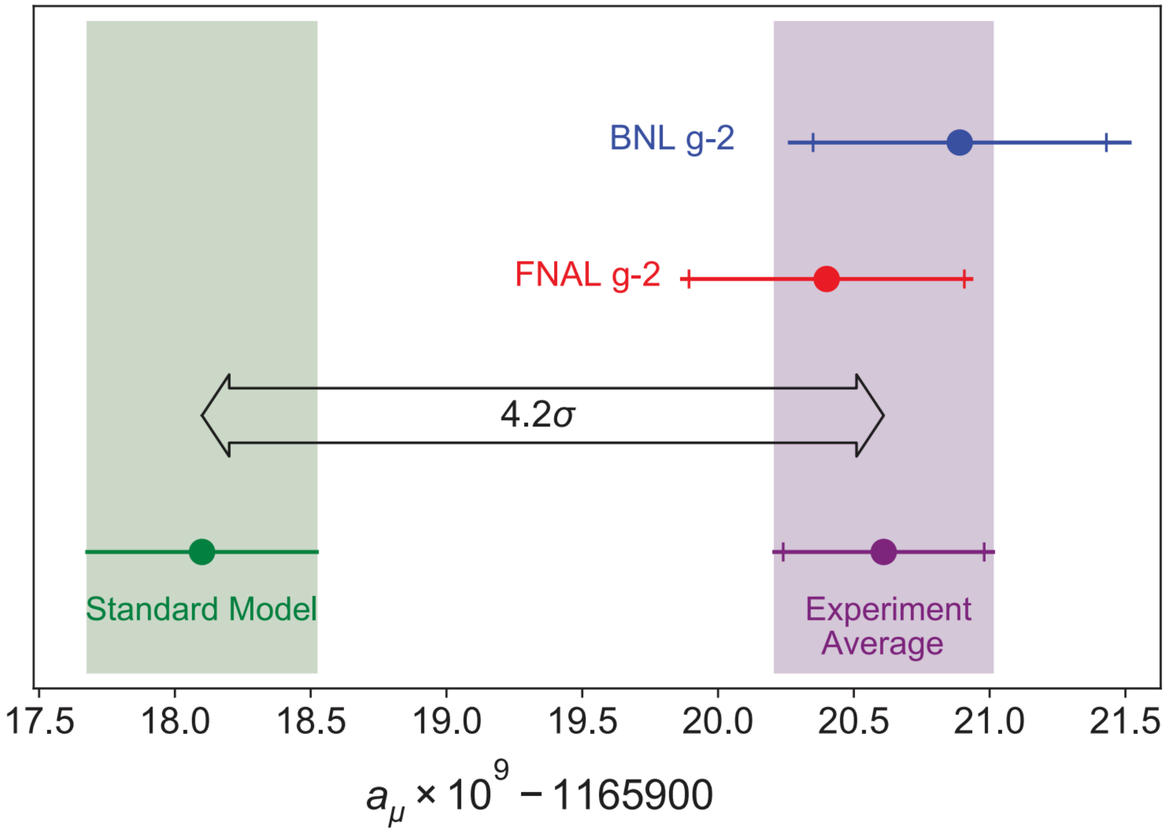
Muon Physics Program (and other μ ideas)

Future Colliders Workshop: Cool Copper Collider R&D

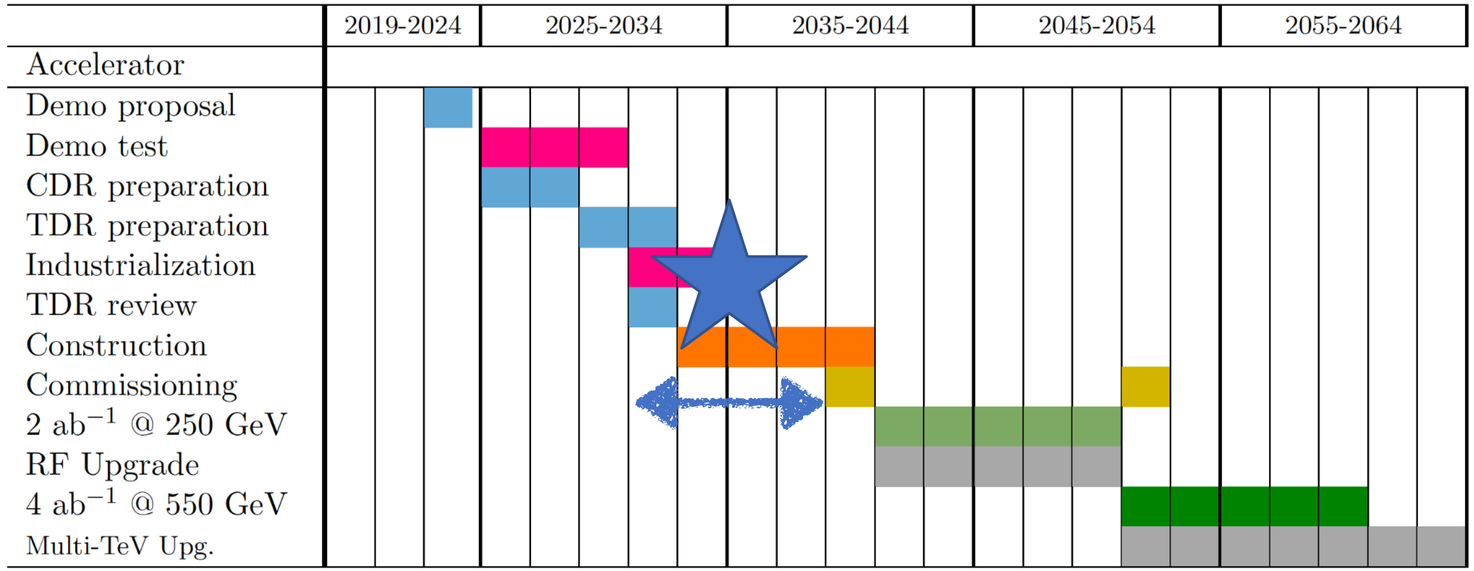
Dylan Rankin [MIT] - May 18th, 2022
(with very helpful and necessary input from Emilio Nanni)

Introduction

- Muons connected to many exciting recent physics results
- Having a (high energy) muon beam opens up many exciting possibilities for physics
- How do we get there? How do we test the technology?
  - What can we do along the way?
- n.b. not a muon collider talk



