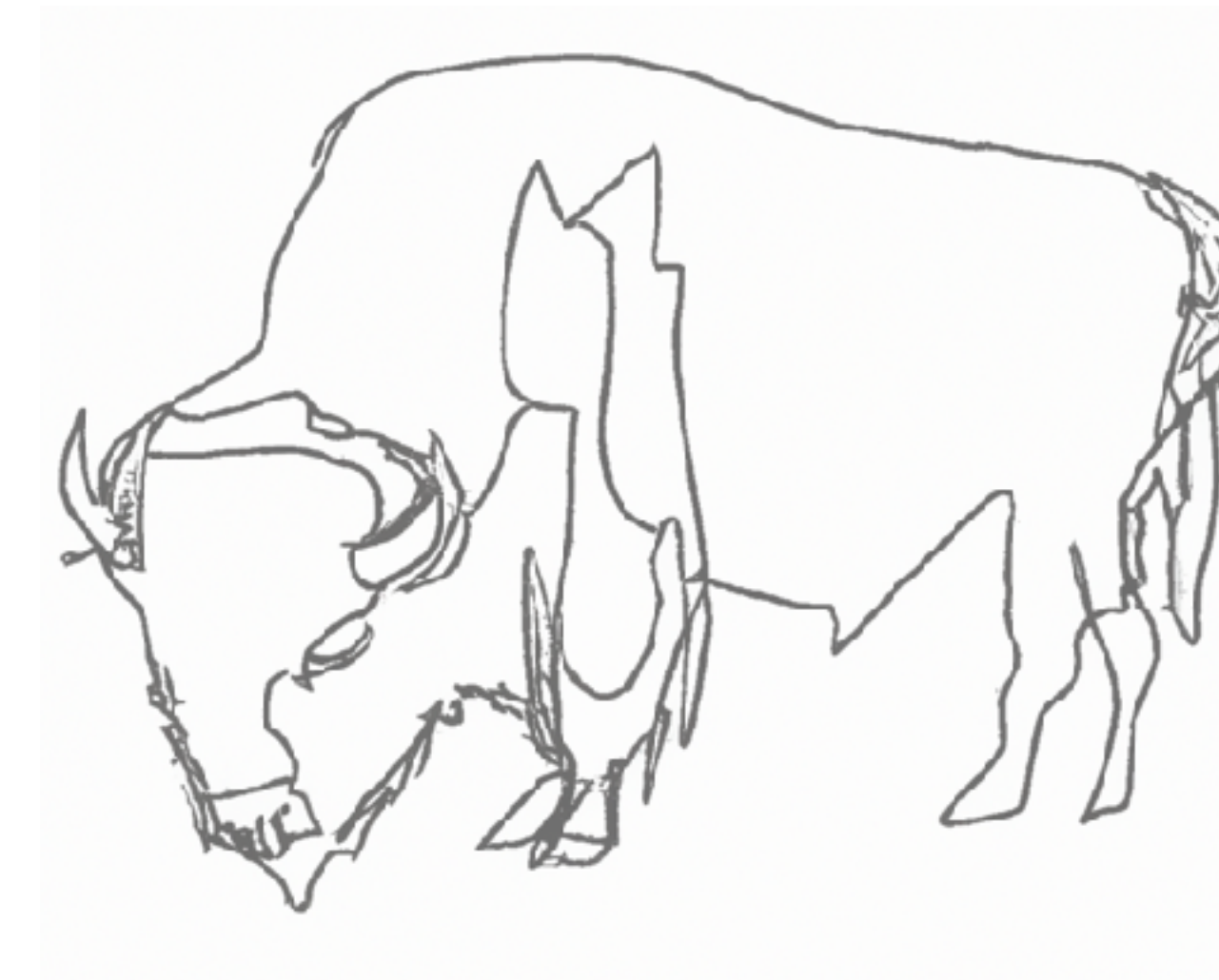


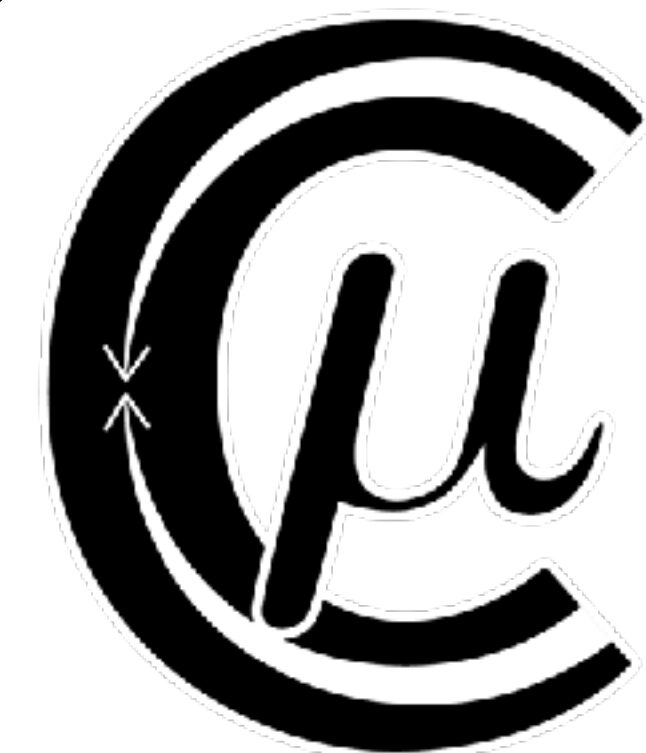
↔ ←

# Physics on the Way to 10 TeV: Auxiliary Experiments to MuC

**IMCC Annual Meeting  
June 20, 2023**



**Cari Cesarotti, MIT CTP**

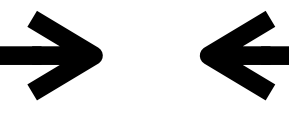


CC, S. Homiller, R. Mishra, M. Reece, PRL  
CC, R. Gambhir, S. Alipour-Fard, 2306.XXXX

*Illustrations by AI*



# Future Collider Community Goals

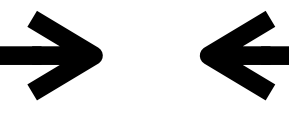


**What do we need out of a future (muon) collider?**



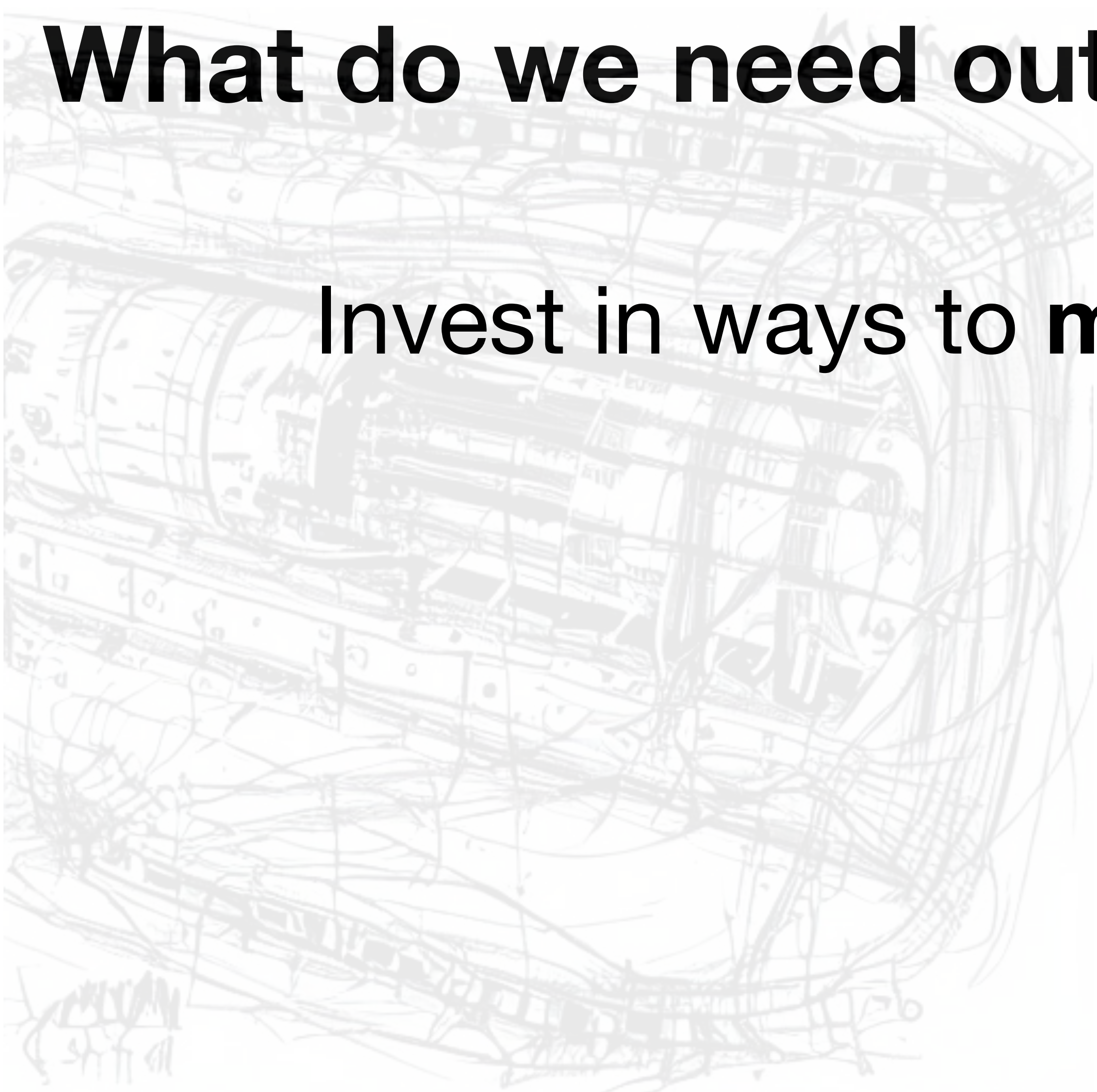


# Future Collider Community Goals



**What do we need out of a future (muon) collider?**

Invest in ways to **maximize** physics potential:





# Future Collider Community Goals

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**What do we need out of a future (muon) collider?**

Invest in ways to **maximize** physics potential:

- Search for robust physics
- Find physics applications of R&D



# Future Collider Community Goals



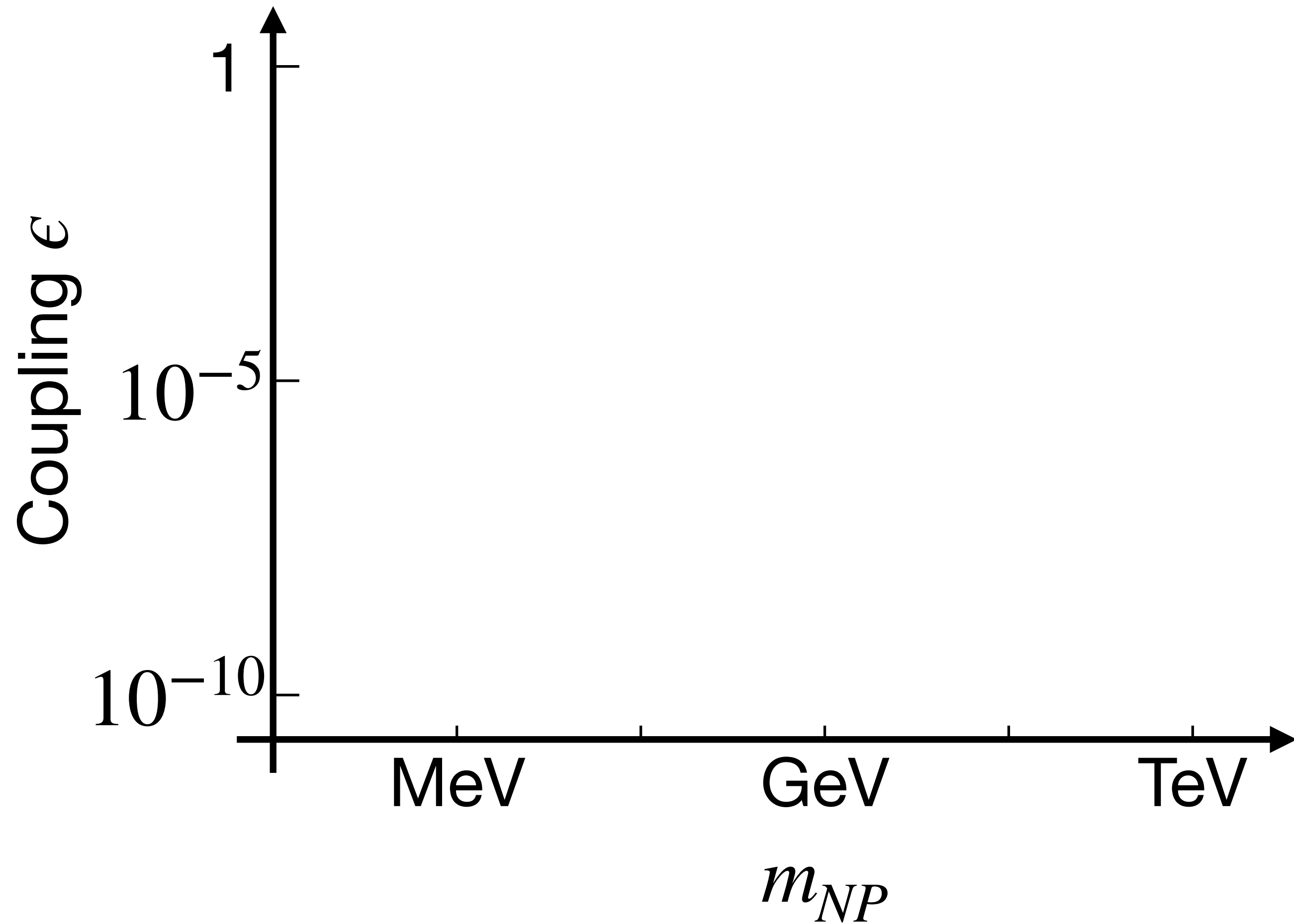
**What do we need out of a future (muon) collider?**

Invest in ways to **maximize** physics potential:

- Search for robust physics
- Find physics applications of R&D

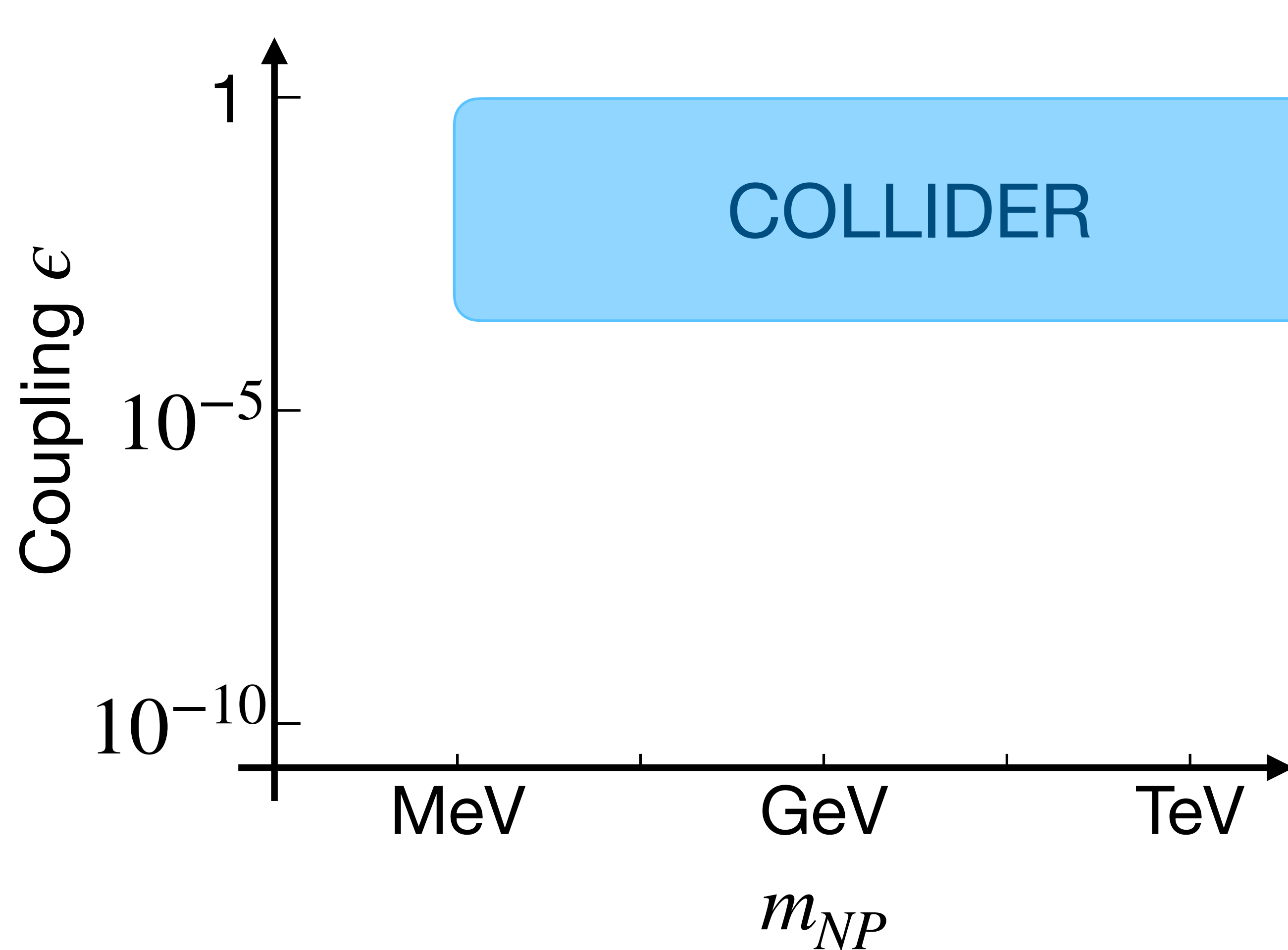
*What can we do on the way to the full  $\sqrt{s}$ ?*

# Generic New Physics Reach



Start Date:

