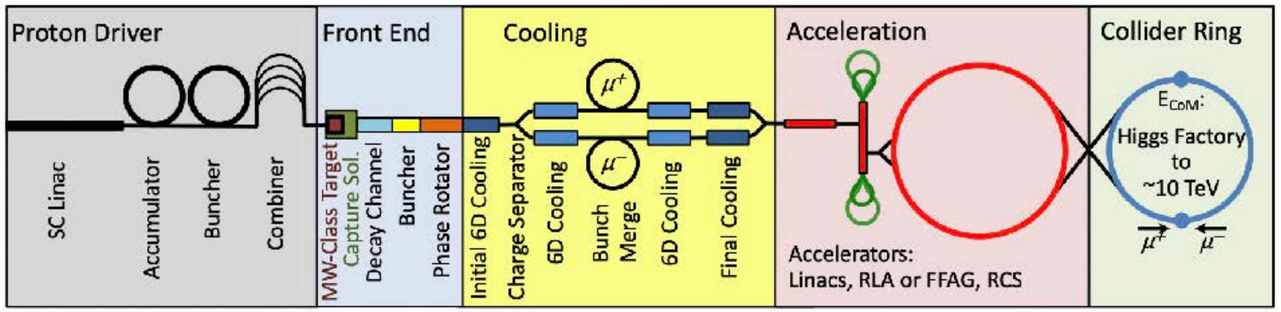

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We are in the business of long time scale, exploratory science programs:
How can we utilize muon beams at all stages of development?

Summary of Muon Beam Experiments

Muon beam experiments have been (will be) used to study...

Properties of the muon **Nuclear structure** **Material Science**

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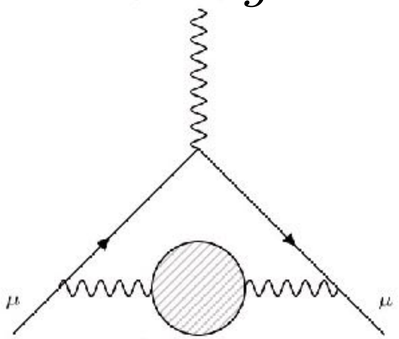
Muon Magnetic Moment

Muon g-2



Violation of Muon Number

$MEG\ (\mu \to e\gamma)$
$Mu2e\ (\mu \to e)$
$Mu3e\ (\mu^+ \to e^+e^+e^-)$
$COMET\ (\mu N \to eN)$

Nuclear structure

Material Science

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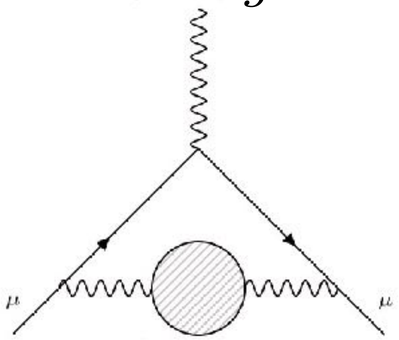

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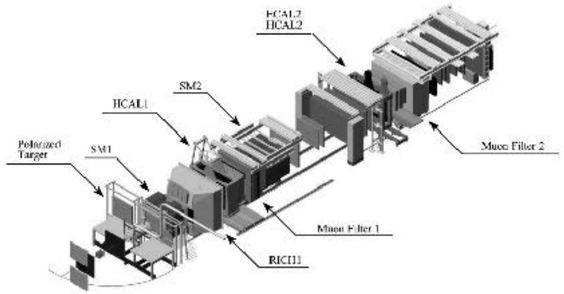
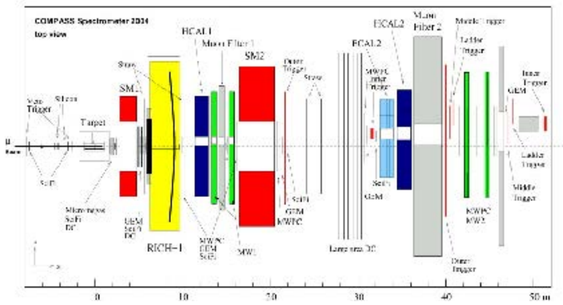
Nuclear structure

Spin structure, polarization, etc.

COMPASS/COMPASS II





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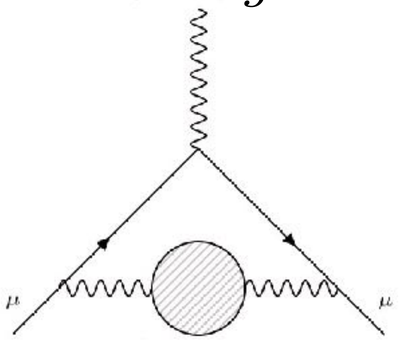

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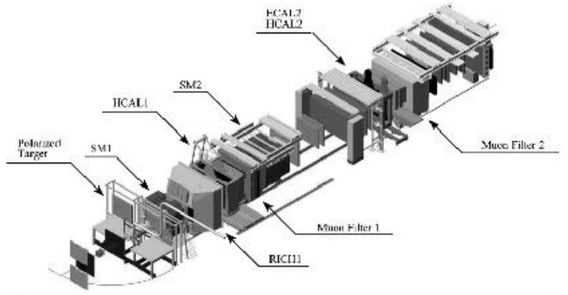
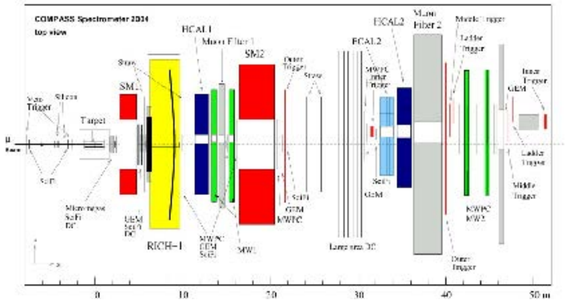
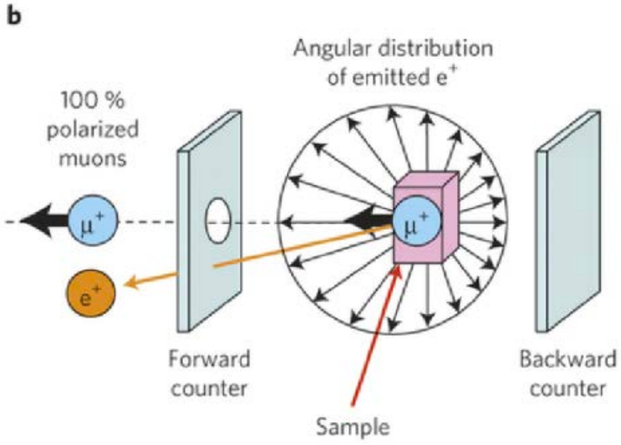




Material Science

μSR: Muon Spin Rotation/Relaxation

PSI & J-PARC



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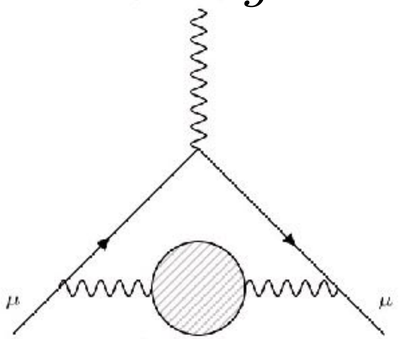

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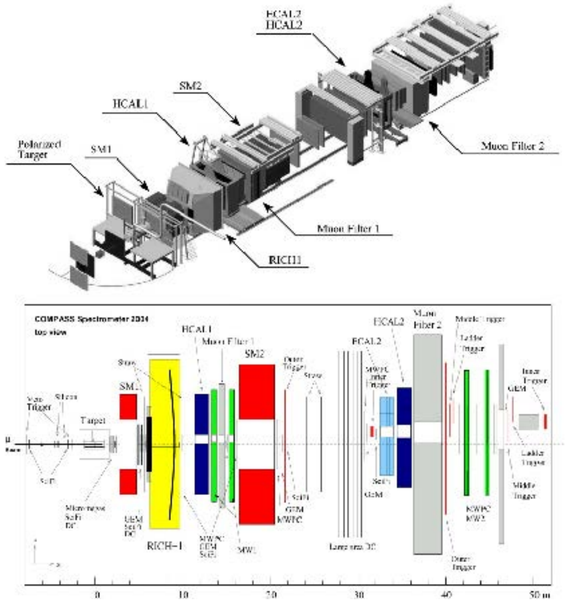