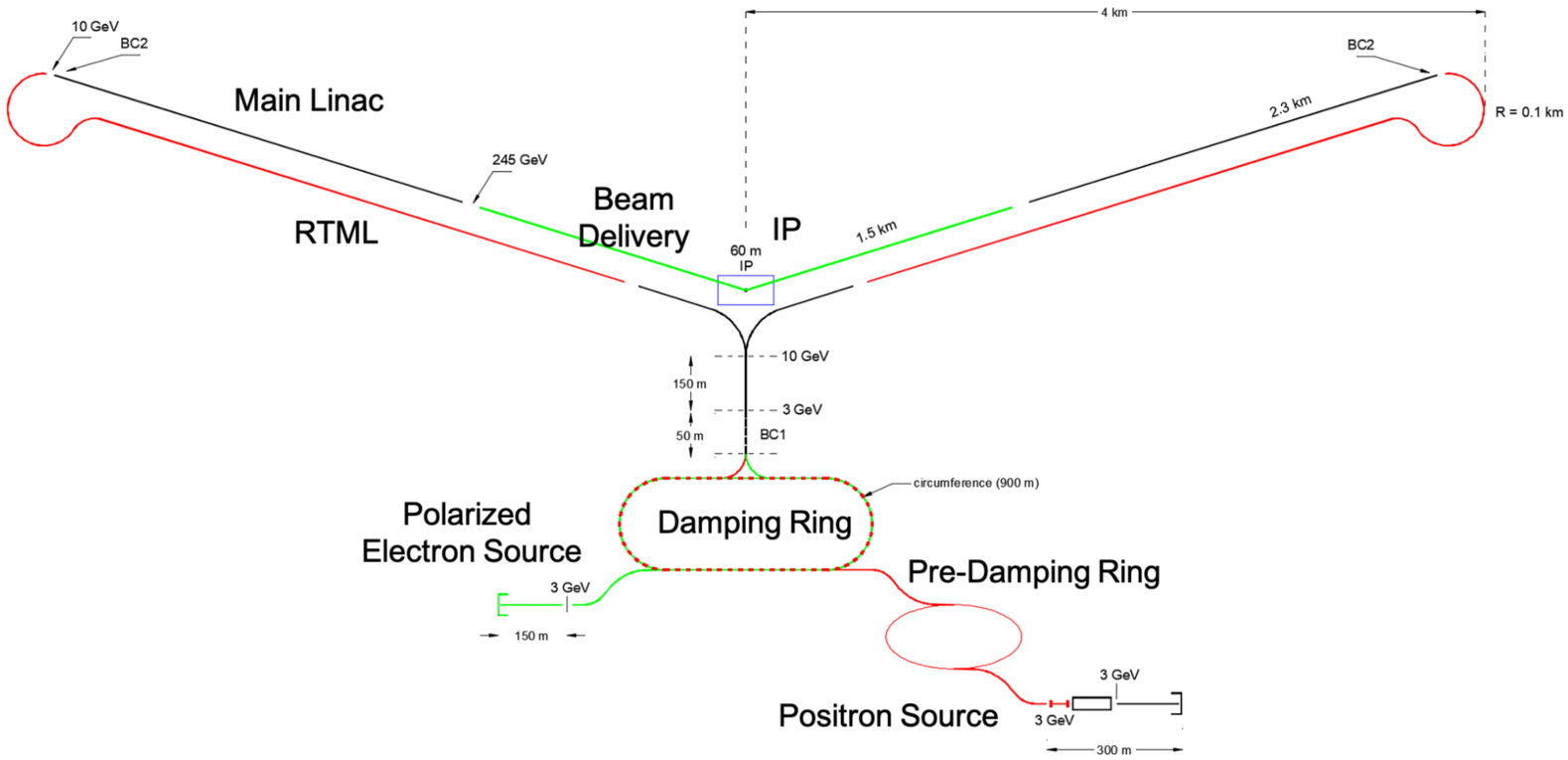
Physics During C³ Construction



- Between end of demonstration plan and first Higgs there is a 10-12 year gap
  - Ongoing industrialization and construction at site – Cryomodules and RF sources are being produced, put in tunnels
- **Could a string test be considered to build confidence in the technology, demonstrate operational parameters for additional sub-systems, train up project workforce and deliver physics?**

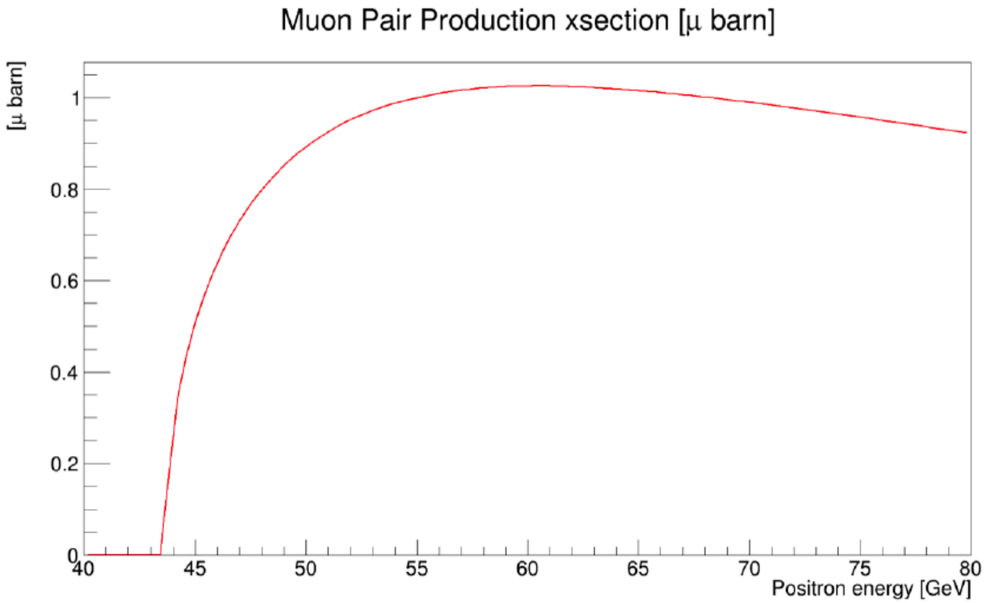
Physics During C³ Construction

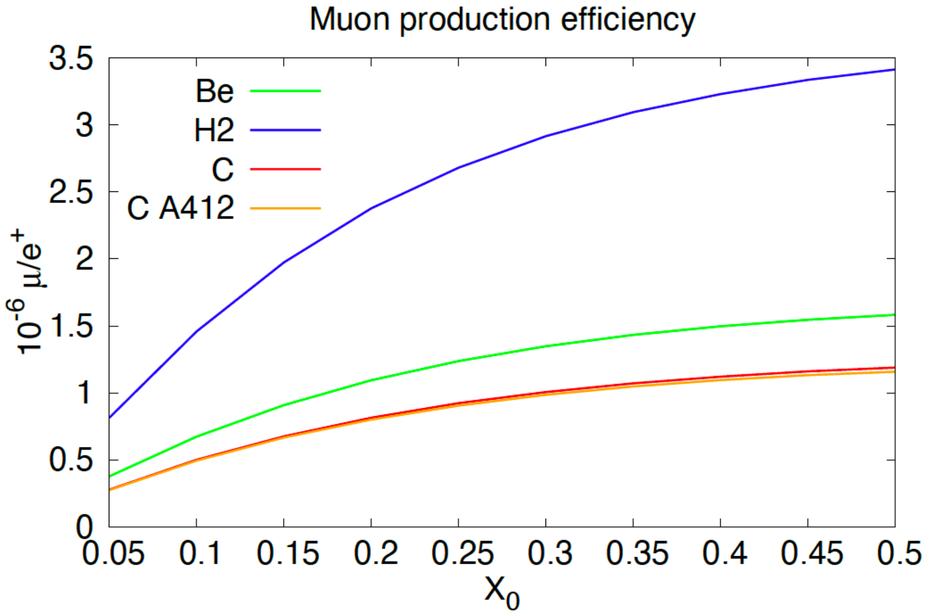
- String Test Elements:
  - Positron Source – Few GeV electron linac, positron target, positron capture
  - Damping ring?
  - Main linac to 45 GeV – ~550-700 m (low to high current), 1 cryo plant

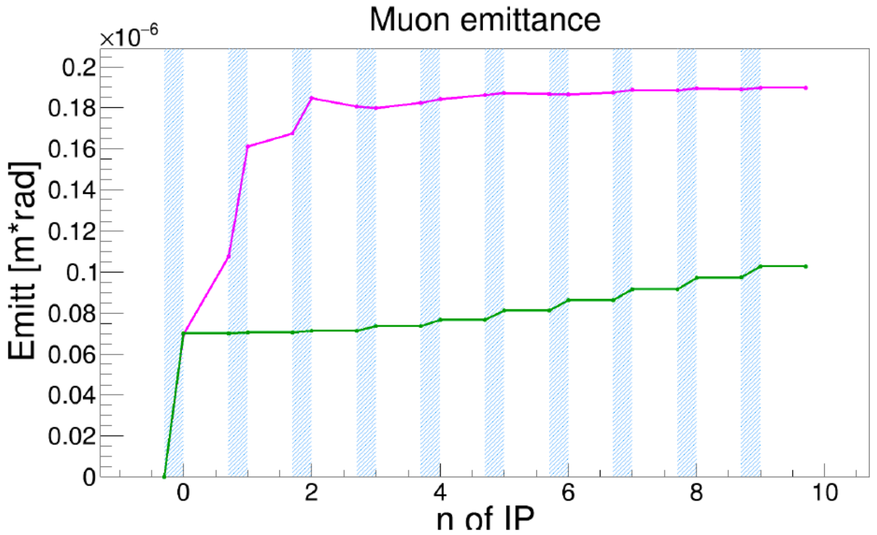


Muon Production with Positrons at 45 GeV

- LEMMA Concept (avoid muon cooling)
- Positron (45 GeV) on fixed low Z target
  - $e^+e^- \rightarrow \mu^+\mu^-$, muons at 22.5 GeV
- High conversion efficiency and low emittance







arXiv:1905.05747v2 [physics.acc-ph] 19 May 2019

Muon Production* with Positrons at 45 GeV for C^3

C3 String Test Low Muon Current

Parameter	Value
Number of RF Pulses Per Year (180 days)	1.87×10^9
RF Pulse Length	700 ns
# of Muons per RF Cycle	1
Muon Δt (smallest)	175 ps
Muons / Year (Max)	7.46×10^{12}

