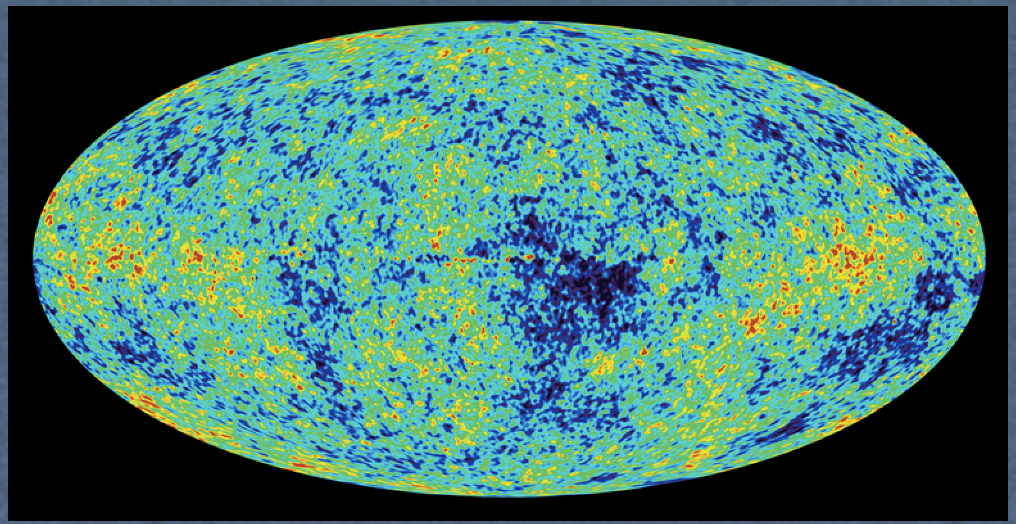
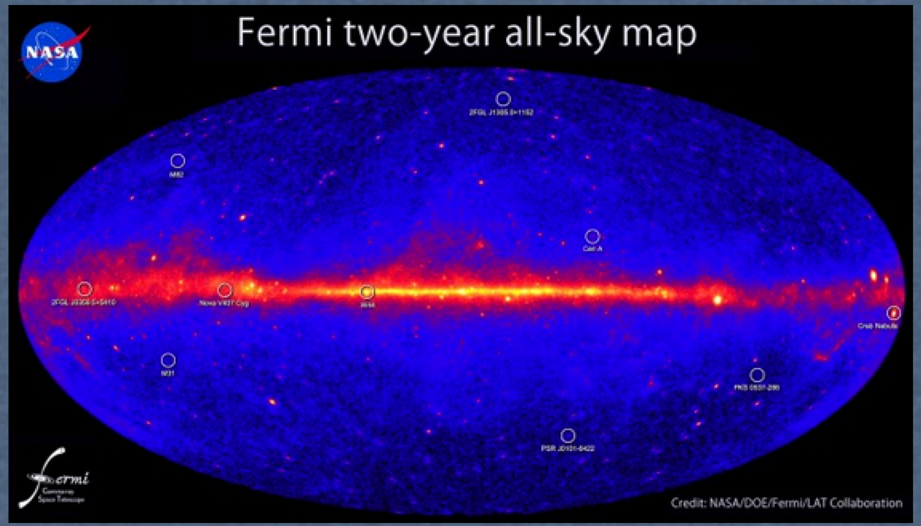
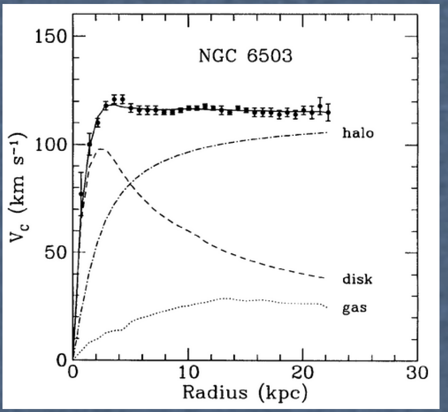
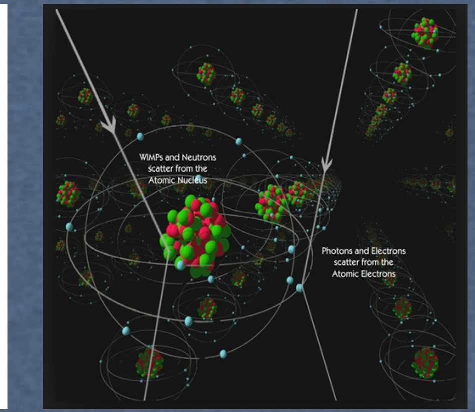
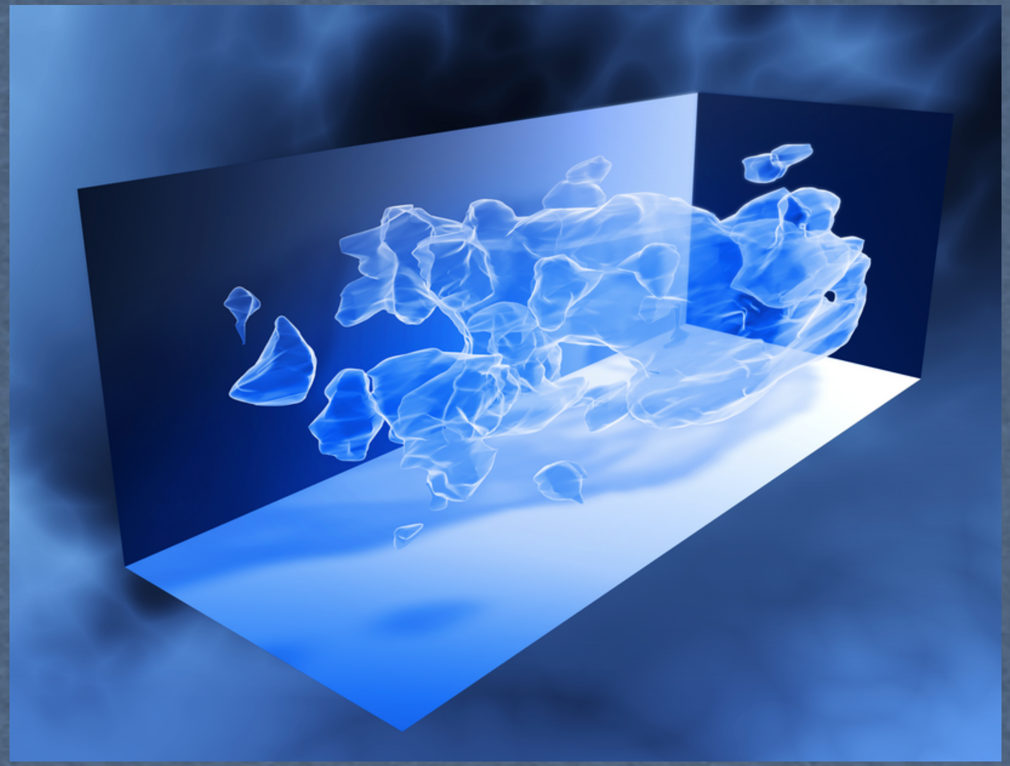
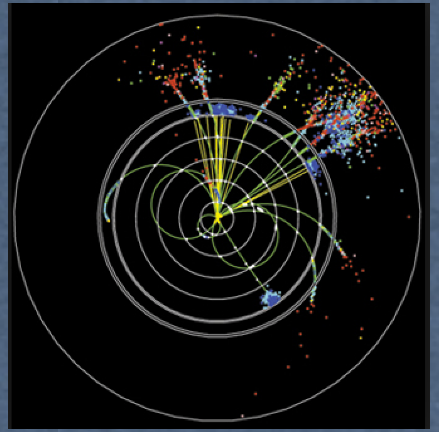












Muon Missing Momentum Experiment at Jefferson Lab KLF (μ3@JLab-KLF)

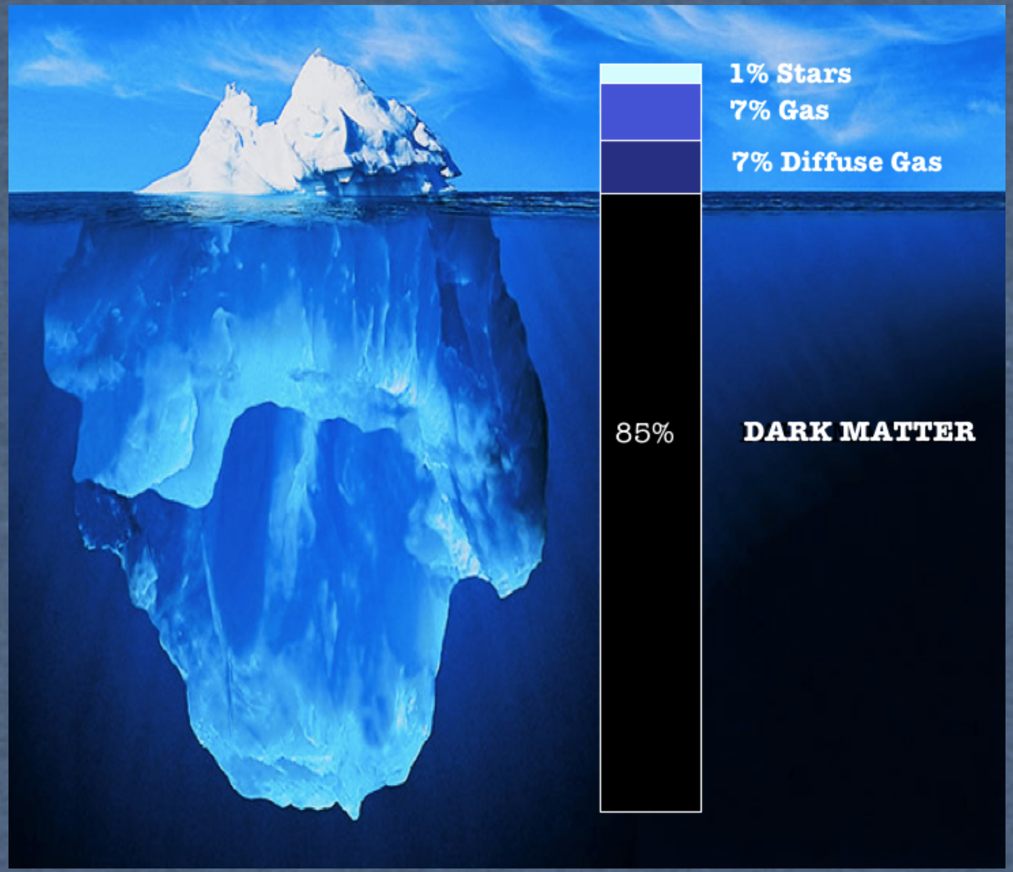
M.Battaglieri (INFN)

Jefferson Lab   clas   e- JLab12   Brookhaven National Laboratory   ePIC   INFN

Dark Matter (DM) vs Baryonic Matter (BM)

Compelling astrophysical evidence for Dark Matter existence, but …

★ How much DM w.r.t. BM?