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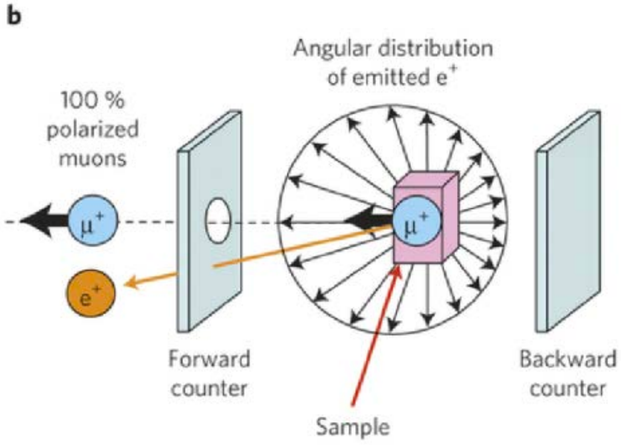
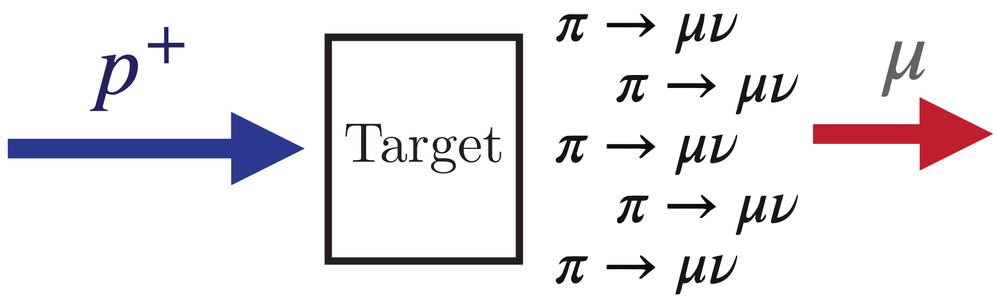


Reminder: all these are also probes of new physics

Not-Accelerated Muon Beams

Where do these muon beams come from?

Capture of tertiary particles in the right momentum range



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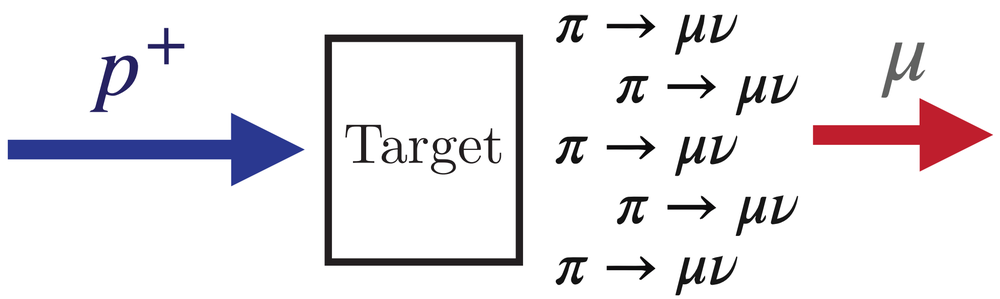


Back-scattered

Magnet-focused

Stopped

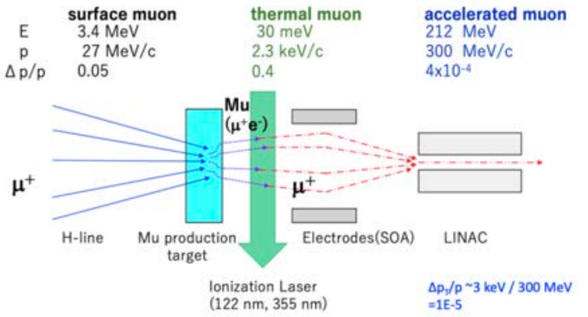
Accelerated?

3 - 400 GeV

Talk by R. Kitano!

Accelerating muons would be a novel technology*

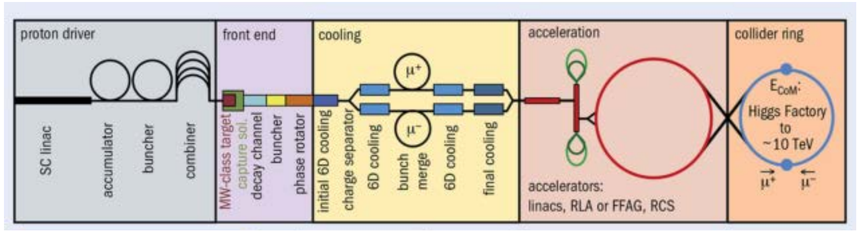
Necessary for collider R&D...and what else?

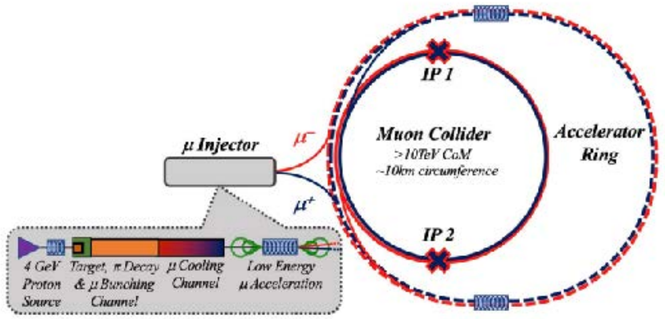


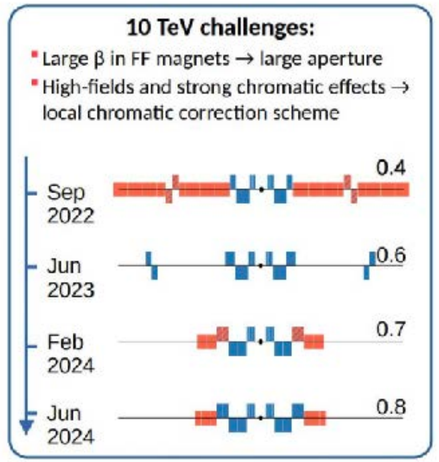
Muon Collider (MuC) & Muon Beam

The time to think about other ways we can use a muon beam is *now*

1. Full scale collider operation is *several decades out*, even if all goes well
2. R&D is highest priority, and *will produce* a muon beam
3. We can have *physics deliverables* well before the collider comes online







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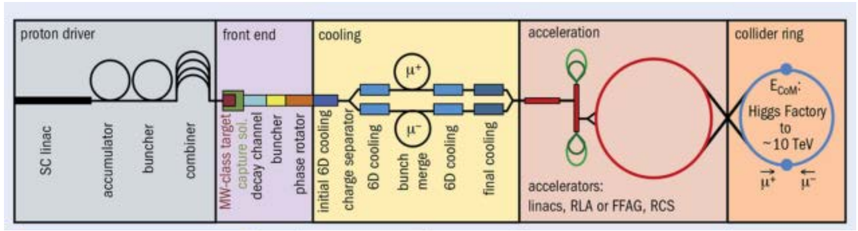
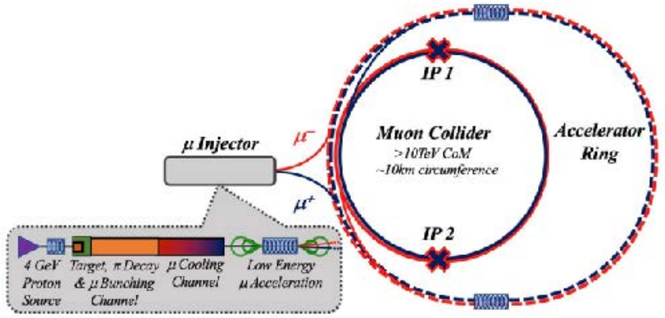
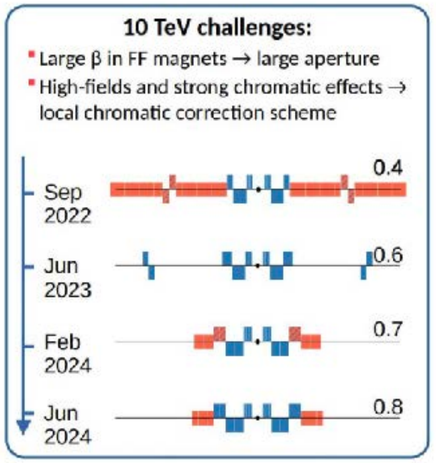






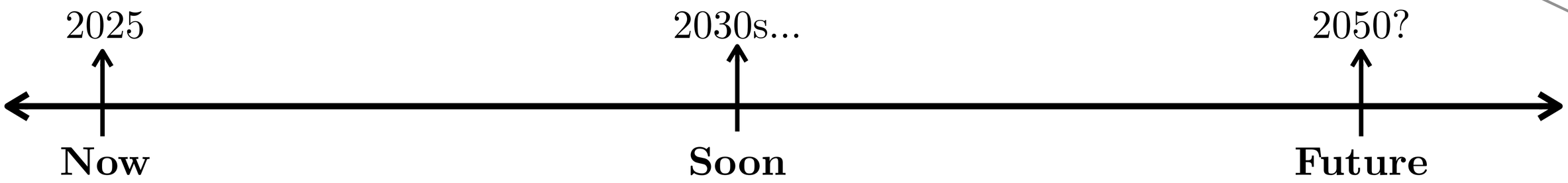
We might *miss opportunities* by not considering auxiliary experiments from the get-go

Muon Beam at MuC Timeline

The time to think about other ways we can use a muon beam is *now*

But when can we expect results?