*LEMMA Target Singe Pass

Includes 10^{-6} efficiency for e^+ conversion

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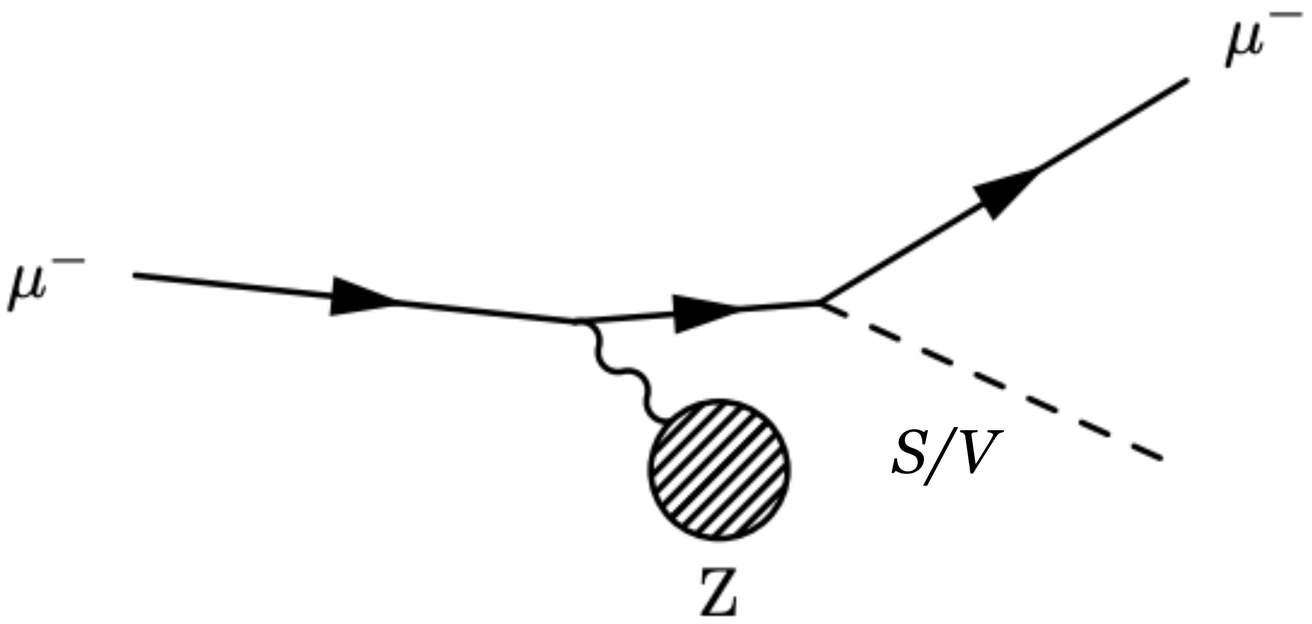
# of Bunches per RF Pulse	133
# of Muons per Bunch	6×10^3
# of Muons per RF Pulse	8×10^5
Muon Δt (smallest)	5.26 ns
Muons / Year (Max)	1.5×10^{15}

Muon Beam Physics

- What physics can be done with this muon beam?
- Muon beam dump
  - Minimal additional infrastructure if beam beam is produced
- Higher energies could allow more tests of muon acceleration
- e-μ collider?

Muon Beam Dump

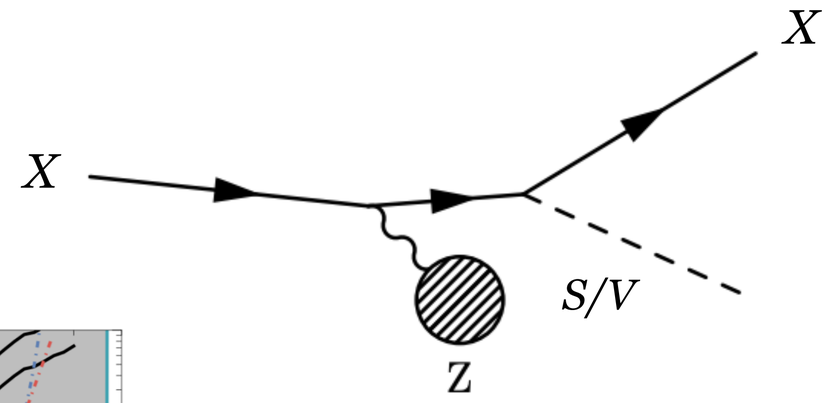
- Muon beam incident on target (Z)

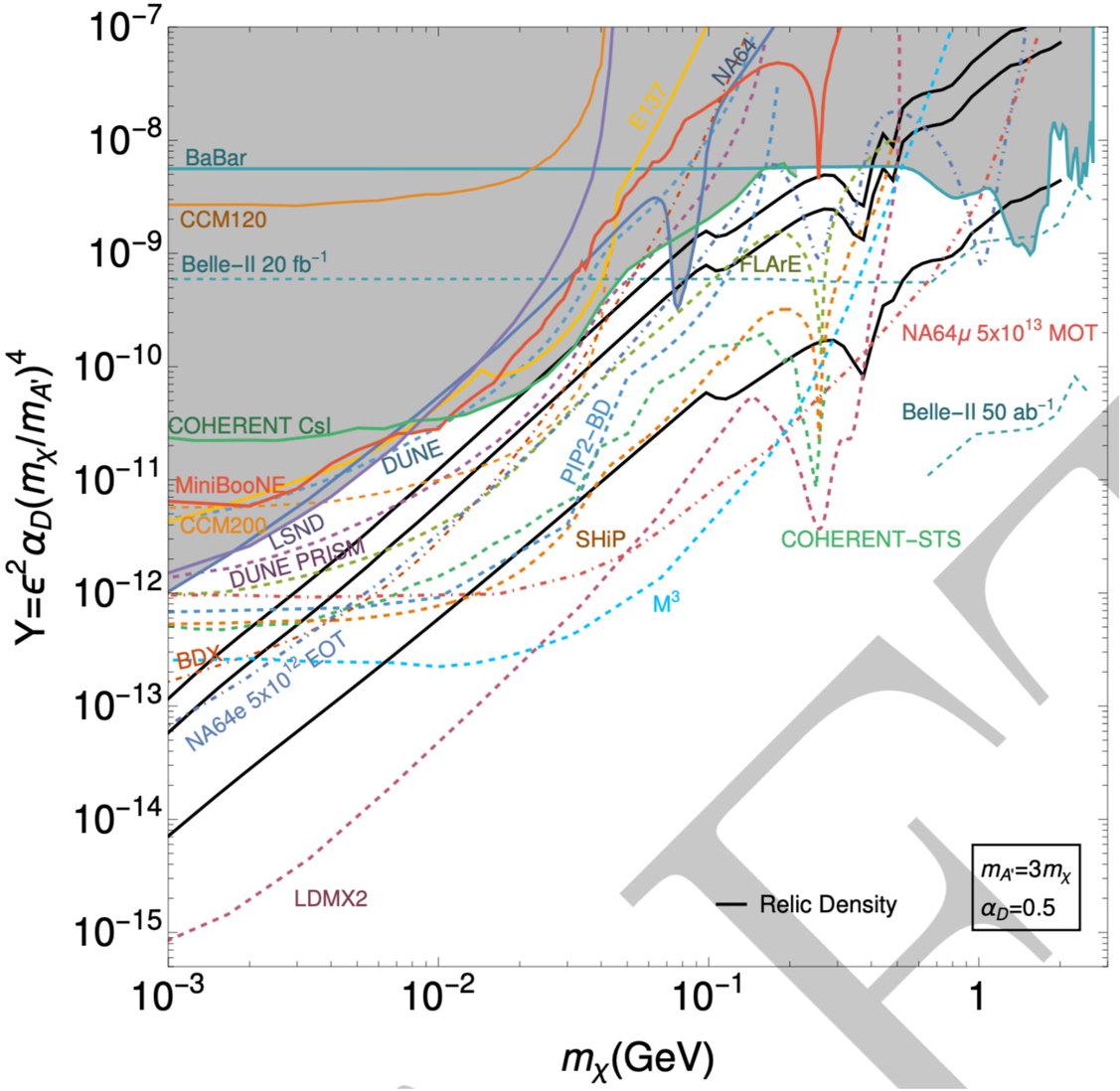


detector

Why a Beam Dump?

