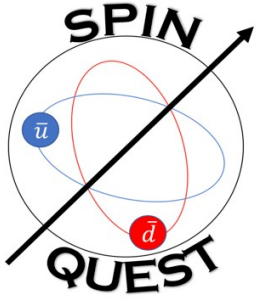




BOSTON UNIVERSITY

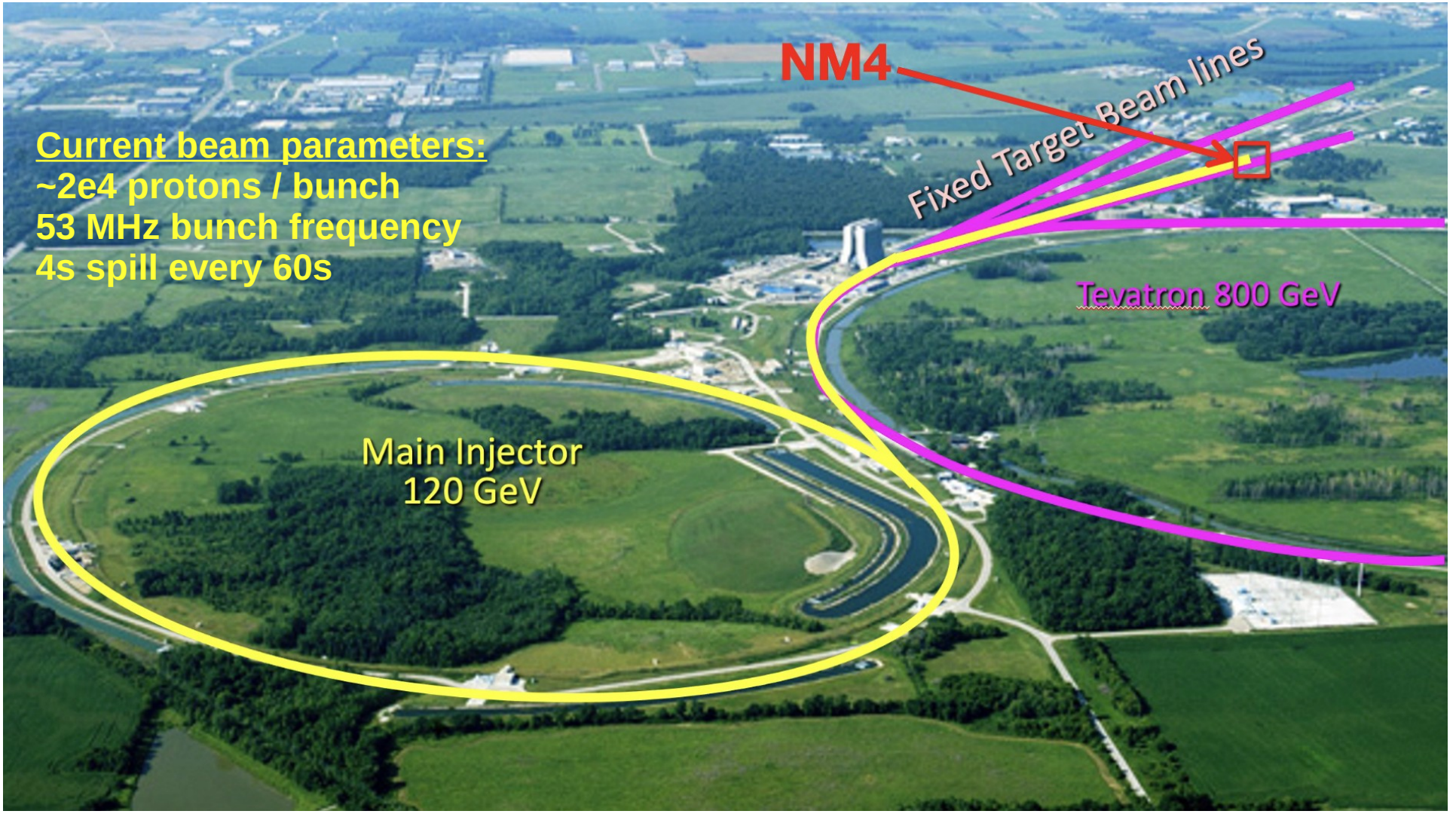
# *Physics Opportunities for Fixed Target and Beam Dump Experiments with the Main Injector 120 GeV Proton Beam*

David Sperka
(Boston University)

A.C.E. Workshop at Fermilab

June 15th 2023

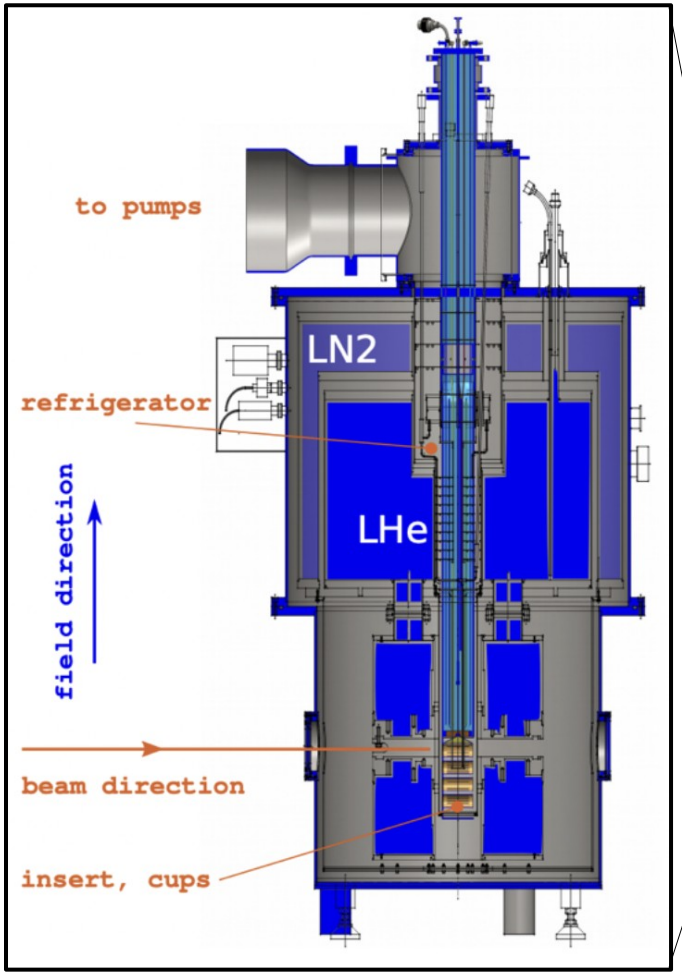
# Main Injector 120 GeV Proton Beam

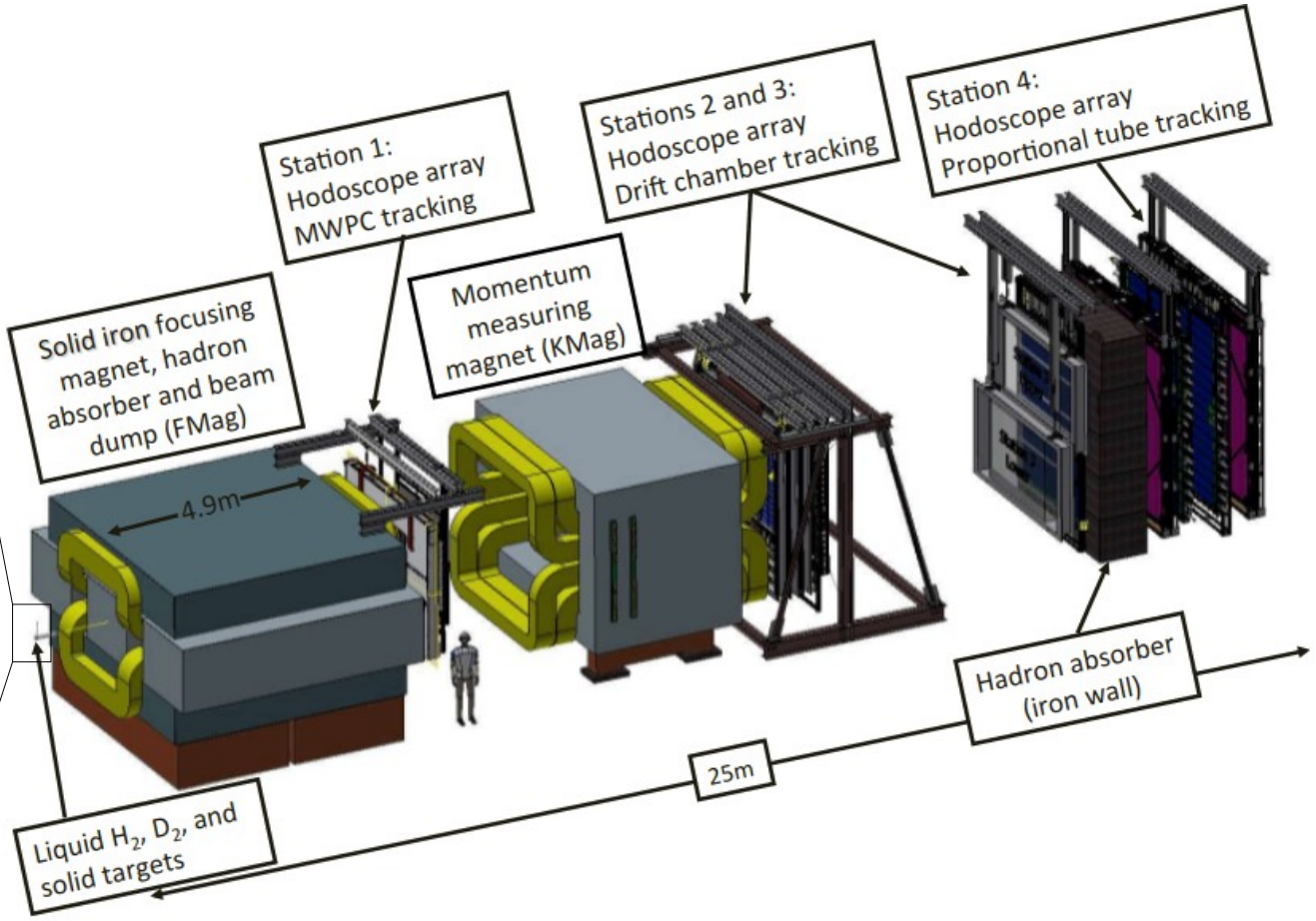



- NM4 experimental hall sits on the 120 GeV Main Injector beamline
  → Expect 1e18 POT in a 2 year run before the PIP-II upgrade
  → For projections have assumed 1e20 POT after the PIP-II upgrade

# SpinQuest Target & Spectrometer

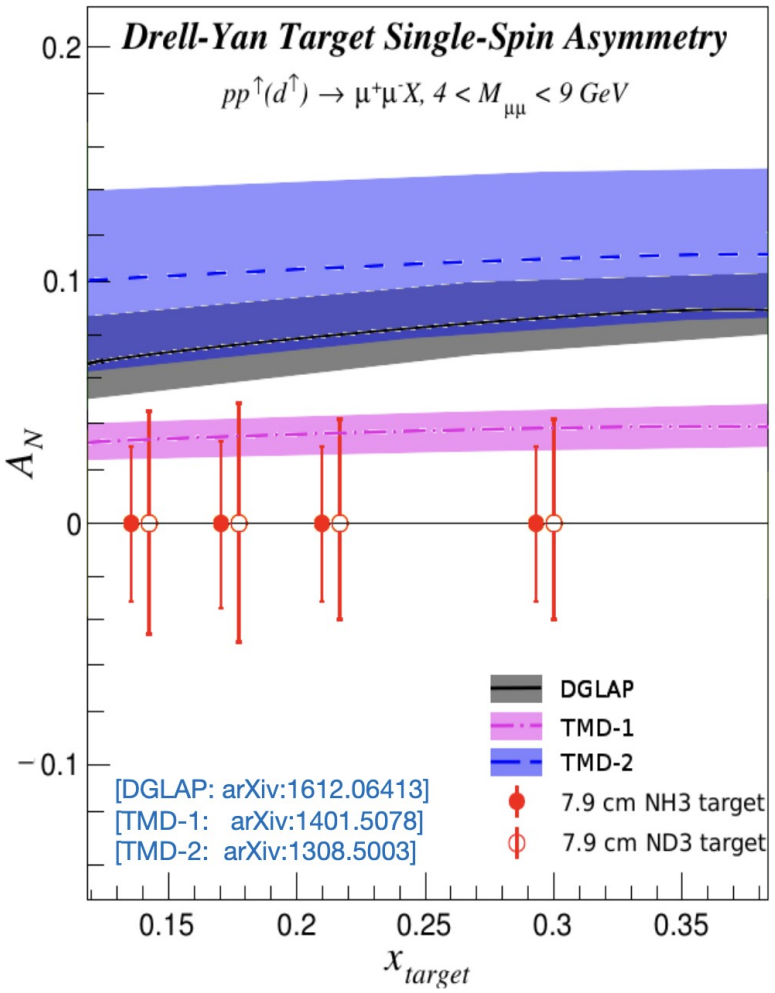
- Spectrometer has 5m thick Fmag (1.8T) as the beam dump and absorber, hollow KMag (0.4T) for tracking, and 4 stations of drift chambers (tracking) and scintillator hodoscopes (triggering)



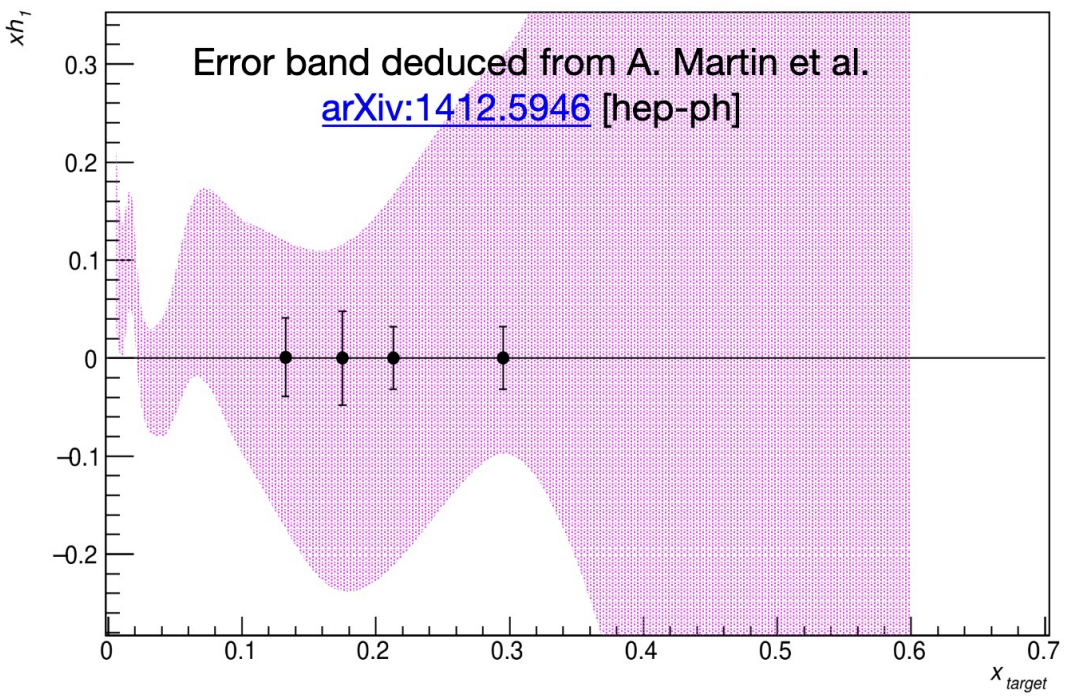



# SpinQuest Nuclear Physics Program

Anticipated Sensitivity

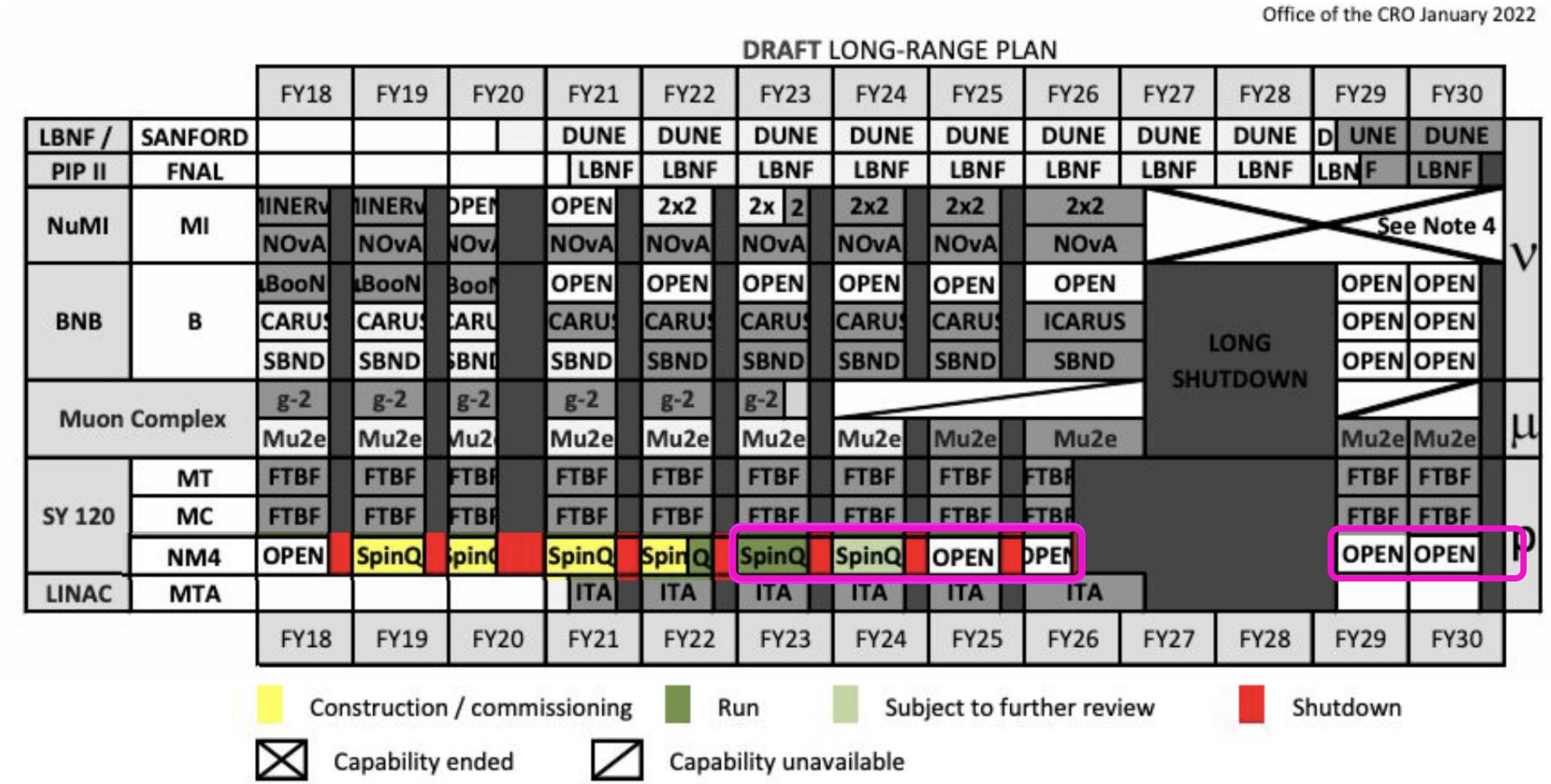



Anticipated seaquark transversity sensitivity




- Specialized cryogenic target to measure the Sea-quark Sivers asymmetry
  - Test of whether sea quarks have orbital angular momentum
- Minor upgrades to the target NMR system enable Transversity measurements

# Main Injector 120 GeV Proton Beam




- SpinQuest approved for a 2 year run. Joint NP/HEP upgrade "DarkQuest" has been presented to the PAC and has received stage 0 and contingent stage 1 approval
  - Subject to the ongoing review process for bringing first beam to NM4 in 2023

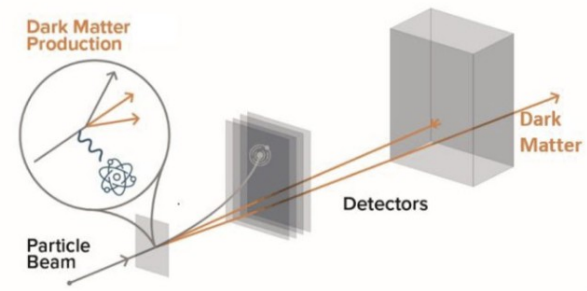
# Physics Goals from Snowmass

We (RF6) defined **three Big Ideas** each with associated ambitious —but achievable—goals for the next decade

**1.** Dark matter production at intensity-frontier experiments

Focus on exploring sensitivity to thermal DM interaction strengths.

https://arxiv.org/abs/2207.00597

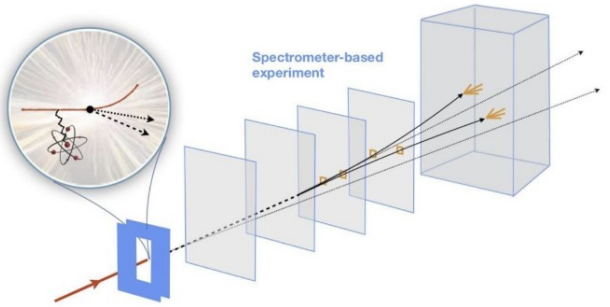



**2.** Exploring dark sector portals with intensity-frontier experiments

Focus on minimal portal interactions.