Karri dies??



Existing beams

R&D products

Full Collider Beam

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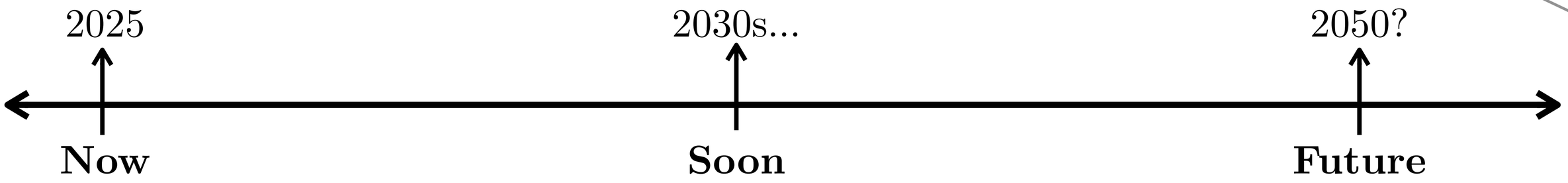

Existing beams

Recast data

R&D products

Neutrino storage ring

Low-energy beam dump

Full Collider Beam

High-energy beam dump

Neutrino long baseline

** Far from an exhaustive list!*

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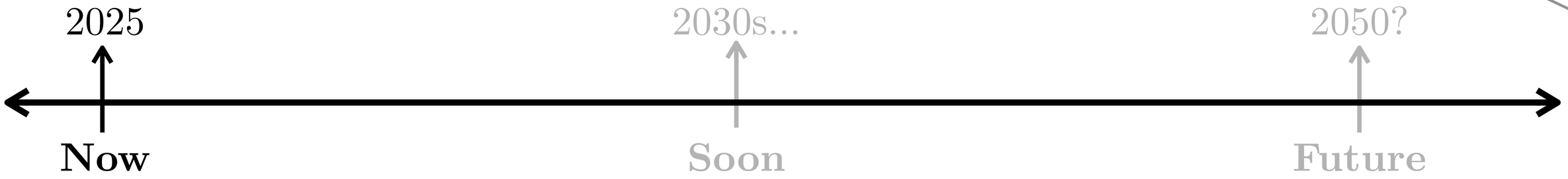

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BSM with Existing Muon Beams

CC, Kahn, Krnjaic, Rocha, Spitz '23

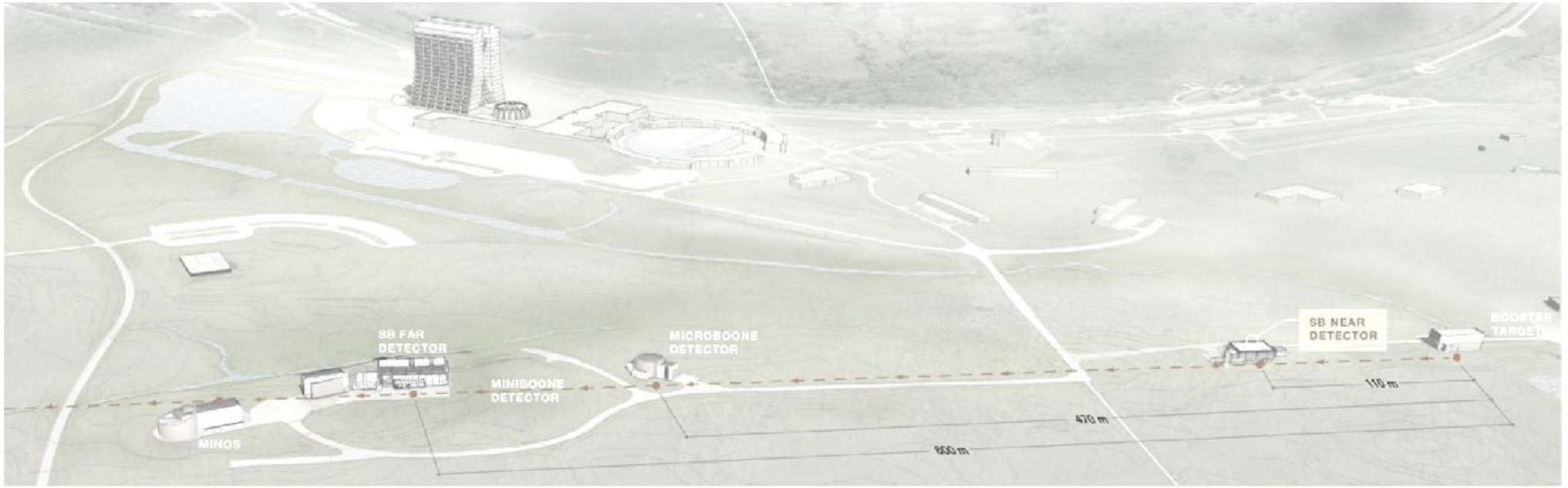
Whenever we have ν sources (from proton-on-target), there are *muons*

Consider Mini/MicroBooNE, ESSνSB, DUNE, etc.

Original purpose: observe neutrino oscillations

Measurement of $\nu_\mu N \to \nu_\mu N \pi_0$, $\pi_0 \to \gamma\gamma$

Possibility for BSM studies?



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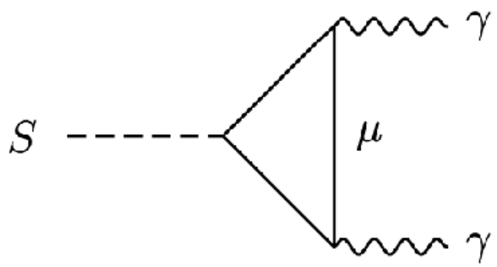
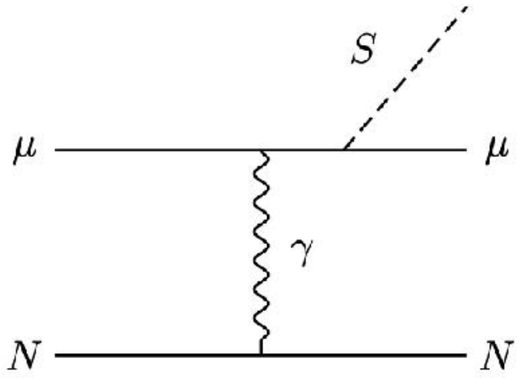
High flux of protons $\longrightarrow$ (less) high flux of muons

No muon acceleration needed to probe rare, light new physics

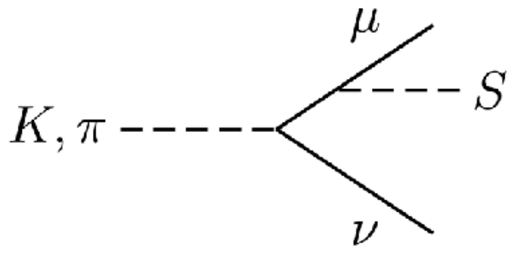
Example: Muon-philic new scalar S

$$\mathscr{L}_{int} \supset y S \mu \bar{\mu}$$





Bremsstrahlung



Meson Decays

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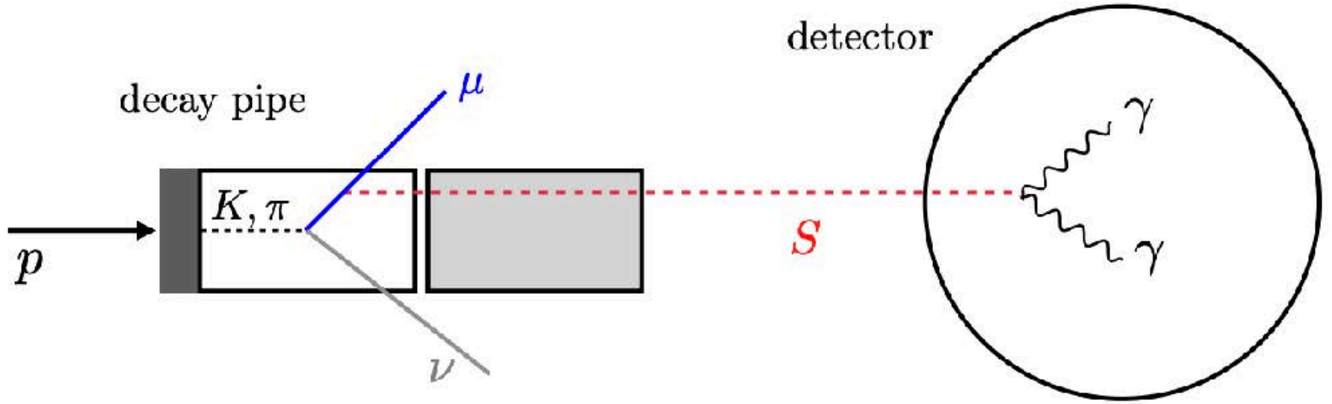