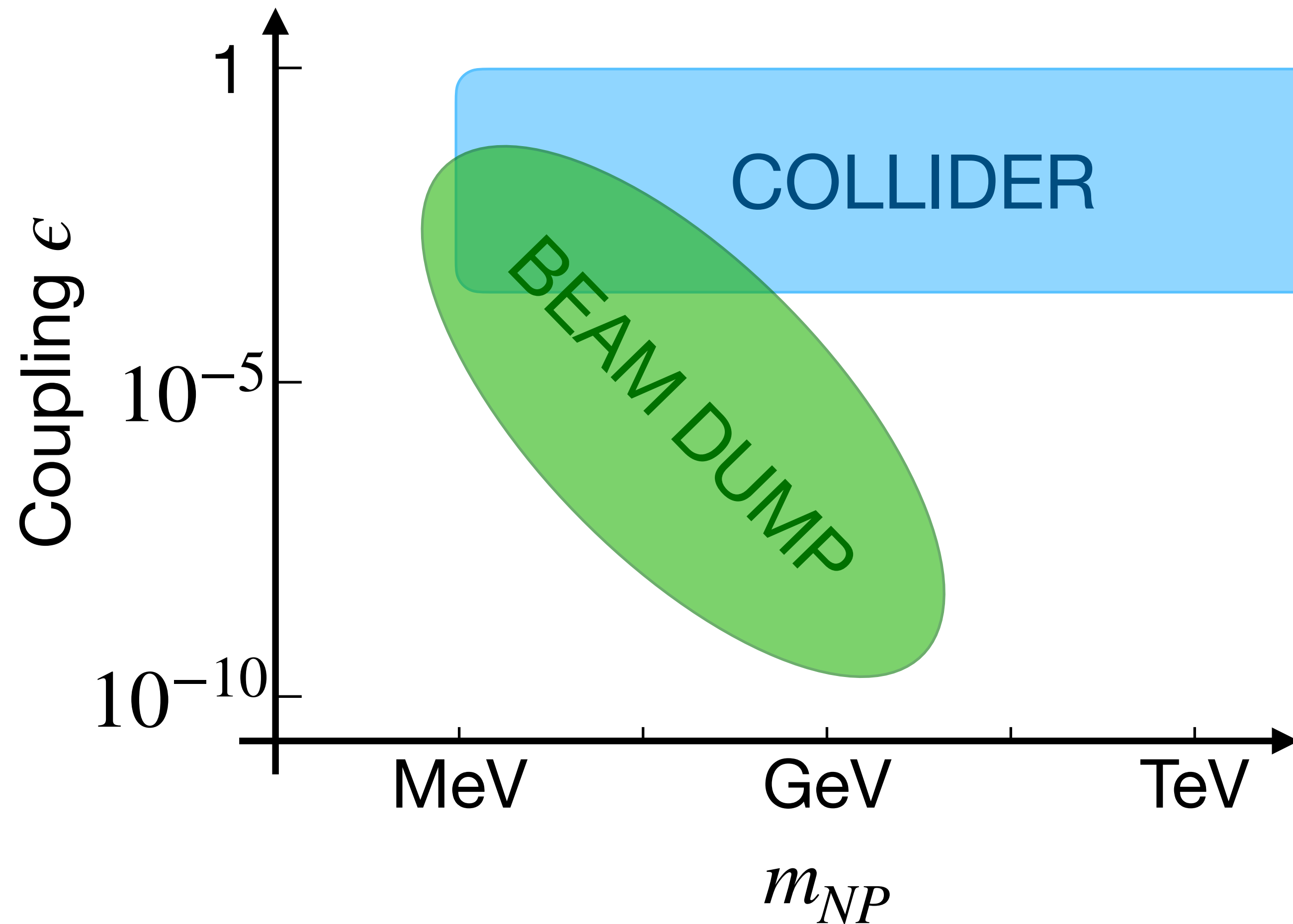
# Generic New Physics Reach



$$m_{NP} \sim \sqrt{s} = 2E$$

Start Date:  
**2045-55**

# Generic New Physics Reach



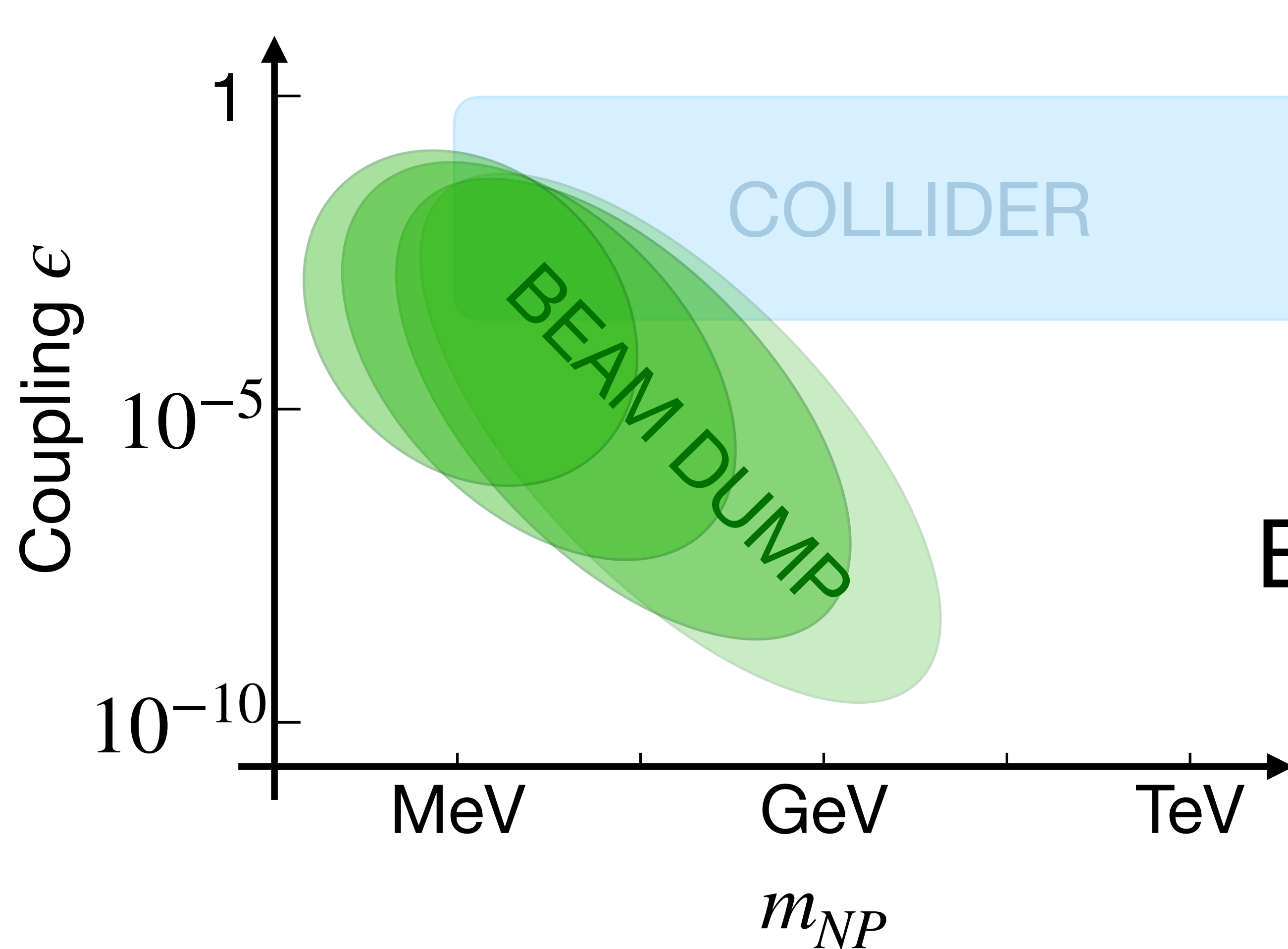
$$m_{NP} \sim \sqrt{s} = 2E$$

$$m_{NP} \sim \sqrt{EM}$$

Start Date:  
**2045-55**



# Generic New Physics Reach



$$m_{NP} \sim \sqrt{s} = 2E$$

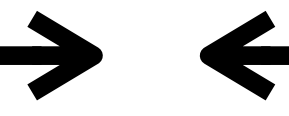
$$m_{NP} \sim \sqrt{EM}$$

Beam from Demonstrators

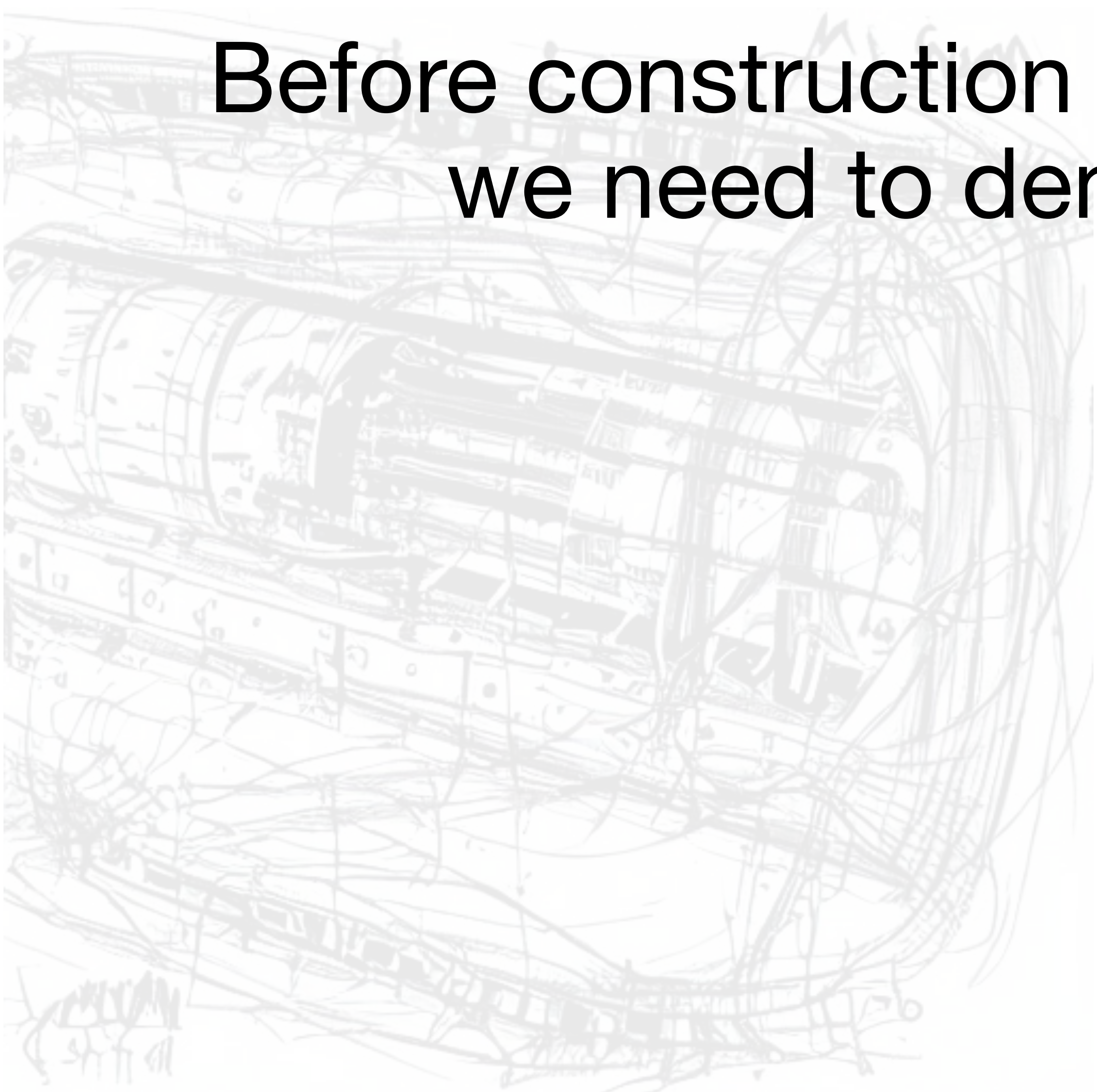
Start Date:

**2030s?**

# Demonstrator Facilities & Beam dump



Before construction (or approval) of a full collider  
we need to demonstrate technologies





# Demonstrator Facilities & Beam dump



Before construction (or approval) of a full collider we need to demonstrate technologies

**Muon Production**

< GeV

**Cooled Muons**

100 MeV

**Acc. Muons**

$\mathcal{O}(10)$  GeV?

**Higgs Factory?**

63 GeV

**EW Probe?**

3 TeV

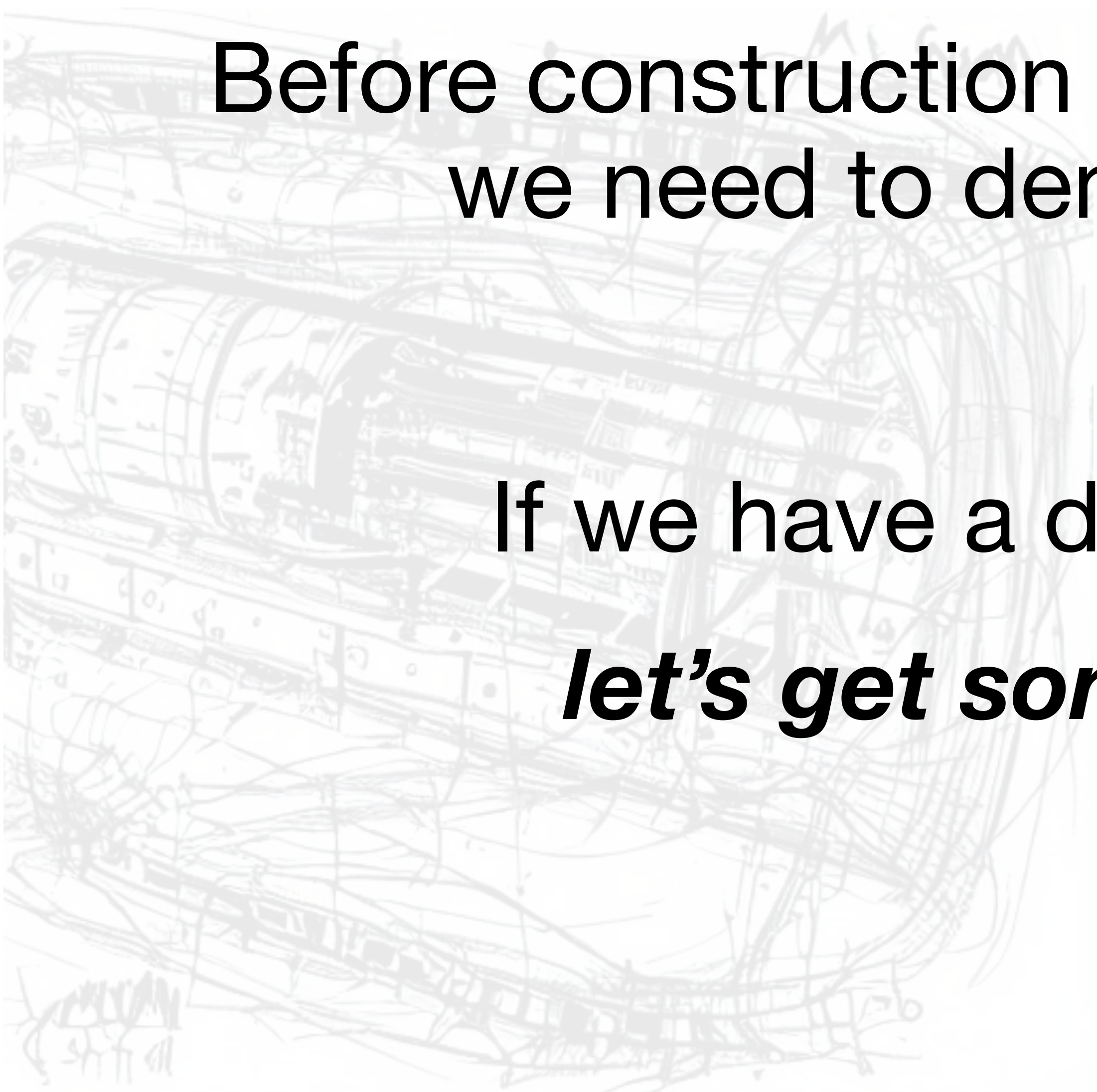


# Demonstrator Facilities & Beam dump



Before construction (or approval) of a full collider  
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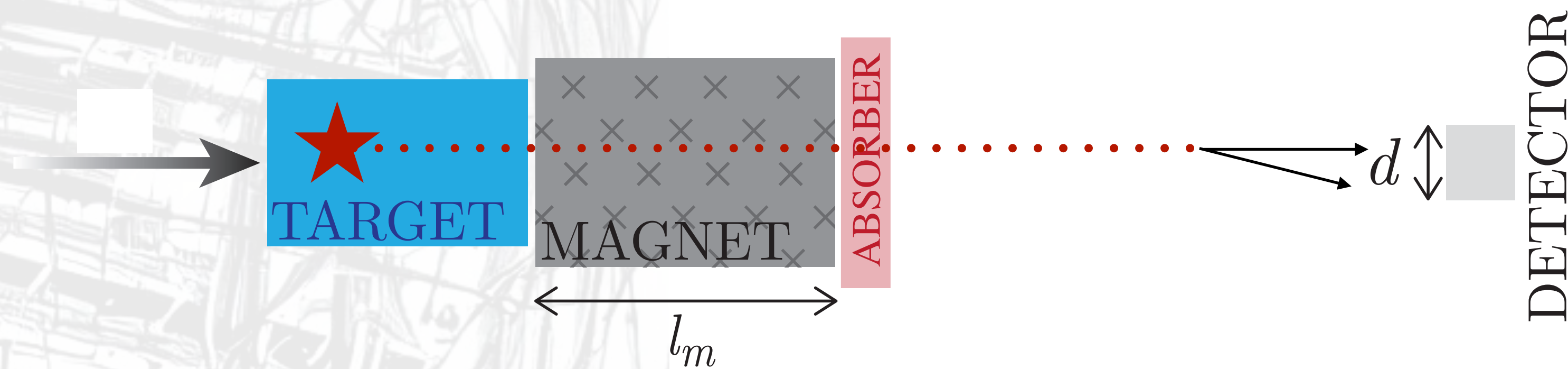
If we have a dedicated muon beam,  
***let's get some physics out of it***





# Demonstrator Facilities & Beam dump

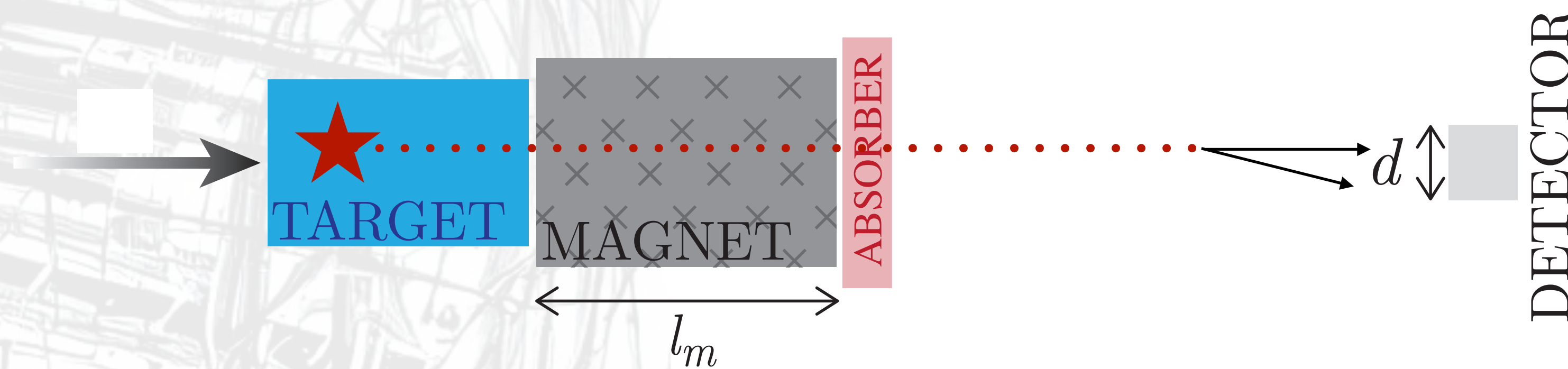
Beam dumps are **low-cost** auxiliary experiments with **complementary** reach to main collider





# Demonstrator Facilities & Beam dump

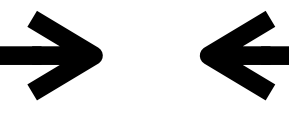
Beam dumps are **low-cost** auxiliary experiments with **complementary** reach to main collider



Synergistic mode to reach **extremely weakly** coupled physics at **moderate** energies