★ Does DM participate to non-gravitational interactions?
★ Is DM a new particle?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weakly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

★ We can use what we know about standard model particles to build a DM theory

Use the SM as an example: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

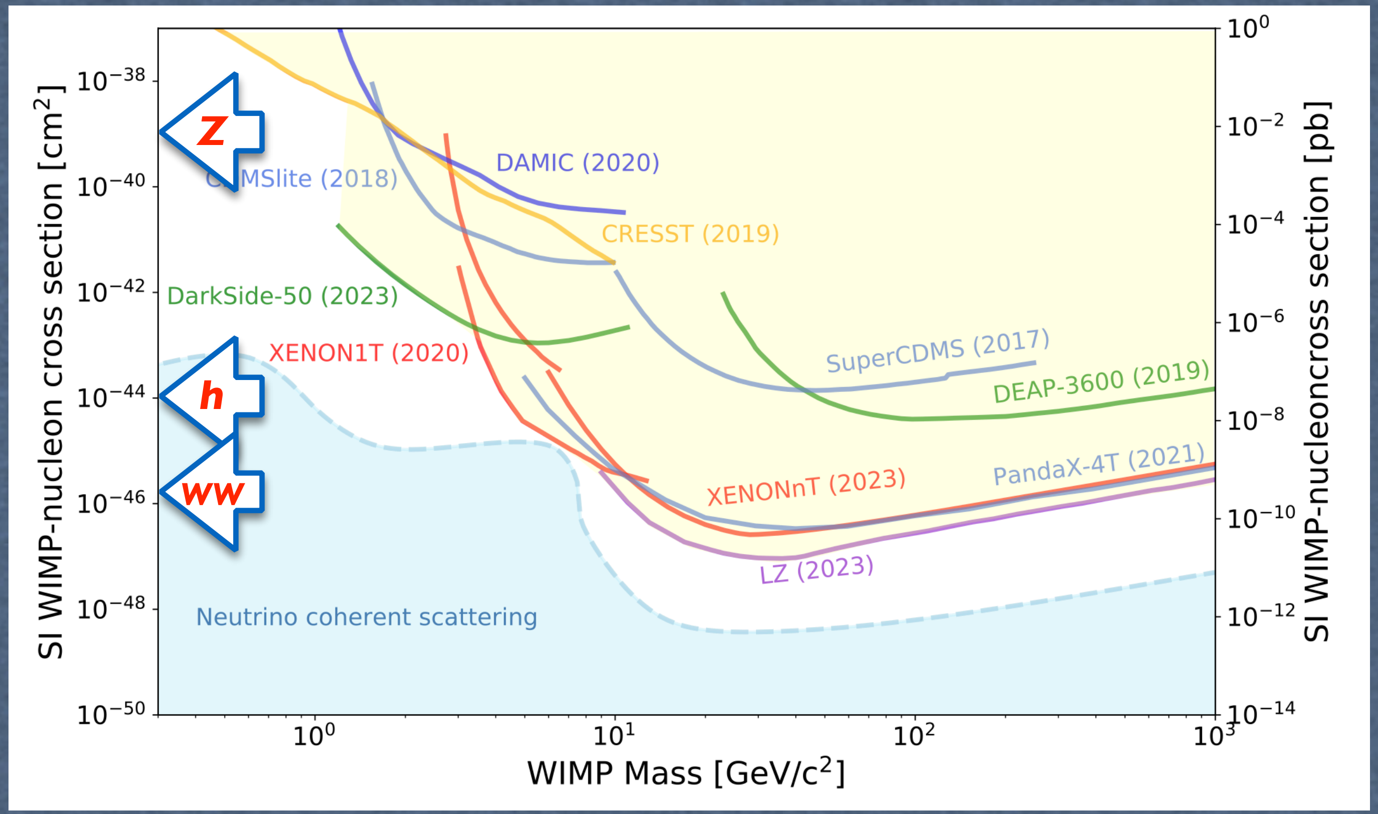
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...

Two options:

★ New matter interacting trough the same forces
★ New matter interacting through new forces

Exploring the WIMP's option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering through Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to irreducible neutrino background

✳ No signal observed in Direct Detection

✳ Experiments have reduced sensitivity to (light) DM (<1 GeV)

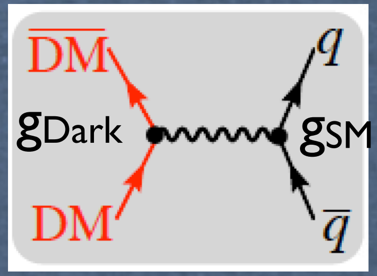
Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

WIMPs paradigm is not the only option (keeping the DM thermal origin)

$\langle \sigma v \rangle \sim g^2_{Dark}\, g^2_{SM}\, M^2_{DM}/M^4_{mediator}$



Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

New interaction

A lesson from history

An historical example of a 'Standard Model' and 'hidden sector'

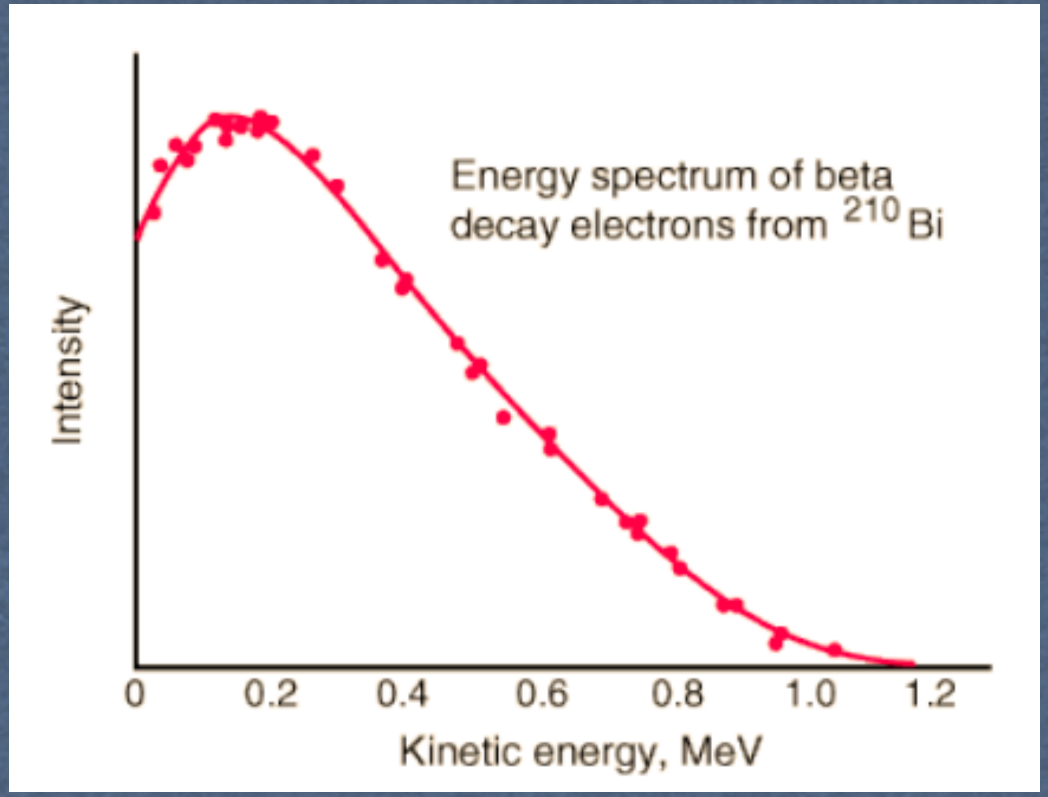
- ★ Back in the '30 the Standard Model of the elementary particles was: photon, electron and nucleons
- ★ Beta decay: Continuous spectrum!

  $n \rightarrow p + e^-$

- ★ Pauli proposes a radical solution - the neutrino!

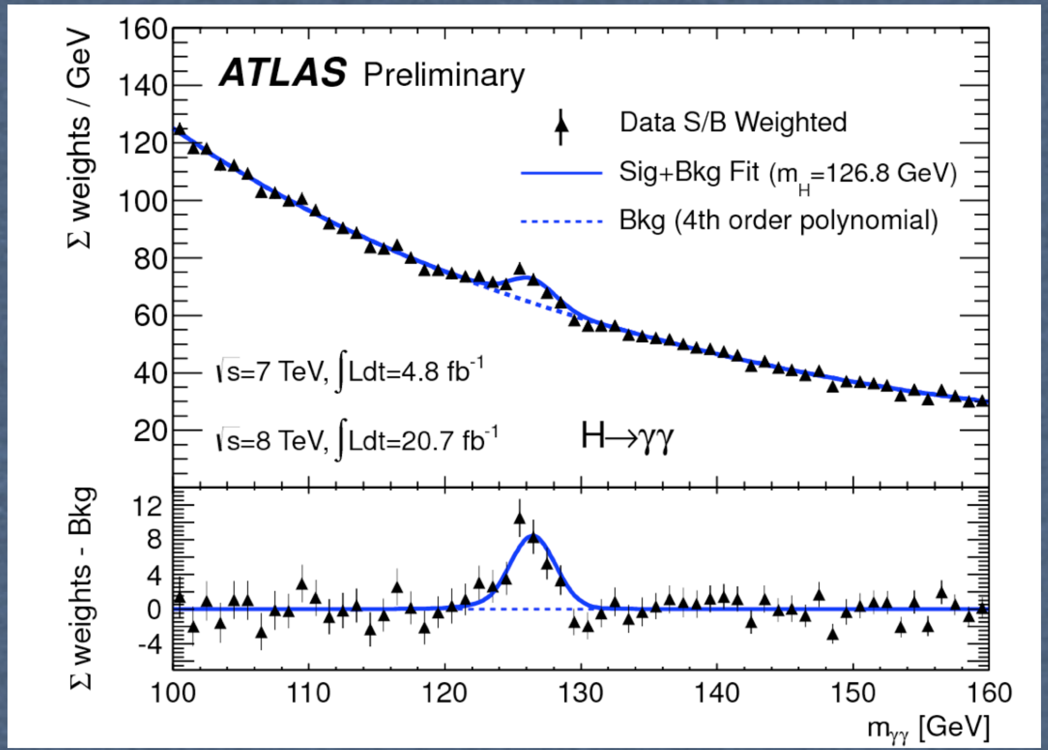
  $n \rightarrow p + e^- + \bar{\nu}$

- ★ Perfect example of a hidden sector!
  - neutrino is electrically neutral
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(p\gamma^\mu n)(e\gamma^\mu \nu)$



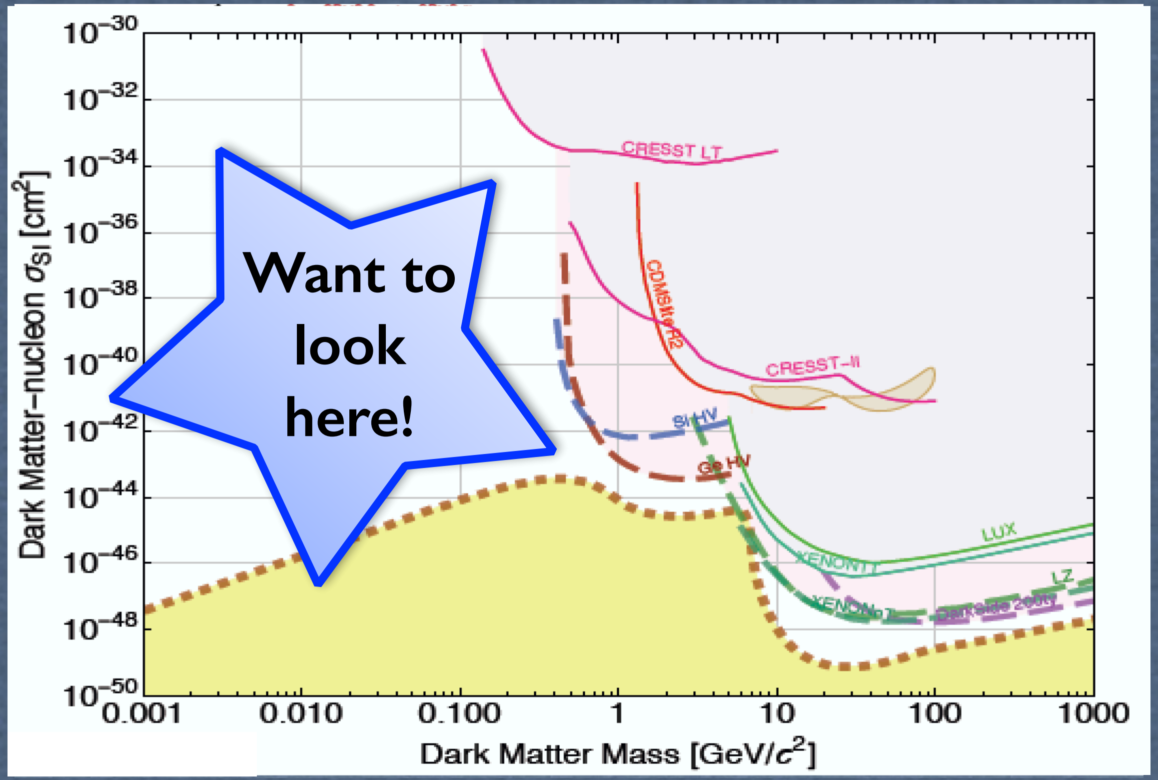
Today?

- ★ Higgs discovery represent the triumph of SM
- ★ but there are still some missing pieces: Dark Matter, baryon asymmetry, neutrino oscillations …
- ★ No guarantee of discoveries but exciting times to look for new physics!