Prompt and long-lived mediators.

https://arxiv.org/abs/2207.06905




**3.** New flavors and rich structures of the dark sector at intensity-frontier experiments

Focus on beyond minimal models.

https://arxiv.org/pdf/2207.08990.pdf

Snowmass RF6 Report: SG, Williams et al., https://arxiv.org/pdf/2209.04671.pdf

Stefania Gori, BNL P5 Townhall Meeting

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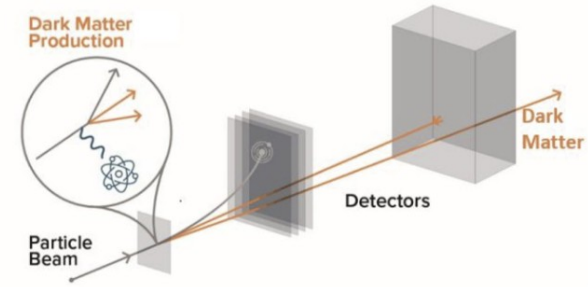


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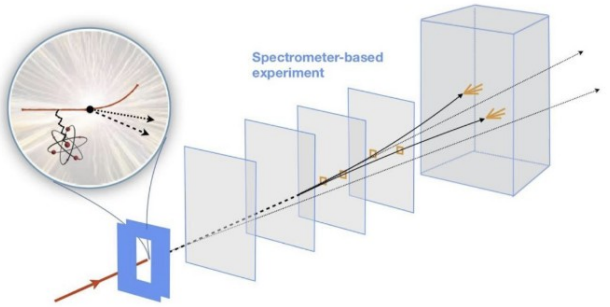


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Stefania Gori, BNL P5 Townhall Meeting

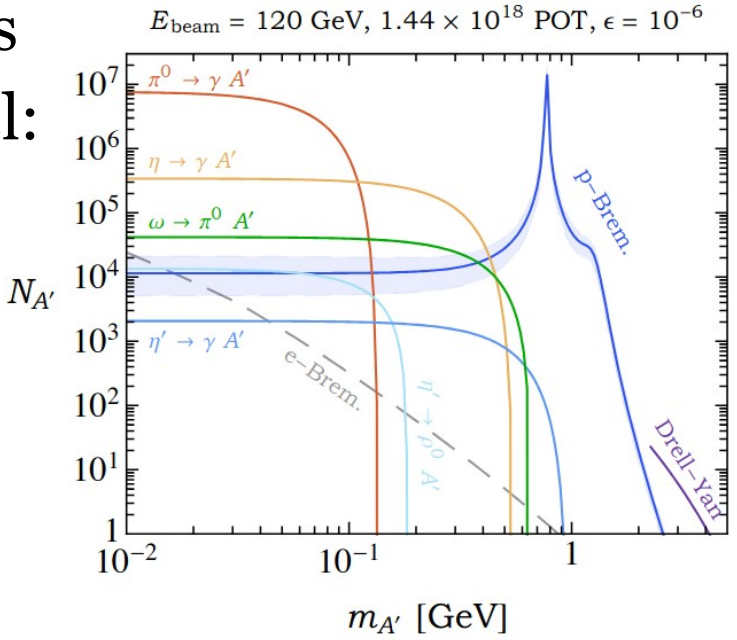
# Dark Sector Particle Production

*A. Berlin, S. Gori, P. Schuster, N. Toro*
arxiv:1804.00661

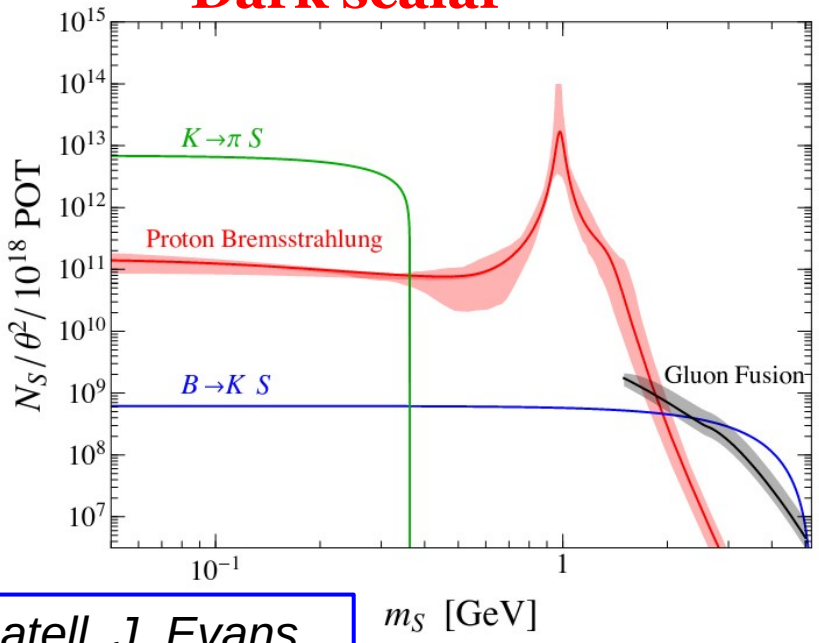
- Copious production of dark sector particles in variety of BSM models
- Mechanism depends on the model:

  → Proton bremsstrahlung, meson decay, tau decay

## Dark vector

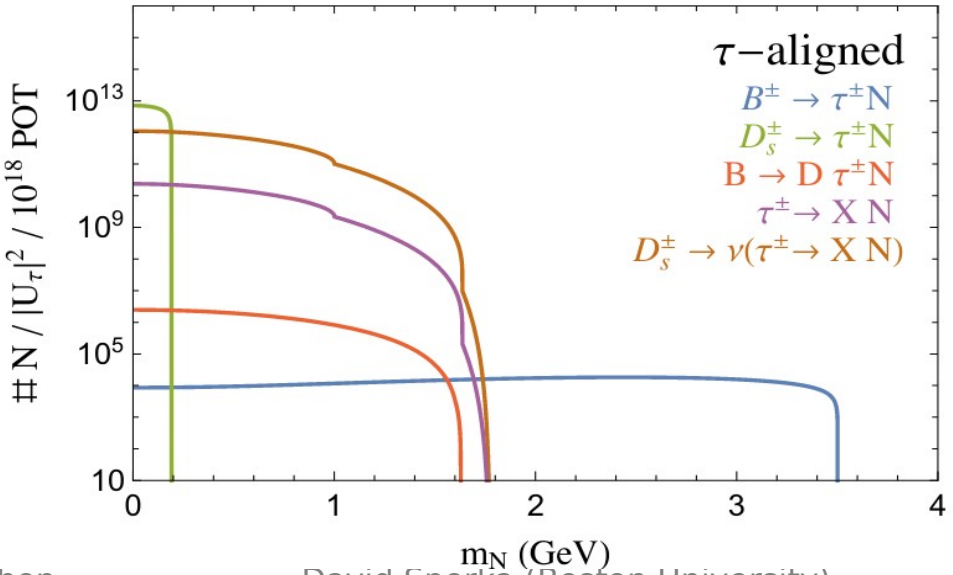



## Dark scalar




*B. Batell, J. Evans, S. Gori, M. Rai*
arxiv:2008.08108

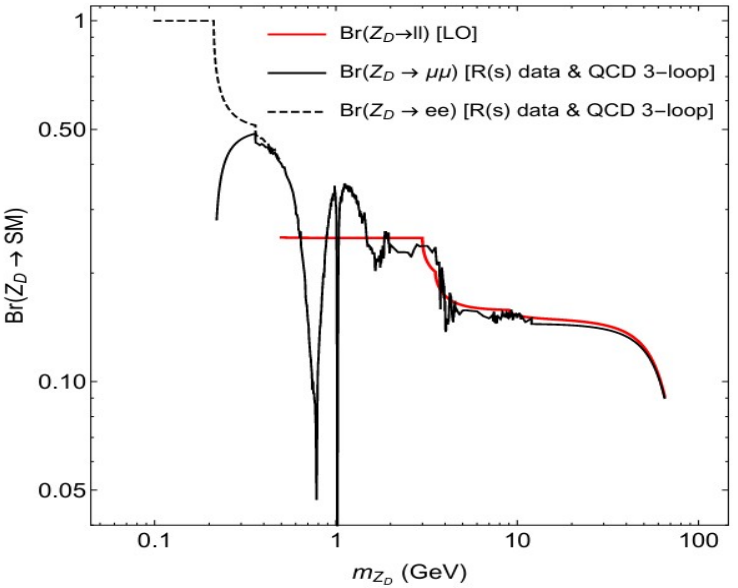
## Heavy Neutral Lepton



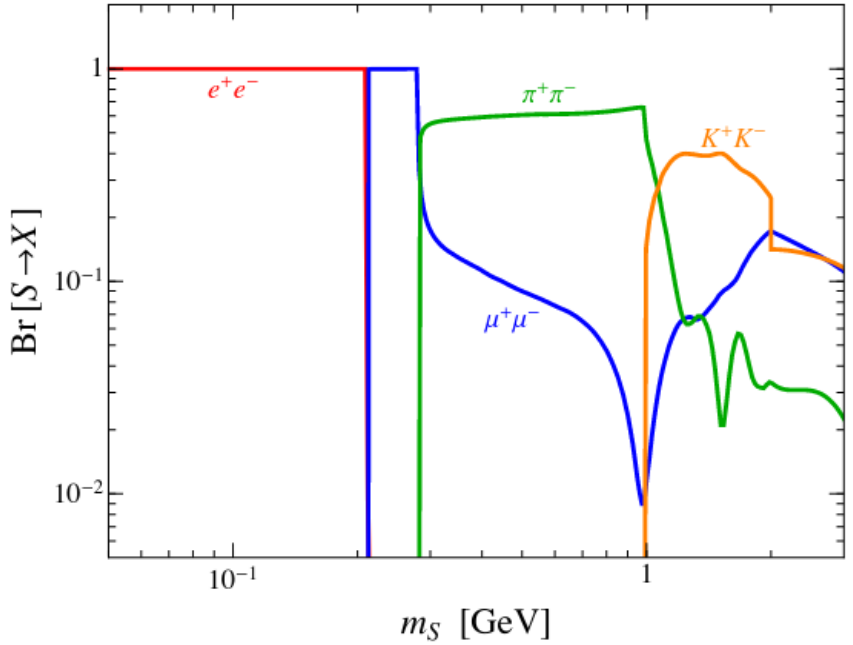
# Dark Sector Particle Decays

- Wide variety of possible decay modes with different detector signatures
- Long-lived neutral Kaon decays, e.g. $K_L^0 \rightarrow \pi^{\pm} e^{\mp} \nu$ , are important backgrounds, can be suppressed with dedicated detectors

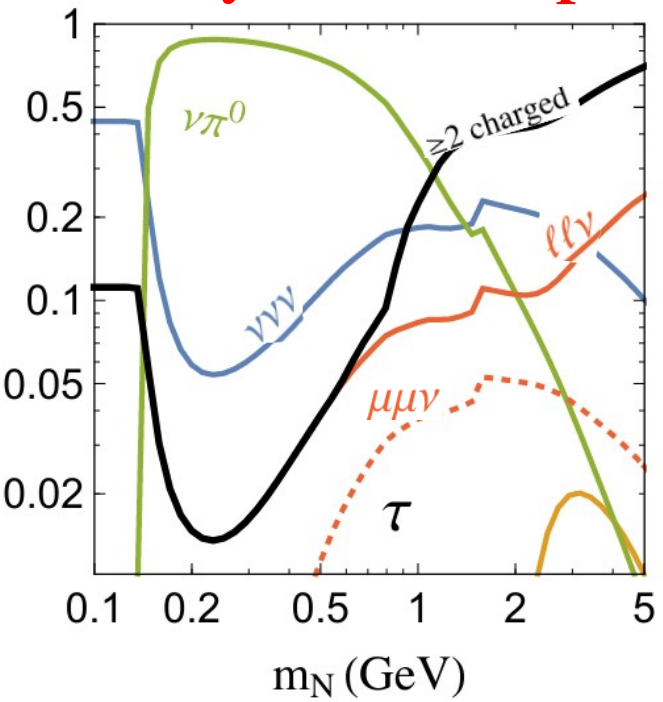
**Dark vector**




**Dark scalar**

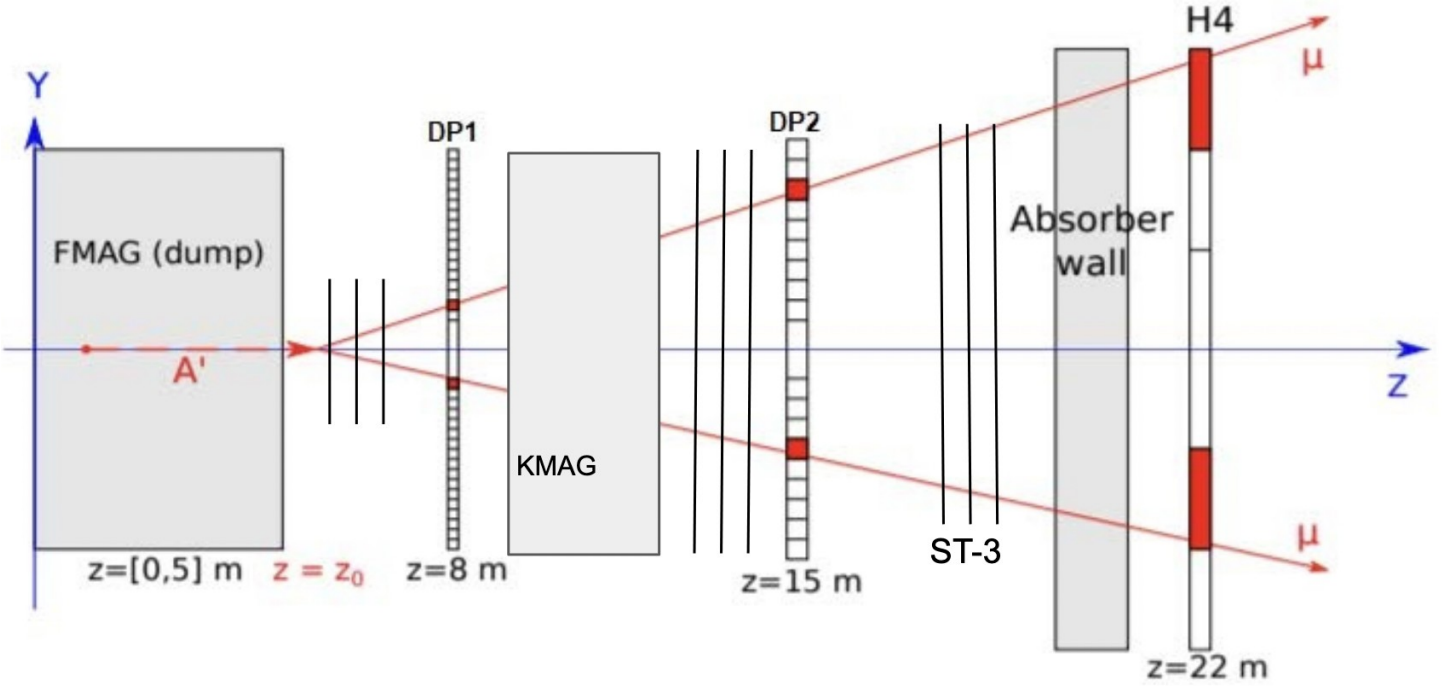


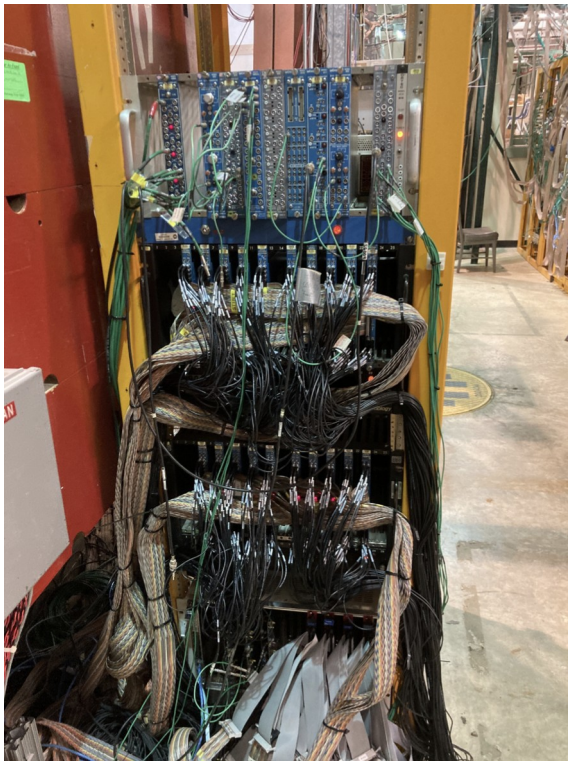

**Heavy Neutral Lepton**



# SpinQuest Dark Photon Trigger

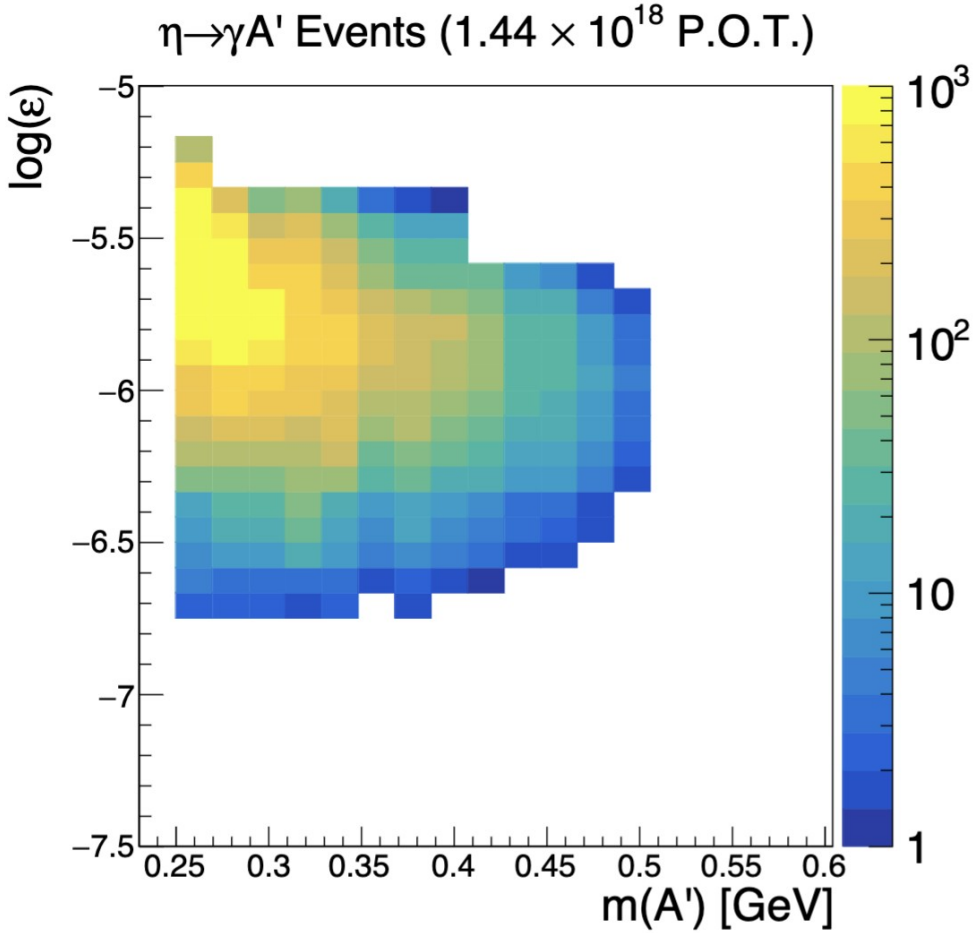
- Installed “DP Hodoscopes” to parasitically trigger on displaced dimuon vertices
- Measurement in non-bending plane gives z-vertex resolution of O(10) cm, eliminate most combinatoric background
- Increase acceptance to low mass signals