# Demonstrator Facilities Siting Options

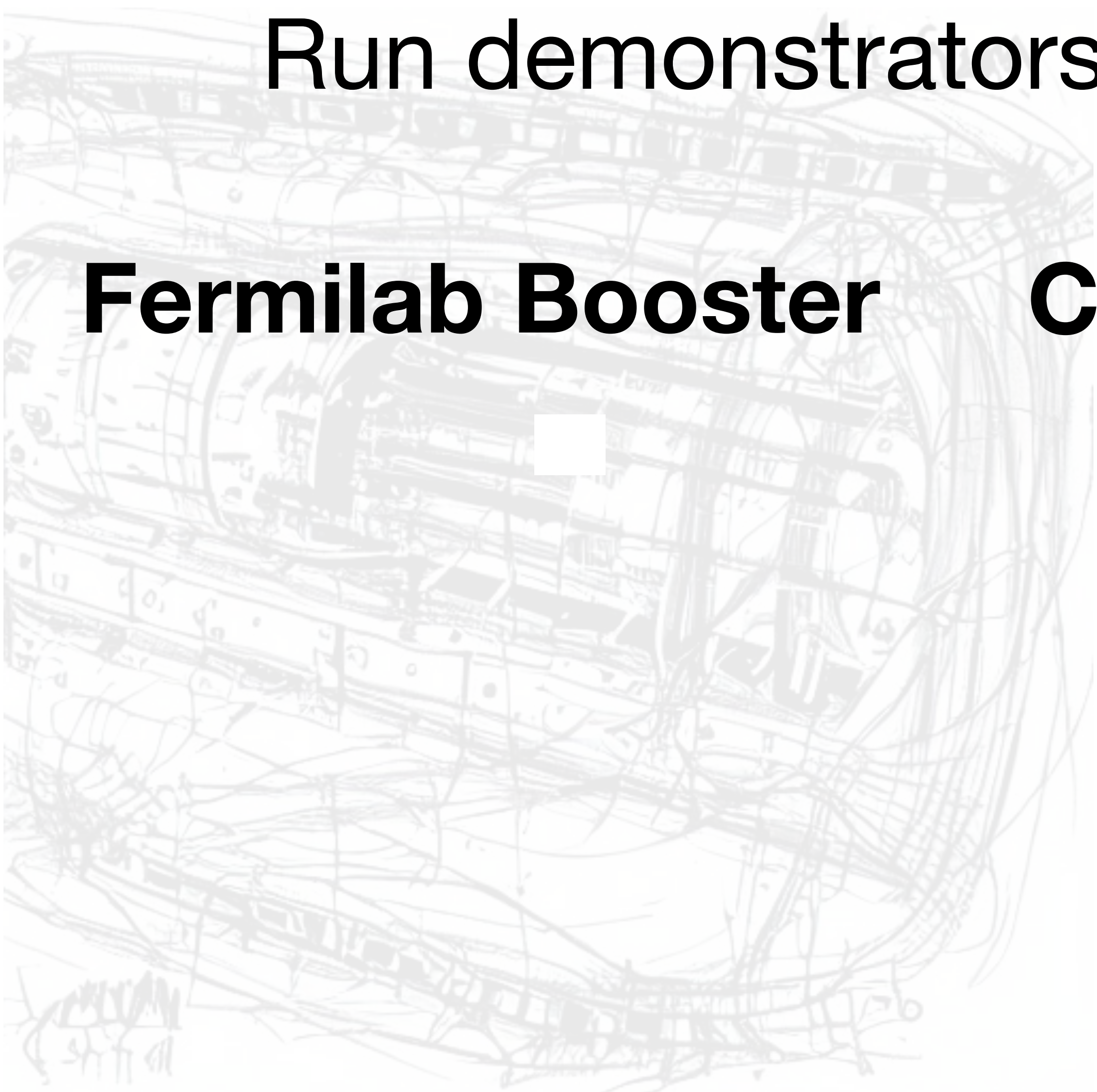


Run demonstrators with existing infrastructure

**Fermilab Booster**

**CERN TT10**

**ESS/SB**





# Demonstrator Facilities Siting Options

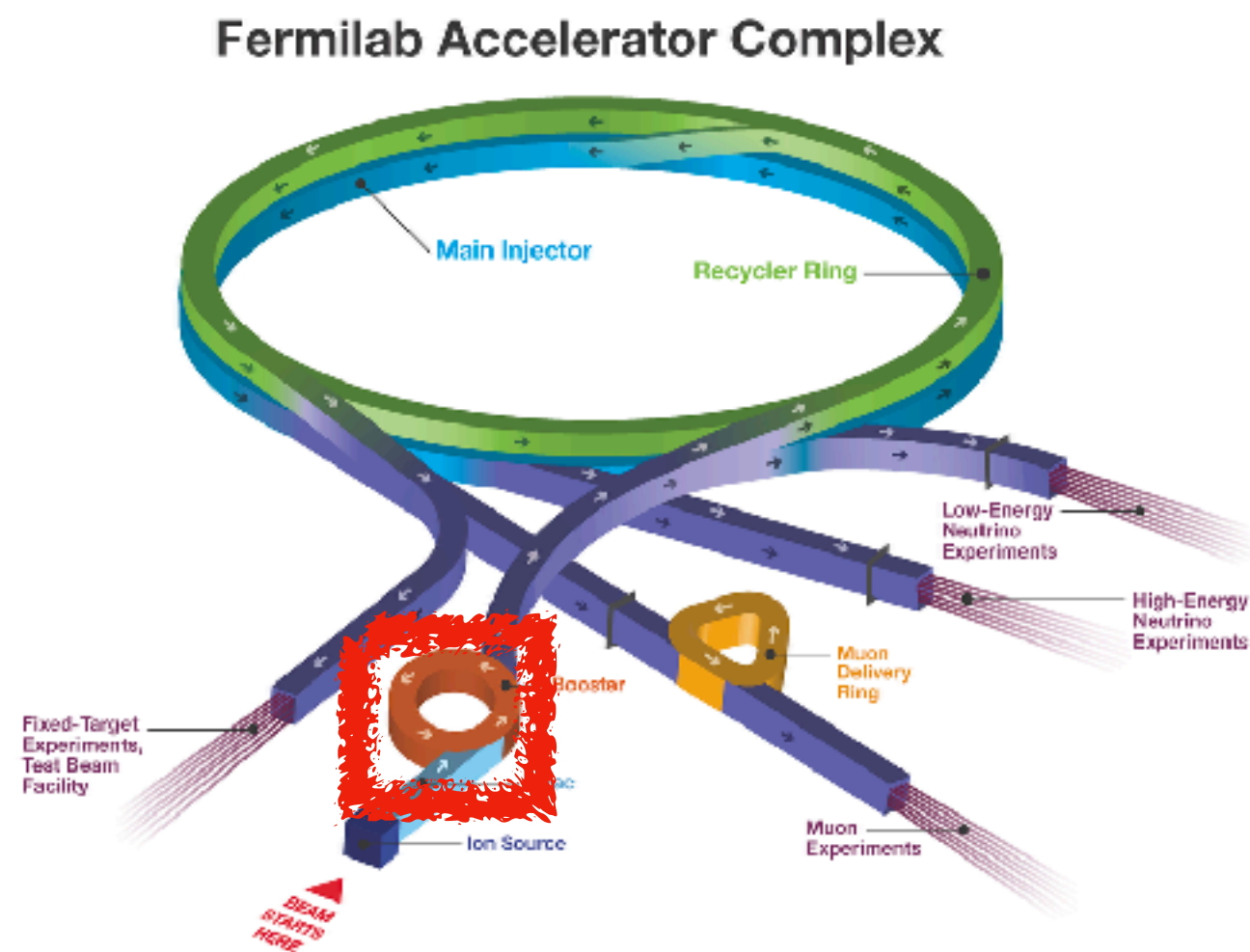
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**Fermilab Booster**

**CERN TT10**

**ESS<sub>ν</sub>SB**

ACE Upgrade





# Demonstrator Facilities Siting Options

Run demonstrators with existing infrastructure

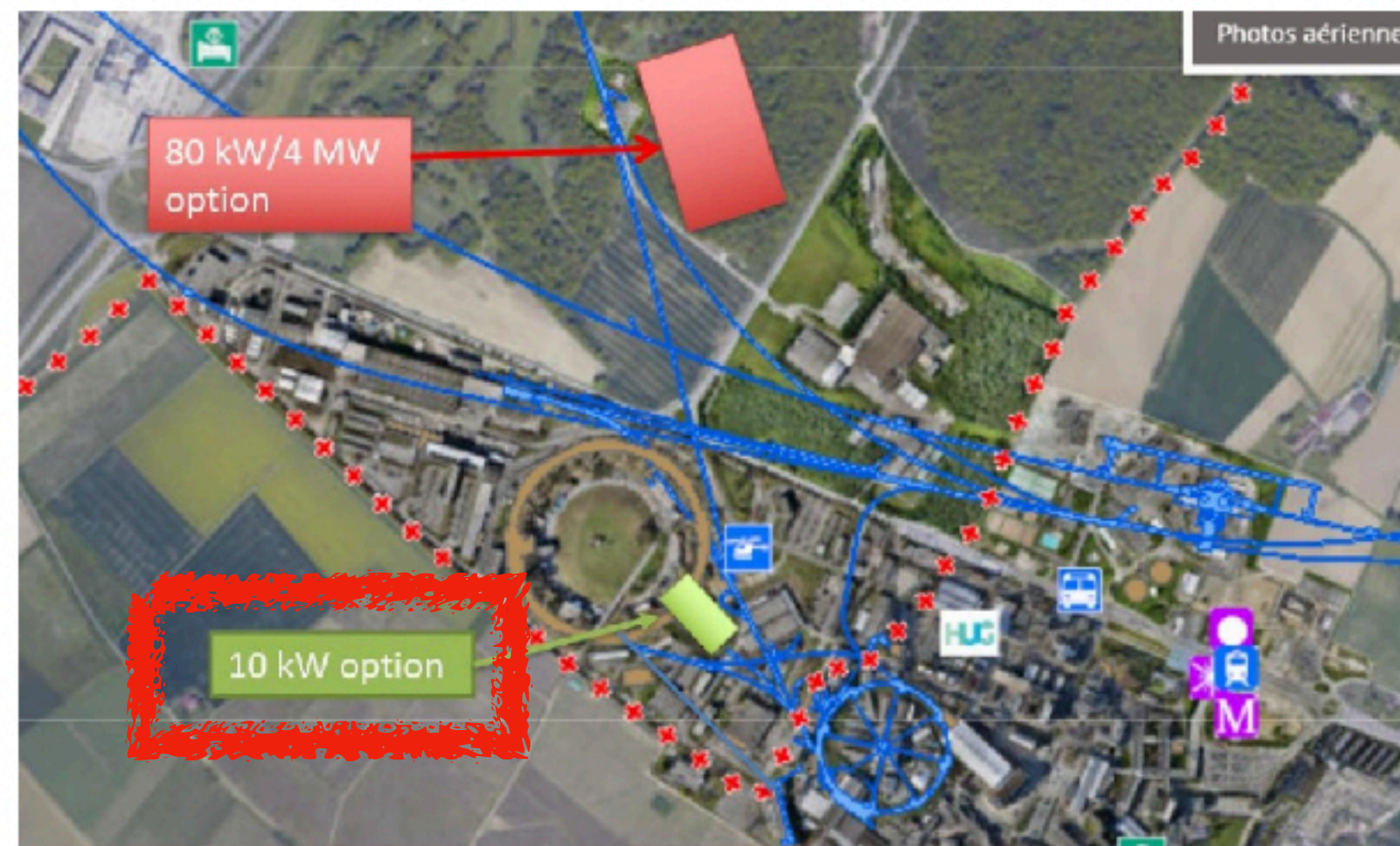
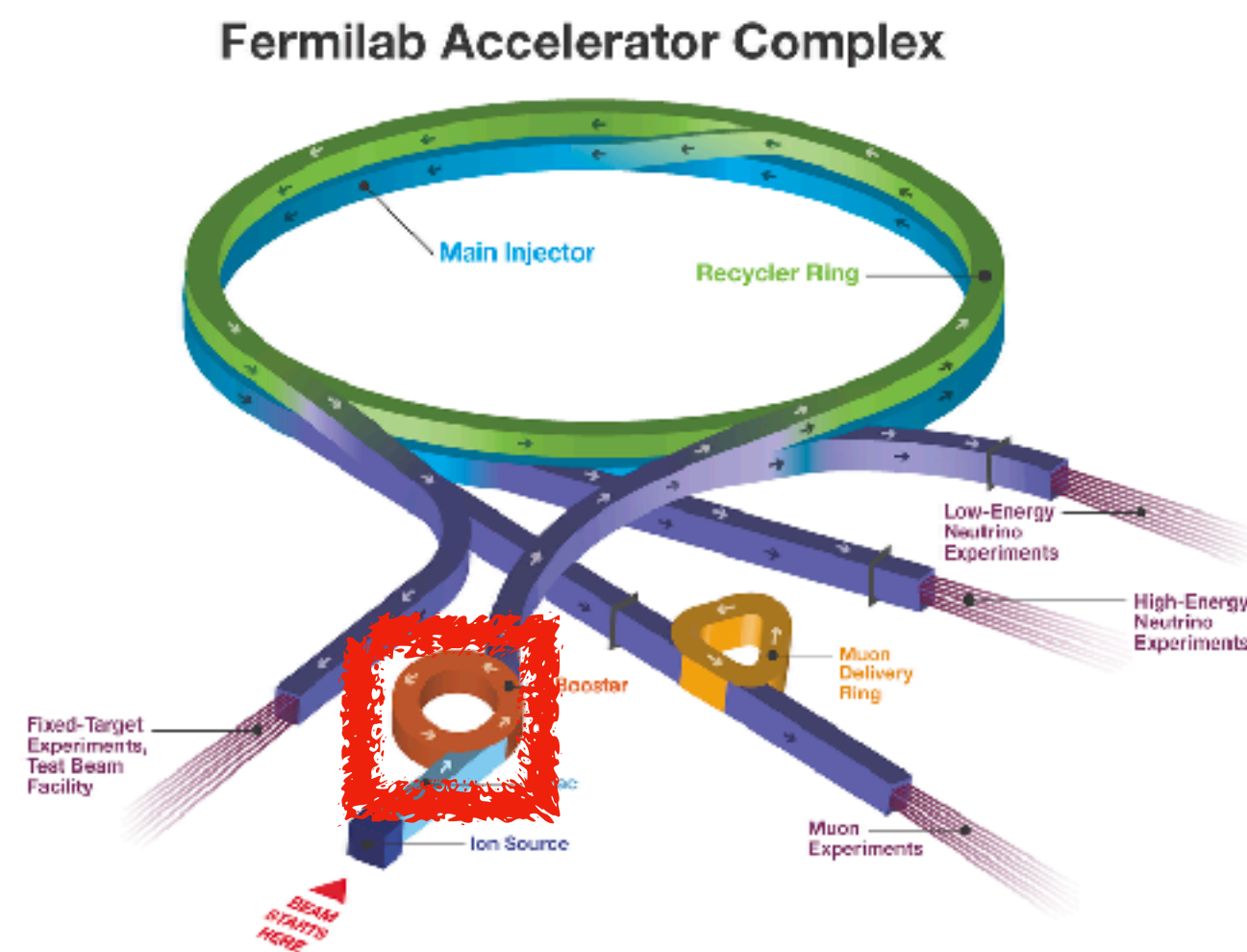
**Fermilab Booster**

ACE Upgrade

**CERN TT10**

10 kW

**ESS/SB**



R. Losito



# Demonstrator Facilities Siting Options

Run demonstrators with existing infrastructure

## Fermilab Booster

ACE Upgrade

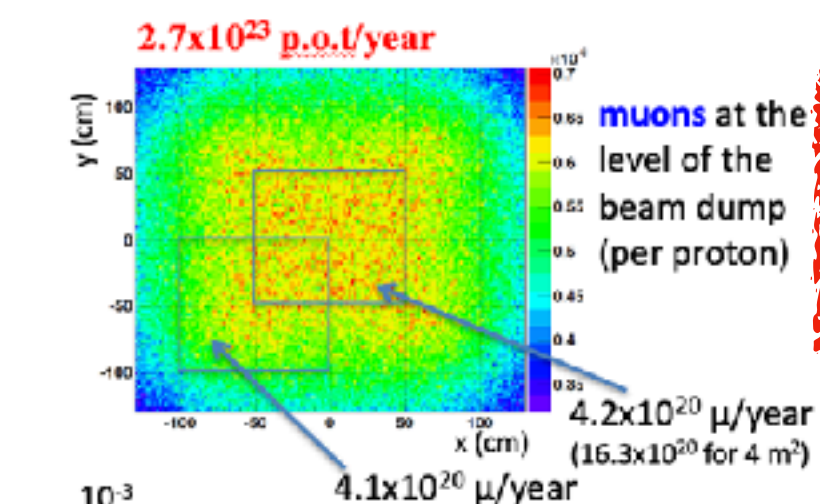
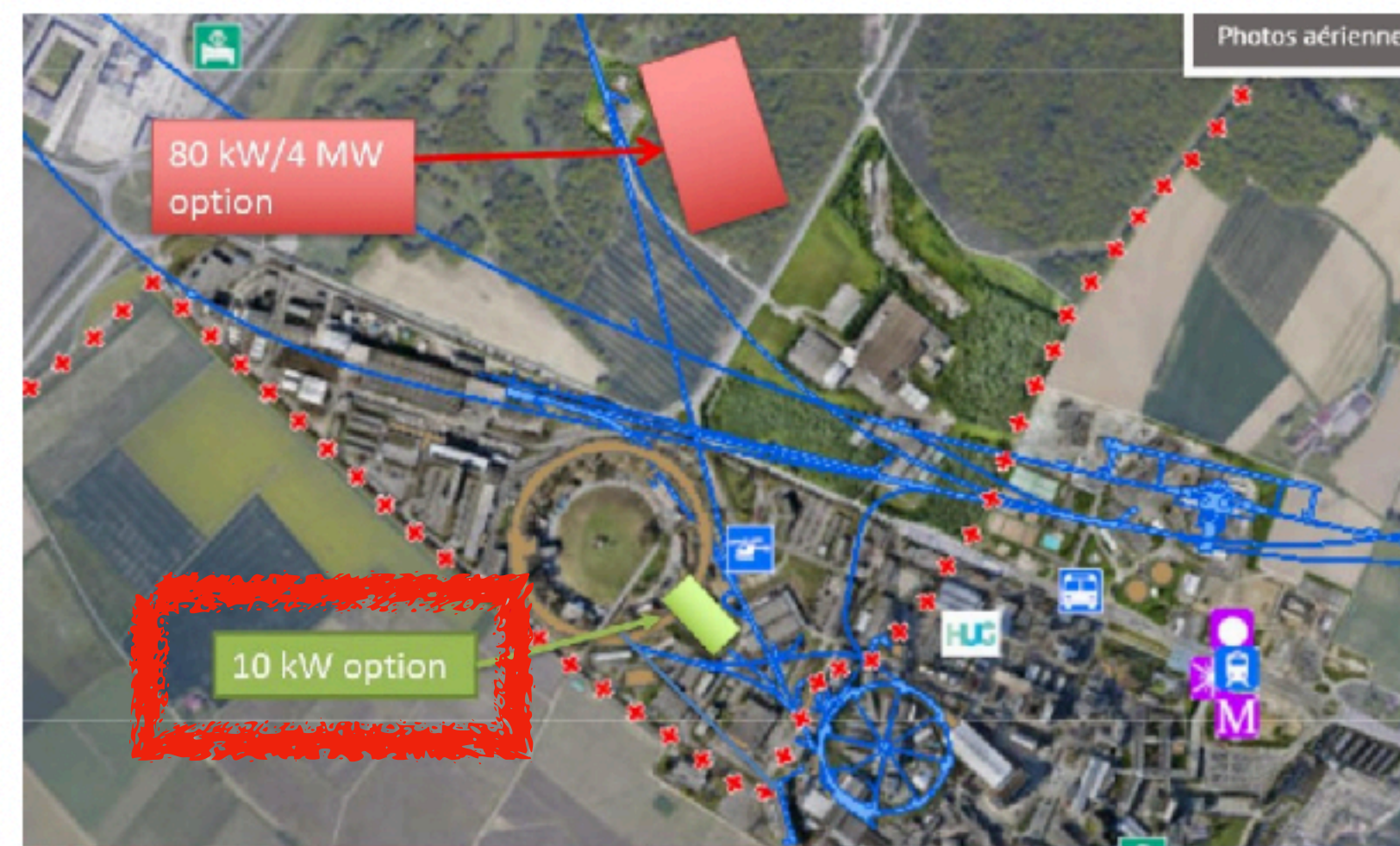
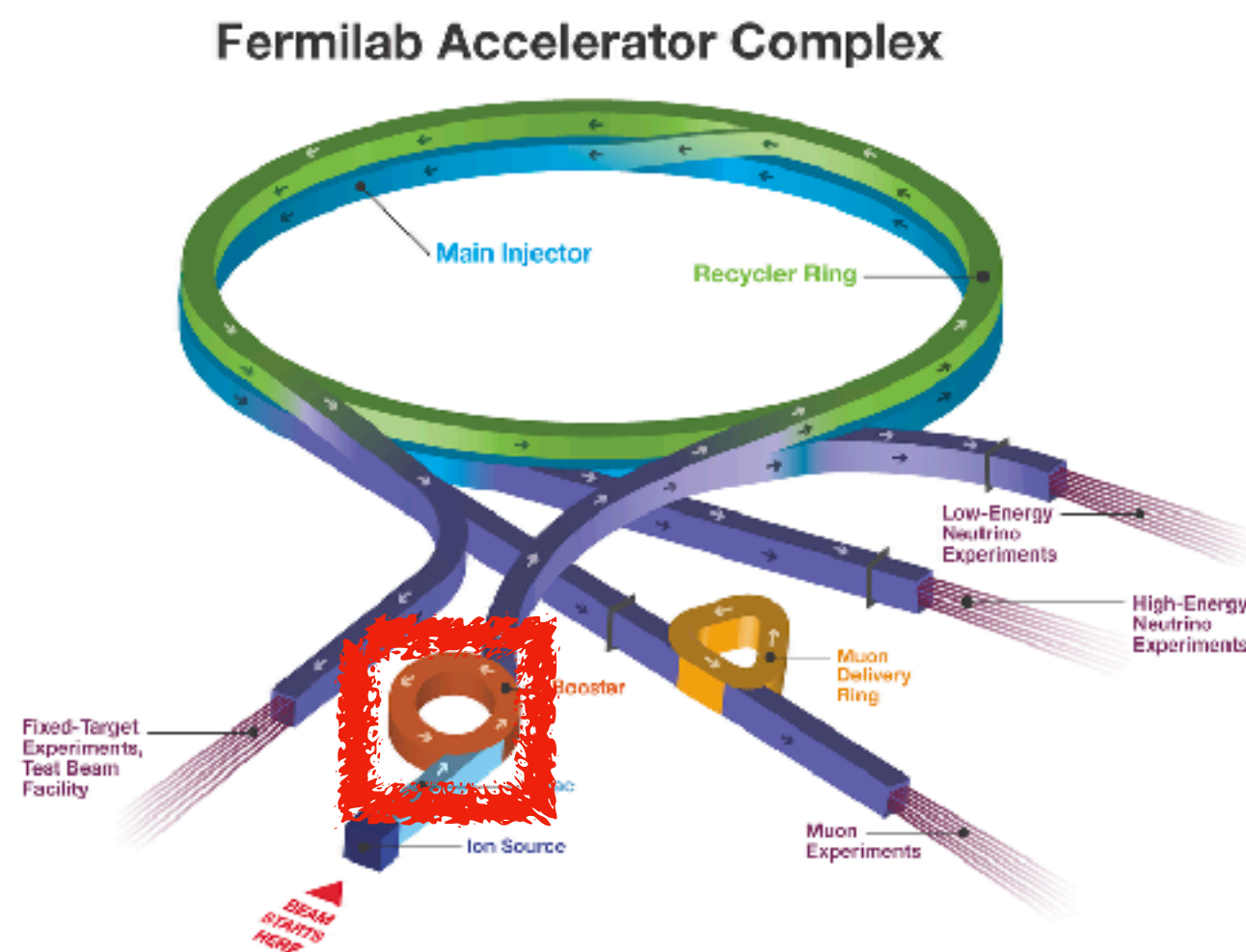
## CERN TT10