μ production $\rightarrow$ S production

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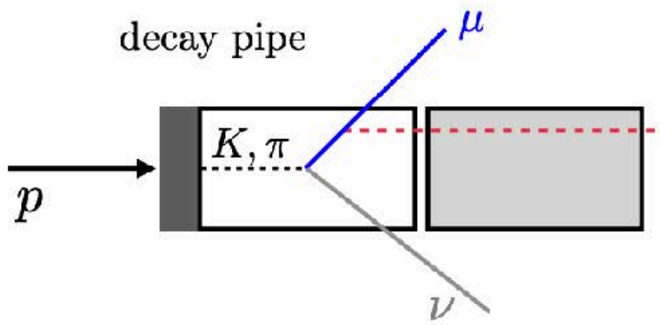

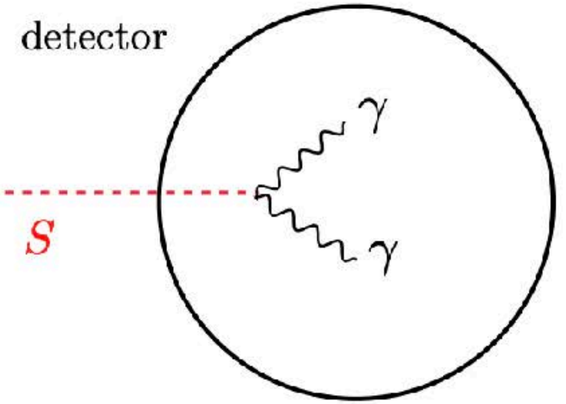

Just Recast!

Beam already exists

Data was already taken

Detector already exists

BSM with Existing Muon Beams

CC, Kahn, Krnjaic, Rocha, Spitz '23*

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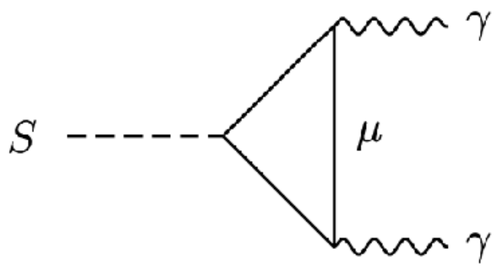

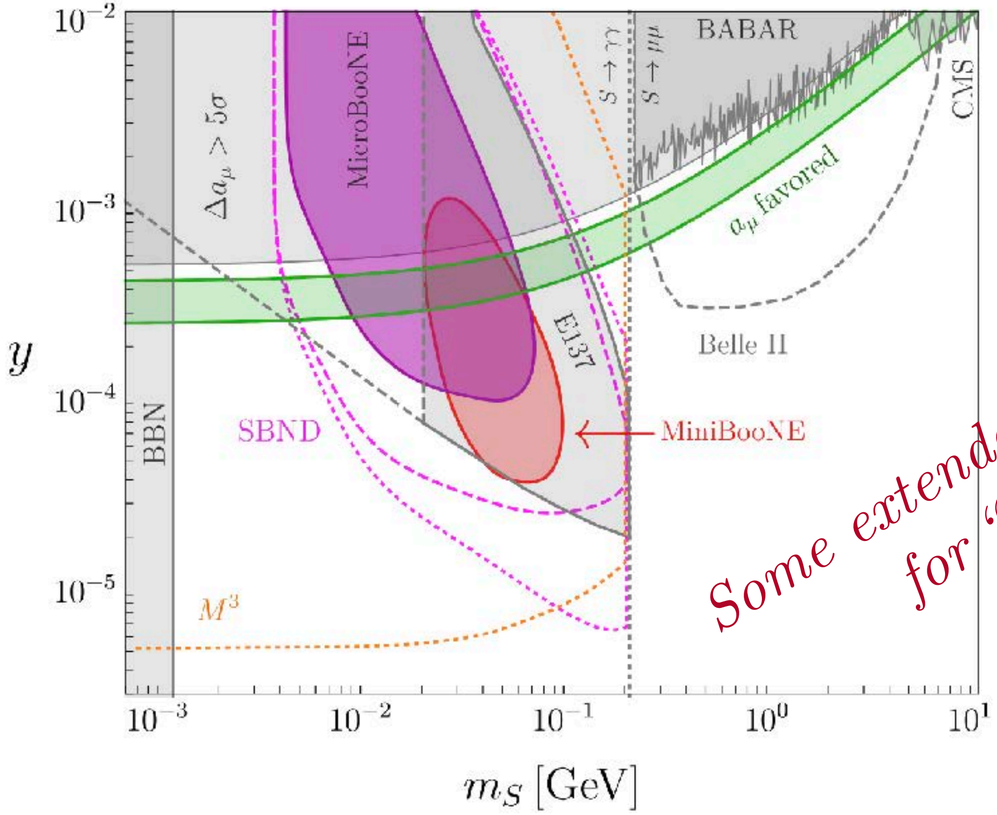

Some extended reach... for "free"

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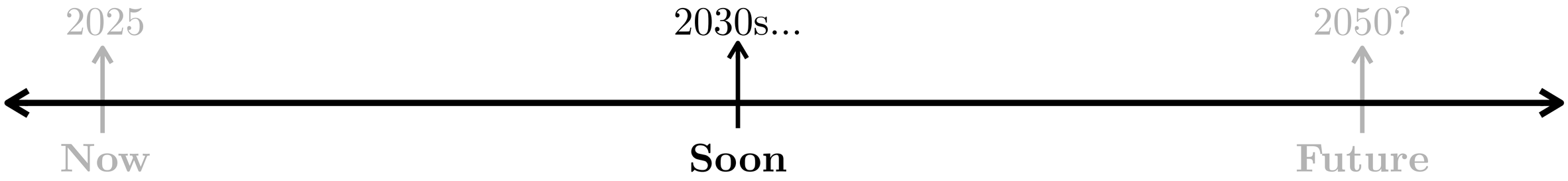

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Low-energy beam dump

Full Collider Beam

High-energy beam dump

Neutrino long baseline

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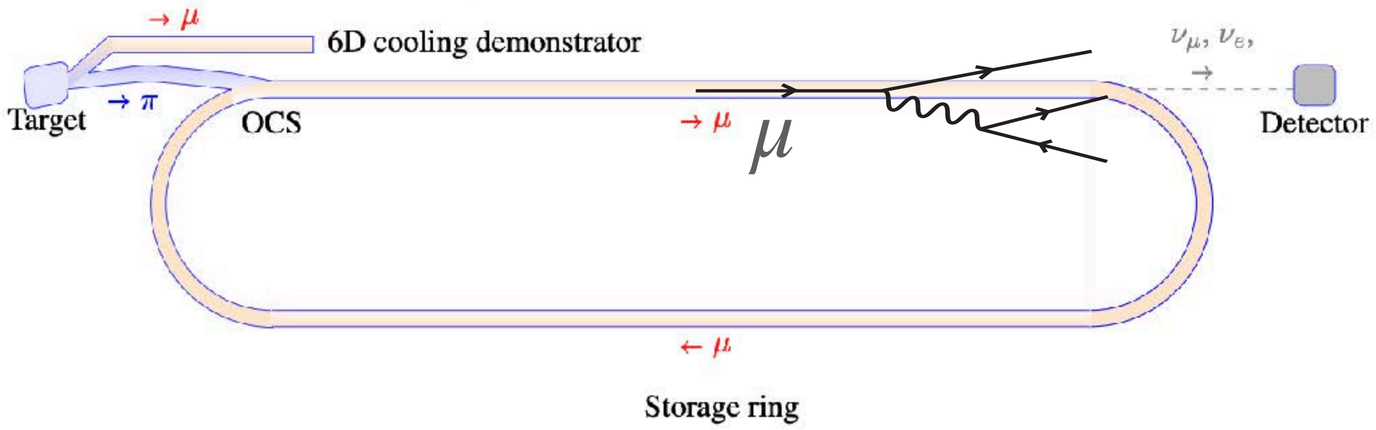
Neutrinos from Muon Beams

NuSTORM '23

Assuming we do modular R&D, there is a muon surplus
(Still no acceleration)