- Dark matter





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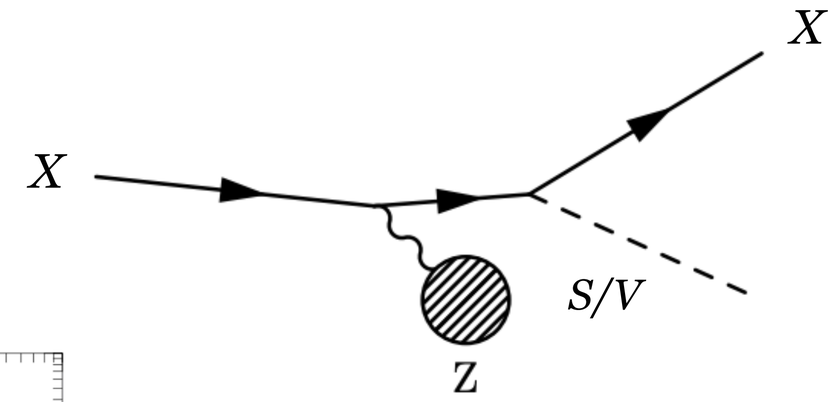
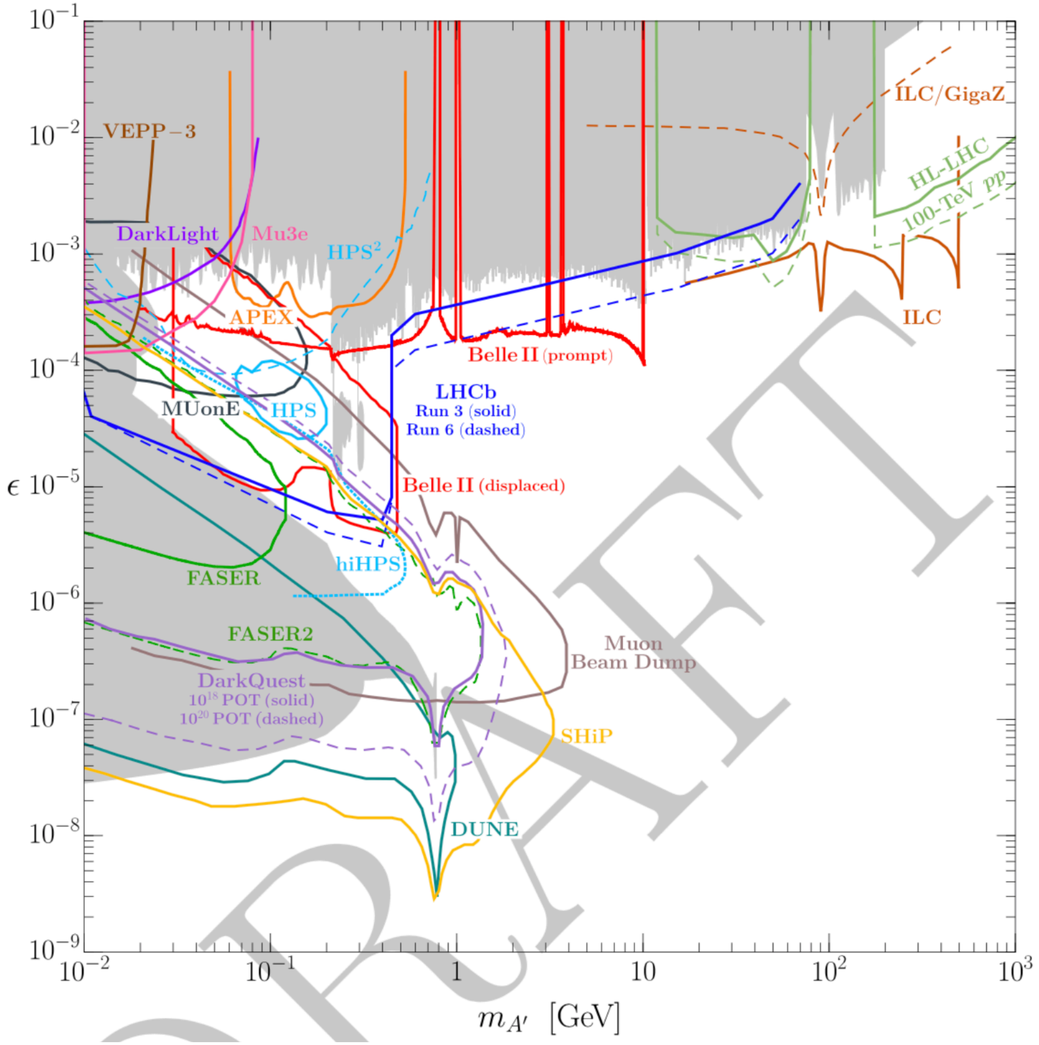
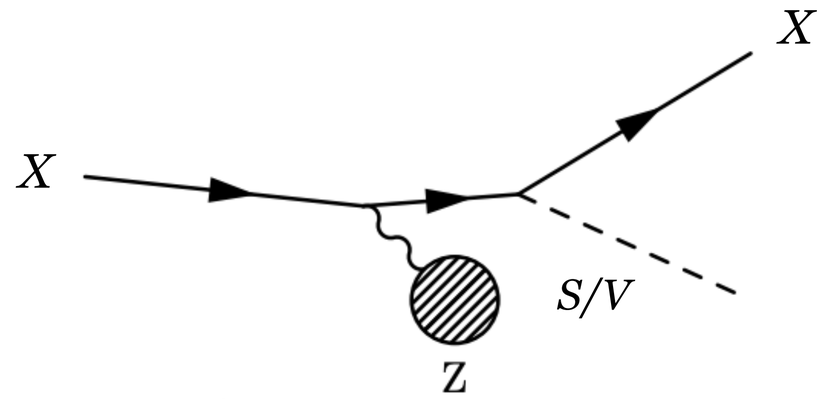


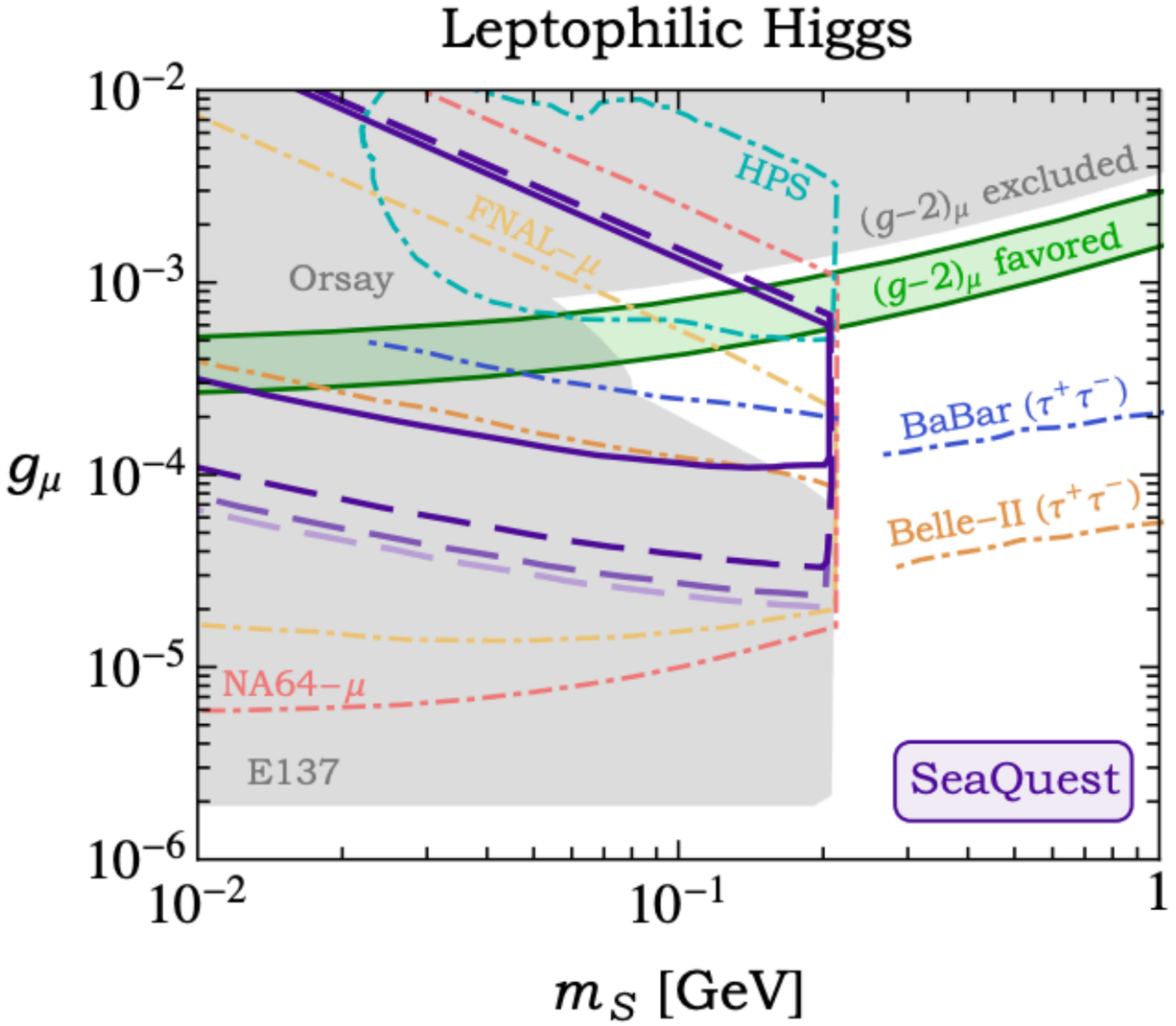
- Dark photon



Why a Beam Dump?

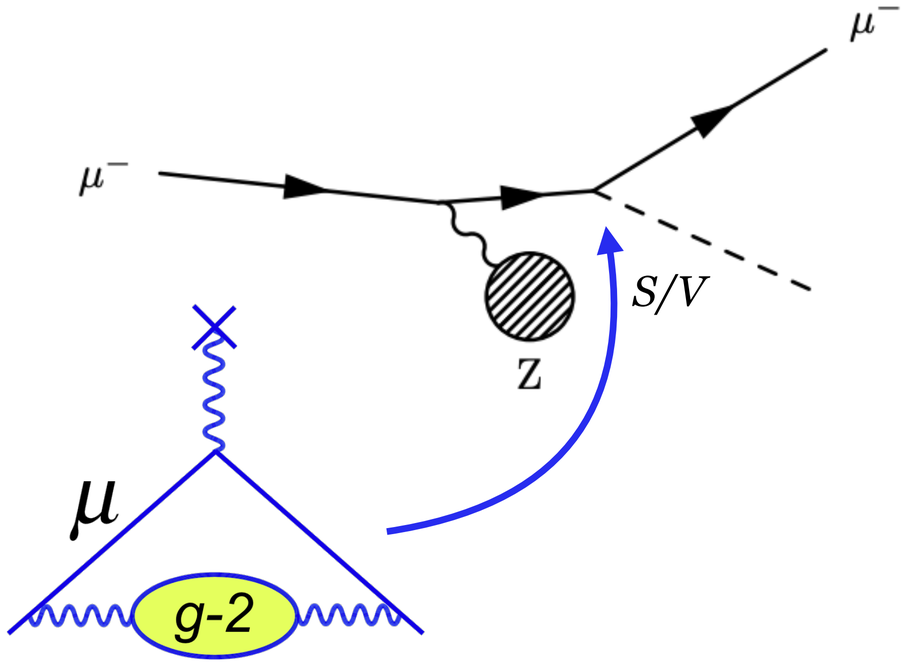
- Weakly coupled scalars
  - eg. $U(1)_{L_\mu - L_\tau}$