10 kW

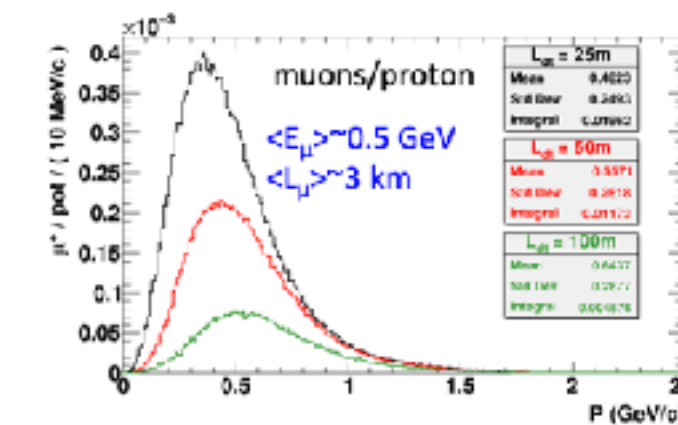
## ESS $\nu$ SB

$10^{20} \mu/\text{year}$

Muons at the level of the beam dump



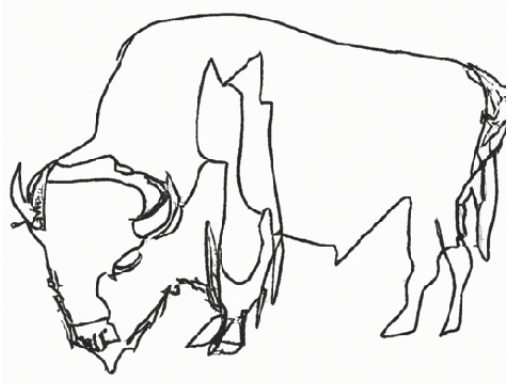
more than  $4 \times 10^{20} \mu/\text{year}$  from ESS compared to  $10^{14} \mu$  used by all experiments up to now ( $10^{18} \mu$  for COMET in the future).



- input beam for future 6D  $\mu$  cooling experiments,
- low energy  $\nu$ STORM,
- Neutrino Factory,
- Muon Collider.

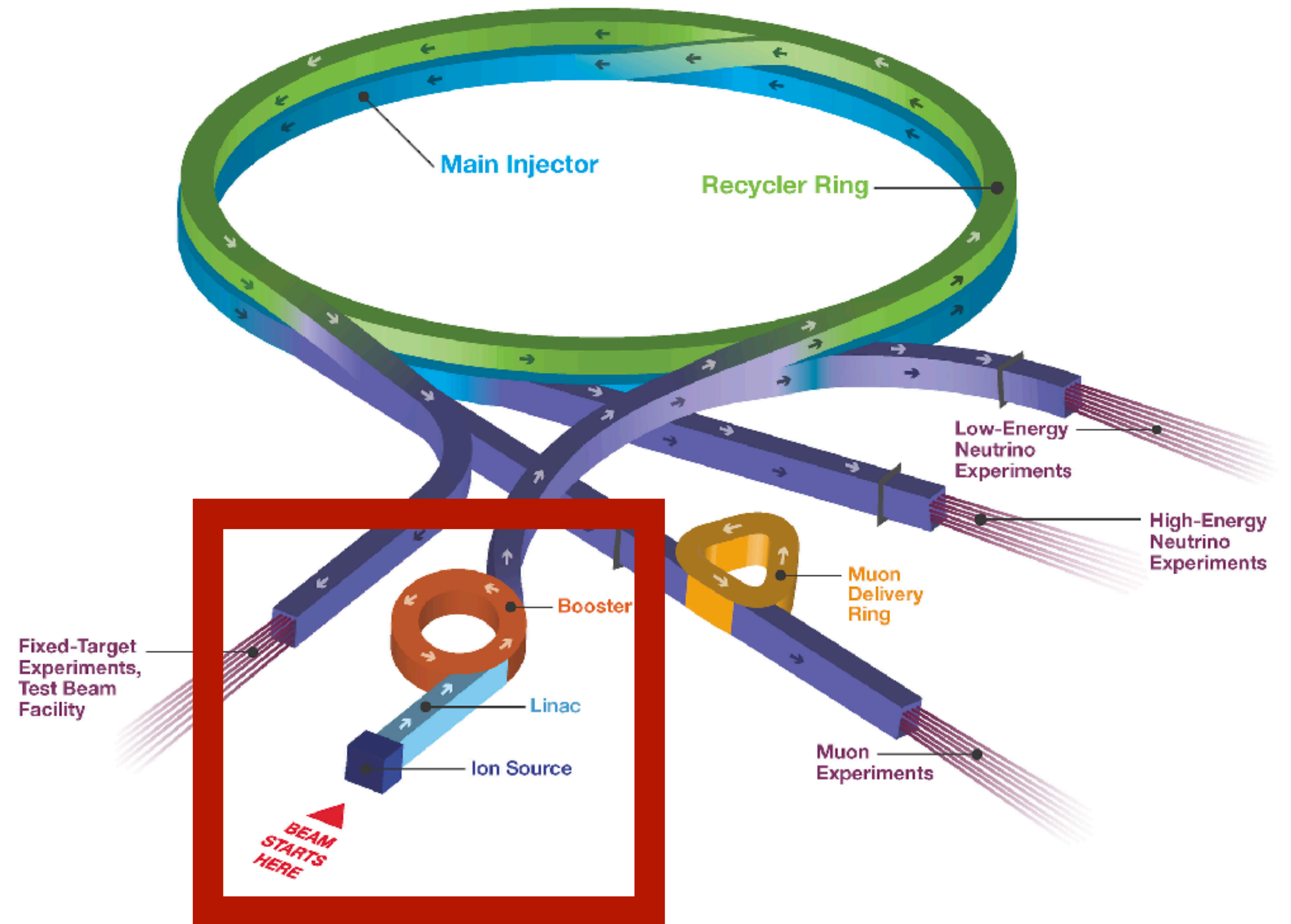


# Demonstrator Facilities @ Fermilab



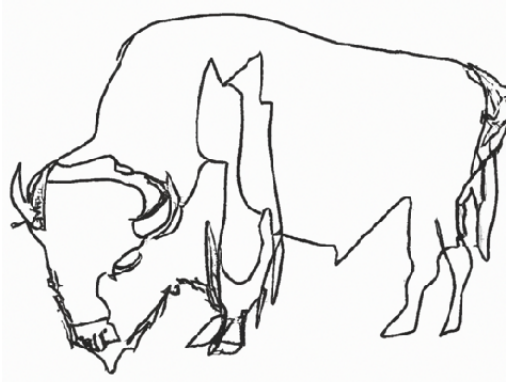
## Upgrades at Fermilab PIP-II

- Linac: 400 MeV → 800 MeV
  - Booster: 15 Hz → 20 Hz
- @ 8 GeV





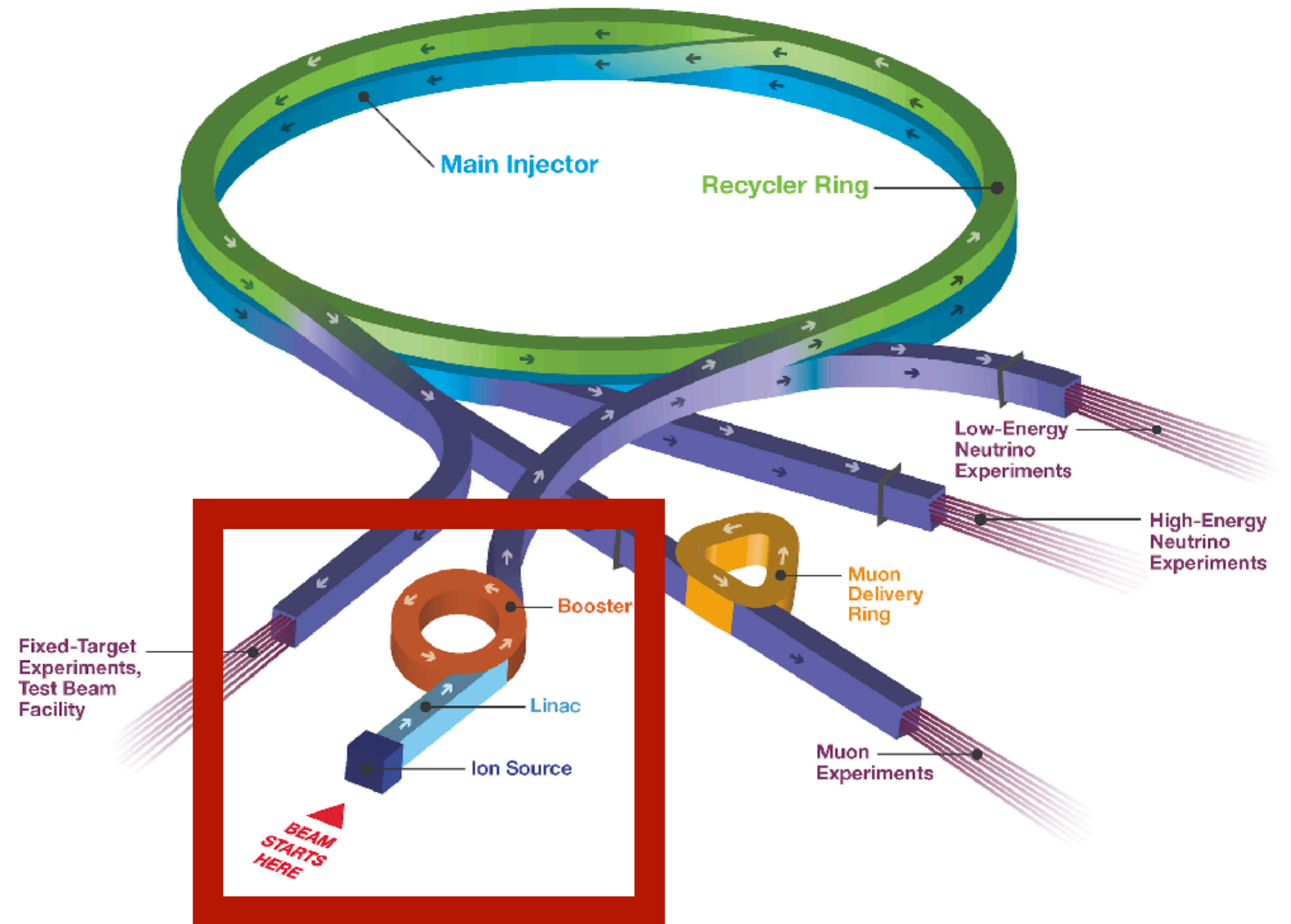
# Demonstrator Facilities @ Fermilab



## Upgrades at Fermilab PIP-II

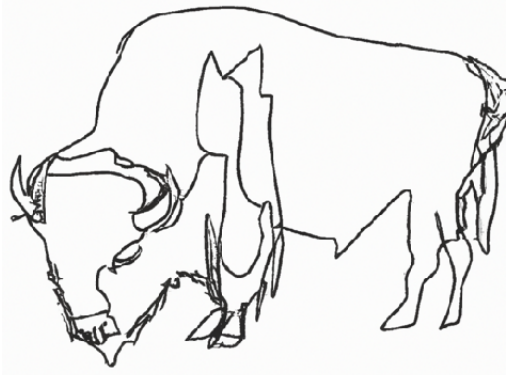
- Linac: 400 MeV → 800 MeV
  - Booster: 15 Hz → 20 Hz
- @ 8 GeV

$$10 \text{ kW} \times (8 \text{ GeV/proton})^{-1} \approx 10^{20} \text{ PoT / y}$$





# Demonstrator Facilities @ Fermilab



## Upgrades at Fermilab ACE (?)

- Linac: 800 MeV → 2 GeV ?
- Booster: Intensity upgrade

$$\sim 0.1 \text{ MW} \times (8 \text{ GeV/proton})^{-1} \approx 10^{21} \text{ PoT / y}$$

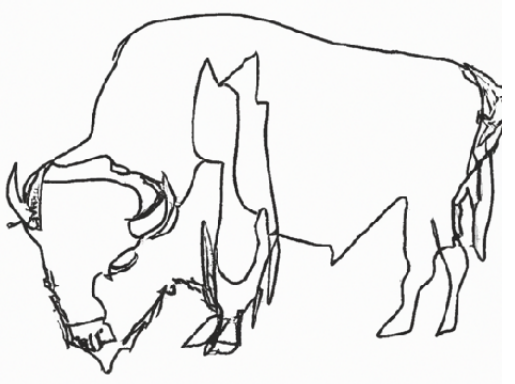
### Booster replacement

- Extend SRF Linac to higher energy or construct new Rapid-Cycling Synchrotron
- Provides
  - 2.4 MW to LBNF
  - 120 GeV beam available for other experiments
- Potential new science 'spigots':
  - 2 GeV Continuous Wave (CW)
  - 2 GeV Pulsed Beam (~ 1MW)
  - 8 GeV Pulsed (~ 1MW)
- Platform for collider R&D
- Front-end for future multi-TeV collider

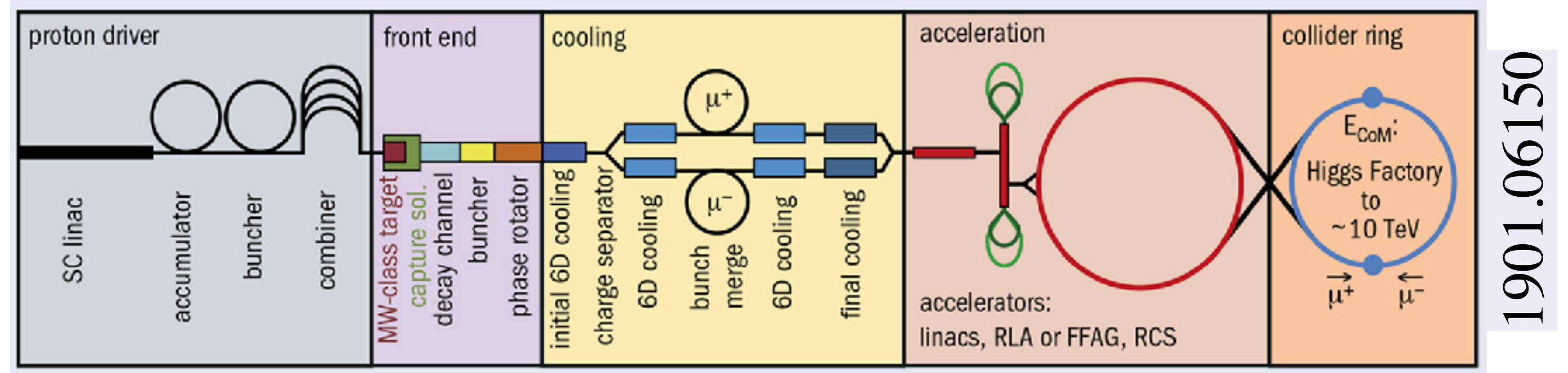
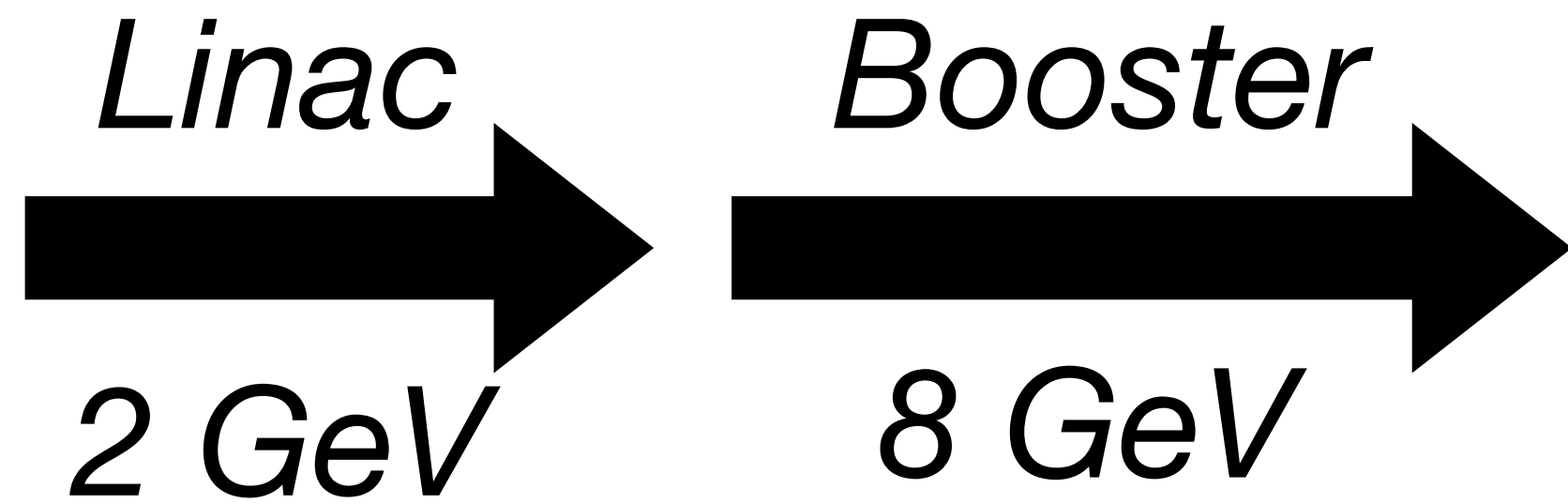
## Projections for ACE Before 2040