Muons to go to R&D



3 GeV μ circulate and decay

Large ν beam with smallest uncertainty ΔE_ν yet

Enables precision measurements of neutrino cross sections & nuclear effects

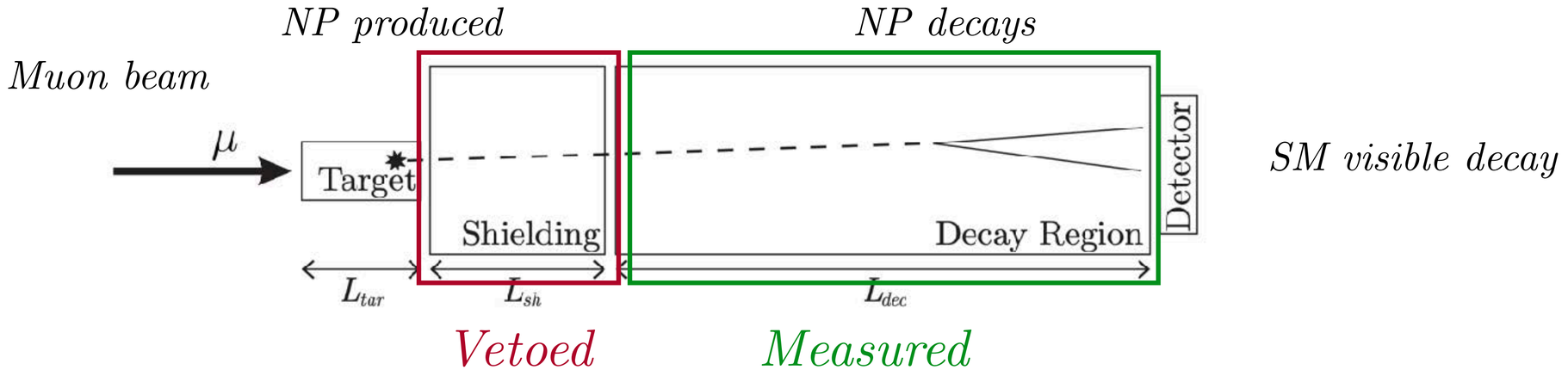
Low-Energy Muon Beam Dump

CC, Homiller, Mishra, Reece '22 · CC, Gambhir '23*

Assume we have *slight* acceleration of muons

What can we do with a muon beam (μ^+ or μ^-) with moderate energy and intensity?

Probe kinda rare, sorta light new physics with *beam dumps*



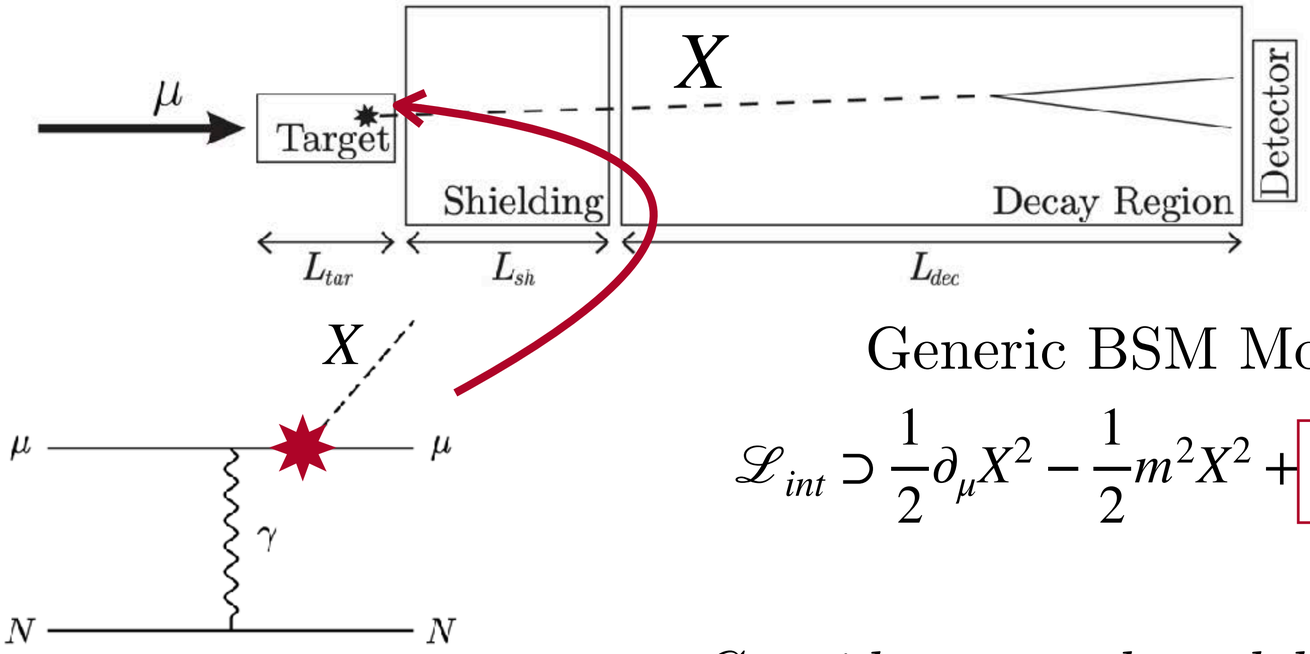
Low-Energy Muon Beam Dump

CC, Homiller, Mishra, Reece '22 · CC, Gambhir '23*

Beam dumps are economical auxiliary experiments with complementary physics reach to the full collider

$$E_{CoM} \sim \sqrt{2E_\mu m_N}$$

...but enhancement on σ (
Avogadro's Number
$\sim 6 \times 10^{23}$



Generic BSM Model:

$$\mathscr{L}_{int} \supset \frac{1}{2}\partial_\mu X^2 - \frac{1}{2}m^2 X^2 + ig_X \mathcal{O}_{\bar{f}fX}$$

Consider several models at various energies...

Low-Energy Muon Beam Dump

CC, Homiller, Mishra, Reece '22 · CC, Gambhir '23*

Goal: Understand reach of beam dump experiments in NP parameter space

Choices to be optimized:
Length of experiment, target size, target material...

Parameters not yet fixed or understood:
Number of μOT, energy E_μ...

So, let's sweep through some theory & experiment options

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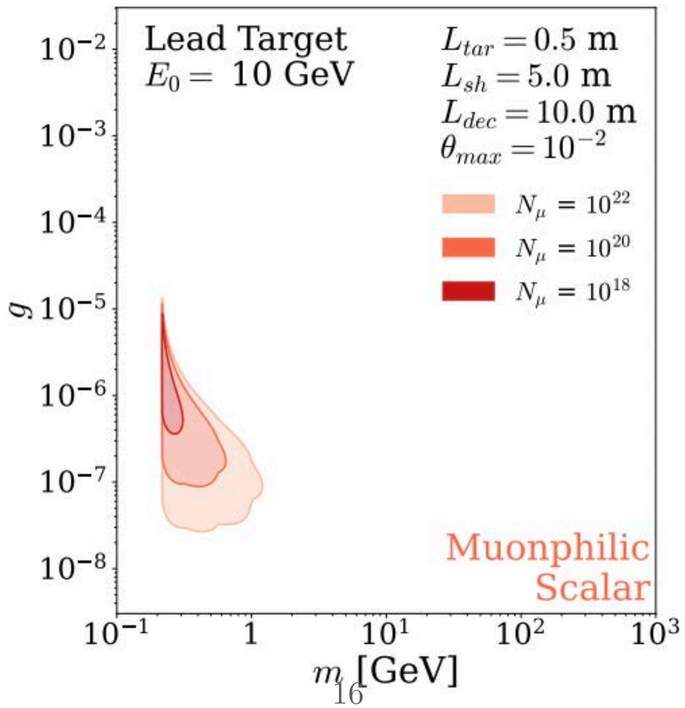
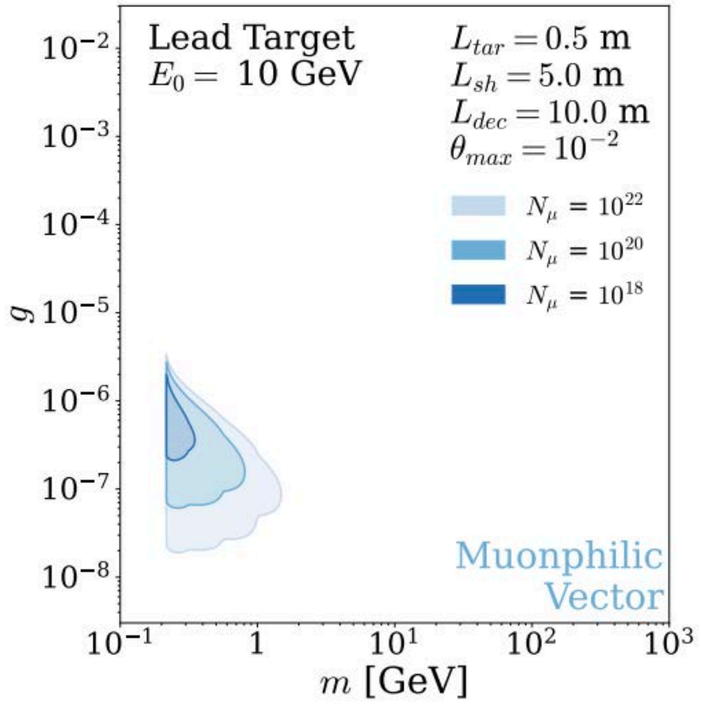
Example:
10 GeV Beams
Muon-philic NP