Light Dark Matter

★ Experimental limits



Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is difficult
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits at large masses

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Moderate energy**

Light Dark Matter | Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

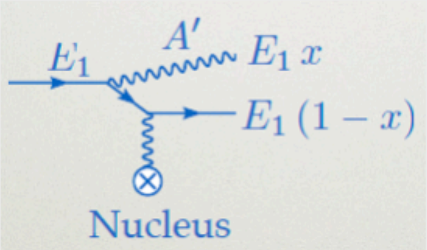
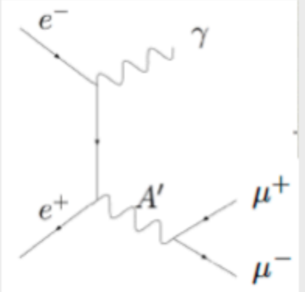
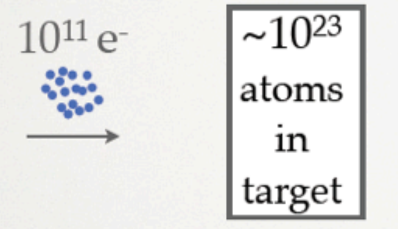
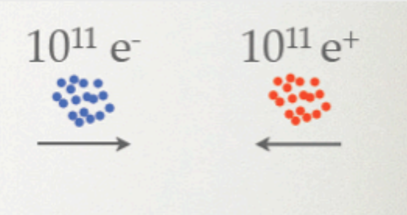
WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Can be explored at accelerators!

Experimental techniques

Fixed target vs. collider

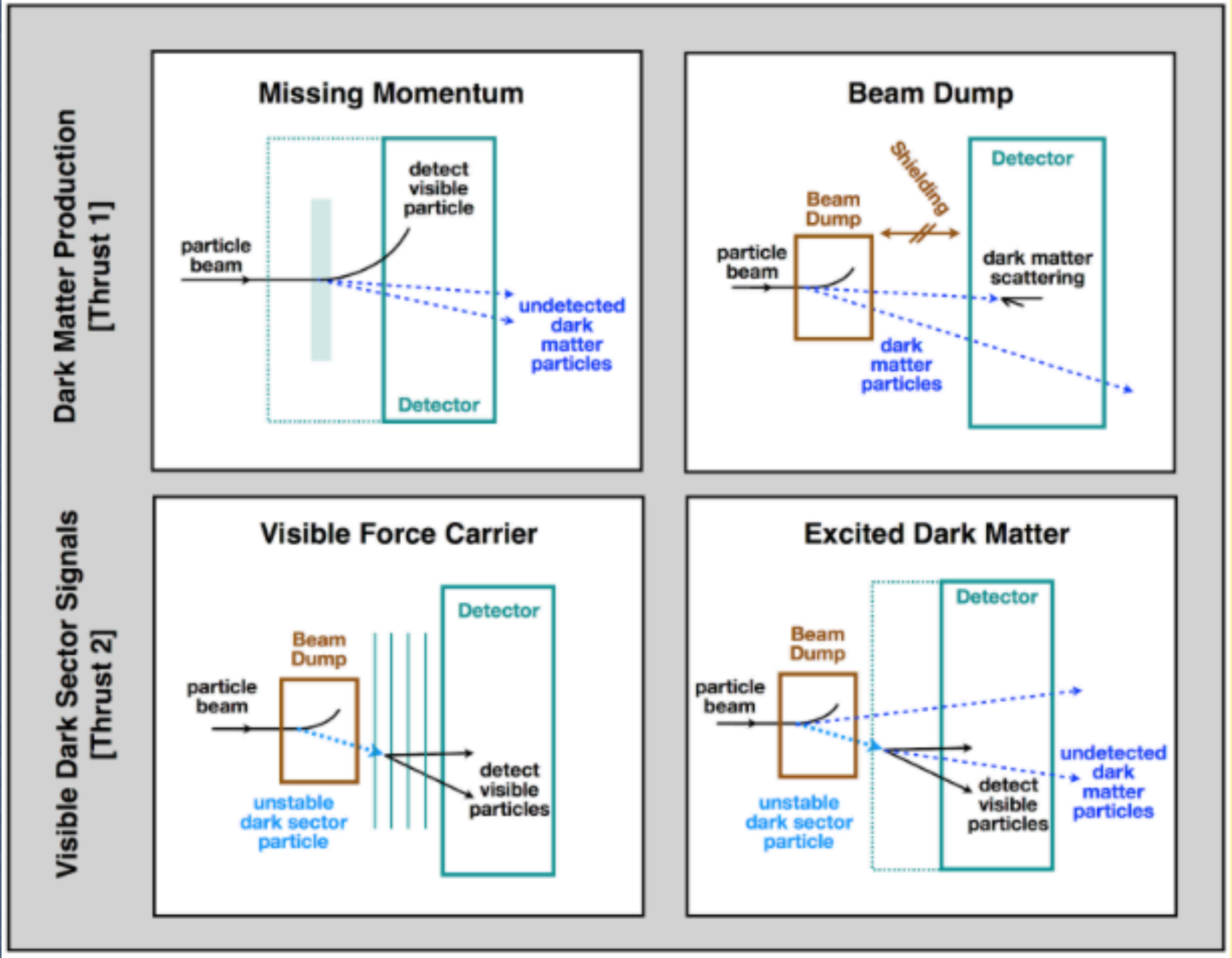
	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

Fixed Target:
- high backgrounds
- limited A' mass

e+e- colliders:
- low backgrounds
- higher A' mass

✳ $1/M_{A'}$ .vs. $1/E_{beam}$
✳ Coherent scattering from Nucleus (~Z^2)

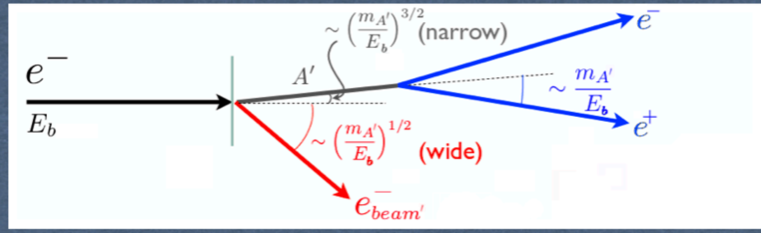
Fixed target

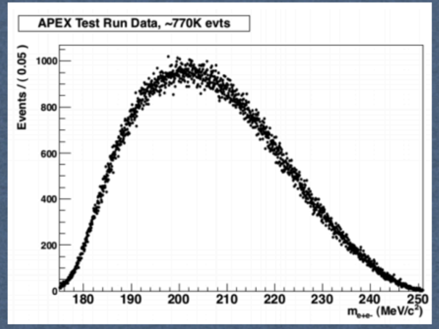


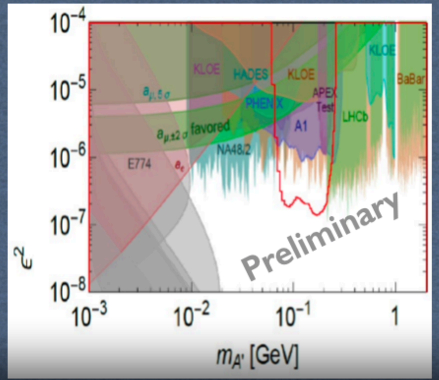
Dark Sector searches at JLab (electron beams)

APEX: A-Prime EXperiment
visible decay

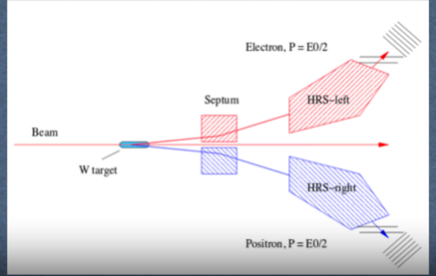
e- fixed target experiment installed in HALL A searching for dark photon visible decay



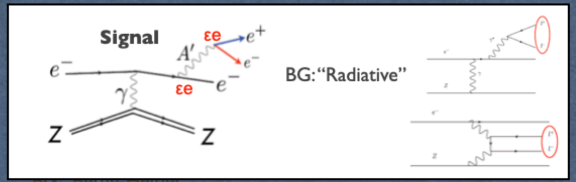


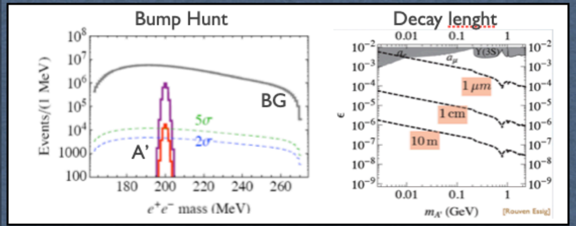


- Dark photon searched as a narrow resonance in e+e- mass over a smooth QED background
- Two High Resolution Spectrometers (HRSs) in coincidence to measure events with an e- in one arm and e+ in the other
- Standard HRS detector stack in both arms: Scintillators: S0 and S2(timing), VDC (tracking), Cherenkov and Calorimeters (PID)



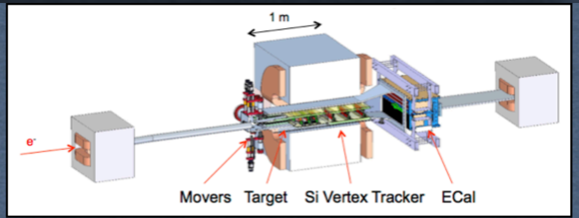
Heavy Photon Search @ JLab
visible decay





Heavy photon signatures in HPS

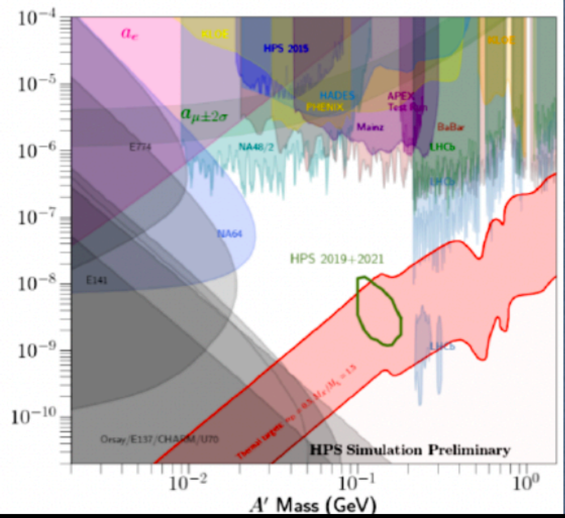
BH + Vertexing = enhanced experimental reach



1) Bump Hunting (BH)
Narrow e+e-resonance over a QED background
➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

2) Secondary decay vertex (vertexing)
Detached vertex from few mm to tens cm
➥ good spacial resolution: σ_{vertex}~1mm

- 105 PAC more days of data taking approved, confirmed by PAC52



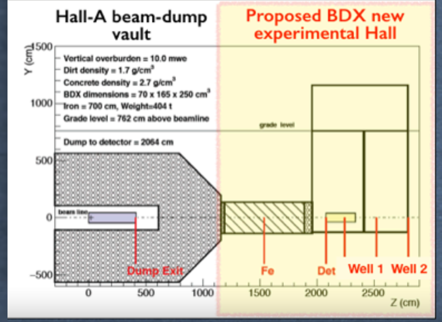
BDX-MINI @JLab
invisible decay

BDX-MINI: small-scale demonstrator to prove the validity and feasibility of the BDX experiment

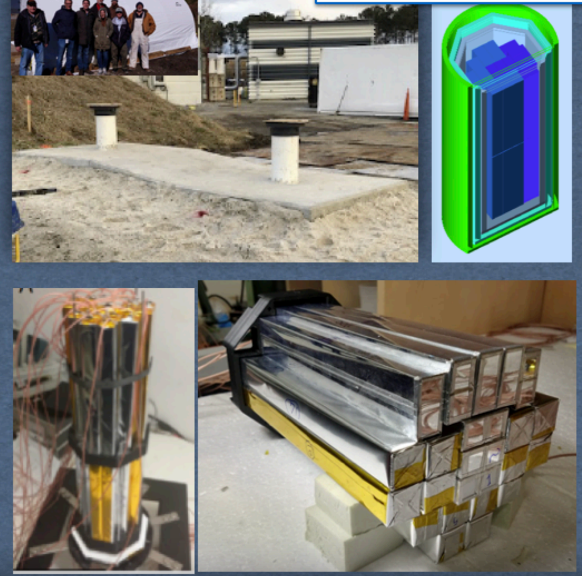
- Installed in March 2019
- Run form Dec 2019 to Aug 2020
- Collected 4e21 EOT (40% BDX!) in ~4 months (+ cosmics)
- Good detector performance with high duty factor
- Data analysis in progress

- Two wells dug for bg muon tests
- E_{beam}=2.2 GeV, no muons
- Limited reach but first physics result!