# ACE & Muon Colliders



2 GeV Linac upgrade is right direction for ~ TeV MuC

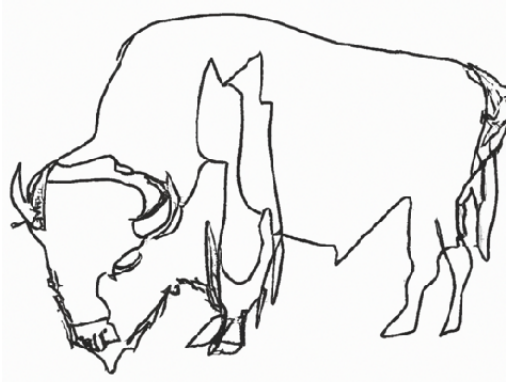


## PIU-CDG

Parameter	PIU scenarios	MuC-PD scenarios
Energy	8 GeV	8-16 GeV
Rep. rate	10-20 Hz	5-20 Hz
Avg. beam power	0.3-1.6 MW	1-4 MW
Proton structure	25-40 e12 over 2 $\mu$ s ring	40-120 e12 in four 1-3 ns bunches



# ACE & Beam Dumps

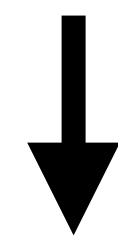


New physics can be studied at low energy  
because of high beam **intensity**

Protons on Target @ 8 GeV

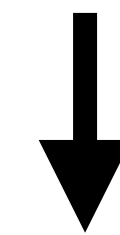
Sufficient for Demonstrators!