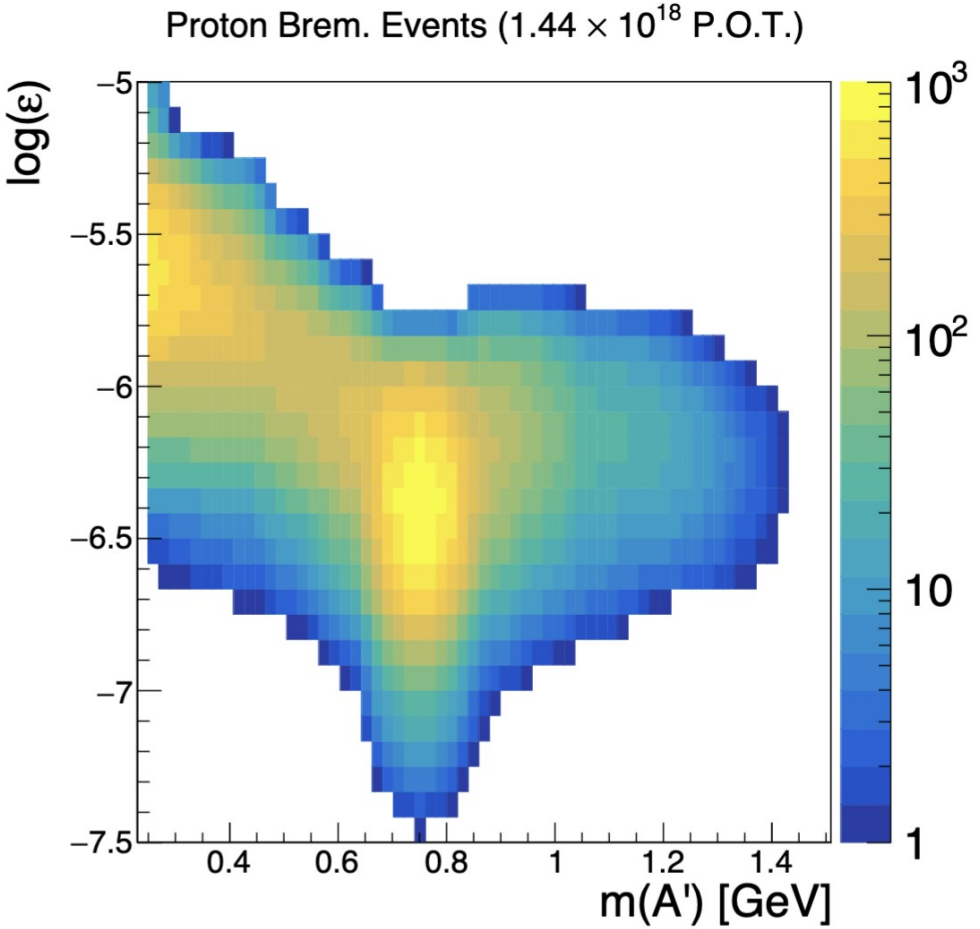


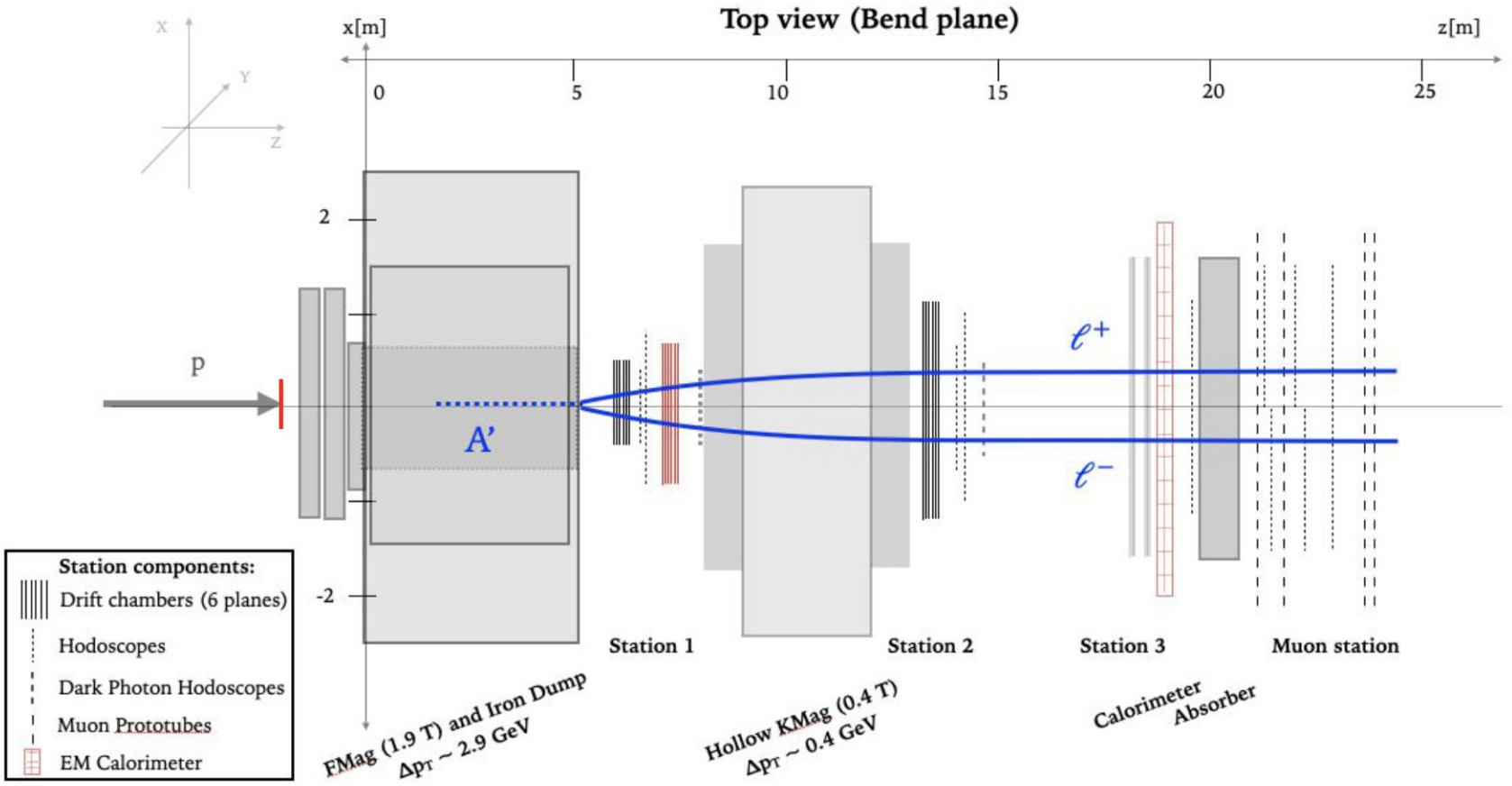
# SpinQuest Dark Photon Trigger

- Expect O(1000) signal events in unexplored parameter space
- Trigger acceptance limited by rate and large combinatoric backgrounds
- Can probe novel parameter space with nominal SpinQuest run



# DarkQuest Upgrade Concept



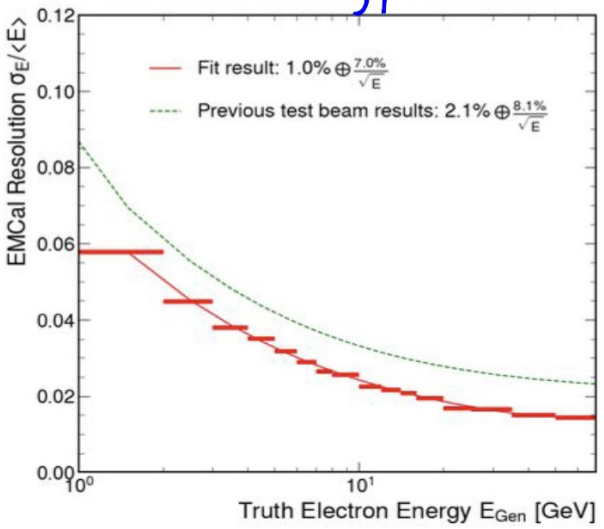

- DarkQuest upgrades the spectrometer with one Electromagnetic calorimeter (EMCal) sector (Pb-scintillator from PHENIX Experiment, 2mx4m)

  → Identify and trigger on e/γ/π; reject muon background
- Opens possibility to search for wider range of dark sector signatures

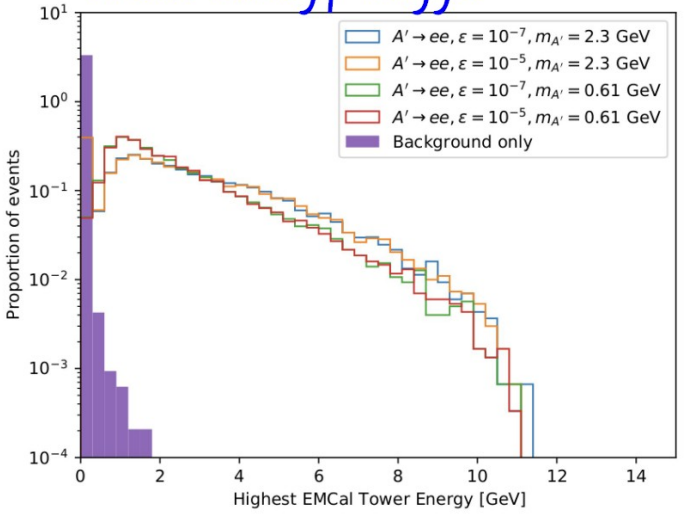
# DarkQuest Upgrade Concept

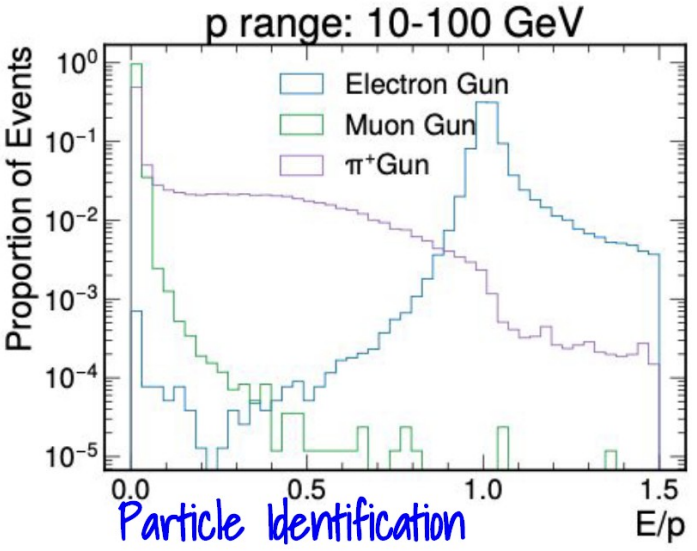
- PHENIX EMCal meets the experimental requirements for a very low total cost
- Good energy resolution for e/γ
- Simple and low rate trigger signature
- E/p provides good particle identification to separate e/μ/π
- Total cost of upgrade ~$1.5M