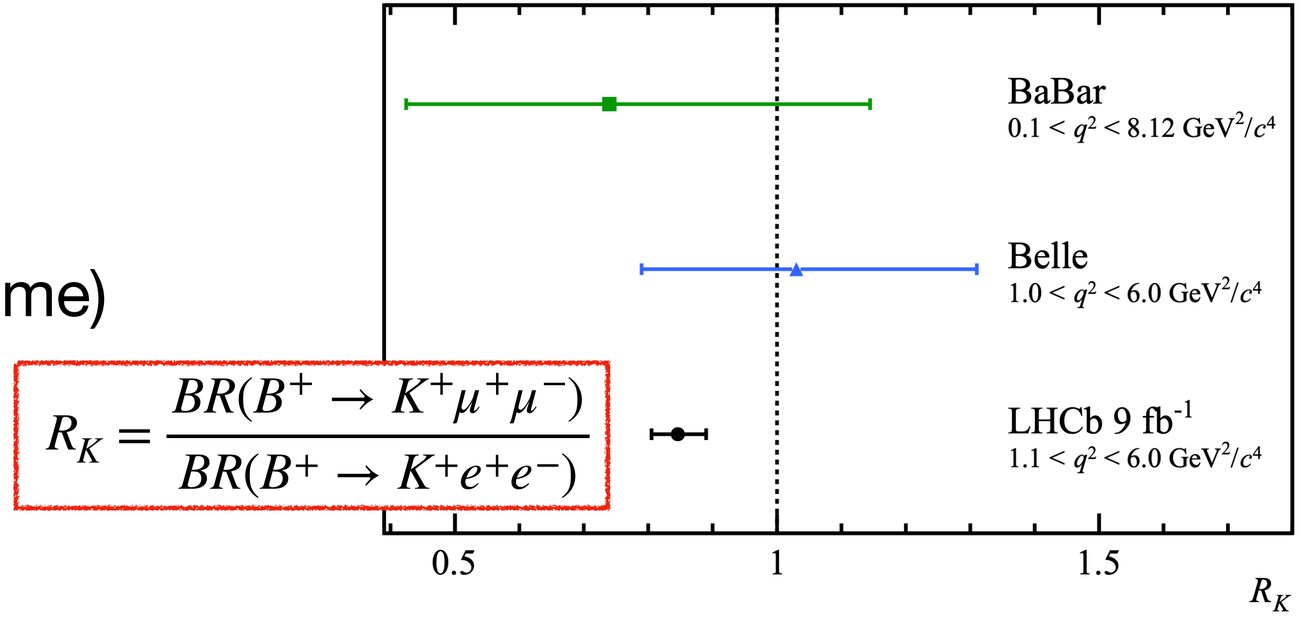


Why Muons?

- Many existing beam dump experiments with electrons
- Two main advantages for muons:
  - Preferential new physics couplings to muons
    - g-2, R_K (& R_{K^*}, R_D, R_{D^*})
  - Higher beam energies
    - Different scenarios (mass, lifetime)

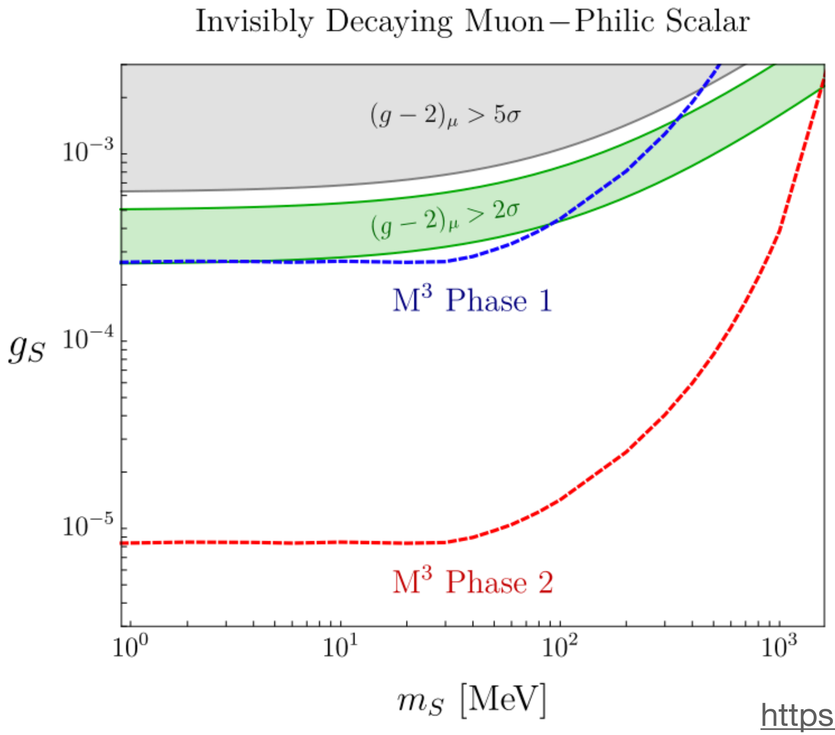


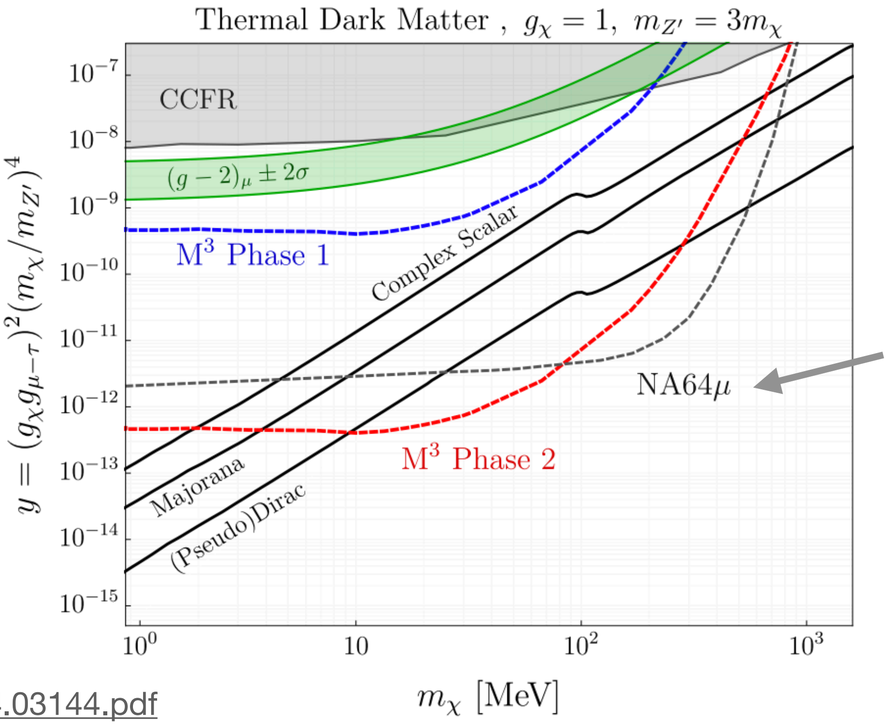
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$



Muon Missing Momentum (M^3)

- 15 GeV muon beam
- Phase 1: 10^{10} muons on target (MOT), probe large part of $(g\text{-}2)_\mu$ region
- Phase 2: 10^{13} MOT, thermal muon-philic DM search