PIP-II  
10 kW



$10^{20}$  protons/year

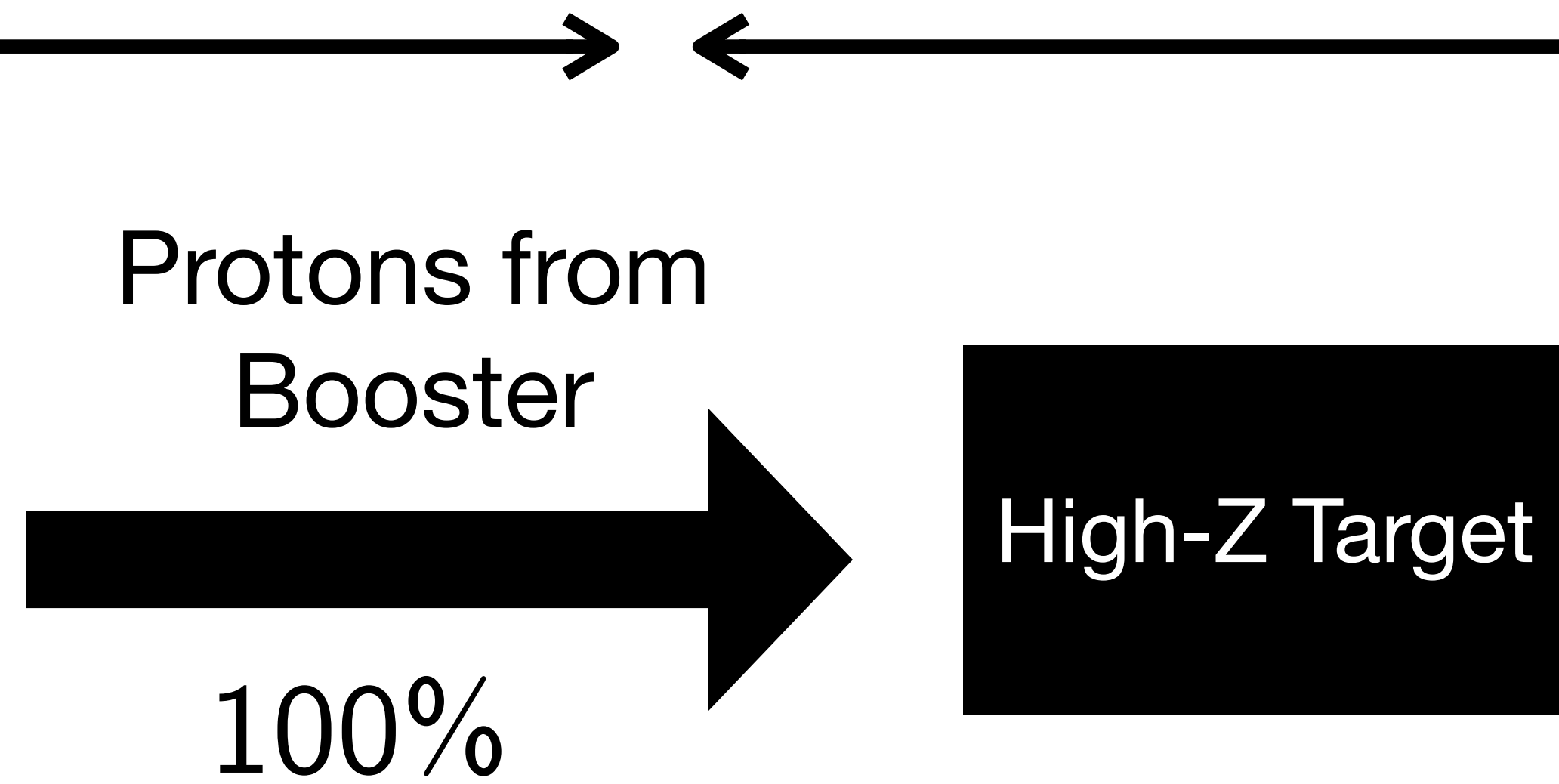
ACE-BR  
100 kW



$10^{21}$  protons/year

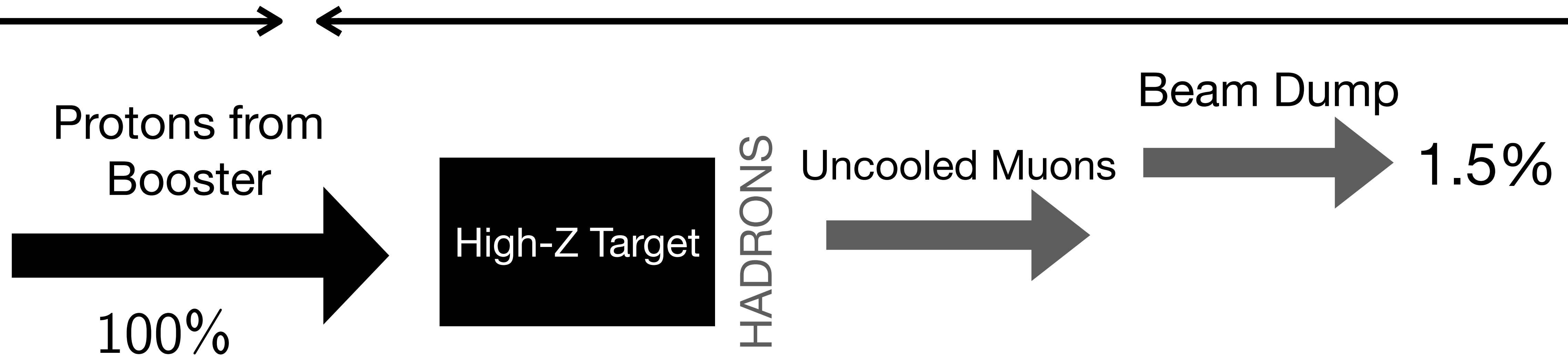


# Demonstrators & Beam Dumps



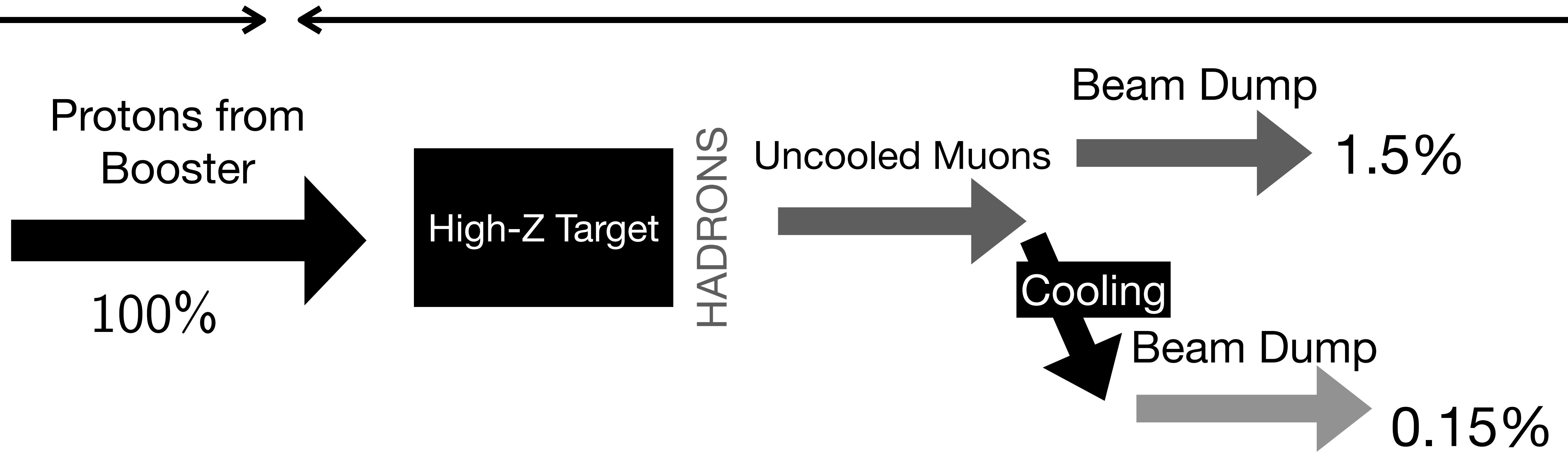


# Demonstrators & Beam Dumps



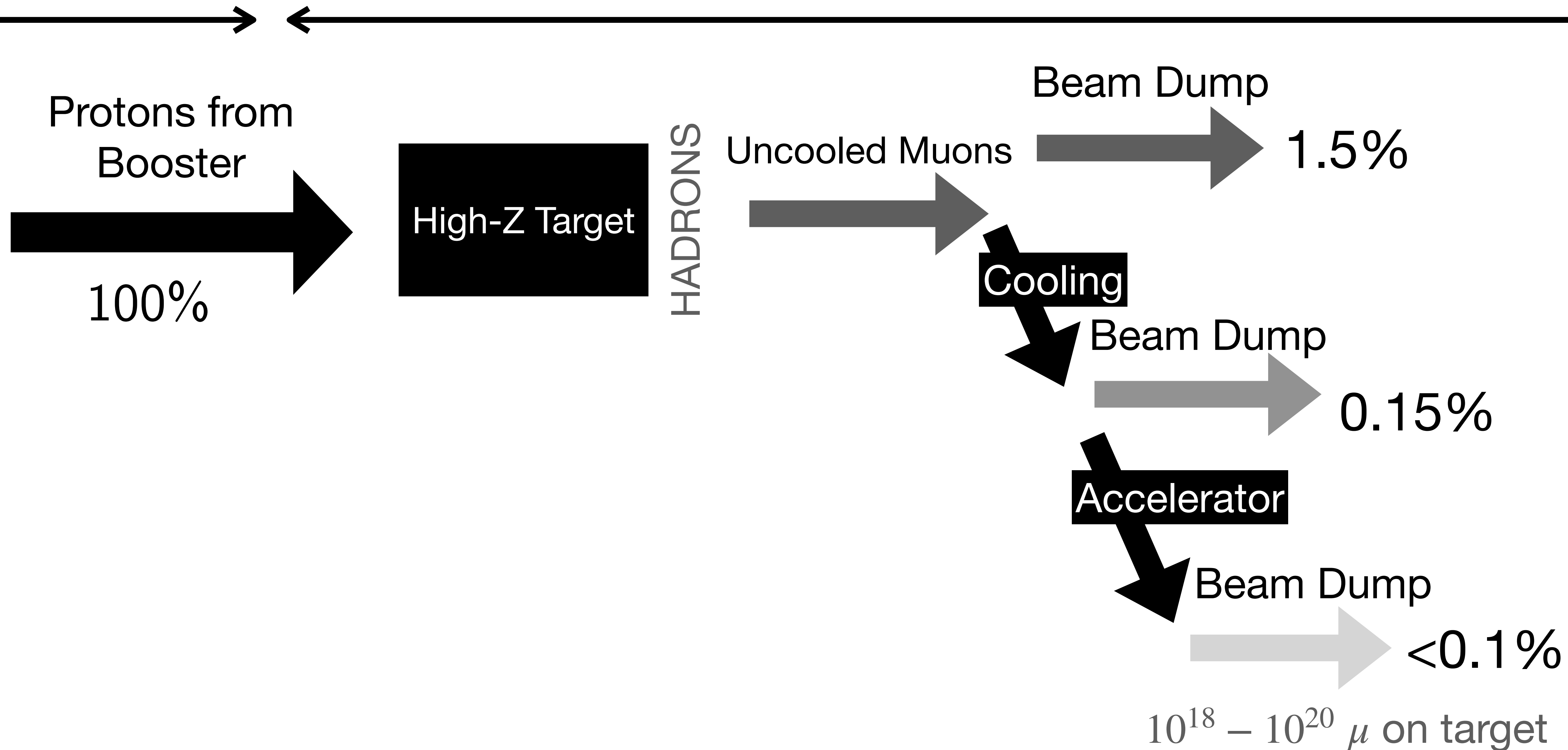


# Demonstrators & Beam Dumps



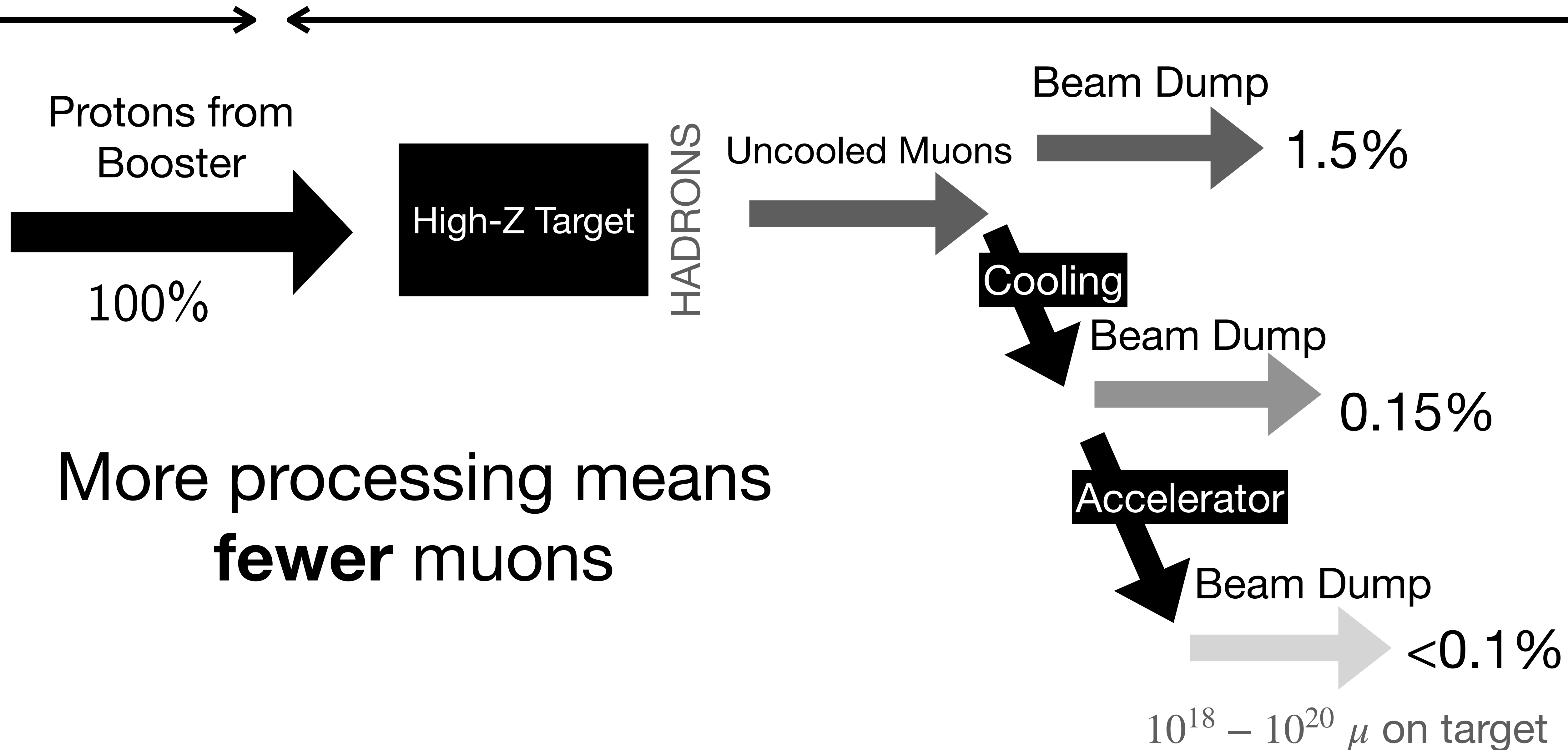


# Demonstrators & Beam Dumps



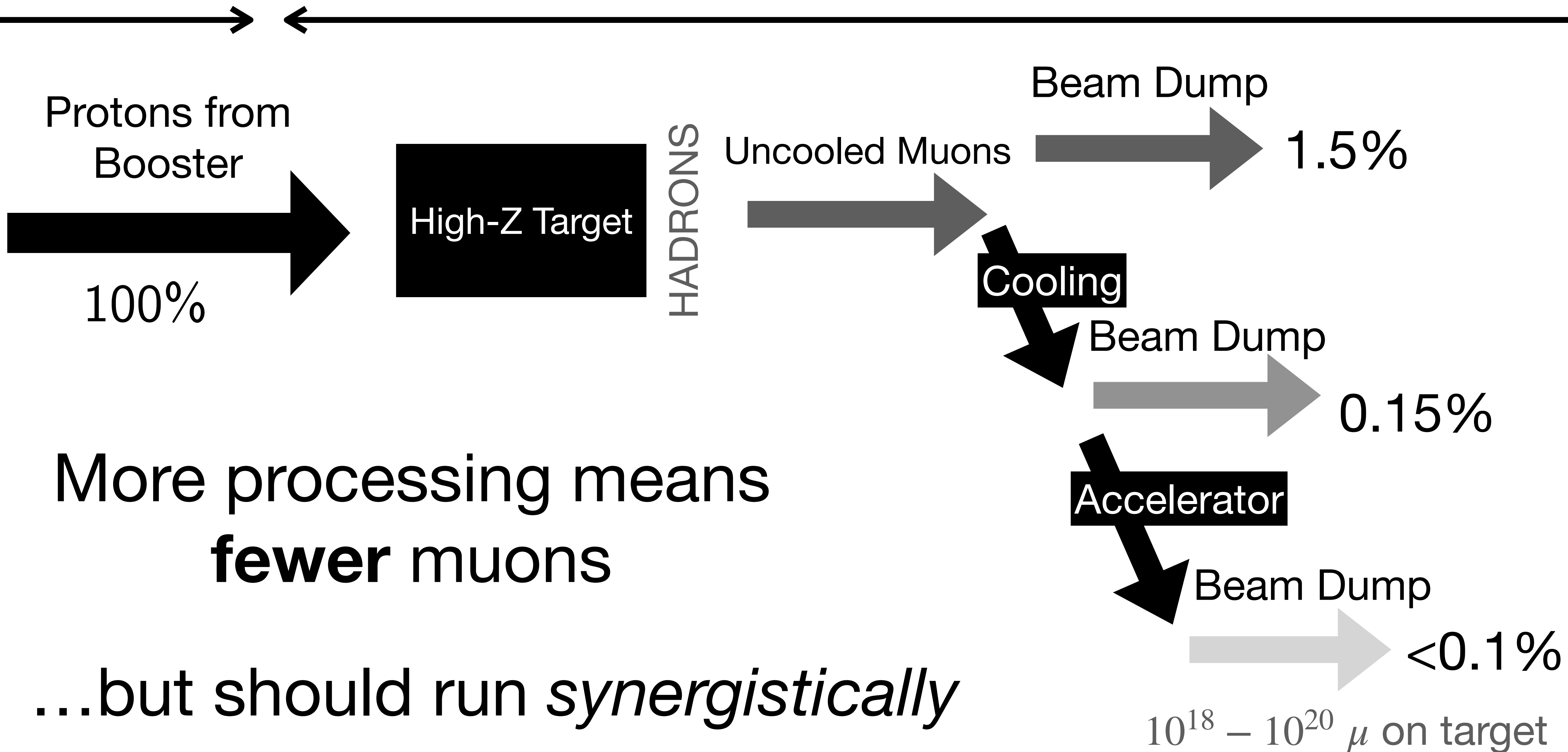


# Demonstrators & Beam Dumps





# Demonstrators & Beam Dumps





# Models for Beam Dumps



## Dark Photon

$$\mathcal{L}_V \supset -i\epsilon e Z'_\mu \sum_{l \in e, \mu, \tau} \bar{l} \gamma^\mu l$$

Improved from high energy

$$\mathcal{L}_V \supset \mp ig Z'_\mu \sum_{l \in \mu, \tau} (\bar{l} \gamma^\mu l + \bar{\nu}_l \sigma^\mu \nu_l)$$

Improved from second generation

# Models for Beam Dumps

## Dark Photon

$$\mathcal{L}_V \supset -i\epsilon e Z'_\mu \sum_{l \in e, \mu, \tau} \bar{l} \gamma^\mu l$$

Improved from high energy

$$L_\mu - L_\tau$$

$$\mathcal{L}_V \supset \mp ig Z'_\mu \sum_{l \in \mu, \tau} (\bar{l} \gamma^\mu l + \bar{\nu}_l \sigma^\mu \nu_l)$$

Improved from second generation

Generic New Physics Models

$$\mathcal{L} \supset -ig X \bar{\psi} (\gamma^i) \psi$$

- Muonphilic ( $g_\mu \neq 0$ )
- Yukawa-like ( $g \sim m_l/v$ )
- ...



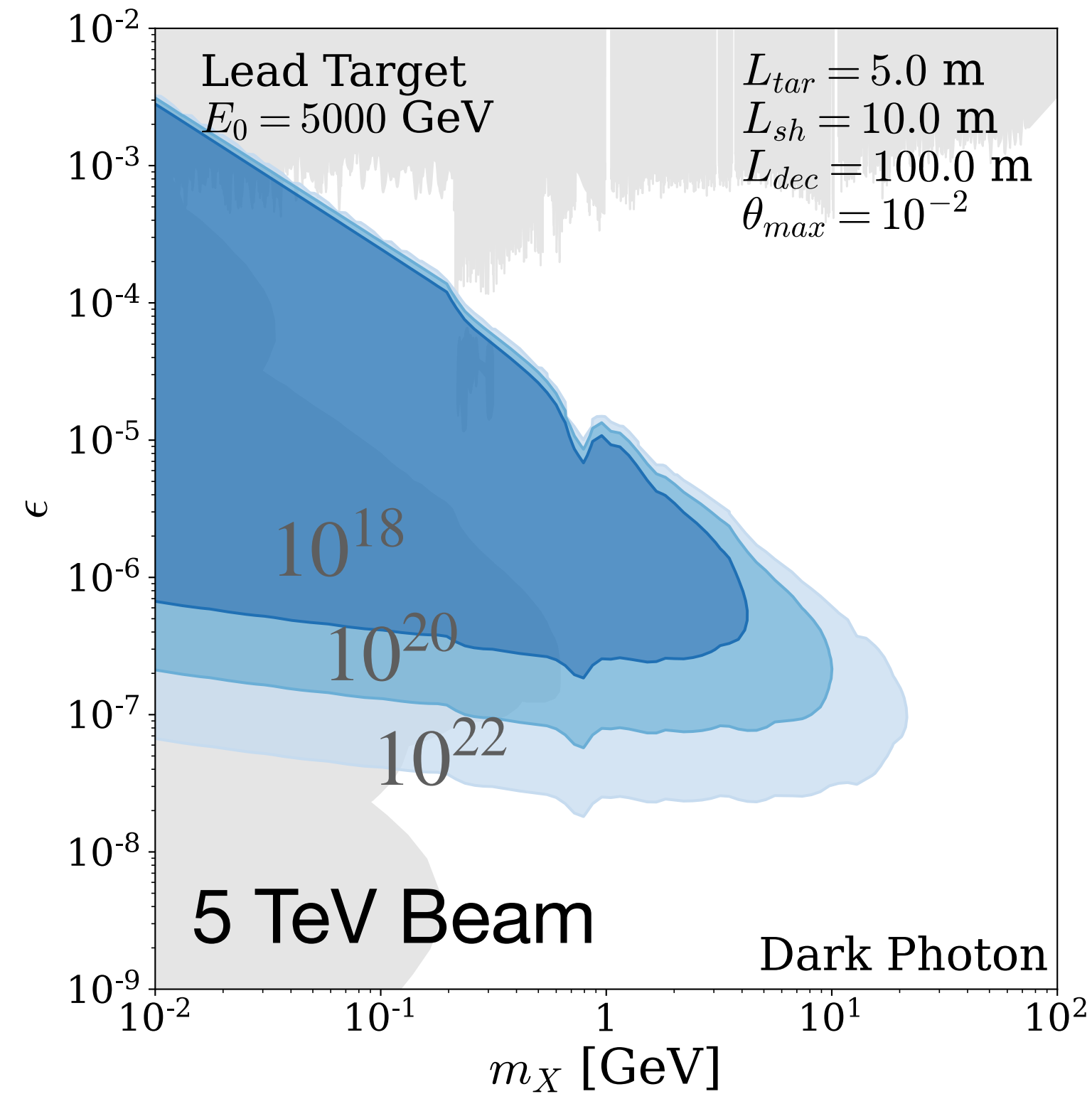
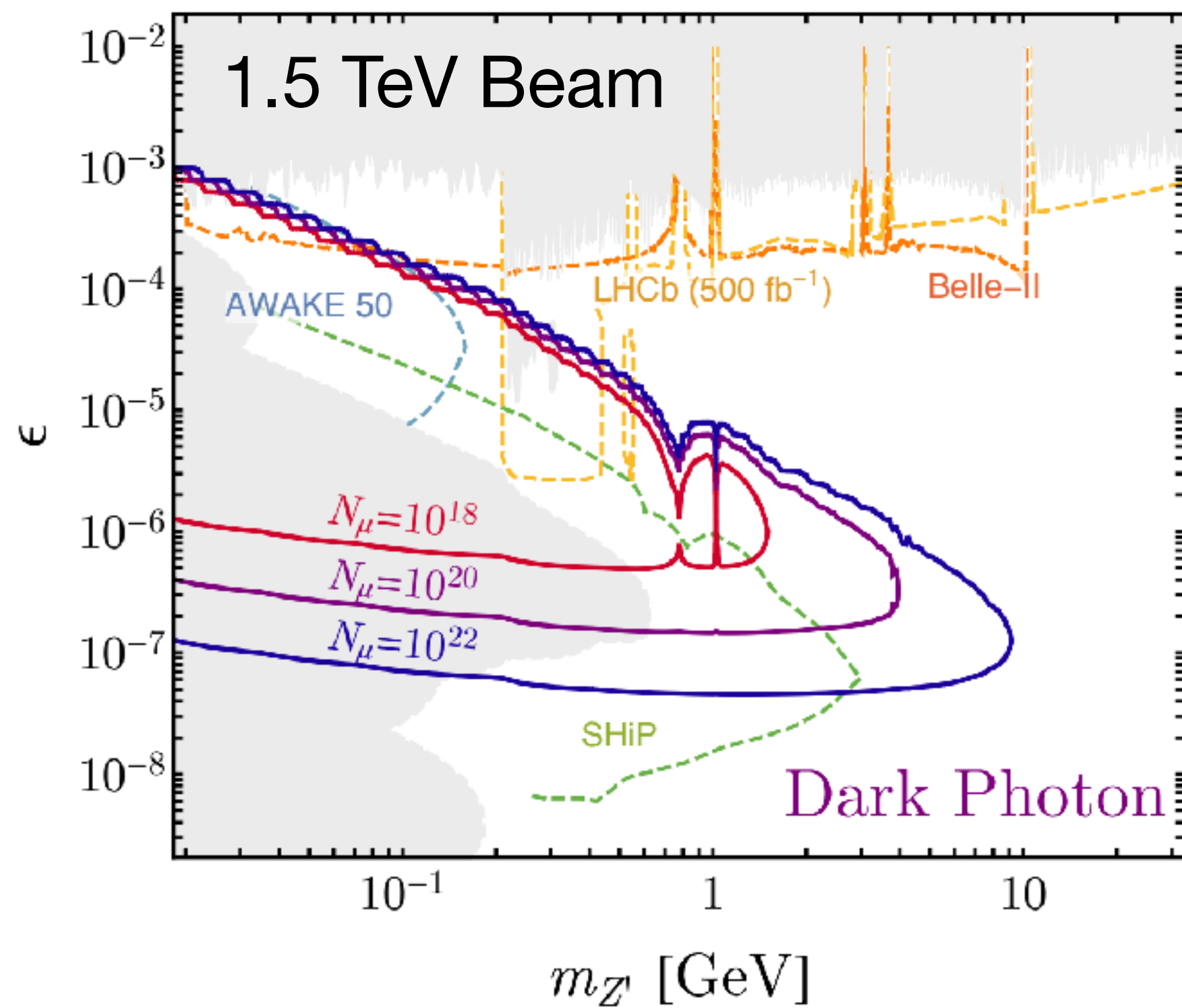
# Muon Collider Beam Dump

Examples of Physics Deliverables, in reverse order  
of MuC Maturity

2050ish



CC, S. Homiller, R. Mishra,  
M. Reece PRL



CC, R. Gambhir, S. Alipour-Fard  
2306.XXXX

3, 10 TeV MuC

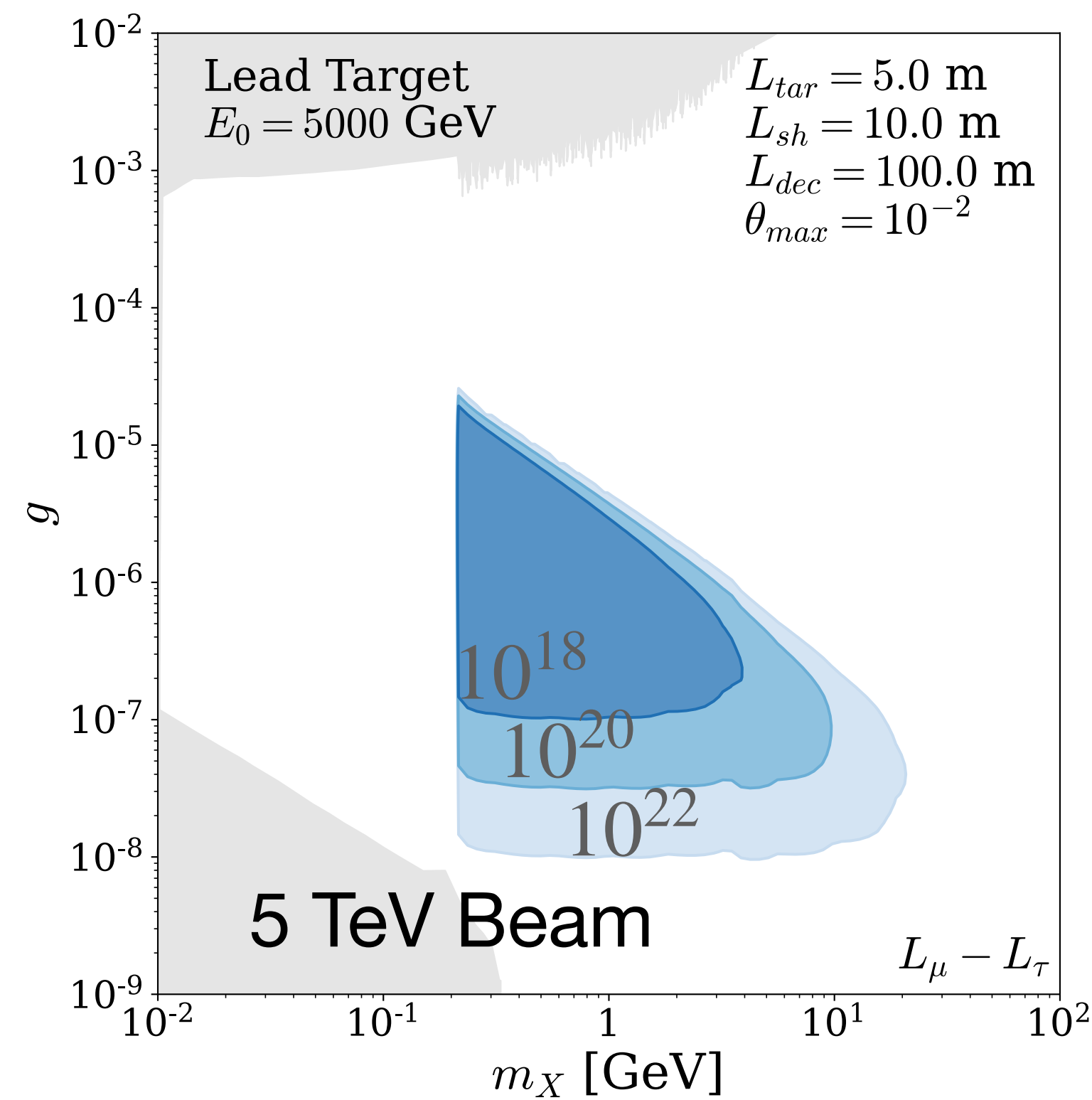
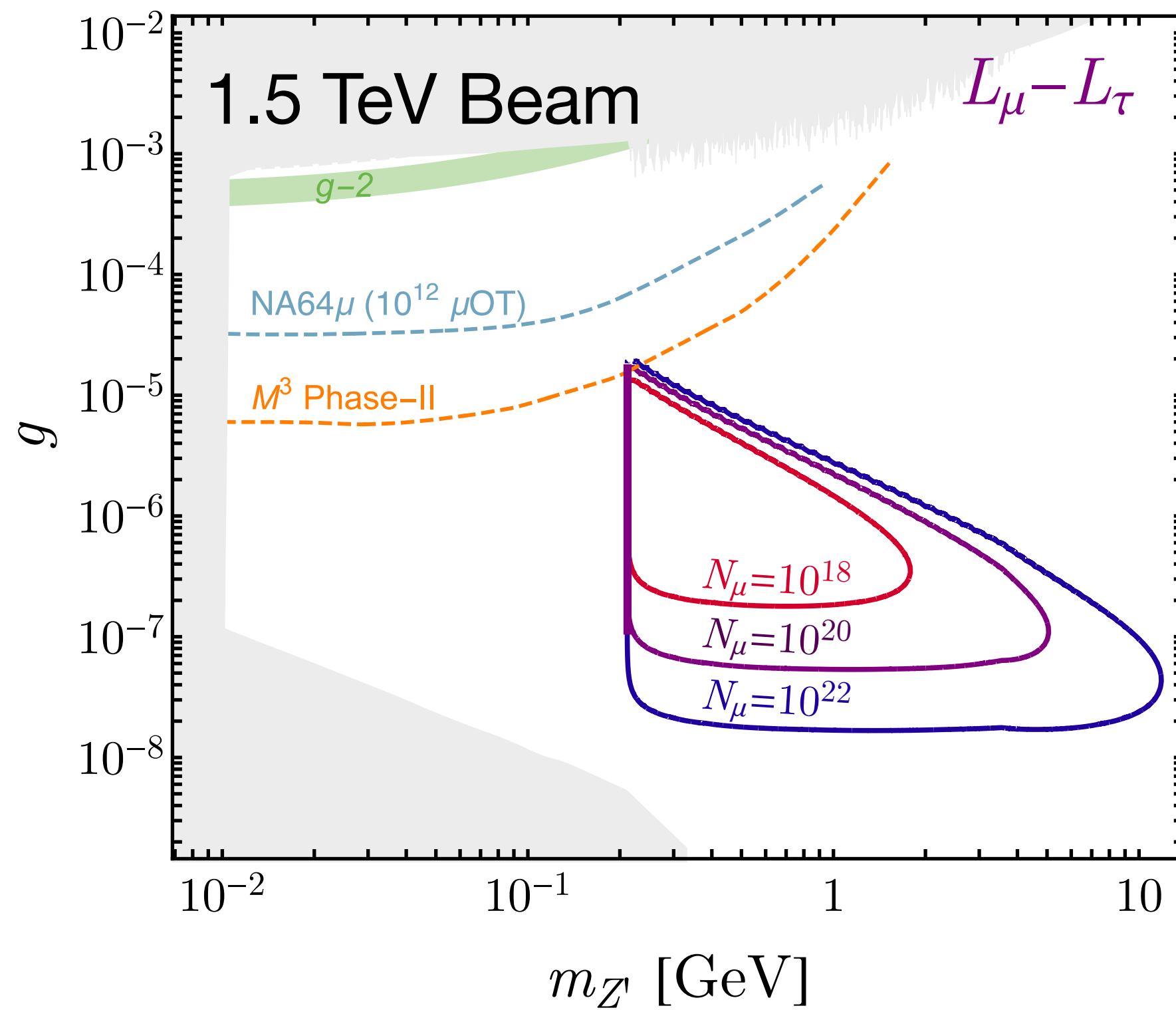
# Muon Collider Beam Dump