Electron energy resolution



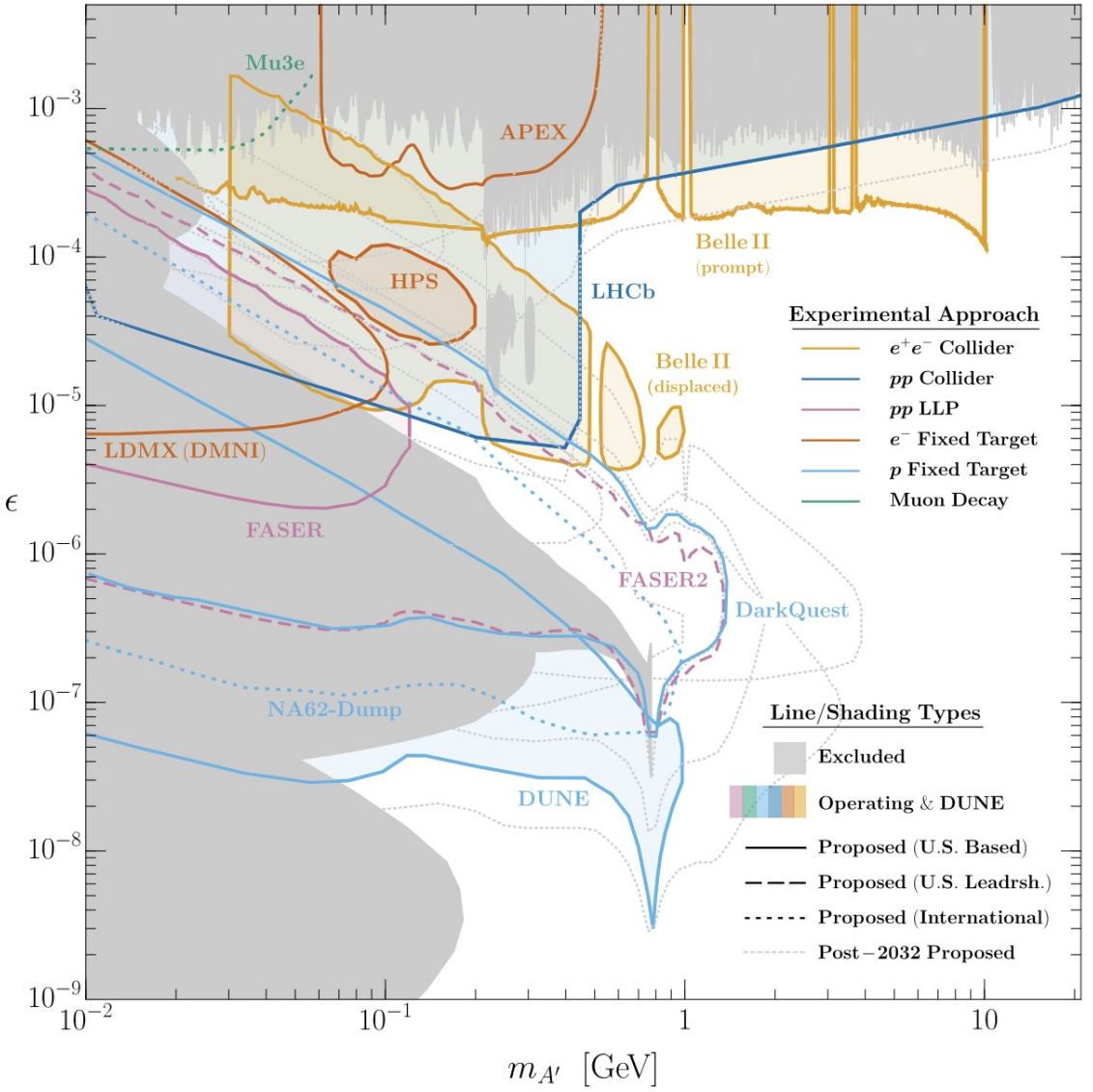

EMCal Energy Trigger



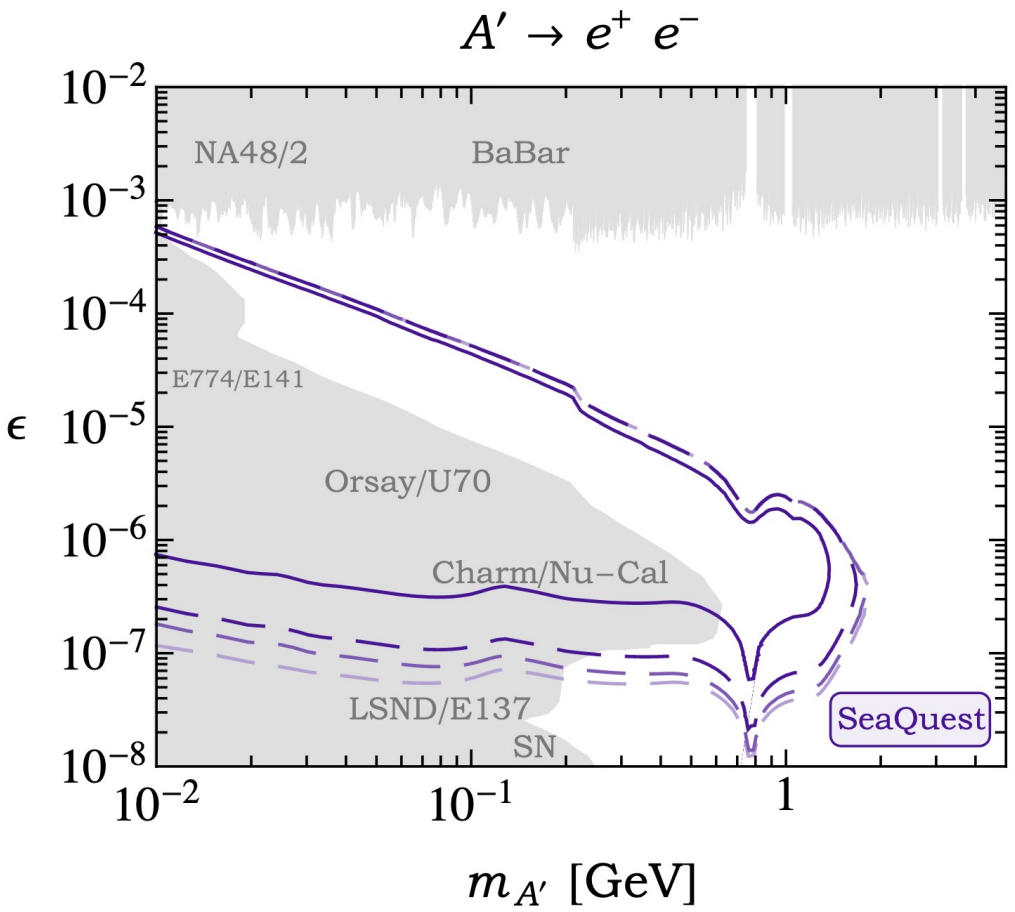



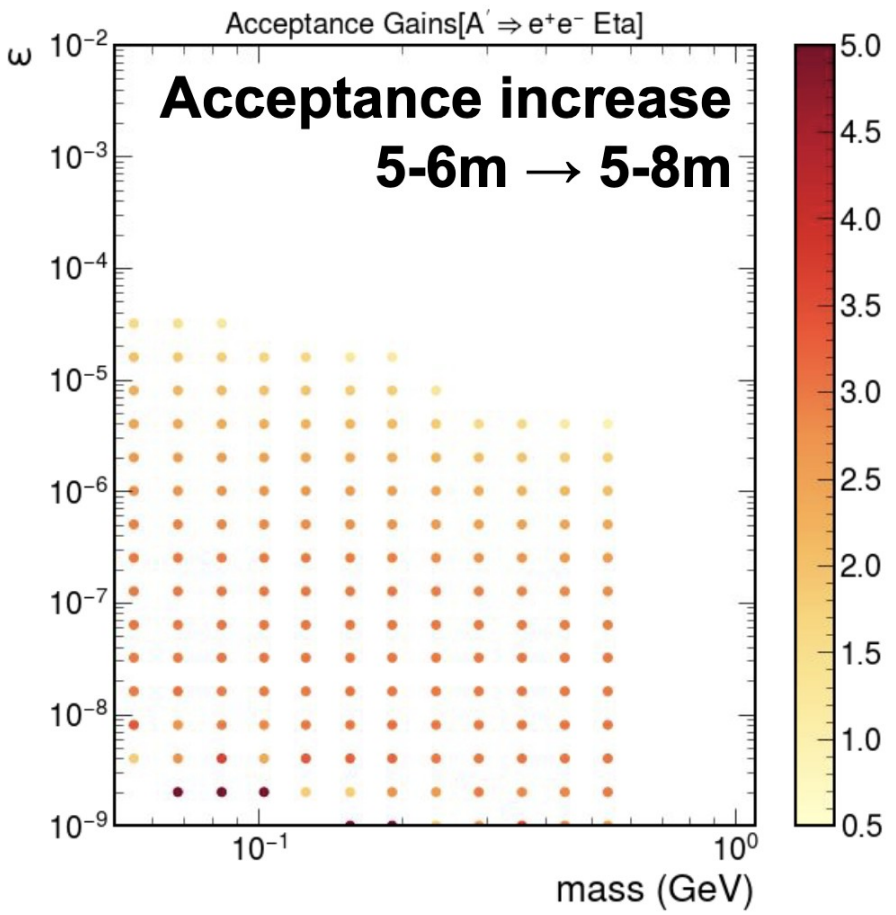
# Dark Sector Sensitivity Projections

- Dark Photon benchmark
- Comparable or better limits compared to other experiments for lower cost and shorter time scale
- Excellent complementarity with other experiments including DUNE
- DarkQuest will explore sub-GeV mass range for couplings $10^{-5}$ – $10^{-6}$
- Upgrades to the experiment can push bounds in any direction (higher mass, larger or smaller couplings)



# Decay Volume Acceptance




Estimated bounds for different intensity scenarios and decay regions:

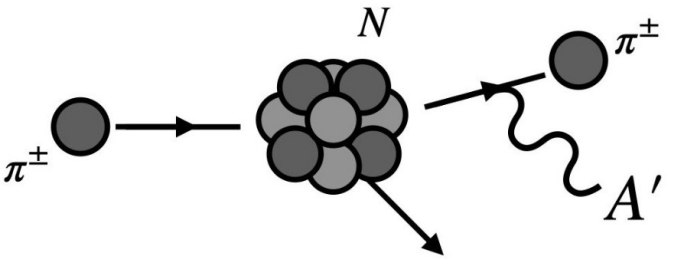
→ 5m–6m: After FMAG and before station 1.

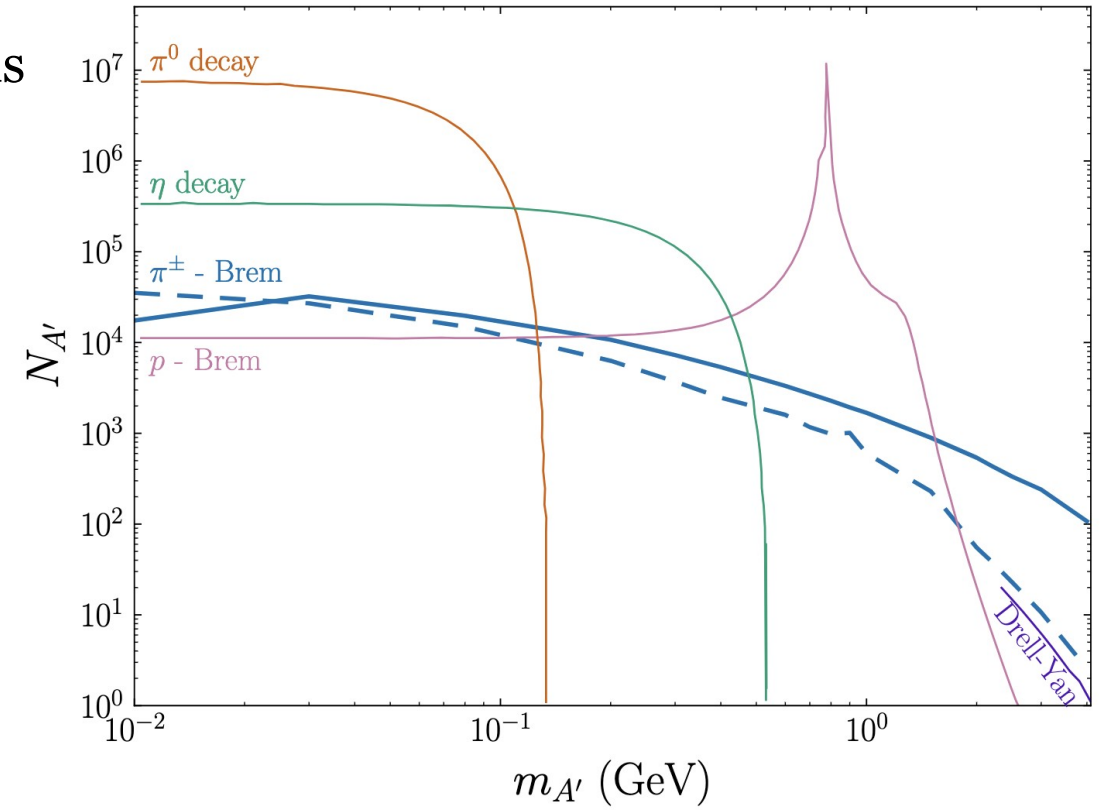
→ 5m–9m: After FMAG and before KMAG.

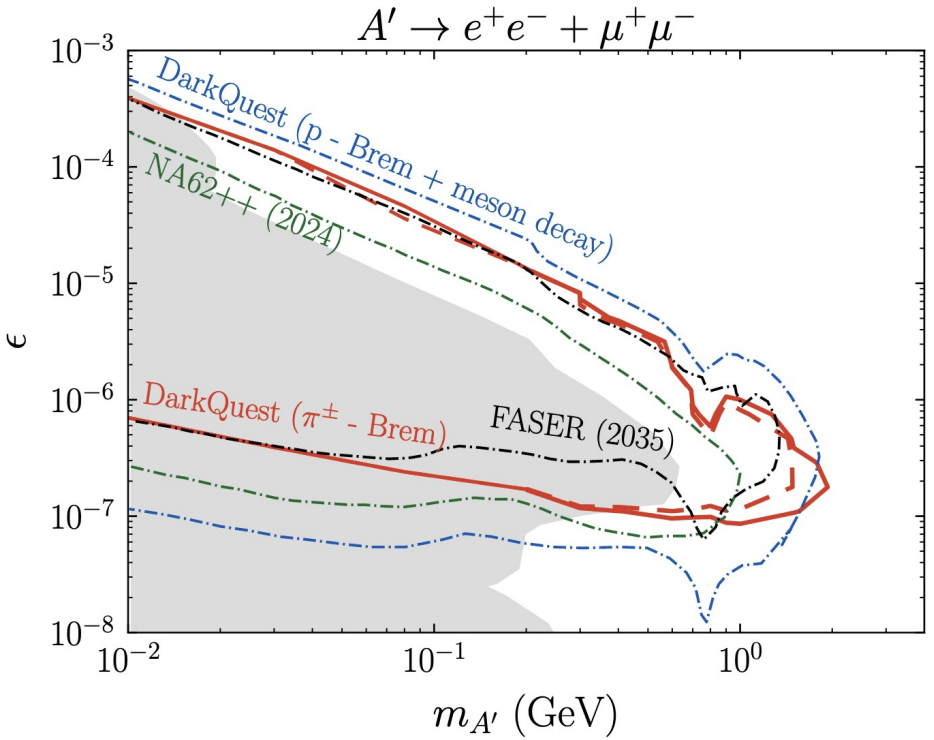
→ 5m–12m: After FMAG and before the end of KMAG

# Pion Bremsstrahlung

- Recent phenomenological study on another dark photon production mechanism: pion bremsstrahlung
- Subdominant below 1 GeV, but exceeds DY production for higher masses
- With more P.O.T. will start to become sensitive to this mechanism and can extend sensitivity to higher masses



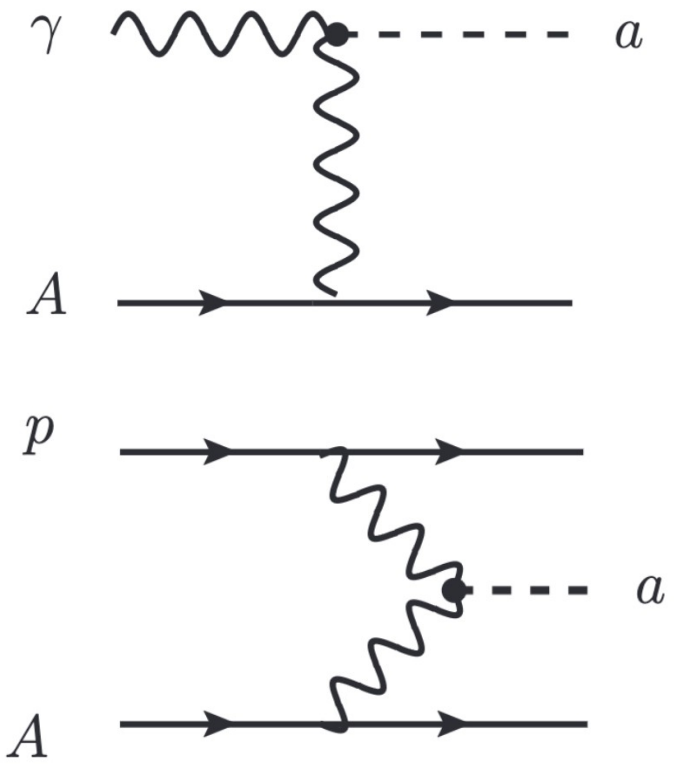



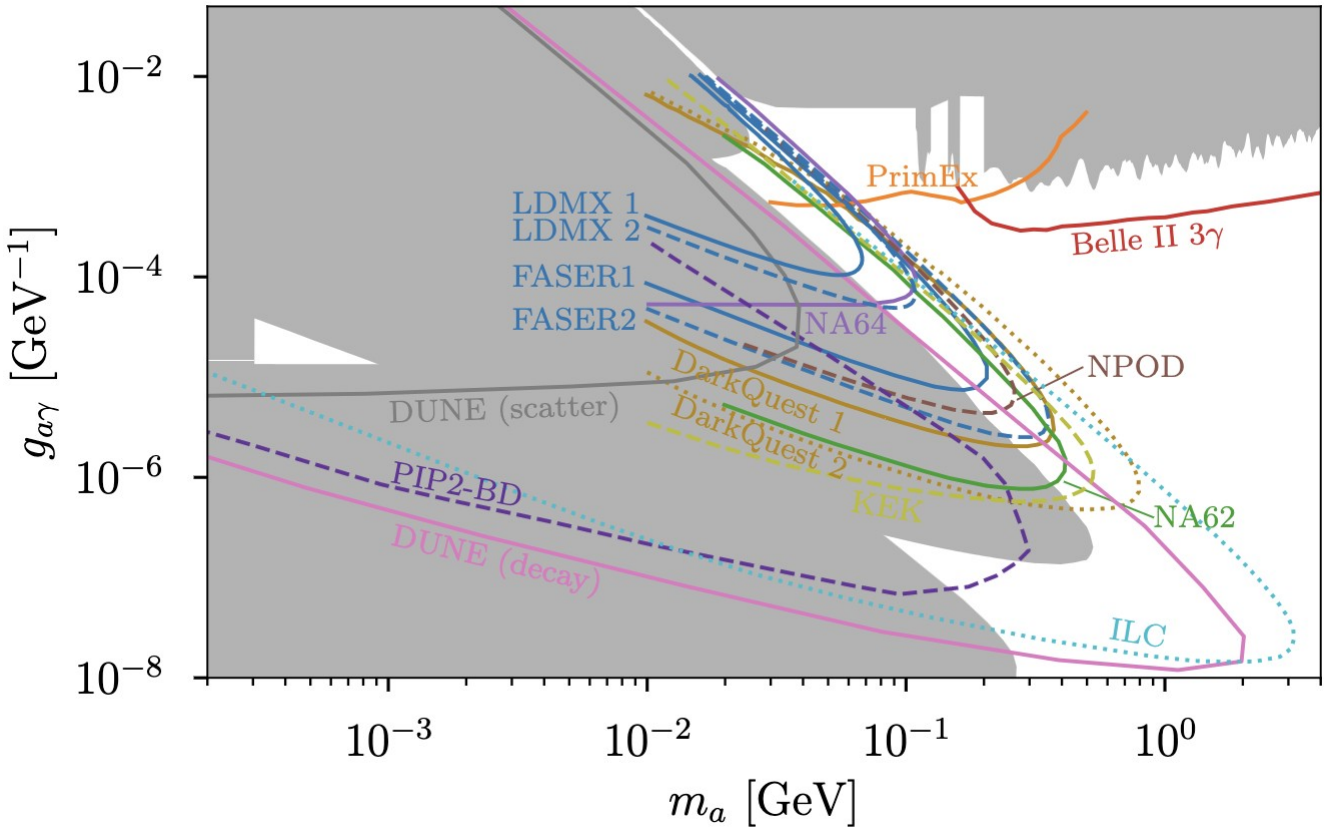




*D. Curtin, Y. Kahn, R. Nguyen*
arxiv:2305.19309

# Axion-Like Particles

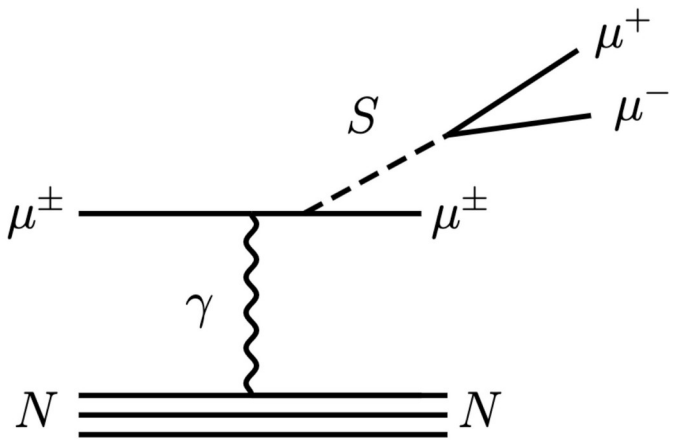
- DarkQuest will have excellent sensitivity to photon coupled ALPs
- Produced through Primakoff process or photon fusion
- Again, excellent complementary coverage compared with DUNE

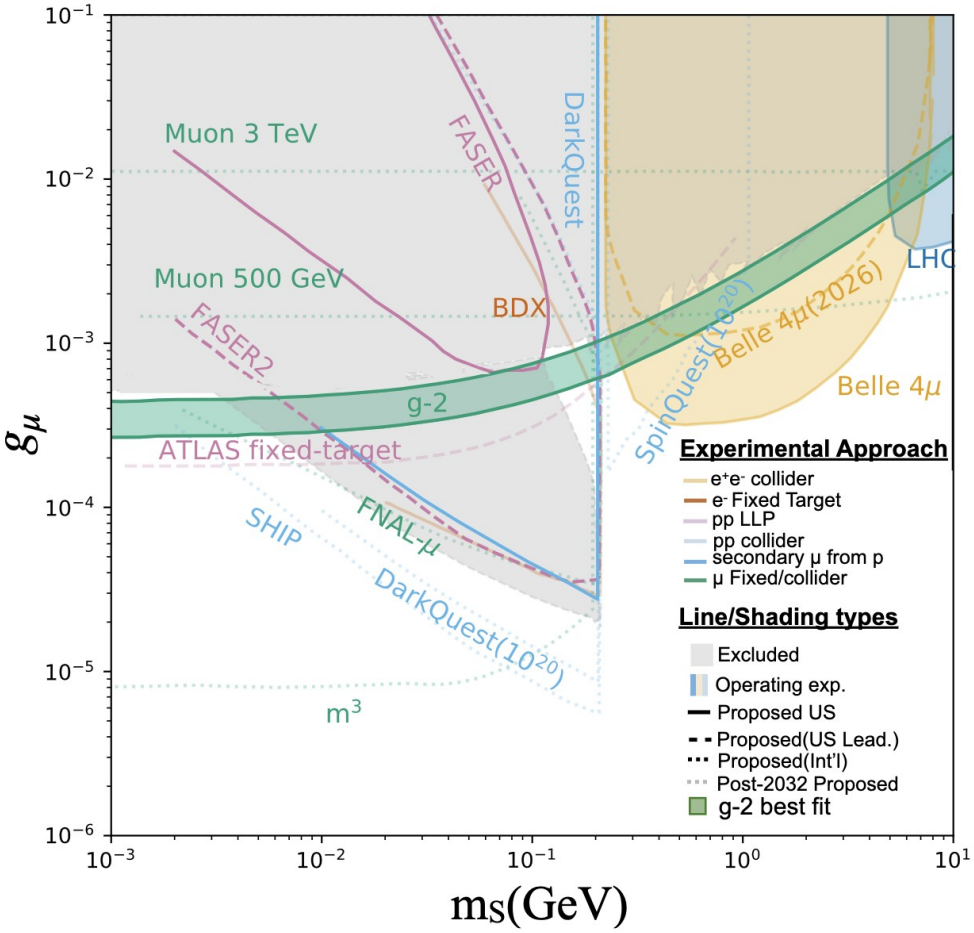


# Scalar Models for $(g-2)_\mu$

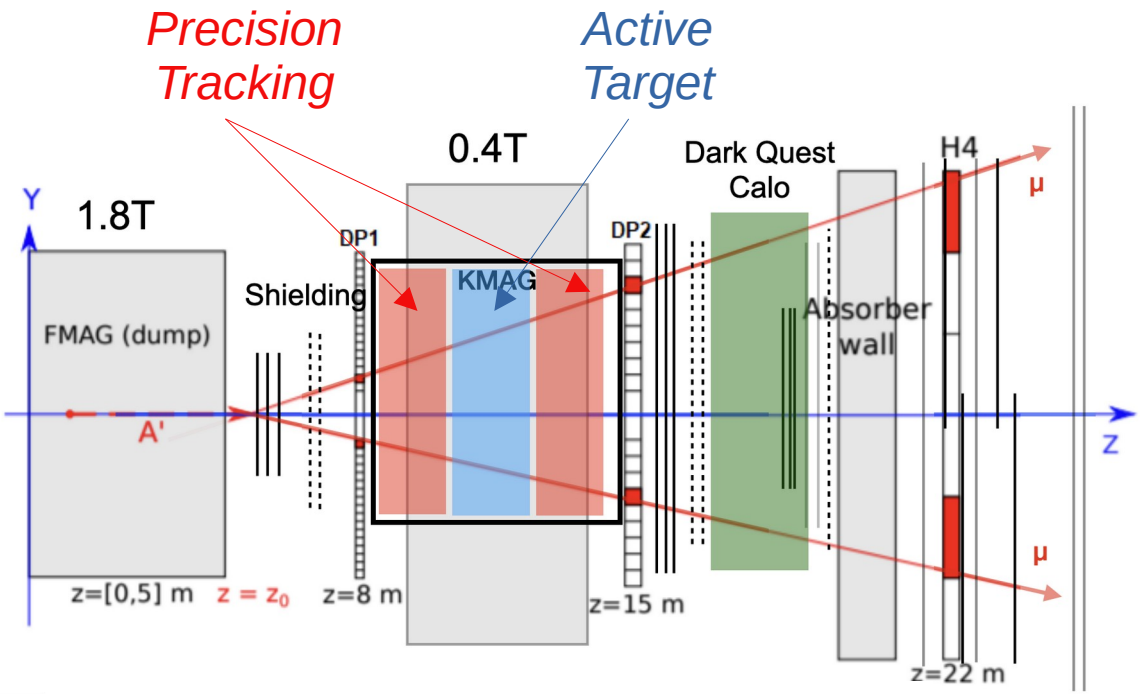
- One model which can resolve $(g-2)_\mu$ is a light scalar singlet
- Large secondary production of muons from $\pi/K$ in the DarkQuest beam dump
- For $m_s > 2\ m_\mu$, decay is prompt, to $\mu^+\mu^-$ (SpinQuest)
- For $m_s < 2\ m_\mu$, decay is displaced, to $\gamma\gamma$ (DarkQuest)
- DarkQuest can cover most of the remaining parameter space with $m_S \sim 2\ m_\mu$