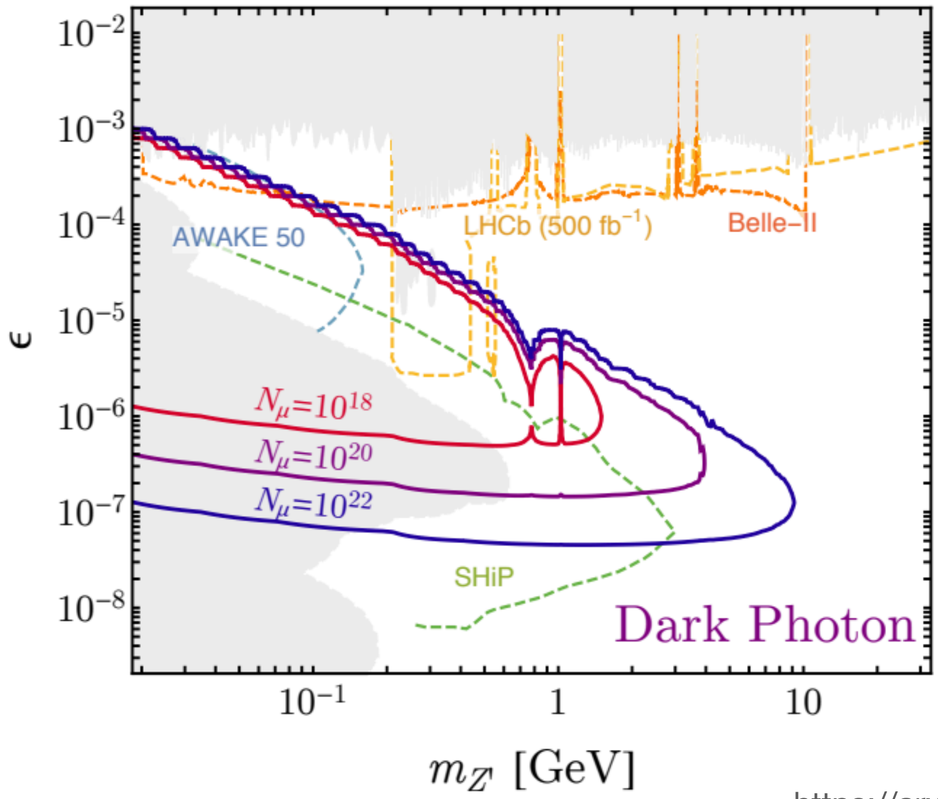


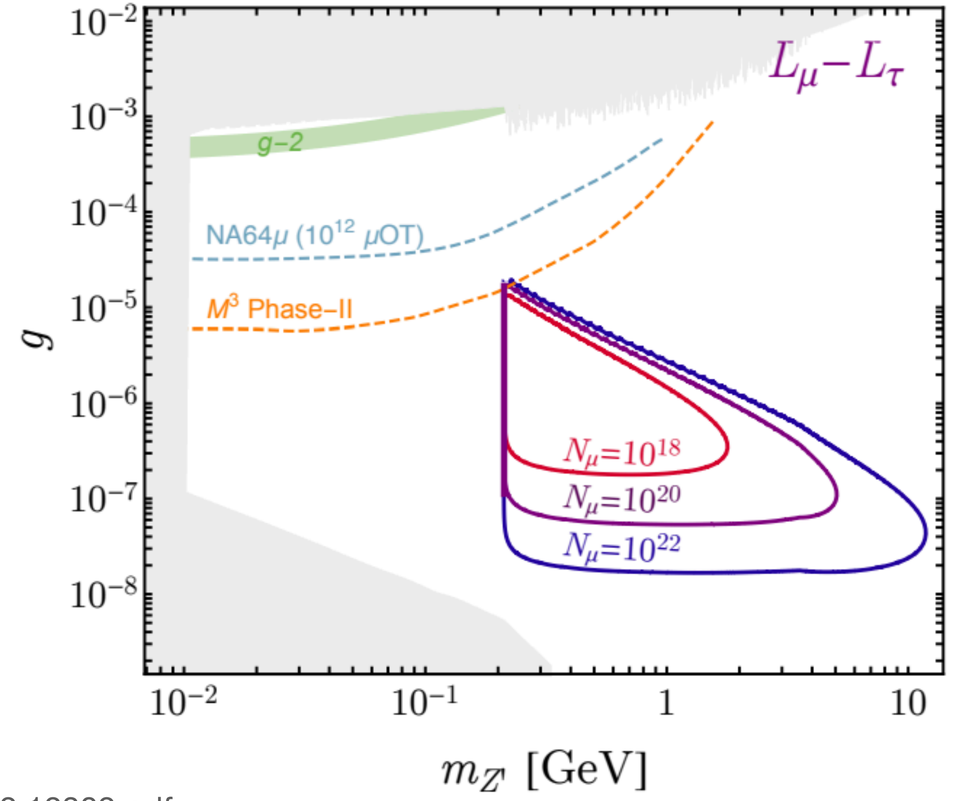
also muon beam dump

https://arxiv.org/pdf/1804.03144.pdf

High-Energy Muon Beam Dump

- Envisioned for 3 TeV muon collider (1.5 TeV μ)
- 10^{18} - 10^{22} MOT





https://arxiv.org/pdf/2202.12302.pdf

M^3 (Phase 1)

- Fermilab Main Injector beamline provides proton beam of 120 GeV with an RF frequency of 53 MHz
  - 4.2 s spills
  - Final expected rate is 10^5 muons per spill
- 10–30 GeV muon beam
  - Transverse beam size is roughly a few centimeters in x and y
- The time between spills is approximately one minute
- Over one week of continuous running, this sums to approximately 10^9 MOT
  - **2.5 x 10^{10} MOT / yr**

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Muons / Year (Max)	**7.46 x 10^{12}**

(Taken from https://arxiv.org/pdf/1804.03144.pdf)

M^3 (Phase 2 +)

- Phase 2 requires upgrades to accelerator (beamline), detector (trigger)
  - 10^7 muons per spill
- **2.5 x 10^{12} MOT / yr**

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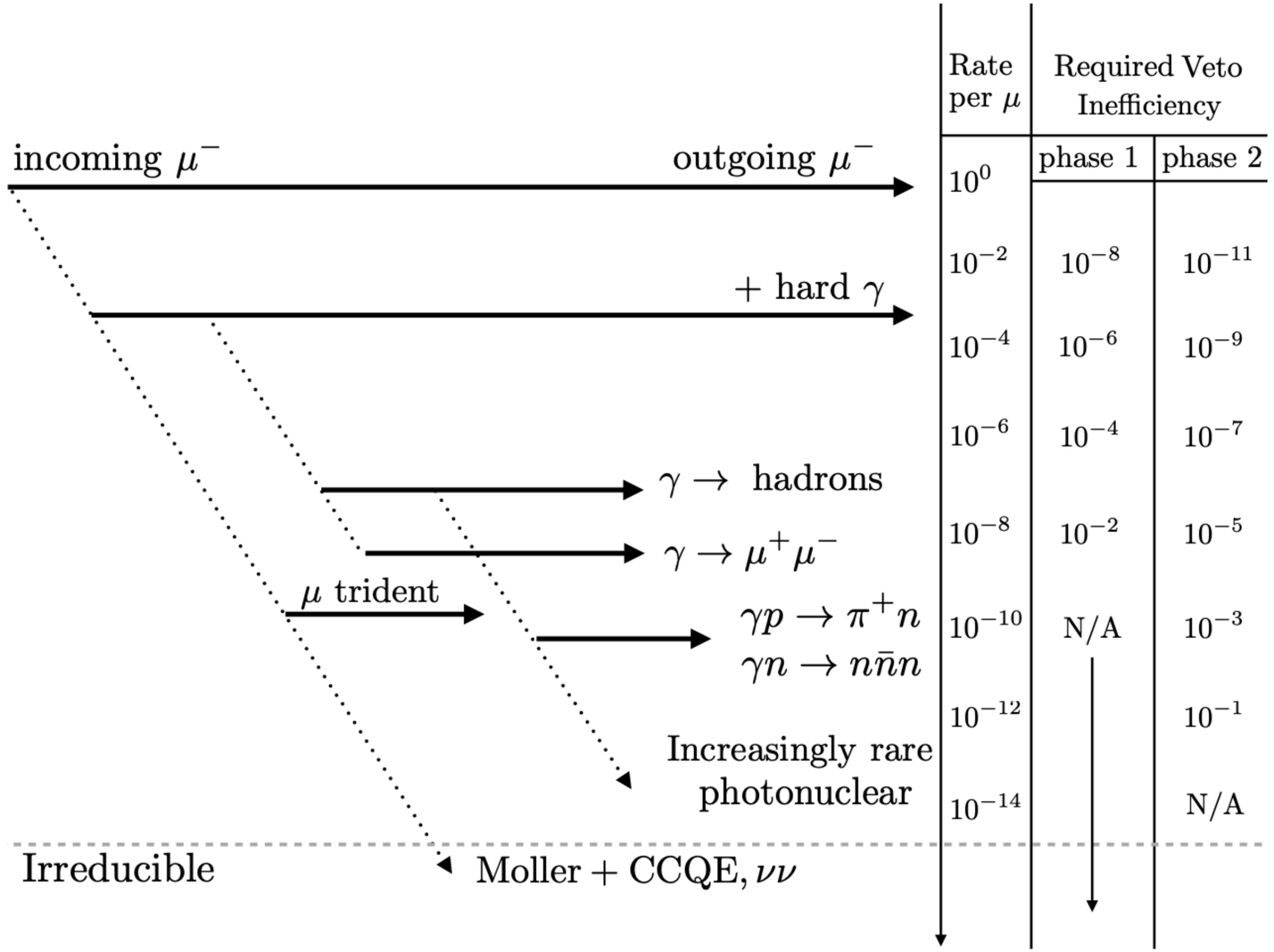
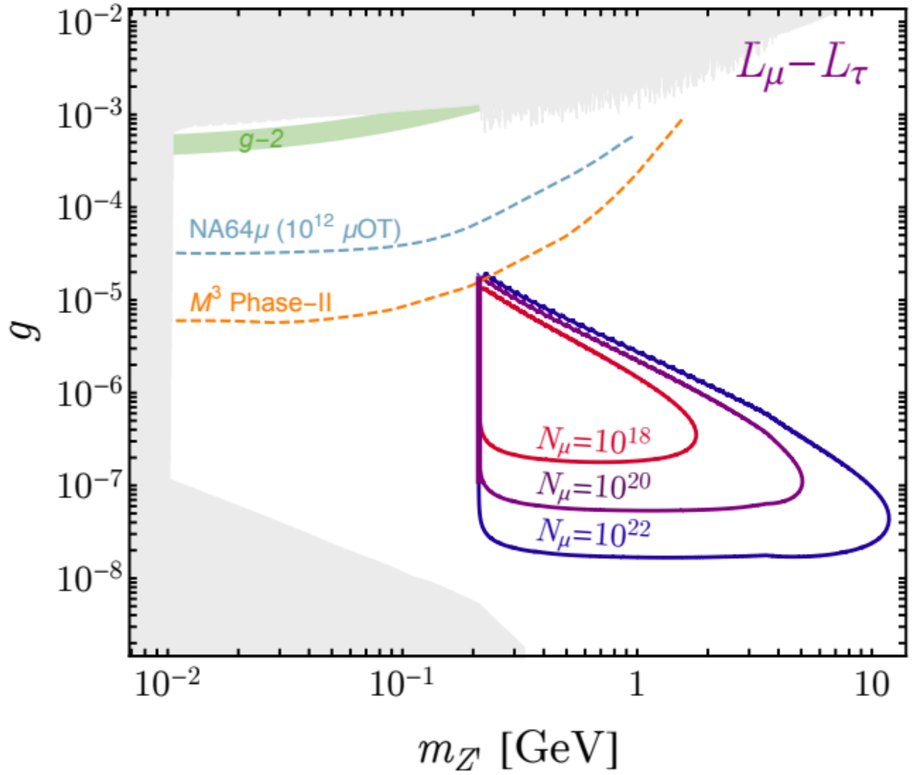
M³ (Phase 2 +)