2050ish



3, 10 TeV MuC

CC, S. Homiller, R. Mishra,  
M. Reece PRL



CC, R. Gambhir, S. Alipour-Fard  
2306.XXXX



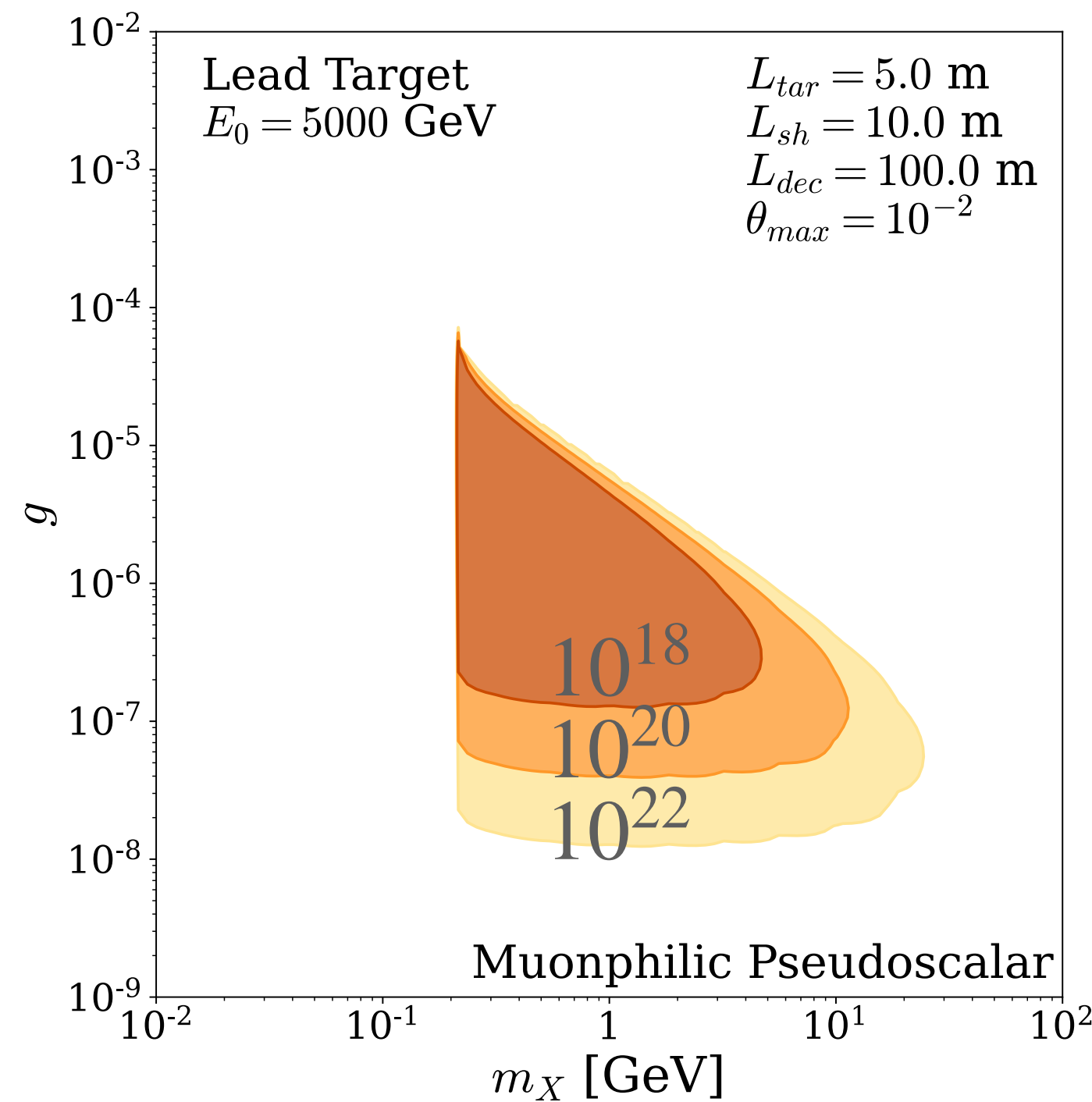
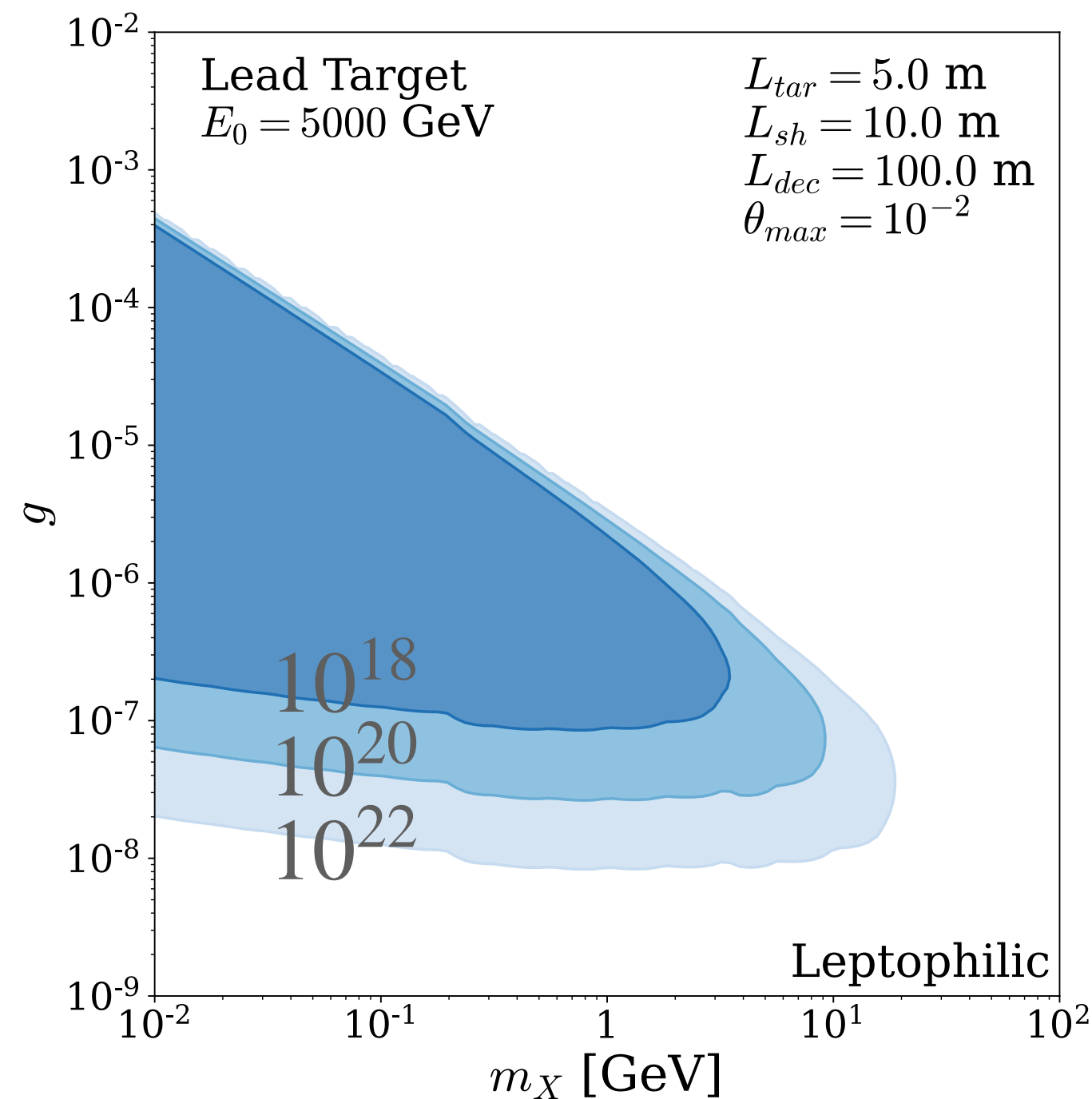
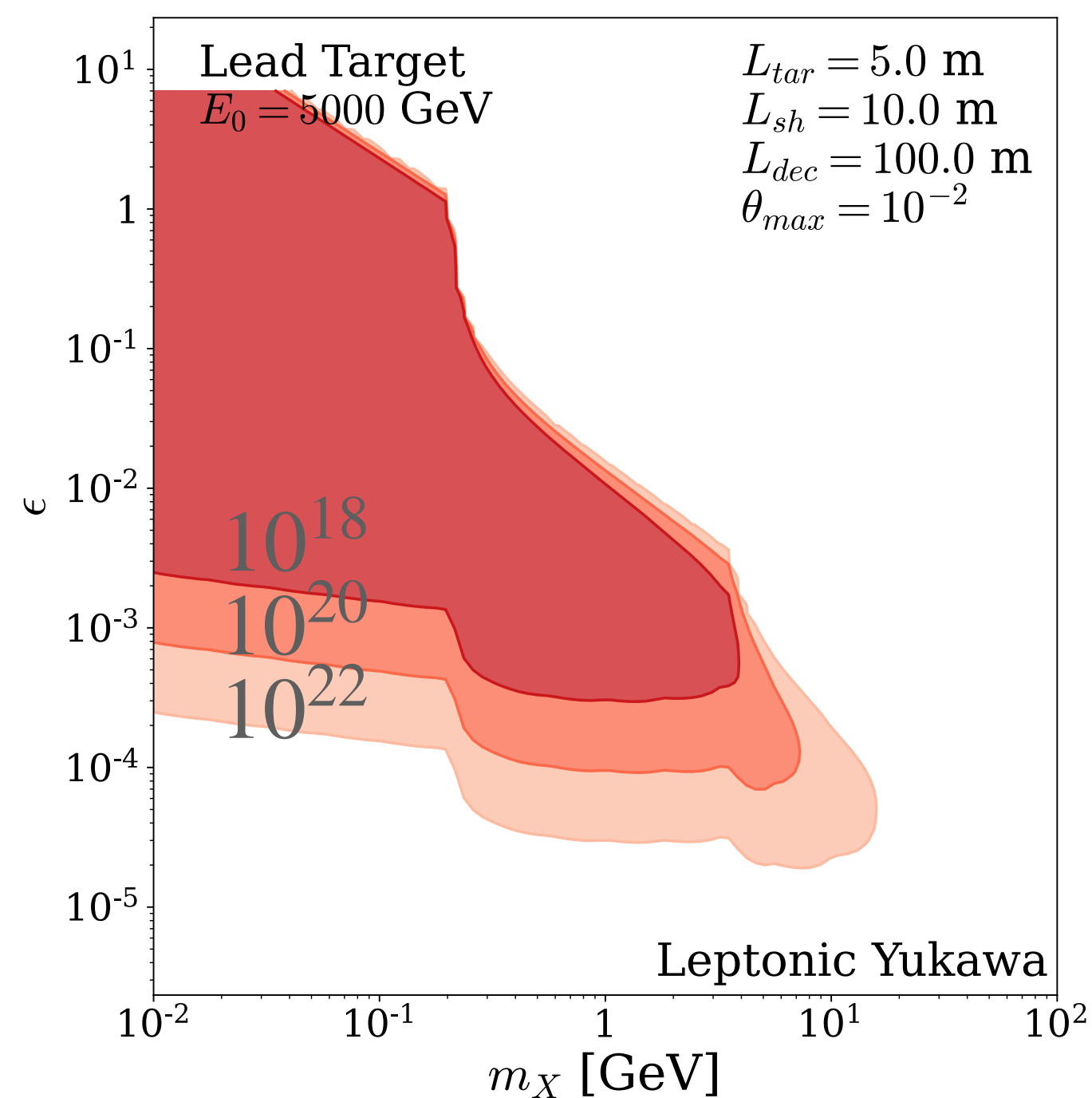
# Muon Collider Beam Dump

2050ish



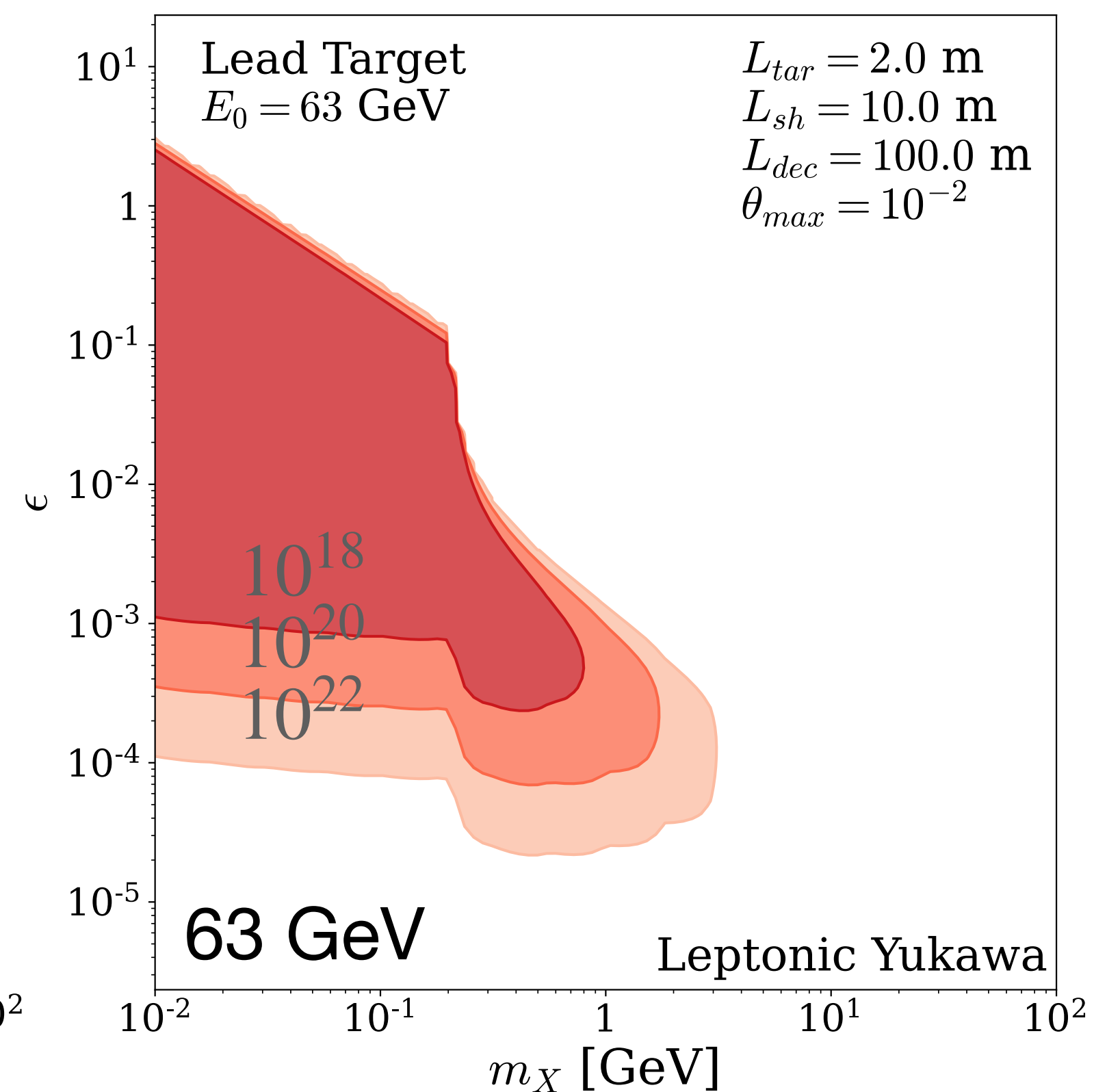
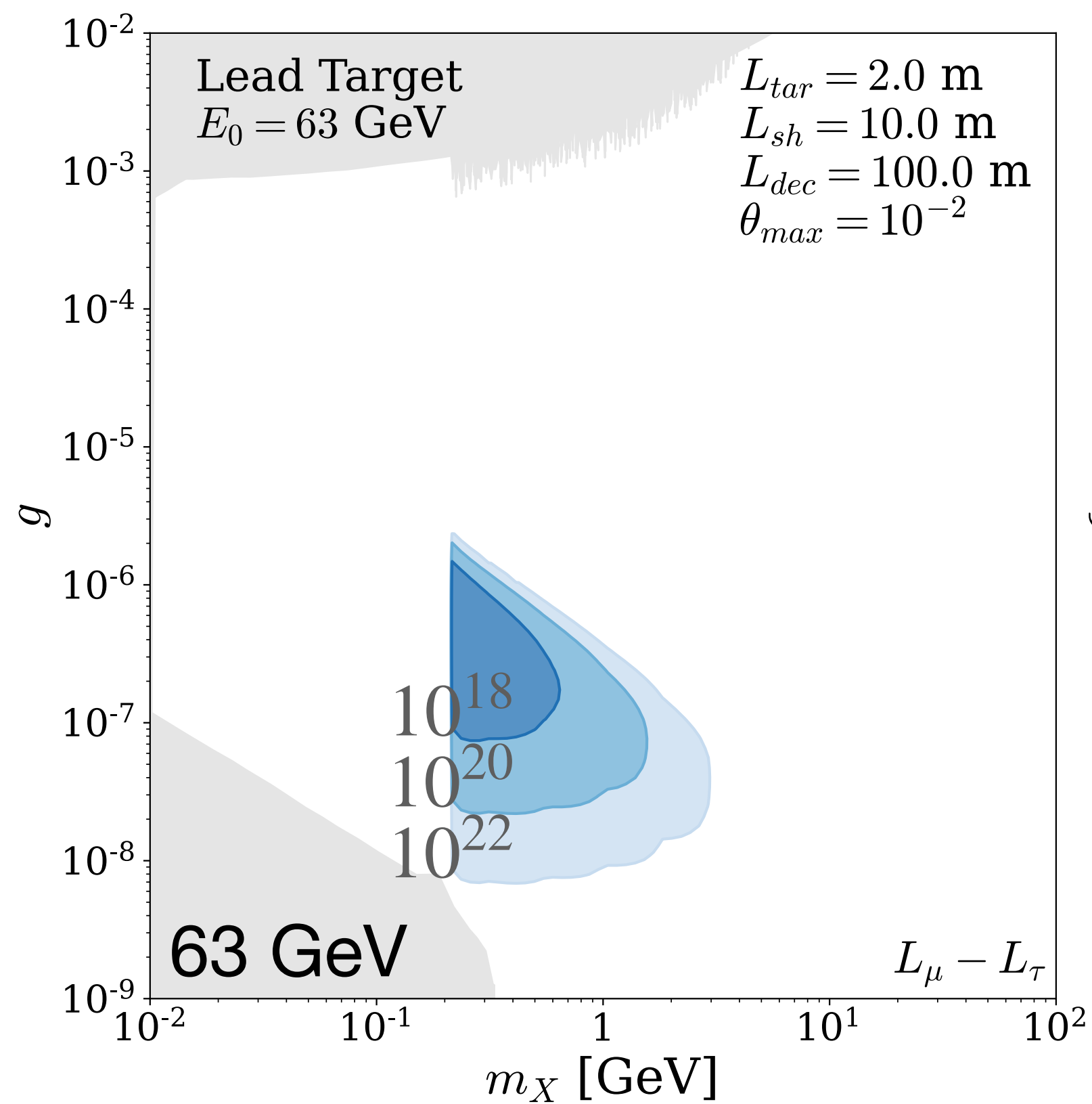
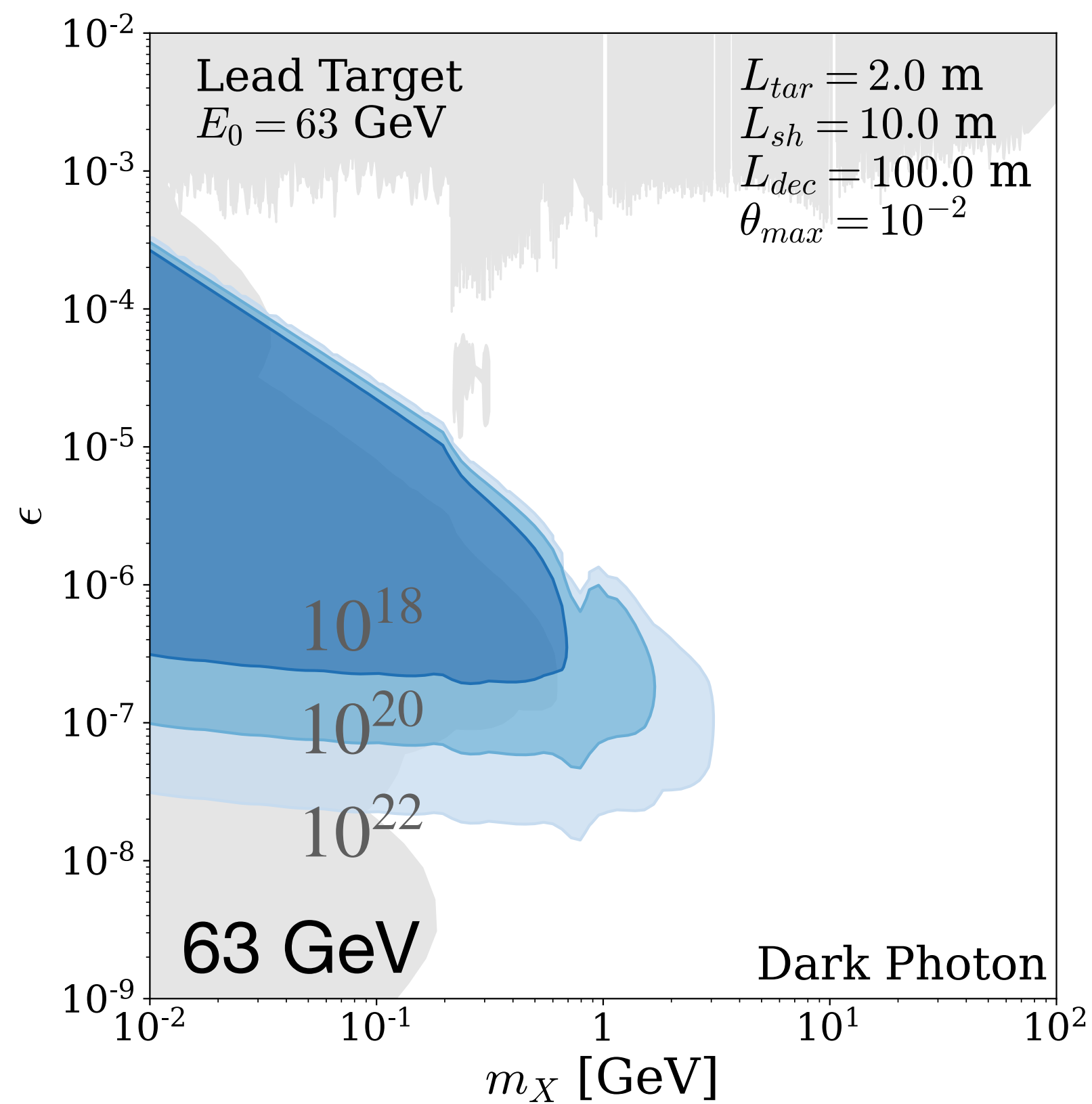
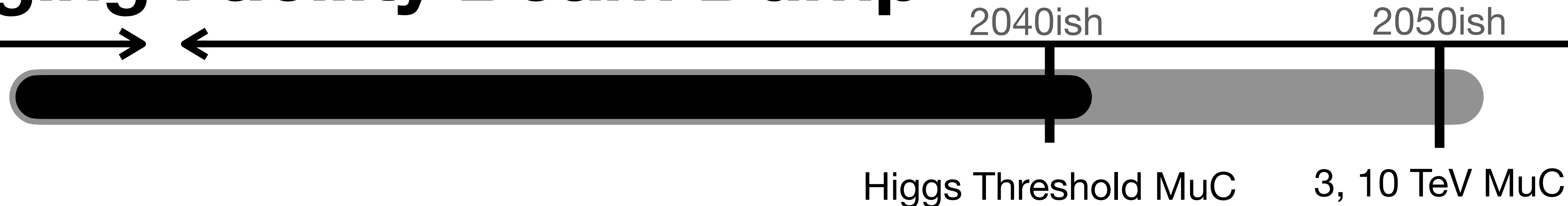
Unconstrained parameter space beyond  $m_X \sim \mathcal{O}(100)$