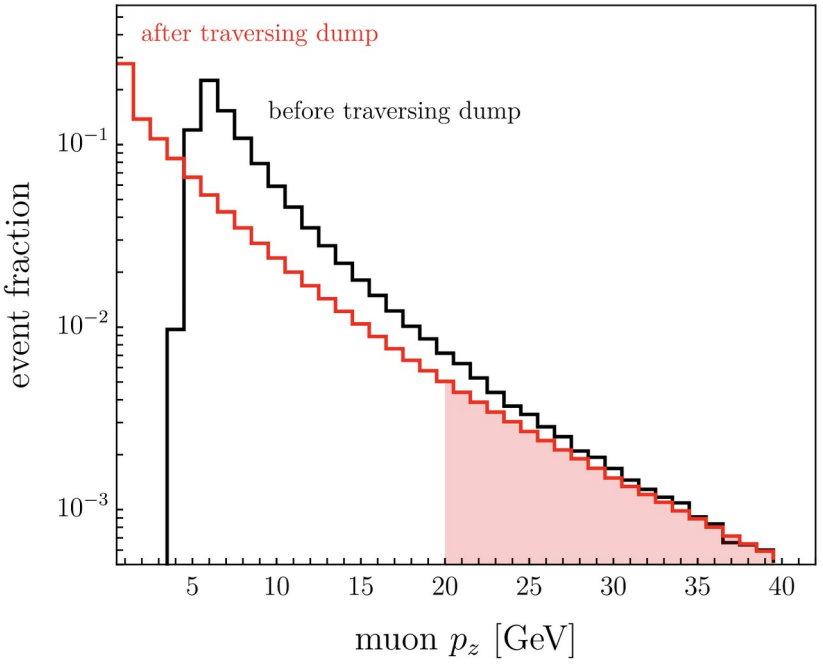


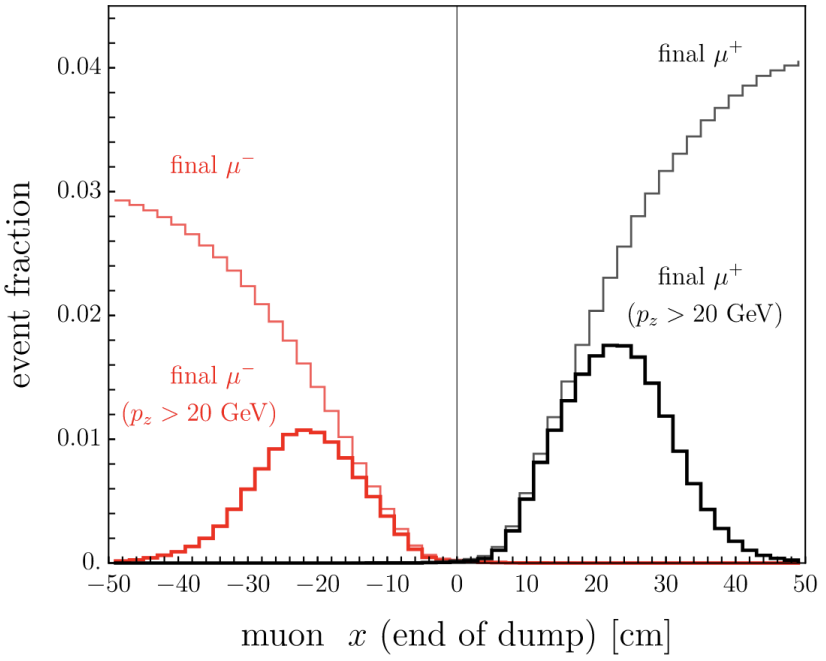



# Muon Missing Momentum in DarkQuest

- Large muon flux could be used for a M$^3$ like detector within DarkQuest
  - 2e8 muons / spill
  - 5e13 muons / year
- Exploring different detector concepts and feasibility

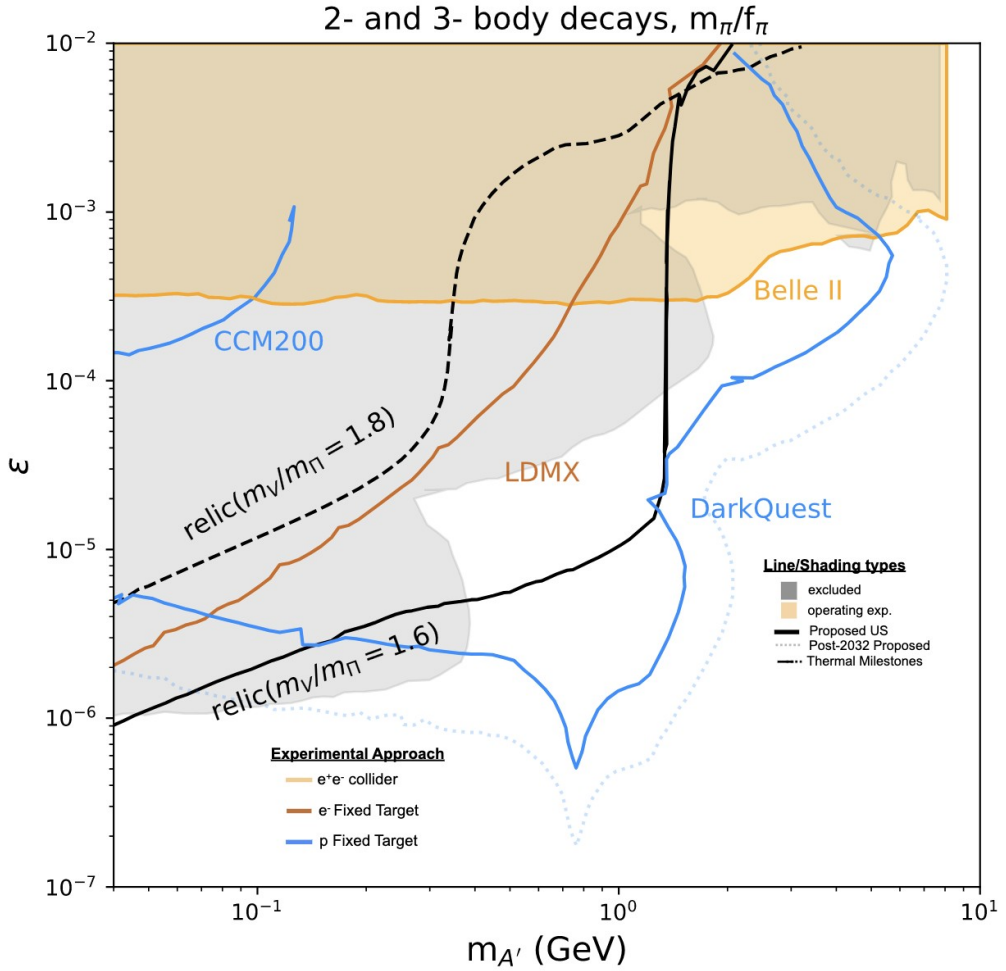


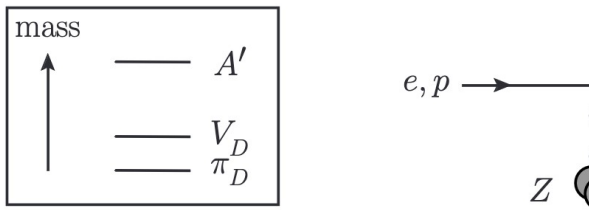



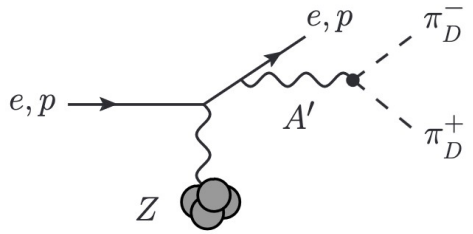



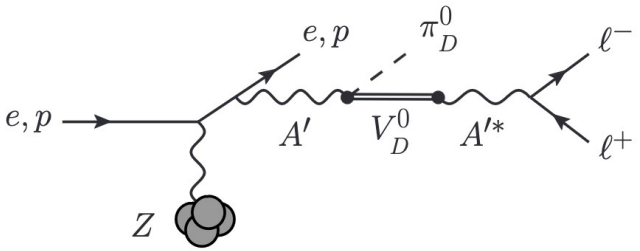
# Strongly Interacting Dark Matter

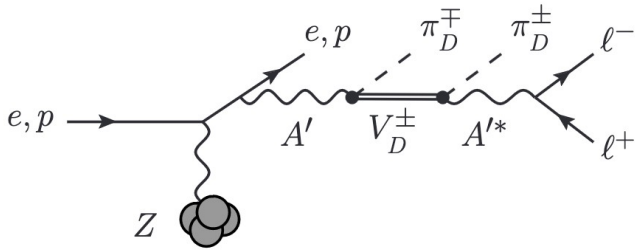
- Generic framework where DM is the lightest state of a strongly coupled hidden sector (HS) that is uncharged under SM forces
- Dark matter is composed of the lightest states in this sector
- DarkQuest can probe cosmologically-motivated parameter space that has not been tested by previous experiments
- Different decay product energy spectrum



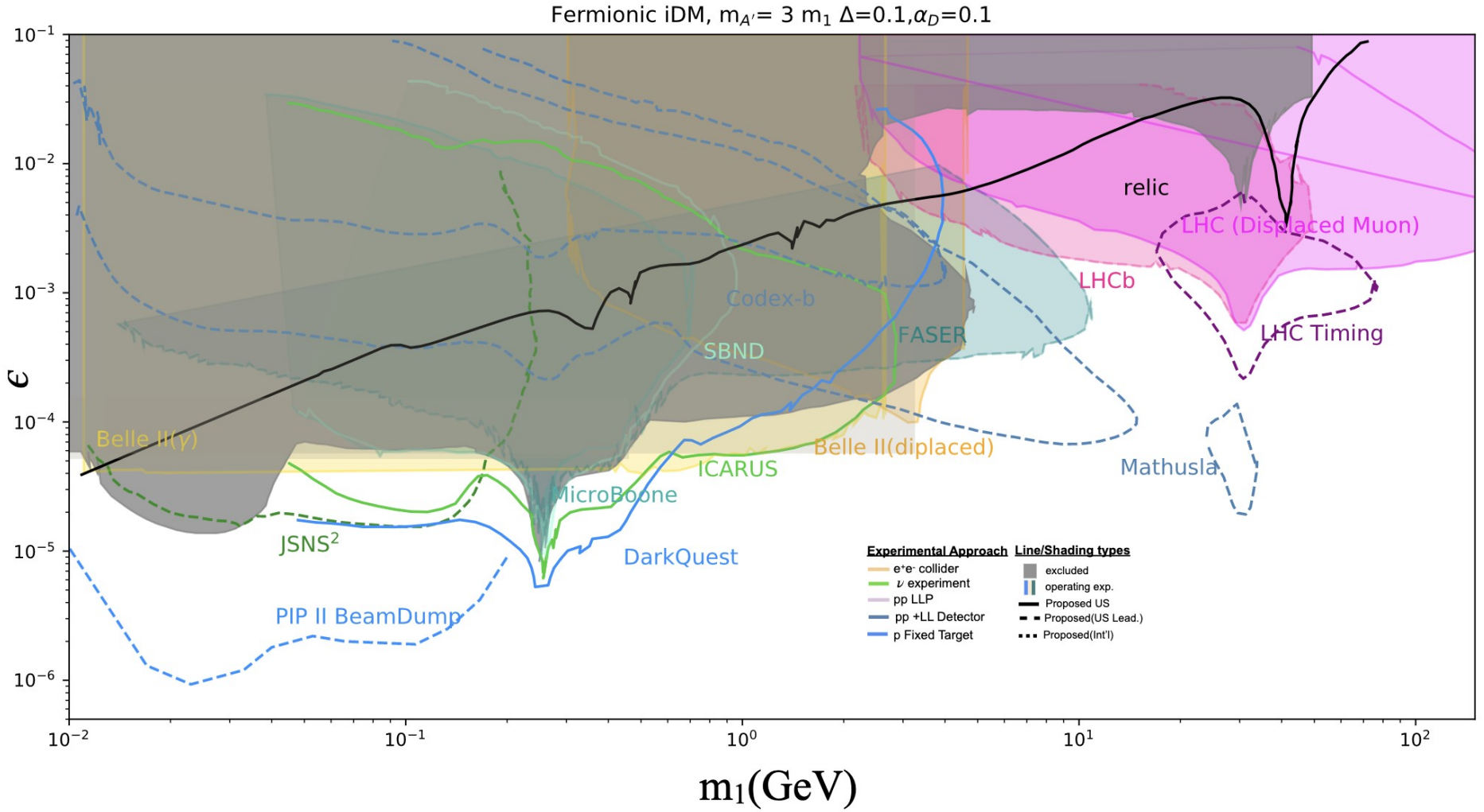



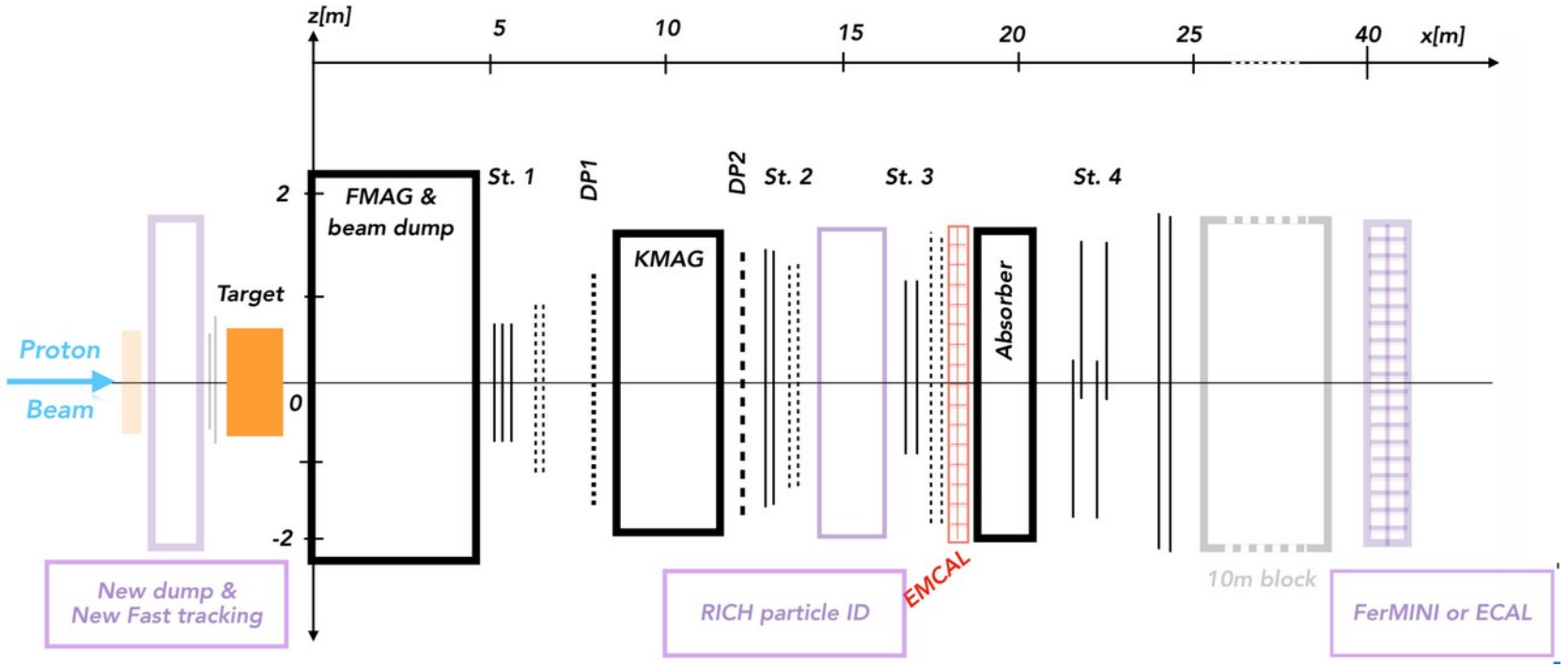
# Inelastic Dark Matter

- Non-resonant electrons coming from decay $A' \rightarrow \chi_2\chi_1 \rightarrow e^+e^-\chi_1\chi_1$
- Softer energy and off-axis production vs. minimal dark photon
- Uncovered parameter space can be probed by DarkQuest