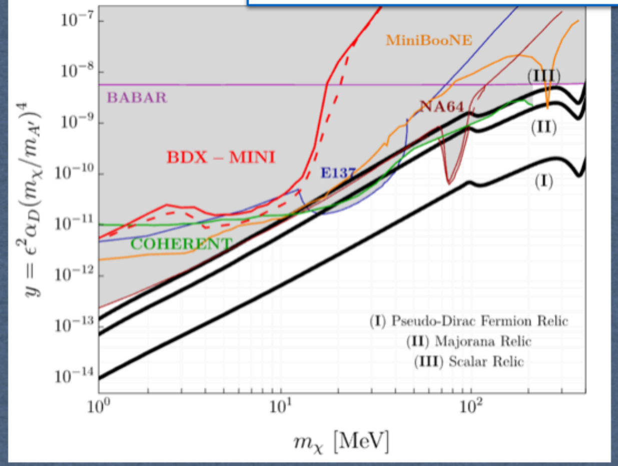
- 44 PbWO4 PANDA/FT-Cal crystals (~1% BDX active volume)
- 6x6 mm2 SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding



M.Battaglieri et al. EPJC (2021) 81: 164



M.Battaglieri et al. arXiv:2208.01387 accepted bt PRD



- Data-taking completed, analysis completed
- Results provide exclusion limits similar to the best existing experimnts (E137, NA64, BaBar, …)

X17 search at JLab
visible decay

- Search for the X17 in e+e- invariant mass
- Presented to JLab PAC 49 in Aug 21 and granted a C2 approval

Search for Hidden Sector New Particles in the 3 – 60 MeV Mass Range

Proposal submitted to JLab PAC49

- New (hidden) particle in MeV-scale mass range in forward electroproduction reactions from a heavy A solid target.

$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta^*,$$
$X \rightarrow e^+e^-$ (with tracking)
or $X \rightarrow \gamma\gamma$ (without tracking)

Mass range: [3 ÷ 60] MeV

- Target: Tantalum ($_{73}Ta^{181}$) film, thickness: 1 μm, 2.5x10^{-4} r.l.
  density: 16.69 g/cm^3
  N(Ta) = 0.56x10^{+19} atoms/cm^2

Experimental method:
✓ "bump hunting" in the invariant mass spectrum over the beam background.
✓ direct detection of decay particles (e⁺e⁻) and scattered e⁻

Detection criteria:
- scattered electron is in the PbWO₄ acceptance with E_e = [30MeV to 0.7xE_{beam}];
- decay e⁻ and e⁺ are in the PbWO₄ within energy: [0.03 – 0.8xE_{beam}]
- Target to PbWO4 distance L=7.5 m beam energy optimized for E_e = 2.2 GeV and 3.3 GeV

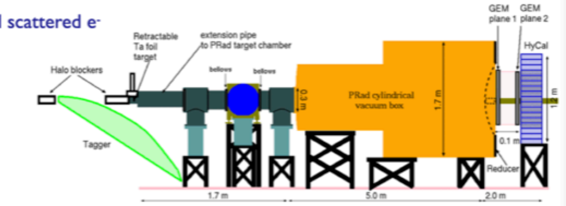
Beam time request

	Time [days]
Setup checkout, tests and calibration	4.0
Production at 2.2 GeV @ 50 nA	20.0
Production at 3.3 GeV @ 100 nA	30.0
Energy change	0.5
No target background sampling at 2.2 & 3.3 GeV	5.5
Total	60.0

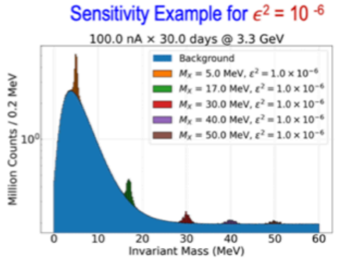
Search sensitivity

m_X MeV	σ_{m_X} MeV	Background Counts	Signal Counts (5.0 Significance)	Lowest ϵ^2	lowest ϵ^2
30 days of 3.3 GeV at 100 nA					combined with signal from 20 days at 2.2 GeV
5.0	0.263	22.02M	23.48k	6.86E-09	5.94E-09
17.0	0.467	3.60M	9.50k	9.83E-09	8.51E-09
30.0	0.692	3.06M	8.76k	2.60E-08	2.25E-08
40.0	0.938	4.08M	10.11k	5.71E-08	4.94E-08
50.0	1.009	4.38M	10.48k	8.37E-08	7.24E-08

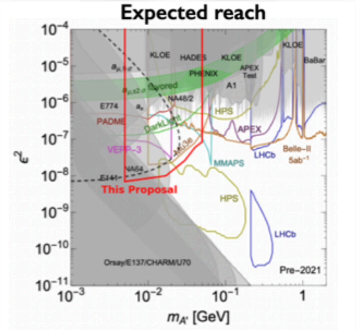
Experimental Setup (Side View)



Sensitivity Example for $\epsilon^2 = 10^{-6}$



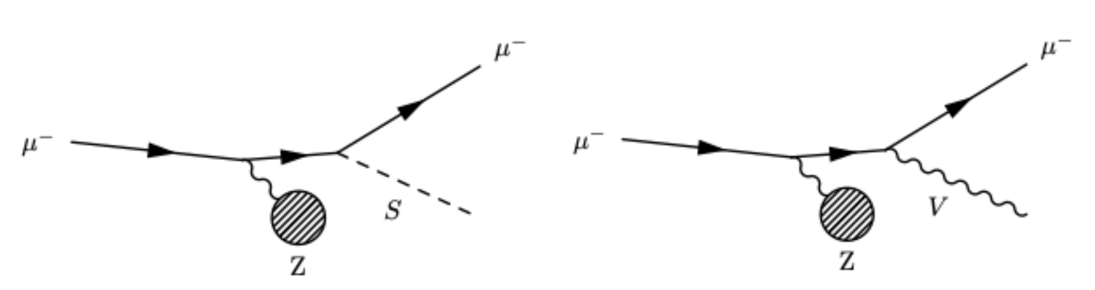
Expected reach



+ PAC approved experiments (e.g., BDX)

Probing muon-philic forces with secondary muon beam

- Goal: extending LDM searches to muon-philic scenarios requires intense muon beams

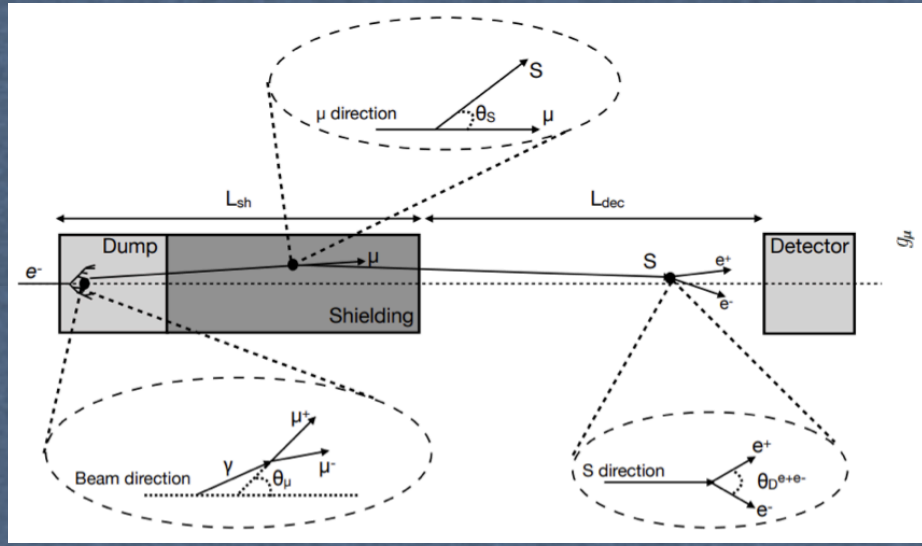


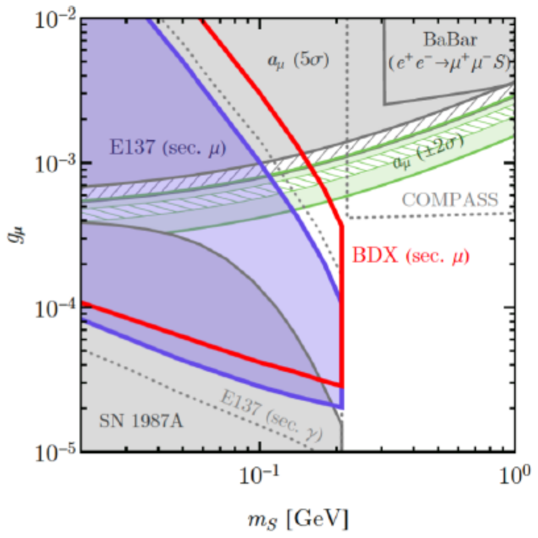
- VECTOR or SCALAR mediator produced with a similar mechanism of A'

μBDX @ JLab

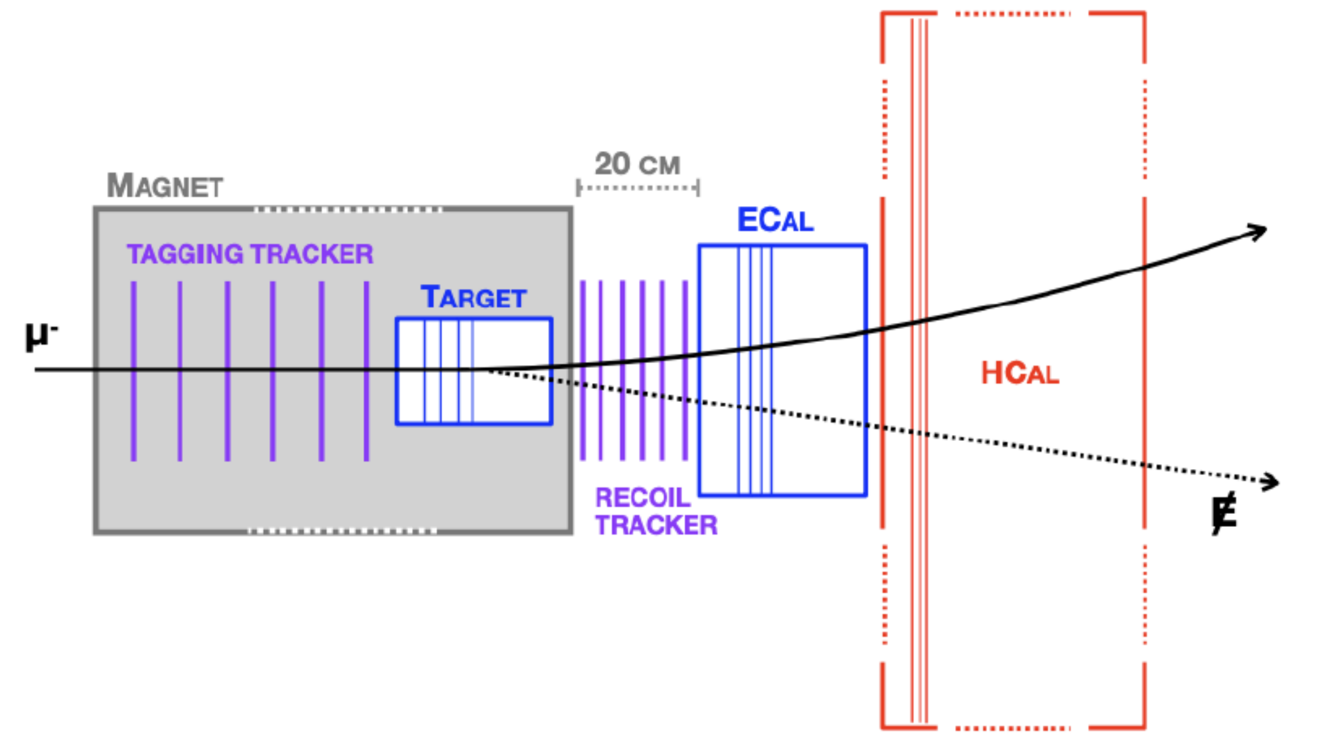
- Muon beam dump experiment to probe the visible decay into e+e-(γγ)
- Same infrastructure requested by BDX

L. Marsicano et al., PRD 98, 115022 (2018)





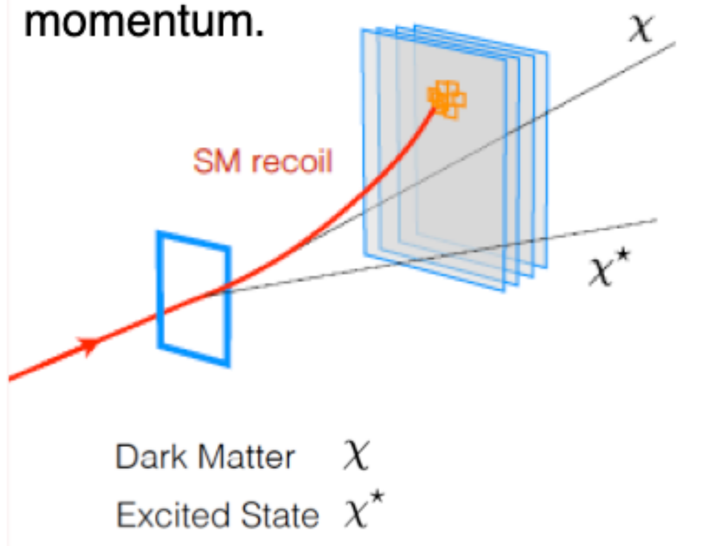
Muon Missing Momentum (μ³BDX @ JLab)