- 10^{15} MOT from C³ gets to irreducible background floor for M³
- Nice place to be
  - Increase in MOT would not improve limits significantly



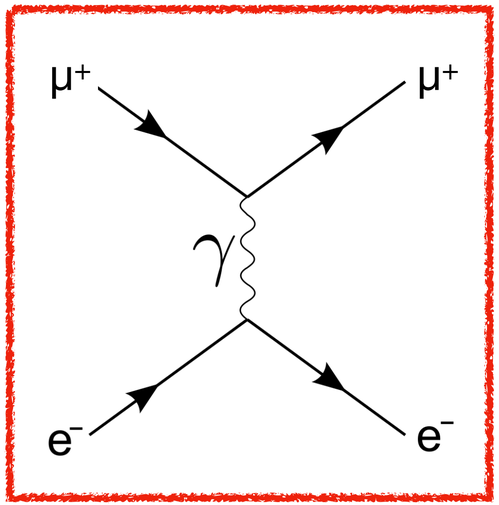
High-Energy Muon Beam Dump

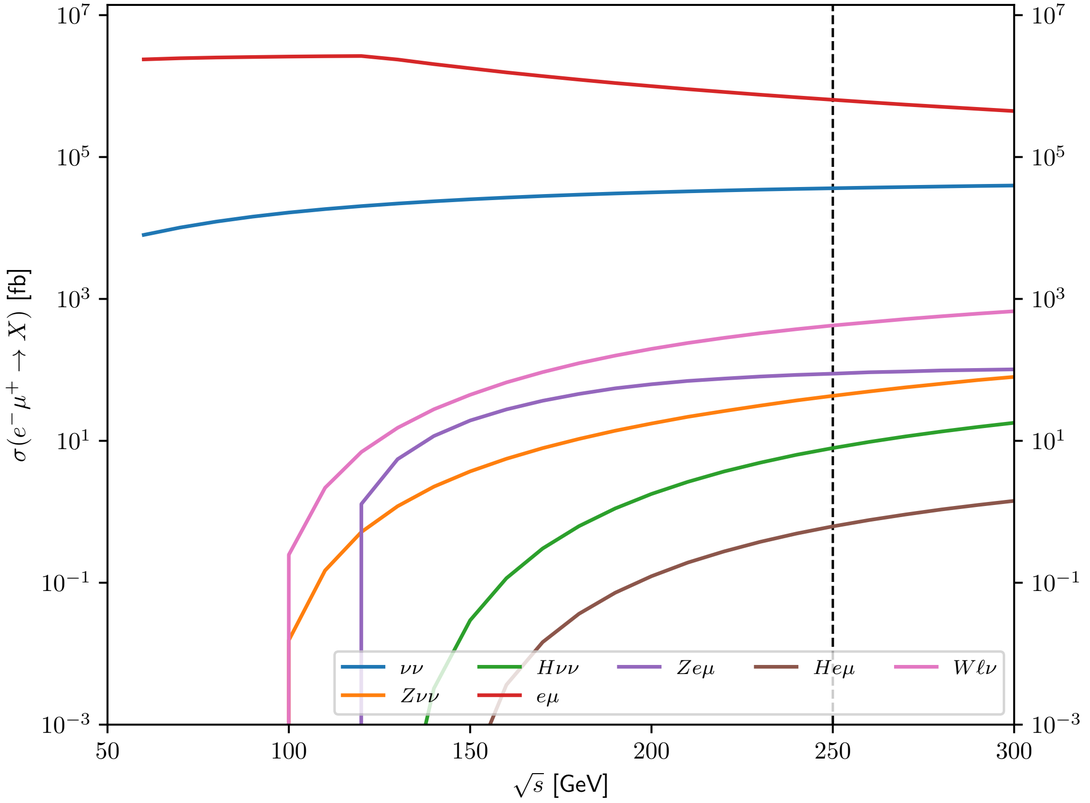
- What is gained from increasing muon energy?
- From physics perspective, adjust the probed parameter space
  - e.g. for DM, increased E_μ → increased m_{med}
    - 500 GeV beam → 20 GeV m_{med}
    - 50 GeV beam → 5 GeV m_{med}
- What else could be done?



Just one idea: e-μ Collider

- Would have muons in C³ complex, could you use them for collisions?
- e-μ collider
  - t-channel, very low backgrounds
  - LFV (H, Z)? Leptoquarks?