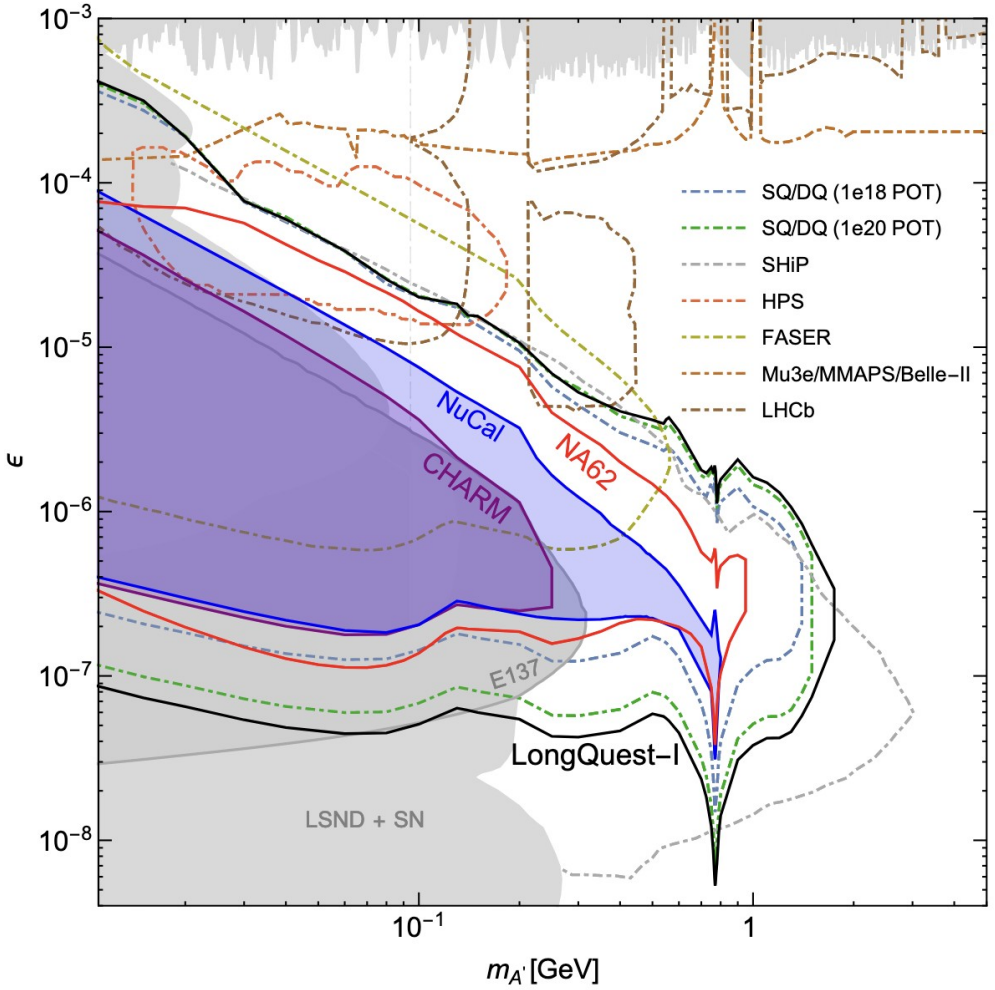
# Further Spectrometer Upgrades

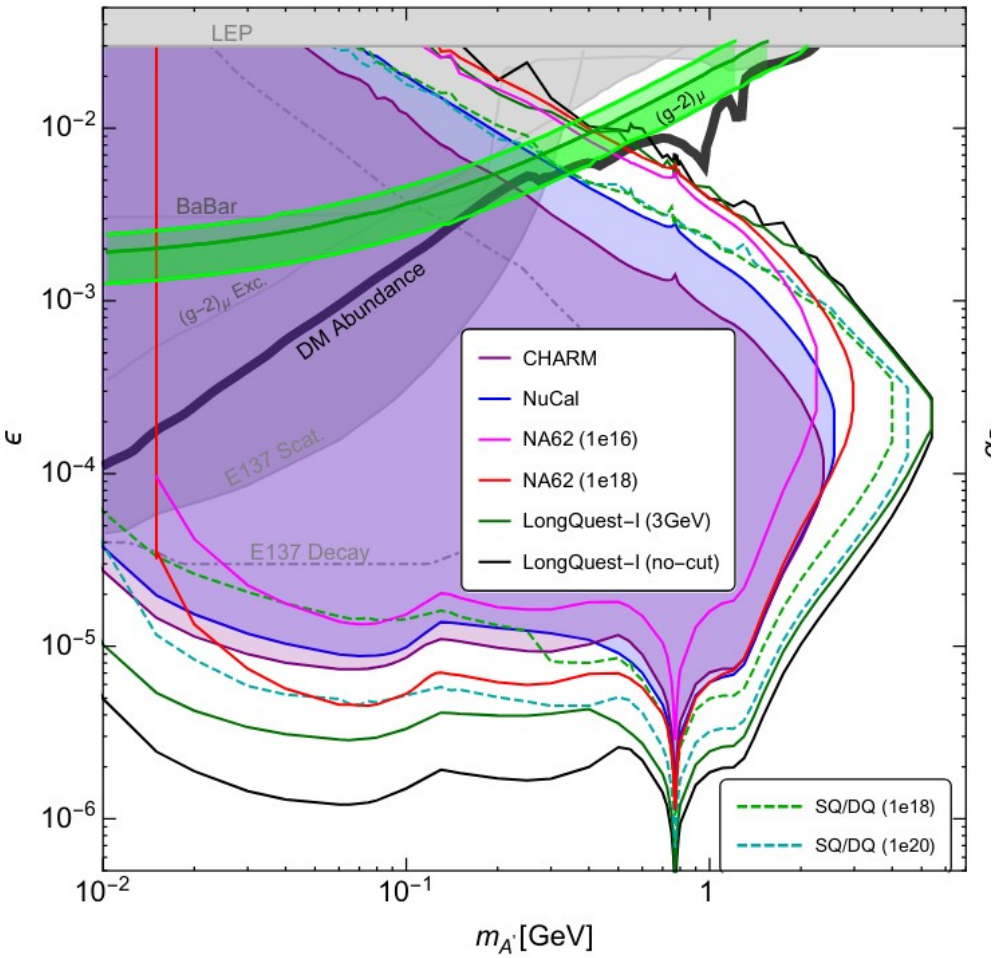
*Y. Tsai, P. deNiverville, M. Liu*
arxiv:1908.07525




- Possible further upgrades extend coverage and sensitivity
- Adding PID detector, new dump and fast tracking, and /or second ECAL
- Shorten the beam dump to be sensitive to intermediate lifetimes
- Upgraded Trigger/DAQ to handle higher rates

# Sensitivity Projections for “LongQuest”




- Increased sensitivity from RICH Detector to discriminate $e^+/\pi^+$
- Can turn off Kmag to increase acceptance for softer electrons
- Results in improved sensitivity throughout parameter space

# Summary

- **Proton Fixed Target Experiments on the 120 GeV beamline offer a compelling multi-frontier physics program**
  - ➔ Better understanding of the proton PDF and origin of its spin
  - ➔ Dark Sector searches sensitive to a wide range of models
- **DarkQuest upgrade would be a springboard for a long term dark sector program**
  - ➔ Makes use of existing infrastructure in NM4 and can explore new parameter space on a short timescale
  - ➔ Further detector/beam upgrades could enhance sensitivity
    - CW slow extracted beam, new dump, silicon tracking, etc.
- **This program complements well other efforts and would positions FNAL as a world leader in dark sector searches**

# Backup

# DarkQuest Collaboration

**Aram Apyan[1], Brian Batell[2], Asher Berlin[3], Nikita Blinov[4], Caspian Chaharom[5], Sergio Cuadra[6], Zeynep Demiragli[5], Adam Duran[7], Yongbin Feng[3], I.P. Fernando[8], Stefania Gori[9], Philip Harris[6], Duc Hoang[6], Dustin Keller[8], Elizabeth Kowalczyk[10], Monica Leys[2], Kun Liu[11], Ming Liu[11], Wolfgang Lorenzon[12], Petar Maksimovic[13], Cristina Mantilla Suarez[3], Hrachya Marukyan[14], Amitav Mitra[13], Yoshiyuki Miyachi[15], Patrick McCormack[6], Eric A. Moreno[6], Yasser Corrales Morales[11], Noah Paladino[6], Mudit Rai[2], Sebastian Rotella[6], Luke Saunders[5], Shinaya Sawada[21], Carli Smith[17], David Sperka[5], Rick Tesarek[3], Nhan Tran[3], Yu-Dai Tsai[18], Zijie Wan[5], and Margaret Wynne[12]**

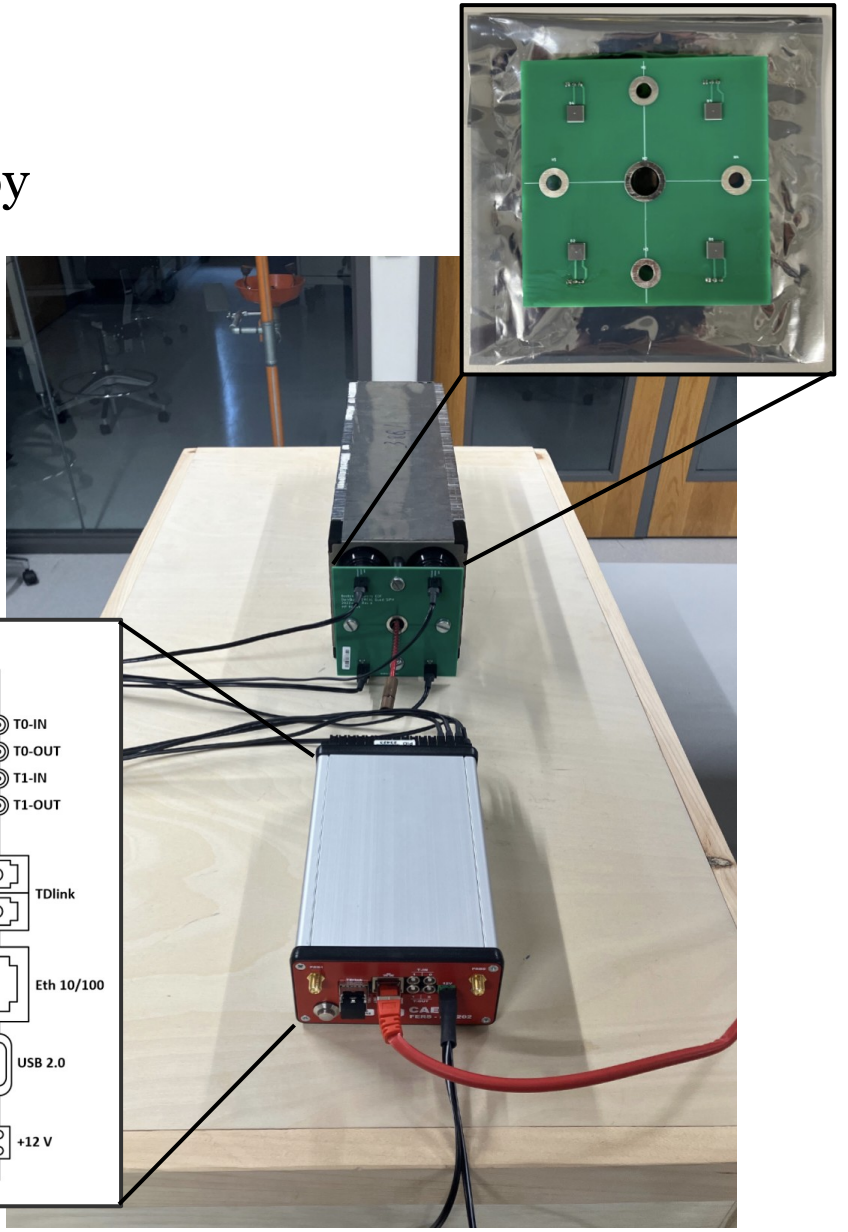
[1]Brandeis University, Waltham, MA 02453, USA
[2]University of Pittsburgh, Pittsburgh, PA 15260, USA
[3]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[4]University of Victoria, Victoria, BC V8P 5C2, Canada
[5]Boston University, Boston, MA 02215, USA
[6]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[7]San Francisco State University, San Francisco, CA 94132, USA
[8]University of Virginia, Charlottesville, VA 22904, USA
[9]University of California Santa Cruz, Santa Cruz, CA 95064, USA
[10]Michigan State University, East Lansing, Michigan 48824, USA
[11]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[12]University of Michigan, Ann Arbor, MI 48109, USA
[13]Johns Hopkins University, Baltimore, MD 21218, USA
[14]Yamagata University, Yamagata, 990-8560, Japan
[15]KEK Tsukuba, Tsukuba, Ibaraki 305-0801 Japan
[16]Yerevan Physics Institute, Yerevan, 0036, Republic of Armenia
[17]Penn State University, State College, PA 16801, USA
[18]University of California Irvine, Irvine, CA 92697, USA

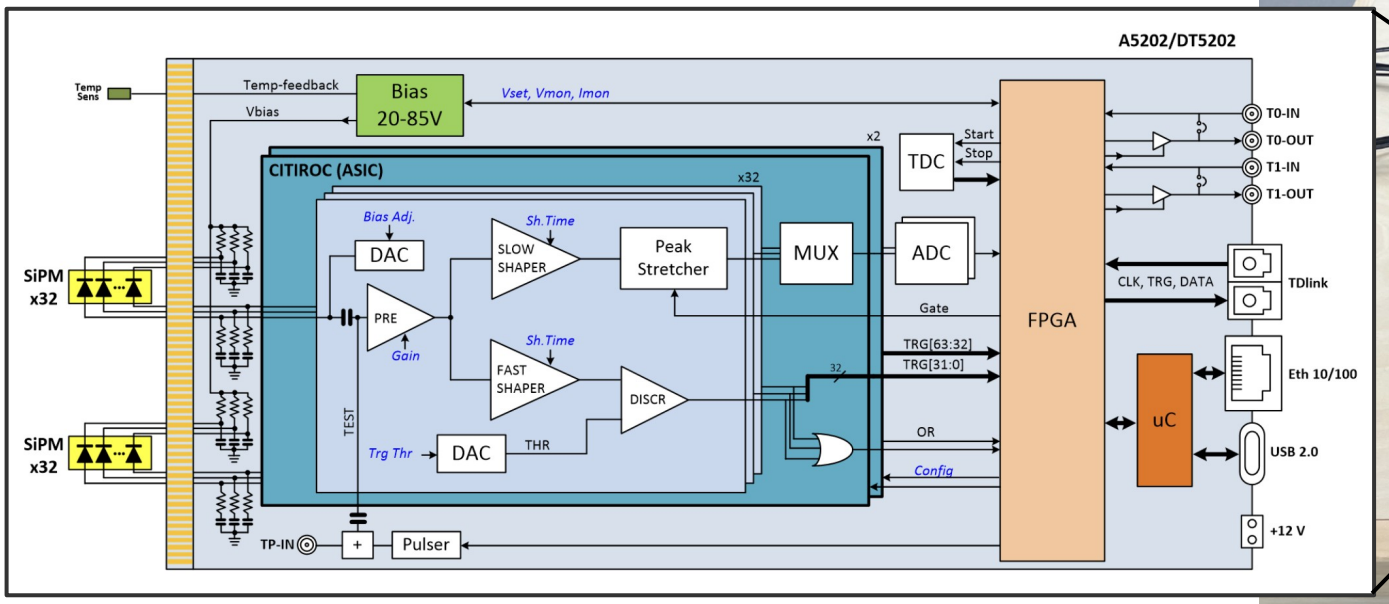
- Strong team of both Experimentalists and Theorists
- Regular meetings for almost 4 years
- Fully Integrated with current SpinQuest collaboration

arxiv:2203.08322

# DarkQuest EMCal Upgrade

- PHENIX EMCal PMTs to be replaced with SiPMs
- Custom 4-ch front end SiPM board has been developed at Boston University
- Commercial off-the-shelf ASIC board designed by CAEN for ADC and triggering





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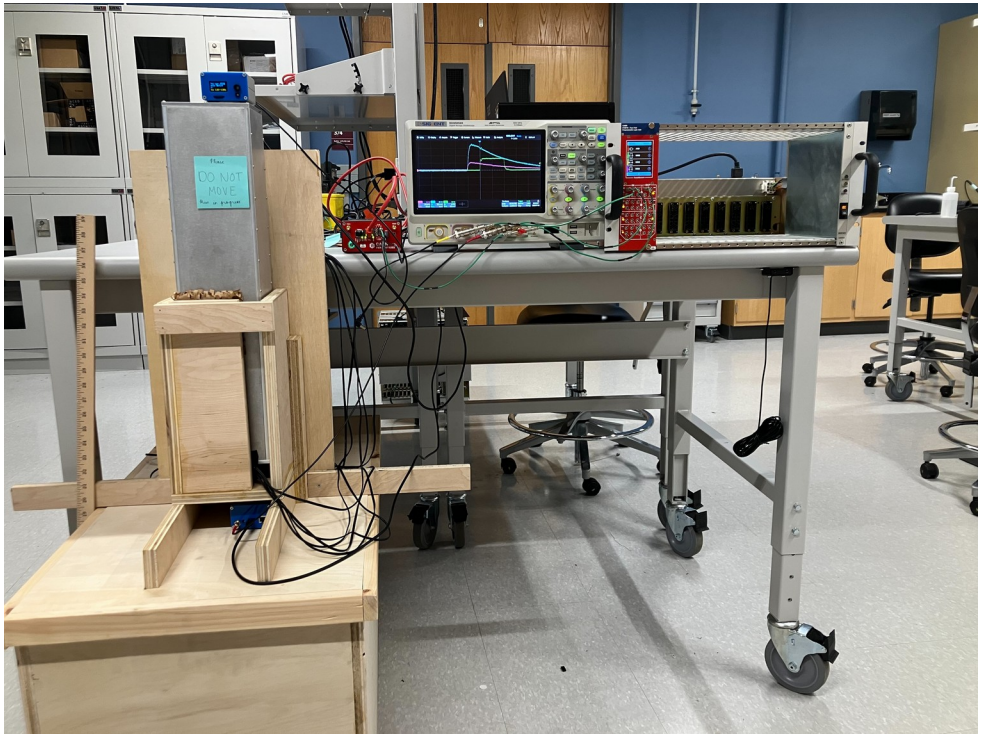
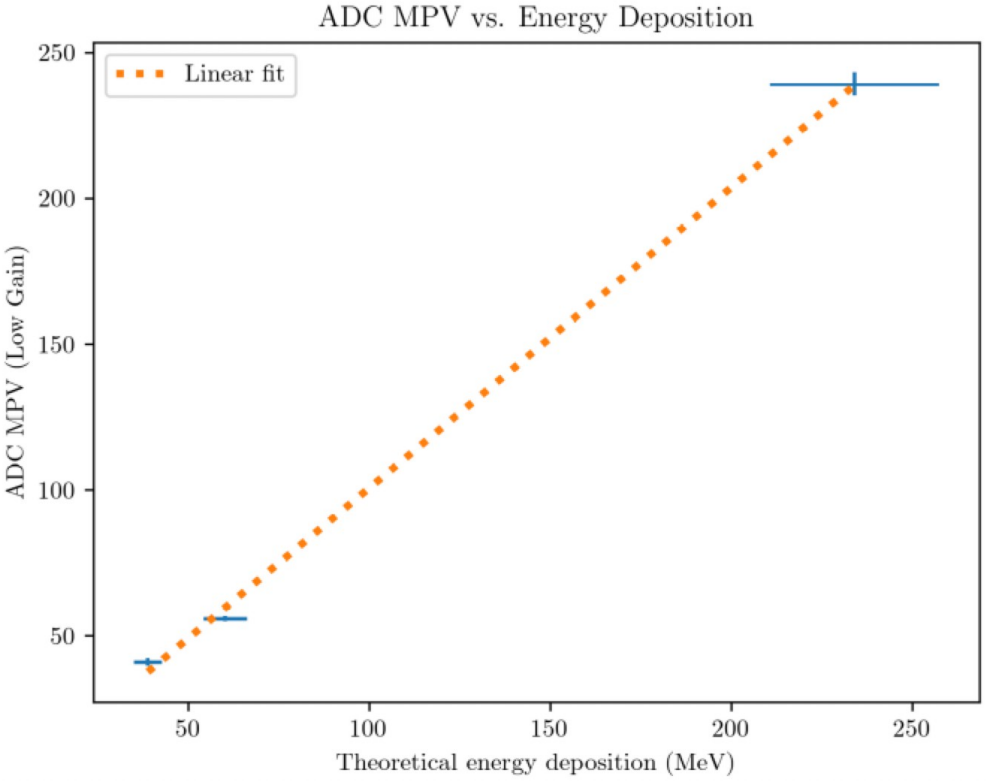
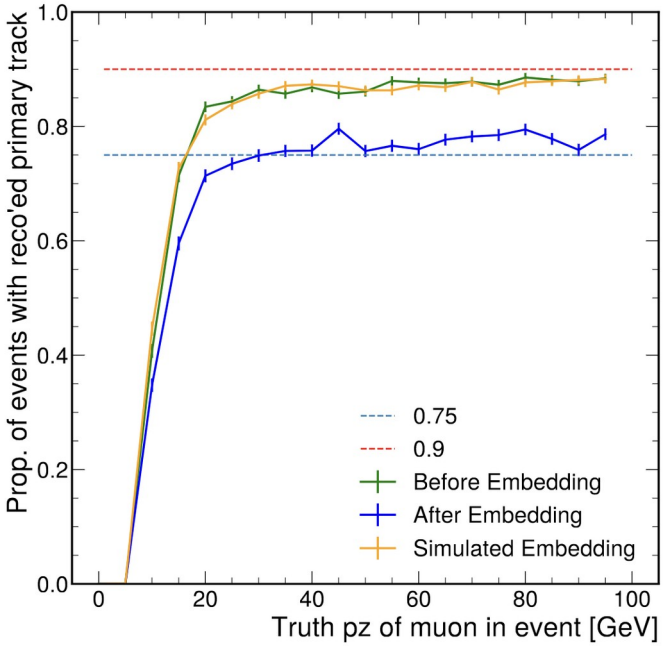