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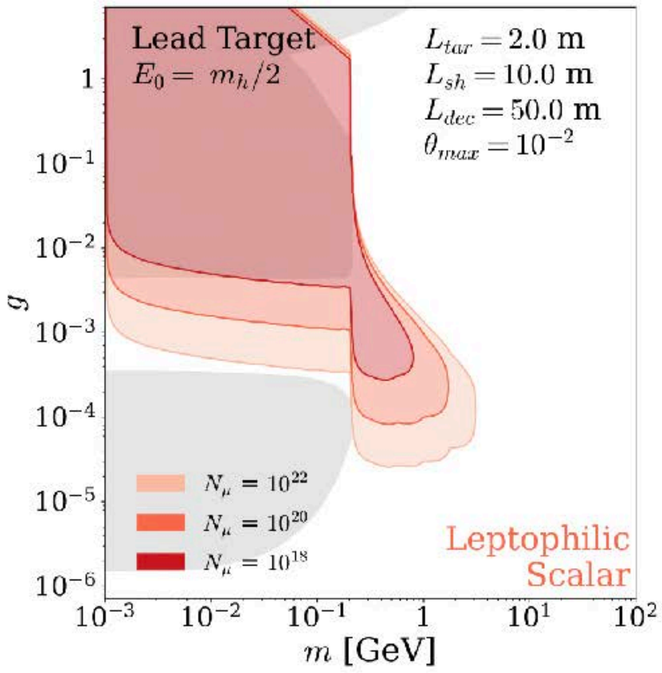
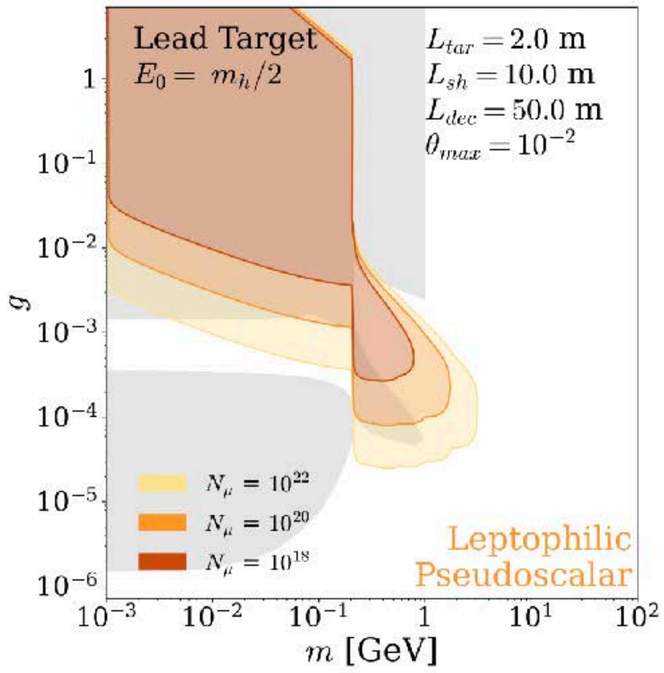
Number of μOT, energy E_μ...

Example:
63 GeV Beams
Leptophilic NP





Low-Energy Muon Beam Dump

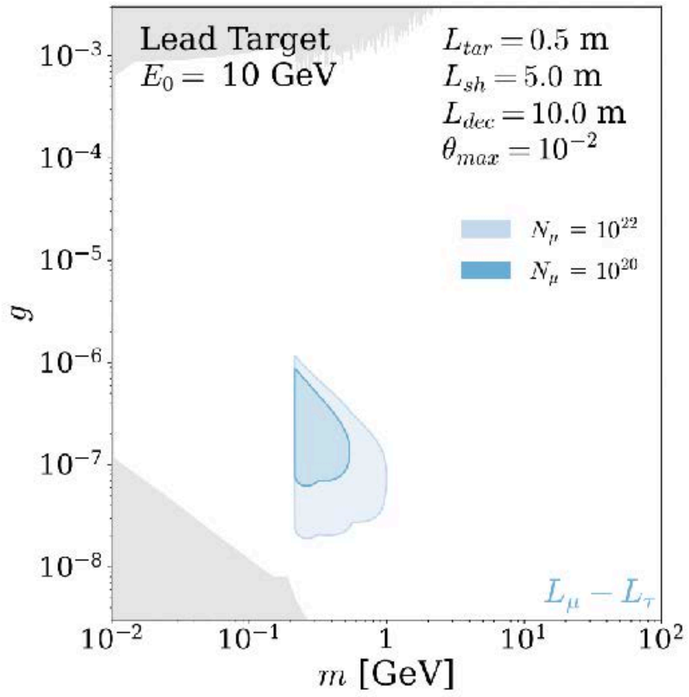
CC, Homiller, Mishra, Reece '22 · CC, Gambhir '23*

Goal: Understand reach of beam dump experiments in NP parameter space

Choices to be optimized:
Length of experiment, target size, target material...

Parameters not yet fixed or understood:
Number of μOT, energy E_μ...

Example:
10 GeV Beams
$L_\mu - L_\tau$ model



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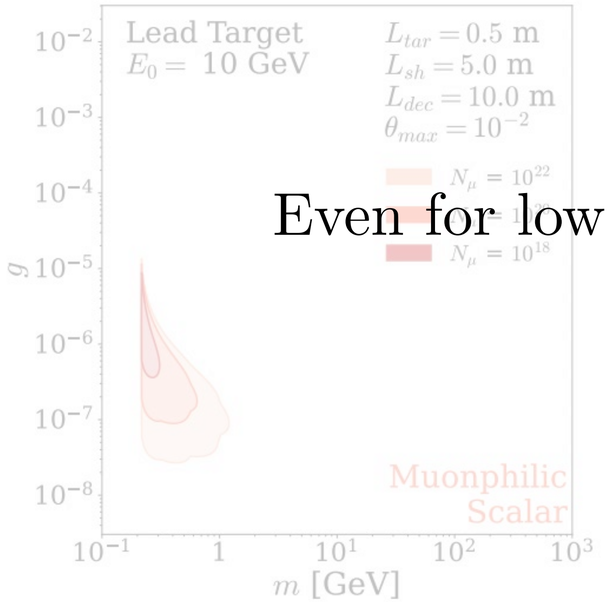
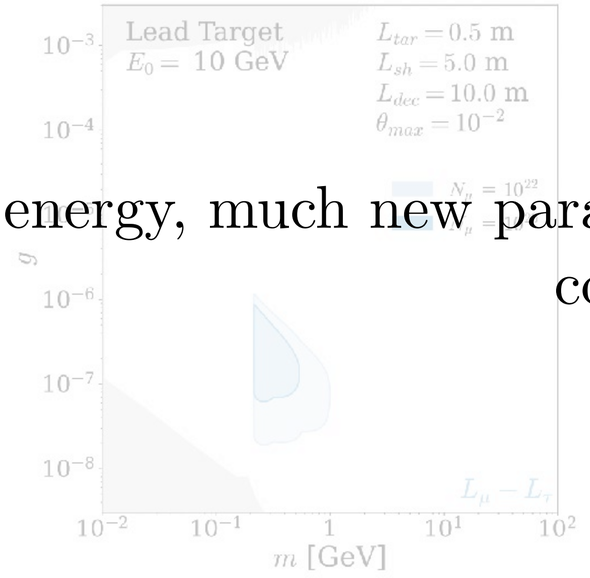
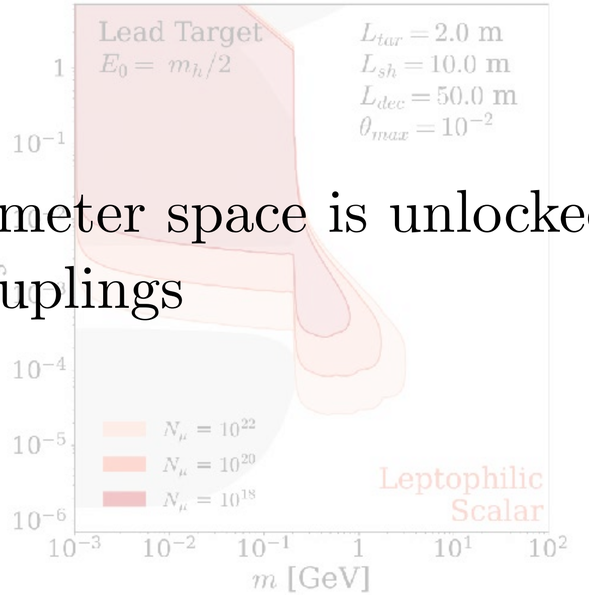
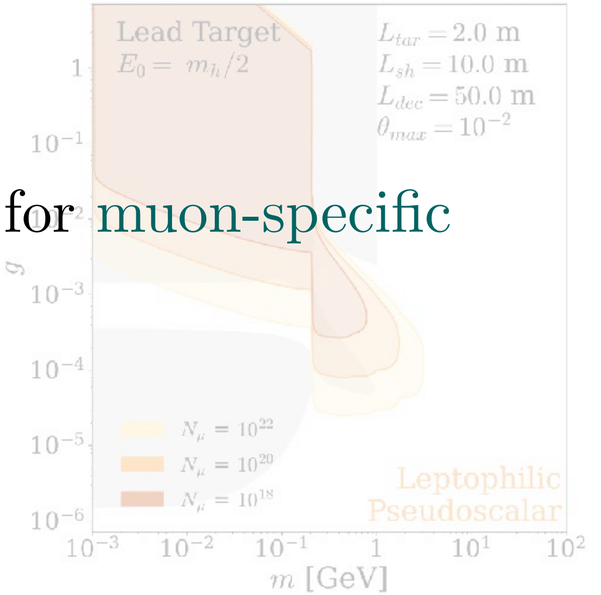