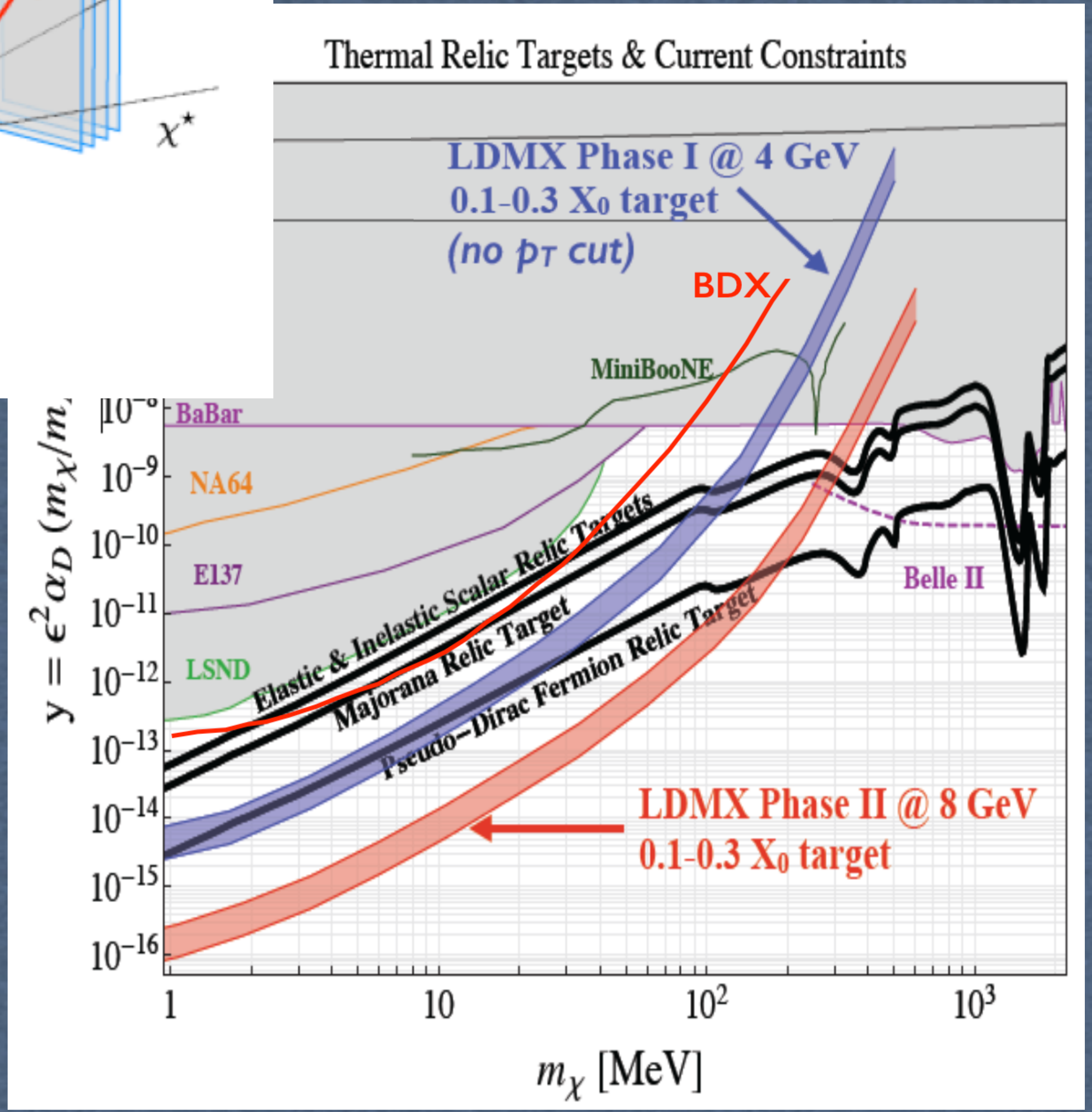


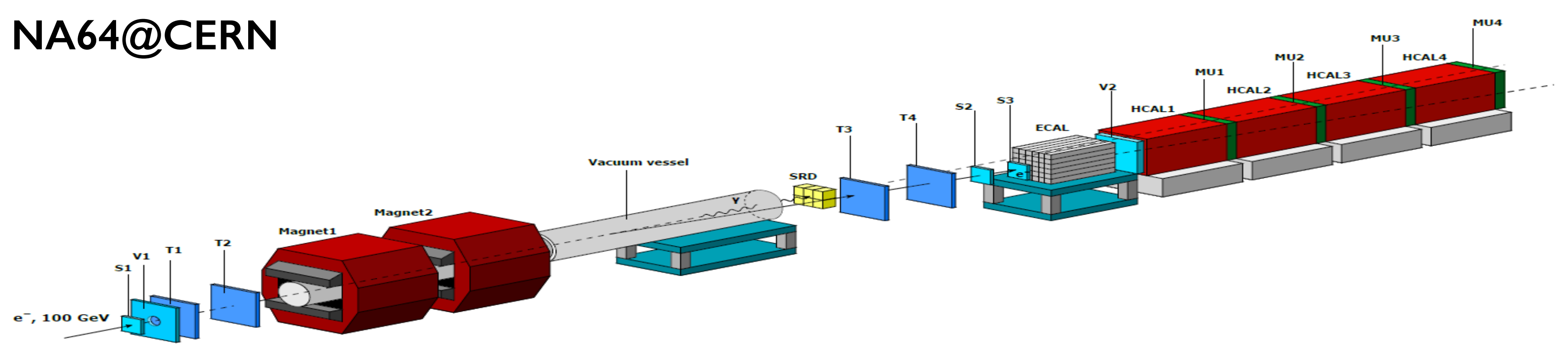
- Fixed-target, missing-momentum experiment to probe invisibly decaying particles
- BSM Light gauge boson couples predominantly to muon and or tau
- Scalar or vector mediator of a new force
- Its existence would be a viable explanation of g-2 anomaly
- This experiment is similar to M³ experiment proposed at FERMILAB
  - PROS: Bremsstrahlung backgrounds suppressed, compact experiment, high precision (magnetic spectrometer)
  - CONS: requires a intense high-energy muon beam

Missing energy/momentum BD experiments

"Disappearance" of a sizable fraction of the beam energy/ momentum.

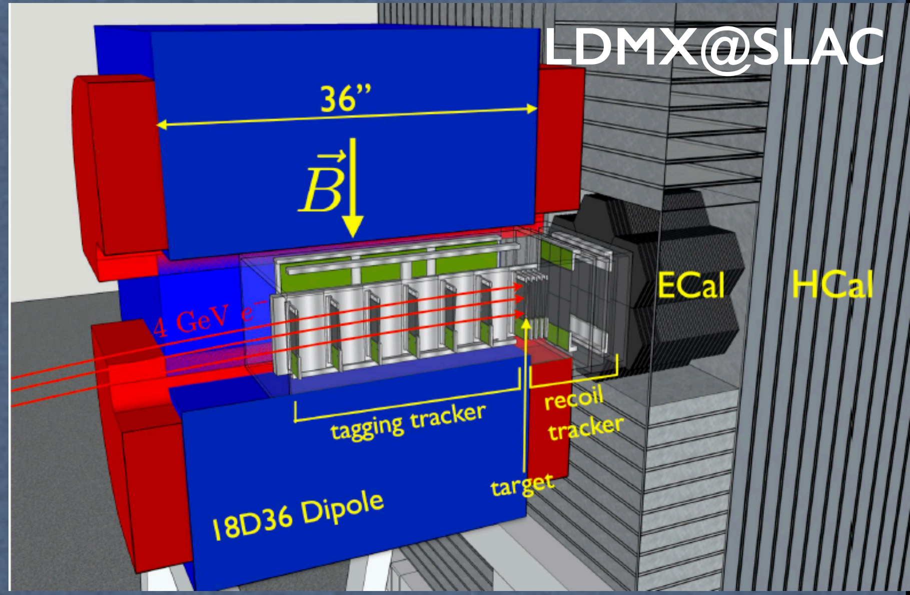






- *Active* beam-dump experiment
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3x10⁹ EOT

… and future BD experiments



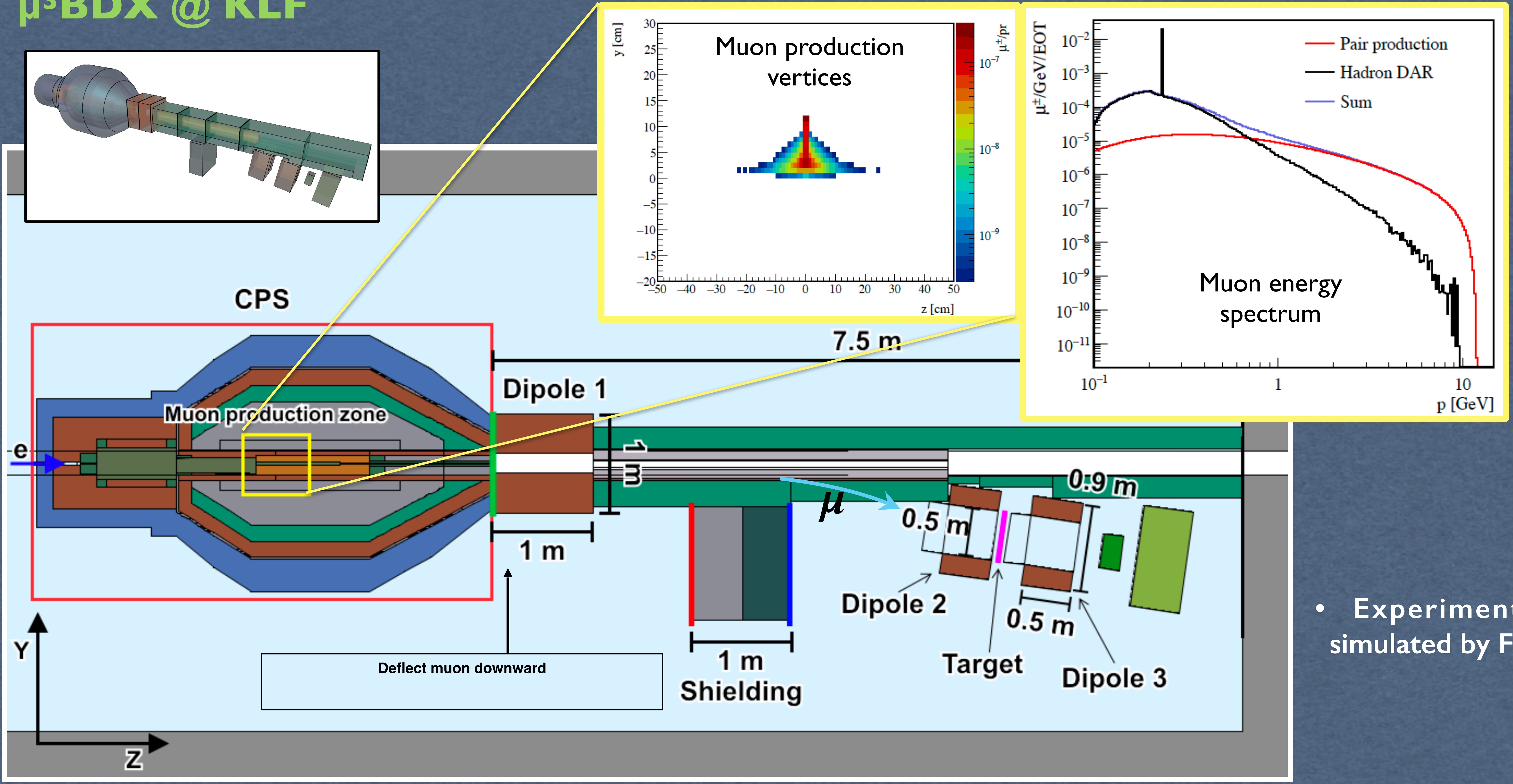
- LDMX: missing momentum exp proposed at SLAC-LCLS-II 4 GeV e- beam, (*Active* beam-dump)

MissingMomentum vs BeamDump (*disappearance* vs *appearance*)

… **more sensitive** in the exclusion plots but **less reliable/convincing** in case of positive finding!