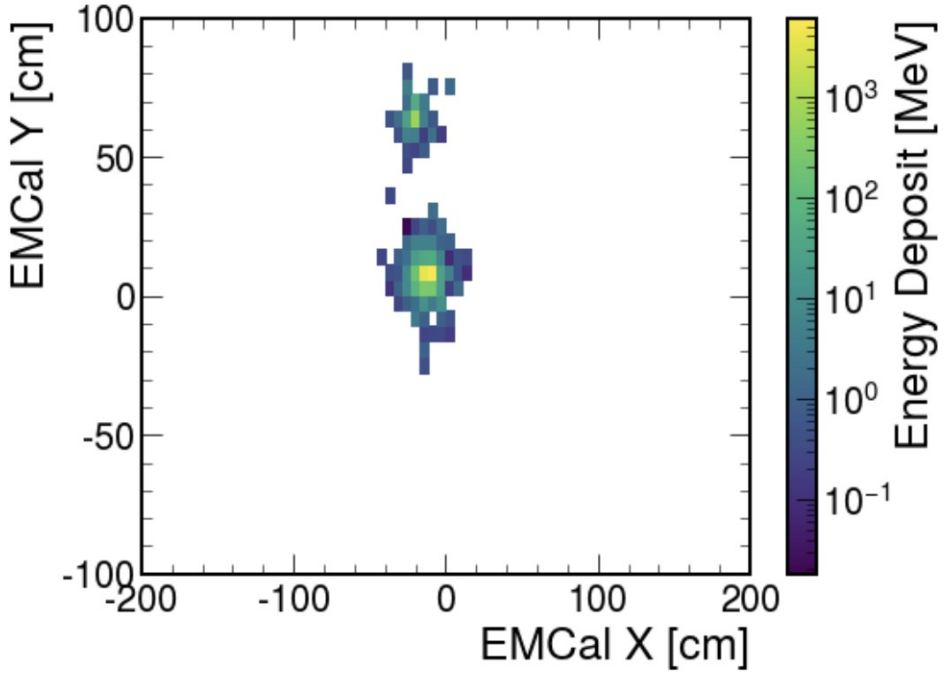



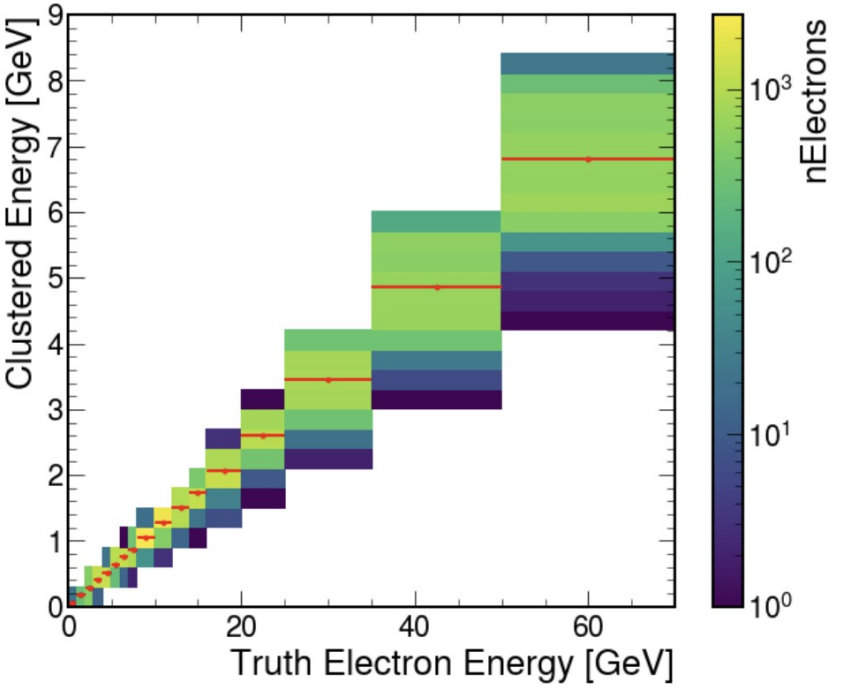
# DarkQuest Reconstruction/Simulation

- Commissioning displaced tracking using full SpinQuest simulation and reconstruction framework

  → First step for a dimuon search
- EMCal integrated in to detector simulation, reconstruction algorithms are well-advanced

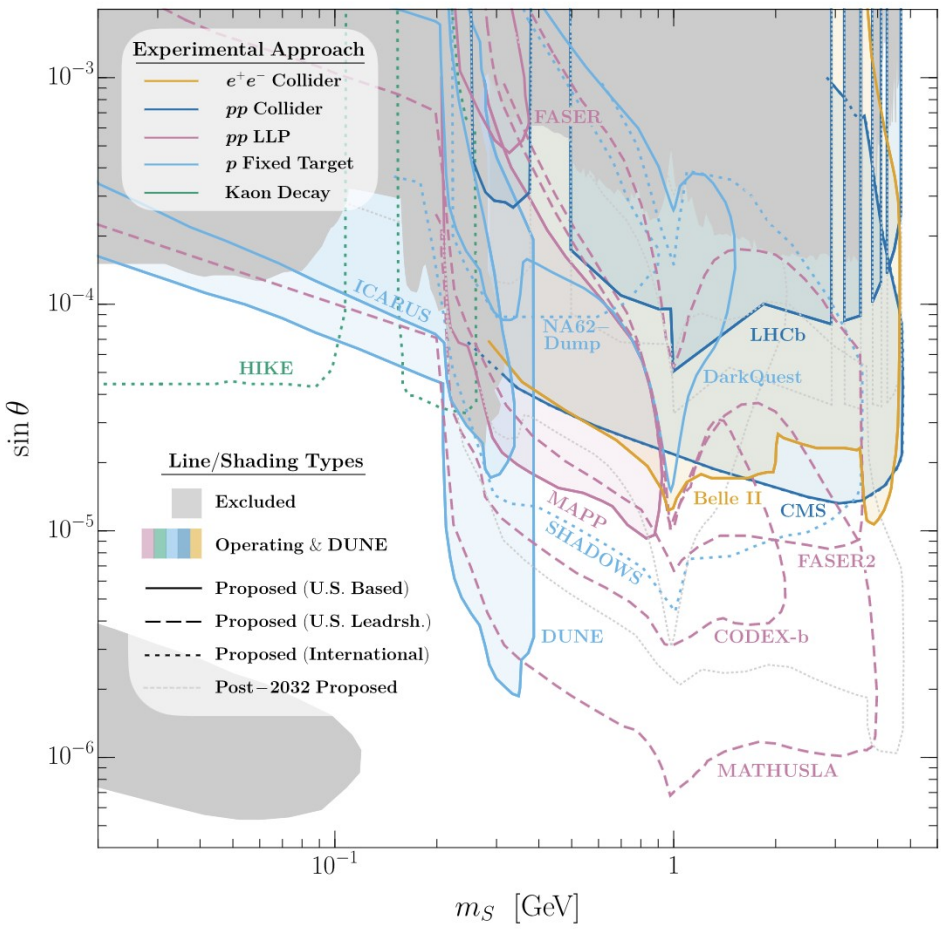


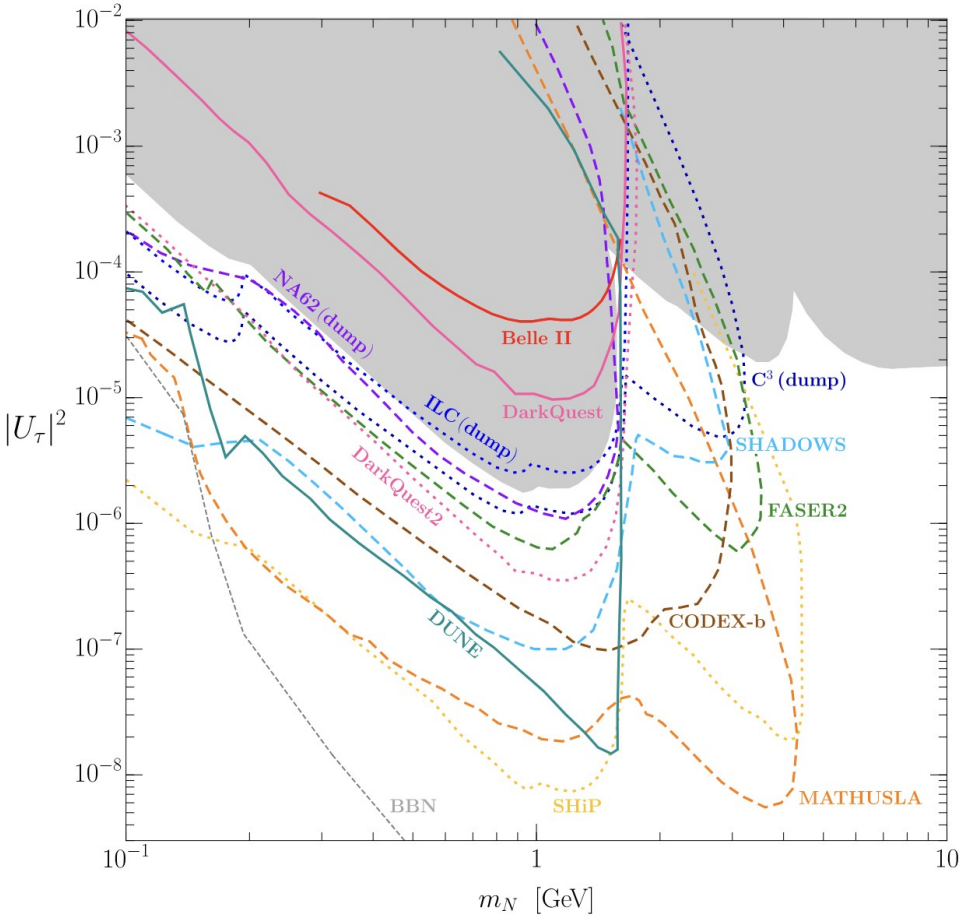



# Dark Sector Sensitivity Projections

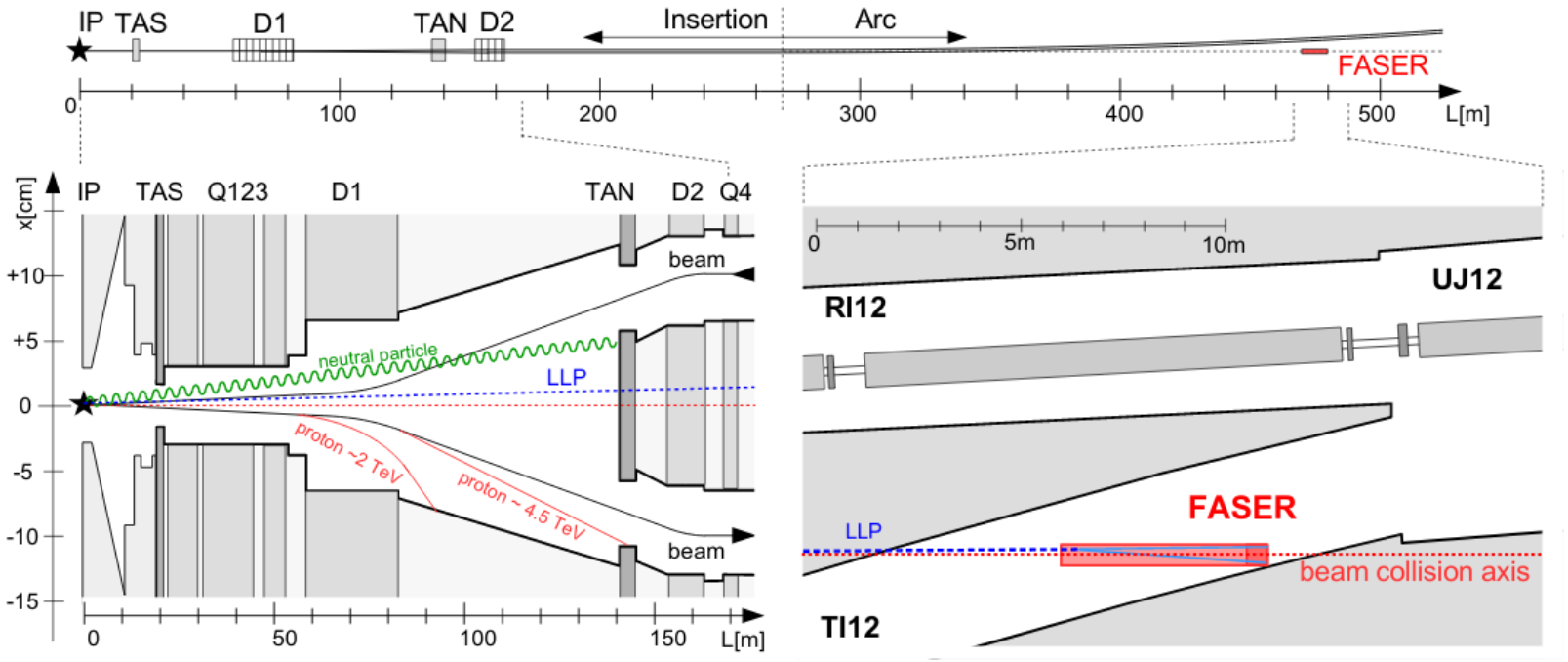
## Dark scalar

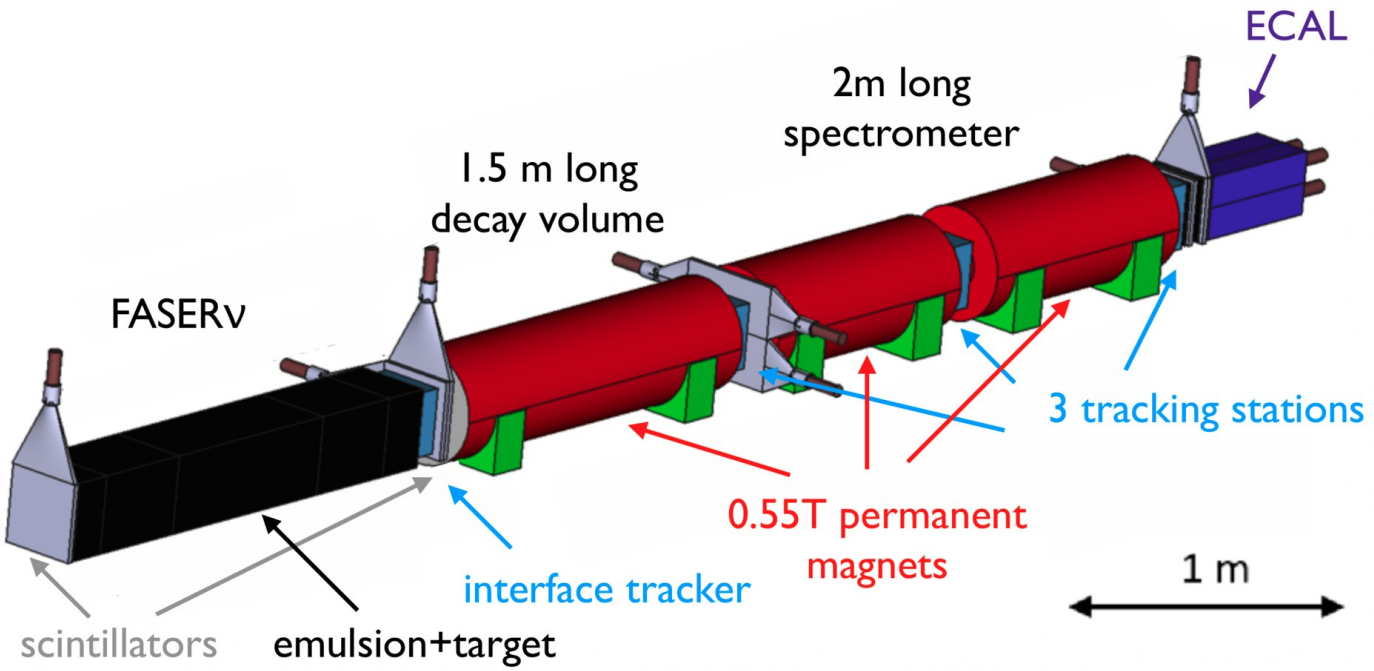



## Heavy Neutral Lepton

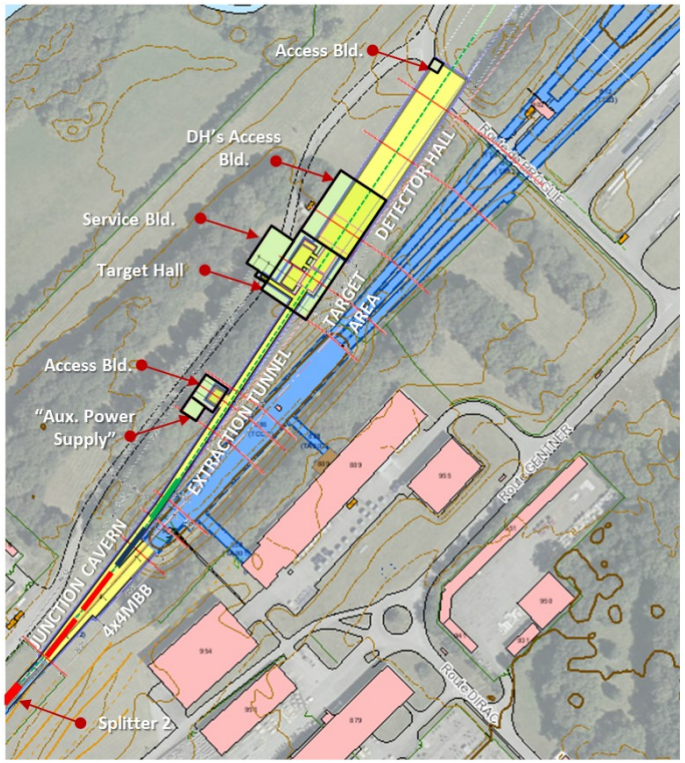


# Faser


IP TAS
D1
TAN D2
Insertion
Arc
FASER
0
100
200
300
400
500
L[m]
IP
TAS
Q123
D1
TAN
D2
Q4
x[cm]
+10
+5
0
-5
-10
-15
beam
neutral particle
LLP
proton ~2 TeV
proton ~ 4.5 TeV
beam
0
50
100
150
L[m]
0
5m
10m
RI12
UJ12
FASER
LLP
beam collision axis
TI12