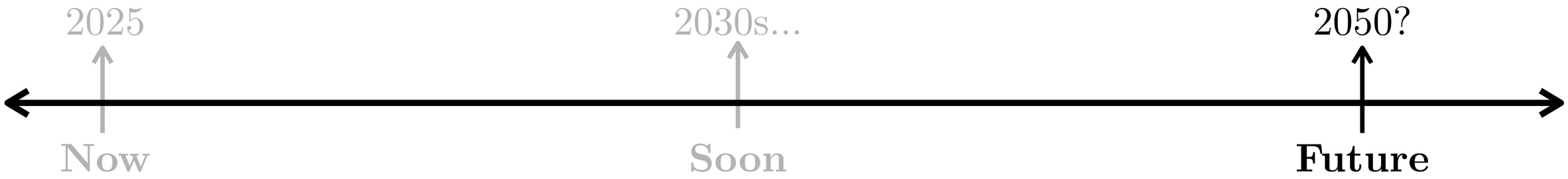


Even for low energy, much new parameter space is unlocked for muon-specific couplings

Muon Beam at MuC Timeline

The time to think about other ways we can use a muon beam is *now*

But when can we expect results?



Existing beams

Recast data

R&D products

Neutrino storage ring

Low-energy beam dump

Full Collider Beam

High-energy beam dump

Neutrino long baseline

** Far from an exhaustive list!*

High-Energy Muon Beam Dump

CC, Homiller, Mishra, Reece '22 · CC, Gambhir '23*

Consider Full MuC energies (3 TeV, 10 TeV stages)

$\mathscr{L} \sim n_\mu^2$ — number density of muons per bunch

Could be advantageous to *dump* beam and inject more frequently

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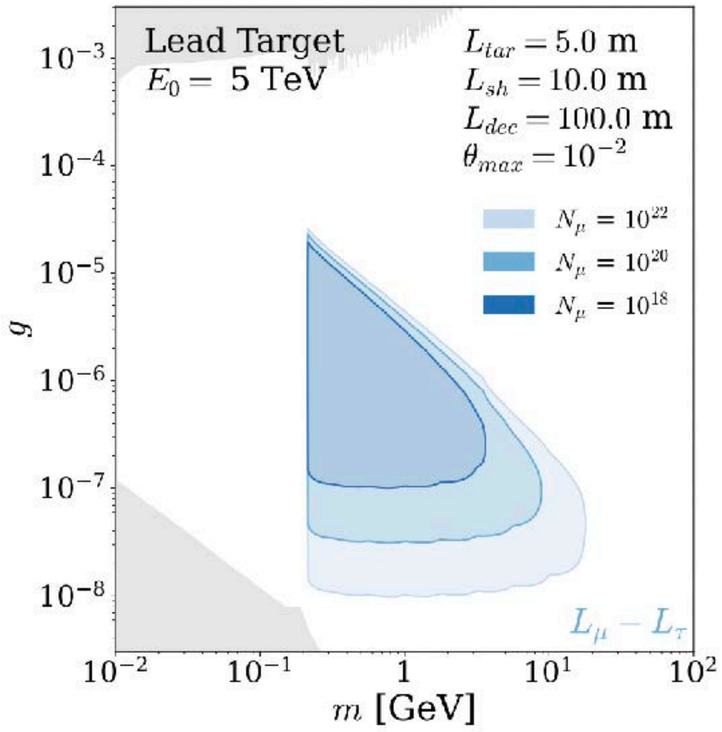

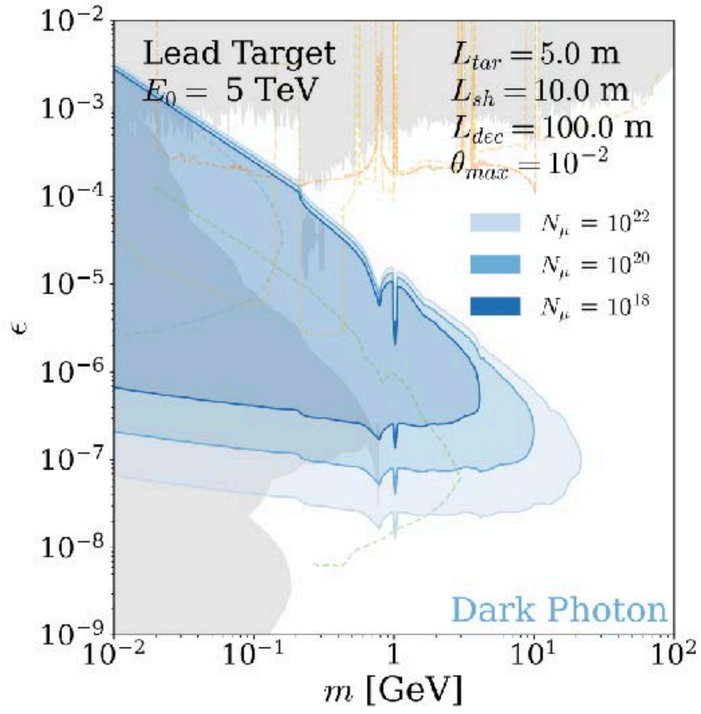

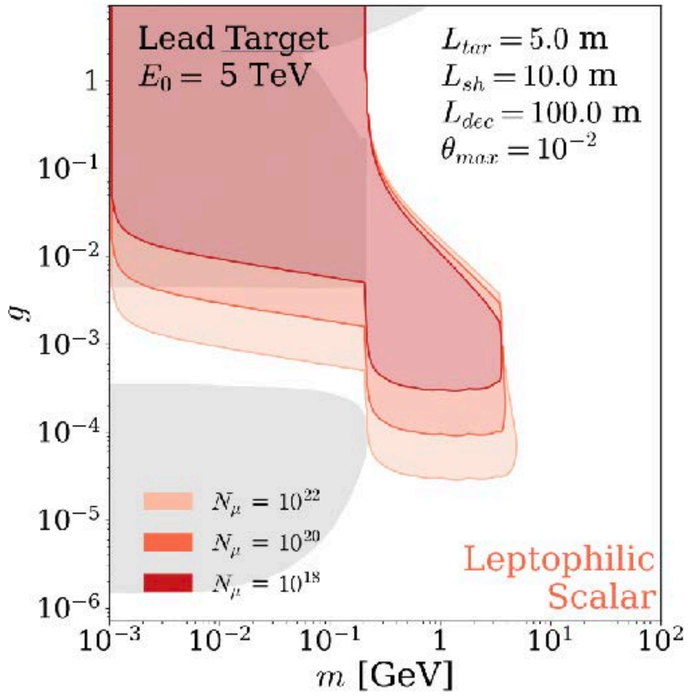

High-Energy Muon Beam Dump

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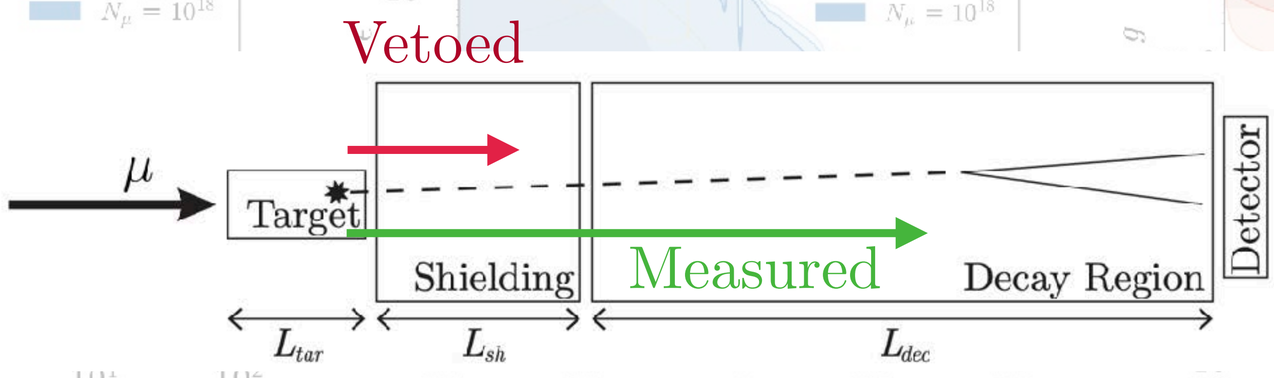
$\mathscr{L} \sim n_\mu^2$ — number density of muons per bunch