The two experimental approaches are complementary

μ³BDX @ KLF

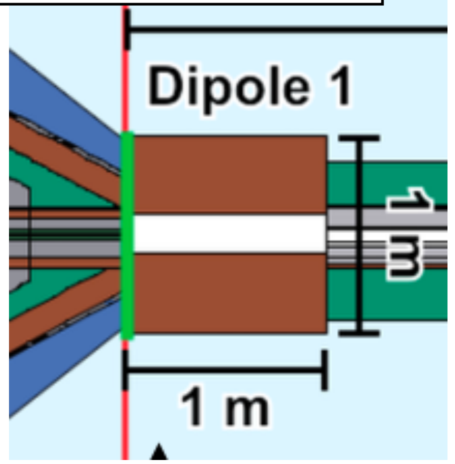


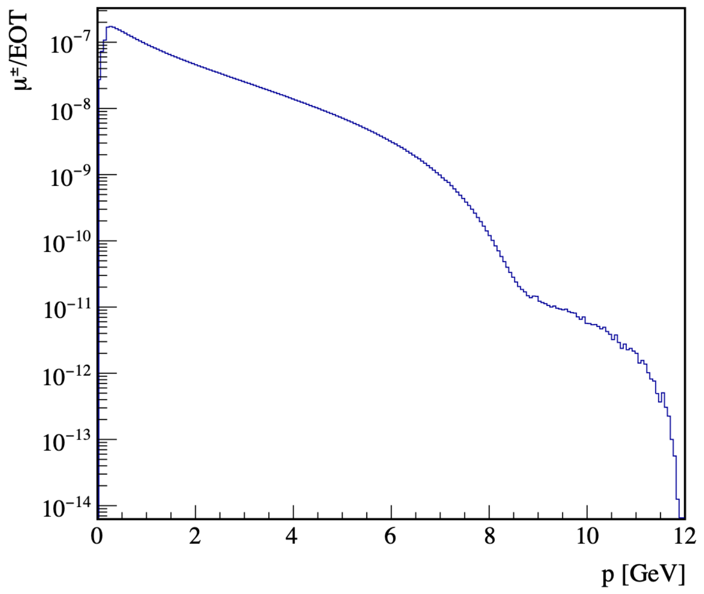
- Experimental setup simulated by FLUKA

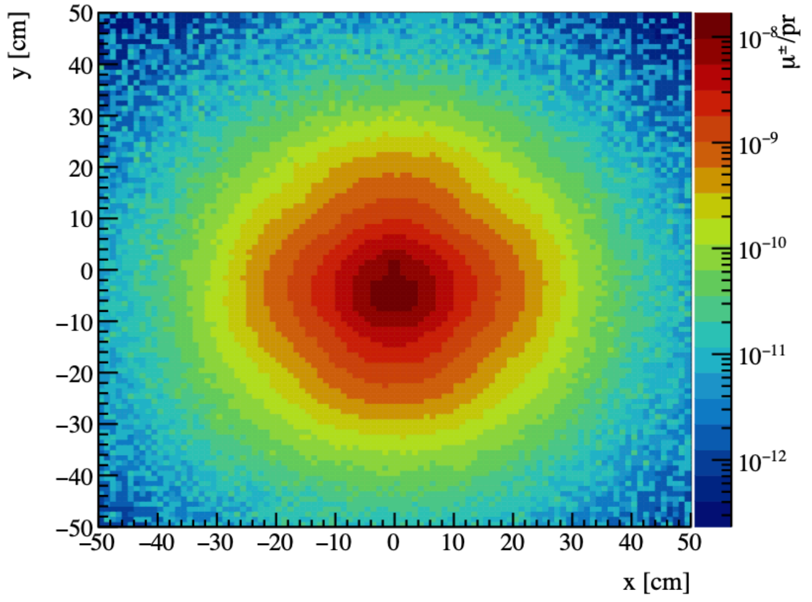
μ³BDX @ KLF

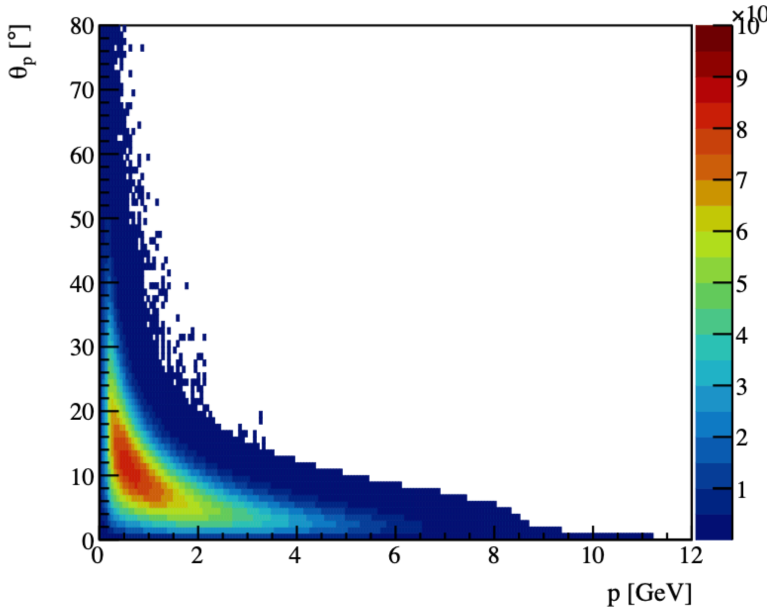
Element		Material	Dimension (x,y,z) [cm]	Magnetic field (B_x,B_y,B_z) [T]
Dipole 1	Yoke	Iron	92, 100, 100	0, 0, 0
	Bore	Vacuum	10, 20, 100	2, 0, 0
Dipole 2	Yoke	Iron	80, 90, 50	0, 0, 0
	Bore	Vacuum	20, 50, 50	−2, 0, 0
Dipole 3	Yoke	Iron	80, 90, 50	0, 0, 0
	Bore	Vacuum	20, 50, 50	2, 0, 0
Shielding	1st half	Lead	100, 114, 50	0, 0, 0
	2nd half	Concrete	100, 114, 50	0, 0, 0