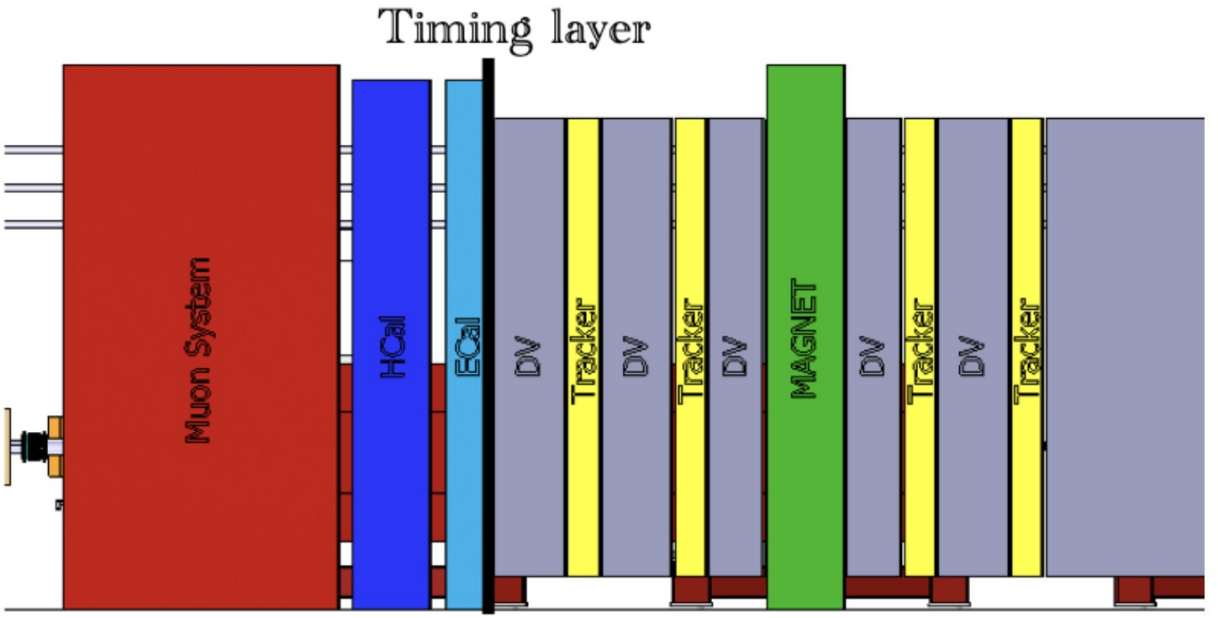

ECAL
2m long
spectrometer
1.5 m long
decay volume
FASERν
3 tracking stations
0.55T permanent
magnets
interface tracker
1 m
scintillators
emulsion+target

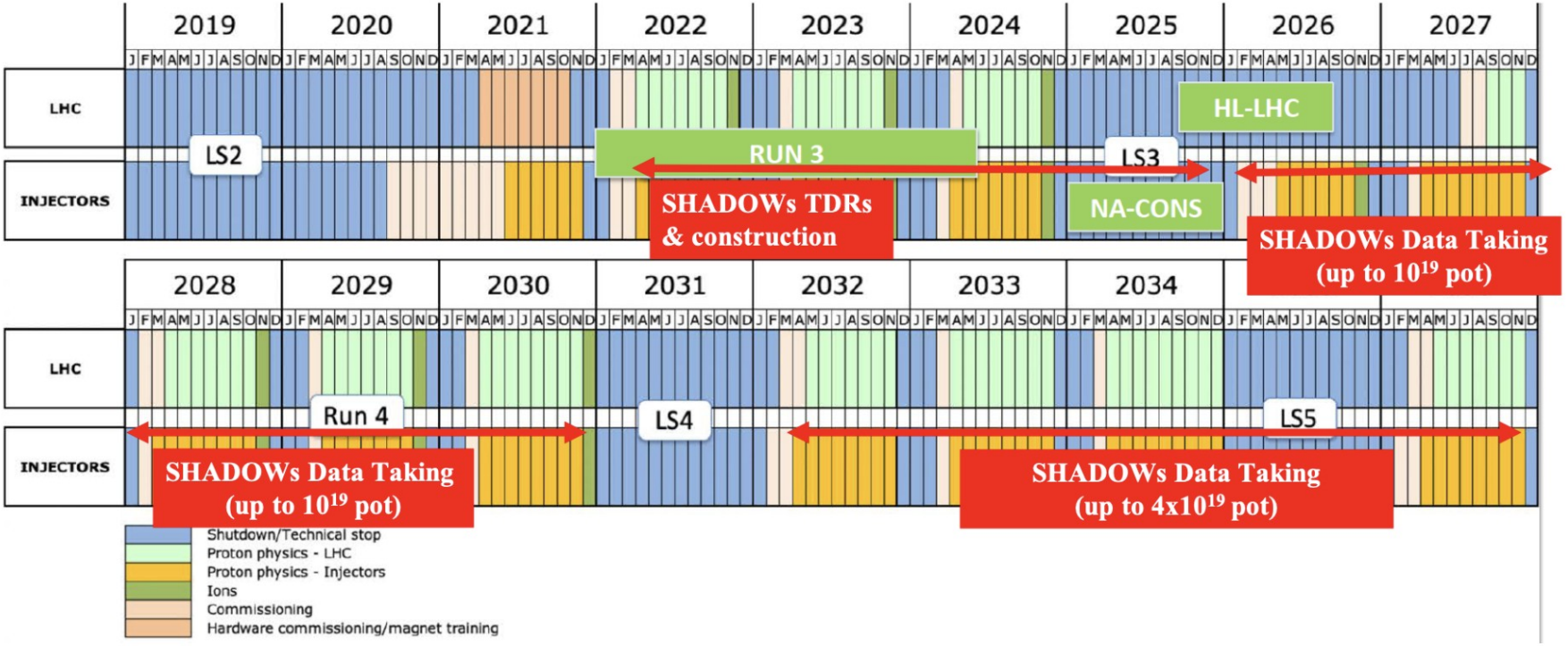
# SHiP


Access Bld.
DH's Access Bld.
Service Bld.
Target Hall
DETECTOR HALL
TARGET AREAS
Access Bld.
"Aux. Power Supply"
EXTRACTION TUNNEL
JUNCTION CAVERN
4x4MBB
Splitter 2

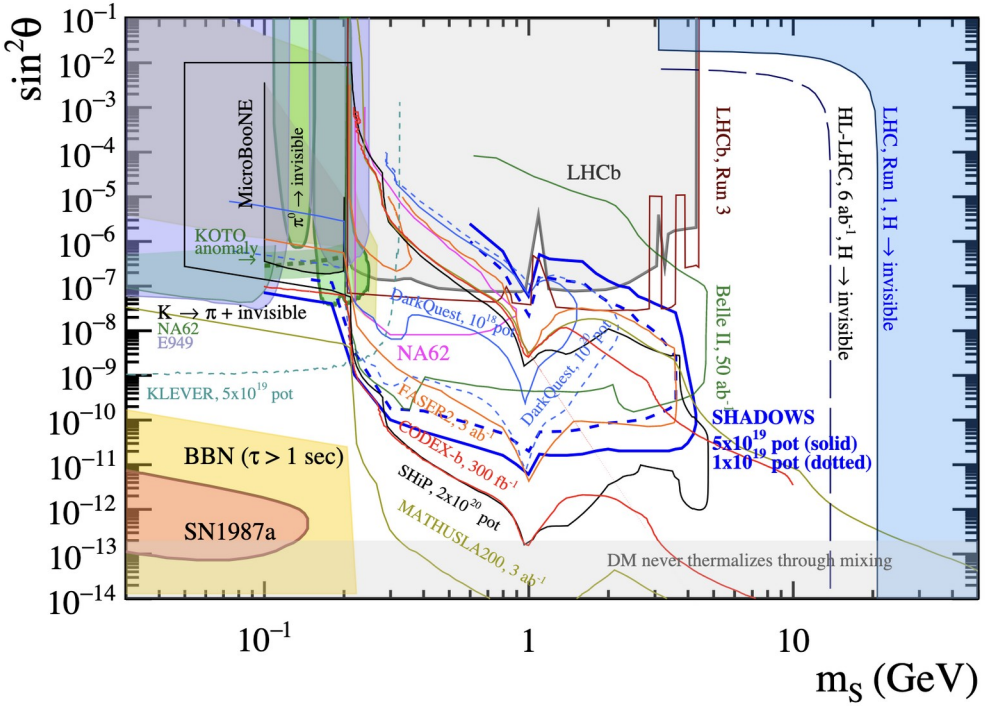
Target
Active Muon Shield
Muon Magnetic Spectrometer
Electromagnetic/Hadronic Calorimeter
Goliath Magnet
HS Vacuum Vessel
Spectrometer Timing Detector
HS Spectrometer Magnet
Neutrino Emulsion Target and Target Tracker
Drift Tube Tracker
Upstream Veto Tagger
Straw Veto Tagger
Surround Background Tagger
Spectrometer Straw Tracker
Muon Detector

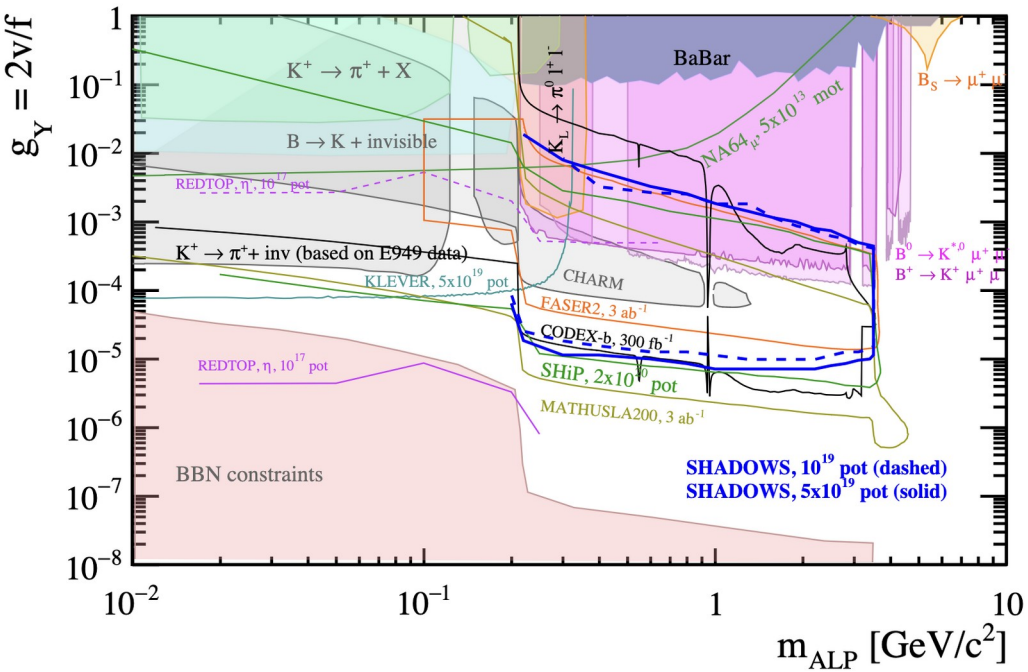
# SHADOWS

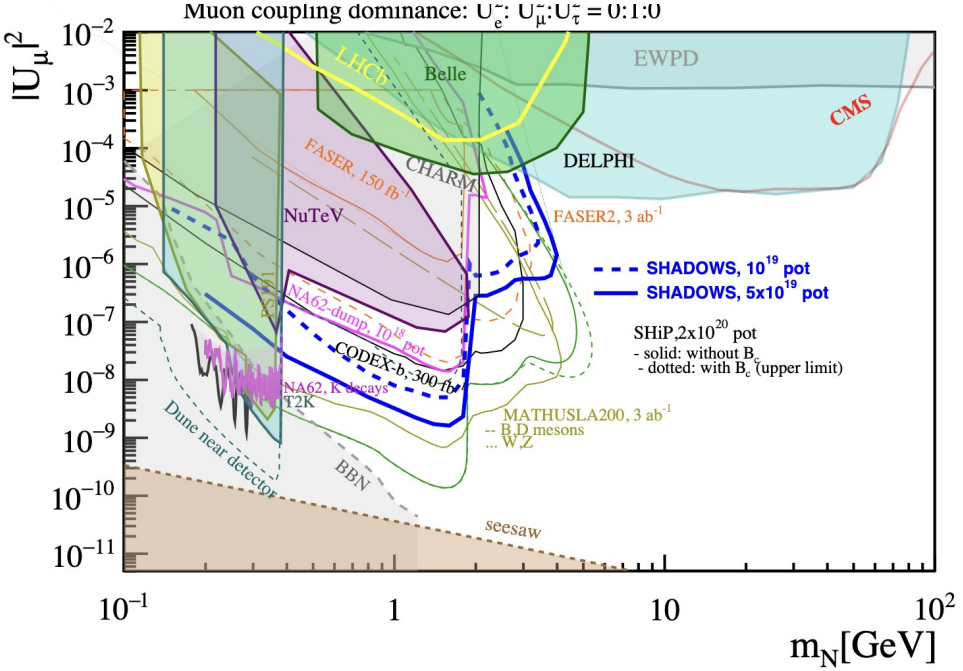

Timing layer
Muon System
HCal
ECal
DV
Tracker
DV
Tracker
DV
MAGNET
DV
Tracker
DV
Tracker

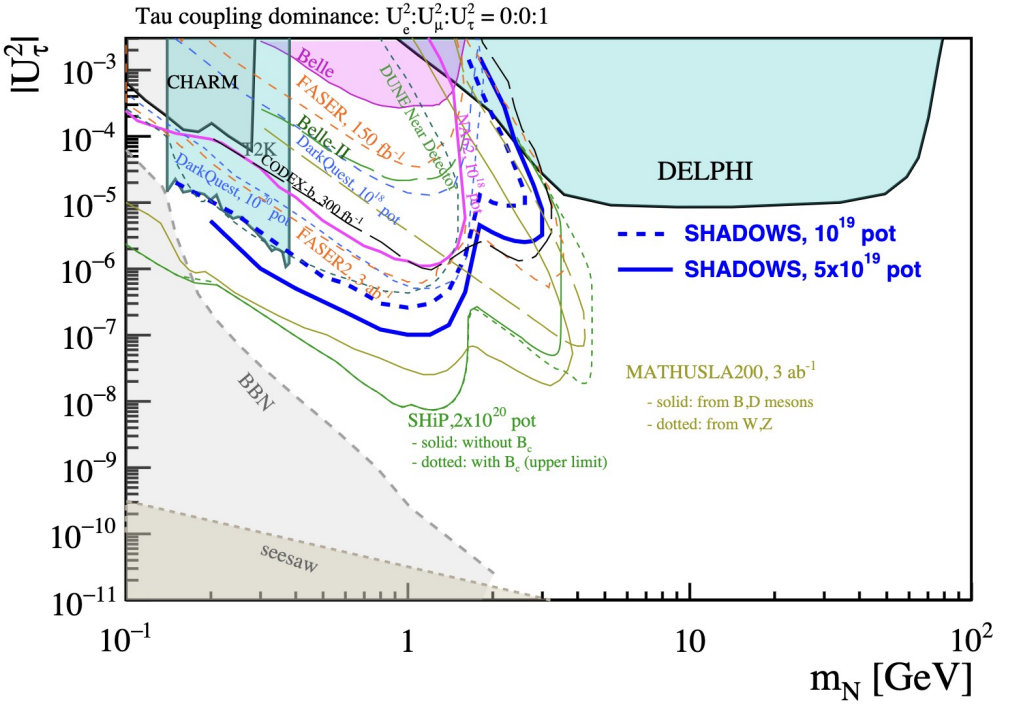

2019
2020
2021
2022
2023
2024
2025
2026
2027
LHC
INJECTORS
LS2
RUN 3
LS3
HL-LHC
SHADOWs TDRs & construction
NA-CONS
SHADOWs Data Taking (up to 10^19 pot)
2028
2029
2030
2031
2032
2033
2034
LHC
INJECTORS
Run 4
LS4
LS5
SHADOWs Data Taking (up to 10^19 pot)
SHADOWs Data Taking (up to 4x10^19 pot)
Shutdown/Technical stop
Proton physics - LHC
Proton physics - Injectors
Ions
Commissioning
Hardware commissioning/magnet training

# SHADOWS


sin²θ
MicroBooNE
π⁰ → invisible
KOTO anomaly
LHCb
LHCb, Run 3
Belle II, 50 ab⁻¹
HL-LHC, 6 ab⁻¹, H → invisible
LHC, Run 1, H → invisible
K → π + invisible
NA62
E949
KLEVER, 5x10¹⁹ pot
DarkQuest, 10¹⁸ pot
NA62
FASER2, 3 ab⁻¹
CODEX-b, 300 fb⁻¹
SHiP, 2x10²⁰ pot
MATHUSLA200, 3 ab⁻¹
DarkQuest, 10²⁰ pot
SHADOWS
5x10¹⁹ pot (solid)
1x10¹⁹ pot (dotted)
BBN (τ > 1 sec)
SN1987a
DM never thermalizes through mixing
m_S (GeV)


g_Y = 2v/f
K⁺ → π⁺ + X
B → K + invisible
K⁺ → π⁺+ inv (based on E949 data)
REDTOP, η, 10¹⁷ pot
KLEVER, 5x10¹⁹ pot
BaBar
K_L → π⁰ l⁺ l⁻
NA64 μ, 5x10¹³ mot
B_S → μ⁺ μ⁻
B⁰ → K*⁰ μ⁺ μ⁻
B⁺ → K⁺ μ⁺ μ⁻
CHARM
FASER2, 3 ab⁻¹
CODEX-b, 300 fb⁻¹
SHiP, 2x10¹⁹ pot
MATHUSLA200, 3 ab⁻¹
BBN constraints
SHADOWS, 10¹⁹ pot (dashed)
SHADOWS, 5x10¹⁹ pot (solid)
m_ALP [GeV/c²]


Muon coupling dominance: U_e²: U_μ²:U_τ² = 0:1:0
|U_μ|²
LHCb
Belle
EWPD
CMS
DELPHI
CHARM
NuTeV
FASER, 150 fb⁻¹
FASER2, 3 ab⁻¹
SHADOWS, 10¹⁹ pot
SHADOWS, 5x10¹⁹ pot
NA62-dump, 10¹⁸ pot
CODEX-b, 300 fb⁻¹
NA62, K decays
T2K
SHiP,2x10²⁰ pot
- solid: without B_c
- dotted: with B_c (upper limit)
MATHUSLA200, 3 ab⁻¹
-- B,D mesons
... W,Z
Dune near detector
BBN
seesaw
m_N[GeV]


Tau coupling dominance: U_e²:U_μ²:U_τ² = 0:0:1
|U_τ²|
CHARM
Belle
FASER, 150 fb⁻¹
DUNE Near Detector
Belle-II
DarkQuest, 10¹⁸ pot
T2K
CODEX-b, 300 fb⁻¹
DarkQuest, 10²⁰ pot
FASER2, 3 ab⁻¹
DELPHI
SHADOWS, 10¹⁹ pot
SHADOWS, 5x10¹⁹ pot
MATHUSLA200, 3 ab⁻¹
- solid: from B,D mesons
- dotted: from W,Z
SHiP,2x10²⁰ pot
- solid: without B_c
- dotted: with B_c (upper limit)
BBN
seesaw
m_N [GeV]