Could be advantageous to *dump* beam and inject more frequently

High energy can push to lower couplings because the particle lifetime is extended

$$\tau \sim l_{\rm exp} \sim \gamma\tau_0$$

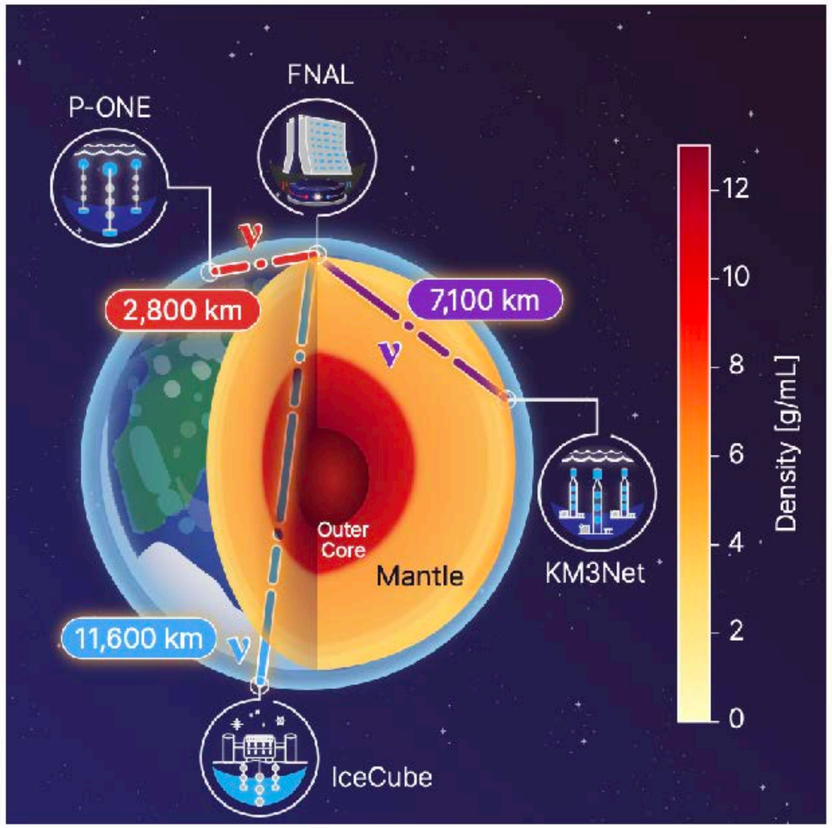


High-Energy Neutrino Beams

Putnam, Kamp '25 (to appear)

Consider Full MuC energies (3 TeV, 10 TeV stages)

Orient straight sections to point towards a neutrino detector



$$\text{Angular width of beam } \sim \frac{1}{\gamma}, \mathcal{O}(100m)$$

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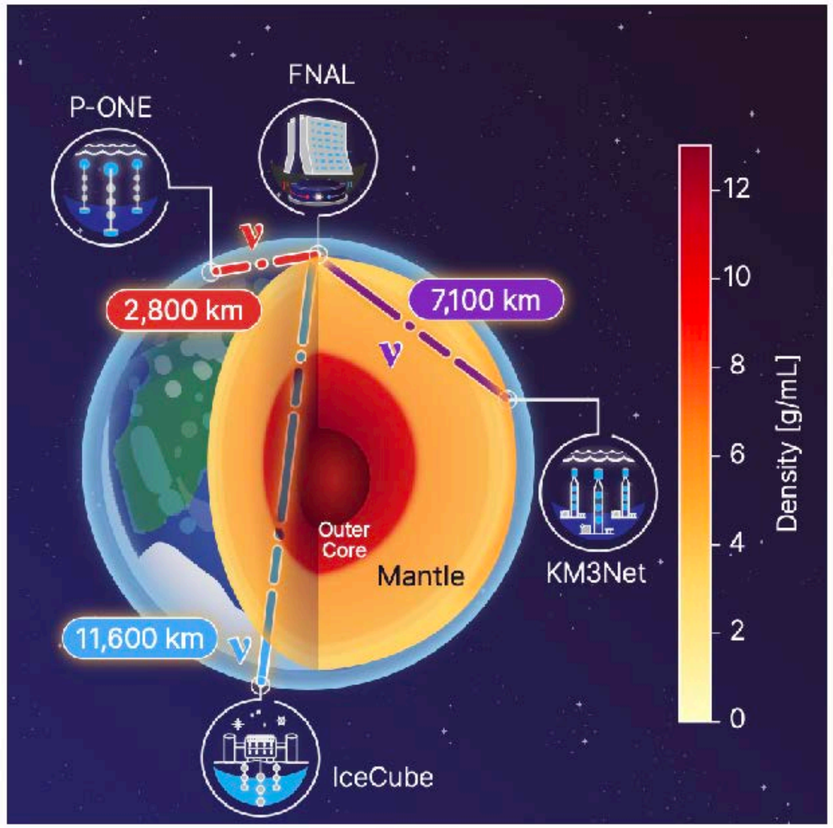
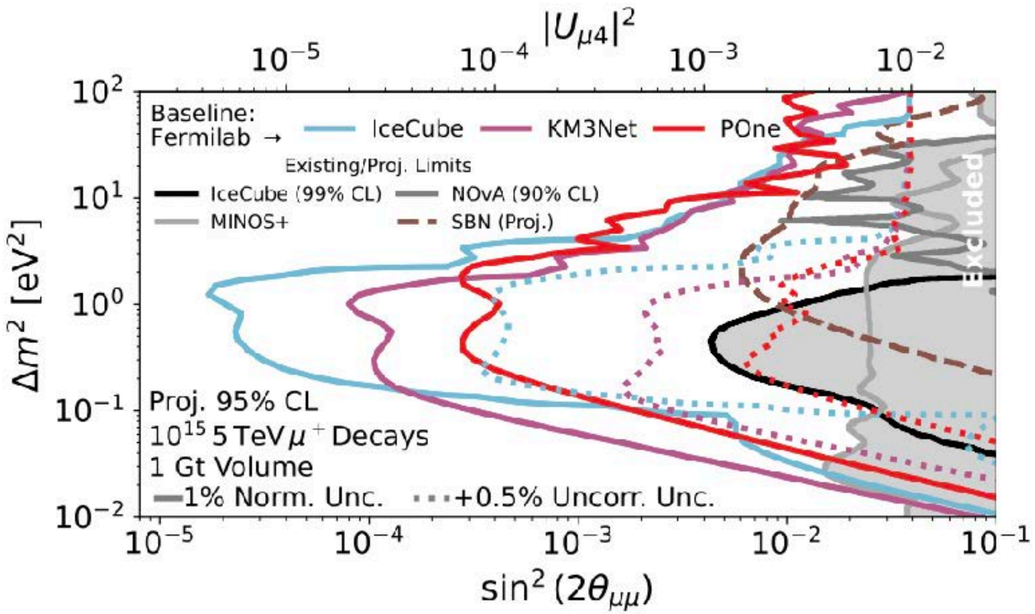


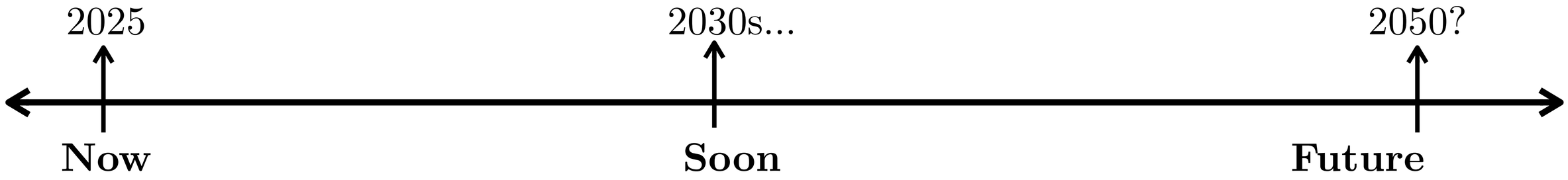
$$\text{Angular width of beam } \sim \frac{1}{\gamma}, \mathcal{O}(100m)$$

Used to study BSM ν oscillations

Ex: sterile neutrinos



Outlook for Muon Beams



Existing beams

R&D products

Full Collider Beam

There are two fundamentally novel features of muon beams: 2nd generation particles, potentially high energy

Progress in muon beam technology comes in stages which we can utilize as available

Now is the time to include auxiliary concepts in full design

Continue to think about synergies in ν measurements, precision measurements, flavor violation, and more!