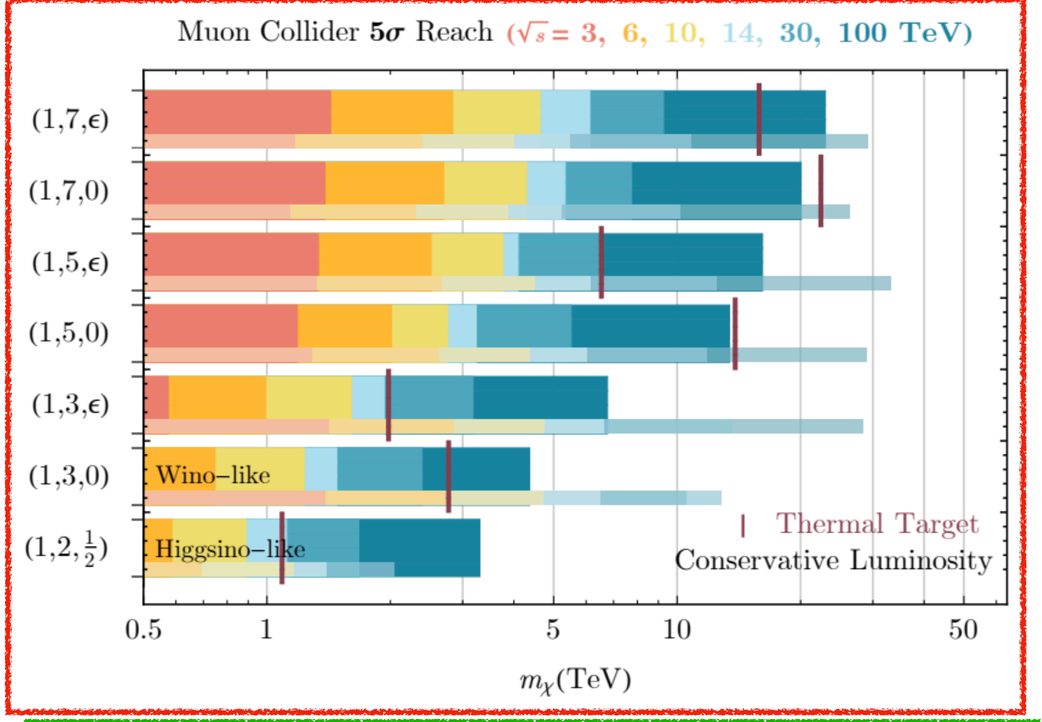
Conclusions

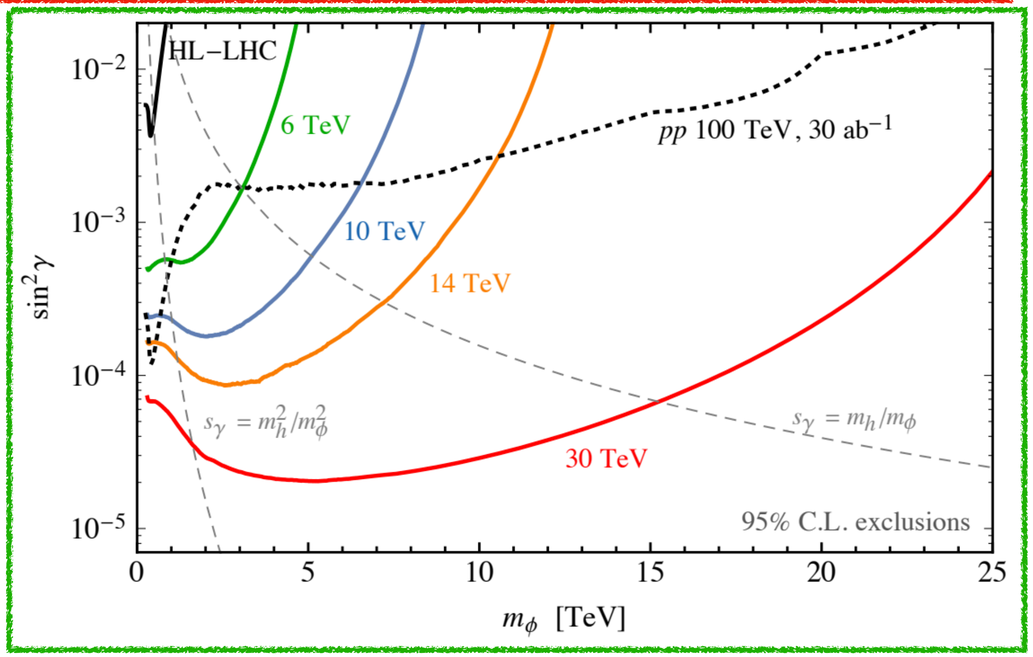
- C^3 construction period lasts 10 years
- Simultaneous tests could have many benefits
  - Test the technology, demonstrate operational parameters, deliver physics?
- Muon beam dumps are a very attractive idea for this
  - Minimal additional infrastructure
  - Strong test of muon production
  - Rough numbers for C^3 are in the ballpark (or better) than what would be needed
- Should explore other ideas too
  - e-μ? Low energy muon collider?
  - Also not dependent on muons: e^+/e^- beam dump?

BACKUP

Muon Collider

- Muon collider provides ability to probe/ discover range of physics
  - Generic BSM modifications
  - Dark matter
  - Heavy scalars
  - Composite/Twin Higgs
- Complementarity in many cases





https://arxiv.org/pdf/2103.14043.pdf

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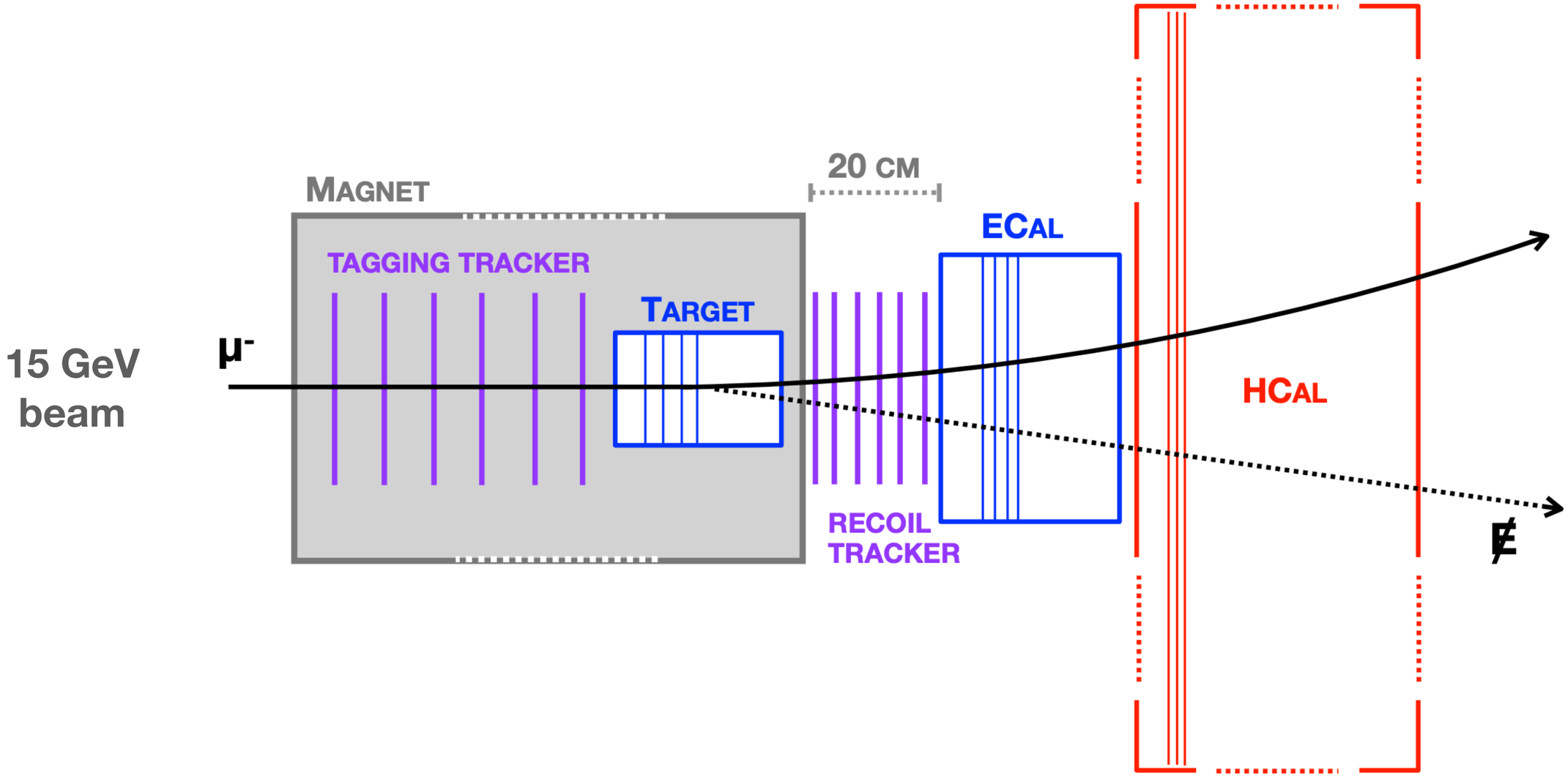

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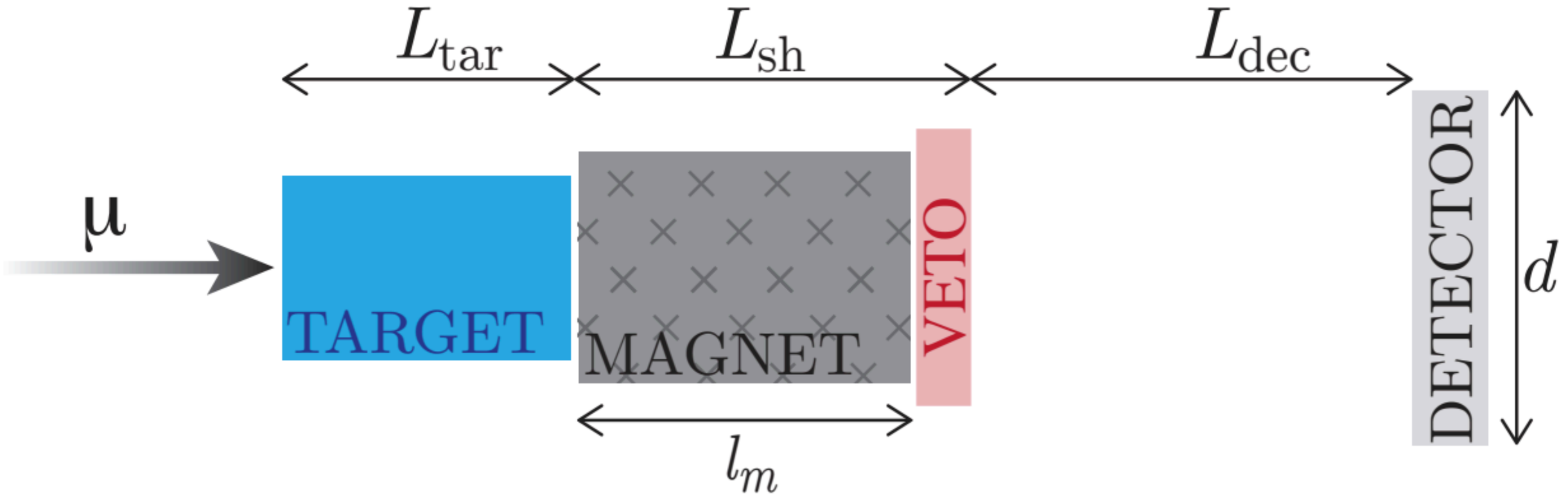

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