3, 10 TeV MuC



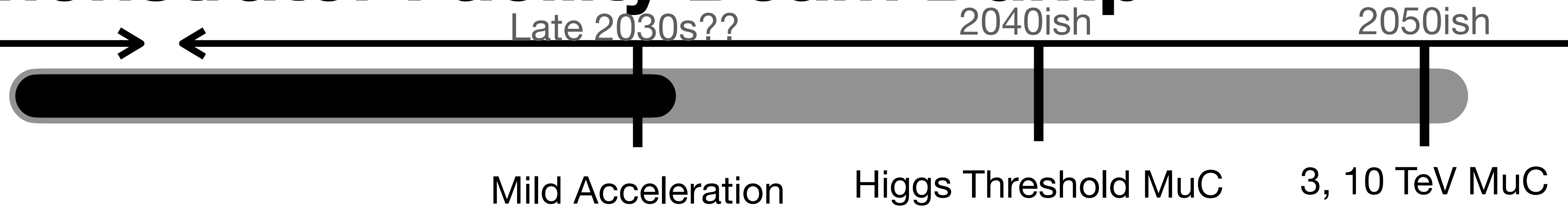
CC, R. Gambhir, S. Alipour-Fard  
2306.XXXX

# Staging Facility Beam Dump

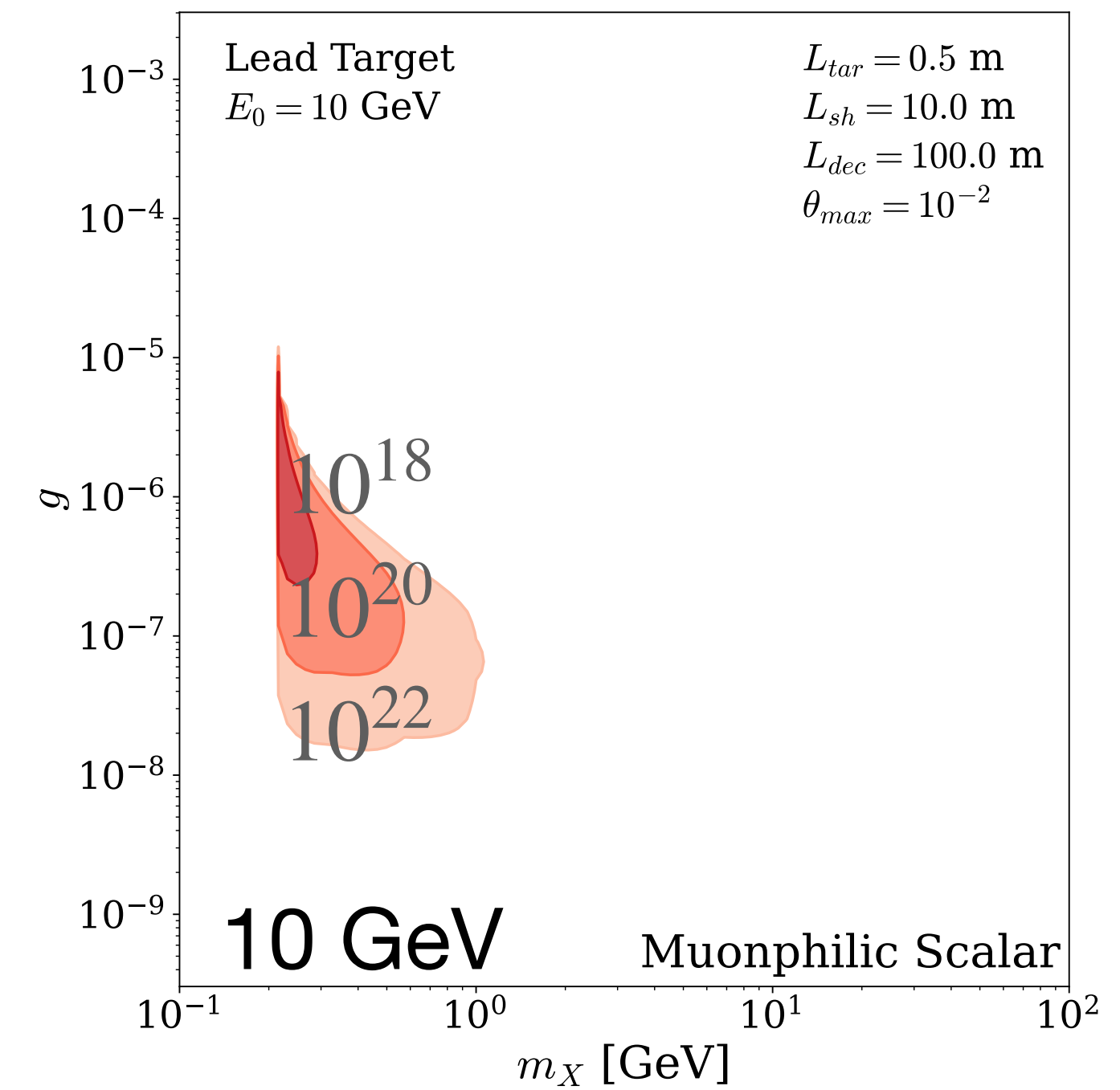
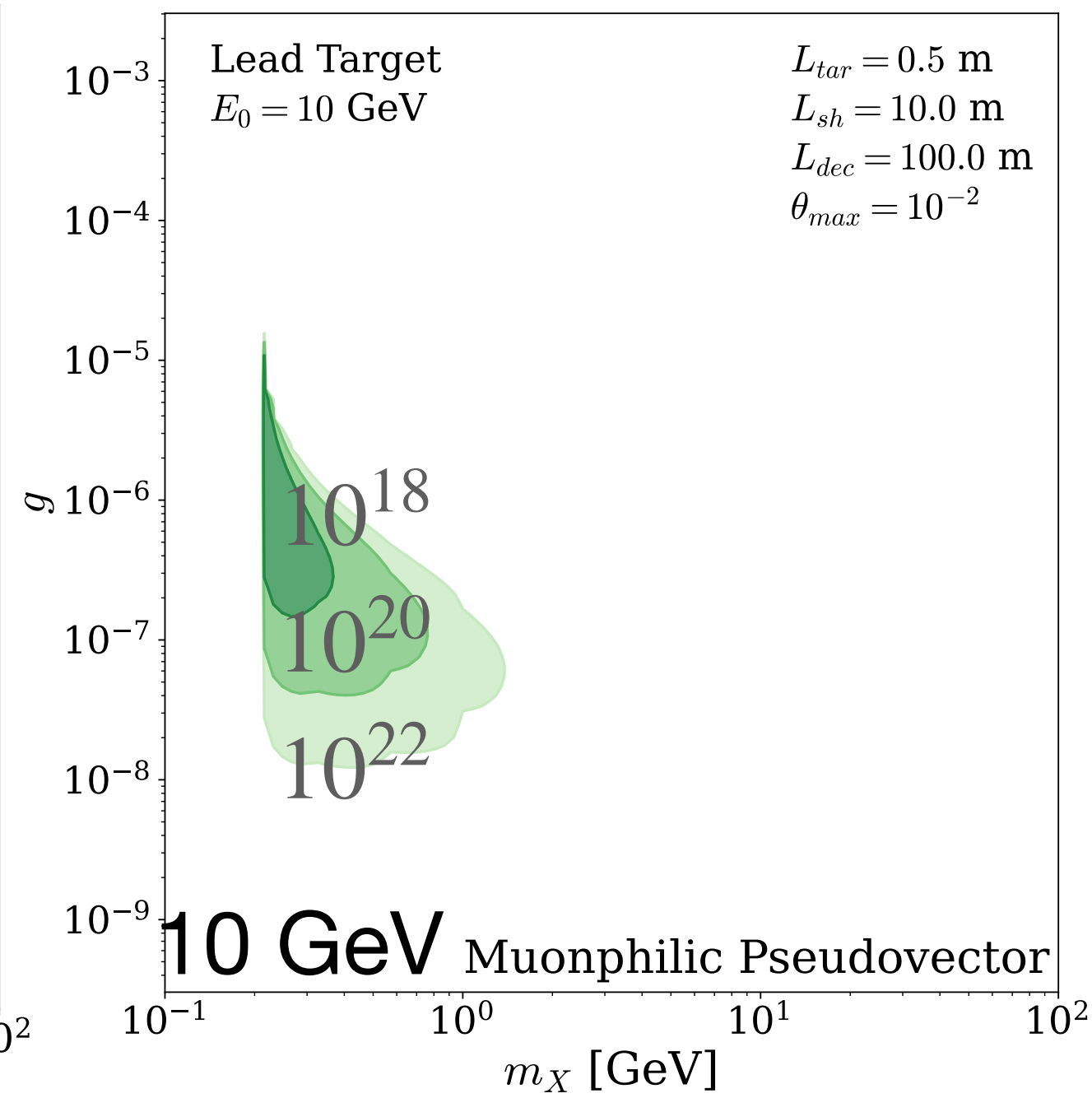
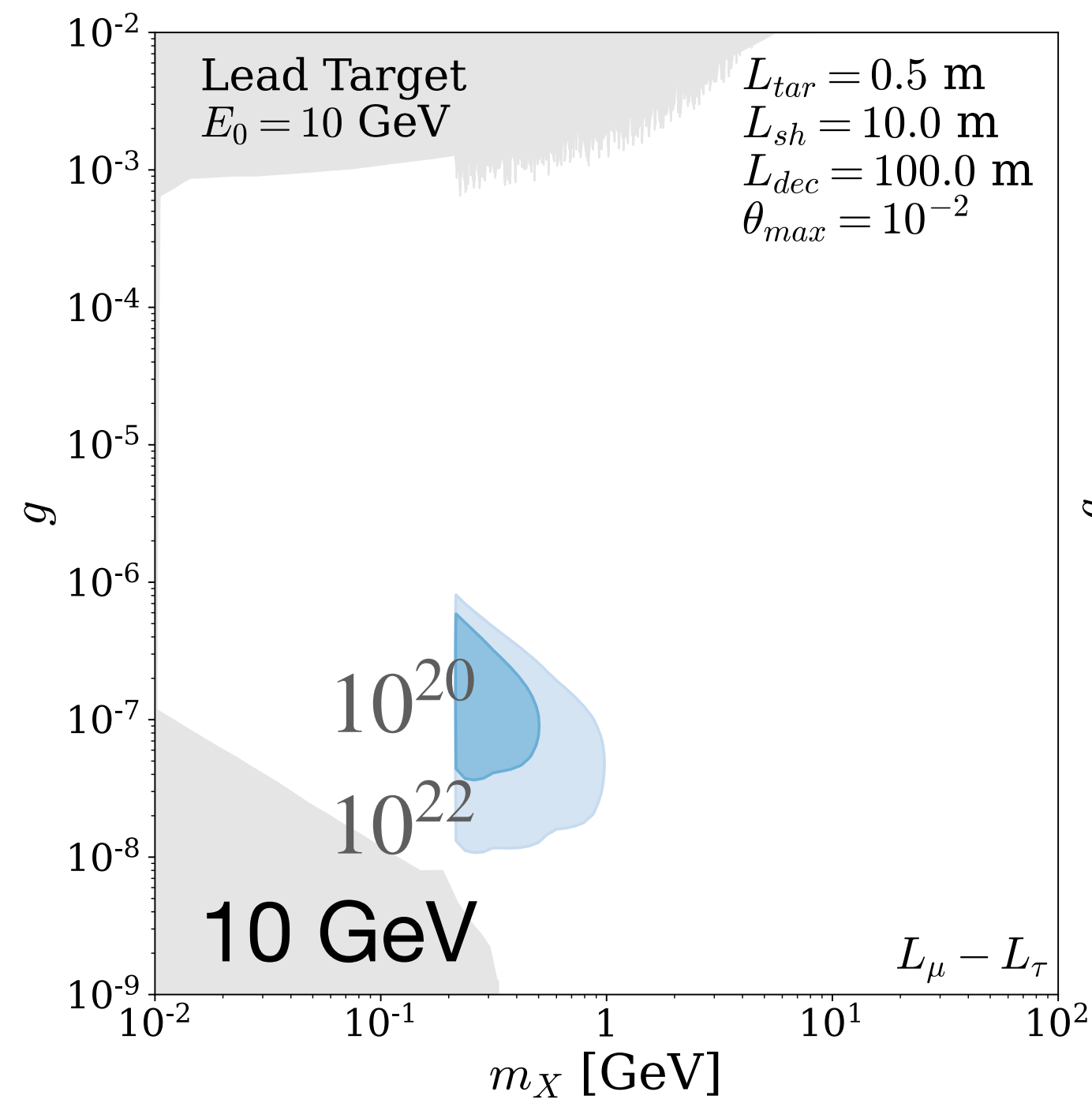




# Demonstrator Facility Beam Dump



CC, R. Gambhir, S. Alipour-Fard  
2306.XXXX



# 6D Cooling Beam Dump



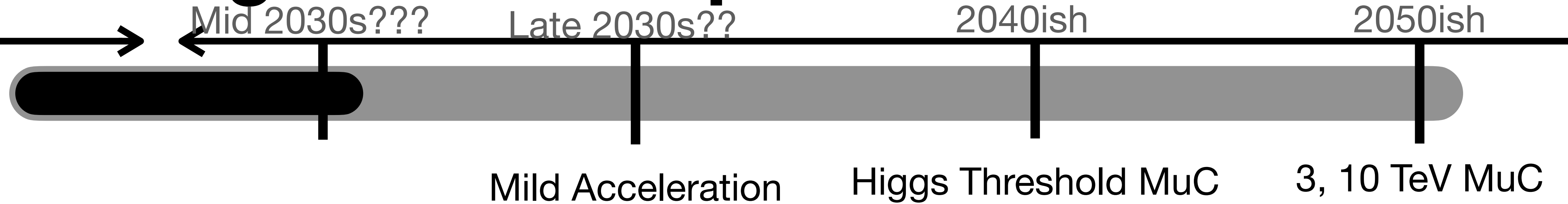
Proton  
Beam Dump?  
  
After LINAC?  
At 8 GeV?

Pion  
Bremsstrahlung?  
  
D. Curtin, Y. Kahn,  
R. Nguyen

$\mu$  at 200 MeV  
Beam Dump?  
  
WiP w/ M. Furslund  
& P. Meade



# 6D Cooling Beam Dump



Proton  
Beam Dump?  
  
After LINAC?  
At 8 GeV?

Pion  
Bremsstrahlung?  
  
D. Curtin, Y. Kahn,  
R. Nguyen

$\mu$  at 200 MeV  
Beam Dump?  
  
WiP w/ M. Furslund  
& P. Meade

The more physics cases we have,  
the more likely to get funded

# Conclusions

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There are **synergies** to be done with **demonstrators**

We **don't need to wait** for a full MuC to start probing  
new physics

Progress to be made with **beam dump** experiments