- Muon flux downstream of Dipole 1

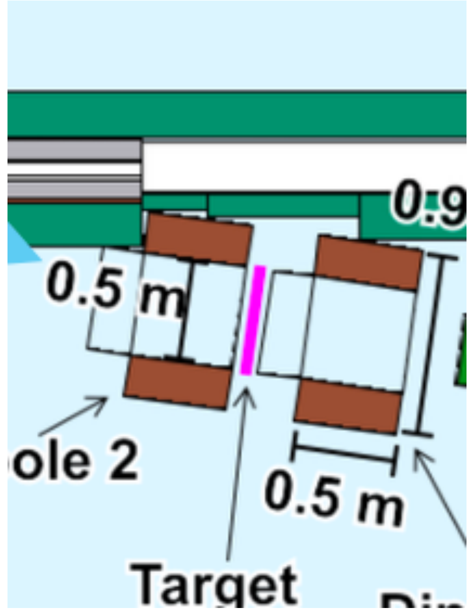


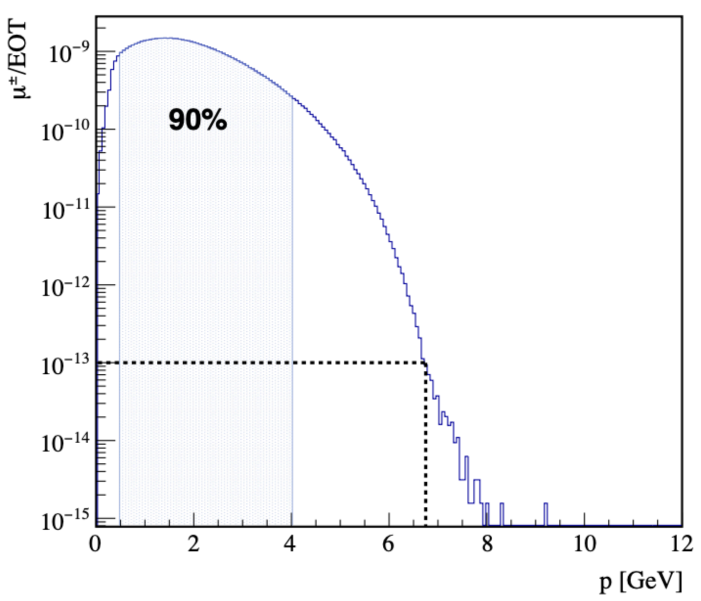


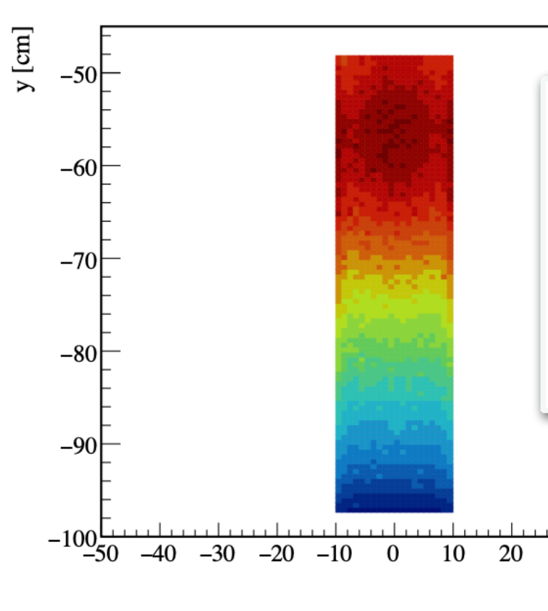




- Muon flux at the target position





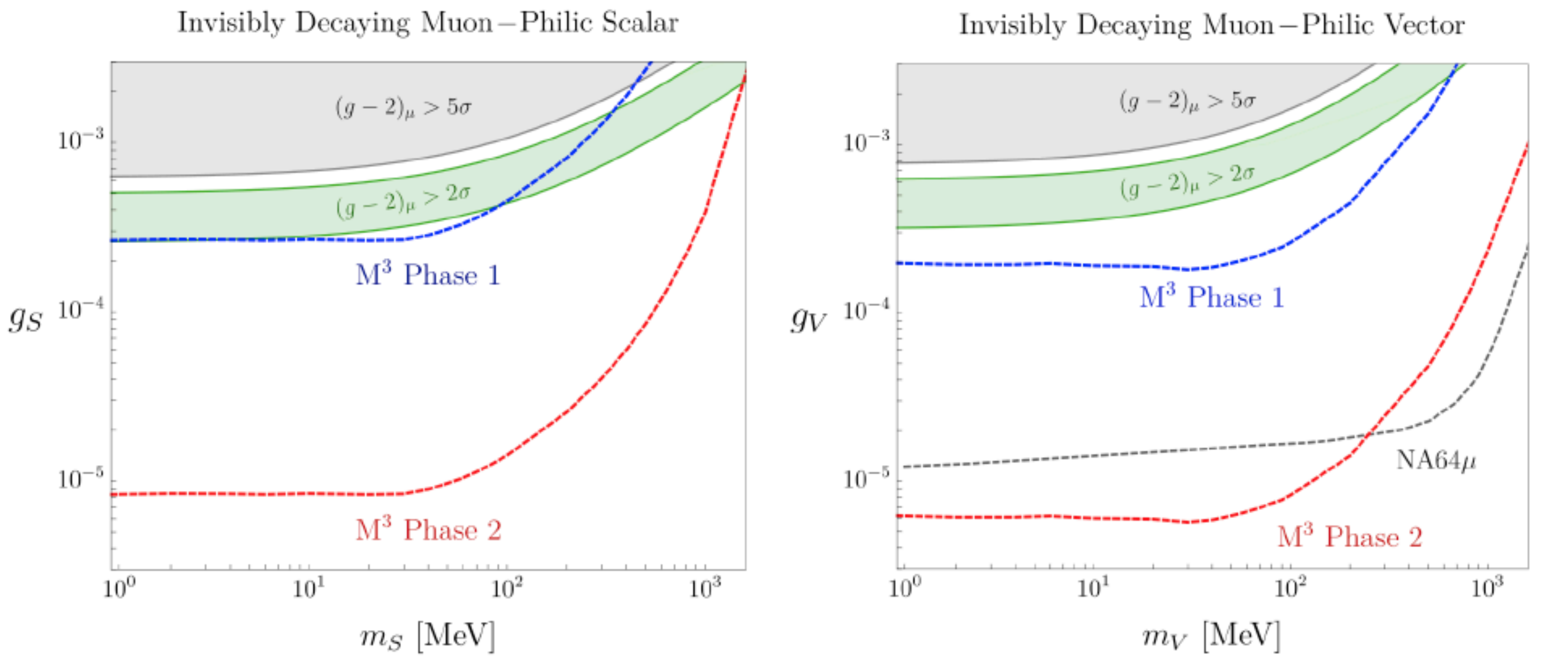


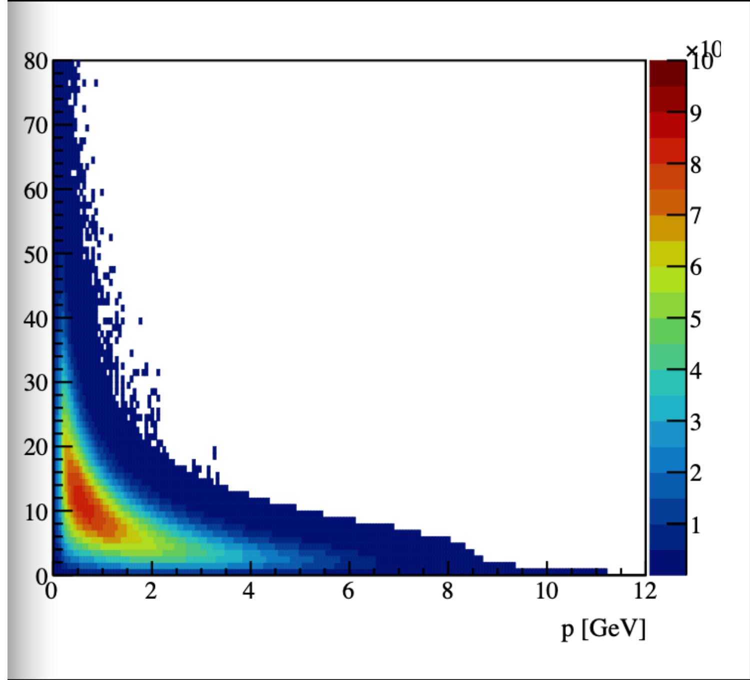
Location	Flux μ/s	σ_x (cm)	σ_y (cm)
CPS's exit	6.75×10^7	7.80	8.09
Target	$\sim 10^4$	$I_e = 2.7$uA	

μ³BDX @ KLF

- Mu
Dip

- Mu
the
pos





n	Flux μ/s	σ_x (cm)	σ_y (cm)
it	6.75×10^7	7.80	8.09
	~ 10^4	I_e = 2.7uA	

- muon beam ~ 15 GeV
- Phase 1: 10^{10} MOT
- Phase 2: 10^{13} MOT

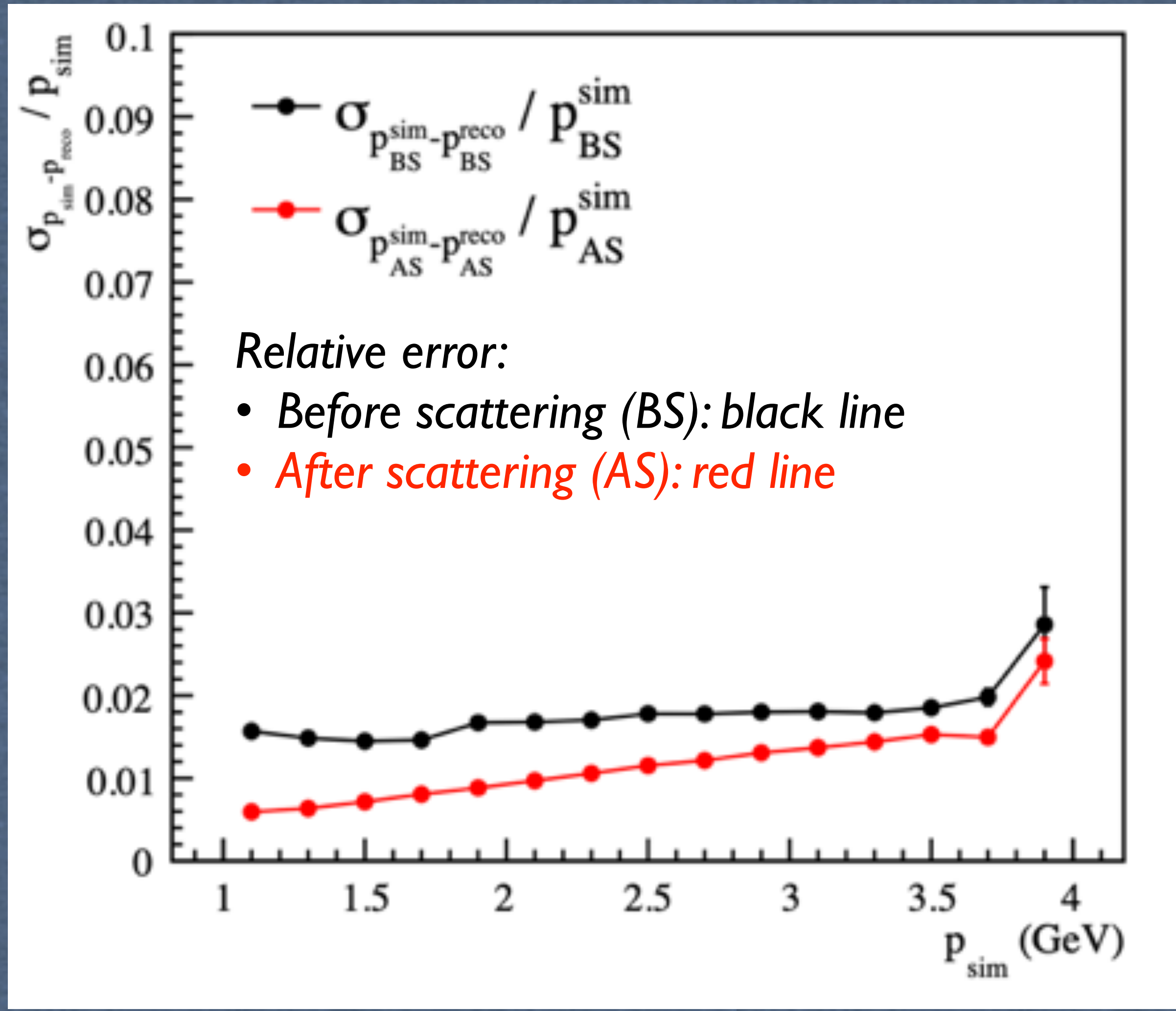
Similar M3@FNAL PhaseI MOT in 2 weeks of run!

(Phase II in ~3 years (with optimization))

μ^3BDX @ KLF

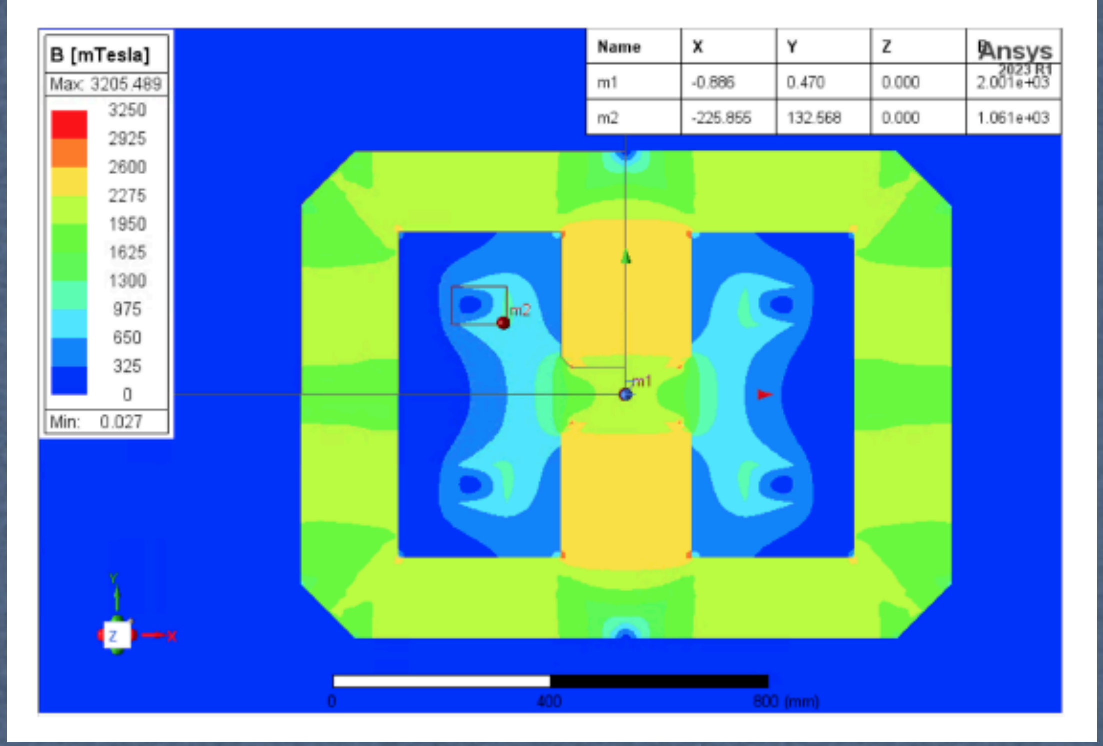
Assumptions

- No dead time between hits on the flux detectors, perfect particle Id
- The magnetic field of the dipoles is ideal (2 T on the axes)
- Tracking planes at the entrance of each dipole are separated by 20 cm
- Tracker resolution:
  - δX and δY: 75 μm
  - δZ: 250 μm
- Cut on incoming particles: 1 GeV < p_μ < 4 GeV



Realistic Magnet design

- 2 windings , 40 turns each with I=5kA
- The field at the center is ~1.95T, ITot=of 400 kA for each coil.



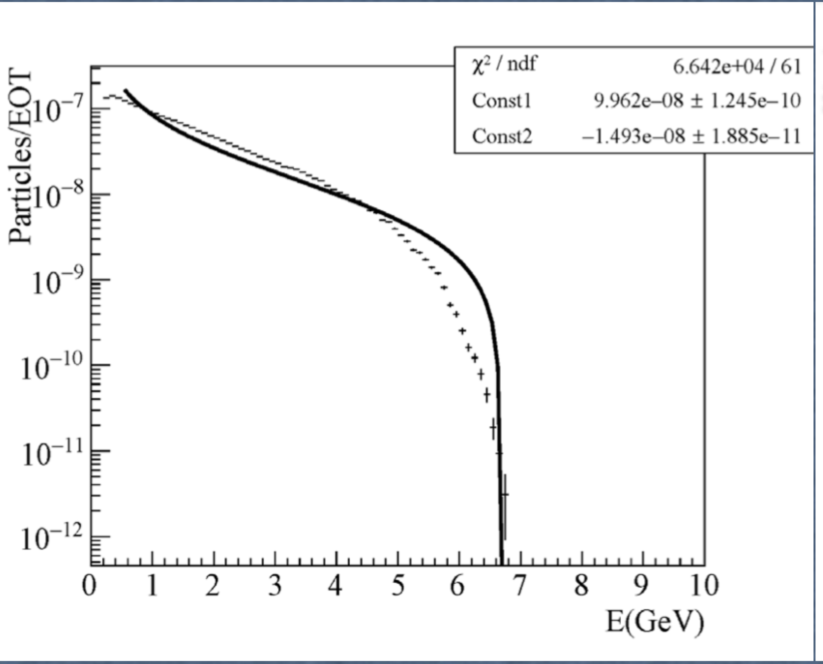
Results:

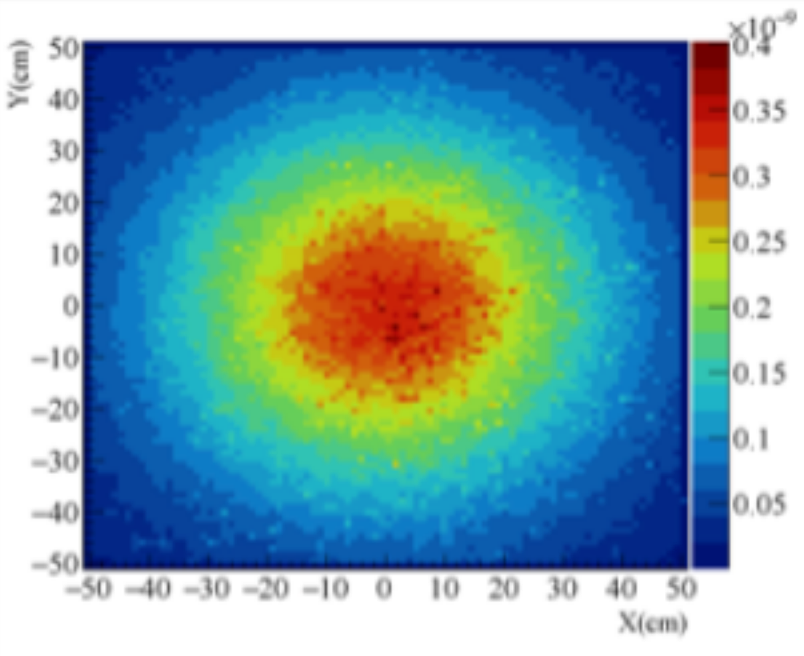
- **Momentum error < 5% for 1 < p_μ < 4 GeV**
- Error increases with momentum:
  - Higher pμ → smaller dipole displacement
  - Arc reconstruction in yz-plane worsens
  - Momentum measurement becomes less precise

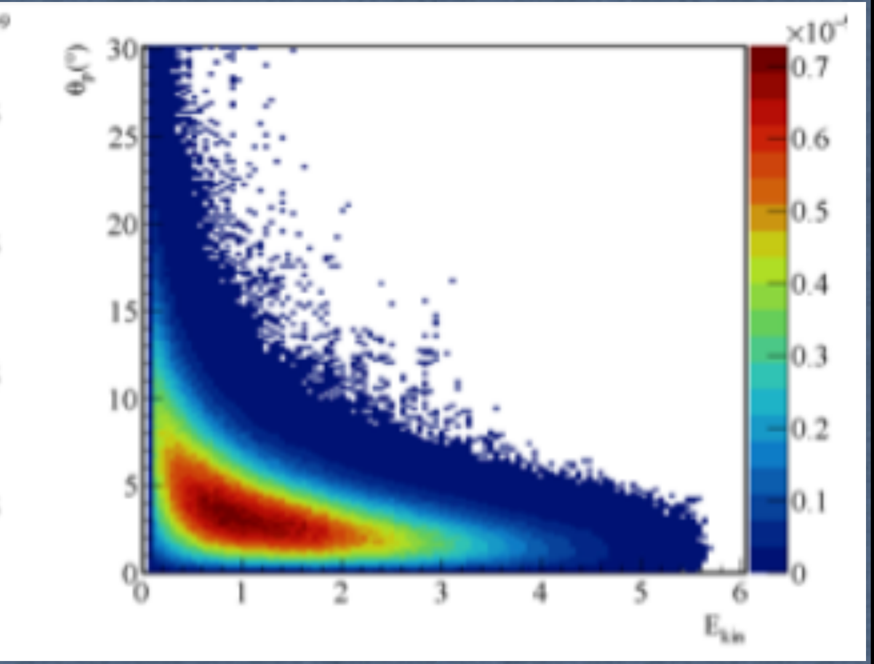
μ^3@KLF measurement would be sensitive to a missing momentum ~5%, down to ~ 50 - 200 MeV/c

- **Final reach of the experiment (upper limits) in progress**

Secondary beams @ JLab (Hall-A BemaDump)

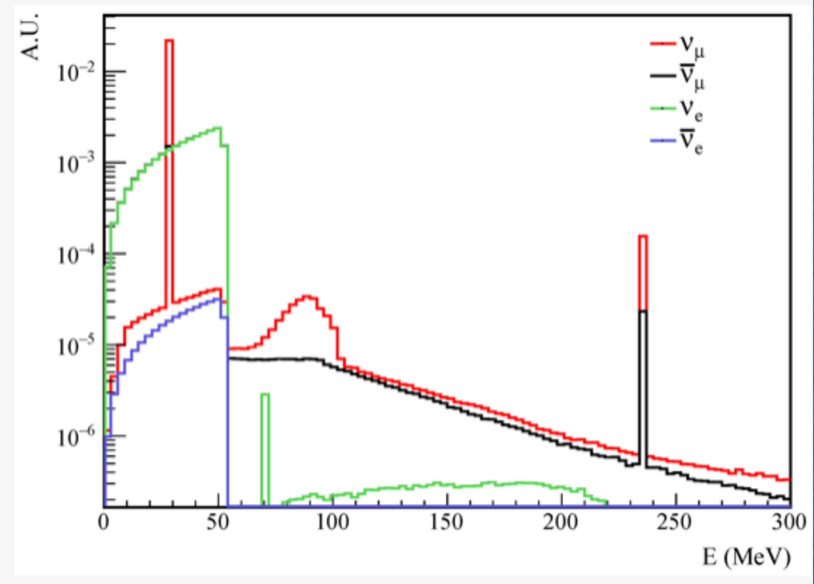






Muon beam

- Flux: 9 10^{-7} μ/EOT (Rate ~ 3 10^{8} μ/s for Ie=50uA)
- Up to 6 GeV, Bremms.-like E spectrum
- 20x20 cm2 beam spot

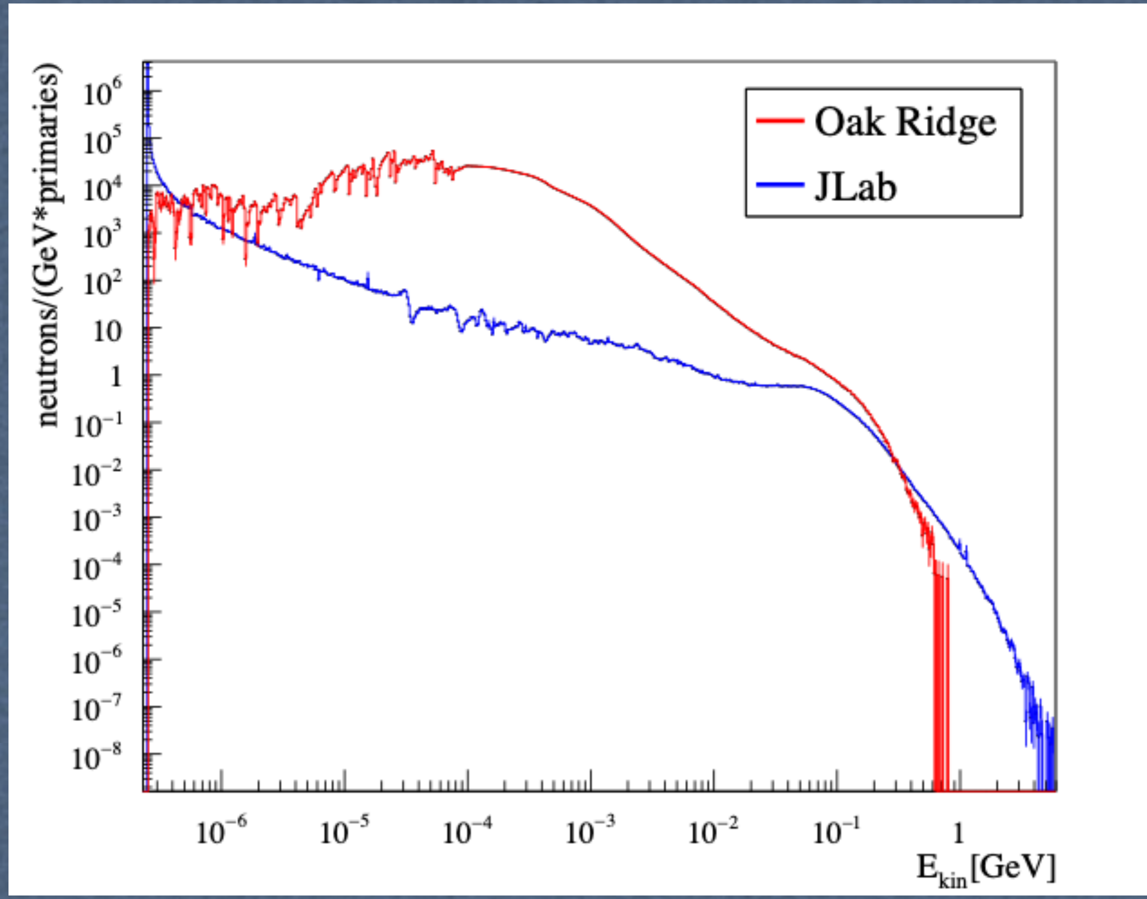


Neutrino beam

- Flux: 3 10^{17} ν/m^2/year (1 year corresponding to 10^{22} EOT)
- Decay-At-Rest energy spectrum (0-50 MeV)

Neutron beam

Energy Range	Jlab (n/s)	Oak Ridge (n/s)	Ratio (J/O)
0 - 6GeV	7.86e+13	1.41e+17	0.001
0.1eV - 100.0eV	0.00e+00	0.00e+00	inf
100.0eV - 100.0keV	2.13e+13	2.17e+16	0.001
100.0keV - 1.0MeV	4.51e+12	8.60e+16	0.000
1.0MeV - 100.0MeV	4.16e+13	3.26e+16	0.001
100.0MeV - 2.0GeV	1.14e+13	3.43e+14	0.033
2.0GeV - 11.0GeV	2.07e+09	0.00e+00	inf



BDX & beyond

Goal

explore opportunities offered by secondary beams at Jefferson Lab to leveraging BDX infrastructures

Format

sharing thoughts and ideas on muon, neutrino, neutron and LDM beams @ JLab

Program

two days of presentations, discussion time, flash talks

(Expected) outcome

to build a new user community e deliver soon after a white paper with results of the brainstorming

Opportunities with secondary beams

- muons (published https://doi.org/10.3390/instruments8010001)
- neutrinos (published https://doi.org/10.3390/instruments8010001)
- neutrons (paper in preparation)

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Physics > Accelerator Physics

[Submitted on 6 Oct 2025]

A Beamdump Facility at Jefferson Lab

Patrick Achenbach, Andrei Afanasev, Pawel Ambrozewicz, Adi Ashkenazi, Dipanwita Banerjee, Marco Battaglieri, Jay Benesch, Mariangela Bondi, Paul Brindza, Alexandre Camsonne, Eric M. Christy, Ethan W. Cline, Chris Cuevas, Jens Dilling, Luca Doria, Stuart Fegan, Marco Filippini, Antonino Fulci, Simona Giovannella, Stefano Grazzi, Heather Jackson, Douglas Higinbotham, Cynthia Keppel, Vladimir Khachatryan, Michael Kohl, Hanjie Liu, Zhen Liu, Camillo Mariani, Ralph Marinaro, Kevin McFarland, Claudio Montanari, Vishvas Pandey, Eduard Pozdeyev, Jianwei Qiu, Patrizia Rossi, Riccardo Rossini, Todd Satogata, Glenn Schrader, Adrian Signer, Daniel Sn[illegible], Marco Spreafico, Diktys Stratakis, Manjukrishna Suresh, Holly Szumila, Julia [illegible] Vidal, Davide Terzania, Charlie Velasquez, Michael Wood, Takay[illegible]zaki, Yuhong Zhang

This White Paper is exploring the potential of inte[illegible] muon, neutrino, and (hypothetical) light dark matter beams produced [illegible] of high-intensity electron beams with beam dumps. Light dark m[illegible] with the approved Beam Dump eXperiment (BDX) are driving the [illegible] new underground vault at Jefferson Lab that could be extended to a Be[illegible] Facility with minimal additional installations. The paper summarizes [illegible] discussions from the International Workshop on Secondary Beams at J[illegible]rson Lab (BDX & Beyond). Several possible muon physics applications and neutr[illegible]o detector technologies for Jefferson Lab are highlighted. The potential of a secondary neutron beam will be addressed in a future edition.

Comments: 34 pages, 16 figures, refers to: International Workshop on Secondary Beams at Jefferson Lab (BDX & Beyond)
Subjects: Accelerator Physics (physics.acc-ph); High Energy Physics - Experiment (hep-ex); Nuclear Experiment (nucl-ex)
Report number: JLAB-PHY-25-4560, DOE/OR/23177-8015
Cite as: arXiv:2510.09652 [physics.acc-ph]
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Conclusions

✳ Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass

✳ Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)

✳ Jefferson Lab is the world-leader facility for present and near-future LDM searches: APEX, HPS, DarkLight, BDX (and possibly e+ annihilation and LDMX)

✳ Significant interests from funding agencies (DOE/NSF) and labs (CERN and JLab) to run small scale experiments with a great discovery potential

✳ With a modest investment it would be possible to deploy a unique experiment using an opportunistic μ-beam at KLF

✳ A μ^3@KLF experiment will be competitive with state-of-the art experiments (e.g. μNA64 @ CERN)

✳ Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!